Progress in the Partial-Wave Analysis Methods at COMPASS

Julien Beckers and Florian Kaspar for the COMPASS Collaboration

HADRON 2023: Analysis tools

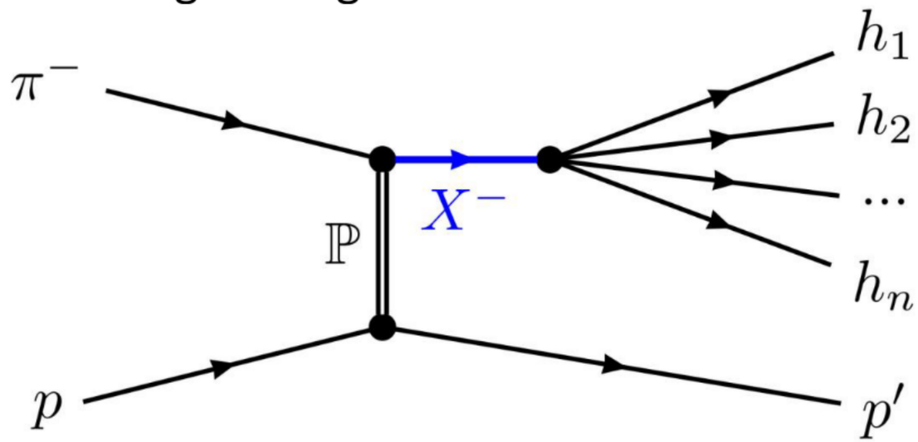
June 8th, 2023

julien.beckers@tum.de florian.kaspar@tum.de

funded by the DFG under Germany's Excellence Strategy – EXC2094 – 390783311 and BMBF Verbundsforschung 05P21WOCC1 COMPASS

Excited Light Mesons at COMPASS

- Inelastic scattering reactions of high-energetic meson beam



- Strong interaction (Pomeron exchange) between beam meson and target proton
- Intermediate hadronic resonances X^- are created, then decay into n-body final state

  → wide range of allowed (spin) quantum numbers

- Final-state particles measured

The COMPASS Experiment

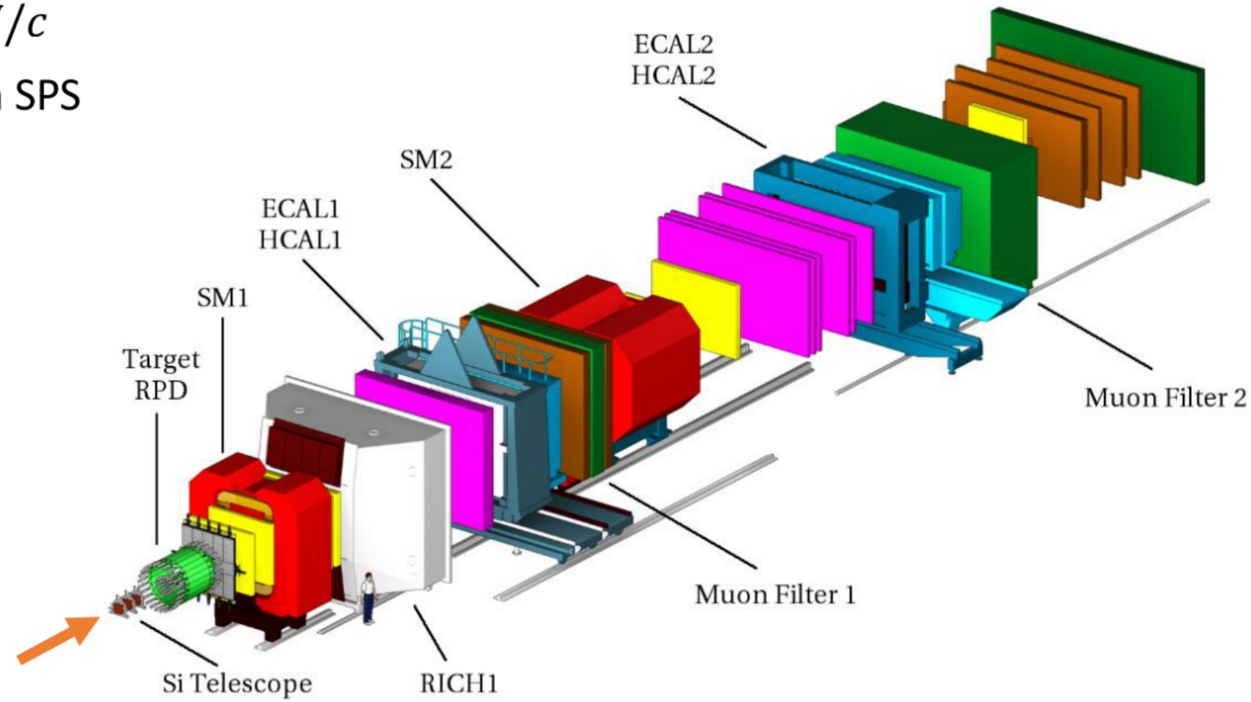
Large-acceptance magnetic spectrometer @ CERN-SPS

Beam:

- Secondary hadrons (π^-, K^-) at $190\ \mathrm{GeV}/c$
- produced via primary proton beam from SPS

Spectrometer:

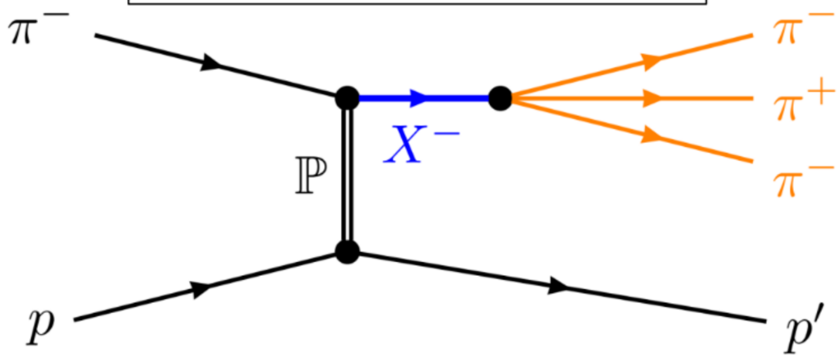
- Liquid-hydrogen target
- Two-stage spectrometer setup around two dipole magnets SM1/2



From COMPASS Collab., The COMPASS Setup for Physics with Hadron Beams (Nucl. Instrum. Methods Phys. Res. A 779 (2014), pp. 69–115)

Excited Light Mesons at COMPASS

$\boldsymbol{\pi^- + p \rightarrow \pi^-\pi^-\pi^+ + p}$



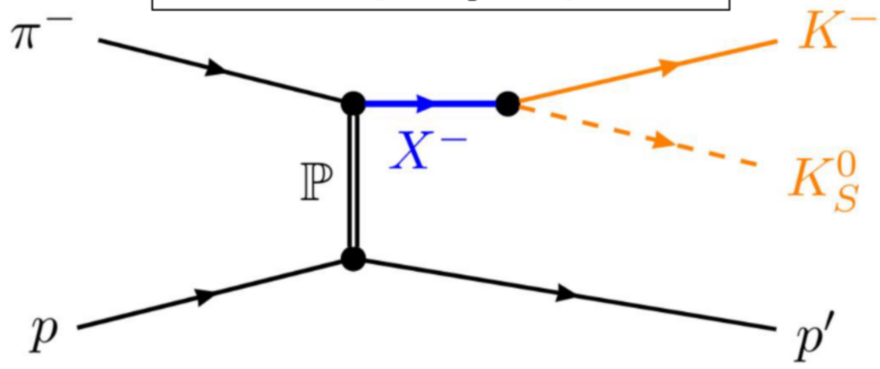
- Allowed quantum numbers:

  $J^{PC} = 0^{-+}, 1^{-+}, 1^{++}, \ldots$

  → $\boldsymbol{\pi_J}$ and $\boldsymbol{a_J}$ resonances

- COMPASS flagship channel: 115×10^6 evts

$\boldsymbol{\pi^- + p \rightarrow K_S^0 K^- + p}$



- Allowed quantum numbers:

  $J^{PC} = 1^{--}, 2^{++}, 3^{--}, \ldots$ from decay

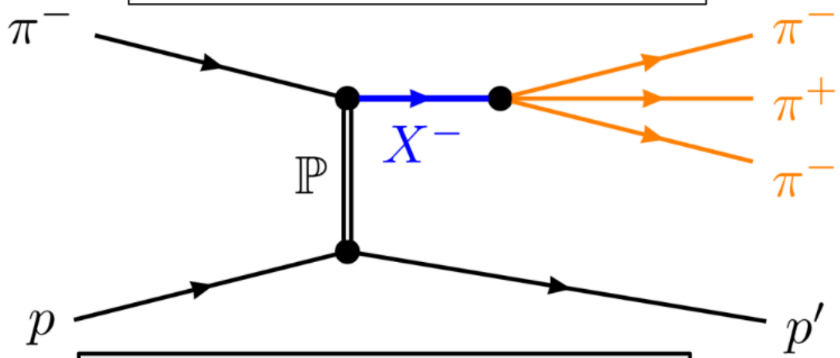
  Dominated by Pomeron exchange

  → $\boldsymbol{a_J}$ for even J

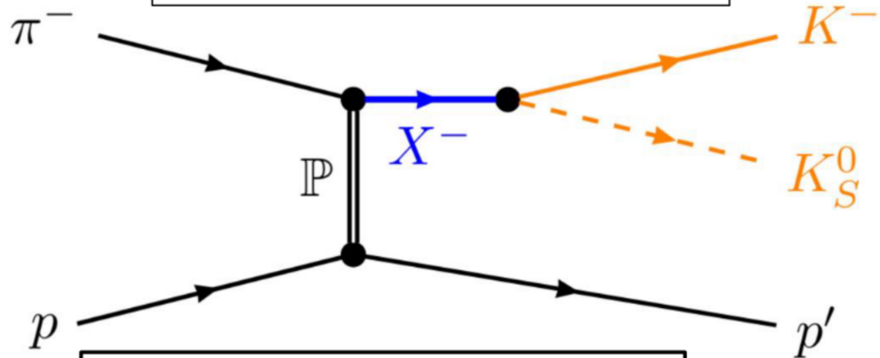
- Highly selective → search for a_4', a_6

Excited Light Mesons at COMPASS

$\pi^- + p \rightarrow \pi^-\pi^-\pi^+ + p$

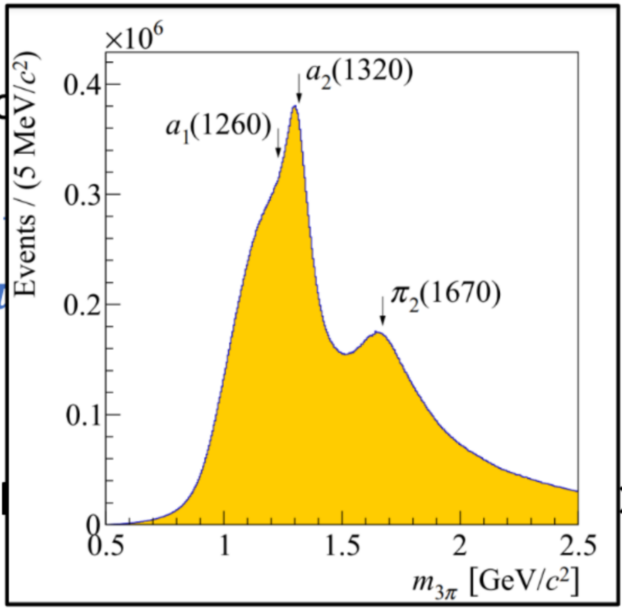


$\pi^- + p \rightarrow K_S^0 K^- + p$



- All

  → π
- CO $\times 10^6$ evts

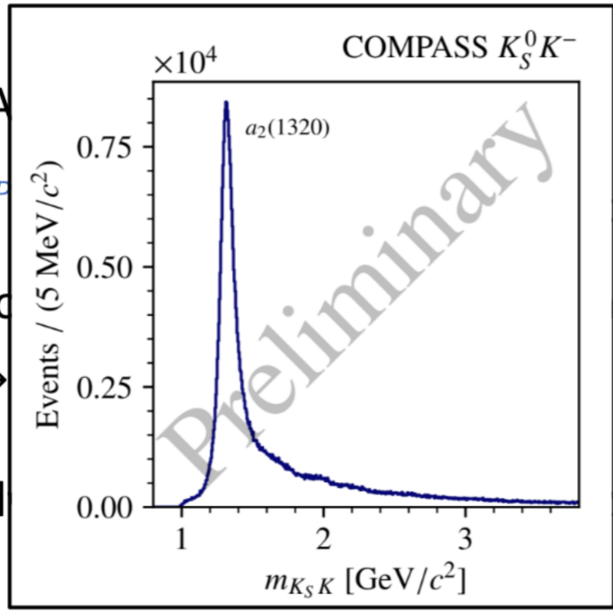


- A

  J^P decay

  Do ge

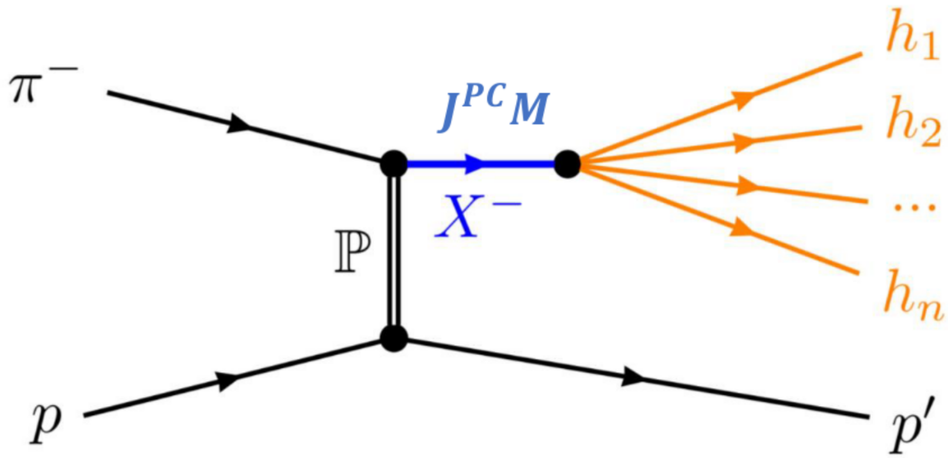
  →
- High 6



Partial-Wave Decomposition

$$I(m_X, t'; \tau_n) = \left|M_{fi}\right|^2$$

- Separate process amplitude into **partial waves**
  - Spin $\boldsymbol{J}$ and spin-projection $\boldsymbol{M}$
  - Parity $\boldsymbol{P}$, charge conjugation $\boldsymbol{C}$
  - …
  - $\rightarrow$ Partial wave index a



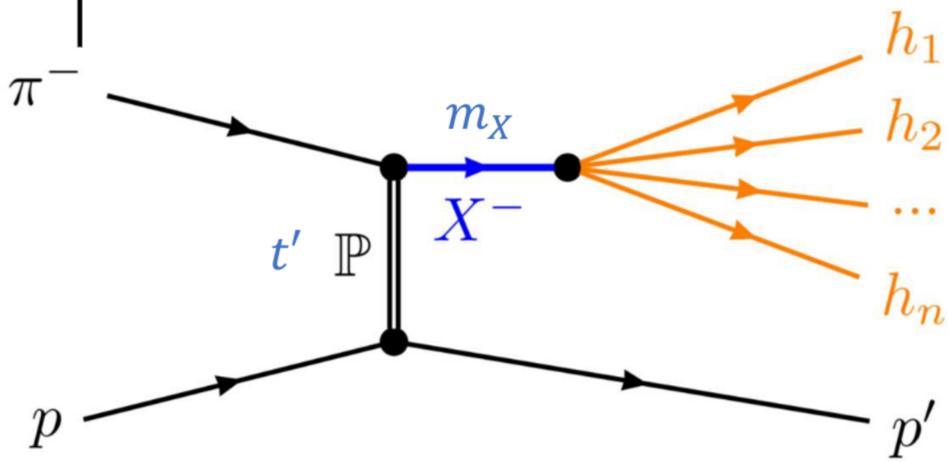
Partial wave $\boldsymbol{a}$:
specific $(J^{PC}M)$

Partial-Wave Decomposition

$$I(m_X, t'; \tau_n) = \left| \sum_a T_a(m_X, t')\, \psi_a(m_X, \tau_n) \right|^2$$

- Separate process amplitude into **partial waves**
  → Partial wave index a

- Production, propagation of X^-: $\boldsymbol{T_a(m_X, t')}$



Partial wave $\boldsymbol{a}$:
specific $(\boldsymbol{J^{PC}M})$

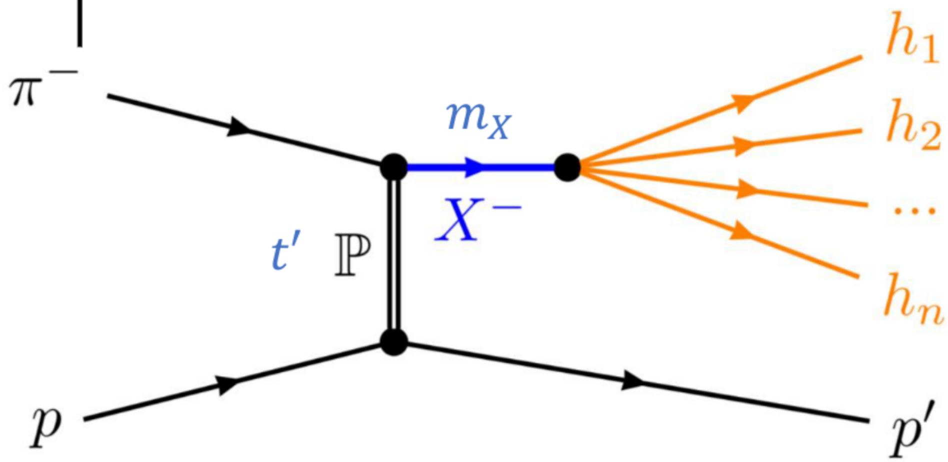
Partial-Wave Decomposition

$$I(m_X, t'; \tau_n) = \left| \sum_a T_a(m_X, t')\, \psi_a(m_X, \tau_n) \right|^2$$

- Separate process amplitude into **partial waves**
  → Partial wave index a

- Production, propagation of X^-: $\boldsymbol{T_a(m_X, t')}$

- Decay of X^-: $\boldsymbol{\psi_a(m_X, \tau_n)}$

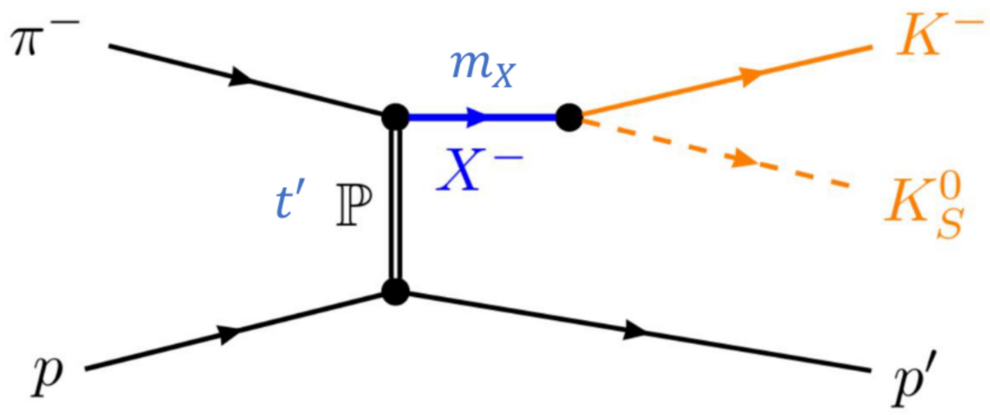


Partial wave a:
specific $(J^{PC}M)$

Partial-Wave Decomposition

$$I(m_X, t'; \tau_n) = \left| \sum_a T_a(m_X, t')\, \psi_a(m_X, \tau_n) \right|^2$$

