Highlights from the COMPASS experiment -- Hadron spectroscopy & excitations

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on behalf of the COMPASS collaboration

4th International Conference on New Frontiers in Physics, ICNFP2015, Kolymbari, Crete, 23rd – 30th August 2015

bmb+f - Förderschwerpunkt COMPASS Großgeräte der physikalischen Grundlagenforschung

Outline

- **Introduction**
  - COMPASS physics adressed
  - The COMPASS experiment
- **Results on hadron excitations**
  - Measurement of pion polarisibility
  - Measurement of chiral dynamics
  - Measurements of radiative widths
- **Results on hadron spectroscopy**
  - Observation of a new axial vector state
  - Search for spin-exotic mesons
  - Search for the $Z_c(3900)$
- **Summary & outlook**

COMPASS: The facility to study QCD

Physics with Muon & Hadron beams

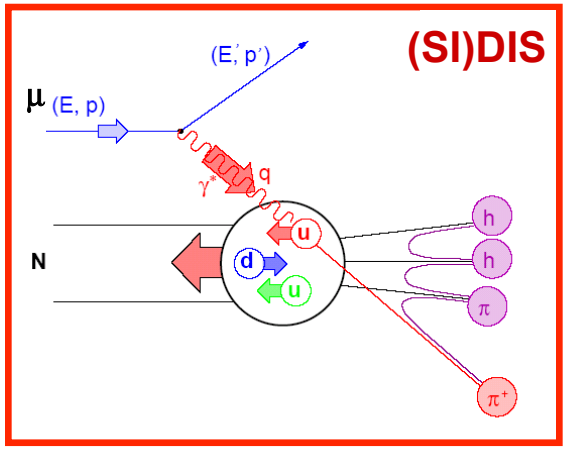
The goal:

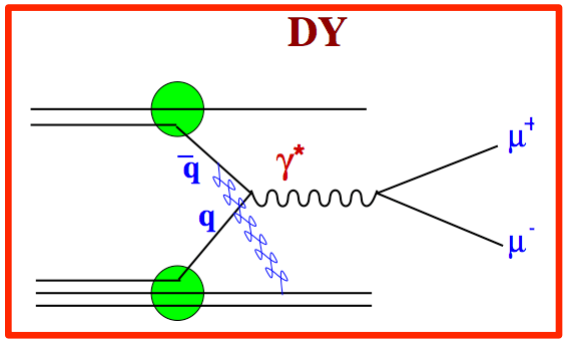
- Study (non-)pertubative regime of QCD & Probe structure and dynamics of hadrons
- Complementary methods:

Large Q^2:

Nucleon structure:

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

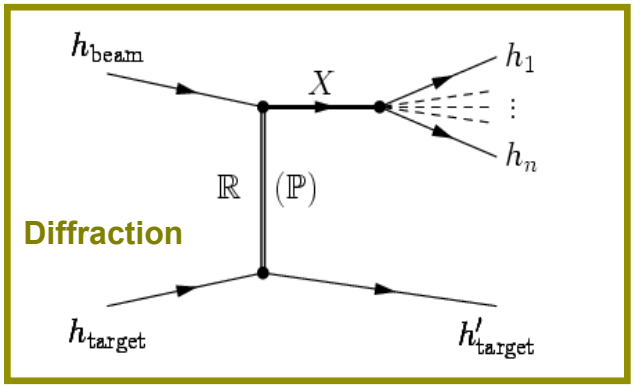


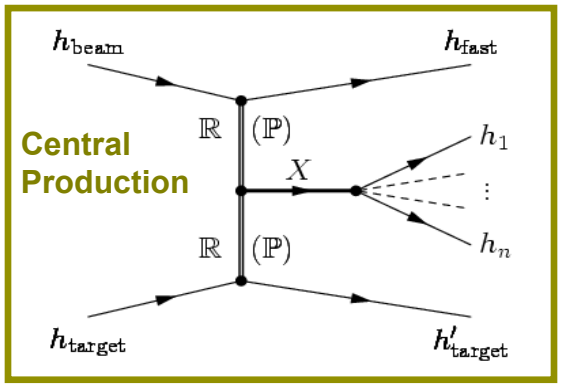


Low Q^2:

Spectroscopy

- Mass spectrum of hadrons
- Gluonic excitations (spin-exotics)

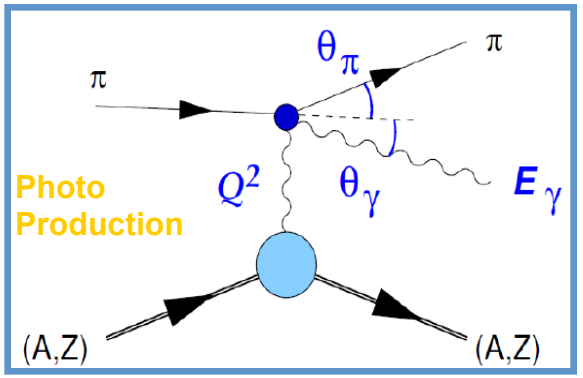




Very low Q^2:

Chiral dynamics

- Pion, Kaon polarisibilities
- Chiral Anomaly $F_{3\pi}$ (future)



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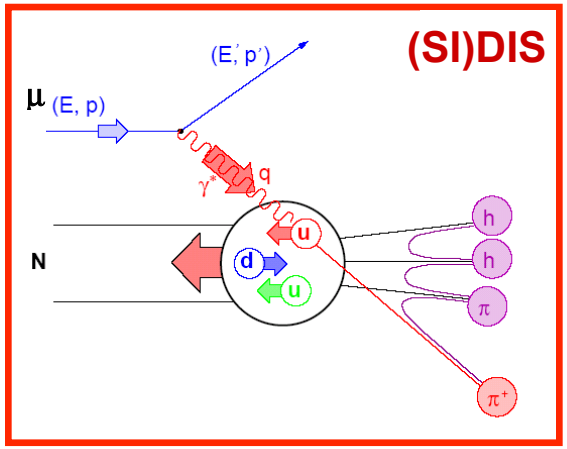

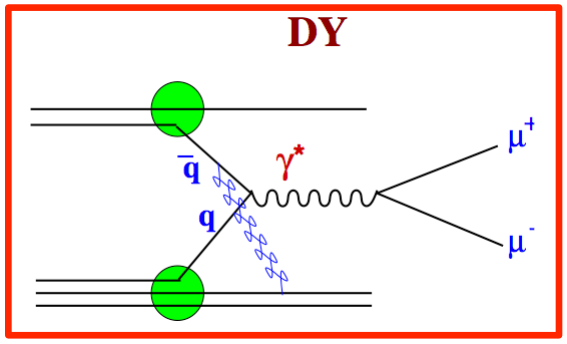

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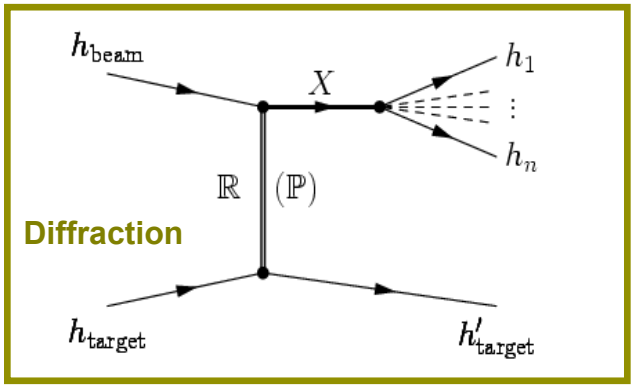

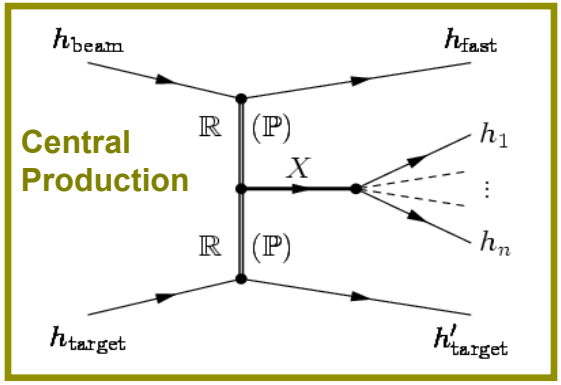

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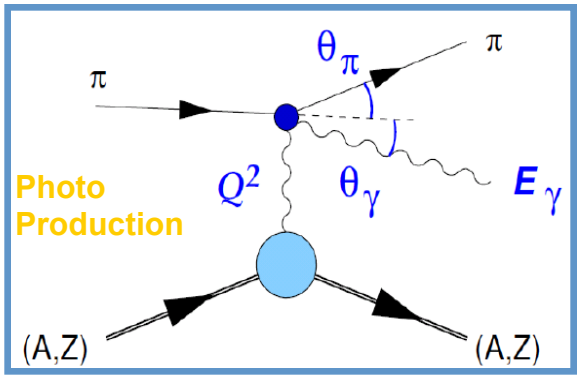
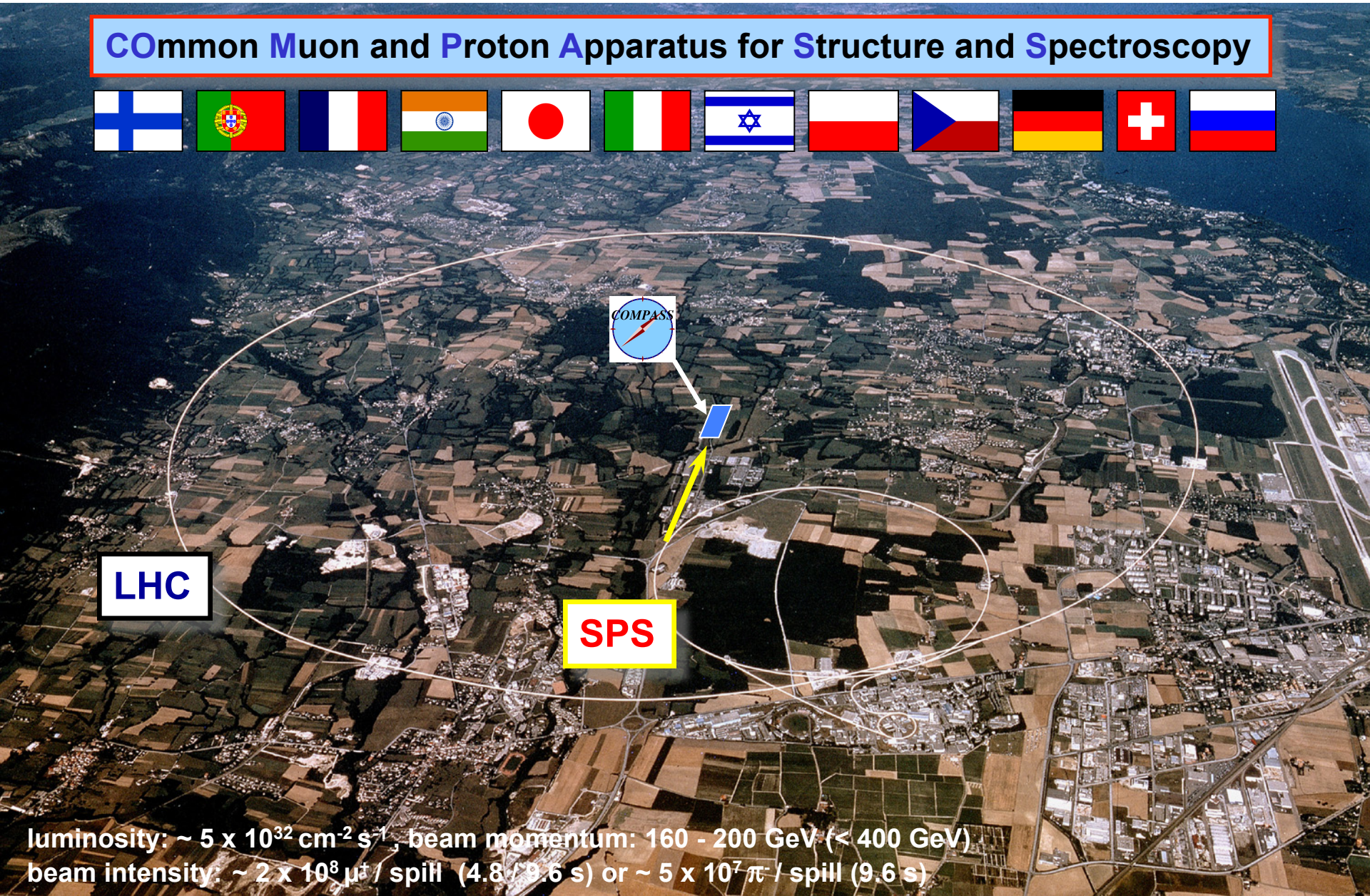


This talk, focus on:

Hadron spectroscopy & excitations

The COMPASS Experiment at CERN

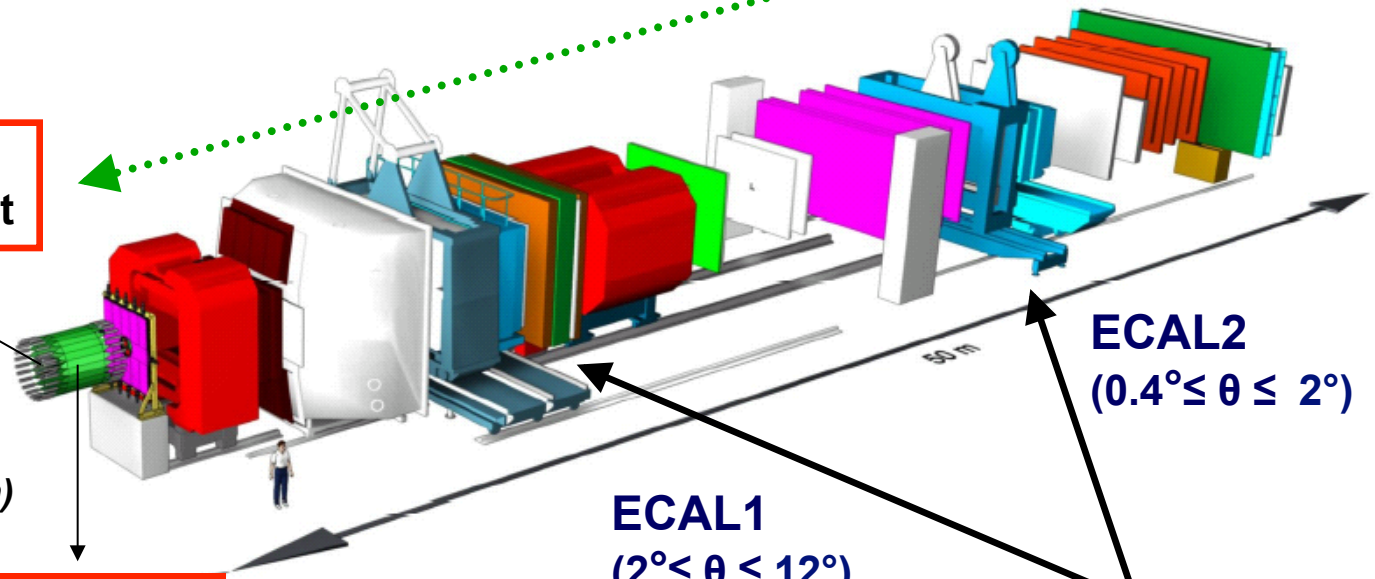
COmmon Muon and Proton Apparatus for Structure and Spectroscopy



luminosity: ~ 5 x 10^{32} cm^{-2} s^{-1} , beam momentum: 160 - 200 GeV (< 400 GeV)
beam intensity: ~ 2 x 10^{8} μ^{+} / spill (4.8 / 9.6 s) or ~ 5 x 10^{7} π^{-} / spill (9.6 s)

COMPASS spectrometer: Hadron setup
(2008/09) -- main changes w.r.t. muon setup

COMPASS trackers (upgraded close to beam):
SciFi, Si, MM, GEM, DC, Straw, MWPC



0.4m
liquid H_2 target

Beam

(muon or hadron)

Recoil detector (RPD)
to trigger on reactions
inside target

ECAL2
($0.4° \leq \theta \leq 2°$)

ECAL1
($2° \leq \theta \leq 12°$)

Electromagnetic calorimeters

PID using
RICH & CEDARs

(final states involving neutrals,
e.g. π^0, η, or η')

Physics with hadron beams

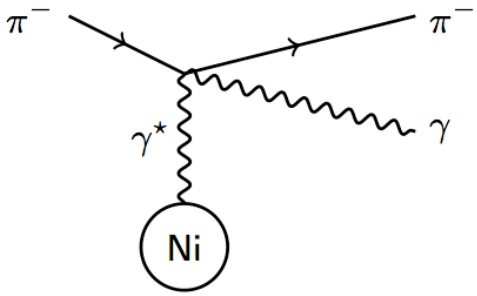
very low Q^2

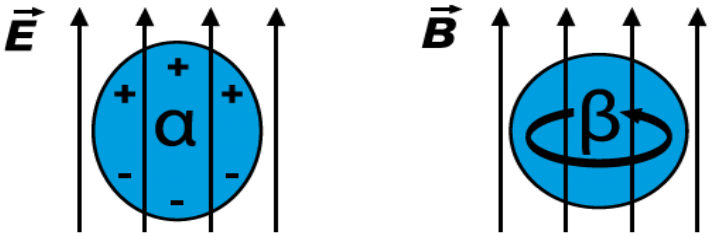
Pion polarisability

Pion in strong electromagnetic field

- Measurement of fundamental pion (kaon) polarisability
- Prediction by χPT: $2\alpha_\pi = \alpha_\pi - \beta_\pi = (5.7 \pm 1.0) \times 10^{-4}$ fm^3

  [J.Gasser et al., Nucl. Phys. B745 (2006) 84]





Measurement

- Deviation of cross-section from expectation for point-like particle
- Experimentally demanding, systematics precisely to be controlled
- Assumption: $\alpha_\pi = -\beta_\pi$
- COMPASS: use pion and muon beam to measure fake-polarisability of the muon to validate simulations

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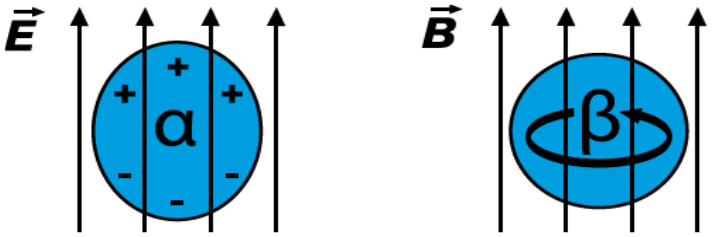

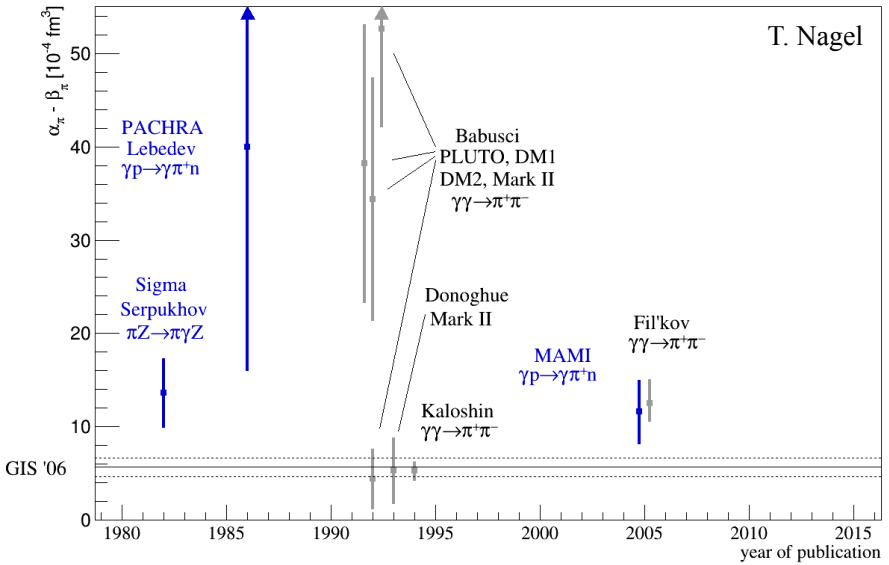

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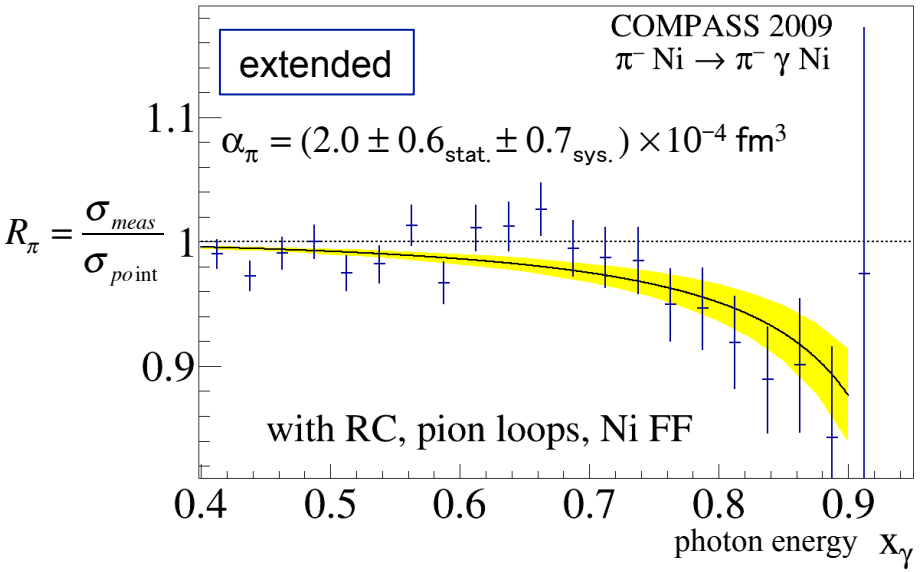
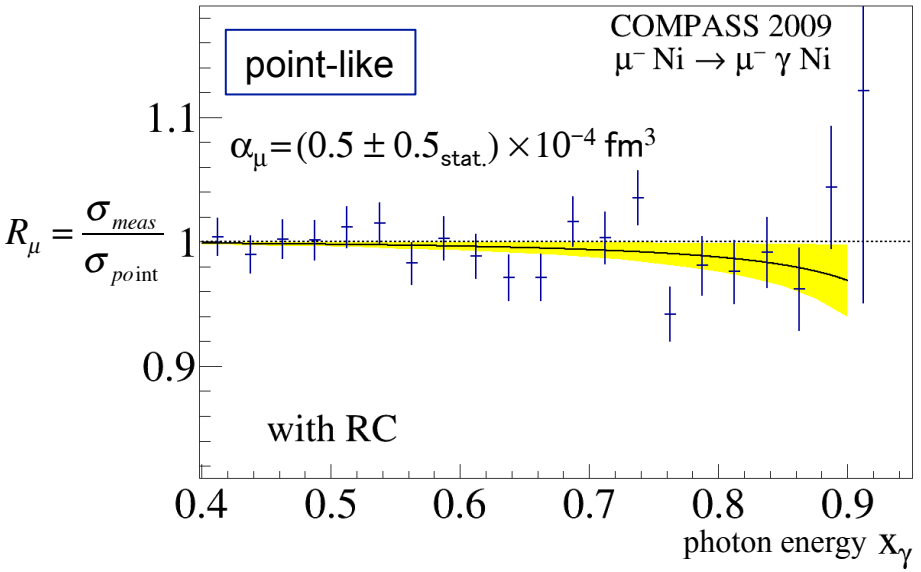
Pion polarisibility

Published in PRL: $\alpha_\pi = (2.0 \pm 0.6_{stat.} \pm 0.7_{sys.}) \times 10^{-4}$ fm^3

- In tension with previous measurements
- In agreement with predictions from χPT





[hep-ex/1405.6377; PRL 114 (2015) 062002]

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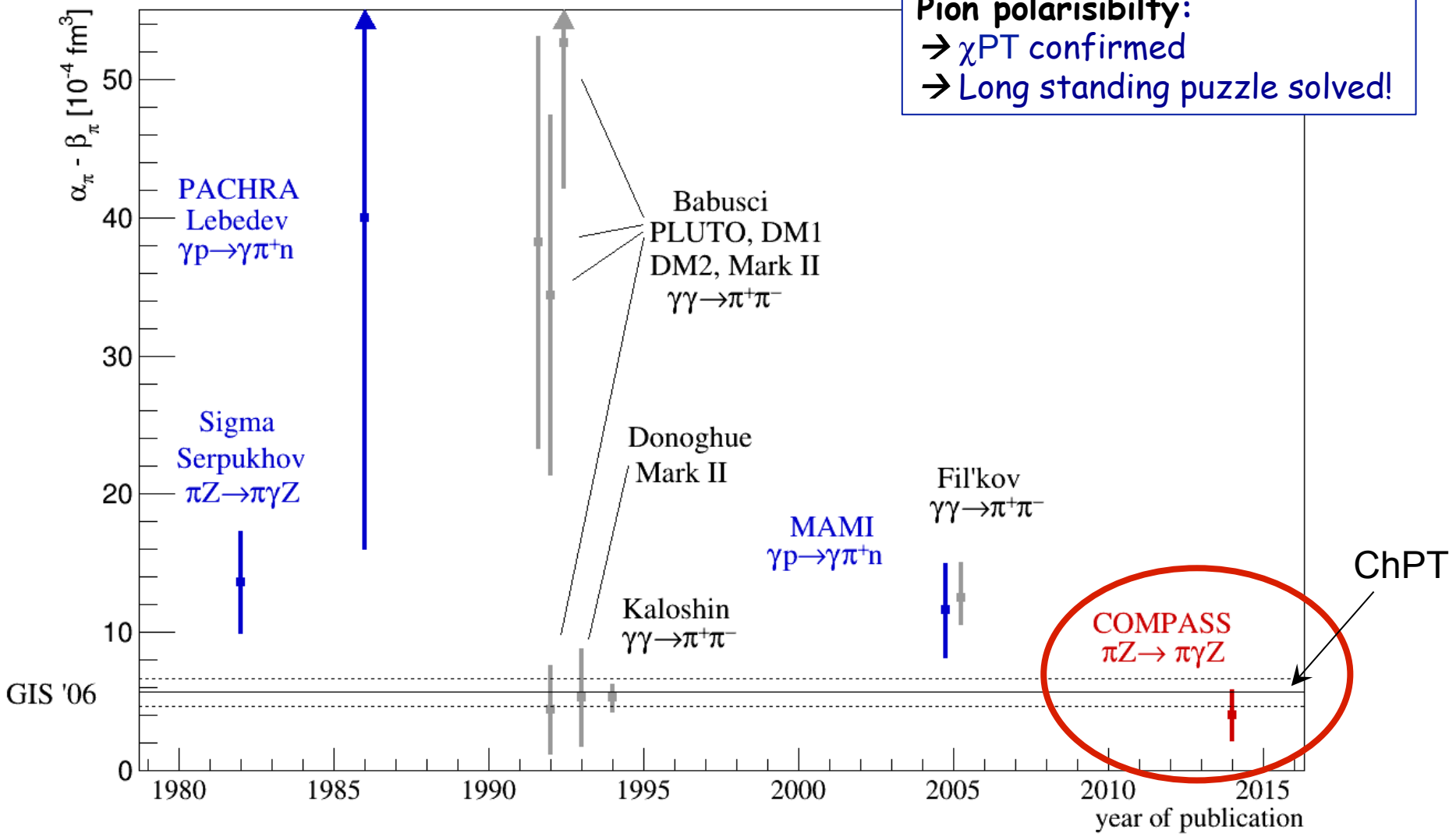
Pion polarisibilty:
→ χPT confirmed
→ Long standing puzzle solved!



