Meson Spectroscopy at COMPASS

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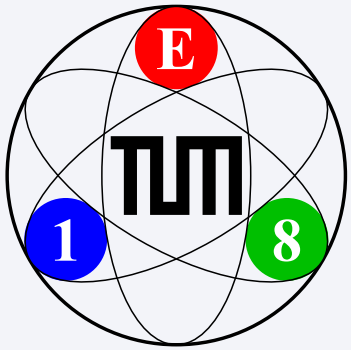

Outline

Mesons in the Constituent Quark Model (CQM)

Mesons

- Color-singlet $|q\bar{q}'\rangle$ states, grouped into $SU(3)_{\text{flavor}}$ multiplets

Spin-parity rules for bound $q\bar{q}$ system

- Quark spins couple to total intrinsic spin $S = 0$ or 1
- Orbital angular Momentum $\vec{L}$ and total spin $\vec{S}$ couple to meson spin $\vec{J} = \vec{L} + \vec{S}$
- Parity $P = (-1)^{L+1}$
- Charge conjugation $C = (-1)^{L+S}$
- Forbidden J^{PC}: 0^{--}, even^{+-}, odd^{-+}

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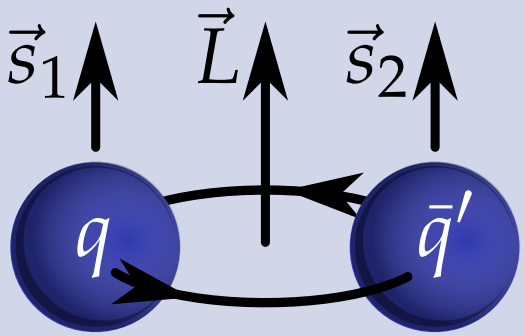

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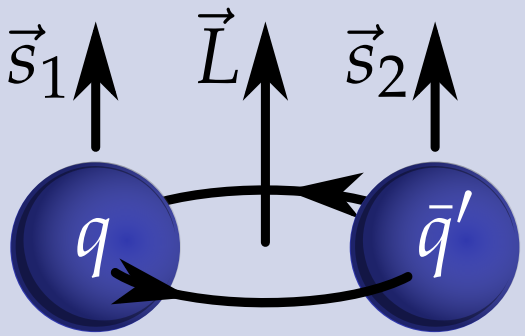
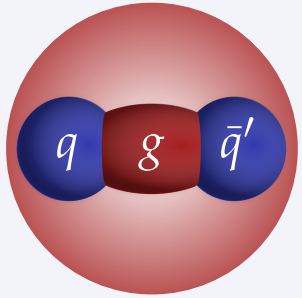


Possible New Forms of Matter

Hybrids $|q\bar{q}g\rangle$: states with **excited gluonic fields**

- Glue component contributes to quantum numbers
  - *All* J^{PC} allowed
- Lightest predicted hybrid: spin-exotic $J^{PC} = 1^{-+}$



Glueballs $|gg\rangle$: states with **no valence quarks**

- Lightest predicted glueball: ordinary $J^{PC} = 0^{++}$
  - Will strongly mix with nearby conventional $J^{PC} = 0^{++}$ states

Multi-quark states

- Tetraquarks $|qq\,\bar{q}\bar{q}\rangle$: compact
- Molecules $|q\bar{q}\,q\bar{q}\rangle$: extended

Physical states defined by quantum numbers

- Linear superpositions of *all* allowed basis states: $|q\bar{q}\rangle, |q\bar{q}g\rangle, |gg\rangle, |q^2\bar{q}^2\rangle, \ldots$; amplitudes not directly observable

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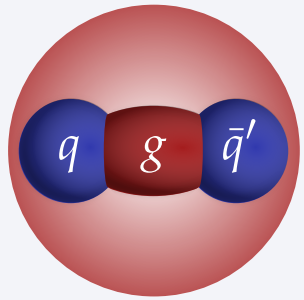

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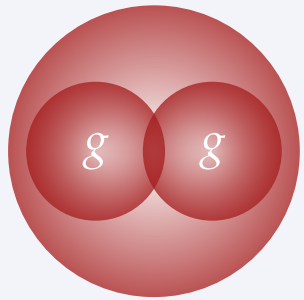

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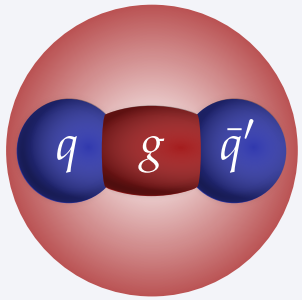

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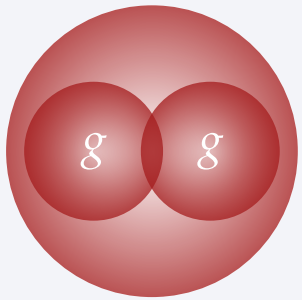

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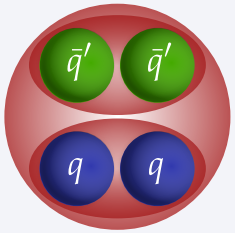

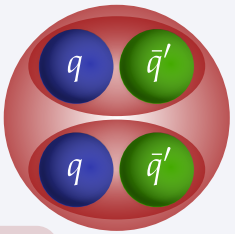

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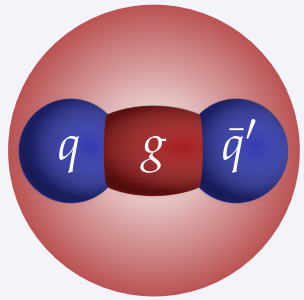

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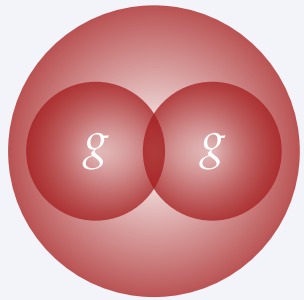

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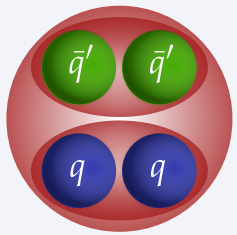

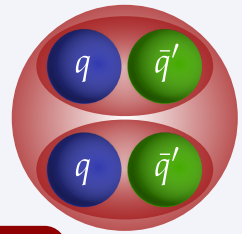

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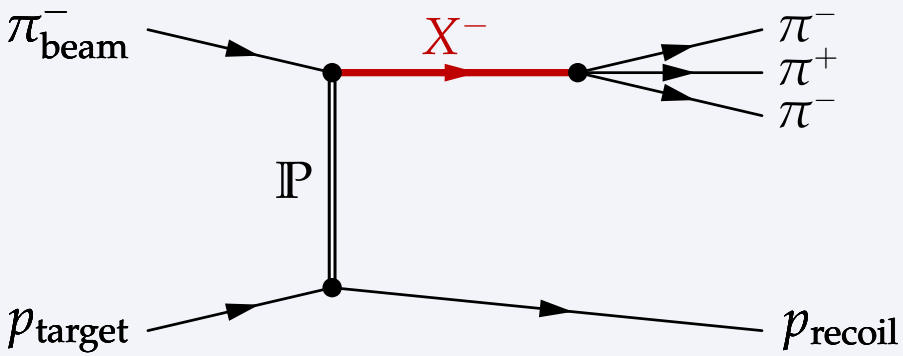
Meson Production in High-Energy Scattering

$\pi^-\pi^+\pi^-$ Production with 190 GeV/c π^- Beam at COMPASS



- Soft scattering of beam particle off target via strong interaction
  - Small momentum and energy transfer to target
  - Target particle stays intact
- Beam particle gets excited into intermediate resonance X
- Decay of X into 3 forward-going pions
  - Measured by spectrometer
- Same final state $\Longrightarrow$ interference of different X

- $50 \cdot 10^6$ $\pi^-\pi^+\pi^-$ events
- $3.5 \cdot 10^6$ $\pi^-\pi^0\pi^0$ events

