Studies of light mesons at COMPASS

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On Behalf of the COMPASS Collaboration

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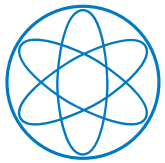
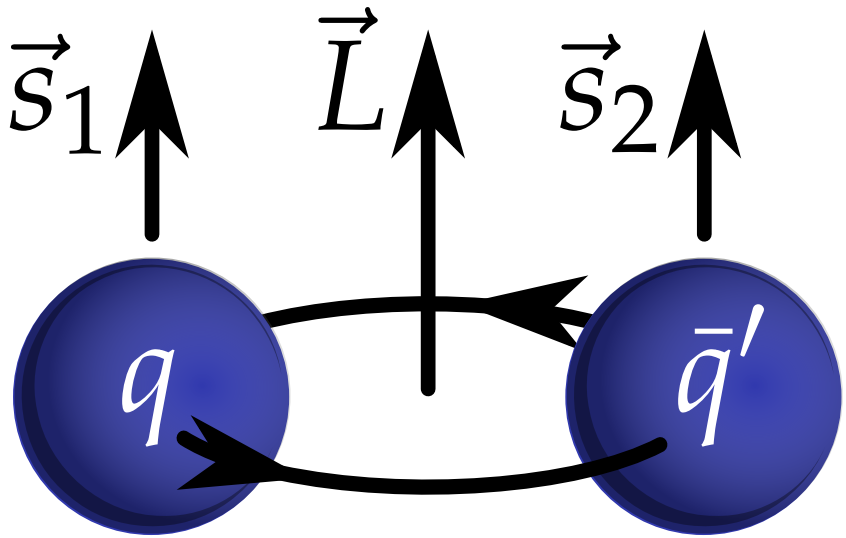


PANIC2014 28.08.2014

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 $C = (-1)^{L+S}$
- forbidden J^{PC}: $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$



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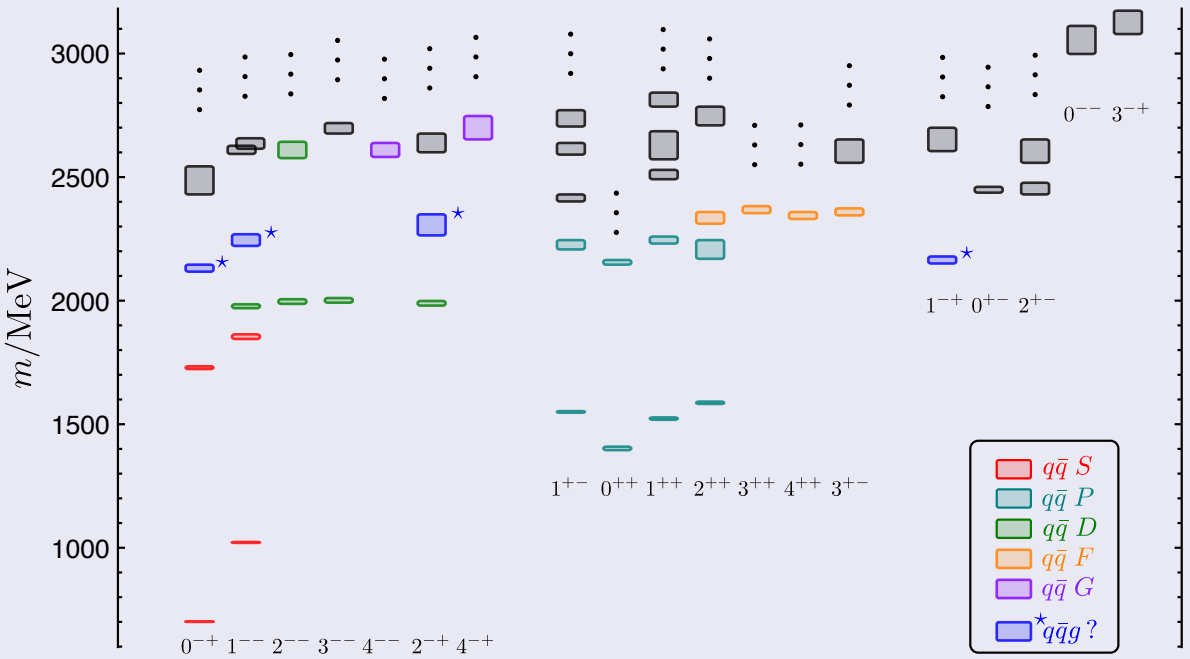


J.Dudek, Phys.Rev.D84 (2011) 074023

Beyond the CQM: i.e. lattice QCD

isovector states

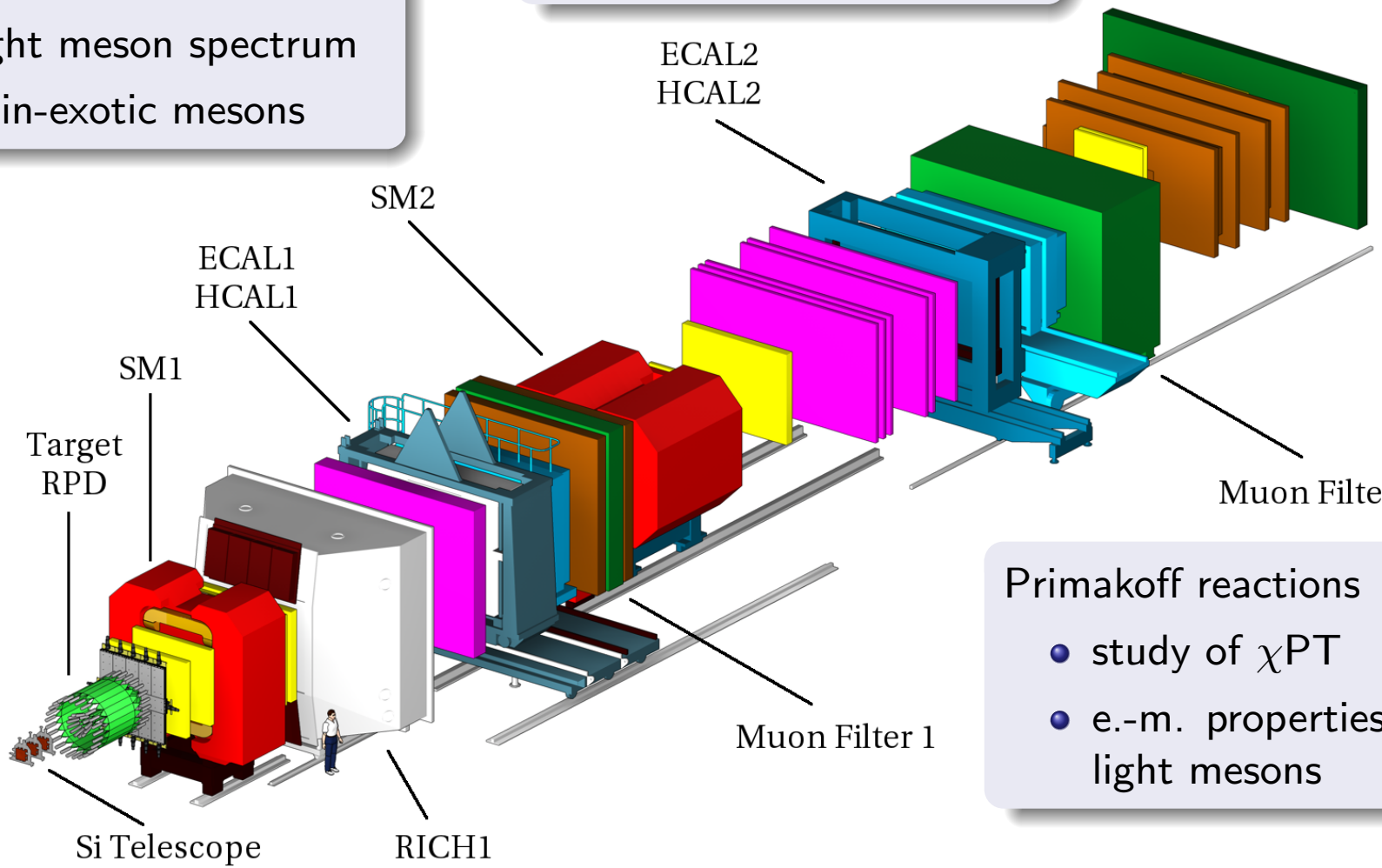
- prediction of states outside CQM
- hybrid candidate ($q\bar{q}g$)
- lightest candidate in 1^{-+}

in addition:

- (isoscalar) glueballs
- pure glue
- quantum numbers J^{PC}: 0^{++}, ...

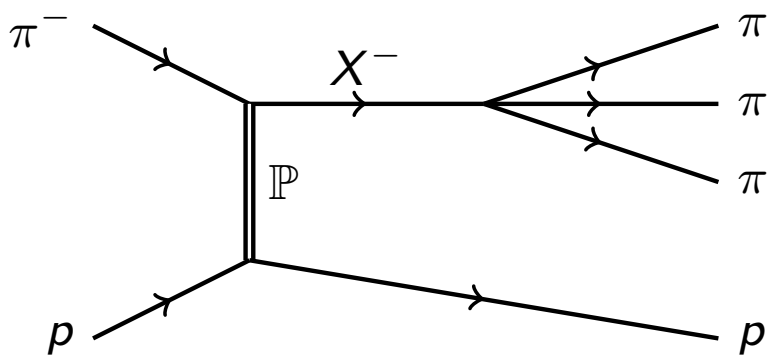
central production
- glue-rich environment
- scalar resonances

diffractive dissociation
- light meson spectrum
- spin-exotic mesons

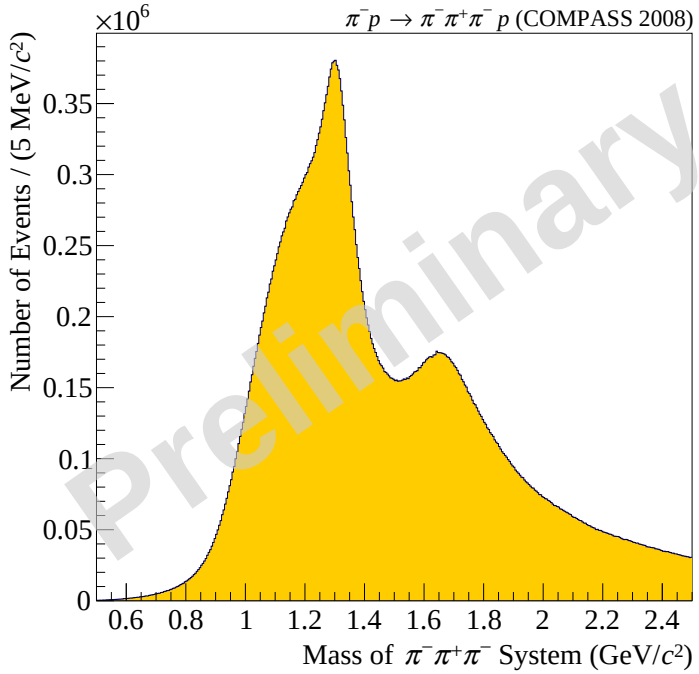


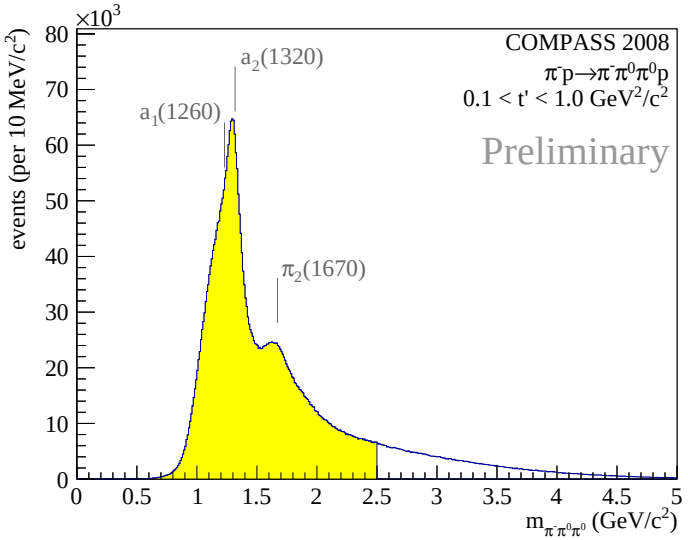
Primakoff reactions
- study of χPT
- e.-m. properties of light mesons

