Light (and heavy) meson Spectroscopy with COMPASS

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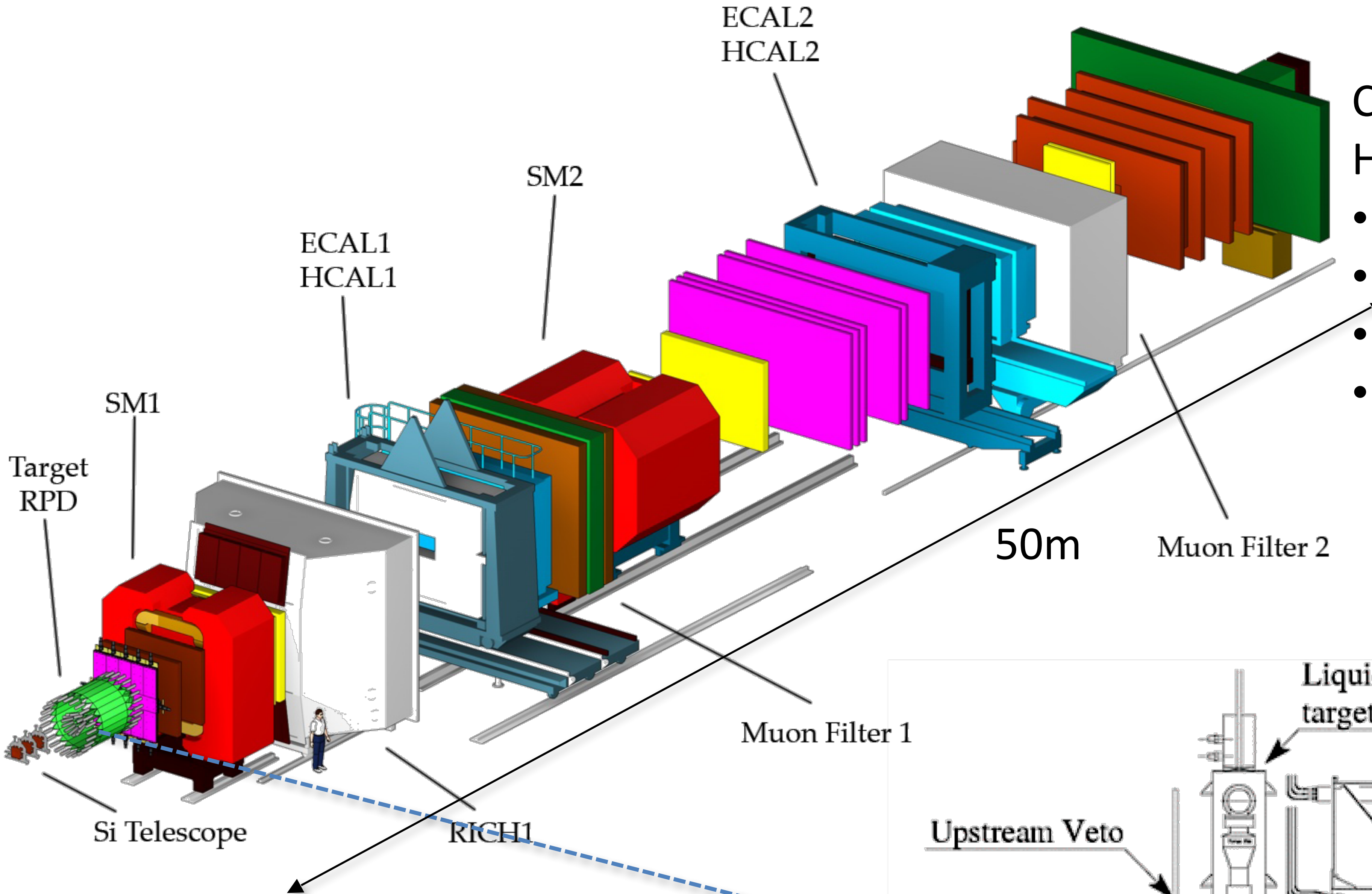
Brief Overview

COMPASS performs physics with p, K, π (μ) beams

Examples will be given on

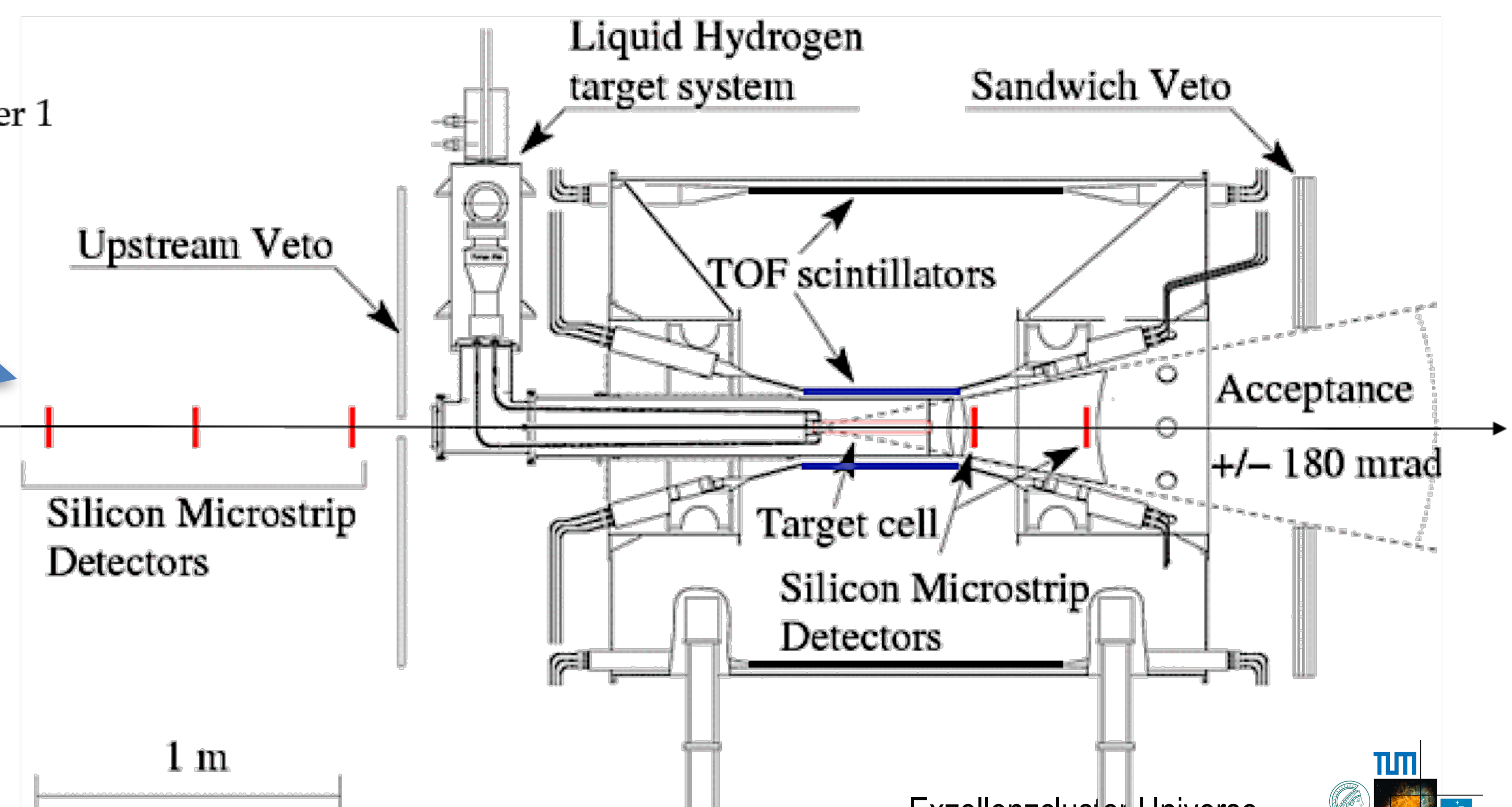
- Diffraction with π into 3π (this talk)
- Spectroscopy in strong interaction
  - Introduction
  - Identification method (PWA)
  - results for a_J and π_J states
- New insights into production/decay dynamics
- Other topics….
- Conclusions

The COMPASS Experiment

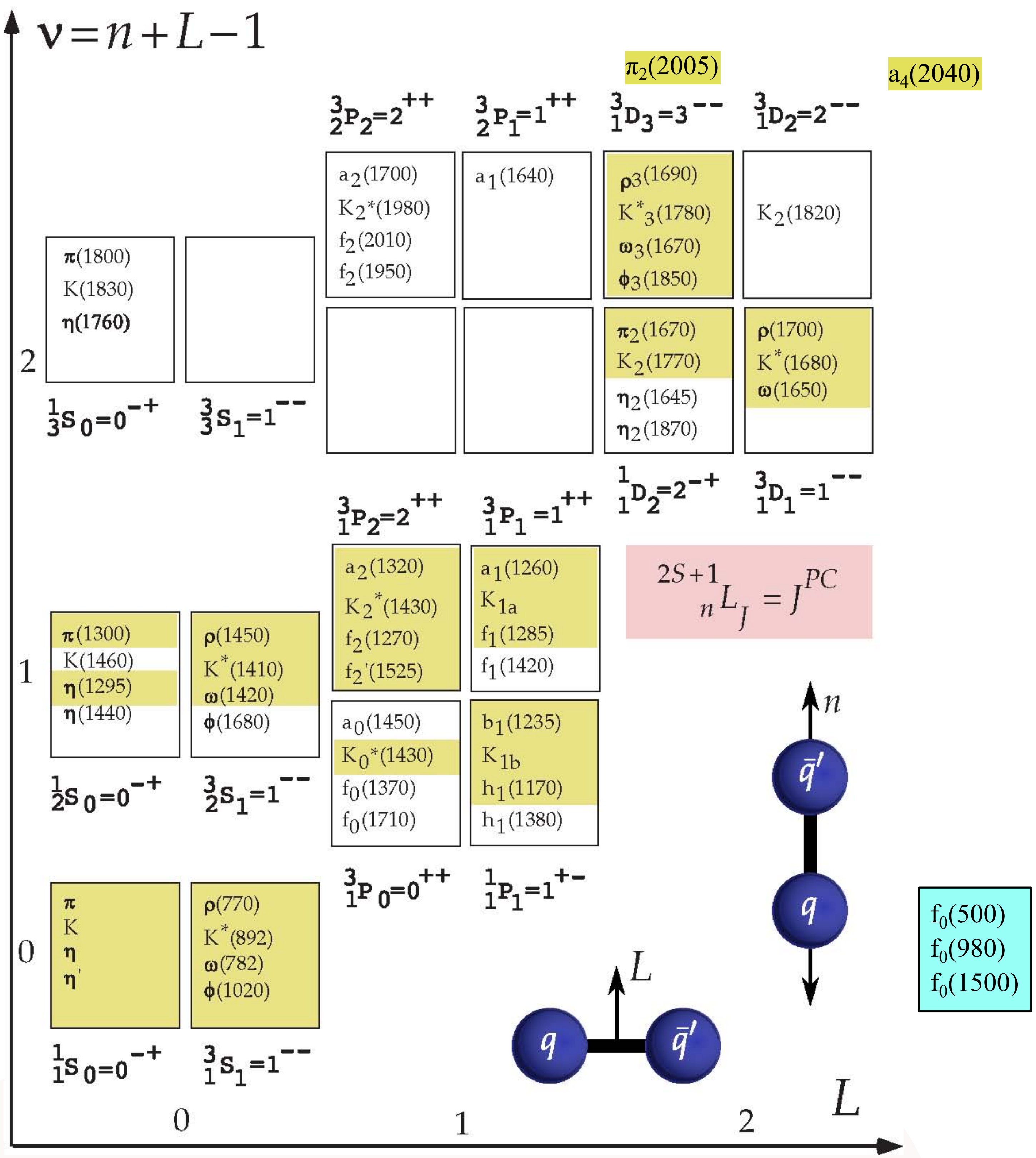


CERN SPS
Hadron beam:

- 190 GeV/c π, K, p
- $5 \cdot 10^{7}$ particles/SPS-spill
- 60 days data taking 2008
- Trigger: RPD hit, beam veto

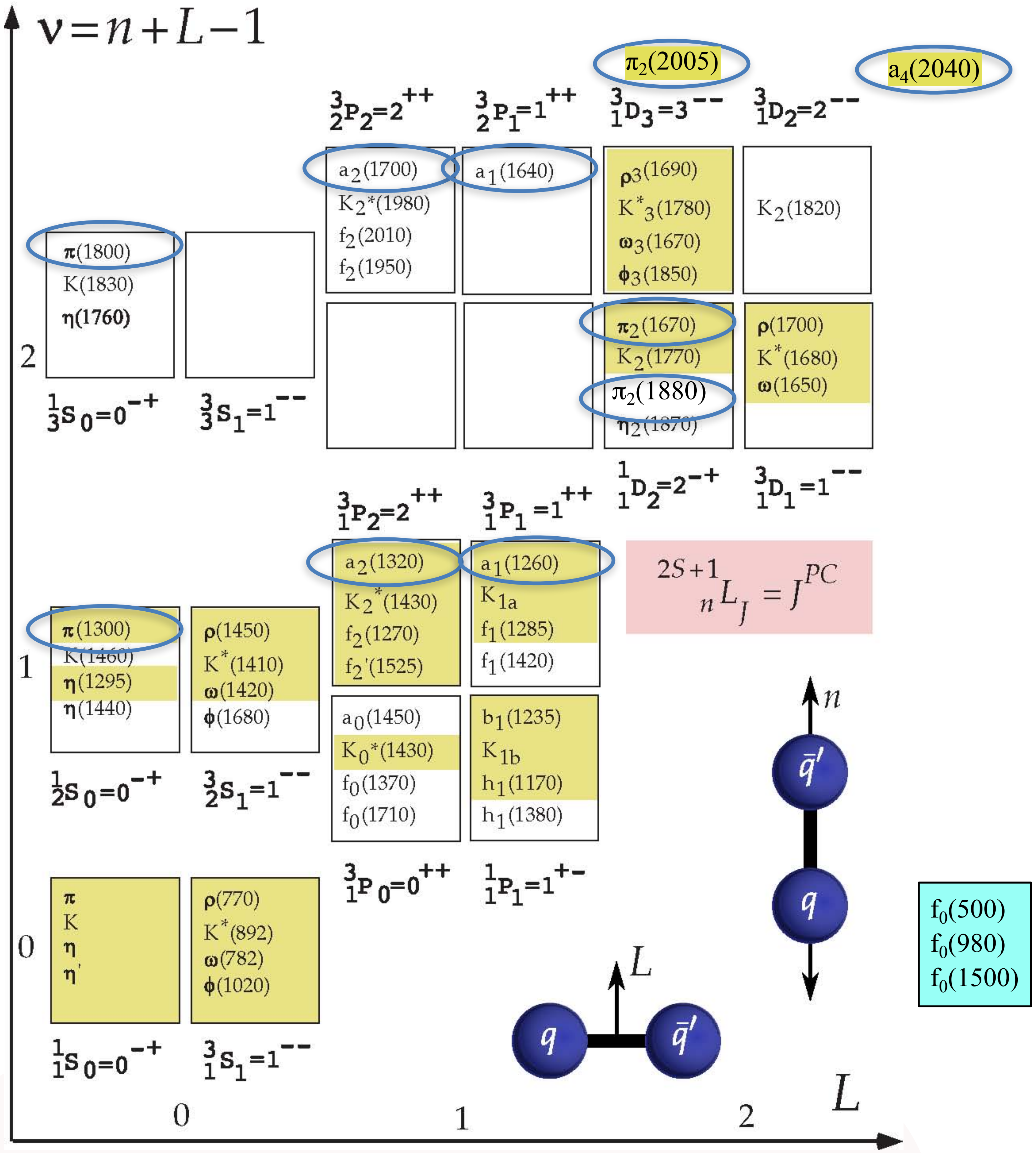


Constituent Quarks and Mesons



C. Amsler *et al.*, Phys. Rept. 389, 61 (2004)

Constituent Quarks and Mesons



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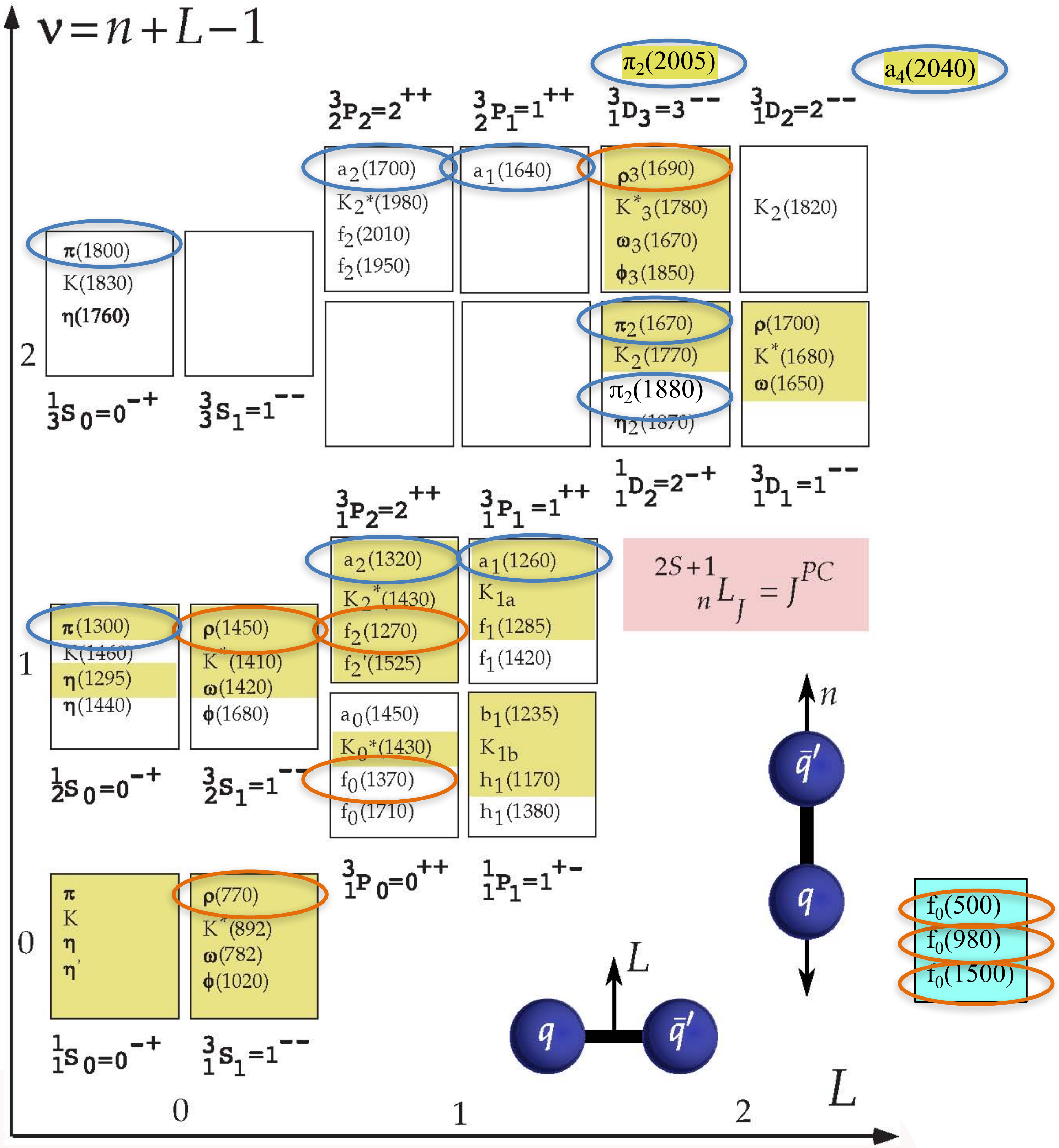

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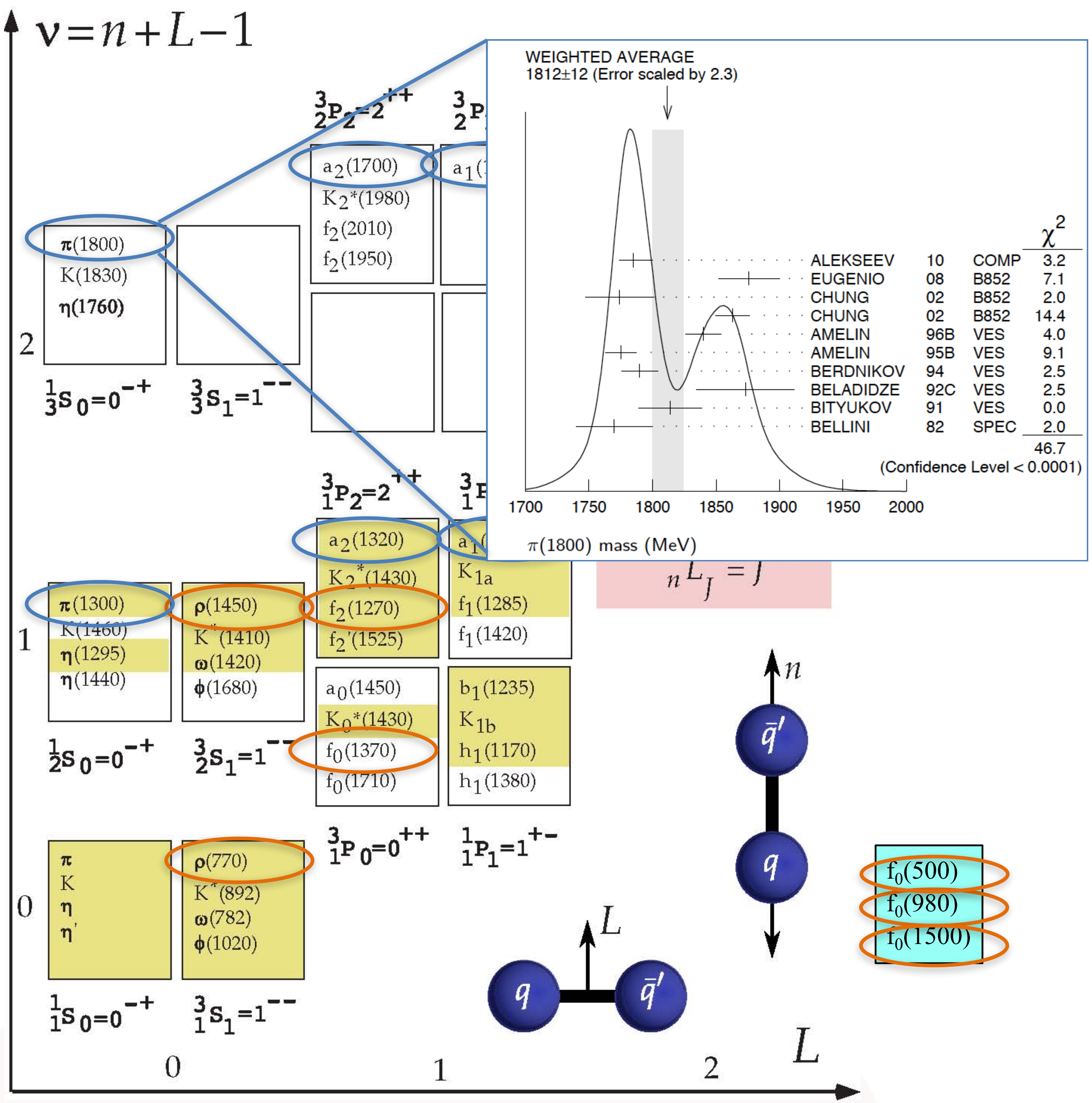

