Virtues and challenges 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

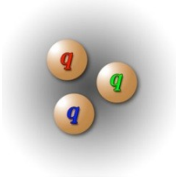
Excellence Cluster Universe

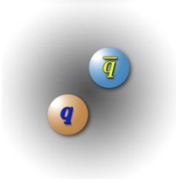
Brief Overview

- 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
- Left out: Central production, Photo production, $\eta\pi$, $\eta'\pi$, $\eta\eta\pi$..

From Quarks to Hadrons

- Hadron: colour neutral system of quarks
  - Baryon (qqq)
  - Meson ($q\bar{q}$)





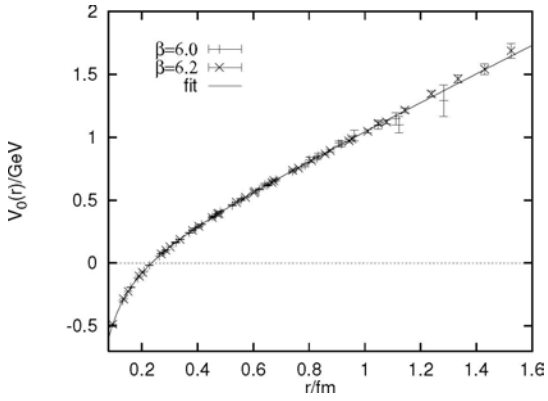
- At small energy scales
  - QCD not analytically solvable
  - Effective degrees of freedom: constituent quarks

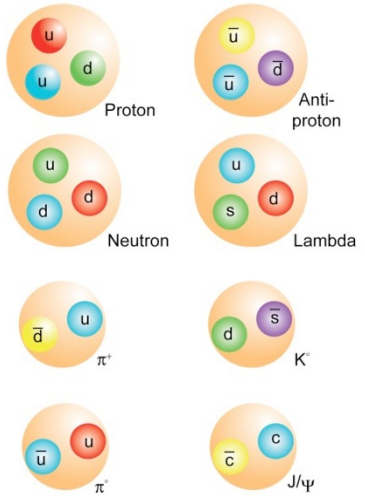
    Coupling quarks with gluon field (99% of p-mass)

    $m_u = m_d = 310$ MeV/c^2 ; $m_s = 485$ MeV/c^2

    Use effective potential
  - Use symmetries flavour, spin,colour

    build ‚Periodic table' of hadrons





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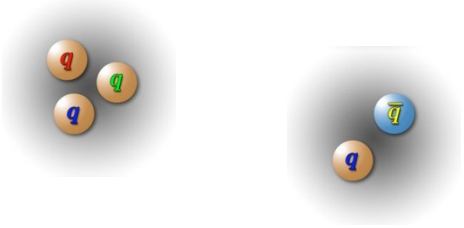

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    Use effective potential
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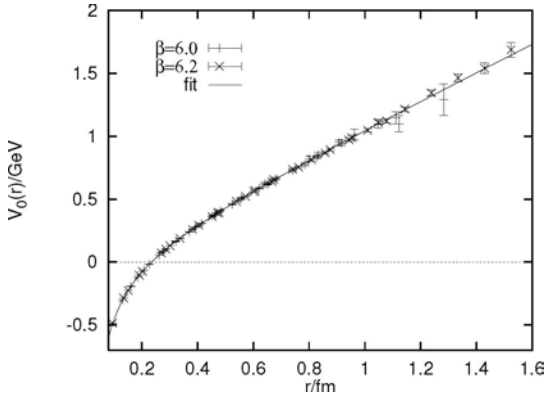
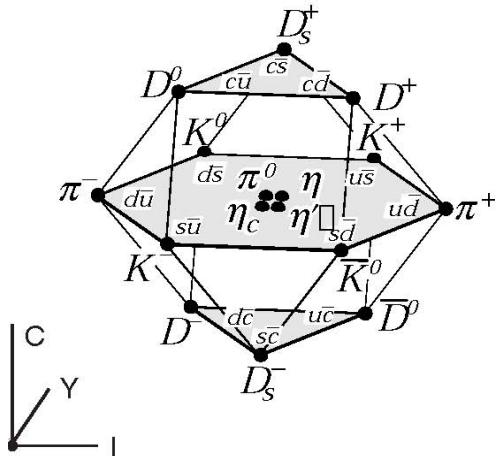
    build ‚Periodic table' of hadrons
  - Classify into multiplets

    Hadron masses are sum of quark masses
  - Use hyperfine-interaction (spin-spin interaction) mass spectrum surprisingly well described

- effective $q\bar{q}$ potential





Constituent Quark Model Mesons

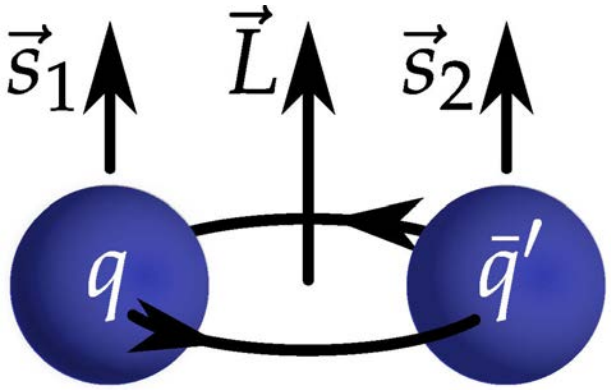
Spin-Parity selection rules for bound $q\bar{q}'$ system

- Quark spins couple to total intrinsic spin S

  $S = 0$ (singlet) or $S=1$ (triplet)

- Relative orbital angular momentum L couples with total spin S to J

  Meson spin: $\vec{J} = \vec{L} + \vec{S}$



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- Isospin: $I = 1$ for u,d quarks, $I=0$ for other quarks

  $I_z(\mathrm{u}) = +½$

  $I_z(\mathrm{d}) = -½$

  light Mesons: $I = 0 \text{ or } 1$

  other Mesons: $I = 0 \text{ or } ½$

- Parity: $P = (-1)^{L+1}$
- Charge conjugation: $C = (-1)^{L+S}$
- G-parity: $G = C \cdot e^{i\pi I_z} = (-1)^{I+L+S}$

Constituent Quark Model II Mesonen

- Allowed J^{PC} combinations:

  $L = 0$ → pseudo-scalar 0^{-+}, Vector 1^{--}

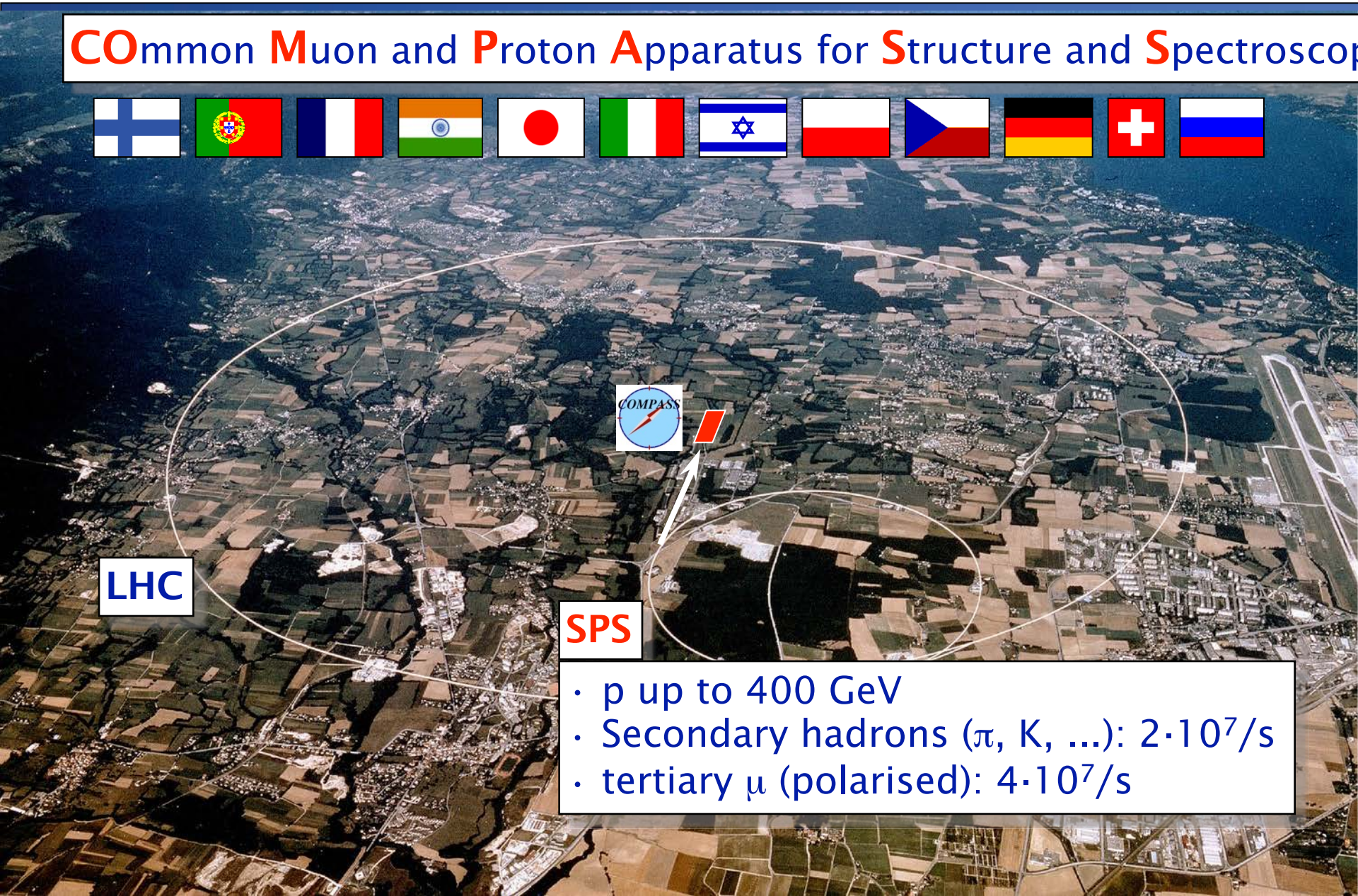
  $L = 1$ → scalar 0^{++}, axial-vector 1^{+-}, 1^{++} and tensor 2^{++}

- Forbidden J^{PC} combinations: 0^{--} , 0^{+-} , 1^{-+} , 2^{+-} , 3^{+-} …..

- Same quantum numbers mix

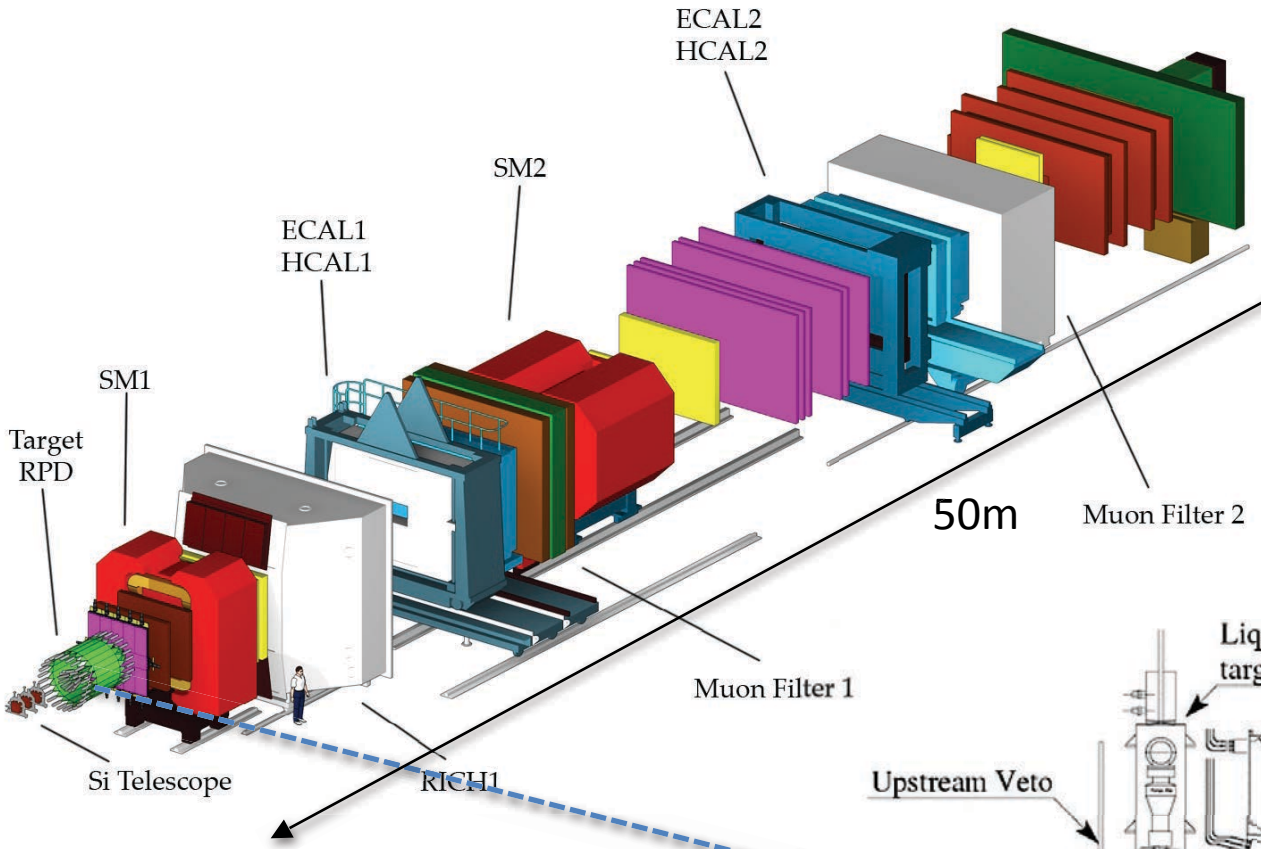
COMPASS am CERN

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



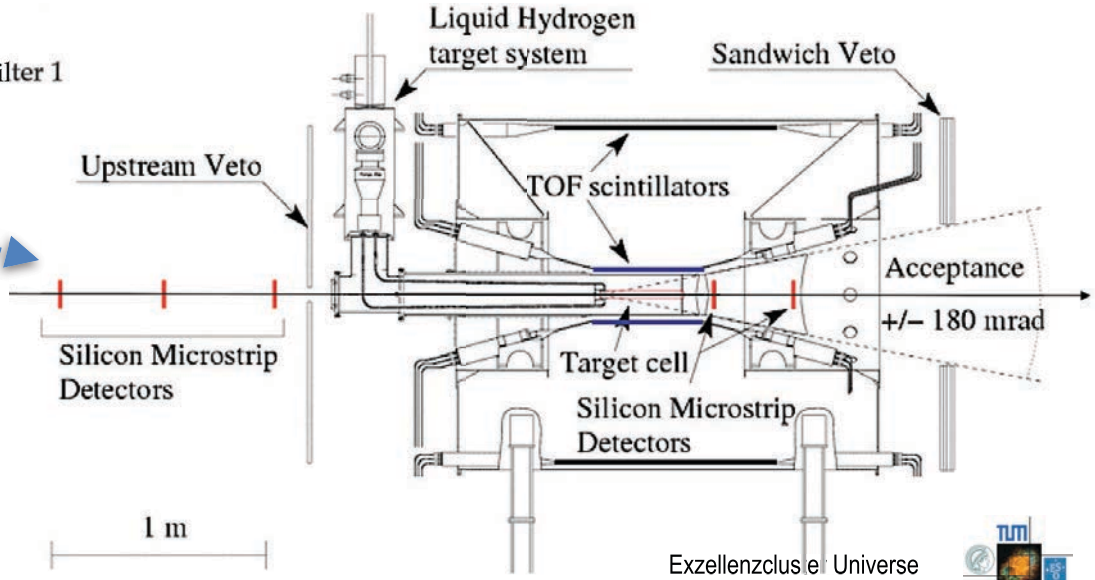
- p up to 400 GeV
- Secondary hadrons (π, K, ...): $2 \cdot 10^7$/s
- tertiary μ (polarised): $4 \cdot 10^7$/s

The COMPASS Experiment



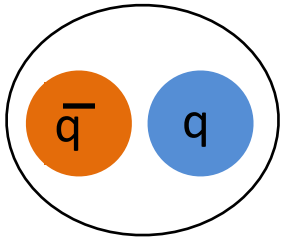
CERN SPS
Hadron beam:

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

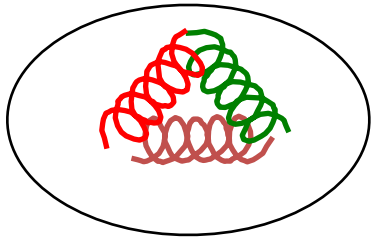


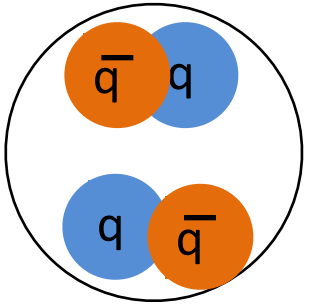
Light Mesons, Quarks and Gluons

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



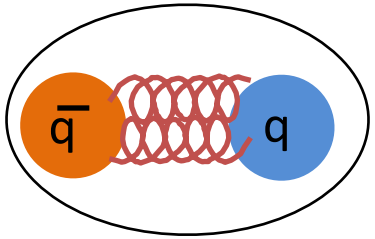
- Glueballs (gluons and no valence quarks)



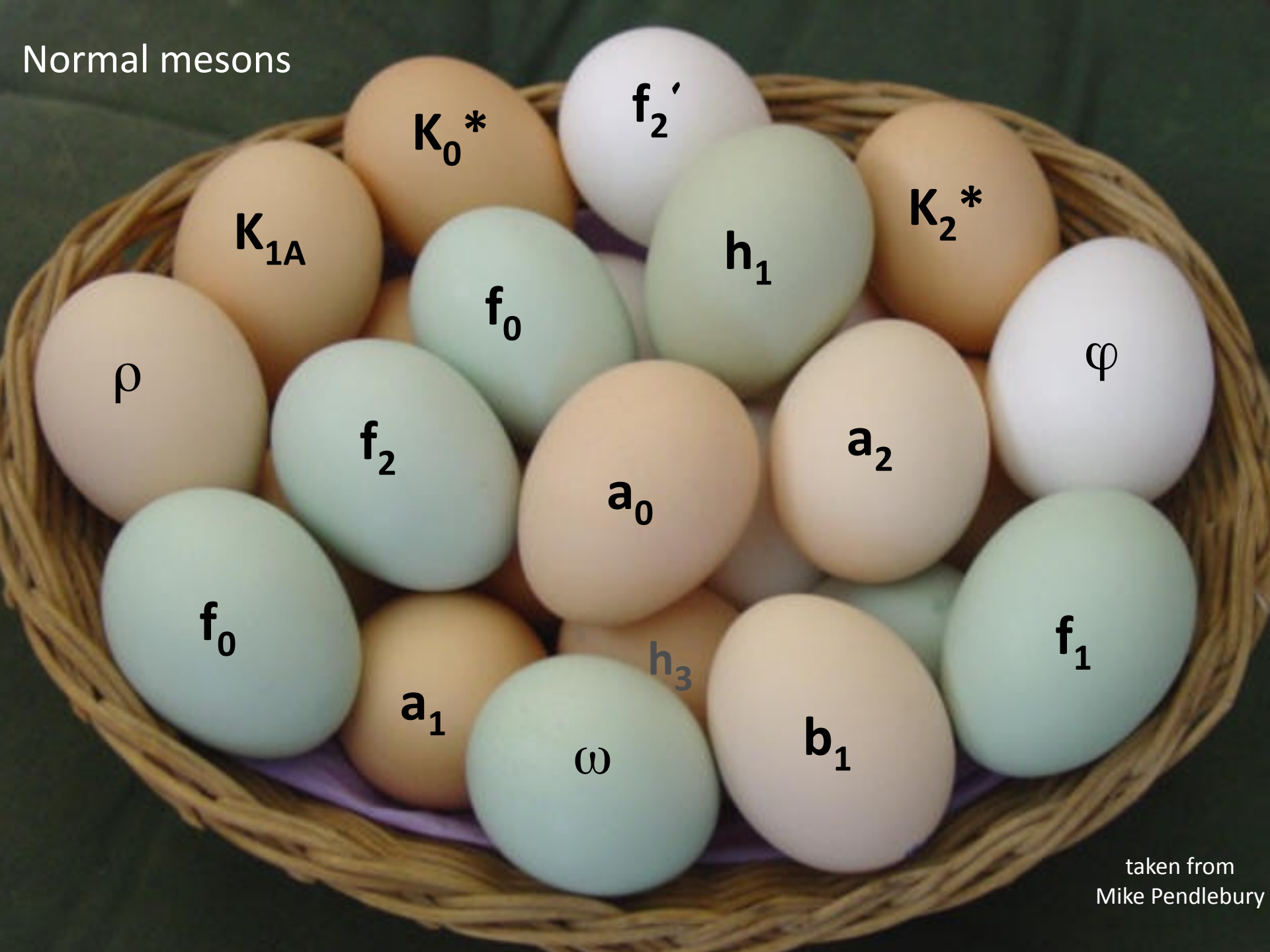


  - Multiquarks (quark-antiquark pairs)

