The virtue of precision spectroscopy :
A new axial-vector meson
and
a look behind the scenery of light meson decays

Stephan Paul

for the COMPASS collaboration

TUM

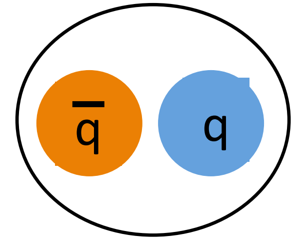
Excellence Cluster
Universe

Brief Overview

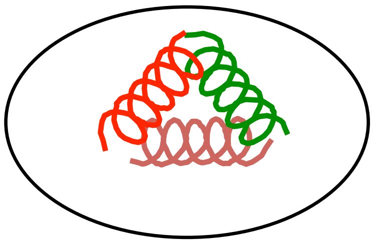
- Introduction
- Data-set and PWA analysis
  - Method and Analysis Model
  - Results
    - Light meson resonances revisited
    - A new meson $a_1(1420)$
- How to observe decay dynamics
  - Example: $\pi\pi$ S-wave extraction
    - Role of $f_0(980)$
- Radiative meson-decays
- Conclusions

Light Mesons, Quarks and Gluons

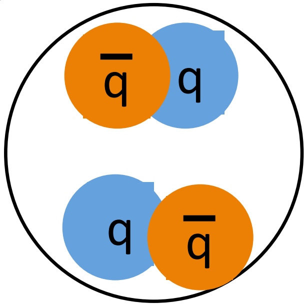
- Quark model mesons (u, d, s quarks)



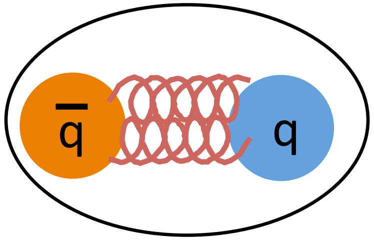
- Glueballs (gluons and no valence quarks)



- Multiquarks (quark-antiquark pairs)

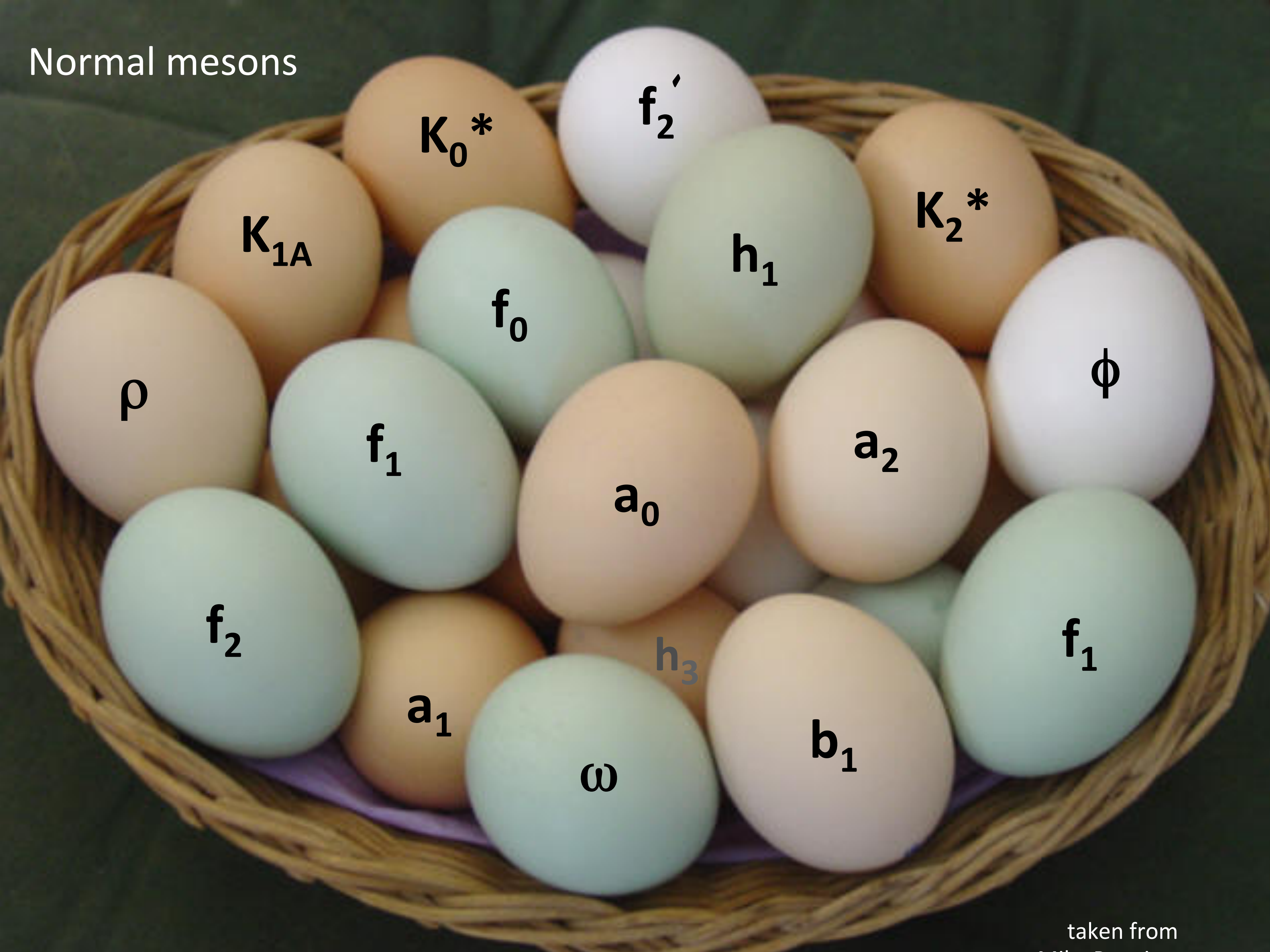


- Hybrids (quarks and gluonic excitation, which contribute to static properties)



Klempt Zaitsev Phys Rep 454 (2007) 1

Normal mesons



taken from


More Surprising States?
taken from
Mike Penning

How to produce “other” mesons

- Diffraction: $\pi p_{target} \rightarrow X + p_{recoil} \rightarrow n\pi + p_{recoil}$
  - isospin = 1 (high spin (J) states accessible)
  - spin-alignment M of resonance X w.r.t. production plane normal
  - PWA to disentangle all possible X
  - isospin = 0 possible in decay products of X

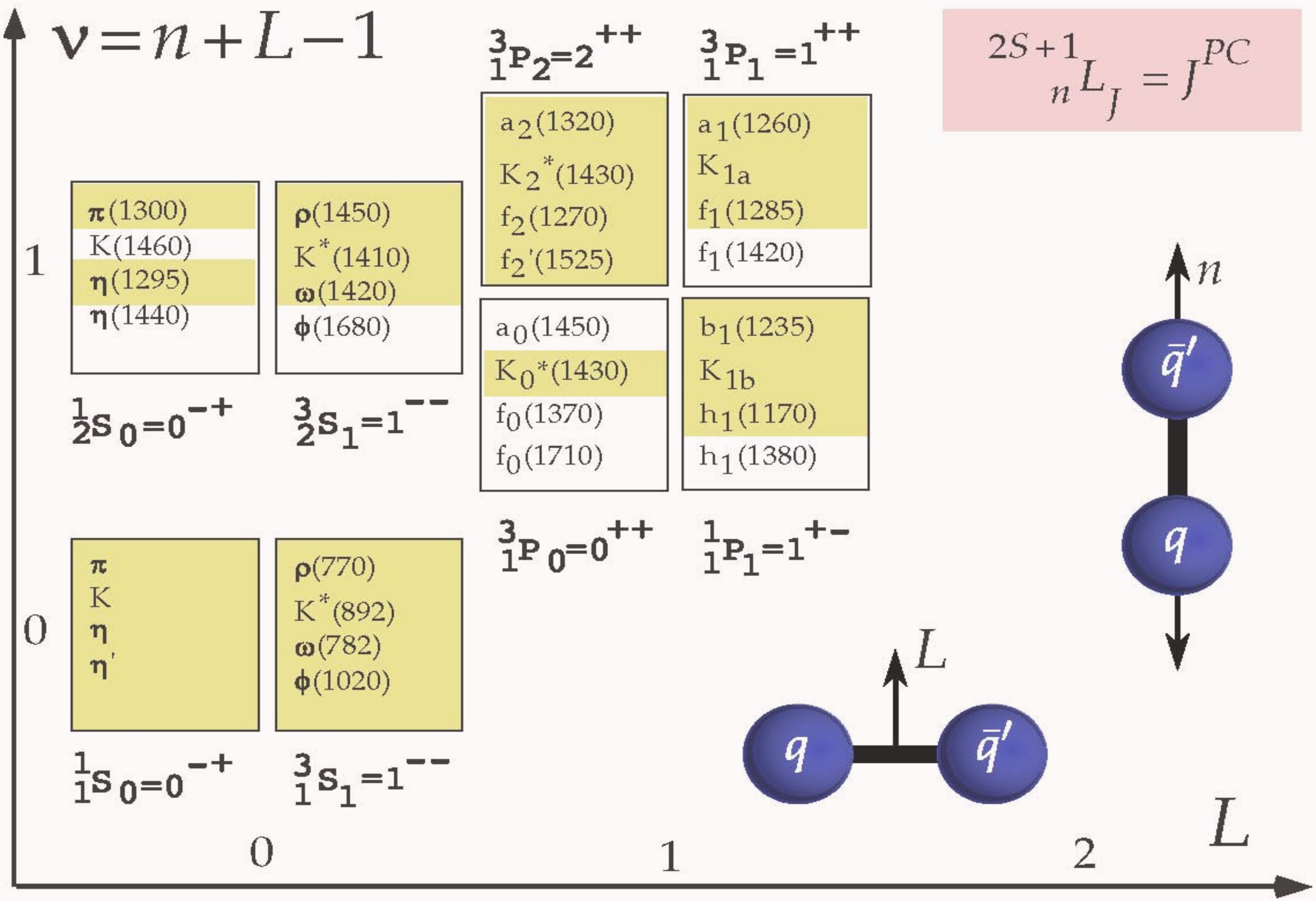
- Central production: $pp_{target} \rightarrow p_{fast} + X + p_{recoil}$

  $\rightarrow p_{fast} + n\pi/K/\eta + p_{recoil}$
  - isospin = 0 (typically populating low spin states)
  - “glue-rich” systems

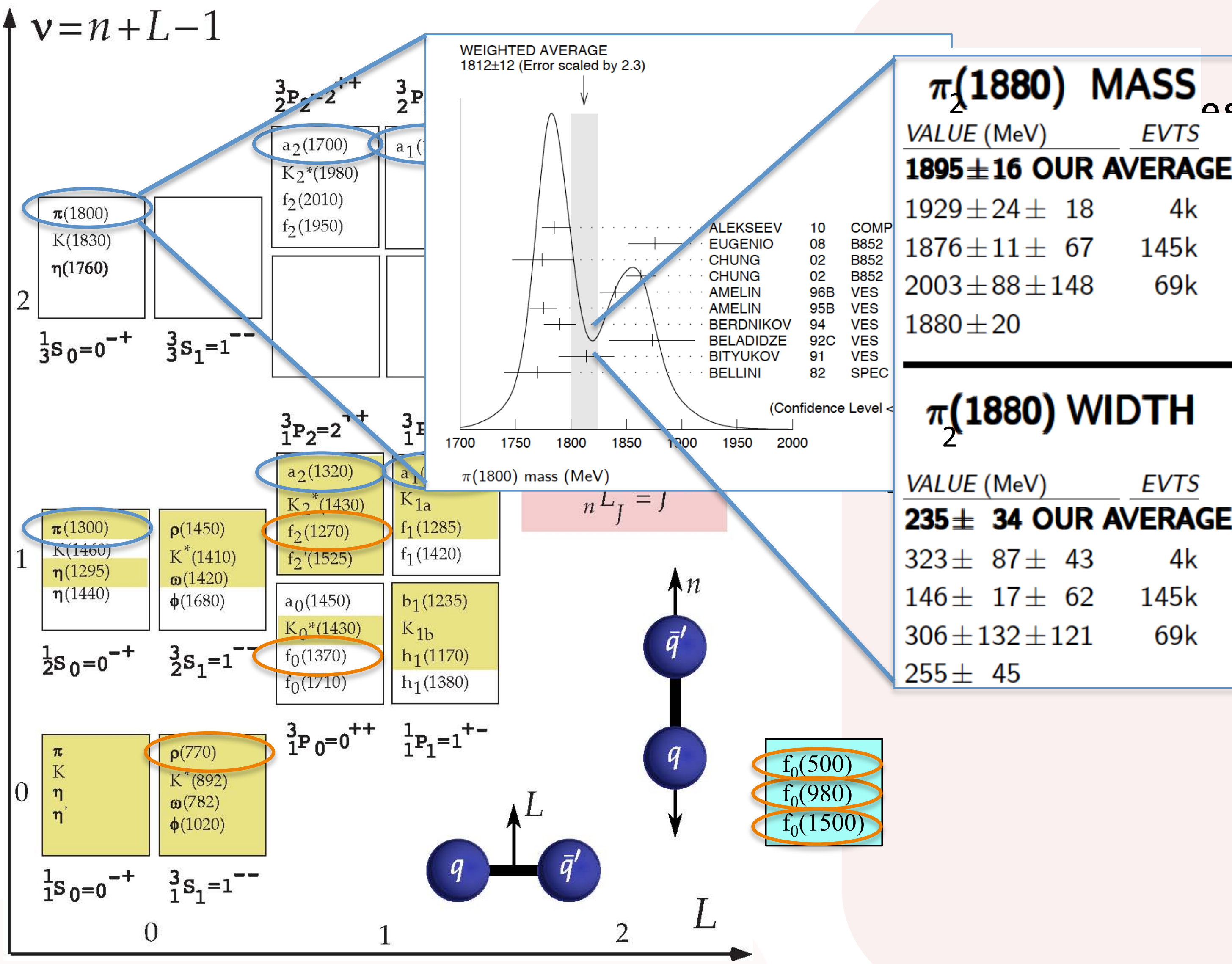
- J/ψ-decays: $J/\psi \rightarrow X + \gamma_{recoil}$
- $\bar{p}p$-annihilations or heavy meson decays (Dalitz plot analysis)
  - typically populating low spin states

Constituent Quarks and Mesons

Spectrum of light mesons:



Constituent Quarks and Mesons



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

...esons

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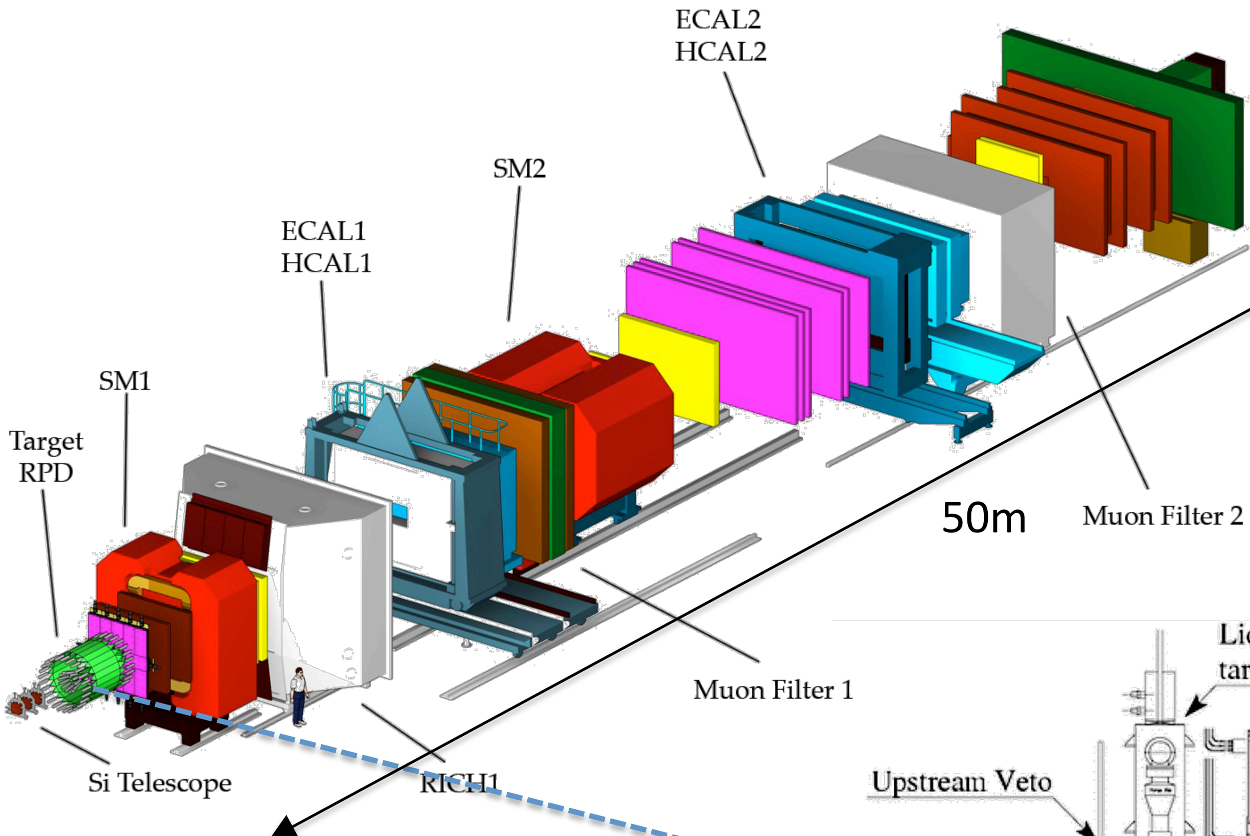
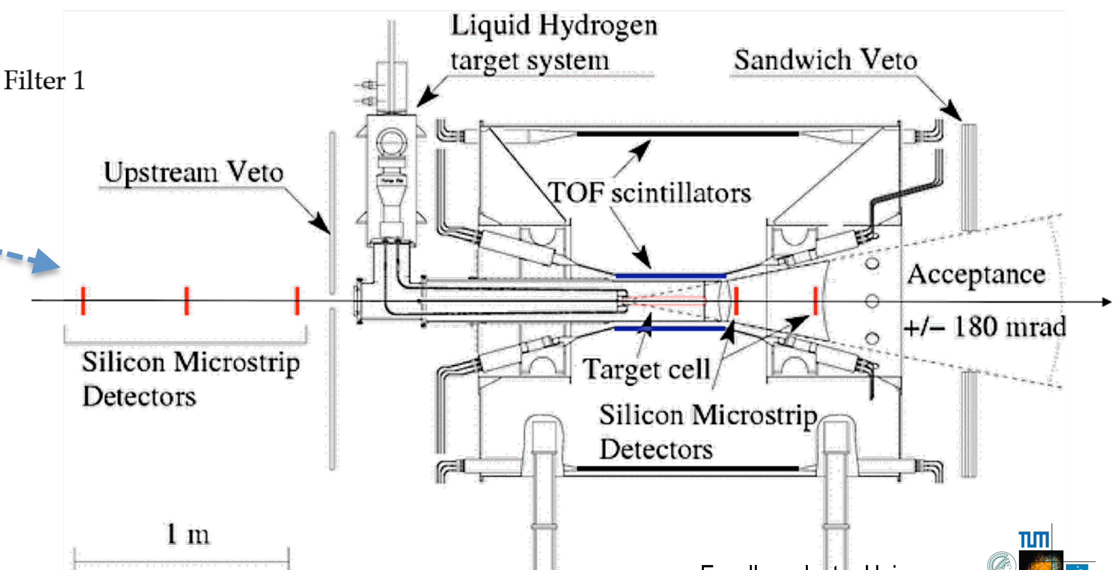
The COMPASS Experiment

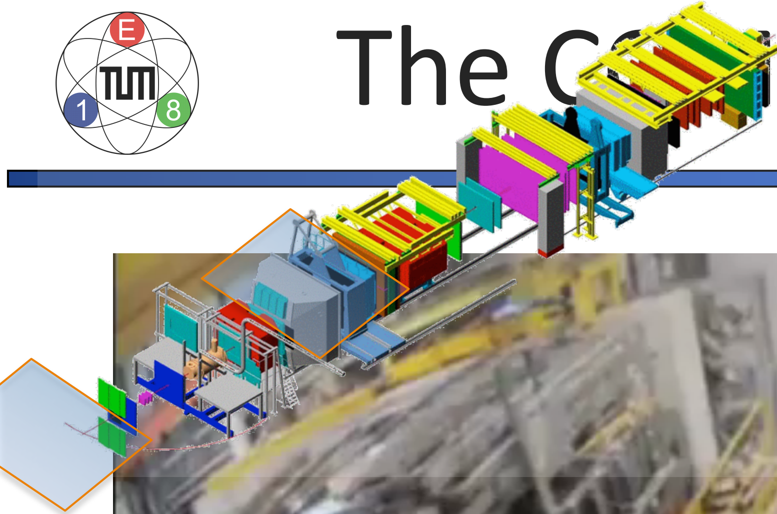


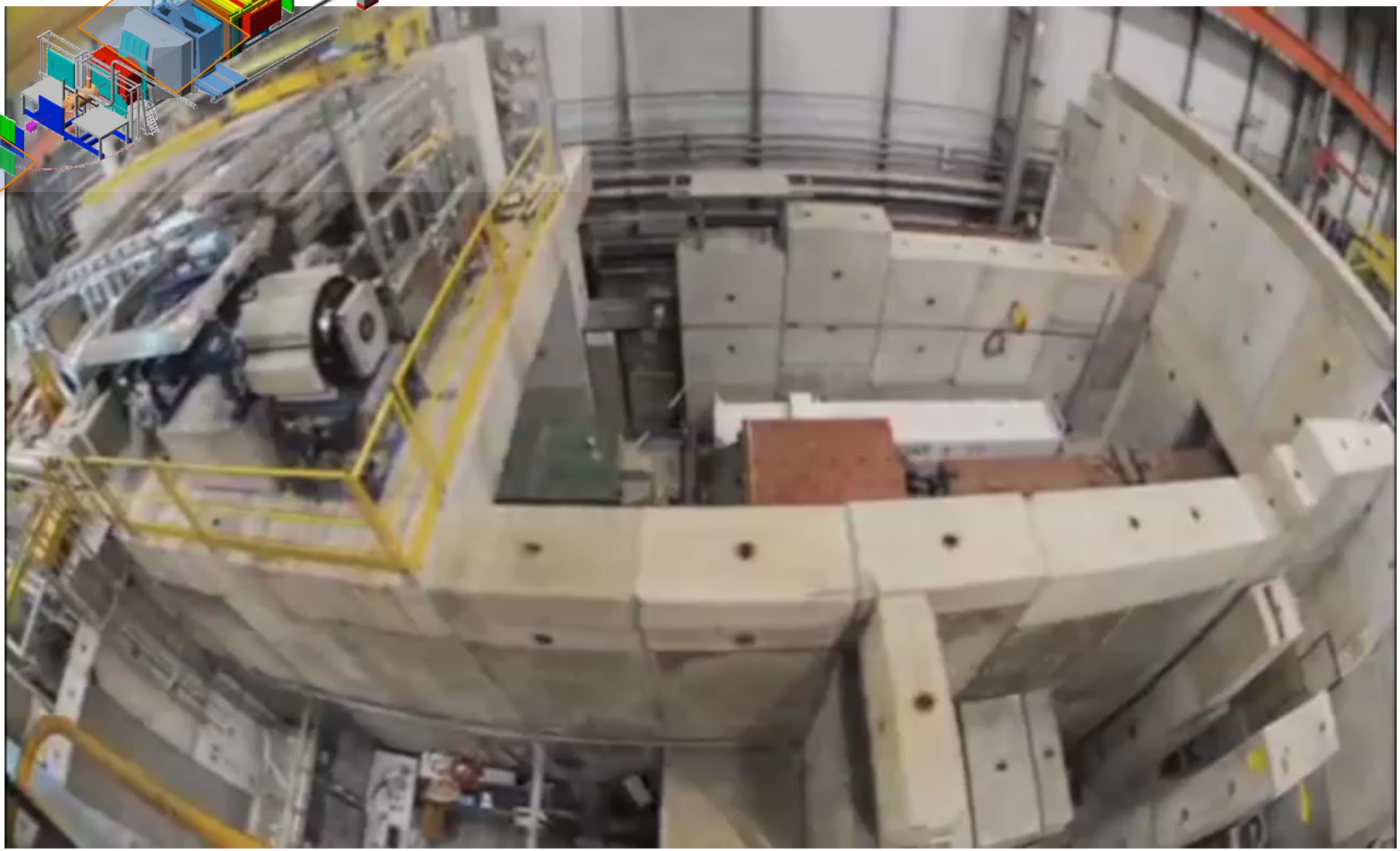
CERN SPS
Hadron beam:

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



The COMPASS Experiment





COMPASS Physics

- μ-beam (nucleon structure)
  - Longitudinal spin-structure
  - Transversal spin structure : COMPASS + **COMPASS II**
  - Partonic momentum distributions
  - Generalized Parton distributions (GPD) $\longrightarrow$ **COMPASS II**

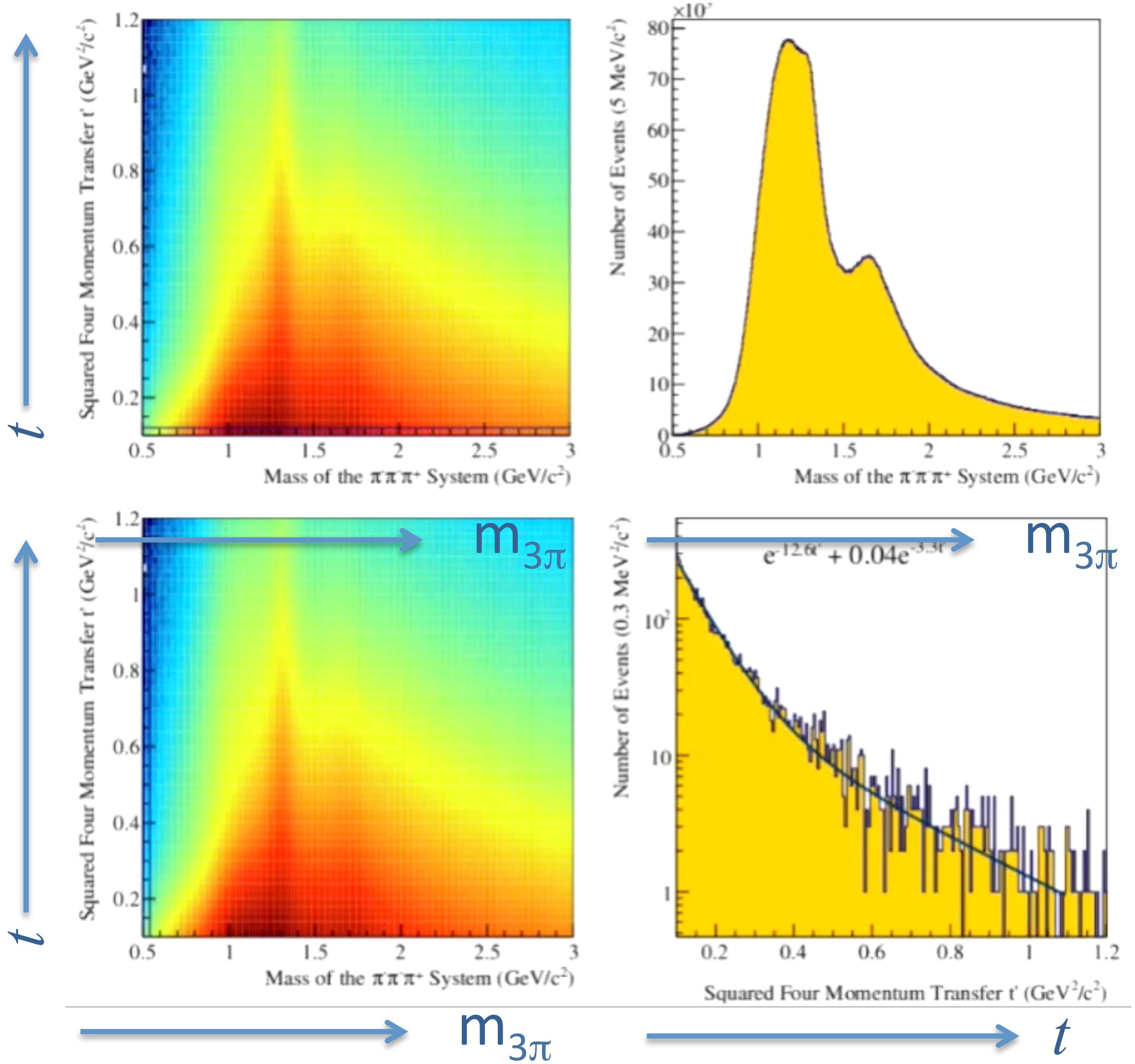
- hadron beam (structure and spectroscopy)
  - Light meson spectroscopy
    - Diffraction, central production, photo-production
  - Light baryon spectroscopy
  - Meson polarizabilities : COMPASS + **COMPASS II**
  - Mesonic dynamics (low energy - χPT)