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



- 190 GeV/c π^- beam on ℓH_2 target
- exclusive $\pi^- p \to (3\pi)^- p$ reaction
- two channels in COMPASS
  - $\pi^-\pi^-\pi^+$
  - $\pi^-\pi^0\pi^0$
- high-t' region: $0.1 < t' < 1.0\,\mathrm{GeV}^2/c^2$
- huge dataset
  - 50 million $\pi^-\pi^-\pi^+$ events
  - 3.5 million $\pi^-\pi^0\pi^0$ events





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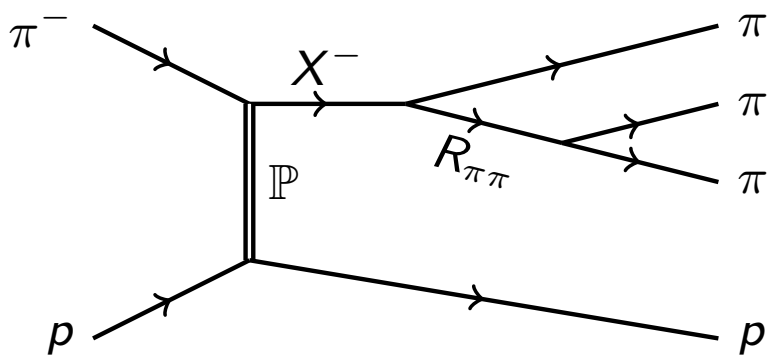

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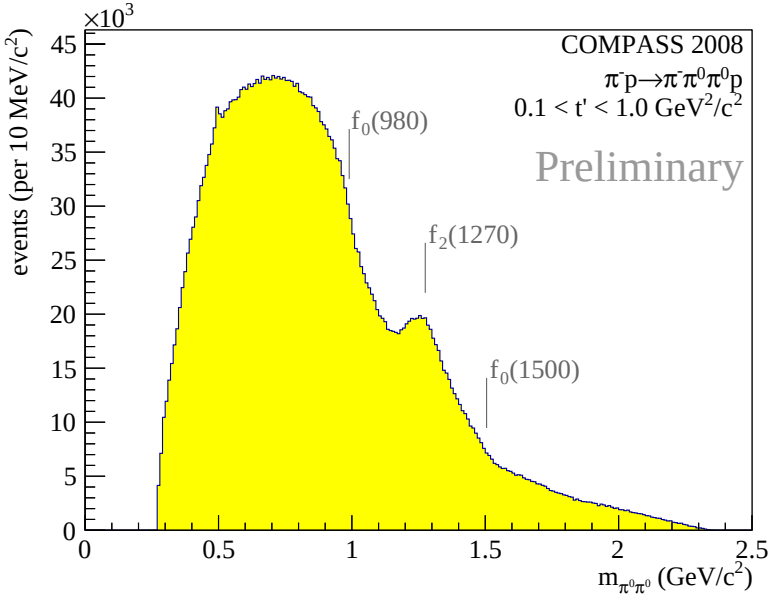
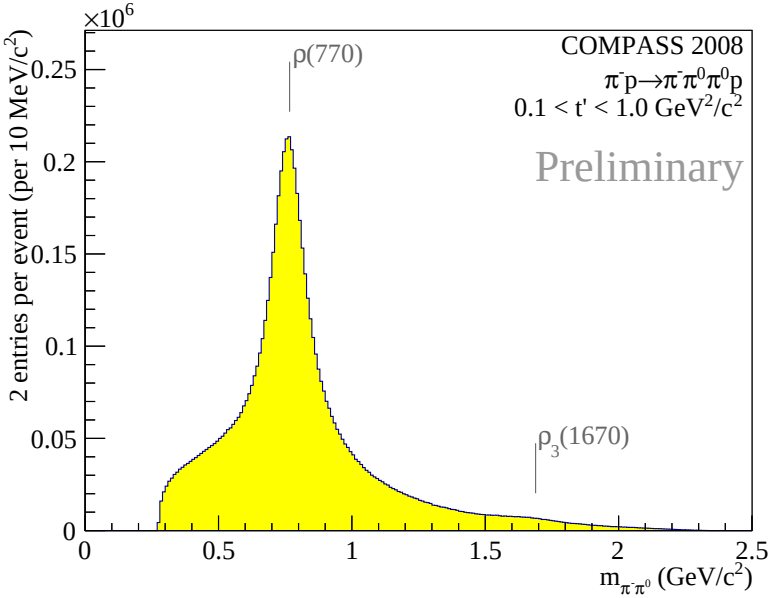
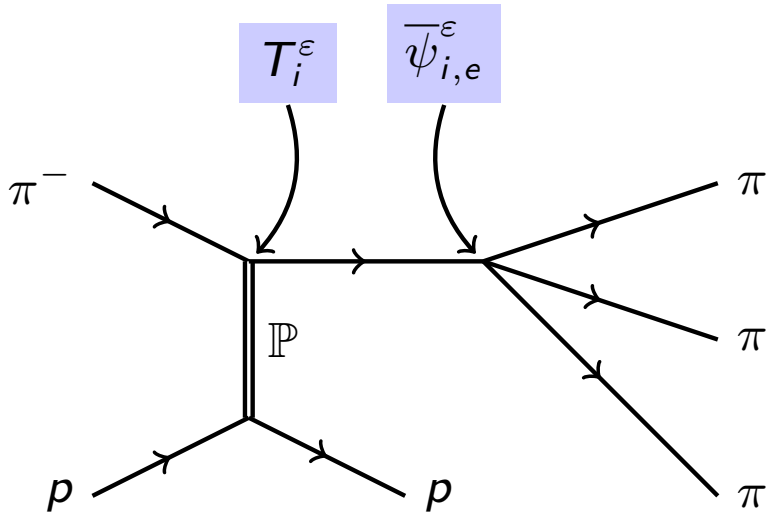
- partial-wave analysis using isobar model



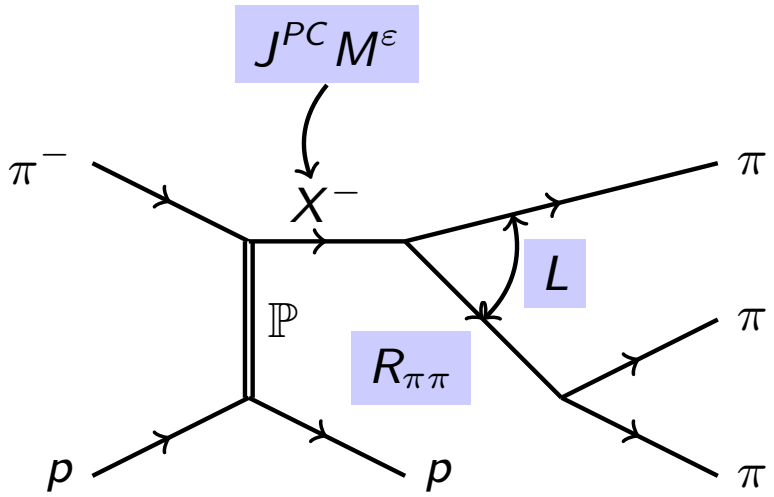


Partial-Wave Analysis



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

Partial-Wave Analysis

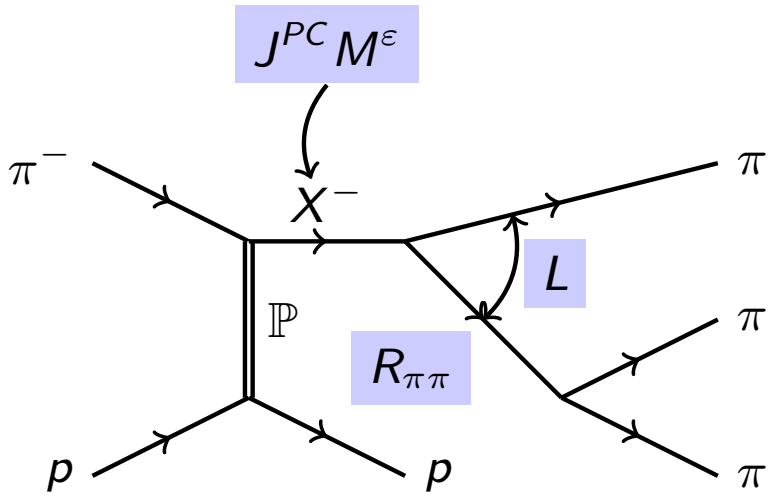


- process can be factorized
  - production T_i^{ε}
  - decay $\overline{\psi}_{i,e}^{\varepsilon}$
- two-step approach

