Meson - Spectroscopy with
with
COMPASS at CERN

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TU München

Excellence Cluster Universe

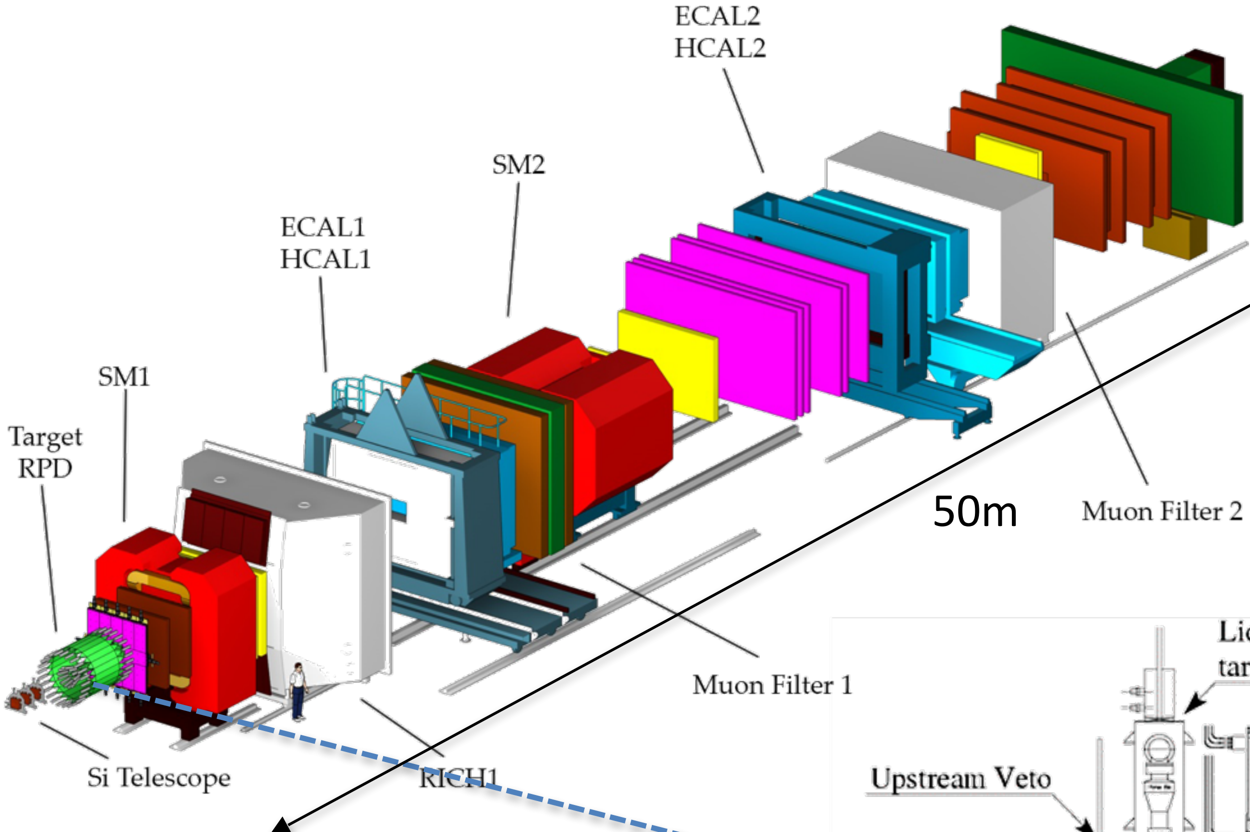
Brief Overview

COMPASS performs physics with p, K, π beams

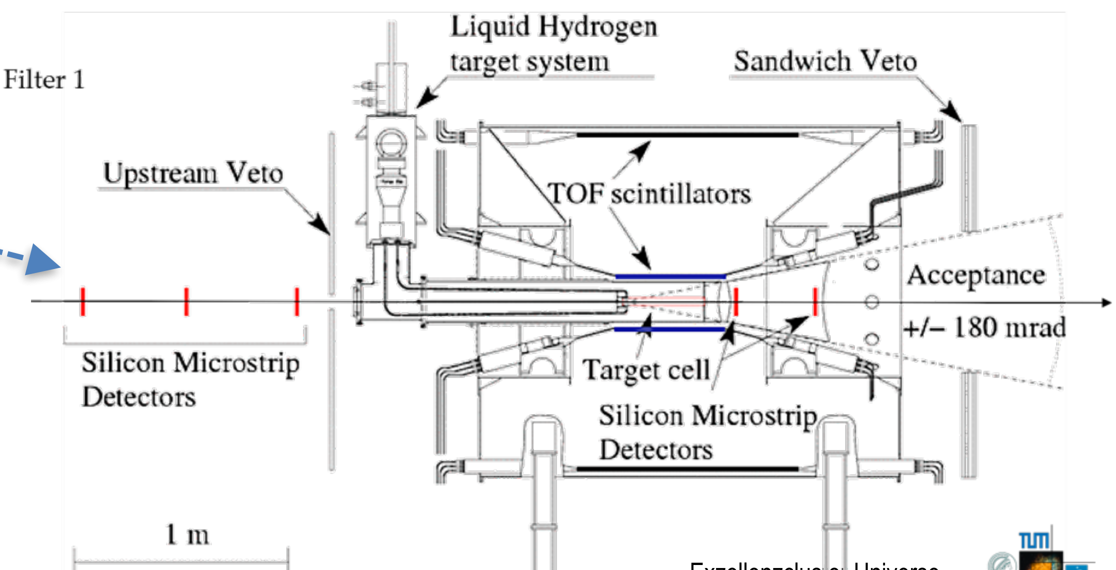
Examples will be given on

- 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
- Conclusions

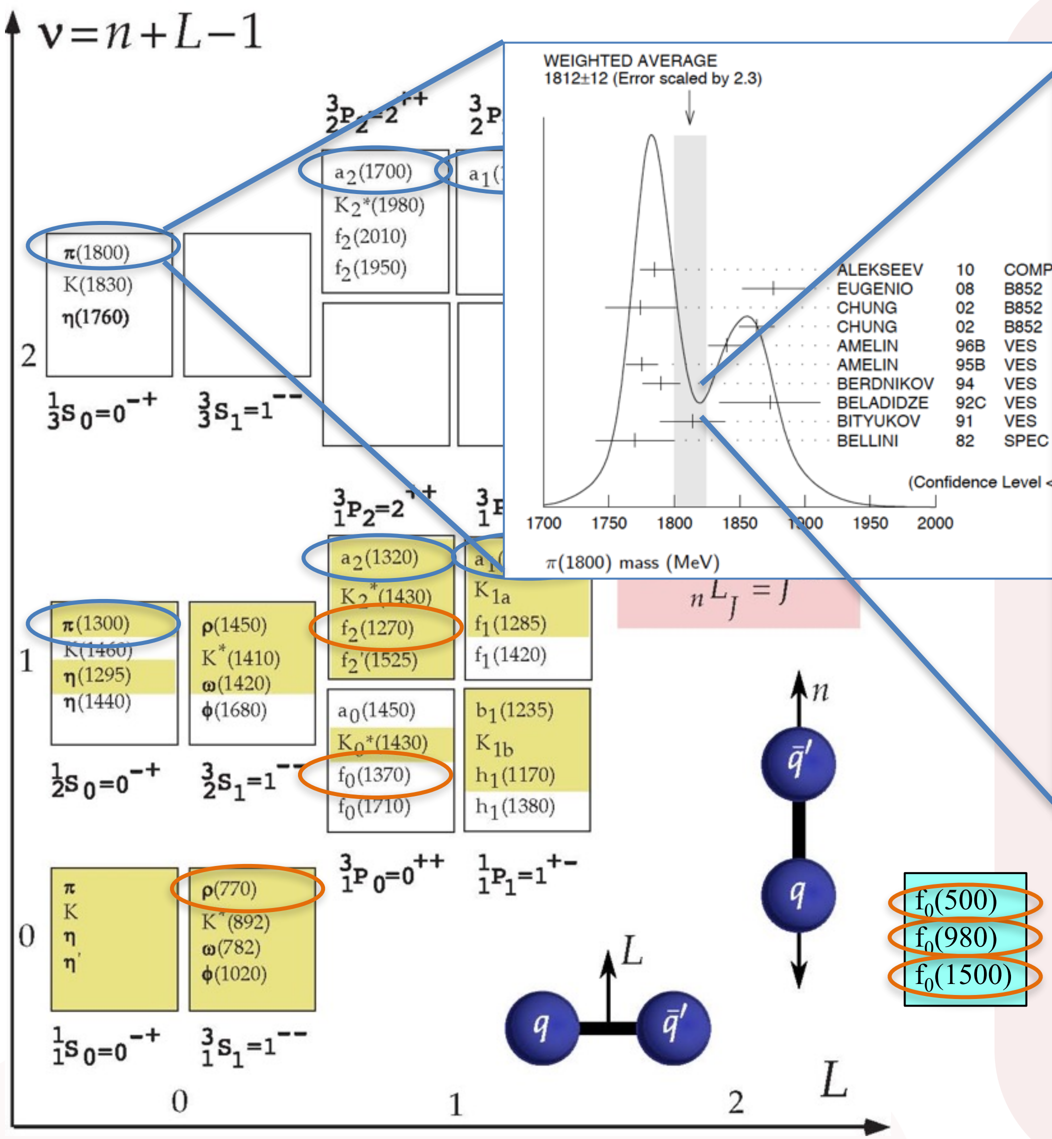
The COMPASS Experiment



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)