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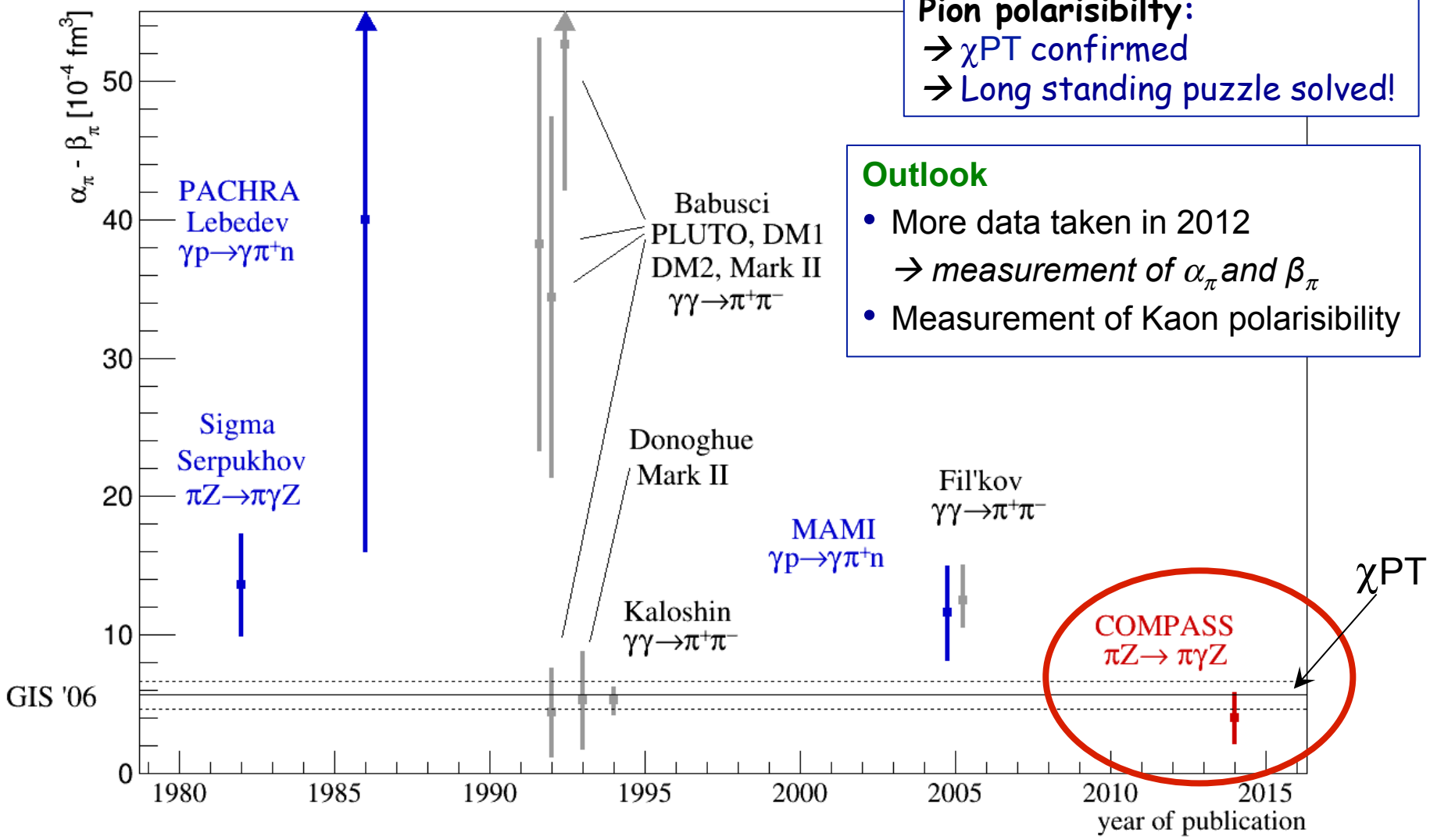

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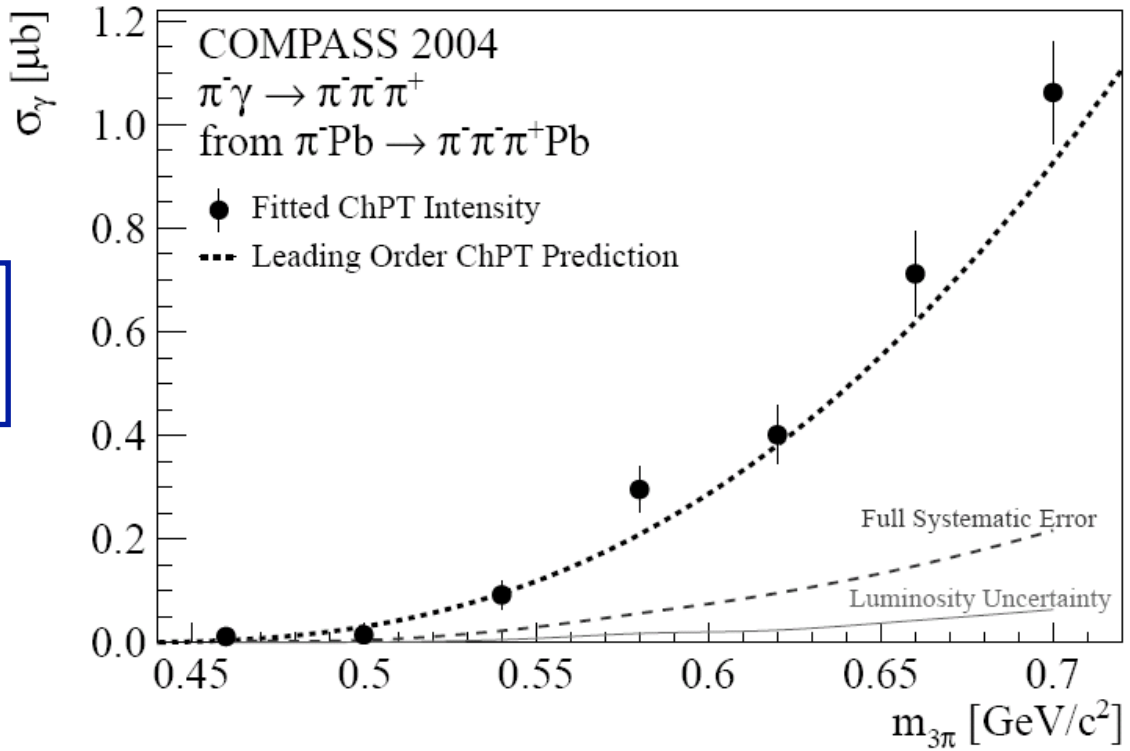
Outlook
- More data taken in 2012
  → *measurement of α_π and β_π*
- Measurement of Kaon polarisibility

Measurement of Chiral dynamics in 3π final states

(Coulomb region, very low momentum transfer t′ < 0.001 GeV²/c²)

PWA including amplitude from χPT calculations substituting isobaric waves at low masses



First measurement of cross-section in this range:

- Results in agreement with LO ChPT calculations
- More data available from 2009 run (Ni target)

[hep-ex/1111.5954, PRL 108 (2012) 192001]

Measurement of radiative widths

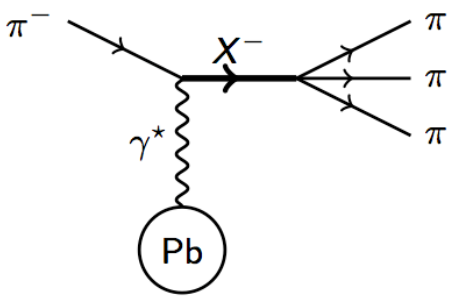
- Access to electromagnetic transitions via decay $X \to \pi\gamma$
  - $a_2(1320) \to \pi\gamma$ magnetic quadrupole moment
  - $\pi_2(1670) \to \pi\gamma$ electric quadrupole moment

- Direct measurement of $\pi\gamma$ experimentally challenging
- Inverse process: scattering of a pion off a Coulomb potential
  - quasi-real photons in the vicinity of heavy nuclei

- Cross-section for Primakoff produced X
  - $\sigma_{\text{Primakoff, X}} \sim \Gamma_0(X \to \pi\gamma)$

$$\Gamma_0(X \to \pi\gamma) = \frac{N_{X,\text{prim}}/\epsilon_X}{C_X \cdot L \cdot \text{CG} \cdot \text{BR} \cdot \epsilon_{\text{resol}}}$$

$$\pi^- Pb \to \pi^-\pi^-\pi^+ Pb$$



Identify Primakoff contribution: $\pi^-\gamma \to \pi^-\pi^-\pi^+$

- Primakoff produced states have spin projection M=1
- Cross-section for diffractively produced states

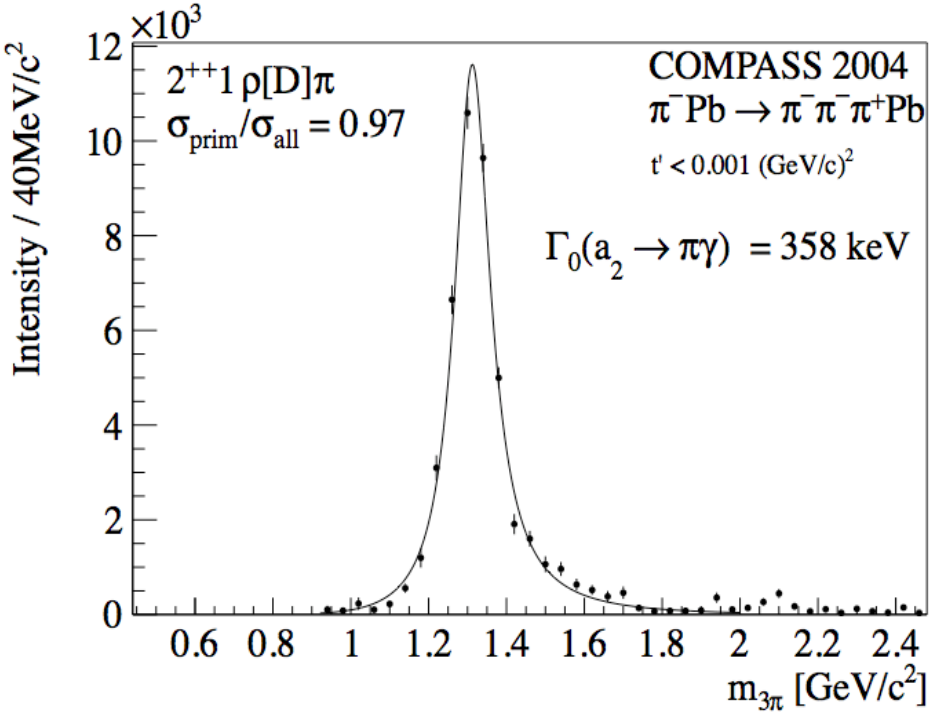
$$\sigma \sim t'^{M} e^{-bt'}$$

- at small t', states with M=1 predominantly Primakoff produced
- Partial-wave analysis to identify states with M=1
- Count number of final states to get cross-section

Measurement of radiative widths -- $a_2(1320)$
M2 transition

Theoretical predictions

- Vector Meson Dominance Model
  375 keV (Rosner, 1981)
- Relativistic Quark Model
  324 keV (Aznauryan & Ogamesyan, 1988)
- Covariant Oscillator Quark Model
  235 keV (Ishida et al., 1989)



Experimental measurements

- SELEX (2001): (284 ± 25 ± 25) keV
- E272 (1982): (295 ± 60) keV
- May et al. (1977): (460 ± 110) keV

COMPASS: (358 ± 6 ± 42) keV

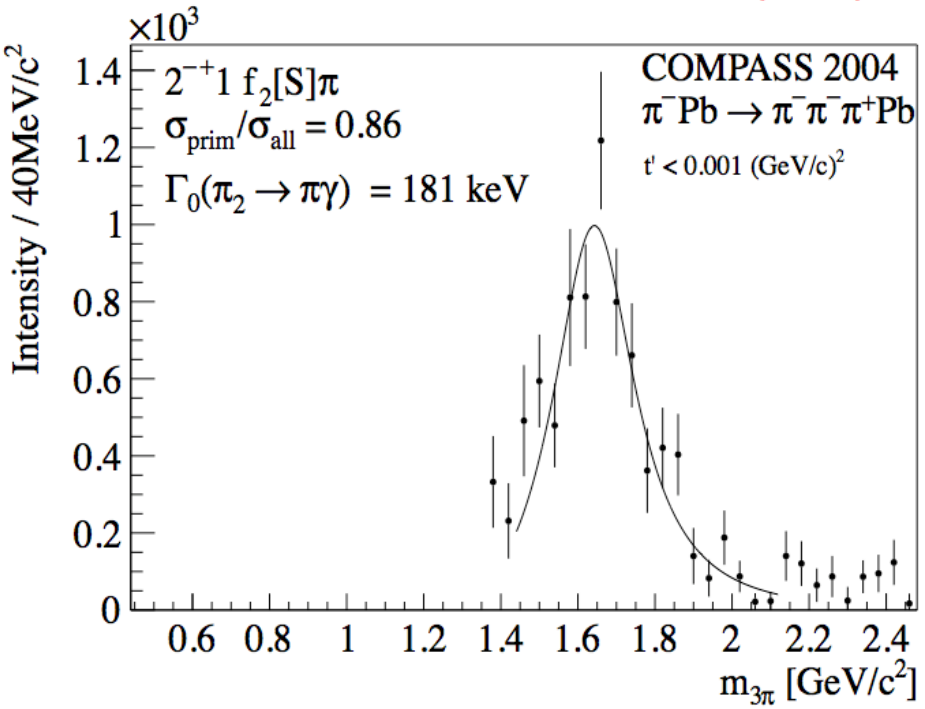
EPJ A Highlight 2014

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

Measurement of radiative widths -- $\pi_2(1670)$
E2 transition

Theoretical predictions

- Covariant Oscillator Quark Model
  335 keV and 521 keV
  (both in Maeda et al., 2013)



