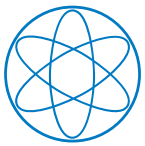
Studies of light mesons at COMPASS

Sebastian Uhl
On Behalf of the COMPASS Collaboration

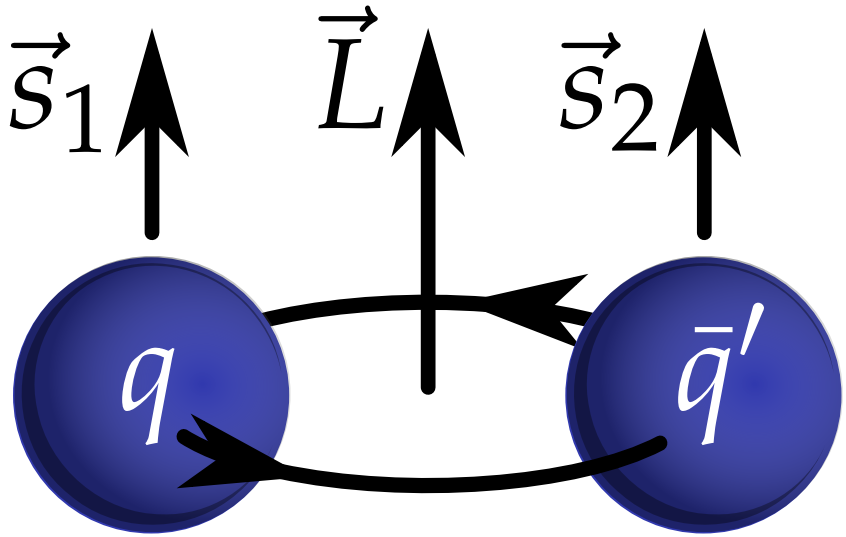
Physik Department E18
Technische Universität München



ICNFP 2016 09.07.2016

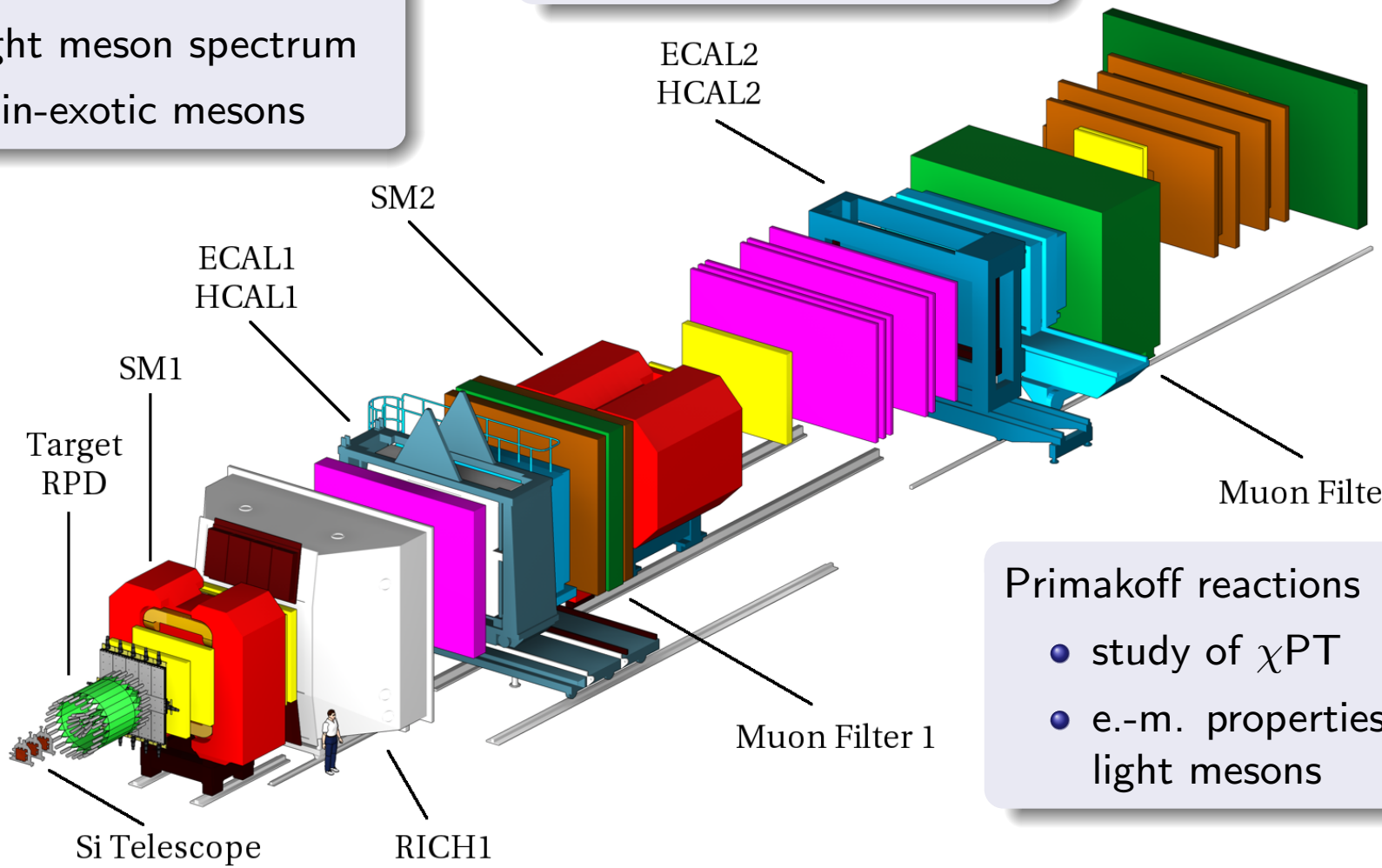
Naïve Constituent Quark Model

- Quark spins couple to total intrinsic spin $S = 0$ (singlet) or 1 (triplet)
- Relative 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 $C = (-1)^{L+S}$
- isospin I
- G-parity $G = (-1)^{L+S+I}$

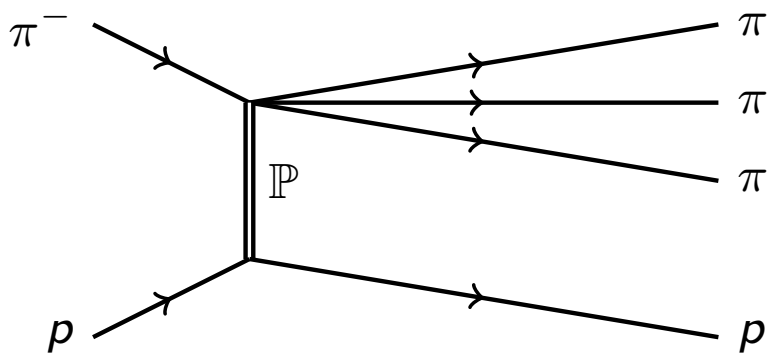


central production
- glue-rich environment
- scalar resonances

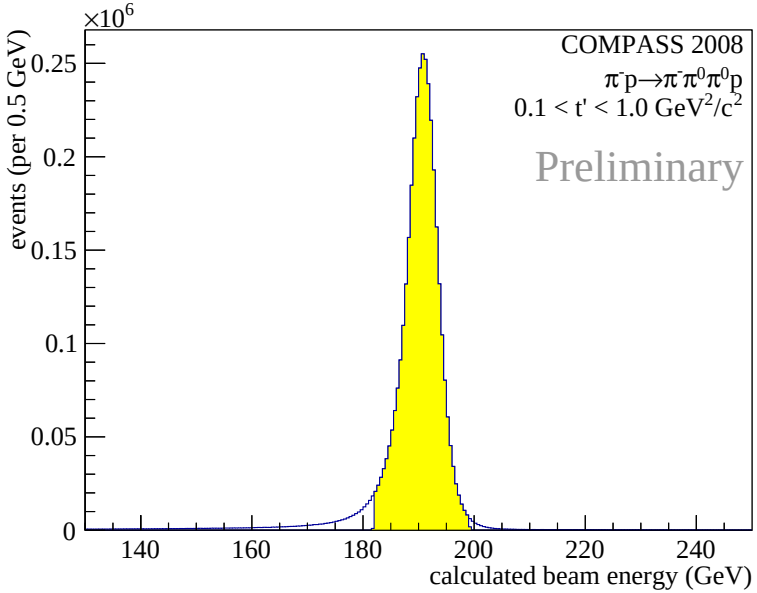
diffractive dissociation
- light meson spectrum
- spin-exotic mesons

