Preserving Partial-Wave Analysis Results from COMPASS on HEPData

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Max Planck Institute for Physics

COMAP V: Best Practices in Data Anslysis and Preservation
December 14, 2023

COMPASS

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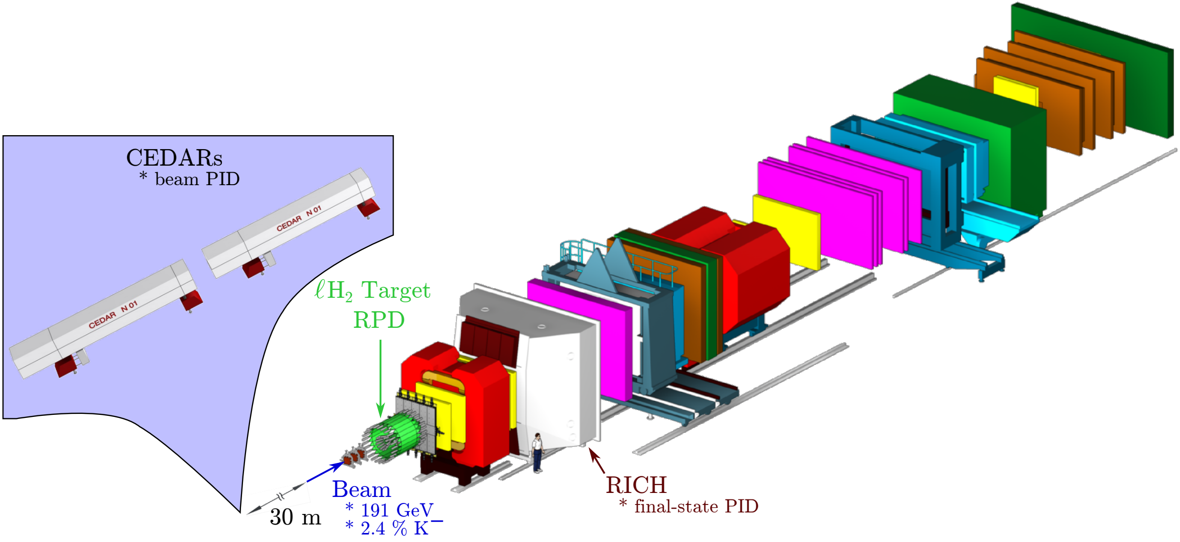
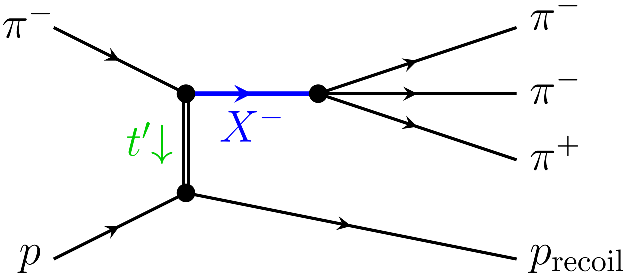
[COMPASS, Nucl. Instrum. Methods **779** (2015) 69]

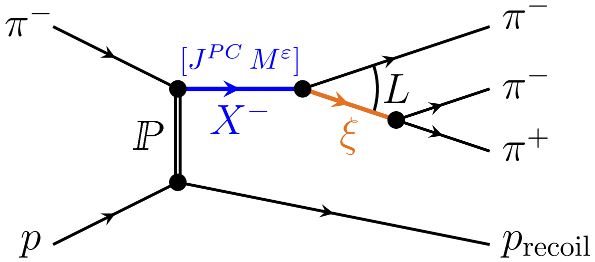




- Diffractive scattering of high-energy π^-/K^- beam
- Mesons appear as intermediate resonances X^-
- Decay to multi-body hadronic final states
- $\pi^-\pi^-\pi^+$ final state

Partial wave: $J^{PC}\, M^{\varepsilon}\, \xi\, \pi\, L$

- J^{PC} spin, parity, and charge conjugation
- M^{ε} spin projection
- ξ isobar resonance
- b^{-} bachelor particle
- L orbital angular momentum



