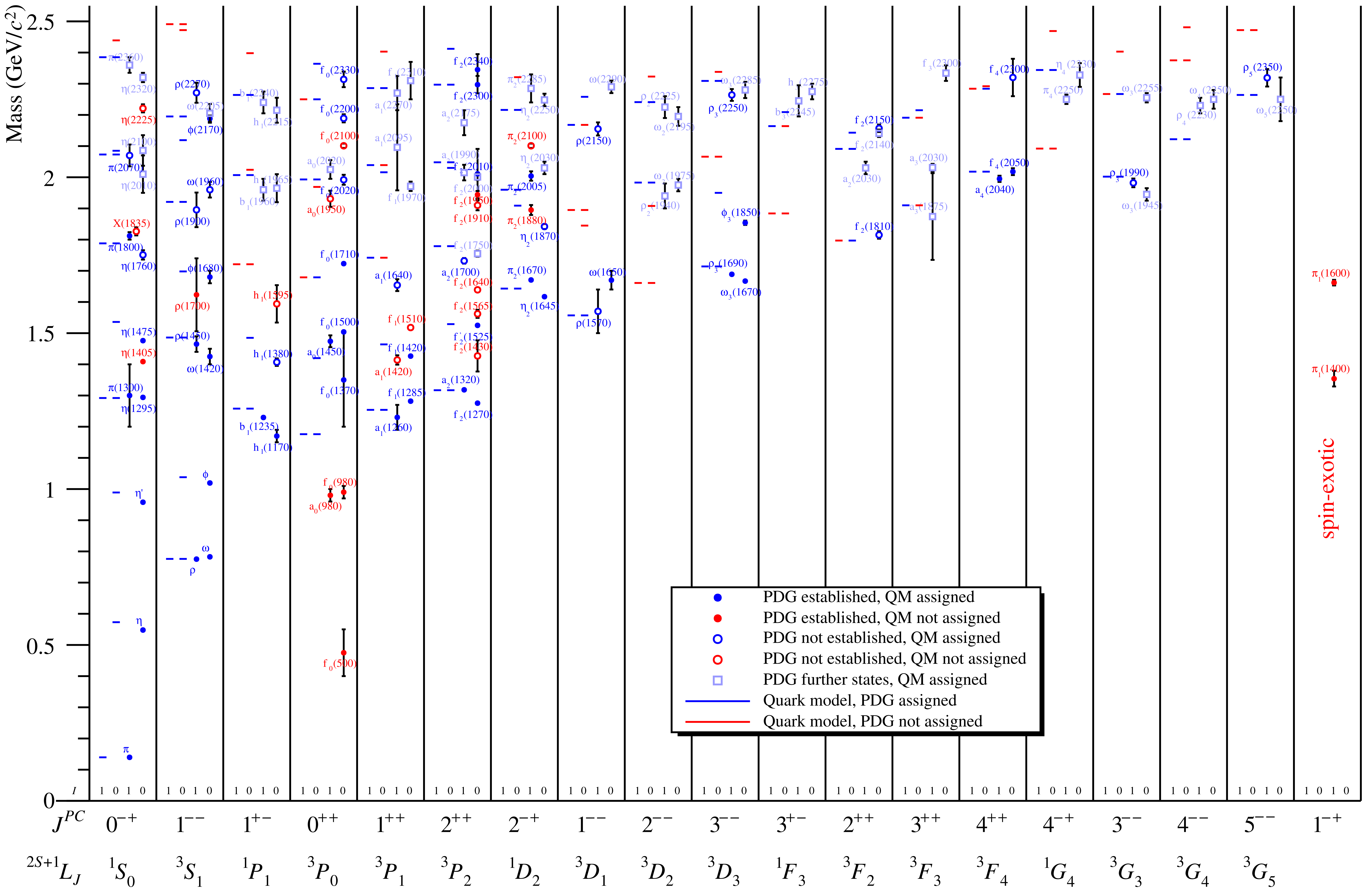
Light Meson Spectroscopy
COMPASS Legacy seen in 2022
-
Results and „the making of“

Stephan Paul
TU München/CERN

Hadron Spectrum - PDG Wisdom

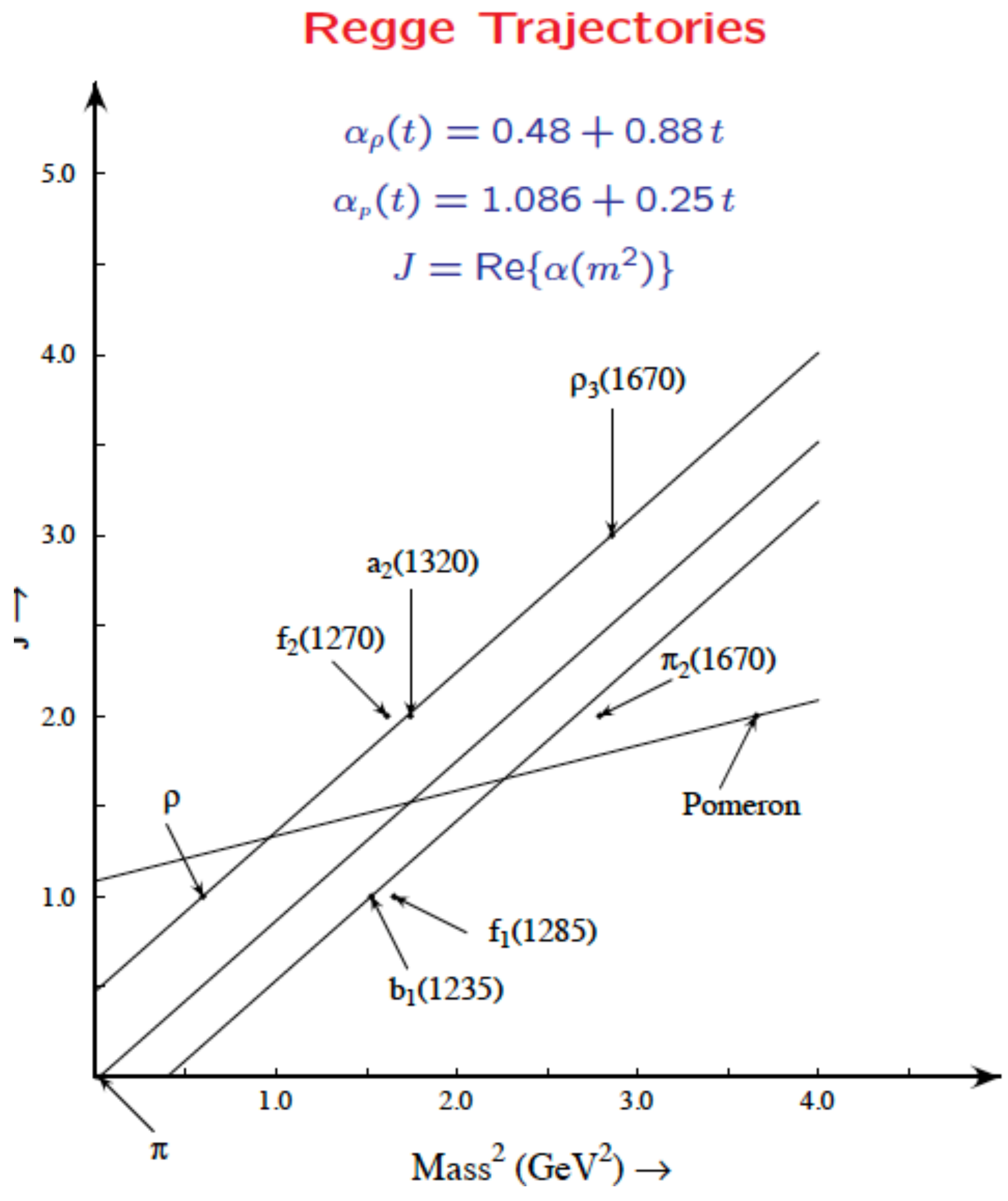
Exzellenzcluster ORIGINS

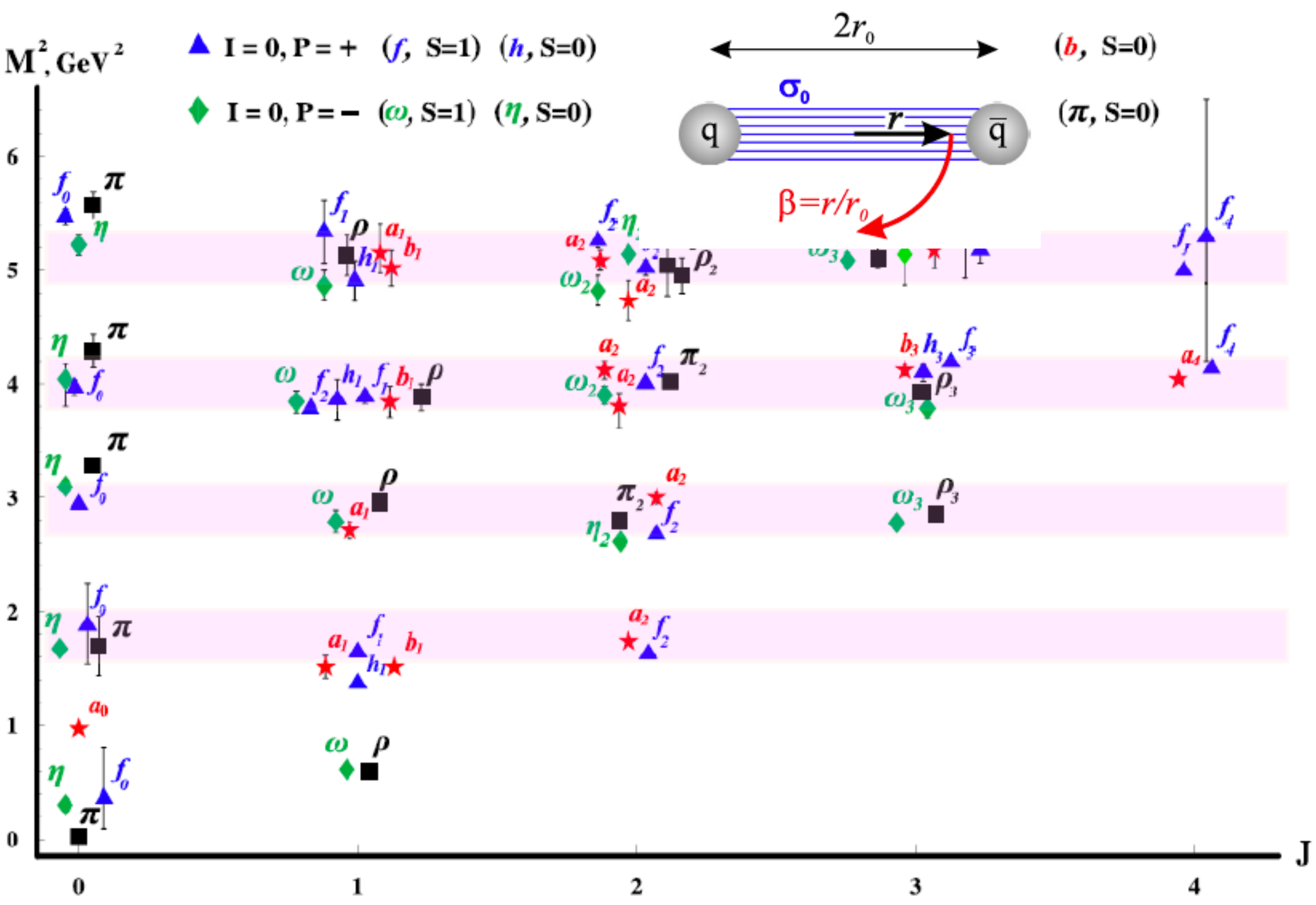


Theory Input: Systematics of Hadron Spectrum

Exzellenzcluster ORIGINS

- Regge picture relates spin J to M^2 - „simple“ mesonic (string) structure





Theory Input Quantitative

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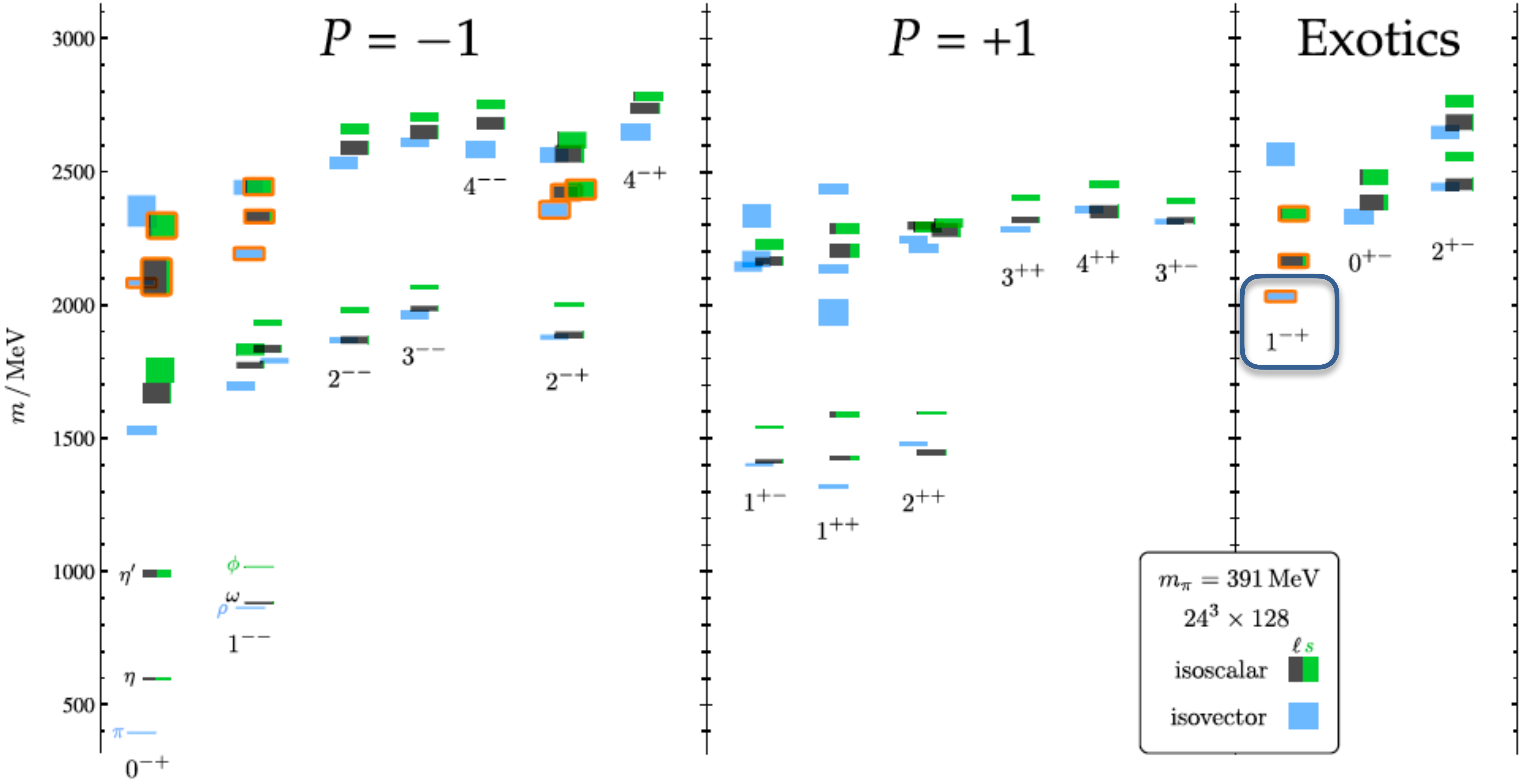
- lattice calculations give mass spectrum (also for exotics)
- future: lattice will give width and couplings



The Method

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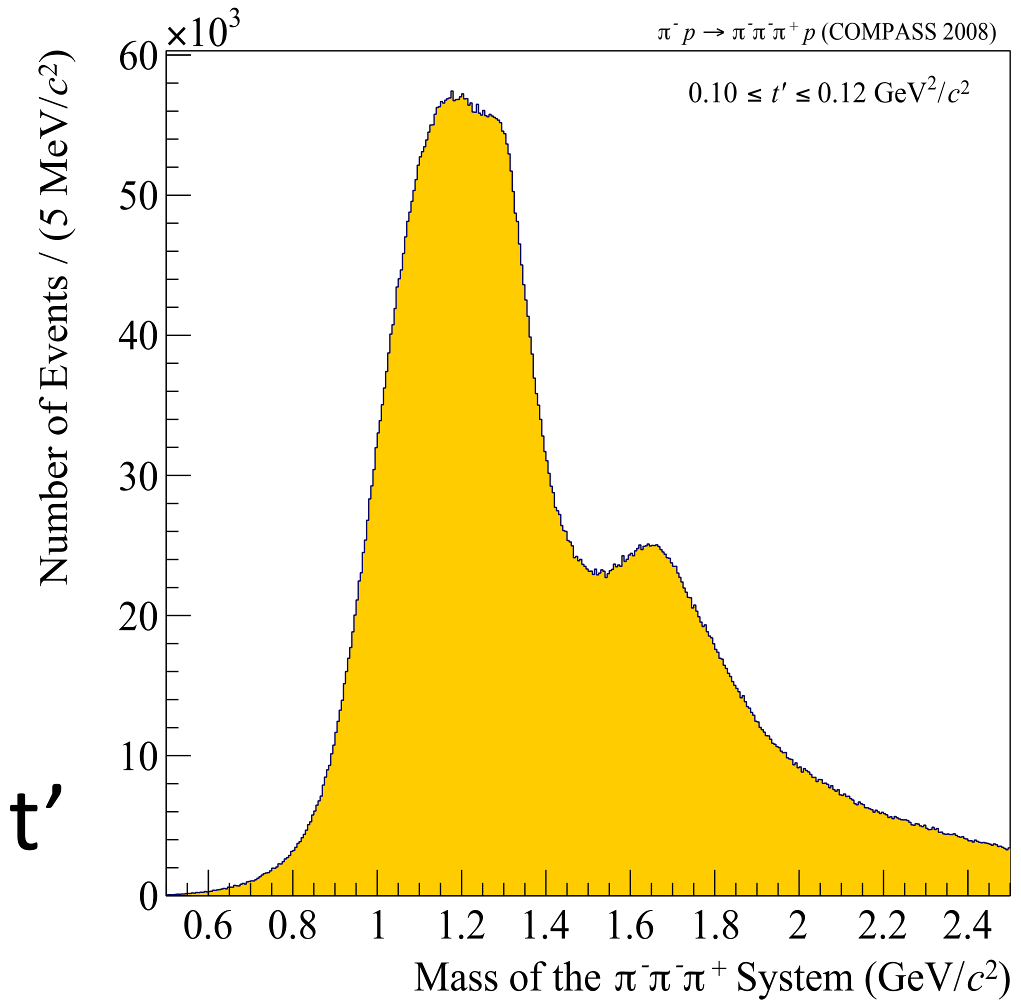
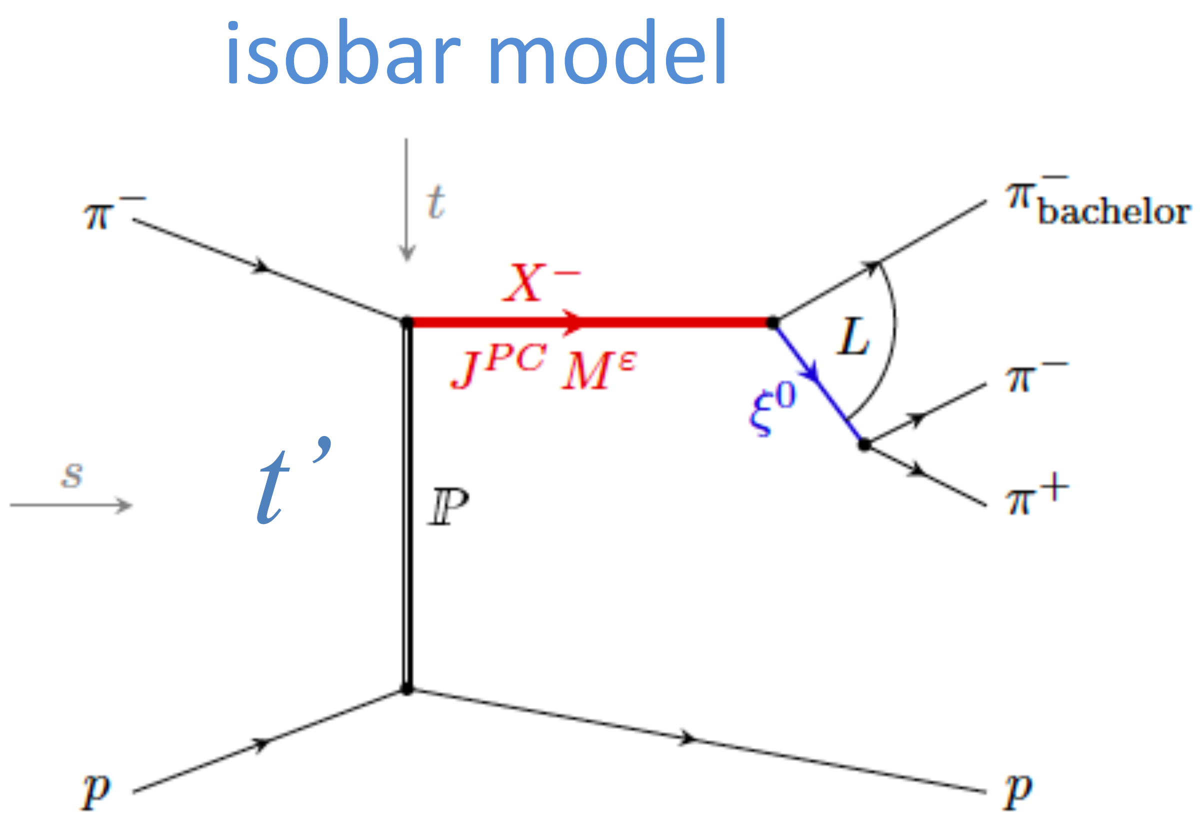
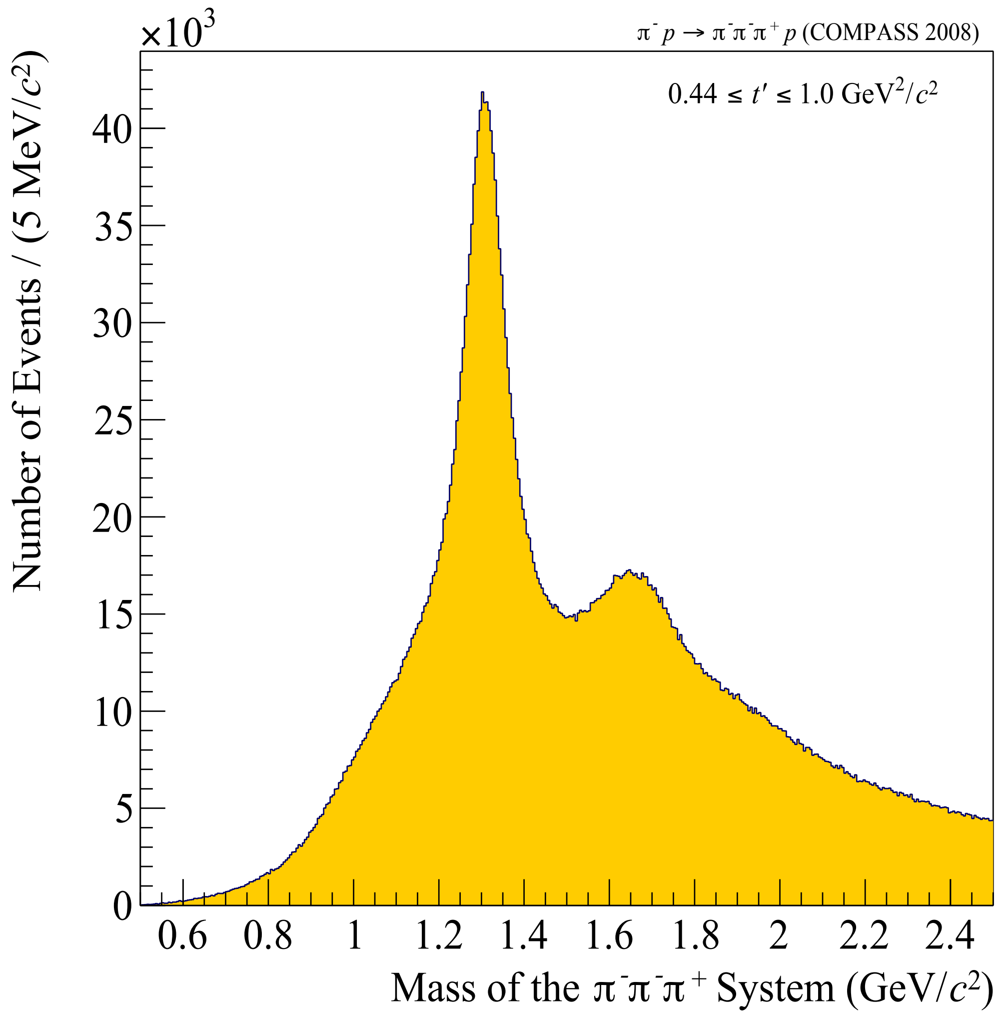
Study 3-body final state

- vary momentum transfer in reaction
  - ⇨ vary relative strength of various subprocesses/resonances
- 5-dimensional phase space

low t’



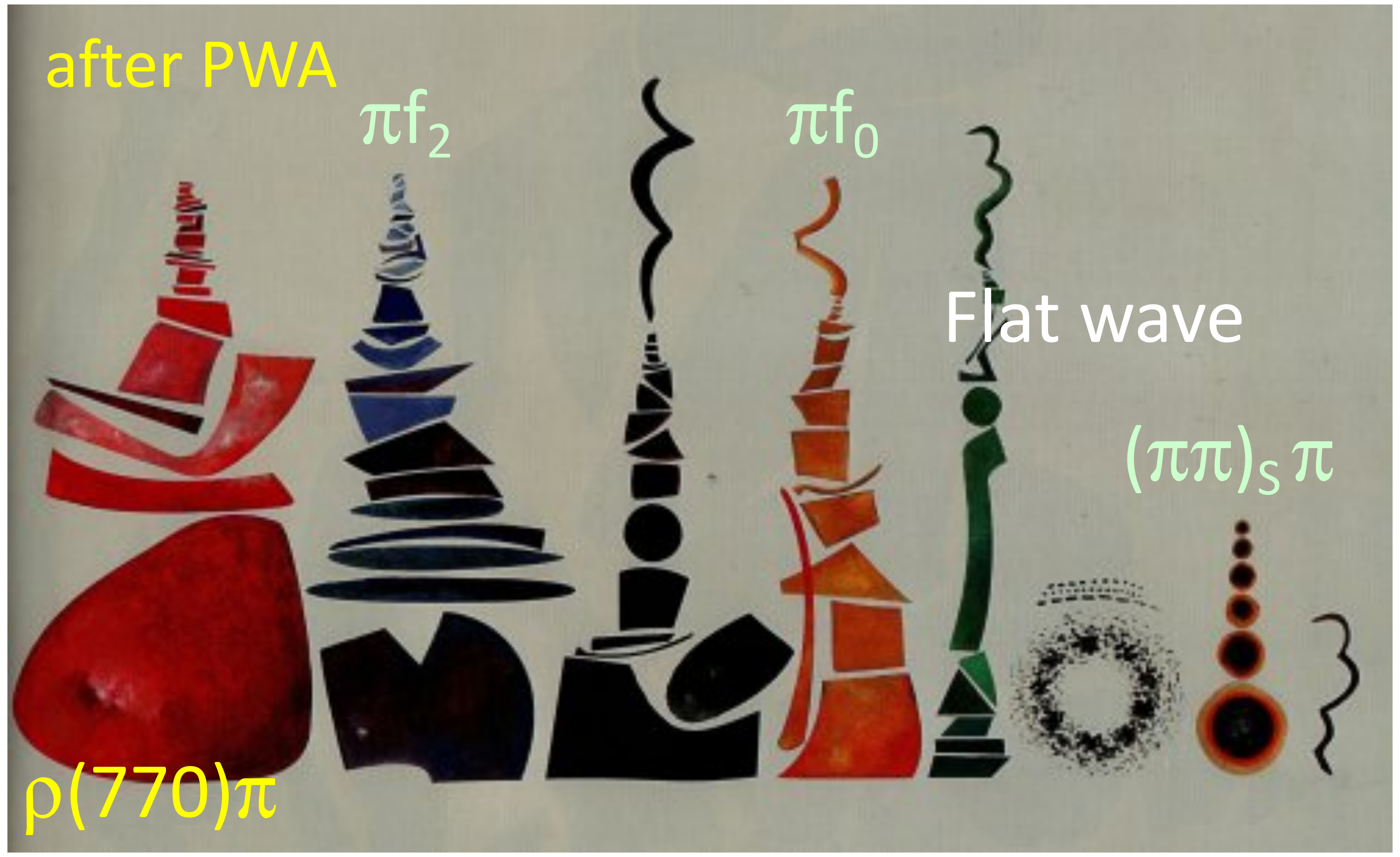




high t’

Partial Wave Analysis

inspired by M. Pennington



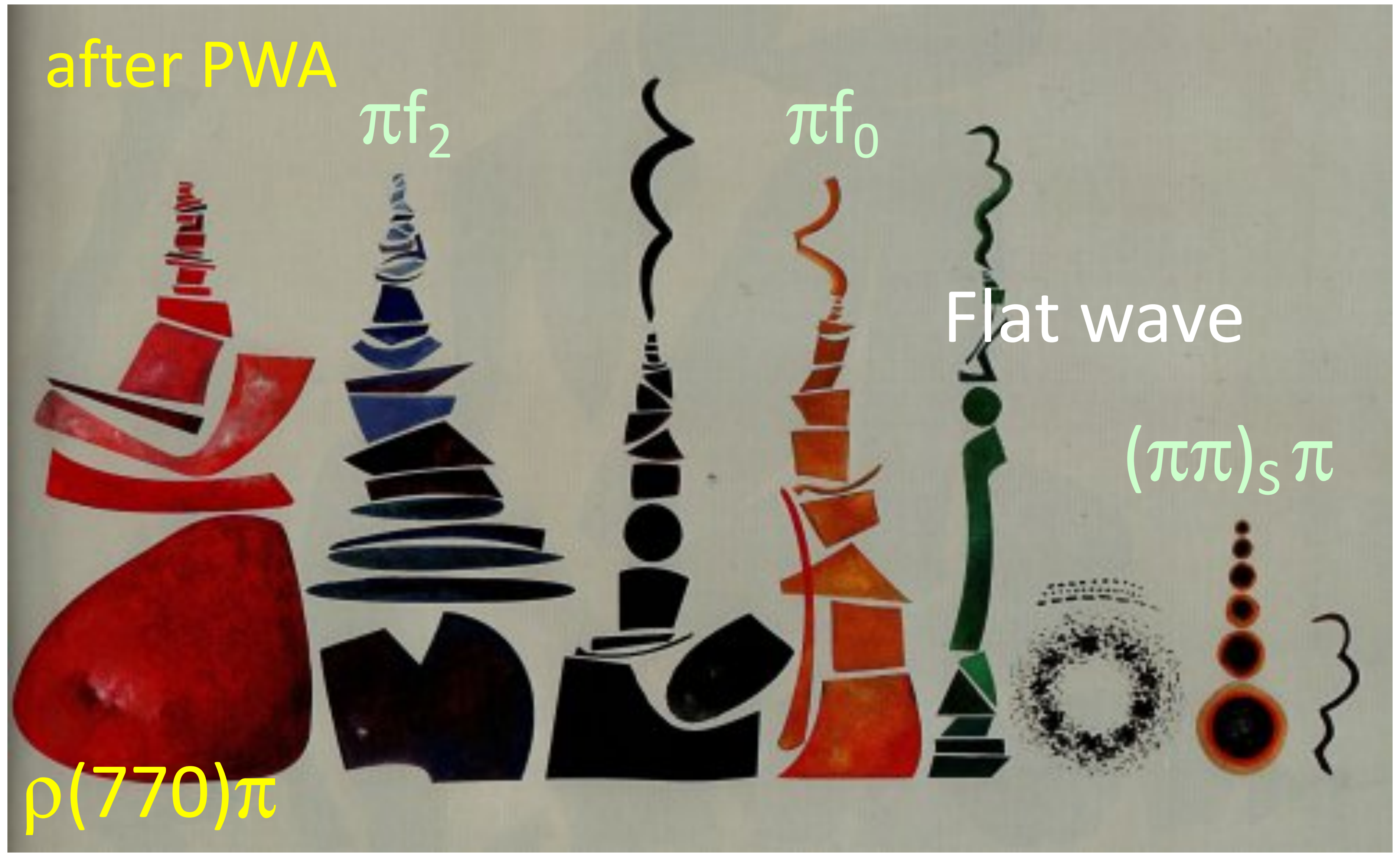
Art taken from Urs Wehrli: “Kunst aufgeräumt”

Partial Wave Analysis

Exzellenzcluster ORIGINS

Decomposition of a complex System (without interference)

inspired by M. Pennington



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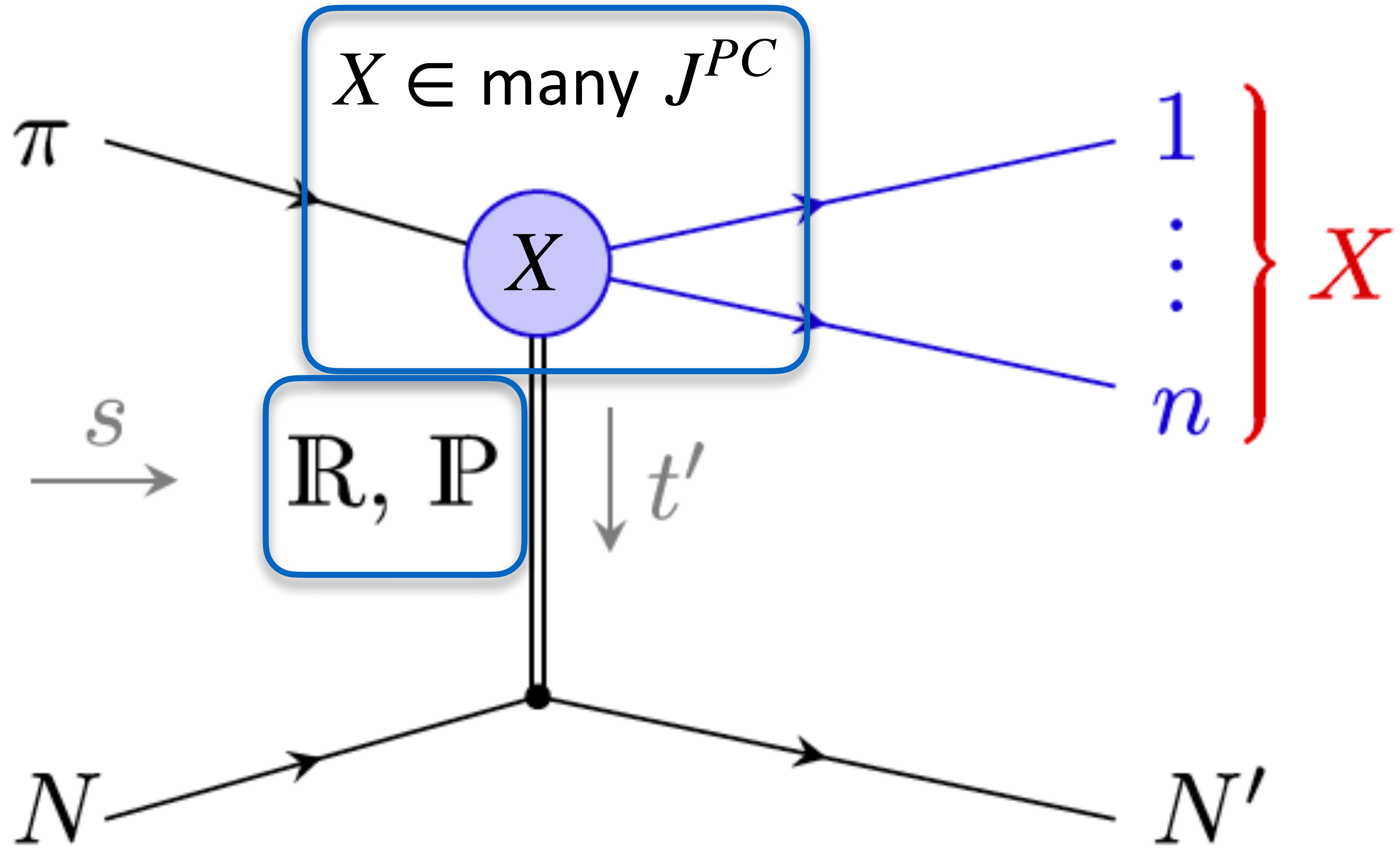
Partial Wave Analysis

