High Energy Physics at Low Q^2

-

Using COMPASS to search for Exotics Structures and Dynamics

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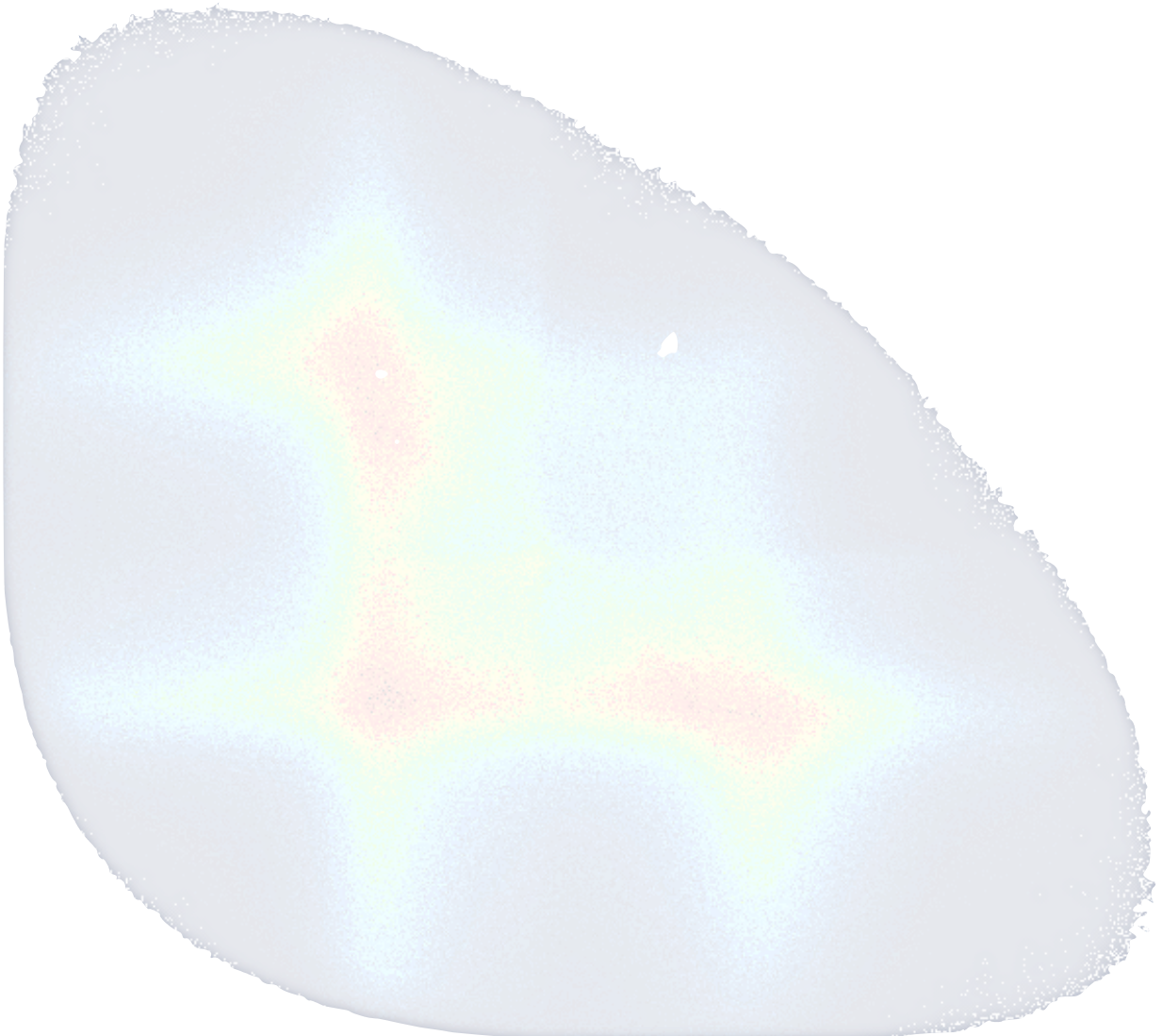
bmb+f - Förderschwerpunkt
COMPASS
Großgeräte der physikalischen Grundlagenforschung

Overview



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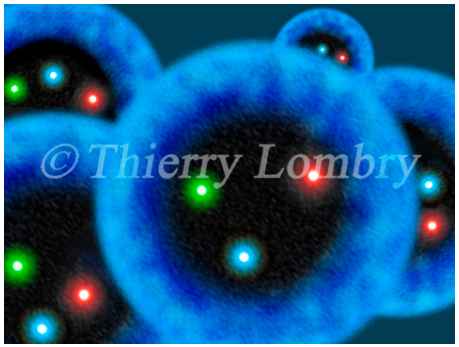
  - Structure of matter and hadrons
  - The spectrum of mesons
  - Exotic structures



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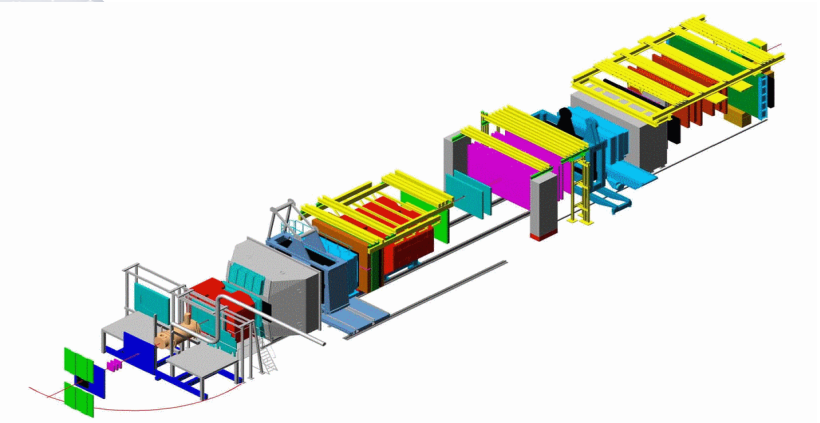
  - The COMPASS Experiment



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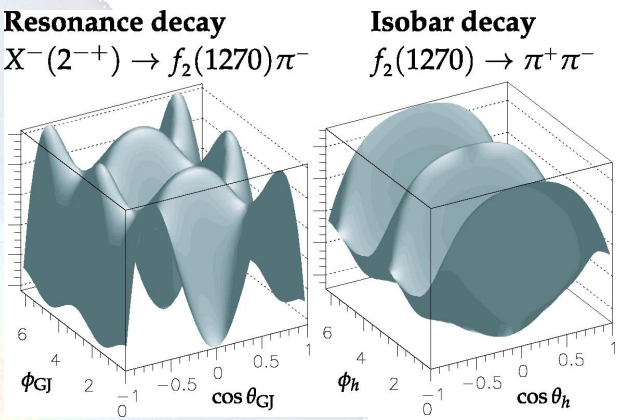

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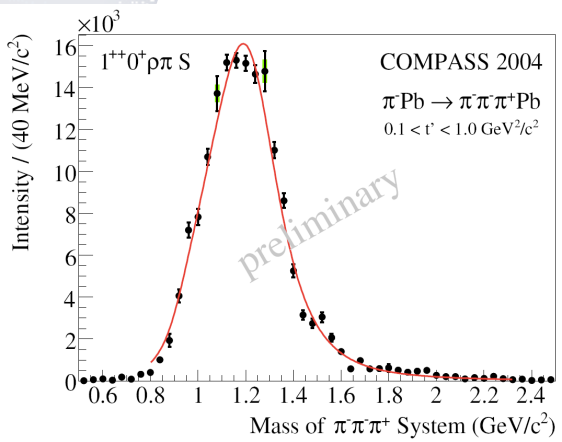

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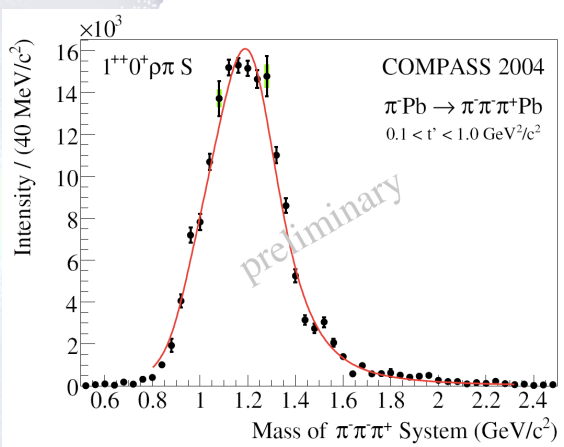

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- Ongoing work
  - Mesons und Baryons

Constituent Quark Model Mesons

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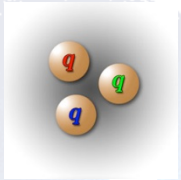
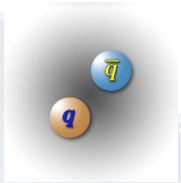
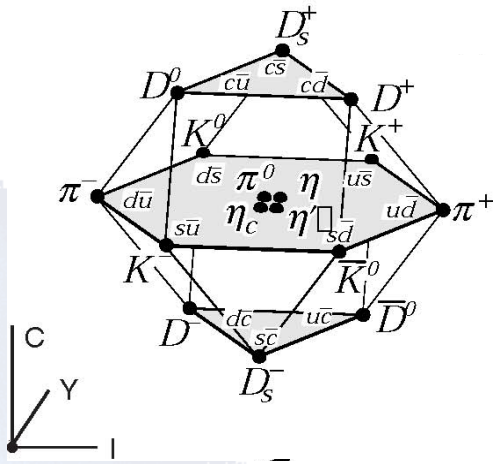
Hadrons: colour neutral system of quarks

- Baryon (qqq)
- Meson ($q\bar{q}$)







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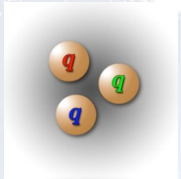

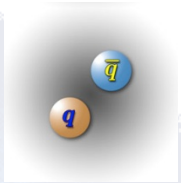

Spin-Parity selection rules for bound $q\bar{q}'$ system

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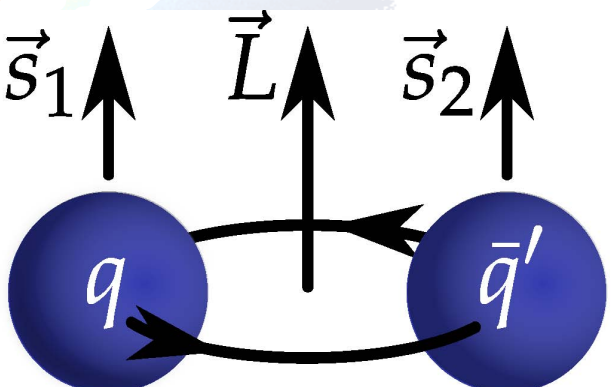

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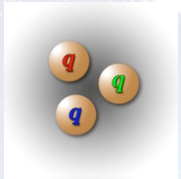

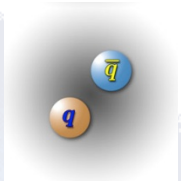

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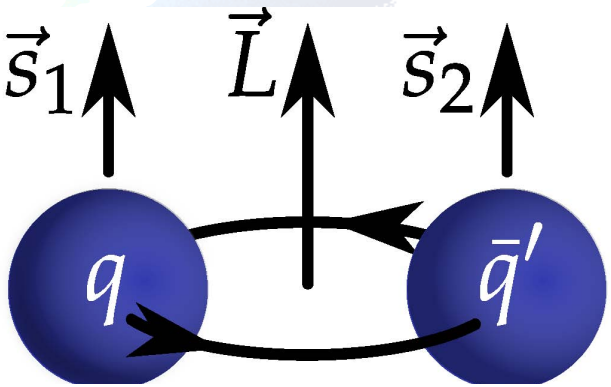

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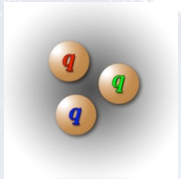

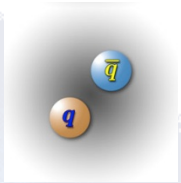

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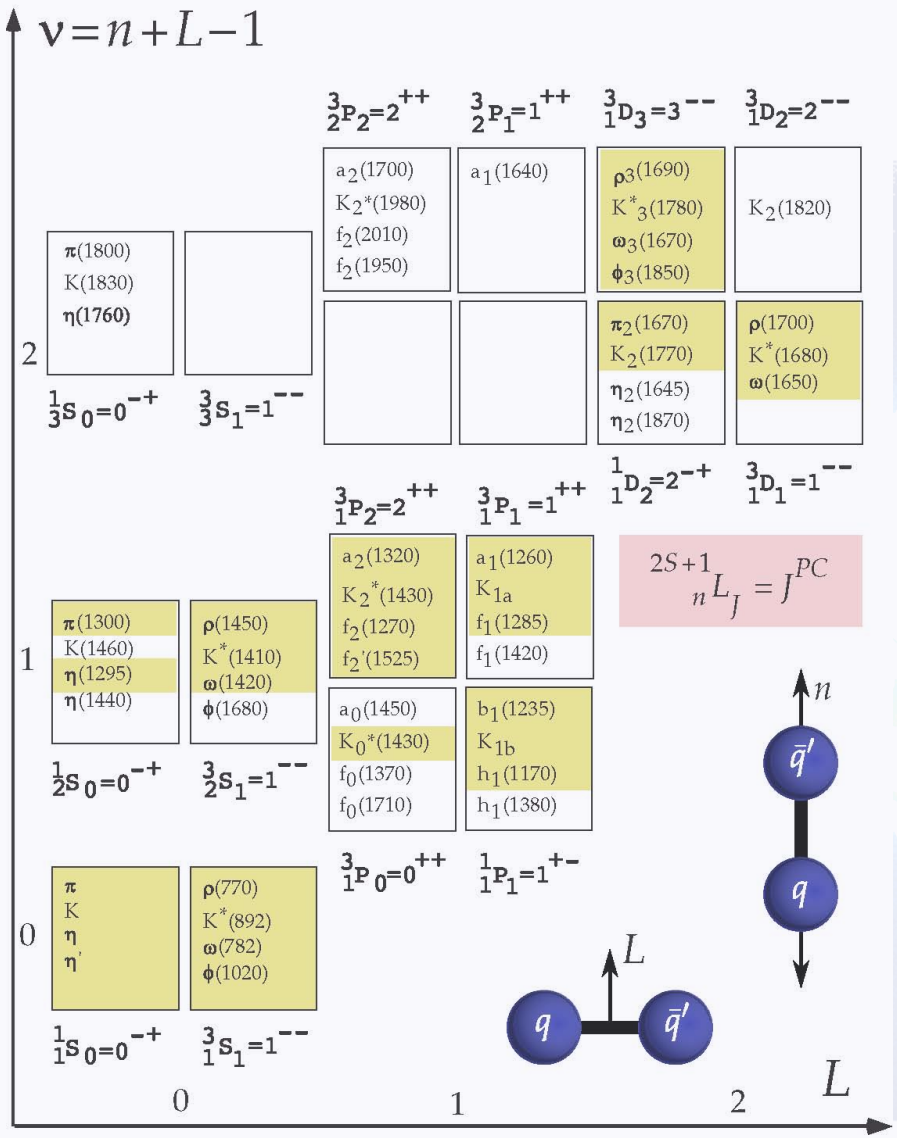
- Parity: $P = (-1)^{L+1}$
- Charge conjugation: $C = (-1)^{L+S}$
- G-parity: $G = C \cdot e^{i\pi I_z} = (-1)^{I+L+S}$

Constituent Quark Model II

- Allowed J^{PC} combinations:
  - $L = 0$ → pseudo-scalar 0^{-+}, Vector 1^{--}
  - $L = 1$ → scalar 0^{++}, axial-vector 1^{+-}, 1^{++} and tensor 2^{++}
- Forbidden J^{PC} combinations: 0^{--} , 0^{+-} , 1^{-+} , 2^{+-} , 3^{+-} .....
- Same quantum numbers mix

Constituent Quark Model III



C. Amsler *et al.*, Phys. Rept. 389, 61 (2004)

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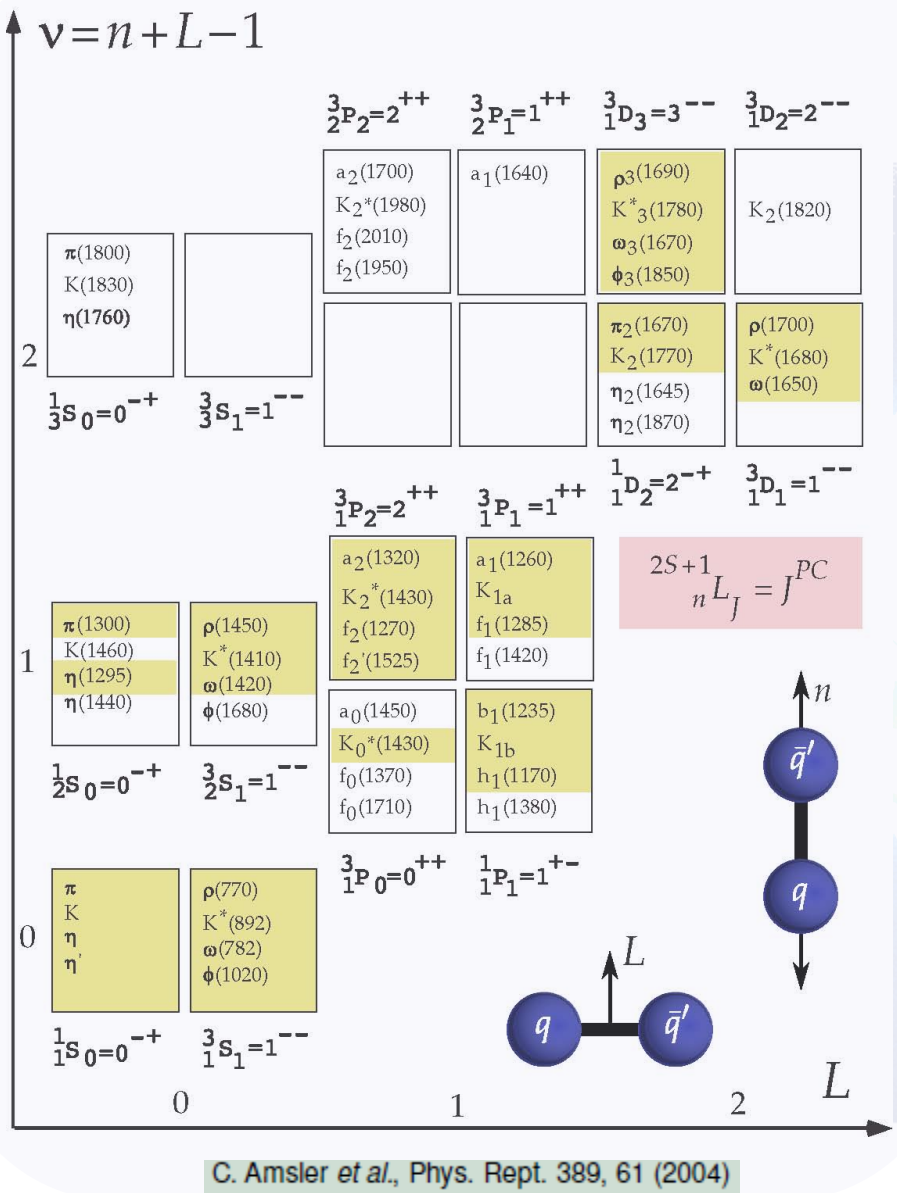

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  m ~ 2 GeV/c^2

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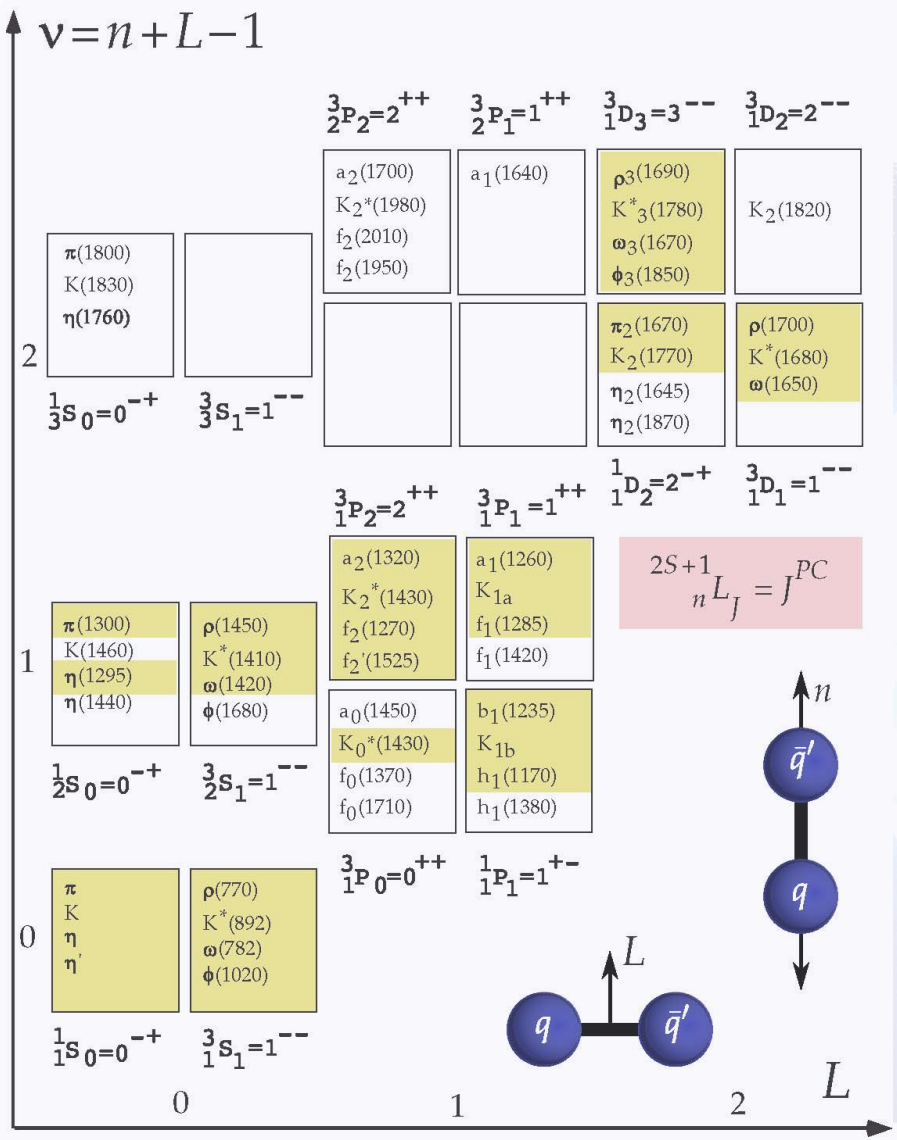

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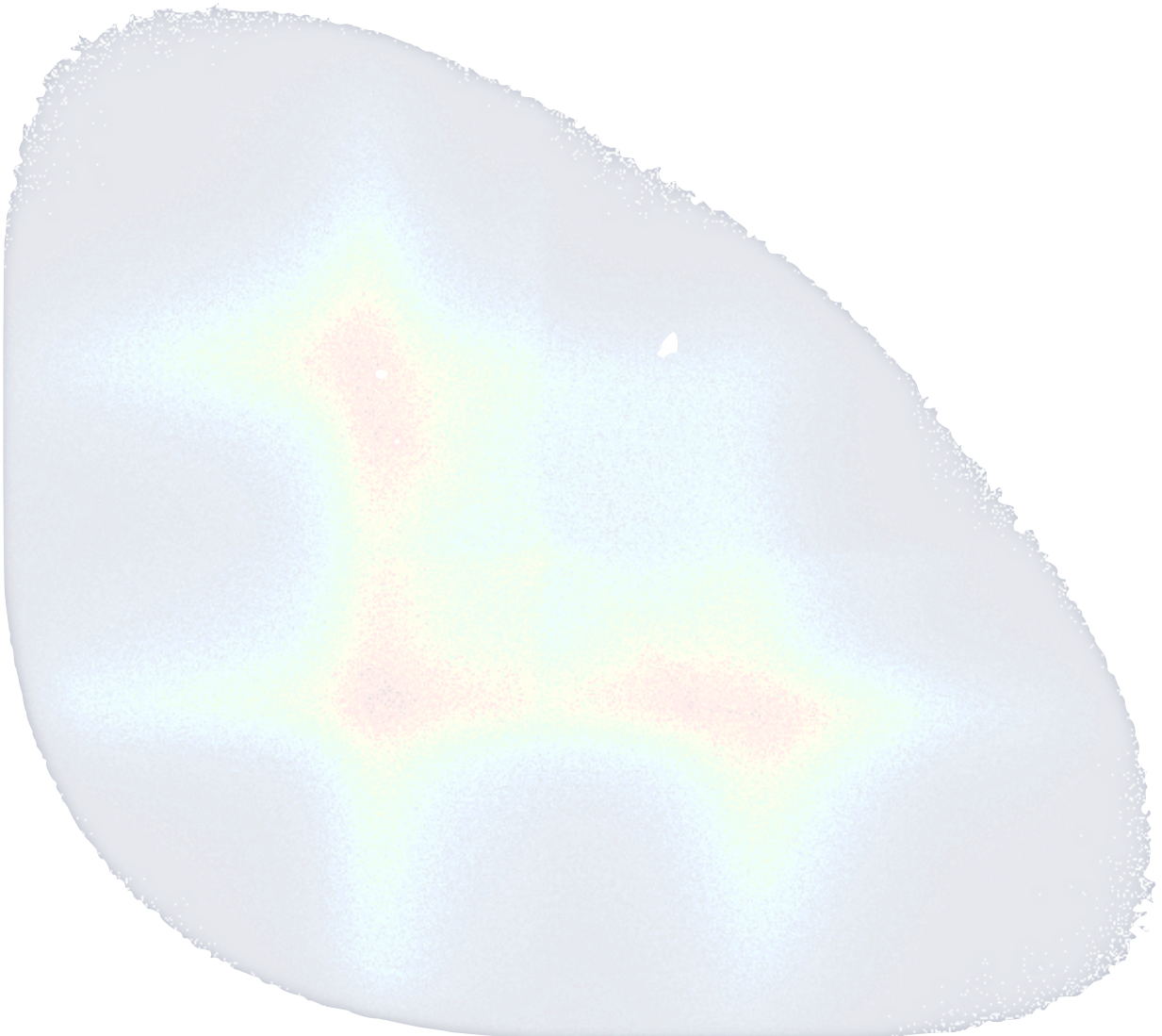
Boundary of light mesons:

- Many missing/disputed States in mass region

  $m \sim 2\ GeV/c^2$

- Identification heavier states difficult
  - Broad states
  - Large number of states

Extension of Model



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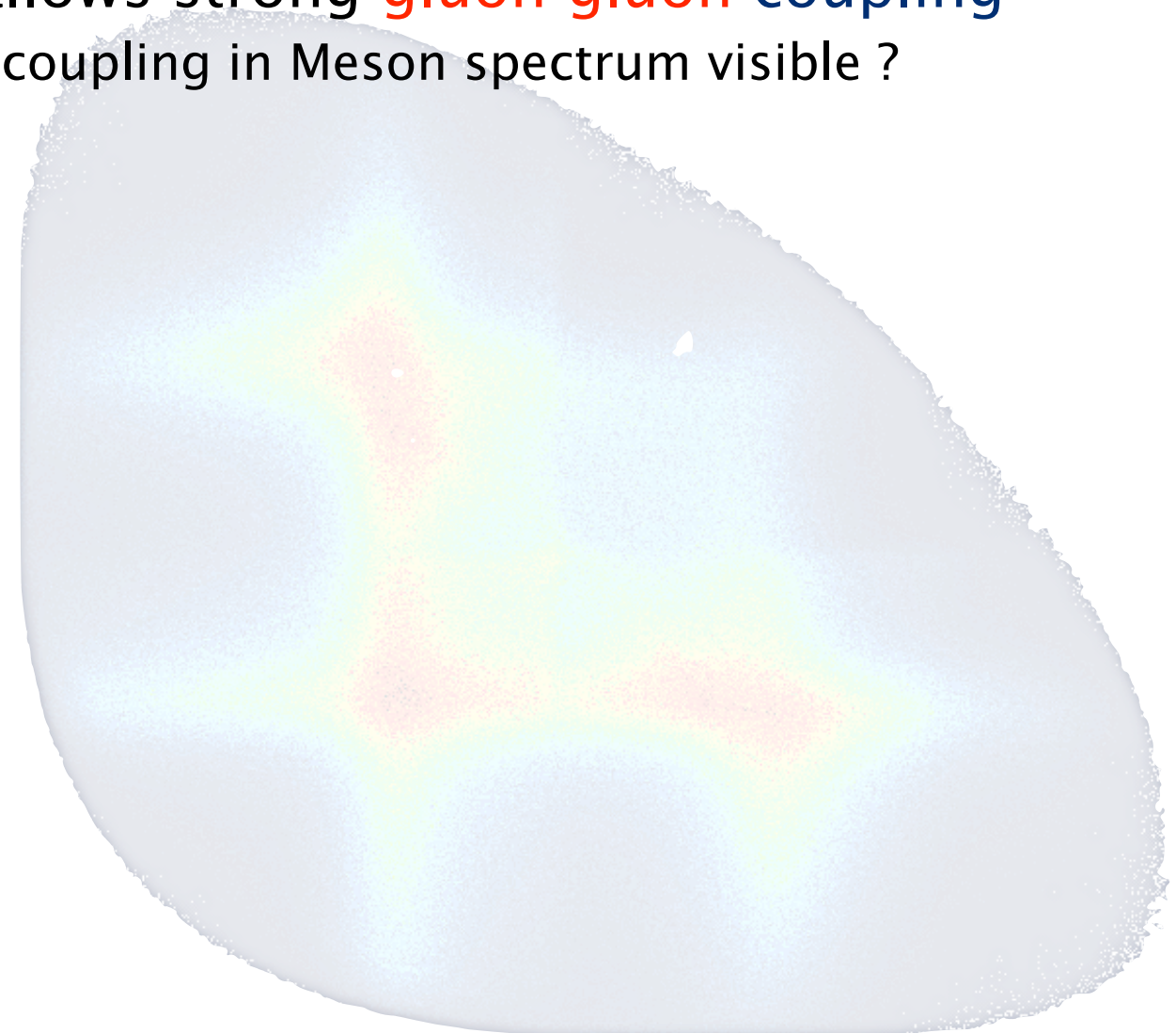

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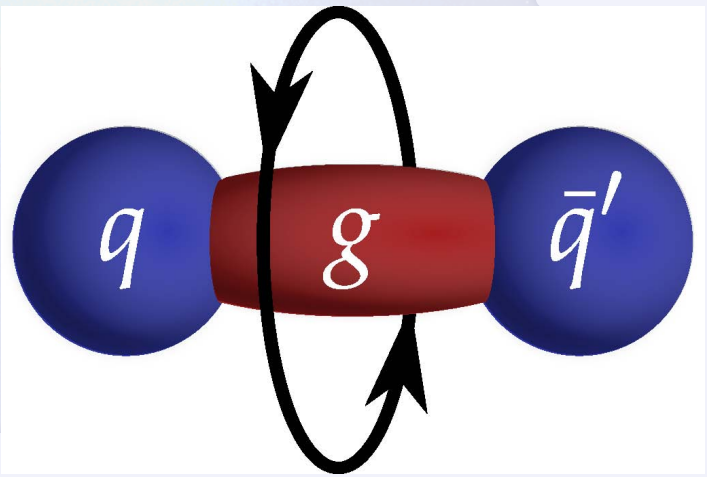

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  - Description of gluon excitation is model dependent
  - E.g. flux-tube Model:
    - „Flux-tube“: Gluon field between static colour charges
    - Transversal excitation: angular momentum of flux-tube couples with (L,S) of mesons to J
    - Different from $|q\bar{q}'>$ no restrictions to J^{PC}
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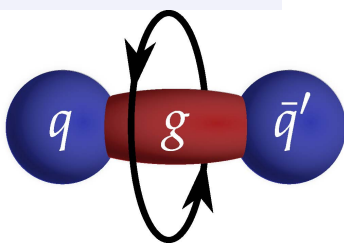

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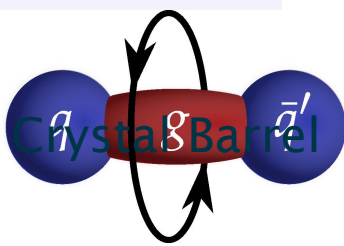

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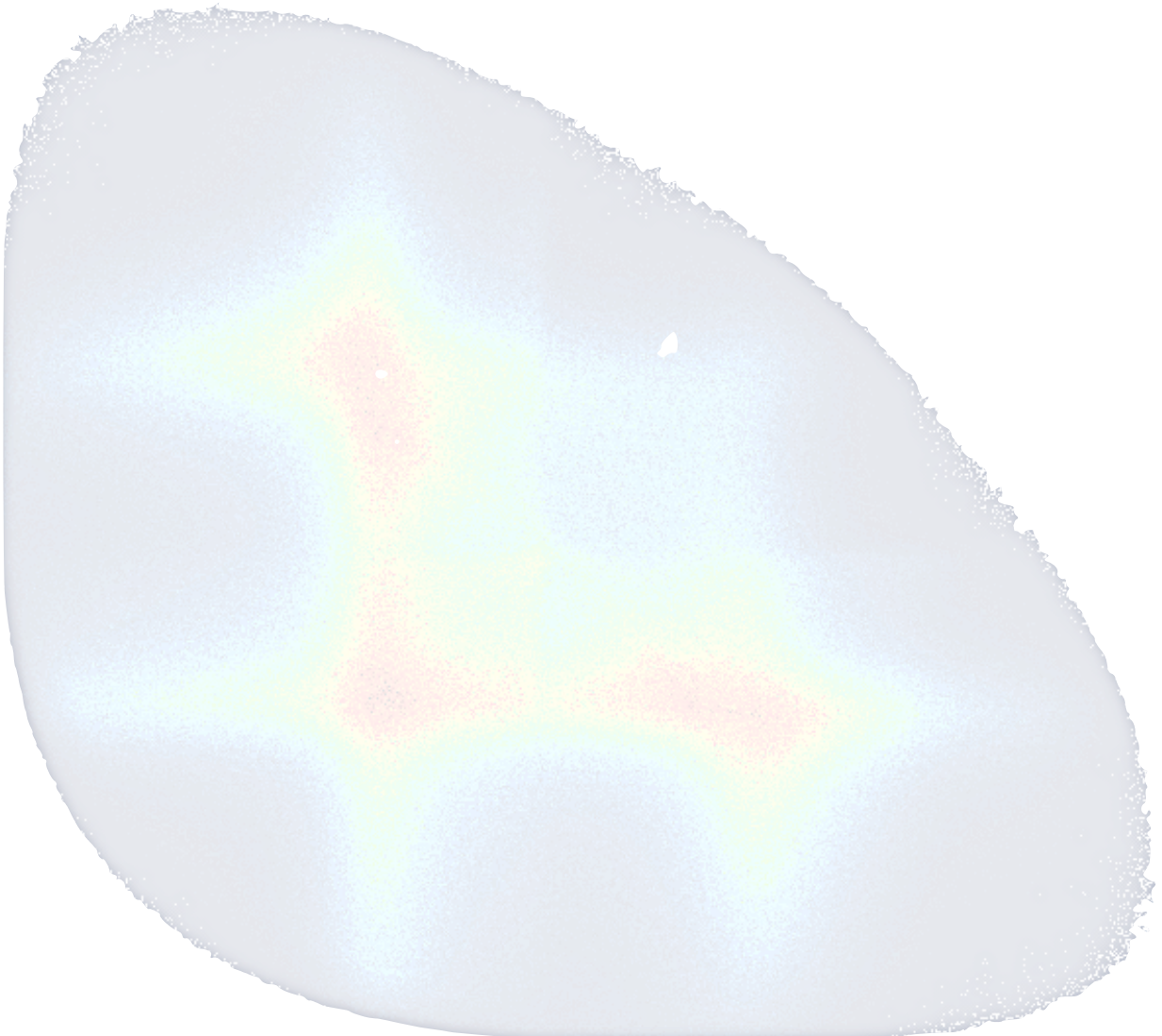

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Glueballs

- Bound system from gluons (without valence quarks)
  - ‚Ground state' expected as 0^{++}
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  - Identification via decay
    - No inherent flavour → flavour-democratic decay (KK, $\pi\pi$)
    - Observe characteristic final states (e.g. η')
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Predictions Lattice QCD

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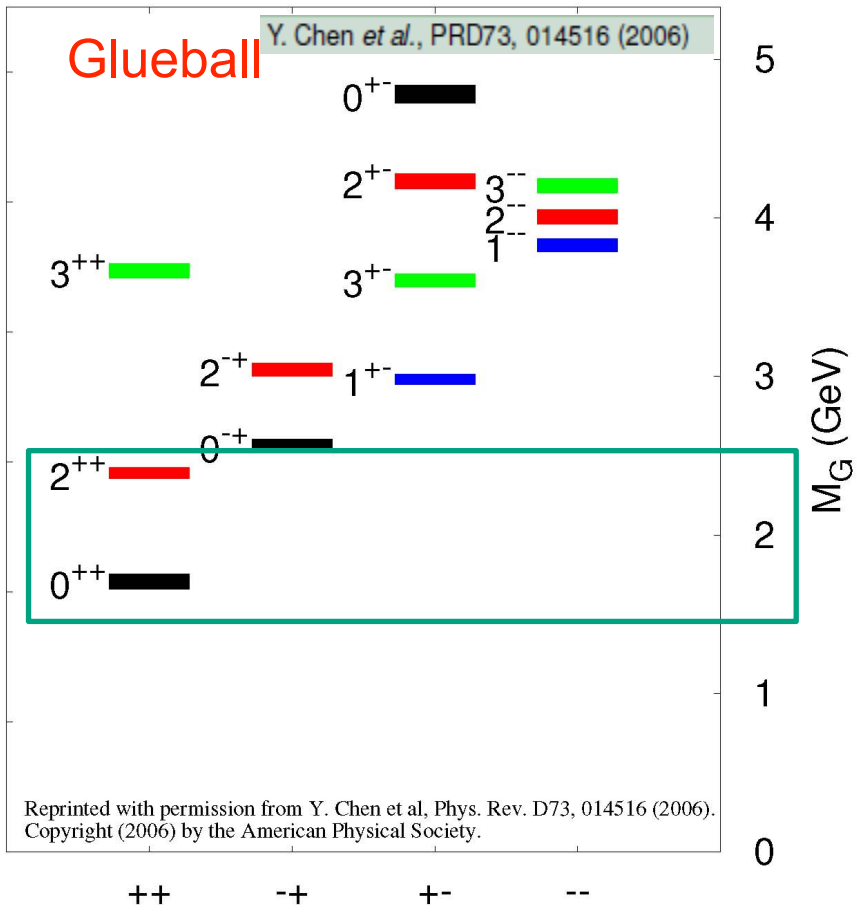
Quenched L-QCD prediction



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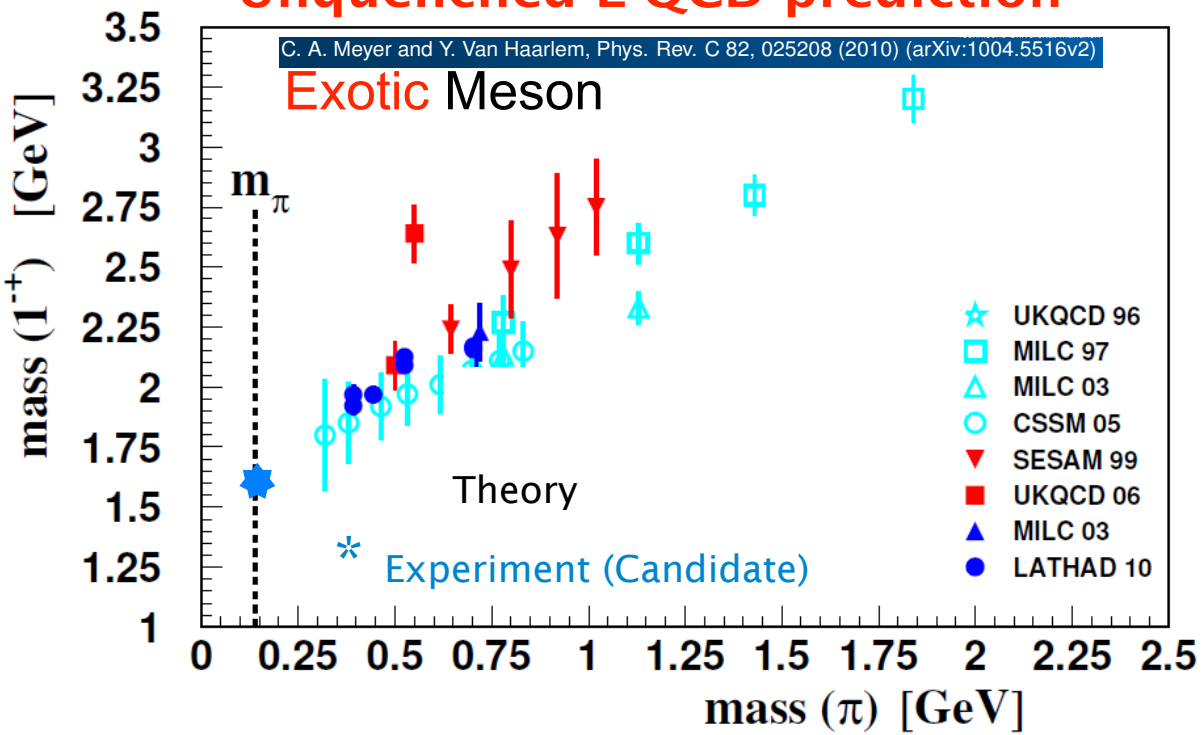

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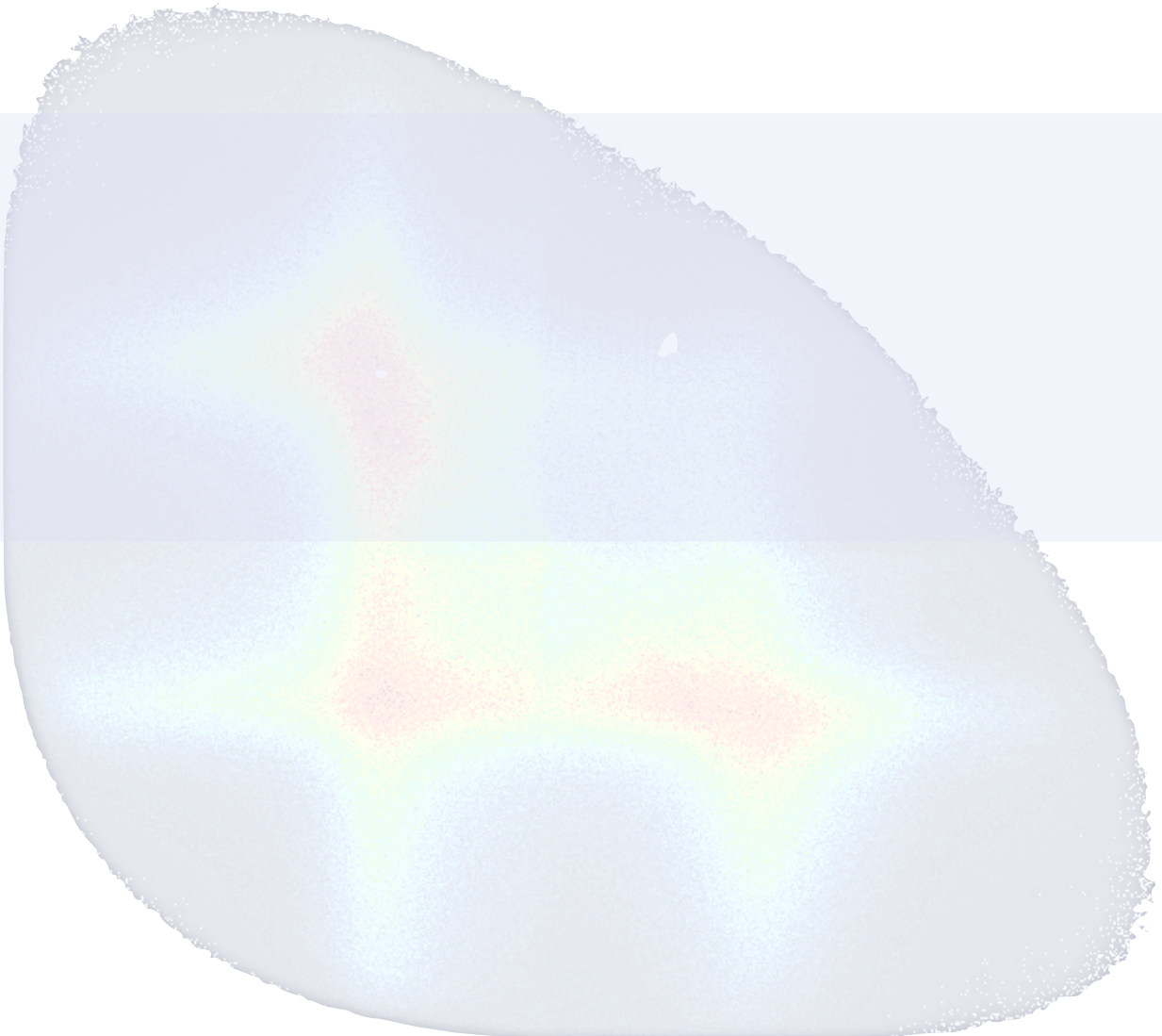

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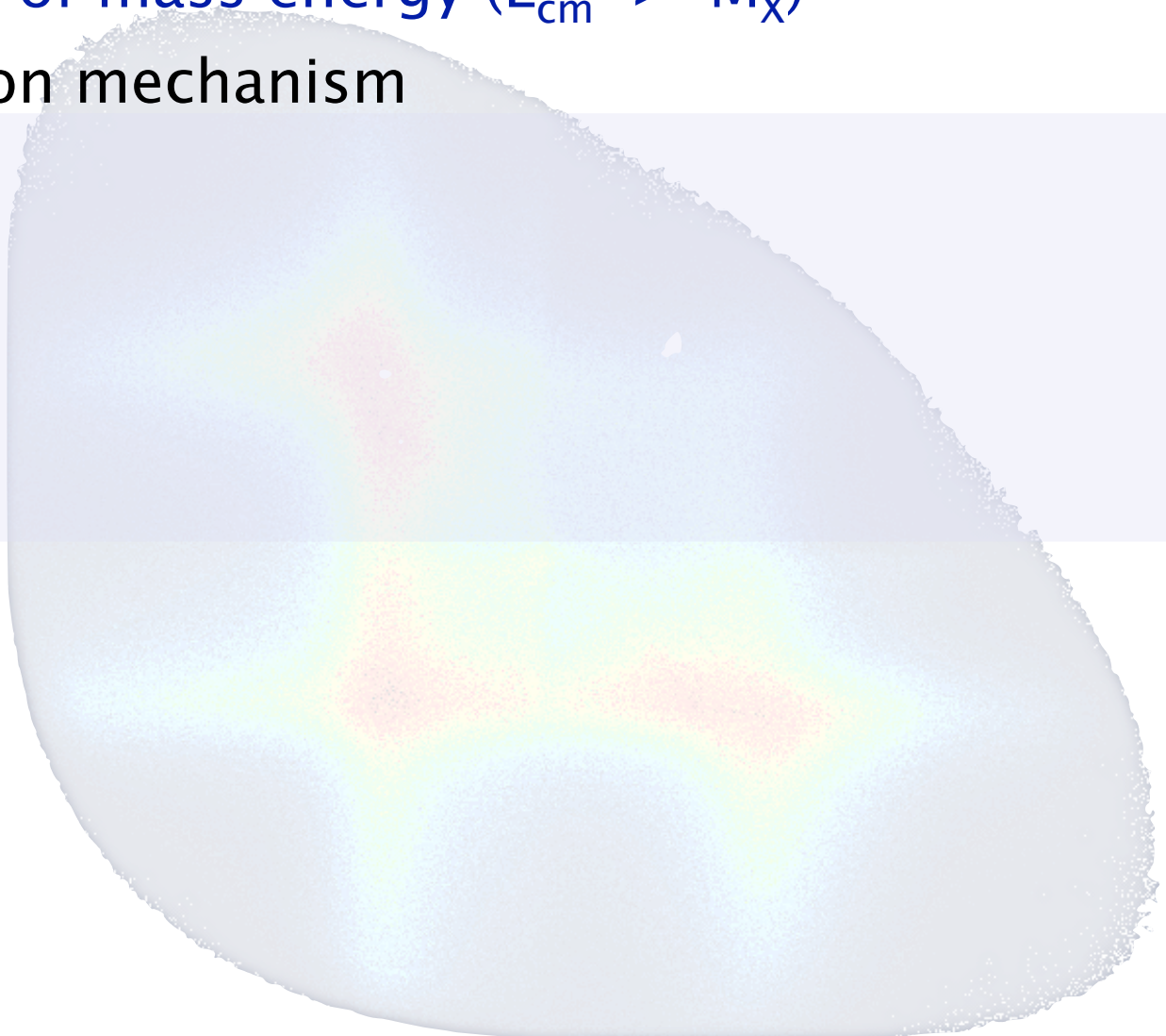

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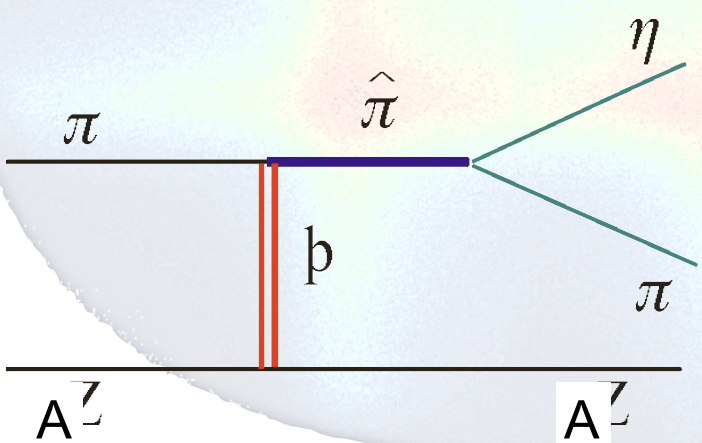

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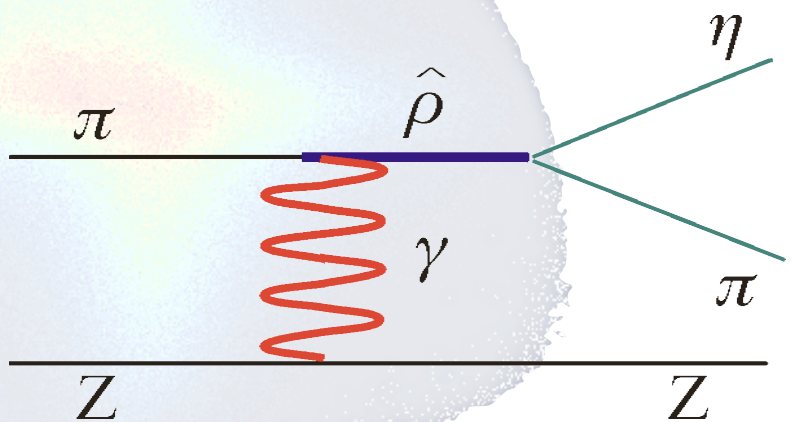

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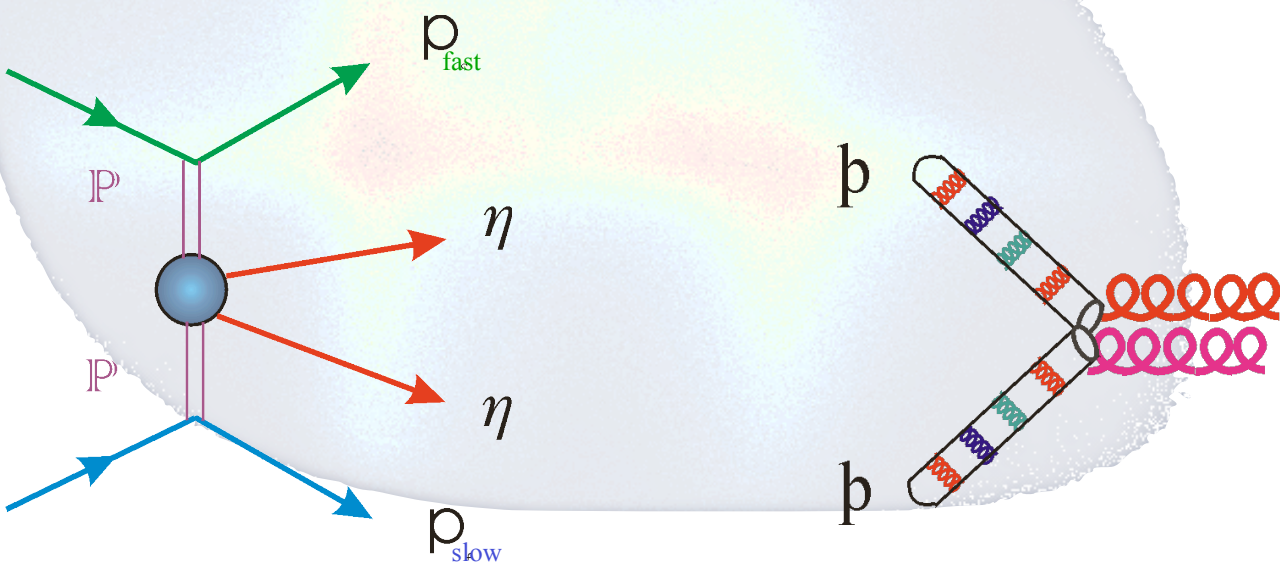

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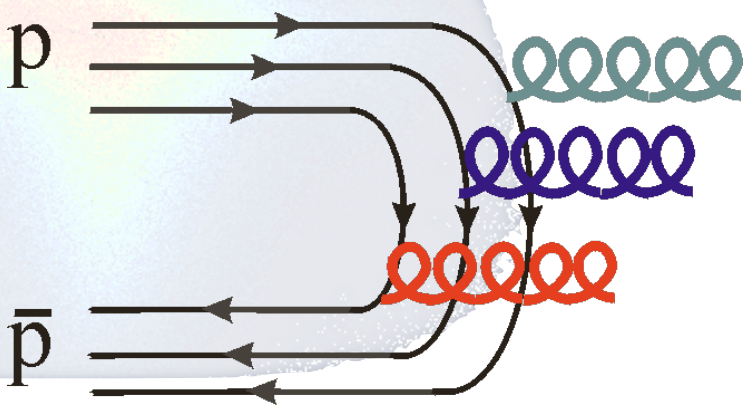

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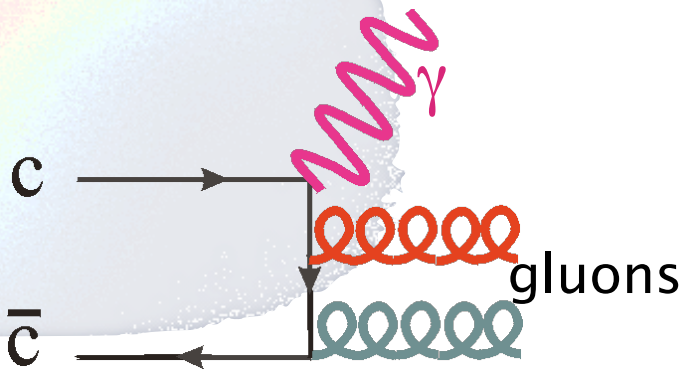
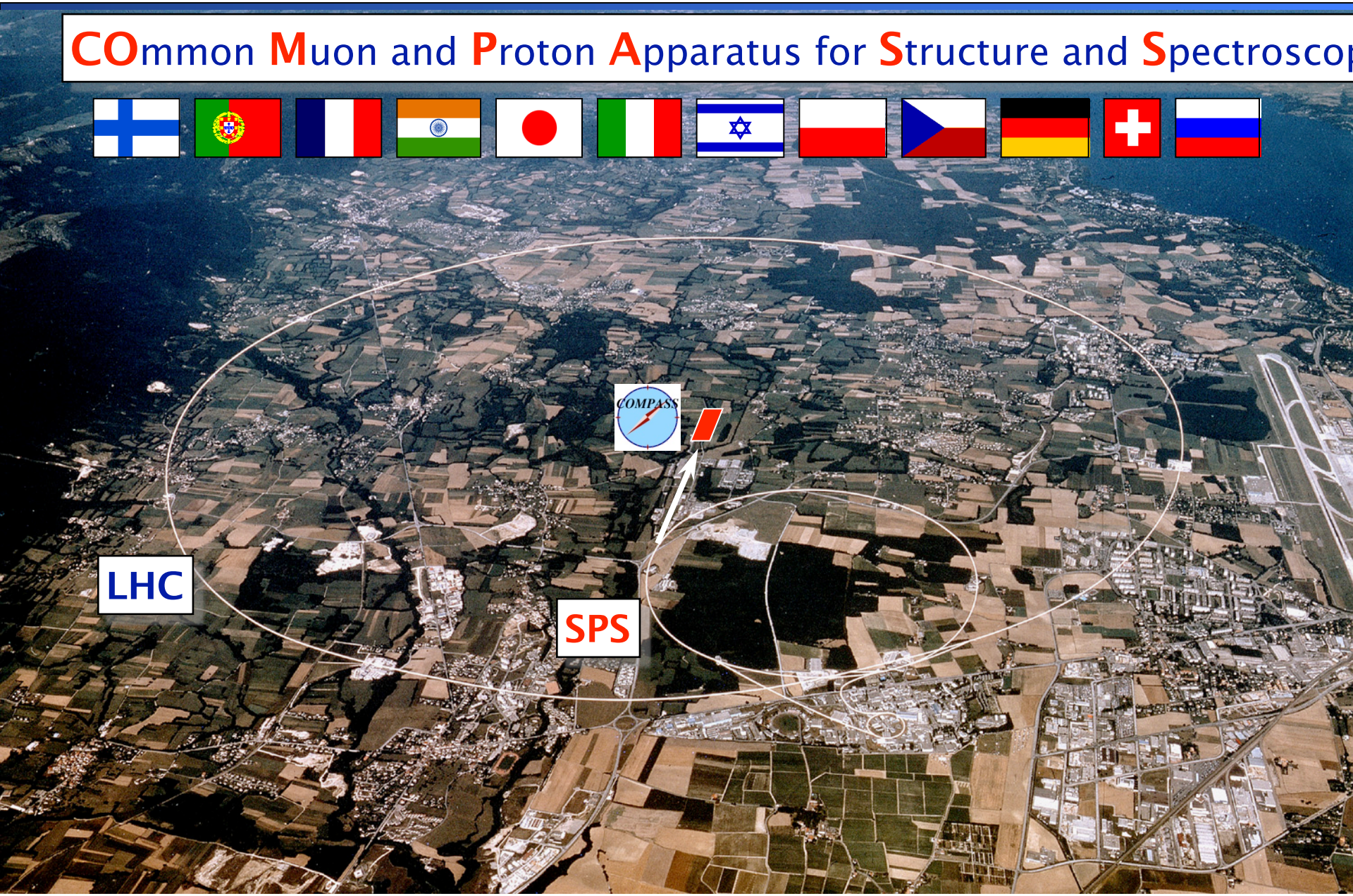
  - Decays of heavy mesons (e.g. J/Ψ)
    - Gluon rich final state

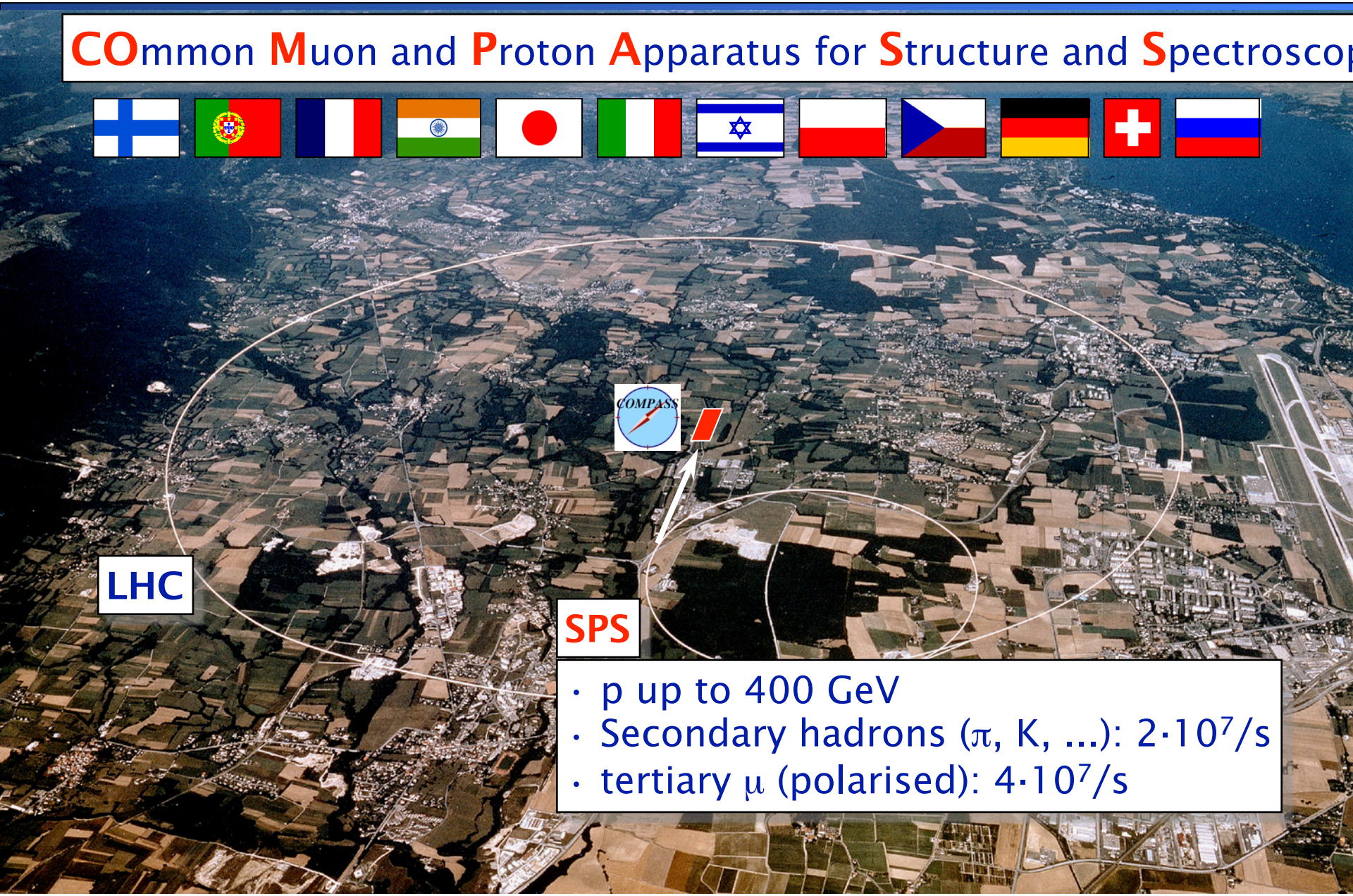


COMPASS at CERN



COMPASS at CERN

COmmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectrosco

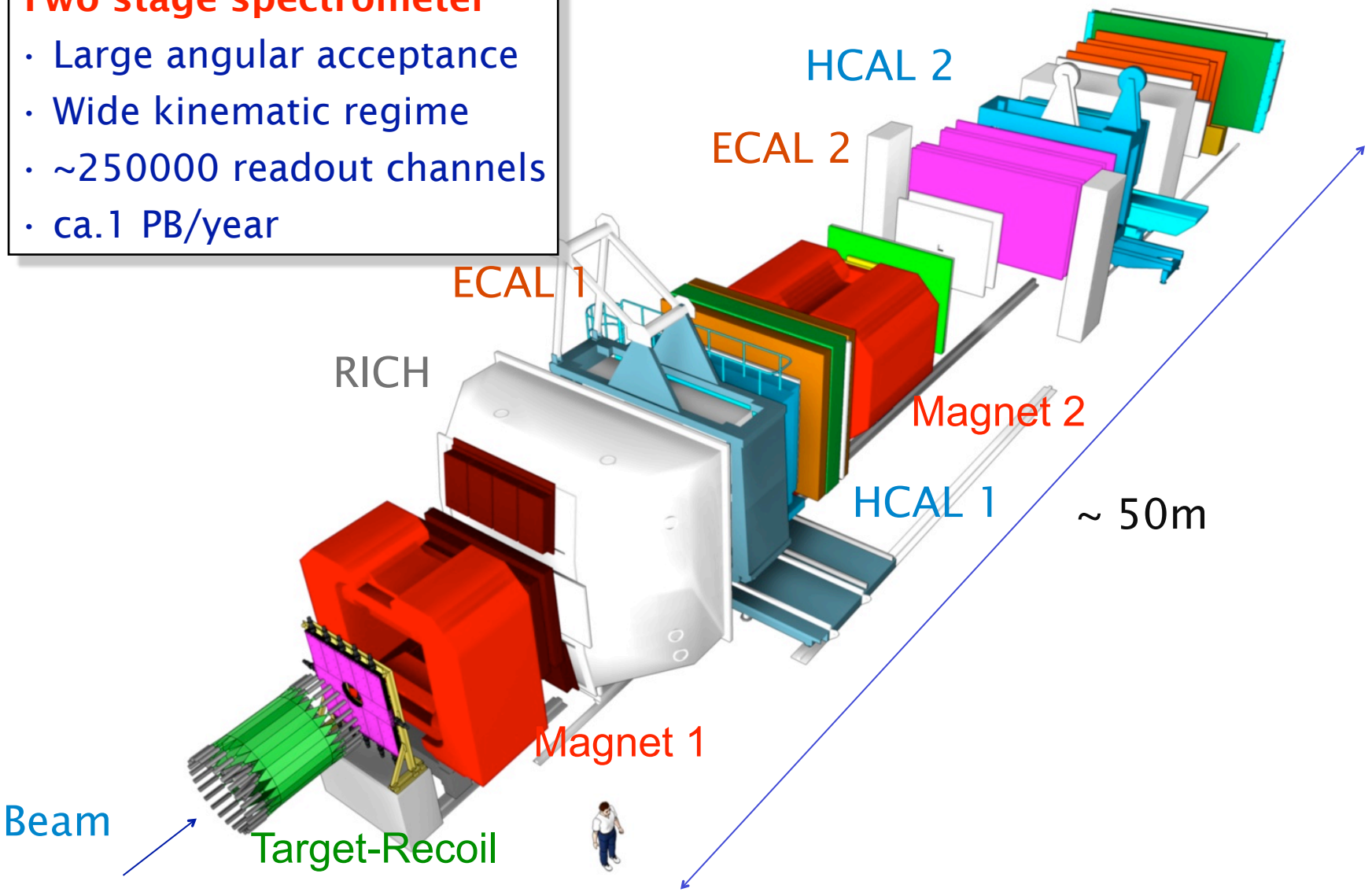


- p up to 400 GeV
- Secondary hadrons (π, K, ...): $2 \cdot 10^7$/s
- tertiary μ (polarised): $4 \cdot 10^7$/s

Spectrometer - 2008

Two stage spectrometer

- Large angular acceptance
- Wide kinematic regime
- ~250000 readout channels
- ca.1 PB/year



