Hadron Spectroscopy at COMPASS

Stefan Wallner
for the COMPASS Collaboration

Physik Department E18 - Technische Universität München

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Jefferson Lab
Hadron Physics with Lepton and Hadron Beams

PDG meson listings [PDG 2017]

- 80 light unflavored mesons (47 in summary table)
- $>$ 100 possible further states
- 28 strange mesons (15 in summary table)

Important quantum numbers

$$J^P$$

- J: Spin of the meson
- P: Eigenvalue under parity conjugation of the meson

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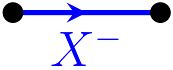
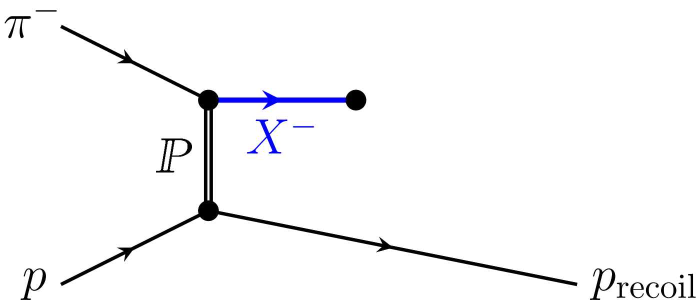


- Excited mesons appear as intermediate states
- Various reactions to produce them: diffractive production in πp scattering
- Various final states: $\pi^-\pi^-\pi^+$ final state



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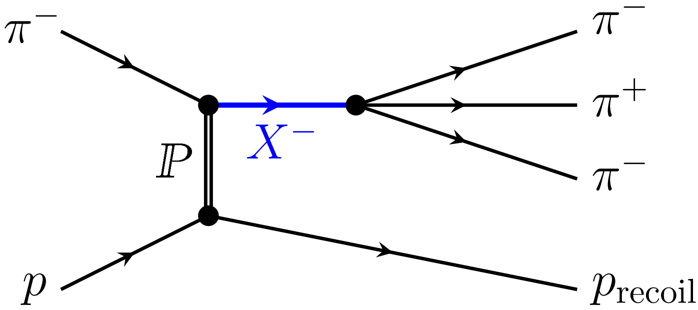

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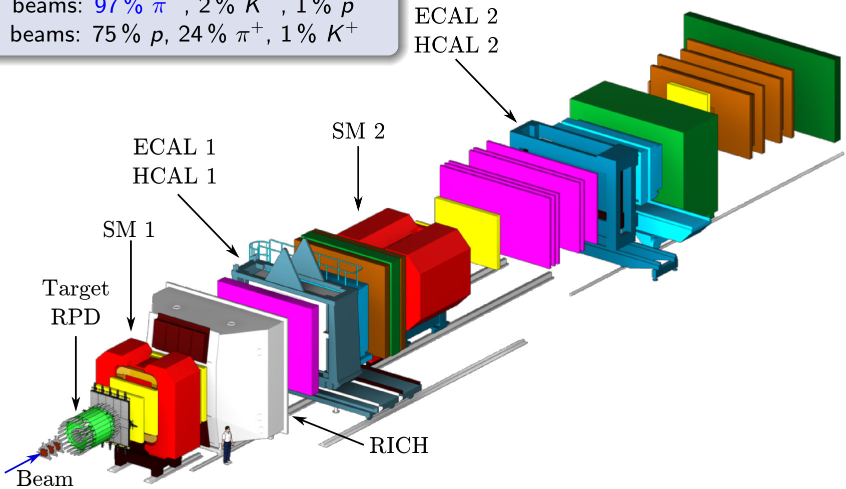
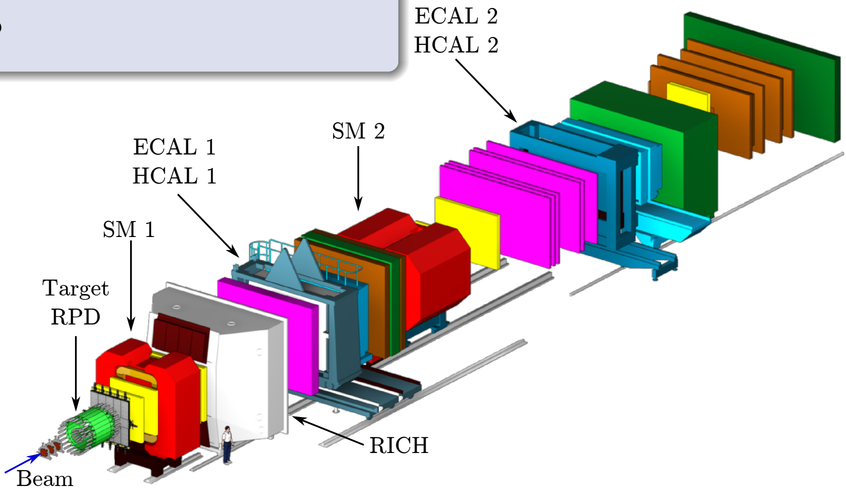
M2 beam line

- Located at CERN (SPS)
- 190 GeV/c secondary hadron beams
  - h^- beams: 97 % π^-, 2 % K^-, 1 % $\bar{p}$
  - h^+ beams: 75 % p, 24 % π^+, 1 % K^+



