Mesons: Searching for new properties and rare species

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New Precision Experiments with COMPASS at CERN

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Excellence Cluster Universe

Brief Overview

- Pion-Polarizability $\vec{P} = \alpha \cdot \vec{E}$
- Radiative excitations
- Spectroscopy in strong interaction
  - Introduction
  - Identification method (PWA)
  - Result summary and a new meson
- New insights into production/decay dynamics
- Conclusions

How to measure α ?

- Atomic physics: deflection of an atom in a laser field

$$\vec{F} = \alpha \cdot \vec{E} \cdot \nabla E$$

  - Need strong fields and strong gradients (laser cavity)

$$E = 10^6 V / cm \qquad \nabla E = 10^{11} \mathrm{V/cm}^2$$

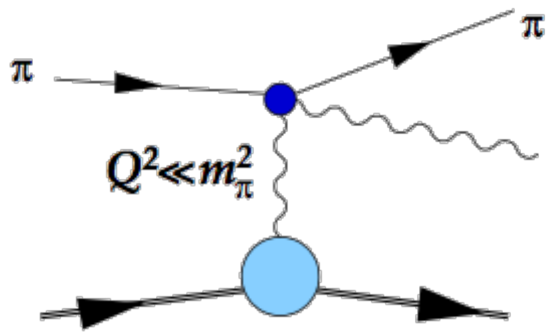
- Particle physics: scatter high energy π from photon source
  - Photon source: high Z nucleus
  - High gradients: relativistic amplification

$$E = 10^5 V / fm$$

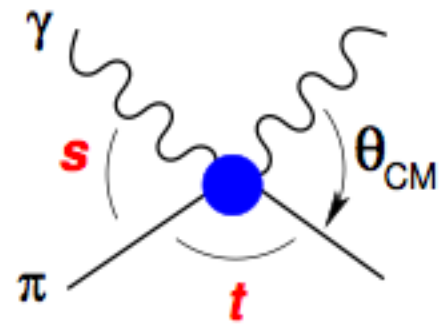
  - Charged particle is deflected in field (Born term)
  - Deflection altered by induced dipole moment (polarizability)

COMPASS Measurement

- Use Compton scattering
  - π instable: inverse kinematics
  - μ as point like reference



190 GeV/c beam particles



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

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

Compton

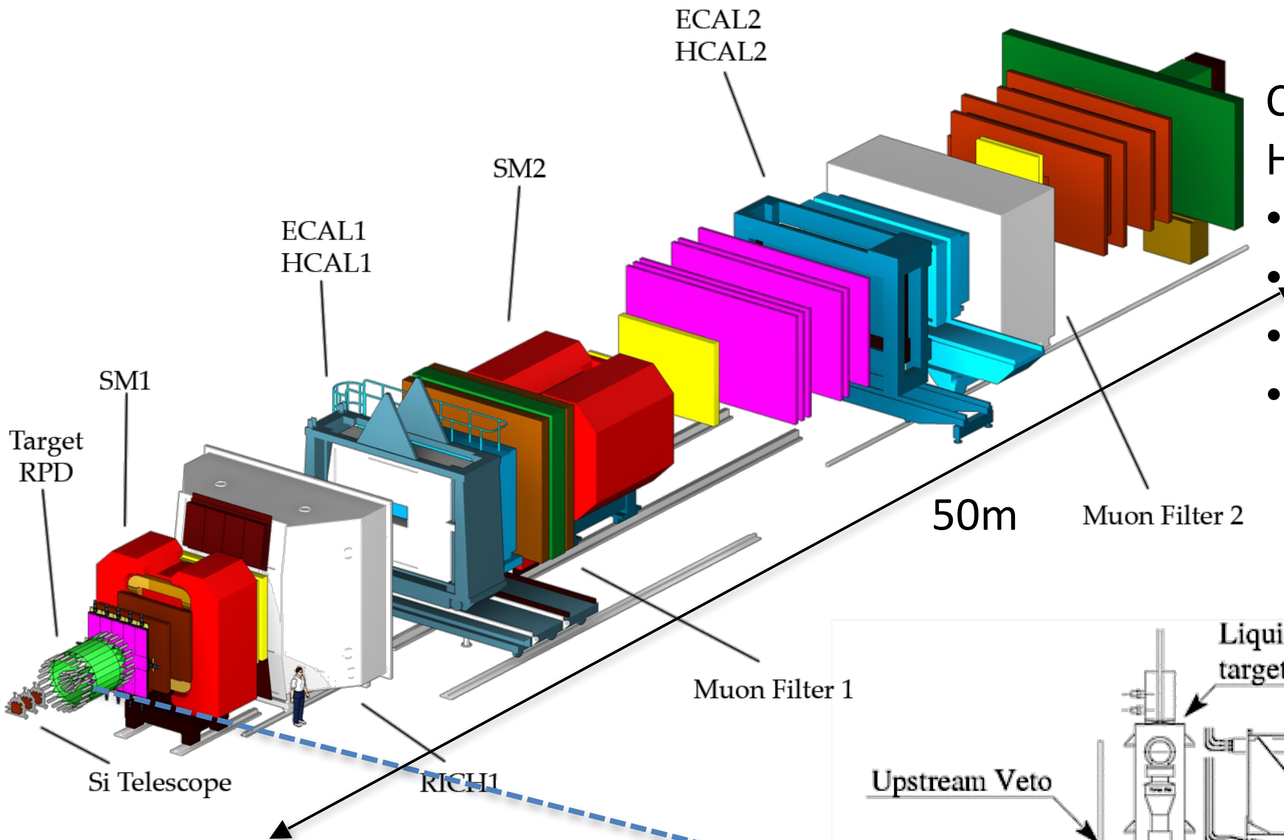
Extended object

$$\mathcal{P} = z_-^2\,(\alpha_\pi - \beta_\pi) + \;\; ....$$

elasticity:

$$s = p_\gamma^2 + p_\pi^2 < (2m_\pi)^2$$

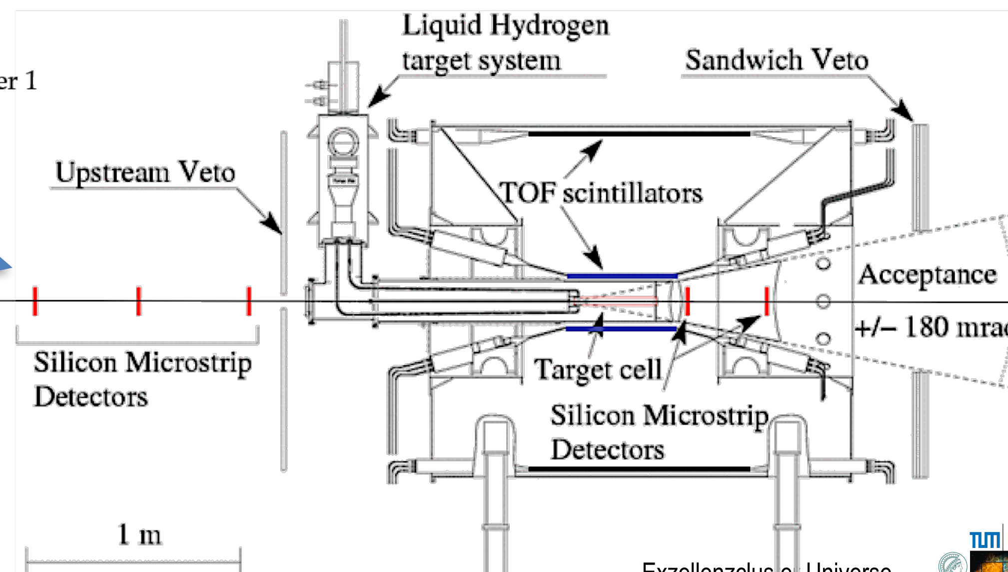
The COMPASS Experiment



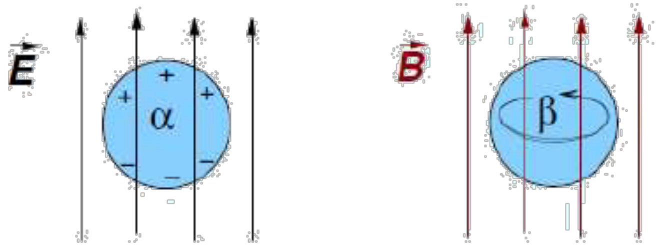
CERN SPS

Hadron beam:

- 190 GeV/c π, K, p
- $5 \cdot 10^7$ particles/SPS-spill
- 60 days data taking 2008
- Trigger: RPD hit, beam veto



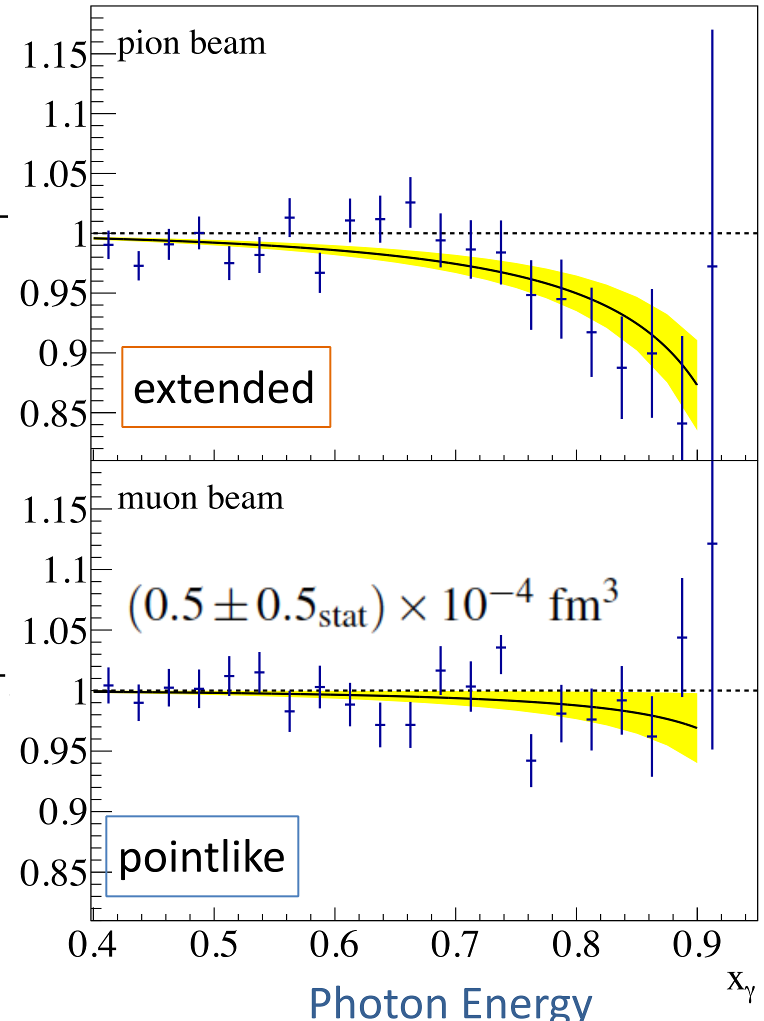
COMPASS Measurement



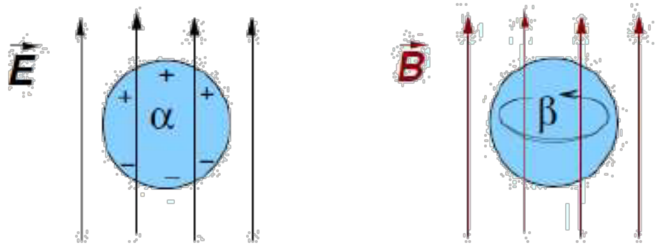
$$\alpha_\pi = (2.0 \pm 0.6_{stat} \pm 0.7_{syst}) \times 10^{-4}\,\mathrm{fm}^3$$

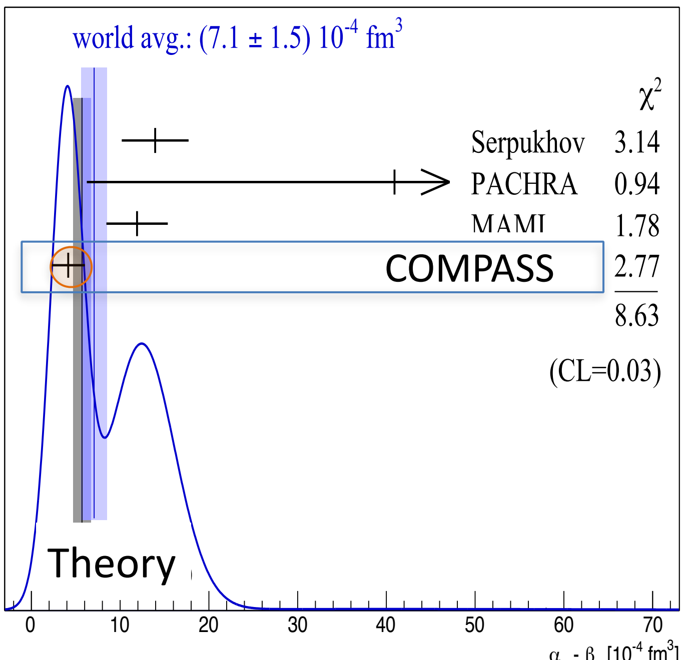
$$R_\pi = \frac{\sigma_{meas}}{\sigma_{point}}$$

