(Light-meson) exotic resonances by COMPASS

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Physik-Department, TU München

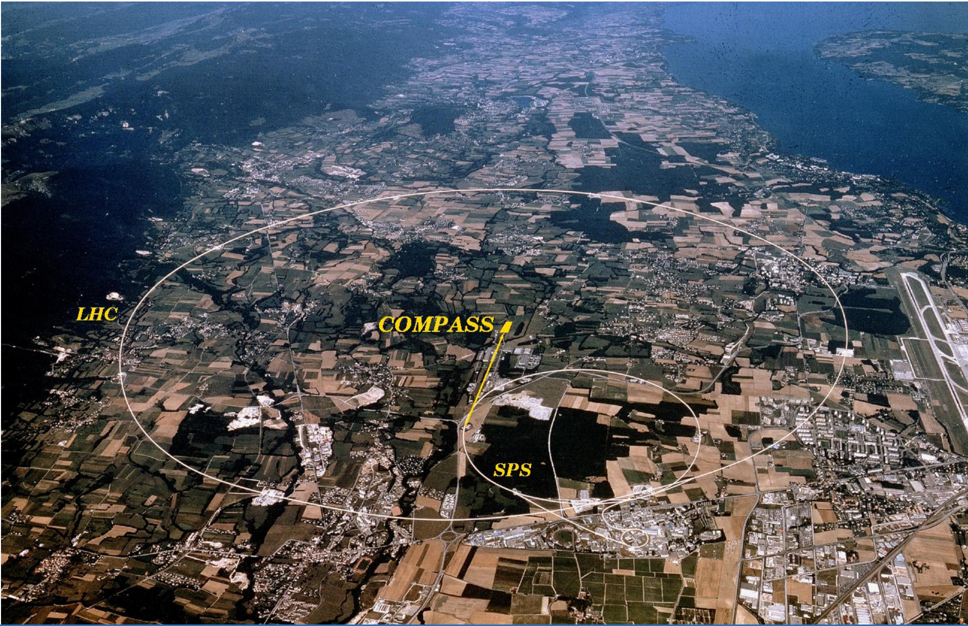
COMPASS collaboration

Resonance Workshop, Bergamo
October 12, 2017

COMPASS MLL TUM LMU Bundesministerium für Bildung und Forschung CERN

The COMPASS experiment

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



The COMPASS experiment

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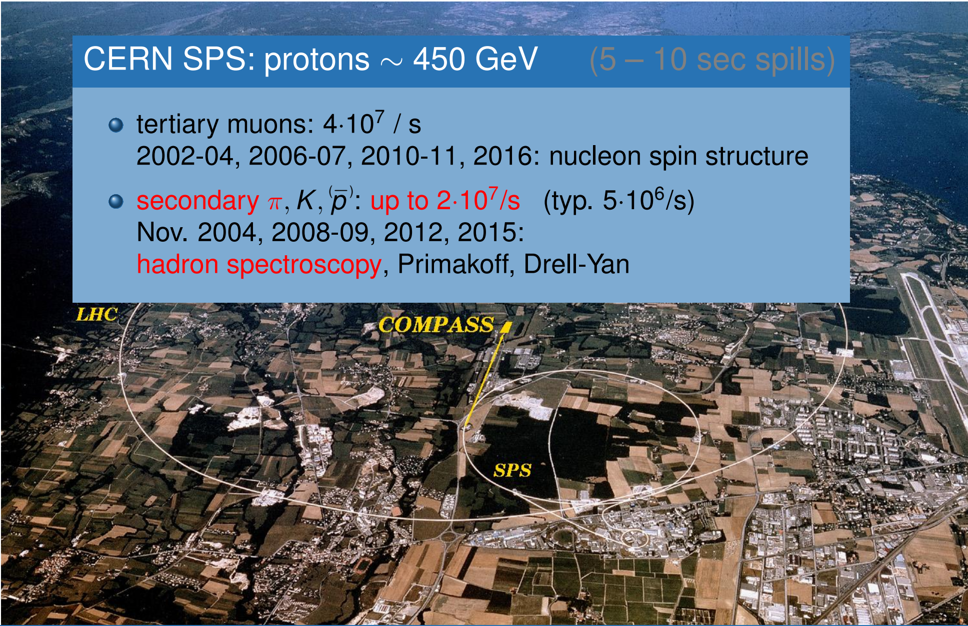
CERN SPS: protons ~ 450 GeV (5 – 10 sec spills)

- tertiary muons: $4{\cdot}10^7$ / s
  2002-04, 2006-07, 2010-11, 2016: nucleon spin structure
- secondary $\pi, K, \overset{(-)}{p}$: up to $2{\cdot}10^7$/s (typ. $5{\cdot}10^6$/s)
  Nov. 2004, 2008-09, 2012, 2015:
  hadron spectroscopy, Primakoff, Drell-Yan



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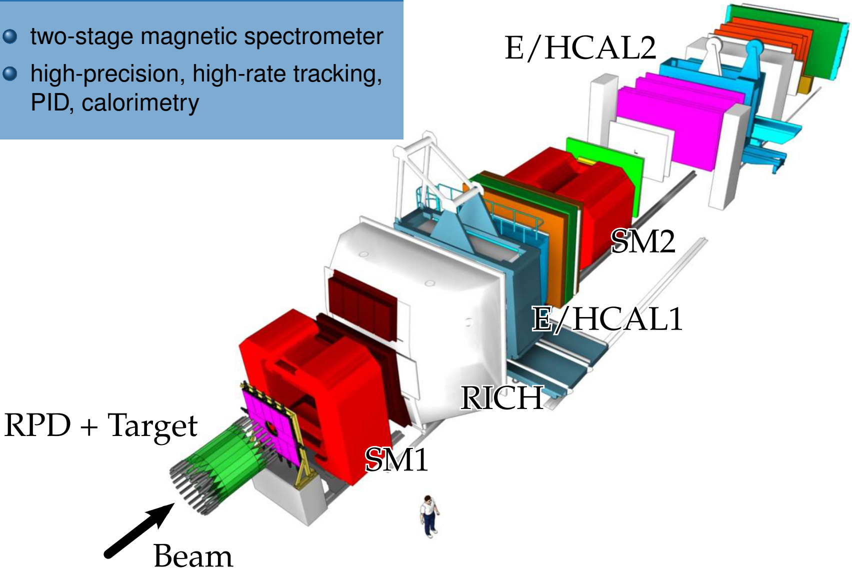
Fixed-target experiment

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



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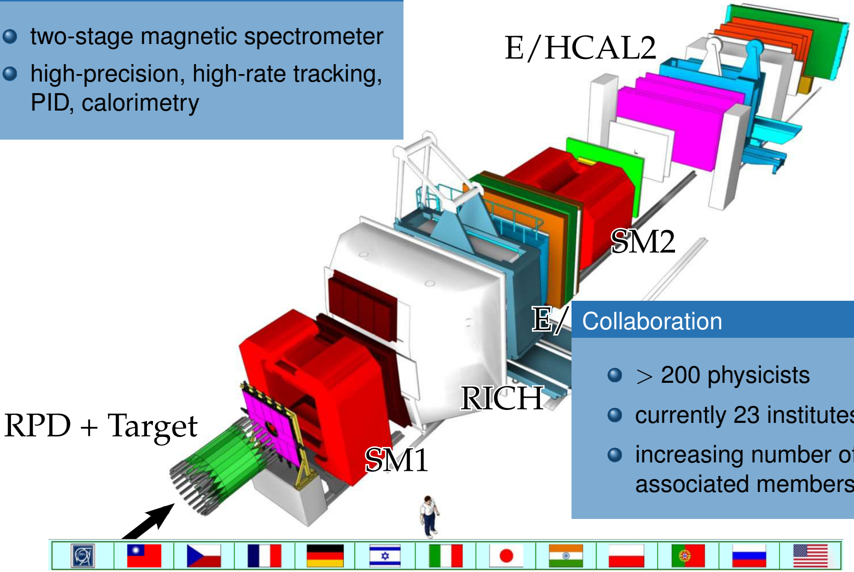


Collaboration

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

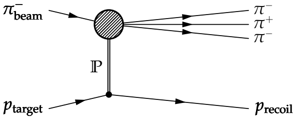
Diffractive 3π production

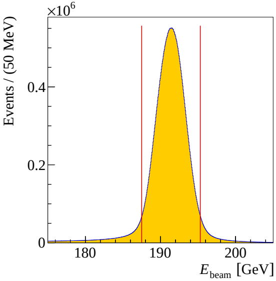
- COMPASS: World's currently largest data set for the diffractive process

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

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

- Exclusive measurement





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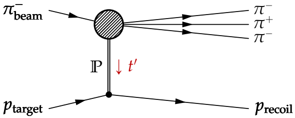
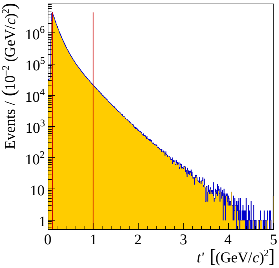
- Squared four-momentum transfer t' by Pomeron $\mathbb{P}$





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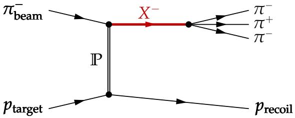
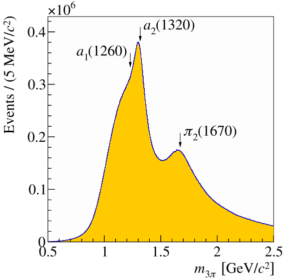
- Rich structure in $\pi^-\pi^+\pi^-$ mass spectrum: Intermediary states X^-





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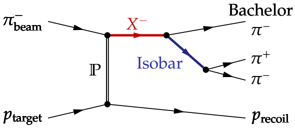

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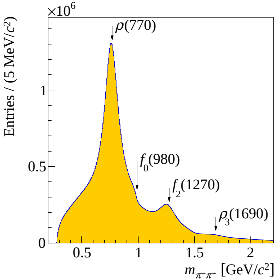

- Also structure in $\pi^+\pi^-$ subsystem: Intermediary states ξ (Isobar)

Wanted: really good fits

(1) all details of the three-body phase-space shall be matched, including momentum transfer dependence

(2) Breit-Wigner resonances + smoother non-resonant contributions

The isobar model

- Intermediate states appear as dynamic amplitudes $\Delta(m)$:
  Complex-valued functions of invariant mass m

