Light Meson Spectroscopy with COMPASS

PANDA Physics Workshop - Uppsala

Johannes Bernhard (CERN PH-SME)
on behalf of the COMPASS collaboration

10.06.2015

Outline

- The Compass Experiment
- Light Meson Spectroscopy with Compass
  - 3π channel: $\pi_1(1600)$, $a_1(1440)$
  - $\pi\eta'$ / $\pi\eta$ channel
  - Central production (K^+K^-)
  - Radiative widths of $a_2(1320)$ and $\pi_2(1670)$
  - Search for $Z_c^{\pm}(3900)$
- Pion polarisability
- Conclusions and Outlook

COMPASS - A facility to study QCD

Large Q^2:

Nucleon structure

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

Low Q^2:

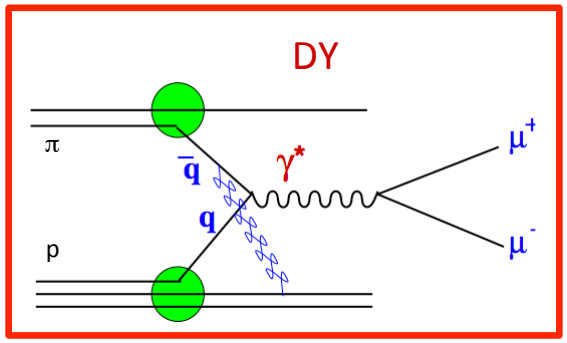
Spectroscopy

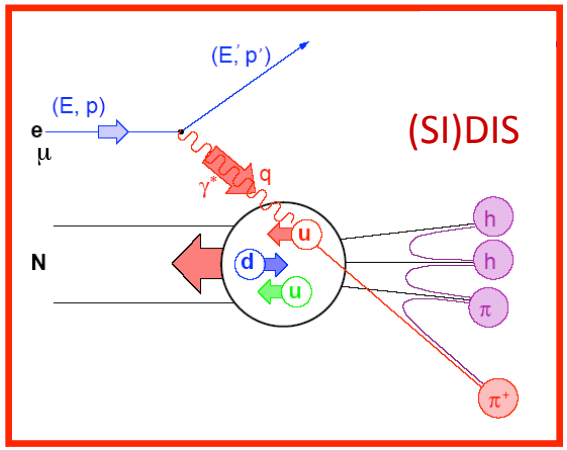
- Hadronic mass spectrum
- Gluonic excitations / spin-exotics

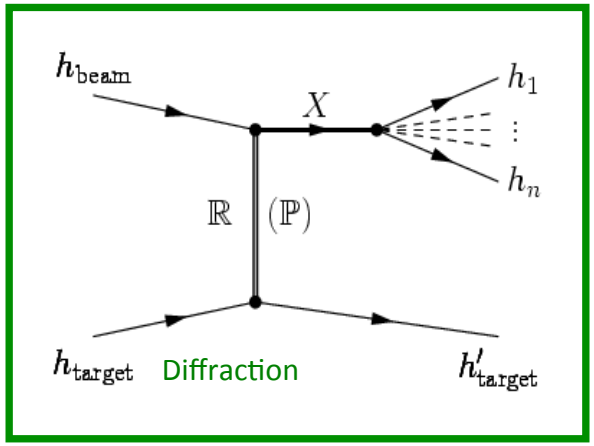
Very low Q^2:

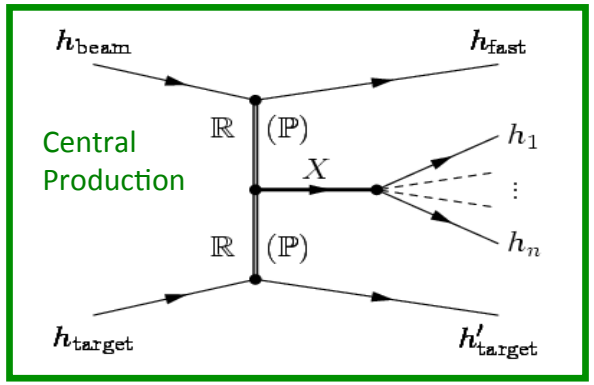
Chiral dynamics

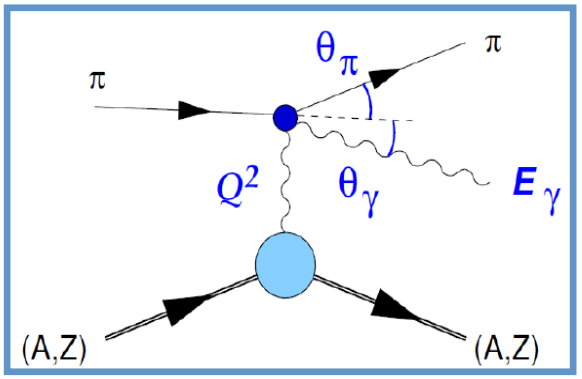
- π and K polarisibilities
- radiative widths