Experimental measurements

- First measurement by COMPASS

COMPASS: (181 ± 11 ± 27) keV

EPJ A Highlight 2014

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Physics with hadron beams
low Q^2

Mesons and Spin Exotic States

Constituent quark model

- Color neutral $q\bar{q}$ systems
- Quantum numbers $I^G J^{PC}$
- $P = (-1)^{L+1}$ $C = (-1)^{L+S}$ $G = (-1)^{I+L+1}$
- J^{PC} *multiplets:* $0^{++}, 0^{-+}, 1^{--}, 1^{+-}, 1^{++}, 2^{++}, \ldots$
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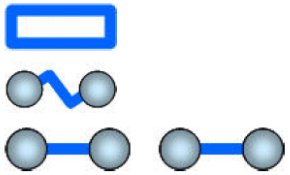
QCD: meson states beyond

- Glue-balls: gg, ggg
- Hybrids: $q\bar{q}g$
- Tetraquarks: $(q\bar{q})(q\bar{q})$



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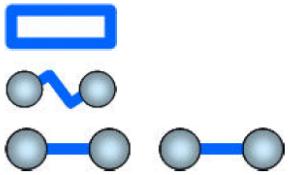
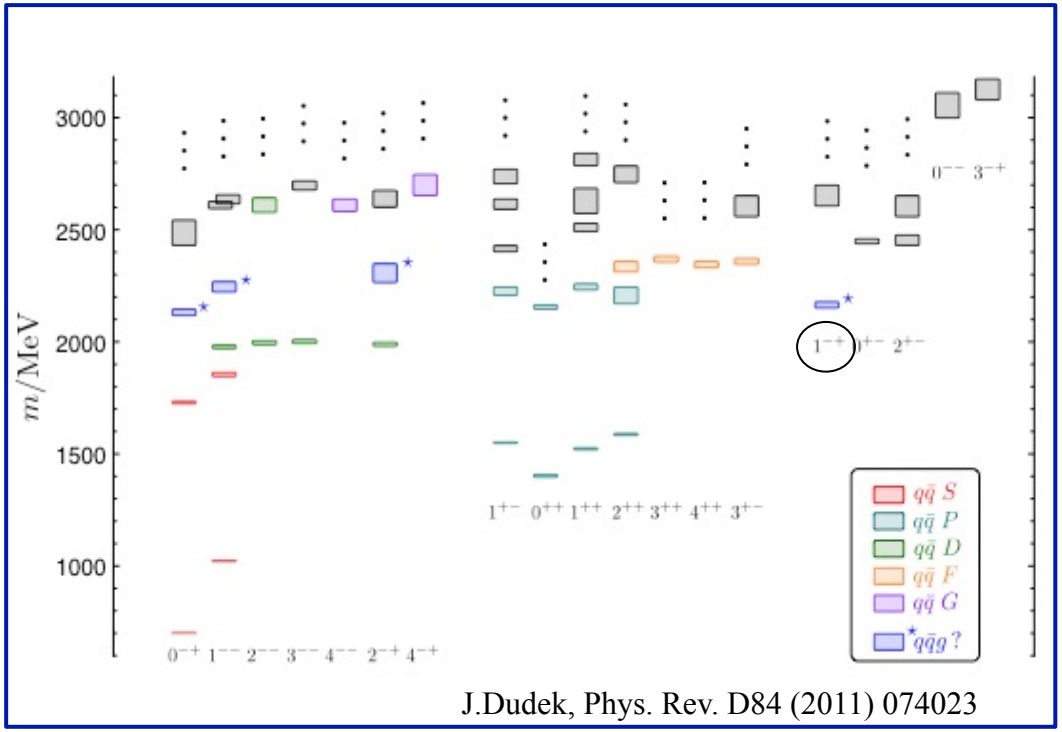


Lattice calculations:

- Constituent quark states
- Exotic mesons
- Light hybrid, exotic $J^{PC} = 1^{-+}$



J.Dudek, Phys. Rev. D84 (2011) 074023

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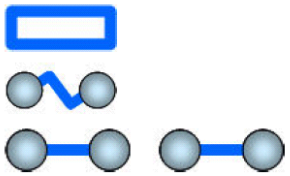

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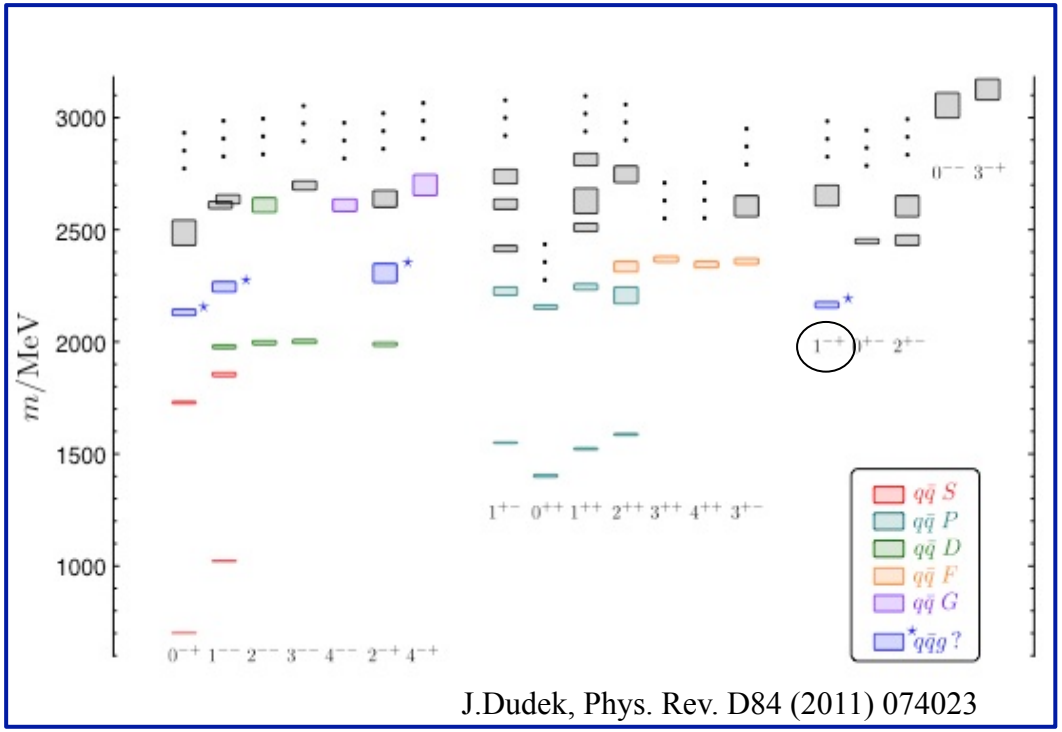

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Experiment (1.3 - 2.2 GeV/c²):

Hybrid candidates, exotic $J^{PC} = 1^{-+}$

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

…. still controversial → COMPASS

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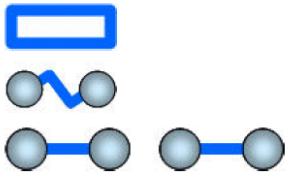

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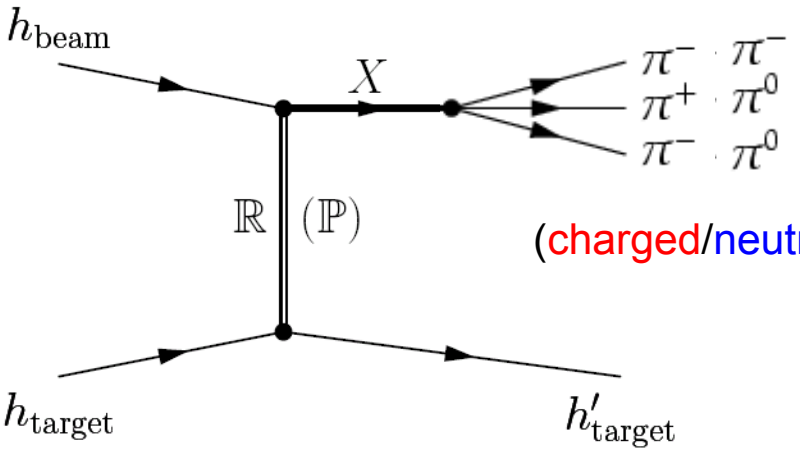
Diffractive production of e.g. 3π



(charged/neutral)

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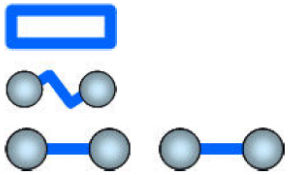

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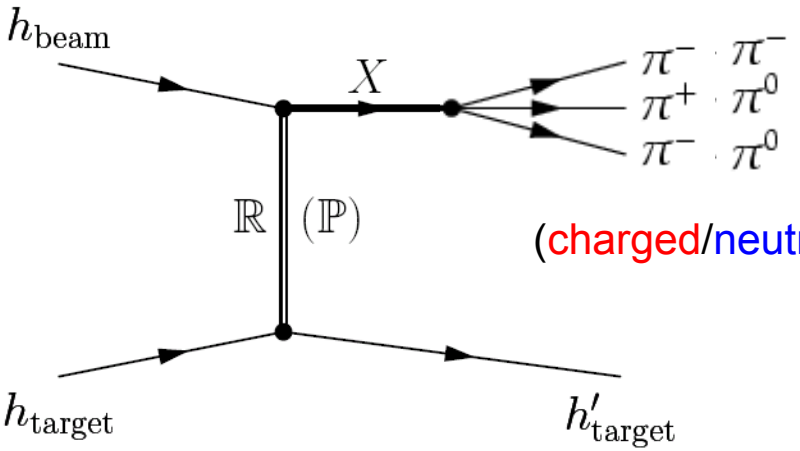
…. still controversial → COMPASS

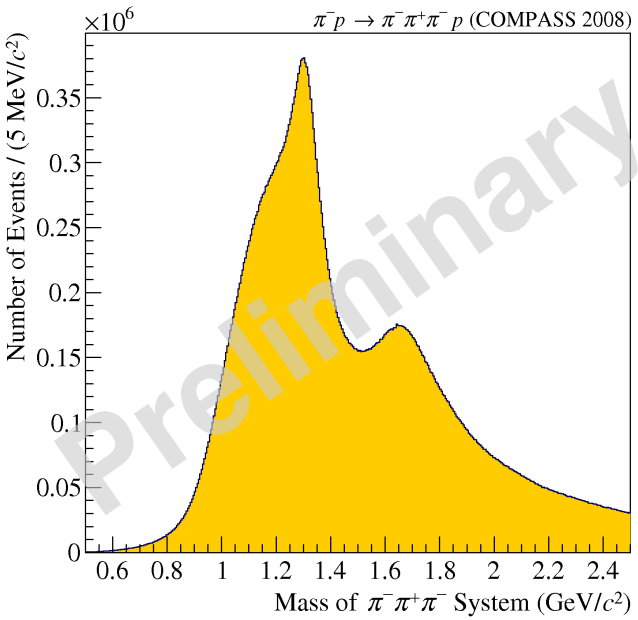
Diffractive production of e.g. 3π



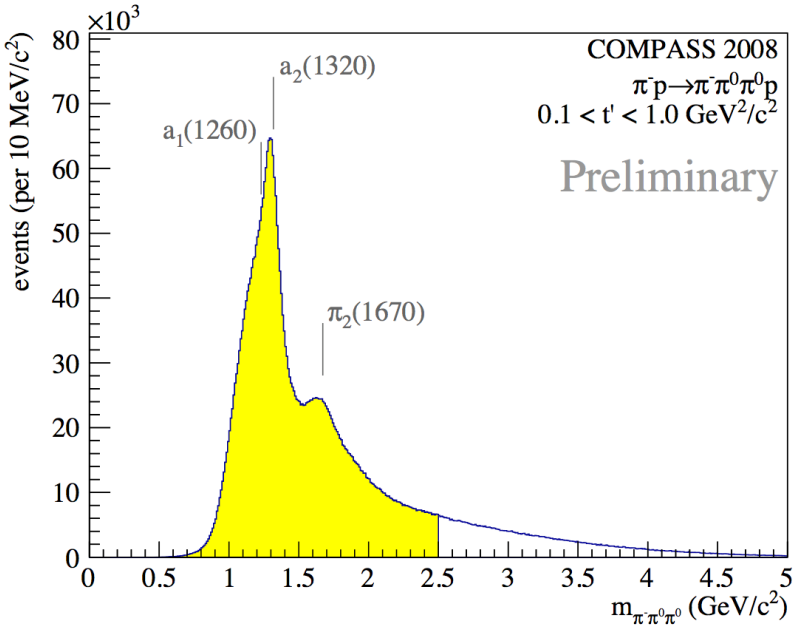
(charged/neutral)

Diffractive dissociation into 3π final states
(2008 data, proton target)

Mass of outgoing 3π system – charged mode: $\pi^- p \rightarrow \pi^-\pi^+\pi^- p$



Mass of outgoing 3π system – neutral mode: $\pi^- p \rightarrow \pi^-\pi^0\pi^0 p$