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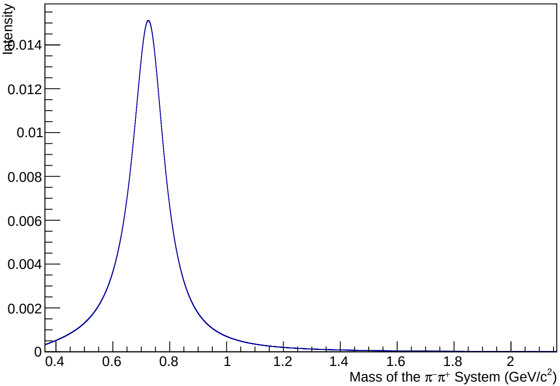
The isobar model

- Inter
  Com
- Simp | width Γ_0:
- Anal | erred form
  the c
- Dyna

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



The isobar model

- Inter
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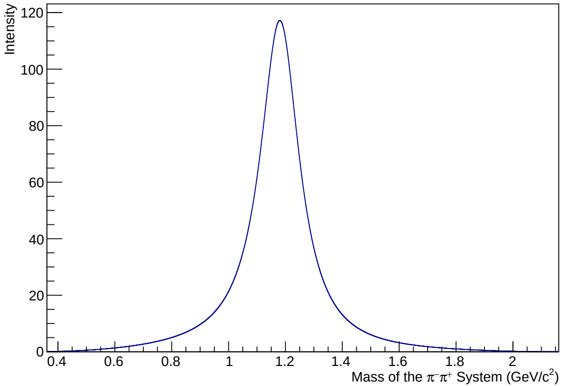
Dynamic isobar amplitude: f_2 (1270), $J^{PC} = 2^{++}$



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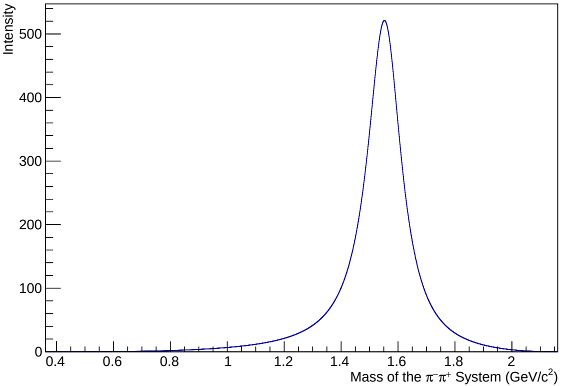
Dynamic isobar amplitude: $\rho_3\,(1690)$, $J^{PC} = 3^{--}$



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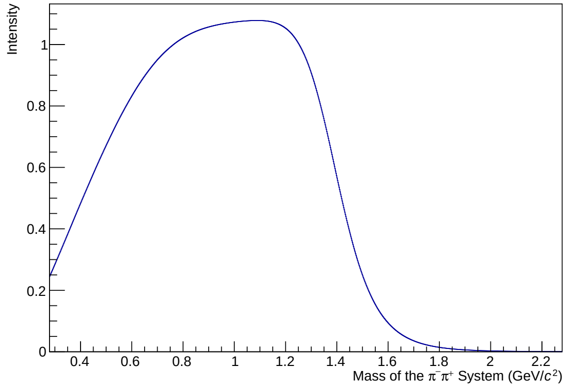
Dynamic isobar amplitude: $[\pi\pi]_S$ wave, $J^{PC} = 0^{++}$



The isobar model

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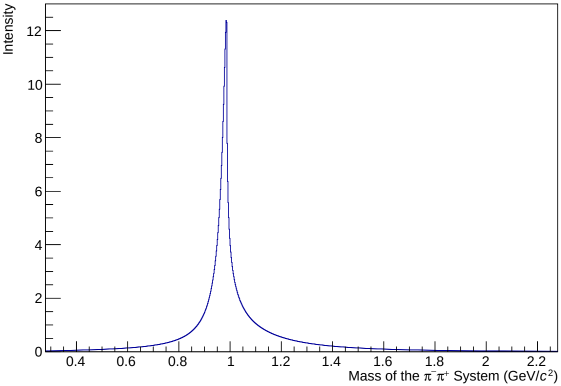
Dynamic isobar amplitude: f_0 (980), $J^{PC} = 0^{++}$



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- True dynamic isobar amplitudes may differ from the model
- Free parameters in dynamic isobar amplitudes computationally unfeasible

Freed isobars: powerful test of the assumptions

Step-like isobar amplitudes

- 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 $\mathcal{T}_i^{\text{bin}} = \mathcal{T}_i \mathscr{T}_i^{\text{bin}}$:

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

as function of ph…

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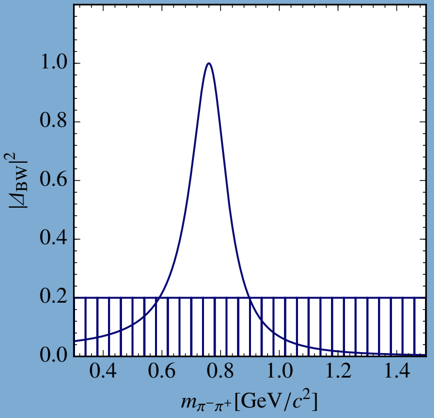
Illustration



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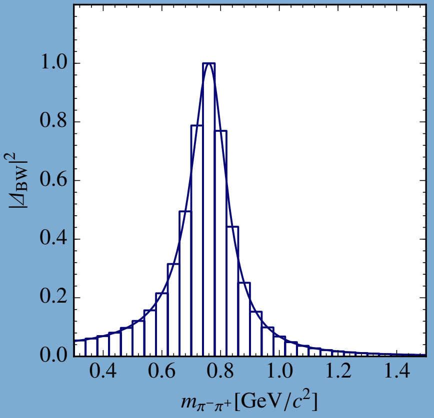
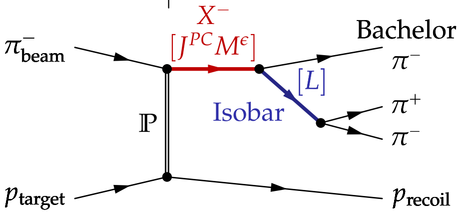


Partial-Wave Analysis

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

Waves specified by:

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



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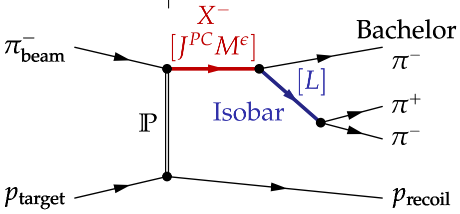

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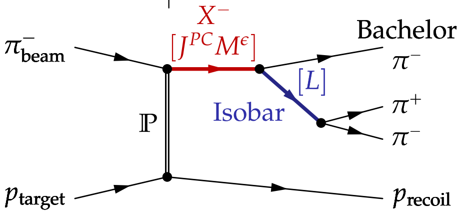

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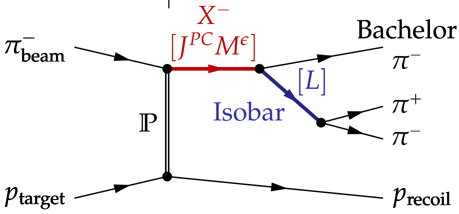

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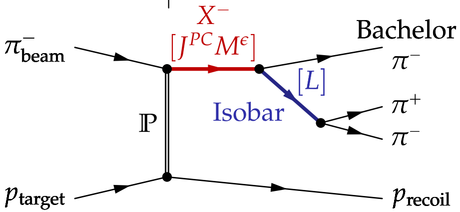

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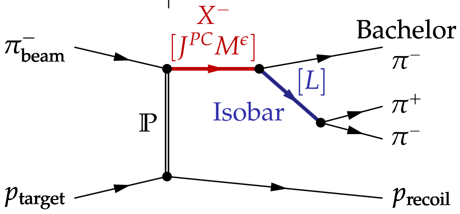

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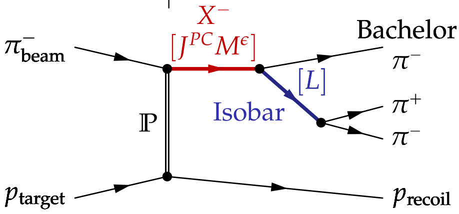

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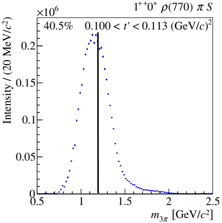
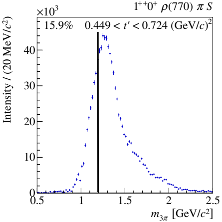
88 waves needed to describe the data ("hand-selected")
interference terms → get (relative) phases

Step 1: Partial-Wave Analysis

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

Low t'



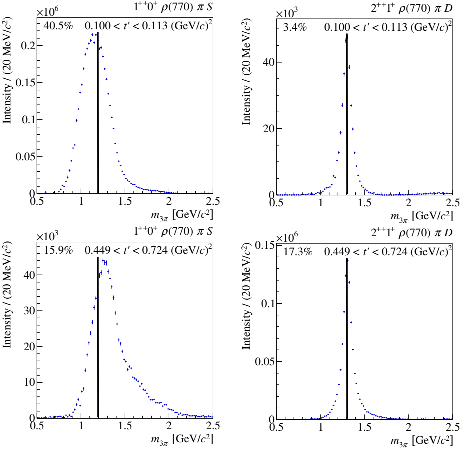


High t'

Step 1: Partial-Wave Analysis

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

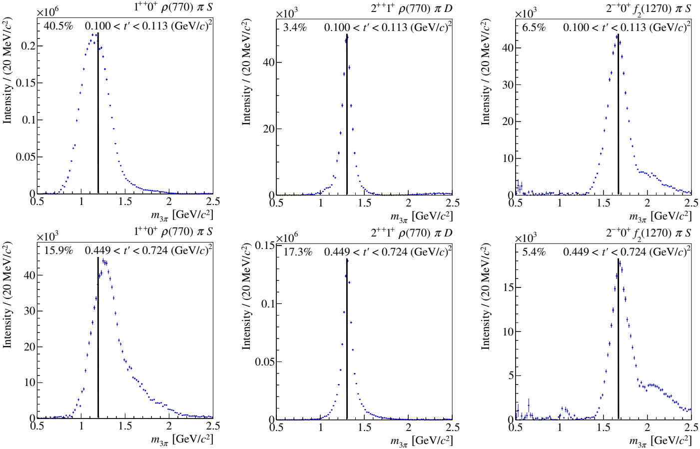
Low t'



High t'

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

Low t'