- Separate process amplitude into **partial waves**
  → Partial wave index a



- Production, propagation of X^-: $\boldsymbol{T_a(m_X, t')}$

- Decay of X^-: $\boldsymbol{\psi_a(\tau_n) = Y_J^M(\theta, \phi)}$

$$\boldsymbol{\tau_n = (\theta, \phi)}$$

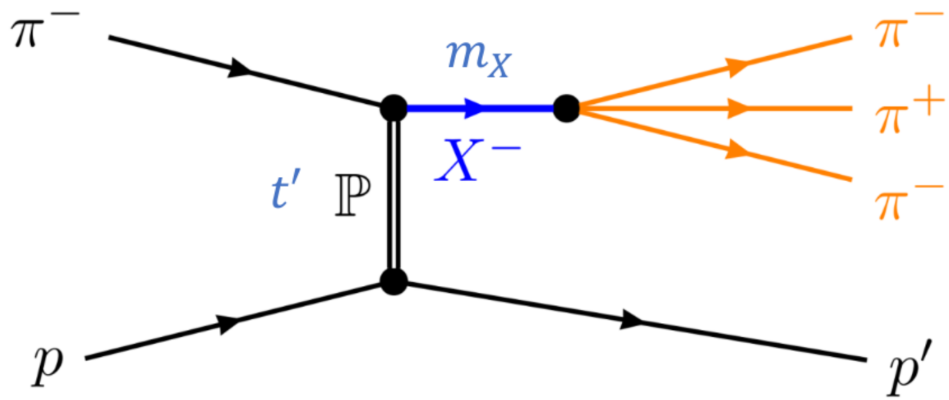
Partial wave $\boldsymbol{a}$:
specific $\boldsymbol{(J^{PC}M)}$

$\boldsymbol{K_S^0 K^-}$

Partial-Wave Decomposition

$$I(m_X, t'; \tau_n) = \left| \sum_a T_a(m_X, t')\, \psi_a(m_X, \tau_n) \right|^2$$

- Separate process amplitude into **partial waves**
  → Partial wave index a



- Production, propagation of X^-: $\boldsymbol{T_a(m_X, t')}$

- Decay of X^-: via **isobar model**

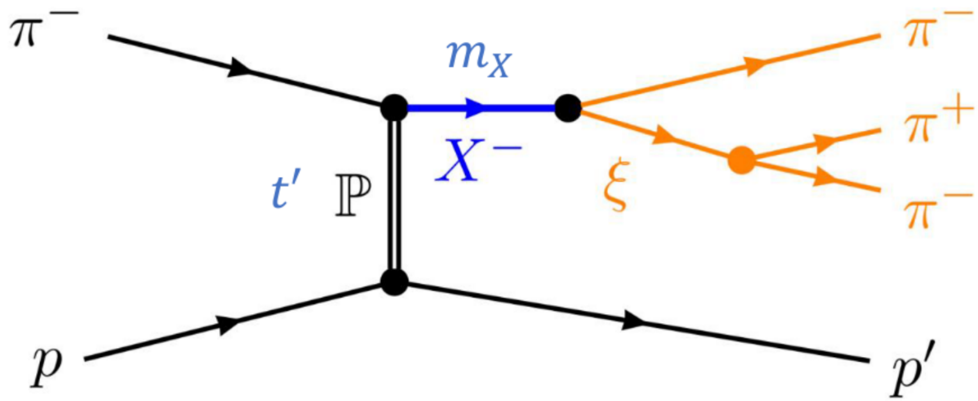
Partial wave a:
specific $(J^{PC}M)$

$\boldsymbol{\pi^-\pi^-\pi^+}$

Partial-Wave Decomposition

$$I(m_X, t'; \tau_n) = \left| \sum_a T_a(m_X, t')\, \psi_a(m_X, \tau_n) \right|^2$$

- Separate process amplitude into **partial waves**
  → Partial wave index a



- Production, propagation of X^-

- Decay of X^-: via isobar model

$$\boldsymbol{\tau_n = (\theta_{GJ}, \phi_{GJ}, m_\xi, \theta_{HF}, \phi_{HF})}$$

$$\boldsymbol{\psi_a = \psi_X(m_X, \theta_{GJ}, \phi_{GJ}) \cdot \psi_\xi(m_\xi, \theta_{HF}, \phi_{HF})}$$

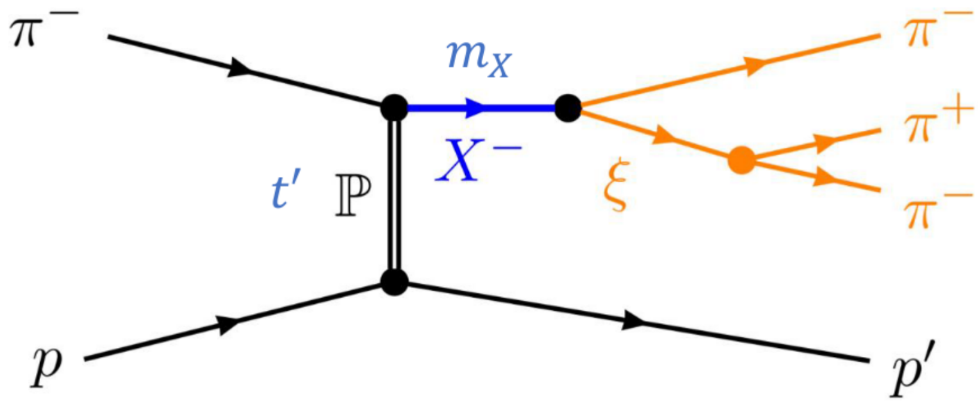
Partial wave a:
specific $(J^{PC} + \text{decay})$

$\boldsymbol{\pi^-\pi^-\pi^+}$

Partial-Wave Decomposition

$$I(m_X, t'; \tau_n) = \left| \sum_a T_a(m_X, t')\, \psi_a(m_X, \tau_n) \right|^2$$

- Separate process amplitude into **partial waves**
  → Partial wave index a
- Production, propagation of X^-
- Decay of X^-: via isobar model
- Fit $I(m_X, t'; \tau_n)$ to data **in (m_X, t') bins**
  → parametrize T_a as step-wise functions
  → extract constant T_a in each bin



Partial wave a:
specific $(J^{PC} + \text{decay})$

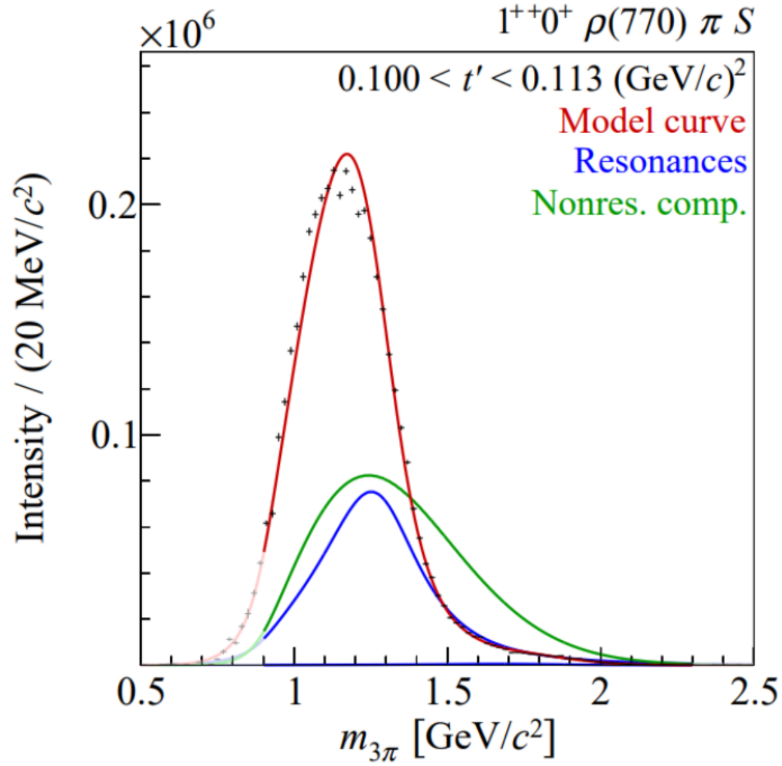
Resonance-Model Fit

Second step: **extract resonance parameters**

- Build model for **mass dep. of partial-wave amplitudes**:
  resonant (e.g. Breit-Wigner distribution)
  + **non-resonant background** components

- χ^2 fit to output of partial-wave decomposition

→ get masses and widths of parameterized resonances



COMPASS PRD 98 (2018) 092003

Understanding the Ambiguities in the Partial-Wave Decomposition of the $K_S^0 K^-$ Final State

Ambiguities in the Partial-Wave Decomposition

For any final state with **two spinless** particles ($\pi\pi, KK, \eta\pi$, …):

- Decomposition of intensity into $\{T_J\}$ is not **unique** (see derivation later)

→ Several sets of $\{T_J\}$ lead to the **same** $\boldsymbol{I(\theta,\phi)}$ in each (m_X, t') bin

$$I(\theta,\phi) = \left|\sum_{JM} T_{JM}^{(1)}\,\psi_{JM}(\theta,\phi)\right|^2 = \left|\sum_{JM} T_{JM}^{(2)}\psi_{JM}(\theta,\phi)\right|^2$$

- The fit cannot distinguish between the **mathematically equivalent** solutions!

Ambiguities in the Partial-Wave Decomposition

$$I(\theta,\phi) = \left| \sum_{JM} T_{JM}\, \psi_{JM}(\theta,\phi) \right|^2$$

Assume strong dominance of $|M| = 1$ *

- Pomeron exchange dominant $\rightarrow M \neq 0$
- Higher $|M|$ suppressed

*using reflectivity basis for ψ_{JM} :
doi.org/10.1103/PhysRevD.11.633

Ambiguities in the Partial-Wave Decomposition

$$I(\theta, \phi) = \left| \sum_J T_J \, \psi_J(\theta, \phi) \right|^2$$

Assume strong dominance of $|M| = 1$ *

- Pomeron exchange dominant $\rightarrow M \neq 0$
- Higher $|M|$ suppressed

*using reflectivity basis for ψ_{JM} :
doi.org/10.1103/PhysRevD.11.633

Ambiguities in the Partial-Wave Decomposition

$$I(\theta,\phi) = \left|\sum_J T_J\, \psi_J(\theta,\phi)\right|^2 = \Bigg|\underbrace{\sum_J T_J\, Y_J^1(\theta,0)}_{\boldsymbol{a(\theta)}}\Bigg|^2 \; |\sin\phi|^2$$

$$Y_J^1(\theta,0) = \sum_{j=0}^{J-1} y_j \tan^{2j}\theta$$

Polynomial in $\tan^2\theta$

$$a(\theta) = \sum_{j=0}^{\boldsymbol{J_{\max}-1}} c_j\big(\{T_J\}\big)\, \tan^{2j}(\theta) = c(\{T_J\}) \prod_{k=1}^{J_{\max-1}} \Big(\tan^2(\theta) - \boldsymbol{r_k}\big(\{T_J\}\big)\Big)$$

root decomposition

$a(\tan^2\theta = r_k) = 0$

"Barrelet zeros"

Chung, PRD 56 7299–7316 (1997)

Barrelet, *Nuov Cim A* **8**, 331–371 (1972)

Ambiguities in the Partial-Wave Decomposition

$$a(\theta) = c(\{T_J\}) \prod_{k=1}^{J_{\max-1}} \left(\tan^2(\theta) - \boldsymbol{r_k}(\{T_J\})\right)$$

$$I(\theta,\phi) = \left|\sum_J T_J\, Y_J^1(\theta,0)\right|^2 |\sin\phi|^2$$

$$= \left|\sum_{j=0}^{J_{\max}-1} c_j(\{T_J\})\, \tan^{2j}(\theta)\right|^2 |\sin\phi|^2$$

$$= c^2 \prod_{k=1}^{J_{\max-1}} |\tan^2(\theta) - \boldsymbol{r_k}|^2\ |\sin\phi|^2 \quad = c^2 \prod_{k=1}^{J_{\max-1}} |\tan^2(\theta) - \boldsymbol{r_k^*}|^2\ |\sin\phi|^2$$

$\{c_j'\}$

$\{T_J'\} \neq \{T_J\}$

Study of the Ambiguities

- How do the ambiguous solutions look like (**continuity, signals, …**)?
- What are the effects of the **partial-wave decomposition fit** on **finite data** on the ambiguities?

I. Continuous intensity model

- create an amplitude model for selected partial waves
- calculate exact ambiguities

II. Finite pseudo-data

- generate pseudo-data according to model
- perform partial-wave decomposition

Continuous Amplitude Model

I. Continuous intensity model

- create an amplitude model for four selected partial waves
- In $1.0 < m_X < 2.5\ \mathrm{GeV}/c^2$
- m_X-dependence by Breit-Wigner amplitudes (PDG parameters)

$$T(m_X) = \underbrace{\sqrt{m_X}\,\sqrt{\rho_2(m_X)}}_{\text{phase-space factor}} \cdot \underbrace{Ce^{i\phi}}_{\text{complex scale}} \cdot \underbrace{D_{BW}(m_X; M_0, \Gamma_0)}_{\frac{M_0\,\Gamma_0}{M_0^2 - m_X^2 - iM_0\Gamma_0}}$$

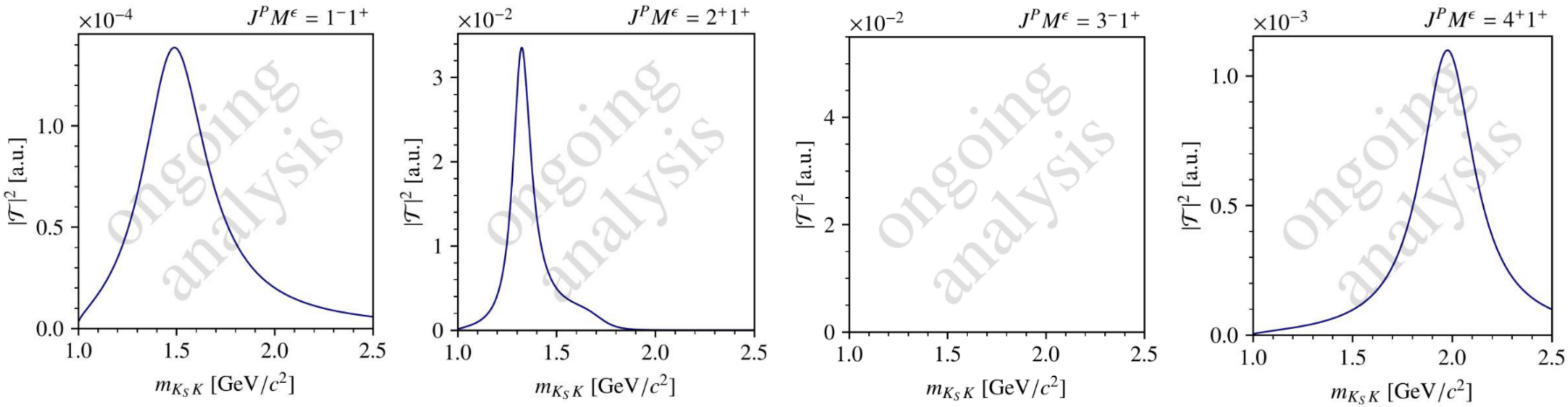
J^{PC}	Resonances
$\mathbf{1}^{--}$	$\rho(1450)$
$\mathbf{2}^{++}$	$a_2(1320), a_2'(1700)$
$\mathbf{3}^{--}$	None
$\mathbf{4}^{++}$	$a_4(1970)$

Continuous Amplitude Model

I. Continuous intensity model

J^{PC}	Resonances
$\mathbf{1^{--}}$	$\rho(1450)$
$\mathbf{2^{++}}$	$a_2(1320), a_2'(1700)$
$\mathbf{3^{--}}$	None
$\mathbf{4^{++}}$	$a_4(1970)$

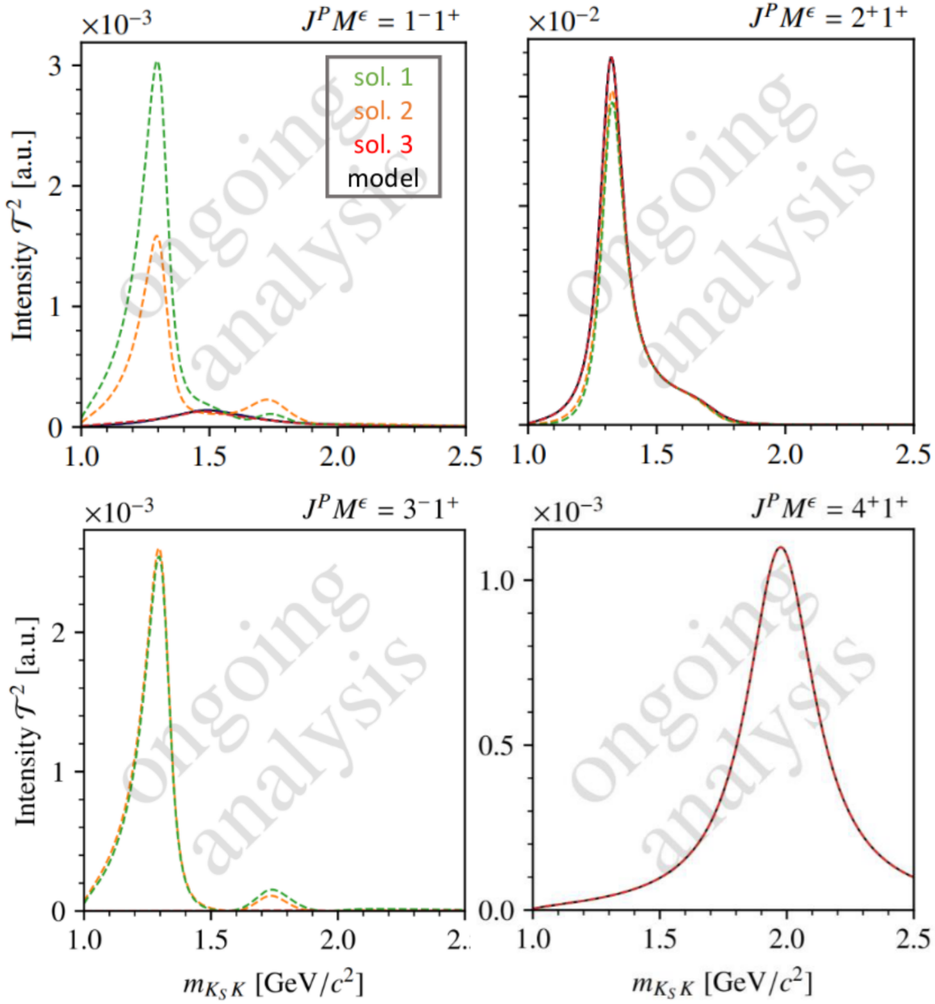
- create an amplitude model for four selected partial waves
- In $1.0 < m_X < 2.5\ \mathrm{GeV}/c^2$
- m_X-dependence by Breit-Wigner amplitudes (PDG parameters)



Continuous Amplitude Model

I. Continuous intensity model $N_a = 3$

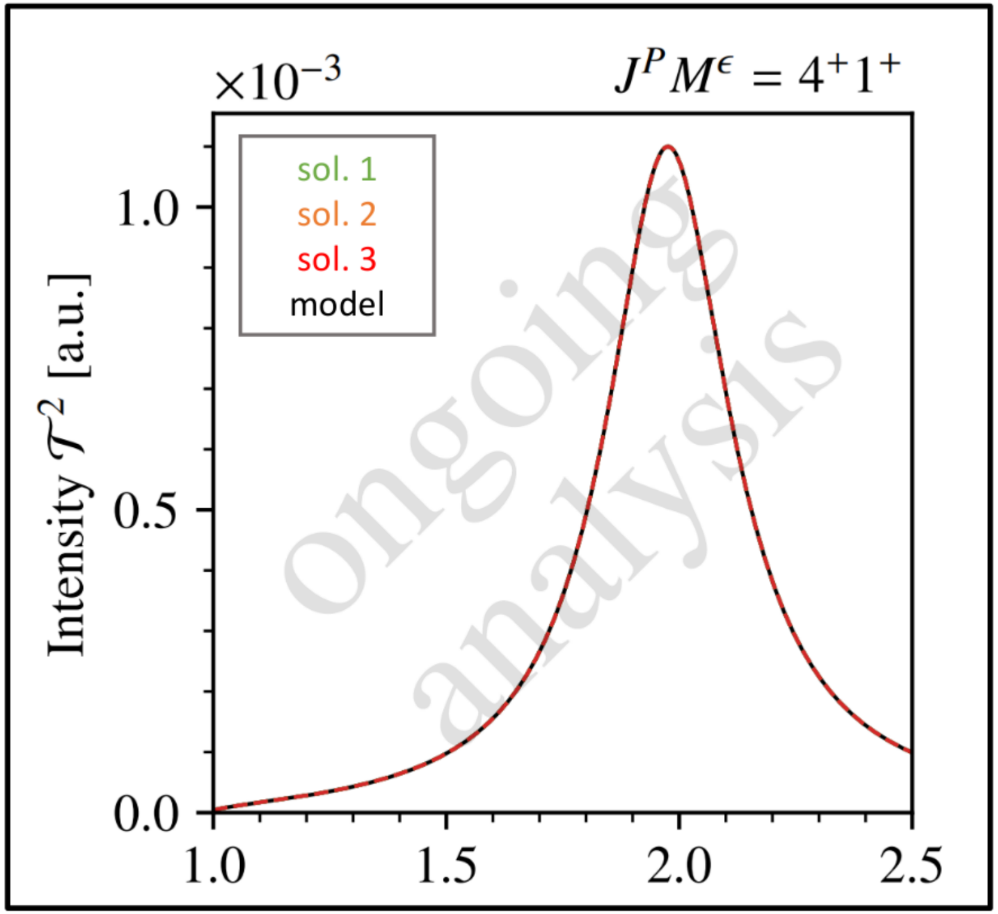
- Sample points in m_X and calculate ambiguous solutions
- Ambiguous intensities are also continuous
- Not all solutions are different from each other!
- Highest-spin (4^{++}) intensity is invariant!



