



Light Meson Spectroscopy with COMPASS

Johannes Bernhard (CERN)
on behalf of the COMPASS collaboration
Baryons 2016 – Tallahassee, FL



ENGINEERING
DEPARTMENT

Outline

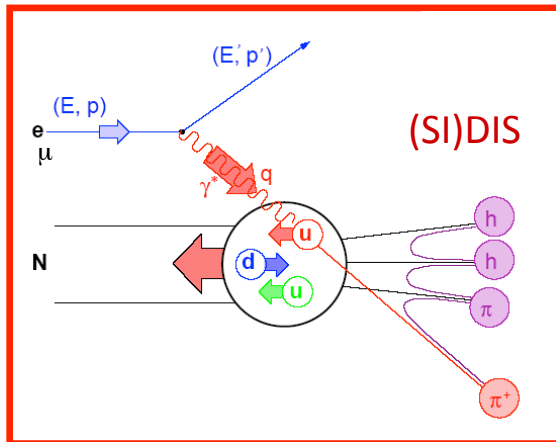
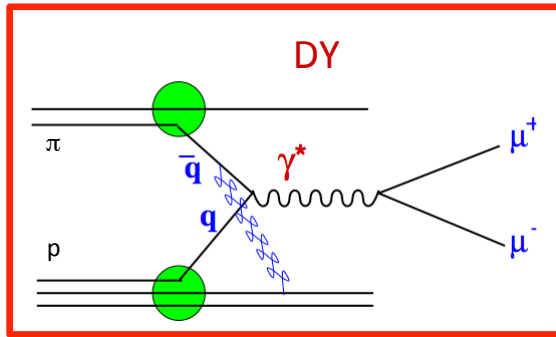
- The Compass Experiment
- Light Meson Spectroscopy with Compass
 - 3π channel: $a_1(1440)$, $\pi_1(1600)$
 - $\pi\eta' / \pi\eta$ channel
 - Central production (K^+K^-)
 - Radiative widths of $a_2(1320)$ and $\pi_2(1670)$
 - Pion polarisability
- Conclusions and Outlook

COMPASS - A facility to study QCD

Large Q^2 :

Nucleon structure

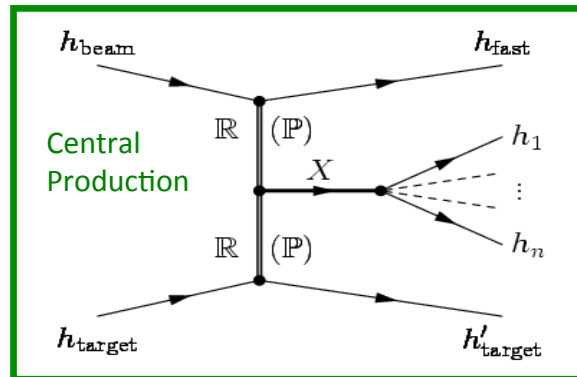
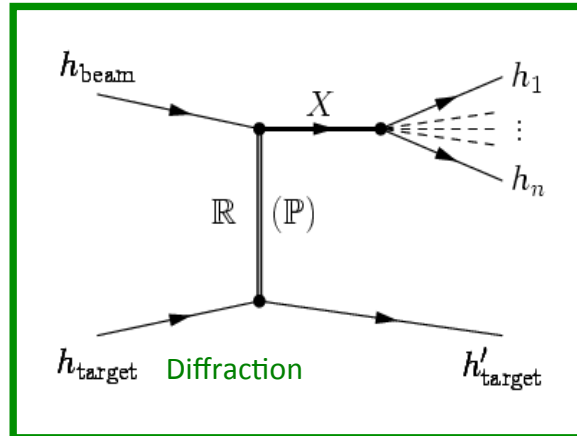
- Helicity, transversity PDFs
- TMDs and GPDs (2015-17)



Low Q^2 :

Spectroscopy

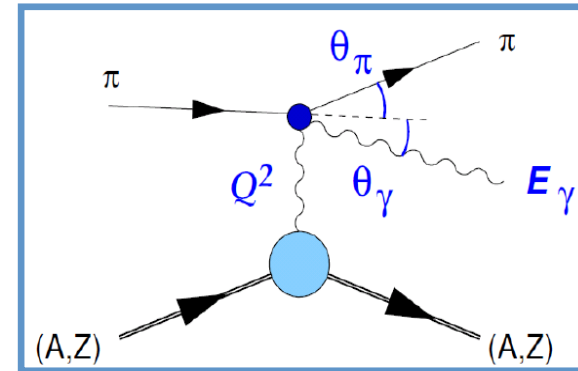
- Hadronic mass spectrum
- Gluonic excitations / spin-exotics



Very low Q^2 :

Chiral dynamics

- π and K polarisabilities
- radiative widths



The COMPASS experiment at CERN

Common Muon and Proton Apparatus for Structure and Spectroscopy

13 countries 24 institutions 220 physicists



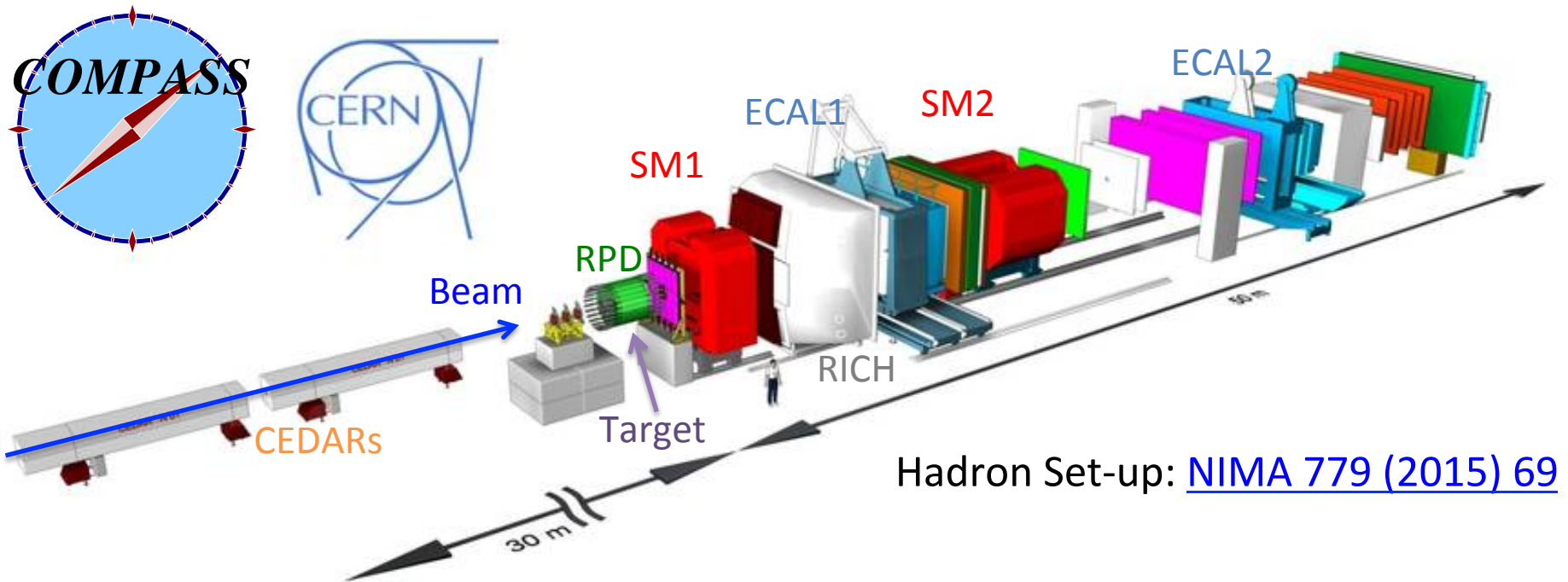
LHC
Large Hadron Collider

COMPASS



SPS
Super Proton Synchrotron

The COMPASS spectrometer



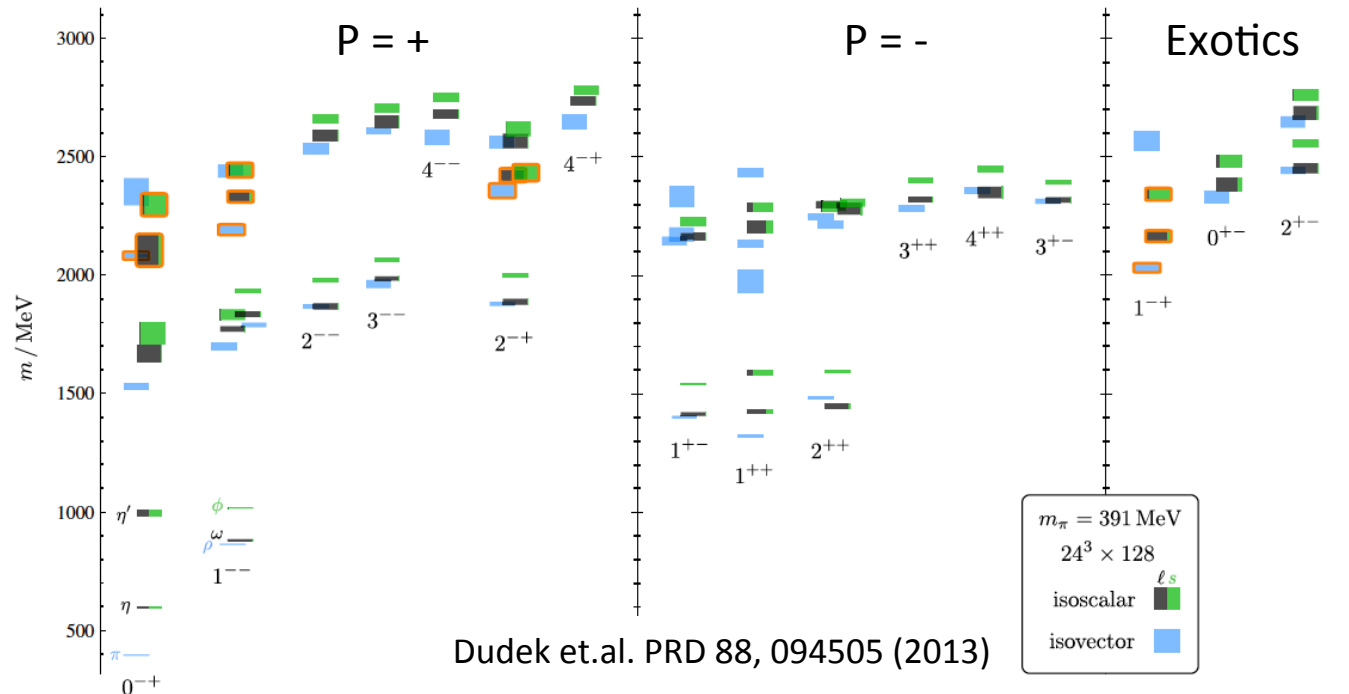
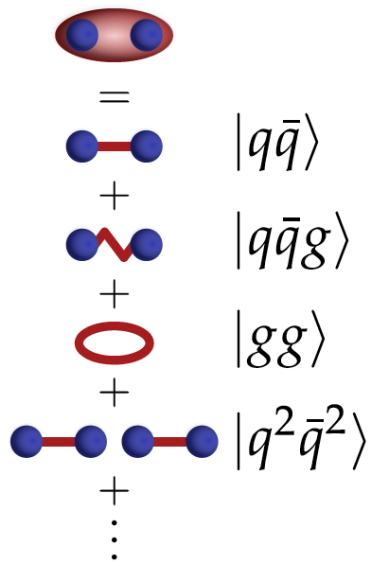
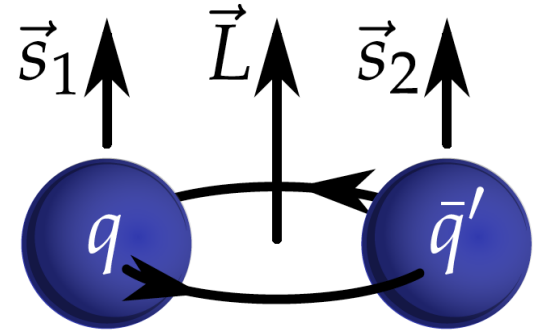
Hadron Set-up: [NIMA 779 \(2015\) 69](#)