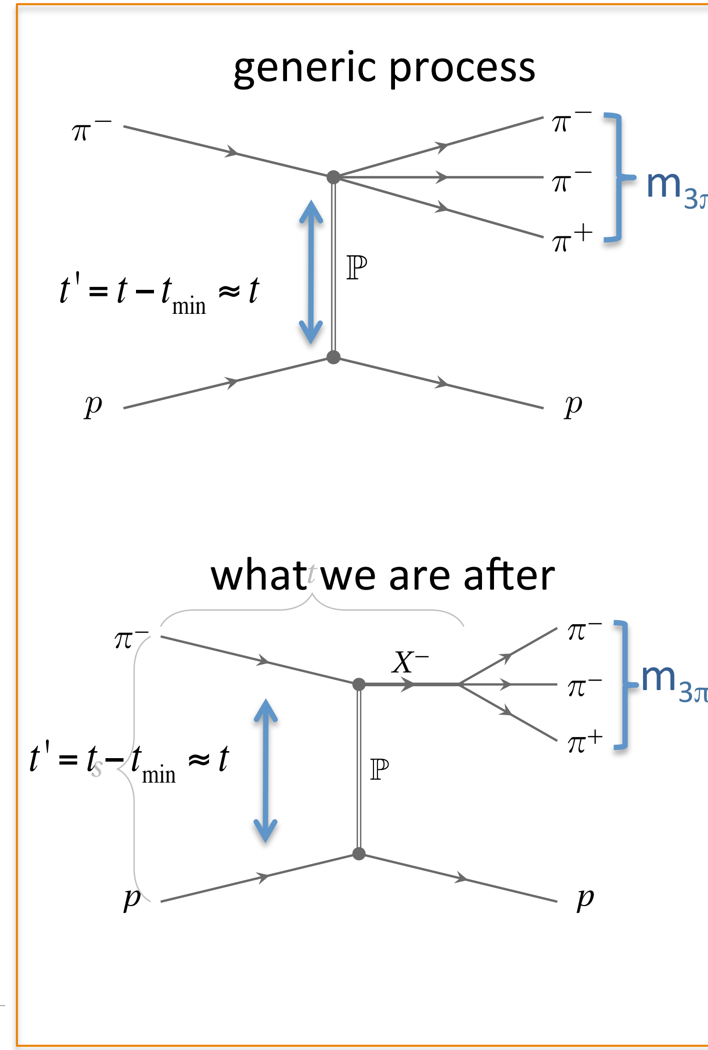
Kinematics and Isobars

grid of t used

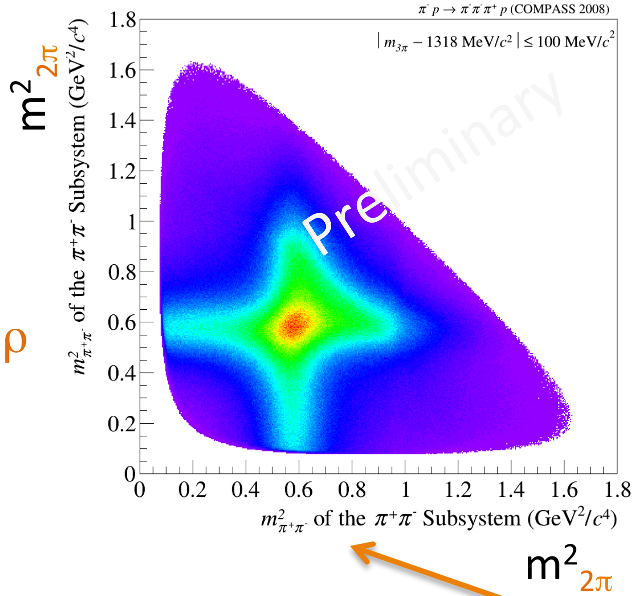
Δm: 20 MeV/c^2

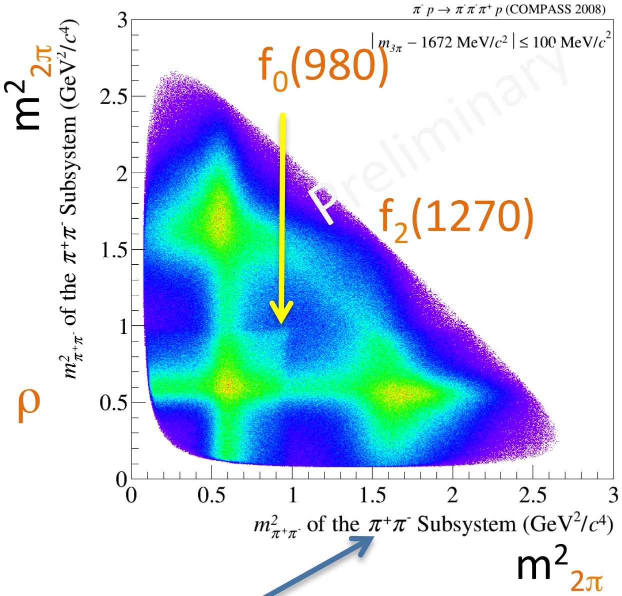
exclusive reaction

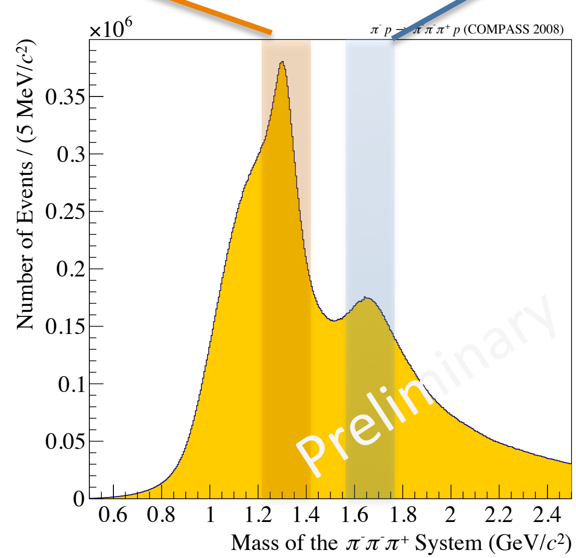


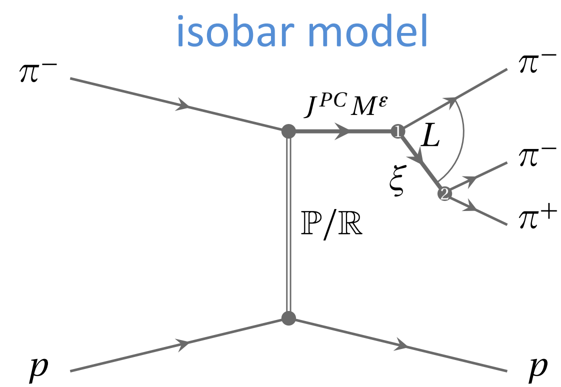


First Impressions
Motivation for Isobar Model





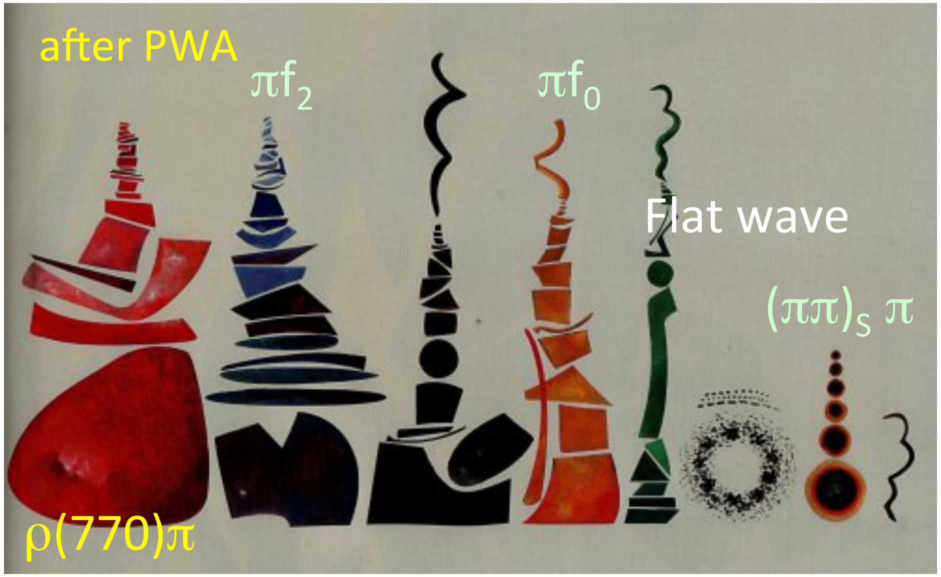




Exzellenzcluster Universe

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 $\pi\pi\pi$: determine which coherent combination of waves fits distribution best
- Obtain spin-density matrix

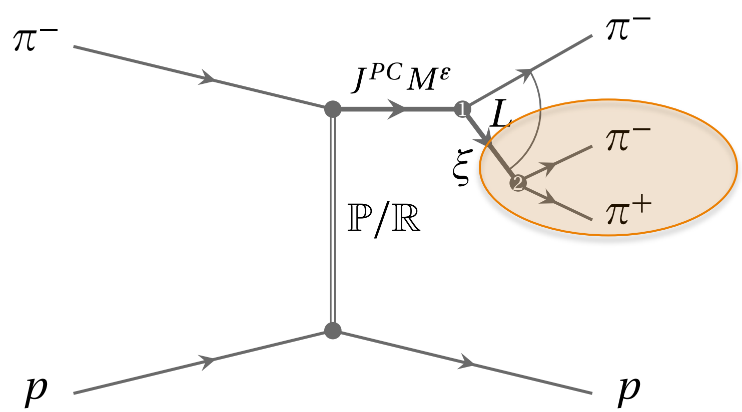
step 2

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

Fit Model - Isobars

Particle	J^{PC}	Mass [MeV/c^2]	Width [MeV/c^2]
$f_0(500)$	0^{++}	400 to 550	400 to 700
$f_0(980)$	0^{++}	990 ± 20	40 to 100
$f_2(1270)$	2^{++}	1275.1 ± 1.2	$185.1^{+2.9}_{-2.4}$
$f_0(1370)$	0^{++}	1200 to 1500	200 to 500
$f_0(1500)$	0^{++}	1505 ± 6	109 ± 7
$\rho(770)$	1^{--}	775.49 ± 0.34	149.1 ± 0.8
$\rho(1450)$	1^{--}	1465 ± 25	400 ± 60
$\rho_3(1690)$	3^{--}	1688.8 ± 2.1	161 ± 10

$[\pi\pi]_S$



Exzellenzcluster Universe

Major waves

Major waves

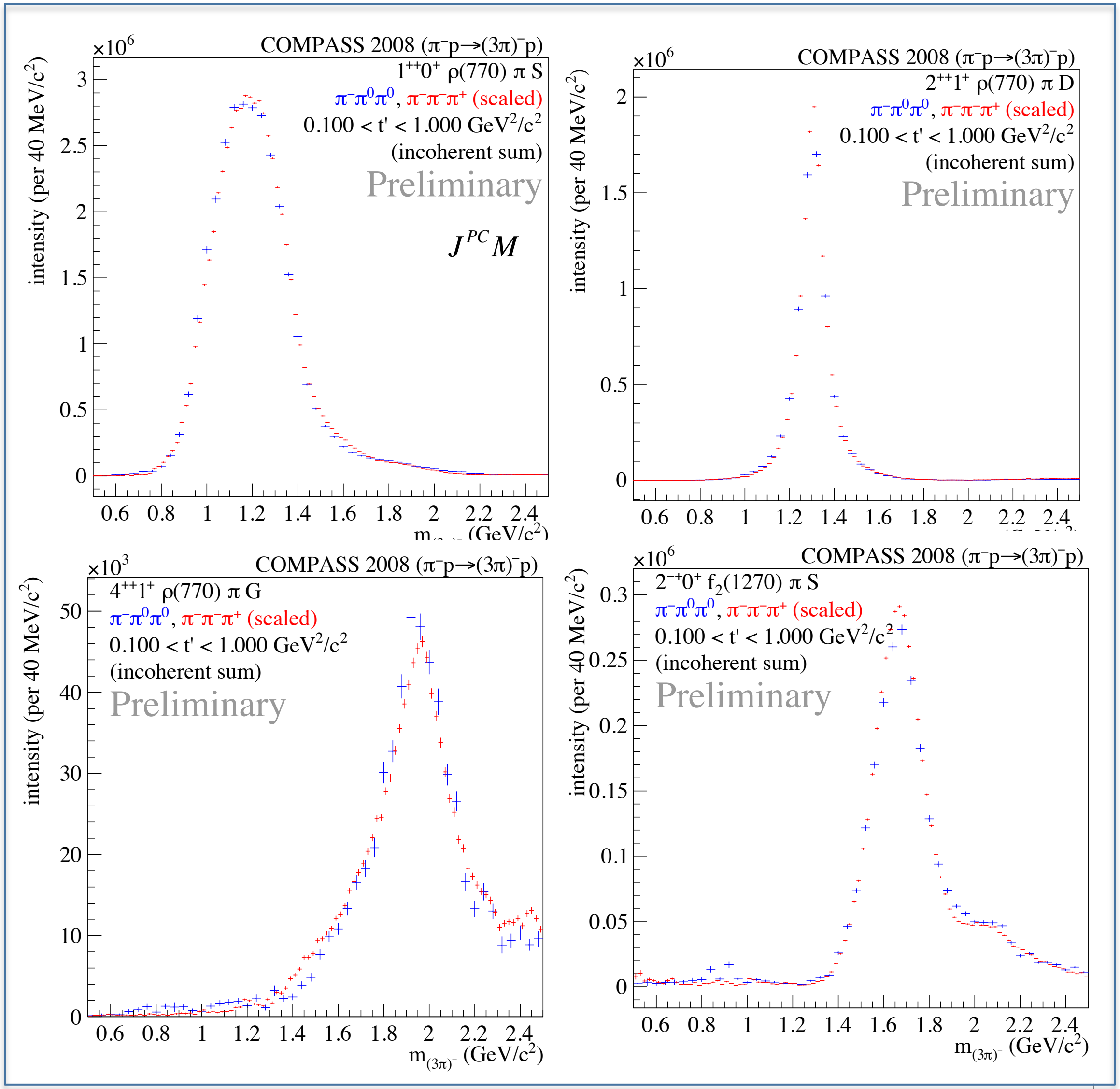
$J^{PC}M^{\varepsilon}[isobar]\pi L$

$1^{++}M^{+}[\rho]\pi S$
$2^{++}M^{+}[\rho]\pi D$
$2^{-+}M^{+}[f_2(1270)]\pi S$
$4^{++}M^{+}[\rho]\pi G$