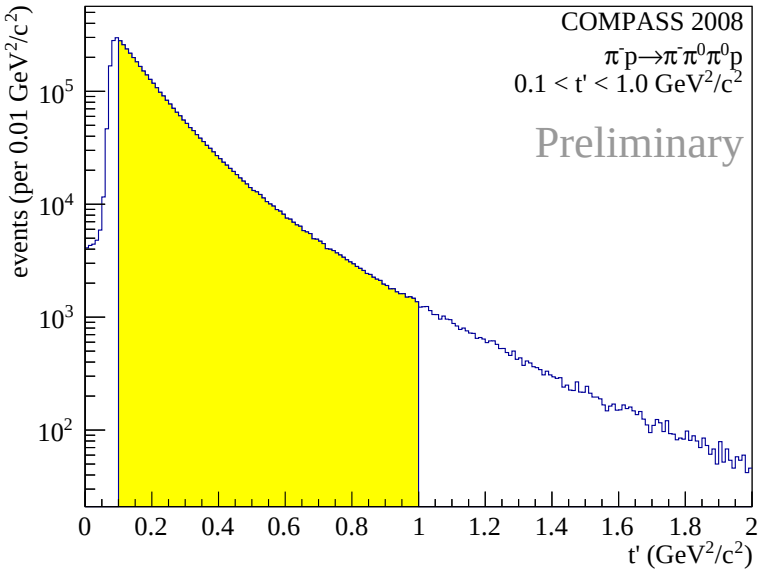


Primakoff reactions
- study of χPT
- e.-m. properties of light mesons

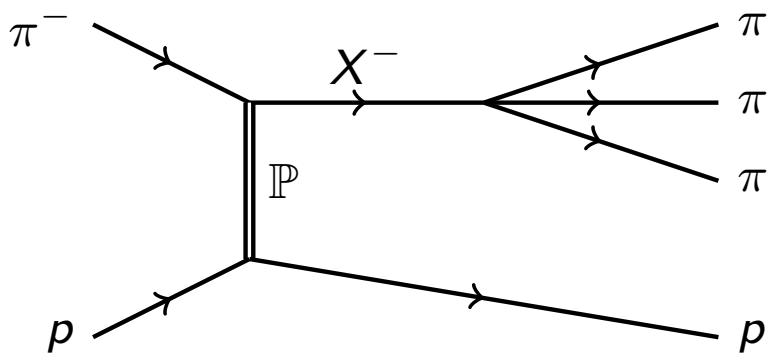


- 190 GeV/c π^- beam on ℓH_2 target
- exclusive measurement of reaction $\pi^- p \to (3\pi)^- p$
- two channels in COMPASS
  - $\pi^-\pi^-\pi^+$
  - $\pi^-\pi^0\pi^0$
- t' region: $0.1 < t' < 1.0$ (GeV/c)^2





$\pi^- p \to (3\pi)^- p$



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  - $\pi^-\pi^-\pi^+$
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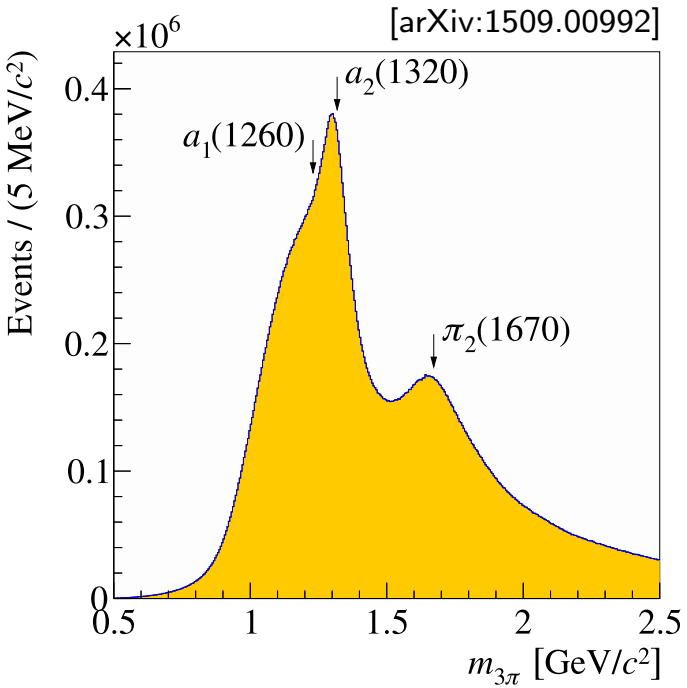
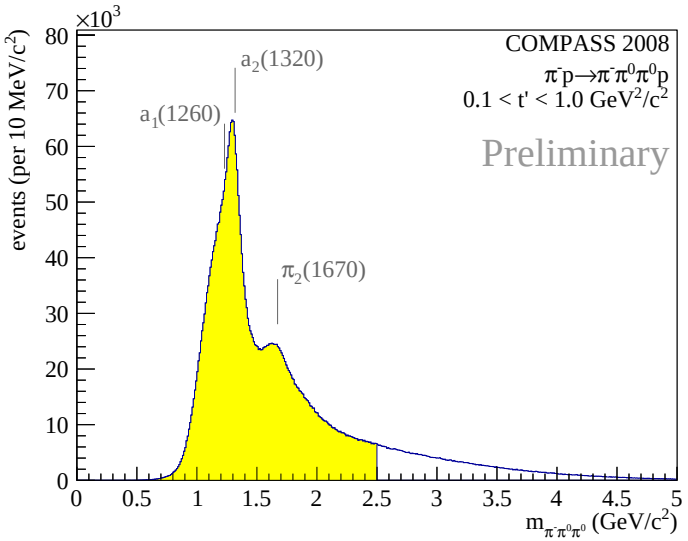
- t' region: $0.1 < t' < 1.0$ (GeV/c)^2
- huge dataset
  - 50 million $\pi^-\pi^-\pi^+$ events
  - 3.5 million $\pi^-\pi^0\pi^0$ events





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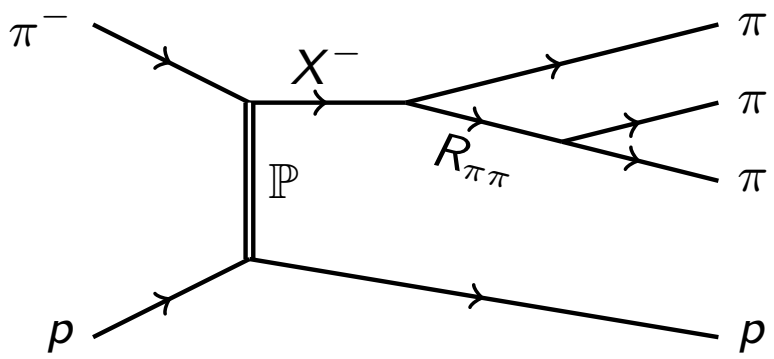