Data: 50 M diffractively produced $\pi^-\pi^-\pi^+$ candidates

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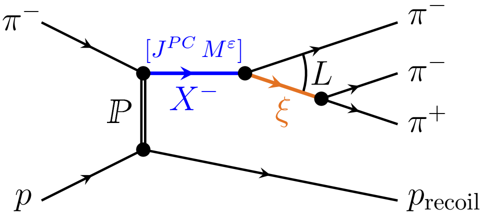
(I) Partial-Wave Decomposition
Performed independently in narrow $(m_{3\pi}, t')$ cells
No assumption about $\pi\pi\pi$ resonances

Partial waves: Intensities and relative phases as a function of $(m_{3\pi}, t')$



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Partial waves: Intensities and relative phases as a function of $(m_{3\pi}, t')$

- Measured intensity distribution is modeled by coherent sum of partial waves a
- Decay amplitude Ψ_a modeled
- Transition amplitudes $\mathcal{T}_a$ measured in each $(m_{3\pi}, t')$ cell

$$I(\tau; m_{3\pi}, t') = \left| \sum_a \mathcal{T}_a(m_{3\pi}, t')\, \Psi_a(\tau, m_{3\pi}) \right|^2$$

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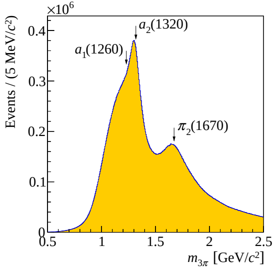

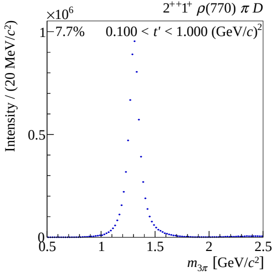

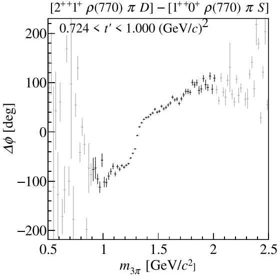

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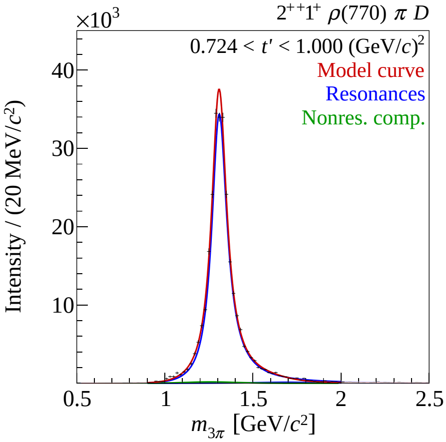
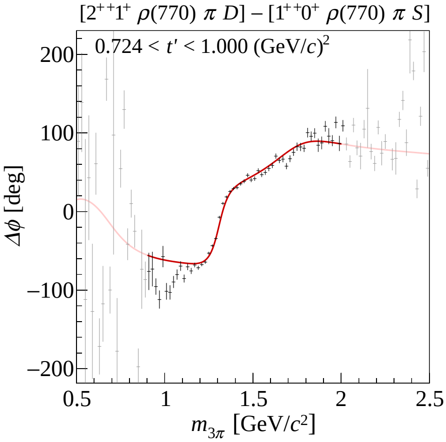
Partial waves: Intensities and relative phases as a function of $(m_{3\pi}, t')$

(II) Resonance-Model Fit
Model $m_{3\pi}$ dependence of partial waves
$\pi\pi\pi$ resonances and background

Resonance parameters: Masses and widths of the meson resonances


$2^{++}1^{+}$ $\rho(770)$ π D
$\times 10^3$
$0.724 < t' < 1.000$ $(\text{GeV}/c)^2$
Model curve
Resonances
Nonres. comp.
Intensity / (20 MeV/c^2)
40
30
20
10
0.5
1
1.5
2
2.5
$m_{3\pi}$ [GeV/c^2]


[$2^{++}1^{+}$ $\rho(770)$ π D] – [$1^{++}0^{+}$ $\rho(770)$ π S]
$0.724 < t' < 1.000$ $(\text{GeV}/c)^2$
$\Delta\phi$ [deg]
200
100
0
−100
−200
0.5
1
1.5
2
2.5
$m_{3\pi}$ [GeV/c^2]

