Diffractive Processes at COMPASS

- Status and Perspectives -

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for the
COMPASS Collaboration

First SaporeGravis Workshop (SGW 2013)
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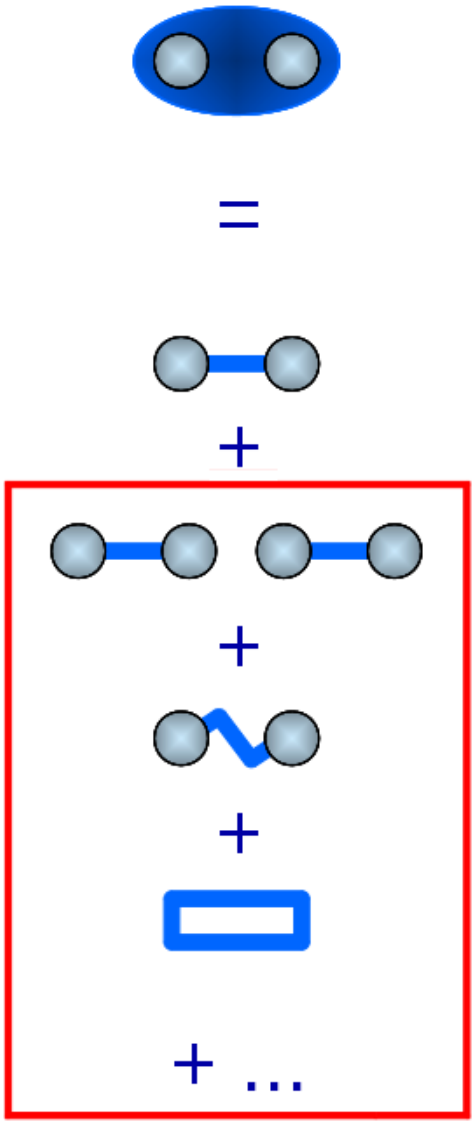
Nantes, France

Supported by

Meson Spectroscopy



$(q\bar{q})_0$

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

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

Hybrid

gg

Glueball

Constituent Quark Model (CQM)

- Bound state of $q\bar{q}$
- Quantum numbers: $I^G(J^{PC})$

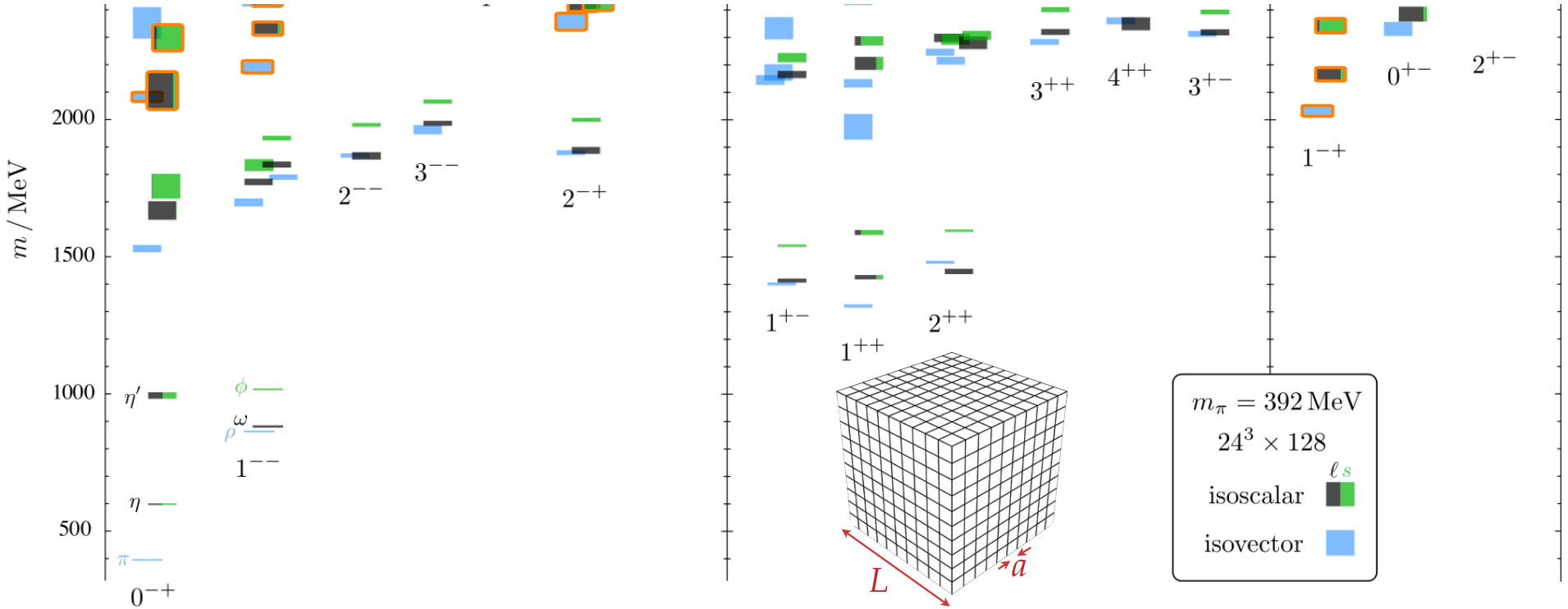
Quantum ChromoDynamics

- Other allowed colour-neutral configurations
- Study spectrum and properties (width, decay, ...) of mesons

Light Meson Spectroscopy

- Many missing and disputed states
- Broad and overlapping resonances
- Exotic quantum numbers $(0^{--}, 0^{+-}, 1^{-+}, ...)$

Light Meson Spectrum in LQCD

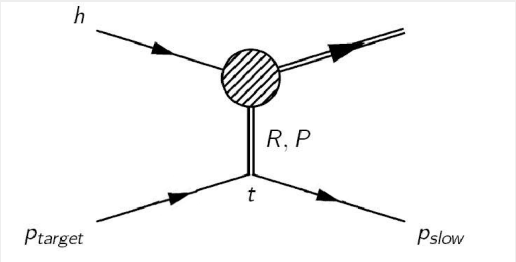


J.J. Dudek et al. [Phys. Rev. D 88 (2013)]

- Tremendous progress in recent years
- Excited states, spin-identified spectra, chromomagnetic content
- Experimental results need to reach equivalent precision
- Resonance parameters and decay modes not (yet) accessible

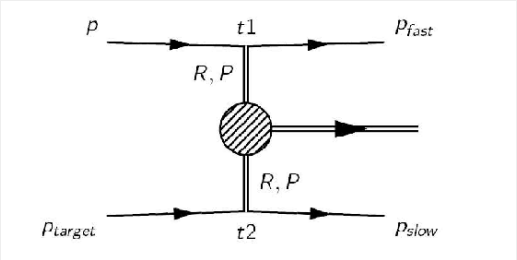
Diffractive Processes

Diffractive Dissociation:



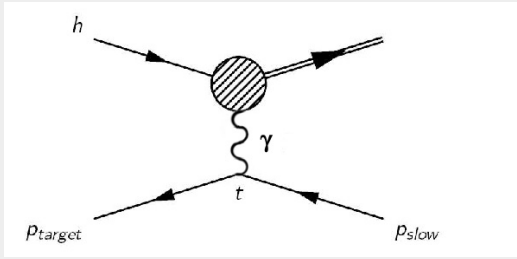
- Explore light meson spectrum
- Evidence for spin-exotic mesons

Central Production:



- Glue-rich environment (DPE)
- Supernumurous scalar resonances

Photo-production:



- Study of chiral dynamics
- Measurement of e.-m. properties

Experimental requirements:

- Variable apparatus to cover the three fields
- Precise detection of different decay modes in order to determine the nature of the produced resonances

The COMPASS Experiment

Beams from CERN SPS

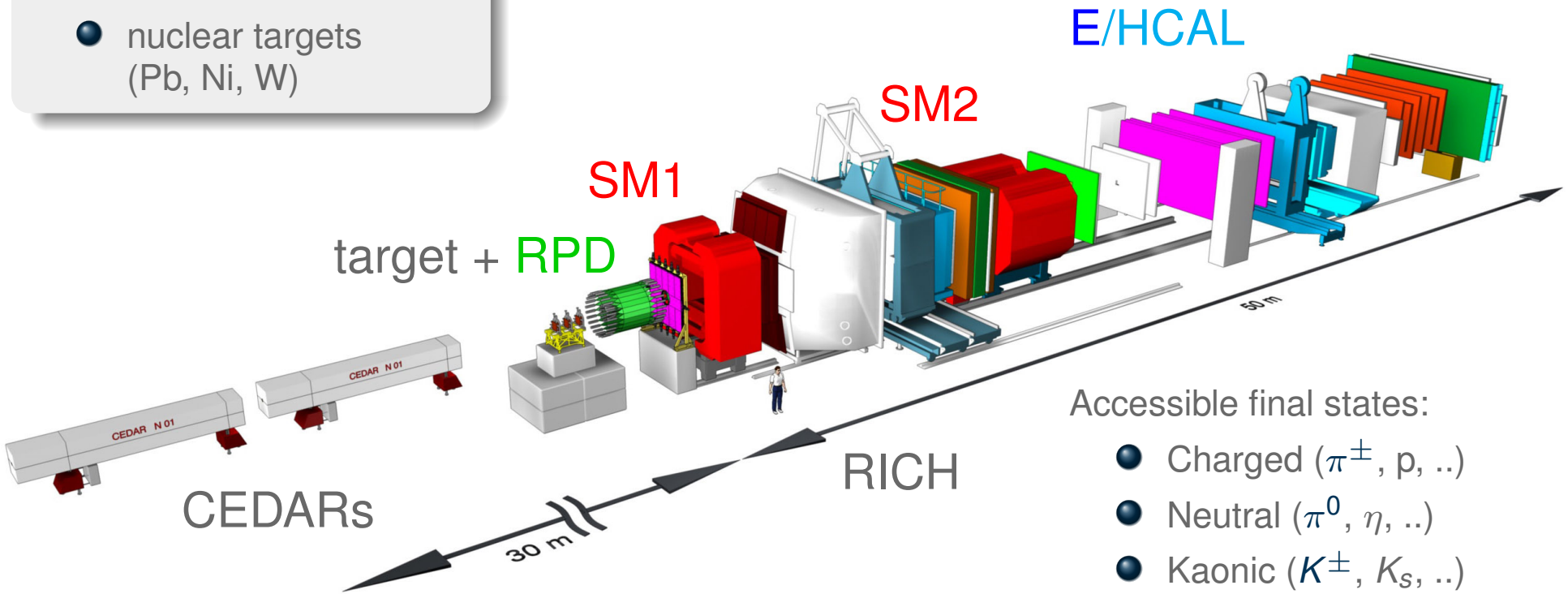
- 190 GeV/c π^-, K^-
- 190 GeV/c p, π^+, K^+

Targets

- liquid H_2
- nuclear targets (Pb, Ni, W)

Two-stage magnetic spectrometer

- Large angular acceptance
- Broad kinematic range
- Tracking, calorimetry, particle ID

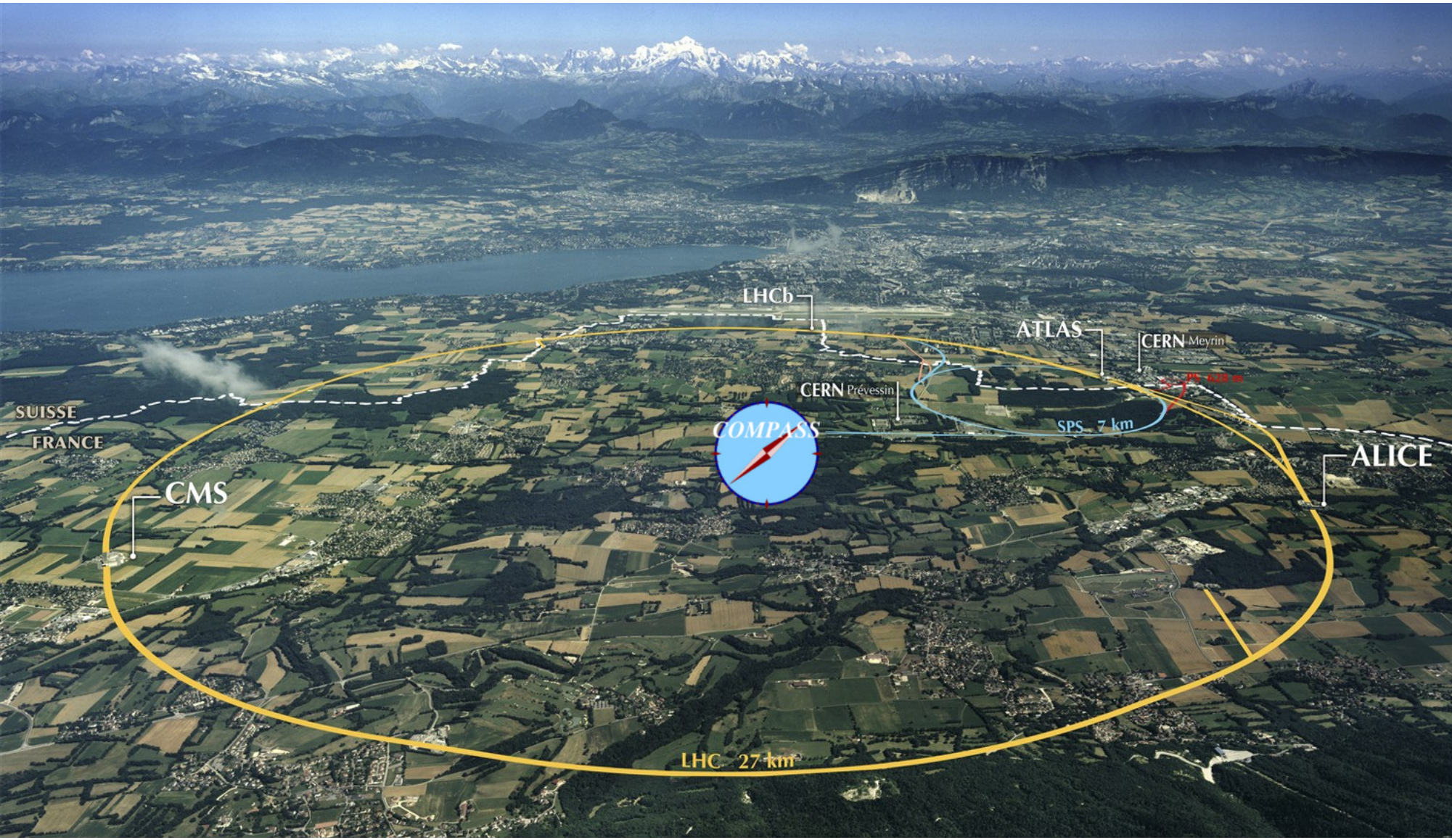


Accessible final states:

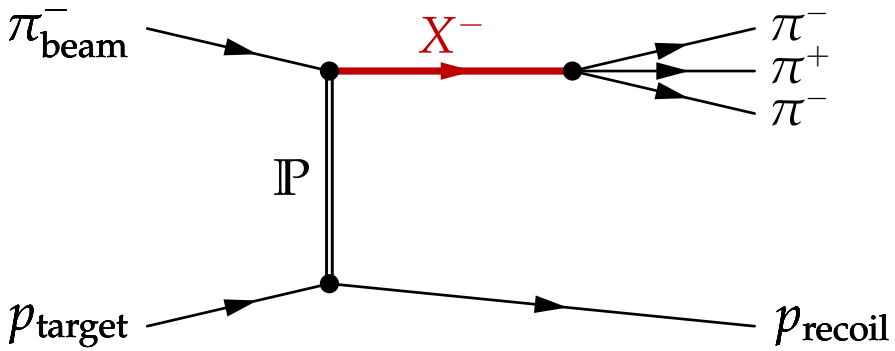
- Charged ($\pi^{\pm}$, p, ..)
- Neutral (π^0, η, ..)
- Kaonic ($K^{\pm}$, K_s, ..)

