COMPASS: Meson Spectroscopy and Low-Energy Meson Dynamics

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COMPASS collaboration

MESON 2018

Krakow
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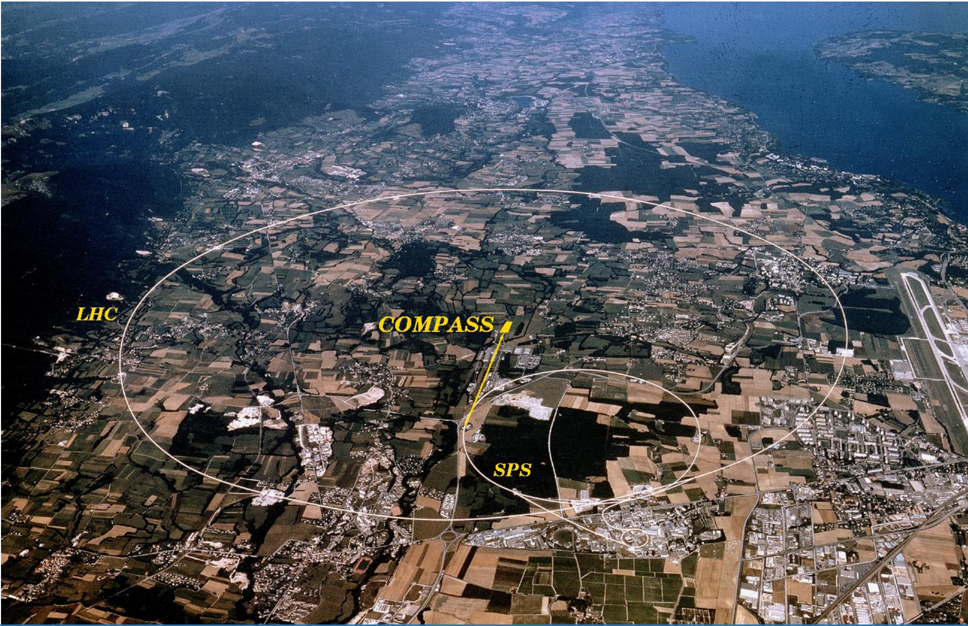
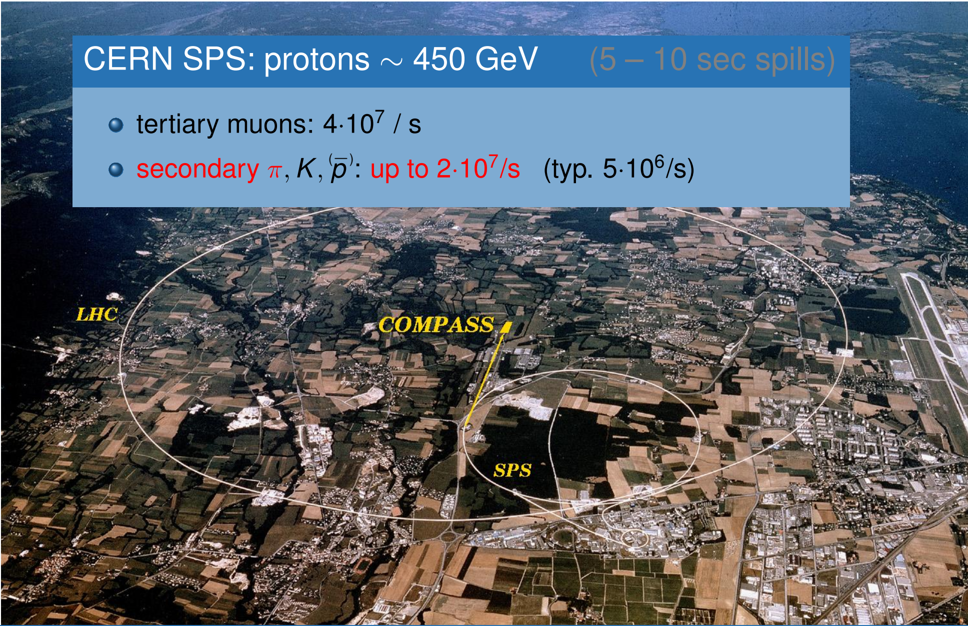
The COMPASS experiment

Commom **M**uon **P**roton **A**pparatus for **S**tructure and **S**pectroscopy



CERN SPS: protons $\sim$ 450 GeV (5 – 10 sec spills)

- tertiary muons: $4{\cdot}10^7$ / s
- secondary $\pi, K, \overset{(-)}{p}$: up to $2{\cdot}10^7$/s (typ. $5{\cdot}10^6$/s)

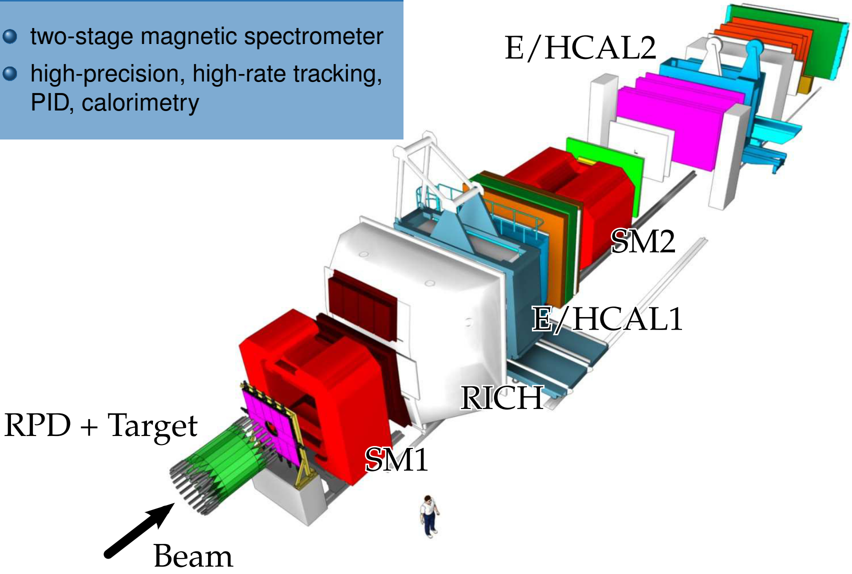


The COMPASS experiment

Commom **M**uon **P**roton **A**pparatus for **S**tructure and **S**pectroscopy

Fixed-target experiment

- two-stage magnetic spectrometer
- high-precision, high-rate tracking, PID, calorimetry



The COMPASS experiment

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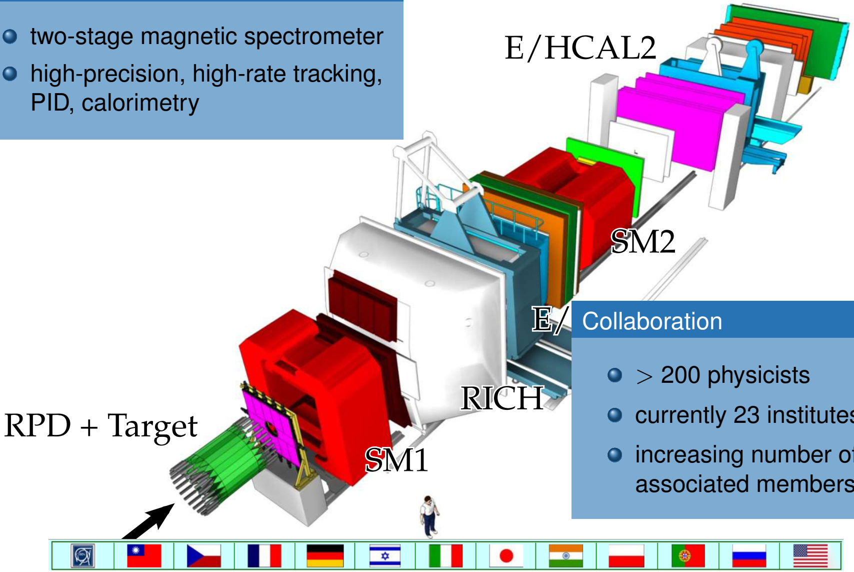
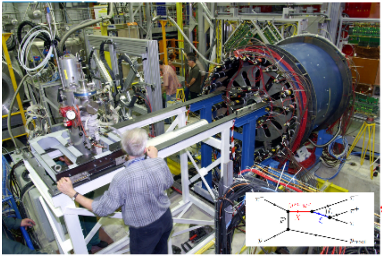