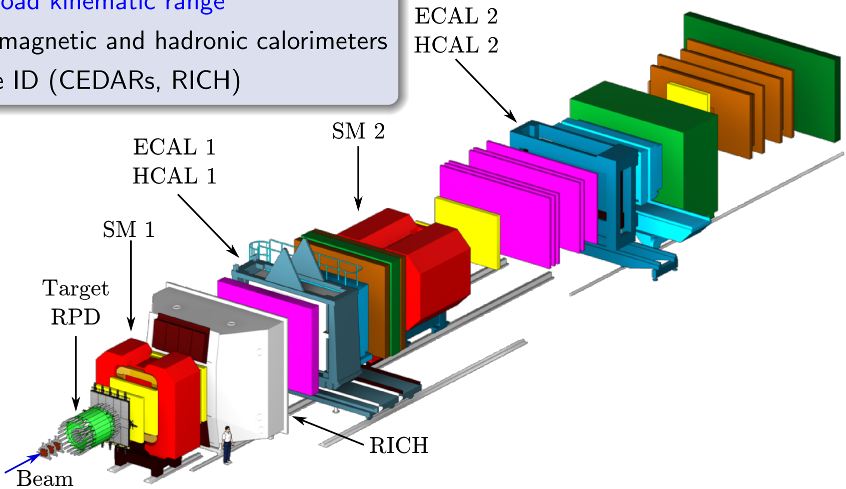
Target

- Various targets:
  - ℓH_2
  - Ni
  - Pb
  - W

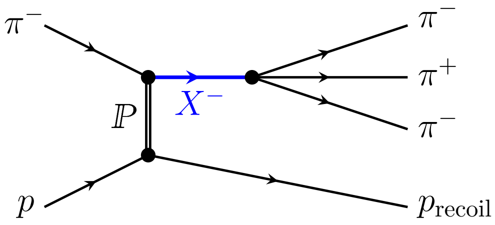


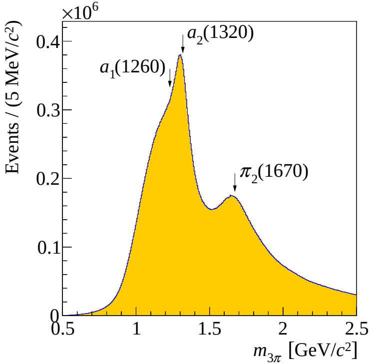
COMPASS spectrometer

- Two-stage magnetic spectrometer
  - ➥ Large acceptance
  - ➥ Broad kinematic range
- Electromagnetic and hadronic calorimeters
- Particle ID (CEDARs, RICH)



[Adolph et al., PRD 95, 032004 (2017)]

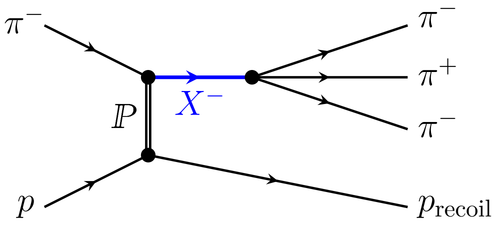


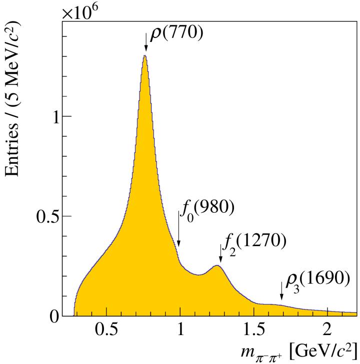


- Rich spectrum of overlapping and interfering X^-
  - Dominant states
  - "Hidden" states with lower intensity
- Also structure in $\pi\pi$ subsystem
  - ➡ Successive 2-body decay via $\pi\pi$ resonance called isobar
- Also structure in angular distributions

Partial-Wave Analysis
Motivation

[Adolph et al., PRD 95, 032004 (2017)]





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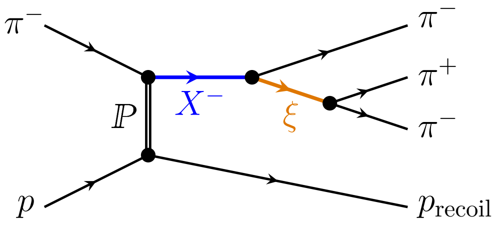

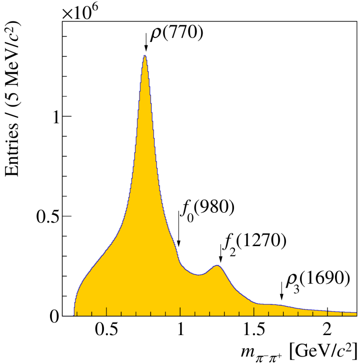

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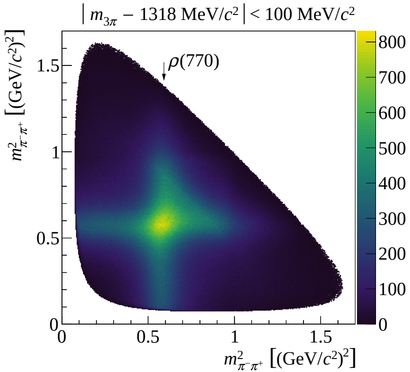

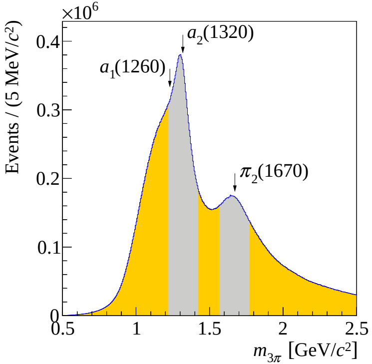

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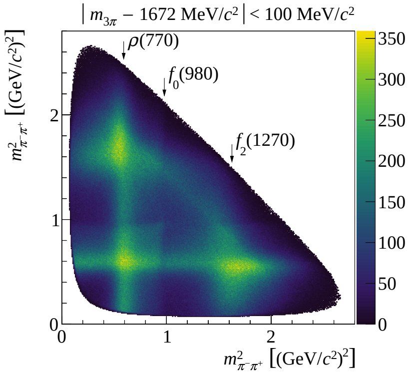

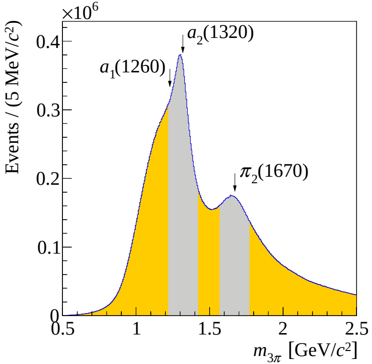

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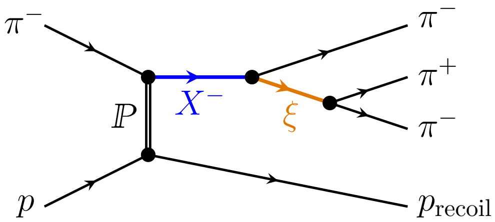