$$R_\mu = \frac{\sigma_{meas}}{\sigma_{point}}$$



COMPASS Measurement





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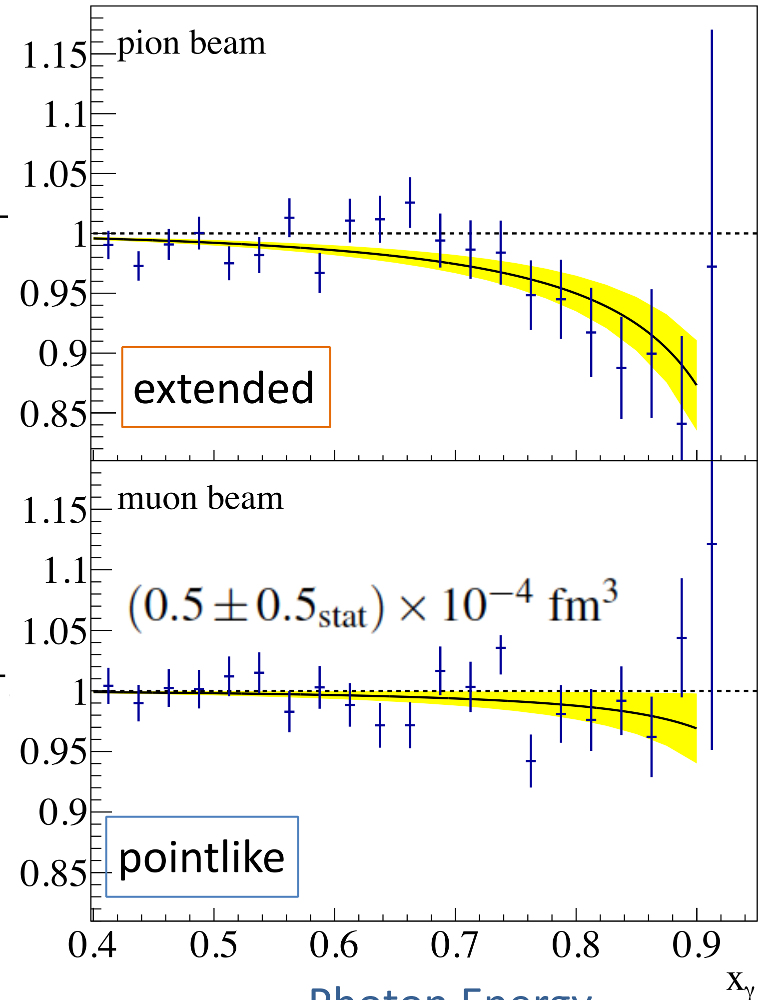
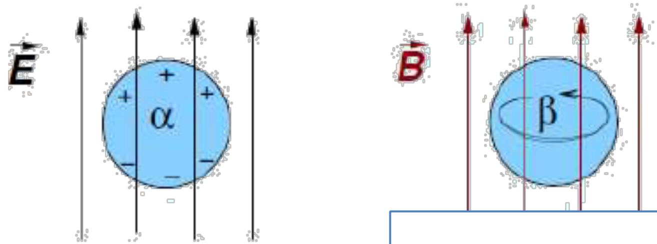


π polarizability: χPT confirmed

Long standing puzzle solved !

COMPASS Measurement



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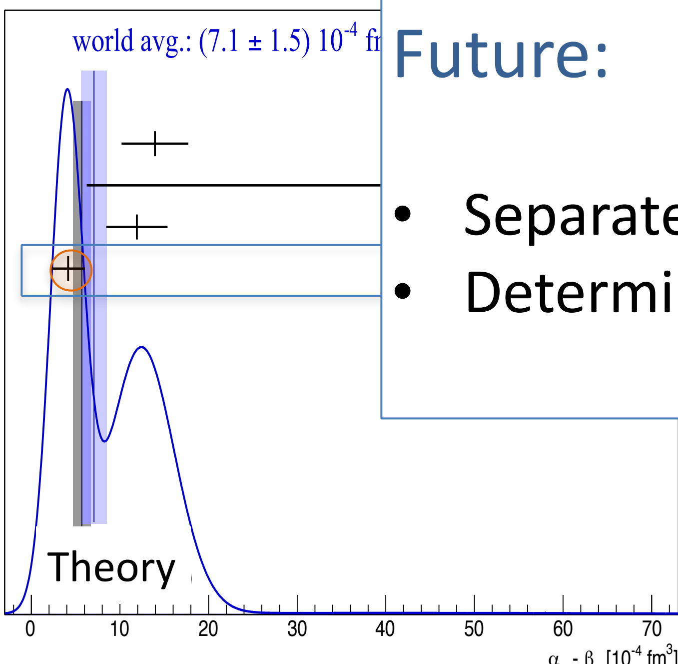
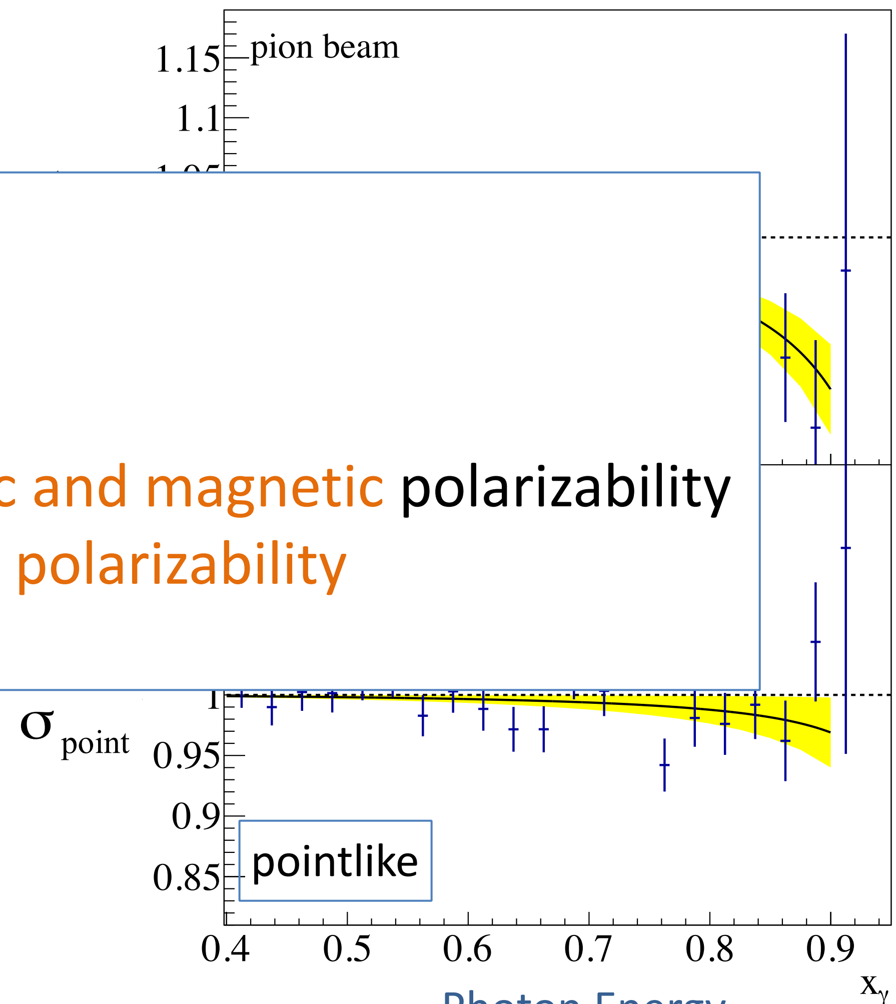




Future:

- Separate electric and magnetic polarizability
- Determine kaon polarizability

π polarizability: χPT confirmed

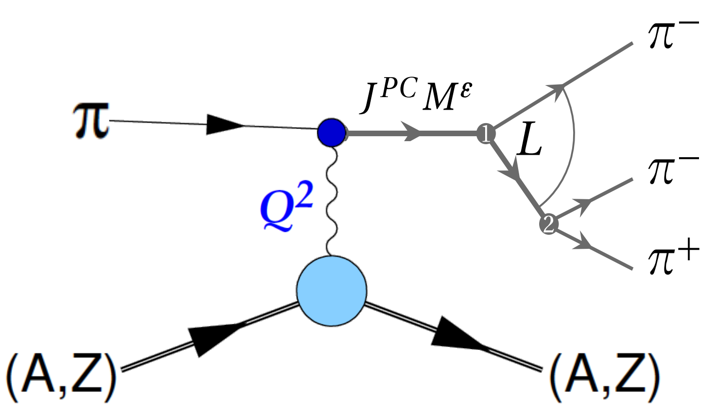
Long standing puzzle solved !

Radiative Width

- Study resonances with electromagnetic probe
  - similar to photo-production of Δ^+ off protons
  - radiative transitions of charmonia
- Competition by strong interaction (with same final state)
  - Photon: $S = 1$ and $H = \pm 1$

    Helicity conservation ➝ Spin alignment of resonance X^-
  - Diffraction: need angular momentum for Spin alignment

    Suppressed in forward production



Identify photo-production via spin alignment

$M = 1$ at low $t' < 10^{-3}\ GeV^2/c^2$

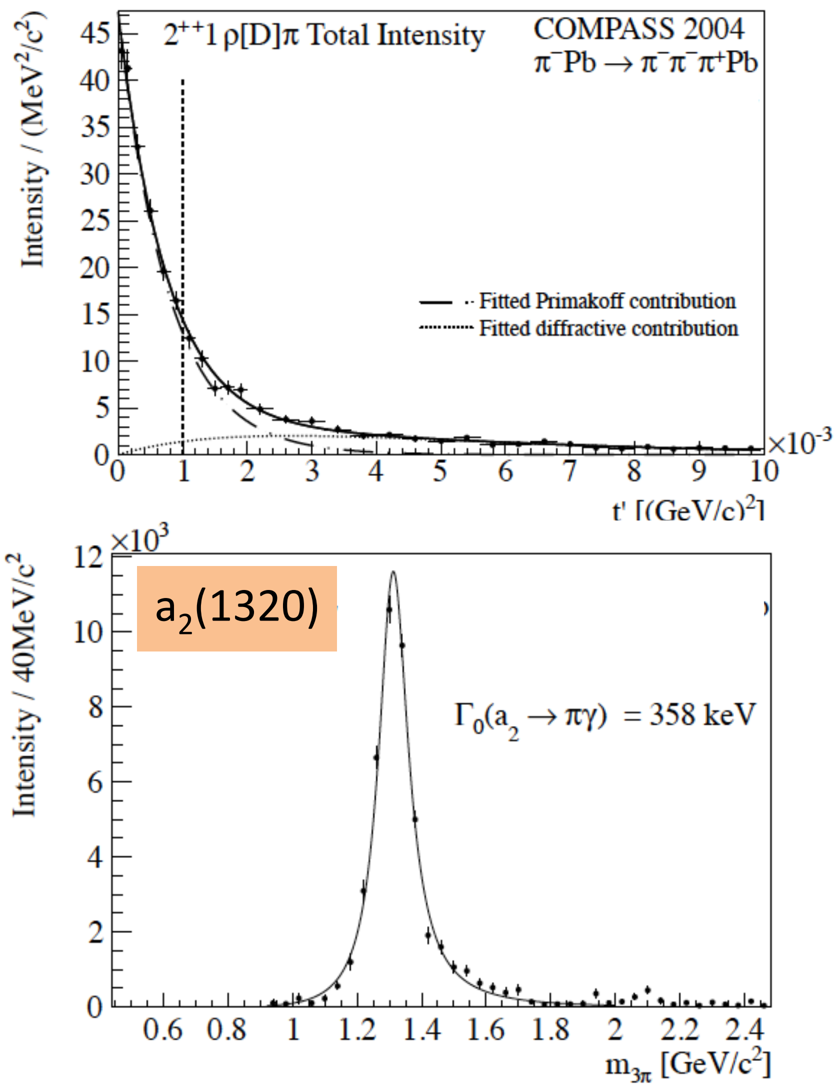
$$\sigma_{Photo} \approx e^{-b_{photo} t'}$$

$$\sigma_{diffract} \approx t'^{M} \cdot e^{-b_{diff} t'} \qquad b_{photo} >> b_{diffract}$$

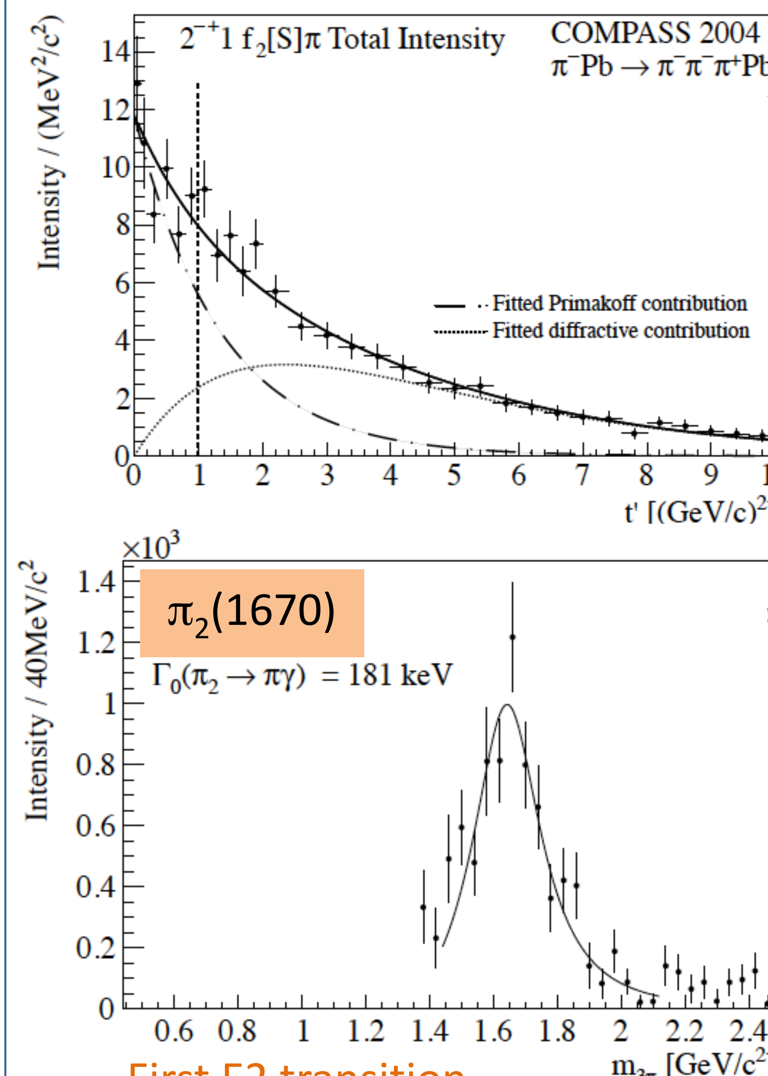
$\rightarrow M = 1$ is suppressed in diffraction