π_2(1880) MASS

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

π_2(1880) WIDTH

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

…sons

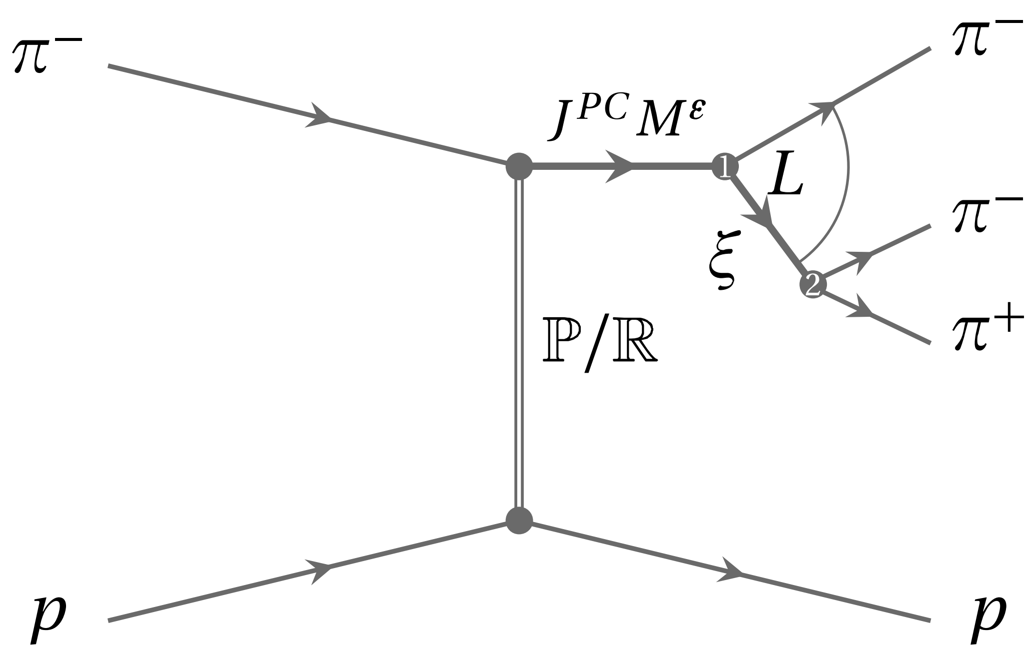
…puted

…ion

…eavy

…ing

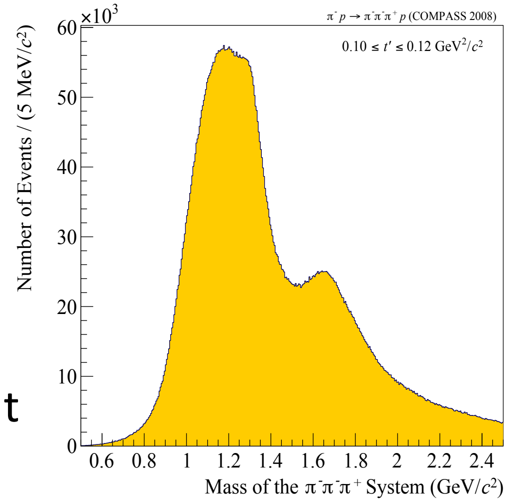
Kinematics



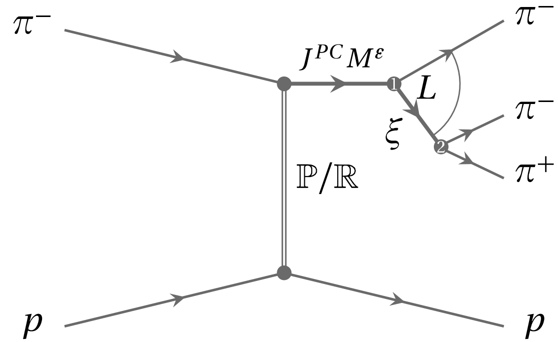
Example: production of 3π

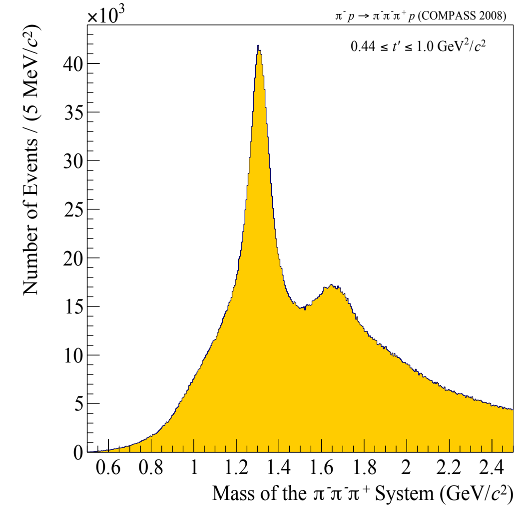
Kinematics and Isobars

low t

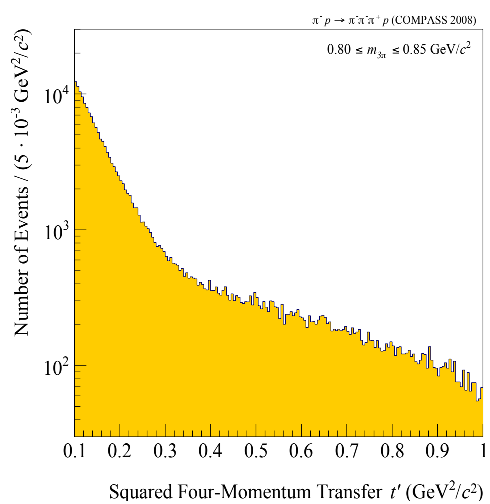


isobar model

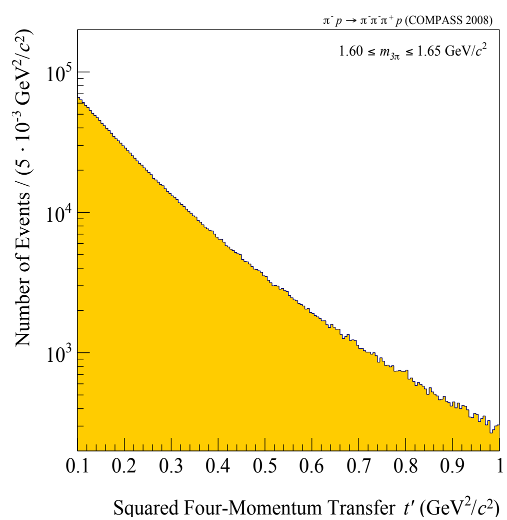




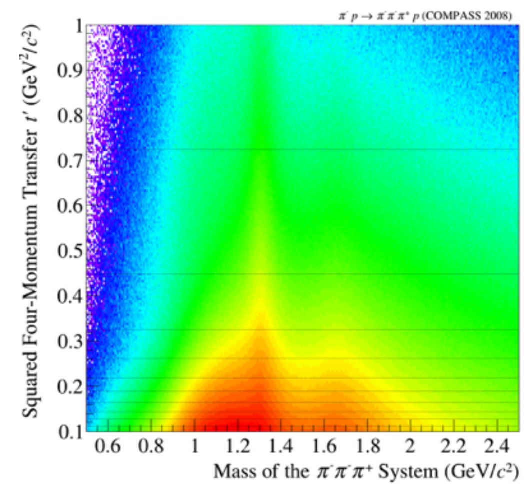
high t



$0.8 < m_{3\pi} < 0.85$



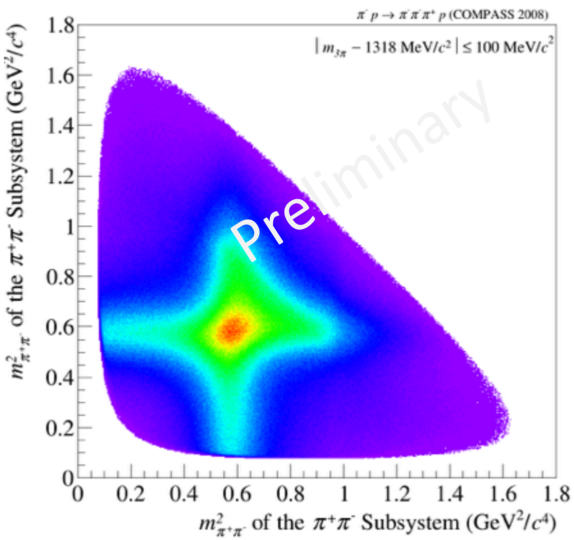
$1.6 < m_{3\pi} < 1.65$

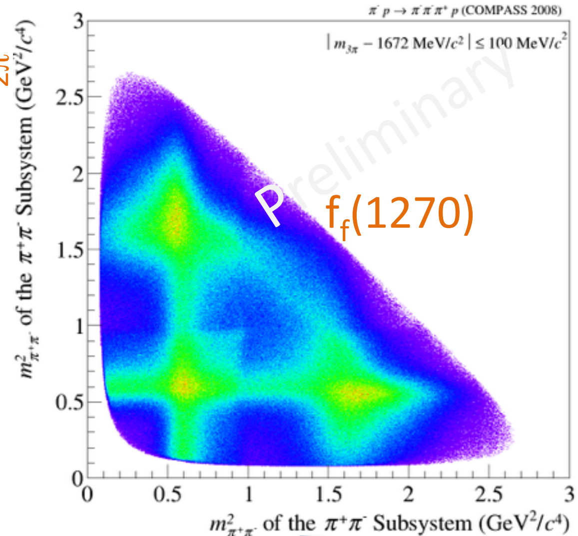


grid of t used

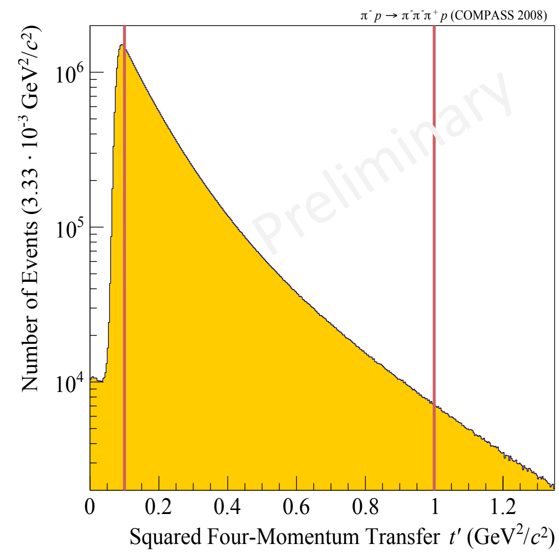
Δm: 20 MeV/c^2

First Impressions
Motivation for Isobar Model



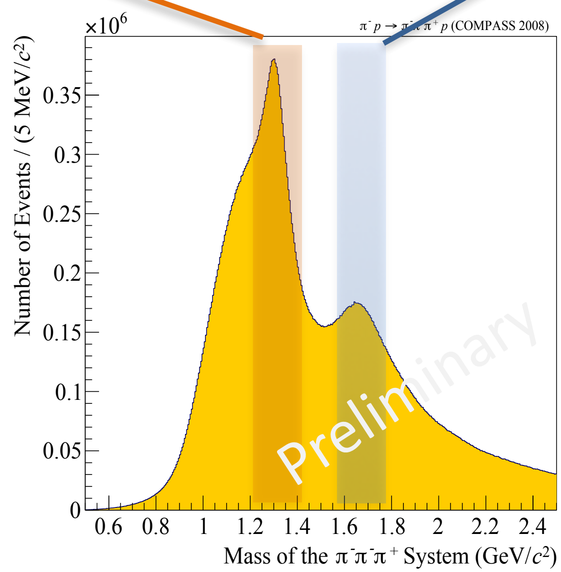


$m^2_{2\pi}$ $m^2_{2\pi}$

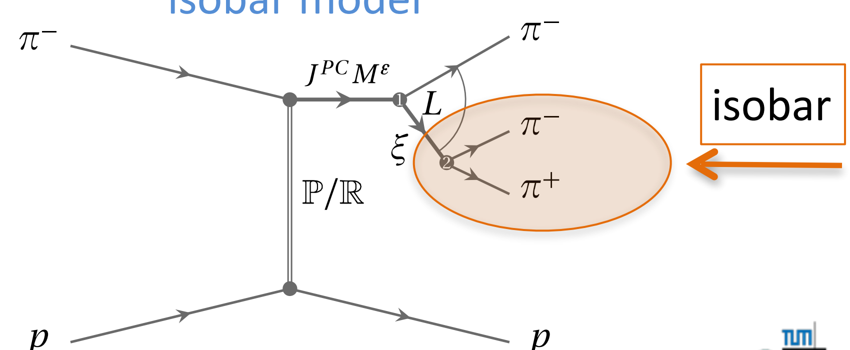


$t_{3\pi}$

used in analysis

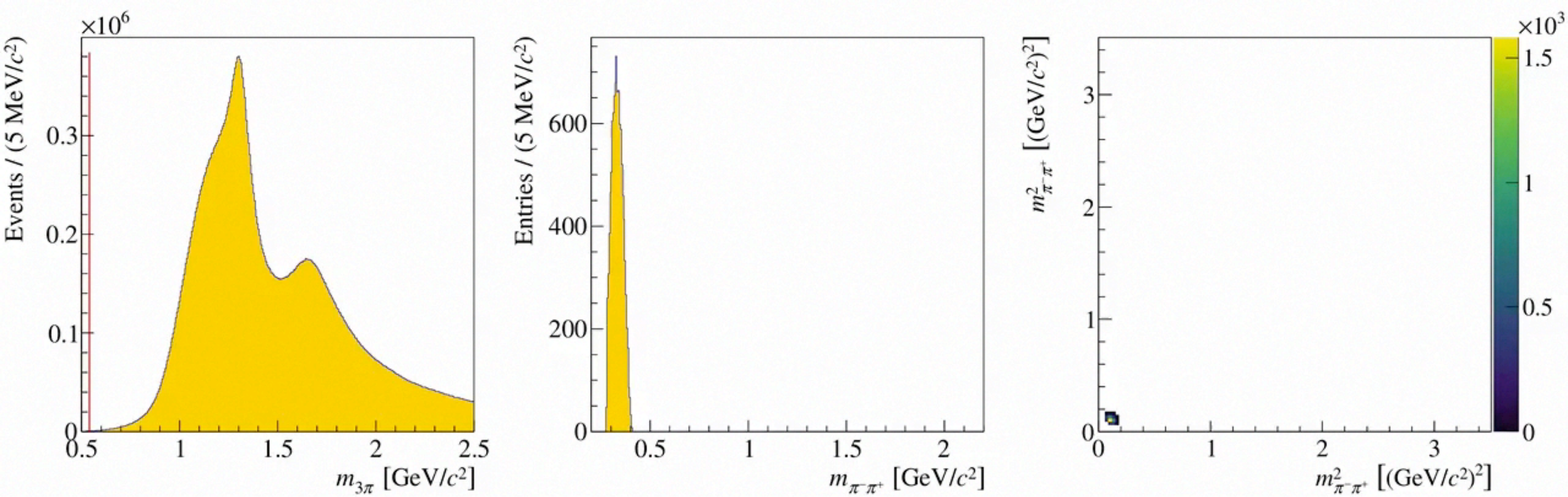


isobar model

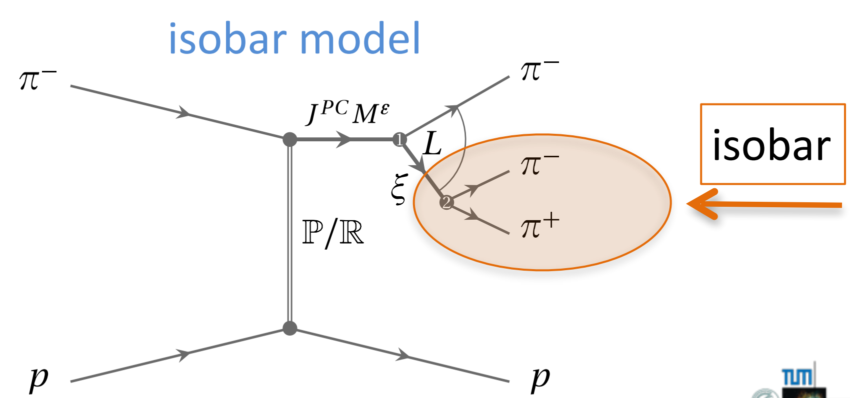


Exzellenzcluster Universe

First Impressions
Motivation for Isobar Model

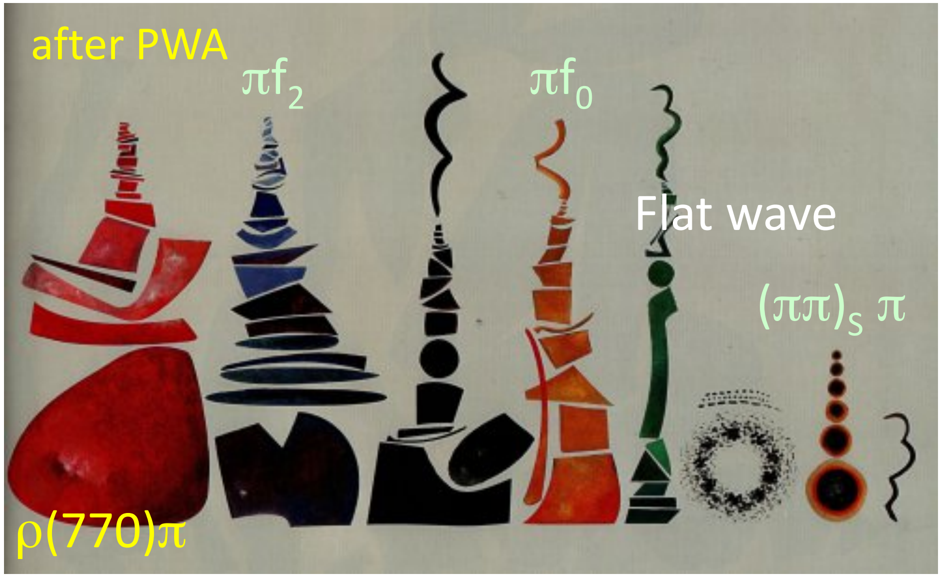


Preliminary



Partial wave analysis

inspired by M. Pennington



Art taken from Urs Wehrli: “Kunst aufgeräumt”

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

Partial wave analysis

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step 2

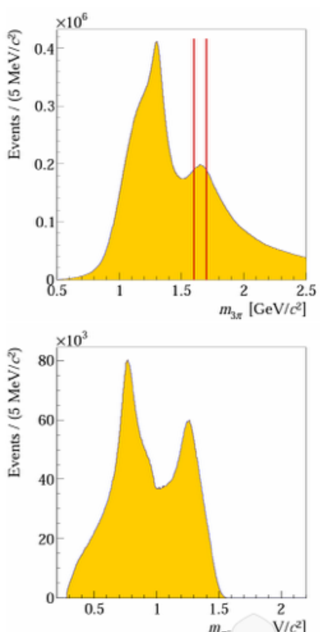
- Describe spin density matrix (submatrix) by model containing resonances and non-resonant contributions connecting all mass bins
- Determine resonance parameters

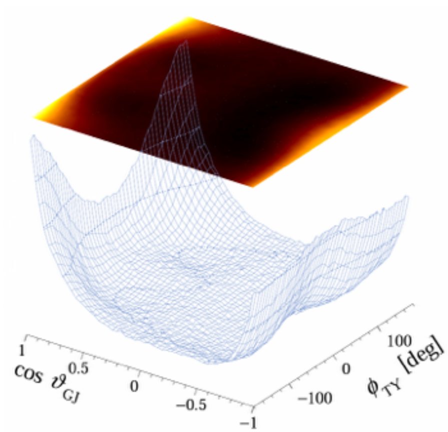
Amplitude Analysis

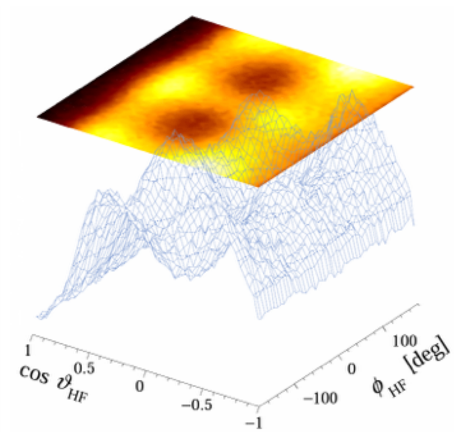
Use helicity amplitudes :

5-dimensional phase space:

mass of 3π	2 angles in 3π rest frame	2 angles in isobar rest frame







Amplitude Analysis

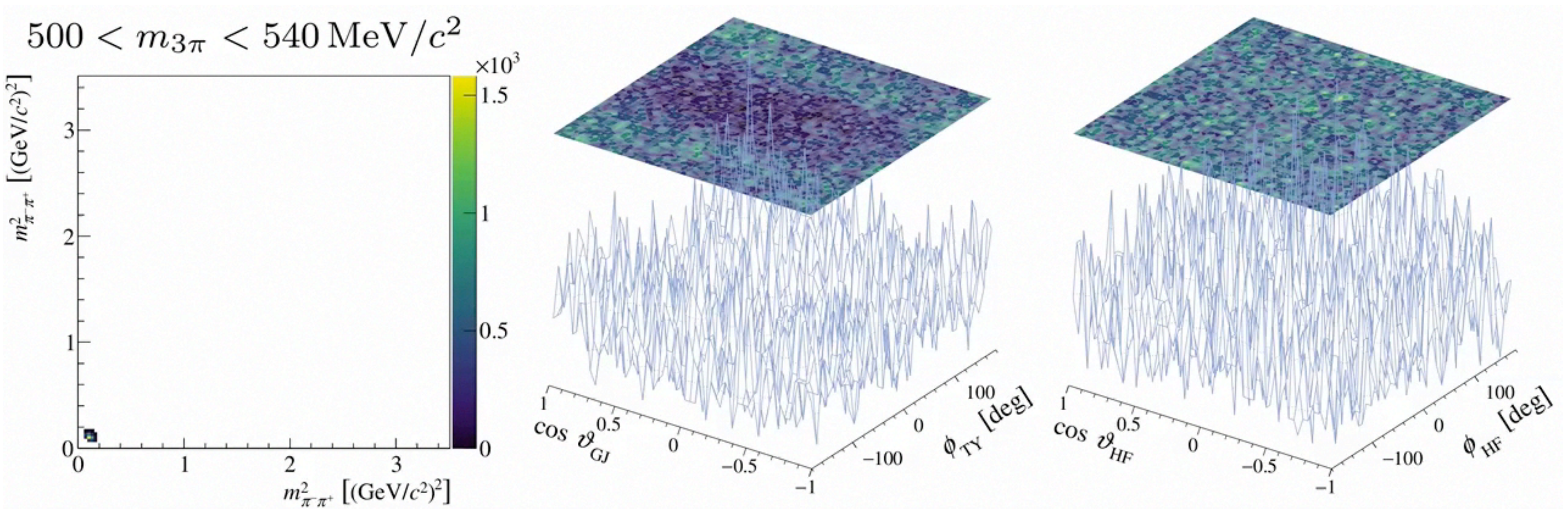
Use helicity amplitudes :

5-dimensional phase space:

Dalitz plot

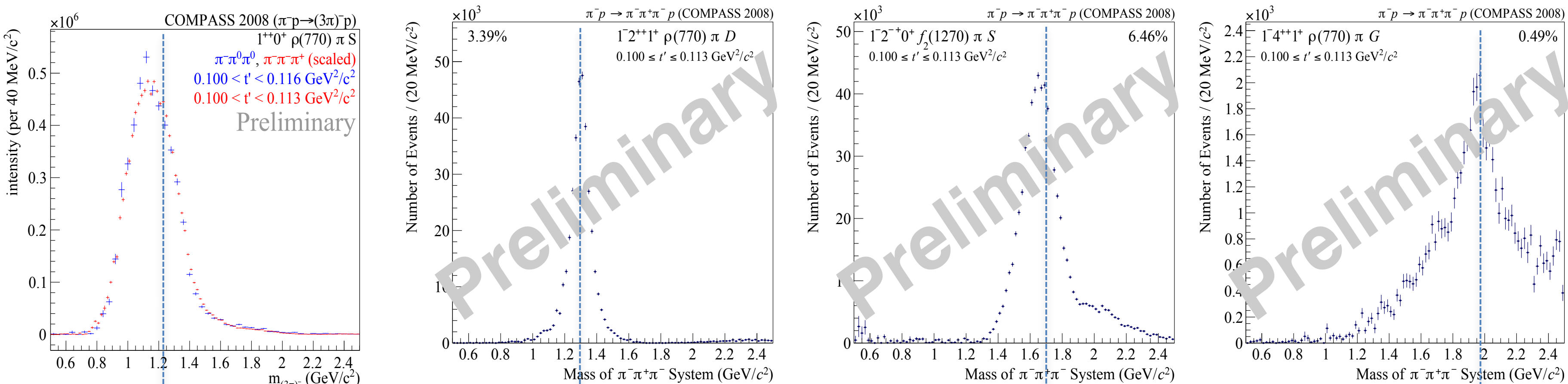
2 angles in 3π rest frame

2 angles in isobar rest frame

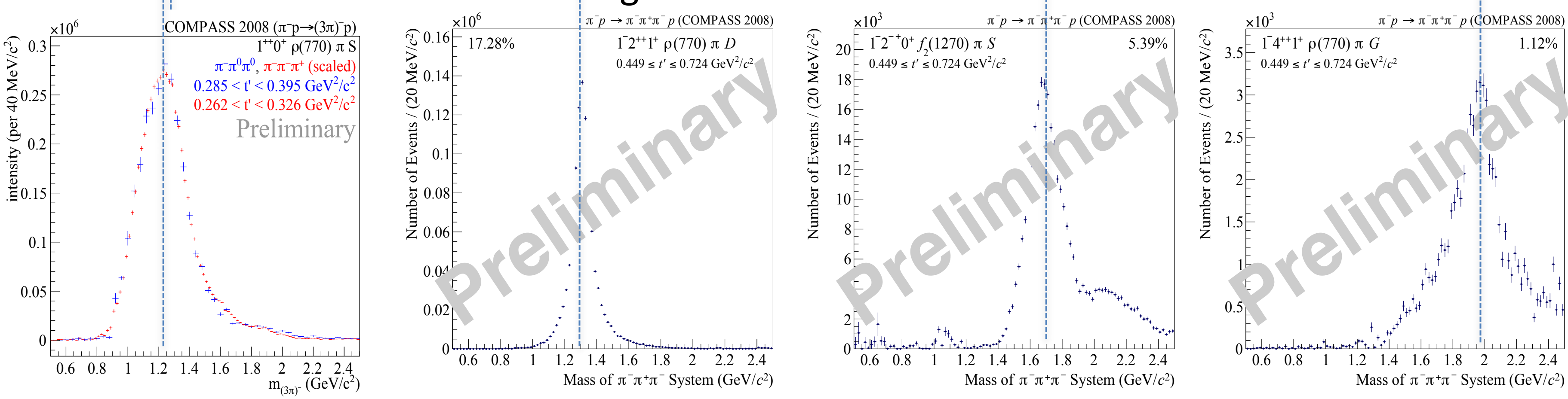


Spectral shape of waves
t dependence

low t



high t

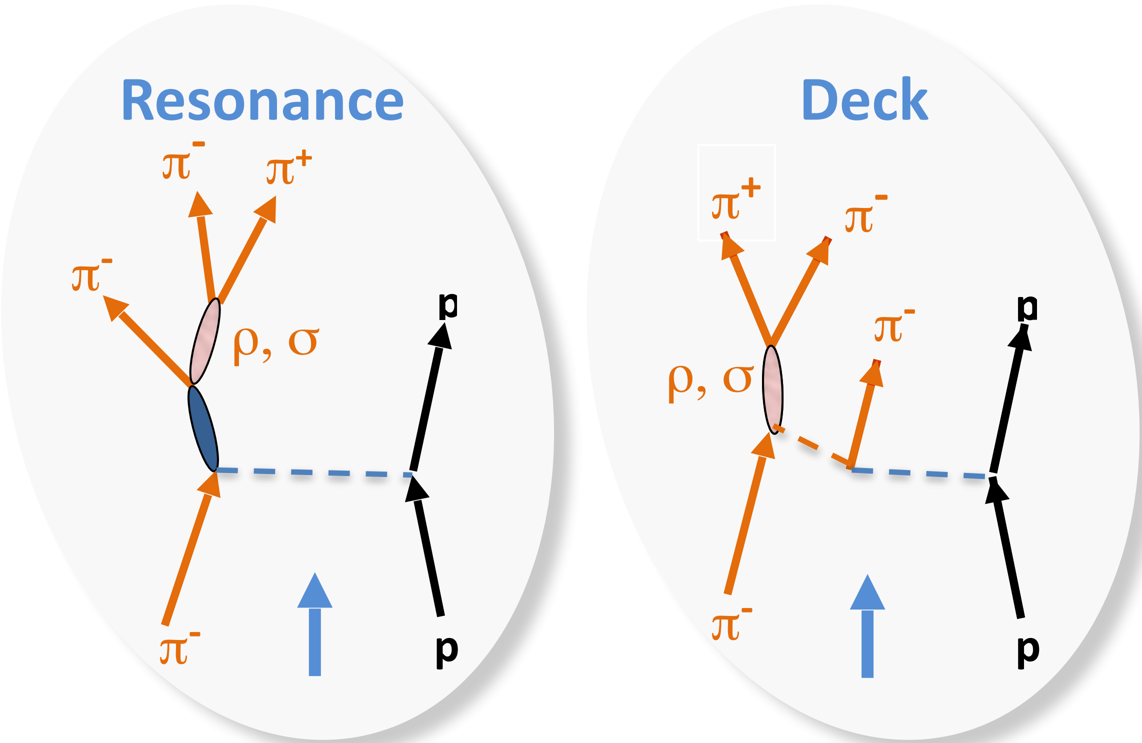


$1^{++}0^{+}\rho\pi$ S | $2^{++}1^{+}\rho\pi$ D | $2^{-+}0^{+} f_2\,\pi$ S | $4^{++}1^{+}\rho\pi$ G

Model for Spin Density Matrix

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

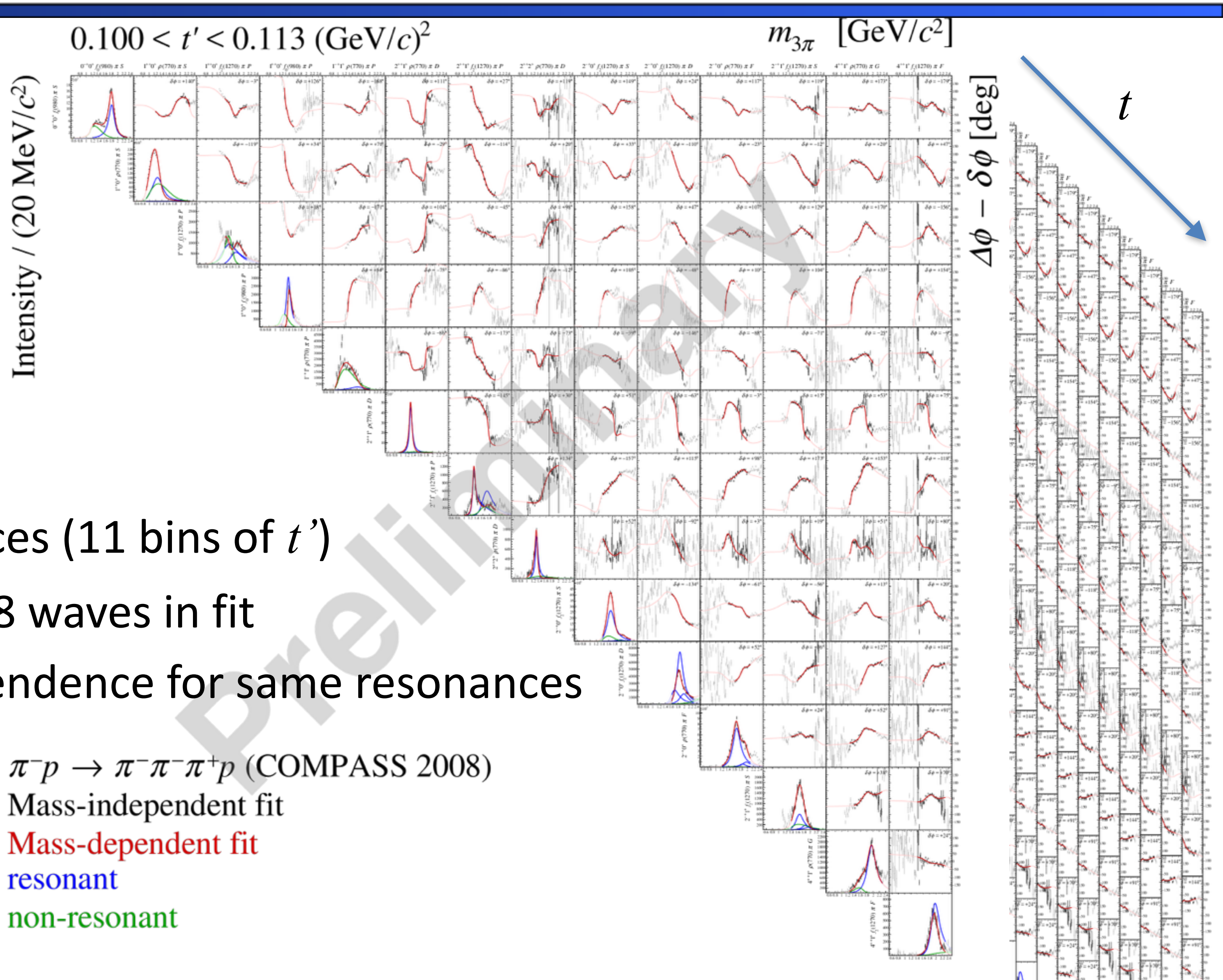
- select physics contributions
- fit to spin density matrix (not only to simple mass spectra)
- use 14 waves (out of all 88 waves)
  - 722 free parameters
  - 76505 data points