COMPASS at CERN SPS

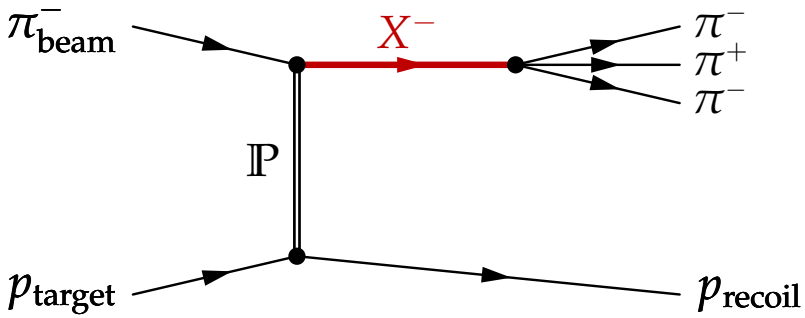
Technische Universität München



Diffractive Dissociation into 3-Pion Final States

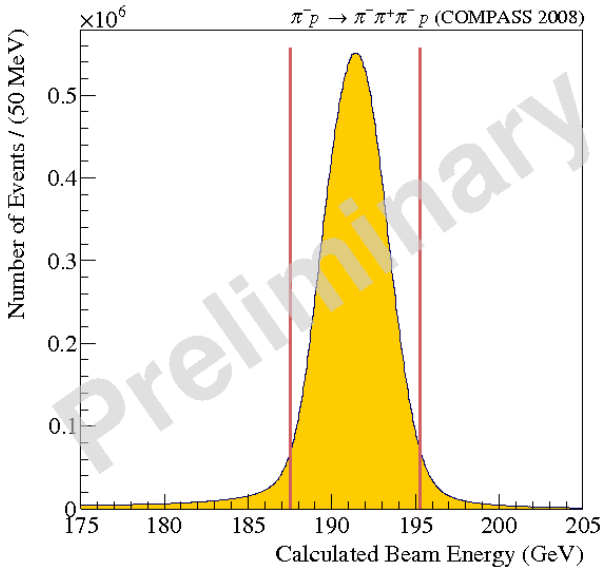


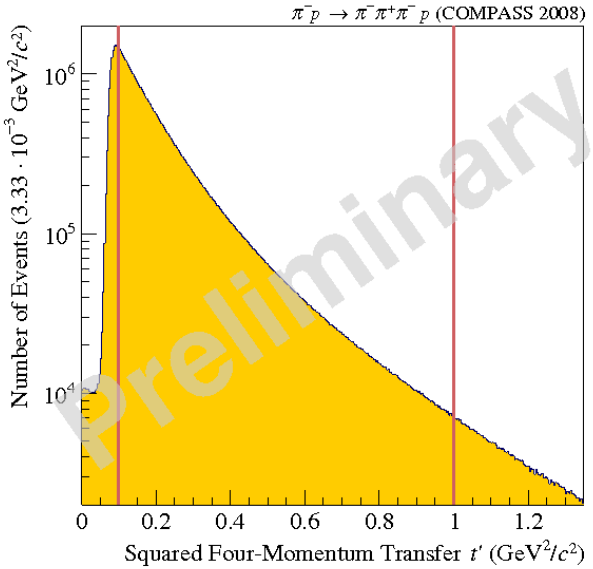
3π Final-States



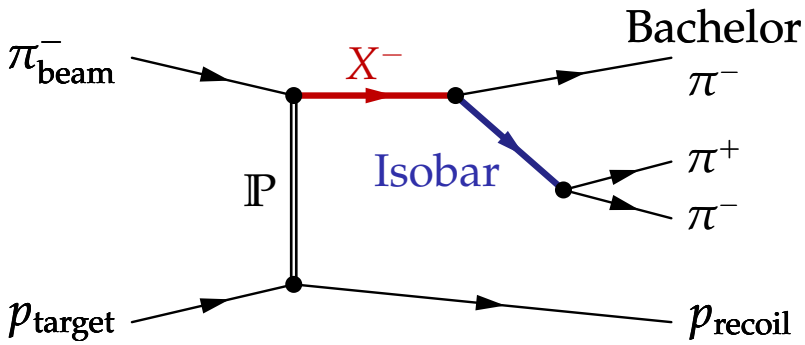
$\pi^- p \to \pi^- \pi^+ \pi^- p$

- 190 GeV/c π^- on lH_2 target
- $\approx$ 50M exclusive events
  $\rightarrow$ unprecedented precision
- Squared 4-momentum transfer
  $0.1 < t' < 1 (\text{GeV}/c)^2$



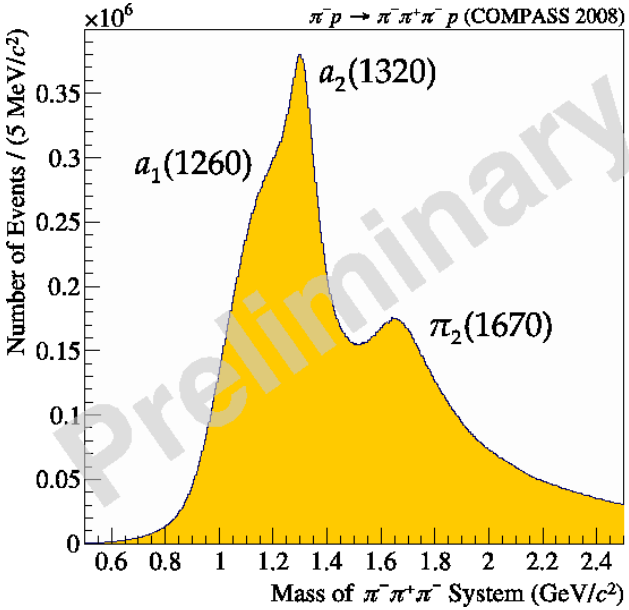


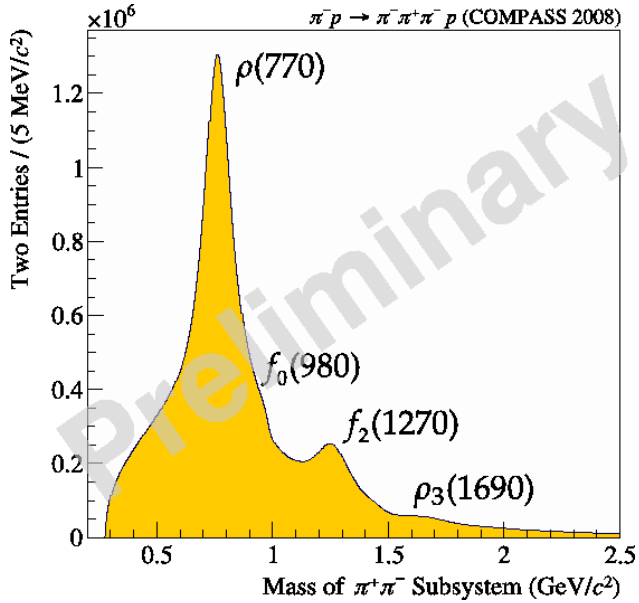
3π Final-States



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

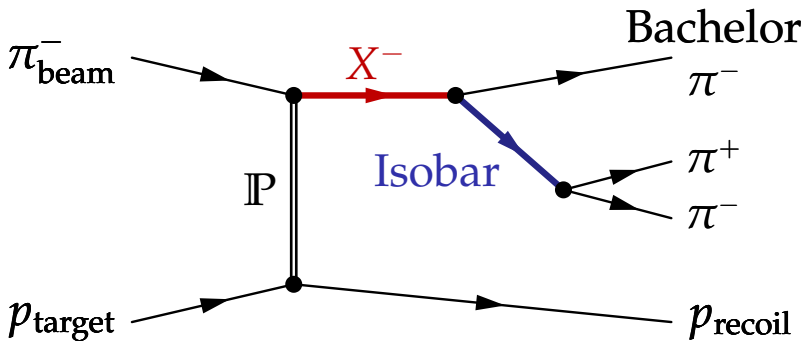
- Sequential 2-body decays
- Isobar Model: intermediate $\pi^+\pi^-$ resonance
- In general: isobar with fixed parametrisation





+ $(\pi\pi)_S$, $f_0(1500)$

3π Final-States



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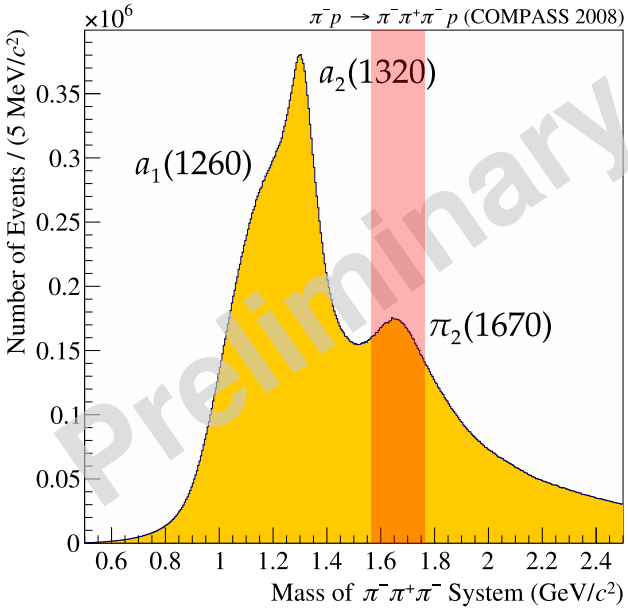
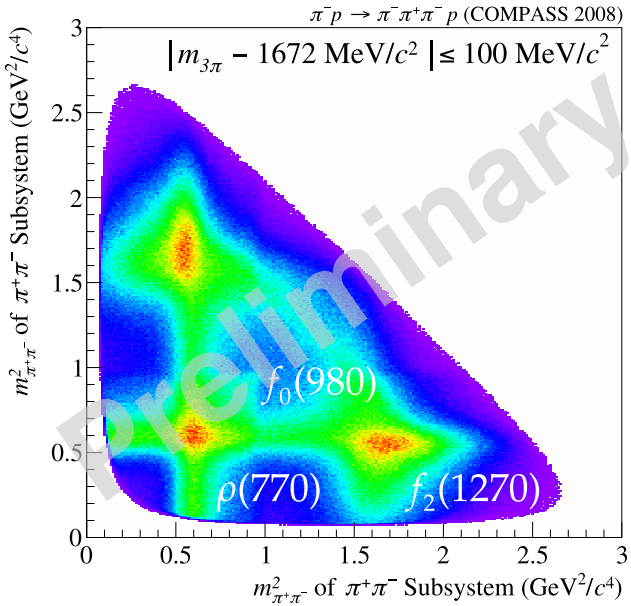
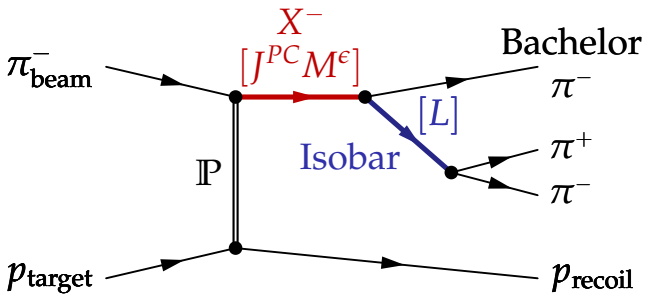




Partial-Wave Analysis



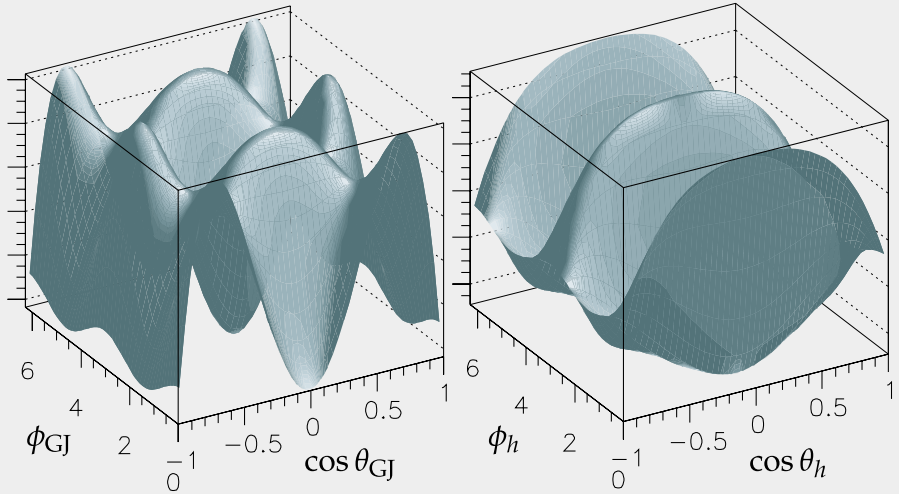
Decay Amplitude in Isobar Model

- Partial-wave : unique combination of $J^{PC}M^{\varepsilon}$ isobar πL
- Kinematics in fixed 3π mass bin given by 5 phase-space variables τ

Example: angular distribution for $2^{-+}1^+$ $f_2(1270)\pi D$ wave

Resonance decay
$X^-(2^{-+}) \to f_2(1270)\pi^-$

Isobar decay
$f_2(1270) \to \pi^+\pi^-$



[Dzierba et al., PRD73 (2006)]

Partial-Wave Analysis Technique

Expand cross section $\sigma(\tau)$ in terms of partial-waves for narrow mass bins m_X:

$$\sigma(m_X, \tau) = \sigma_0 \left| \sum_{\text{waves}} T_{\text{wave}}(m_X)\, A_{\text{wave}}(m_X, \tau) \right|^2$$

- Complex transition amplitudes T_{wave}, no assumption on 3π resonances
- Truncated wave set: iterative selection based on experience and fit results
- Largest wave set ever used: 88 waves, with 6 isobars, L and J up to 6

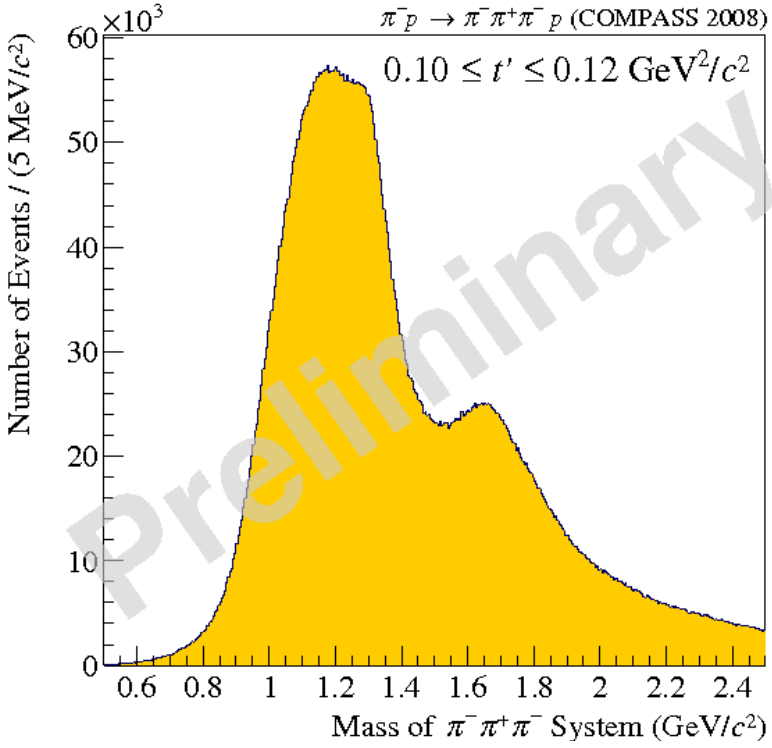
Independent Maximum Likelihood Fits in Mass Bins

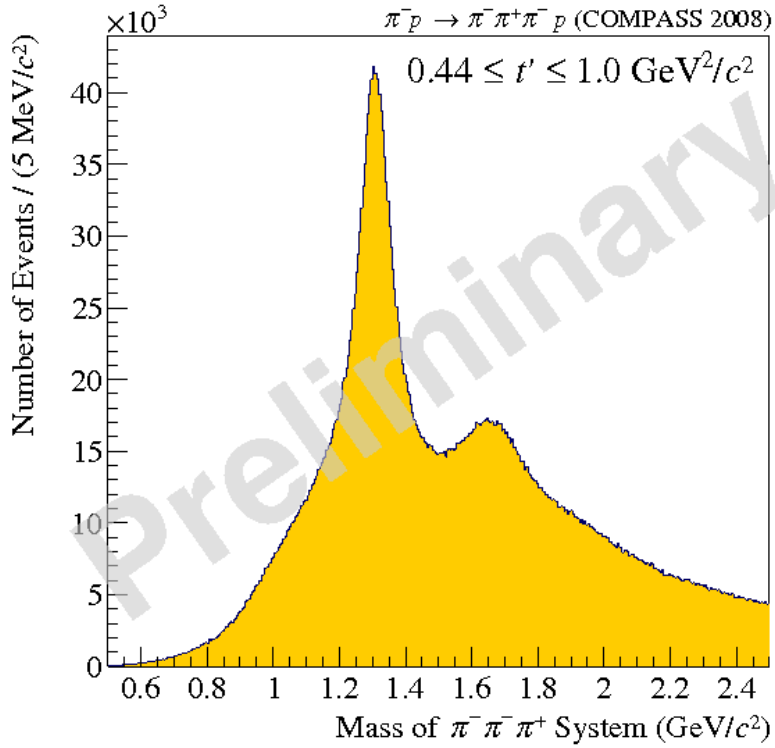
$$\ln L = \sum_{\text{events}} \ln \sigma(\tau) - \int d\tau\, \sigma(\tau)\, \eta(\tau)$$

- Normalisation integral is evaluated by a phase-space Monte Carlo sample
- Challenges: huge data set, precise experimental acceptance, computing