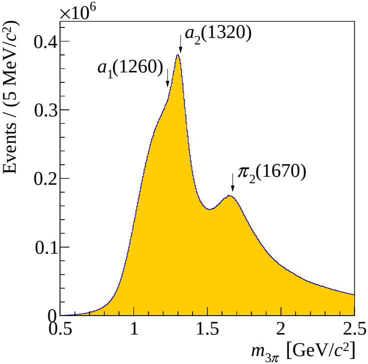

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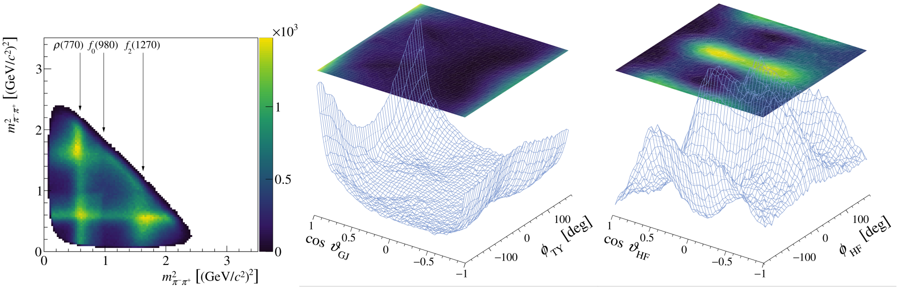
$1640 < m_{3\pi} < 1680\,\mathrm{MeV}$



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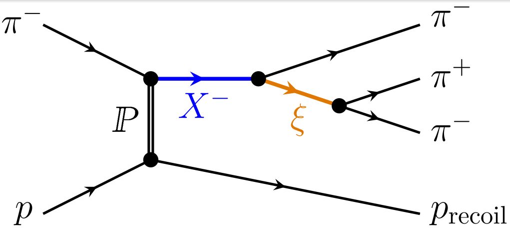
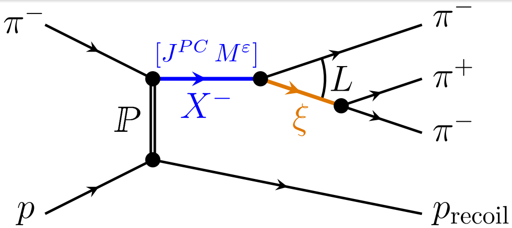


- Given partial wave $J^{PC}\, M^{\varepsilon}\, \xi\, \pi\, L$ at a fixed mass $m_{3\pi}$
  - ➥ Calculate 5D decay phase-space distribution of final state
- Measured phase-space distribution
  - ➥ contains coherent contributions of various partial waves

$$\mathcal{I}(\tau) = \left| \sum_{i} \mathcal{T}_i\, \psi_i(\tau) \right|^2$$

  - ➥ Perform maximum-likelihood fit in bins of $m_{3\pi}$ ("mass-independent fit")
    - ➥ Decompose data into partial waves
    - ➥ Extract $m_{3\pi}$ dependence of partial-wave amplitudes



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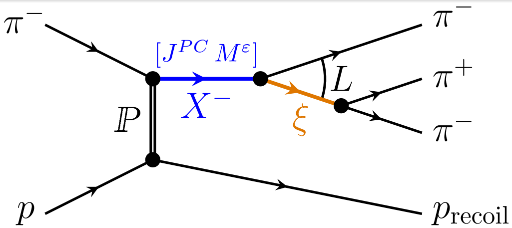

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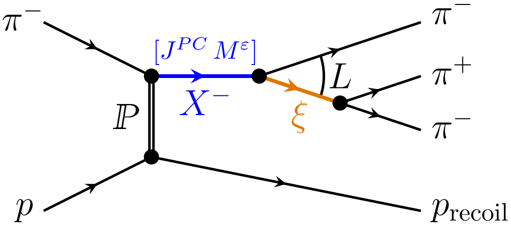
Partial-Wave Analysis
Isobar Model



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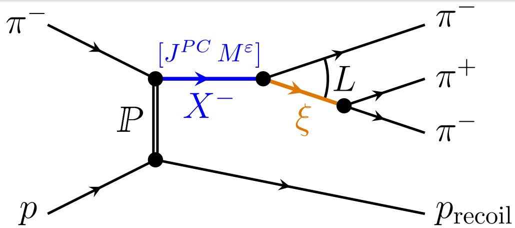

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Wave Set

- 88 partial waves for $\pi^- + p \to \pi^-\pi^-\pi^+ + p_{\text{recoil}}$
  - Largest wave set used so far in PWA of 3π final state
  - Spin J up to 6
  - Angular momentum L up to 6
  - 6 different $\pi^-\pi^+$ isobars

Challenge: Construction of the partial-wave set — Work in progress

- Semi-automatized model selection from data:
  - Starting with a large pool of possible waves
  - Find the best subset of waves that describe the data
    - Adding a penalty term to the log-likelihood, which suppresses small intensities
  - Challenge: Shape of the penalty term, parameter tuning, ...

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Model Building

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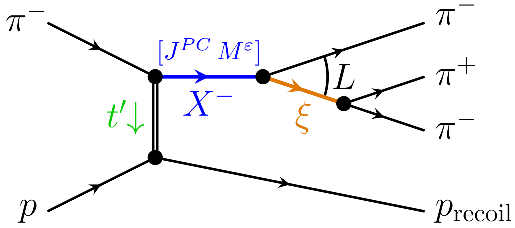

Challenge

- Production also depends on t'

- Large data set ($\approx$ 50 M exclusive events)
  - ➥ Perform PWA also in narrow bins of t' (t'-resolved analysis)
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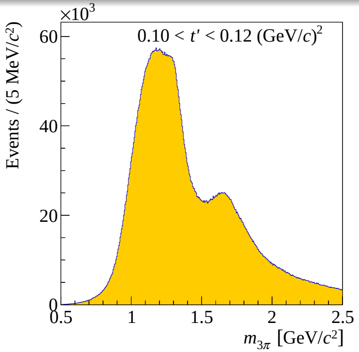

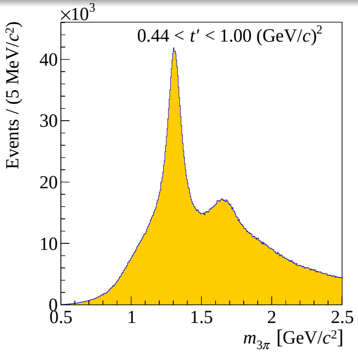

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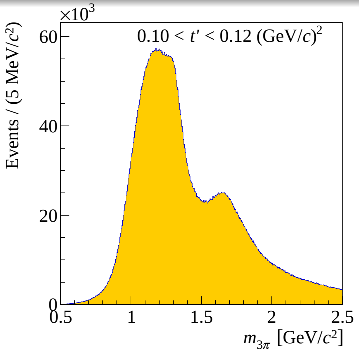

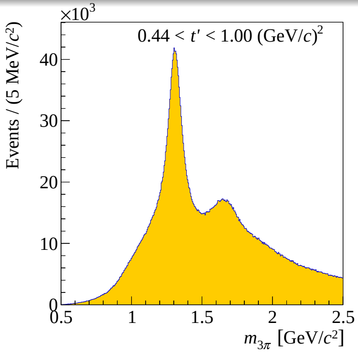

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Partial-Wave Analysis
Results