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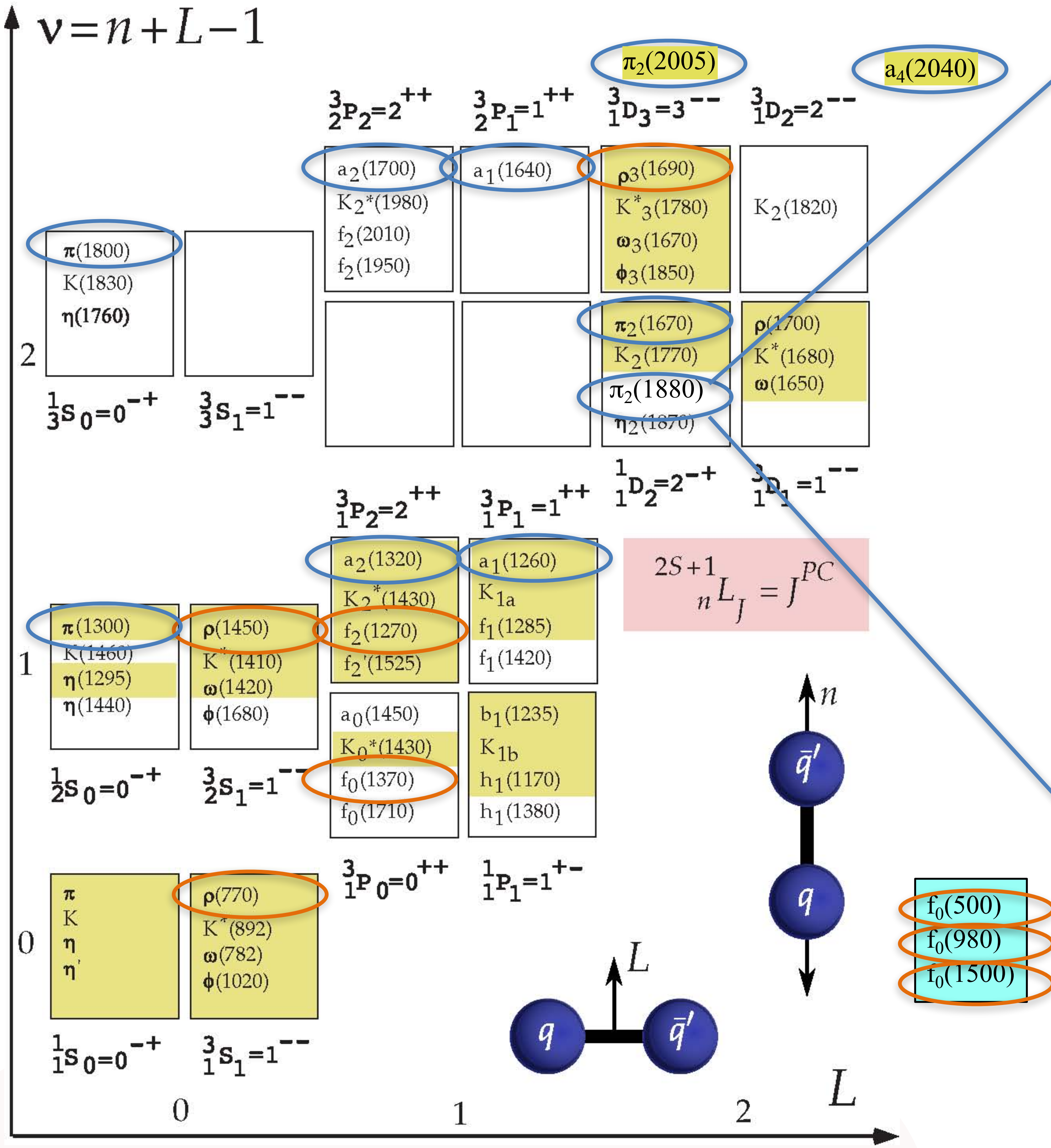


$\pi_2(1880)$ MASS

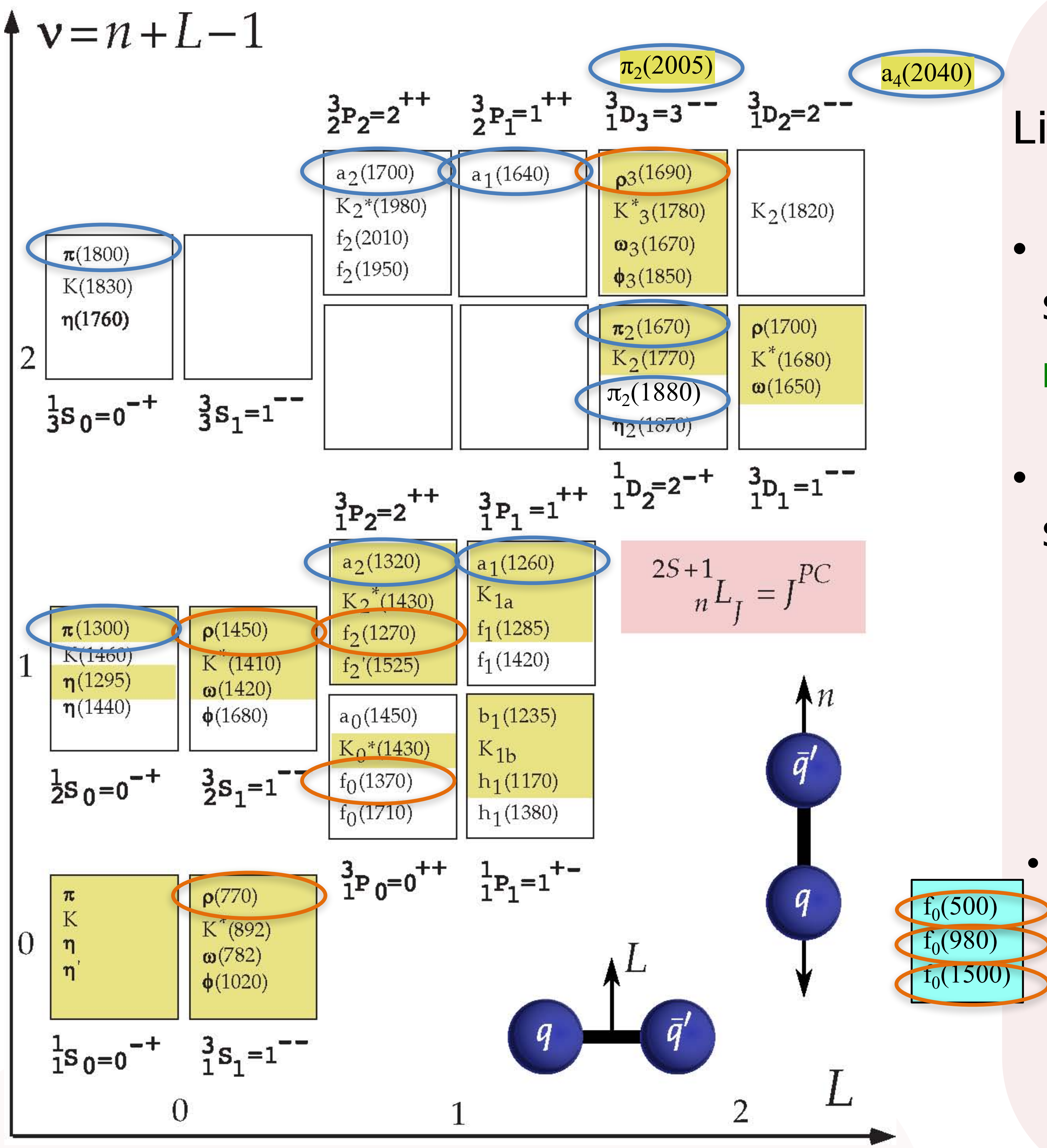
VALUE (MeV)	*EVTS*
1895±16 OUR AVERAGE	
1929±24± 18	4k
1876±11± 67	145k
2003±88±148	69k
1880±20	

$\pi_2(1880)$ WIDTH

VALUE (MeV)	*EVTS*
235± 34 OUR AVERAGE	
323± 87± 43	4k
146± 17± 62	145k
306±132±121	69k
255± 45	

C. Amsler *et al.*, Phys. Rept. 389, 61 (2004)

Constituent Quarks and Mesons



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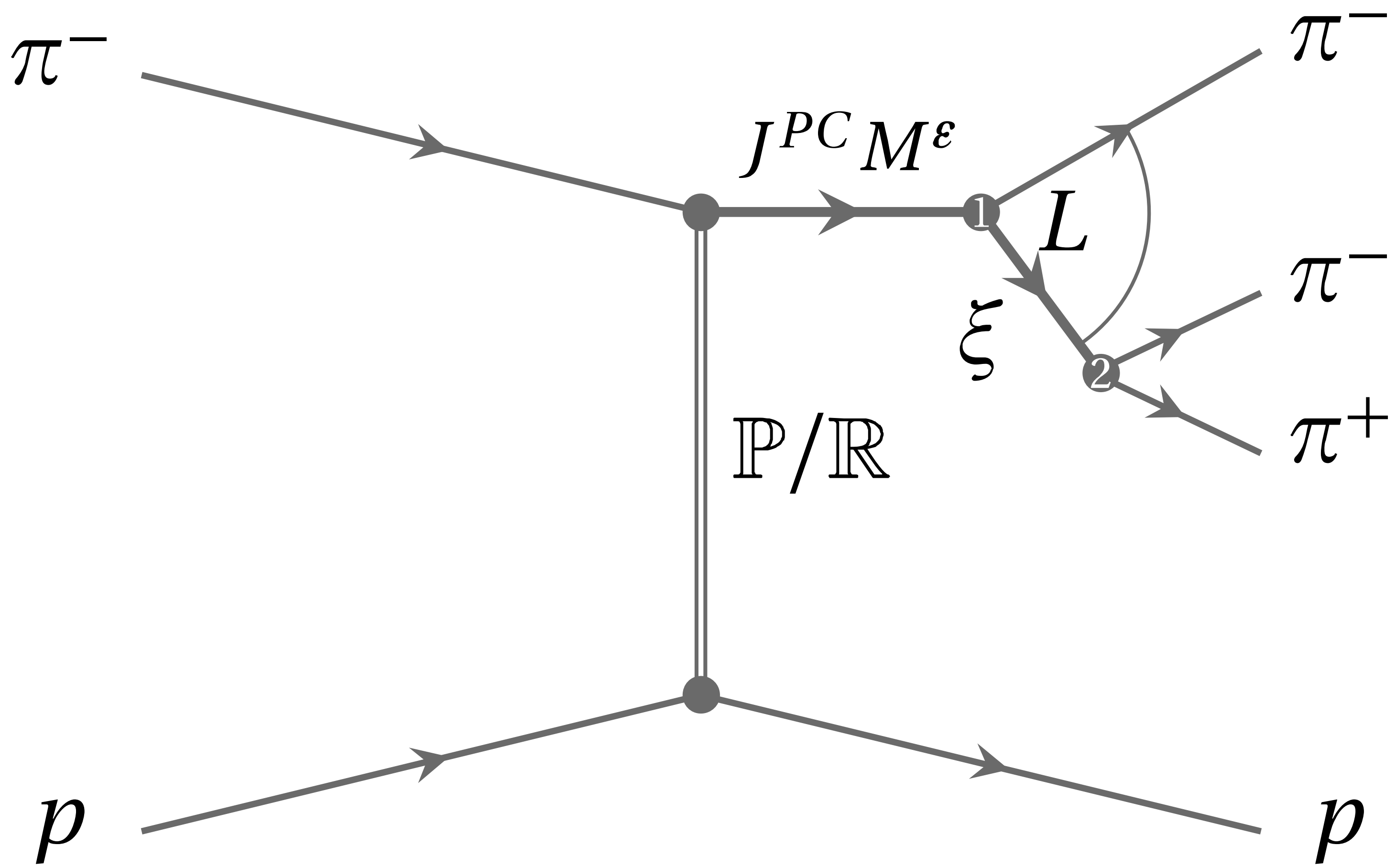
Limits for light mesons

- many missing/disputed states in mass region $m \sim 2\ \mathrm{GeV}/c^2$
- Identification of heavy states difficult
  - broad states
  - large number
  - overlap + mixing
- Extend to strangeness sector

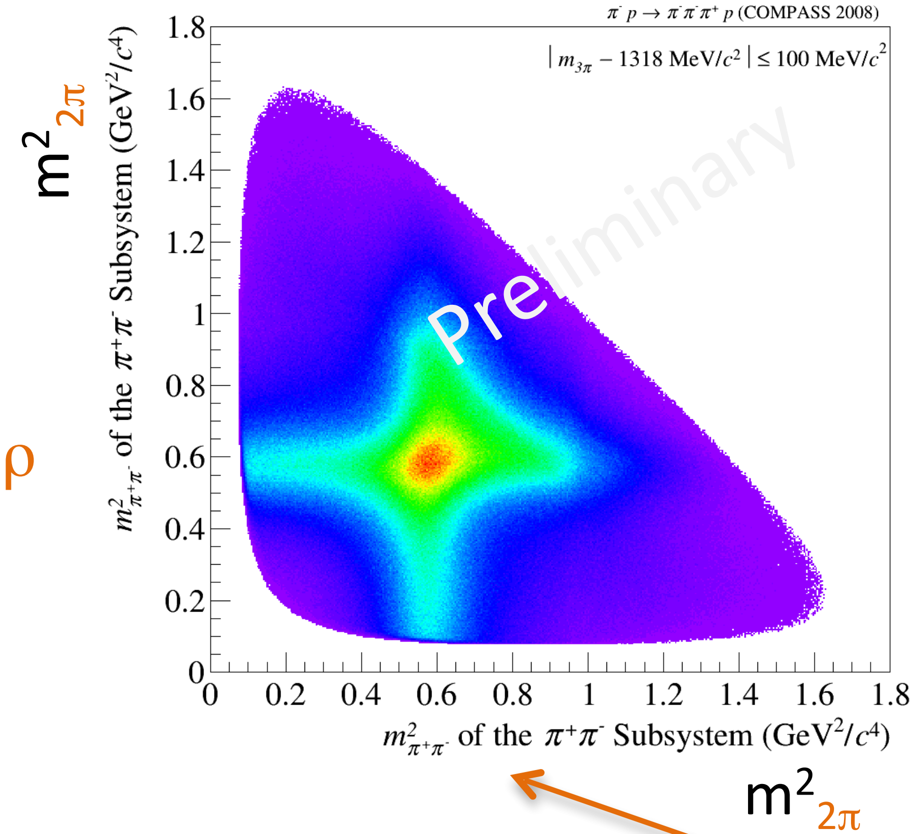
Kinematics

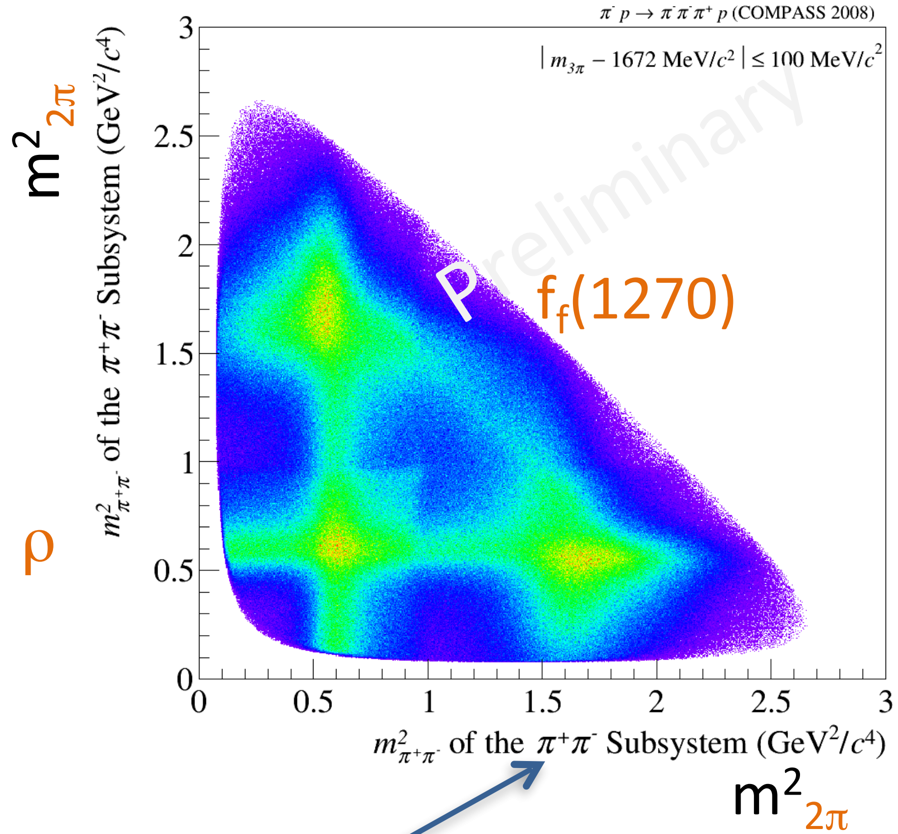


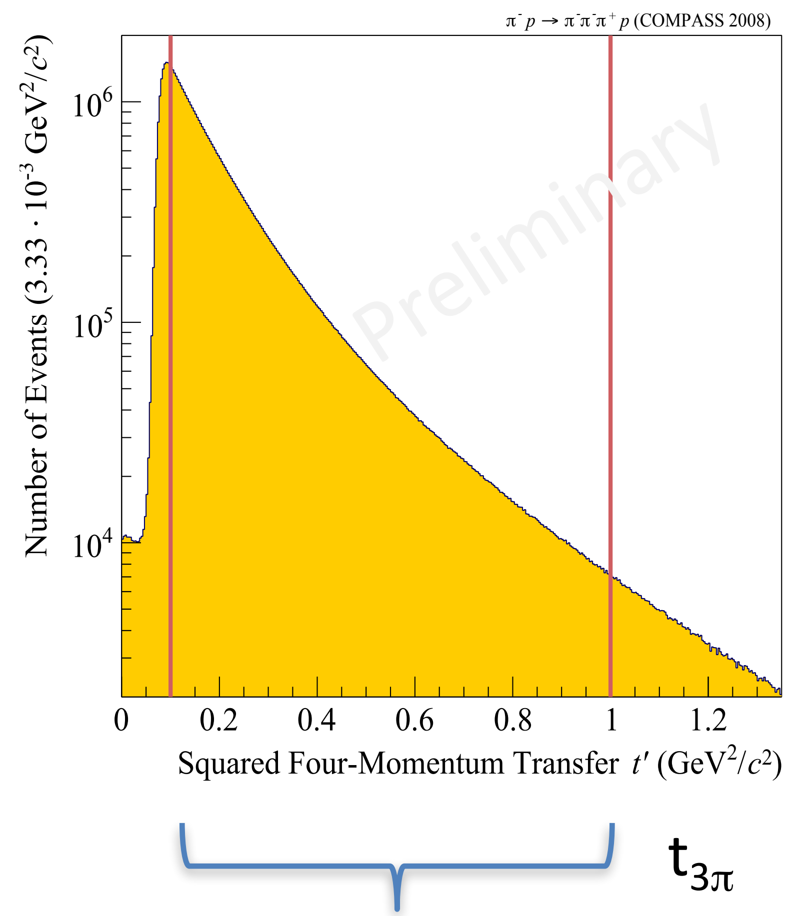
Example: production of 3π

5-dimensional phase space

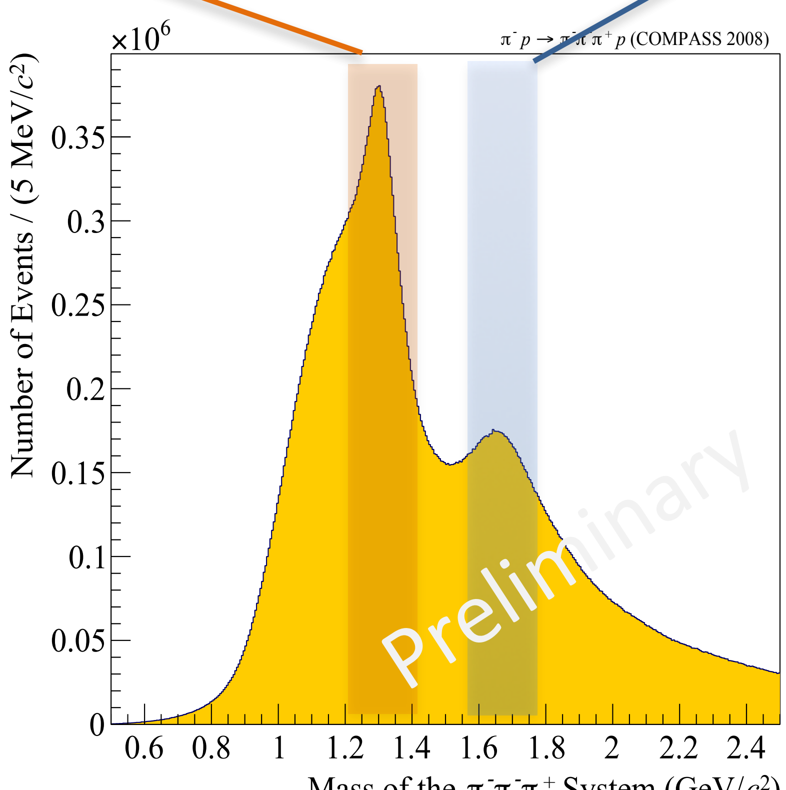
First Impressions
Motivation for Isobar Model



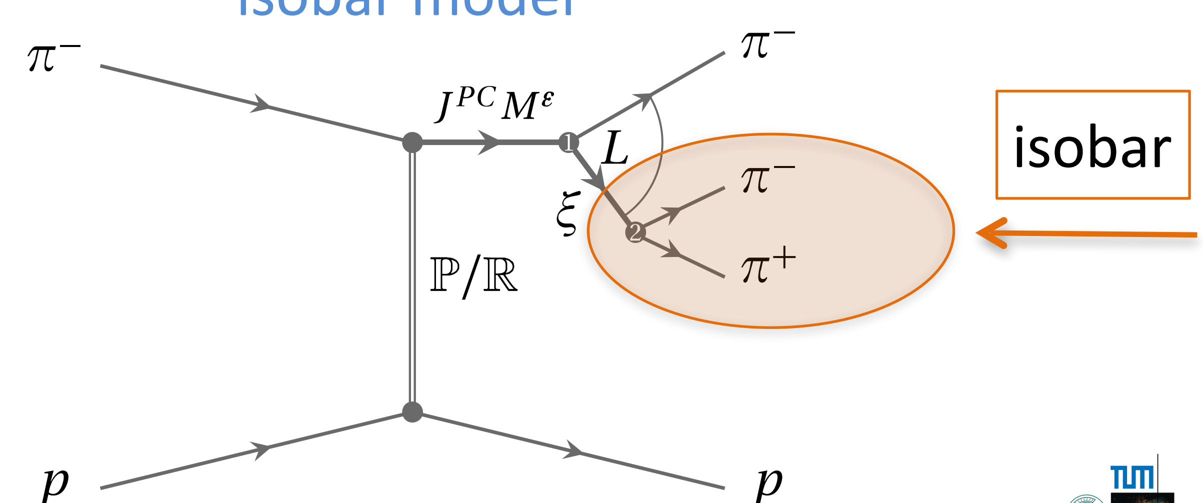




used in analysis



isobar model



Exzellenzcluster Universe

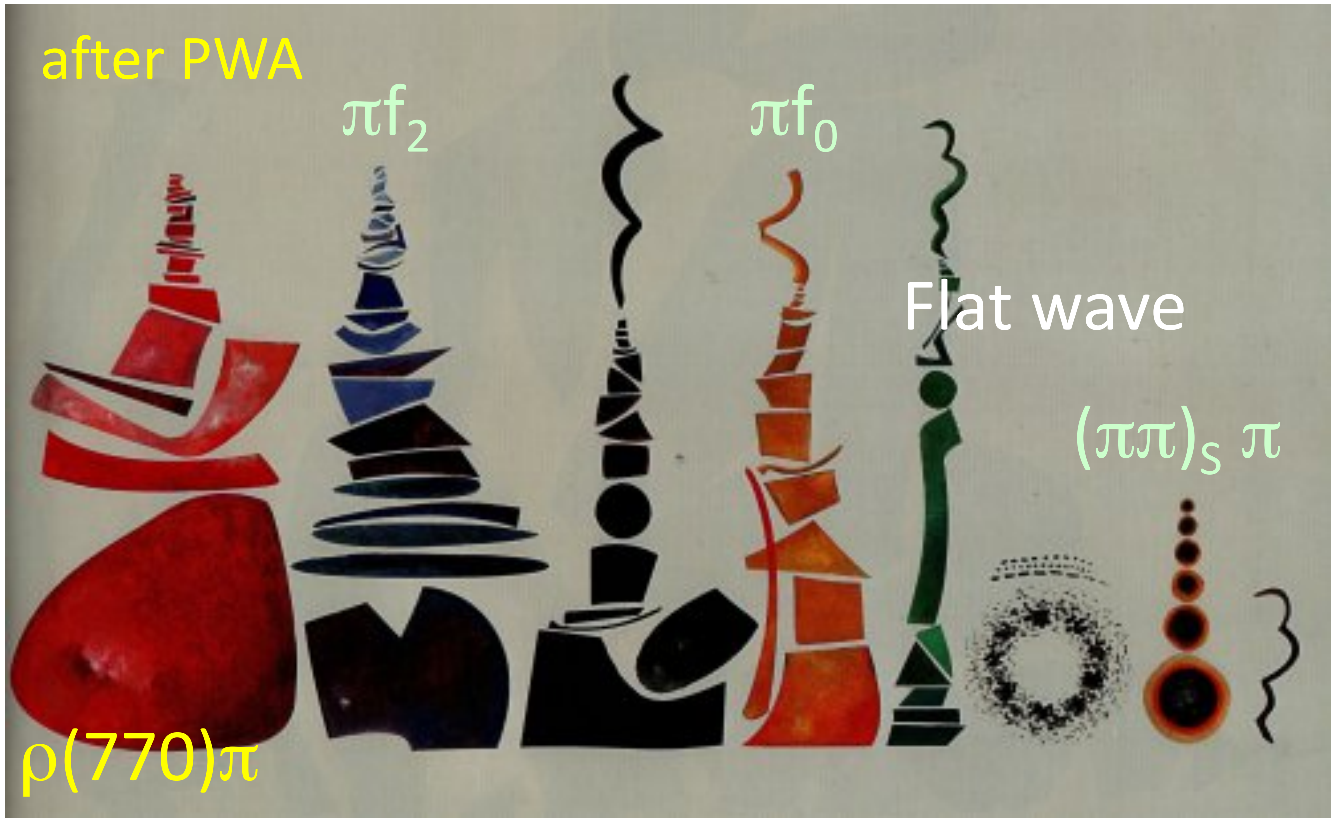
Partial wave analysis

inspired by M. Pennington

Art taken from Urs Wehrli: “Kunst aufgeräumt”

Partial wave analysis

inspired by M. Pennington



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Partial wave analysis

What is PWA ?