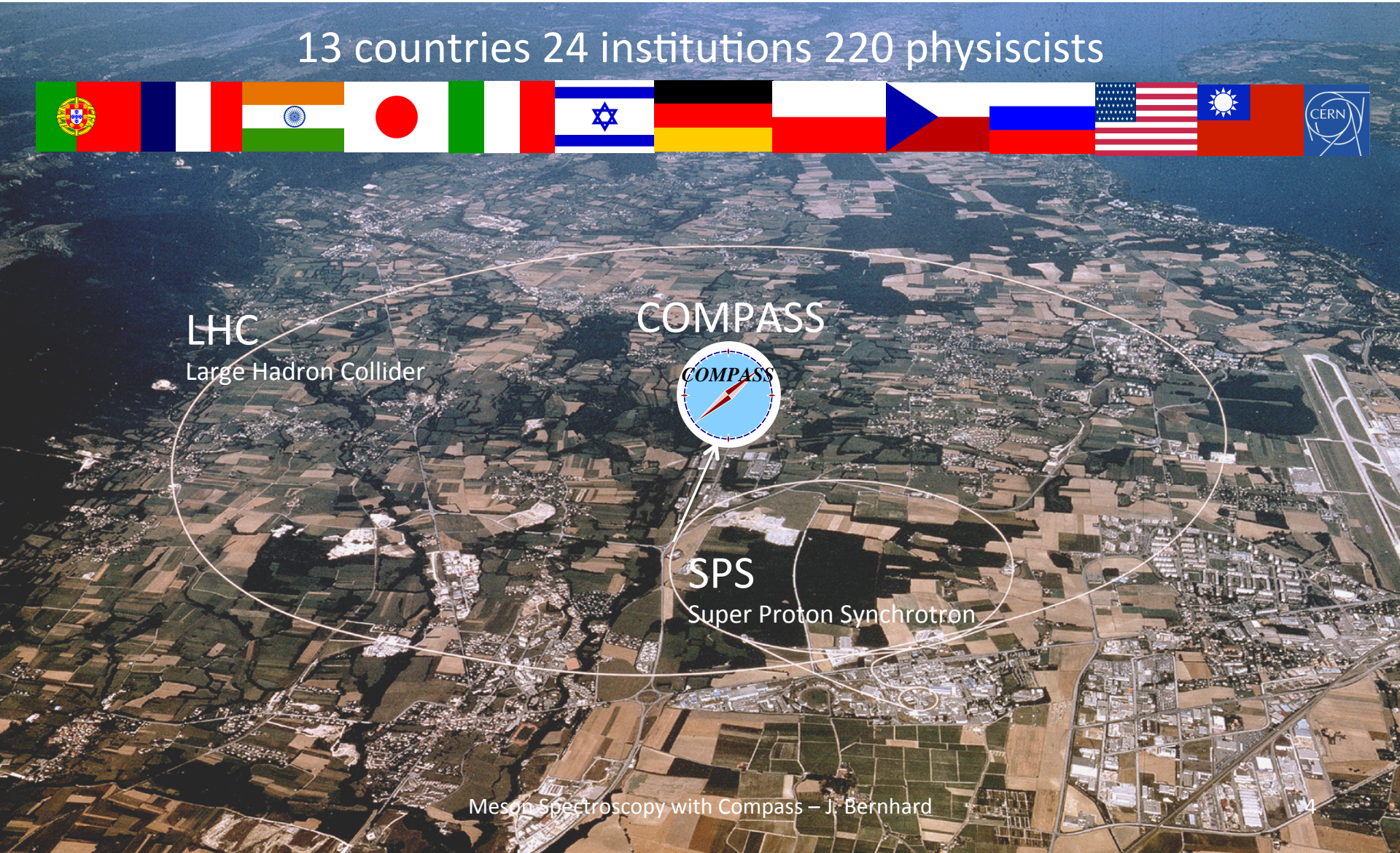




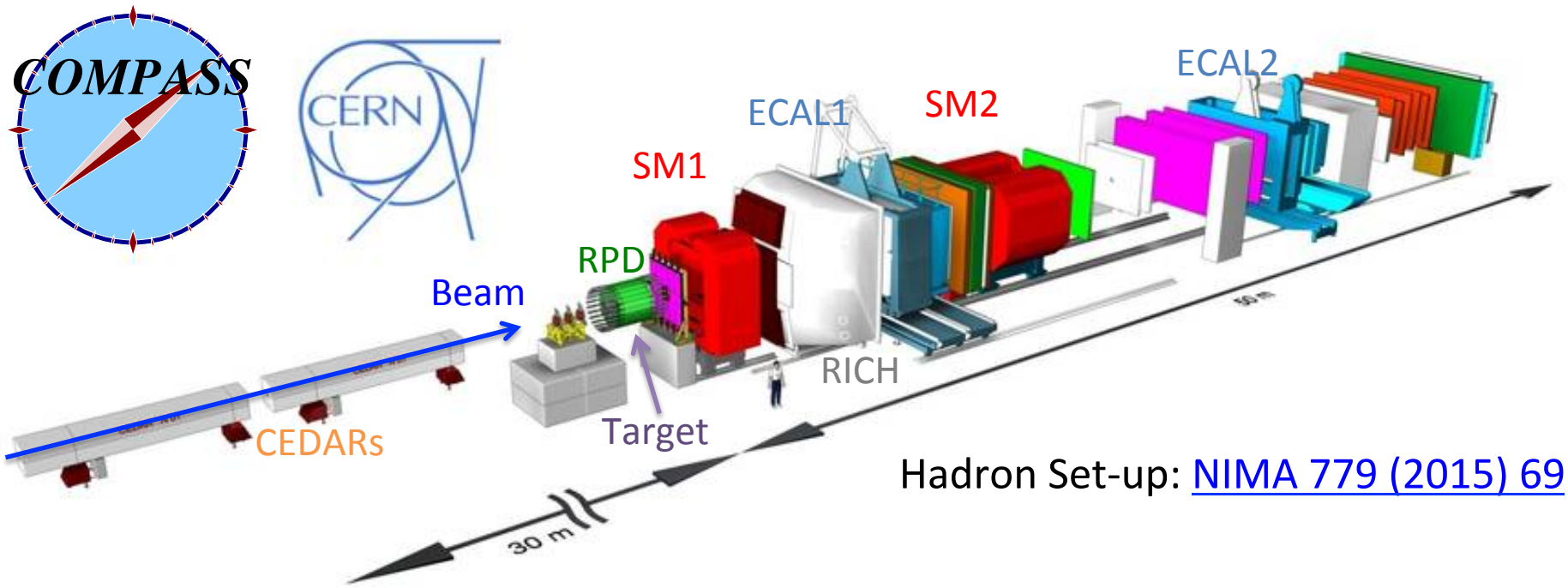


The COMPASS experiment at CERN

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



The COMPASS spectrometer



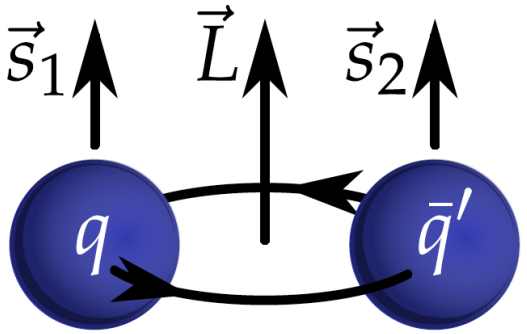
Hadron Set-up: NIMA 779 (2015) 69

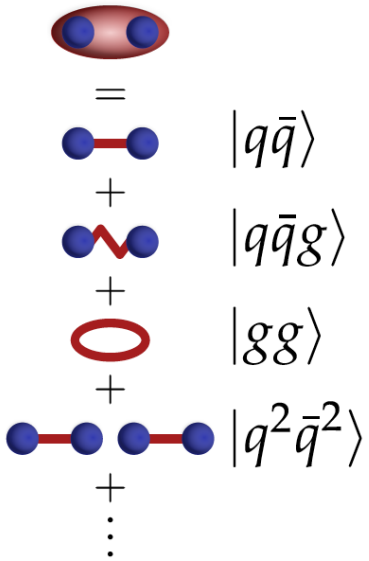
- Data taking in 2008 and 2009 with 190 GeV/*c* hadron beam ($\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$)
- $5 \cdot 10^7$ particles/10 s SPS-spill on 40cm liquid hydrogen target
- Trigger: Recoil Proton Detector + beam (minimum bias on forward system)

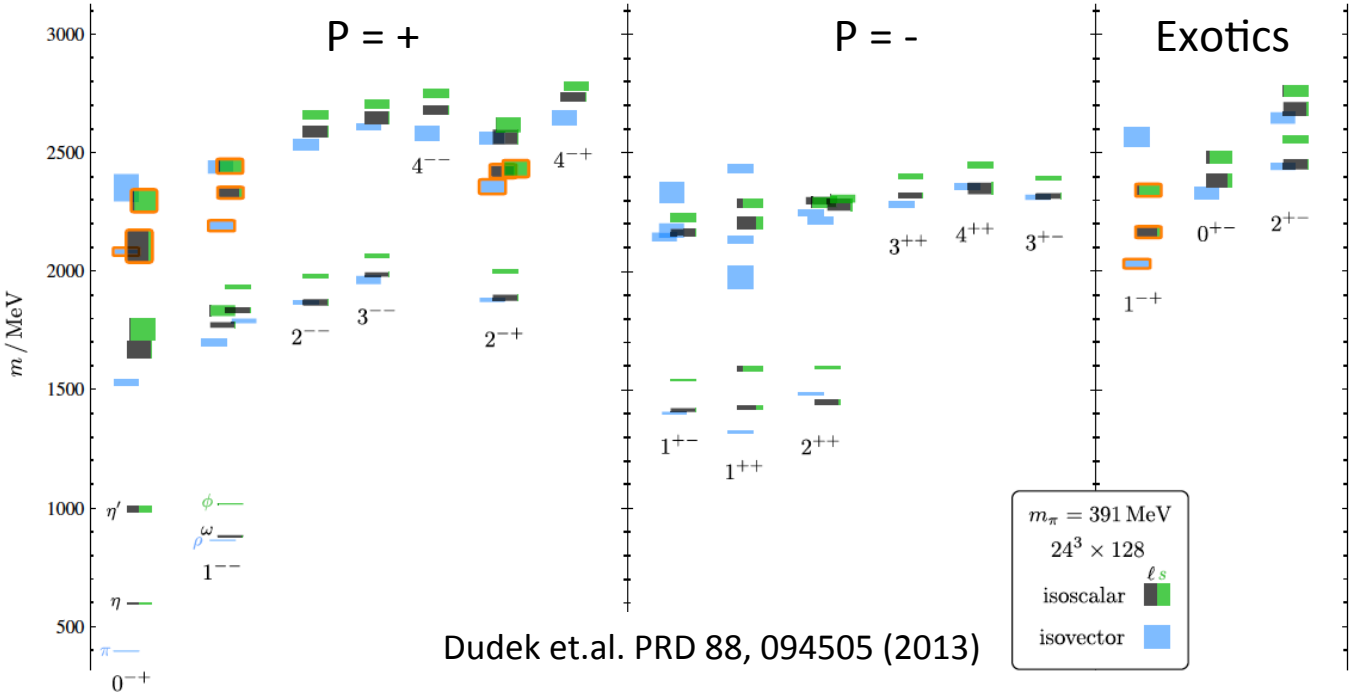
Meson Spectroscopy

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)

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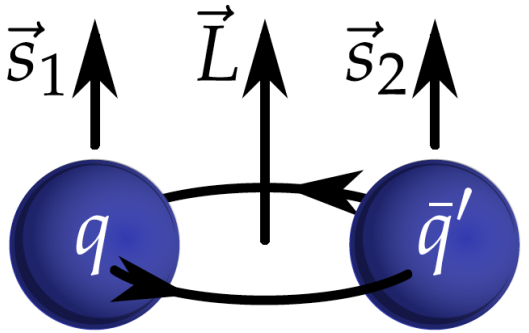
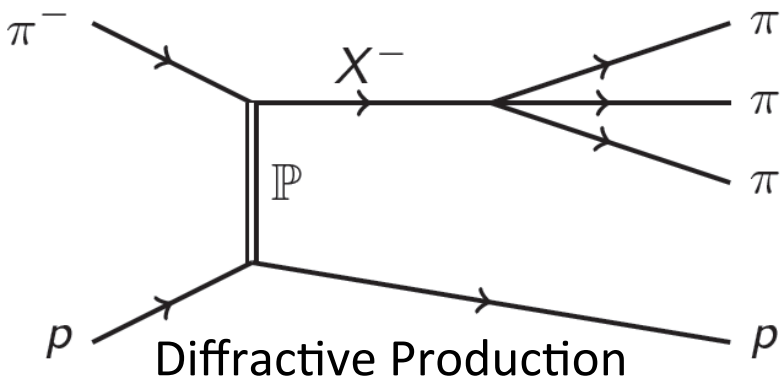


Experiment (1.3 - 2.2 GeV/c²):

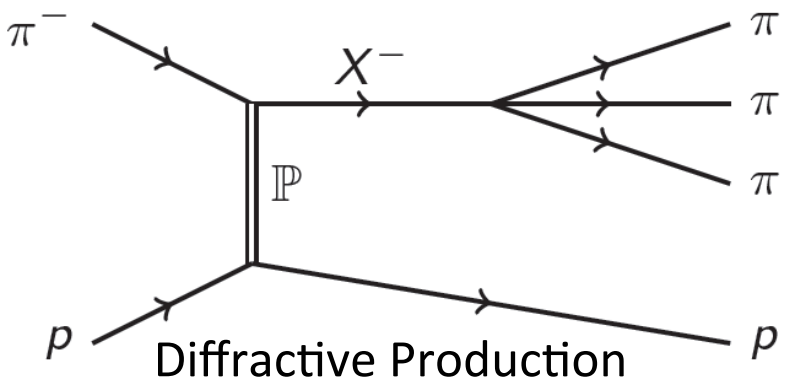
hybrid candidates with exotic $J^{PC} = 1^{-+}$

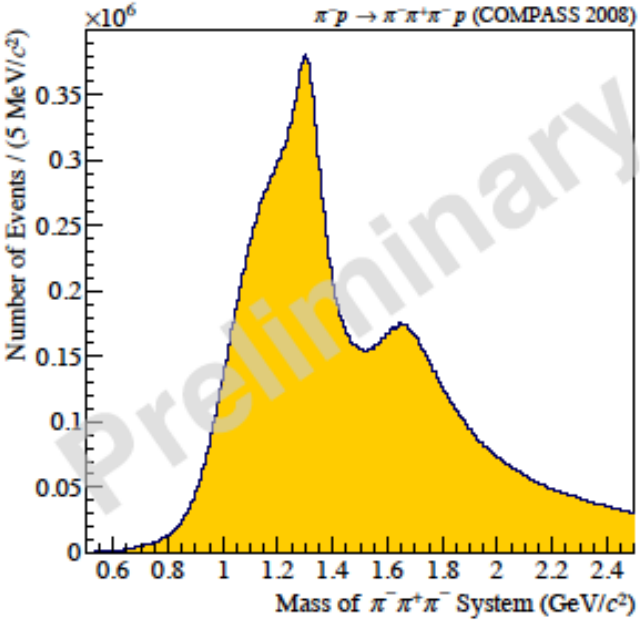
- $\pi_1(1400)$: VES, E852 –> $\eta\pi$
- $\pi_1(1600)$: E852, VES –> $\rho\pi$, $\eta'\pi$, $f_1\pi$, $b_1\pi$
  COMPASS (2004) –> $\rho\pi$
- $\pi_1(2000)$: E852 –> $f_1(1285)\pi$, $b_1(1235)\pi$