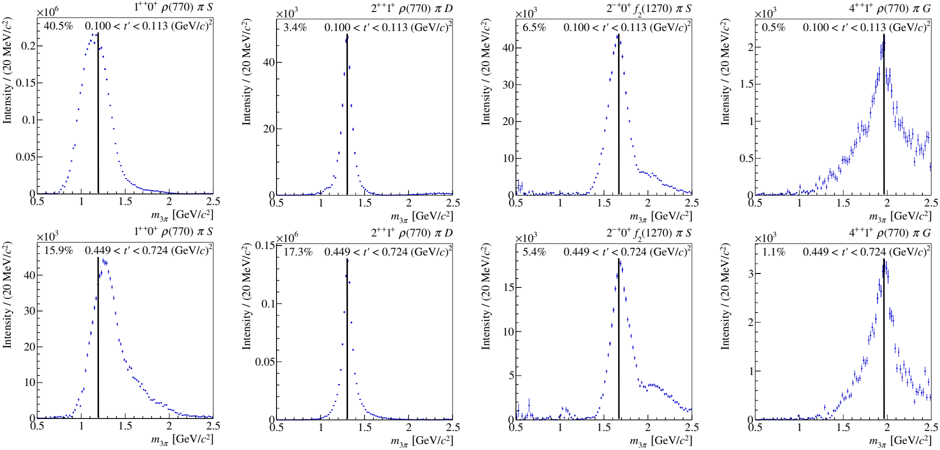


High t'

Step 1: Partial-Wave Analysis

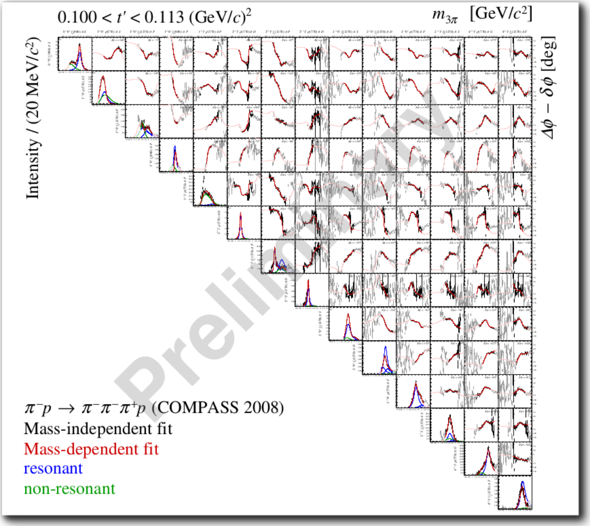
Selected Waves (4 of 88) in two of the 11 independent t' bins

Low t'



High t'

Step 2: Resonance model fit



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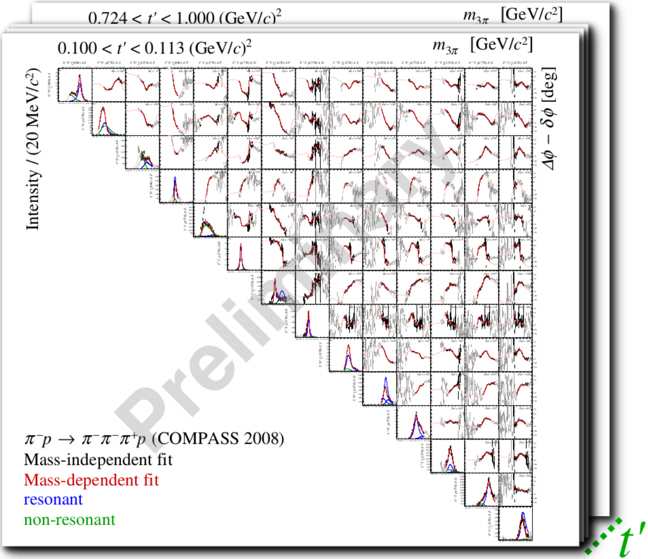
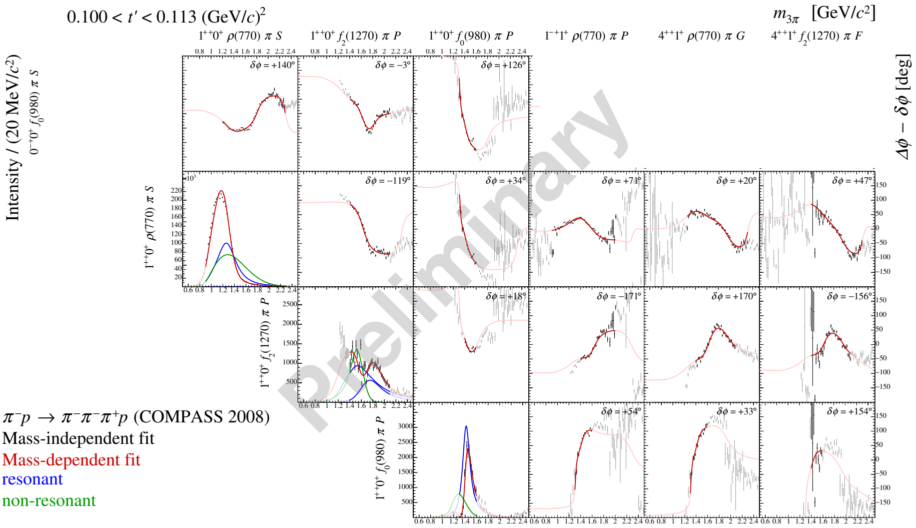


$\times 11$ bins in t'

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



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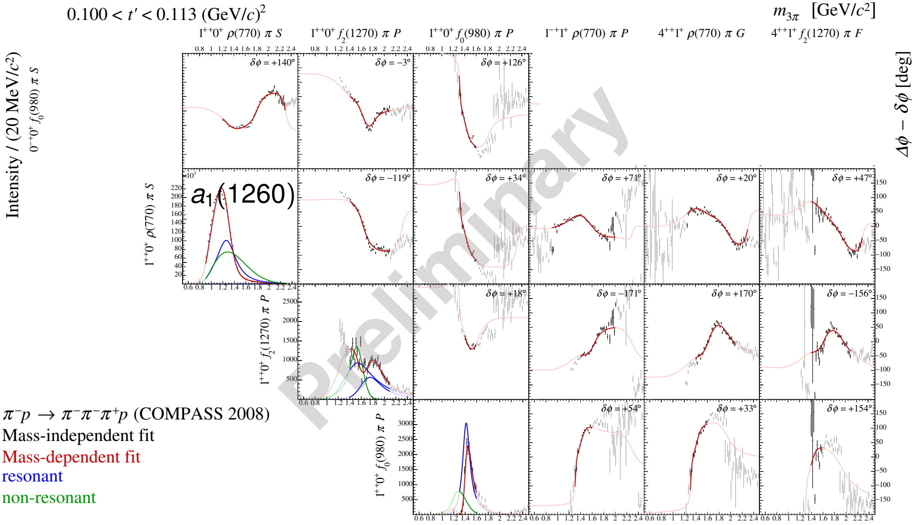
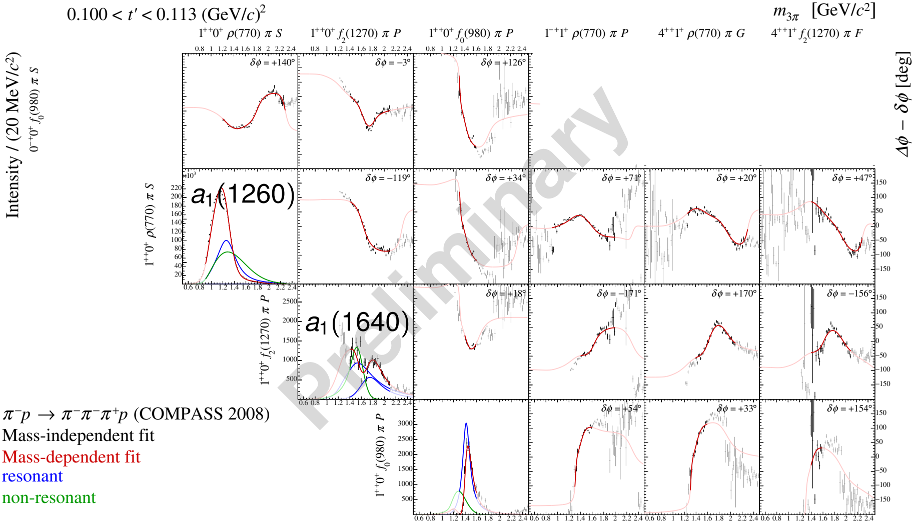


$\pi^- p \to \pi^-\pi^-\pi^+ p$ (COMPASS 2008)
Mass-independent fit
Mass-dependent fit
resonant
non-resonant

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



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

Mass-independent fit

Mass-dependent fit

resonant

non-resonant

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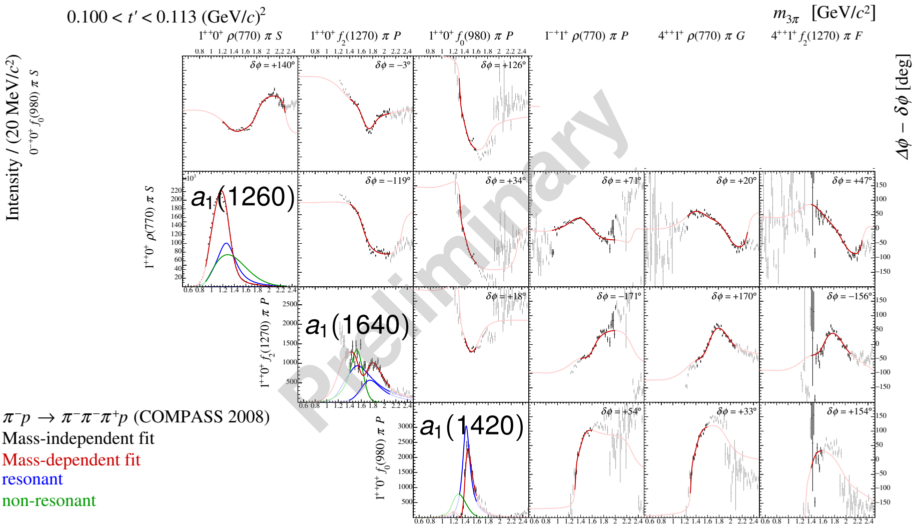