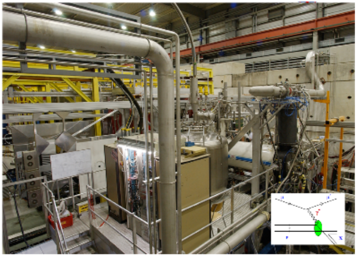
Collaboration

- $>$ 200 physicists
- currently 23 institutes
- increasing number of associated members



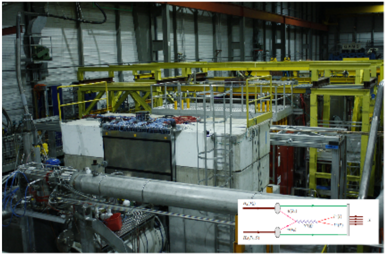
COMPASS-I
1997-2011

*** extension ***
& 2021

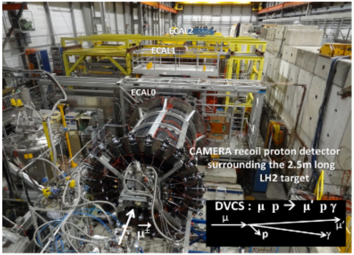


Hadron Spectroscopy & Chiral Dynamics

Polarised SIDIS



COMPASS-II
2012-2020

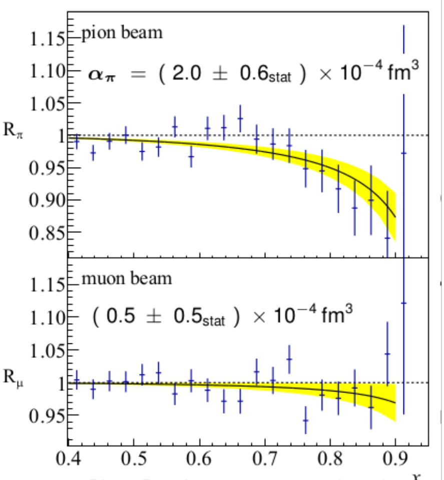


Polarised Drell-Yan

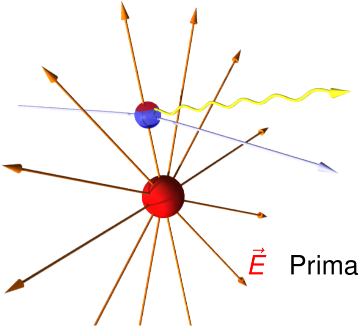
DVCS (GPDs) + unp. SIDIS

The pion polarisability measurement

- Pion polarisability: prediction $\alpha_\pi(ChPT) = 2.79 \cdot 10^{-4}\ \mathrm{fm}^3$
- Previous experimental determinations since 1982 were about twice as large
- COMPASS measurement confirms ChPT within the experimental uncertainties



Phys. Rev. Lett. 114, 062002 (2015)

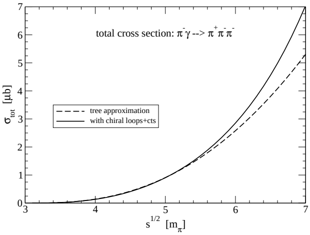


$\vec{E}$ Primakoff technique: photon exchange at $Q^2 \lesssim 0.001\,\mathrm{GeV}^2/c^2$

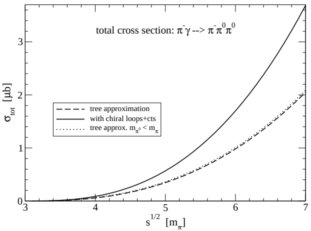
Chiral dynamics in $\pi\gamma \to 3\pi$

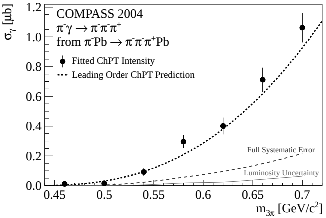
relevant physics: pion scattering lengths, pion loop contributions

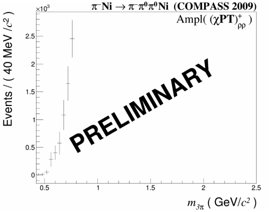
$\pi^-\pi^-\pi^+$



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



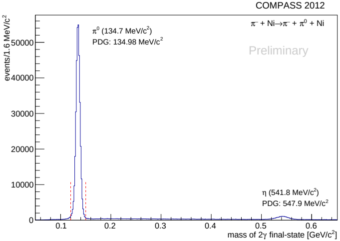


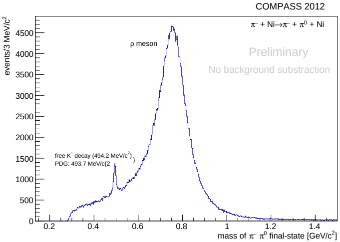


published in PRL 108 (2012) 192001

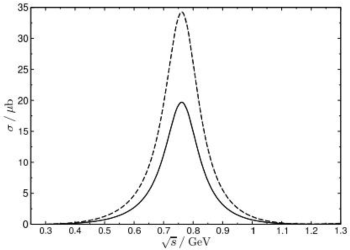
normalization: analysis ongoing

Chiral anomaly in $\pi^-\gamma \to \pi^-\pi^0$



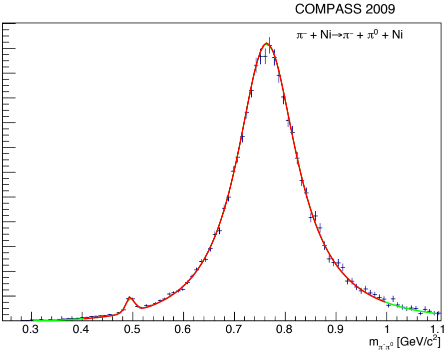


- contributions from chiral anomaly $F_{3\pi}$ and the $\rho(770)$ resonance
- can be described by a dispersive method $\to$ increased sensitivity to the chiral anomaly
- uncertainty estimate $< 1\%$



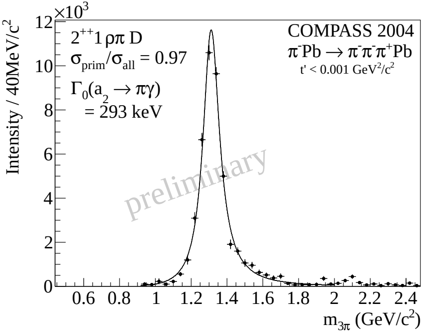
Hoferichter et al., PRD86 (2012) 116009

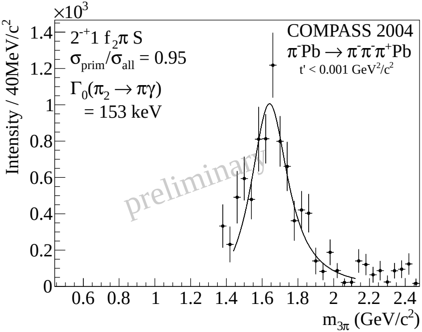
Chiral anomaly in $\pi^-\gamma \to \pi^-\pi^0$



- in-flight decay of Kaons (2.4% of beam) $\to$ normalization
- background from $\pi^-\pi^0\pi^0$ subtracted
- luminosity determination ongoing (in common with $\pi^-\pi^0\pi^0$)

Radiative Coupling of $a_2(1320)$ and $\pi_2(1670)$





$\Gamma_0(a_2(1320) \to \pi\gamma)$ *M2* $\quad$ $\Gamma_0(\pi_2(1670) \to \pi\gamma)$ *E2*

$\Leftrightarrow$ meson wave functions: $\Gamma_{i\to f} \propto |\,\langle \Psi_f |\, e^{-i\vec{q}\cdot\vec{r}}\, \hat{\epsilon}\cdot\vec{p}\,| \Psi_i \rangle\,|^2$