Continuous Amplitude Model

I. Continuous intensity model $N_a = 3$

- Sample points in m_X and calculate ambiguous solutions
- Ambiguous intensities are also continuous
- Not all solutions are different from each other!
- Highest-spin (4^{++}) intensity is invariant!



Study of the Ambiguities

II. Finite pseudo-data

J^{PC}	Resonances
$\mathbf{1}^{--}$	$\rho(1450)$
$\mathbf{2}^{++}$	$a_2(1320), a_2'(1700)$
$\mathbf{3}^{--}$	None
$\mathbf{4}^{++}$	$a_4(1970)$

- reality: **finite data** and **amplitudes unknown**
- generate pseudo-data according to model (10^5 events)
- perform a partial-wave decomposition fit

→ 3000 attempts with random start values

Partial-Wave Decomposition Fits on Pseudodata

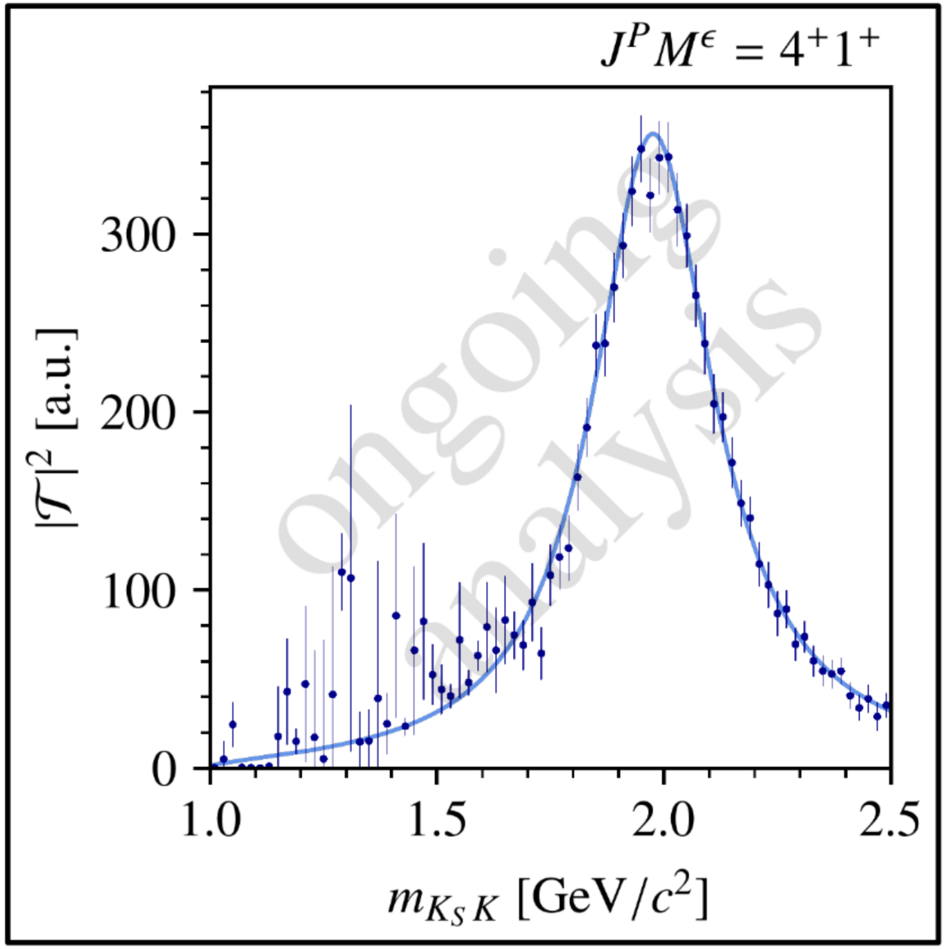
II. Finite pseudo-data

- 4^{++} intensity is still invariant!

- Overall, amplitude values found by the fit follow the calculated distributions

- Not all solutions are found in each m_X bin

→ PWD fit distorts the intensity distribution!

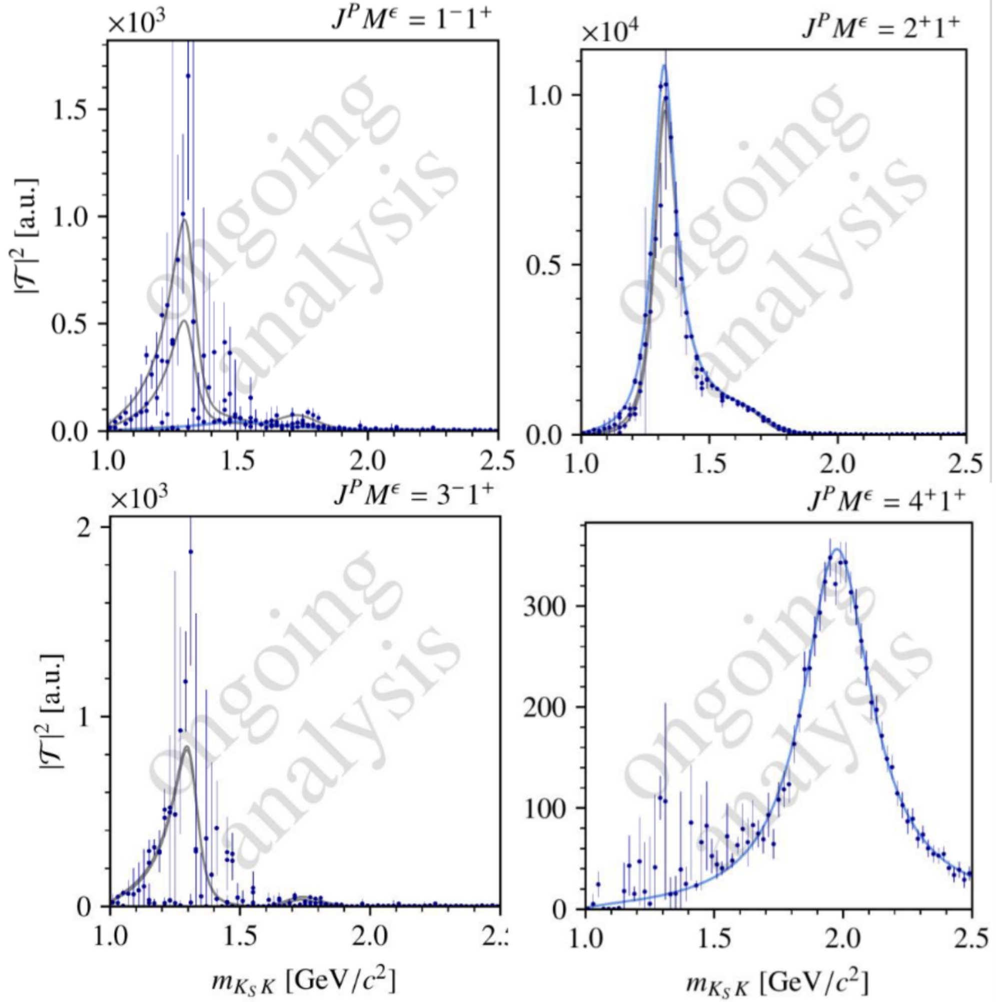


Partial-Wave Decomposition Fits on Pseudodata

II. Finite pseudo-data

- 4^{++} intensity is still invariant!
- Overall, amplitude values found by the fit follow the calculated distributions
- Not all solutions are found in each m_X bin

→ PWD fit distorts the intensity distribution!

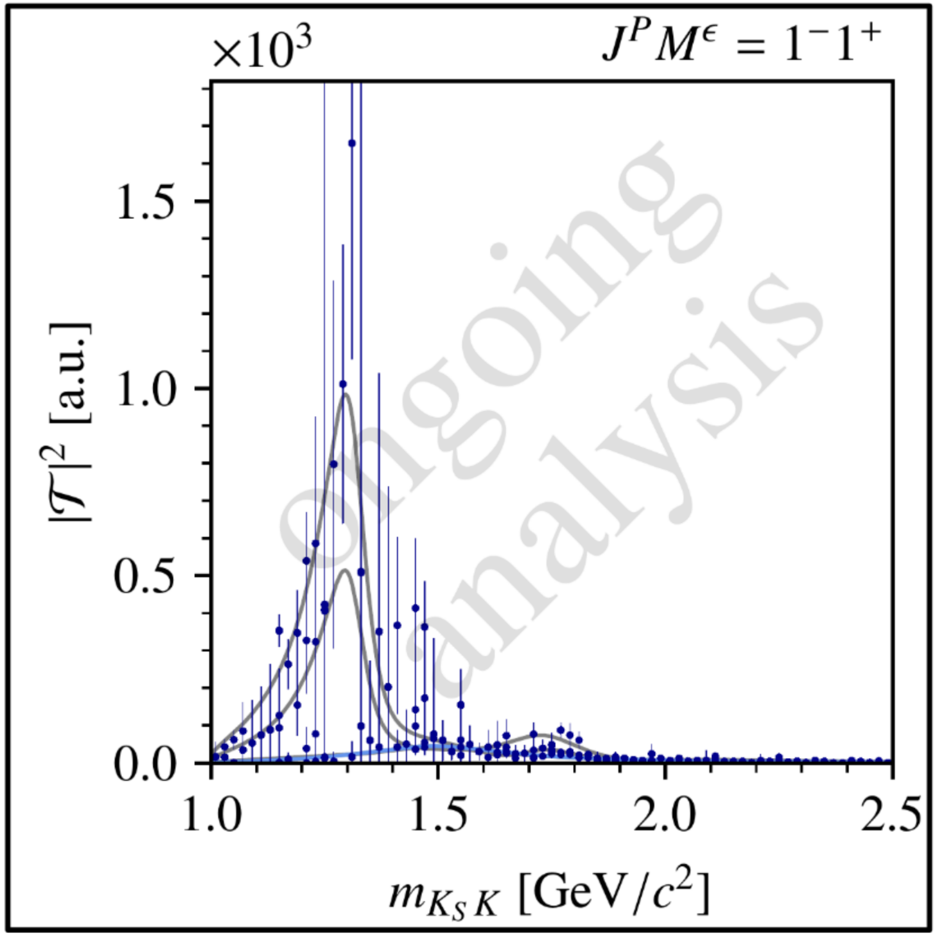


Partial-Wave Decomposition Fits on Pseudodata

II. Finite pseudo-data

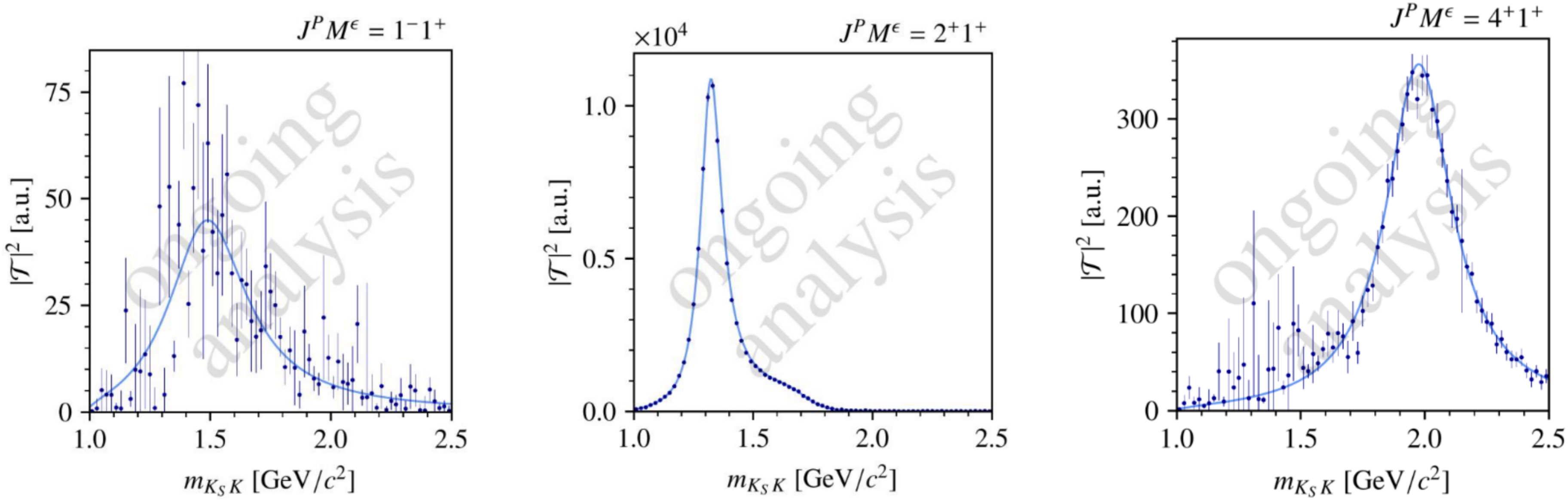
- 4^{++} intensity is still invariant!
- Overall, amplitude values found by the fit follow the calculated distributions
- Not all solutions are found in each m_X bin

→ PWD fit distorts the intensity distribution!



Reducing the Ambiguities

- Intensity of highest-spin wave is unaffected by ambiguities
- Including $M \geq 2$ → allows for additional angular structure → **resolves ambiguities**
- Remove one wave with $J < J_{\max}$ → **resolves ambiguities**



Continuity Constraints for Partial-Wave Analyses

julien.beckers@tum.de

Conventional Partial-Wave Analysis

We have some knowledge about the partial-wave amplitudes $T(m_X, t')$:

- Physics should be (mostly) **continuous** in m_X and t'

→ Solutions in neighboring bins should be similar (→ correlations between bins)

- Amplitudes should follow **phase-space** and **production kinematics**

Limitations of conventional PWA:

$$I(m_X, t'; \tau_n) = \left| \sum_{\text{waves}} T_i(m_X, t') \, \psi_i(m_X, \tau_n) \right|^2$$

- Binned analysis limits statistics, especially for small signals
- Continuity information is not imposed in the model
- We need to **select ("small") subset of partial waves** to include in the model

→ important source of systematic uncertainty

Constraints for Partial-Wave Analyses

Make use of this information to stabilize partial-wave decomposition fit:

→ Replace discrete amplitudes with **smooth, non-parametric curves**

→ Incorporate **kinematic factors**

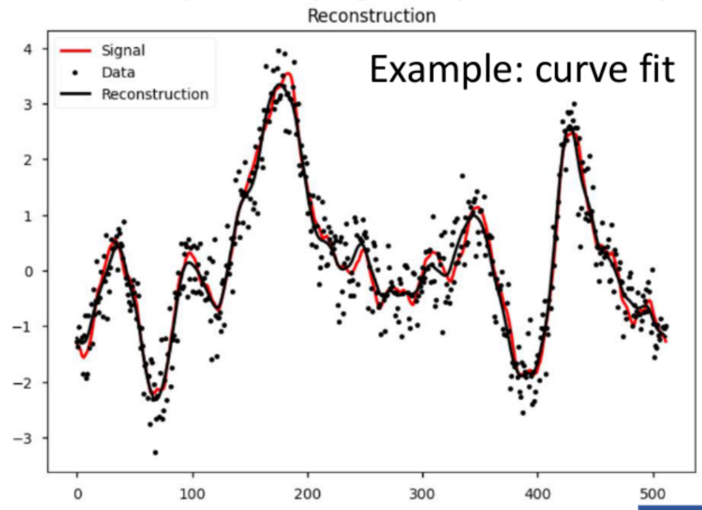
→ Include **regularization** for small amplitudes

NIFTY

https://ift.pages.mpcdf.de/nifty/

Framework by team from the Max-Planck Institute for Astrophysics:

NIFTY: "**N**umerical **I**nformation **F**ield **T**heory"



- Provides continuous non-parametric models
- Adapt to partial-wave analysis model
- **Learns smoothness and shape** of the amplitude curves

This work is done in collaboration with Jakob Knollmueller (TUM / ORIGINS Excellence Cluster)

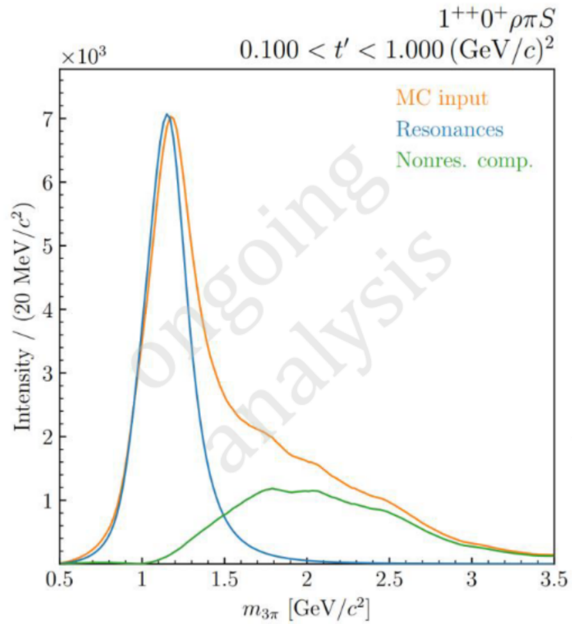
Input-Output Study

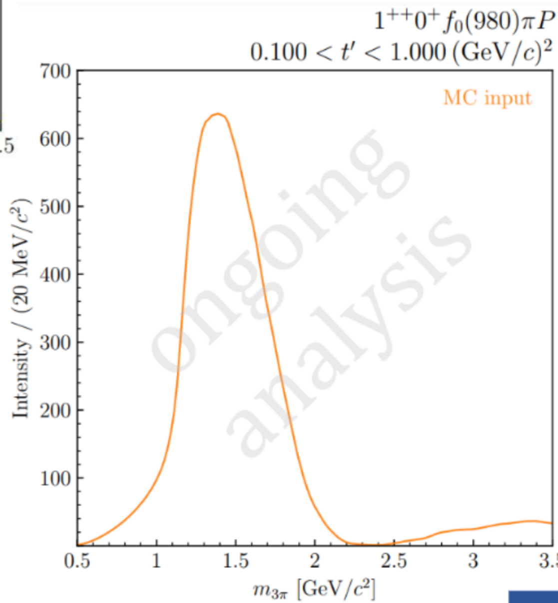
Verification on pseudodata:

- Generate pseudodata according to:
  - smooth model in mass
  - 81 partial waves
  - 5 resonances in selected waves

