Mesons: Searching for new properties and rare species

-

New Precision Experiments with COMPASS at CERN

Stephan Paul

TU München

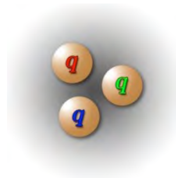
Excellence Cluster Universe

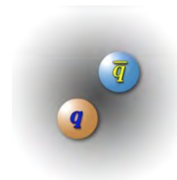
Brief Overview

- Polarizabilities
  - Analogies with atoms
  - Pion polarisability
- Radiative excitations
- Spectroscopy in strong interaction
  - Introduction
  - Identification method (PWA)
  - Result summary and a new meson
- New insights into production/decay dynamics
- Conclusions

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)

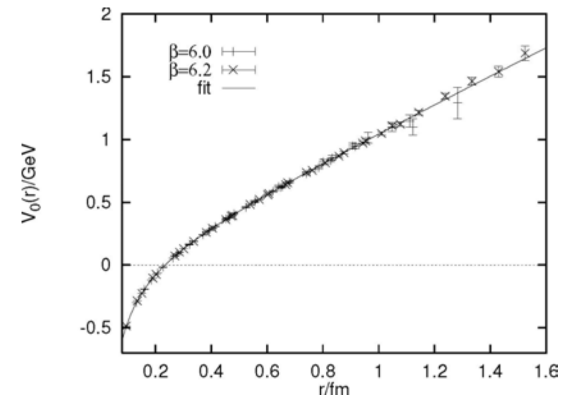
    $m_u = m_d = 310\ MeV/c^2$; $m_s = 485\ MeV/c^2$

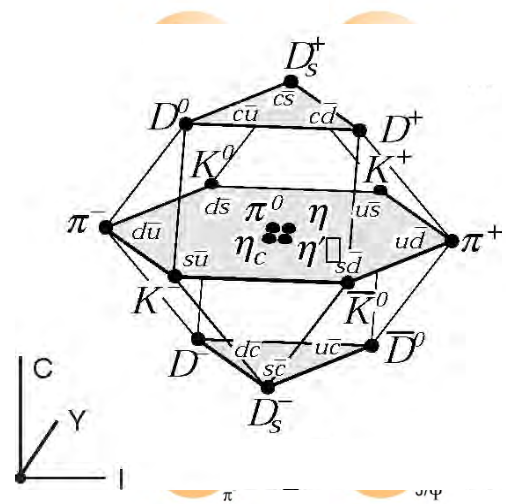
    Use effective potential
  - Use symmetries flavour, spin,colour

    build ‚Periodic table' of hadrons
  - 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: $\vec{J} = \vec{L} + \vec{S}$

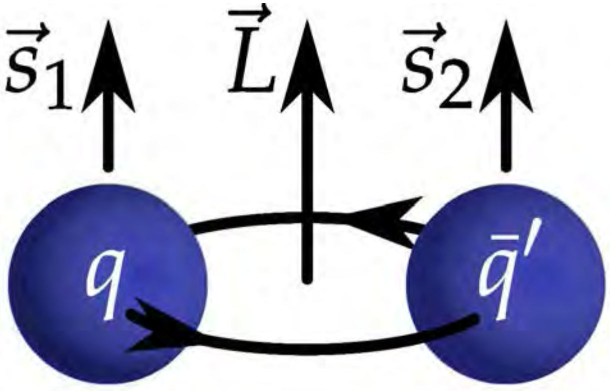
- Isospin: $I = 1$ for u,d quarks, $I=0$ for other quarks

  $I_z\,(\mathrm{u}) = ½$

  $I_z\,(\mathrm{d}) = -½$

  light Mesons: $I = 0$ or 1

  other Mesons: $I = 0$ 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:

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

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

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

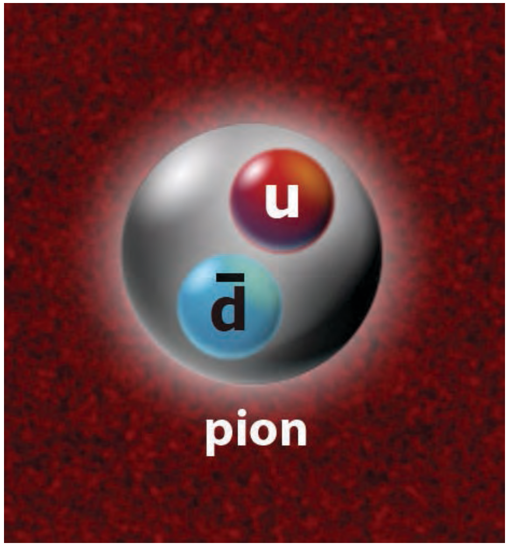
- Same quantum numbers mix

Some facts about the Pion

- Pion is lightest composite system
- Properties:
  - $M_{\pi^+} = 139.57$ MeV/c^2
  - $M_{\pi^0} = 134.97$ 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)

  - $\sqrt{\langle r^2 \rangle} = 0.672 \pm 0.008 \text{ fm} = (0.672 \pm 0.008) \cdot 10^{-15} \text{m}$



Question: what is it‘s macroscopic structure ?

Properties of basic matter

Refractive index n

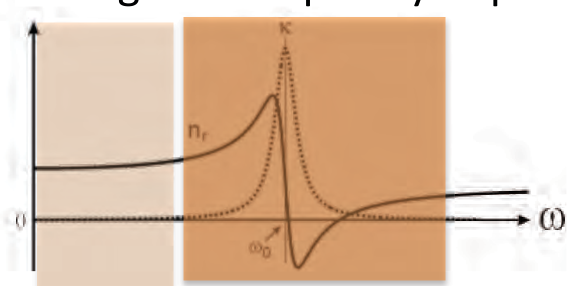
- Macroscopically: dielectric constant $\tilde{\varepsilon} = \varepsilon_1 + i\varepsilon_2 = n + i\kappa$
- Microscopically:
  - Light wave polarizes atoms ➛ induced dipole moment: $\vec{P} = \alpha \cdot \vec{E}$

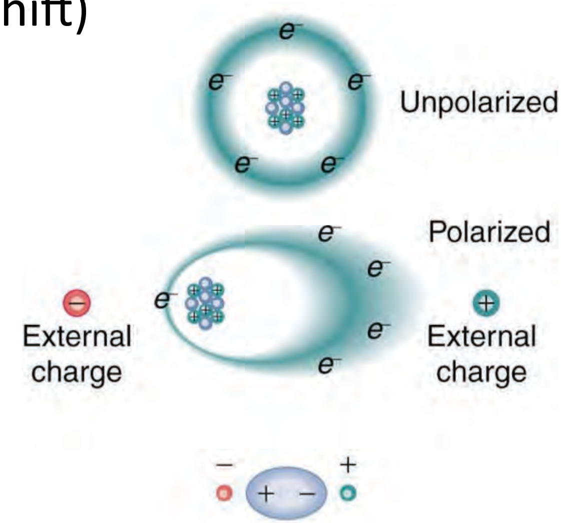
    α: electric polarisability
  - Relaxation ➛ dipole radiation (delayed – phase shift)

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

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

  - Strength is frequency dependent (dispersion)





How about the Pion ?

- „stable" object with smallest „Bohr" radius
- Polarizability
  - strong interaction $\Delta E(\pi \rightarrow \rho) \approx 600 \text{ MeV}$
  - electromagnetic $\Delta E(H_{1S} \rightarrow H_{2S}) \approx 10 \text{ eV}$

Indicator for stiffness of system

  - Difference in stiffness: $\frac{\alpha_{em}}{\alpha_{strong}} = \frac{1/137}{0.7} \approx 0.01$

$$\frac{\alpha_\pi}{<r_\pi^{em}>^3}(\pi) \approx \frac{1}{100} \frac{\alpha_{atom}}{a_{Bohr}^3}(atom) \cdot \left(q_{eff}^\pi\right)^2 << \frac{\alpha_{atom}}{a_{Bohr}^3}(atom) \qquad <r_\pi^{em}>^2 \approx 0.45 \pm 0.01 fm^2$$

- 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)

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

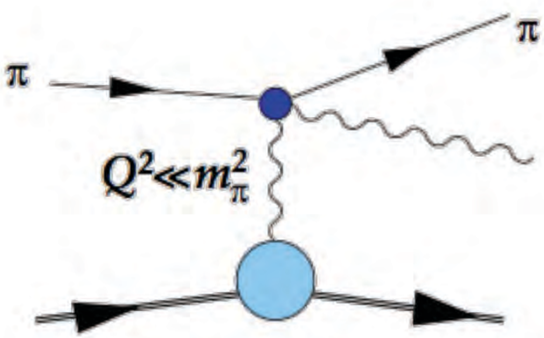
- Particle physics: scatter high energy π from photon source
  - Photon source: high Z nucleus
  - High gradients: relativistic amplification

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

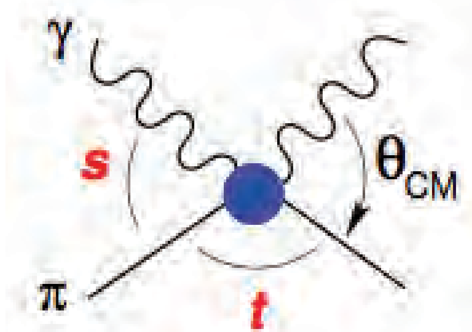
  - Charged particle is deflected in field (Born term)

COMPASS Measurement

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



190 GeV/c beam particles



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

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

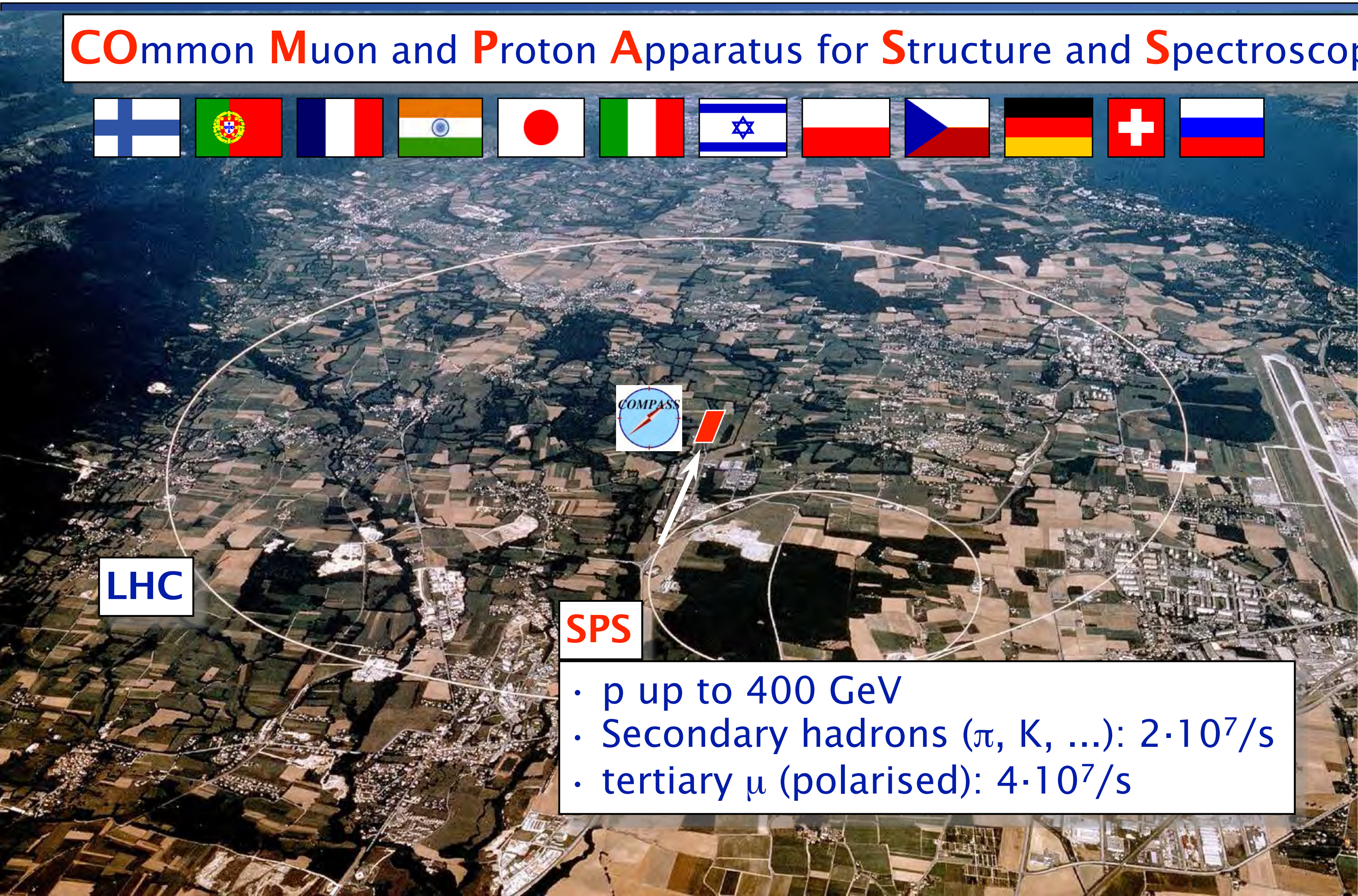
$$\mathcal{P} = z_-^2 (\alpha_\pi - \beta_\pi) + \; ....$$

elasticity:

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

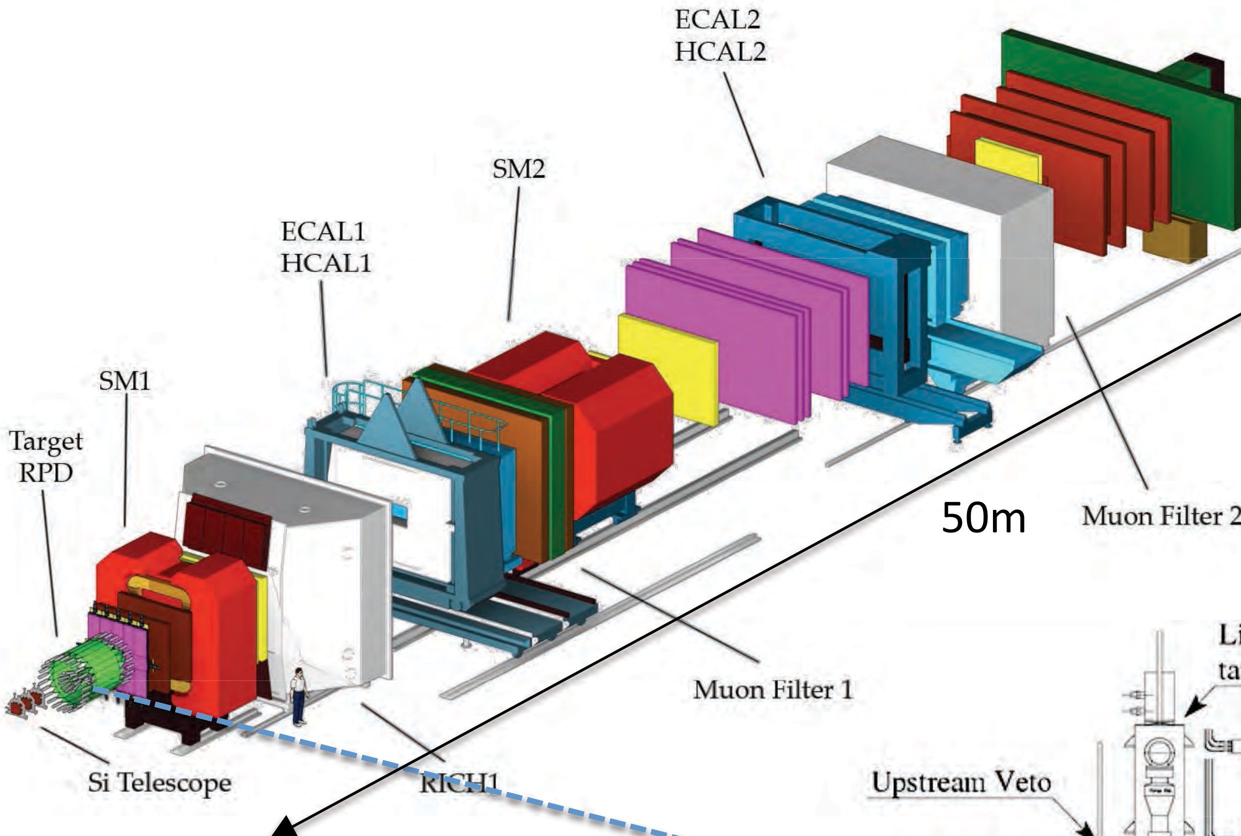
COMPASS am CERN

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

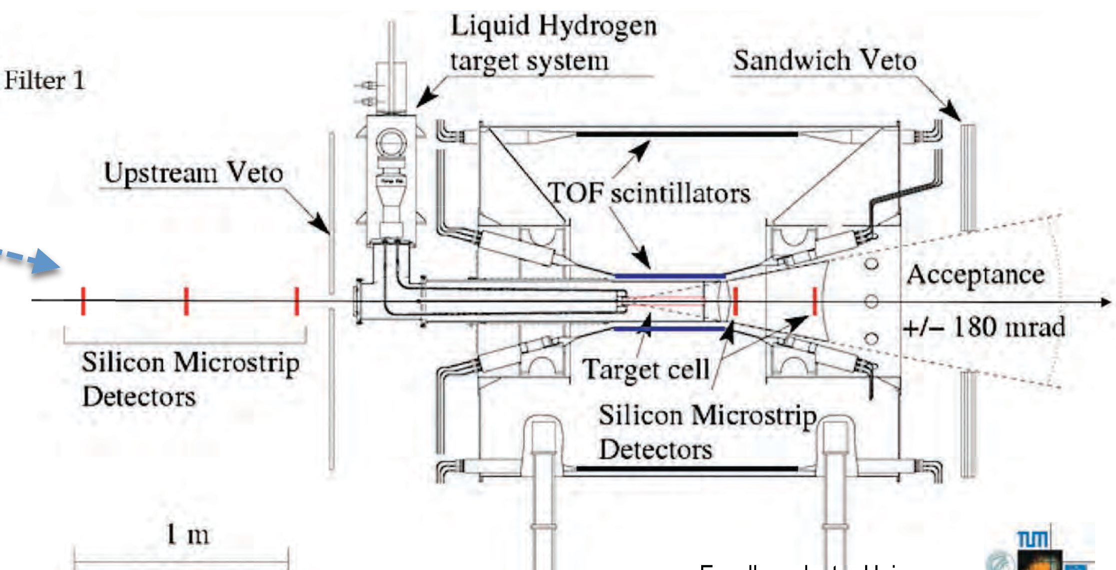
The COMPASS Experiment



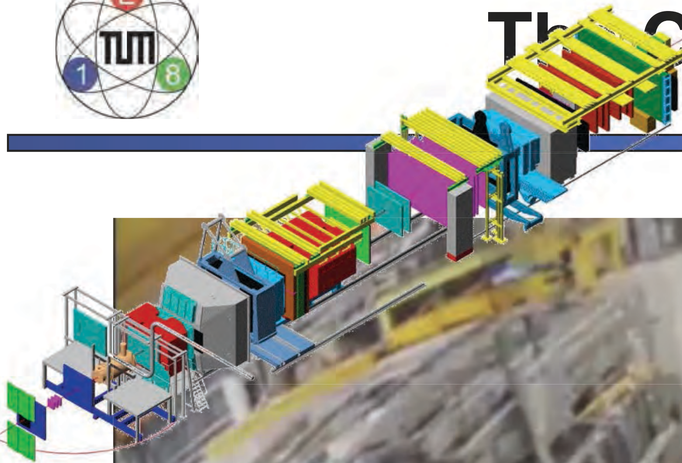
CERN SPS

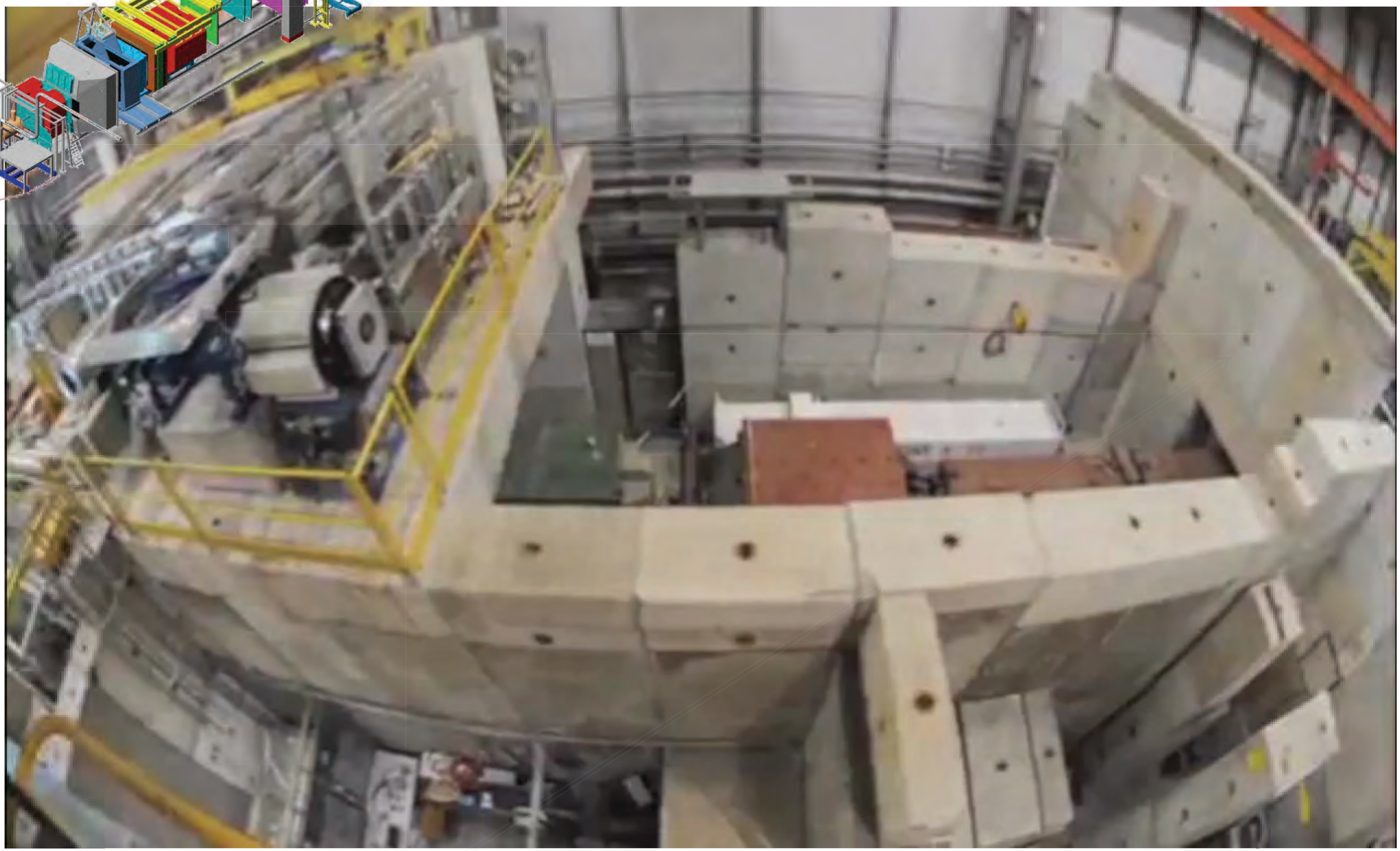
Hadron beam:

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

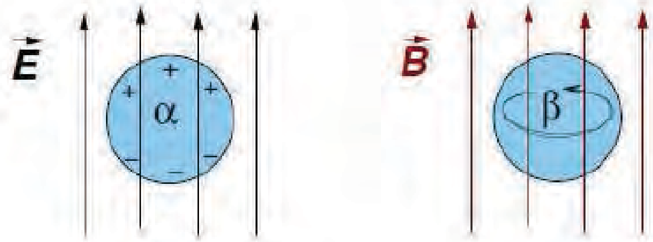


The COMPASS Experiment

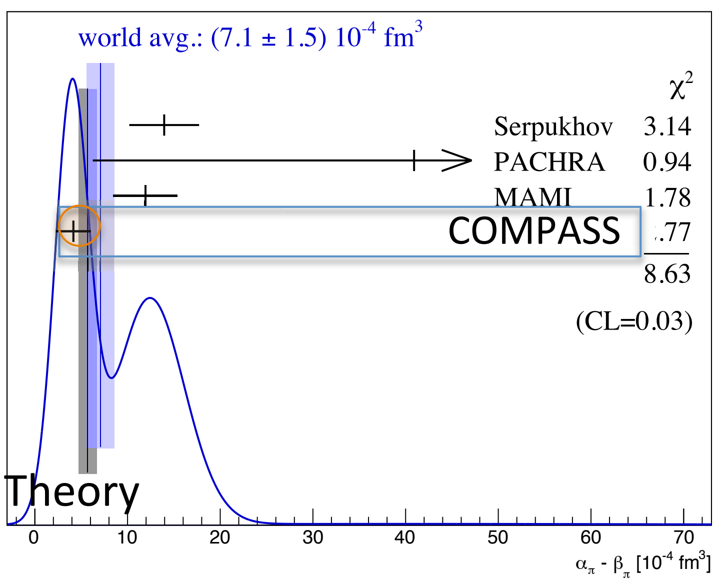




COMPASS Measurement

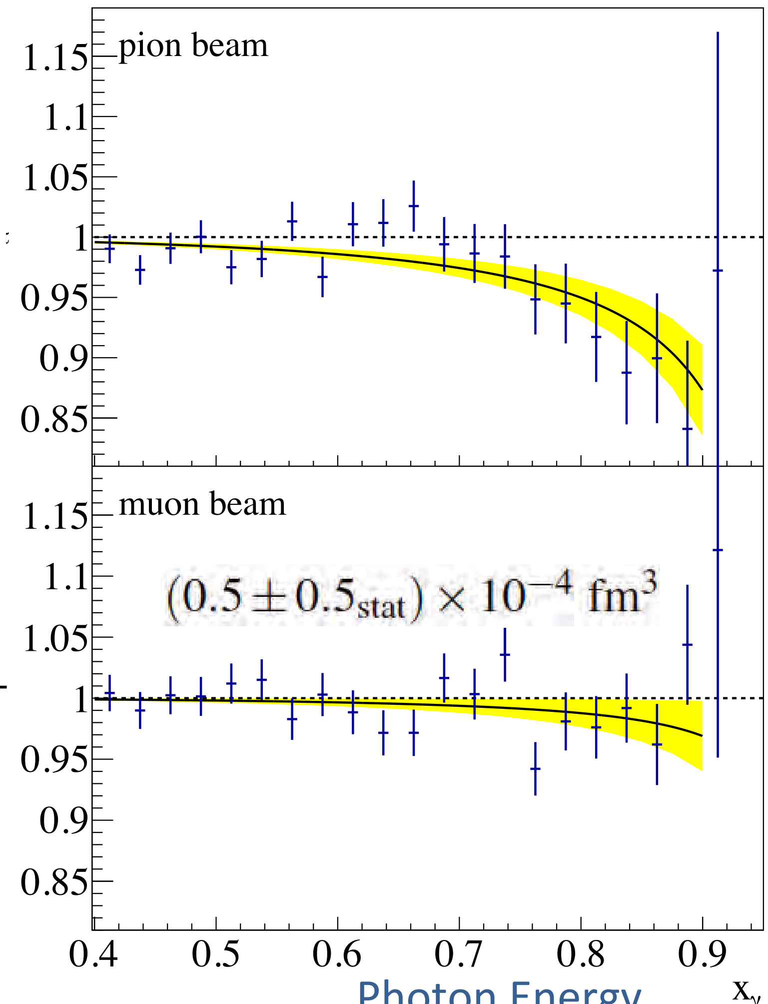


$$\alpha_\pi = (2.0 \pm 0.6_{stat} \pm 0.7_{syst}) \times 10^{-4}\,\mathrm{fm}^3$$



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

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

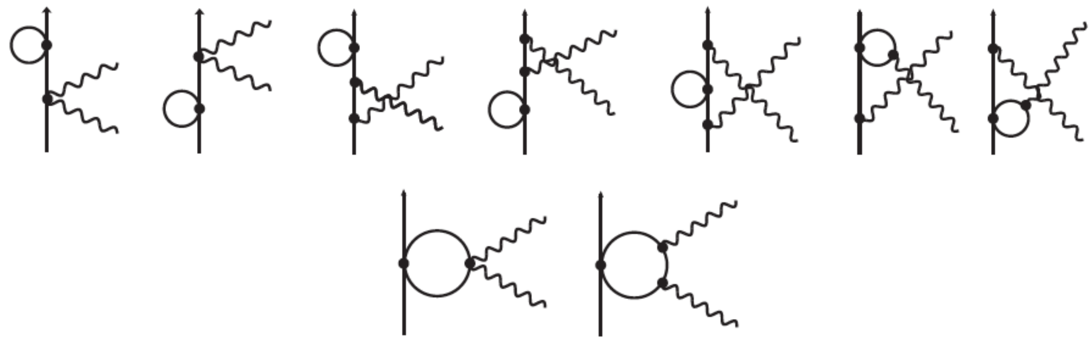


π polarizability: χPT confirmed

Long standing puzzle solved !

So What ?

- Pion is GoldstoneBoson of spontaneous chiral symmetry breaking
- Massless excitation of ground state
- Long wavelength description of QCD
  - Polarisability is basic interaction with electromagnetic field

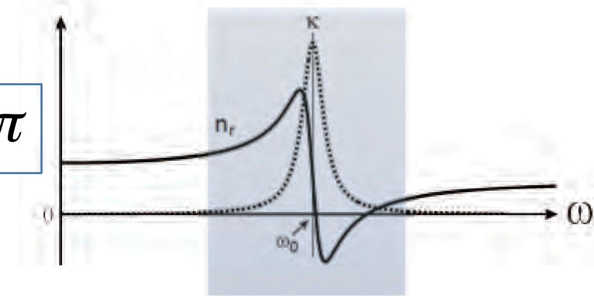


  - Photon scattering of pion cloud of pion
  - Correct results (2-loop calculation) gives VERY Strong support for SSB scenario

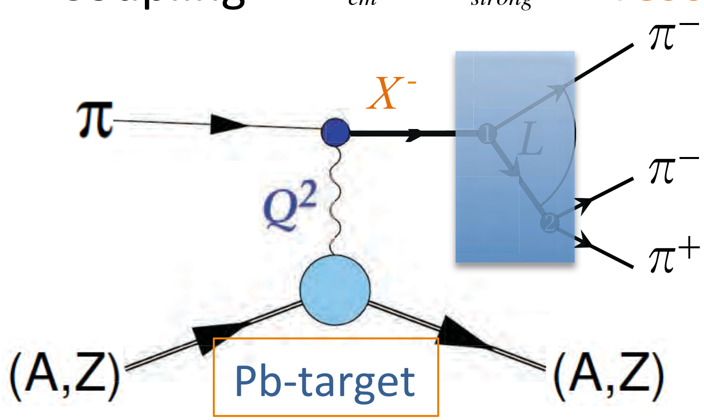
Resonant Excitation

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

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



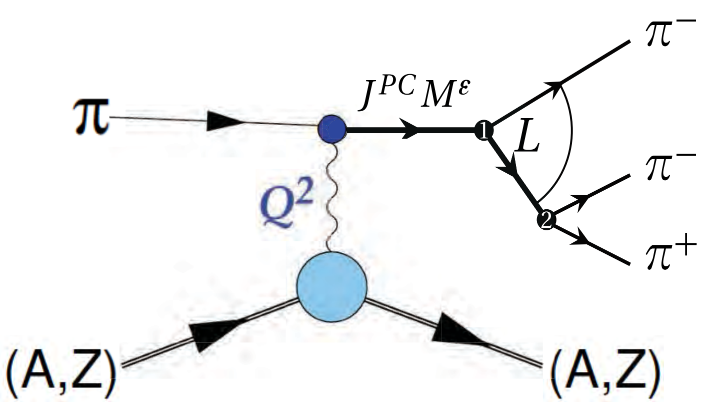
- Various multipole excitations possible
  - Determine angular distribution in de-excitation process
- For Primakoff reactions: wide range of photon energies
  - Analysis of final state determines reaction type and excitation energy
  - Coupling $\alpha_{em} << \alpha_{strong} \rightarrow$ resonance 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 $t' < 10^{-3}\ GeV^2/c^2$