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



Klempt Zaitsev Phys Rep 454 (2007) 1

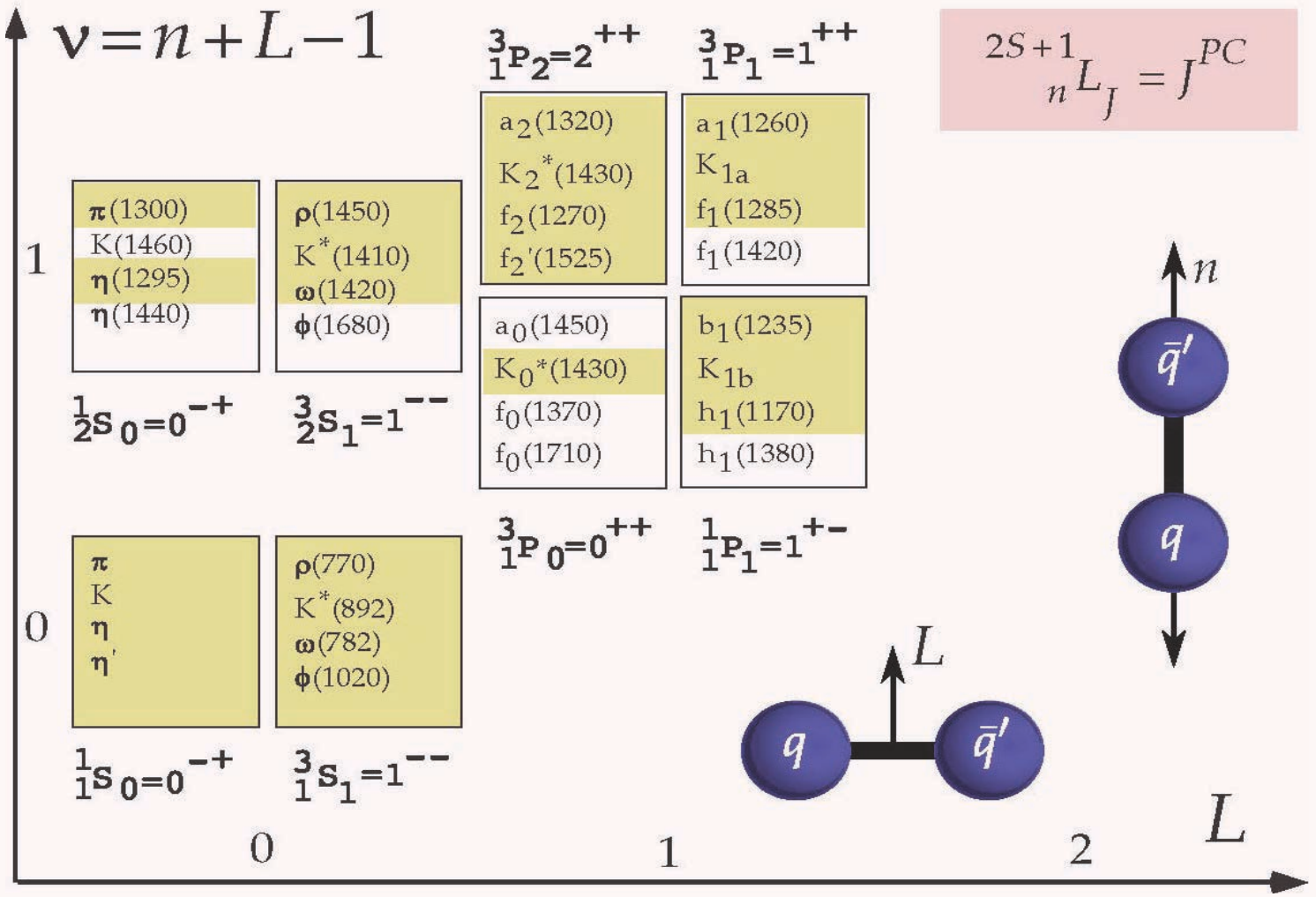

Normal mesons
K_0^*
f_2'
K_{1A}
h_1
K_2^*
f_0
ρ
φ
f_2
a_0
a_2
f_0
h_3
f_1
a_1
ω
b_1
taken from
Mike Pendlebury

More Surprising States?

taken from
Mike Pendlebury

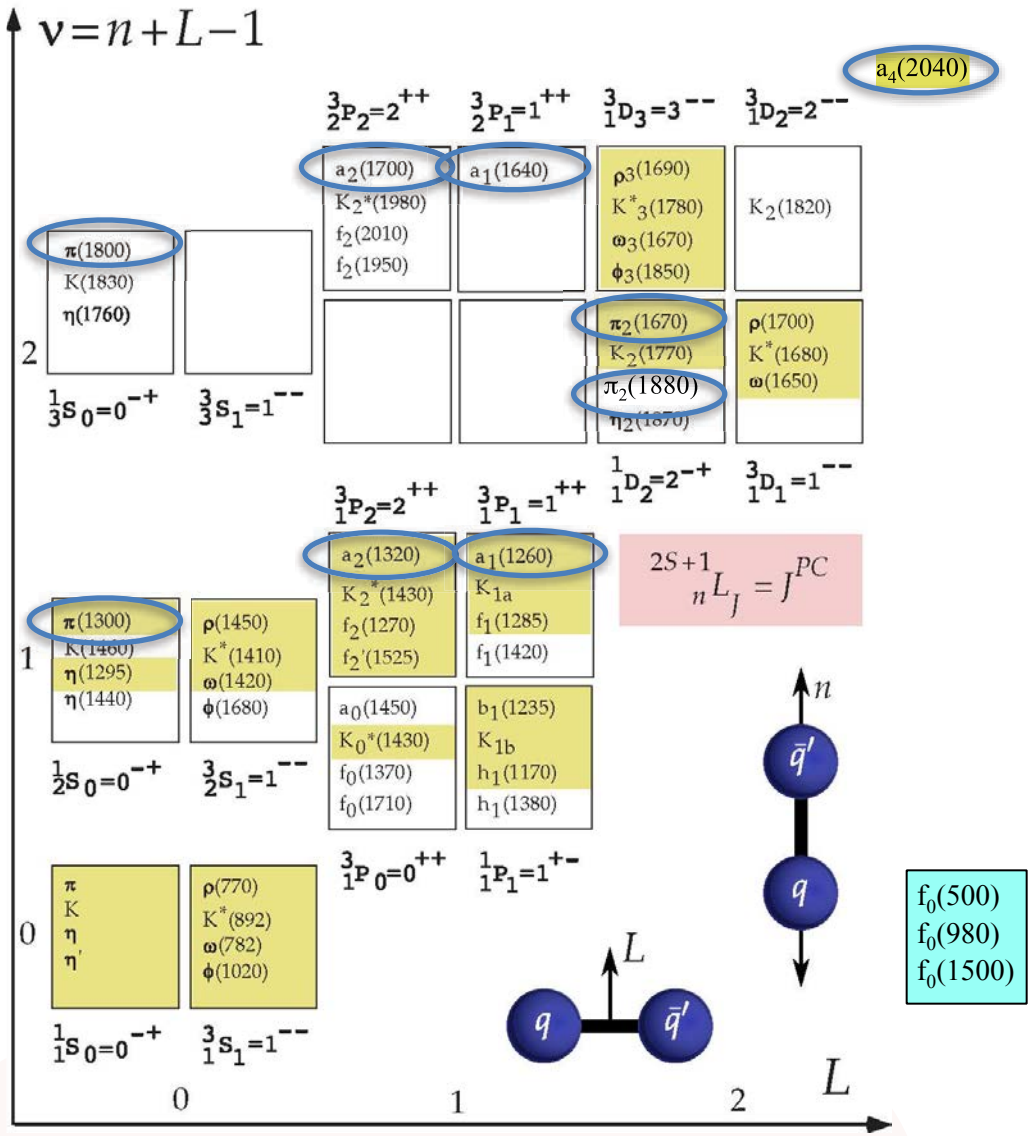
Constituent Quarks and Mesons

Spectrum of light mesons:



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

Constituent Quarks and Mesons



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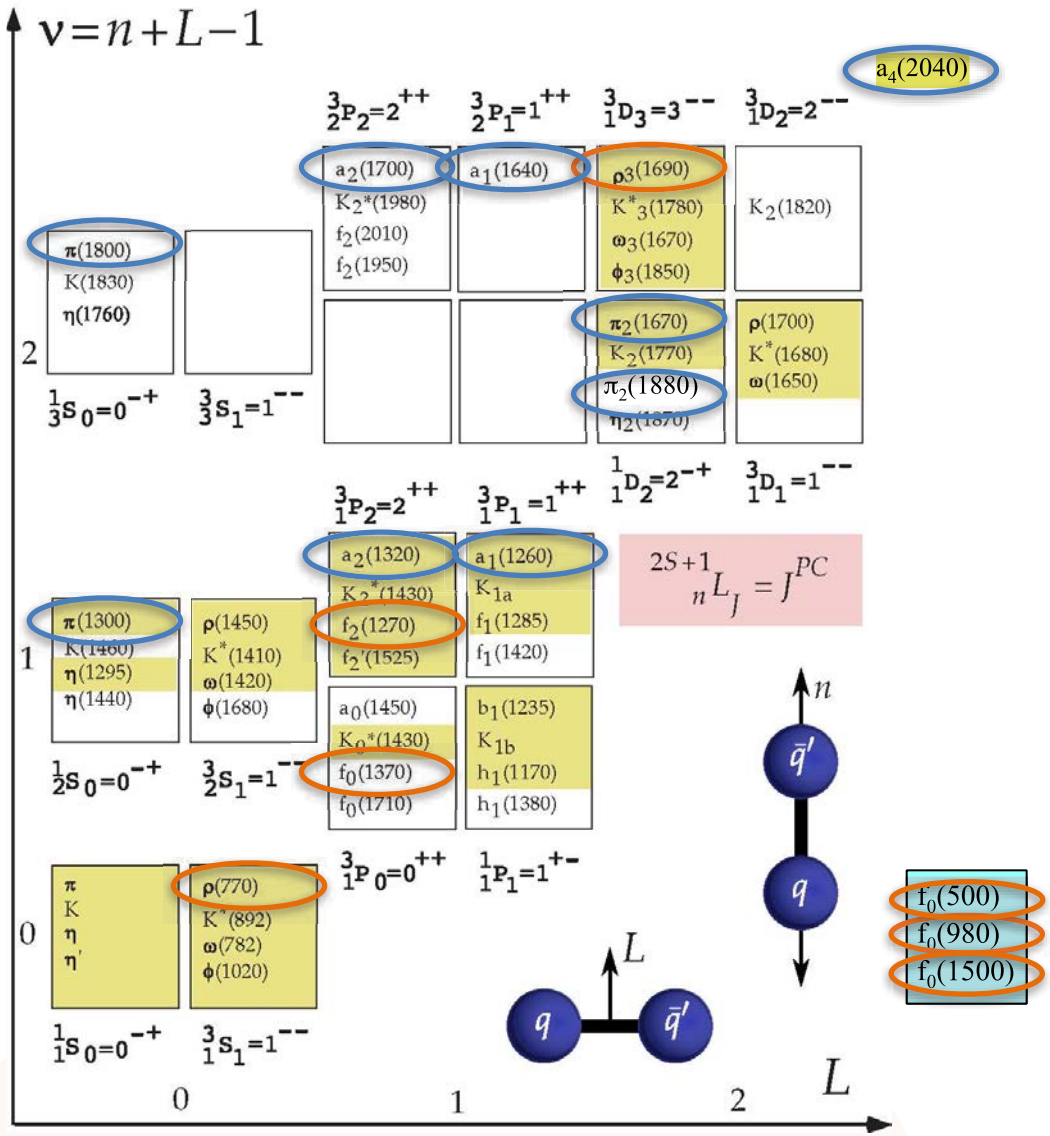

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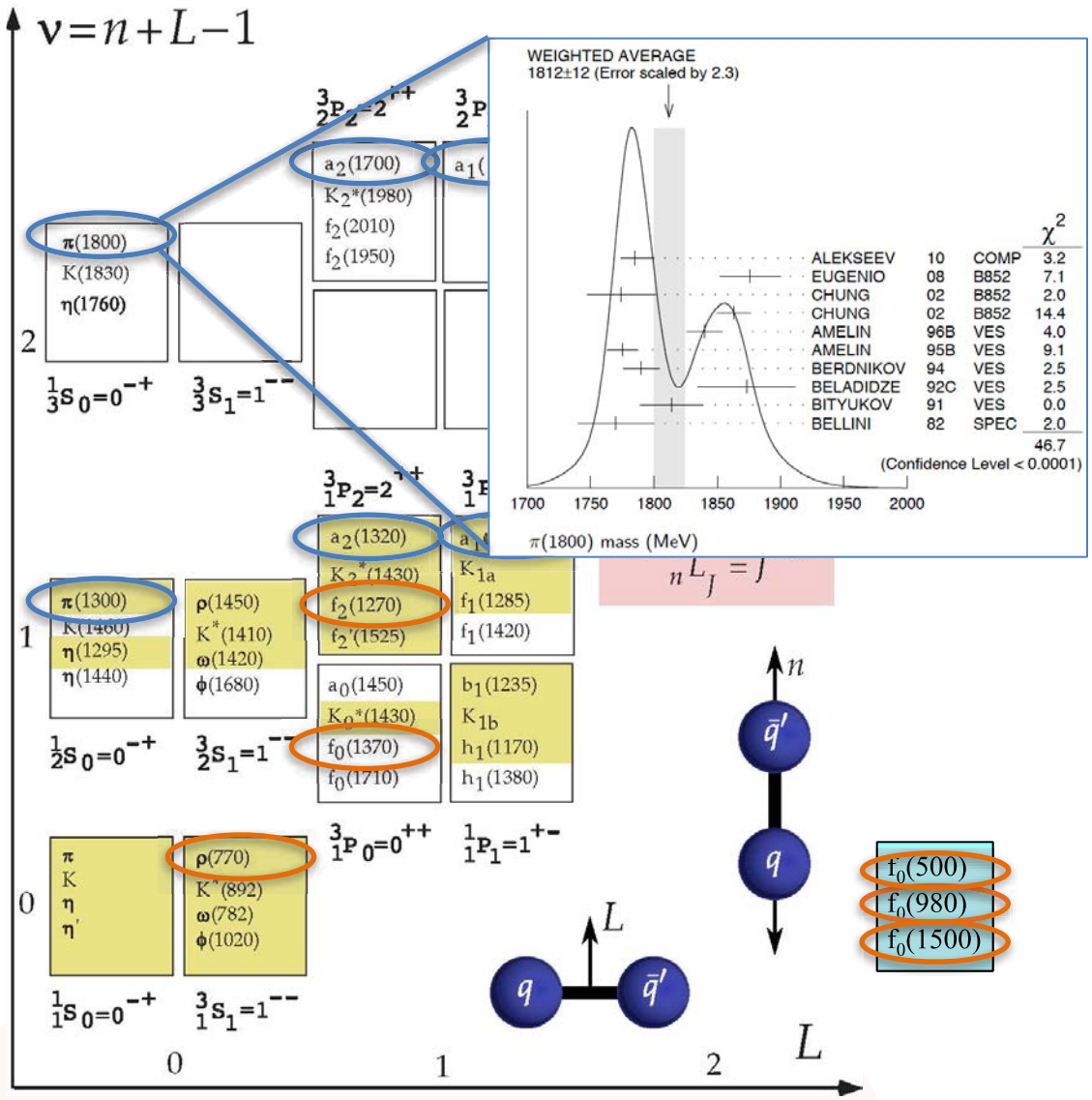

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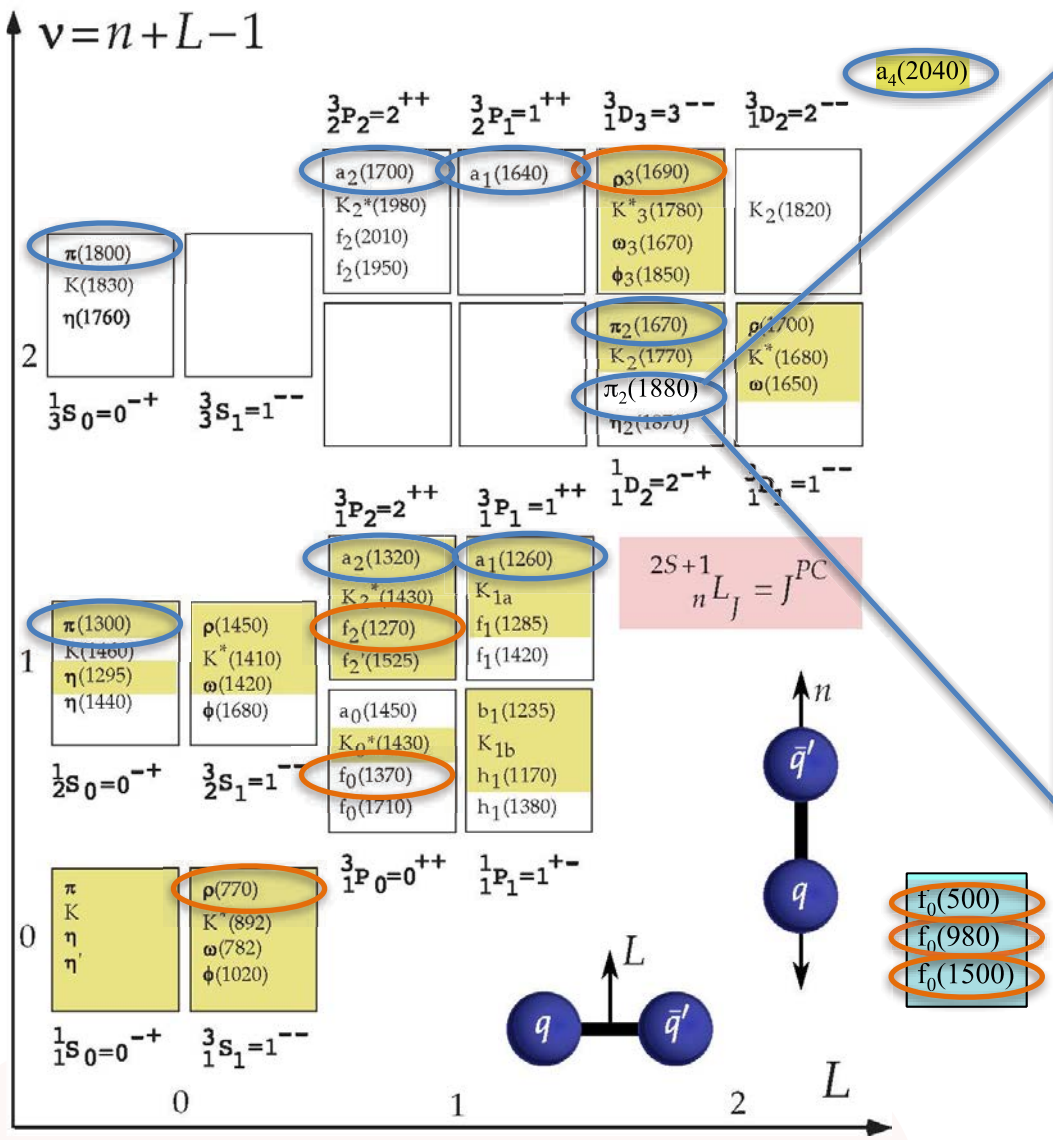