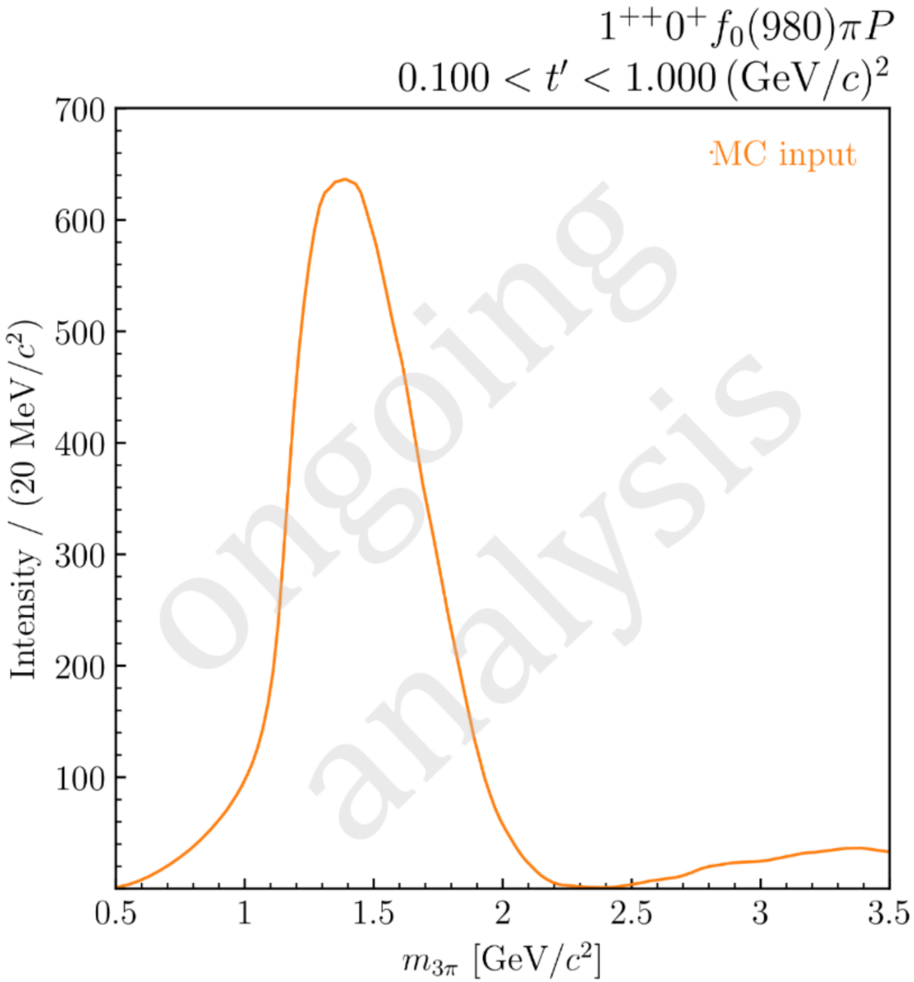
- resonance(s) (Breit-Wigner)
- nonres. component (broad curve)
- Combined signal → **input model**

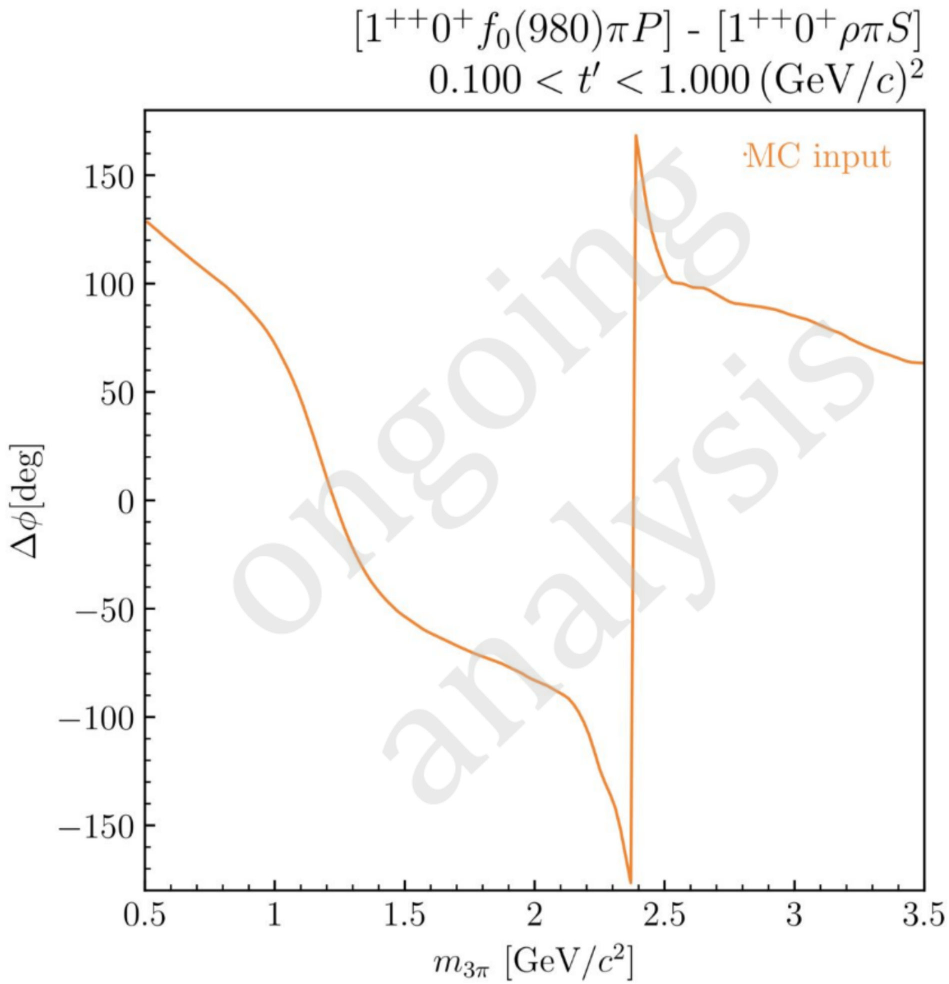
- Perform PWA fit with NIFTy model on generated dataset
  - Same set of partial waves