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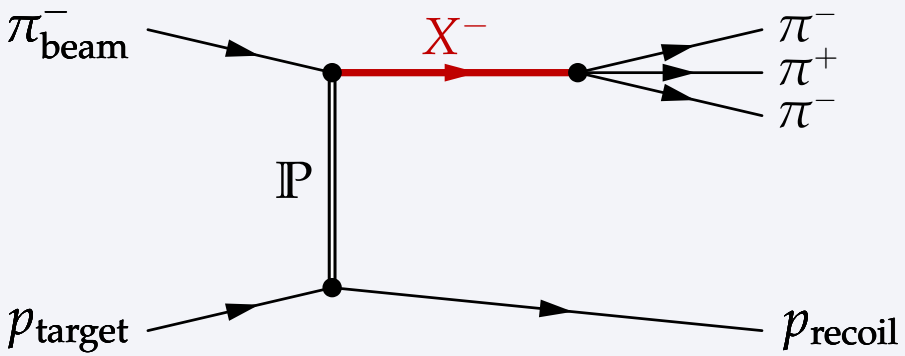

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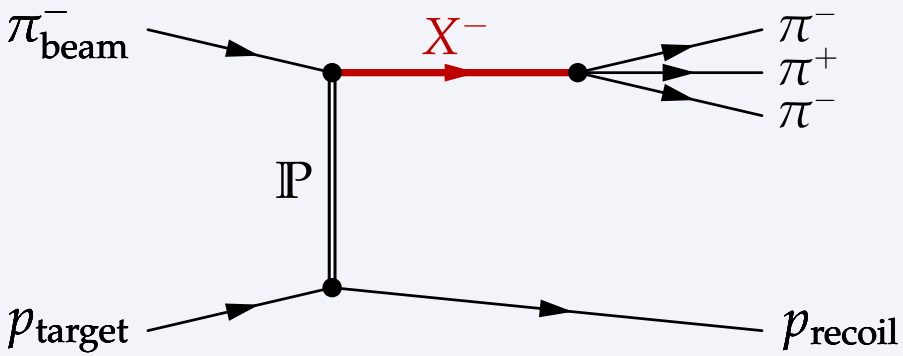

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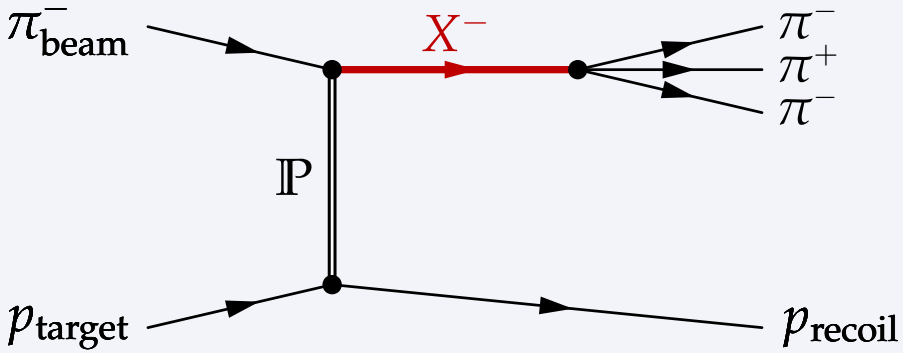

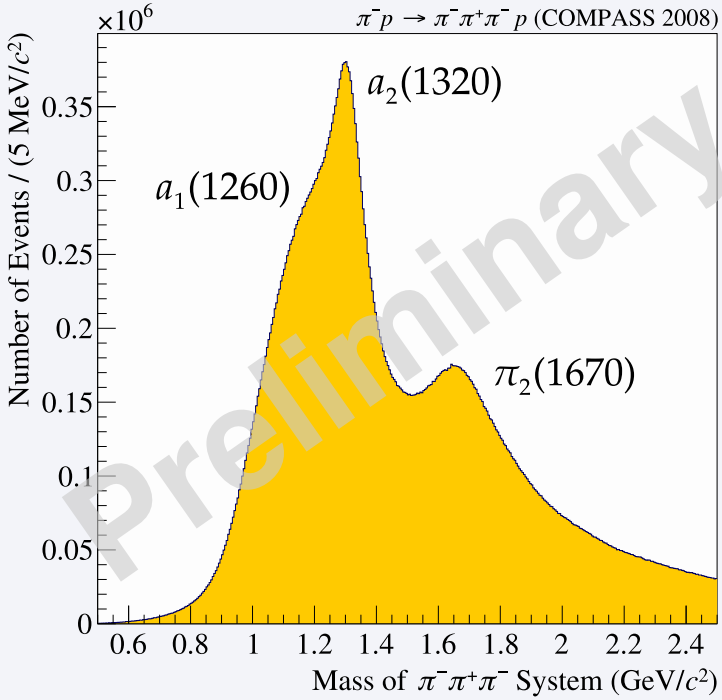

- *Goal:* find all resonances X
  - Determine their mass, width, and quantum numbers
- *Method:* partial-wave analysis
  - Exploit interference patterns to disentangle states
  - "Amplitude analysis"
  - Phase information

Model assumption: X^- decays via $\pi^+\pi^-$ resonance $\Longrightarrow$ **"isobar"**

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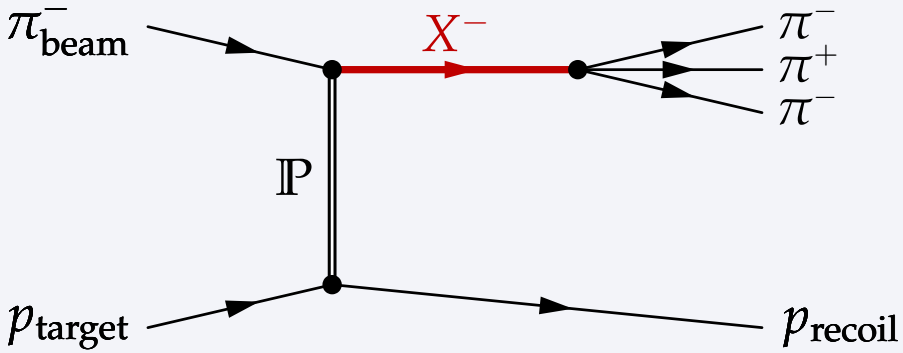

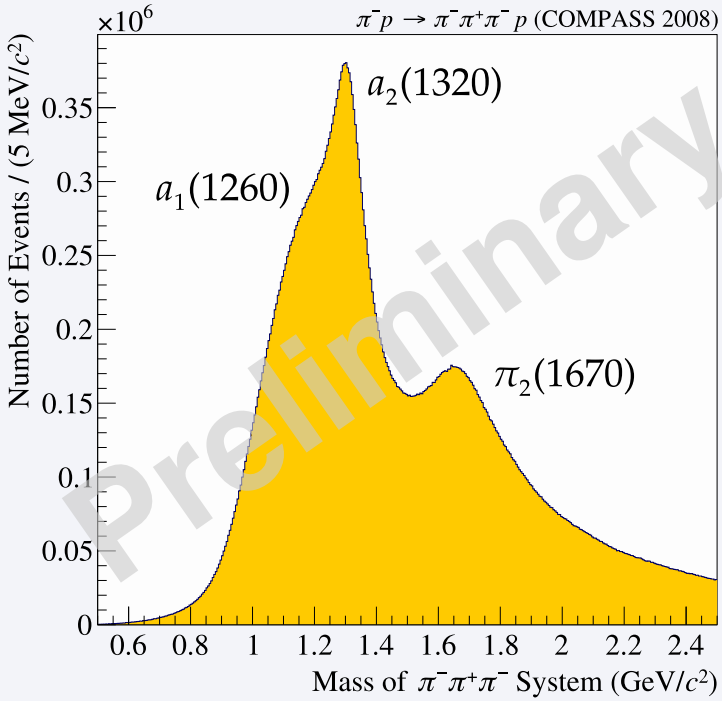

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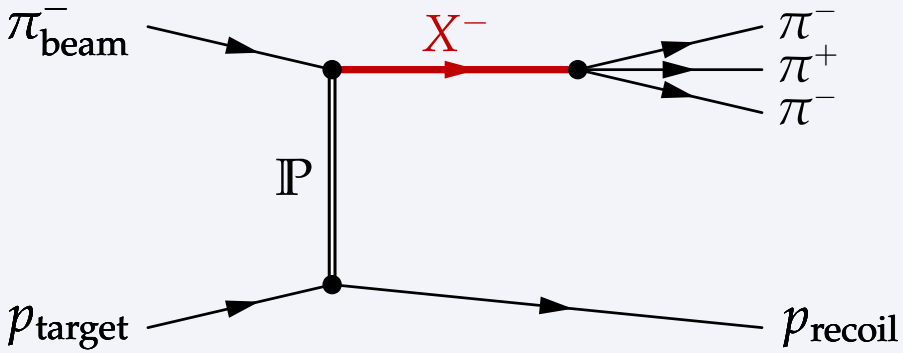