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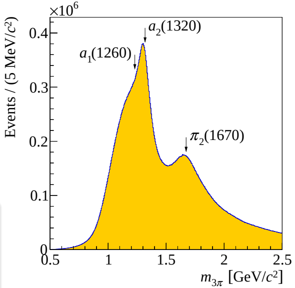

- $1^{++}\,0^+\,\rho(770)\,\pi\,S$
  - $a_1(1260)$
- $2^{++}\,1^+\,\rho(770)\,\pi\,D$
  - $a_2(1320)$
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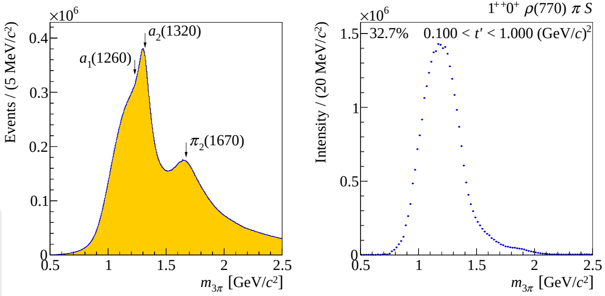

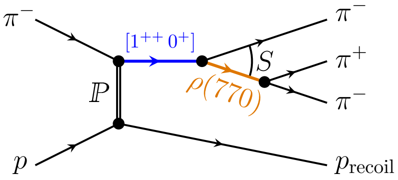

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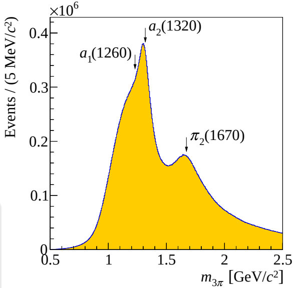

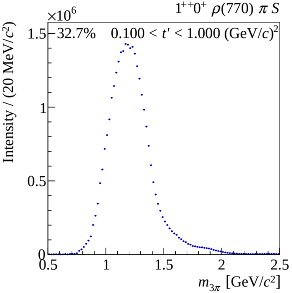

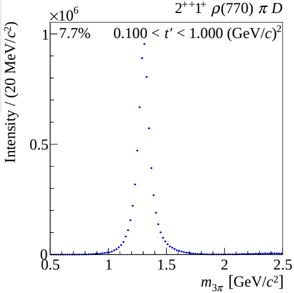

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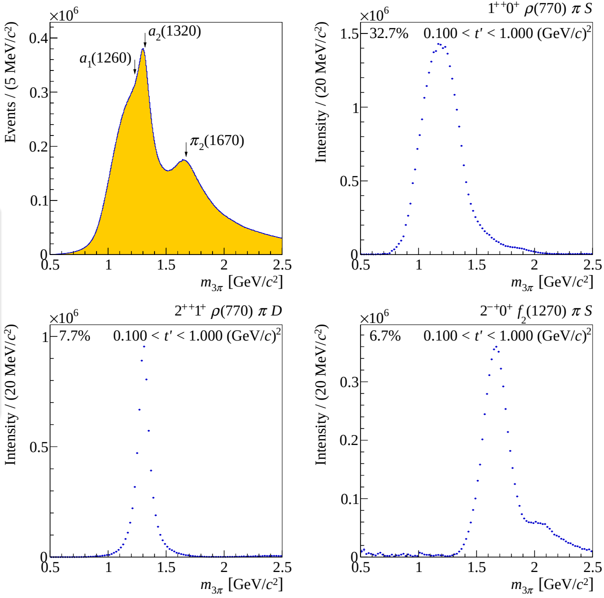
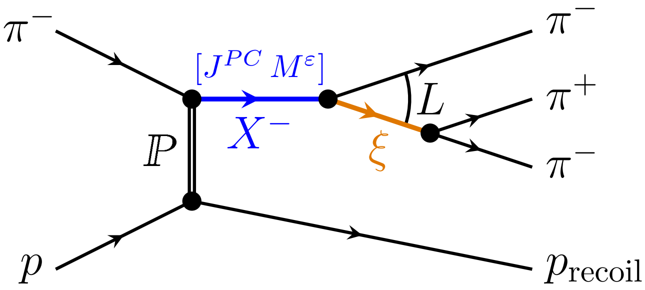
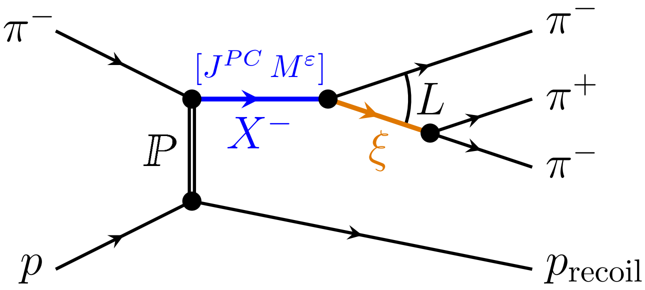




Challenge

Needs knowledge of isobar amplitude

- How good are the parameterizations?
  - Single isobar may not be approximated well by a Breit-Wigner amplitude
- Real shape may be complicated
- How good is the isobar model
  - Effects of rescattering?



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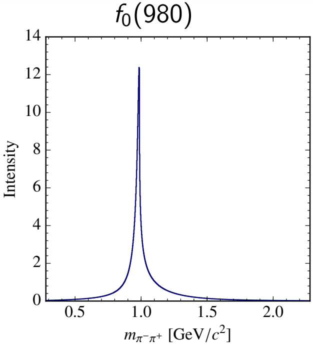

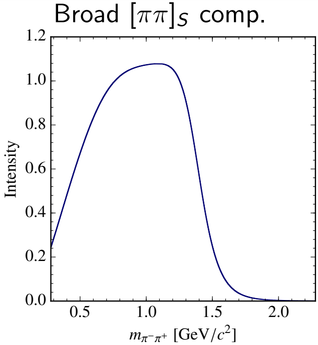

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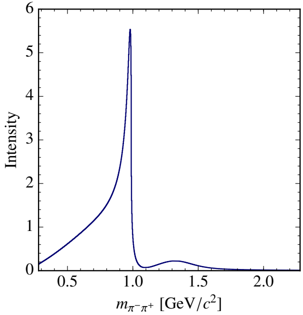
Example: Effective amplitude from interference of $[\pi\pi]_S$ and $f_0(980)$