3π Final-States: A Complication

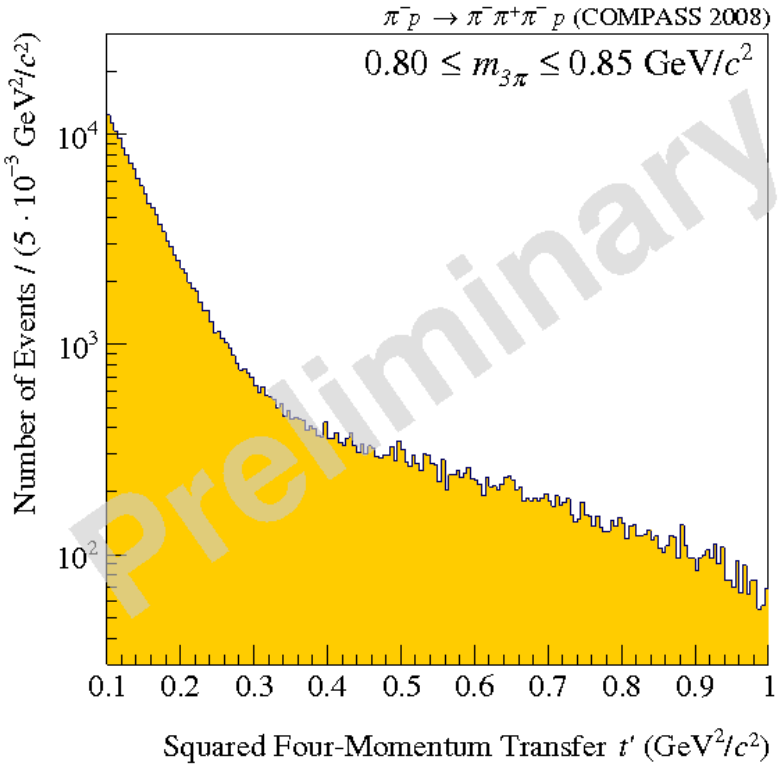
- 3π invariant mass depends on t'

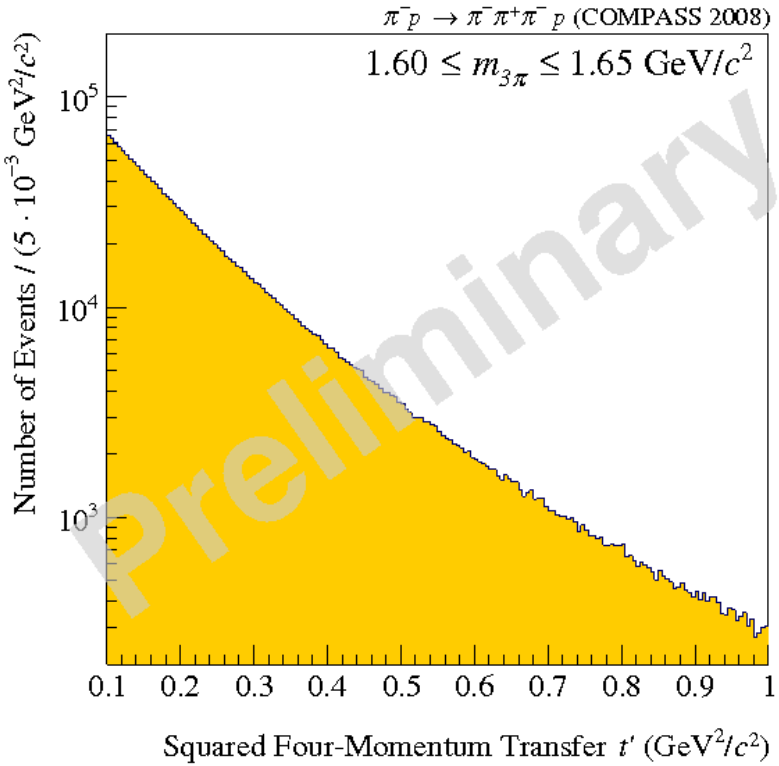




3π Final-States: A Complication

- 3π invariant mass depends on t'
- t' spectrum depends on 3π invariant mass

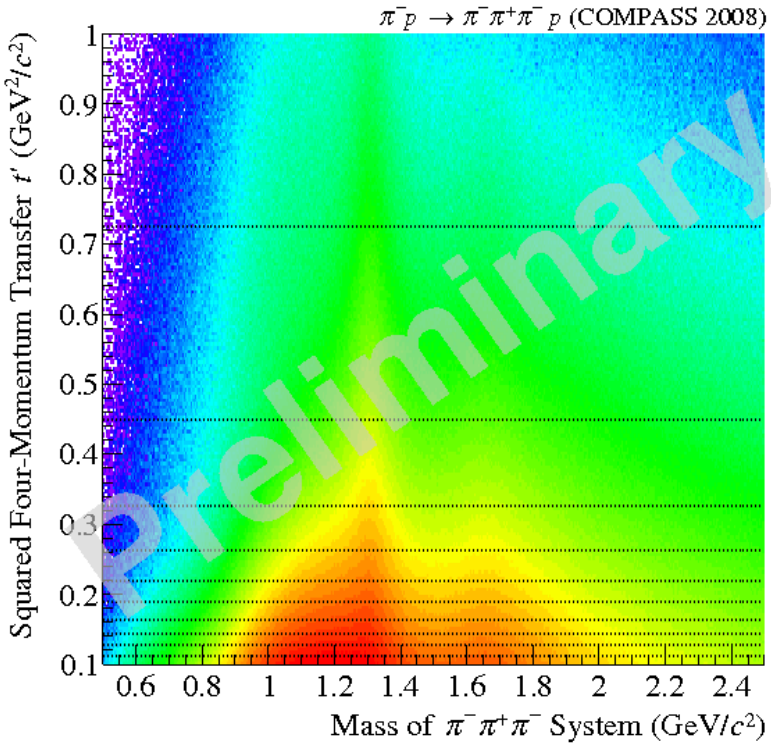




3π Final-States: A Complication

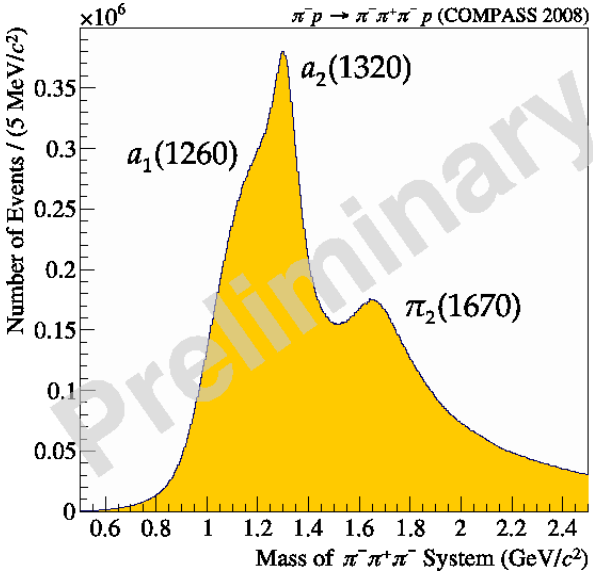
- 3π invariant mass depends on t'
- t' spectrum depends on 3π invariant mass

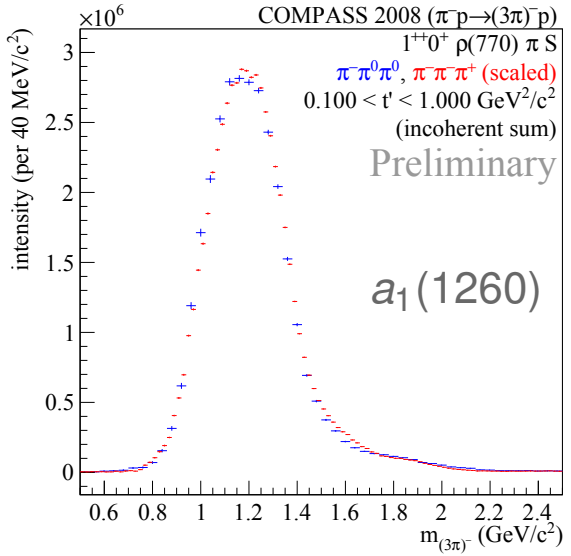
$\Rightarrow$ Fit in bins of m_X and t' to avoid model bias

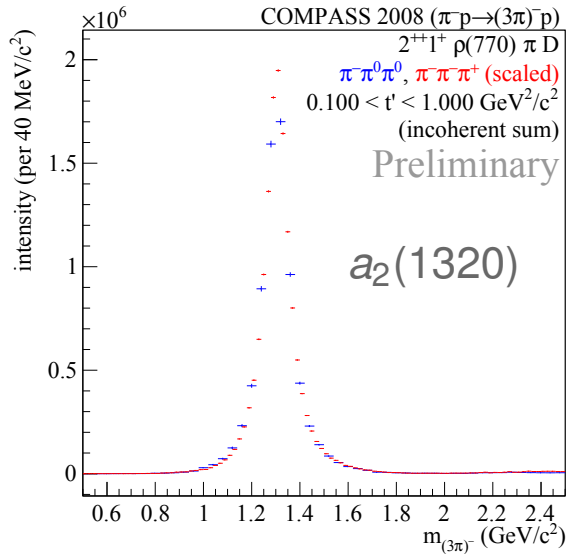


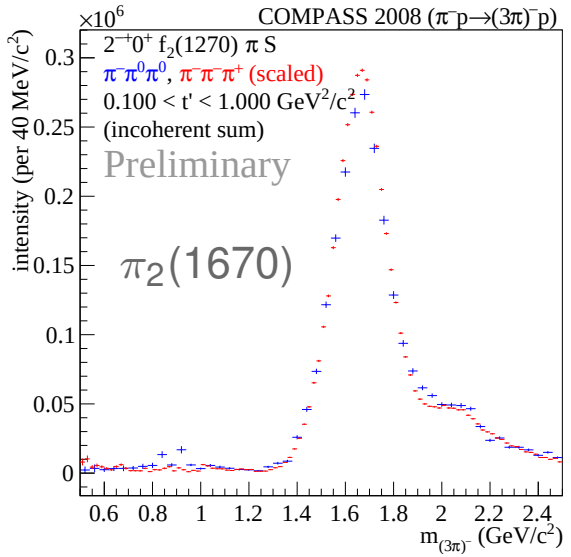
Major Waves

- ≈50M $\pi^-\pi^+\pi^-$ (scaled individually)
- ≈3.5M $\pi^-\pi^0\pi^0$ (consistency check, very different acceptance)
- incoherent sum over 11/8 t' bins









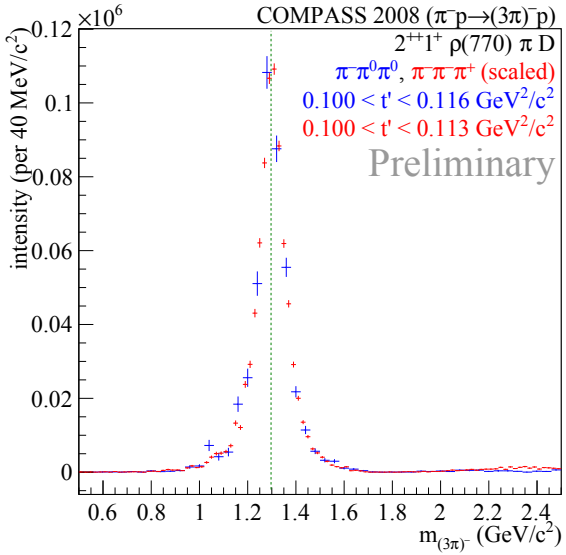
t'-Dependence

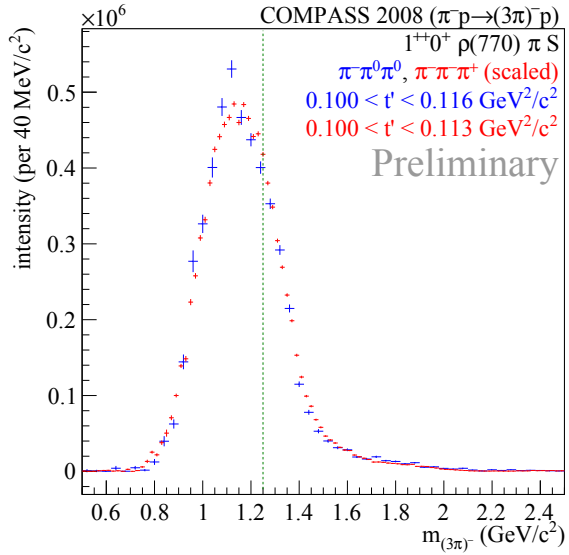
Lowest t' bin

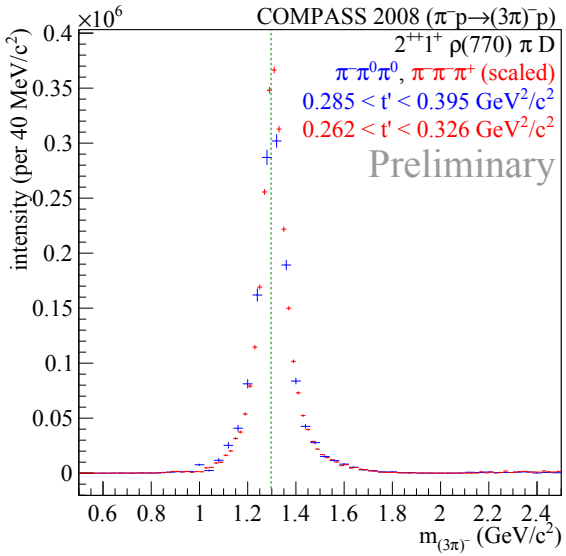
- $2^{++}1^+\ \rho(770)\,\pi D$ $a_2(1320)$
- $1^{++}0^+\ \rho(770)\,\pi S$ $a_1(1260)$

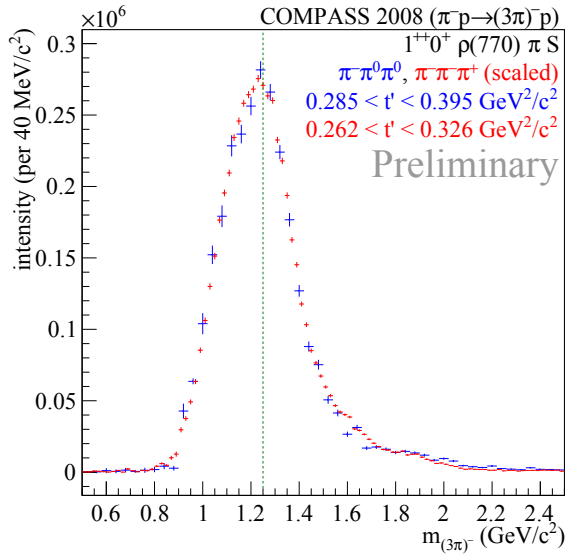
High t' bin

- $a_2(1320)$ peak does not change with t'
- $a_1(1260)$ shifts due to interference with non-resonant contribution



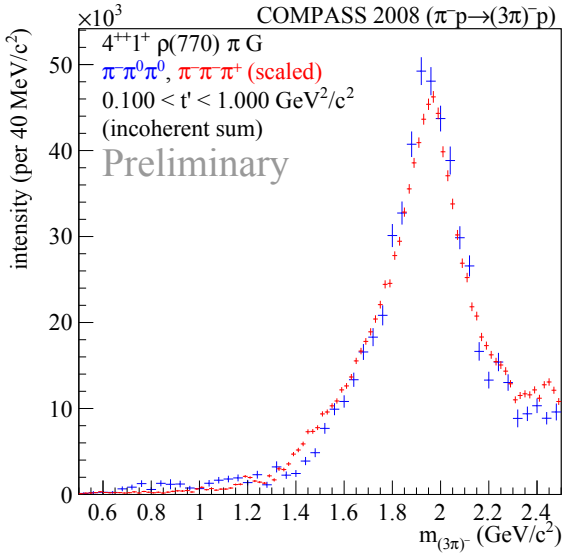






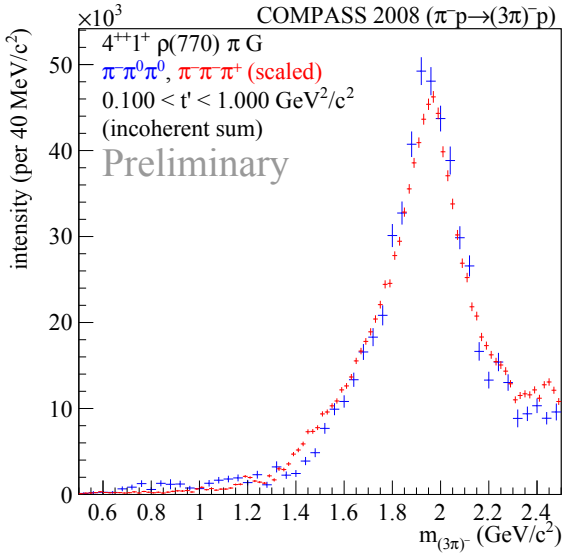
Selected Minor Waves

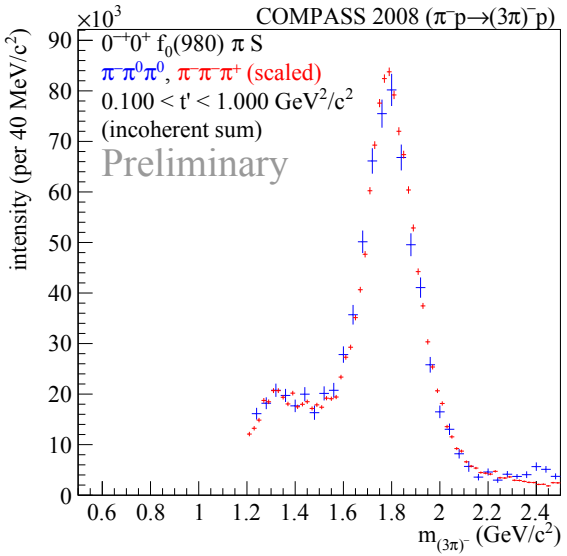
- $4^{++}1^{+}\ \rho(770)\,\pi G$ $a_4(2040)$



