Challenging Low-Energy QCD: New Insight into the Light-meson Spectrum and Low-Energy Processes with Pions

New experimental results with COMPASS at CERN

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Excellence Cluster Universe

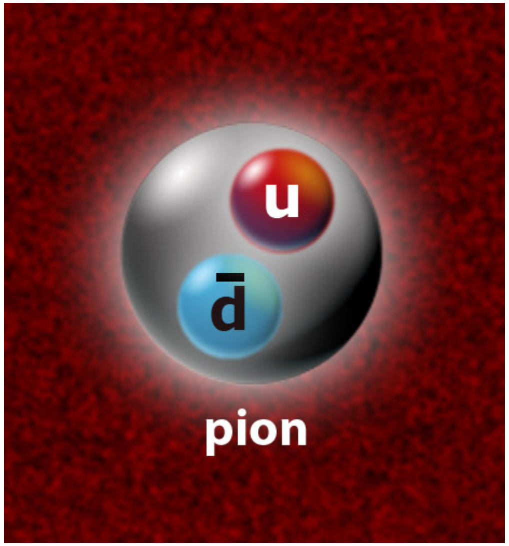
Brief Overview

- Polarizabilities
  - Analogies with atoms
  - Pion polarisability
- Radiative excitations
- Spectroscopy in strong interaction
  - Introduction
  - A new meson nobody has asked for
- New insights into production/decay dynamics
- Conclusions

Some facts about the Pion

- Pion is lightest composite system
- Properties:
  - $M_{\pi^+} = 139.57\ \mathrm{MeV/c^2}$
  - $M_{\pi^0} = 134.97\ \mathrm{MeV/c^2}$
  - Spin $S = 0$
  - *Lifetime* $\tau = 2.603 \cdot 10^{-8}$ s

    Flightpath $\Delta x = 10.6$ km (at p = 190 GeV/c)
  - $\sqrt{\langle r^2 \rangle} = 0.672 \pm 0.008\ \mathrm{fm} = (0.672 \pm 0.008) \cdot 10^{-15}\mathrm{m}$



Question: what is it's macroscopic structure ?

Properties of basic matter

Refractive index n

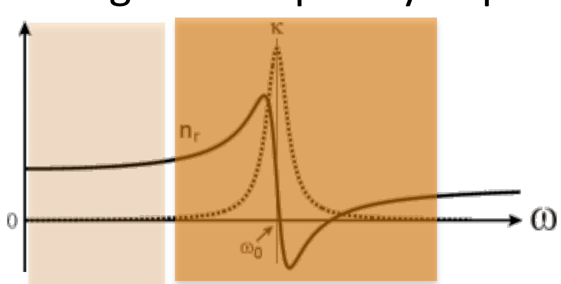
- Macroscopically: dielectric constant $\tilde{\varepsilon} = \varepsilon_1 + i\varepsilon_2 = n + i\kappa$
- Microscopically:
  - Light wave polarizes atoms ➛ induced dipole moment: $\vec{P} = \alpha \cdot \vec{E}$

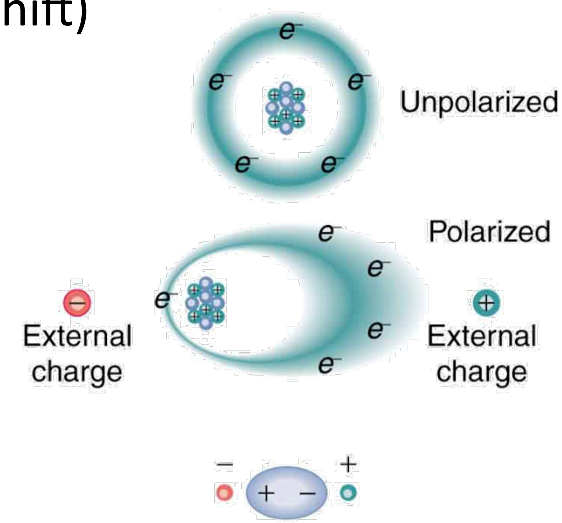
    α: electric polarisability
  - Relaxation ➛ dipole radiation (delayed – phase shift)

    superimposing incoming field ➛ $c_{matter} = \frac{c_{Vac}}{n}$

$$\alpha(\omega) = \frac{n(\omega)-1}{2\pi} \text{Å}^3 \approx \frac{9}{2} a_{Bohr}^3 \qquad \alpha_{He} = 9.3\text{Å}^3$$

  - Strength is frequency dependent (dispersion)





Exzellenzcluster Universe

How about the Pion ?

- „stable“ object with smallest „Bohr“ radius
- Polarizability
  - strong interaction $\Delta E(\pi \to \rho) \approx 600 \text{ MeV}$
  - electromagnetic $\Delta E(H_{1S} \to H_{2S}) \approx 10 \text{ eV}$
  - Difference in stiffness: $\frac{\alpha_{em}}{\alpha_{strong}} = \frac{1/137}{0.7} \approx 0.01$

Indicator for stiffness of system

$$\frac{\alpha_\pi}{<r_\pi^{em}>^3}(\pi) \approx \frac{1}{100}\frac{\alpha_{atom}}{a_{Bohr}^3}(atom)\cdot\left(q_{eff}^\pi\right)^2 << \frac{\alpha_{atom}}{a_{Bohr}^3}(atom)$$

$$<r_\pi^{em}>^2 \approx 0.45 \pm 0.01 fm^2$$

- Theory: $\chi PT: \quad \alpha_\pi = 2.85 \pm 0.5 \cdot 10^{-4} fm^3$
  $Others: \quad \alpha_\pi = 4 - 10 \cdot 10^{-4} fm^3$

How to measure α ?

- Atomic physics: deflection of an atom in a laser field

$$\vec{F} = \alpha \cdot \vec{E} \cdot \nabla E$$

  - Need strong fields and strong gradients (laser cavity)

$$E = 10^6 V / cm \qquad \nabla E = 10^{11} \mathrm{V/cm}^2$$

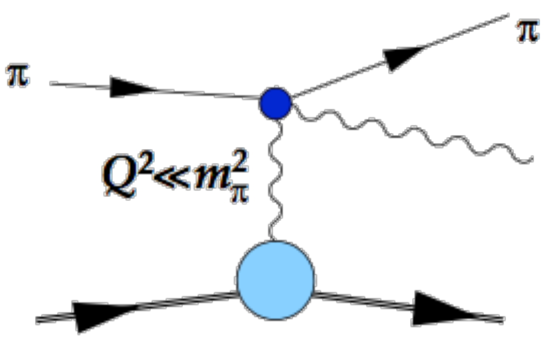
- Particle physics: scatter high energy π from photon source
  - Photon source: high Z nucleus
  - High gradients: relativistic amplification

$$E = 10^5 V / fm$$

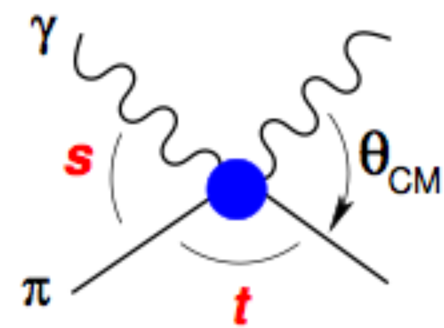
  - Charged particle is deflected in field (Born term)

COMPASS Measurement

- Use Compton scattering
  - π instable: inverse kinematics
  - μ as point like reference



190 GeV/c beam particles



$$z_\pm = 1 \pm \cos\theta_{cm}$$

$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \underbrace{\frac{\alpha^2(s^2 z_+^2 + m_\pi^4 z_-^2)}{s(sz_+ + m_\pi^2 z_-)^2}}_{\text{Compton}} - \underbrace{\frac{\alpha\, m_\pi^3\,(s - m_\pi^2)^2}{4s^2(sz_+ + m_\pi^2 z_-)} \cdot \mathcal{P}}_{\text{Extended object}}$$

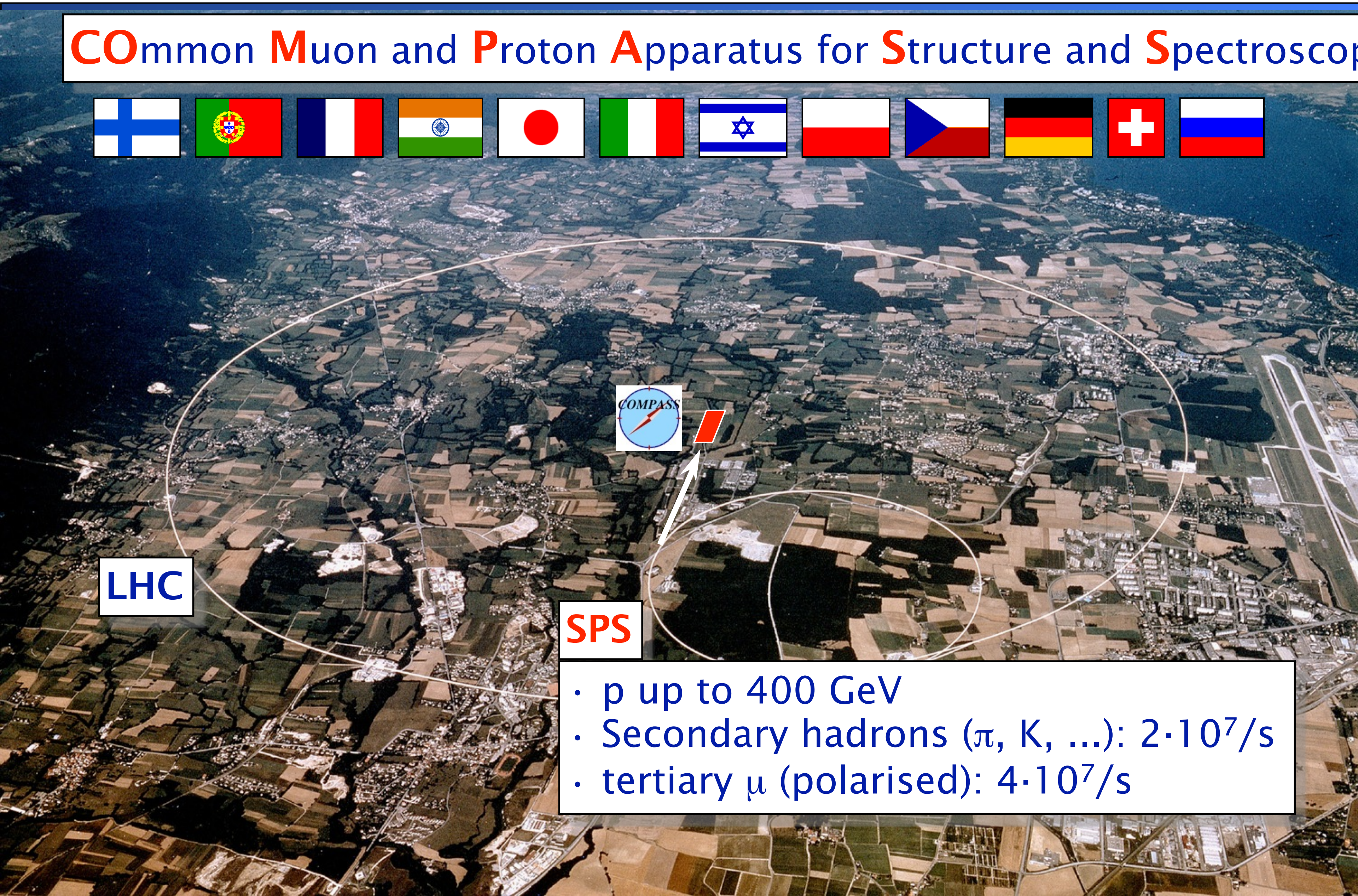
$$\mathcal{P} = z_-^2\,(\alpha_\pi - \beta_\pi) + \; ....$$

elasticity:

$$s = p_\gamma^2 + p_\pi^2 < (2m_\pi)^2$$

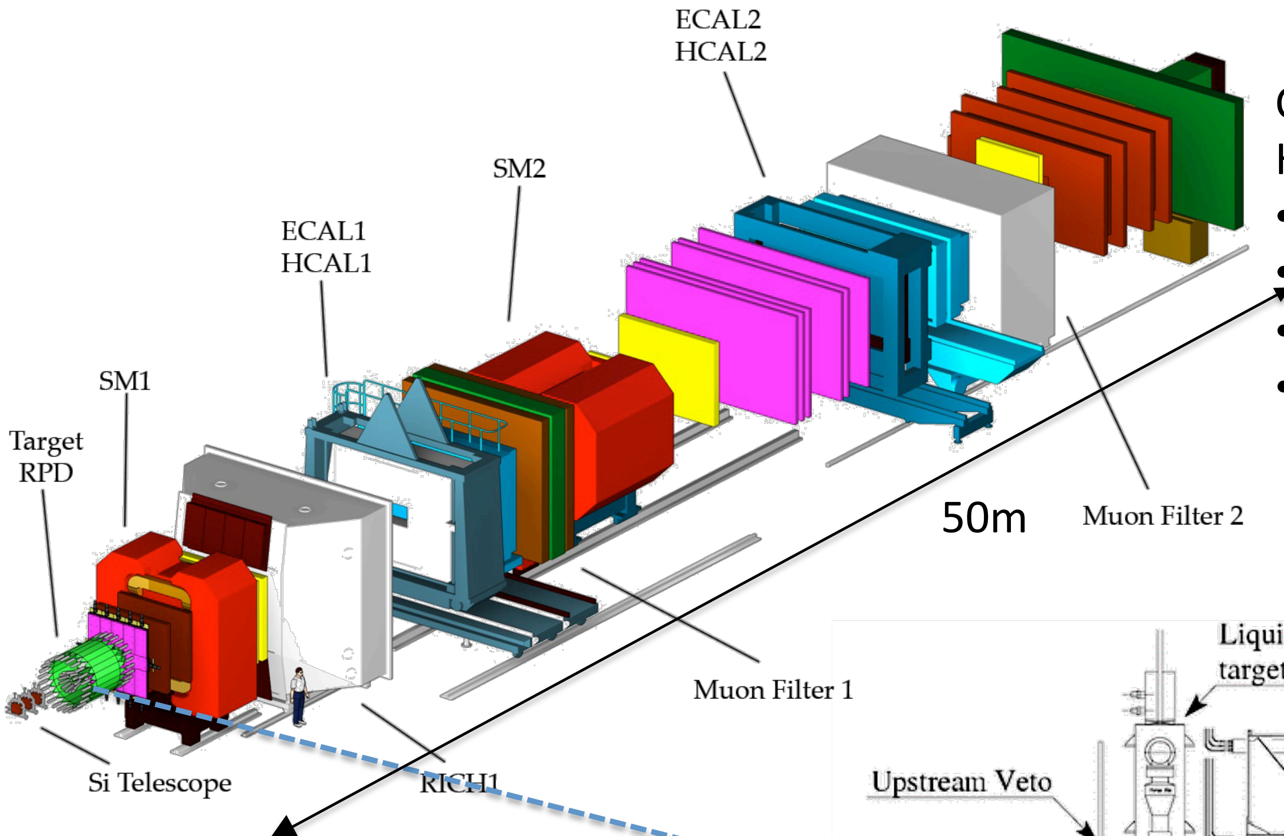
COMPASS am CERN

COmmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscop



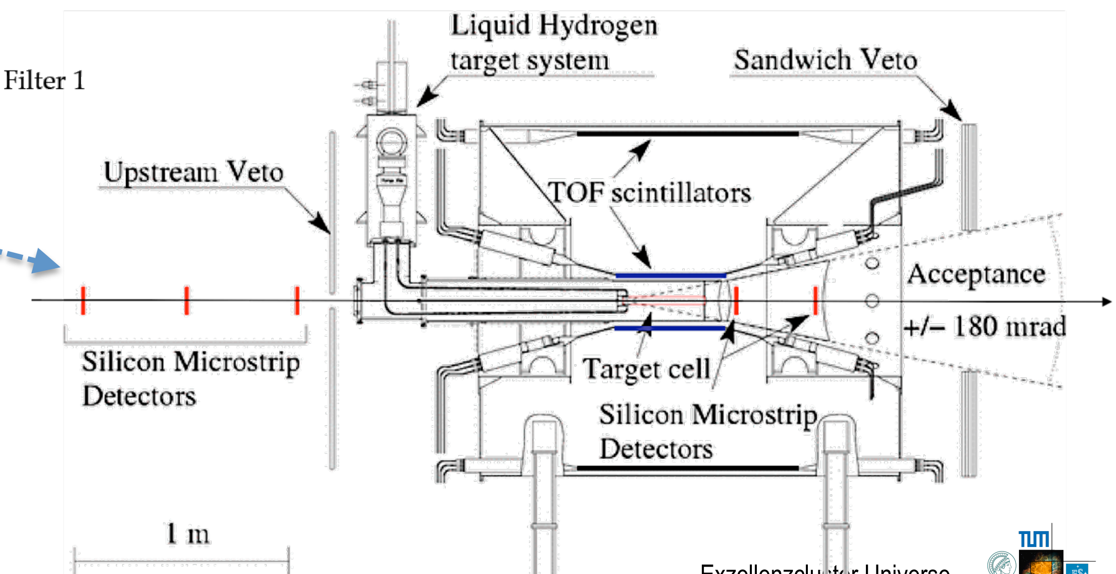
- p up to 400 GeV
- Secondary hadrons (π, K, ...): $2 \cdot 10^7$/s
- tertiary μ (polarised): $4 \cdot 10^7$/s

The COMPASS Experiment

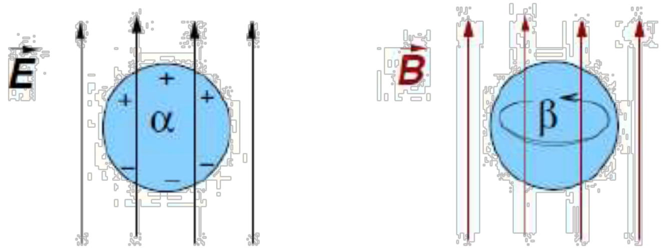


CERN SPS
Hadron beam:

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



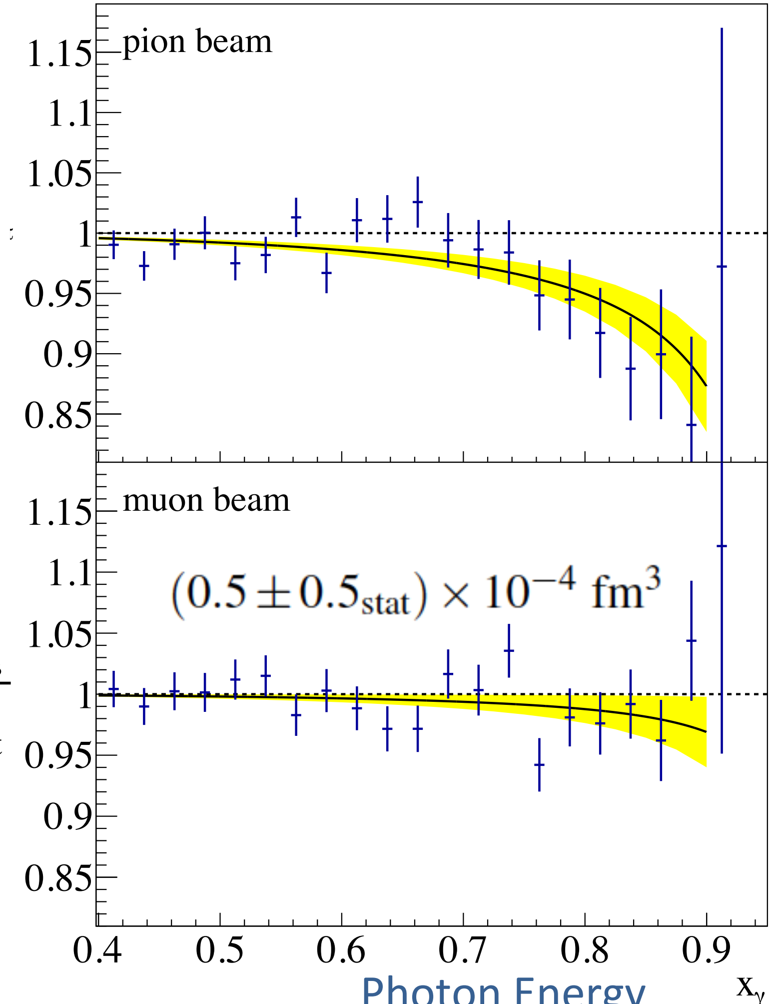
COMPASS Measurement

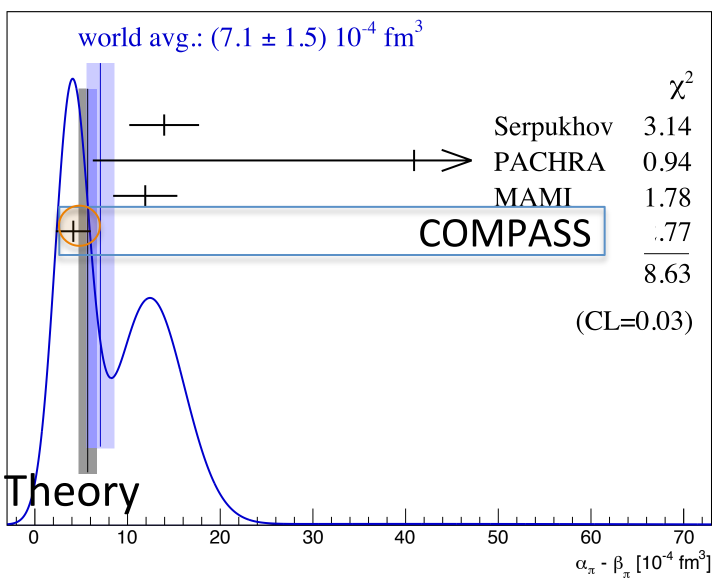


$$\alpha_\pi = (2.0 \pm 0.6_{stat} \pm 0.7_{syst}) \times 10^{-4}\,\mathrm{fm}^3$$

$$R_\pi = \frac{\sigma_{meas}}{\sigma_{point}}$$

$$R_\mu = \frac{\sigma_{meas}}{\sigma_{point}}$$





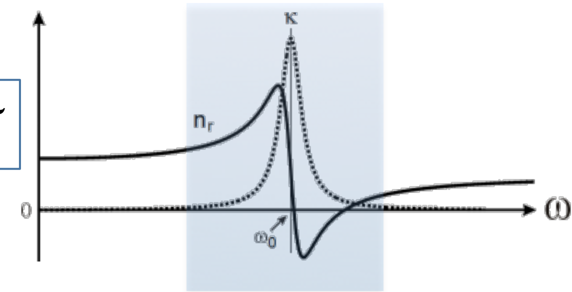
π polarizability: χPT confirmed

Long standing puzzle solved !

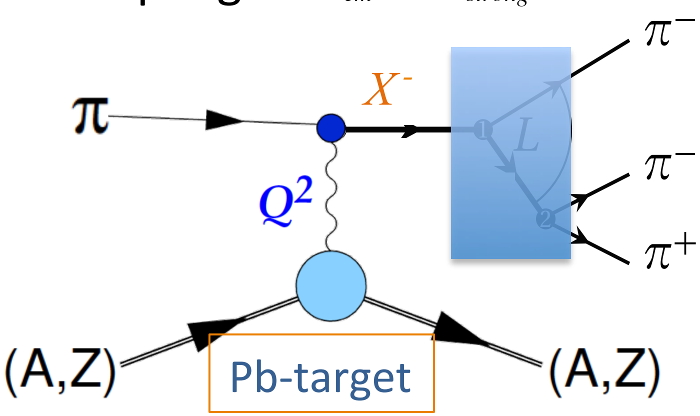
Resonant Excitation

- So far: excitations far below resonance region (elastic scattering)
- Higher energies: photon-scattering inelastic
  - Atoms: electronic excitations
  - Hadrons: resonance production

$$\delta\varphi_{out-in} = \pi$$



- Various multipole excitations possible
  - Determine angular distribution in de-excitation process
- For Primakoff reactions: wide range of photon energies
  - Analysis of final state determines reaction type and excitation energy
  - Coupling $\alpha_{em} << \alpha_{strong} \rightarrow$ resonance will decay via strong interaction (PWA)



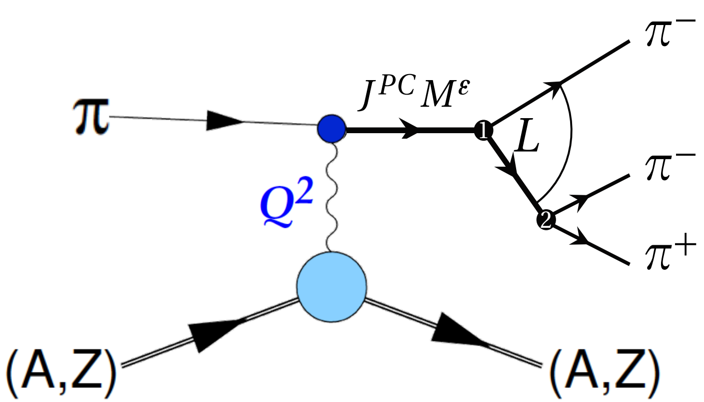
$$A(\pi\gamma) << A(\pi\pi\pi)$$

Radiative Width

- Study resonances with electromagnetic probe
  - similar to photo-production of Δ^+ off protons
  - radiative transitions of charmonia
- Competition by strong interaction (with same final state)
  - Photon: $S = 1$ and $H = \pm 1$

    Helicity conservation ➛ Spin alignment of resonance X^-
  - Diffraction: need angular momentum for Spin alignment

    Suppressed in forward production



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

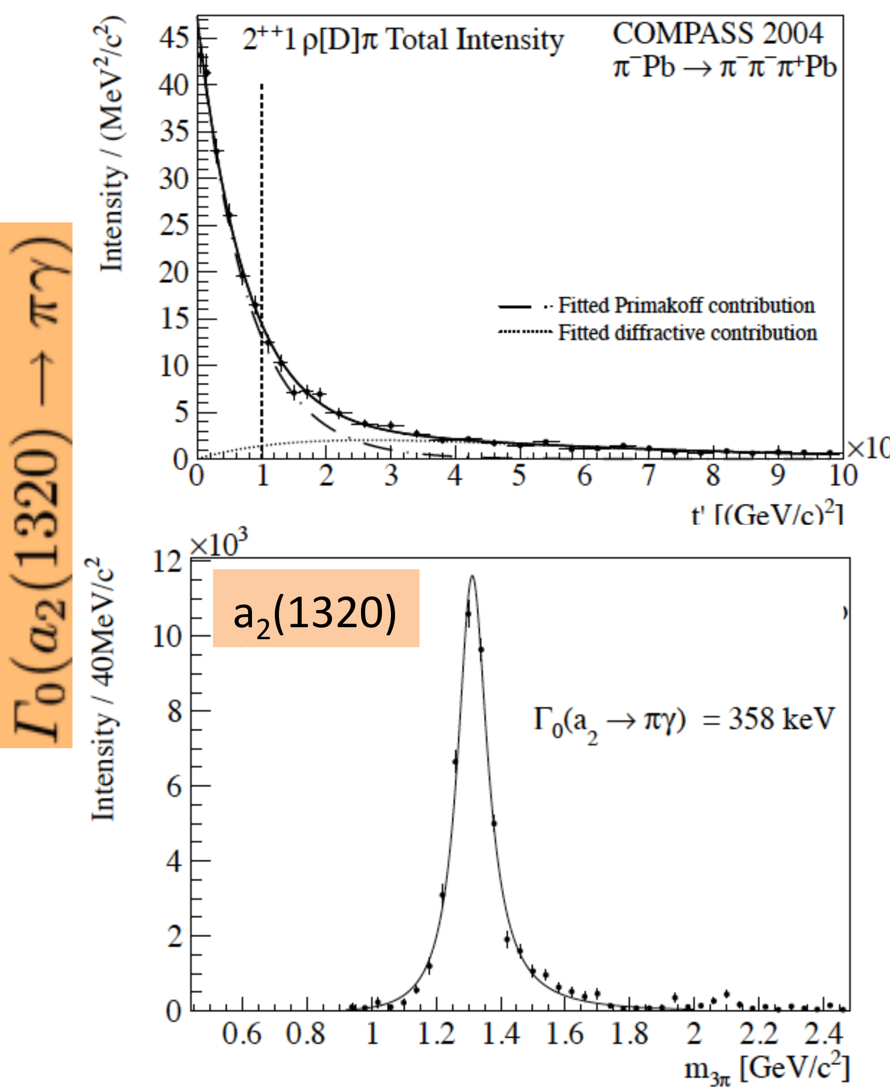
$$\sigma_{Photo} \approx e^{-b_{photo} t'}$$

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

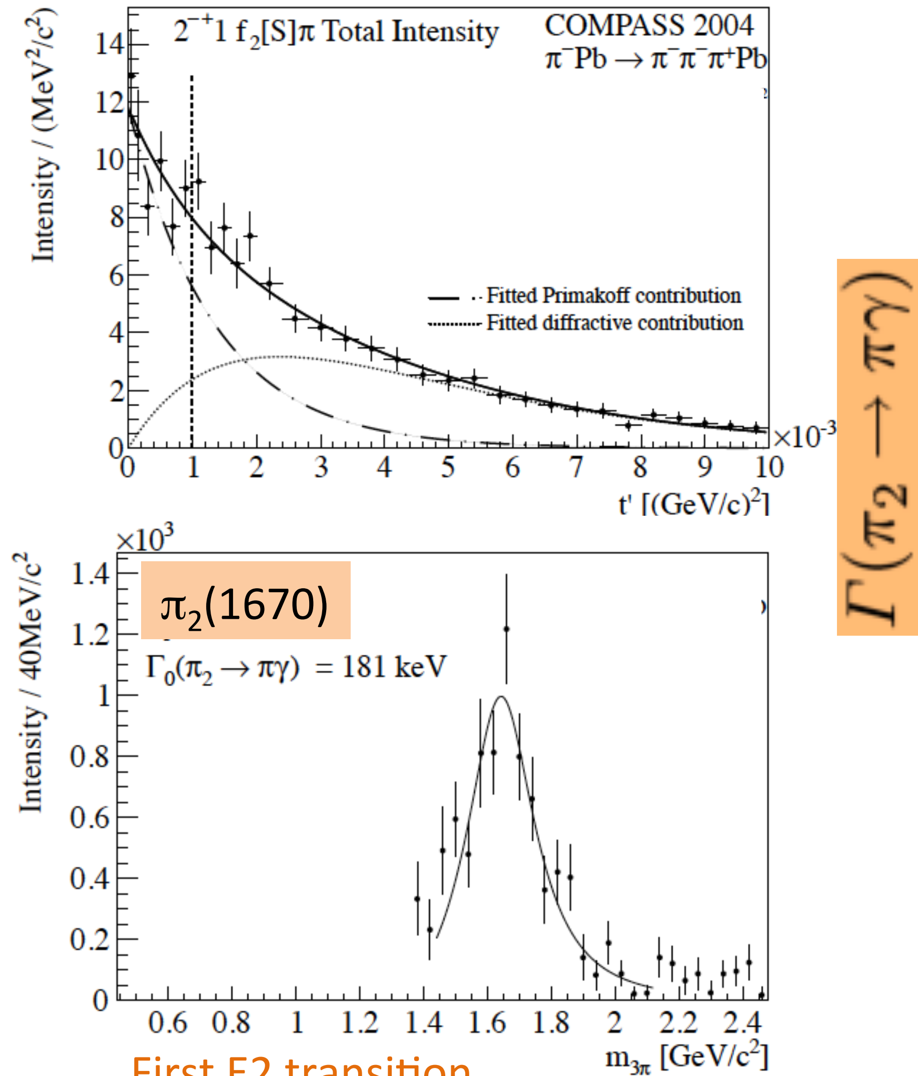
$$b_{photo} >> b_{diffract}$$

$\rightarrow M = 1$ is suppressed in diffraction

EM-Transitions for Mesons



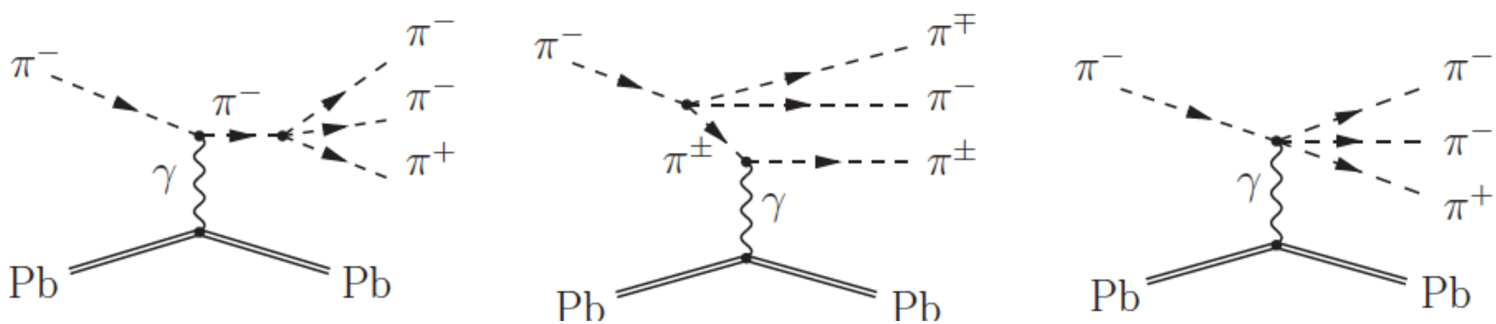
M2 transition



First E2 transition
observed for mesons

Testing Dynamics

- Consider non-resonant inelastic $\gamma\pi^- \rightarrow \pi^+\pi^-\pi^-$ scattering ($t' < 10^{-3}$ $(GeV/c)^2$)
  - Low masses: no resonances, just pion scattering
  - → tree diagrams from ChPT predictions