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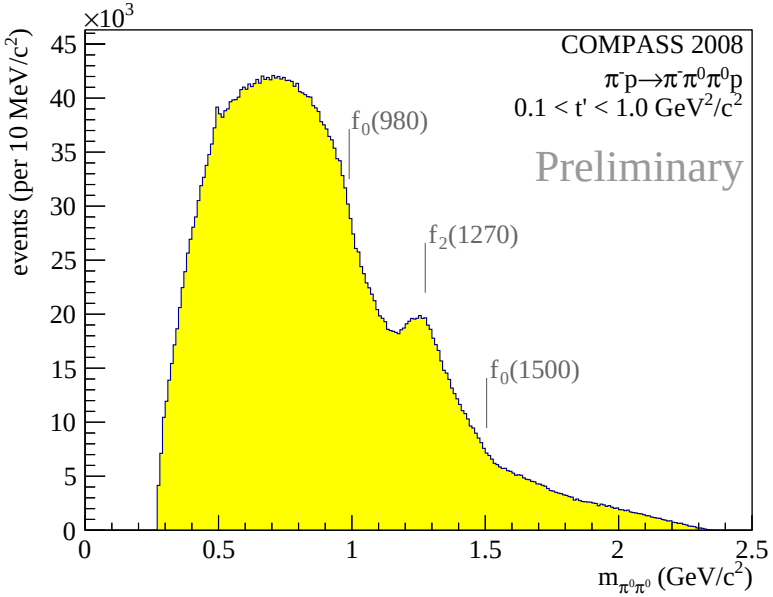
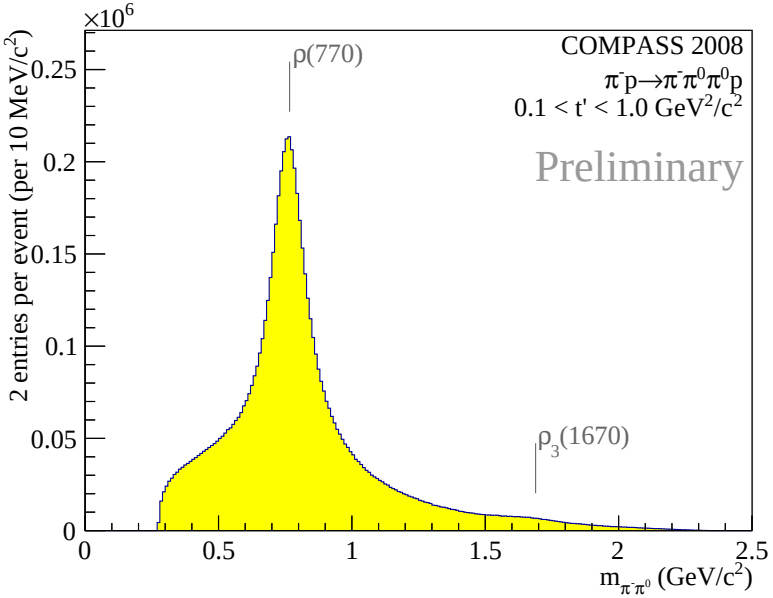
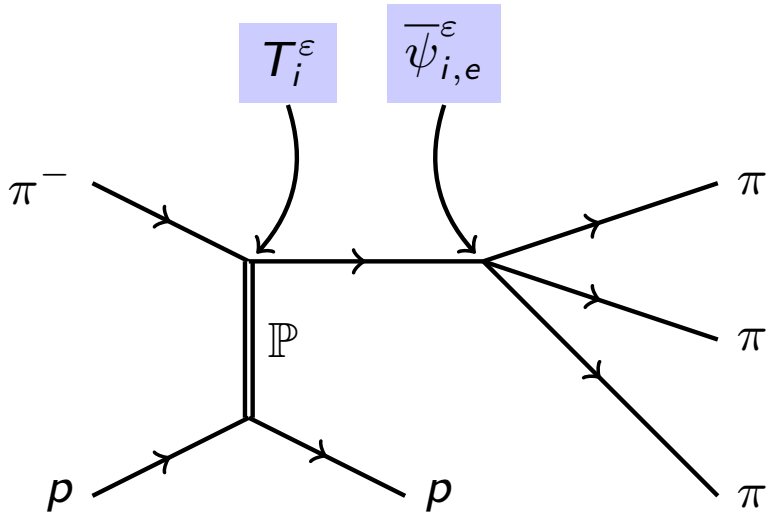
- partial-wave analysis using isobar model





Partial-Wave Analysis



- process can be factorized
  - production T_i^ε
  - decay $\overline{\psi}_{i,e}^\varepsilon$

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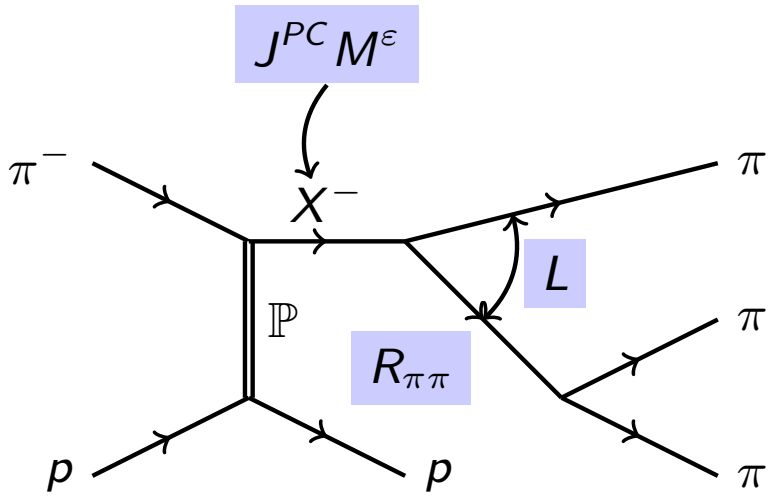
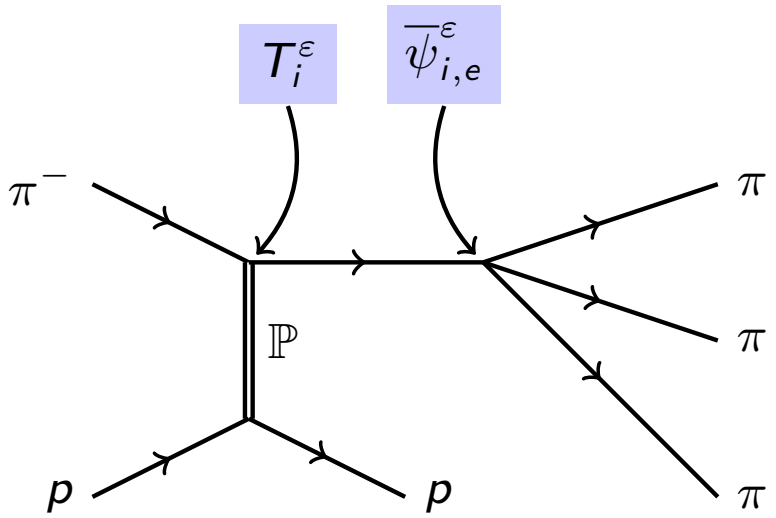


- process can be factorized
  - production T_i^{ε}
  - decay $\overline{\psi}_{i,e}^{\varepsilon}$

- 88 waves
  - 80 with positive reflectivity
  - 7 with negative reflectivity
  - flat wave
- spin J up to 6
- angular momentum L between bachelor π and isobar up to 6
- used isobars:
  with isospin $I = 0$:
  $(\pi\pi)_S$, $f_0\,(980)$, $f_2\,(1270)$, $f_0\,(1500)$
  with isospin $I = 1$:
  $\rho\,(770)$, $\rho_3\,(1690)$
- for $\pi^-\pi^-\pi^+$ all isobars are $\pi^-\pi^+$
- for $\pi^-\pi^0\pi^0$:
  - $I = 0$ in $\pi^0\pi^0$
  - $I = 1$ in $\pi^-\pi^0$

Partial-Wave Analysis



- process can be factorized
  - production T_i^ε
  - decay $\overline{\psi}_{i,e}^\varepsilon$
- two-step approach

1. fit in mass and t' bins
   - extract production amplitudes T_i^ε
2. fit of mass dependence of spin-density matrix
   - extract resonance parameters

