Hadron spectroscopy with COMPASS – newest results

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for the COMPASS Collaboration

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Outline:

- **Introduction**
  - Physics adressed by COMPASS
  - The COMPASS experiment
- **First results using hadron beams**
  - Spectroscopy – Search for spin-exotic mesons
    - Partial-wave analysis-method *(using published results, 2004 data)*
    - Status of search for spin-exotic mesons *(diffractive production, 2008 data*
    - Search for scalar glueballs *(central production)*
  - Further measurements *(Primakoff, photo-production, OZI violation …)*
- **Summary & outlook**

bmb+f - Förderschwerpunkt
COMPASS
Großgeräte der physikalischen Grundlagenforschung

COMPASS – The facility to study QCD

Physics with Muon & Hadron beams

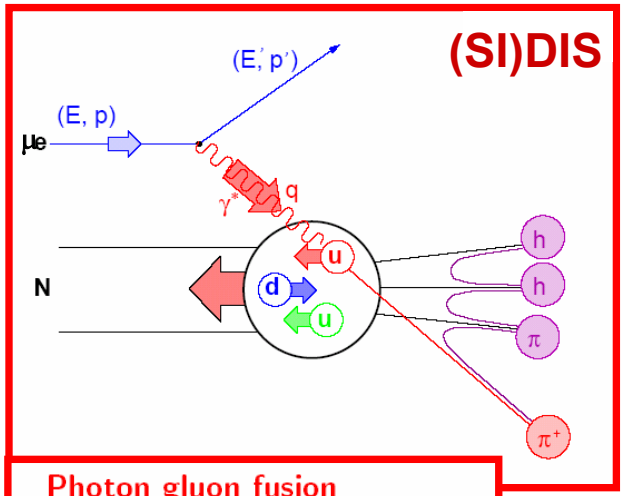
The goal:

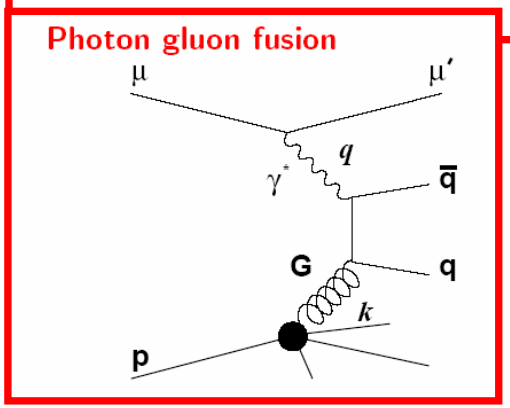
Study non-pertubative regime of QCD & probe structure and dynamics of hadrons, complementary methods:

Large Q^2:

Nucleon structure:

- Helicitiy, transversity PDFs
- Generalised PDFs (future)

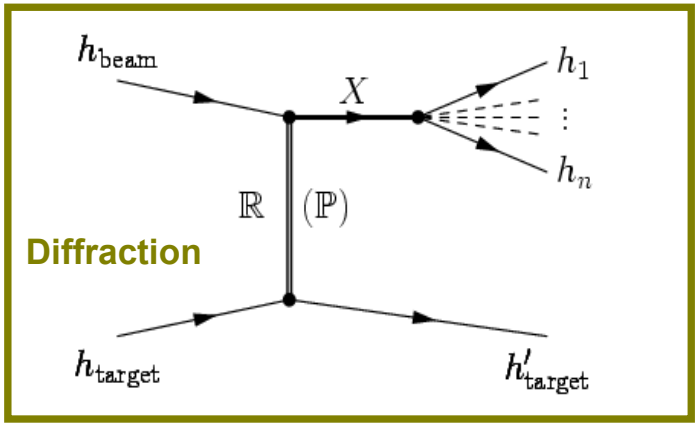


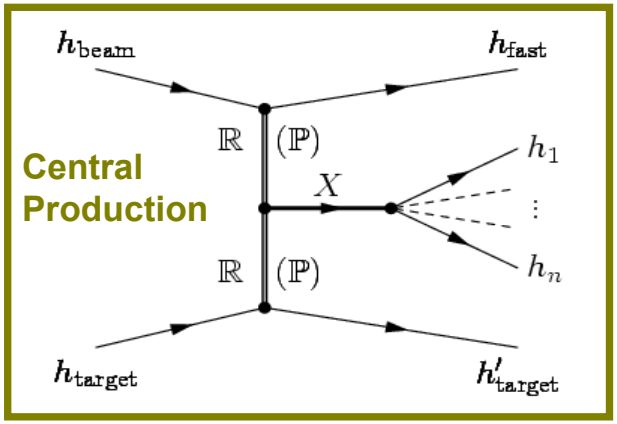


Low Q^2:

Spectroscopy

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

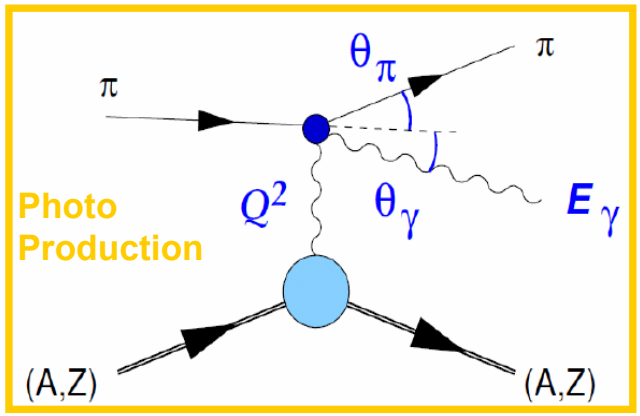




Very low Q^2:

Chiral dynamics

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



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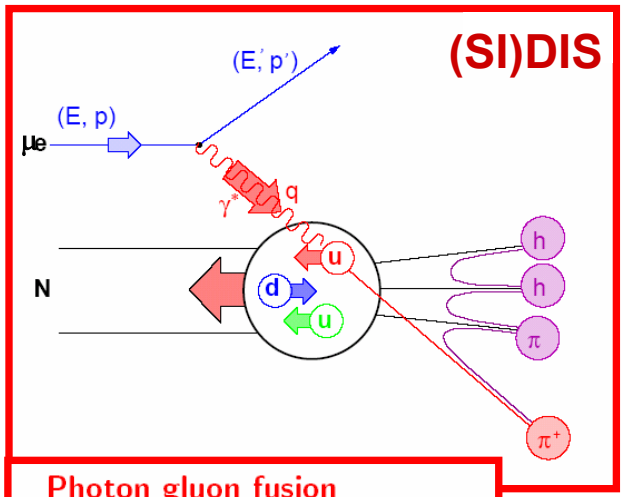