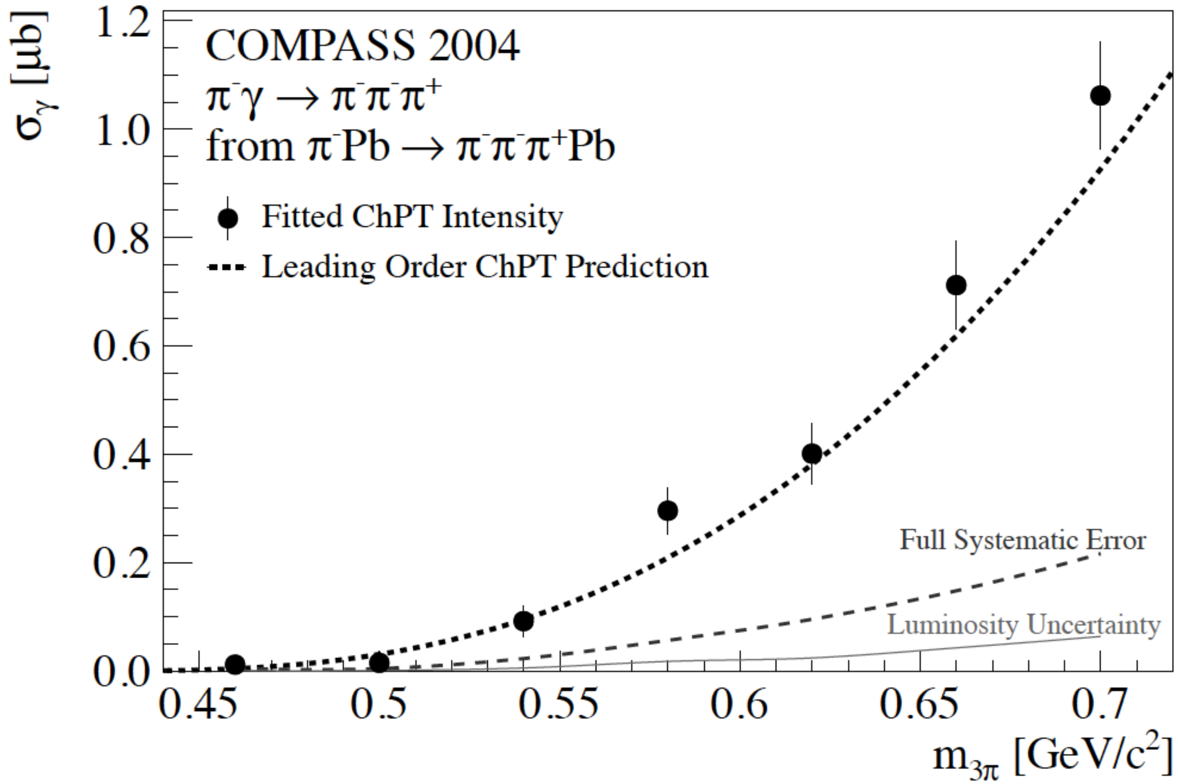


- Fit ChPT Amplitude (as single partial wave) to 5-dimensional phase space

  Describe all waves with $m = 1$ for low masses
  - ChPT valid (at least) $0.5\ GeV/c^2 < m_{3\pi} < 0.7\ GeV/c^2$
  - Higher masses: Isobaric decays

Testing Dynamics

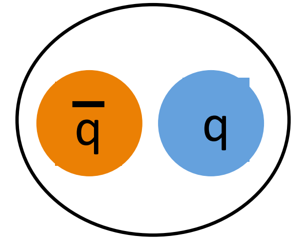
- Results



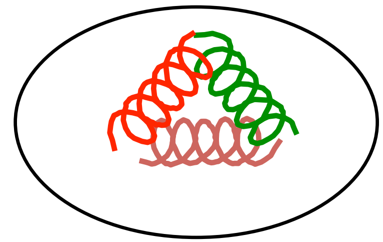
- Next Step: Measure effect of loops in $\gamma\pi^- \rightarrow \pi^0\pi^0\pi^-$

Light Mesons, Quarks and Gluons

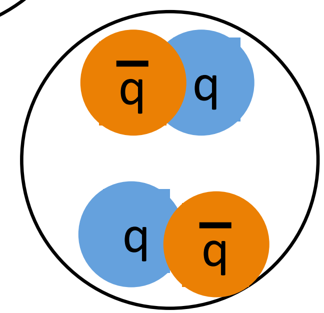
- Quark model mesons (u, d, s quarks)



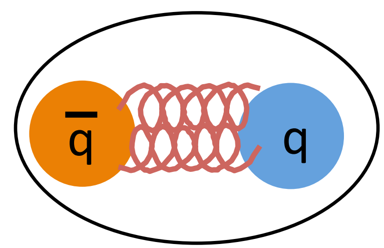
- Glueballs (gluons and no valence quarks)



- Multiquarks (quark-antiquark pairs)

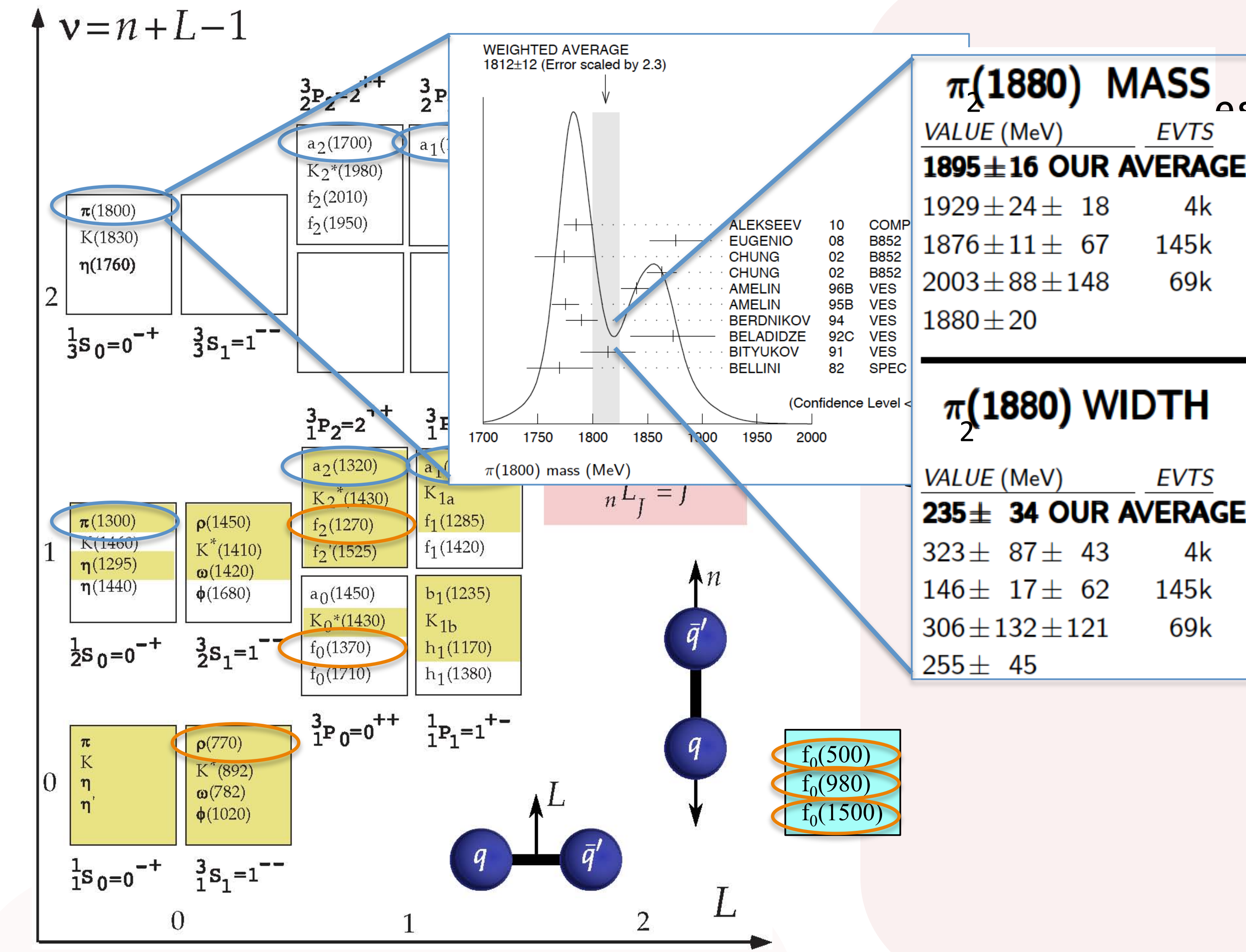


- Hybrids (quarks and gluonic excitation, which contribute to static properties)



Klempt Zaitsev Phys Rep 454 (2007) 1

Constituent Quarks and Mesons



$\pi_2(1880)$ 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	

...esons
...puted
...ion
...eavy
...ing

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

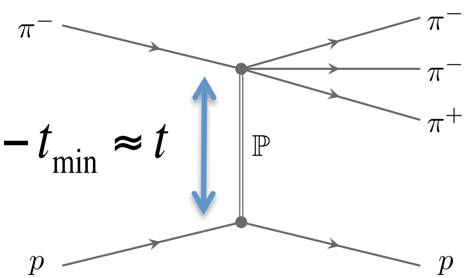
More Surprising States?

taken from
Mike pendlebury

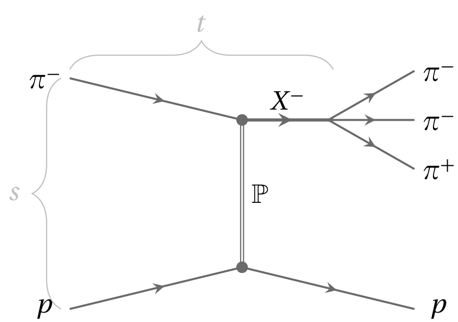
The Diffraction Process

generic process

$$t' = t - t_{\text{min}} \approx t$$

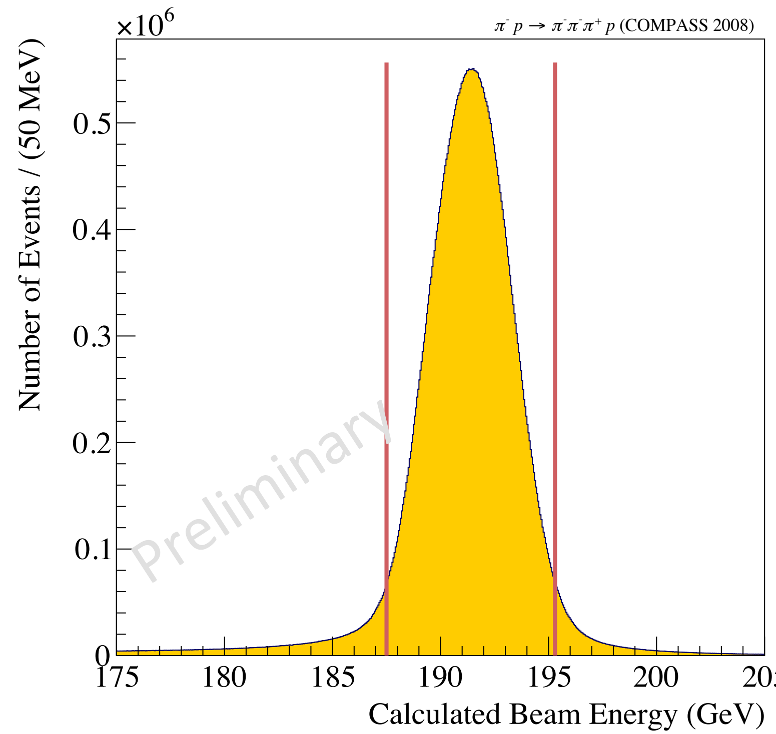


what we are after



$5 \cdot 10^7$ evts

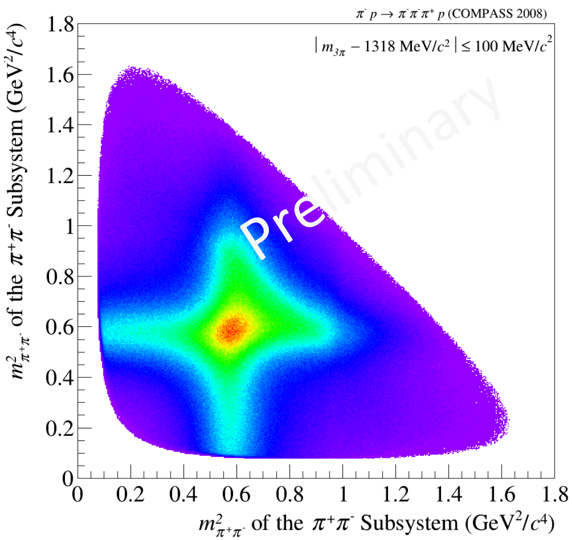
exclusive reaction



Motivation for Isobar Model

$m^2_{2\pi}$

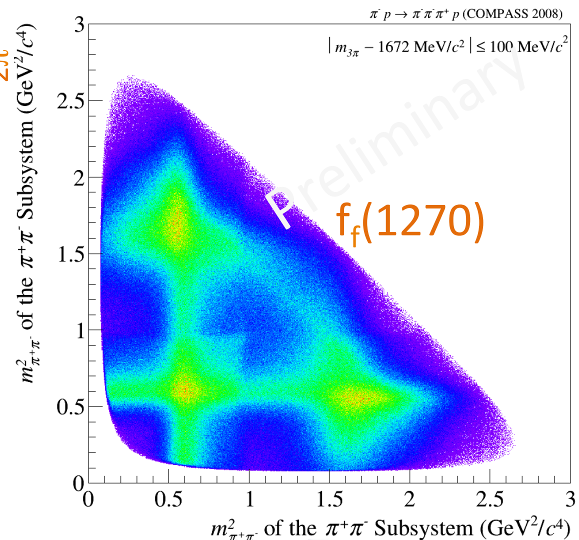
ρ



$m^2_{2\pi}$

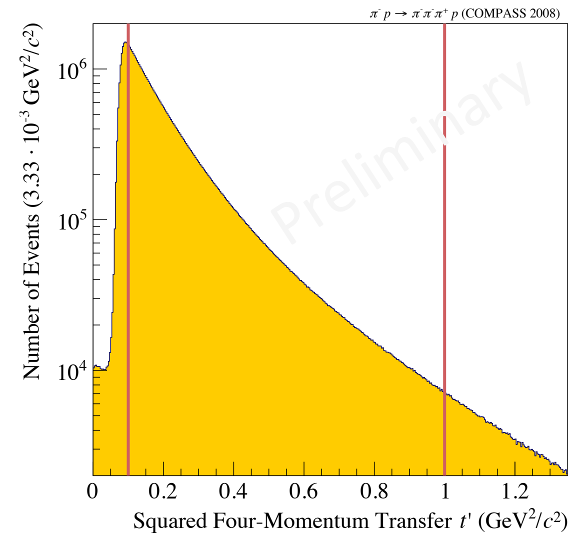
$m^2_{2\pi}$

ρ



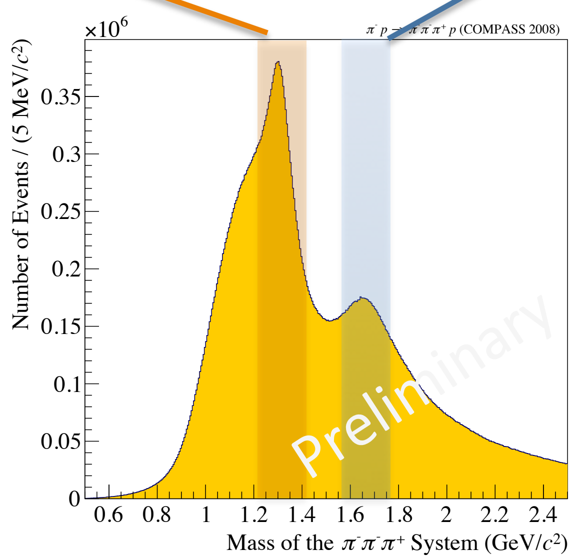
$f_f(1270)$

$m^2_{2\pi}$

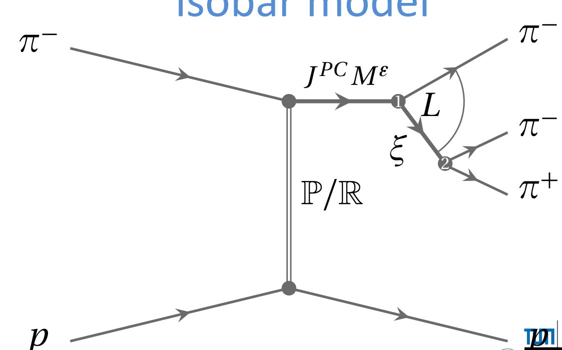


used in analysis

$t'_{3\pi}$



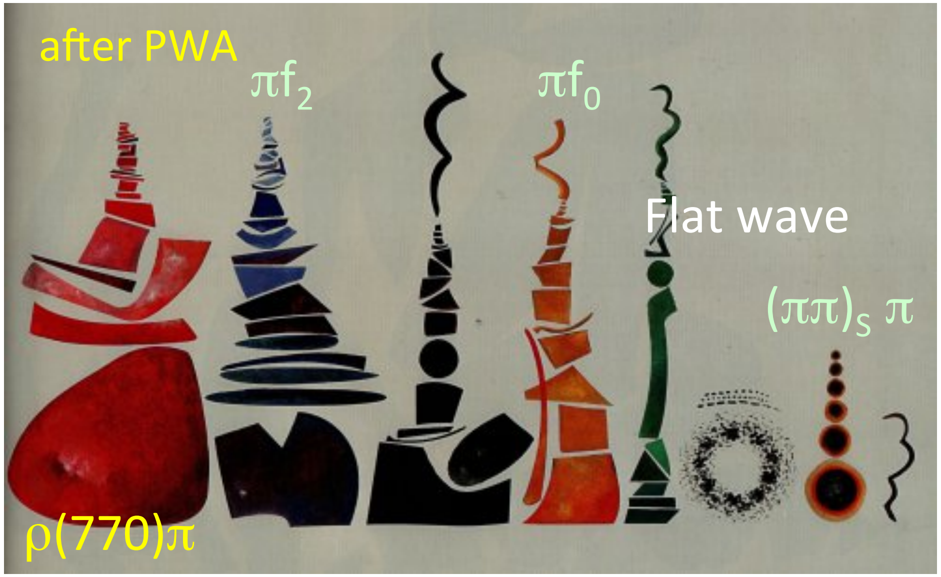
isobar model



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

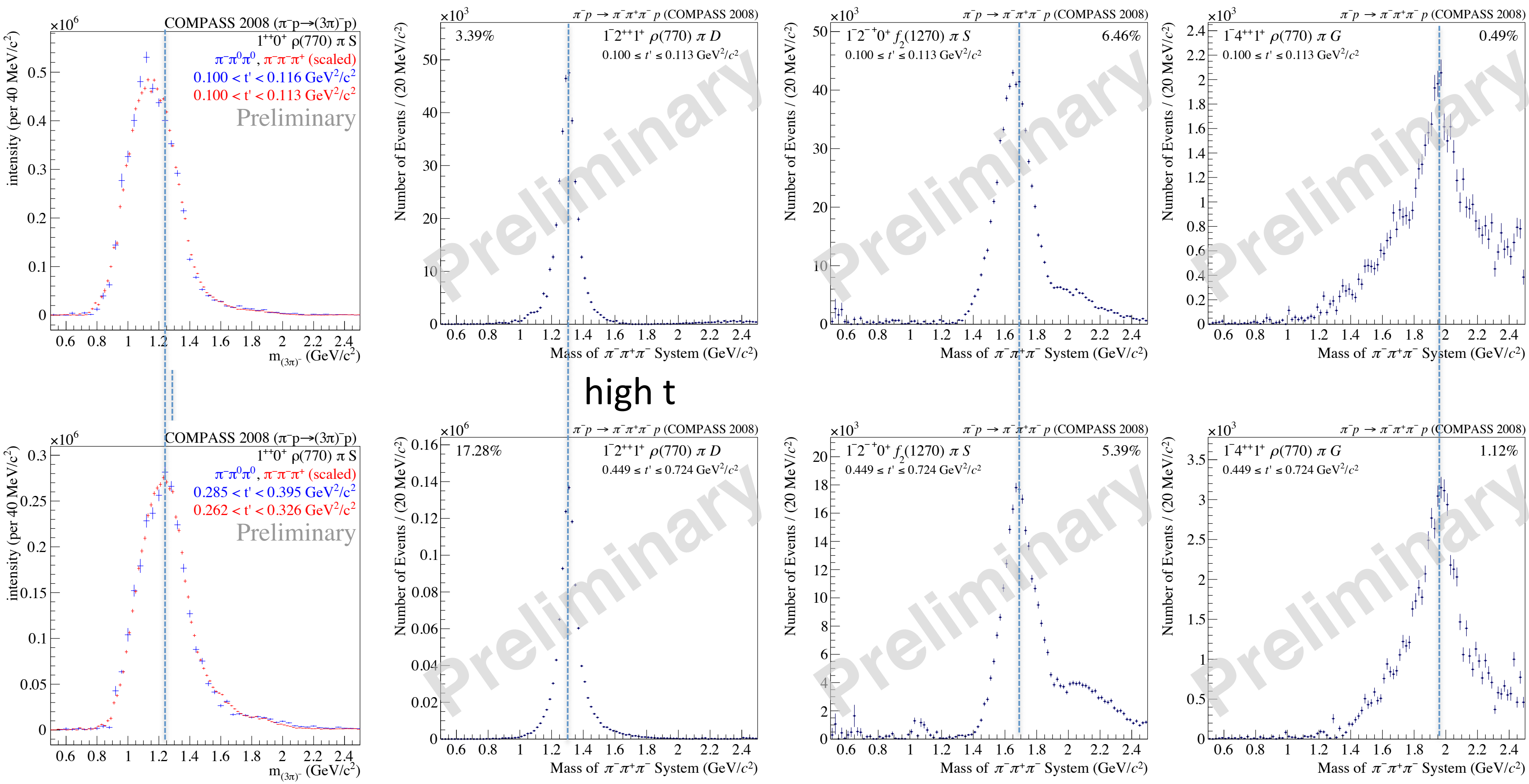
step 2

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

t dependence of mass distributions

low t

high t



1++0+ρπ S

2++1+ ρπ D

2-+0+ f2 π S

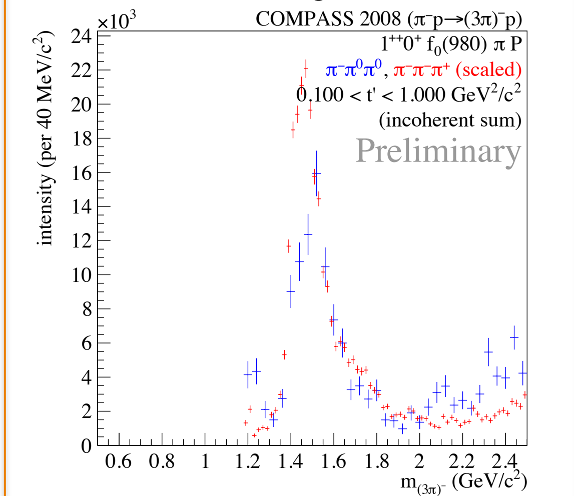
4++1+ ρπ G

Exzellenzcluster Universe

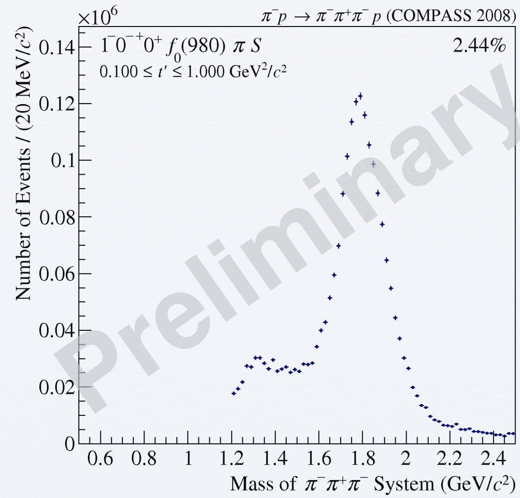
Waves involving $f_0(980)$ $[\pi\pi]_S$

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

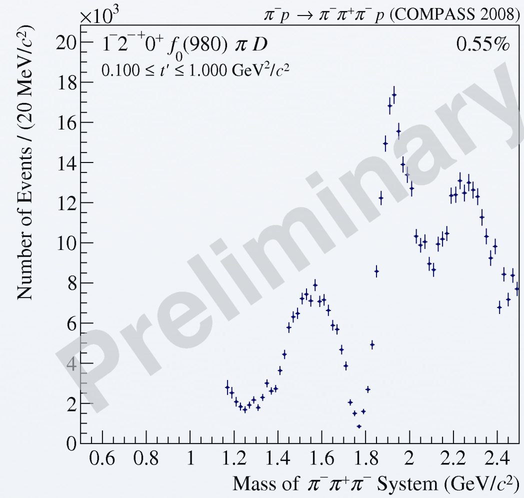
$1^{++}0^+ f_0(980)\ \pi\ P$

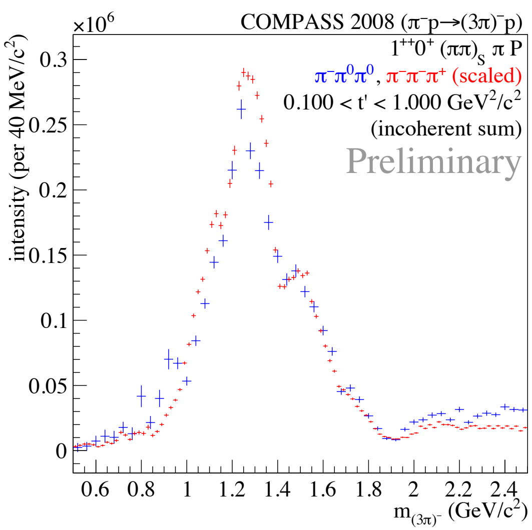


$0^{-+}0^+ f_0(980)\ \pi\ S$



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





experts only

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

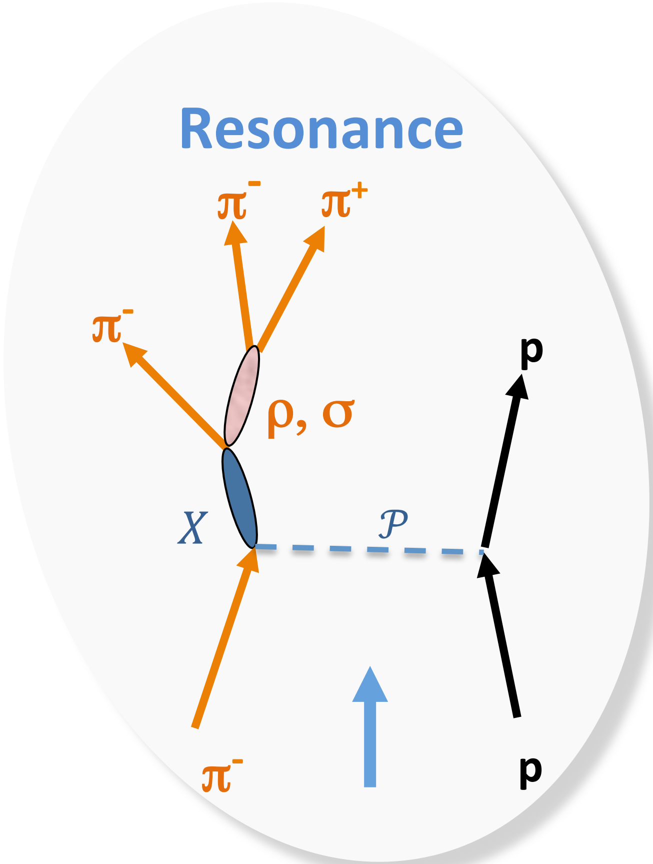
$0^{-+}0^+[\pi\pi]_S\ \pi\ S$

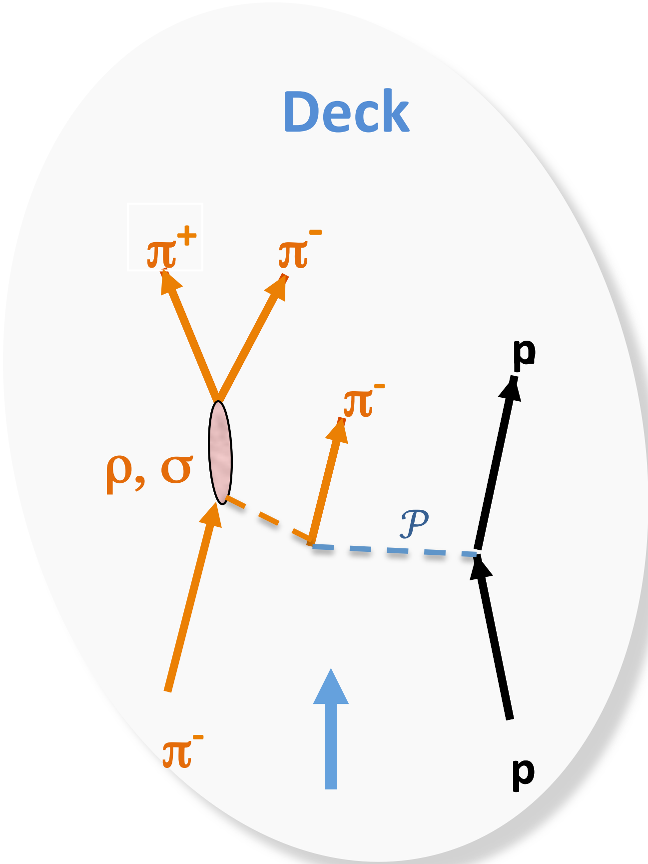
$J^{PC}M^{\varepsilon}[\text{isobar}]\ \pi\ L$

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)