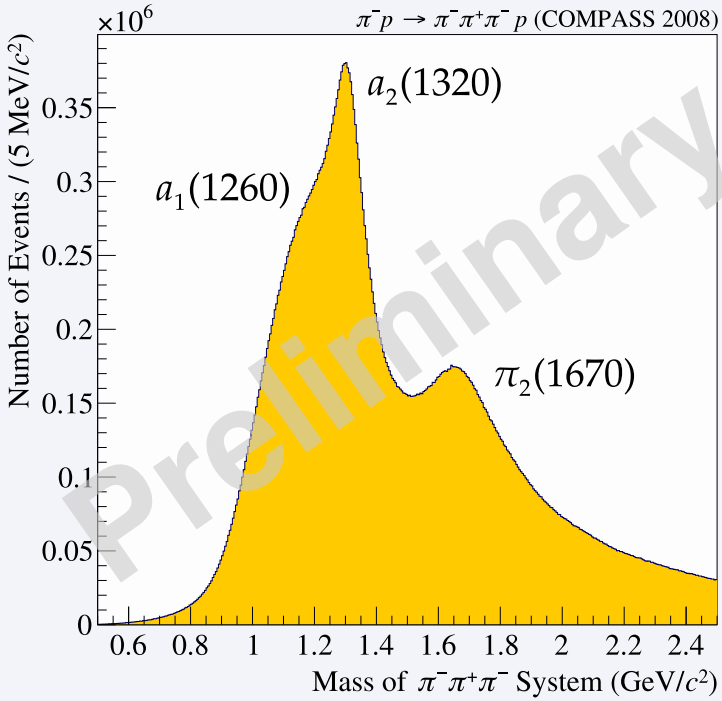

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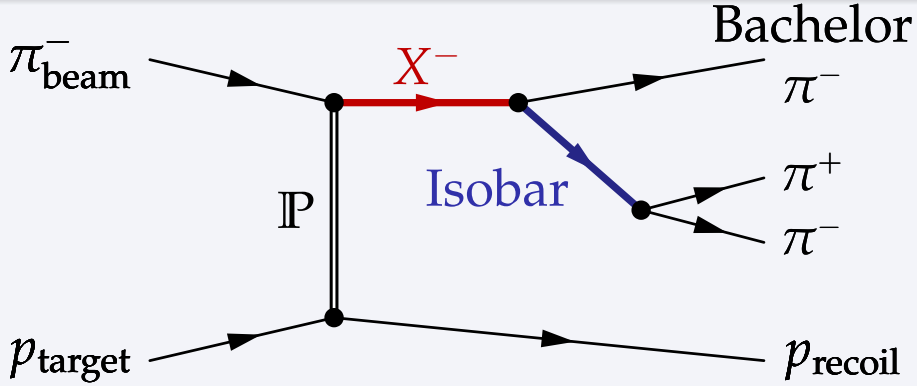