EM-Transitions for Mesons

$\Gamma_0(a_2(1320) \to \pi\gamma)$



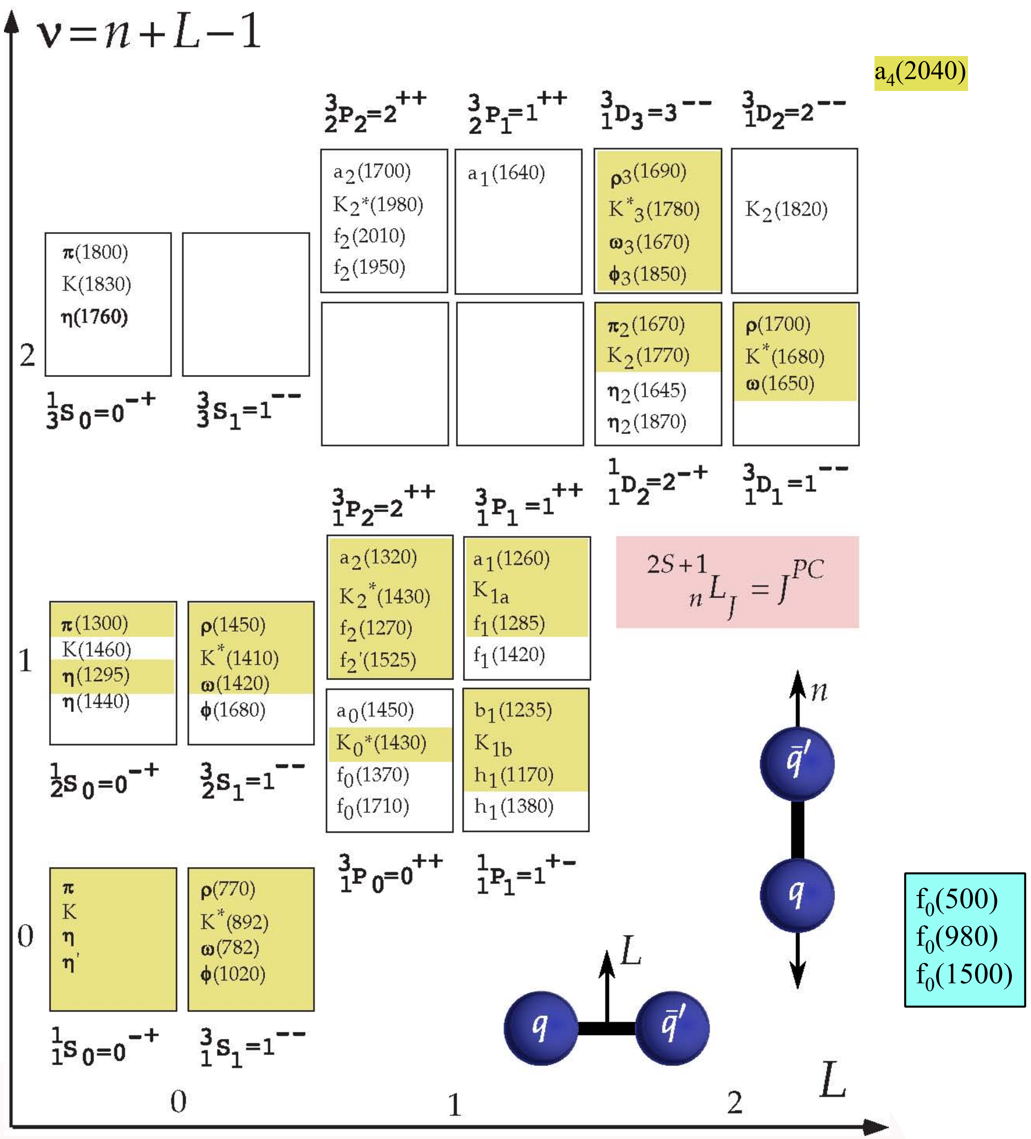
M2 transition



$\Gamma(\pi_2 \to \pi\gamma)$

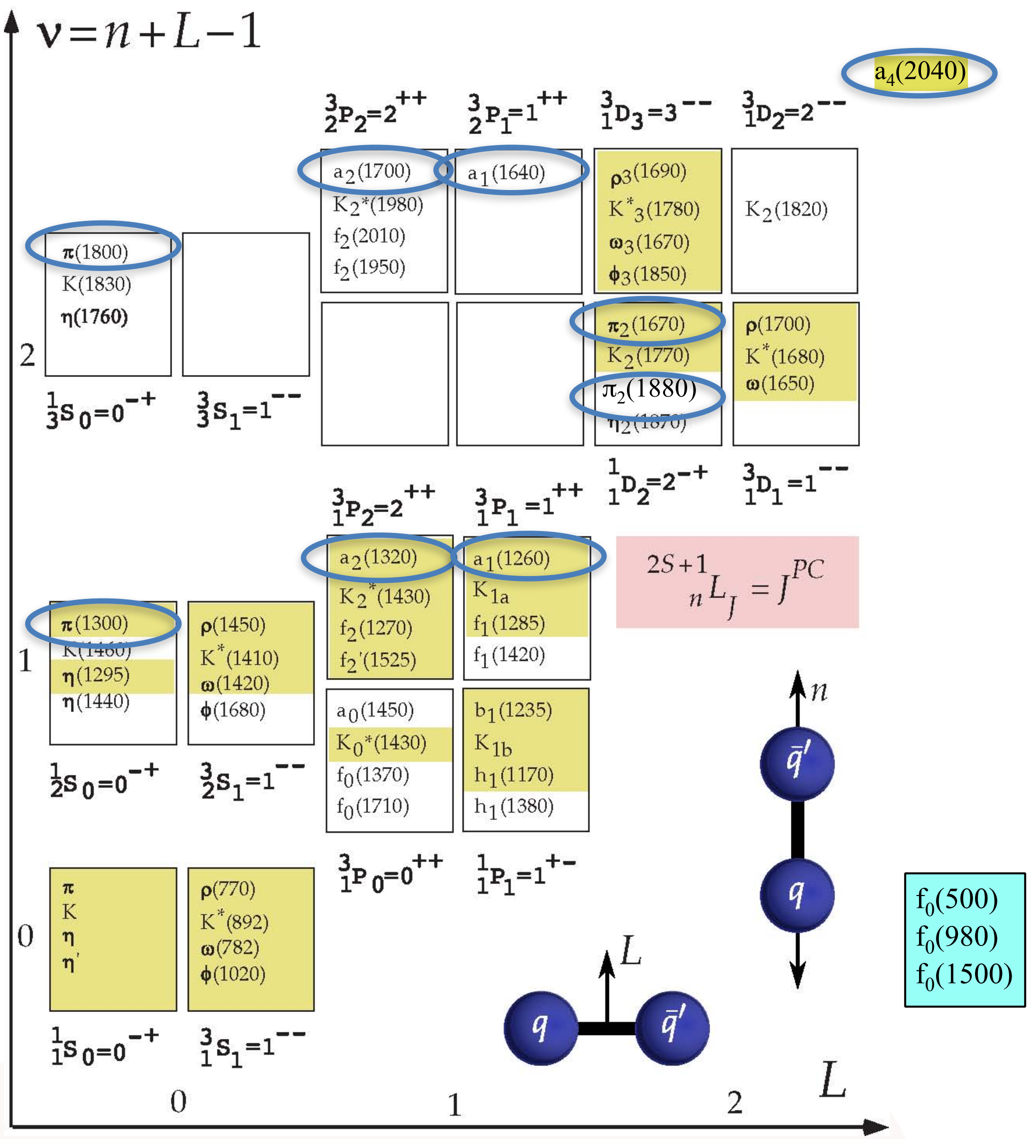
First E2 transition
observed for mesons

Constituent Quarks and Mesons



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

Constituent Quarks and Mesons



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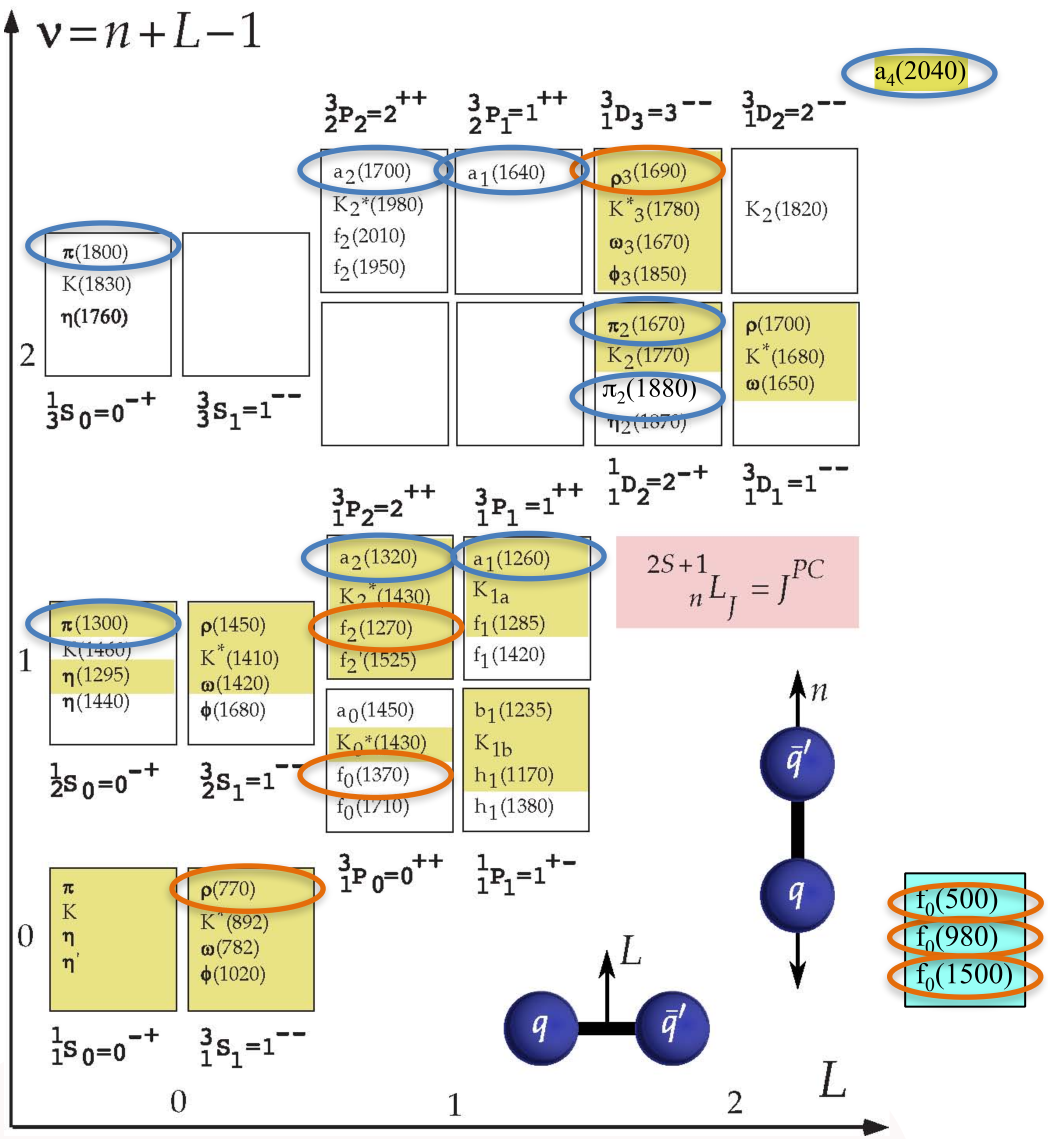

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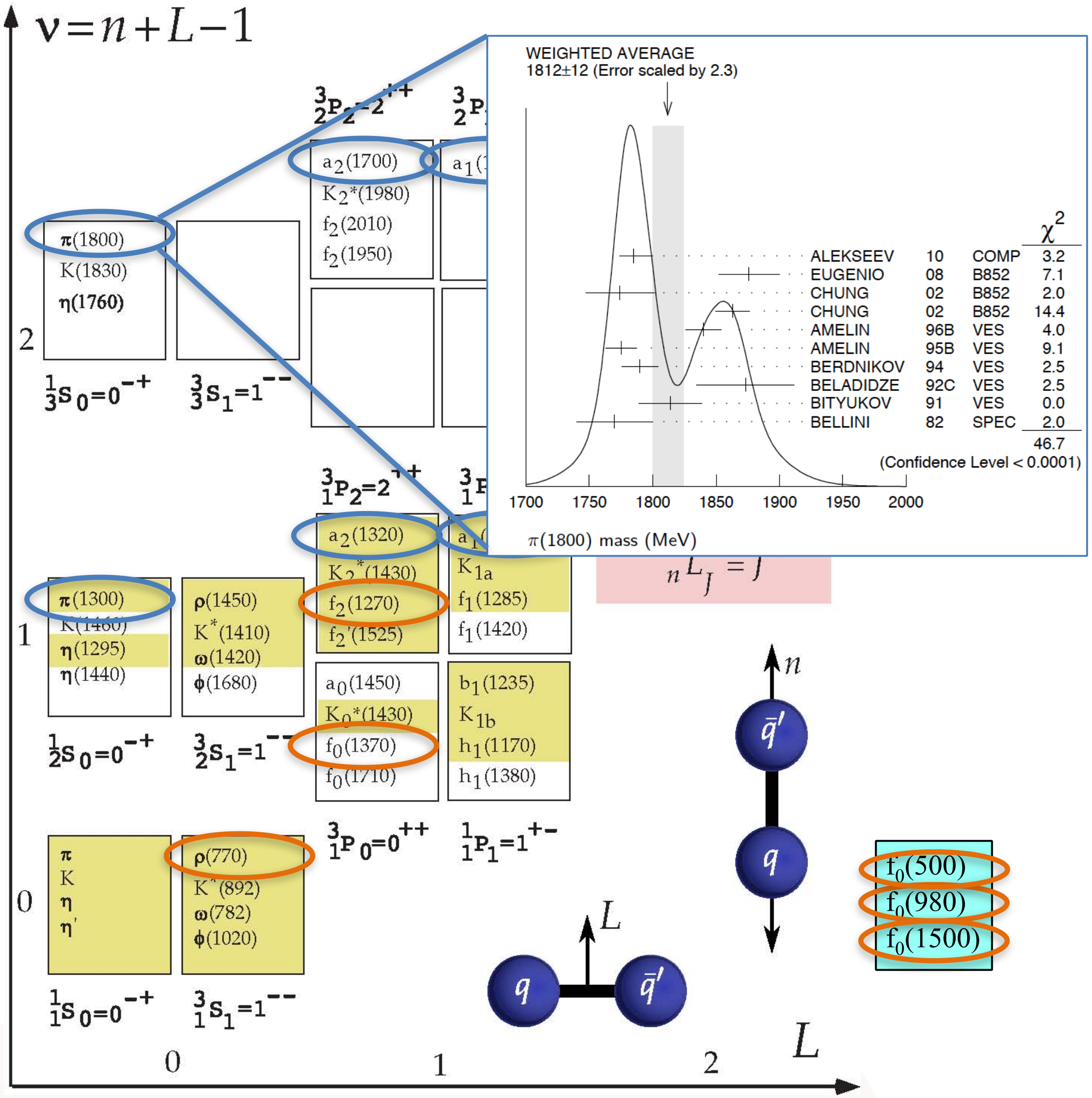