Selected Minor Waves

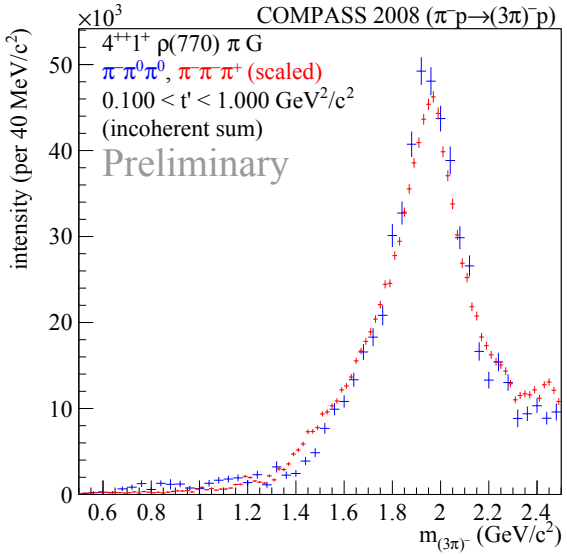
- $4^{++}1^{+}\ \rho(770)\,\pi G$ $a_4(2040)$
- $0^{-+}0^{+}\ f_0(980)\,\pi S$ $\pi(1800)$

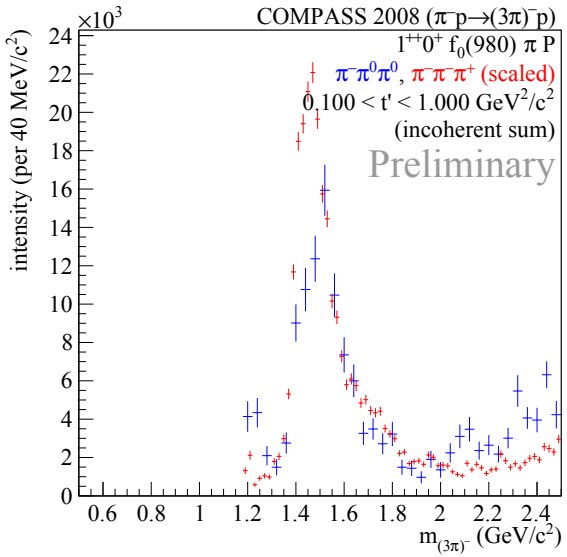


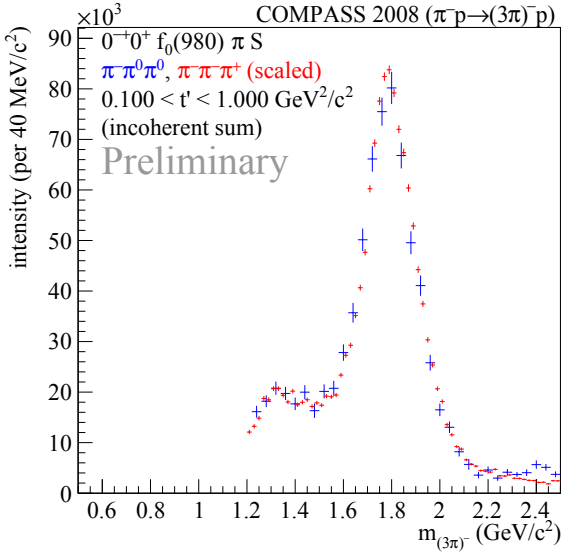


Selected Minor Waves

- $4^{++}1^{+}\ \rho(770)\,\pi G$ $a_4(2040)$
- $0^{-+}0^{+}\ f_0(980)\,\pi S$ $\pi(1800)$
- $1^{++}0^{+}\ f_0(980)\,\pi P$ new signal '$a_1(1420)$'

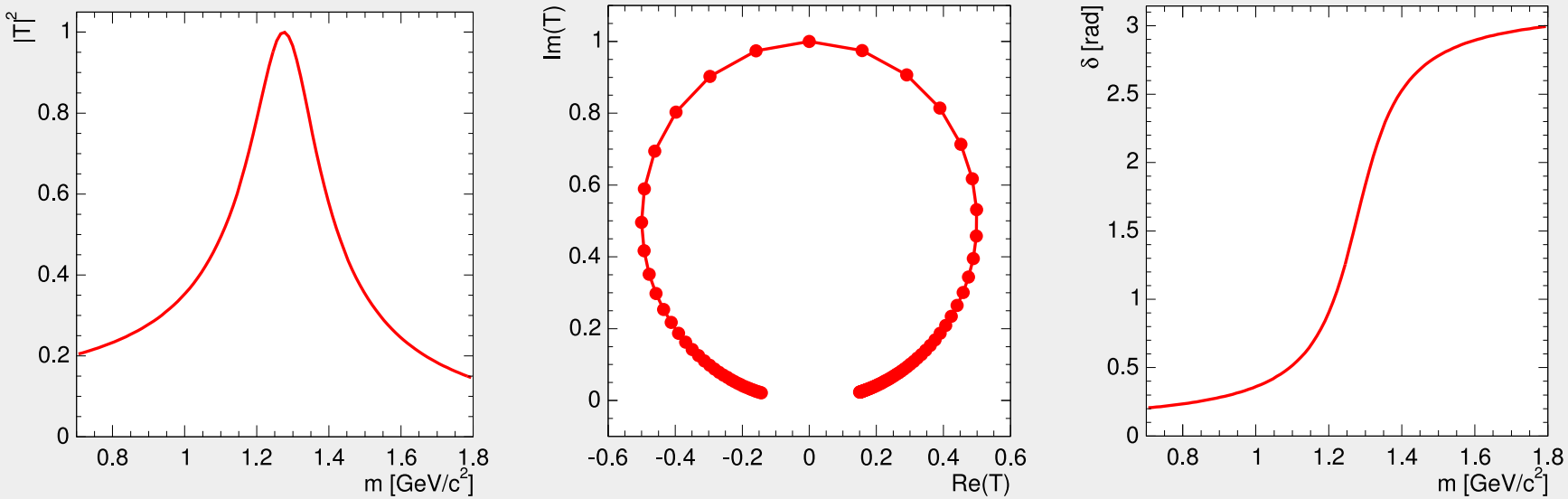






Extraction of resonance parameters

Example: amplitude of a single narrow relativistic Breit-Wigner resonance



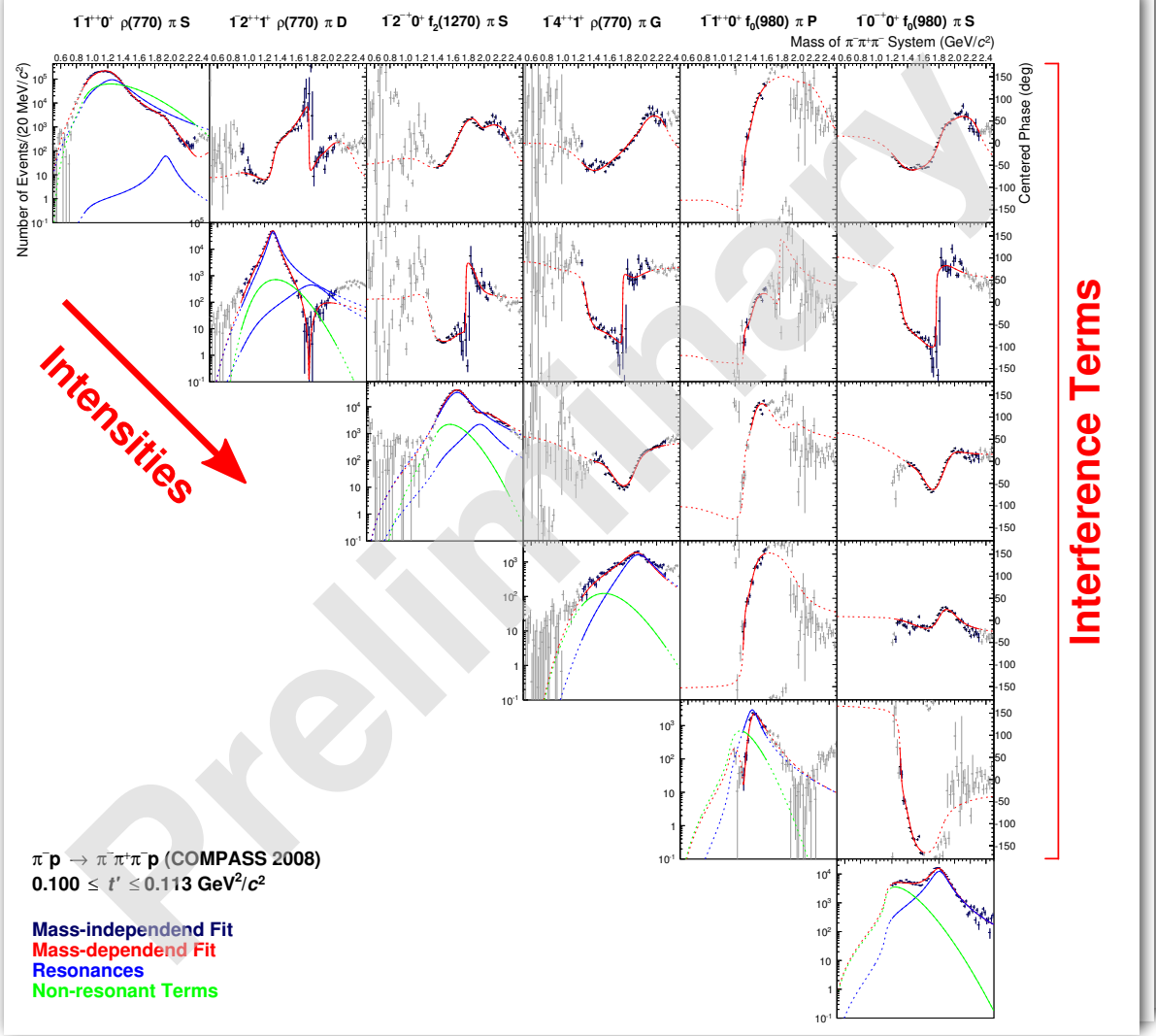
[K. Peters, arXiv:hep-ph/0412069]

- 'Phase motion': δ rises by π and is $\pi/2$ at peak position
- Coherent non-resonant term in each wave (phenomenological)

χ^2-fit to mass dependence of spin-density matrix

- Combined fit for 6 partial waves in 11 t' bins (354 parameters, $\approx$15 000 data points)
- Resonance parameters fixed across all t' bins

χ^2-Fit to Mass Dependence



$1^{++}0^+\ \rho(770)\,\pi S$
$a_1(1260) + a_1'$

$2^{++}1^+\ \rho(770)\,\pi D$
$a_2(1370) + a_2'$

$2^{-+}0^+\ f_2(1270)\,\pi S$
$\pi_2(1670) + \pi_2'$

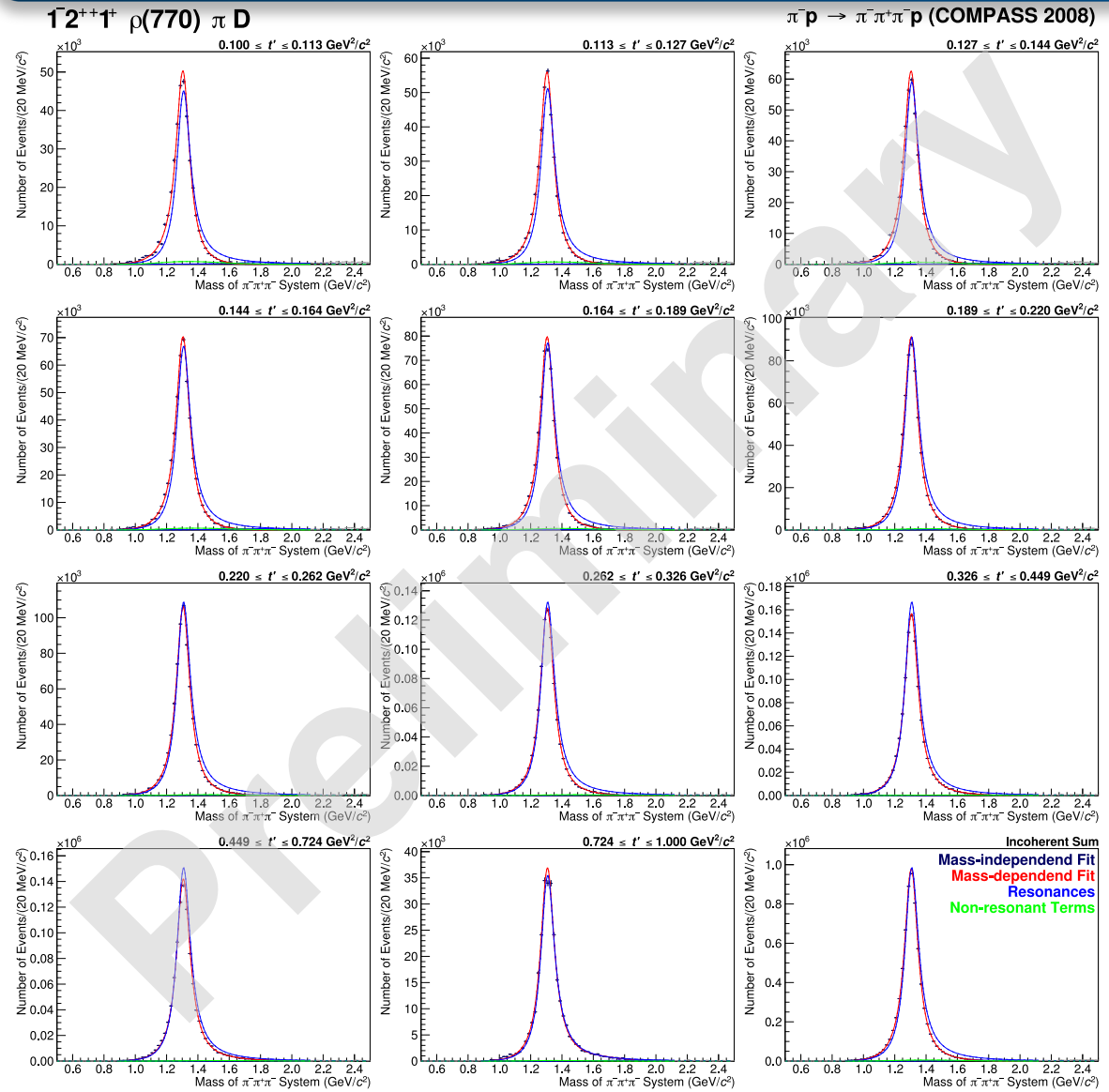
$4^{++}1^+\ \rho(770)\,\pi G$
$a_4(2040)$

$1^{++}0^+\ f_0(980)\,\pi P$
'$a_1(1420)$'

$0^{-+}0^+\ f_0(980)\,\pi S$
$\pi(1800)$

11 t' Bins

$2^{++}1^{+}\,\rho\pi D$



$a_2(1320)$ parameters

- $M = 1312\text{-}1315\,\text{MeV}/c^2$
- $\Gamma = 108\text{-}115\,\text{MeV}/c^2$

PDG 2012

- $M = 1318.3^{+0.5}_{-0.6}\,\text{MeV}/c^2$
- $\Gamma = 107 \pm 5\,\text{MeV}/c^2$

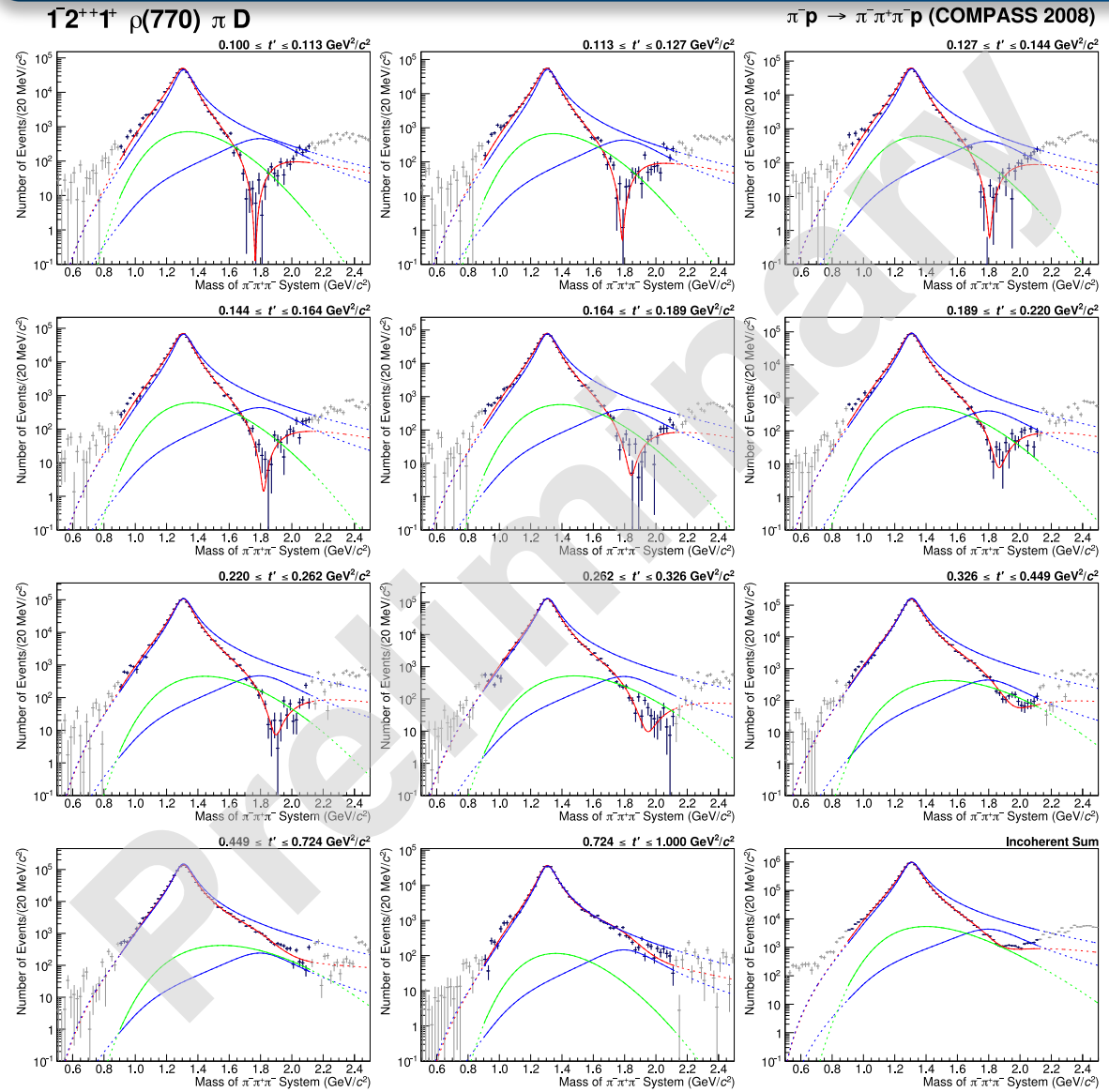
a_2' parameters

- $M = 1740\text{-}1890\,\text{MeV}/c^2$
- $\Gamma = 300\text{-}555\,\text{MeV}/c^2$