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

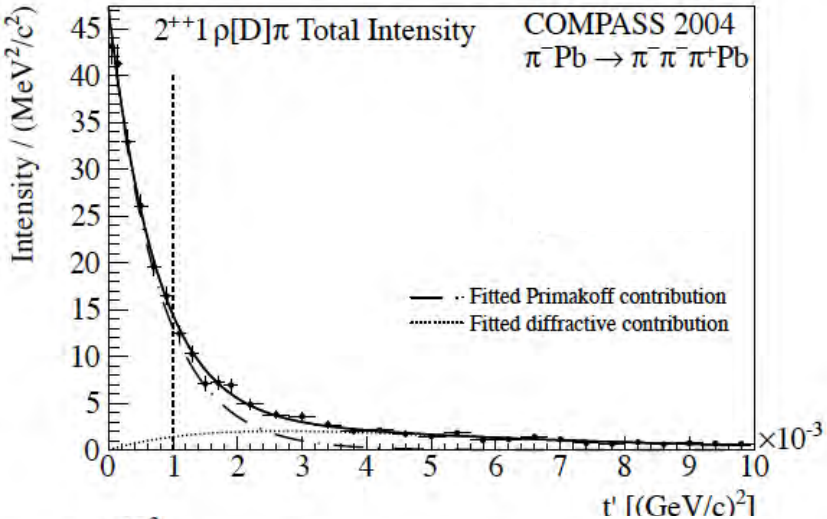
$$\sigma_{diffract} \approx t'^{M} \cdot e^{-b_{diff}t'}$$

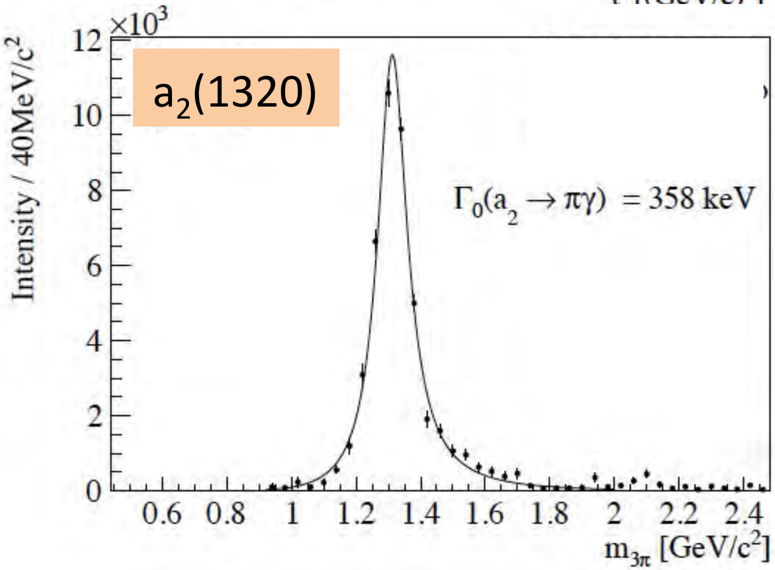
$$b_{photo} >> b_{diffract}$$

→ $M = 1$ is suppressed in diffraction

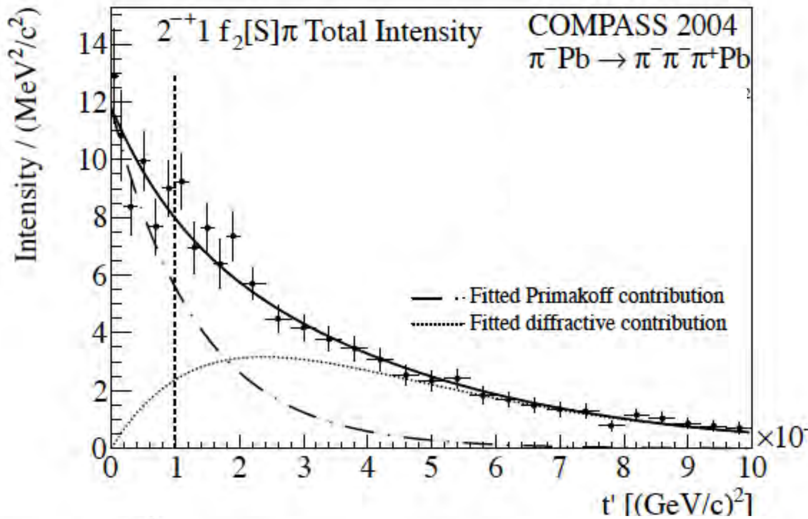
EM-Transitions for Mesons

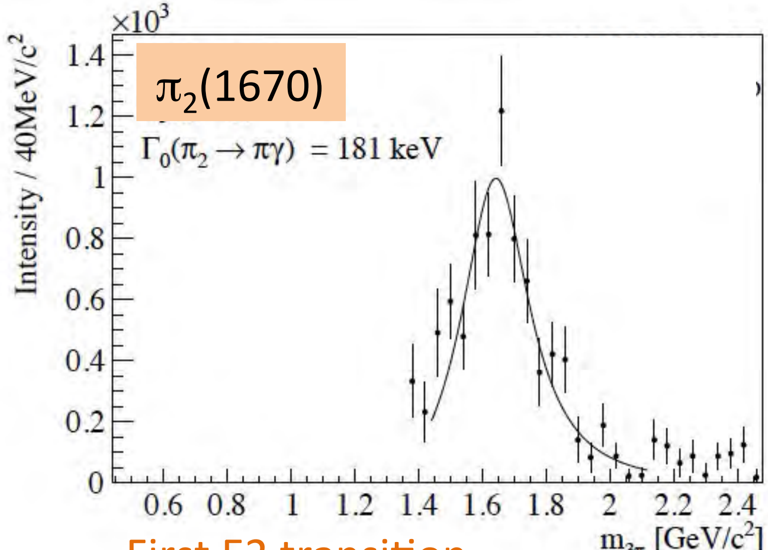
$\Gamma_0(a_2(1320) \to \pi\gamma)$





M2 transition



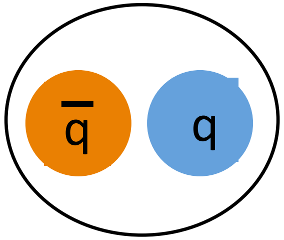


$\Gamma(\pi_2 \to \pi\gamma)$

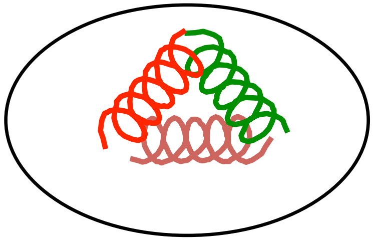
First E2 transition observed for mesons

Light Mesons, Quarks and Gluons

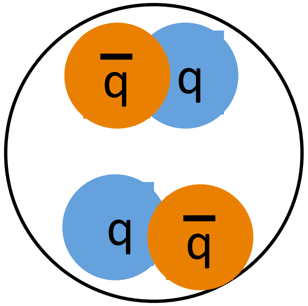
- Quark model mesons (u, d, s quarks)



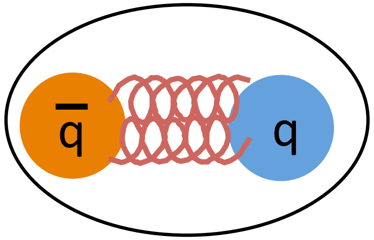
- Glueballs (gluons and no valence quarks)



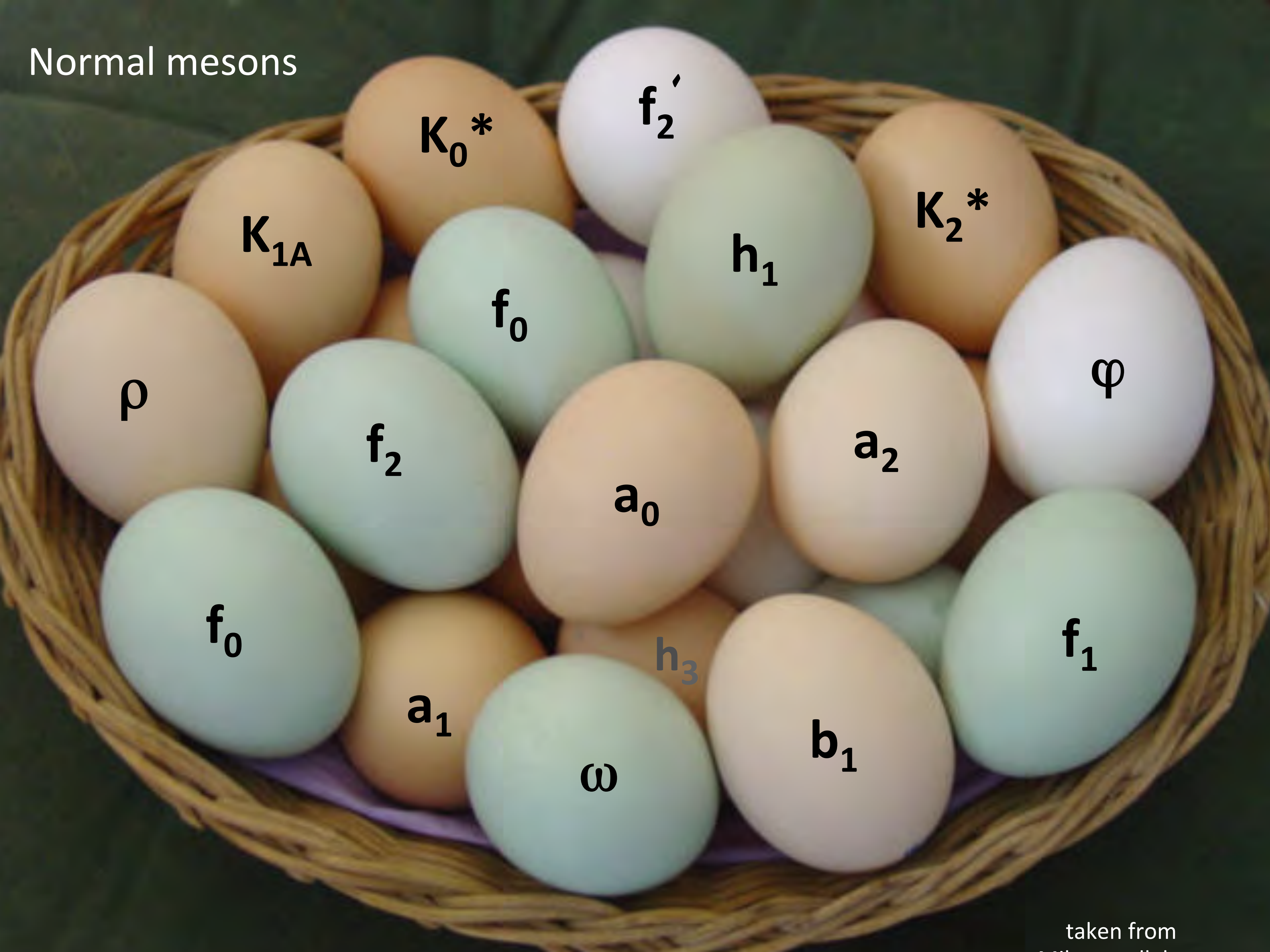
- Multiquarks (quark-antiquark pairs)



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



Klempt Zaitsev Phys Rep 454 (2007) 1

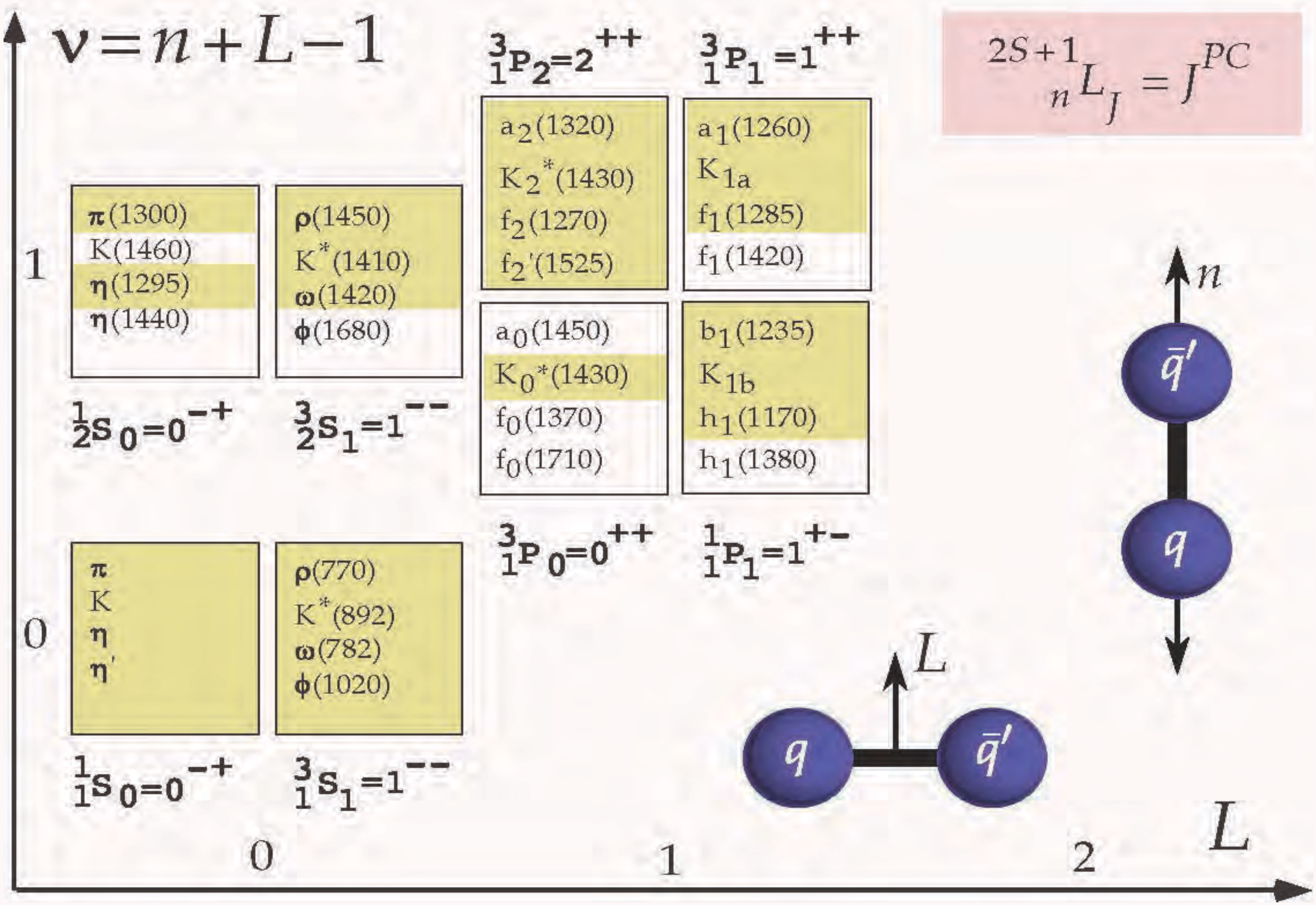

Normal mesons
K_0^*
f_2'
K_{1A}
h_1
K_2^*
f_0
ρ
φ
f_2
a_2
a_0
f_0
f_1
h_3
a_1
b_1
ω
taken from

More Surprising States?