Preserving the Results of the Partial-Wave Decomposition

- Results of the partial-wave decomposition are the transition amplitudes $\mathcal{T}_a$
- Direct physics meaning
  - Allow to develop, test, and measure phenomenological models
- Not afflicted with experimental acceptance (acceptance corrected)
- Only weak model dependence compared to resonance-model fit

➥ Valuable input to further analyses

Preserving the Results of the Partial-Wave Decomposition

Challenges

Large amount of data

- Values of transition amplitudes: Complex number per wave a and per $(m_{3\pi}, t')$ cell
  - For all 88 partial waves: About 200 k values
  - We published only 14 selected waves: About 30 k values
- Covariance matrix of transition amplitudes: One matrix per $(m_{3\pi}, t')$ cell
  - For all 88 partial waves: About 30 M values
  - For 14 selected partial waves: About 900 k values

➥ Requires well defined data structure

Choice of representation

- Different representations of transition amplitudes $\mathcal{T}^a \in \mathbb{C}$ possible
  - Intensity and phase: $|\mathcal{T}_a|^2$, $\phi_a = \mathrm{Arg}[\mathcal{T}_a]$
  - Real and imaginary part: $\Re[\mathcal{T}_a]$, $\Im[\mathcal{T}_a]$

Uncertainties

- Goals: Preserved quantities should be Gaussian distributed
- Problem: Intensities near zero are non-Gaussian (studied in Bootstrapping resampling distributions)
- Real and imaginary parts better approximated by Gaussian

Preserve transition amplitudes as real and imaginary parts

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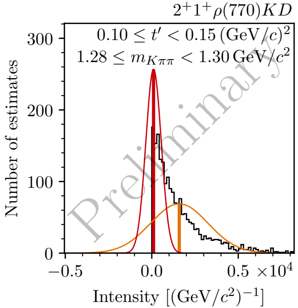

Resampling distribution, Gaussian approximation, Fit estimate

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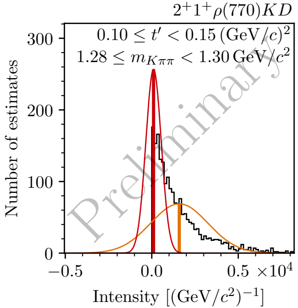

Resampling distribution, Gaussian approximation, Fit estimate

Undefined global phase per $(m_{3\pi}, t')$ cell

- Absolute phase of total amplitude $\mathcal{A}$ undetermined as we measure intensities $|\mathcal{A}|^2$
- In the partial-wave decomposition fit: Fix one $\mathcal{T}_{\text{ref}}$ to be real-valued and positive (reference wave)

➥ All other amplitudes are measured with respect to reference wave
  - Only relative phase can be measured: $\Delta\phi_a = \phi_a - \phi_{\text{ref}}$
  - Also $\Re[\mathcal{T}_a]$, $\Im[\mathcal{T}_a]$ are given only relative to the reference wave

➥ Reference wave needs to be know when further using data

➥ Complicated parameter mapping in covariance matrix
  - N_{waves} complex-valued transition amplitudes, but covariance matrix
    - has $(2N_{\text{wave}} - 1)$ values, or
    - is singular

➥ Non-linear uncertainty propagation necessary when changing the reference wave (rotation in amplitude space)

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Auxiliary information

- Often auxiliary information is needed to further use the data
- Transition amplitudes are normalized such that $|\mathcal{T}_a|^2$ corresponds to number of events
- Normalization integrals of decay amplitudes needed to formulate model of measured transition amplitude
  - ➥ Published also normalization integrals (decay phase-space volume of partial waves)

Systematic uncertainties

- Systematic effects highly non-linear $\Rightarrow$ non-Gaussian
  - ➥ Giving single number as systematic uncertainty of transition amplitude not meaningful
- Full uncertainty propagation: Change studied aspect and repeat the analysis including resonance-model fit
- Preserving systematic uncertainties on transition amplitudes requires preserving multiple results with varied systematics
- Not (yet) available for COMPASS results