1. fit in mass and t' bins
   - extract production amplitudes T_i^{ε}

- 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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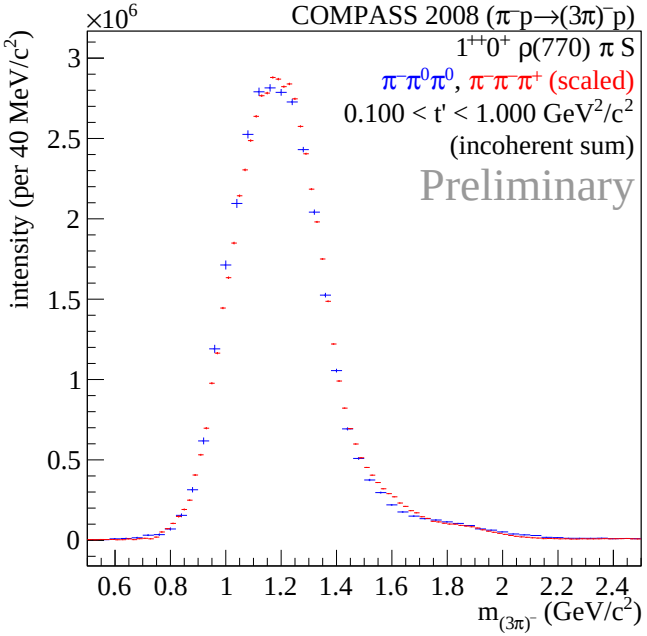
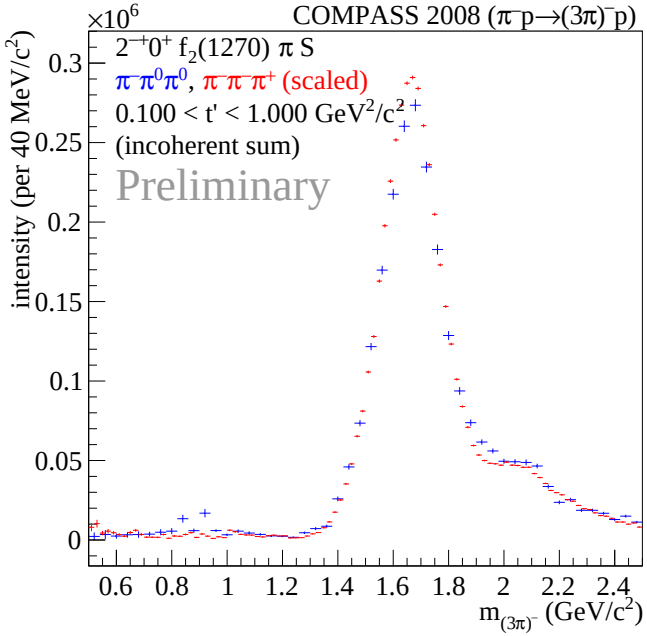
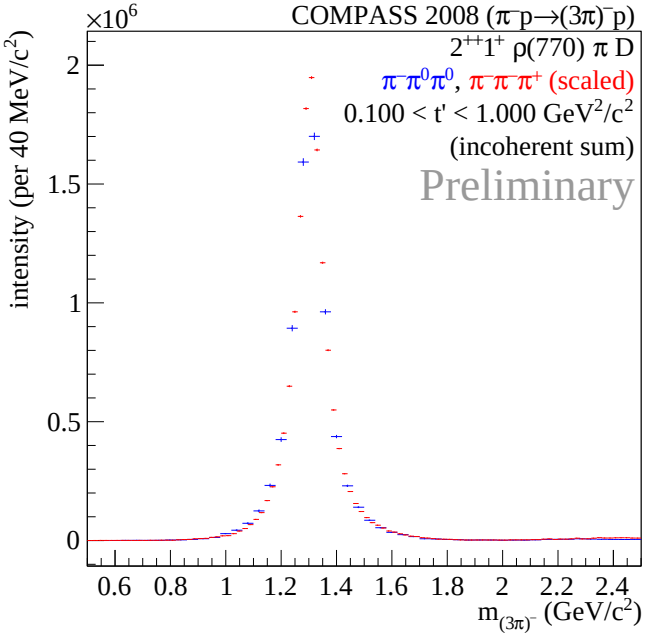
Mass-independent fit

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

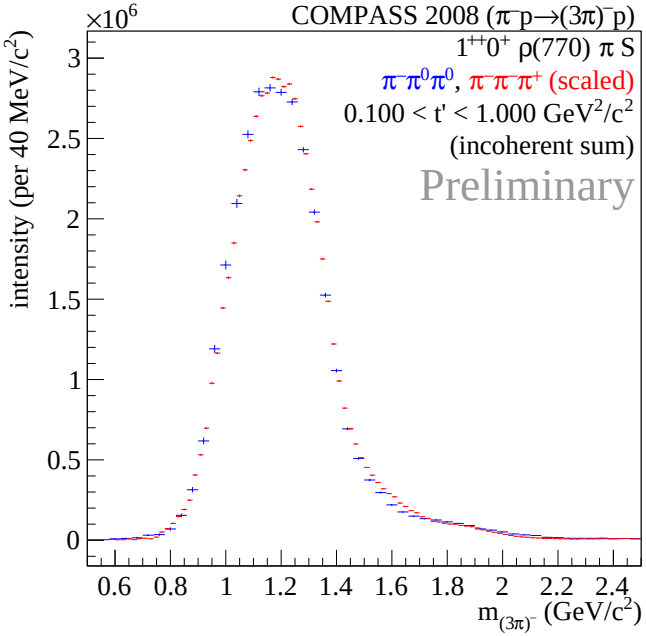
Mass-independent fit

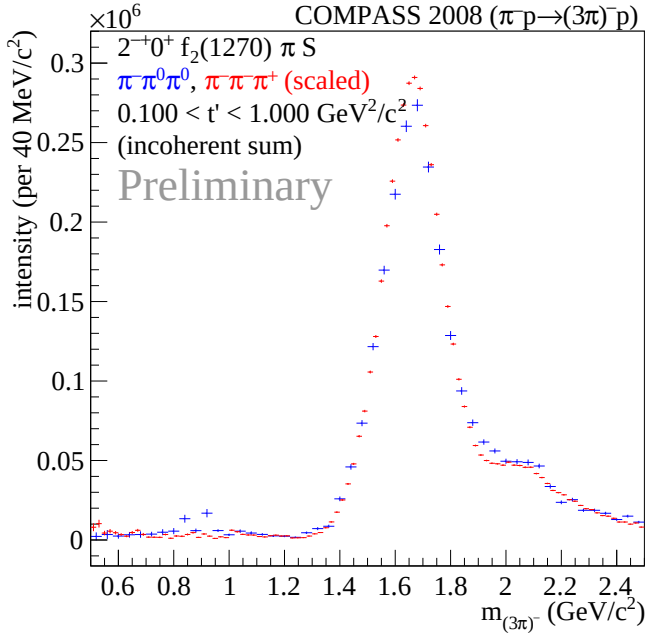
major and minor waves

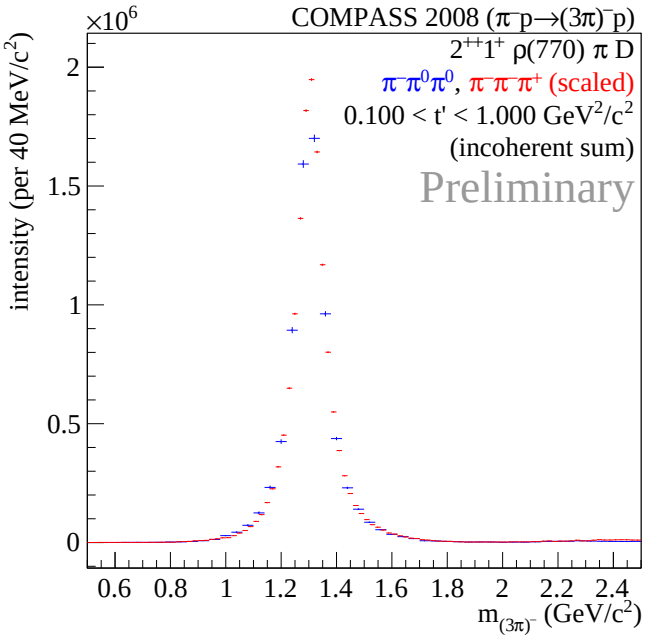
- $1^{++}0^{+}\rho(770)\pi S$
- $2^{-+}0^{+}f_2(1270)\pi S$
- $2^{++}1^{+}\rho(770)\pi D$
- $0^{-+}0^{+}f_0(980)\pi S$

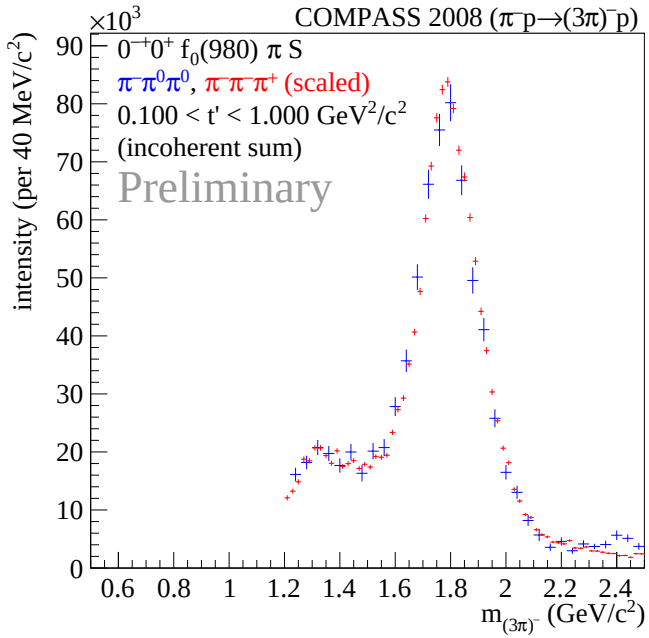
stable fits also for small waves

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







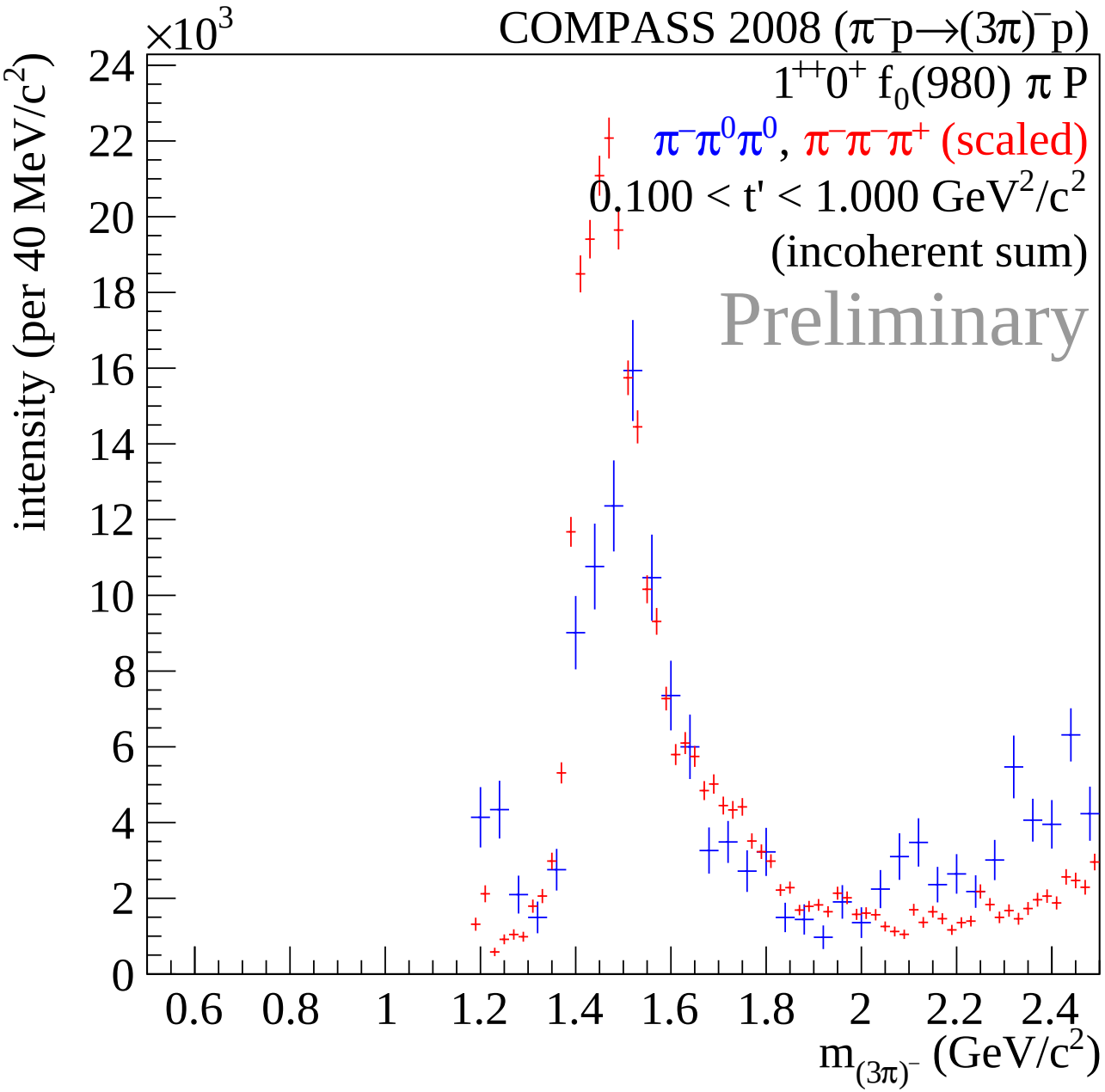


Mass-independent fit

$f_0(980)$ isobar

- $1^{++}0^+ f_0(980)\,\pi P$
- stable fits also for small waves
- 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