- Data taking in 2008 and 2009 with 190 GeV/c hadron beam (π^\pm , K^\pm , p , \bar{p})
- $5 \cdot 10^7$ particles/10 s SPS-spill on 40cm liquid hydrogen target
- Trigger: Recoil Proton Detector + beam (minimum bias on forward system)

Meson Spectroscopy

Constituent quark model: color neutral $q\bar{q}$ systems

- quantum numbers $I^G J^{PC}$
- $P = (-1)^{L+1}$ $C = (-1)^{L+S}$ $G = (-1)^{I+L+1}$
- Allowed J^{PC} : 0^{++} , 0^{-+} , 1^{--} , 1^{+-} , 1^{++} , ...
- Forbidden: 0^{--} , 0^{+-} , 1^{-+} , ...

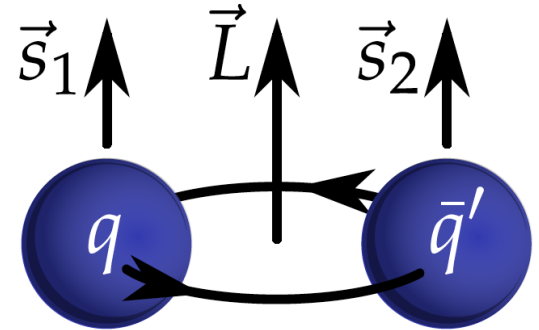


Dudek et.al. PRD 88, 094505 (2013)

Meson Spectroscopy

Constituent quark model: color neutral $q\bar{q}$ systems

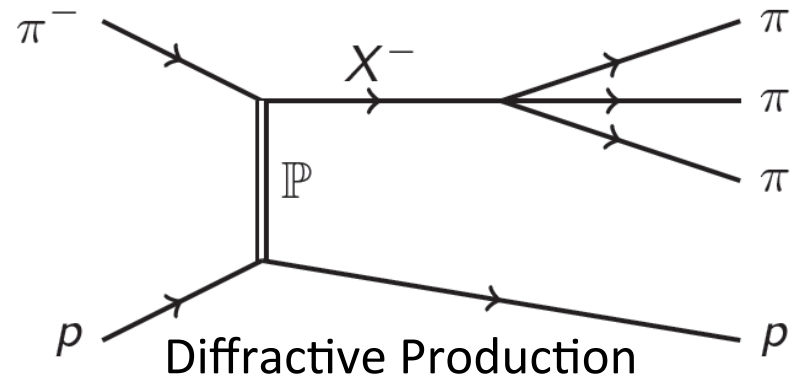
- quantum numbers $I^G J^{PC}$
- $P = (-1)^{L+1}$ $C = (-1)^{L+S}$ $G = (-1)^{I+L+1}$
- Allowed J^{PC} : 0^{++} , 0^{-+} , 1^{--} , 1^{+-} , 1^{++} , ...
- Forbidden: 0^{--} , 0^{+-} , 1^{-+} , ...



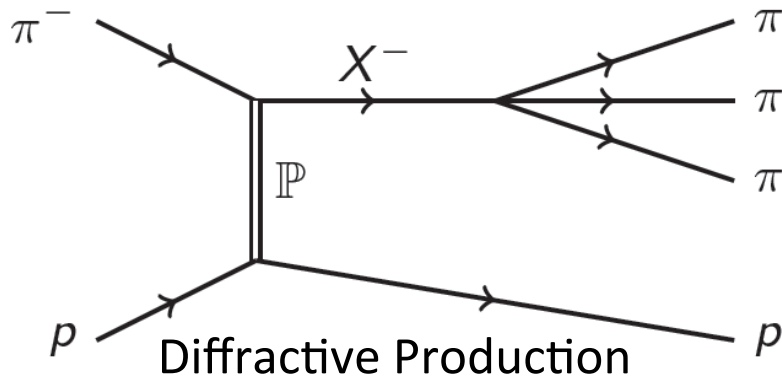
Experiment (1.3 - 2.2 GeV/c²):

hybrid candidates with exotic $J^{PC} = 1^{-+}$

- $\pi_1(1400)$: VES, E852 $\rightarrow \eta\pi$
- $\pi_1(1600)$: E852, VES $\rightarrow \rho\pi$, $\eta'\pi$, $f_1\pi$, $b_1\pi$
COMPASS (2004) $\rightarrow \rho\pi$
- $\pi_1(2000)$: E852 $\rightarrow f_1(1285)\pi$, $b_1(1235)\pi$

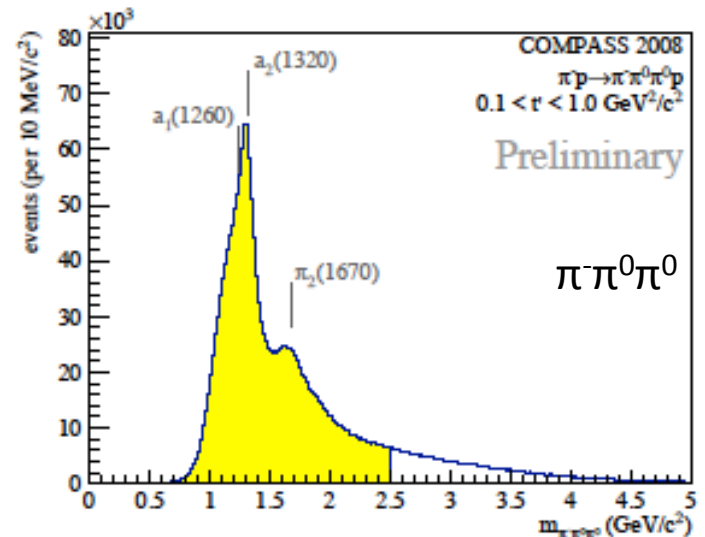
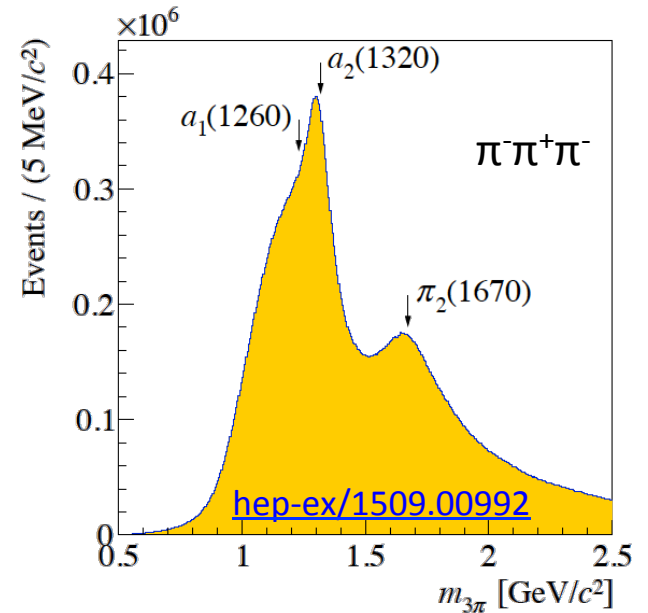