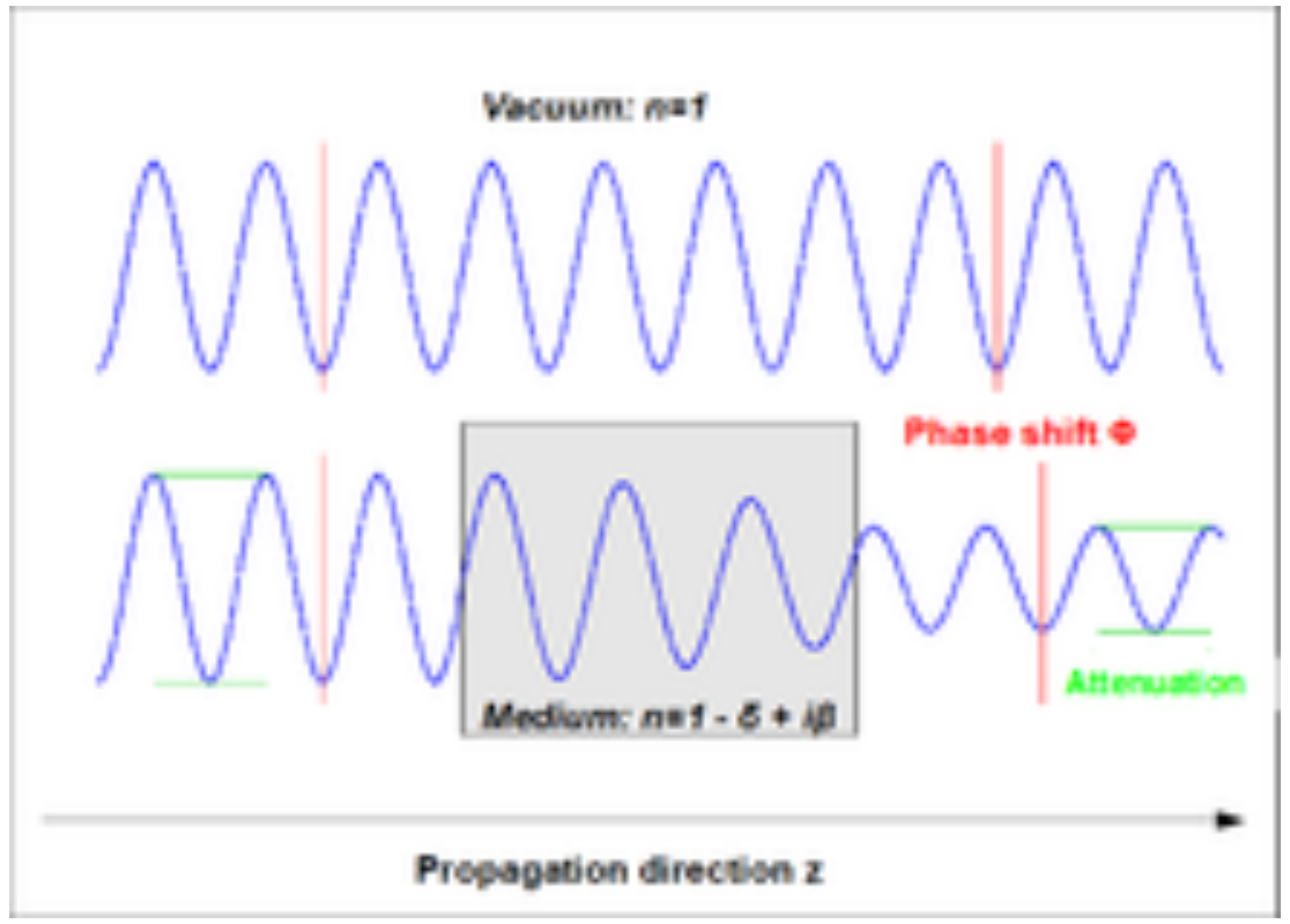
Decomposition of a complex System (without interference)

But: Quantum mechanics involves interference



Vertue of Interference - Phase contrast tomography

lline



$n=1-\delta+i\beta$

X-rays

Bright field microscopy
maps distribution of imaginary part of refractive index

Peak hunting

Phase contrast microscopy
maps distribution of complex refractive index modulation using interference effects

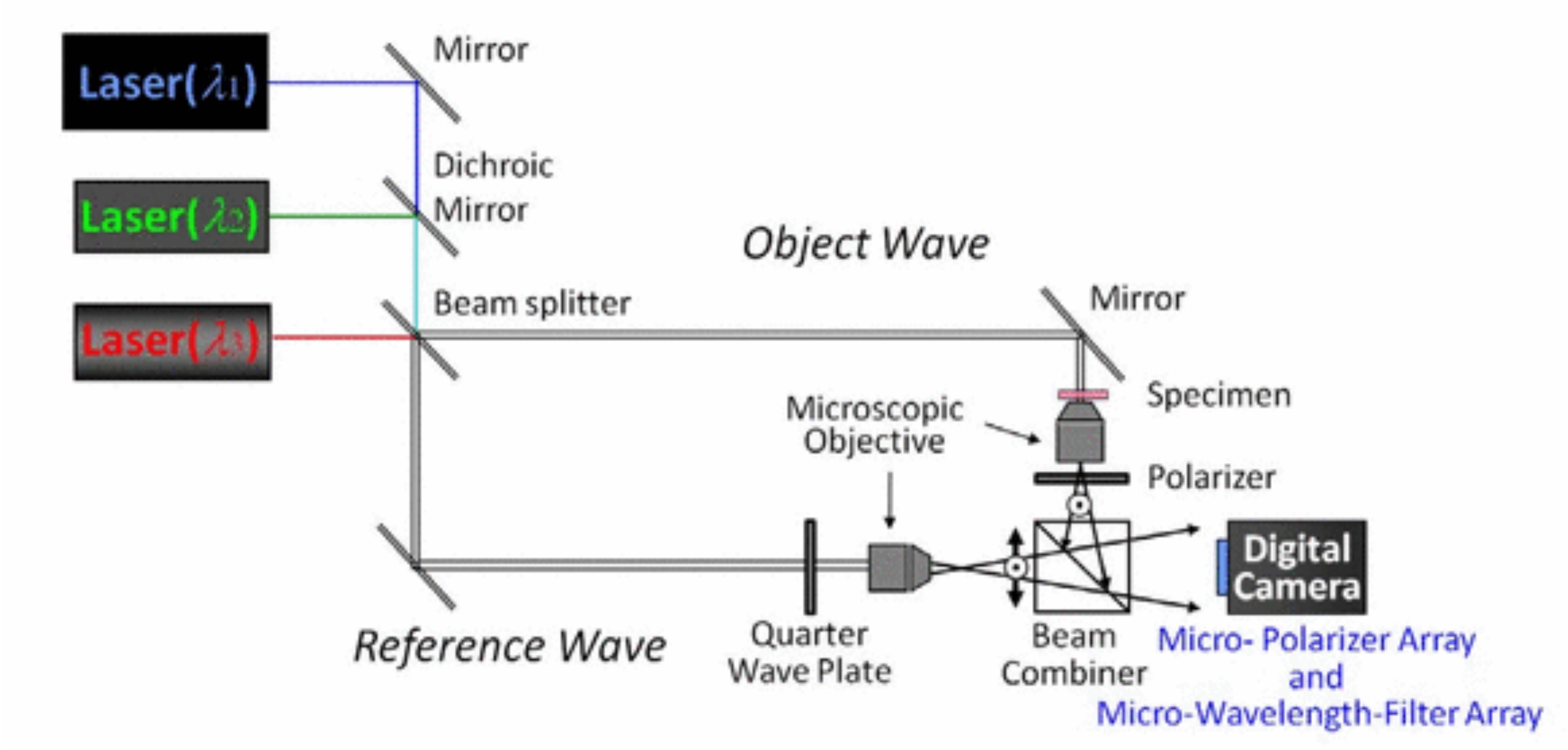
Dalitz plot analysis

Add more dynamics

Optical methods:

If you have enough lasers.. you can add color to your phase shift holography

- solves sign of phase shift ambiguities
- useful for recording dynamic processes



Compass: Combine results at different t’

Partial Wave Analysis

Exzellenzcluster ORIGINS

What is PWA ?

step 1

Describe population in 5-dimensional phase space in $\pi\pi\pi$ by model

- Define a set of quantum numbers J^{PC}
- Define a set of possible decay channels for each J^{PC}

  ($X^- \rightarrow$ isobar + π; isobar$\rightarrow\pi\pi$) : wave (88 waves used)

  - each such "wave" has a pre-determined population in phase space
  - each wave may have alignment of *J* described by quantum number M
- For each bin of 20 MeV/c² mass of $\pi\pi\pi$: determine which coherent combination of waves fits distribution best
- Obtain spin-density matrix

step 2

Partial Wave Analysis

Exzellenzcluster ORIGINS

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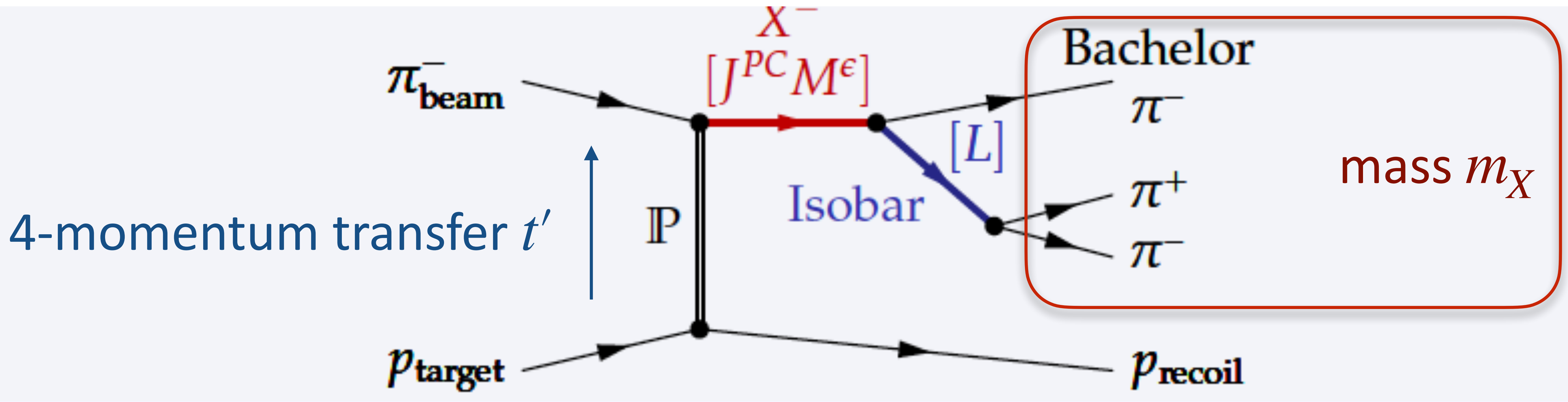
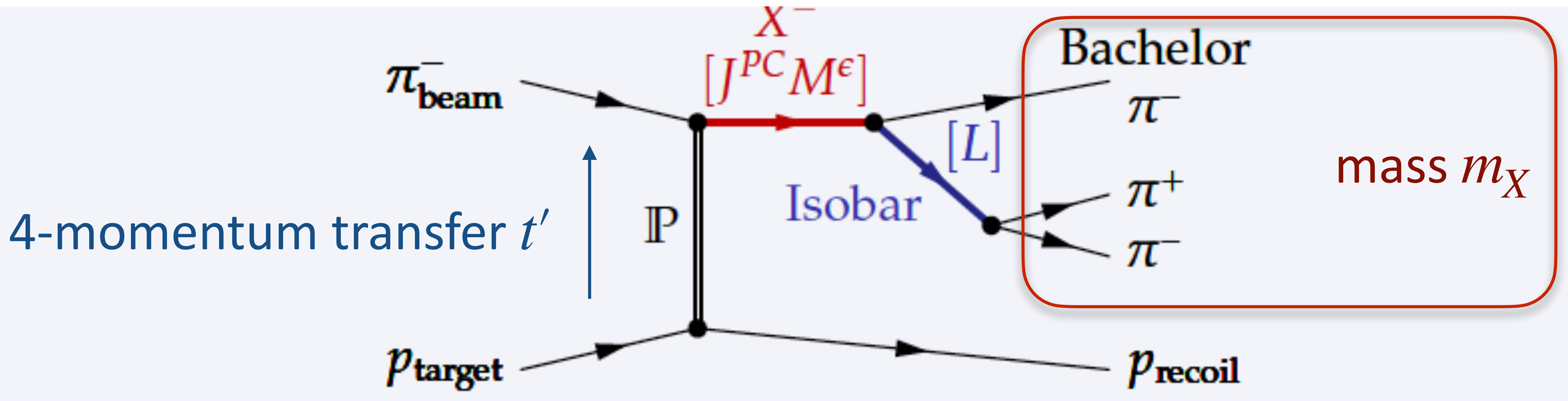
Mass independent fit



Mass independent fit

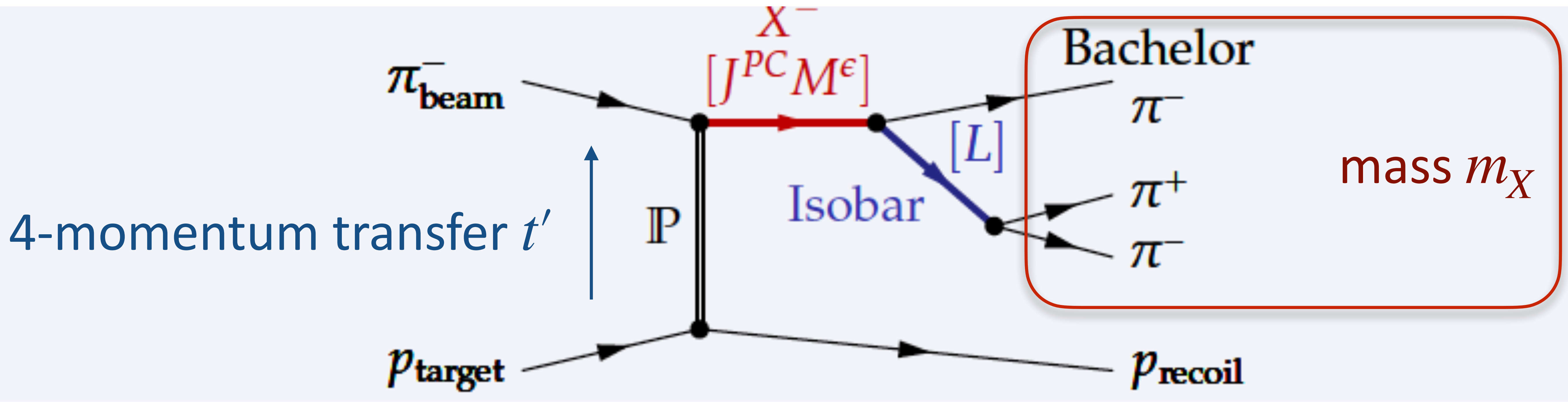


Consider isobar model: Intensity is constructed from coherent sums known (model) amplitudes

$$\mathcal{I}(\tau_n; m_X, t') = \left| \sum_i^{N_{\text{waves}}} \mathcal{T}_i^{r\varepsilon}(m_X, t')\, \Psi_i^\varepsilon(\tau_n; m_X) \right|^2 + |\mathcal{T}_{\text{flat}}(m_X, t')|^2$$

$$= \sum_{\varepsilon=\pm 1} \sum_{i,j}^{N_{\text{waves}}} \overline{\Psi}_i^\varepsilon(\tau_n; m_X)\, \overline{\varrho}_{ij}^\varepsilon(m_X, t')\, \overline{\Psi}_j^{\varepsilon*}(\tau_n; m_X) + |\overline{\mathcal{T}}_{\text{flat}}(m_X, t')|^2$$

Mass independent fit



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incoherent sectors in data sample

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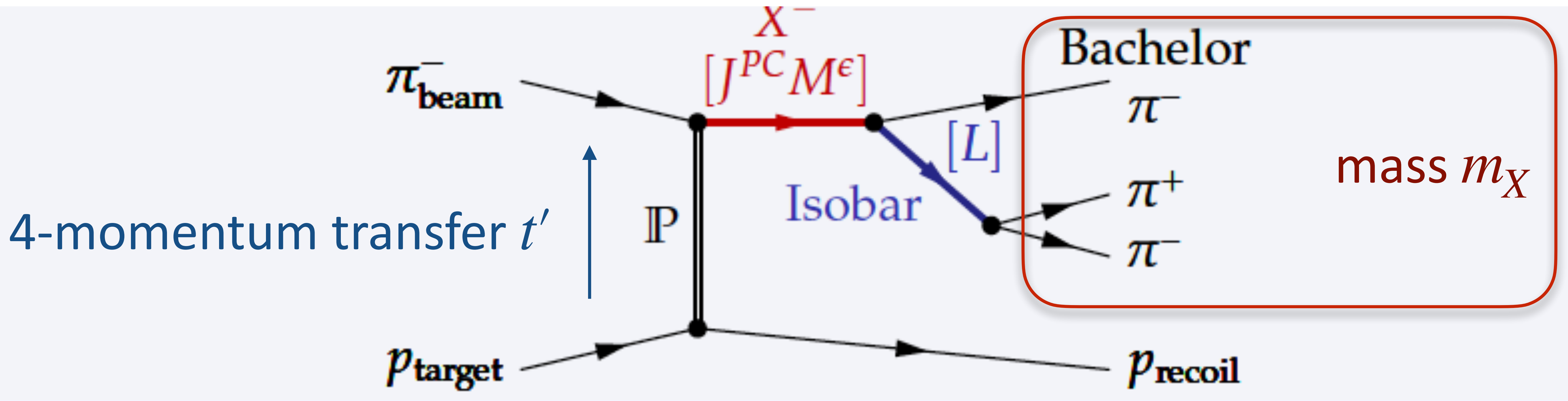

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incoherent production processes

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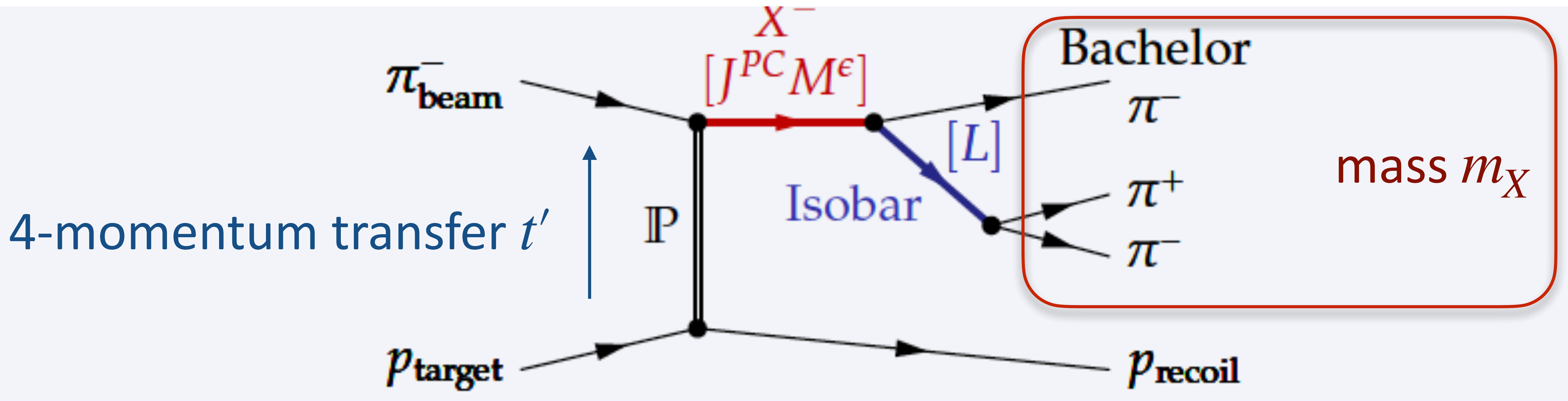
Mass independent fit



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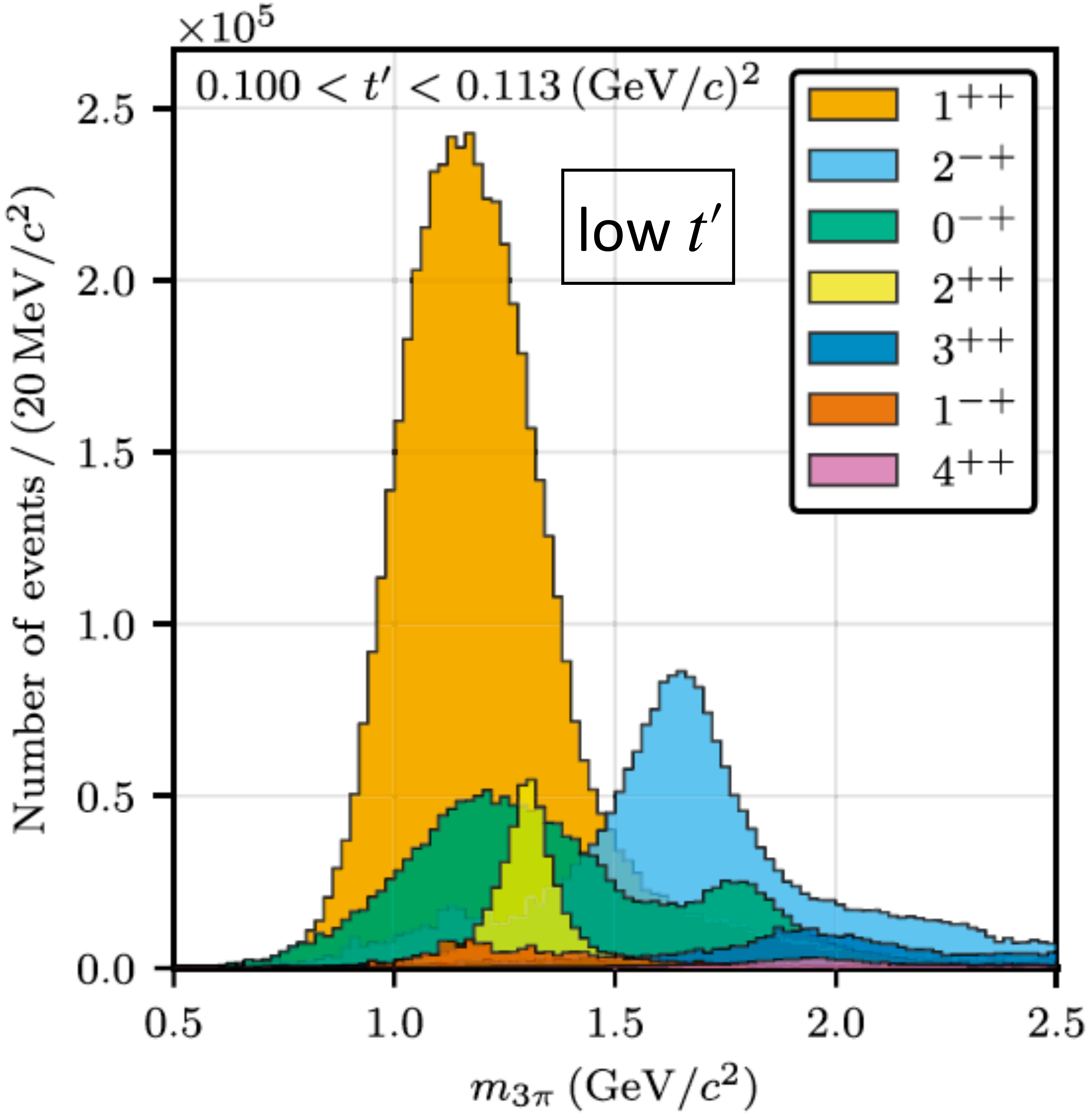
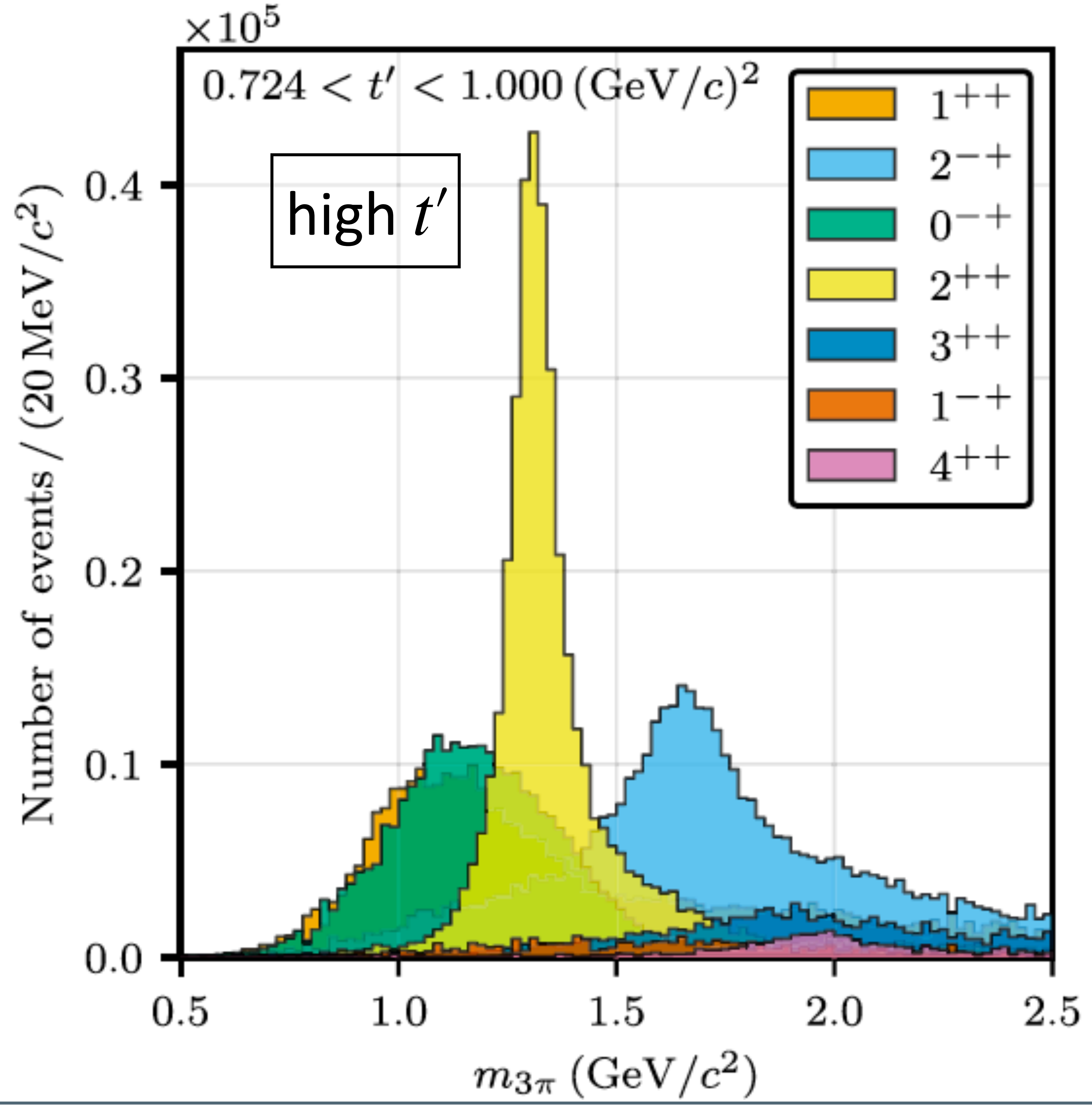
fit result

PWA Result („spin totals“)

Decomposition of the mass spectrum in terms of J^{PC}





Legacy Plots

Partial wave analysis

Exzellenzcluster ORIGINS

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- For each bin of 20 MeV/c² mass of $\pi\pi\pi$: determine which coherent combination of waves fits distribution best
- Obtain spin-density matrix

step 2

- Describe spin density matrix (submatrix) by model containing resonances and non-resonant contributions connecting all mass bins
- Determine resonance parameters

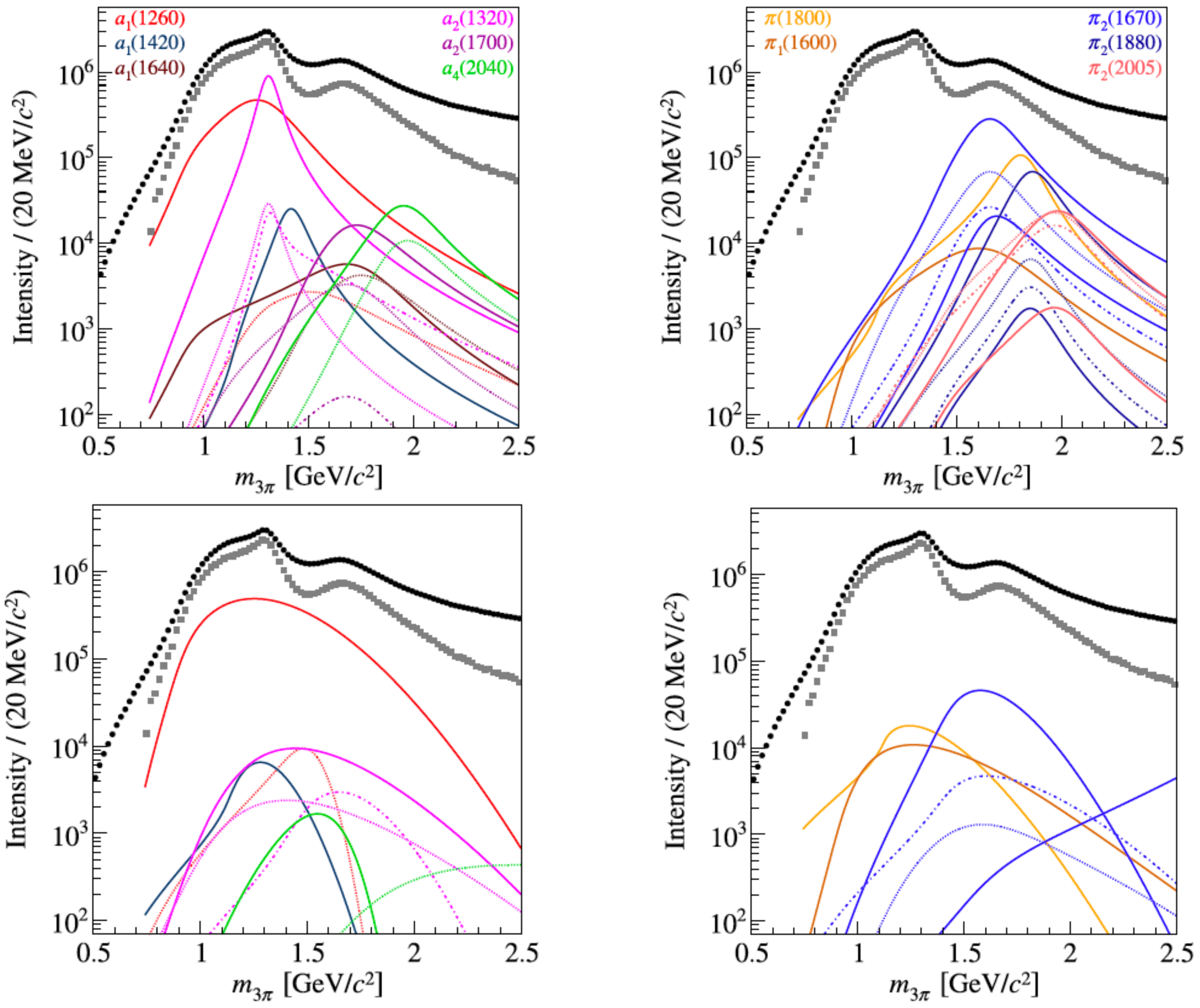
PWA Result „individual (interfering) Components“

Extraction of individual resonances

- several resonances with same J^{PC}
- several resonances per wave
- with same $([\pi\pi]_{JPC}\ \pi)_L$

and non-resonant contributions

- one per wave $([\pi\pi]_{JPC}\ \pi)_L$

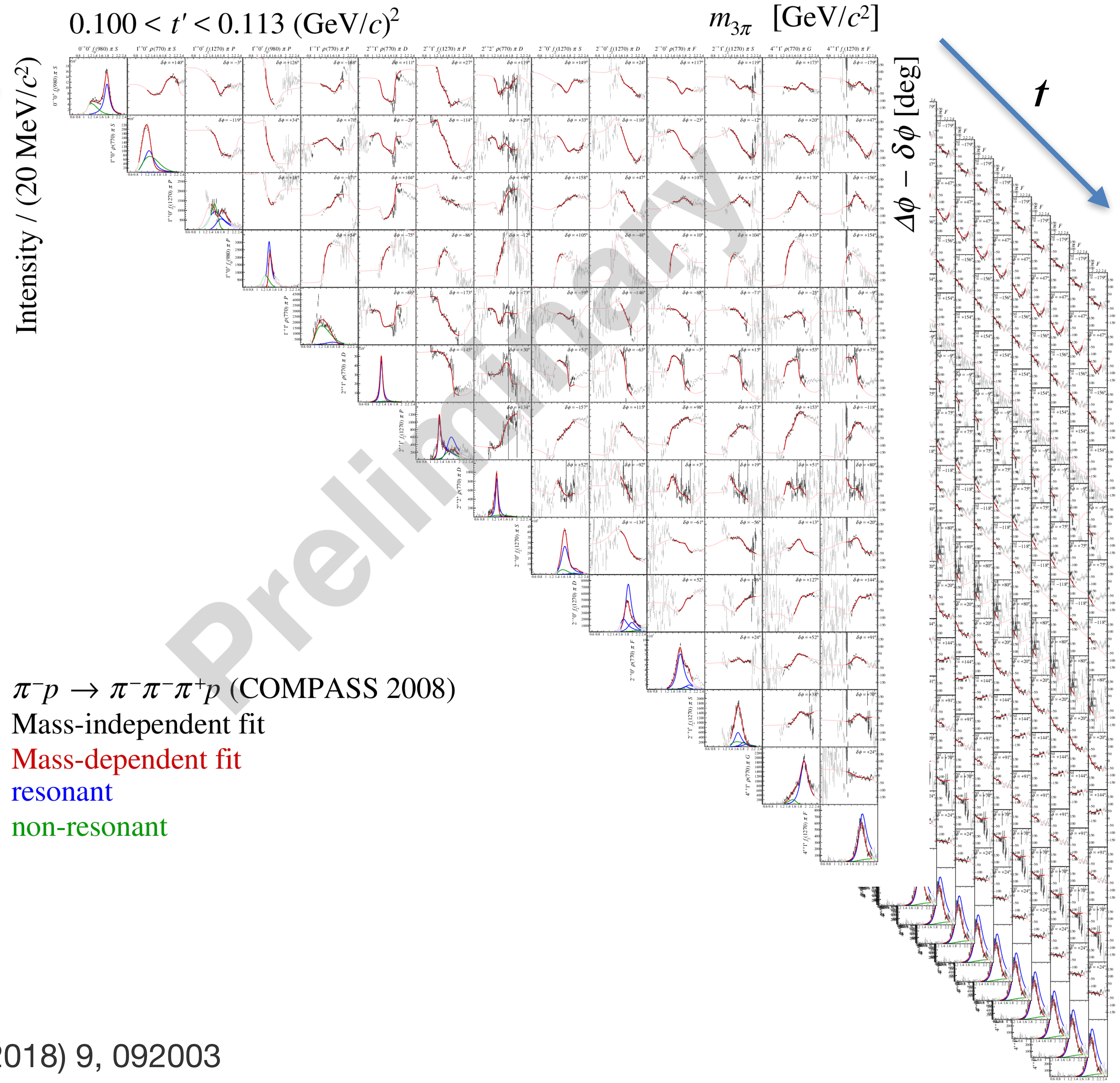


Find the Resonances (legacy slide)

The spin density matrix

plot intensities (diagonal) and phases

Reference wave



11 matrices (11 bins of t')

use only 14/88 waves in fit

fix t-dependence for same resonances

COMPASS *Phys.Rev.D* 95 (2017) 3, 032004 COMPASS *Phys.Rev.D* 98 (2018) 9, 092003