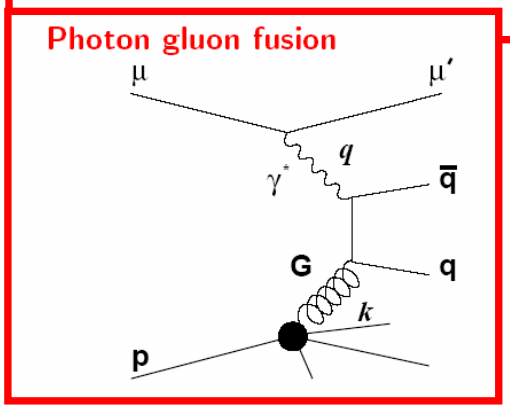

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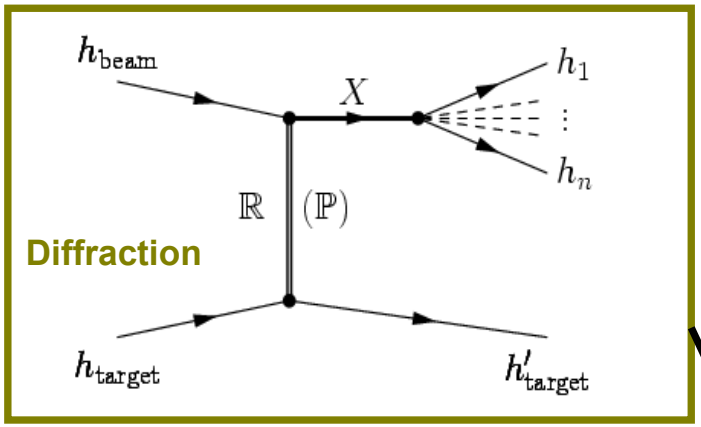

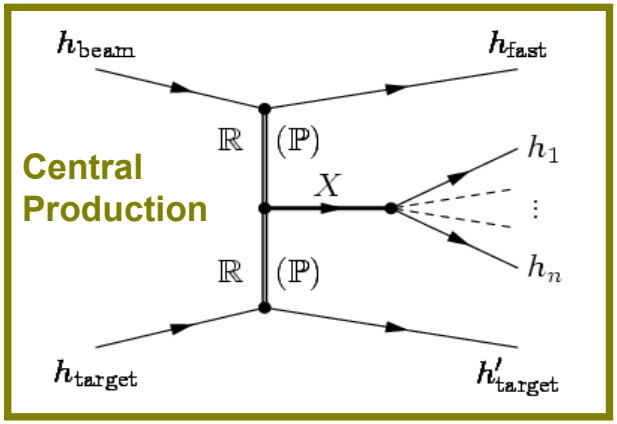

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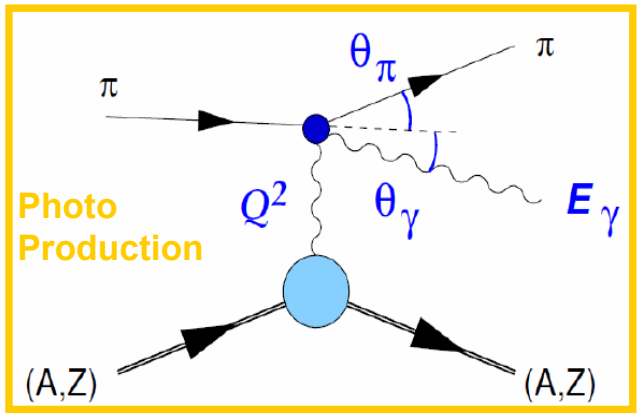
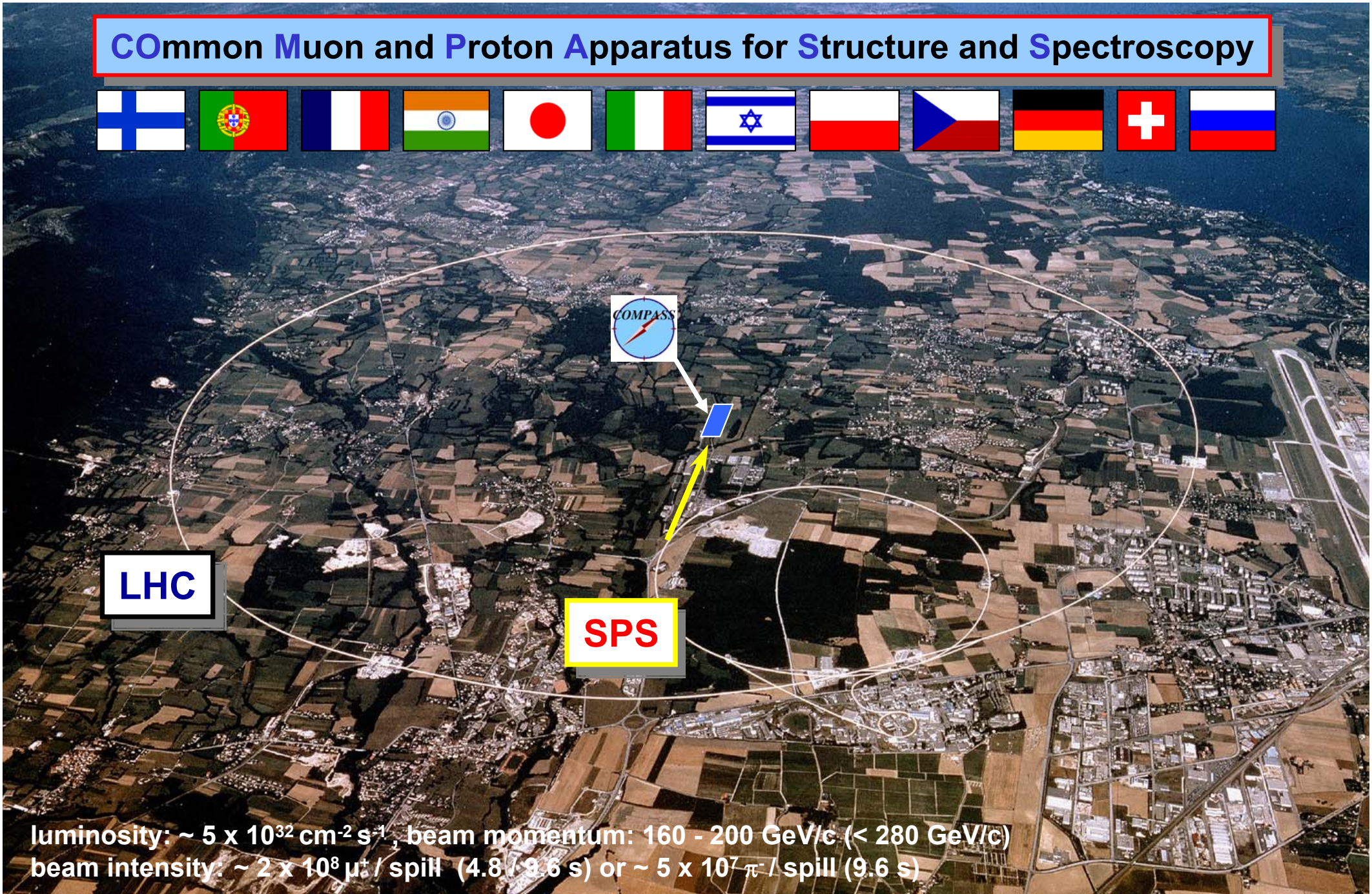