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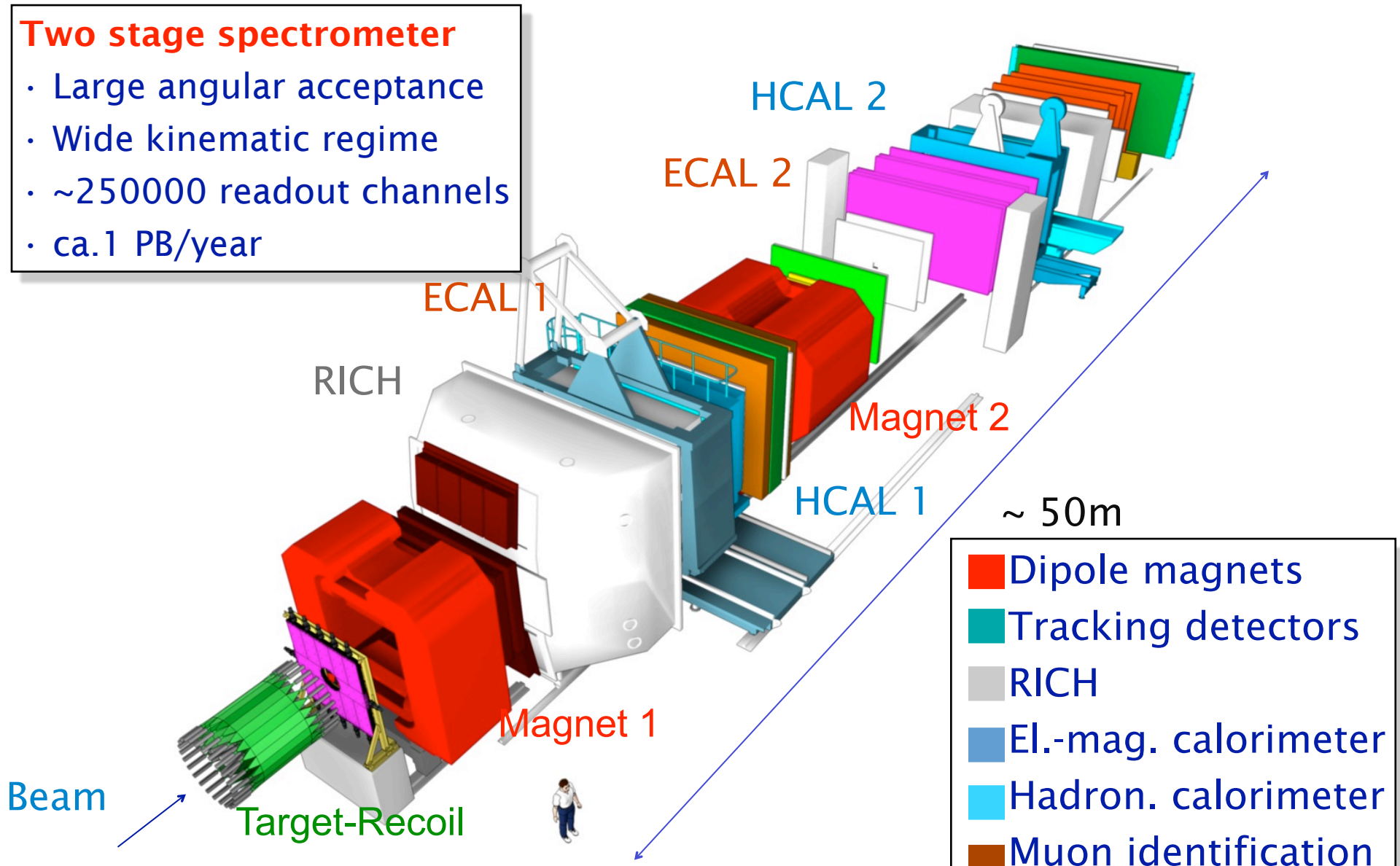
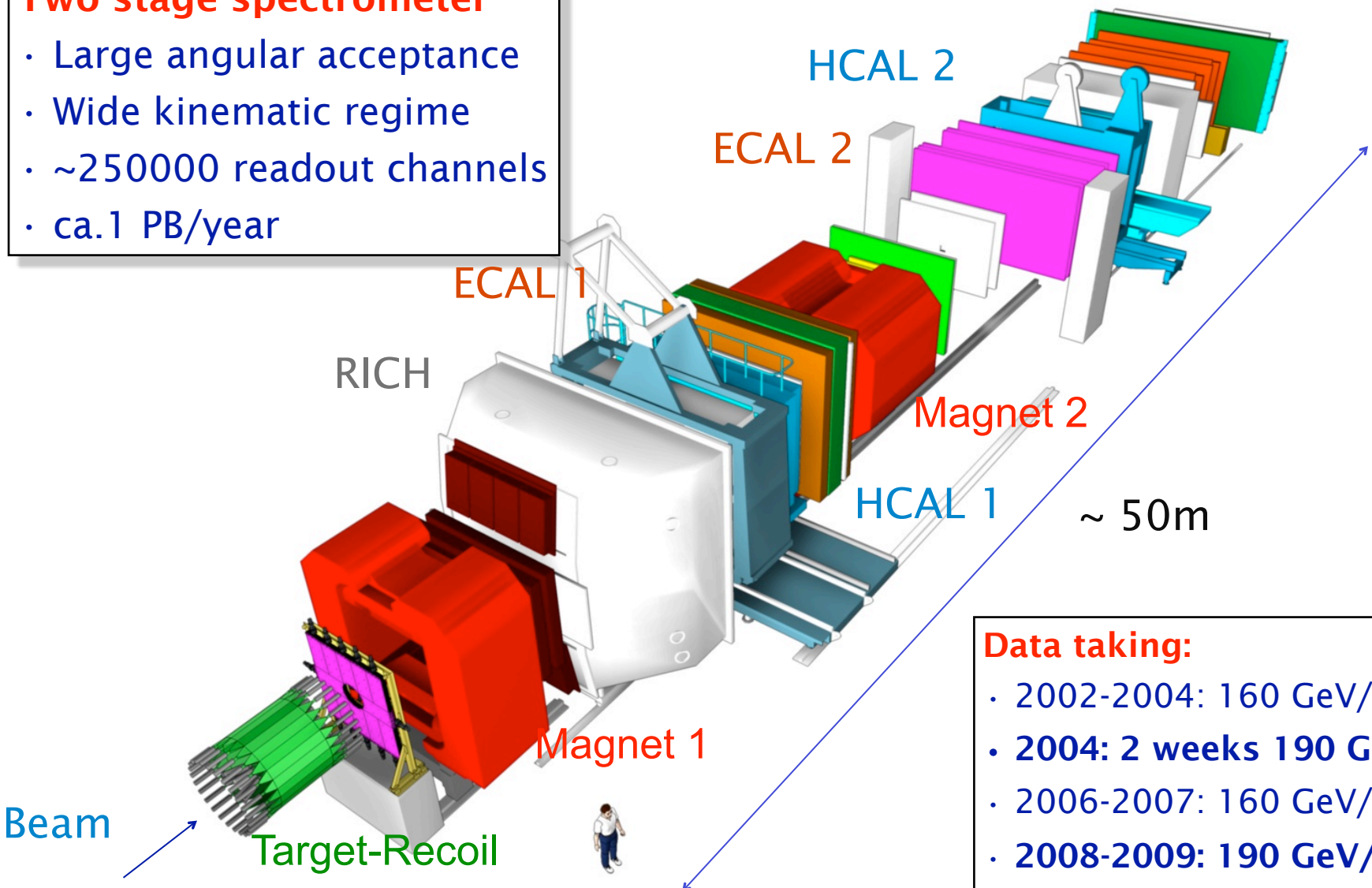


Spectrometer - 2008

Two stage spectrometer

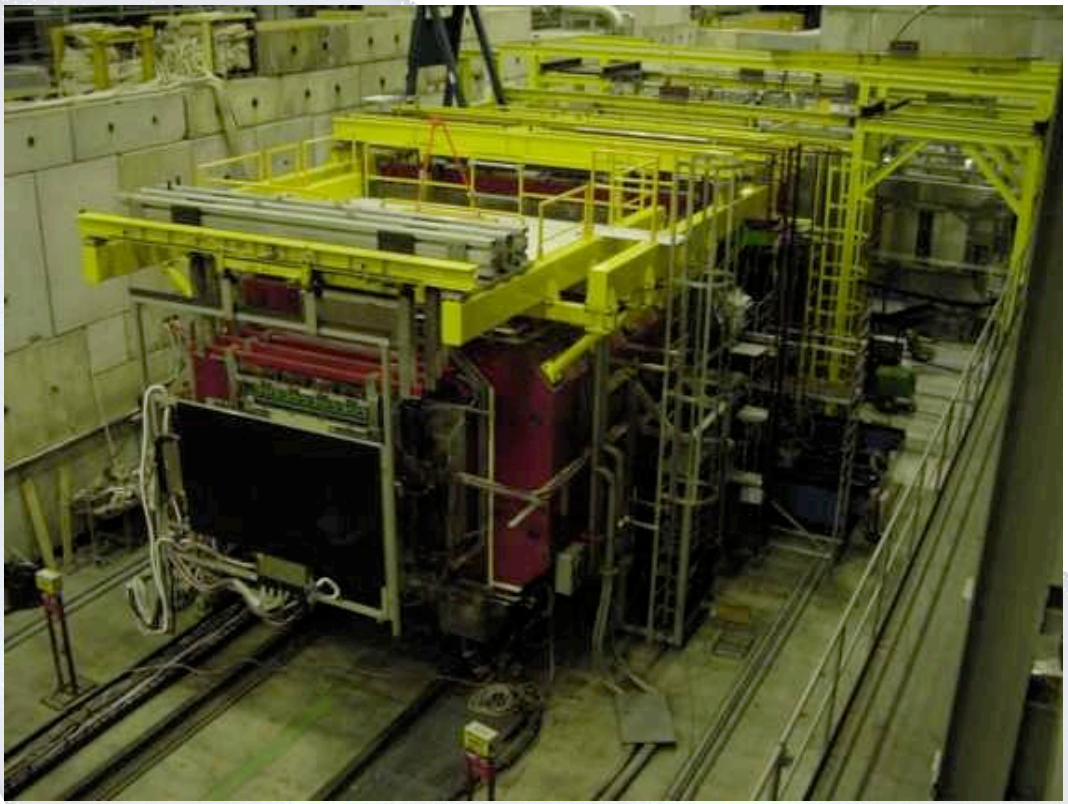
- Large angular acceptance
- Wide kinematic regime
- ~250000 readout channels
- ca.1 PB/year



Data taking:

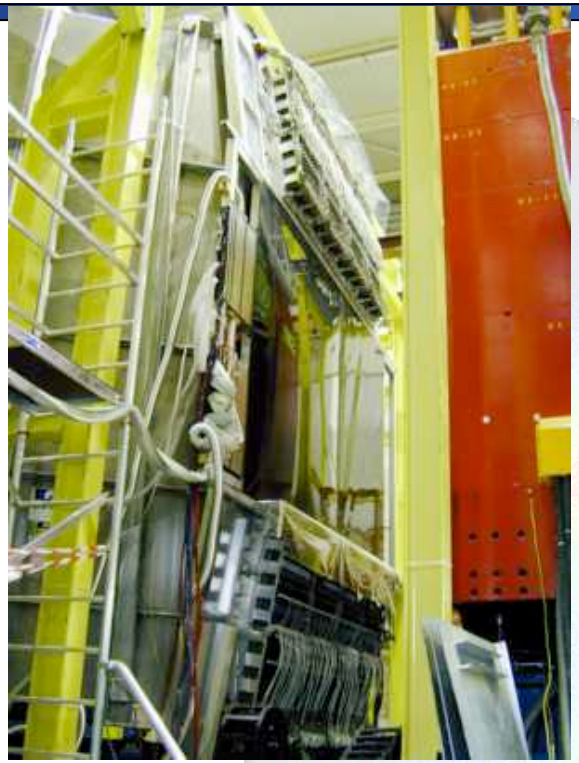
- 2002-2004: 160 GeV/c μ^+
- **2004: 2 weeks 190 GeV/c π^-**
- 2006-2007: 160 GeV/c μ^+
- **2008-2009: 190 GeV/c p,π^-**
- 2010-2011: 160 GeV/c μ^+

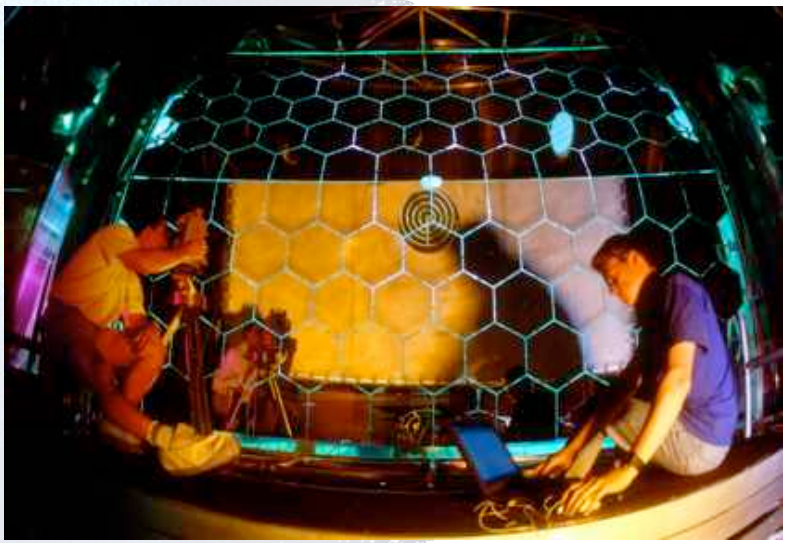
Impressions



Impressions

RICH

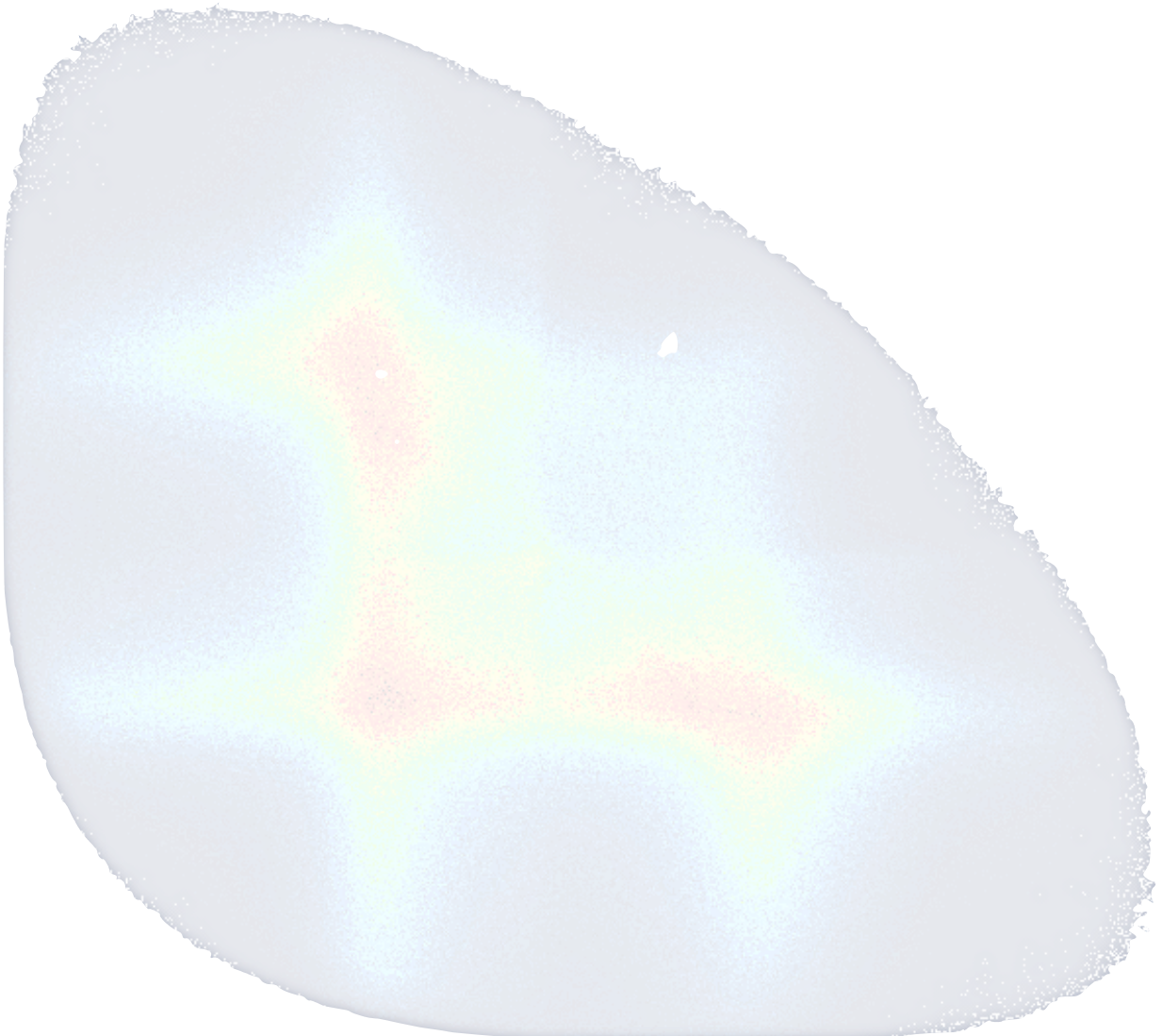




Impressions

Heavy Equipment

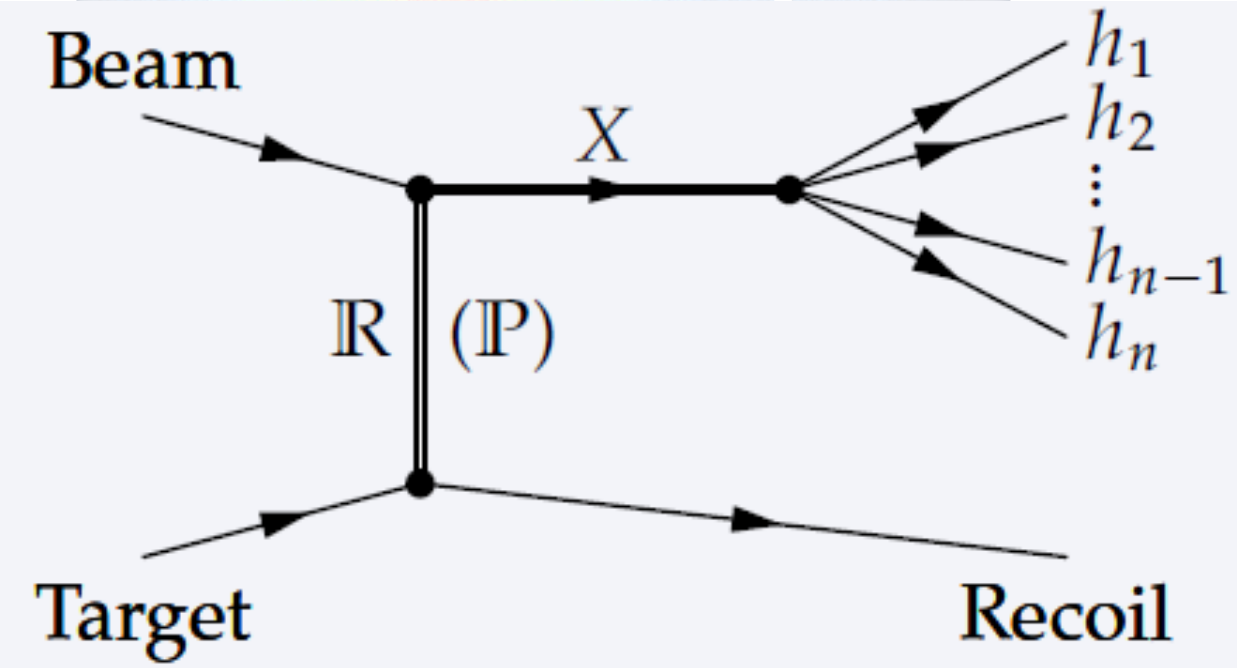
Analysis - Diffractive Production



Analysis - Diffractive Production

Beam particle gets excited to state X – total cross section ist $\mathcal{O}$(mb)

- State X decays in n-Hadrons
- Target takes up recoil, stays intact



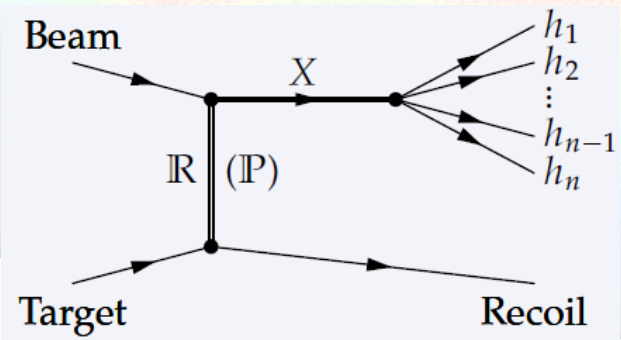
Analysis - Diffractive Production

Beam particle gets excited to state X – total cross section ist $\mathcal{O}$(mb)

- State X decays in n-Hadrons
- Target takes up recoil, stays intact

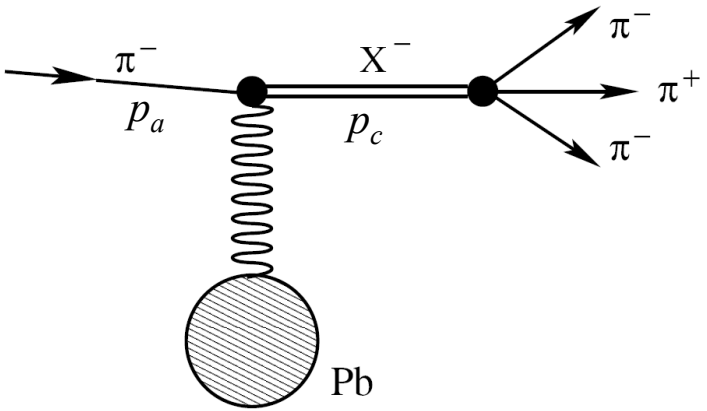
What can I say about X ?

- Angular momentum production via
  - Spin flip of target (not with pure Pomeron-exchange)
  - Orbital angular momentum (pomeron-projectile) in reaction
  - Projection of orbital angular momentum to X with m=0
  - ‚Pomeron' 0^{++} exchange: no Quantum Numbers are exchanged
  - 4-momentum transfer t determines mass spectrum



Diffractive Reactions at COMPASS

Example: $\pi^- + \mathrm{Pb} \rightarrow \pi^-\pi^-\pi^+ + \mathrm{Pb}$



- 4π vertex in Pb target
- Exclusivity ⇨ target stays intact
- Momentum transfer

$$-t \equiv Q^2 = -(p_a - p_c)^2$$

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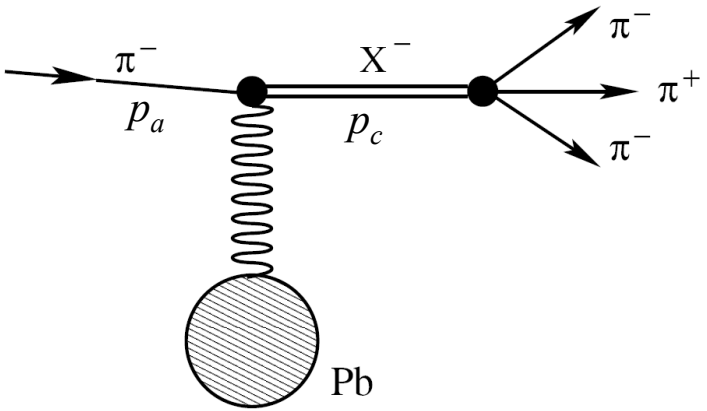

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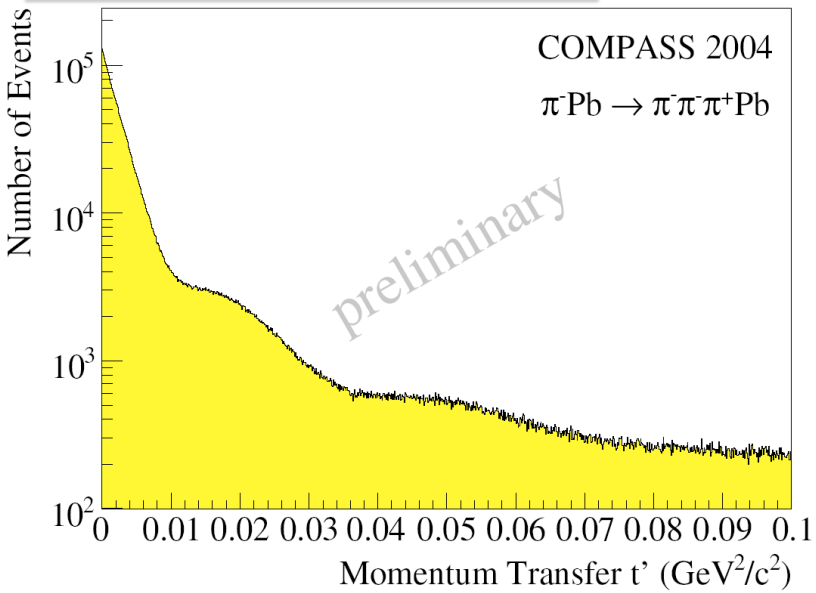
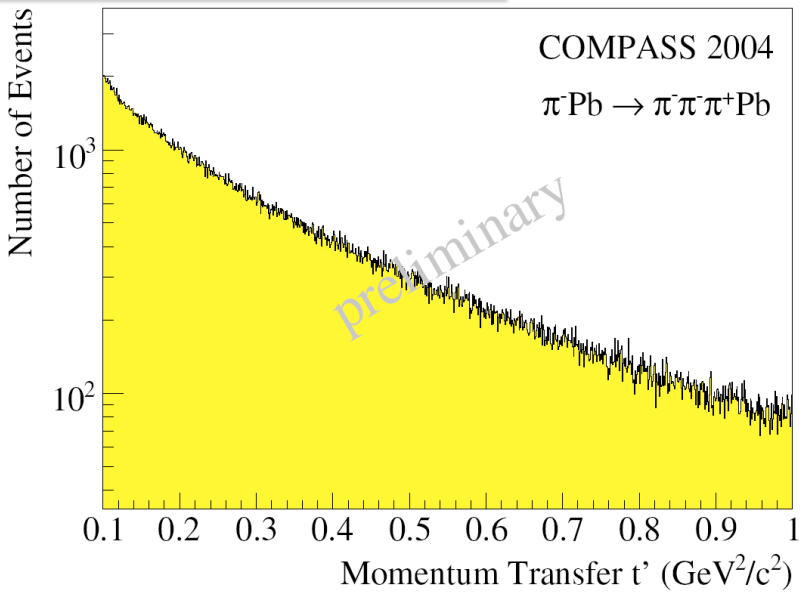
Diffraction on Pb nuclei



Diffraction on nucleons



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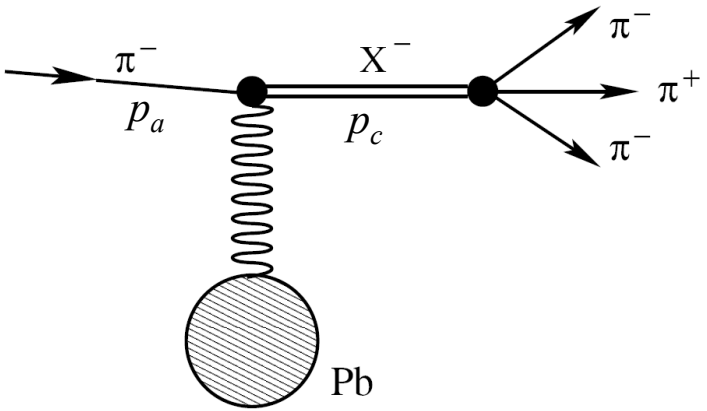

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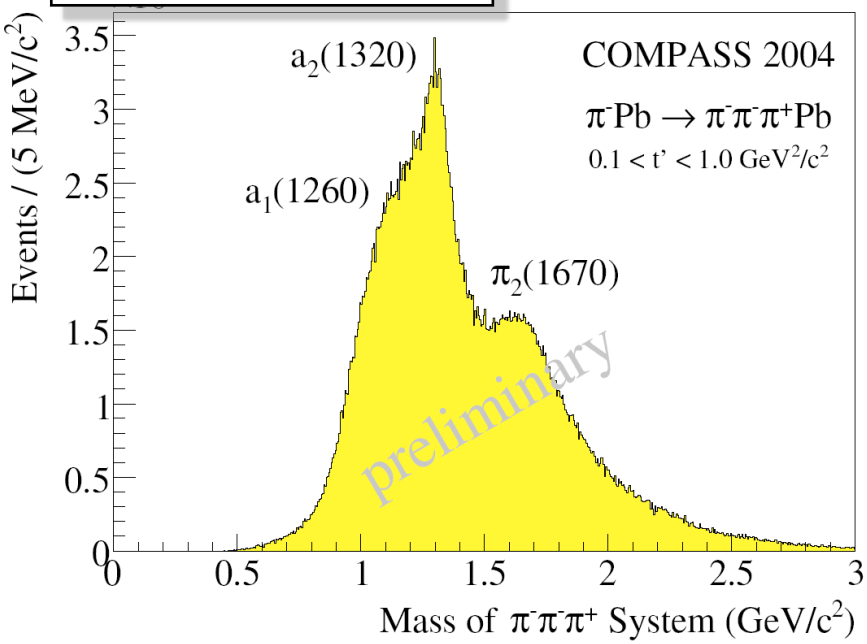
3π invariant mass



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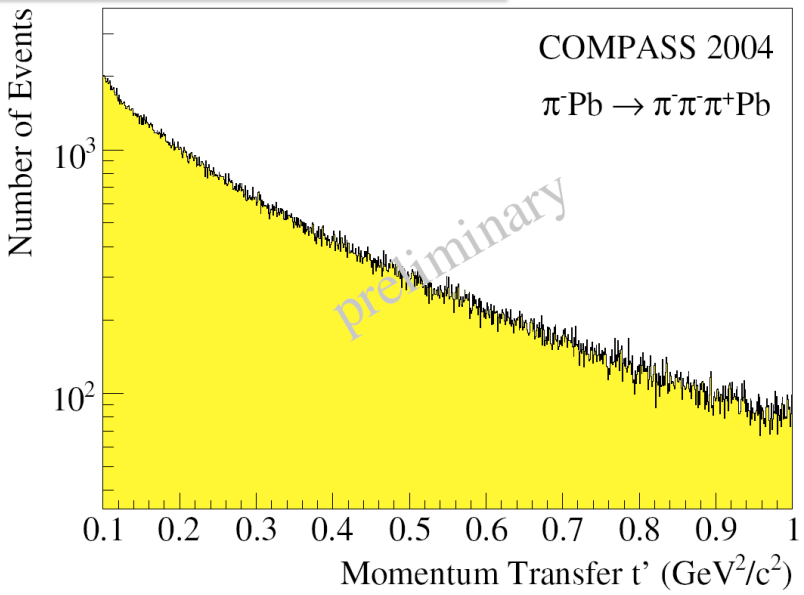
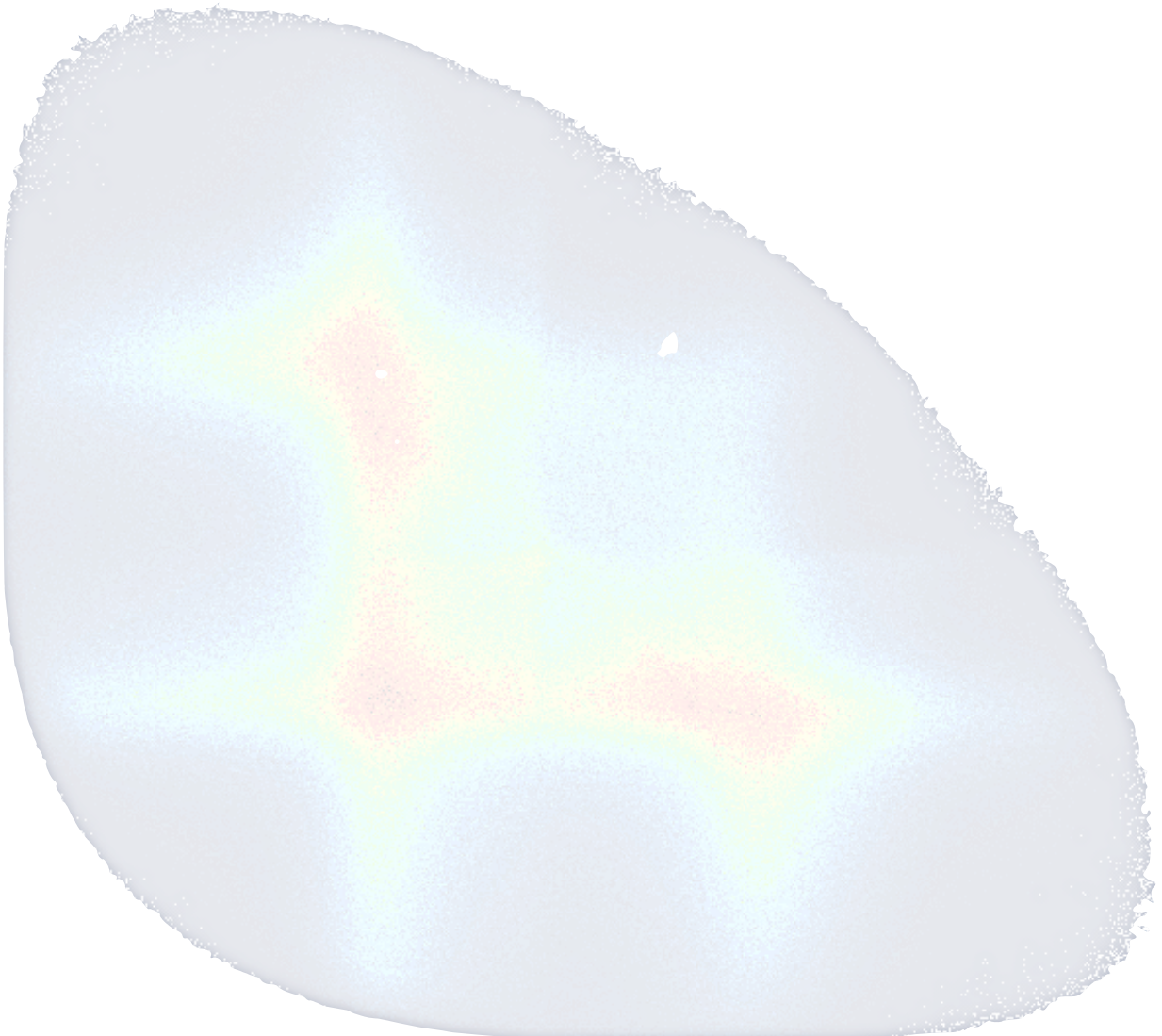


Analysis Inelastic Final State II



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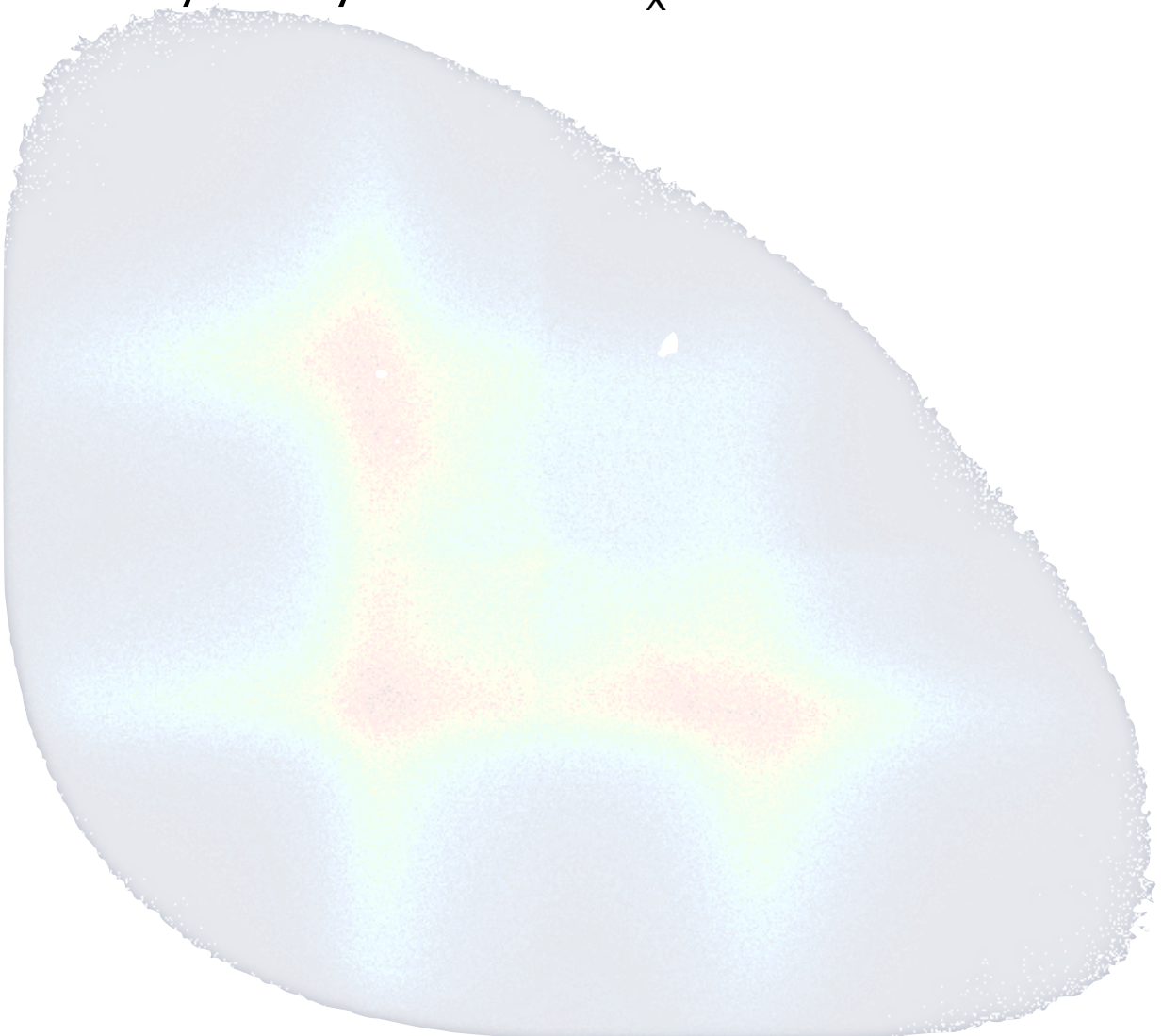

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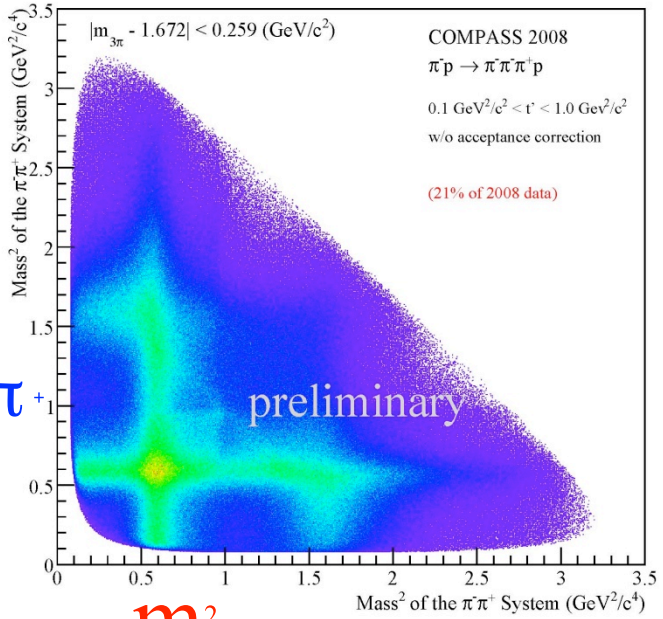
  $\pi_1^- \pi_2^-$ are not distinguishable

  built $m_{\pi_1^- \pi^+}$ and $m_{\pi_2^- \pi^+}$

- Enhancements are sign for decay into isobars

Dalitzplot



$m^2_{\pi_1^-\pi^+}$

$m^2_{\pi_2^-\pi^+}$

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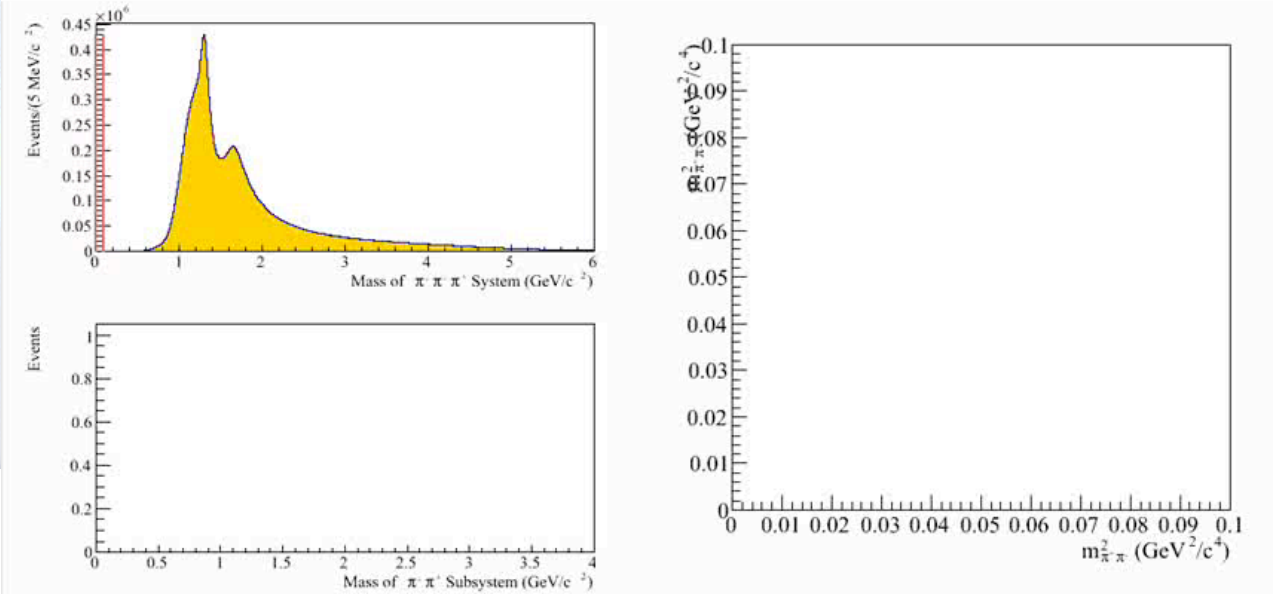

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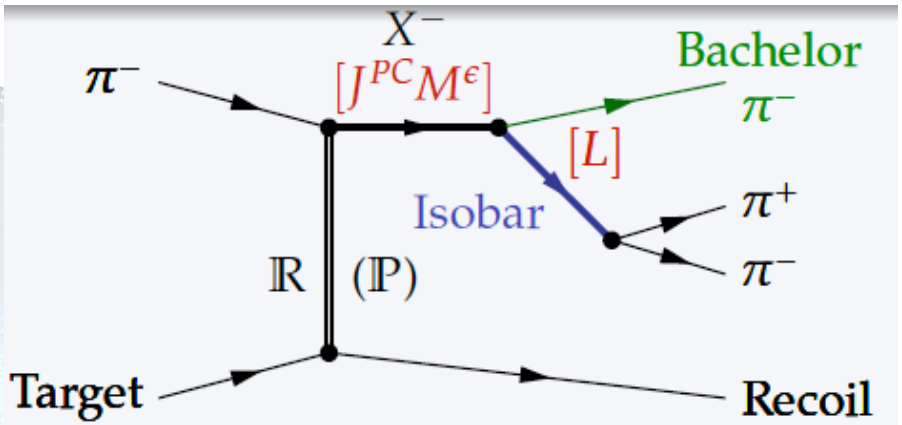

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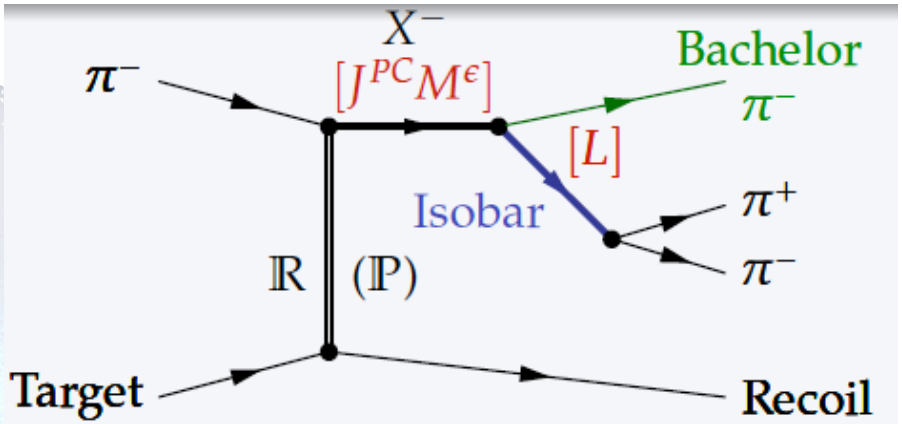

- Enhancements are sign for decay into isobars
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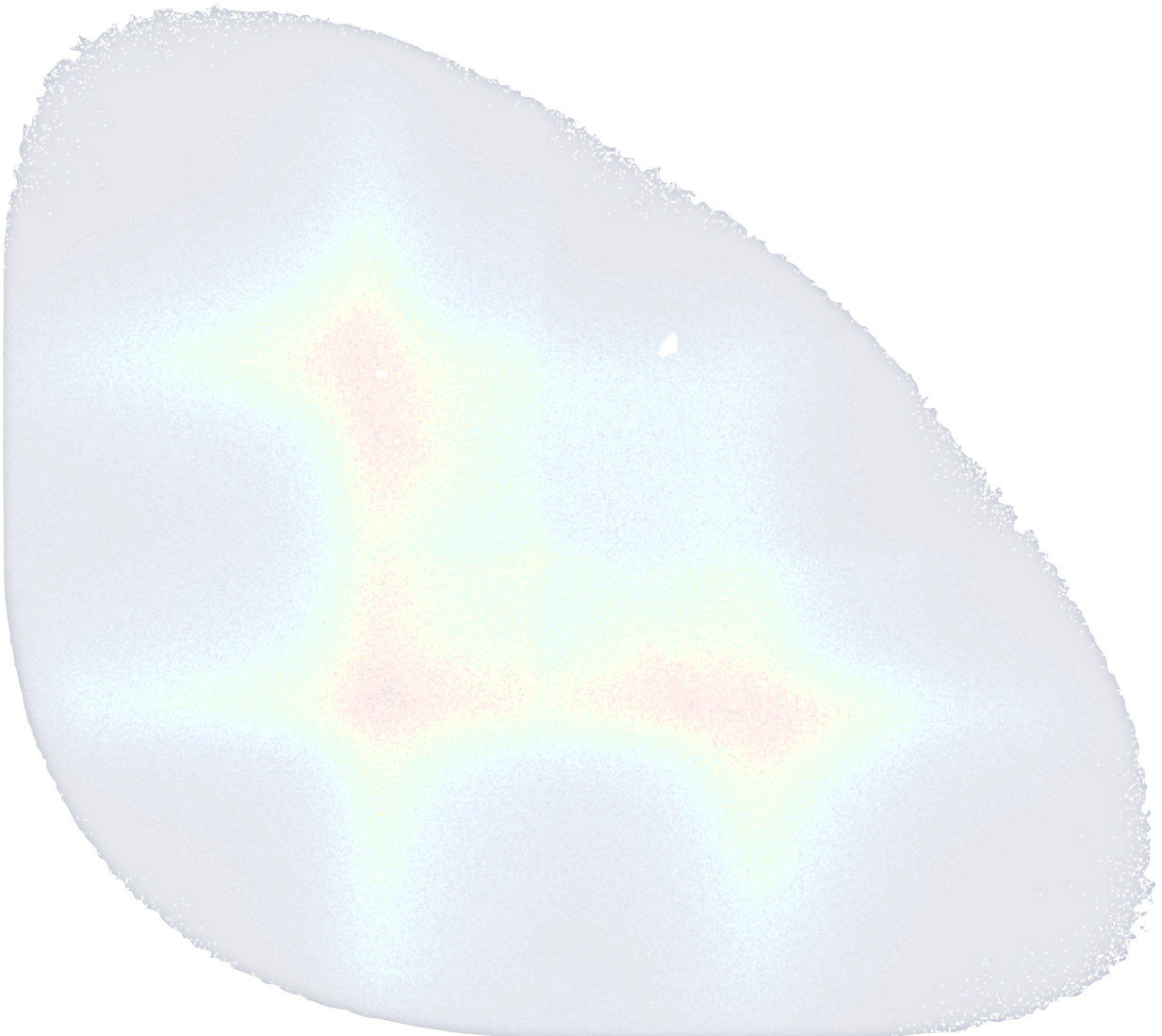
- Proceed in 2-step process
  - Analyze fixed mass bin: obtain production amplitudes T_i
    → spin densitiy Matrix
  - Combine T_i of all mass bins: obtain resonance parameters of individual J^{PC}

Wave Set for the Fit

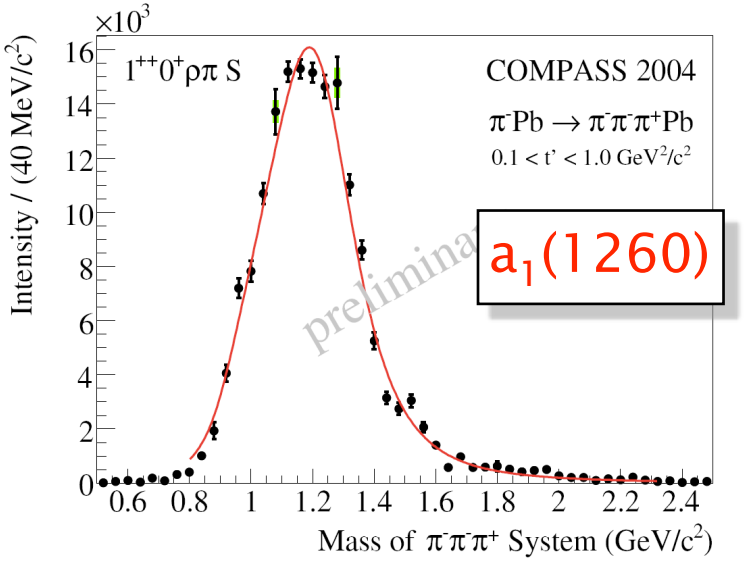


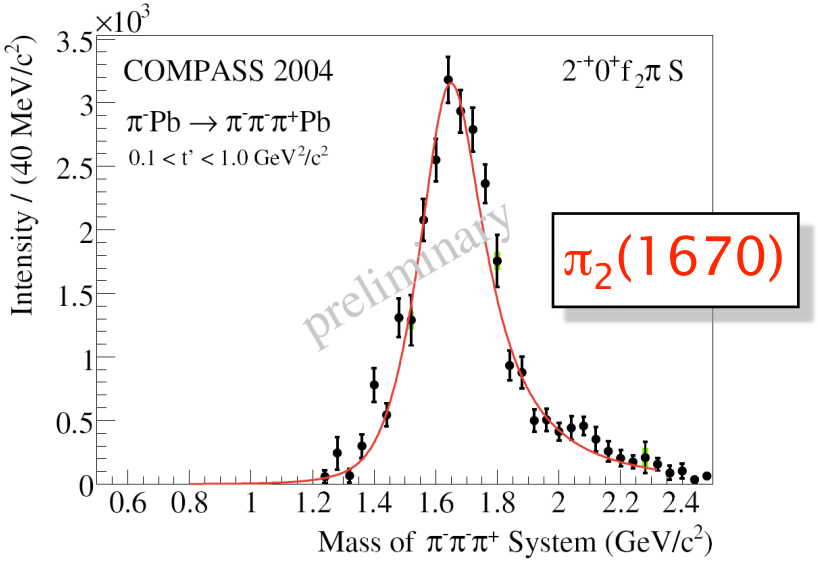
Wave Set for the Fit

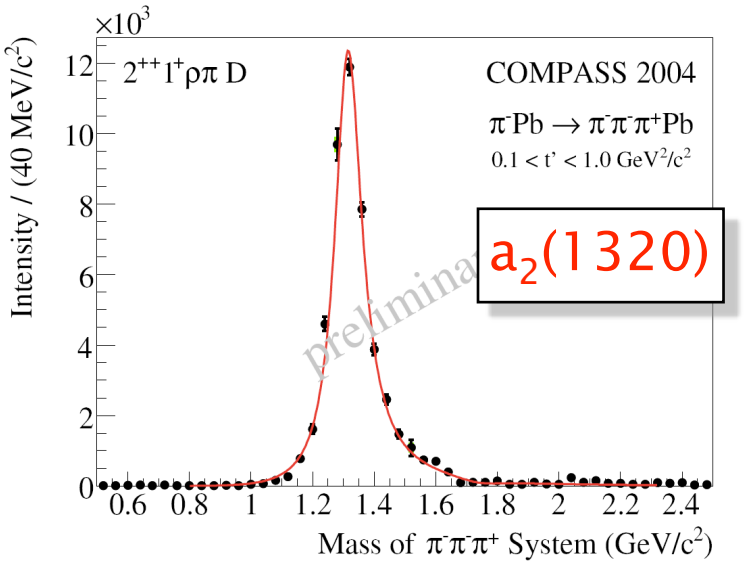
$J^{PC}M^{\epsilon}$	L	Isobar π	Cut [GeV]
$0^{-+}0^{+}$	S	$f_0\pi$	1.40
$0^{-+}0^{+}$	S	$(\pi\pi)_s\pi$	-
$0^{-+}0^{+}$	P	$\rho\pi$	-
$1^{-+}1^{+}$	P	$\rho\pi$	-
$1^{++}0^{+}$	S	$\rho\pi$	-
$1^{++}0^{+}$	P	$f_2\pi$	1.20
$1^{++}0^{+}$	P	$(\pi\pi)_s\pi$	0.84
$1^{++}0^{+}$	D	$\rho\pi$	1.30
$1^{++}1^{+}$	S	$\rho\pi$	-
$1^{++}1^{+}$	P	$f_2\pi$	1.40
$1^{++}1^{+}$	P	$(\pi\pi)_s\pi$	1.40
$1^{++}1^{+}$	D	$\rho\pi$	1.40
$2^{-+}0^{+}$	S	$f_2\pi$	1.20
$2^{-+}0^{+}$	P	$\rho\pi$	0.80
$2^{-+}0^{+}$	D	$f_2\pi$	1.50
$2^{-+}0^{+}$	D	$(\pi\pi)_s\pi$	0.80
$2^{-+}0^{+}$	F	$\rho\pi$	1.20
$2^{-+}1^{+}$	S	$f_2\pi$	1.20
$2^{-+}1^{+}$	P	$\rho\pi$	0.80
$2^{-+}1^{+}$	D	$f_2\pi$	1.50
$2^{-+}1^{+}$	D	$(\pi\pi)_s\pi$	1.20
$2^{-+}1^{+}$	F	$\rho\pi$	1.20

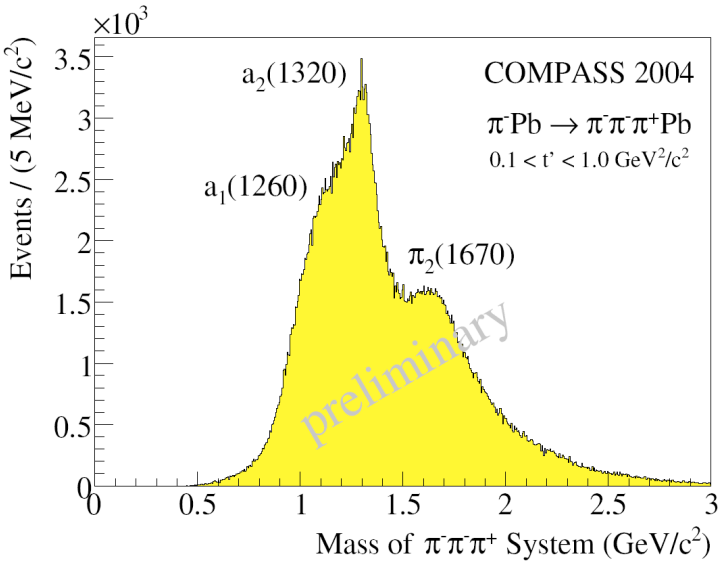
$J^{PC}M^{\epsilon}$	L	Isobar π	Cut [GeV]
$2^{++}1^{+}$	P	$f_2\pi$	1.50
$2^{++}1^{+}$	D	$\rho\pi$	-
$3^{++}0^{+}$	S	$\rho_3\pi$	1.50
$3^{++}0^{+}$	P	$f_2\pi$	1.20
$3^{++}0^{+}$	D	$\rho\pi$	1.50
$3^{++}1^{+}$	S	$\rho_3\pi$	1.50
$3^{++}1^{+}$	P	$f_2\pi$	1.20
$3^{++}1^{+}$	D	$\rho\pi$	1.50
$4^{-+}0^{+}$	F	$\rho\pi$	1.20
$4^{-+}1^{+}$	F	$\rho\pi$	1.20
$4^{++}1^{+}$	F	$f_2\pi$	1.60
$4^{++}1^{+}$	G	$\rho\pi$	1.64
$1^{-+}0^{-}$	P	$\rho\pi$	-
$1^{-+}1^{-}$	P	$\rho\pi$	-
$1^{++}1^{-}$	S	$\rho\pi$	-
$2^{-+}1^{-}$	S	$f_2\pi$	1.20
$2^{++}0^{-}$	P	$f_2\pi$	1.30
$2^{++}0^{-}$	D	$\rho\pi$	-
$2^{++}1^{-}$	P	$f_2\pi$	1.30
FLAT			

Most Prominent Partial Waves









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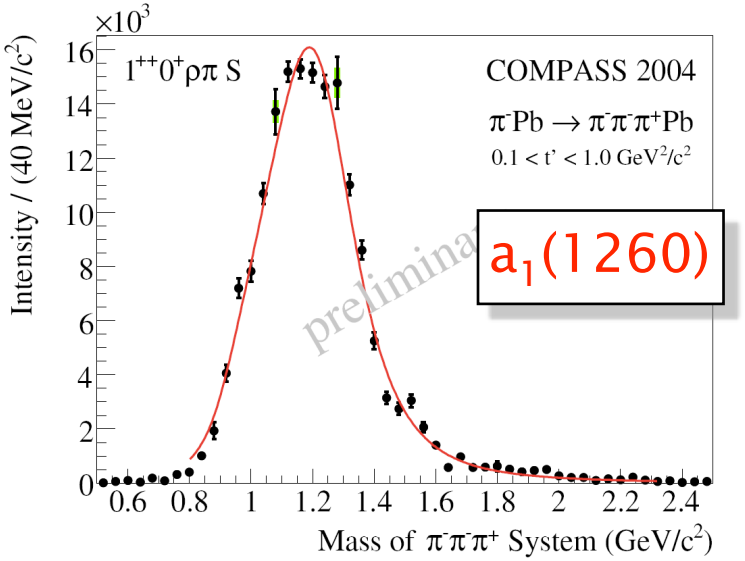

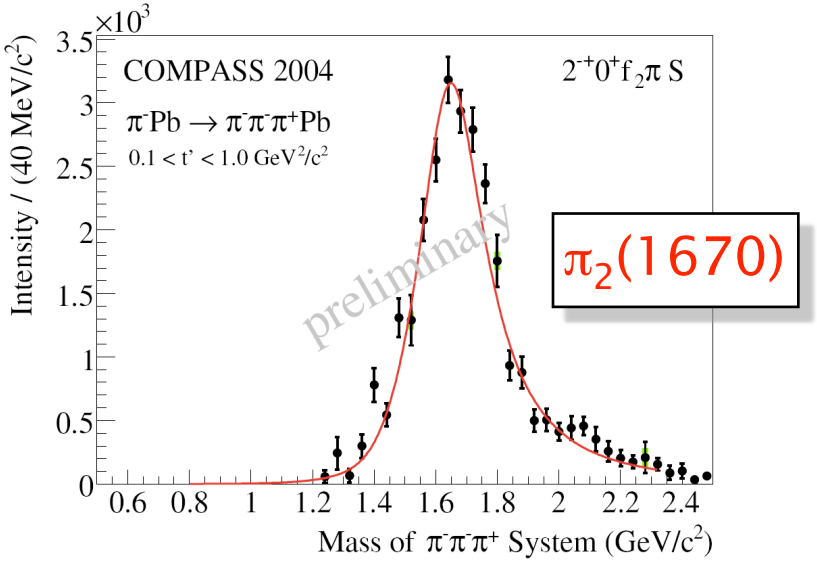

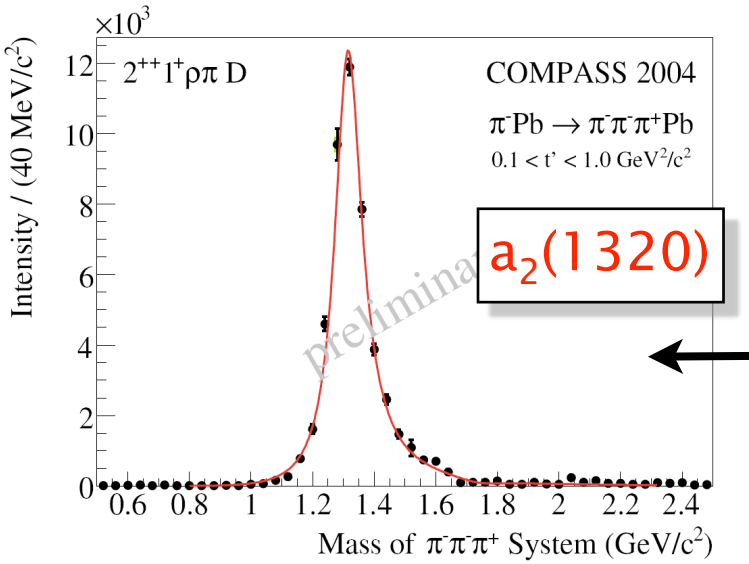

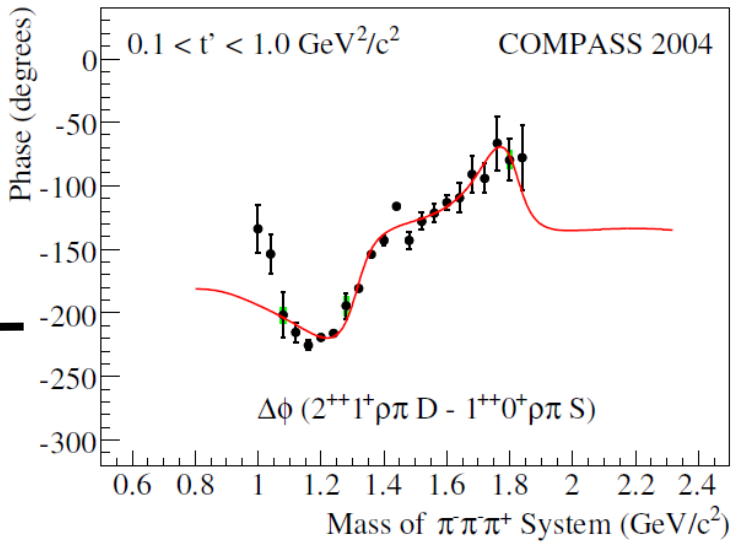

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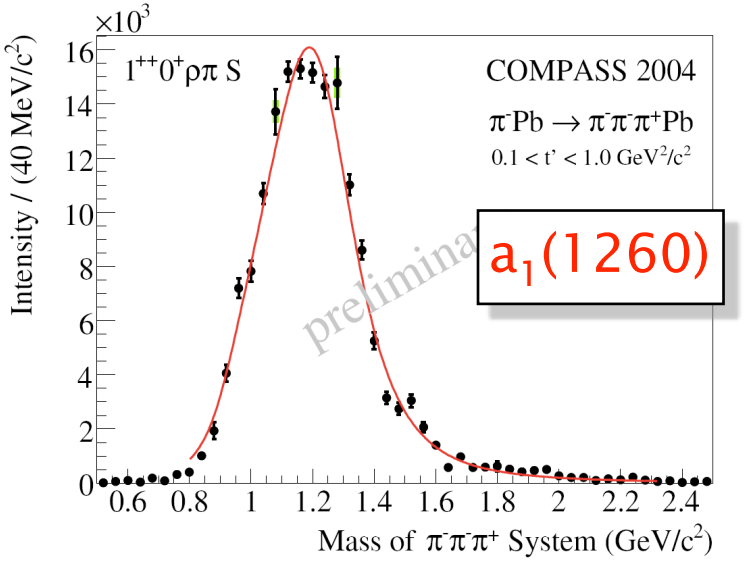
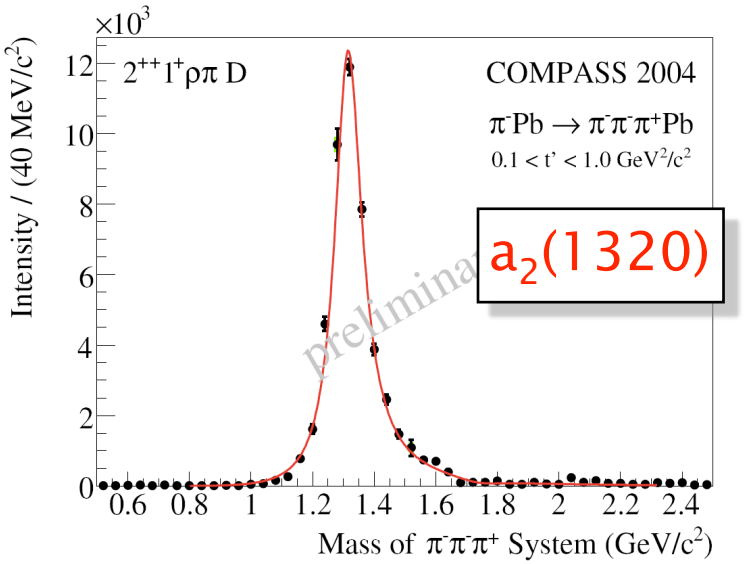
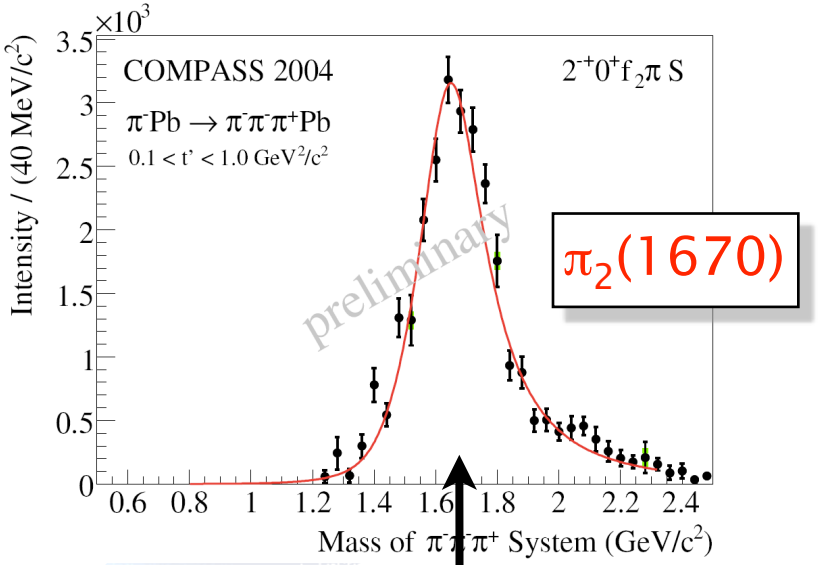
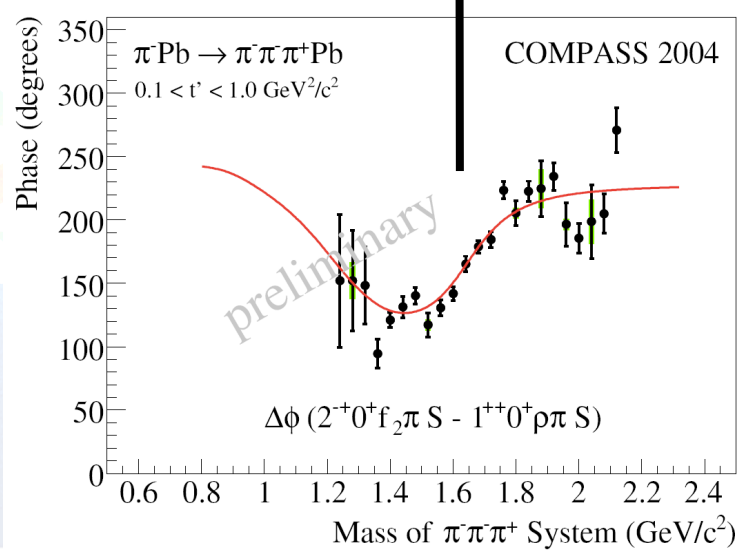
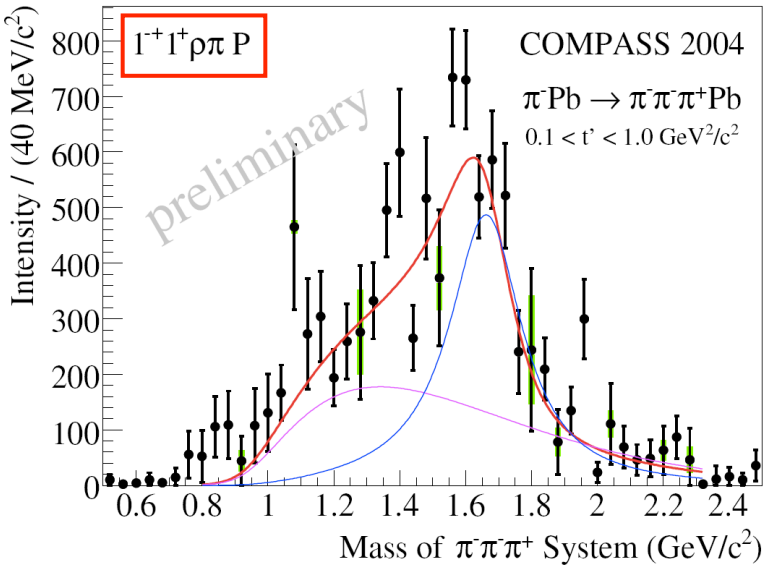








$\pi_1(1600)$



PRL 1ß4 241803 (2010)

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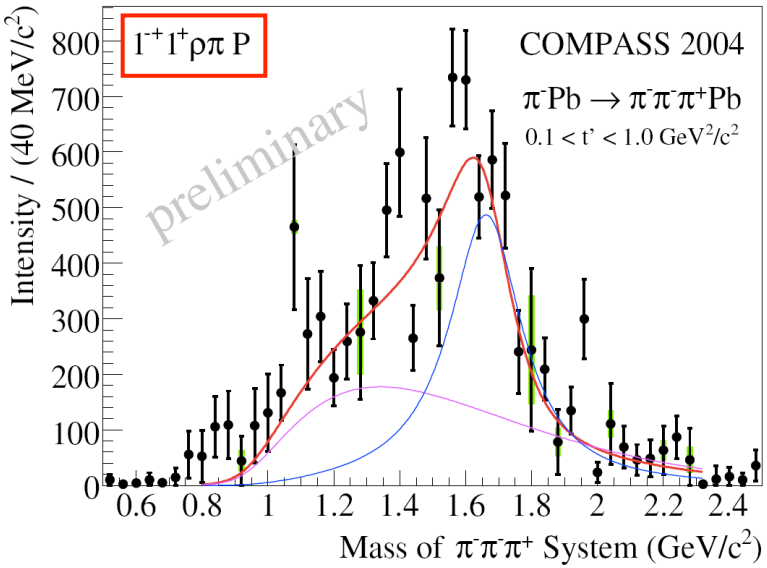