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

step 1

- 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/c^2 mass of $\pi\pi\pi$ and bin of t: determine which coherent combination of waves fits distribution best
- Obtain spin-density matrix

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step 2

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

Amplitude Analysis

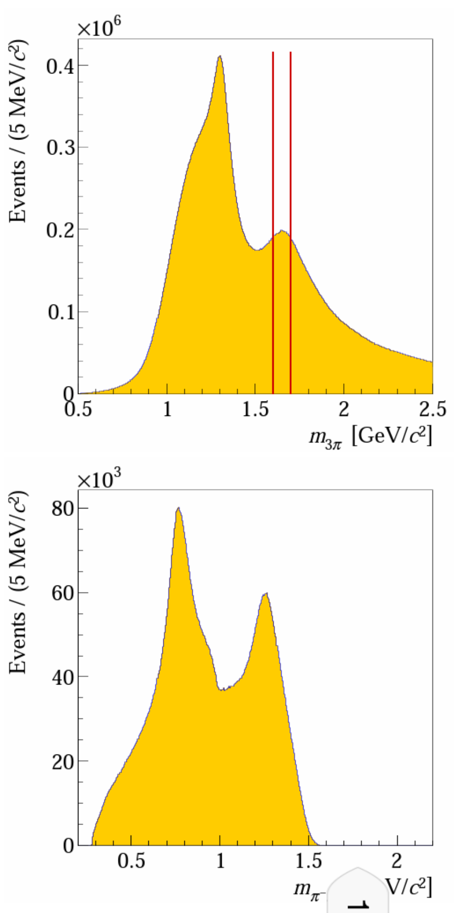
Use helicity amplitudes :

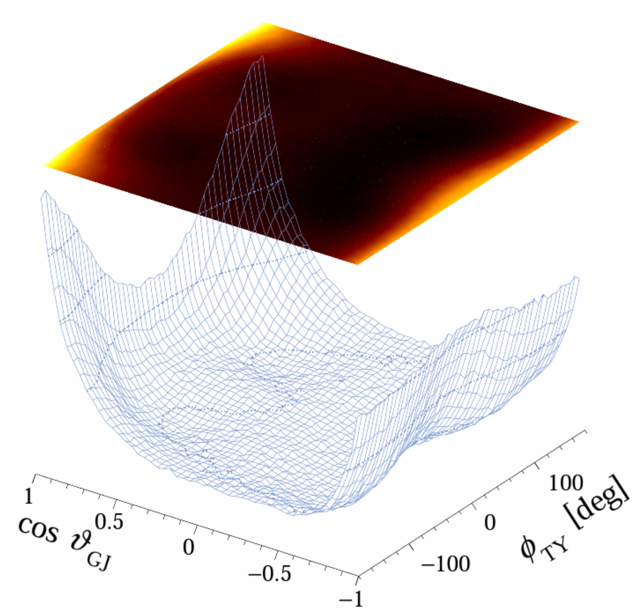
5-dimensional phase space:

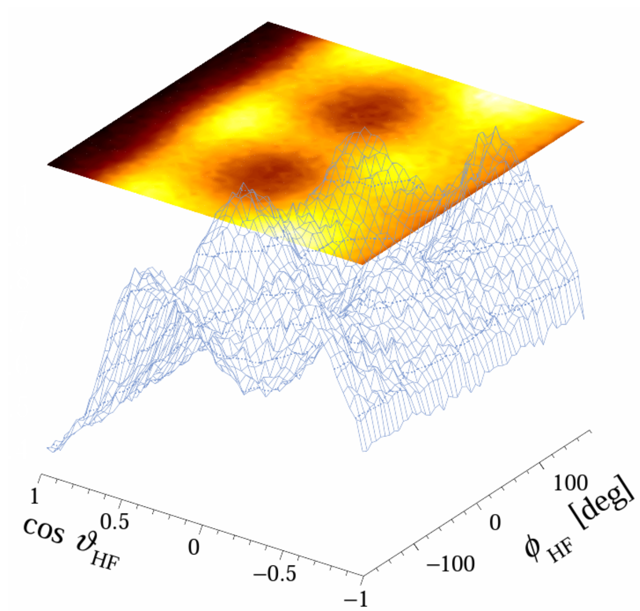
mass of 3π

2 angles in 3π rest frame

2 angles in isobar rest frame

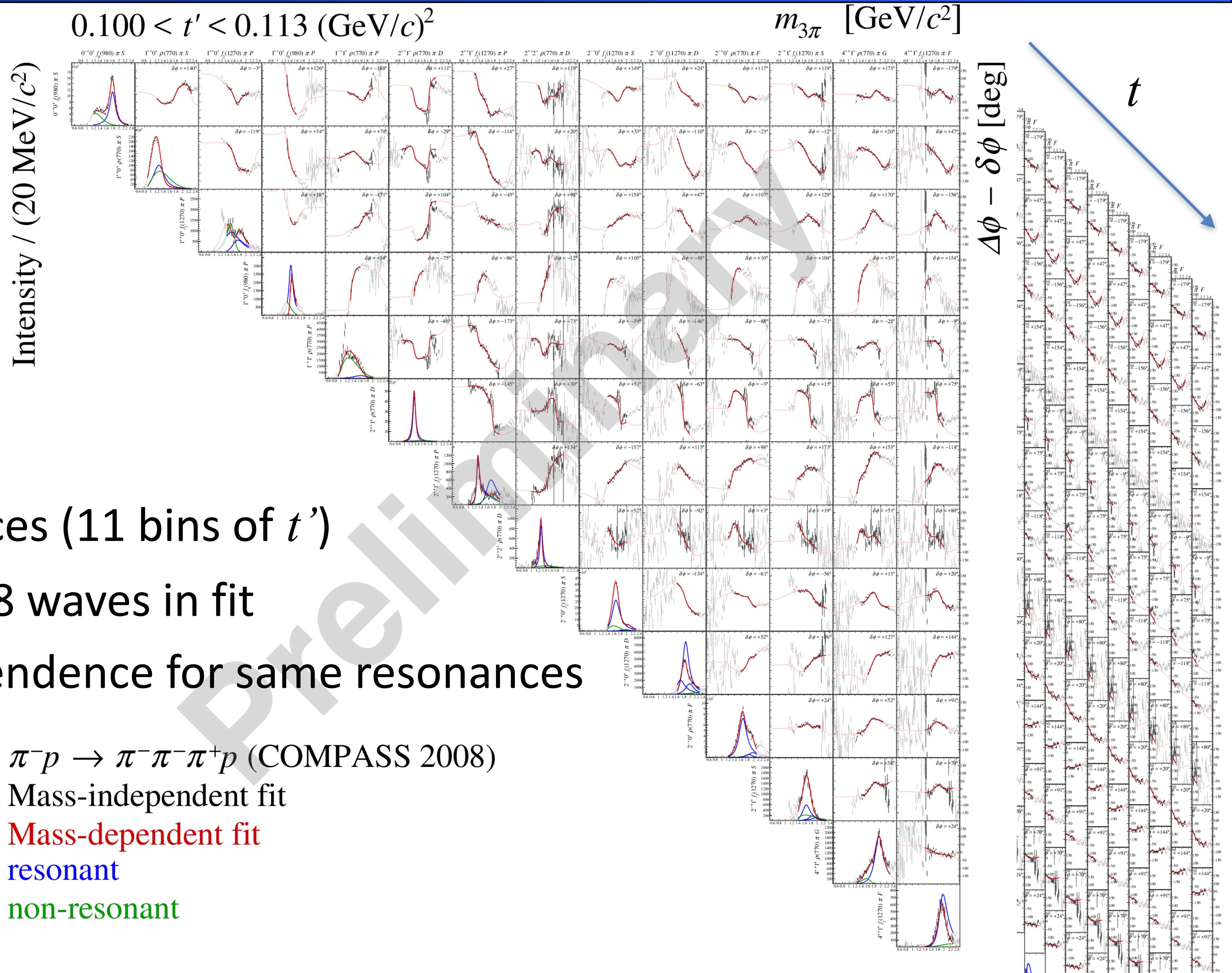






Find the Resonances

Reference wave



- 11 matrices (11 bins of t')
- use 14/88 waves in fit
- fix t-dependence for same resonances

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

Mass-independent fit

Mass-dependent fit

resonant

non-resonant

Model for Spin Density Matrix

Describe the results obtained independently in different mass bins by a model

- select physics contributions
- fit to spin density matrix (not only to simple mass spectra)
- use 14 waves (out of all 88 waves)
  - 722 free parameters
  - 76505 data points

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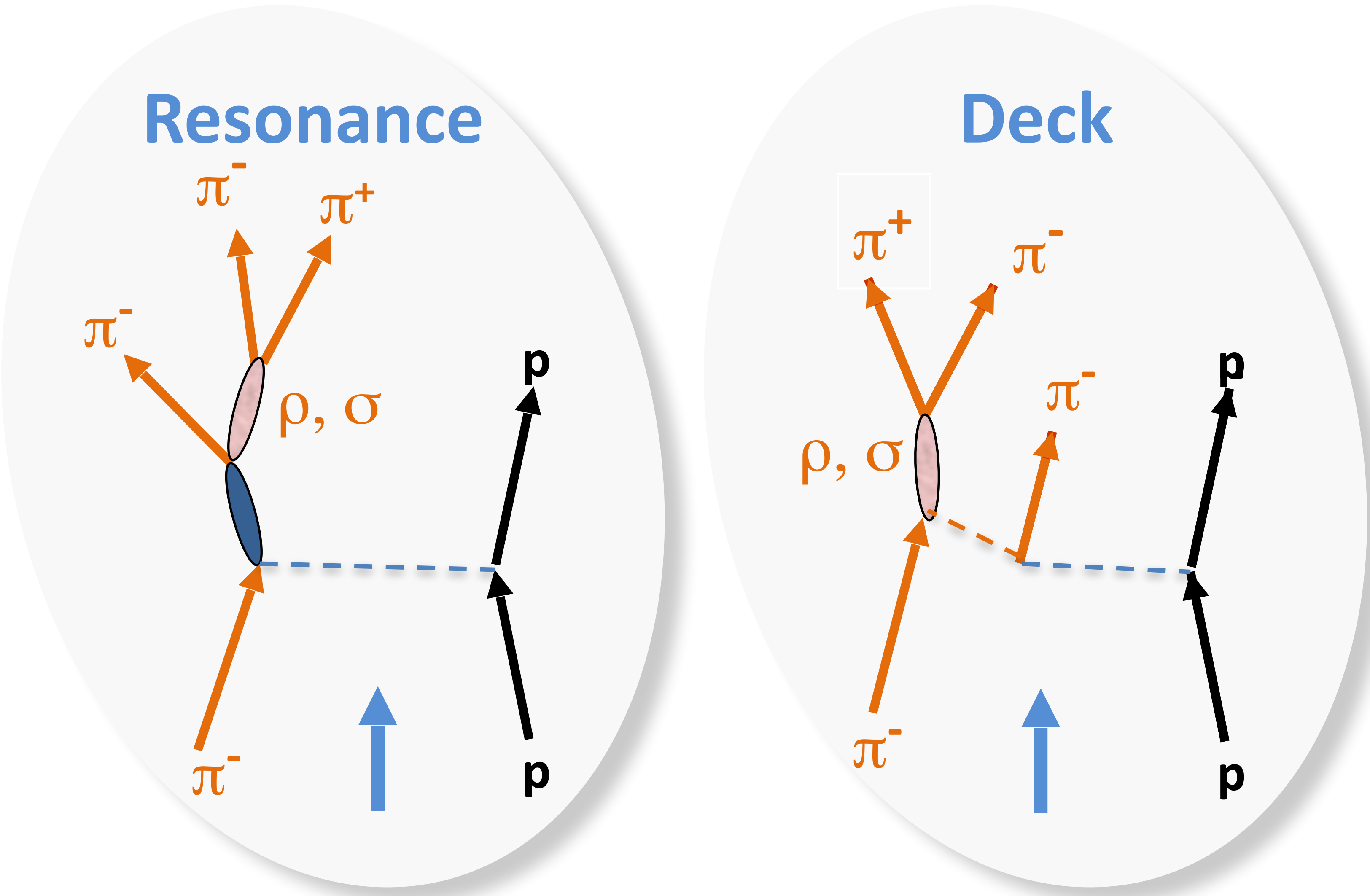
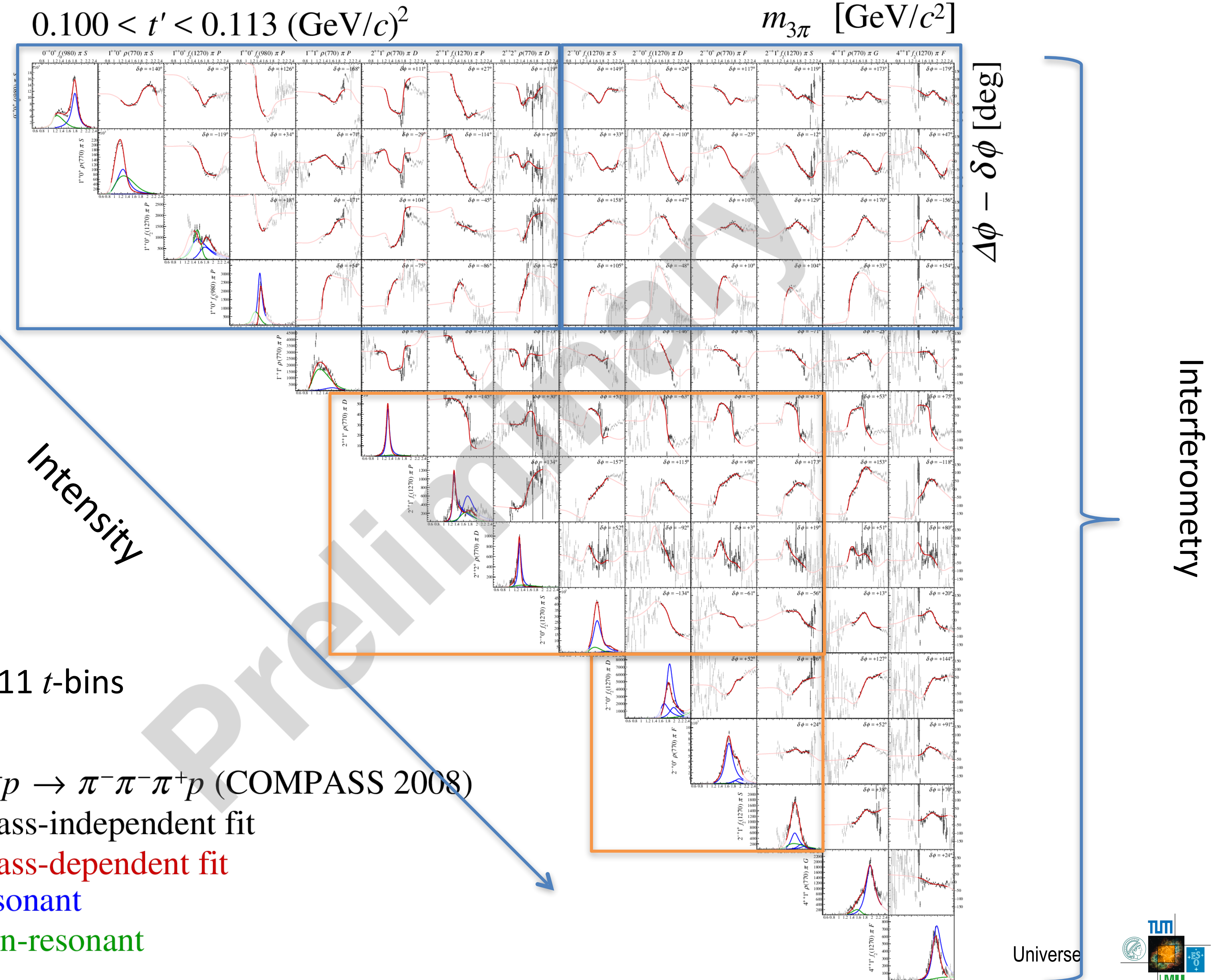