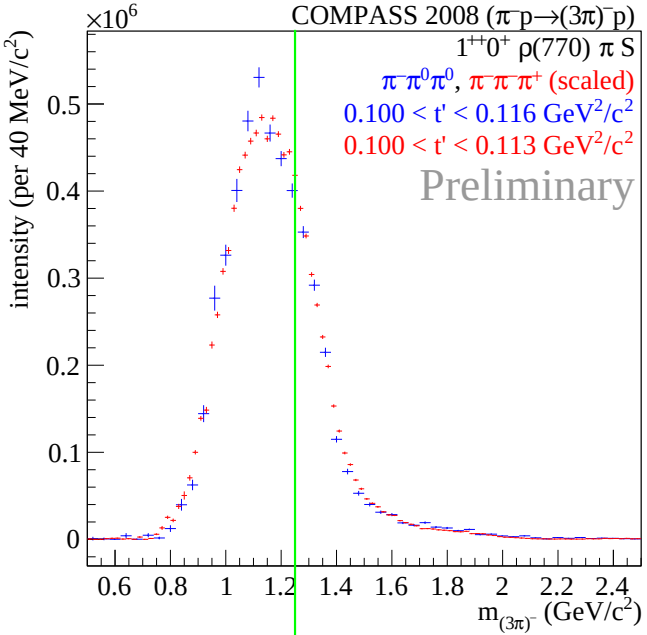


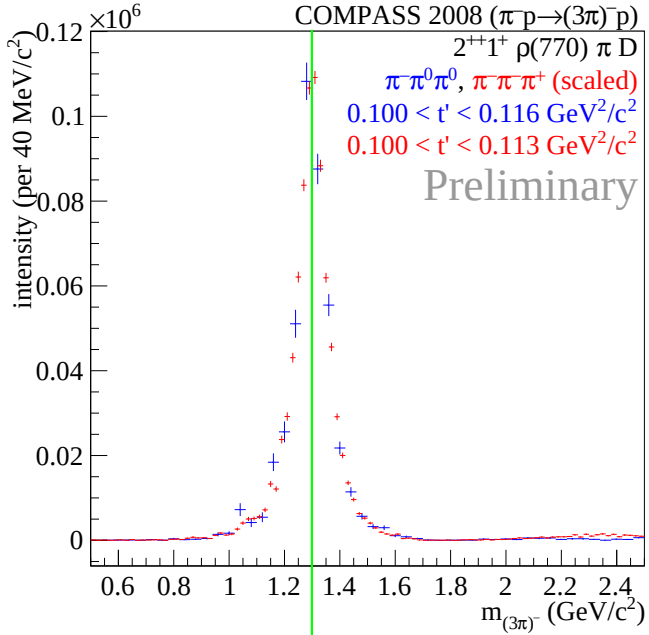
Mass-independent fit

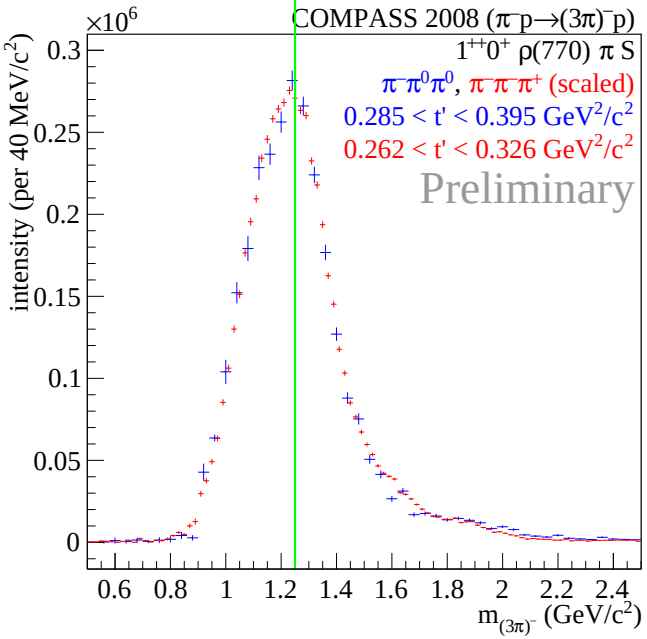
different t' bins

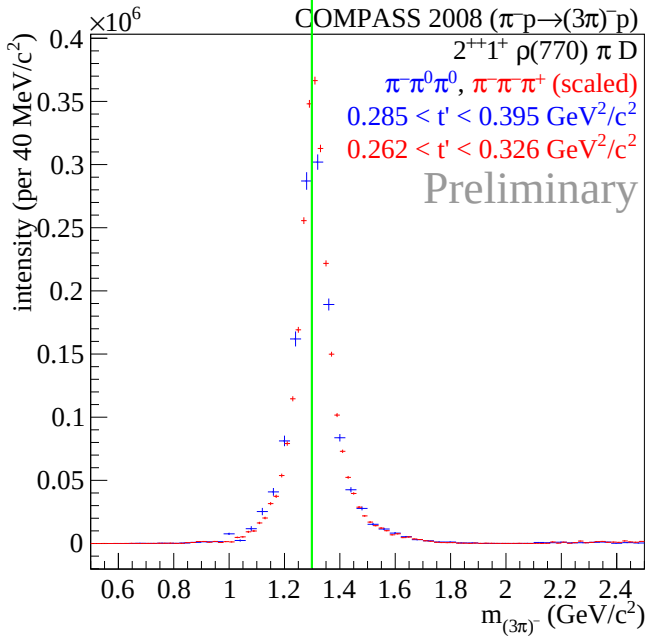
- $1^{++}0^{+}\rho(770)\pi S$
- $2^{++}1^{+}\rho(770)\pi D$
- position of peak in $1^{++}0^{+}$ changes
- a_2 not affected