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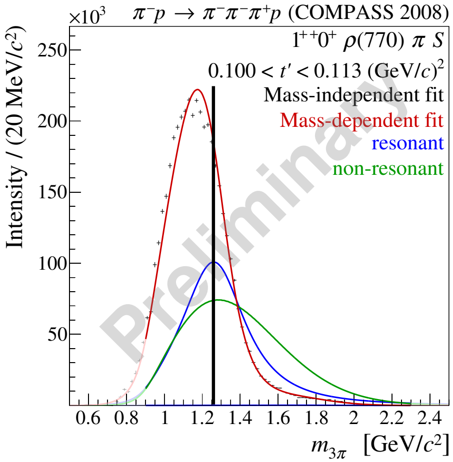
$a_1(1260)$

- resonance parameters do not depend on production mechanism



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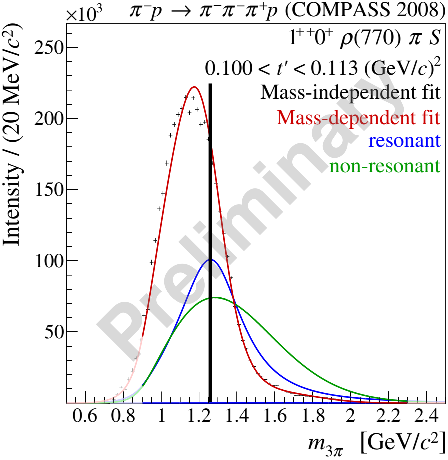

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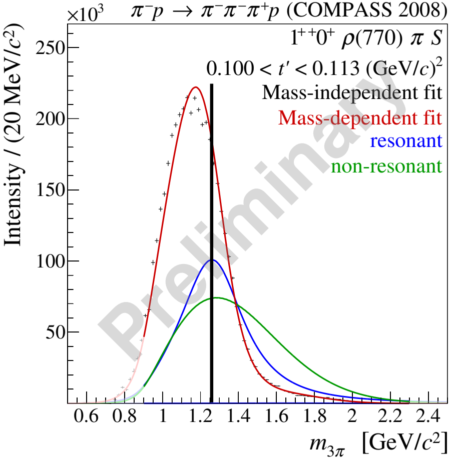

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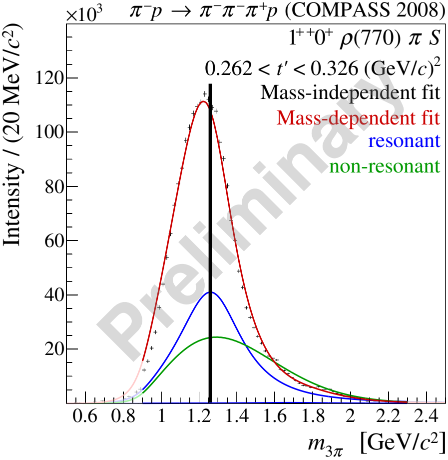

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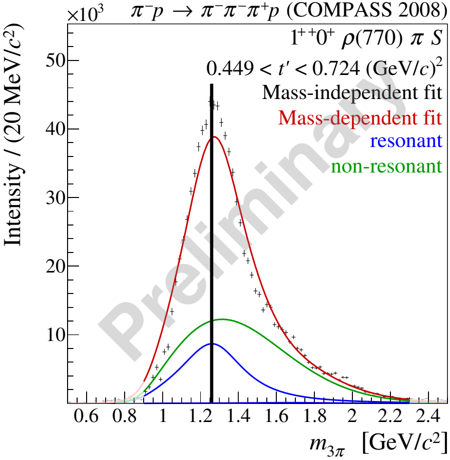

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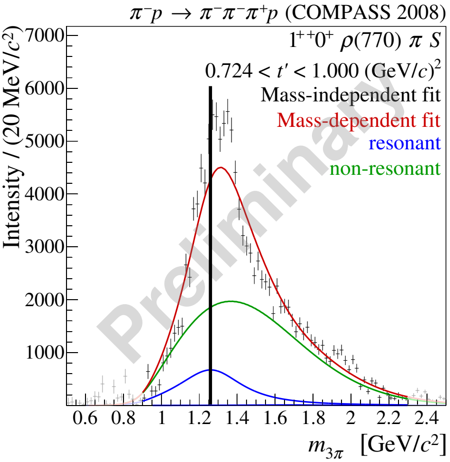

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$$m^{PDG} = 1230 \pm 40\ \text{MeV}/c^2$$
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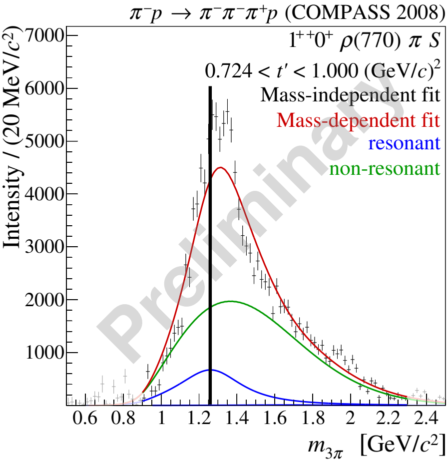

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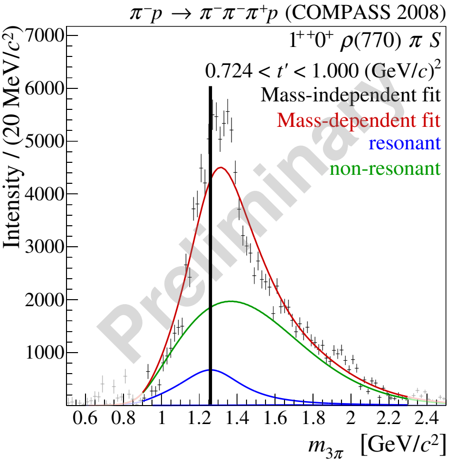
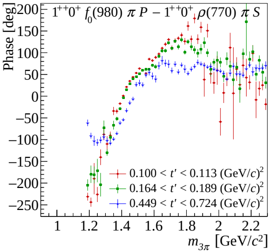
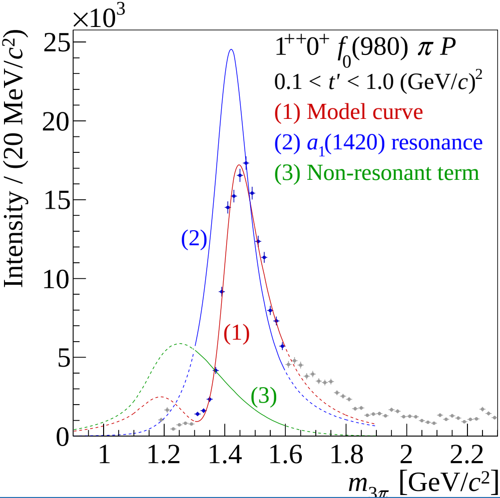
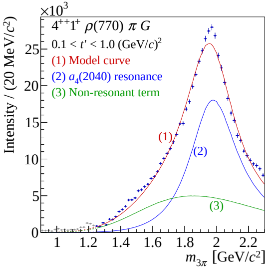
- weak signal for $a_1(1640)$




$1^{++}0^{+}$ $f_0(980)$ π P – $1^{++}0^{+}$ $\rho(770)$ π S
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
$m_{3\pi}$ [GeV/c^2]


$\times 10^3$
Intensity / (20 MeV/c^2)
$1^{++}0^{+}$ $f_0(980)$ π P
$0.1 < t' < 1.0$ (GeV/c)^2
(1) Model curve
(2) $a_1(1420)$ resonance
(3) Non-resonant term
(1)
(2)
(3)
$m_{3\pi}$ [GeV/c^2]



$\times 10^3$
$4^{++}1^{+}$ $\rho(770)$ π G
$0.1 < t' < 1.0$ $(\mathrm{GeV}/c)^2$
(1) Model curve
(2) $a_4(2040)$ resonance
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Intensity / (20 MeV/c^2)
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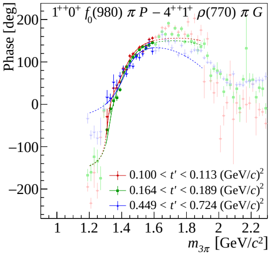

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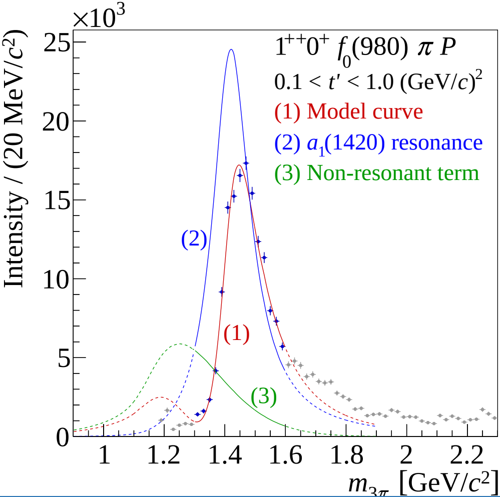

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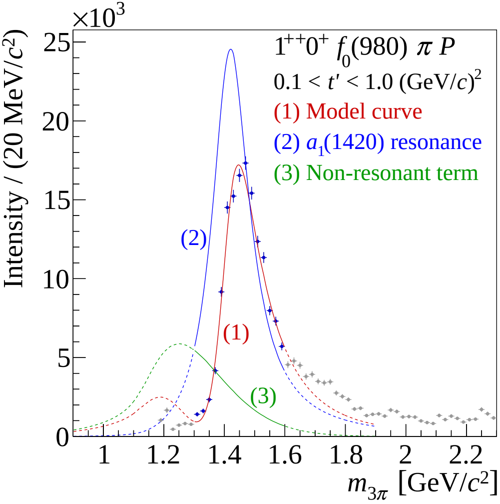
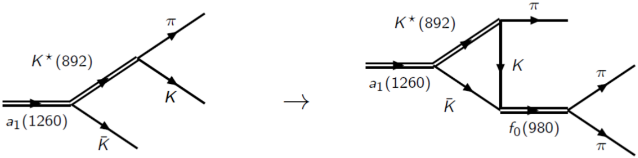
- decay into $f_0(980)\pi$