C. Amsler *et al.*, Phys. Rept. 389, 61 (2004)

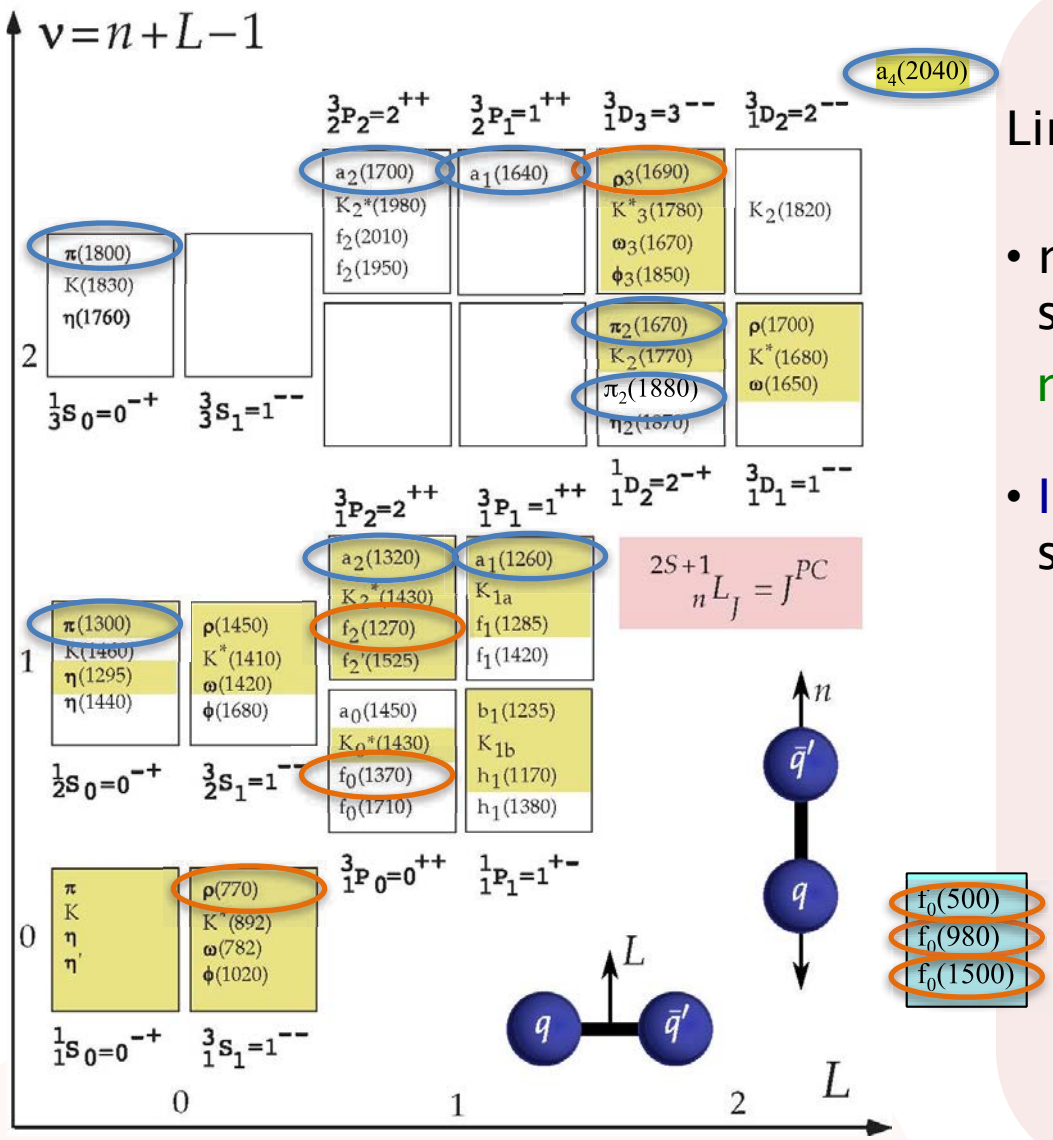
$\pi_2(1880)$ MASS

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	

Constituent Quarks and Mesons



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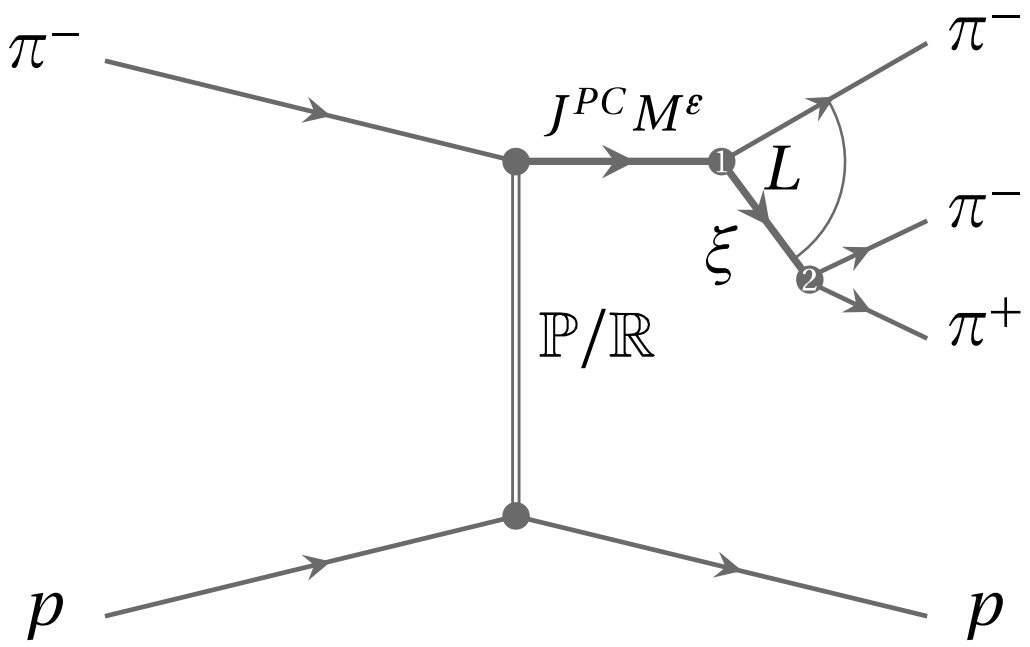
Limits for light mesons

- many missing/disputed states in mass region

  m ~ 2 GeV/c²

- Identification of heavy states difficult
  - broad states
  - large number
  - overlap + mixing

Kinematics for today



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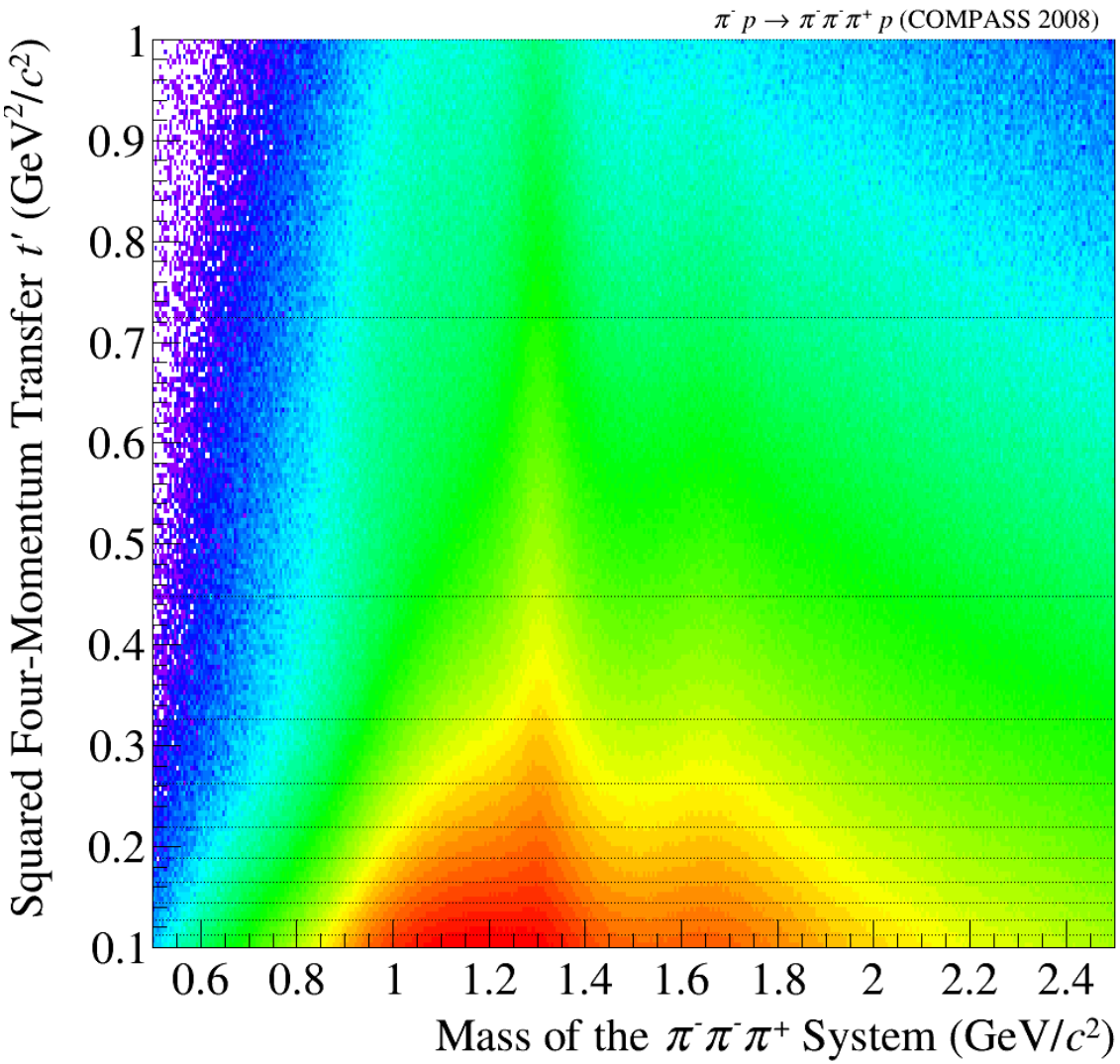
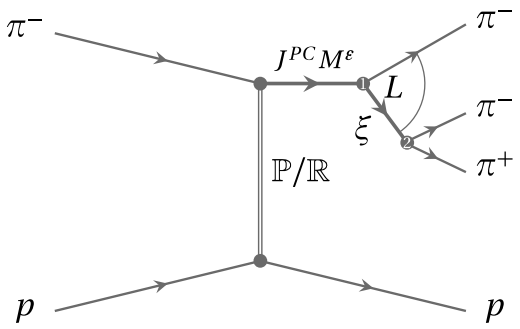
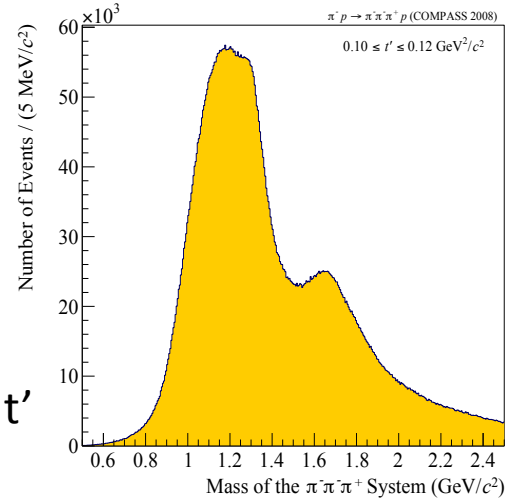




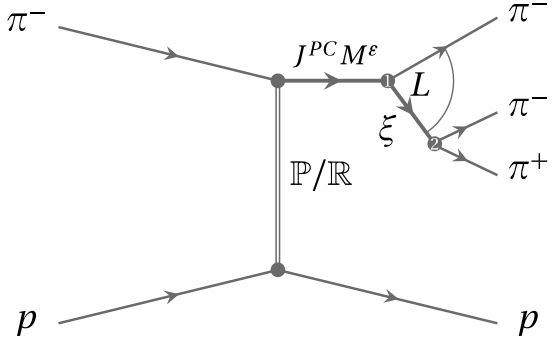
grid of t' used
Δm: 20 MeV/c^2

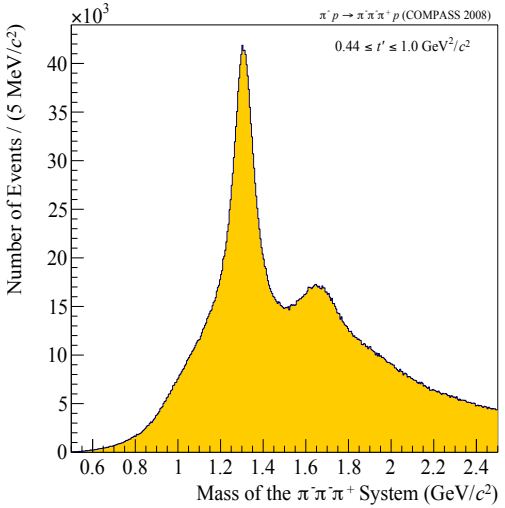
Kinematics and Isobars

low t’

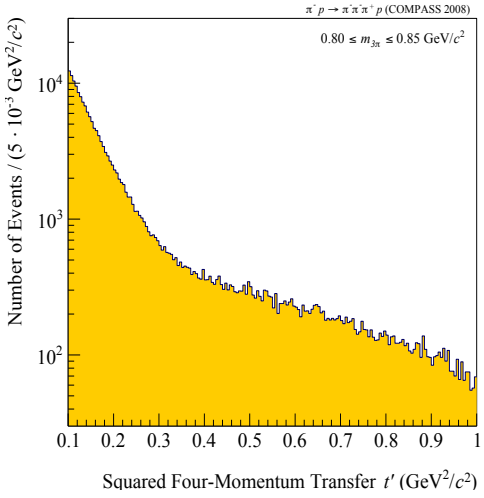


isobar model

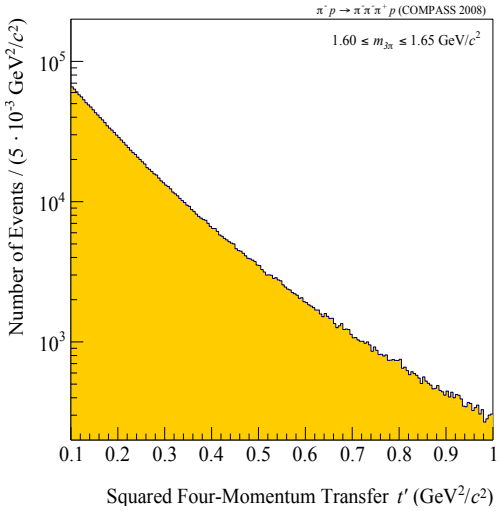




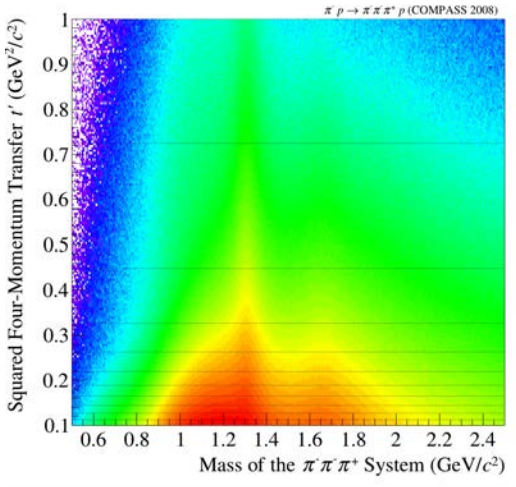
high t’