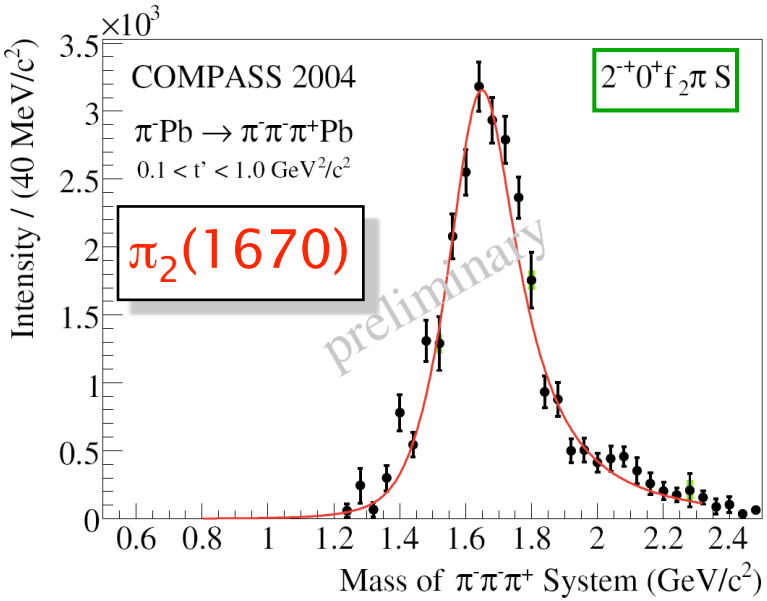

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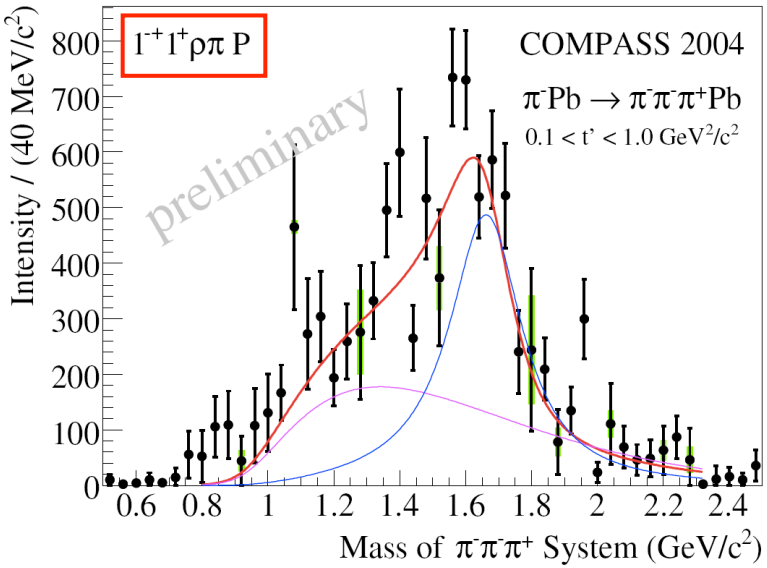


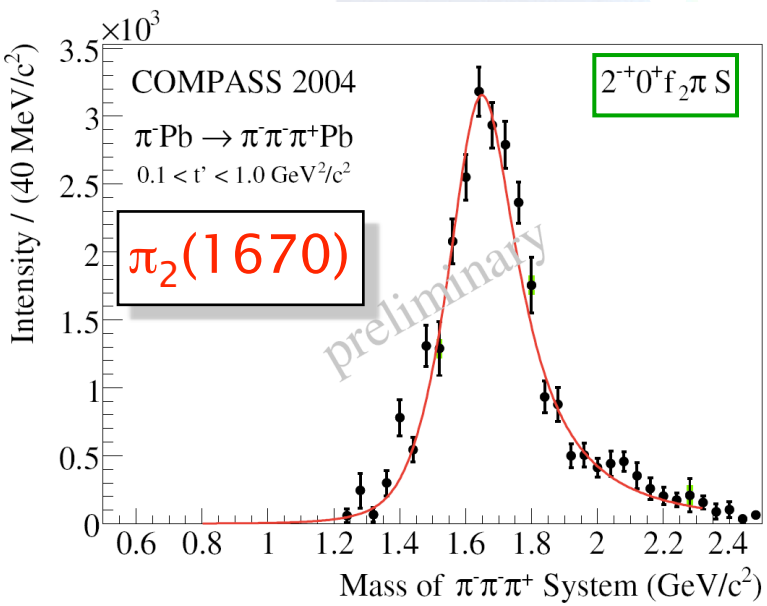
- BW parameter for $\pi_1(1600)$

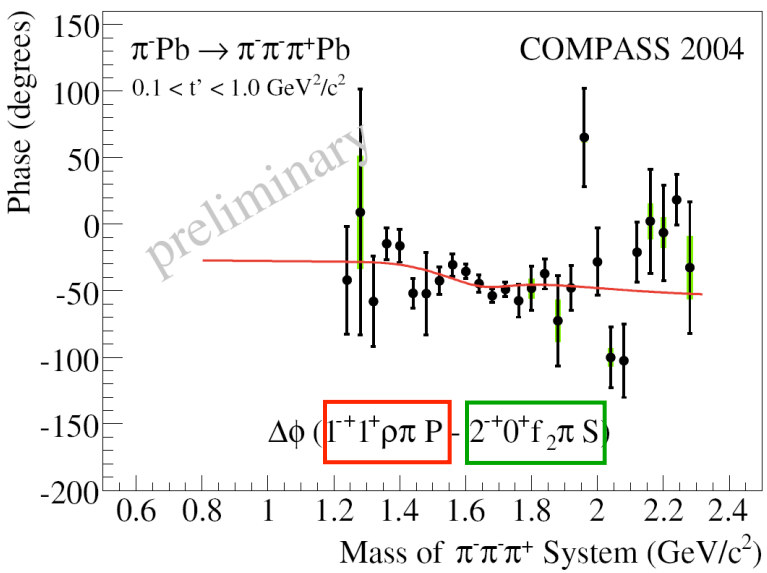
$$M = \left(1.660 \pm 0.010\,^{+0.000}_{-0.064}\right) \text{GeV}/c^2$$

$$\Gamma = \left(0.269 \pm 0.021\,^{+0.042}_{-0.064}\right) \text{GeV}/c^2$$

- Negligible 'miss-ID'

PRL 1ß4 241803 (2010)





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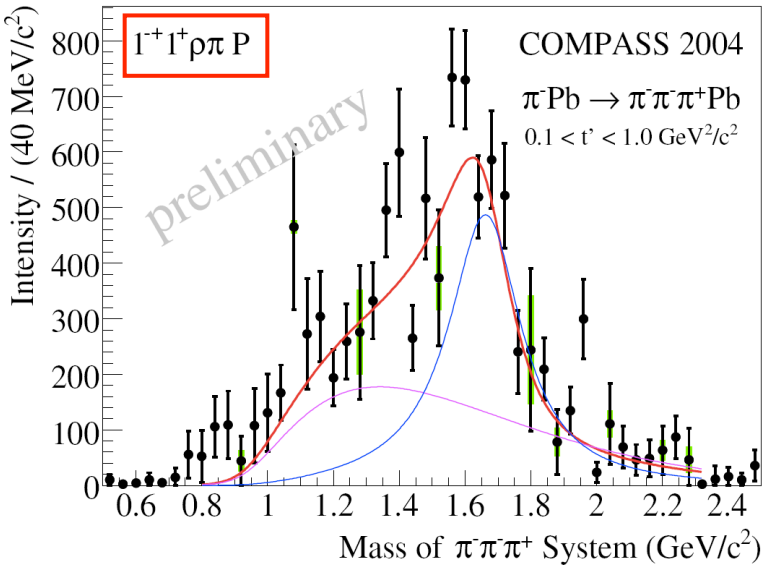

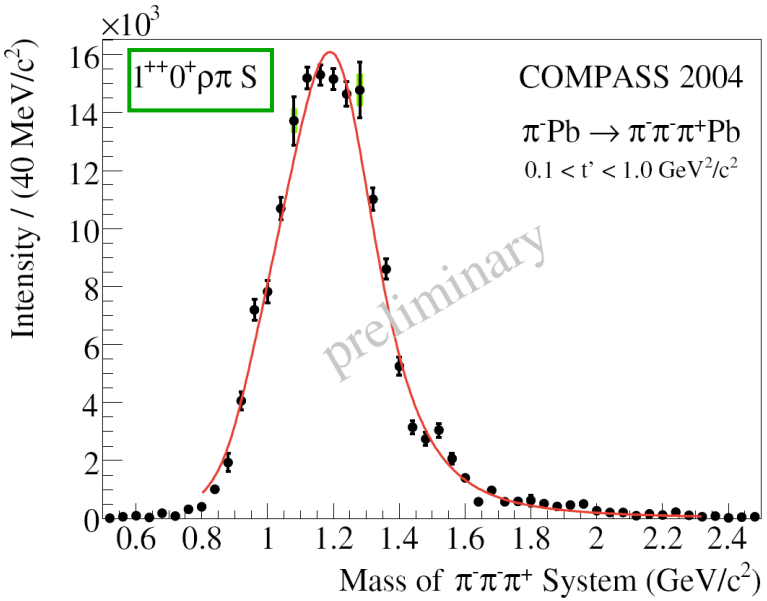

PRL 1ß4 241803 (2010)

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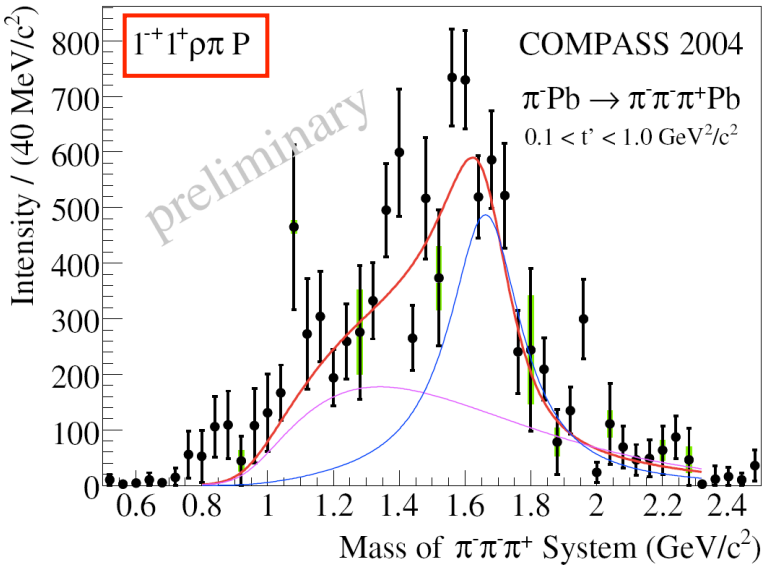

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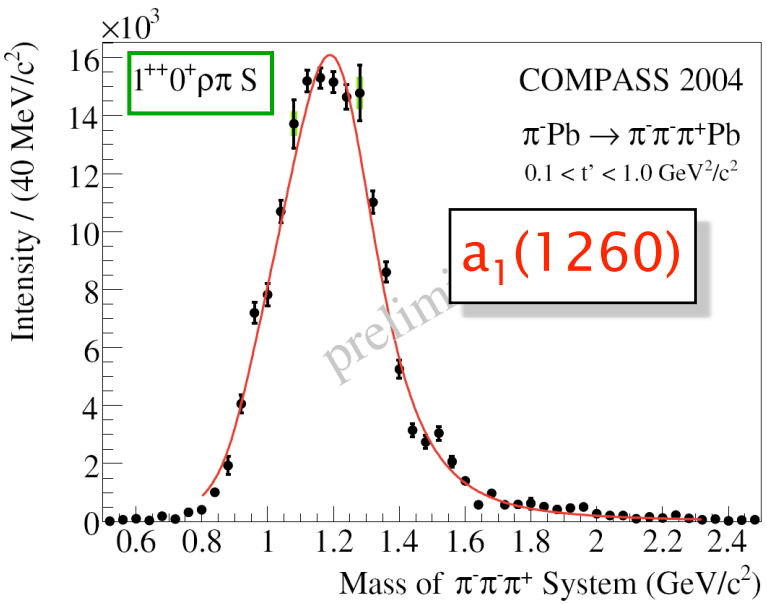
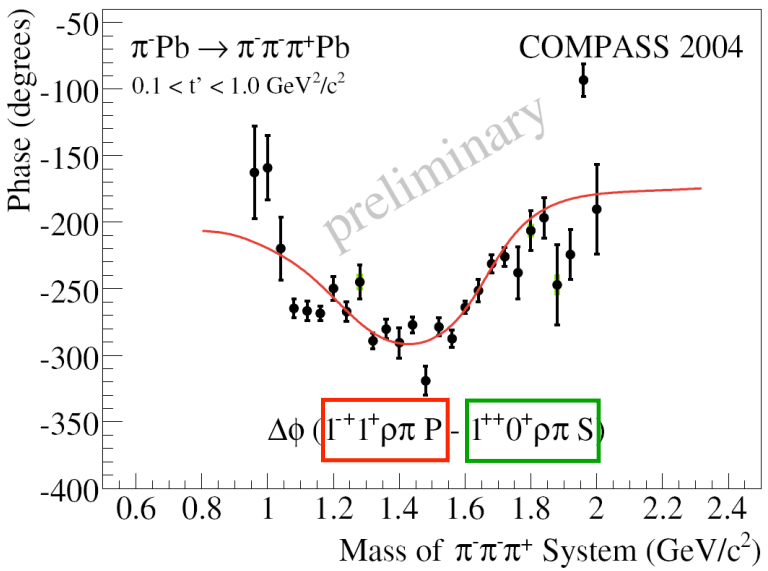
PRL 1ß4 241803 (2010)





Nuclear Effect – $\pi^-\pi^-\pi^+$

- Compare intensities of $a_1(1260)$ and $\pi_2(1670)$ from **Pb** and **H_2** targets
- Normalise to intensity of $a_2(1320)$ ($J^{PC}M^{\varepsilon} = 2^{++}1^{+}$)
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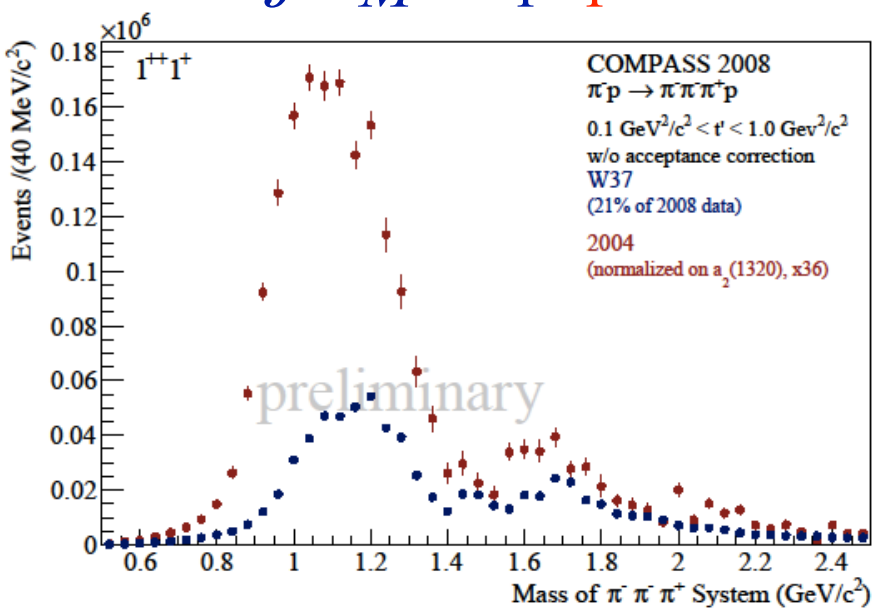

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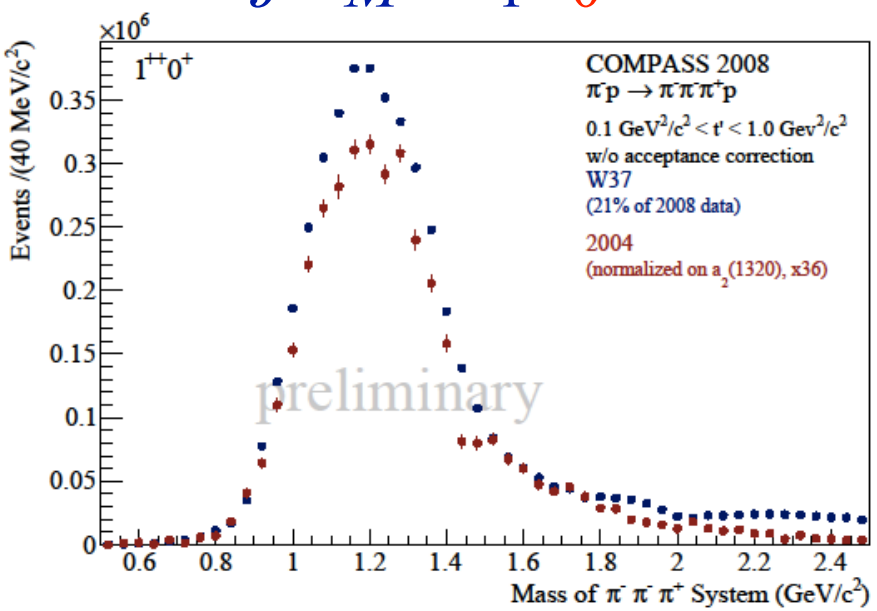

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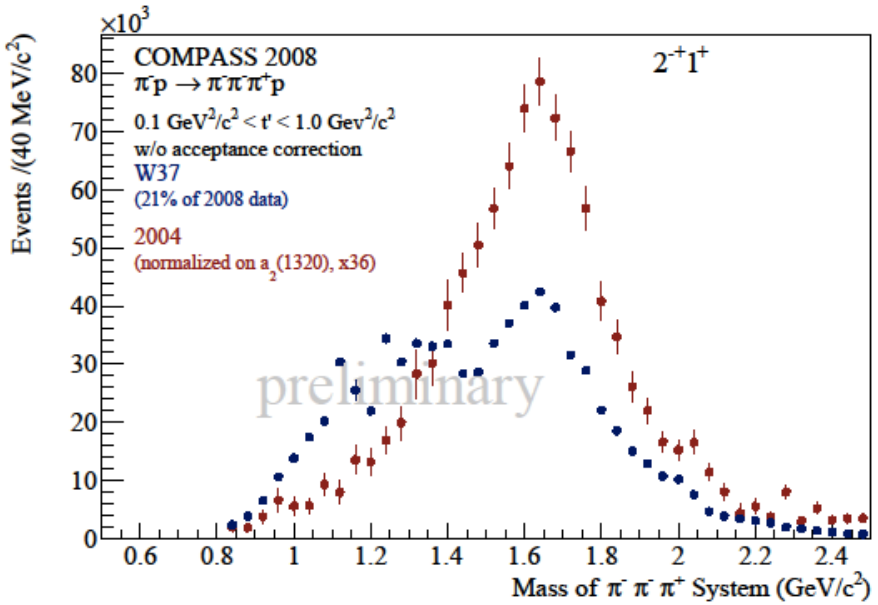

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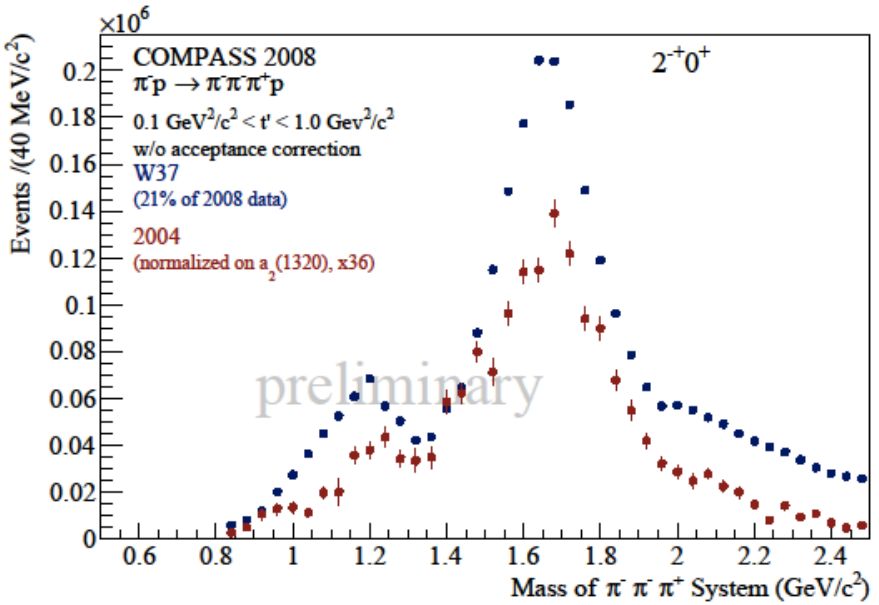

Nuclear Effect – $\pi^-\pi^-\pi^+$

$$\left[\frac{Intensity(M=1)}{Intensity(M=0)}\right]_{Pb} > \left[\frac{Intensity(M=1)}{Intensity(M=0)}\right]_{H_2}$$

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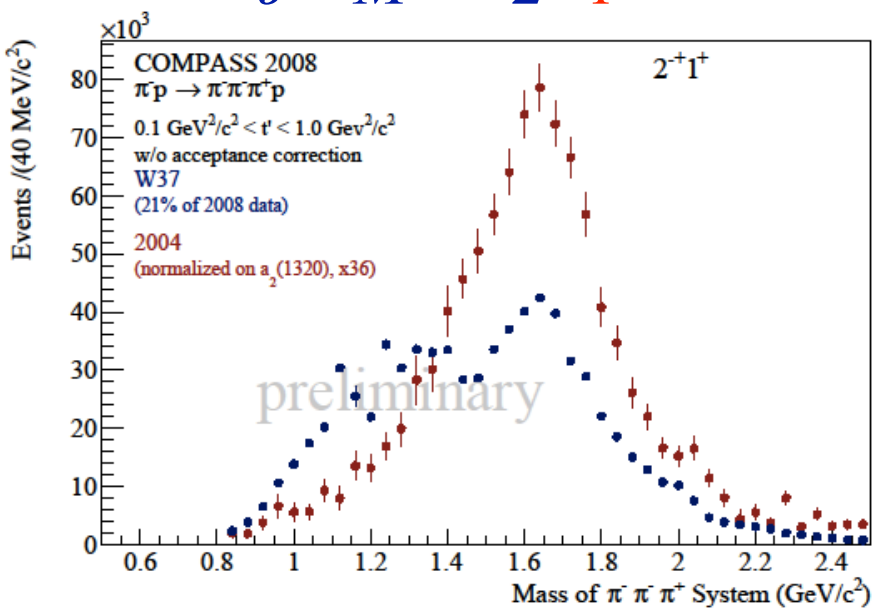

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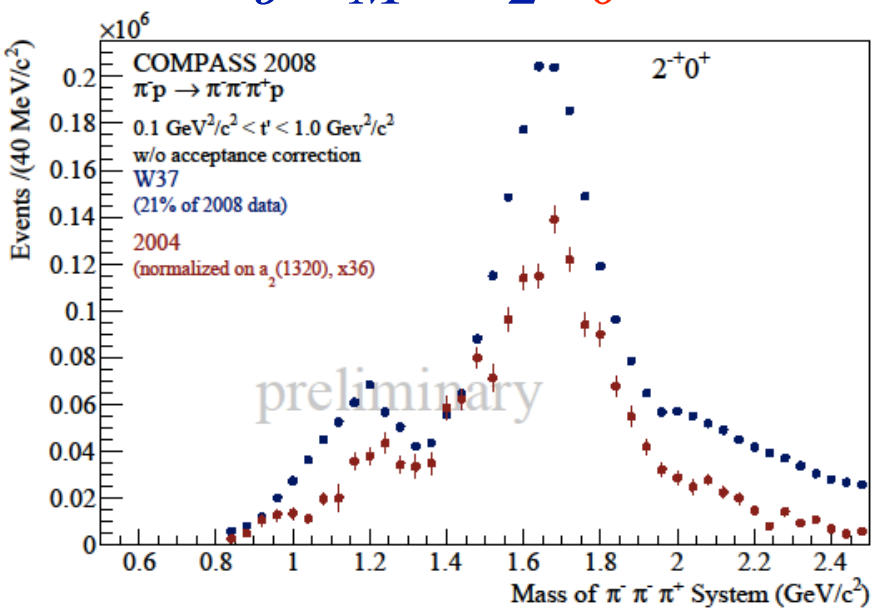

Data with Proton Beam

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- Beam: 190 GeV/c, 71.5% p, 25.5% π, 3.0% K
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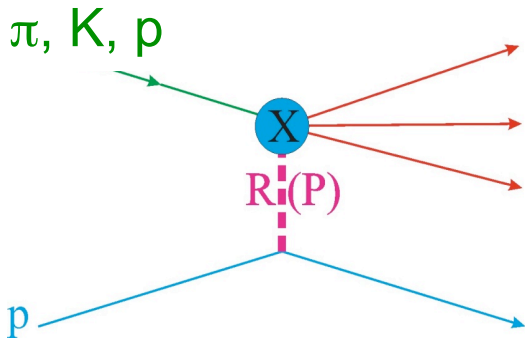

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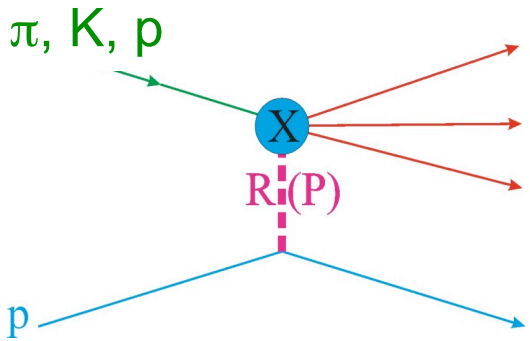
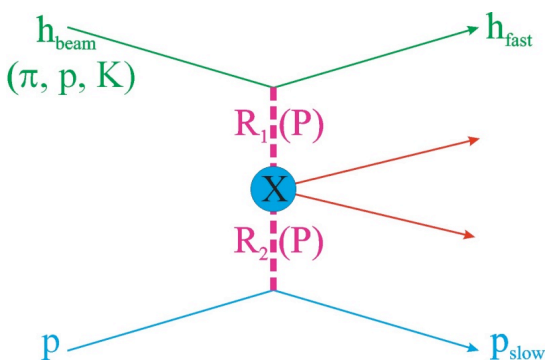


- Central Production

$$pp \rightarrow p_f \pi^+ \pi^- p_s$$
$$pp \rightarrow p_f \pi^+ \pi^- \pi^+ \pi^- p_s$$
$$pp \rightarrow p_f K \bar{K} p_s$$



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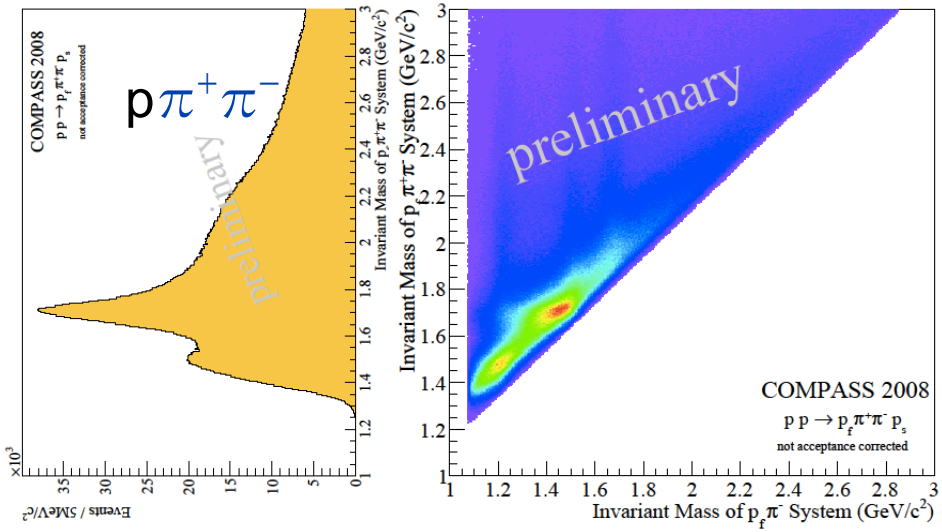

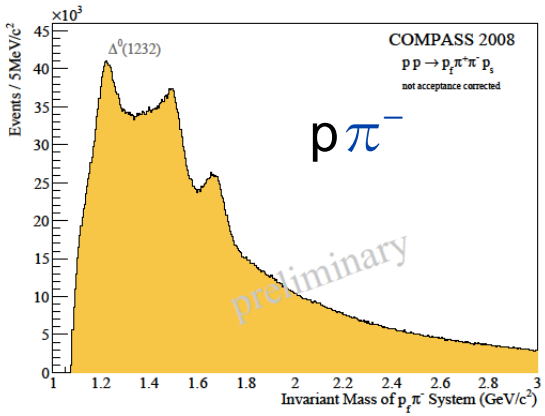

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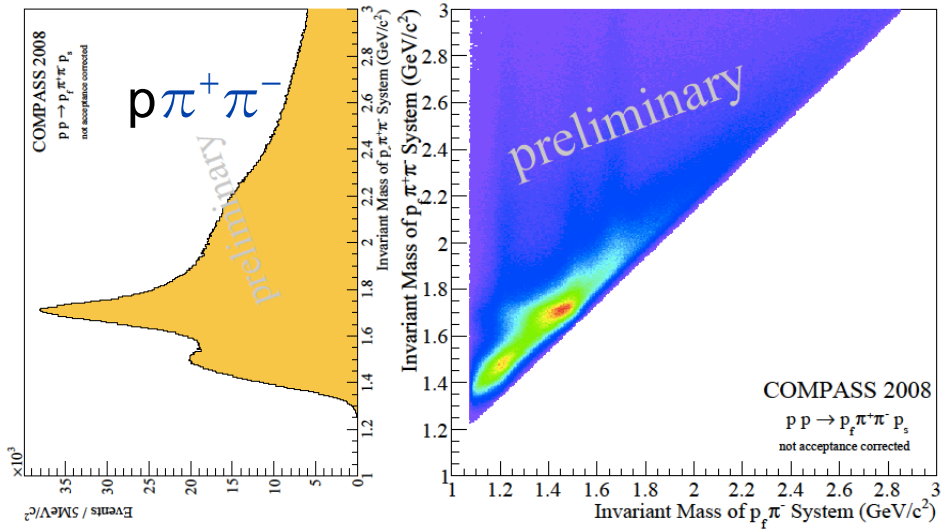

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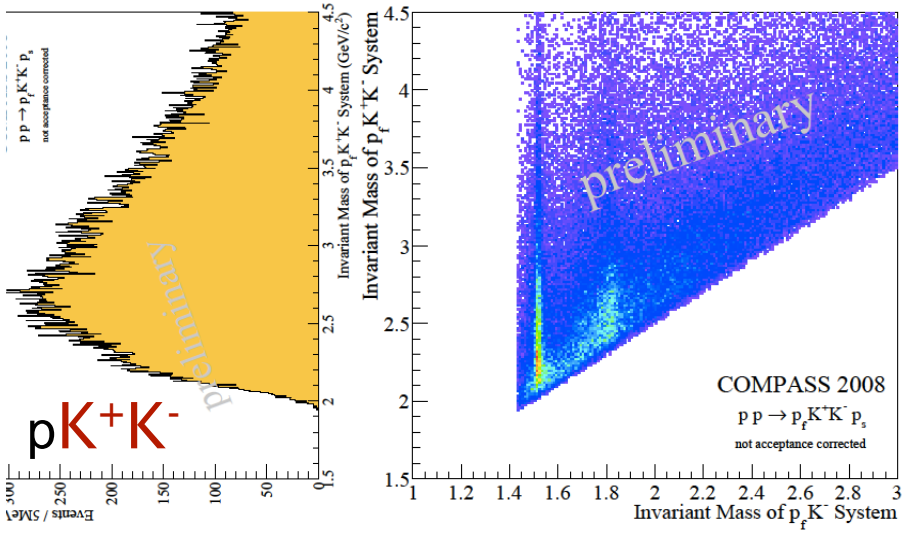
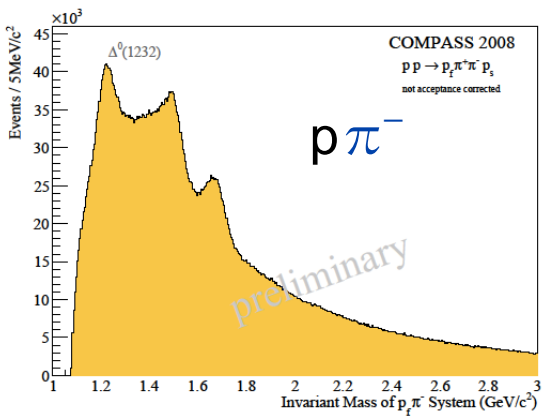
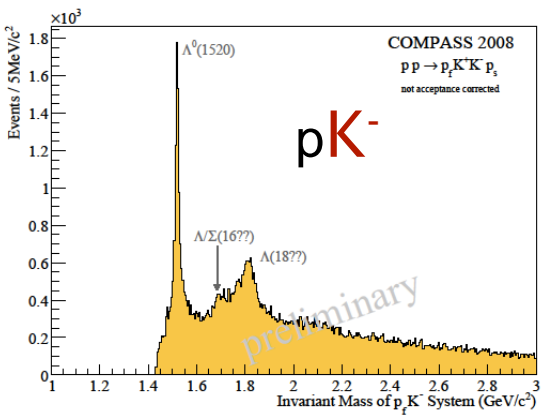
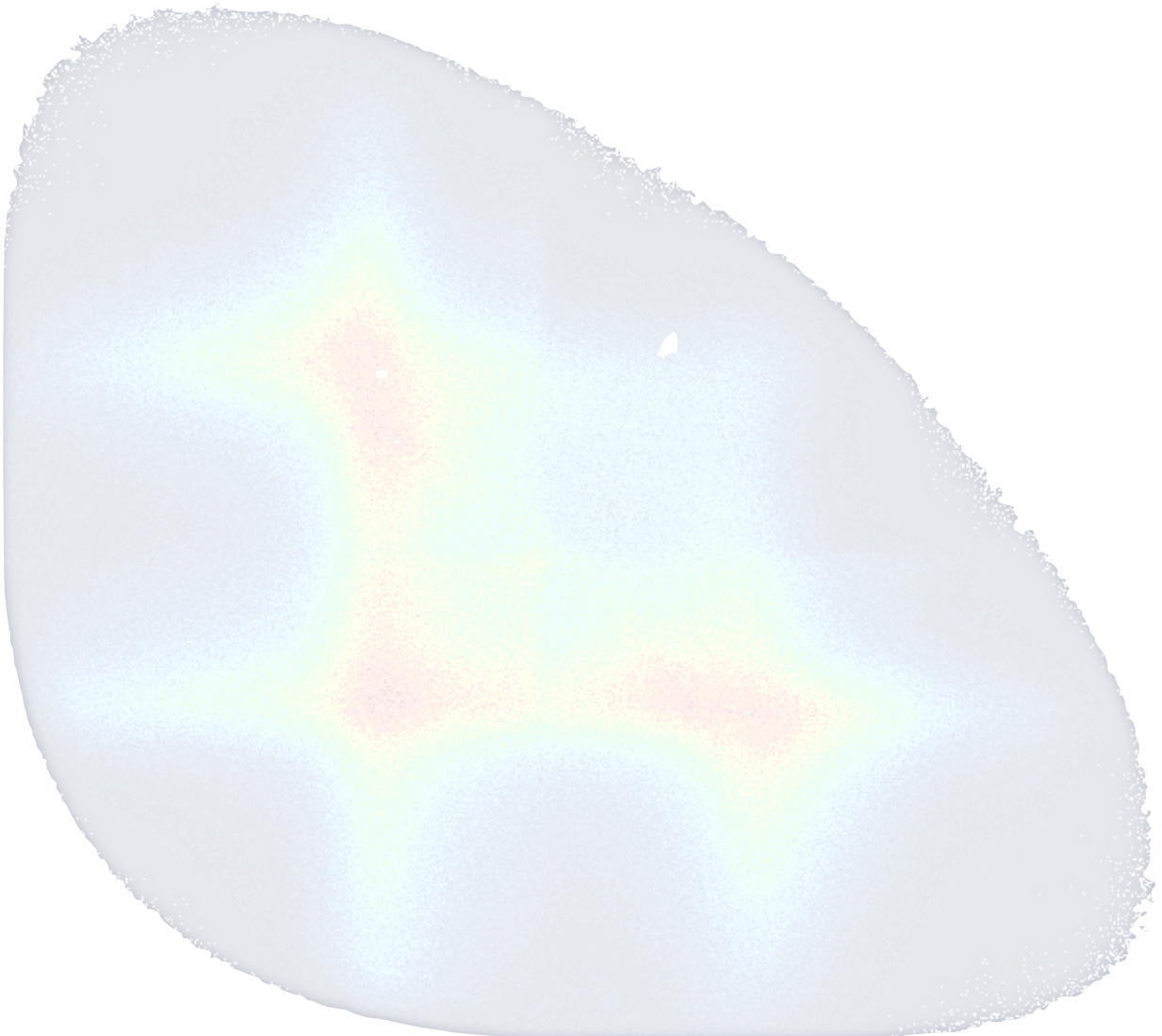






- final states containing charged and neutral particles
- Masses up to ~3 GeV/c² accessible

Photo-Induced Reactions



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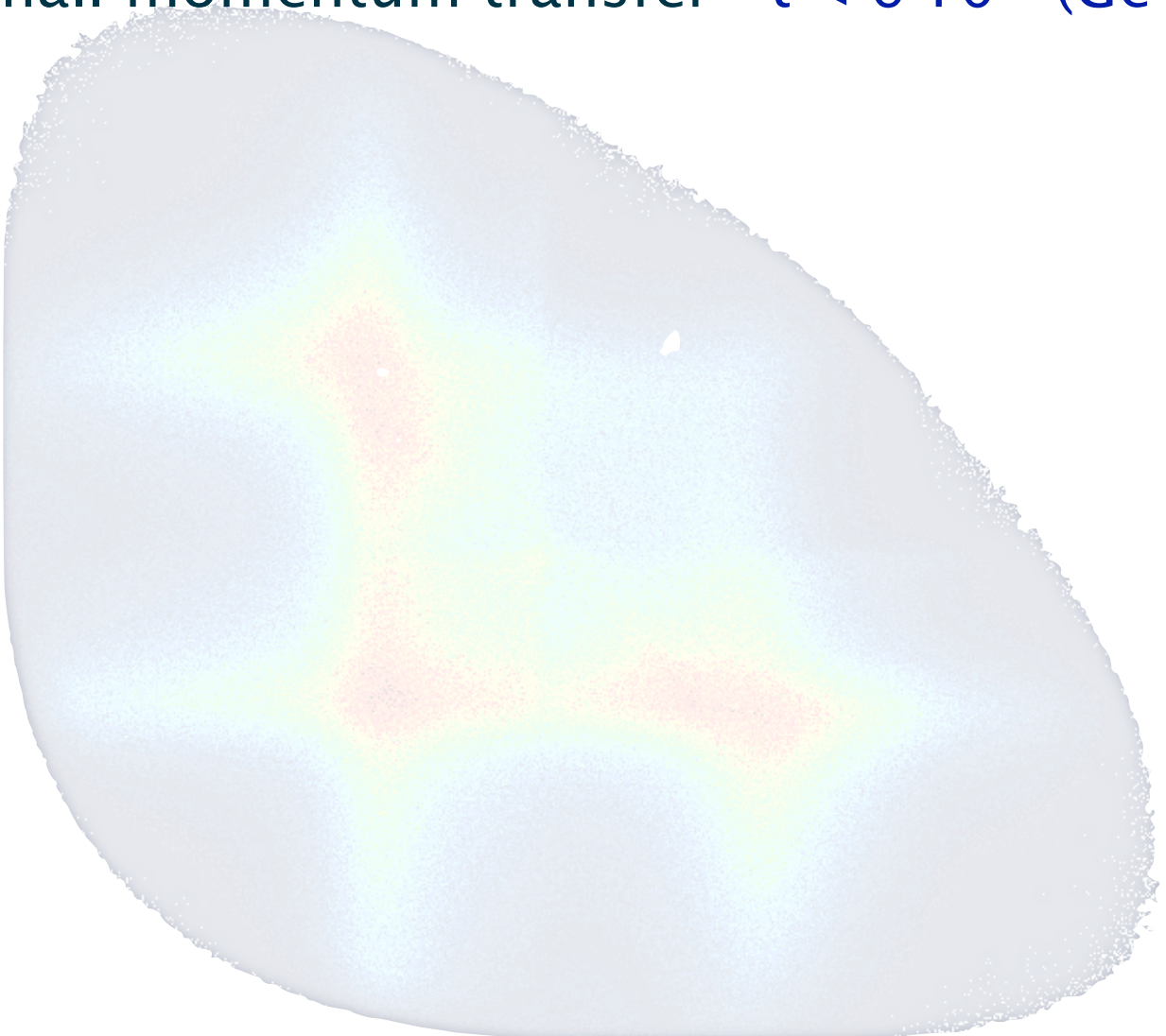
- Very small momentum transfer - $t < 6 \cdot 10^{-4}$ $(GeV/c)^2$



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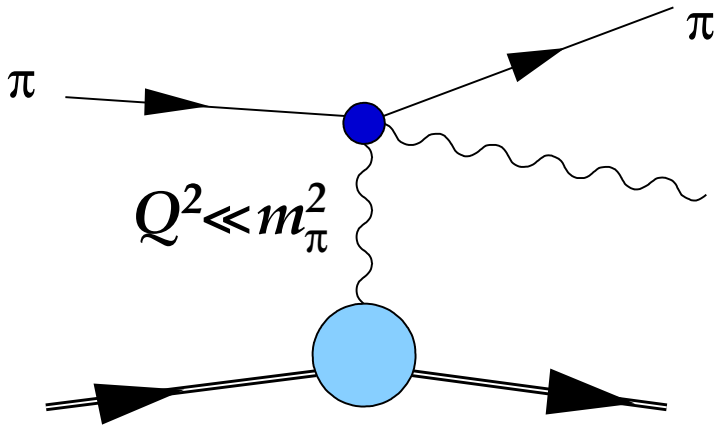

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- Very small momentum transfer - $t < 6 \cdot 10^{-4}$ $(GeV/c)^2$
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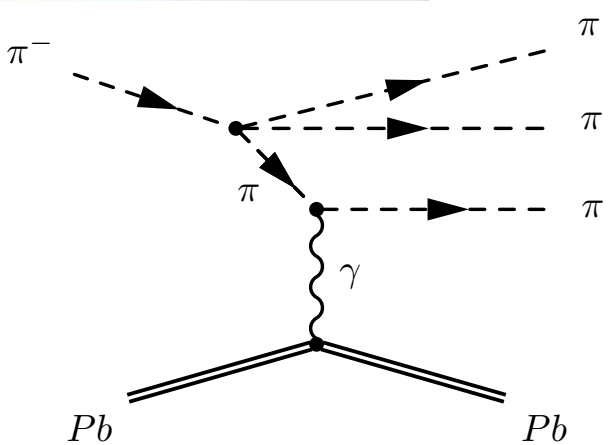

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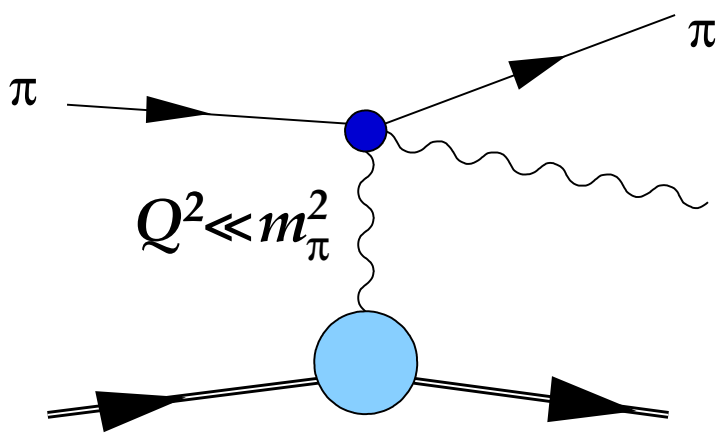

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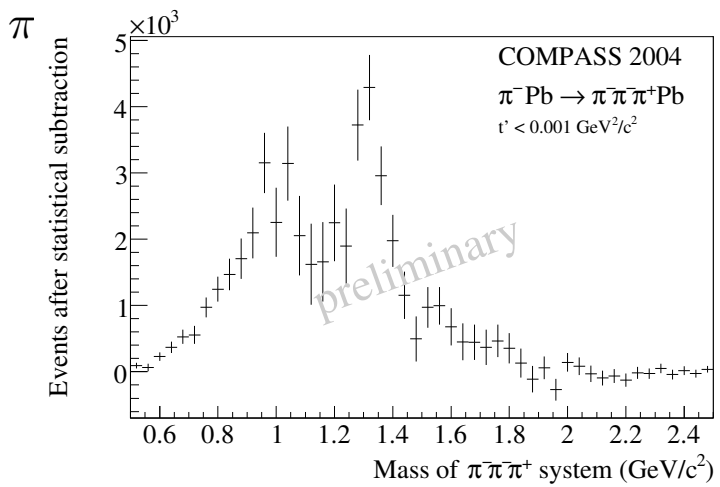

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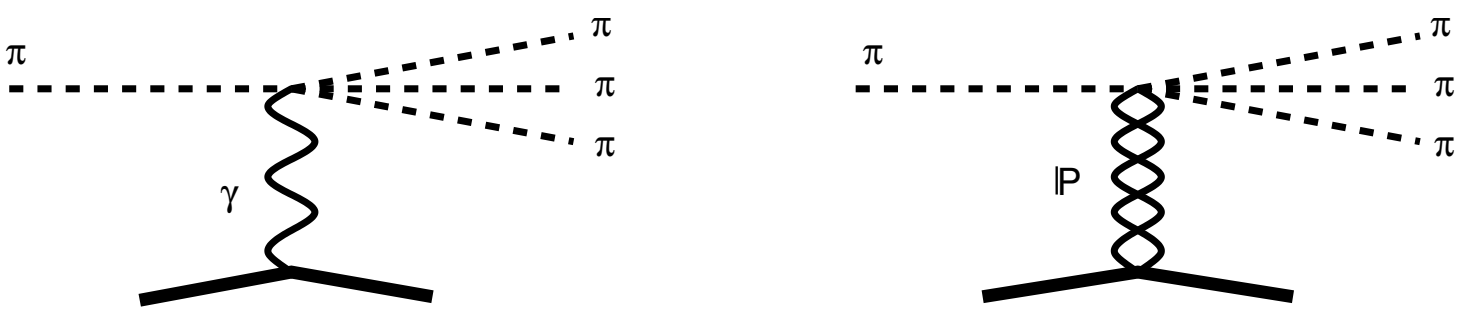
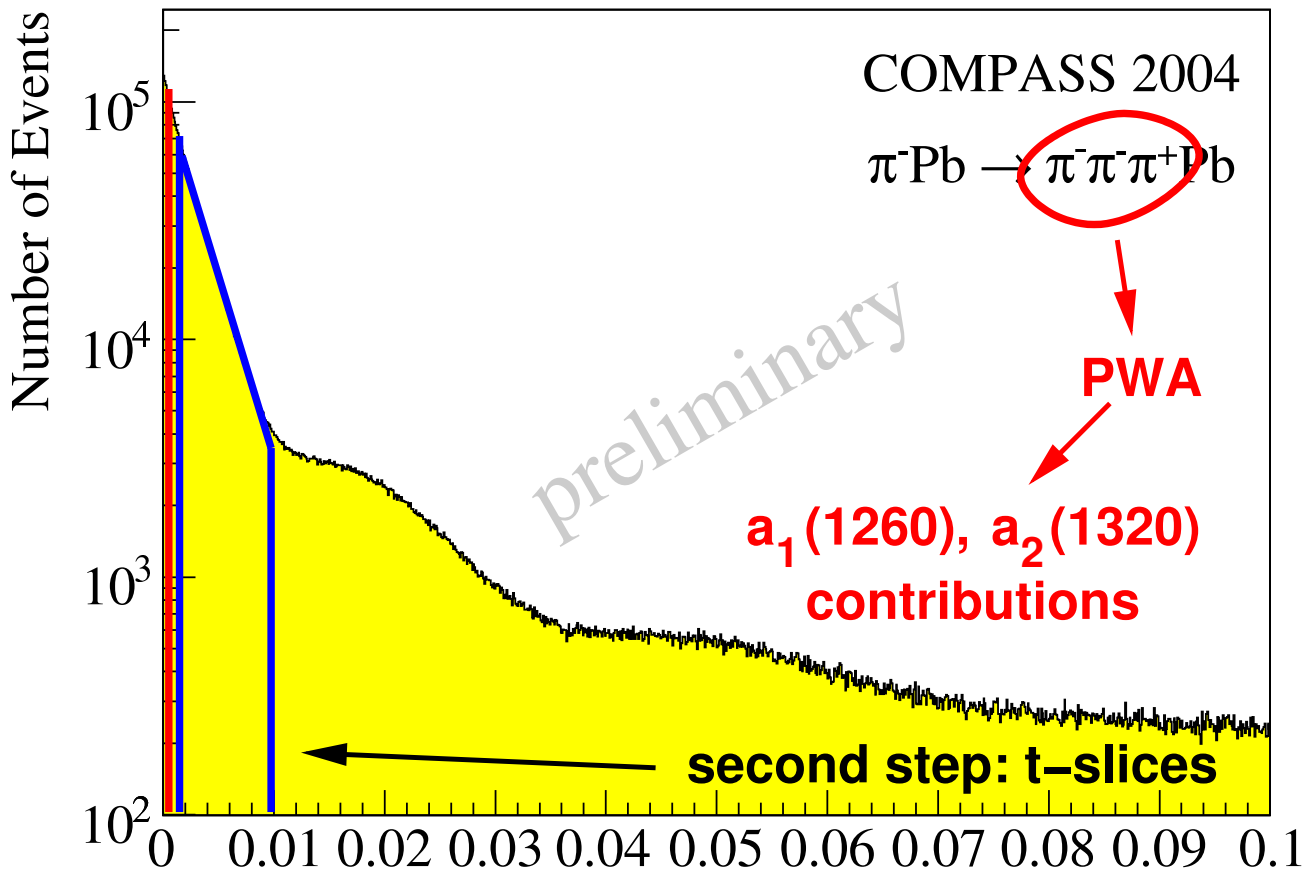
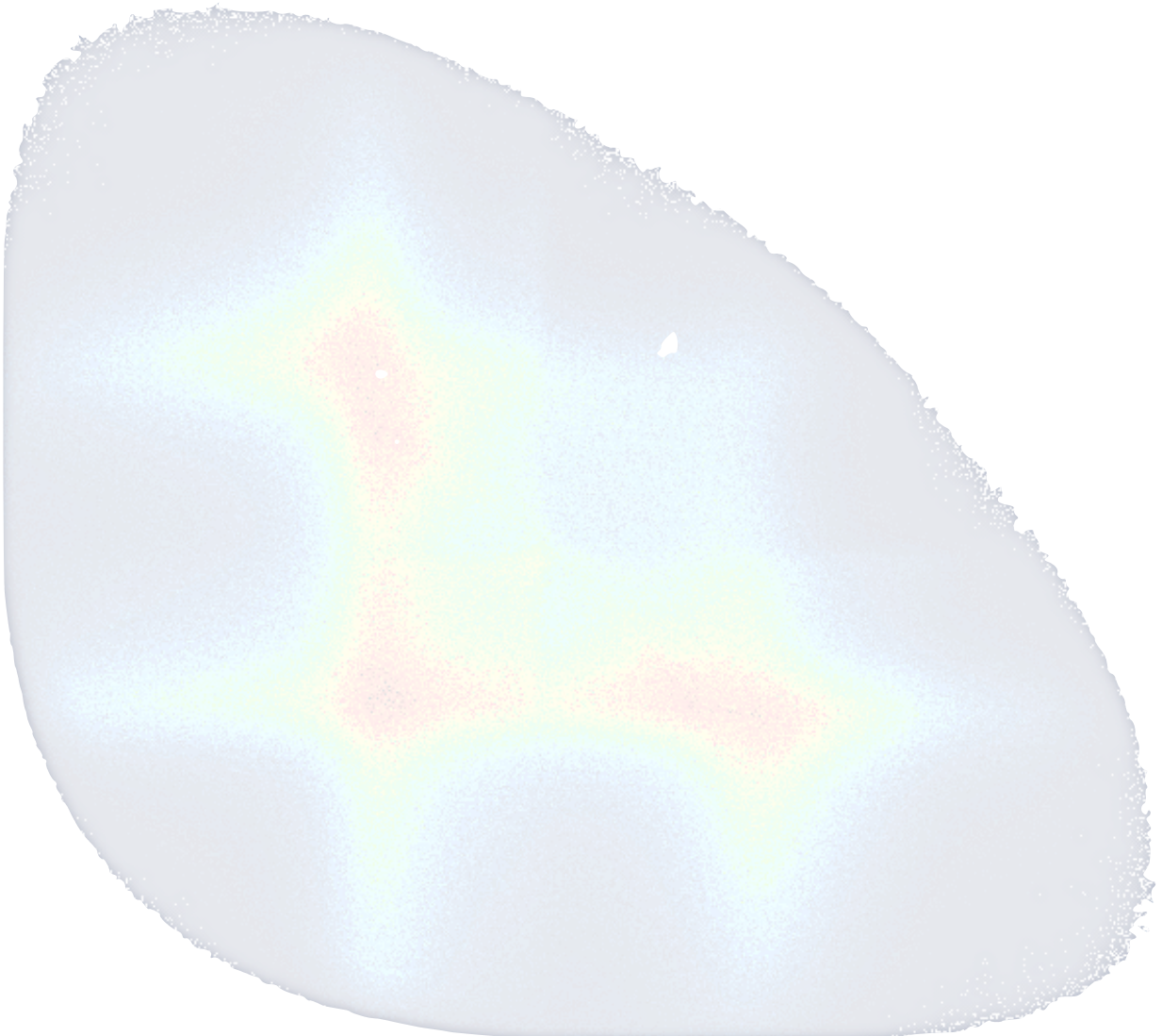


Primakoff 2004



- "Low t'": $10^{-3}\,(\mathrm{GeV}/c)^2 < t' < 10^{-2}\,(\mathrm{GeV}/c)^2$ $\sim 2\,000\,000$ events
- "Primakoff region": $t' < 10^{-3}\,(\mathrm{GeV}/c)^2$ $\sim 1\,000\,000$ events

Nuclear-Coulomb Interference



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- Consider production of 3π at smallest $t < 0.001$ on Pb
  - Scattering in Coulomb field (Primakoff) ($\sigma \sim Z^2$)
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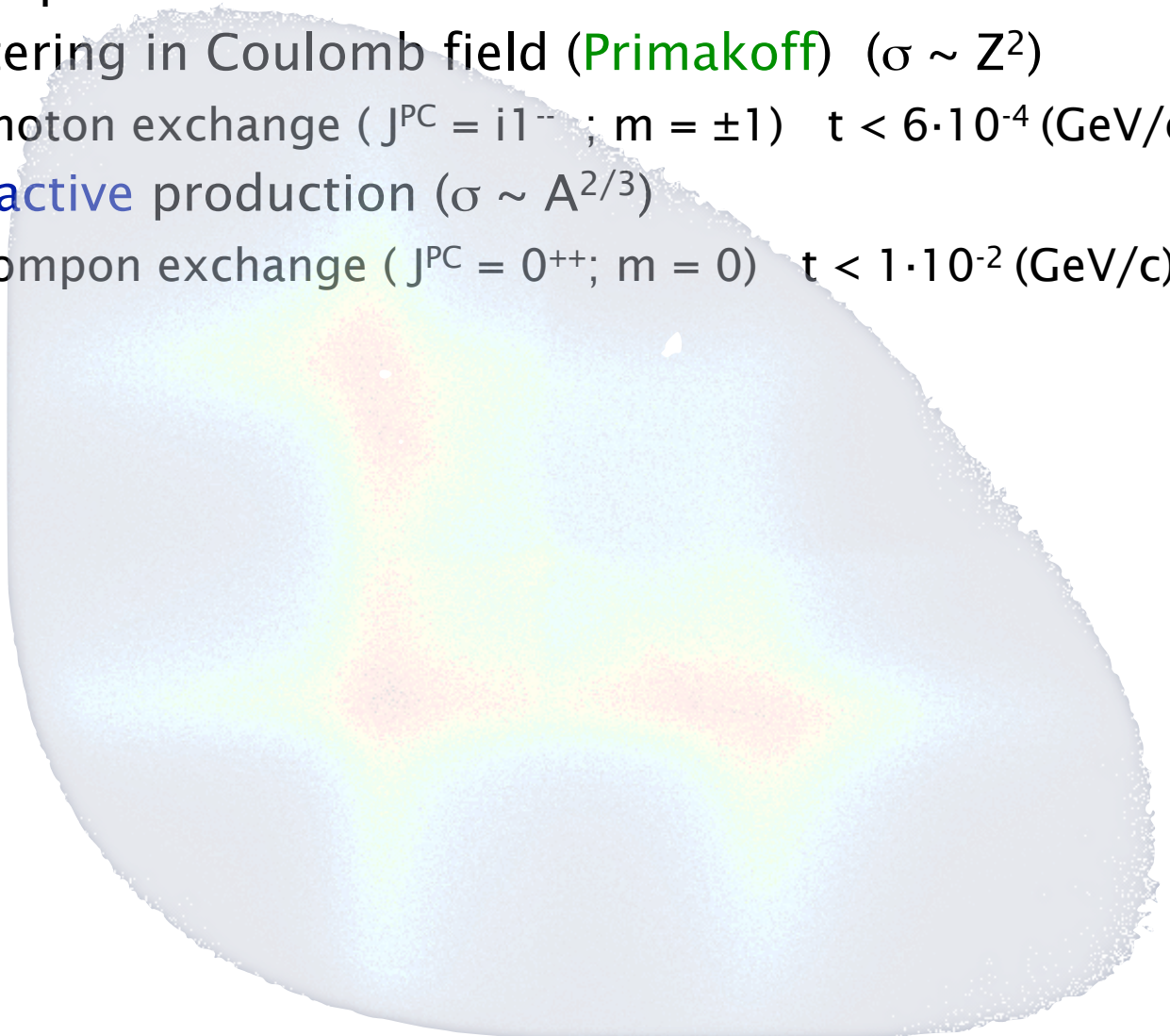

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  - $a_1(1285) : J^{PC} = 1^{++}$ (Δl=1 only via P-exchange for m=0)
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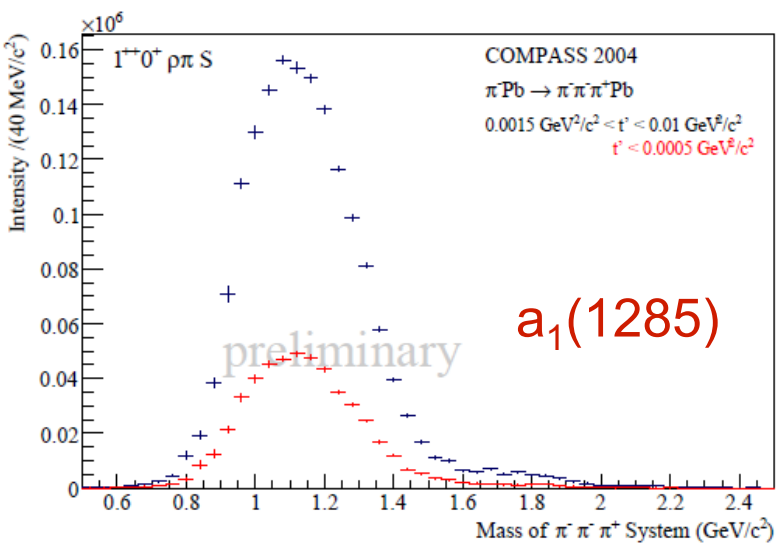

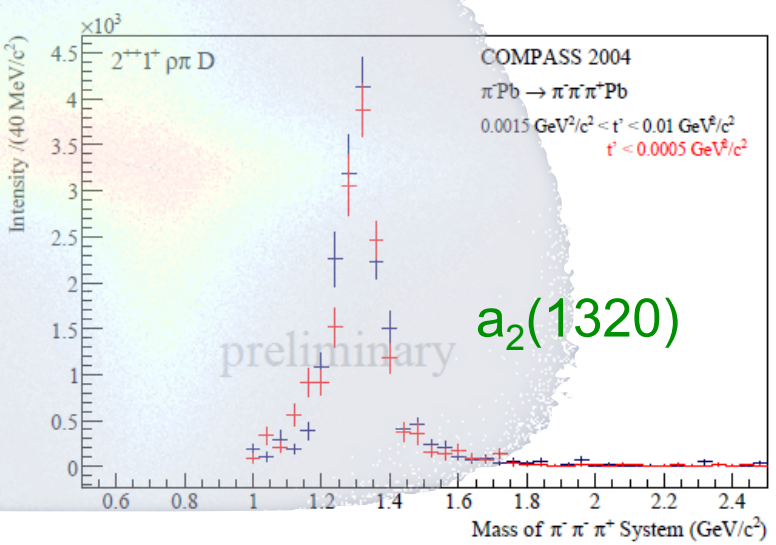

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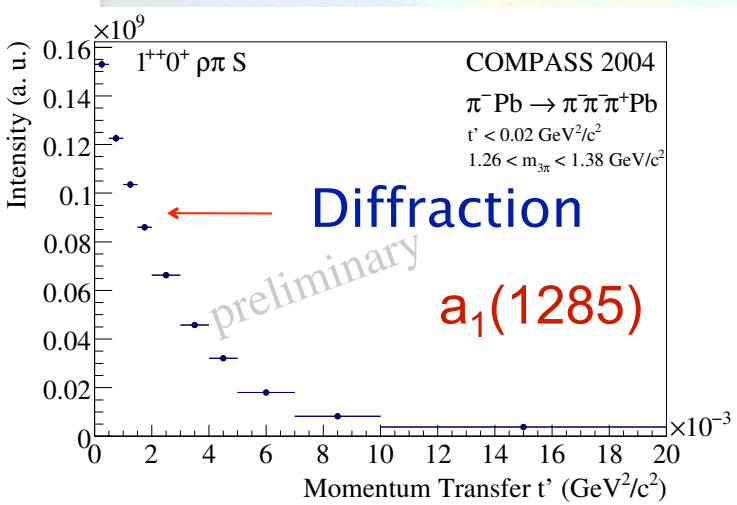

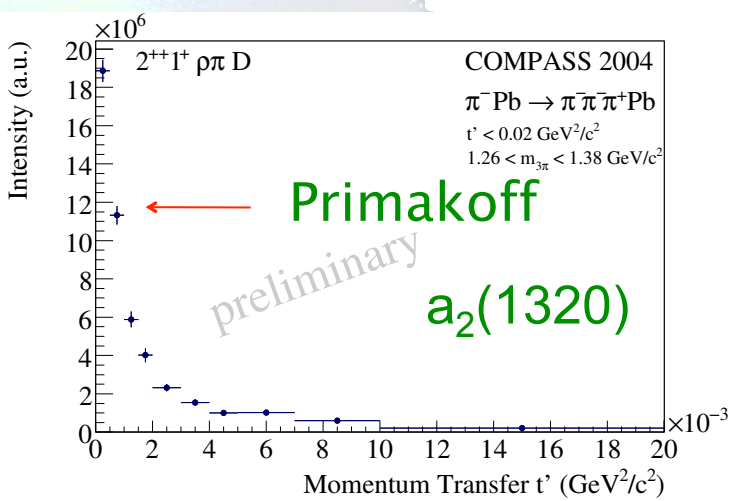

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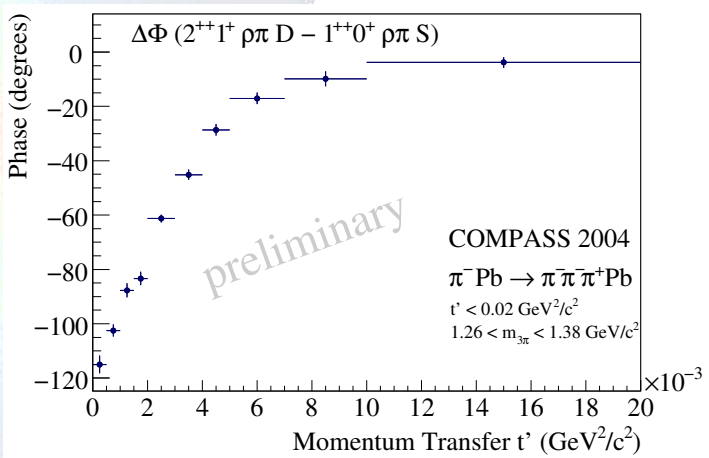
    - t ~ 0:
      - $\Delta\varphi$ (Coulomb/diffractive) ~ 90^0
      - diffractive amplitude purely imaginary
    - for t: 0 → 10^{-2} Diffraction becomes dominant
      Coulomb ~ $1/t^2$
    - Exchange processes well identifiable



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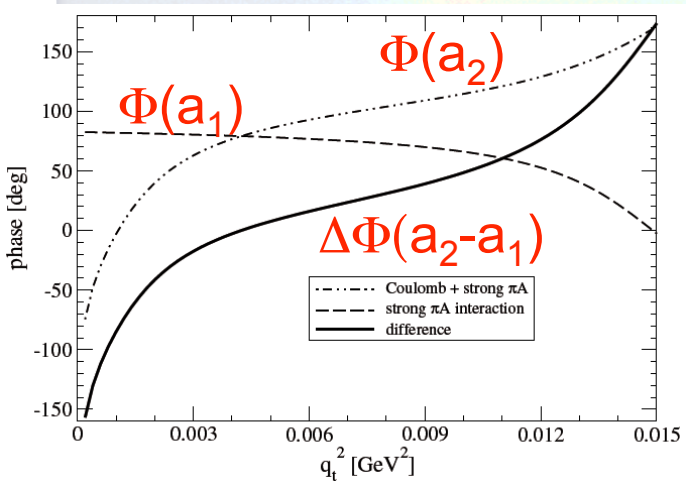
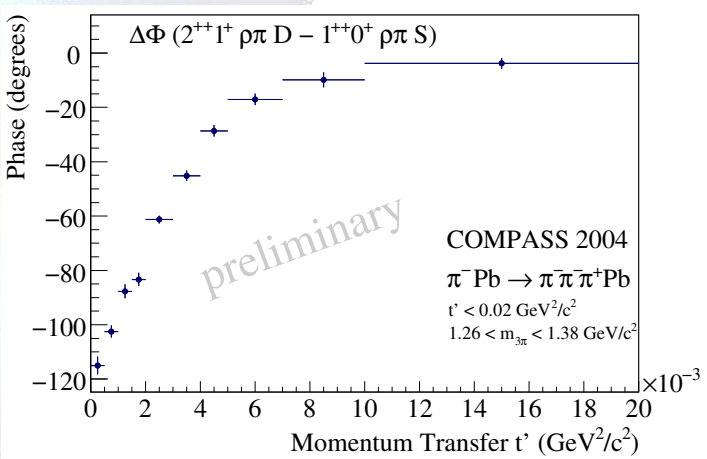
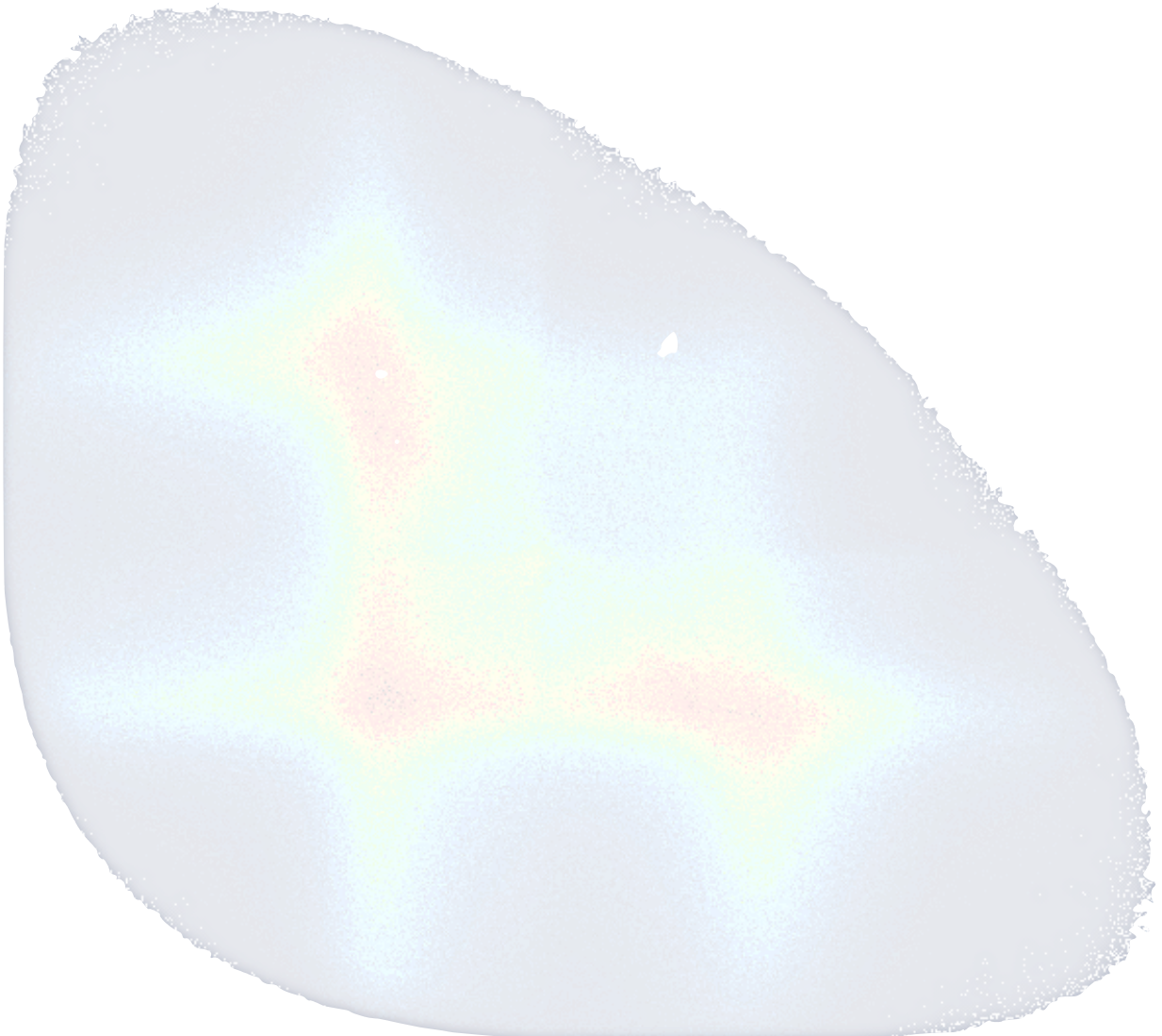