Meson Spectroscopy at COMPASS: 3π

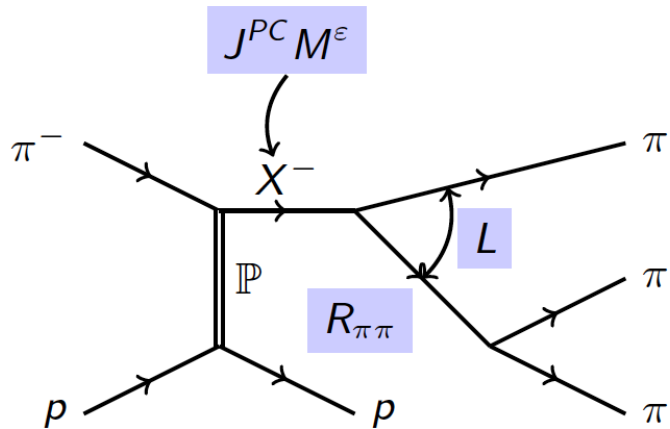


Exclusive 3π events in $\pi p \rightarrow \pi\pi\pi p_{\text{recoil}}$

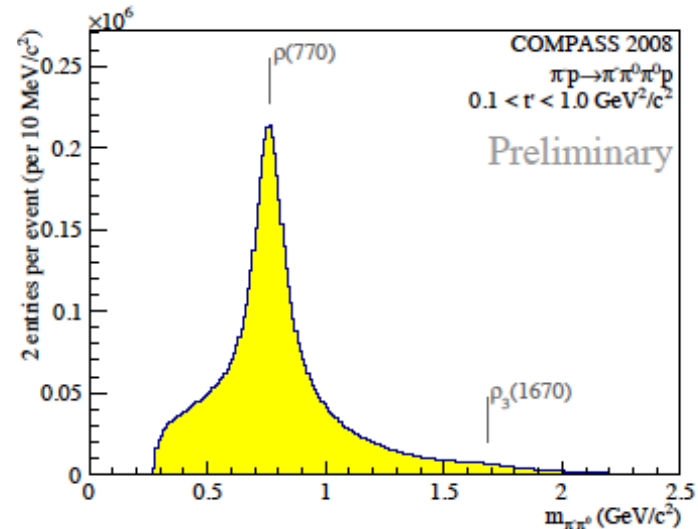
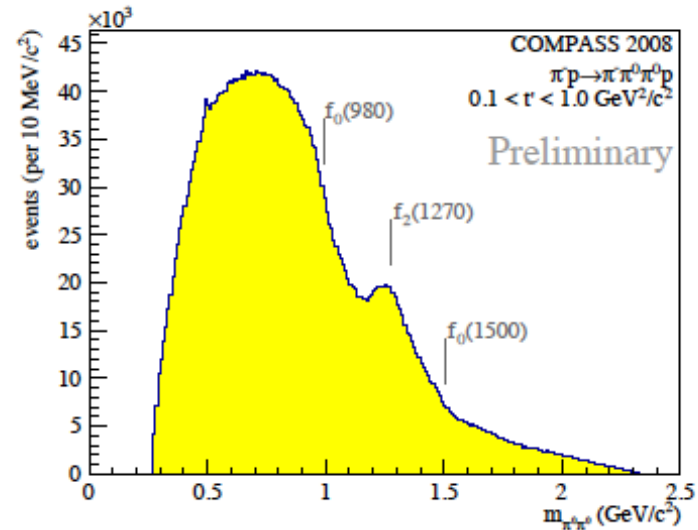
- channels: $\pi^-\pi^+\pi^-$, $\pi^-\pi^0\pi^0$
- high t' region: $0.1 \text{ (GeV/c)}^2 < t' < 1 \text{ (GeV/c)}^2$
- large data set
 - 50 Million events for $\pi^-\pi^+\pi^-$
400 mass bins & 11 bins of t'
 - 3.5 Million events for $\pi^-\pi^0\pi^0$
200 mass bins & 8 bins of t'



Partial Wave Analysis 3π

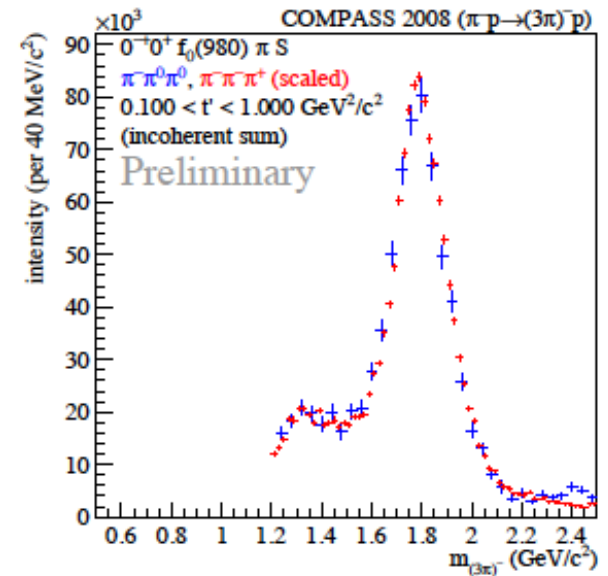
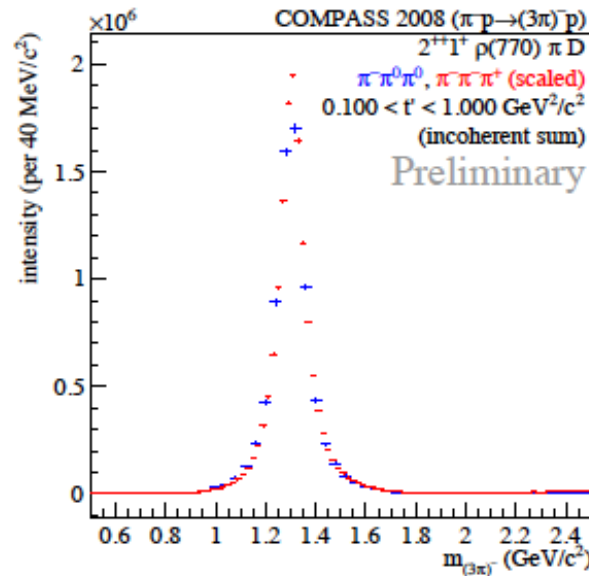
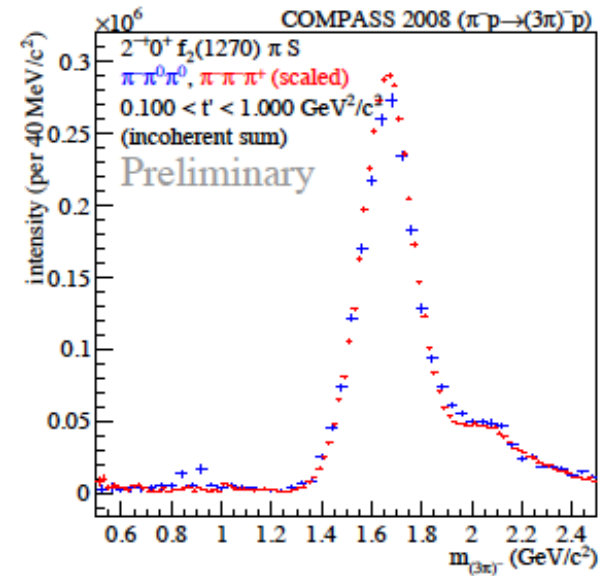
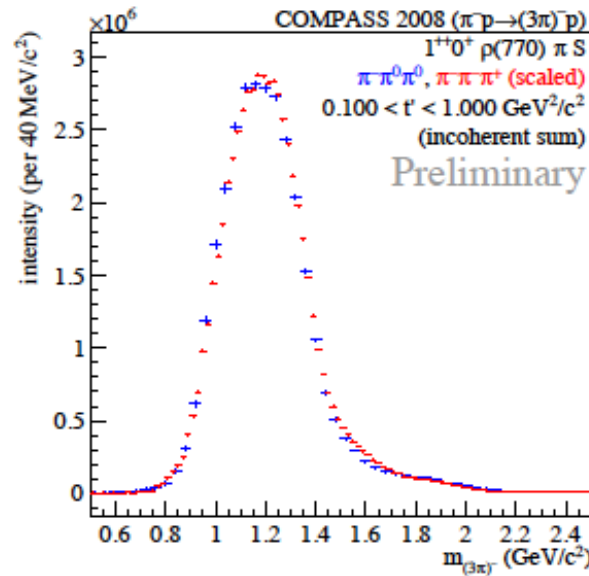


- Isobar Model
- Acceptance correction
- Factorisation of process with production and decay amplitude
- Fit in two steps:
 - fit in mass and t' bins -> production amplitudes
 - fit mass dependence of spin-density matrix -> resonance parameters



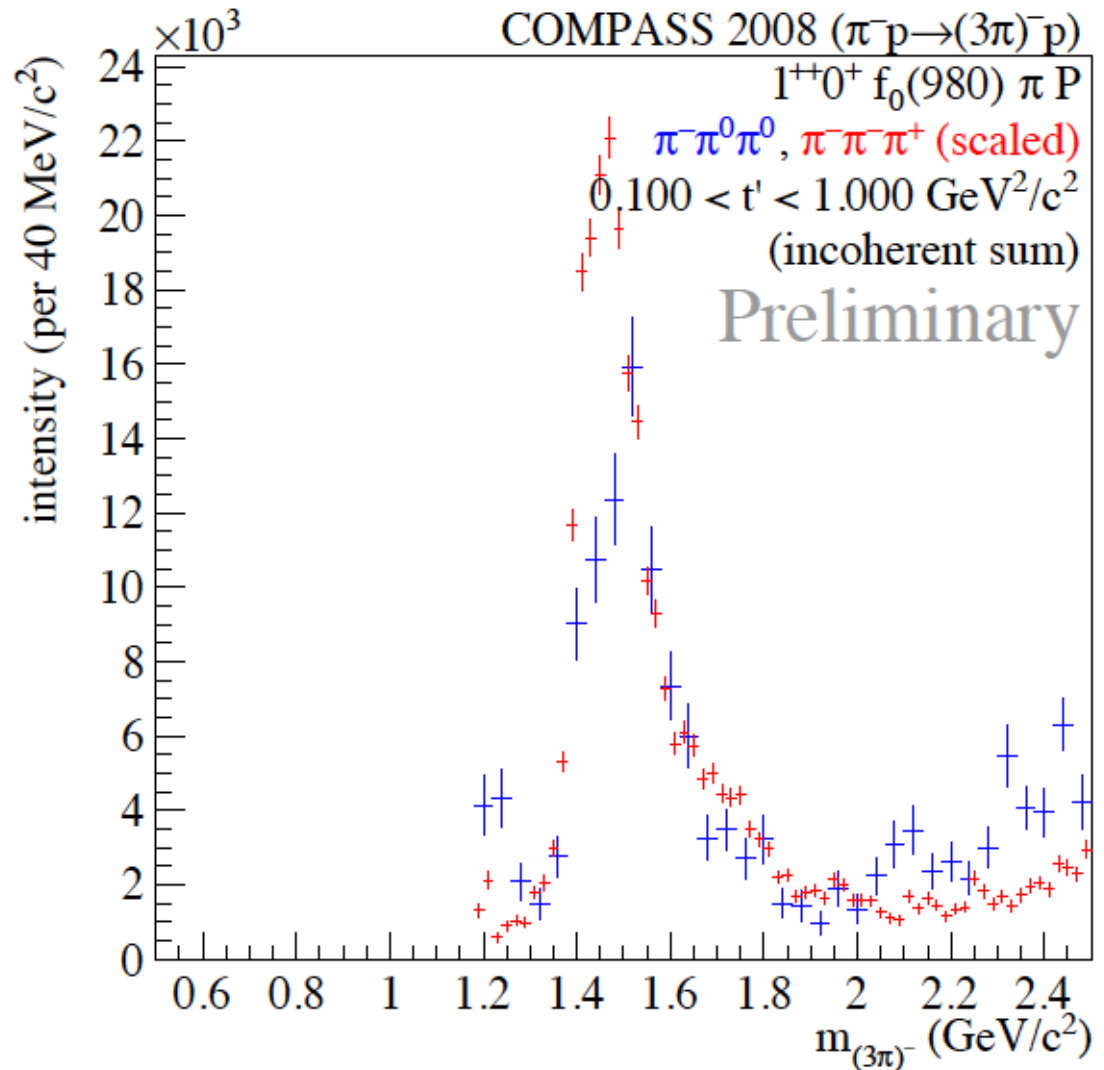
Partial Wave Analysis 3π

- 87 waves + flat wave
- crosscheck:
 $\pi^-\pi^0\pi^0$ scaled to $\pi^-\pi^+\pi^-$
- good agreement between channels