Main focus in this talk

- Hadron physics, first results from diffractive production

The COMPASS Experiment at CERN

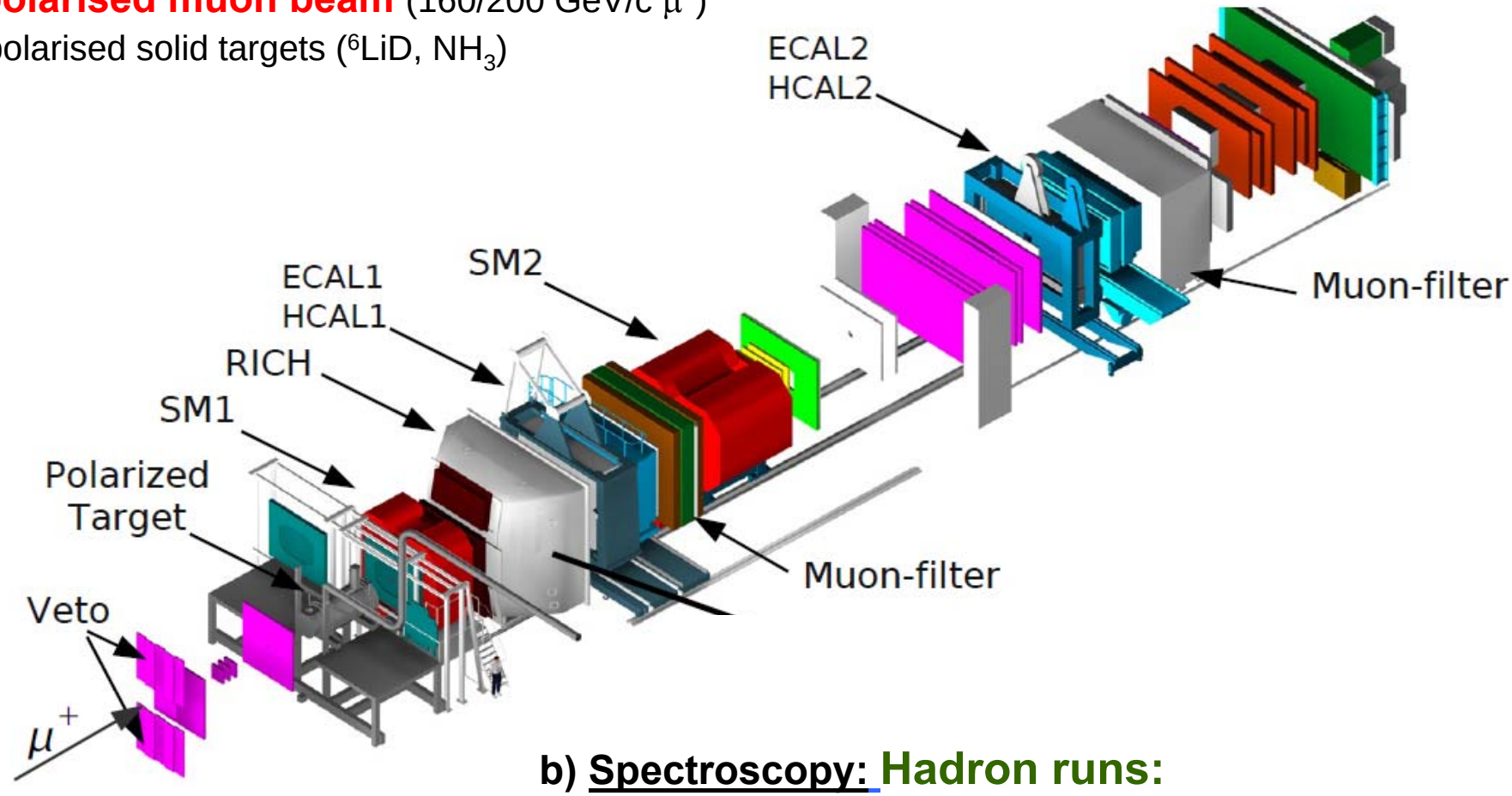


COMPASS spectrometer: Muon setup
(2002-07, 2010/11)

a) Nucleon spin structure:

→ **polarised muon beam** (160/200 GeV/c μ^+)

polarised solid targets (^{6}LiD, NH_3)



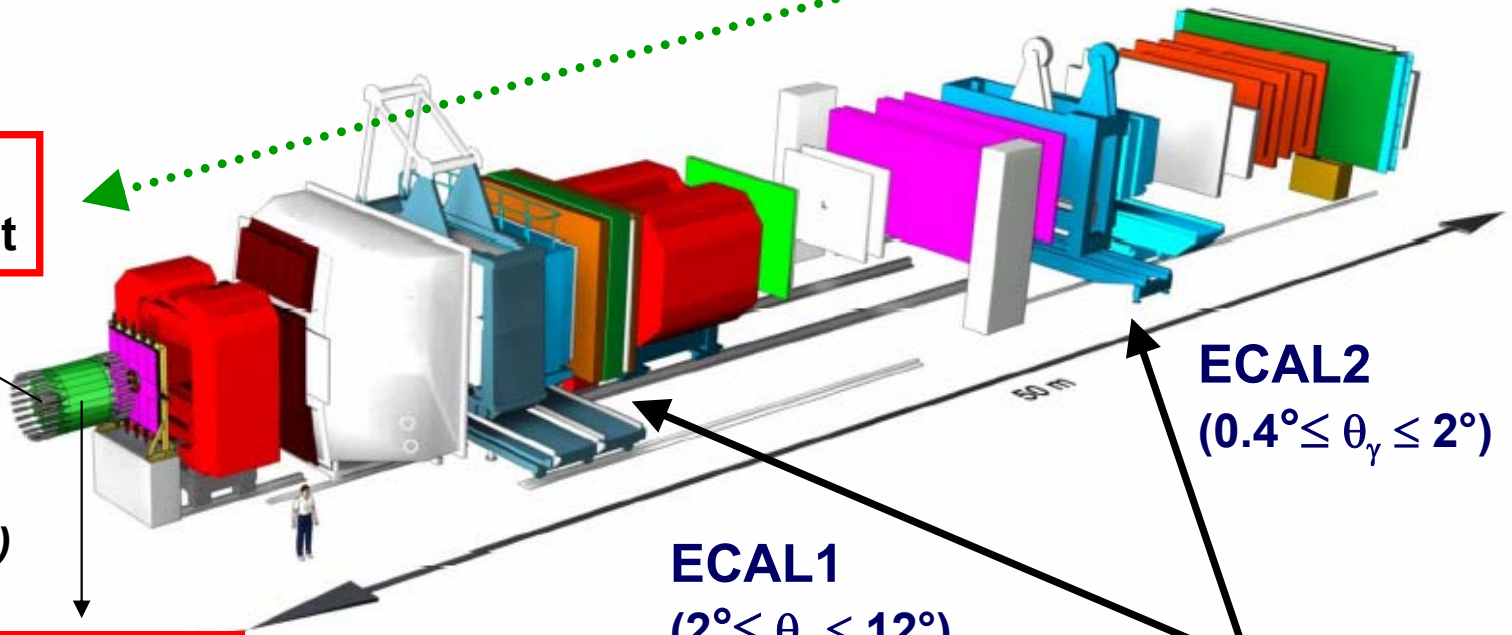
b) Spectroscopy: Hadron runs:

- **2004 pilot run** (4 days 190 GeV/c π^-, Pb target: ~BNL stats.)
- **2008/09** (large statistics, 190 GeV/c LH_2 target, $\pi^\pm$, $K^\pm$, $p^\pm$ beam, and some data on nuclear targets)

COMPASS spectrometer: Hadron setup

(2008/09) -- main changes w.r.t. muon setup

All 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
($0.4° \leq \theta_\gamma \leq 2°$)

ECAL1
($2° \leq \theta_\gamma \leq 12°$)

Electromagnetic calorimeters

PID using RICH & CEDARs

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

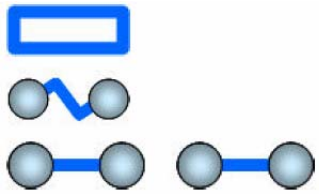
Mesons and Spin Exotic States

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: $0^{++}, 0^{-+}, 1^{--}, 1^{+-}, 1^{++}, 2^{++}, \ldots$
- Forbidden: $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$

QCD: meson states beyond

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



Hybrid candidates (1.3 - 2.2 GeV/c²):

lightest hybrid predicted: exotic $J^{PC} = 1^{-+}$

- $\pi_1(1400)$: VES, E852, Crystal Barrel → $\eta\pi$
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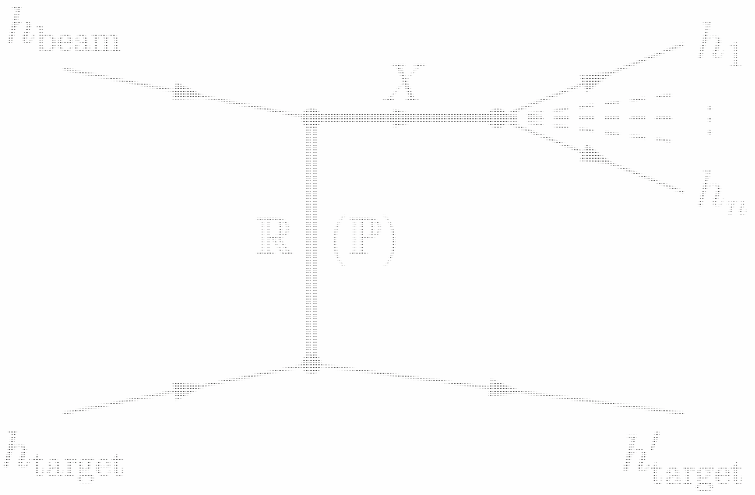
Diffractive scattering

- study of J^{PC} exotic mesons
- t-channel Reggeon exchange
- forward kinematics, target stays intact
- small momentum transfer



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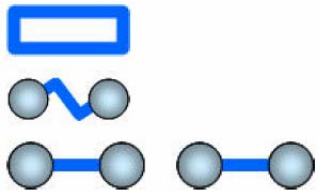

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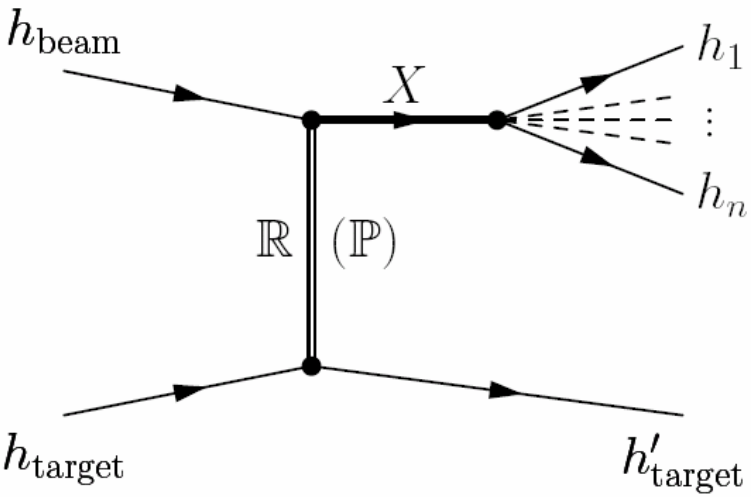

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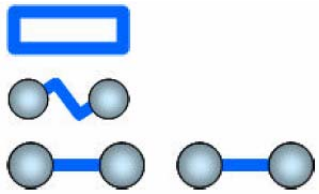

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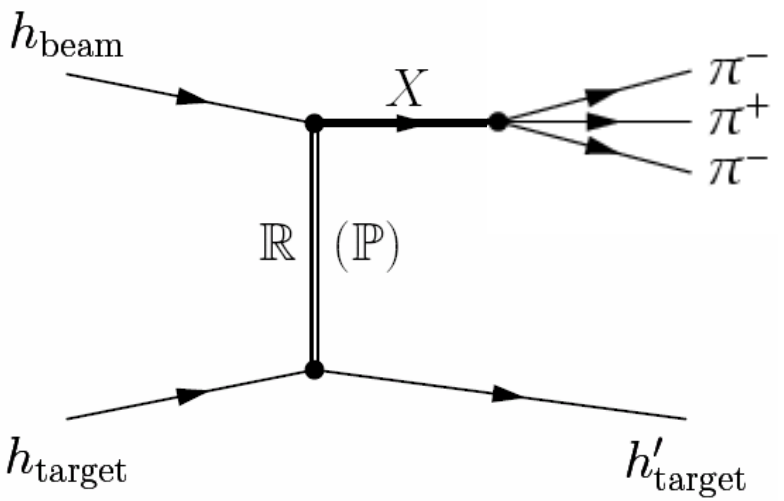
COMPASS (2004 pilot run)

- 190 GeV π^- beam *(Pb target)*
- studied $\rho\pi$ decay channel via

  π^- **Pb** —> $\pi^-\pi^+\pi^-$ **Pb**

Diffractive pion dissociation

- incoming π^- excited to resonance X^-
- X^- decays into final state, e.g. $(3\pi)^-$:



The $\pi_1(1600)$ in the 1^{-+} partial-wave
controversy -- some history

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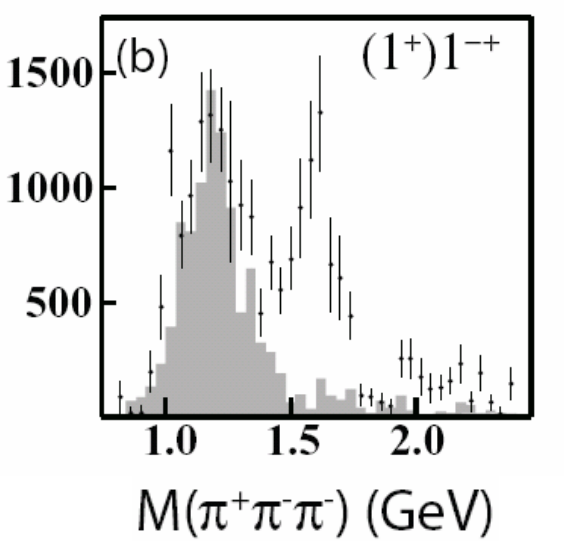
BNL/E852:
- 250k events (charged), 18 GeV/c, 21 waves