- normalization via beam kaon decays
- large Coulomb correction

published in EPJ A50 (2014) 79

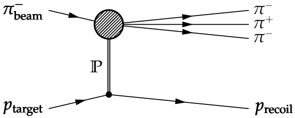
Diffractive 3π production

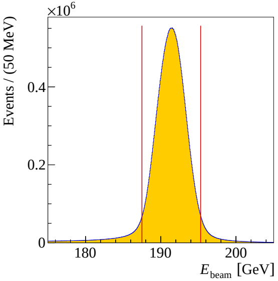
- COMPASS: World's currently largest data set for the diffractive process

$$p + \pi^-_{\mathrm{beam}} \to p + \pi^-\pi^+\pi^-$$

  taken in 2008
  ($\sim 46 \cdot 10^6$ exclusive Events)

- Exclusive measurement





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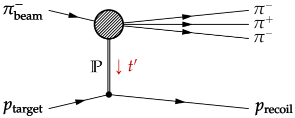
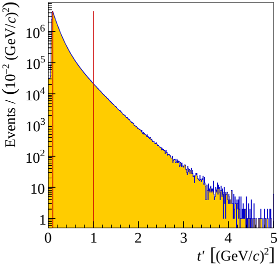
- Squared four-momentum transfer t' by Pomeron $\mathbb{P}$





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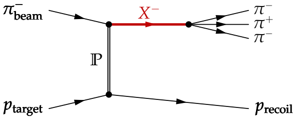

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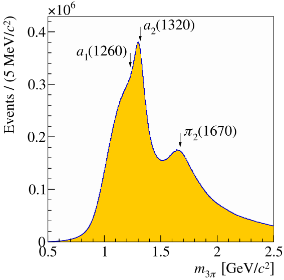


- Rich structure in $\pi^-\pi^+\pi^-$ mass spectrum: Intermediate states X^-

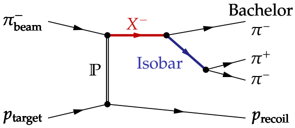
Diffractive 3π production

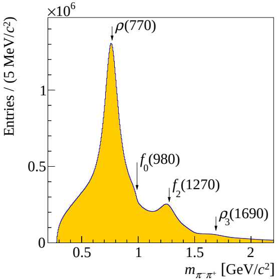
- COMPASS: World's currently largest data set for the diffractive process

$$p + \pi^-_{\text{beam}} \rightarrow p + \pi^-\pi^+\pi^-_{\text{bachelor}}$$

taken in 2008
($\sim 46 \cdot 10^6$ exclusive Events)

- Exclusive measurement
- Squared four-momentum transfer t' by Pomeron $\mathbb{P}$
- Rich structure in $\pi^-\pi^+\pi^-$ mass spectrum: Intermediate states X^-
- Also structure in $\pi^+\pi^-$ subsystem: Intermediate states ξ (Isobar)





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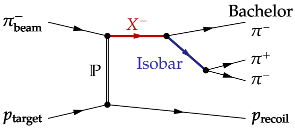
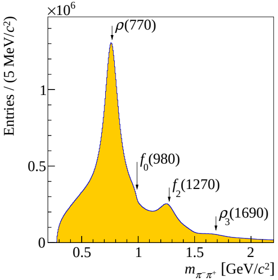




The isobar model

- Intermediate states appear as dynamic amplitudes $\Delta(m)$: Complex-valued functions of invariant mass m
- Simplest example: Breit-Wigner amplitude with mass m_0 and width Γ_0:

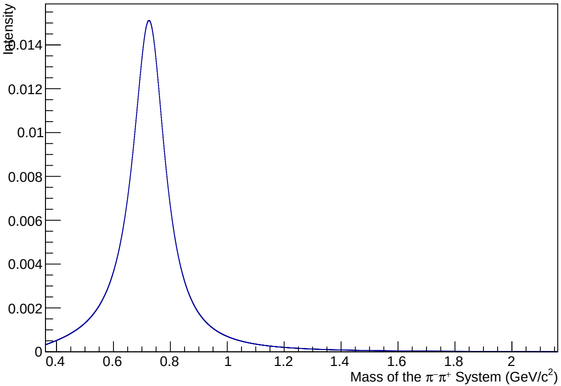
$$\Delta_{\mathrm{BW}}(m) = \frac{m_0\Gamma_0}{m_0^2 - m^2 - i m_0\Gamma_0}$$

- Analysis in bins of $m_{X^-} = m_{3\pi}$. Dynamic amplitude of X^- inferred form the data
- Dynamic amplitude of ξ: Model input in conventional PWA
- True dynamic isobar amplitudes may differ from the model
- Free parameters in dynamic isobar amplitudes computationally unfeasible

The isobar model

- Inter
  Com
- Simp l width Γ_0:
- Anal erred form
  the c
- Dyn
- True
- Free lly unfeasible

Dynamic isobar amplitude: $\rho(770)$, $J^{PC} = 1^{--}$



The isobar model

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- Simp | width Γ_0:
- Anal | erred form
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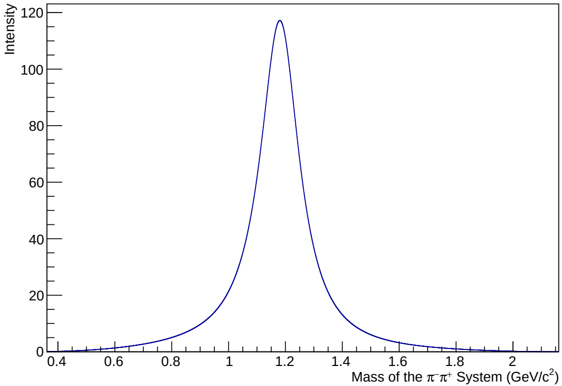
Dynamic isobar amplitude: $f_2\,(1270)$, $J^{PC} = 2^{++}$



The isobar model

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- Simp   width Γ_0:
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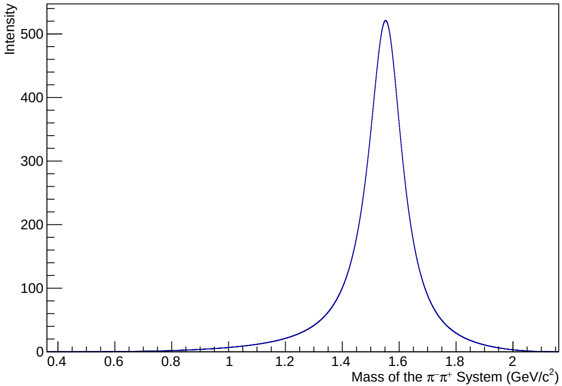
Dynamic isobar amplitude: $\rho_3\,(1690)$, $J^{PC} = 3^{--}$



The isobar model

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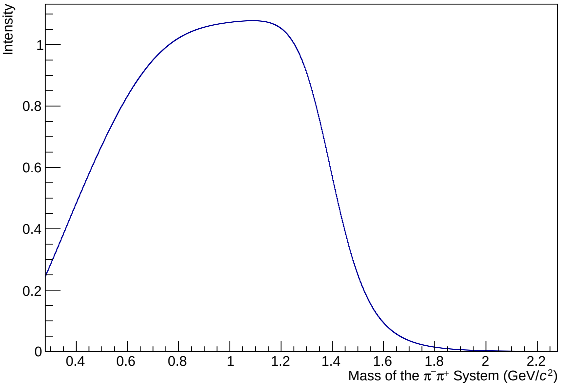
Dynamic isobar amplitude: $[\pi\pi]_S$ wave, $J^{PC} = 0^{++}$