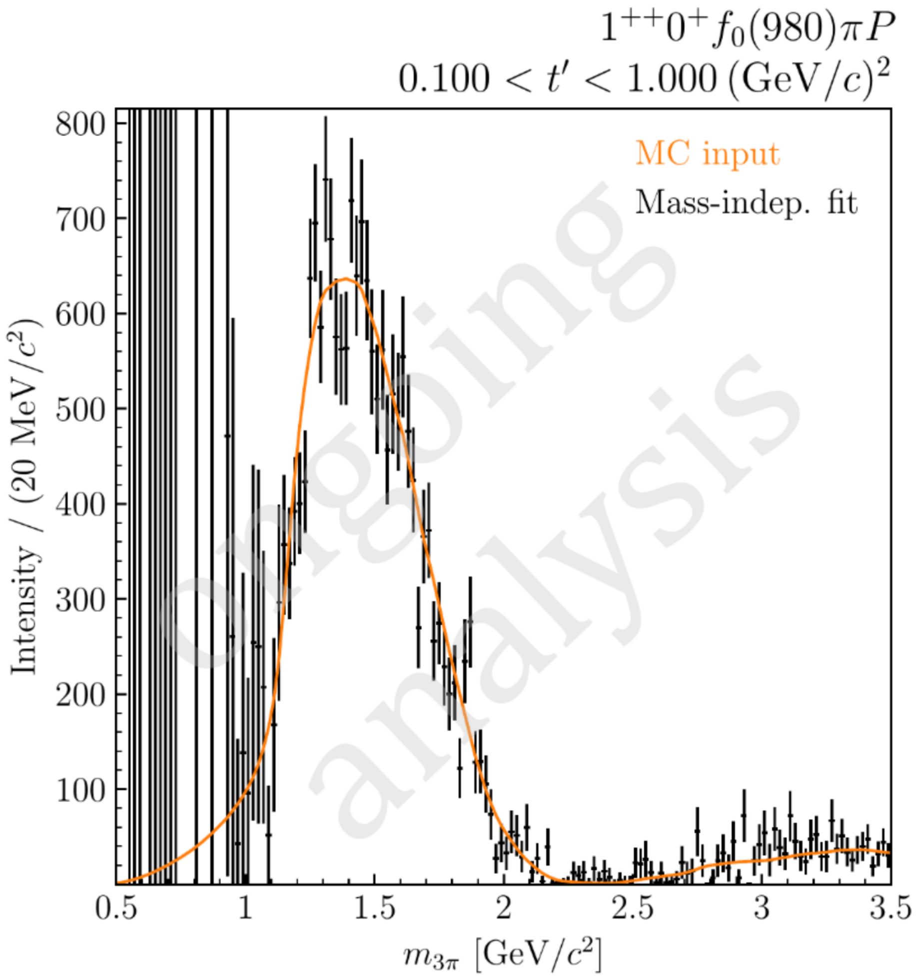


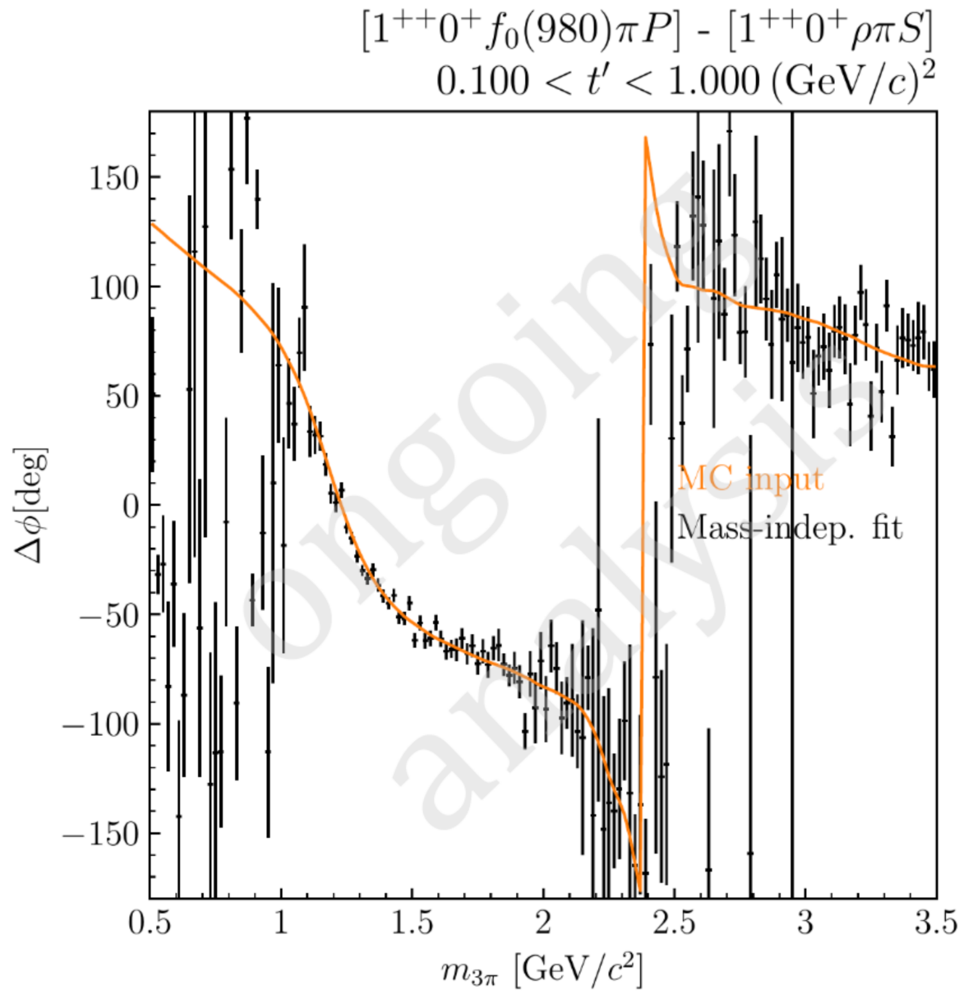
Input-Output Study



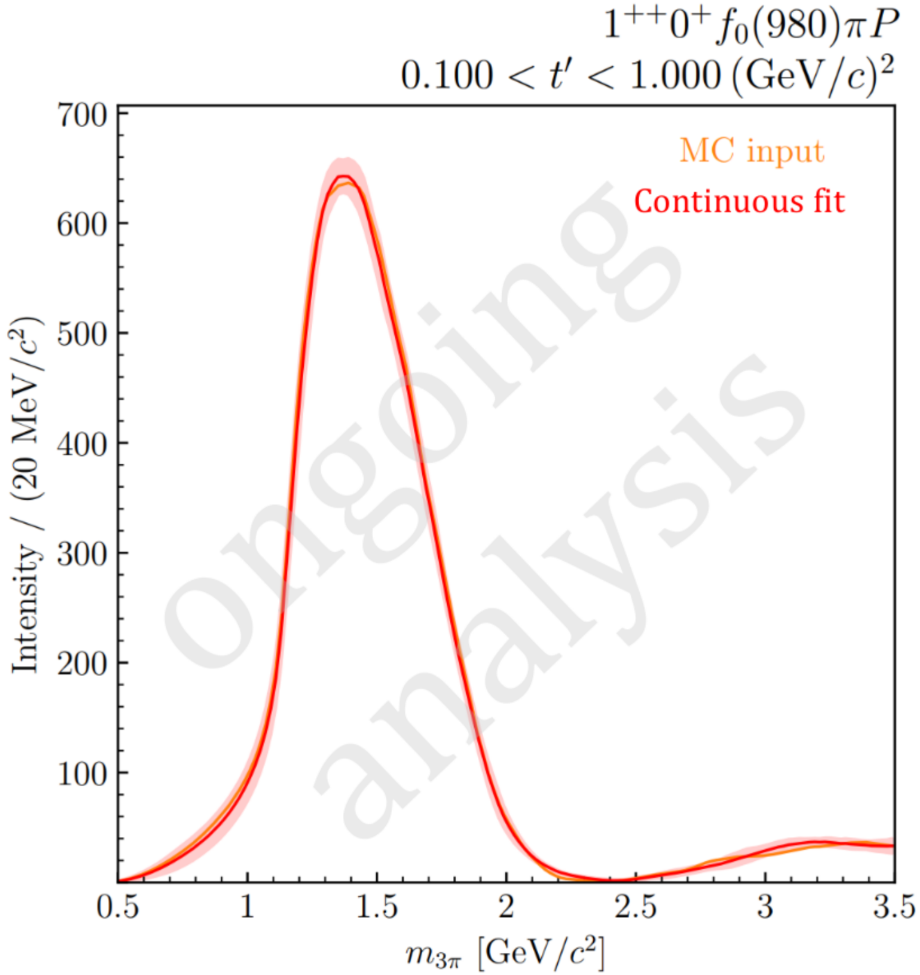


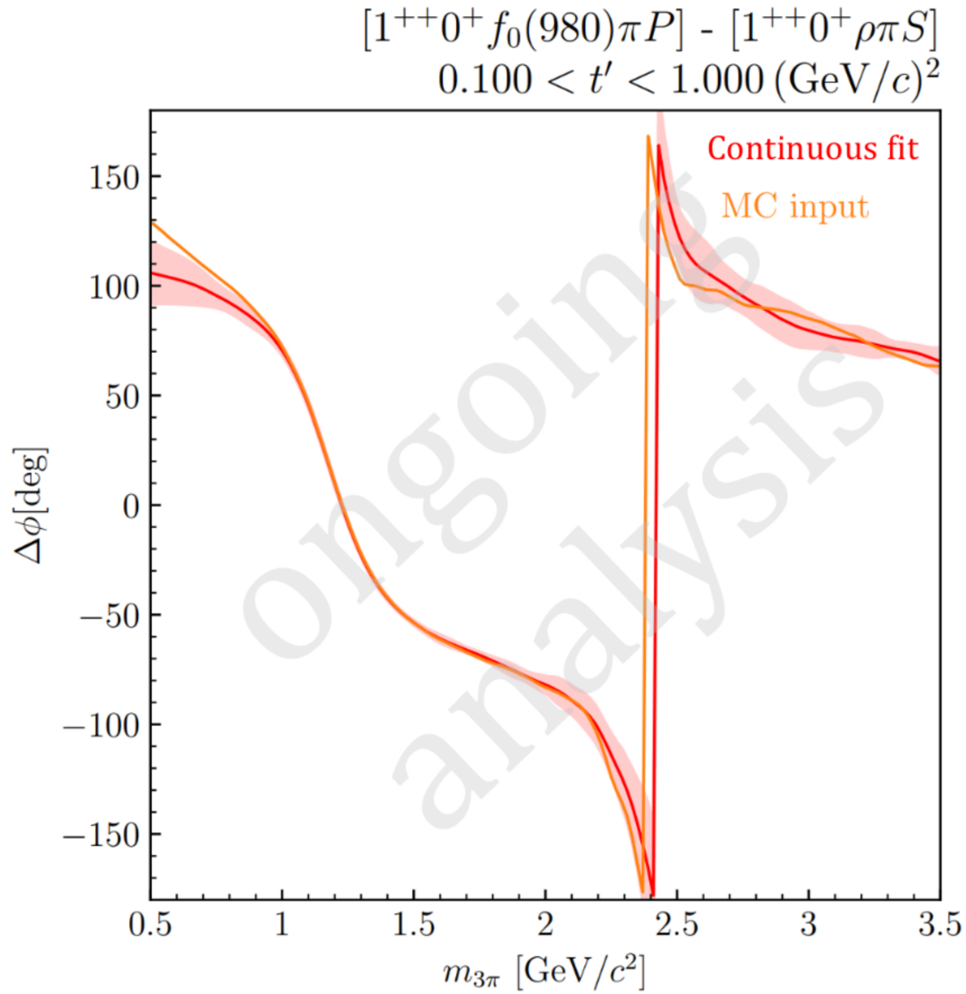
Input-Output Study



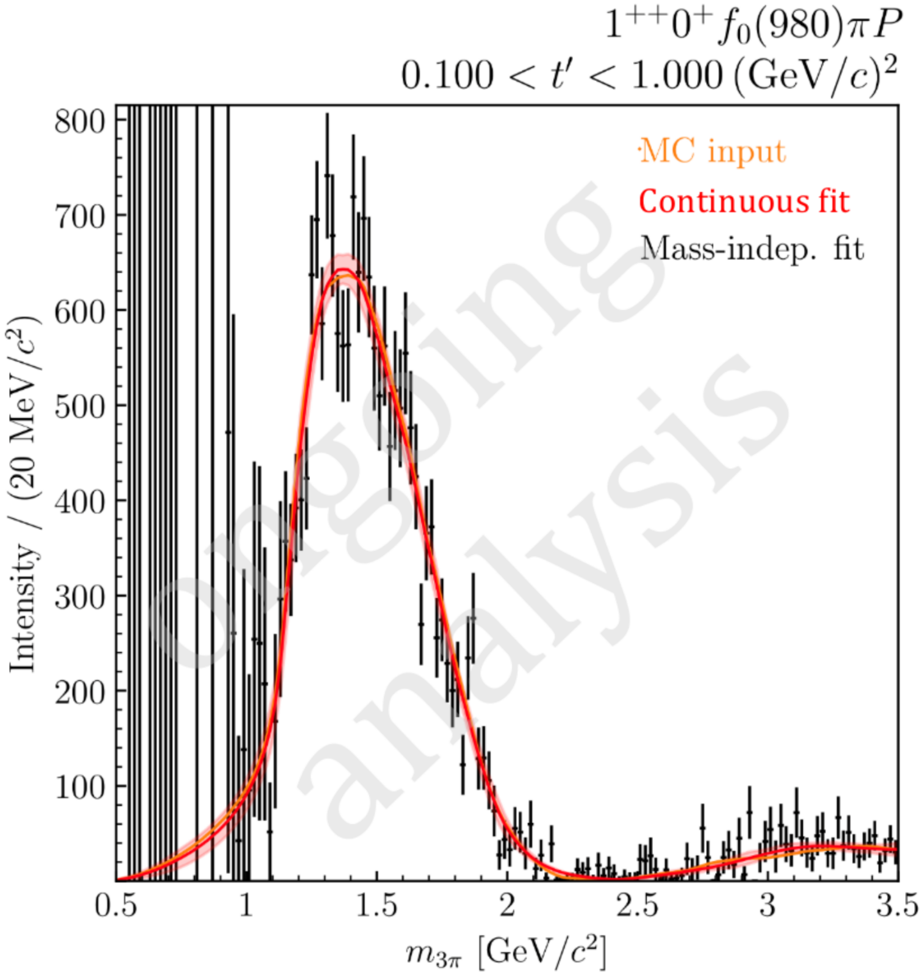


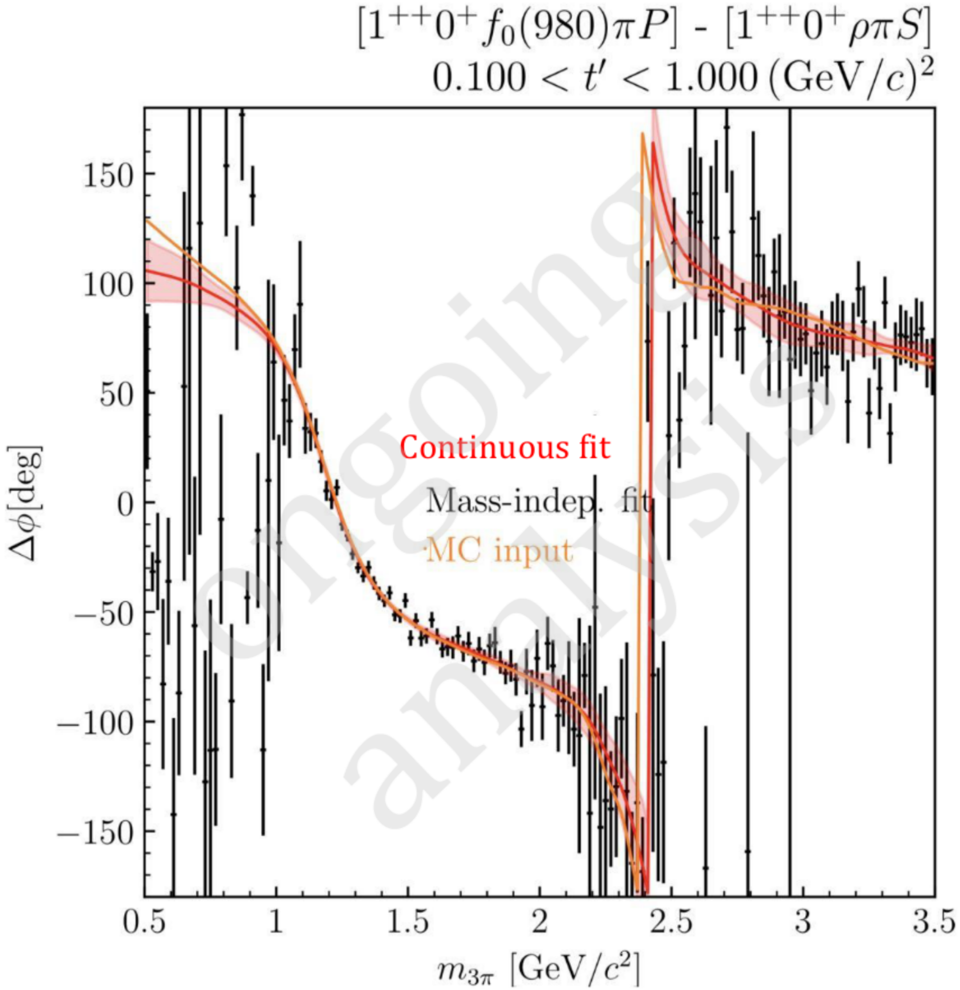
Input-Output Study





Input-Output Study





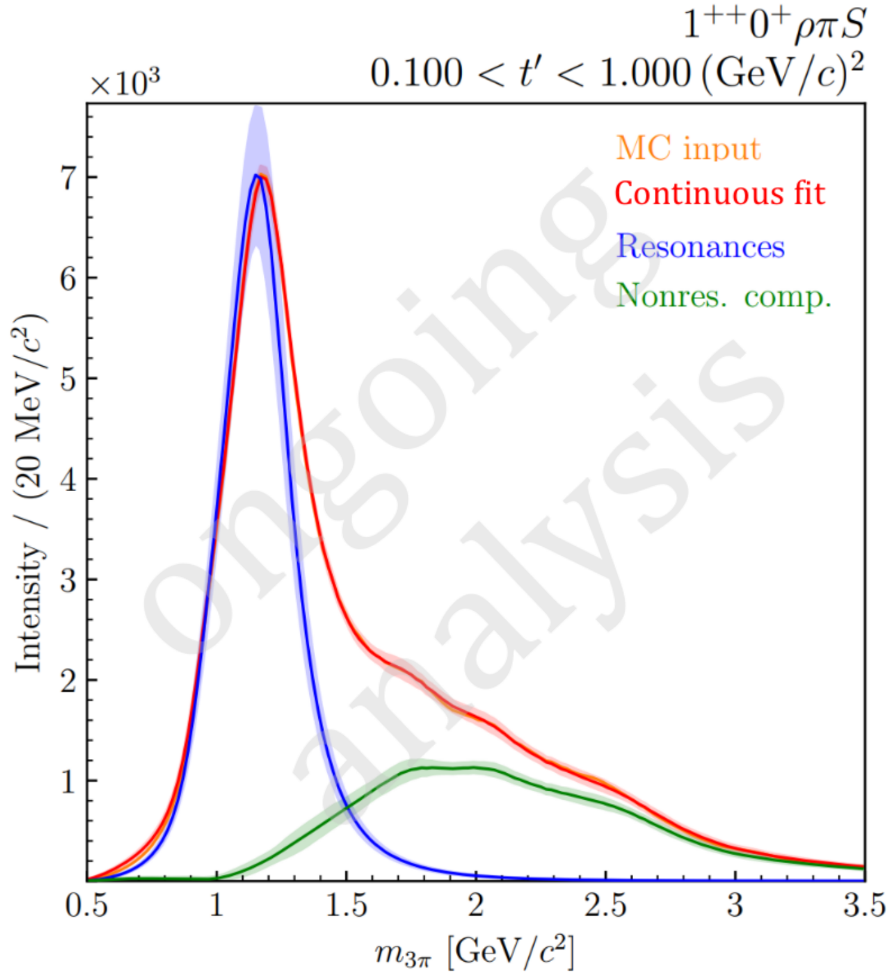
Single-Step Resonance Model Fit

We can go one step further!

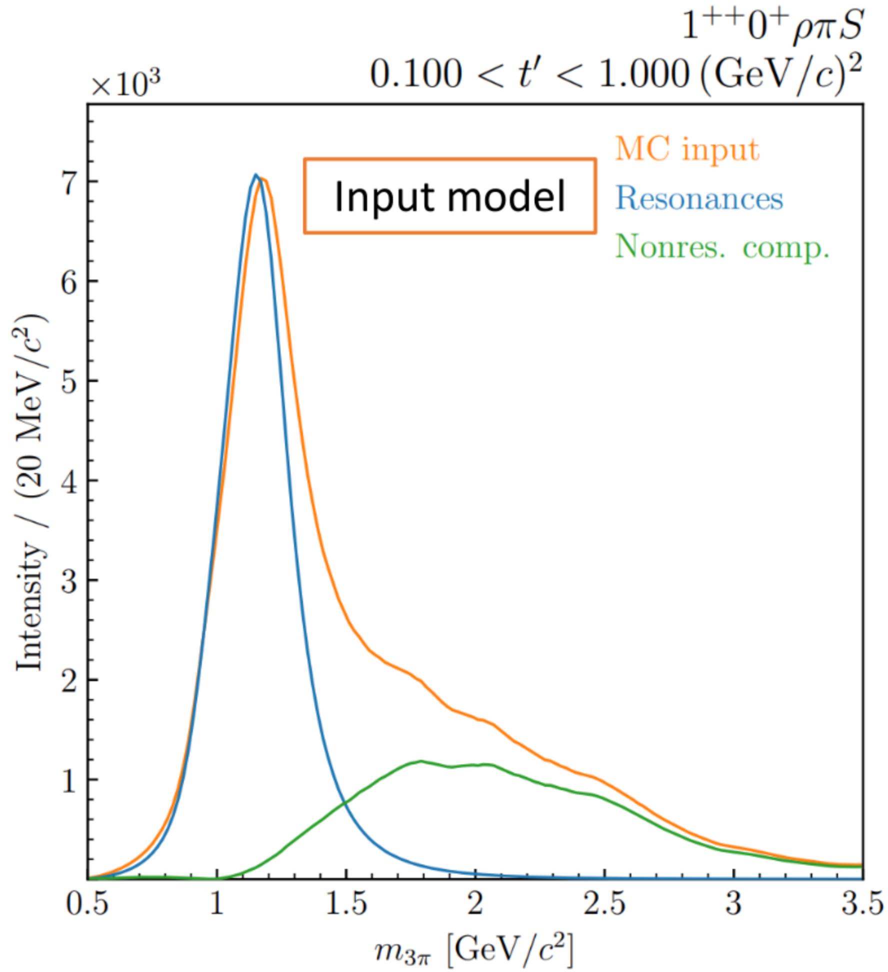
In **selected waves**:

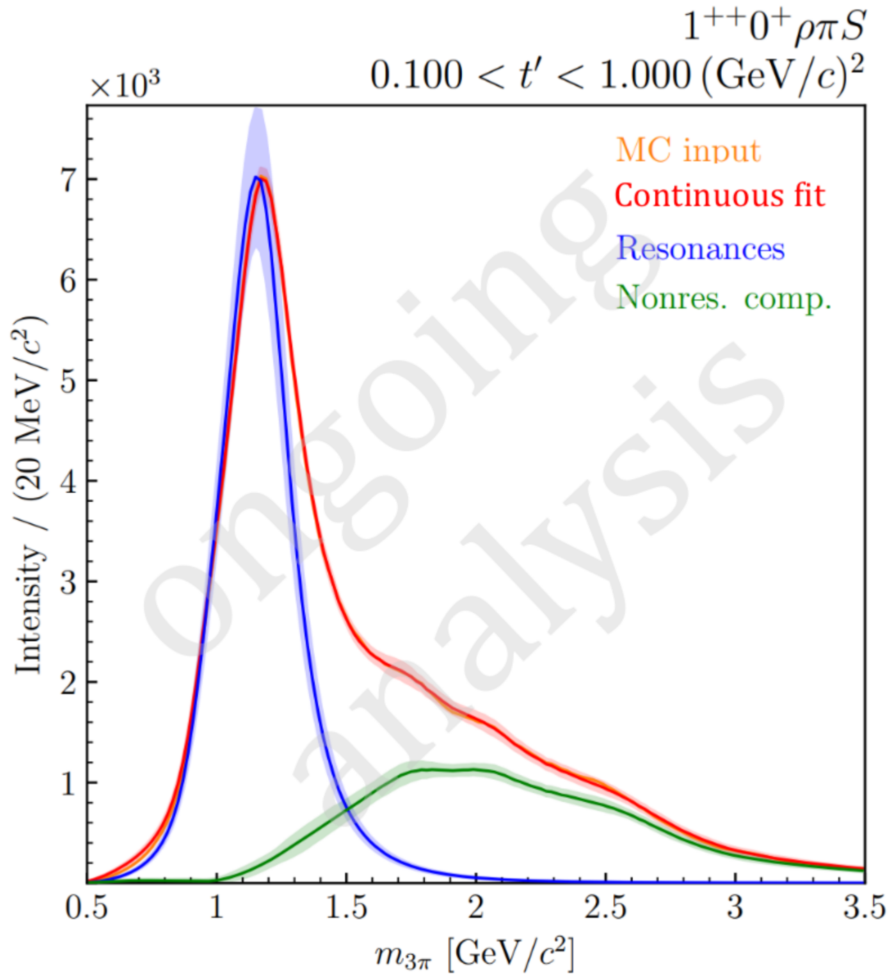
- add **resonant part**
  (e.g. as sum of Breit-Wigner distributions)
- use NIFTy as **flexible non-res. background**
- amplitude described by coherent sum

→ extract resonance parameters **in a single fit**



Single-Step Resonance Model Fit





Conclusion

High-precision data from COMPASS in $\pi^-\pi^-\pi^+$ and $K_S^0 K^-$ allow in-depth study of a_J and π_J states

Ambiguities appear in the partial-wave decomposition of two-body states

- Ambiguous amplitudes are **continuous** and can be calculated
- PWD fit/finite data has an effect on ambiguous solutions
- **Choice of included partial waves** may suppress the ambiguities

NIFTy: new approach to partial-wave analysis

- **Includes continuity, kinematics and regularization**
- Overcomes limitations of conventional approach
- Can include resonance-model fit
- Demonstrated in Monte Carlo pseudodata studies

Outlook

We can combine both presented topics

→ Apply NIFTy method on ambiguity problem in $K_S^0 K^-$

- Use continuity constraints to separate ambiguous solutions over entire mass range
- Improve fit quality

Partial-wave analysis using NIFTy model is being successfully applied on real data

Thank you for your attention!

julien.beckers@tum.de

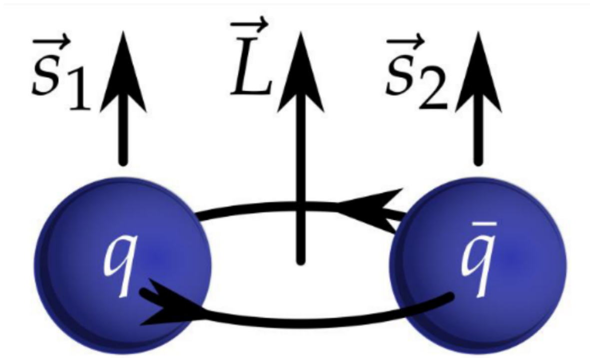
BACKUP

QCD in the Resonance Region

- At low energies (hadron regime): **QCD not solvable perturbatively**

- Theory: rely on models and effective theories, e.g. **quark model** (hadrons as bound states of **valence quarks**)

- Experimentally: **precision measurements** of hadronic states and search for so-called **exotic states** (forbidden in the quark model)



From Prog.Part.Nucl.Phys. 113 (2020) 103755

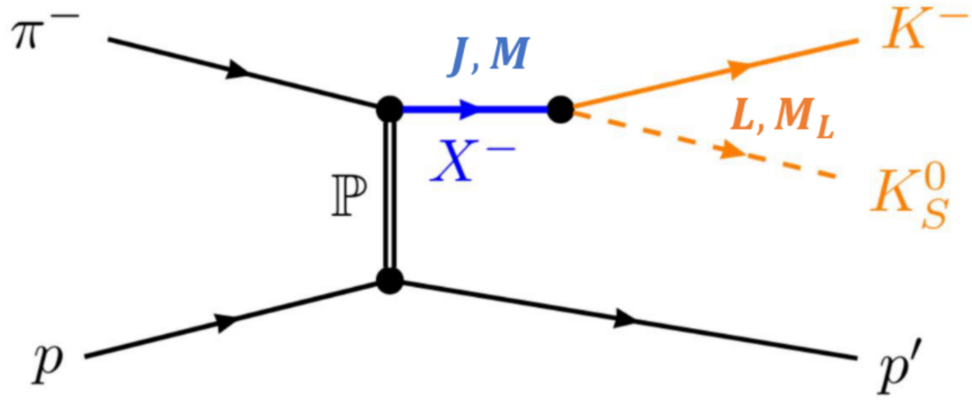
Partial-Wave Decomposition

$$I(m_X, t'; \theta, \phi) = \frac{dN}{dm_X dt' d\theta d\phi} = \left|M_{fi}\right|^2$$

- Separate process amplitude into **partial waves**
  - Spin $\boldsymbol{J}$ and spin-projection $\boldsymbol{M}$

$$\boldsymbol{J} = \boldsymbol{L}, \boldsymbol{M} = \boldsymbol{M_L}$$

$$\boldsymbol{P} = \boldsymbol{C} = (-\boldsymbol{1})^{\boldsymbol{J}}$$



Partial wave:
specific $(\boldsymbol{J^{PC}M})$

Partial-Wave Decomposition

$$I(m_X, t'; \theta, \phi) = \frac{dN}{dm_X dt' d\theta d\phi} = \left| \sum_J T_J(m_X, t')\, \psi_J(\theta, \phi) \right|^2$$

- Separate process amplitude into **partial waves**
  - Spin $\boldsymbol{J}$ and spin-projection $\boldsymbol{M}$

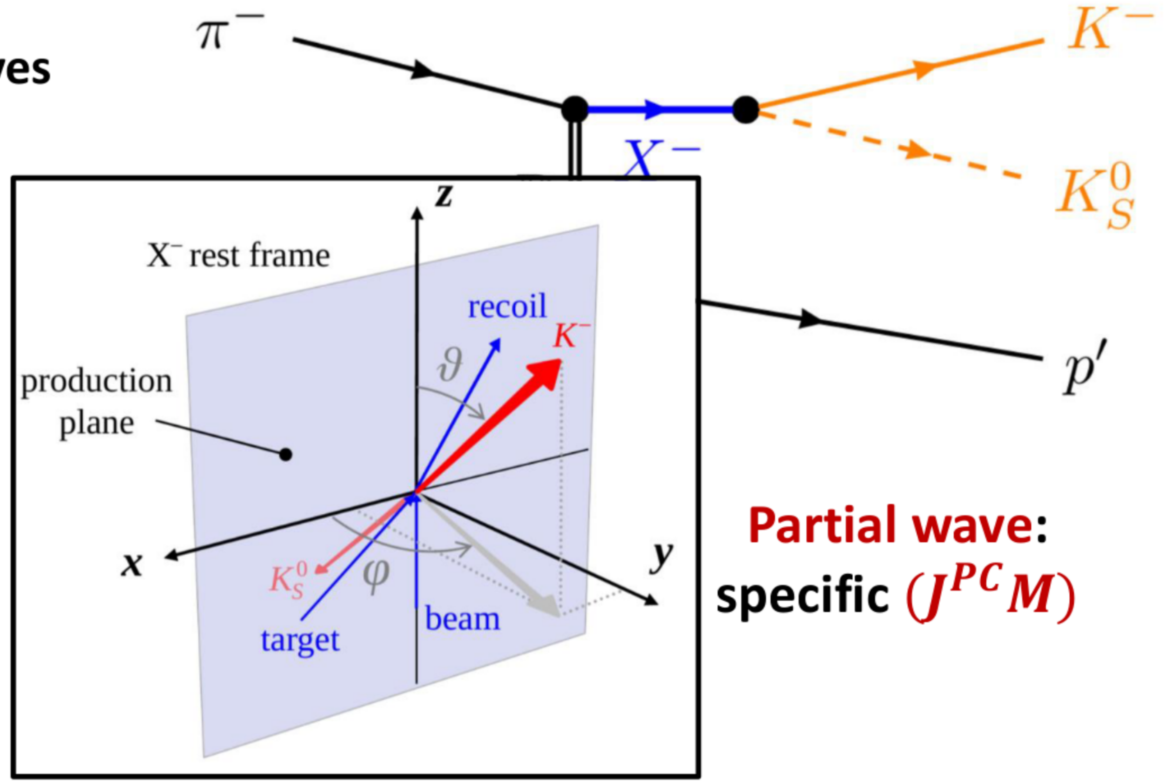
- Production, propagation and decay of X^-

$$\boldsymbol{T_{JM}(m_X, t')}$$

$$\boldsymbol{\psi_J(\theta, \phi) = Y_J^1(\theta, \phi)}$$

$$\boldsymbol{M = 1}$$

(reflectivity basis, $\varepsilon = -1$ suppressed $\rightarrow$ M $\neq$ 0)



Partial wave: specific $(J^{PC}M)$

Partial-Wave Decomposition

$$I(m_X, t'; \theta, \phi) = \frac{dN}{dm_X dt' d\theta d\phi} = \left| \sum_J T_J(m_X, t')\, \psi_J(\theta, \phi) \right|^2$$

- Separate process amplitude into **partial waves**
  - Spin $\boldsymbol{J}$ and spin-projection $\boldsymbol{M}$

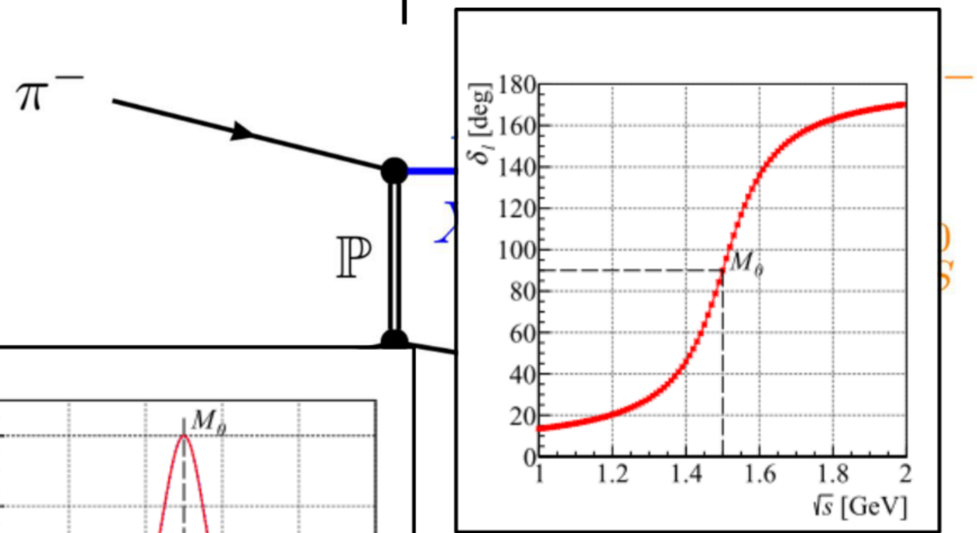
- Production, propagation and decay of X^-