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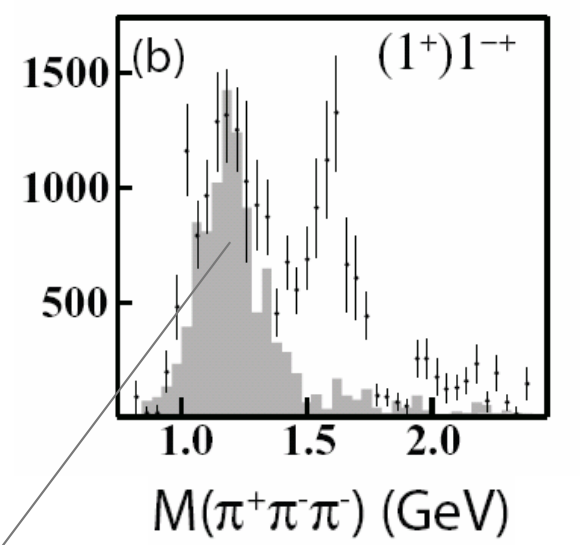

validated to be leakage from $a_2(1320)$

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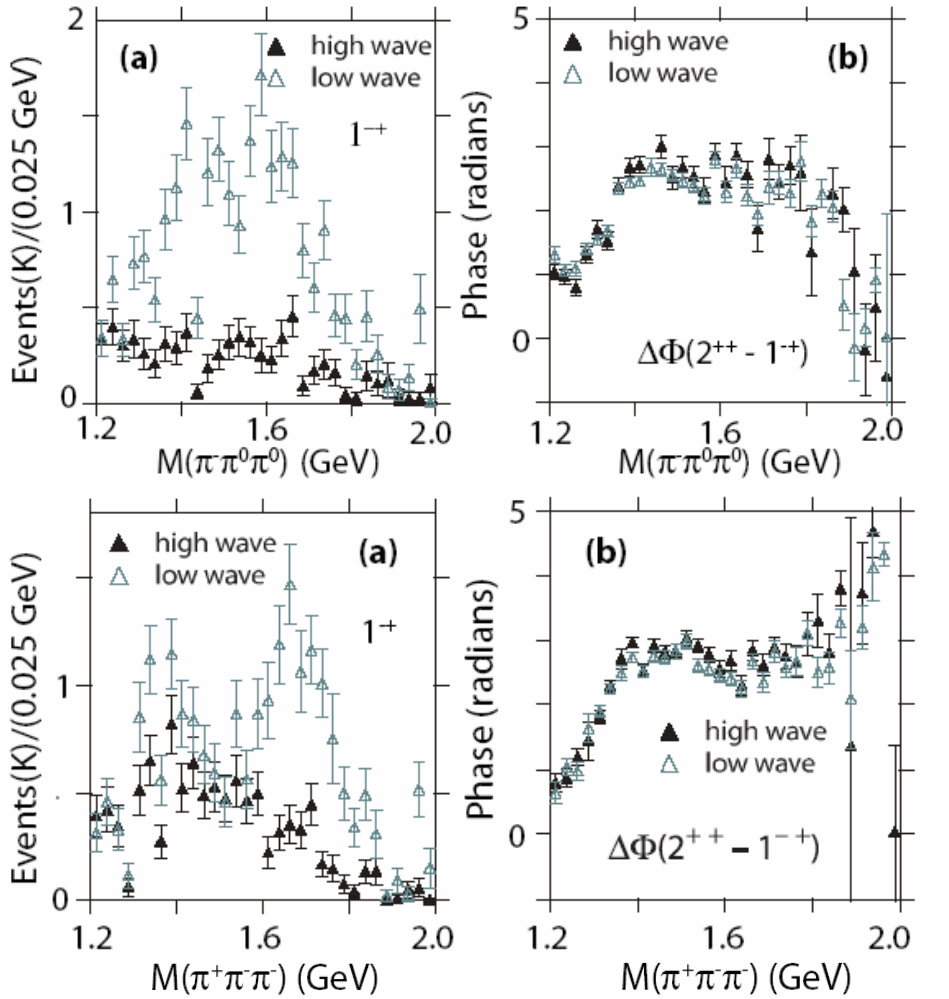
E852-IU re-analysis:
- higher statistics: 3M & 2.6M (neutral & charged)
- extended wave-set (35 waves) => 1^{-+} object vanished



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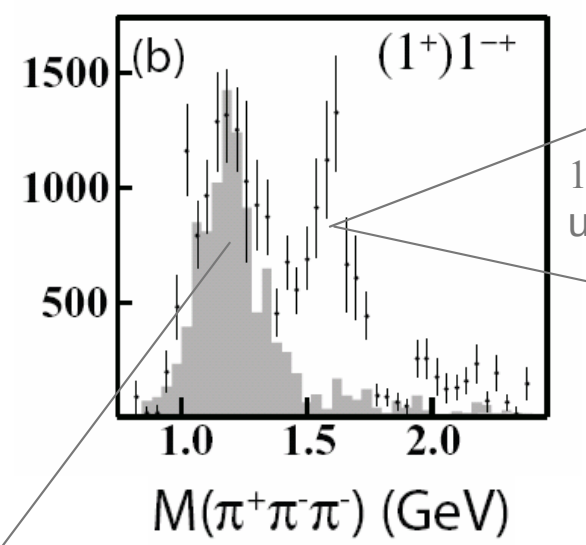

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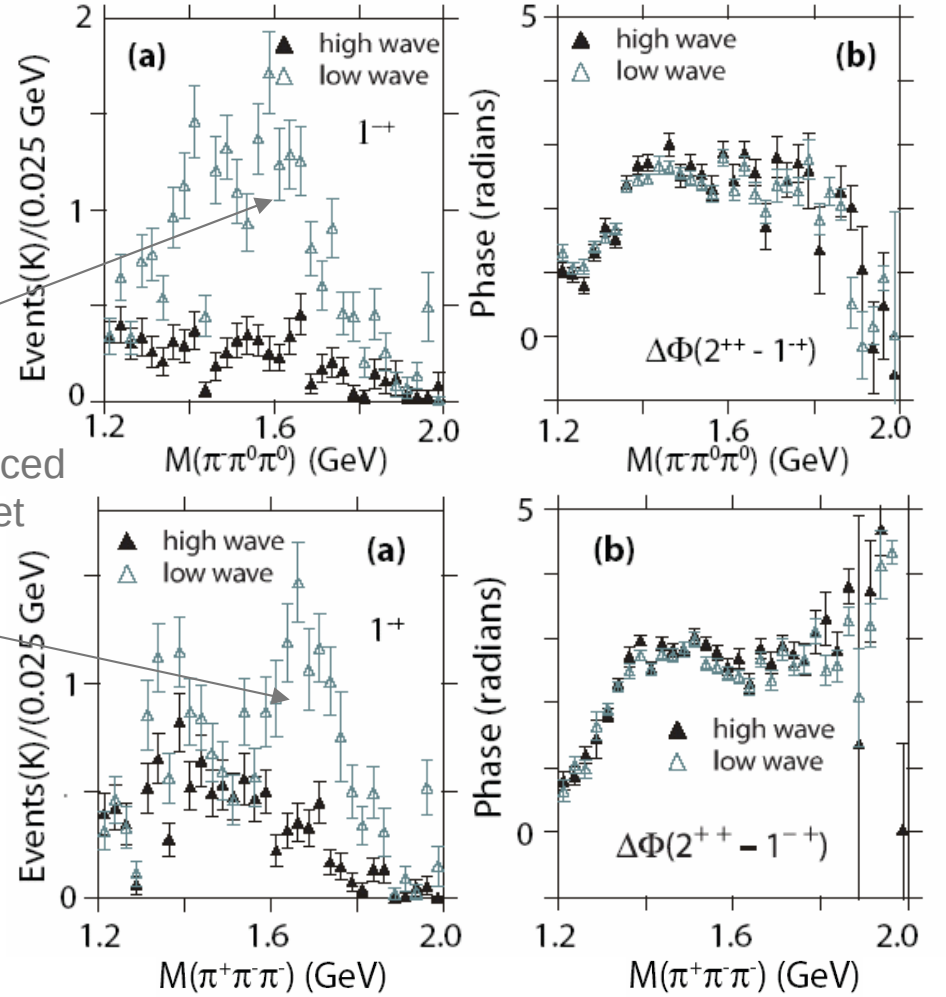