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









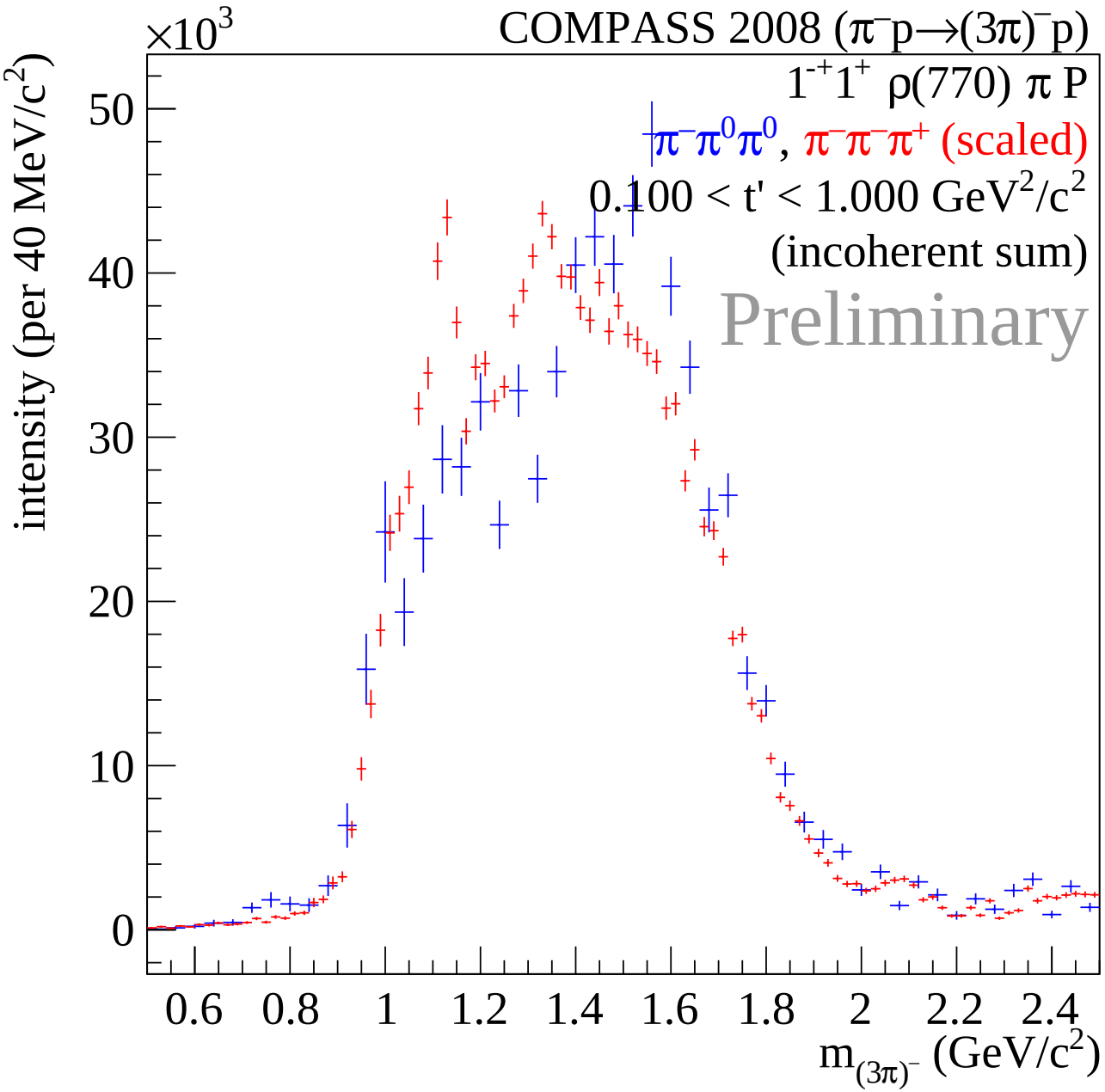
Exotic $J^{PC} = 1^{-+}$ wave

$1^{-+}1^{+}\rho(770)\pi P$

complete t' range

- some differences between channels
- no clear $\pi_1(1600)$ peak

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



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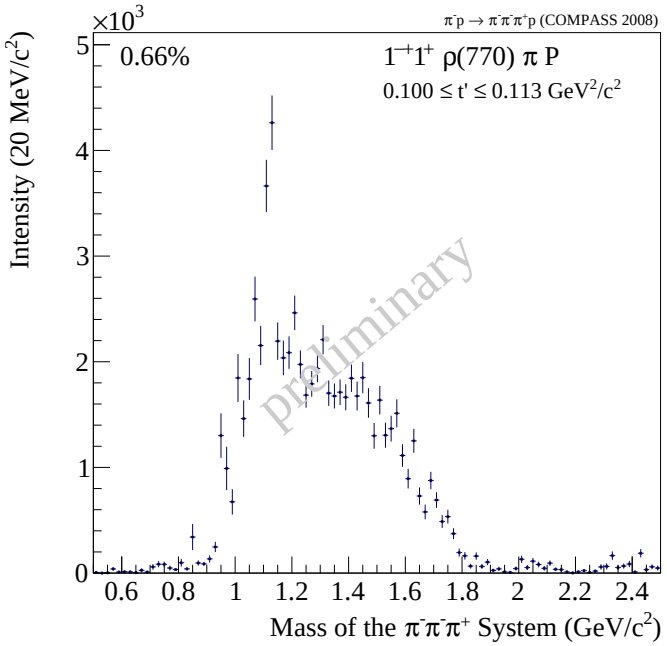
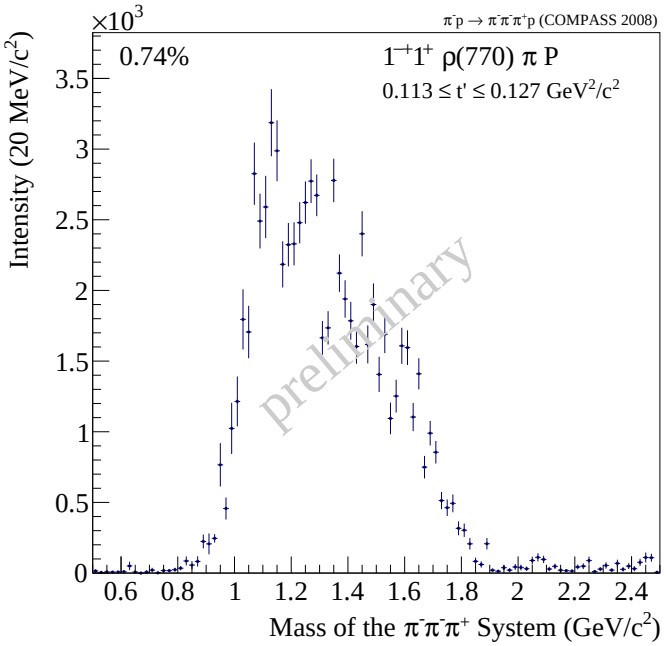
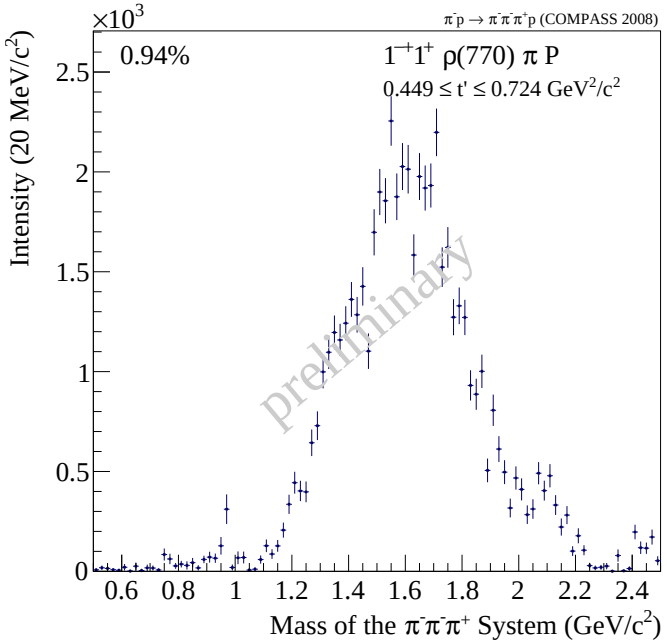
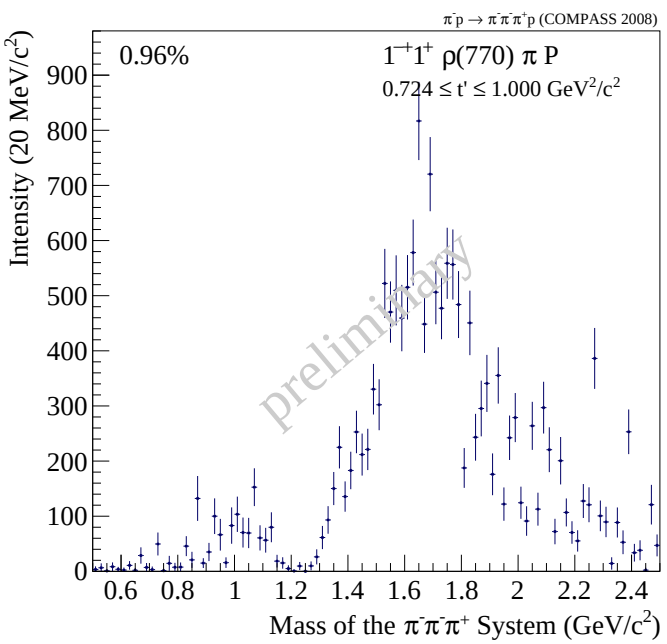
individual t' bins

- peak at $1.6\,\mathrm{GeV}/c^2$ at higher t'
- non-resonant contribution at low t'









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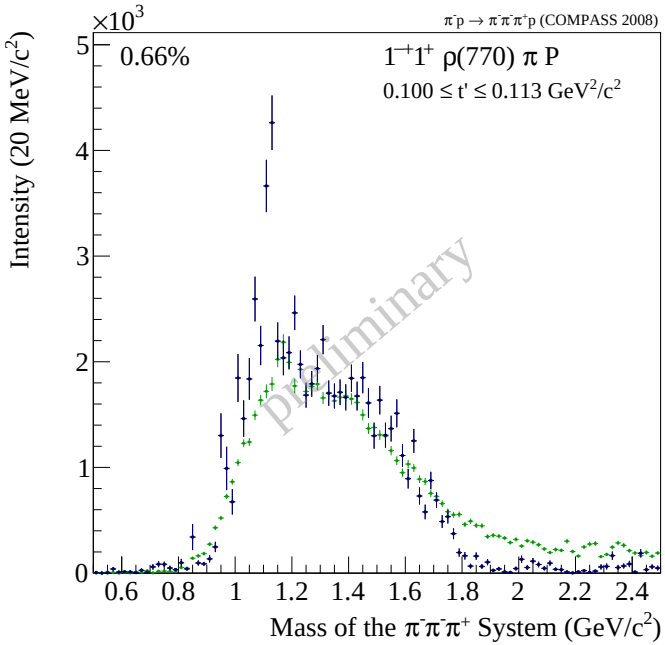
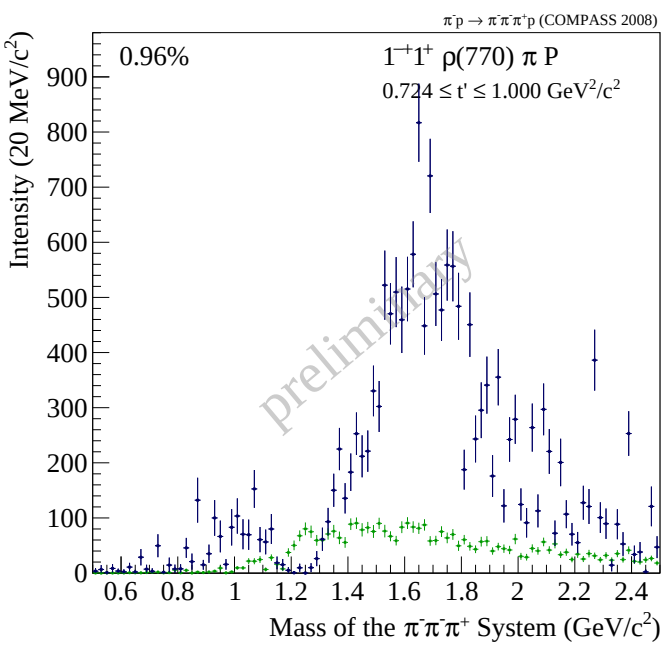
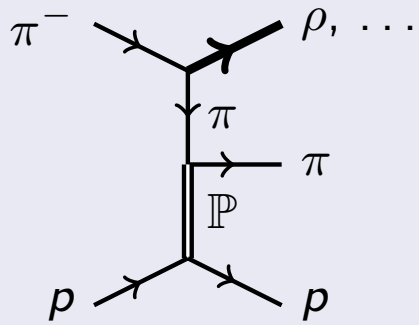




Deck effect



- Deck model projected to individual waves
- scaled to the sum of intensities over all t' bins for each wave
- large contribution at low t' predicted for $1^{-+}1^{+}\rho(770)\pi P$

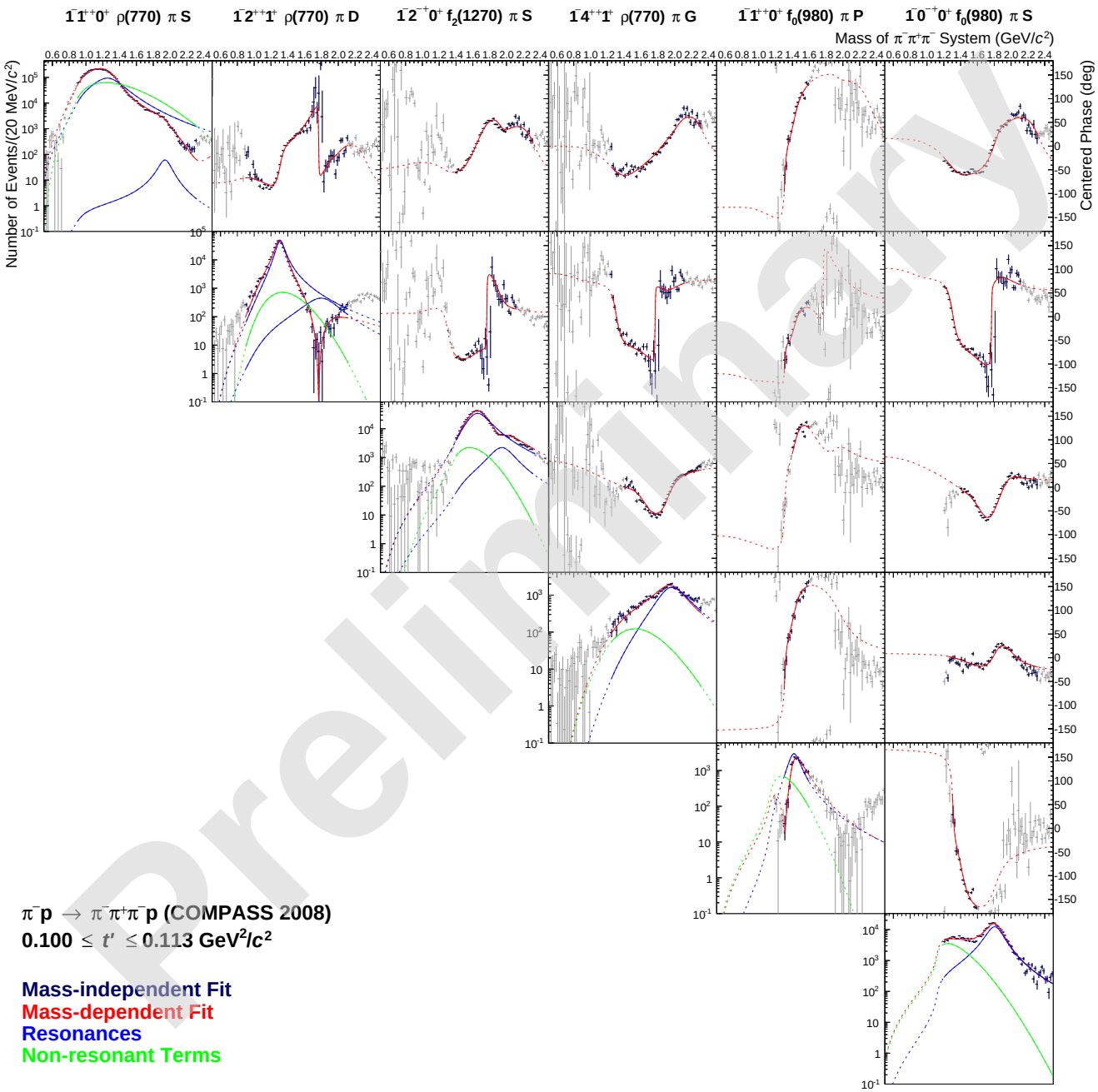
Model

- for the moment six waves
  - three major waves and three smaller waves
- describe spin-density sub-matrix with Breit-Wigner functions