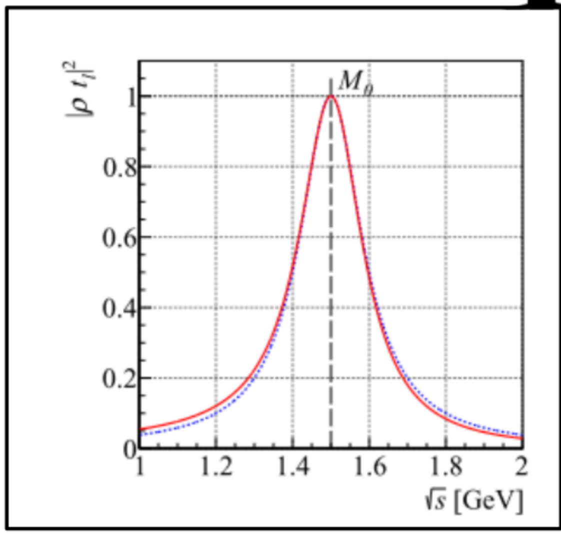
$$\boldsymbol{T_J(m_X, t') = P(m_X, t')\, D(m_X)}$$

$$\boldsymbol{\psi_J(\theta, \phi) = Y_J^M(\theta, \phi)}$$

$$\boldsymbol{M = 1}$$

- Fit $I(m_X, t'; \theta, \phi)$ to data **in** $(\mathbf{m_X}, \mathbf{t'})$ **bins**:
- Choose finite set of $\{J^{PC}\}$





Partial wave: specific (J^{PC})

From B. Ketzer et al., Prog.Part.Nucl.Phys. 113 (2020) 103755, Light-Meson Spectroscopy with COMPASS

Ambiguities in Incoherent Sectors

$$\boldsymbol{\varepsilon = \pm 1}: \quad I(m_X, t'; \theta, \phi) = \left| \sum_{JM} T^{+}_{JM}(m_X, t')\, \psi^{+}_{JM}(\theta, \phi) \right|^2 + \left| \sum_{JM} T^{-}_{JM}(m_X, t')\, \psi^{-}_{JM}(\theta, \phi) \right|^2$$

$$a_0^- = \sum_{J=0}^{J^-_{\max}} T^-_{J0}\, Y_J^0(\theta, 0) \qquad \varepsilon = -1, M = 0$$

$$a_1^- = \sum_{J=1}^{J^-_{\max}} T^-_{J1}\, Y_J^1(\theta, 0) \qquad \varepsilon = -1, M = 1$$

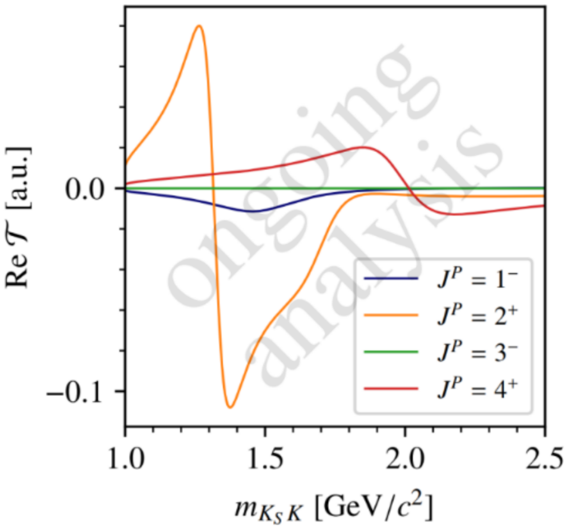
$$a_1^+ = \sum_{J=1}^{J^+_{\max}} T^+_{J1}\, Y_J^1(\theta, 0) \qquad \varepsilon = +1, M = 1$$

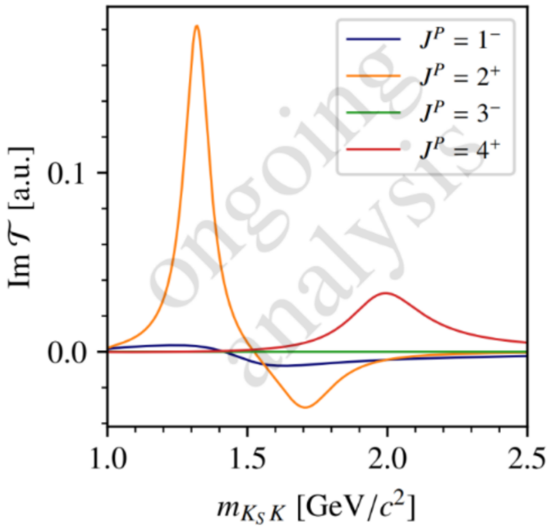
- $a_S^- = a_0^- + a_1^-$, then same procedure as for a single sector
- New amplitudes for $\varepsilon = +1$: $|a_1^+|^2 = |a_1^-|^2 - \text{const.}$ → **positivity requirement**!

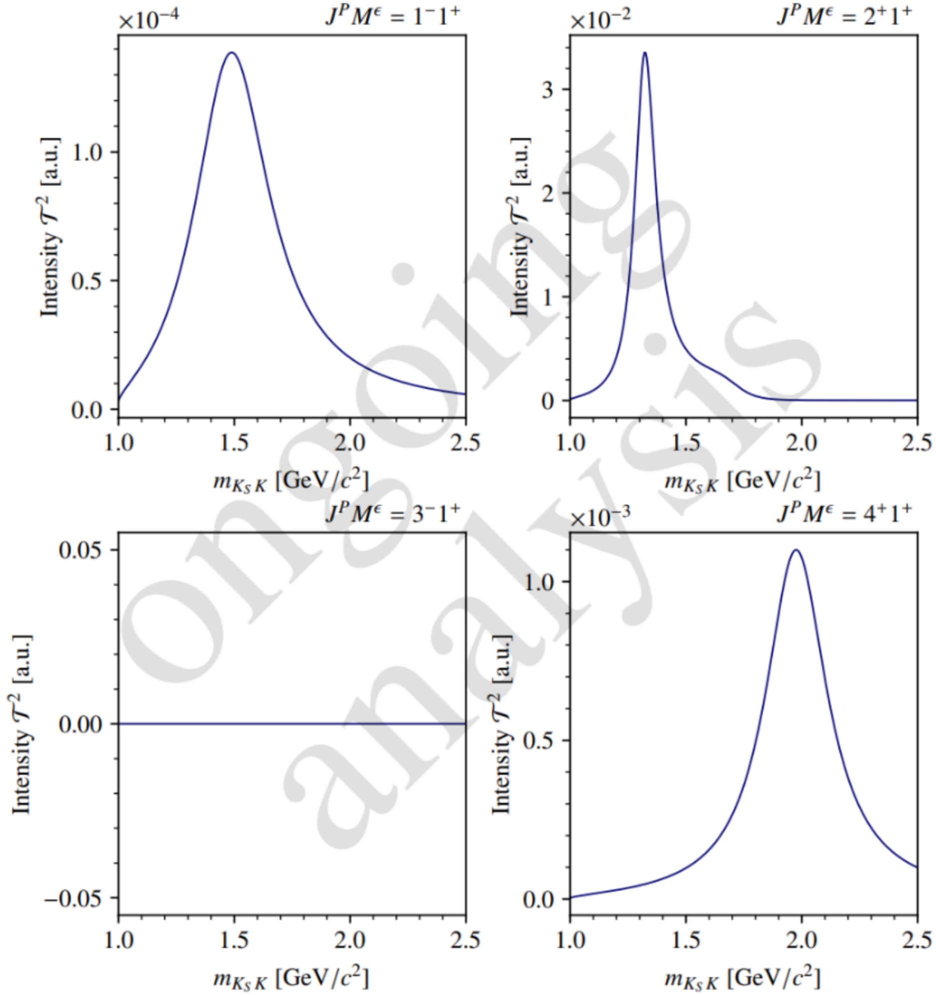
Continuous Amplitude Model

I. Continuous intensity model

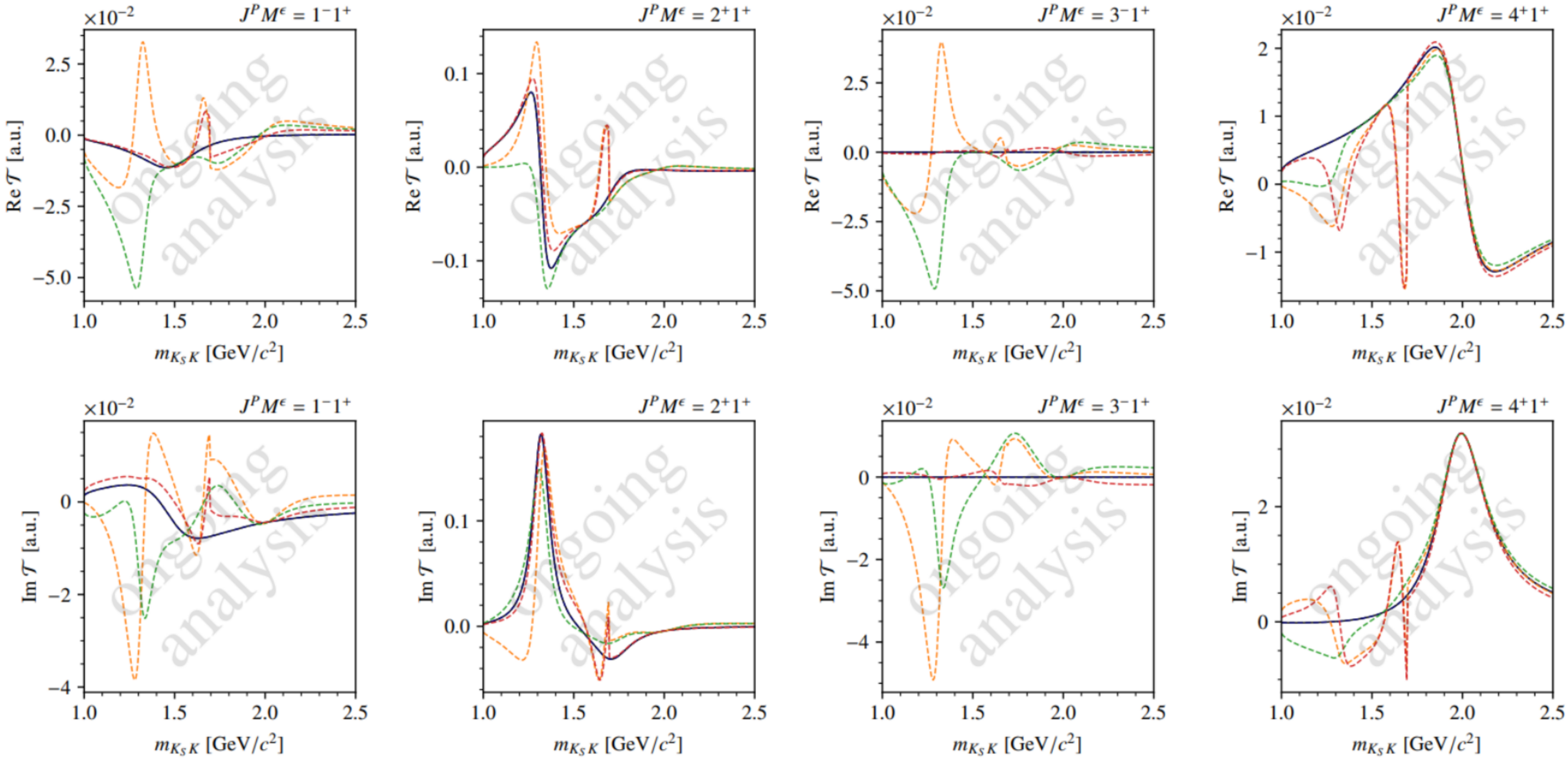
- create a model for the amplitudes in four waves
- m_X-dependence by Breit-Wigner amplitudes



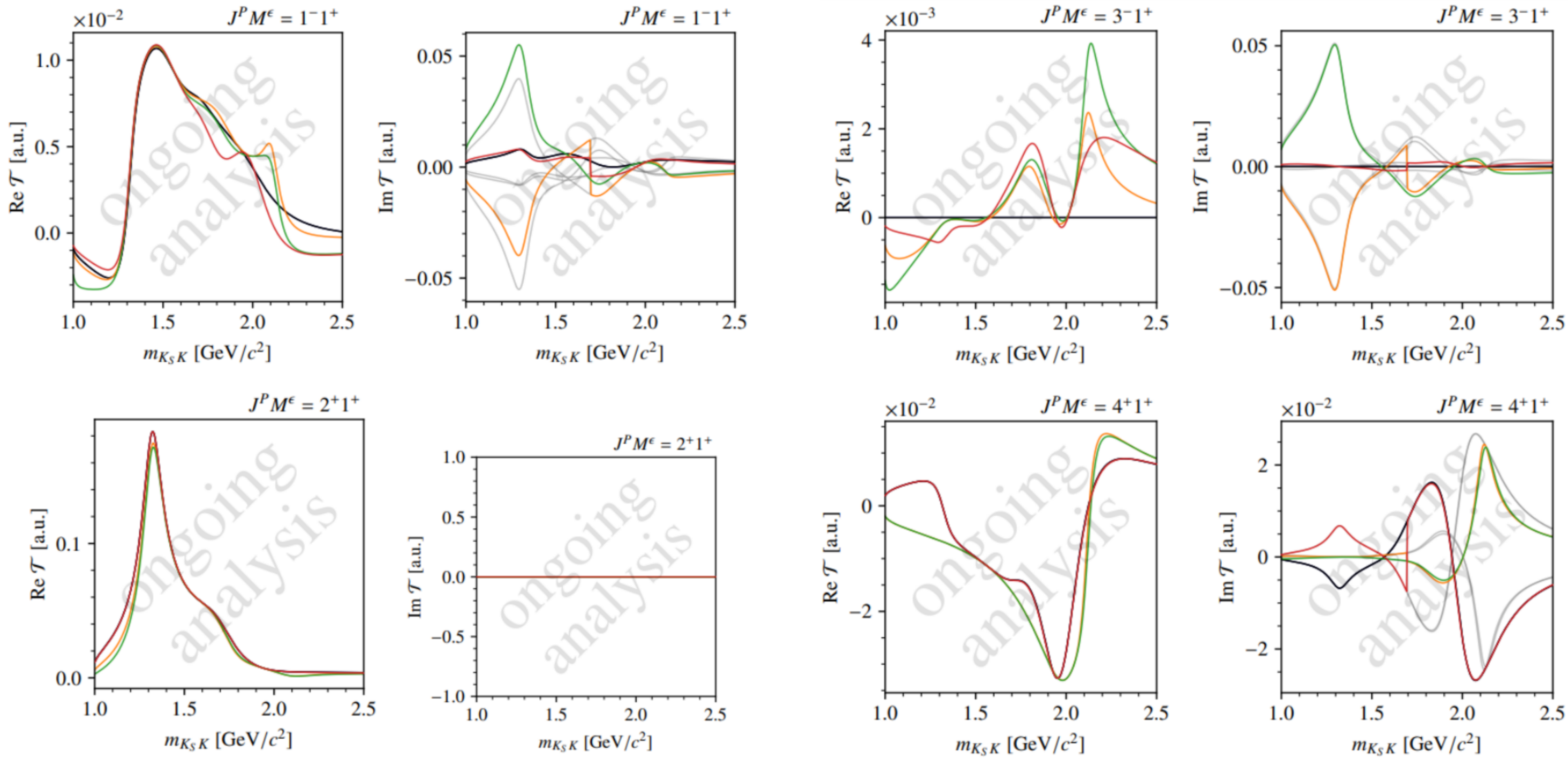


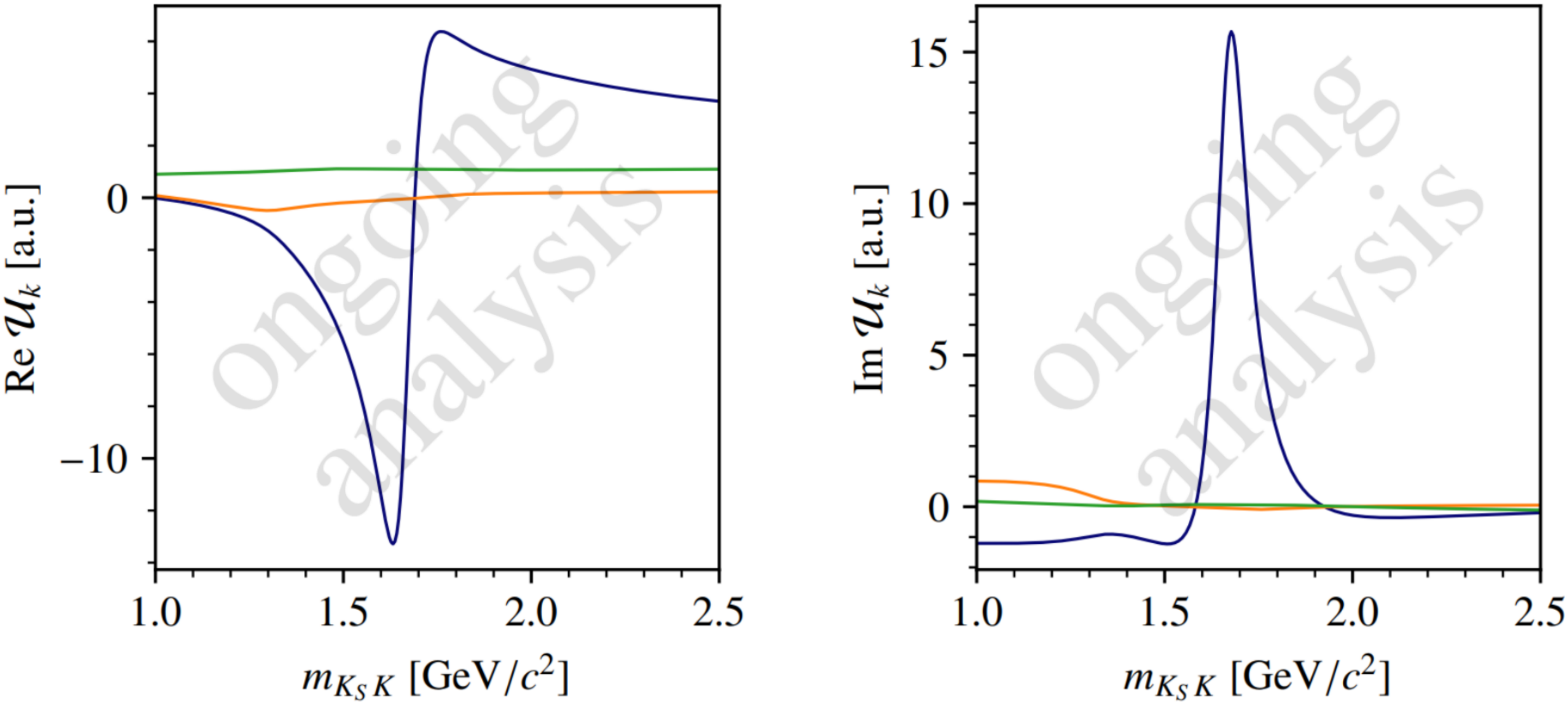


J^P	resonance content	m_0 [GeV/c^2]	Γ_0 [GeV/c^2]	c	ϕ
1^-	$\rho(1450)$	1.465	0.400	0.0564	1.8023
2^+	$a_2(1320)$	1.3181	0.1098	1	0
	$a_2(1700)$	1.698	0.265	0.1480	π
3^-	None	x	x	x	x
4^+	$a_4(1970)$	1.967	0.324	0.1274	6.0072