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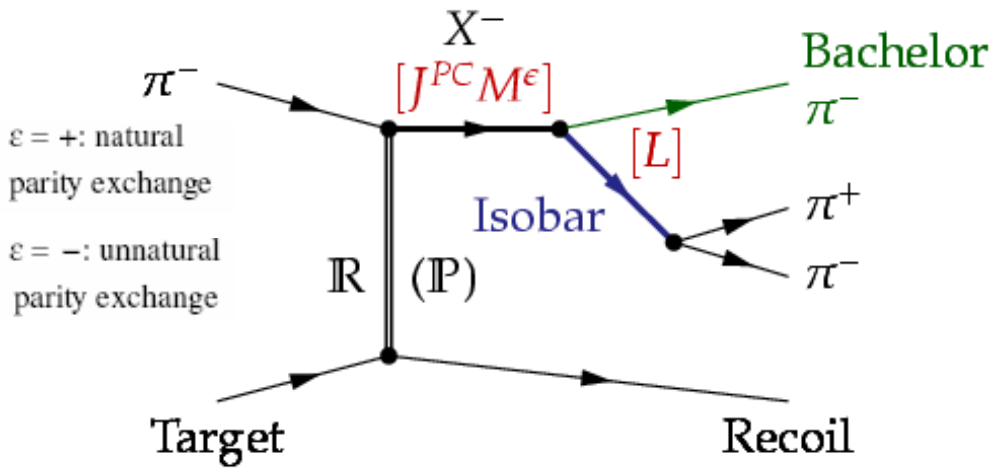
COMPASS PWA method



X^- decay described using isobar model:

- Intermediate di-pion resonance (isobar)
  - *Spin S and rel. orbital angular momentum L w.r.t bachelor π^-*
  - *L+S couple to J*
- Partial waves (reflectivity basis): $J^{PC}\ M^{\varepsilon}$ [isobar] L

Partial wave analysis:

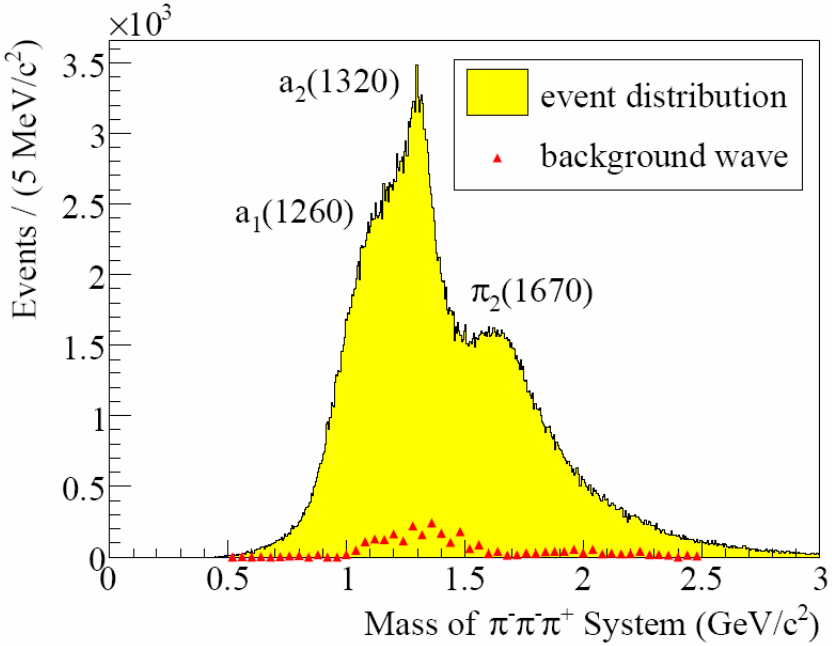
- **Isobars:** All possible, needed isobars
- **Acceptance:** corrections included (normalisation integrals)

Step 1) Mass independent PWA (loglikelihood fit)

Step 2) Mass dependent χ^2 fit: (to mass independent result)

- Main partial waves chosen, parameterised by Breit-Wigner
- Non-resonant background for some waves

Diffractive dissociation into 3π final states
(2004 data, Pb target) [PRL 104 (2010) 241803]



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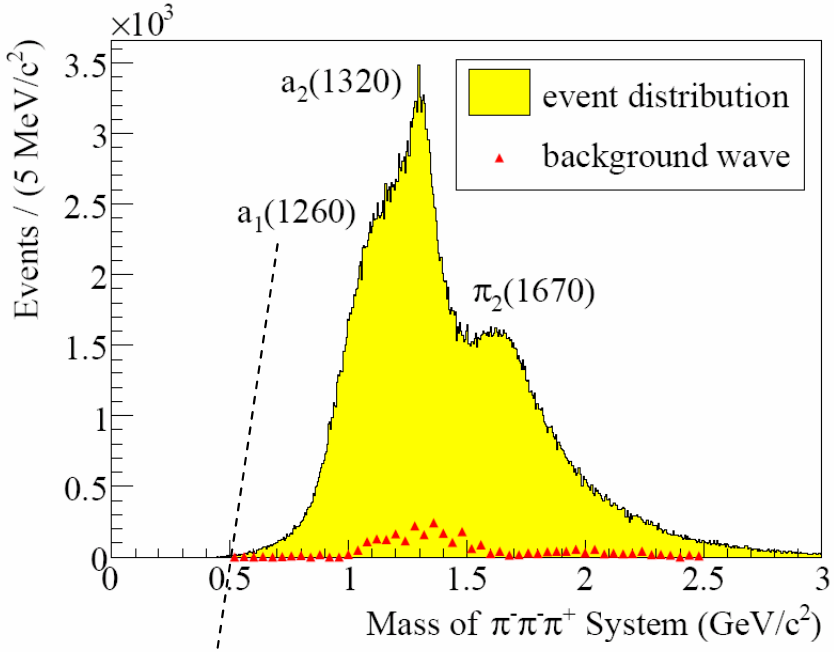