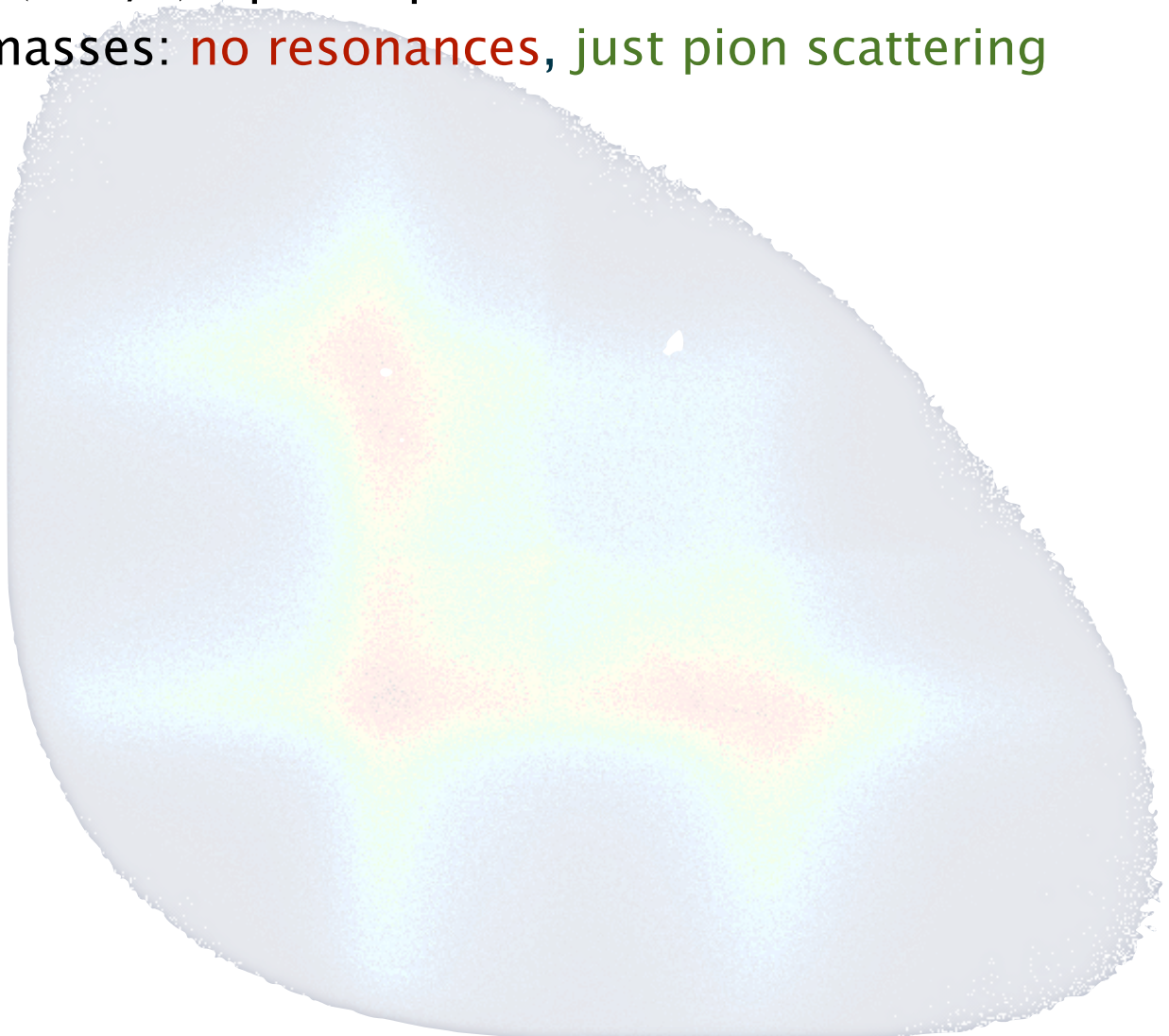


Chiral Dynamics



Chiral Dynamics

- $t' < 10^{-3}$ $(GeV/c)^2$: photo production in M=1 waves
  - Low masses: no resonances, just pion scattering



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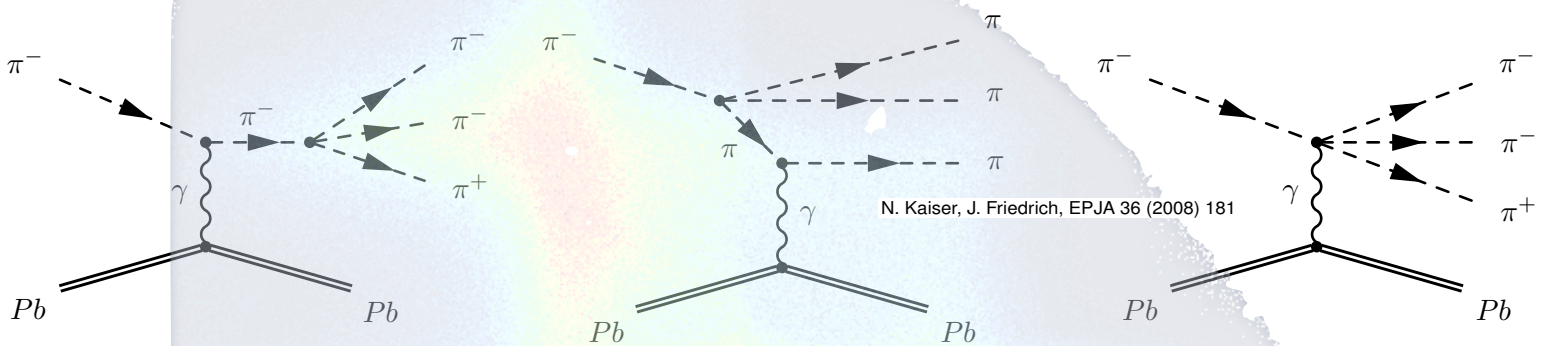

N. Kaiser, J. Friedrich, EPJA 36 (2008) 181

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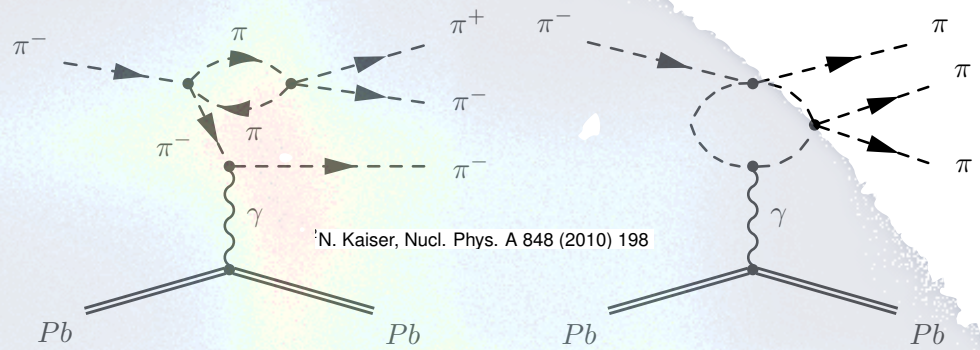

[1] N. Kaiser, Nucl. Phys. A 848 (2010) 198

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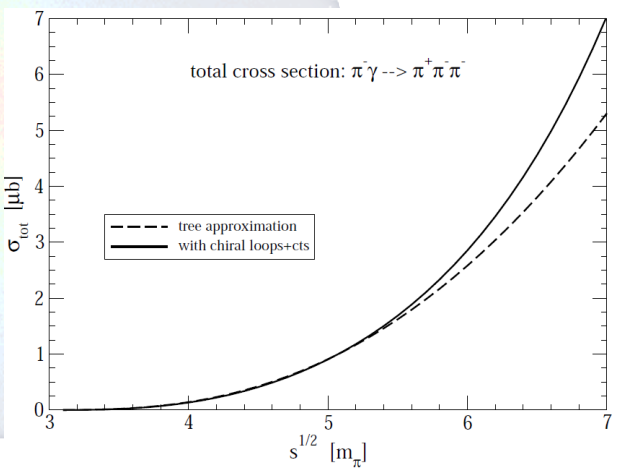
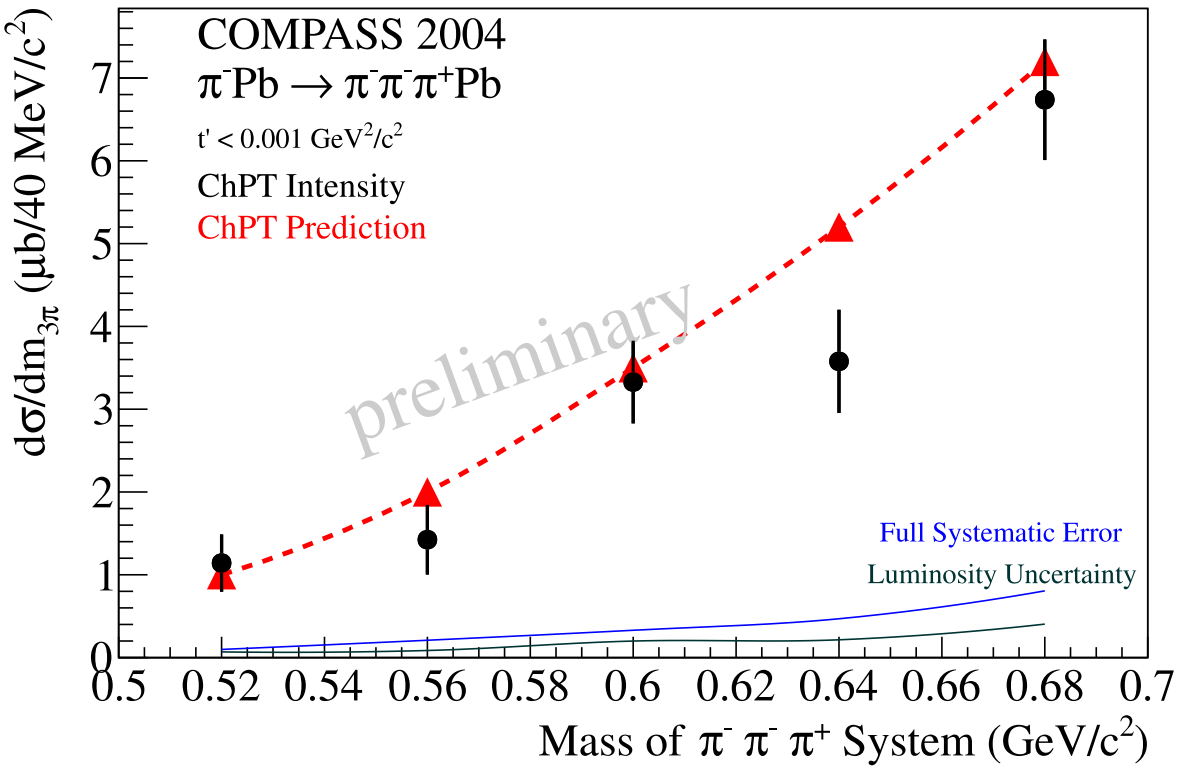
- ChPT Amplitude introduced as single partial wave
  - Not orthogonal to waves in isobar model
  - Replaces (up to 6) $(\pi\pi)_S\,\pi$. And $\rho\pi$ waves by single amplitude
- ChPT valid (at least) 0.5 GeV/c^2 < $m_{3\pi}$ < 0.7 GeV/c^2
- Higher masses: Isobaric decays



Chiral Dynamics

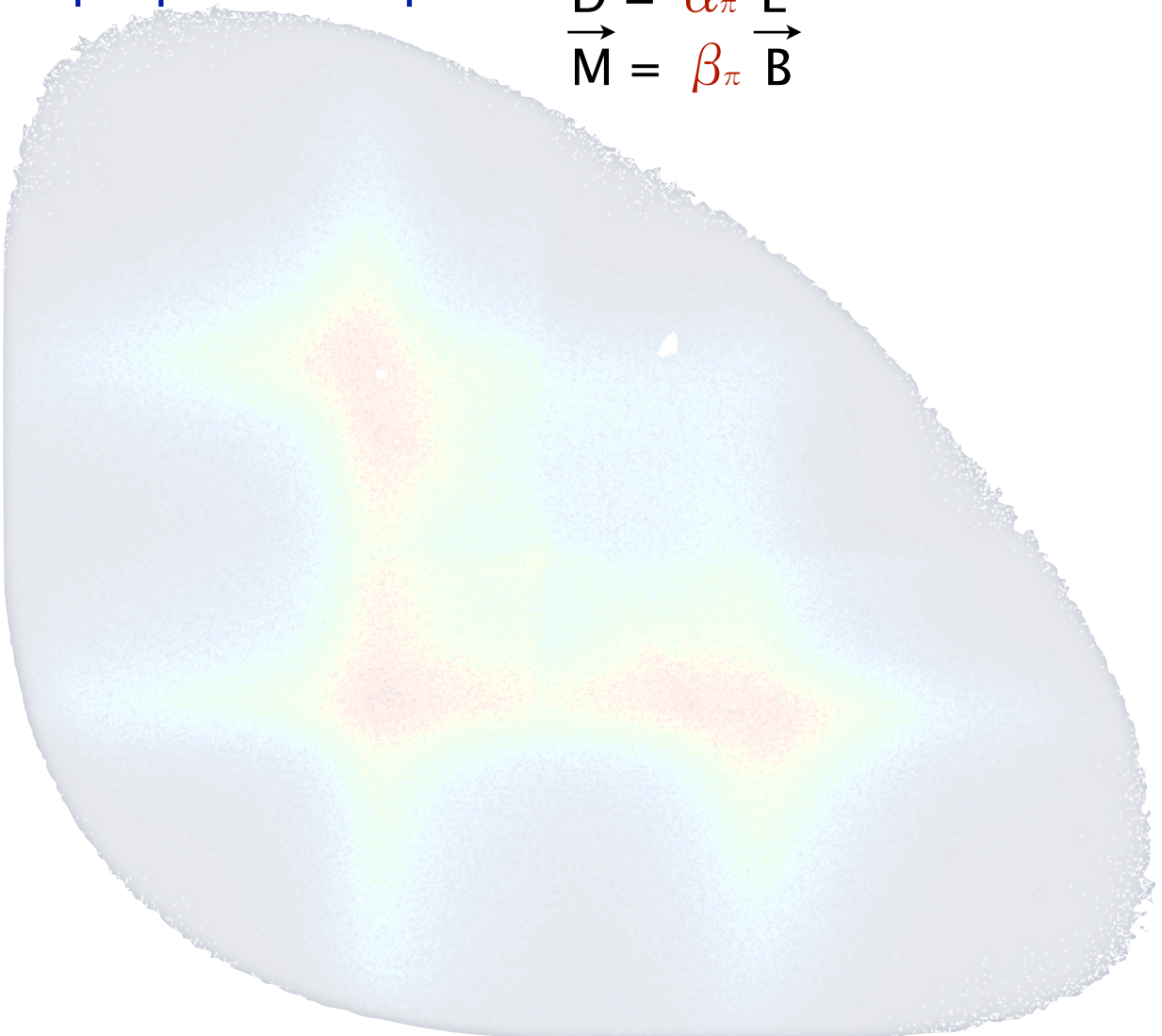


- Fits nicely.....

Polarisabilities

- Determine properties of pion

$$\vec{D} = \alpha_\pi \vec{E}$$
$$\vec{M} = \beta_\pi \vec{B}$$



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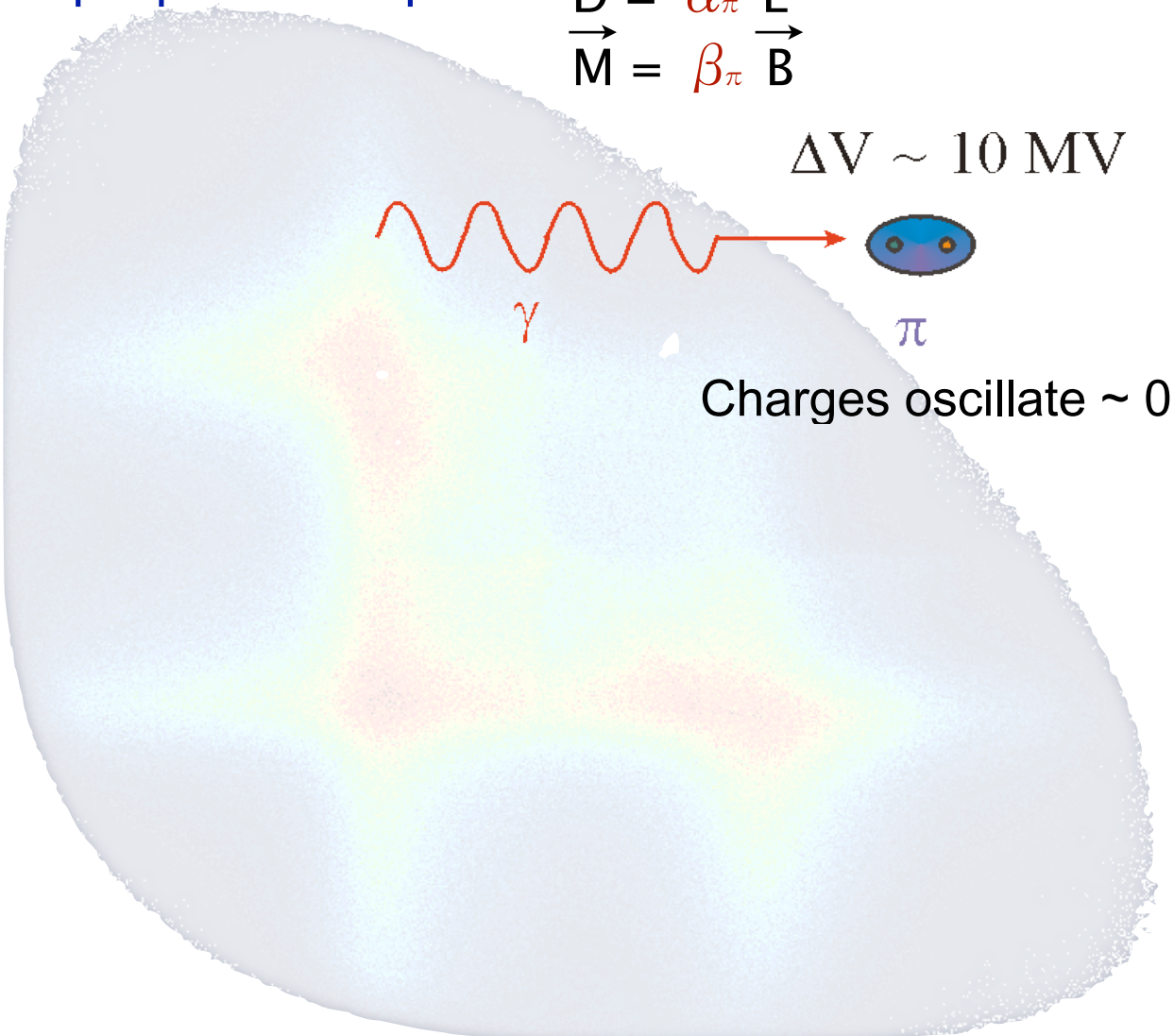

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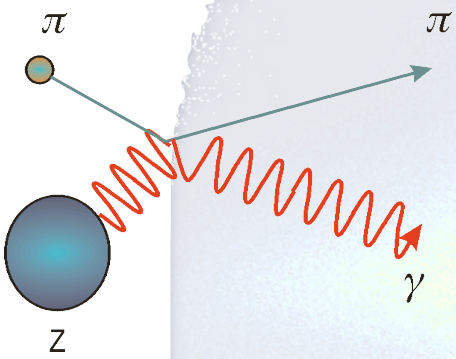

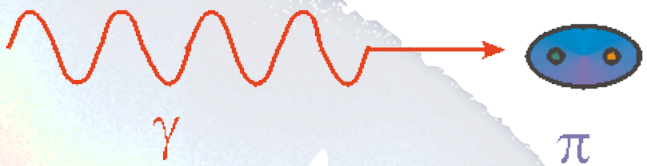

Charges oscillate ~ 0.1% π

Polarisabilities

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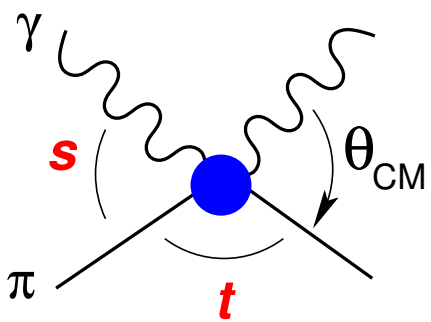

$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \frac{\alpha^2(s^2 z_+^2 + m_\pi^4 z_-^2)}{s(sz_+ + m_\pi^2 z_-)^2} - \frac{\alpha\, m_\pi^3 (s - m_\pi^2)^2}{4s^2(sz_+ + m_\pi^2 z_-)} \cdot \mathcal{P}$$

where

$$z_\pm = 1 \pm \cos\theta_{cm}$$

$$\mathcal{P} = z_-^2(\alpha_\pi - \beta_\pi) + \frac{s^2}{m_\pi^4} z_+^2(\alpha_\pi + \beta_\pi) - \frac{(s - m_\pi^2)^2}{24s} z_-^3(\alpha_2 - \beta_2)$$

Polarisabilities

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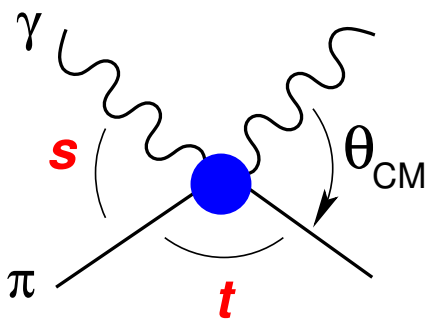

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- leading (non-pointlike) order: $(\alpha_\pi - \beta_\pi)$

  $\longrightarrow$ suppression of large E_γ^{lab}

- next ("*s*-dependent") order: $(\alpha_\pi + \beta_\pi)$ *and* $(\alpha_2 - \beta_2)$

Polarisabilities

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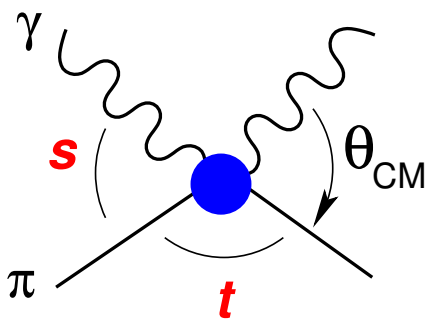

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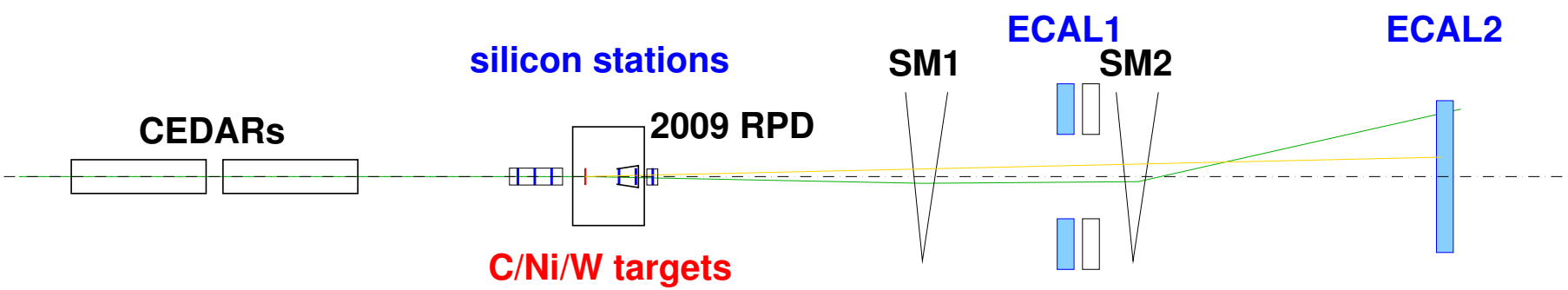
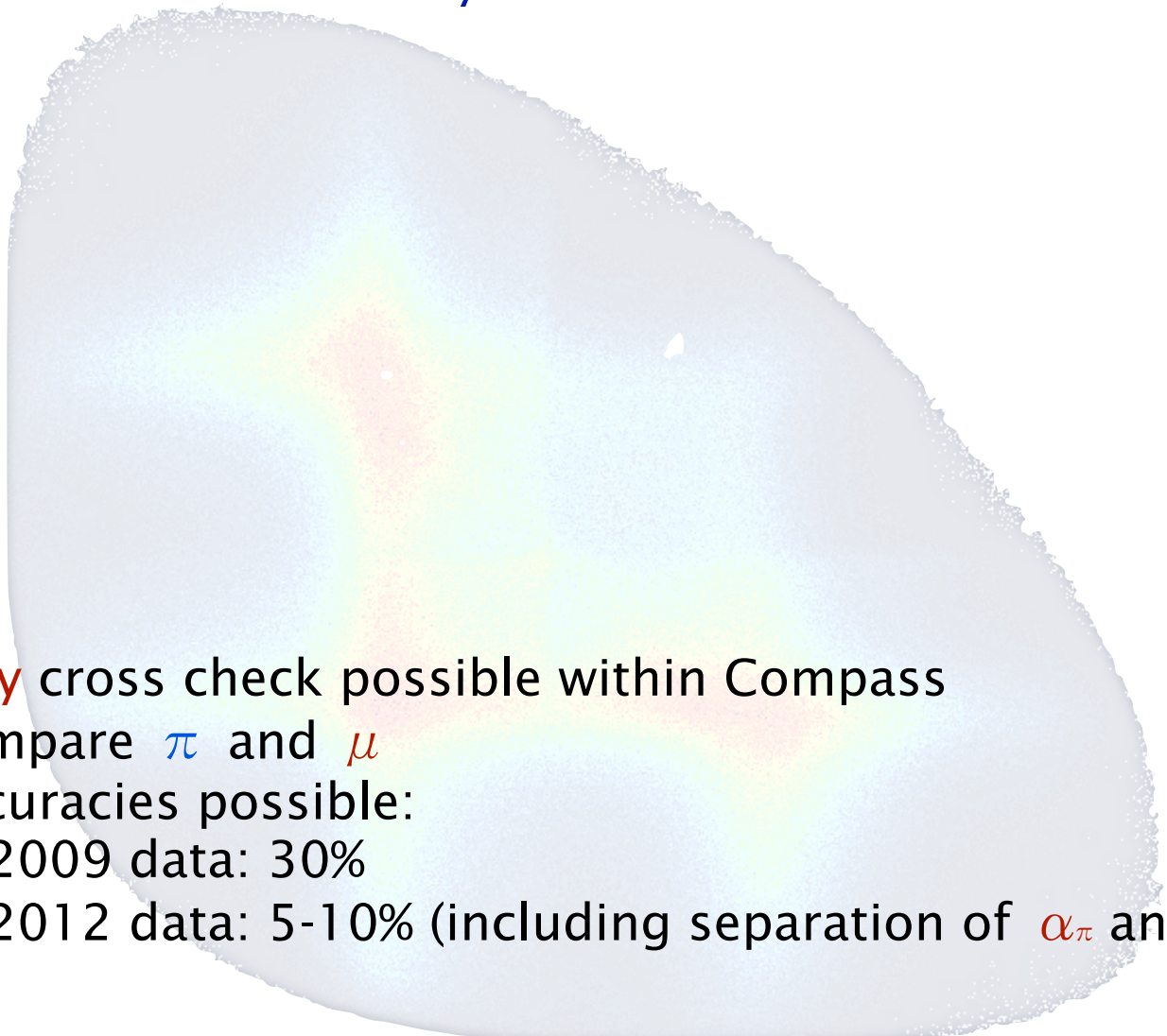


Polarisabilities II

- Where to look kinematically ?



- Quality cross check possible within Compass
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    - 2009 data: 30%
    - 2012 data: 5-10% (including separation of α_π and β_π)

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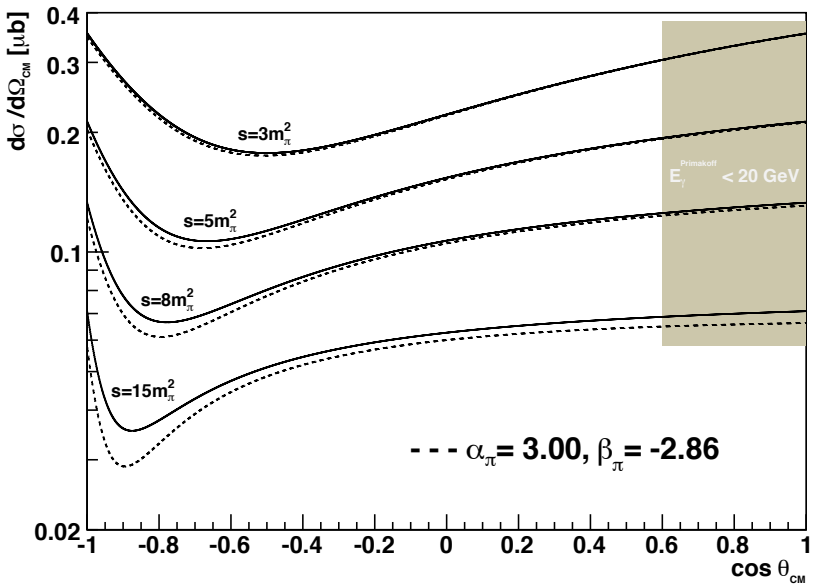

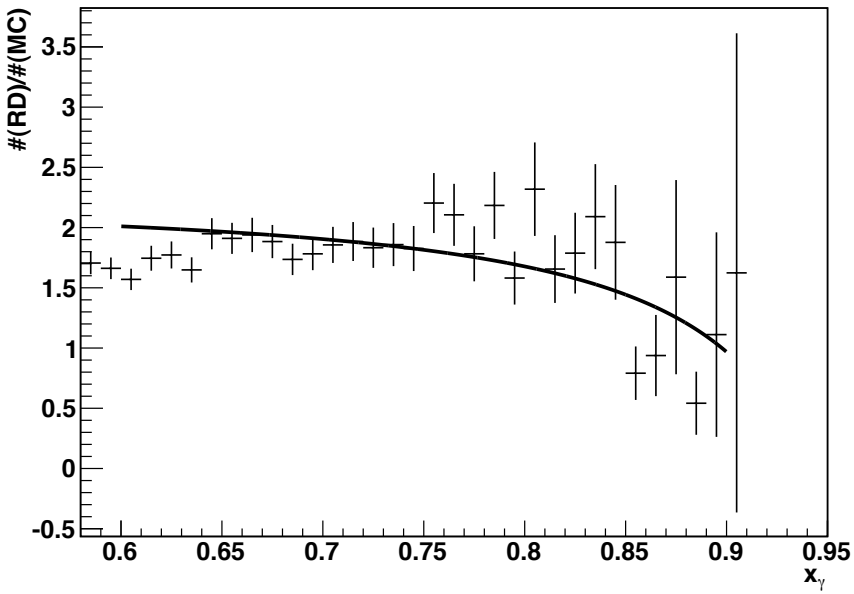

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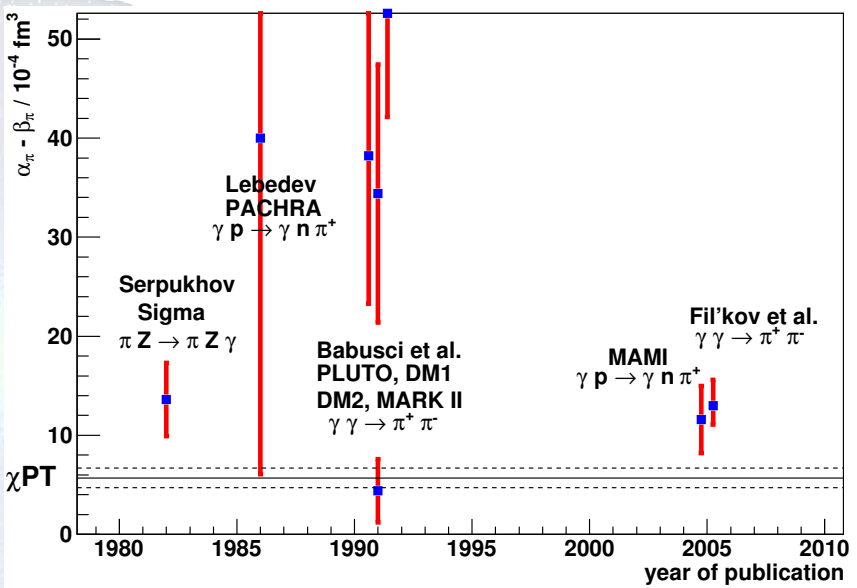

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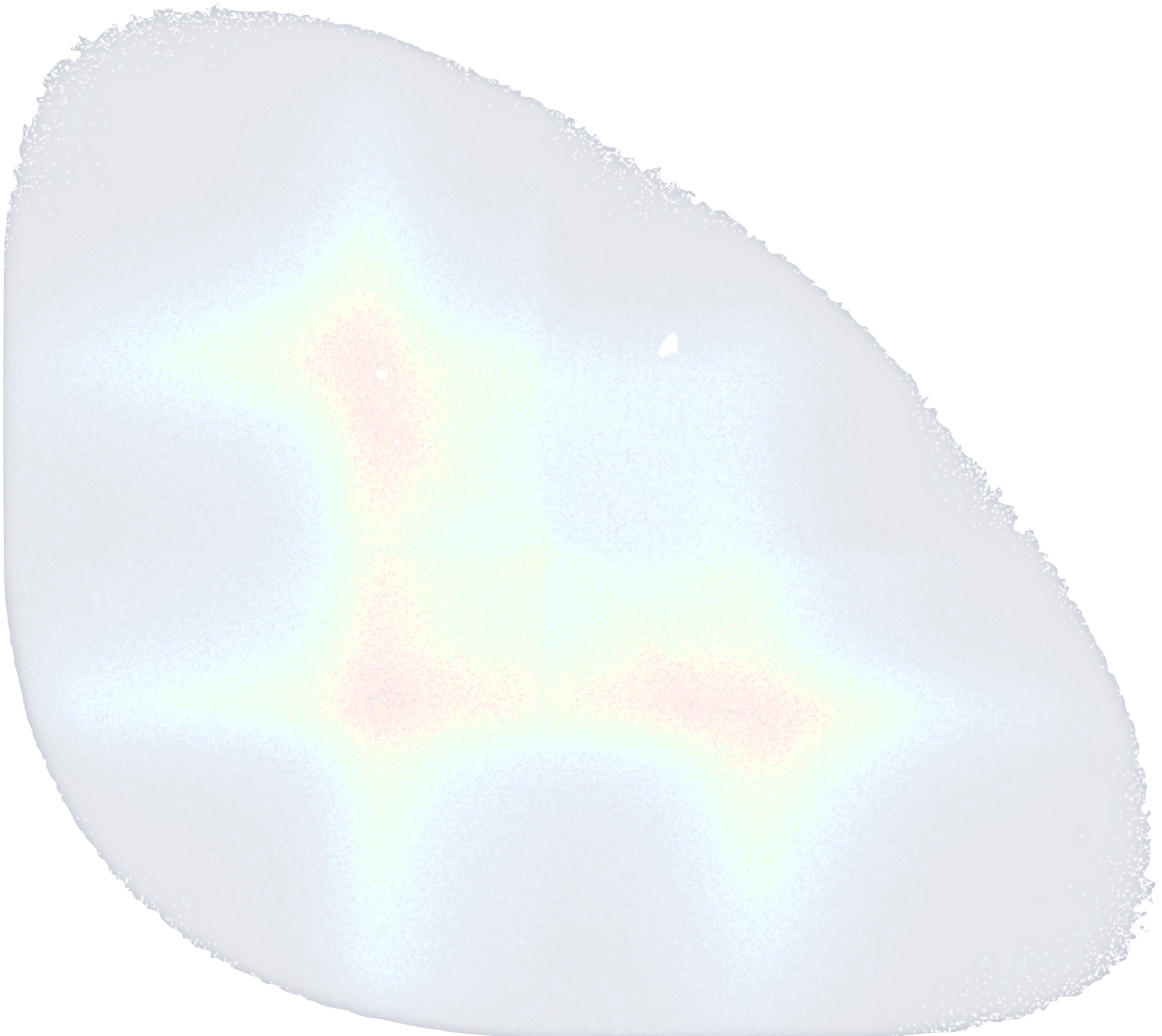
Conclusions

- COMPASS has active spectroscopy program
  - PWA Tools developed
  - More refined PWA underway: larger wave set, Deck effect
  - **High statistics** (partly > 200 times previous work) in many channels
- Results:
  - Observe consistent signal on exotic $\pi_1(1600)$ in diffraction (3π)
  - Nuclear dependence of production characteristics (also seen in 2009)
  - Neutral channels show consistent signals $\pi^-\pi^0\pi^0$
  - 5π analysis ongoing (complex analysis)
  - Central production analysis in 4π and kaonic channels underway
  - Baryon spectroscopy may be add on
  - Primakoff physics reveals many aspects (also new)
  - Coulomb-nuclear interference
- Analysis future: adress high mass region, chiral dynamics, polarisability (run 2012)

More Results ad HADRON2011



From Quarks to Hadrons

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- Hadron: colour neutral system of quarks
  - Baryon (qqq)
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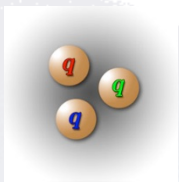

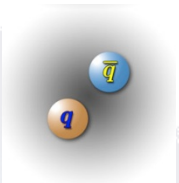

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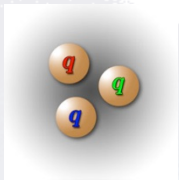

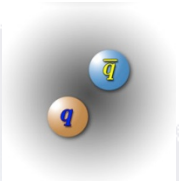

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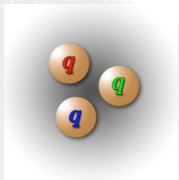

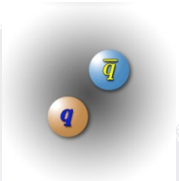

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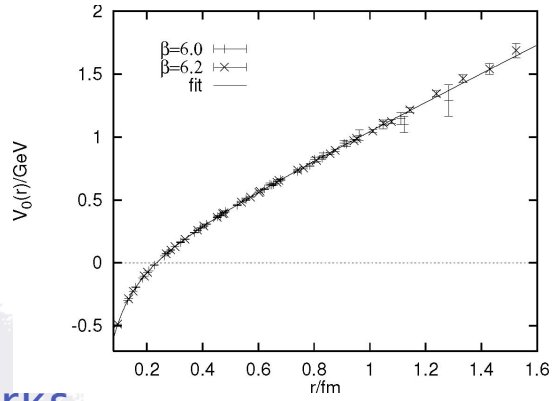

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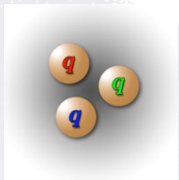

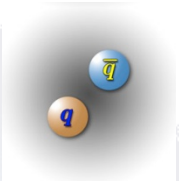

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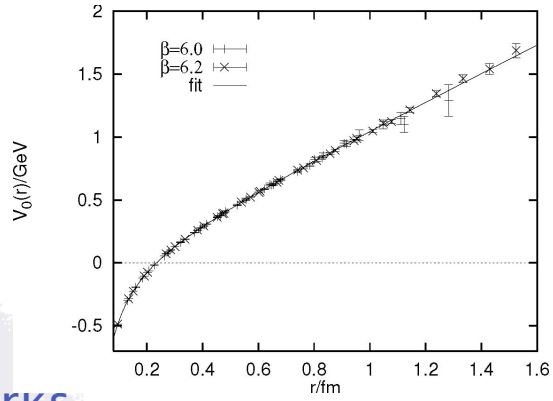

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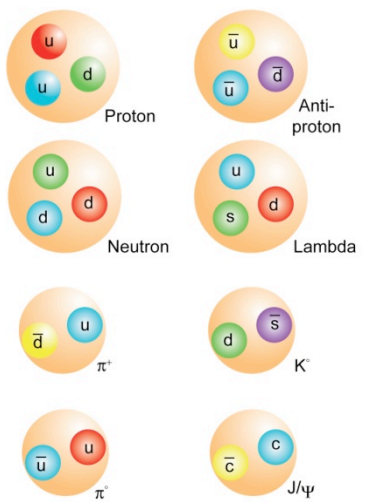

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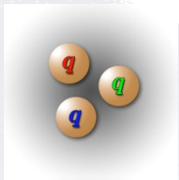

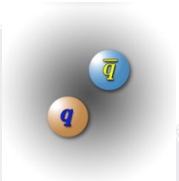

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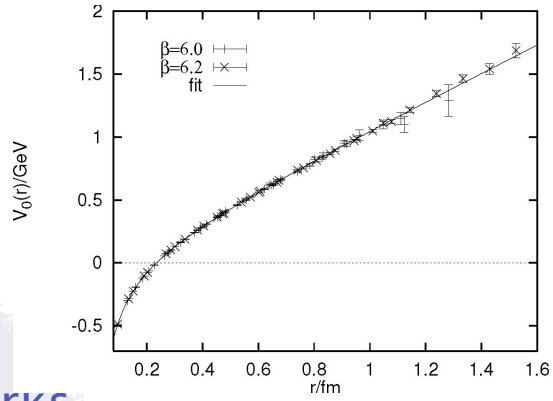

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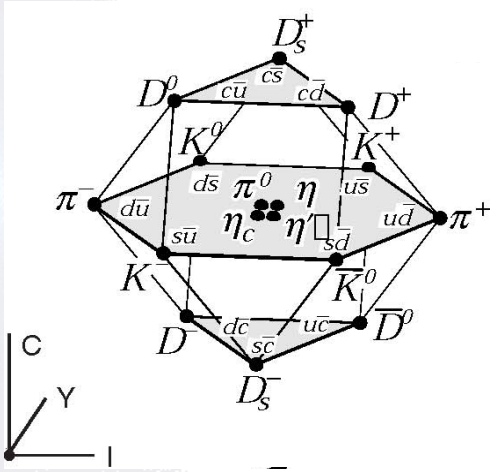
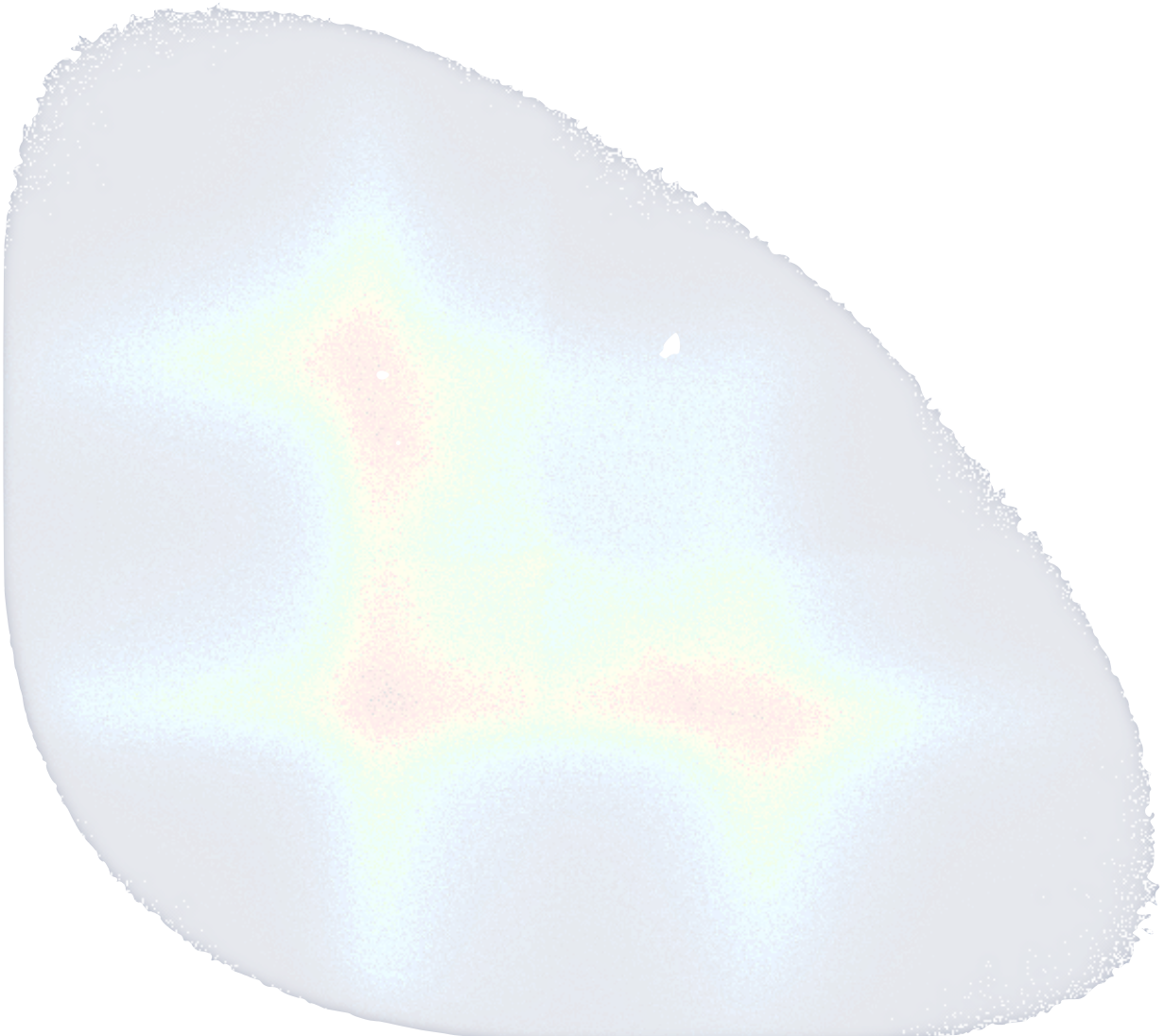
  - Classify into multiplets

    Hadron masses are sum of quark masses



  - Use hyperfine-interaction (spin-spin interaction)
    mass spectrum surprisingly well described

3π Final State: $\pi^- p \rightarrow \pi^- \pi^0 \pi^0 p$



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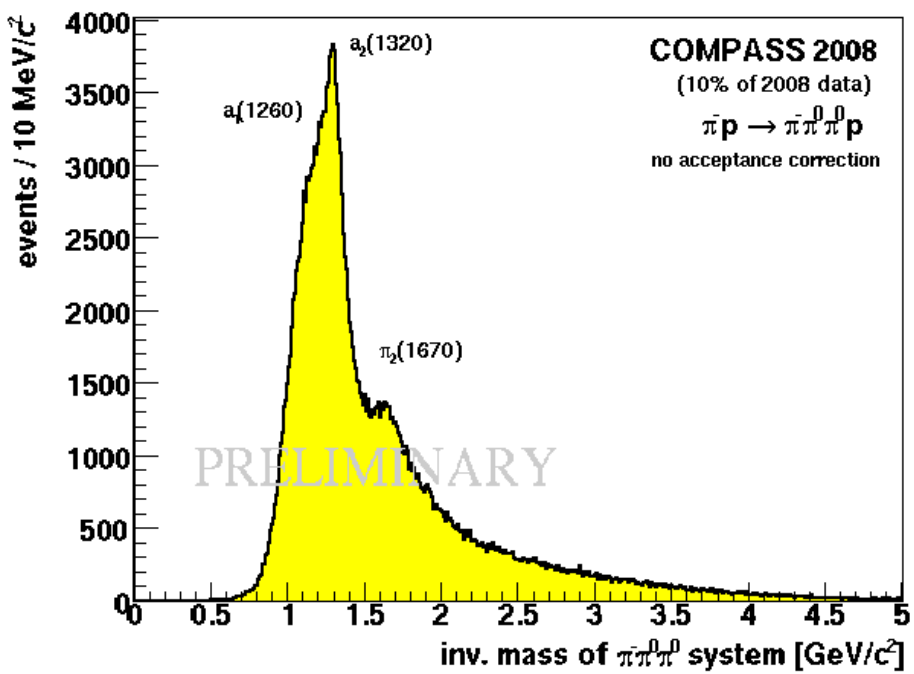

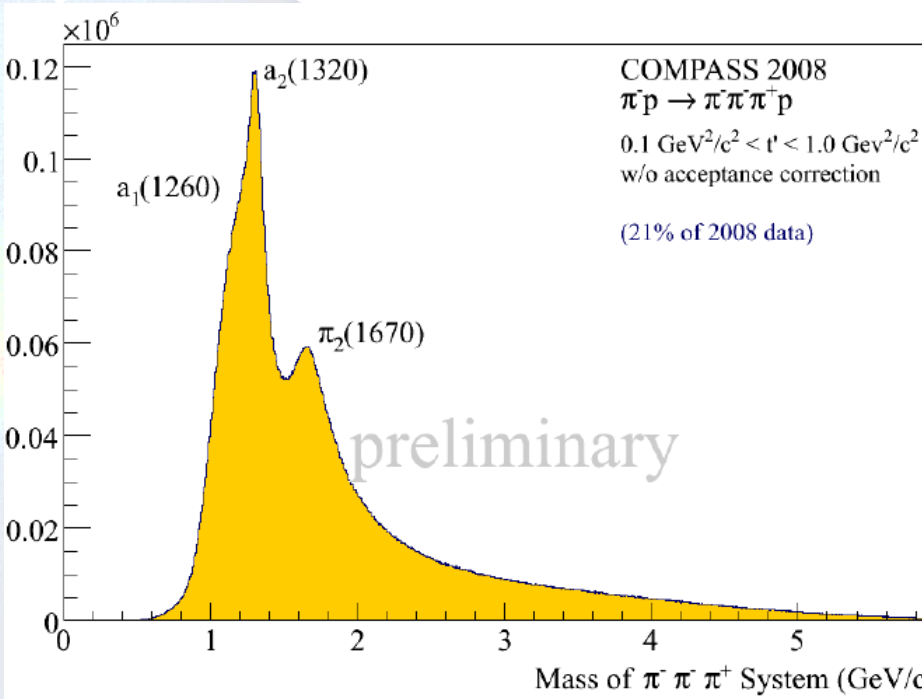

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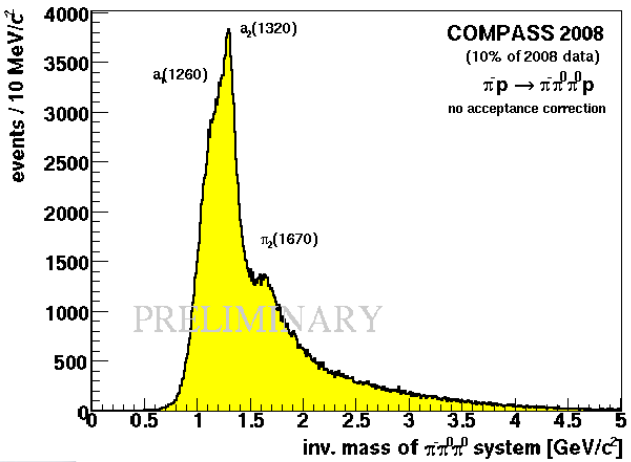

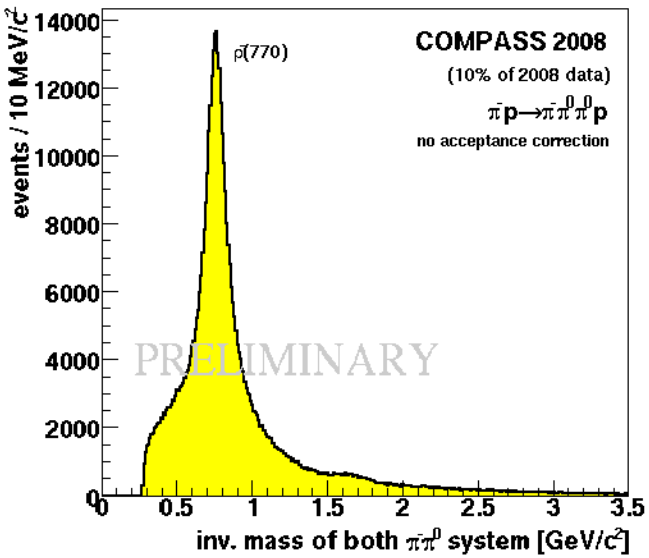

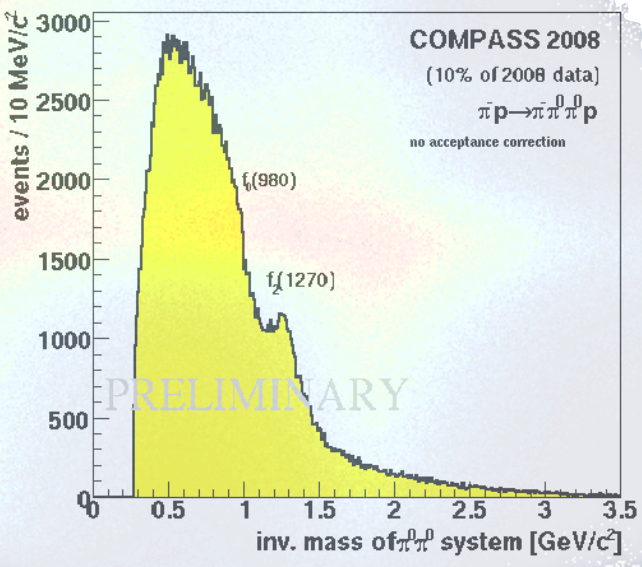

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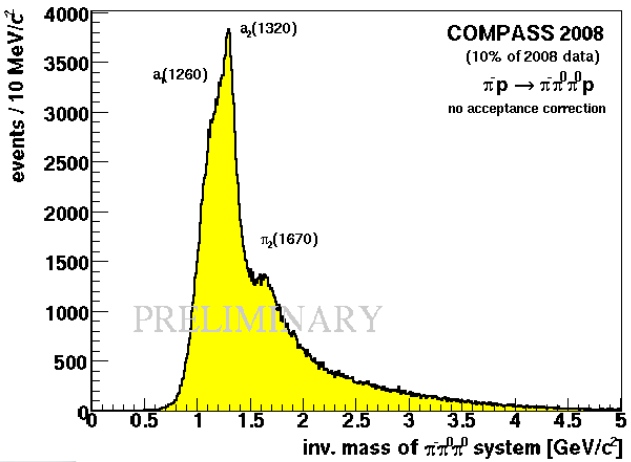

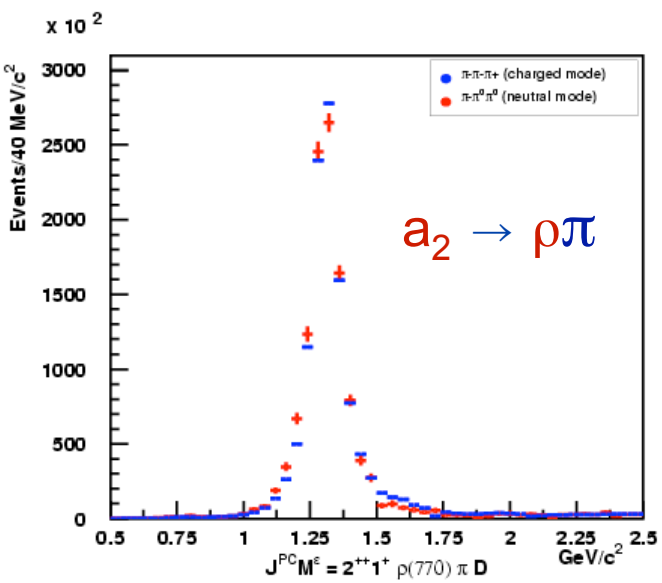

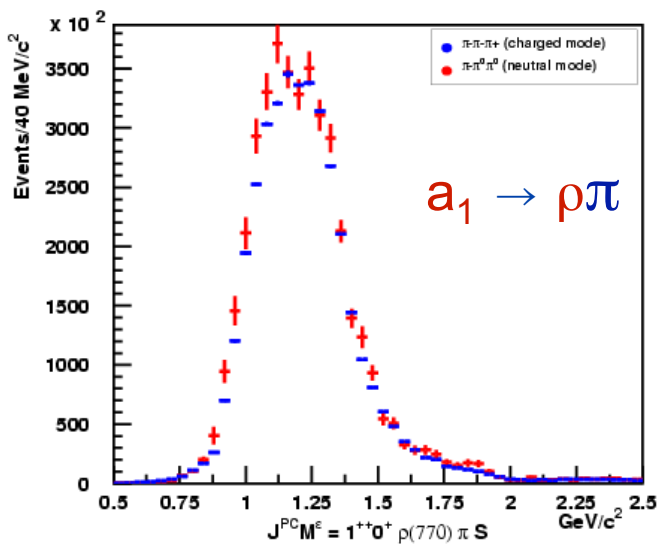

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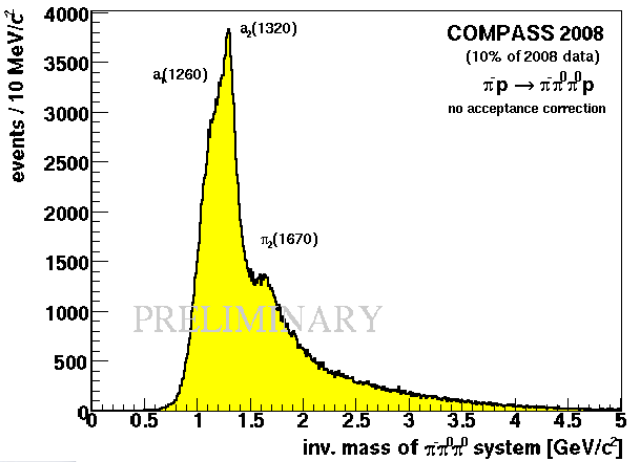
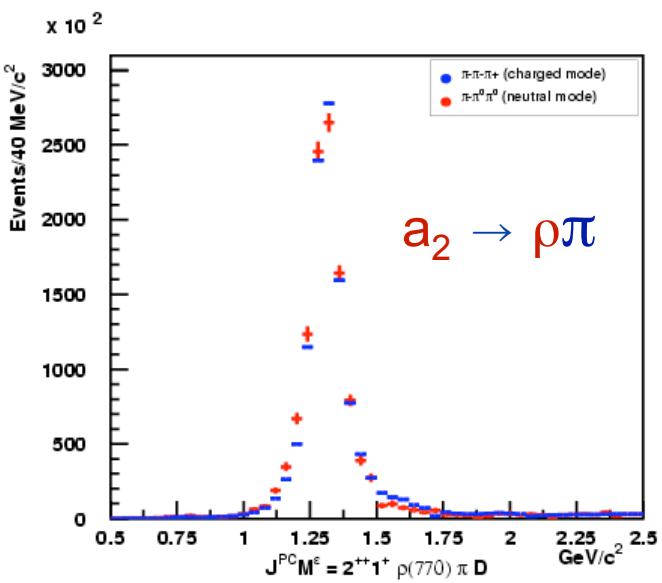
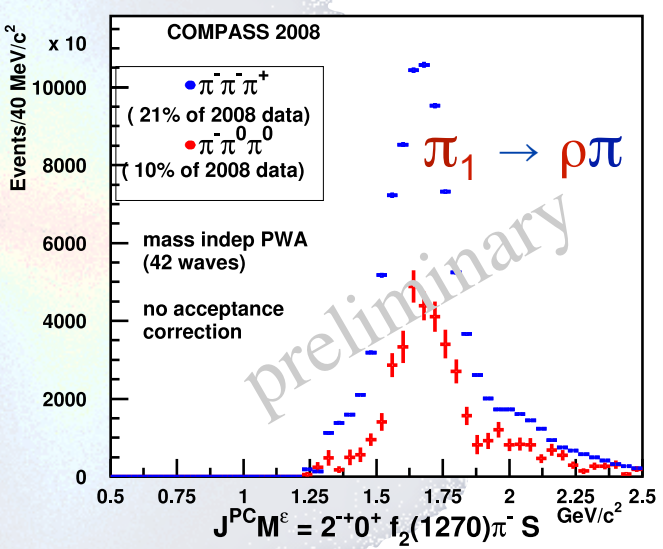
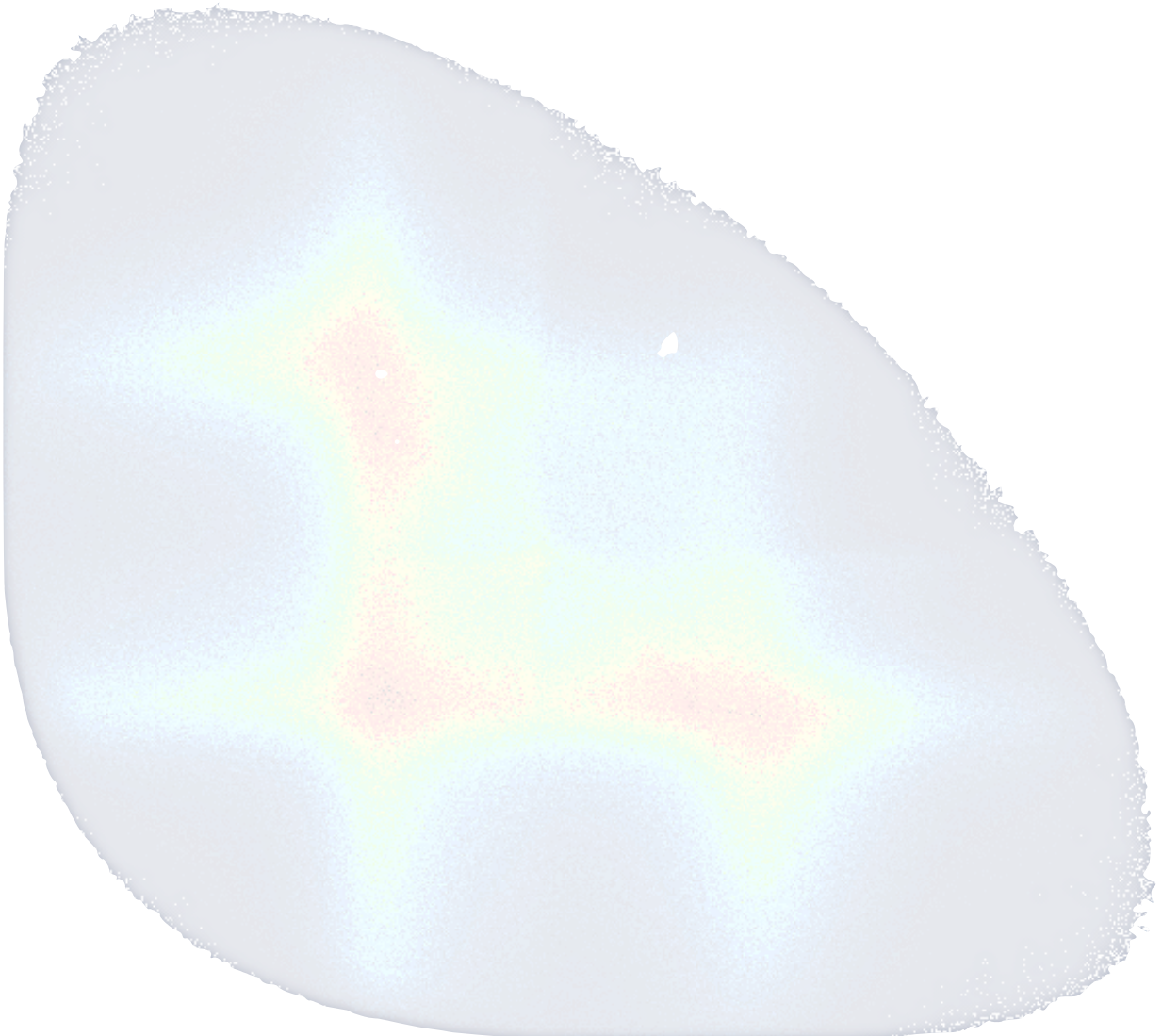






Conclusions



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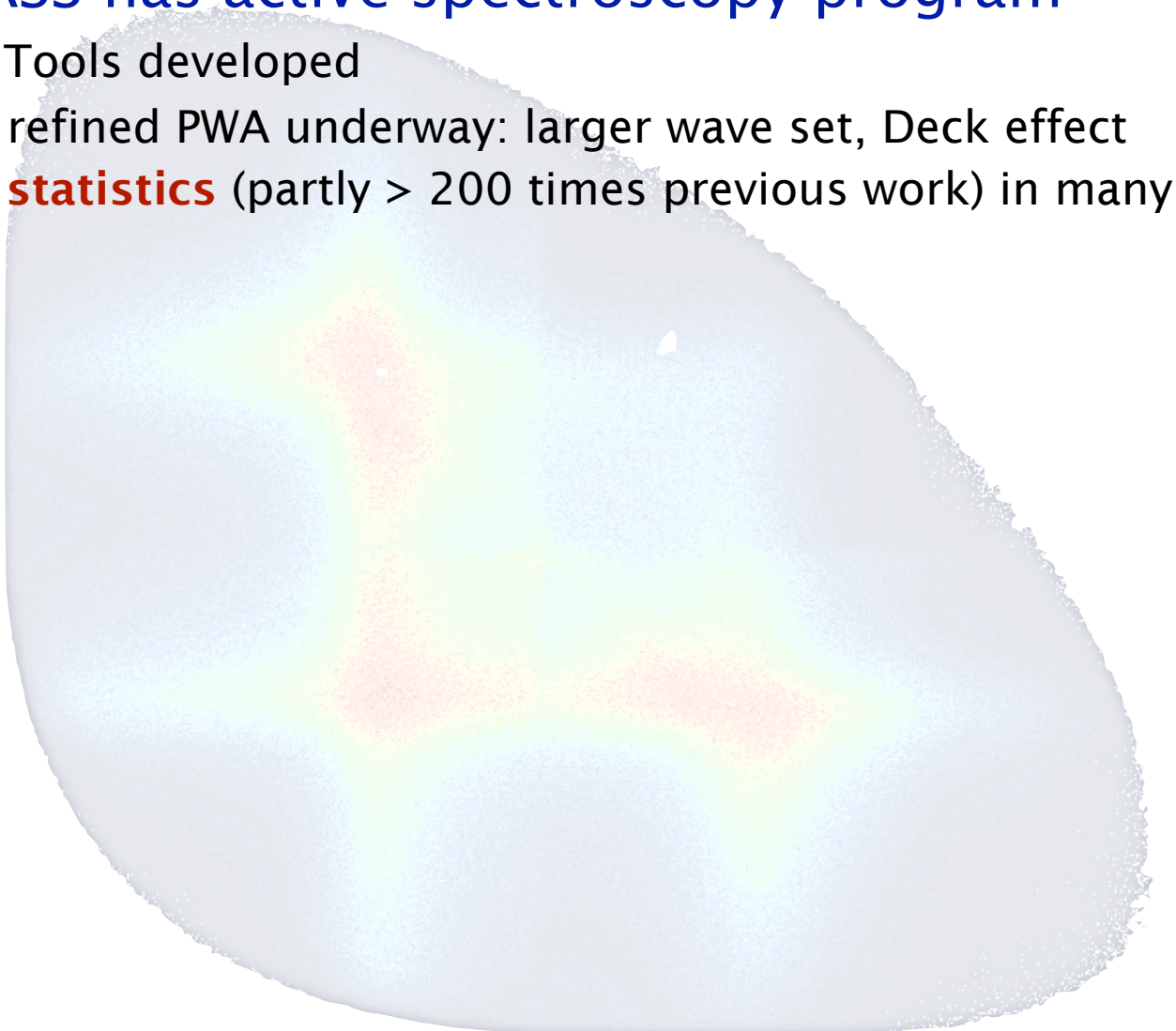