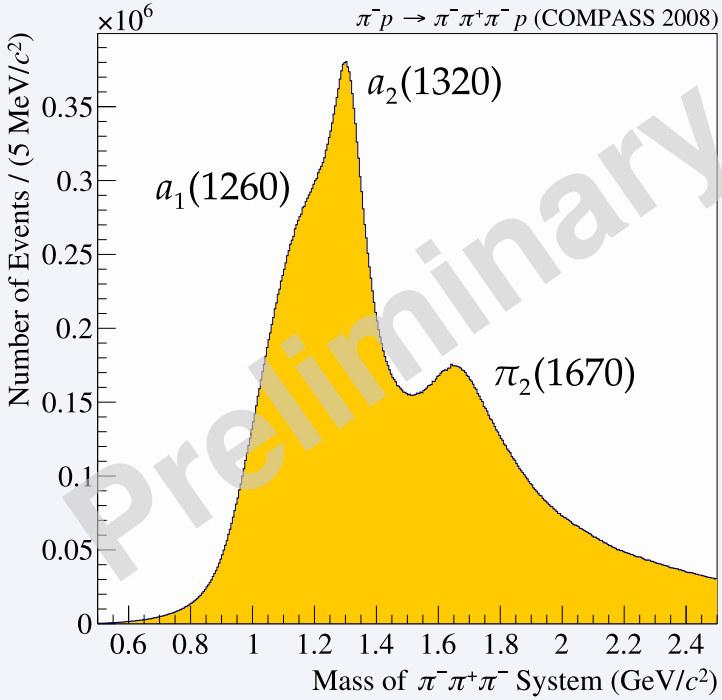

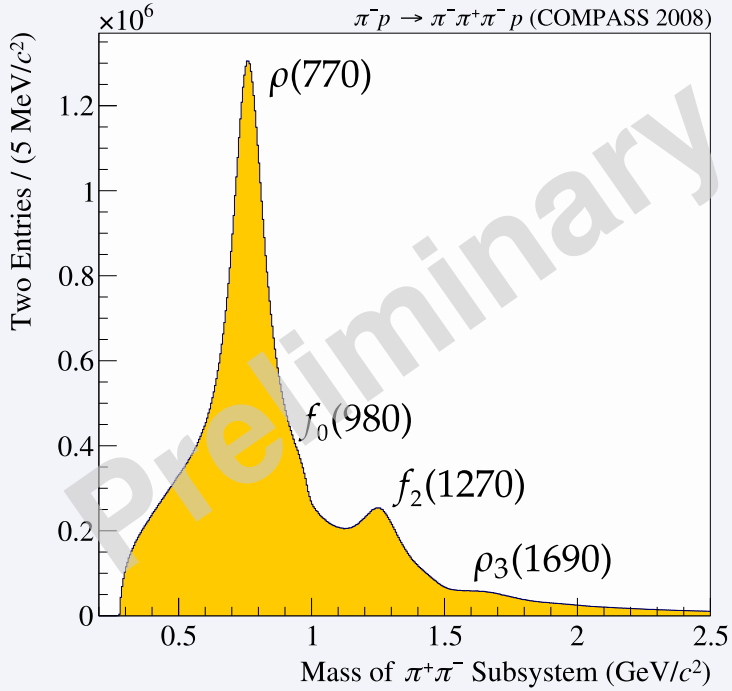

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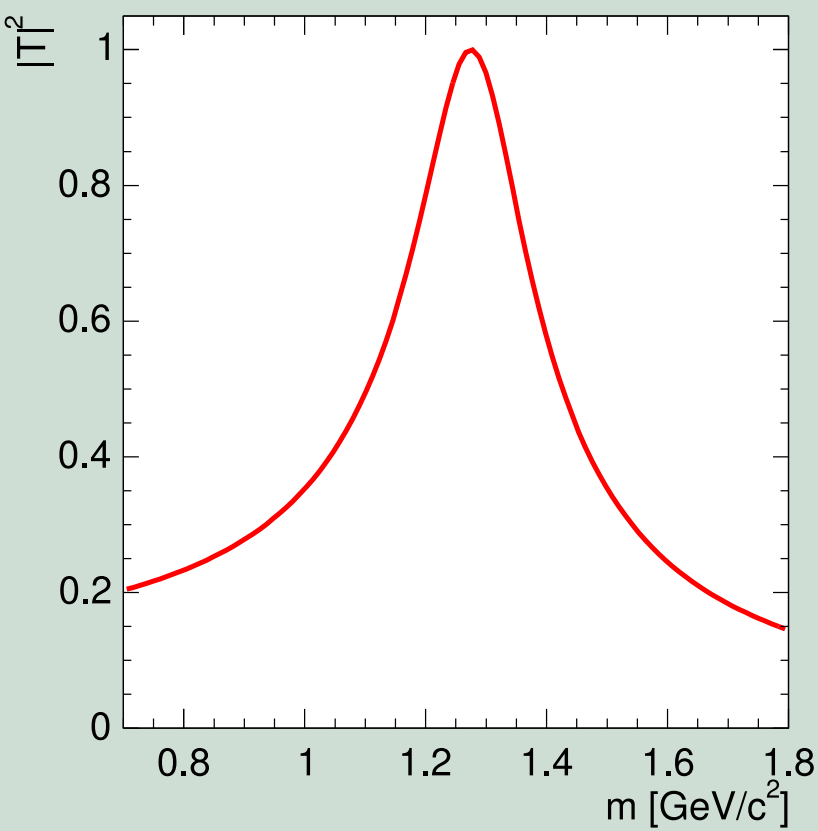
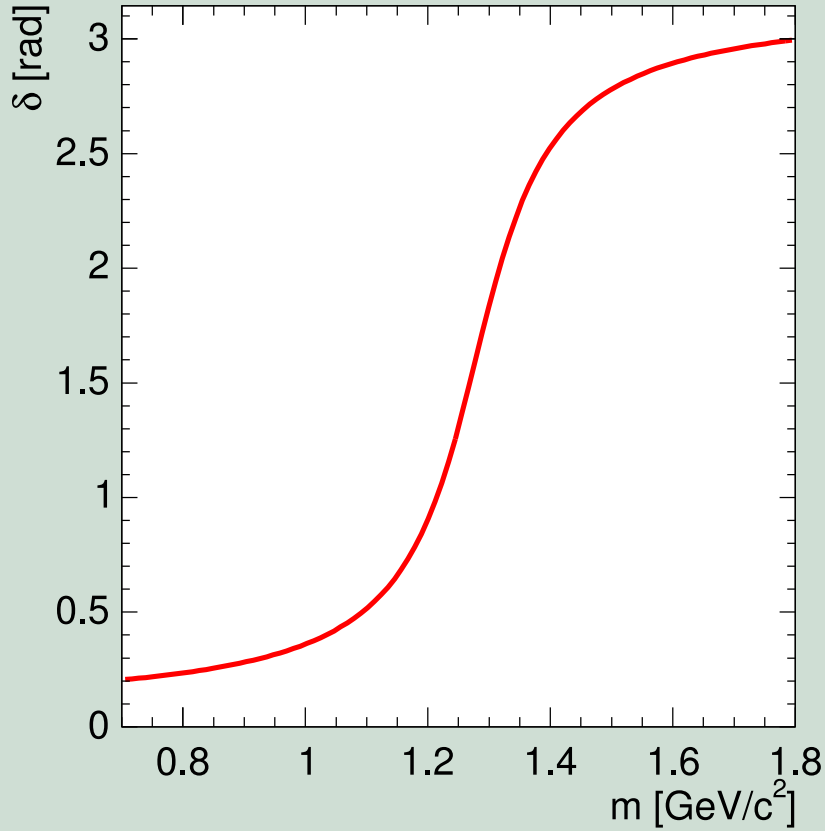
Phase Information

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





Peters, arxiv:hep-ph/0412069

- **"Phase motion":** δ rises from 0 to π and is $\pi/2$ at peak position
  - Analogous to mechanical oscillator

PWA of $\pi^- p \to (3\pi)^- p_{\text{recoil}}$ at COMPASS

Spin-Exotic Signal with $I = 1$ and $J^{PC} = 1^{-+}$ in $\rho(770)\pi$ Decay Channel

- Four-momentum transfer t' between 0.1 and 1.0 $(\text{GeV}/c)^2$
- Largest model used up to now: 88 waves
- Broad intensity bump
- Similar in both channels

$\pi^- \pi^0 \pi^0$

$\pi^- \pi^+ \pi^-$ scaled

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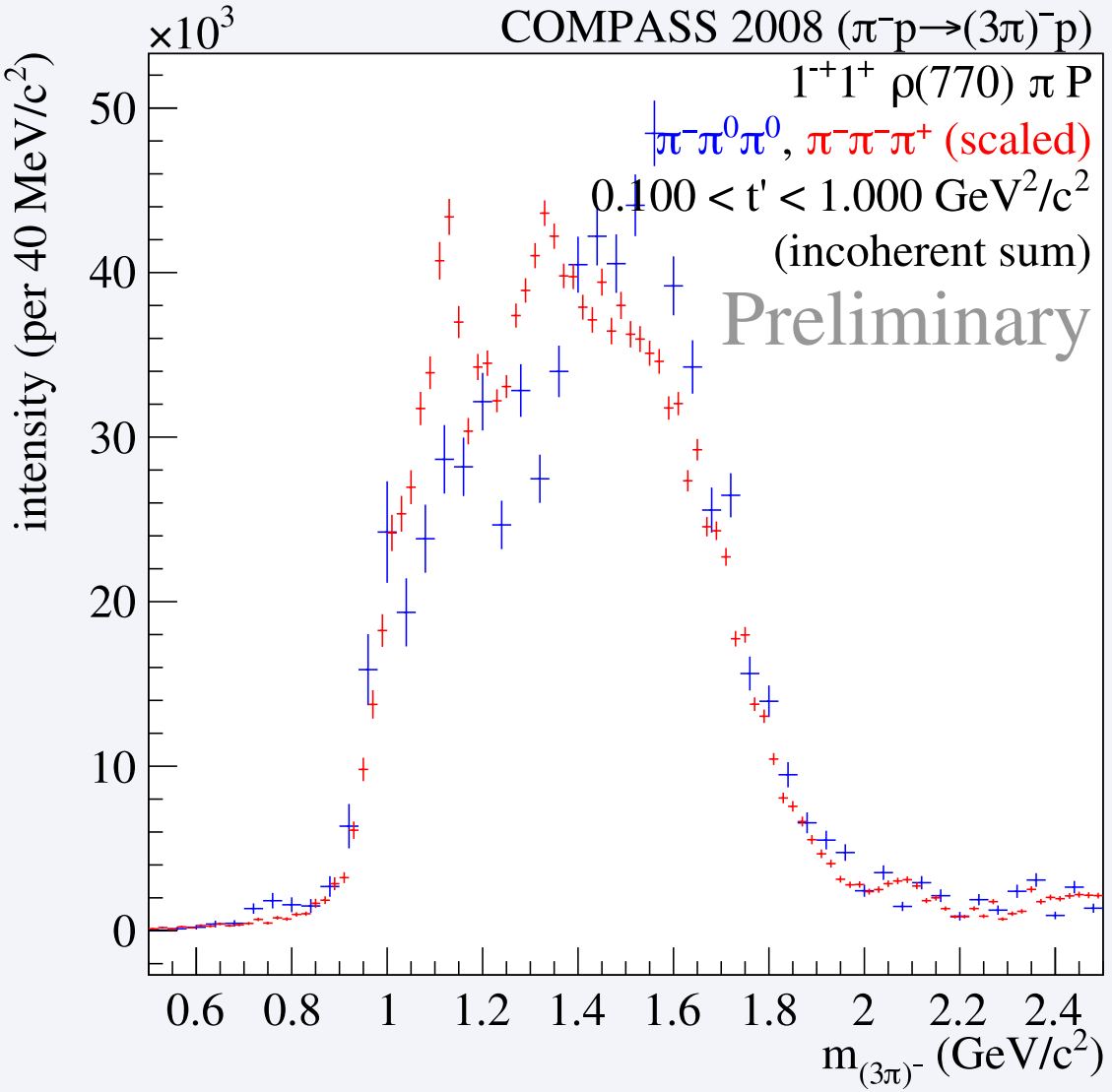