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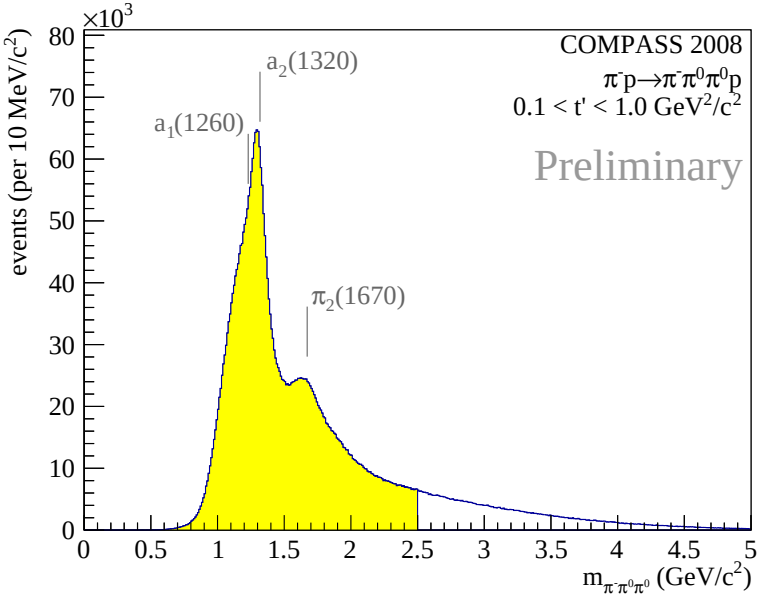
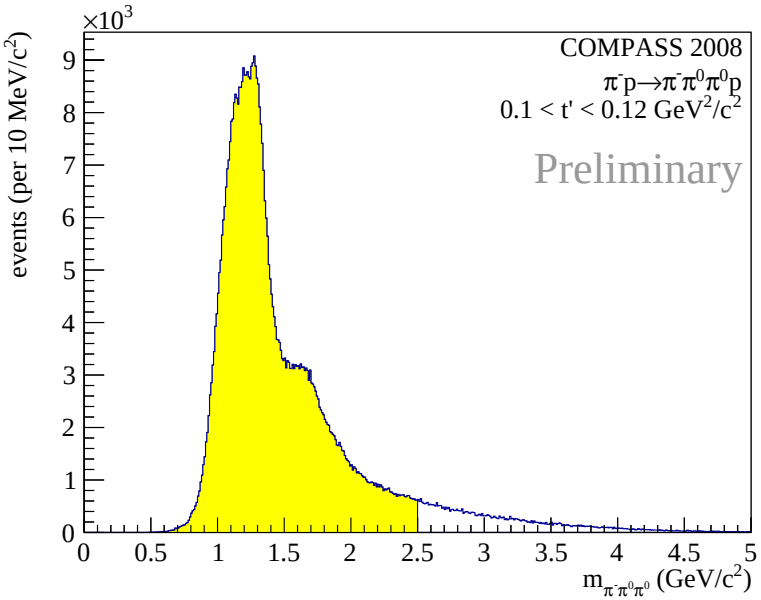
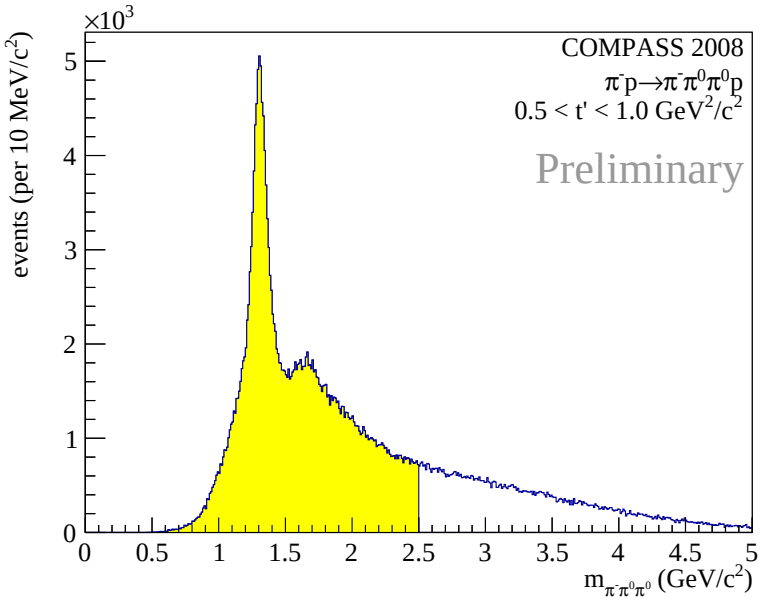
Binning in t'



- mass spectrum depends on t'
- at low-t' $(0.1 < t' < 0.2\ (\mathrm{GeV}/c)^2)$
  - $a_1\,(1260)$ dominates low-mass region
  - $a_2\,(1320)$ hardly visible
- at high-t' $(0.5 < t' < 1.0\ (\mathrm{GeV}/c)^2)$
  - $a_1\,(1260)$ visible only as a shoulder
  - $a_2\,(1320)$ dominant
- no changes above $\pi_2\,(1670)$ region
- binning of data also in t'
  - 11 bins for $\pi^-\pi^-\pi^+$
  - 8 bins for $\pi^-\pi^0\pi^0$