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  - PWA Tools developed
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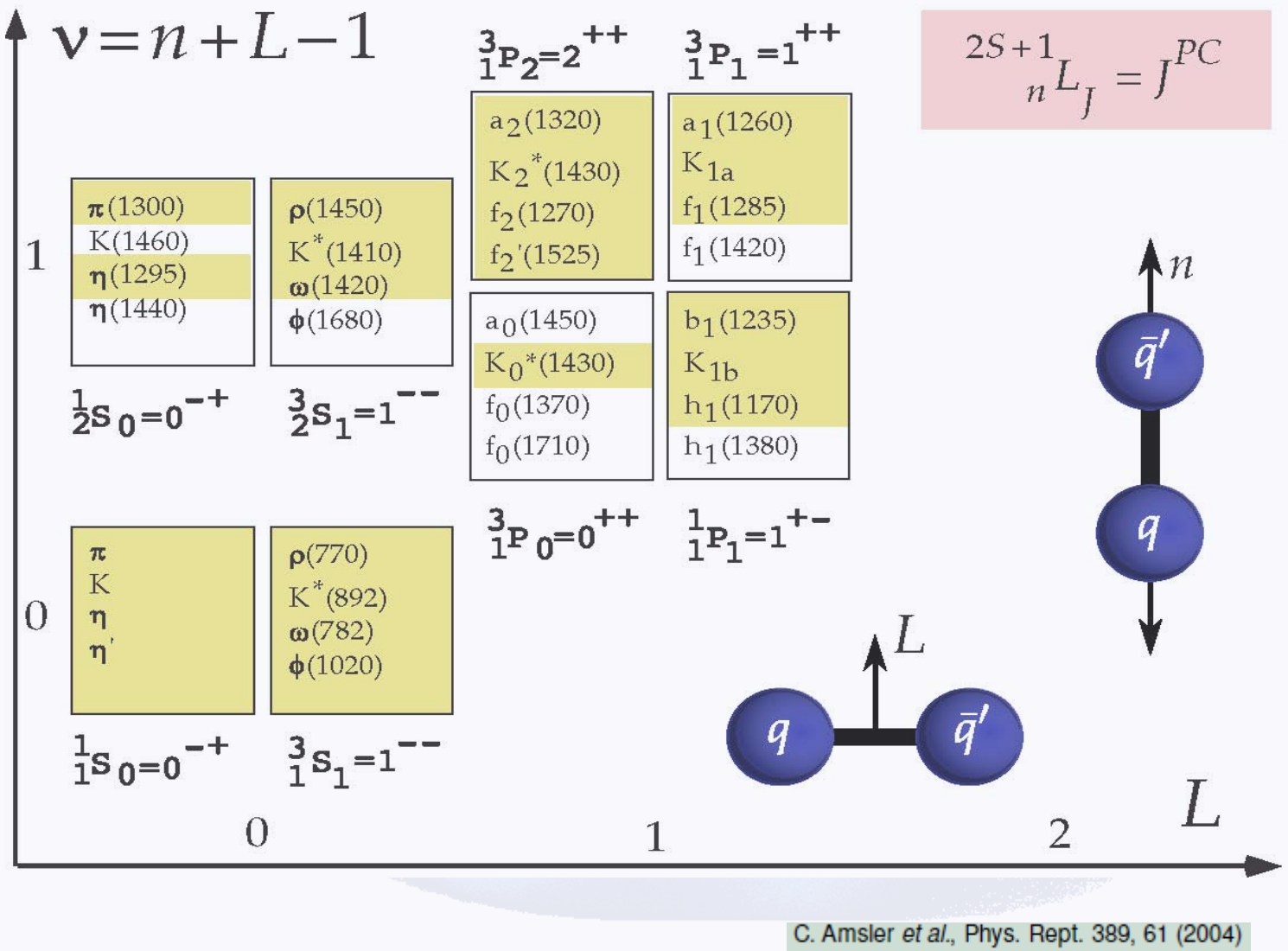
- Analysis future: adress high mass region, chiral dynamics, polarisability

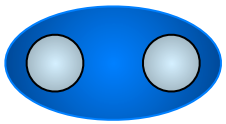
Constituent Quark Model III

Spectrum light mesons:



C. Amsler *et al.*, Phys. Rept. 389, 61 (2004)

Meson-Spectroscopy



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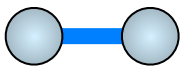

$(q\bar{q})_0$

Quark model: bound states of $q\bar{q}$

Quantum numbers: $I^G\ (J^{PC})$

$P=(-1)^{l+1}$, $C=(-1)^{l+s}$, $G=(-1)^{I+l+s}$

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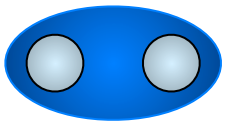

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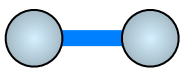

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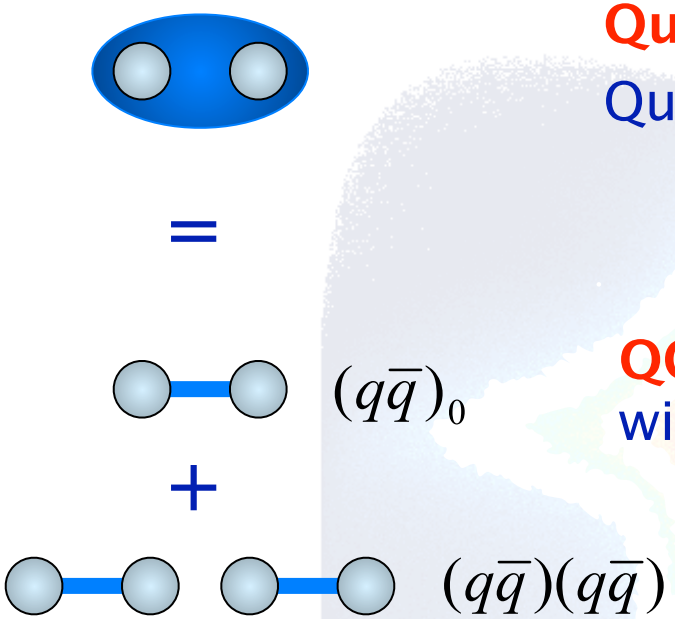

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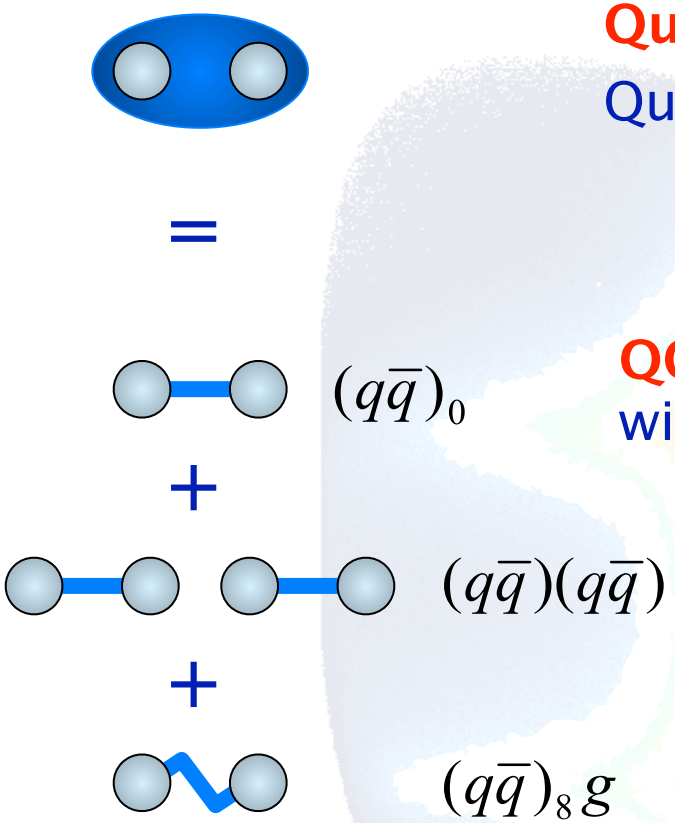

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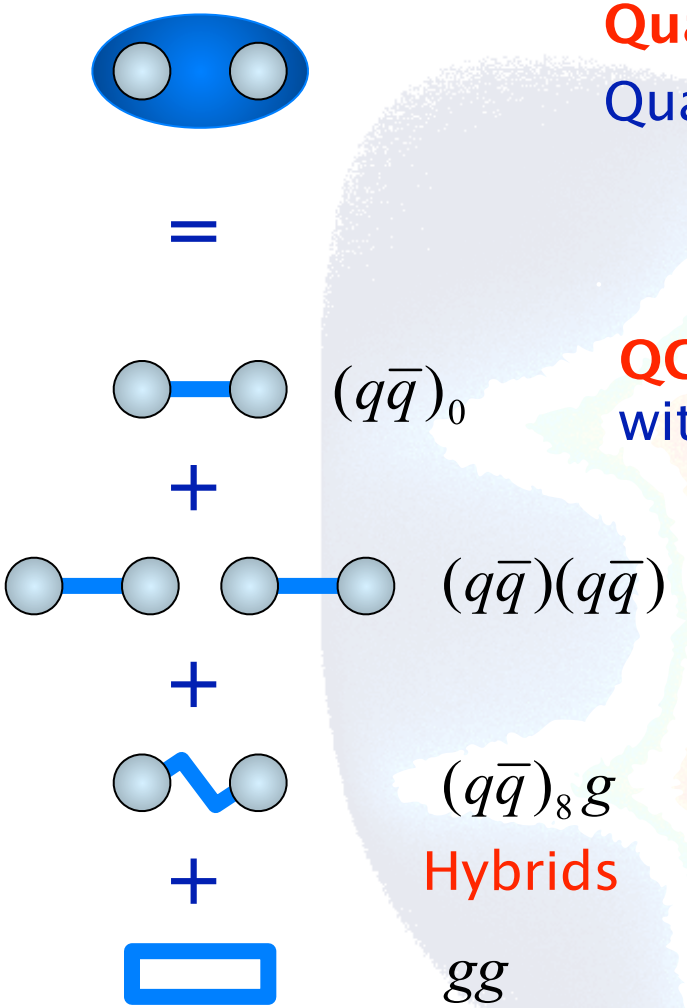

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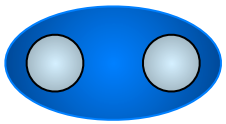
Hybrids

Glueballs

Meson-Spectroscopy



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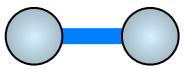

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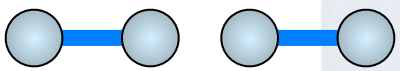
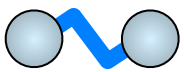


$(q\bar{q})(q\bar{q})$

+



$(q\bar{q})_8 g$

Hybrids

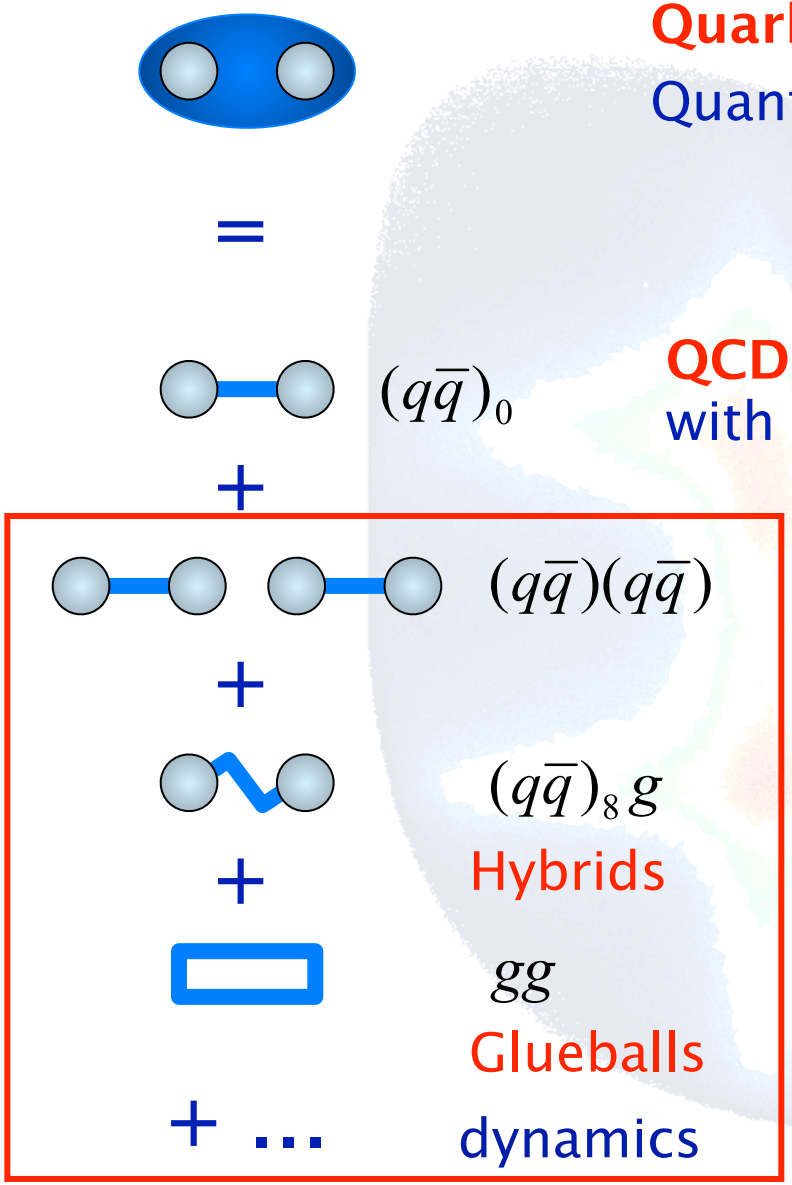
+

gg

Glueballs

+ ... dynamics

Meson-Spectroscopy



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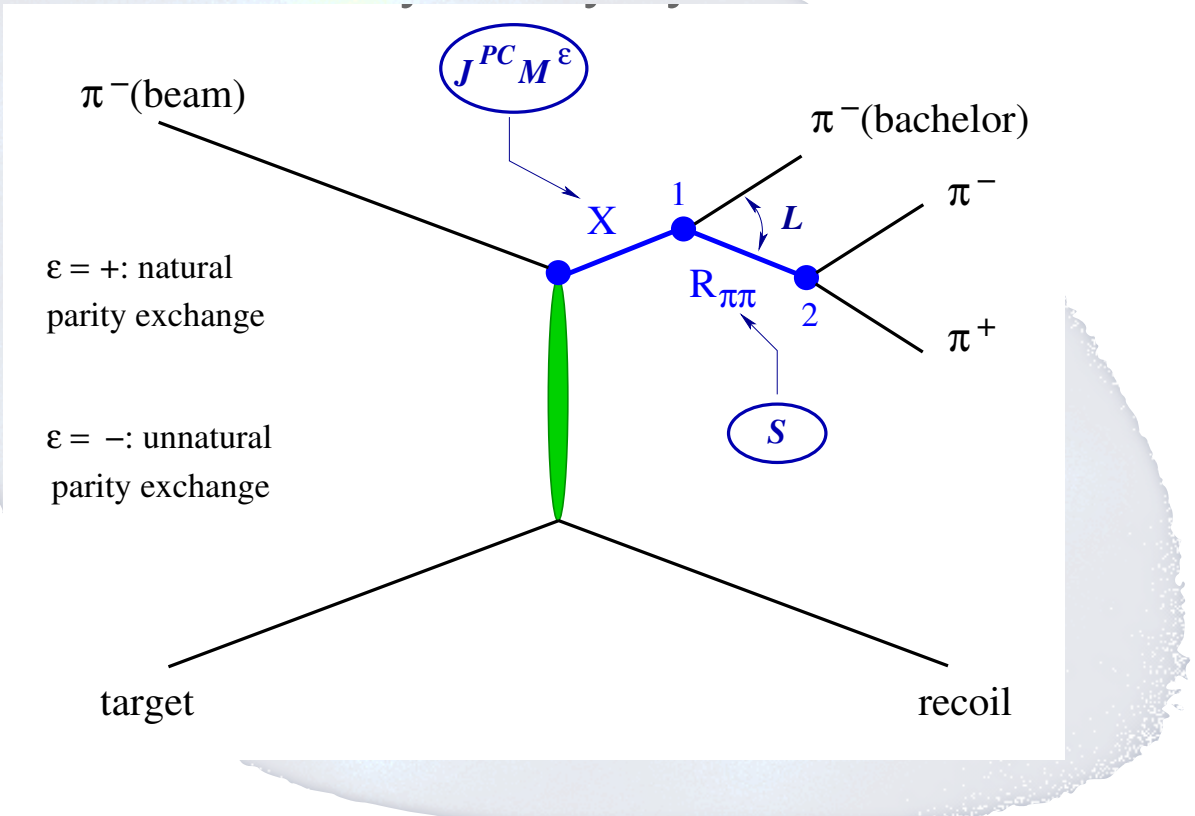
Decoupling only possible for

- narrow states
- No leading $q\bar{q}$ term

⇨ spin-exotic J^{PC}: $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$

Analysis Inelastic Final State IV

- Decay amplitudes $\psi_i(\tau, m)$ calculable
  - 3 variables for each 2-body vertex $m_{\text{mother}}, (\theta, \varphi)$ in mother r.f.
  - 3π decay: $m, \{\theta_{GJ}, \phi_{GJ}, m_R, \theta_H, \phi_H\} \equiv \tau$
  - contain angular distributions and isobar parameterizations

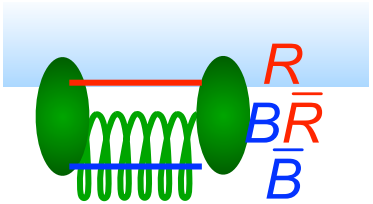


Hybrids

Sector light mesons : exotic $J^{PC}=1^{-+}$:

- $\pi_1(1400)$ (VES, E852, Crystal Barrel)
- $\pi_1(1600)$ (E852, VES)
- $\pi_1(2000)$

still disputed...



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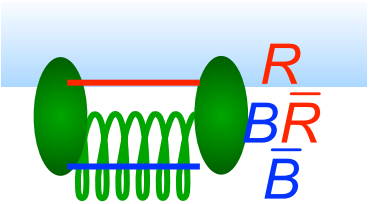

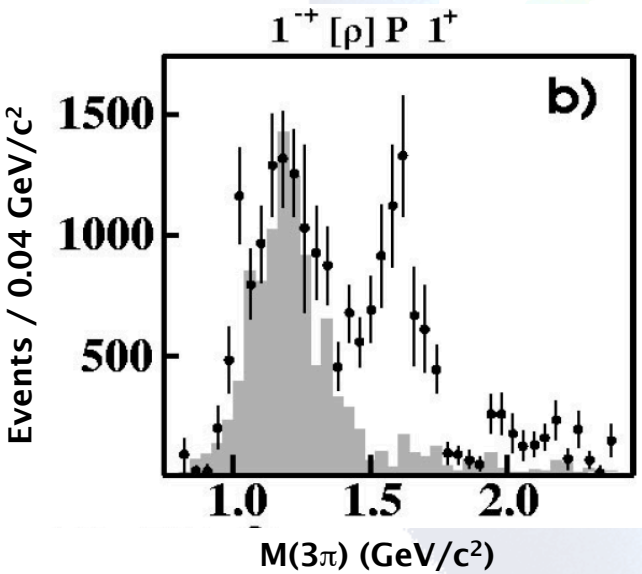

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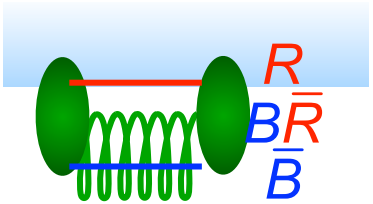

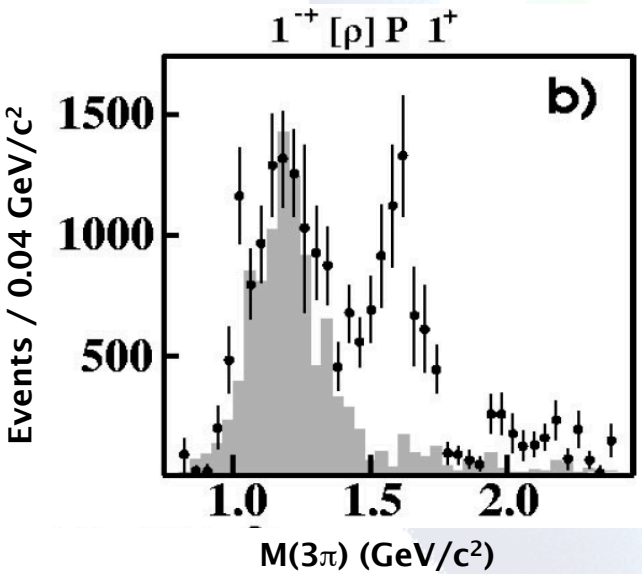

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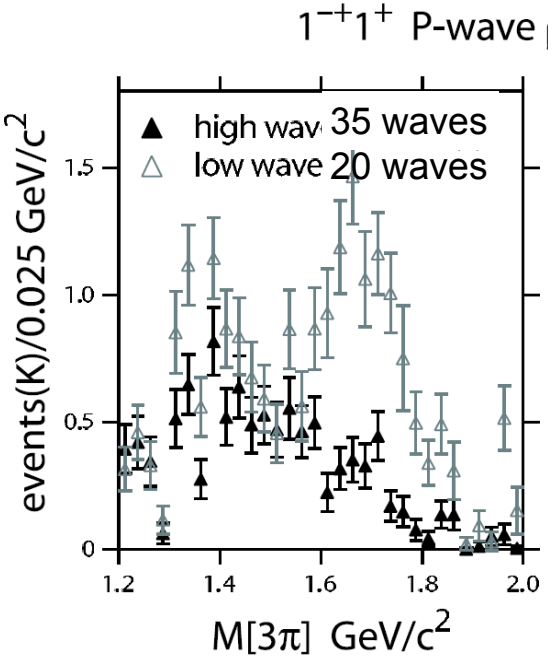

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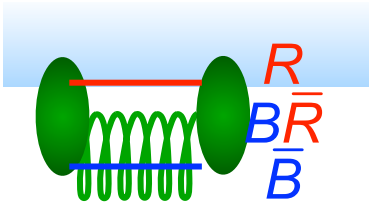

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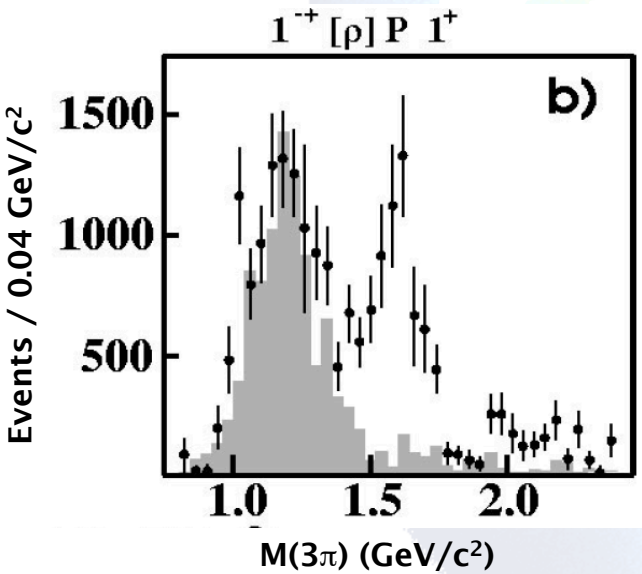

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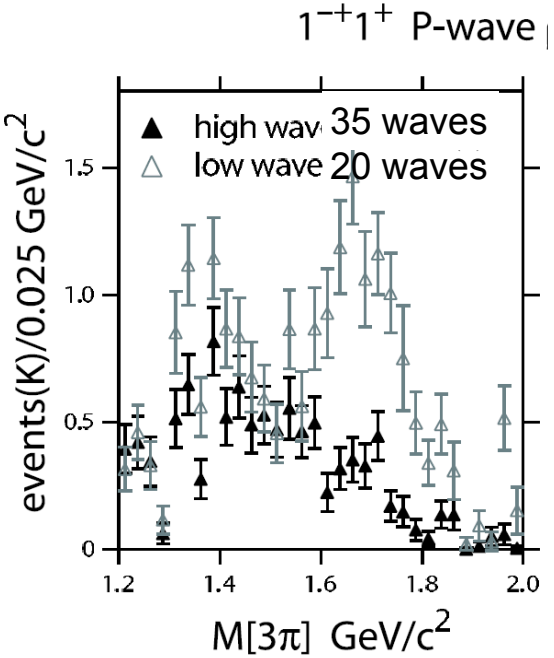

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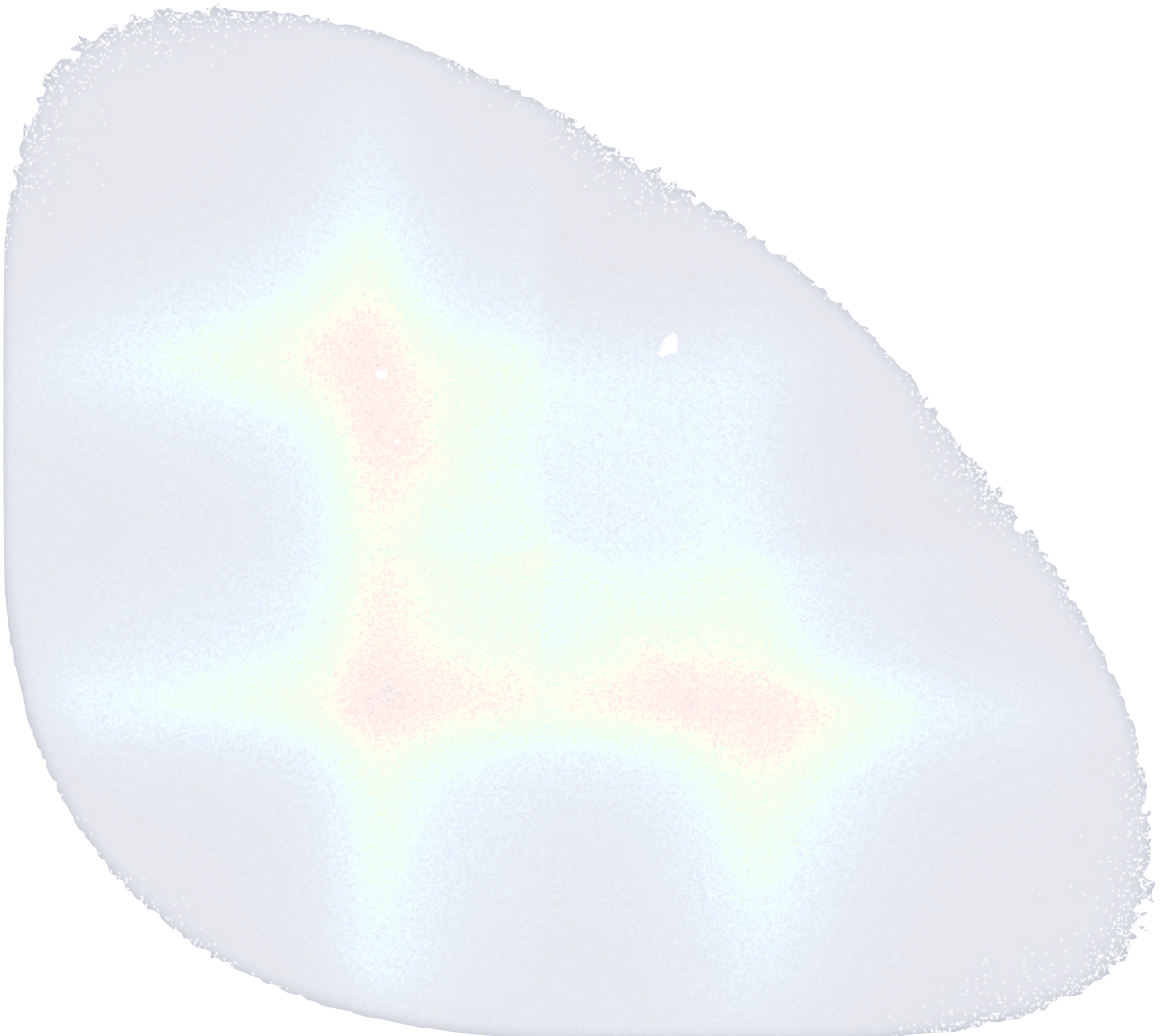
⇨ **COMPASS**

Analyse Inelastic Final State III



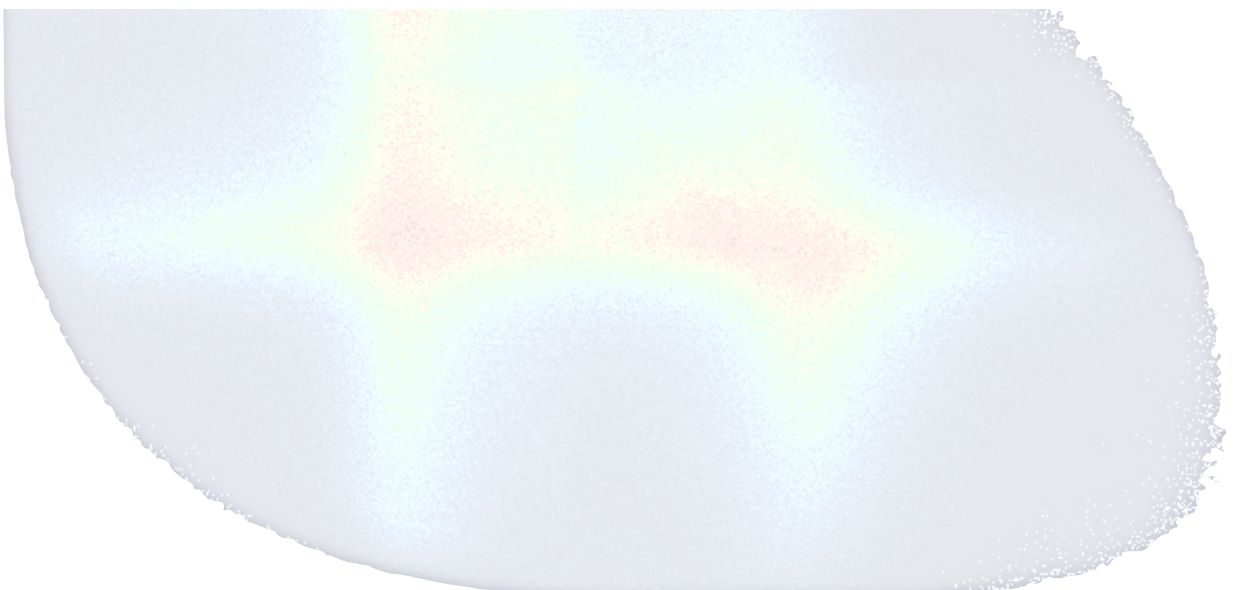
Analyse Inelastic Final State III

Mass-Independent PWA

- Fit angular distributions + isobar systems in independent mass bins

$$\sigma(\tau, m) = \sum_{\epsilon=\pm 1} \sum_{r=1}^{N_r} \left| \sum_i T^{\epsilon}_{ir}(m) \, f^{\epsilon}_i(t') \, \psi^{\epsilon}_i(\tau, m) \right|^2$$

- Production amplitude
- t'-dependence (helicity "flip")
- Decay amplitude (Helicity formalism, reflectivity basis)



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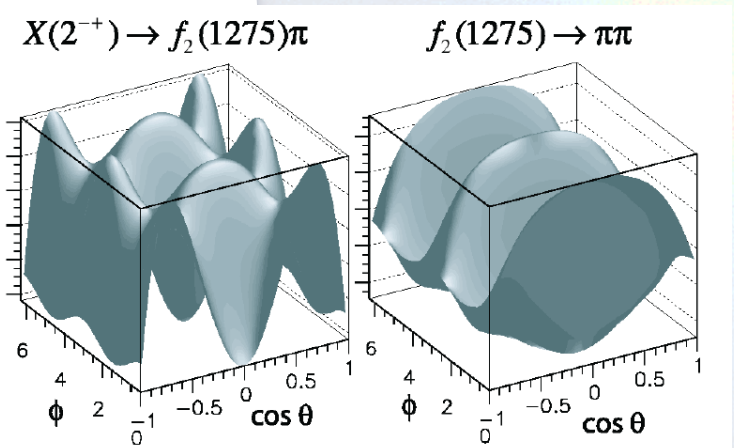

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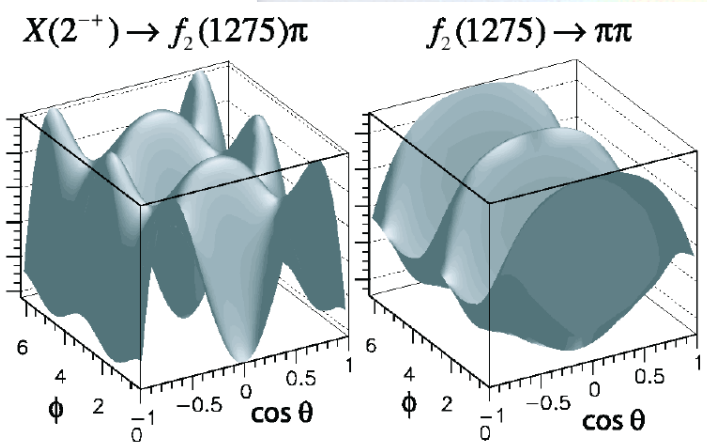

Obtain info about:

$\mathrm{Im}(T_i)$, $\mathrm{Re}(T_i)$, $|T_i|^2$

$T_i(E) = T_i(m_X)$

- Make hypothesis about all i → fit
- Vary hypothesis

Analyse Inelastic Final State III

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Mass-Dependent χ^2 fit $\rightarrow$ Extract Resonance Parameters

- Parameterization of spin-density matrix elements $\sum_r T^{\epsilon}_{ir} T^{\epsilon *}_{jr}(m_x)$
- Takes into account interference terms
- Coherent background for some waves

Zukünftige Arbeiten

$\eta' \to \pi\eta \to \pi\gamma\gamma$

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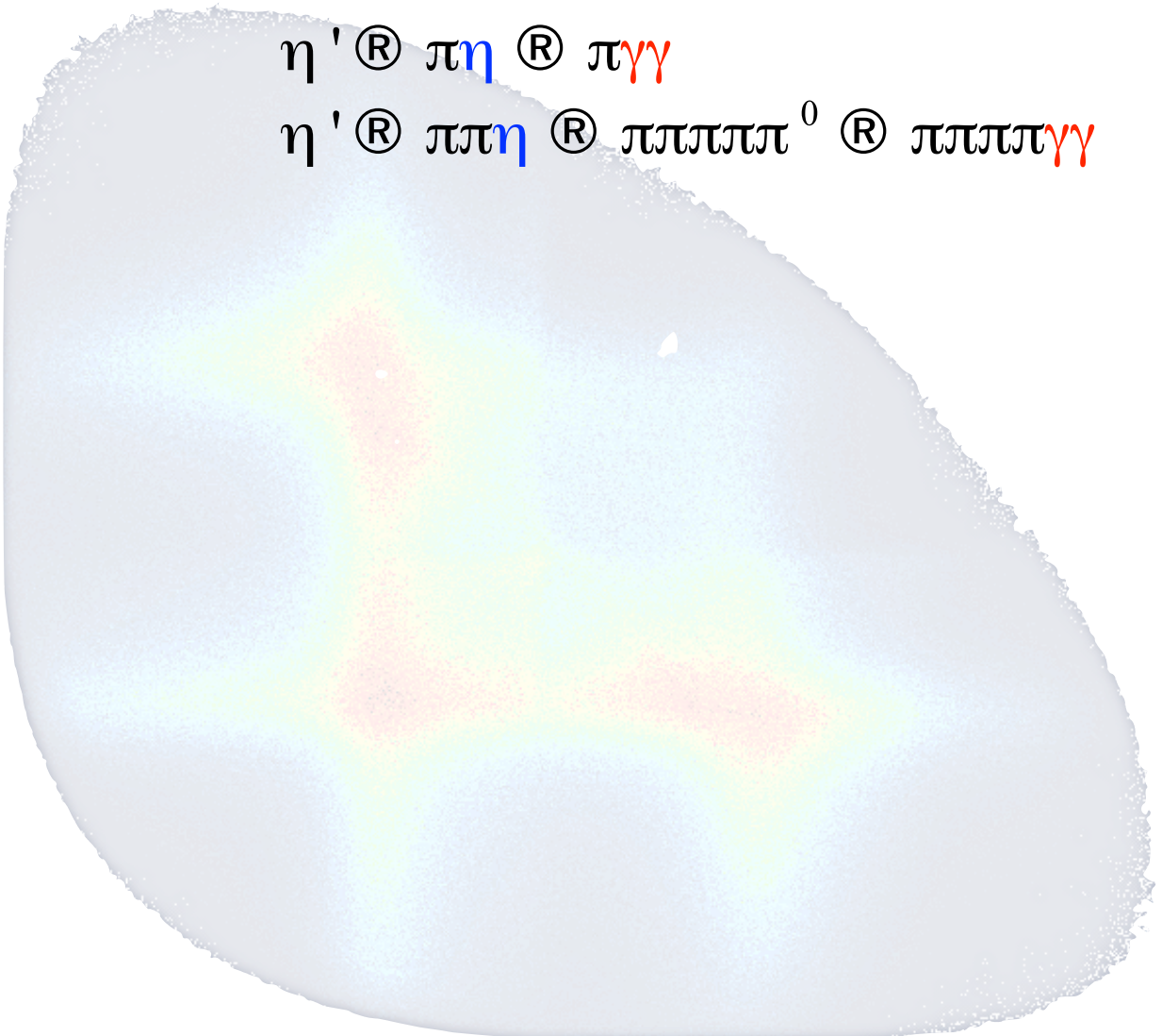

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- COMPASS allows study of multiple final states
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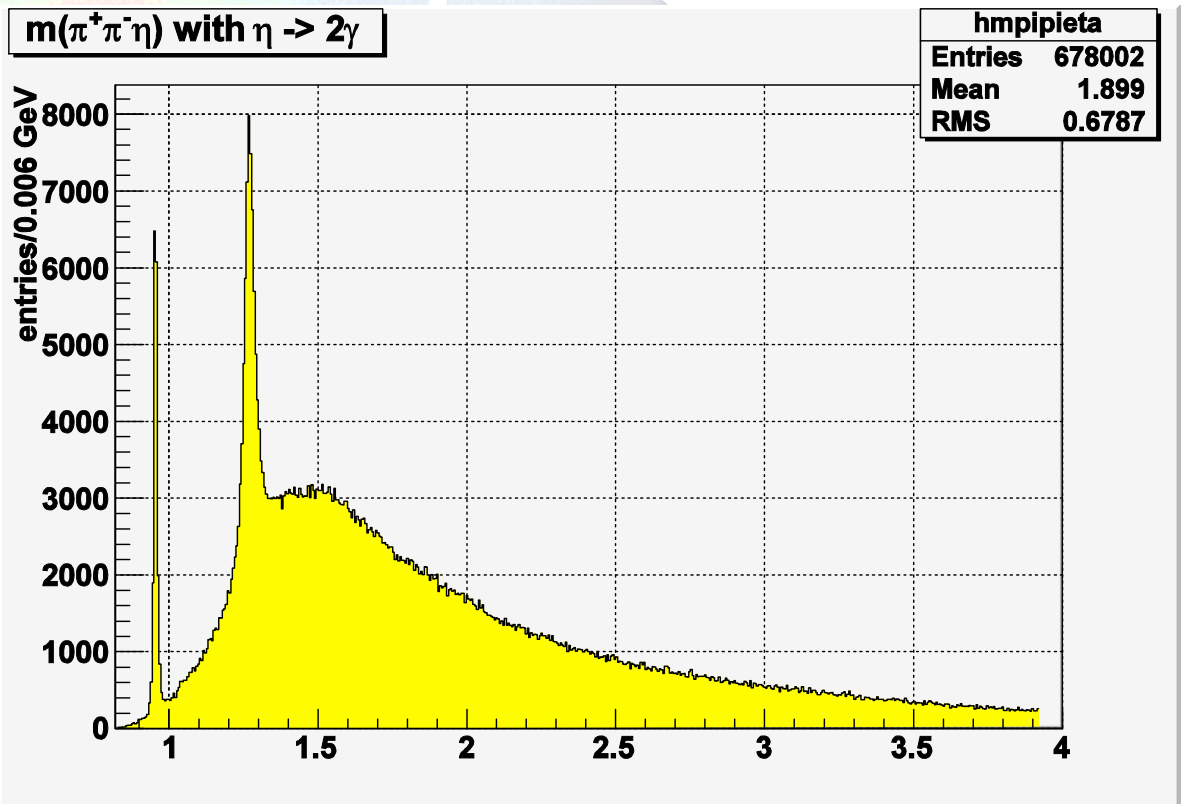
    - Allows search for glue-rich states
  - Kaons: e.g.



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- Reaction: p p $\to p_f$ X p_s
  - central production of X^0
  - diffractive production of N*

Gluebälle in zentraler Produktion

Leichteste Gluebälle:

- $M \sim 1.7\,\mathrm{GeV}/c^2\ (J^{PC} = 0^{++})$
- $M \sim 2.4\,\mathrm{GeV}/c^2\ (J^{PC} = 2^{++})$

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Experimentelle Kandidaten

- $f_0(1500)$ (Crystal Barrel, WA102)

$J^{PC} = 0^{++}$ ⇨ Mischung mit isoskalaren Mesonen

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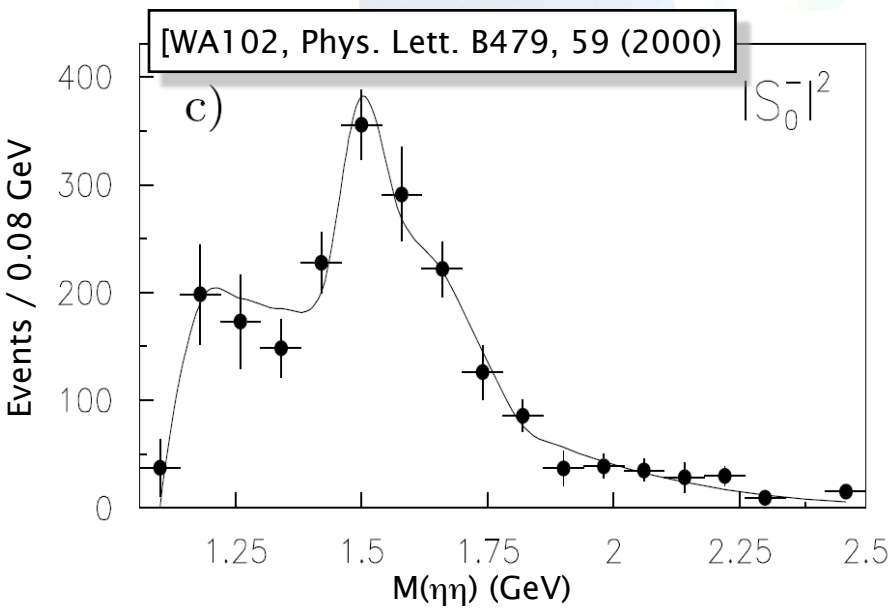

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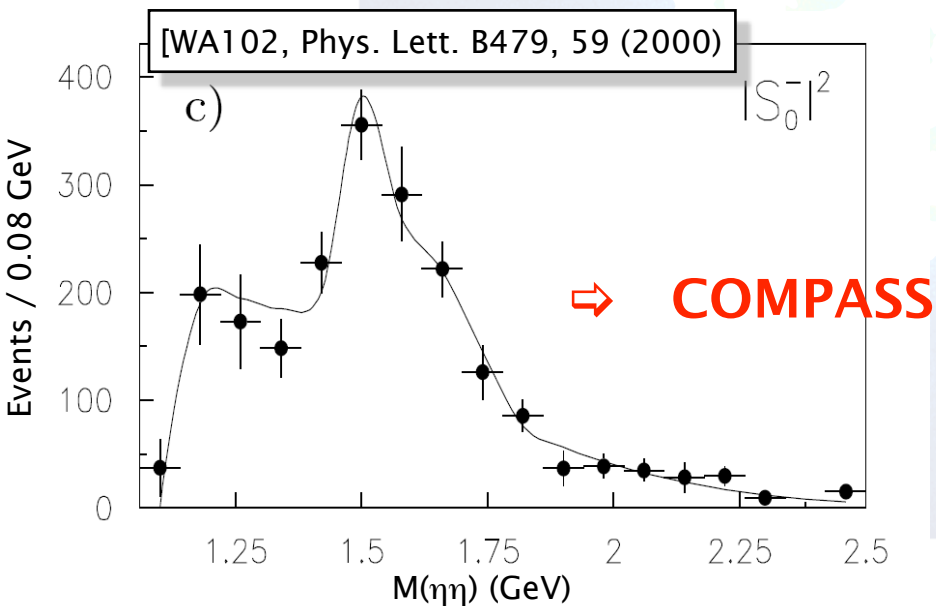
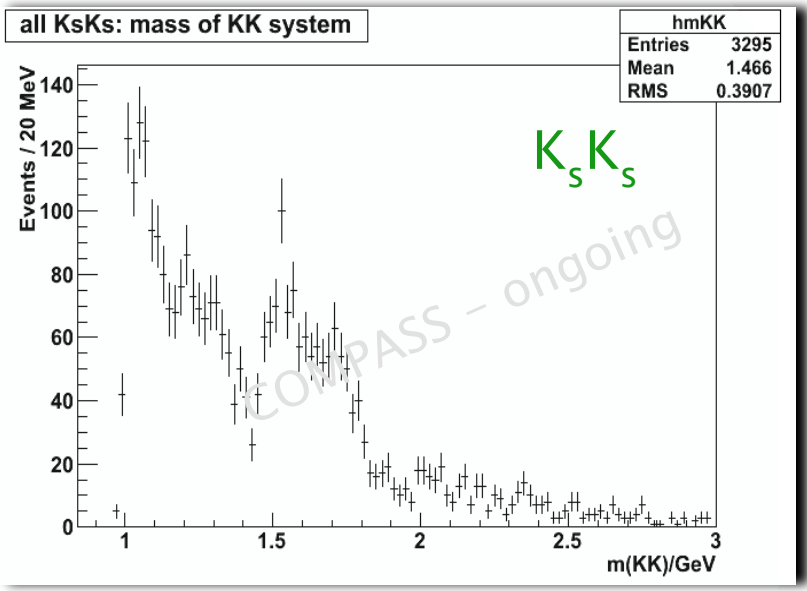
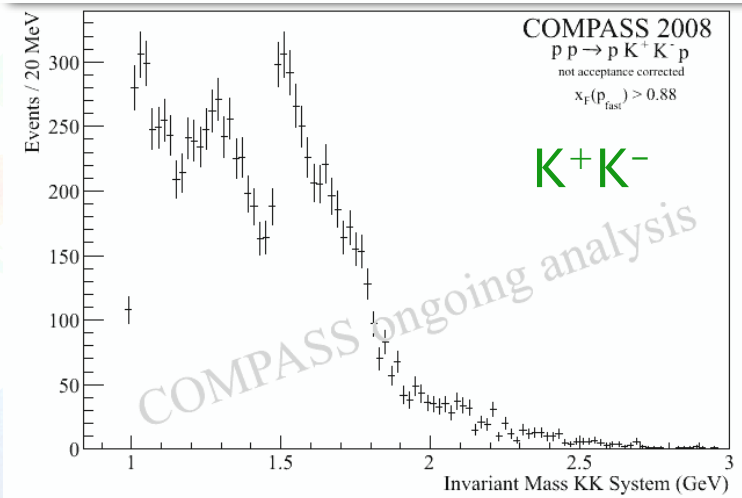


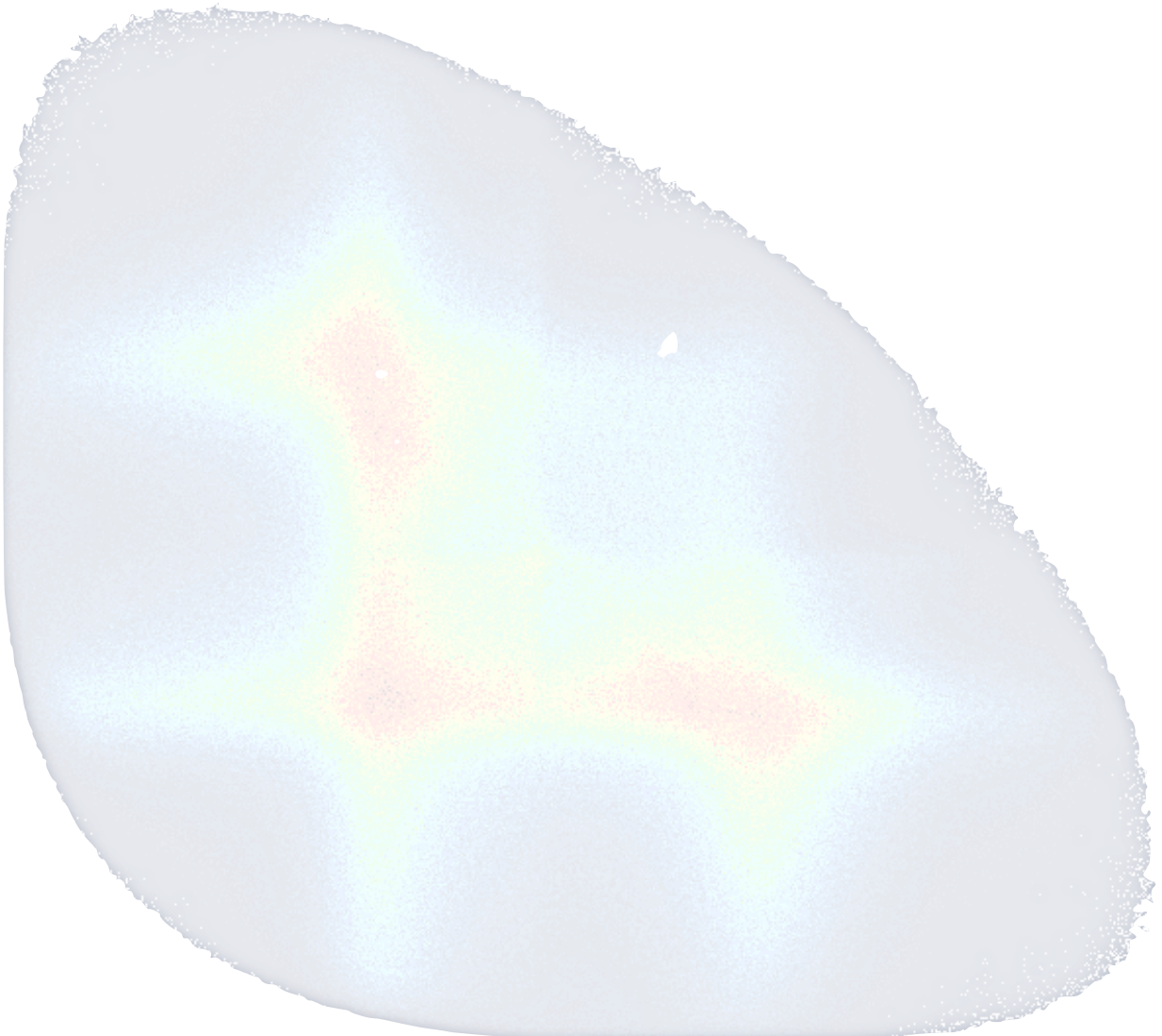
⇨ **COMPASS**





~ 10% der Statistik

Coupling to Strangeness



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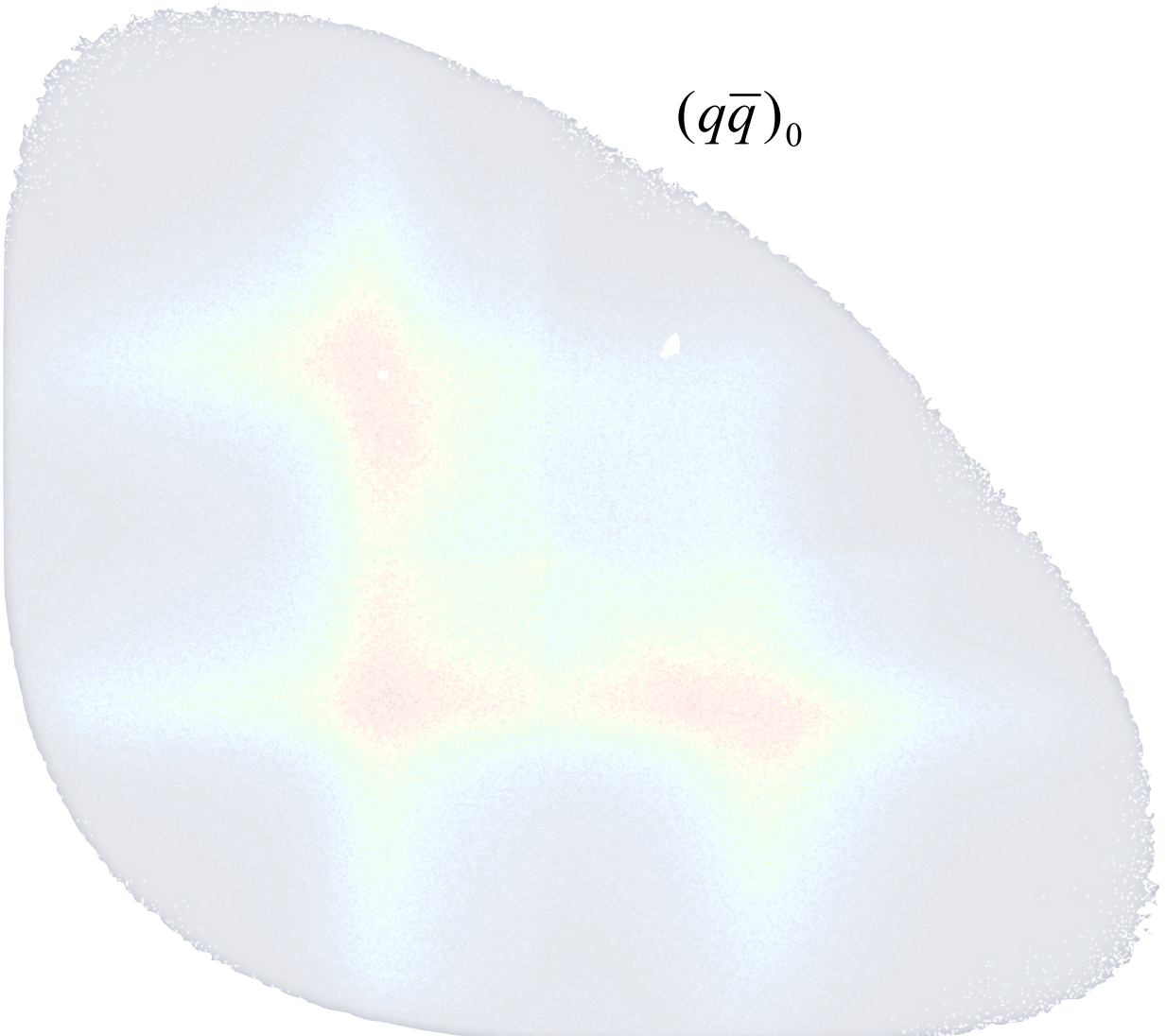
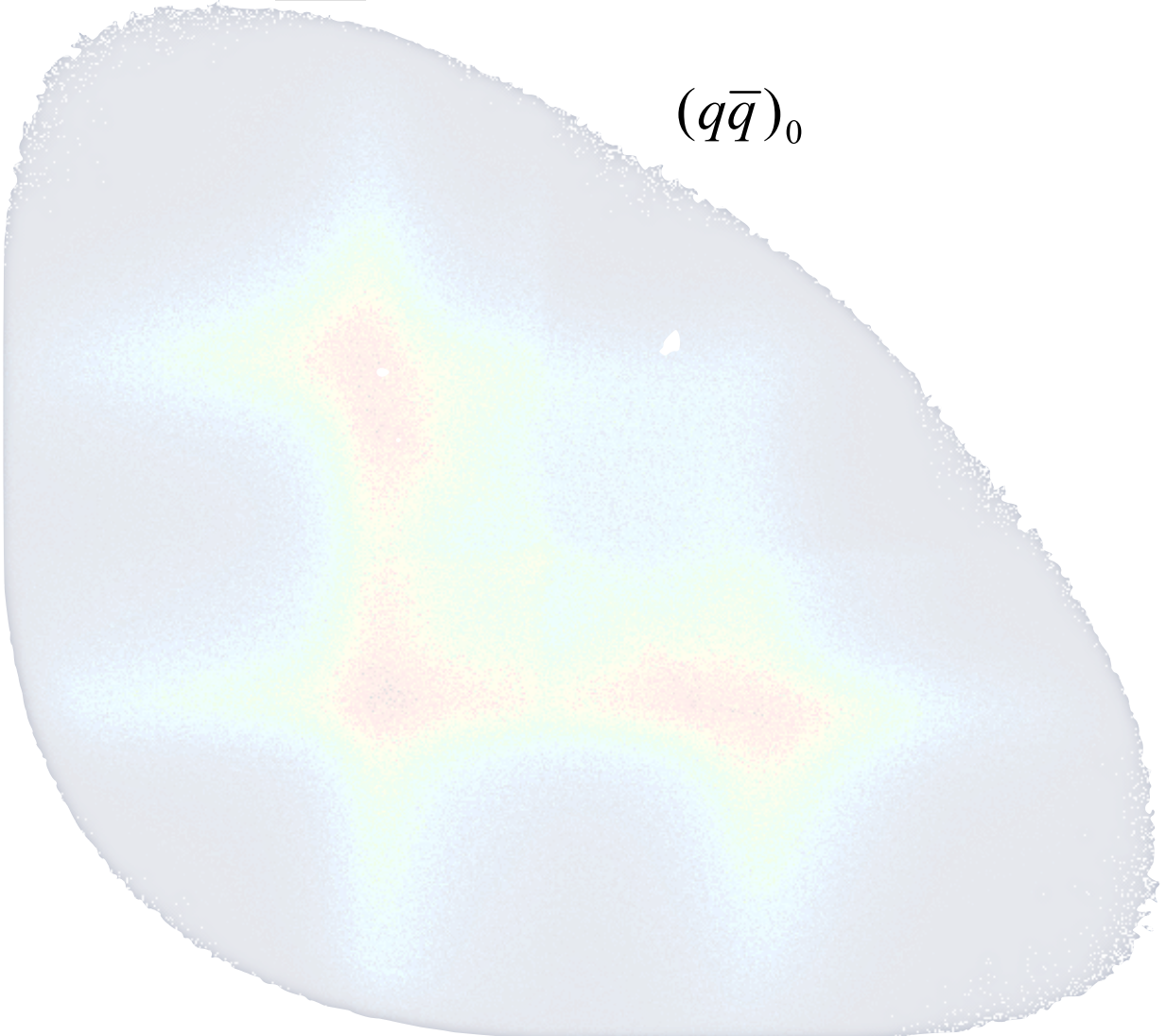


Coupling to Strangeness

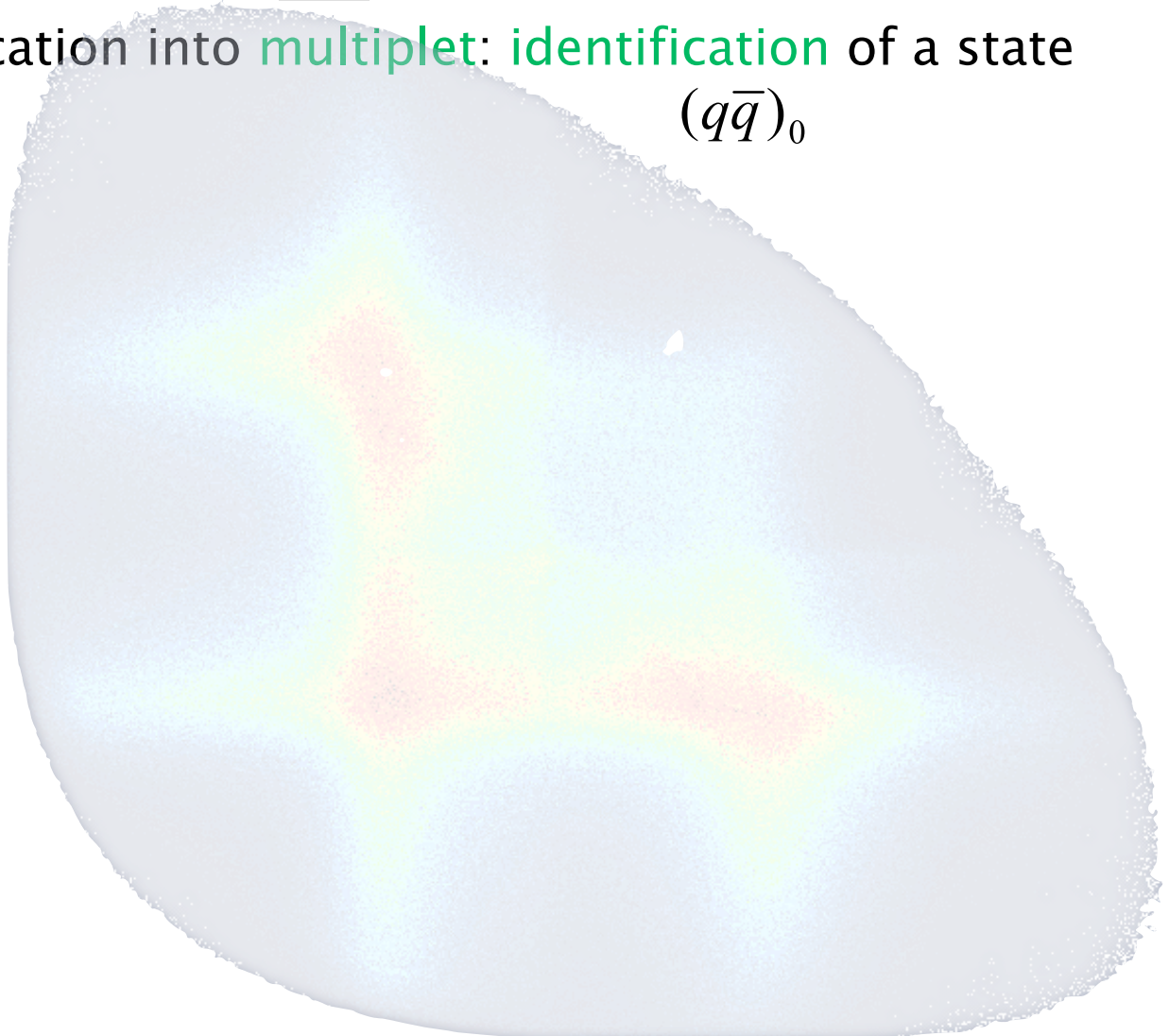
- Quantum numbers and flavour content of a state is relevant



Coupling to Strangeness

- Quantum numbers and flavour content of a state is relevant
- Classification into multiplet: identification of a state

$$(q\bar{q})_0$$



Coupling to Strangeness

- Quantum numbers and flavour content of a state is relevant
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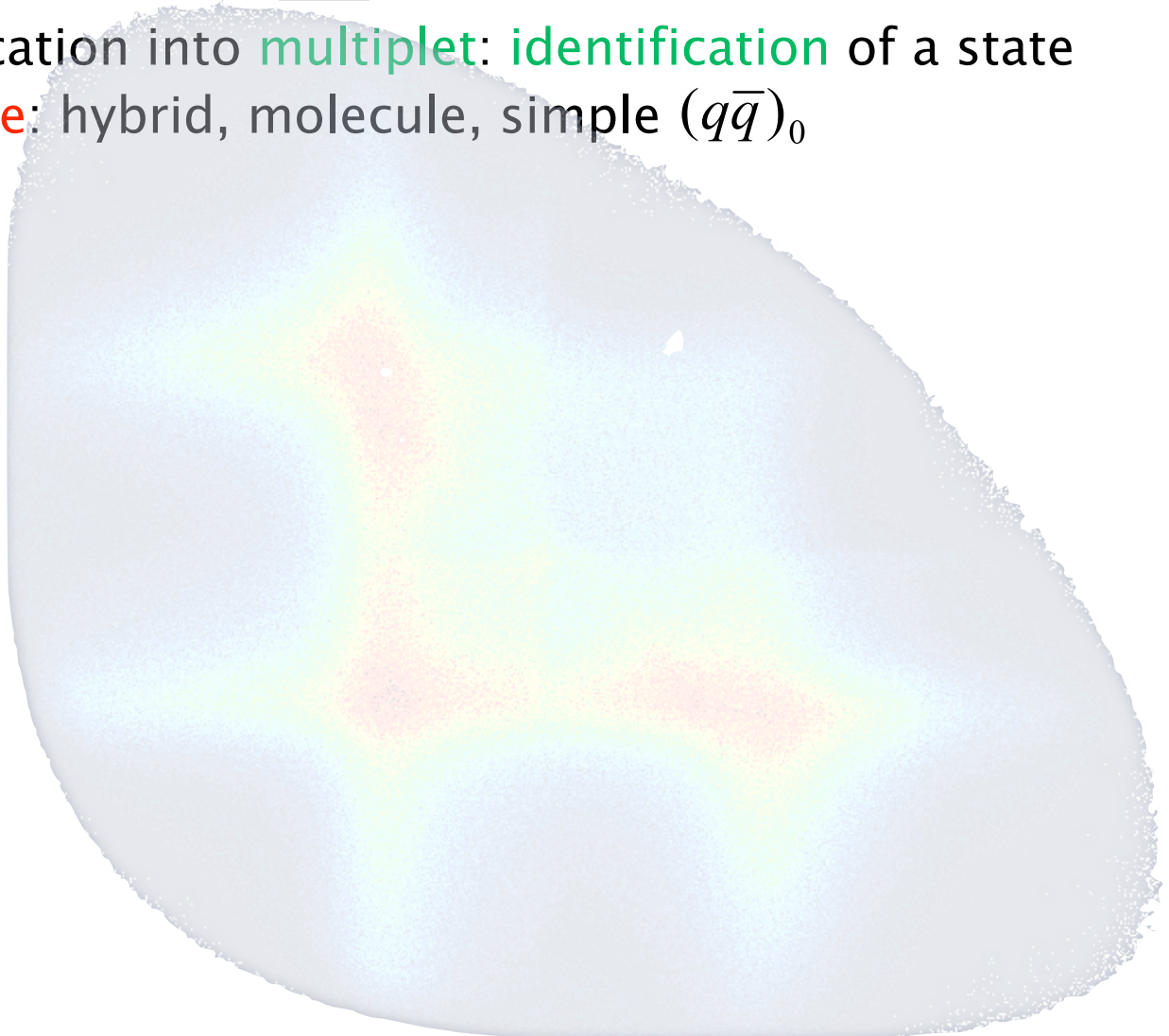
- Structure: hybrid, molecule, simple $(q\bar{q})_0$



Coupling to Strangeness

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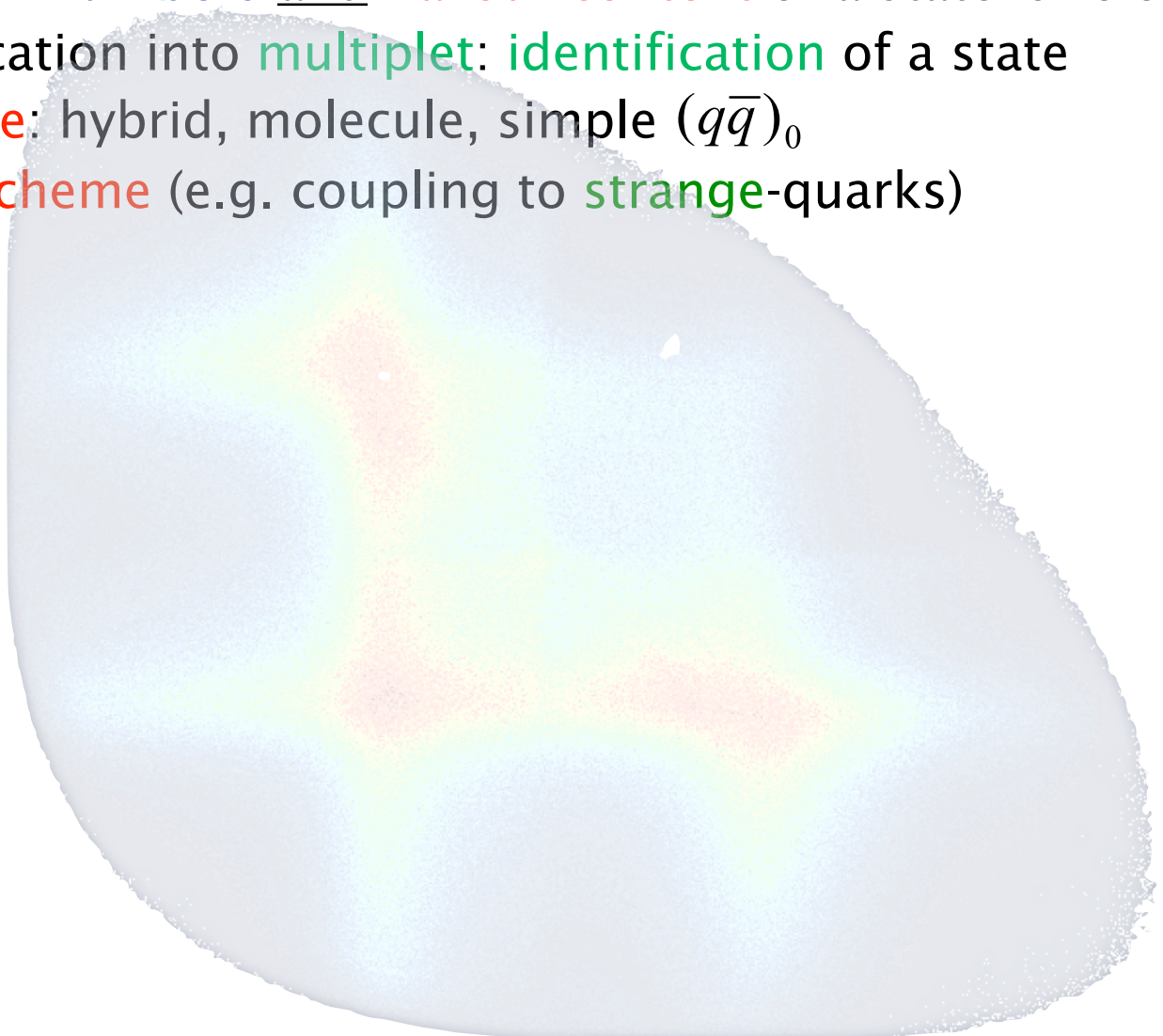
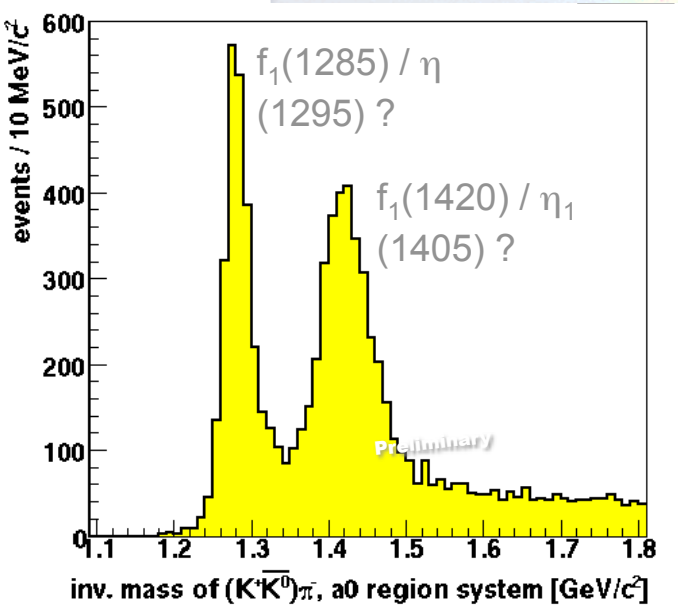