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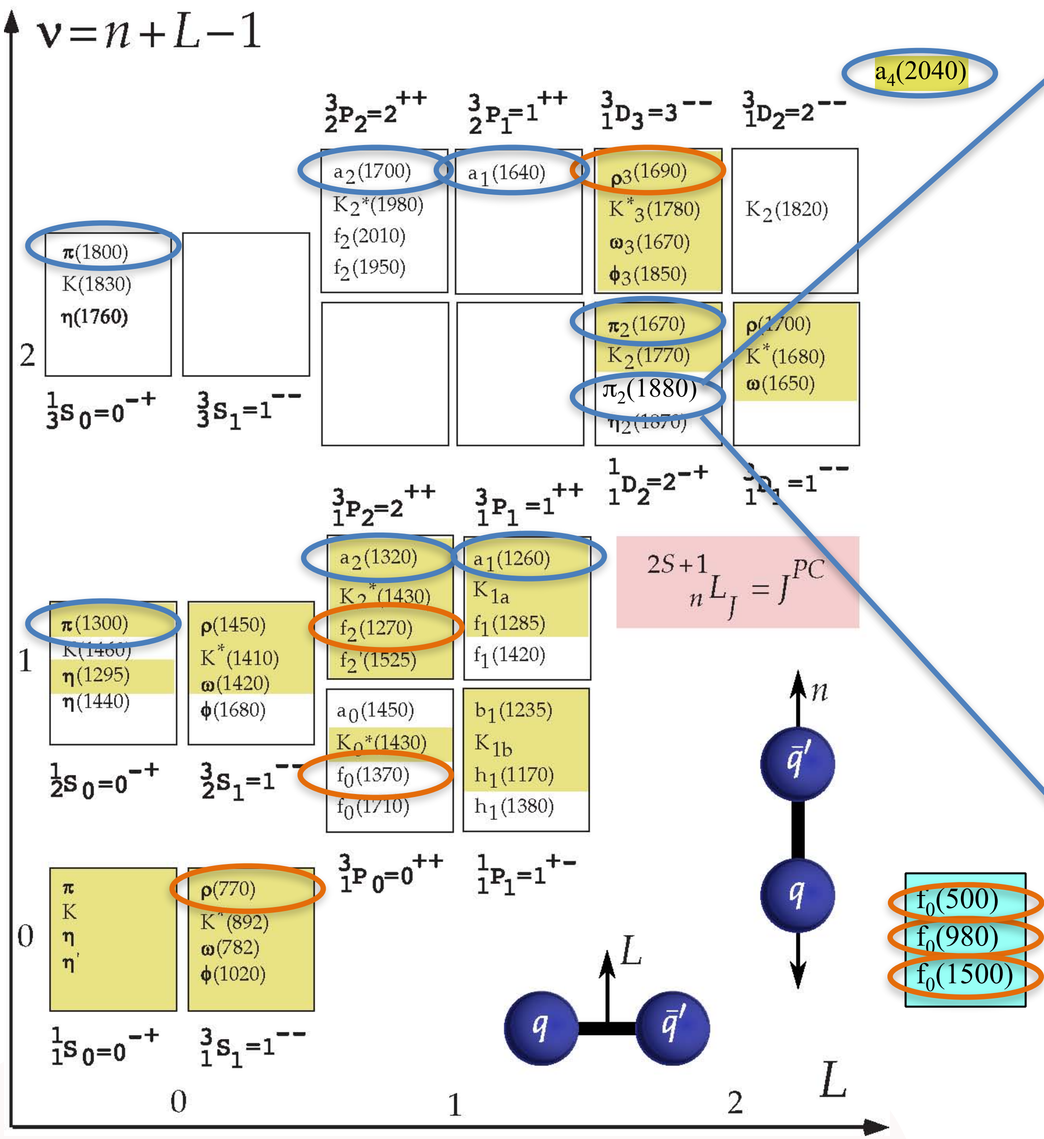

$\pi_2(1880)$ MASS

VALUE (MeV)	EVTS
1895±16 OUR AVERAGE	
1929±24± 18	4k
1876±11± 67	145k
2003±88±148	69k
1880±20	

$\pi_2(1880)$ WIDTH

VALUE (MeV)	EVTS
235± 34 OUR AVERAGE	
323± 87± 43	4k
146± 17± 62	145k
306±132±121	69k
255± 45	

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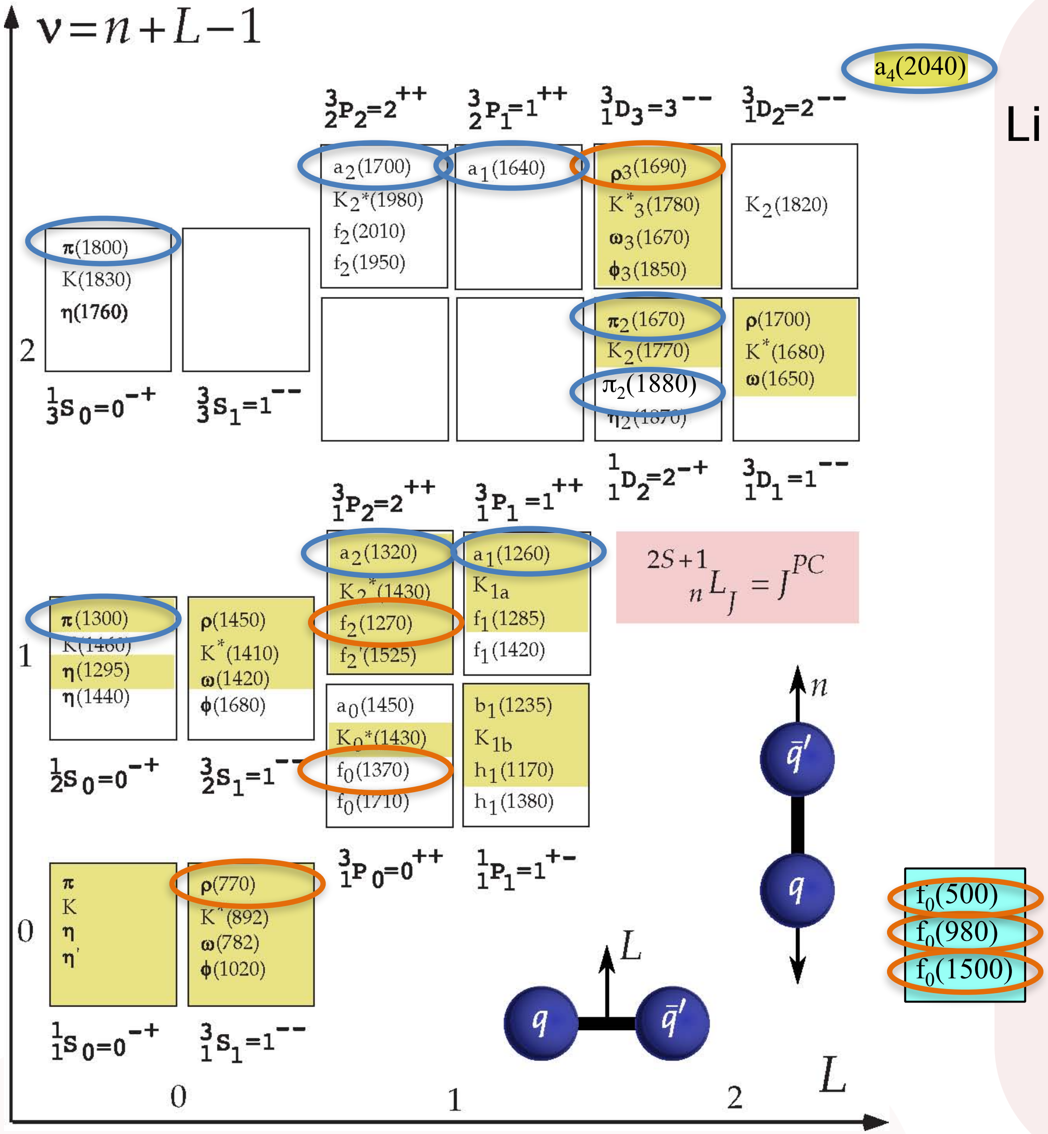
Constituent Quarks and Mesons



Limits for light mesons

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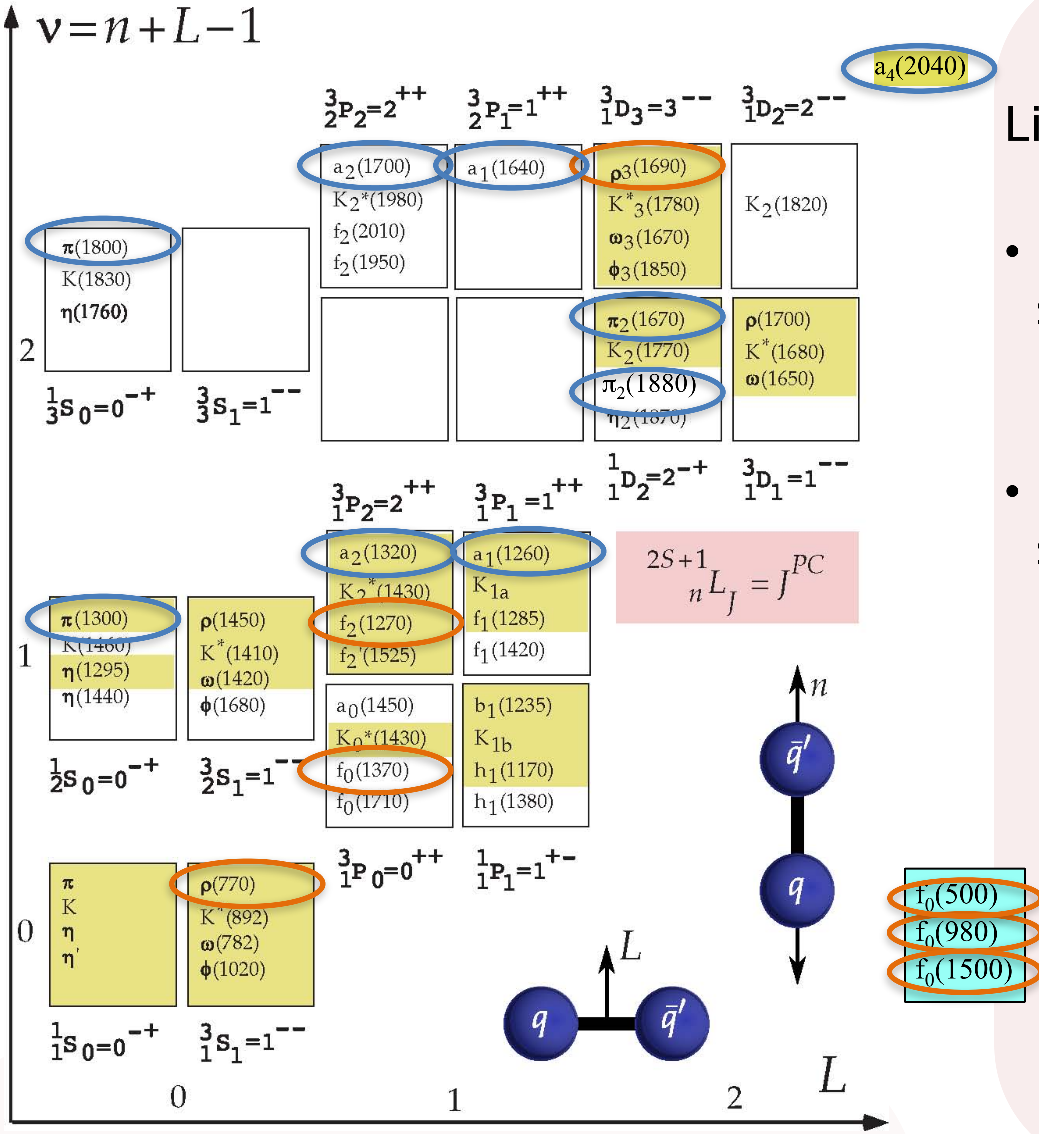