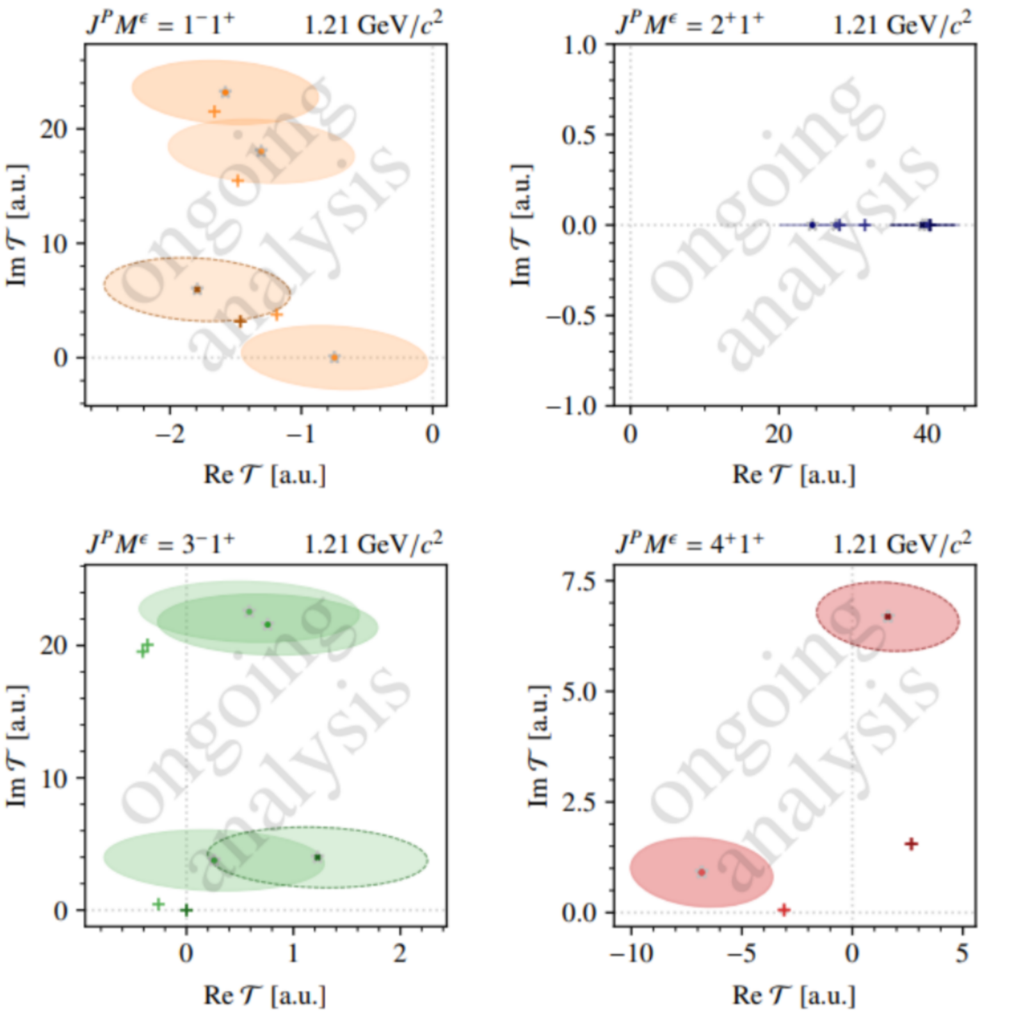


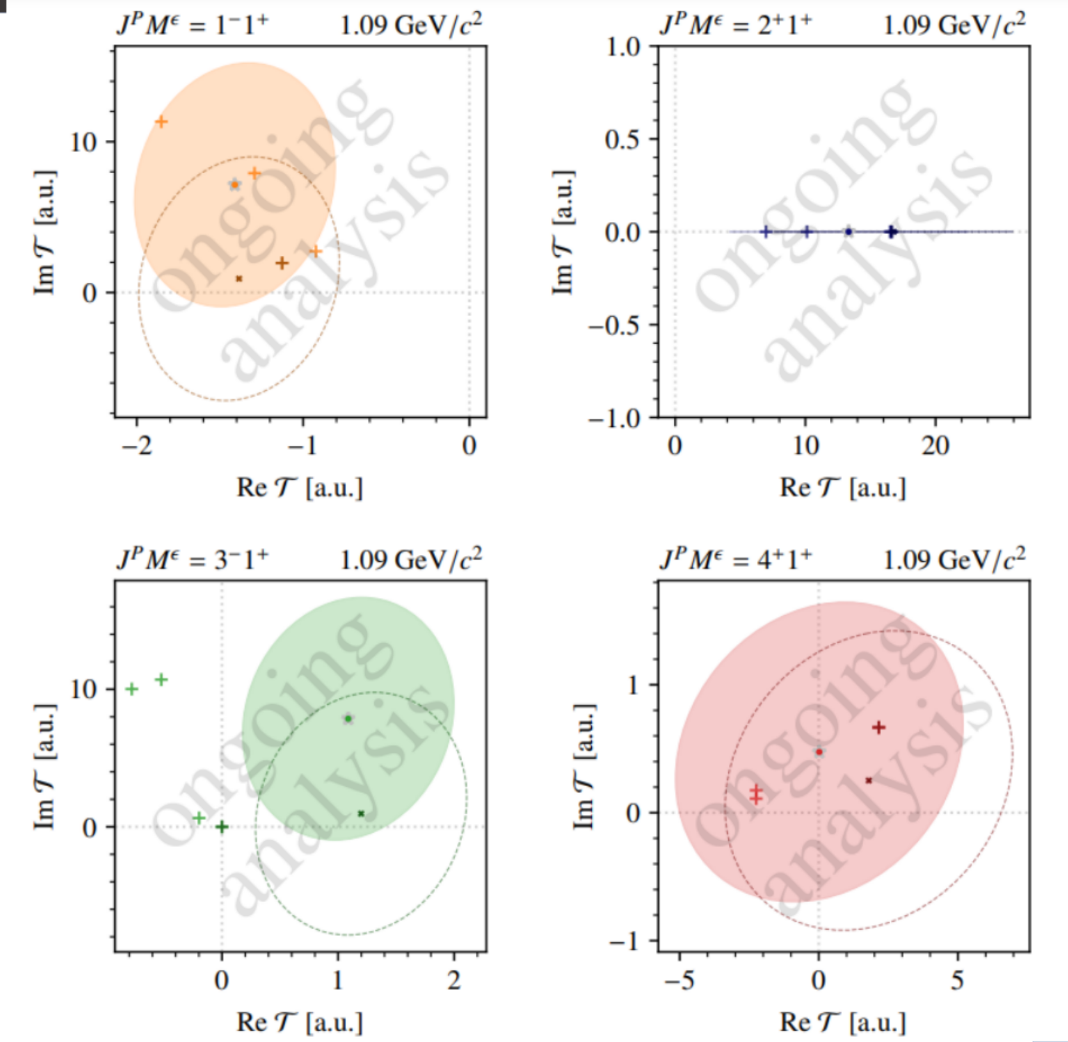
$\times 10^{-2}$ $J^P M^\epsilon = 1^-1^+$
$\times 10^{-2}$ $J^P M^\epsilon = 2^+1^+$
$\times 10^{-2}$ $J^P M^\epsilon = 3^-1^+$
$\times 10^{-2}$ $J^P M^\epsilon = 4^+1^+$
Re $\mathcal{T}$ [a.u.]
Im $\mathcal{T}$ [a.u.]
$m_{K_S K}$ [GeV/c^2]
ongoing analysis

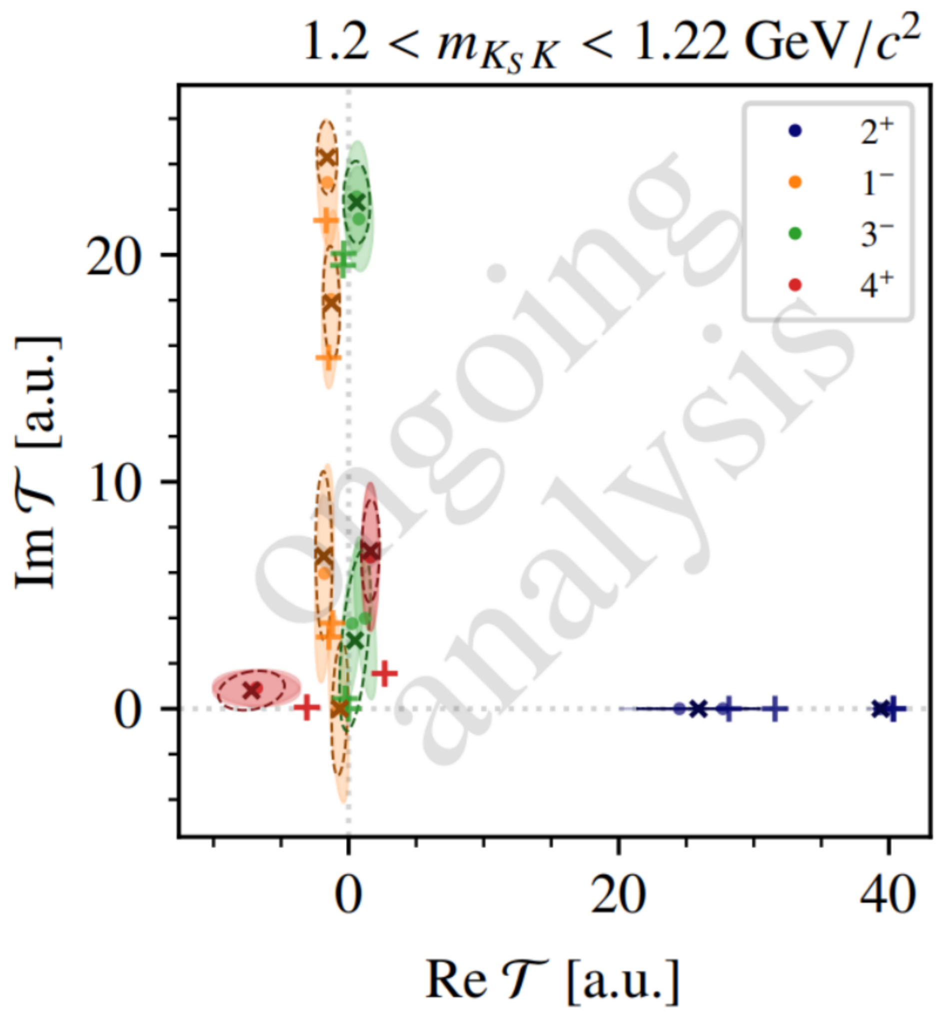

$\times10^{-2}$ $J^P M^\epsilon = 1^- 1^+$
Re $\mathcal{T}$ [a.u.]
$m_{K_S K}$ [GeV/c^2]
$J^P M^\epsilon = 1^- 1^+$
Im $\mathcal{T}$ [a.u.]
$m_{K_S K}$ [GeV/c^2]
$\times10^{-3}$ $J^P M^\epsilon = 3^- 1^+$
Re $\mathcal{T}$ [a.u.]
$m_{K_S K}$ [GeV/c^2]
$J^P M^\epsilon = 3^- 1^+$
Im $\mathcal{T}$ [a.u.]
$m_{K_S K}$ [GeV/c^2]
$J^P M^\epsilon = 2^+ 1^+$
Re $\mathcal{T}$ [a.u.]
$m_{K_S K}$ [GeV/c^2]
$J^P M^\epsilon = 2^+ 1^+$
Im $\mathcal{T}$ [a.u.]
$m_{K_S K}$ [GeV/c^2]
$\times10^{-2}$ $J^P M^\epsilon = 4^+ 1^+$
Re $\mathcal{T}$ [a.u.]
$m_{K_S K}$ [GeV/c^2]
$\times10^{-2}$ $J^P M^\epsilon = 4^+ 1^+$
Im $\mathcal{T}$ [a.u.]
$m_{K_S K}$ [GeV/c^2]
ongoing analysis

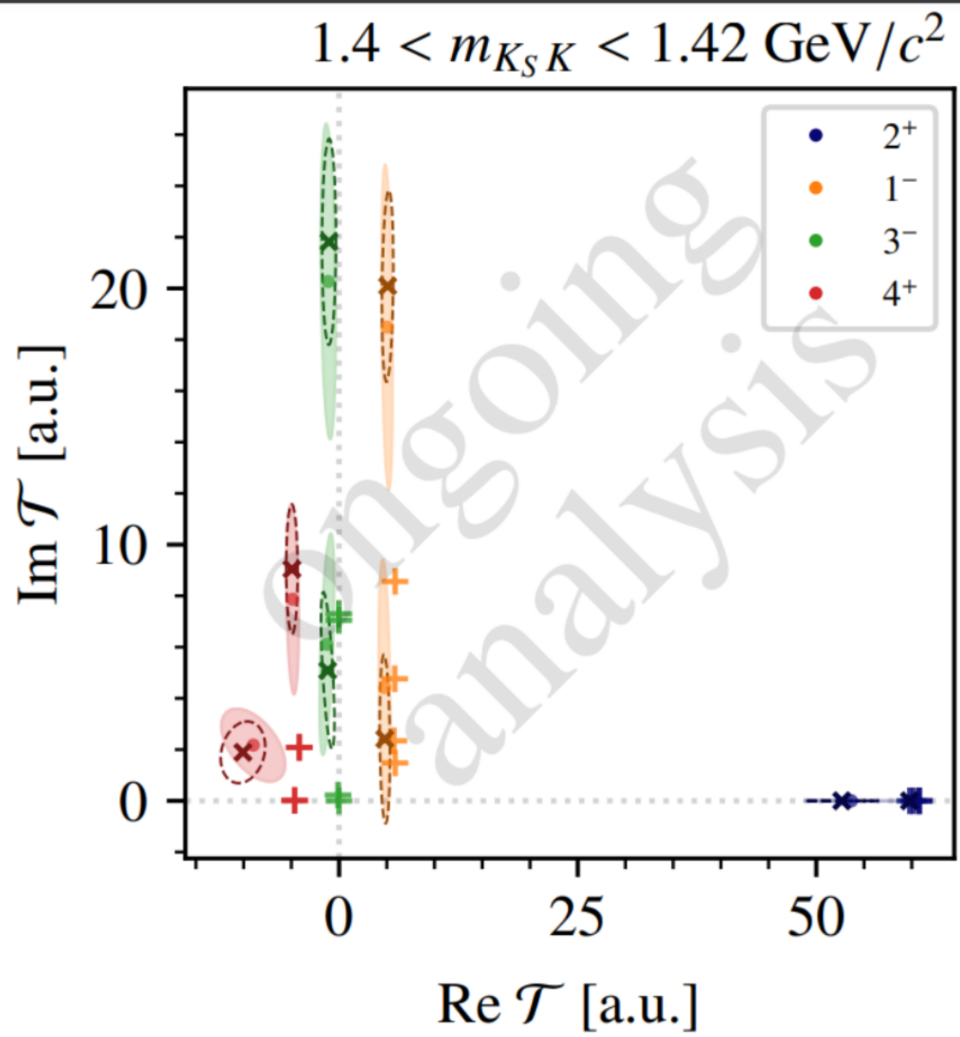


Re $\mathcal{U}_k$ [a.u.]
0
−10
1.0
1.5
2.0
2.5
$m_{K_S K}$ [GeV/c^2]
Im $\mathcal{U}_k$ [a.u.]
15
10
5
0
1.0
1.5
2.0
2.5
$m_{K_S K}$ [GeV/c^2]
ongoing analysis


$J^P M^\epsilon = 1^- 1^+$ 1.21 GeV/c^2
$J^P M^\epsilon = 2^+ 1^+$ 1.21 GeV/c^2
$J^P M^\epsilon = 3^- 1^+$ 1.21 GeV/c^2
$J^P M^\epsilon = 4^+ 1^+$ 1.21 GeV/c^2
Im $\mathcal{T}$ [a.u.]
Re $\mathcal{T}$ [a.u.]
ongoing analysis


$J^P M^\epsilon = 1^- 1^+$ 1.09 GeV/c^2
$J^P M^\epsilon = 2^+ 1^+$ 1.09 GeV/c^2
$J^P M^\epsilon = 3^- 1^+$ 1.09 GeV/c^2
$J^P M^\epsilon = 4^+ 1^+$ 1.09 GeV/c^2
Im $\mathcal{T}$ [a.u.]
Re $\mathcal{T}$ [a.u.]
ongoing analysis


$1.2 < m_{K_S K} < 1.22$ GeV/c^2
2+
1−
3−
4+
ongoing analysis
Im $\mathcal{T}$ [a.u.]
Re $\mathcal{T}$ [a.u.]
0
10
20
0
20
40


$1.4 < m_{K_S K} < 1.42$ GeV/c^2
2+
1−
3−
4+
ongoing analysis
Im $\mathcal{T}$ [a.u.]
Re $\mathcal{T}$ [a.u.]
0
10
20
0
25
50

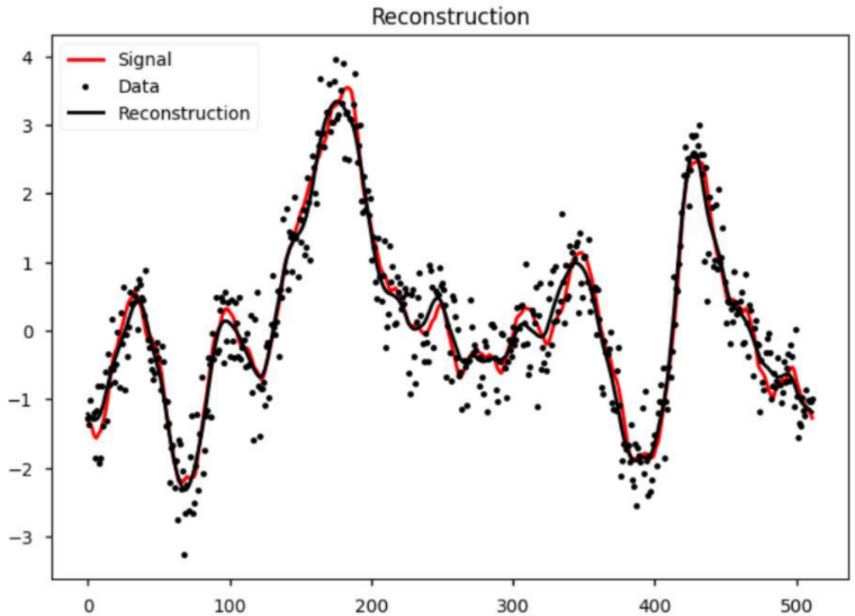
Implementation: NIFTy Framework

Framework by team from the Max-Planck Institute for Astrophysics:

NIFTY: "**N**umerical **I**nformation **F**ield **T**heor**y**"