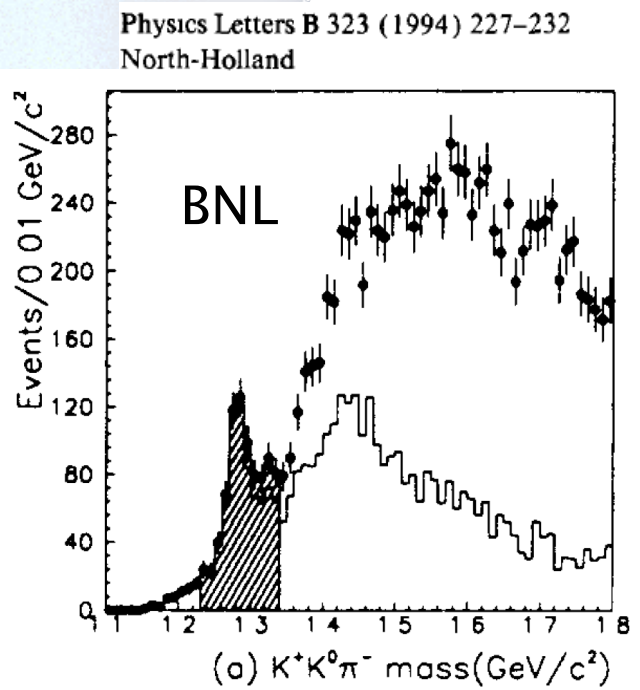
Coupling to Strangeness

- Quantum numbers and flavour content of a state is relevant
- Classification into multiplet: identification of a state
- Structure: hybrid, molecule, simple $(q\bar{q})_0$
- Decay-scheme (e.g. coupling to strange-quarks)
- Consider diffractive production

$\pi^- p \rightarrow \bar{K}K\pi\pi^- p$

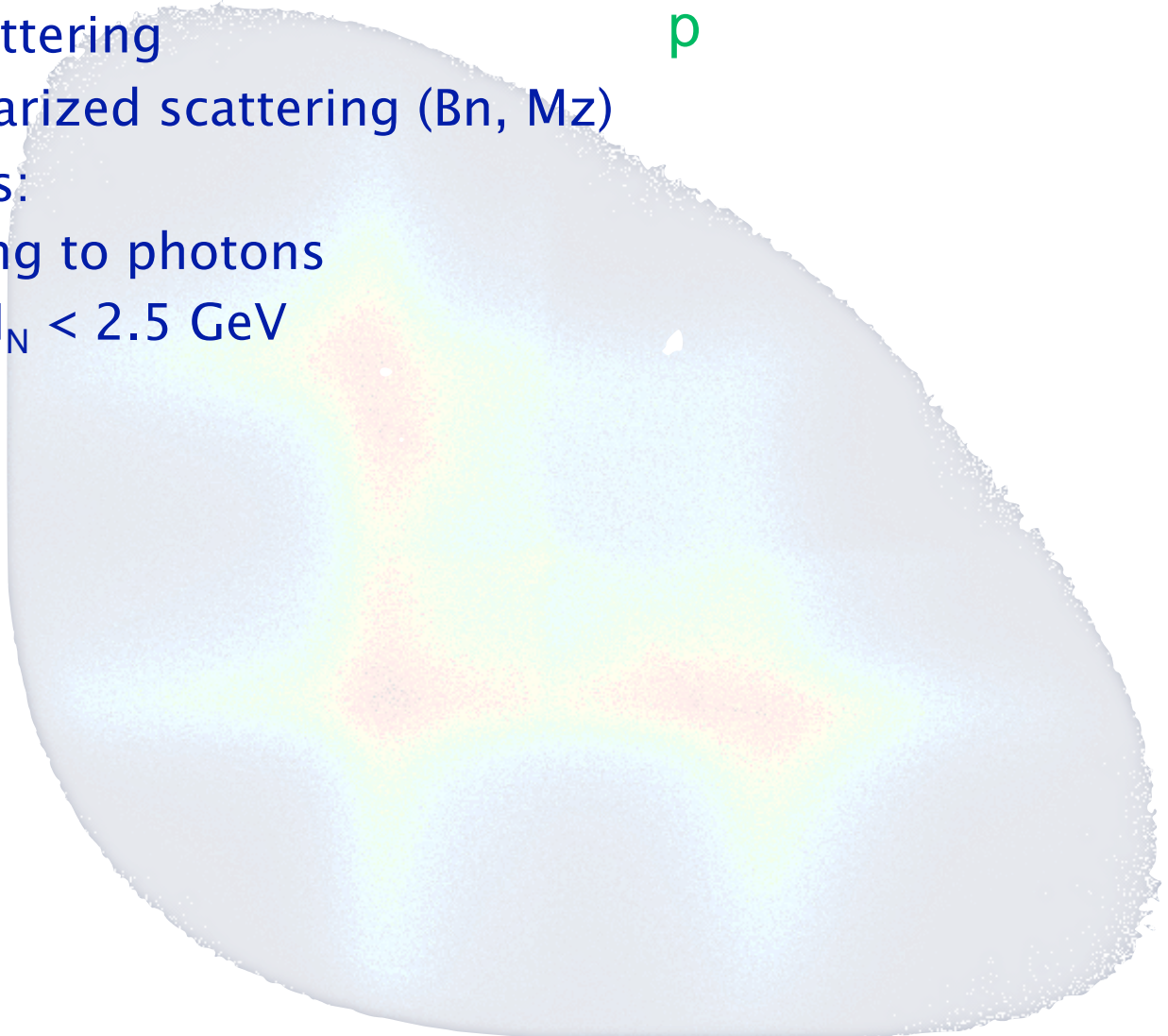
Endzustand: $\bar{K}^0 K^+ \pi^- \pi^-$ und $\bar{K}^- K^0 \pi^+ \pi^-$





Diffractive Baryon Production ($p\pi^+\pi^-$)

- Baryon spectroscopy in
  - πN scattering
  - γN polarized scattering (Bn, Mz)
- Limitations:
  - Coupling to photons
  - Mass $M_N < 2.5$ GeV



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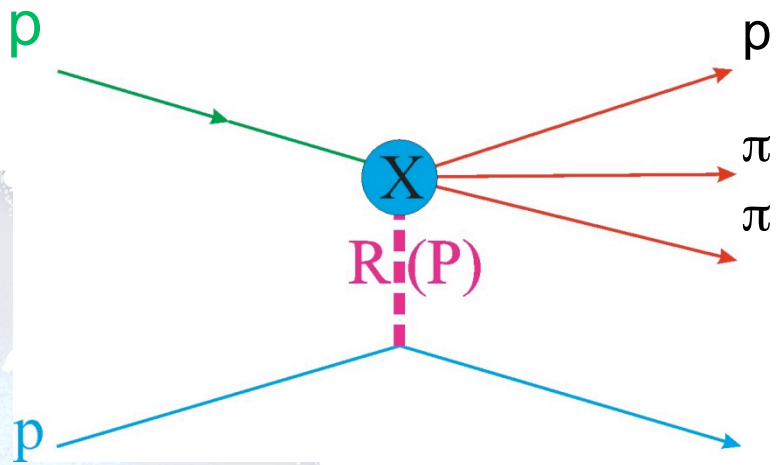

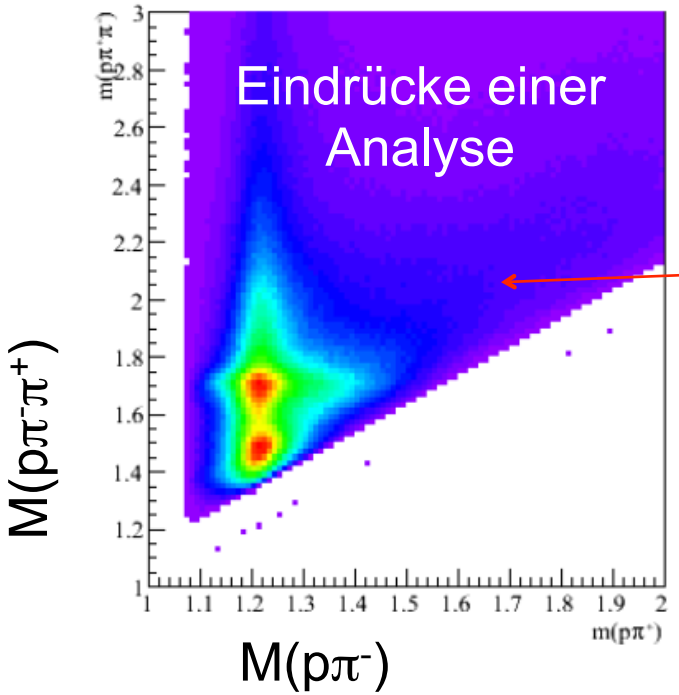

COMPASS can create high masses

Ca. 15% of statistics

PWA formalism being developed

Diffractive Baryon Production ($p\pi^+\pi^-$)

- Baryon spectroscopy in
  - πN scattering
  - γN polarized scattering (Bn, Mz)
- Limitations:
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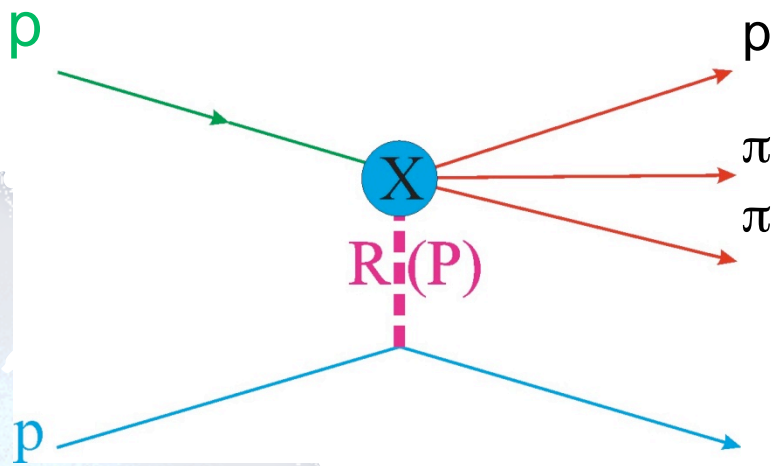
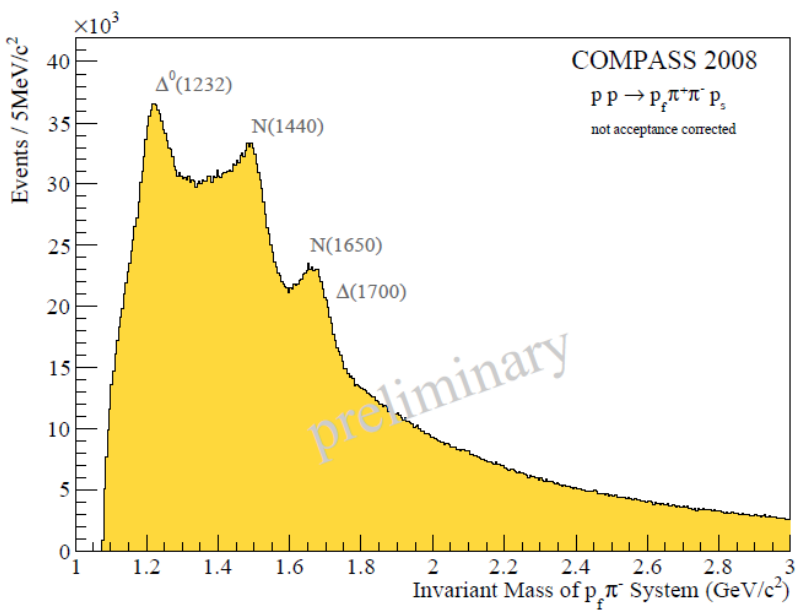
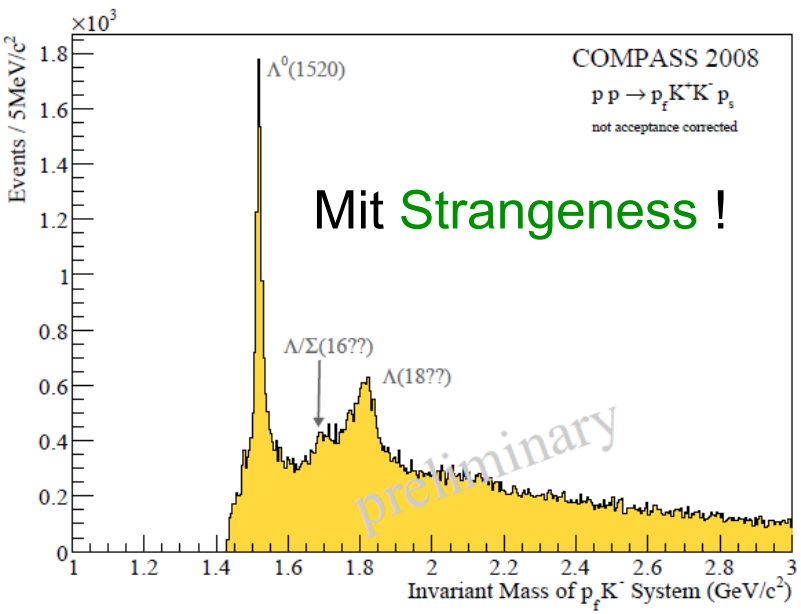
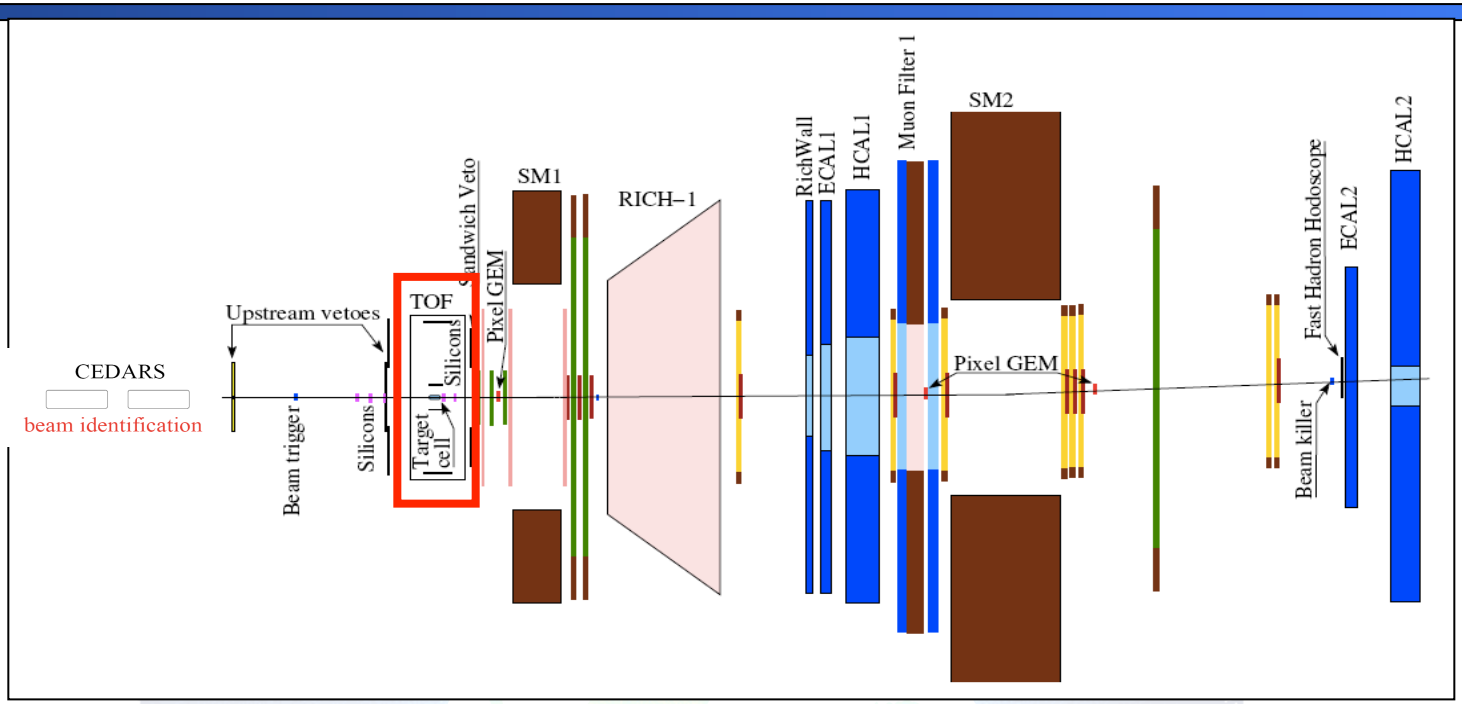


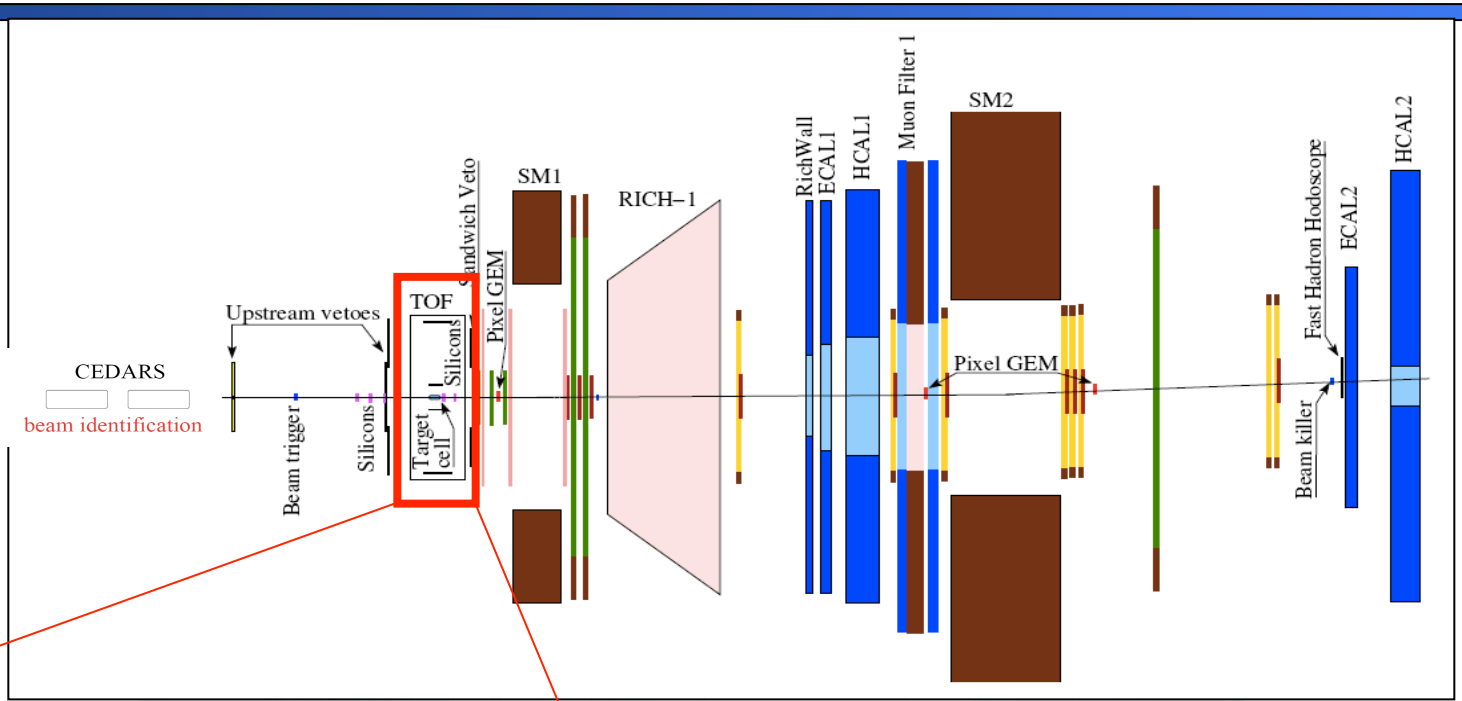


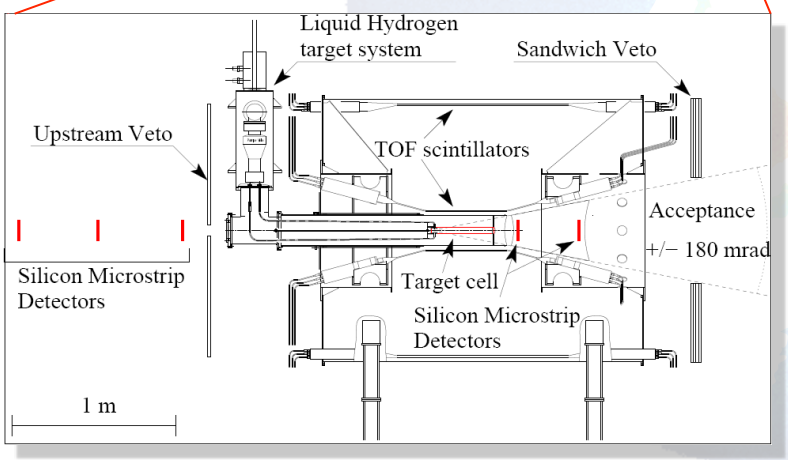


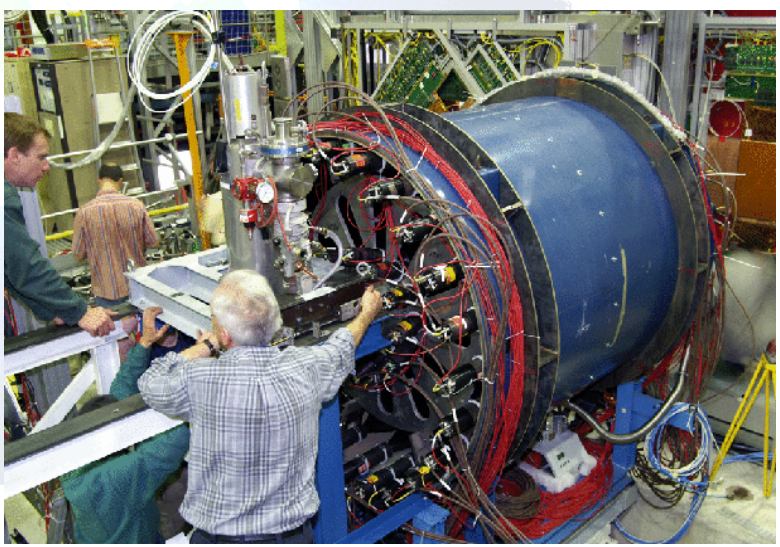
COMPASS in 2008



COMPASS in 2008







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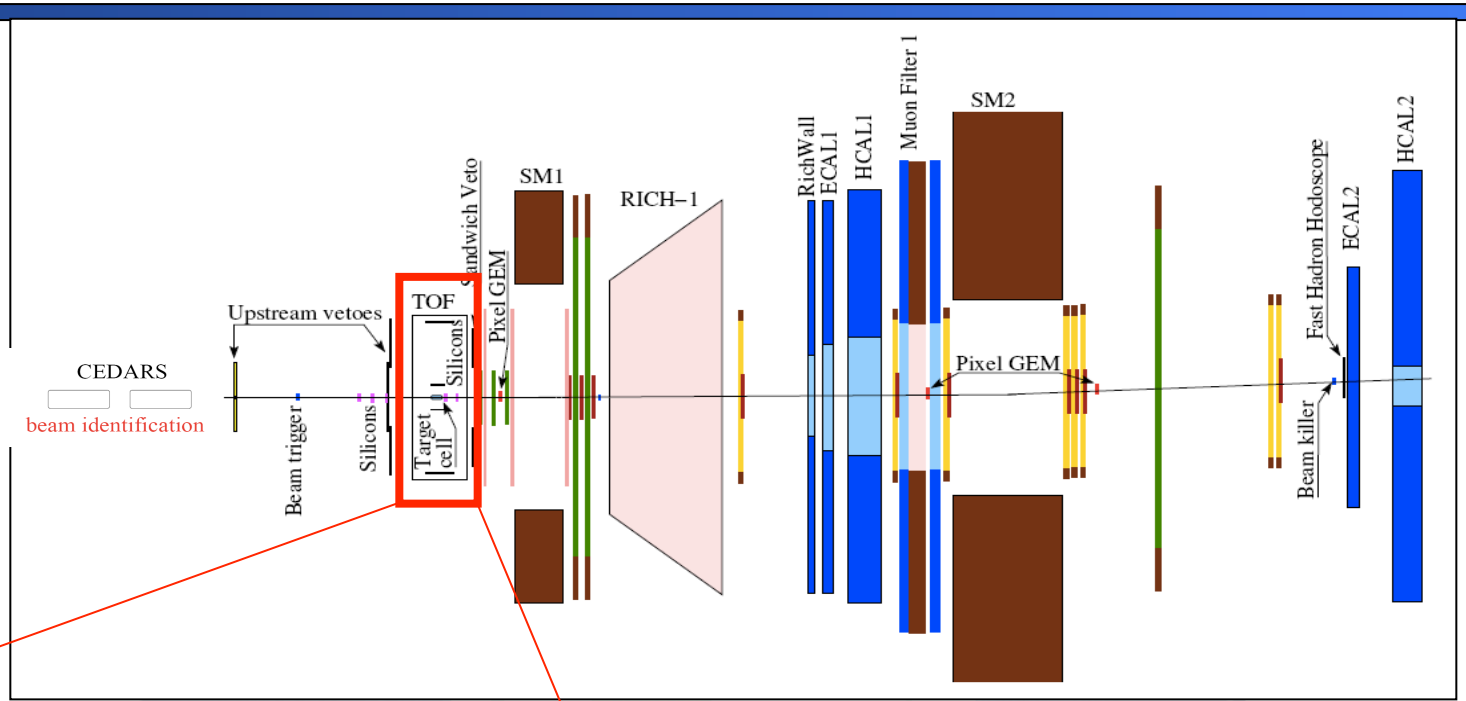
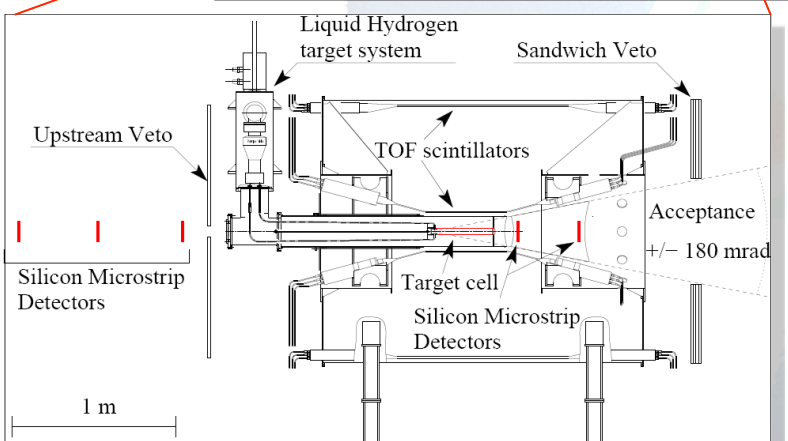
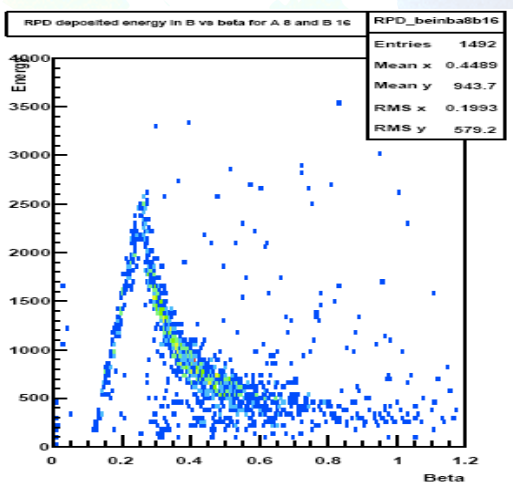
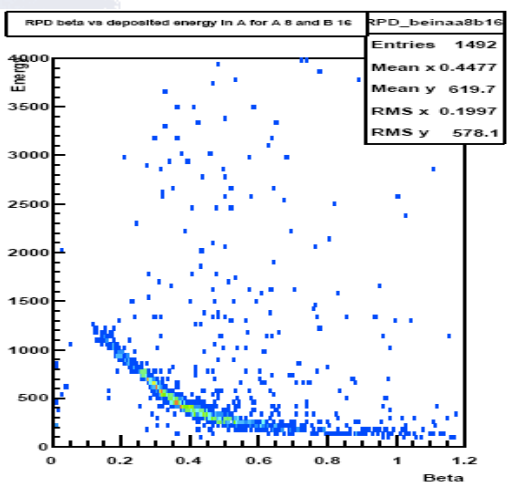
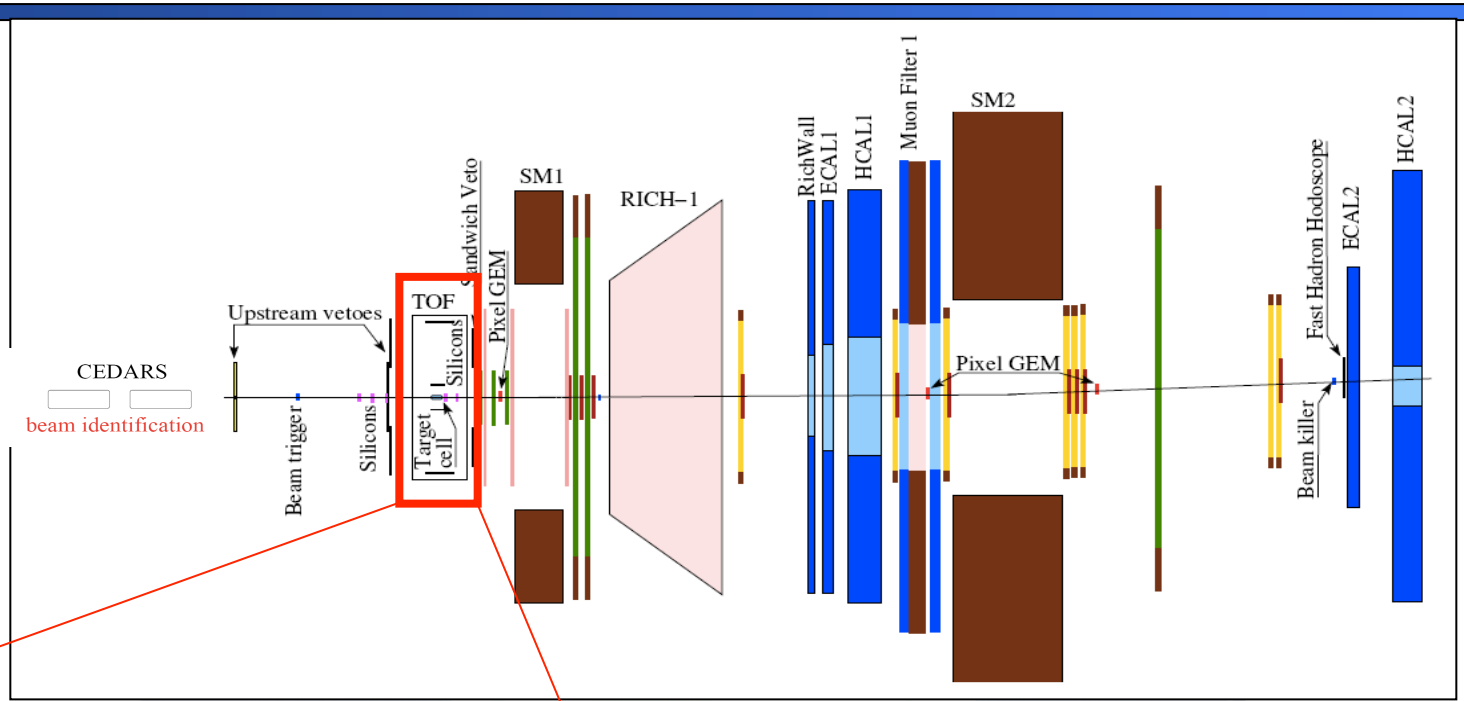


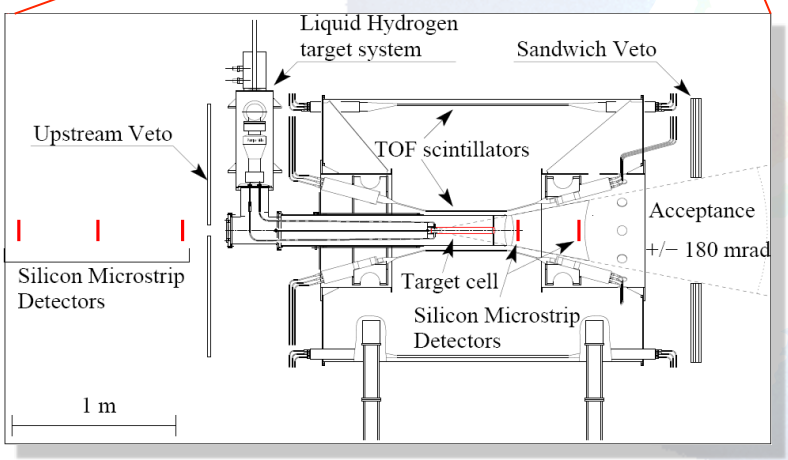


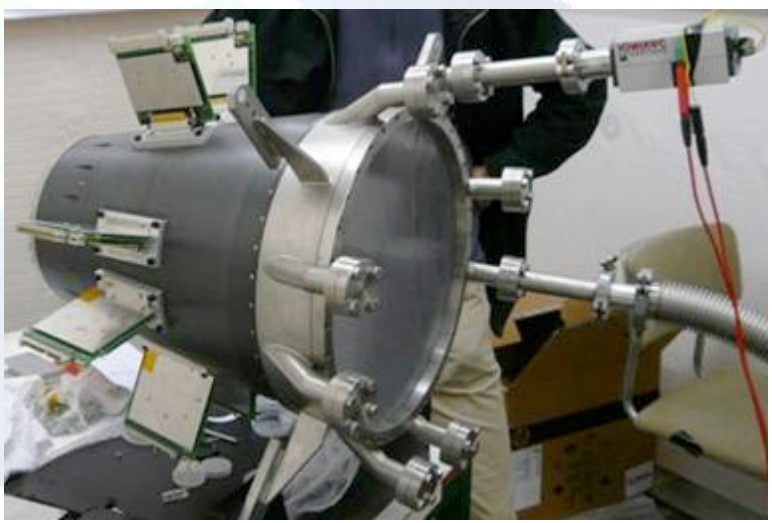




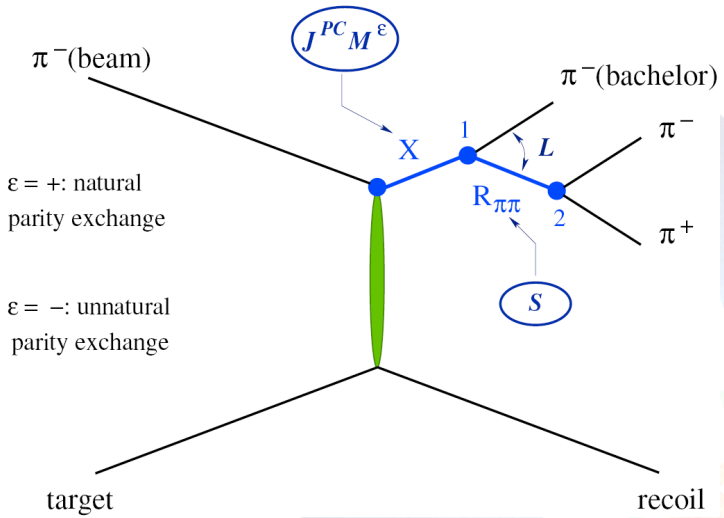
COMPASS in 2008





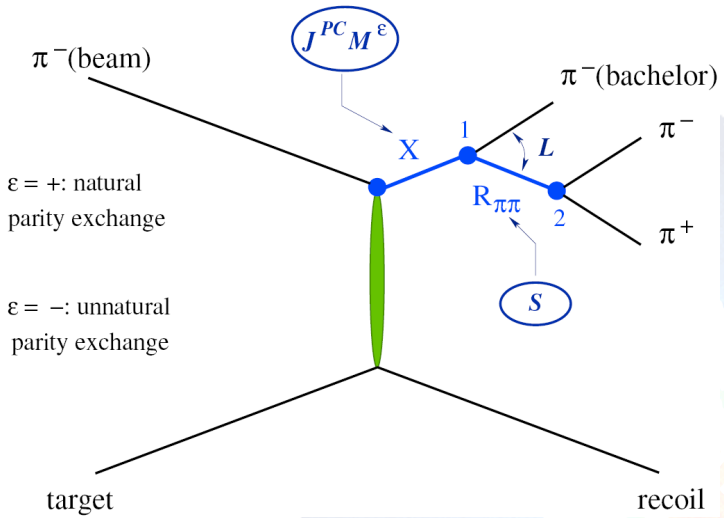


PWA Technique



- high s: t-channel Reggeon exchange
- Reflectivity basis in G-J frame
- $\varepsilon = \eta$ of Regge trajectory
- Isobar model

PWA Technique



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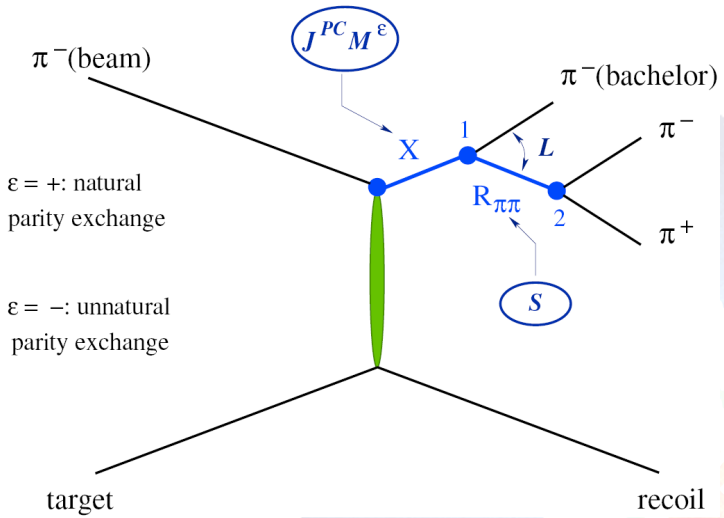
1. **Mass-independent PWA** of angular distributions in 40 MeV mass bins

PWA Technique



- high s: t-channel Reggeon exchange
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1. **Mass-independent PWA** of angular distributions in 40 MeV mass bins

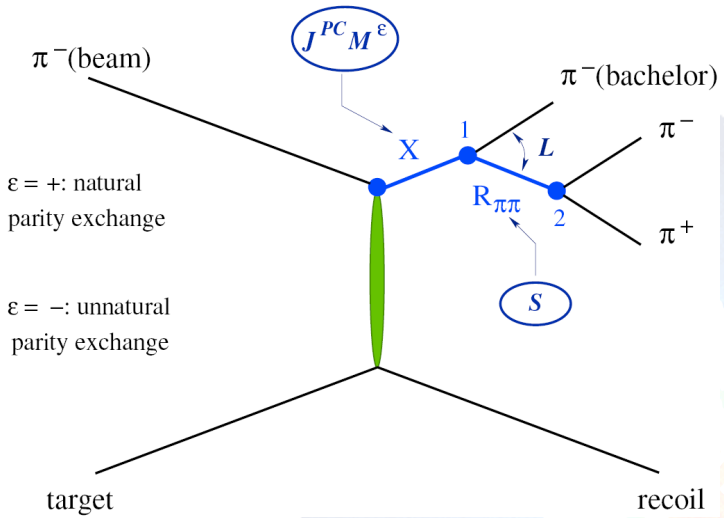
$$\sigma_{\text{indep}}(\tau) = \sum_{\varepsilon=-1}^{1} \sum_{r=1}^{N_r} \left| \sum_i T_{ir}^{\varepsilon} \psi_i^{\varepsilon}(\tau) \Big/ \sqrt{\int \left|\psi_i^{\varepsilon}(\tau')\right|^2 d\tau'} \right|^2$$

- T_{ir}^{ε} production amplitudes - determined by fit

- 42 partial waves $i = J^{PC}M^{\varepsilon}[\ldots]L$

[...] = isobar: $(\pi\pi)_S$, $f_0(980)$, $\rho(770)$, $f_2(1270)$, $\rho_3(1690)$

PWA Technique



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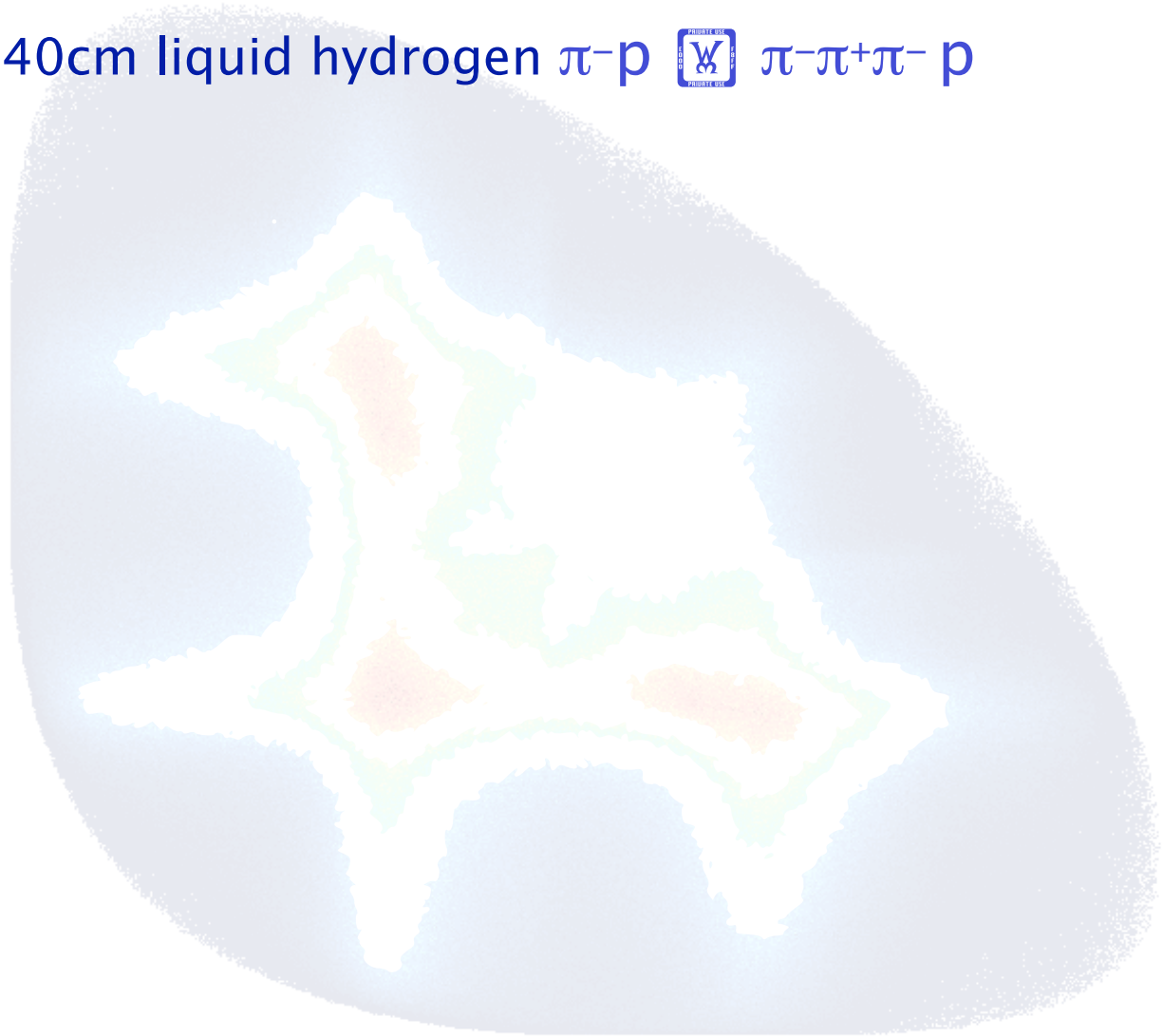
1. **Mass-independent PWA** of angular distributions in 40 MeV mass bins

2. **Mass-dependent χ^2 fit** to results of step 1
   - 6 waves
   - Parameterized by BW (incl. barrier factors and $\Gamma(m)$)
   - Coherent background for some waves

$\pi^-\pi^+\pi^-$ in 2008

- 190 GeV/c hadron beam
- Target: 40cm liquid hydrogen $\pi^- p \rightarrow \pi^-\pi^+\pi^- p$



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  - **$\pi^- p \rightarrow \pi_1(1600)\, p$, $\pi_1(1600) \rightarrow 3\pi$: 200000 events exp.** ✓
  - >200 times statistics of 2004 data

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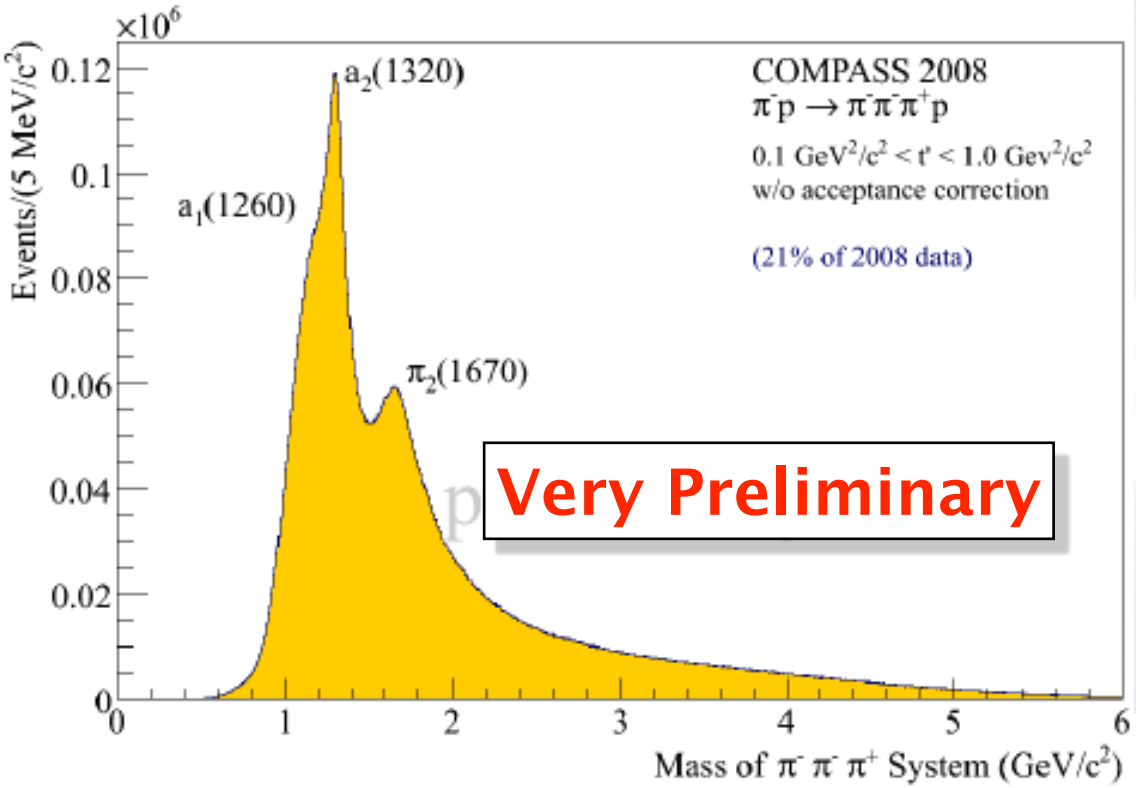

see talk by S. Neubert

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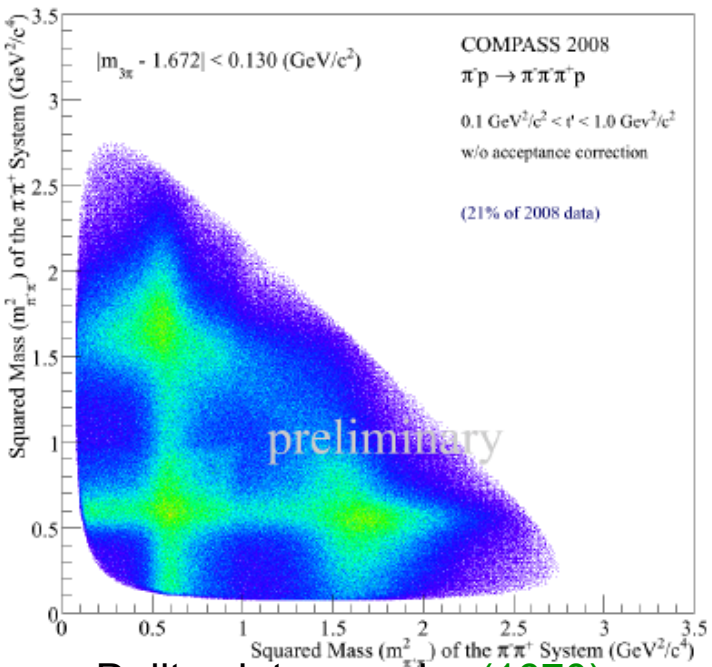

Dalitz plot around $\pi_2(1670)$

see talk by S. Neubert

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- PWA has started
  - ! High statistics requires perfect understanding of physics
  - Deck effect (under study)
  - Up to date parametrization of $\pi\pi$ scattering

see talk by S. Neubert

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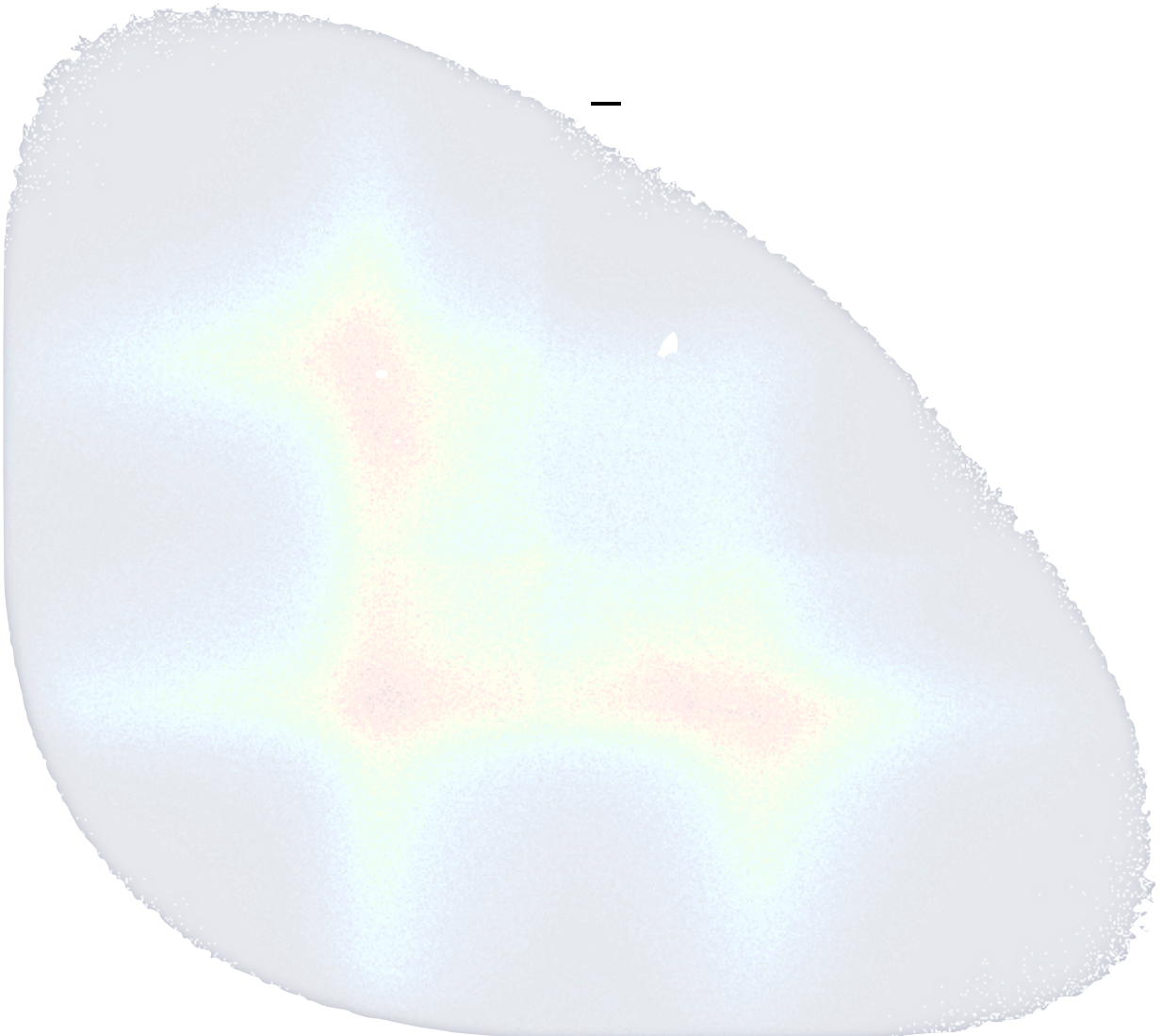
- PWA has started
  - ! High statistics requires perfect understanding of physics
  - Deck effect (under study)
  - Up to date parametrization of $\pi\pi$ scattering
- First result: compare production on proton and lead
  - ! m-population is different: Pb prefers higher m values

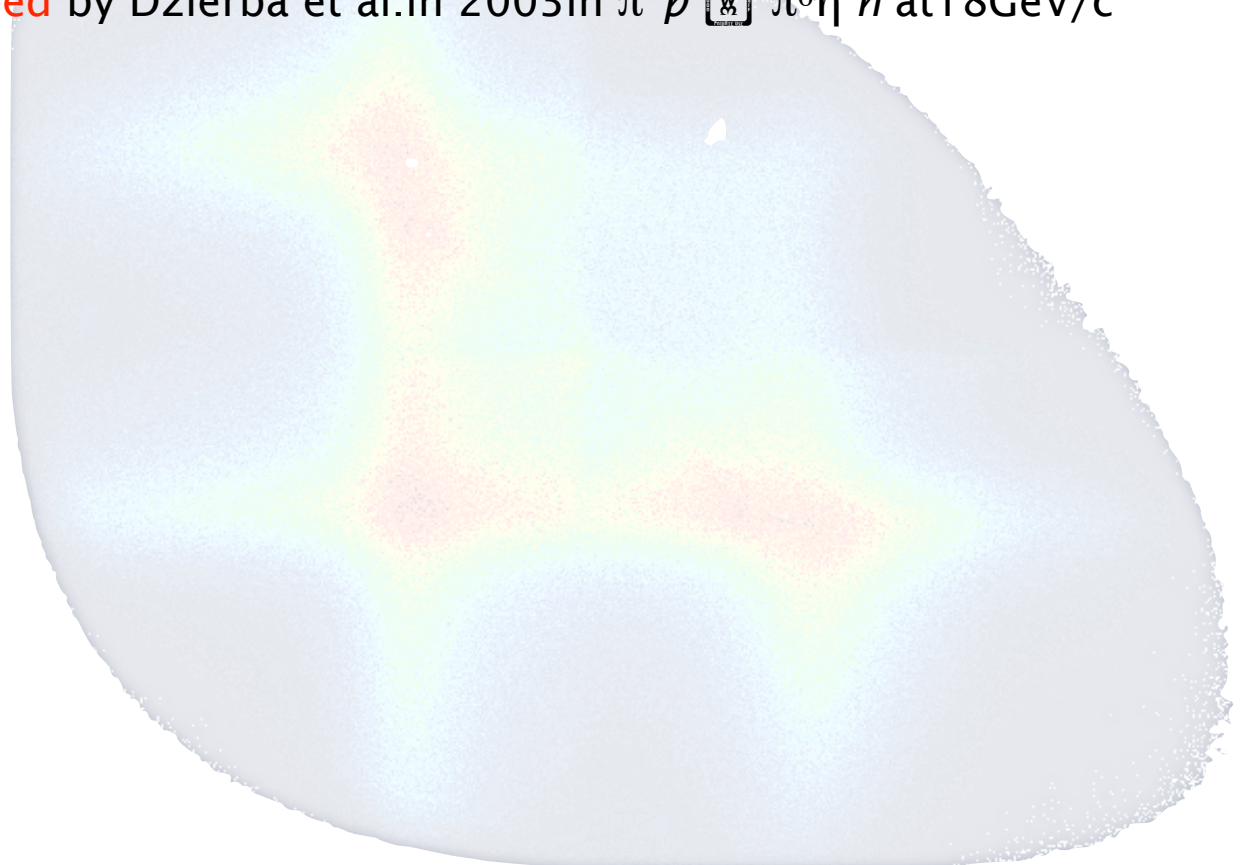
see talk by S. Neubert

(Central) production $\pi^- p \to \pi^- \eta\eta p$



(Central) production $\pi^- p \to \pi^- \eta\eta p$

- Search for exotics - e.g. $\pi(1400) \to \pi^- \eta$
  - Seen by E852 exp. in 1997 $\pi^- p \to \pi^- \eta\, p$ at 18 GeV/c
  - Confirmed by CBAR exp. in 1998 in $pd \to \pi^- \eta \pi^0 p_{spectator}$.
  - Questioned by Dzierba et al.in 2003in $\pi^- p \to \pi^0 \eta\, n$ at18GeV/c



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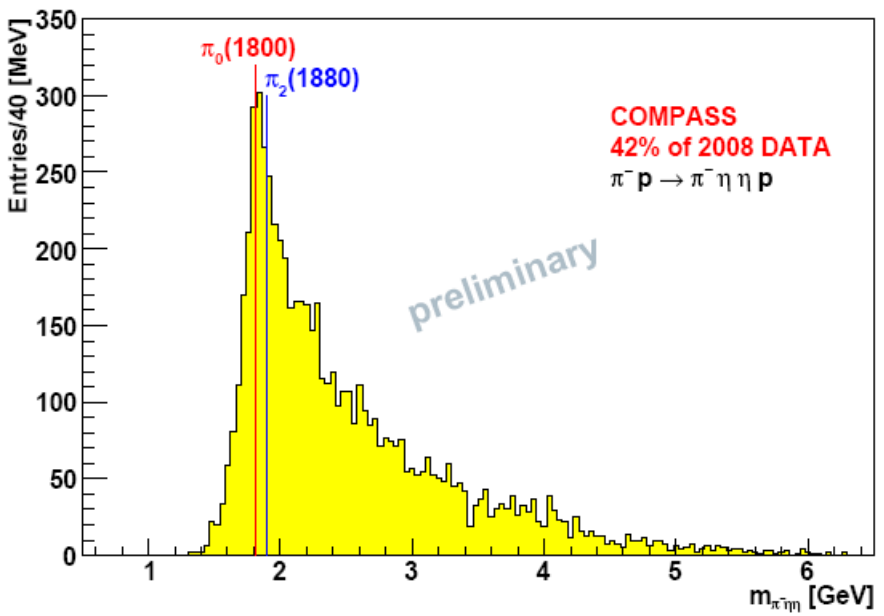
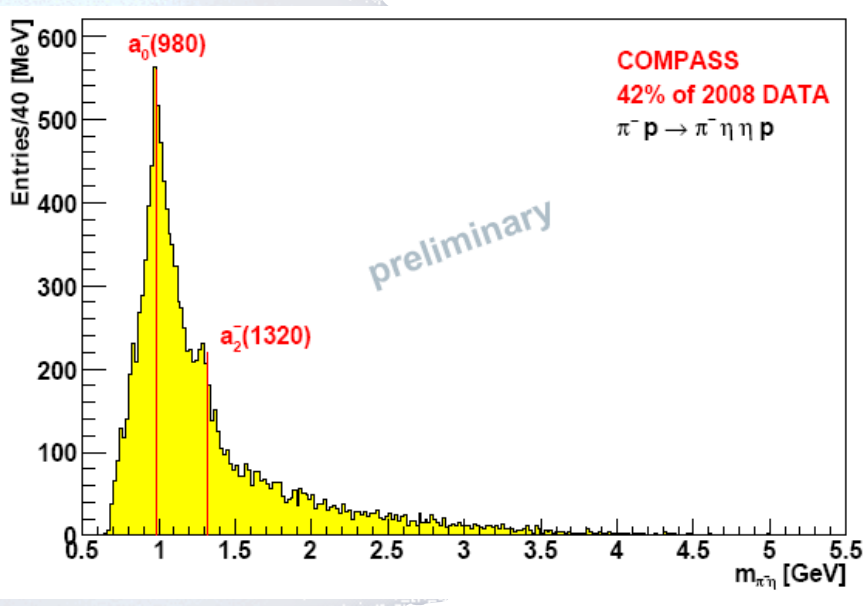
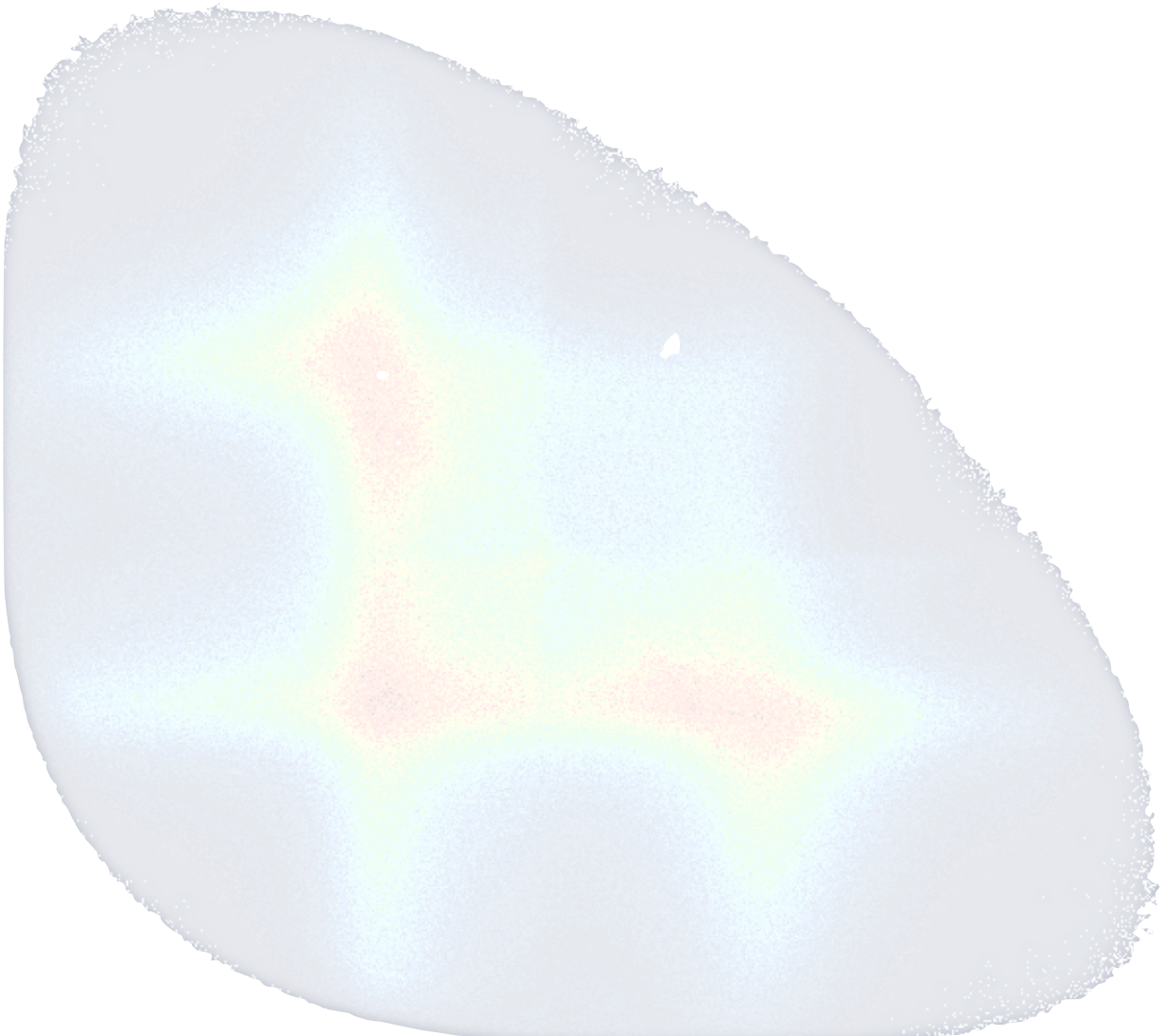
- Diffractive production:



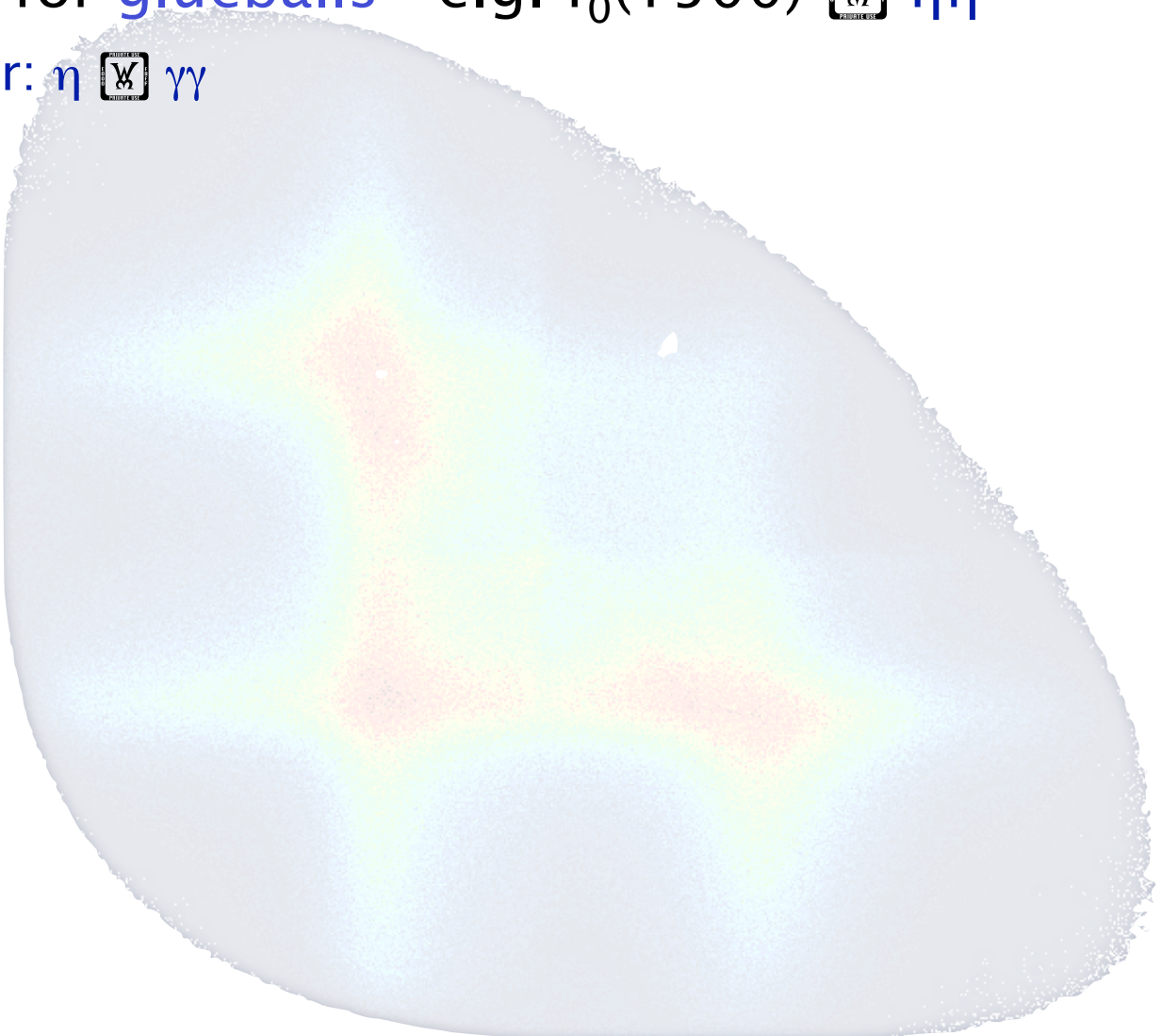


(Central) production $\pi^- p \to \pi^- \eta\eta p$



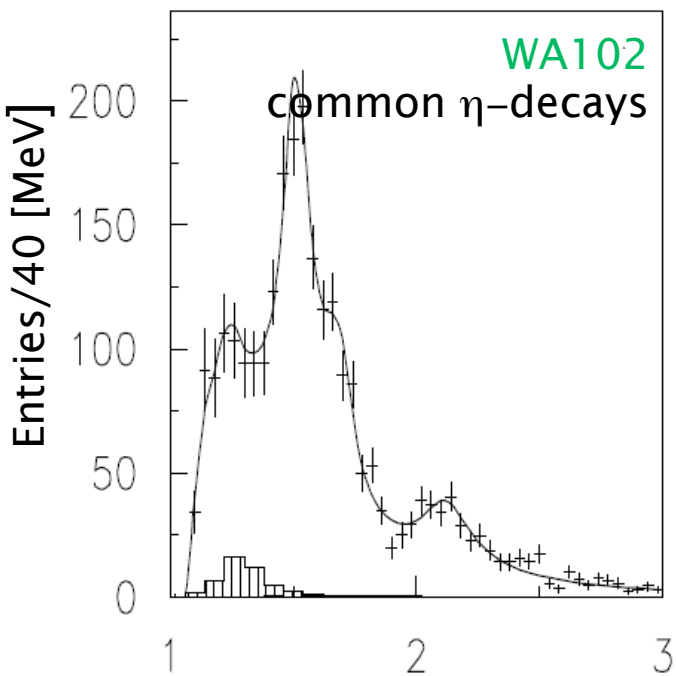
(Central) production $\pi^- p \to \pi^- \eta\eta p$