Two types of contributions

Find the Resonances

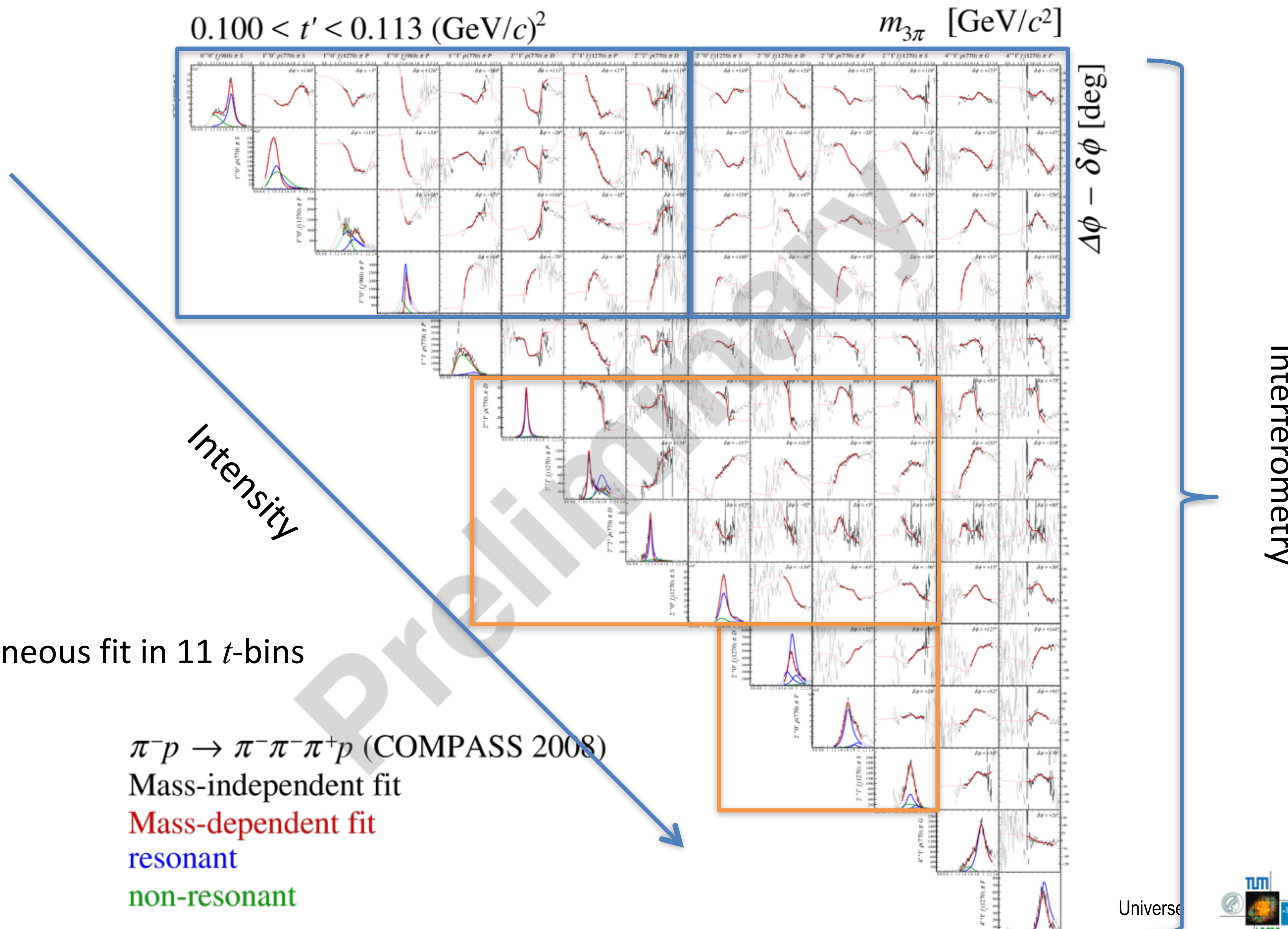
Reference wave



- 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

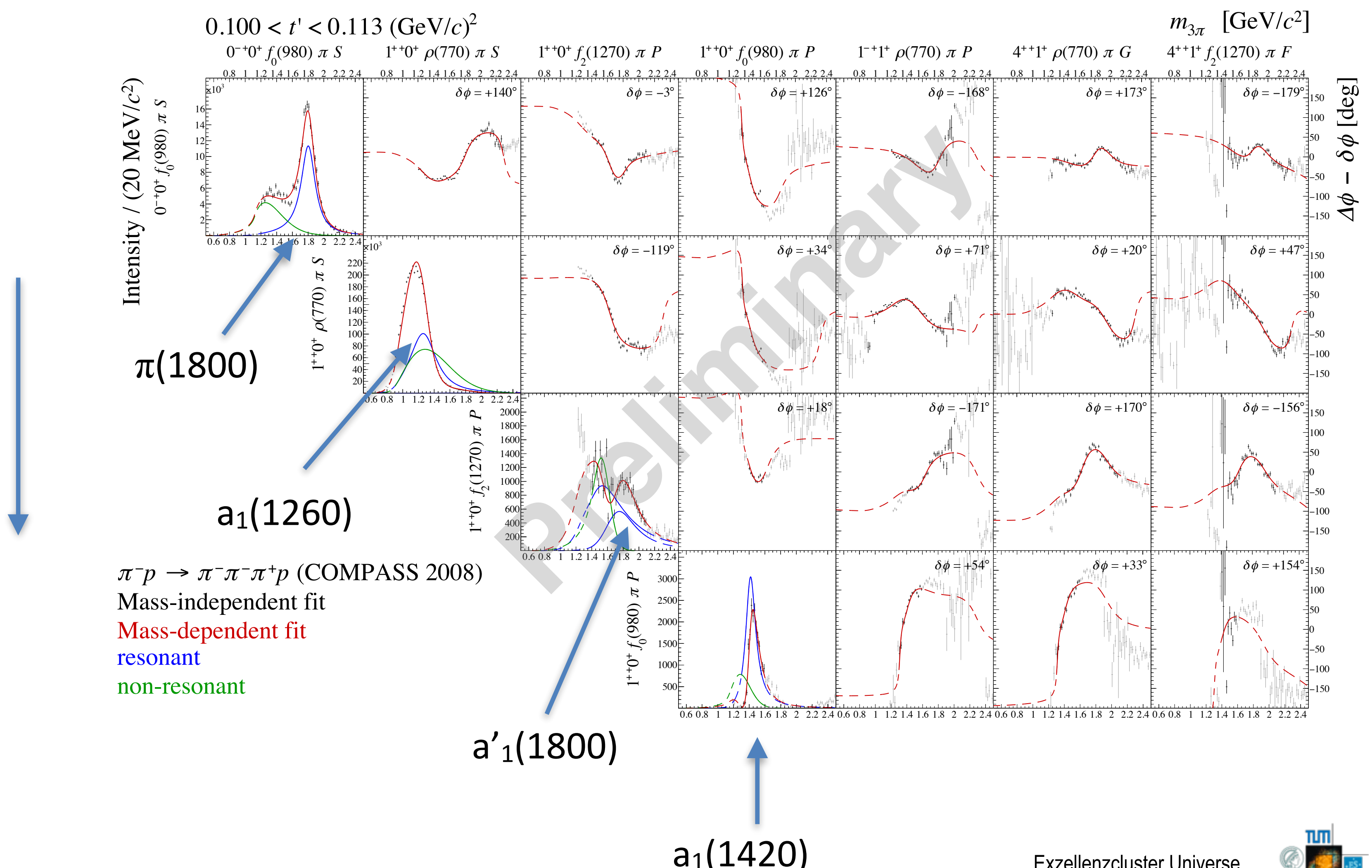
Find the Resonances



simultaneous fit in 11 t-bins

Find the Resonances

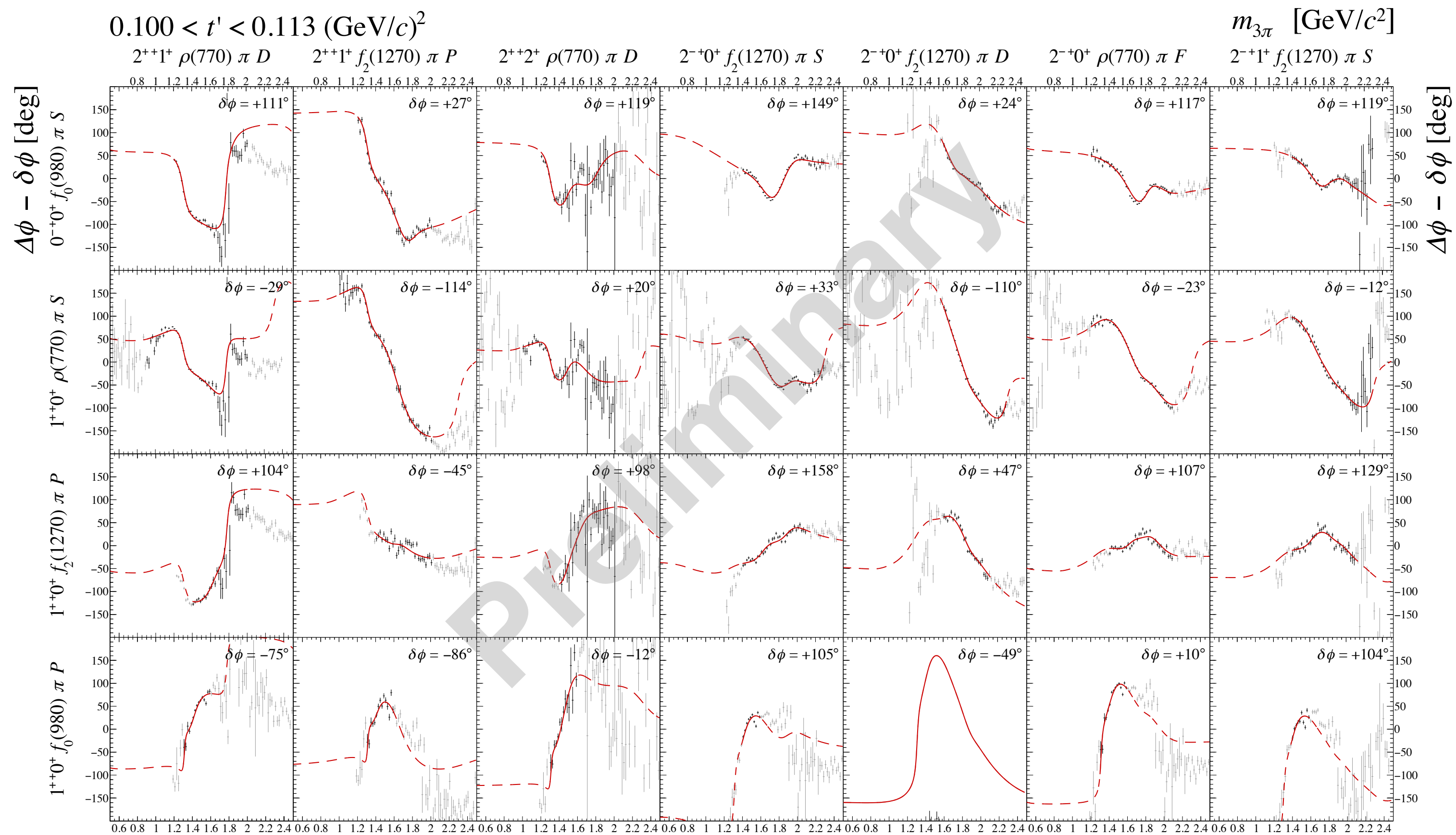
- Axialvector mesons: 1^{++}



Exzellenzcluster Universe

Phases are important ingredient

- Phases axialvector mesons: 1^{++}

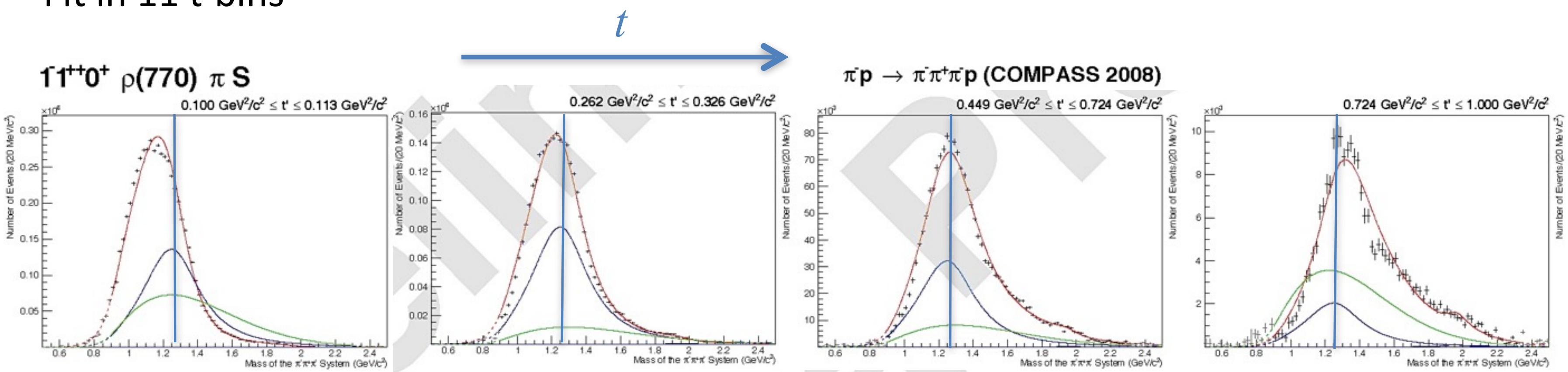


Mass dependent fits

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

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

Fit in 11 t-bins

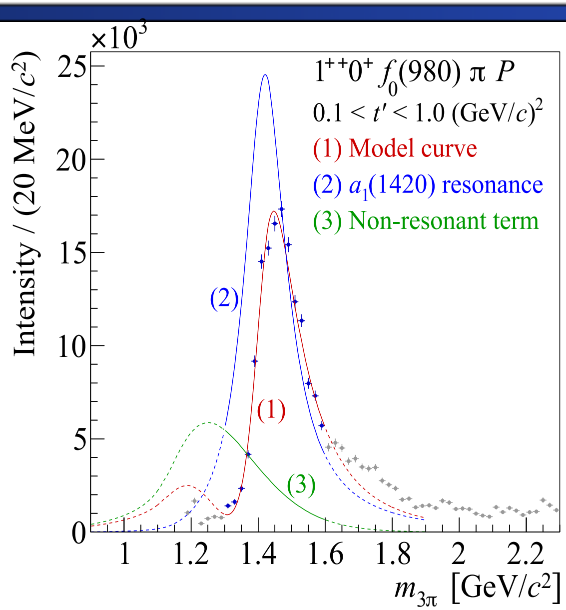


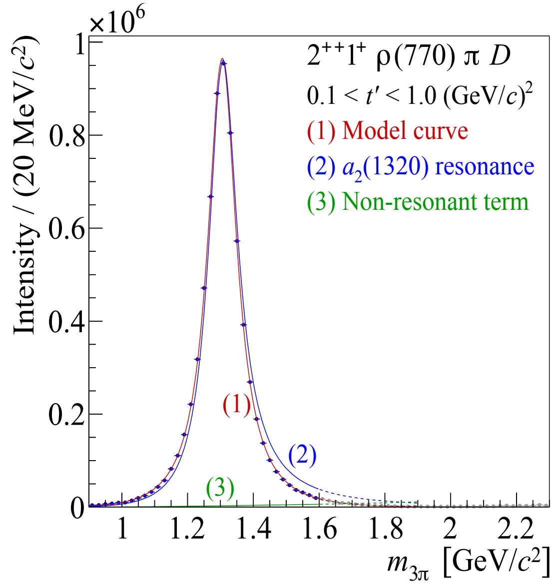
Strongly t-dependent spectral shape around $a_1(1260)$

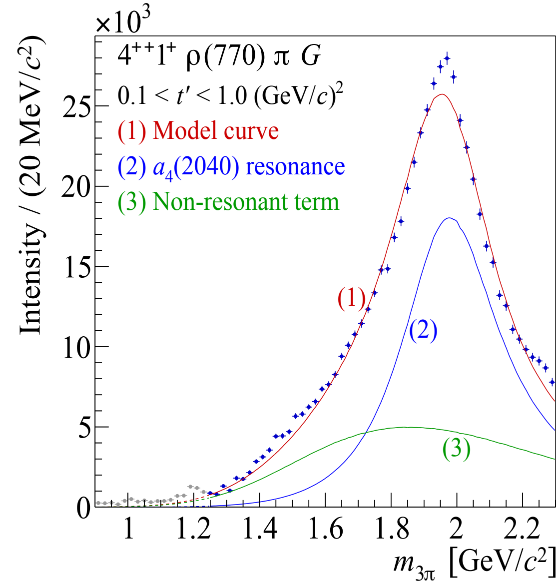
—

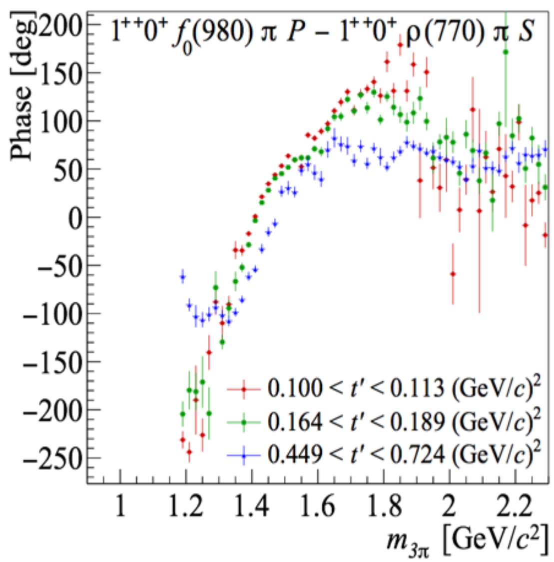
Interference of non-resonant with $a_1(1260)$

New Observation: $a_1(1420)$



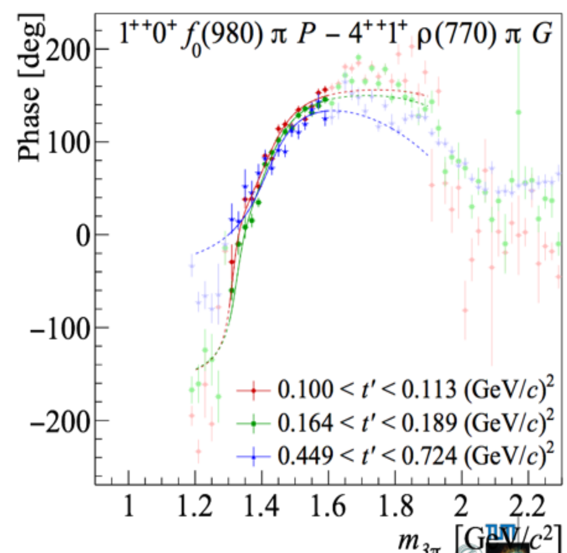






Observation*:*

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



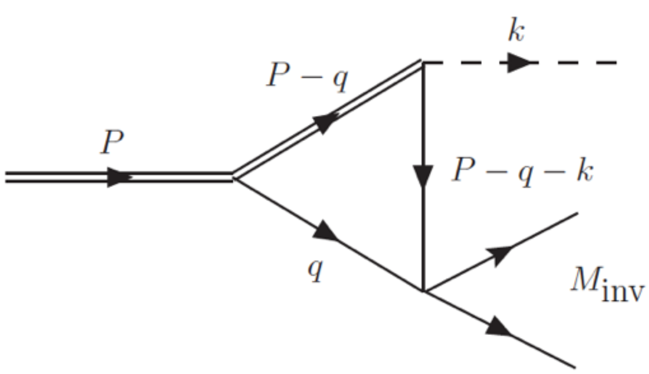
Various explanations proposed for interpretation:

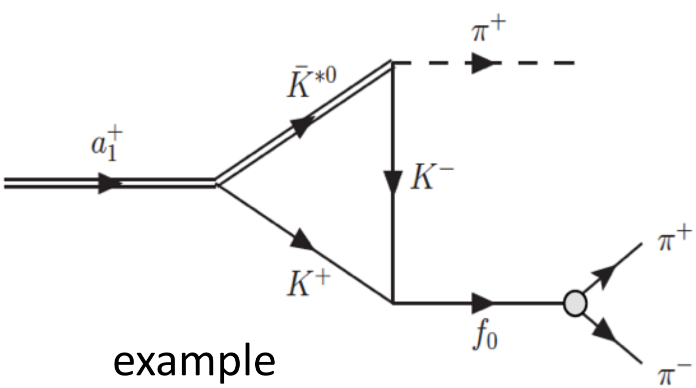
- Dynamics
  - Interference of $a_1(1260)$ with Deck amplitude ($\Delta\phi = 180^0$ shifted by 100 MeV)

    (Berger et al.)
  - triangular anomaly coupling $a_1(1260) \rightarrow KK^* \rightarrow KK\pi$ and $KK \leftrightarrow f_0(980)$ ($\Delta\phi = 90^0$)

    (Mikhasenko et al.)
  - triangular anomaly : $a_1(1260) \rightarrow f_0(980)\pi$ decay shows up 200 MeV above $M(a_1(1260))$

    (Aceti et al.)
  - Requires same t dependence for $a_1(1260)$ and $a_1(1420)$

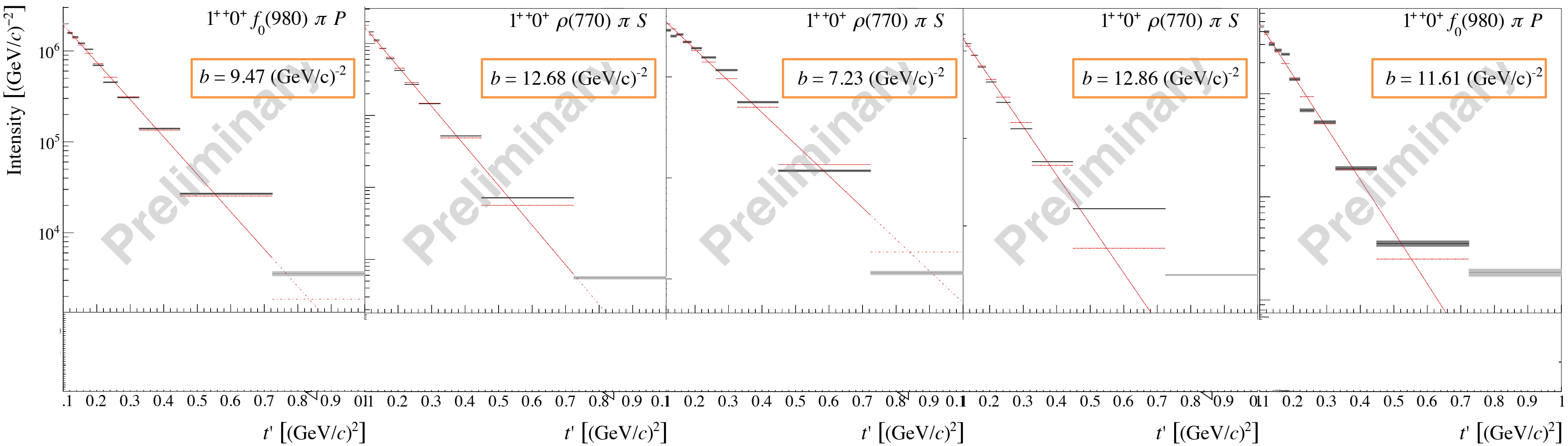




example

Kinematics: Dependence on t

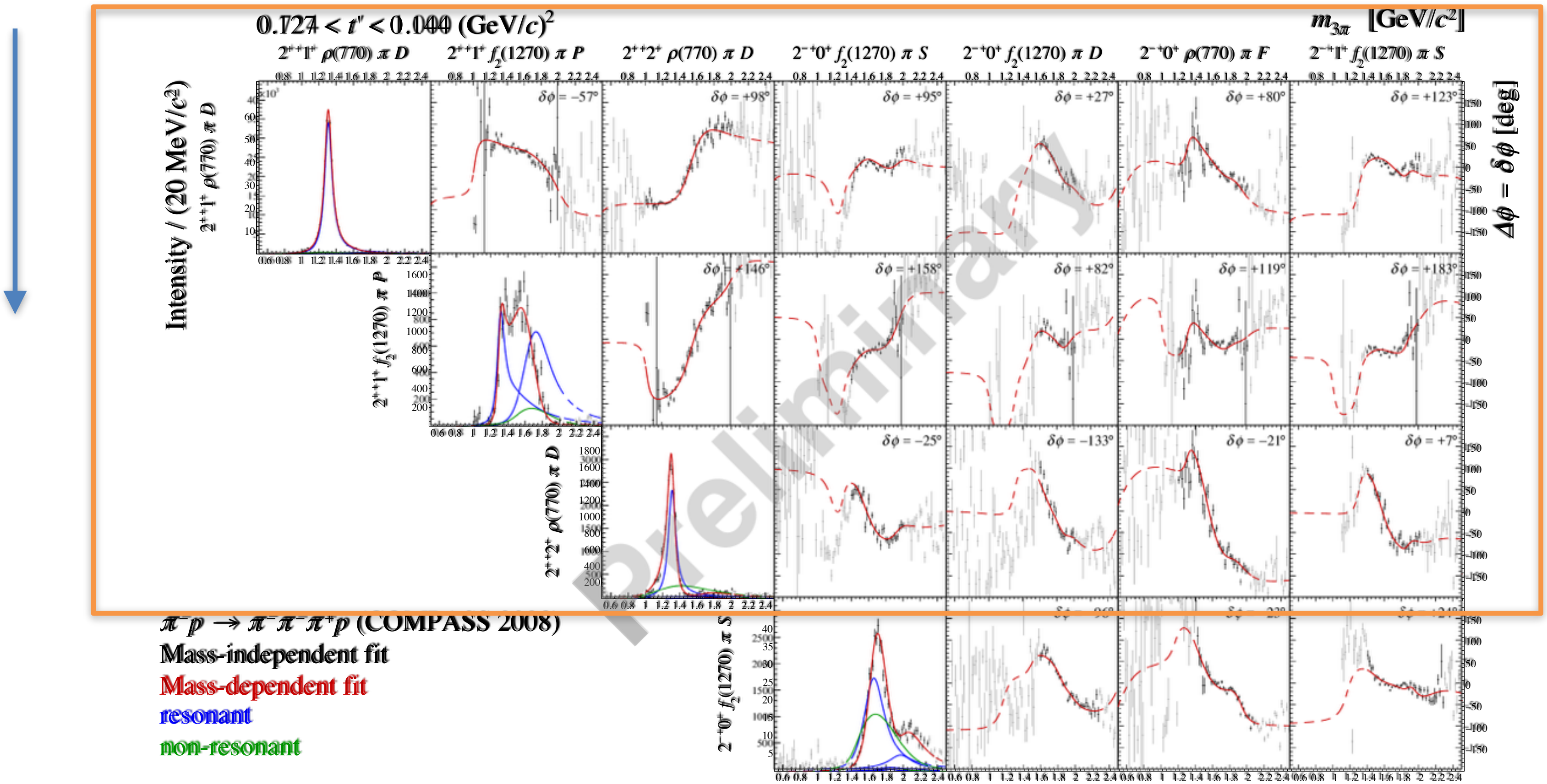
a$_1$ (1420) a$_1$ (1260) a$_1$ (1640) non-resonant



- a$_1$ (1260) has larger slope for t distribution than a$_1$ (1420)
- a$_1$ (1260) slope consistent to non-resonant contributions
- ….but : separation a$_1$ (1260) and non-resonant contribution difficult