Diffractive Production

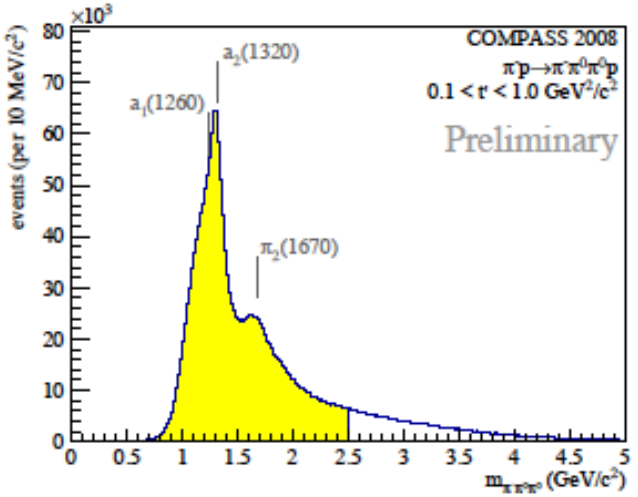
Meson Spectroscopy at COMPASS: 3π



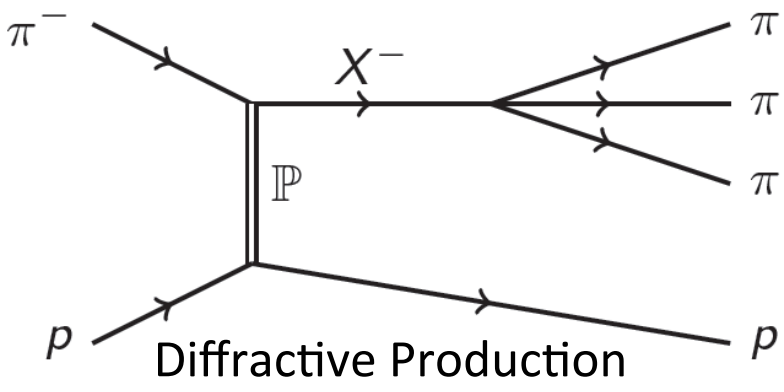


Exclusive 3π events in πp -> πππ p_{recoil}

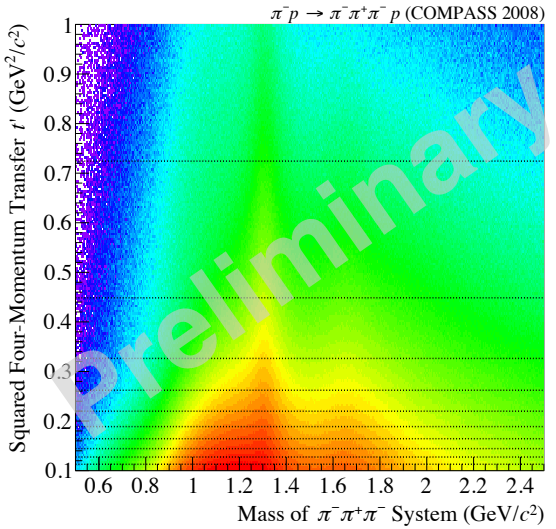
- channels: $\pi^-\pi^+\pi^-$, $\pi^-\pi^0\pi^0$
- high t' region: 0.1 (GeV/c)^2 < t' < 1 (GeV/c)^2
- large data set
  - 50 Million events for $\pi^-\pi^+\pi^-$
  - 3.5 Million events for $\pi^-\pi^0\pi^0$



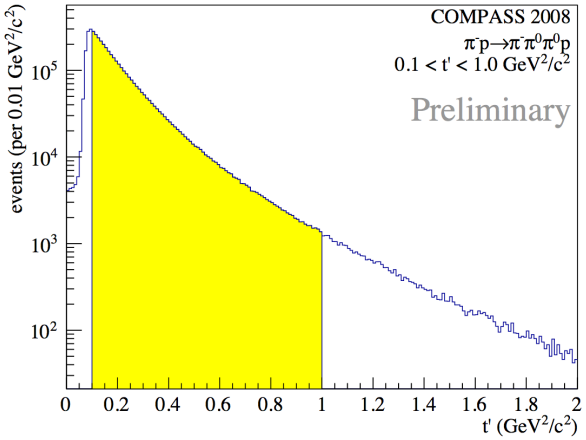
Meson Spectroscopy at COMPASS: 3π



Diffractive Production



400 mass bins & 11 bins of *t'*

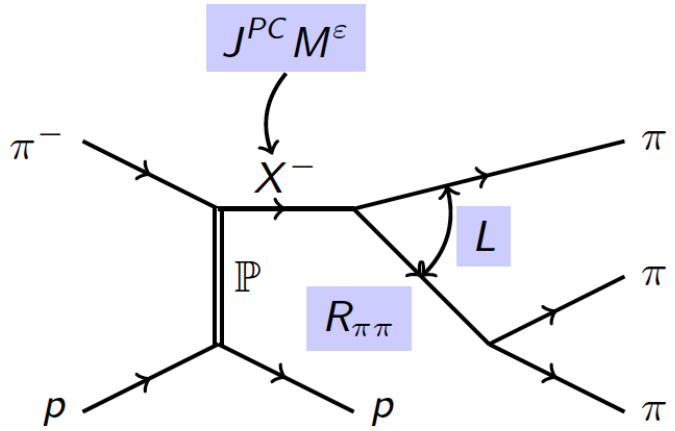


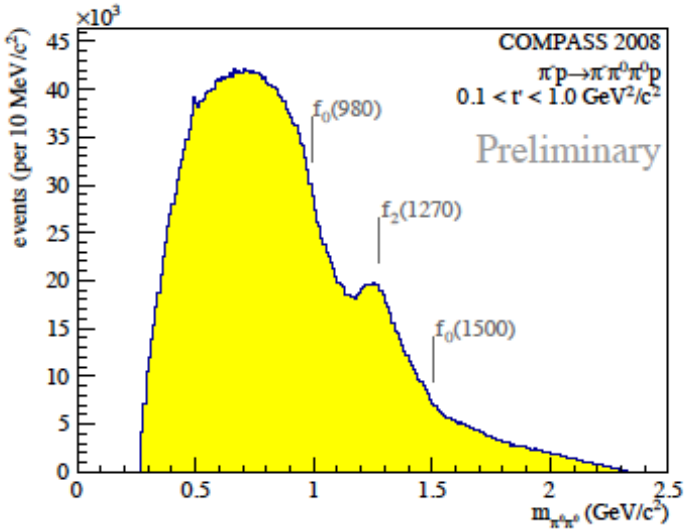
200 mass bins & 8 bins of *t'*

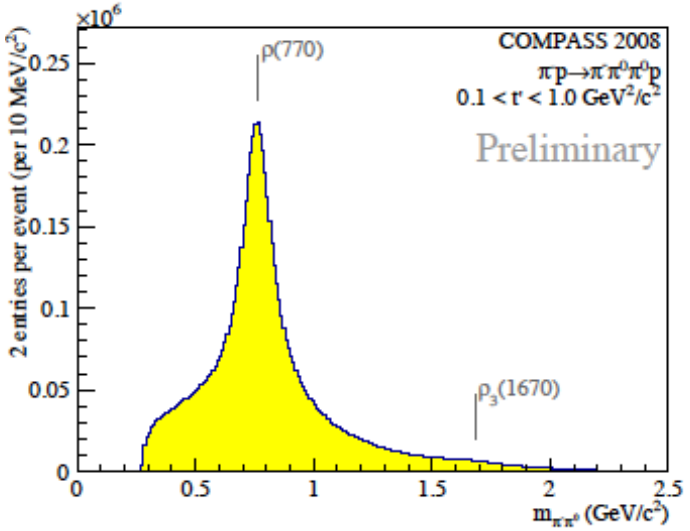
Exclusive 3π events in πp -> πππ p_{recoil}

- channels: $\pi^-\pi^+\pi^-$, $\pi^-\pi^0\pi^0$
- high *t'* region: 0.1 (GeV/*c*)² < *t'* < 1 (GeV/*c*)²
- large data set
  - 50 Million events for $\pi^-\pi^+\pi^-$
  - 3.5 Million events for $\pi^-\pi^0\pi^0$

Partial Wave Analysis 3π



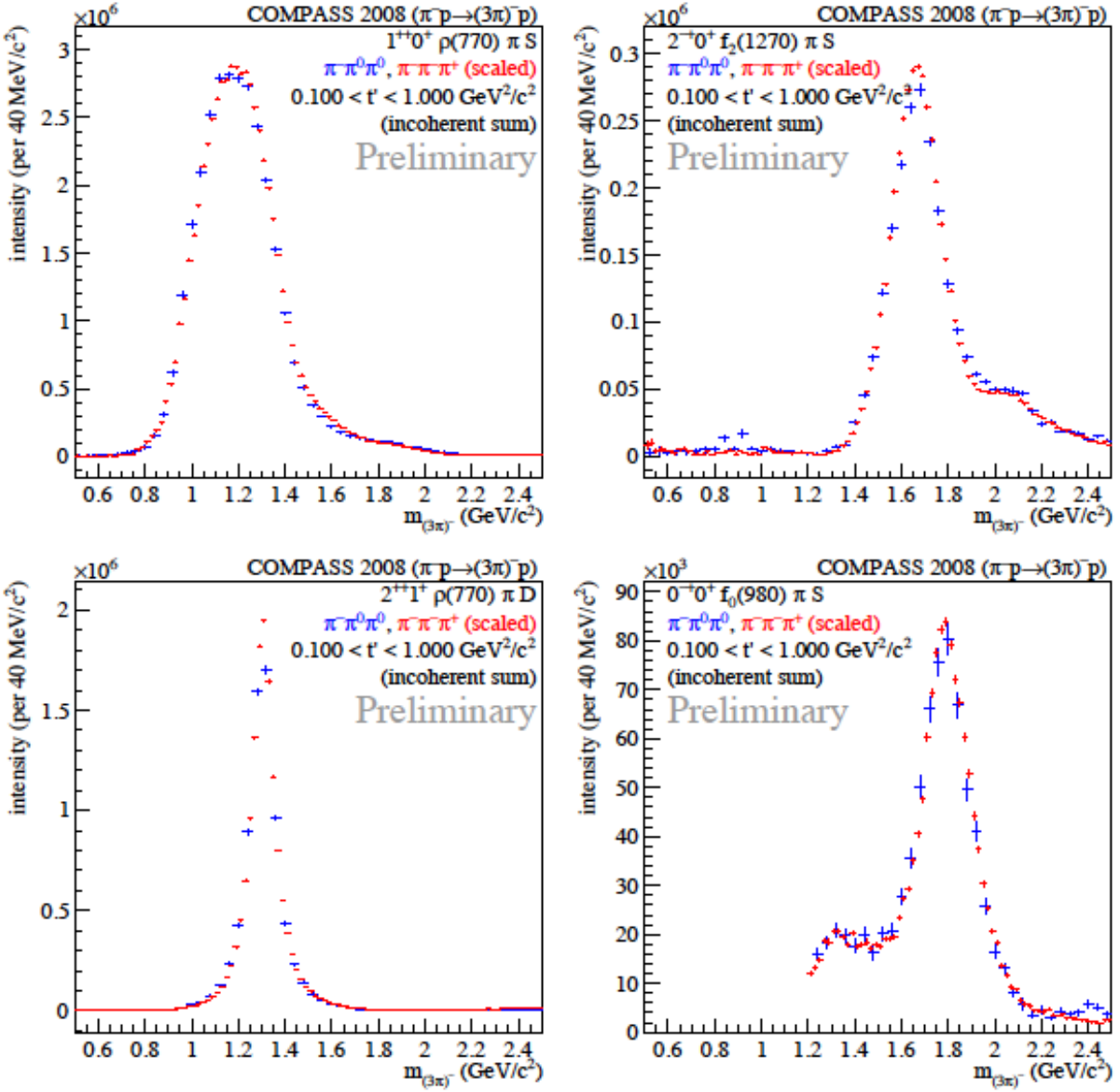




- Isobar Model
- Acceptance correction
- Factorisation of process with production and decay amplitude
- Fit in two steps:
  - fit in mass and *t'* bins -> production amplitudes
  - fit mass dependence of spin-density matrix -> resonance parameters