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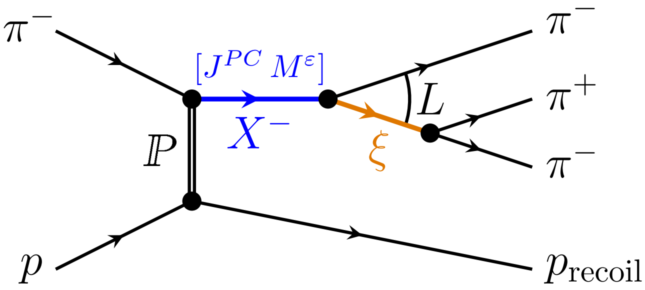

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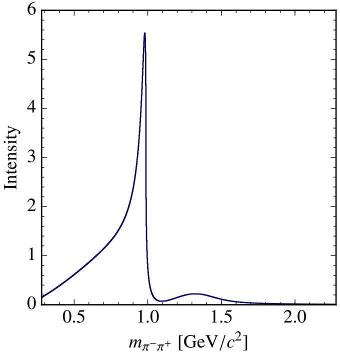

Extract isobar amplitudes from data

- Replace model with step-like isobars
- Extract binned shape in mass-independent fit
- Computationally more expensive
  - Up to 100 additional parameters per wave with freed isobar
- Needs large data sets

Effective amplitude from interference of $[\pi\pi]_S$ and $f_0(980)$

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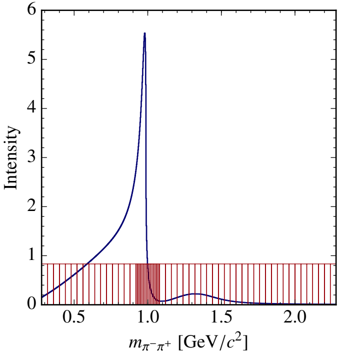

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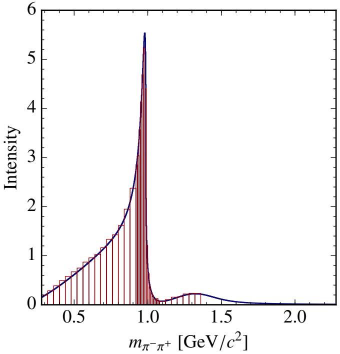
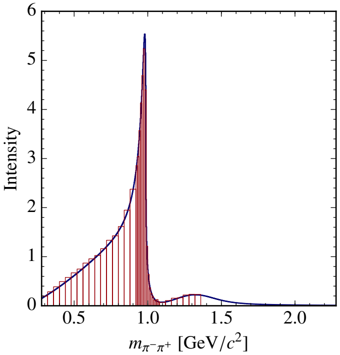


Partial-Wave Analysis
Freed-Isobar Method

Effective amplitude from interference of $[\pi\pi]_S$ and $f_0(980)$



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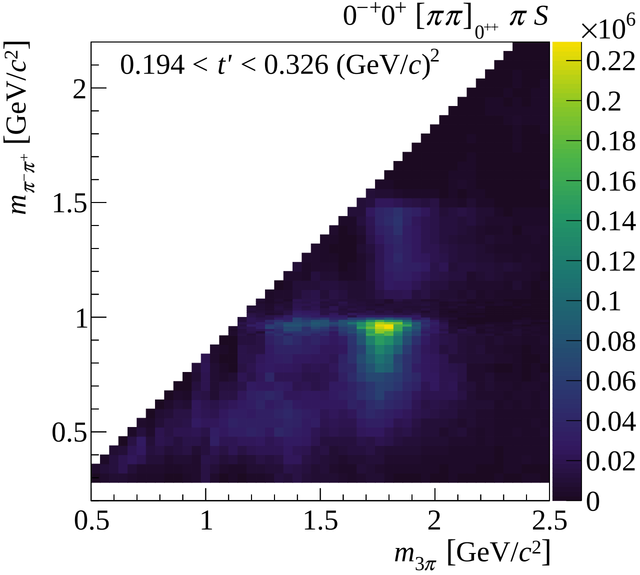
[Adolph et al., PRD 95, 032004 (2017)]



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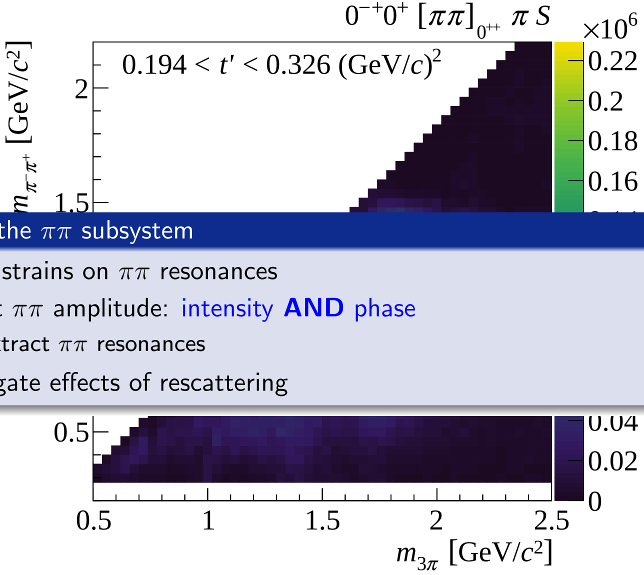


Investigate the $\pi\pi$ subsystem

- No constrains on $\pi\pi$ resonances
- Extract $\pi\pi$ amplitude: intensity **AND** phase
  - Extract $\pi\pi$ resonances
- Investigate effects of rescattering

This is not a Dalitz-plot

Resonance-Model Fit
Method

Data

Resonance Parameters

Masses and widths of the meson resonances

Resonance-Model Fit
Method

Data

(I) Partial-Wave Decomposition

Partial Waves

Intensities and relative phases of the partial waves

Resonance Parameters

Masses and widths of the meson resonances

Data

(I) Partial-Wave Decomposition

Partial Waves

Intensities and relative phases of the partial waves

(II) Resonance-Model Fit

Resonance Parameters

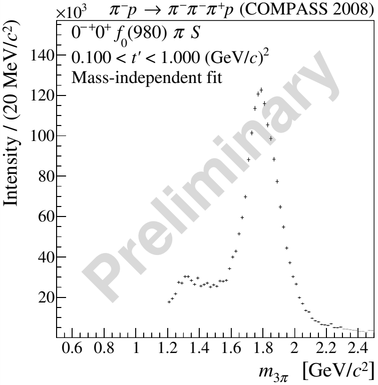
Masses and widths of the meson resonances