Find the Resonances

- Axialvector mesons: 2^{++}



low t

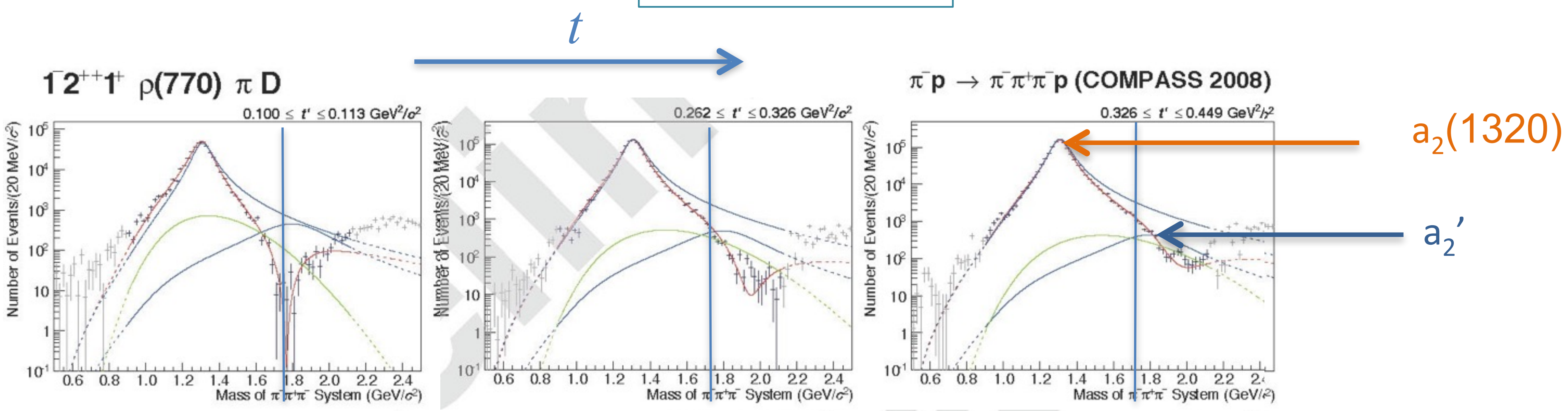
high t

Exzellenzcluster Universe

Mass dependent fits $a_2(1320)$

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

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

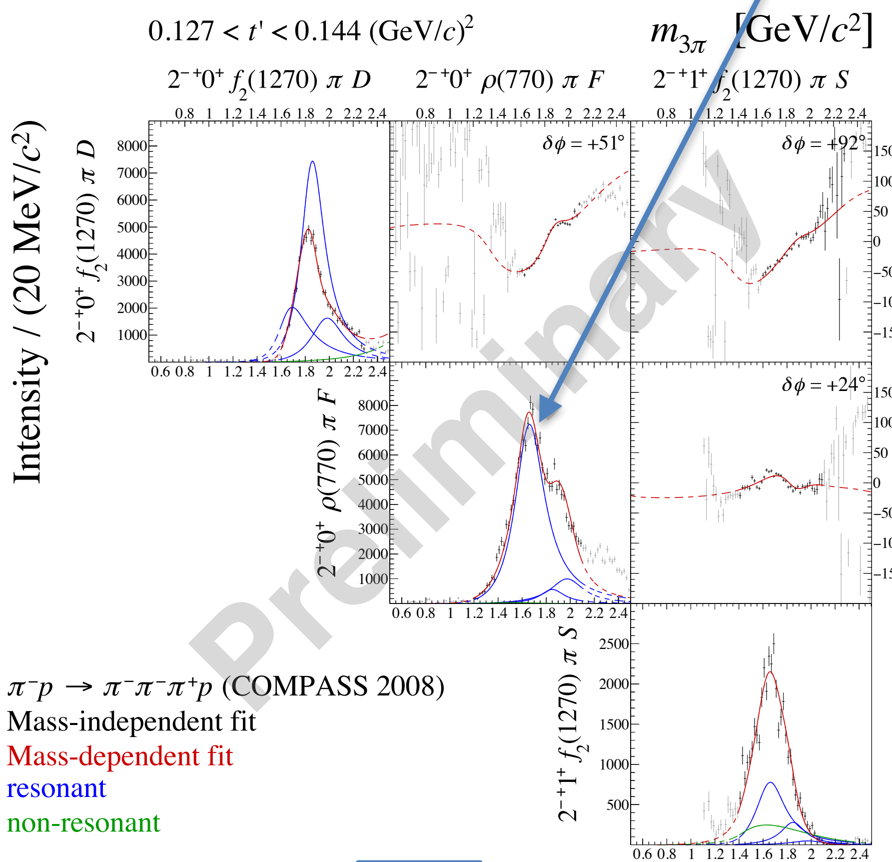


Strongly t-dependent interference effects

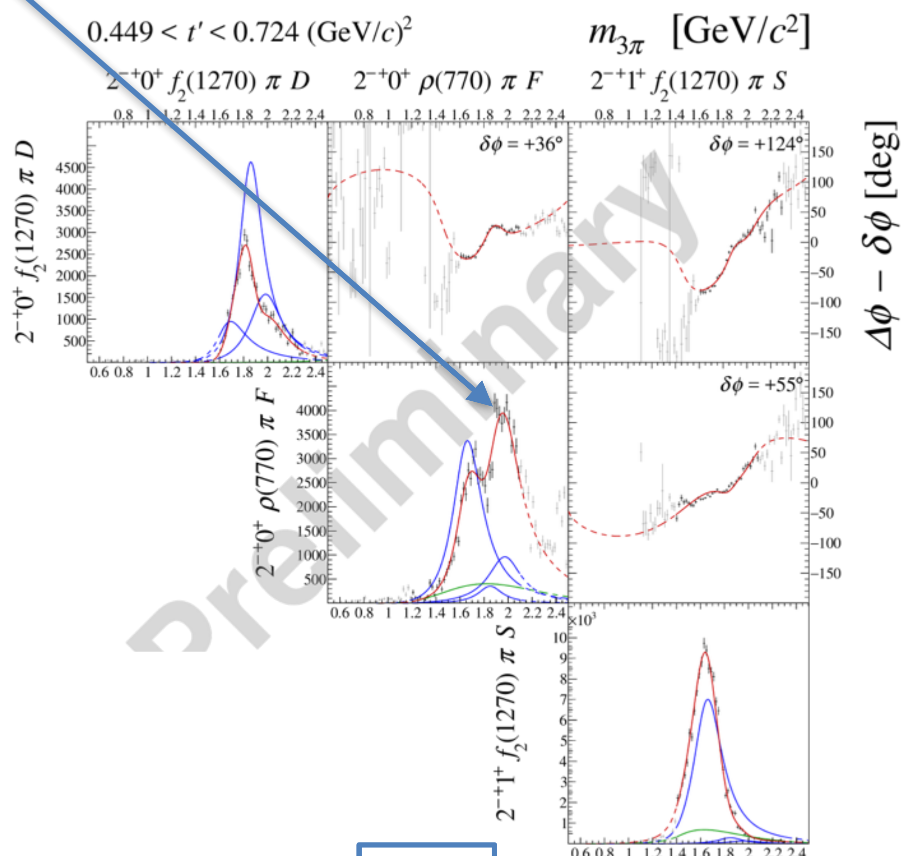
high-mass a_2'

Find the Resonances

- Pseudoscalar mesons: 2^{-+}

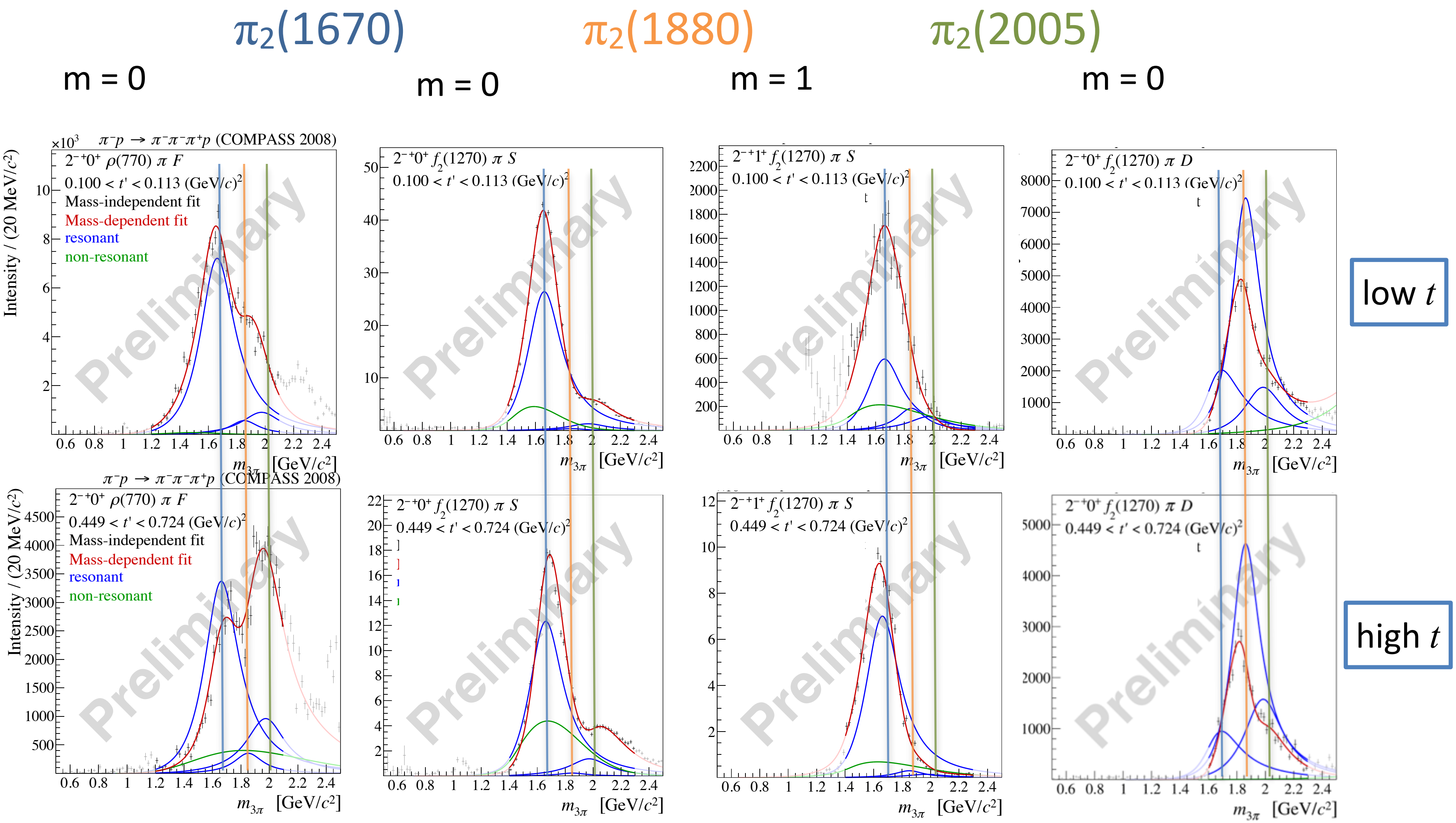


low t



high t

The Case of π_2

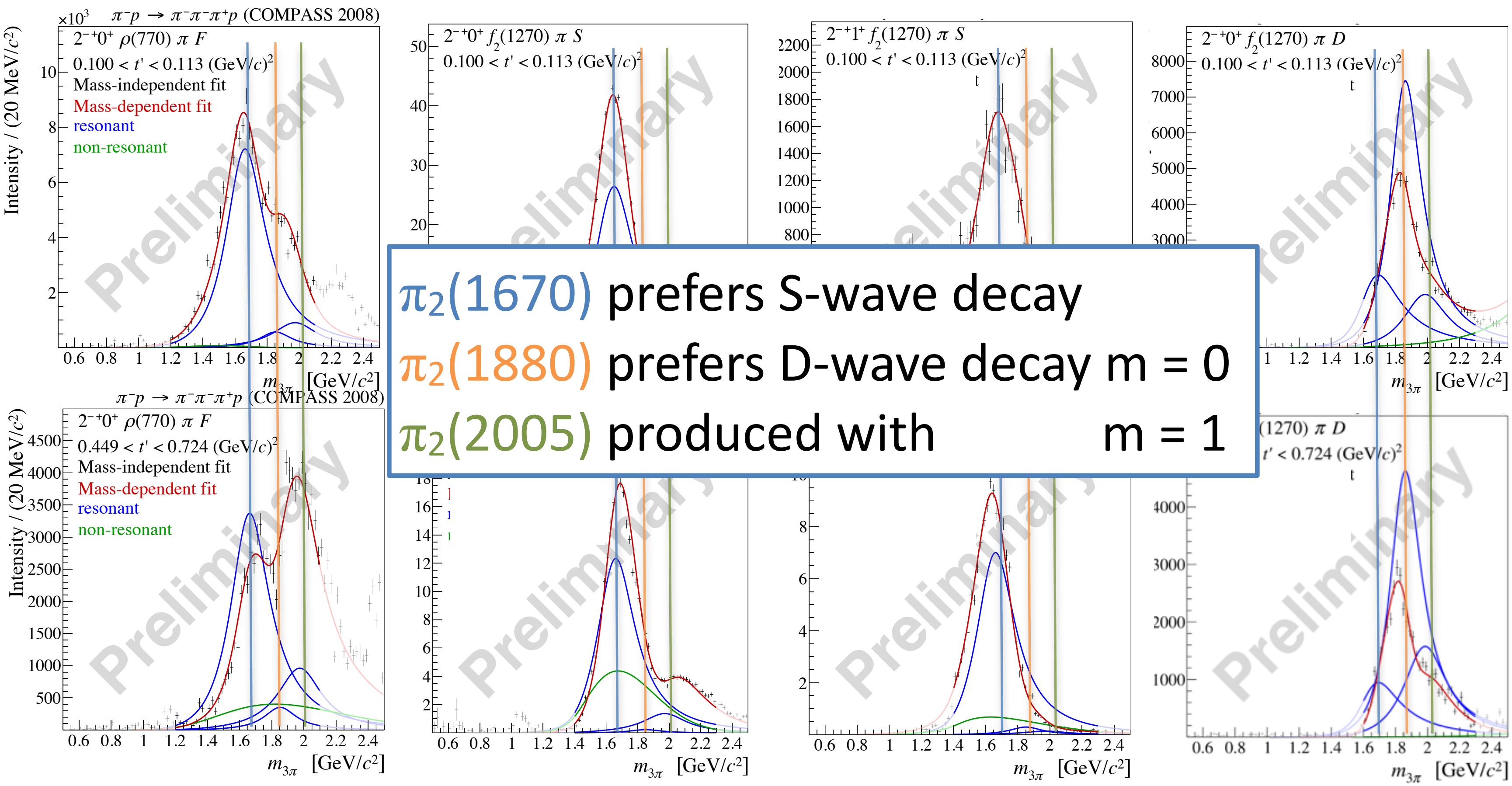


- very different production/decay characteristics

The Case of π_2

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

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



low t'

high t'

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

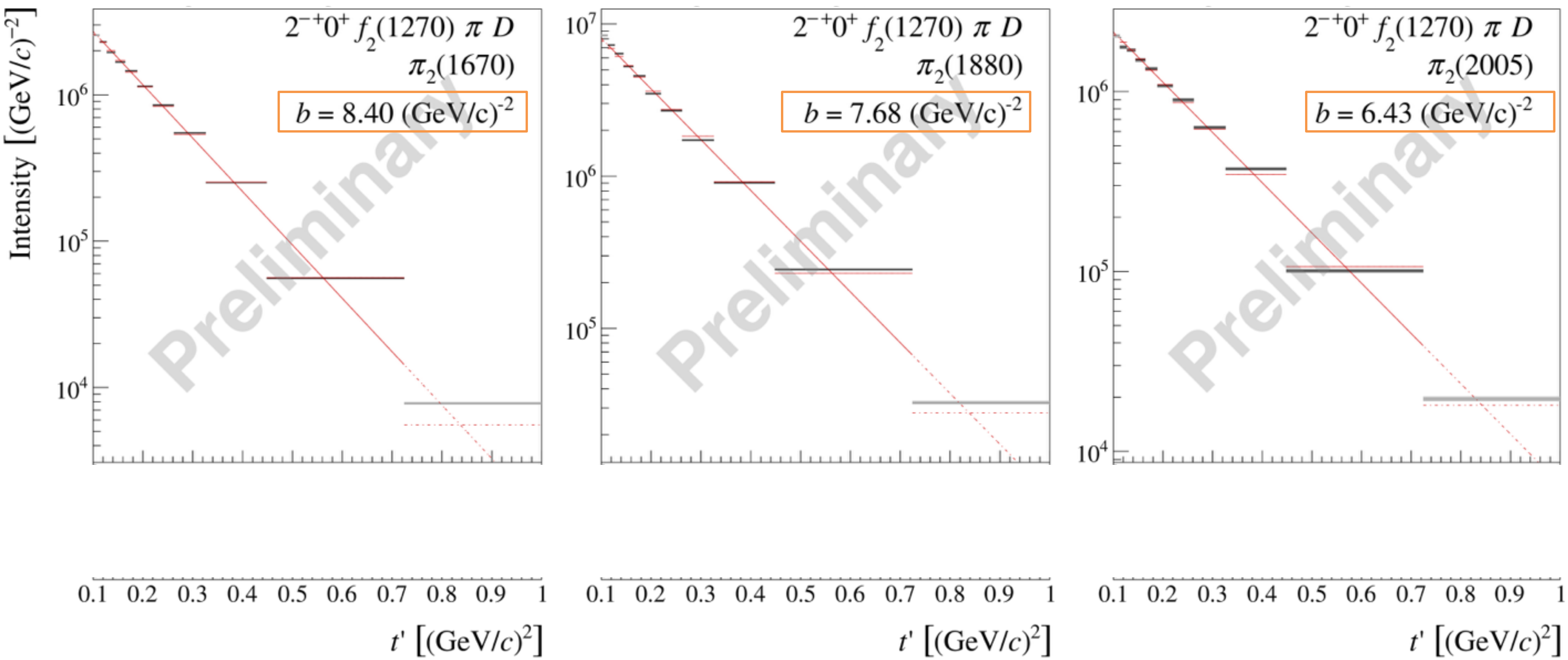
$\pi_2(1880)$ prefers D-wave decay m = 0