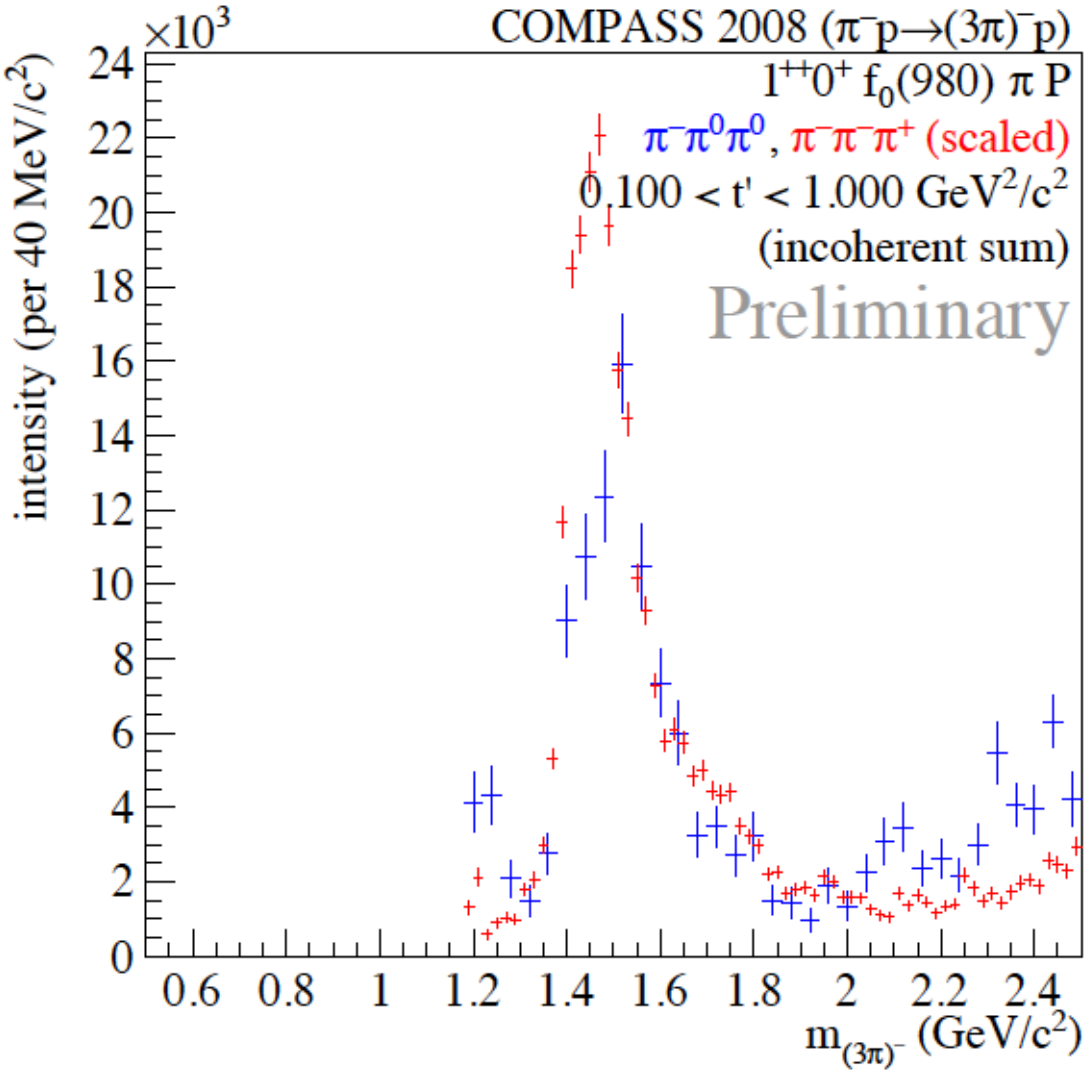
Partial Wave Analysis 3π

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



Partial Wave Analysis 3π

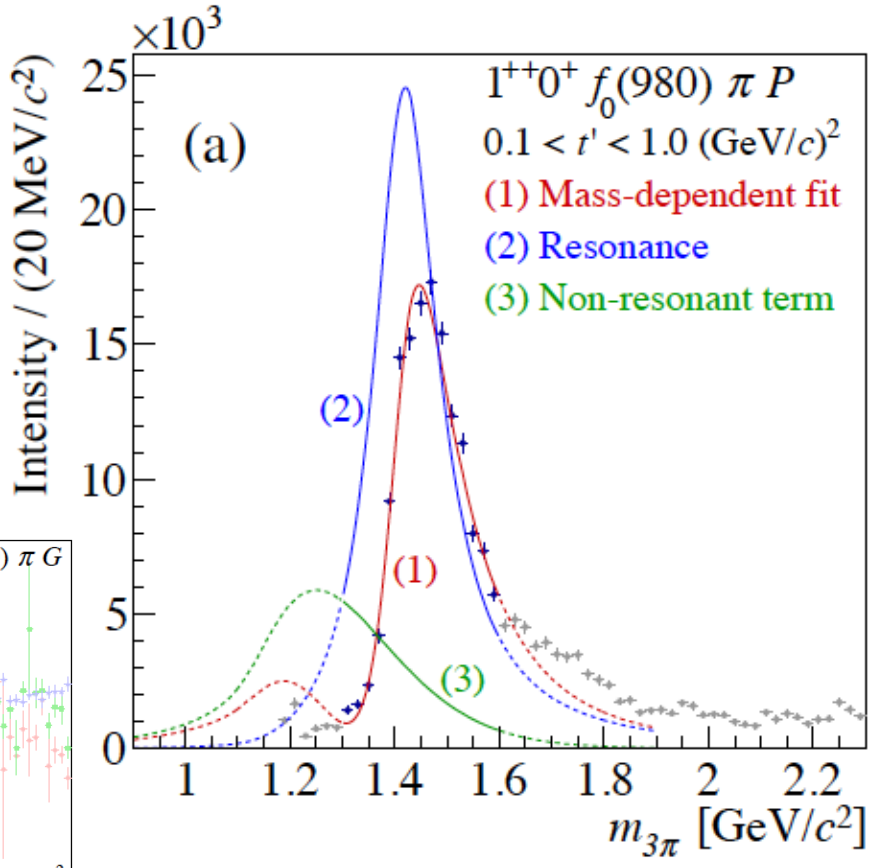
- first observation of structure in 1^{++} $f_0(980)$ π *P*
- small intensity (~0.25%)
- $\pi^-\pi^0\pi^0$ scaled to $\pi^-\pi^+\pi^-$

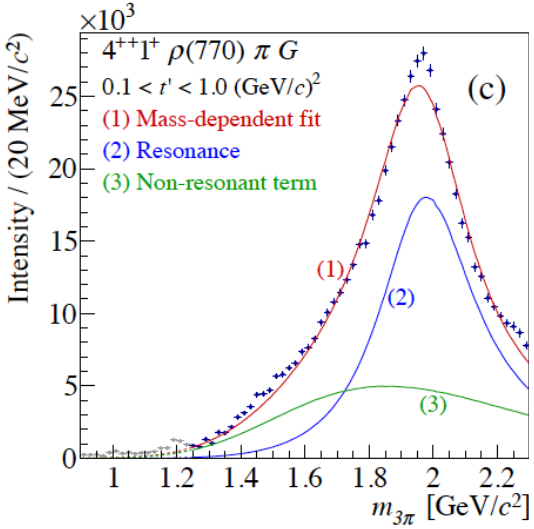


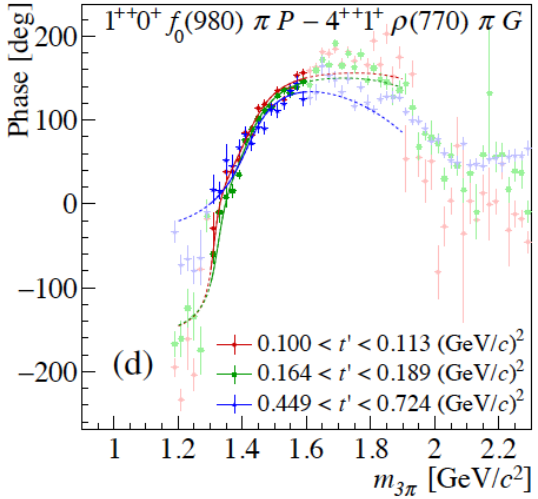
New axial-vector meson

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

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



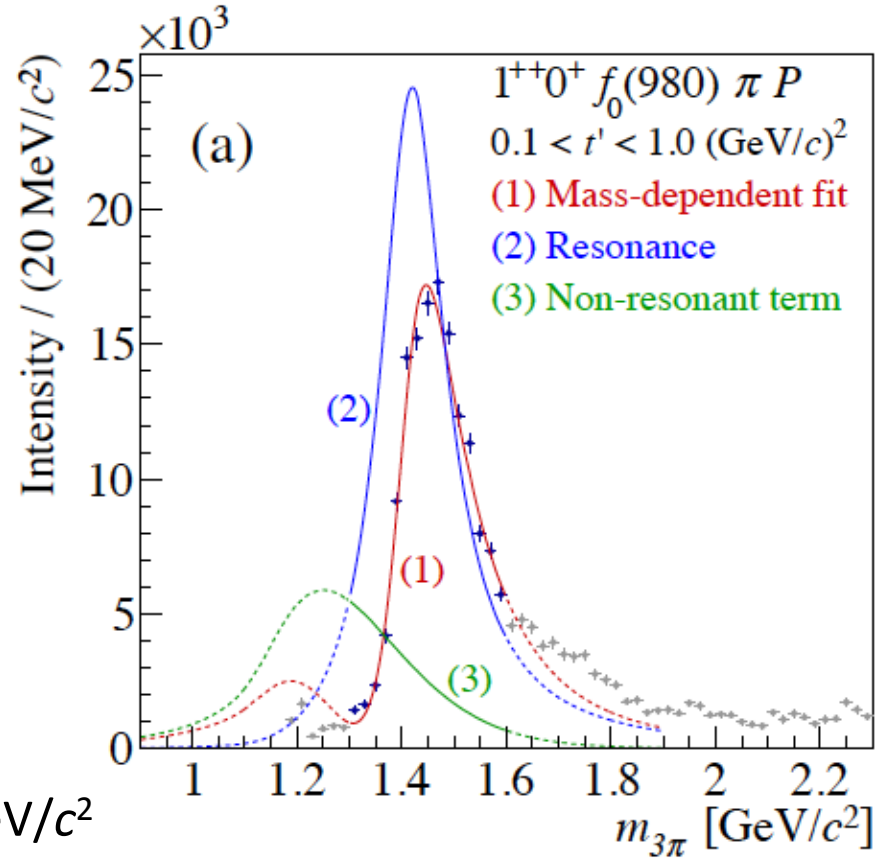




submitted to PRL, [hep-ex/1501.05732](hep-ex/1501.05732)