Data Preservation on HEPData

HEPData

- hepdata.net is an open-access repository for scattering data from experimental particle physics
- Data mainly represented by data tables, e.g. cross section as a function of energy
- Additional resources can be attached to data tables

Data Preservation on HEPData

COMPASS $\pi^-\pi^-\pi^+$ partial-wave amplitudes on HEPData

[https://doi.org/10.17182/hepdata.82958]

- The real and imaginary parts of partial waves are columns
- Rows of the table runs over 100 $m_{3\pi}$ bins
- t' bin is given as "qualifier" to each column, i.e. one column per real/imaginary part per t' bin
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- HEPData web page automatically creates visualization of data table
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Data Preservation on HEPData

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Light isovector resonances in $\pi^- p \to \pi^-\pi^-\pi^+ p$ at 190 GeV/c

The COMPASS collaboration

Aghasyan, M. , Alexeev, M.G. , Alexeev, G.D. , Amoroso, A. , Andrieux, V. , Anfimov, N.V. , Anosov, V. , Antoshkin, A. , Augsten, K. , Augustyniak, W.

Phys.Rev.D 98 (2018) 092003, 2018.

https://doi.org/10.17182/hepdata.82958

Journal | INSPIRE | Resources

Abstract (data abstract)

Selected partial-wave amplitudes from a partial-wave analysis (PWA) of exclusive events from the diffractive-dissociation reaction $\pi^- p \to \pi^-\pi^-\pi^+ p$ with a 191 GeV/c pion beam and a stationary proton target. The PWA was performed in 100 bins of the three-pion mass $m_{3\pi}$ in the range between 0.5 and 2.5 GeV/c^2, and simultaneously in 11 non-equidistant bins of the reduced four-momentum transfer squared t' (see Eq. (2) in the paper) in the range between 0.1 and 1.0 (GeV/c)^2. The PWA model consists of 88 waves (see paper and [Phys. Rev. D 95, 032004 (2017)] for a detailed description of the PWA model). The waves are uniquely defined by the quantum numbers of the 3-pion system (spin J, parity P, C-parity, spin projection $M \geq 0$, and reflectivity $\varepsilon = \pm 1$) and the decay chain ($\pi^-\pi^+$ isobar and orbital angular momentum L between the isobar and the bachelor pion). To identify waves, we use the shorthand notation $J^{PC}M^\varepsilon$[isobar]πL.

Out of the 88 waves, the following subset of 14 waves was selected for a resonance-model fit:

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

Download All

Filter 2 data tables

Transition Amplitudes

Not in the paper

10.17182/hepdata.82958.v1/t1

Real and imaginary parts of the normalized transition amplitudes $\mathcal{T}_a$ of the 14 selected partial waves in the 1100 $(m_{3\pi},...

Decay Phase-Space Volume of Partial Waves

Equation (6) in the paper

10.17182/hepdata.82958.v1/t2

Decay phase-space volume I_{aa} for the 14 selected partial waves as a function of $m_{3\pi}$, normalized such that $I_{aa}(m_{3\pi} =...

Transition Amplitudes 10.17182/hepdata.82958.v1/t1

Resources | https://www.hepdata.net/re | JSON

Not in the paper

Real and imaginary parts of the normalized transition amplitudes $\mathcal{T}_a$ of the 14 selected partial waves in the 1100 $(m_{3\pi}, t')$ cells (see Eq. (12) in the paper). The wave index a represents the quantum numbers that uniquely define the partial wave. The quantum numbers are given by the shorthand notation $J^{PC}M^\varepsilon$[isobar]πL. We use this notation to label the transition amplitudes in the column headers. The $m_{3\pi}$ values that are given in the first column correspond to the bin centers. Each of the 100 $m_{3\pi}$ bins is 20 MeV/c^2 wide. Since the 11 t' bins are non-equidistant, the lower and upper bounds of each t' bin are given in the column headers.