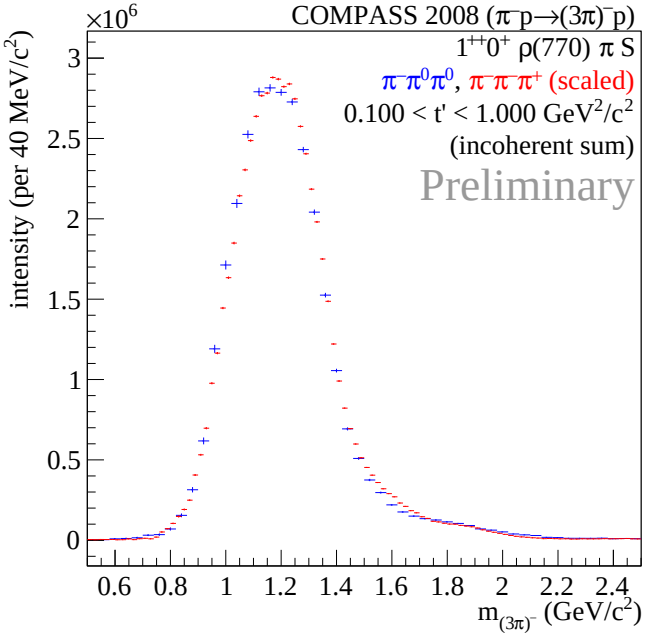


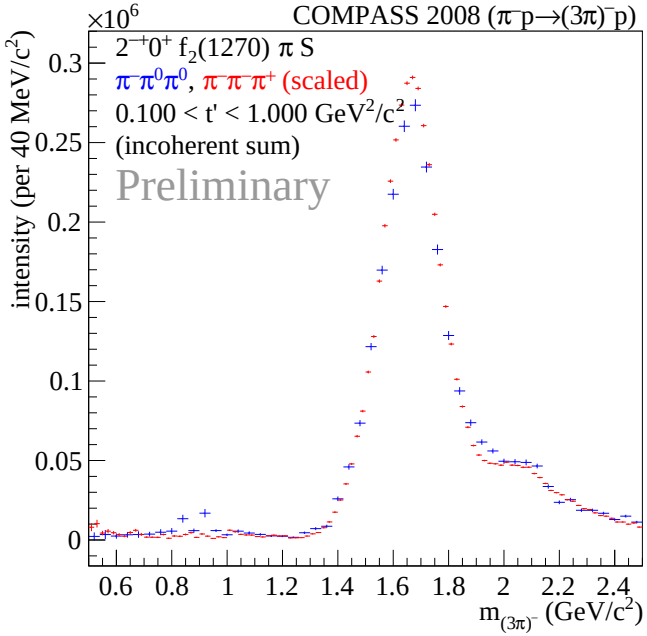


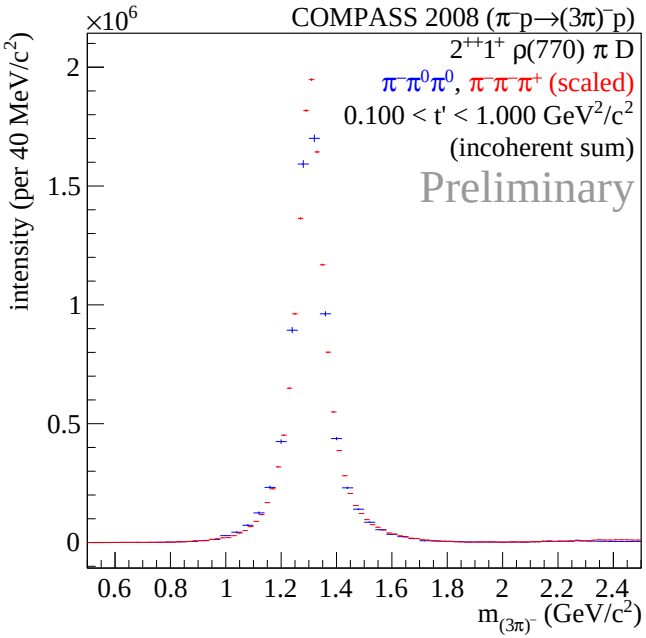
Partial-Wave Decomposition: Major Waves

major waves

- $1^{++}0^{+}\rho(770)\pi S$
- $2^{-+}0^{+}f_2(1270)\pi S$
- $2^{++}1^{+}\rho(770)\pi D$







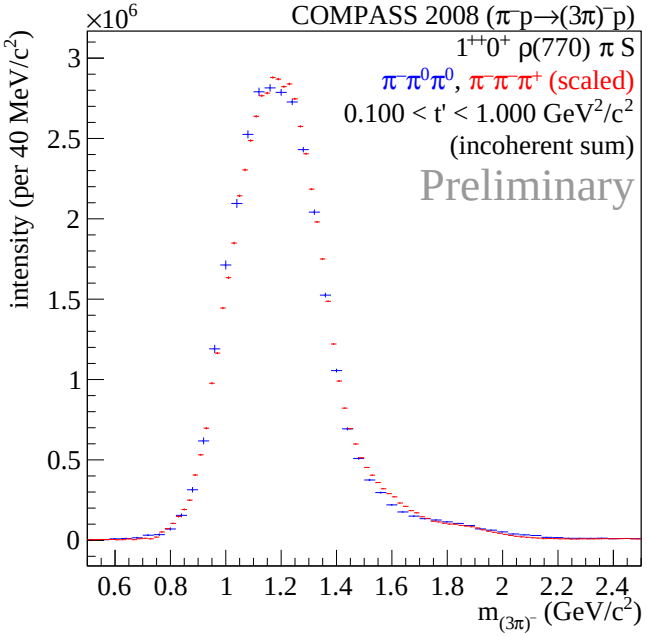
- $\pi^{-}\pi^{0}\pi^{0}$
- $\pi^{-}\pi^{-}\pi^{+}$ (scaled)
- scaled for each plot
- good agreement between channels

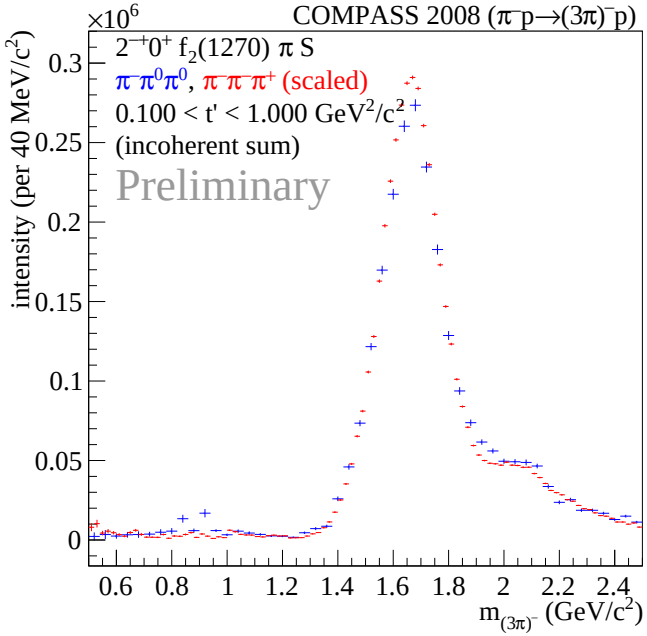
Partial-Wave Decomposition: Major Waves

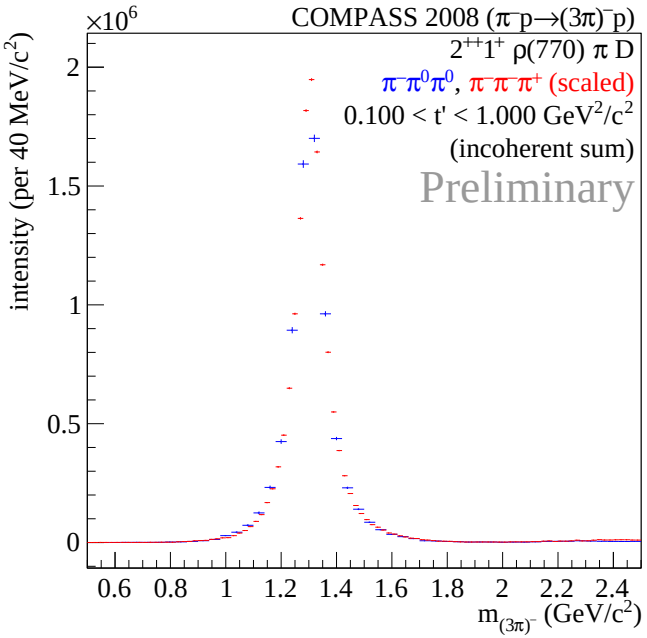
ρ isobar

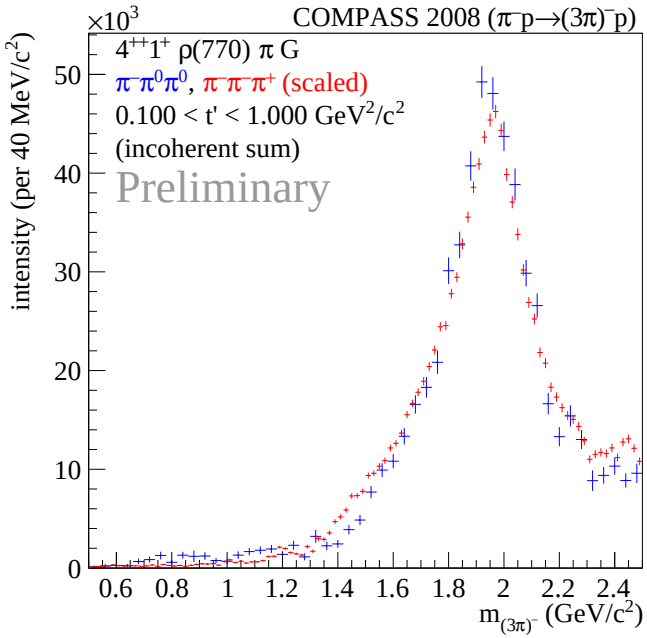
- $1^{++}0^{+}\rho(770)\pi S$
- $2^{-+}0^{+}f_2(1270)\pi S$
- $2^{++}1^{+}\rho(770)\pi D$
- $4^{++}1^{+}\rho(770)\pi G$
- stable fits also for waves with
  - higher spins
  - smaller intensities