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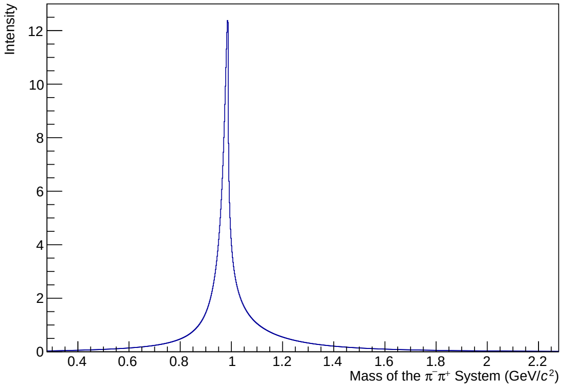
Dynamic isobar amplitude: f_0 (980), $J^{PC} = 0^{++}$



Freed isobars: powerful test of the assumptions

Step-like isobar amplitudes *details: cf. this afternoon's talk by Fabian Krinner*

- Total intensity in each single $(m_{3\pi}, t')$-bin

$$\mathcal{I}(\vec{\tau}) = \left| \sum_{i}^{\text{waves}} \mathcal{T}_i \left[\psi_i(\vec{\tau})\, \Delta_i(m_{\pi^-\pi^+}) + \text{Bose Symm.} \right] \right|^2$$

as function of phase-space variables $\vec{\tau}$

Fit parameters: Production amplitudes $\mathcal{T}_i$

Fixed: Angular distributions $\psi(\vec{\tau})$, dynamic isobar amplitudes $\Delta_i(m_{\pi^-\pi^+})$

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- Fixed isobar amplitude gets replaced by a set of bins:

$$\Delta_i(m_{\pi^-\pi^+}) \to \sum_{\text{bins}} \mathscr{T}_i^{\text{bin}} \underbrace{\Delta_i^{\text{bin}}(m_{\pi^-\pi^+})}_{\substack{1 \quad \text{in the bin,} \\ 0 \quad \text{otherwise}}} \equiv [\pi\pi]_{J^{PC}}$$

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- Each bin introduces an independent Partial Wave $\mathcal{T}_i^{\text{bin}} = \mathcal{T}_i \mathscr{T}_i^{\text{bin}}$:

$$\mathcal{I}(\vec{\tau}) = \left| \sum_{i}^{\text{waves}} \sum_{\text{bins}} \mathcal{T}_i^{\text{bin}} \left[\psi_i(\vec{\tau}) \, \Delta_i^{\text{bin}}(m_{\pi^-\pi^+}) + \text{Bose S.} \right] \right|^2$$

- Total intensity in each single $(m_{3\pi}, t')$-bin

$$\mathcal{I}(\vec{\tau}) \quad \ldots \quad \mathrm{m.}]\Big|^2$$

as function of ph

Fit parameters:

Fixed: Angular ... udes $\Delta_i\,(m_{\pi^-\pi^+})$

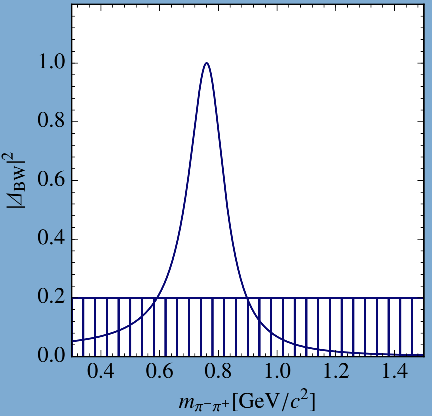
- Fixed isobar am

$$\Delta_i \quad \ldots \quad]_{J^{PC}}$$

- Each bin introdu ... $\mathcal{T}_i \mathscr{T}_i^{\mathrm{bin}}$:

$$\mathcal{I}(\vec{\tau}) = \Big| \sum_i \sum_{\mathrm{bins}} \quad \ldots \quad \mathrm{se\ S.}]\Big|^2$$

Illustration



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as function of pl…

Fit parameters: …

Fixed: Angular … …udes $\Delta_i\,(m_{\pi^-\pi^+})$

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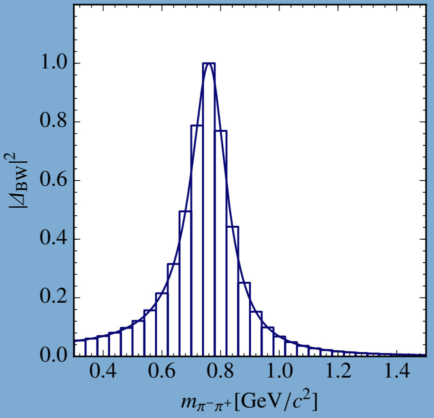
Illustration

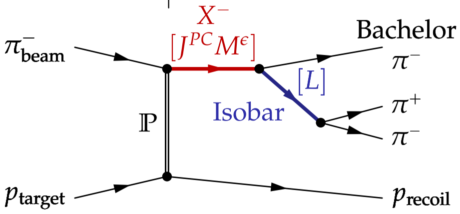


Partial-Wave Analysis

$$\mathcal{I}(\vec{\tau}) = \left|\sum \mathcal{T}_i \psi_i(\vec{\tau})\, \Delta_i(m_{\pi^-\pi^+})\right|^2$$

Waves specified by:

$$J^{PC} M^{\varepsilon} \xi \pi L$$



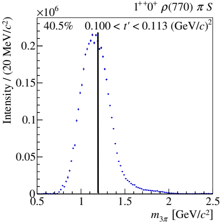
- J^{PC}: spin and eigenvalues under parity and charge conjugation of X^-(or its multiplet)
- M^{ε}: spin projection and naturality of the exchange particle
- π: the bachelor π^-(always the same)
- ξ: the fixed or freed isobar, e.g. $\rho(770)$ or $[\pi\pi]_{1^{--}}$
- L: orbital angular momentum between isobar and bachelor pion

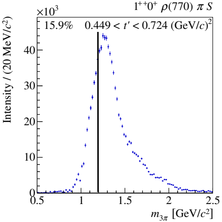
88 waves needed to describe the data (“hand-selected”)
interference terms $\rightarrow$ get (relative) phases

Step 1: Partial-Wave Analysis

Selected Waves (1 of 88) in two of the 11 independent t' bins

Low t'



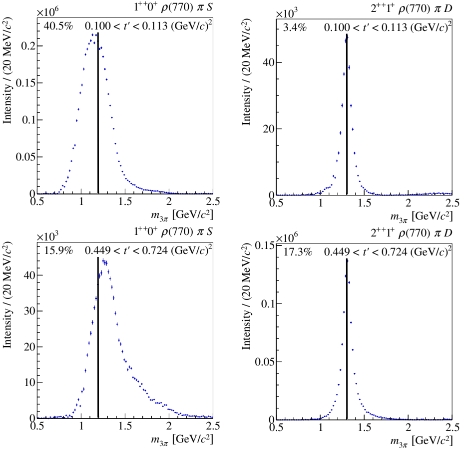


High t'

Step 1: Partial-Wave Analysis

Selected Waves (2 of 88) in two of the 11 independent t' bins

Low t'

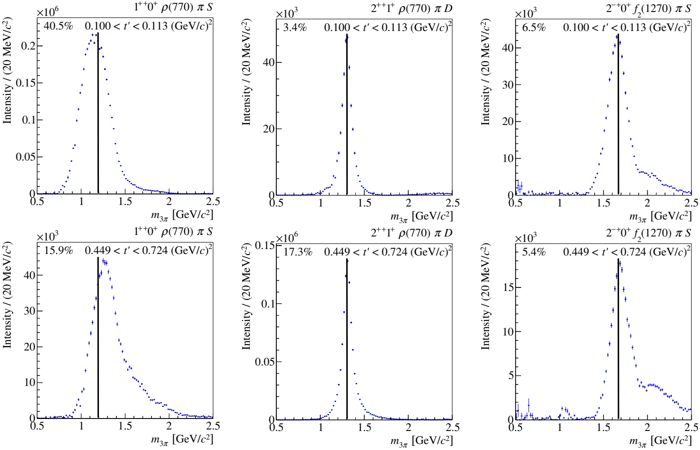


High t'

Step 1: Partial-Wave Analysis

Selected Waves (3 of 88) in two of the 11 independent t' bins

Low t'