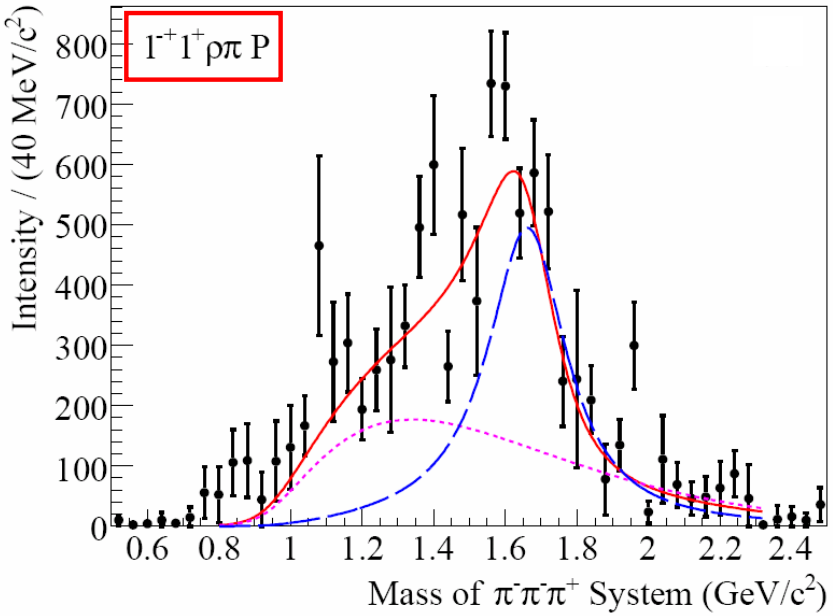

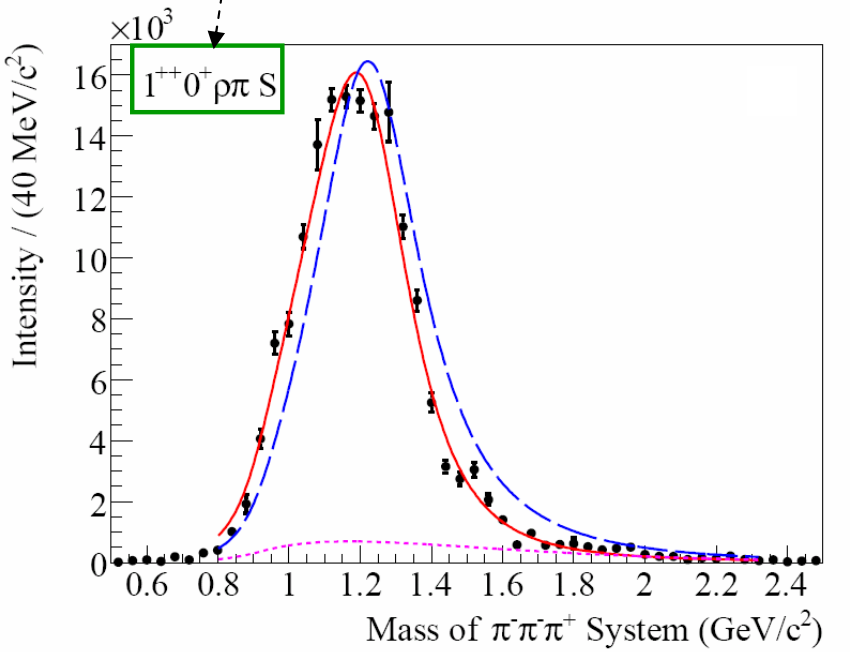

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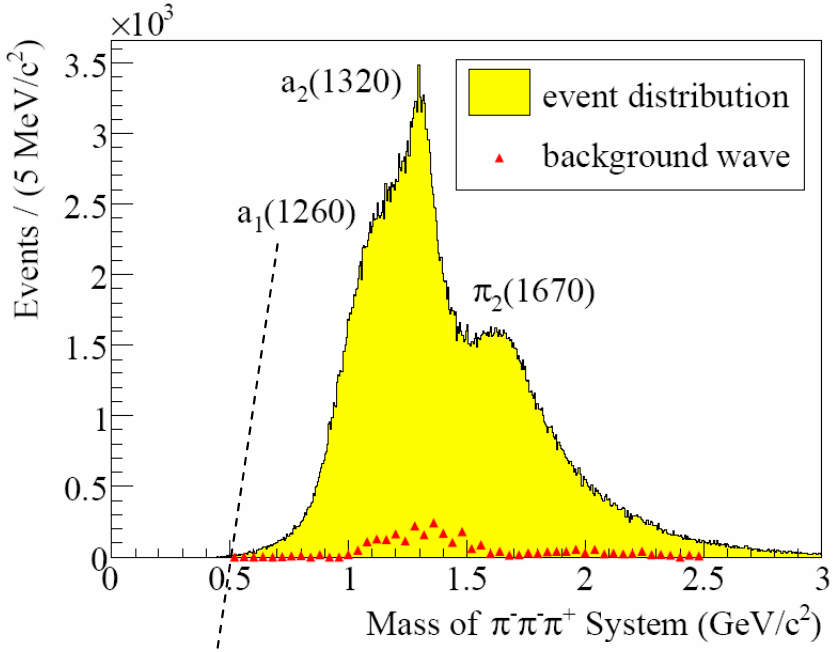