- $\pi^-\pi^0\pi^0$
- $\pi^-\pi^-\pi^+$ (scaled)
- scaled for each plot
- good agreement between channels









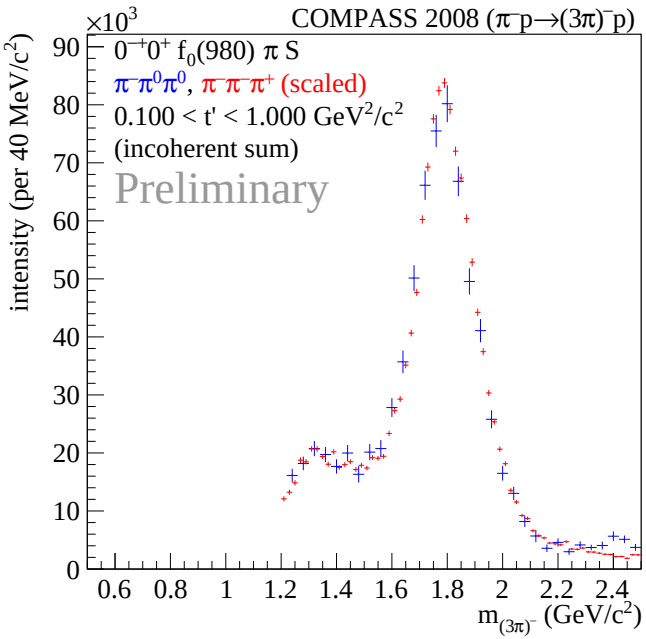
Partial-Wave Decomposition: Waves with $f_0(980)$ Isobars

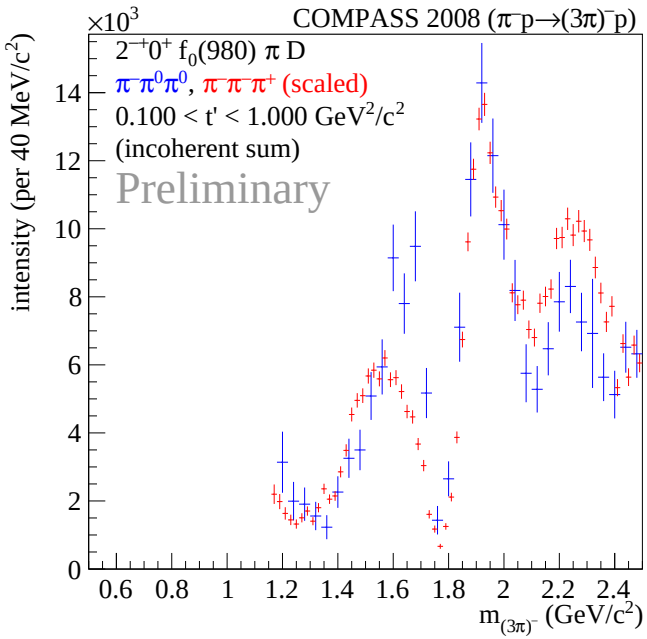
$f_0(980)$ isobar

- $0^{-+}0^+ f_0(980)\,\pi S$
- $2^{-+}0^+ f_0(980)\,\pi D$

- stable fits also for non-ρ isobars

- $\pi^-\pi^0\pi^0$
- $\pi^-\pi^-\pi^+$ (scaled)
- scaled for each plot





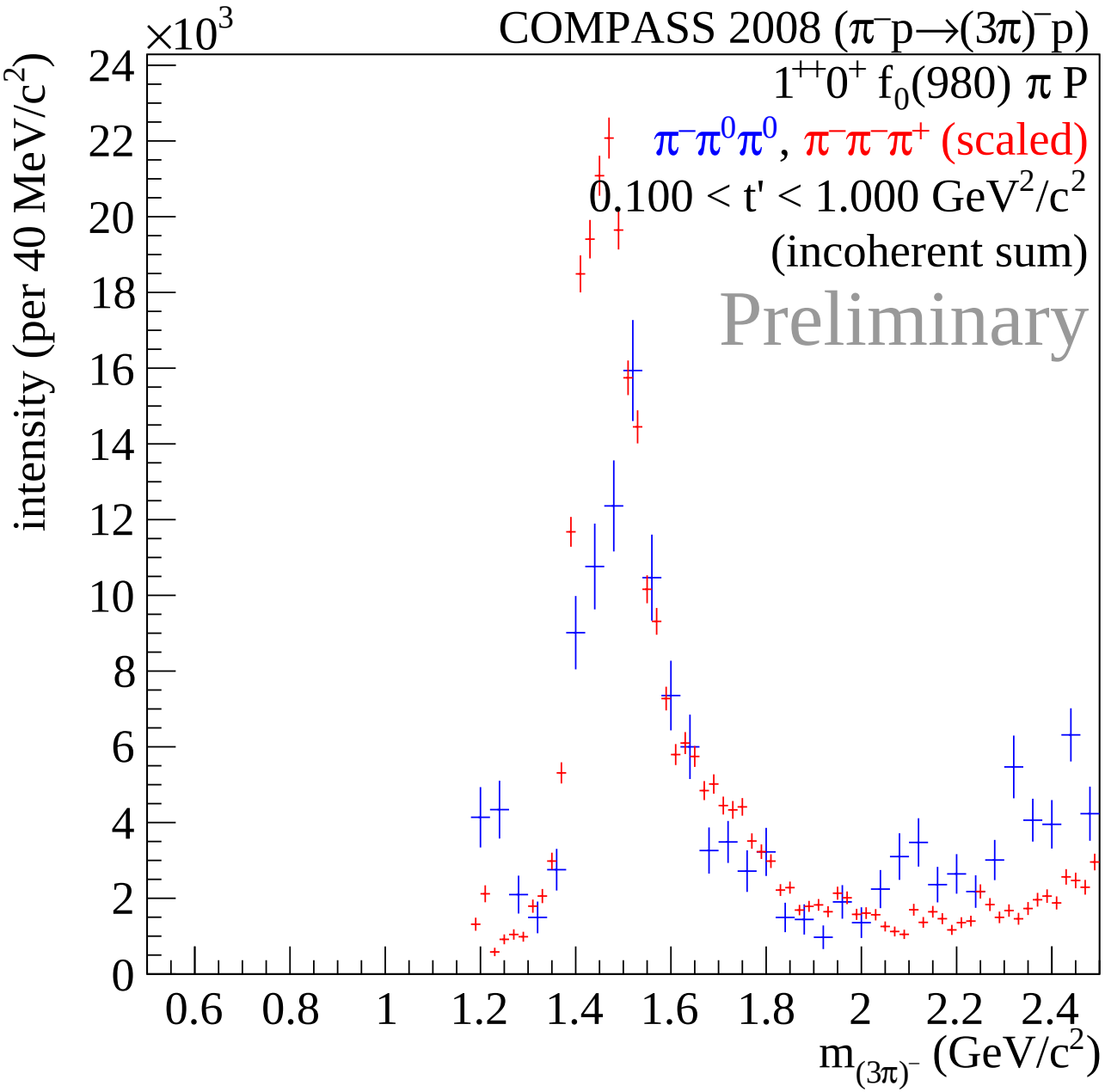
Partial-Wave Decomposition: Waves with $f_0(980)$ Isobars

$f_0(980)$ isobar

- $0^{-+}0^+ f_0(980)\,\pi S$
- $2^{-+}0^+ f_0(980)\,\pi D$
- $1^{++}0^+ f_0(980)\,\pi P$