$1^{++}0^+\rho(770)\pi S$	two BW:	$a_1(1260)$, a_1'
$2^{-+}0^+f_2(1270)\pi S$	two BW:	$\pi_2(1670)$, $\pi_2(1880)$
$2^{++}1^+\rho(770)\pi D$	two BW:	$a_2(1320)$, a_2'
$4^{++}1^+\rho(770)\pi G$	one BW:	$a_4(2040)$
$1^{++}0^+f_0(980)\pi P$	one BW:	$a_1(1420)$
$0^{-+}0^+f_0(980)\pi S$	one BW:	$\pi(1800)$

- non-resonant term for each wave
- extract resonance parameters from all 11 t' bins simultaneously
  - same resonance parameters in all bins
  - couplings may vary
- 352 free parameters, around 15 000 data points

Mass-dependent fit for $\pi^-\pi^-\pi^+$



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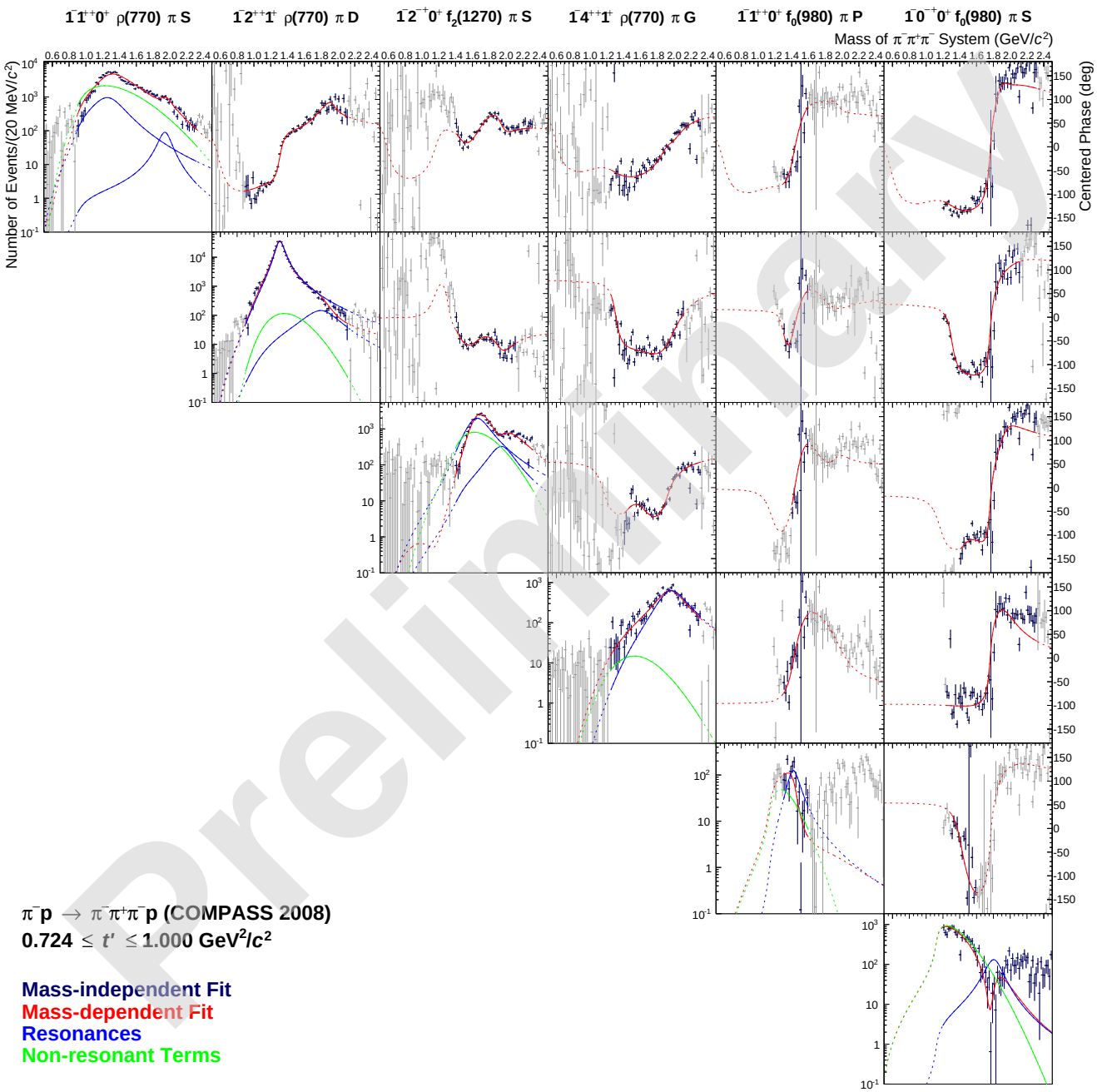
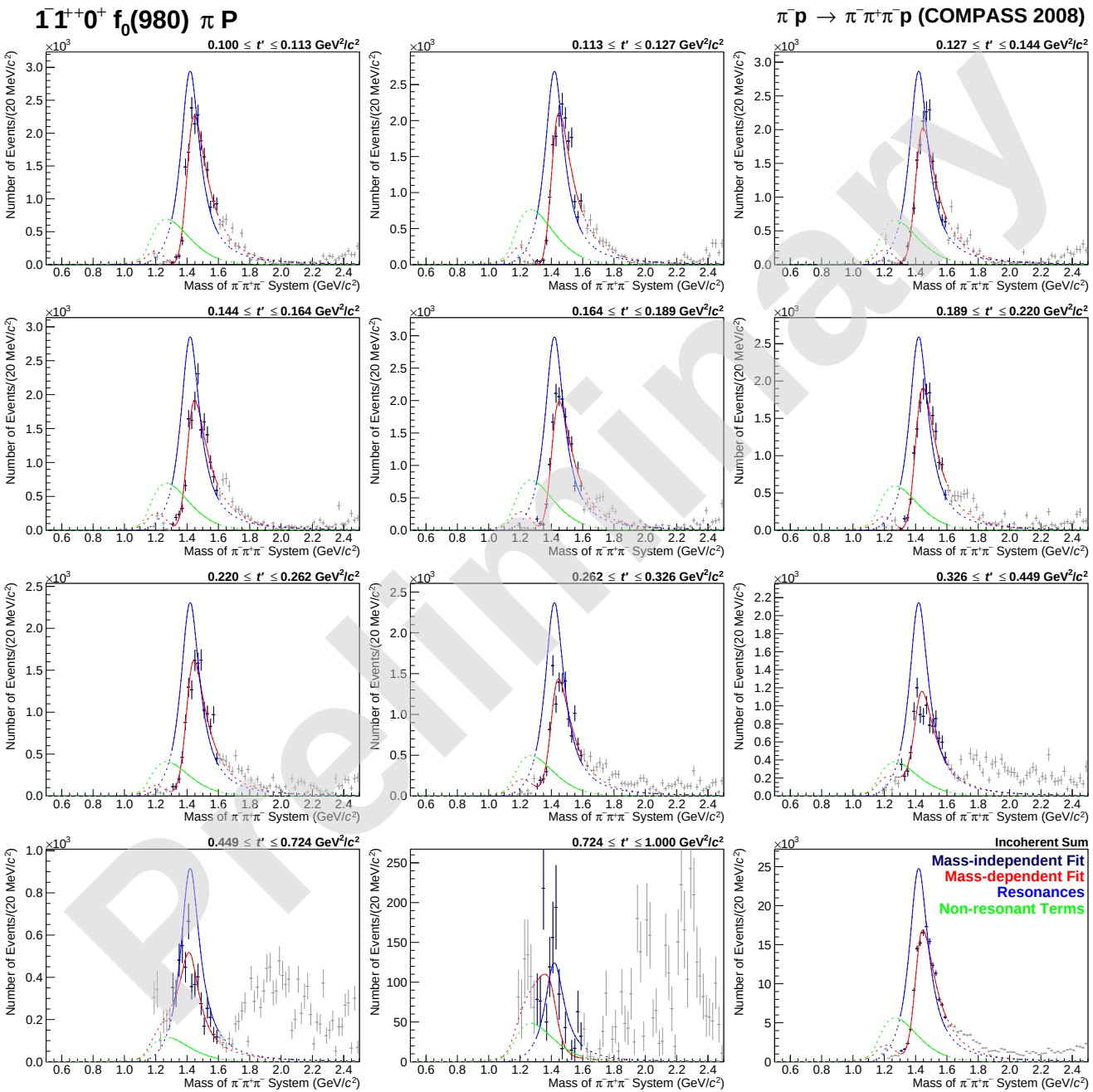


$\pi^-p \rightarrow \pi^-\pi^+\pi^-p$ (COMPASS 2008)
$0.724 \leq t' \leq 1.000$ GeV$^2/c^2$

Mass-independent Fit
Mass-dependent Fit
Resonances
Non-resonant Terms

Mass-dependent fit of $1^{++}0^{+}f_0(980)\pi P$



for new $a_1(1420)$

- mass
  $1412 - 1422\,\mathrm{MeV}/c^2$
- width
  $130 - 150\,\mathrm{MeV}/c^2$
- well determined
- narrow

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, first mass-dependent fit in 11 t' bins
- new resonance $a_1\,(1420)$:
  - $M_{a_1(1420)} = 1412 - 1422\,\mathrm{MeV}/c^2$, $\Gamma_{a_1(1420)} = 130 - 150\,\mathrm{MeV}/c^2$
  - $\sim 180^\circ$ phase motion with respect to reference waves
- detailed study of the 1^{-+} state ($\pi_1\,(1600)$)