taken fron
Mike pendle

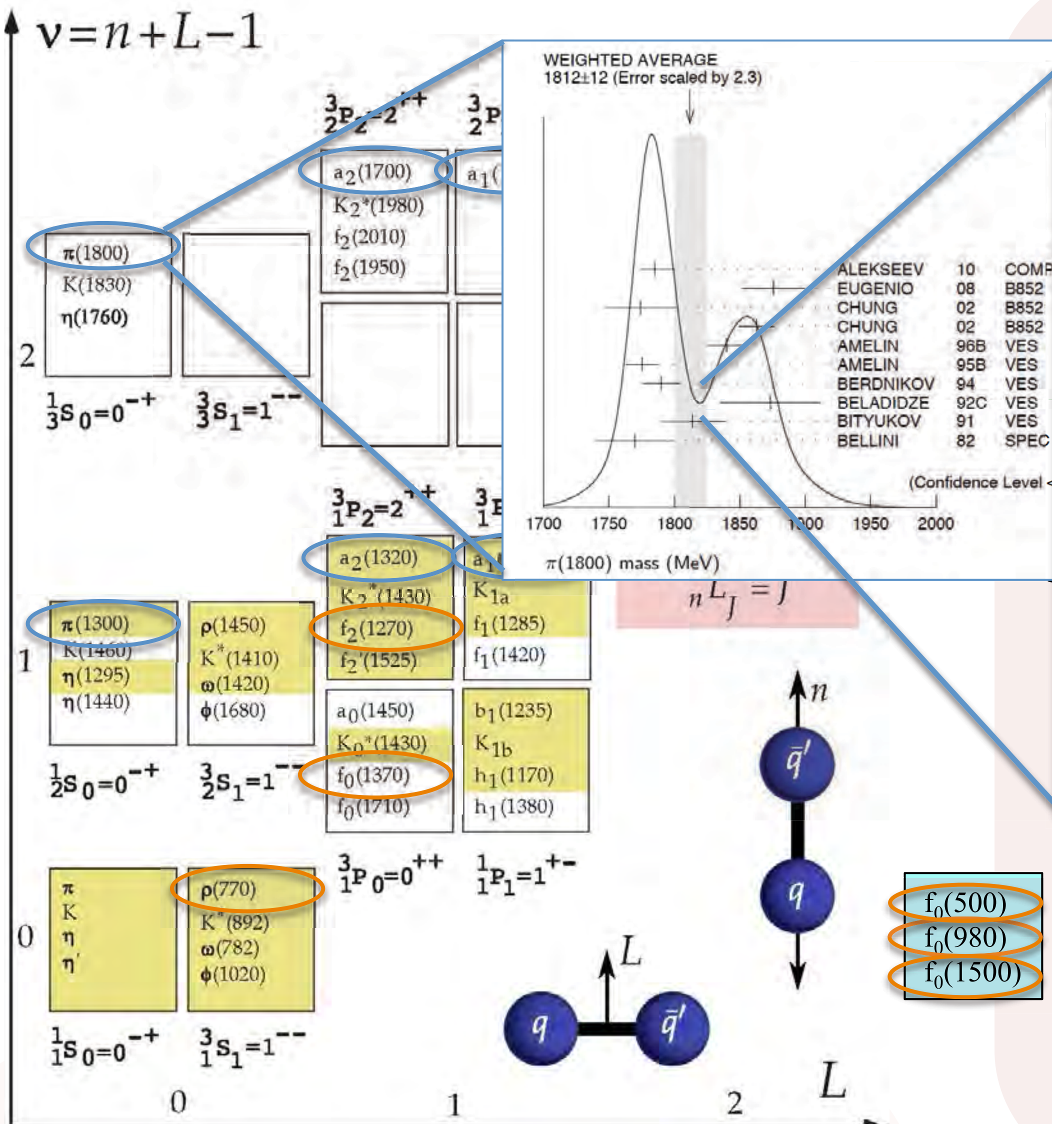
Constituent Quarks and Mesons

Spectrum of light mesons:



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

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

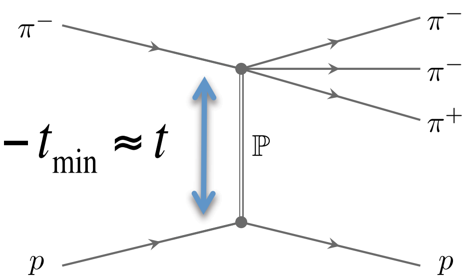
…eavy

…ing

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

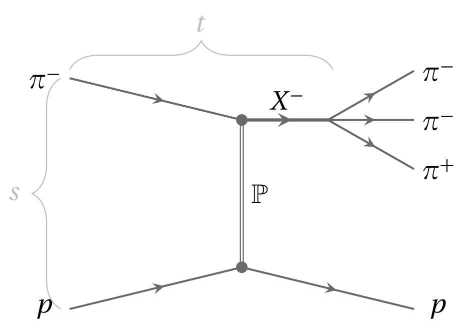
The Process

generic process

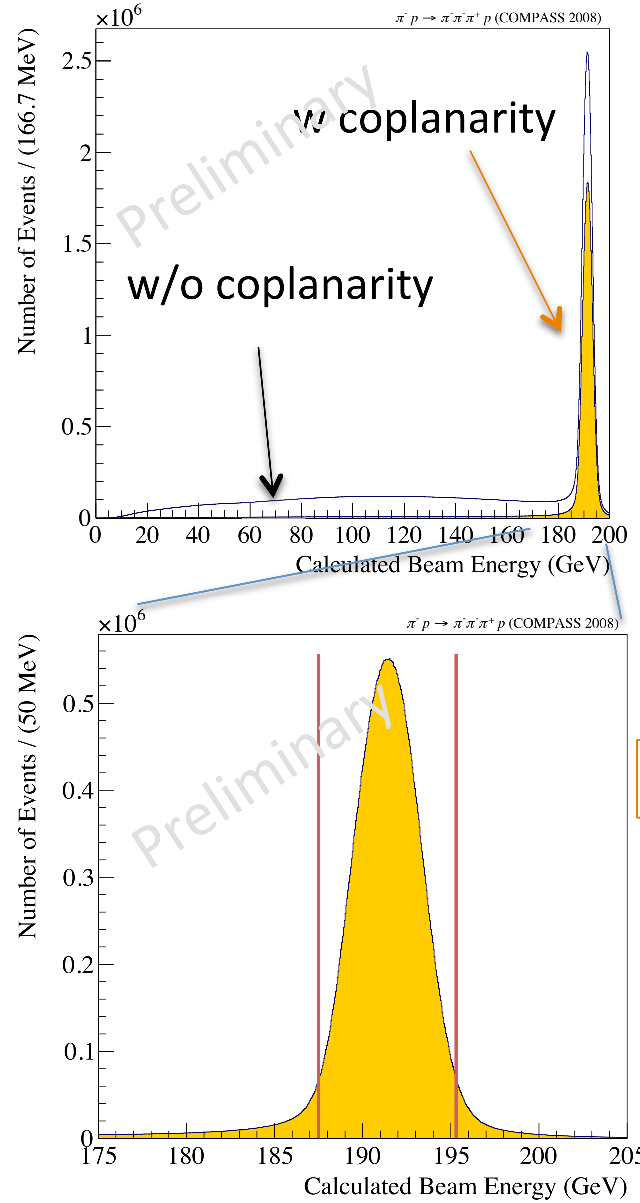


$$t' = t - t_{\min} \approx t$$

what we are after



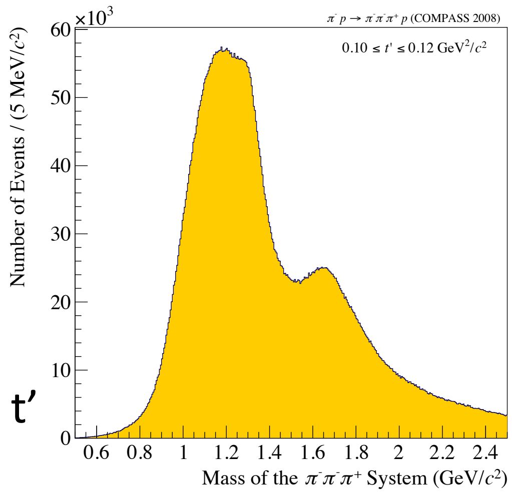
exclusive reaction



zoom

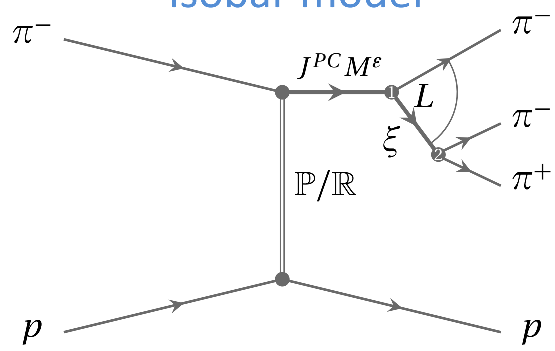
$5 \cdot 10^7$ evts

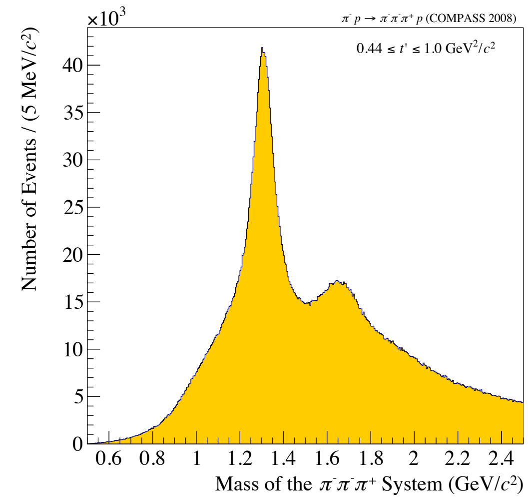
Kinematics and Isobars



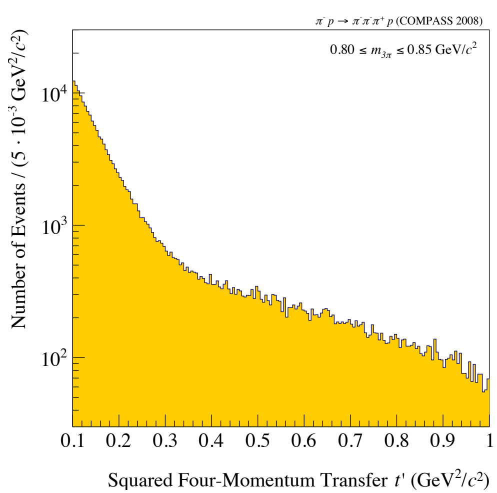
low t'

isobar model

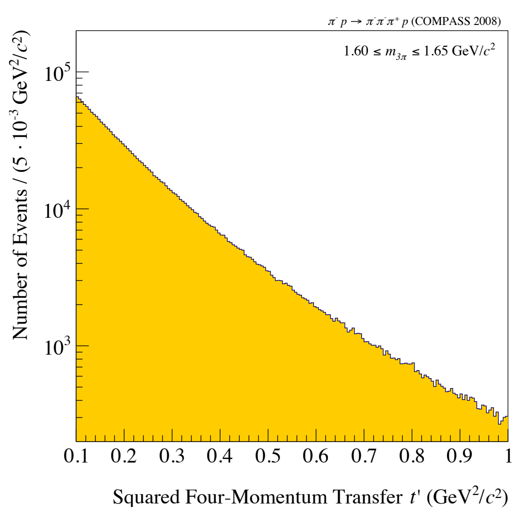




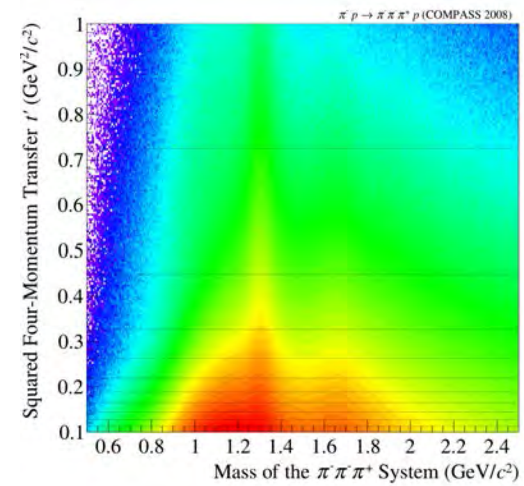
high t'



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



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

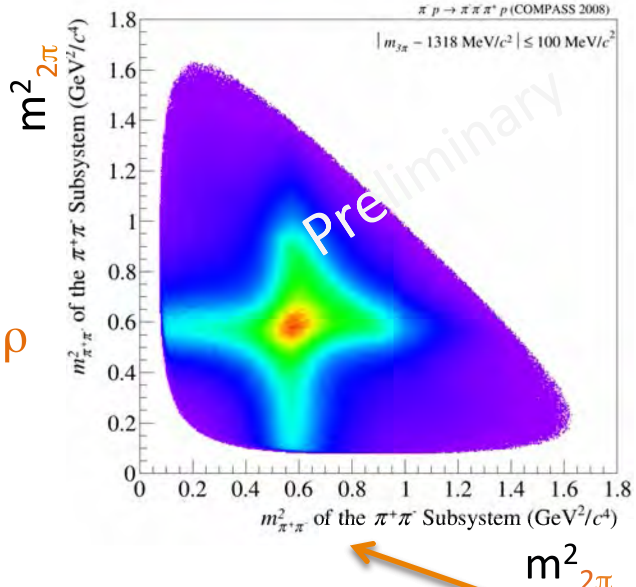


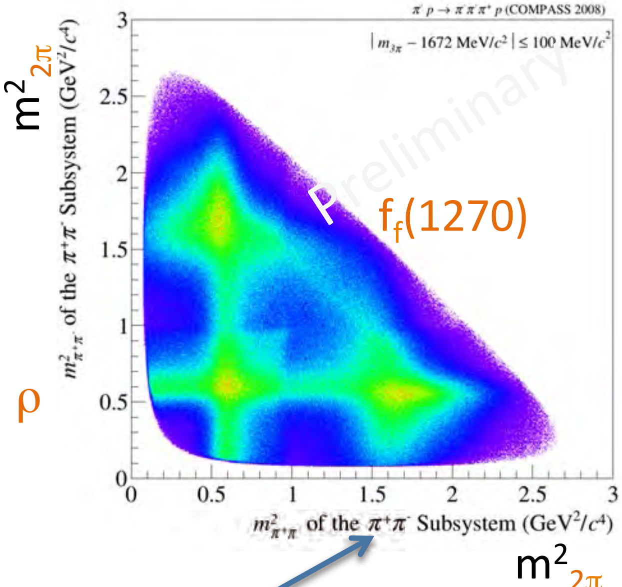
grid of t' used

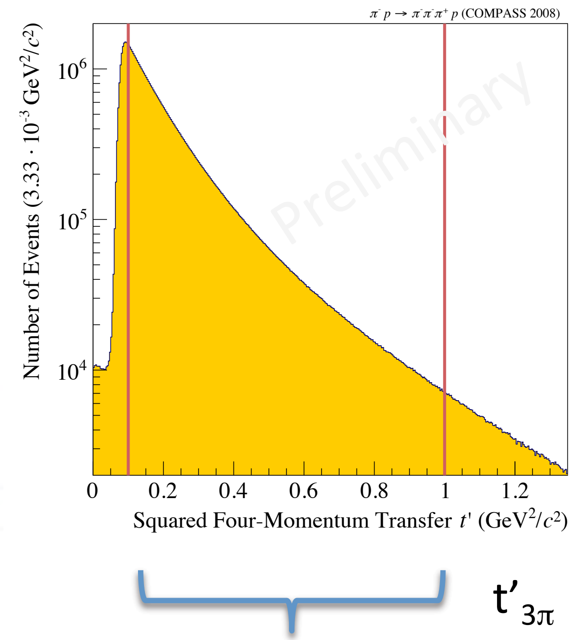
Δm: 20 MeV/c^2

Exzellenzcluster Universe

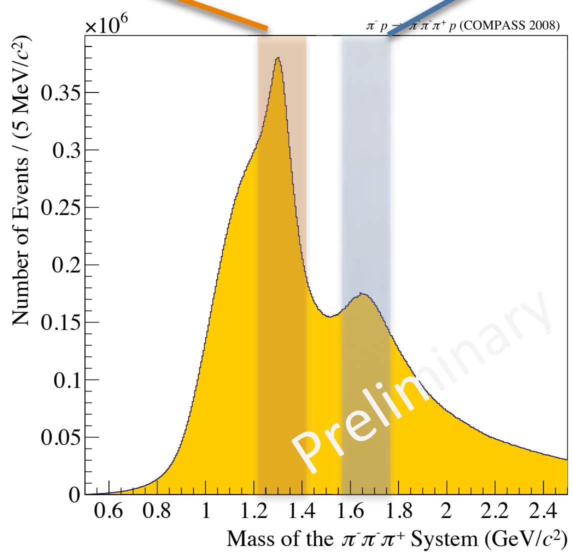
First Impressions
Motivation for Isobar Model