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	$1318.3^{+0.5}_{-0.6}$	$105^{+1.6}_{-1.9}$
$\pi_2(1670)$	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}
$\pi(1800)$	0^{-+}	1790 – 1807	212 – 230	1812 ± 12	208 ± 12
$\pi_2(1880)$	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		

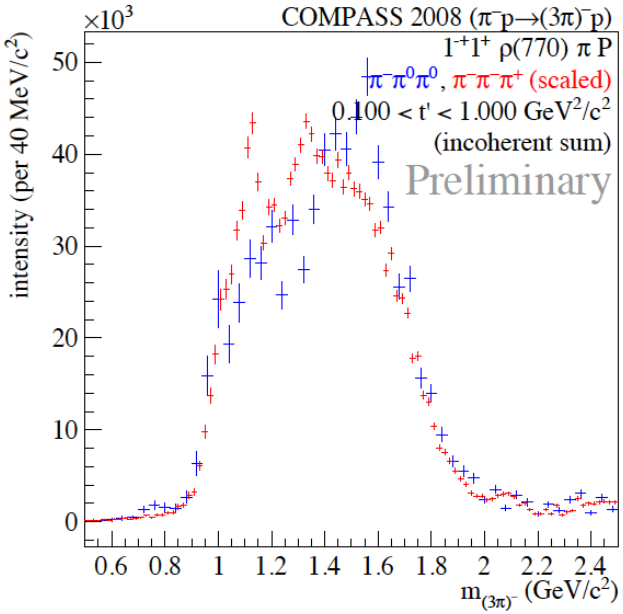


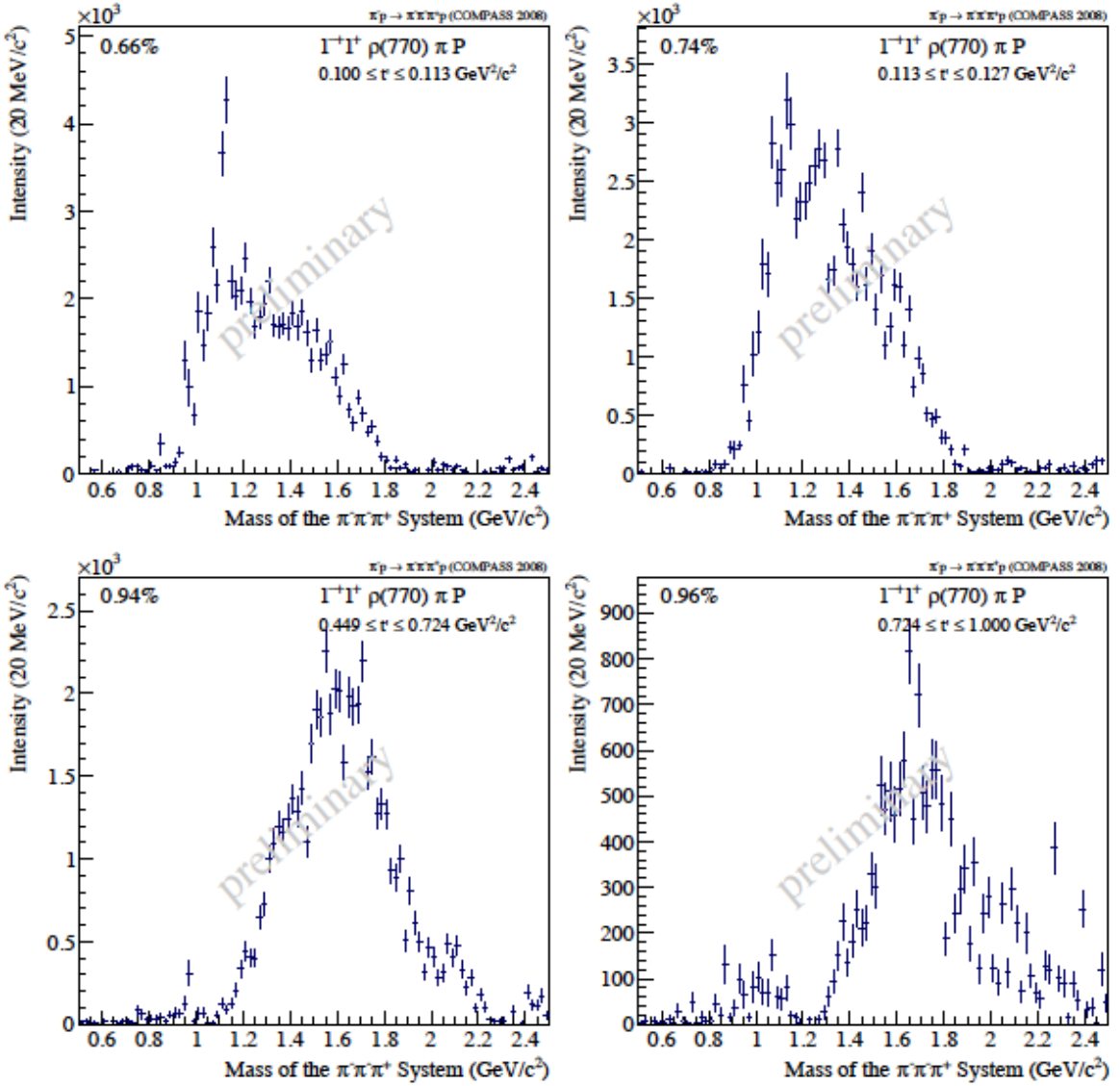
Nature of $a_1(1420)$ still to be understood:

- isospin partner of $f_1(1420)$?
- no quark model state expected at 1.4 GeV/c^2
- ground state $a_1(1260)$ close and wider
- only seen in decays to $f_0(980)\,\pi$, not in $\rho\pi$
- close to $K^*\overline{K^*}$ threshold

submitted to PRL, [hep-ex/1501.05732]

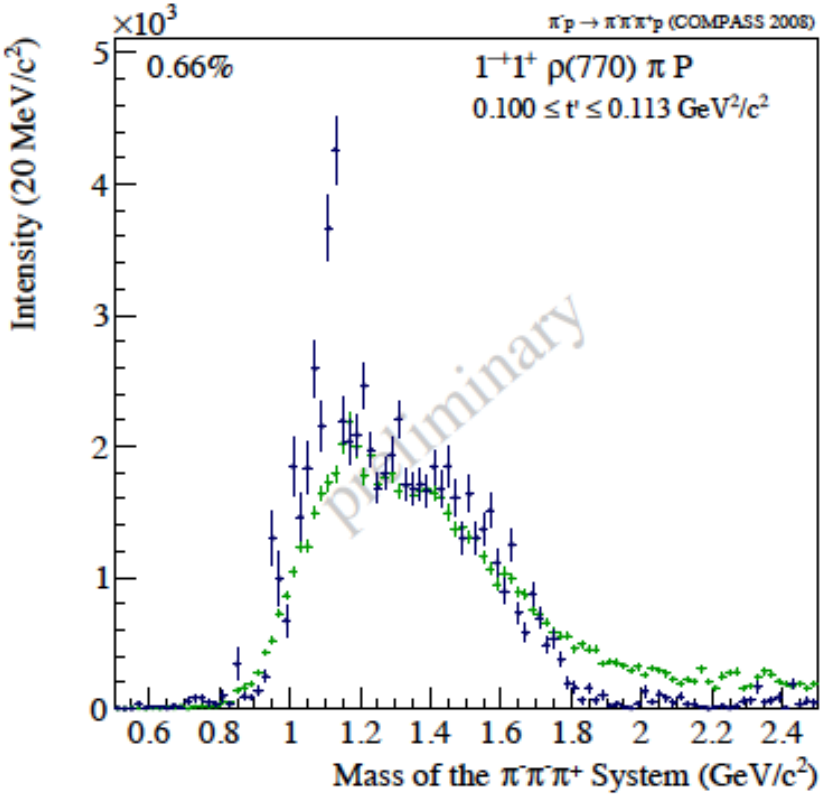
Status of exotic 1^{-+} wave

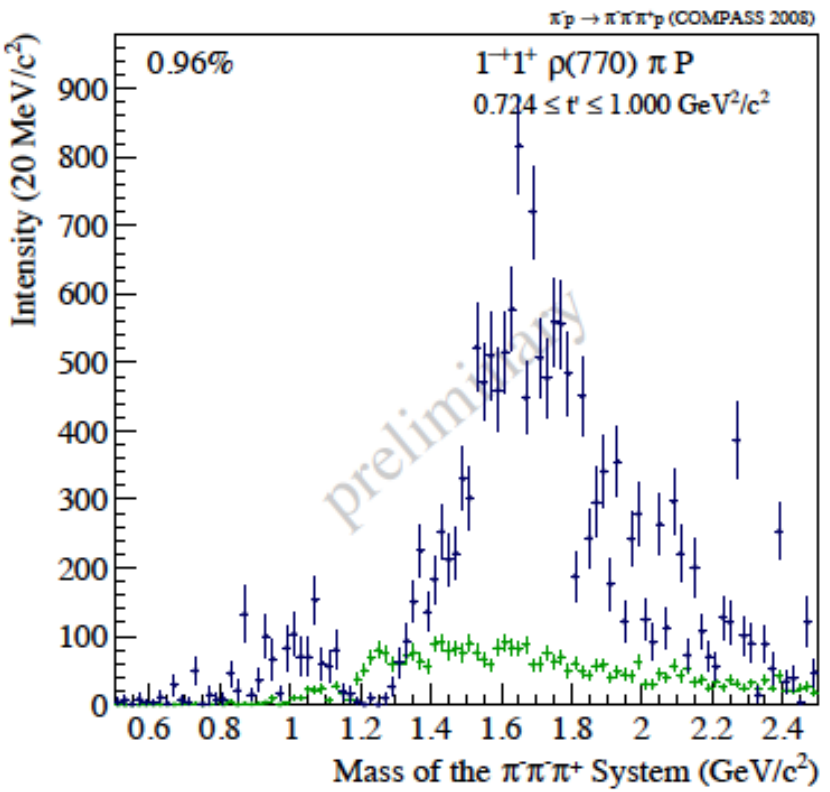




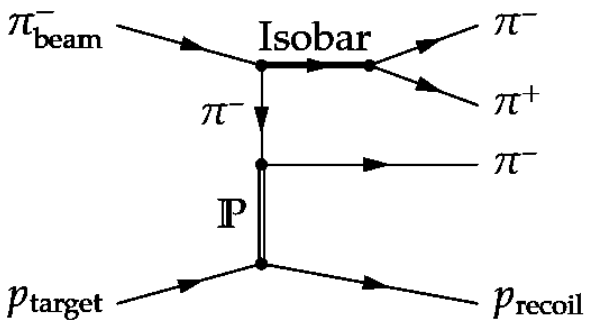
- again, $\pi^-\pi^0\pi^0$ scaled to $\pi^-\pi^+\pi^-$
- some differences between channels
- study in different *t'* bins:
  - peak in high *t'* region
  - structure in low *t'*, non-resonant