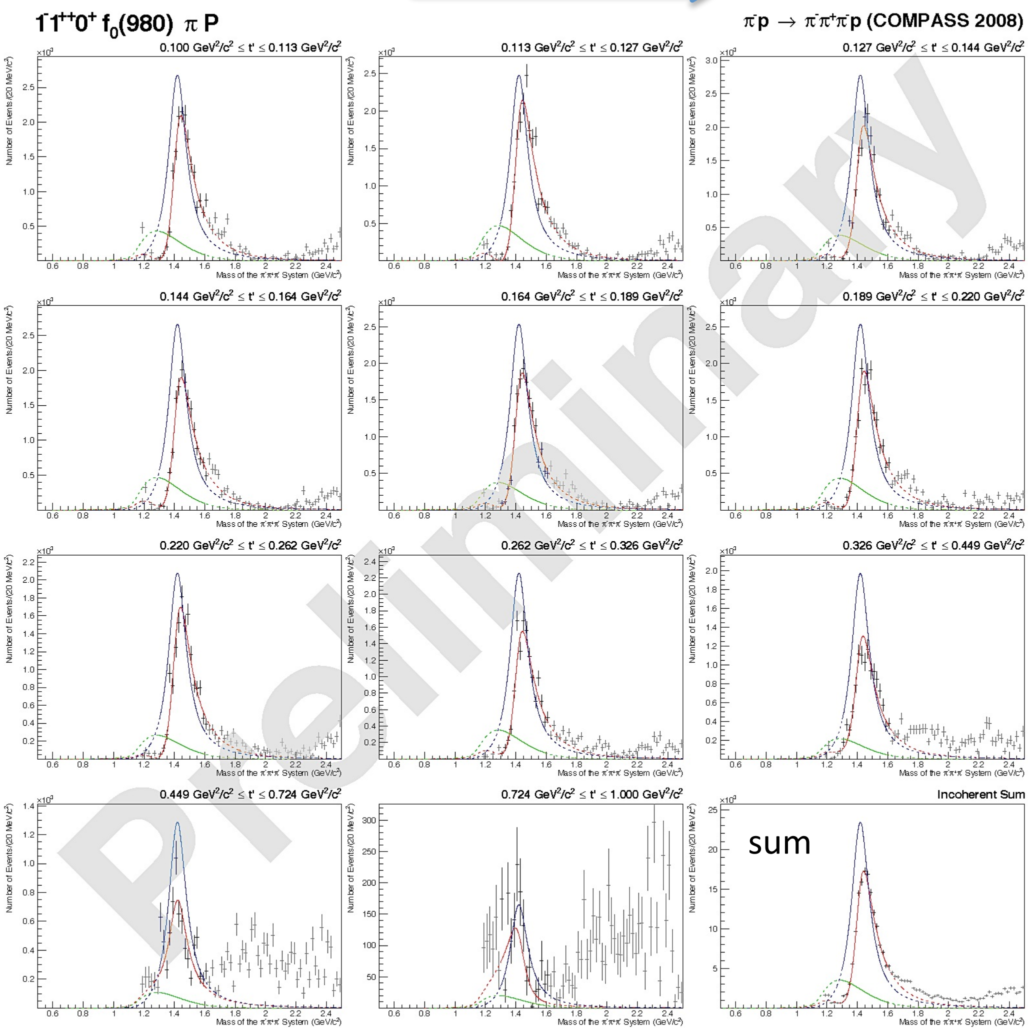


Two types of contributions

Mass dependent fits $a_1(1420)$

Fit in 11 t-bins

t →



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

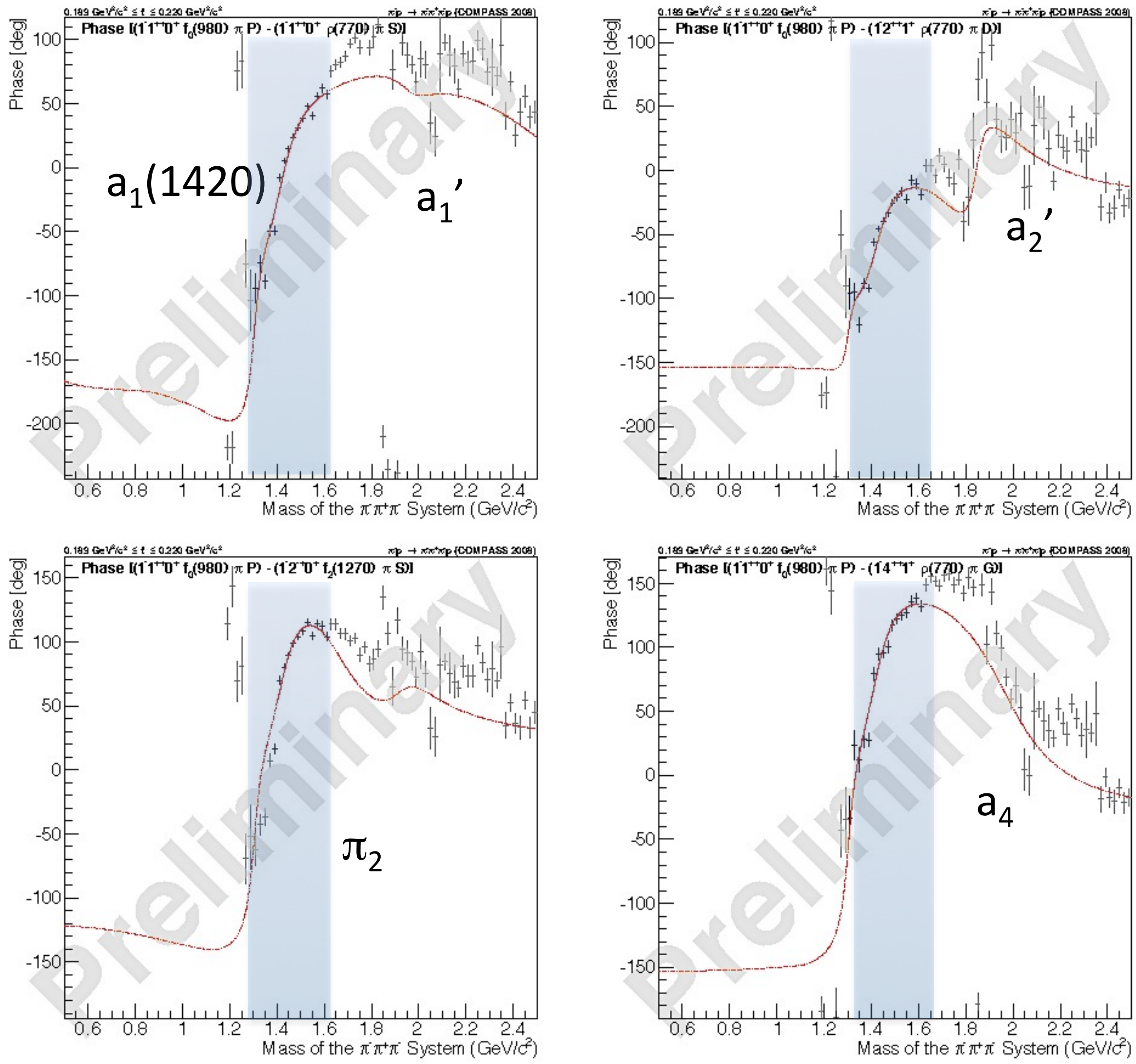
t ↓

NEW

Phase: $a_1(1420)$

Fit in 11 t-bins: medium t

fit range

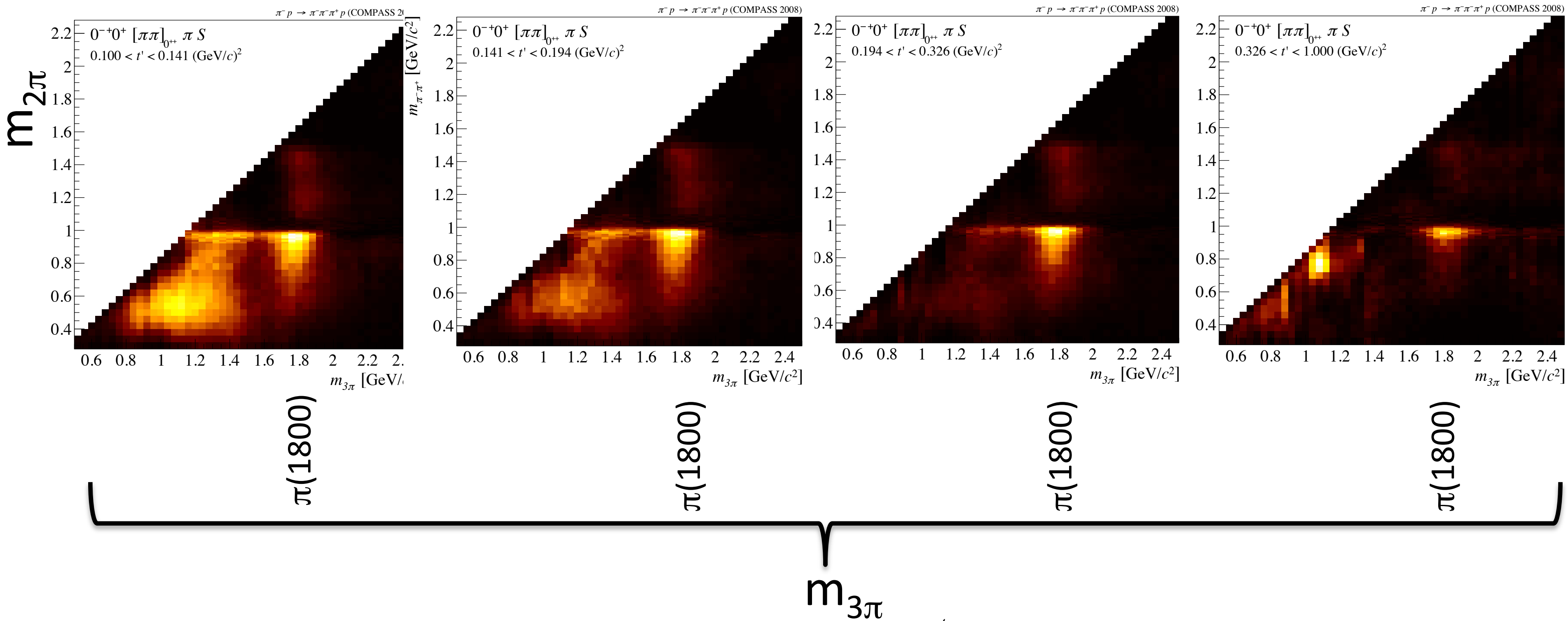


NEW

Exzellenzcluster Universe

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

- Separate resonance decay and production dynamics



t

Hardness of reaction

Exzellenzcluster Universe

Conclusion - Pion

- First precise measurement of π polarizability
  - Pion much stiffer than atom (strong interaction)
  - Excellent agreement with theory (χPT)
  - Future: separate magnetic and electric polarizabilities

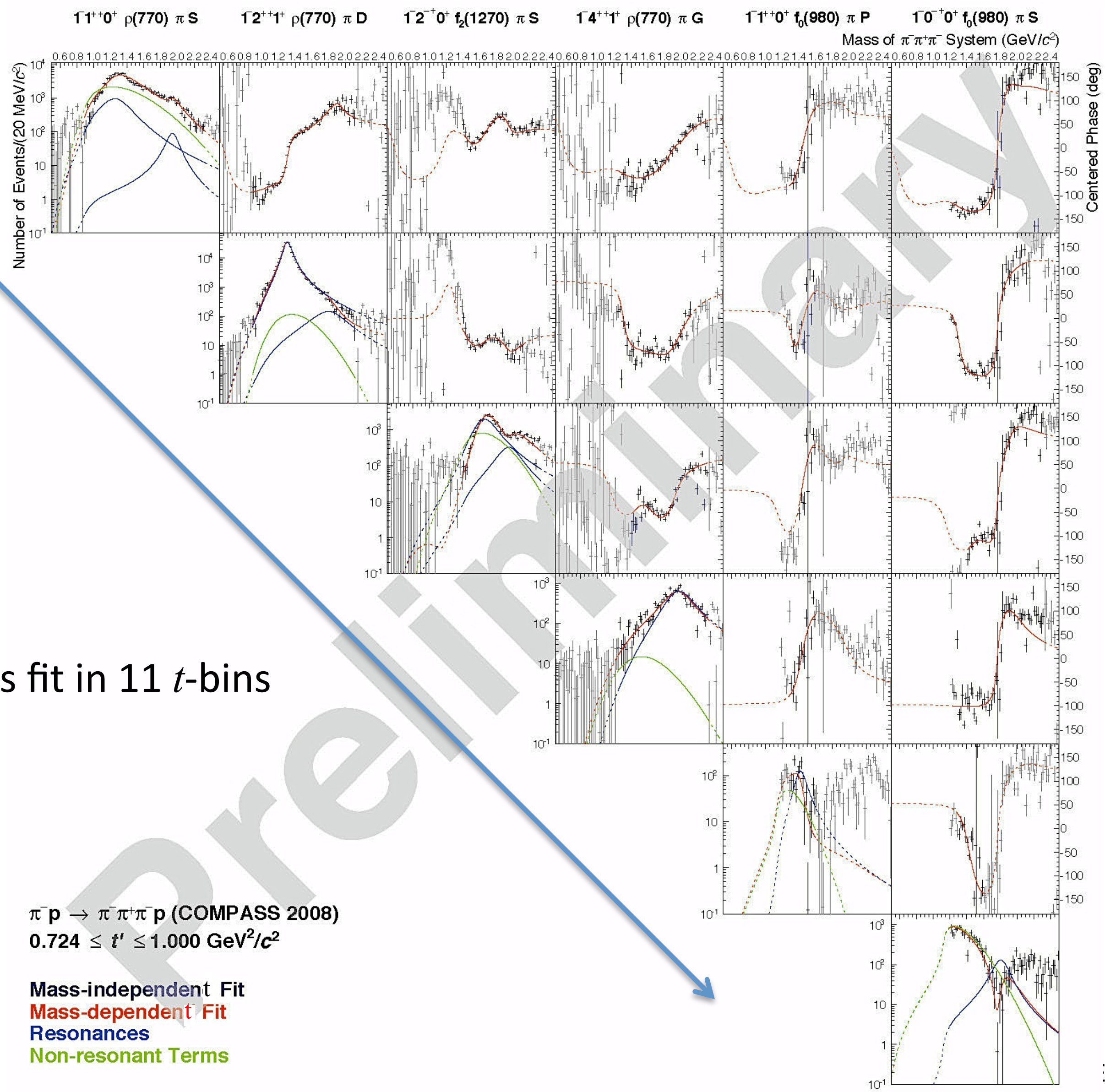
- New path to radiative meson excitations
- Test dynamics with sensitivity to loop contributions

- Diffractive pionic excitations reveal new axial vector meson
  - Partner of $f_1(1420)$? Molecular structure ?
  - Dynamic generation via coupled channel ?

COMPASS "Holography"

Reference waves

simultaneous fit in 11 t-bins



Interferometry

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
  - (exclusive) decay into $f_0(980)\pi$ in relative P-wave

  - 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

- 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 II

- 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

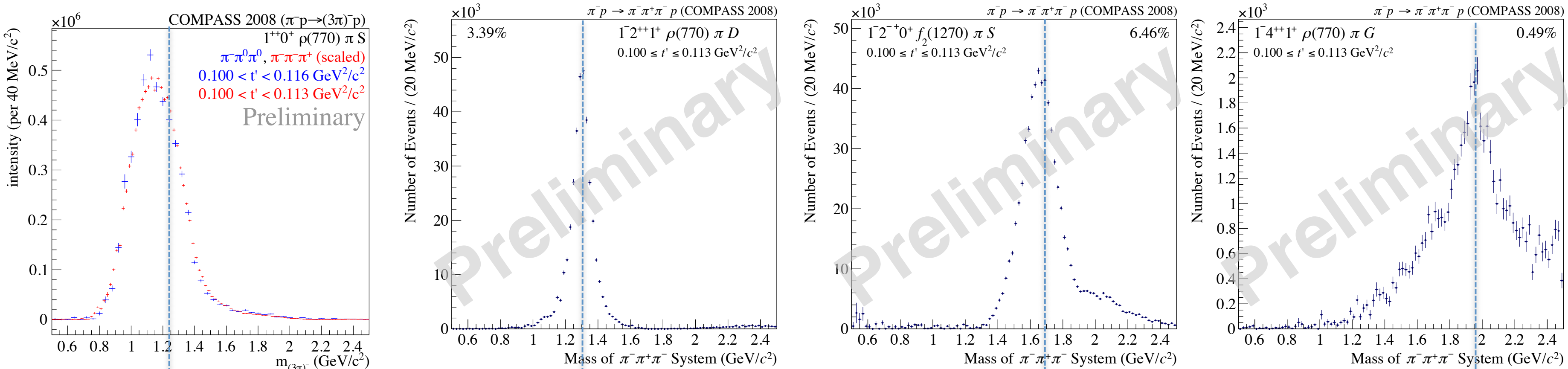
- Radial excitation of π
  - $\pi(1800)$ well known: COMPASS observes decay into $f_0(980)\pi$ and $f_0(1500)$
- Orbital excitation of π
  - $\pi_2(1670)$ well known: COMPASS observes decay into $f_2(1270)\ \pi$

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

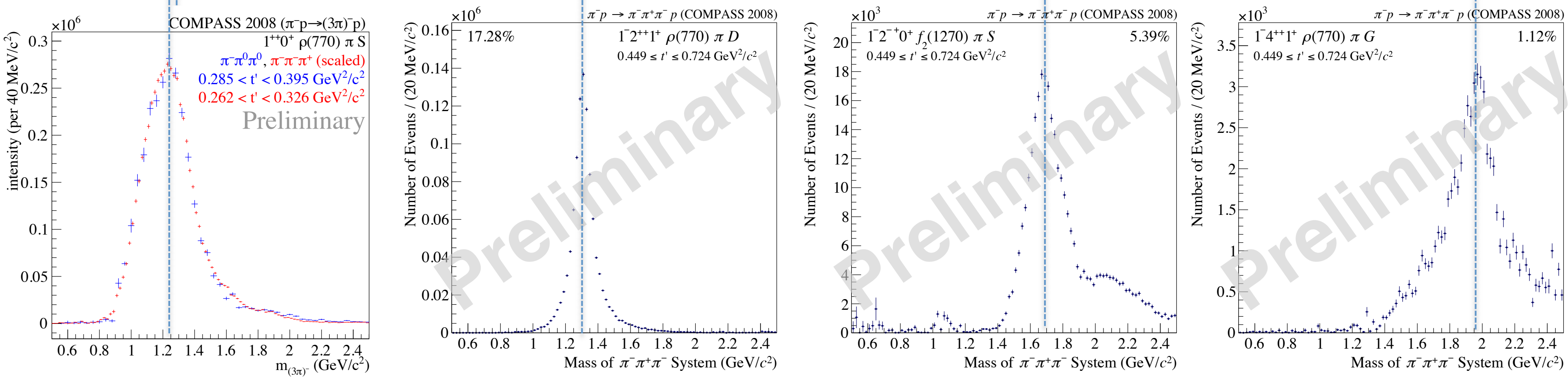
- Radiative decays:
  - First observation of a mesonic E2 transition : $\pi_2(1670) \rightarrow \pi\ \gamma$
  - Good / reasonable agreement with calculations

t dependence of mass distributions

low t



high t

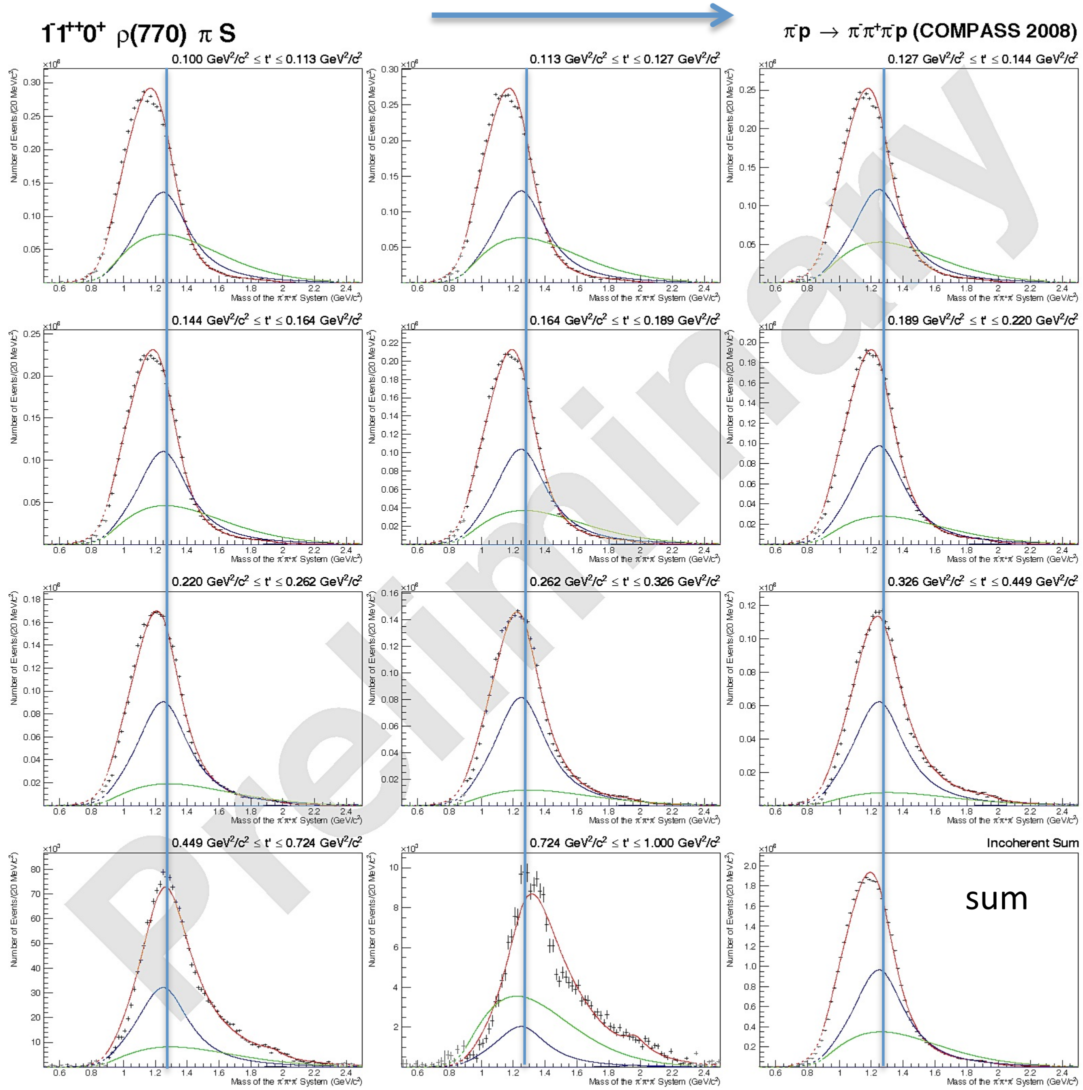


$1^{++}0^{+}\rho\pi$ S | $2^{++}1^{+}$ $\rho\pi$ D | $2^{-+}0^{+}$ f_2 π S | $4^{++}1^{+}$ $\rho\pi$ G

Mass dependent fits

Fit in 11 t-bins

t



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

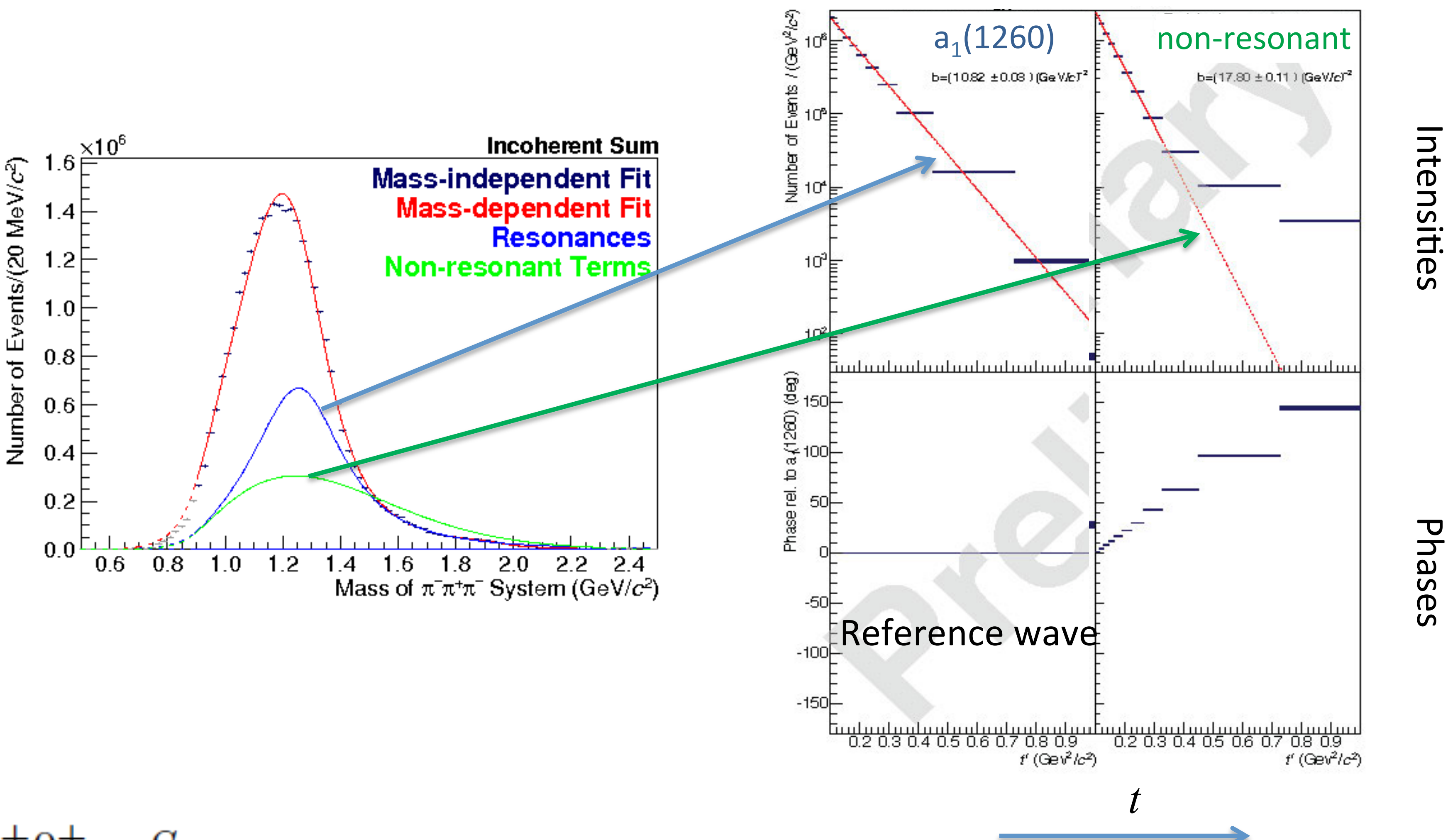
$$1^{++}0^{+}\rho\pi S$$

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

t

Example for t-dependence

$\pi\pi\pi$ COMPASS 2008



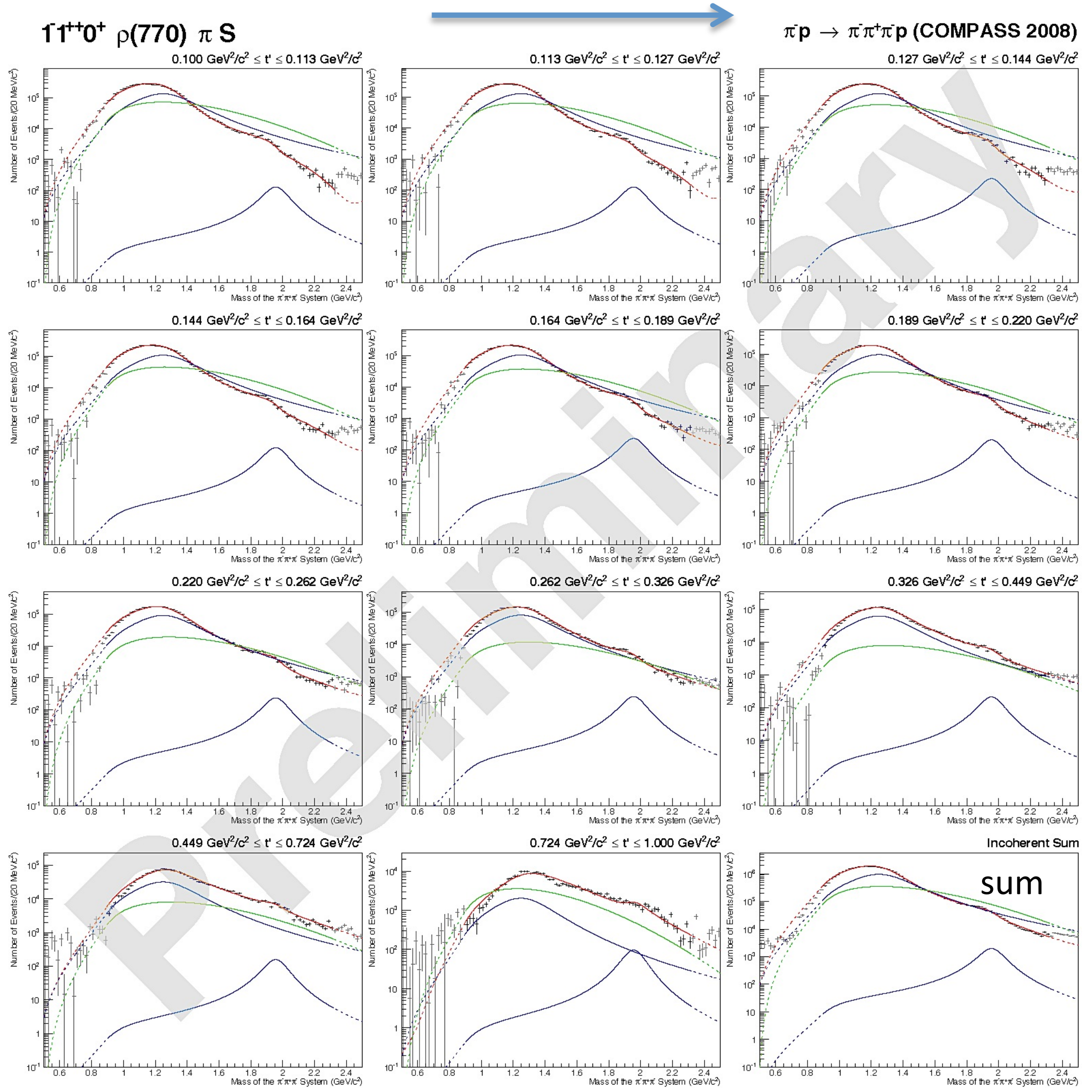
$1^{++}0^{+}\rho\pi S$

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

Mass dependent fits

Fit in 11 t-bins

t →

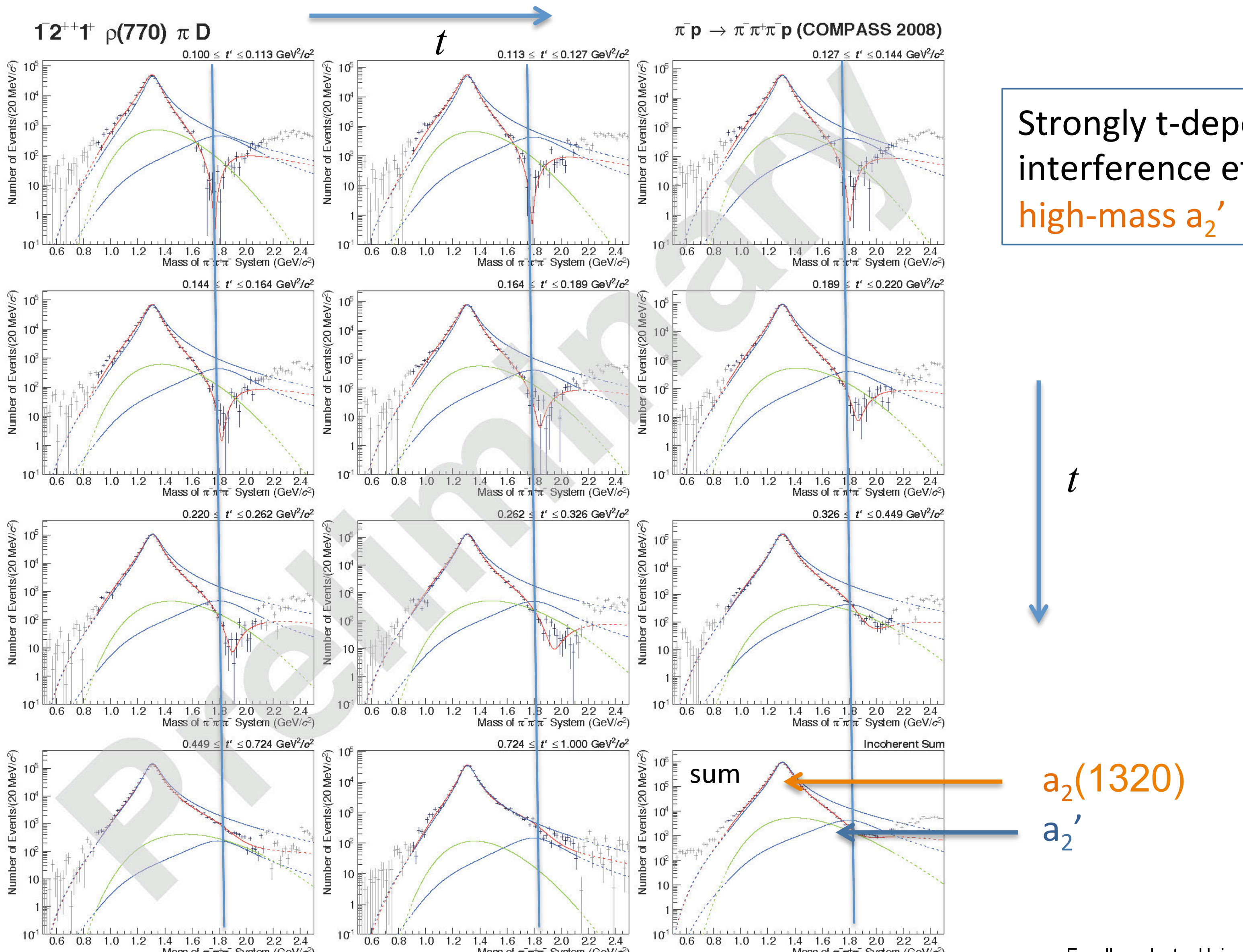


Second high-mass a_1' resonance visible

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

t ↓

Mass dependent fits $a_2(1320)$



Strongly t-dependent interference effects
high-mass a_2'