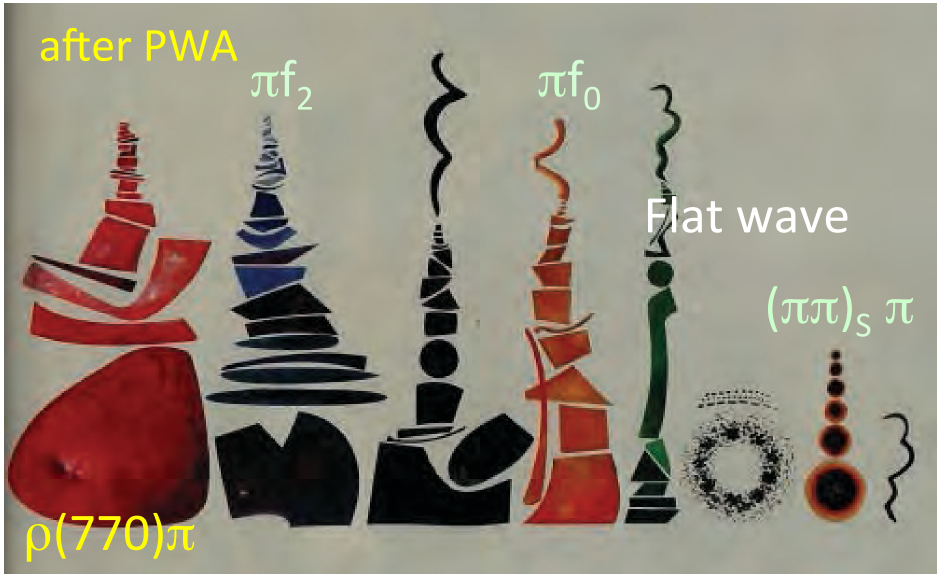
used in analysis



Exzellenzcluster Universe

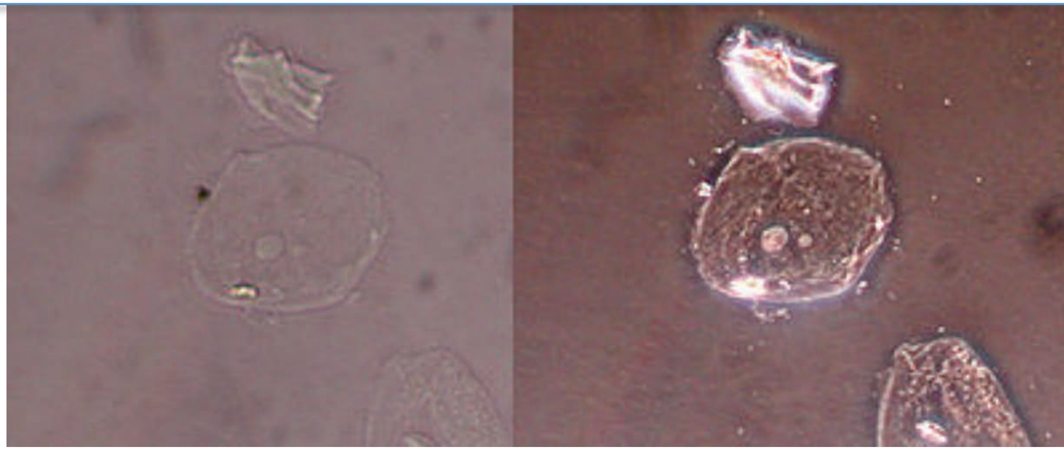
Partial wave analysis

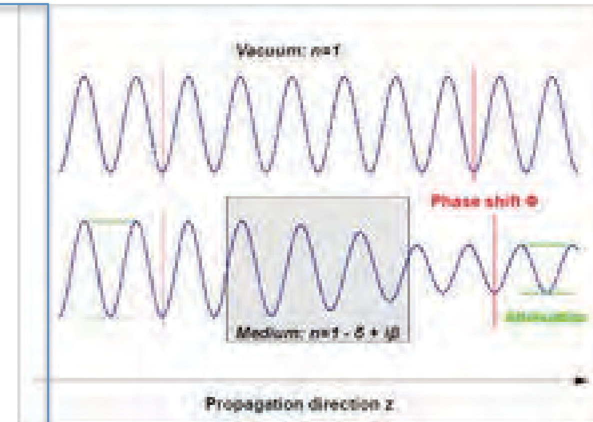
inspired by M. Pennington



Art taken from Urs Wehrli: “Kunst aufgeräumt”

How to observe Structures





Bright field microscopy
maps distribution of imaginary part of refractive index

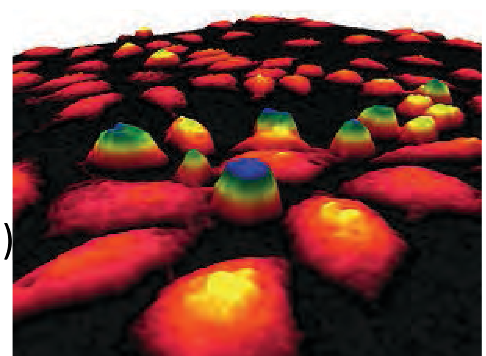
Phase contrast microscopy
maps distribution of complex refractive index modulation using interference effects

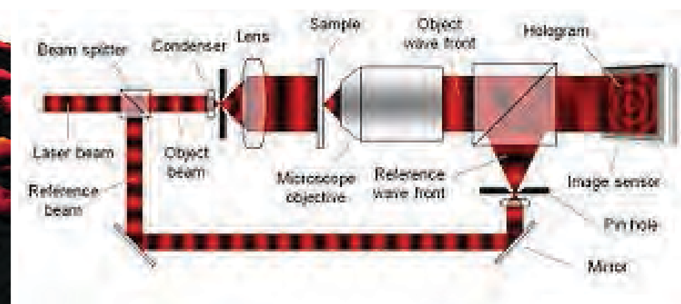
Peak hunting

Dalitz plot analysis

Holographic Phase imaging
maps interference pattern with reference beam
3D image of object (quantitative)

Low statistics PWA

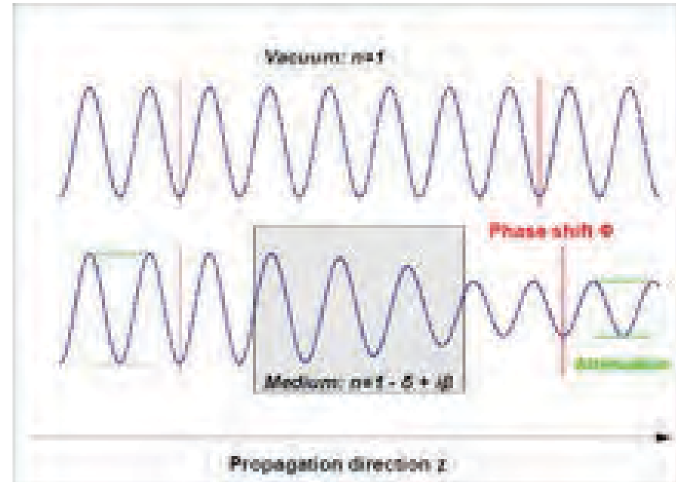




Exzellenzcluster Universe

colour denotes phase shifts

Phase contrast tomography



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

X-rays

Absorption

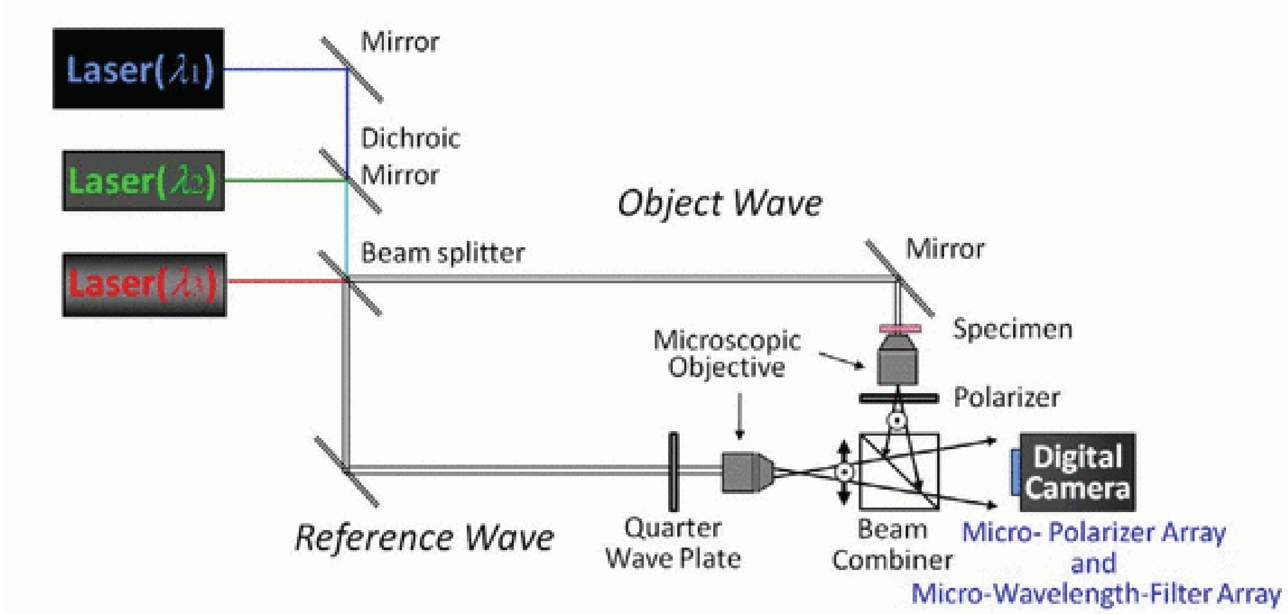
Phase contrast

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'

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

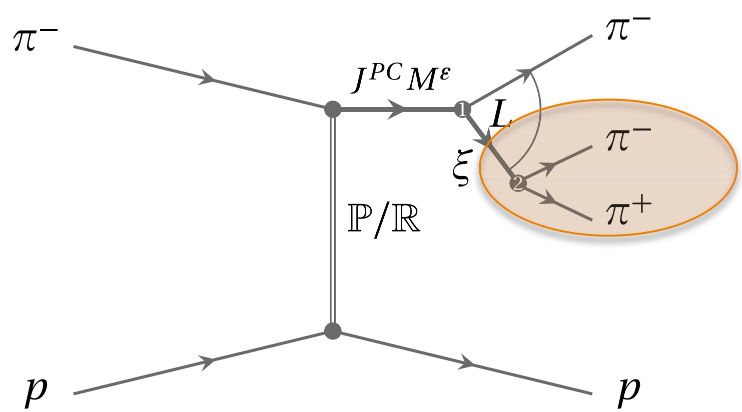
Exzellenzcluster Universe

Fit Model - Isobars

experts only

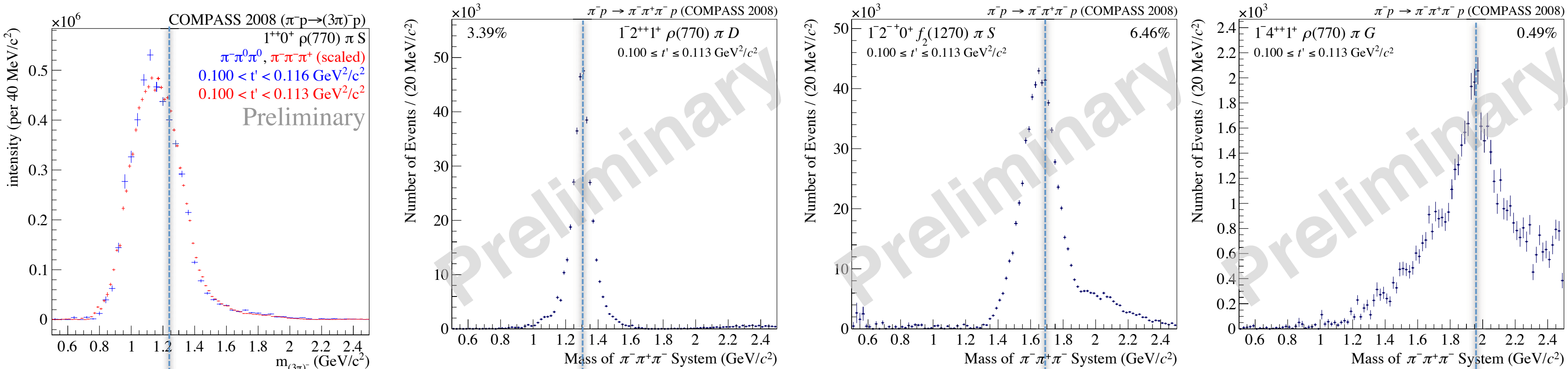
$[\pi\pi]_S$

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
$\rho_3(1690)$	3^{--}	1688.8 ± 2.1	161 ± 10

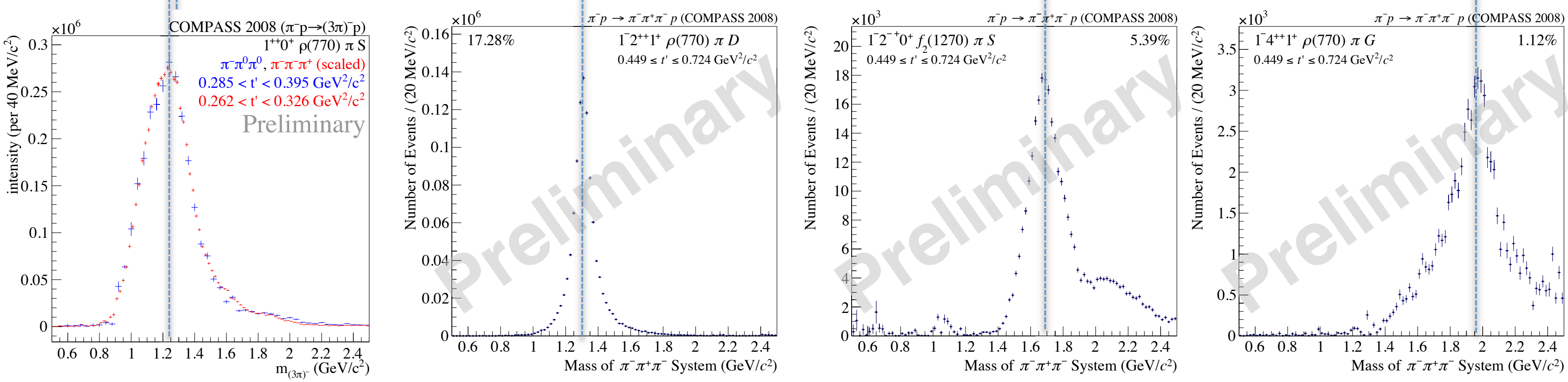


t dependence of mass distributions

low t



high t



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

Exzellenzcluster Universe

More exotic families

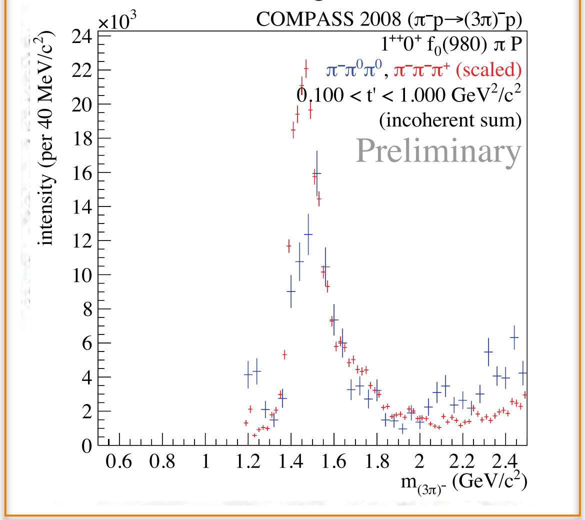
Exzellenzcluster Universe

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

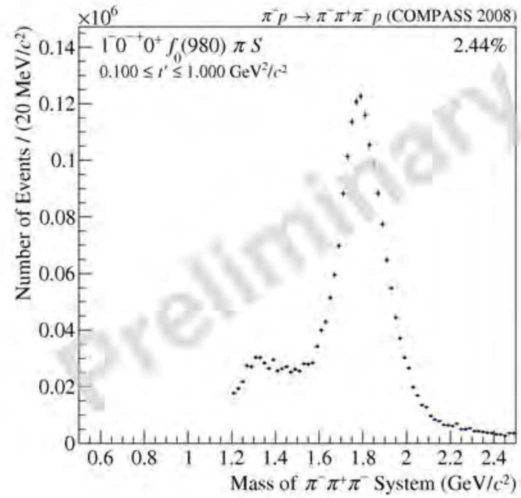
$\pi^-\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$