$a_1(1420)$

a new - quite exotic - signal



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- decay into $f_0(980)\pi$
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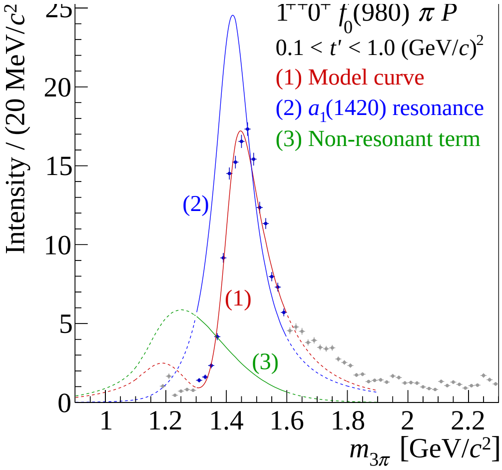
  - two-channel unitarized Deck amplitude *Basdevant, Berger* PRL114 (2015) 192001



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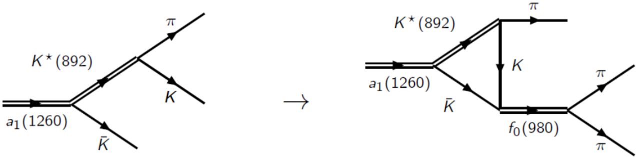

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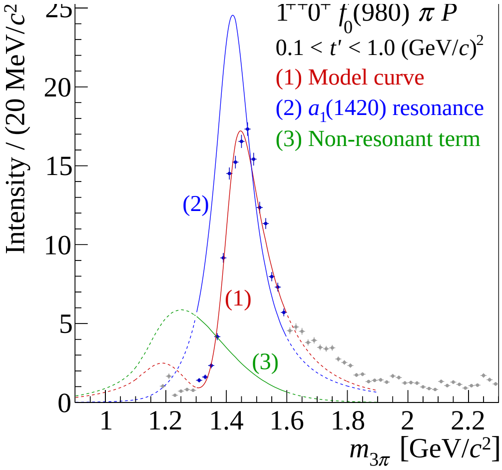
- Mass:
  $m_{a_1(1420)} = 1411.8^{+1.0}_{-4.4}\,\mathrm{MeV}/c^2$
  Width:
  $\Gamma_{a_1(1420)} = 158^{+8}_{-8}\,\mathrm{MeV}/c^2$



Towards another exotic: freed-isobar wave set
Already published

- the analysis so far:
  - Wave set: 88 waves
  - Same data set
  - Same Monte Carlo

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- T
  fr
- F

Matching isobar quantum numbers

$$\left.\begin{array}{l} 0^{-+}0^{+}\,[\pi\pi]_S\,\pi S \\ 0^{-+}0^{+} f_0\,(980)\,\pi S \\ 0^{-+}0^{+} f_0\,(1500)\,\pi S \end{array}\right\} \quad 0^{-+}0^{+}[\pi\pi]_{0^{++}}\pi S$$

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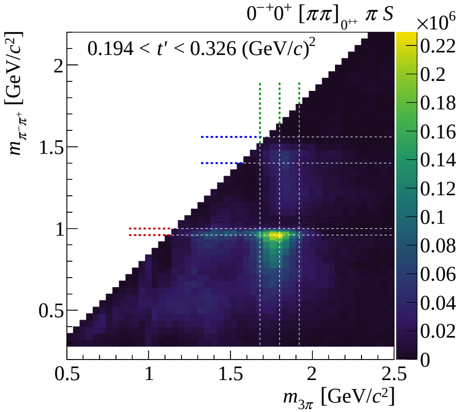
- Replace 7 fixed-isobar waves
- Published in Phys. Rev. **D95** no. 3, (2017) 032004
- Promising results



credit: Fabian Krinner (PhD work, cf. HADRON2017 talk), Dima Ryabchikov

- Extend freed-isobar wave set

Freed-isobar wave set
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Freed isobar wave set

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$1^{++}0^{+}[\pi\pi]_{0^{++}}\pi P$	$2^{-+}0^{+}[\pi\pi]_{1^{--}}\pi F$	$2^{++}1^{+}[\pi\pi]_{1^{--}}\pi D$
$1^{++}0^{+}[\pi\pi]_{1^{--}}\pi S$	$2^{-+}0^{+}[\pi\pi]_{2^{++}}\pi S$	

Freed-isobar wave set
Extended wave set

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- 12 freed- and 72 fixed-isobar waves in the model
- 40 MeV bin width in $m_{3\pi}$ from 0.5 to 2.5 GeV
- 50 bins in $m_{3\pi}$, four bins in t': $4 \times 50 = 200$ independent bins

Zero mode in the spin-exotic wave

What is a “zero mode”?

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

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

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

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

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

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

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

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

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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 $\mathcal{C}$

Zero mode in the spin-exotic wave

Mathematical origin

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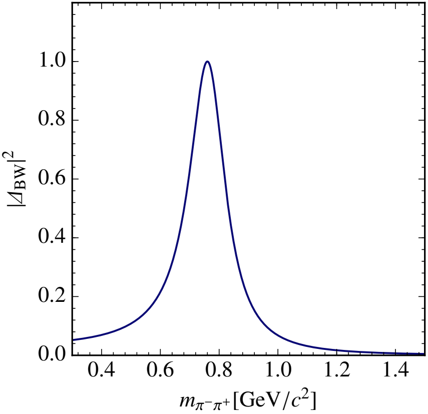
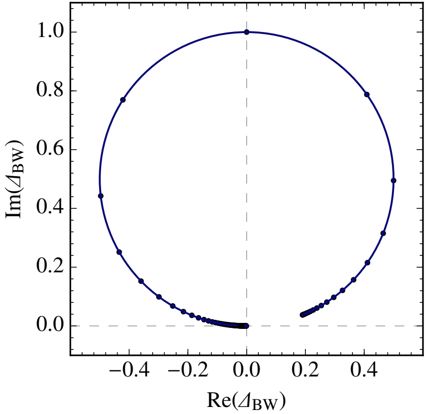
  for any complex-valued zero-mode coefficient $\mathcal{C}$
- $\mathcal{C}$: complex-valued ambiguity in the model

Zero mode in the spin-exotic wave

Effects on dynamic isobar amplitudes

$$\Delta_{\mathrm{BW}}\left(m_{\pi^-\pi^+}\right) + \mathcal{C}\Omega\left(m_{\pi^-\pi^+}\right)$$
$$\mathcal{C} = 0.00 + 0.00i$$





All describe the same 3π-intensity

Zero mode in the spin-exotic wave
Effects on dynamic isobar amplitudes

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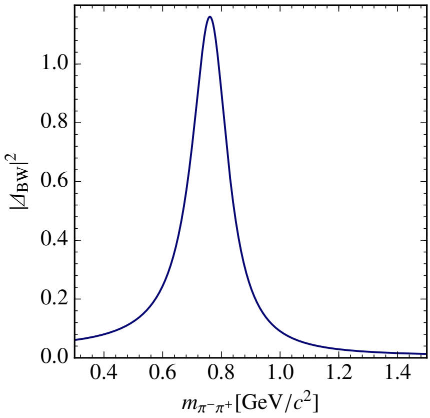
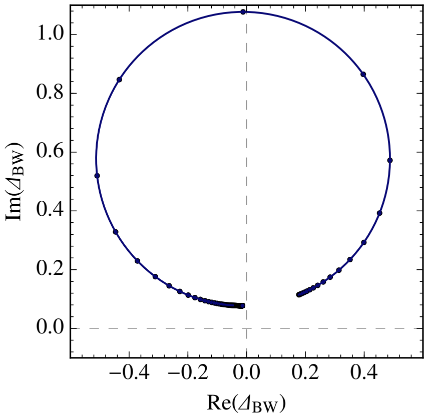
$$\mathcal{C} = -0.01 + 0.08i$$





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Zero mode in the spin-exotic wave

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$$\Delta_{\mathrm{BW}}\left(m_{\pi^-\pi^+}\right) + \mathcal{C}\Omega\left(m_{\pi^-\pi^+}\right)$$

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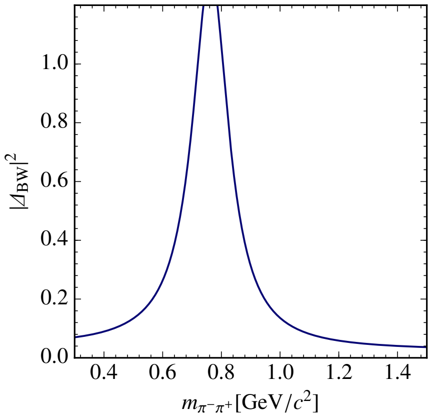

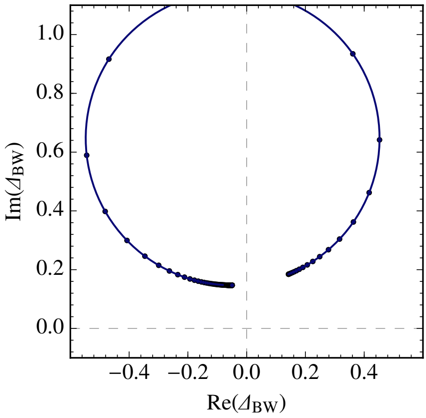

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Zero mode in the spin-exotic wave

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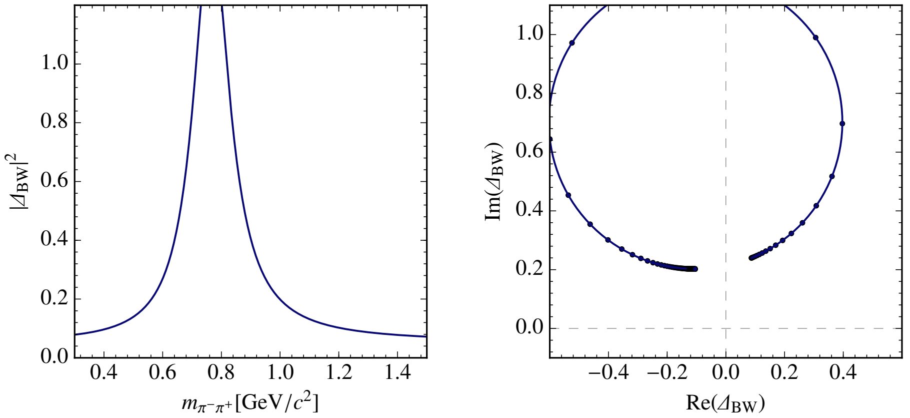
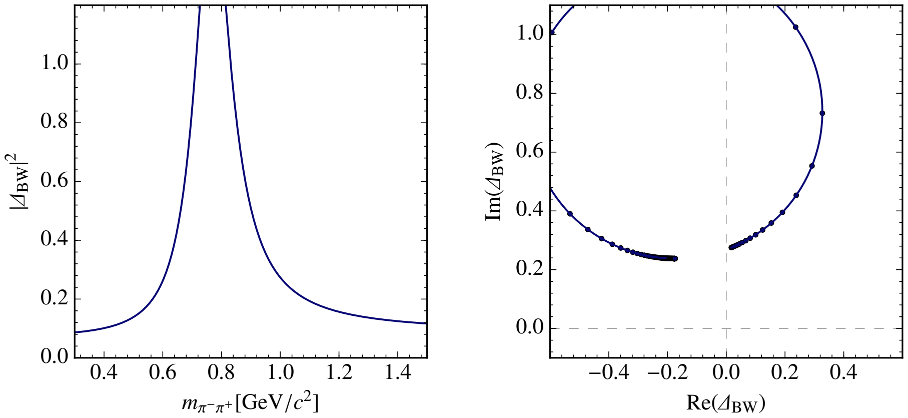