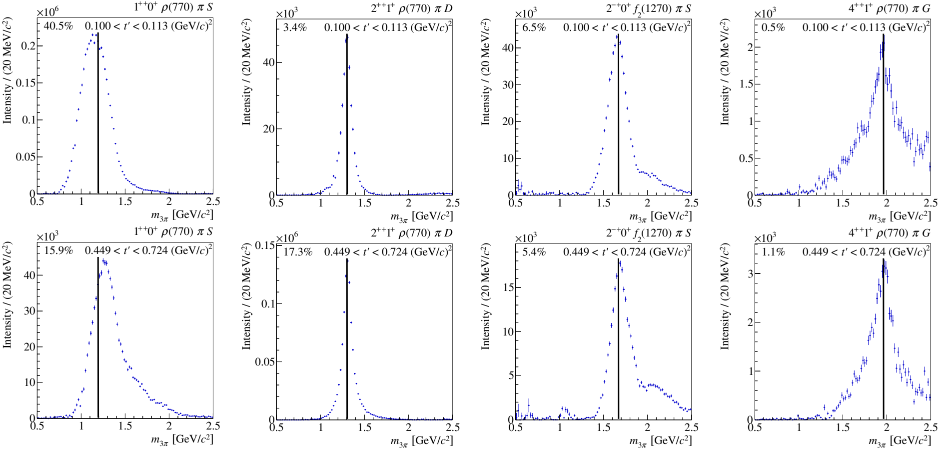


High t'

Step 1: Partial-Wave Analysis

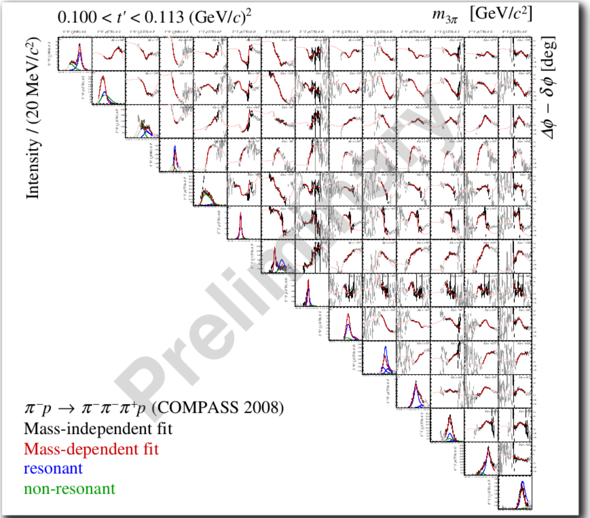
Selected Waves (4 of 88) in two of the 11 independent t' bins

Low t'



High t'

Step 2: Resonance model fit



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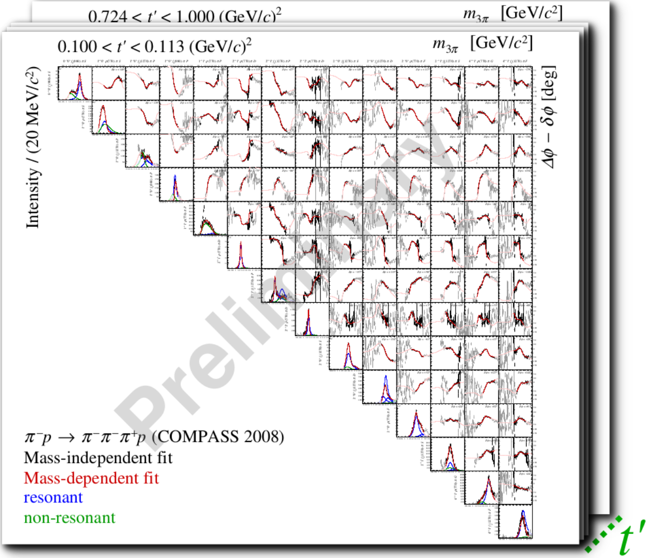
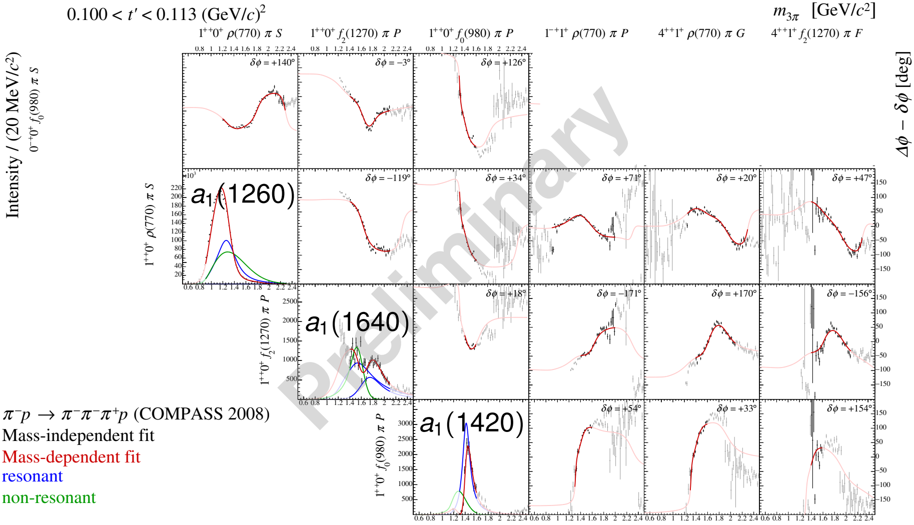


$\times$11 bins in t'

Towards an exotic signal: $J^{PC} = 1^{++}$ sector



$\pi^- p \to \pi^-\pi^-\pi^+ p$ (COMPASS 2008)

Mass-independent fit

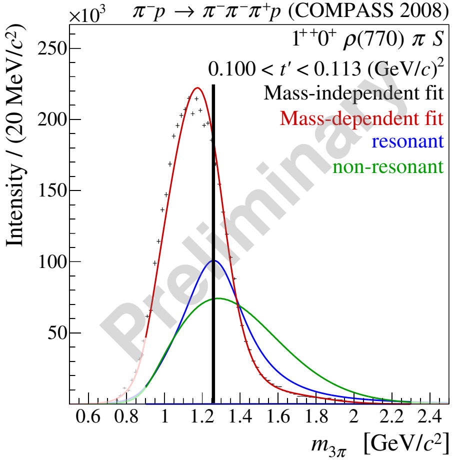
Mass-dependent fit

resonant

non-resonant

$a_1(1260)$

- resonance parameters do not depend on production mechanism



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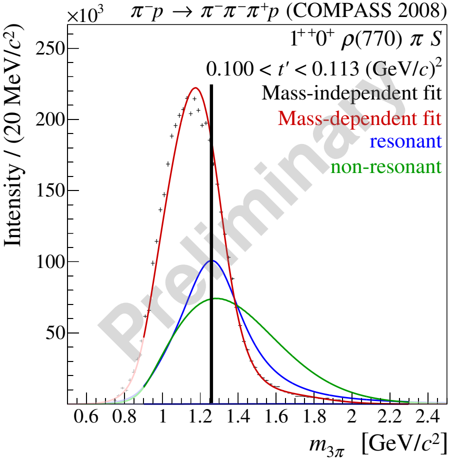
- resonance parameters do not depend on production mechanism
- coupling strength does (form factors) and non-resonant parts may vary with t'



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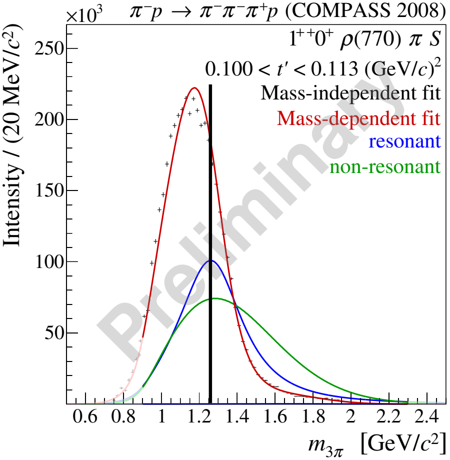