experts only

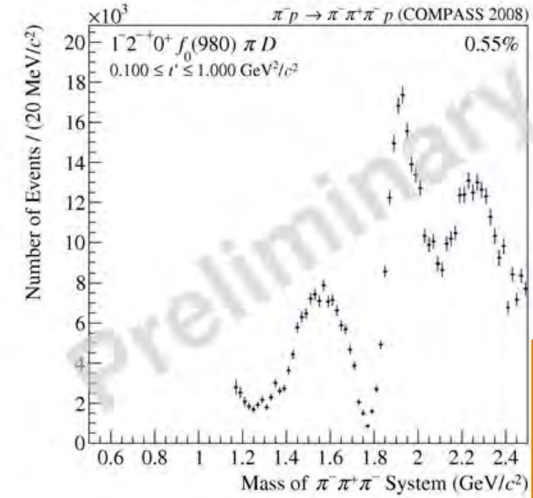
$1^{++}0^+ f_0(980)\,\pi\,P$

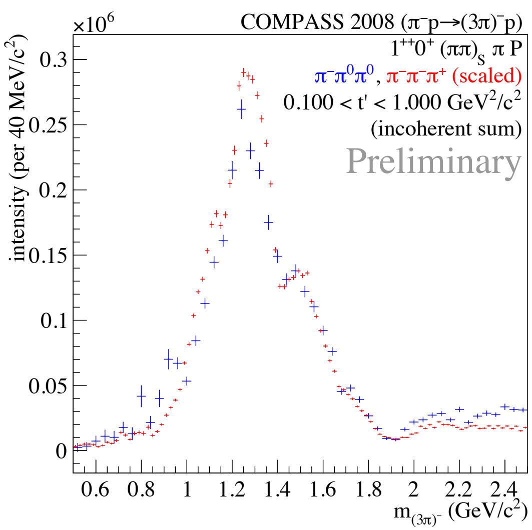


$0^{-+}0^+ f_0(980)\,\pi\,S$

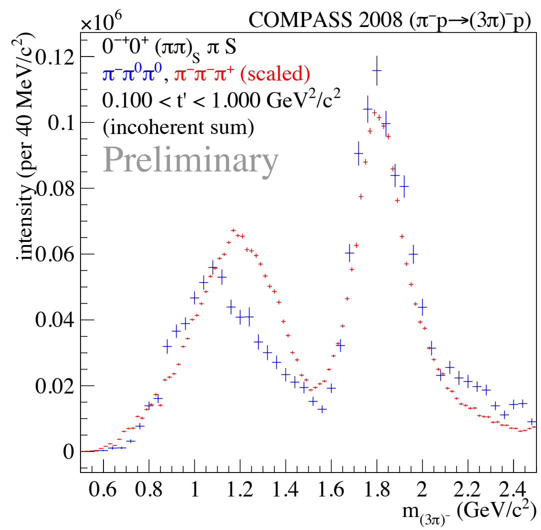


$2^{-+}0^+ f_0(980)\,\pi\,D$

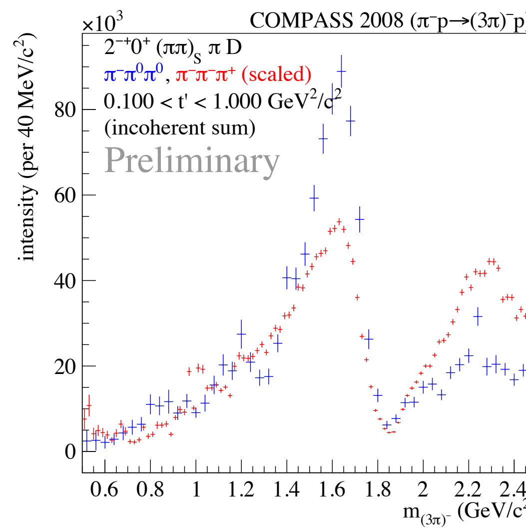




$1^{++}0^+[\pi\pi]_S\,\pi\,P$



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

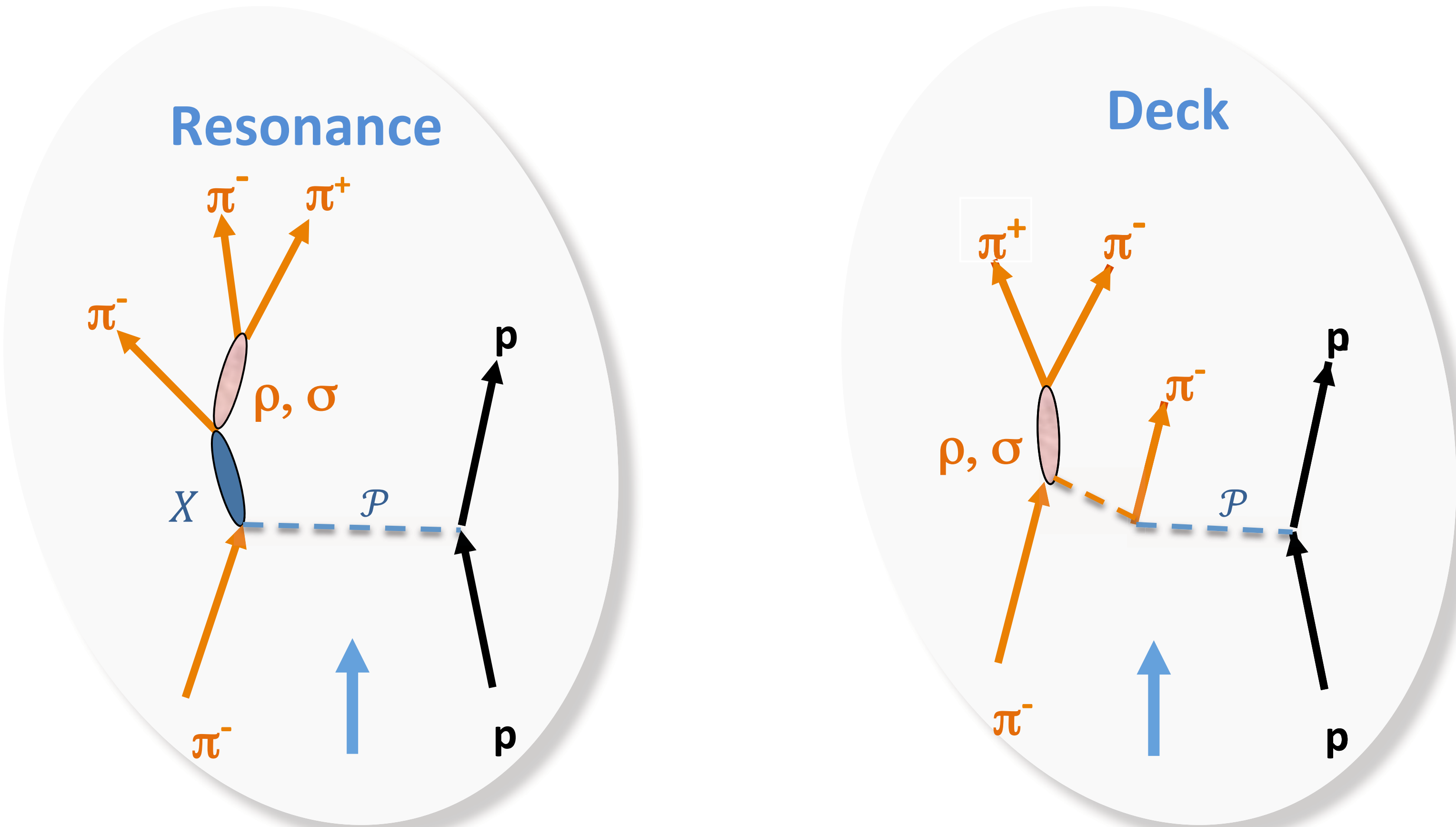


$2^{-+}0^+[\pi\pi]_S\,\pi\,D$

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

experts only

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

This work: 6 waves

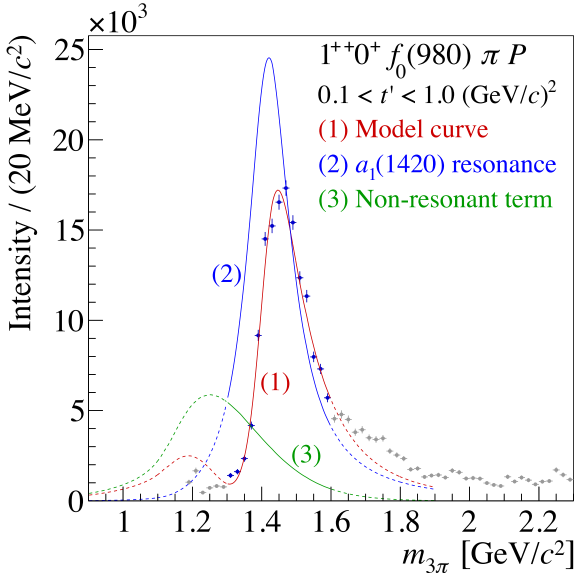
Model:

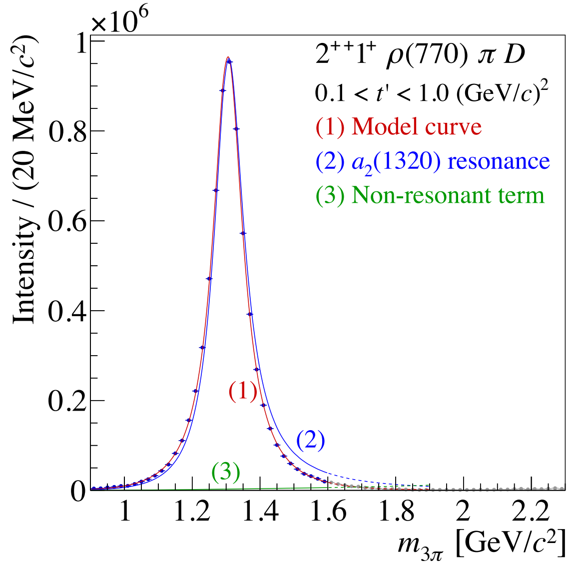
1^{++} $0^+ \rho\, \pi$ S	2 resonances : $a_1(1260)$ and a_1' + non resonant term
2^{++} $1^+ \rho\, \pi$ D	2 resonances : $a_2(1320)$ and a_2' + non resonant term
4^{++} $1^+ \rho\, \pi$ G	1 resonance : $a_4(2040)$ + non resonant term
2^{-+} $0^+ f_2\, \pi$ S	2 resonances : $\pi_2(1670)$ and π_2' +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

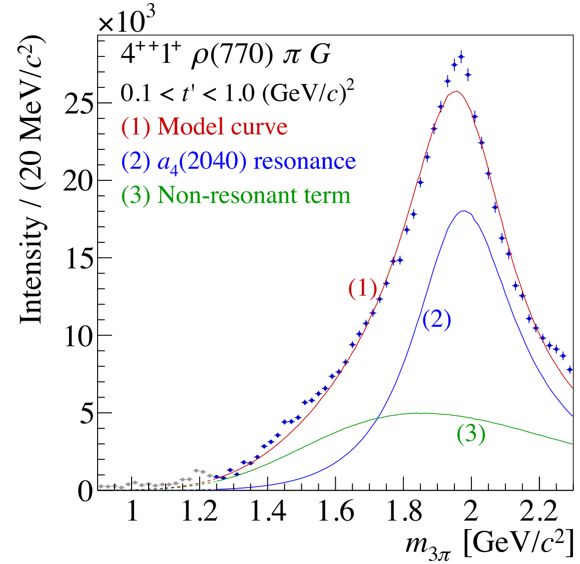
$J^{PC}M^{\varepsilon}[isobar]\pi L$

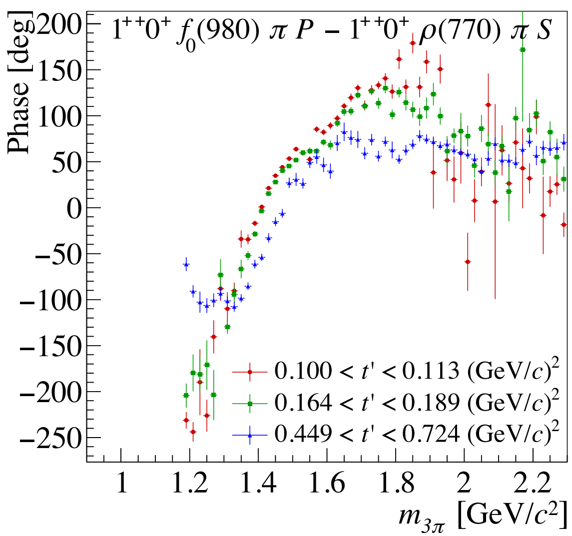
- 231 mass distributions with 23100 data points
- 352 free parameters

New Observation: $a_1(1420)$



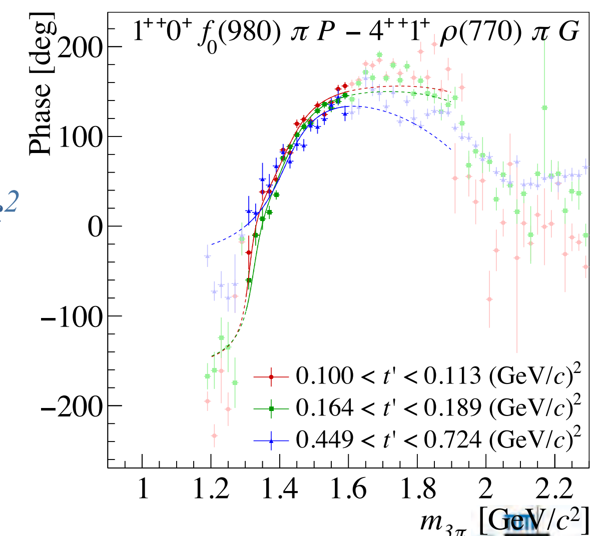






Observation*n:*

- Decay only : [$f_0(980)$] π P
- *Mass : 1413 ± 15± 13 MeV/c²*
- *Width: 157 ± 8 ± 23 MeV/c²*