Two types of contributions

Find the Resonances



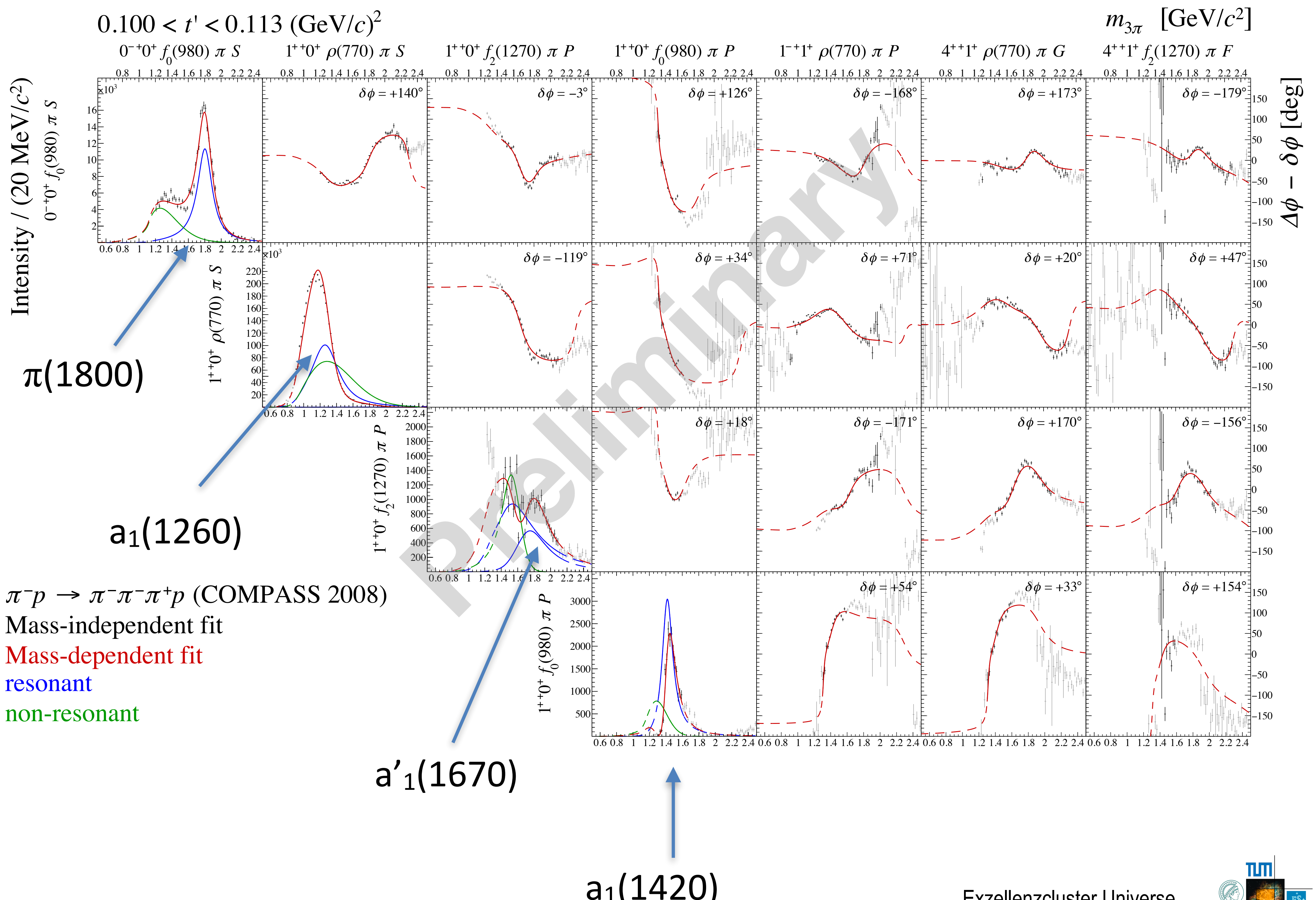
simultaneous fit in 11 t-bins

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

Universe

Find the Resonances

- Axialvector mesons: 1^{++}

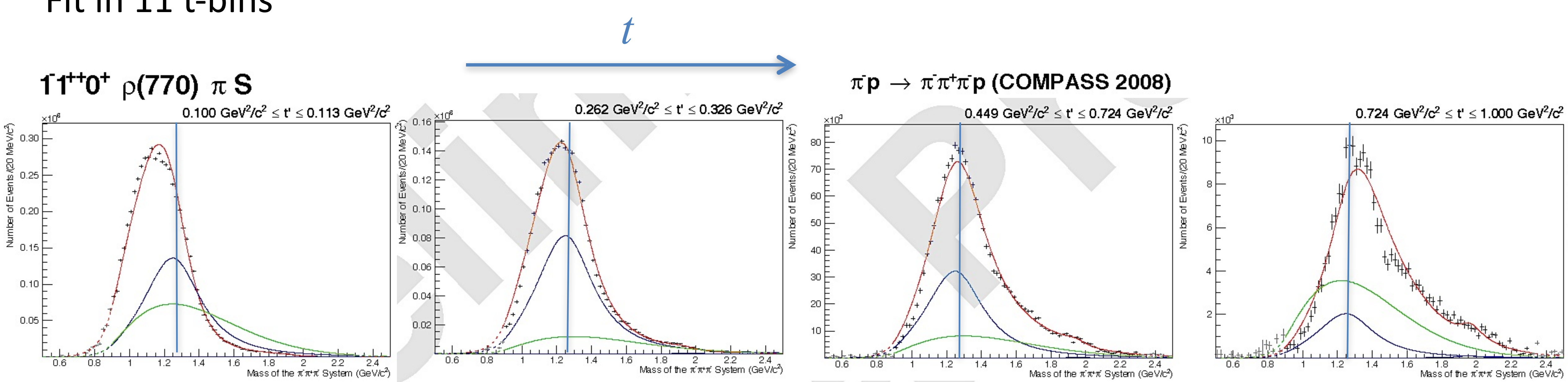


Mass dependent fits

$$1^{++}0^{+}\rho\pi S$$

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

Fit in 11 t-bins

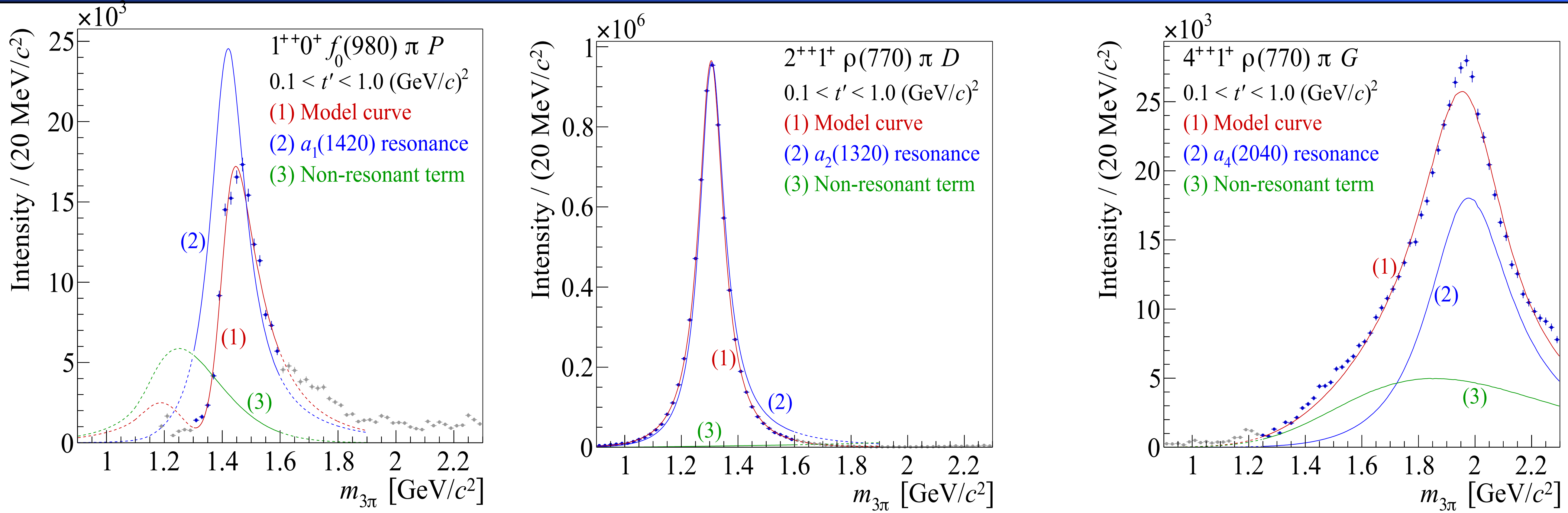


Strongly t-dependent
spectral shape around $a_1(1260)$

—

Interference of non-resonant with
$a_1(1260)$

New Observation: $a_1(1420)$



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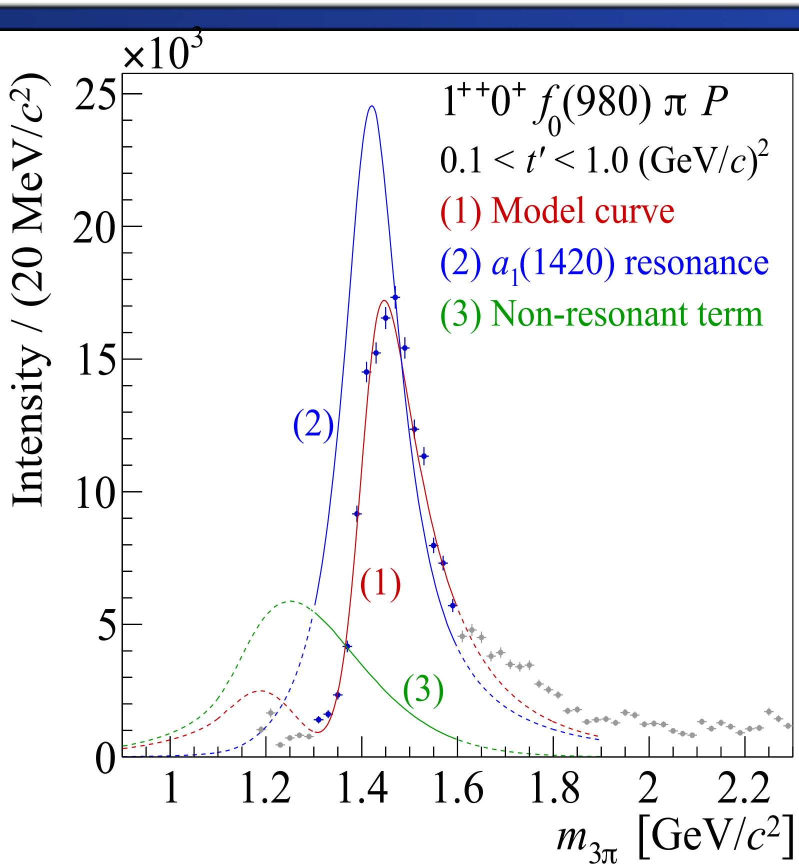
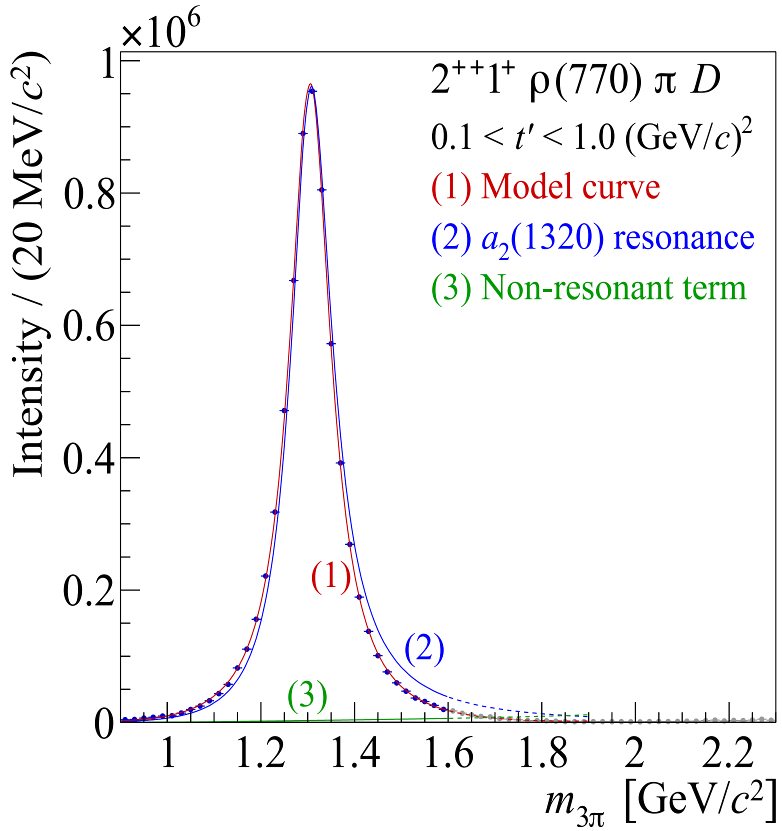
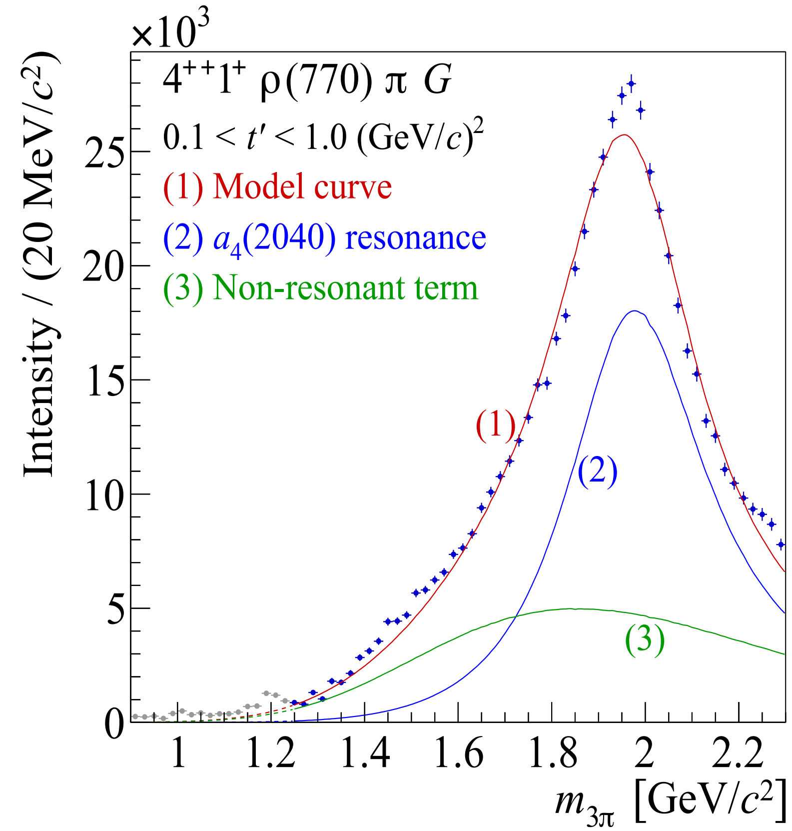
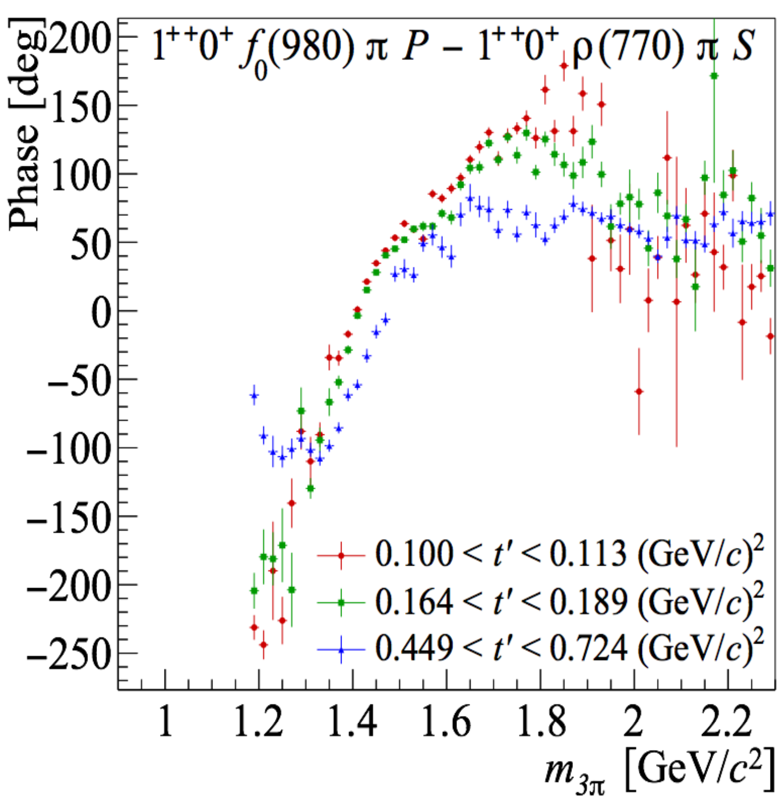


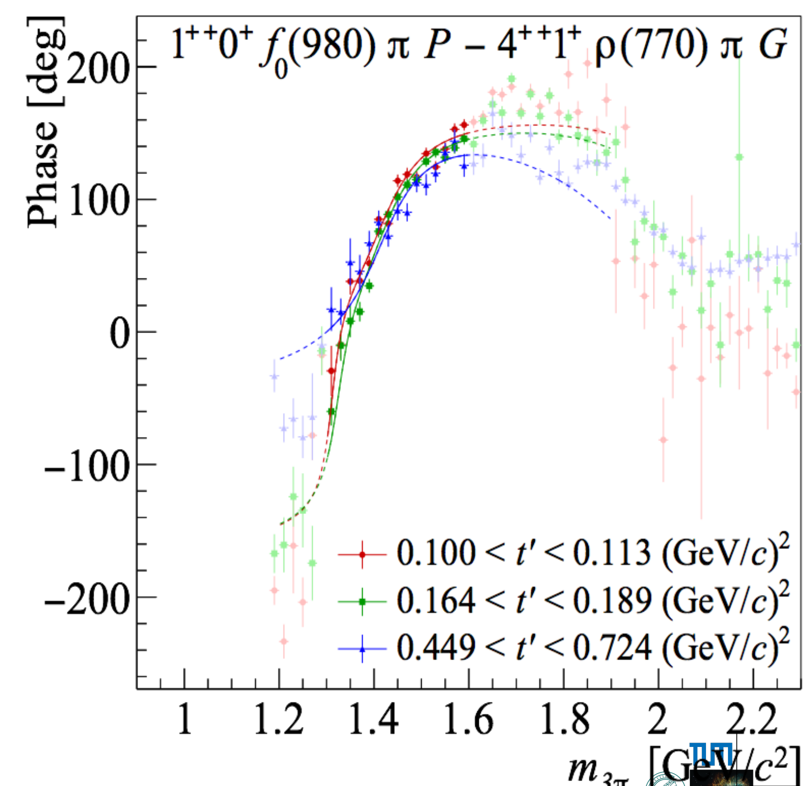






Observation:

- Decay only : $[f_0(980)]\ \pi\ P$
- *Mass : 1413 ± 15± 13 MeV/c^2*
- *Width: 157 ± 8 ± 23 MeV/c^2*

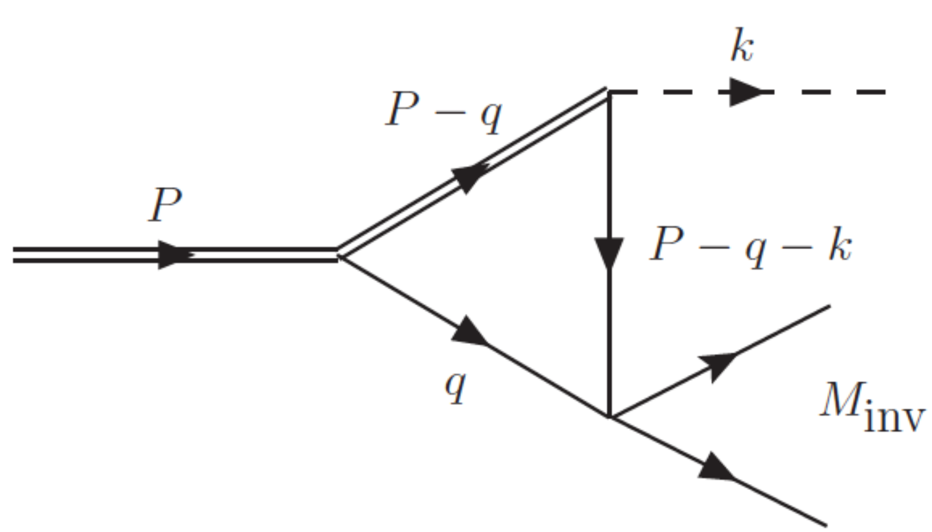


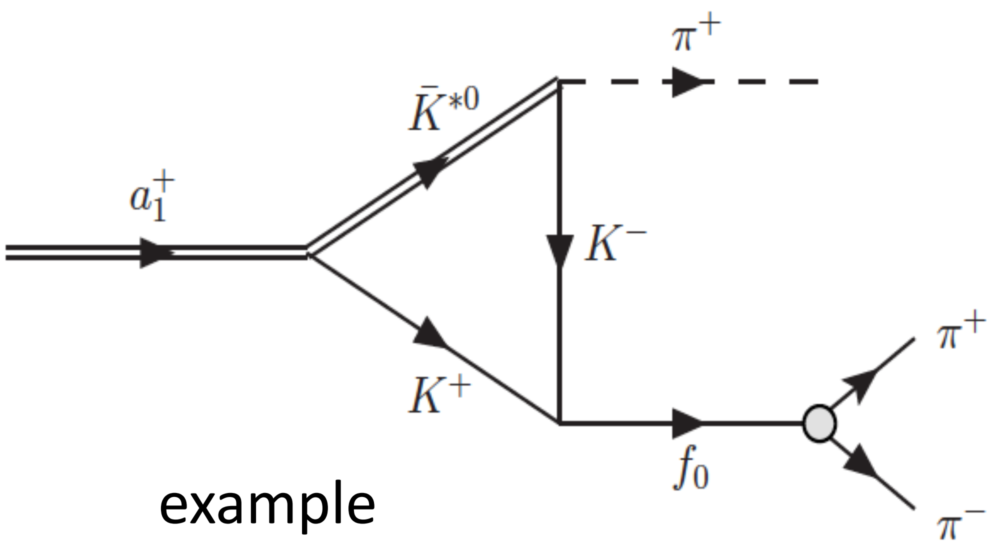
$a_1(1420)$ Interpretations

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 $a_1(1260) \longrightarrow KK^* \longrightarrow KK\pi$ and $KK \longleftrightarrow f_0(980)$ ($\Delta\phi = 90^0$) (Mikhasenko et al.)
- triangular anomaly : $a_1(1260) \longrightarrow f_0(980)\pi$ decay shows up 200 MeV above $M(a_1(1260))$ (Aceti et al.)
- Requires same t dependence for $a_1(1260)$ and $a_1(1420)$





example

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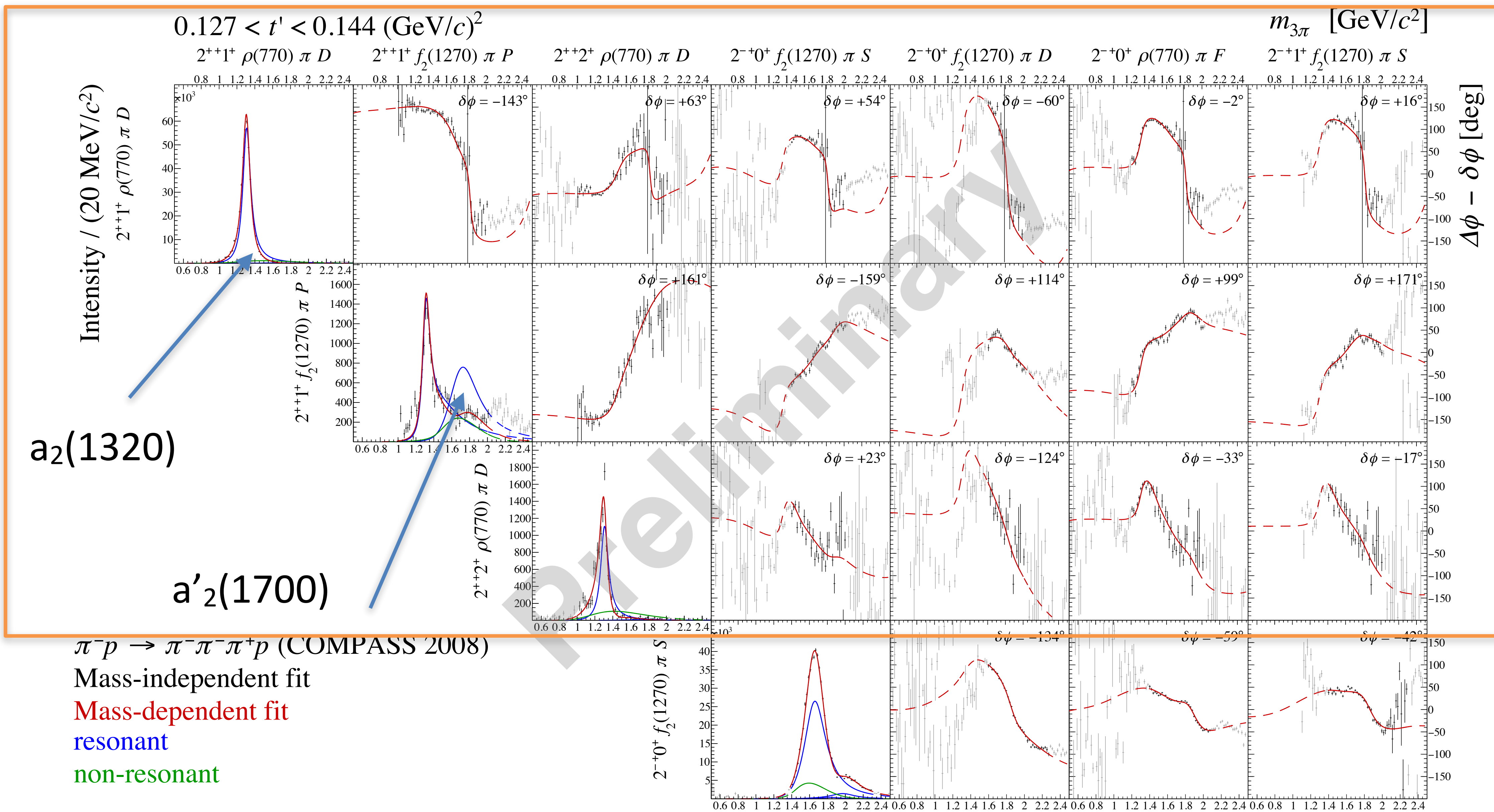
  - Requires same t dependence for $a_1(1260)$ and $a_1(1420)$
- Molecular structure
  - Partner of $f_1(1420)$