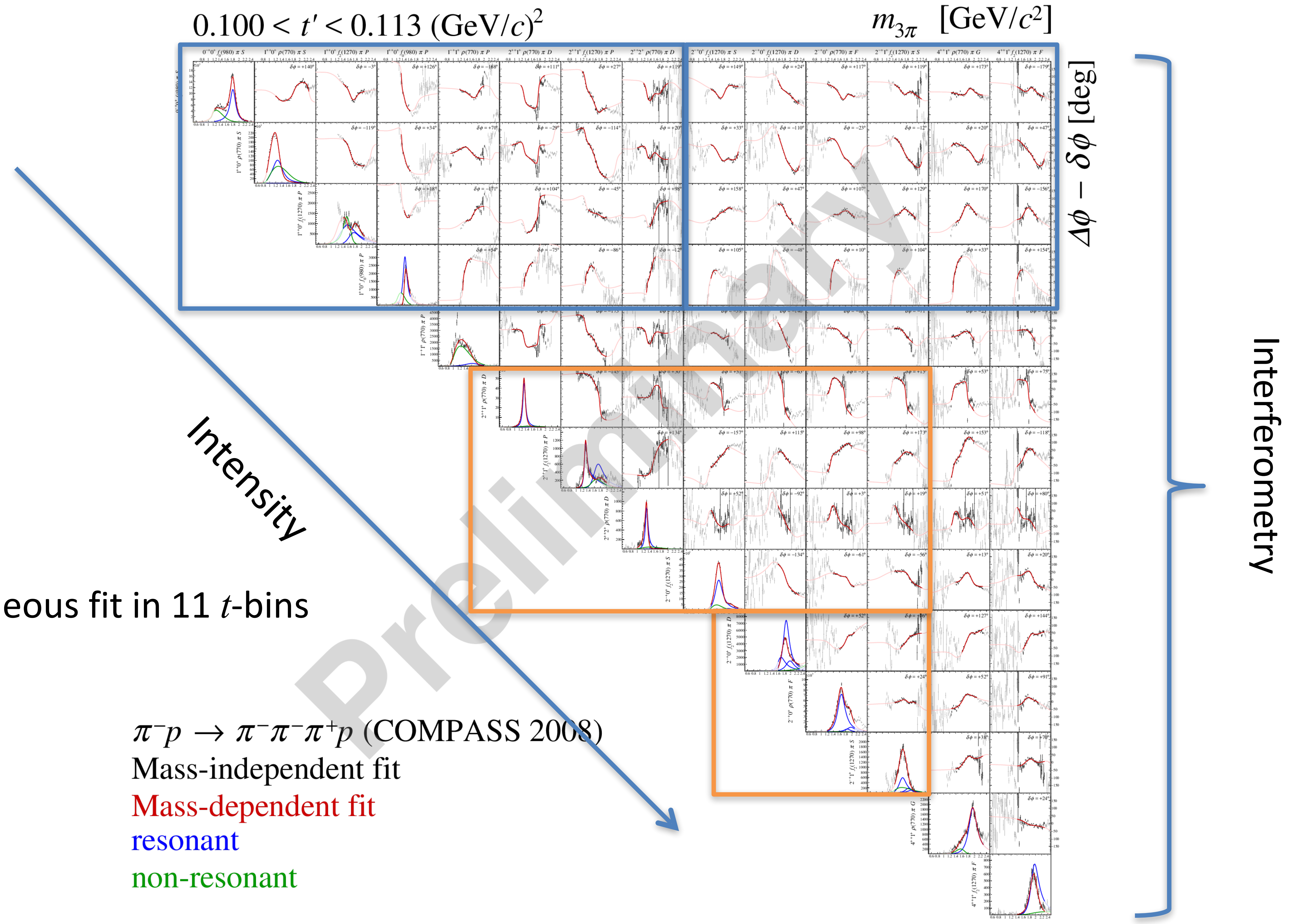
Find the Resonances (legacy slide)

Exzellenzcluster ORIGINS

11 matrices

use 14/88 waves in fit

simultaneous fit in 11 t-bins



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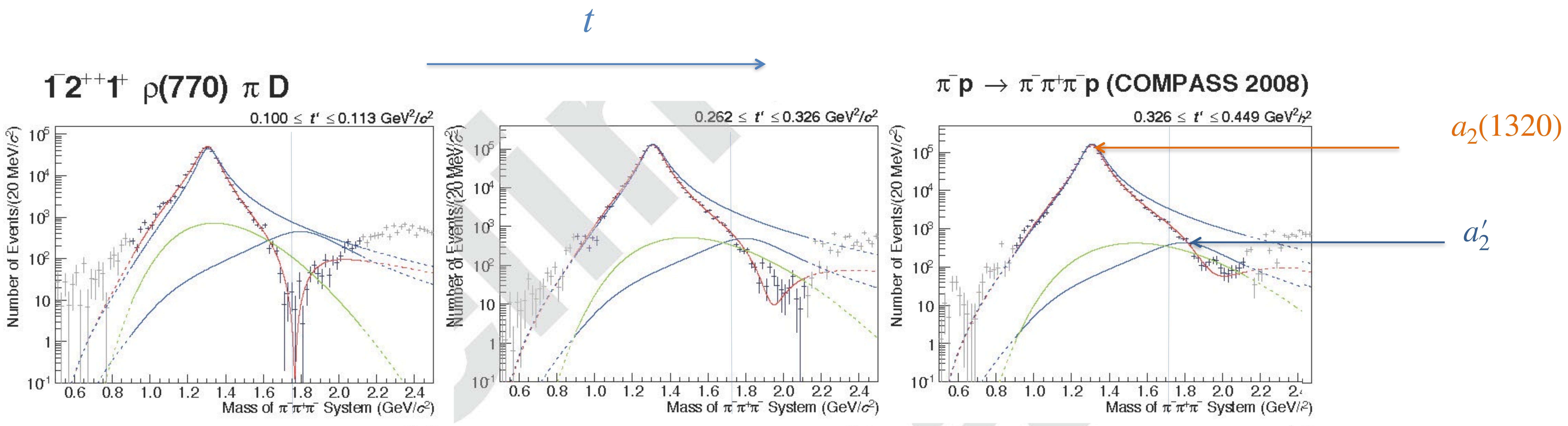
Standard Mesons

Interference - Classical Physics Mirrored in Spectroscopy

Mass dependent fits $a_2(1320)$

$2^{++}1^{+}\rho\,\pi\,D$

$J^{PC}M^{\varepsilon}[isobar]\pi L$



Strongly t-dependent interference effects reveals high-mass a_2'

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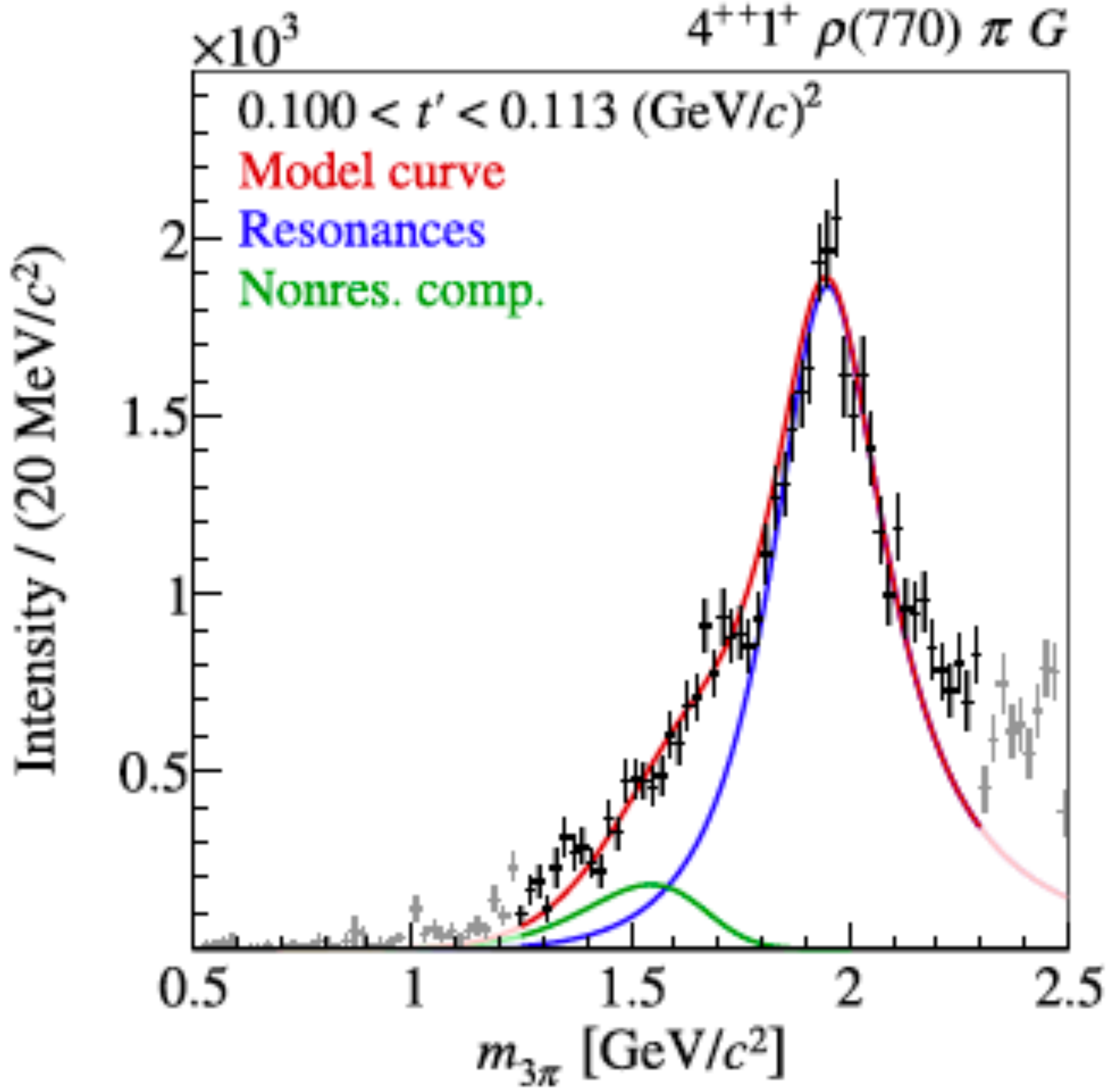
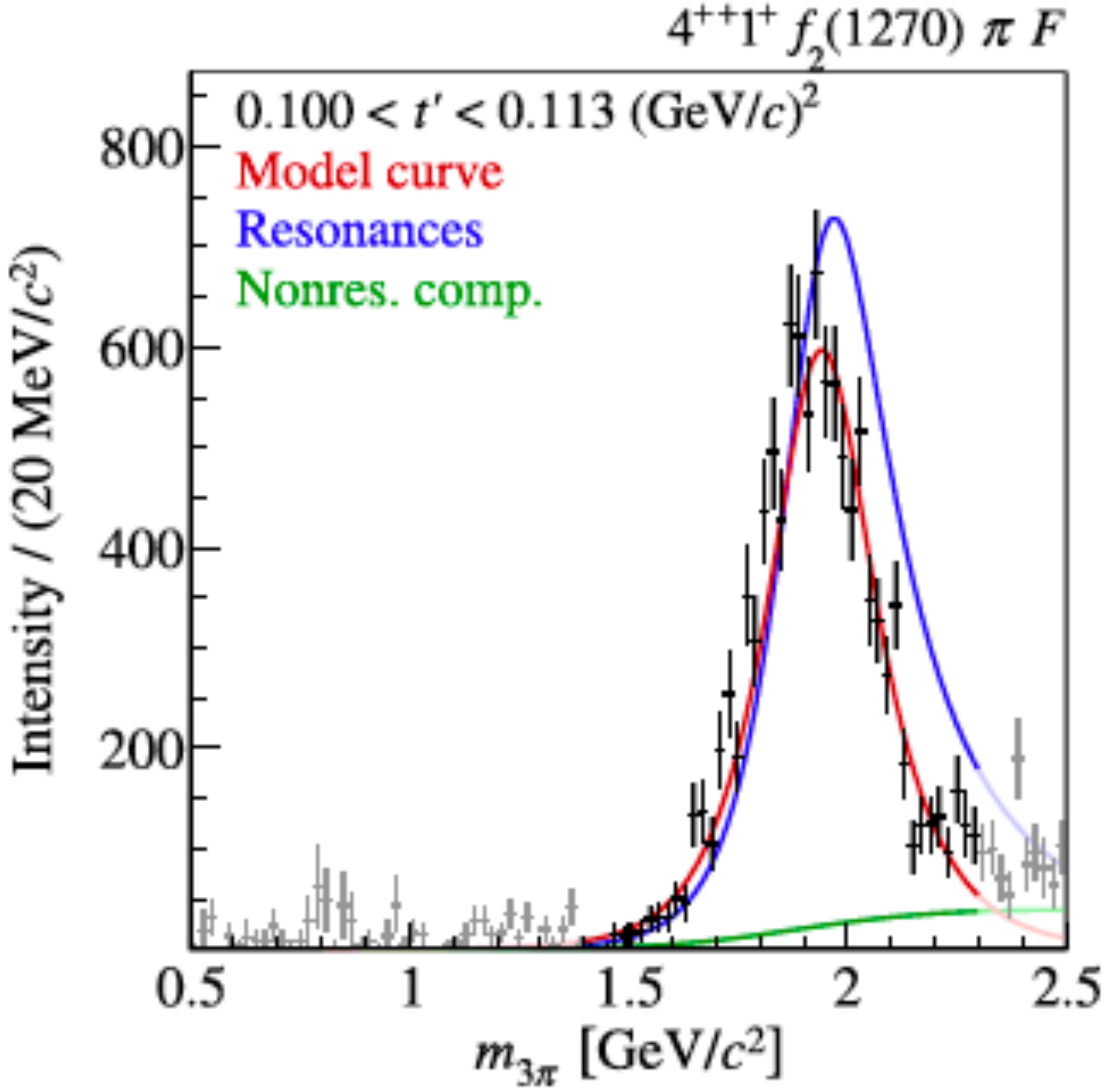
Standard Mesons - COMPASS

Exzellenzcluster ORIGINS

Example: $a_4(1970)$ previously known as $a_4(2040)$





COMPASS *Phys.Rev.D* 98 (2018) 9, 092003

Standard Mesons - COMPASS and the Rest

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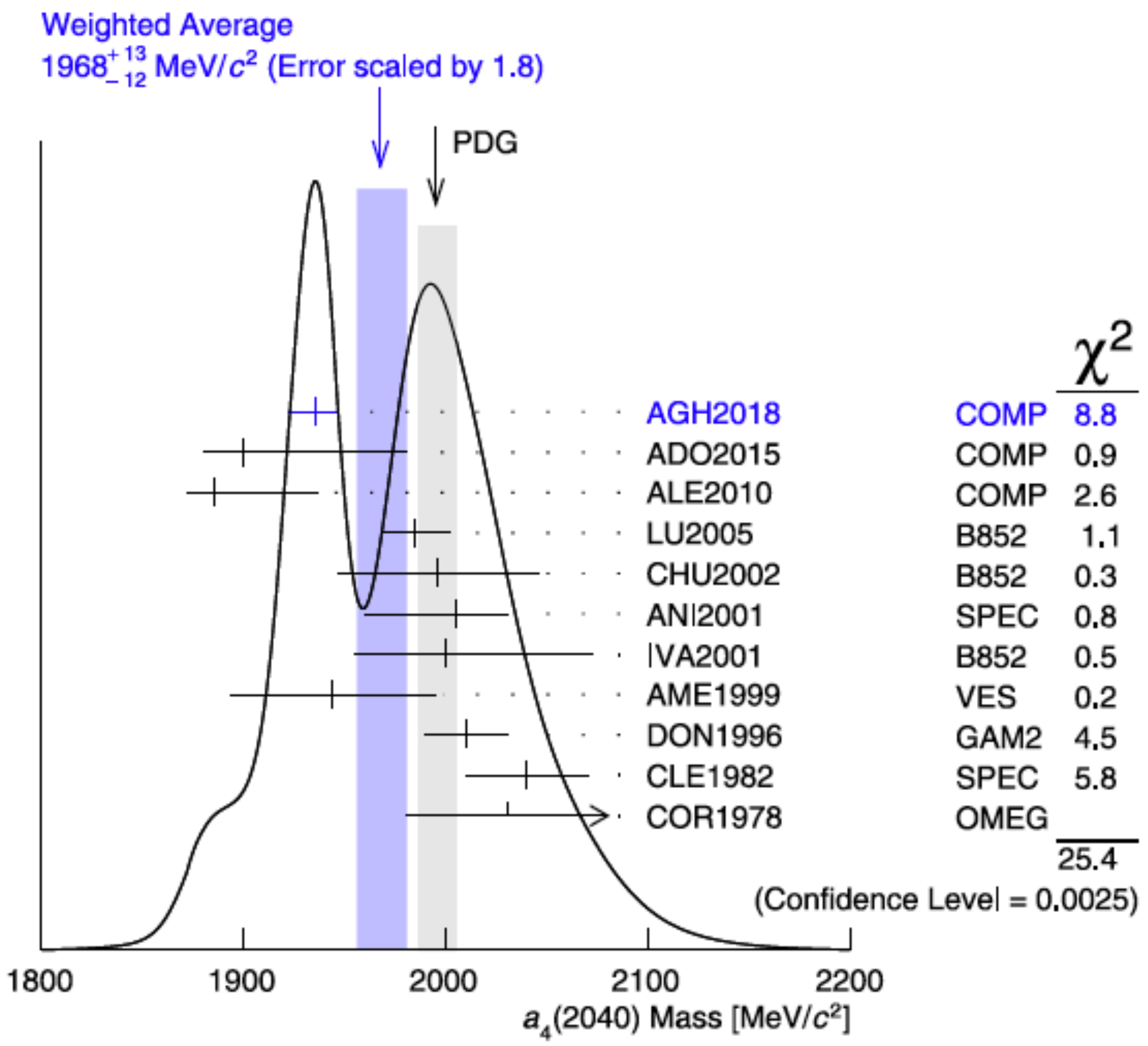

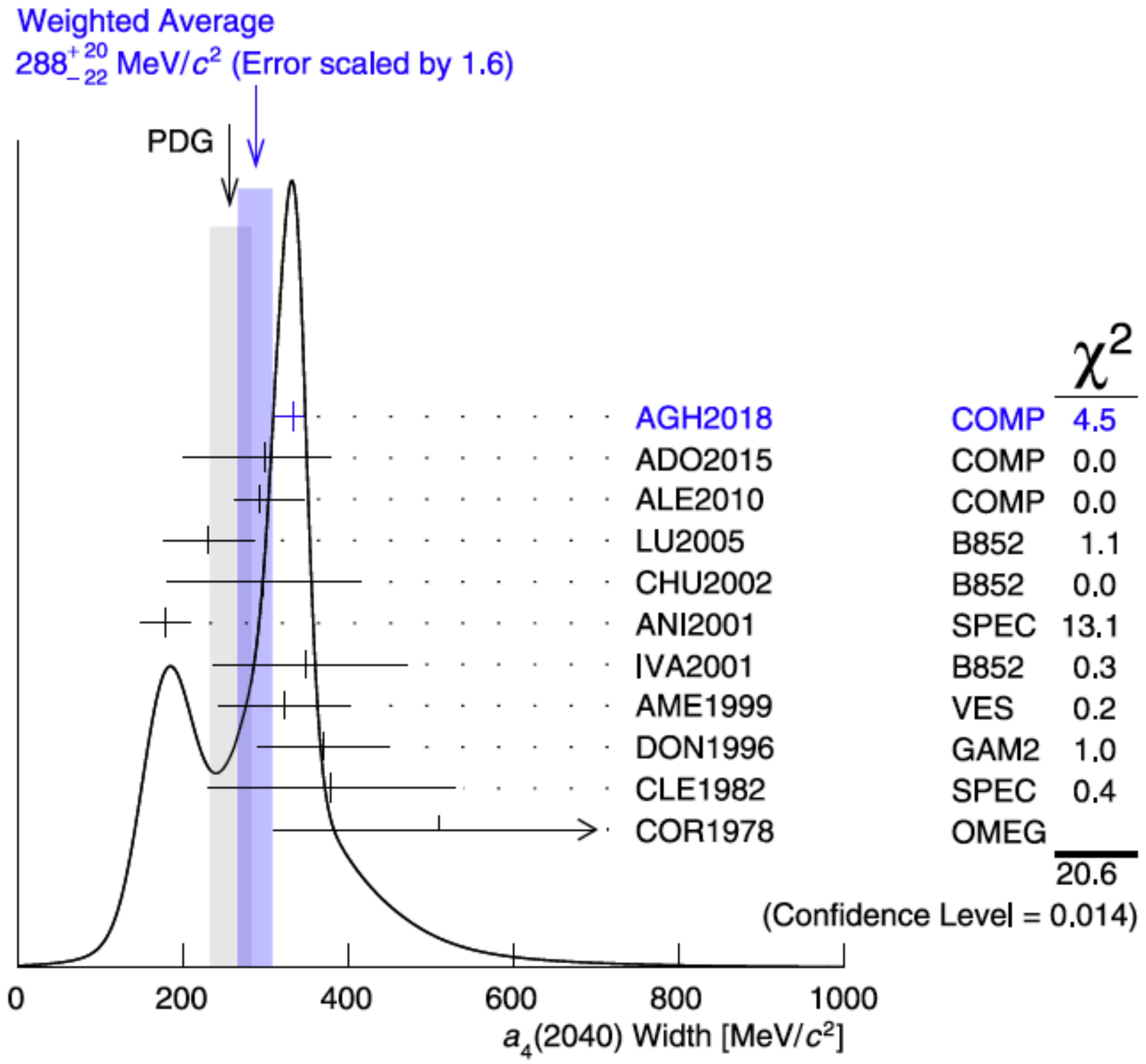

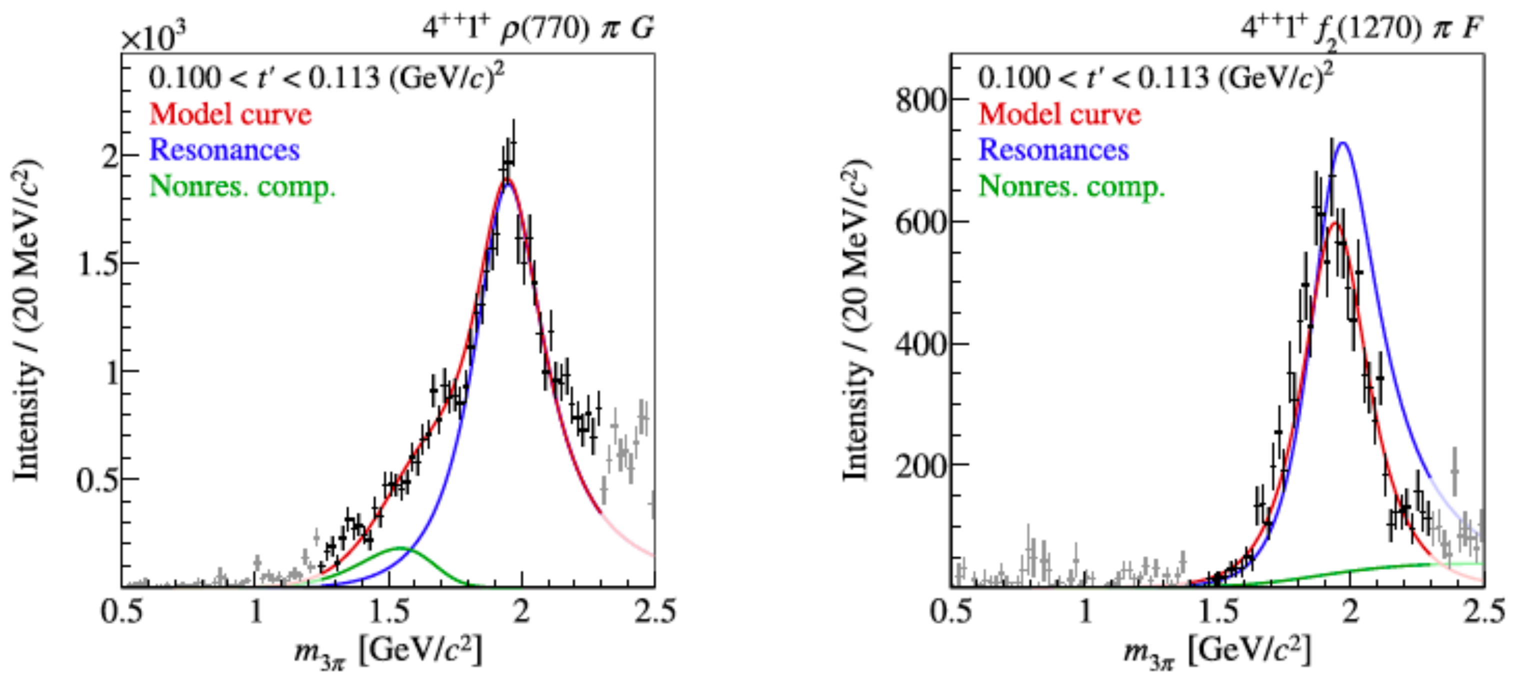

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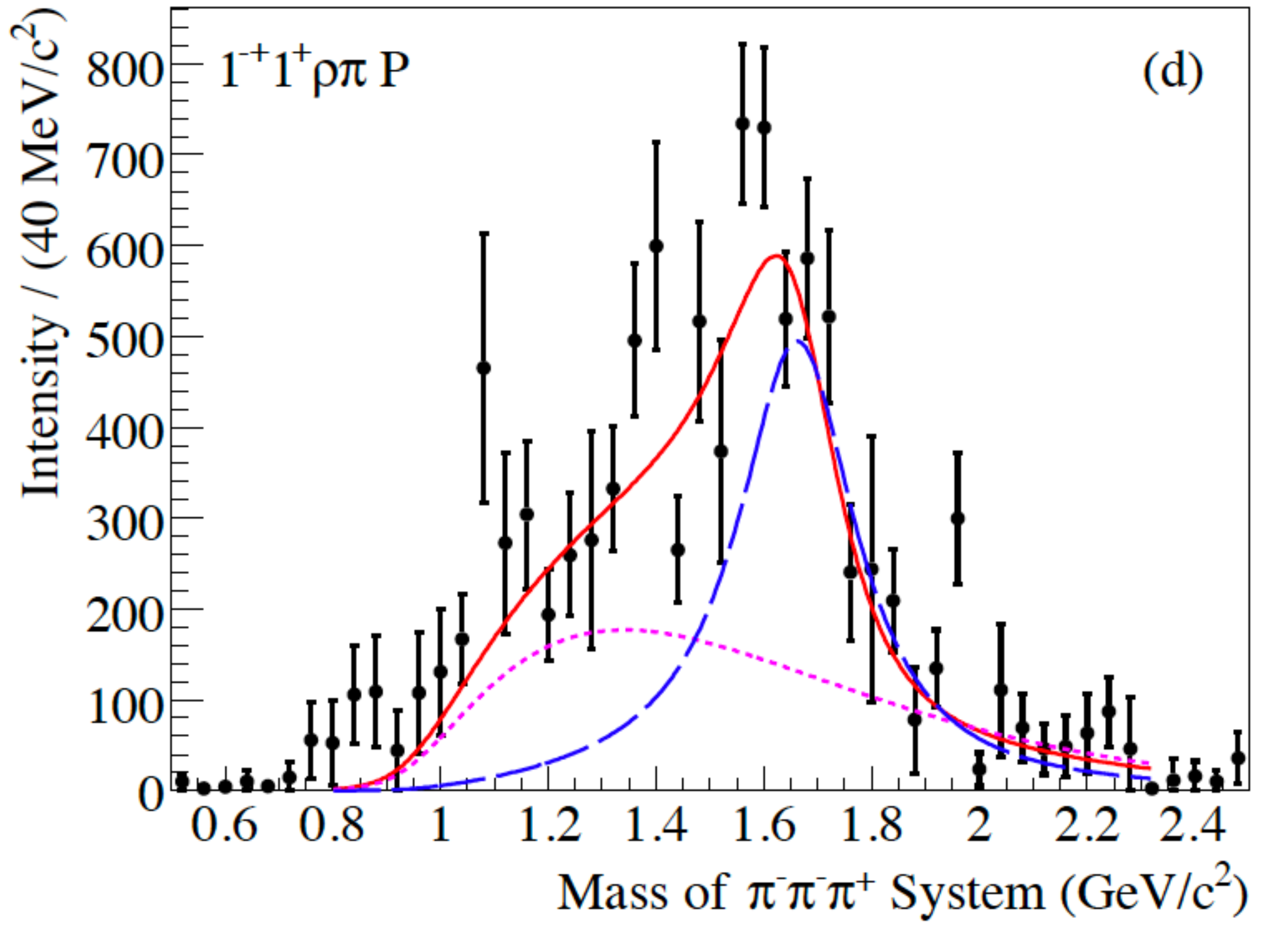
Known Exotica

- Exotic mesons are characterized by
  - non-Q(uark)M(odel) quantum numbers (J^{PC}, flavour, charge)
  - supernumerous states „outside“ symmetry multiplets
  - decay path - coupling (flavour-blind decays)
  - production mechanisms
- First (time stable) exotics in the light sector
  - 0^{++} - $f_0(1500)$ glueball candidate (seen in $\bar{p}p$ annihilation, central production, J/ψ decays)
  - 1^{-+} - $\pi_1(1600)$ (seen in diffractive production)
- States of disputed nature e.g. $f_0(980)$, $\eta(1405)$, $\pi(1800)\ldots$
- Problem with broad (light quark) states: mixing within a J^{PC} sector
- after discovery of $X(3872)$: plethora of new (partly exotic) narrow states with heavy quarks

COMPASS was planned to add information in the light sector

First exotic meson in COMPASS $\pi_1(1600)$

First data from 2004 (pilot run) revealed $J^{PC} = 1^{-+}$



COMPASS *Phys.Rev.Lett.* 104 (2010) 241803

First exotic meson in COMPASS $\pi_1(1600)$

Exzellenzcluster ORIGINS

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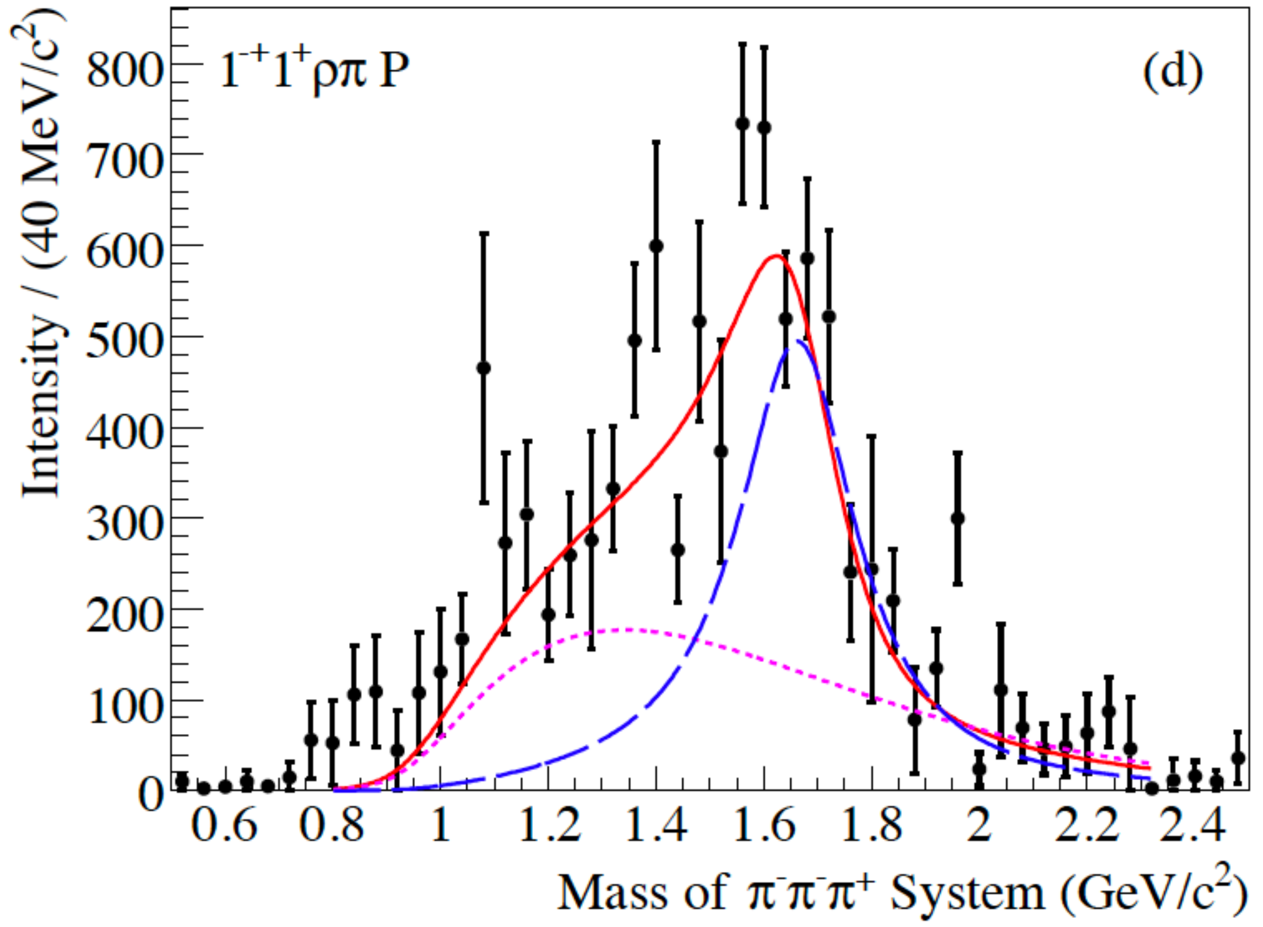
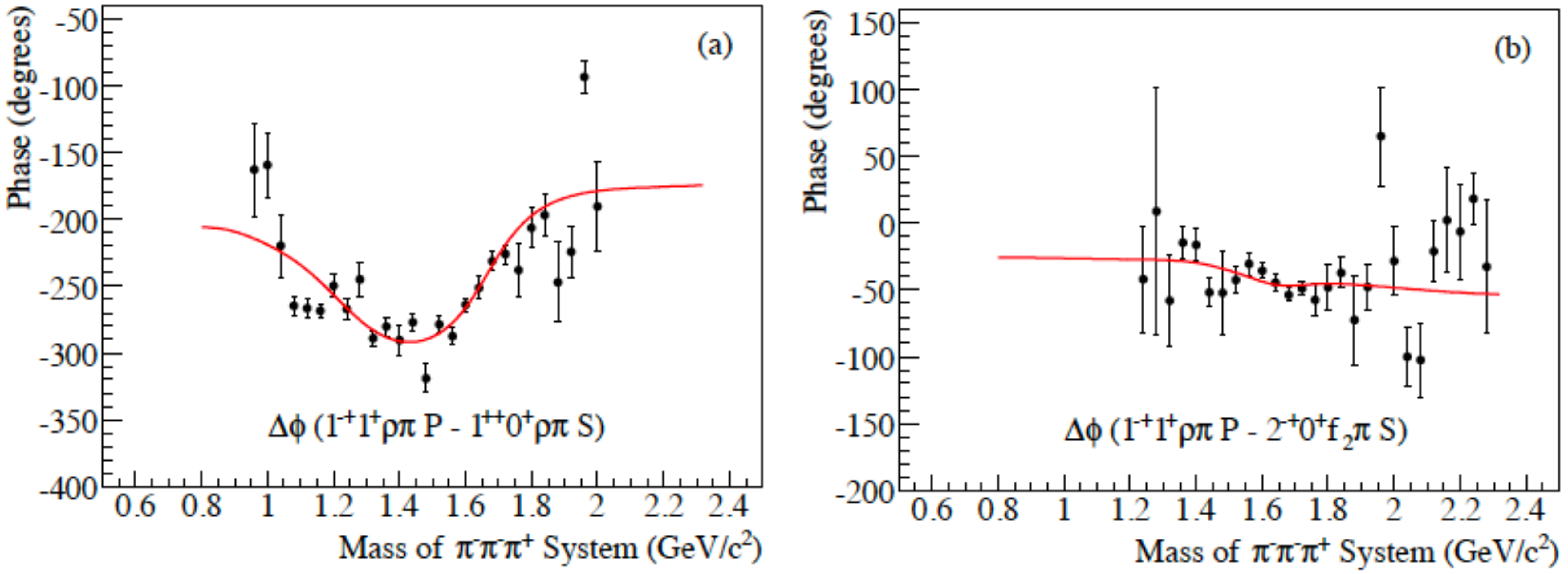
$\pi^- + Pb \rightarrow \pi^-\pi^+\pi^- + Pb'$: 420,000 evts $t' \in [0.1,1.0]$ GeV/c^2