PDG 2012 $a_2(1950)$

- $M = 1950^{+30}_{-70}\,\text{MeV}/c^2$
- $\Gamma = 180^{+30}_{-70}\,\text{MeV}/c^2$

$2^{++}1^{+}\,\rho\pi D$



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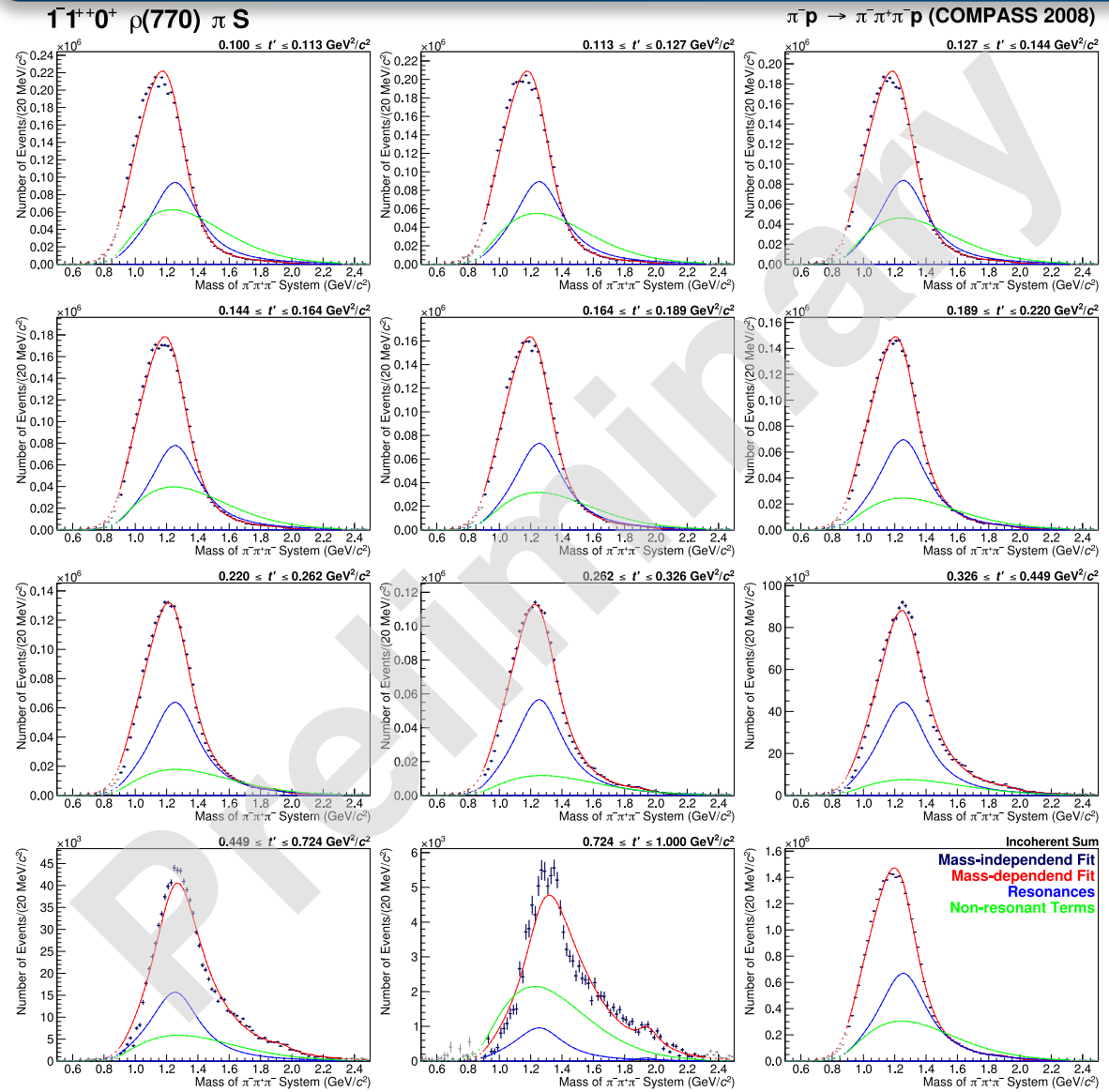
$1^{++}0^+\ \rho\pi S$



$a_1(1260)$ parameters

- $M = 1260\text{-}1290\,\text{MeV}/c^2$
- $\Gamma = 360\text{-}420\,\text{MeV}/c^2$

PDG 2012

- $M = 1230 \pm 40\,\text{MeV}/c^2$
- $\Gamma = 250\text{-}400\,\text{MeV}/c^2$

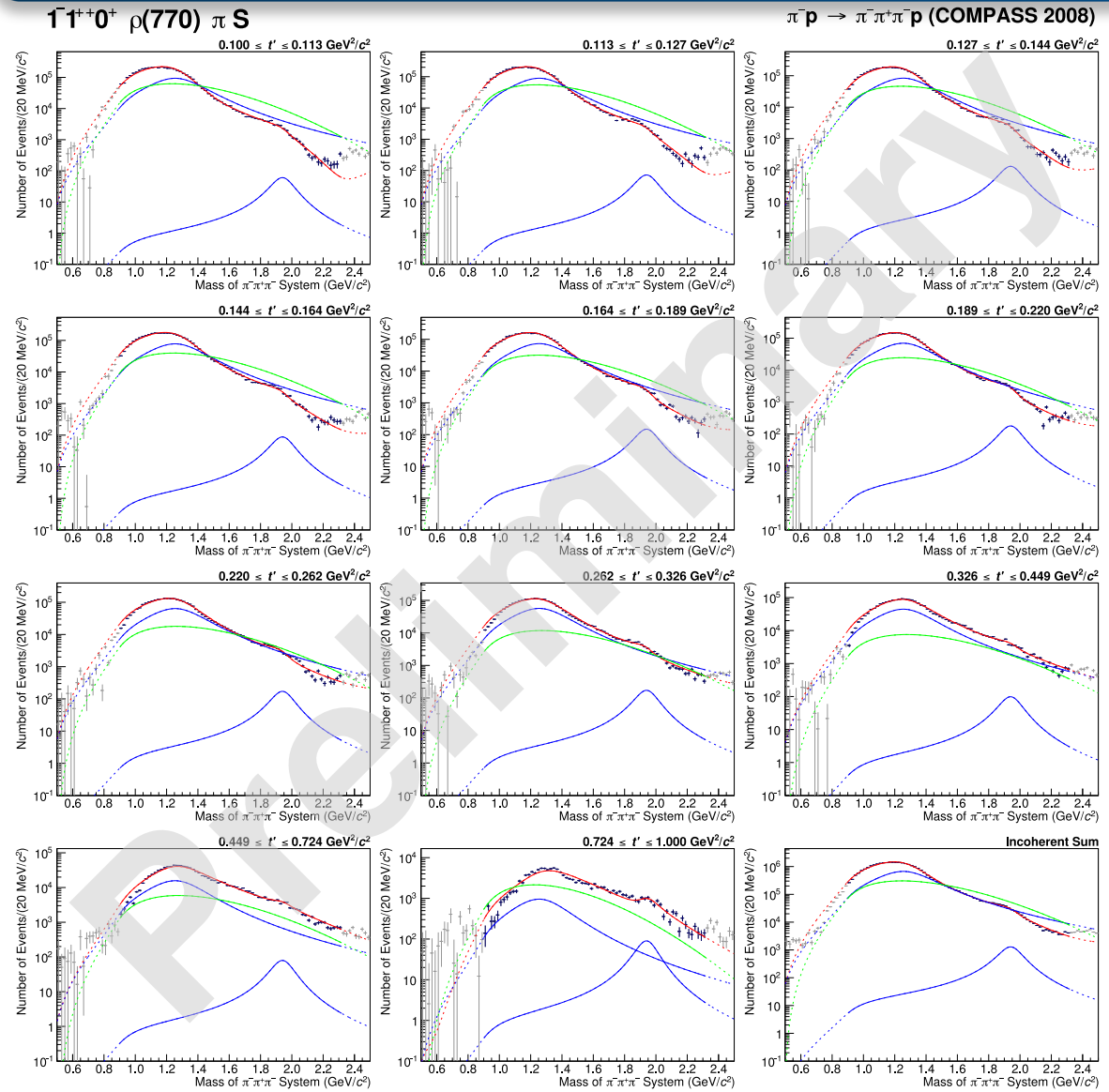
a_1' parameters

- $M = 1920\text{-}2000\,\text{MeV}/c^2$
- $\Gamma = 155\text{-}255\,\text{MeV}/c^2$

PDG 2012 $a_2(1950)$

- $M = 1930^{+30}_{-70}\,\text{MeV}/c^2$
- $\Gamma = 155 \pm 45\,\text{MeV}/c^2$

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



$a_1(1260)$ parameters

- $M = 1260\text{-}1290\,\text{MeV}/c^2$
- $\Gamma = 360\text{-}420\,\text{MeV}/c^2$

PDG 2012

- $M = 1230 \pm 40\,\text{MeV}/c^2$
- $\Gamma = 250\text{-}400\,\text{MeV}/c^2$

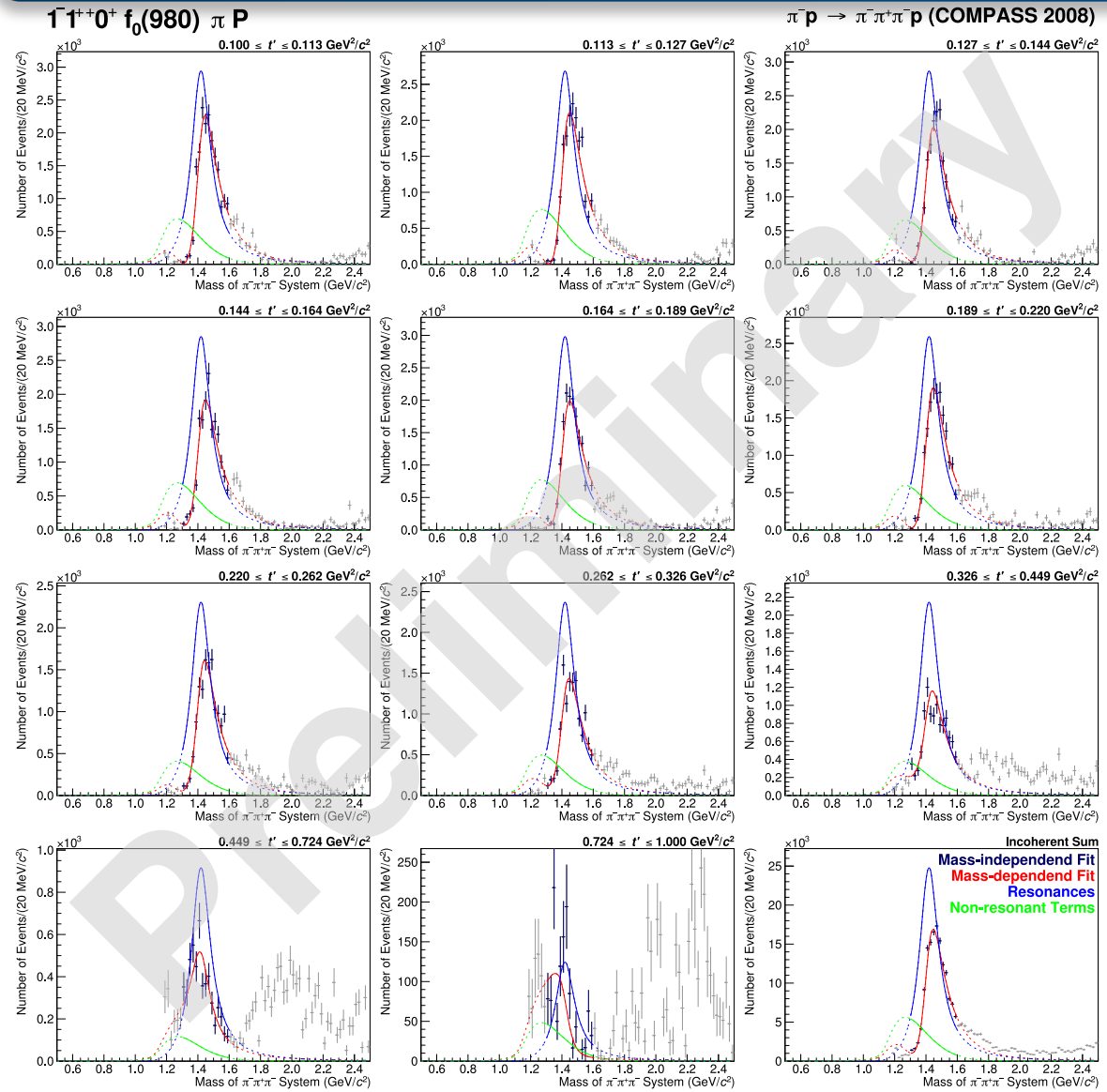
a_1' parameters

- $M = 1920\text{-}2000\,\text{MeV}/c^2$
- $\Gamma = 155\text{-}255\,\text{MeV}/c^2$

PDG 2012 $a_2(1950)$

- $M = 1930^{+30}_{-70}\,\text{MeV}/c^2$
- $\Gamma = 155 \pm 45\,\text{MeV}/c^2$

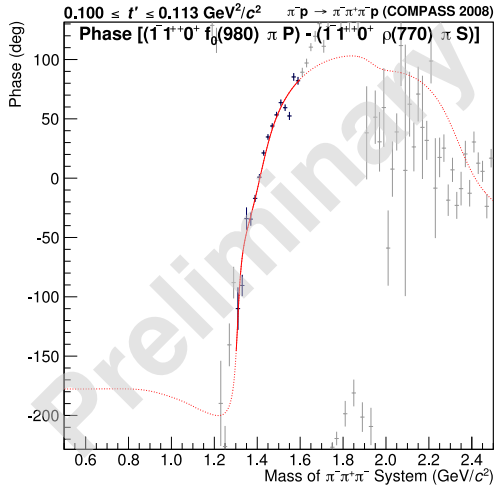
$1^{++}0^+ f_0(980)\,\pi P$



$a_1(1420)$ parameters

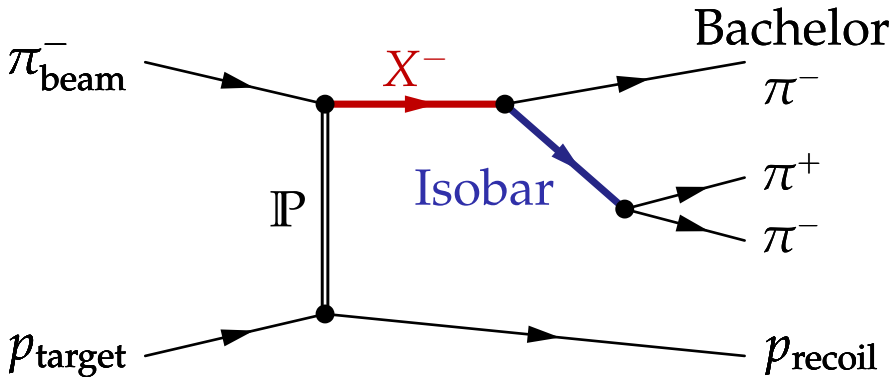
- $M = 1412\text{-}1422\,\text{MeV}/c^2$
- $\Gamma = 130\text{-}150\,\text{MeV}/c^2$