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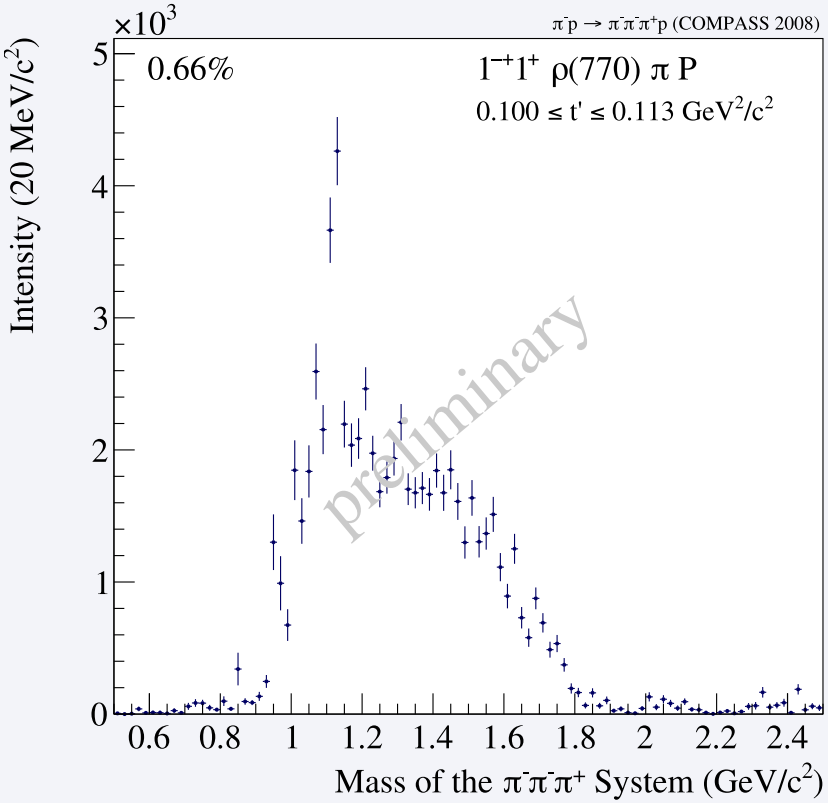
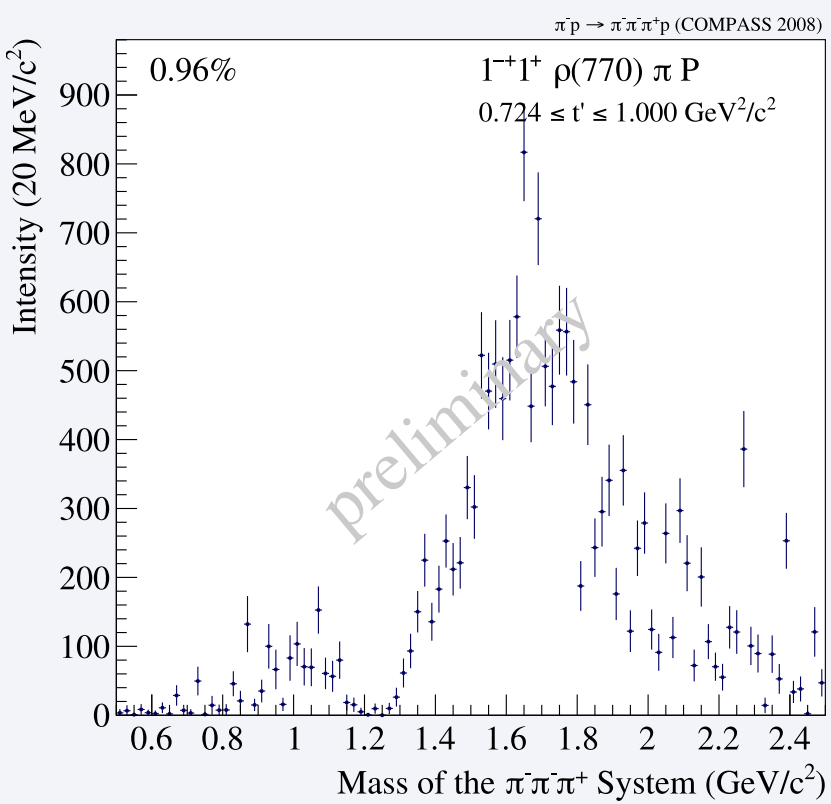
Analysis in t' Bins

"Low" $t' \approx 0.1\ (\text{GeV}/c)^2$

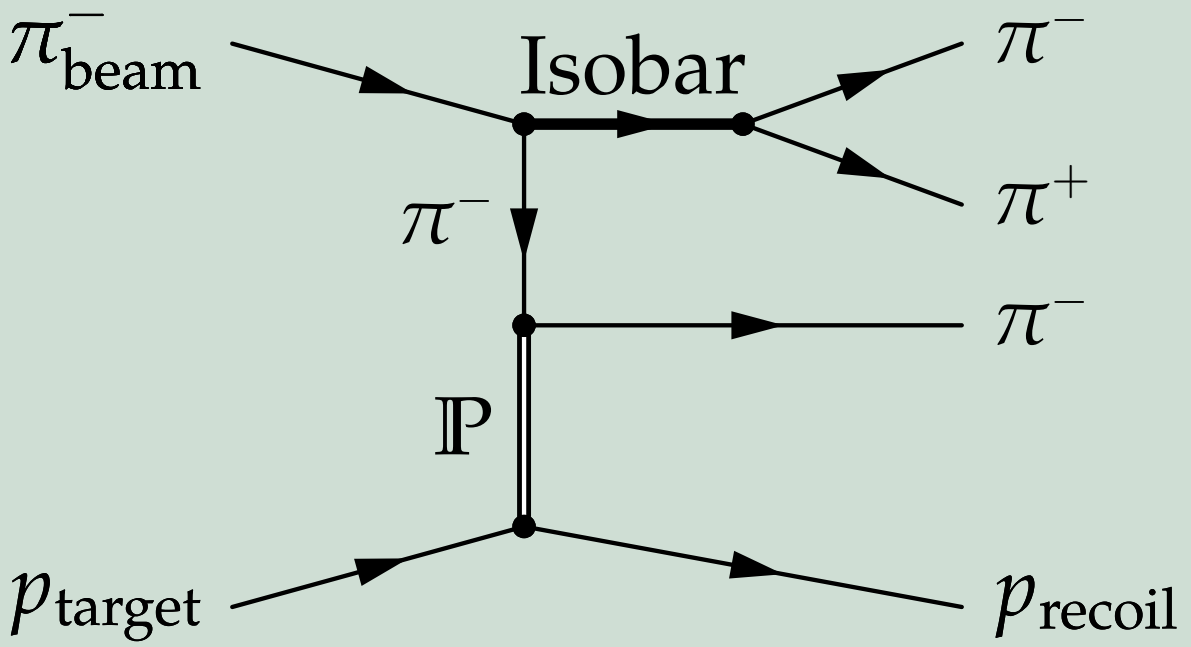


"High" $t' \approx 0.8\ (\text{GeV}/c)^2$



- Strong modulation of mass spectra with t'
- Dominant non-resonant contribution
  - Needs to be understood in order to extract resonances