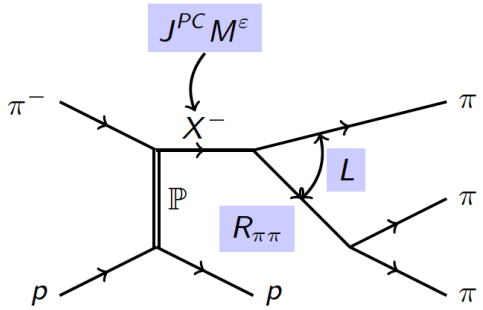
PWA: ~ 50M events

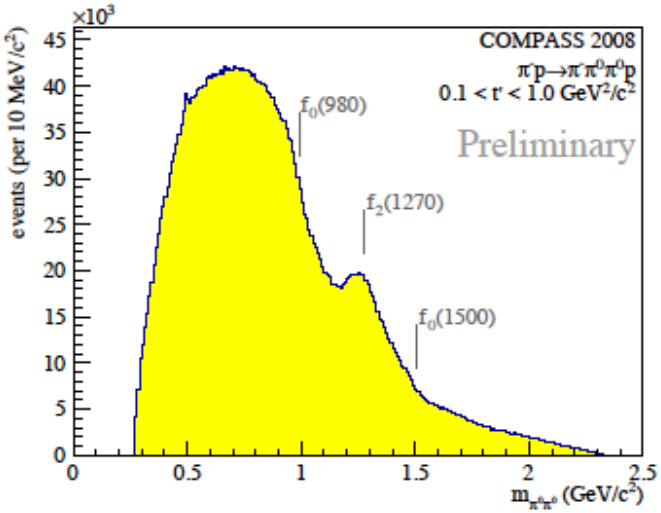
PWA: ~ 3.5M events

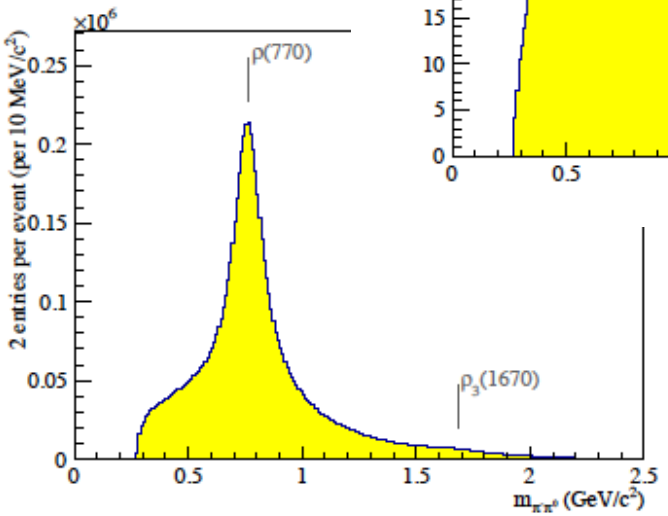
COMPASS PWA Method

Partial wave analysis (isobar model):

- **Isobars:** All possible, needed isobars, 88 partial-waves
- **Acceptance:** Corrections included (normalisation integrals)







Step 1) PWA in mass and t' bins

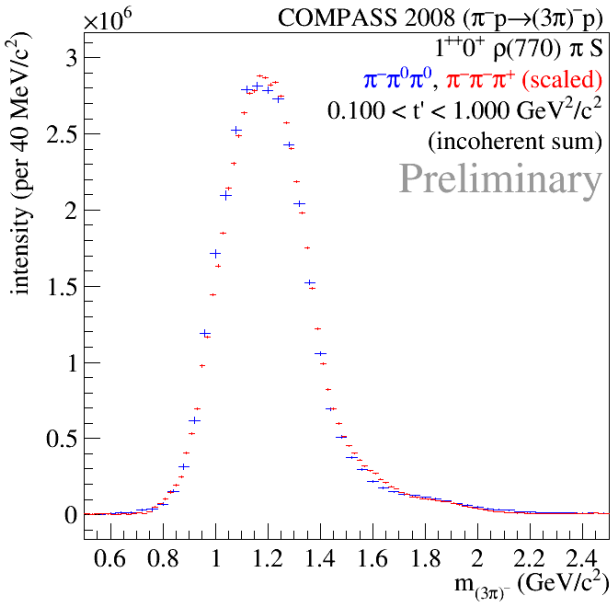
- Extract production amplitudes

Step 2) χ^2 fit of mass dependence of spin density matrix:

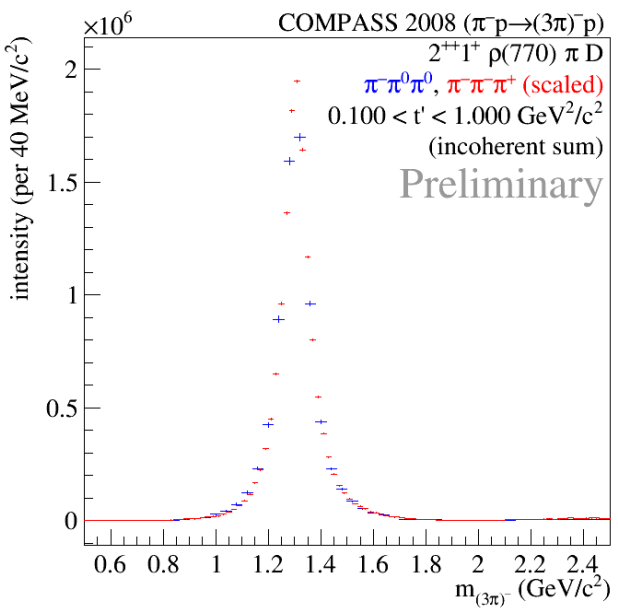
- Applied to 1st step result
- Main partial waves chosen, parameterised by Breit-Wigner
- Non-resonant background for some waves

Comparison neutral vs. charged mode
-- the 3 most prominent resonances

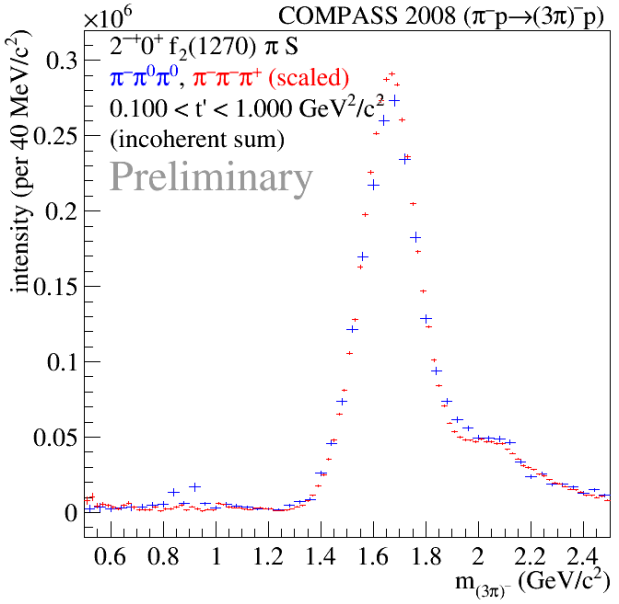
$a_1(1260) \rightarrow \rho\pi$



$a_2(1320) \rightarrow \rho\pi$



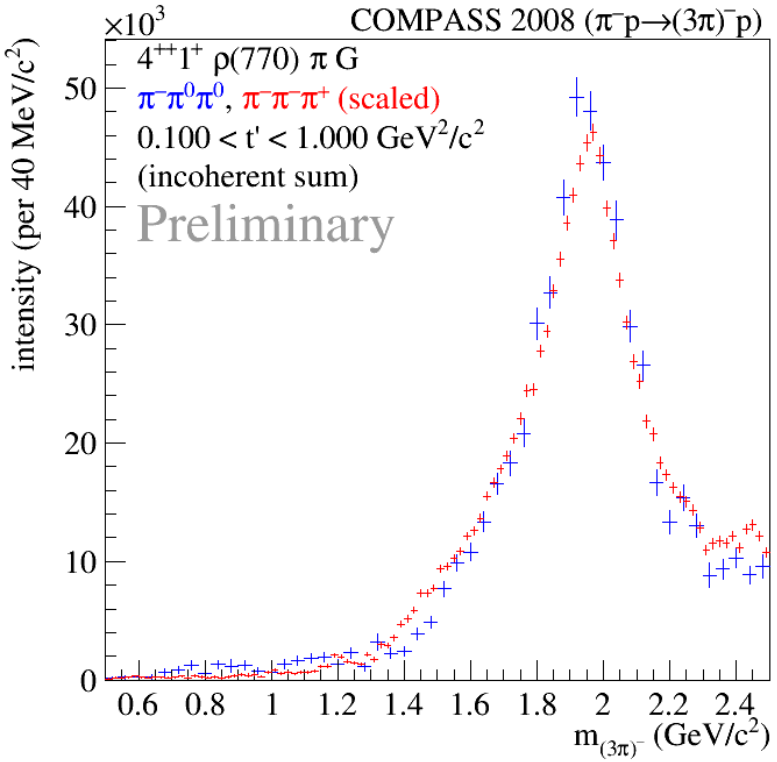
$\pi_2(1670) \rightarrow f_2\pi$



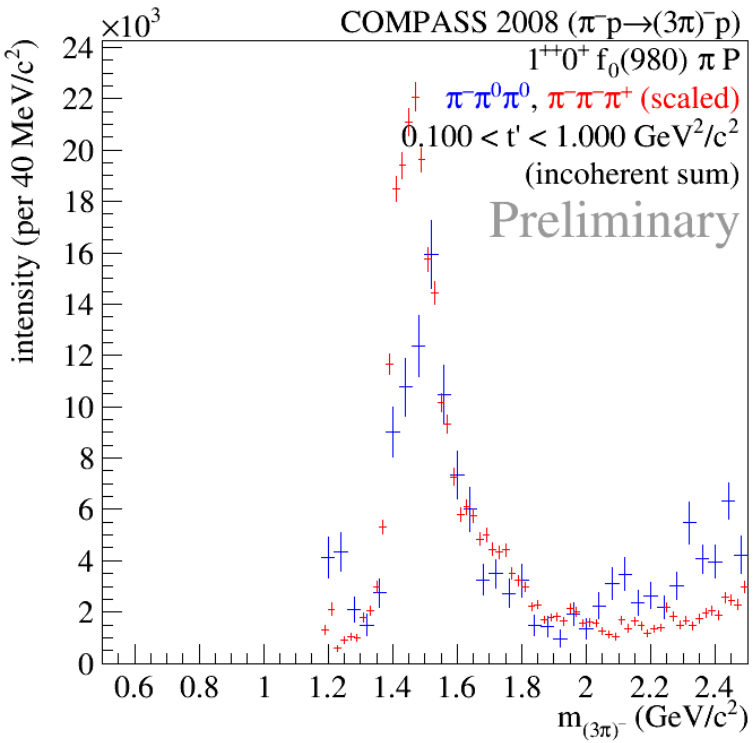
- Charged mode data scaled for each plot (integral) to compare shapes
- Good agreement between the two channels

Comparison neutral vs. charged mode
-- a couple of smaller waves

$a_4(2040) \rightarrow \rho\pi$

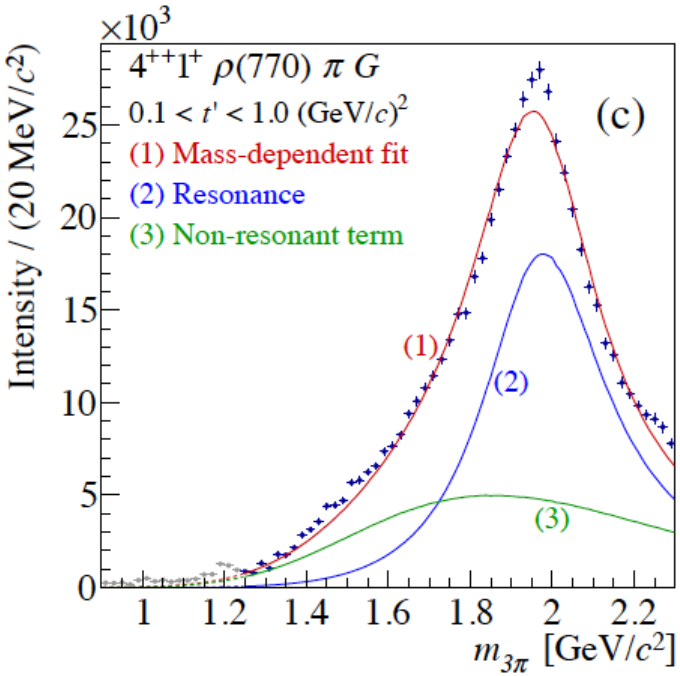


$X(?) \rightarrow f_0\pi$

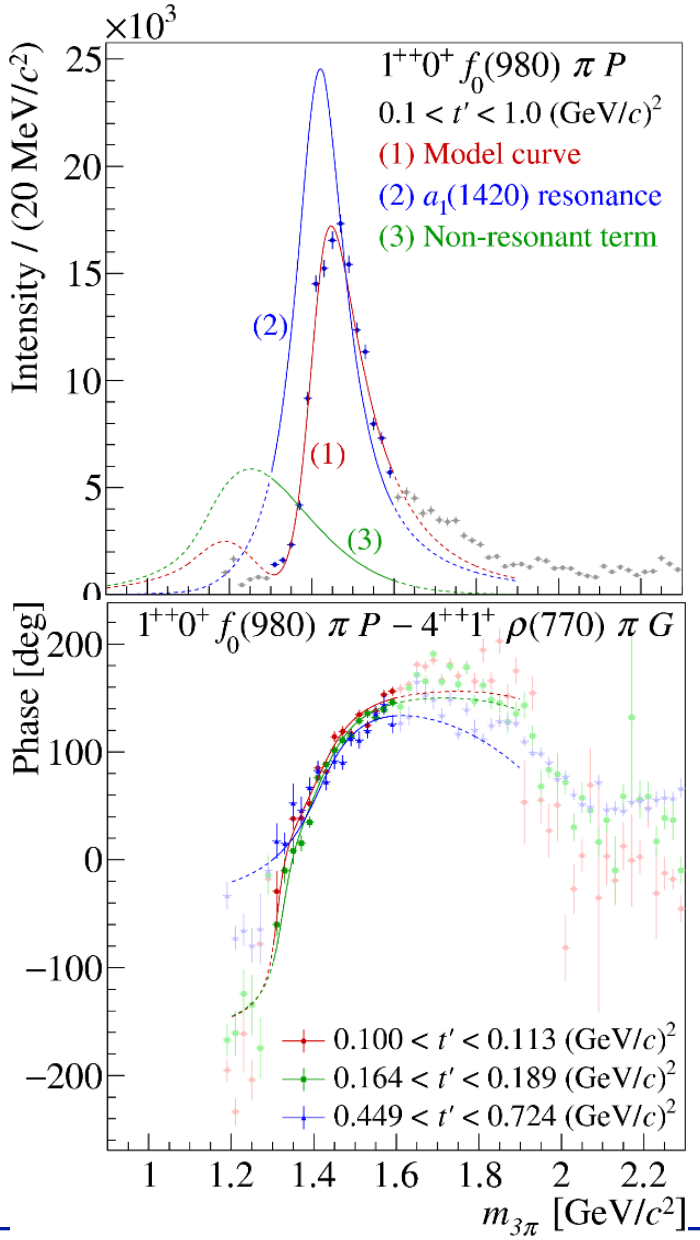


- Charged mode data scaled for each plot (integral) to compare shapes
- (Good) agreement between the two channels (for the 4^{++} wave)

A new axial vector resonance found?