Modeling $m_{3\pi}$ dependence

- Parameterize $m_{3\pi}$ dependence of partial-wave amplitude (intensity & phase)

$$\mathcal{T}_\alpha(m_{3\pi}, t') = \sum_{k \in \mathrm{Comp}_\alpha} \mathcal{C}_\alpha^k(t') \cdot \mathcal{D}^k(m_{3\pi}, t'; \zeta_k)$$

- Dynamic functions $\mathcal{D}^k(m_{3\pi}, t'; \zeta_k)$
  - For resonances: Breit-Wigner amplitude
  - For non-resonant term: Phenomenological parameterization
- "Coupling amplitudes" $\mathcal{C}_\alpha^k(t')$
  - Determine strength and phase of components
  - Independent coupling amplitude for each t' bin



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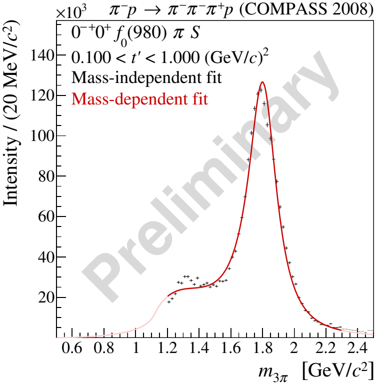

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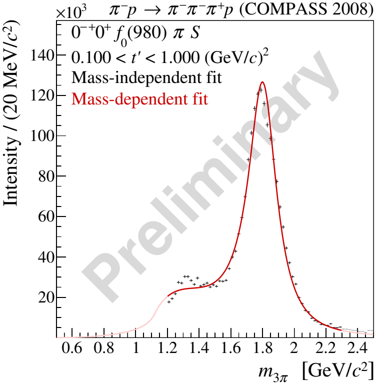

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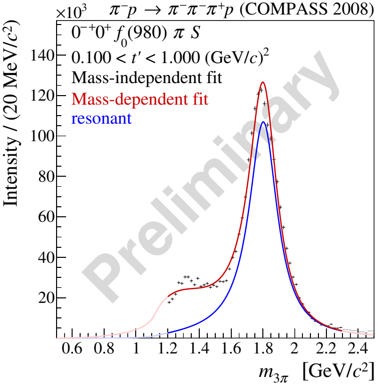

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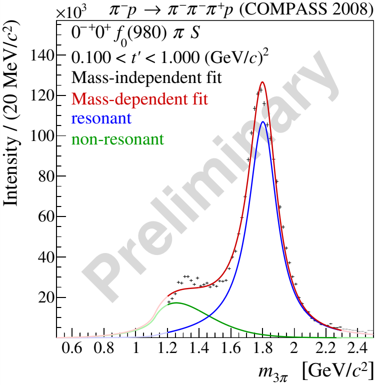

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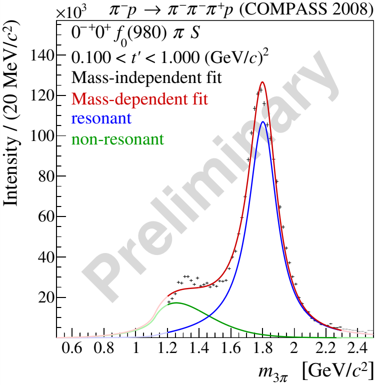
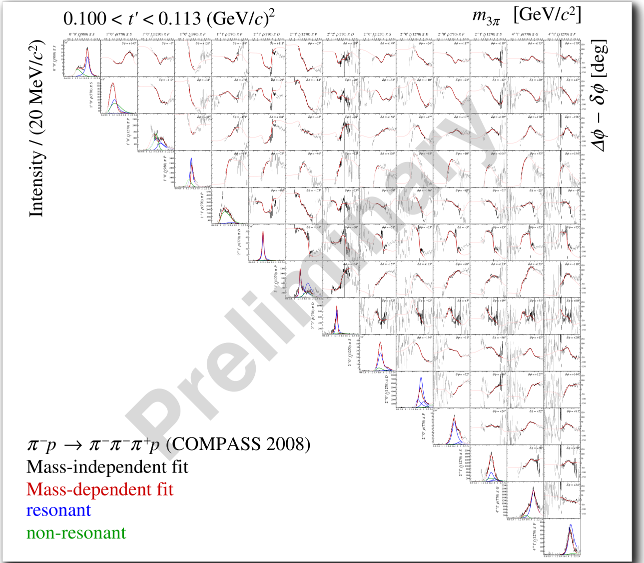


Resonance-Model Fit
Method

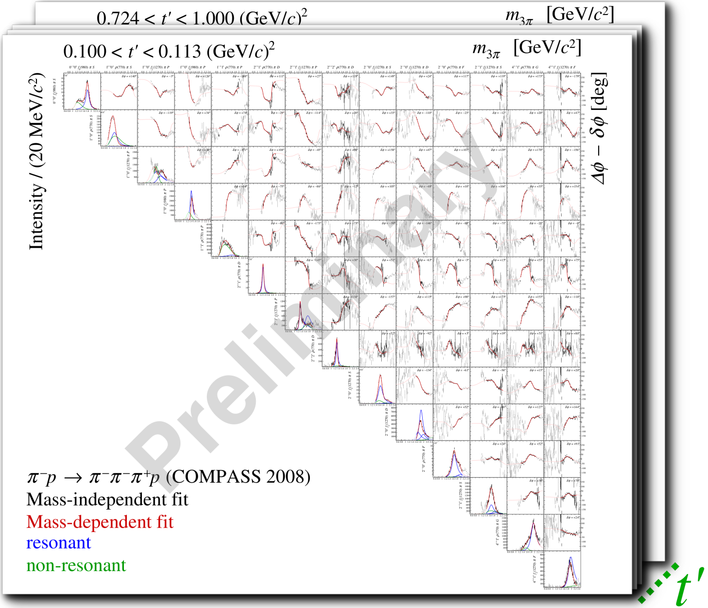
The fit

- Describe large fraction of data consistently
  - Simultaneously fit 14 waves ($\approx 60\,\%$)
  - Including 11 resonance components (a_1, a_2, a_4, π, π_1, π_2)
- Extract t' dependence of model components
- Computationally very expensive
  - 14×14 spin-density matrix $\times 11$ t' bins
  - 76 505 data points
  - 722 real fit parameters (51 shape parameters)
- Multimodality: Fit result depends on start-parameter set and fitting procedure
  - Perform 1000 fit attempts
  - 30 000 CPUh for one fit result