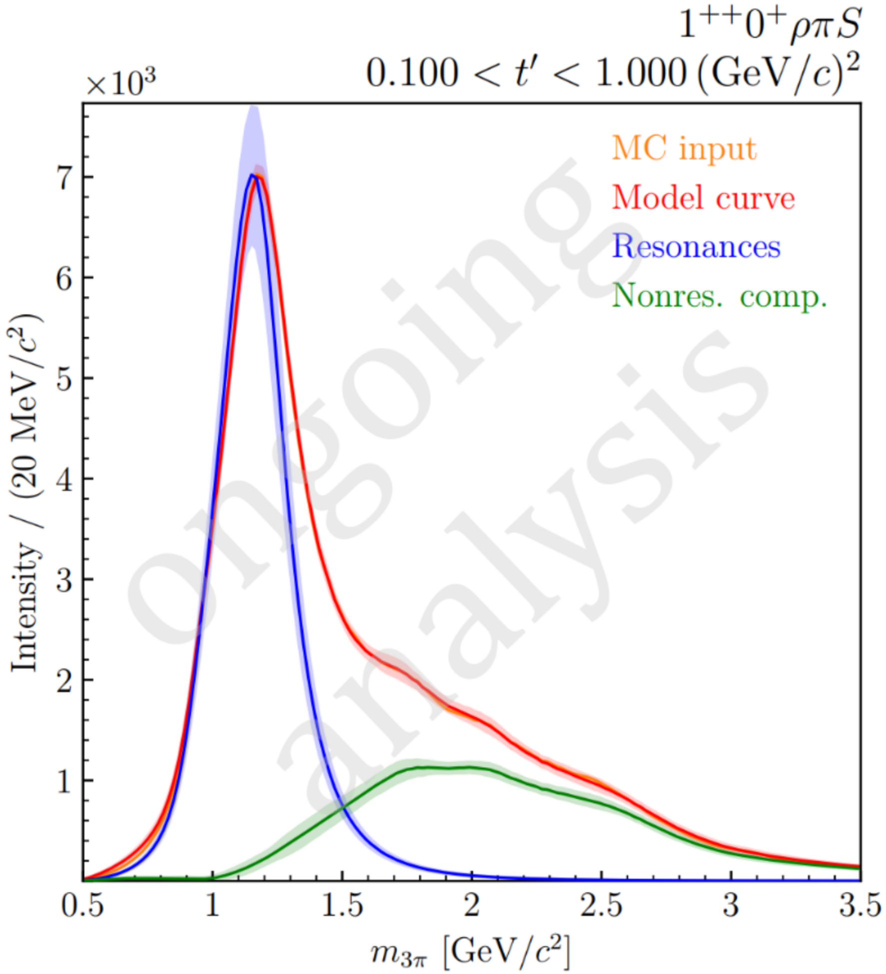
- Provides continuous non-parametric models

https://ift.pages.mpcdf.de/nifty/

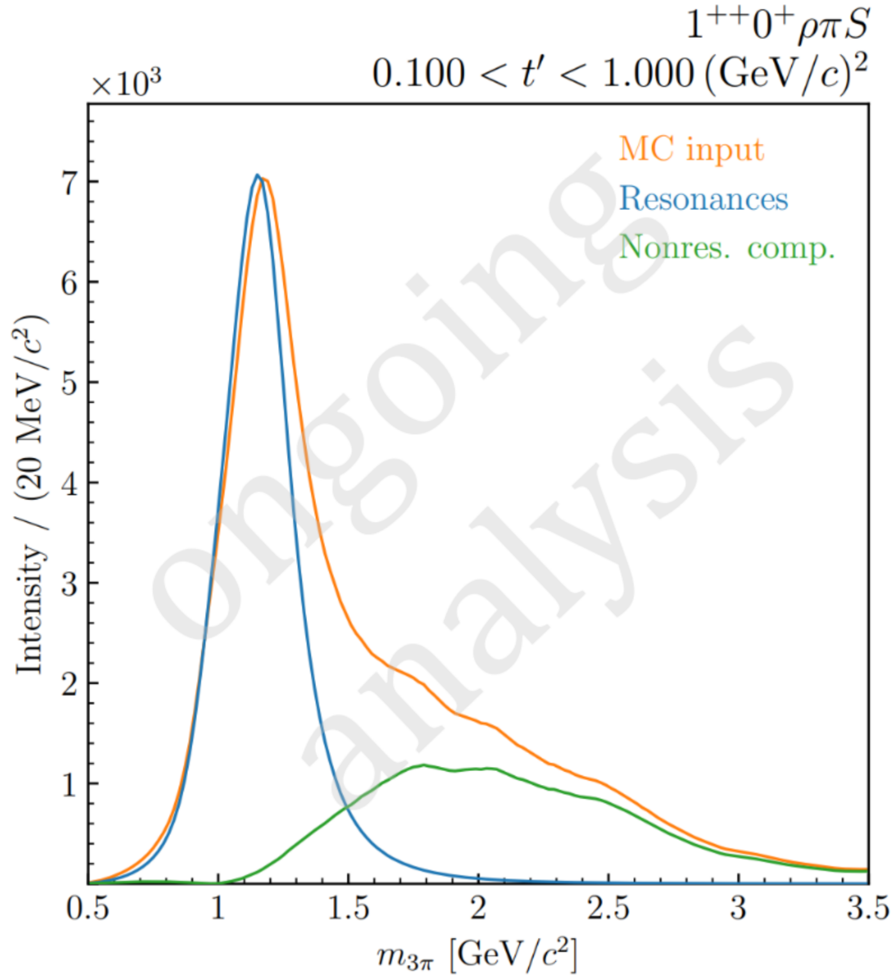


https://ift.pages.mpcdf.de/nifty/user/getting_started_0.html

This work is done in collaboration with Jakob Knollmueller (TUM / ORIGINS Excellence Cluster)

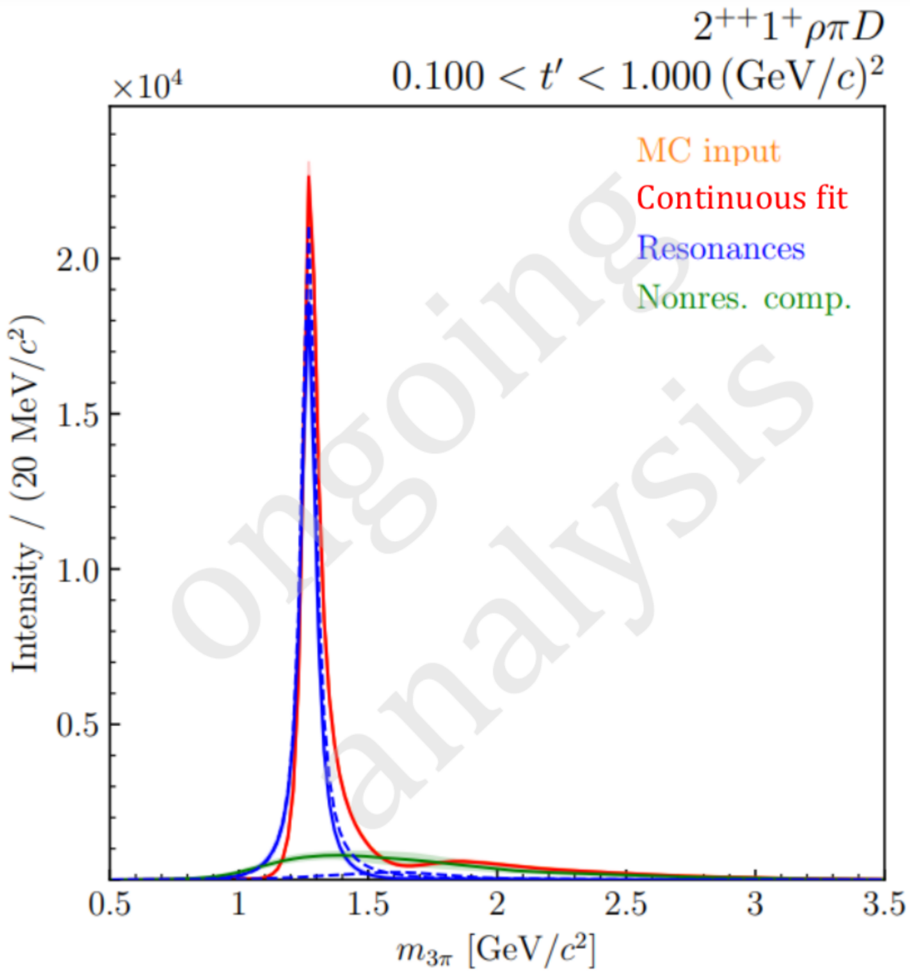


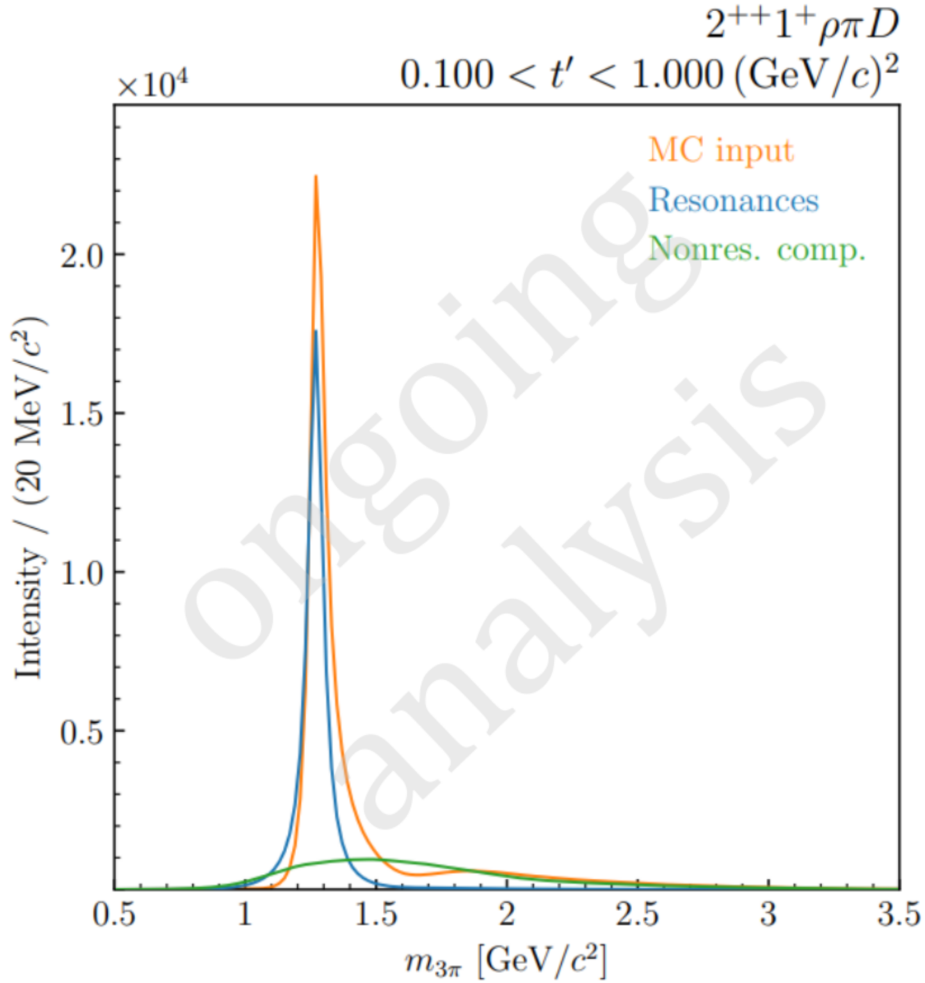
$1^{++}0^{+}\rho\pi S$
$0.100 < t' < 1.000\,(\mathrm{GeV}/c)^2$
$\times 10^3$
MC input
Model curve
Resonances
Nonres. comp.
ongoing analysis
Intensity / (20 MeV/c^2)
$m_{3\pi}$ [GeV/c^2]

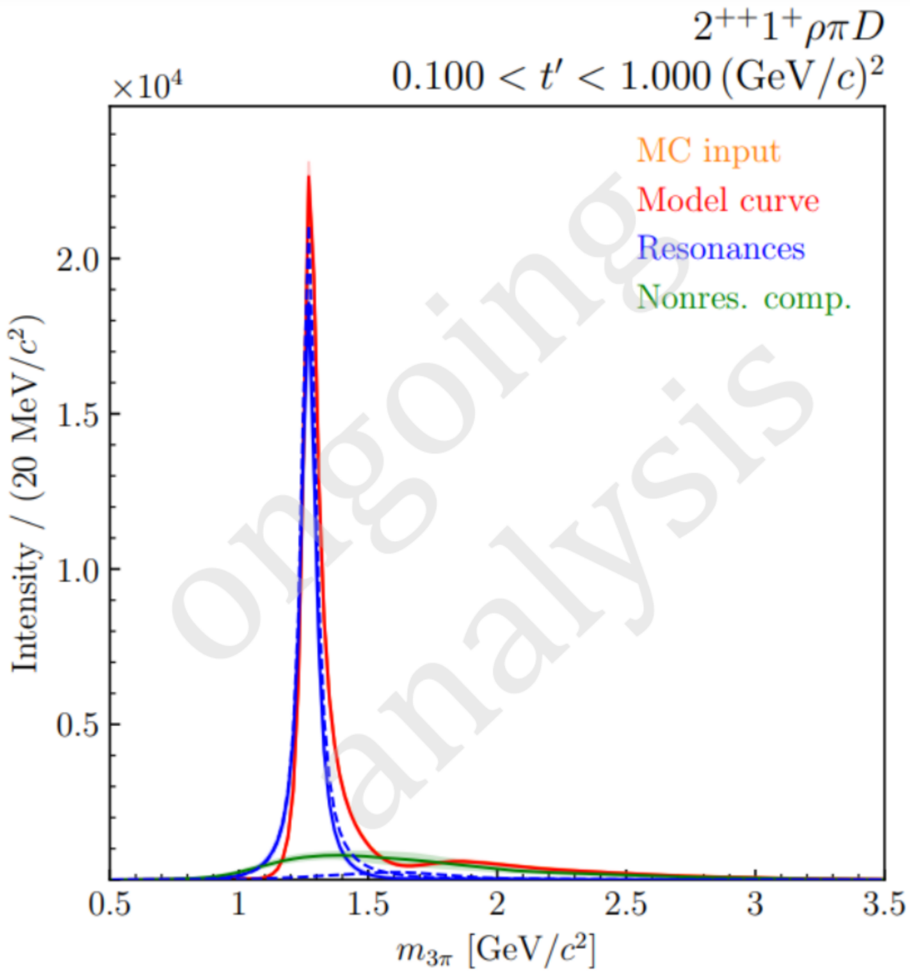


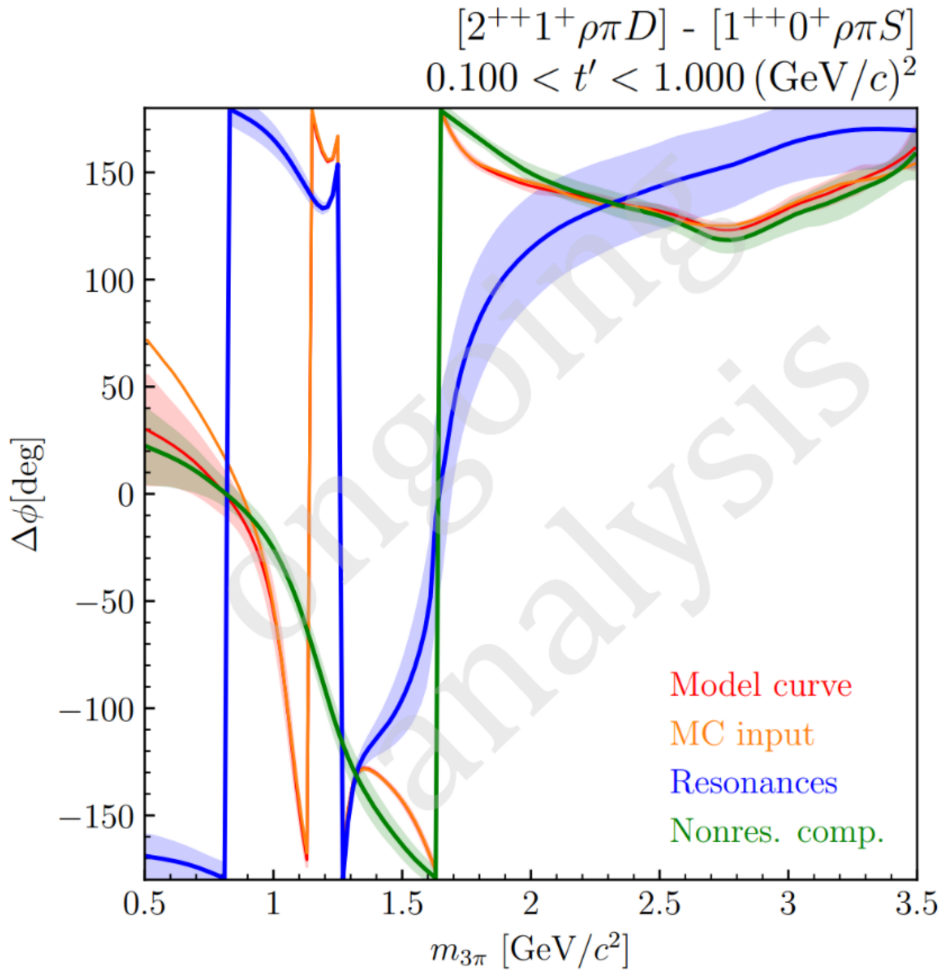
$1^{++}0^{+}\rho\pi S$
$0.100 < t' < 1.000\,(\mathrm{GeV}/c)^2$
$\times 10^3$
MC input
Resonances
Nonres. comp.
ongoing analysis
Intensity / (20 MeV/c^2)
$m_{3\pi}$ [GeV/c^2]

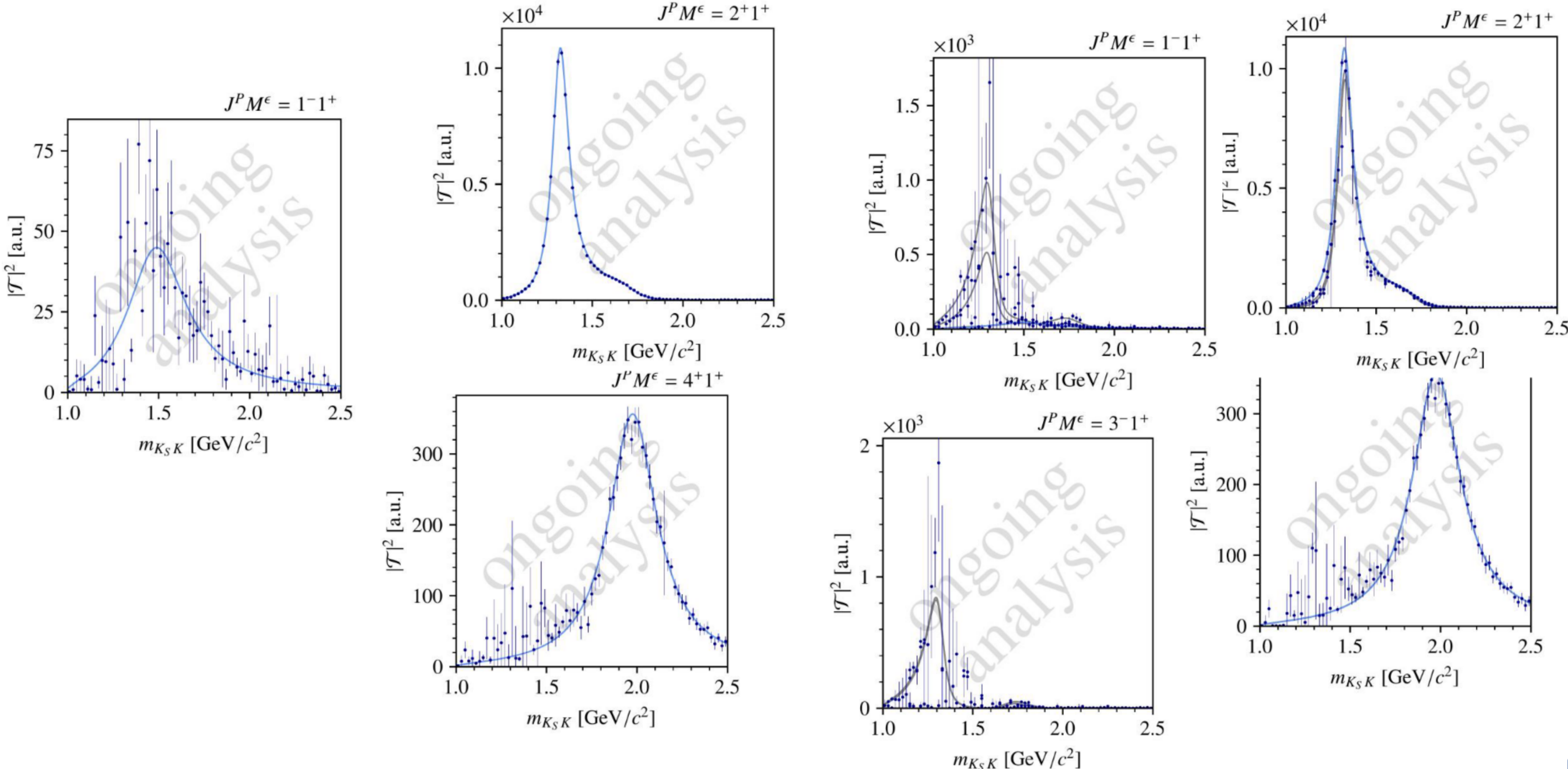
Input-Output Study






$2^{++}1^{+}\rho\pi D$
$0.100 < t' < 1.000\,(\mathrm{GeV}/c)^2$
$\times 10^4$
MC input
Model curve
Resonances
Nonres. comp.
Intensity / (20 MeV/c^2)
$m_{3\pi}$ [GeV/c^2]
ongoing analysis


$[2^{++}1^{+}\rho\pi D]$ - $[1^{++}0^{+}\rho\pi S]$
$0.100 < t' < 1.000\,(\mathrm{GeV}/c)^2$
$\Delta\phi$[deg]
Model curve
MC input
Resonances
Nonres. comp.
$m_{3\pi}$ [GeV/c^2]
ongoing analysis



$J^P M^\epsilon = 1^- 1^+$
$J^P M^\epsilon = 2^+ 1^+$
$J^P M^\epsilon = 4^+ 1^+$
$J^P M^\epsilon = 1^- 1^+$
$J^P M^\epsilon = 3^- 1^+$
$J^P M^\epsilon = 2^+ 1^+$
$\times 10^4$
$\times 10^3$
$|\mathcal{T}|^2$ [a.u.]
$m_{K_S K}$ [GeV/c^2]
ongoing analysis

Outlook: NIFTy on KsK- pseudodata