Partial Wave Analysis 3π

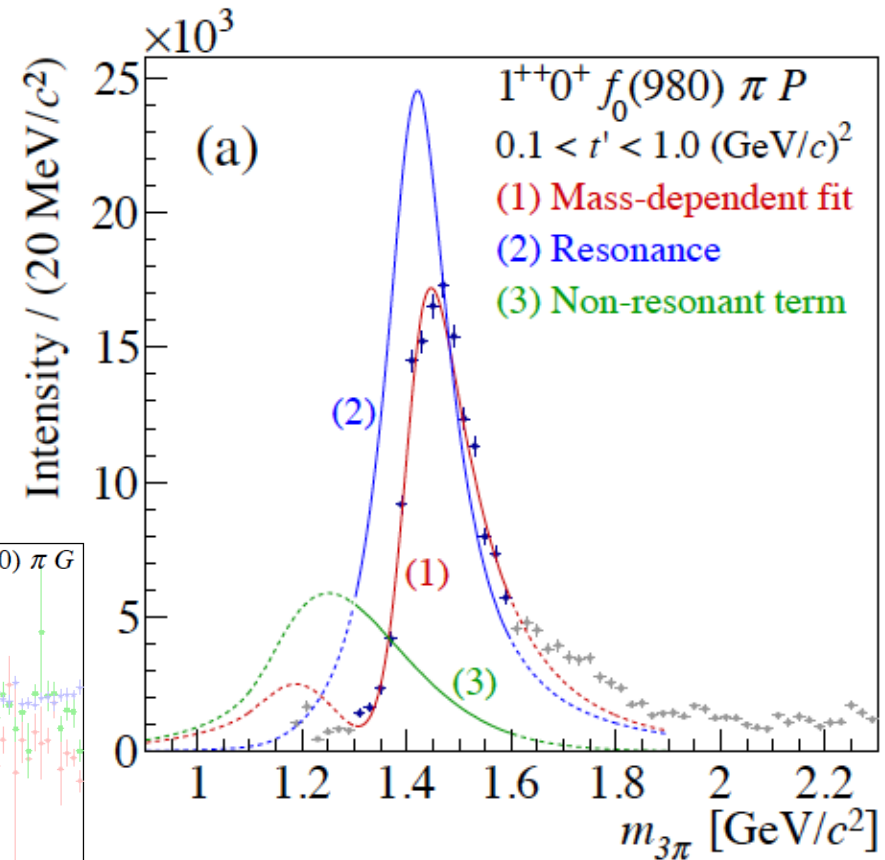
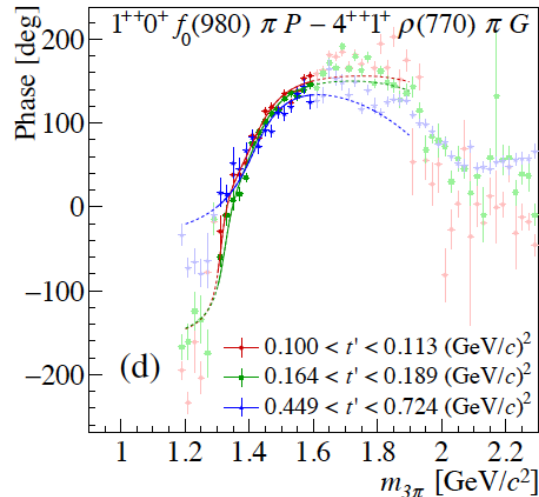
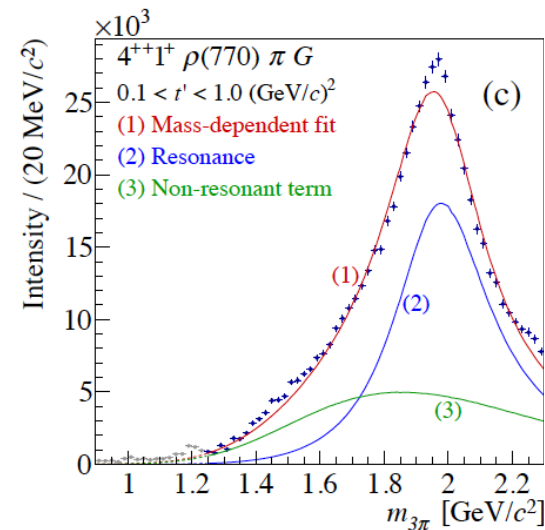
- first observation of structure in $1^{++} f_0(980) \pi P$
- small intensity ($\sim 0.25\%$)
- $\pi^- \pi^0 \pi^0$ scaled to $\pi^- \pi^+ \pi^-$



New axial-vector meson

Mass dependent fit for $\pi^-\pi^+\pi^-$ reveals
new resonance: **$a_1(1420)$**

- Mass $1414^{+15}_{-13} \text{ MeV}/c^2$
- Width $153^{+8}_{-23} \text{ MeV}/c^2$



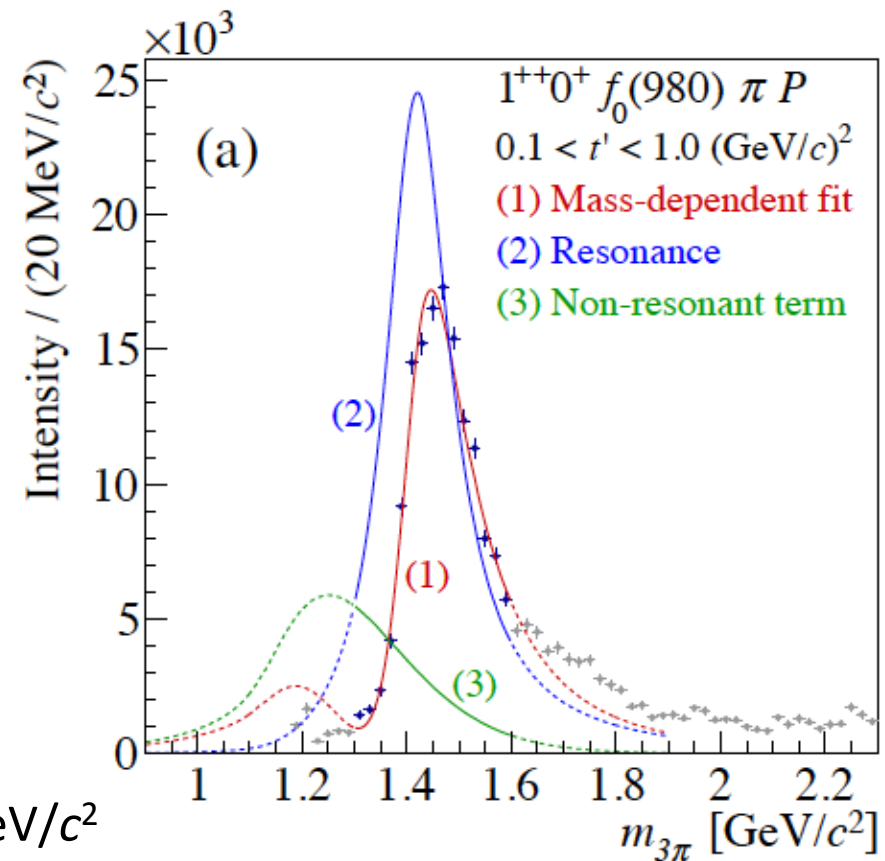
[PRL 115 \(2015\) 082001](#)

New axial-vector meson

| | J^{PC} | mass range (MeV/c ²) | width range (MeV/c ²) | PDG | |
|---------------------------------|----------|-------------------------------------|--------------------------------------|------------------------|---------------------|
| major waves | | | | | |
| a_1 (1260) | 1^{++} | 1260 – 1290 | 360 – 420 | 1230 ± 40 | $250 - 400$ |
| a_2 (1320) | 2^{++} | 1312 – 1315 | 108 – 115 | $1318.3^{+0.5}_{-0.6}$ | $105^{+1.6}_{-1.9}$ |
| π_2 (1670) | 2^{-+} | 1635 – 1663 | 265 – 305 | 1672.2 ± 3.0 | 260 ± 9 |
| a_4 (2040) | 4^{++} | 1928 – 1959 | 360 – 400 | 1996^{+10}_{-9} | 255^{+28}_{-24} |
| π (1800) | 0^{-+} | 1790 – 1807 | 212 – 230 | 1812 ± 12 | 208 ± 12 |
| π_2 (1880) | 2^{-+} | 1900 – 1990 | 210 – 390 | 1895 ± 16 | 235 ± 34 |
| 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} |
| a_1 (1420) | 1^{++} | 1412 – 1422 | 130 – 150 | | |