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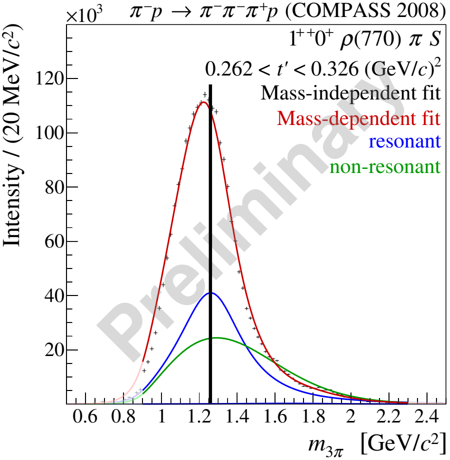

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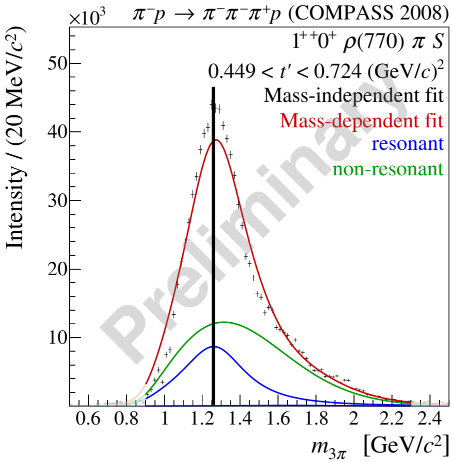

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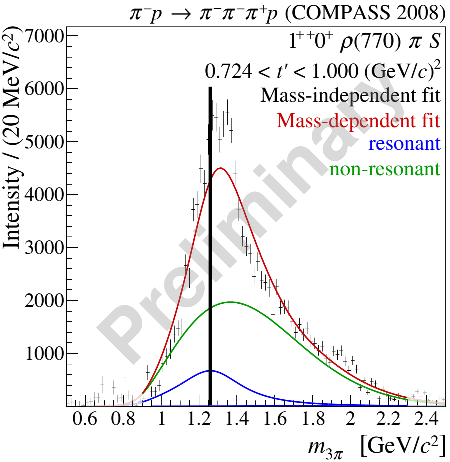

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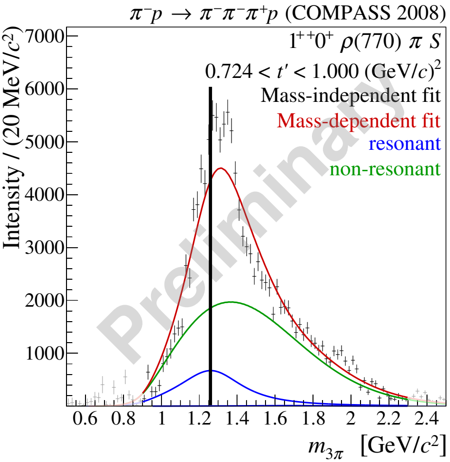
- $a_1(1260)$ reproduced:

$$m^{fit} = 1298^{+13}_{-22}\ \mathrm{MeV}/c^2$$
$$m^{PDG} = 1230 \pm 40\ \mathrm{MeV}/c^2$$
$$\Gamma^{fit} = 403^{+0}_{-100}\ \mathrm{MeV}/c^2$$
$$\Gamma^{PDG} = 250 - 600\ \mathrm{MeV}/c^2$$



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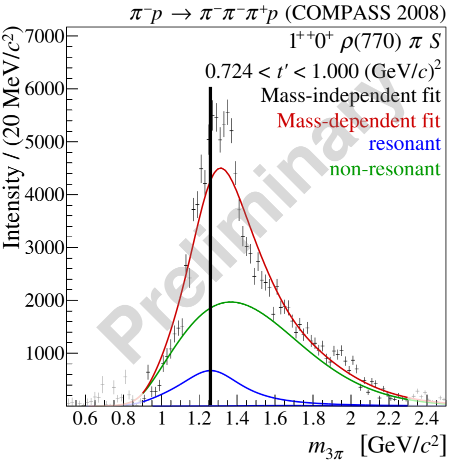
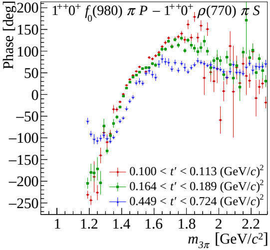
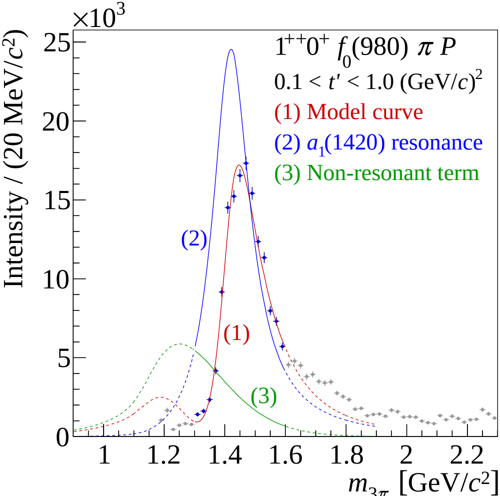
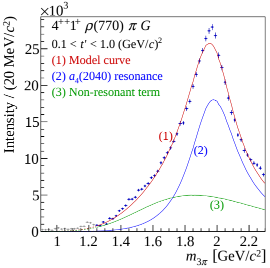
- weak signal for $a_1(1640)$



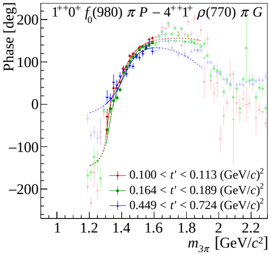
a new - quite exotic - signal



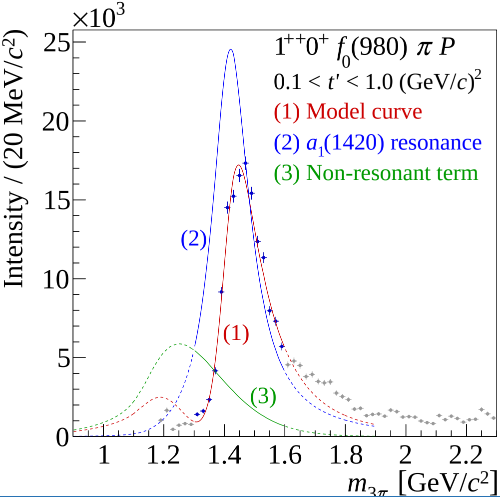




×10³
4⁺⁺1⁺ ρ(770) π G
0.1 < t' < 1.0 (GeV/c)²
(1) Model curve
(2) a₄(2040) resonance
(3) Non-resonant term
Intensity / (20 MeV/c²)
m₃π [GeV/c²]

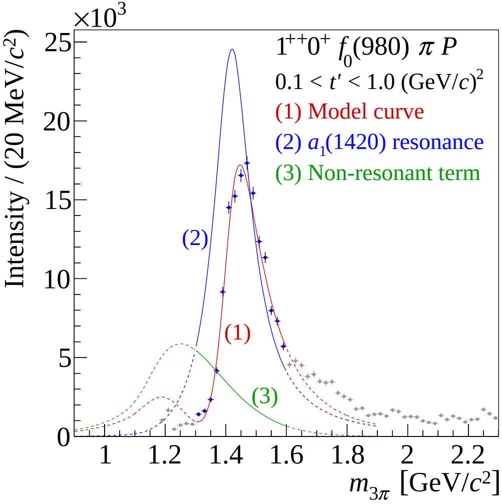


1⁺⁺0⁺ f₀(980) π P − 4⁺⁺1⁺ ρ(770) π G
Phase [deg]
0.100 < t' < 0.113 (GeV/c)²
0.164 < t' < 0.189 (GeV/c)²
0.449 < t' < 0.724 (GeV/c)²
m₃π [GeV/c²]