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



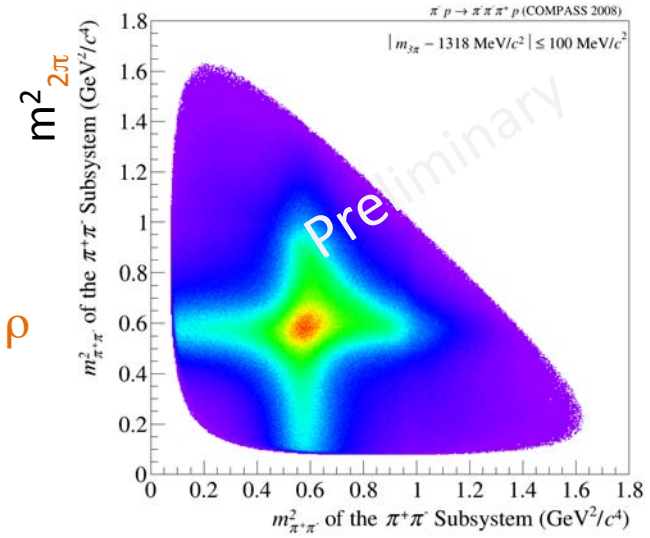
$1.6 < m_{3\pi} < 1.65$

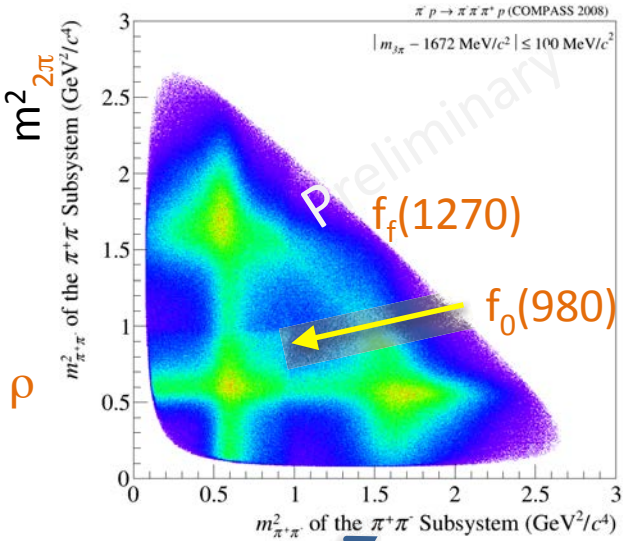


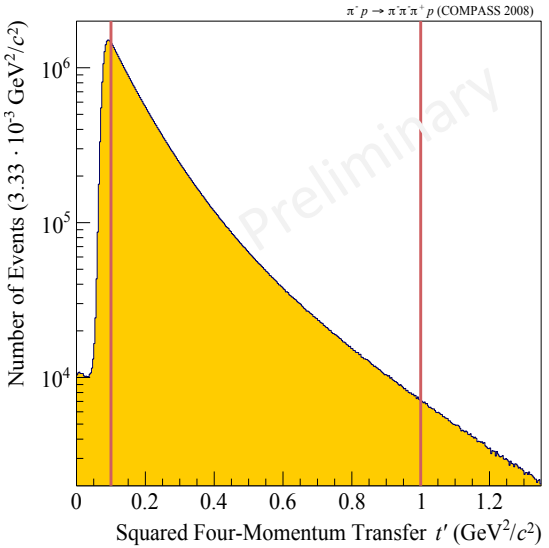
grid of t’ used

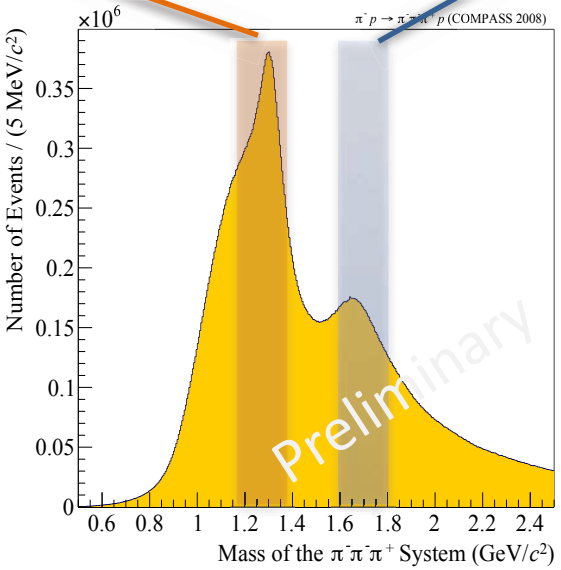
Δm: 20 MeV/c^2

First Impressions
Motivation for Isobar Model



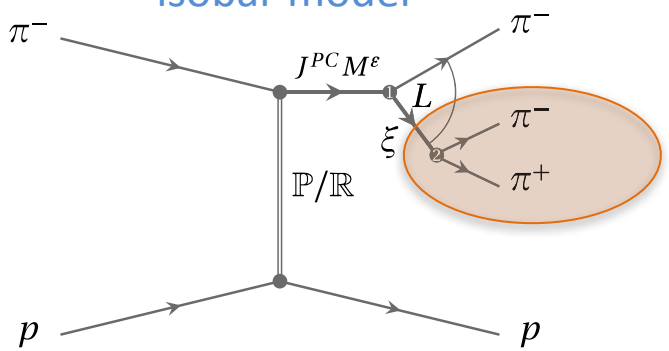






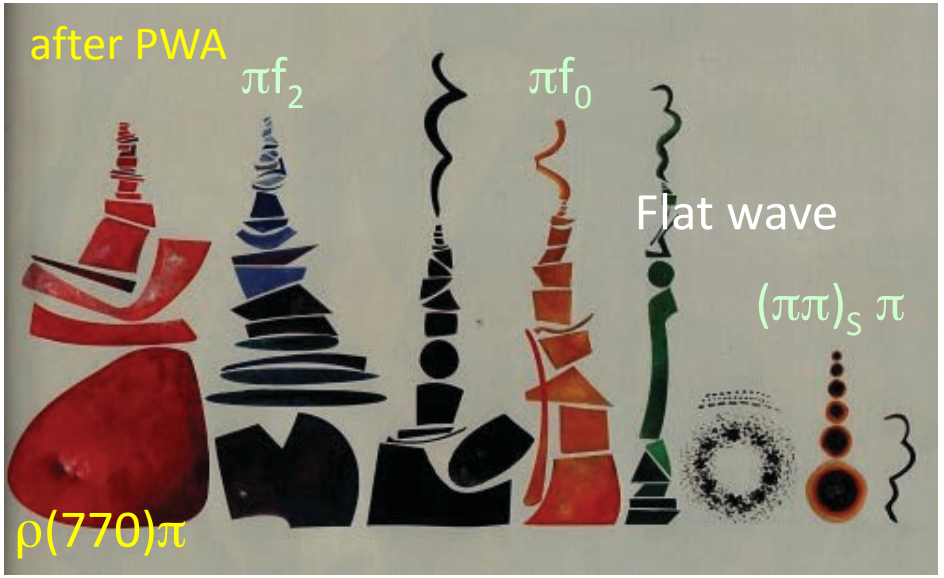
used in analysis

isobar model



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$\rightarrow\pi\pi$) : wa… …es used)
  - each such "wave" has a pre-d… …population in phase space
  - each wave may have … of J described by quantum number M

Mass independent fit

- 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

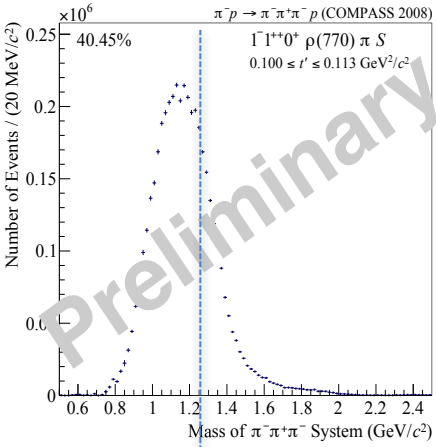
step 2

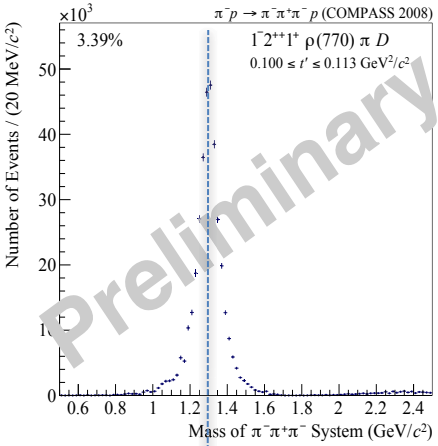
- Describe spin density matrix (su… …) by model containing resonances and non-reso… …tributions connecting all mass bins
- Determine resonanc… …meters

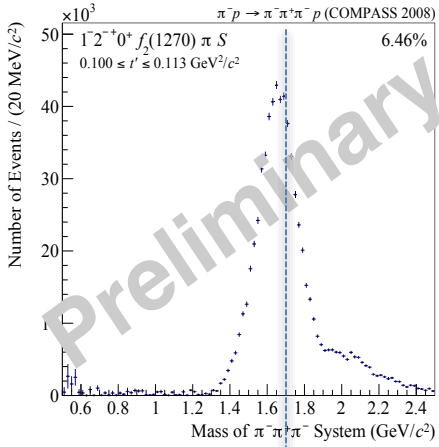
Mass dependent fit

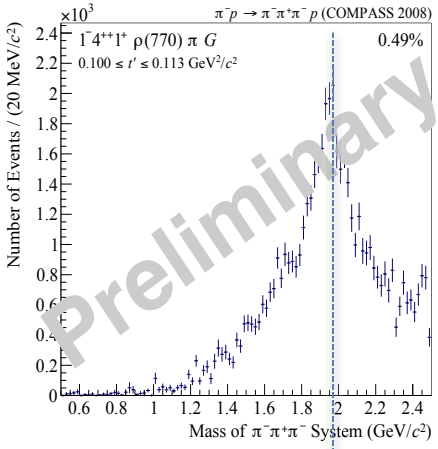
t dependence of mass distributions

low t

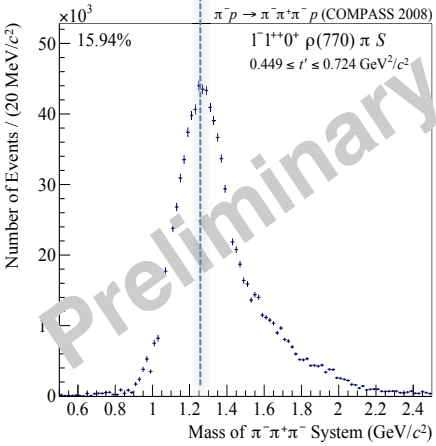


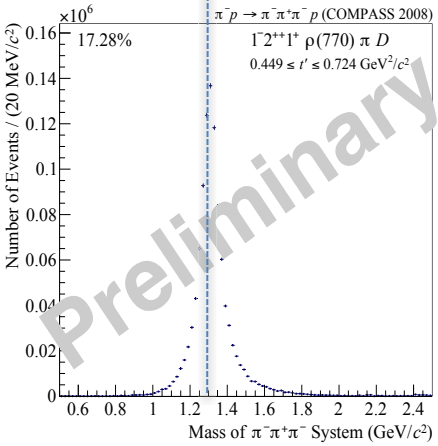


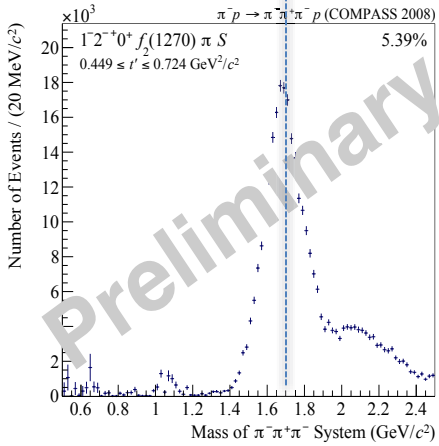


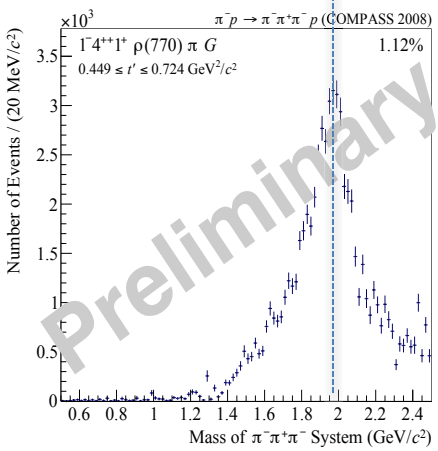


high t





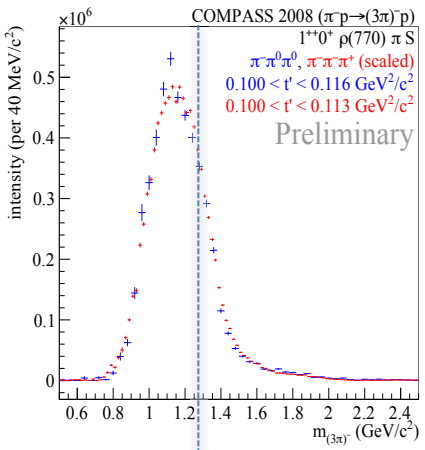


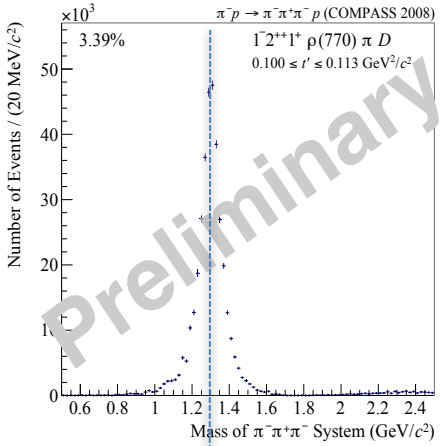


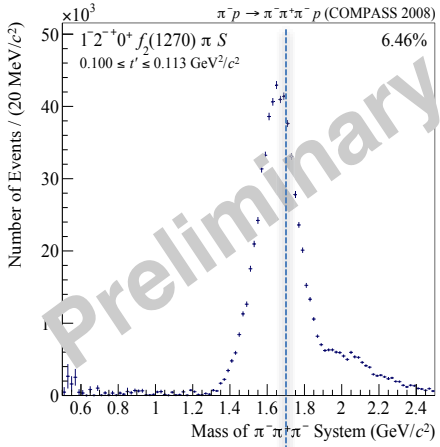
$1^{++}0^+\rho\pi$ S | $2^{++}1^+\rho\pi$ D | $2^{-+}0^+ f_2\,\pi$ S | $4^{++}1^+\rho\pi$ G

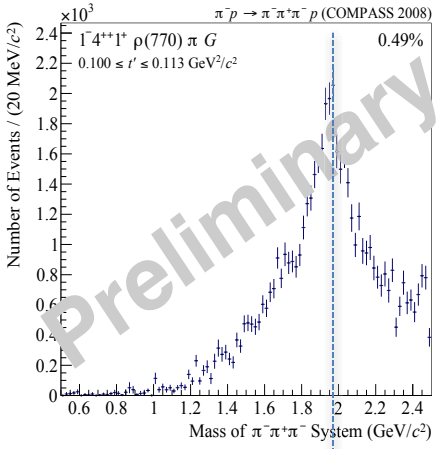
t dependence of mass distributions

low t

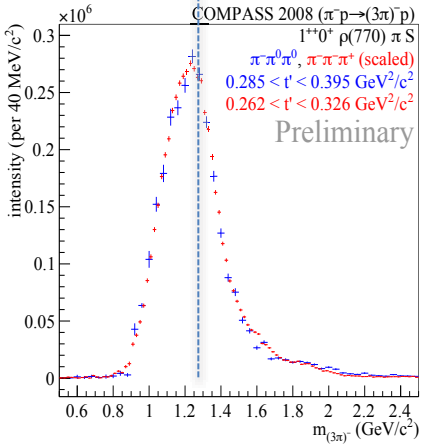


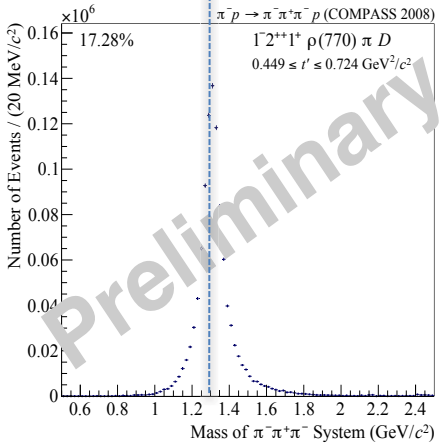


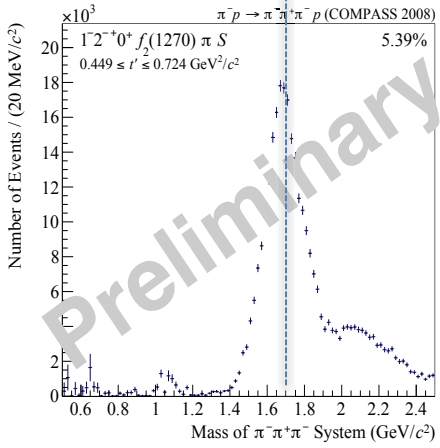


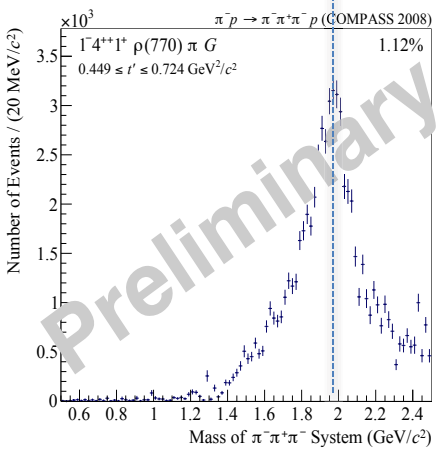


high t







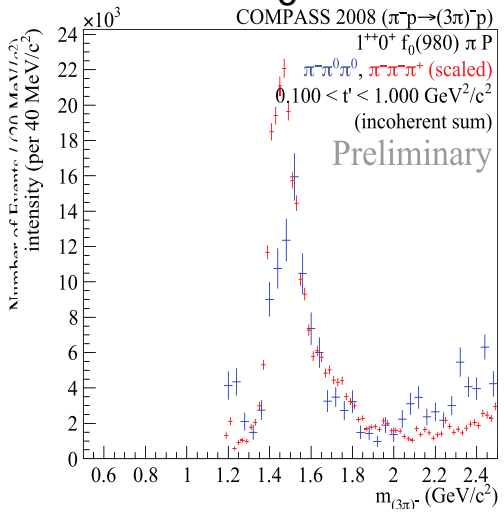


$1^{++}0^+\rho\pi$ S | $2^{++}1^+\rho\pi$ D | $2^{-+}0^+ f_2\,\pi$ S | $4^{++}1^+\rho\pi$ G

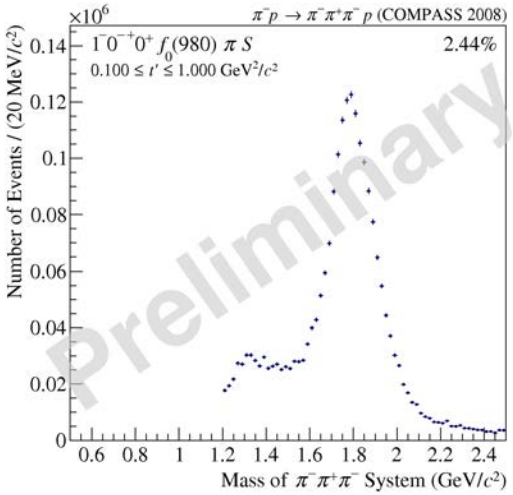
More exotic families

Waves involving $f_0(980)$

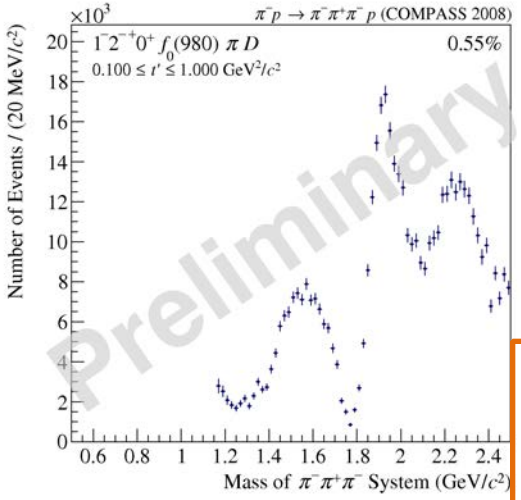
$1^{++}0^+ f_0(980)\,\pi$ P



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



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



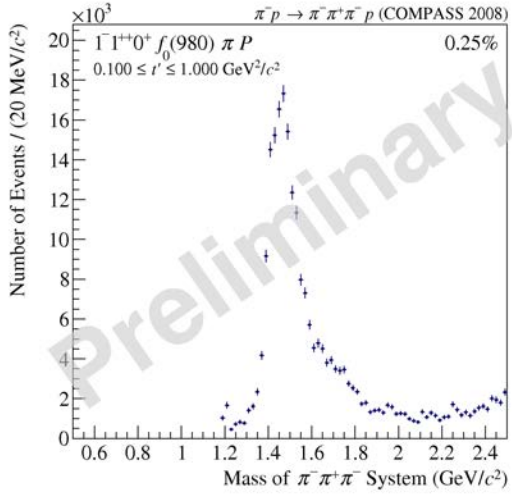
$\pi^-\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$

experts only

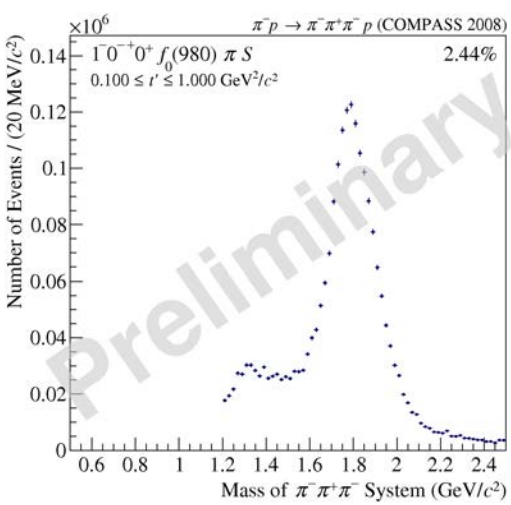
Waves involving $f_0(980)$

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

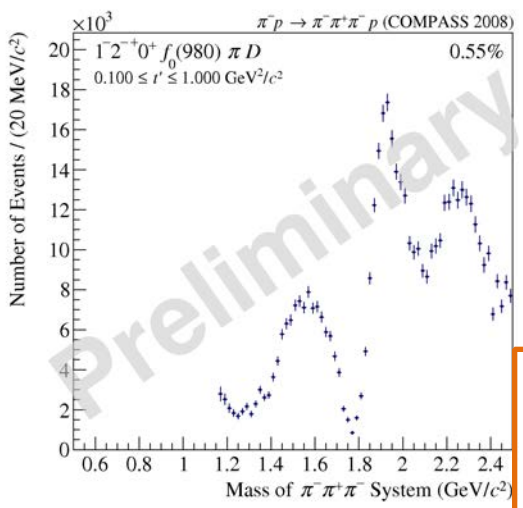
$1^{++}0^+ f_0(980)\,\pi$ P



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



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



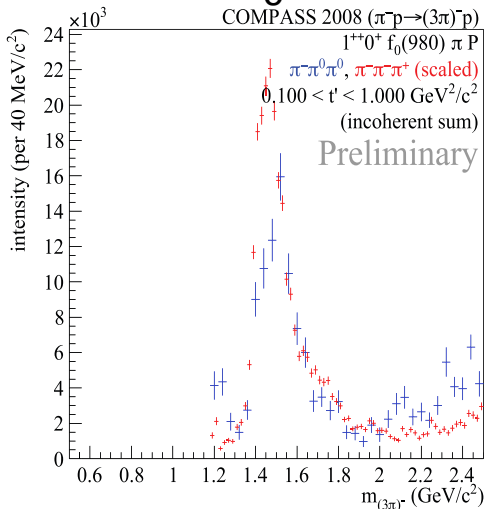
experts only

Waves involving $[\pi\pi]_S$

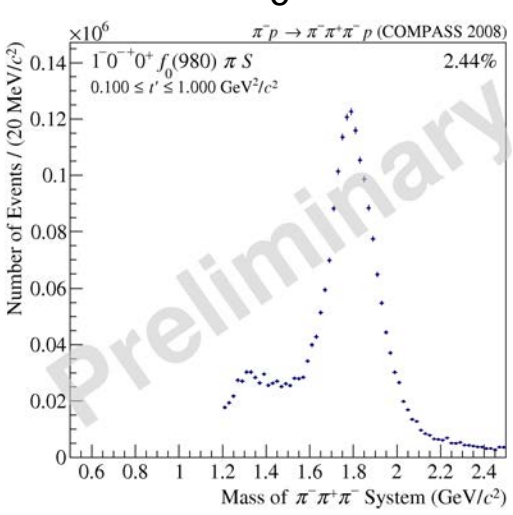
$\pi^-\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$