Deck effect

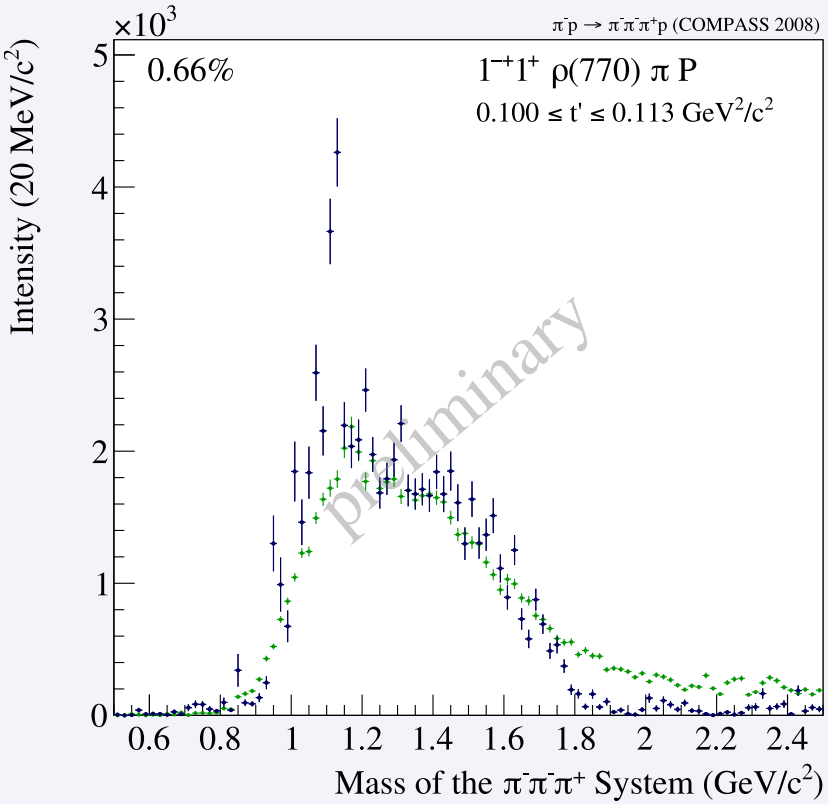


- MC pseudodata generated according to Deck amplitude
- Analyzed like real data

PWA of $\pi^- p \to (3\pi)^- p_{\text{recoil}}$ at COMPASS

Deck-Model for Non-Resonant Component

"Low" $t' \approx 0.1\ (\text{GeV}/c)^2$



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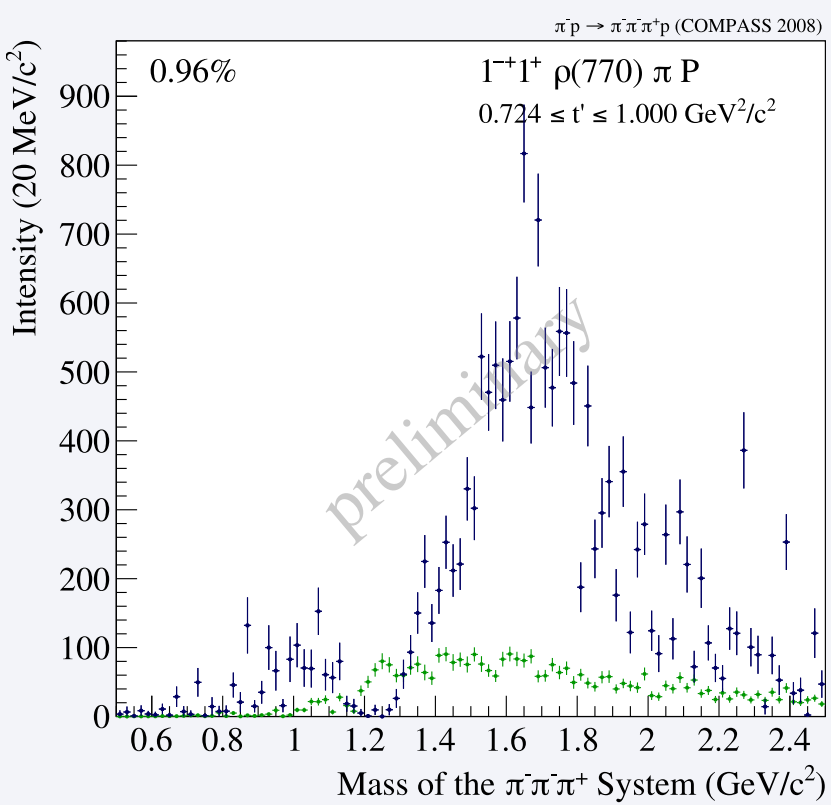
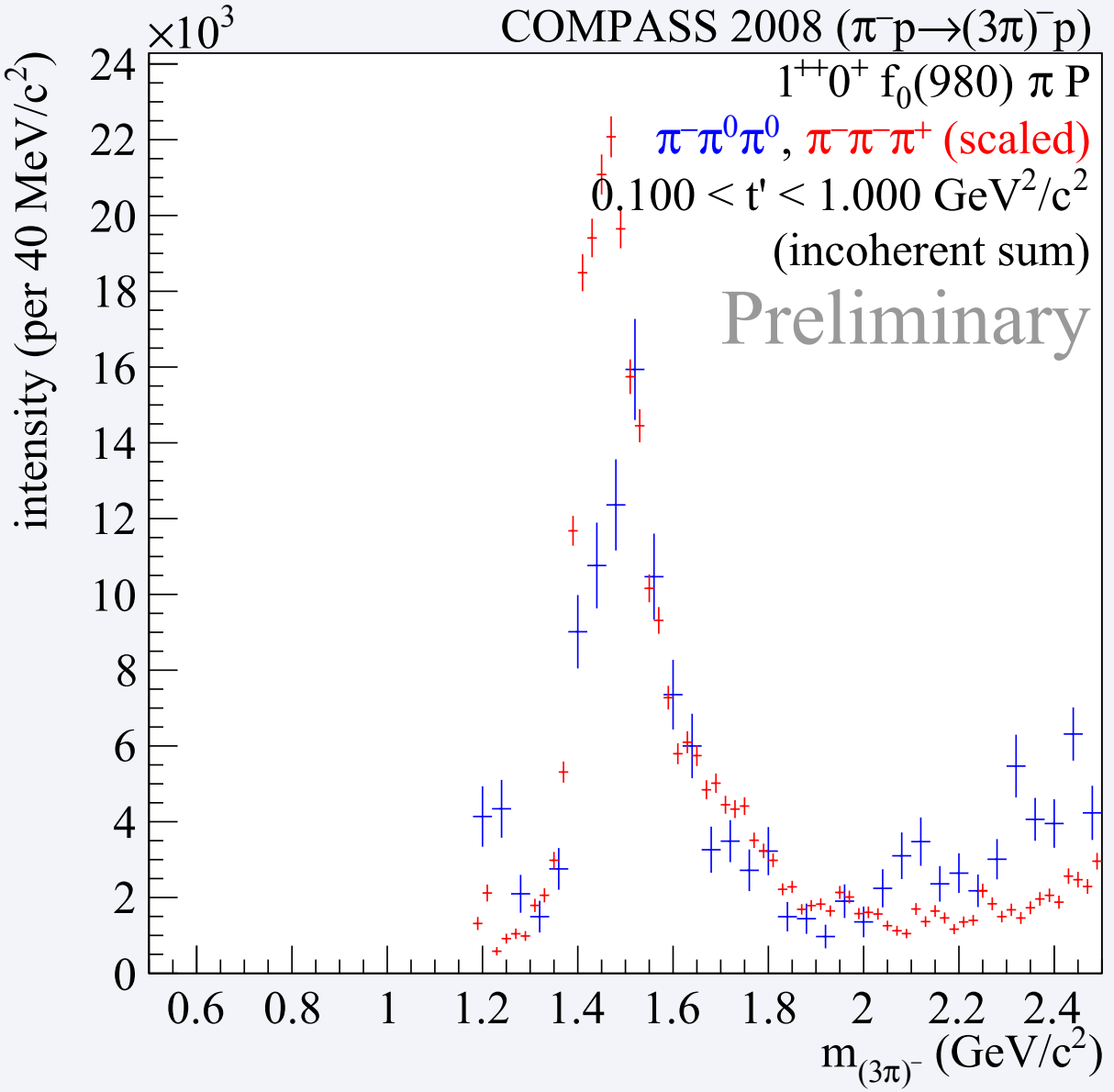


- Deck MC scaled to t'-summed intensity
- Include amplitude in PWA?