All describe the same 3π-intensity

$$\Delta_{\mathrm{BW}}\left(m_{\pi^-\pi^+}\right) + \mathcal{C}\Omega\left(m_{\pi^-\pi^+}\right)$$
$$\mathcal{C} = -0.17 + 0.24i$$



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Zero mode in the spin-exotic wave

Effects on dynamic isobar amplitudes

$$\Delta_{\text{BW}}\left(m_{\pi^-\pi^+}\right) + \mathcal{C}\Omega\left(m_{\pi^-\pi^+}\right)$$

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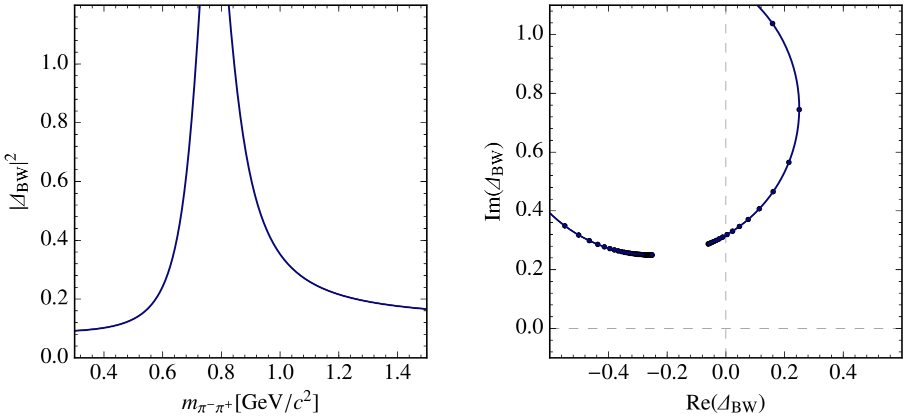

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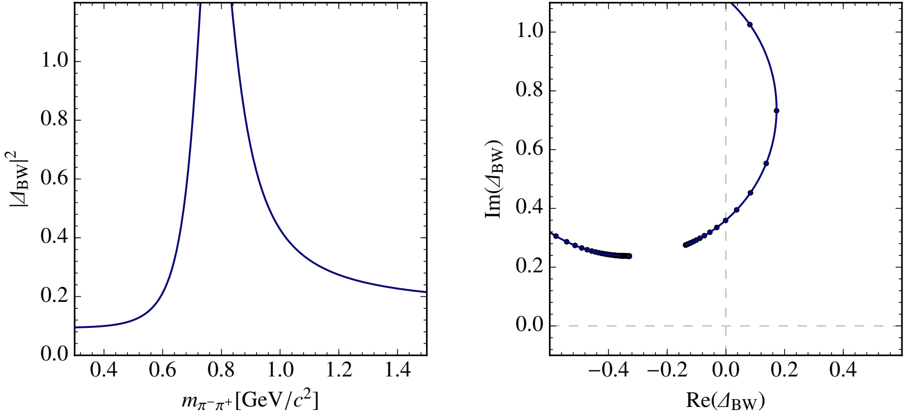

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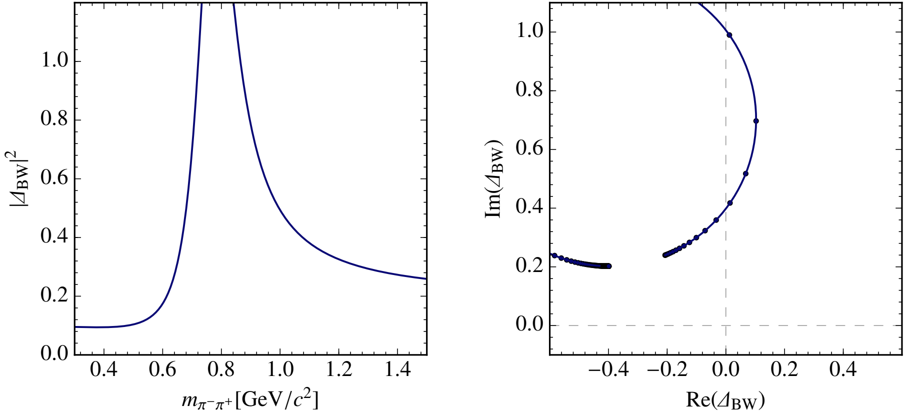

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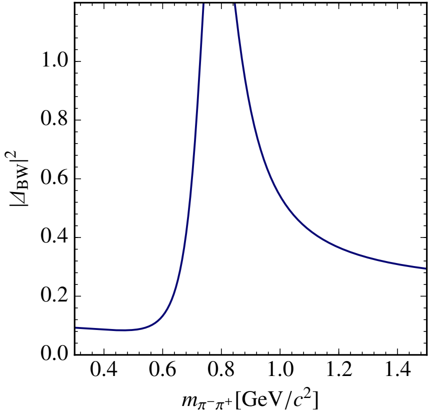

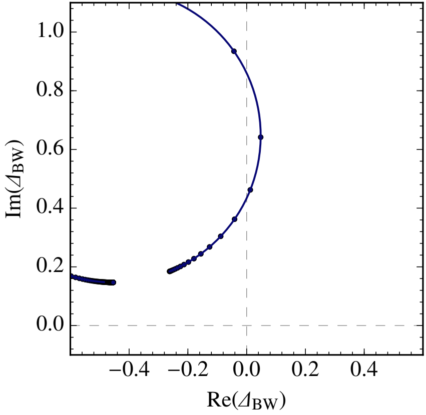

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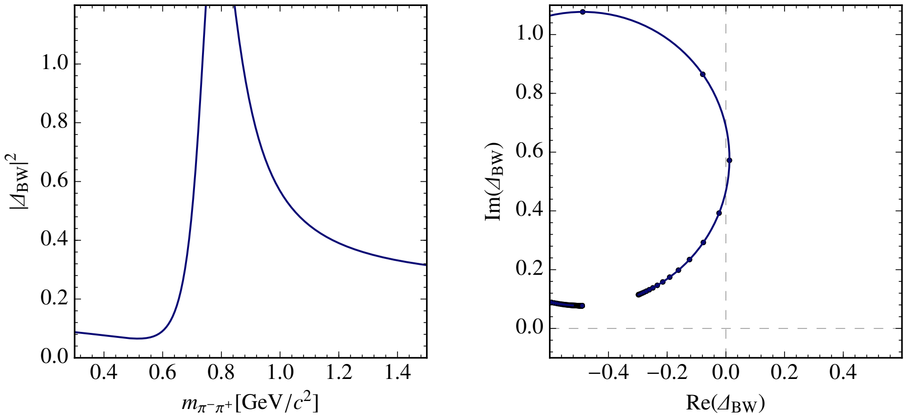

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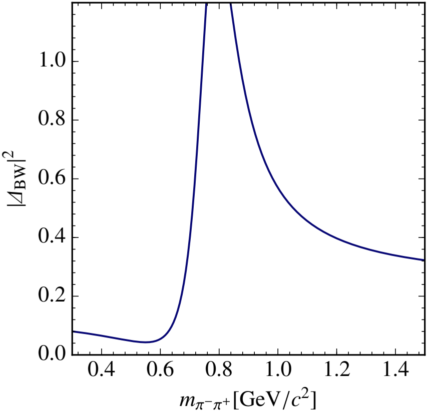

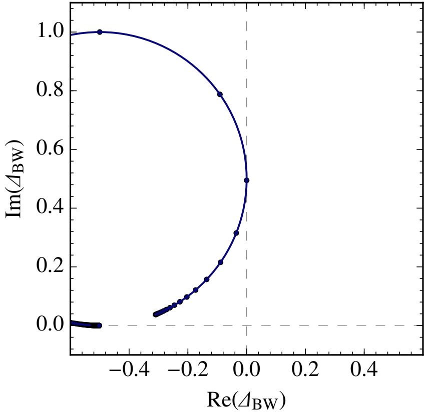

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$$\Delta_{\mathrm{BW}}(m_{\pi^-\pi^+}) + \mathcal{C}\Omega(m_{\pi^-\pi^+})$$
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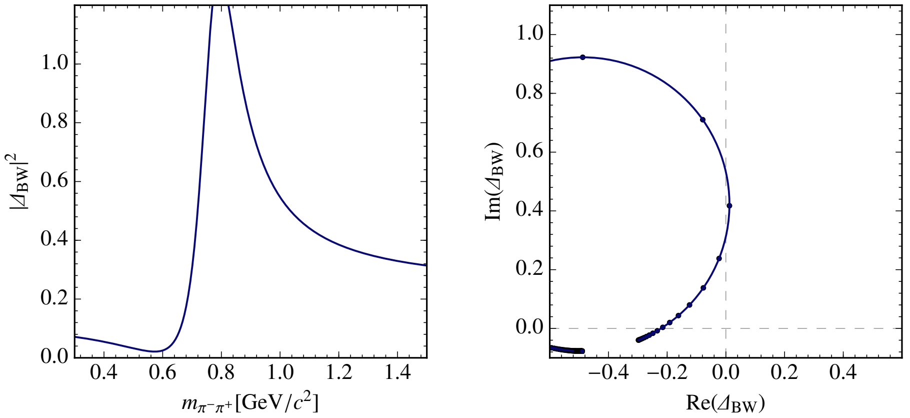

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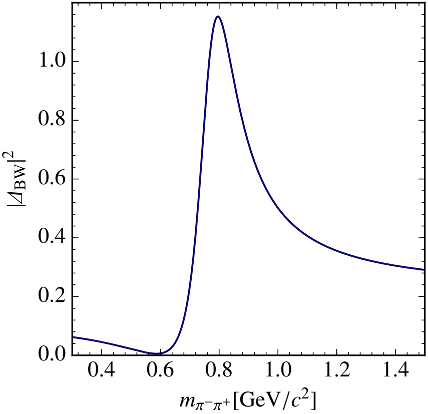