experts only

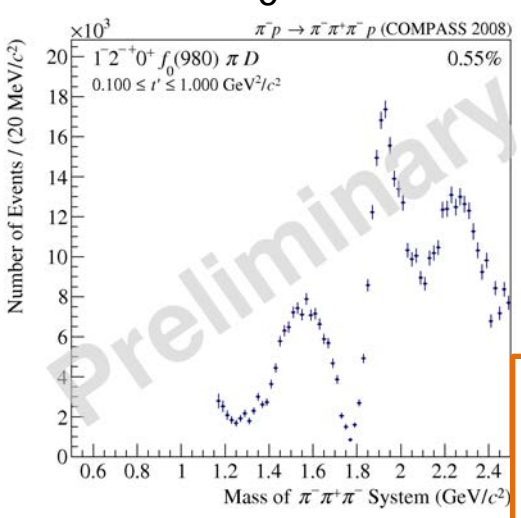
$1^{++}0^+ f_0(980)\,\pi\,P$

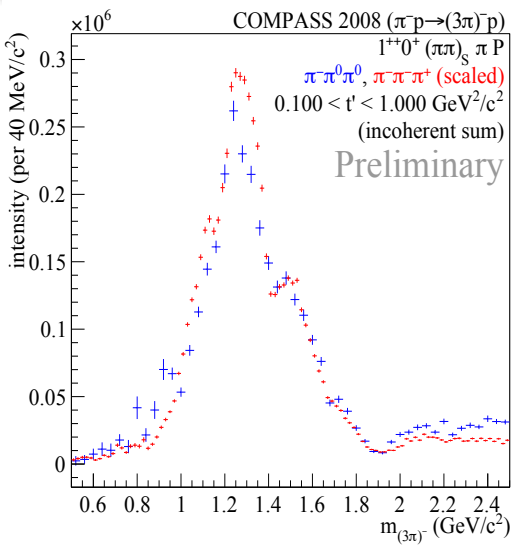


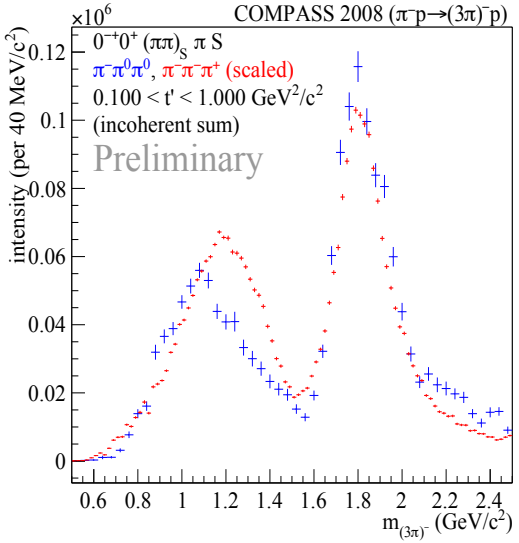
$0^{-+}0^+ f_0(980)\,\pi\,S$

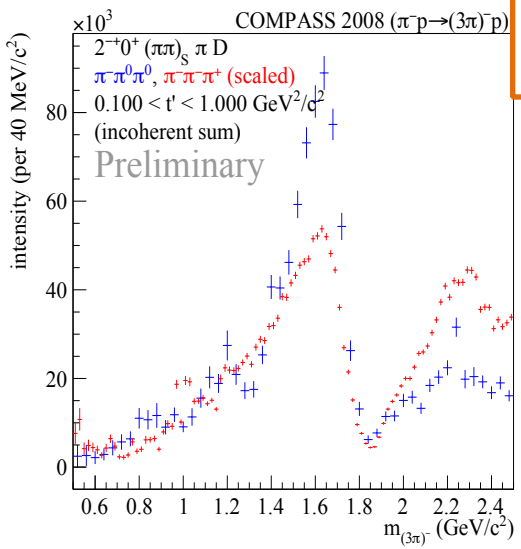


$2^{-+}0^+ f_0(980)\,\pi\,D$







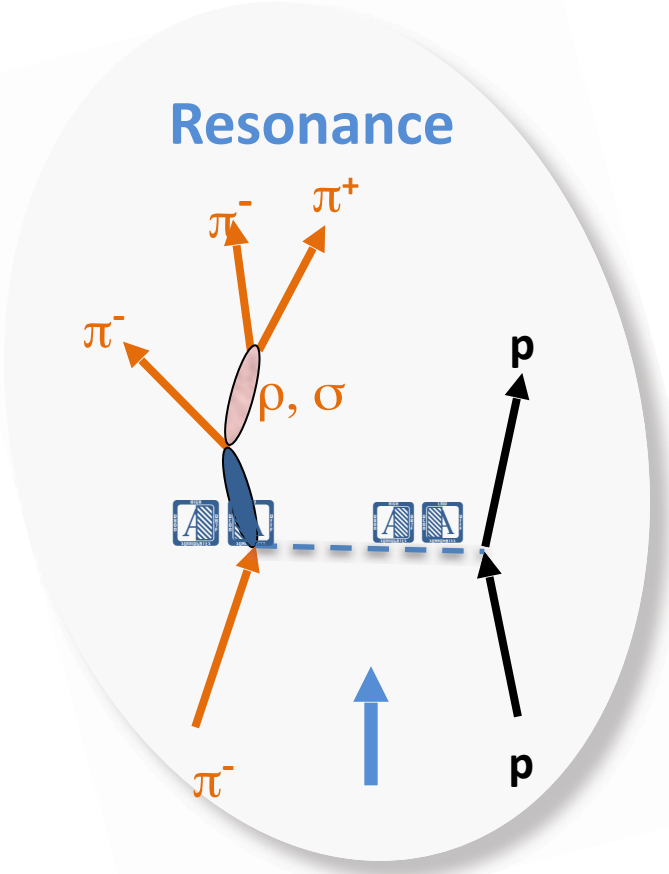


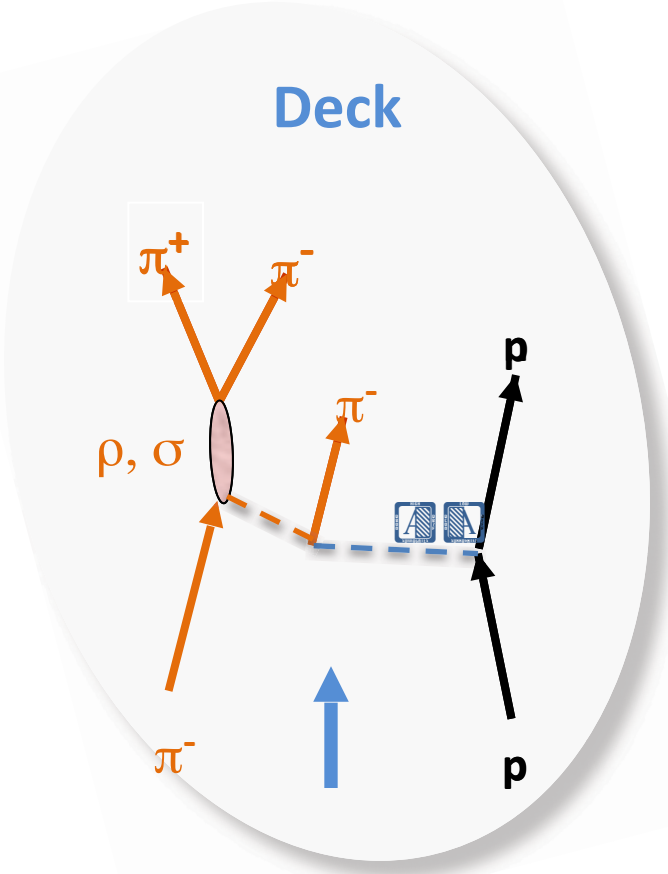
$1^{++}0^+[\pi\pi]_S\,\pi\,P$ $0^{-+}0^+[\pi\pi]_S\,\pi\,S$ $2^{-+}0^+[\pi\pi]_S\,\pi\,D$

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 (simple)

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

This work: 4 waves

Model:

experts only

2^{++} 1^{+} ρ π D

4^{++} 1^{+} ρ π G

2 resonances : $a_2(1320)$ and a_2' + non resonant term

1 resonance : $a_4(2040)$ + non resonant term

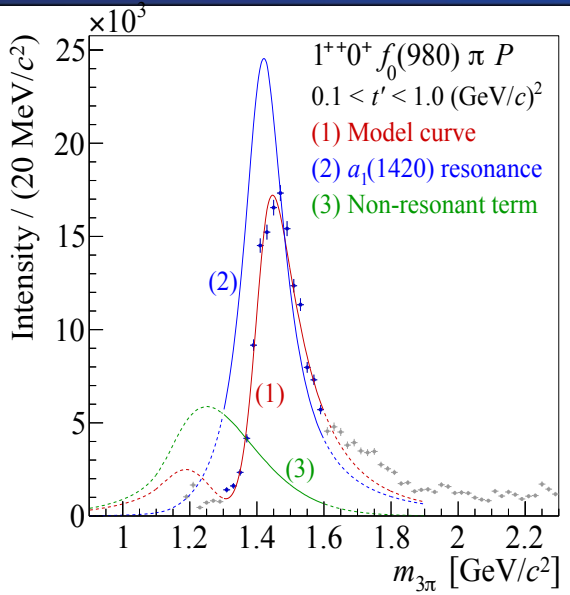
1^{++} 0^{+} $f_0(980)$ π P

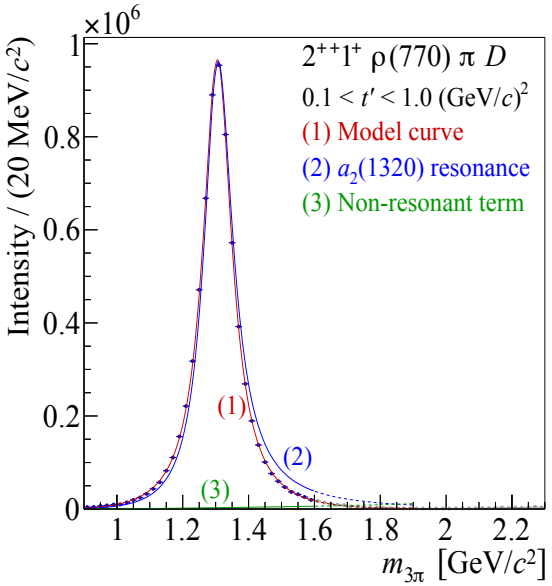
1 resonance : $a_1(1420)$ + non resonant term

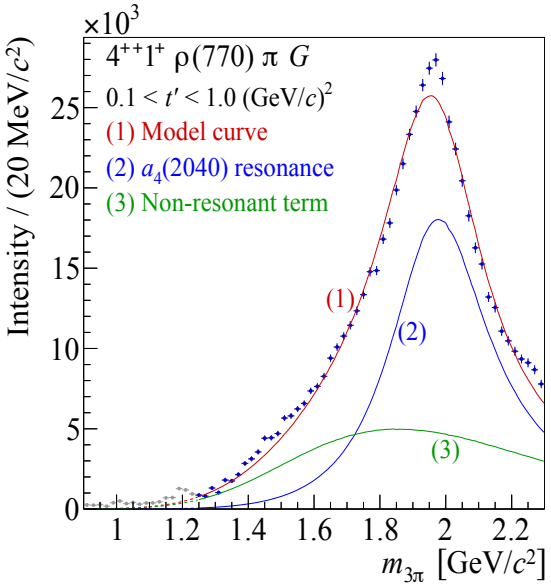
$J^{PC}M^{\varepsilon}[isobar]\pi L$

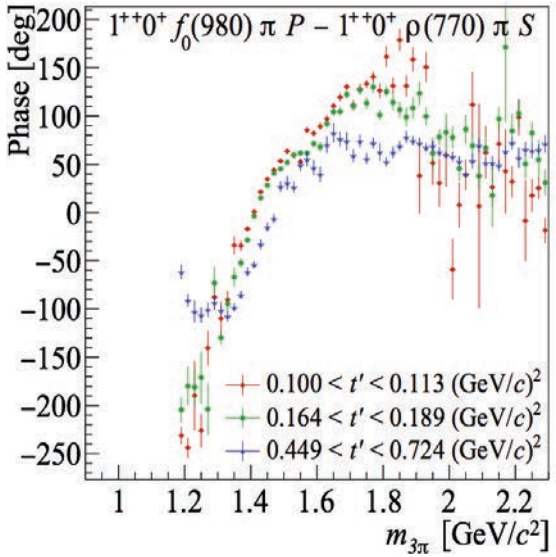
- 133 free parameters
- fix BW resonance parameter for all 11 bins of t`

New Observation: $a_1(1420)$



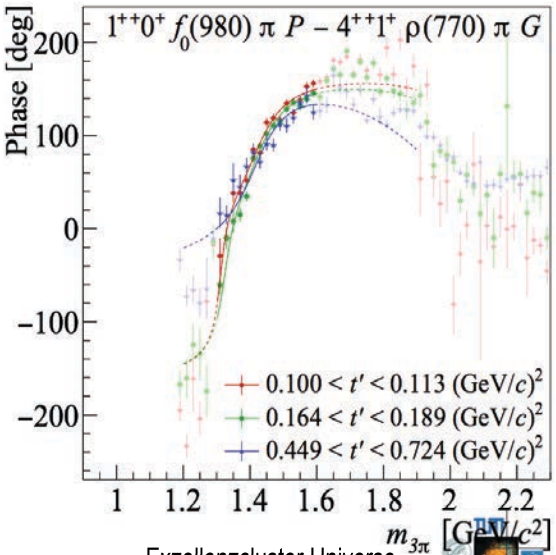






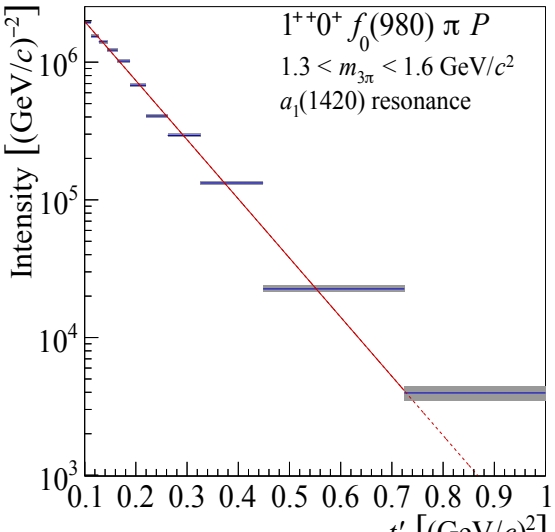
Observation*:*

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



$a_1(1420)$ and Production

- Various explanations proposed for interpretation:
  - Dynamics
    - Interference of $a_1(1260)$ with Deck amplitude ($\Delta\phi = 180^0$ shifted by 100 MeV)
    - triangular anomaly coupling $a_1(1260) \rightarrow KK^* \rightarrow KK\pi$ and $KK \leftrightarrow f_0(980)$ ($\Delta\phi = 90^0$) (see talk Mikhasenko)
    - Requires same t´ dependence for $a_1(1260)$ and $a_1(1420)$
  - Molecular structure
    - Partner of $f_1(1420)$

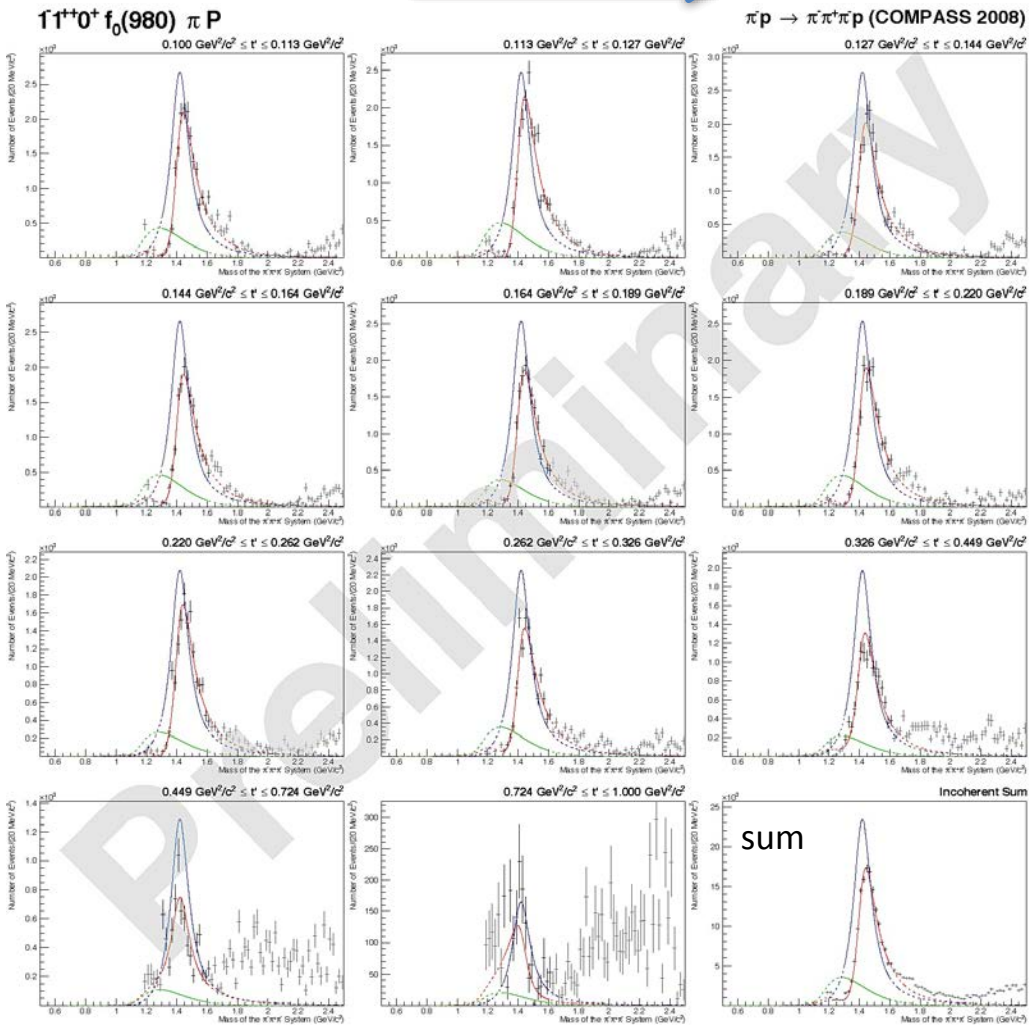


- At present: slope difference Δb is 2 units
- Uncertainty in extraction of resonance in 1^{++} $\rho\pi$ S-wave gives uncertainty for $b_{a1(1260)}$