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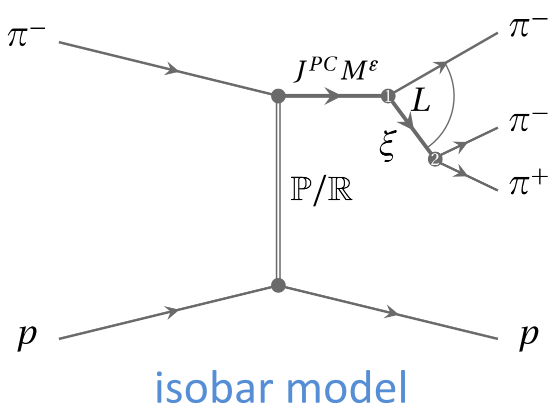
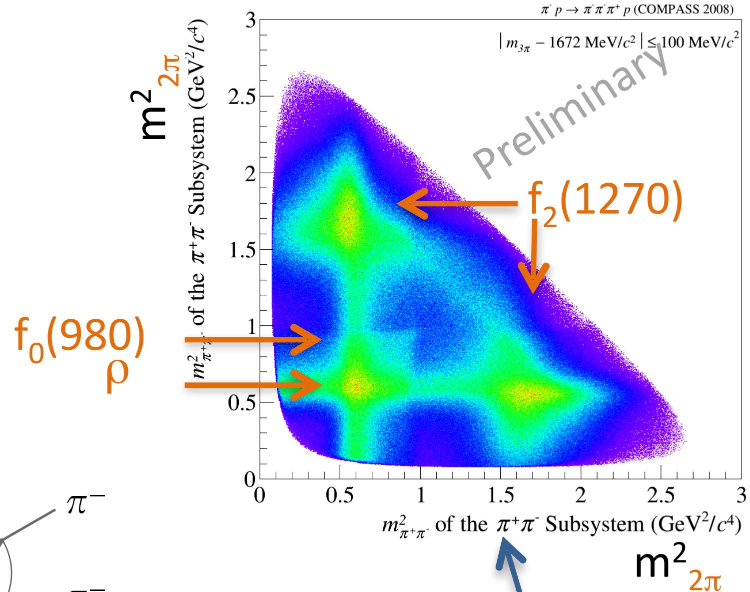
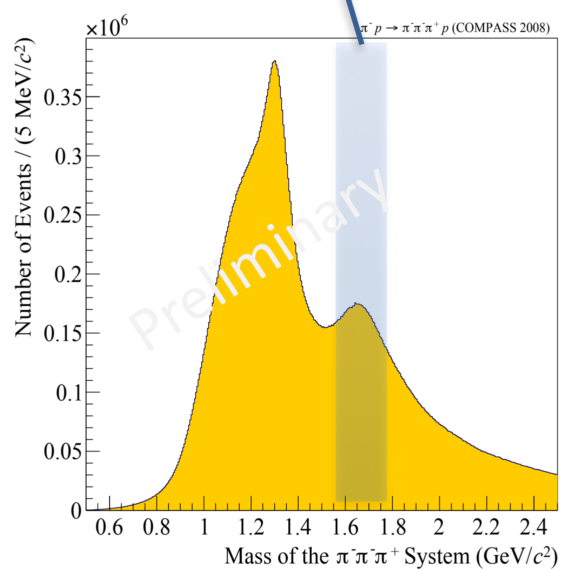
Limits for light mesons

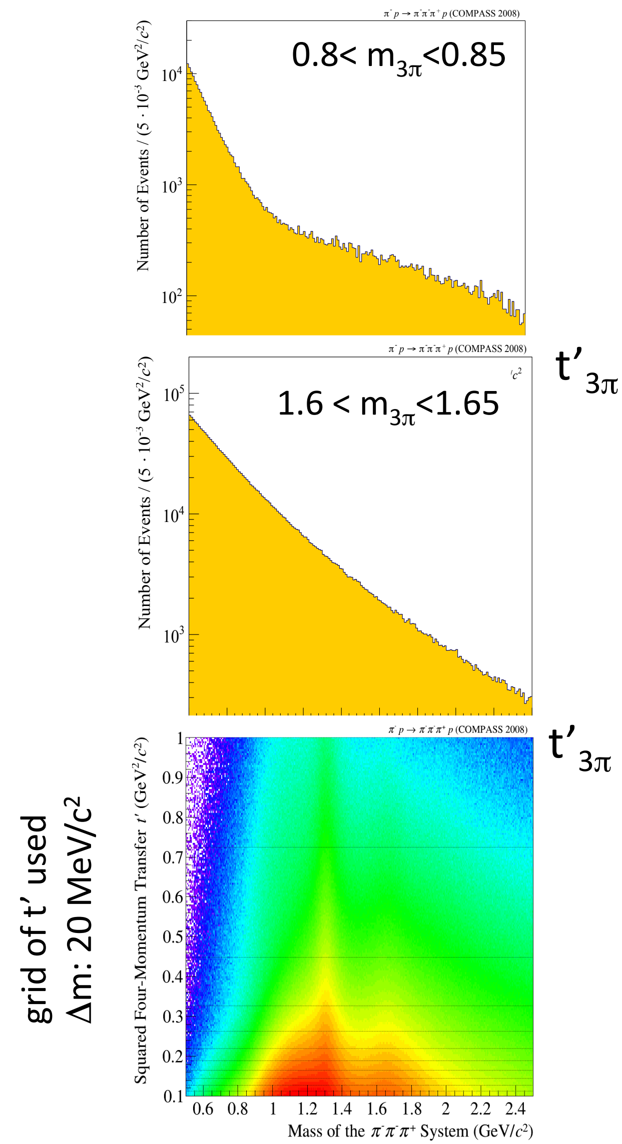
- many missing/disputed states in mass region $m \sim 2\ \mathrm{GeV}/c^2$
- Identification of heavy states difficult
  - broad states
  - large number
  - overlap + mixing

Motivation for Isobar Model and $t'_{3\pi}$-dependence









Partial wave analysis

What is PWA ?

Describe population in 5-dimensional phase space in $\pi\pi\pi$ by model

step 1

- Define a set of quantum numbers J^{PC}
- Define a set of possible decay channels for each J^{PC}

  ($X^- \rightarrow$ isobar + π; isobar$\rightarrow\pi\pi$) : wave (88 waves used)

  - each such "wave" has a pre-determined population in phase space
  - each wave may have alignment of *J* described by quantum number M
- For each bin of 20 MeV/c^2 mass of $\pi\pi\pi$: determine which coherent combination of waves fits distribution best
- Obtain spin-density matrix

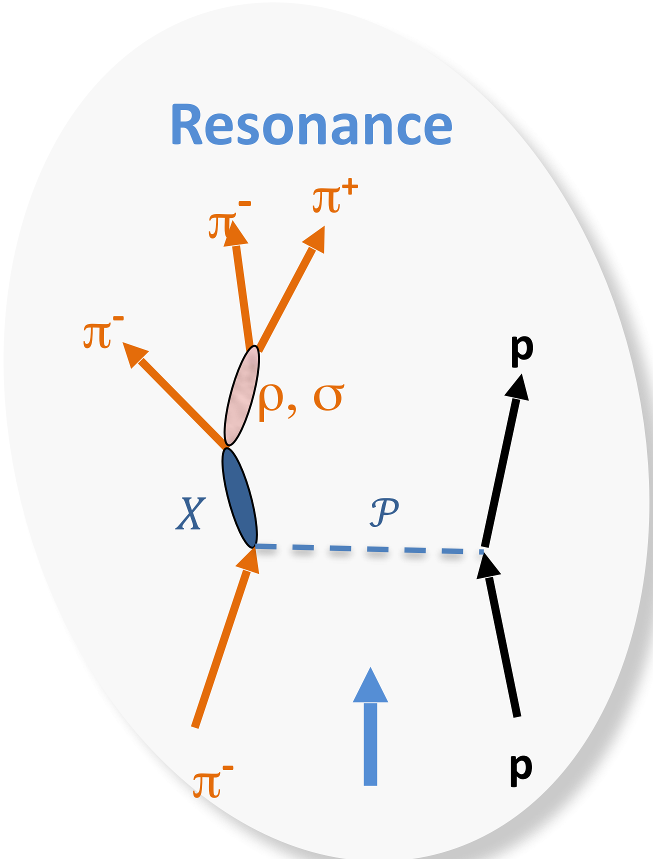
step 2

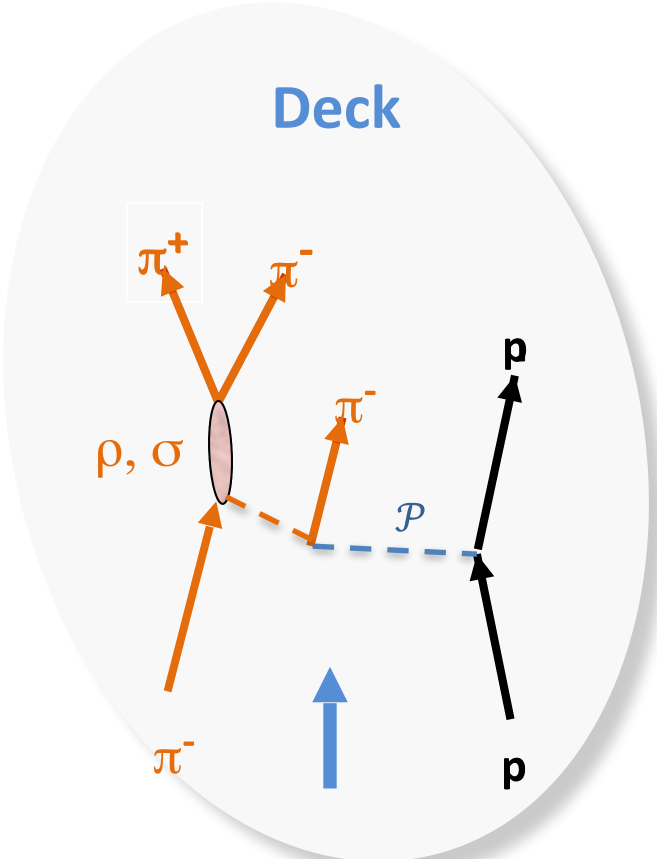
- Describe spin density matrix (submatrix) by model containing resonances and non-resonant contributions connecting all mass bins
- Determine resonance parameters

Model for Spin Density Matrix

Describe the results obtained independently in different mass bins by a model

- select physics contributions
- fit to spin density matrix (not only to simple mass spectra)



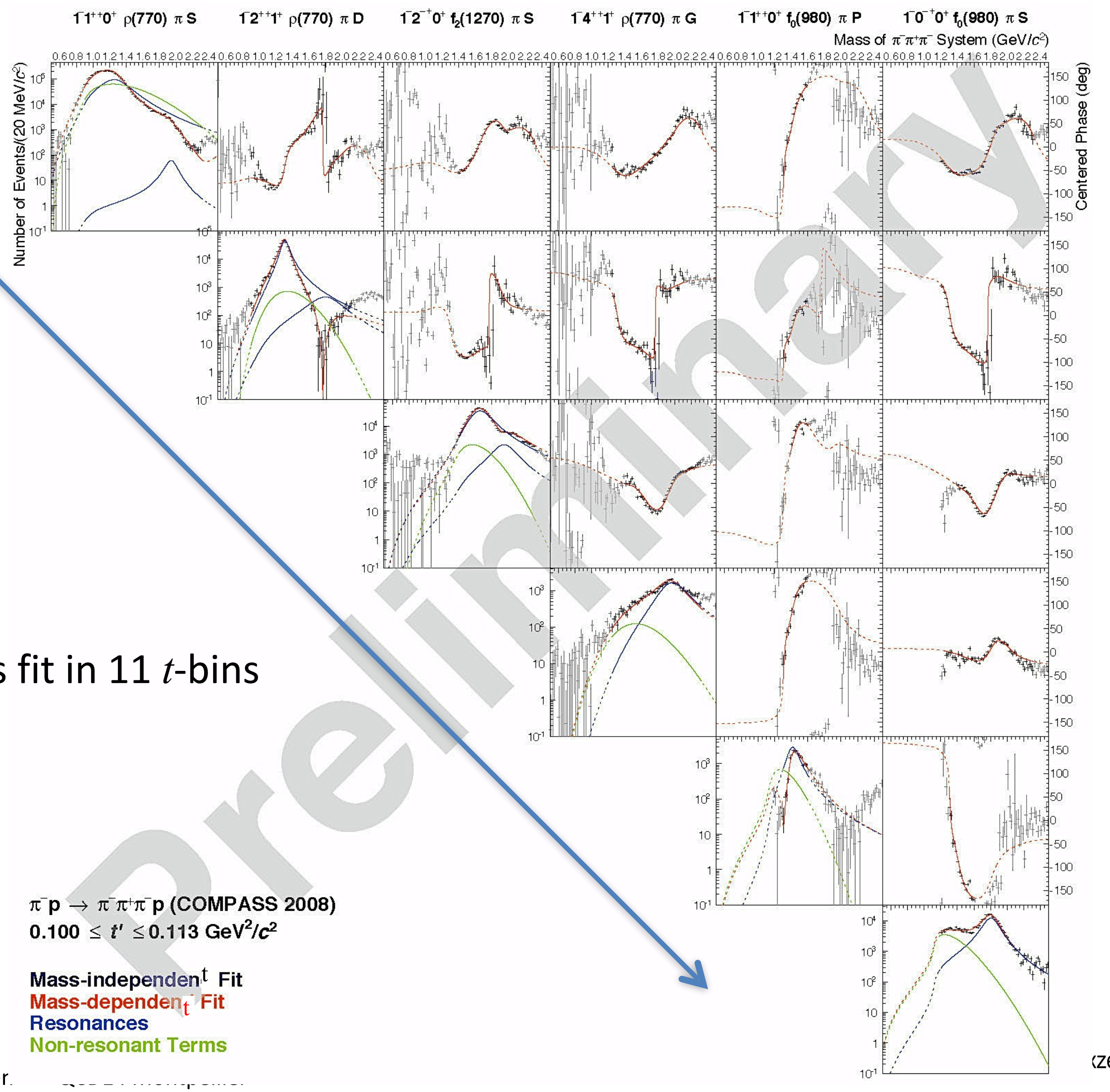


Two types of contributions

COMPASS “Holography”