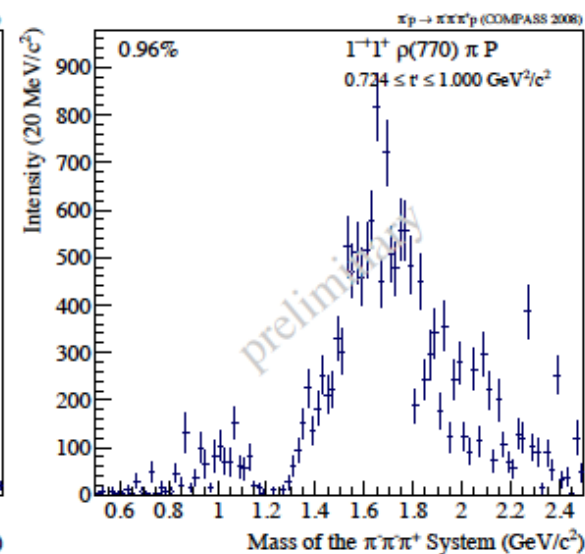
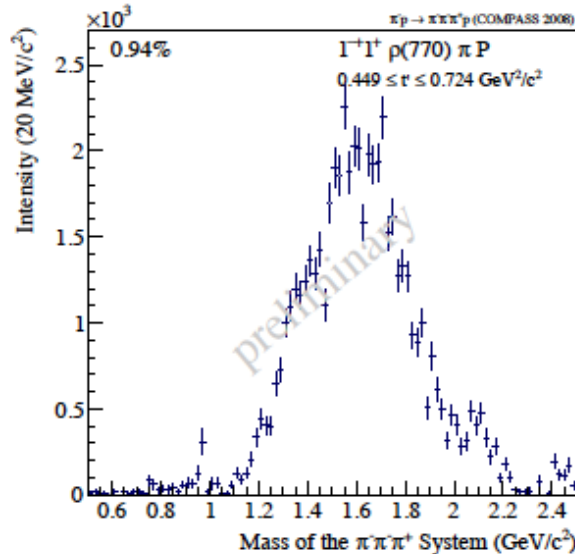
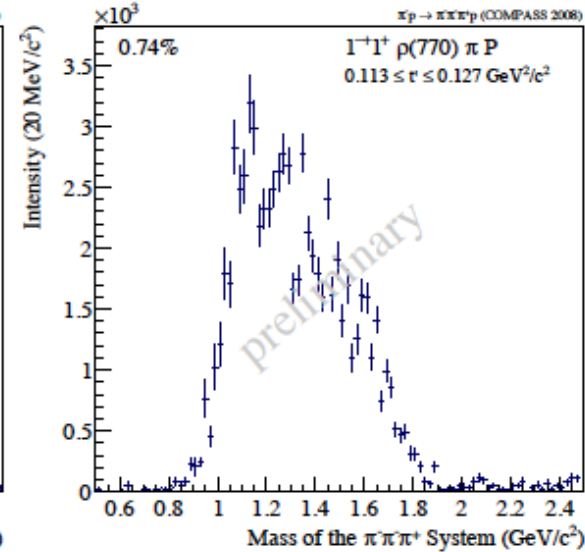
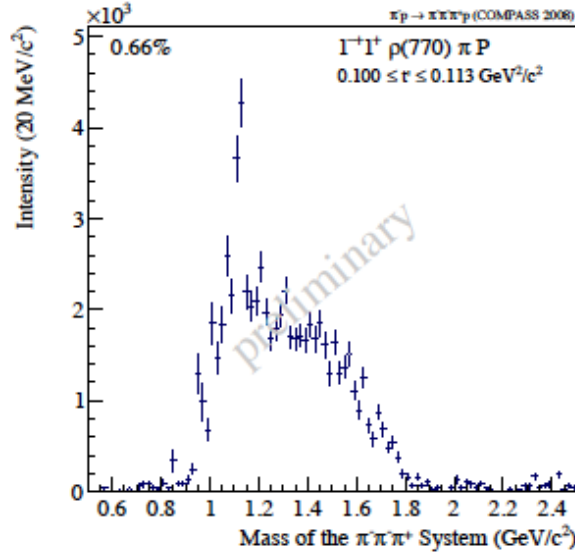
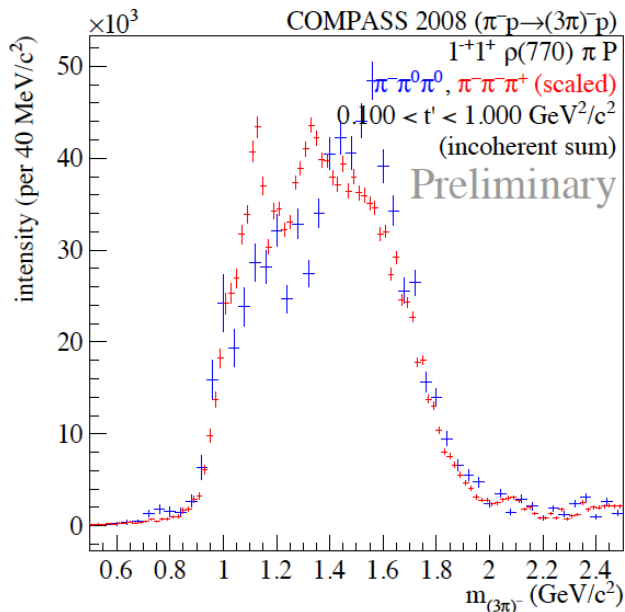
Nature of $a_1(1420)$ still to be understood:

- isospin partner of $f_1(1420)$?
- no quark model state expected at 1.4 GeV/c²
- ground state $a_1(1260)$ close and wider
- only seen in decays to $f_0(980) \pi$, not in $\rho\pi$
- close to $K^*\bar{K}^*$ threshold



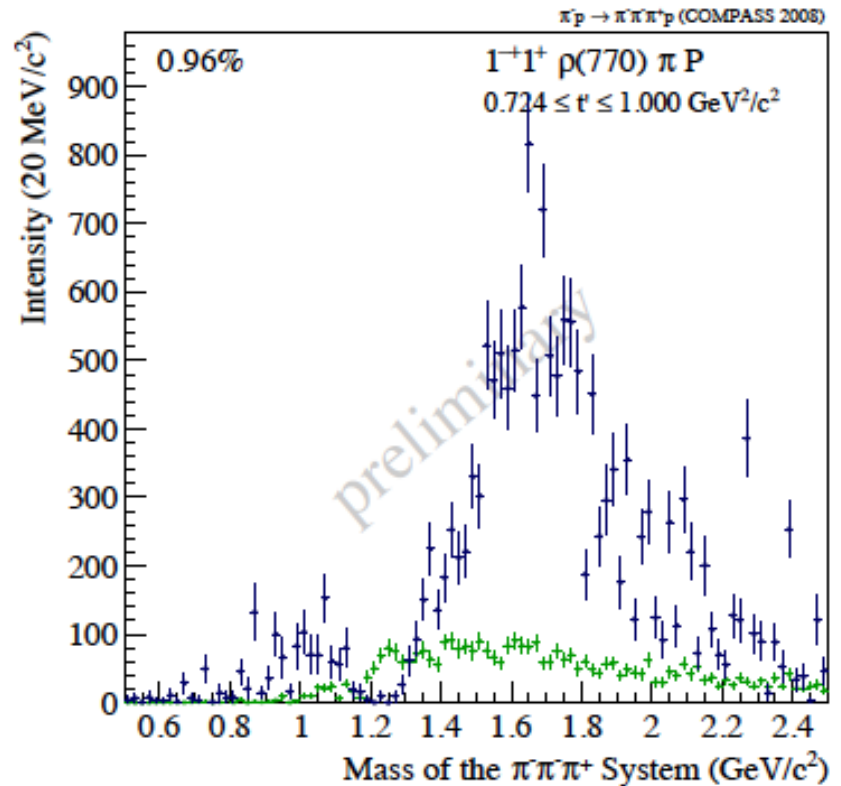
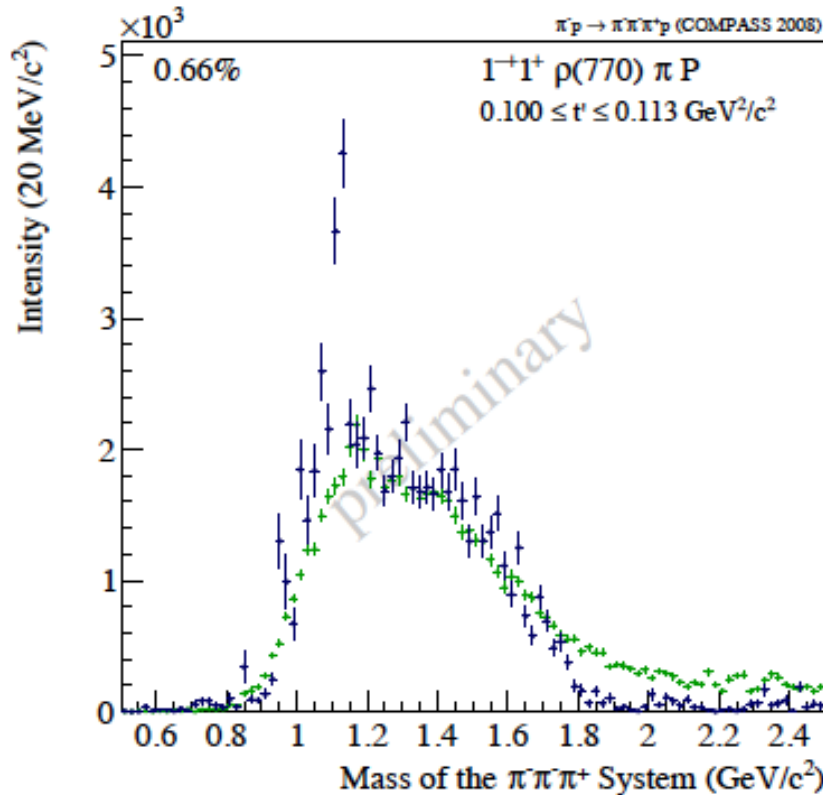
[PRL 115 \(2015\) 082001](#)

Status of exotic 1^- wave

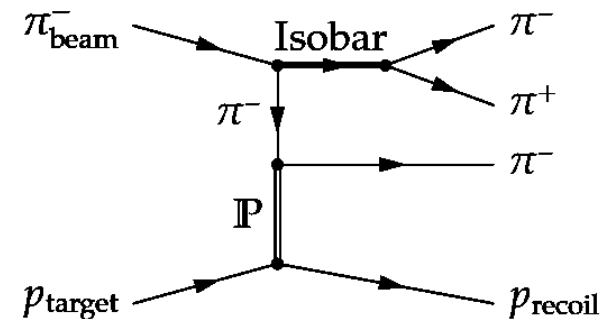


- again, $\pi^-\pi^0\pi^0$ scaled to $\pi^-\pi^+\pi^-$
- some differences between channels
- study in different t' bins:
 - peak in high t' region
 - structure in low t' , non-resonant