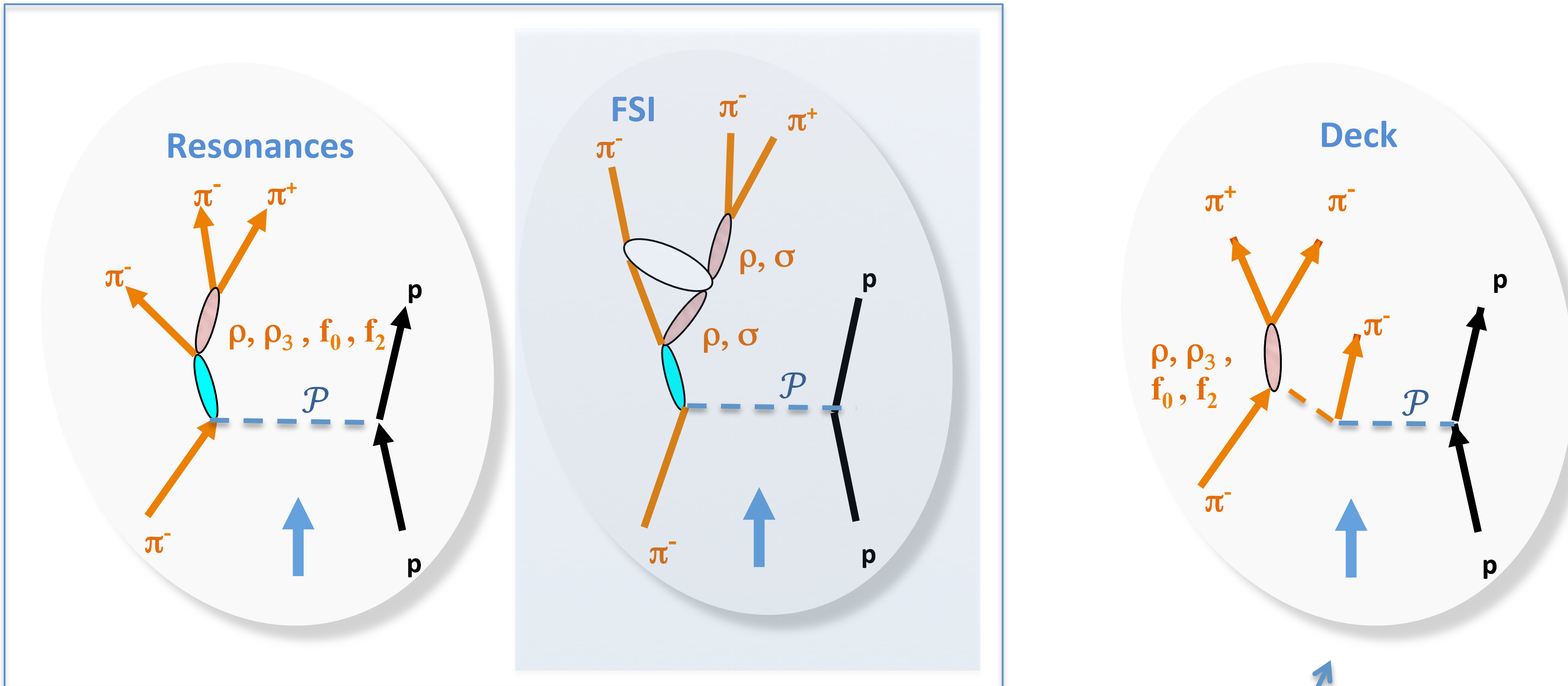
Some Results

Particle	J^{PC}	Mass Range $[\mathrm{MeV}/c^2]$	Width Range $[\mathrm{MeV}/c^2]$	PDG Values $m\ [\mathrm{MeV}/c^2]$	PDG Values $\Gamma\ [\mathrm{MeV}/c^2]$
				PDG	
"Established" states					
$a_1(1260)$	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

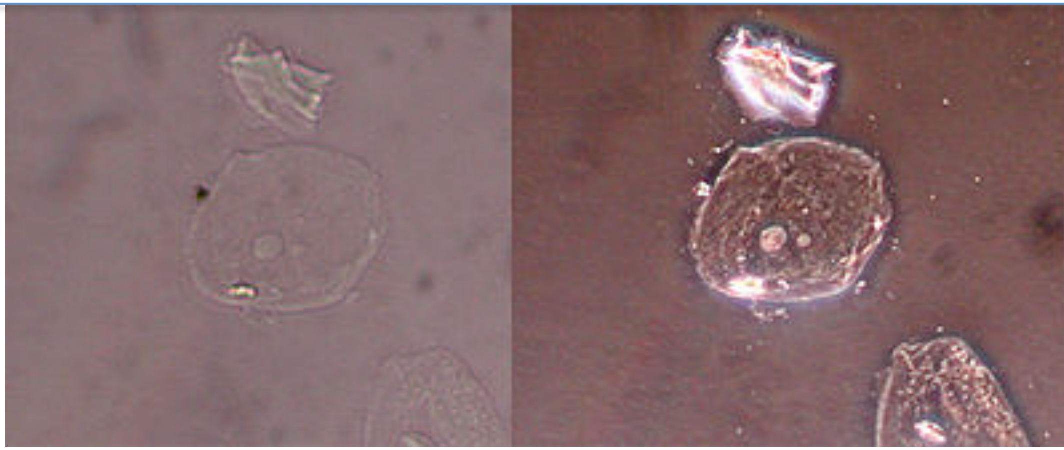
- We have solved a puzzle – but were the building blocks correct ?

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)

How to reconstruct an Image

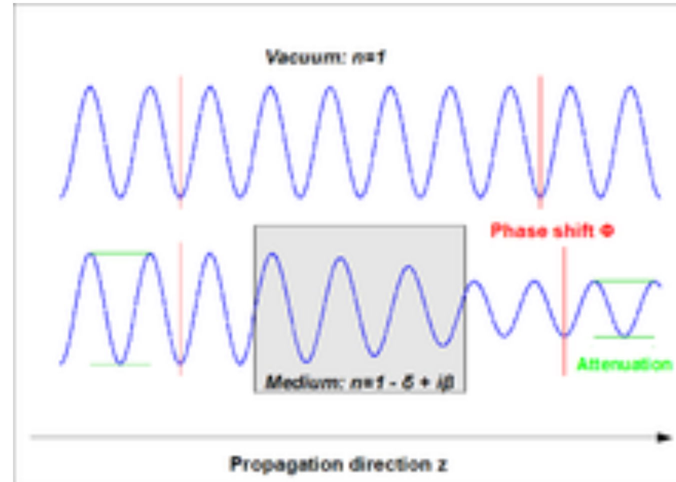


Bright field microscopy maps distribution of imaginary part of refractive index

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

Peak hunting

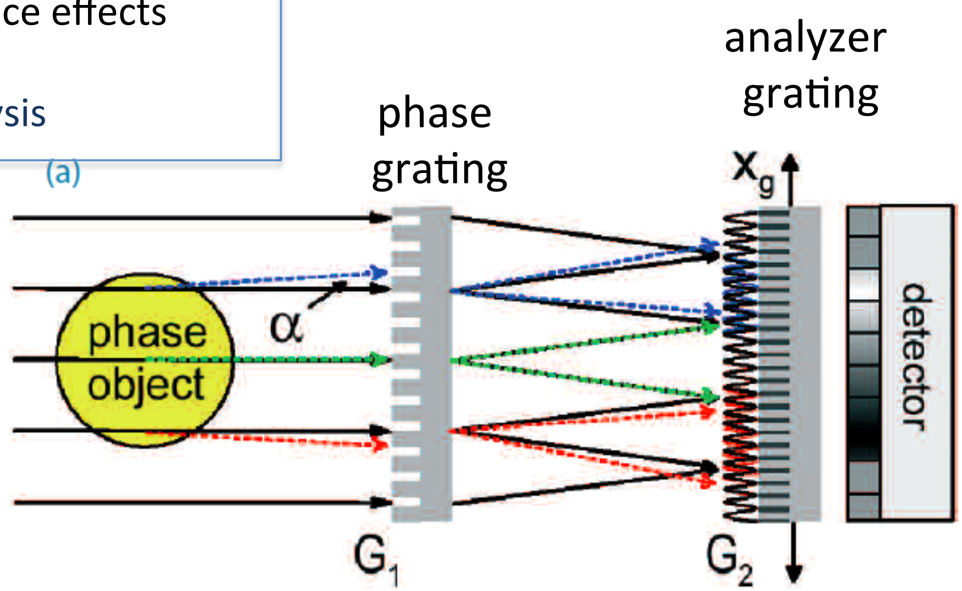
Dalitz plot analysis



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

with X-rays:

- *Re(n) < 1*
- Phase shift translated into deflection
- detect via X-ray grating
- Measure with reference(analyzer) grating



Major waves

Major waves

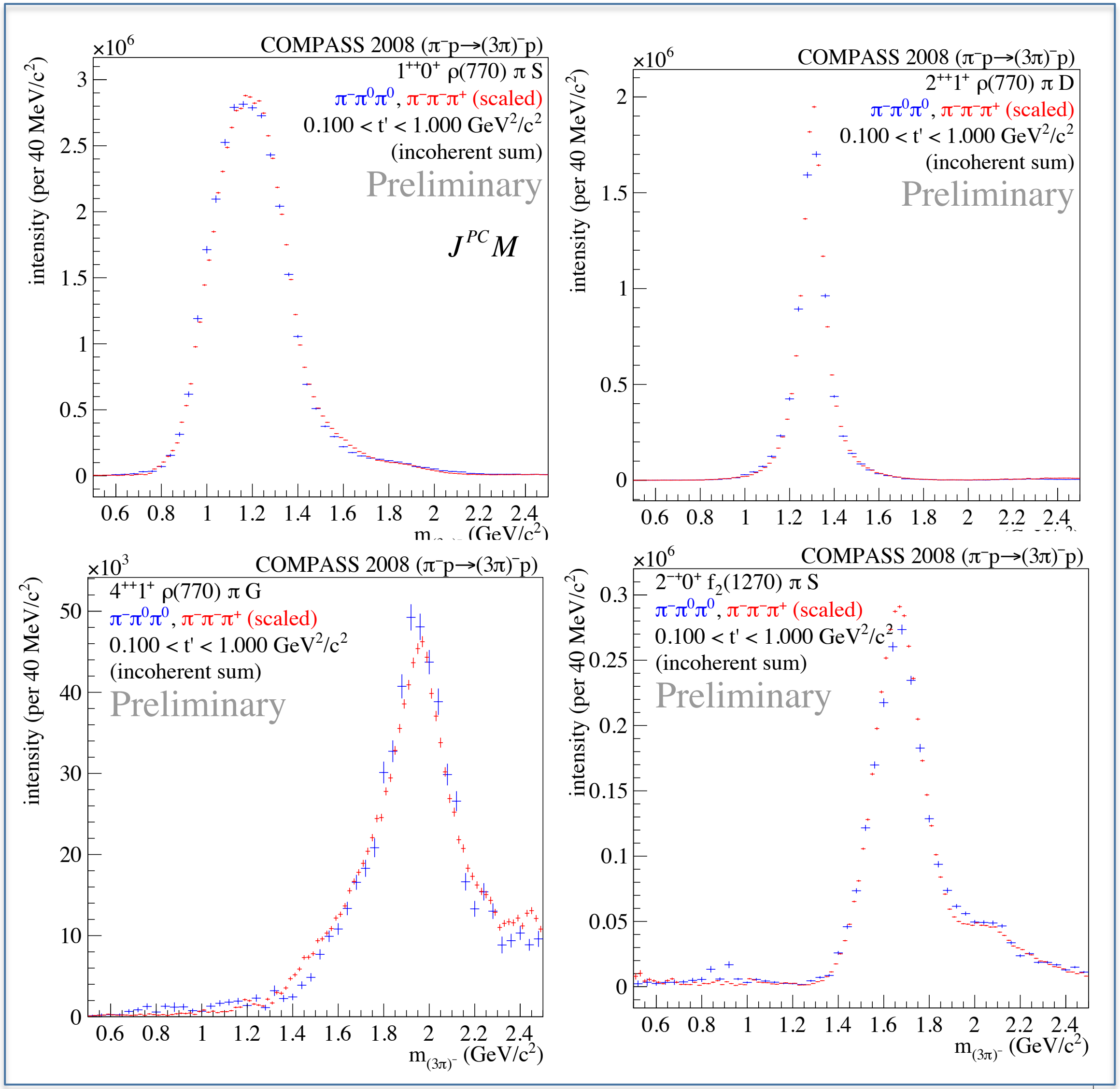
$J^{PC} M^{\varepsilon} [isobar] \pi L$

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

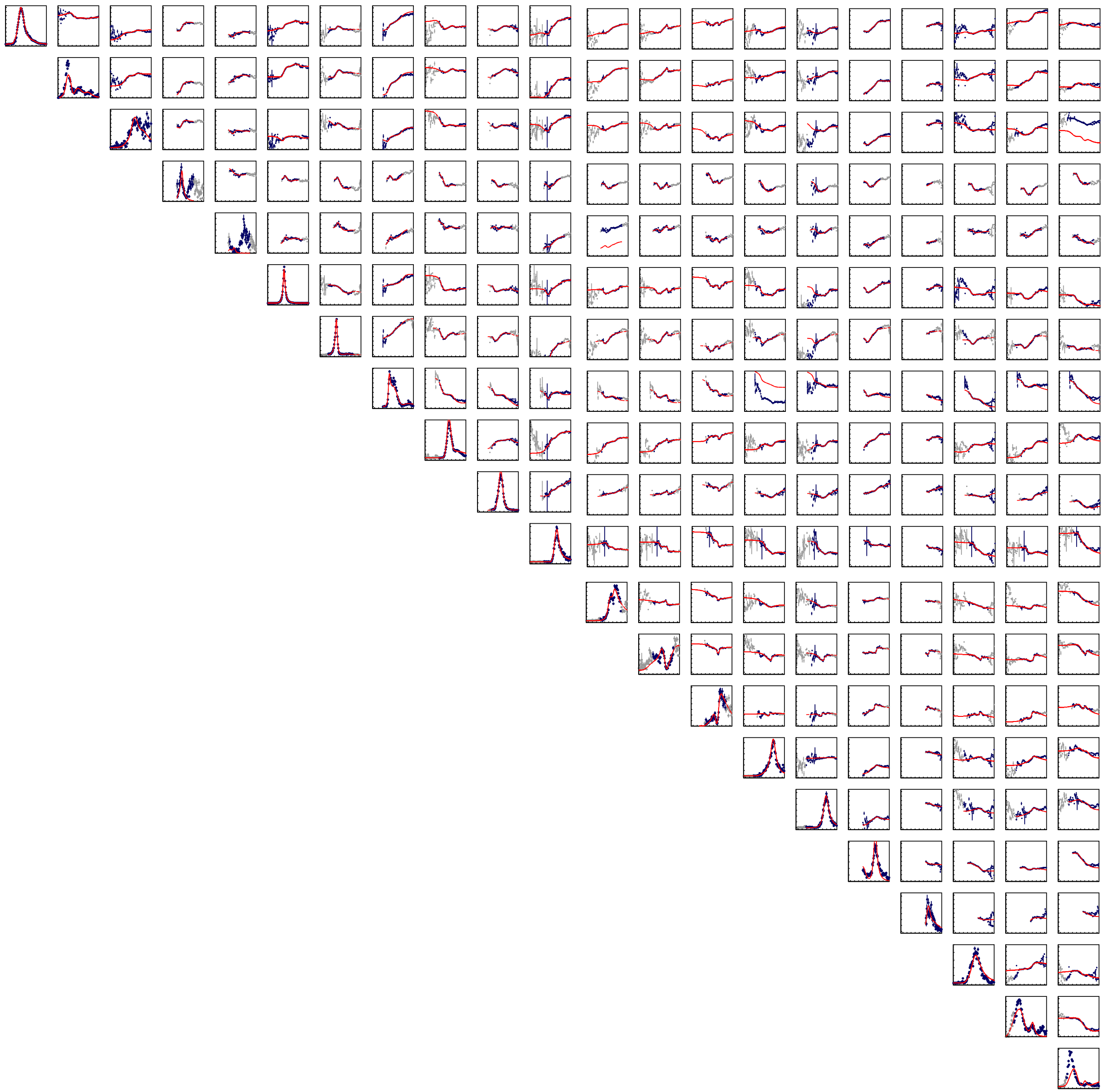
$1^{++} M^{+} [f_0(980)] \pi P$
$0^{-+} M^{+} [f_0(980)] \pi S$

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

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

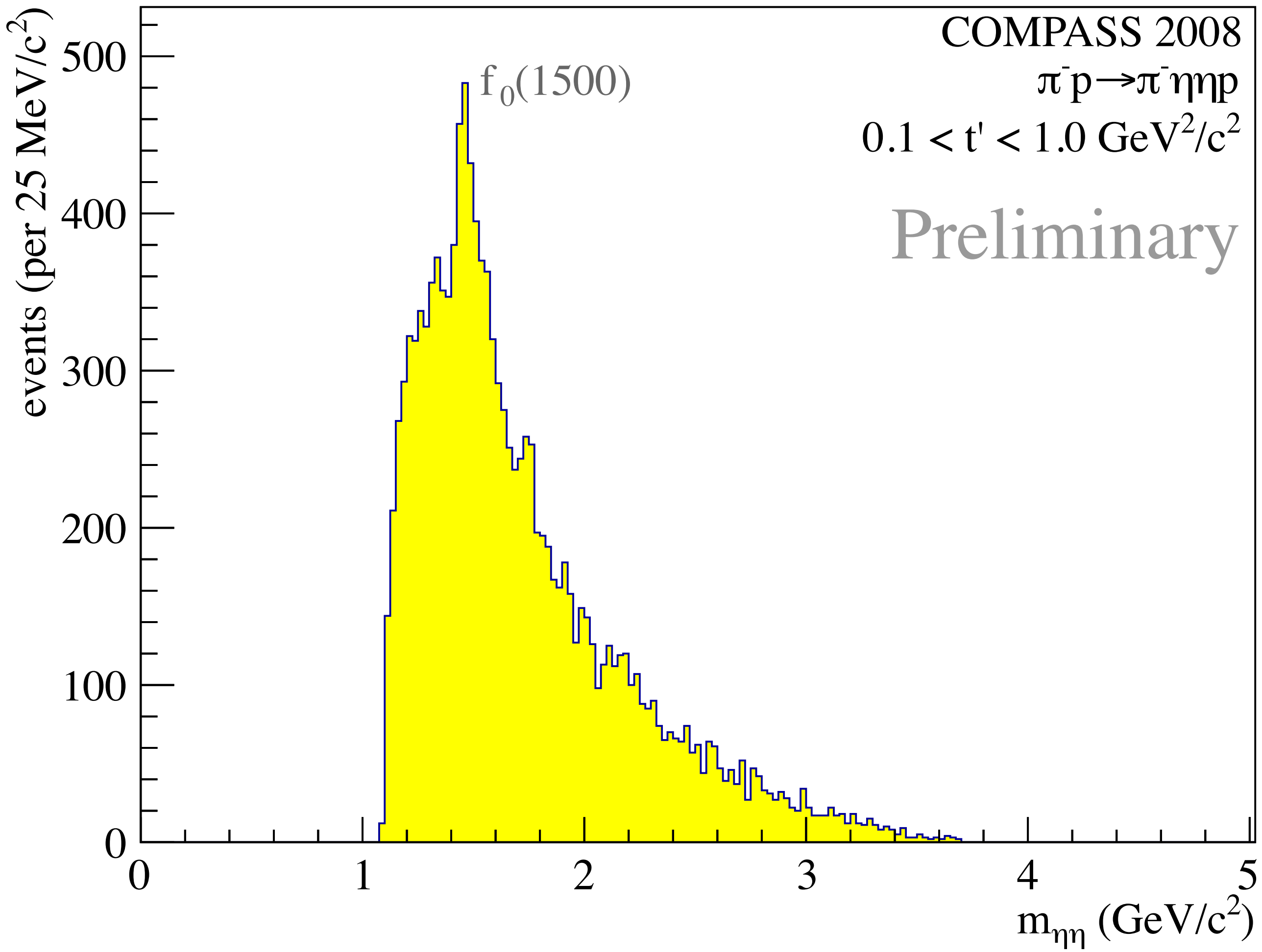


Sneak Preview – Large Fits



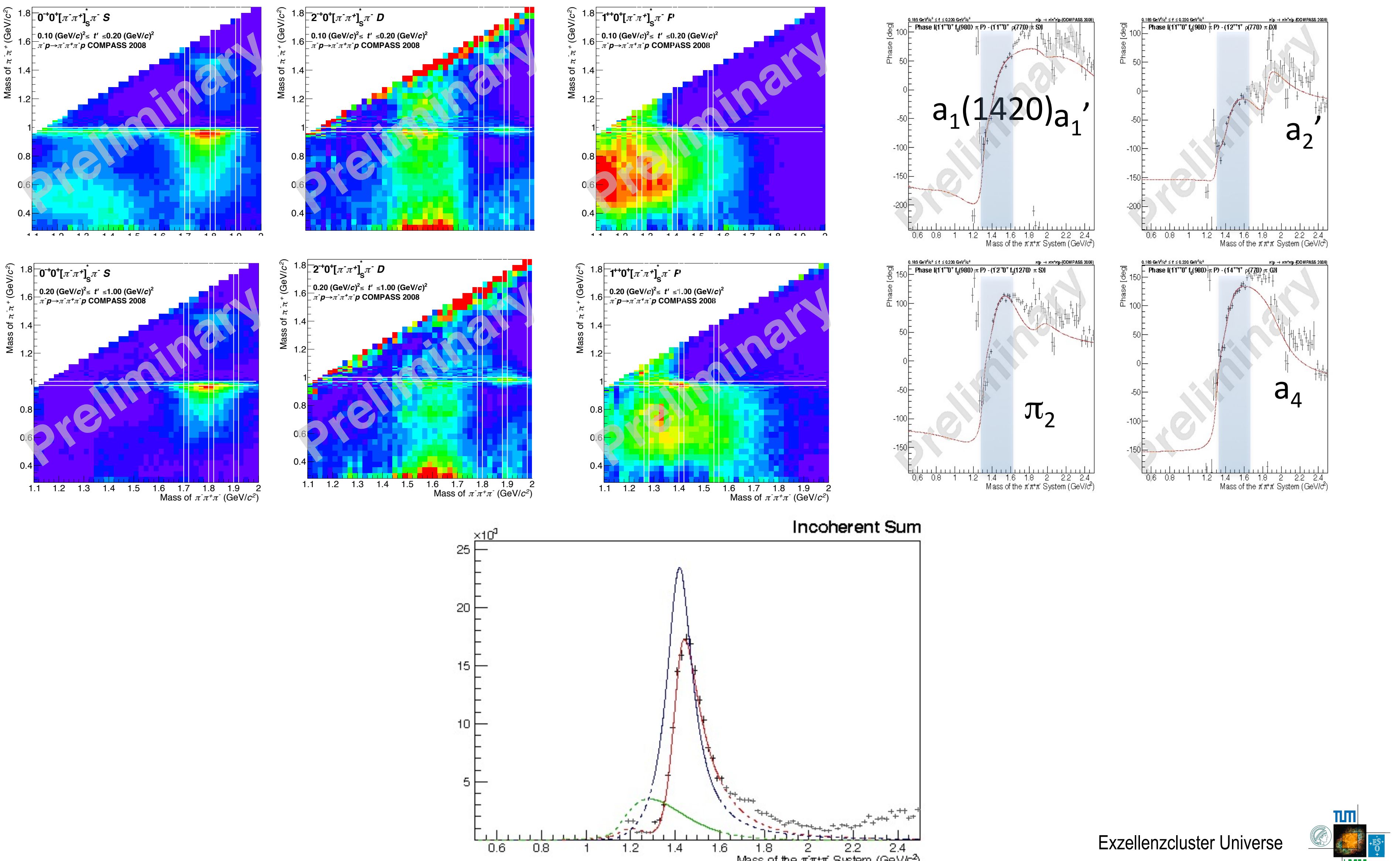
Preview to
21 wave-fit
in 2 bins of t'

Preview into πηη



Exzellenzcluster Universe

The End

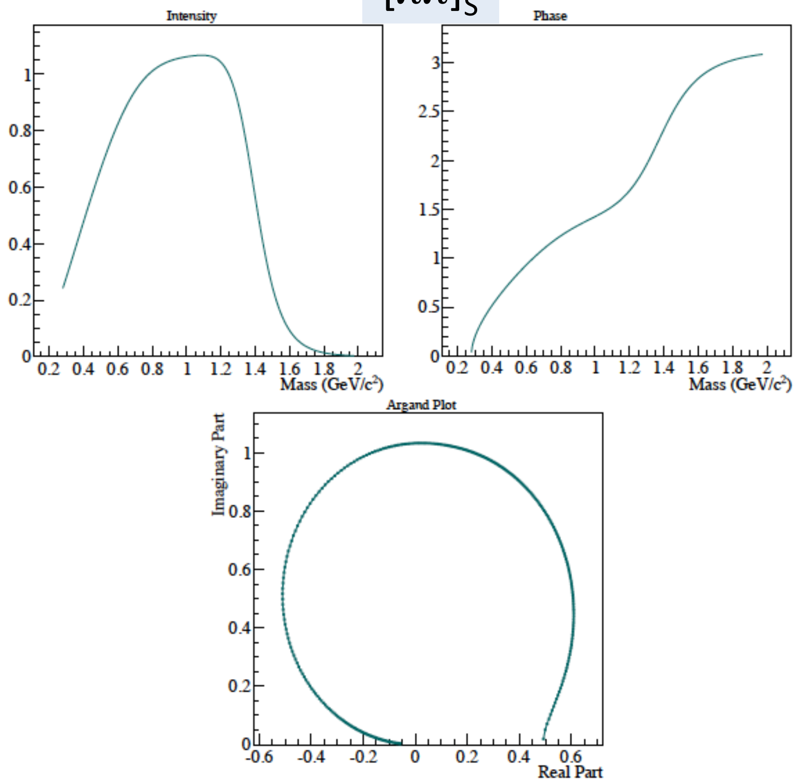


Exzellenzcluster Universe

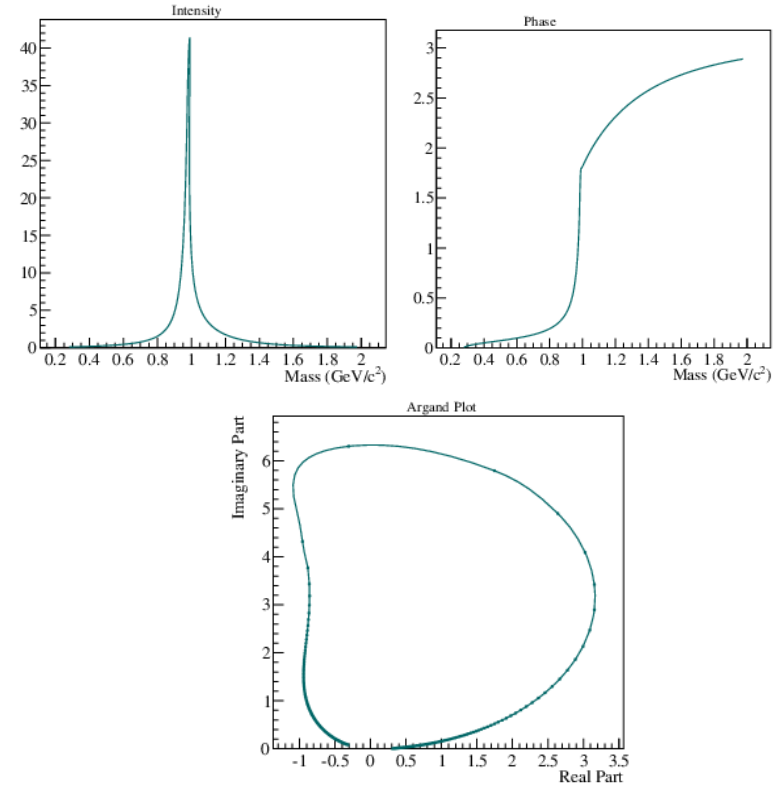
Isobars: an Example

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

$[\pi\pi]_S$



$f_0(980)$ parametrization



use BES parametrization: as it decays into ππ and KK (threshold effect)

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

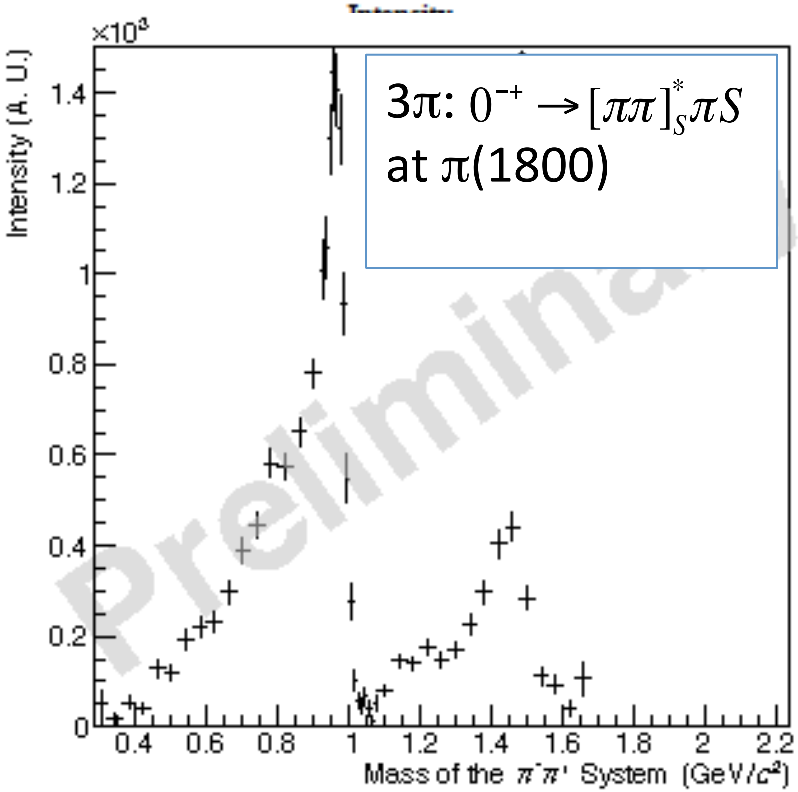
Isobars: $[\pi\pi]^*_S$

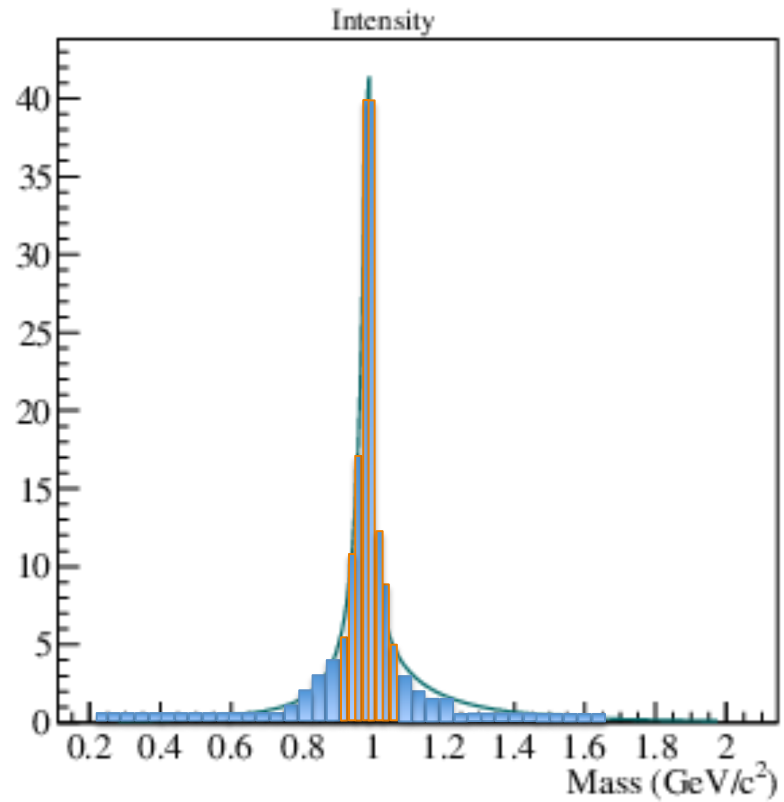
Phys. Rev. D35 1633, Au, Morgan, Pennington