Reference waves

simultaneous fit in 11 t-bins



Interferometry

COMPASS “Holography”

Reference waves

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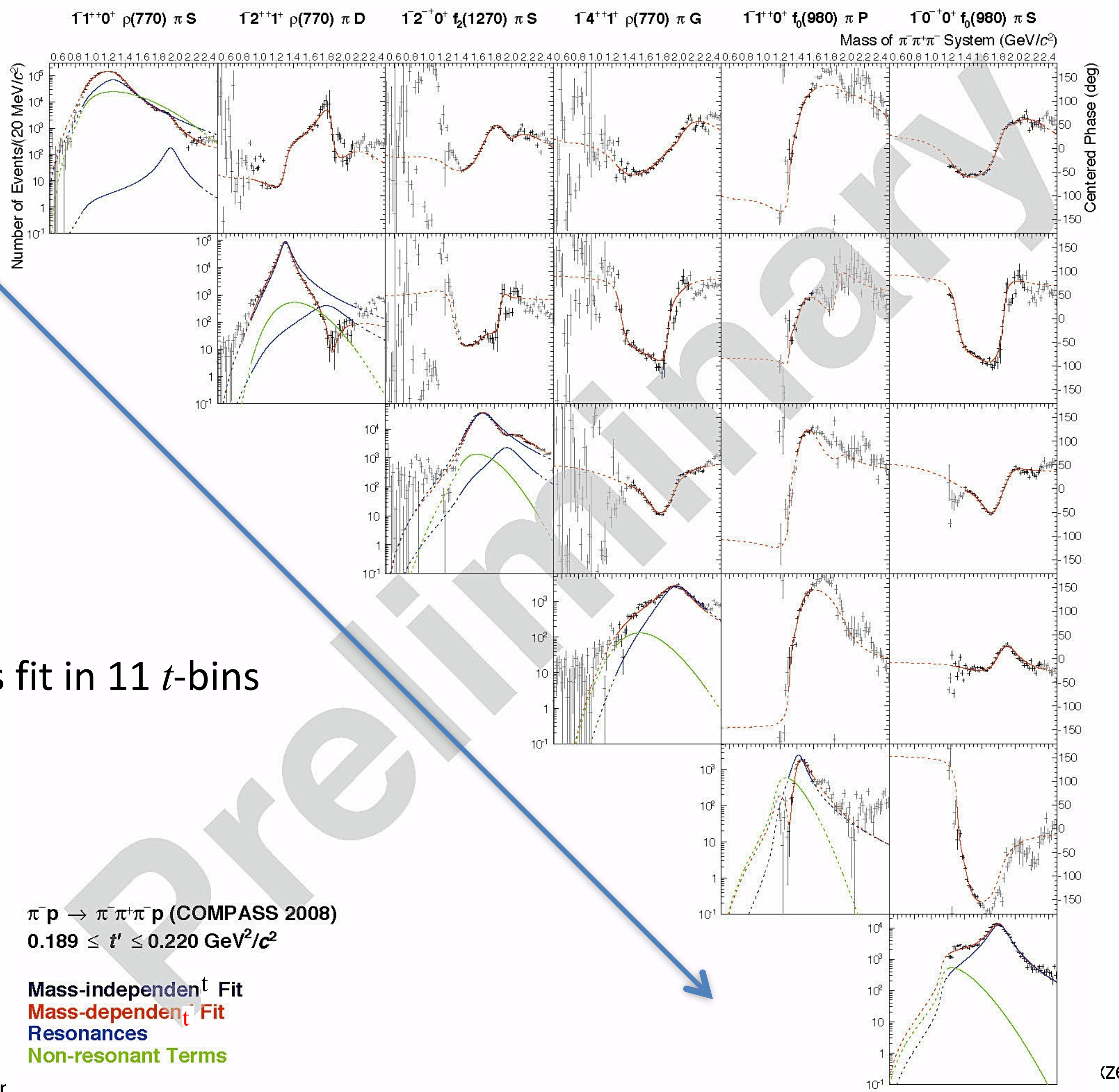

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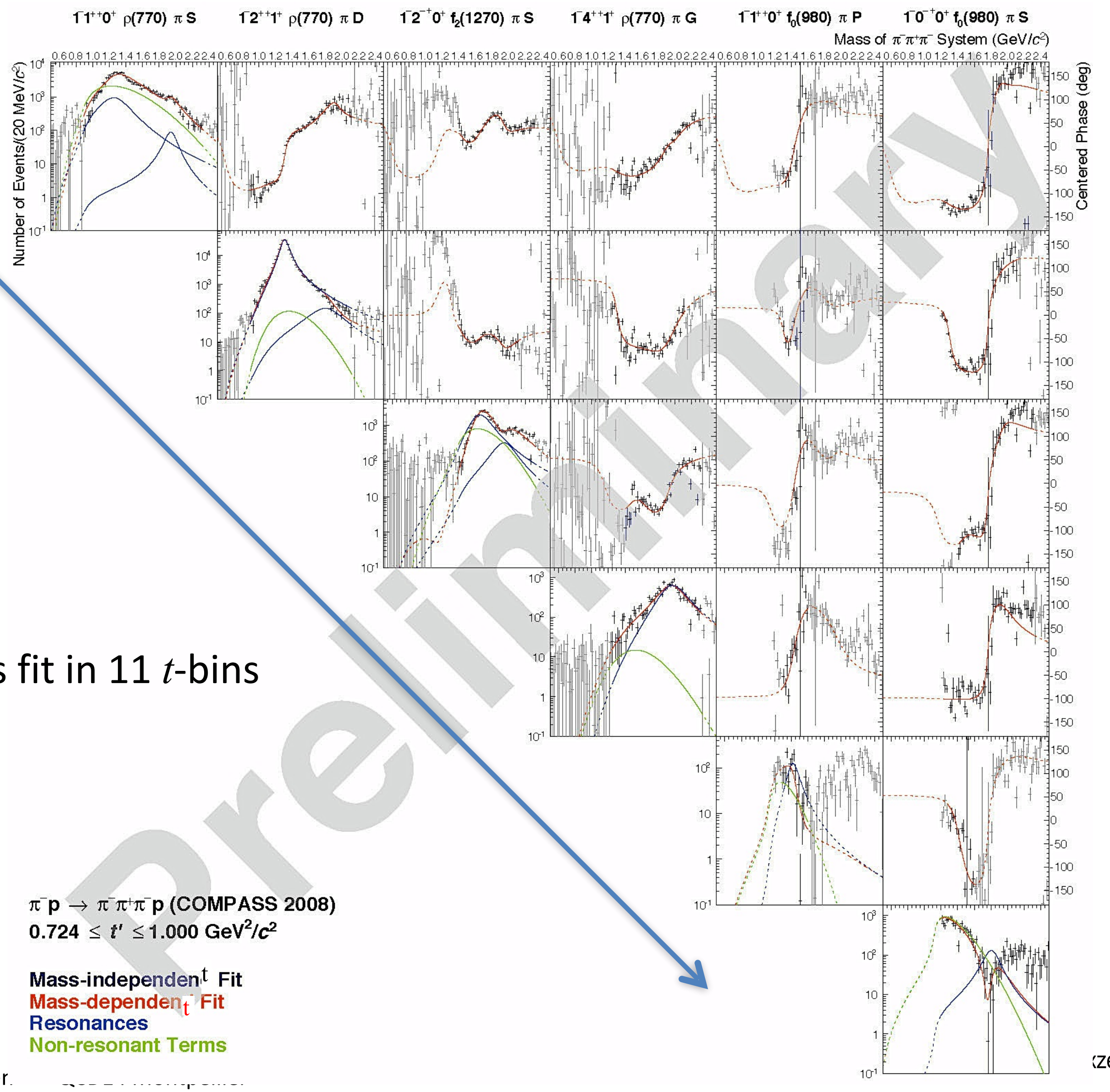
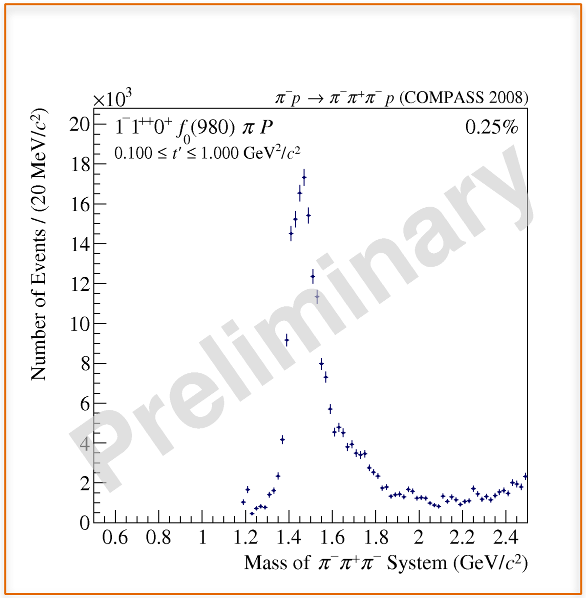


Interferometry

Phase: $a_1(1420)$

$1^{++}0^{+}\ f_0(980)\ \pi\ P$

Fit in 11 t-bins:



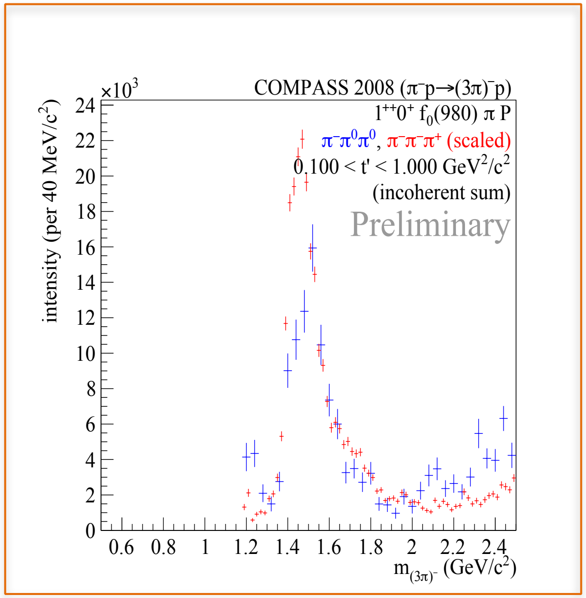
NEW

Phase: $a_1(1420)$

$1^{++}0^{+}$ $f_0(980)$ π P

Fit in 11 t-bins:

$\pi^-\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$



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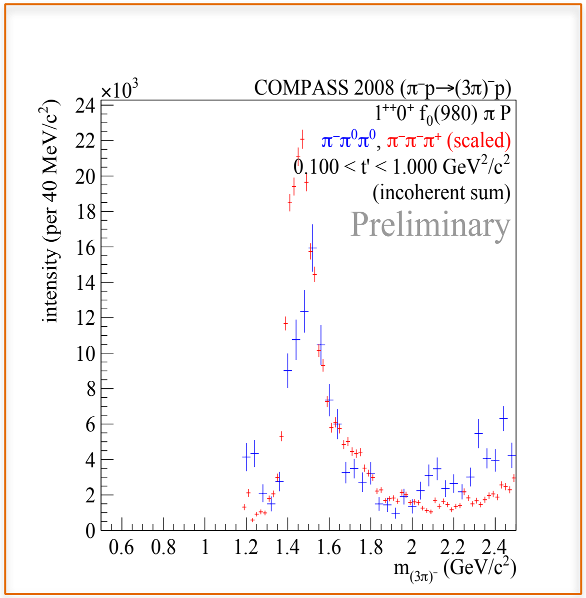
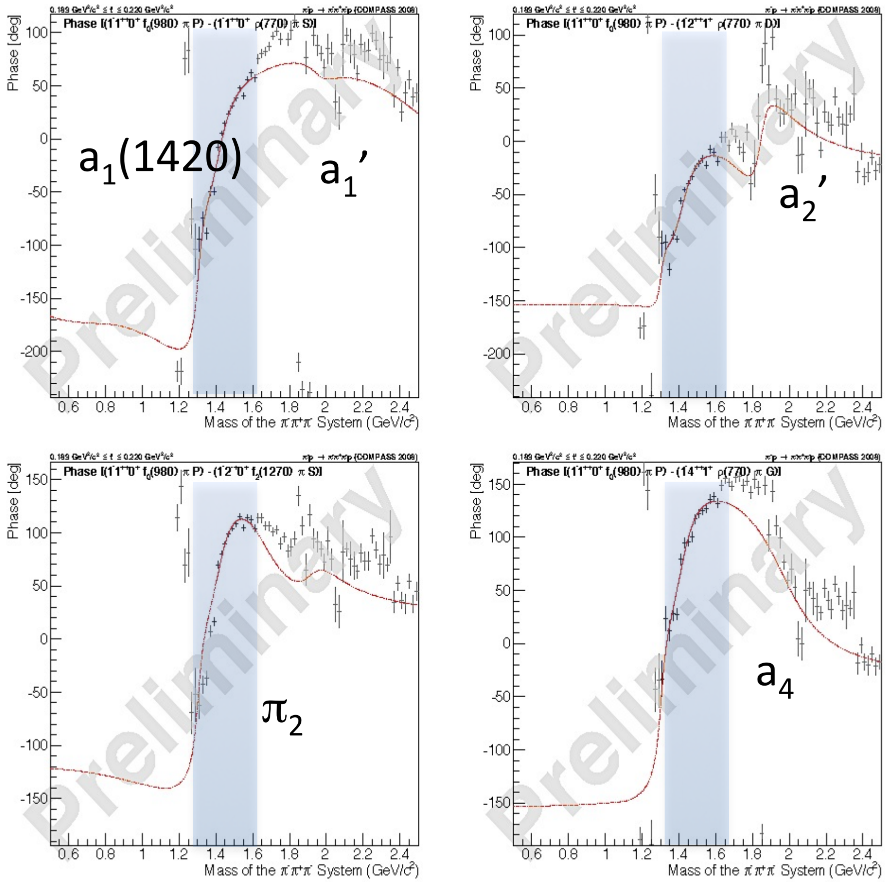