Status of exotic 1^{-+} wave

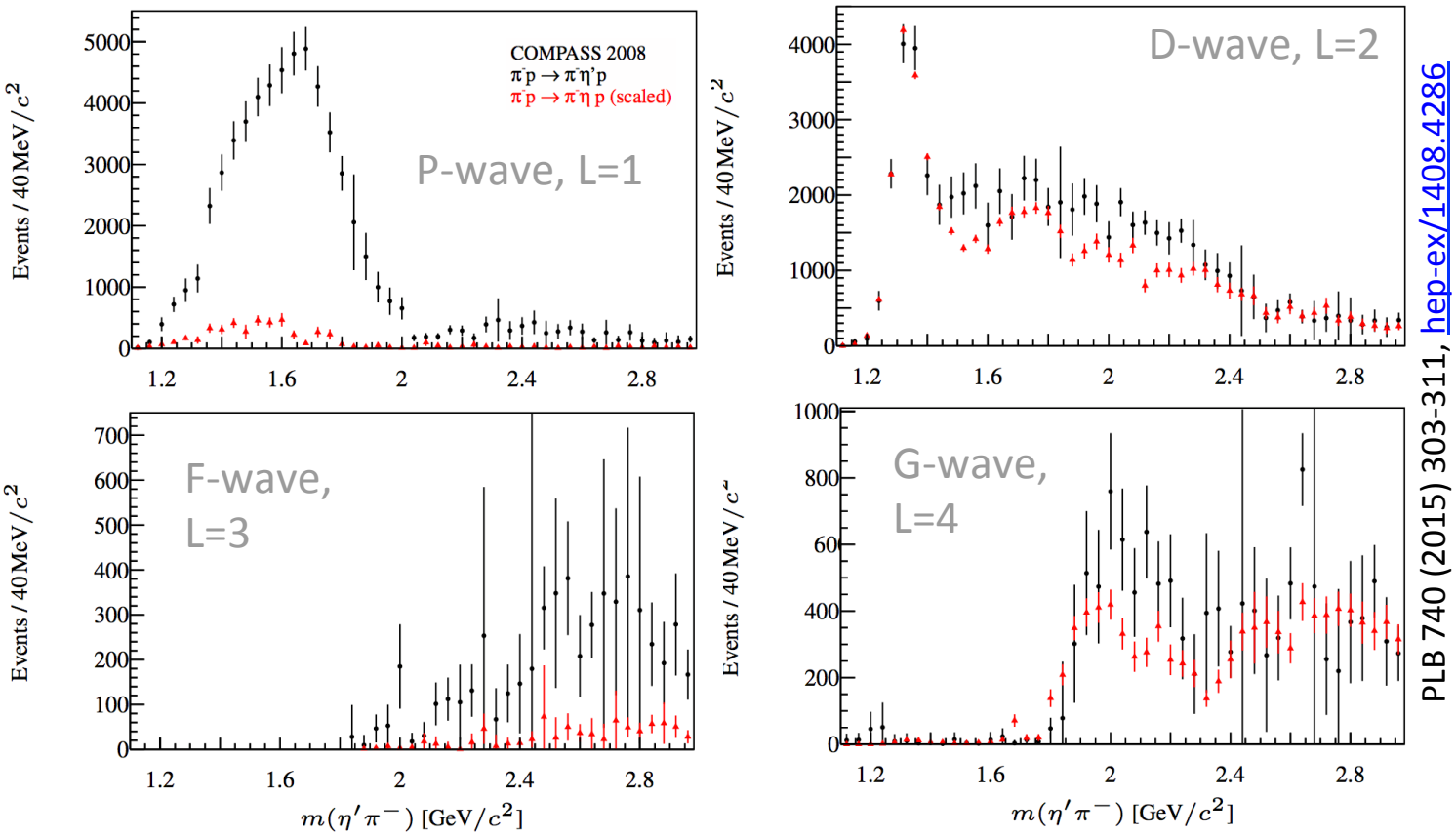




- MC data generated with Deck-amplitude
- analysed like real data and scaled to integrated intensity of each *t'* bins
- to be included in PWA



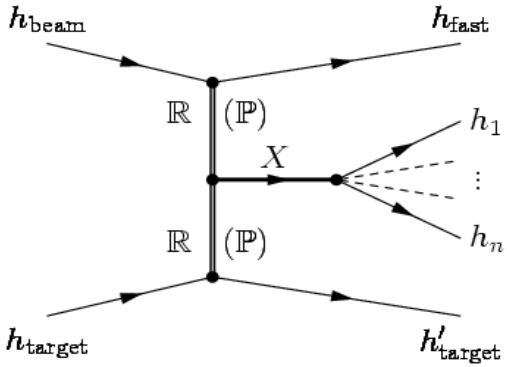
Partial wave analysis πη / πη‘

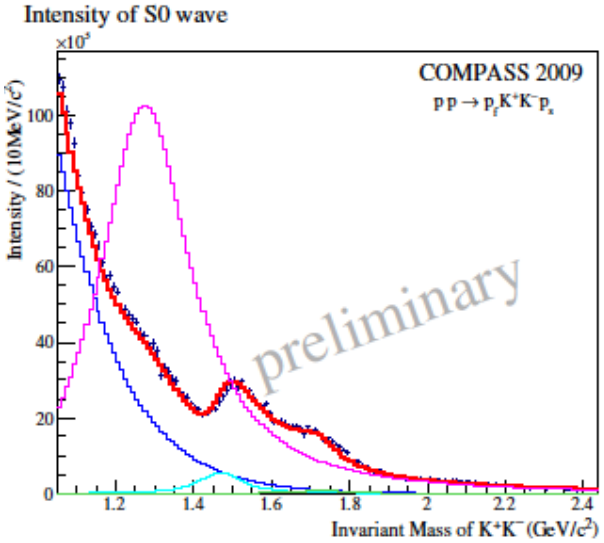


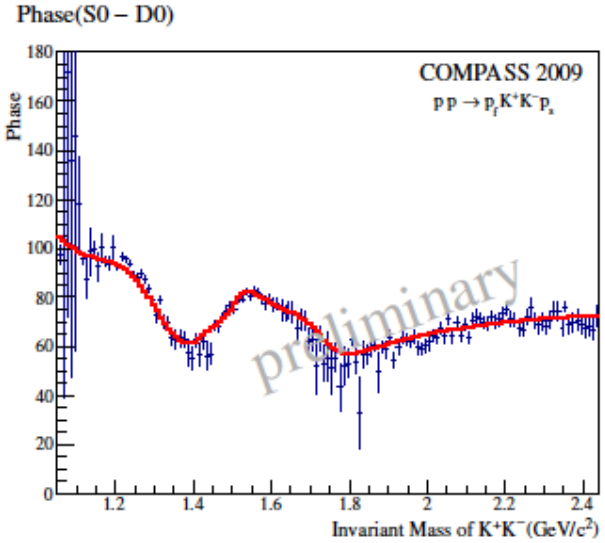
PLB 740 (2015) 303-311, hep-ex/1408.4286

- Even-L waves: similar intensity distributions in η and η’
- Odd-L waves: suppressed in ηπ by factor 5-10
- mass dependent fits highly model dependent

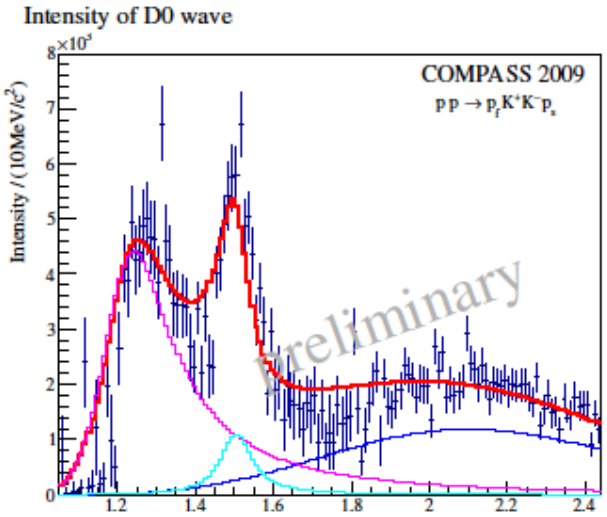
Central Production



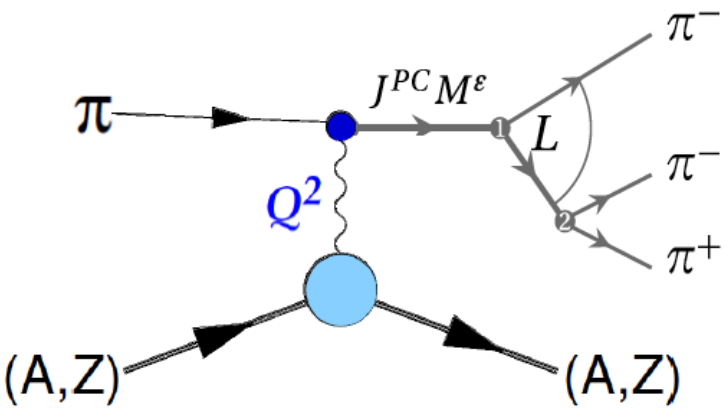




- "glue-rich" process: search for glueballs
- mass-dependent fits with phases available
- $f_0(980)$, $f_0(1500)$, $f_0(1710)$ found, hints for further states beyond 2 GeV/c^2
- analysis to be improved (handling of ambiguities, model dependence)



Very low *t'* region



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

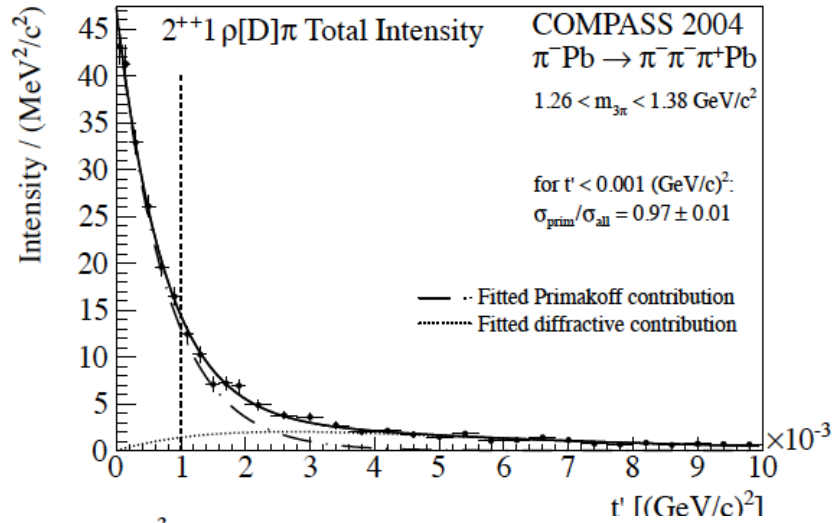
Analysis:

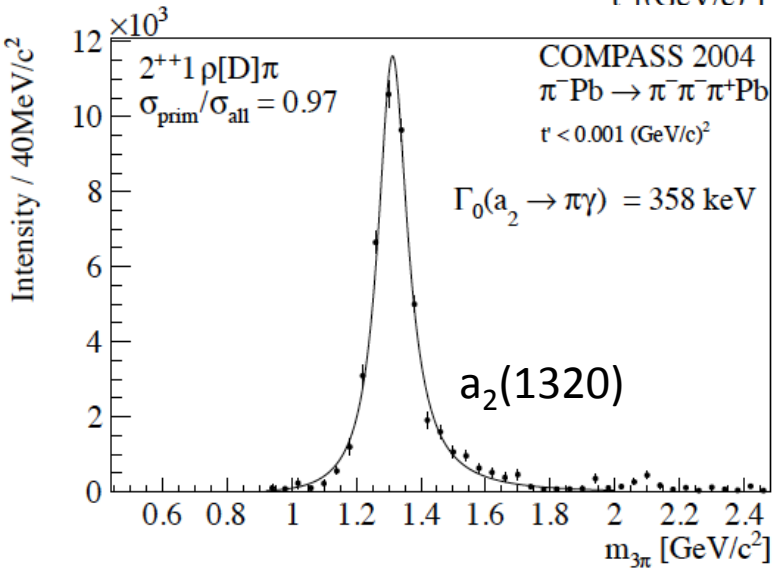
- photo-production (Primakoff): cross section proportional to $e^{-at'}$
- diffractive production: cross section proportional to $(t')^M e^{-bt'}$
- distinguish by spin projection M with partial wave analysis
- include chiral amplitude in PWA instead of isobars for very low masses

Radiative widths

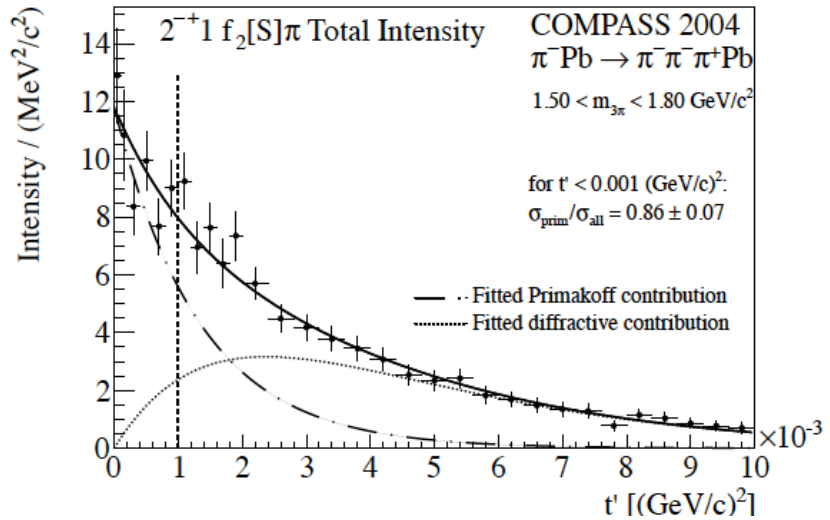
[hep-ex/1403.2644, EPJ A 50 (2014) 79]

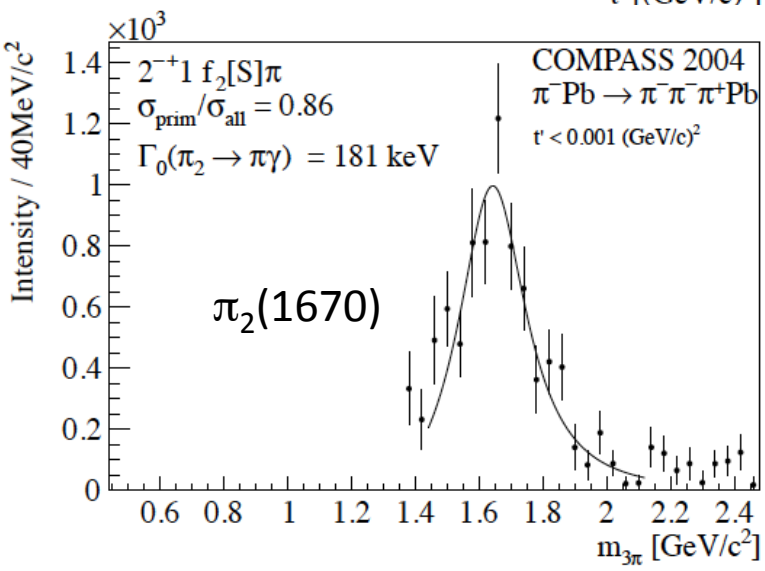
$\Gamma_0(a_2(1320) \to \pi\gamma)$





M2 transition

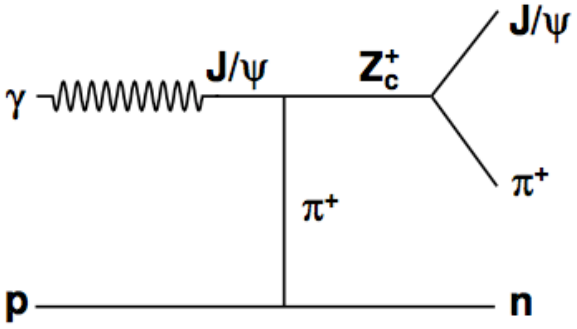




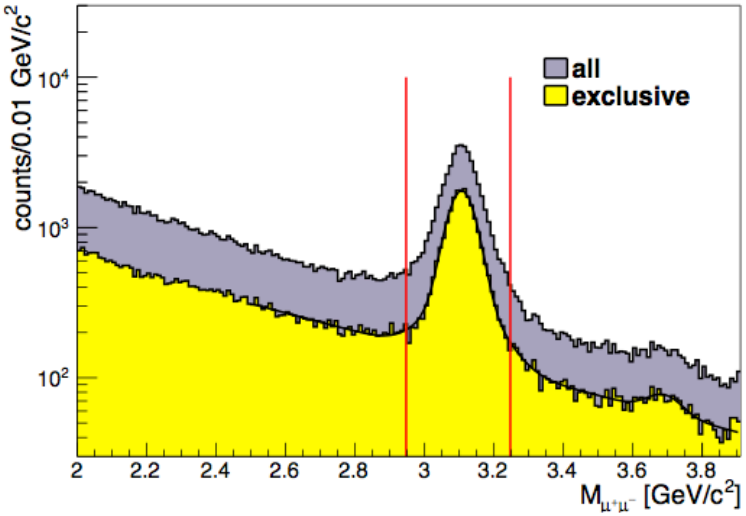
$\Gamma(\pi_2 \to \pi\gamma)$

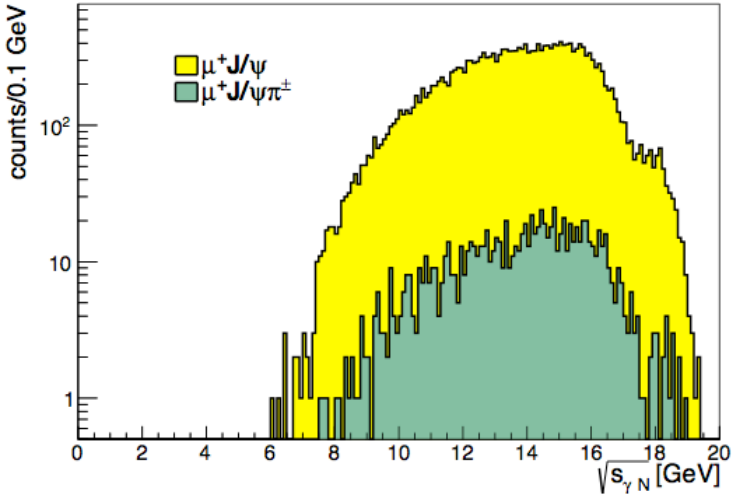
First E2 transition observed for mesons

Search for $Z_c^{\pm}(3900)$

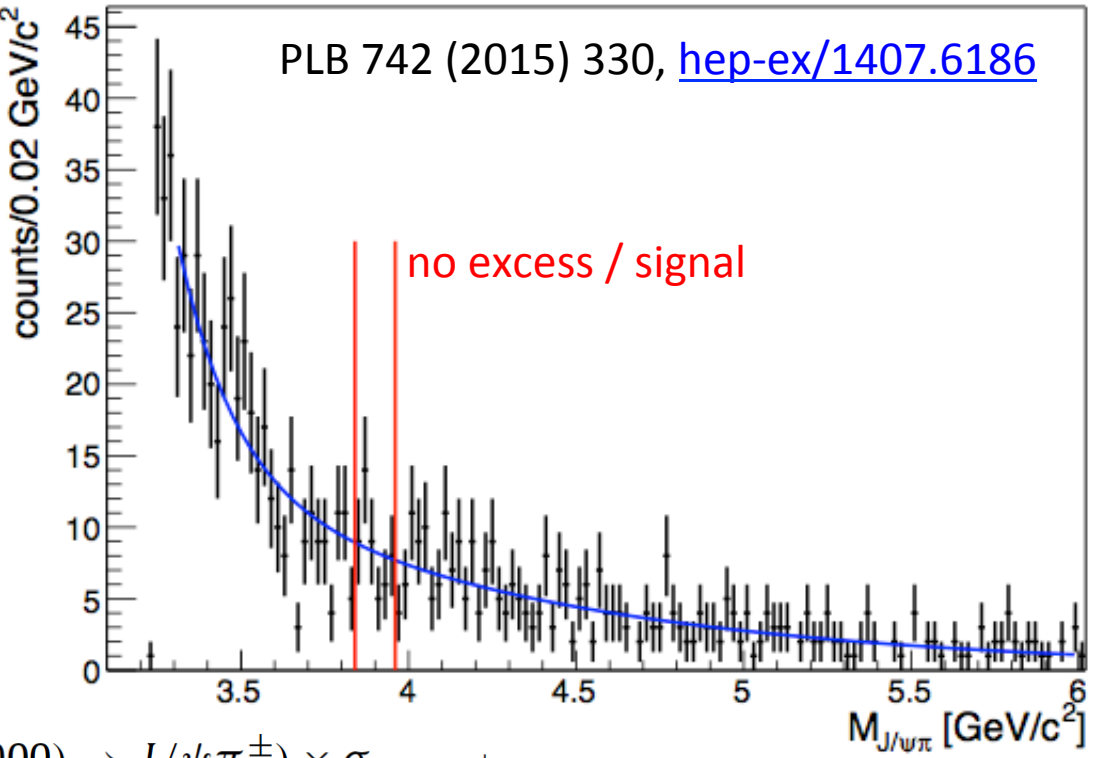


- sizable cross section [Q.-Y. Lin et al., PRD 88 114009 (2013)]
- branching ratio seems to be small
- search with exclusive J/ψ $\pi^{\pm}$, J/ψ -> μμ production in muon beam data
- normalise to μN -> J/ψ N cross section (acceptances cancel largely, only acceptance for $\pi^{\pm}$ left)