PWA of $\pi^- p \to (3\pi)^- p_{\text{recoil}}$ at COMPASS

Unexpected $I = 1$ Signal with $J^{PC} = 1^{++}$ in $f_0(980)\pi$ Decay Channel

- **Peak around $1.4\,\text{GeV}/c^2$**
- Small intensity: $\approx 0.3\%$



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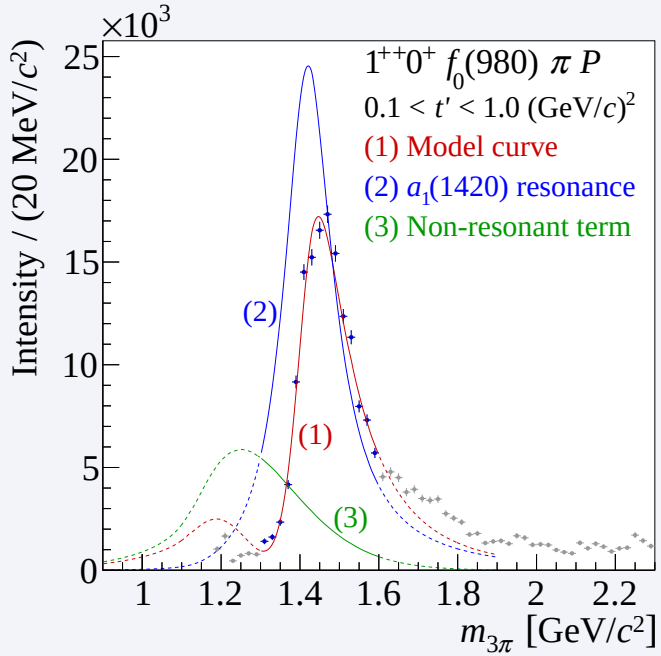
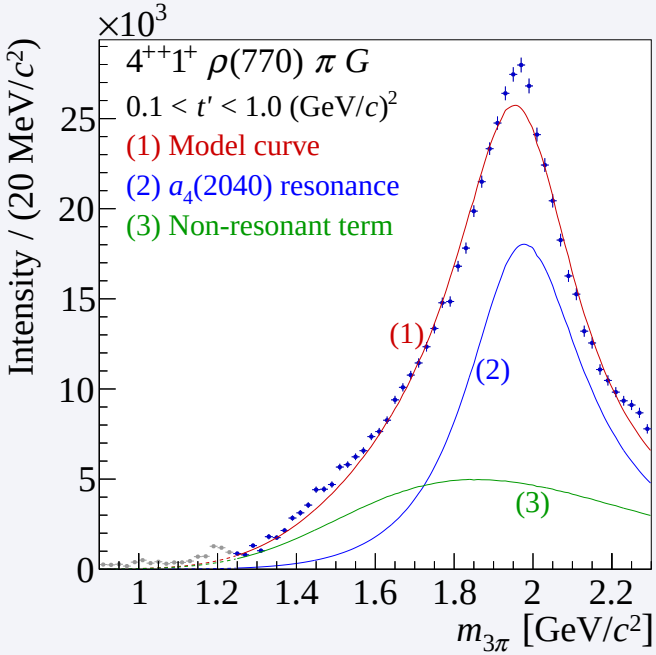
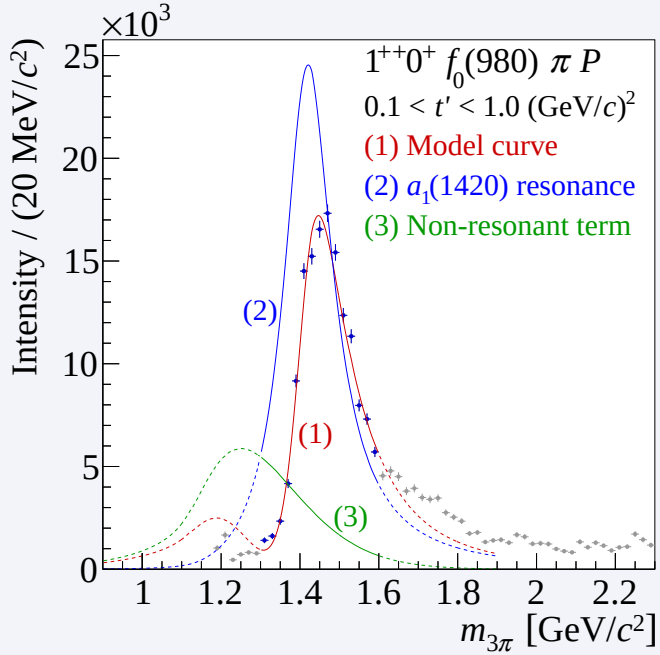
PWA of $\pi^- p \to \pi^-\pi^+\pi^- p_{\text{recoil}}$ at COMPASS [arXiv:1501.05732]



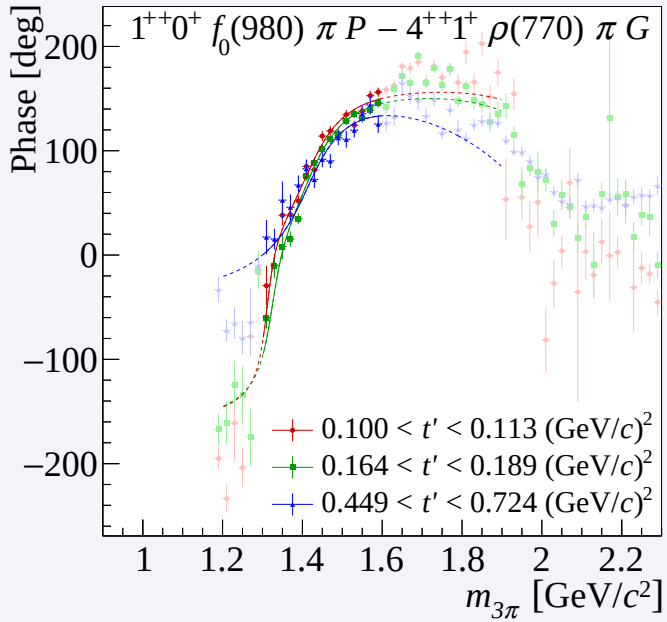
- Consistent with Breit-Wigner resonance
- $a_1(1420)$:
  $M_0 = 1414^{+15}_{-13}\,\text{MeV}/c^2$
  $\Gamma_0 = 153^{+8}_{-23}\,\text{MeV}/c^2$

PWA of $\pi^- p \to \pi^-\pi^+\pi^- p_{\text{recoil}}$ at COMPASS [arXiv:1501.05732]





- Consistent with Breit-Wigner resonance
- $a_1(1420)$:
  $M_0 = 1414^{+15}_{-13}\,\text{MeV}/c^2$
  $\Gamma_0 = 153^{+8}_{-23}\,\text{MeV}/c^2$



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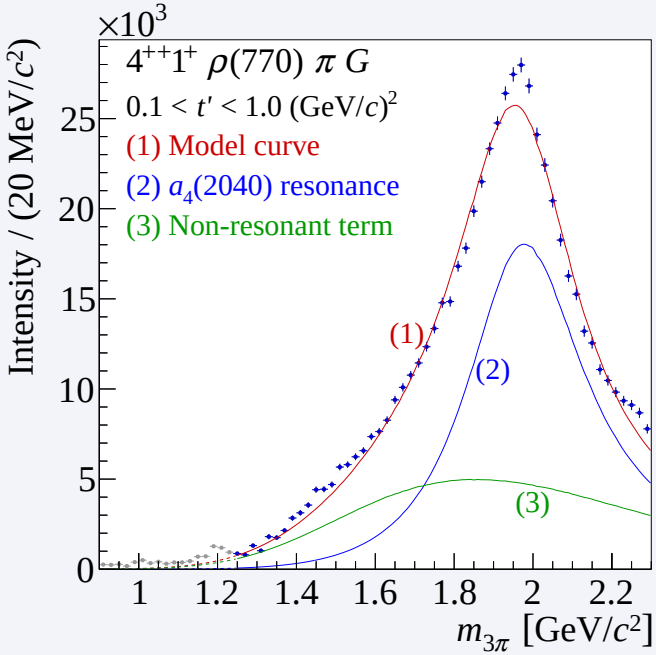