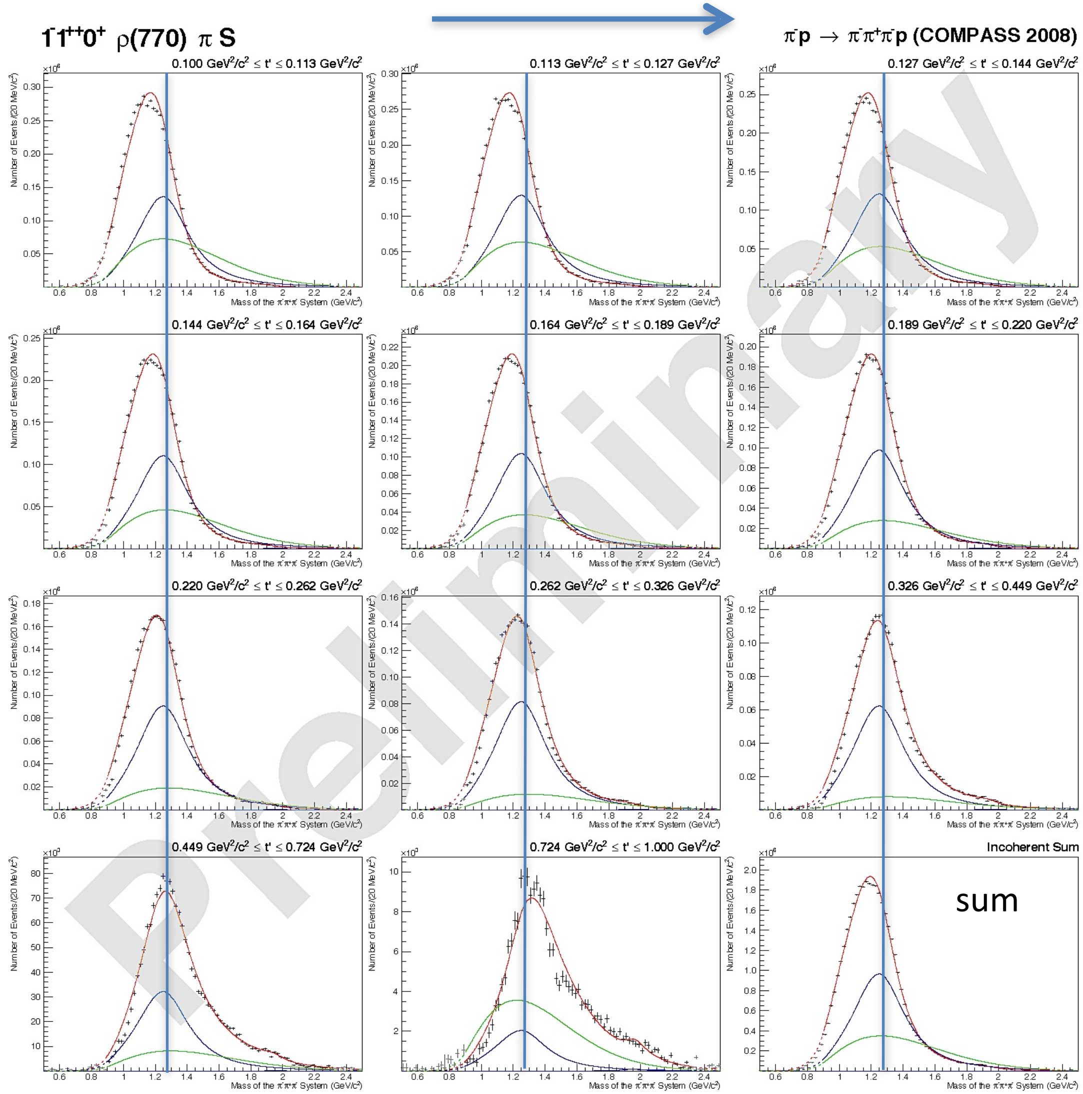
fit range



NEW

Mass dependent fits a_1

Fit in 11 t-bins



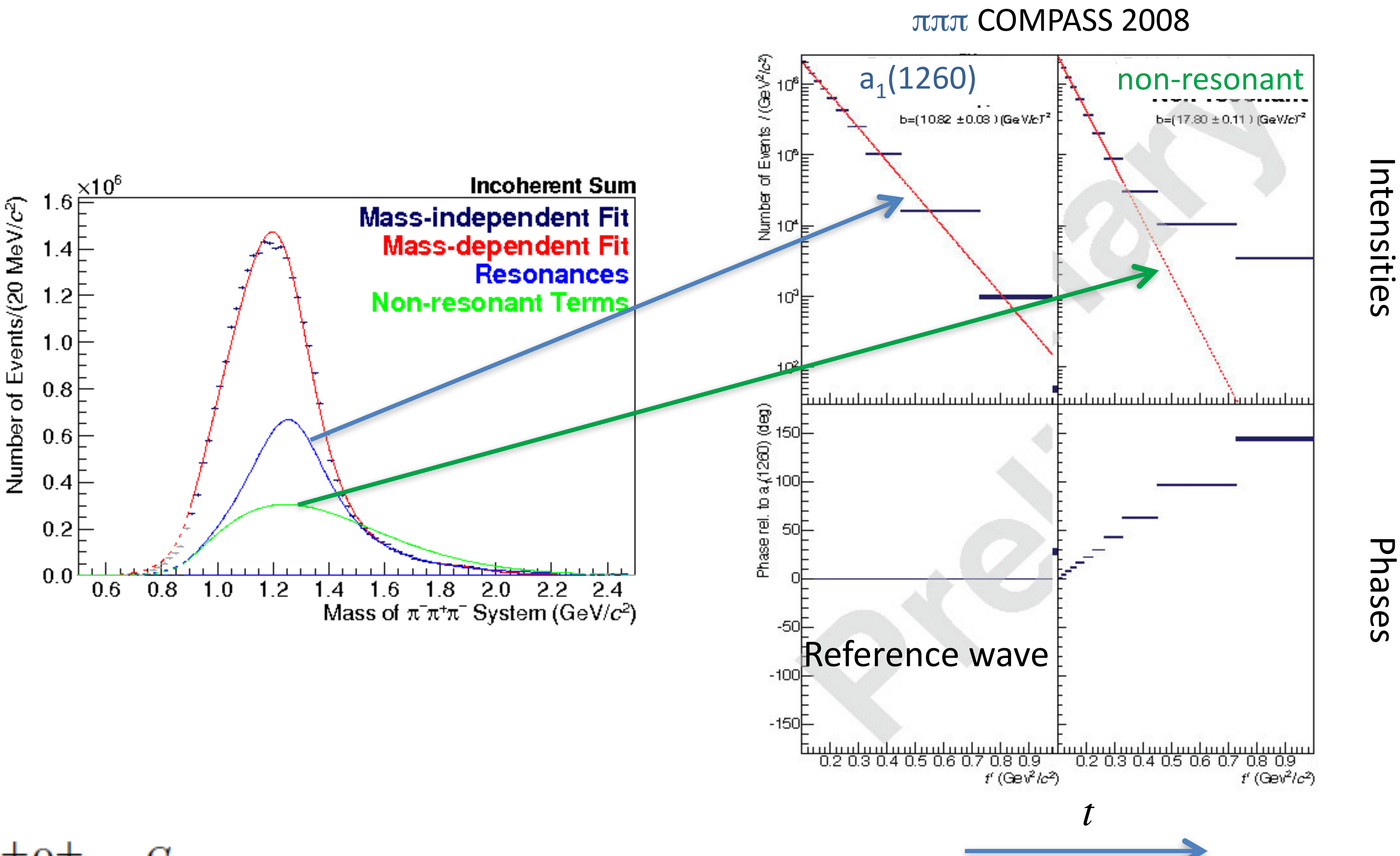
Strongly t-dependent spectral shape around $a_1(1260)$

$$1^{++}0^{+}\rho\pi S$$

$$J^{PC}M^{\varepsilon}[isobar]\pi L$$

t

Example for t-dependence



$$1^{++}0^{+}\rho\pi S$$

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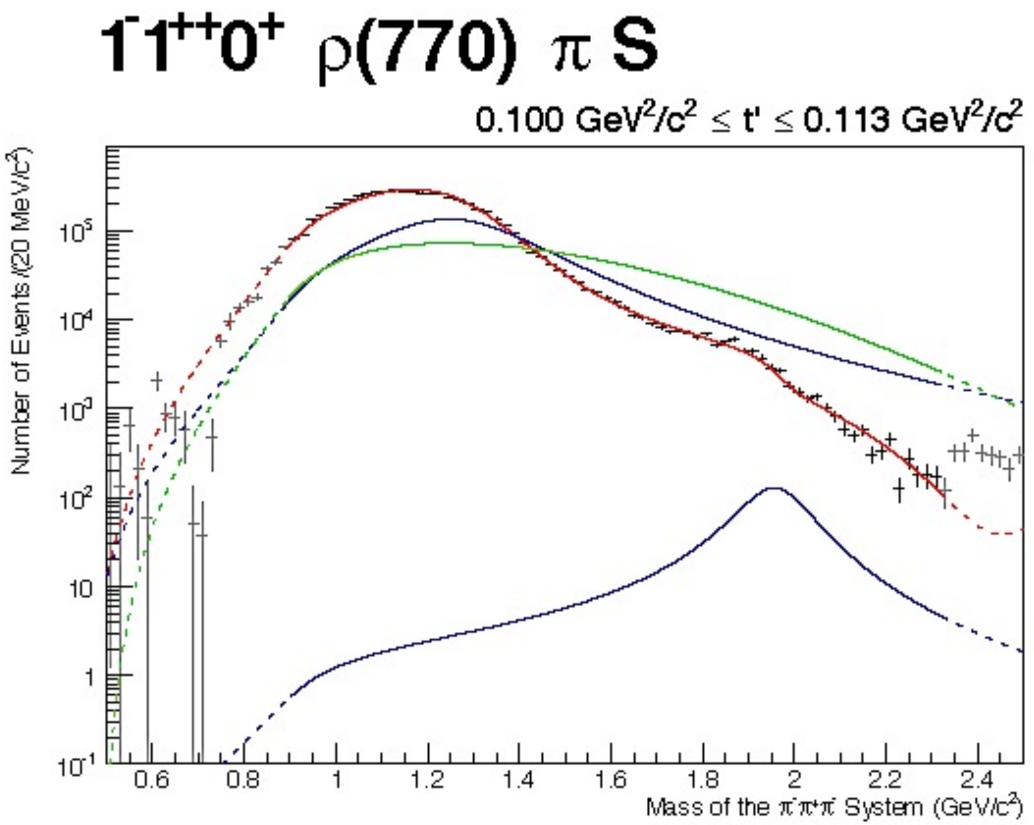
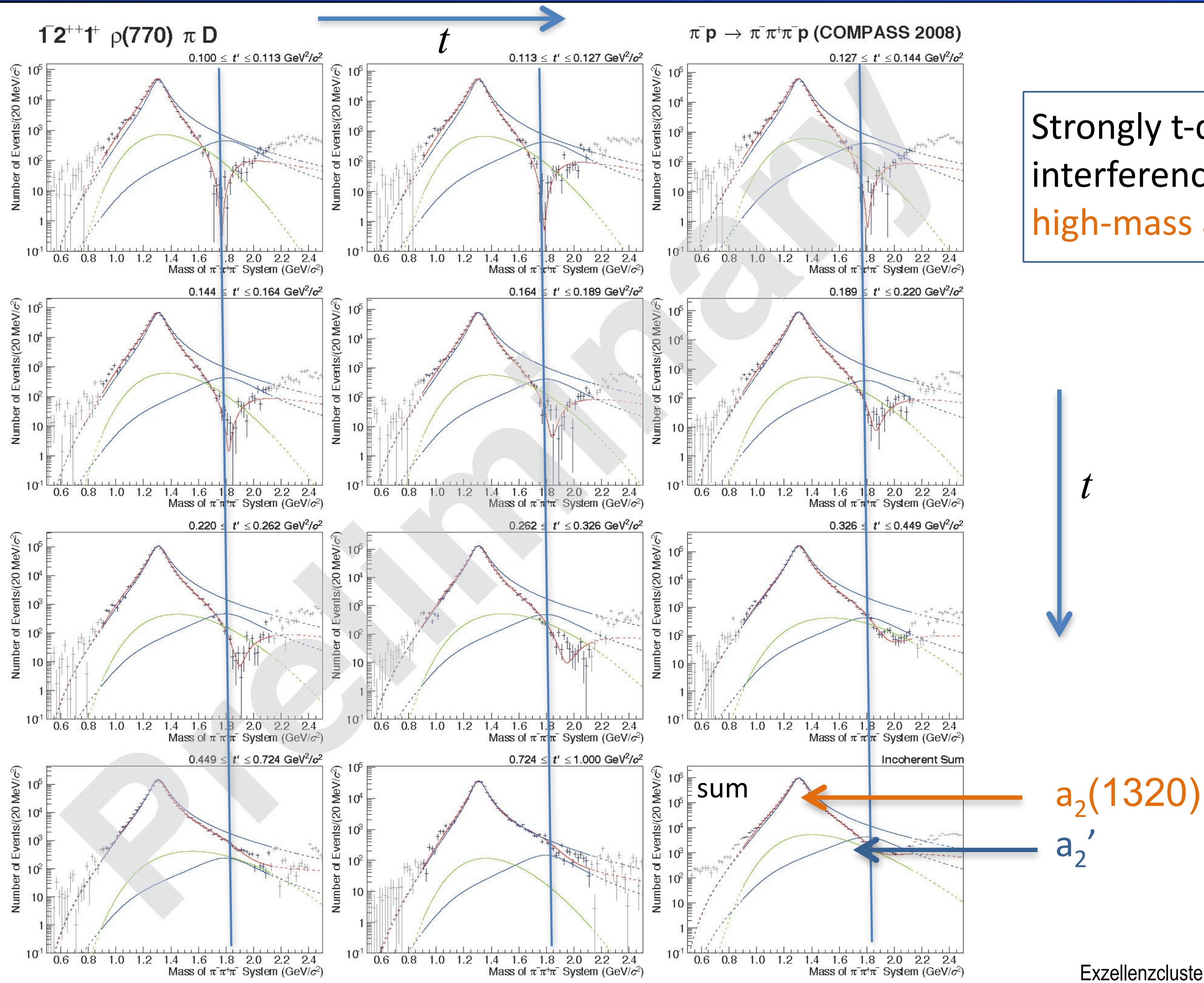
Mass dependent fits