Find the Resonances

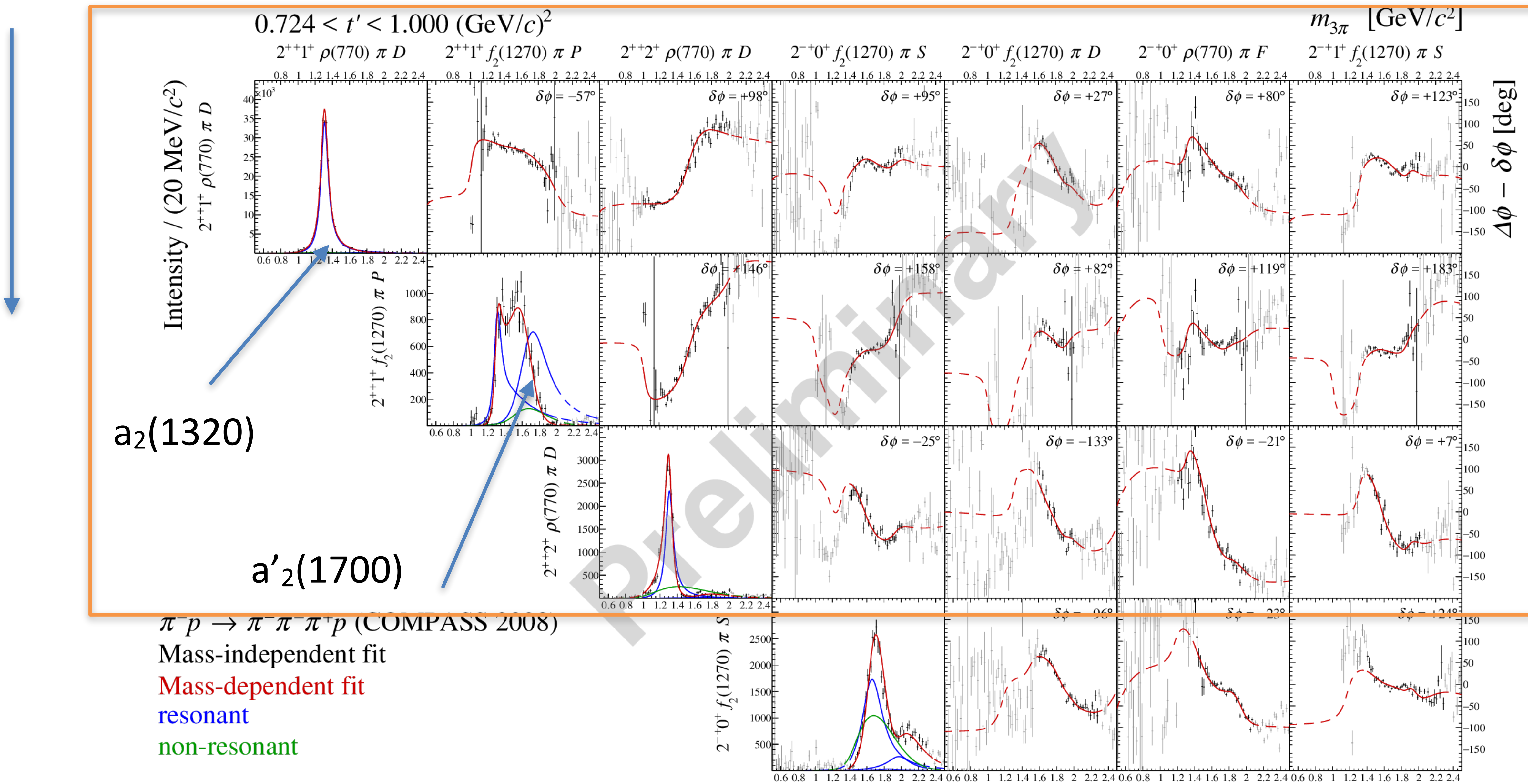
- Axialvector mesons: 2^{++}



low t

Find the Resonances

- Axialvector mesons: 2^{++}

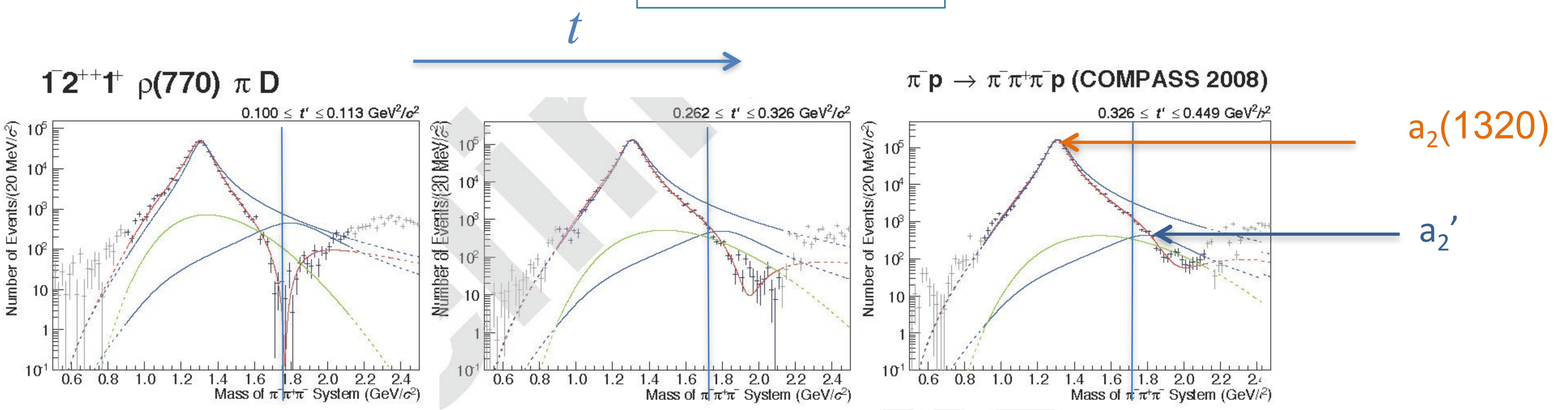


high t

Mass dependent fits $a_2(1320)$

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

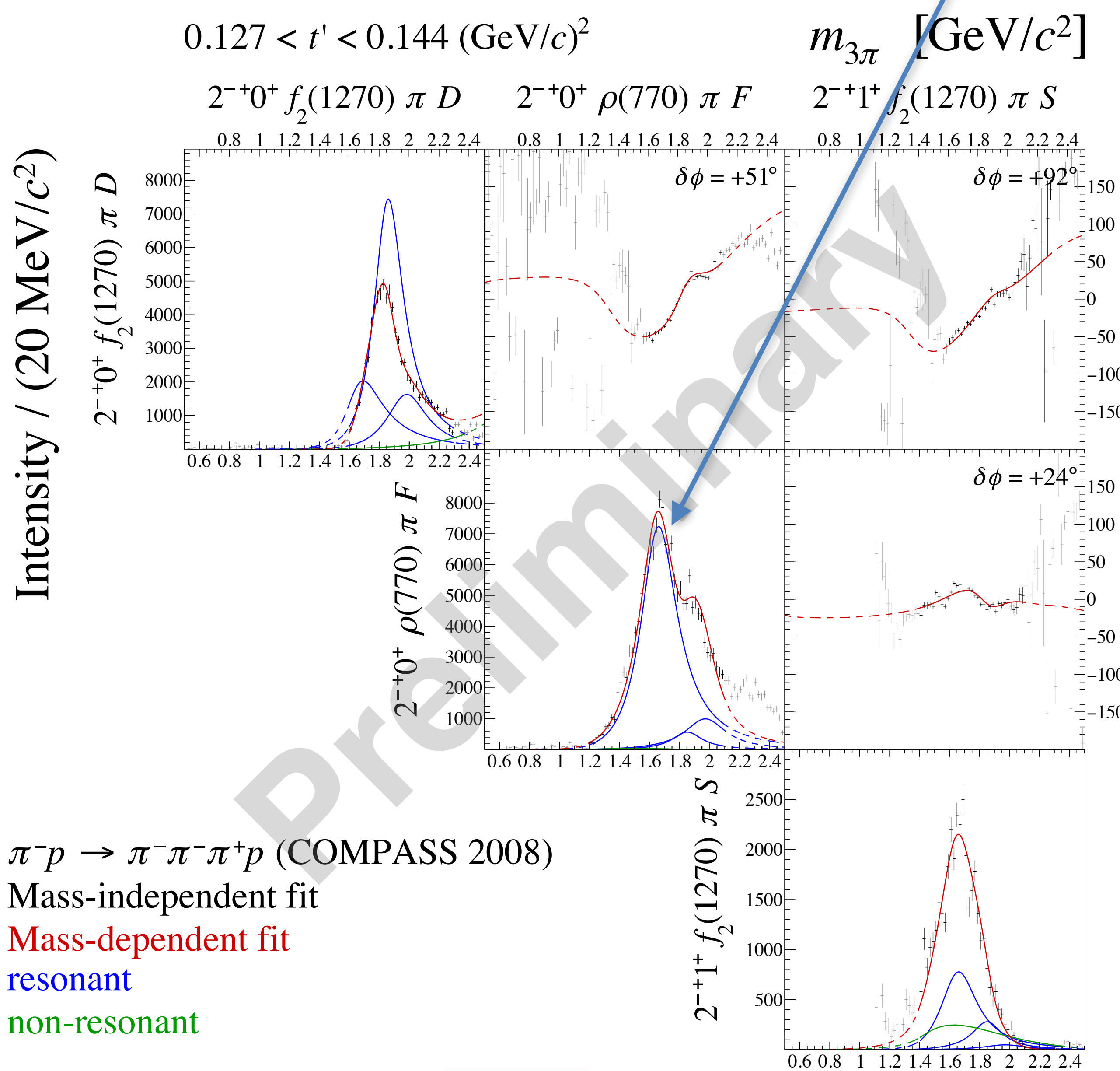
$J^{PC}M^{\varepsilon}[isobar]\pi L$



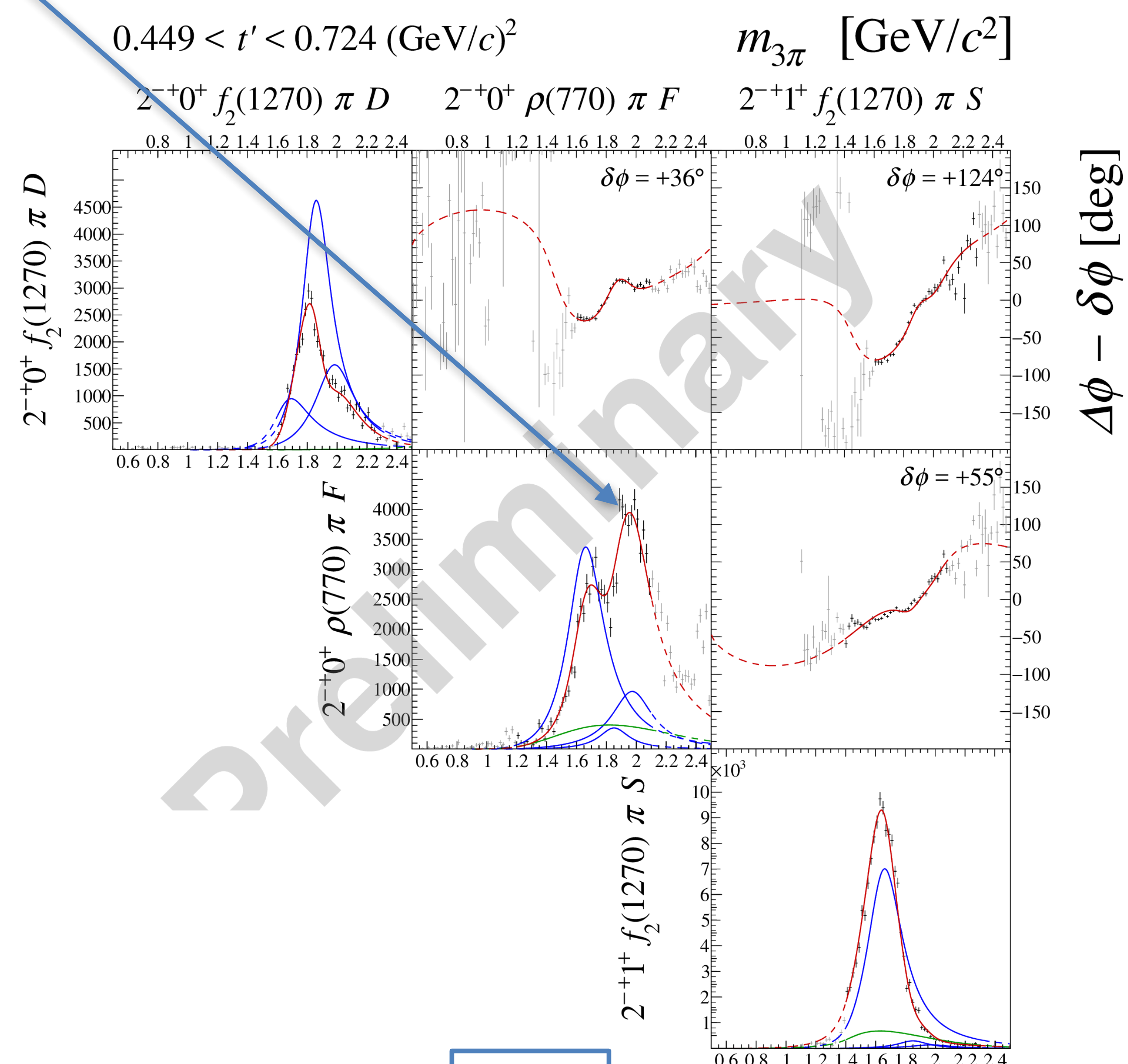
Strongly t-dependent interference effects
high-mass a_2'

Find the Resonances

- Pseudotensor mesons: 2^{-+}



low t

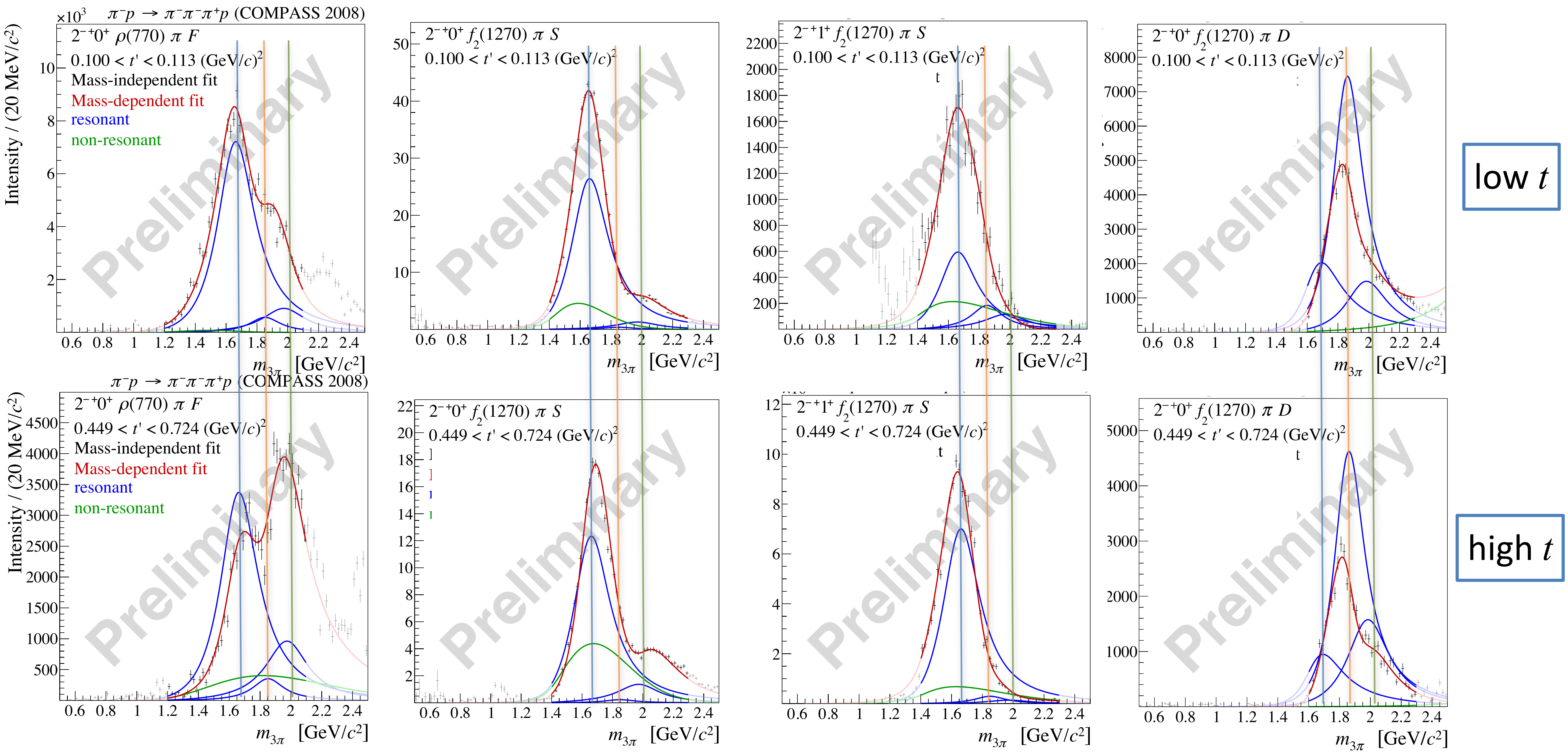


high t

The Case of π_2

$\pi_2(1670)$ $\pi_2(1880)$ $\pi_2(2005)$

m = 0 m = 0 m = 1 m = 0



- very different production/decay characteristics

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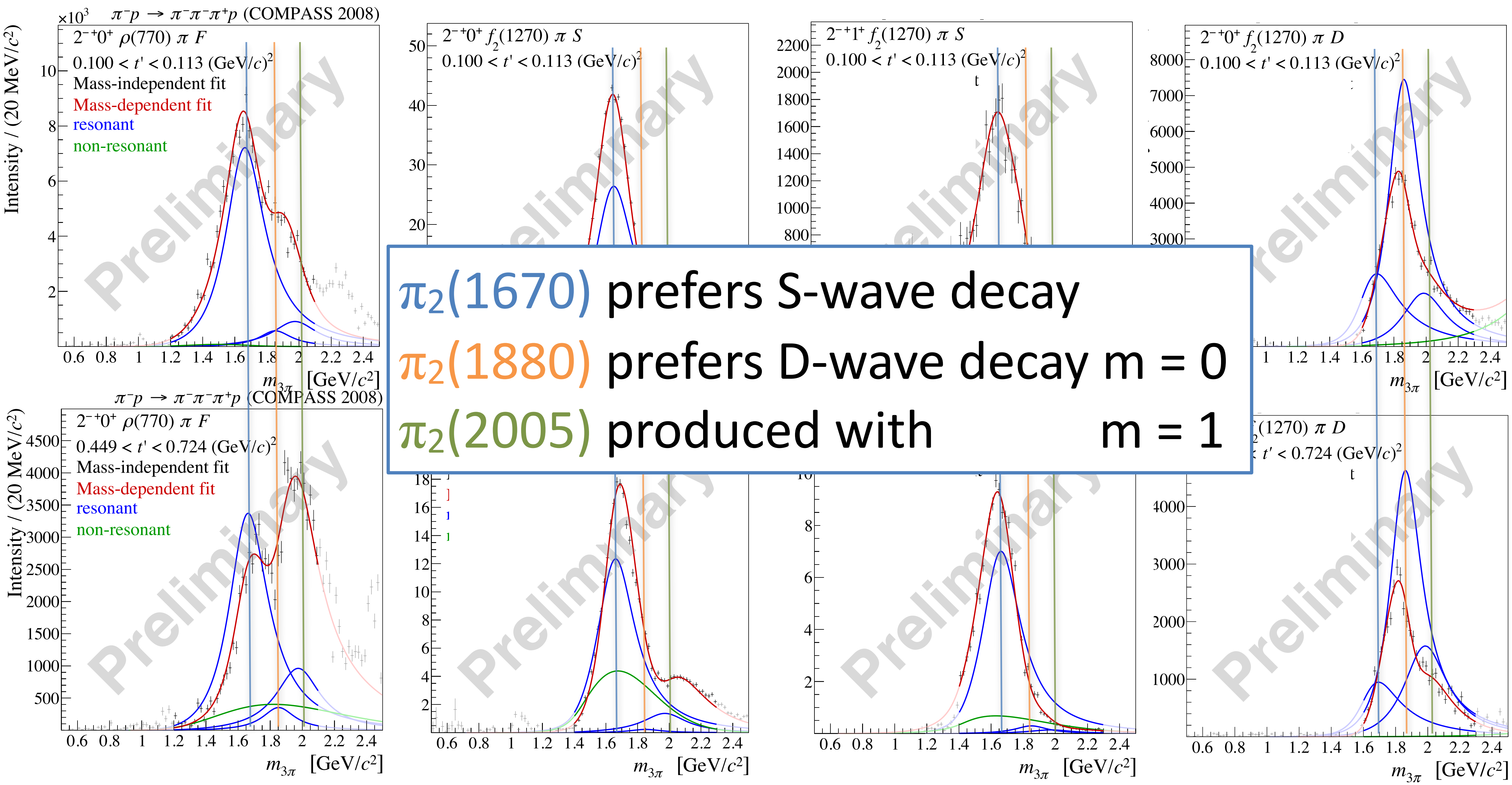