PWA model : 42 waves





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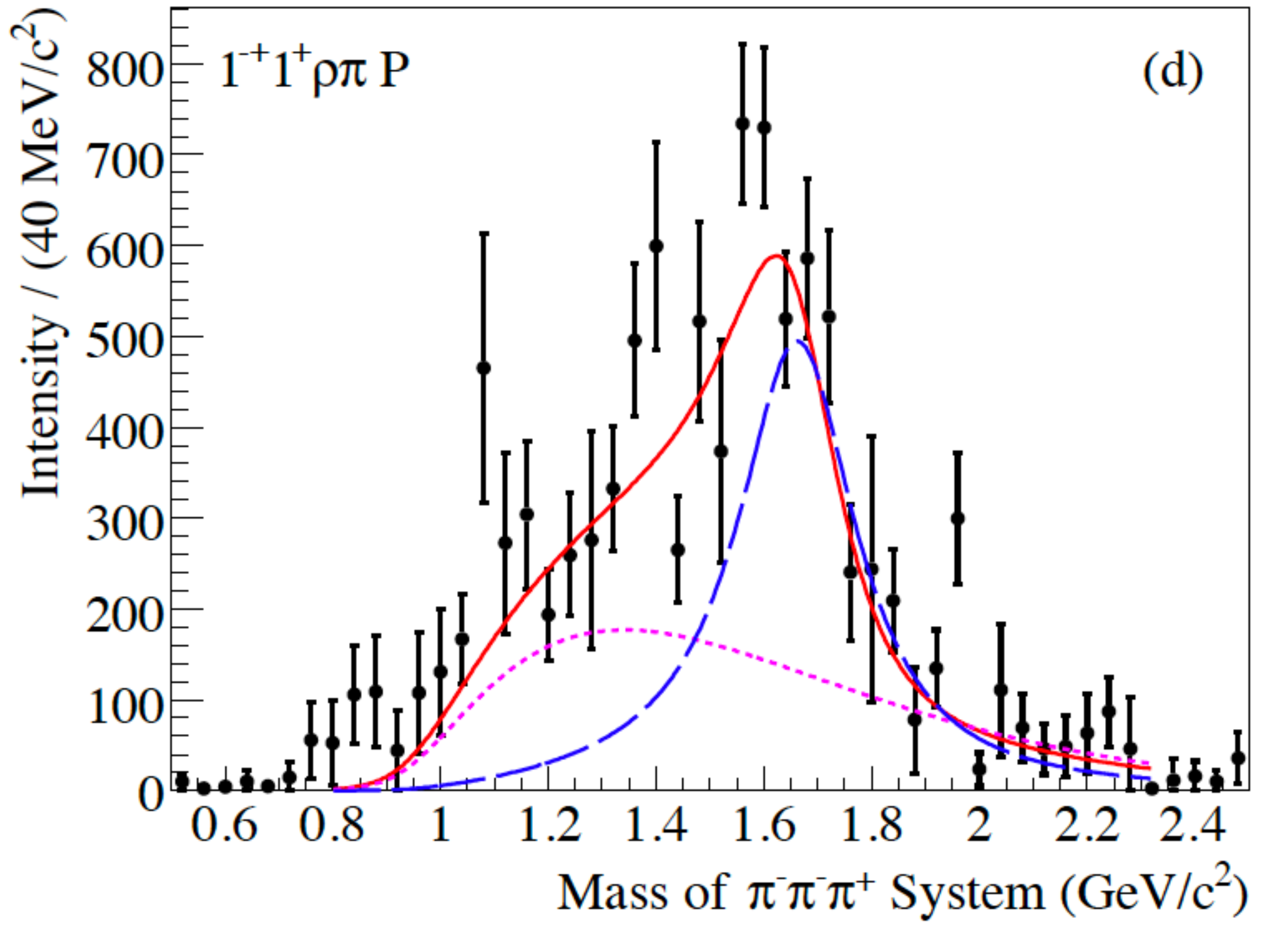
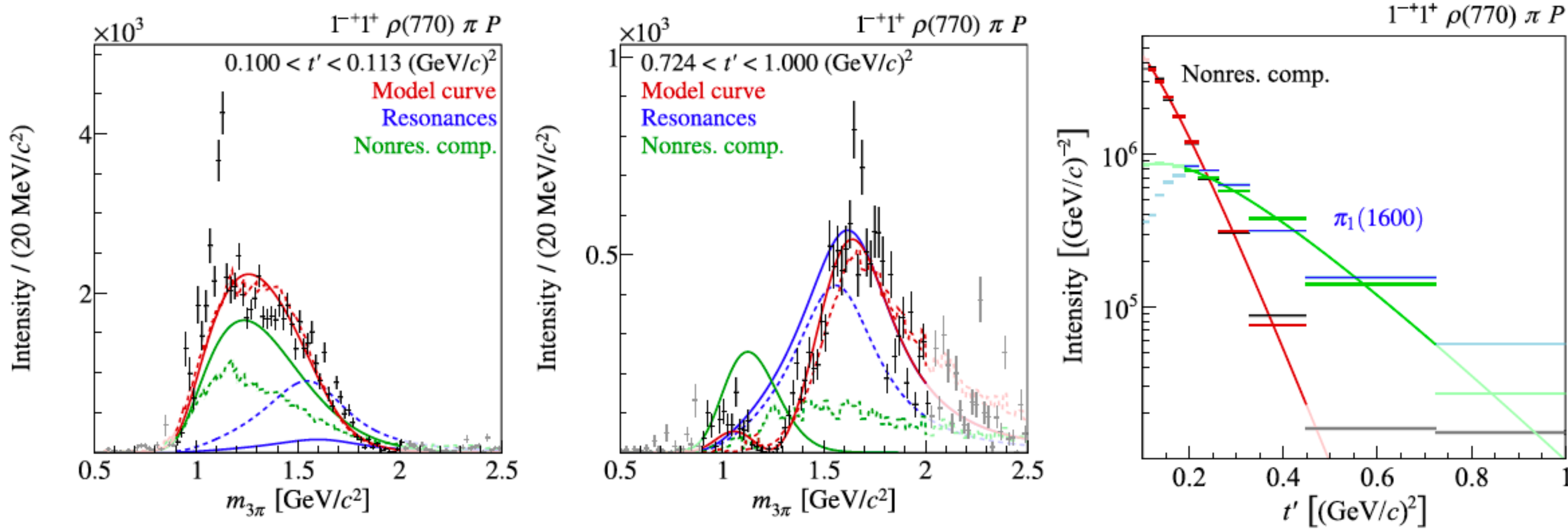


Data from 2008 confirmed observation

$\pi^- + p \rightarrow \pi^-\pi^+\pi^- + p' : 45 \cdot 10^6$ evts

PWA model : 88 waves



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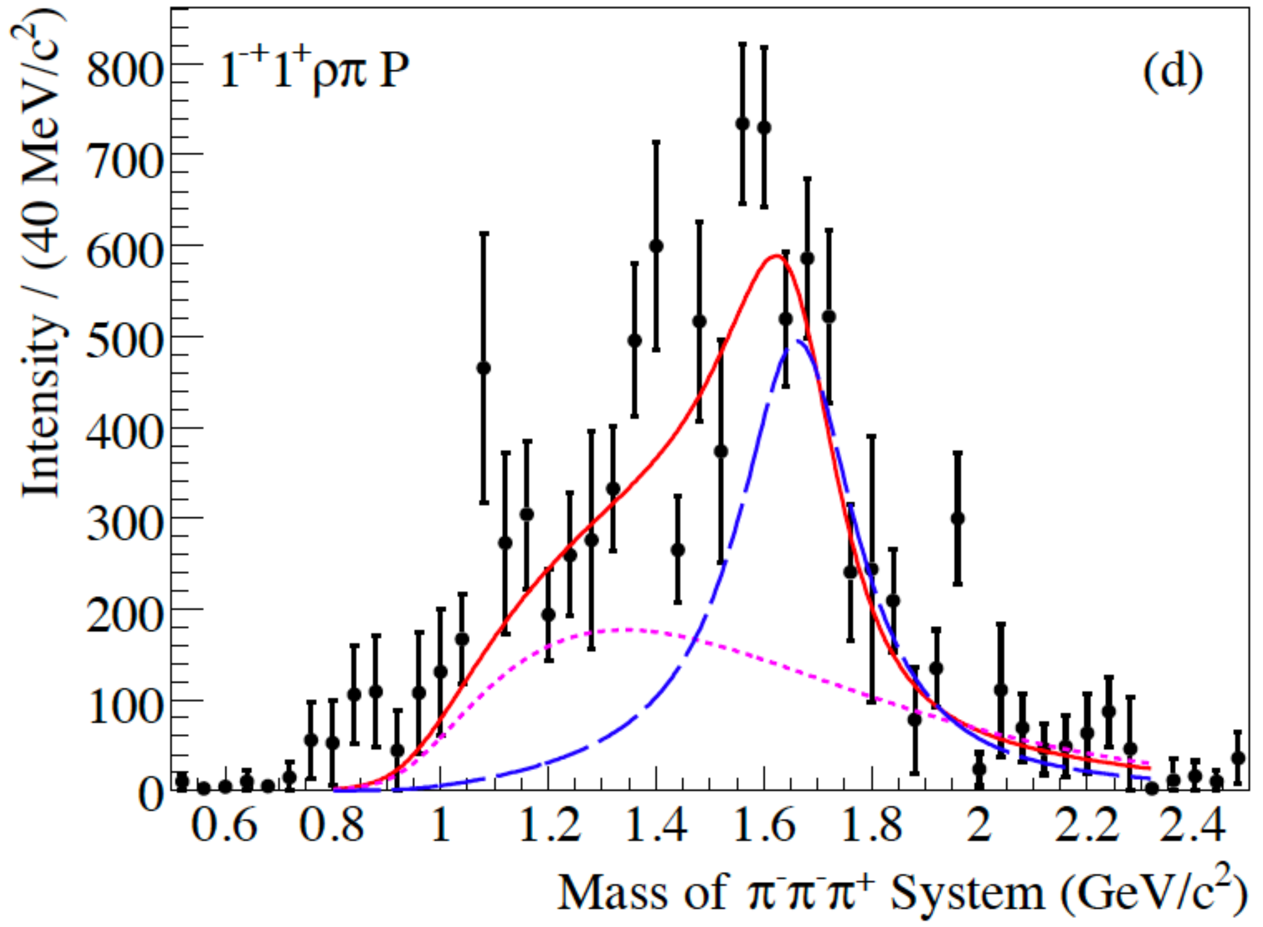

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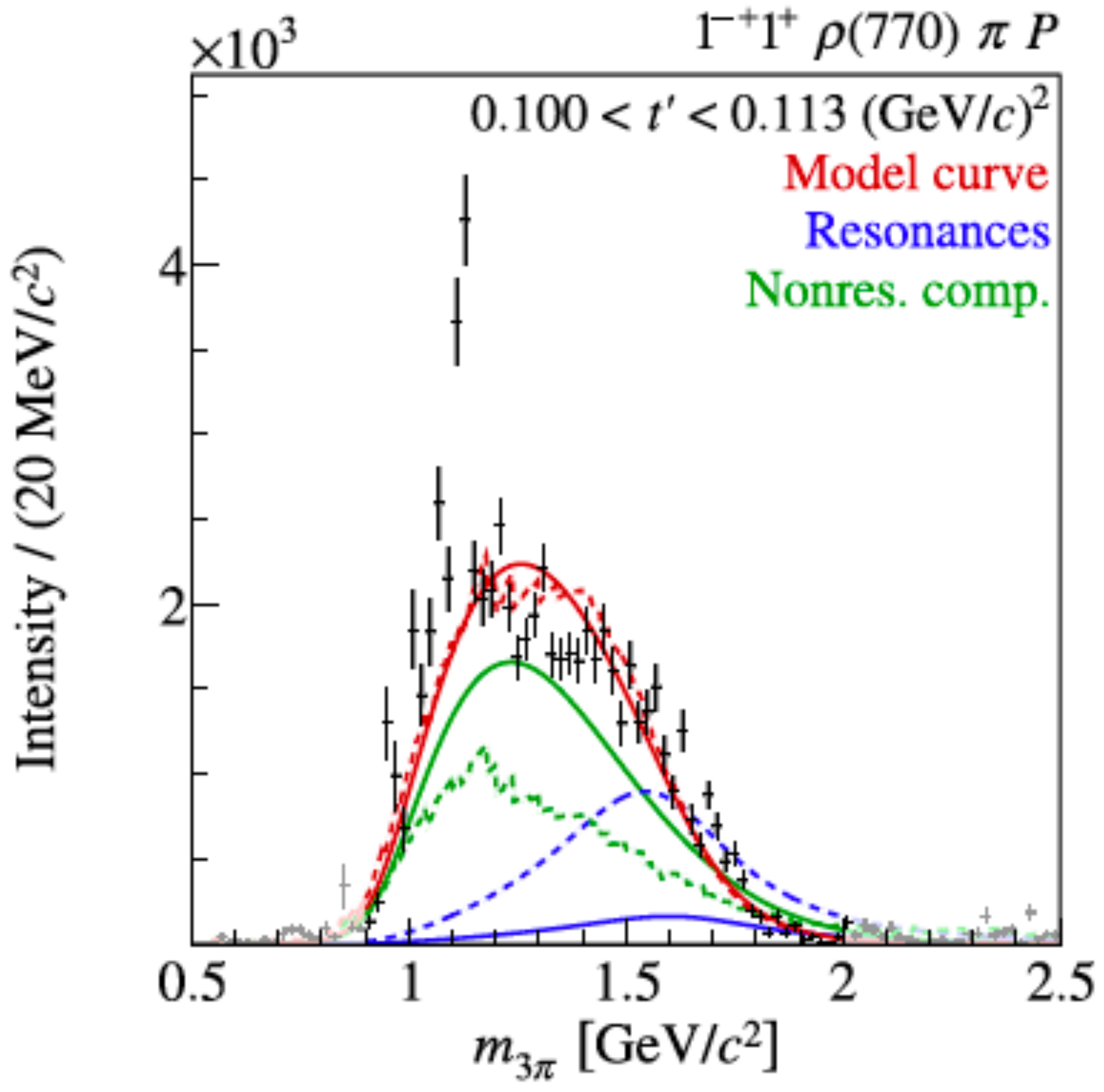
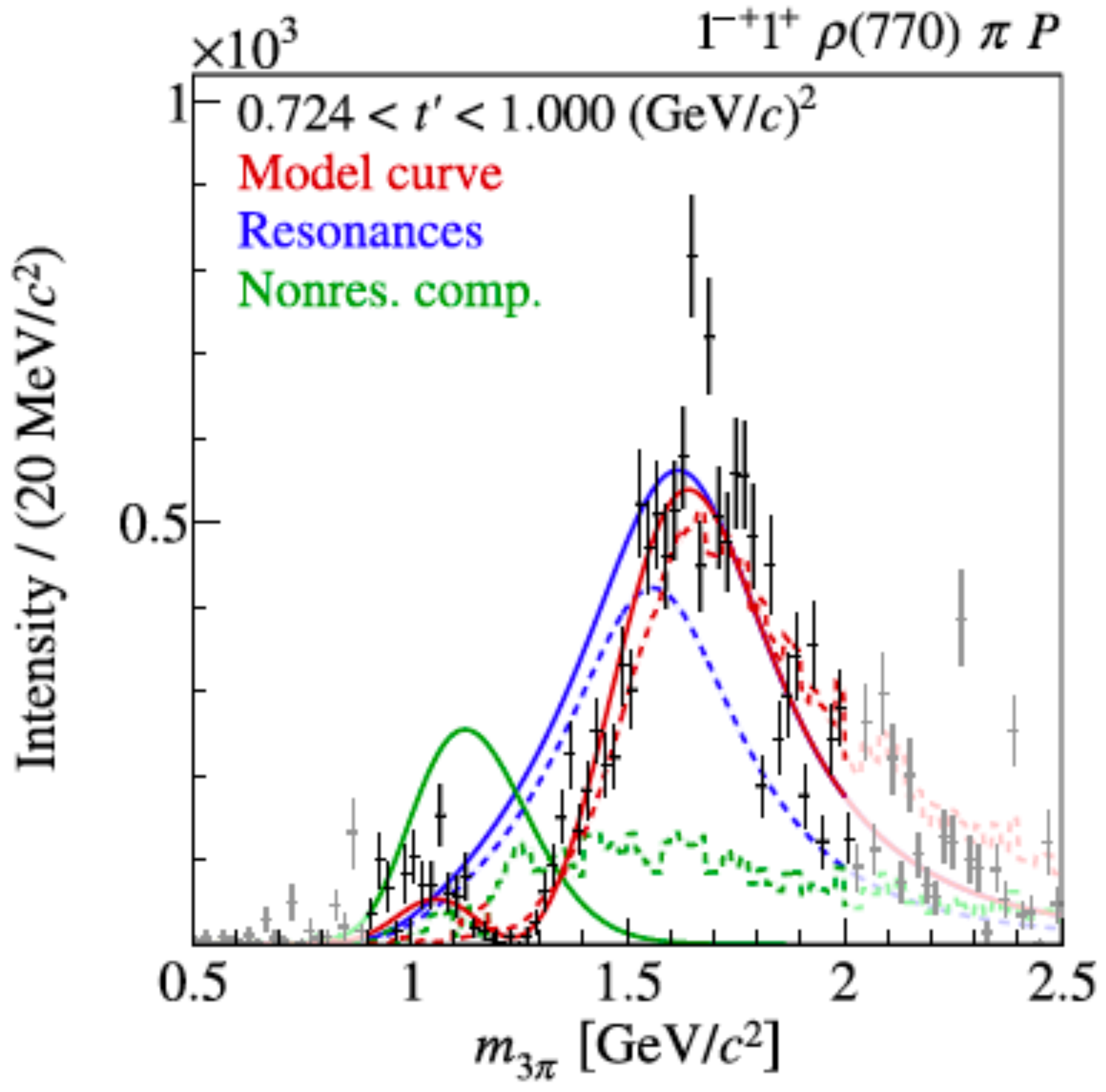
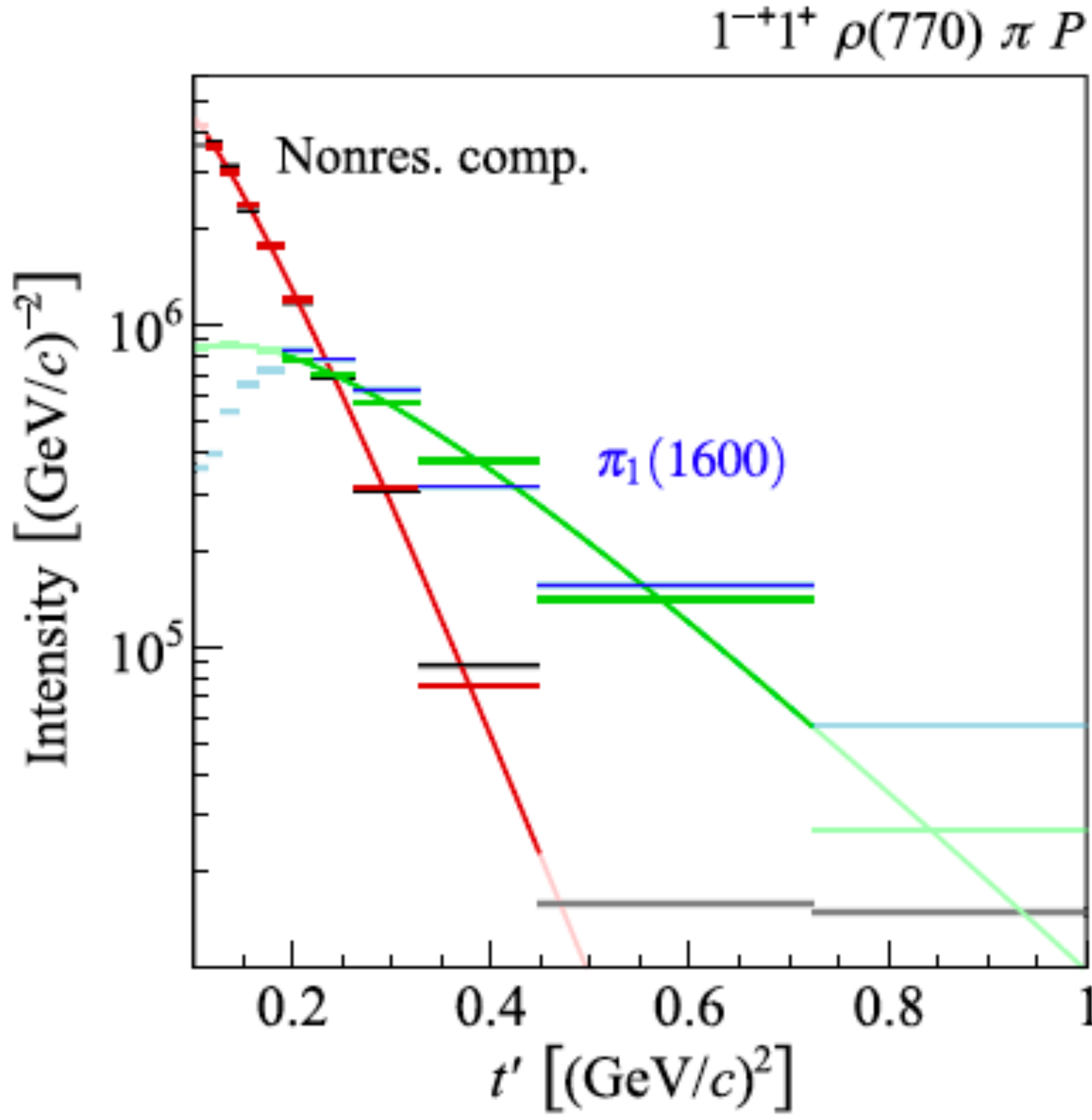


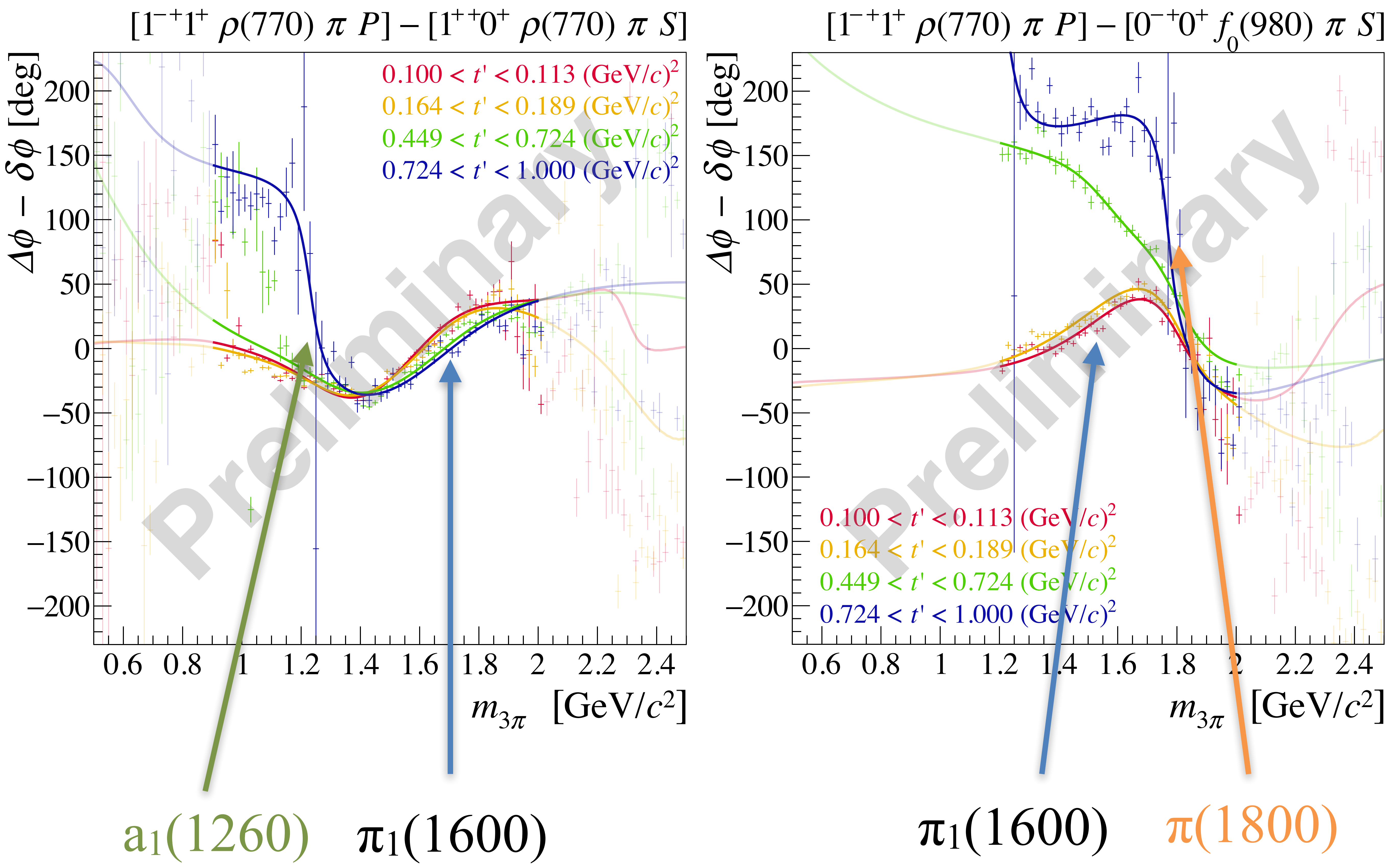




COMPASS *Phys.Rev.Lett.* 104 (2010) 241803

Find the Exotic - Phases

- Exotic mesons: 1^{-+}



Establishment of exotic meson !

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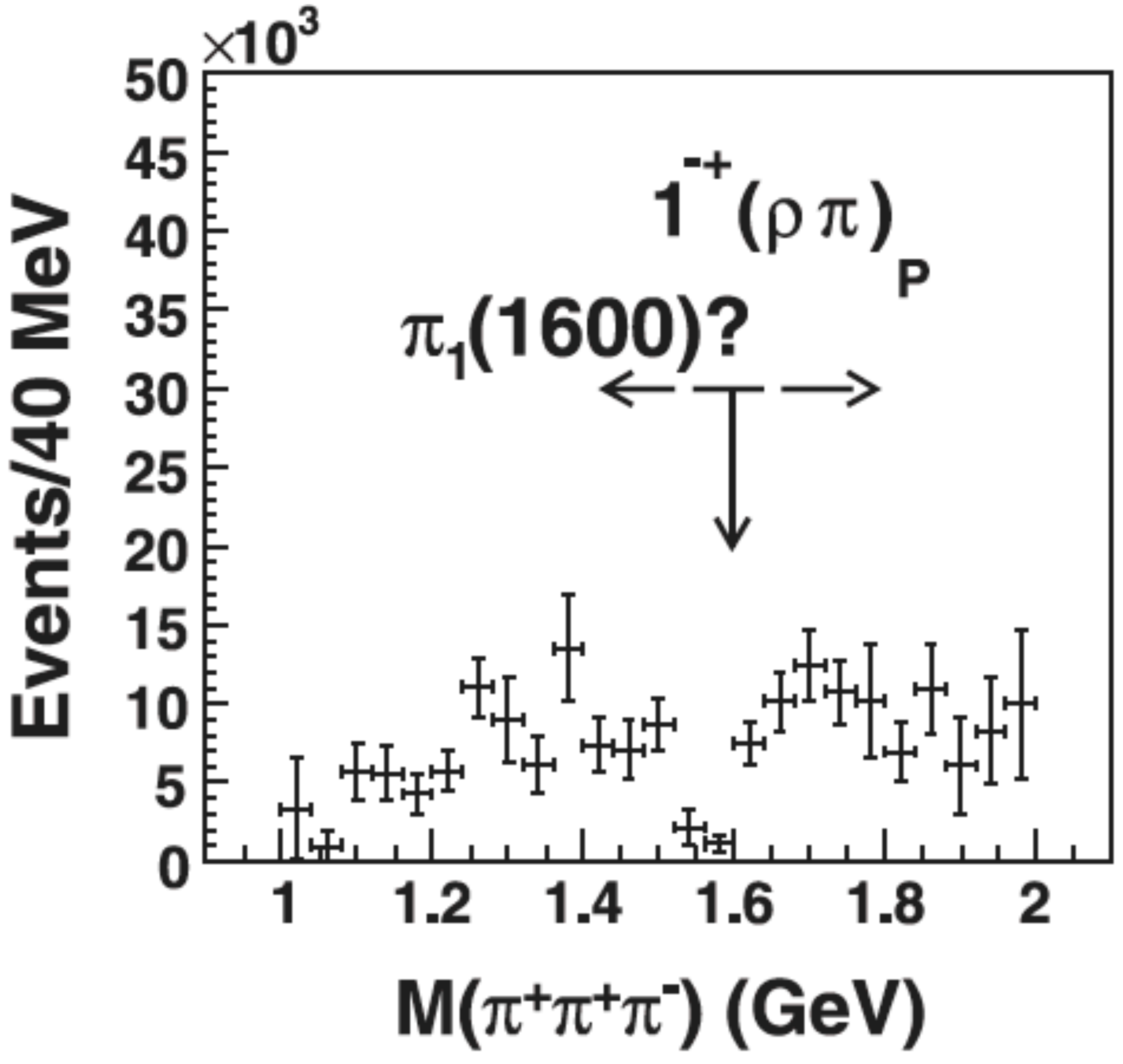
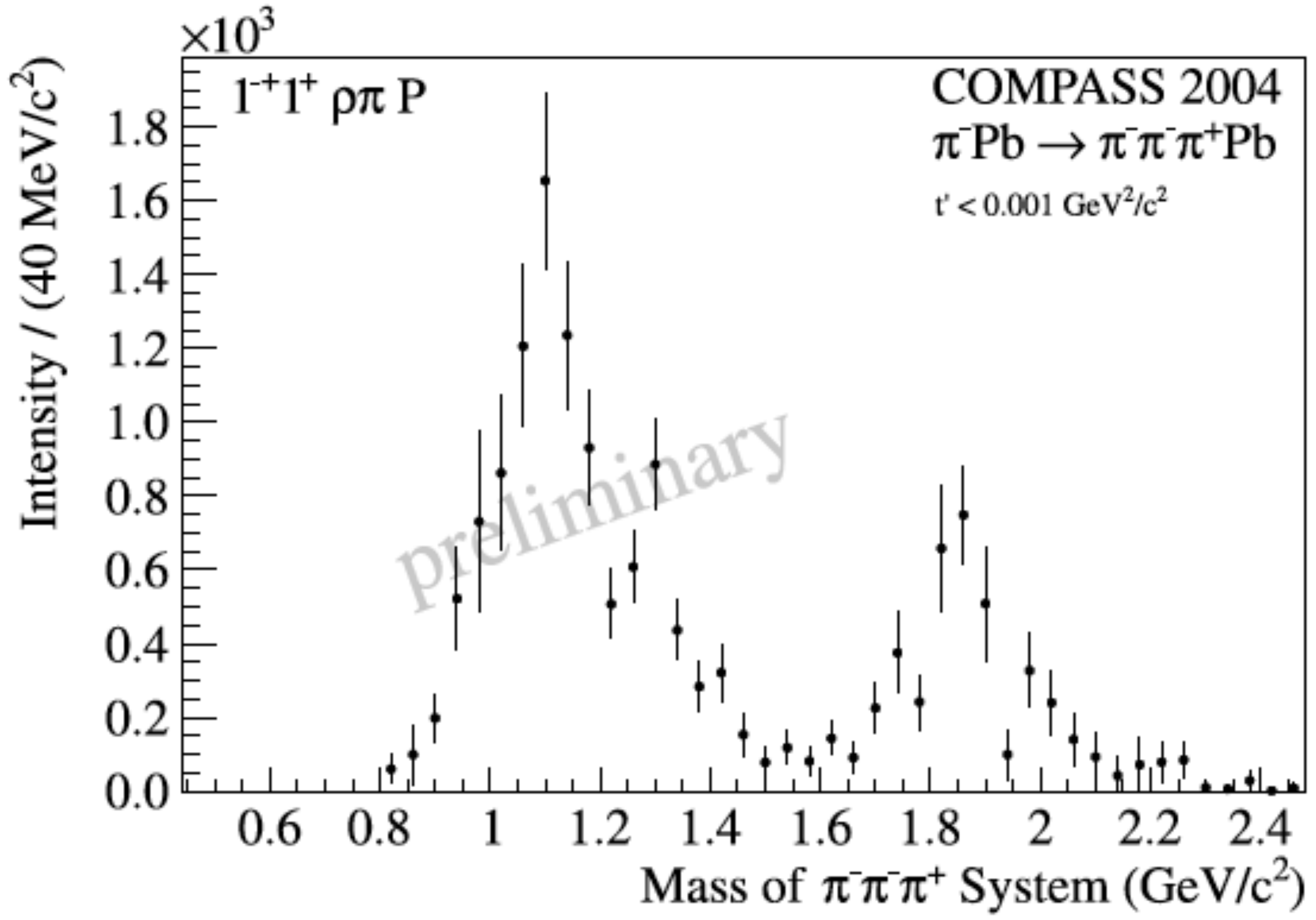
Exotic in Photo Production ?

Coupling to ρ mesons suggests production by photons (VDM)

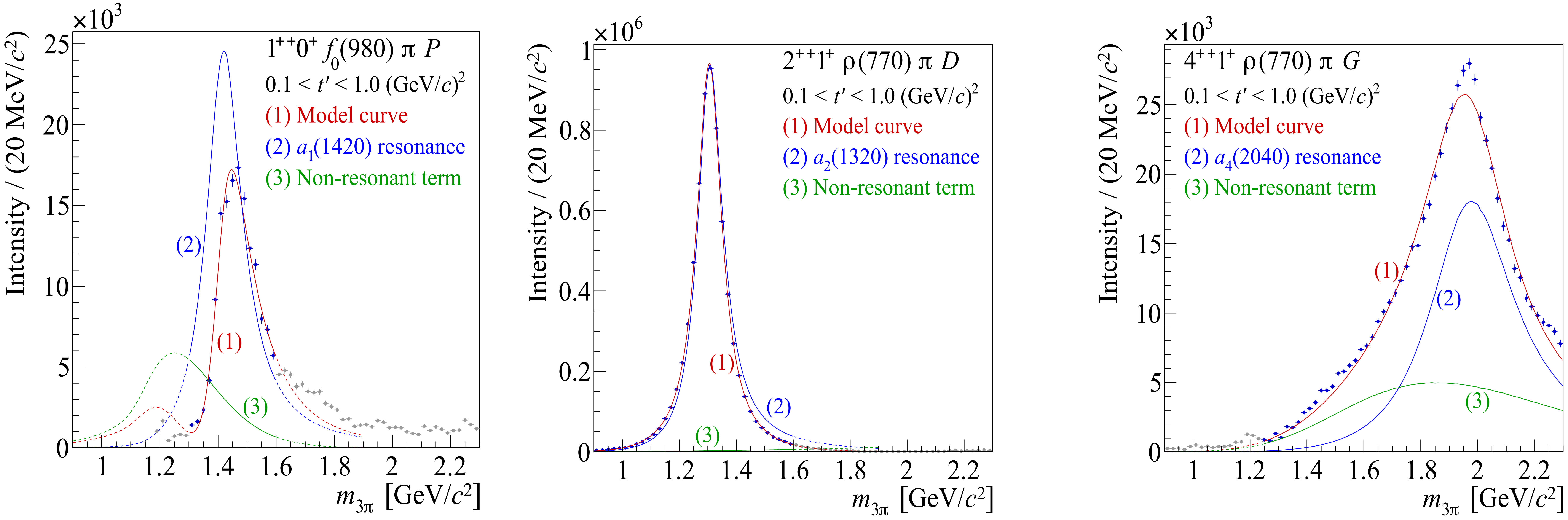
- Argument for GLueX real (tagged) photon beam
- Searches by CLAS and COMPASS (Primakoff) negative so far