- No entry in PDG 2012
- Significant phase motion w.r.t. all other waves



- Consistent with BW resonance

$(\pi\pi)_S$-Wave Extraction from 3π



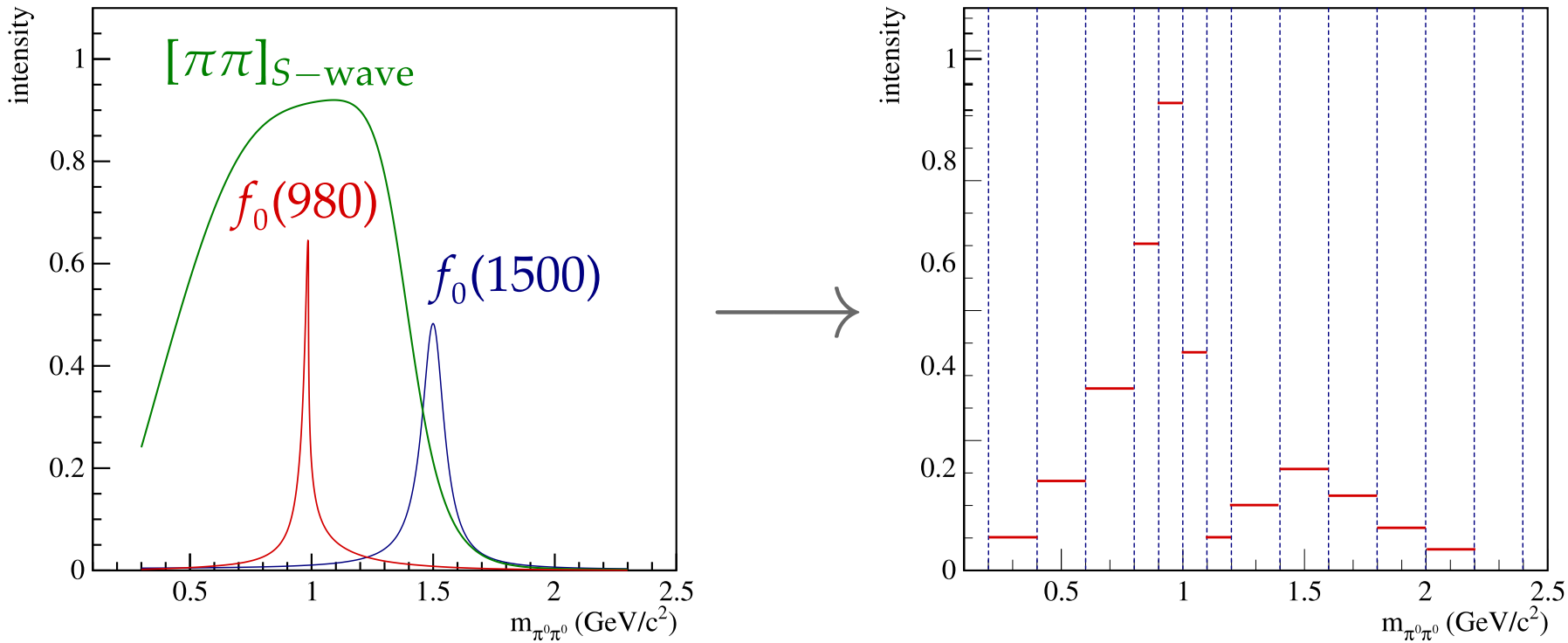
Is the $a_1(1420)$ an artifact of the isobar parametrisation?

$(\pi\pi)_S$-Wave Extraction from 3π

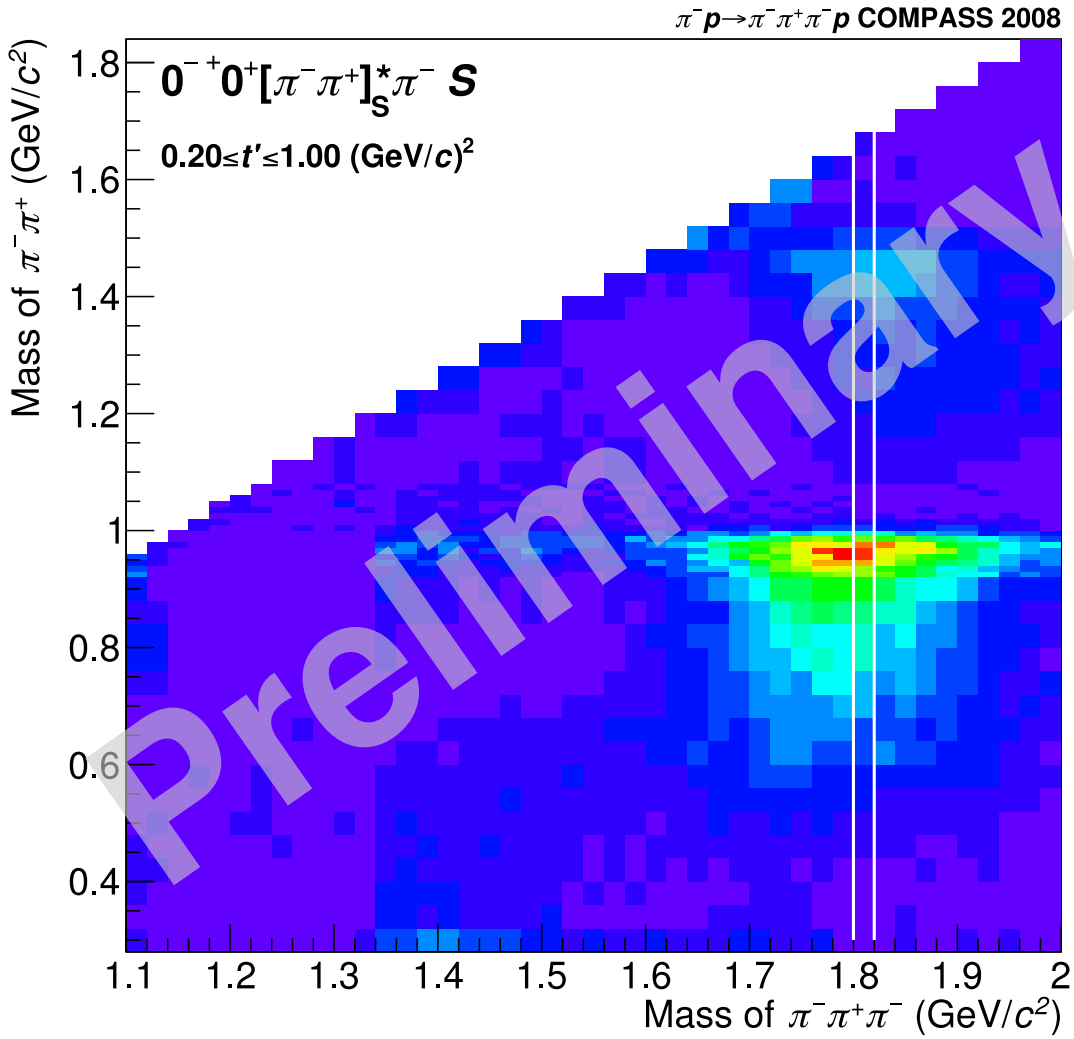
Technische Universität München

Novel analysis method

- $J^{PC} = 0^{++}$ isobar amplitudes $\longrightarrow$ piece-wise constant amplitude in $M_{\pi\pi}$ bins
- Extract $J^{PC} = 0^{++}$ isobar amplitude from data as a function of $M_{3\pi}$
- Drastic reduction of model bias, but significant increase in number of parameters