Status of exotic 1^- wave

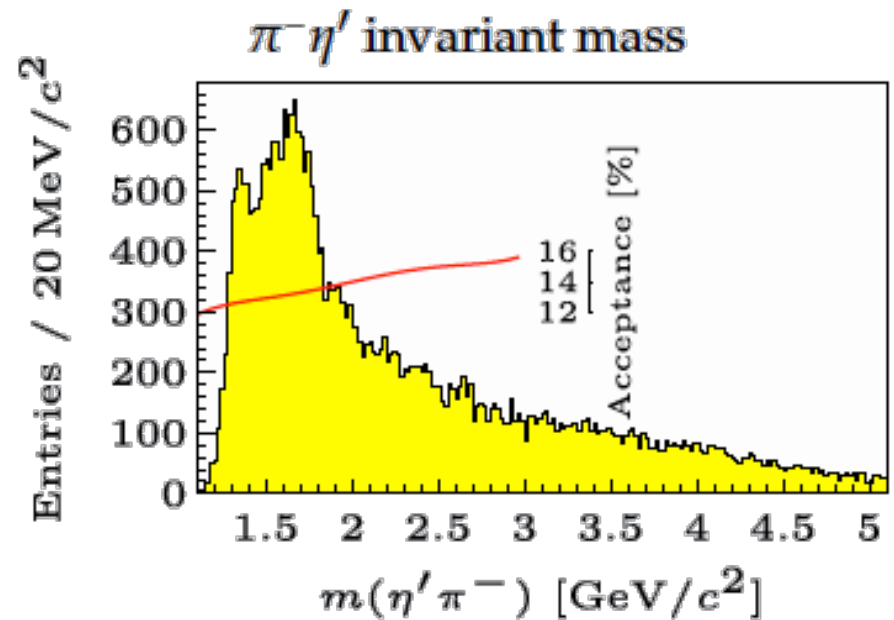
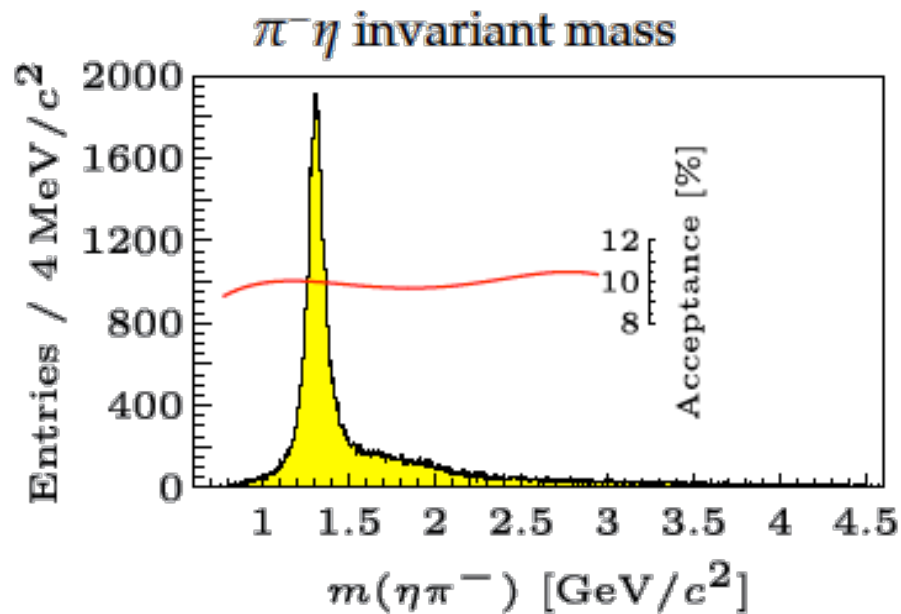


- MC data generated with Deck-amplitude
- analysed like real data and scaled to integrated intensity of each t' bins
- to be included in PWA



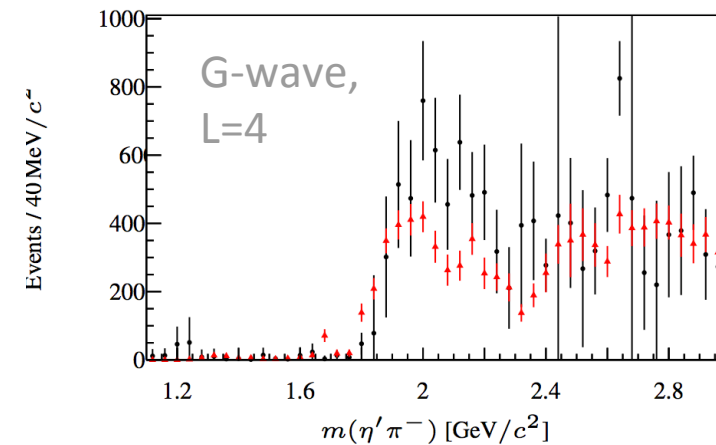
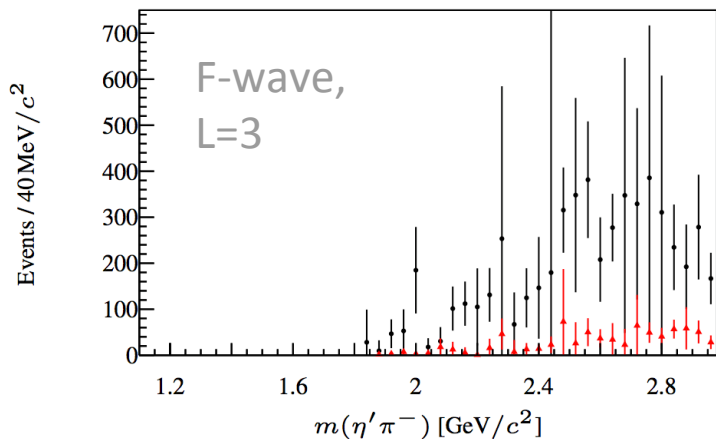
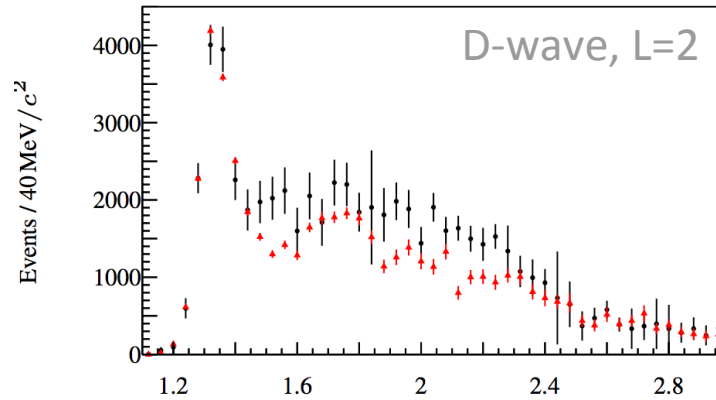
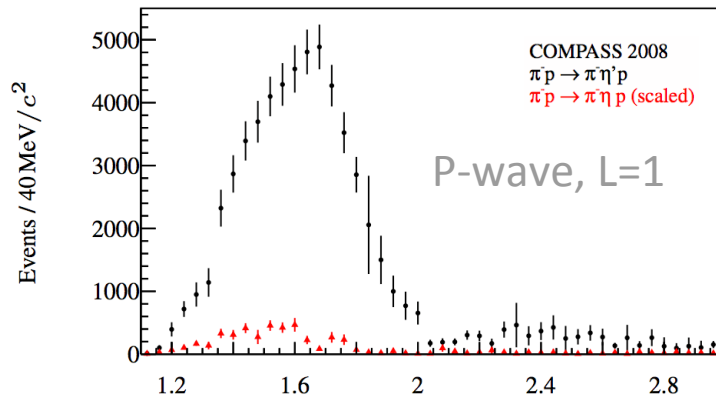
Partial wave analysis $\pi\eta / \pi\eta'$

- Disputed findings in odd-L waves
 - $\pi(1400)$ claimed in $\pi\eta$
 - $\pi(1600)$ claimed in $\pi\eta'$
- Comparison of channels yields information about flavour structure



PLB 740 (2015) 303-311, [hep-ex/1408.4286](https://arxiv.org/abs/hep-ex/1408.4286)

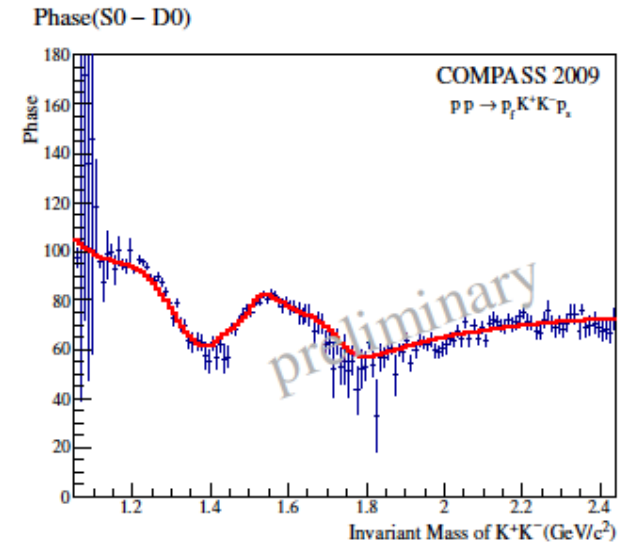
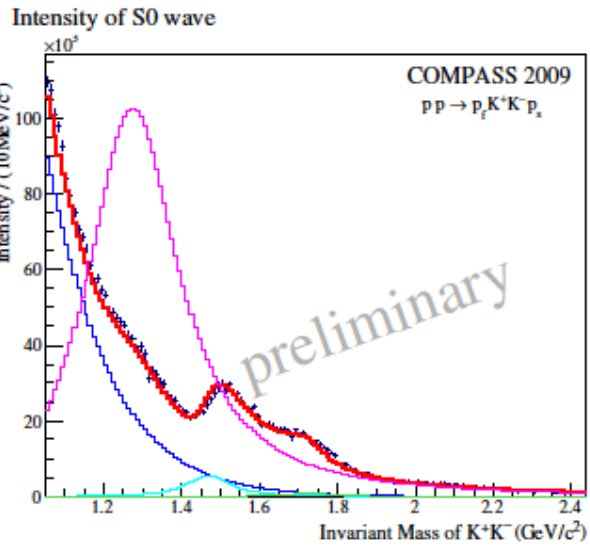
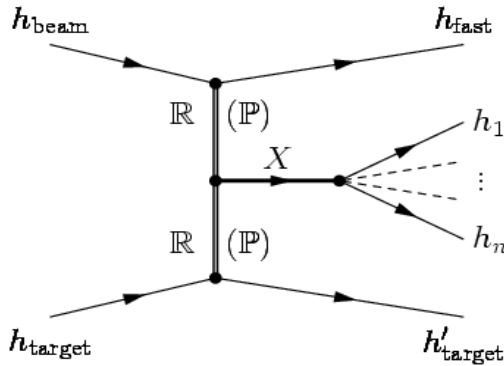
Partial wave analysis $\pi\eta / \pi\eta'$