$1^{++}M^{+}[f_0(980)]\pi P$
$0^{-+}M^{+}[f_0(980)]\pi S$

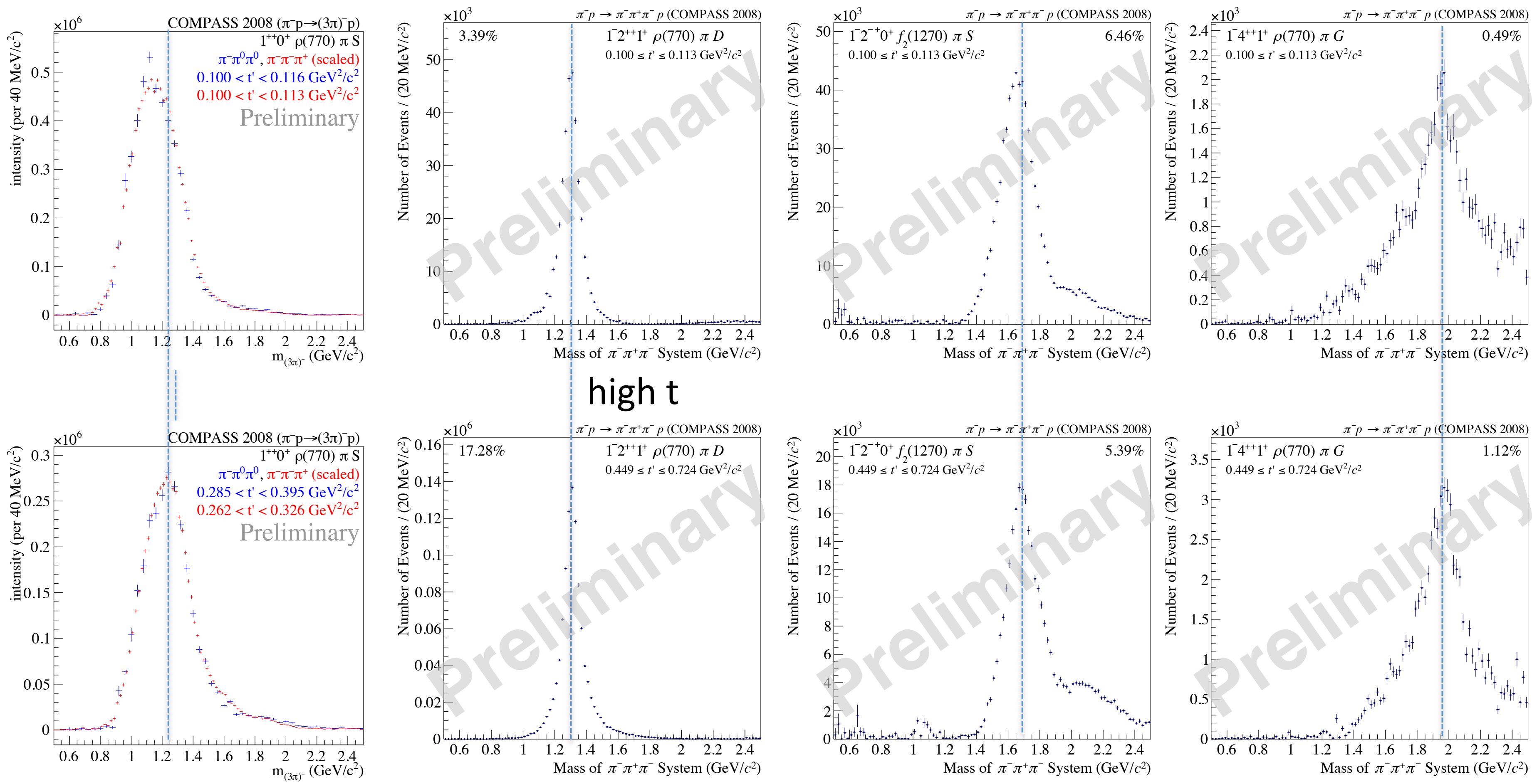
mass independent fits
minimal M = (0,1) waves

compare: $\pi^-\pi^+\pi^-$ and : $\pi^-\pi^0\pi^0$



t dependence of mass distributions

low t



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

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

$2^{-+}0^+$ f_2 π S

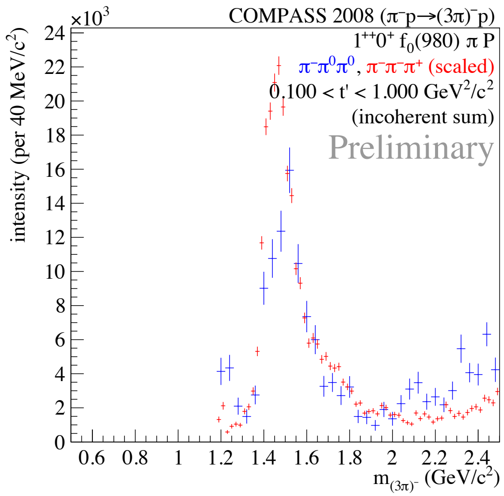
$4^{++}1^+$ $\rho\pi$ G

More exotic families

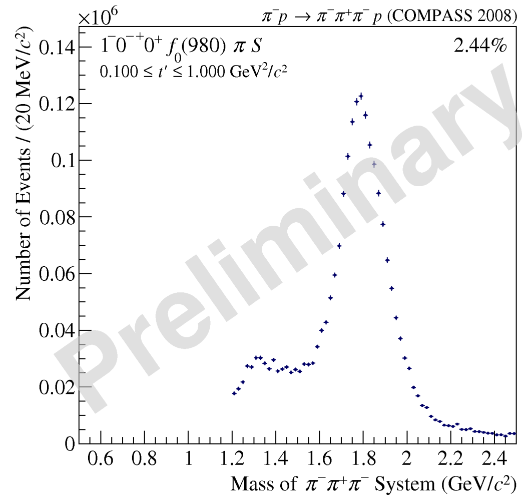
Waves involving $f_0(980)$ $[\pi\pi]_S$

$\pi^-\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$

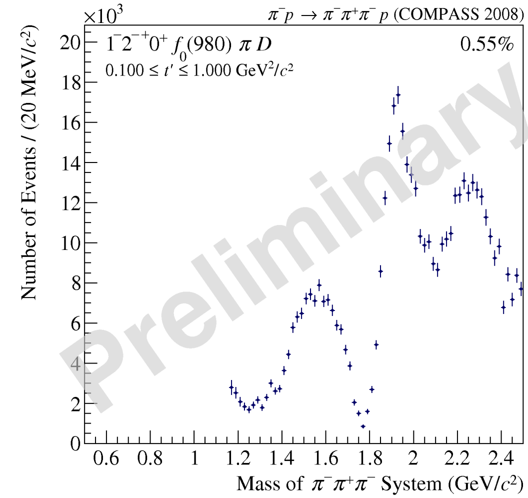
$1^{++}0^+ f_0(980)\ \pi\ P$

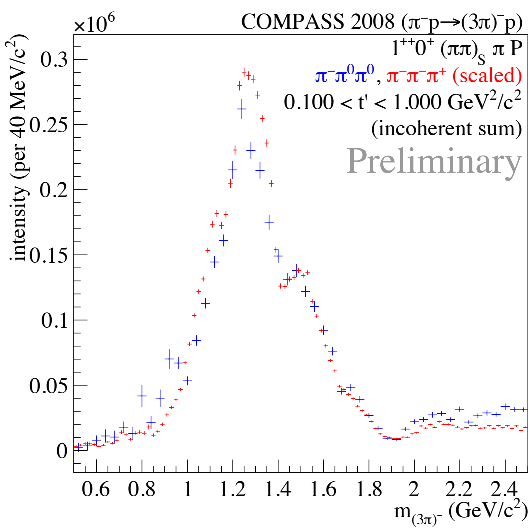


$0^{-+}0^+ f_0(980)\ \pi\ S$

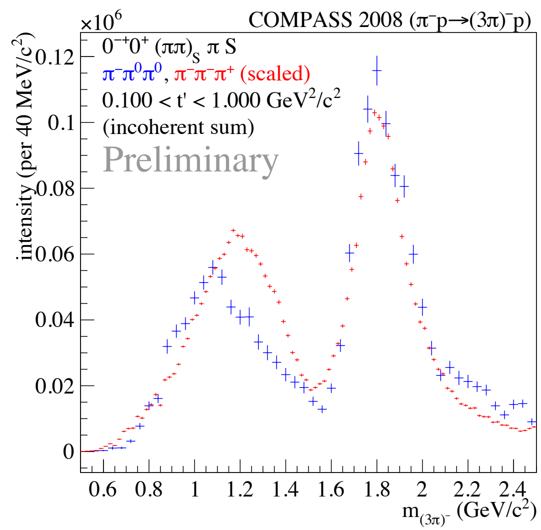


$2^{-+}0^+ f_0(980)\ \pi\ D$

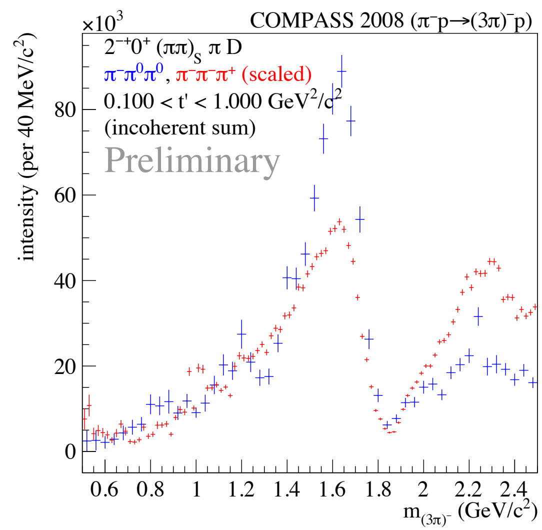




$1^{++}0^+[\pi\pi]_S\ \pi\ P$



$0^{-+}0^+[\pi\pi]_S\ \pi\ S$

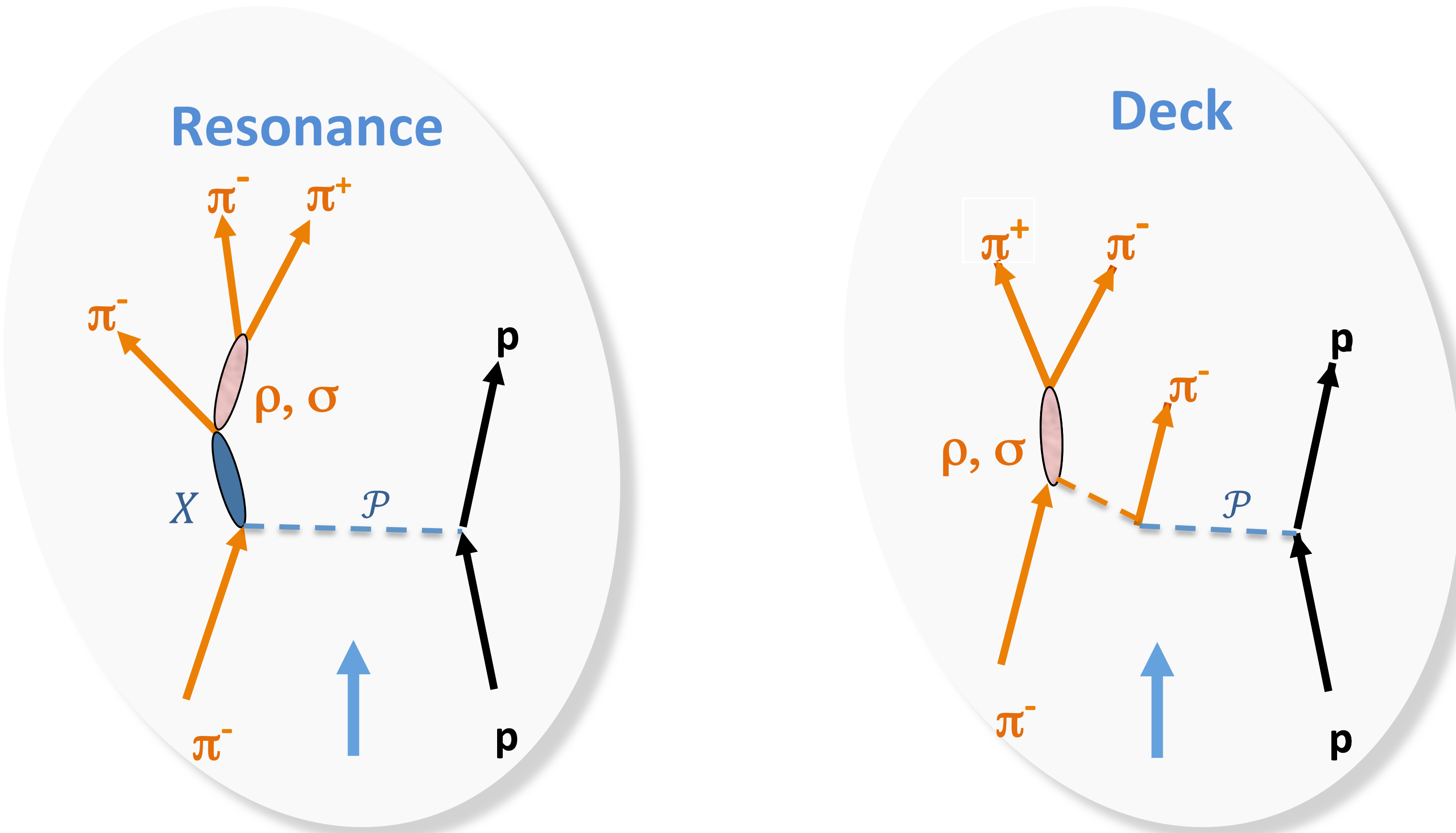


$2^{-+}0^+[\pi\pi]_S\ \pi\ D$

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)



Two types of contributions

Mass-dependent fit

Use only lowest $M = 0,1$ waves (so far)

This work: 6 waves

Model:

1^{++} $0^+ \rho\, \pi$ S	2 resonances : $a_1(1260)$ and a_1' + non resonant term
2^{++} $1^+ \rho\, \pi$ D	2 resonances : $a_2(1320)$ and a_2' + non resonant term
4^{++} $1^+ \rho\, \pi$ G	1 resonance : $a_4(2040)$ + non resonant term
2^{-+} $0^+ f_2\, \pi$ S	2 resonances : $\pi_2(1670)$ and π_2' + non resonant term
1^{++} $0^+ f_0(980)\, \pi$ P	1 resonance : $a_1(1420)$ + non resonant term
0^{-+} $0^+ f_0(980)\, \pi$ S	1 resonance : $\pi\,(1800)$ + non resonant term

