Study of the $\pi^-\pi^+$ subsystem with $J^{PC} = 1^{--}$ in the diffractively produced $\pi^-\pi^-\pi^+$ final state at COMPASS

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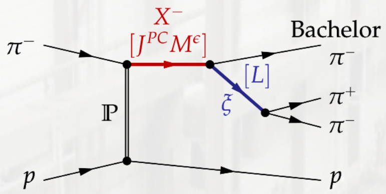
Diffractive $\pi^-\pi^-\pi^+$ Production at COMPASS

- 190 GeV π^- beam on p target
- World's largest sample: 46×10^6 exclusive events
- Data binned in $(m_{3\pi}, t')$ cells
- So far, focus on 3π resonances
  - Most detailed partial-wave analysis [1]
  - a_J and π_J states, such as $a_1(1420)$ or $\pi_1(1600)$



This analysis: Detailed Study of the $\pi^-\pi^+$ Subsystem Amplitude

- Measure $\pi^-\pi^+$ amplitudes with well-defined J^{PC} quantum numbers using novel approach
- Study resonance content of amplitudes and extract pole parameters of $\pi^-\pi^+$ resonances
  - Test and study resonance models
  - Study source dependence and effects of the bachelor π^- on resonances
- Proof-of-principle analysis: study $\rho(770)$

Conventional Partial-Wave Analysis (PWA)

- Isobar model: decay of 3π resonances X^- via $\pi^-\pi^+$ isobar resonance
- Simplified intensity model in single $(m_{3\pi}, t')$ cell as function of 5-dimensional phase-space variables $\vec{\tau}$:

$$\mathcal{I}(\vec{\tau}) = \left| \sum_i \mathcal{T}_i \Psi_i(\vec{\tau}) \right|^2$$

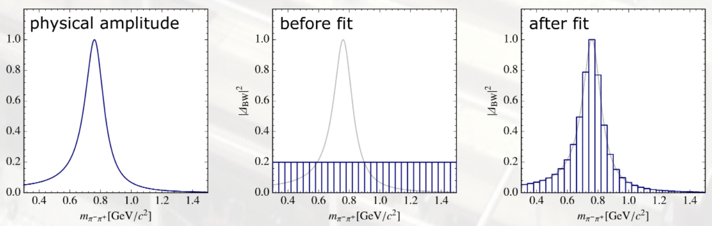
- i represents partial wave: $J_X^{PC} M^\epsilon \xi \pi L$
  - ξ is isobar resonance, e.g. $\rho(770)$
- Transition amplitudes $\mathcal{T}_i$ determined from data in cells of $(m_{3\pi}, t')$
- Known decay amplitudes $\Psi_i(\vec{\tau}) = \psi_i(\vec{\tau})\,\Delta_\xi(m_{\pi^-\pi^+})$ + Bose symm.
  - Spin amplitude $\psi(\vec{\tau})$ given by first principles
  - Dynamic isobar amplitude $\Delta_\xi(m_{\pi^-\pi^+})$ modeled, e.g. using relativistic Breit-Wigner with fixed mass m_0 and width Γ_0

Novel Method: Freed-Isobar Partial-Wave Analysis

- Reduce model bias from assuming fixed parametrizations for dynamic isobar amplitudes Δ_ξ by replacing them with step-like functions ("freed isobars"):

$$\Delta_\xi(m_{\pi^-\pi^+}) \rightarrow \Delta_i(m_{\pi^-\pi^+}) = \sum_{\text{bin}}^{\text{bins}} \mathscr{T}_i^{\text{bin}} \Pi_i^{\text{bin}}(m_{\pi^-\pi^+}) = \text{"}[\pi\pi]_{J^{PC}}\text{"}$$

$$\Pi_i^{\text{bin}}(m_{\pi^-\pi^+}) = \begin{cases} 1, & \text{if } m_{\pi^-\pi^+} \text{ in the bin} \\ 0, & \text{otherwise} \end{cases}$$



- Measure dynamic isobar amplitudes $\mathscr{T}_i$ of the $\pi^-\pi^+$ subsystem with well-defined $(J^{PC})_\xi$ from the data as function of $m_{\pi^-\pi^+}$, $m_{3\pi}$, and t'
  - No assumptions on resonance content of the $\pi^-\pi^+$ subsystem
- Freed-isobar PWA model includes 8 waves with $(J^{PC})_\xi = 1^{--}$:

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

References

[1] M. Aghasyan *et al.* [COMPASS], PRD 98 (2018) 092003, arXiv:1802.05913

[2] M.G. Alexeev *et al.* [COMPASS], PRD 105 (2022) 012005, arXiv:2108.01744

[3] Lukas Bayer, Bachelor's thesis 2019, University of Bonn

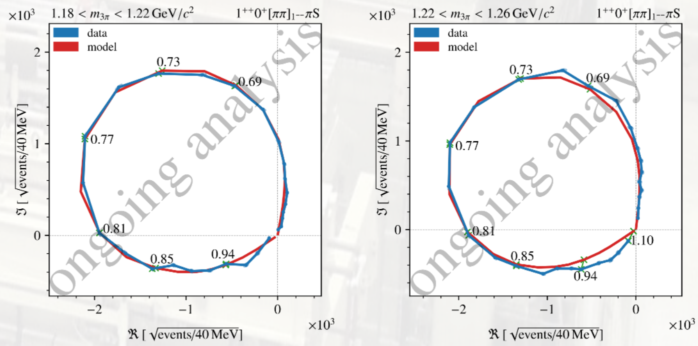
[4] R. Garcia-Martin *et al.*, PRD 107 (2011) 072001, arXiv:1107.1635

Resonance Model for the $\pi^-\pi^+$ Subsystem with $(J^{PC})_\xi = 1^{--}$ [3]

- Model for $\mathscr{T}_i$ based on $\rho(770)$ form factor $\mathcal{F}(s)$ as function of $s = m^2_{\pi^-\pi^+}$
  - $\mathcal{F}(s)$ based on Lippmann-Schwinger equations and on Gounaris-Sakurai parametrization of pion form factor:

$$\mathcal{F}(s) = \left\{ 1 - g_1{}^2 \left[a_1 + \Sigma(0) \right] - a_1 \frac{m_1{}^2 g_1{}^2}{s - m_1{}^2} \right\} \Big/ \left\{ 1 + \left(\frac{m_1{}^2 g_1{}^2}{s - m_1{}^2} \right) \Sigma(s, m_1) \right\}$$

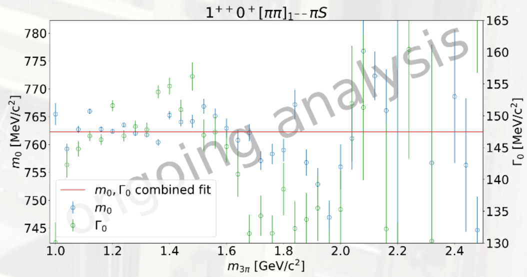
  - m_1 and g_1: global fit parameters; a_1: free parameter for each $(m_{3\pi}, t')$ cell
  - Σ is self energy
- Simultaneous χ^2 fit of model to all measured amplitudes $\mathscr{T}_i$ for given wave i



- Data reasonably well described given their very small statistical uncertainties
- Search for pole in complex s plane
  - Extract $\rho(770)$ parameters: $\sqrt{s_{\text{pole}}} = m_0 - \mathrm{i}\,\Gamma_0/2$
  - Less process-dependent than Breit-Wigner parameters

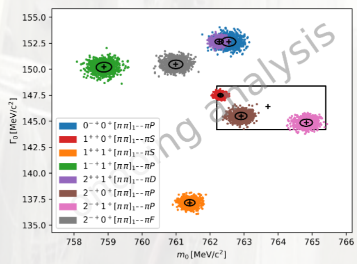
Fits in Individual $(m_{3\pi}, t')$ Cells: Example $1^{++}0^+[\pi\pi]_{1^{--}}\pi S$ Wave

- Fit range limited to $m_{\pi^-\pi^+} < 1.12\,\text{GeV}/c^2$ to isolate the $\rho(770)$
- Reliable extraction of $\rho(770)$ parameters for $1.0\,\text{GeV}/c^2 \lesssim m_{3\pi} \lesssim 1.6\,\text{GeV}/c^2$
- Small deviations from combined fit of all $(m_{3\pi}, t')$ cells (see below)
- No striking systematic dependence on $m_{3\pi}$ or t'



Combined Fit of All $(m_{3\pi}, t')$ Cells for Individual Waves

- Fit all $(m_{3\pi}, t')$ cells simultaneously
- $\rho(770)$ resonance parameters have small statistical uncertainties
  - Estimated using Monte-Carlo uncertainty propagation (data points)
- Systematic uncertainties: work in progress, but probably dominant



- Comparable results for most of the 8 studied partial waves
- Deviations of $\pm 4\,\text{MeV}/c^2$ for m_0 and $\pm 8\,\text{MeV}/c^2$ for Γ_0
  - May partly be due to crossed-channel effects and/or 3π-source dependence
- Black box from Ref. [4]: $m_0 = 763.7^{+1.7}_{-1.5}\,\text{MeV}/c^2$, $\Gamma_0 = 146.4^{+2.0}_{-2.2}\,\text{MeV}/c^2$

Conclusions

- World's largest sample of diffractively produced $\pi^-\pi^-\pi^+$ final state
- Successful extraction of $\rho(770)$ pole parameters from results of novel freed-isobar PWA for 8 partial waves with $(J^{PC})_\xi = 1^{--}$
- Small deviations of pole parameters could be hints of crossed-channel effects → Need to study systematic effects and uncertainties
- Future work: Extend fit range to study excited ρ states

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