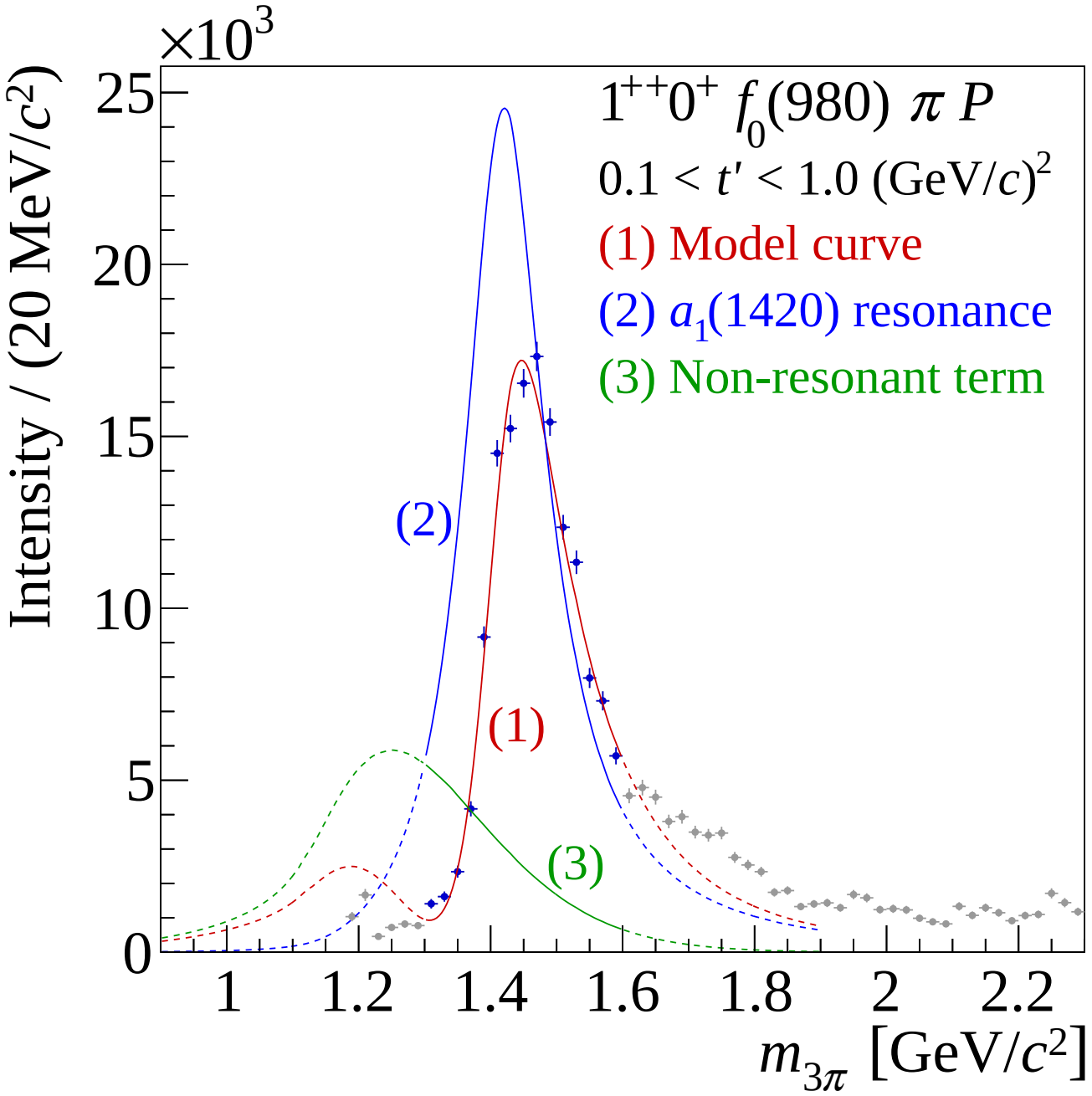
- stable fits also for non-ρ isobars
- first observation of a signal in $1^{++}0^+ f_0(980)\,\pi P$ around $1.4\,\mathrm{GeV}/c^2$

- $\pi^-\pi^0\pi^0$
- $\pi^-\pi^-\pi^+$ (scaled)
- scaled for each plot



a_1 (1420)

- shape consistent with Breit-Wigner
- mass: 1414^{+15}_{-13} MeV/c^2
- width: 153^{+8}_{-23} MeV/c^2



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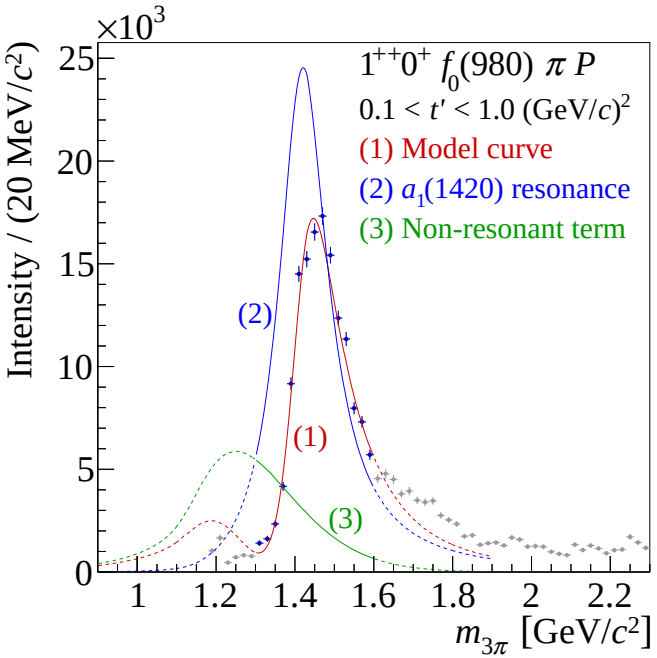
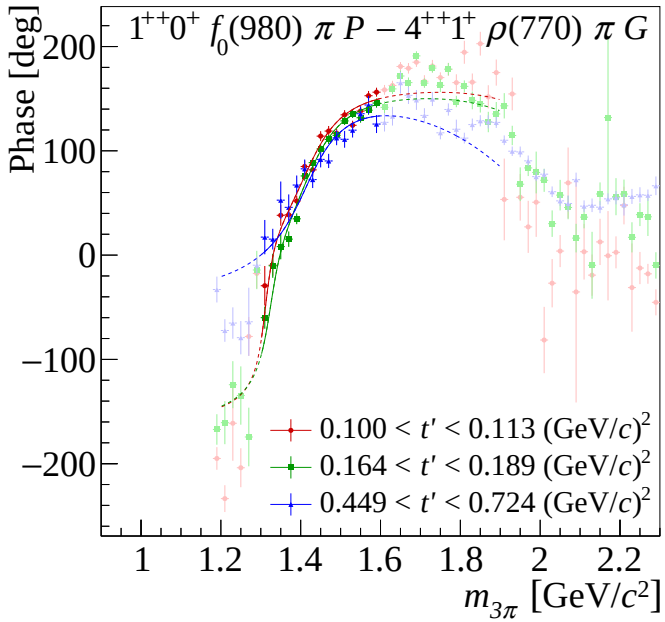
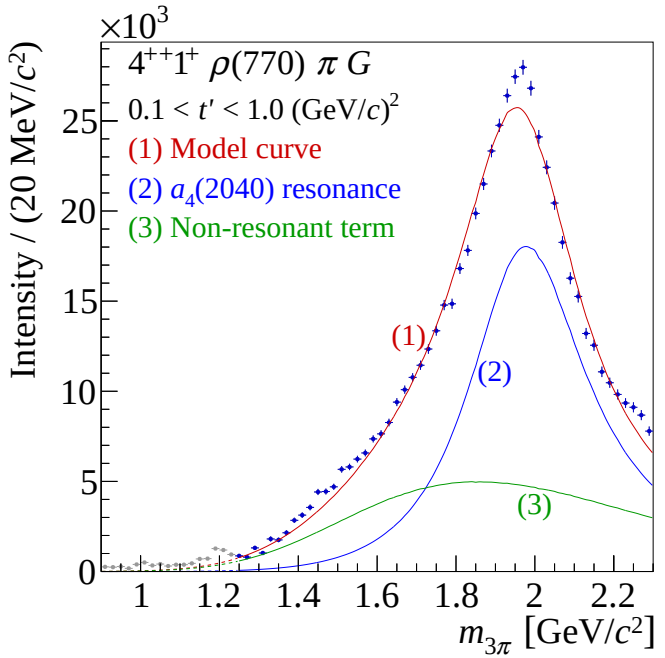