Fit in 11 t-bins



Second high-mass a_1' resonance visible

Mass dependent fits $a_2(1320)$

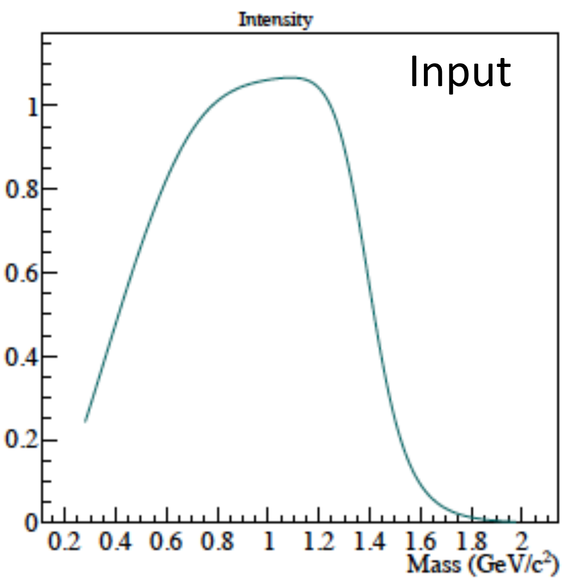


Strongly t-dependent interference effects

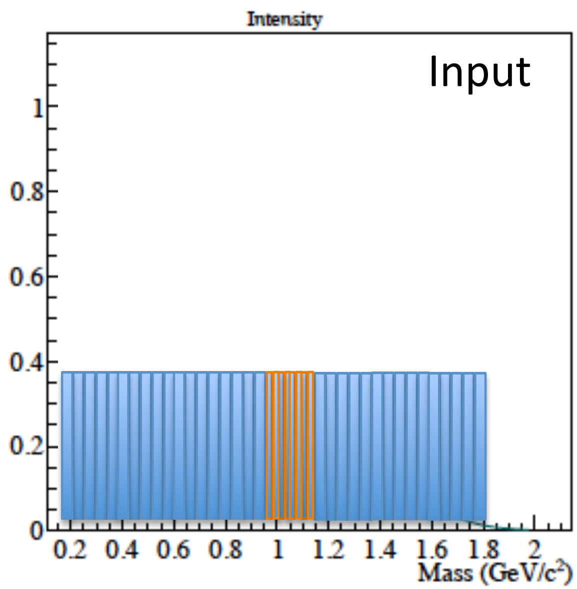
high-mass a_2'

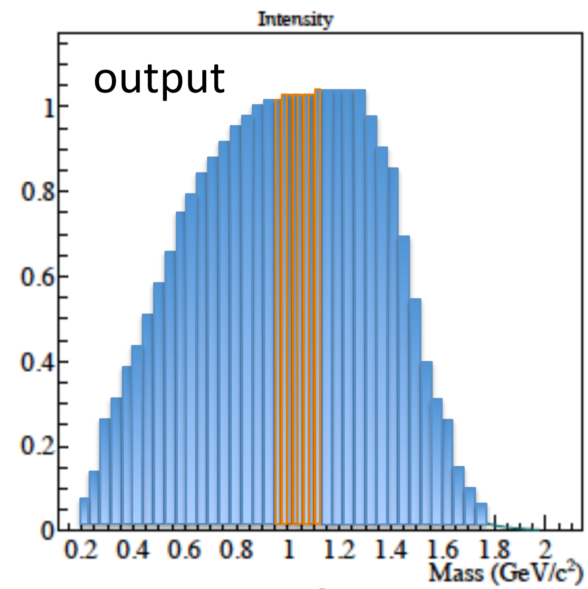
New Paths to Meson Decays

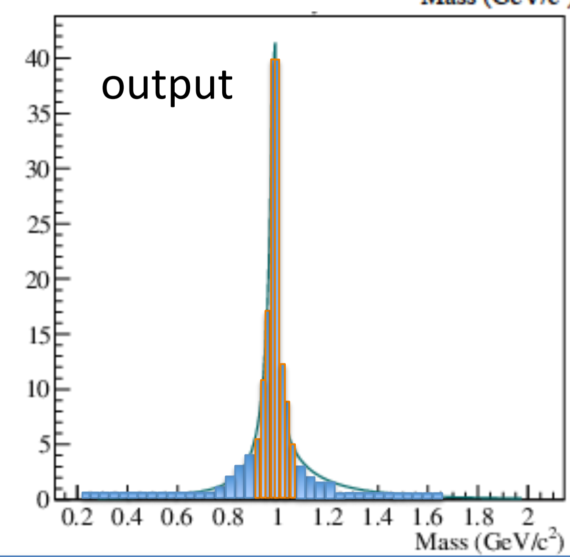
Isobar model



De-isobared analysis

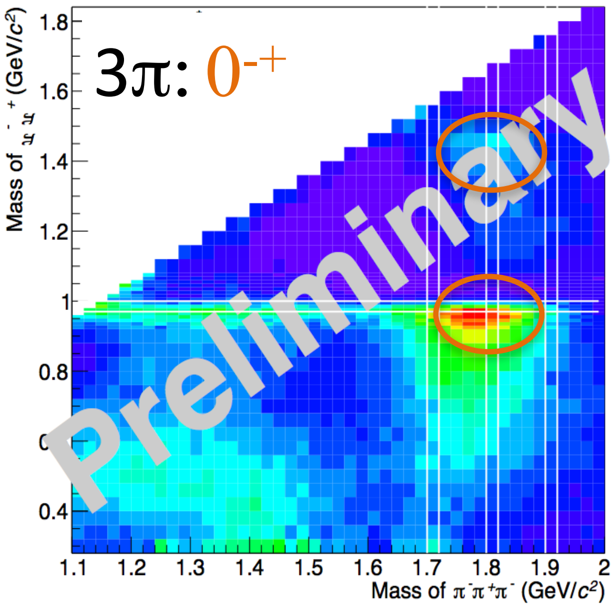






- Select J^{PC} via PWA
- For each J^{PC} and mass-bin in 3π :
  - determine composition and shapes of 2π isobars
  - complex couplings
  - non-resonant contributions (via t-dependence)

Correlation: $m_{2\pi}(0^{++})$ *vs* $m_{3\pi}(J^{PC})$



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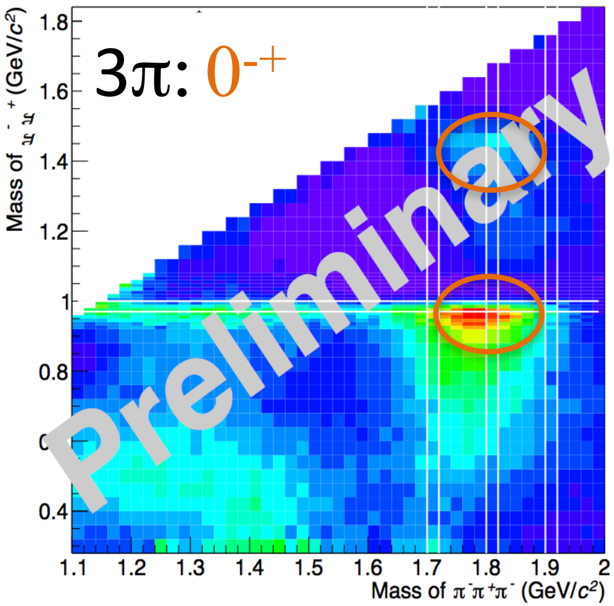

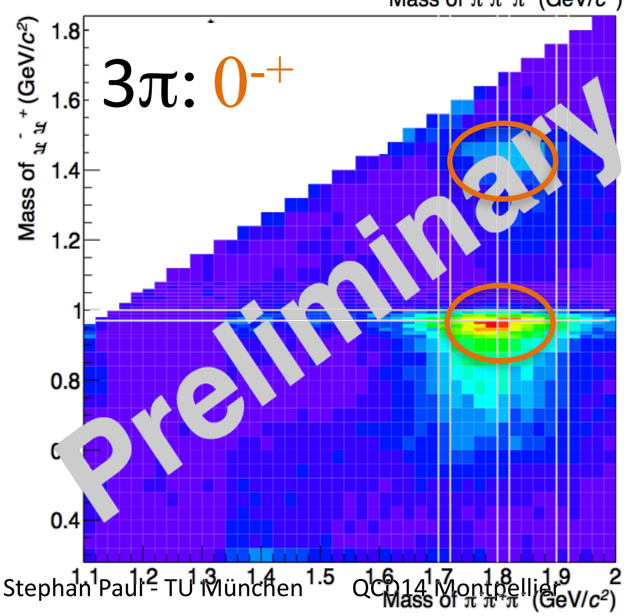

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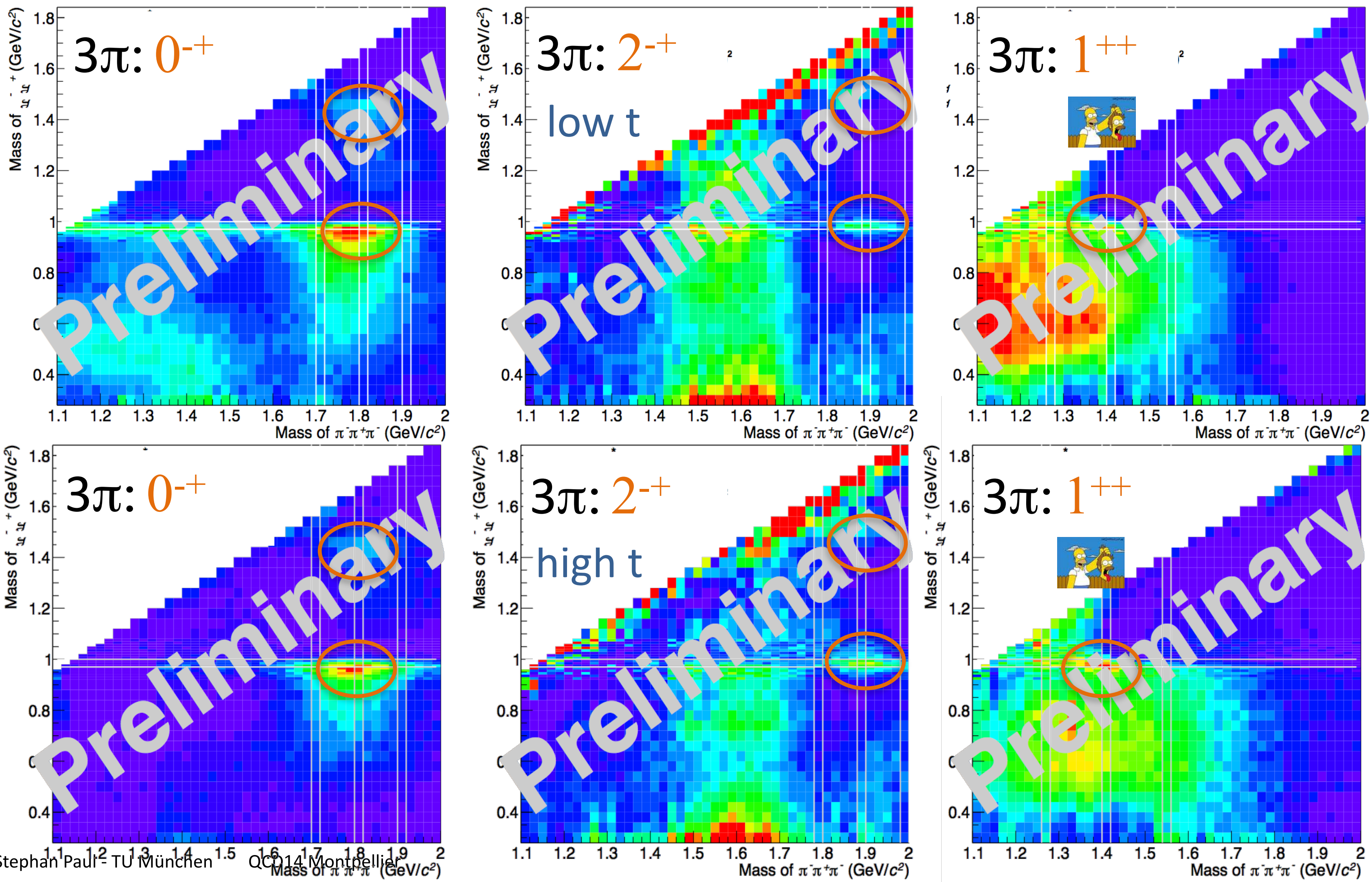

Conclusion

- First precise measurement of π polarizability
  - Pion much stiffer than atom (strong interaction)
  - Excellent agreement with theory (χPT)
  - Future: separate magnetic and electric polarizabilities, kaons

- New path to radiative meson excitations (E2-transition observed)
- New path to meson spectroscopy (PWA on PWA-selected waves)
  - PWA uses dynamics of production process
  - New method to look into the dynamics
- New axial vector meson found $a_1(1420)$
  - Nature of $a_1(1420)$?

    Isospin partner of $f_1(1420)$ (considered to be exotic) ?

    Dynamically generated through $a_1(1260) \leftrightarrow KK^* \leftrightarrow f_0\,(980)\pi$ channel ?
- Other final states investigated ($\pi^-\pi^0\pi^0$, $\eta\eta\pi^-$, $KK\pi^-$ … etc.)