Mass dependent fits $a_1(1420)$

Fit in 11 t-bins

t



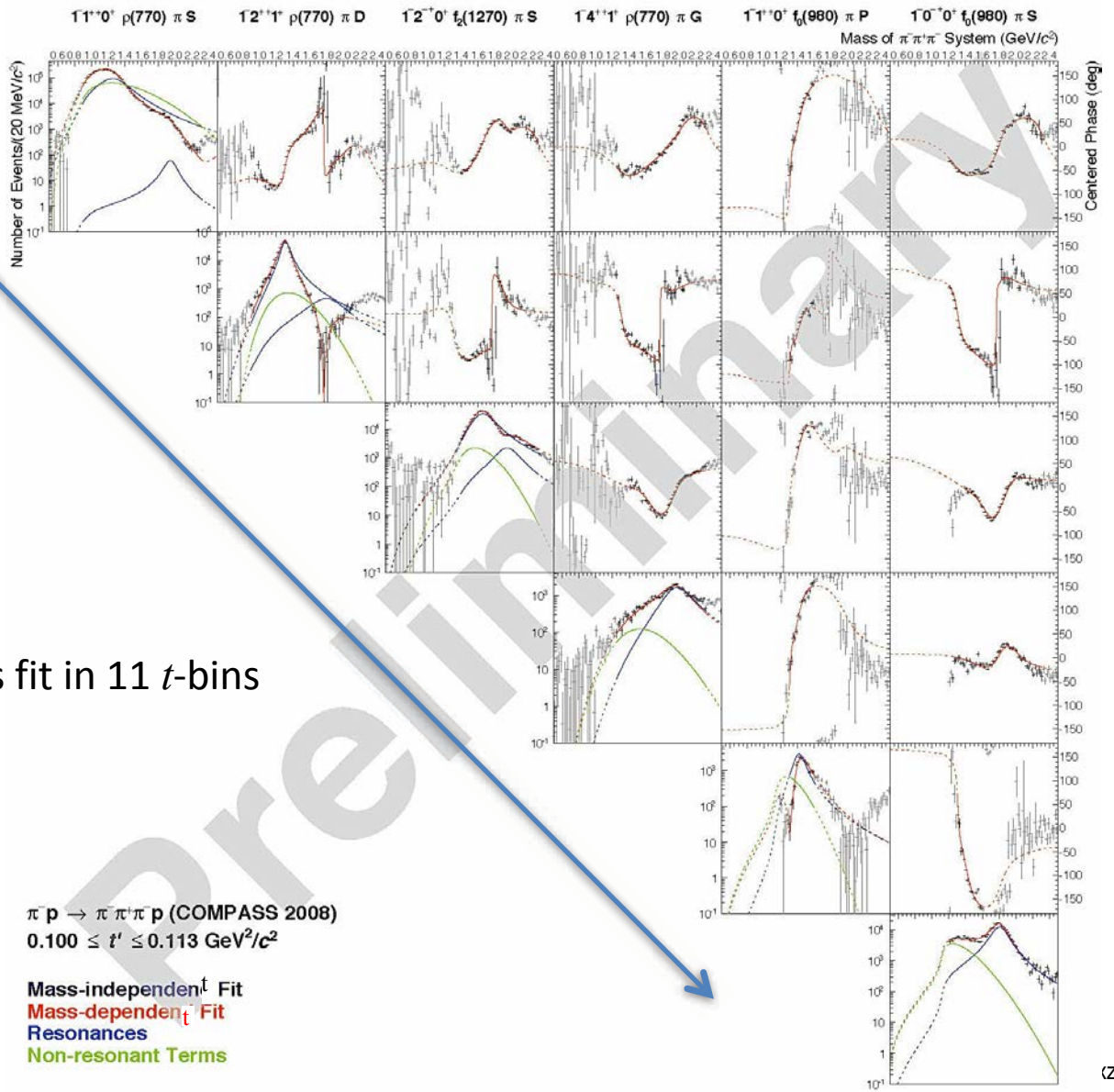
$1^{++}0^{+} f_0(980)\pi P$

t

NEW

COMPASS “Holography”

Reference waves

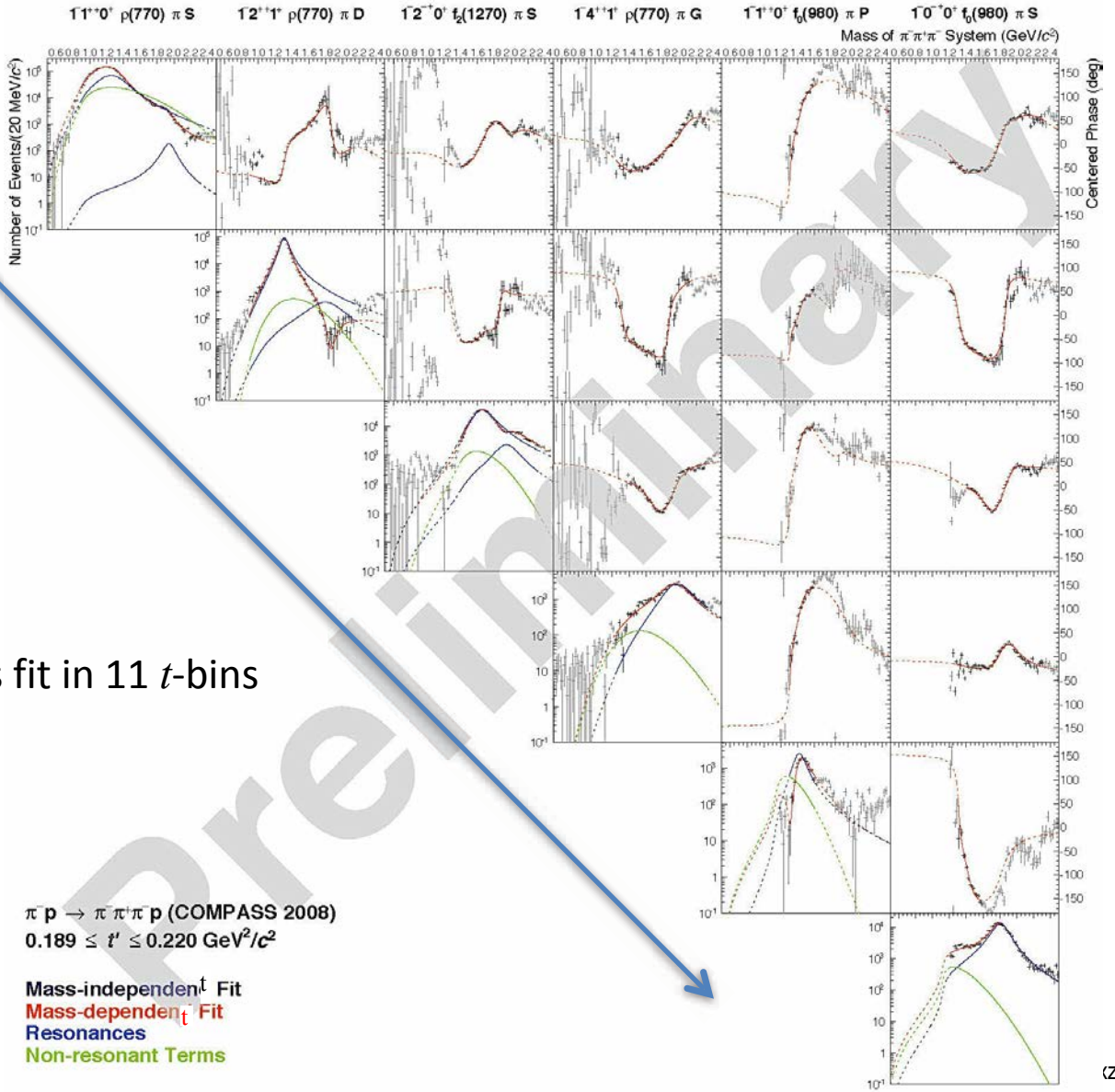


simultaneous fit in 11 t-bins

Interferometry

COMPASS “Holography”

Reference waves



Interferometry

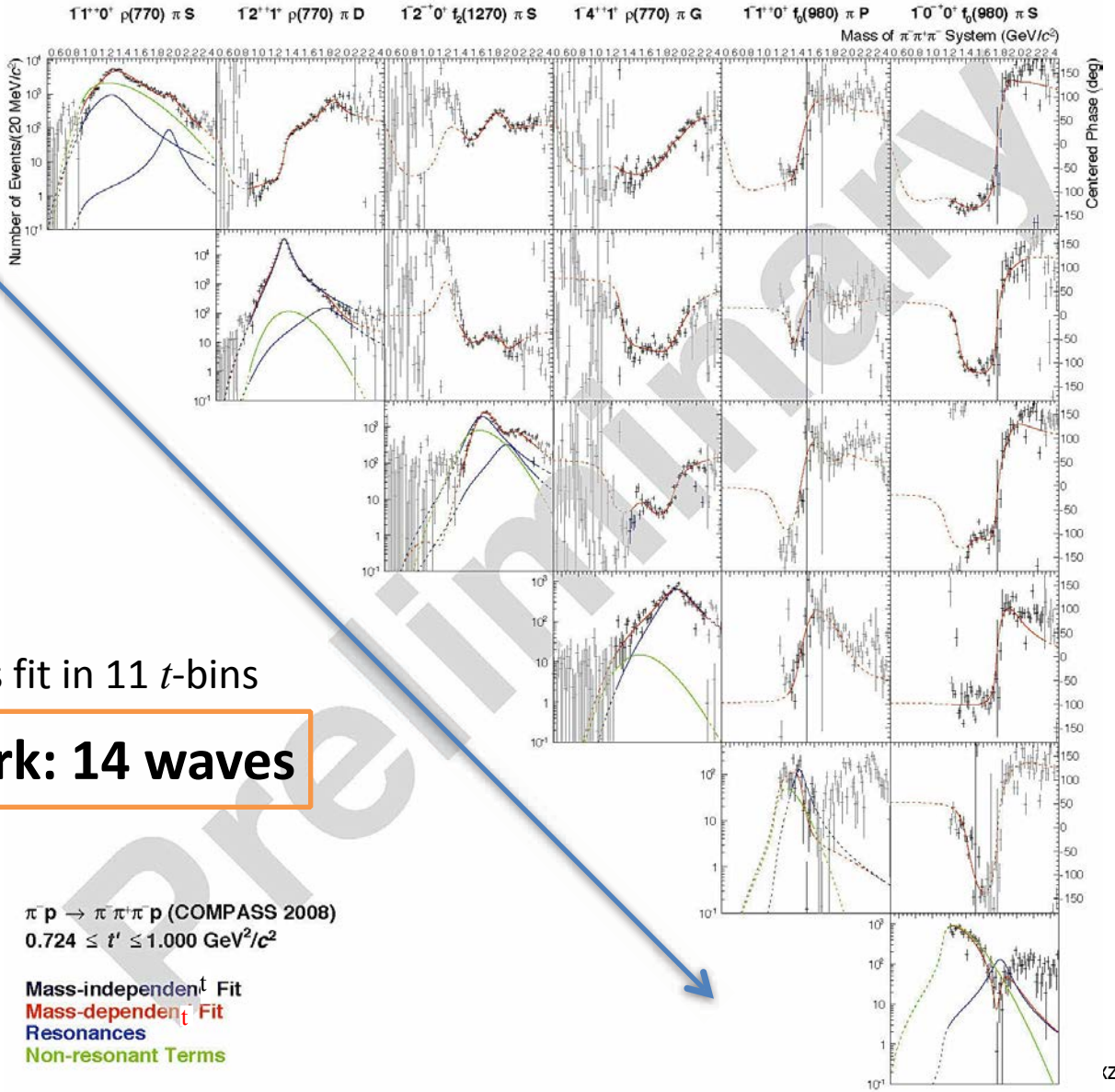
simultaneous fit in 11 t-bins

$\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$ (COMPASS 2008)
$0.189 \leq t' \leq 0.220$ GeV$^2/c^2$

Mass-independent Fit
Mass-dependent Fit
Resonances
Non-resonant Terms

COMPASS “Holography”

Reference waves



Interferometry

simultaneous fit in 11 t-bins

latest work: 14 waves

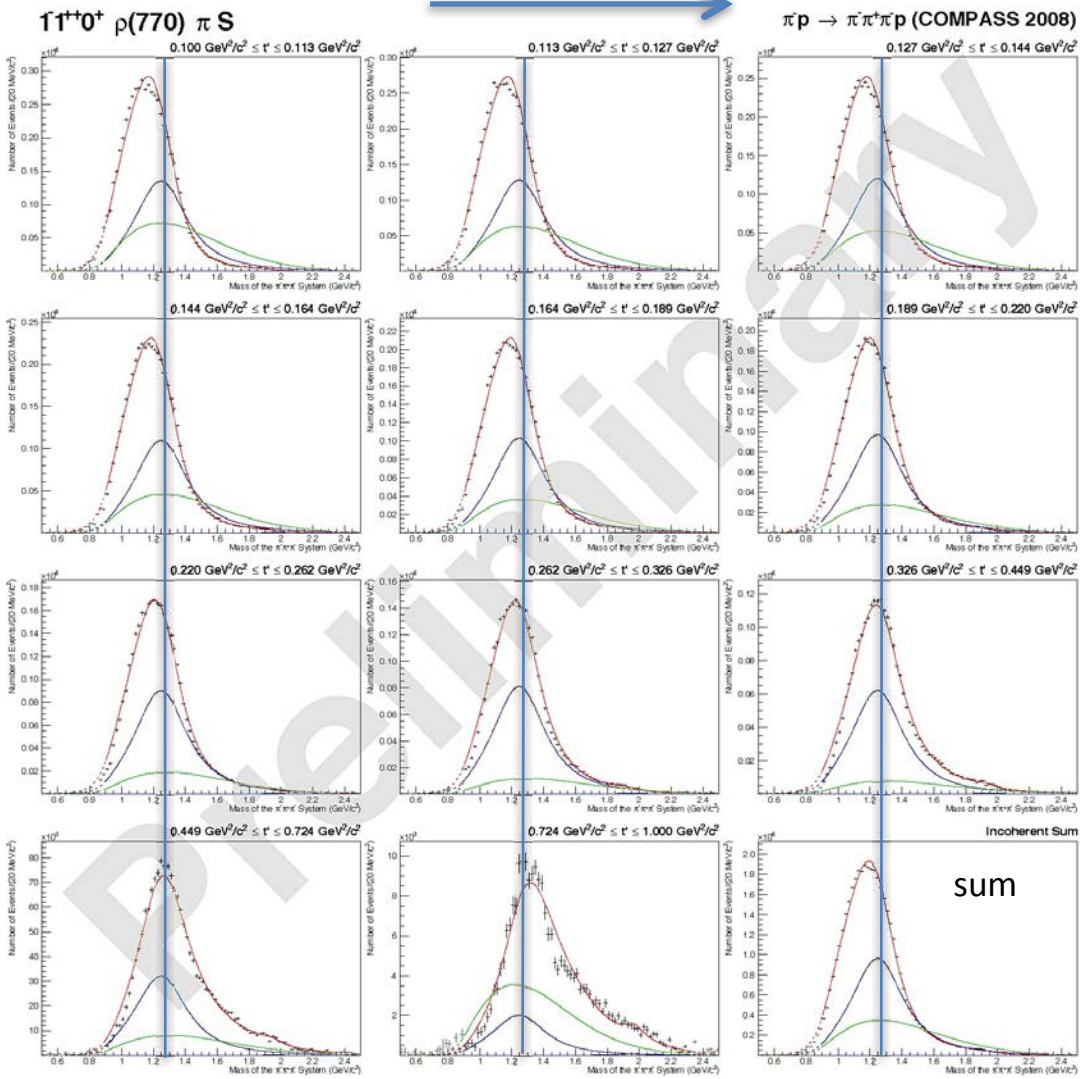
$\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$ (COMPASS 2008)
$0.724 \leq t' \leq 1.000$ GeV$^2/c^2$