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)



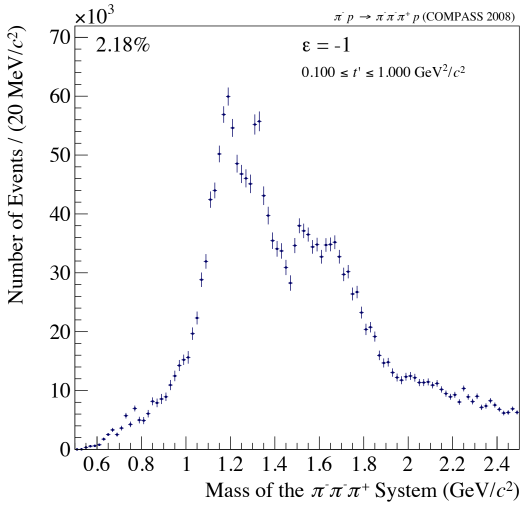


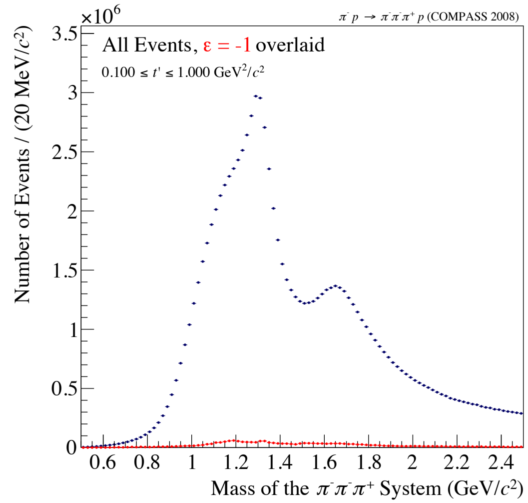
Extra Material

Theory predictions α_π

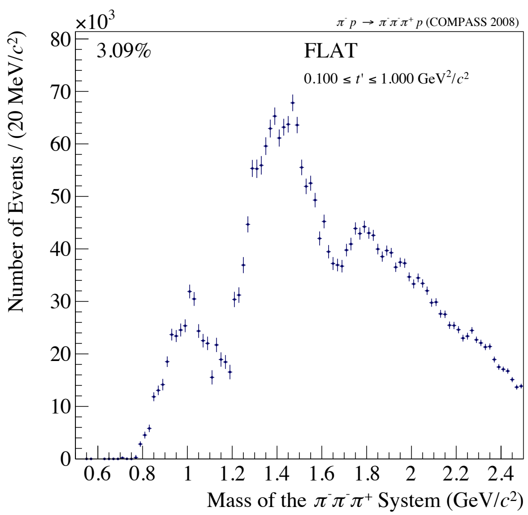
- chiral perturbation theory
  - ⋆ $(\alpha+\beta)_{\pi^+} = 0$ in leading order $\mathcal{O}(p^4)$
    $(\alpha+\beta)_{\pi^+} = (0.3 \pm 0.1) \times 10^{-4}\mathrm{fm}^3$ in order $\mathcal{O}(p^6)$
  - ⋆ $(\alpha-\beta)_{\pi^+} \approx 5.4 \times 10^{-4}\mathrm{fm}^3$ one loop (Bijens, Cornet, 1988; Danoghue, Holstein 1989; Belluci, Gasser, Sainio, 1994)
    $(\alpha-\beta)_{\pi^+} = (4.4 \pm 1.0) \times 10^{-4}\mathrm{fm}^3$ two loops (Bürgi, 1997)
- Nambu-Jona-Lasino model
  $\alpha = -\beta = (3.0 \pm 0.6) \times 10^{-4}\mathrm{fm}^3$; $(\alpha-\beta)_{\pi^+} = (6.0 \pm 0.8) \times 10^{-4}\mathrm{fm}^3$
- Dispersion relations
  $(\alpha-\beta)_{\pi^+} = (10.3 \pm 1.9) \times 10^{-4}\mathrm{fm}^3$ (Lev Fil'kov, Kashevarov, 1999)
- non linear σ model
  $(\alpha-\beta)_{\pi^+} = 20 \times 10^{-4}\mathrm{fm}^3$ (Bernard, Hiller, Weise, 1988)
- Dubna quark confinement model
  $(\alpha-\beta)_{\pi^+} = 7.05 \times 10^{-4}\mathrm{fm}^3$ (Ivanov, Mizutani, 1992)

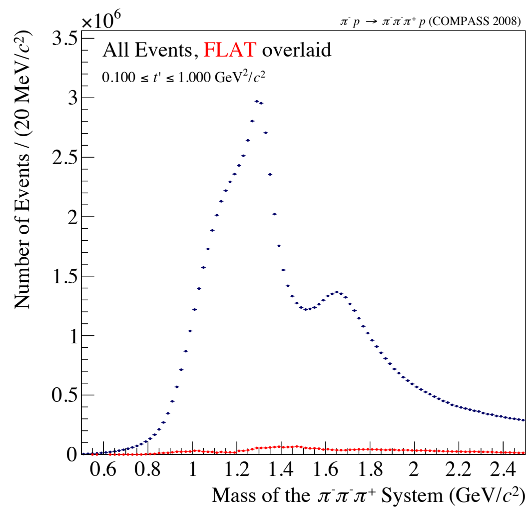
Quick Check for “odd” waves

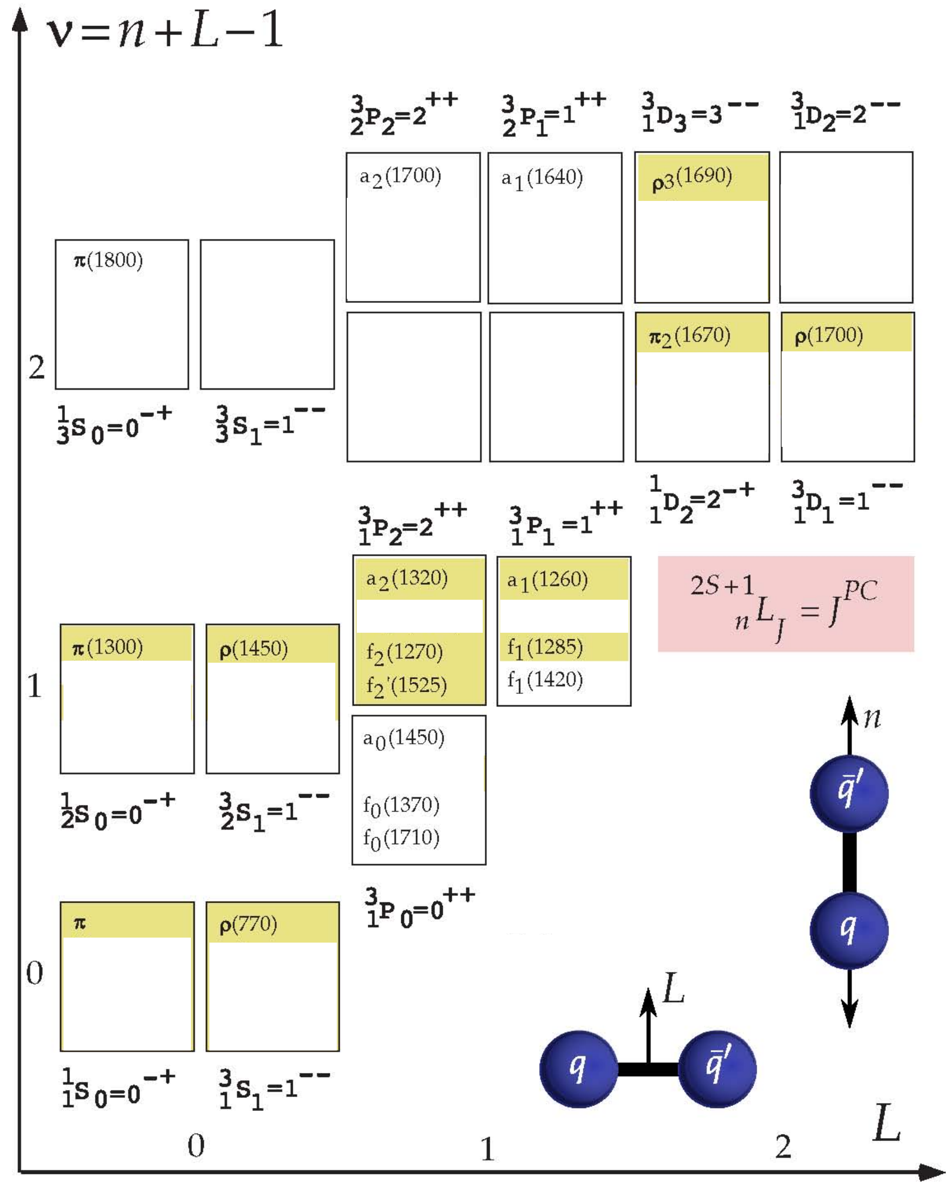




About 5% absorbed by “odd” waves





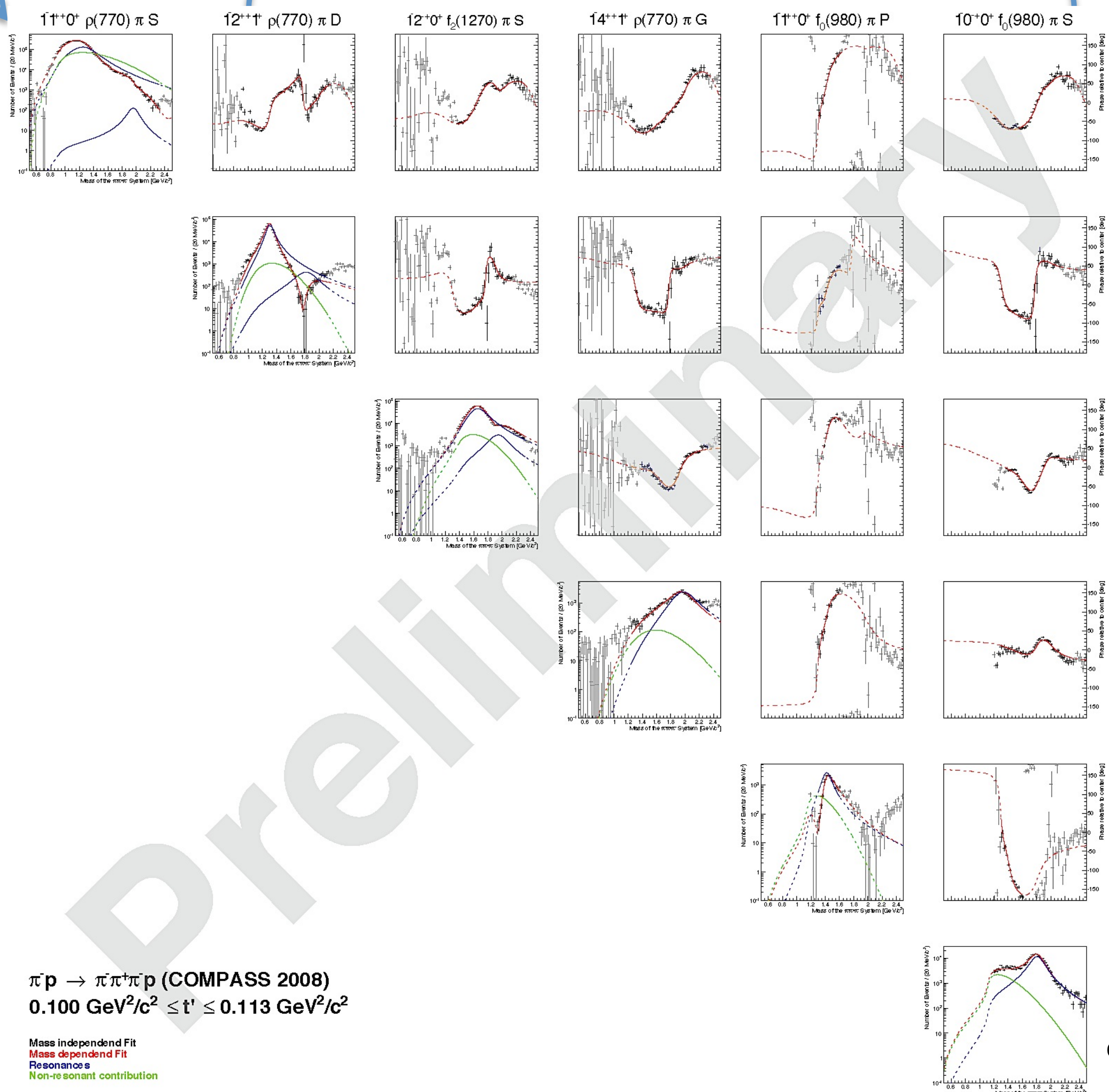


ν=n+L−1
3 2 P2=2++
3 2 P1=1++
3 1 D3=3−−
3 1 D2=2−−
a2(1700)
a1(1640)
ρ3(1690)
π(1800)
π2(1670)
ρ(1700)
2
1 3 S0=0−+
3 3 S1=1−−
3 1 P2=2++
3 1 P1=1++
1 1 D2=2−+
3 1 D1=1−−
a2(1320)
f2(1270)
f2'(1525)
a1(1260)
f1(1285)
f1(1420)
2S+1 n LJ = J^PC
π(1300)
ρ(1450)
1
a0(1450)
f0(1370)
f0(1710)
1 2 S0=0−+
3 2 S1=1−−
3 1 P0=0++
n
q̄'
q
π
ρ(770)
0
L
q
q̄'
1 1 S0=0−+
3 1 S1=1−−
0
1
2
L

COMPASS Spin-Density Matrix

Reference waves

Interferometry



low t'-slice only

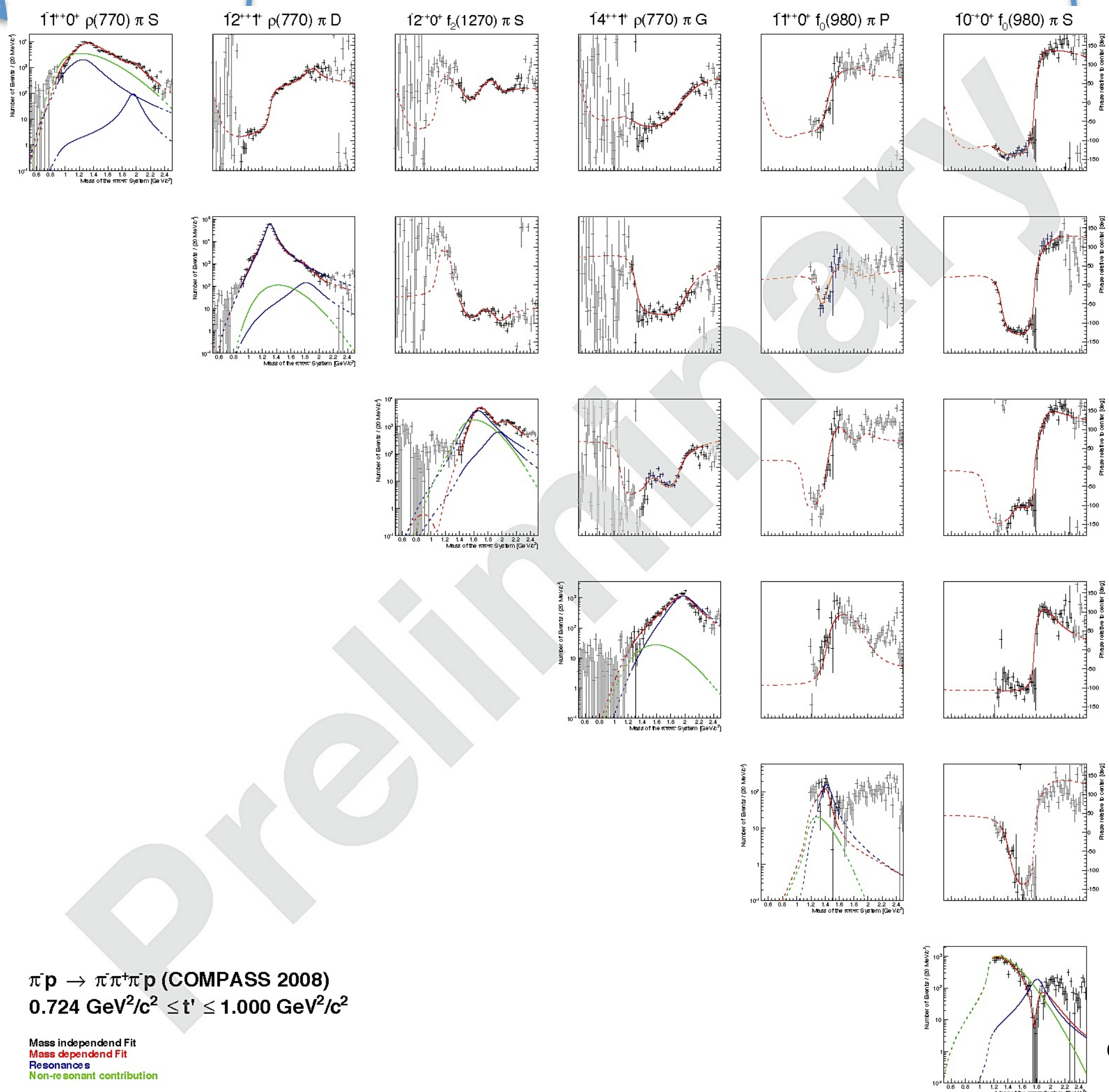
enzcluster Universe

COMPASS Spin-Density Matrix

Reference waves

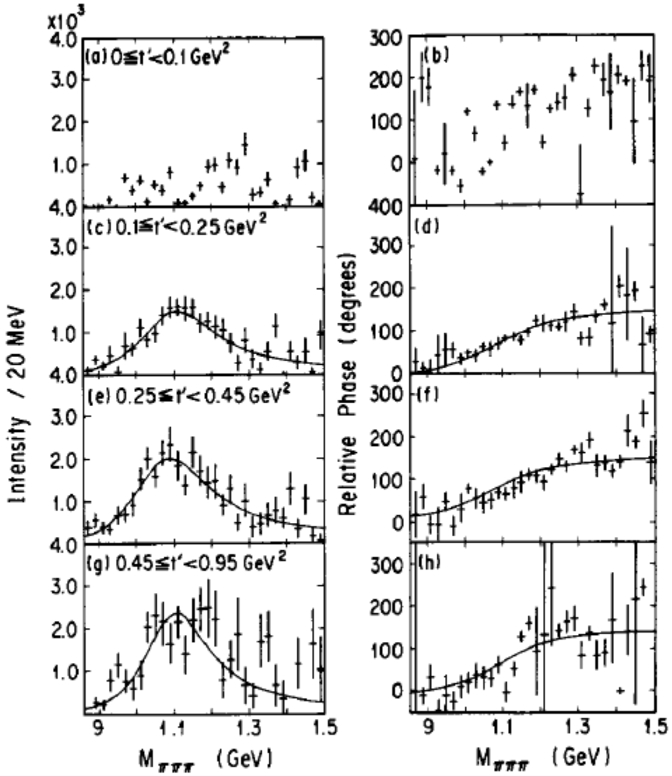
Interferometry

high t'-slice only



Examples for $a_1(1260)$ and $a_2(1420)$

- CEX reaction at 8 GeV : $\pi^- p \rightarrow \pi^0 \pi^+ \pi^-$

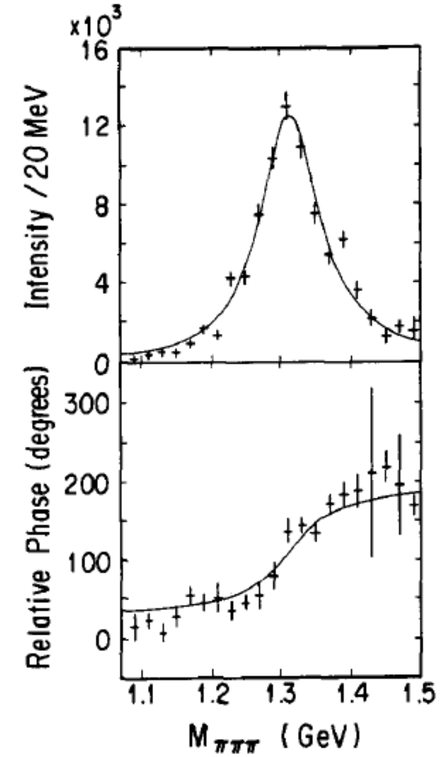


$$T = T_0 + B\, e^{i\delta}[\cos\delta + (\alpha/k)\sin\delta]$$

Deck

a_1

a_2

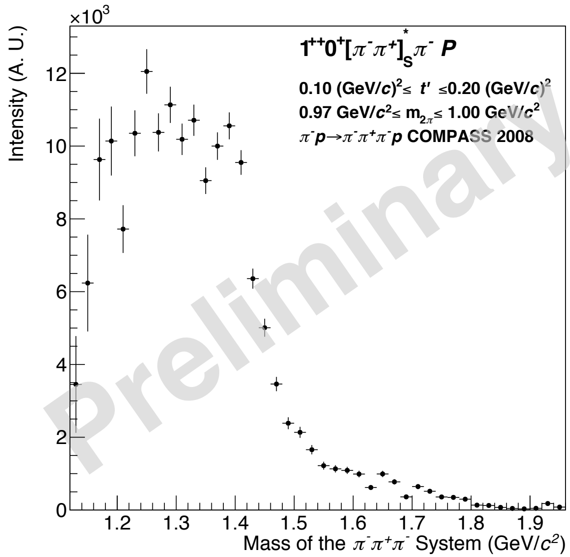


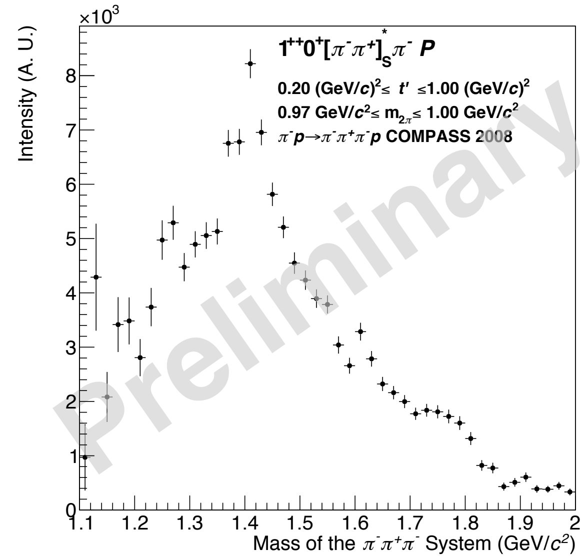
t' $(\mathrm{GeV}/c)^2$	Breit–Wigner		Bowler 1 incl. Deck	
	M (MeV)	Γ (MeV)	M (MeV)	Γ (MeV)
0.00–0.10	–	–	–	–
0.10–0.25	1126±11	251±15	1146±27	226±48
0.25–0.45	1111±16	262±40	1125±13	278±17
0.45–0.95	1119±15	218±17	1114±17	236±69

t' $(\mathrm{GeV}/c)^2$	M (MeV)	Γ (MeV)
0.00–0.10	1319±6	93± 6
0.10–0.25	1315±6	103± 6
0.25–0.45	1311±6	99± 6
0.45–0.95	1335±6	127±10

Study of $(\pi\pi=f_{980})^*_{S\text{-wave}}\ 1^{++}$

low t’



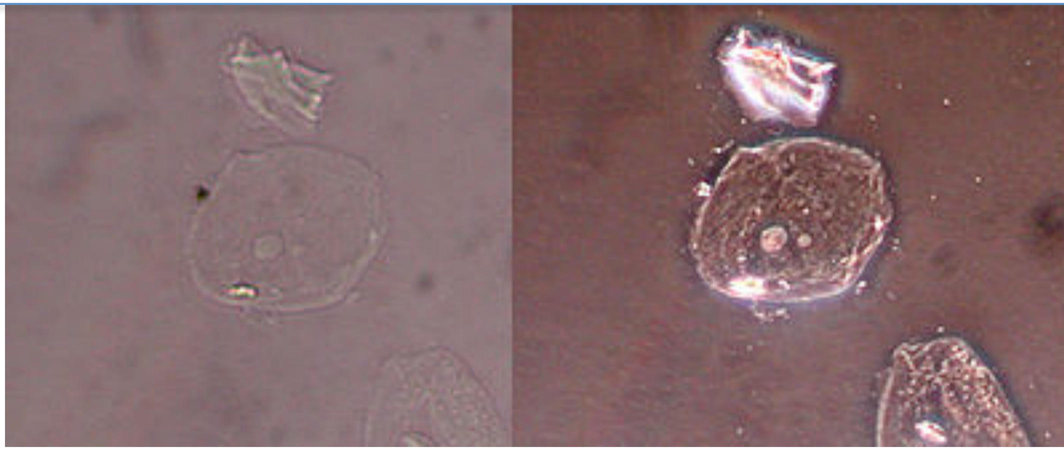


high t’

- $f_0(980)$ correlated with $a_1(1420)$
- non-resonant contributions at low t’
- warning !! just intensity cuts, amplitude selection

☞ mass dependent fit

How to reconstruct an Image

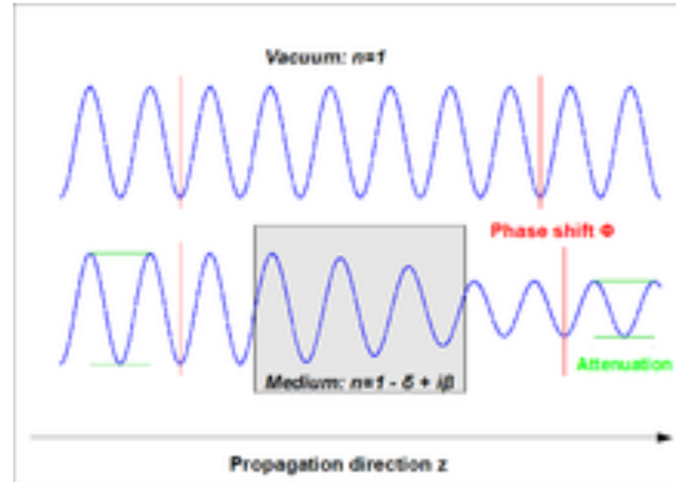


Bright field microscopy
maps distribution of imaginary part of refractive index

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

Peak hunting

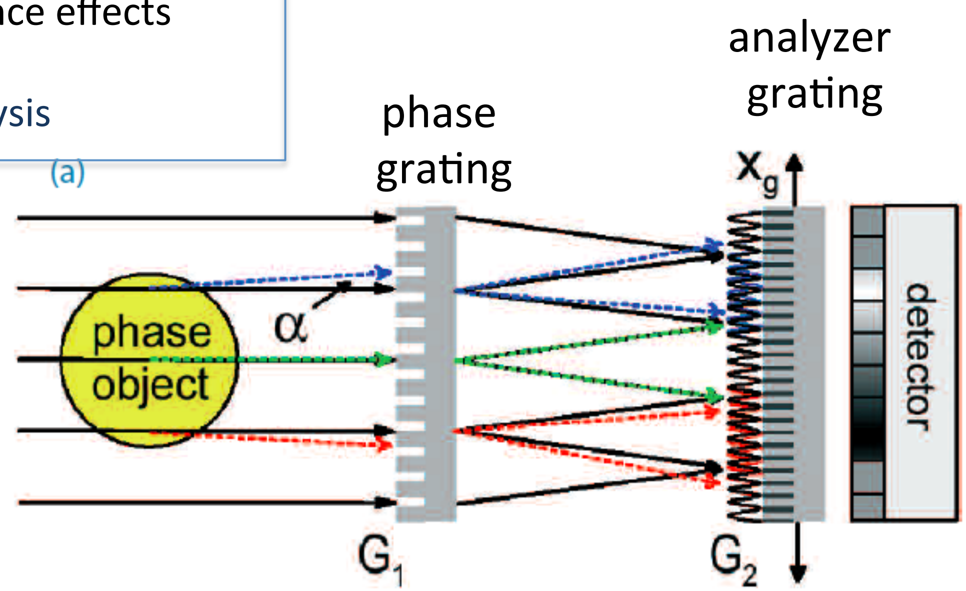
Dalitz plot analysis



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

with X-rays:

- *Re(n) < 1*
- Phase shift translated into deflection
- detect via X-ray grating
- Measure with reference(analyzer) grating

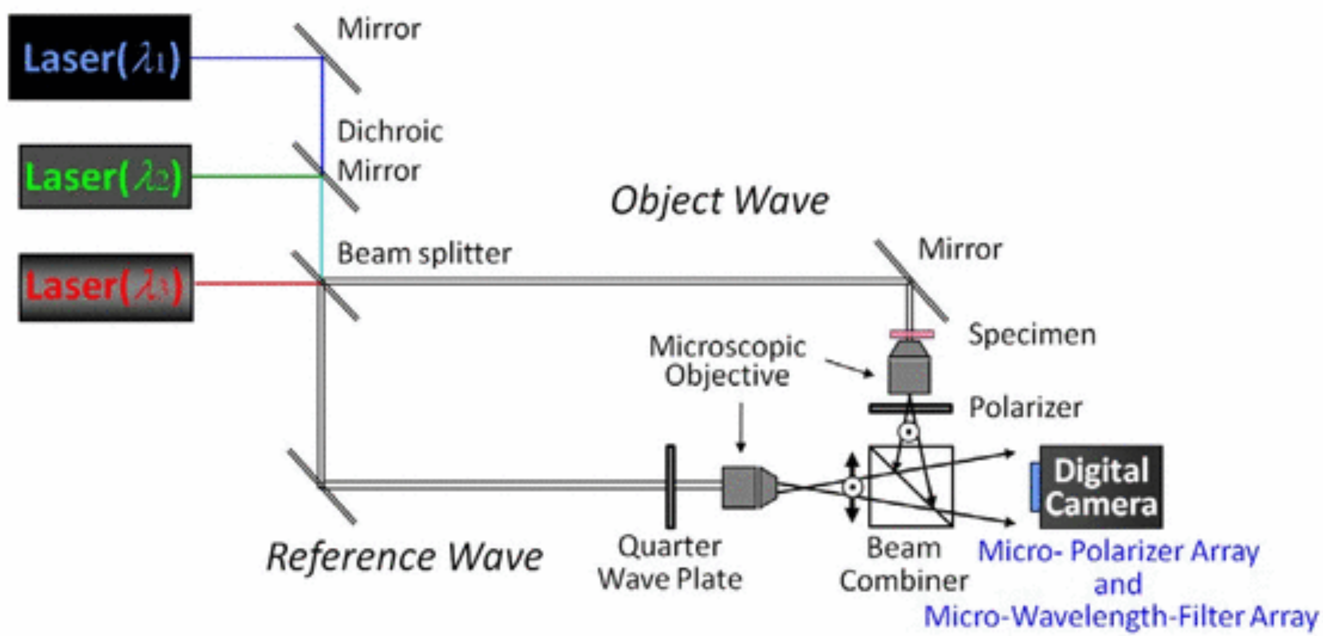


Add more dynamics

Optical methods:

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

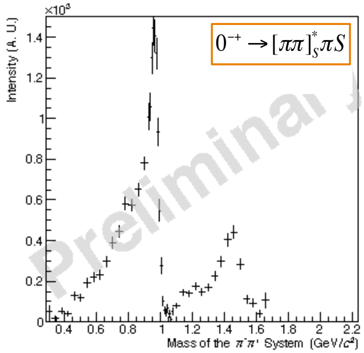
- solves sign of phase shift ambiguities
- useful for recording dynamic processes

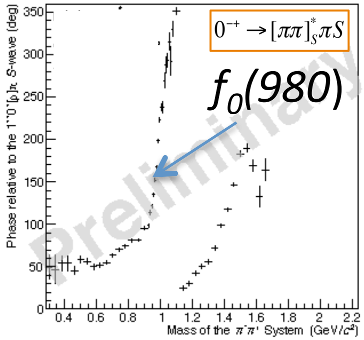


Compass: Combine results at different t'

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

at π(1800)





$\pi\pi_S$ Intensities

$\pi\pi_S$ phases

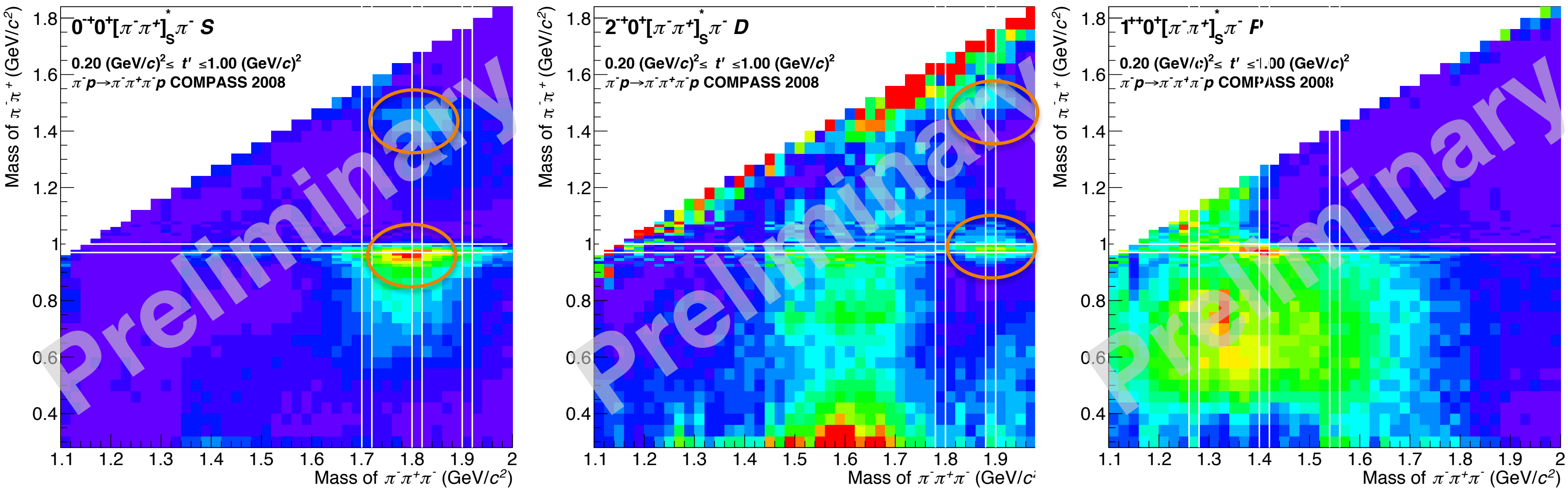
$$\phi_{tot} = \phi^{3\pi}_{production} + \varphi^{2\pi}_{decay}$$

$\pi\pi_S$ Argand diagram

high t

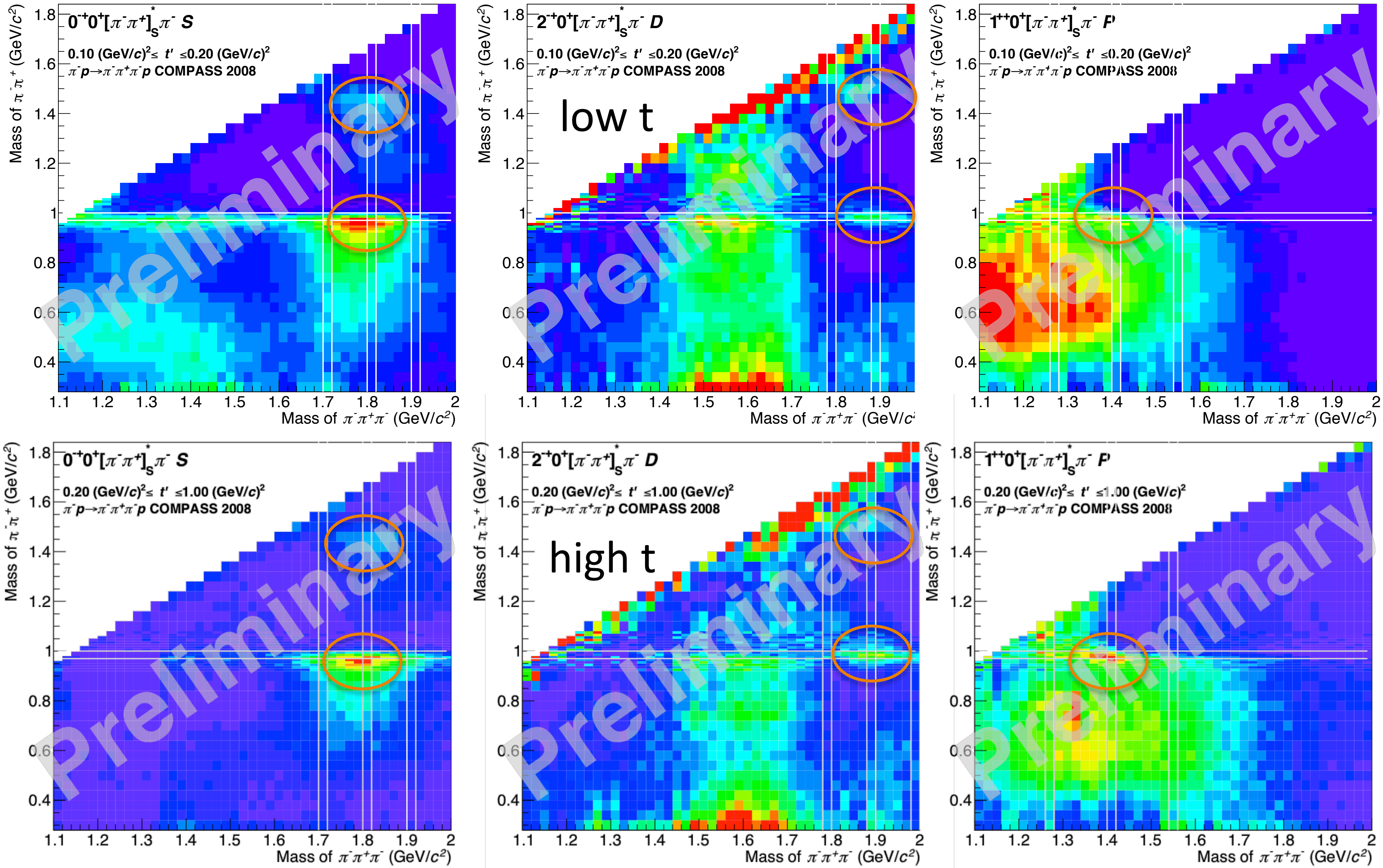
Exzellenzcluster Universe

Correlation: $m_{2\pi} - m_{3\pi}$



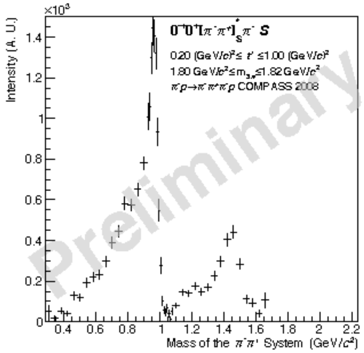
high t'

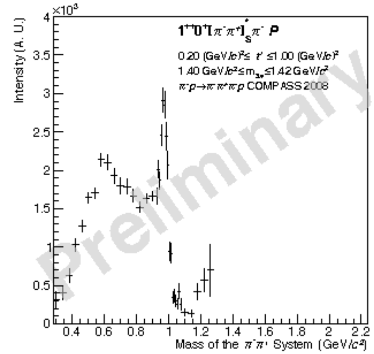
Correlation: $m_{2\pi} - m_{3\pi}$

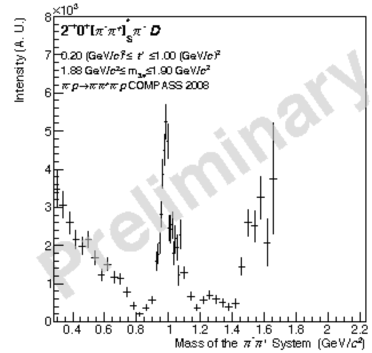


Details on $(\pi\pi)_{S\text{-wave}}$

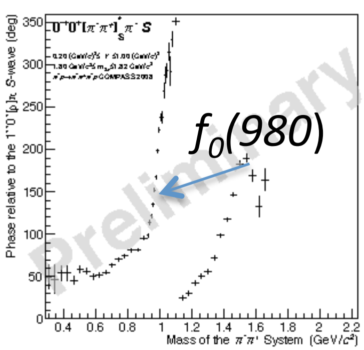
at $\pi(1800)$	at $a_1(1420)$	at $\pi_2(1880)$

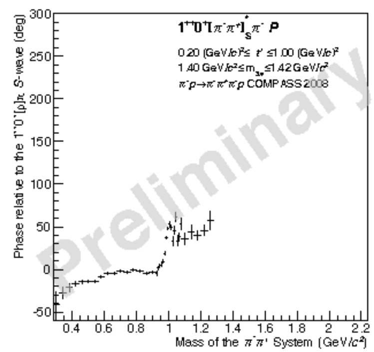


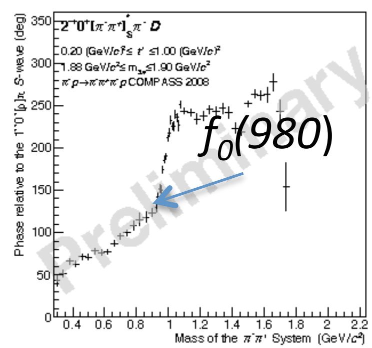




$\pi\pi_S$ Intensities in the resonance region

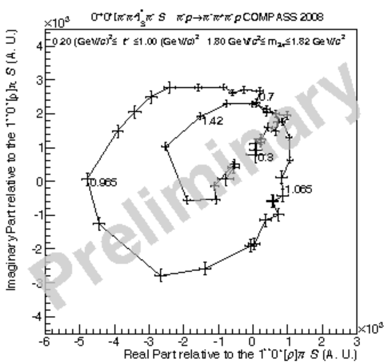


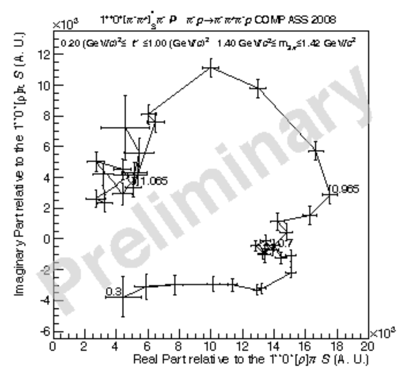


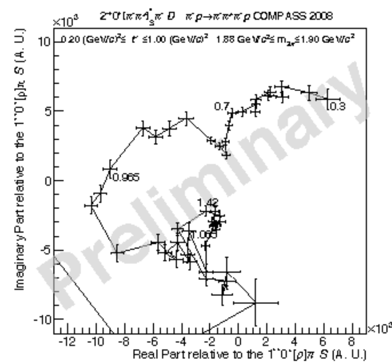


$\pi\pi_S$ phases in the resonance region

$\phi_{production}$ + ϕ_{decay}



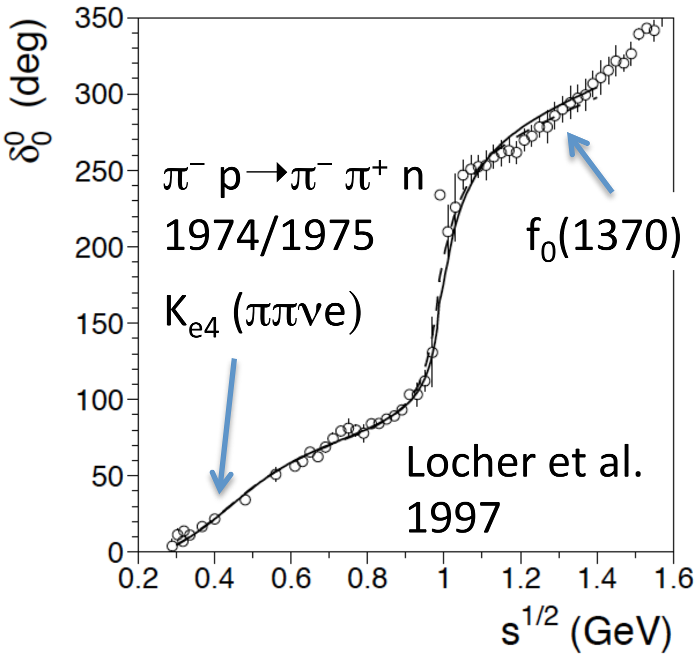


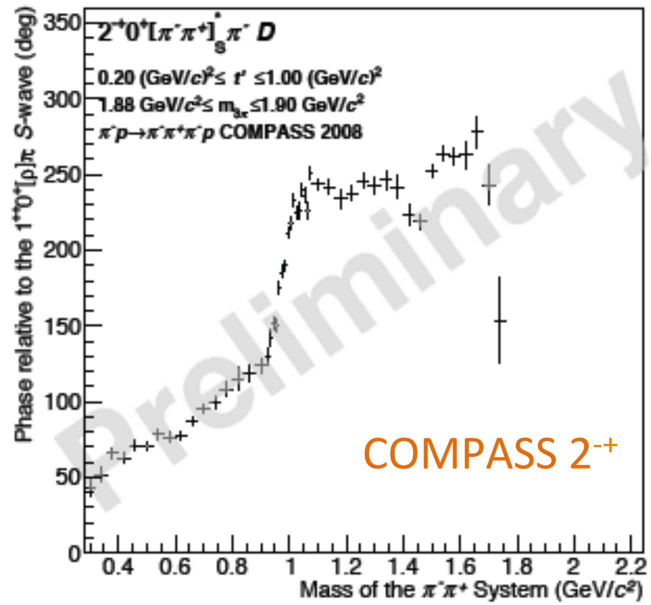


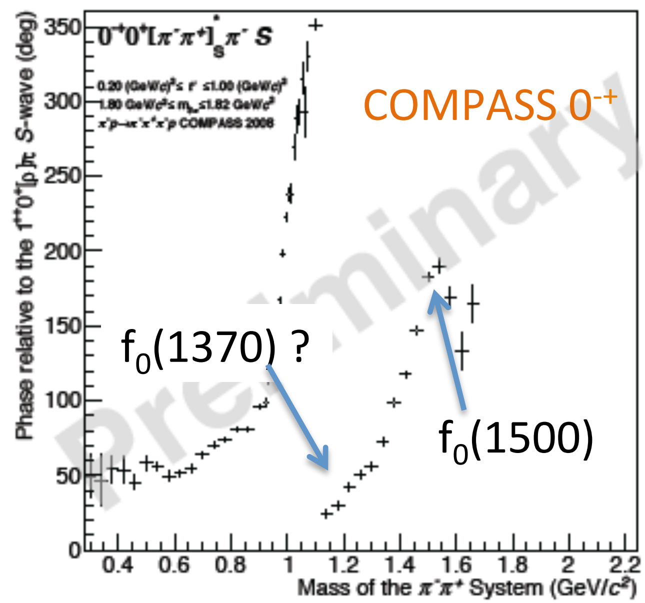
high t'

Exzellenzcluster Universe

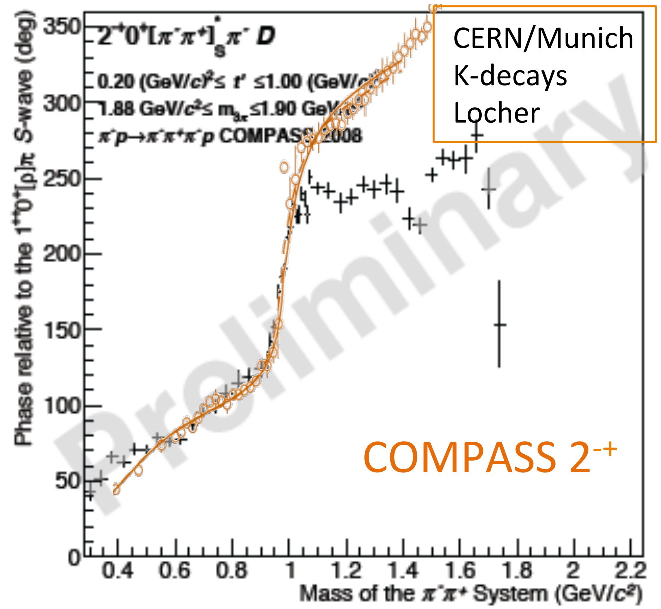
Some intriguing aspects

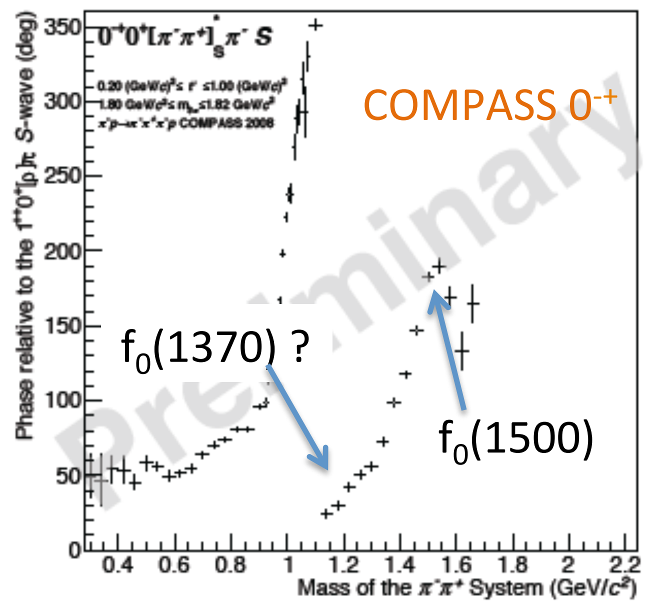


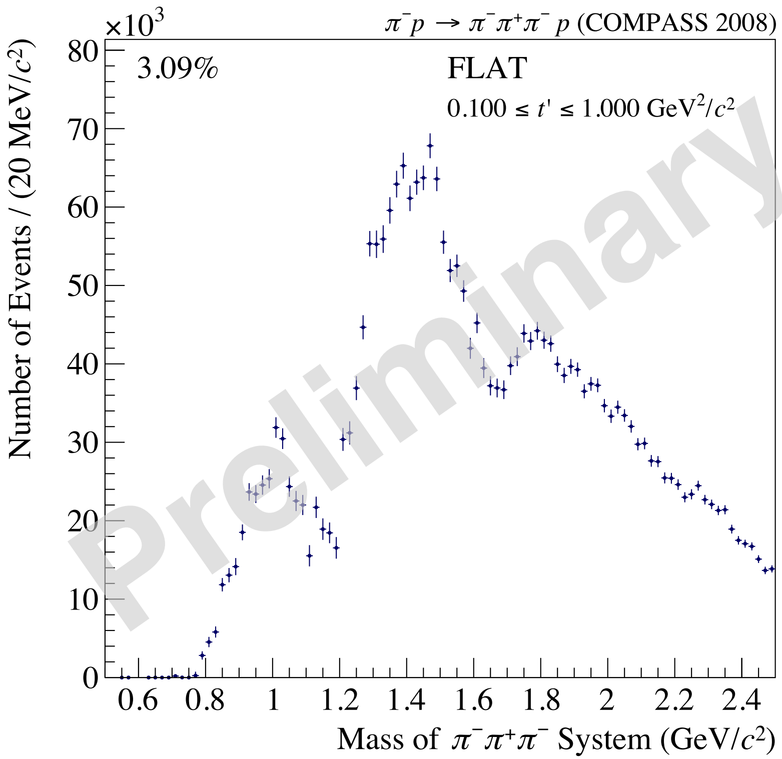




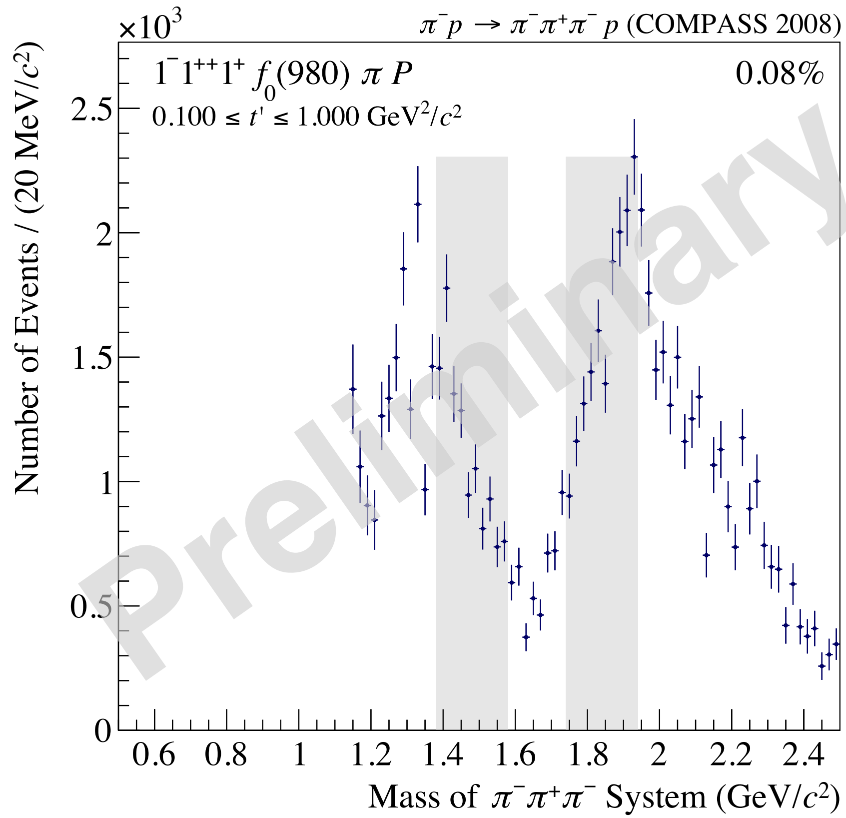
Some intriguing aspects





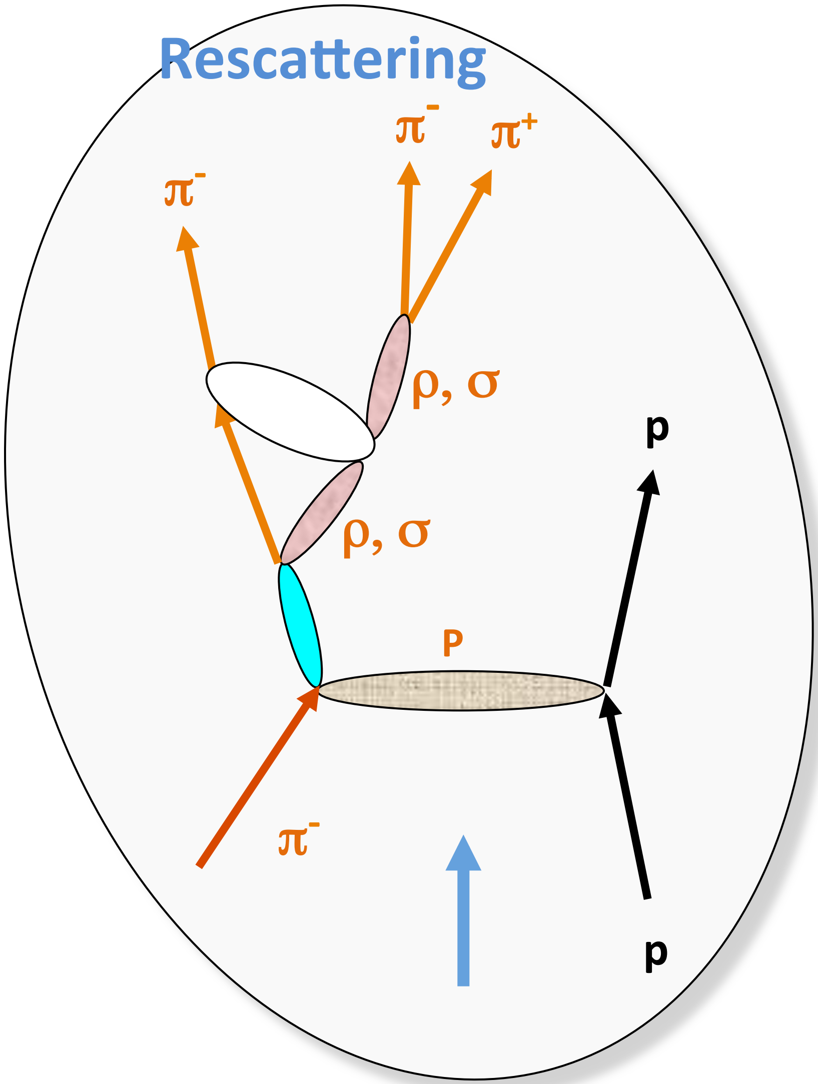


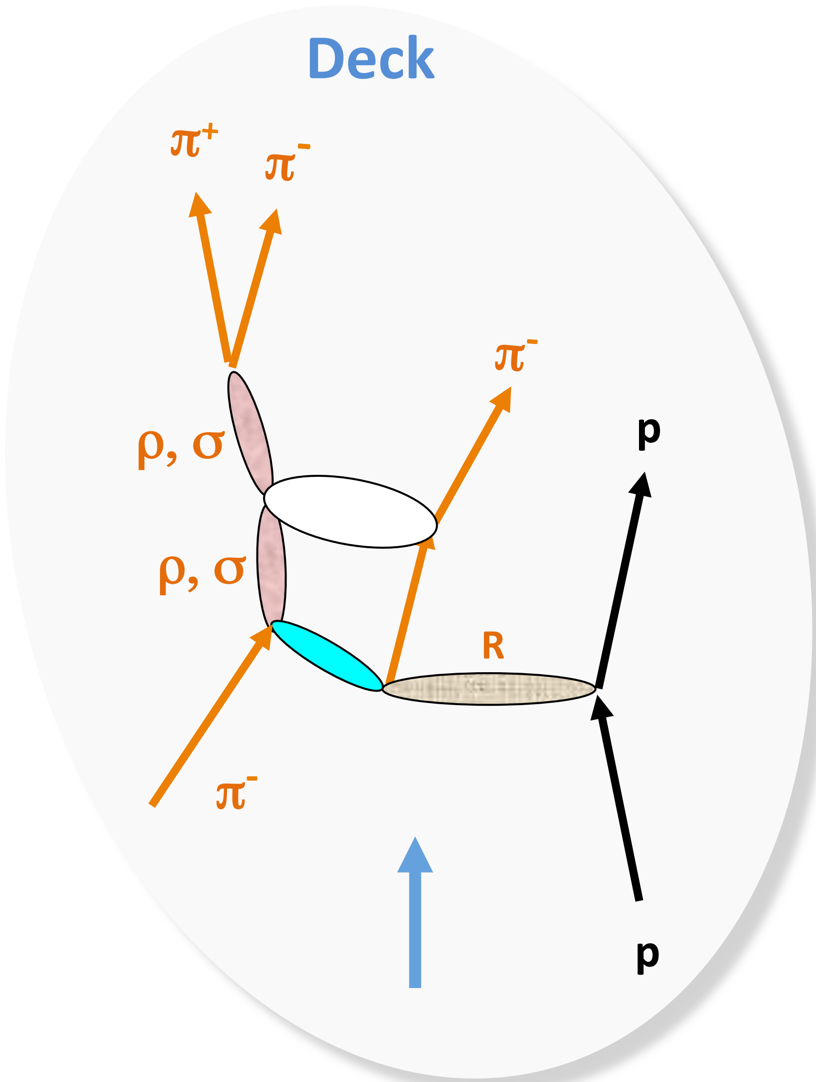
×10^3
π⁻p → π⁻π⁺π⁻ p (COMPASS 2008)
3.09%
FLAT
0.100 ≤ t' ≤ 1.000 GeV²/c²
Number of Events / (20 MeV/c²)
Mass of π⁻π⁺π⁻ System (GeV/c²)
Preliminary



×10^3
π⁻p → π⁻π⁺π⁻ p (COMPASS 2008)
1⁻1⁺⁺1⁺ f0(980) π P
0.08%
0.100 ≤ t' ≤ 1.000 GeV²/c²
Number of Events / (20 MeV/c²)
Mass of π⁻π⁺π⁻ System (GeV/c²)
Preliminary