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

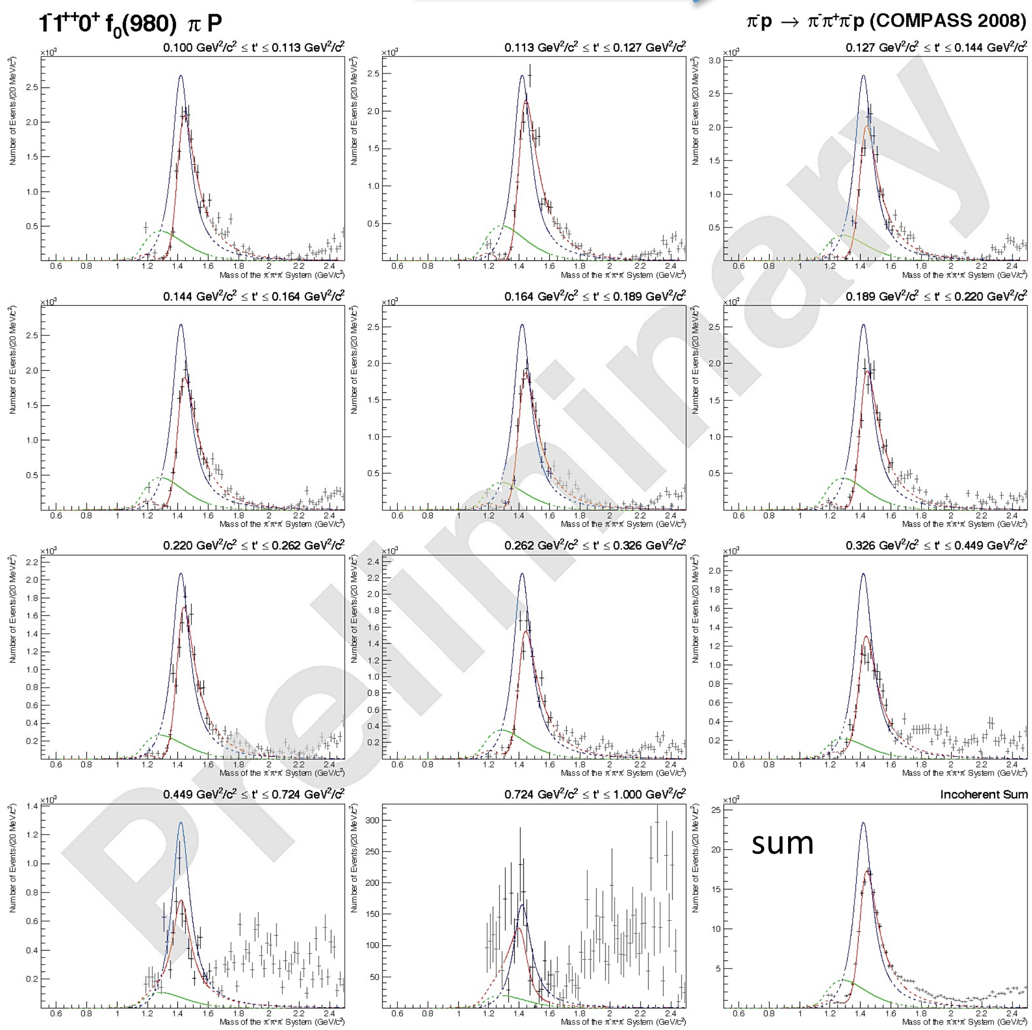
– 231 mass distributions with 23100 data points

– 352 free parameters

Mass dependent fits $a_1(1420)$

Fit in 11 t-bins

t →



t ↓

$$1^{++}0^{+} f_0(980)\pi P$$

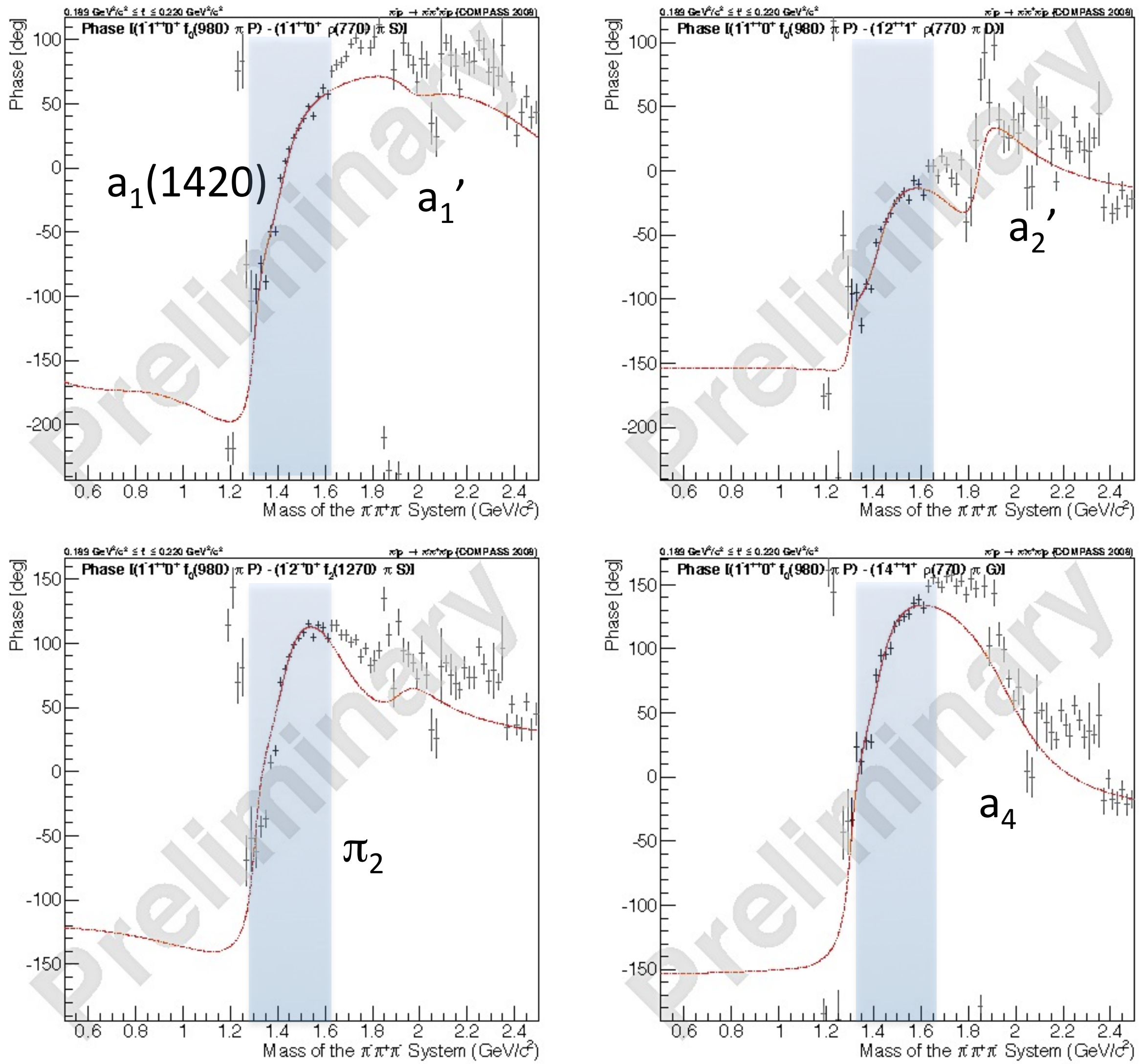
NEW

Exzellenzcluster Universe

Phase: $a_1(1420)$

Fit in 11 t-bins: medium t

fit range



NEW

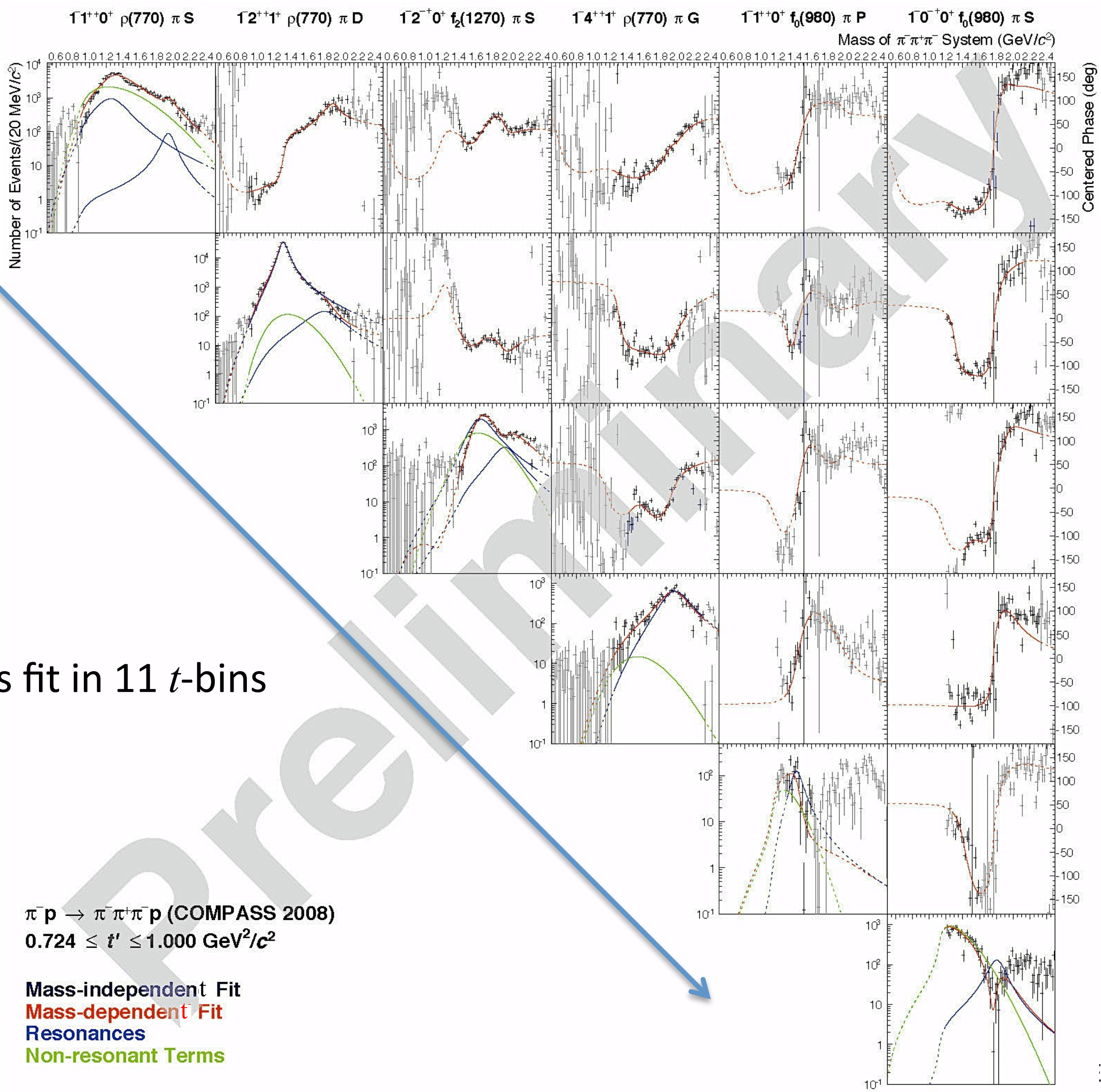
Exzellenzcluster Universe

COMPASS “Holography”