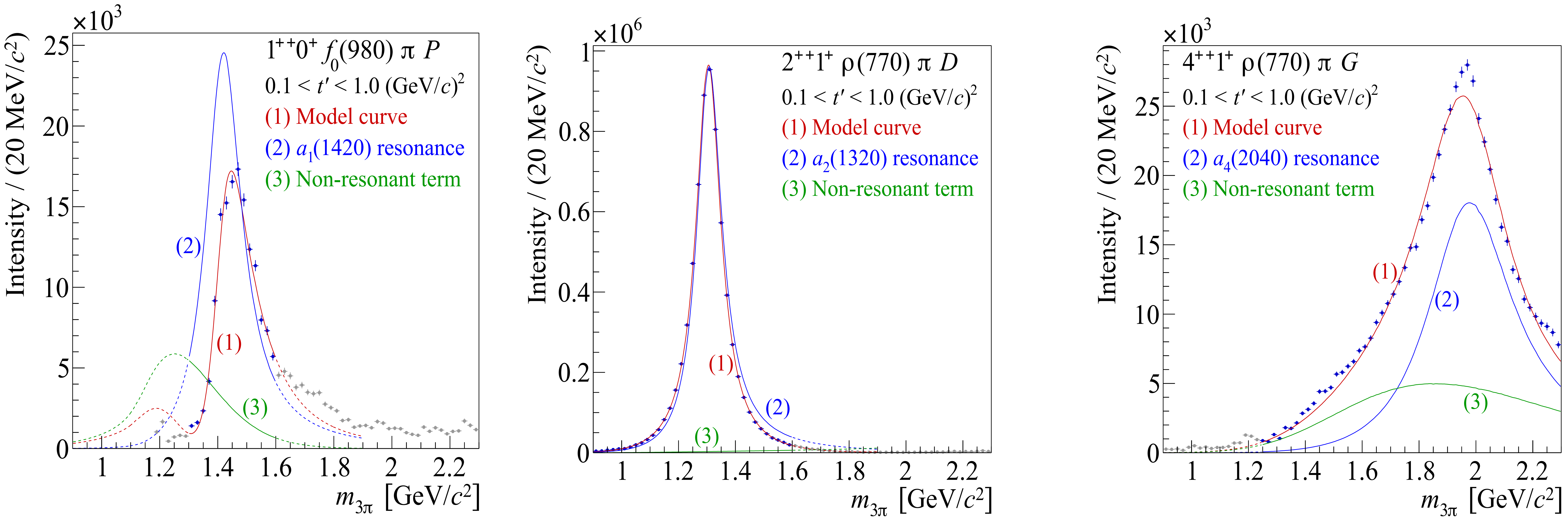
Unknown (New) Exotica

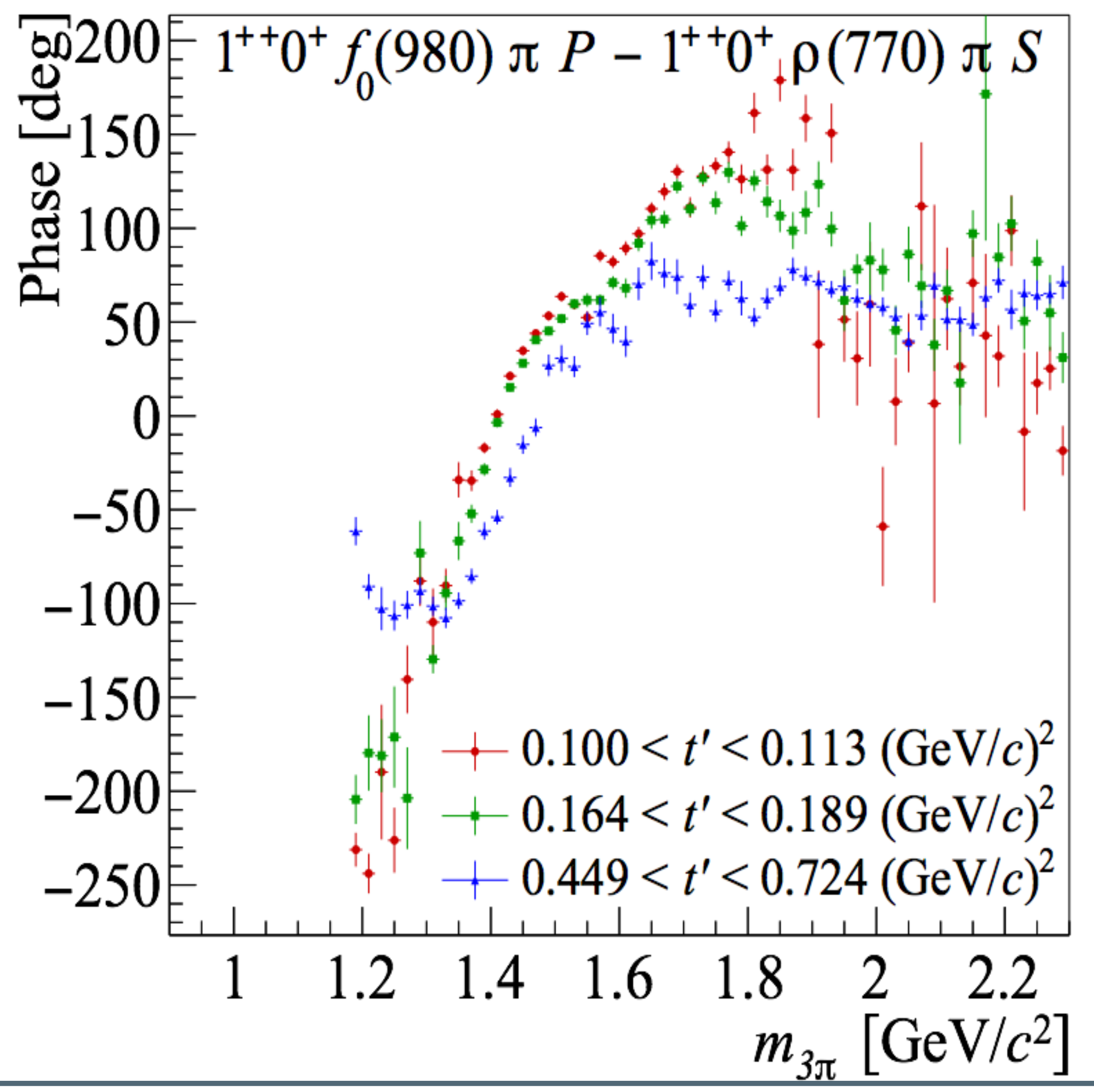
Observation: $a_1(1420)$



COMPASS *Phys.Rev.Lett.* 115 (2015) 8, 082001

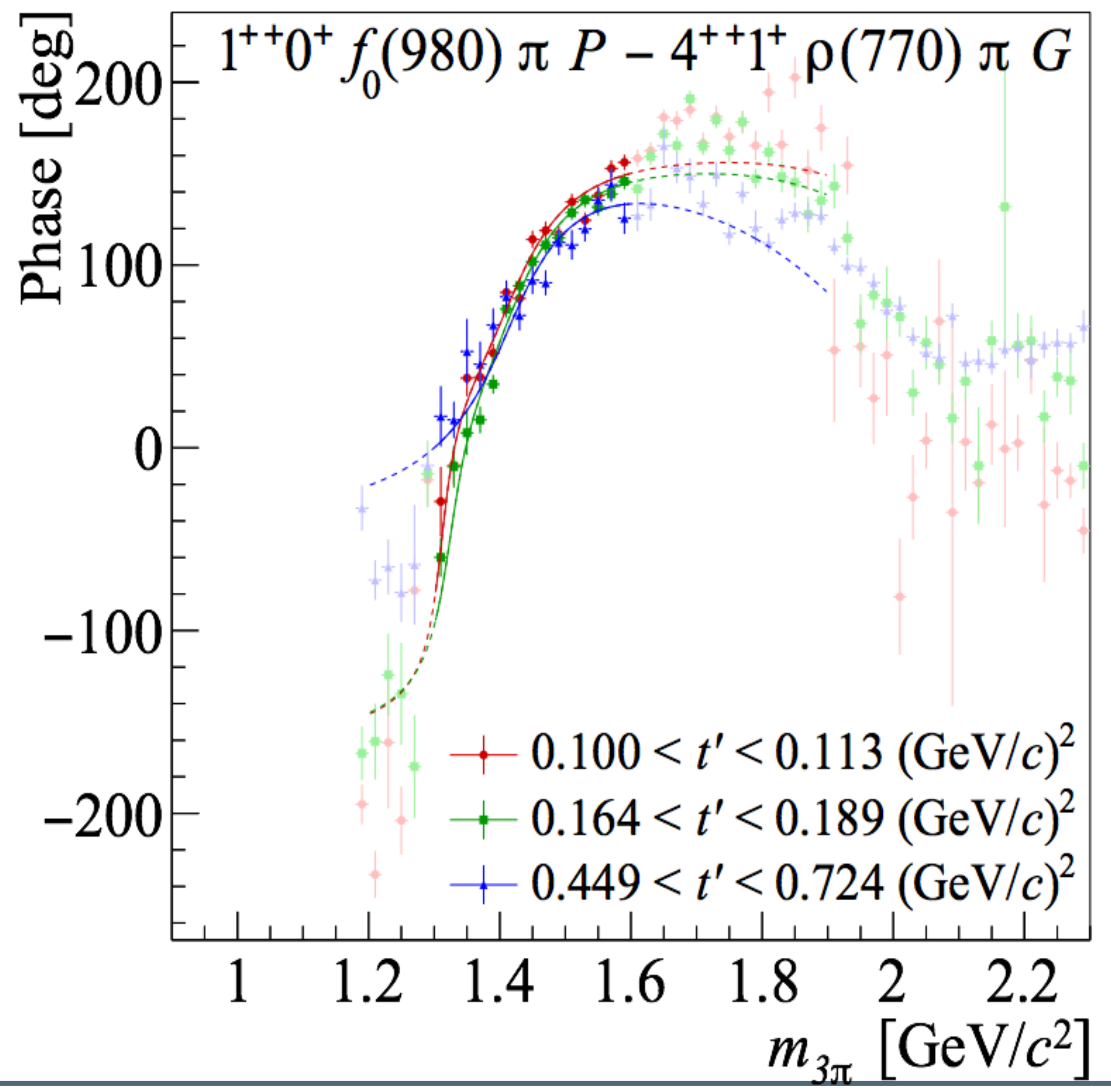
Observation: $a_1(1420)$





Observation*:*

- Decay only : [$f_0(980)$] π *P*
- *Mass : 1413 ± 15± 13 MeV/c²*
- *Width: 157 ± 8 ± 23 MeV/c²*



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$a_1(1420)$ Interpretations

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$a_1(1420)$ Interpretations

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Various explanations proposed for interpretation:

- Dynamics
  - Interference of $a_1(1260)$ with Deck amplitude ($\Delta\phi = 180^0$ shifted by 100 MeV) (Berger et al.)

COMPASS Phys.Rev.Lett. 127 (2021) 8

a_1(1420) Interpretations

Various explanations proposed for interpretation:

– Dynamics

- Interference of a_1(1260) with Deck amplitude ($\Delta\phi = 180^0$ shifted by 100 MeV) (Berger et al.)
- triangular anomaly coupling $a_1(1260) \to KK^* \to KK\pi$ and $KK \leftrightarrow f_0(980)$ ($\Delta\phi = 90^0$)
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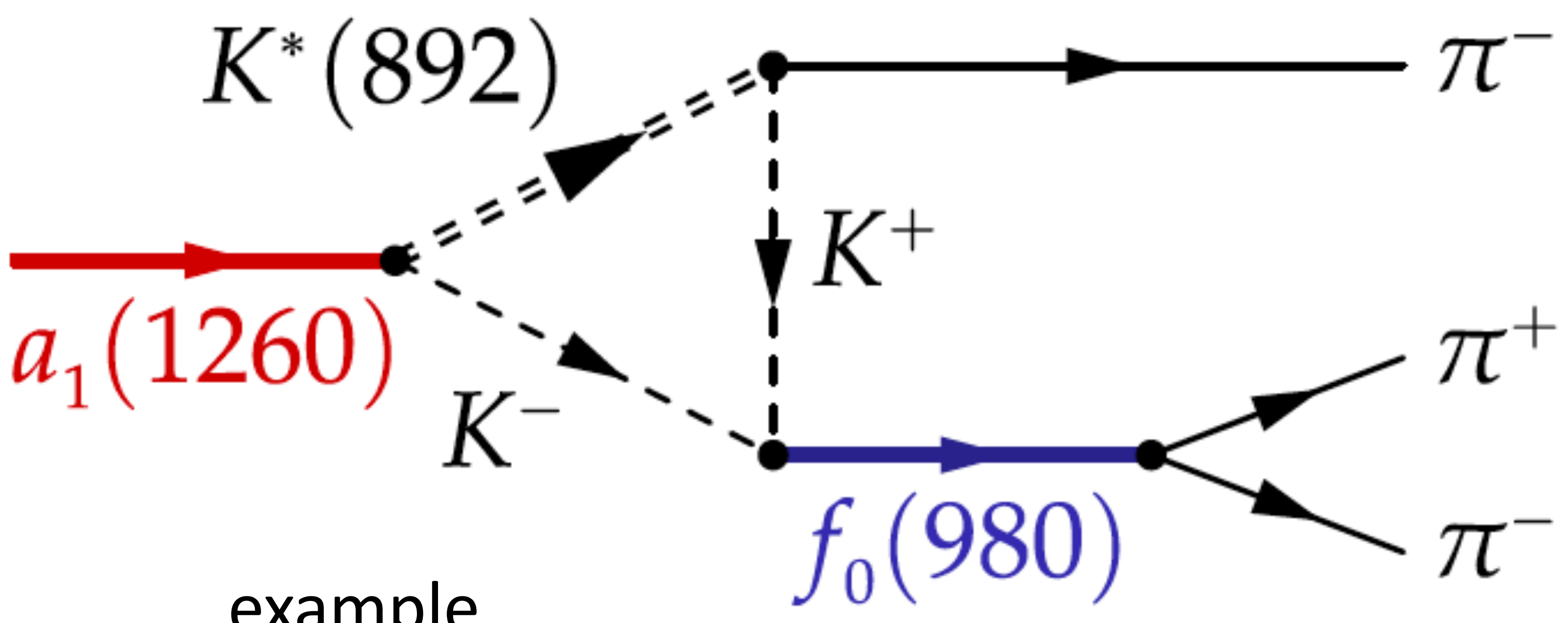

example

COMPASS Phys.Rev.Lett. 127 (2021) 8

$a_1(1420)$ Interpretations

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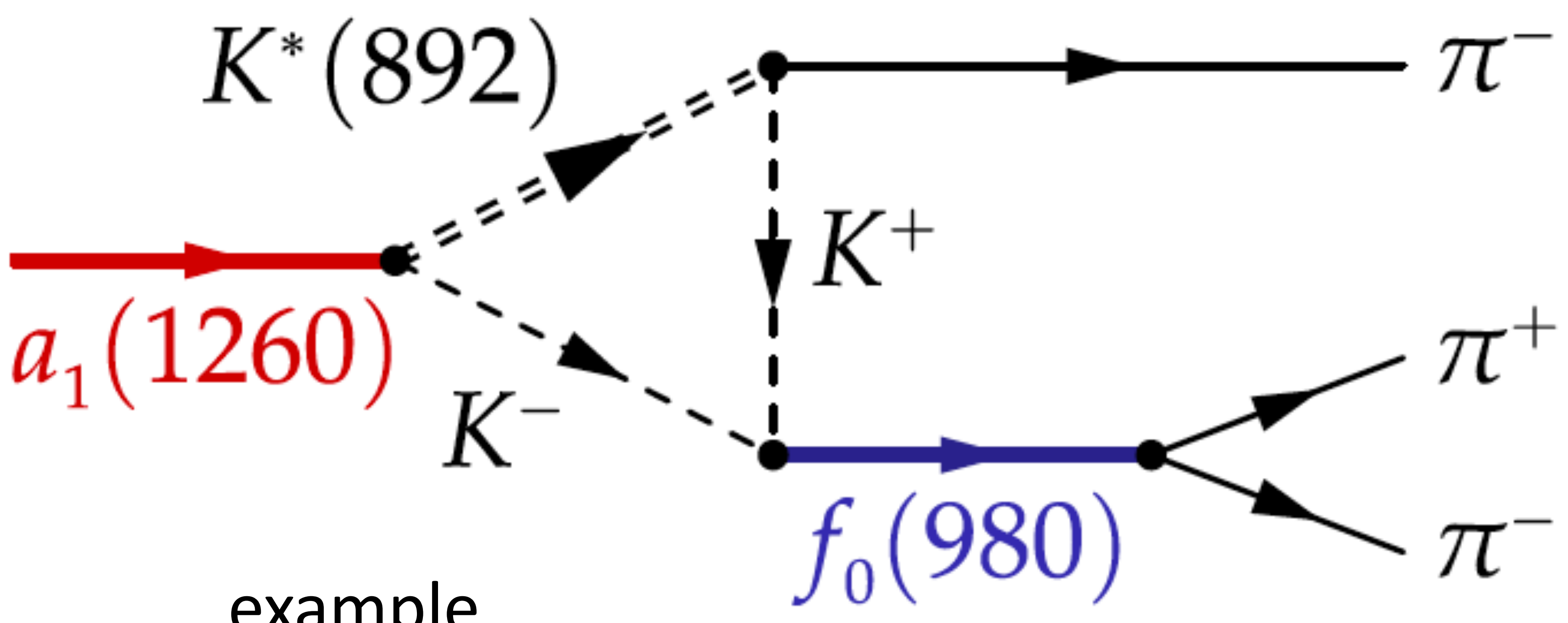
– Molecular structure

- Partner of $f_1(1420)$



example

COMPASS *Phys.Rev.Lett.* 127 (2021) 8

a_1(1420) Interpretations

Exzellenzcluster ORIGINS

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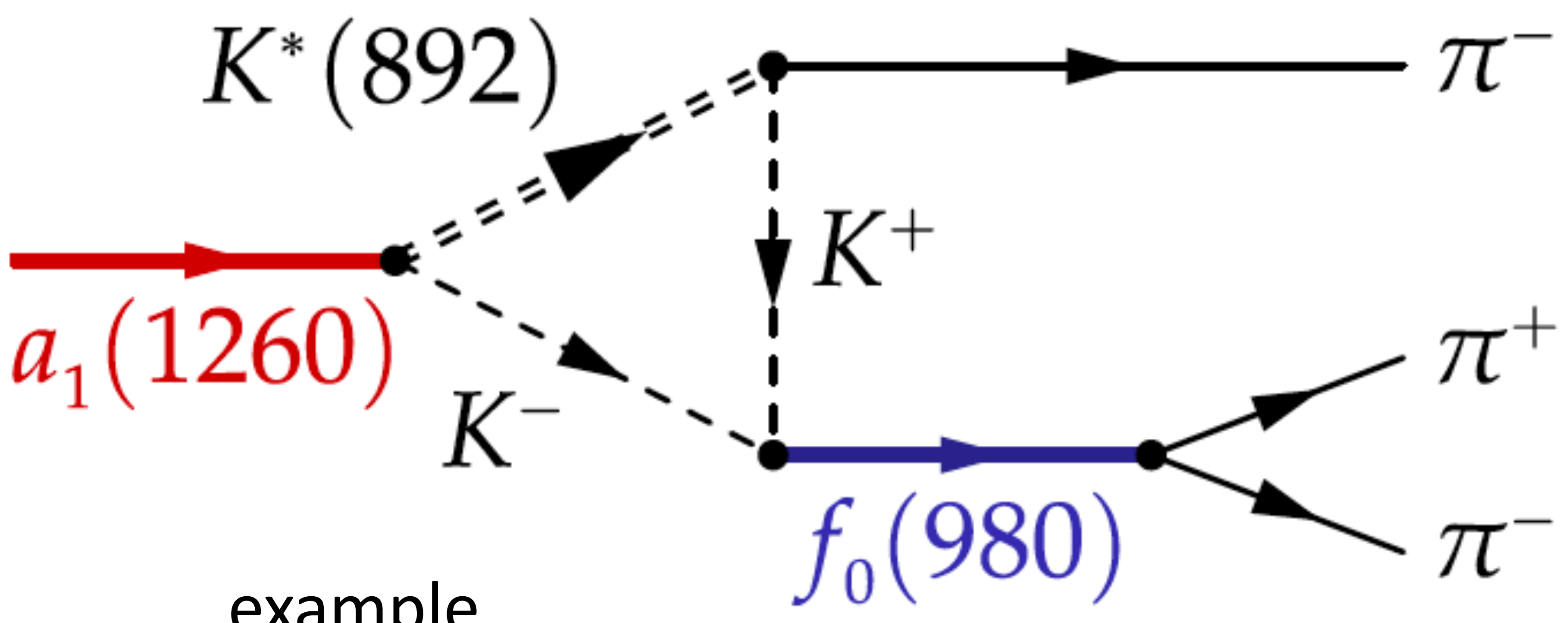
– Molecular structure

- Partner of f_1(1420)

Analysis of 3π τ lepton decays crucial

- ongoing using Belle/Belle 2 data



example

COMPASS Phys.Rev.Lett. 127 (2021) 8

A New Pionic State ?

A New Pionic State ?

- Ground state and radially excited pions have $J^{PC} = 0^{-+}$
- known states: π(140), π(1300), π(1800)
- Data sets:
  - LH_2: (2008/2009 reprocessed) $164 \cdot 10^6$ evts. - $t' \in [0.1,1.0]$ GeV/c^2
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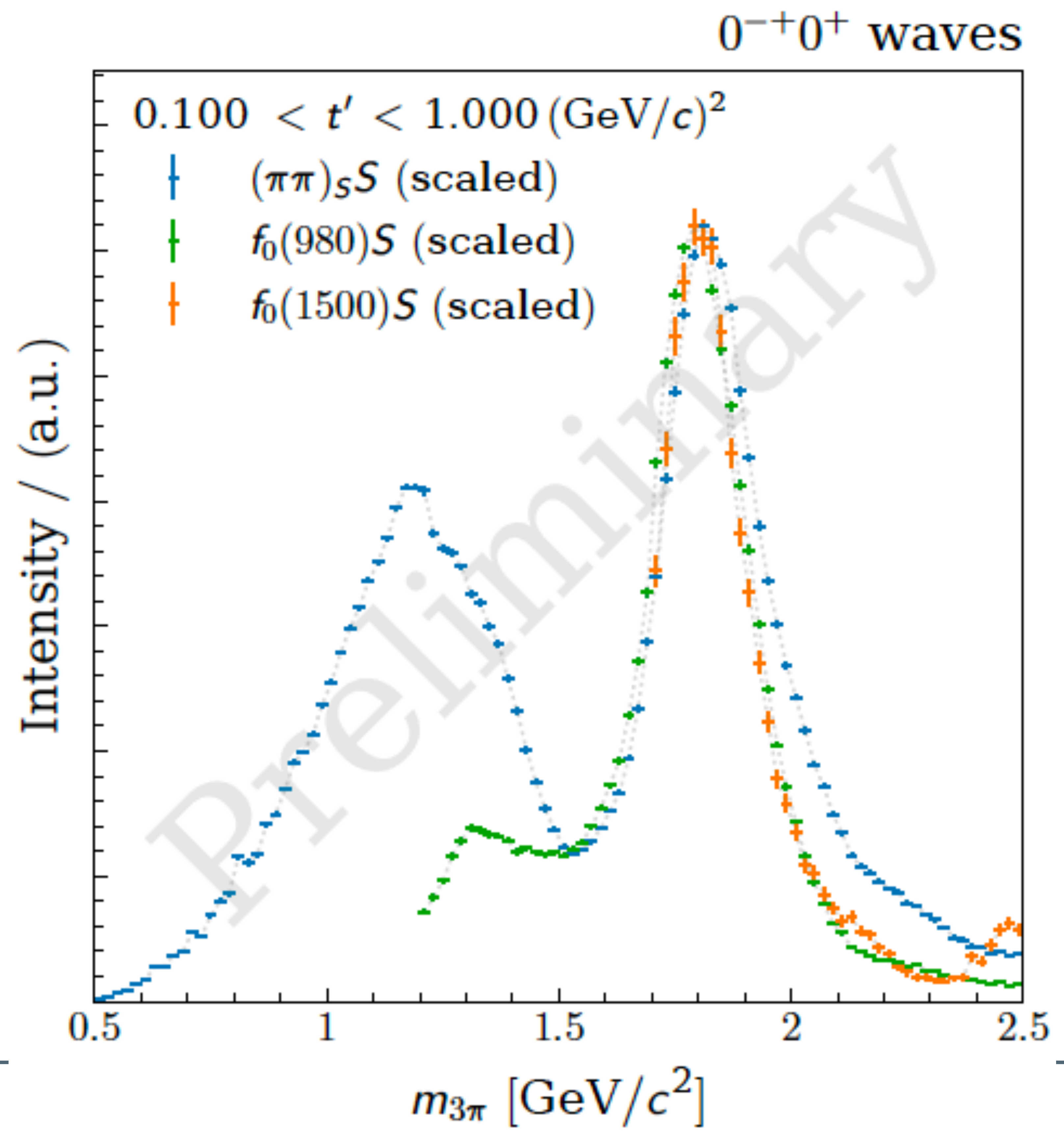

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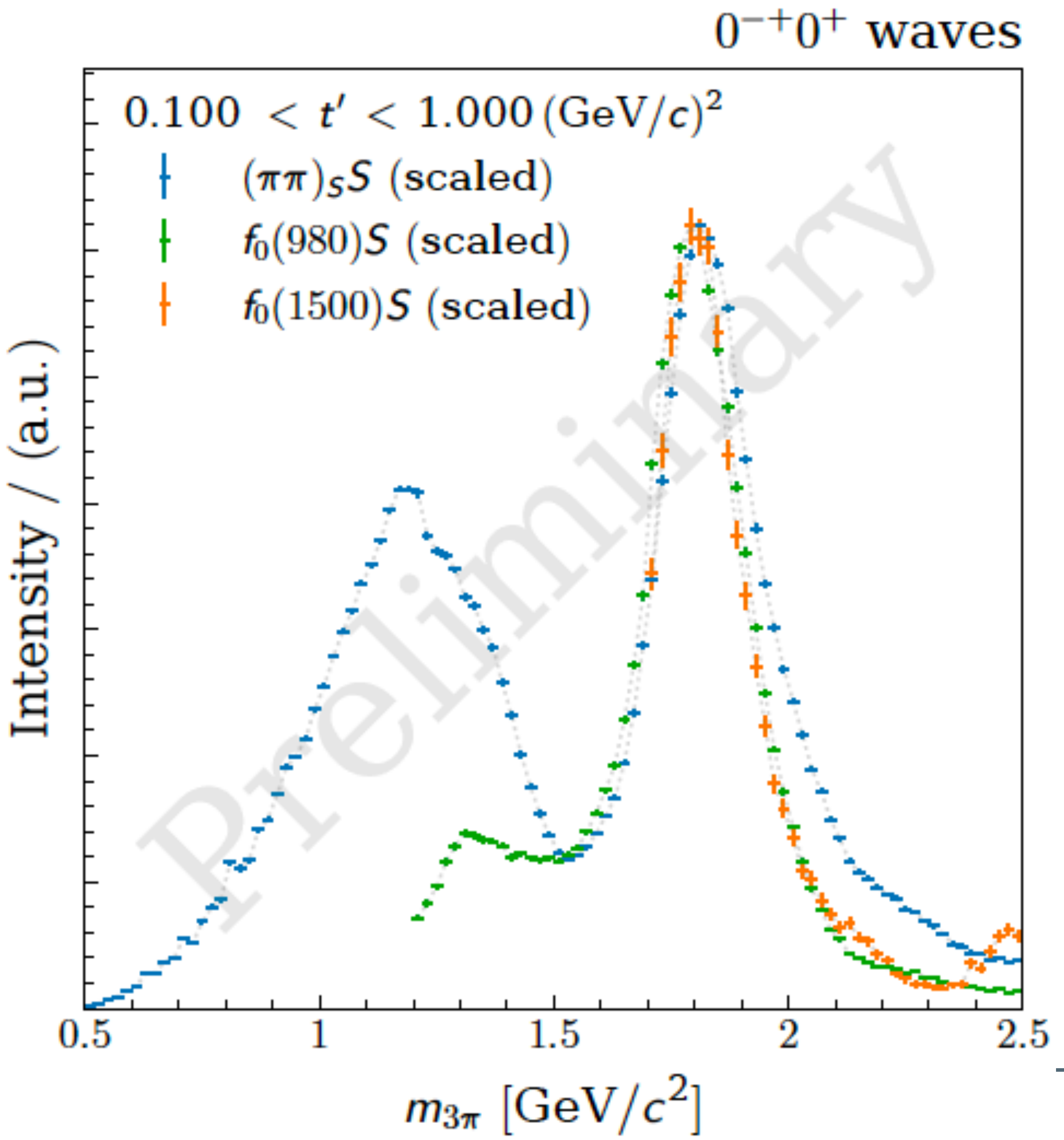

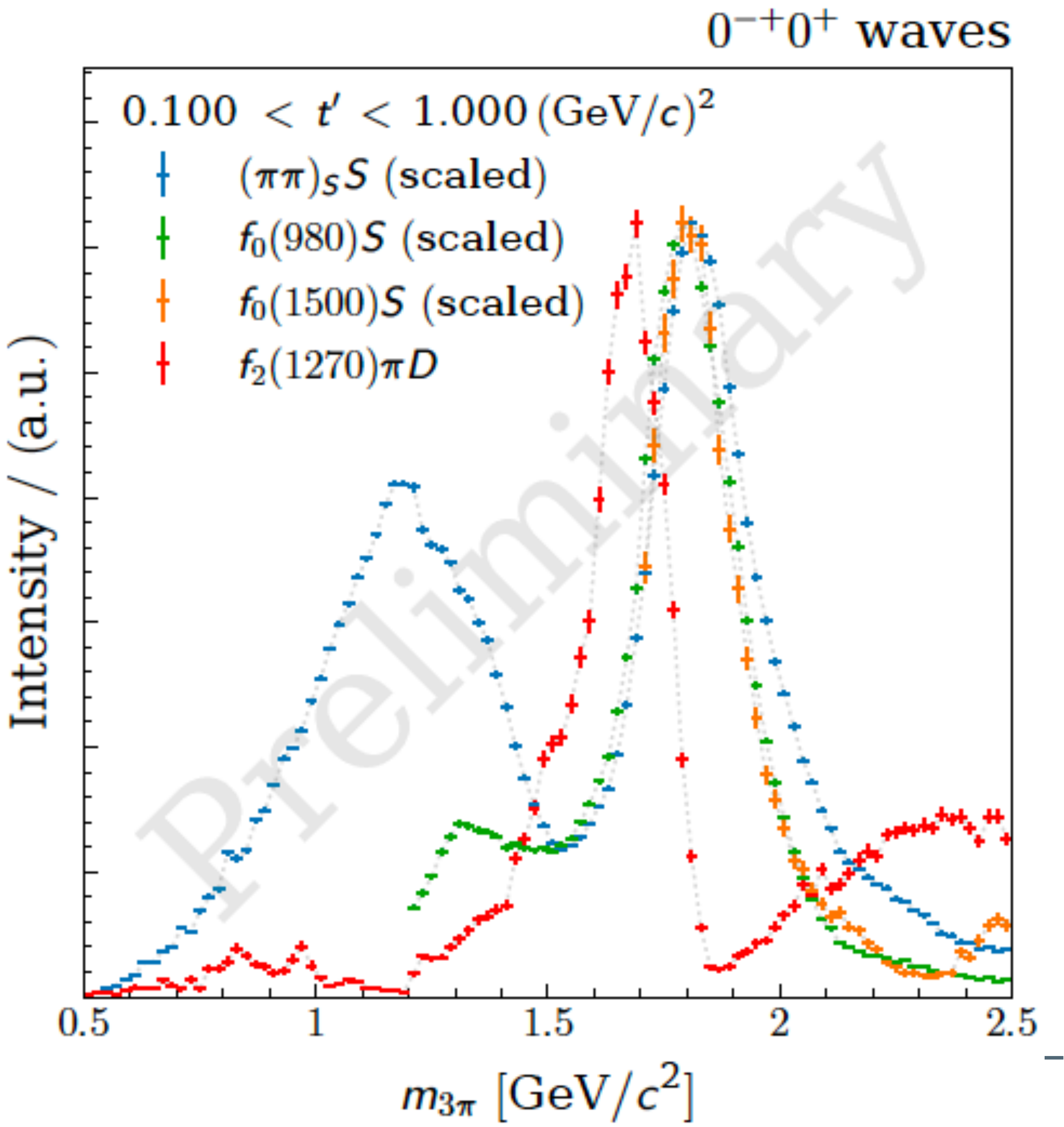

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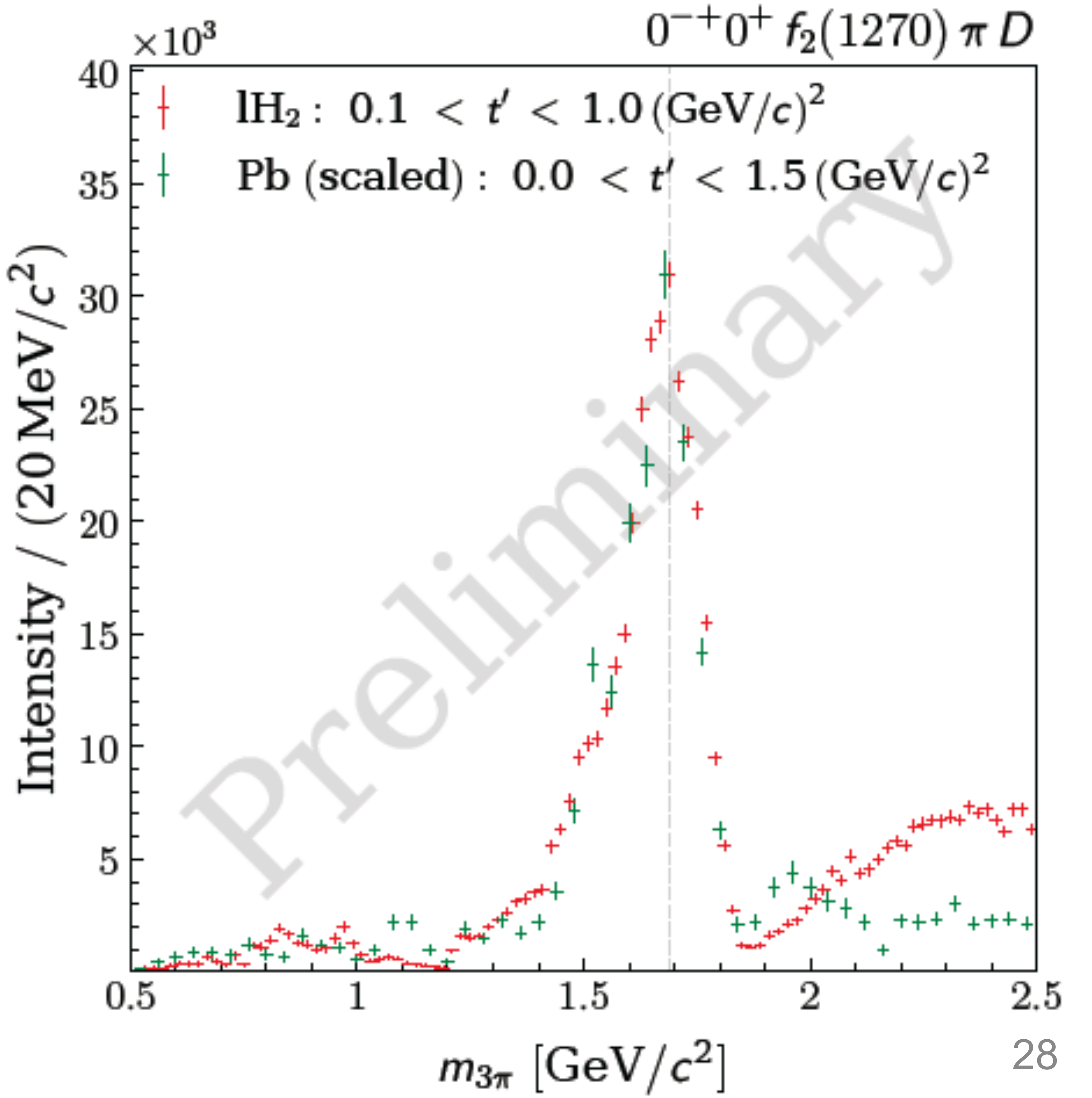
    - $\pi^- + p \rightarrow \pi^-\pi^+\pi^- + p'$
  - Pb/Ni: (2009) $25 \cdot 10^6$ evts. - $t' \in [0., 1.0]$ GeV/c^2
    - $\pi^- + Ni \rightarrow \pi^-\pi^+\pi^- + Ni'$
    - $\pi^- + Pb \rightarrow \pi^-\pi^+\pi^- + Pb'$



COMPASS Spectroscopy - Partial Wave Truncation

Wave selection:

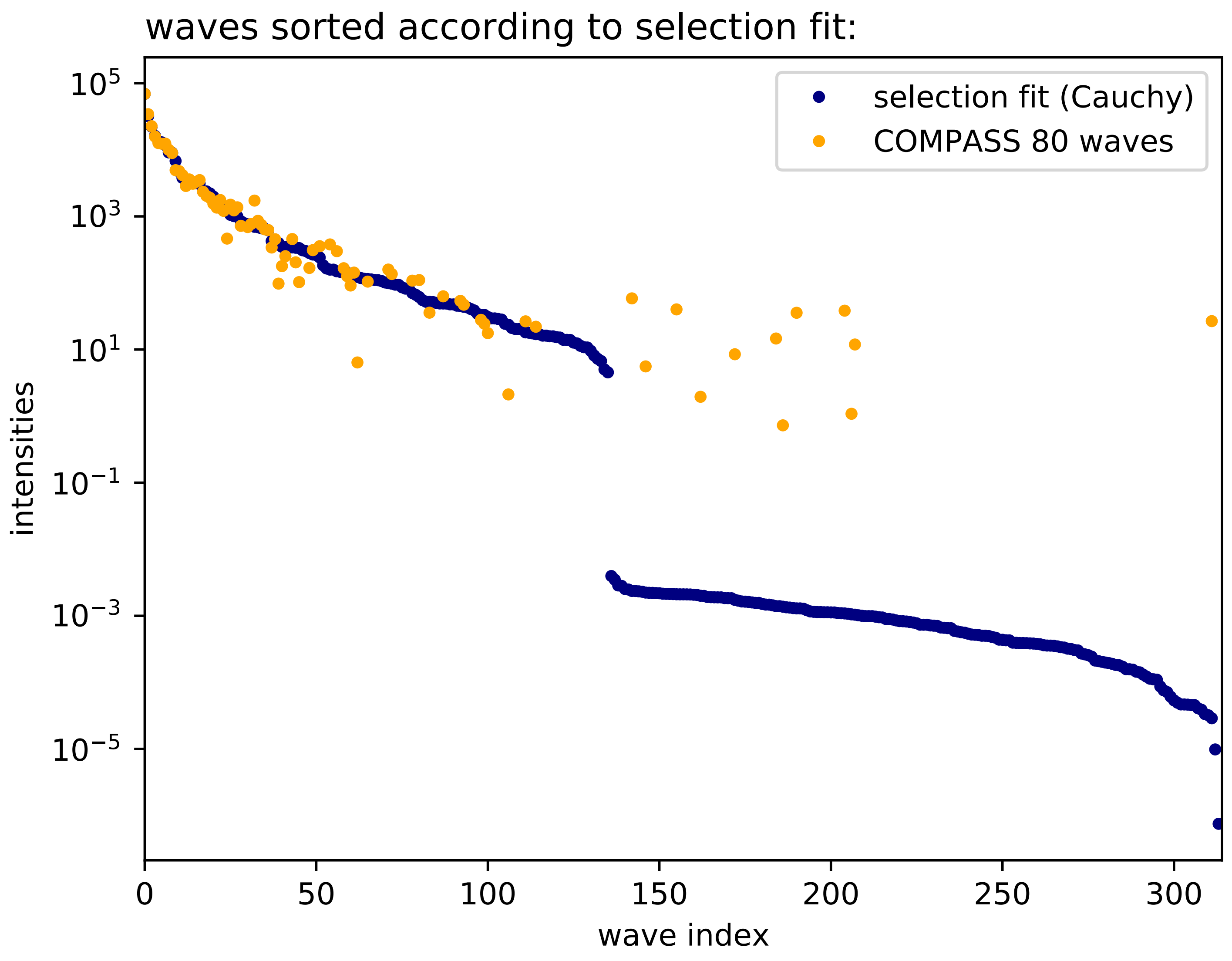
$$\mathcal{I}(\tau_n; m_X, t') = \sum_{\varepsilon=\pm1} \sum_{r=1}^{N_r} \left| \sum_{i}^{N_{\text{waves}}} \mathcal{T}_i^{r\varepsilon}(m_X, t') \Psi_i^{\varepsilon}(\tau_n; m_X) \right|^2 + |\mathcal{T}_{\text{flat}}(m_X, t')|^2$$

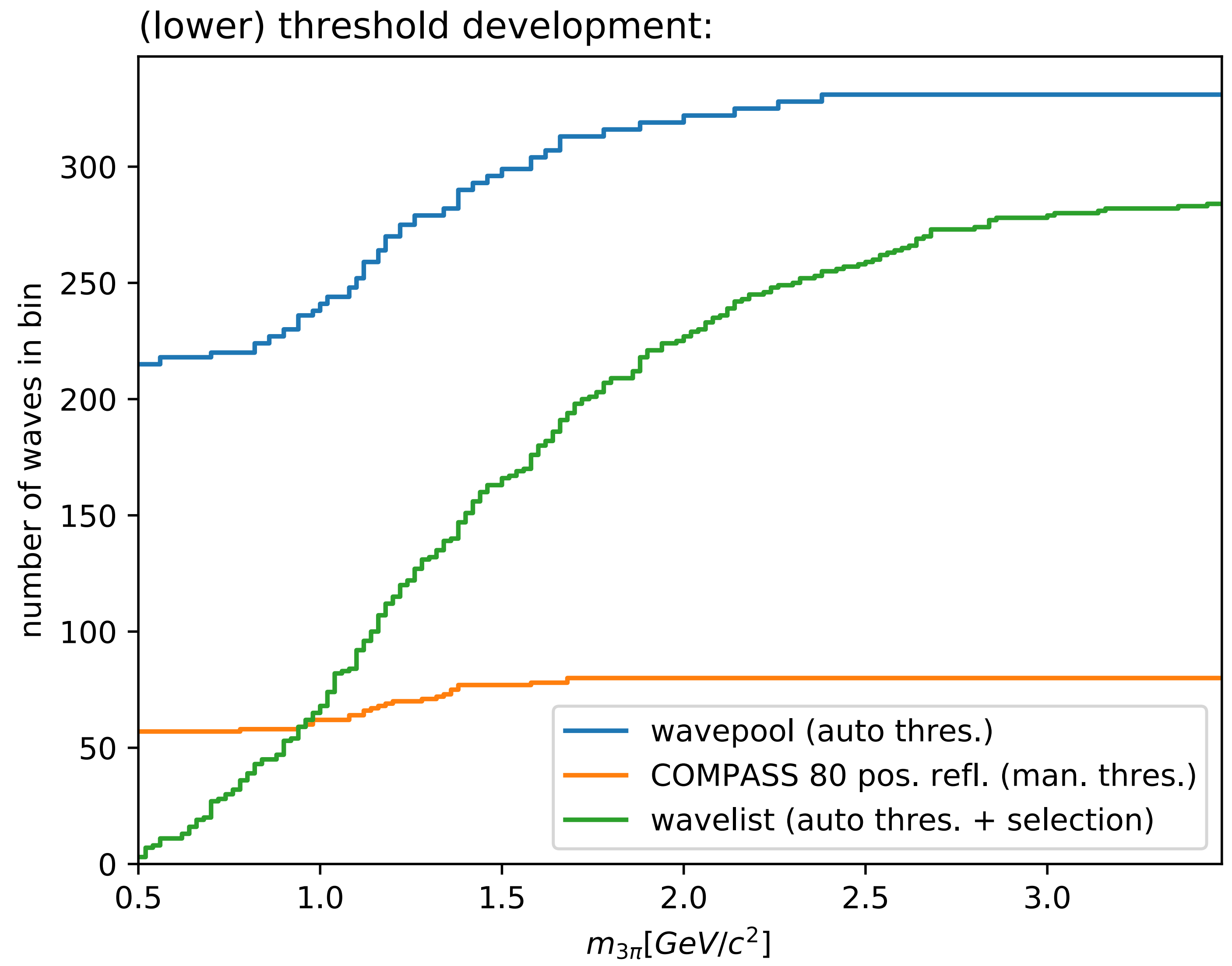
$$= \sum_{\varepsilon=\pm1} \sum_{i,j}^{N_{\text{waves}}} \overline{\Psi}_i^{\varepsilon}(\tau_n; m_X) \overline{\varrho}_{ij}^{\varepsilon}(m_X, t') \overline{\Psi}_j^{\varepsilon^*}(\tau_n; m_X) + |\overline{\mathcal{T}}_{\text{flat}}(m_X, t')|^2$$

- mathematically: write PWA expansion as infinite series
- practically: impossible

But where to put cut-off ?