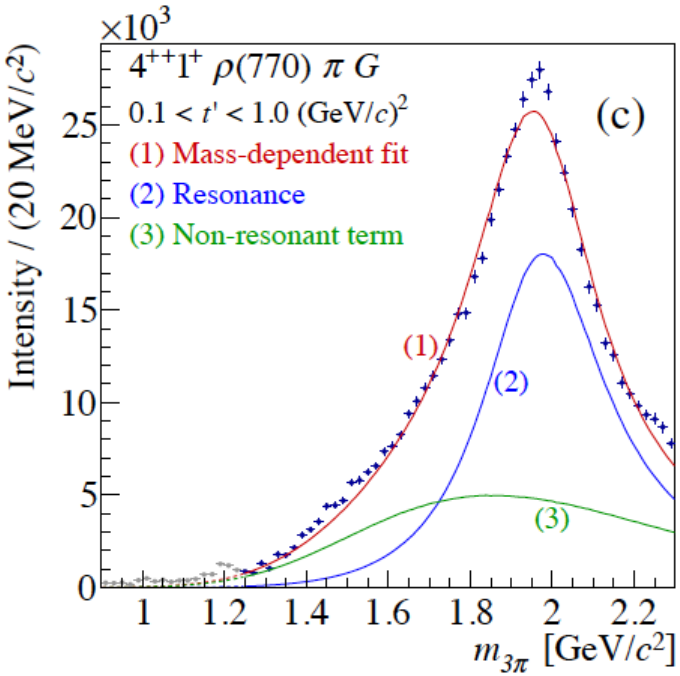


[subm. PRL; hep-ex/1501.05732]

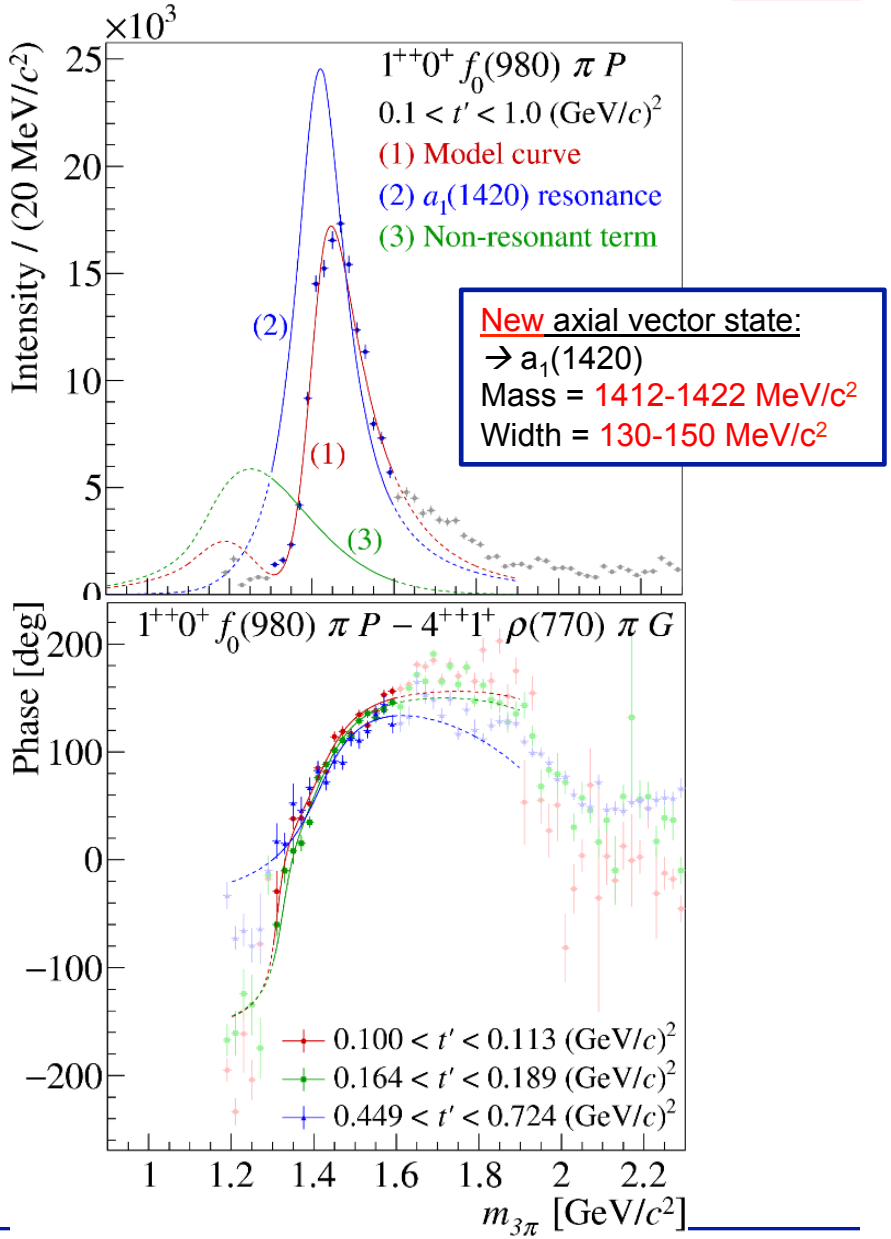


- 2nd step analysis result overlaid
  (charged mode only presently)
- New axial vector state observed
- Coupling to $K\bar{K}$, and not seen in ρπ
  → *isospin partner of $f_1(1420)$?*

A new axial vector resonance found?



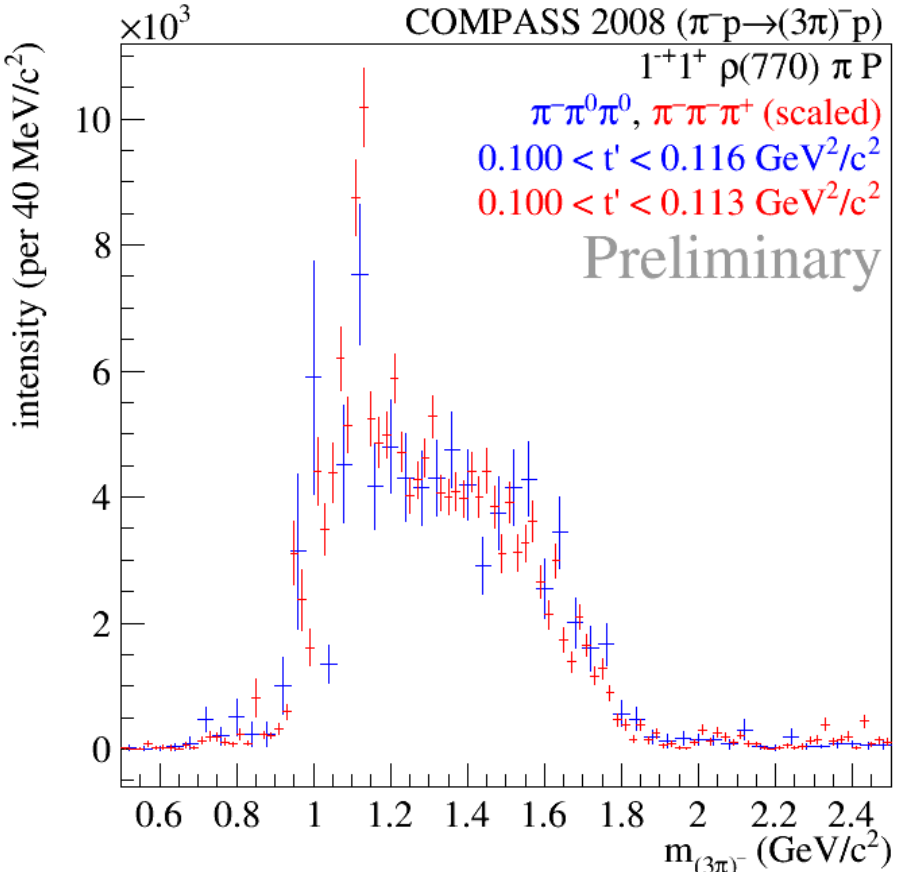
[subm. PRL; hep-ex/1501.05732]

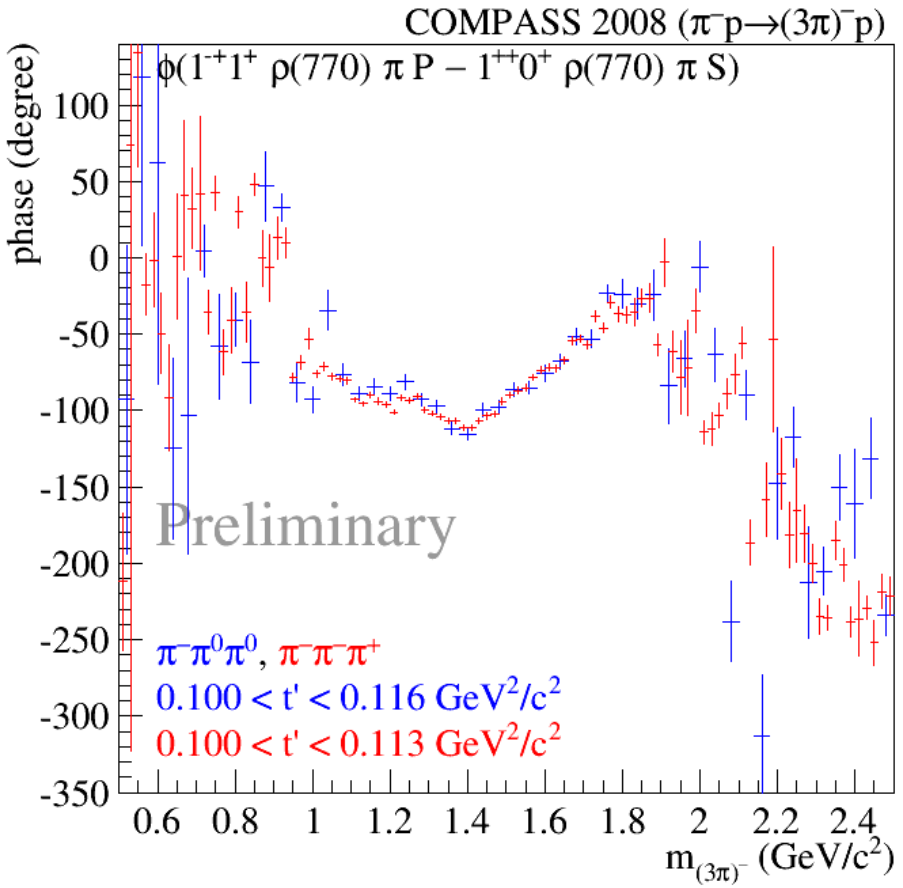


New axial vector state:
→ $a_1(1420)$
Mass = 1412-1422 MeV/c^2
Width = 130-150 MeV/c^2

- 2nd step analysis result overlaid
  (charged mode only presently)
- New axial vector state observed
- Coupling to $K\bar{K}$, and not seen in $\rho\pi$
  → *isospin partner of $f_1(1420)$?*