Reference waves

simultaneous fit in 11 t-bins

Interferometry

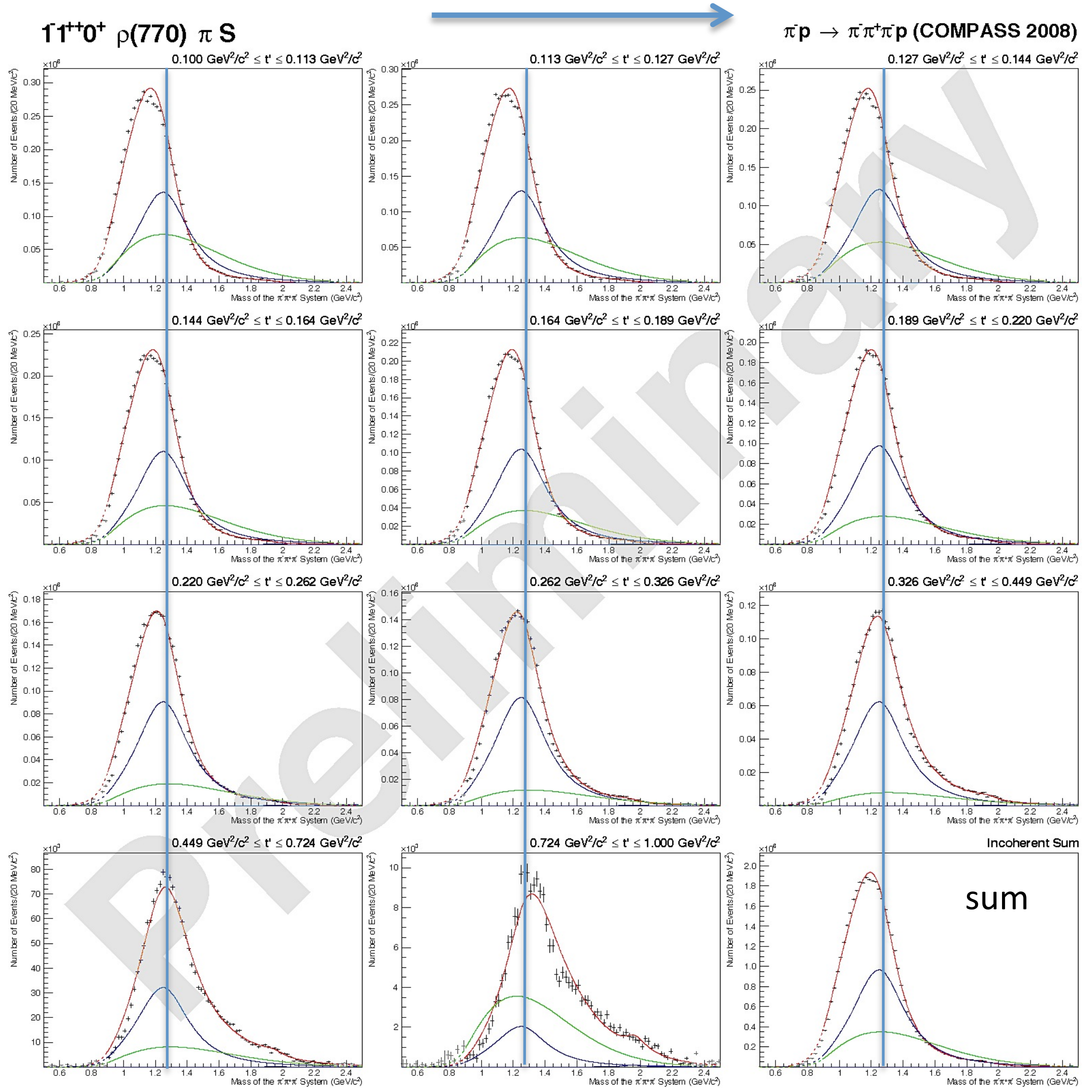


Exzellenzcluster Universe

Mass dependent fits

Fit in 11 t-bins

t



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

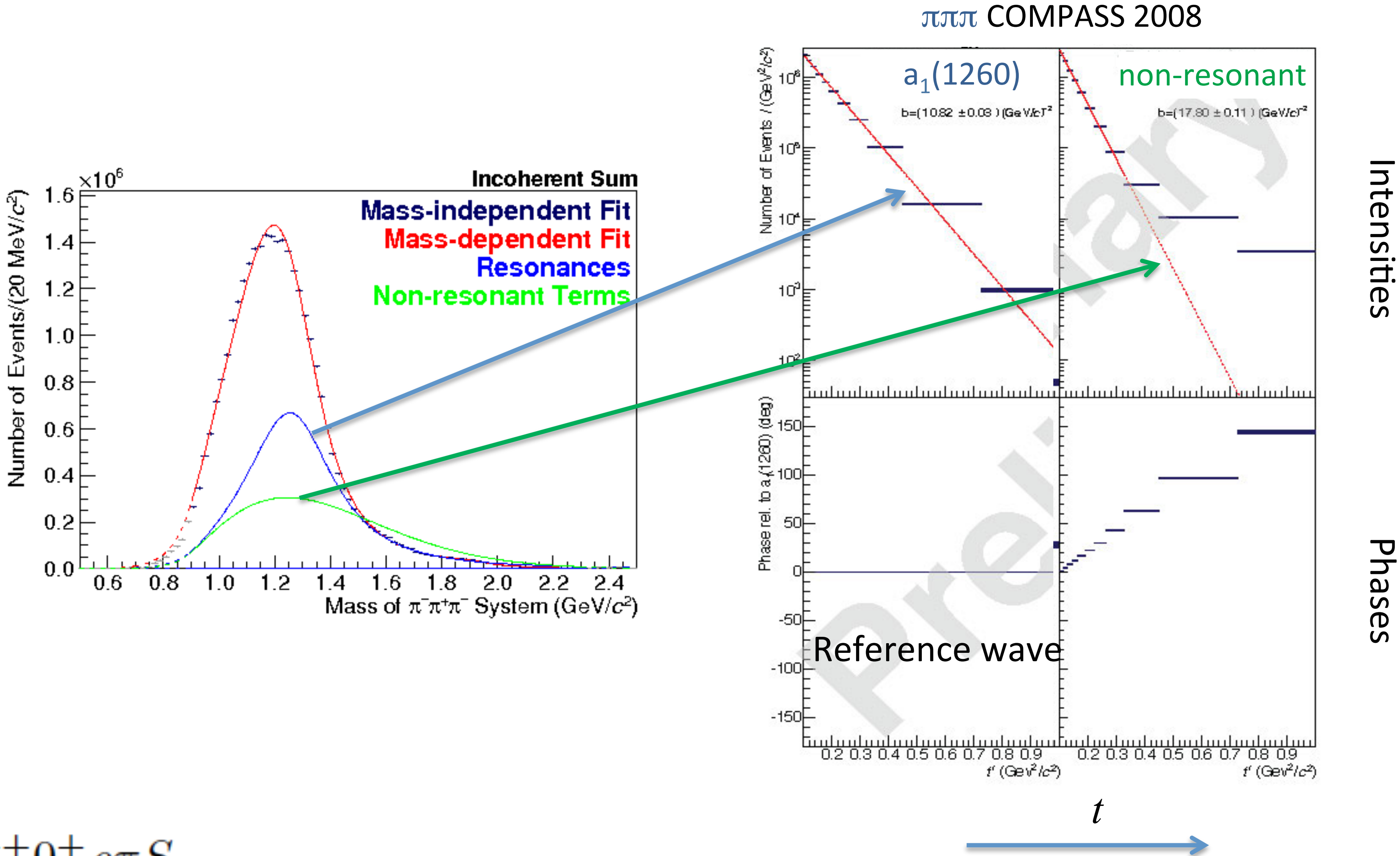
$1^{++}0^{+}\rho\pi S$

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

t

Exzellenzcluster Universe

Example for t-dependence



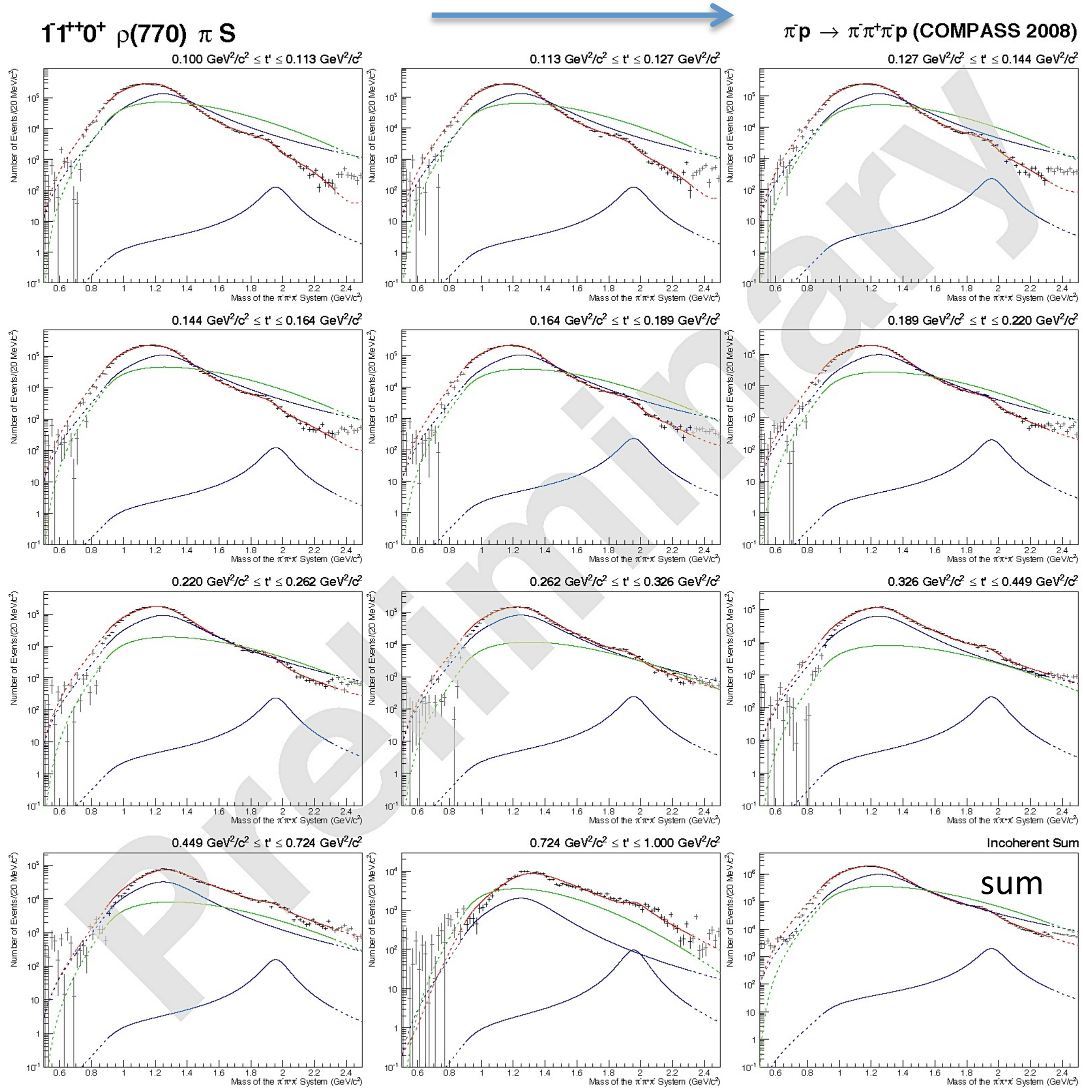
$1^{++}0^{+}\rho\pi S$

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

Mass dependent fits

Fit in 11 t-bins

t →

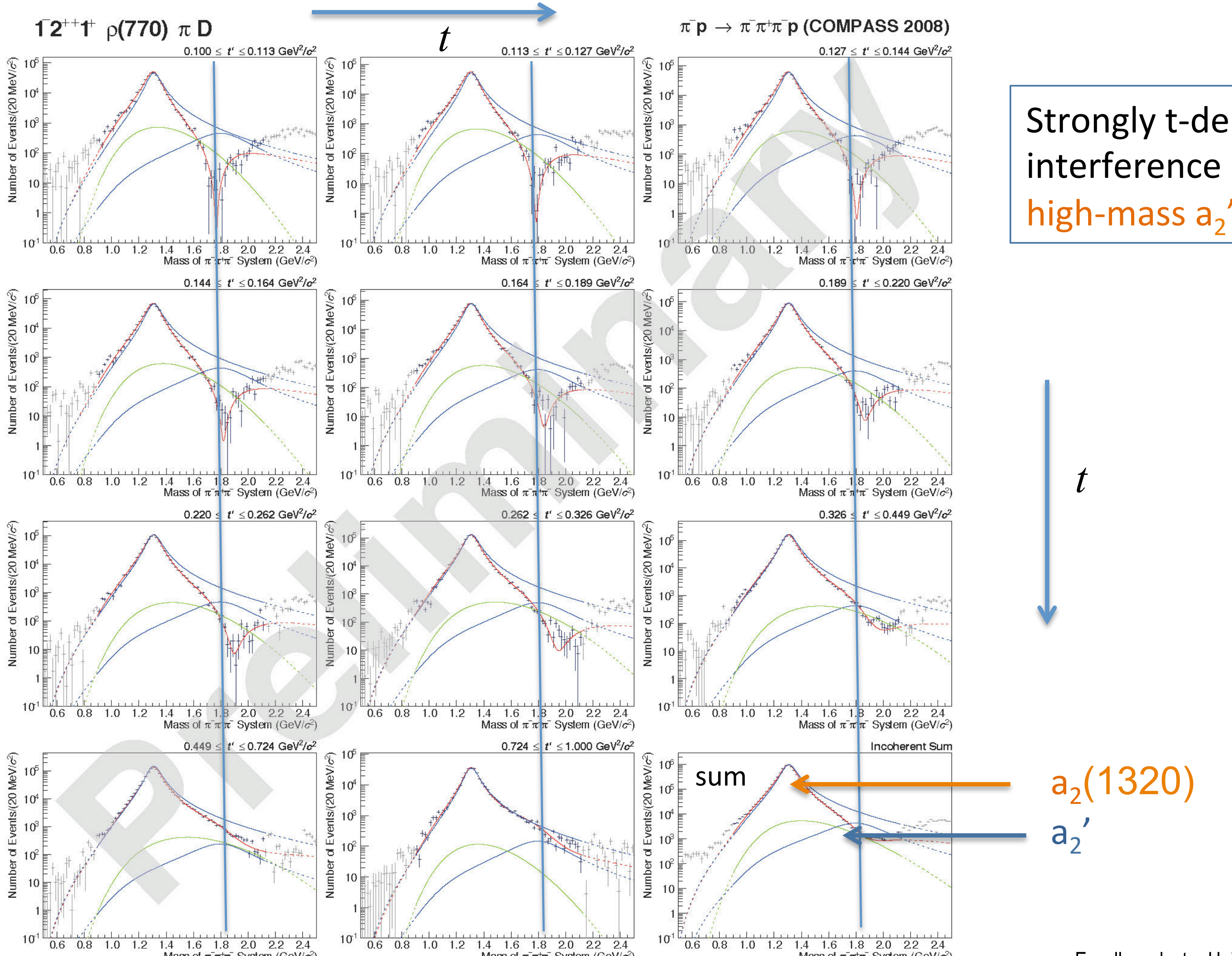


Second high-mass a_1' resonance visible

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

t ↓

Mass dependent fits $a_2(1320)$



Strongly t-dependent interference effects high-mass a_2'

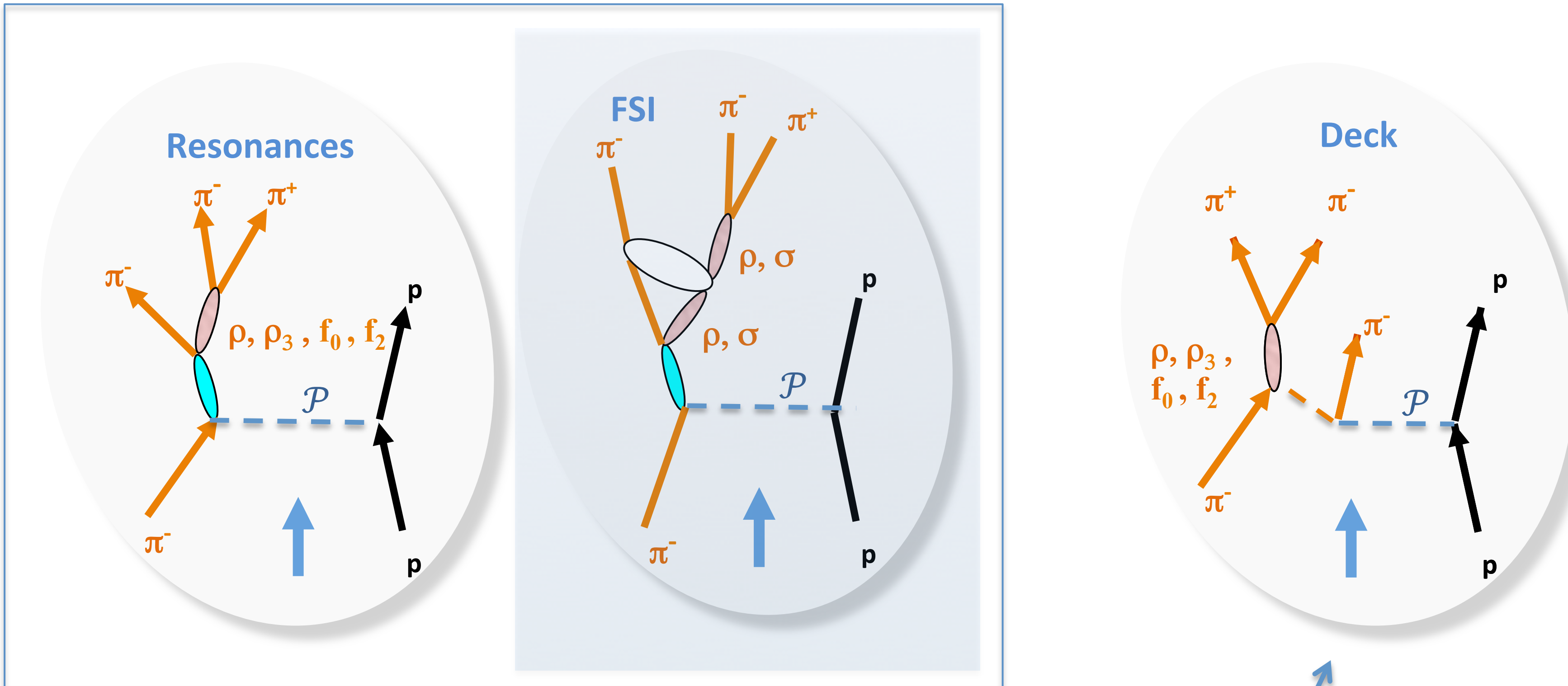
Some Results

Particle	J^{PC}	Mass Range $[\mathrm{MeV}/c^2]$	Width Range $[\mathrm{MeV}/c^2]$	PDG Values $m\ [\mathrm{MeV}/c^2]$	PDG Values $\Gamma\ [\mathrm{MeV}/c^2]$
"Established" states				PDG	
$a_1(1260)$	1^{++}	1260–1290	360–420	1230 ± 40	250–600
$a_2(1320)$	2^{++}	1312–1315	108–115	$1318.3^{+0.5}_{-0.6}$	107 ± 5
$a_4(2040)$	4^{++}	1928–1959	360–400	1996^{+10}_{-9}	255^{+28}_{-24}
States not in PDG summary table					
$a_1(1930)$	1^{++}	1920–2000	155–255	1930^{+30}_{-70}	155 ± 45
$a_2(1950)$	2^{++}	1740–1890	300–555	1950^{+30}_{-70}	180^{+30}_{-70}
truly new states					
$a_1(1420)$	1^{++}	1412–1422	130–150		