Resonance Model

- uses three waves in all t' bins
- describes a_2 (1320), a_4 (2040) and a_1 (1420)
- non-resonant contribution in each wave
- also describes the phases between waves
- extension to more partial waves in progress



Still unclear

- $J^{PC} = 1^{++}$ ground state is $a_1(1260)$
  - Mass: $1230 \pm 40\,\mathrm{MeV}/c^2$
  - Width: 250 to $400\,\mathrm{MeV}/c^2$
- No quark-model states expected at $1.4\,\mathrm{GeV}/c^2$
  - First excited 1^{++} state expected to be heavier and wider

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- Isospin partner of narrow $f_1(1420)$?
- $a_1(1420)$ has peculiar decay mode
  - Only seen in $f_0(980)\,\pi$ decay
  - $f_0(980)$ has large $s\bar{s}$ content
  - Some models explain $f_0(980)$ as tetra-quark state
- $a_1(1420)$ lies suspiciously close to $K\bar{K}^*$ threshold

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Genuine resonance

- Two-quark-tetraquark mixed state [Wang, arXiv:1401.1134]
- Tetraquark with mixed flavor symmetry [Chen *et al.*, PRD **91** (2015) 094022]

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Effect in $a_1(1260)$ production

- Two-channel unitarized Deck amplitude + direct $a_1(1260)$ production
  [Basdevant and Berger, PRL **114** (2015) 192001 and arXiv:1501.04643]

Still unclear

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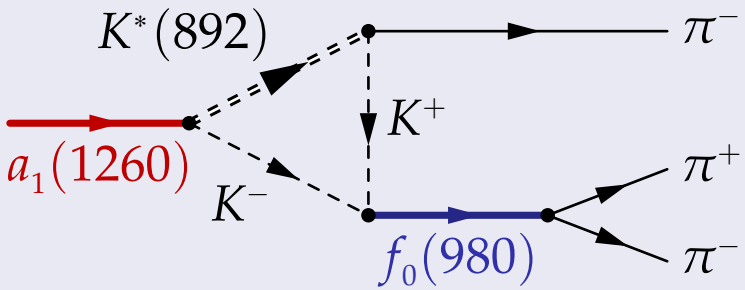
Effect in $a_1(1260)$ decay

- Singularity in triangle diagram [Mikhasenko *et al.*, PRD **91** (2015) 094015; Aceti *et al.*, arXiv:1606.06893]



Summary

COMPASS is a precision experiment to study light mesons

- unchallenged dataset for $\pi^-\pi^-\pi^+$
- charged and neutral particles with the same experimental setup

partial-wave analysis is a versatile tool for spectroscopy

- various channels under study
- t'-resolved analysis
  - better separation of resonant and non-resonant contributions
  - first resonance-model fit in 11 t' bins
- new state $a_1(1420)$
  - observed in intensity and phase motion with respect to reference waves
  - $M_{a_1(1420)} = 1414^{+15}_{-13}\,\mathrm{MeV}/c^2$, $\Gamma_{a_1(1420)} = 153^{+8}_{-23}\,\mathrm{MeV}/c^2$

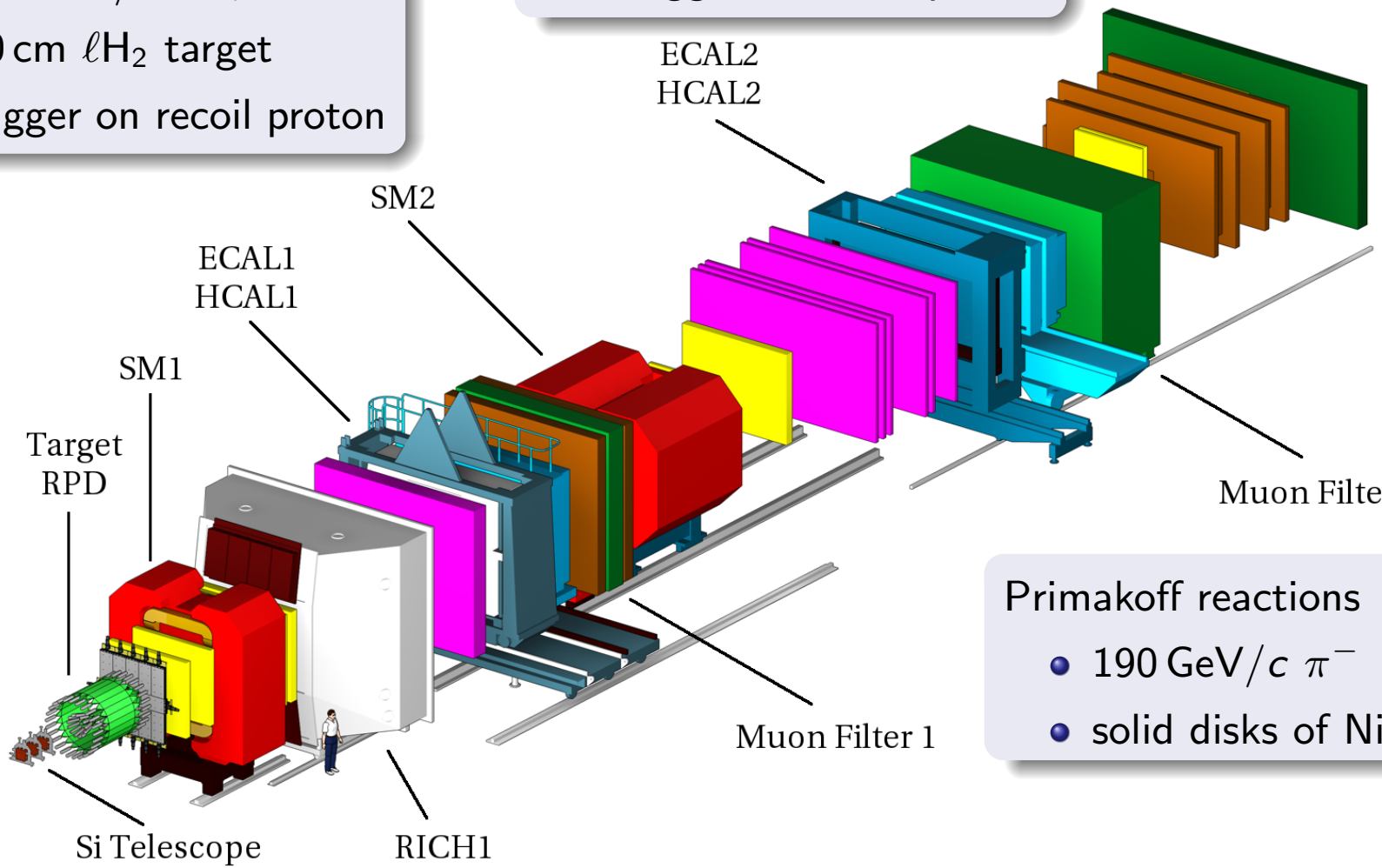
Backup

central production

- 190 GeV/c p
- 40 cm ℓH_2 target
- trigger on recoil proton

diffractive dissociation

- 190 GeV/c π^-, K^-
- 40 cm ℓH_2 target
- trigger on recoil proton



Primakoff reactions

- 190 GeV/c π^-
- solid disks of Ni or Pb

Partial-Wave Decomposition

different t' bins

- $1^{++}0^{+}\rho(770)\pi S$
- $2^{++}1^{+}\rho(770)\pi D$
- position of peak in $1^{++}0^{+}$ changes
- a_2 not affected

- $\pi^-\pi^0\pi^0$
- $\pi^-\pi^-\pi^+$ (scaled)
- scaled for each plot
- good agreement between channels