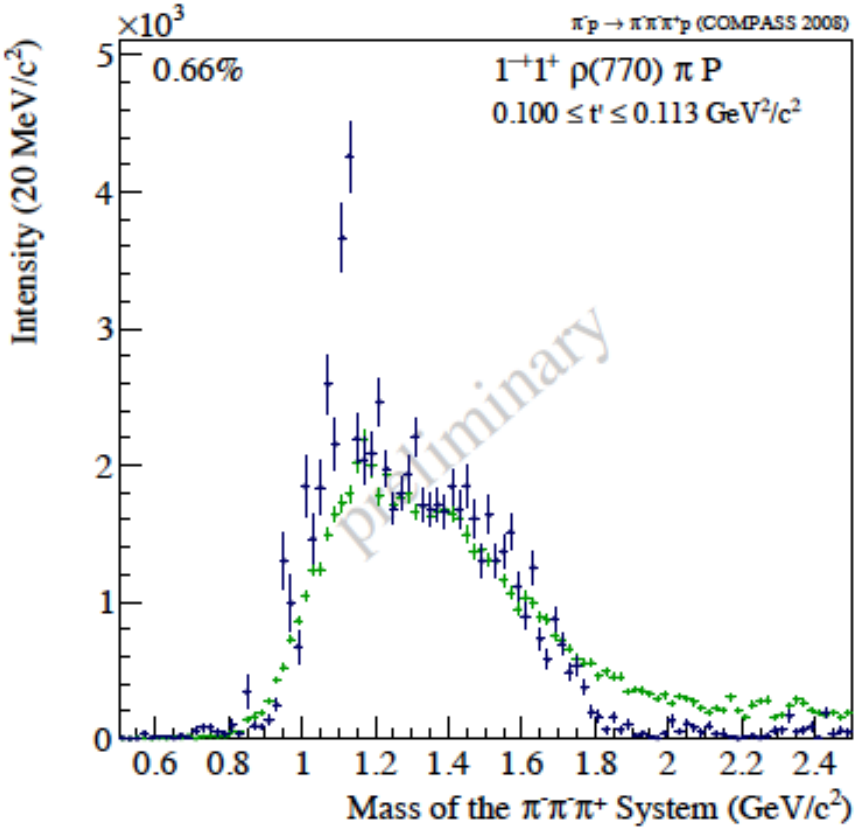
Spin exotic 1^{-+} wave

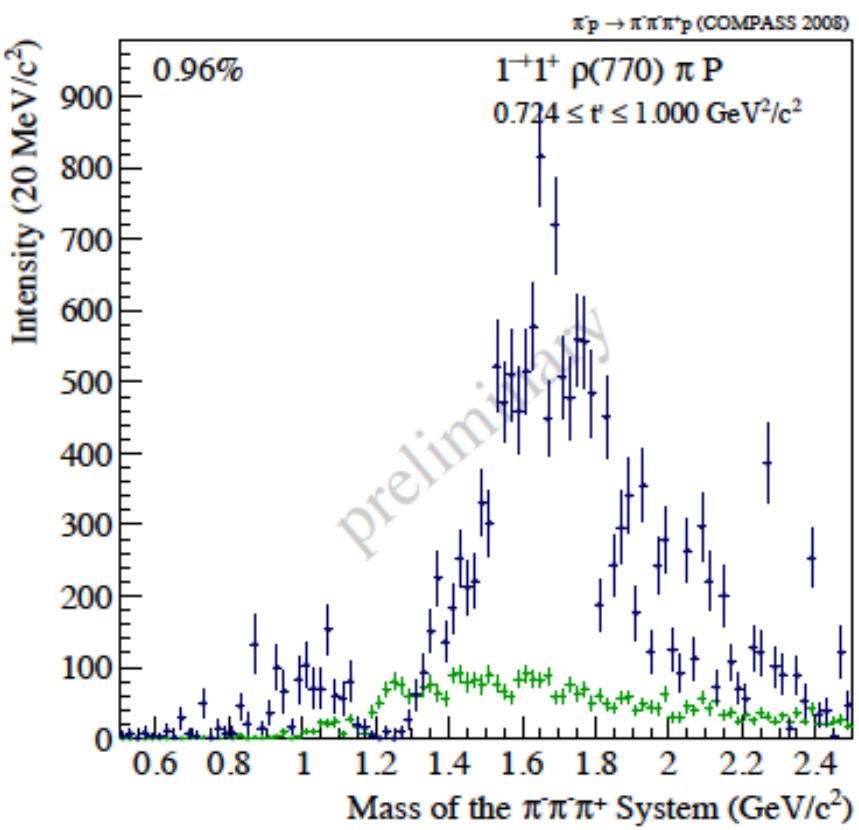




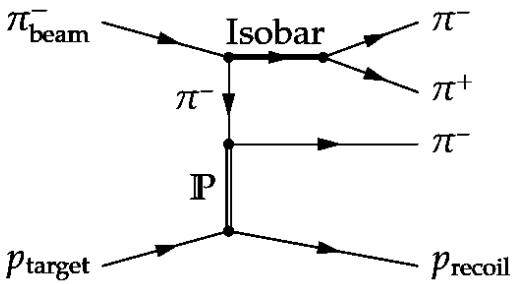
- Charged mode data scaled for each plot (integral) to compare shapes
- Good agreement between the two channels, differences depending on t'
- Deck contribution amplitude to be included → *describe large background*

Spin exotic 1^{-+} wave

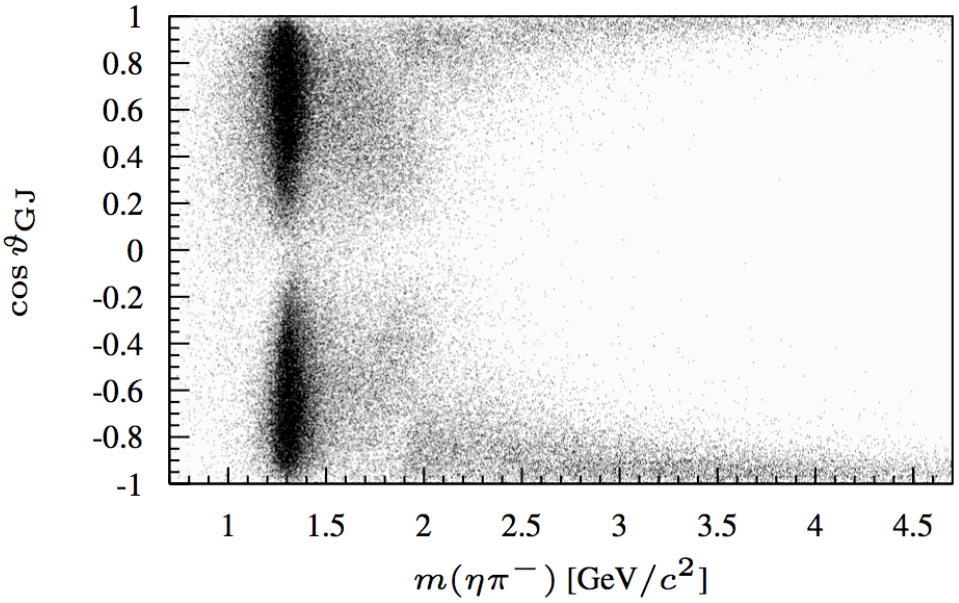


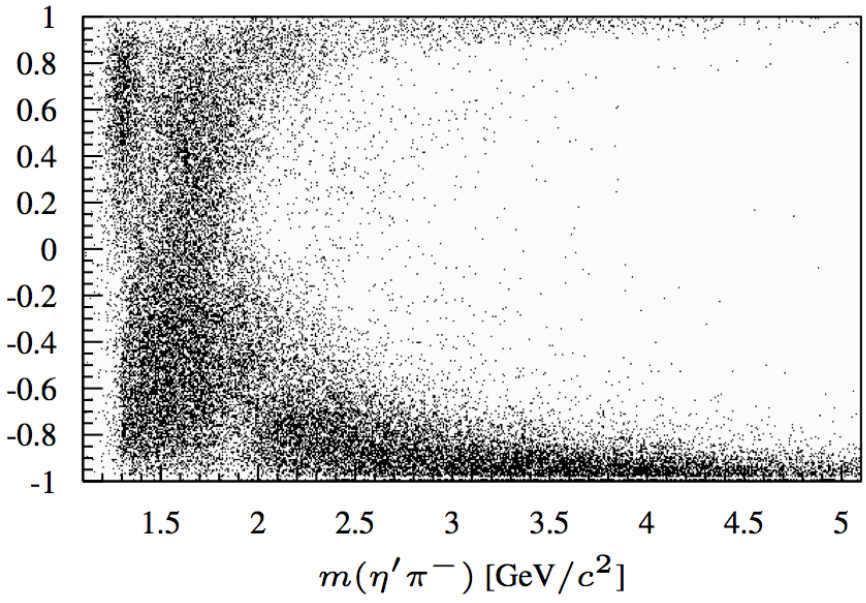


- MC simulated data generated with Deck-amplitude
- Analysis same as real data,
- Scaled to integrated intensity of each *t'* bins
- To be included, completed



Different channel for the search:
$\pi^- + p \rightarrow \pi^- \eta' / \pi^- \eta + p$



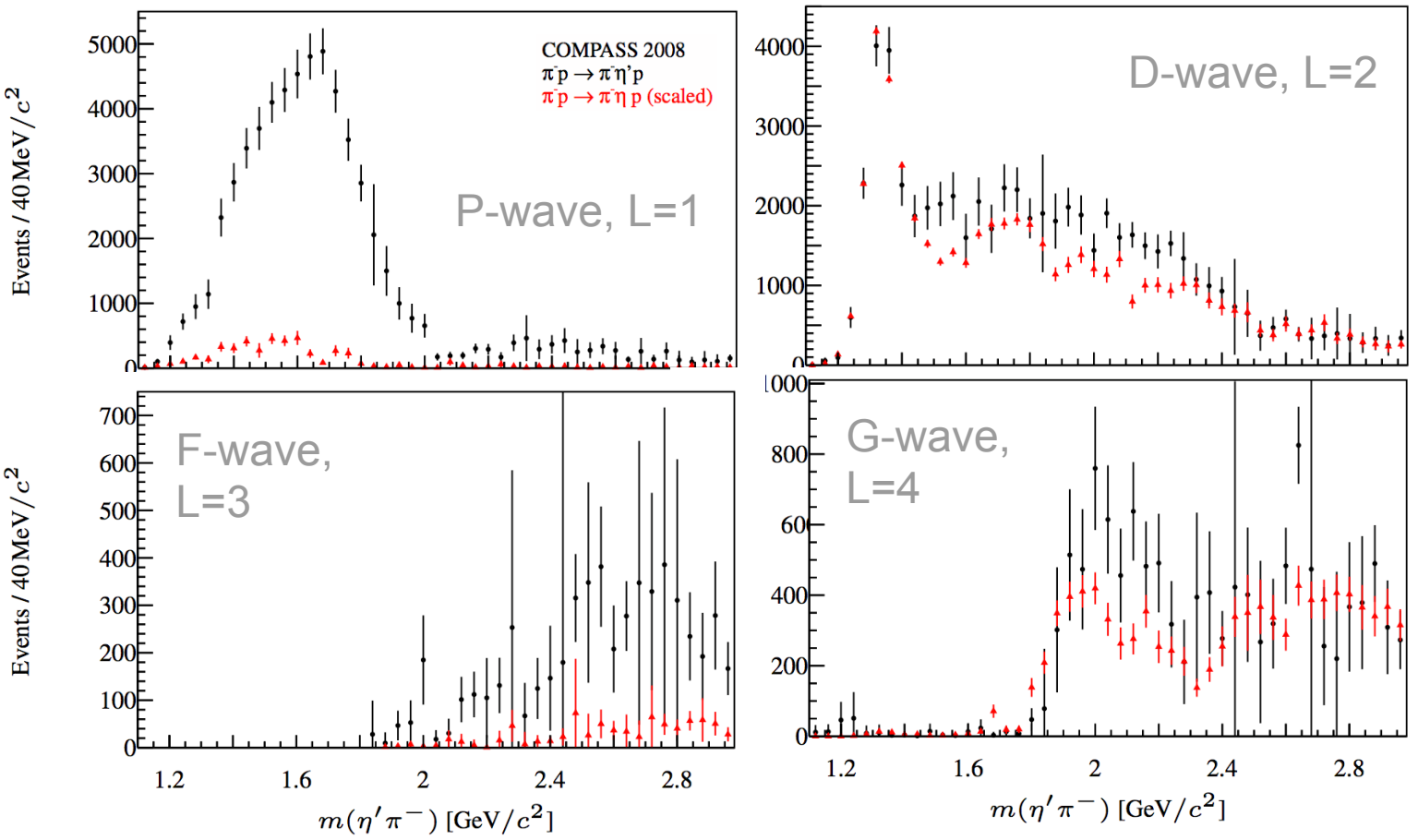


→ Both channels similar, different interference effects

[PLB 740 (2015) 303; hep-ex/1408.4286]

Different channel for the search: $\pi^-+p \rightarrow \pi^-\eta`/\pi^-\eta+p$

corrected for phase-space:



→ Even-L partial-waves: similar intensity distributions in η and η'

→ Odd-L partial-waves, in particular the P wave, are suppressed in ηπ by factor 5-10

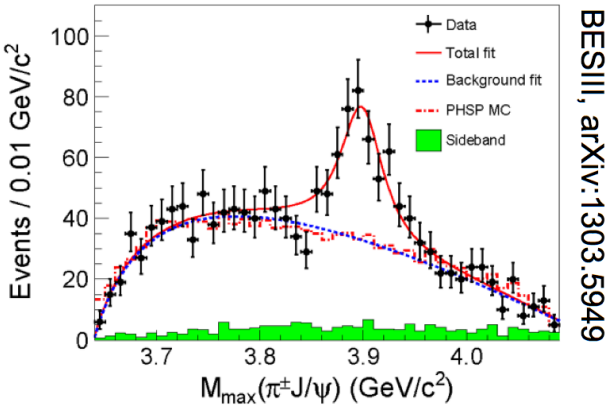
[PLB 740 (2015) 303; hep-ex/1408.4286]

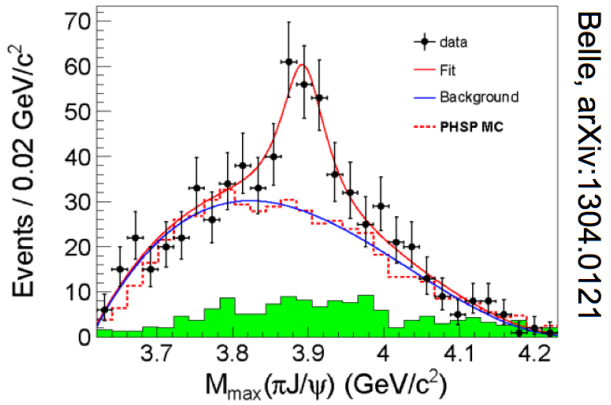
Hadron spectroscopy with muon beams
Large Q^2

Search for charmonium-like (exotic) state $Z_c(3900)$

Highlight in 2013:

- Discovery of charged $c\bar{c}$ state
- $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ ($\sqrt{s} = 4.26$ GeV), decay: $Z_c(3900) \rightarrow J/\psi\,\pi^\pm$

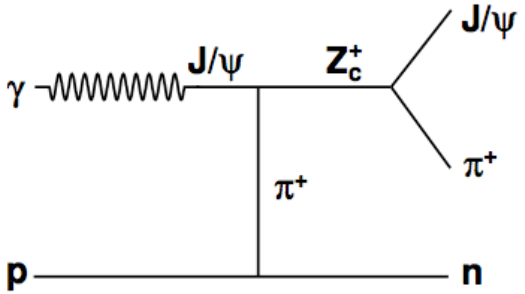




COMPASS:

- Photon may behave like a J/ψ (VMD model)

  → $Z_c(3900)$ production via interaction of incoming photon with virtual charged pion (target nucleon)



→ sizable cross-section

[14] Q.-Y. Lin et al., Phys. Rev. D 88, 114009 (2013),

- Exclusive production channel:

exclusively produced

$$\mu^+ N \rightarrow \mu^+ Z_c^\pm(3900)\, N \rightarrow \mu^+ J/\psi \pi^\pm N \rightarrow \mu^+\mu^+\mu^-\pi^\pm N$$

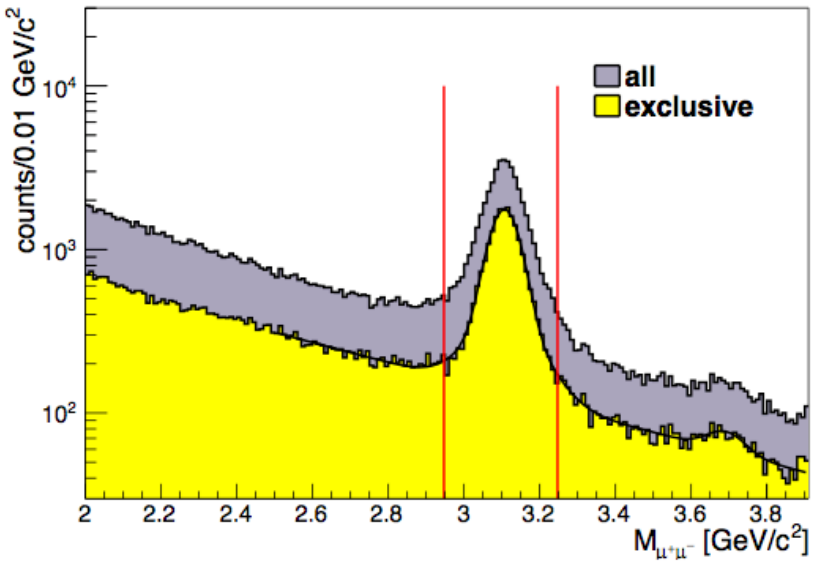
[hep-ex/1407.6186, submitted to PLB]

Search for charmonium-like (exotic) state $Z_c(3900)$

Selection of exclusive $\mu^+ J/\psi\, \pi^\pm$ sample

- Vertex, exactly 3 outgoing muons, 1 pion
- Mass cut on $J/\psi\,(\rightarrow \mu^+\mu^-)$
- Energy balance
- Momentum cut for $\pi^\pm$ (>2GeV/c)

  → *reduce background of pomeron exchange*

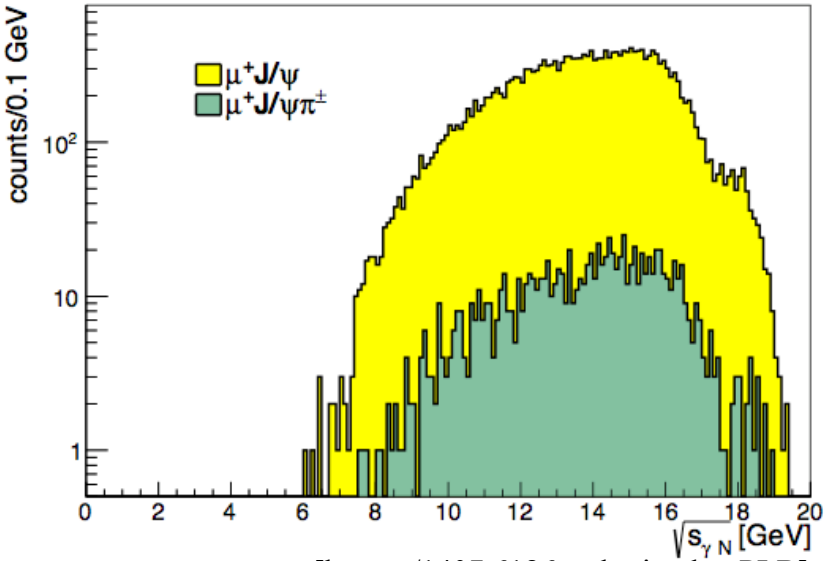


Selection of exclusive $\mu^+ J/\psi$ sample

- $\mu^+ N \rightarrow \mu^+ J/\psi N$ *(incoherent excl. prod.)*
- Used for absolute normalisation

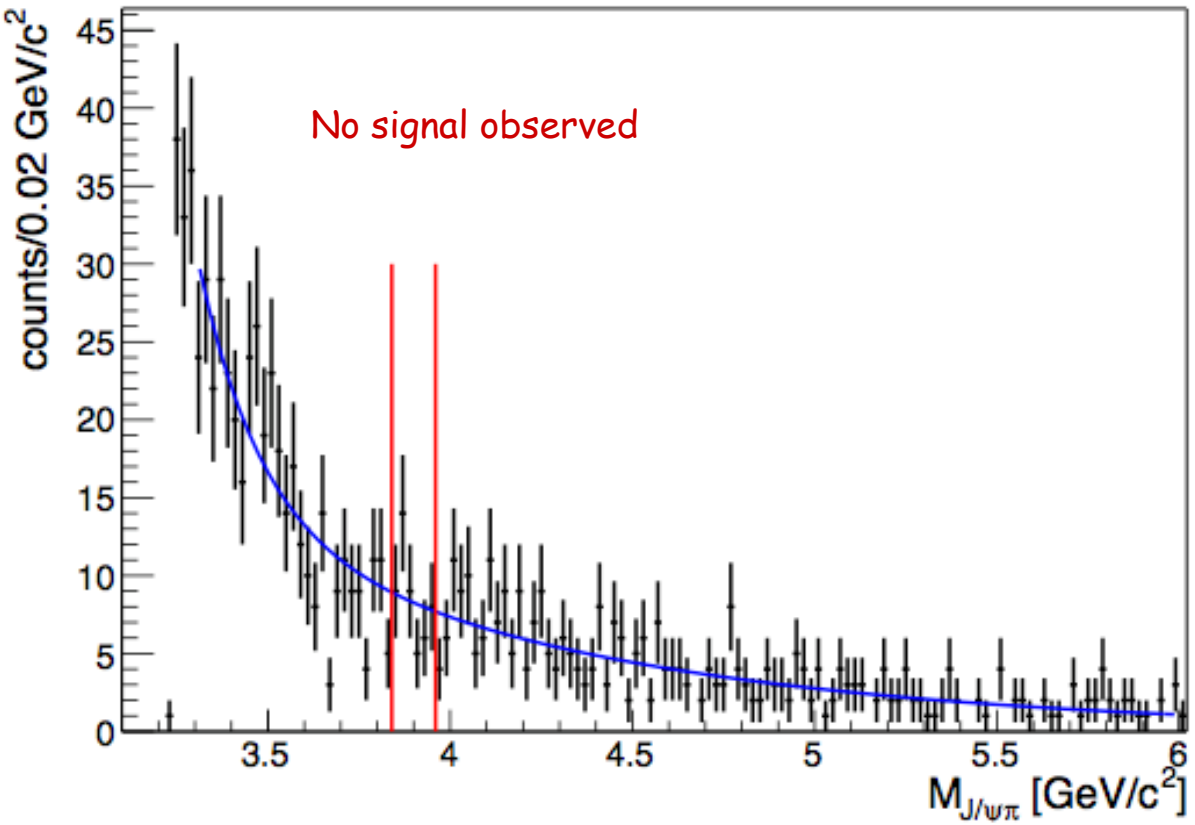
  (cross-section $\sigma_{\gamma N \rightarrow J/\psi N}$ from NA14)
- Same selection criteria

→ *Ratio of acceptances for both samples equals about the acceptance for the additional pion (~0.5)*



[hep-ex/1407.6186, submitted to PLB]

Search for charmonium-like (exotic) state $Z_c(3900)$



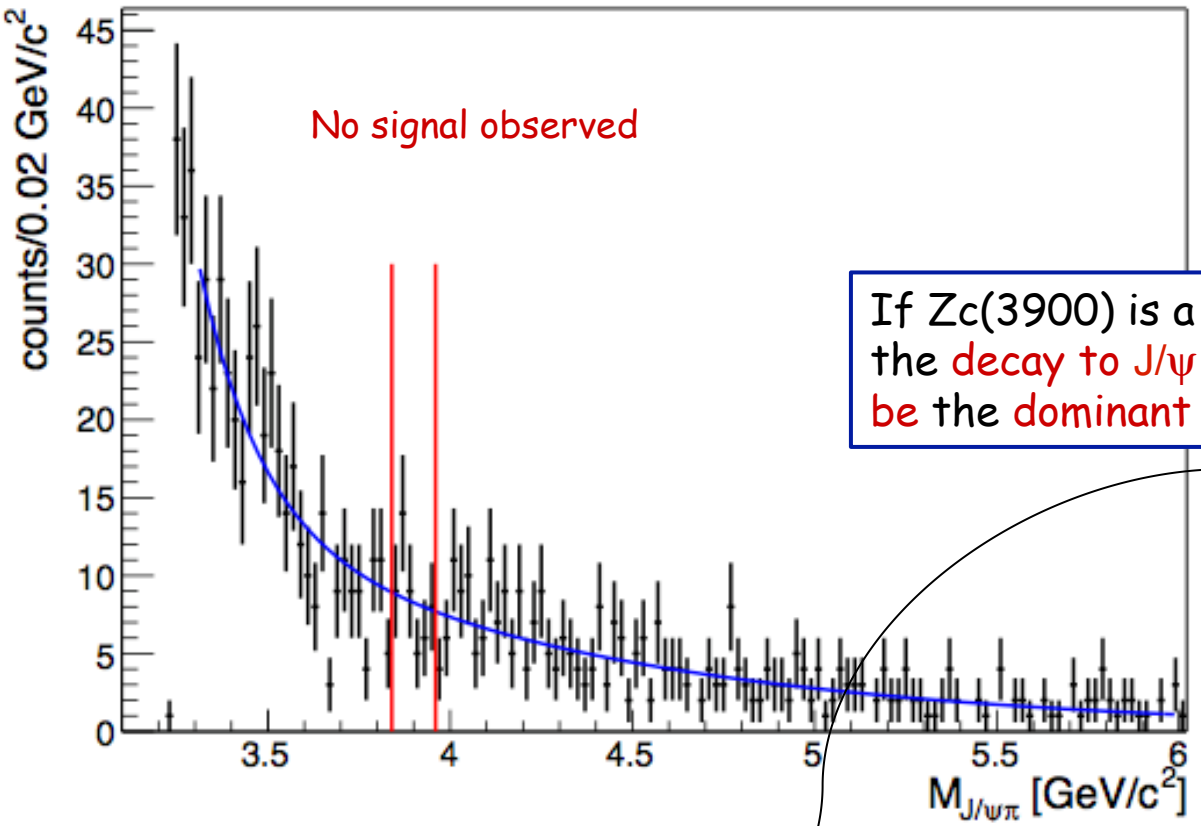
$$\left.\frac{BR(Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}) \times \sigma_{\gamma\, N \to Z_c^{\pm}(3900)\, N}}{\sigma_{\gamma\, N \to J/\psi\, N}}\right|_{\langle\sqrt{s_{\gamma N}}\rangle=13.8\ \text{GeV}} < 3.7 \times 10^{-3}$$

$$\left.BR(Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}) \times \sigma_{\gamma\, N \to Z_c^{\pm}(3900)\, N}\right|_{\langle\sqrt{s_{\gamma N}}\rangle=13.8\ \text{GeV}} < 52\ \text{pb}$$

NA14

[hep-ex/1407.6186, submitted to PLB]

Search for charmonium-like (exotic) state $Z_c(3900)$



If Zc(3900) is a resonance, the decay to $J/\psi\,\pi^{\pm}$ cannot be the dominant one ...

$$\left.\frac{BR(Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}) \times \sigma_{\gamma\, N \to Z_c^{\pm}(3900)\, N}}{\sigma_{\gamma\, N \to J/\psi\, N}}\right|_{\langle\sqrt{s_{\gamma N}}\rangle=13.8\ \text{GeV}} < 3.7 \times 10^{-3}$$

NA14

$$\left.BR(Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}) \times \underbrace{\sigma_{\gamma\, N \to Z_c^{\pm}(3900)\, N}}_{\text{sizeable [14]}}\right|_{\langle\sqrt{s_{\gamma N}}\rangle=13.8\ \text{GeV}} < 52\ \text{pb}$$

[hep-ex/1407.6186, submitted to PLB]

Summary

Results from COMPASS hadron programme

- First precise measurement of pion polarisibility
- New path to radiative meson excitations
- High potential for light mesons spectroscopy & spin-exotic search
- Hadron spectroscopy with muon data: Charmonium region

Outlook

- Higher statistics data on tape
- ChPT with neutral pions
- Solve puzzle of disputed $\pi_1(1600)$

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COMPASS is the facility to study QCD
-- nucleon structure and spectroscopy

Outlook

- Higher statistics data on
- ChPT with neutral pions
- Solve puzzle of disputed $\pi_1(1600)$