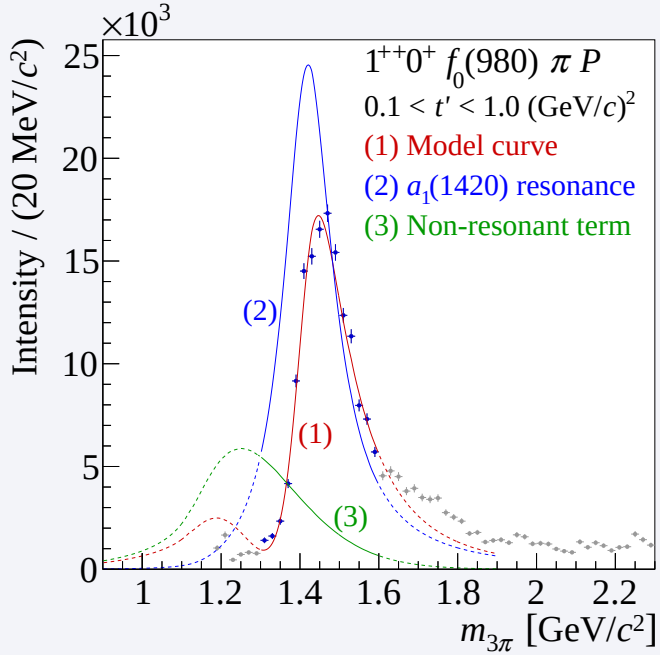

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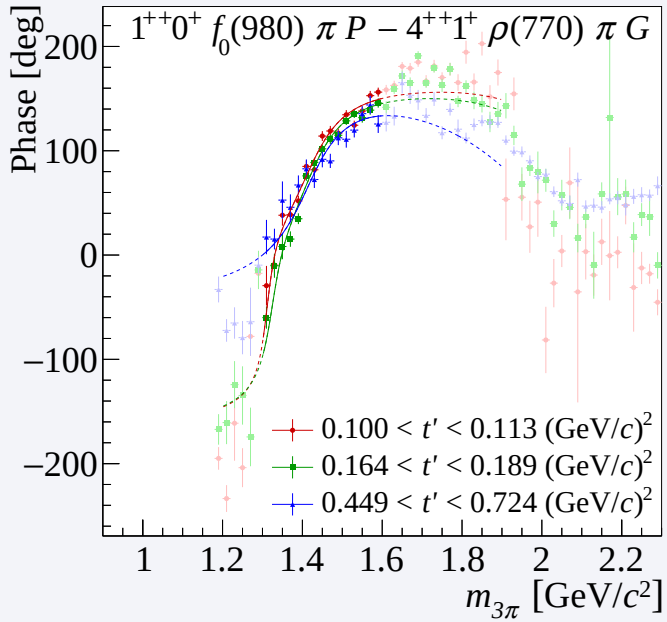

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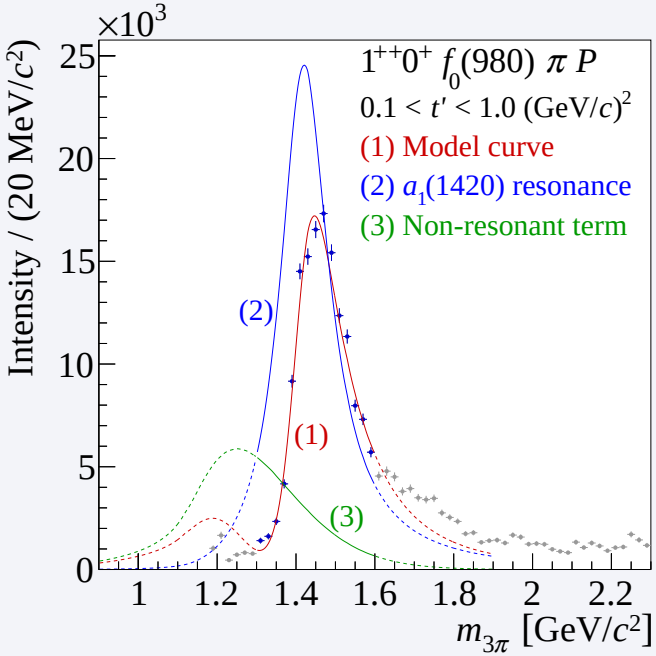

Nature of $a_1(1420)$ unclear

- No quark-model states expected at $1.4\,\text{GeV}/c^2$
- Ground state $a_1(1260)$ very close and wider
- Seen only in $f_0(980)\pi$ decay mode
- Isospin partner of narrow $f_1(1420)$?
- Suspiciously close to $K\bar{K}^*$ threshold

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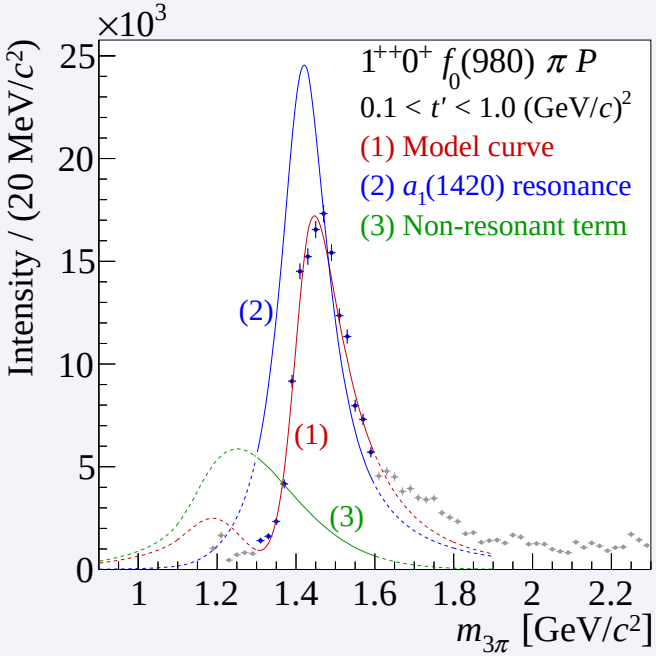

Several proposed explanations

- Two-quark-tetraquark mixed state [Wang, arXiv:1401.1134]
- Tetraquark with mixed flavor symmetry

  [Chen *et al.*, Phys. Rev. **D91** (2015) 094022]
- Resonant re-scattering corrections in Deck process

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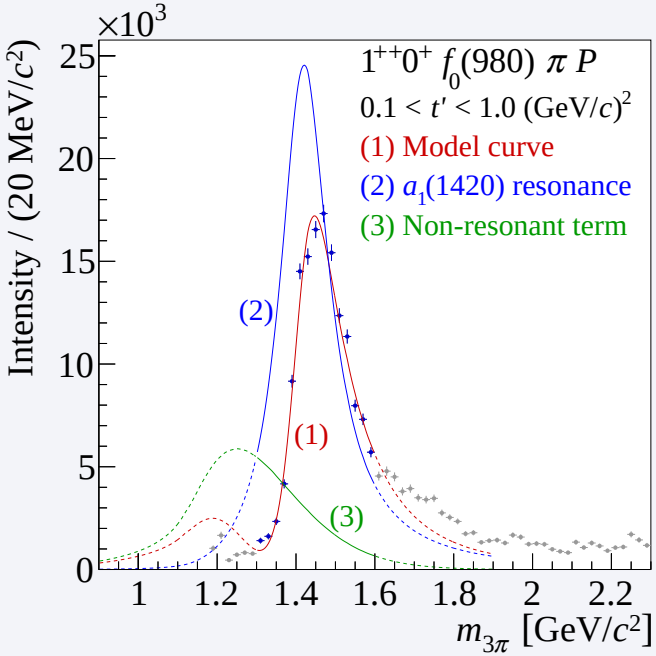

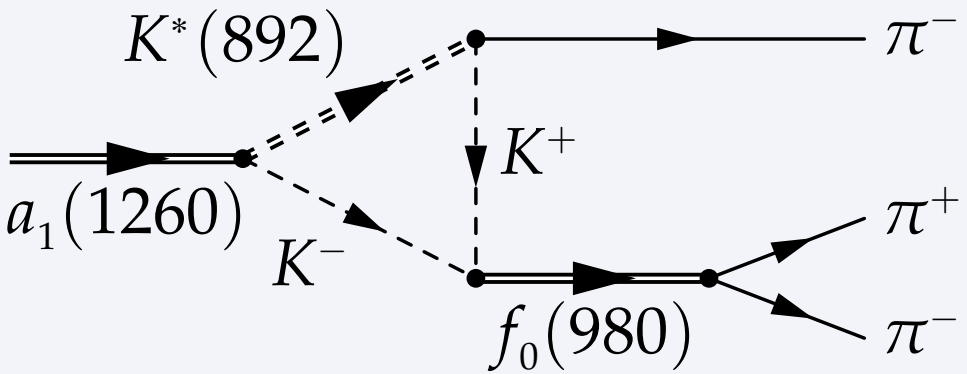

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Conclusions and Outlook

World's largest $\pi^-\pi^+\pi^-$ data set

- Crosscheck systematics with $\pi^-\pi^0\pi^0$ data
- *Novel analysis scheme:* binning in t'
  - Better separation of resonant and non-resonant contribution
- Significant intensity in $J^{PC} = 1^{-+}$ spin-exotic wave
  - Resonance interpretation work in progress
- New axial-vector state $a_1(1420)$
  - Surprising find
  - Peculiar properties
- Extraction of resonance parameters limited by understanding of non-resonant contribution
  - Improved models needed

Other channels

- Pion diffraction into $\pi^-\eta$, $\pi^-\eta'$, $\pi^-\eta\eta$, $\pi^-\pi^0\omega$, $K\bar{K}\pi$, $K\bar{K}\pi\pi$, ...
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