The transition amplitudes define the spin-density matrix elements ϱ_{ab} for waves a and b according to Eq. (18). The spin-density matrix enters the resonance-model fit via Eqs. (33) and (34). The transition amplitudes are normalized via Eqs. (9), (16), and (17) such that the partial-wave intensities $\varrho_{aa} = |\mathcal{T}_a|^2$ are given in units of acceptance-corrected number of events. The relative phase $\Delta\phi_{ab}$ between two waves a and b is given by $\arg(\varrho_{ab}) = \arg(\mathcal{T}_a) - \arg(\mathcal{T}_b)$. Note that only relative phases are well-defined. The phase of the $1^{++}0^+\rho(770)\pi S$ wave was set to 0° so that the corresponding transition amplitudes are real-valued. In the PWA model, some waves are excluded in the region of low $m_{3\pi}$ (see paper and [Phys. Rev. D 95, 032004 (2017)] for a detailed description of the PWA model). For these waves, the transition amplitudes are set to zero.

The tables with the covariance matrices of the transition amplitudes for all 1100 $(m_{3\pi}, t')$ cells can be downloaded via the 'Additional Resources' for this table.

cmenergies: 19.0

observables: AMP

phrases: Pion-Proton Scattering, Exclusive, Diffractive, Light-Meson Spectroscopy, Amplitude Analysis, Isobar Model

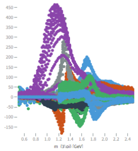
reactions: PI- P --> PI- PI- PI+ P, PI- P --> PI- RHO0 P, PI- P --> PI- F0(980) P, PI- P --> PI- F2(1270) P, PI- P --> A1(1260)- P, PI- P --> A2(1320)- P

Showing 50 of 100 values | Show All 100 values

RE	PI- P --> PI- PI- PI+ P
PLAB	191 GeV
SQRT(S)	19.0 GeV
t' bin lower limit	0.100 GeV**2
t' bin upper limit	0.113 GeV**2

$m_{3\pi}$ [GeV]	RE(AMP($0^{-+}0^+ f_0(980)\pi S$)) [SQRT(NUM EVENTS)]	IM(AMP($0^{-+}0^+ f_0(980)\pi S$)) [SQRT(NUM EVENTS)]	RE(AMP($1^{++}0^+ \rho(770)\pi S$)) [SQRT(NUM EVENTS)]	IM(AMP($1^{++}0^+ \rho(770)\pi S$)) [SQRT(NUM EVENTS)]	RE(AMP($1^{++}0^+ f_0(980)\pi P$)) [SQRT(NUM EVENTS)]	IM(AMP($1^{++}0^+ f_0($ [SQRT(NU EVENTS)]
0.51	0.0	-0.0	13.265772499950481	-0.0	0.0	-0.0

Visualize



Sum errors ☑ Log Scale (X) ☐ Log Scale (Y) ☐

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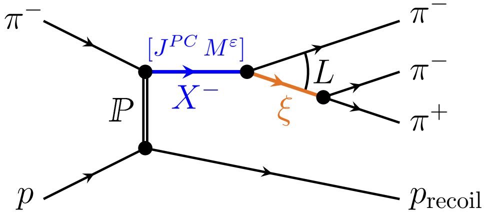
COMPASS freed-isobar $\pi^-\pi^-\pi^+$ results on HEPData

[https://doi.org/10.17182/hepdata.114098]

- Freed-isobar analysis allows to also measure amplitude of $\pi^-\pi^+$ subsystem in $\pi^-\pi^-\pi^+$ final state
- Measured amplitude of $1^{-+}\,1^+\,[\pi\pi]_P\,\pi\,P$ wave also published on HEPData
- Due to the more data complex structure, only the total intensity is shown as HEPData tables
- All other information (amplitudes, covariance matrices, ..) are published as additional resources
- Further challenges, e.g. singular covariance matrices due to mathematical ambiguities (zero modes)



Conclusion and Outlook

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- Partial-wave amplitudes contain rich variety of physics worth to preserve and to share
- Various challenges when sharing this data: choice of representation, uncertainties, ...
- HEPData is a good place to preserve our data, but no standardized data structure for partial-wave analysis results
- HEPData stores “only” data, while analysis model is documented in paper

Outlook

- Continue preserving upcoming results ($K^-\pi^-\pi^+$, $\omega\pi^-\pi^0$, ...) on HEPData
- Use standardized data formats

Publishing data should not prevent exchange, but should encourage it!

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Backup

Outline