low t

high t

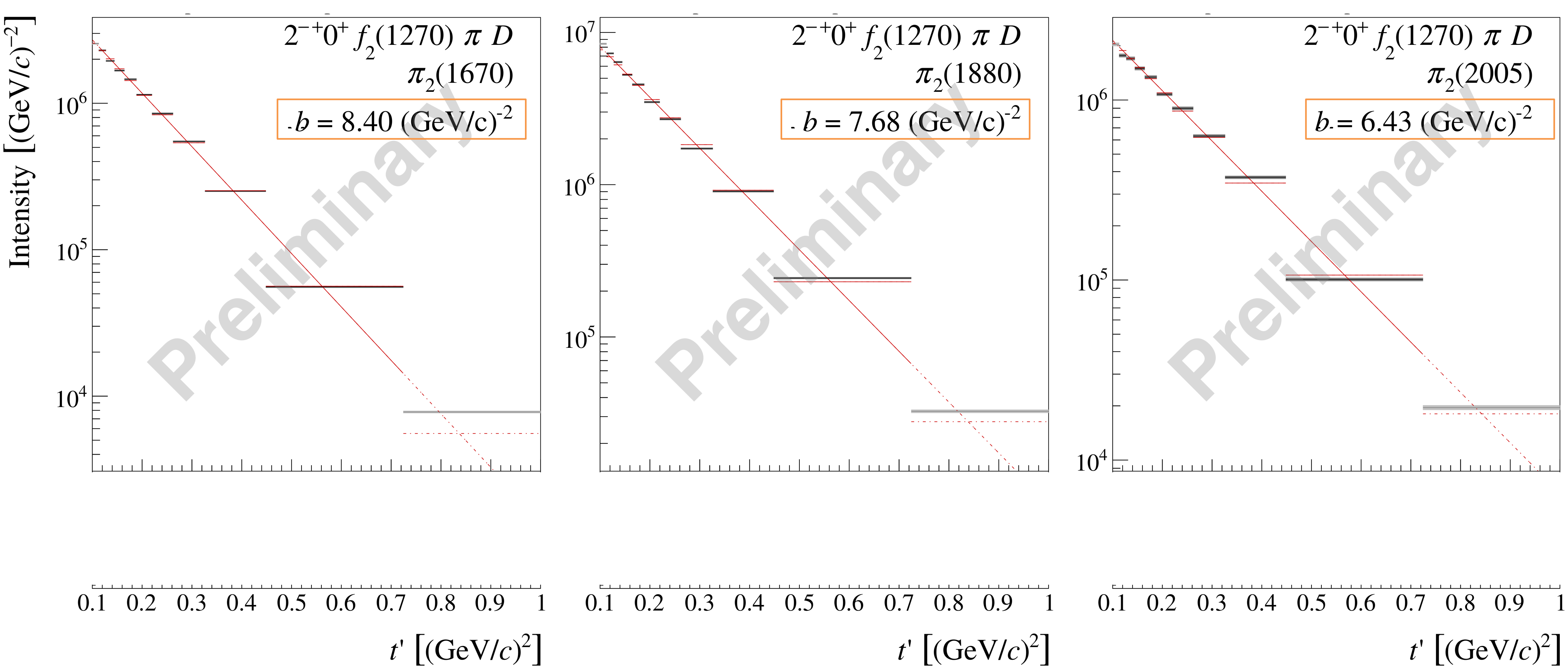
$\pi_2(1670)$ prefers S-wave decay

$\pi_2(1880)$ prefers D-wave decay m = 0

$\pi_2(2005)$ produced with m = 1

- very different production/decay characteristics

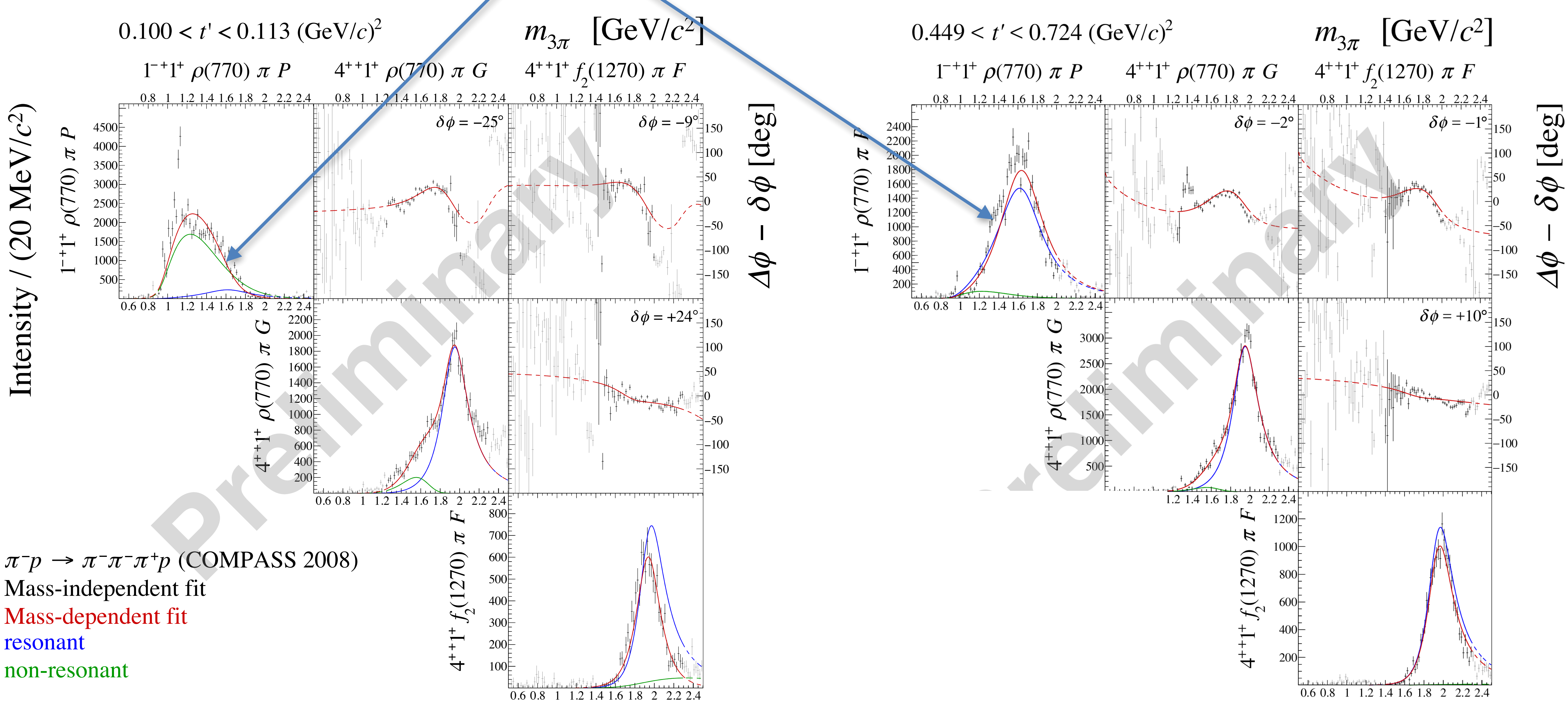
Kinematics: Dependence on t



Background: b = $(13.5\ \mathrm{GeV/c})^{-2}$

Find the Resonances

- Exotic mesons: 1^{-+}



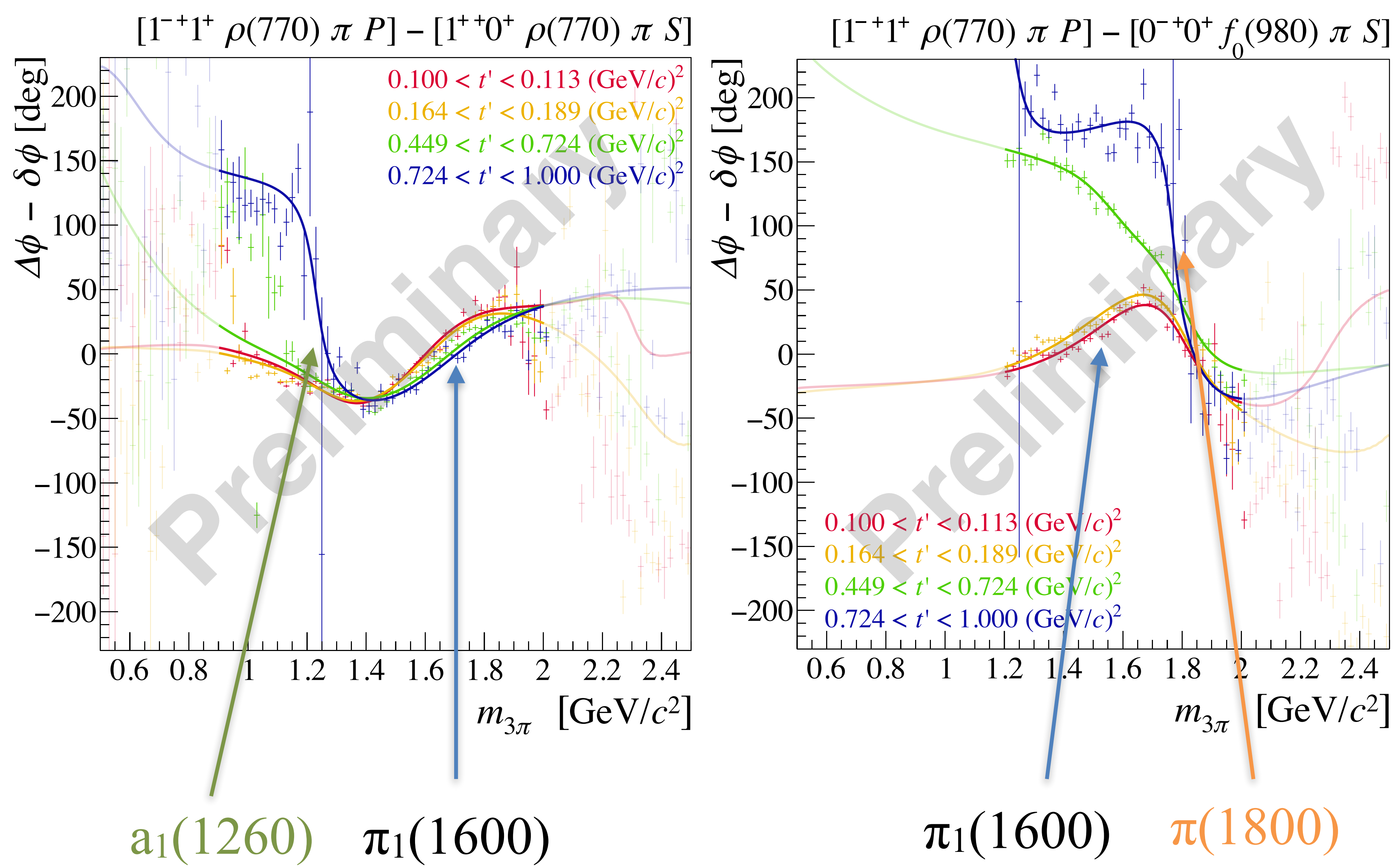
low t

high t

Exzellenzcluster Universe

Find the Resonances - Phases

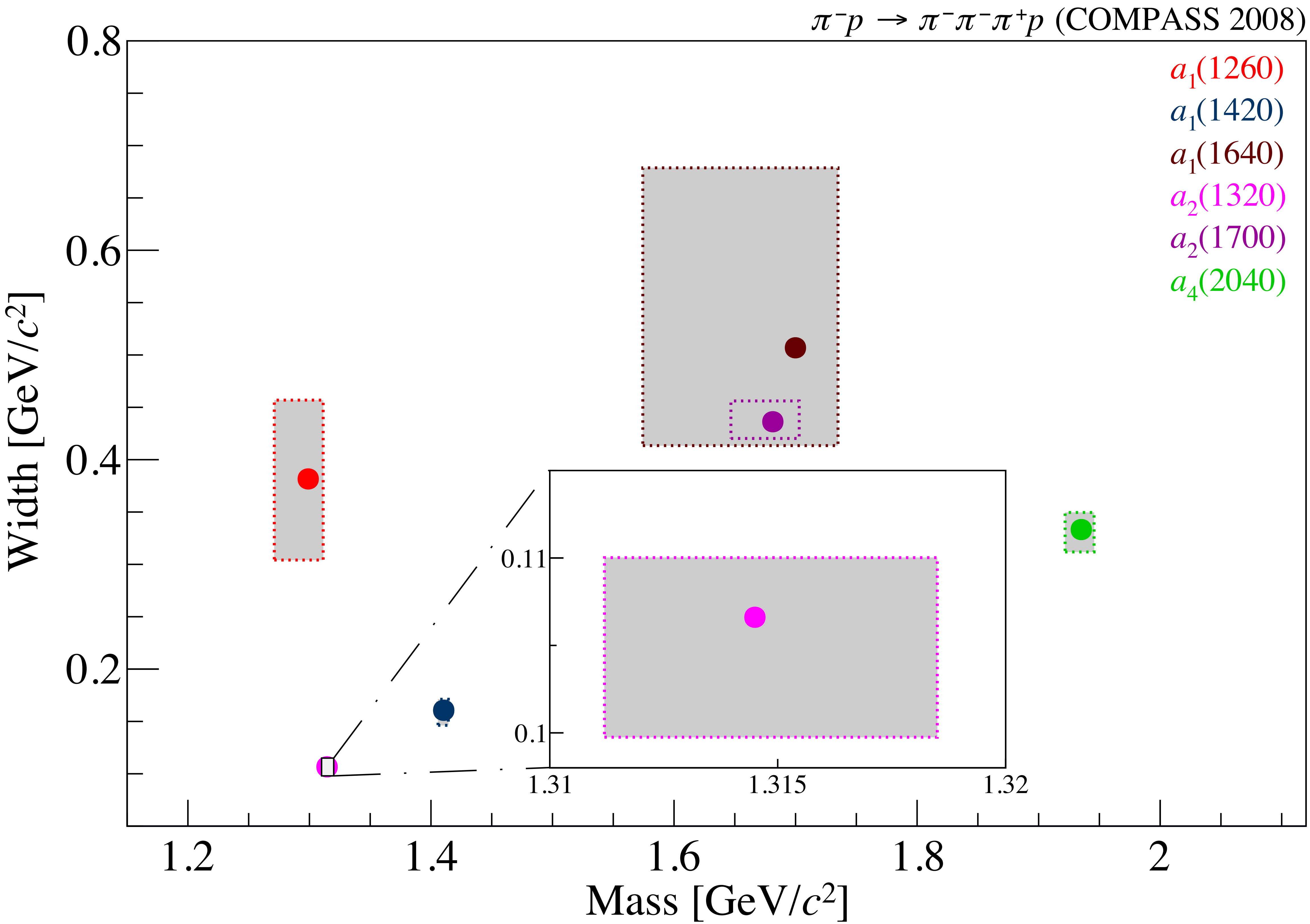
- Exotic mesons: 1^{-+}



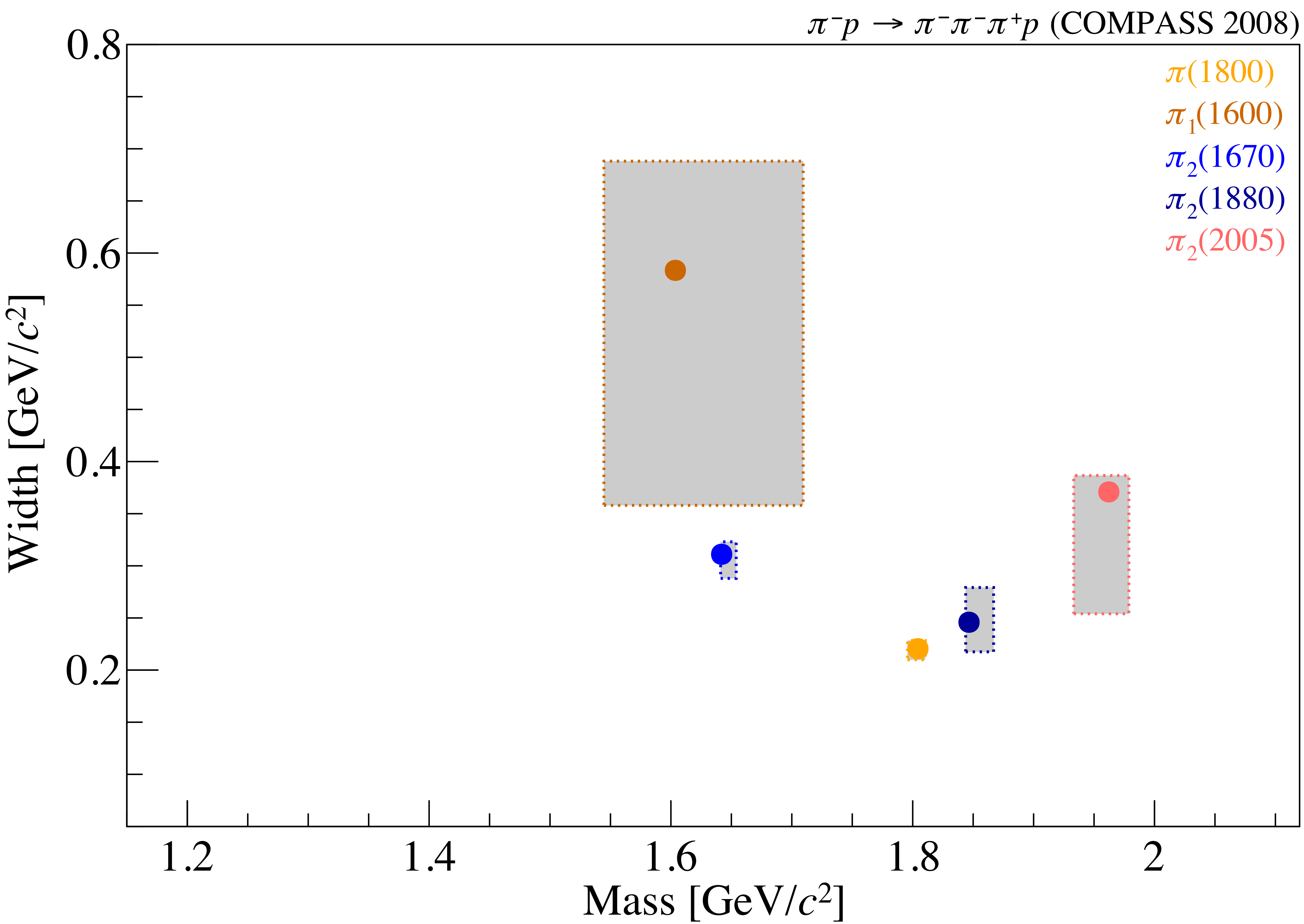
Systematic Studies

- Largest set of systematic studies done ever
  - Omitting waves
  - Modification of resonance models
  - Variation of NR parametrization (analytical function vs. Deck MC)
  - Modified χ^2 use of correlation in spin-density matrix
  - alternating fit order of 700 parameters
  - vary selection criteria
- Biggest influence on
  - $a_1(1260)$, $a_2(1700)$, $\pi_1(1600)$
  - strong correlation $a_1(1260)$ - $\pi_1(1600)$ resonance parameters found

Axialvector Mesons



Pseudo-Scalar/Tensor Mesons



Exzellenzcluster Universe

Challenging PWA

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Key ingredients into PWA

- PWA: Expansion and Truncation
  - developed new method for automatic wave selection
  - picks out also small waves
  - robust towards large interference effects

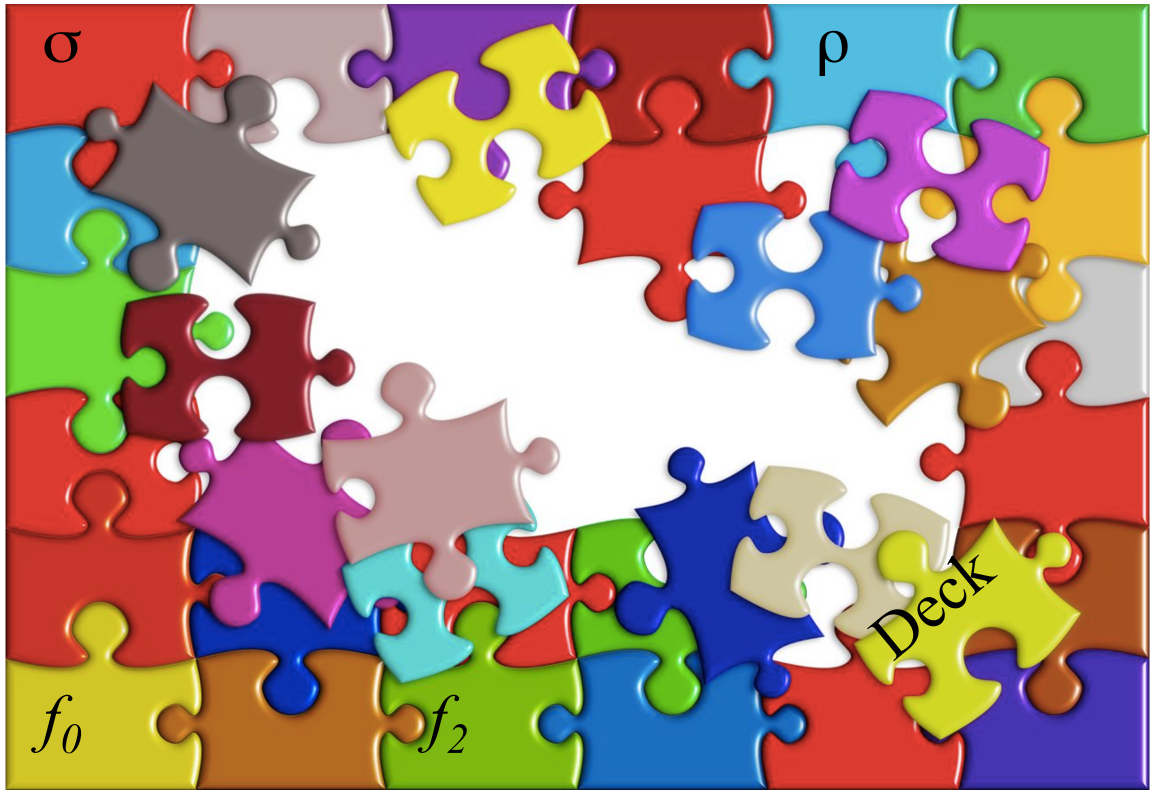
Challenging PWA

Key ingredients into PWA

- PWA: Expansion and Truncation
  - developed new method for automatic wave selection
  - picks out also small waves
  - robust towards large interference effects
- Amplitude modelling (Isobar model)

What about the building blocks

- We have solved a puzzle – but were the building blocks correct ?



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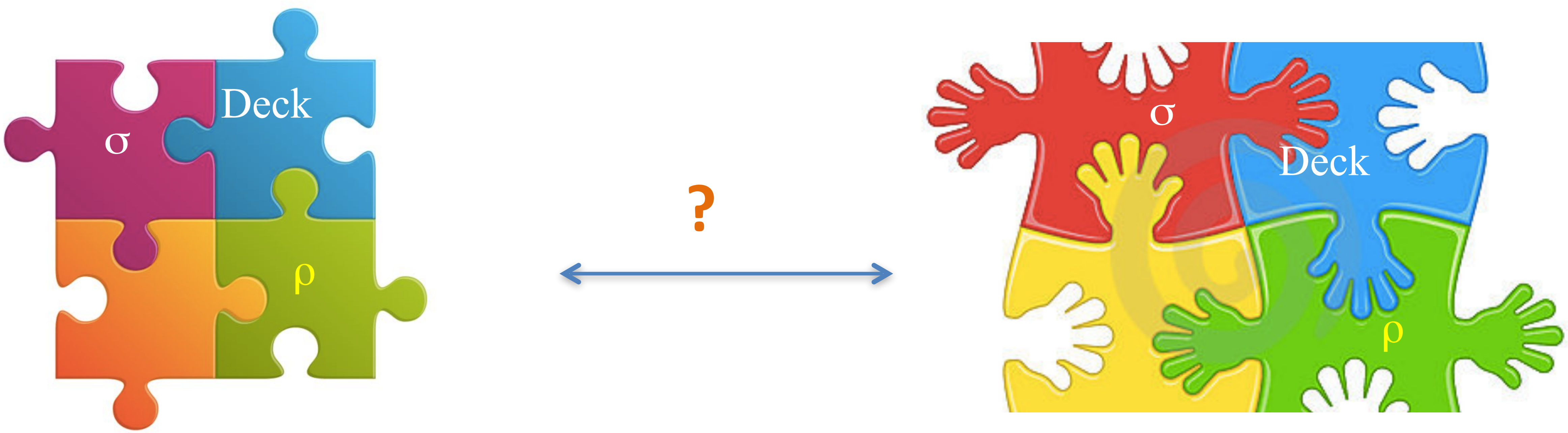
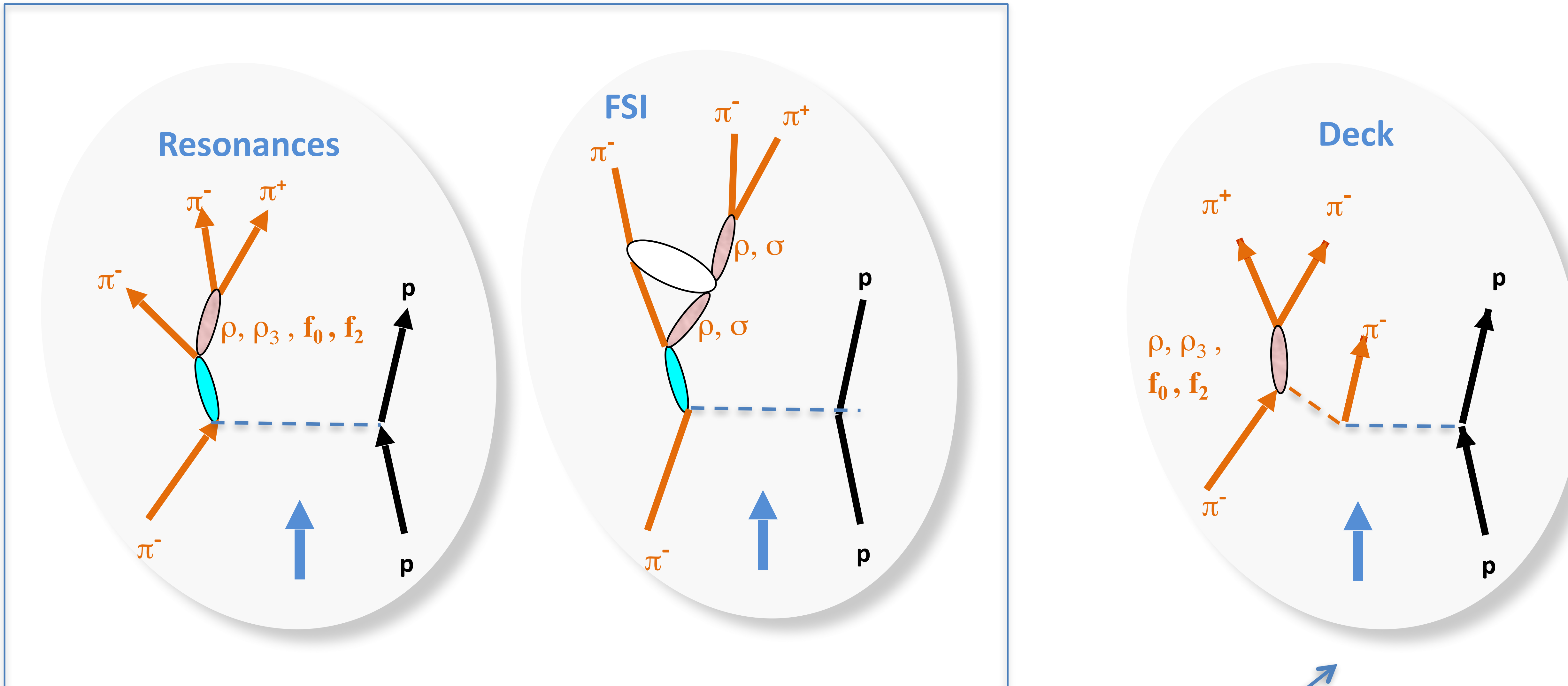


New Paths to Meson Decays



- Select J^{PC} via PWA
- For each J^{PC} and mass-bin in 3π :
  - determine composition and shapes of 2π isobars
  - complex couplings
  - non-resonant contributions (via t-dependence)

Isobars: $[\pi\pi]^*_S$

Phys. Rev. D35 1633, Au, Morgan, Pennington

continuum - $[\pi\pi]_S$

$f_0(980)$

fixed functional form – variable intensity/phase (2 parameters)

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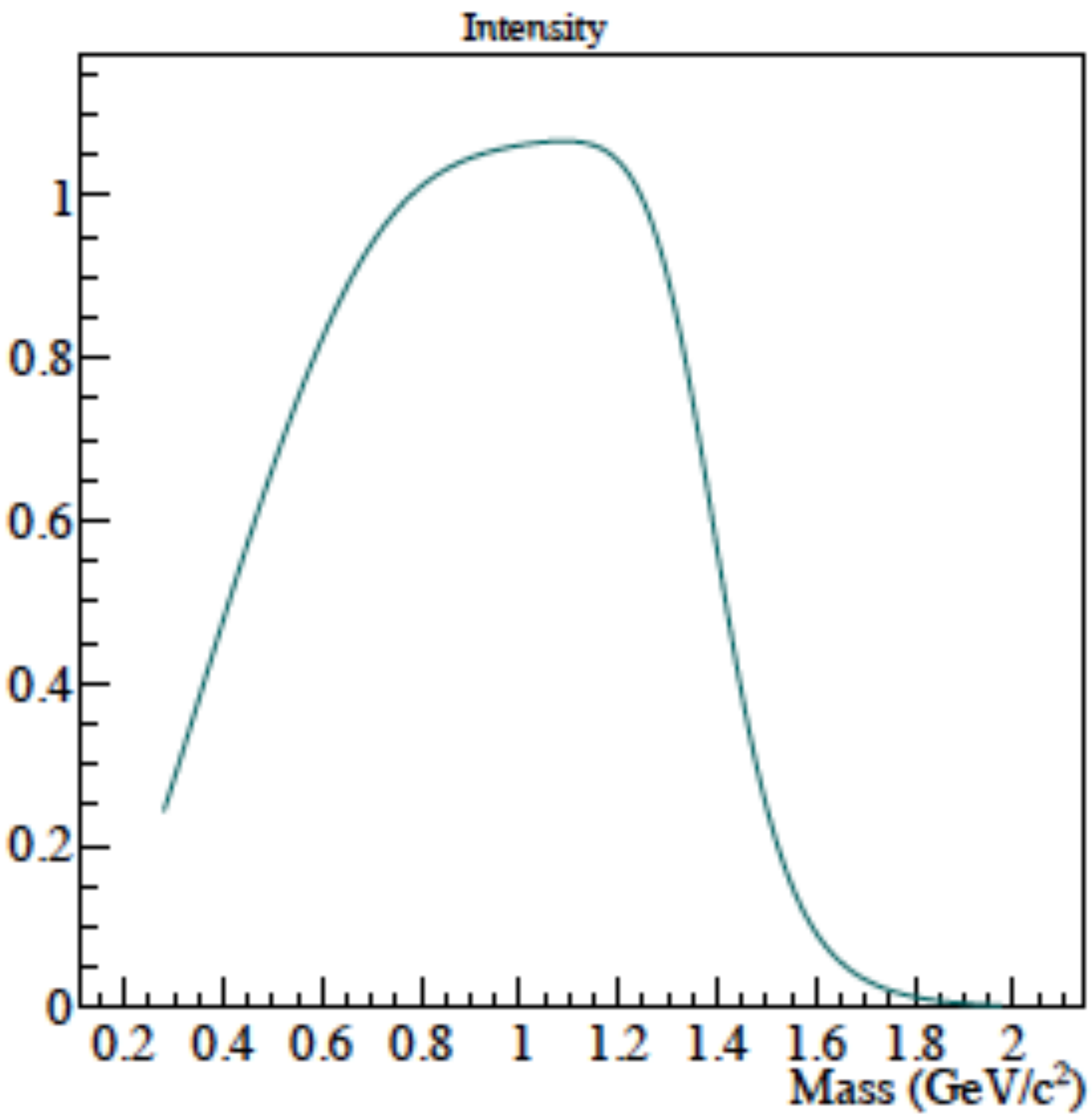
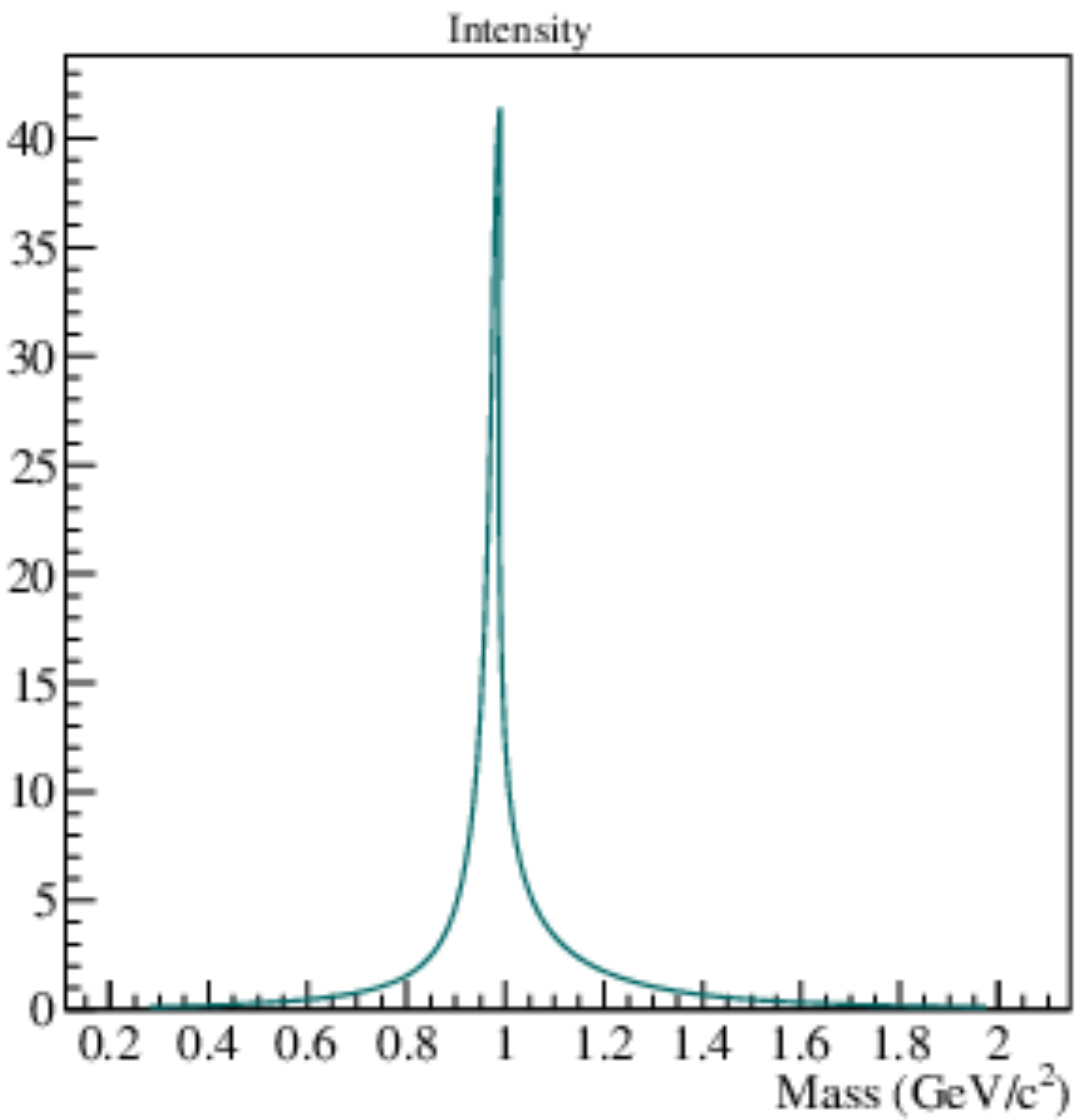
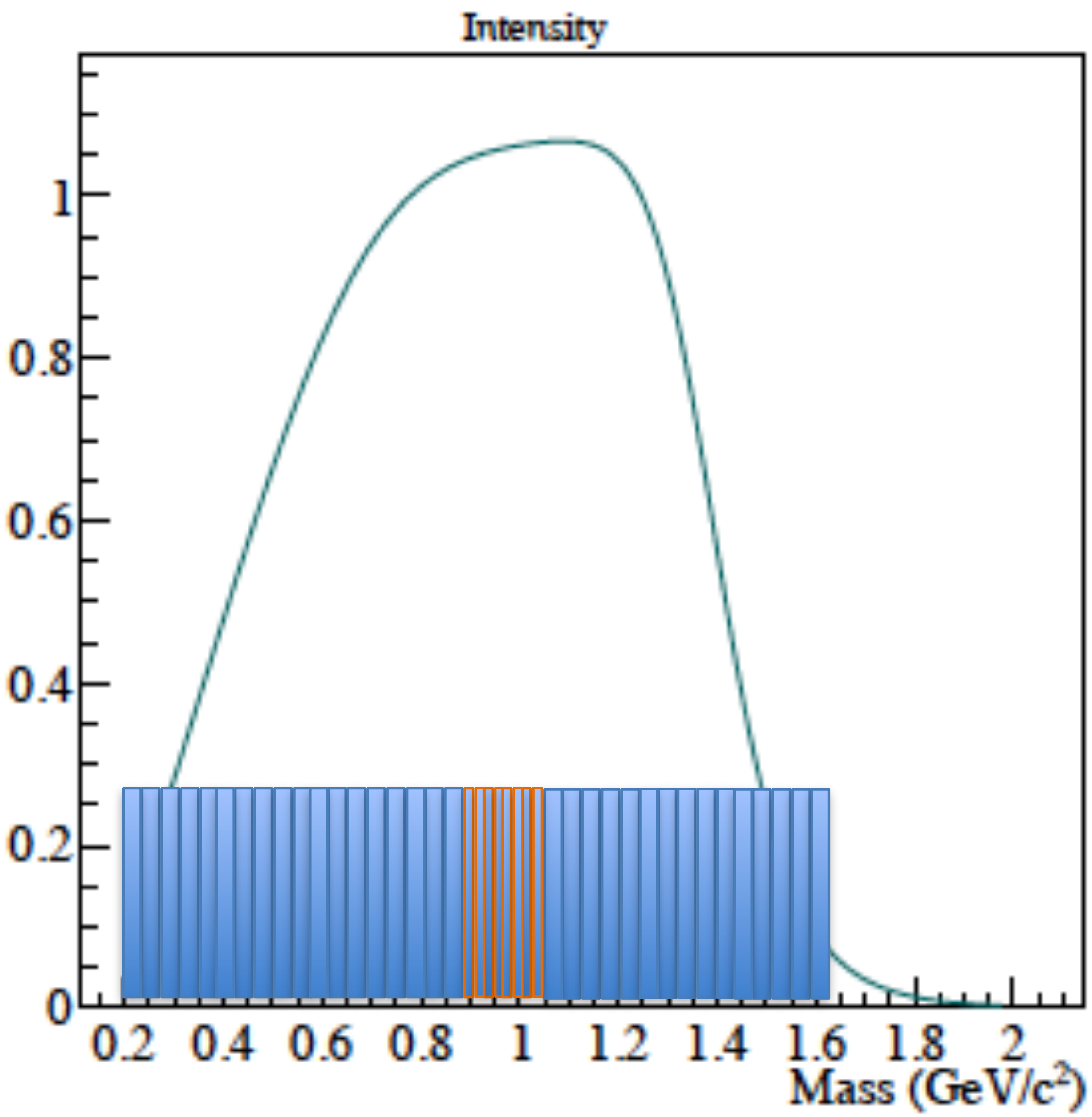