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

- very different production/decay characteristics

Exzellenzcluster Universe

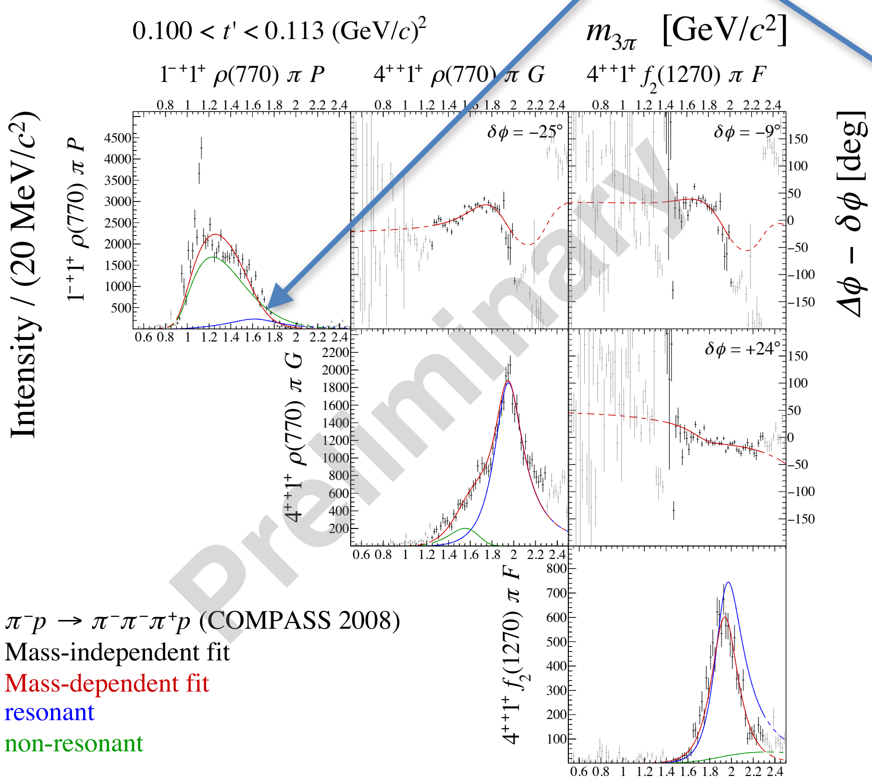
Kinematics: Dependence on t

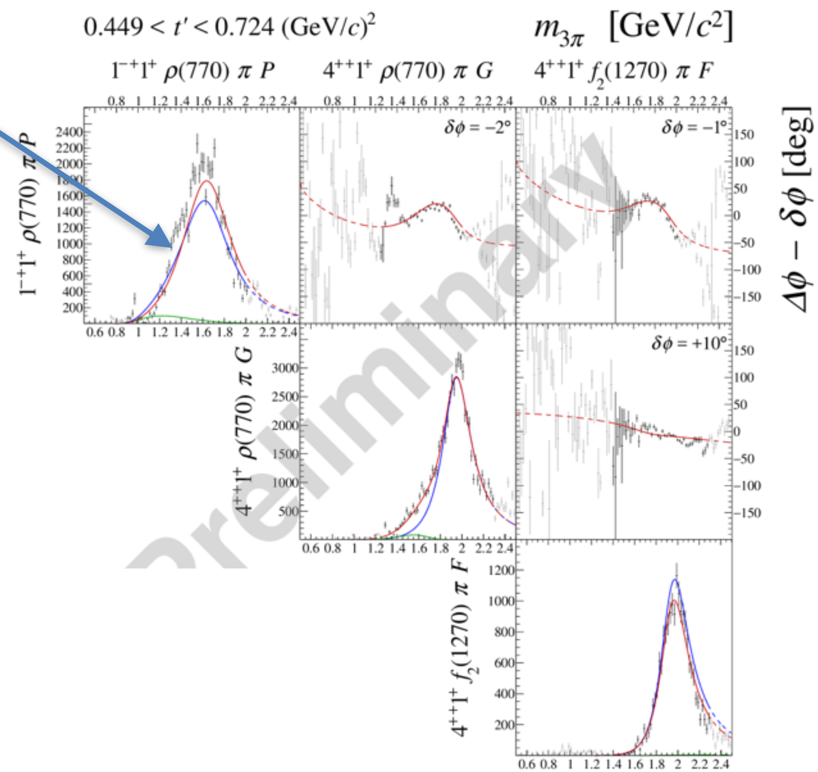


Background: $b = (13.5\ \text{GeV}/c)^{-2}$

Find the Resonances

- Exotic mesons: 1^{-+}





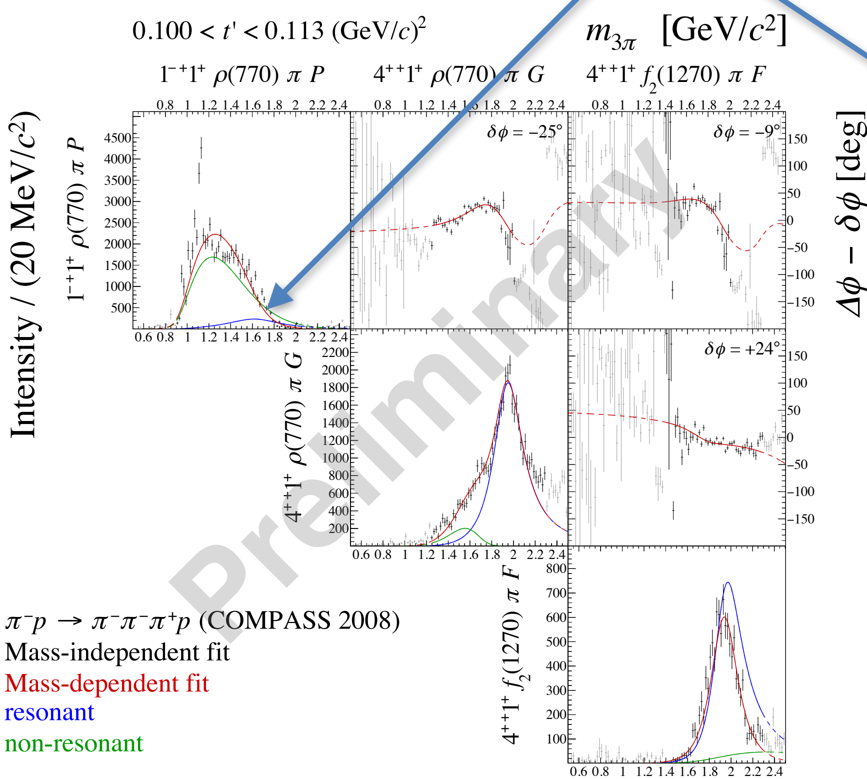
low t

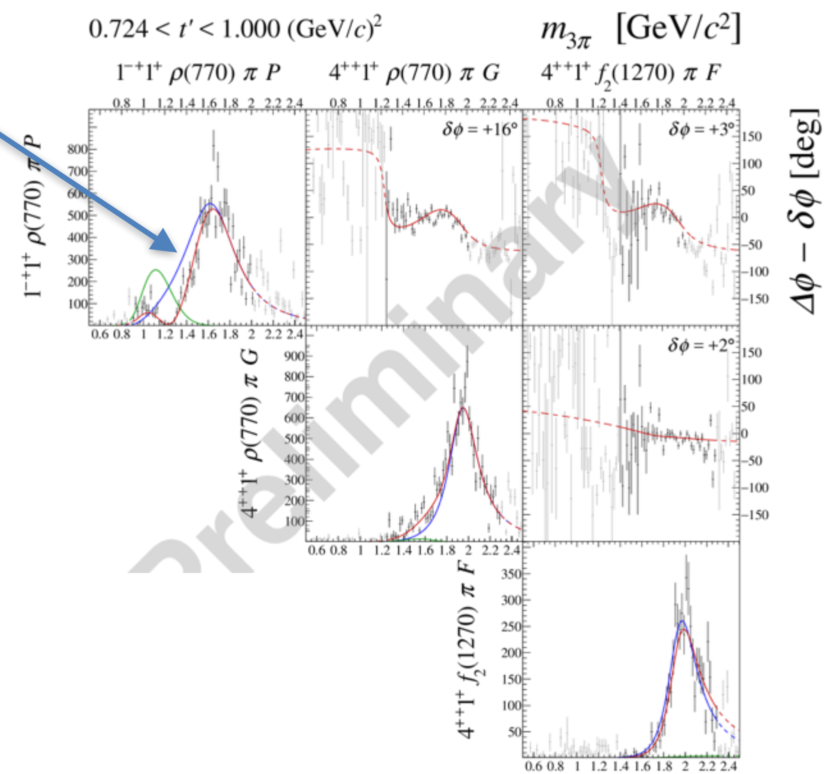
high t

Exzellenzcluster Universe

Find the Resonances

- Exotic mesons: 1^{-+}



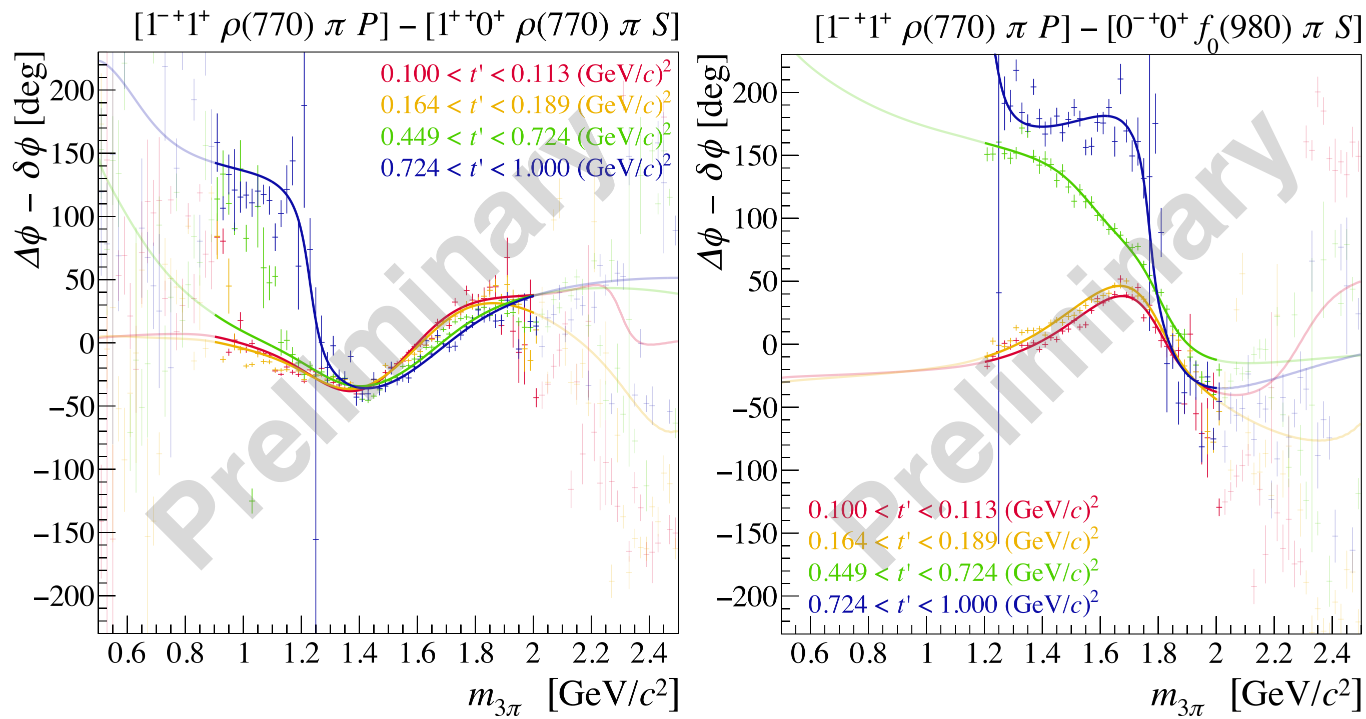


low t

high t

Find the Resonances - Phases

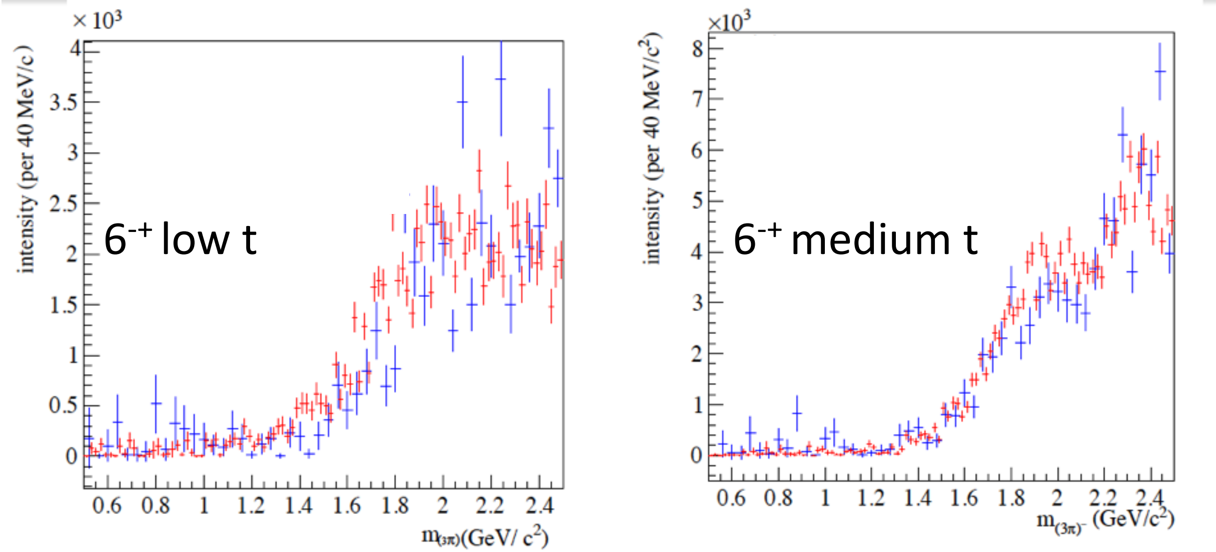
- Exotic mesons: 1^{-+}



6^{-+} Deck Simulations - Data

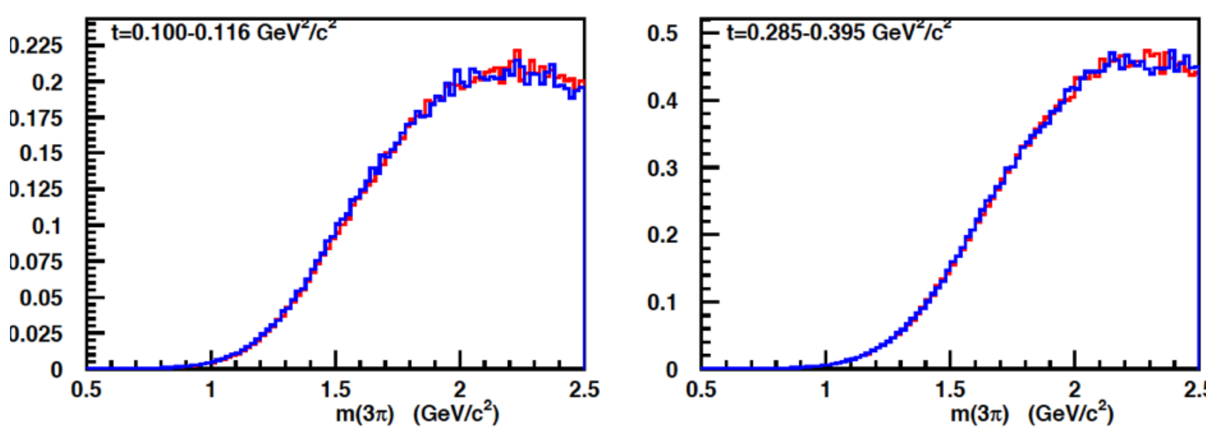
- wave w/o resonance
- compare final states