Non-resonant processes

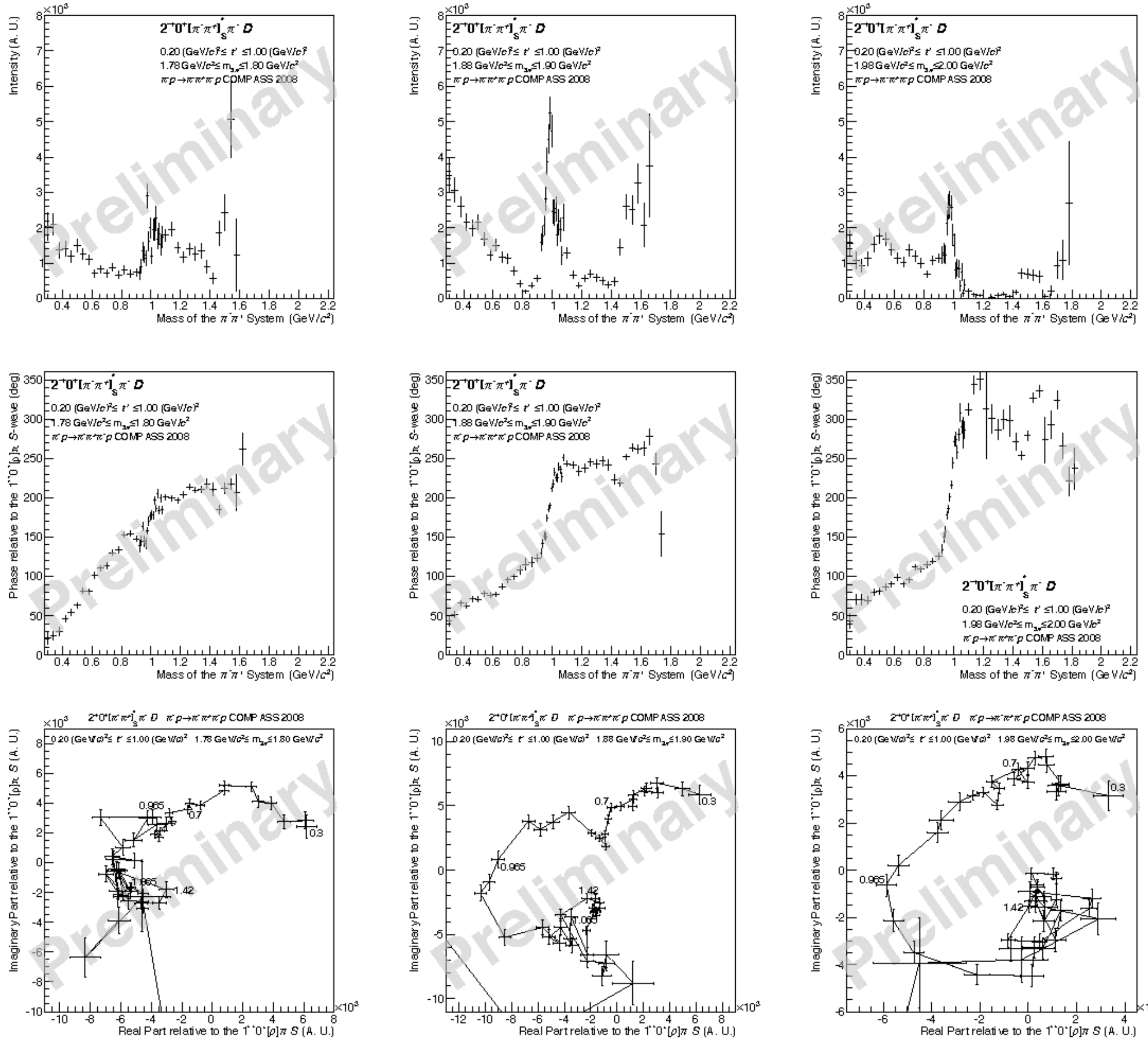




$(\pi\pi)^*_{\text{S-wave}}\ 2^{-+}$

below resonance	at $\pi_2(1880)$	above resonance

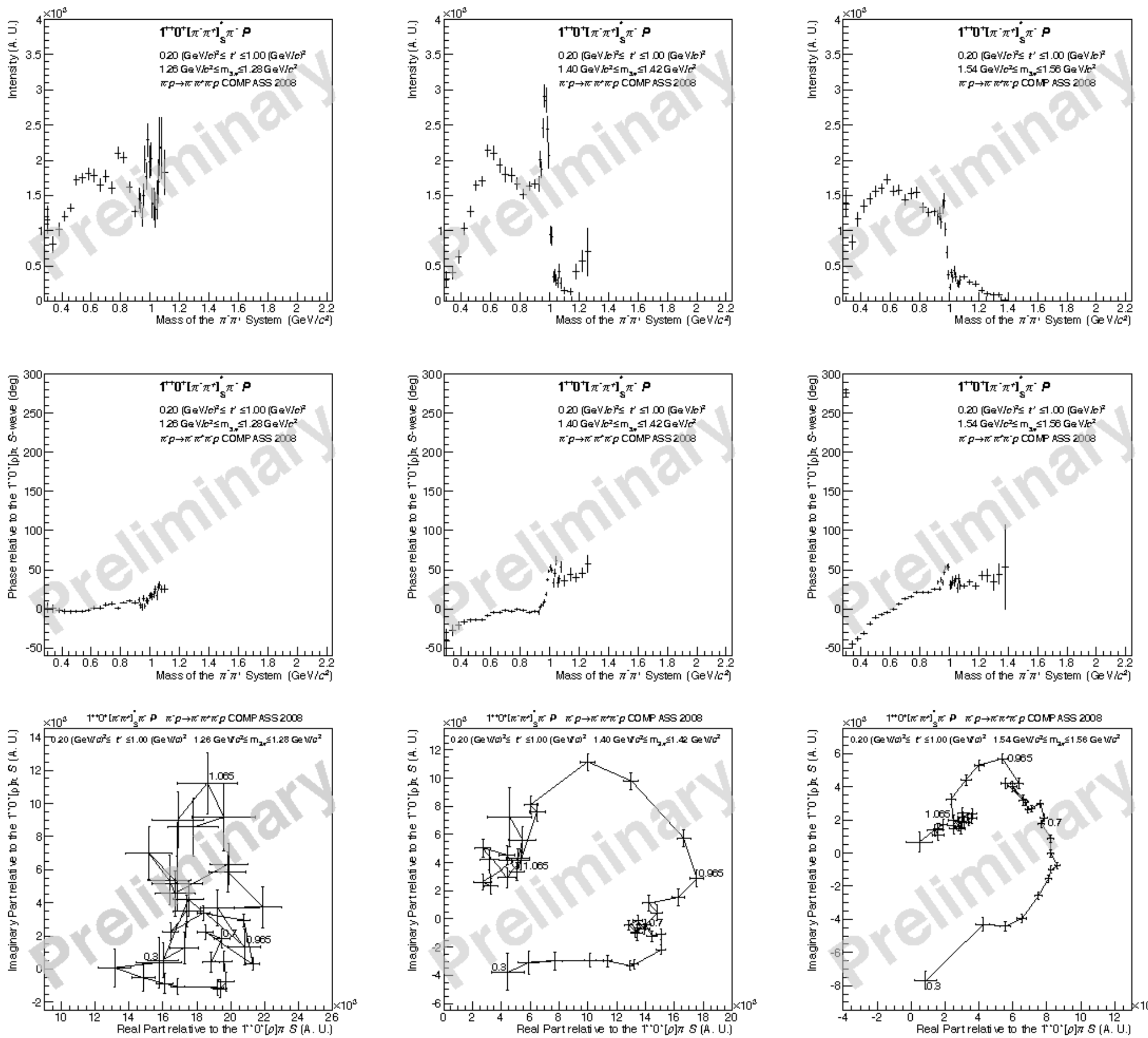
high t’



$(\pi\pi)^*_{S\text{-wave}}\ 1^{++}$

below resonance	at $a_1(1420)$	above resonance

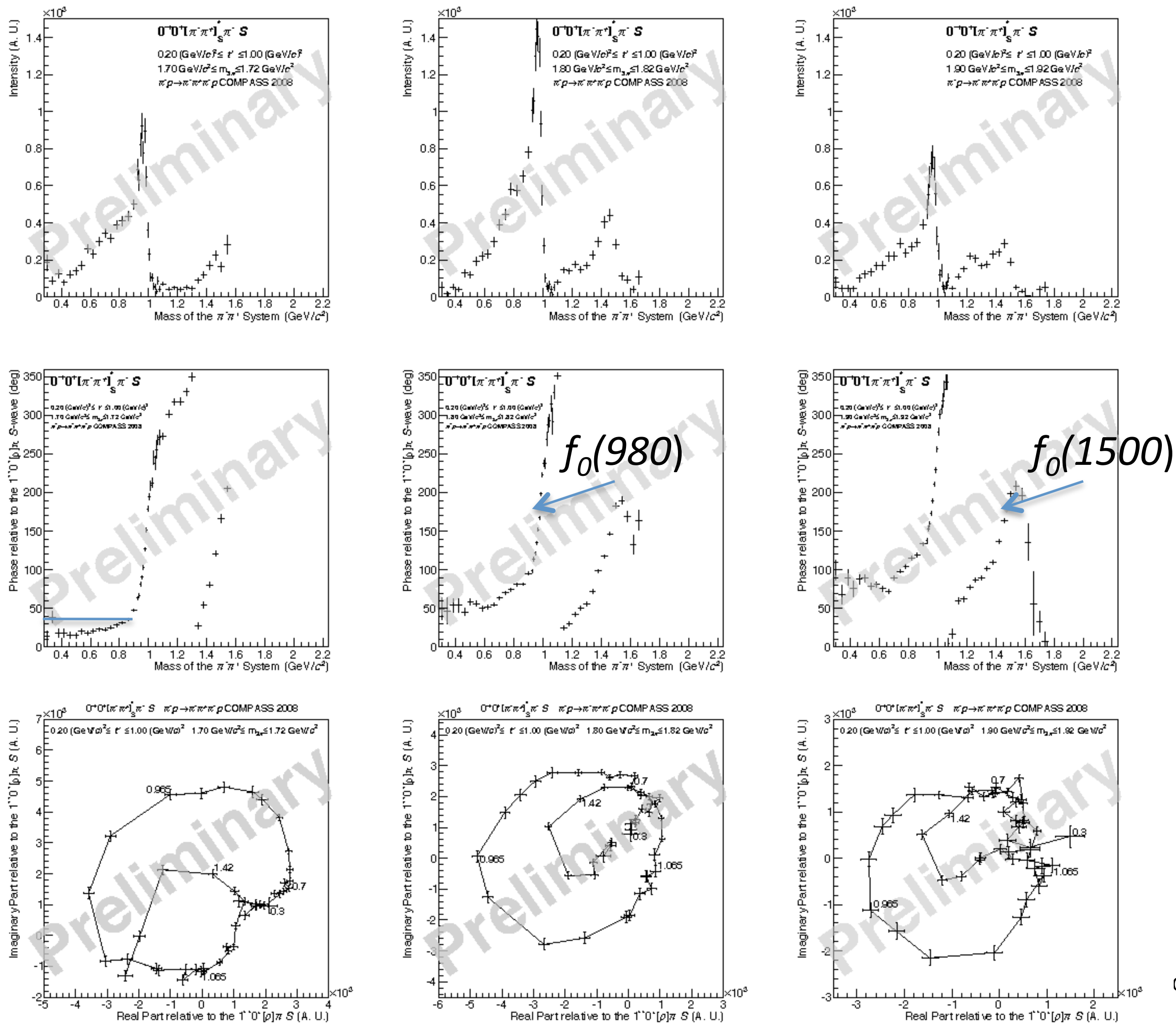
high t'



$(\pi\pi)^*_{S\text{-wave}}\ 0^{-+}$

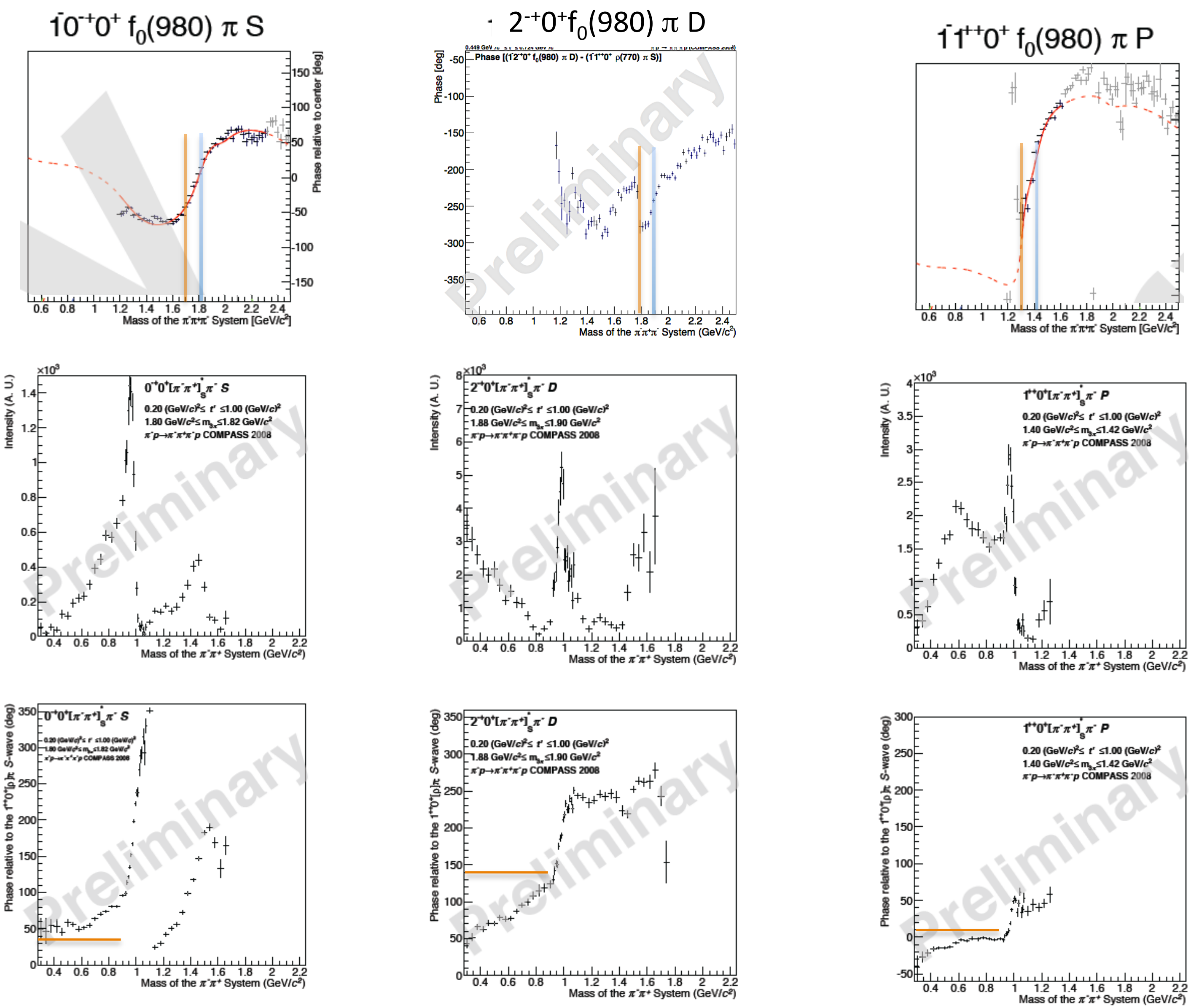
below resonance | at $\pi(1800)$ | above resonance

high t'



cluster Universe

Discussion of $\pi\pi$–Phases



Production phase using $f_0(980)$

$\pi\pi_S$ Intensities in the resonance region

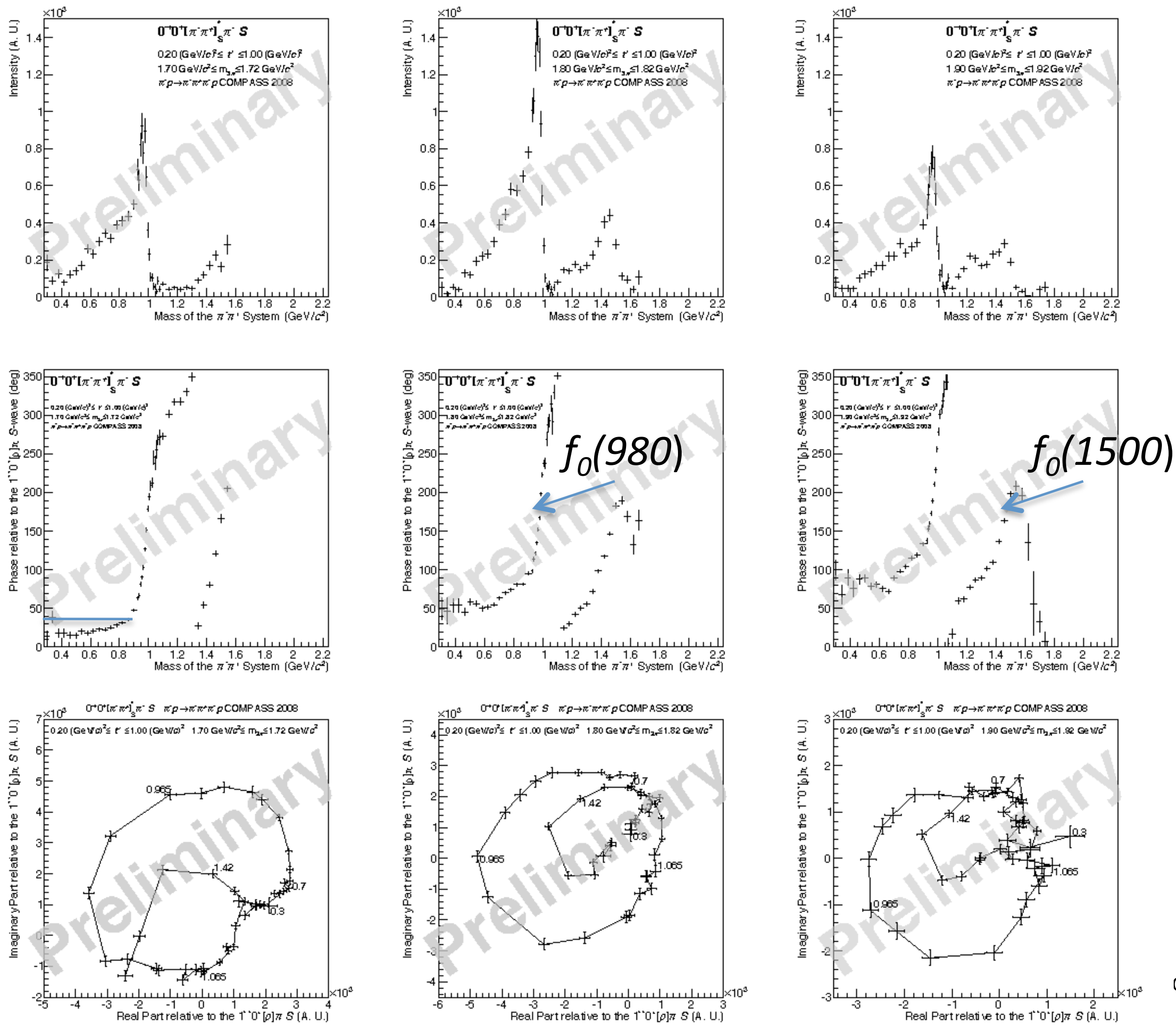
$\pi\pi_S$ phases in the resonance region

$\phi_{production}$ + ϕ_{decay}

$(\pi\pi)^*_{S\text{-wave}}\ 0^{-+}$

below resonance | at π(1800) | above resonance

high t’



cluster Universe

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

- absorb complex strength functions f_k into $T^{k,\varepsilon}_{\alpha r,J^{PC}[\pi^+\pi^-]_{\text{S-wave}}}$
- write intensity as: $\mathcal{I}(\tau) = \sum_{r=1}^{N_r} \sum_{\varepsilon=\pm 1} \left| \sum_{\alpha} T^{\varepsilon}_{\alpha r} \psi^{\varepsilon}_{\alpha}(\tau) \right|^2 + T^2_{FLAT}$

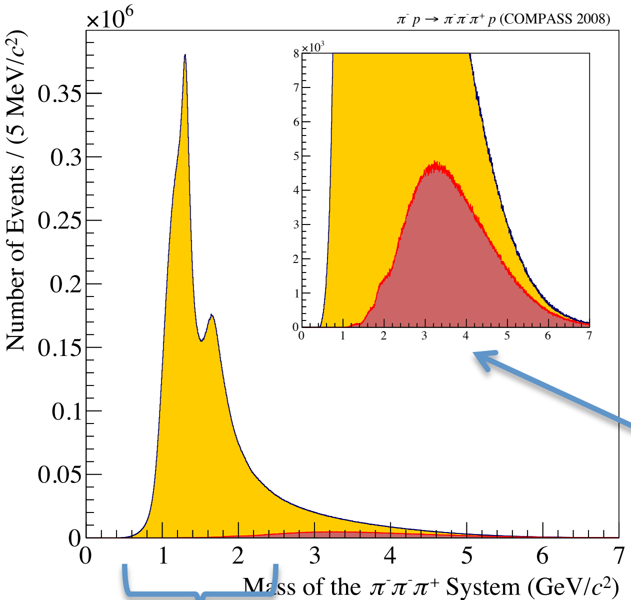
  and fit f_k :
  - for each 2-body mass bin k (bin width variable)
  - for each 3-body mass bin m_X (bin width 20 MeV/c^2)
- Determine phase as usual : w.r.t. $1^{++}0^{+}\rho\pi S$
- Mass dependent fit:
  - use anchor wave with parametrization of 2π-isobars
  - use model for 3π-isobars and 2π-isobars:

    $f0(600),\ f0(980),\ f0(1370),\ f0(1500) \quad exp(-\alpha p^2)$

$$\rho_{0,j}(m_X) = \left(\sum_k C_{0k} BW_{0k}(m_{3\pi}) \right)^* \cdot \left(\sum_{k,q} C_{jkq} BW_{jk}(m_{3\pi}) BW_{kq}(m_{2\pi}) \right)$$

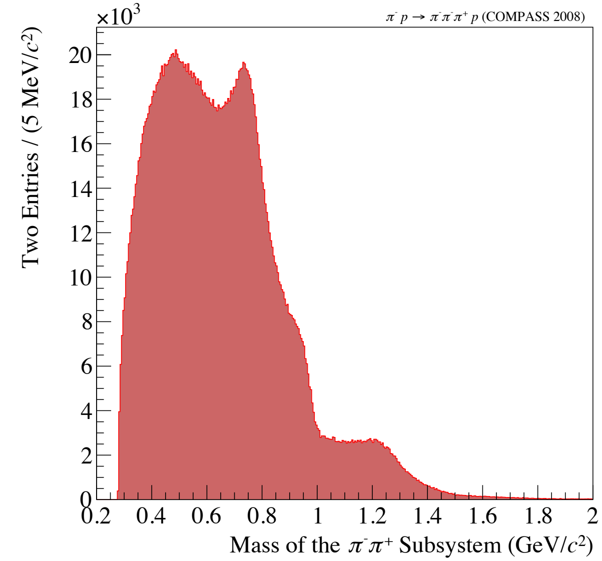
Mass distributions

$m_{3\pi}$



$m_{3\pi}$
rejected by CP-cut

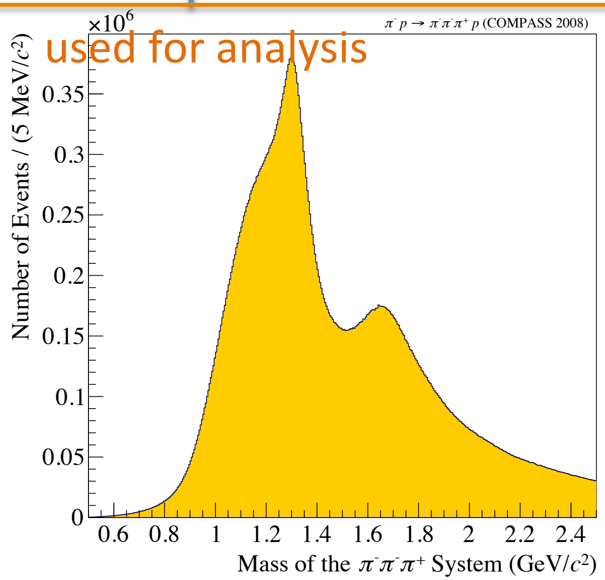
$m_{2\pi}$

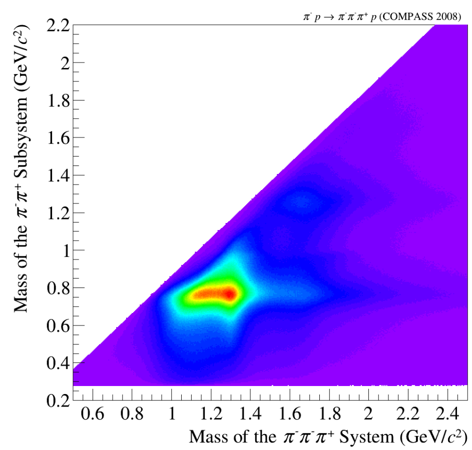


used for analysis

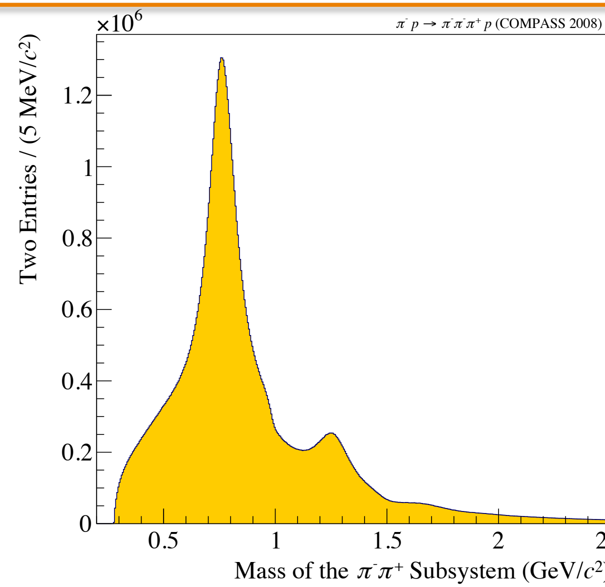
after all cuts

$m_{3\pi}$

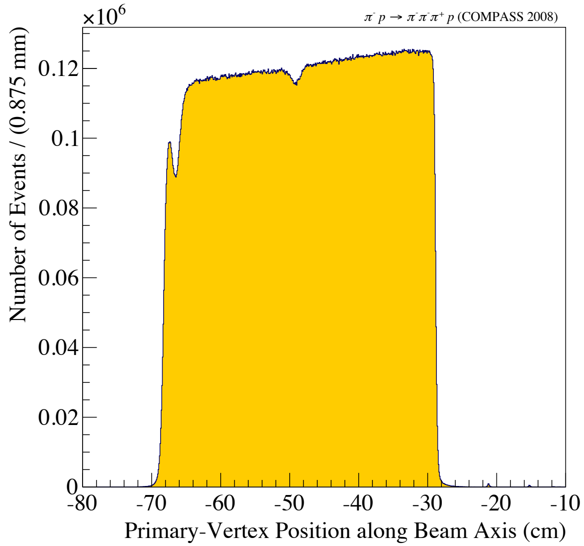




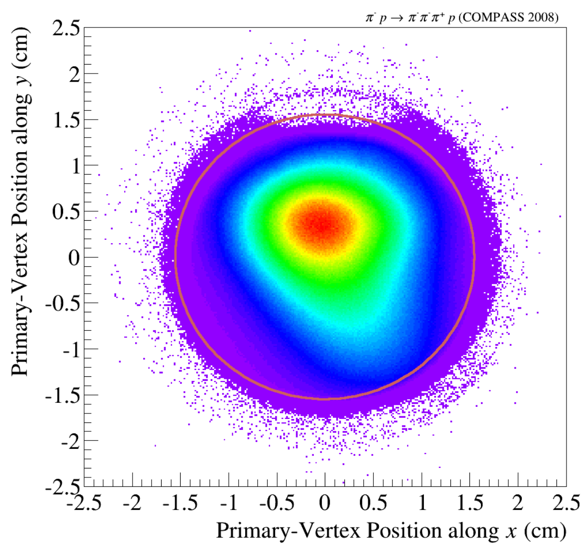
$m_{2\pi}$



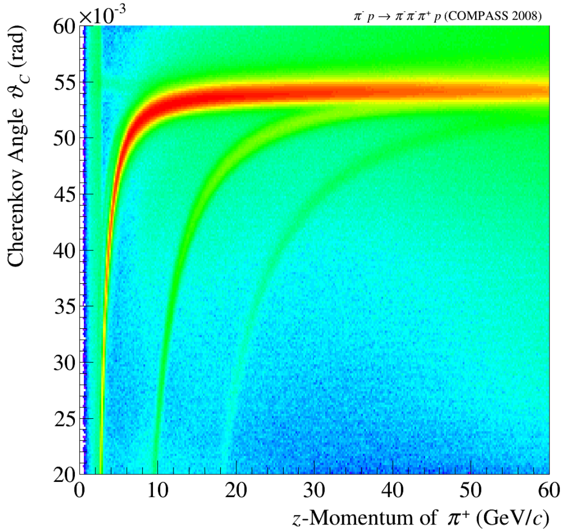
Technical plots



z-vertex



x/y-vertex



RICH before PID cuts

of parameters

- 6 waves: (9 BW + 6 NR)*11(t'-bins)=165 couplings
  - for each complex coupling: 2 parameters
  - minus 11 since 1 coupling for each t' bin is real
  - 319 parameters
- 18 parameters for BW
- 15 parameters for NR

- Total: 352 real parameters

Mass dependent fit

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

Model:

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

#	Partial Wave	Lower Bound [GeV/c^2]	Upper Bound [GeV/c^2]
1	$1^{++}0^{+}\rho\pi S$	0.90	2.32
2	$2^{++}1^{+}\rho\pi D$	0.90	2.12
3	$2^{-+}0^{+}f_2(1270)\pi S$	1.40	2.32
4	$4^{++}1^{+}\rho\pi G$	1.25	2.32
5	$1^{++}0^{+}f_0(980)\pi P$	1.30	1.60
6	$0^{-+}0^{+}f_0(980)\pi S$	1.20	2.50

Fit Functions

Resonances

Simple fixed-width Breit-Wigner:

$$\mathcal{F}(m) = \frac{\sqrt{m_0\,\Gamma_0}}{m_0^2 - m^2 - i\,m_0\,\Gamma_0}$$

Breit-Wigner with mass-dependent width for one decay channel:

$$\mathcal{F}(m) = \frac{\sqrt{m_0\,\Gamma_0}}{m_0^2 - m^2 - i\,m_0\,\Gamma(m)}; \quad \Gamma(m) = \Gamma_0\,\frac{m_0}{m}\,\frac{q\,F_L^2(q)}{q_0\,F_L^2(q_0)}$$

Breit-Wigner with mass-dependent width for decay channels:

$$\mathcal{F}(m) = \frac{\sqrt{m_0\,\Gamma_0}}{m_0^2 - m^2 - i\,m_0\,\Gamma(m)}; \quad \Gamma(m) = \Gamma_0\,\frac{m_0}{m}\left[(1-x)\frac{q_1\,F_L^2(q_1)}{q_{1,0}\,F_L^2(q_{1,0})} + x\,\frac{q_2\,F_L^2(q_2)}{q_{2,0}\,F_L^2(q_{2,0})}\right]$$

Bowler parametrization:

$$\mathcal{F}(m) = \frac{\sqrt{m_0\,\Gamma_0}}{m_0^2 - m^2 - i\,m_0\,\Gamma_B(m)}; \quad \Gamma_B(m) = \Gamma_0\,\frac{m_0}{m}\,\frac{\phi_3(m)}{\phi_3(m_0)}$$

non-resonant

$$\mathcal{F}_{\mathrm{NR},1}(m, t') = (m - m_0)^{c_0}\,e^{(c_1 + c_2 t + c_3 t^2)\,q^2}$$