- use physics intuition
  - first analysis: use wave set from BNL (42 waves)
  - second analysis: develop hand made wave set (88 waves)
- extract cut-off from data
  - new analysis: develop automatic wave selection algorithm (457 waves selected out of 789 waves offered - mass dependent





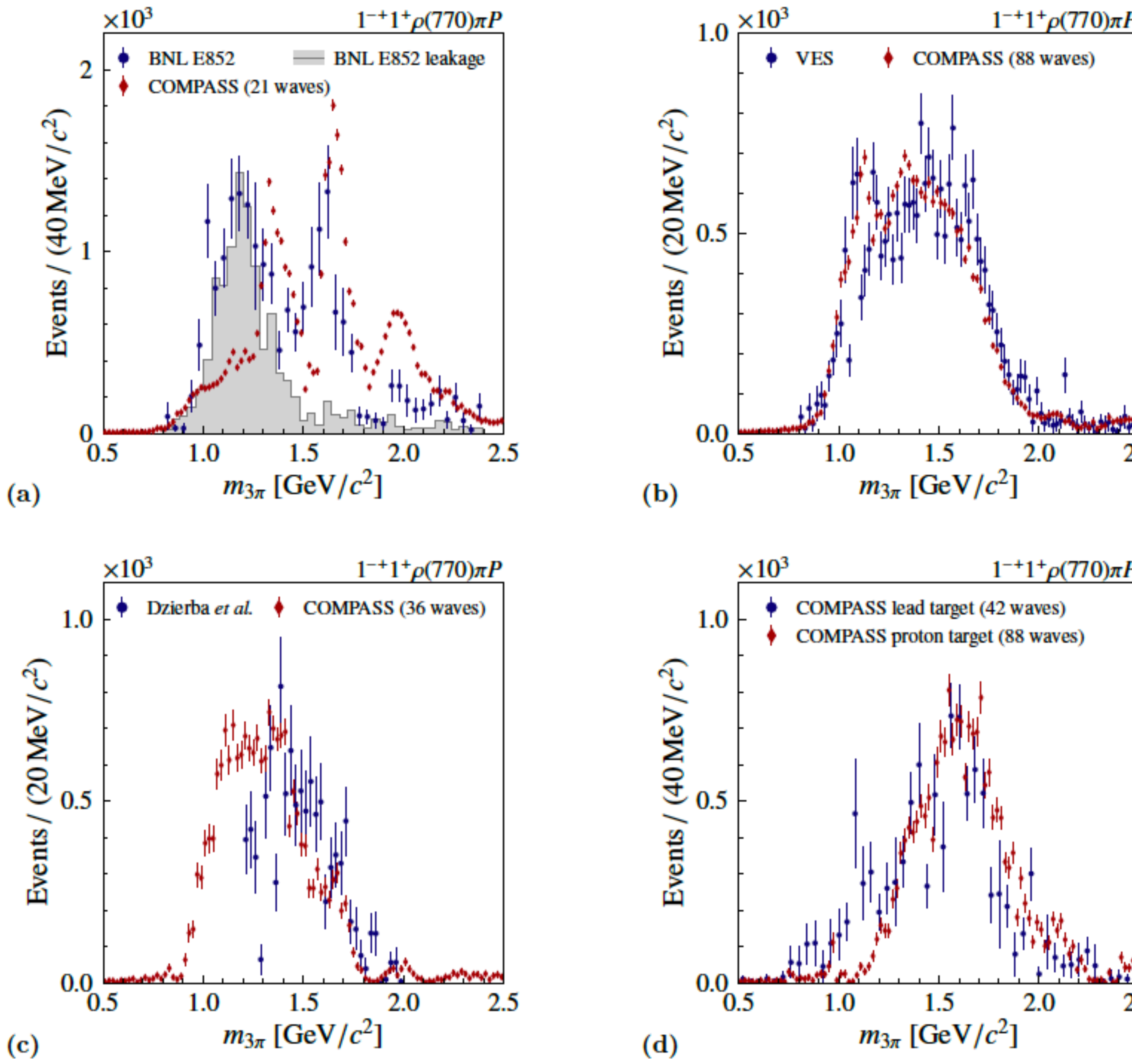
Kaspar et al., HADRON 2019, 471-476 • e-Print: 1912.09849

PWA Model and The Spin Exotic $\pi_1(1600)$

Confusion about shape and existence of $\pi_1(1600)$ from previous experiments

- different wave sets (size !!)
- different t' range

COMPASS could reconcile previous observations and resolve disagreements



The Isobar Model and Beyond

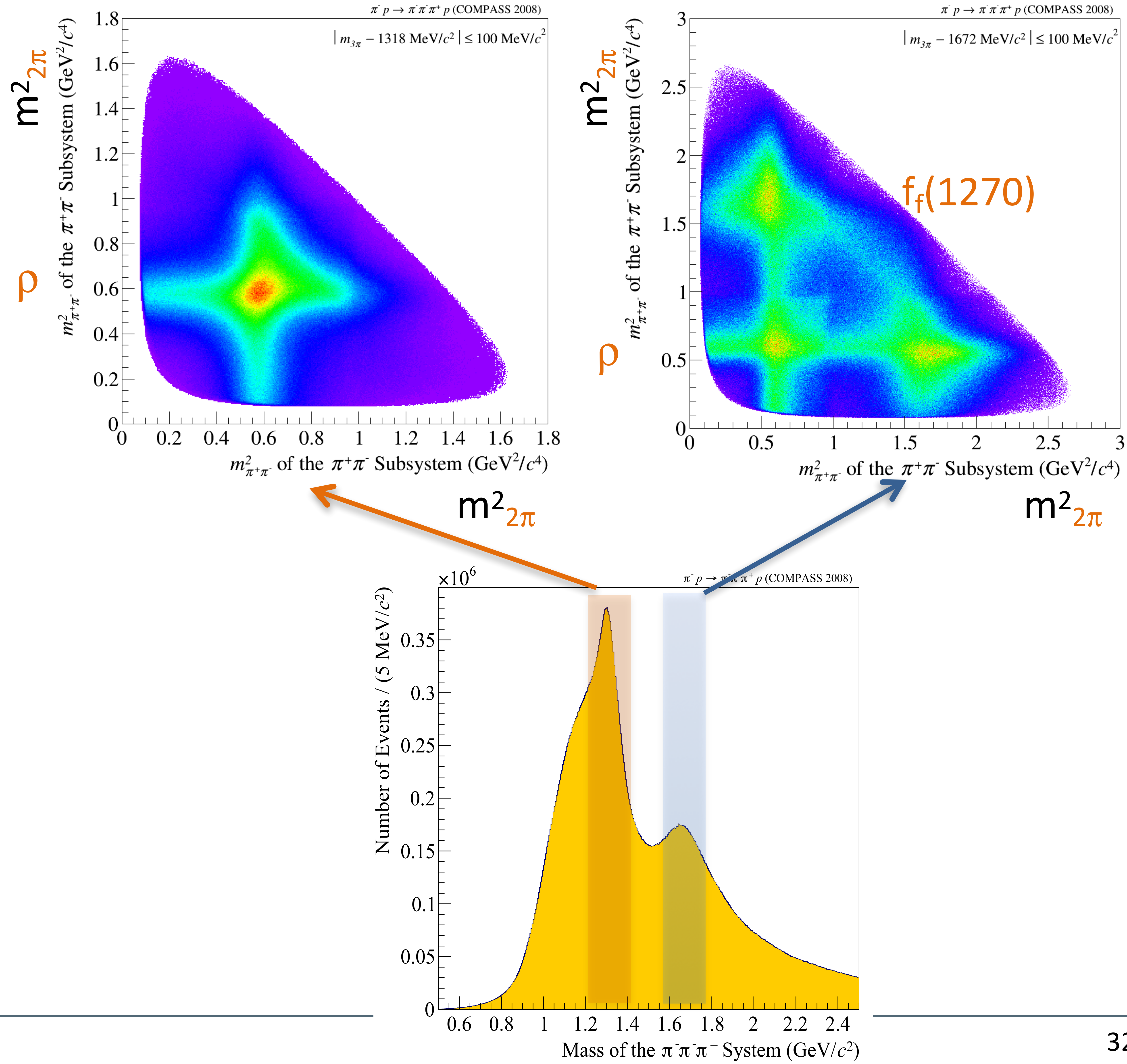
Motivation for Isobar Model

Exzellenzcluster ORIGINS

Standard PWA in production or decay

- analyze (model) Dalitz plot
  - one fixed mass ($\bar{p}p$, B, D meson decays)
  - diffractive production, τ or radiative decays: one Dalitz plot for each 3-body mass bin
- model Dalitz plot through set of amplitudes to minimize χ^2, $\mathscr{L}$
- each amplitude corresponds to ONE isobar state (known or new assumed meson)

Extract content from Dalitz plot for each J^{PC} from data (freed isobar)



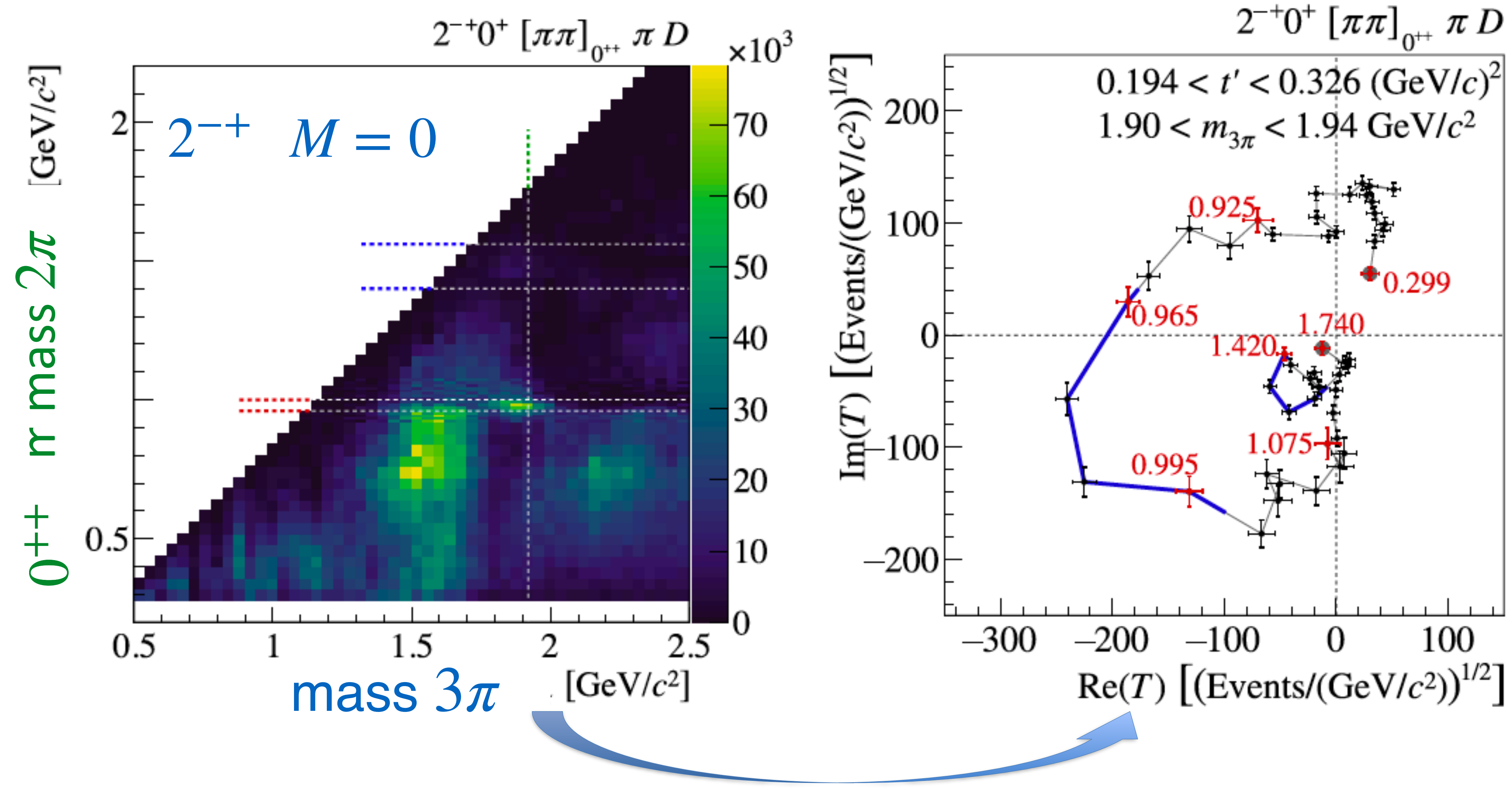
Studying the Isobar Structure

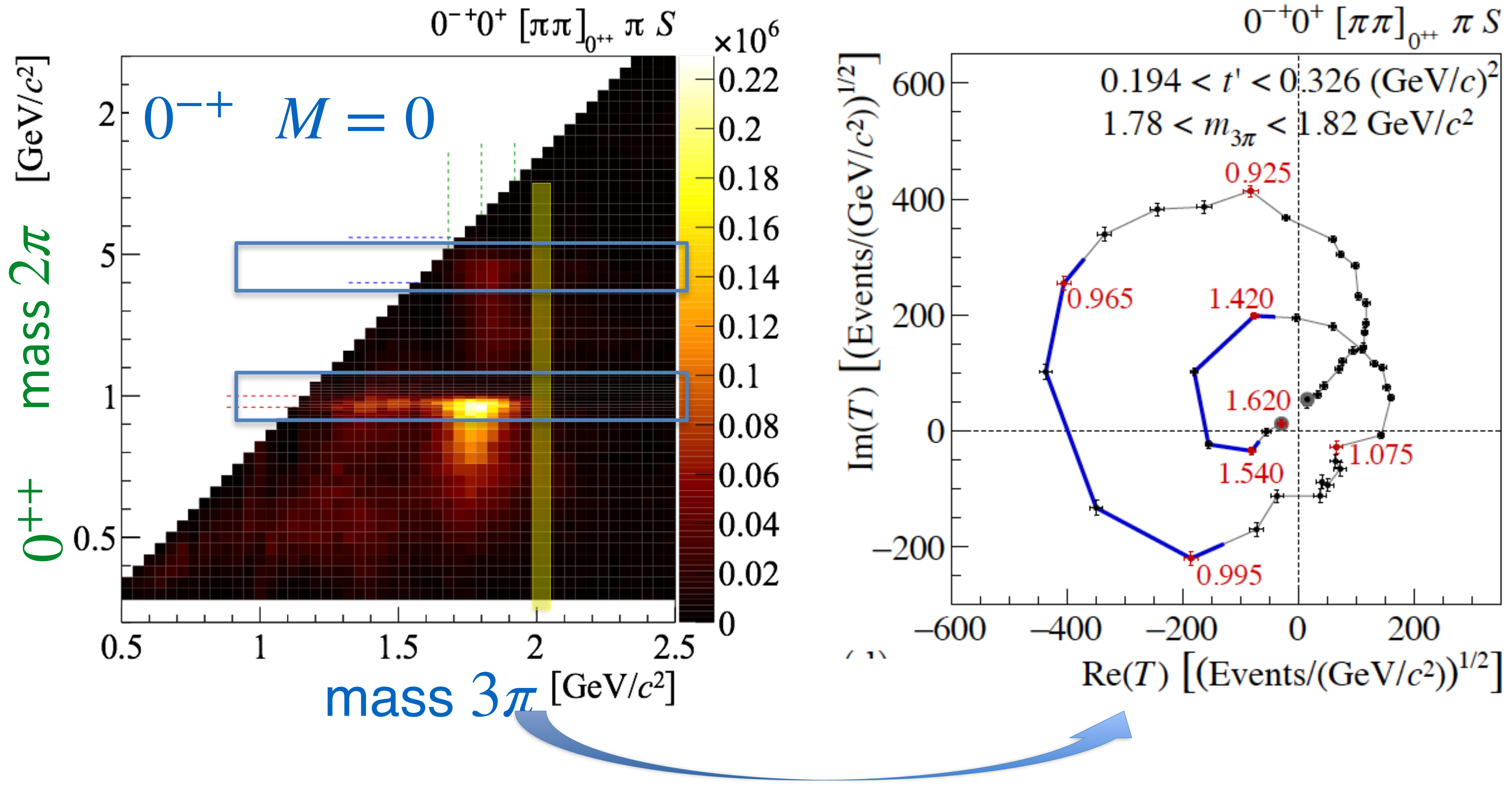
Exzellenzcluster ORIGINS

- COMPASS
  - extract $J^{PC}_{2\pi}$ isobar structure for each quantum number $J^{PC}_{3\pi}$ of 3π system
  - analyze Argand diagram (complex 2π amplitude)

- Why do so ?
  - avoid unitarity problem with overlapping isobars
  - study isobar structure (spectroscopy)
  - account for non-resonant contributions (e.g. rescattering)

- affects result of PWA (redistribution of intensities among PW)





Argand Diagram

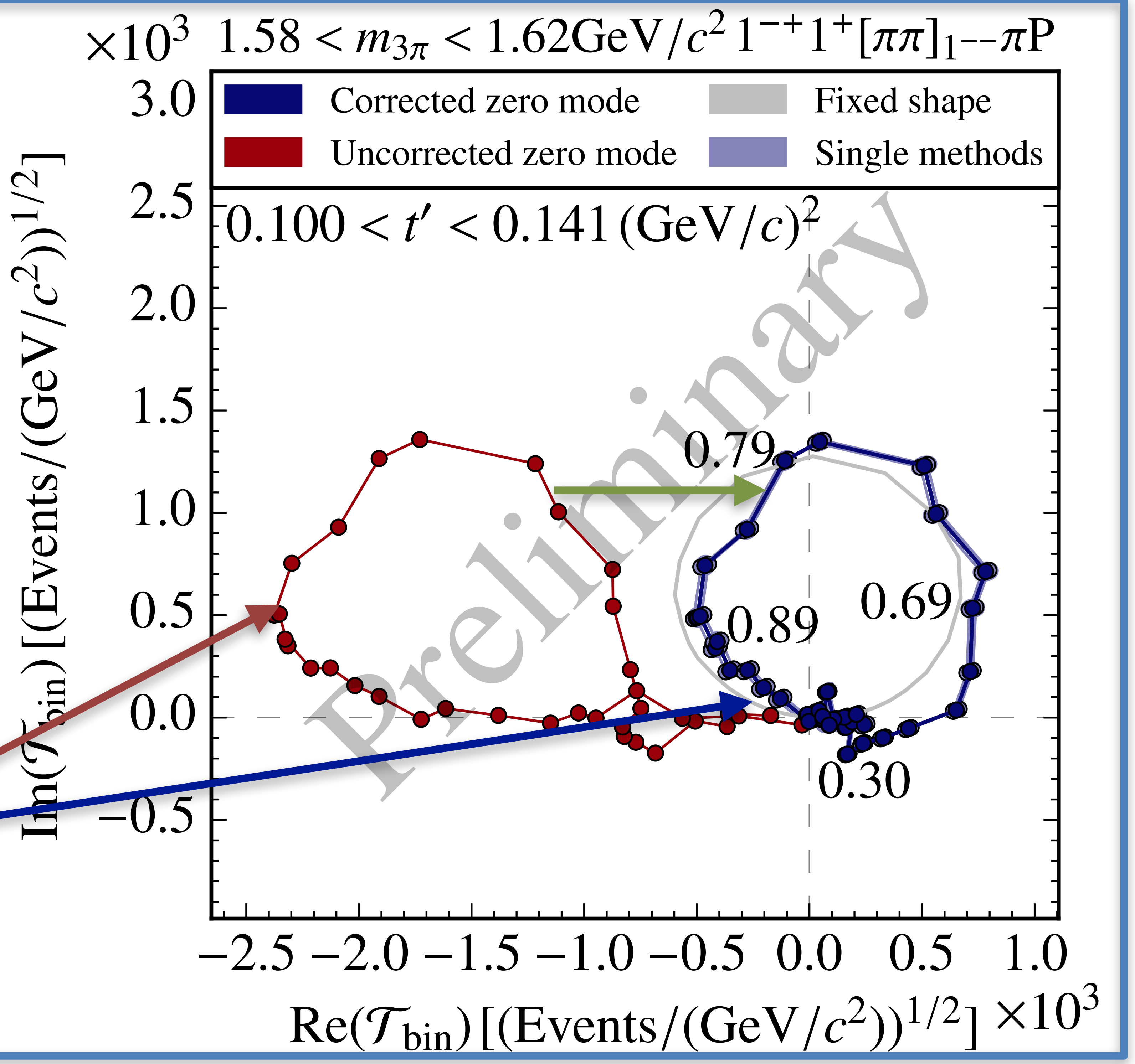
COMPASS *Phys.Rev.D* 95 (2017) 3, 032004   Krinner et al., Phys.Rev.D 97 (2018) 11

Constrained Freedom for all isobars !!

- Ambiguities can be resolved
  - minimal assumptions like: one BW resonance within isobar
  - finds resonance parameters itself
  - unconstrained shape

- Isobar model:
  - force amplitude on Argand circle
- freed isobar technique:
  - unconstrained path along circle

Both solutions give same 3π amplitude



Information from Analysis

Krinner&Paul *Nucl.Part.Phys.Proc.* 312-317 (2021) 48-52,
Nucl.Part.Phys.Proc. 312 (2021) 317

COMPASS *Phys.Rev.D* 105 (2022) 1

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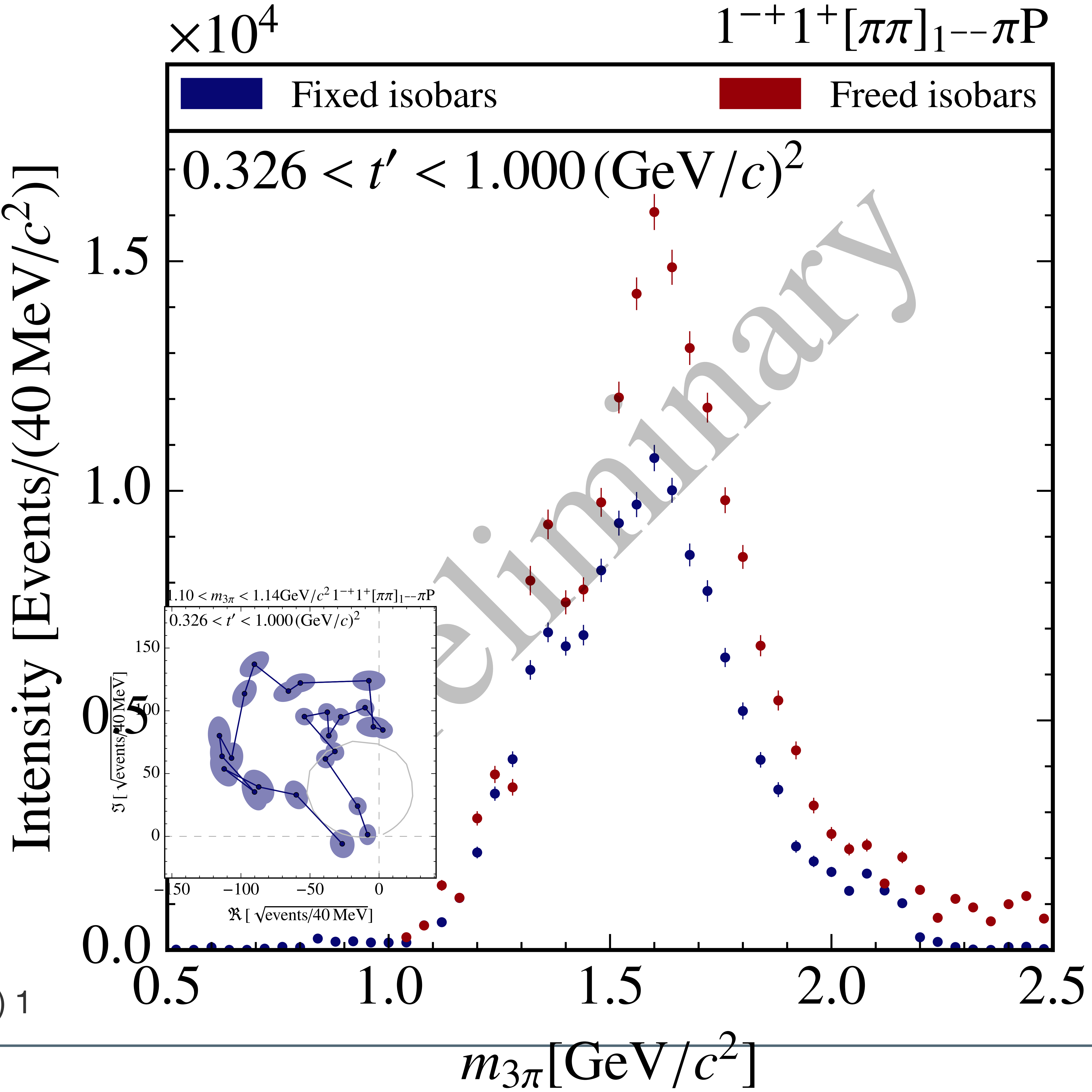

COMPASS *Phys.Rev.D* 105 (2022) 1

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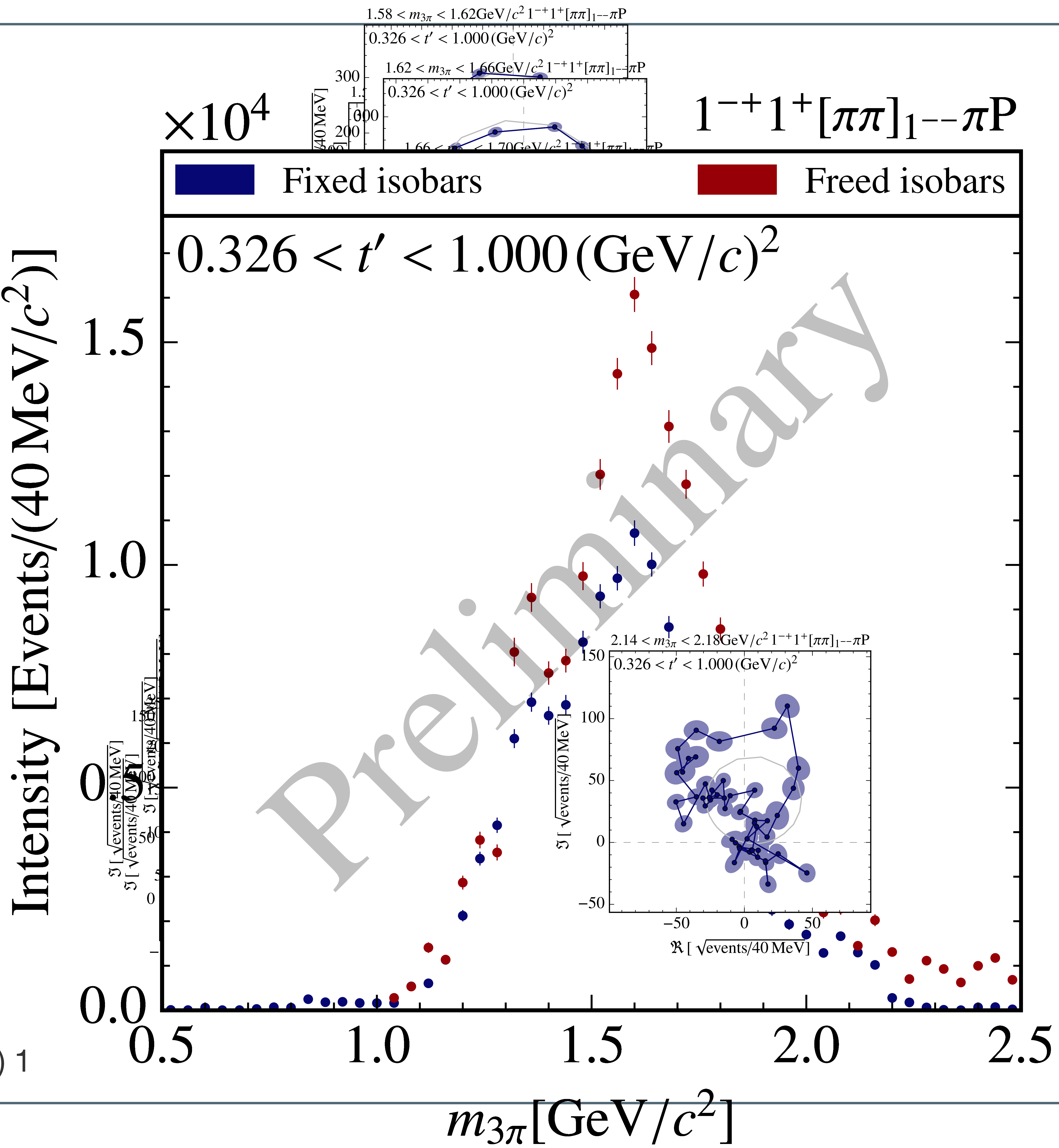


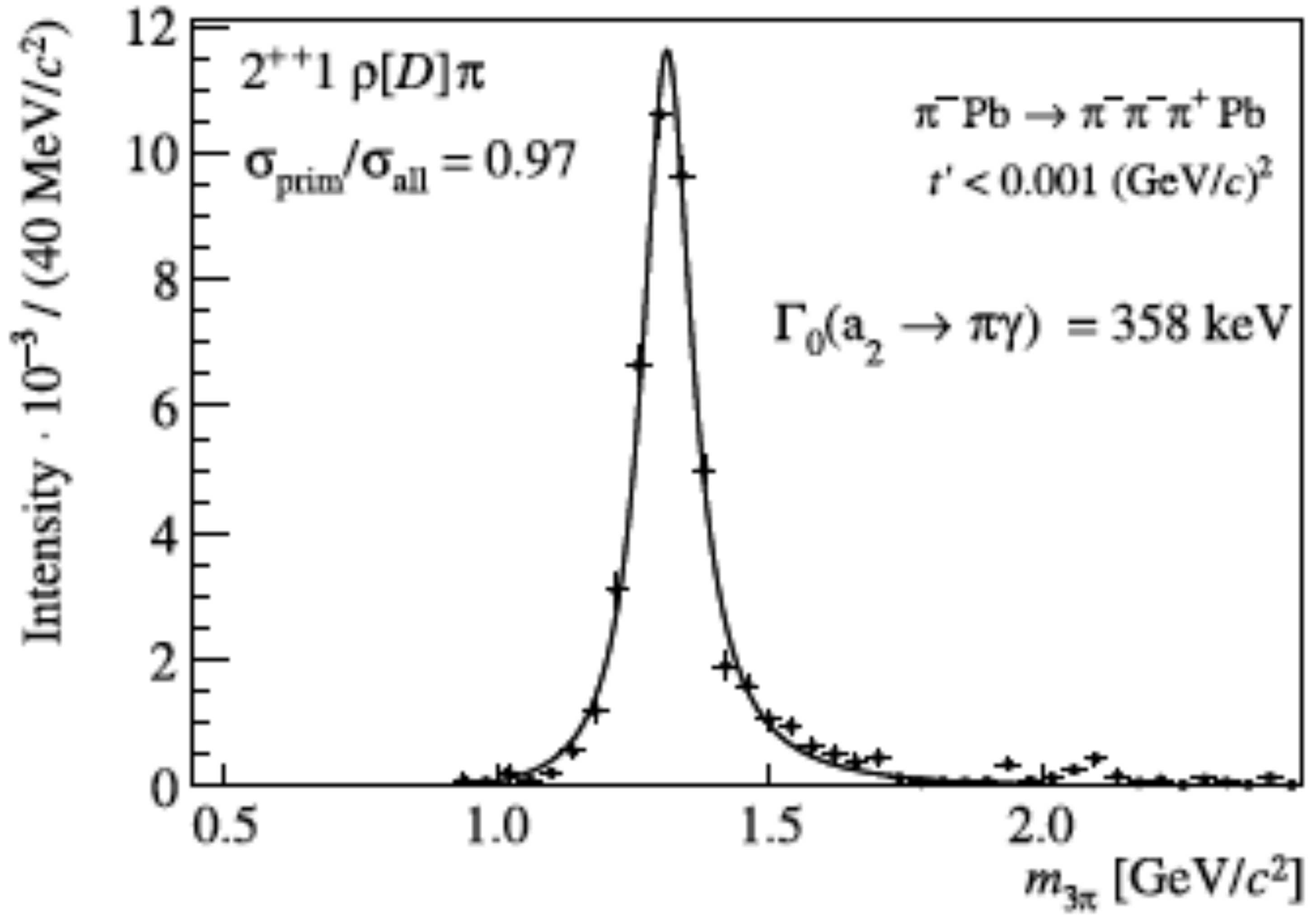
COMPASS *Phys.Rev.D* 105 (2022) 1

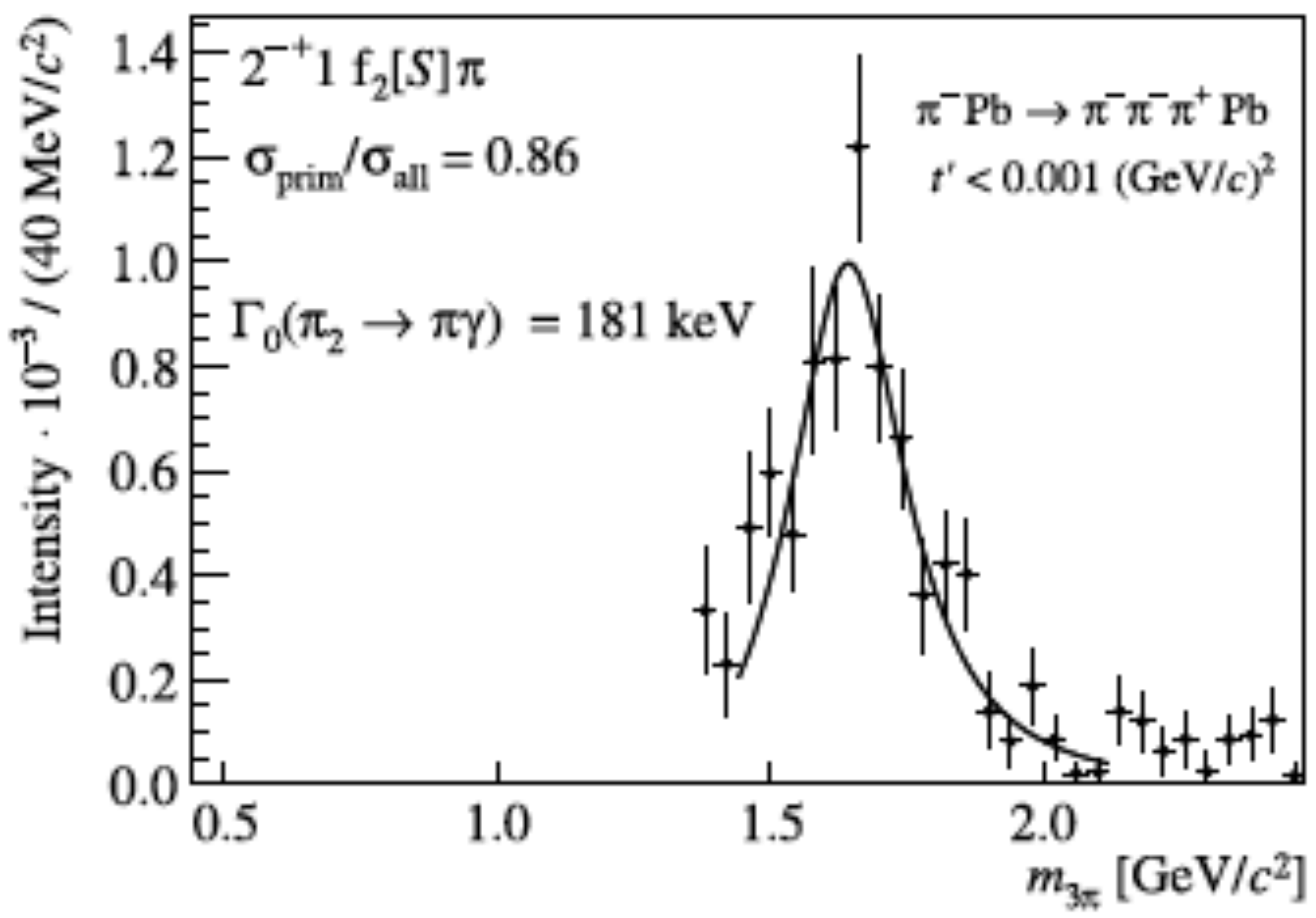
Use Primakoff Reactions

Radiative Widths of Excited Mesons

Primakoff reactions allow to probe $\pi^- + \gamma \rightarrow X \rightarrow \pi^-\pi^+\pi^-$ via $\pi^- + Z \rightarrow \pi^-\pi^+\pi^- + Z'$