Data



$\pi^- p \to \pi^- \pi^- \pi^+ p$ $\quad$ $\pi^- p \to \pi^- \pi^0 \pi^0 p$

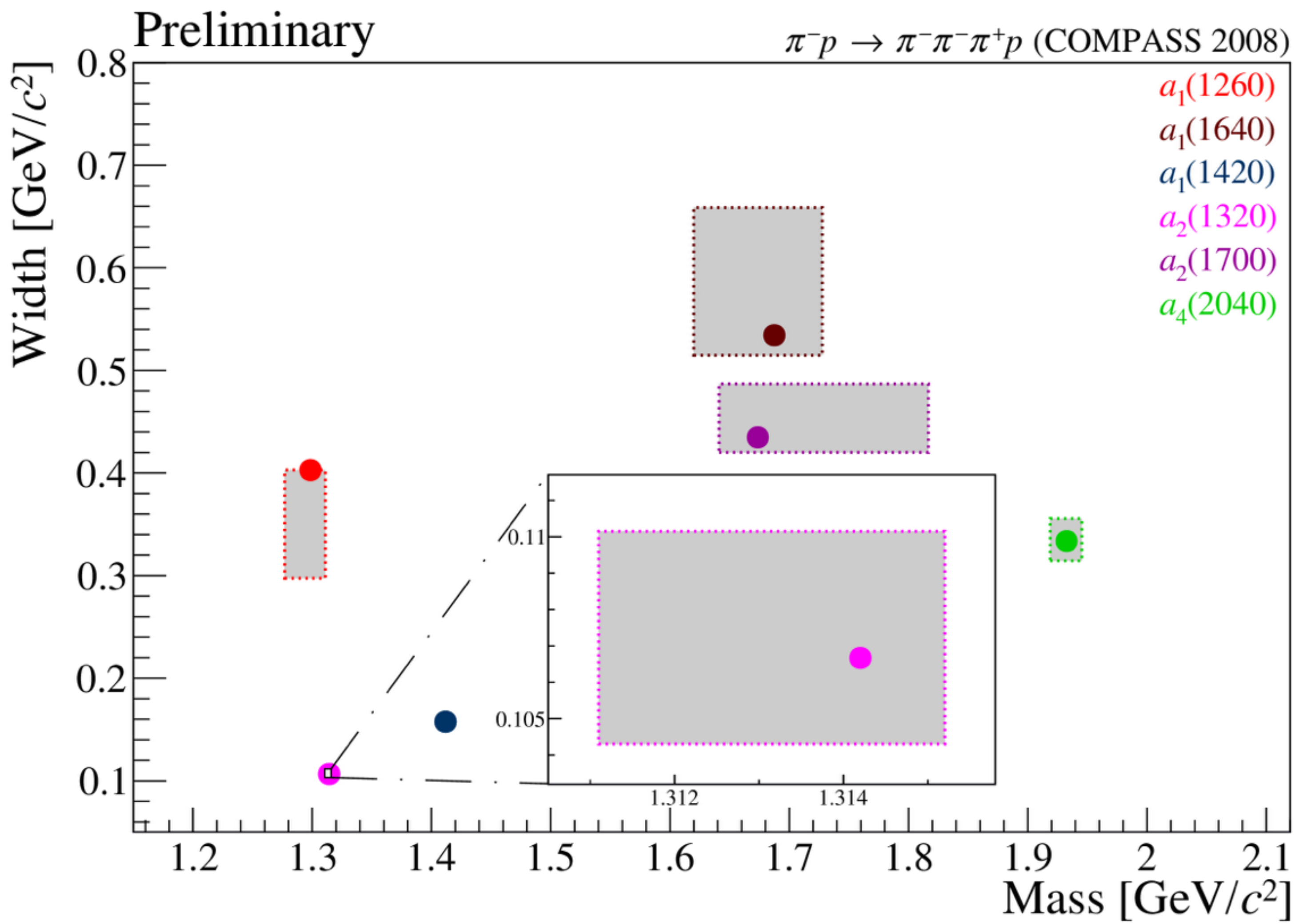
Deck MC



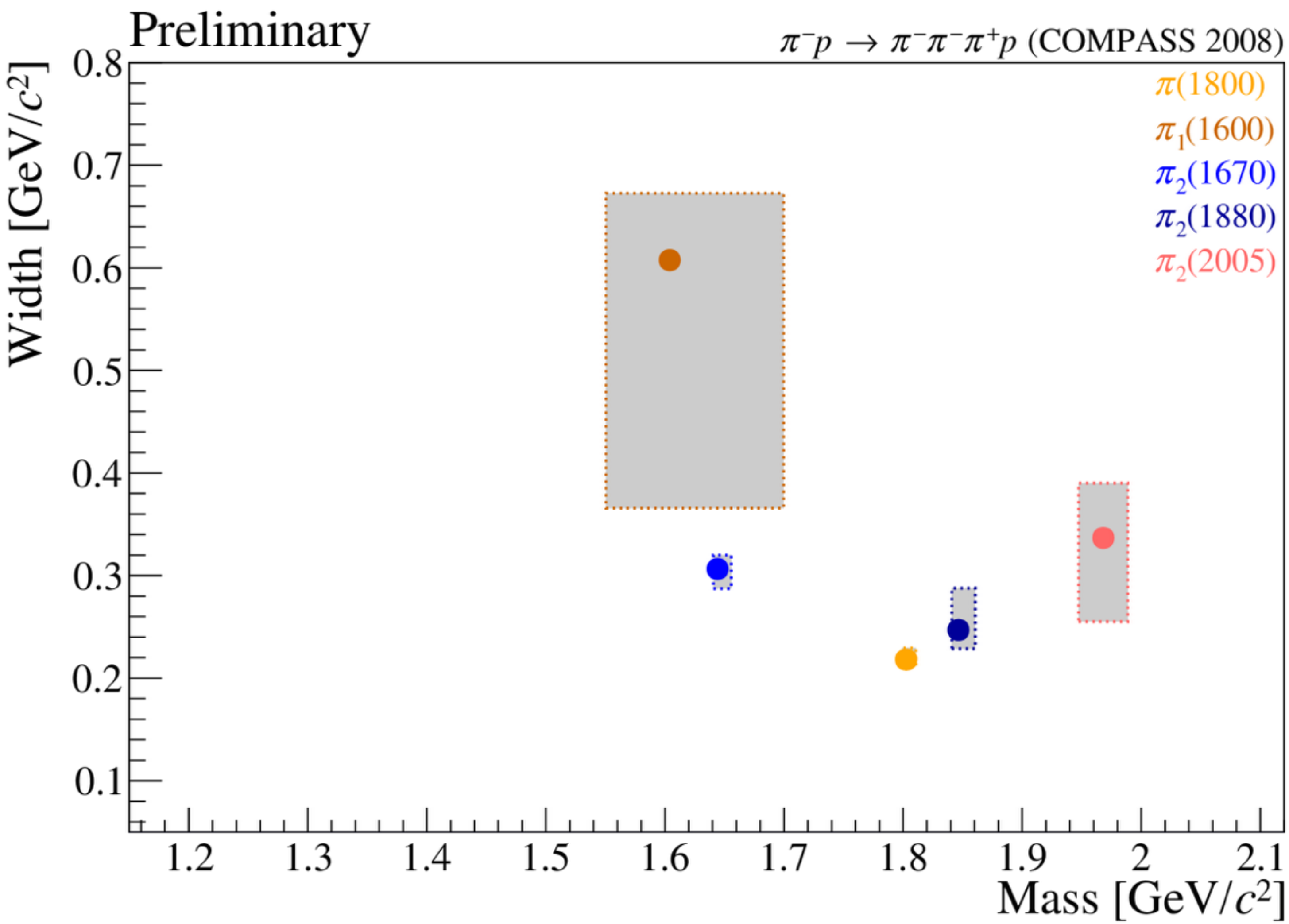
Systematic Studies

- 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
- Biggest influence on
  - $a_1(1260)$, $a_2(1700)$, $\pi_1(1600)$
  - strong correlation $a_1(1260)$ - $\pi_1(1600)$ resonance parameters found

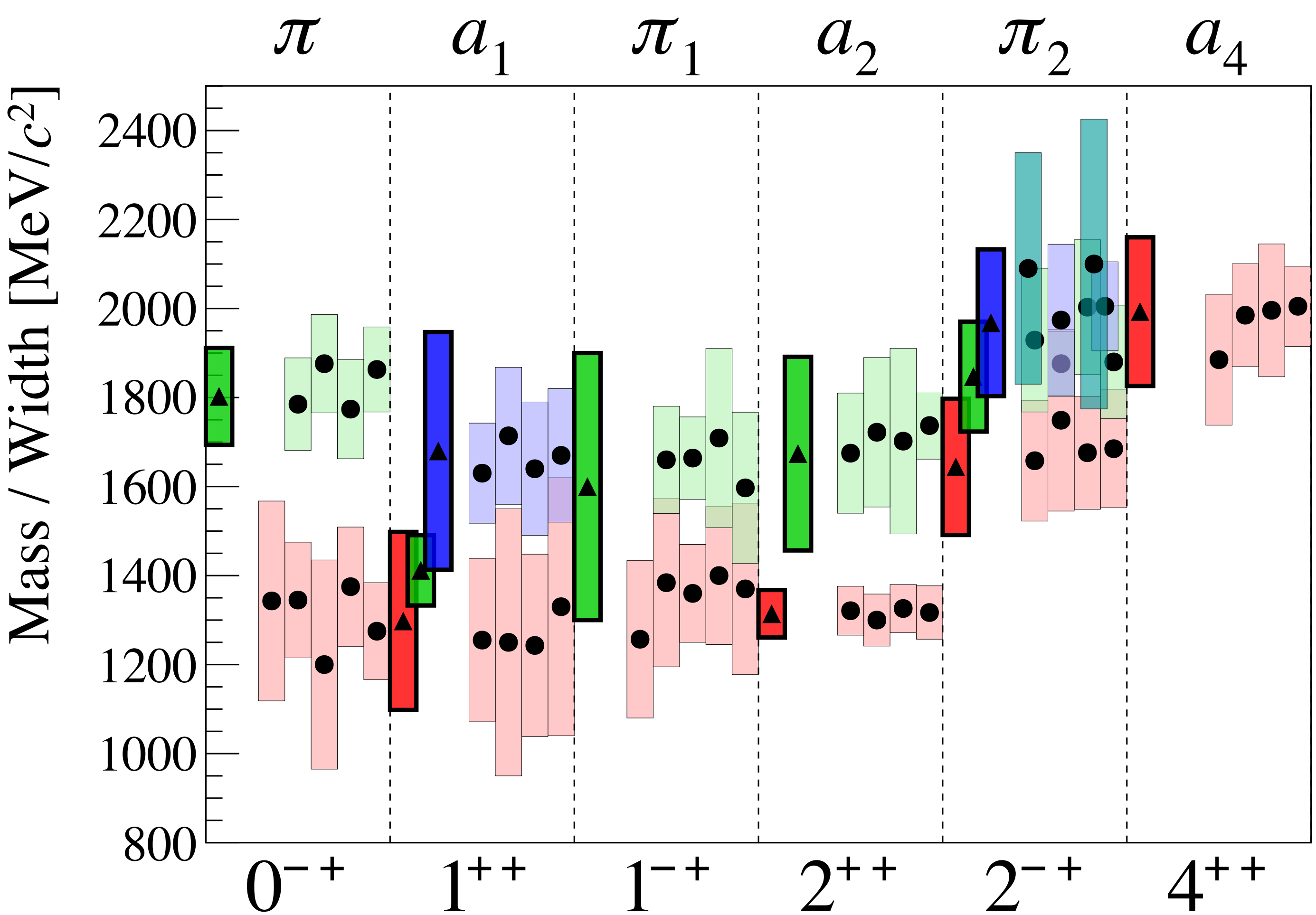
Axialvector Mesons



Pseudoscalar Mesons

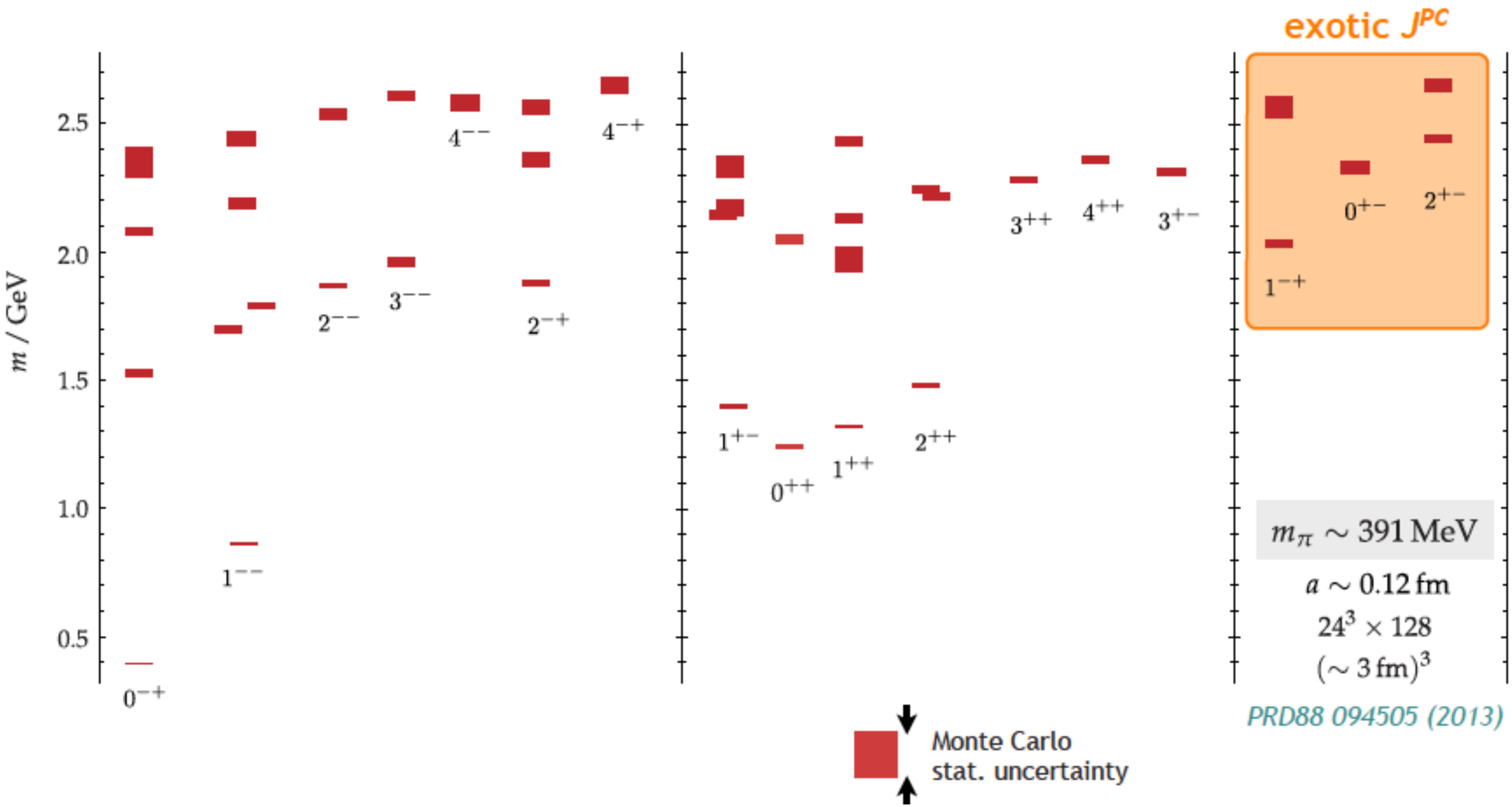


Summary - Resonances



- COMPASS provides consistent analysis and realistic uncertainties

Mesons on the Lattice

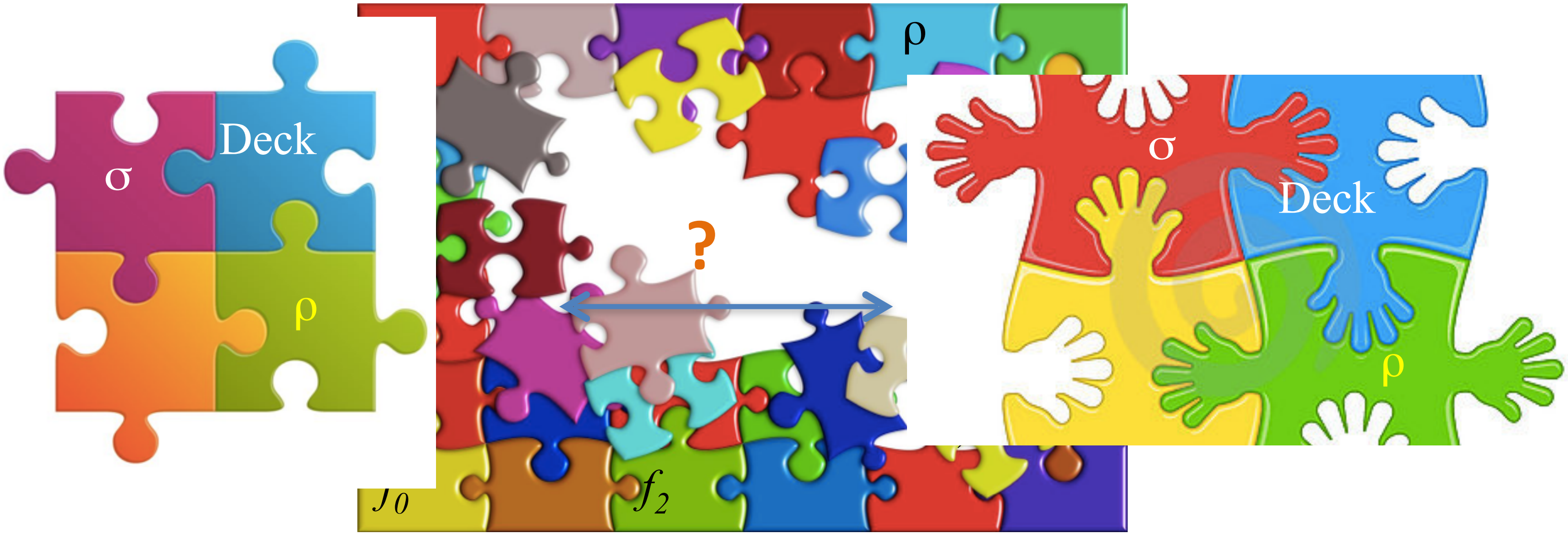


PRD88 094505 (2013)

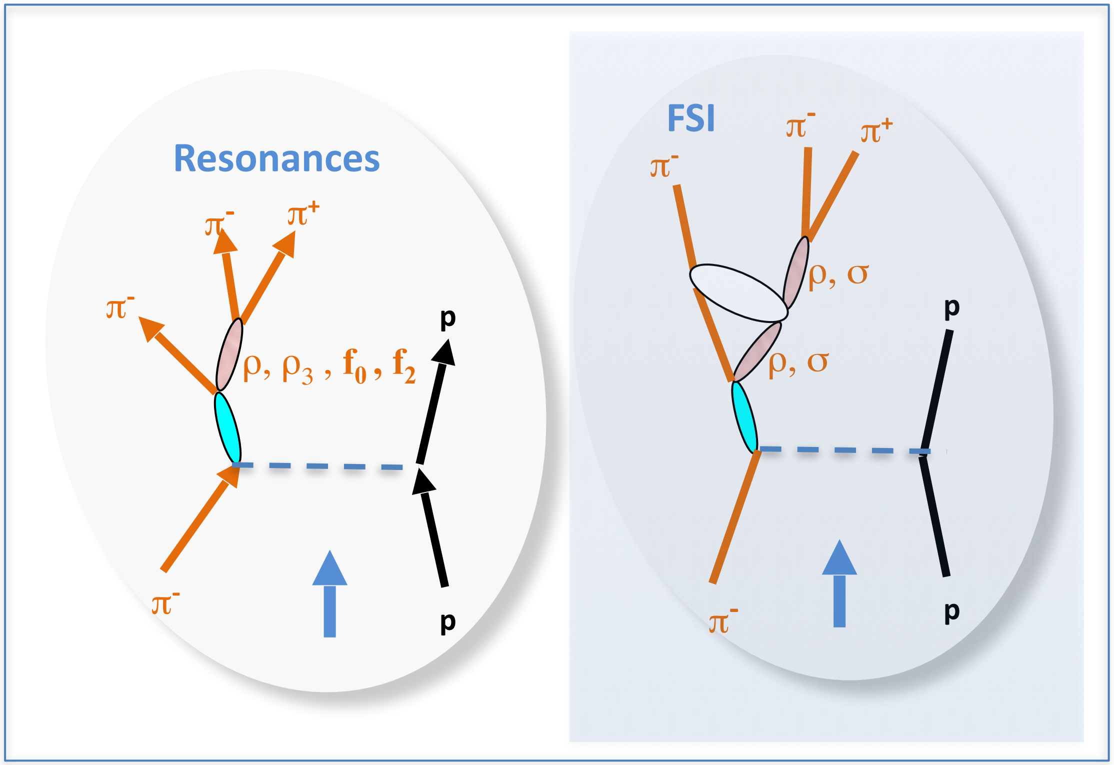
Dudek at al.