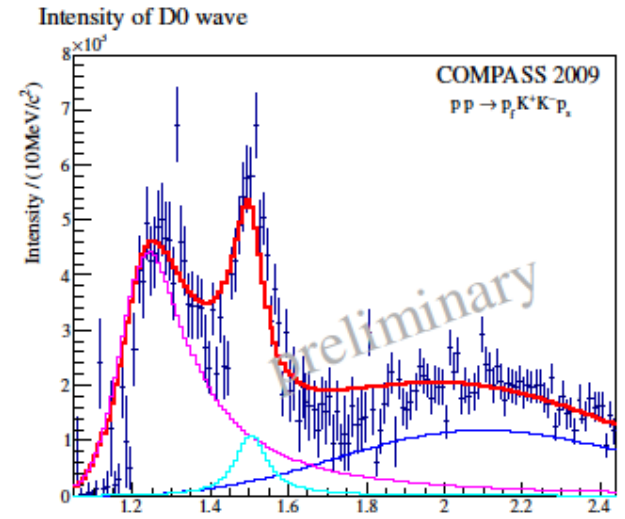
PLB 740 (2015) 303-311, [hep-ex/1408.4286](https://arxiv.org/abs/hep-ex/1408.4286)

- Even-L waves: similar intensity distributions in η and η'
- Odd-L waves: suppressed in $\eta\pi$ by factor 5-10
- mass dependent fits highly model dependent

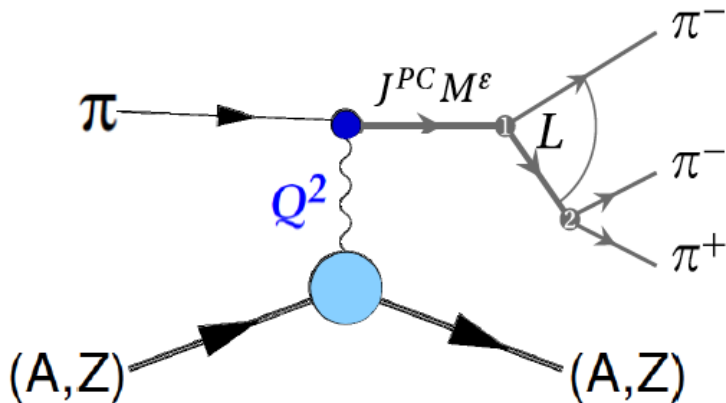
Central Production



- “glue-rich” process: search for glueballs
- mass-dependent fits with phases available
- $f_0(980)$, $f_0(1500)$, $f_0(1710)$ found, hints for further states beyond 2 GeV/c²
- analysis to be improved (handling of ambiguities, model dependence)



Very low t' region



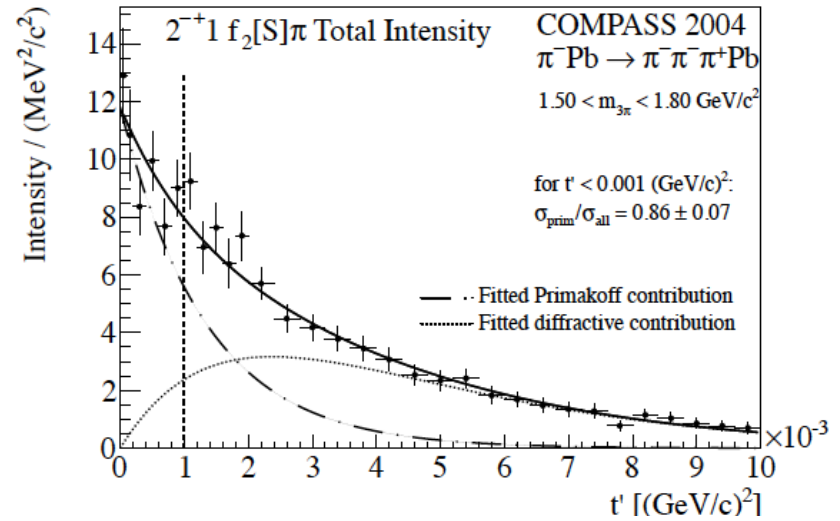
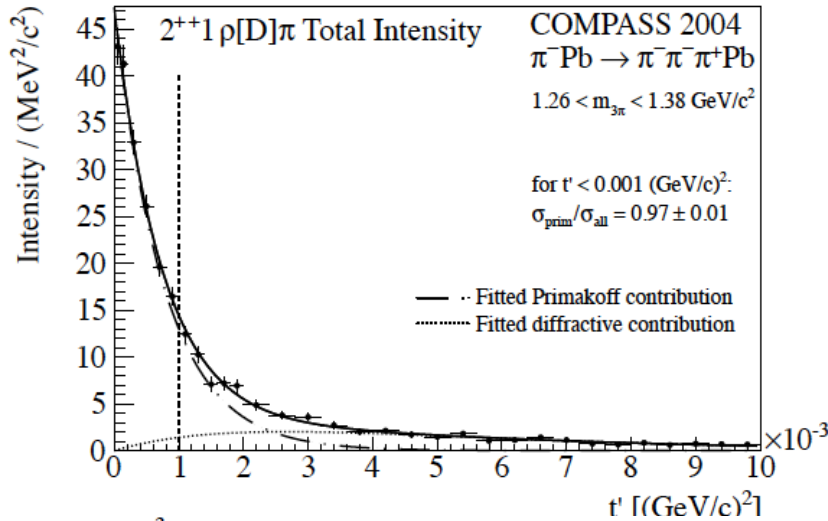
- study resonances with electromagnetic probes, but “inverted”: Coulomb field of heavy target (Pb) becomes photon target
- $t' < 0.001 \text{ (GeV/c)}^2$

Analysis:

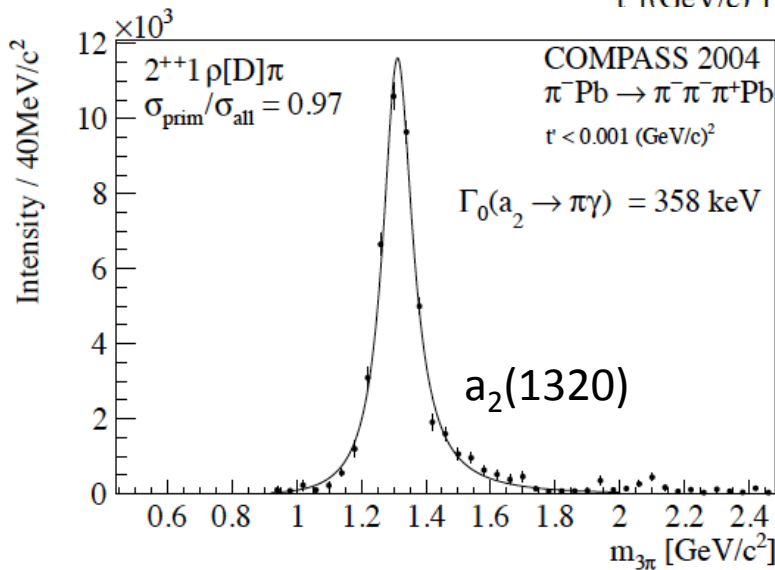
- photo-production (Primakoff): cross section proportional to $e^{-at'}$
- diffractive production: cross section proportional to $(t')^M e^{-bt'}$
- distinguish by spin projection M with partial wave analysis
- include chiral amplitude in PWA instead of isobars for very low masses

Radiative widths

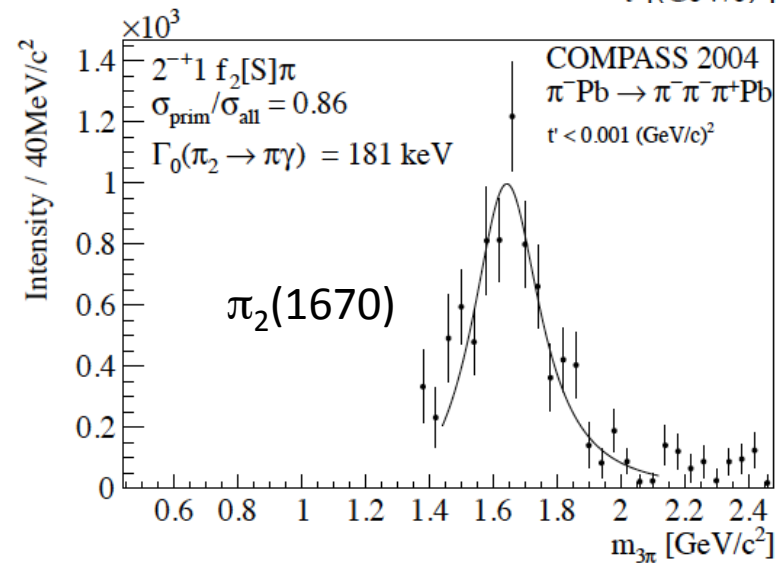
[hep-ex/1403.2644, EPJ A 50 (2014) 79]