- use spin projection $M = 1$ to identify Primakoff at very low t'
- extract Primakoff signal and use interference with diffraction (Phase $\Delta\Phi_{\gamma\mathbb{P}} \approx \pi/2$)
- perform PWA at very low t'
- extract radiative width ($\Gamma_{\gamma\pi}$) of $a_2(1320)$, $\pi_2(1670)$





COMPASS *Eur.Phys.J.A* 50 (2014) 79

A First 2-Body Analysis

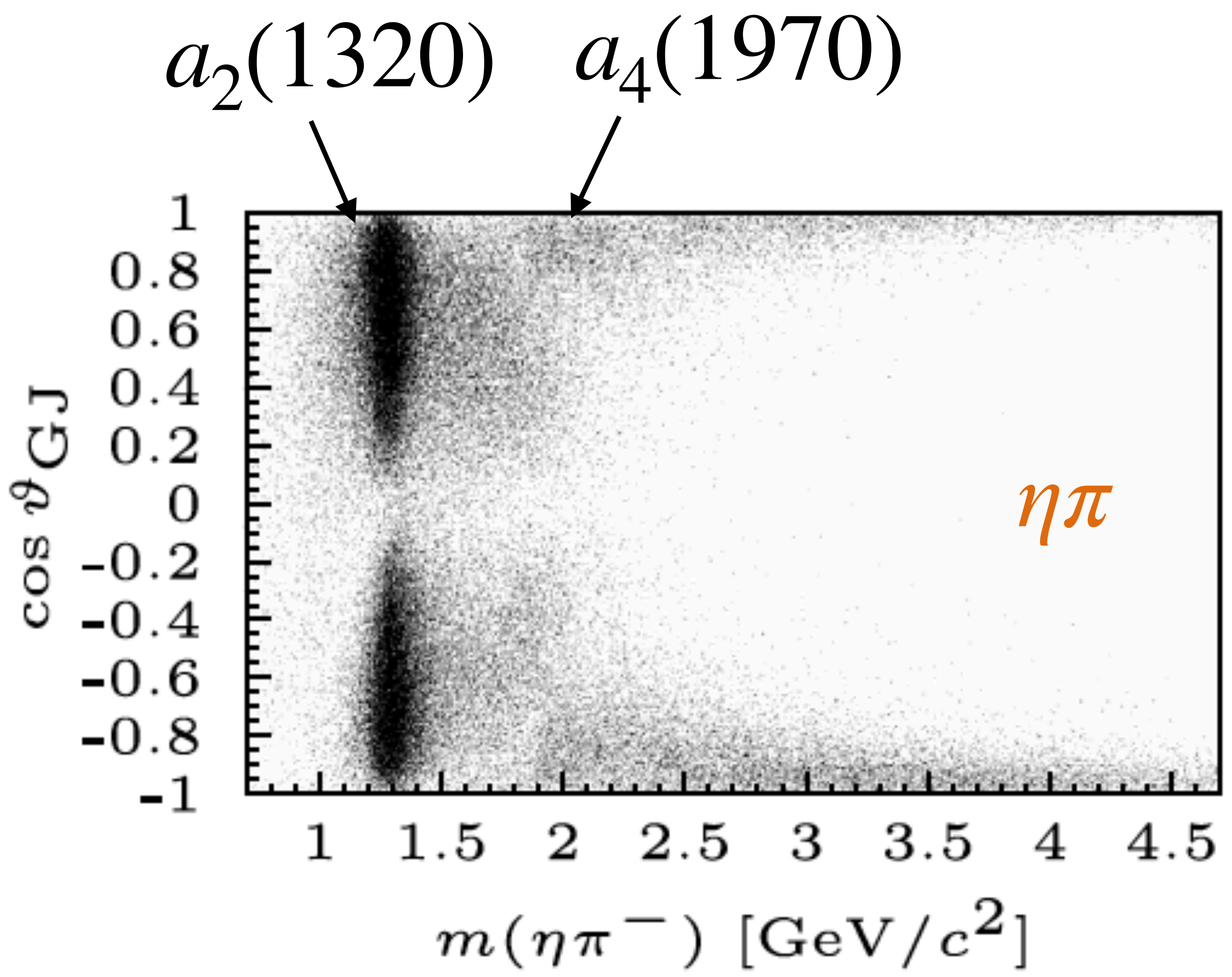
A 2-body final state ($\eta\pi$ and $\eta'\pi$)

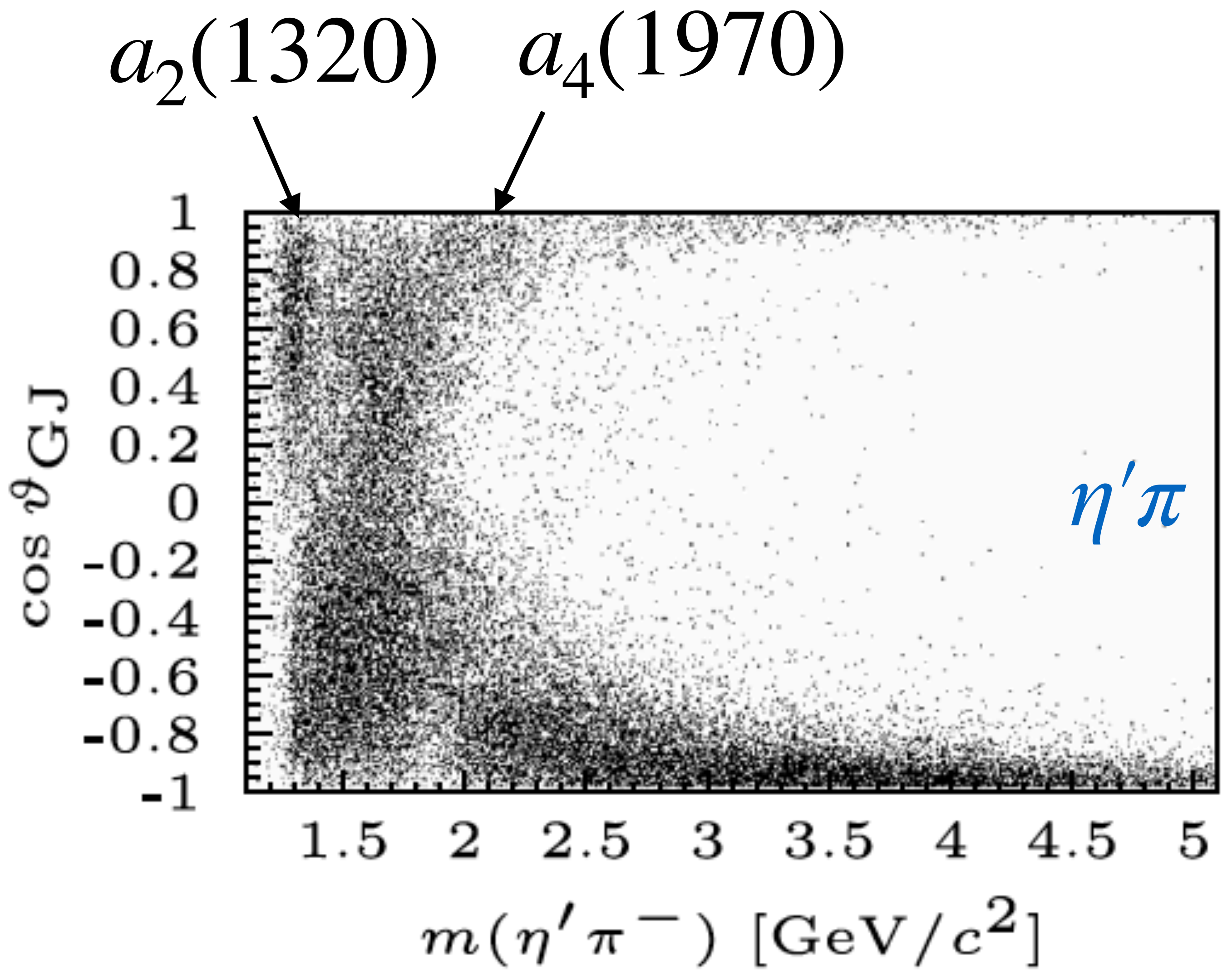
Exotic states observed previously by BNL in $\eta\pi$ and $\eta'\pi$

- Partial wave analysis (expansion in Legendre polynoms)
- Striking difference in angular distribution in both resonance region and continuum
- Different P(mostly $\eta\pi$)/D(mostly $\eta'\pi$)-wave amplitudes and interferences

emission along the beam ←

emission opposing the beam ←



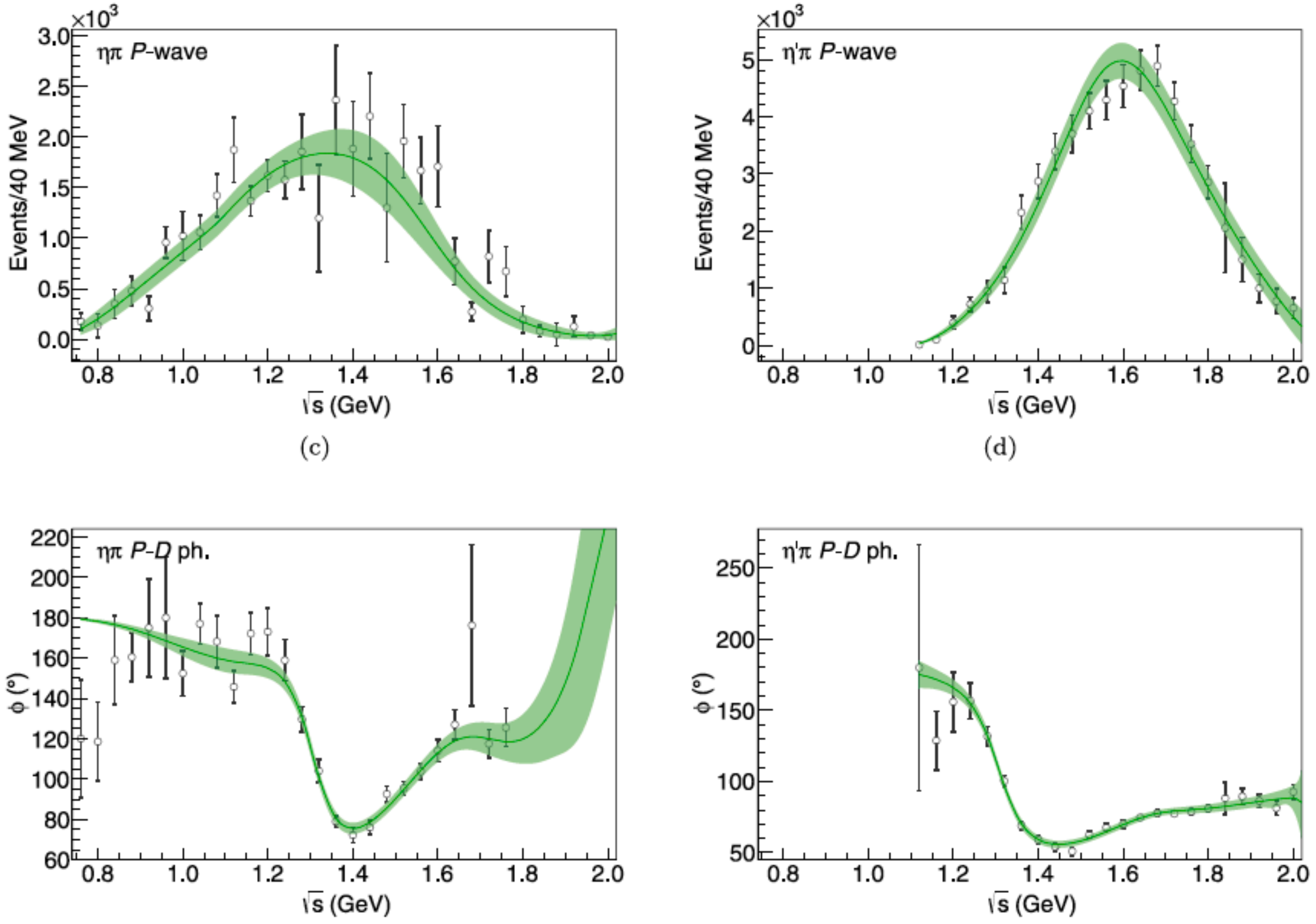


COMPASS Phys.Lett.B 740 (2015) 303-311, *Phys.Lett.B* 811 (2020) 135913 (erratum)

A 2-body final state ($\eta\pi$ and $\eta'\pi$)

BNL claimed $\pi_1(1400)$ and $\pi_1(1600)$

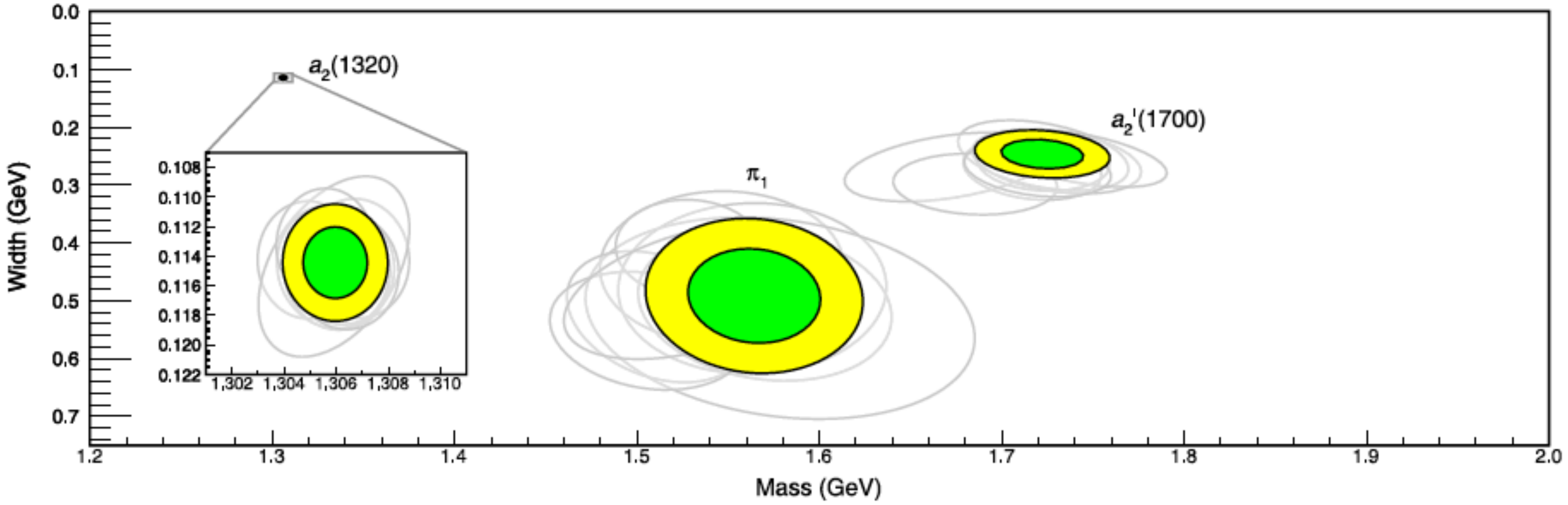
- Classical resonance fit inconclusive on resonance for $J^{PC} = 1^{-+}$
- In cooperation with JPAC: new description using unitarity constrained coupled channel pole-fit with 2 waves
- 2 known poles in $J^{PC} = 2^{++}$ $a_2(1320), a_2'(1700)$
- only 1 known pole in $J^{PC} = 1^{-+}$ $\pi_1(1600)$ in $\eta'\pi$



Conclusions:

- $\pi_1(1400)$ likely a fit artifact
- coupled channel pole fit is reliable tool
- JPAC very helpful for spectroscopy

Thanks to Mike Pennington

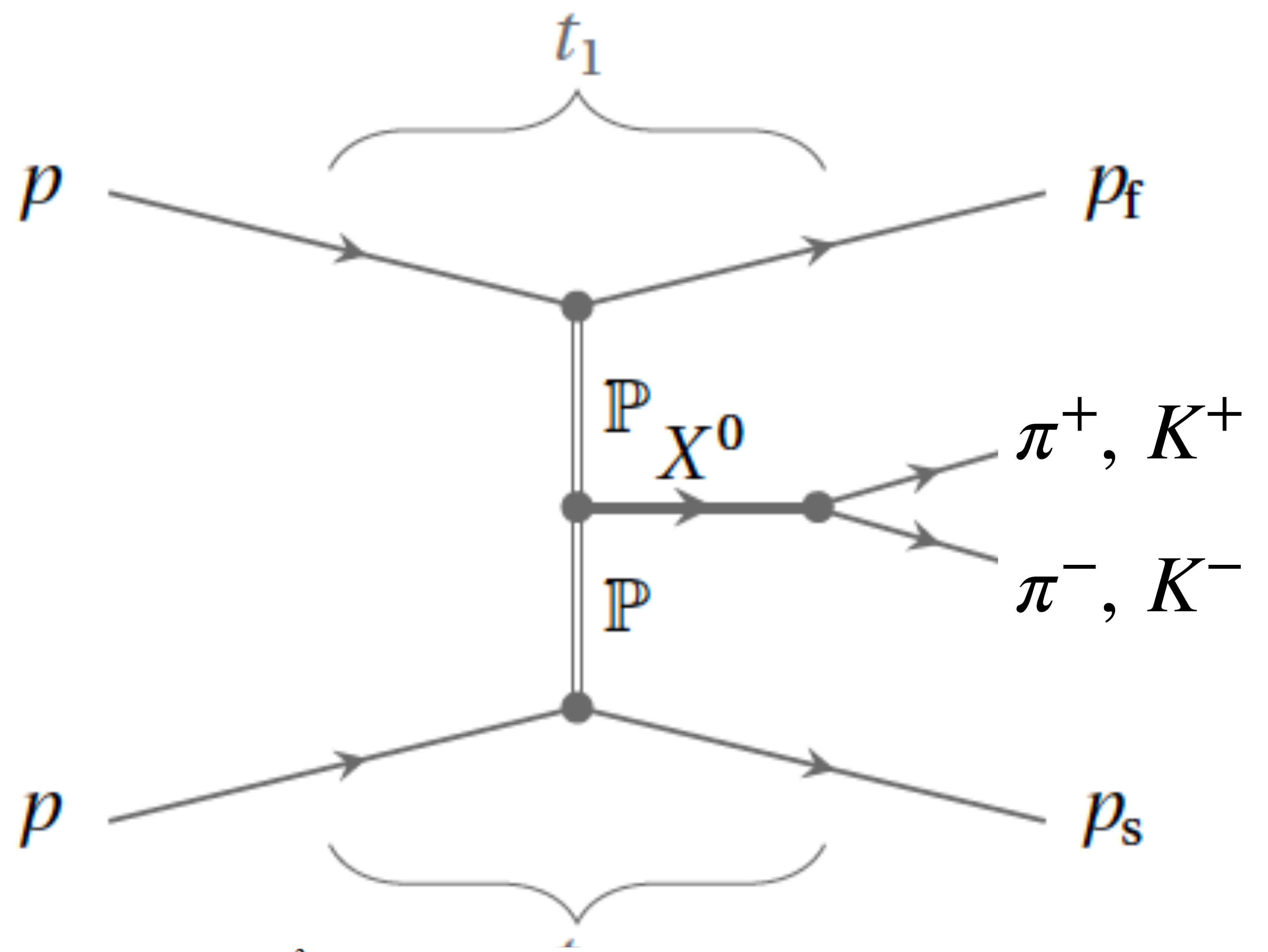


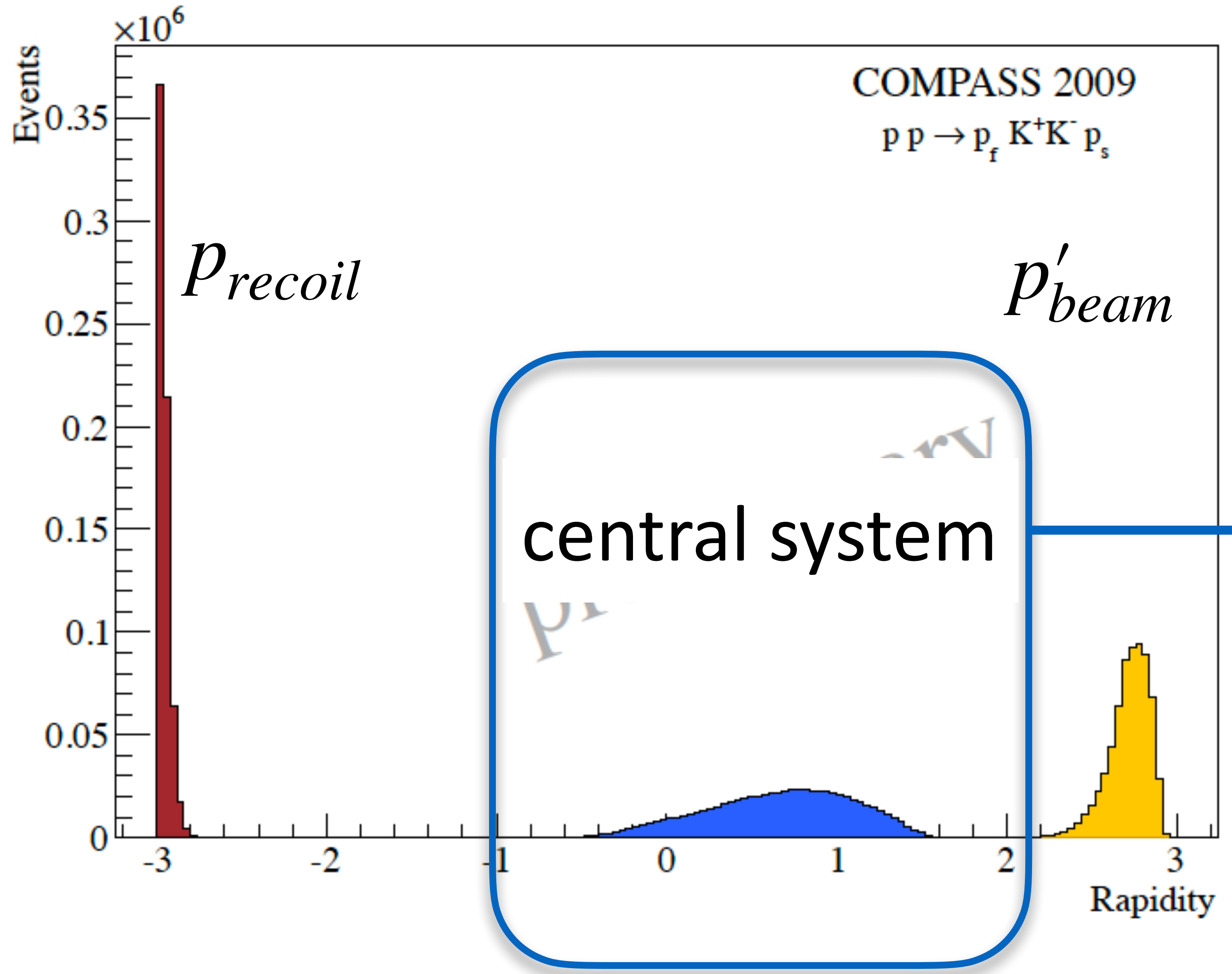
JPAC & COMPASS *Phys.Lett.B* 779 (2018) 464-472

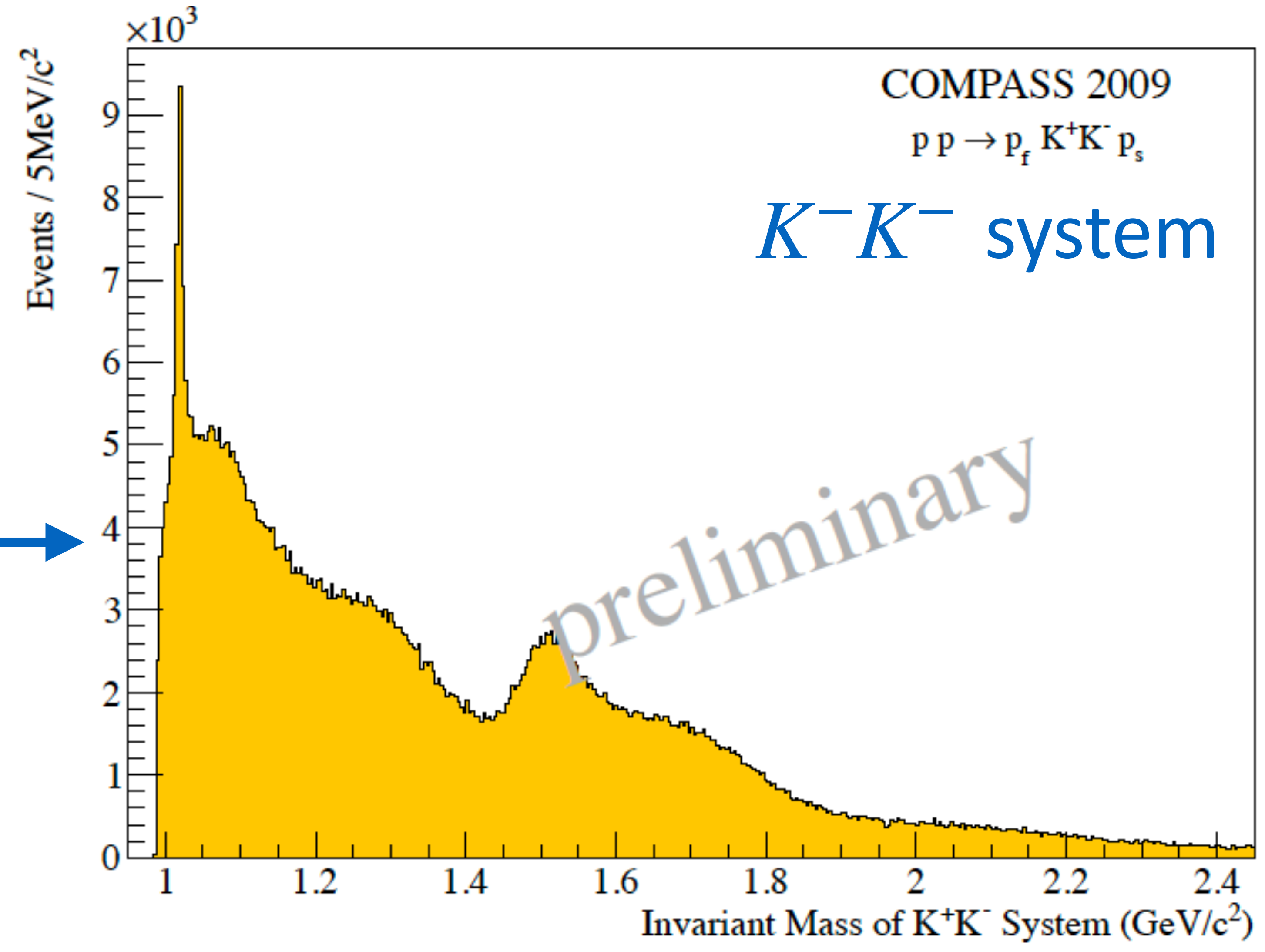
Central Production - A Glueball Filter

Central Production

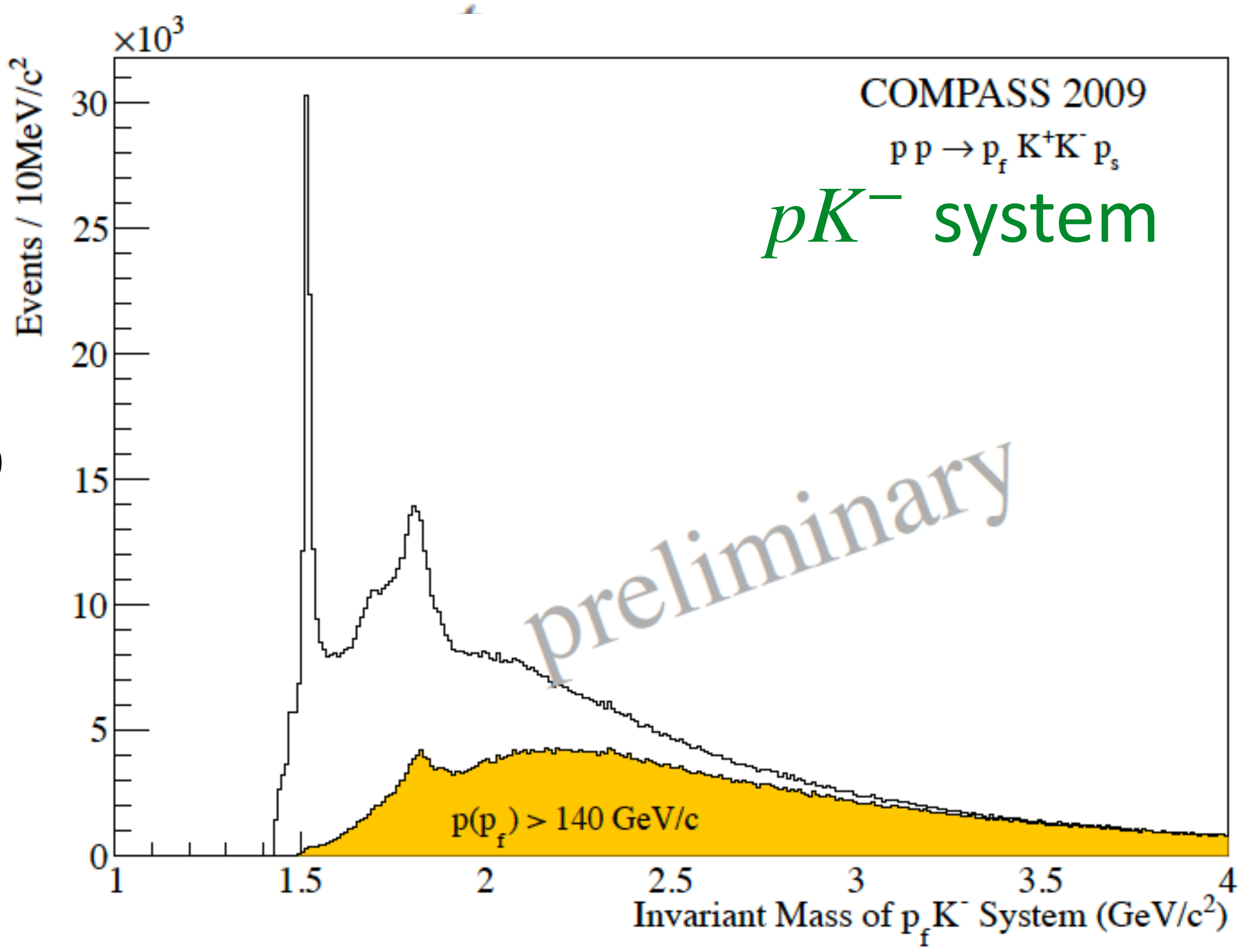
- Concept: Central production is mediated via double Pomeron exchange
- kinematic signature: rapidity gap of central system
- requires high energy beams
  - Regge exchange competing at lower energies
  - rapidity gap smeared at low energies







but also



$(hh)^0$ S-wave

Results stayed unpublished !!