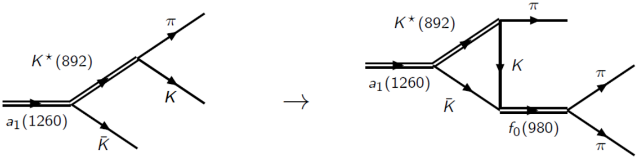


×10³
1⁺⁺0⁺ f₀(980) π P
0.1 < t' < 1.0 (GeV/c)²
(1) Model curve
(2) a₁(1420) resonance
(3) Non-resonant term
Intensity / (20 MeV/c²)
m₃π [GeV/c²]

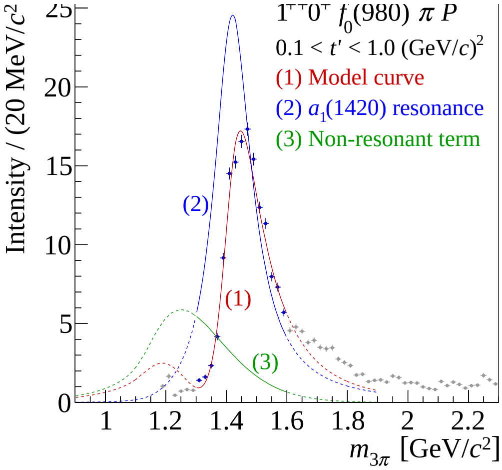
- new signal: $a_1(1420)$
- decay into $f_0(980)\pi$



$a_1(1420)$
a new - quite exotic - signal



- new signal: $a_1(1420)$
- decay into $f_0(980)\pi$
- possible explanations:
  - triangle diagram *Mikhasenko, Ketzer, Sarantsev* PRD91 (2015) 094015
  - two-channel unitarized Deck amplitude *Basdevant, Berger* PRL114 (2015) 192001



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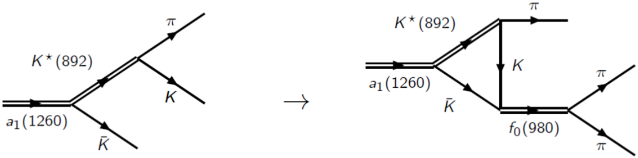

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- possible explanations:
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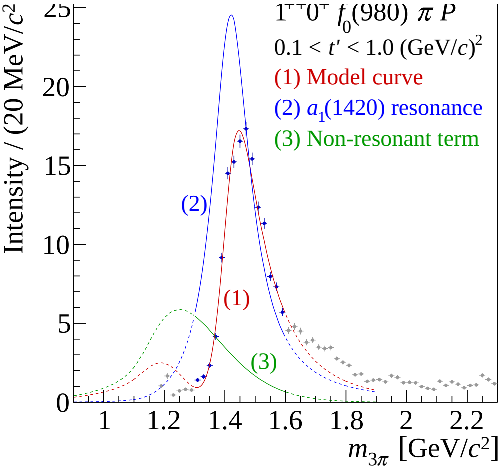
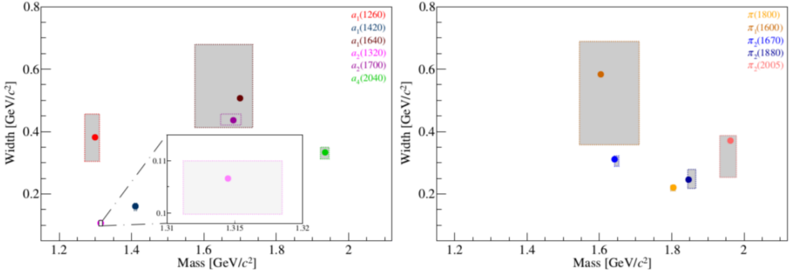
  - two-channel unitarized Deck amplitude *Basdevant, Berger* PRL114 (2015) 192001
- Mass:
  $m_{a_1(1420)} = 1411.8^{+1.0}_{-4.4}\,\mathrm{MeV}/c^2$
  Width:
  $\Gamma_{a_1(1420)} = 158^{+8}_{-8}\,\mathrm{MeV}/c^2$



Resonance parameters



- resonance parameters with unprecedented precision and systematic investigations of 6 *a*-like and 5 π-like states
- 75-pages PRD recently accepted:
  Light isovector resonances in $\pi^- p \to \pi^-\pi^-\pi^+ p$ at 190 GeV$/c$
- recently published: PLB779(2018)464
  New analysis of $\eta\pi$ tensor resonances measured at the COMPASS experiment (together with JPAC): better constraints on $a_2'(1700)$

Some math: zero mode in the spin-exotic wave

What is a “zero mode”?

- Freed-isobar analysis: much more freedom than fixed-isobar analysis
- introduces continuous mathematical ambiguities in the model

arxiv.org/abs/1710.09849
F. Krinner *et al*, Resolving ambiguities in model-independent partial-wave analysis of three-body decay
talk this afternoon by Fabian Krinner

Some math: zero mode in the spin-exotic wave
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- “Zero mode”: dynamic isobar amplitudes $\Omega\left(m_{\pi^-\pi^+}\right)$ that do not contribute to the **total** 3π-amplitude
- Spin-exotic wave:

$$\psi\left(\vec{\tau}\right)\Omega\left(m_{\pi^-\pi^+}\right) + \text{Bose S.} = 0$$

at **every point** $\vec{\tau}$ in phase space

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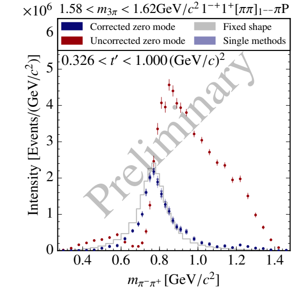
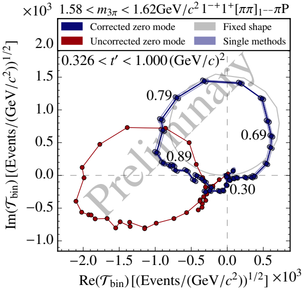
The spin-exotic wave

- Example: One bin in $(m_{3\pi}, t')$
  - $1.58 < m_{3\pi} < 1.62\,\mathrm{GeV}/c^2$
  - $0.326 < t' < 1.000\ (\mathrm{GeV}/c)^2$





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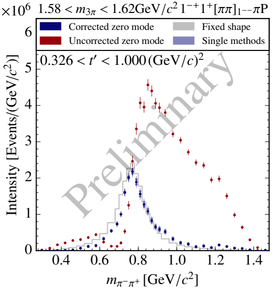

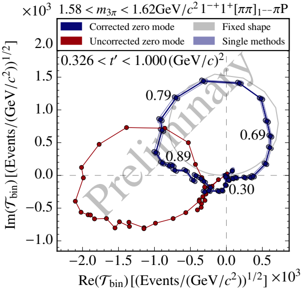

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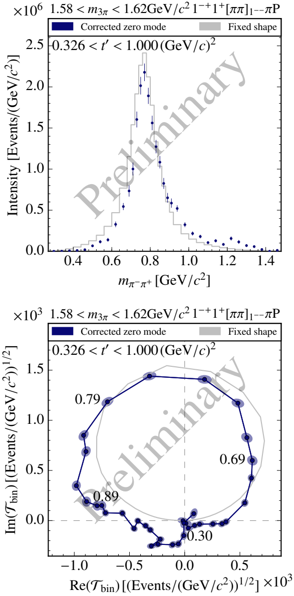

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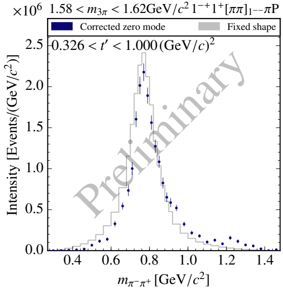
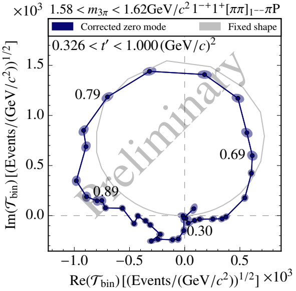
- Dynamic isobar amplitude dominated by $\rho(770)$





COMPASS on chiral dynamics:

- Measurement of the pion polarisability at COMPASS
  - via the Primakoff reaction, COMPASS has determined

$$\boxed{\alpha_\pi \; = \; (\; 2.0 \; \pm \; 0.6_{\text{stat}} \; \pm \; 0.7_{\text{syst}} \;) \; \times 10^{-4}\,\text{fm}^3}$$

  - most direct access to the $\pi\gamma \to \pi\gamma$ process
  - most precise experimental determination
  - control of systematics: $\mu\gamma \to \mu\gamma$, $K^- \to \pi^-\pi^0$
  - more data ($\times 4$) on tape
- Related topics at COMPASS:
  radiative widths and
  chiral dynamics in $\pi^-\gamma \to \pi^-\pi^0$ and $\pi\gamma \to \pi\pi\pi$
  - chiral anomaly *on the way*

Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016)

$\boxed{\pi^\pm}$ $I^G(J^P) = 1^-(0^-)$

π ELECTRIC POLARIZABILITY α_π

See HOLSTEIN 14 for a general review on hadron polarizability.