$0.100 < t' < 0.113$ (GeV/c)^2
$m_{3\pi}$ [GeV/c^2]
Intensity / (20 MeV/c^2)
$\Delta\phi - \delta\phi$ [deg]
Preliminary
$\pi^- p \to \pi^-\pi^-\pi^+ p$ (COMPASS 2008)
Mass-independent fit
Mass-dependent fit
resonant
non-resonant

Resonance-Model Fit
Method



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Challenge: Many systematic effects may influence the fit result

- Included resonances and non-resonant terms
- Parameterization of resonances and non-resonant terms
- Selected subset of waves
- Fitting ranges
- ...
- Systematic uncertainties one order of magnitude larger than statistical ones

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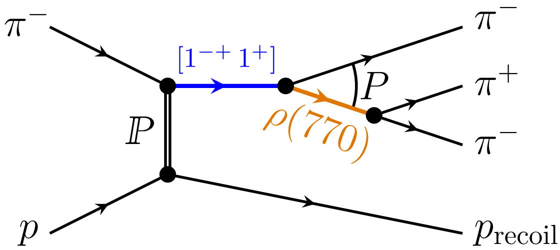
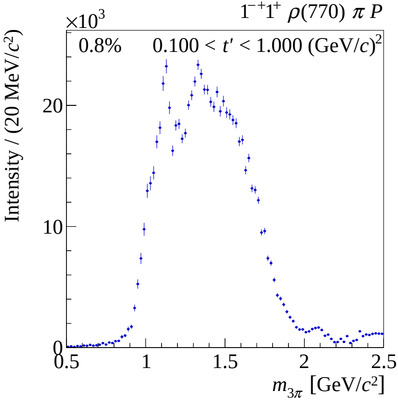


- 1^{-+}: spin-exotic π_1-like quantum numbers
  - Forbidden quantum numbers for $q\bar{q}$ system (non-rel.)
  - Lattice-QCD: lightest hybrid predicted with 1^{-+} quantum numbers
- Broad intensity distribution
- Strong evolution with t'

Results: $J^{PC} = 1^{-+}$ Partial Wave

Partial-Wave Decomposition



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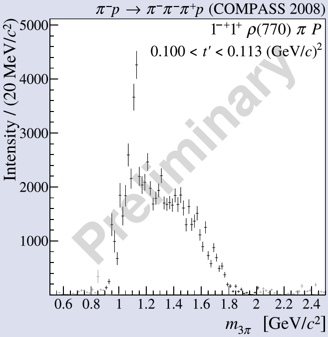

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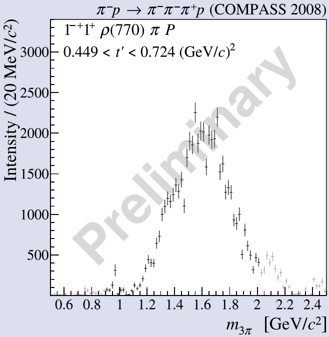

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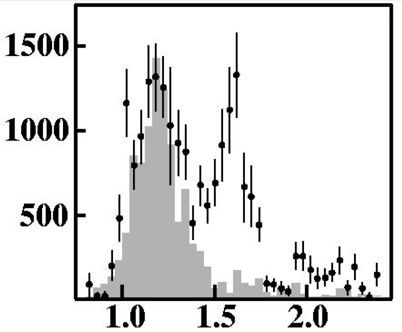
BNL E852 21 waves



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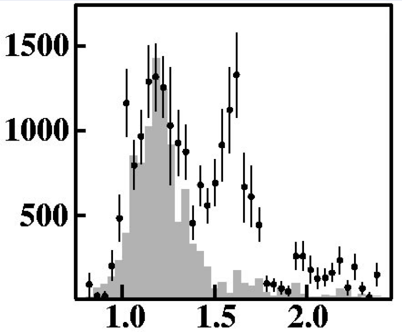
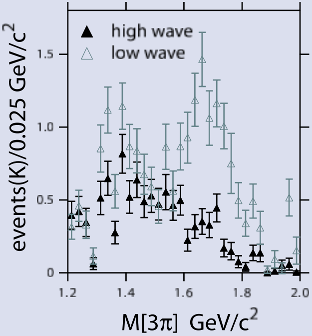


BNL E852 36 (high) vs 21 (low) waves



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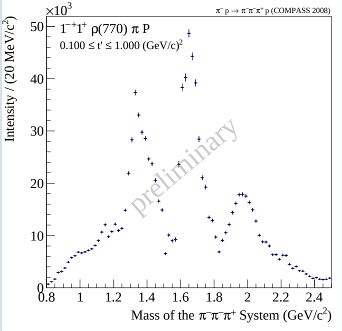

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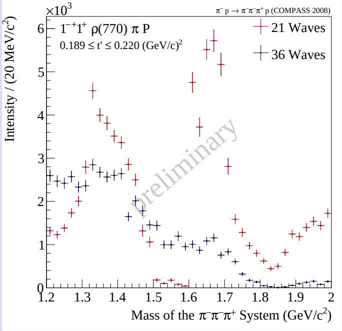

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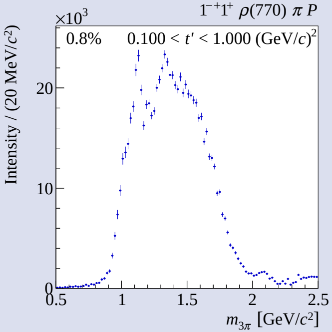
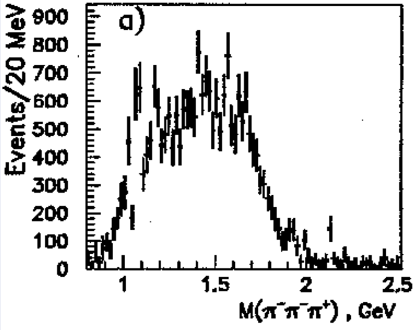


VES



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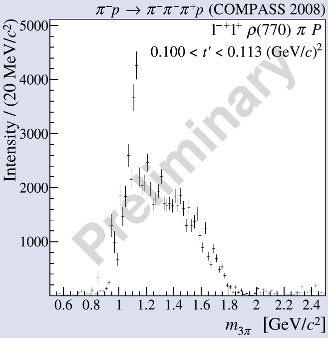
COMPASS 2008 88 waves (low t')