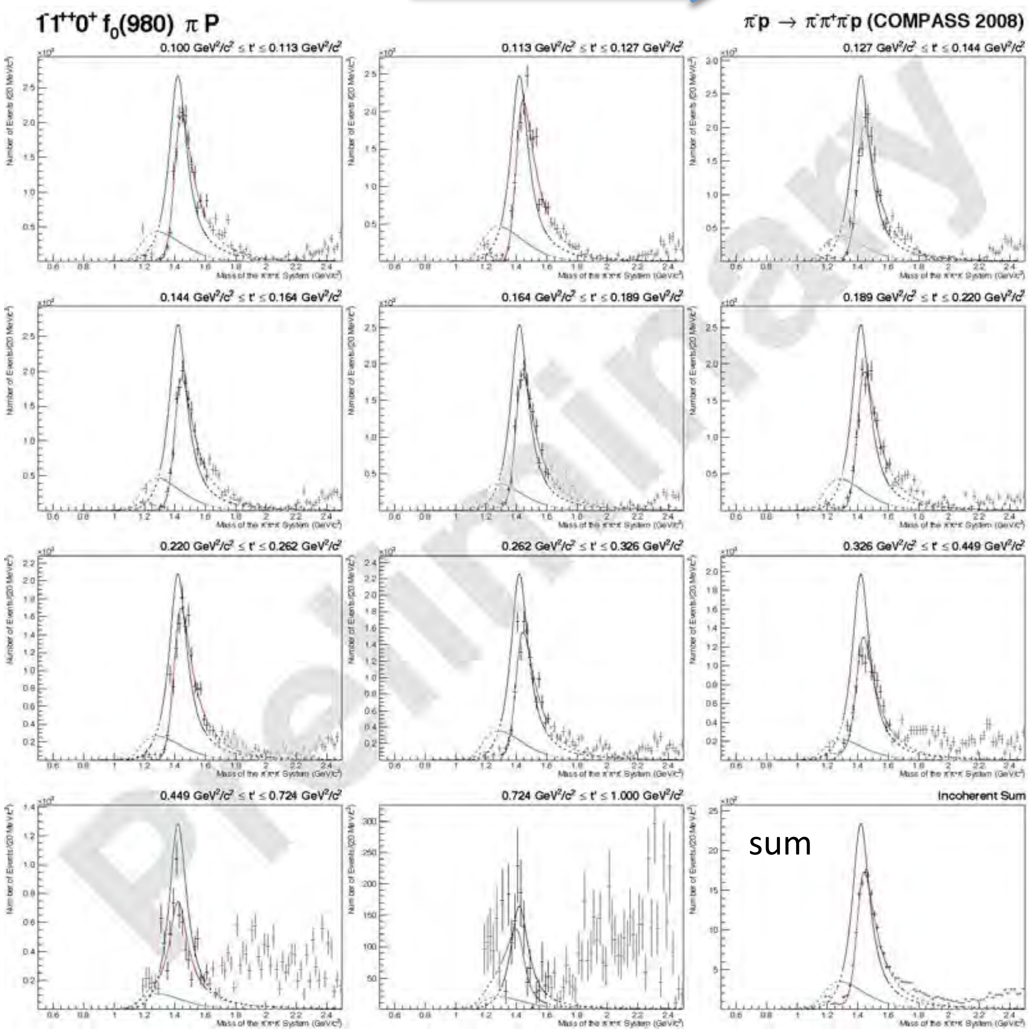


Exzellenzcluster Universe

Mass dependent fits $a_1(1420)$

Fit in 11 t-bins

t



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

t

NEW

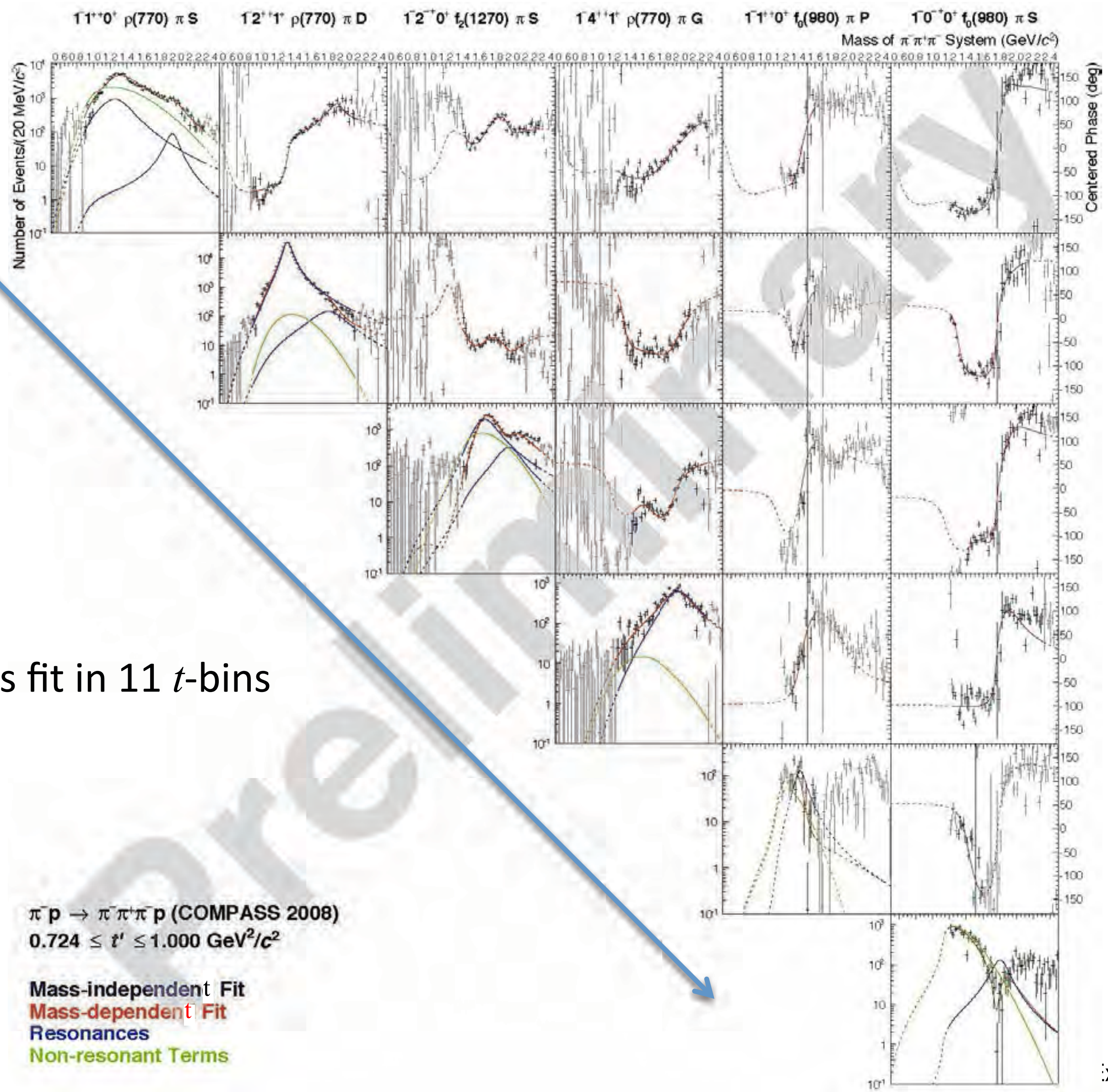
Exzellenzcluster Universe

COMPASS "Holography"

Reference waves

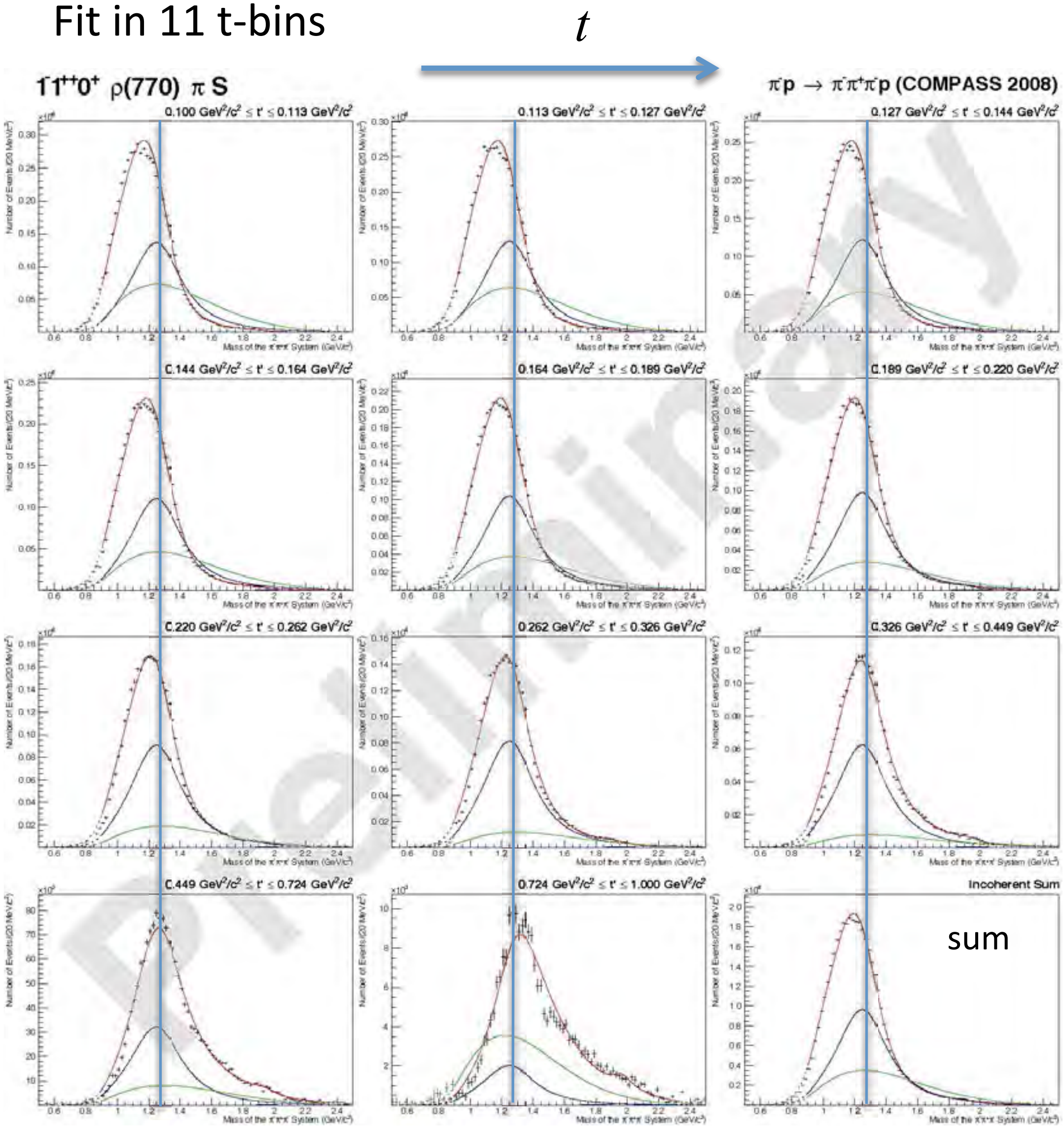
simultaneous fit in 11 t-bins

Interferometry



Mass dependent fits

Fit in 11 t-bins

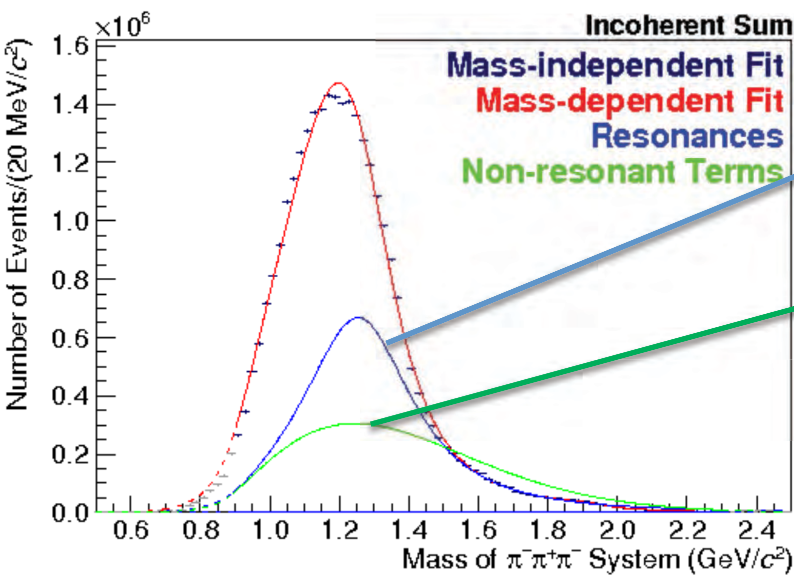


Strongly t-dependent spectral shape around a$_1$(1260)