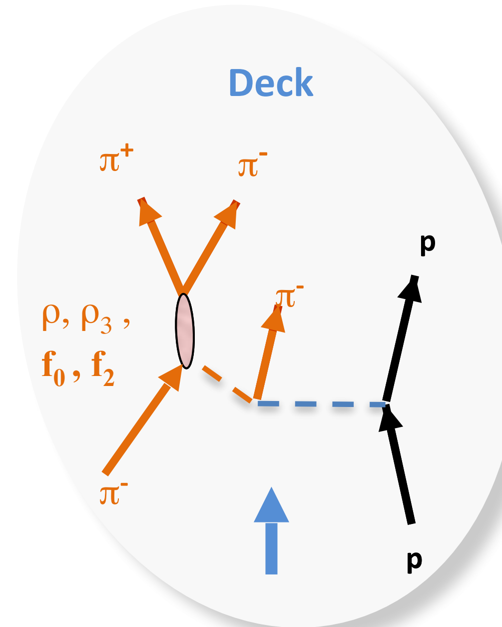
What about the building blocks

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



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)

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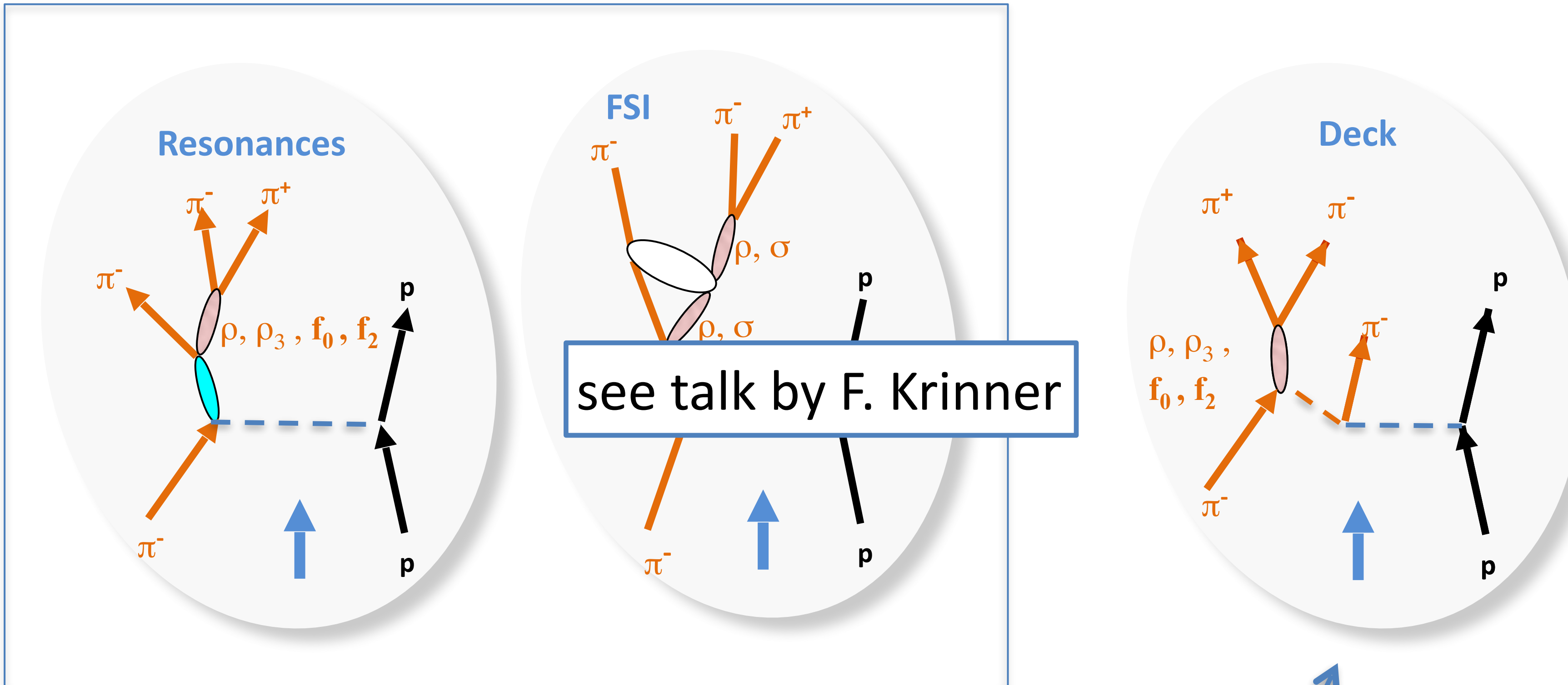

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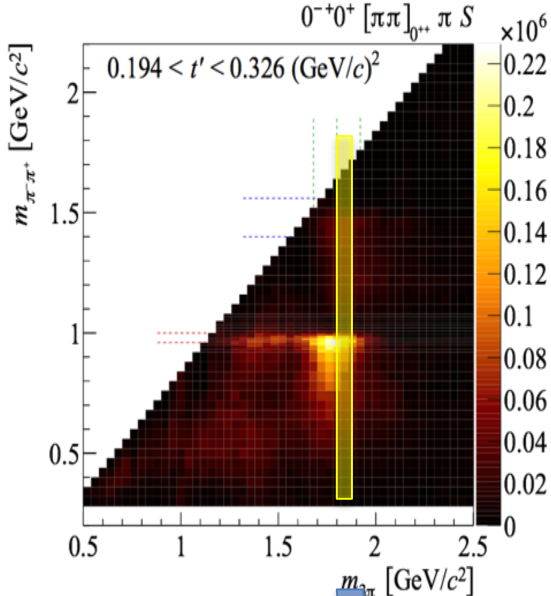
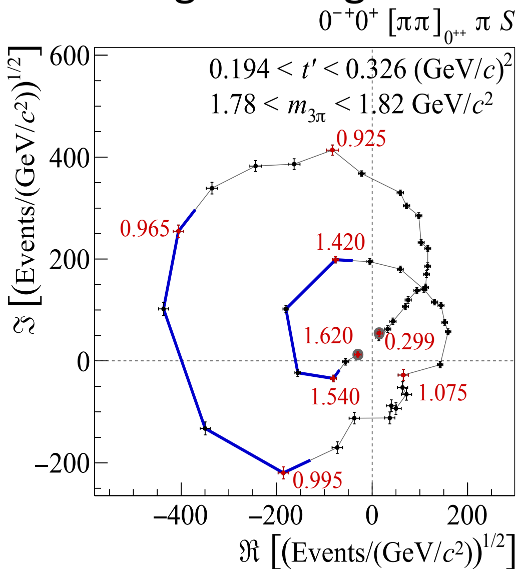
Studying the Structure of Decays

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)

Exzellenzcluster Universe

Studying the Structure of Decays

Study decay of π(1800) into 3π

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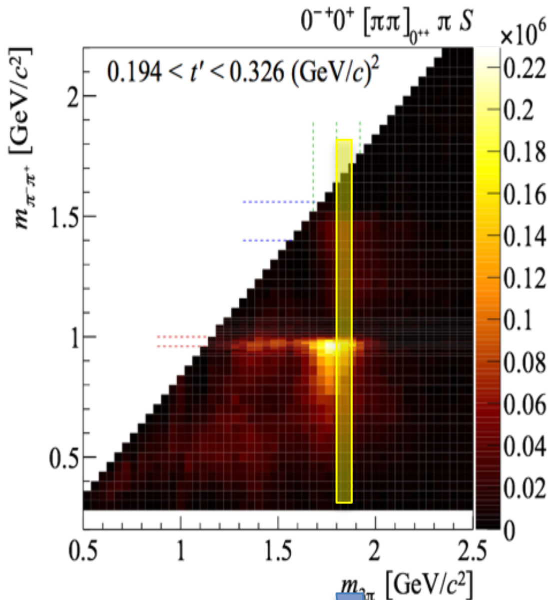
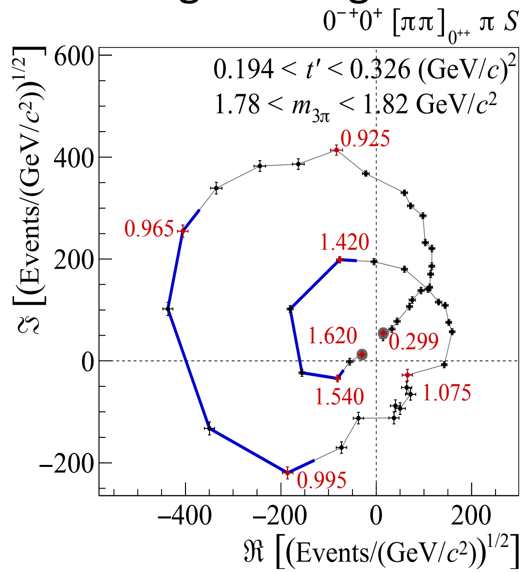
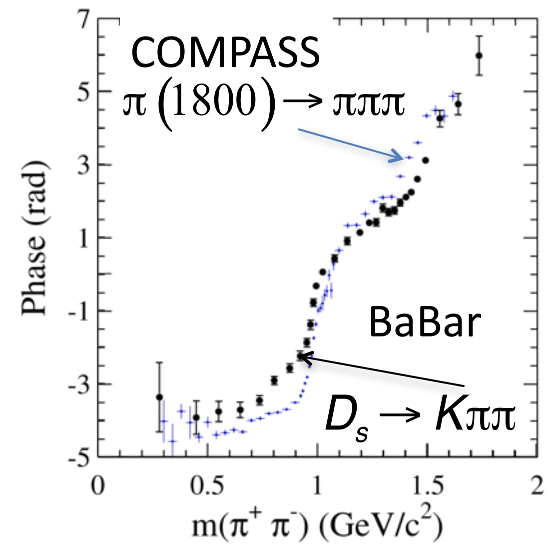


Argand Diagram



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



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

Subtle differences will tell us more

Ongoing Projects

Ongoing theory support allows to address challenging tasks

- Fit to ππ S-wave using known scattering amplitudes
  - Known up to 1.2 GeV/c^2
  - Combine with knowledge about higher mass scalars

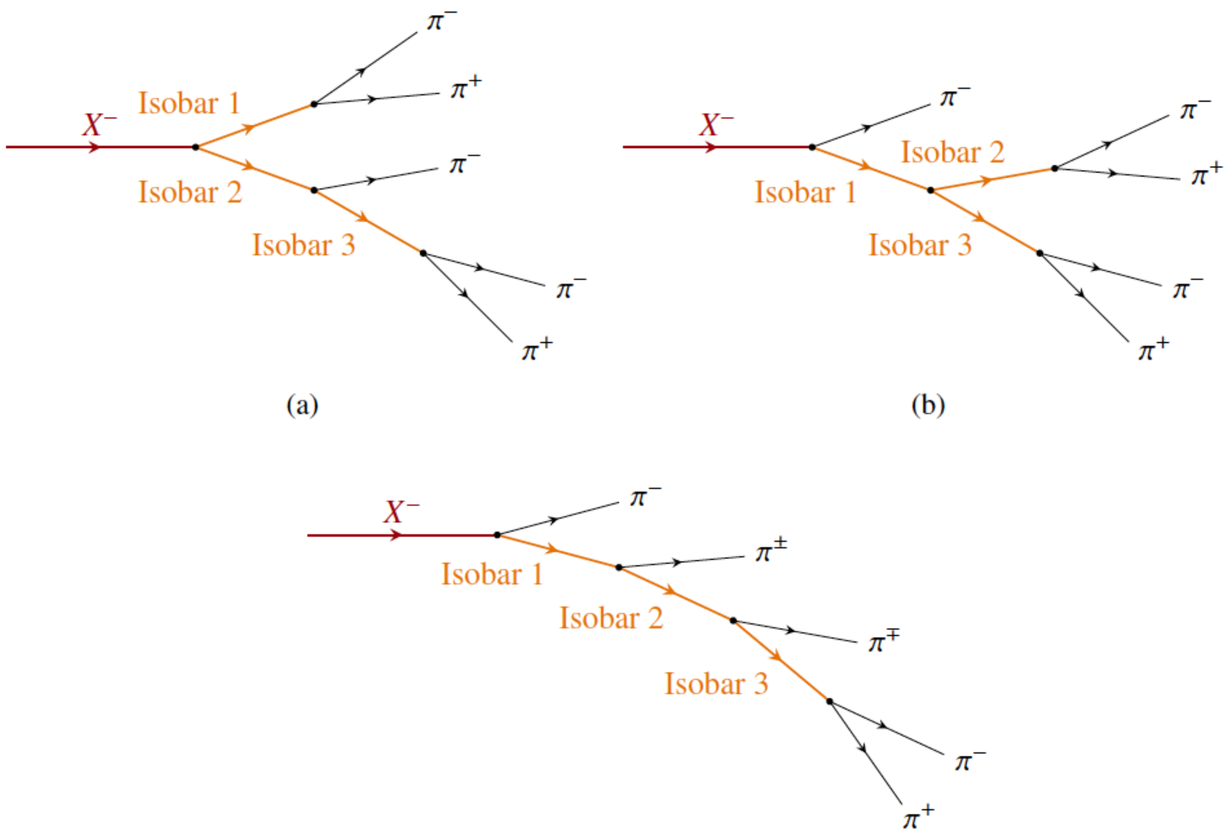
- Include more 3π J^{PC} in freed- isobar analysis
- Includes more 2π J^{PC} in freed- isobar analysis

- Fit to spin-density matrix without BW
  - Use K-matrix parametrisation with analytical function and poles
  - Extract pole parameters

- Joint fit of $\pi^-\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$ data

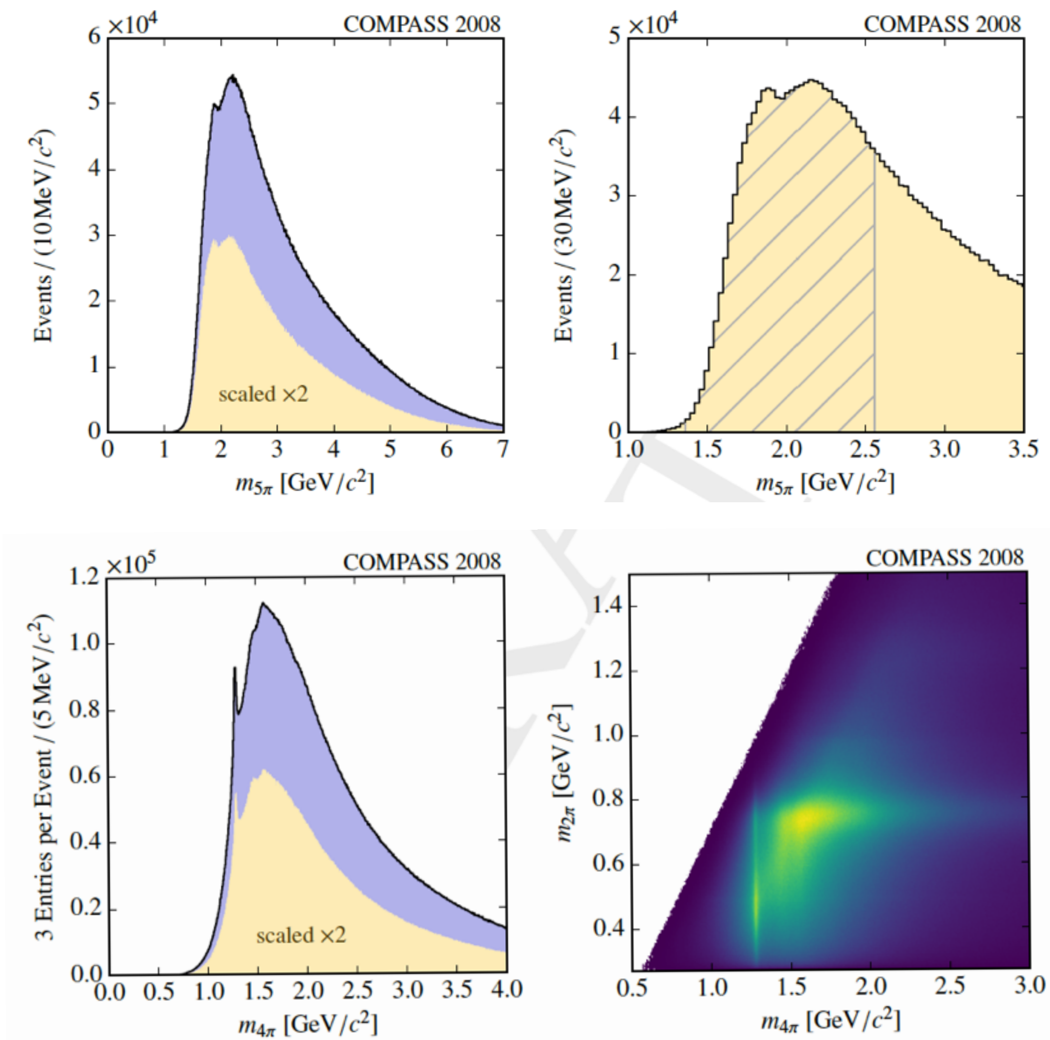
5π Final State

- Isobar model for 5π
- about 1500 possible amplitudes (L < 3)



5π Final State

- Access high mass resonances - investigate heavy isobars



- select low t (0.1 < t < 0.15)
  little non-exclusive bkgd.
- consider only small values $L<3$

5π Final State

Status

- Develop method to select most significant amplitudes
- Problems
  - Selection must be smooth across all mass bins
  - High sensitivity to isobar parametrization
  - Phase information much reduced
  - Many similarities to $\eta\pi\pi\pi$

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

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 !!