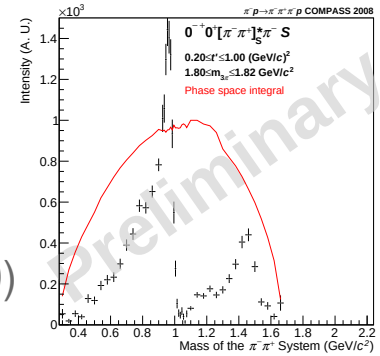


$0^{-+}0^{+}(\pi\pi)_S\pi S$

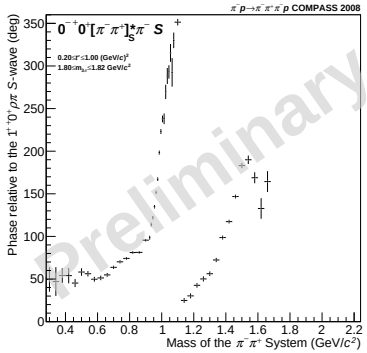


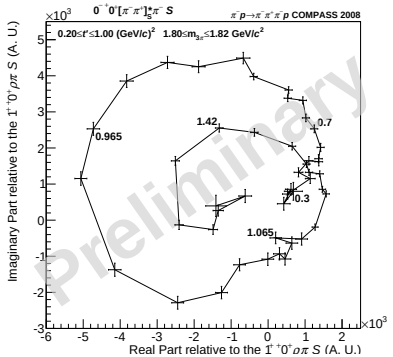
$\pi(1800)$

$f_0(1500)$

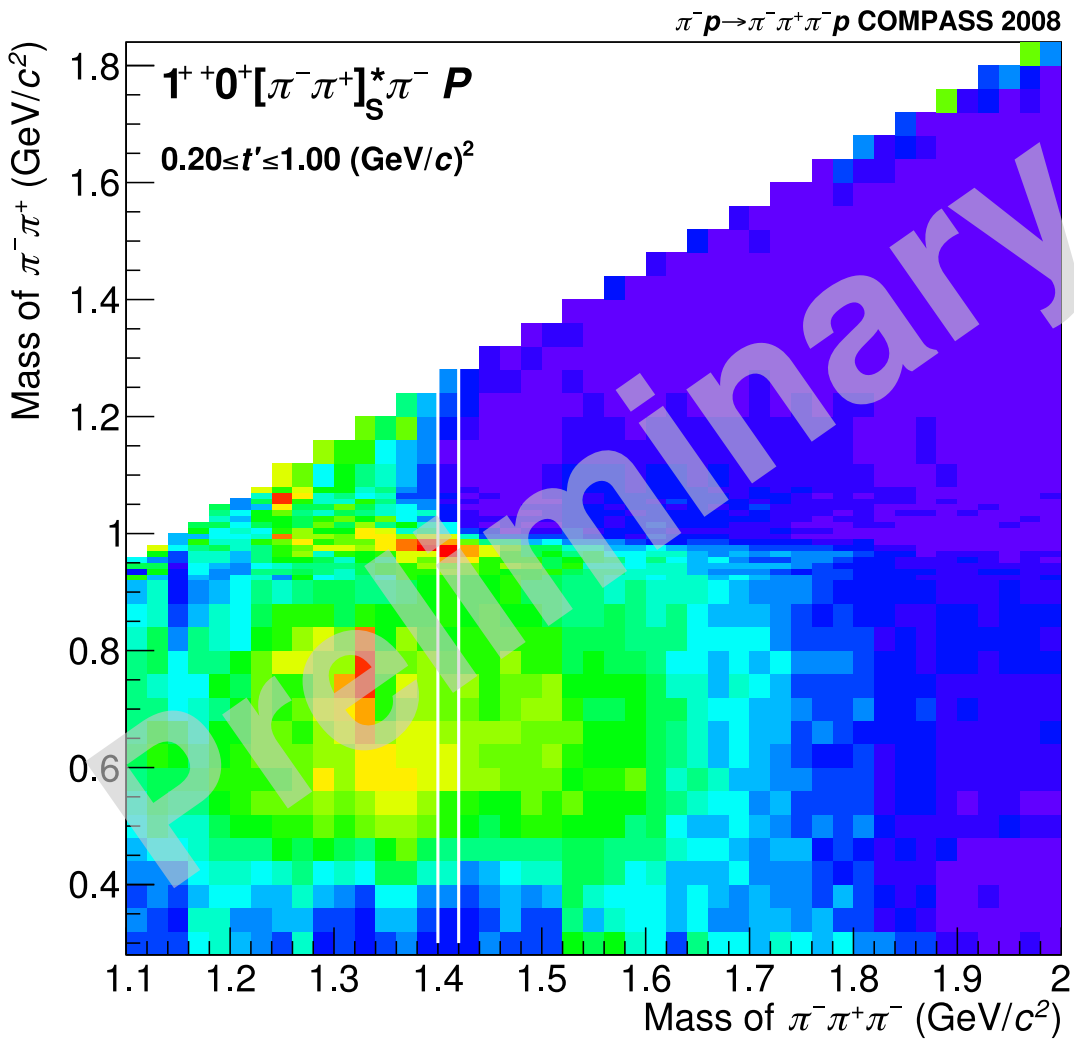


$f_0(980)$



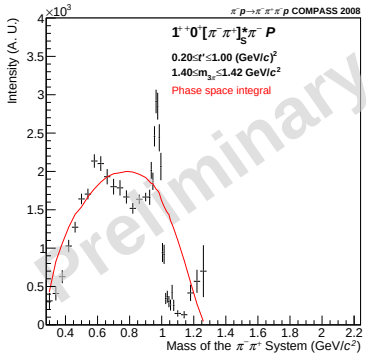


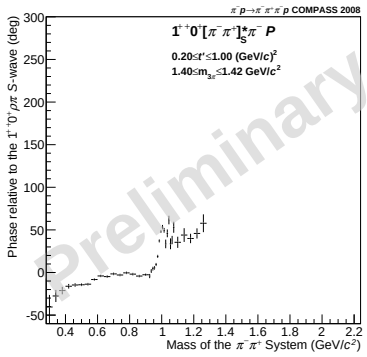
$1^{++}0^{+}(\pi\pi)_S\,\pi P$

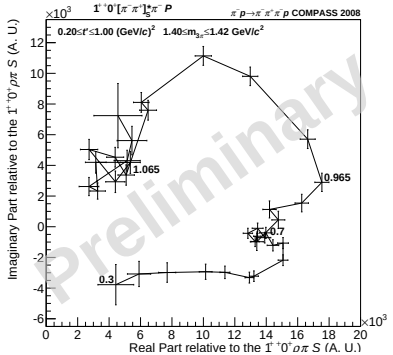


$a_1(1420)$

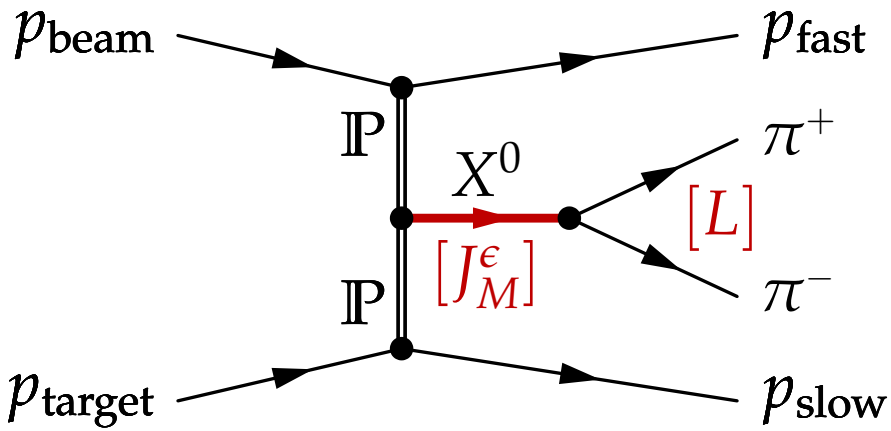
$f_0(980)$



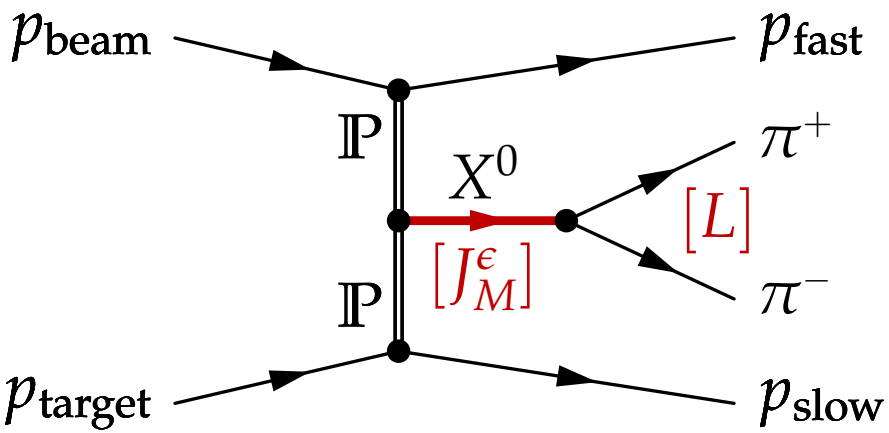


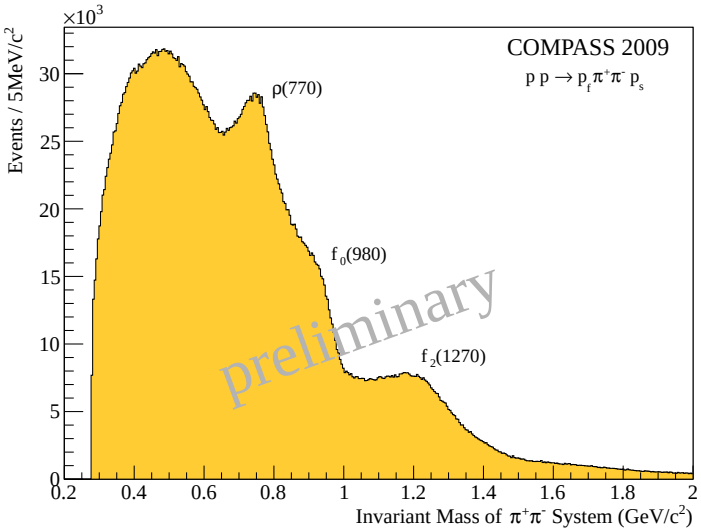


Central Exclusive Production of Two-Pseudoscalar Final-States



Central Exclusive Production

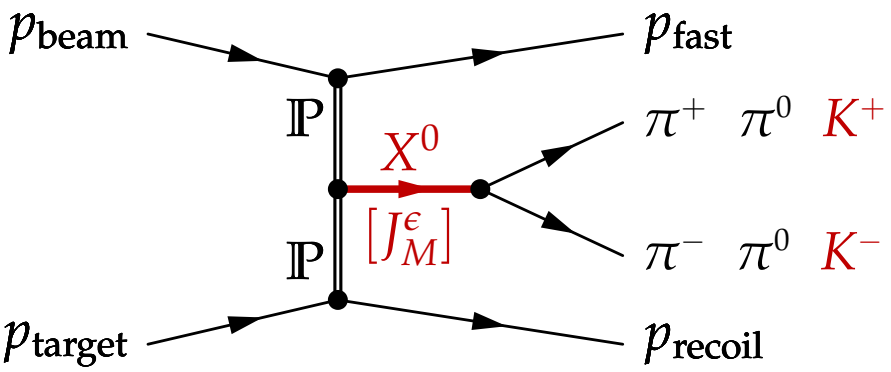


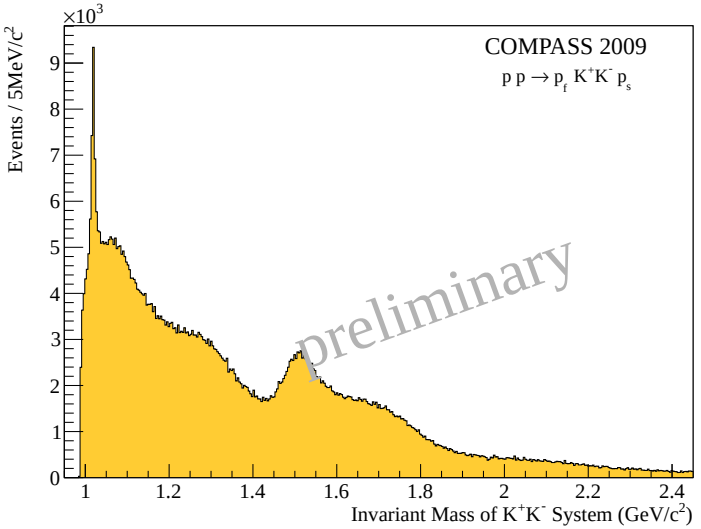


$p\,p \to p_{\text{fast}}\,X\,p_{\text{slow}}$

- Proton beam impinging on liquid hydrogen target
- Double-Pomeron Exchange as glue-rich environment
  $\Rightarrow$ Production of non-$q\bar{q}$-mesons (Glue Balls, Hybrids) at central rapidities
- Decay into two-pseudoscalar final state ($\pi^+\pi^-$, $\pi^0\pi^0$, K^+K^-, $\eta\,\eta$, ..)

Central Exclusive Production





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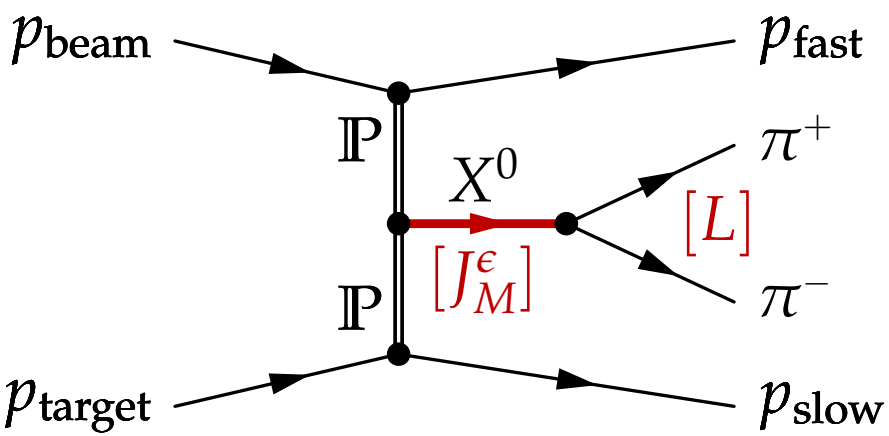
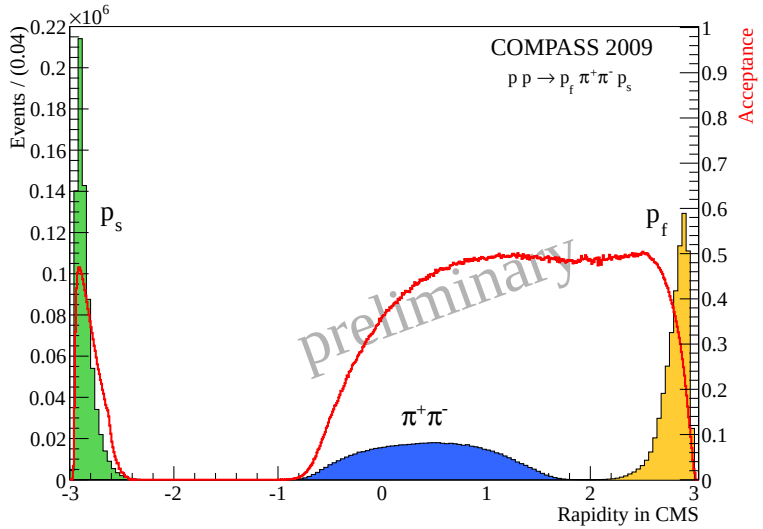
Central Exclusive Production





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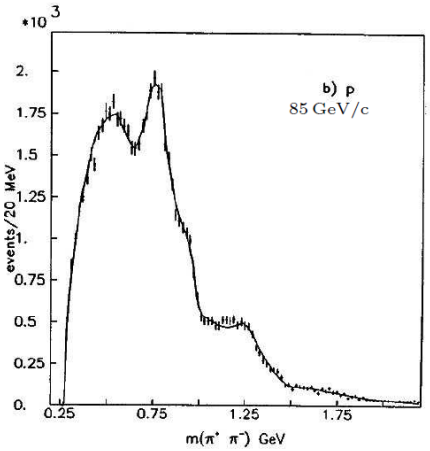
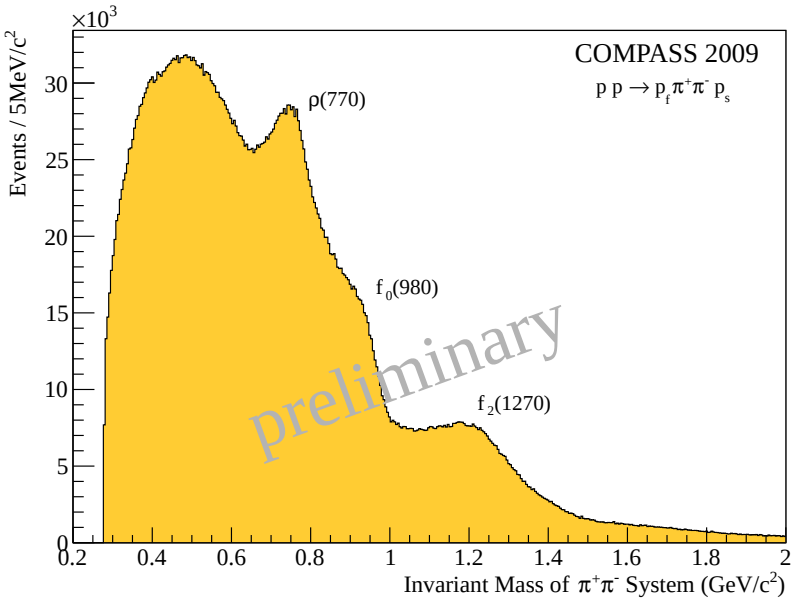
- Decay into two-pseudoscalar final state ($\pi^+\pi^-$, $\pi^0\pi^0$, K^+K^-, $\eta\,\eta$, ..)
- Rapidity gap between p_s and the central system X introduced by the trigger

$\sqrt{s}$-Dependence

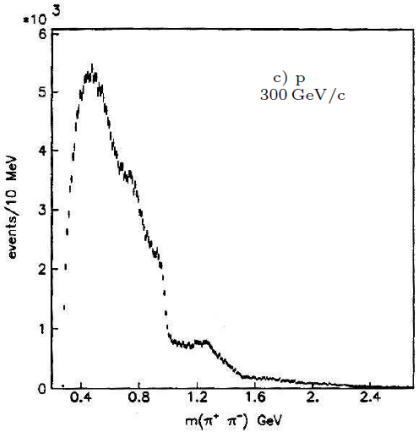
T.A. Armstrong et al. [Z. Phys. C51 (1991)]



$\sqrt{s} = 12.7\,\mathrm{GeV}/c^2$



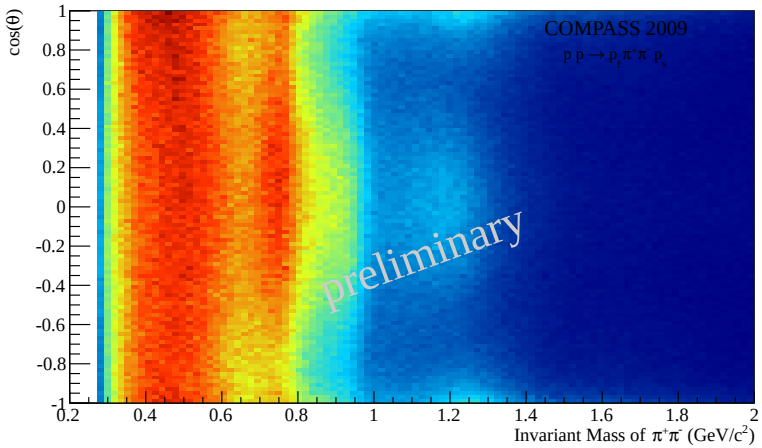
$\sqrt{s} = 18.9\,\mathrm{GeV}/c^2$

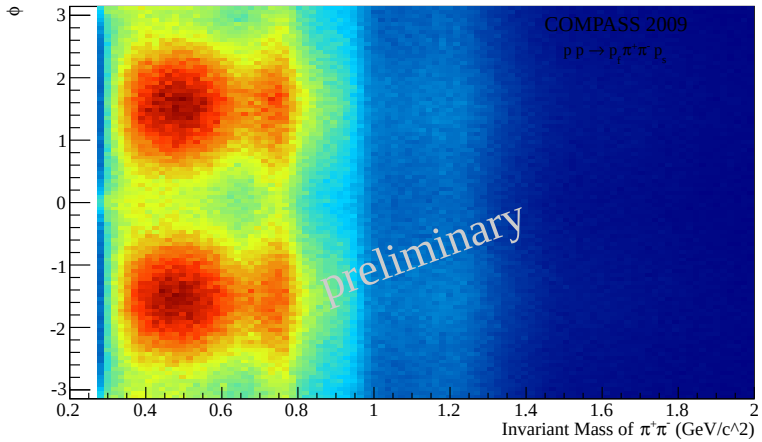


$\sqrt{s} = 23.7\,\mathrm{GeV}/c^2$

- Production of $\rho(770)$ disappears rapidly with increasing $\sqrt{s}$
- Low-mass enhancement and $f_0(980)$ remain practically unchanged
  $\rightarrow$ characteristic for s-independent Pomeron-Pomeron scattering
- Kinematic selection cannot single out pure DPE sample

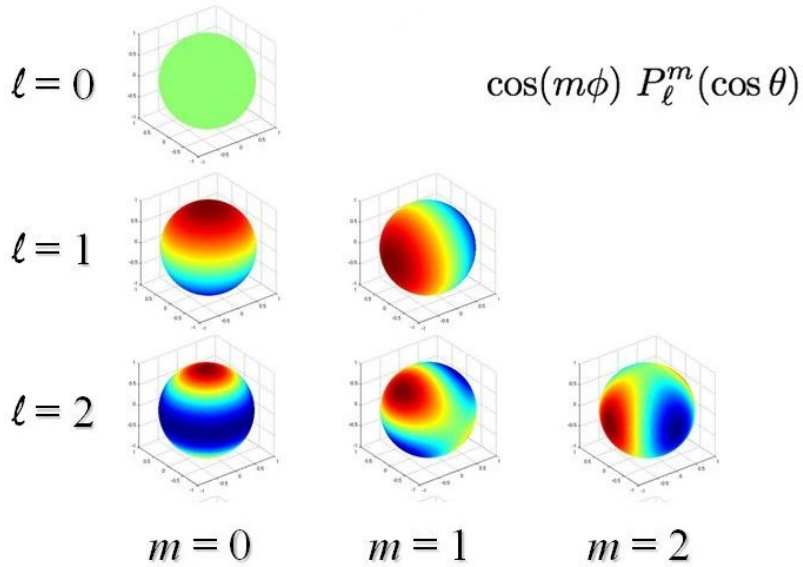
Partial-Wave Analysis





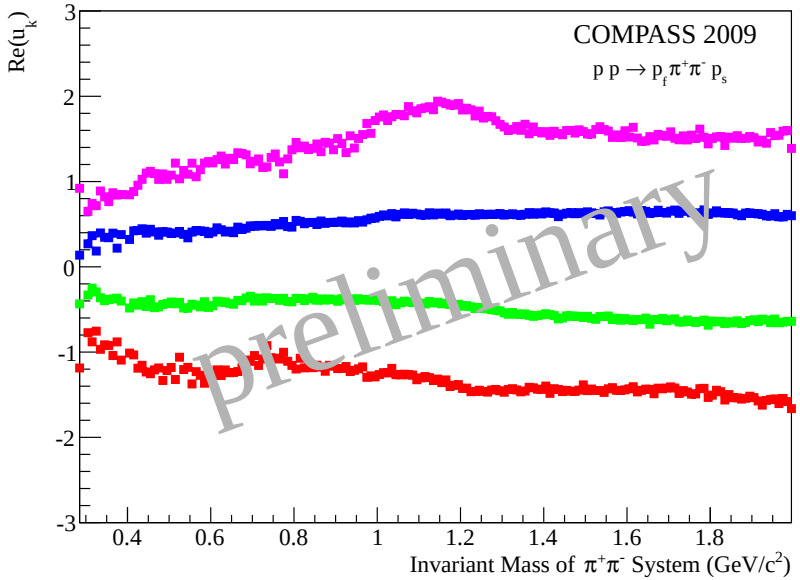
$X \to \pi^+\pi^-$

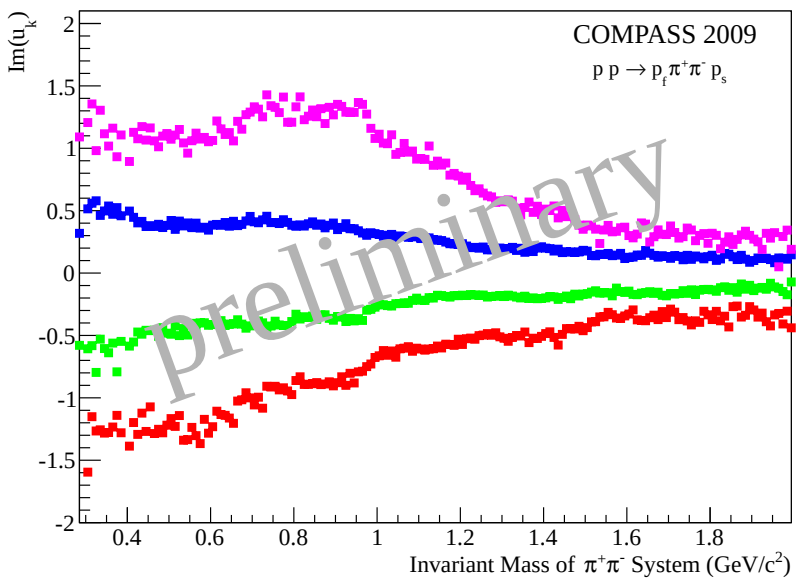
- **Assumption:** collision of two space-like exchange particles $(\mathbb{P}, \mathbb{R})$
- Decay fully described by $M(\pi^+\pi^-)$, $\cos(\theta)$ and ϕ
- Fit complex production amplitudes in mass bins to match spin contributions and interference pattern



Ambiguities

- 8 mathematically ambiguous solutions result in the same angular distribution
- Analytical computation via method of Barrelet Zeros





- Real (left) and imaginary (right) part of polynomial roots
- Well separated, imaginary parts do not cross the real axis

$\Rightarrow$ Solutions can be uniquely identified and linked from mass bin to mass bin

Ambiguities in the $\pi\pi$ Systems

$\pi^+\pi^-$ System

- 8 different solutions can be calculated analytically
- Differentiation requires additional input
  (e.g. behaviour at threshold, physics content)

$\pi^0\pi^0$ System

- Identical particles, only even waves allowed
- Reduces number of ambiguities to 2

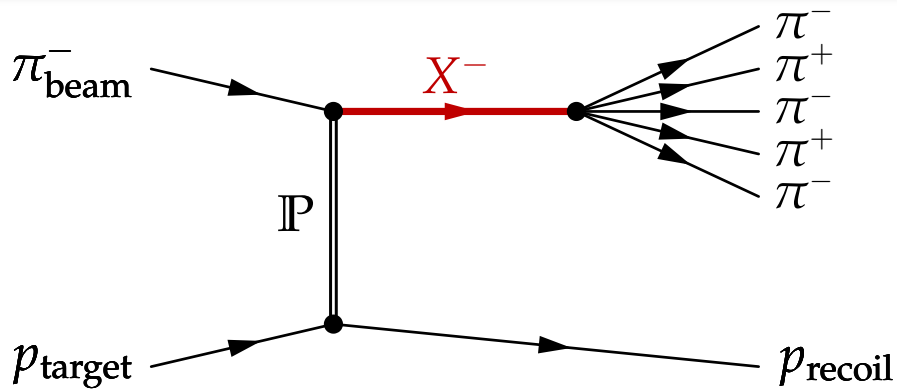
Combination of $\pi\pi$ Systems

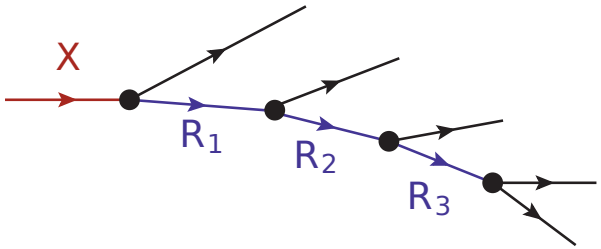
- Consistent picture of the reaction, measured with different parts of experimental setup
- Interpretation with mass dependent parametrisation under way!