Search for $Z_c^{\pm}(3900)$



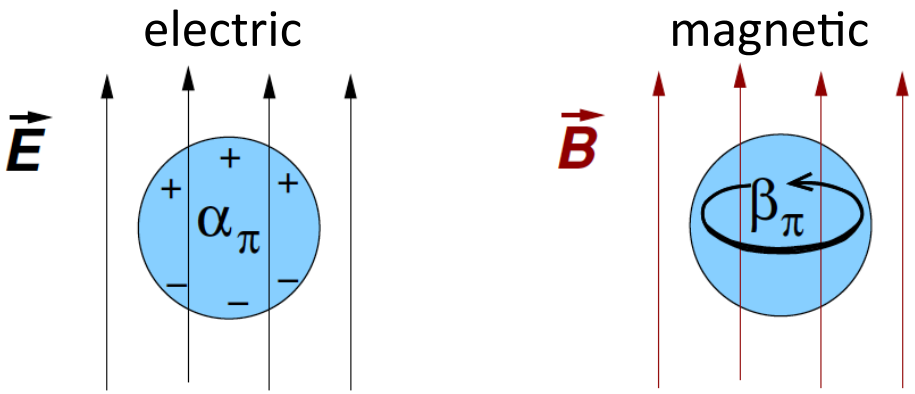
- $\frac{BR(Z_c^{\pm}(3900) \rightarrow J/\psi\pi^{\pm}) \times \sigma_{\gamma N \rightarrow Z_c^{\pm}(3900)N}}{\sigma_{\gamma N \rightarrow J/\psi N}}$ < 3.7 10^{-3}

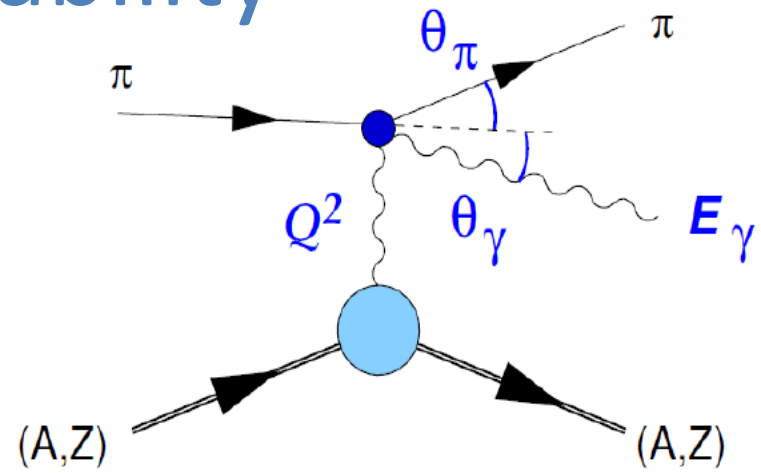
- use NA14 cross section for μN -> J/ψ N for normalisation:

  $BR(Z_c^{\pm}(3900) \rightarrow J/\psi\pi^{\pm}) \times \sigma_{\gamma N \rightarrow Z_c^{\pm}(3900)N}$ < 52 pb

- Conclusion: $Z_c^{\pm}(3900)$ -> > $J/\psi\,\pi^{\pm}$ not dominant decay mode

Pion polarisability

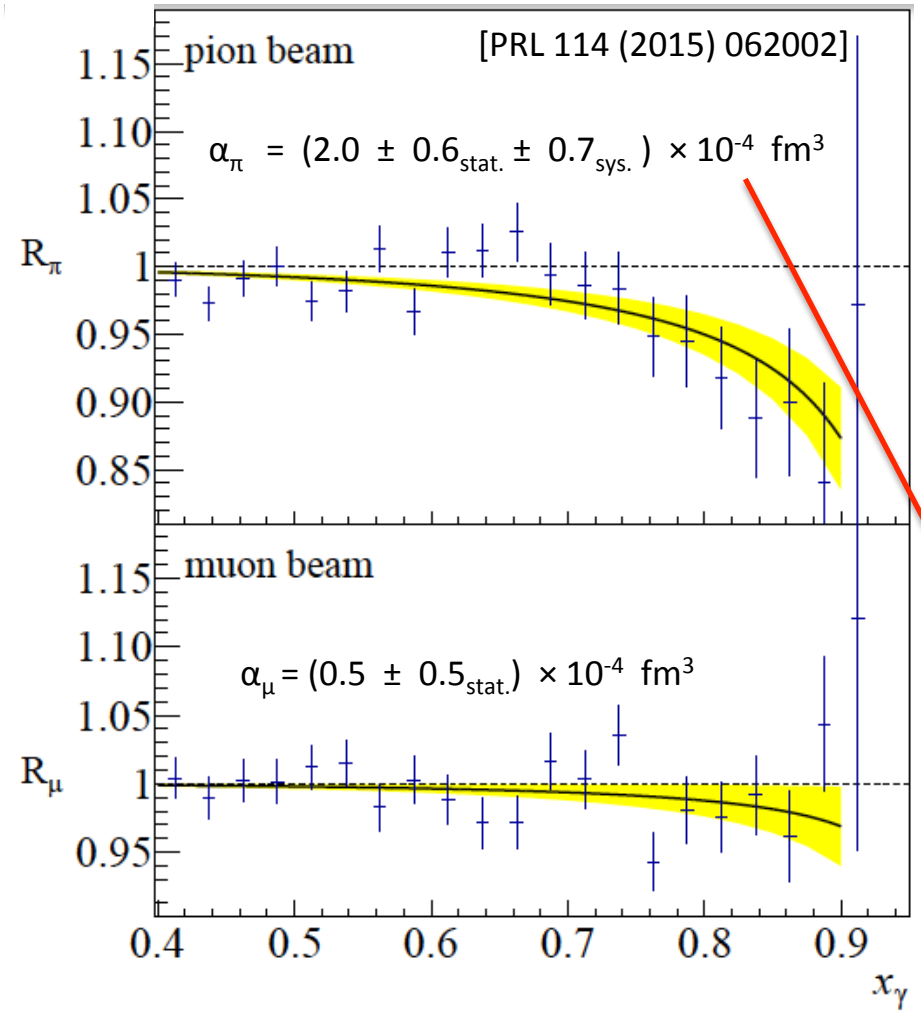


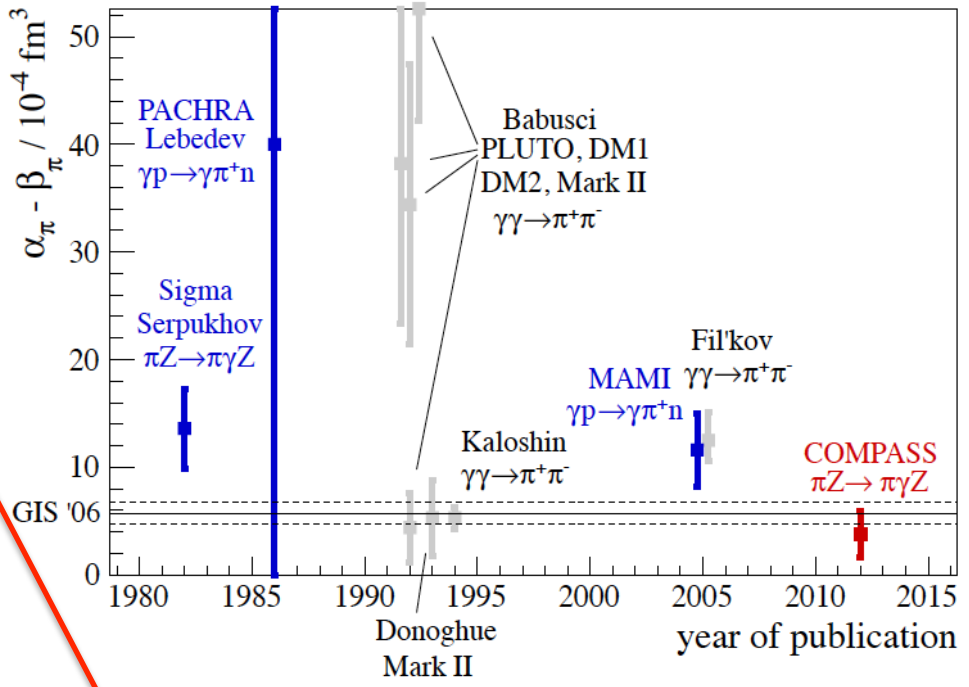


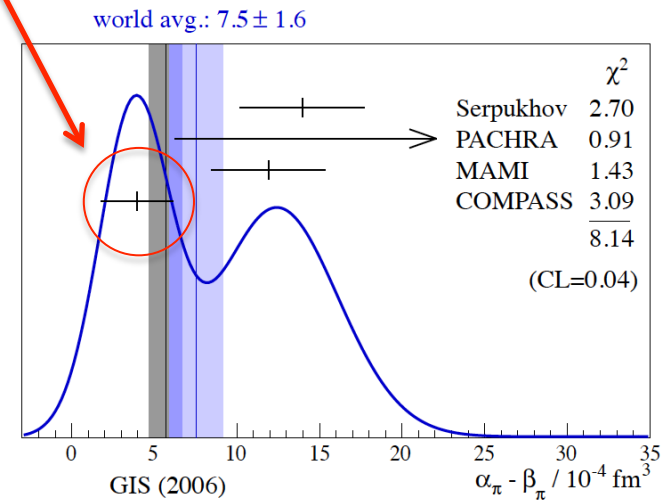
- χPT prediction (2-loop):
  - $\alpha - \beta = (5.7 \pm 1.0)\ 10^{-4}\ \mathrm{fm}^3$
  - $\alpha + \beta = (0.2 \pm 0.1)\ 10^{-4}\ \mathrm{fm}^3$
- Experimental results vary: $\alpha - \beta = (4\ldots14)\ 10^{-4}\ \mathrm{fm}^3$ (assuming $\alpha + \beta = 0$)

- 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



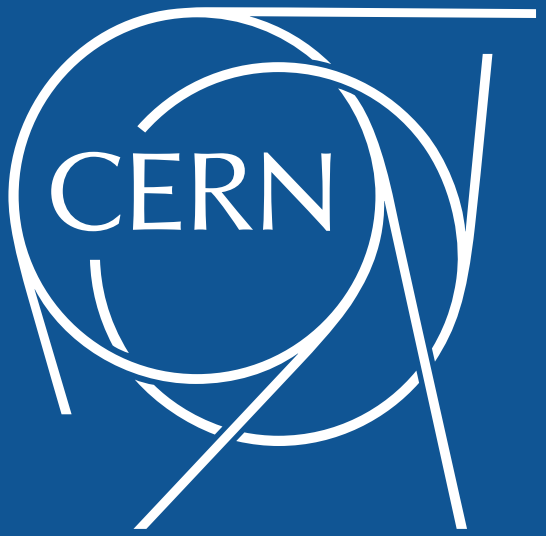




- result confirms χPT prediction
- in tension with former experiments

Conclusions and Outlook

- COMPASS high precision spectroscopy program
- Unchallenged data sets (e.g. $\pi^-\pi^+\pi^-$) 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 χPT 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], baryons, 5π channel, etc.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