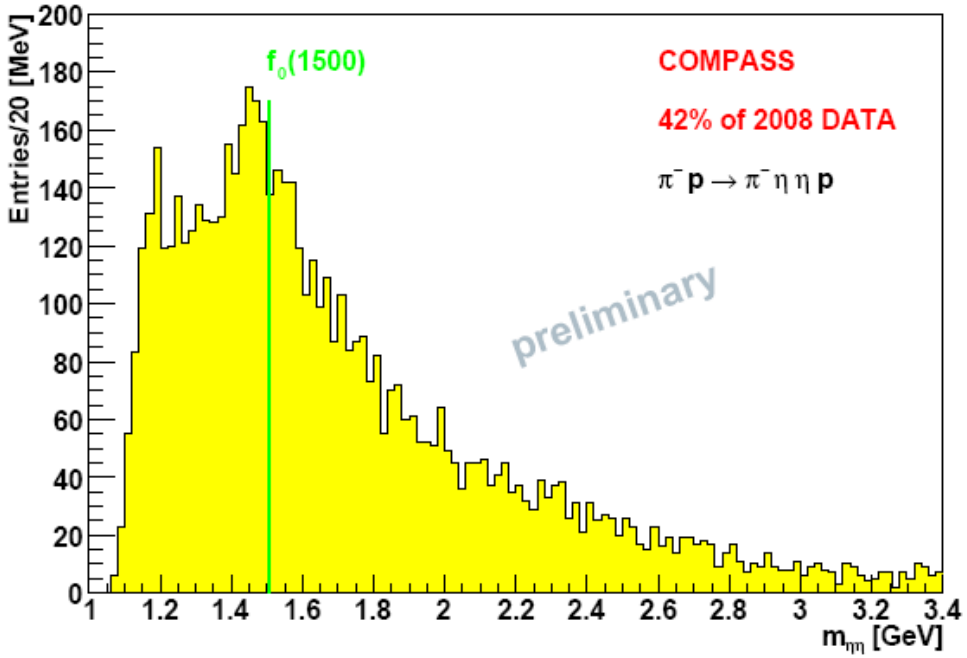
- Search for glueballs - e.g. $f_0(1500) \to \eta\eta$
  - So far: $\eta \to \gamma\gamma$



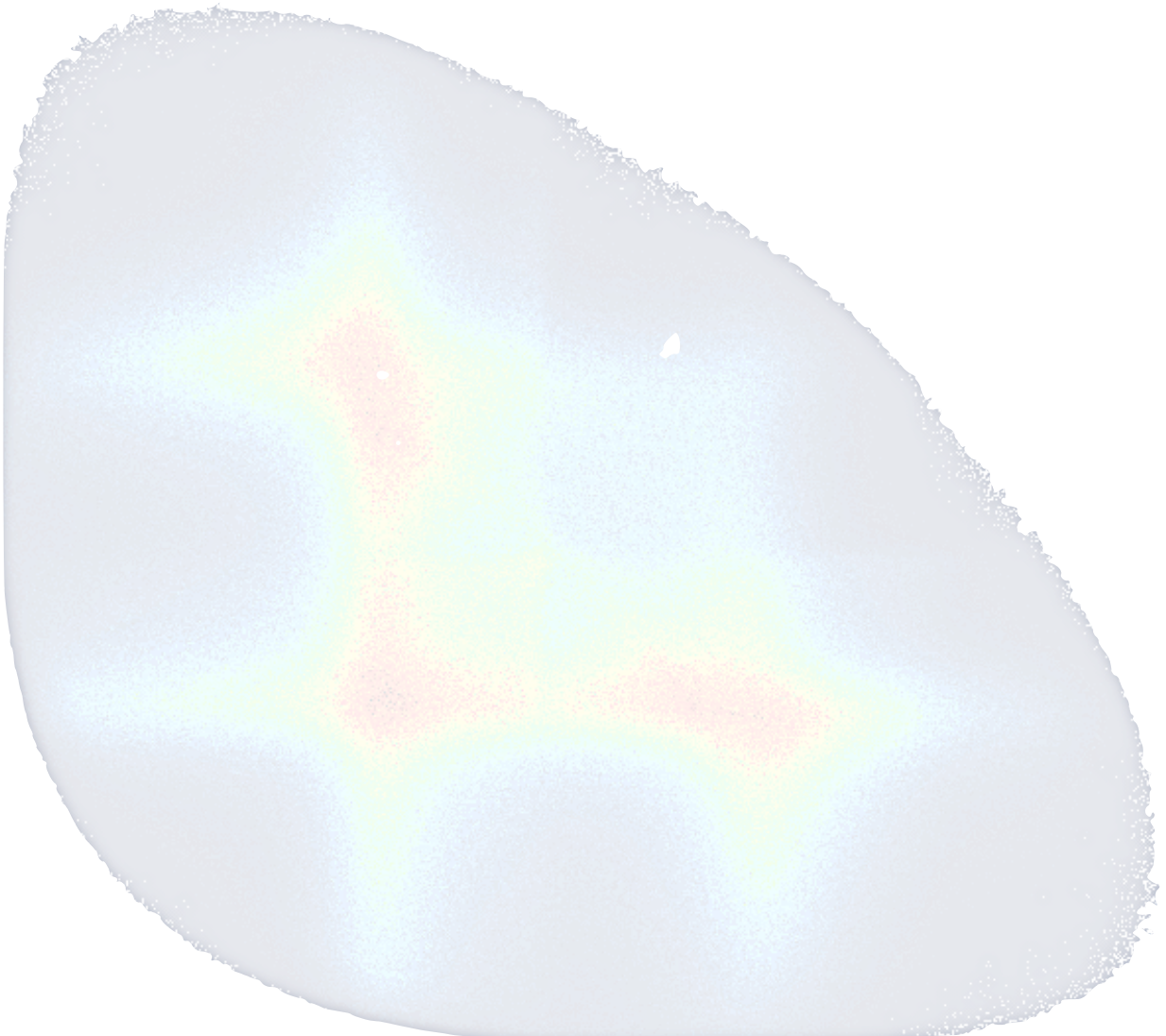
(Central) production $\pi^- p \to \pi^- \eta\eta p$

- Search for glueballs - e.g. $f_0(1500) \to \eta\eta$
  - So far: $\eta \to \gamma\gamma$
- Central Production assumed:
  - Structure consistent with $f_0(1500)$ observed
  - > 10 times statistics of WA102



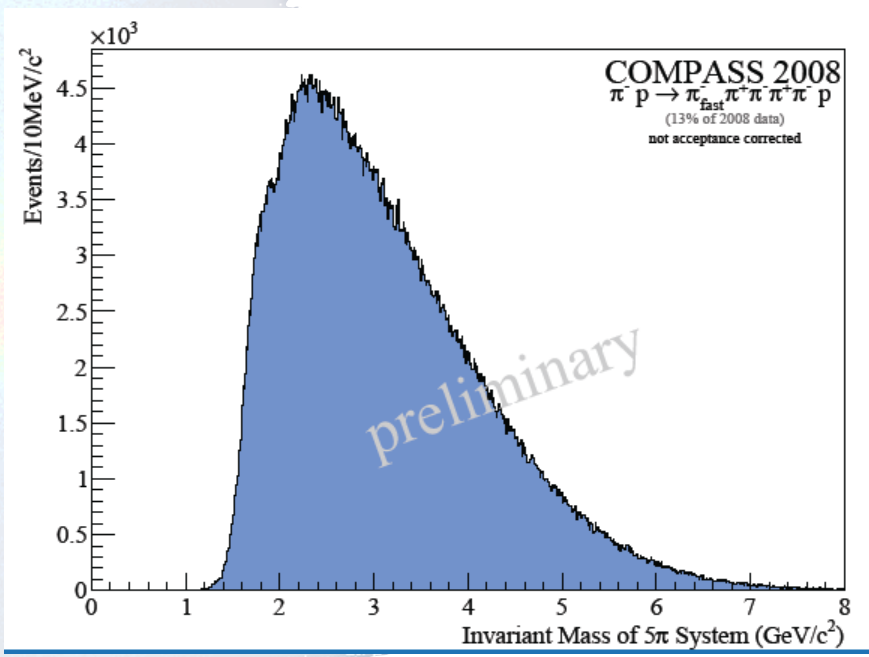


Multi π final states $\pi^- p \to \pi^-\pi^+\pi^-\pi^+\pi^- p$



Multi π final states $\pi^- p \to \pi^-\pi^+\pi^-\pi^+\pi^- p$

- Access $m_X > 2$ GeV/c^2



see talk by S. Neubert

Multi π final states $\pi^-p \to \pi^-\pi^+\pi^-\pi^+\pi^-p$

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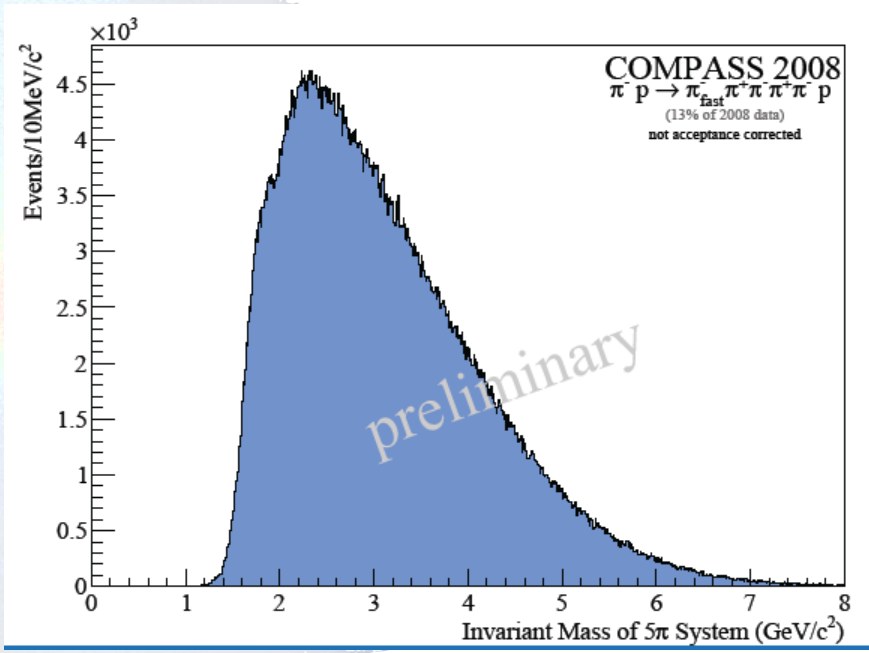

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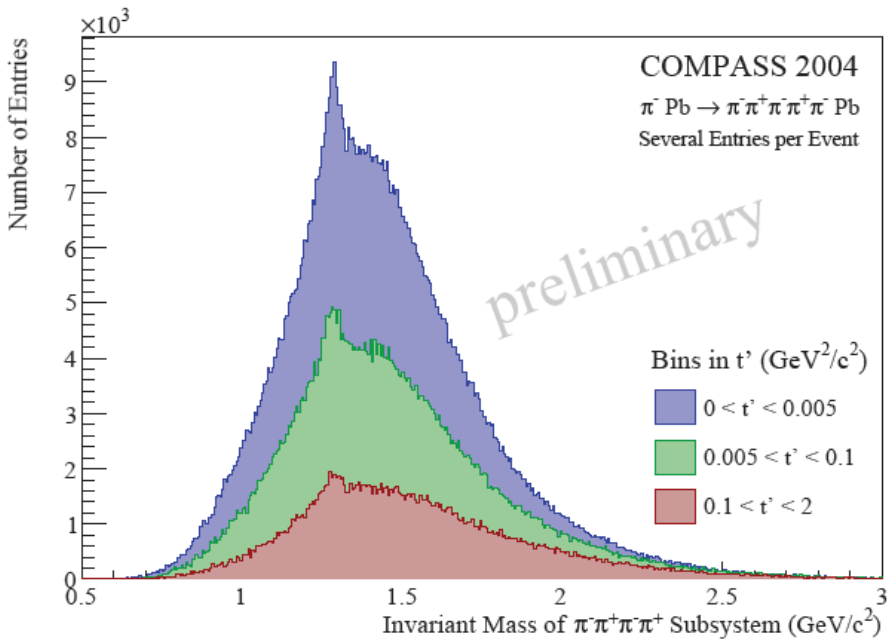
Cut 4π spectrum:



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  - b_1, f_1, η', $\rho(1450)$.....

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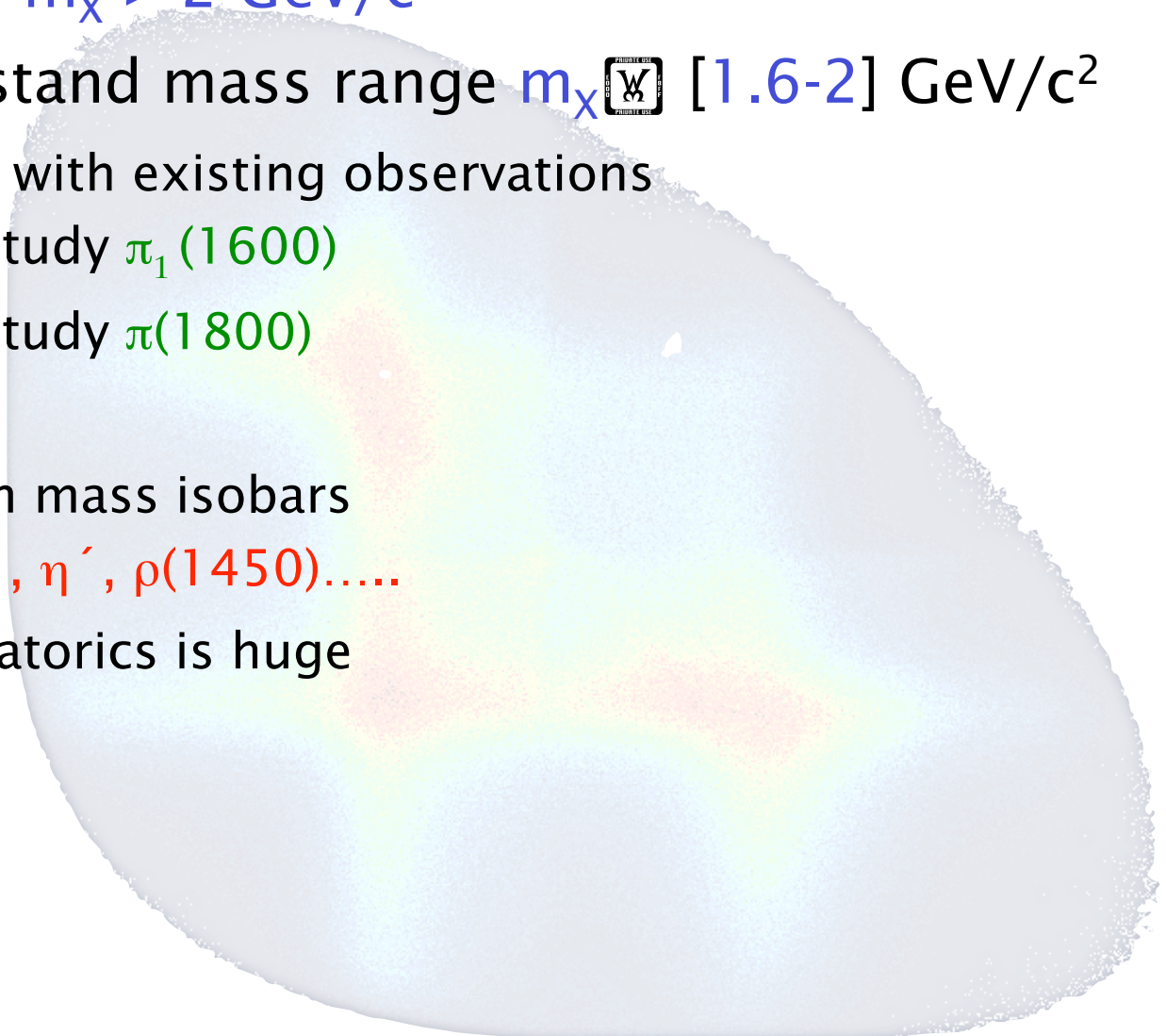

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see talk by S. Neubert

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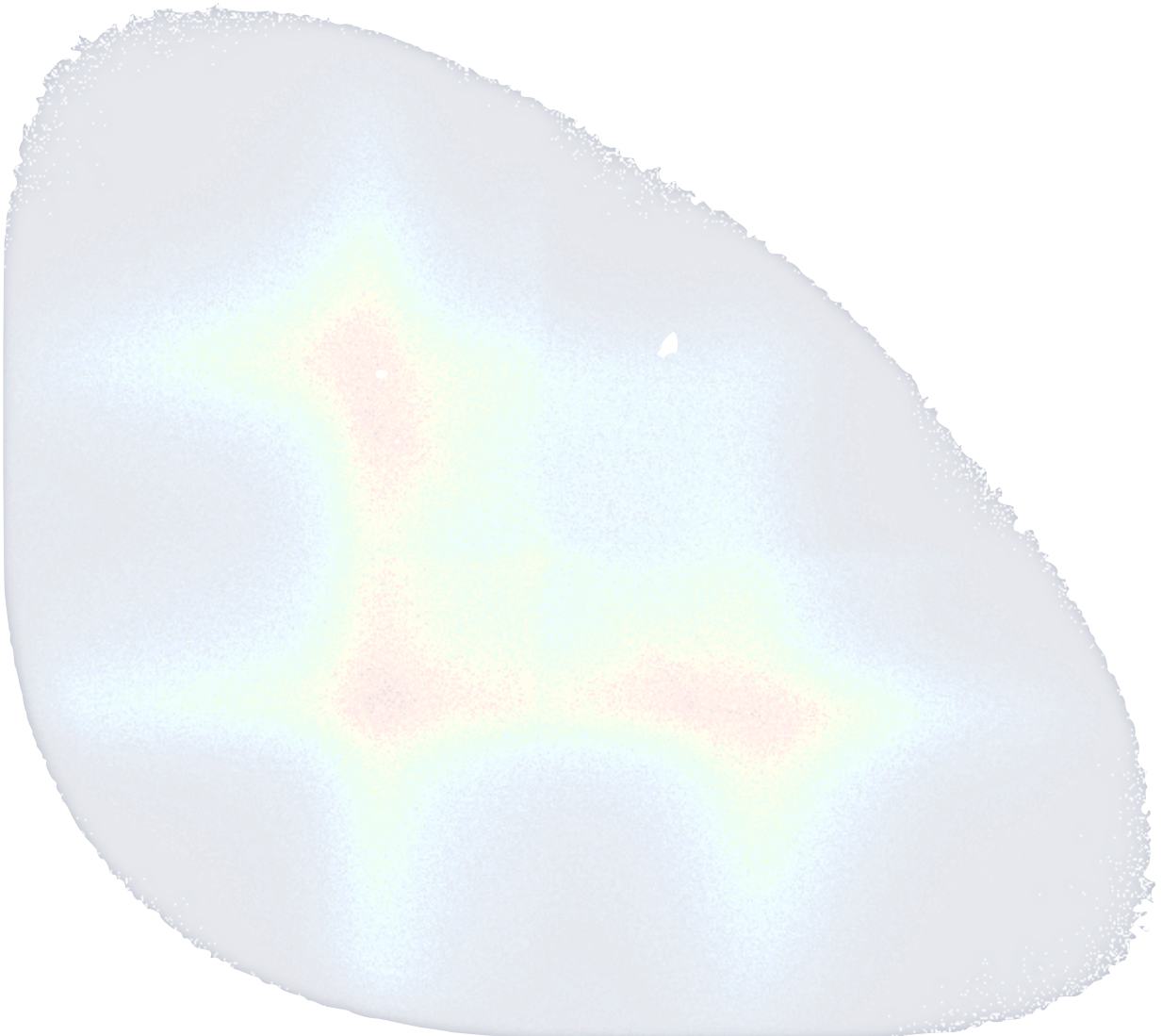
- PWA being started – high statistics

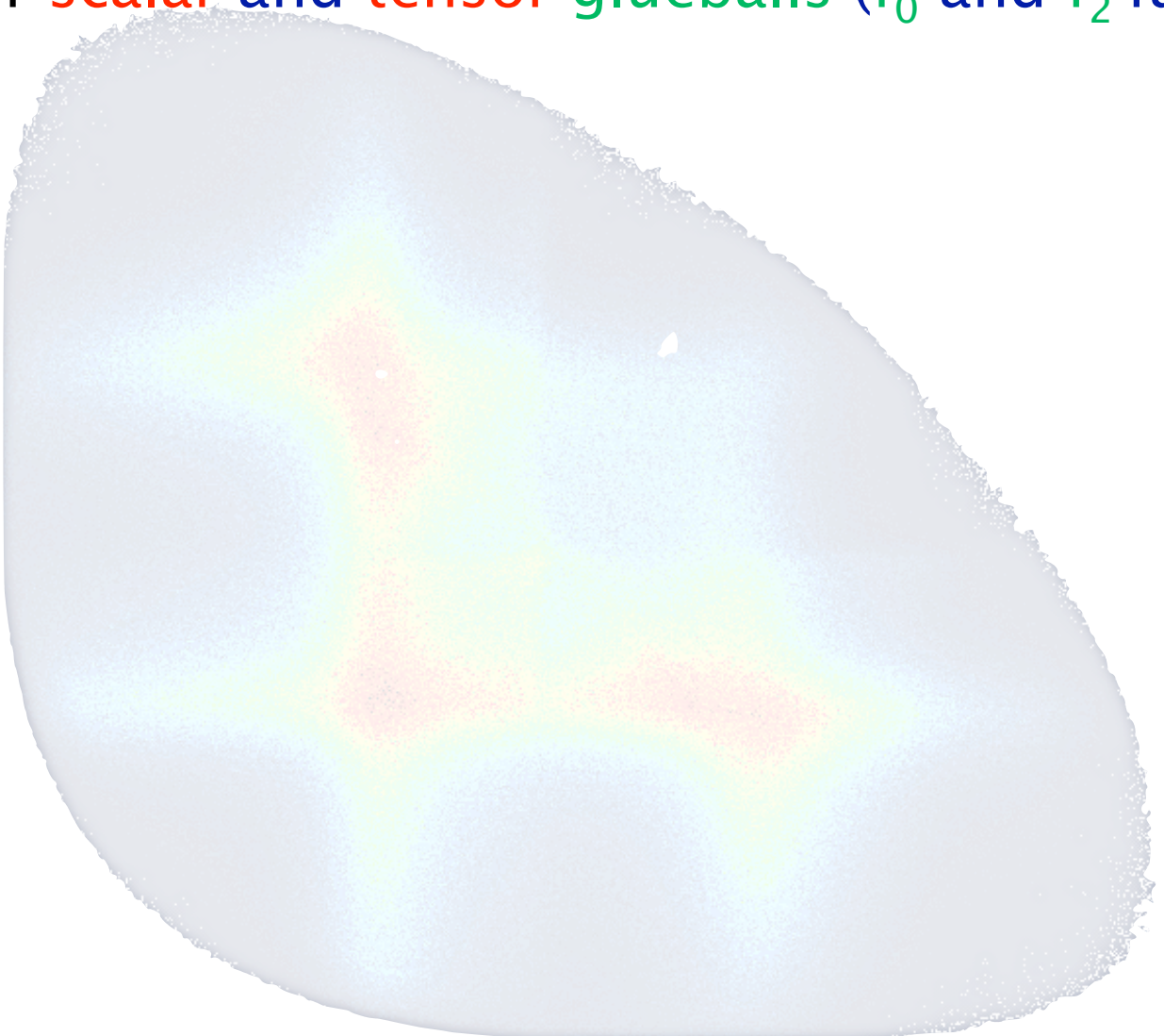
see talk by S. Neubert

Central production $\pi^-p \to \pi^-\pi^+\pi^-\pi^+\pi^-p$



Central production $\pi^-p \to \pi^-\pi^+\pi^-\pi^+\pi^-p$

Search for scalar and tensor glueballs (f_0 and f_2 family)



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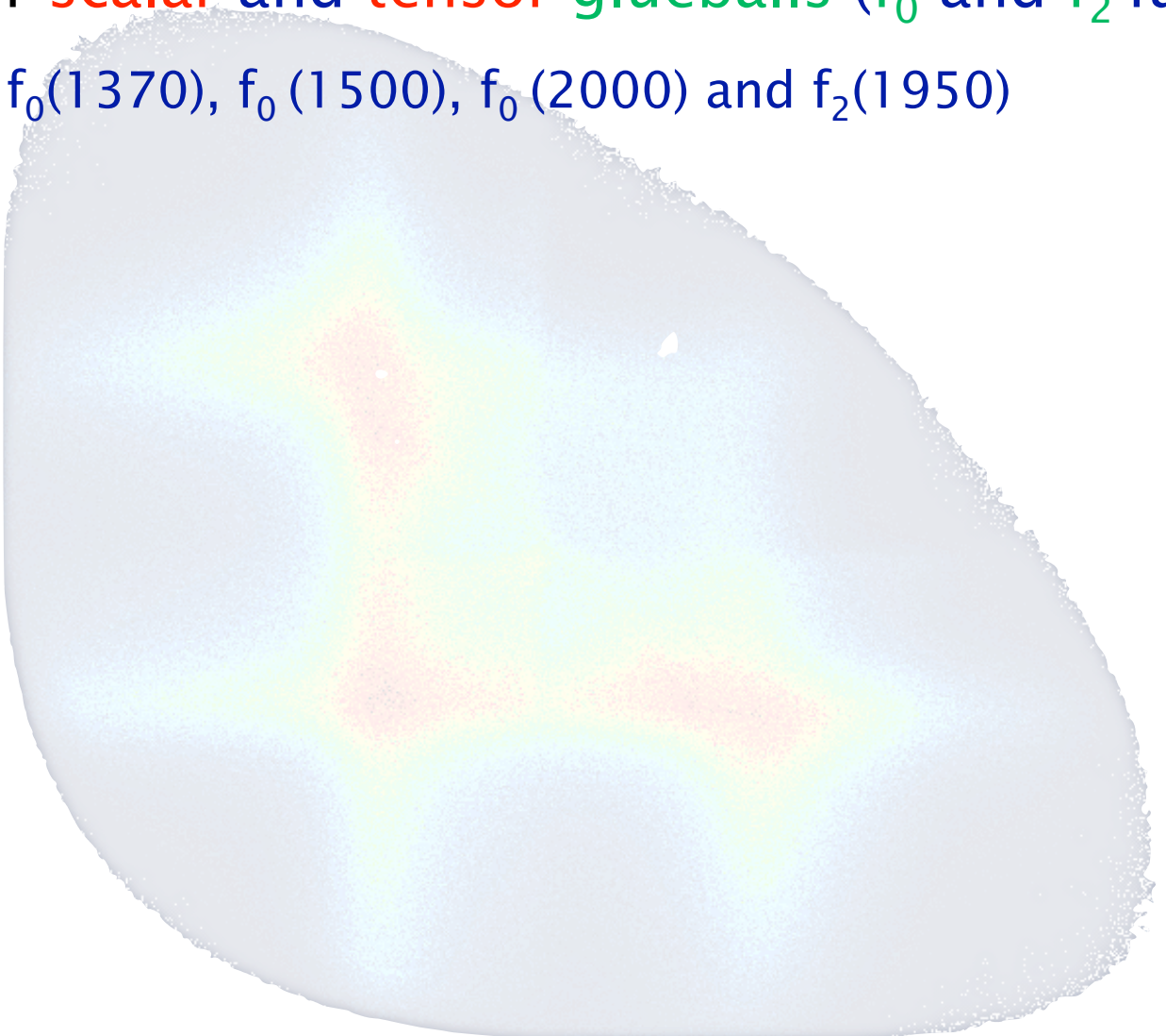
Search for scalar and tensor glueballs (f_0 and f_2 family)

- WA102: $f_0(1370)$, $f_0(1500)$, $f_0(2000)$ and $f_2(1950)$



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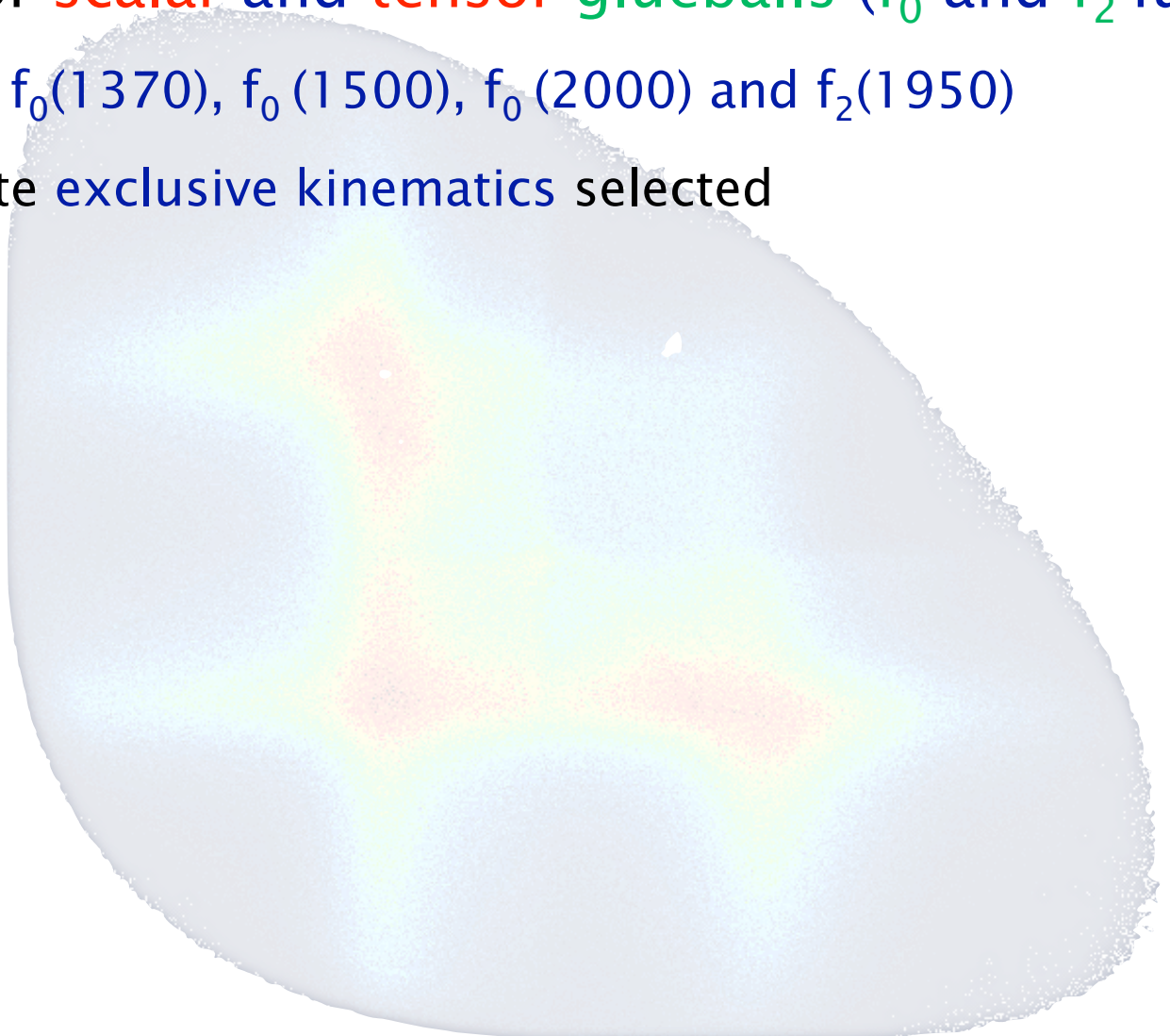

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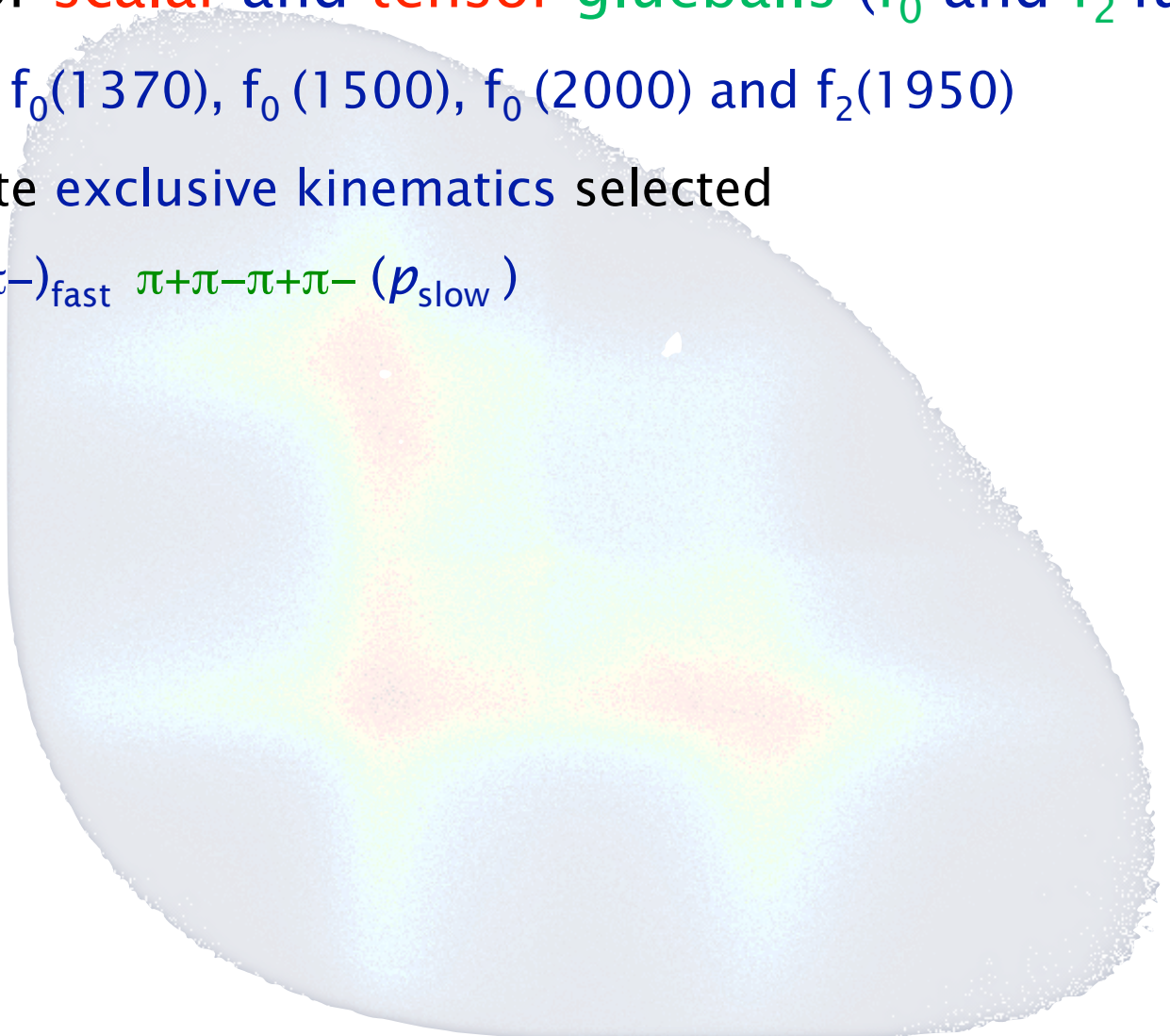

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  - WA102: pp collisions only
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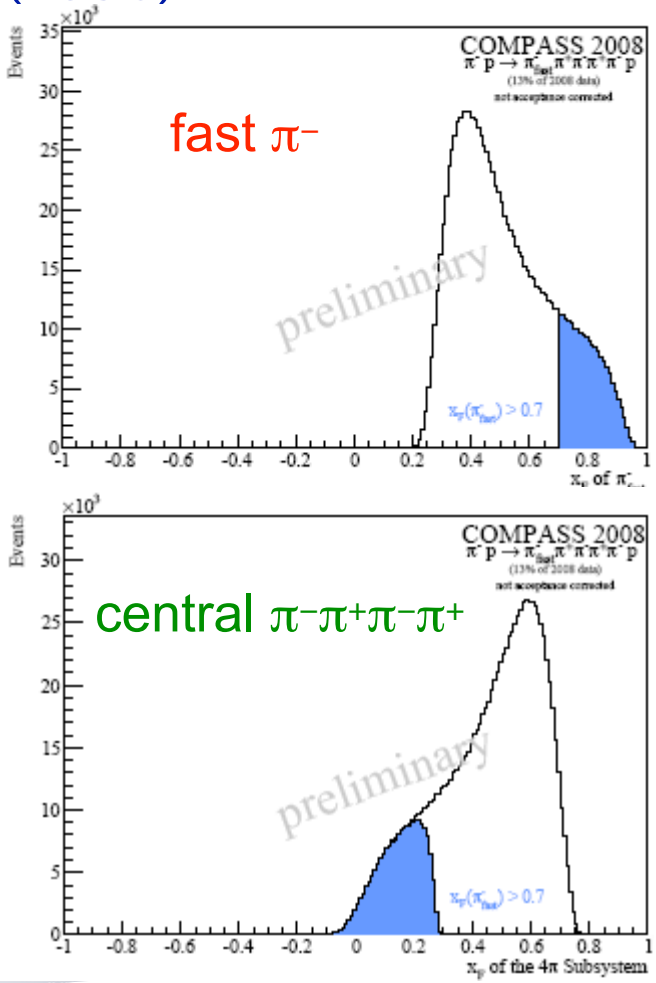

see talk by J. Bernhard

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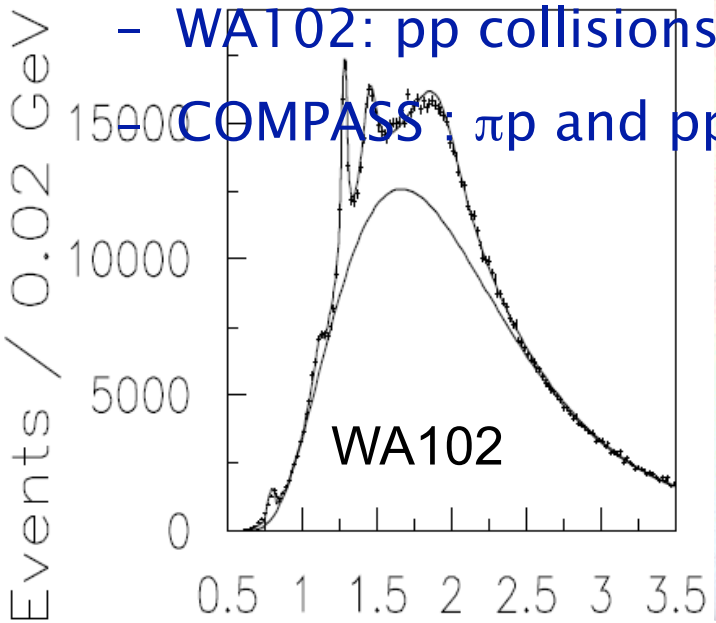

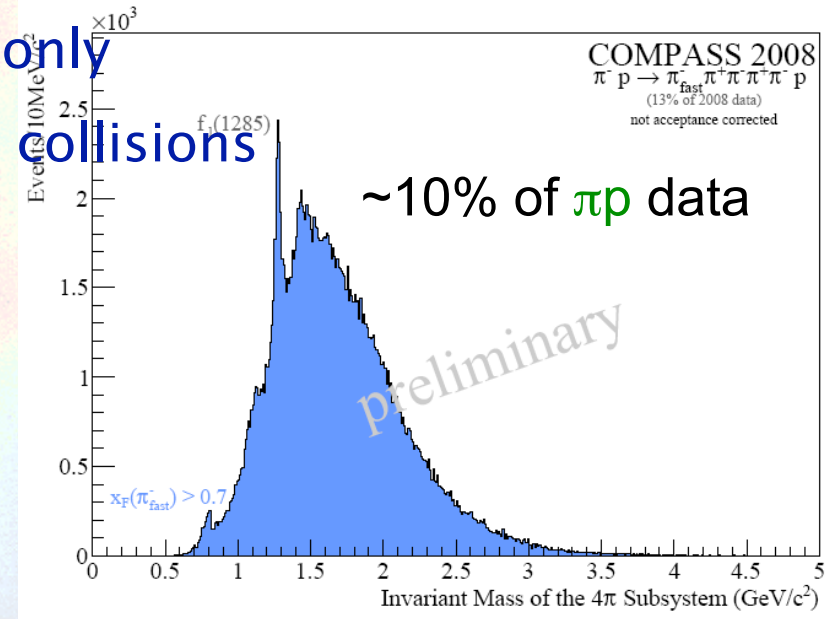

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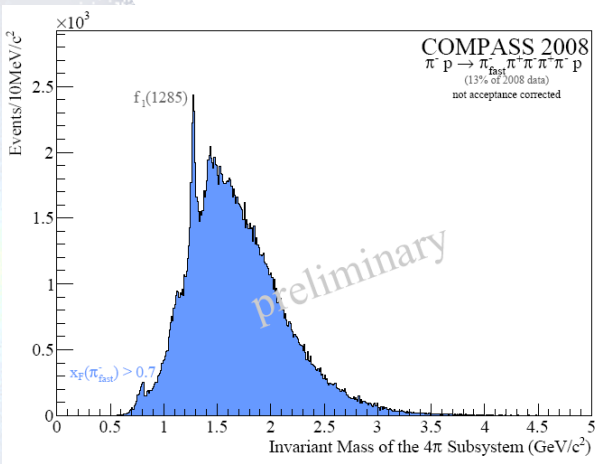

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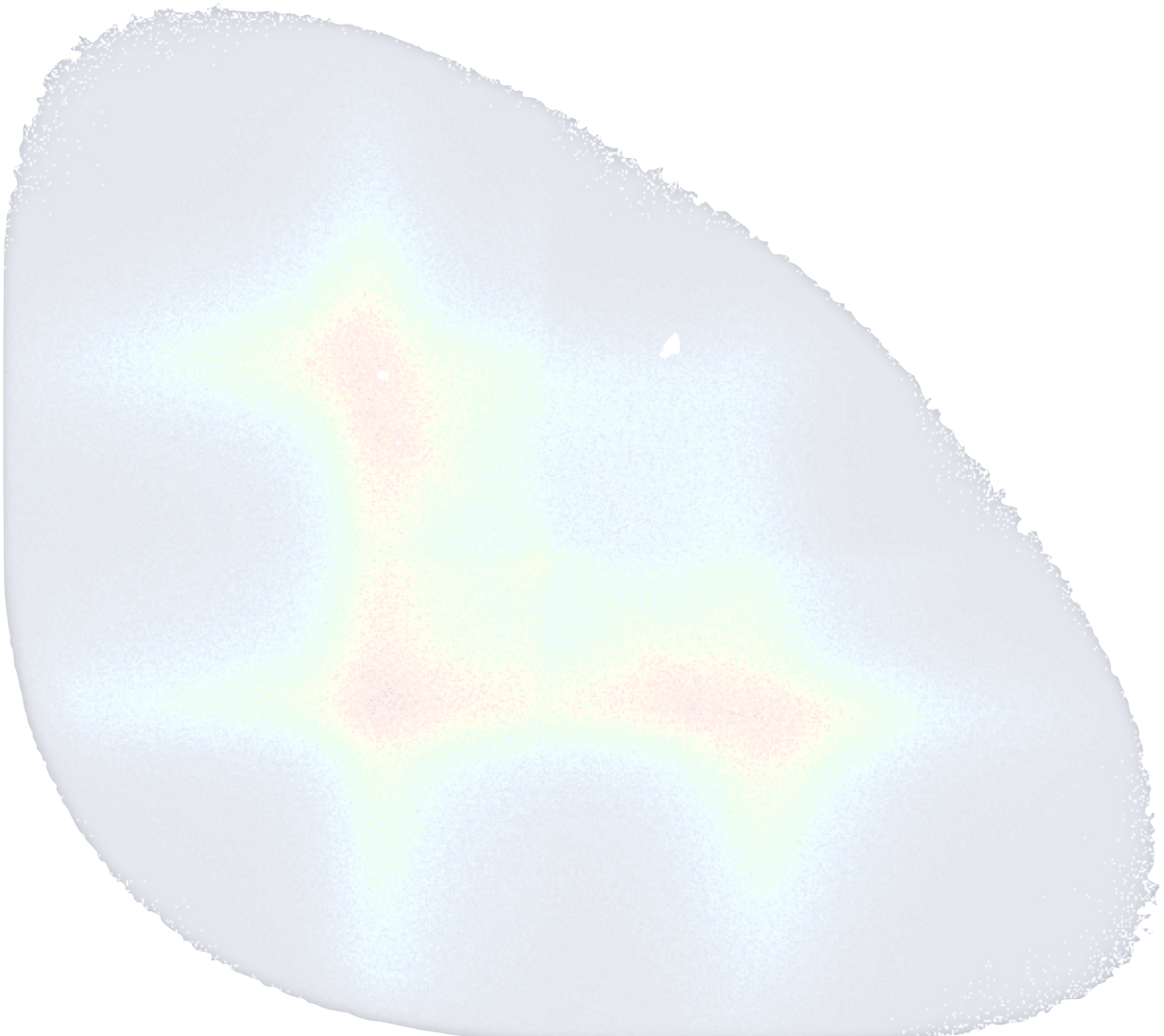
Strangeness in final states πp → πKKp



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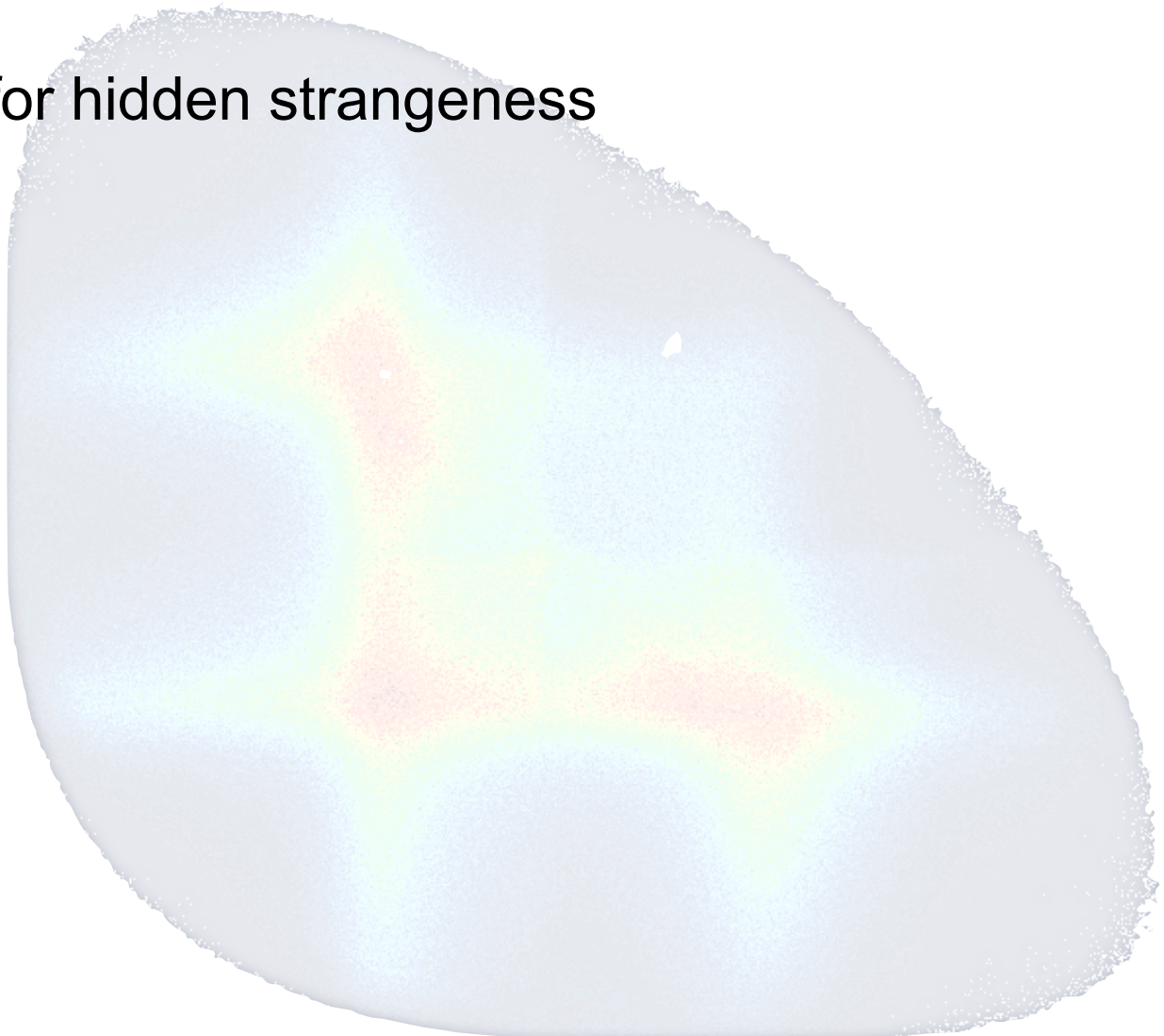
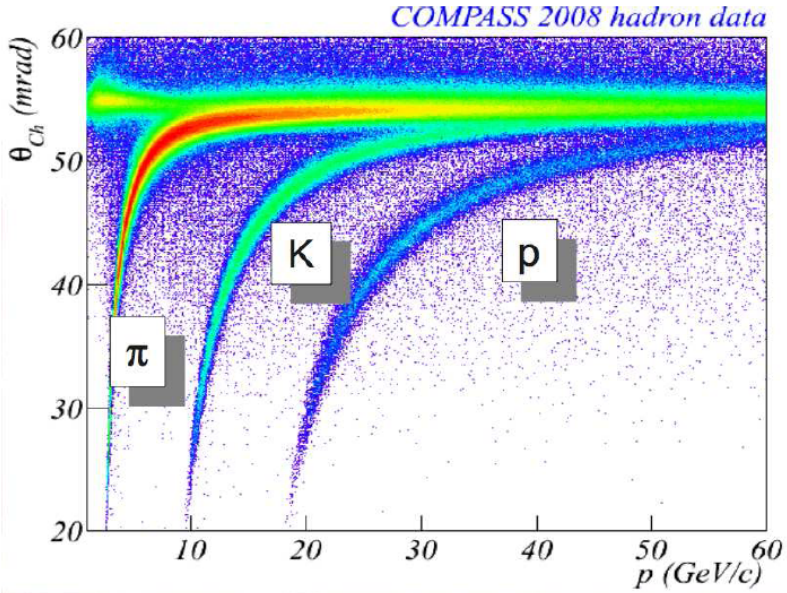
Search for hidden strangeness



Strangeness in final states πp → πKKp

Search for hidden strangeness

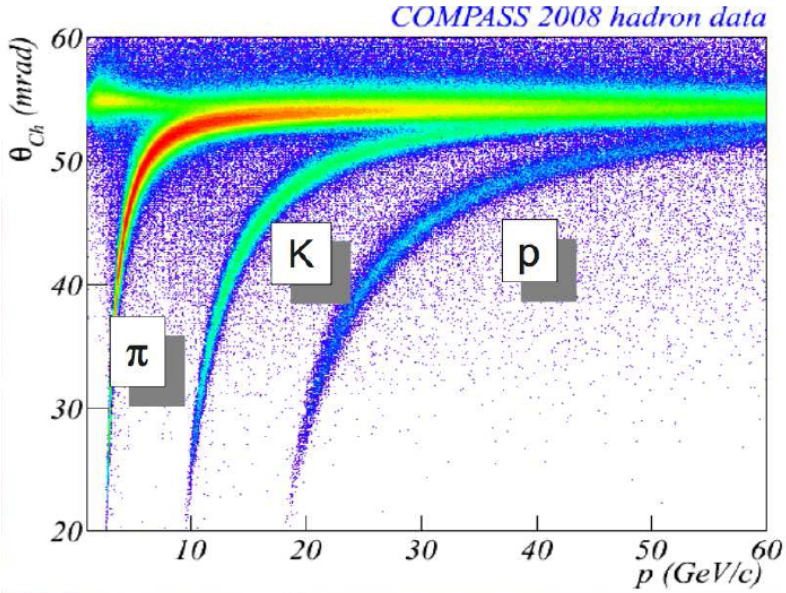
- Neutral and charged kaon channels

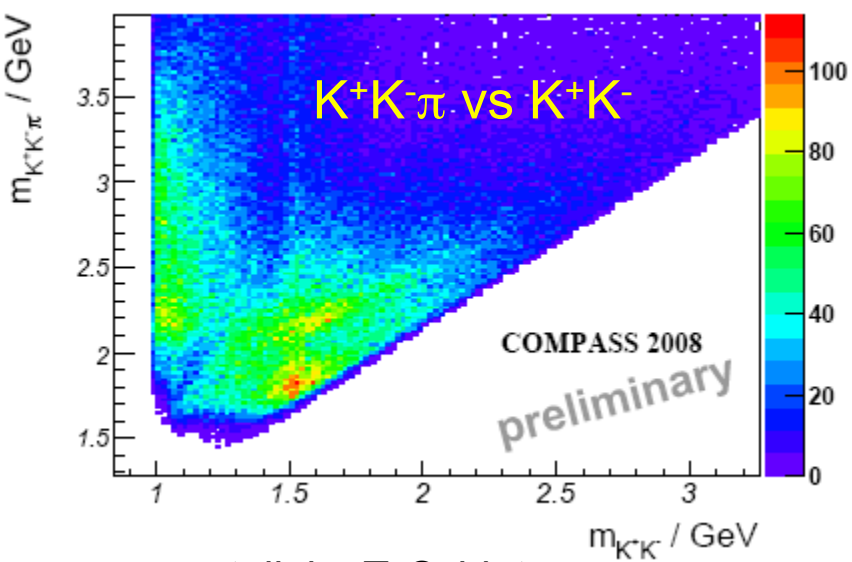


Strangeness in final states πp → πKKp

Search for hidden strangeness

- Neutral and charged kaon channels
- High mass isobars observed cleanly
- Glueball search decaying into KK
- Hybrids decaying into KKπ
- Information on nature of states
  - — branching fraction
  - — decay chain





see talk by T. Schlüter

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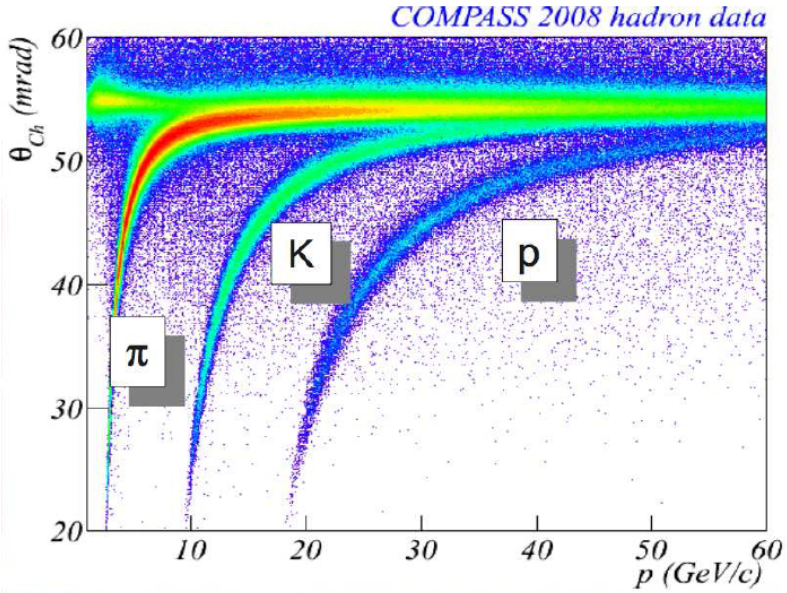

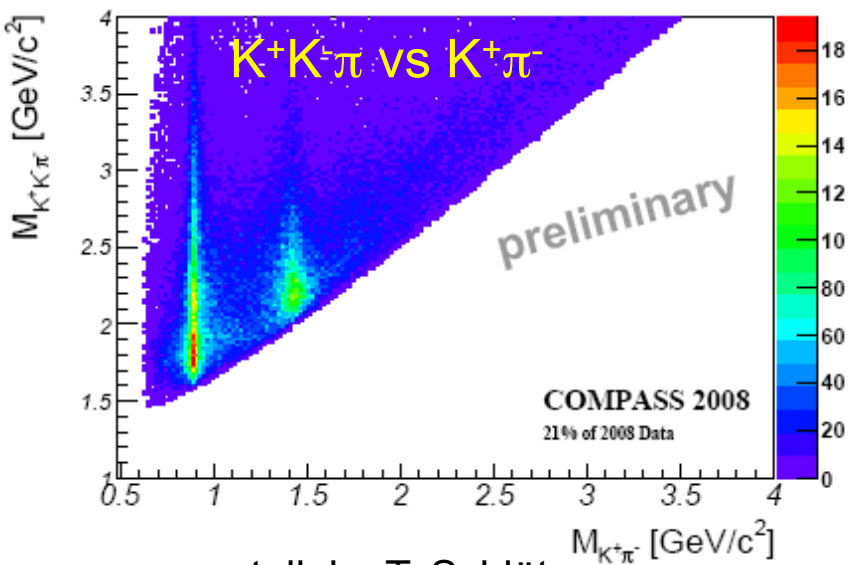

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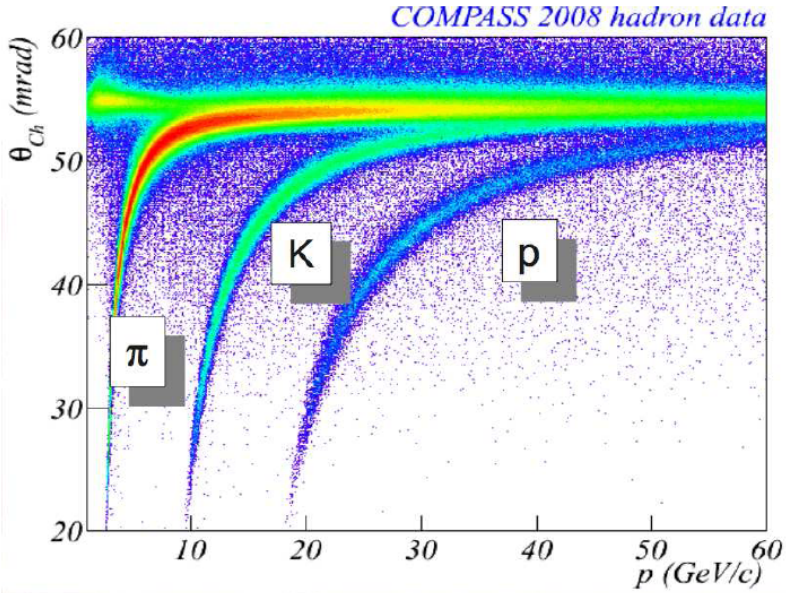
- PWA being prepared



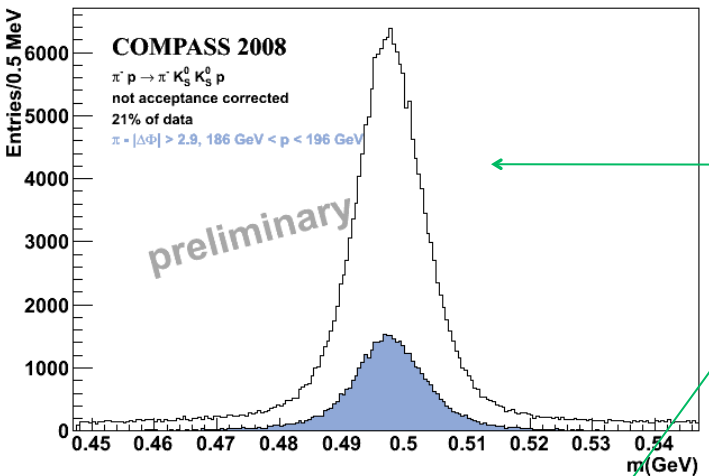
see talk by T. Schlüter

Central Production (KK)

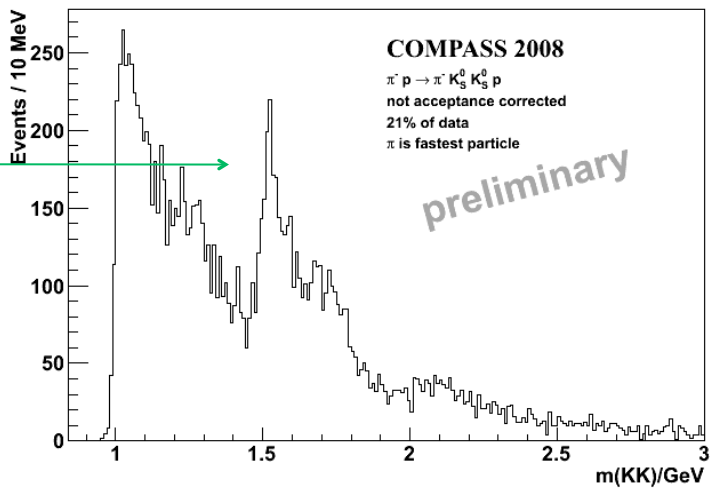
- Central production used to search for glue-rich states
  - WA102 was successful studying f_0 mixing scheme
- Study central production with mesons and protons
  - In ideal world: production very similar (except for spin effects)
  - At COMPASS: Pomeron-Pomeron (DPE) not clearly separable from simple Reggeon exchange
  - Mixture of diffraction and central production
- Kaons are promising selective final states

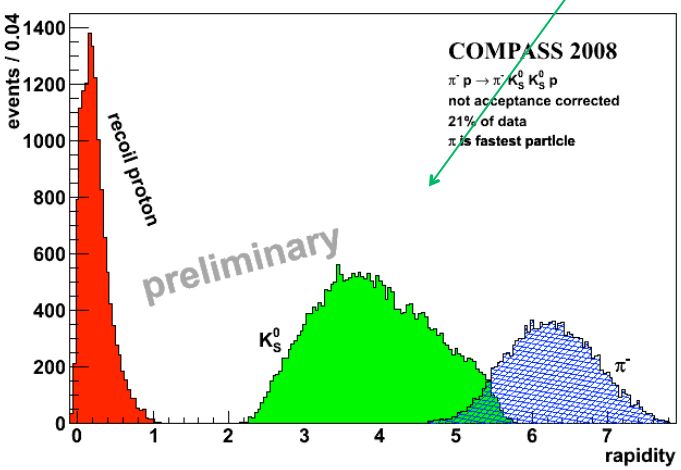
state	allowed J^{PC}				
$K^0_S K^0_S$	0^{++}		2^{++}		4^{++}
$K^0_S K^0_L$		1^{--}		3^{--}	
$K^+ K^-$	0^{++}	1^{--}	2^{++}	3^{--}	4^{++}

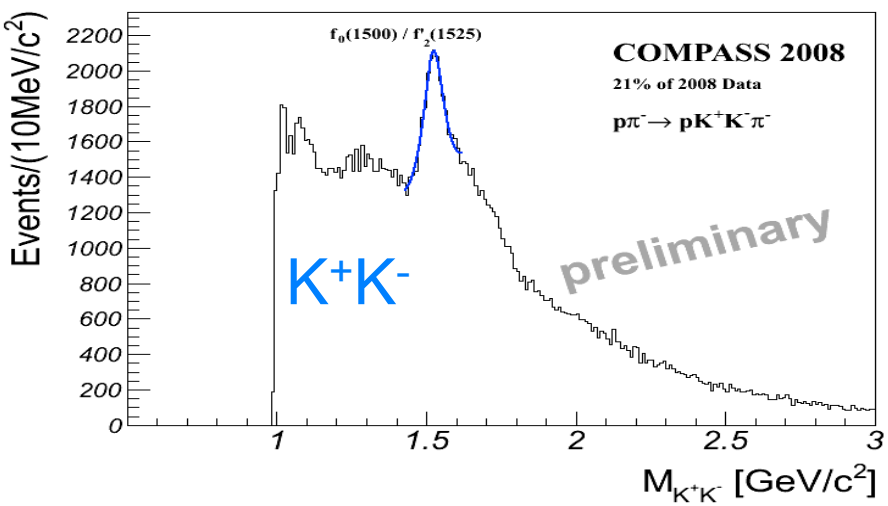
Central Production (KK)