VALUE (10^{-4} fm^3)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.0±0.6±0.7	63k	[1] ADOLPH	15A	SPEC	$\pi^-\gamma \to \pi^-\gamma$ Compton scatt.

[1] Value is derived assuming $\alpha_\pi = -\beta_\pi$.

$\boxed{a_1(1420)}$ $I^G(J^{PC}) = 1^-(1^{++})$

OMITTED FROM SUMMARY TABLE

$a_1(1420)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
$\mathbf{1414^{+15}_{-13}}$	[1] ADOLPH	15C	COMP	190 $\pi^- p \to \pi^-\pi^+\pi^- p$

[1] Using the isobar model and partial-wave analysis with 88 waves.

some of the new COMPASS entries
in the RPP2016 edition

Conclusions and Outlook

COMPASS on exotic mesons:

- partial-wave decomposition of $\pi^-\pi^+\pi^-$ with 88 waves
- conclusions on two exotic signals:
  - $a_1(1420)$ *supernumerous*
    - matches a Breit-Wigner description with $\Gamma = 158$ MeV$/c^2$
    - position at $K^*\bar{K}$ threshold $\rightarrow$ rescattering interpretation
    - and/or Deck interference
  - $\pi_1(1600)$ *spin-exotic*
    - at small t' dominant background
    - slow phase motion, much broader than previous analyses
- ongoing developments
  - refine non-resonant (Deck) background description
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- low statistics for incoming K^- beams $\rightarrow$ future option:
  dedicated RF-separated beam, part of upcoming Letter of Intent
  Mini-Workshop (half-day) on June 20, 2pm, CERN / vidyo

Thank you for your attention!

Zero mode in the spin-exotic wave
Mathematical origin

- Process: $X^- \to \xi\pi_3^- \to \pi_1^-\pi_2^+\pi_3^-$.
- Partial-wave amplitude

$$\psi\left(\vec{\tau}\right)\Omega\left(m_{12}\right) + \text{Bose S.} = 0 \tag{1}$$

- Tensor formalism (X^- rest frame) for 1^{-+}

$$\psi\left(\vec{\tau}\right) \propto \vec{p}_1 \times \vec{p}_3$$

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- Fulfill (1) at every point in phase space $\Rightarrow \Omega\left(m_\xi\right) = \mathrm{const.}$

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$$\left|\psi(\vec{\tau})\,\Delta^{\text{phys}}(m_\xi) + \text{B. S.}\right|^2 = \left|\psi(\vec{\tau})\left[\Delta^{\text{phys}}(m_\xi) + \mathcal{C}\Omega(m_\xi)\right] + \text{B. S.}\right|^2$$

for any complex-valued zero-mode coefficient $\mathcal{C}$

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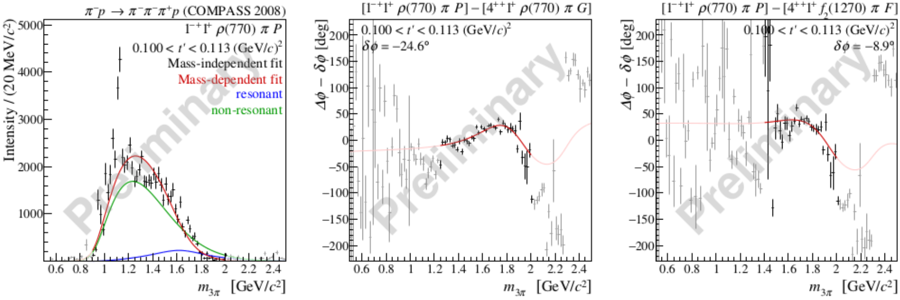
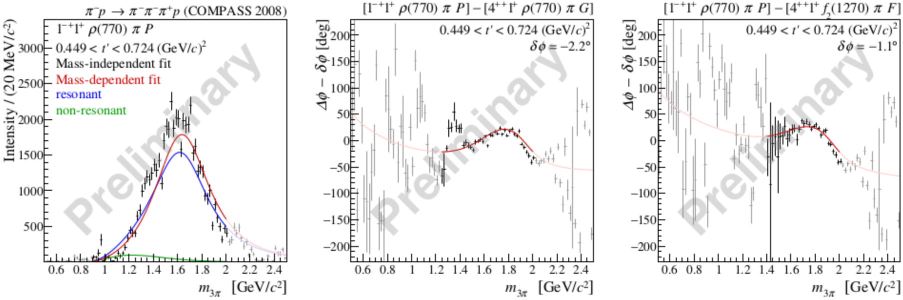
  for any complex-valued zero-mode coefficient $\mathcal{C}$
- $\mathcal{C}$: complex-valued ambiguity in the model

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



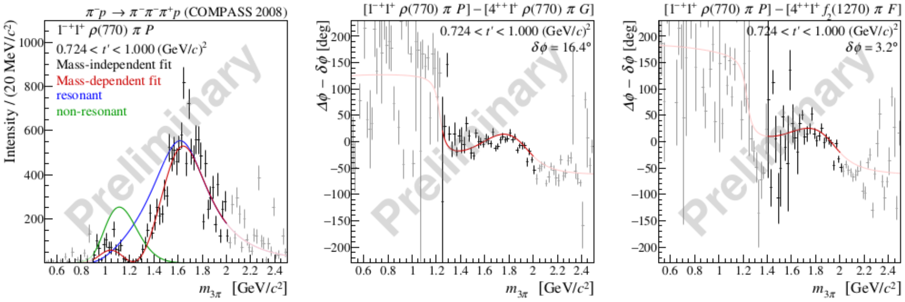
at low t' very weak resonant component

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



at higher t' resonant component dominant

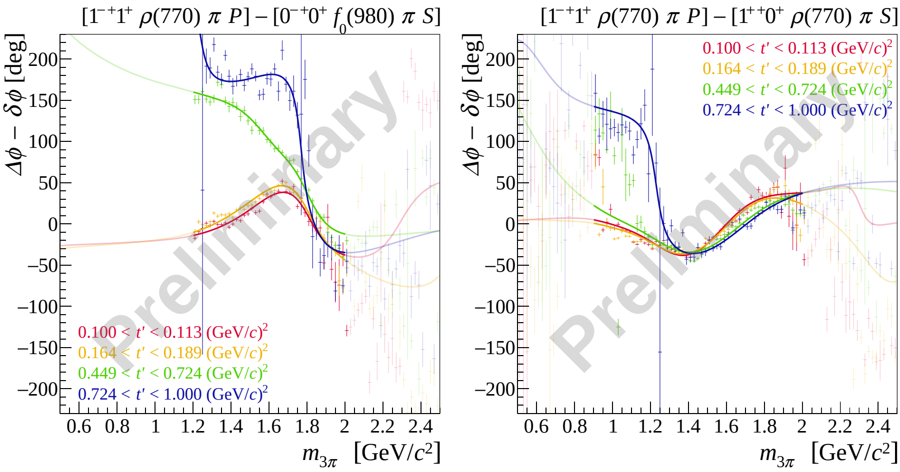
The $1^{-+}1^{+}\rho(770)\pi P$ wave



at higher t' resonant component dominant

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

Phase motion



resonance with mass $\sim$1600 MeV/c^2 very broad Γ $\sim$600 MeV/c^2