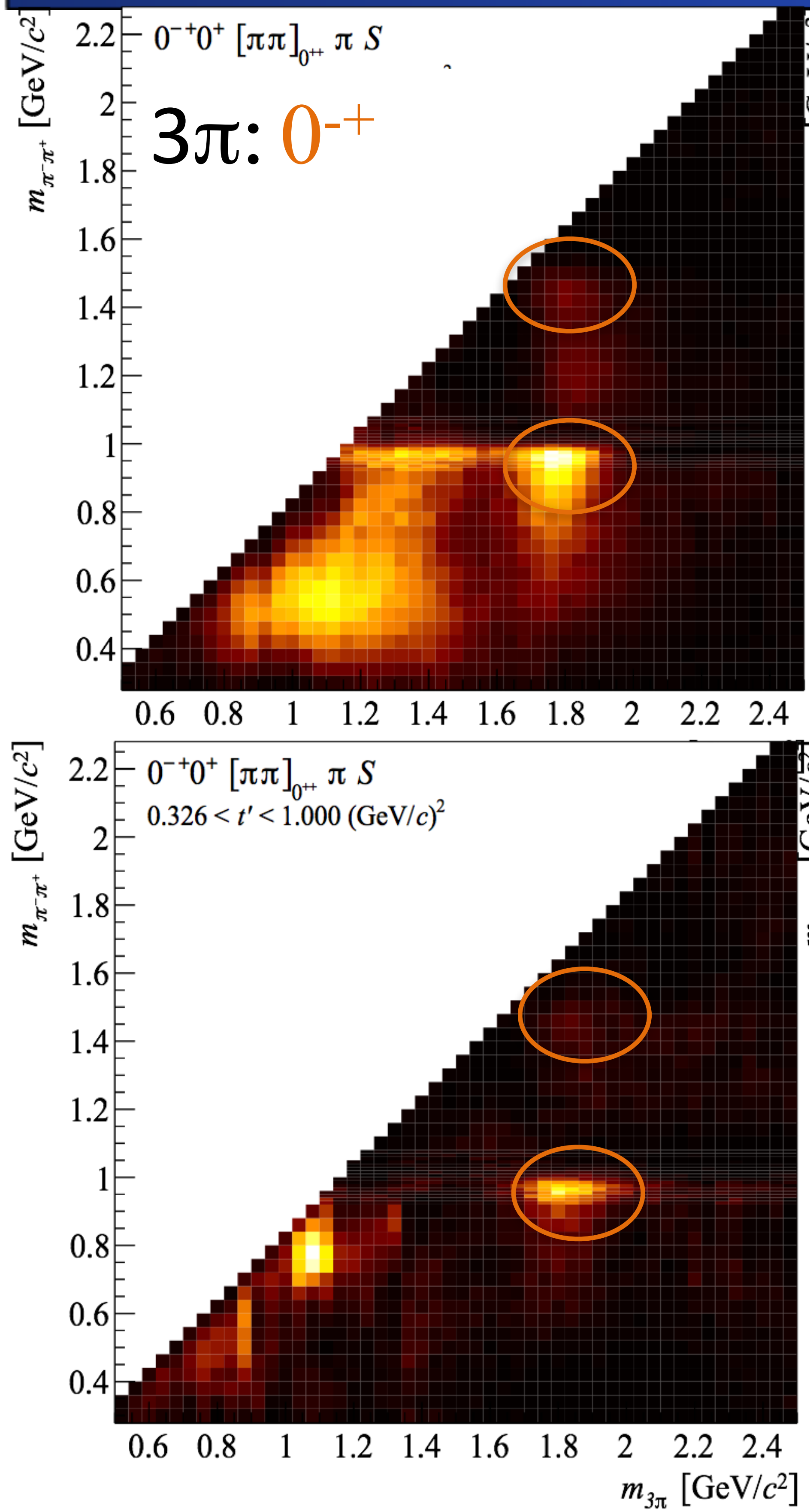


Isobars: $[\pi\pi]^*_S$

replaced by ONE $[\pi\pi]^*_S$ histogram with n-bins
($2n$ parameters determined by fit)



Correlation: $m_{2\pi}(0^{++})$ *vs* $m_{3\pi}(J^{PC})$



COMPASS Phys.Rev. D95 (2017) no.3, 032004

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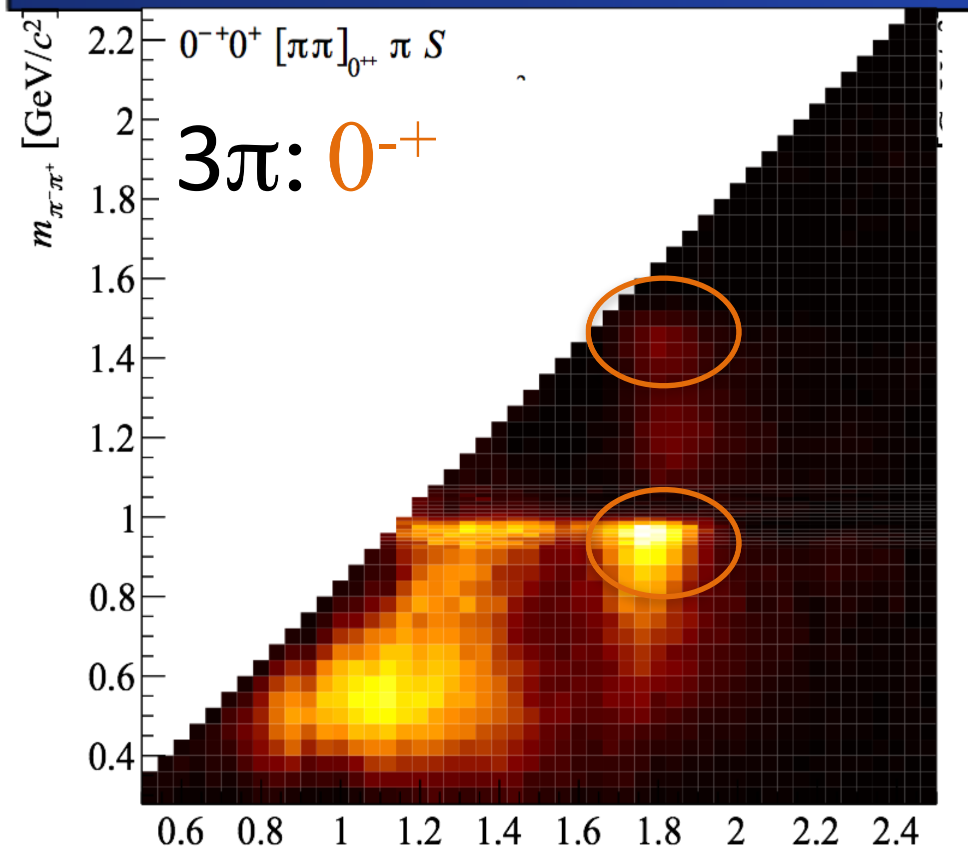

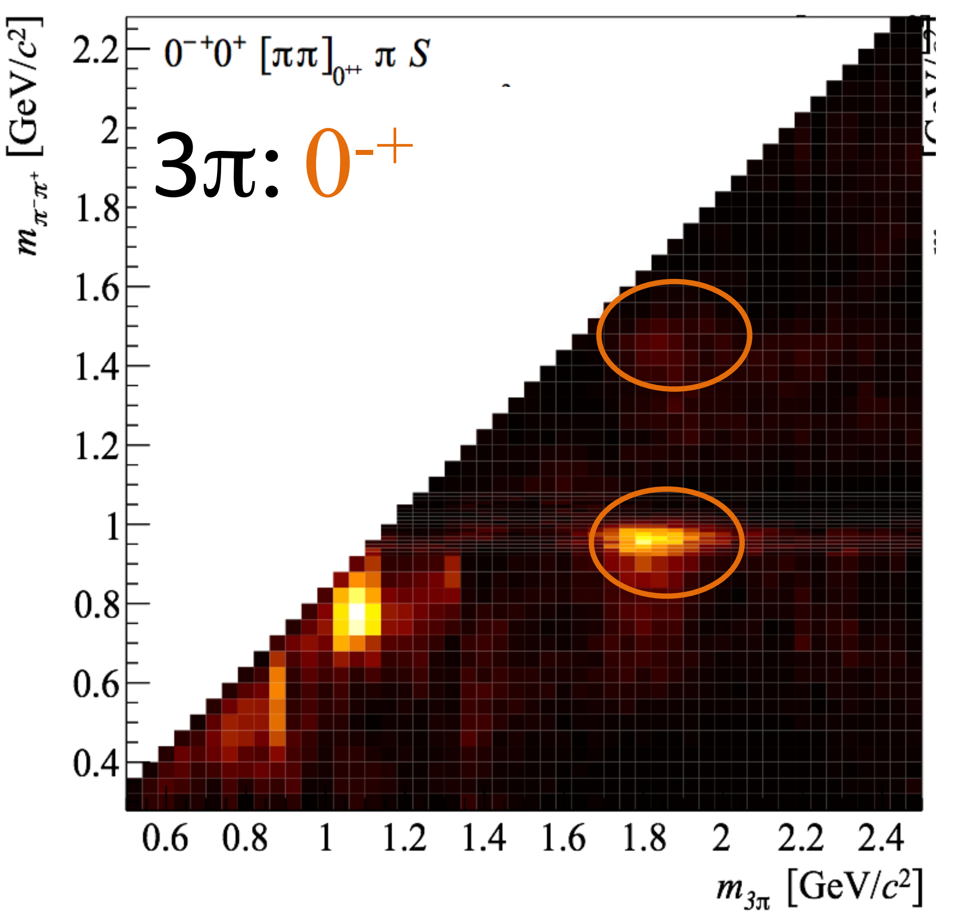

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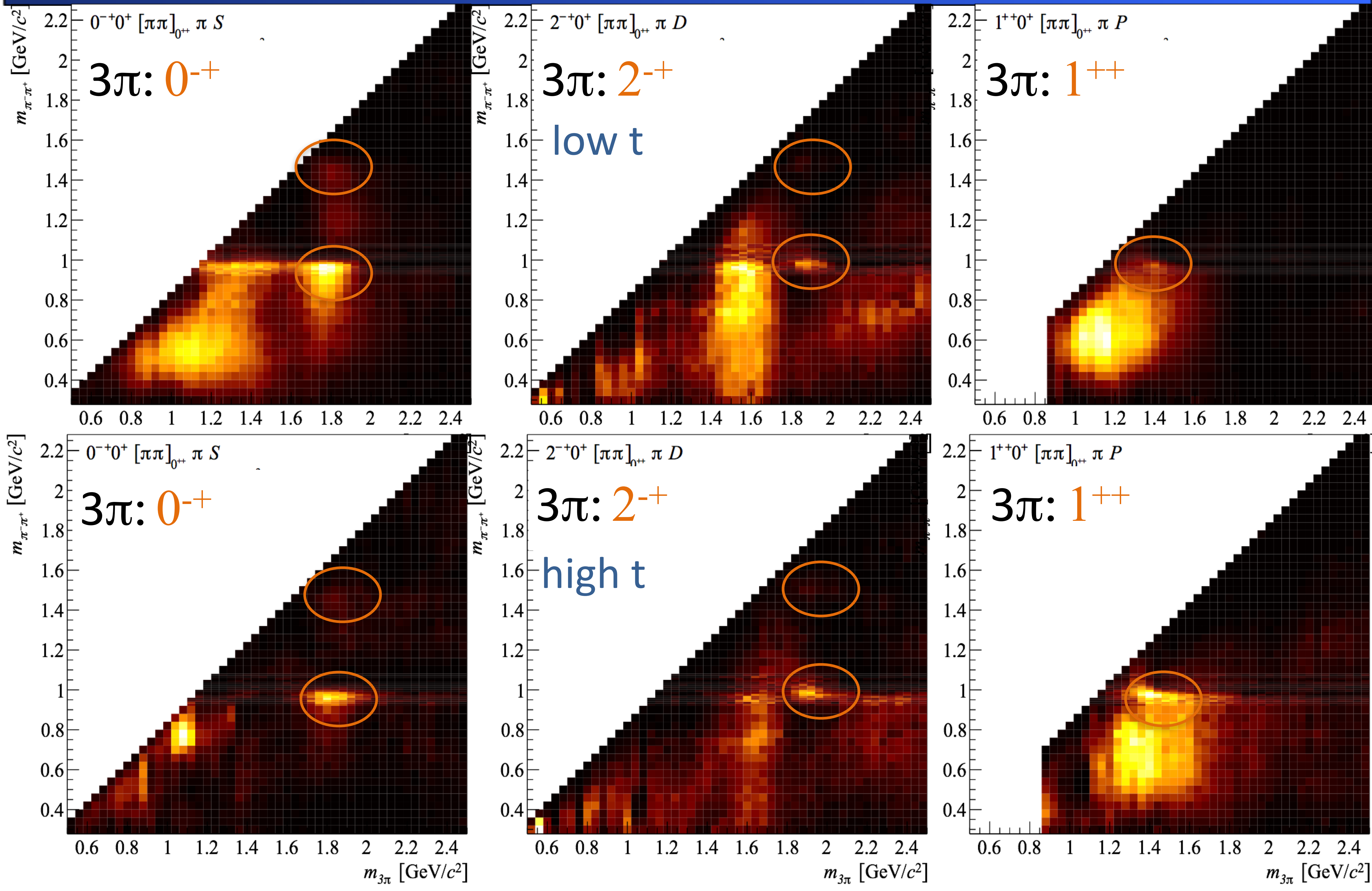

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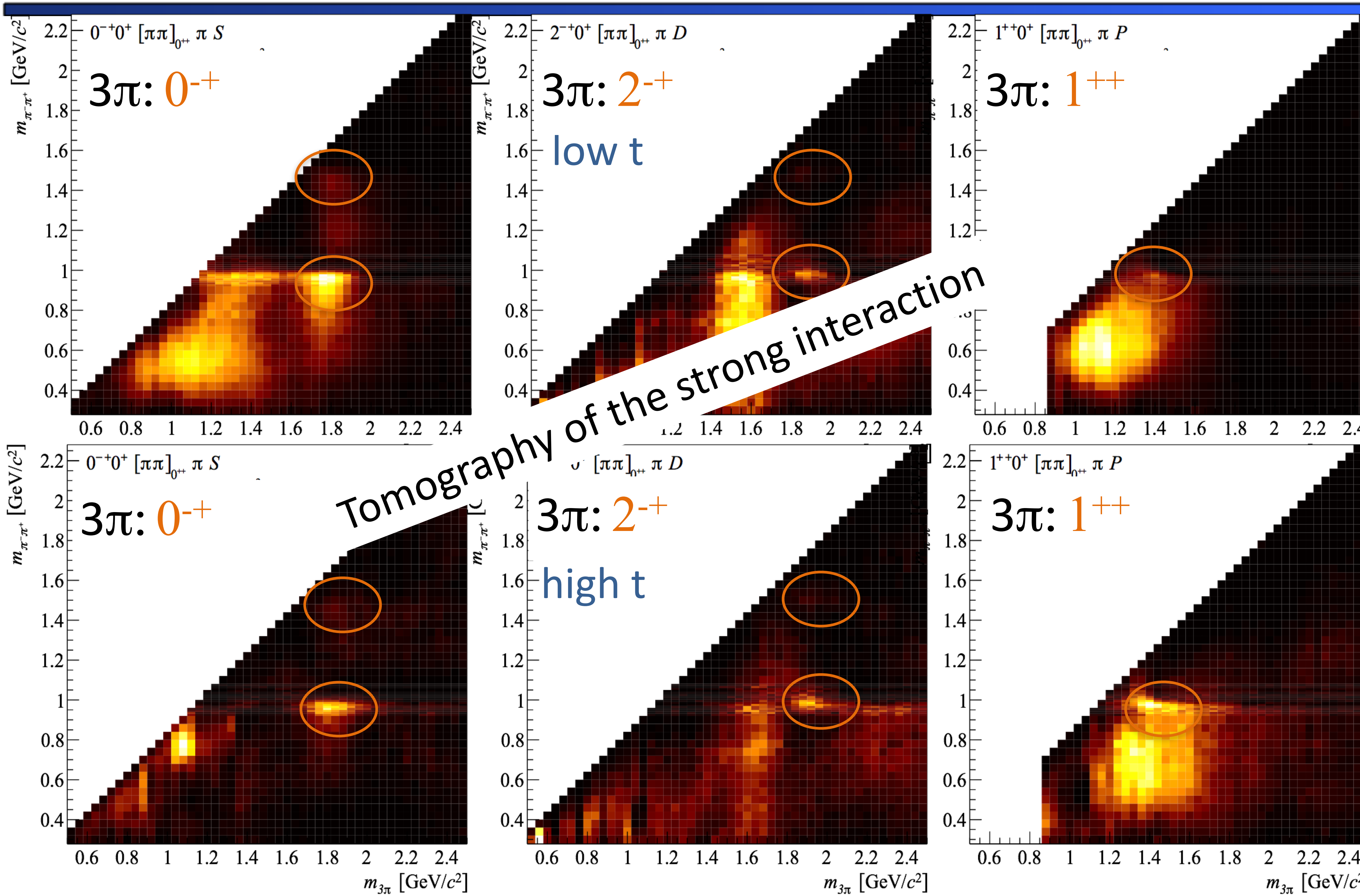
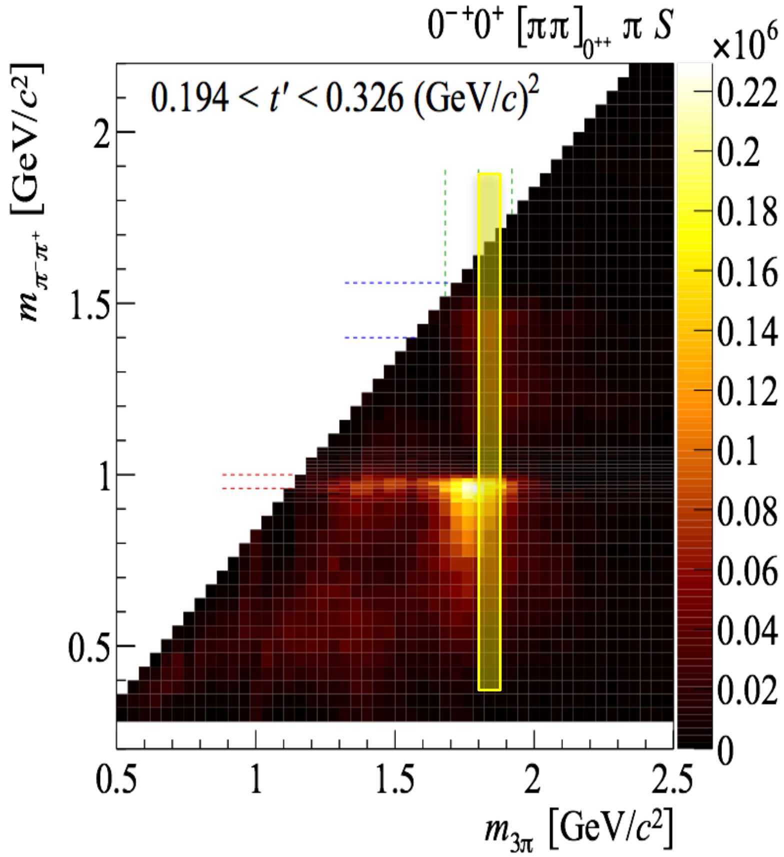


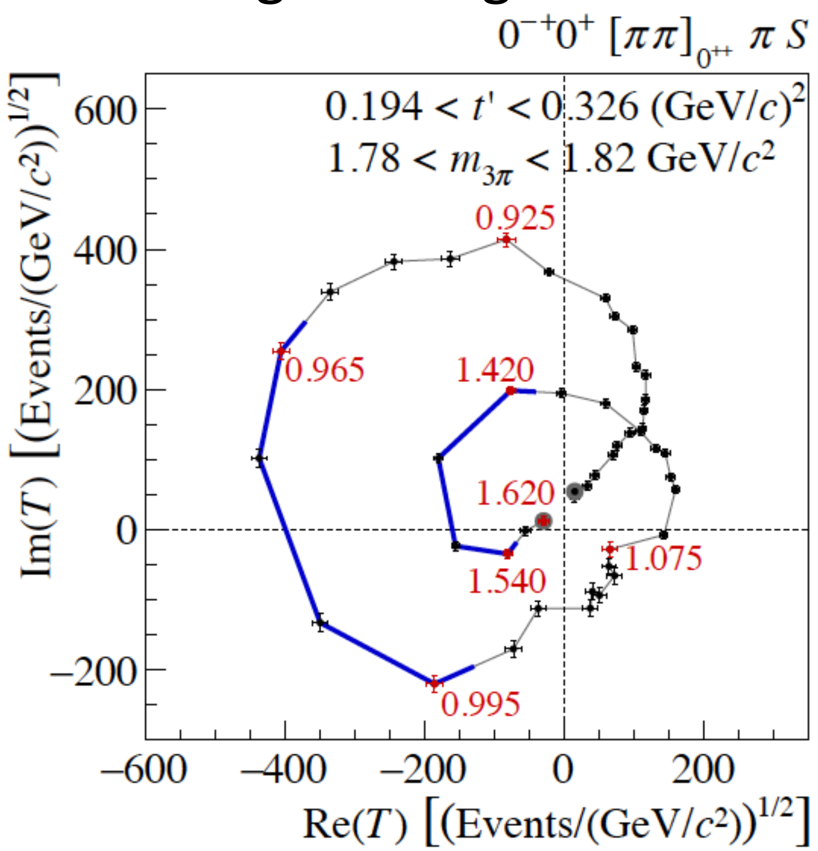
Studying the Structure of Decays

Study decay of π(1800) into 3π

Here: 2π S-wave intermediate state



Argand Diagram



Perform de-isobaring of analysis extract 2π from data „model independent“ (HQ decay language)