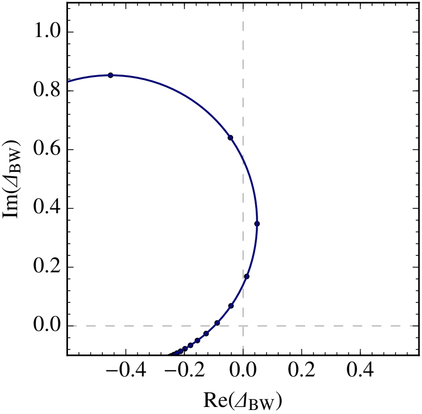

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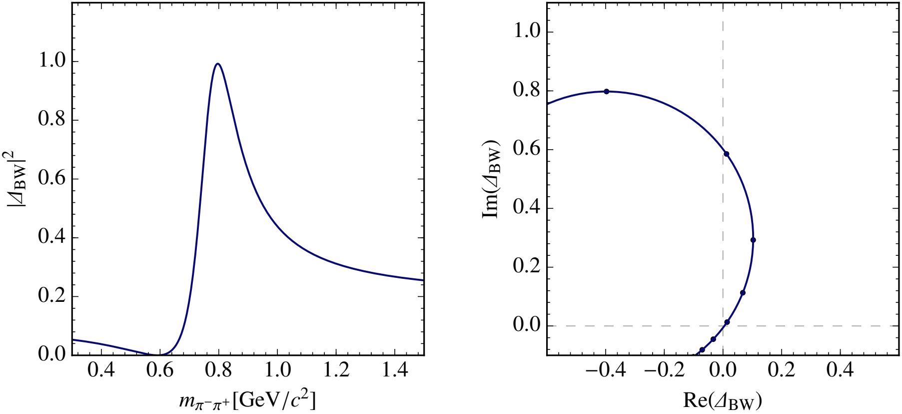

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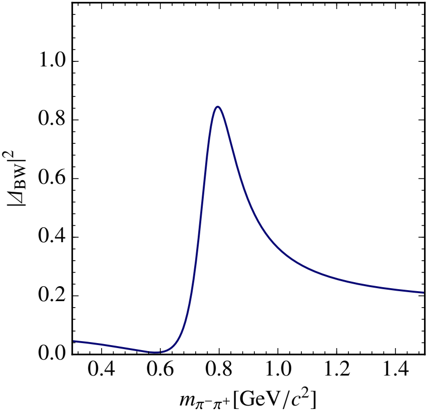

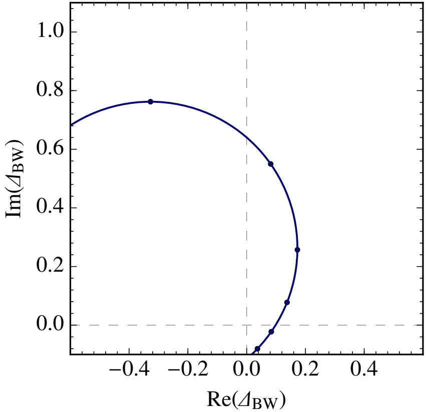

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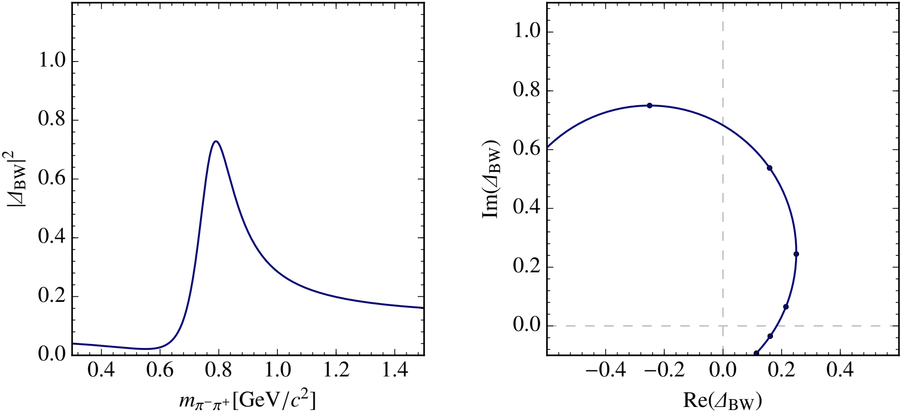

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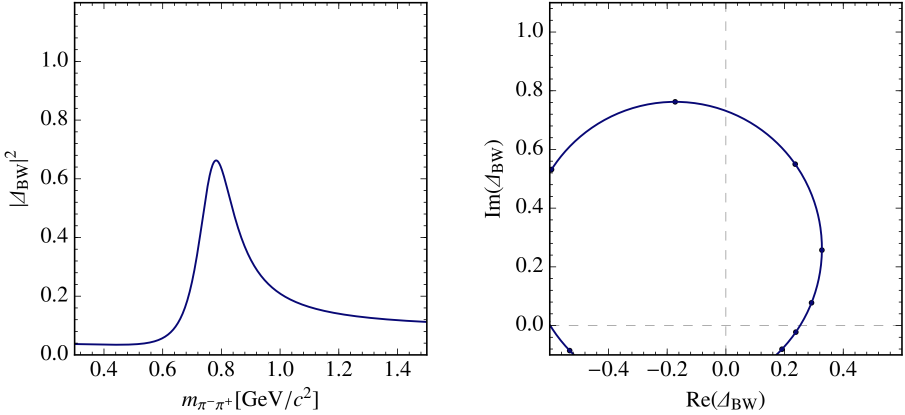

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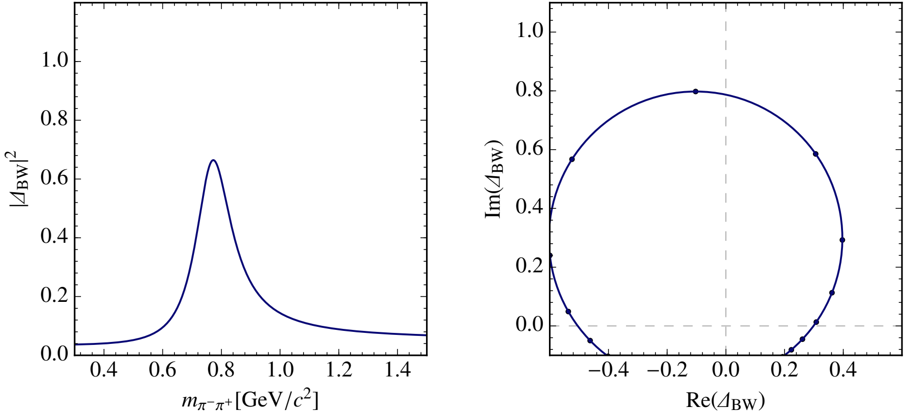

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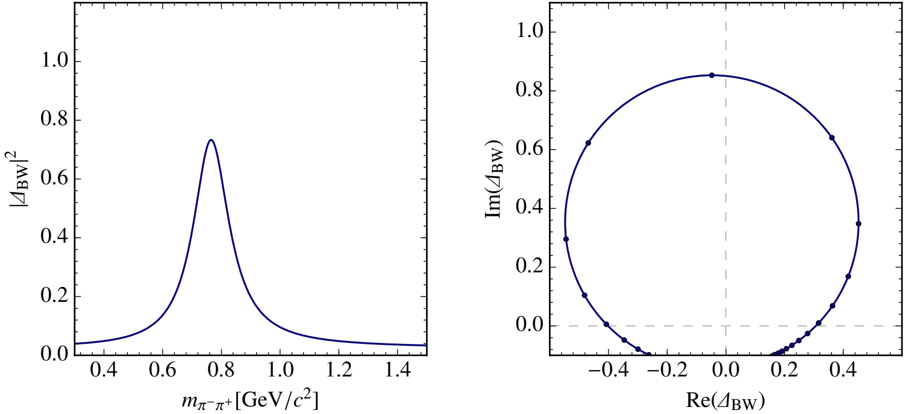

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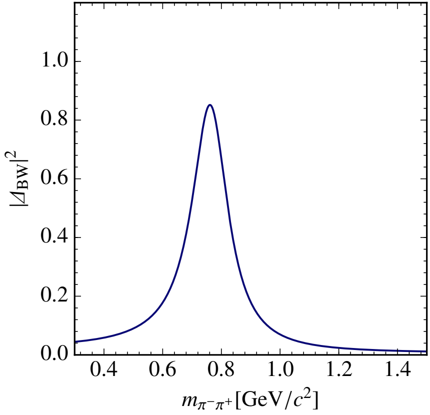

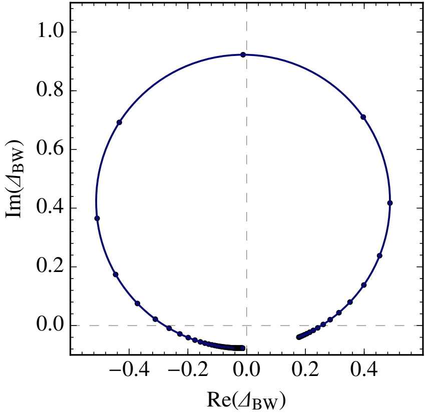

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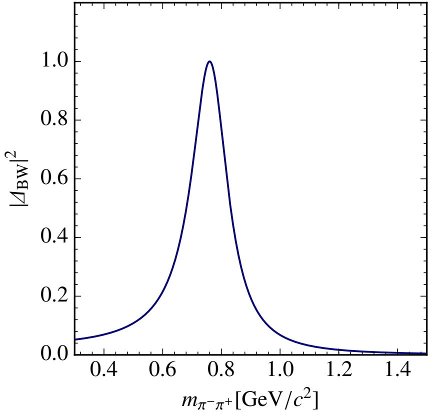

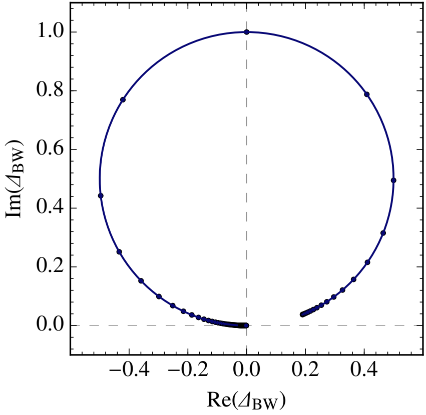

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Zero mode in the spin-exotic wave
Resolving the ambiguity

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  $n_{\rm bins}-1$ complex-valued d.o.f. remain free.