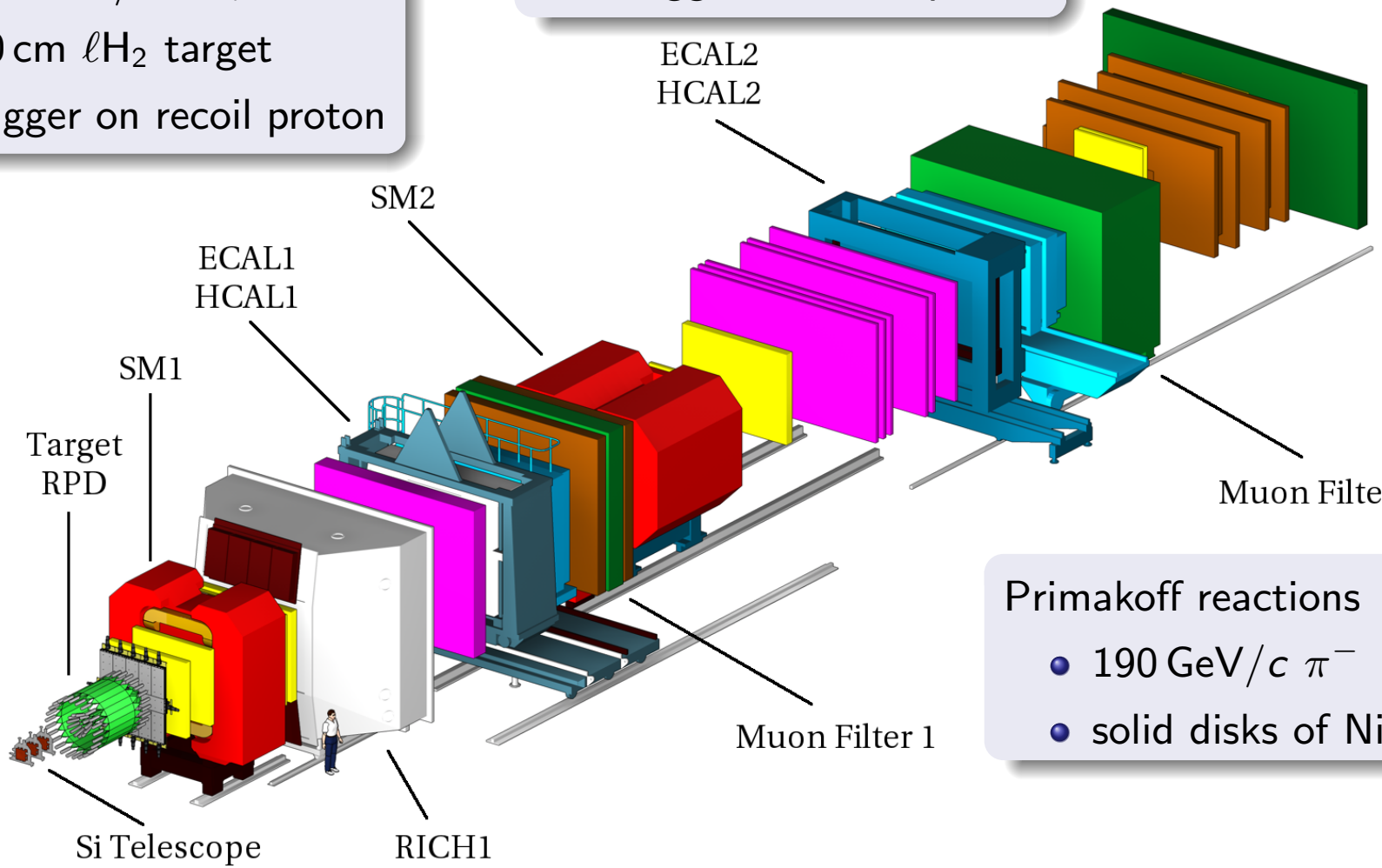
further analyses in the COMPASS hadron program

- spectroscopy also in central production reactions
- measurement of radiative width of $a_2\,(1320)$ and $\pi_2\,(1670)$
- measurement of π polarizability and other tests of χPT
- measurement of OZI violation

Backup

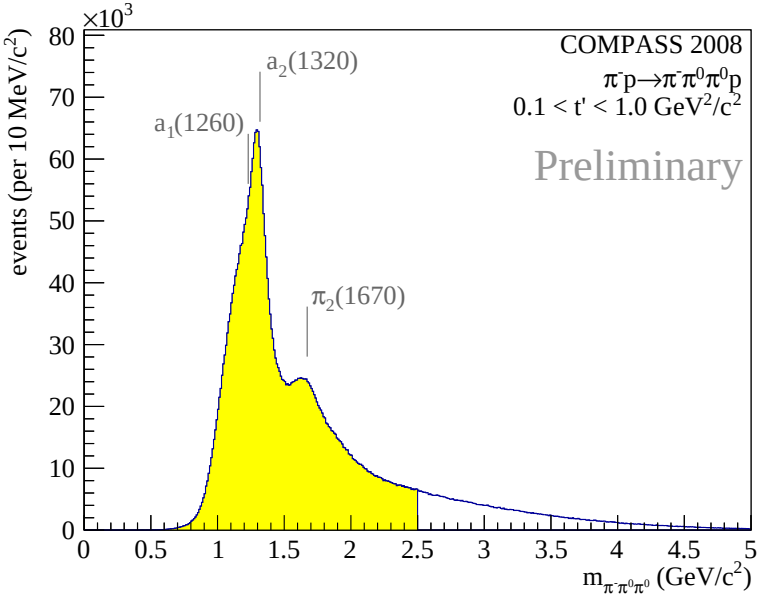
central production
- 190 GeV/c p
- 40 cm ℓH_2 target
- trigger on recoil proton

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

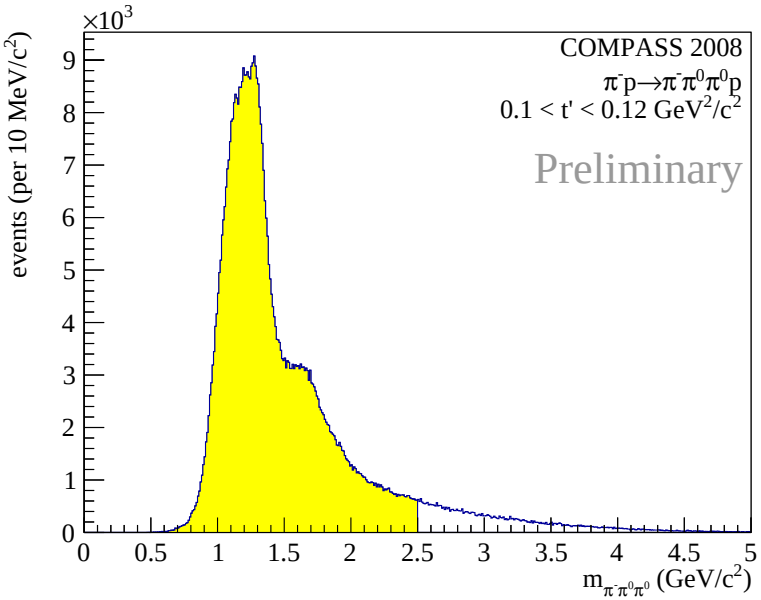


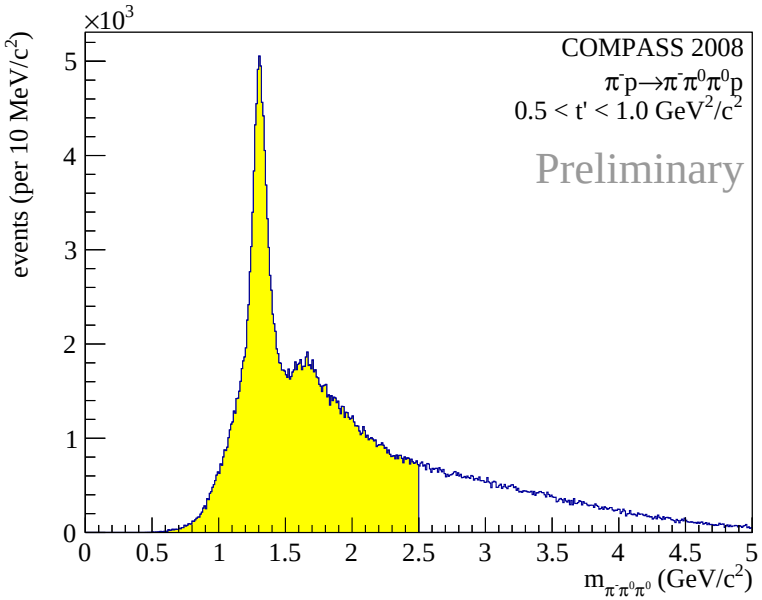
Primakoff reactions
- 190 GeV/c π^-
- solid disks of Ni or Pb

Binning in t'



- mass spectrum depends on t'
- at low-t' $(0.1 < t' < 0.2\,\mathrm{GeV}^2/c^2)$
  - $a_1\,(1260)$ dominates low-mass region
  - $a_2\,(1320)$ hardly visible
- at high-t' $(0.5 < t' < 1.0\,\mathrm{GeV}^2/c^2)$
  - $a_1\,(1260)$ 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 $\pi^-\pi^0\pi^0$





data binned

- in 50 mass bins of $40\,\mathrm{MeV}/c^2$ width
- in 8 t' bins with equal amount of statistics

in each mass and t' bin optimize

$$\log \mathcal{L} = -\sum_{e}^{\text{RD evts.}} \log\left(\sum_{\varepsilon}^{\text{refl.}} \left|\sum_{i}^{\text{waves}} T_i^{\varepsilon} \cdot \overline{\psi}_{i,e}^{\varepsilon}\right|^2\right) + \sum_{\varepsilon}^{\text{refl.}} \left(\sum_{i,j}^{\text{waves}} T_i^{\varepsilon} \cdot \left(T_j^{\varepsilon}\right)^* \cdot \overline{\mathcal{A}}_{ij}^{\varepsilon}\right)$$

Spin-density matrix

$$\rho_{ij}^{\varepsilon} = T_i^{\varepsilon} \cdot \left(T_j^{\varepsilon}\right)^*$$

intensity

$$I_i^{\varepsilon} = \rho_{ii}^{\varepsilon}$$

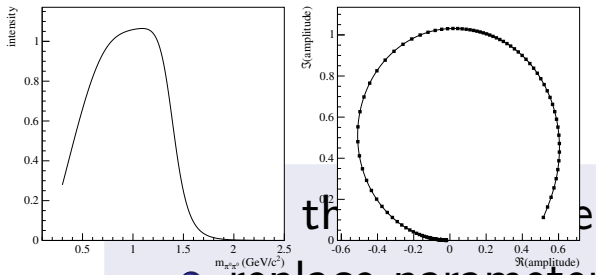
absolute value and phase

$$\rho_{ij}^{\varepsilon} = r_{ij}^{\varepsilon} e^{i \cdot \varphi_{ij}^{\varepsilon}}$$

Extraction of $(\pi\pi)_S$ wave from data

- for the mass-independent fit
- replace parameterizations
  - Au, Morgen, Pennington M-solution for $(\pi\pi)_S$ wave
  - Flatté parameterization from BES-II for $f_0\,(980)$
  - Breit-Wigner for $f_0\,(1500)$
- by piecewise constant amplitude in bins of $m_{\pi\pi}$
  - $10\,\mathrm{MeV}/c^2$ wide around the $f_0\,(980)$
  - $40\,\mathrm{MeV}/c^2$ wide elsewhere

Extraction of $(\pi\pi)_S$ wave from data



- th… ependent fit
- replace parameterizations
- org… ton M-solution for
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- Wig… 500)
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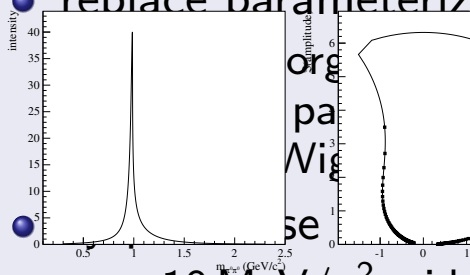