Studying the Structure of Decays

Study decay of π(1800) into 3π

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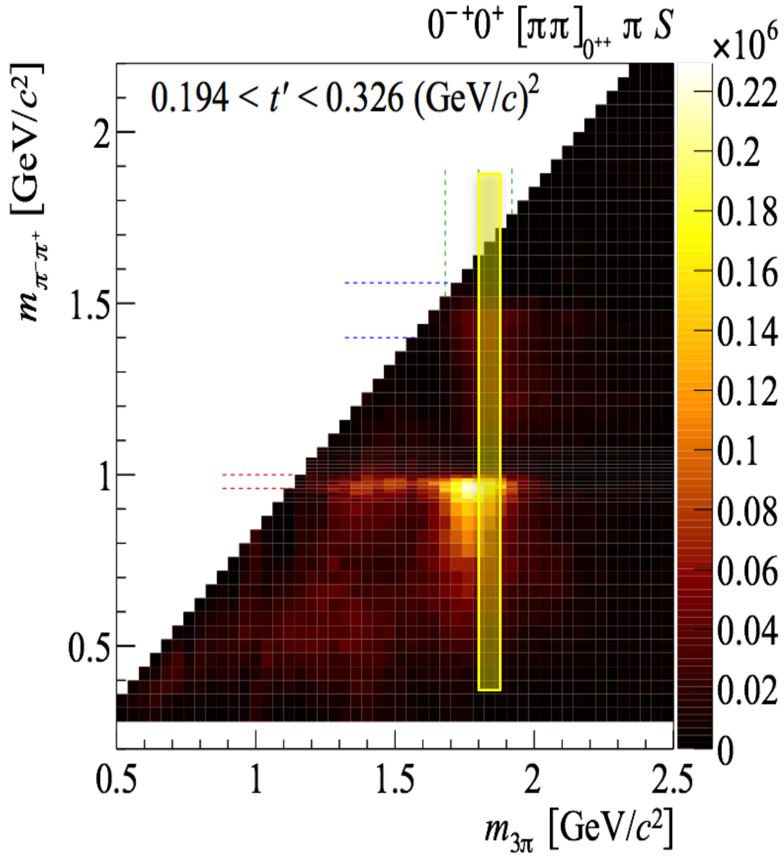

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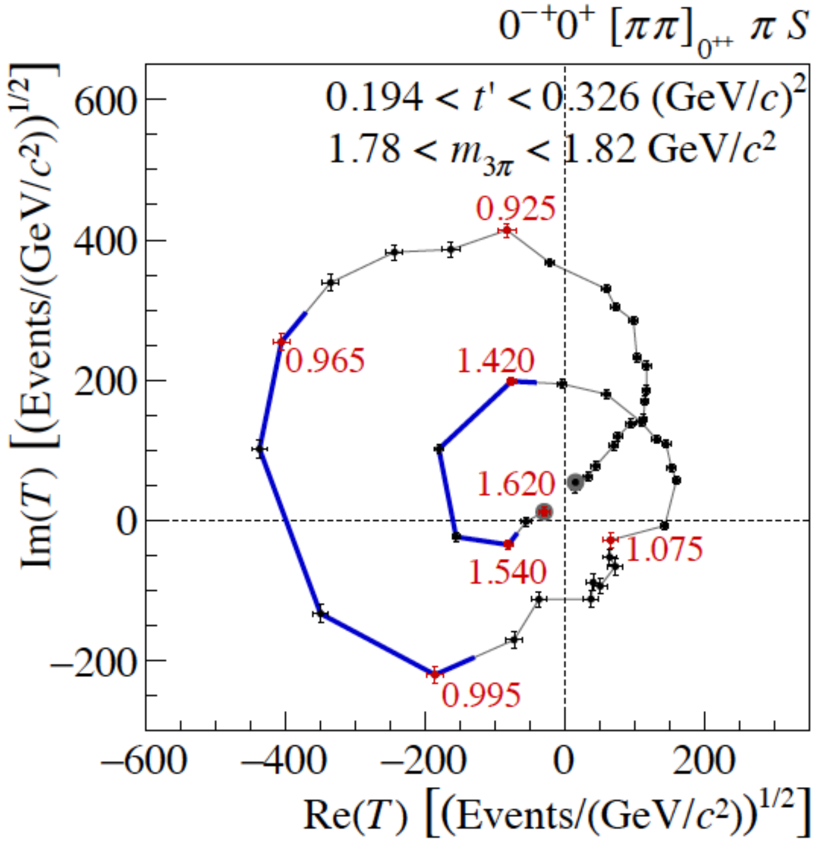
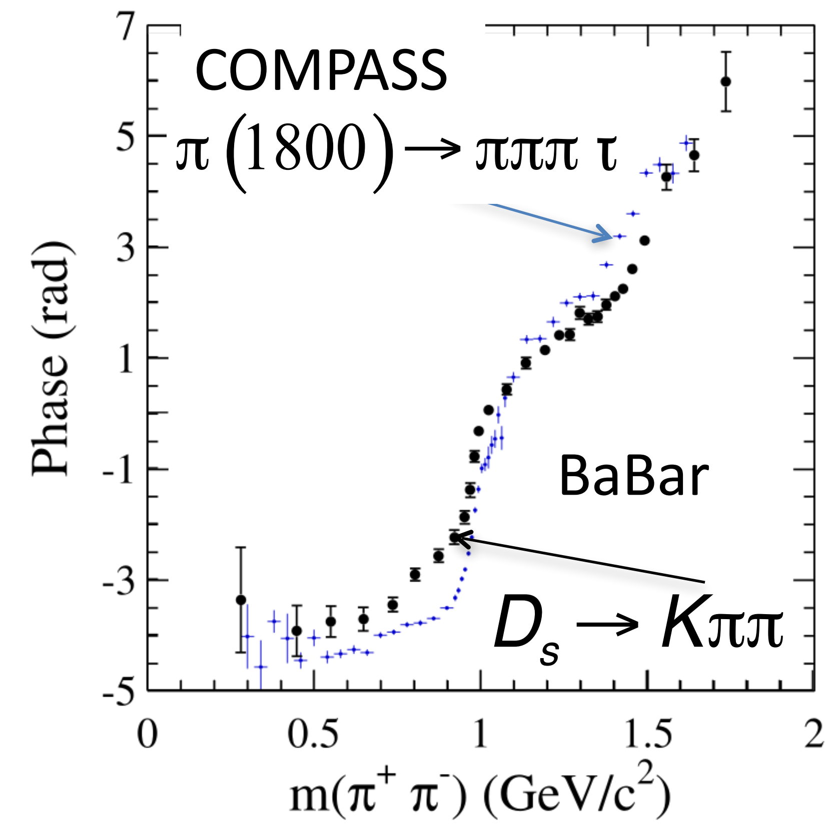


$(\pi\pi)_{\text{S-wave}}$



$(\pi\pi)_{\text{S-wave}}$ Similar for weak and strong decays !!

Subtle differences will tell us more

„Full“ freed-isobar fit

- performance 88-wave fit
- replace 18 waves by freed-isobar
  - reduces these to 14 waves

$0^{-+}0^{+}[0^{++}]\ \pi S$	$0^{-+}0^{+}[0^{++}]\ \pi S$
$0^{-+}0^{+}[1^{--}]\ \pi P$	$0^{-+}0^{+}[1^{--}]\ \pi P$
$1^{++}0^{+}[0^{++}]\ \pi P$	$1^{++}0^{+}[0^{++}]\ \pi P$
$1^{++}0^{+}[1^{--}]\ \pi S$	$1^{++}0^{+}[1^{--}]\ \pi S$
$1^{++}1^{+}[1^{--}]\ \pi S$	$1^{++}1^{+}[1^{--}]\ \pi S$
$2^{-+}0^{+}[0^{++}]\ \pi D$	$2^{-+}0^{+}[0^{++}]\ \pi D$
$2^{-+}0^{+}[1^{--}\ \pi P$	$2^{-+}0^{+}[1^{--}\ \pi P$
$2^{-+}0^{+}[1^{--}]\ \pi F$	$2^{-+}0^{+}[1^{--}]\ \pi F$
$2^{-+}0^{+}[2^{++}]\ \pi S$	$2^{-+}0^{+}[2^{++}]\ \pi S$
$2^{-+}1^{+}[1^{--}]\ \pi P$	$2^{-+}1^{+}[1^{--}]\ \pi P$
$2^{++}1^{+}[1^{--}]\ \pi D$	$2^{++}1^{+}[1^{--}]\ \pi D$
$3^{++}1^{+}[1^{--}]\ \pi D$	$4^{++}1^{+}[1^{--}]\ \pi G$
$3^{++}1^{+}[2^{++}]\ \pi P$	$4^{++}1^{+}[2^{++}]\ \pi F$
$3^{++}1^{+}[3^{--}]\ \pi S$	

Can we simultaneously free many isobars ?

Idea: fully „unconstrained“ PWA analysis

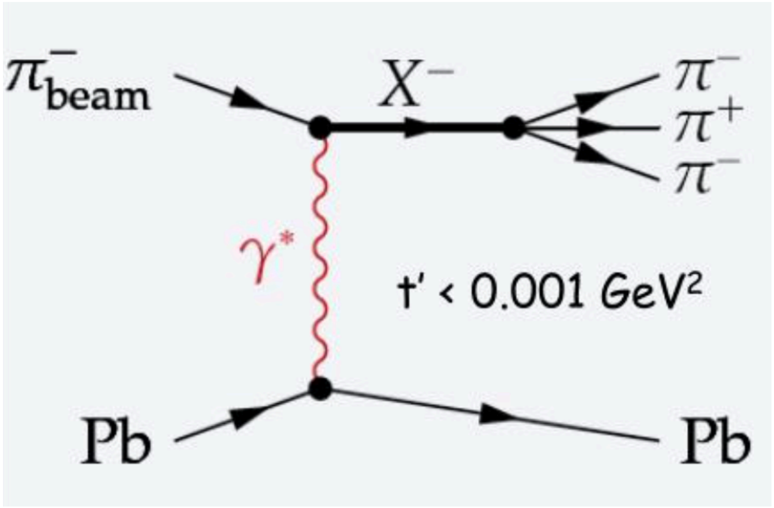
- Problem identified: Bose symmetrization introduces linear dependencies among isobars connected to one J^{PC}
- Ambiguities identified as „zero modes“
- Can be resolved with minimal assumptions on isobars
  - a resonance structure within one of the isobar
  - …..
- More subtle issues found…

Method also applicable to heavy mesons/tau decays

Isobar Model

- First Experimental validation of Isobar model
  - Shapes of isobars well described by „free resonances“
  - FSI plays only a small role (qualitative statement)
    - Refinement of isobar description w.r.t. resonances necessary for precision physics (e.g. CP violation, spectroscopy)
  - freed-isobar fits required for multiple structures within isobar
    - $f_0(980)$, $f_0(1500)$, $\pi\pi$ S-wave
- Question: How to use the wealth of information ?

Other projects/results



Examples:

- Primakoff production of multi-pion states
- virtual photo-exchange at small momentum transfer

  $t' < 2 \times 10^{-3}\ (\mathrm{GeV}/c)^2$

  - radiative width
    - published: $a_2(1260)$ and $\pi_2(1670)$ $\quad \pi^- + A \rightarrow \pi^-\pi^+\pi^- + A'$
    - in progress: $a_4(2040)$, $\pi_1(1600)$ $\quad \pi^- + A \rightarrow \pi^-\pi^+\pi^- + A'$
    - in progress: $\rho(770)$, $\rho_3(1670)$ $\quad \pi^- + A \rightarrow \pi^-\pi^0 + A'$

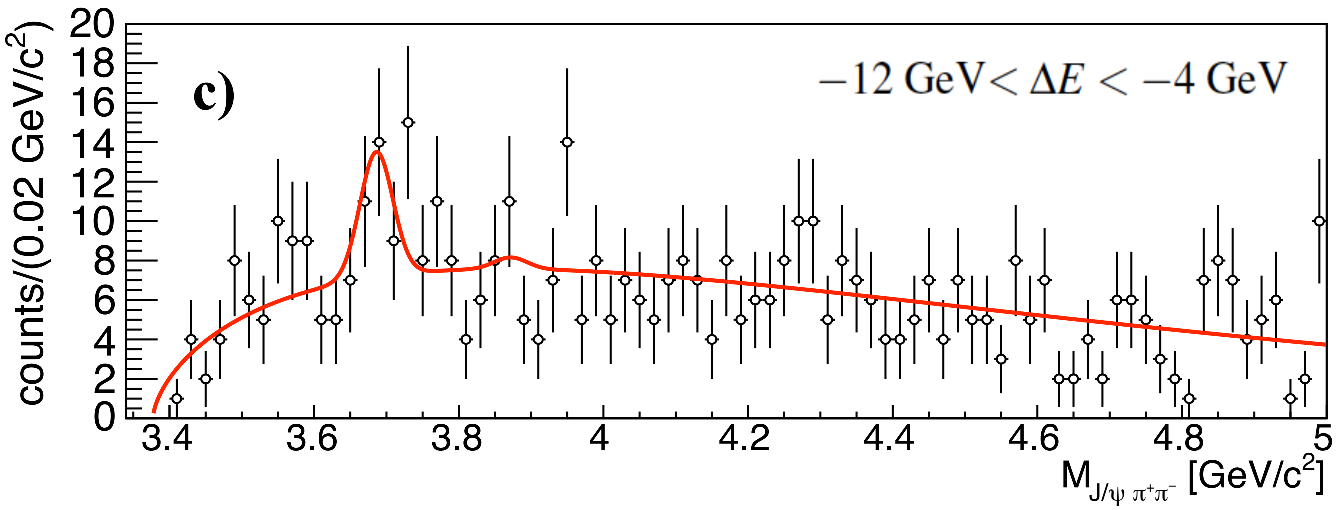
  PWA

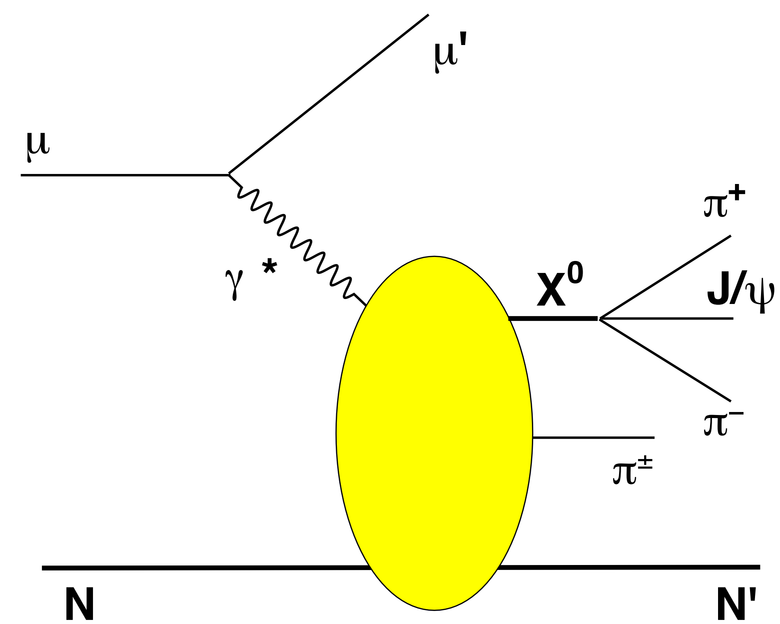
  angular analysis

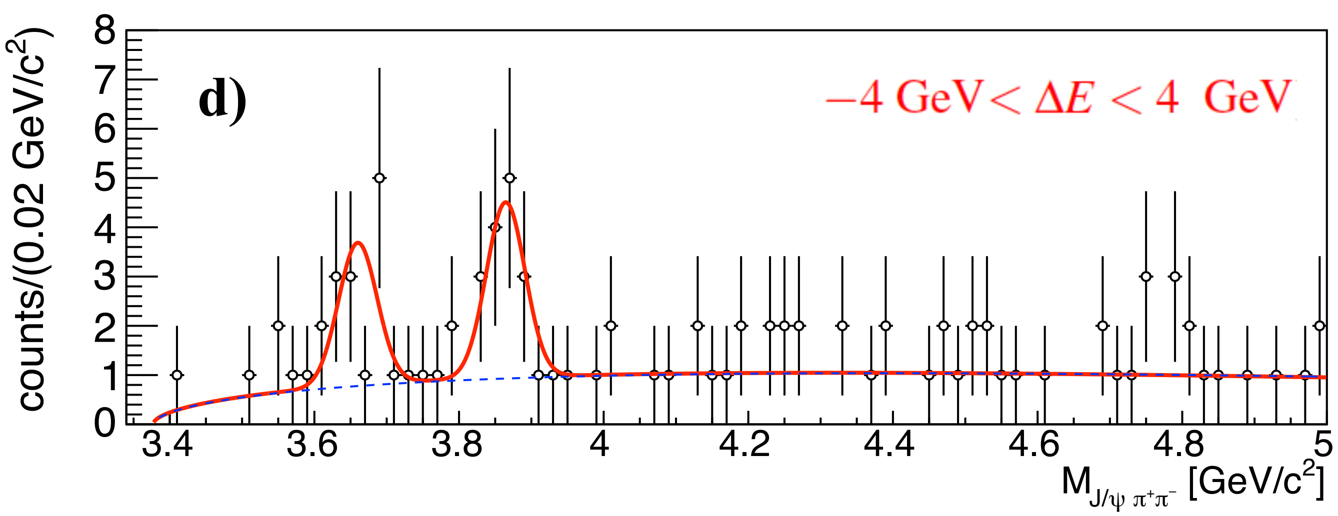
  - π polarizability - update (5x statistical accuracy) in progress
  - chiral anomaly and $f_{3\pi}$ (systematics limited)

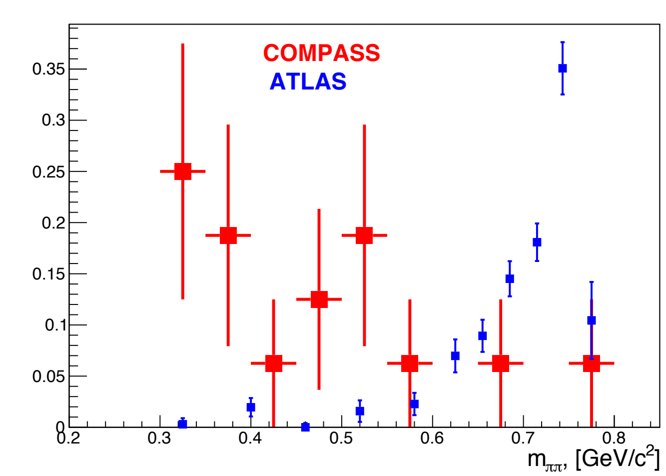
Lepto-production X(3872)

- 10 years integrated luminosity muon scattering
  - various targets, „exclusive“ reaction $\mu^+ N \to \mu^+ X^0 \pi^\pm N' \to \mu^+ (J/\psi \pi^+ \pi^-) \pi^\pm N'$
  - significance > 6 σ for large missing masses (M_{miss} > 3 GeV/c^2)
  - ππ spectrum differs from previous observations









Exzellenzcluster Universe

Conclusion

Using new “2D” fit method to perform PWA in $m_{3\pi}$ and t :

- Find new iso-vector state $a_1(1420)$
  - $M_{a1(1420)}$ = 1412-1422 MeV/c^2 , $\Gamma_{a1(1420)}$ = 130-150 MeV/c^2
  - (exclusive) decay into $f_0(980)\pi$ in relative P-wave
  - Nature of $a_1(1420)$?
- Determine resonance parameters from largest ever fit to spin density matrix
  - Coherent determination of a_J and π_J states
  - Largely consistent parameters with previous experiments
  - Reveal systematic uncertainties
  - existences of $\pi_1(1600)$ required
- Analysis requires three π_2 states
- Primakoff allows access to radiative decays of excited mesons

Conclusion

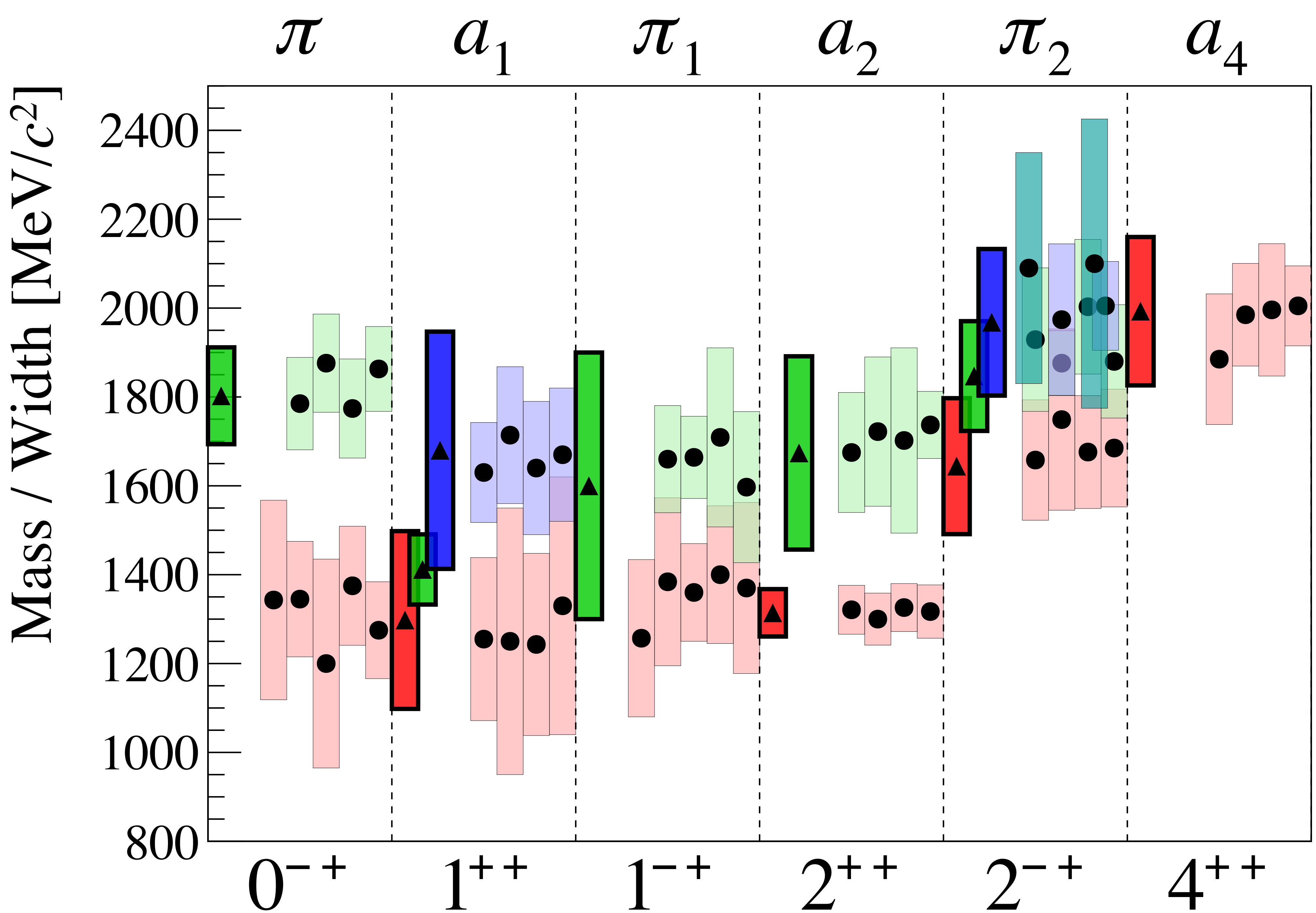
- Developed new method to establish shape of isobar-spectrum
  - first application: $[\pi\pi]_S^*$:
    - Strongly depends on $m_{3\pi}$ and on J^{PC} of mother wave
  - Reveals information on scalar isobars (measure phases in decays)
  - Extend to full isobar-free analysis (ongoing)
    - Iterative (bootstrapping) approach does not work !
    - Artifacts !! can be removed by proper treatment (work in progress)
    - Applications to heavy meson decays
- Kaon beam data analysis started

Open Path to Dalitz-plot analysis using PWA

from PWA identified states

Needs high statistics !!

Summary - Resonances



- COMPASS provides consistent analysis and realistic uncertainties