What about the building blocks

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

New Paths to Meson Decays

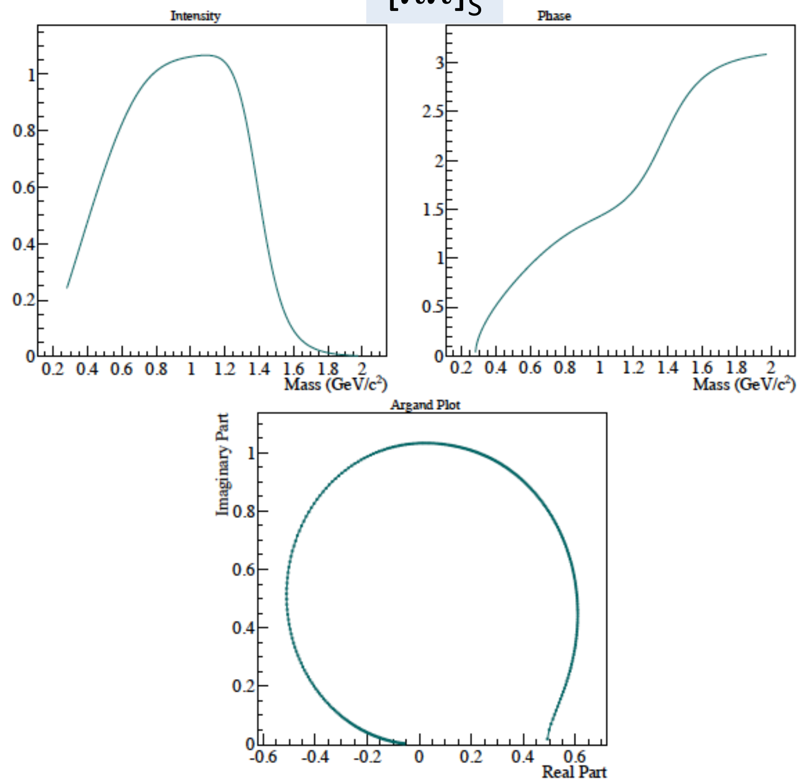


- Select J^{PC} via PWA
- For each J^{PC} and mass-bin in 3π :
  - determine composition and shapes of 2π isobars
  - complex couplings
  - non-resonant contributions (via t-dependence)

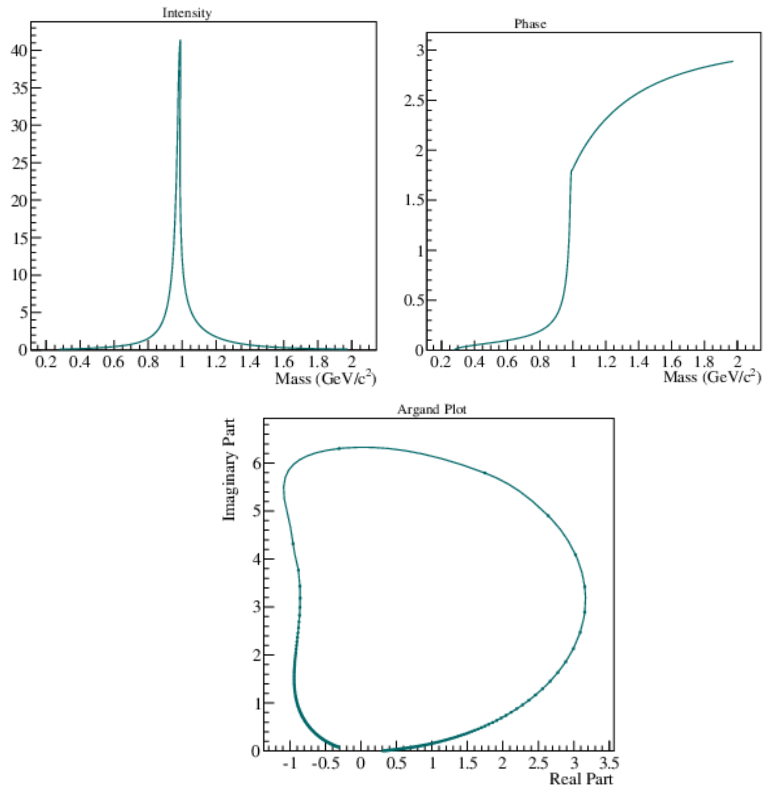
Isobars: an Example

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

$[\pi\pi]_S$



$f_0(980)$ parametrization



use BES parametrization: as it decays into $\pi\pi$ and KK (threshold effect)

$$A_{\text{Flatté}} = \frac{1}{m_0^2 - m^2 - i(\rho_1 g_1^2 + \rho_2 g_2^2)}$$

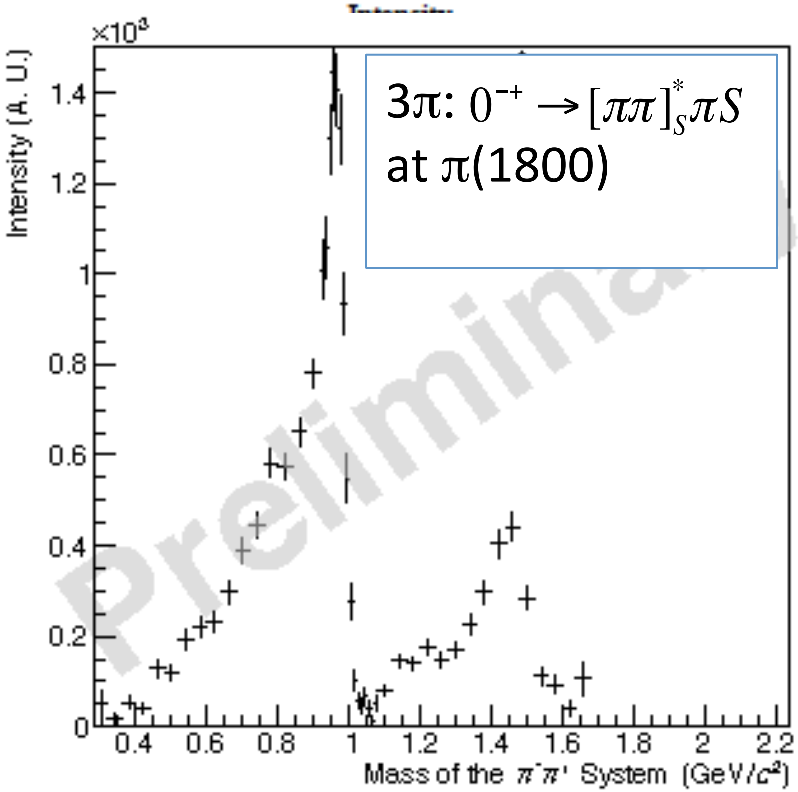
Isobars: $[\pi\pi]^*_S$

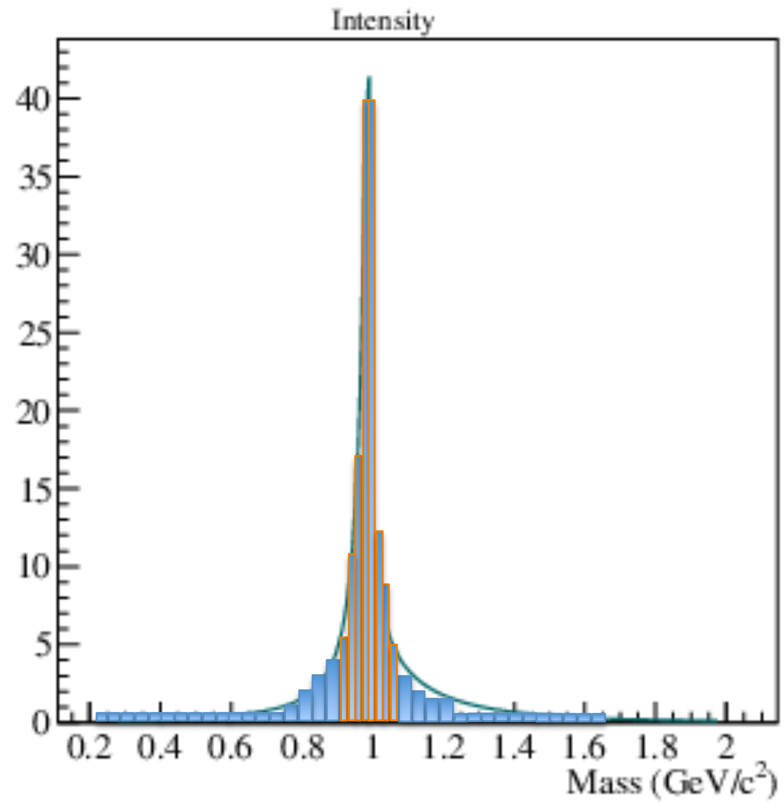
Phys. Rev. D35 1633, Au, Morgan, Pennington

continuum - $[\pi\pi]_S$

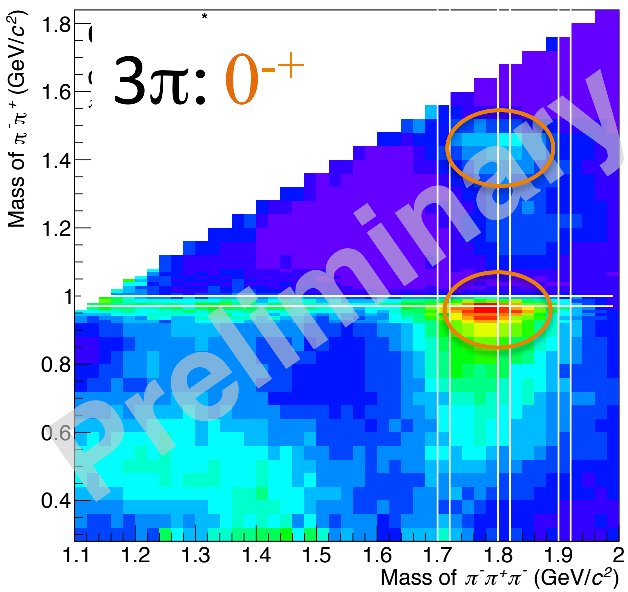
$f_0(980)$

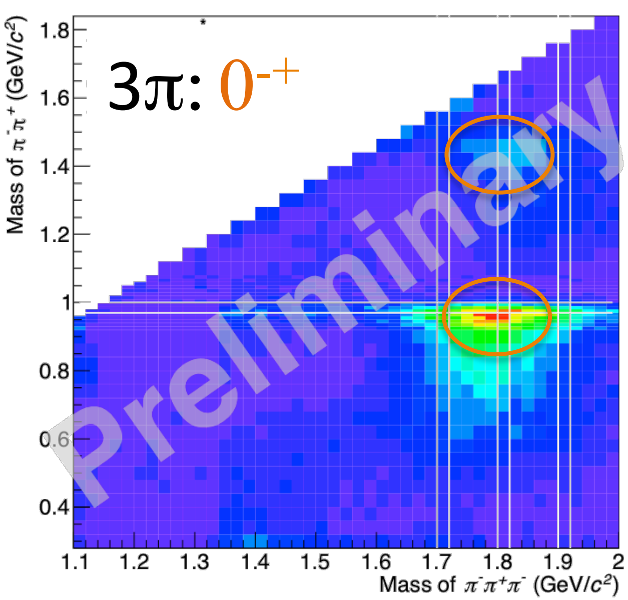
fixed functional form – variable intensity/phase (2 parameters)
replaced by ONE $[\pi\pi]^*_S$ histogram with n-bins
(2n parameters determined by fit)





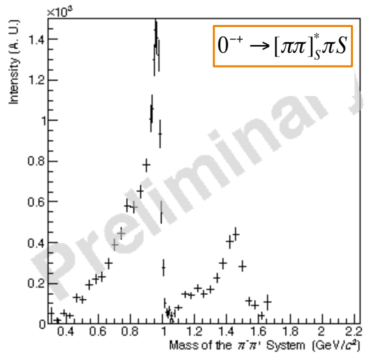
Correlation: $m_{2\pi}(0^{++})$ *vs* $m_{3\pi}(J^{PC})$



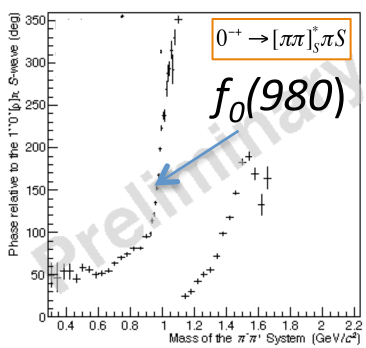


Details on $(\pi\pi)_{S\text{-wave}}$

at π(1800)