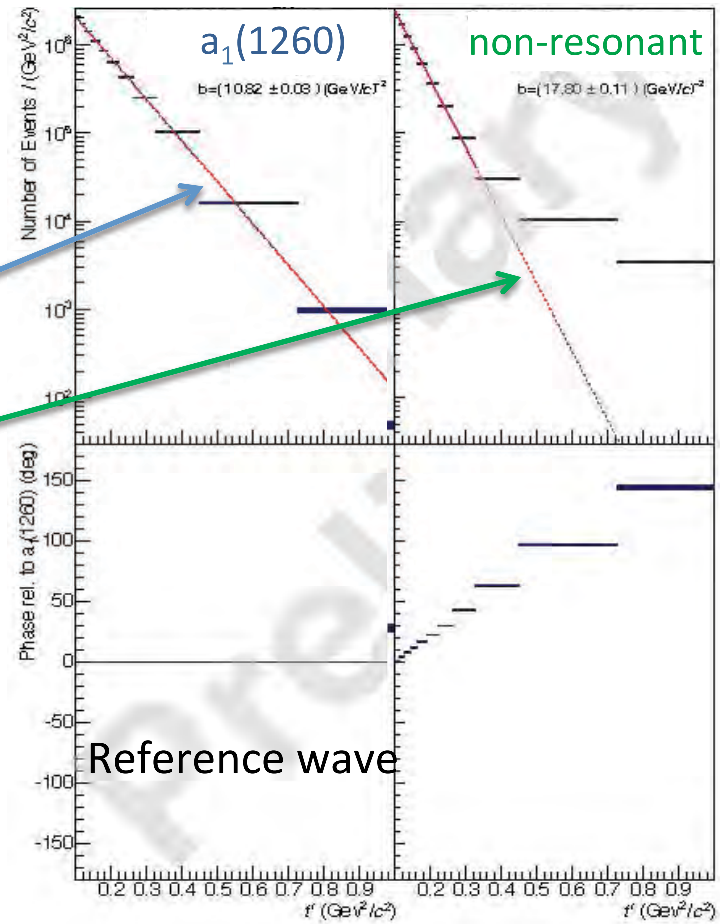
$$1^{++}0^{+}\,\rho\pi S$$

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

Example for t-dependence



πππ COMPASS 2008



Intensities

Phases

t

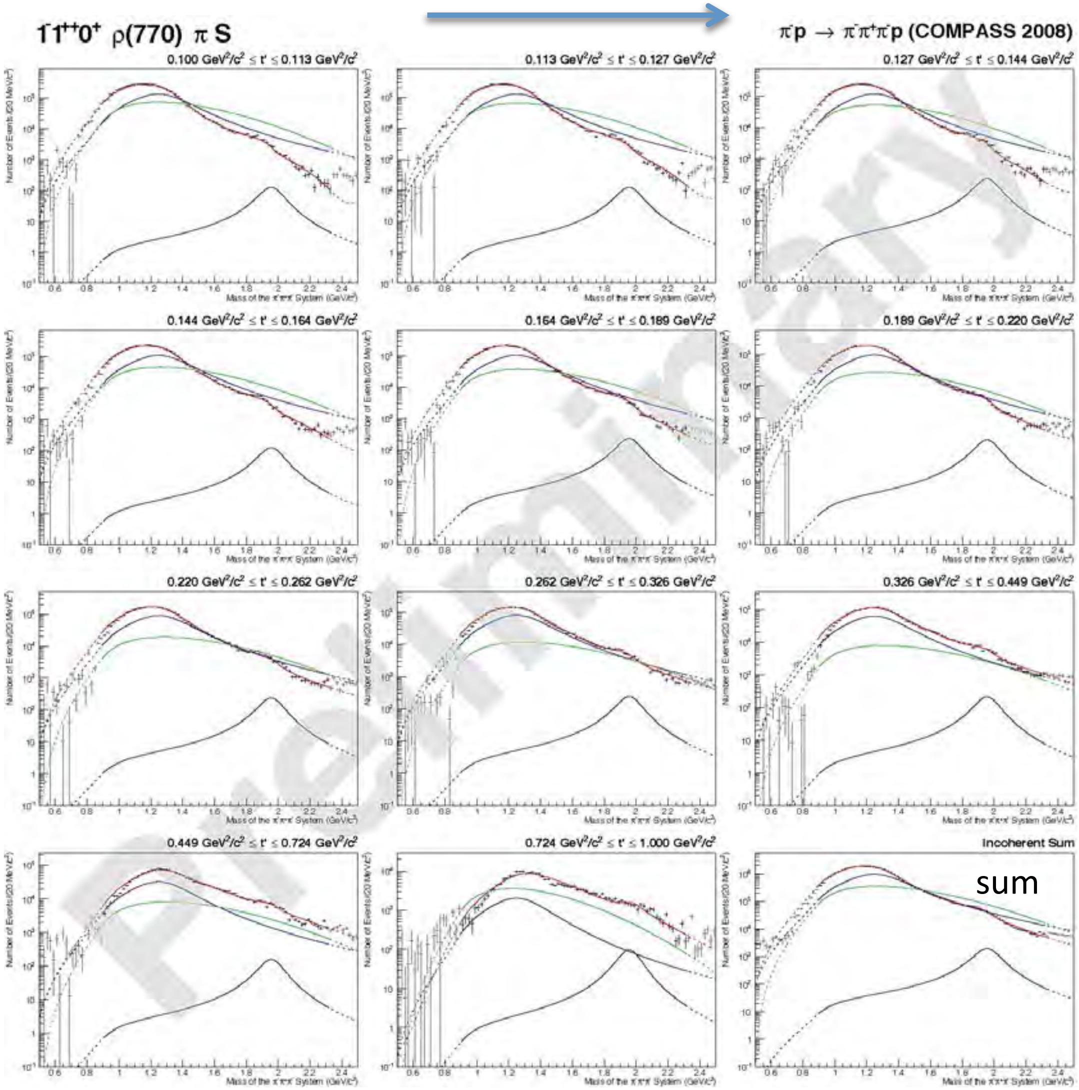
$1^{++}0^{+}\rho\pi S$

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

Mass dependent fits

Fit in 11 t-bins

t



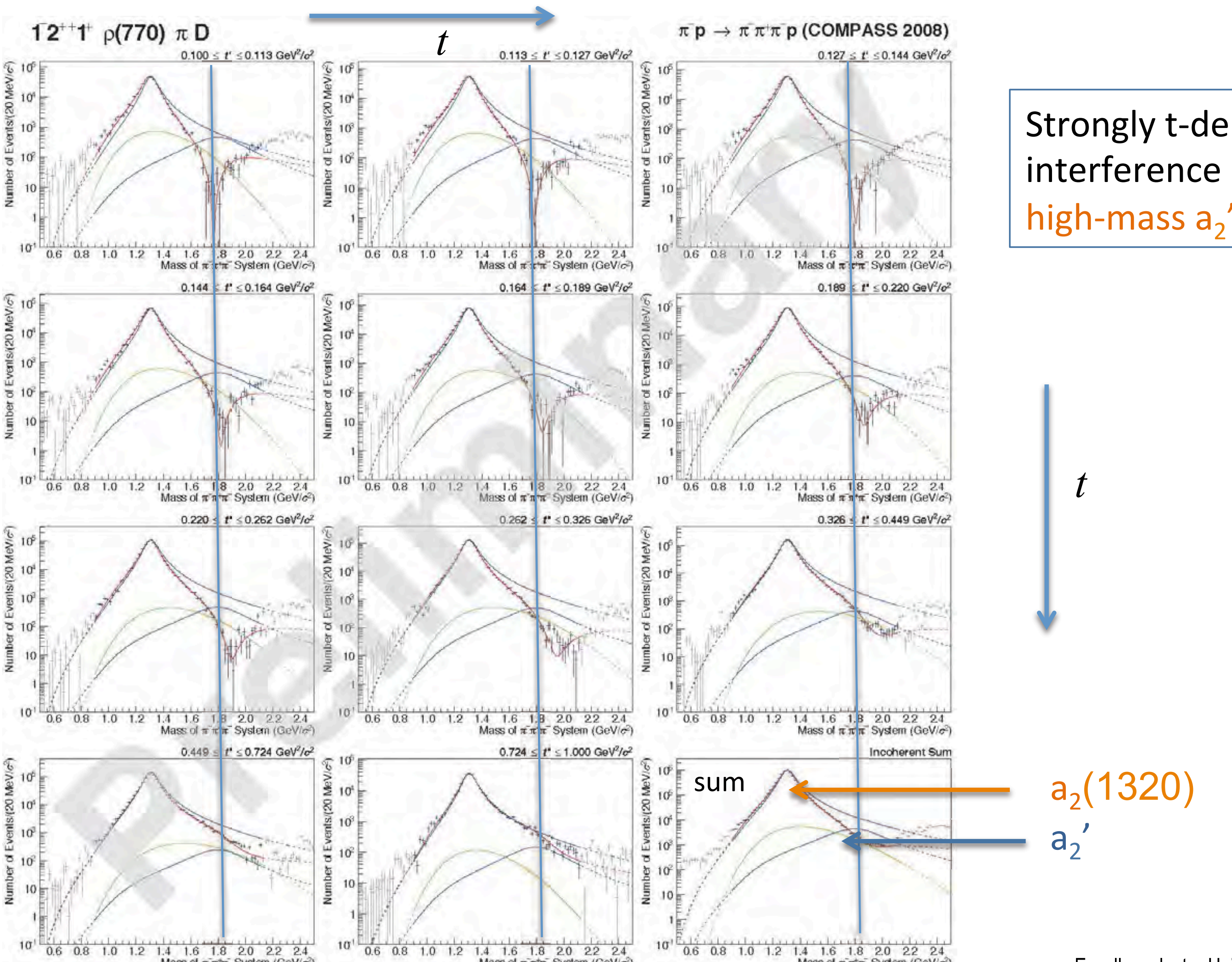
Second high-mass a_1' resonance visible

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

t

Exzellenzcluster Universe

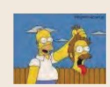
Mass dependent fits $a_2(1320)$



Strongly t-dependent interference effects

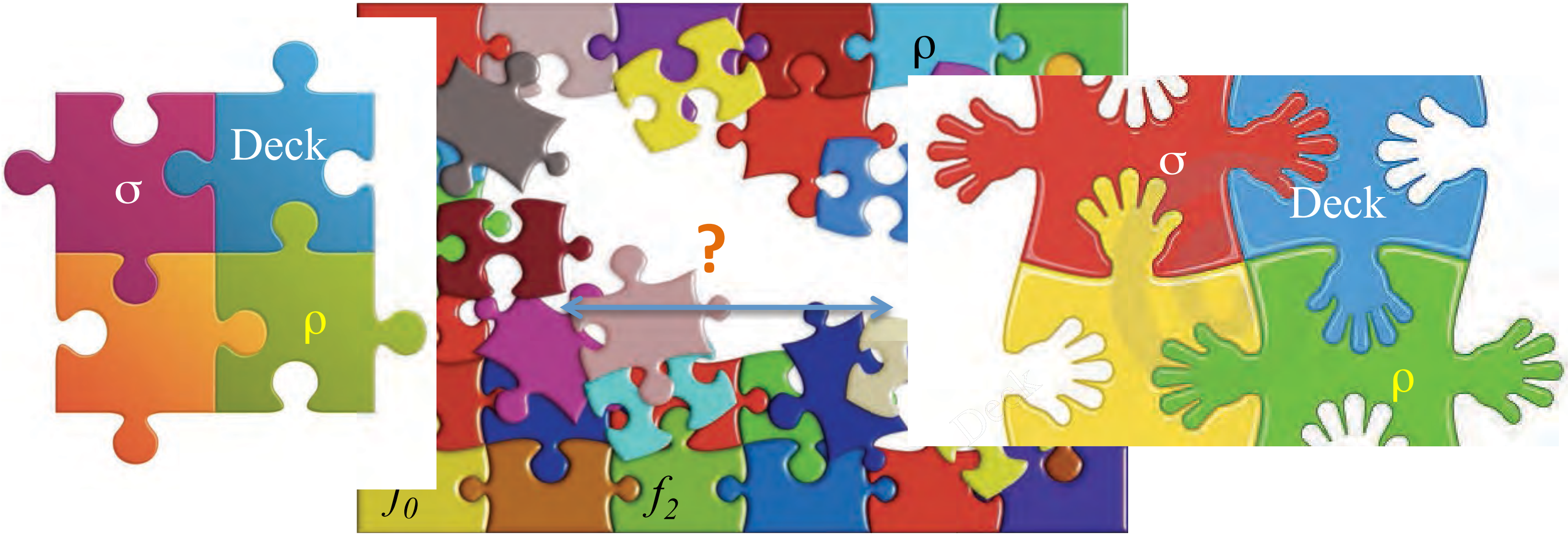
high-mass a_2'

Some Results

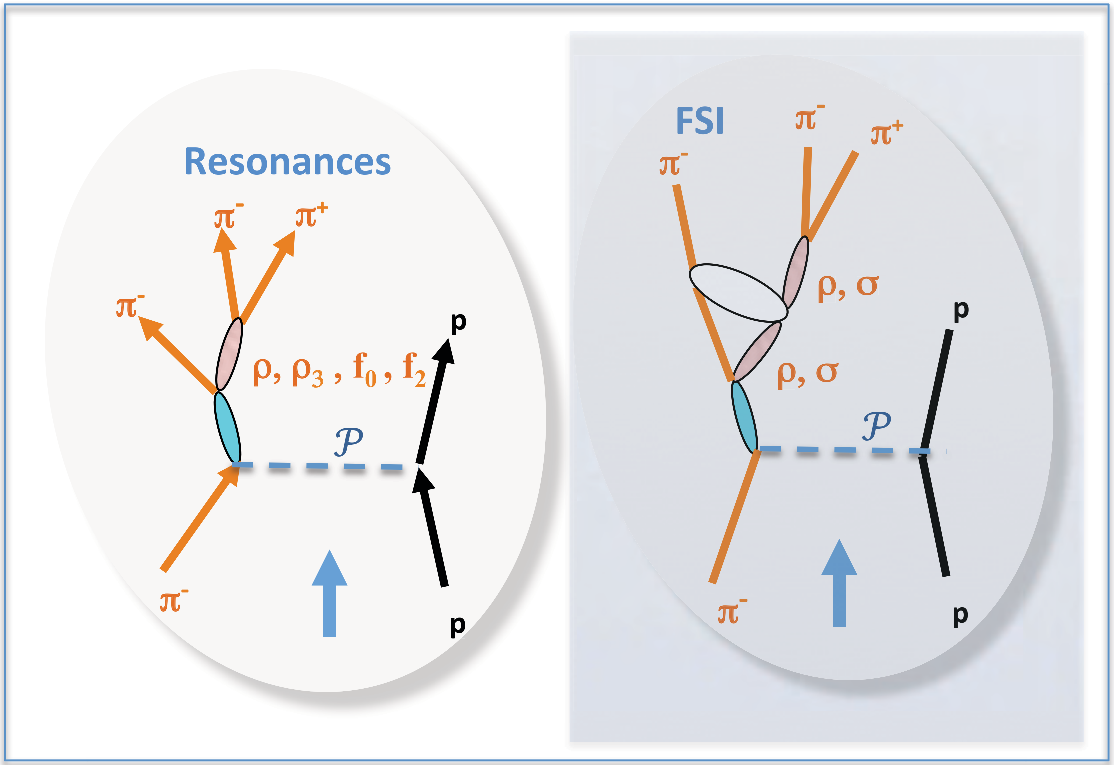
Particle	J^{PC}	Mass Range $[\mathrm{MeV}/c^2]$	Width Range $[\mathrm{MeV}/c^2]$	PDG Values m $[\mathrm{MeV}/c^2]$	PDG Values Γ $[\mathrm{MeV}/c^2]$
				PDG	
"Established" states					
$a_1(1260)$	1^{++}	1260–1290	360–420	1230 ± 40	250–600
$a_2(1320)$	2^{++}	1312–1315	108–115	$1318.3^{+0.5}_{-0.6}$	107 ± 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		

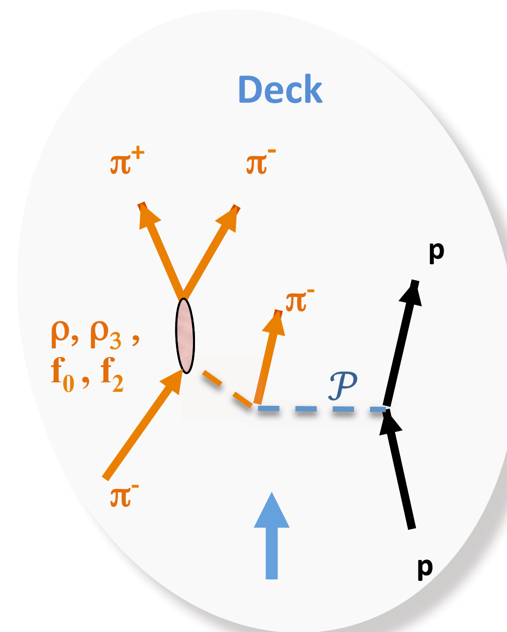
What about the building blocks

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



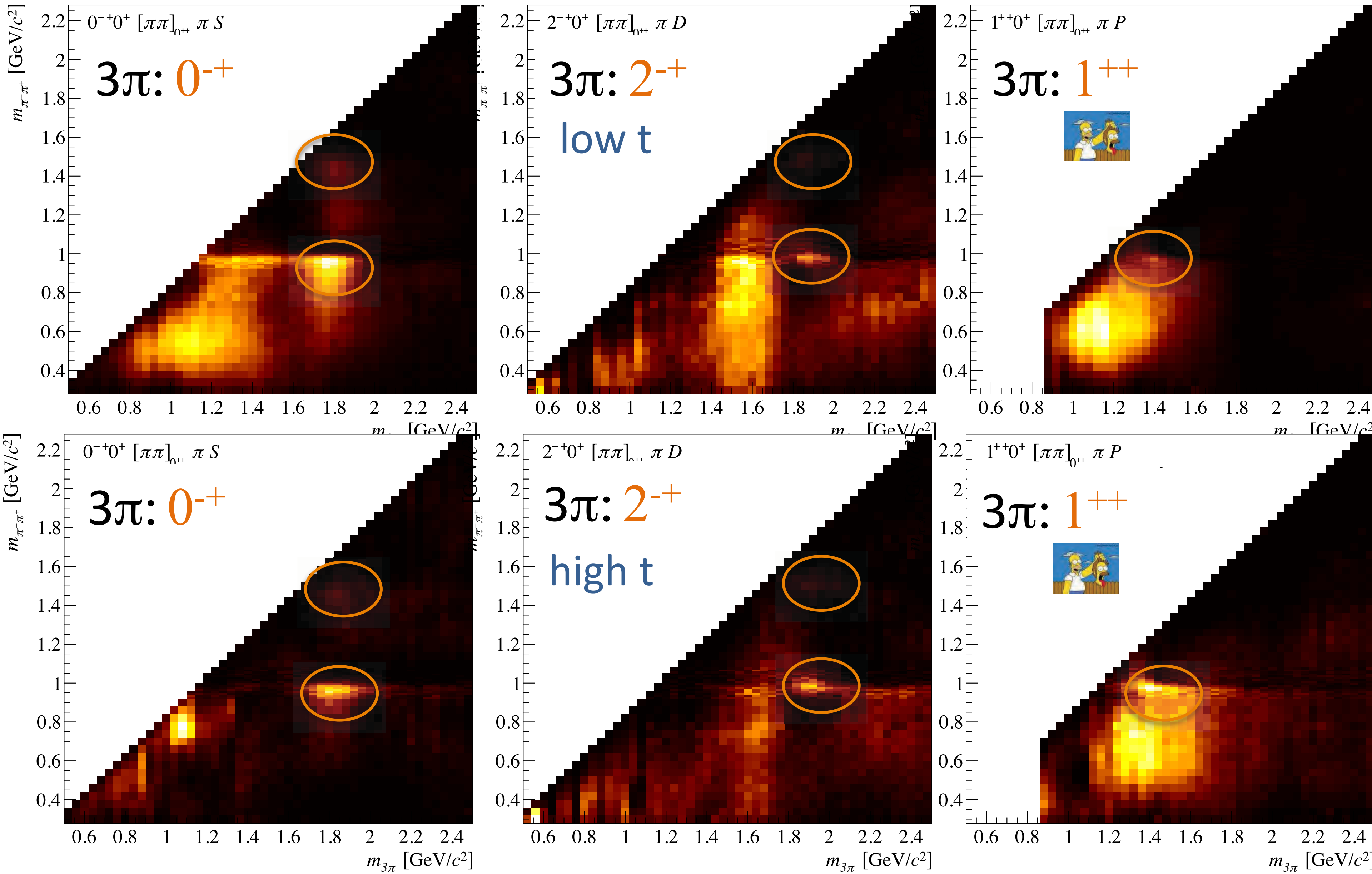
New Paths to Meson Decays





- 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)

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



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

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 ?

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

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 !!