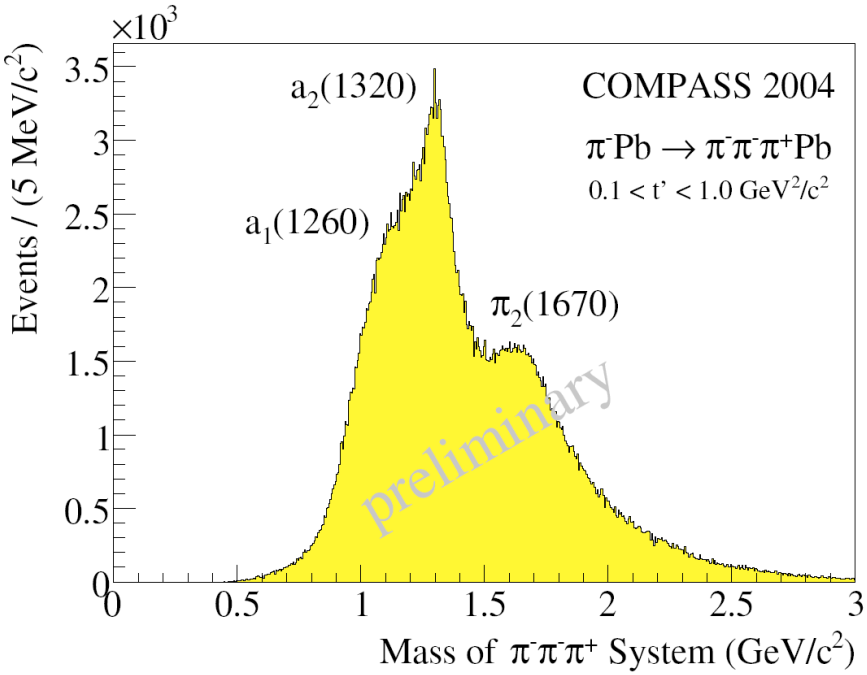
$K^0_S K^0_S$

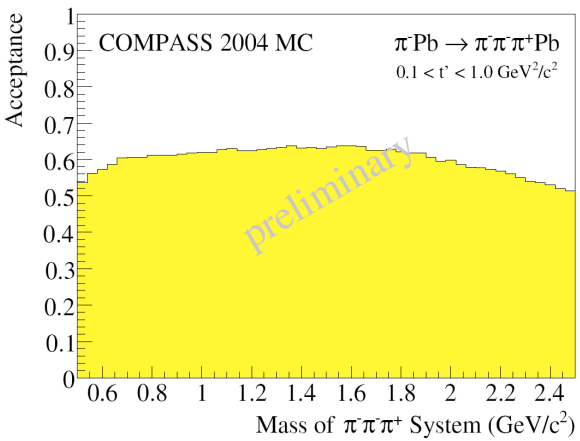


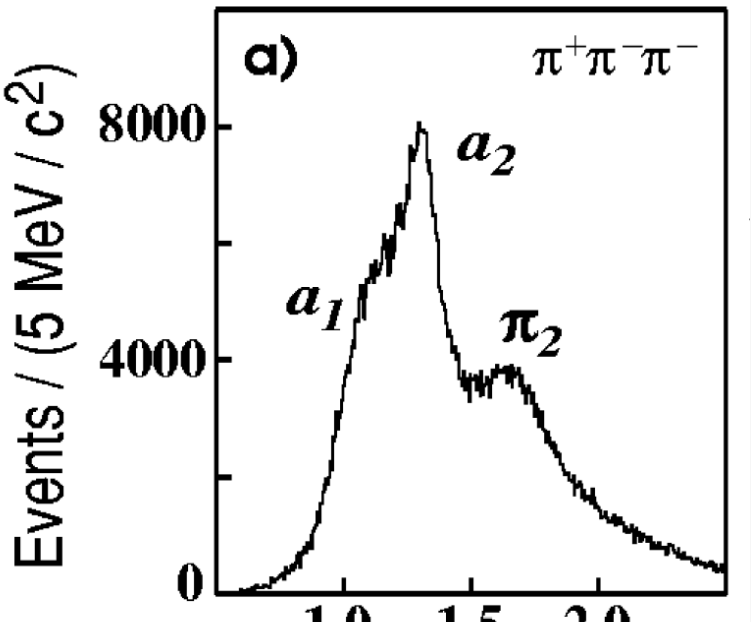


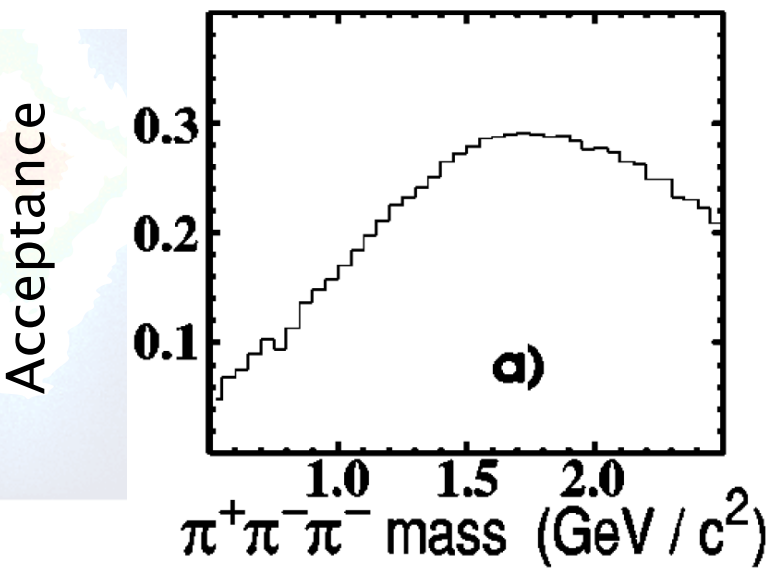


Invariant Mass of 3π System '04

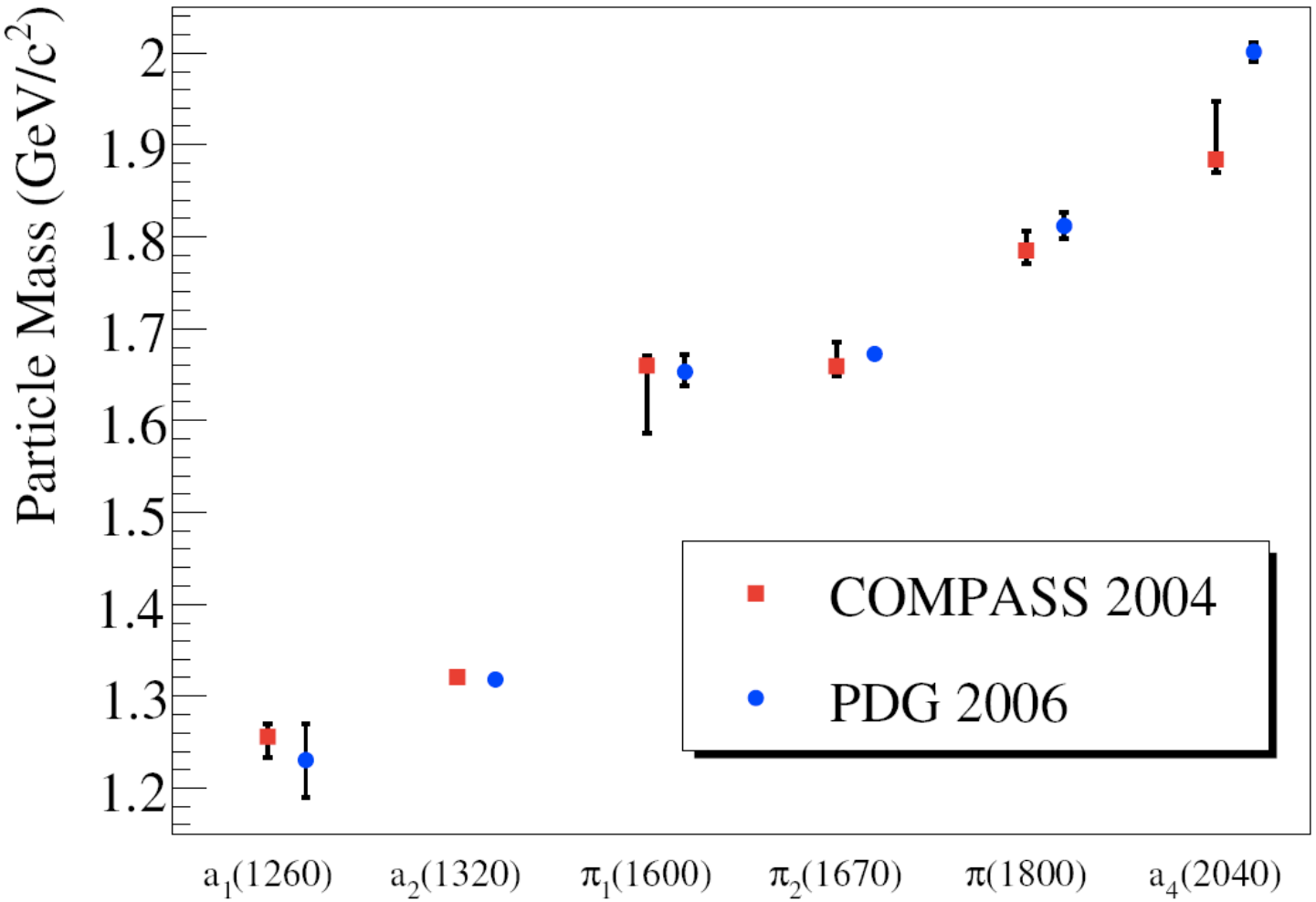








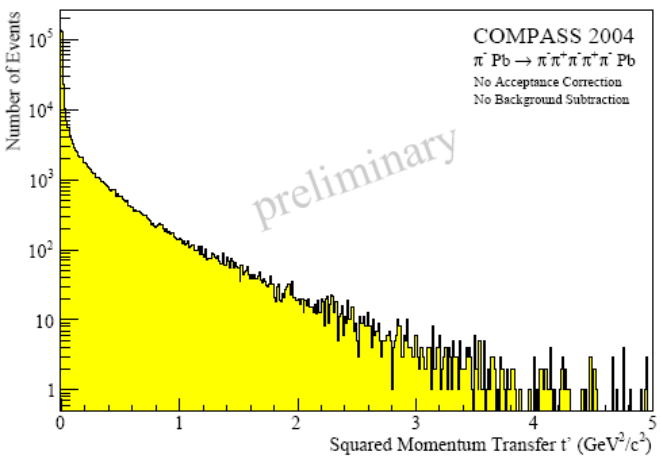
Summary of Waves

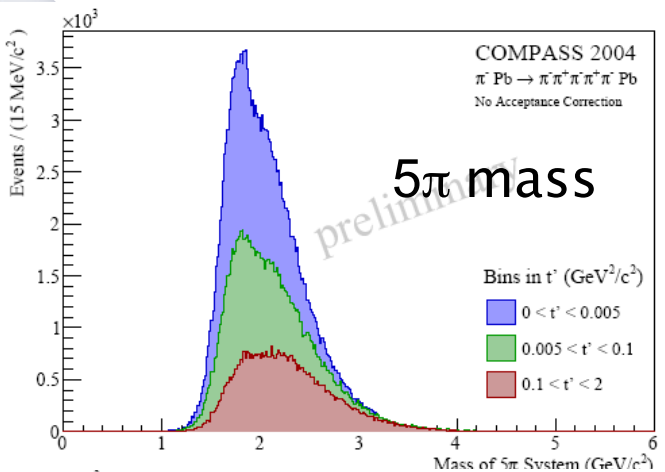


Publication submitted to CERN (preprint)and to PRL

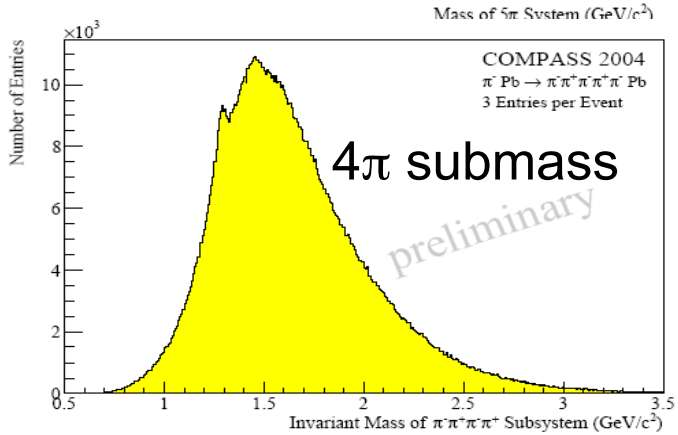
Analysis of 5π

- Need to extend study to high masses
  - Decay of heavy resonances into high mass isobars
  - Multi pion final states
  - Complex analysis (106 waves)

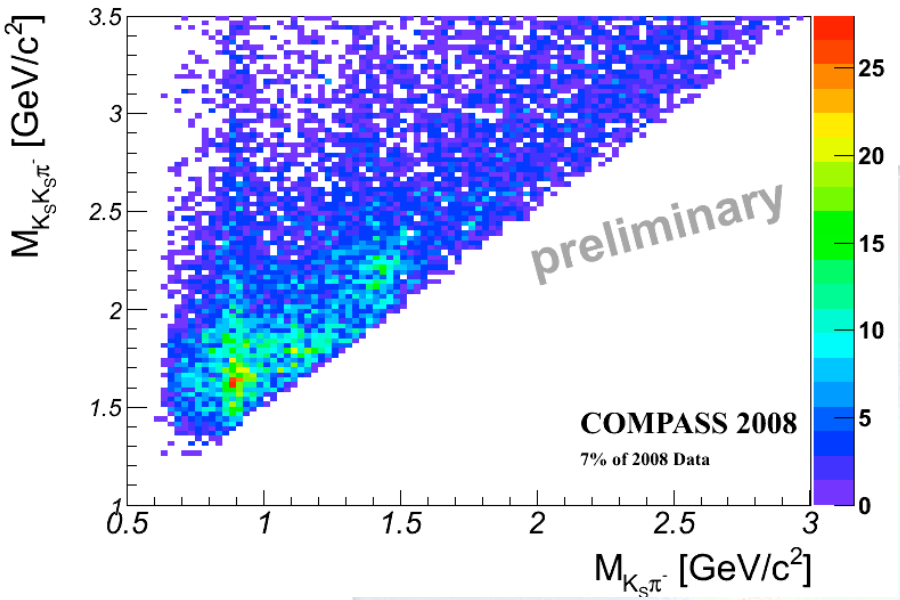


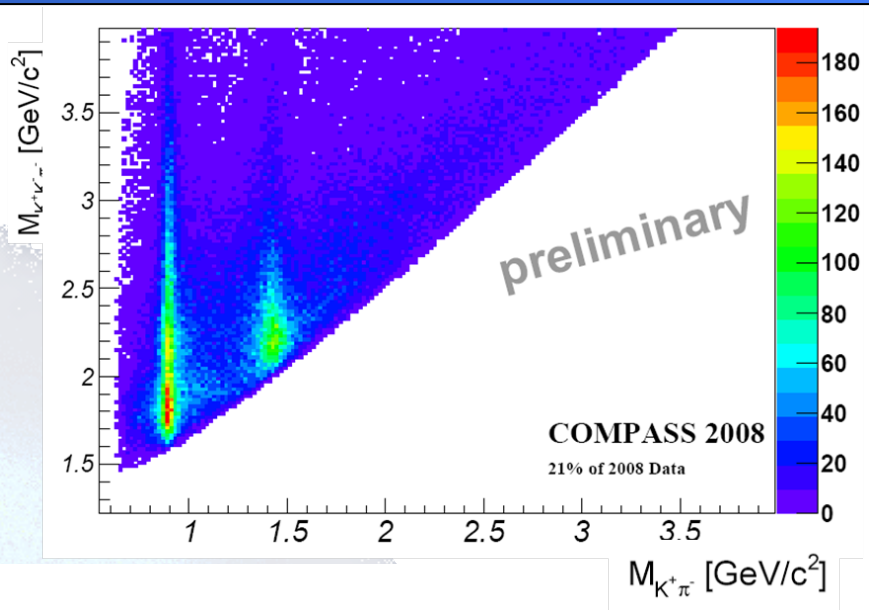


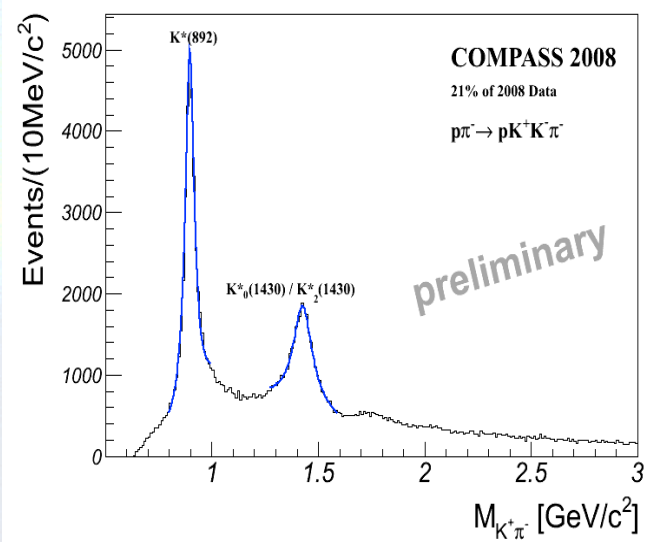
4π Isobars ($G = +1$)			3π Isobars ($G = -1$)		
Name	Mass (MeV/c²)	$I^G(J^{PC})$	Name	Mass (MeV/c²)	$I^G(J^{PC})$
f_0	1370 / 1700	$0^+(0^{++})$			
η'	1403	$0^+(0^{-+})$	a_1	1270	$1^-(1^{++})$
ρ'	1450	$1^+(1^{--})$	a_2	1320	$1^-(2^{++})$
b_1	1235 / 1800	$1^+(1^{+-})$	π'	1300	$1^-(0^{-+})$
f_1	1285 / 1450	$0^+(1^{++})$	π_2	1670	$1^-(2^{-+})$
η_2'	1645	$0^+(2^{-+})$	π_1	1600	$1^-(1^{-+})$
f_2	1565	$0^+(2^{++})$			
ρ_3	1690	$1^+(3^{--})$			
η_1	1600	$0^+(1^{-+})$			
More Exotics	???	$1^+(0^{+-}),1^+(2^{+-})$			



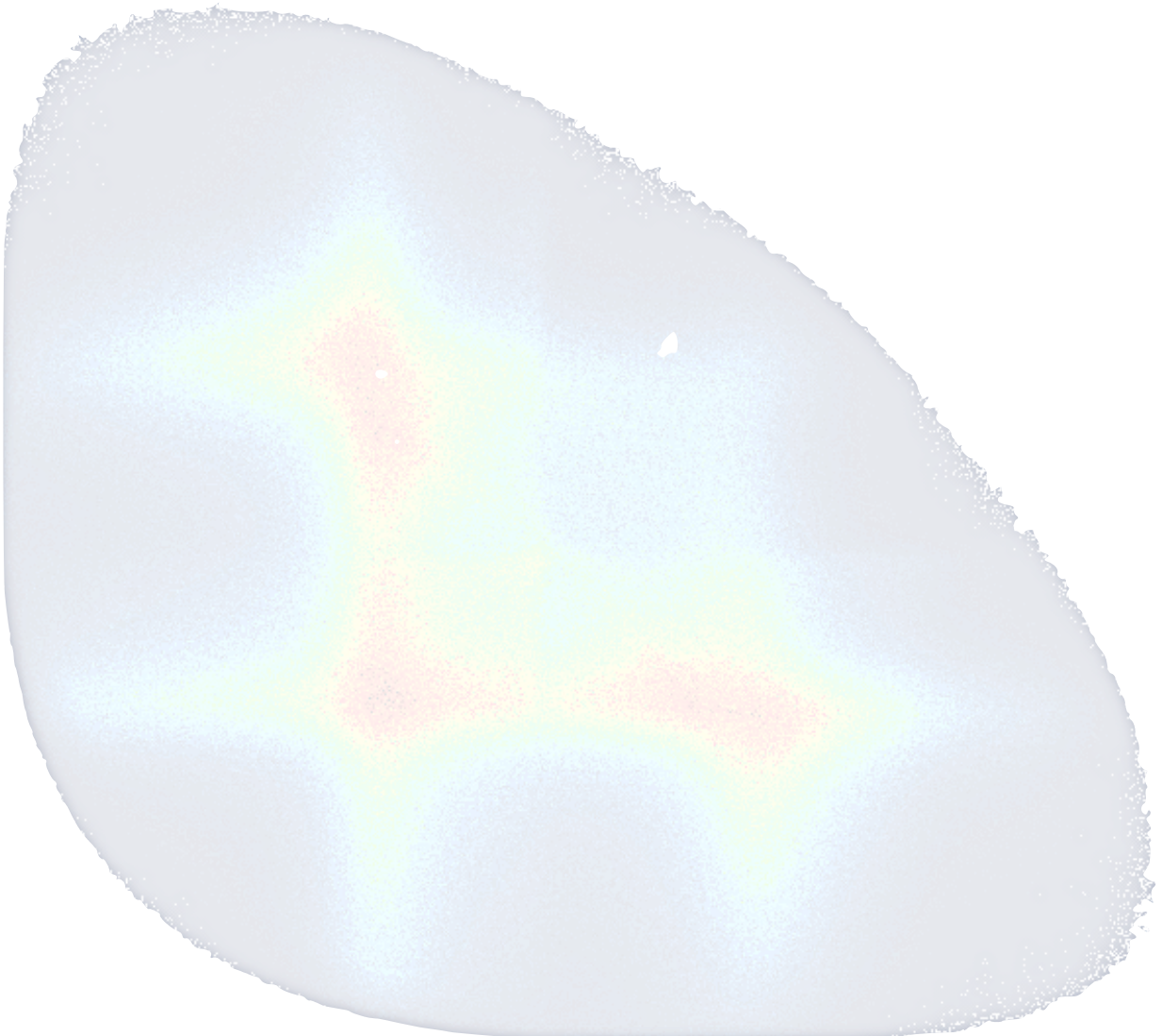
Central Production (KK)







Wave Set Included into Fit



Wave Set Included into Fit

Notation of Partial Waves: $J^{PC} M^{\epsilon}[\ldots]L$

- Spin J, parity P, C-parity C, spin projection M, reflectivity ϵ, decay particles $[\ldots]$ and their relative orbital angular momentum L
- E. g.: $\pi_2(1670)$: $2^{-+}1^{+}[f_2\pi]S$, $2^{-+}0^{+}[\rho\pi]P$, $a_2(1320)$: $2^{++}1^{+}[\rho\pi]D$
- Intensity is a coherent and incoherent ($\epsilon = \pm 1$, flat) sum of partial waves

Wave Set Included into Fit

$J^{PC}M^{\epsilon}$	L	Isobar π	Cut [GeV]
$0^{-+}0^{+}$	S	$f_0\pi$	1.40
$0^{-+}0^{+}$	S	$(\pi\pi)_s\pi$	-
$0^{-+}0^{+}$	P	$\rho\pi$	-
$1^{-+}1^{+}$	P	$\rho\pi$	-
$1^{++}0^{+}$	S	$\rho\pi$	-
$1^{++}0^{+}$	P	$f_2\pi$	1.20
$1^{++}0^{+}$	P	$(\pi\pi)_s\pi$	0.84
$1^{++}0^{+}$	D	$\rho\pi$	1.30
$1^{++}1^{+}$	S	$\rho\pi$	-
$1^{++}1^{+}$	P	$f_2\pi$	1.40
$1^{++}1^{+}$	P	$(\pi\pi)_s\pi$	1.40
$1^{++}1^{+}$	D	$\rho\pi$	1.40
$2^{-+}0^{+}$	S	$f_2\pi$	1.20
$2^{-+}0^{+}$	P	$\rho\pi$	0.80
$2^{-+}0^{+}$	D	$f_2\pi$	1.50
$2^{-+}0^{+}$	D	$(\pi\pi)_s\pi$	0.80
$2^{-+}0^{+}$	F	$\rho\pi$	1.20
$2^{-+}1^{+}$	S	$f_2\pi$	1.20
$2^{-+}1^{+}$	P	$\rho\pi$	0.80
$2^{-+}1^{+}$	D	$f_2\pi$	1.50
$2^{-+}1^{+}$	D	$(\pi\pi)_s\pi$	1.20
$2^{-+}1^{+}$	F	$\rho\pi$	1.20

$J^{PC}M^{\epsilon}$	L	Isobar π	Cut [GeV]
$2^{++}1^{+}$	P	$f_2\pi$	1.50
$2^{++}1^{+}$	D	$\rho\pi$	-
$3^{++}0^{+}$	S	$\rho_3\pi$	1.50
$3^{++}0^{+}$	P	$f_2\pi$	1.20
$3^{++}0^{+}$	D	$\rho\pi$	1.50
$3^{++}1^{+}$	S	$\rho_3\pi$	1.50
$3^{++}1^{+}$	P	$f_2\pi$	1.20
$3^{++}1^{+}$	D	$\rho\pi$	1.50
$4^{-+}0^{+}$	F	$\rho\pi$	1.20
$4^{-+}1^{+}$	F	$\rho\pi$	1.20
$4^{++}1^{+}$	F	$f_2\pi$	1.60
$4^{++}1^{+}$	G	$\rho\pi$	1.64
$1^{-+}0^{-}$	P	$\rho\pi$	-
$1^{-+}1^{-}$	P	$\rho\pi$	-
$1^{++}1^{-}$	S	$\rho\pi$	-
$2^{-+}1^{-}$	S	$f_2\pi$	1.20
$2^{++}0^{-}$	P	$f_2\pi$	1.30
$2^{++}0^{-}$	D	$\rho\pi$	-
$2^{++}1^{-}$	P	$f_2\pi$	1.30
FLAT			

PWA Method

$$\sigma(\tau) = \left| \sum_i T_i \psi_i(\tau) \right|^2$$

τ = kinetische variable (für jedes Ereignis gemessen)

$\psi_i(\tau)$ = Zerfallsamplitude: parametrisiert im Isobarmodell

T_i = Produktionsamplitude (aus Fit)

i = Liste aller Zerfallswege im Massenbin M_X

PWA Method

- Use mass independent fit to angular distributions and sub-mass

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PWA Method

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Differential Cross-Section (mass-independent, 40 MeV bins)

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$$\sigma_{\text{indep}}(\tau) \equiv \sum_{\epsilon} \sum_{r} \left| \sum_{i} T_{ir}^{\epsilon} \psi_i(\tau) \sqrt{\int |\psi_i(\tau')|^2 d\tau'} \right|^2$$

- ϵ: reflectivity, r: rank of density matrix, i: different partial waves
- T: complex production amplitudes (fit parameters!)
- ψ: complex decay amplitudes (coded inside program)
- τ: phase space coordinates (5 parameters for 3-body decay)

PWA Method

- Use mass independent fit to angular distributions and sub-mass

- Use mass dependent fit using results form step 1

$$\sigma(\tau) = \left| \sum_i T_i \psi_i(\tau) \right|^2$$

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T_i = Produktionsamplitude (aus Fit)

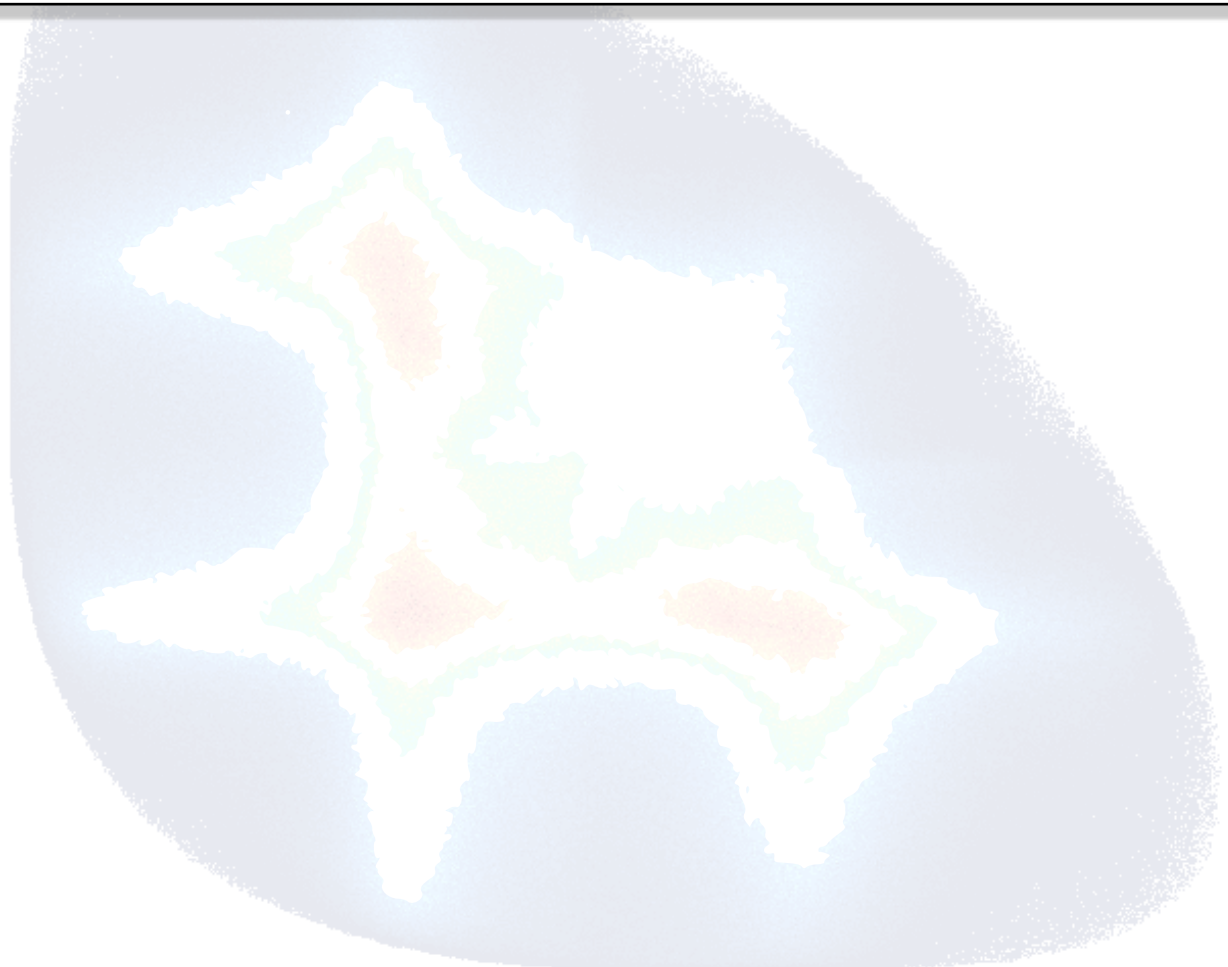
i = Liste aller Zerfallswege im Massenbin M_X

Mass-Dependent Fit using Breit-Wigners (simplified!, precise → note)

$$T^{\epsilon}_{ir}(M_{3\pi}) = \frac{1}{M_{3\pi}} \sum_k C^{\epsilon}_{k,ir}\, \mathrm{BW}_{k,i}(M, M_{0\,k,i}, \Gamma_{0\,k,i}) \sqrt{\int |\psi^{\epsilon}_i(\tau')|^2 \mathrm{d}\tau'}$$

The Goal

Understand hadrons from the dynamics of quarks and gluons



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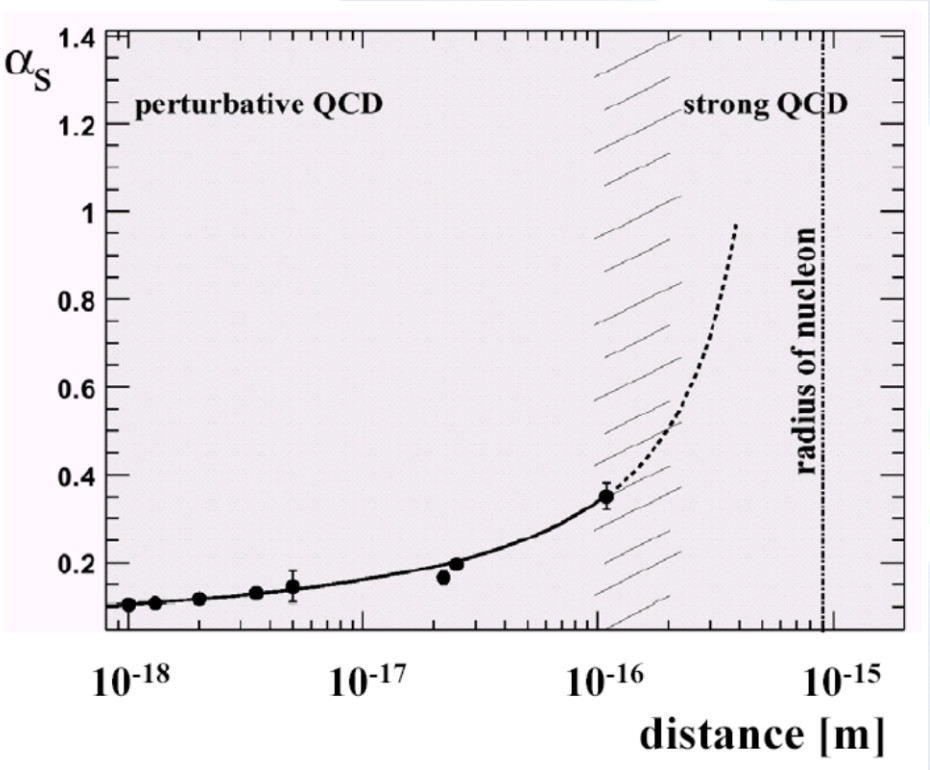

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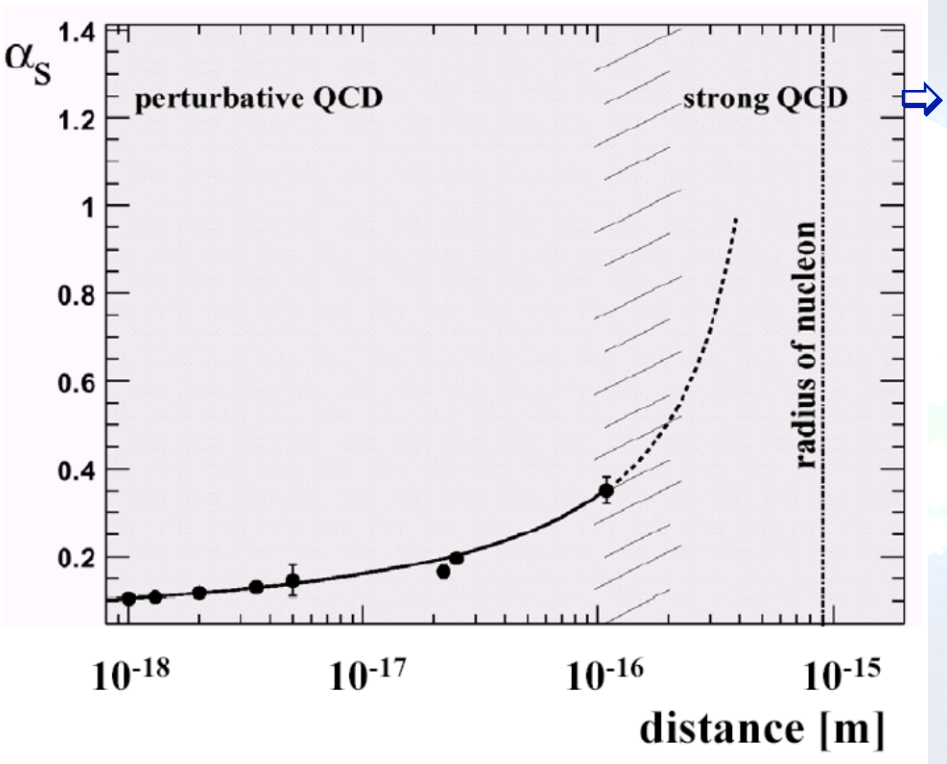
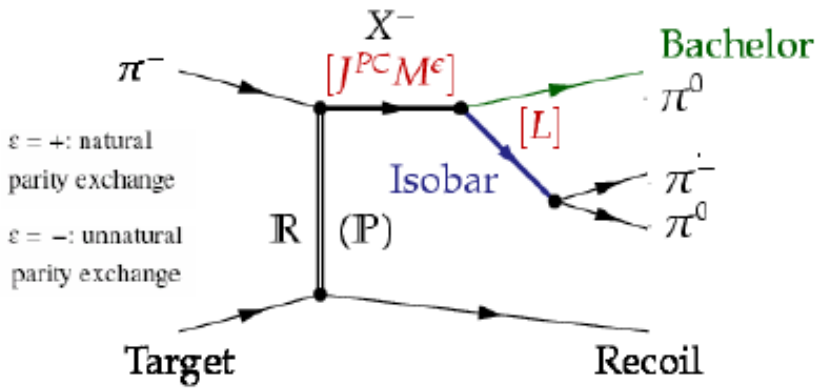


⇨ **non-perturbative regime of QCD**

- Models: QM, bag, flux tube, ...
- Effective theories: χPT, ...
- Lattice-QCD

Backup – $\pi^-\pi^0\pi^0$

PWA using isobar model



X^- decay described using isobar model:

- Intermediate di-pion resonance (isobar)
  - *Spin S and rel. orbital angular momentum L w.r.t bachelor π^-*
  - *L+S couple to J*
- Partial waves: $J^{PC}\ M^{\varepsilon}$ [isobar] L

PWA:

- **program: Illinois/Protvino/Munich (D.Ryabchikov) software (IHEP/VES, TUM/COMPASS)**
- **Isobars:** $(\pi\pi)_S$ [broad $f_0(600)$+$f_0(1370)$], $f_0(980)$, $\rho(770)$, $f_2(1270)$, $\rho_3(1690)$
- **No acceptance correction yet** (assumed flat)

Assumptions:

- *factorisation of beam & target vertex, no final state interactions*
- *I^G conserved at beam vertex (π^- beam: $I^G = 1^-$)*
- *Scattering on nucleons: helicity flip & non-flip amps at target vertex (rank2)*
- *Using reflectivity basis in Gottfried Jackson frame* (at high CM energies: reflectivity ε = naturality of R)

Isospin symmetry: neutral / charge mode

- isobar decaying into **f2** π: 1/2 intensity expected
- isobar decaying into ρ π: 1/1 intensity expected

Pion Polarizabilities

Describe response to external e.m. fields ⇨ stiffness of system

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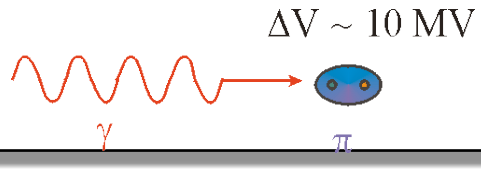

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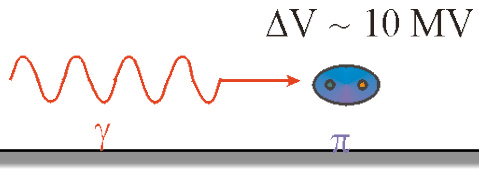

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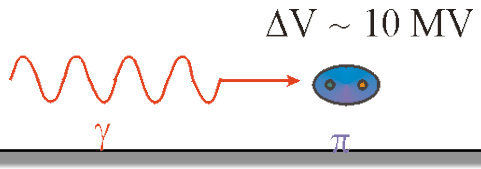

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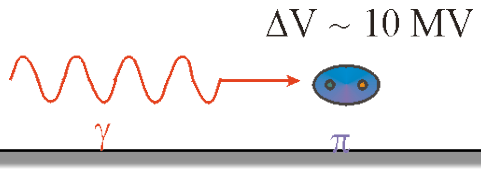

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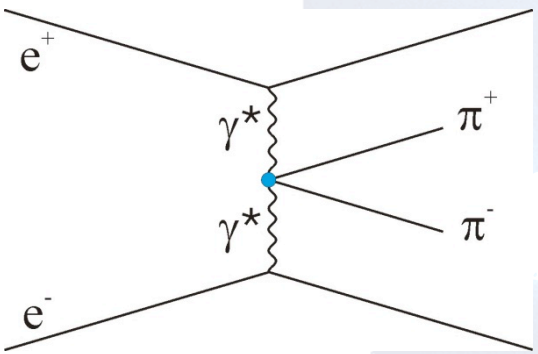

PLUTO
DM1
DM2
Mark II

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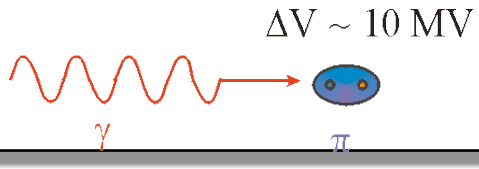

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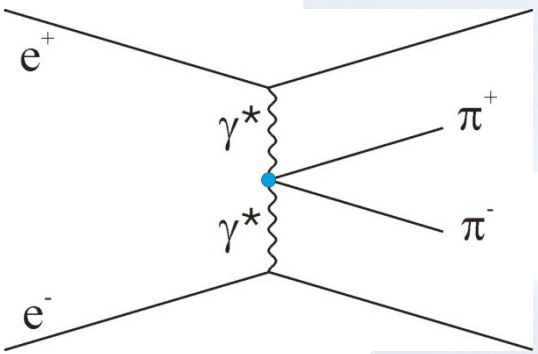
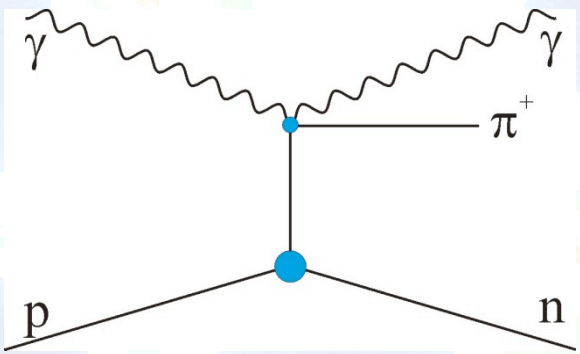


PLUTO
DM1
DM2
Mark II



Lebedev
Mami A2

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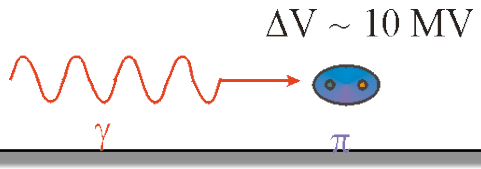

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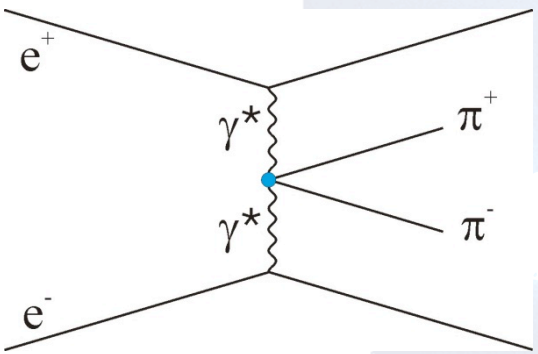
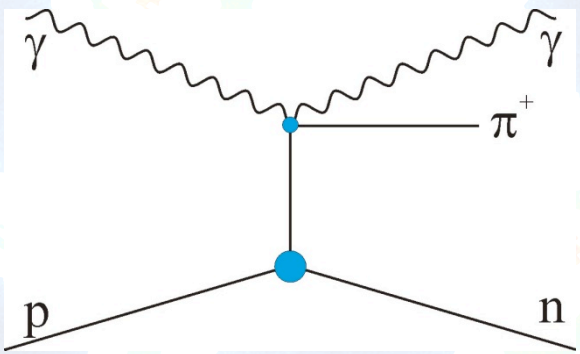
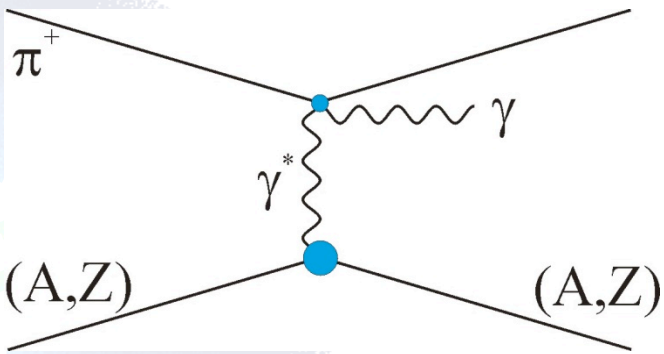


PLUTO
DM1
DM2
Mark II



Lebedev
Mami A2



Serpukhov

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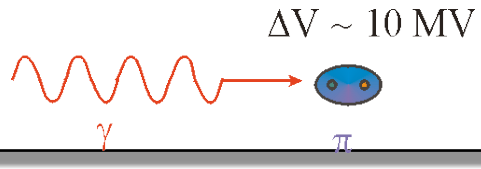

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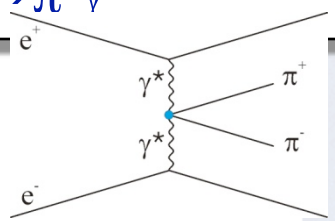
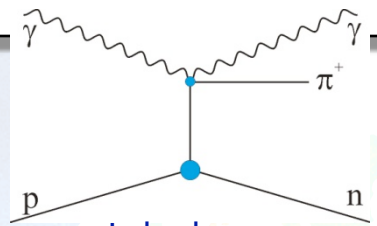
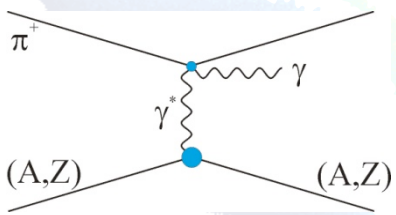


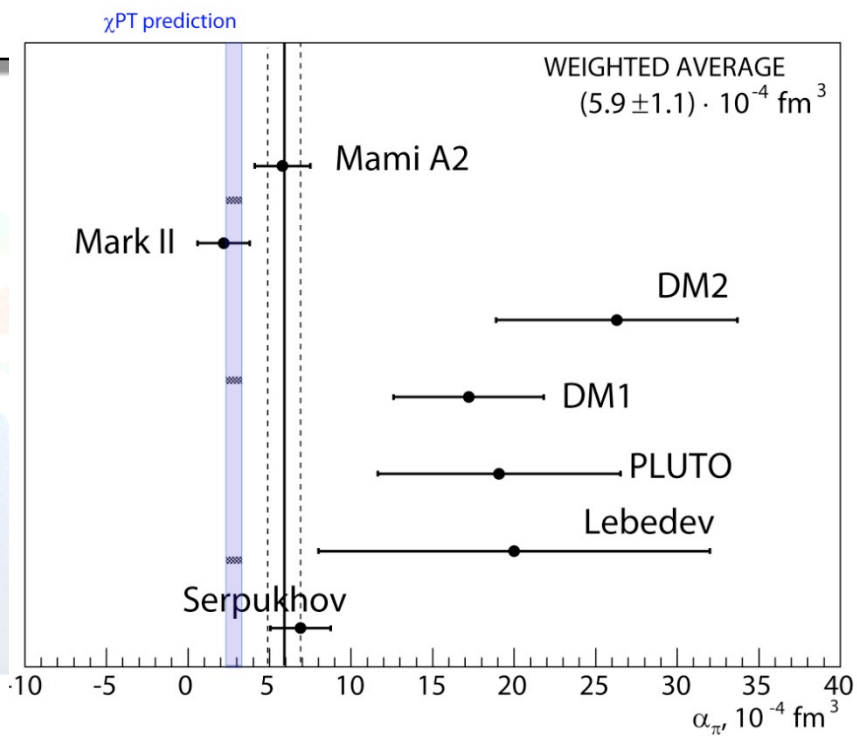
PLUTO
DM1
DM2
Mark II



Lebedev
Mami A2



Serpukhov



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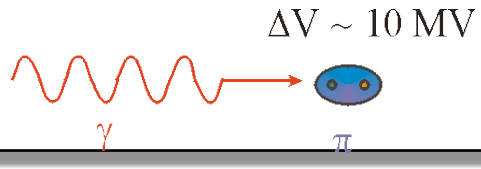

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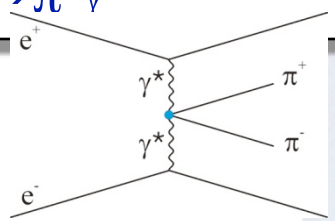
Experiments: pion Compton scattering π

$-\gamma \to \pi - \gamma$



PLUTO
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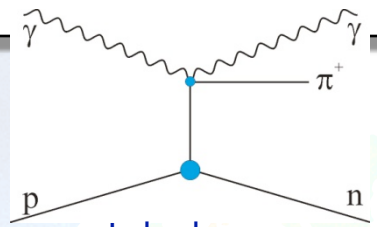
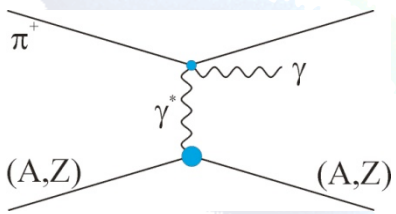
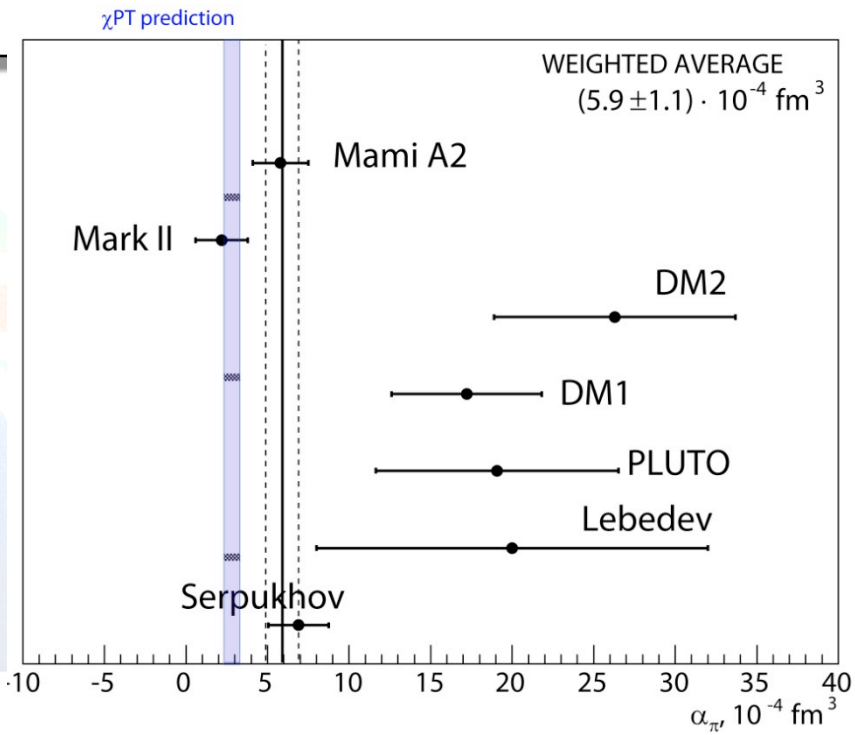


Lebedev
Mami A2



Serpukhov

COMPASS



Cross Section Ratio

$$R(\omega) = \frac{N_{\mathrm{exp}}(\omega)}{N_{\mathrm{MC}}(\omega)} = \frac{\mathrm{d}\sigma_{\gamma\pi}^{\mathrm{Prim}}}{\mathrm{d}\sigma_{\gamma\pi}^{\mathrm{Thomson}}} \cong 1 + \frac{3}{2}\frac{m_\pi^3}{\alpha}\frac{\omega^2}{1-\omega}\bar{\beta}_\pi\,, \quad \left(\bar{\alpha}_\pi + \bar{\beta}_\pi = 0\right)$$

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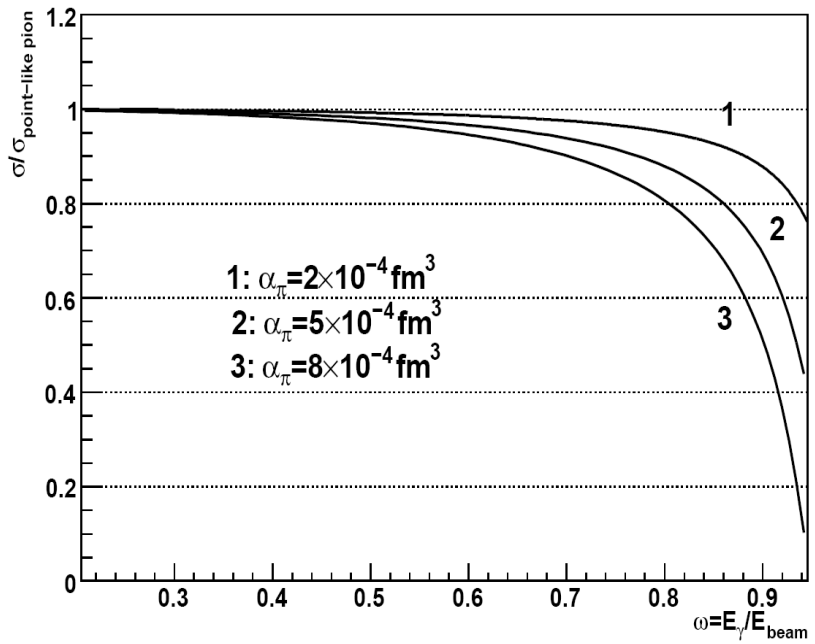

$R(\omega)$ for different values of α_π (β_π)

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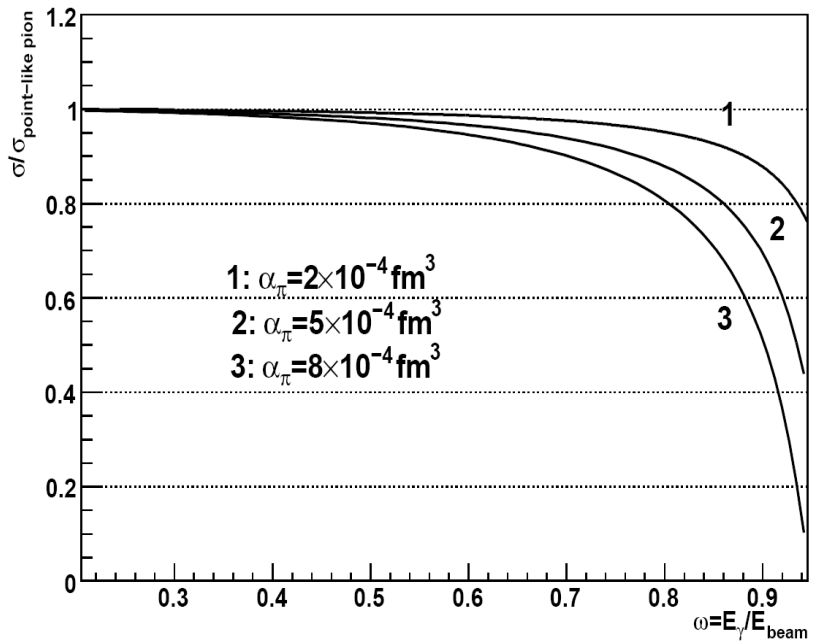

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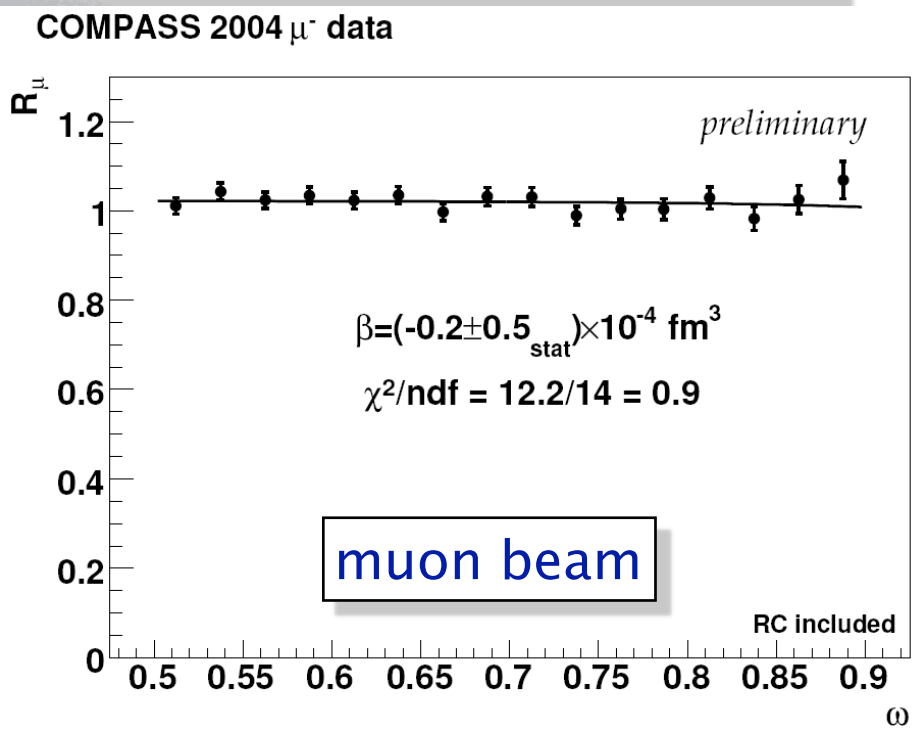
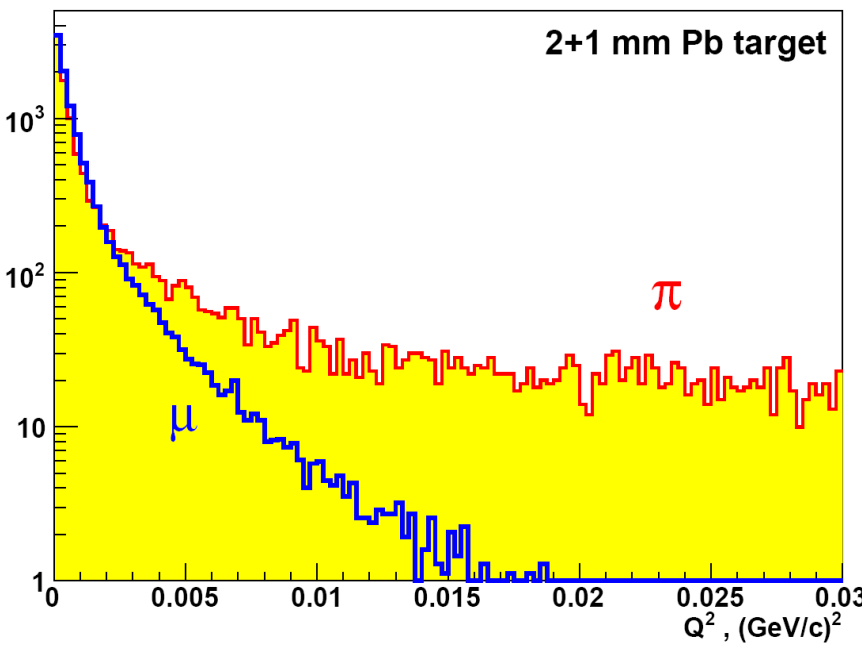
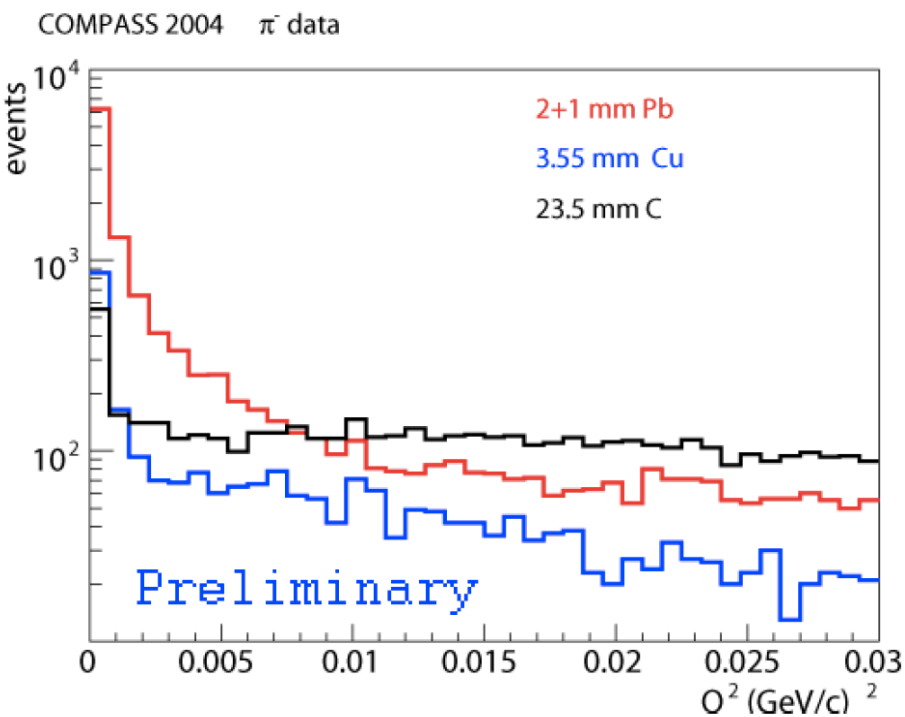


Cross check with μ beam

Q^2 Distributions from Pilot Run

$$\frac{d^3\sigma}{dQ^2\, d\omega\, d\cos\theta} = \frac{\alpha Z^2}{\pi\omega} \times \frac{Q^2 - Q^2_{min}}{Q^4} \times \left|F_Z\left(Q^2\right)\right|^2 \times \frac{d\sigma_{\gamma\pi}(\omega,\theta)}{d\cos\theta}$$





Z^2 Dependence of Cross Section

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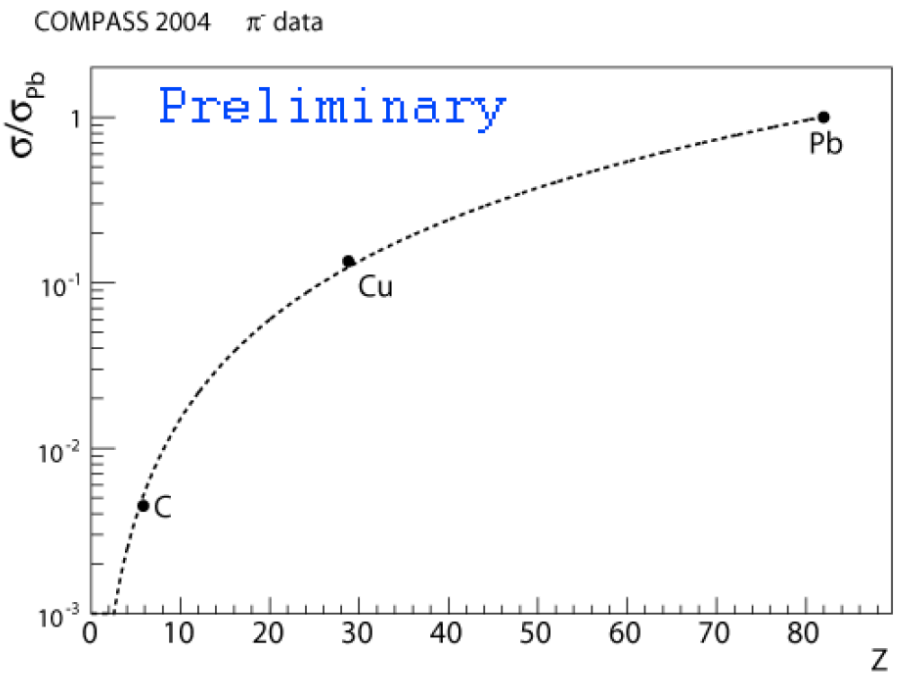

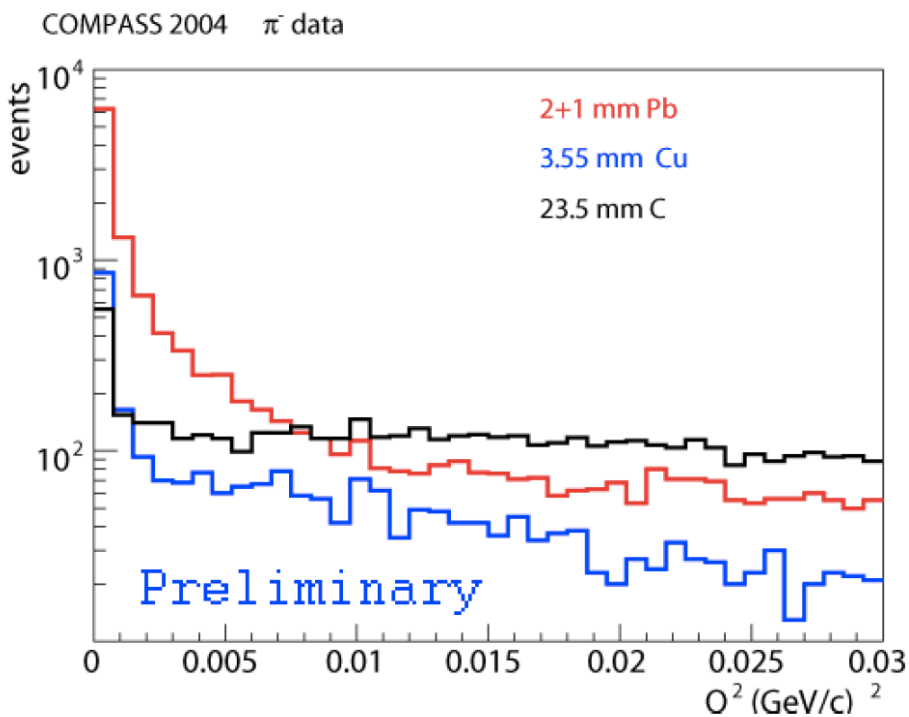

2009 Primakoff Measurement

Major improvements:

- Detector performance: ECAL, μID
- Optimized target: ^{58}Ni
- Radiative corrections
- Beyond Weizsäcker-Williams approach
- Interference with diffractive amplitudes
- Suppression of $\pi^-\pi^0$ background
- MC description of setup

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Prospects (4 weeks):

- $\sigma_{stat} \sim 0.33 \cdot 10^{-4}$ fm^3
- $\sigma_{sys} \sim 0.16 \cdot 10^{-4}$ fm^3
- independent extaction of α_π, β with $\sigma_{stat} \sim 0.5 \cdot 10^{-4}$ fm^3
- $\alpha_\pi(s)$
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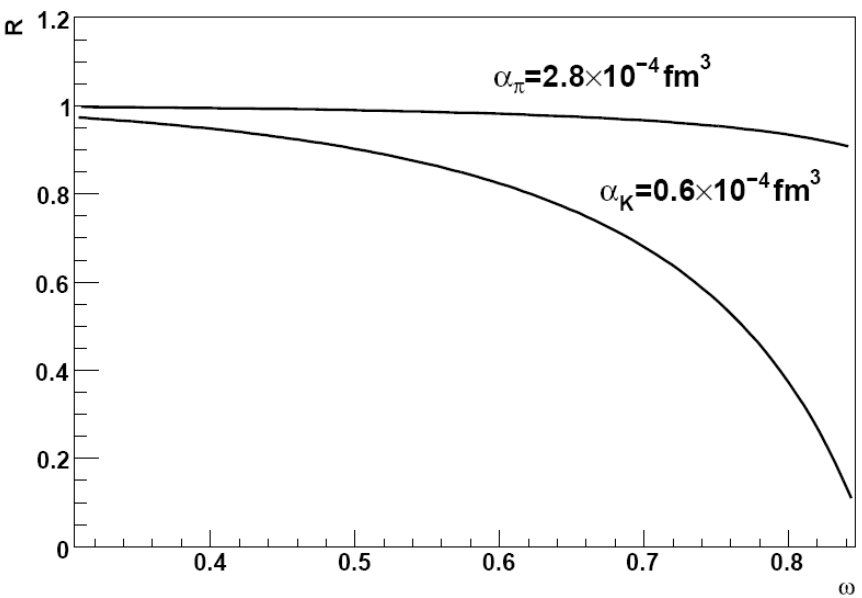
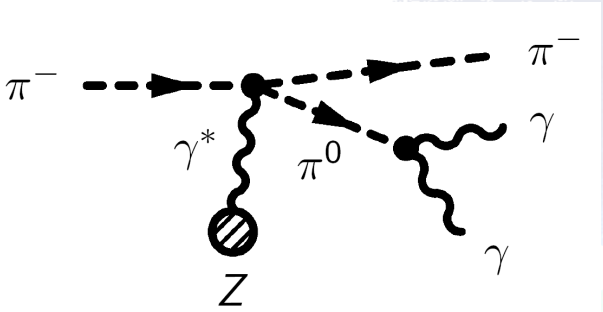


Primakoff Reactions with Neutral

Primakoff π^0 production



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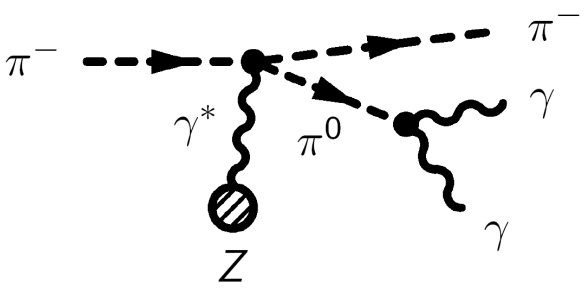
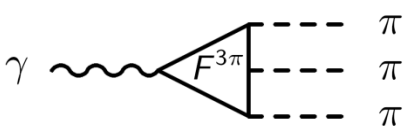
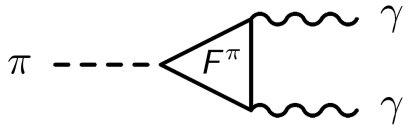


Chiral Perturbation Theory





$$F^{3\pi}(0) = \frac{F^{\pi}(0)}{\sqrt{\pi\alpha}\, f_{\pi^\pm}^2}, \; f_{\pi^\pm} = (130.7 \pm 0.4)\,\mathrm{MeV}$$

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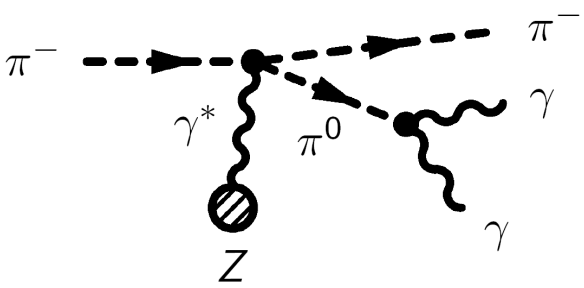

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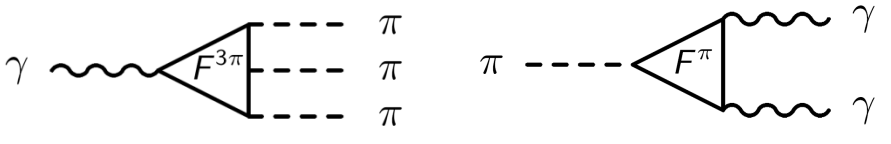

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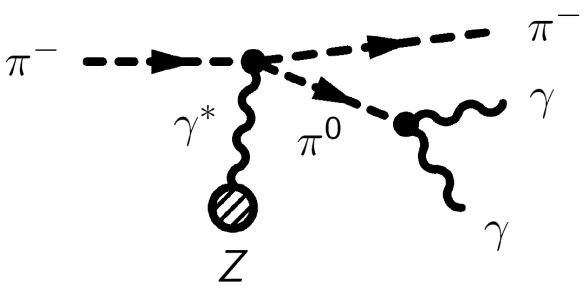

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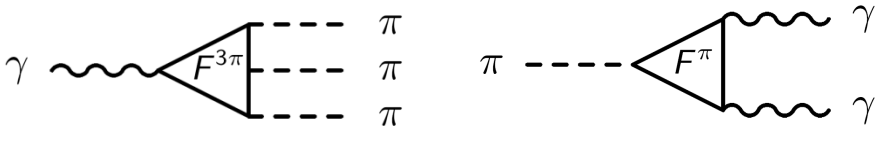

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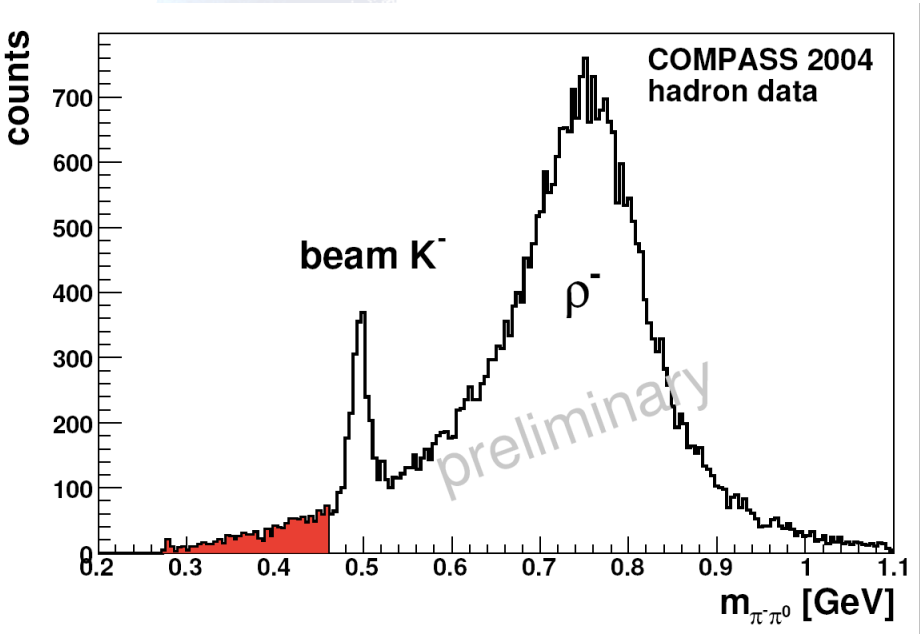

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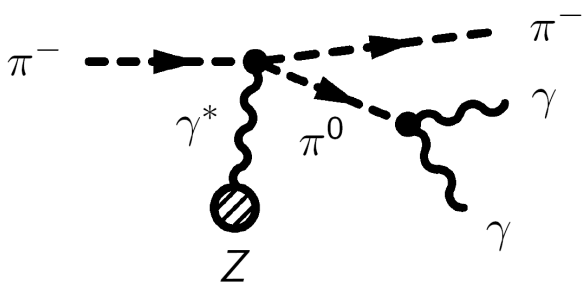

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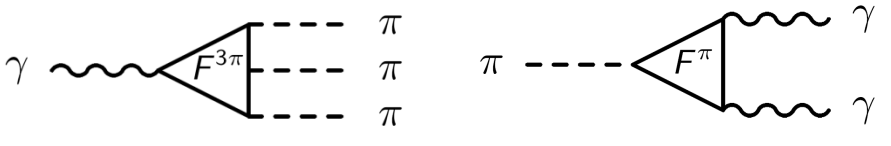

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- Further reactions channels studied in COMPASS: $\pi^- Z \to \pi^- Z \pi^0 \pi^0$

  $\pi^- Z \to \pi^- Z \eta$