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



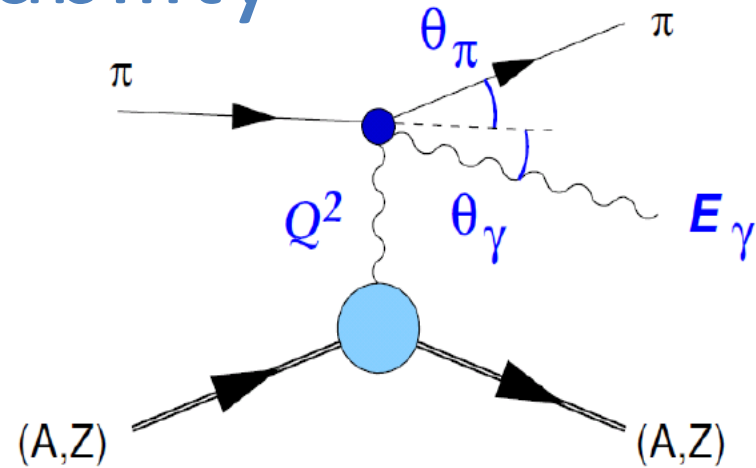
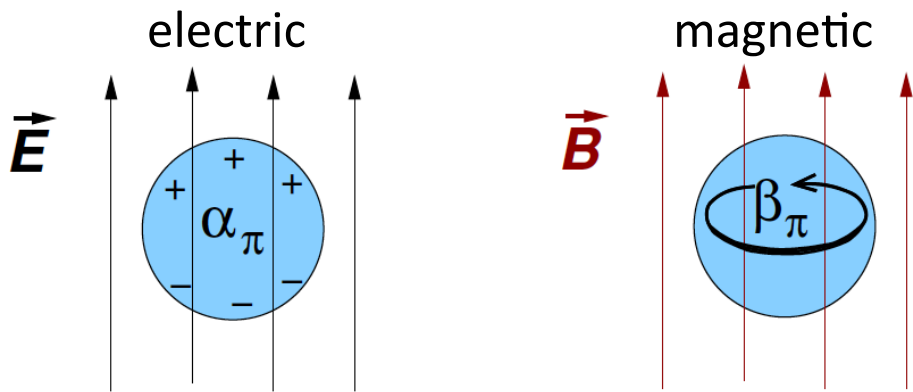
M2 transition



First E2 transition observed for mesons

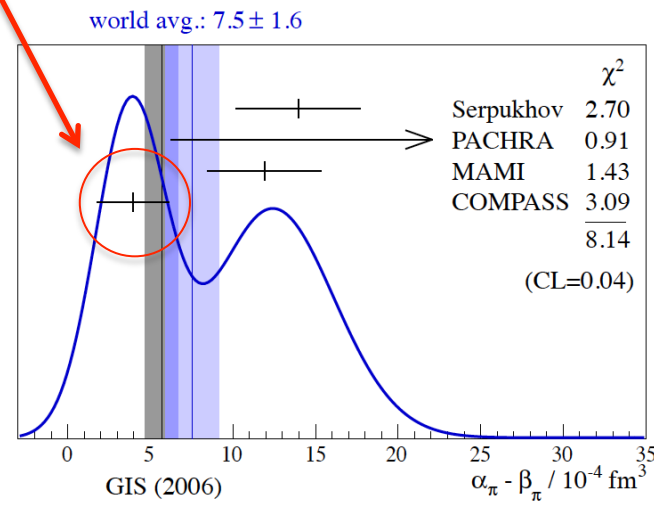
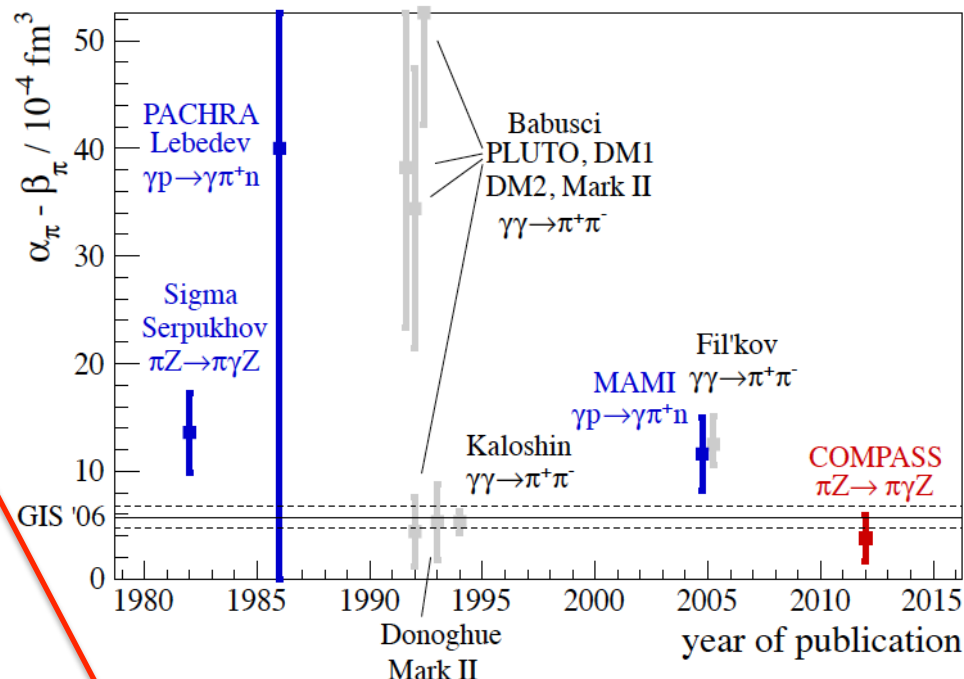
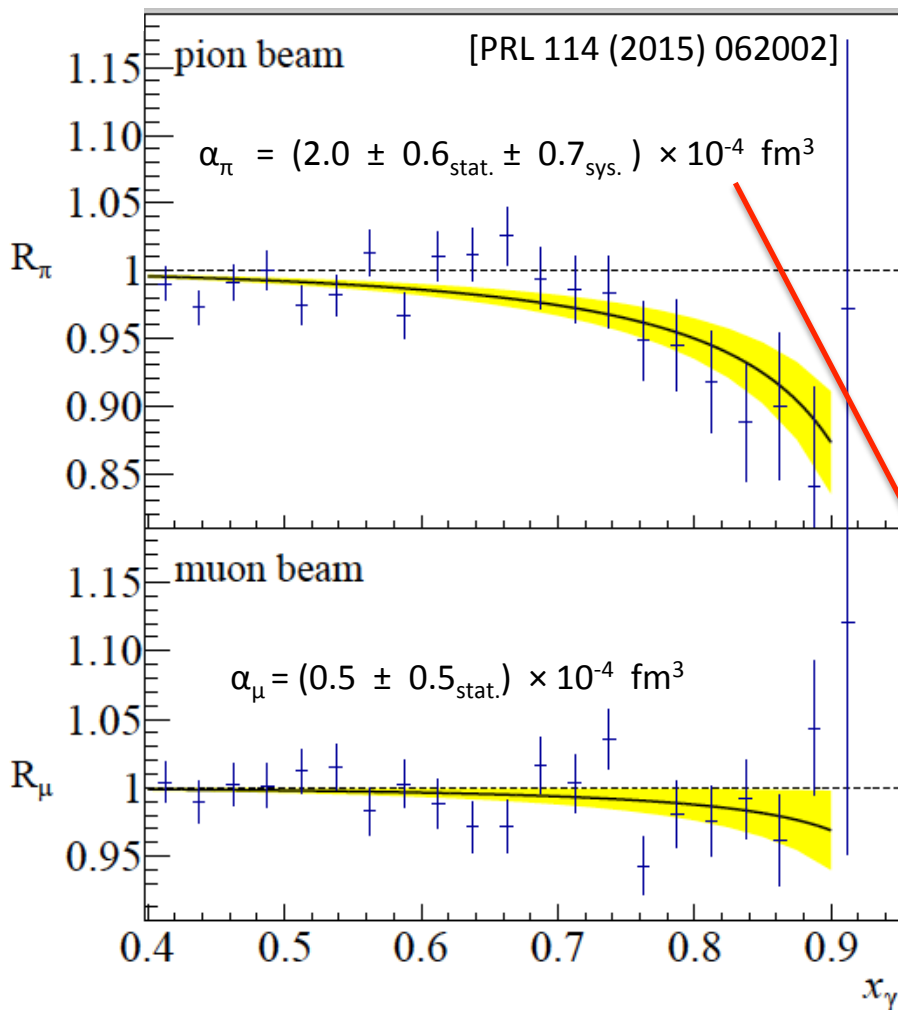
$\Gamma(\pi_2 \rightarrow \pi\gamma)$

Pion polarisability



- χ PT prediction (2-loop):
 - $\alpha - \beta = (5.7 \pm 1.0) 10^{-4} \text{ fm}^3$
 - $\alpha + \beta = (0.2 \pm 0.1) 10^{-4} \text{ fm}^3$
- Experimental results vary: $\alpha - \beta = (4...14) 10^{-4} \text{ fm}^3$ (assuming $\alpha + \beta = 0$)
- Compass study with Primakoff production
- Cross section proportional to $\alpha - \beta$ in LO
- Compare π and μ beam data to search for deviation from cross section of point-like particle

Pion polarisability



- result confirms χ PT prediction
- in tension with former experiments

Conclusions and Outlook

- COMPASS high precision spectroscopy program
- Unchallenged data sets (e.g. $\pi^+\pi^-\pi^0$) with access to charged and neutral channels
- Partial wave analyses extended to m and t' bins
- Found new axial-vector meson $a_1(1420)$, interpretations:
 - Tetra-quark state [Hua-Xing Chen et al., arXiv:1503.02597], [Zhi-Gang Wang, arXiv:1401.1134]
 - Dynamic effect of interference with Deck [Basdevant et al., arXiv:1501.04643]
 - Triangle singularity [Mikhasenko et al., arXiv:1501.07023]
- Precision study of exotic 1^{-+} wave, $\pi_1(1600)$
- Several improvements coming up (e.g. integrate Deck amplitude to 1^{-+} , include de-isobaring: fit isobars with step-wise functions from data)
- π polarisability and tests of χ PT with Primakoff production [PRL 114 (2015) 062002]
- more analyses published and ongoing, but not shown here: study of production mechanisms via OZI violation [NPB 886 (2014) 1078], 5π channel, etc.
- XYZ studies started



ENGINEERING
DEPARTMENT