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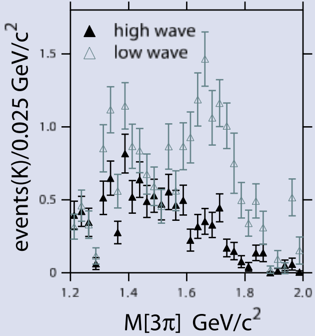

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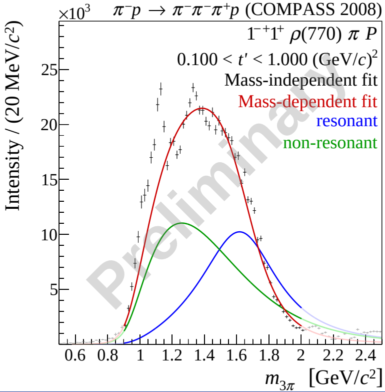

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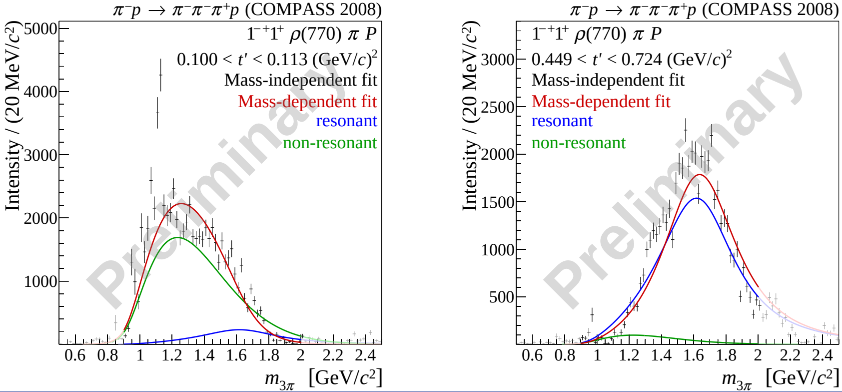

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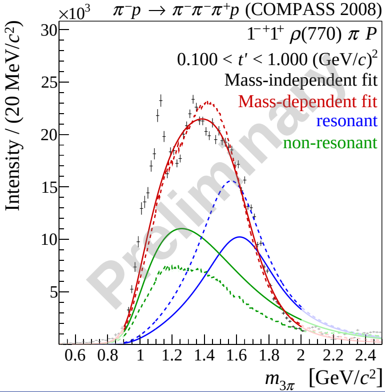

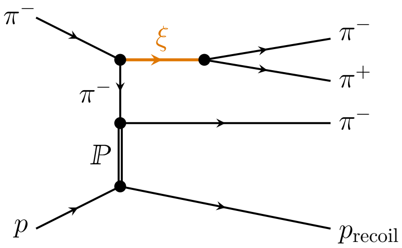

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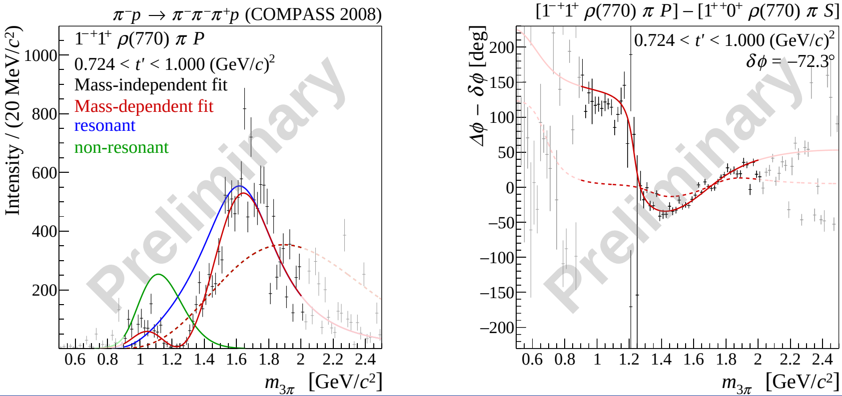

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Resonance-model fits

- Extract Breit-Wigner masses and widths with high statistical precision
- Model yields consistent description of 14 partial wave amplitudes
- Extract t' dependence of model components
- Uncertainties dominated by systematic effects

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

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  - ➥ Large systematic uncertainties e.g. from non-resonant parameterization
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- COMPASS data is consistent with $\pi_1(1600)$ Breit-Wigner component plus non-resonant term

Outlook

[arXiv:1707.02848]

- Further studies of selected J^{PC} sectors
- Advanced parameterizations developed in collaboration with JPAC

Summary & Outlook
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Outlook
Partial-Wave Decomposition

Freed-isobar method

- Allows to study the $\pi\pi$ sub-system
  - As a function of the X^- J^{PC} and mass
- Needs large data sets
- Outlook:
  - Free more partial waves with different isobar-J^{PC}
  - Appearance of continuous ambiguities
    - Resolved by additional constrains

Semi-automatized model selection from data

- Allows to define the wave set with minimal bias
- Which kind of penalty term to use?
- Outlook:
  - First application to 5π and 3π final state
  - Extensive studies of different penalty terms on Monte Carlo data

Freed-isobar method

- Allows to study the $\pi\pi$ sub-system
  - As a function of the X^- J^{PC} and mass
- Needs large data sets
- Outlook:
  - Free more partial waves with different isobar-J^{PC}
  - Appearance of continuous ambiguities
    - Resolved by additional constrains

Semi-automatized model selection from data

- Allows to define the wave set with minimal bias
- Which kind of penalty term to use?
- Outlook:
  - First application to 5π and 3π final state
  - Extensive studies of different penalty terms on Monte Carlo data

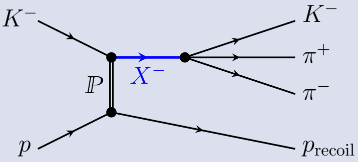
Further Analysis Projects

Further diffractively produced final states

$$\eta\pi^-,\ \eta'\pi^-,\ \omega\pi^-\pi^0,\ \ldots$$

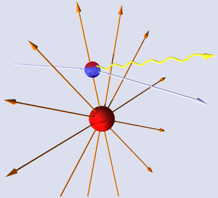
Kaon diffraction

- Using 2 % K^- beam
- Study of kaonic resonances in e.g. $K^-\pi^-\pi^+$ final state



$\pi^-\gamma$ and $K^-\gamma$ Processes (Primakoff)

- Measurement of electric and magnetic polarisability of pions and kaons
- Study of chiral dynamics
- Measurement of radiative couplings



Backup

Outline