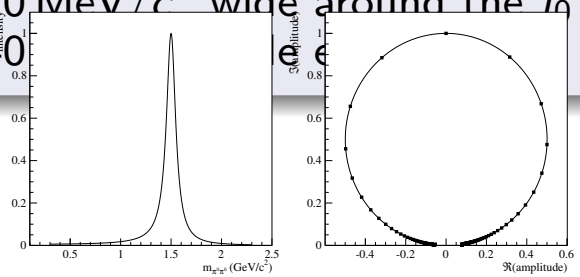

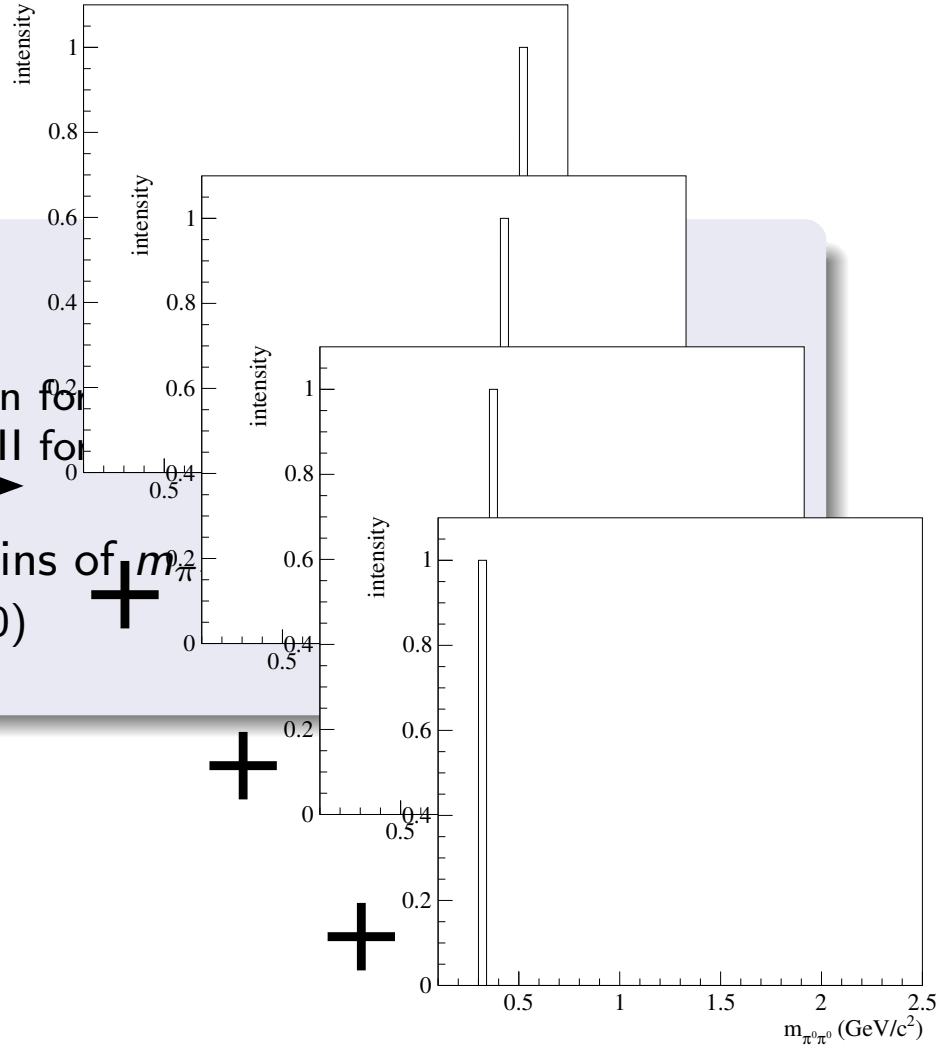

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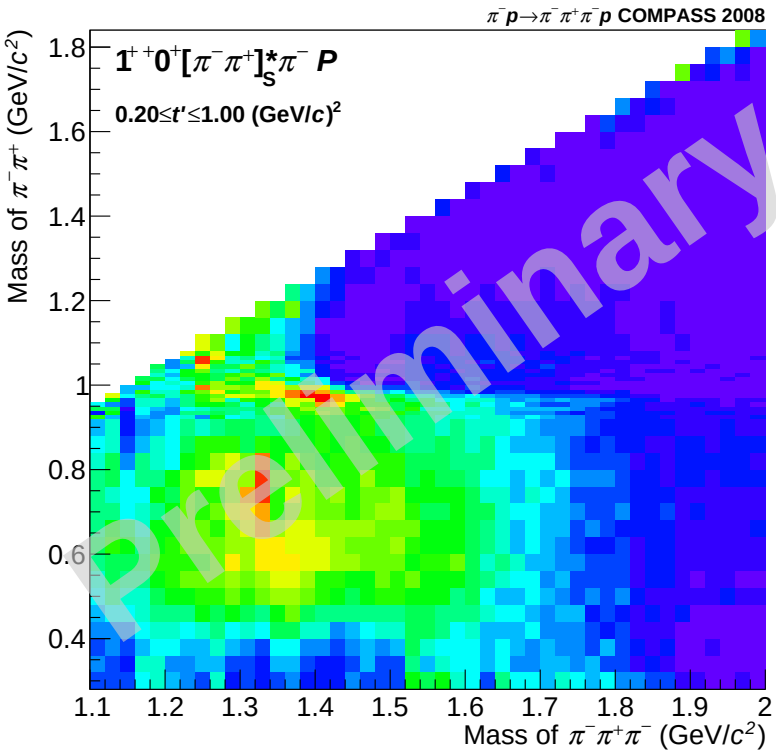
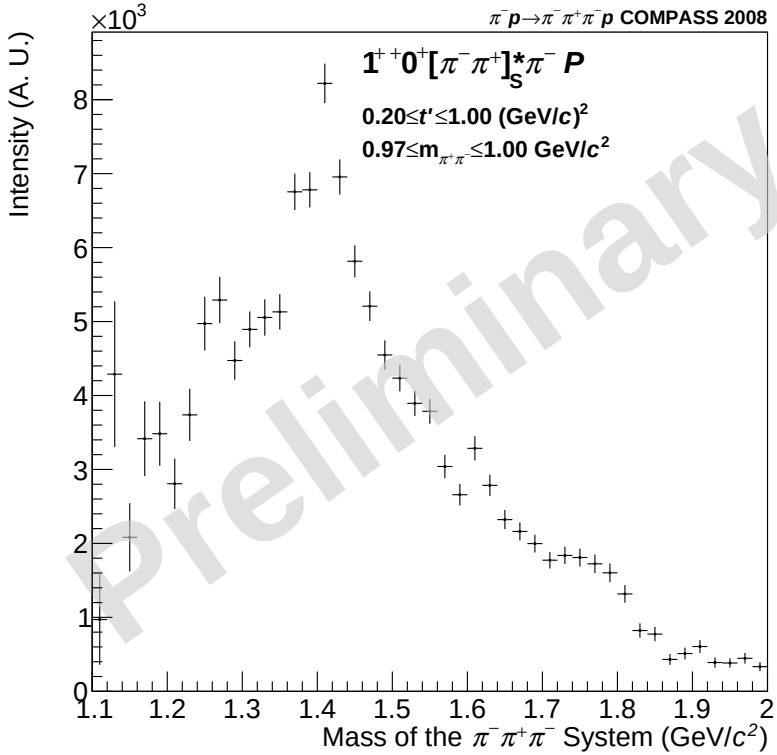
- increase in number of fit parameters
- requires a lot of data
- only done for 0^{-+}, 1^{++}, 2^{-+}

Extraction of $(\pi\pi)_S$ wave from data





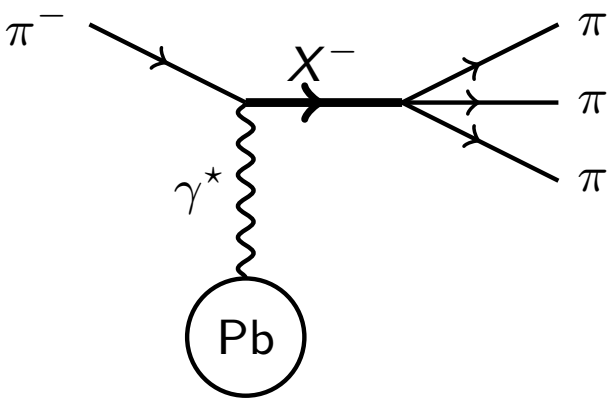
application to 1^{++}

- high-t': $0.2 < t' < 1.0\,\mathrm{GeV}^2/c^2$
- select $m_{2\pi}$ region around $f_0\,(980)$
- correlation of $a_1\,(1420)$ with $f_0\,(980)$

Radiative width

- decay $X \to \pi\gamma$ allows access to electromagnetic transitions
  - $a_2\,(1320) \to \pi\gamma$ magnetic quadrupole moment
  - $\pi_2\,(1670) \to \pi\gamma$ electric quadrupole moment
- direct measurement of $\pi\gamma$ decay is experimentally challenging
- inverse process: scattering of a π off a Coulomb potential
  - quasi-real photons in the vicinity of heavy nuclei
- cross-section for Primakoff produced X

$$\sigma_{\text{Primakoff},X} \propto \Gamma_0\,(X \to \pi\gamma)$$



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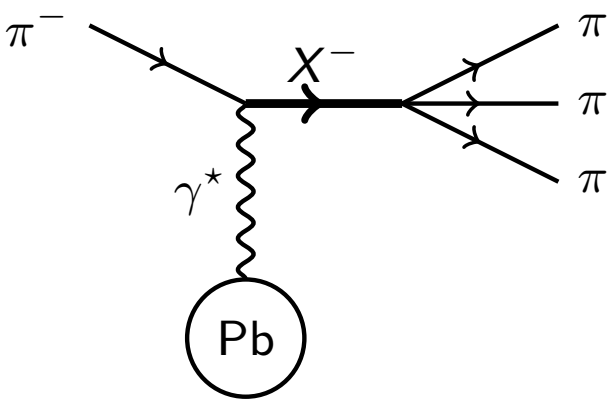


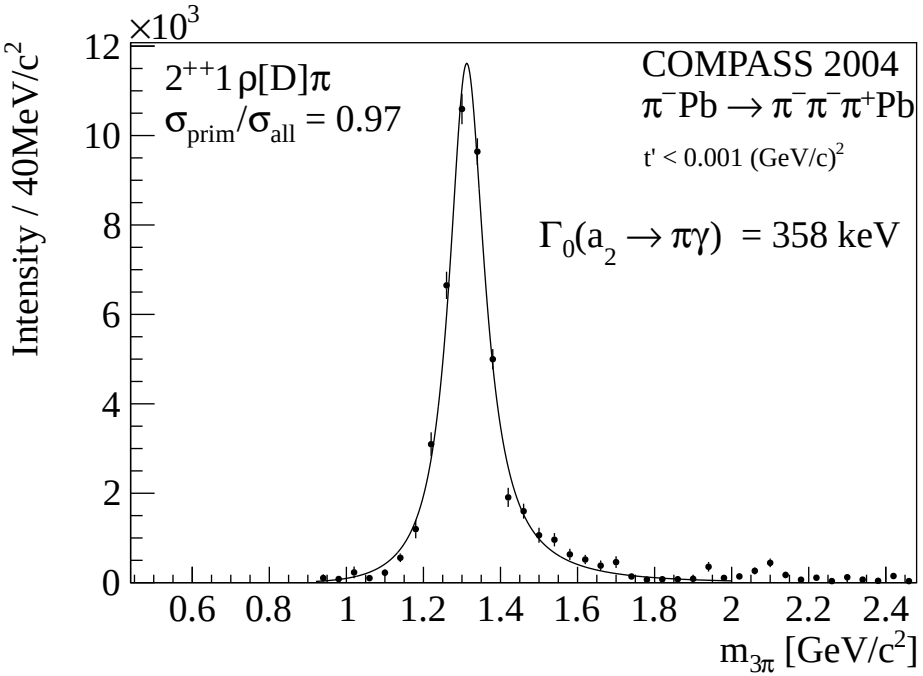
identify Primakoff contribution

- Primakoff produced states have spin projection $M = 1$
- cross-section for diffractively produced states

$$\sigma \propto t'^{M} e^{-bt'}$$

- at small t' $M = 1$ states are predominantly Primakoff produced
- partial-wave analysis to identify the $M = 1$ final states
- get cross-section from partial-wave intensity

Radiative width



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radiative width

- for a_2 (1320):
  $(358 \pm 6 \pm 42)$ keV
- for π_2 (1670):
  $(181 \pm 11 \pm 27)$ keV

first measurement