Zero mode in the spin-exotic wave

Resolving the ambiguity

- Zero-mode cont
- Fitted solution p   l solution
- Find matching C
- In the case of th
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- Final results: we
- **Note:** this fixes
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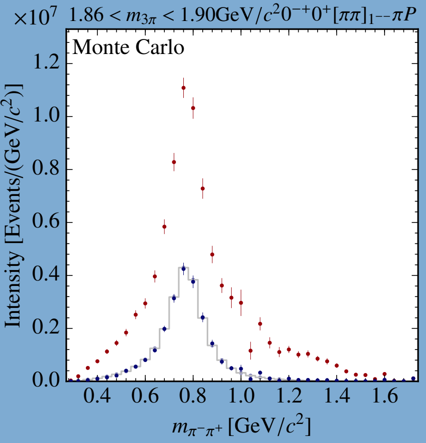
Different constraints



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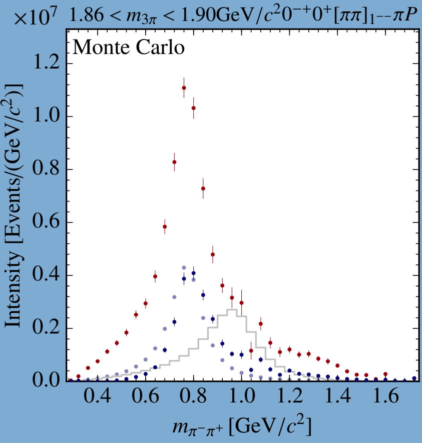

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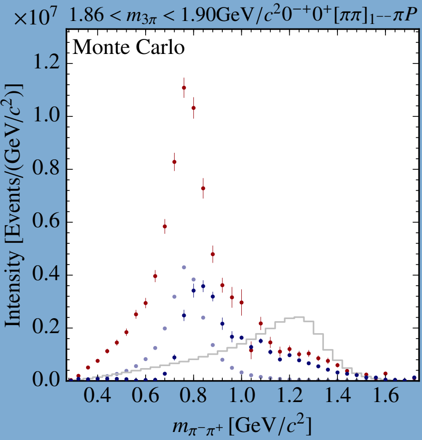
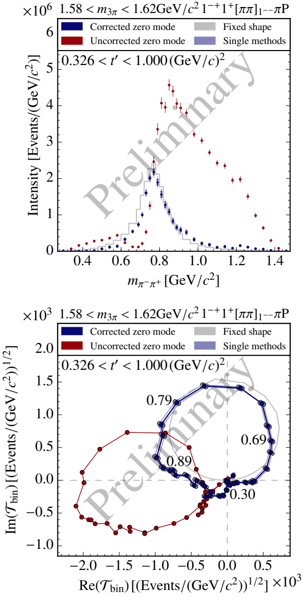


The spin-exotic wave

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



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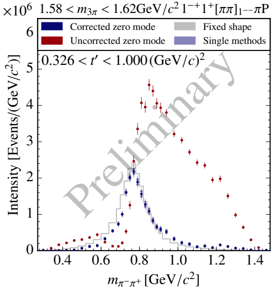

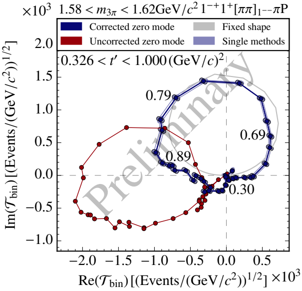

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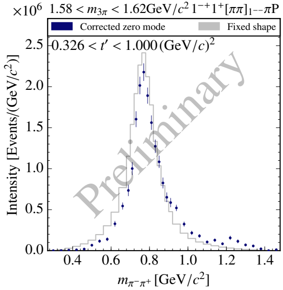

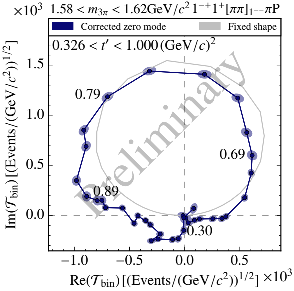

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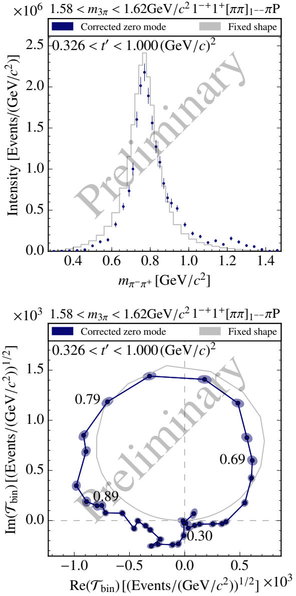

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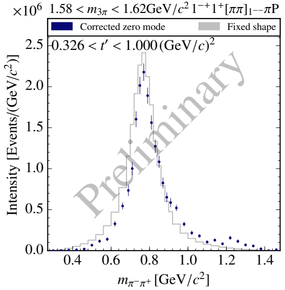
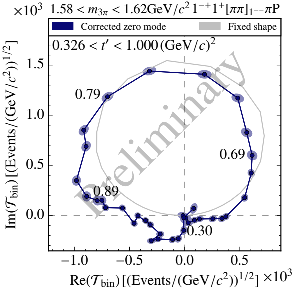
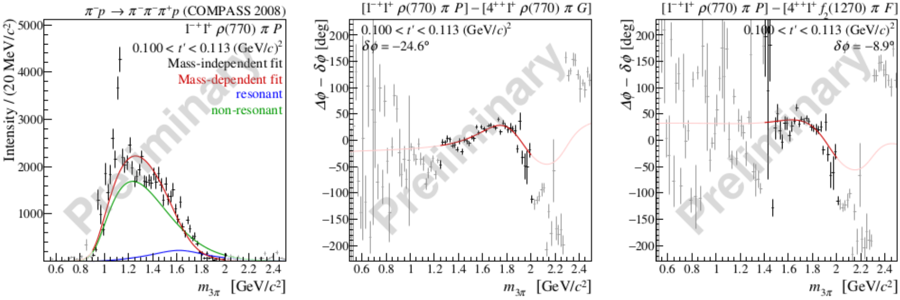
- Still significant deviations from a pure Breit-Wigner shape





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



at low t' very weak resonant component

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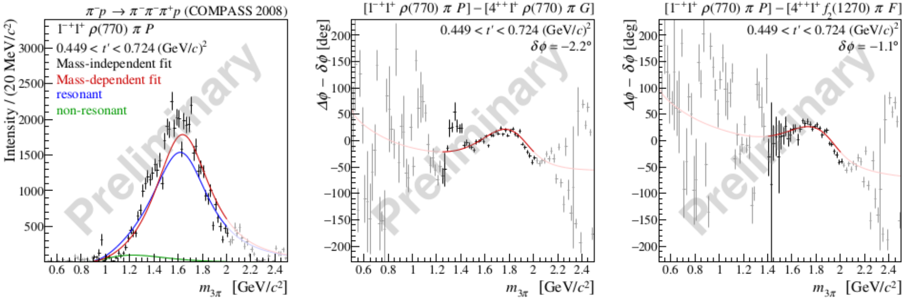

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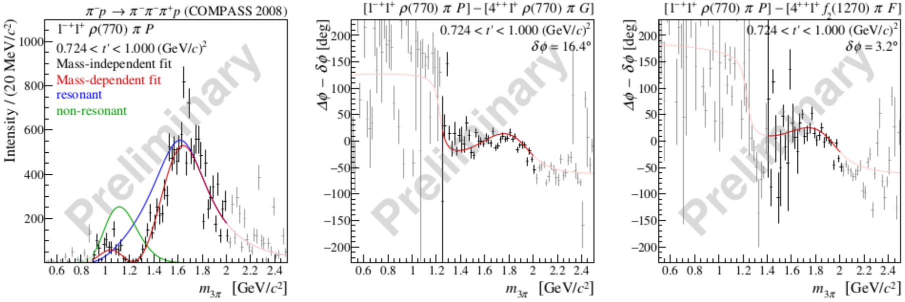

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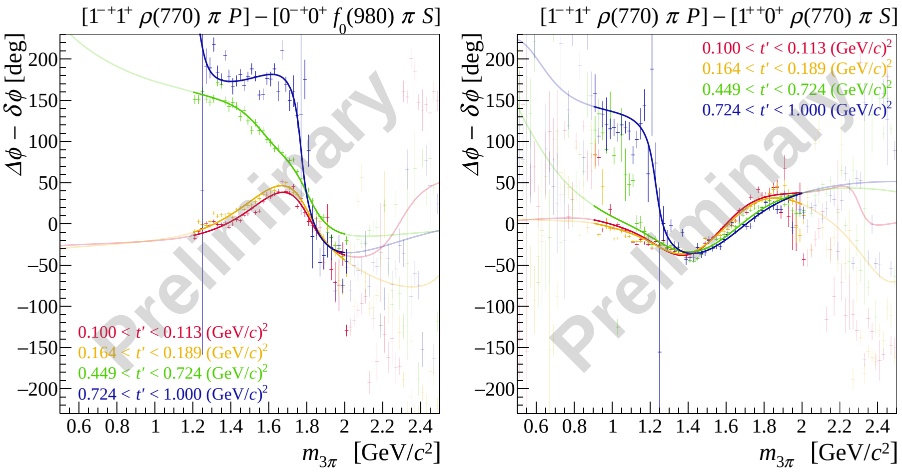
Phase motion



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

Conclusions and Outlook

COMPASS on exotic mesons:

- 46 million events for $\pi^- p \to p\, \pi^- \pi^+ \pi^-$ analyzed
- partial-wave decomposition with 88 waves
- two exotic signals analyzed:
  - $a_1(1420)$ *supernumerous*
    - ★ matches a Breit-Wigner description with $\Gamma = 158\ \mathrm{MeV}/c^2$
    - ★ position at $K^*\bar{K}$ threshold $\to$ rescattering interpretation
    - ★ and/or Deck interference
  - $\pi_1(1600)$ *spin-exotic*
    - ★ at small t' dominant background
    - ★ slow phase motion
    - ★ much broader than previous analyses

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  - refine non-resonant (Deck) background description
  - conclude on the "de-isobaring"
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- more channels to come, including π^0, η, K
- lower statistics for incoming K^- beams
  $\to$ dedicated future option: dedicated RF-separated beam

Thank you for your attention!