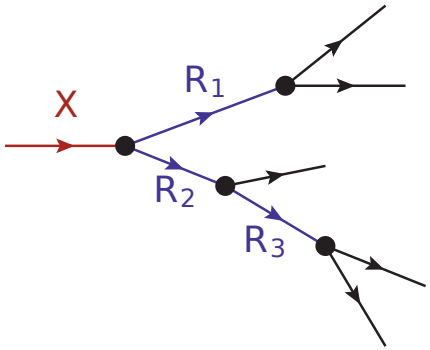
Analysis of Many More Channels

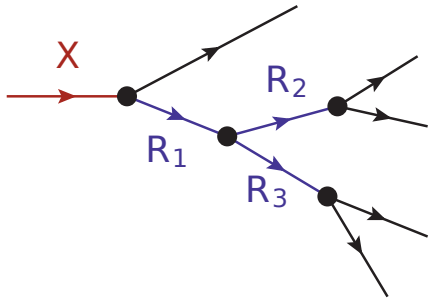
PWA of diffractive 5π

- Access to masses $> 2\,\mathrm{GeV}/c^2$
- Exotic decays: $f_1\pi$, $b_1\pi$
- Study $(4\pi)^0$ subsystem
- Challenge: model selection and non-resonant production









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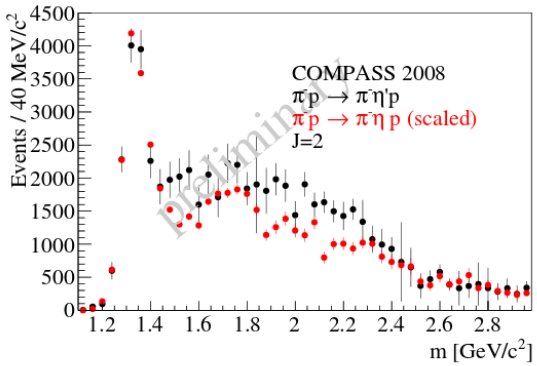
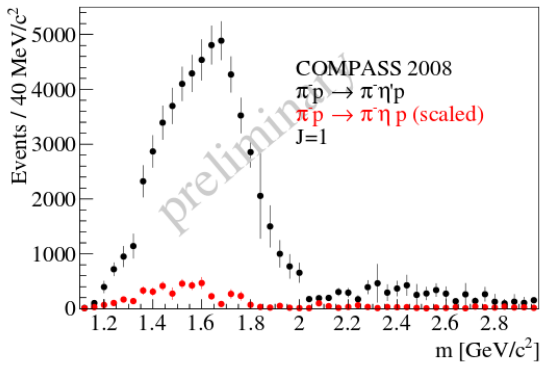
Further diffractive channels

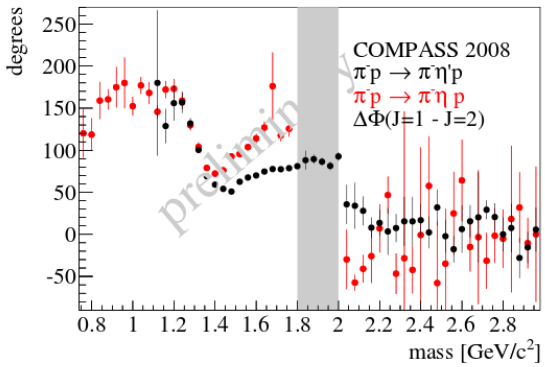
- $\pi^-\eta$ and $\pi^-\eta'$
  [Publication in preparation]
- $\pi^-\eta\eta$, ...



D-wave, $J = 2$



P-wave, $J = 1$



Phase P - D

Analysis of Many More Channels

PWA of diffractive 5π

- Access to masses $> 2\,\mathrm{GeV}/c^2$
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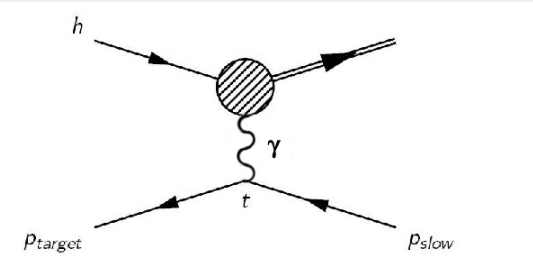
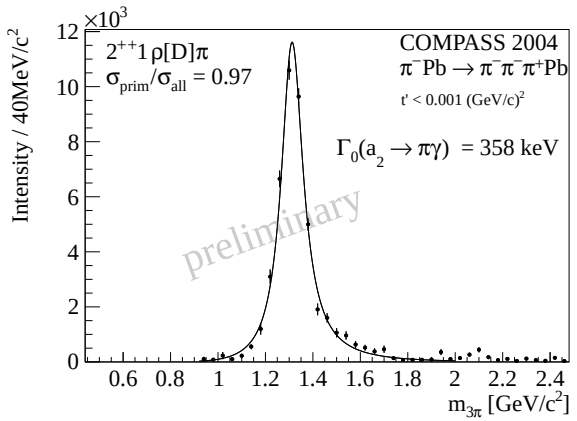
Further diffractive channels

- $\pi^-\eta$ and $\pi^-\eta'$
  [Publication in preparation]
- $\pi^-\eta\eta$, ...

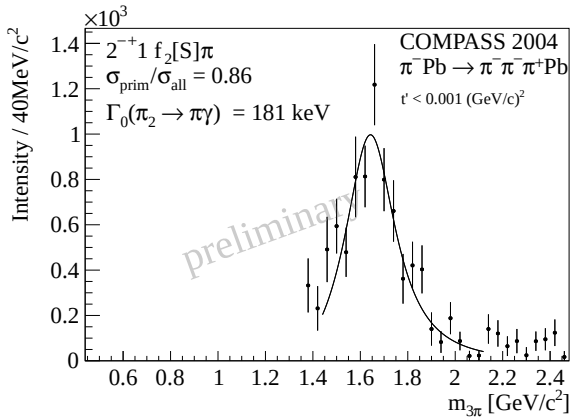
Photoproduction

- Chiral amplitudes [PRL 108 (2013)]
- Radiative width of $a_2(1320)$ and $\pi_2(1670)$ [Publication in preparation]





$a_2(1320)$



$\pi_2(1670)$
first measurement!

Conclusion and Outlook

COMPASS is a unique experiment to study
light-quark hadron spectroscopy

- Similar phenomena at different mass scales
  $\rightarrow$ resonances, reflections, threshold effects, non-resonant production, ...
- Input for heavy meson spectroscopy and *CP*-violation analyses

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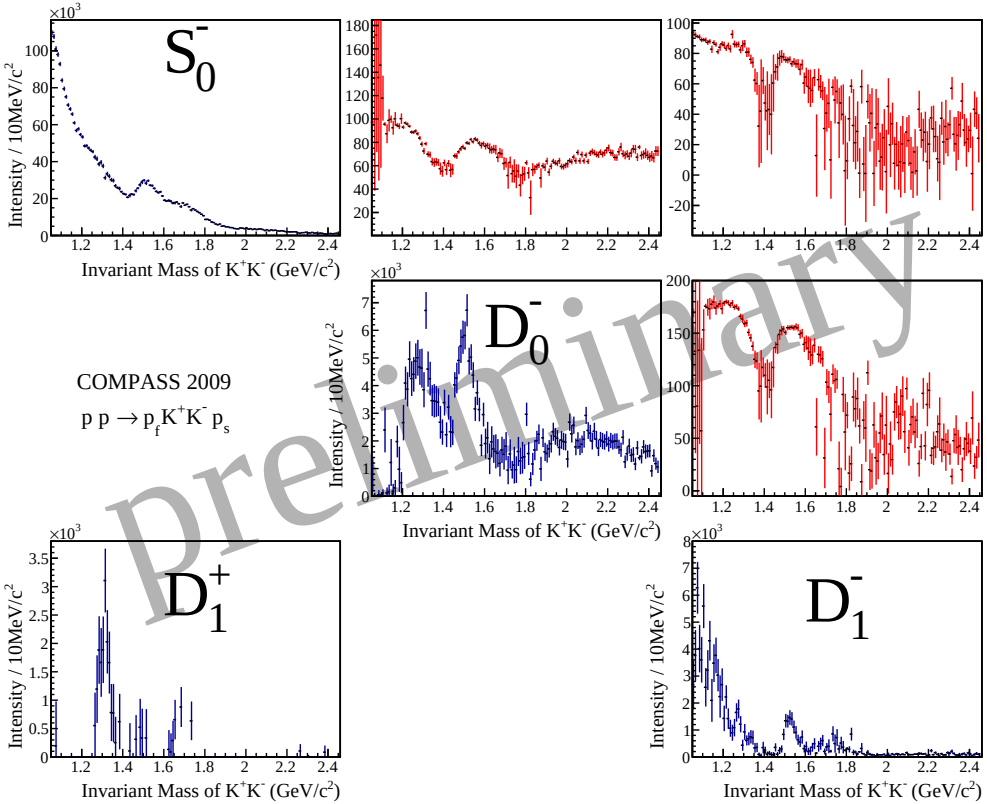
Thank you for your attention!

Backup Slides

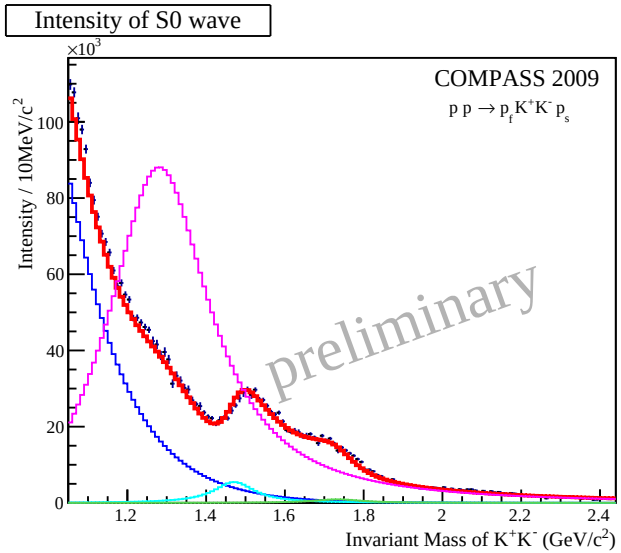
Fit to the K^+K^- System

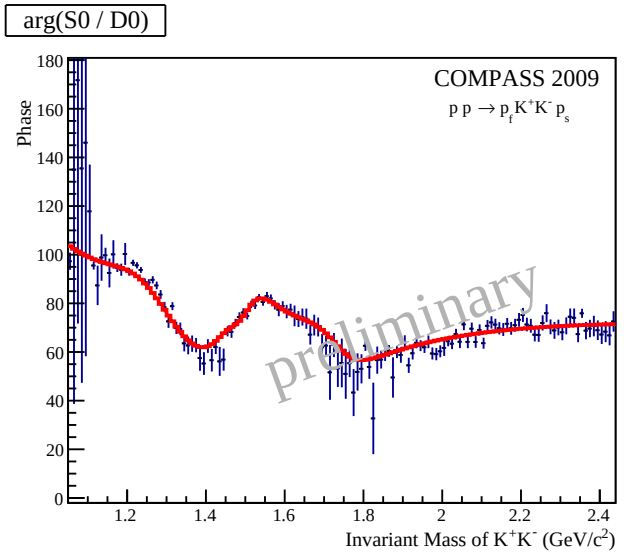


- Similar partial-wave analysis of K^+K^--system
- Odd waves do not play a significant role above the $\phi(1020)$-mass
  $\Rightarrow$ Reduction of ambiguities

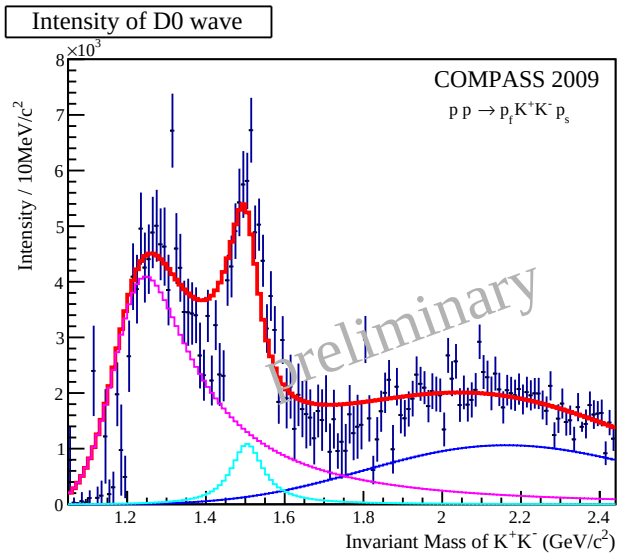
Mass-Dependence of K^+K^-

$f_0(1370)$
$f_0(1500)$
$f_0(1710)$





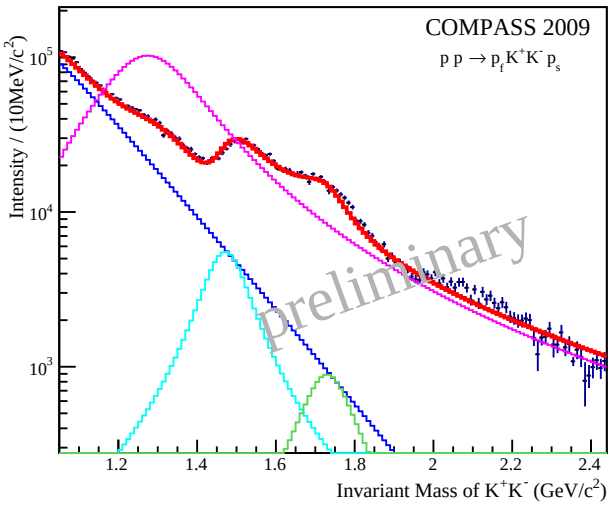
- BW contributions
- non-resonant contribution
- **coherent sum**

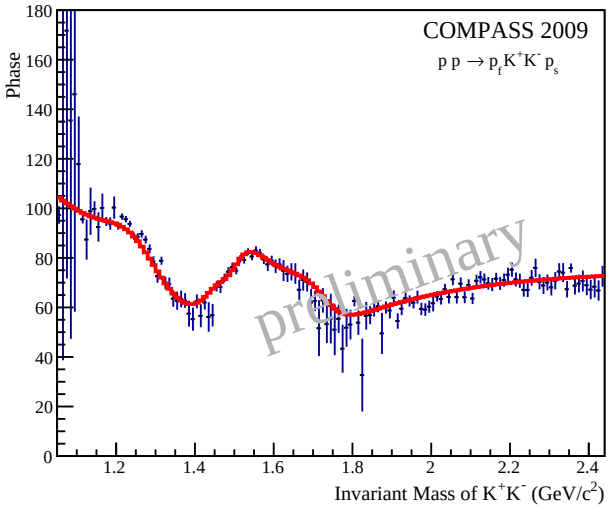


$f_2(1270)$
$f_2'(1525)$

Mass-Dependence of K^+K^-

$f_0(1370)$
$f_0(1500)$
$f_0(1710)$





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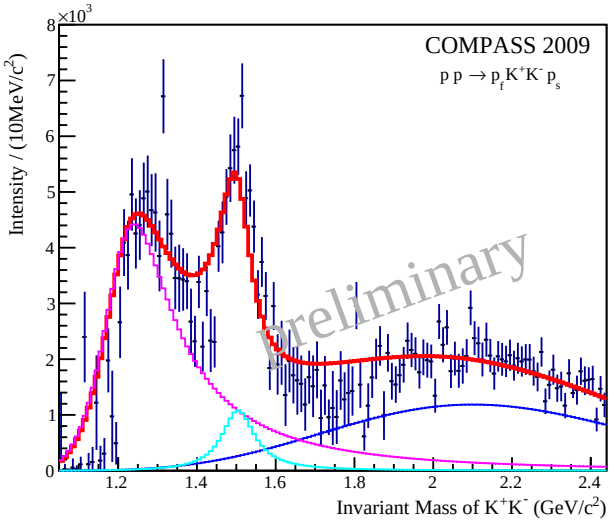

$f_2(1270)$
$f_2'(1525)$