- reaction not isolated
  - irreducible contributions of $\rho(770)$ and $\phi(1020)$
  - PWA requires P-waves
  - model fit to intensities and phases ambiguous
  - $f_0(1370)$ undecided (observation requires large destructive interference)
  - statistics insufficient for higher masses

Beam energy of 190 GeV too small for central production

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Exzellenzcluster ORIGINS

$\pi^+\pi^-$

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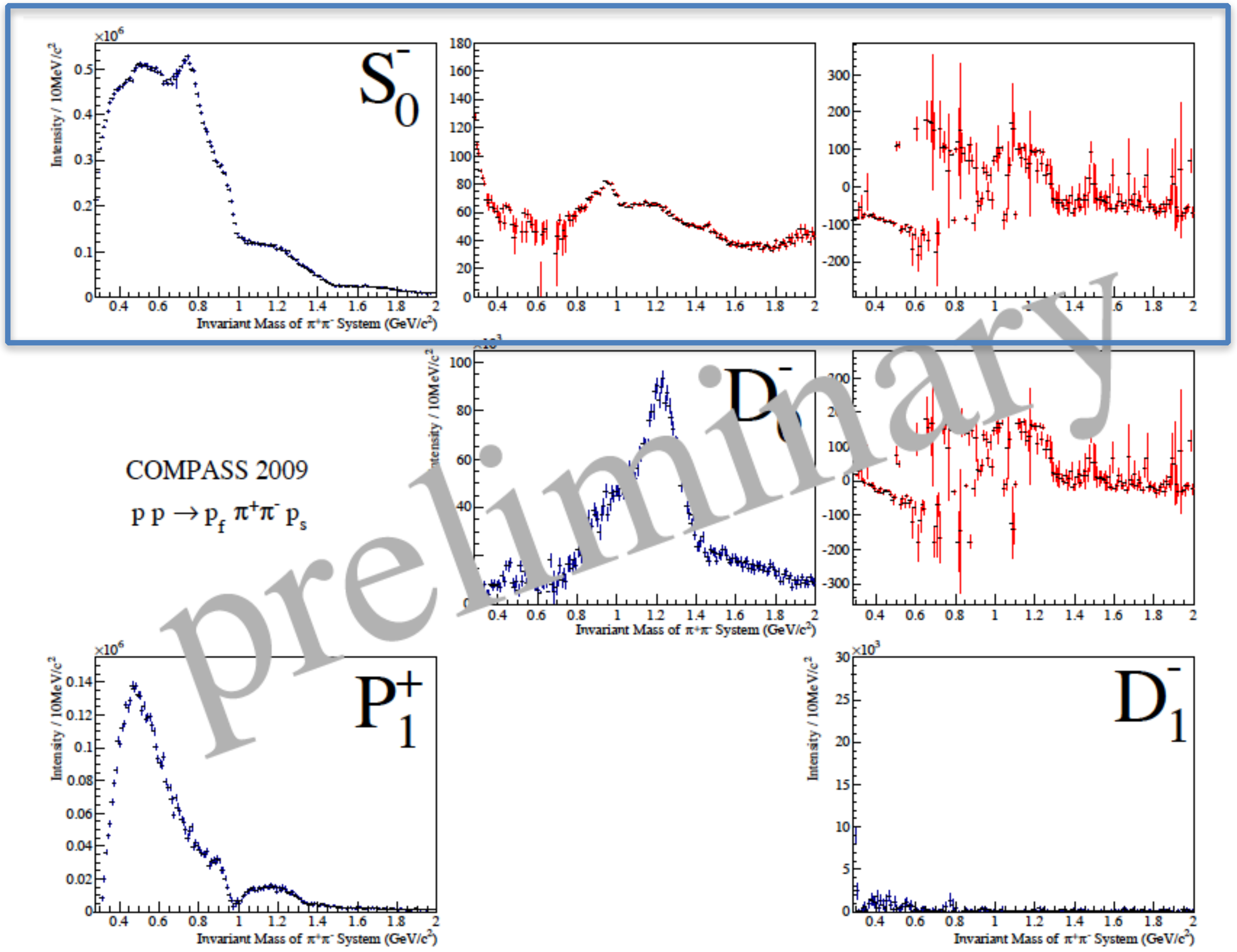
central production



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$K^- K^+$

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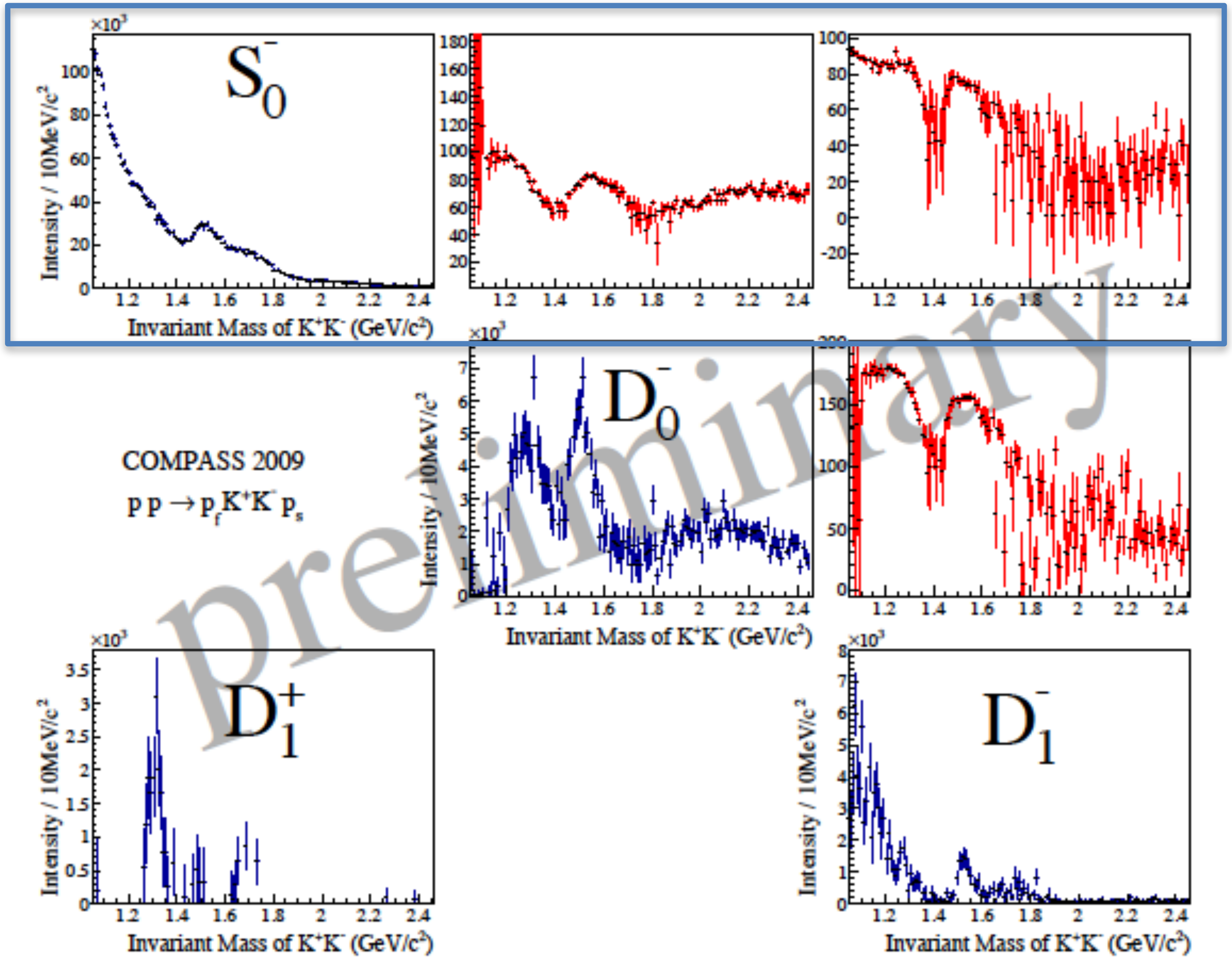

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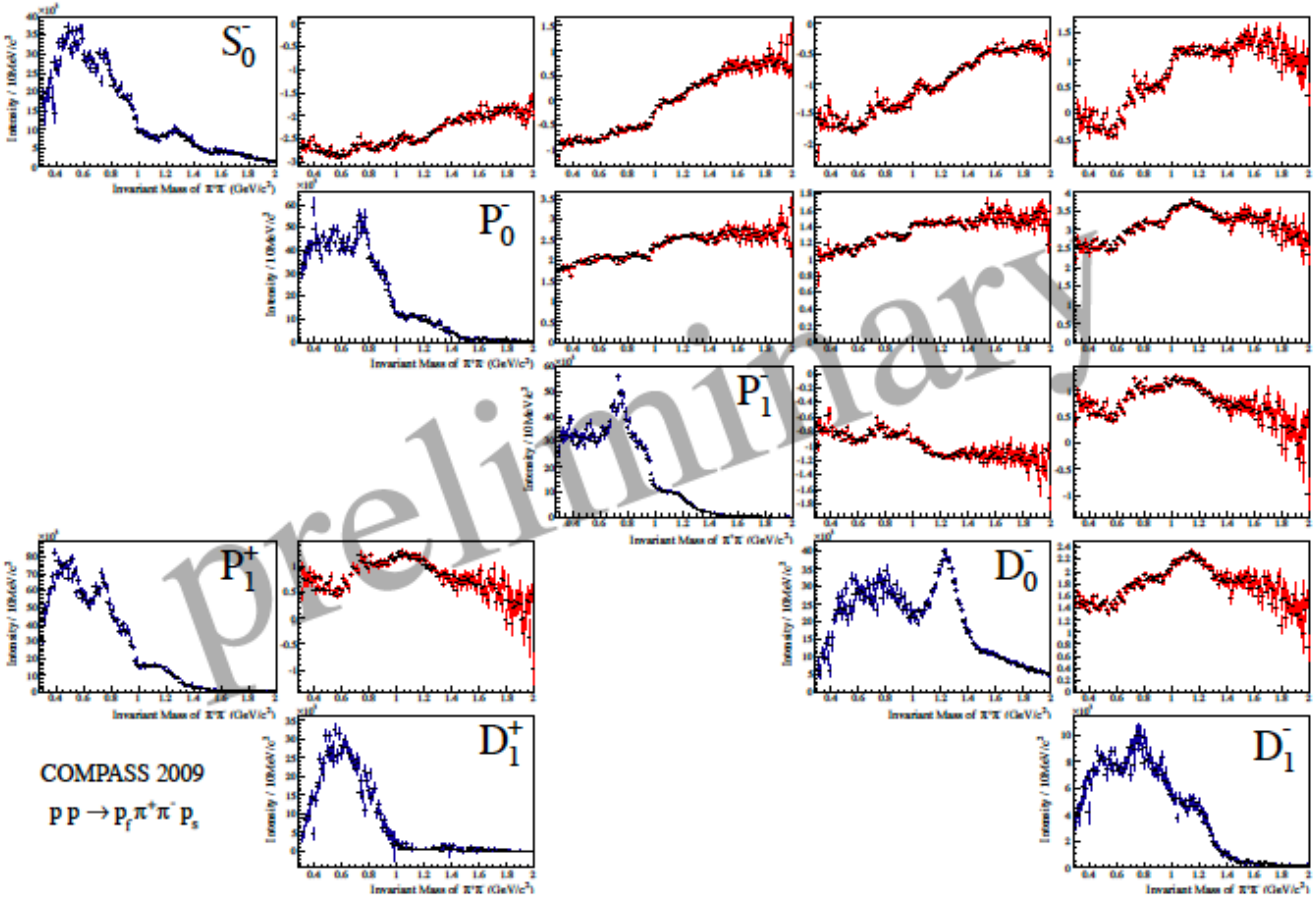

S_0^-
P_0^-
P_1^-
P_1^+
D_0^-
D_1^+
D_1^-
COMPASS 2009
$p\,p \rightarrow p_f \pi^+ \pi^- p_s$
preliminary
Invariant Mass of $\pi^+\pi^-$ (GeV/c^2)

Strangeness

Strange Meson Spectroscopy

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COMPASS hadron beam contains 2% kaons

Strange Meson Spectroscopy

Exzellenzcluster ORIGINS

COMPASS hadron beam contains 2% kaons

- first analysis: $K^- + p \rightarrow K^-\pi^+\pi^- + p'$
- $0.7 \cdot 10^6$ evts in $t' \in [0.1, 1.0]$ GeV/c^2

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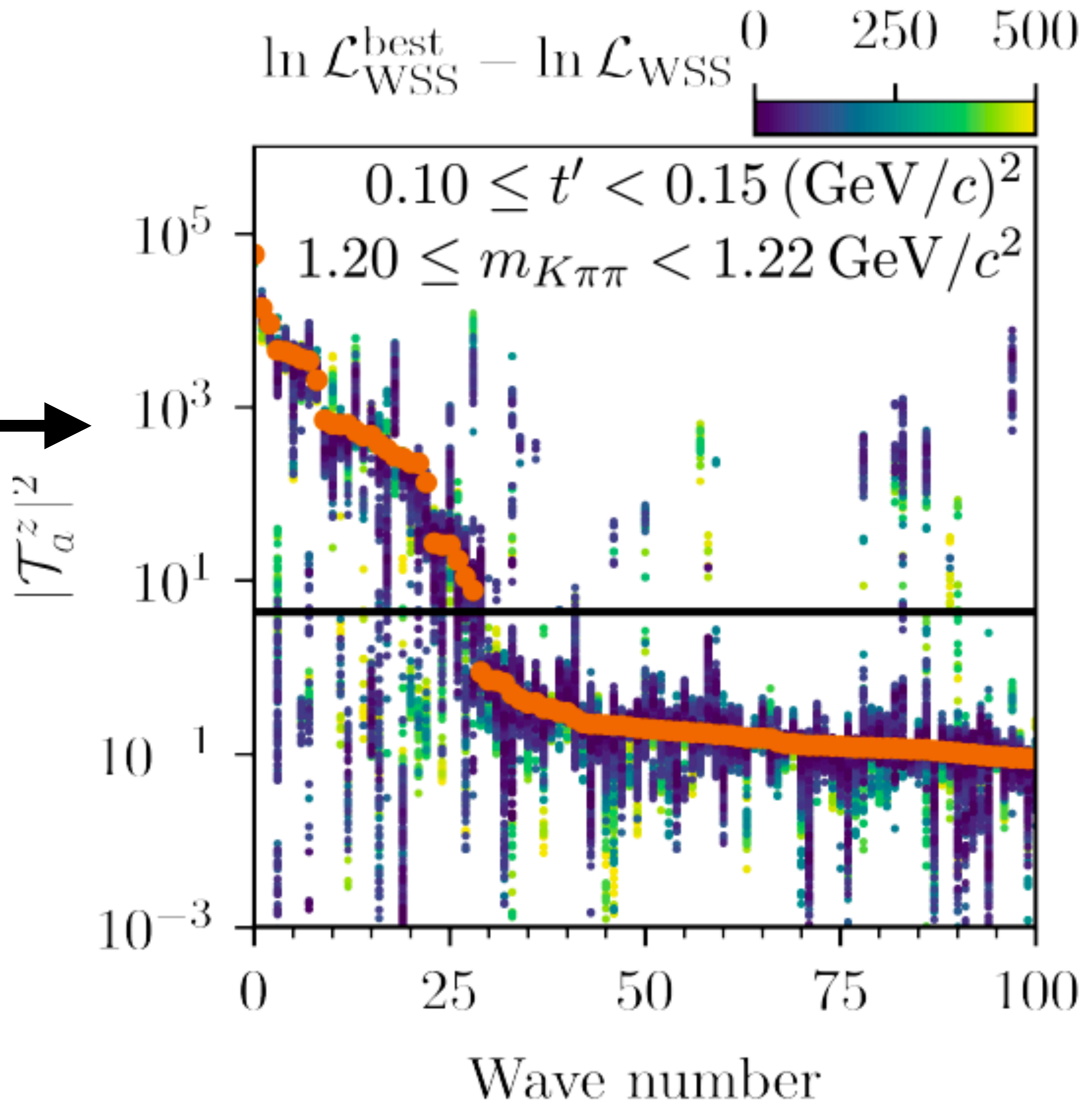
  selection of 15-80 waves ($m_{K\pi\pi}$ dependent) - 238 waves offered



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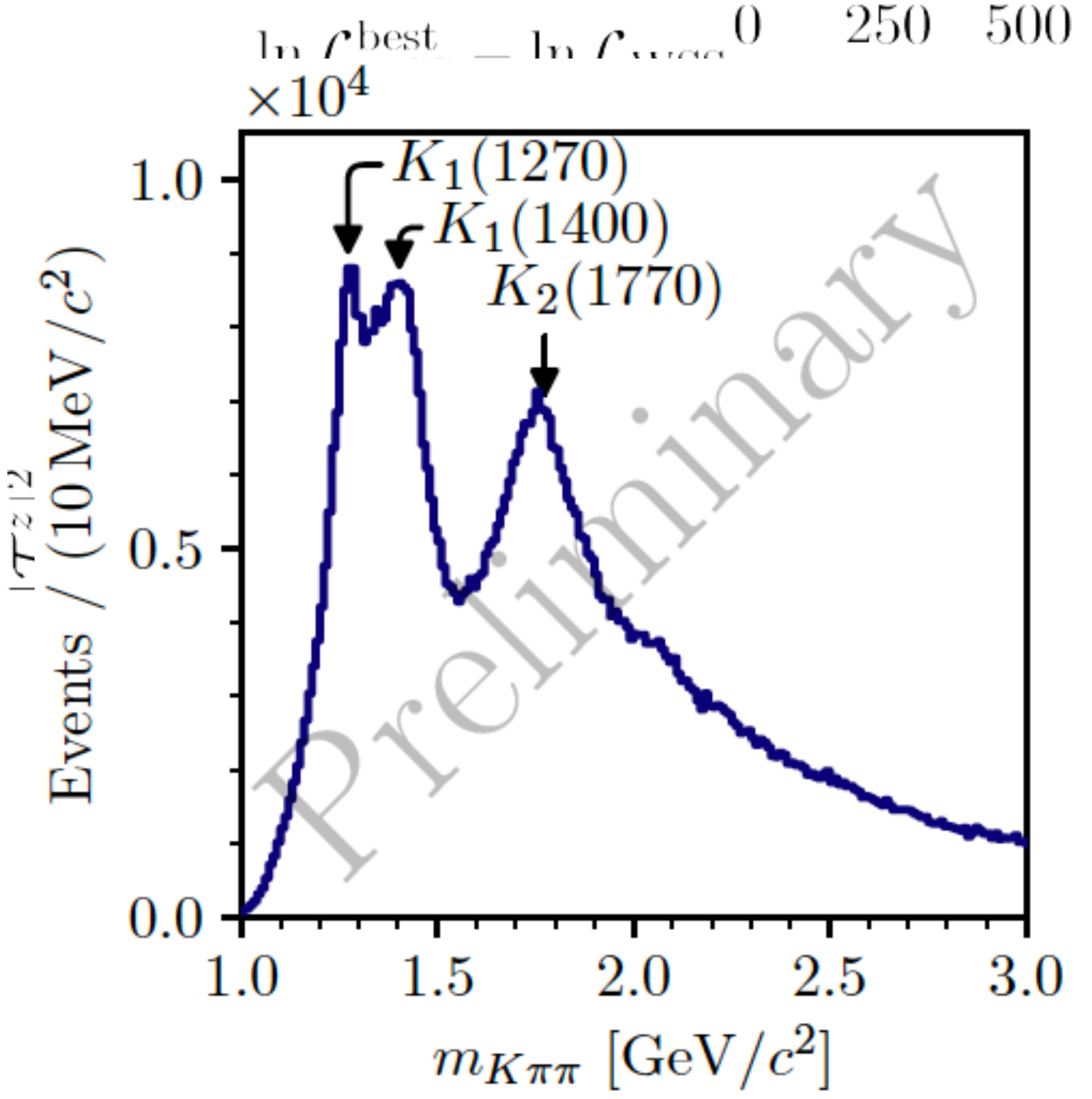

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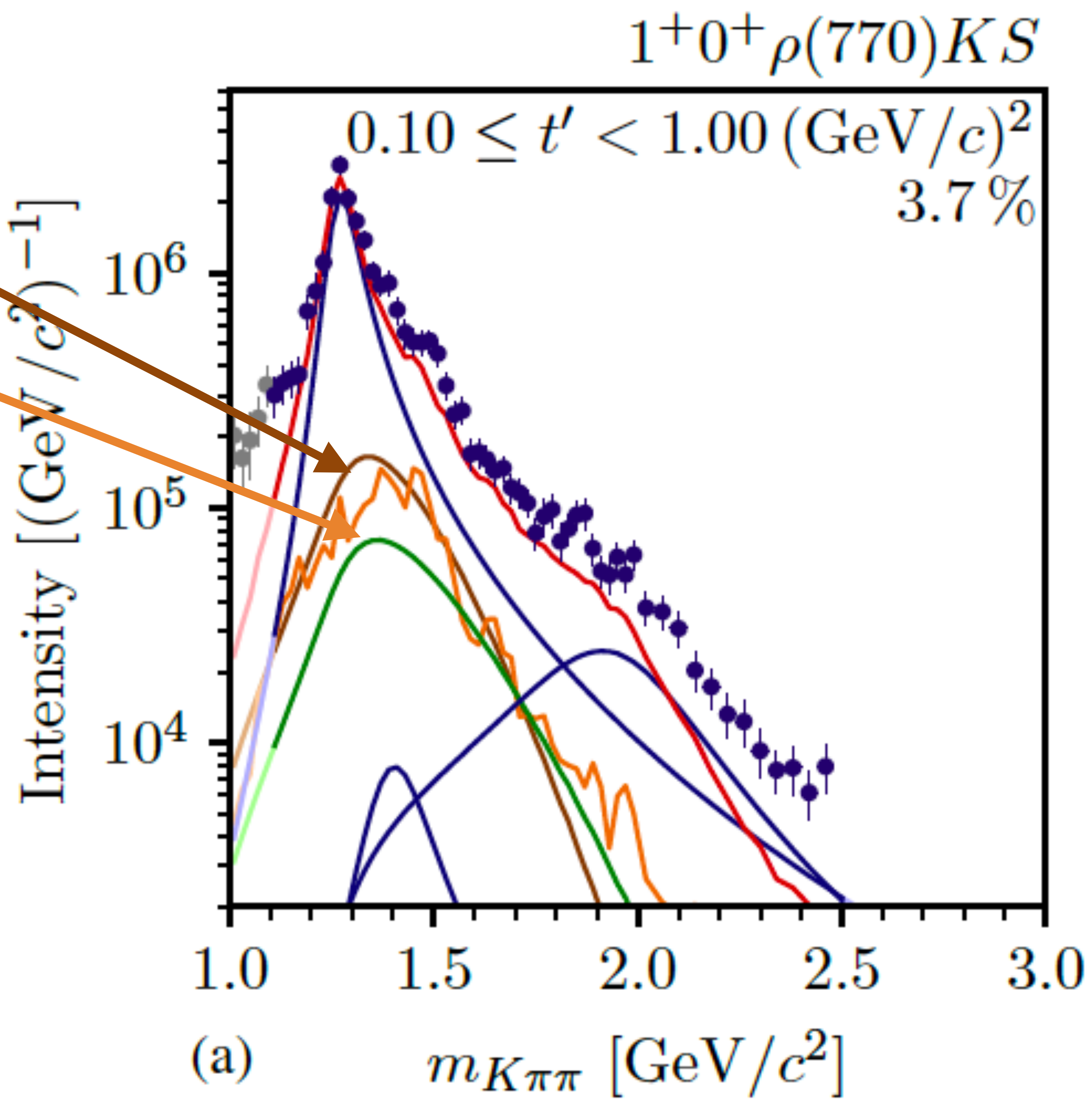
  model BG using COMPASS pion data



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  model BG using COMPASS pion data
- mass dependent fit with 10-14 waves (waiting for release)

Some Examples for Excited (and Exotic) Kaons

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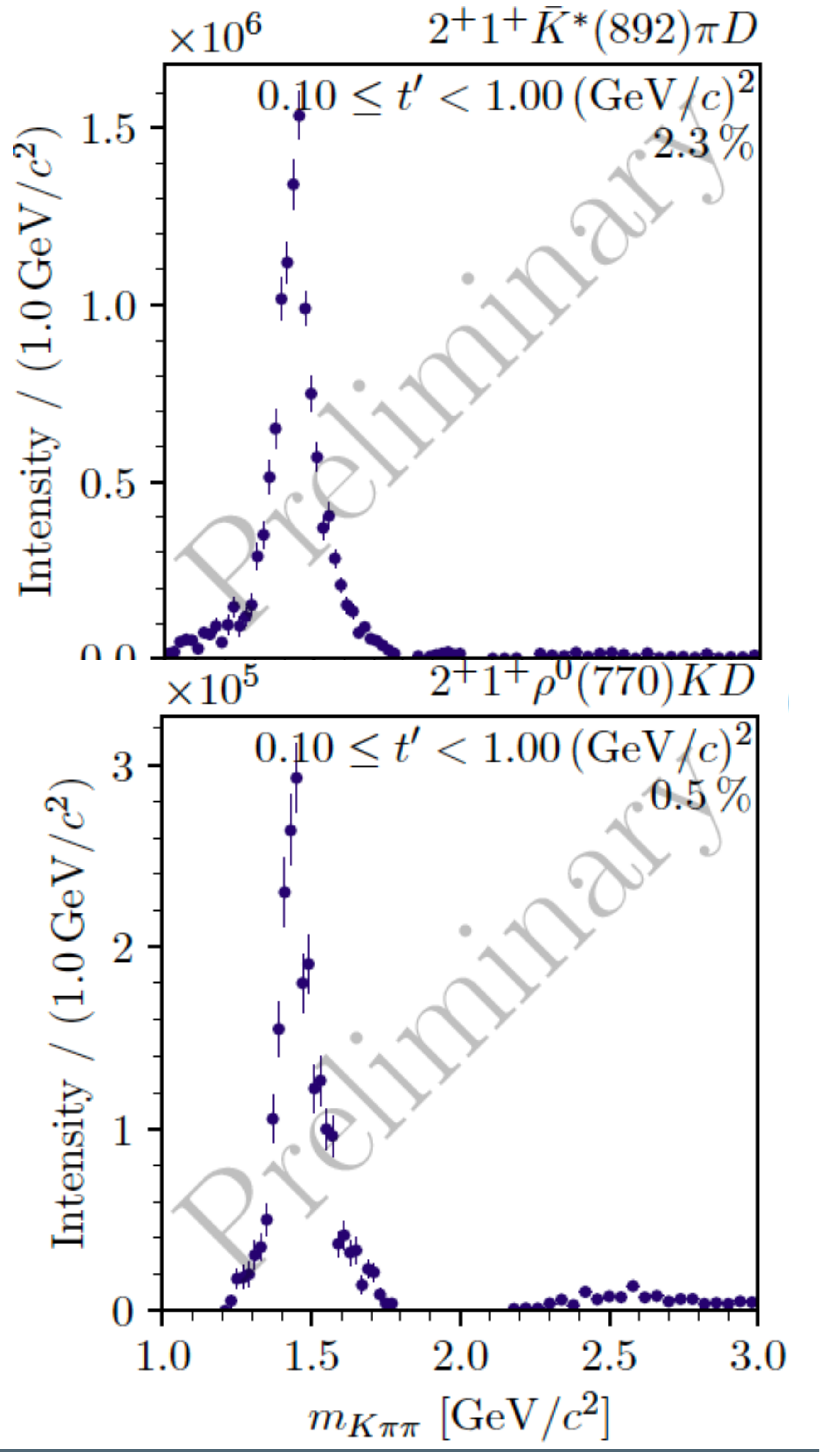
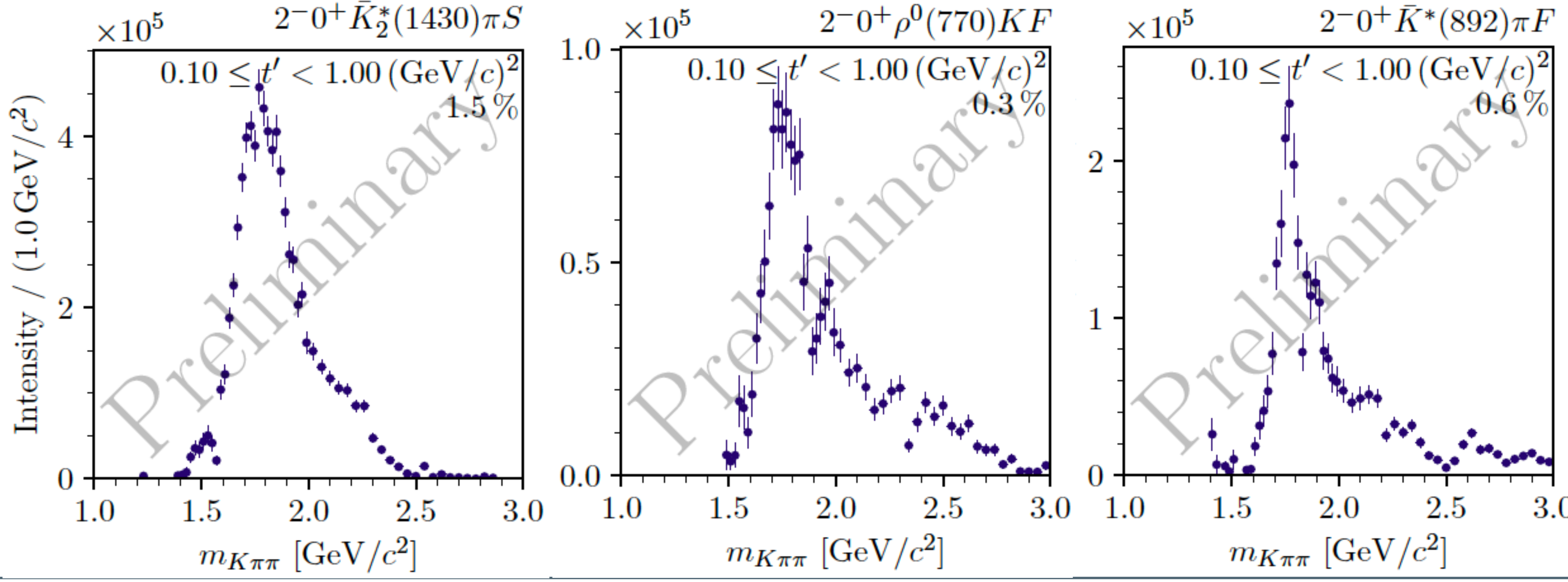
- $J^P = 2^+ :\ K_2^*(1430)$ in $K^*(892)\pi$ and $\rho(770)K$



Some Examples for Excited (and Exotic) Kaons

Exzellenzcluster ORIGINS

- $J^P = 2^+$: $K_2^*(1430)$ in $K^*(892)\pi$ and $\rho(770)K$
- $J^P = 2^-$:
  - $K_2(1770)$
  - $K_2(1820)$
  - $K_2(2250)$ (new)



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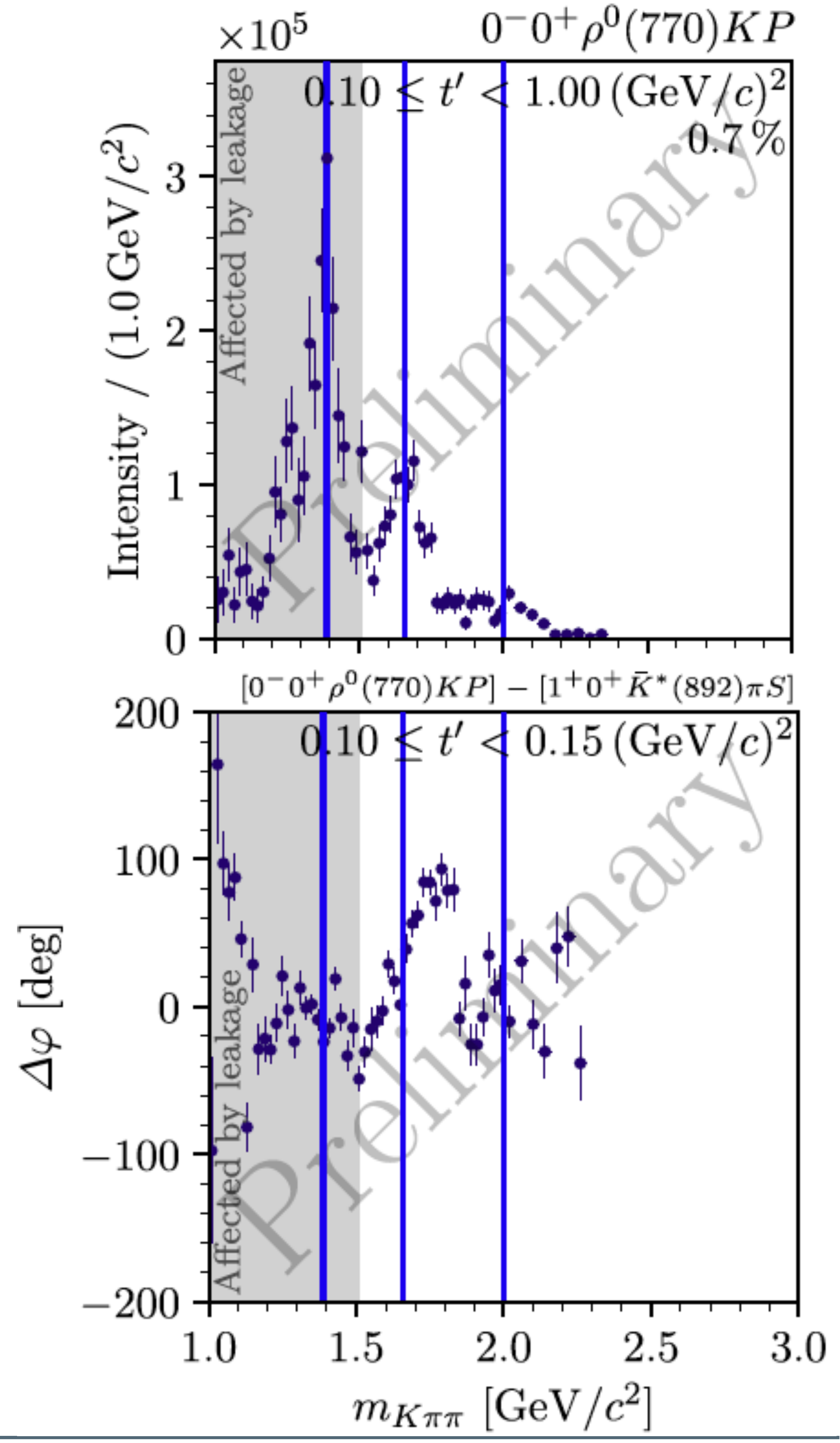
- $J^P = 2^- :$
  - $K_2(1770)$
  - $K_2(1820)$
  - $K_2(2250)$ (new)
- $J^P = 0^- :\ K(1460)$
  - $K(1630)$(supernumerous)
  - $K(1830)$ (weak)

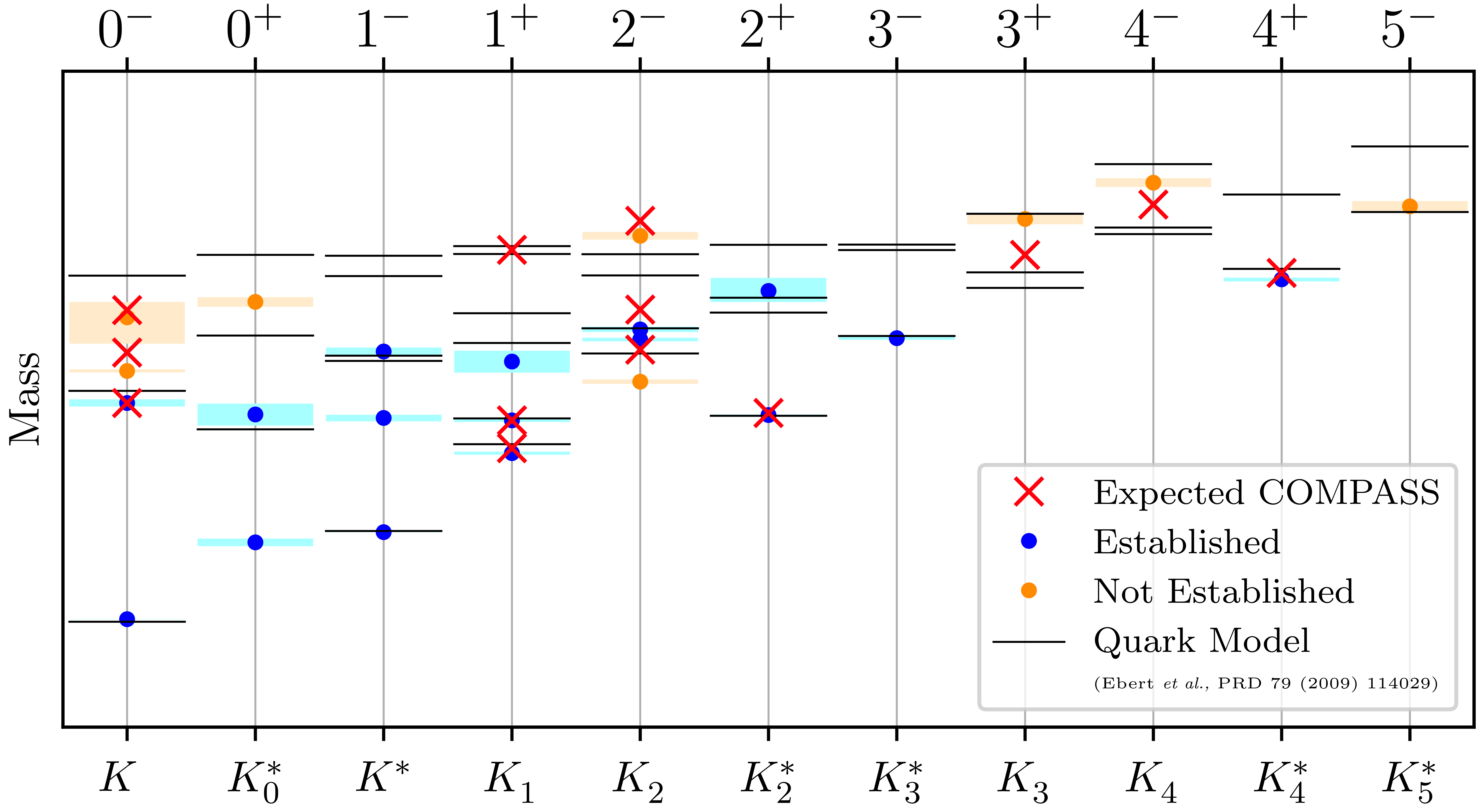


Summary Strange Mesons

Exzellenzcluster ORIGINS

COMPASS will release m_0/Γ of 13 strange mesons using $K^-\pi^-\pi^+$

- K, K_1, K_2^*, K_2, K_3^*, K_3, K_4^*, K_4



Conclusions/Outlook

Conclusions/Outlook

COMPASS has very rich data set (though missing more data with kaons)

- development of new tools and determination of systematics of PWA fits
- light mesons up to $M \sim 3$ GeV/c^2
- „known“ and new exotics found
- big contribution to strange meson sector
- radiative widths and spectroscopy of isobars (both $I = 0$ and $I = 1$)

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Exzellenzcluster ORIGINS

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Review

Light-meson spectroscopy with COMPASS

Check for updates

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Conclusions/Outlook

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COMPASS has very rich data set (though missing more data with kaons)

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- to come:
  - smaller signals at higher masses ($M \in [2.0,\ 3.0]$GeV/c^2) and higher J (e.g. a_6)
  - M_0/Γ of strange mesons
  - 2-body processes (e.g. $K^-\pi^0, \bar{p}\Lambda \ldots$)
  - 5-body with effective 3-body structure (e.g. $\omega\pi^-\pi^0$ including $b_1\pi$) - full 5-body failed
  - baryon spectroscopy (extracted from central production data)