Mass-independent Fit
Mass-dependent Fit
Resonances
Non-resonant Terms

Mass dependent fits

Fit in 11 t-bins

t



sum

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

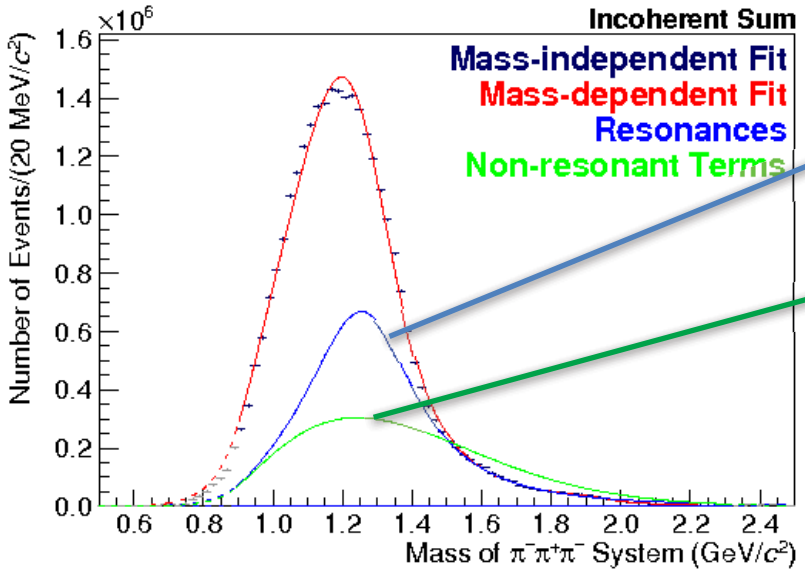
$$1^{++}0^{+}\rho\pi S$$

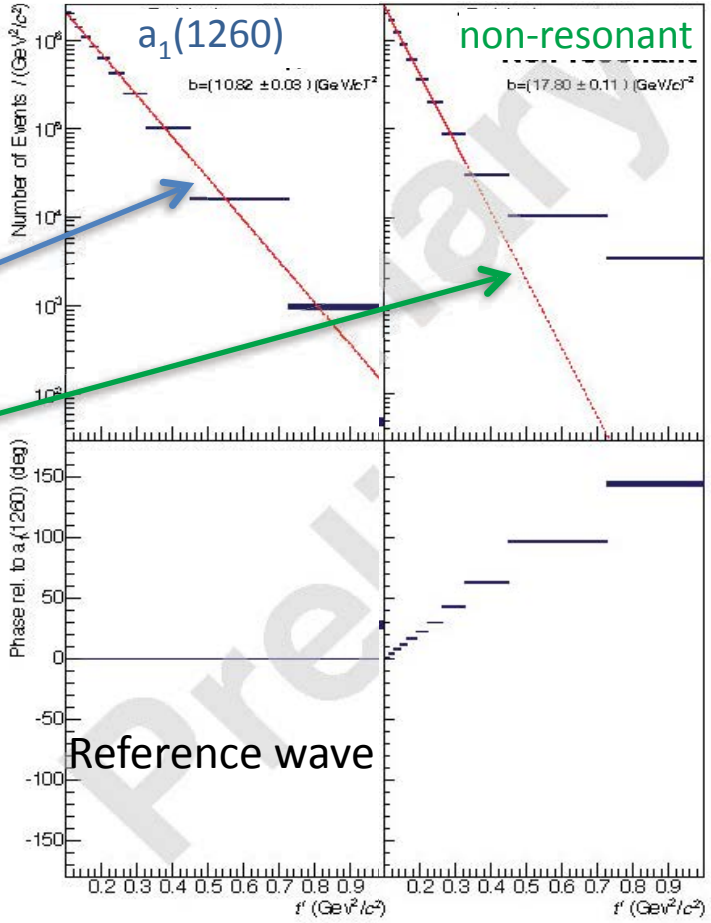
$$J^{PC}M^{\varepsilon}[isobar]\pi L$$

t

Example for t-dependence

$\pi\pi\pi$ COMPASS 2008





Intensities

Phases

t

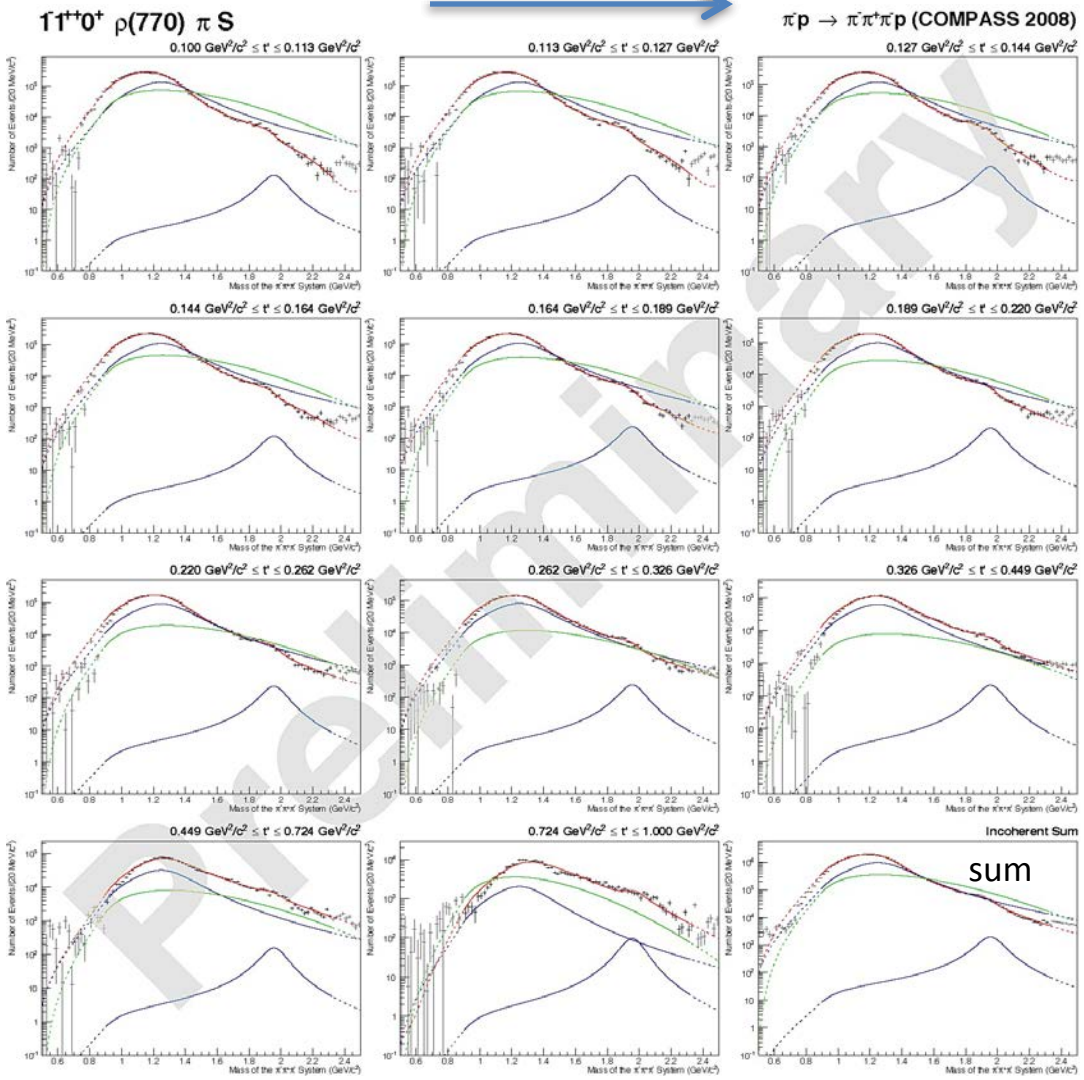
$1^{++}0^{+}\rho\pi S$

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

Mass dependent fits

Fit in 11 t-bins

t

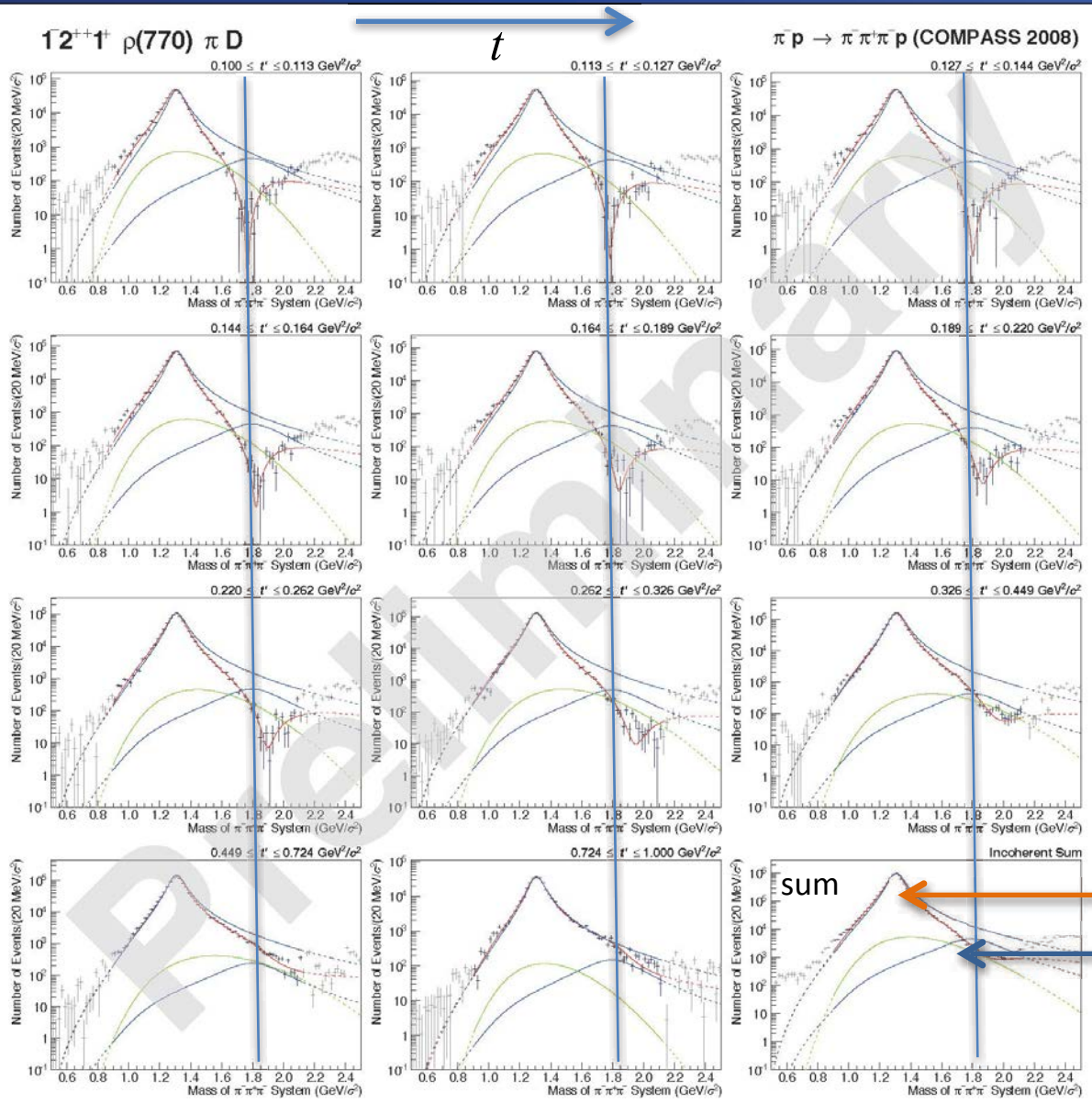


Second high-mass a_1' resonance visible

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

t

Mass dependent fits $a_2(1320)$



Strongly t-dependent interference effects
high-mass a_2'

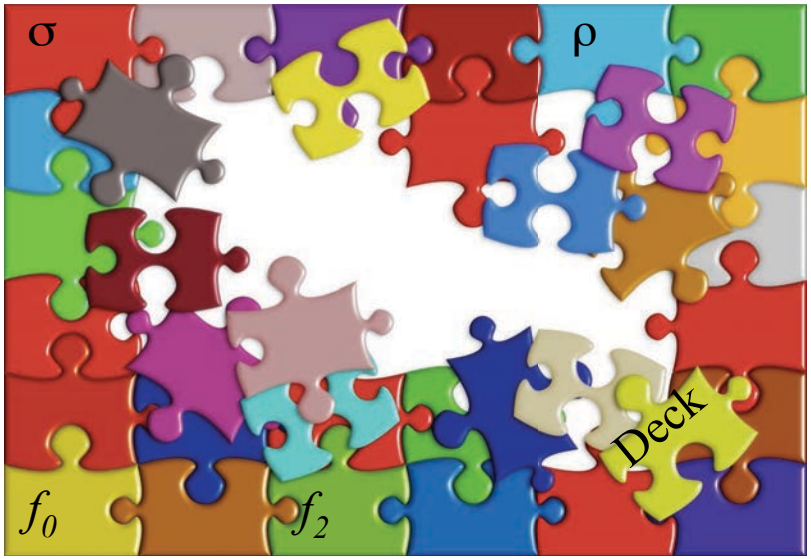
t

$a_2(1320)$

a_2'

What about the building blocks

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



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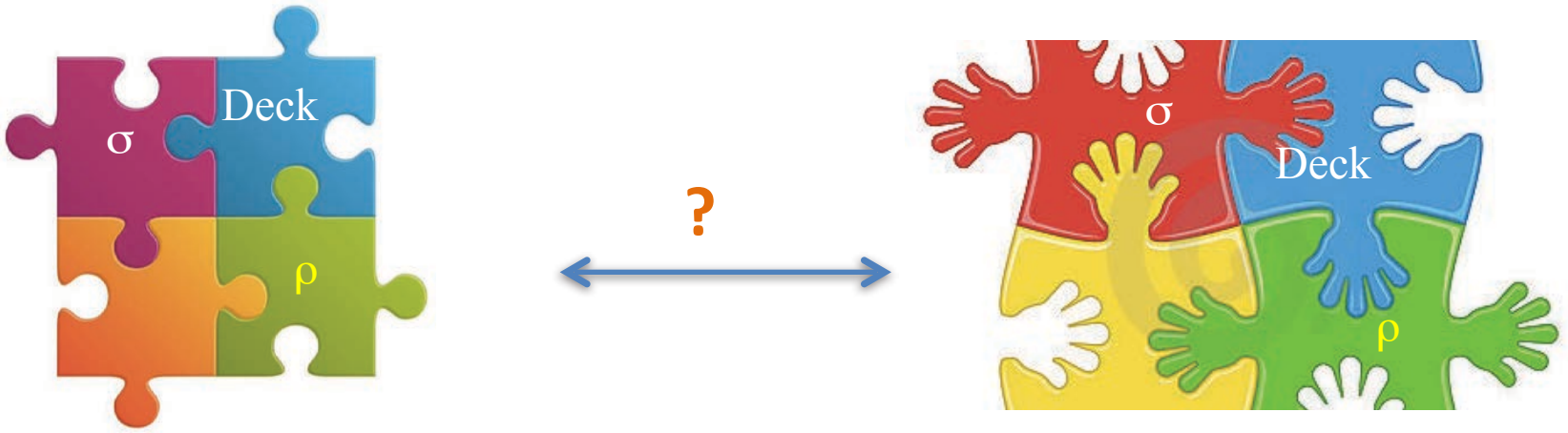
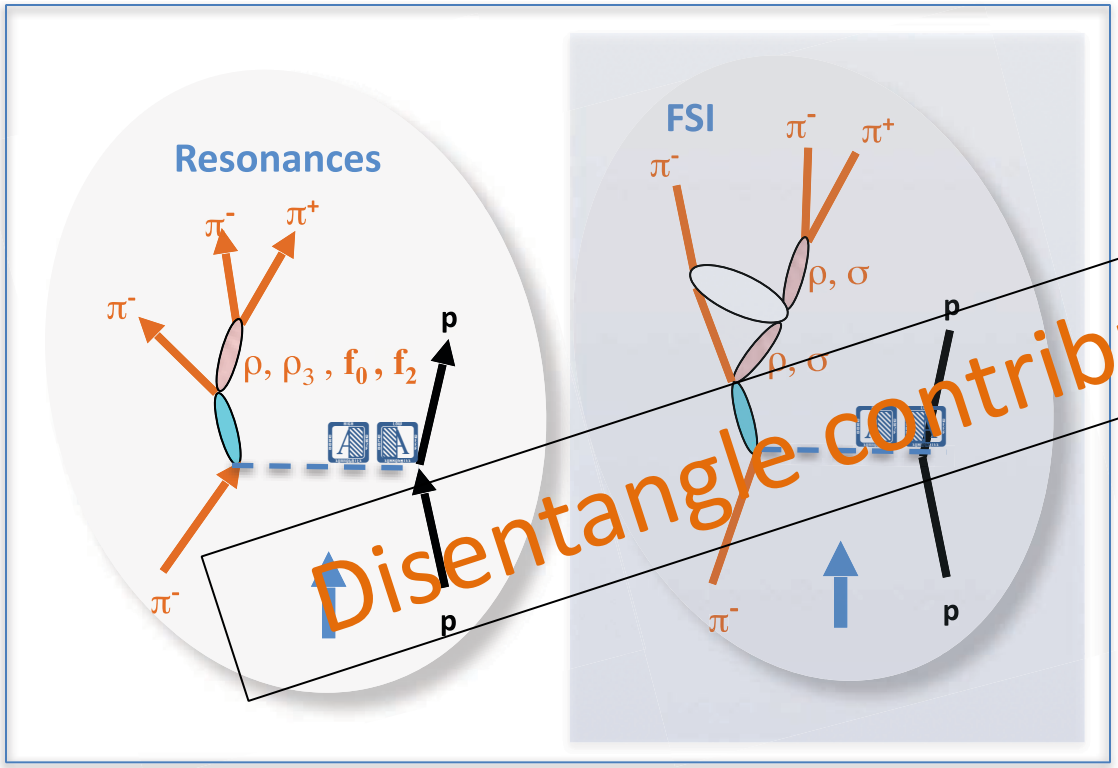


New Paths to Meson Decays



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

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

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

continuum - $[\pi\pi]_S$

$f_0(980)$

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

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

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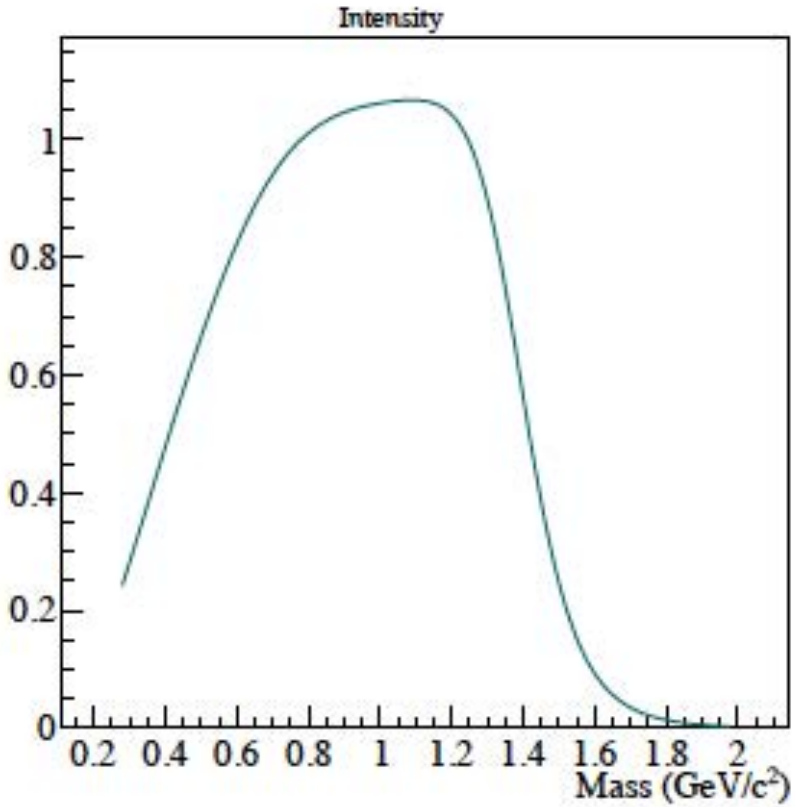
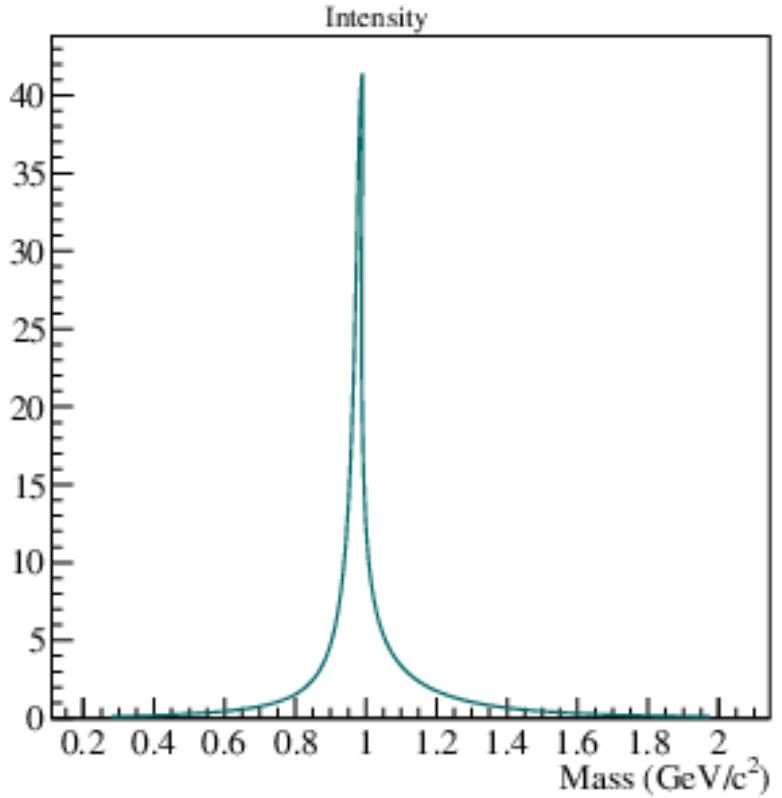
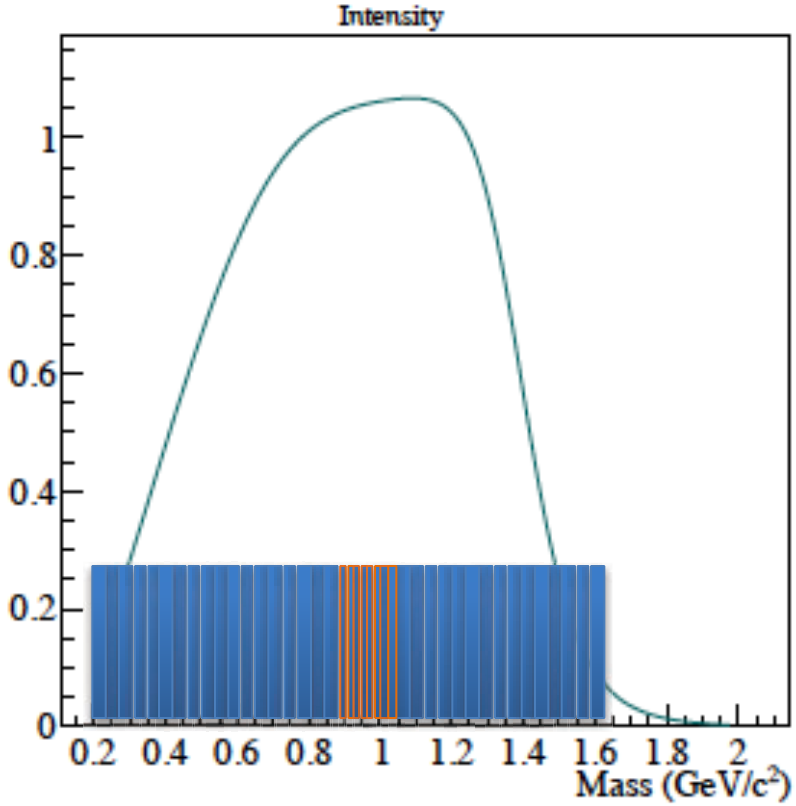