$\pi\pi_S$ Intensities



$\pi\pi_S$ phases

$$\phi_{tot} = \phi^{3\pi}_{production} + \varphi^{2\pi}_{decay}$$

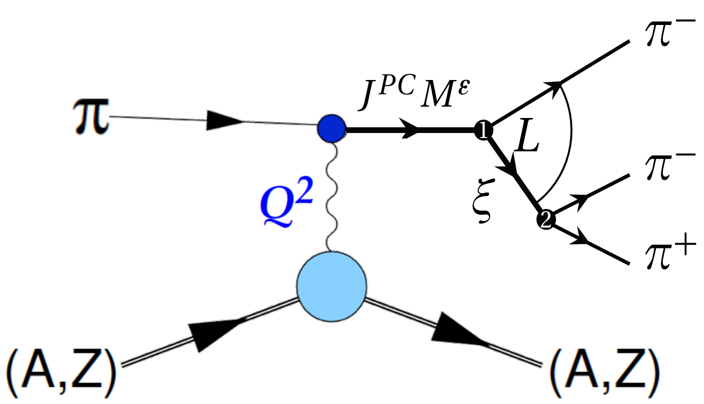
$\pi\pi_S$ Argand diagram

high t

Photo-Production

Radiative Width

- Study resonances with electromagnetic probe
  - similar to photo-production of Δ^+ off protons
  - radiative transitions of charmonia
- Use π as "target" excited by photon beam
  - π instable: inverse kinematics
  - Coulomb field of heavy nucleus acts as photon target



use Pb-target

Identify photo-production via spin alignment
$M = 1$ at low $t' < 10^{-3}\ GeV^2/c^2$

$$\sigma_{Photo} \approx e^{-b_{photo} t'}$$

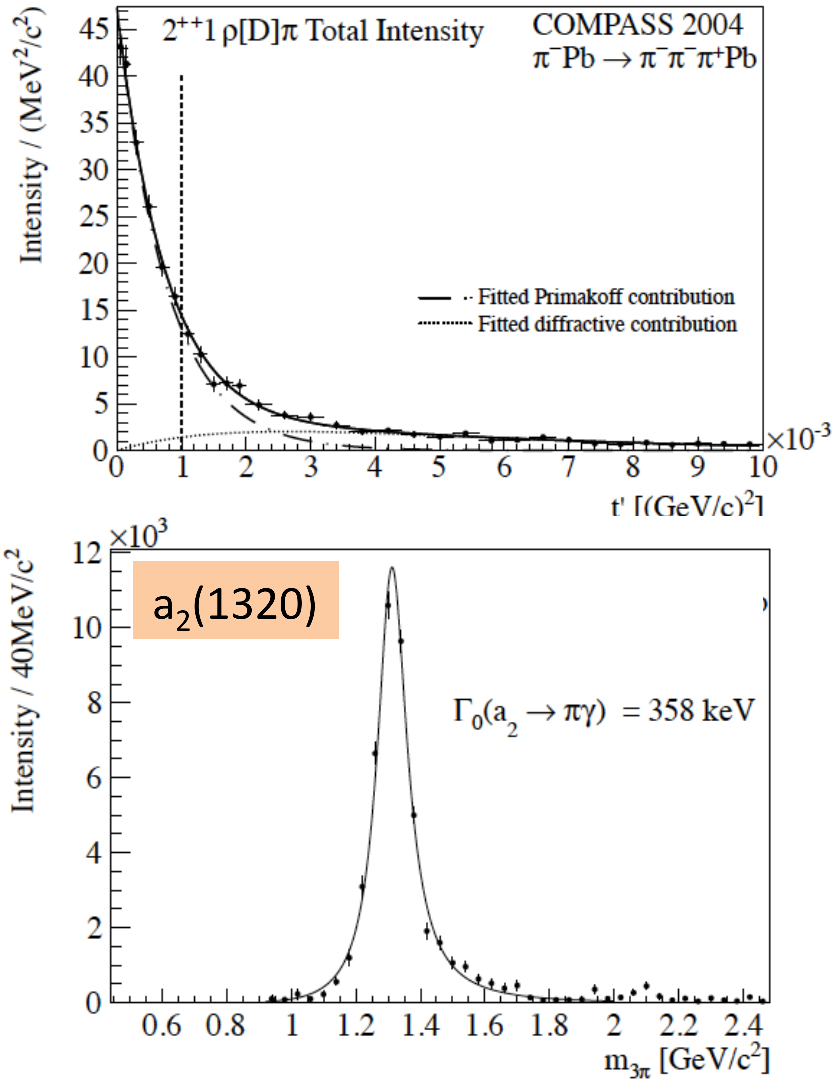
$$\sigma_{diffract} \approx t'^{M} \cdot e^{-b_{diff} t'}$$

$$b_{photo} >> b_{diffract}$$

$\rightarrow M = 1$ is suppressed in diffraction

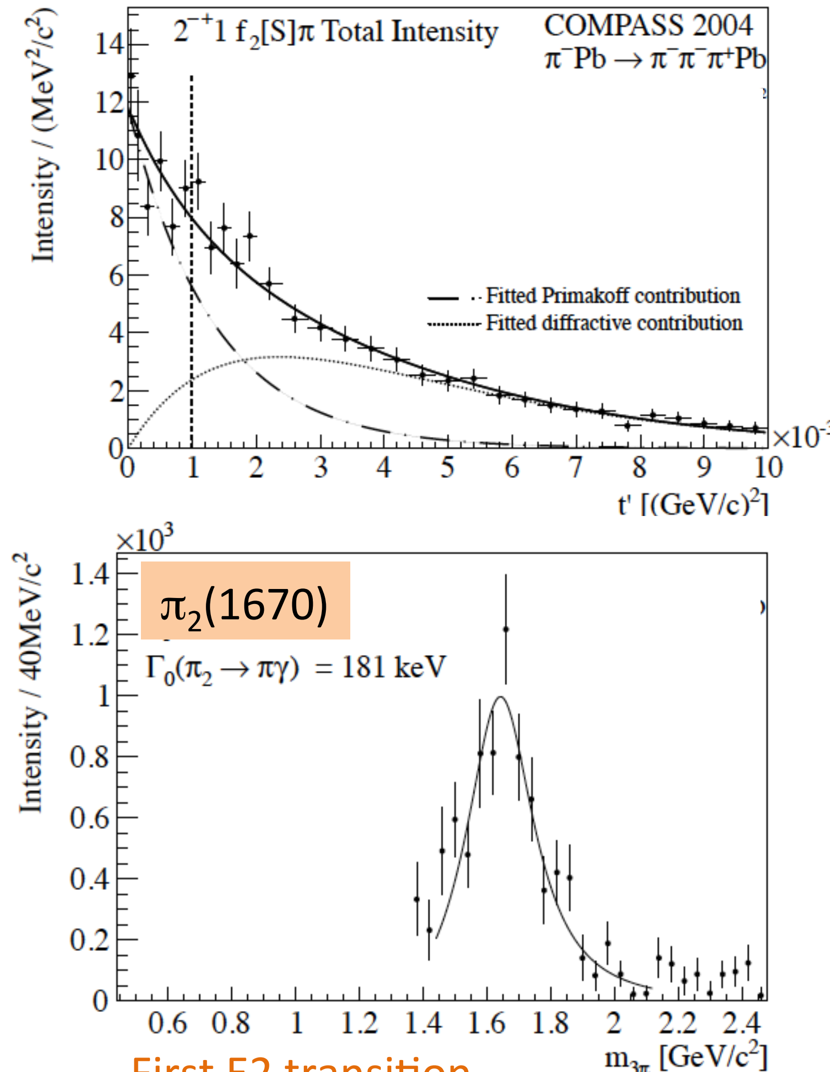
EM-Transitions for Mesons

$\Gamma_0(a_2(1320) \to \pi\gamma)$



M2 transition

$\Gamma(\pi_2 \to \pi\gamma)$



First E2 transition
observed for mesons

Conclusion

- Establish 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
  - decay into $f_0(980)\pi$ in relative P-wave
  - coupling seems exclusively $f_0(980)\pi$
  - Nature of $a_1(1420)$?

    Isospin partner of $f_1(1420)$ (considered to be exotic) ?

    Dynamically generated through $a_1(1260) \leftrightarrow KK^* \leftrightarrow f_0\,(980)\pi$ channel ?

Conclusion II

- Developed new method to establish shape of isobar-spectrum
  - first application: $[\pi\pi]_S^*$:
    - Shows strong dependence on $m_{3\pi}$ and on J^{PC} of mother wave
  - Reveals information on scalar isobars (measure phases in decays)

Open Path to Dalitz-plot analysis using PWA
from PWA identified states

Needs high statistics !!

Conclusion III

- Study of $a_1(1260)$
  - Observe "various components" of $a_1(1260)$ with different t-dependencies:
- Sort out higher excitations of a_1 , a_2

- Radial excitation of π
  - $\pi(1800)$ well known: COMPASS observes decay into $f_0(980)\pi$ and $f_0(1500)$
- Orbital excitation of π
  - $\pi_2(1670)$ well known: COMPASS observes decay into $f_2(1270)\ \pi$

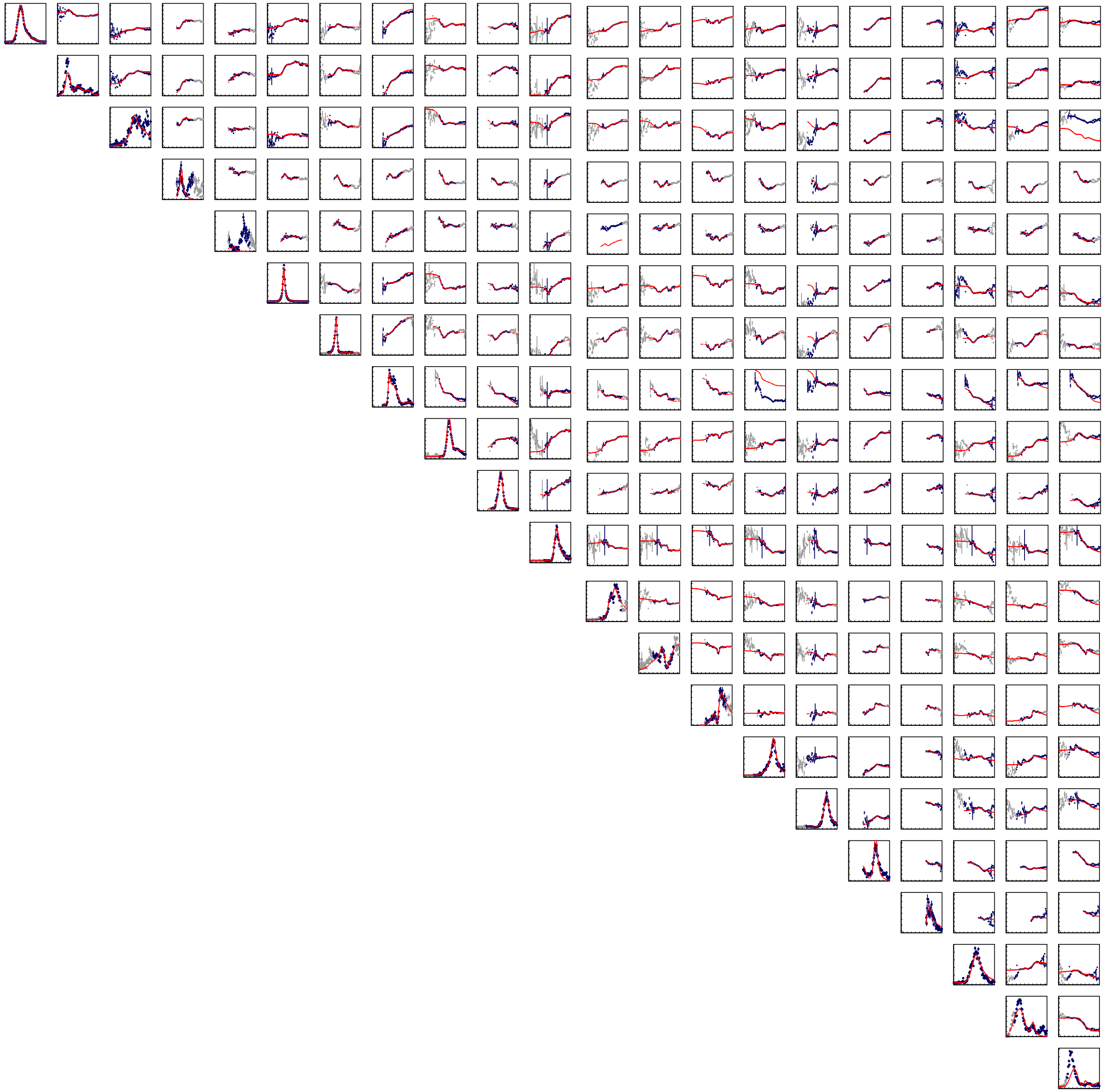
    no evidence so far for strong coupling into $[\pi\pi]_S^*\pi$
  - $\pi_2(1880)$: Clear signal observed in $f_2\pi$ and $f_0\pi$

- Radiative decays:
  - First observation of a mesonic E2 transition : $\pi_2(1670) \rightarrow \pi\ \gamma$
  - Good / reasonable agreement with calculations

Prospects

- Mass dependent fits to 25-20 waves simultaneously (or more)
  - Obtain reliable values for mass, width, branching ratios
  - Identify nature of light meson spectrum and resolve ambiguities
- Extend de-isobarred analysis to $(\pi\pi)_{L=0,1,2}$
- Simultaneous physics description of $M_{2\pi}, M_{3\pi}, \phi_{2\pi}, t$
- Joint fits for: $\pi^-\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$ (possibly also include VES data)
- Other final states 5π, πηη, KK(nπ)..

Sneak Preview – Large Fits



Preview to
21 wave-fit
in 2 bins of t'

Details and more.. on COMPASS

hadron-beam

HK 8.4 Baryon Spectroscopy at COMPASS

HK 38.4 Spectroscopy of final states with neutral particles in COMPASS

HK 38.5 Study of the $\pi^+\pi^-$ System in $\pi^-\pi^+\pi^-$ Final States at COMPASS

HK 38.6 Resonance extraction from diffractively produced $\pi^-\pi^+\pi^-$ final states at COMPASS

HK 47.2 **Gruppenbericht:** Hadron Spectroscopy with COMPASS

HK 47.5 A Partial-Wave Analysis of Centrally Produced Two-Pseudoscalar Final States in pp-Reactions at COMPASS

HK 52.2 Measurement of the Pion Polarizability with COMPASS

μ-beam

HK 17.5 Status Report of K_s^0 Multiplicities from 2006 at COMPASS

HK 17.6 Hadron Multiplicities at COMPASS

HK 37.1 Hard exclusive meson production to constrain GPDs

HK 37.2 COMPASS results on the transverse spin asymmetry in identified dihadron production in SIDIS

HK 37.3 Results on the longitudinal double spin asymmetry A_1^p and g_1^p from the 2011 COMPASS data

HK 46.3 A Geant4 based MC simulation for the COMPASS-II experiment at CERN