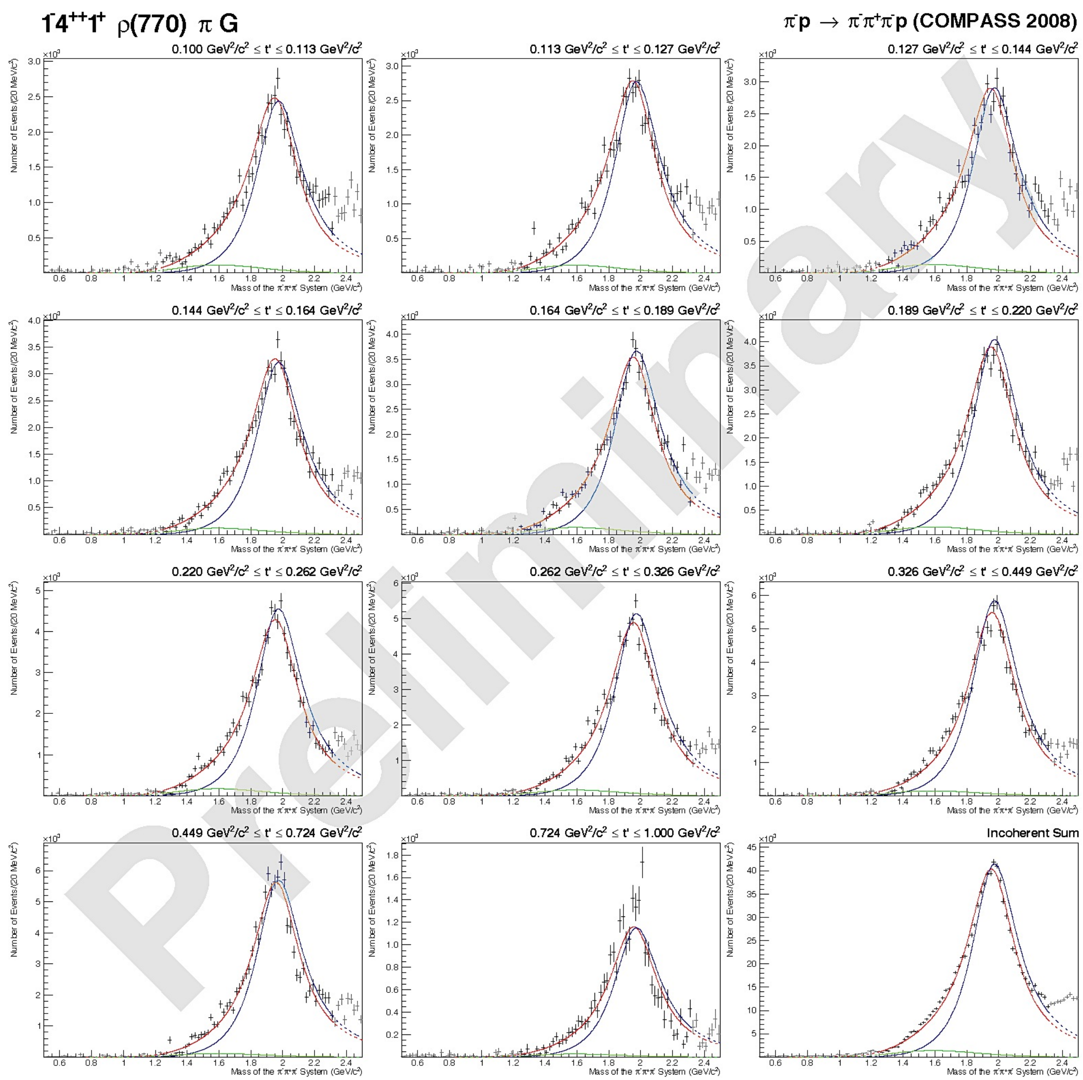
big waves

$$\mathcal{F}_{\mathrm{NR},2}(m) = e^{c_1\,q^2}$$

small waves

Mass dependent fits

Fit in 11 t-bins



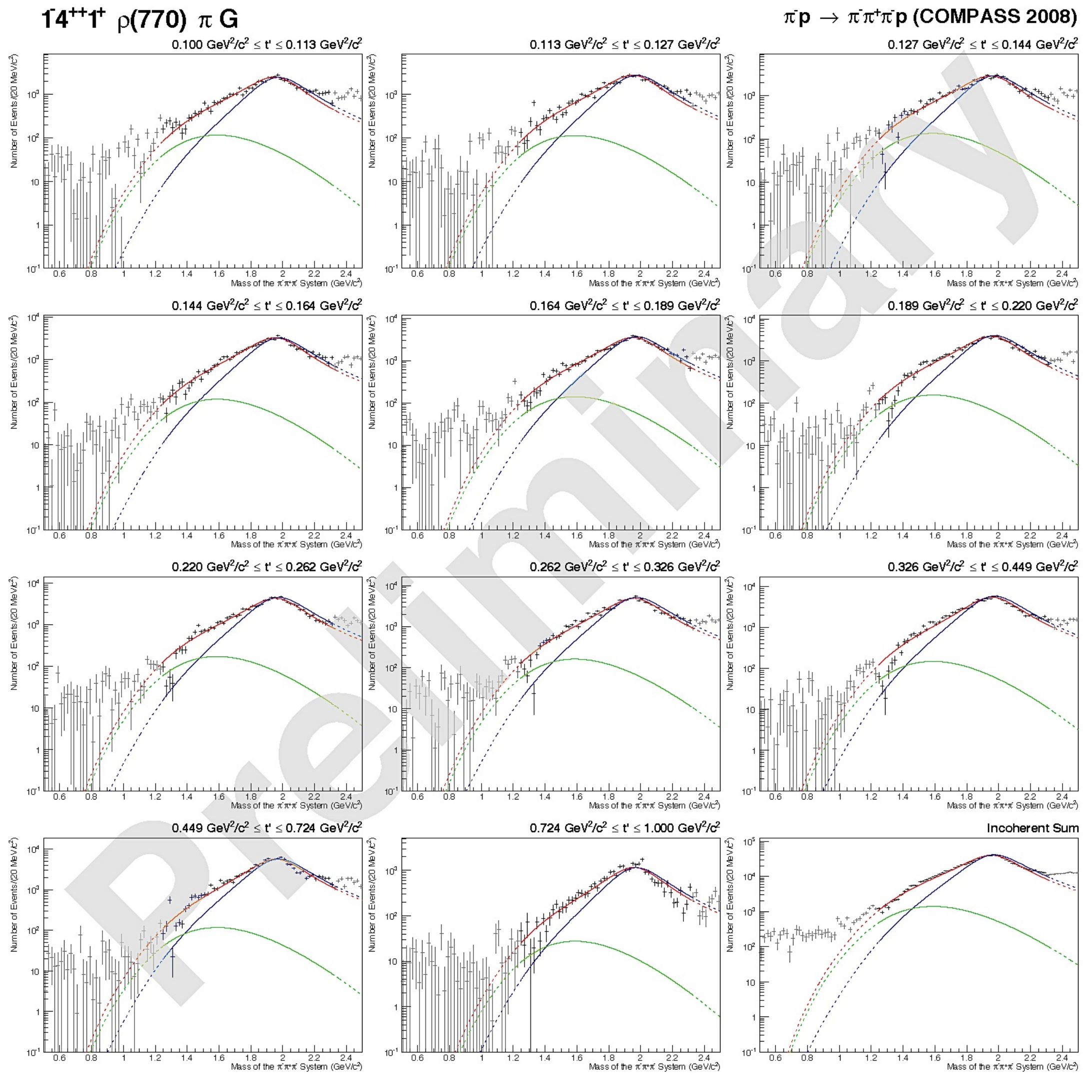
incoherent sum

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

Exzellenzcluster Universe

Mass dependent fits

Fit in 11 t-bins



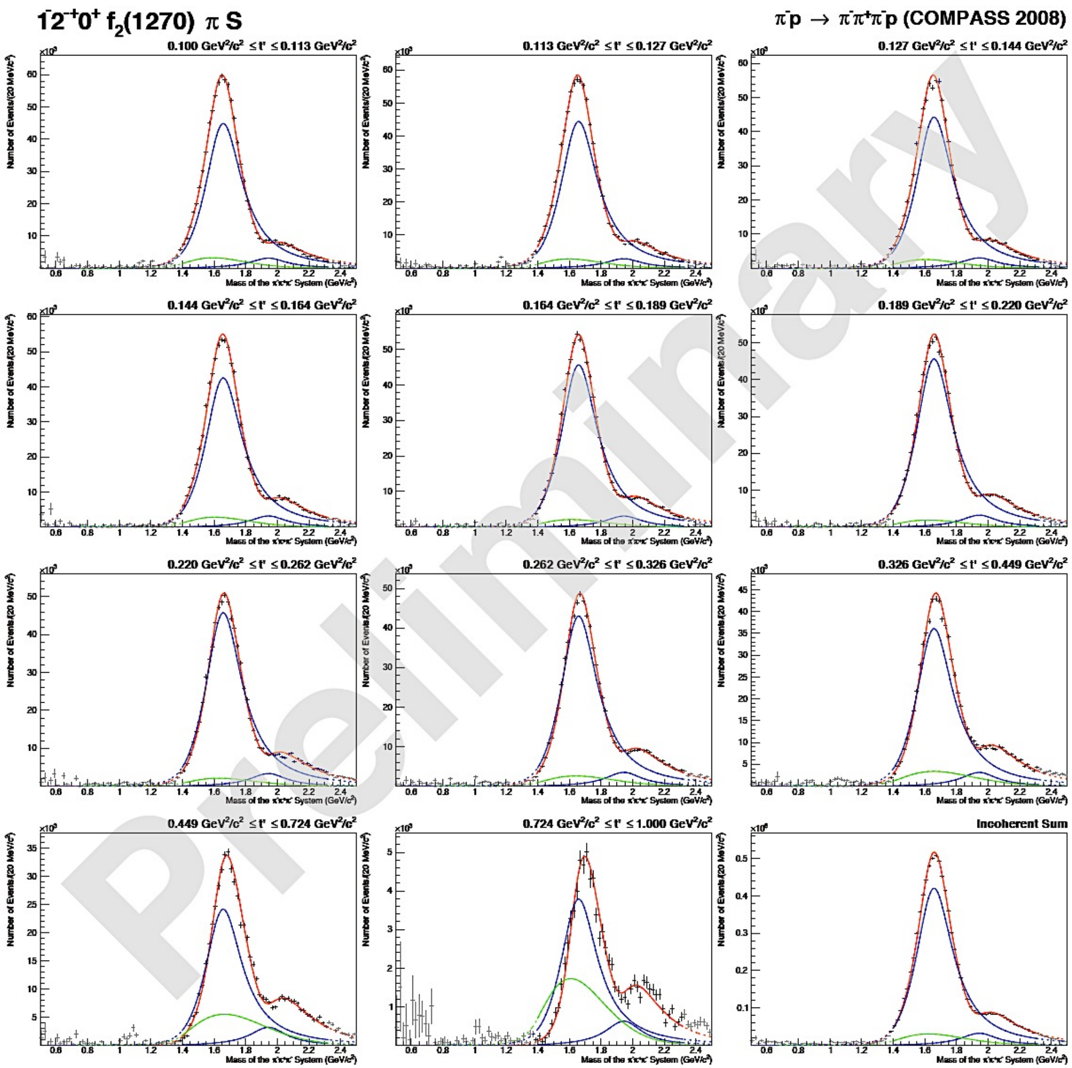
incoherent sum

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

Exzellenzcluster Universe

Mass dependent fits

Fit in 11 t-bins



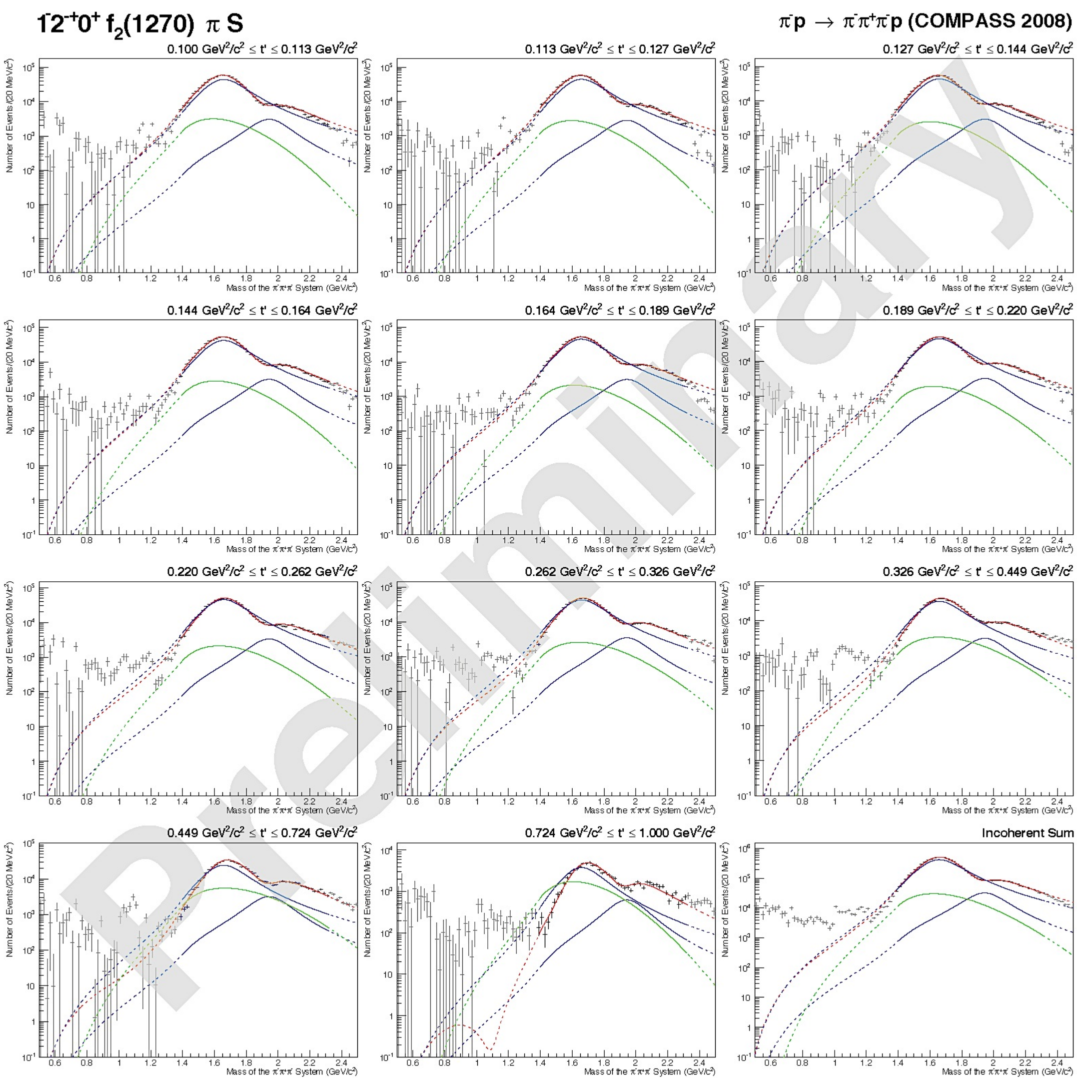
$2^{-+}0^{+} f_2 \pi S$

incoherent sum

Exzellenzcluster Universe

Mass dependent fits

Fit in 11 t-bins



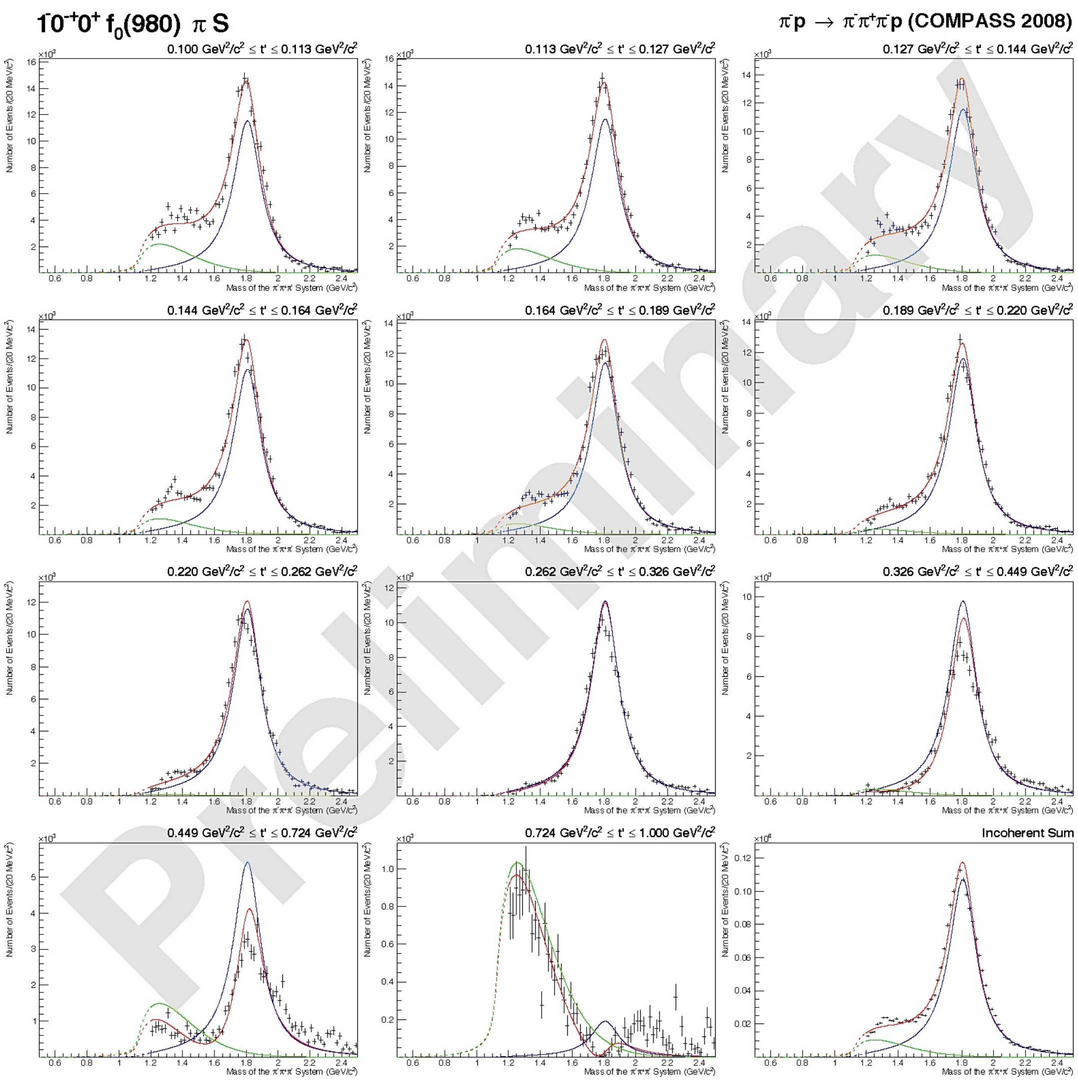
incoherent sum

$2^{-+}0^+ f_2\ \pi\ S$

Exzellenzcluster Universe

Mass dependent fits

Fit in 11 t-bins



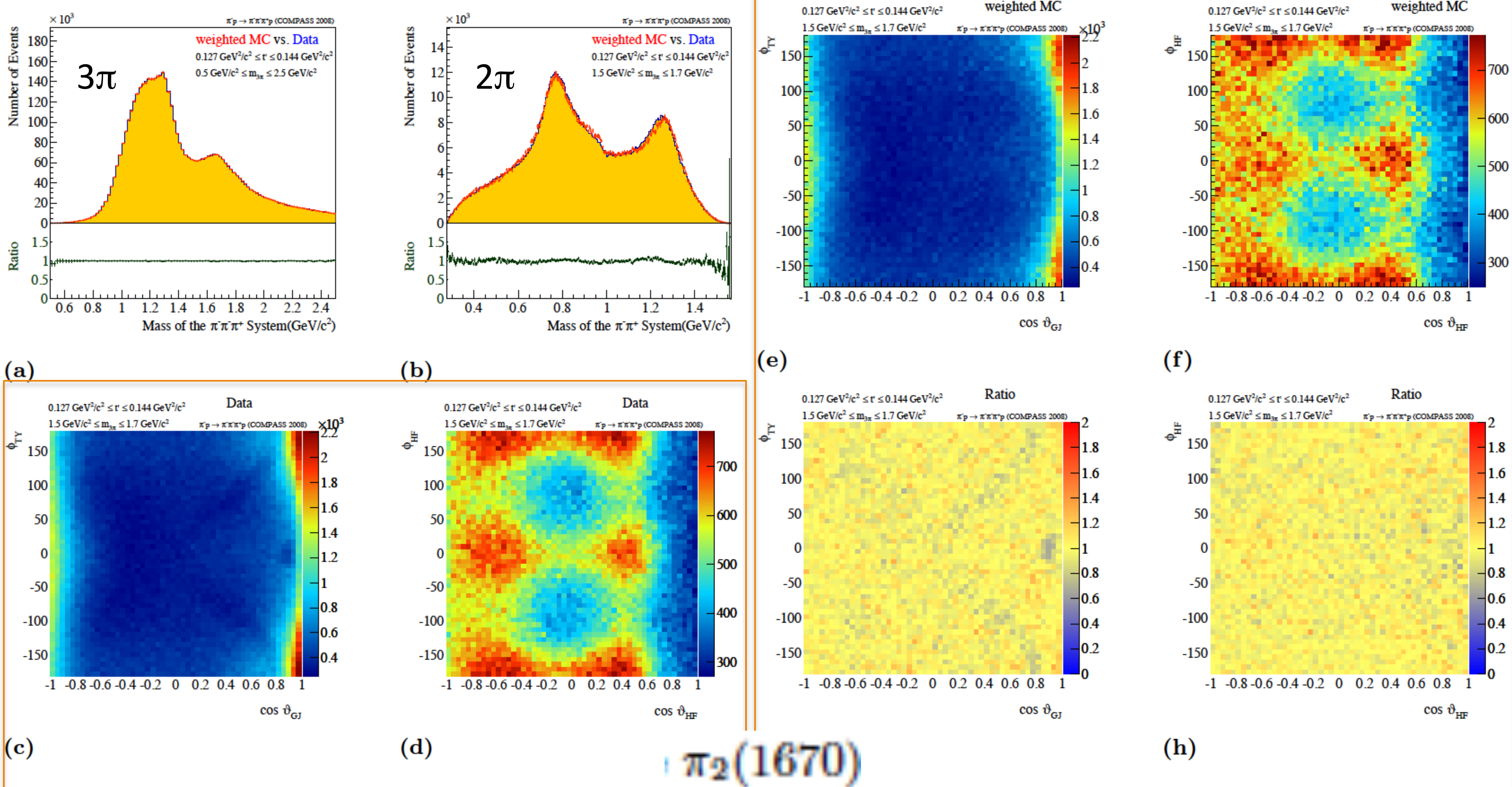
incoherent sum

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

Exzellenzcluster Universe

Data-MC comparison

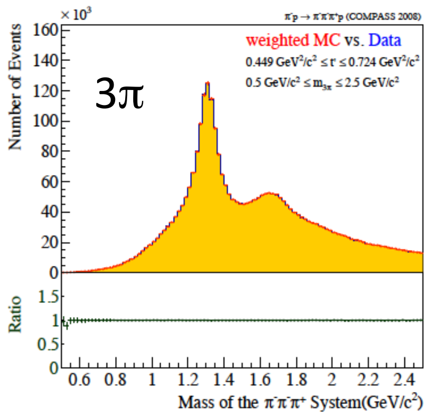
low t'



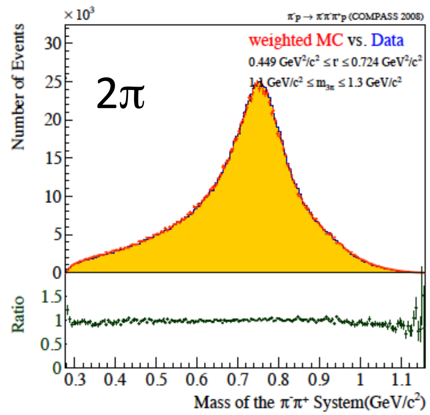
Gottfried-Jackson frame Helicity frame Gottfried-Jackson frame Helicity frame

Data-MC comparison

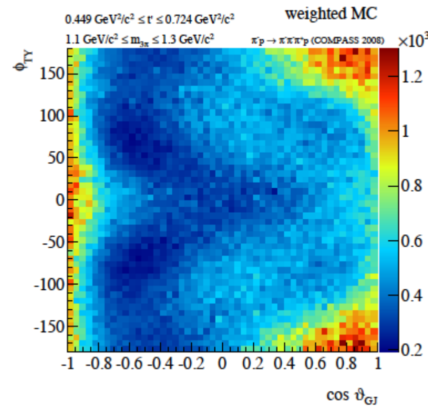
high t'

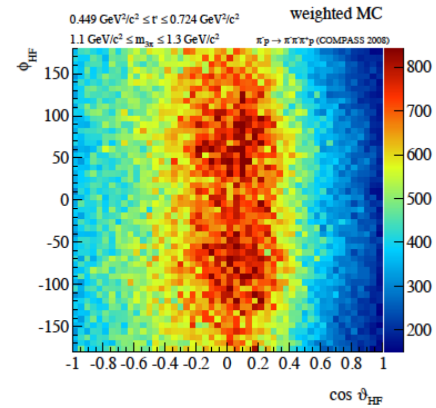


(a)

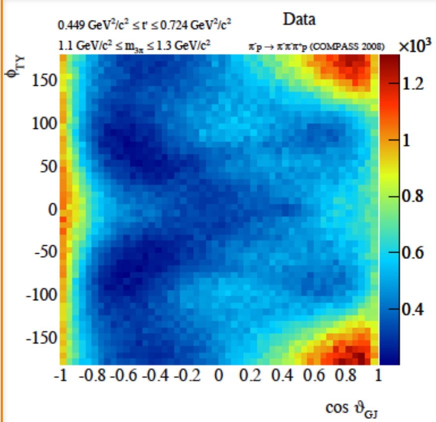


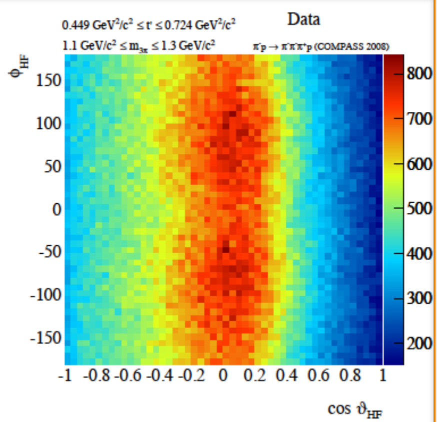
(b)

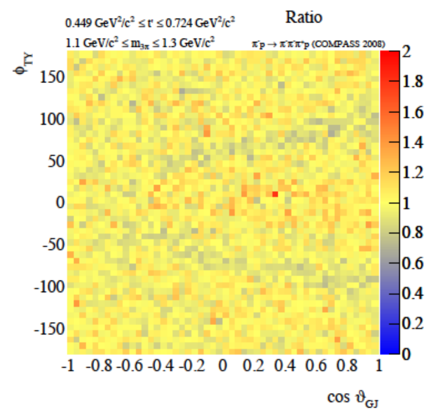


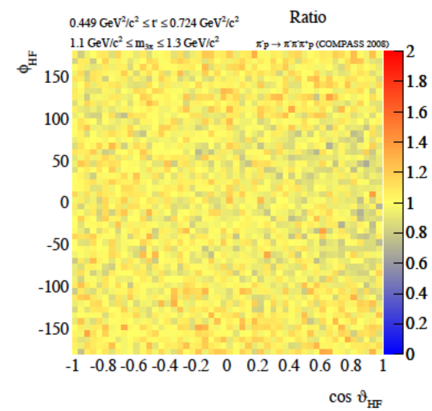


(e) (f)





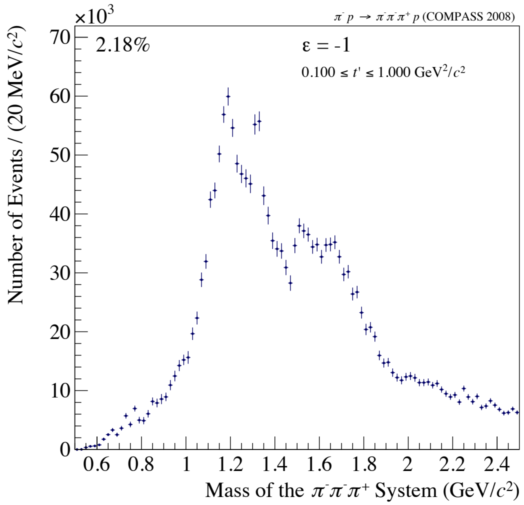


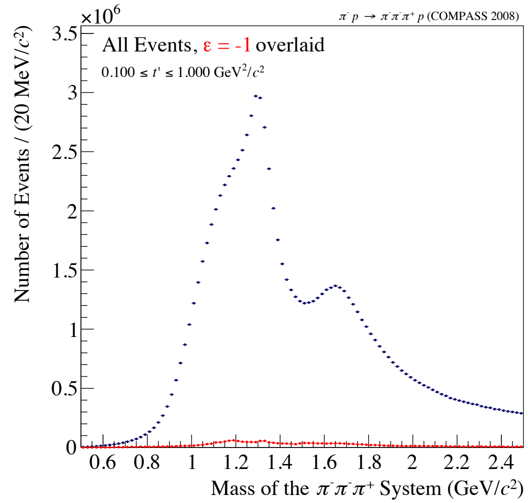


low masses

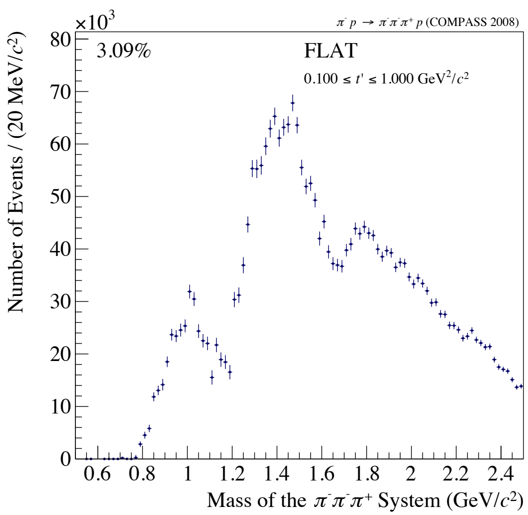
Gottfried-Jackson frame   Helicity frame   Gottfried-Jackson frame   Helicity frame

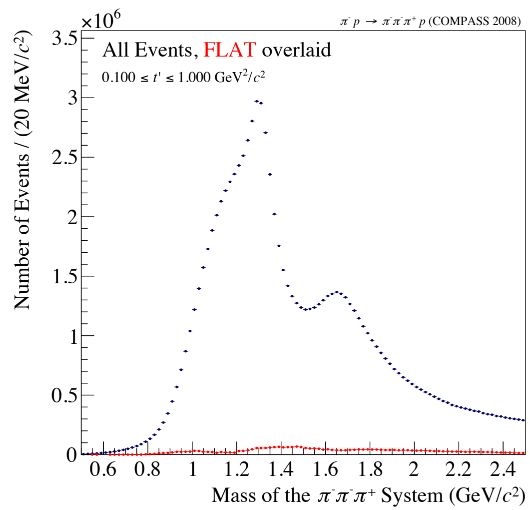
Quick Check for “odd” waves





About 5% absorbed by “odd” waves





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

- and fit decay amplitudes f_k :
  - for each 2-body mass bin k (bin width variable: 10-20 MeV/c²)
  - for each 3-body mass bin m_X (bin width 20 MeV/c²)
- Determine phase as usual : w.r.t. $1^{++}0^{+}\rho\pi S$
- Mass dependent fit:
  - use anchor wave with parametrization of 2π-isobars
  - use model for 3π-isobars and 2π-isobars:

$$f0(600),\ f0(980),\ f0(1370),\ f0(1500)$$

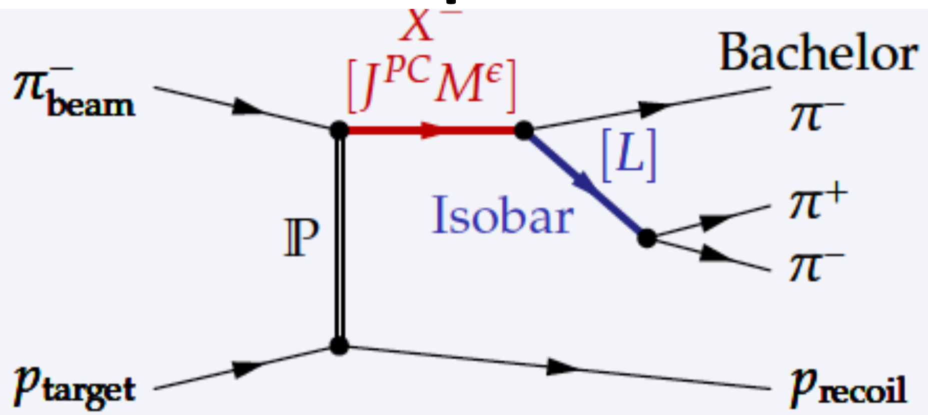
$exp(-\alpha p^2)$ non-resonant

$$\rho_{0,j}(m_X) = \left(\sum_k C_{0k} BW_{0k}(m_{3\pi})\right)^* \cdot \left(\sum_{k,q} C_{jkq} BW_{jk}(m_{3\pi}) BW_{kq}(m_{2\pi})\right)$$

anchor wave

j = 1: 0^{-+} j = 2: 1^{++}

Mass independent fit



Isobar model: spin-parity decomposition

- *Ansatz:* Factorization of production and decay

$$\sigma(m_X, \tau) = \sigma_0 \left| \sum_{\text{waves}} T_{\text{wave}}(m_X)\, A_{\text{wave}}(m_X, \tau) \right|^2$$

  - Transition amplitudes $T_{\text{wave}}(m_X)$ contain interesting physics
- **Determination of $T_{\text{wave}}(m_X)$**
  1. Bin data in m_X
     - Neglect m_X dependence within mass bin
     - No assumptions about 3π resonances
  2. Maximum likelihood fit of 5-dimensional τ distribution in each m_X
     - Takes into account detector acceptance and efficiency
     - Decomposition into (nearly) orthonormal function system $\{A_{\text{wave}}(\tau)\}$

How to produce "other" mesons

- Diffraction: $\pi p_{target} \rightarrow X + p_{recoil} \rightarrow n\pi + p_{recoil}$
  - isospin = 1
  - spin-alignment M of resonance X w.r.t. to production mormal
  - PWA is clean
  - 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
  - "glue-rich" systems
  - PWA with ambiguities for n=2
  - typically populating low spin states J
- 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 J