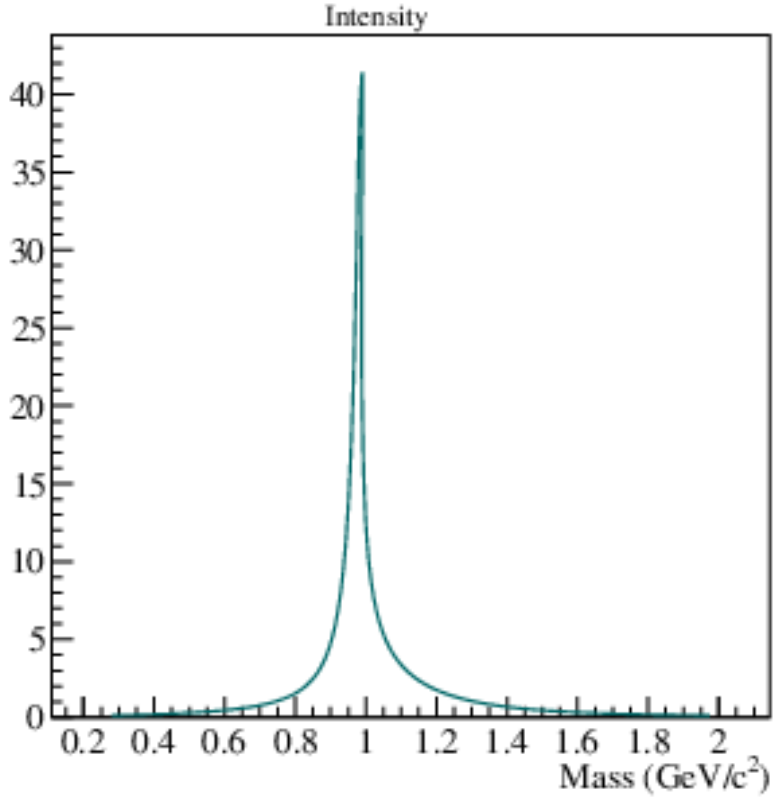


Isobars: $[\pi\pi]^*_S$

replaced by ONE $[\pi\pi]^*_S$ histogram with n-bins

(2n parameters determined by fit)

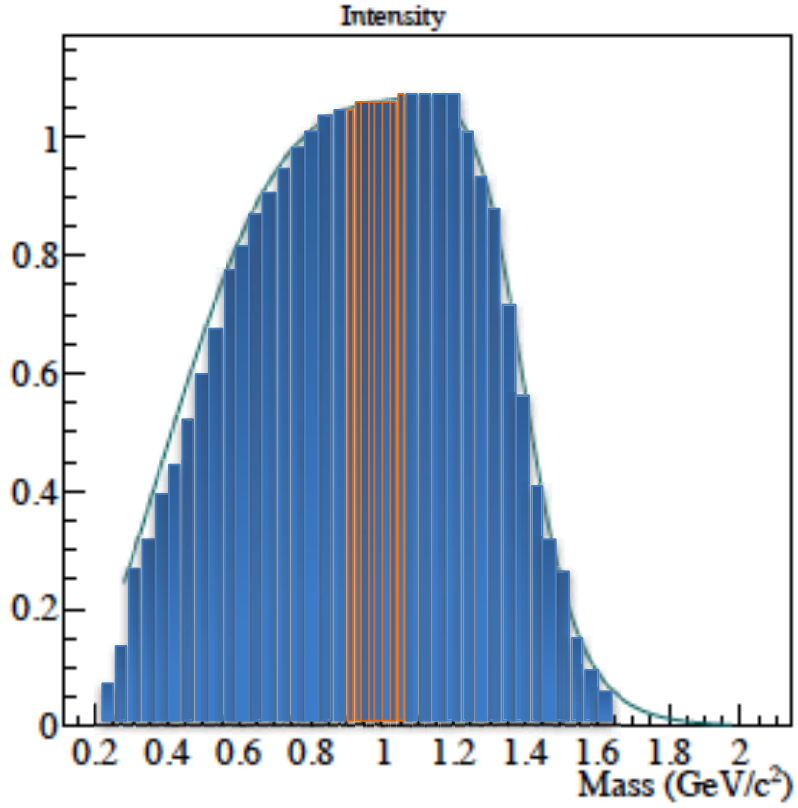


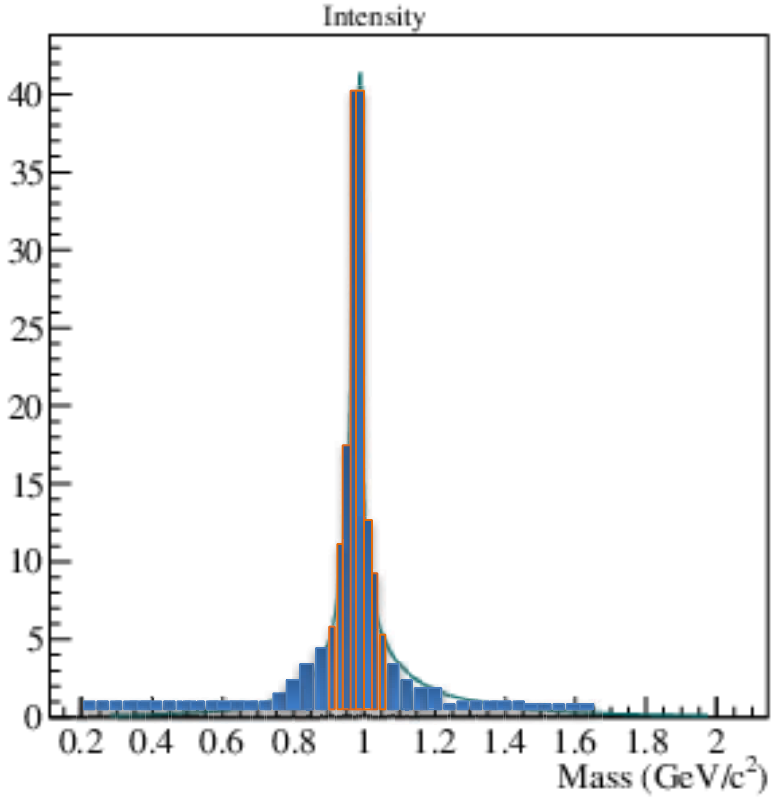


Isobars: $[\pi\pi]^*_S$

replaced by ONE $[\pi\pi]^*_S$ histogram with n-bins

(2n parameters determined by fit)





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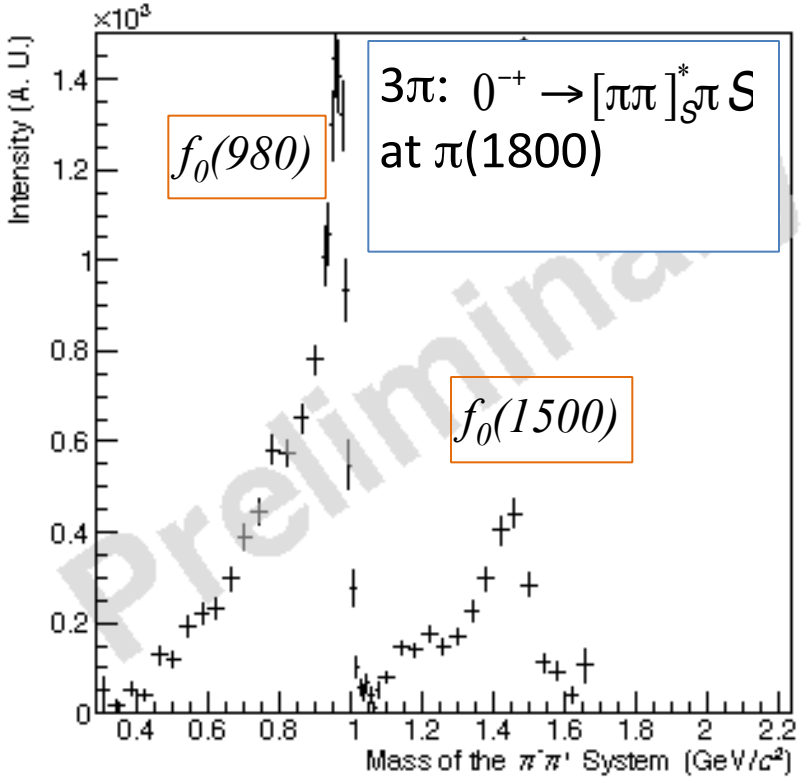
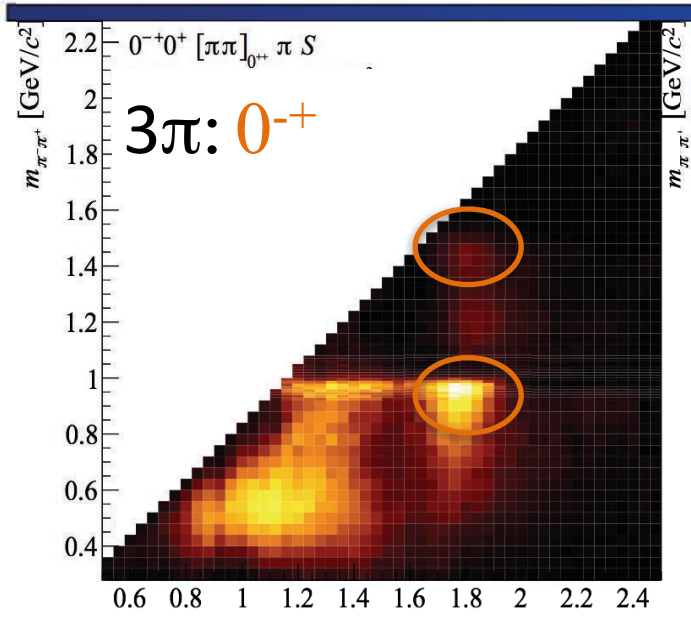
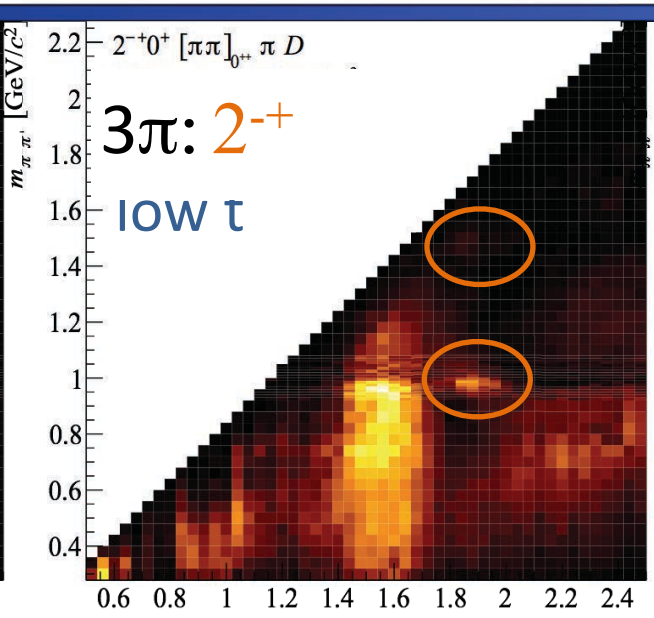
replaced by ONE $[\pi\pi]^*_S$ histogram with n-bins

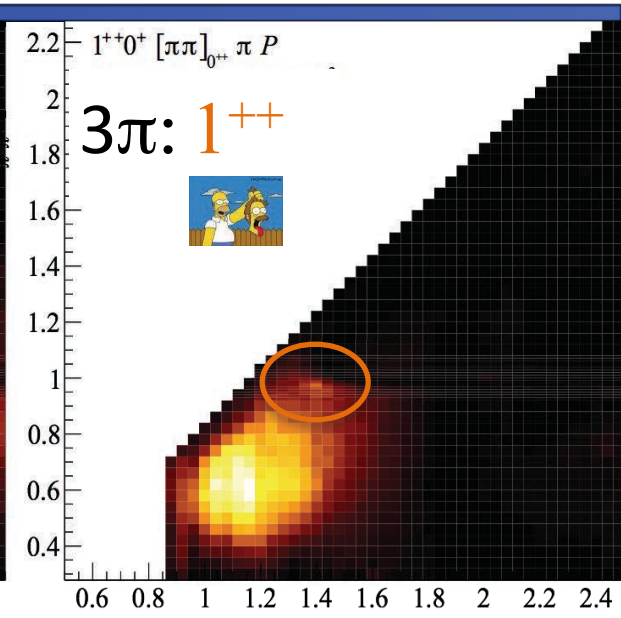
(2n parameters determined by fit)

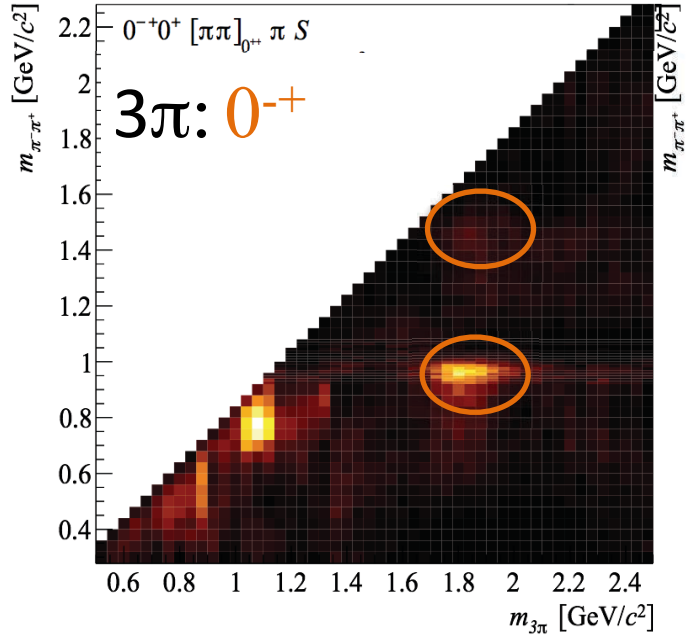


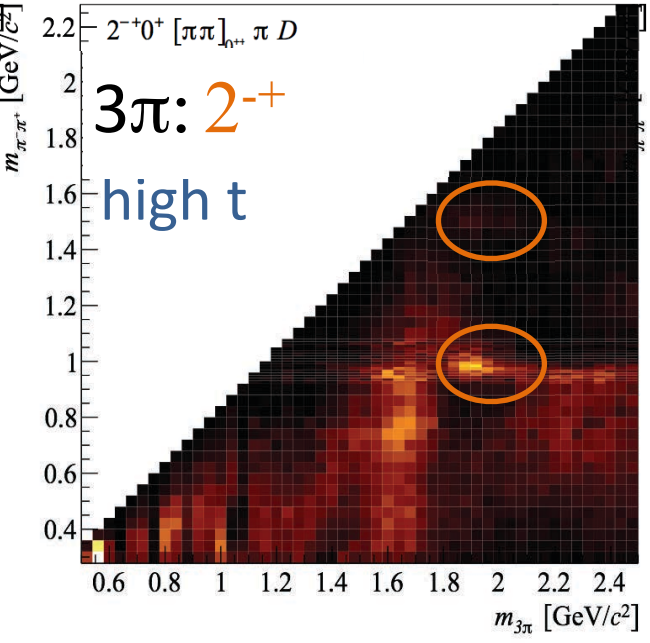
Correlation: $m_{2\pi}(0^{++})$ *vs* $m_{3\pi}(J^{PC})$

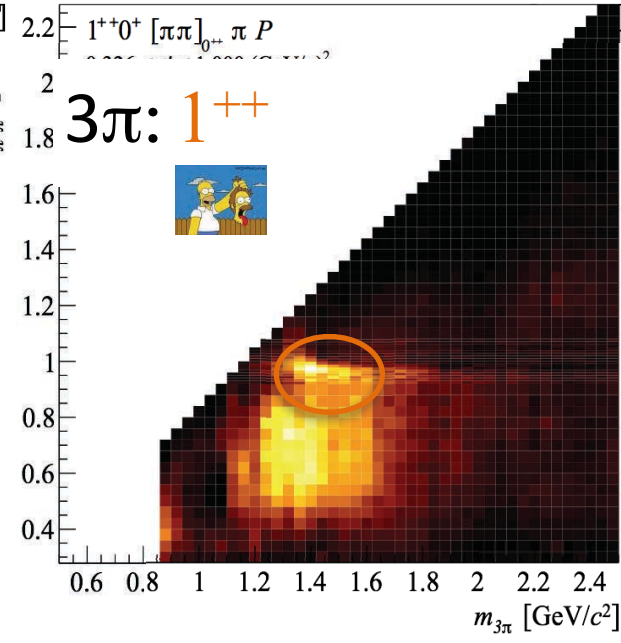






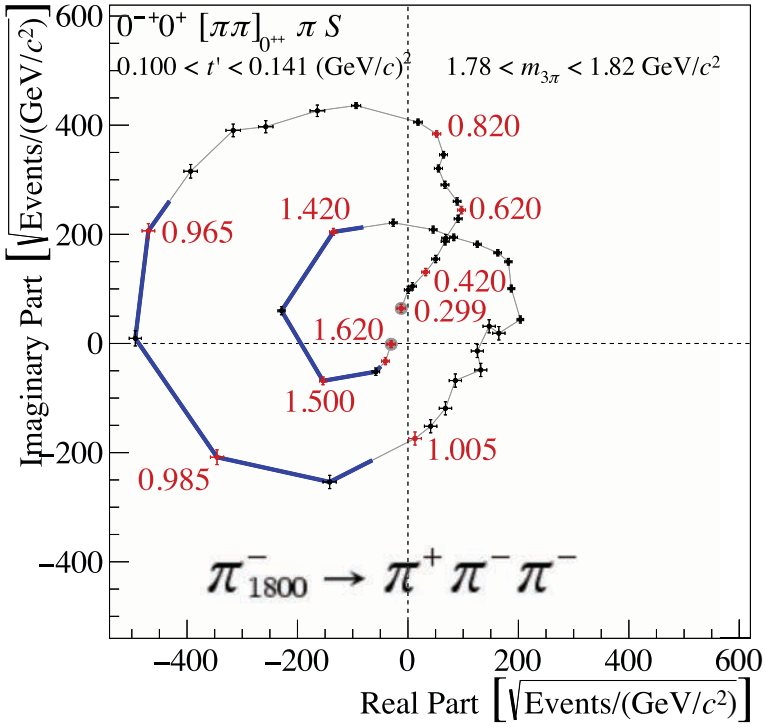






What about ππ S-wave phase shifts ?

- Extracting ππ S-wave phase shifts : not trivial
  - Additional phases arise from
    - Deck effect (non-resonant)
    - 3π phase w.r.t to reference
    - Phase due to „third“ π (rescattering effect)



Summary

- Establish new "2D" fit method to perform PWA in $m_{3\pi}$ and t
  - Allows to "separate" non-resonant and resonant production
  - Cleaner access to resonances

- 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 ?

    Interference of $a_1(1260)$ with non resonant amplitudes ?

Summary – Analyses Concepts

- Developed new methods 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)
  - Extend to "all" isobaric systems

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

Needs high statistics !!

- New mindset for analysis : include production amplitudes (non-resonant)
- Include relativistic effects into amplitudes
- New (CPU intensive) methods to determine systematics on resonance parameters