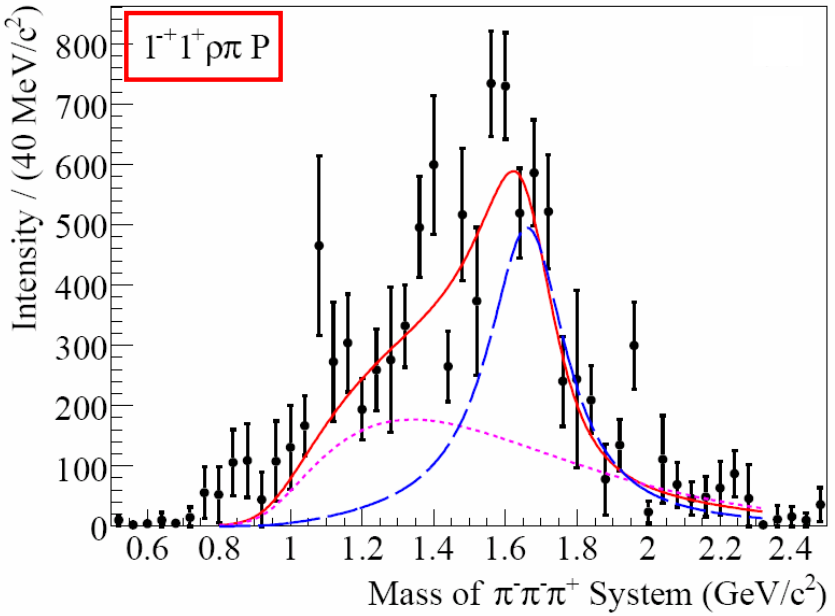

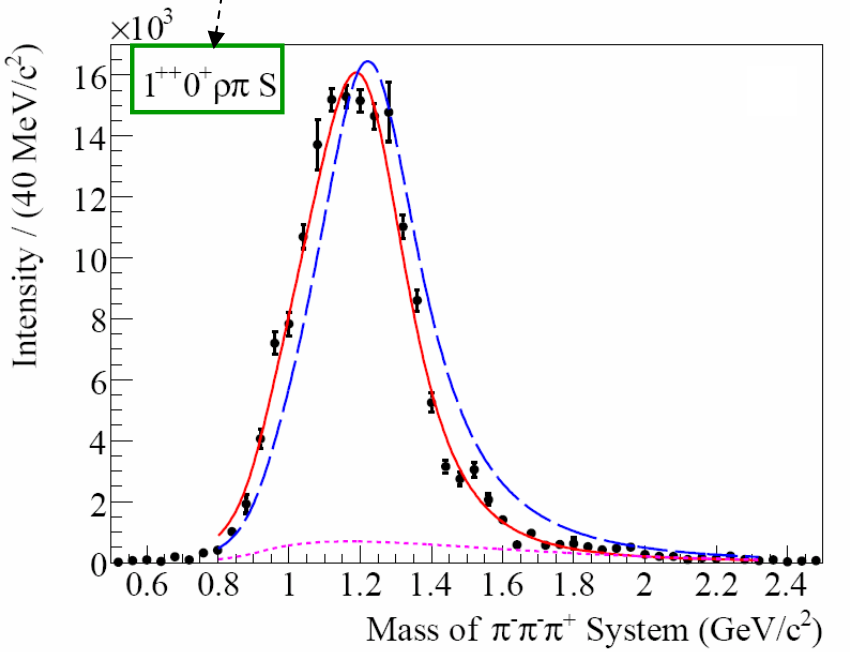

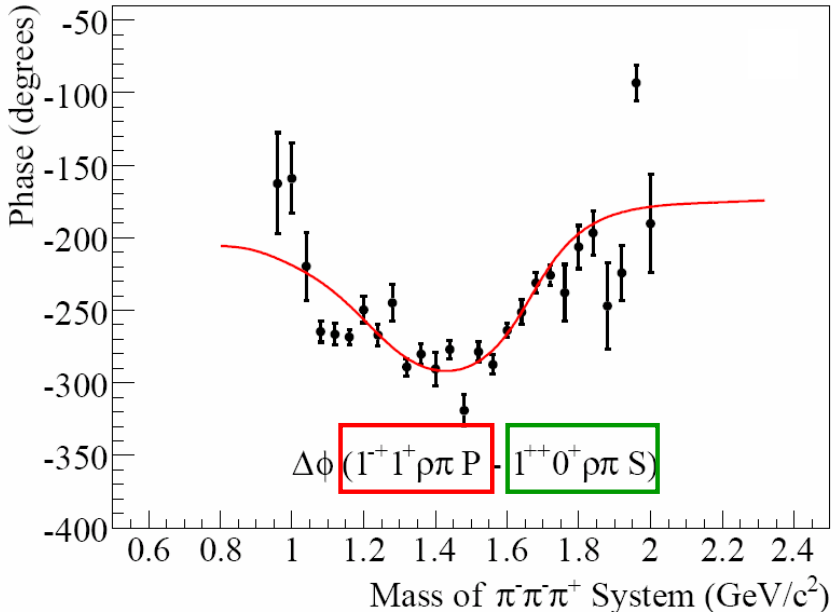

Study of the exotic 1^{-+} wave
-- different decay channels …

Hybrid candidates (1.3 - 2.2 GeV/c²):

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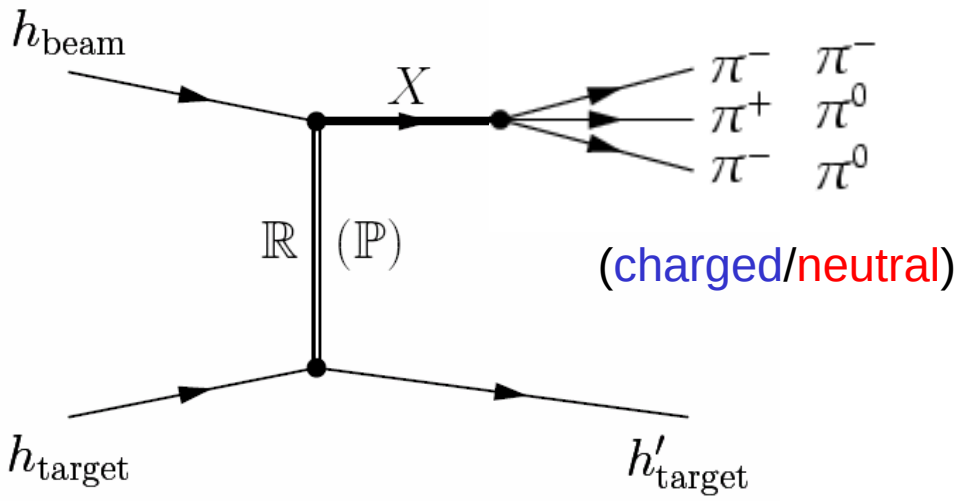

COMPASS (2008/09 data), lets focus on:

- 190 GeV π^- beam *(proton target)*

- study of $\rho\pi$ decay channel via:
  - a) π^- **p** —> $\pi^-\pi^+\pi^-$ **p** (charged mode)
  - b) π^- **p** —> $\pi^-\pi^0\pi^0$ **p** (neutral mode)

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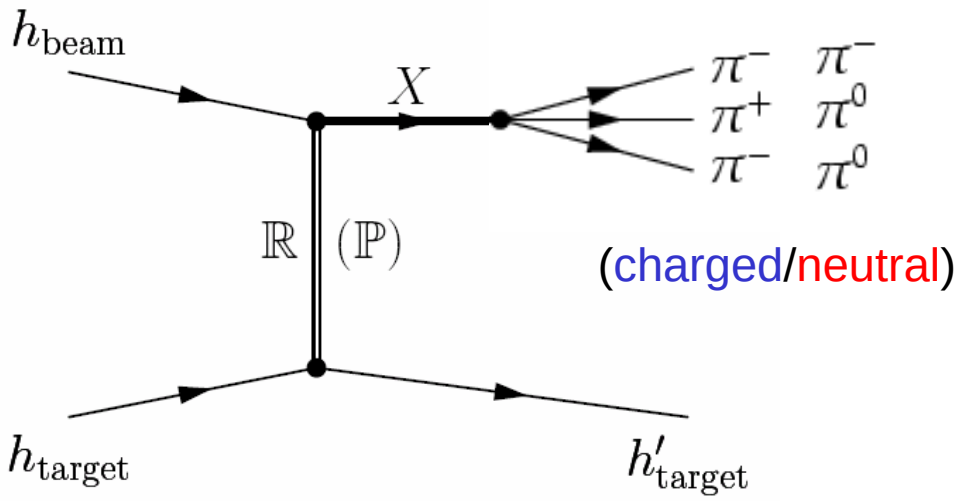

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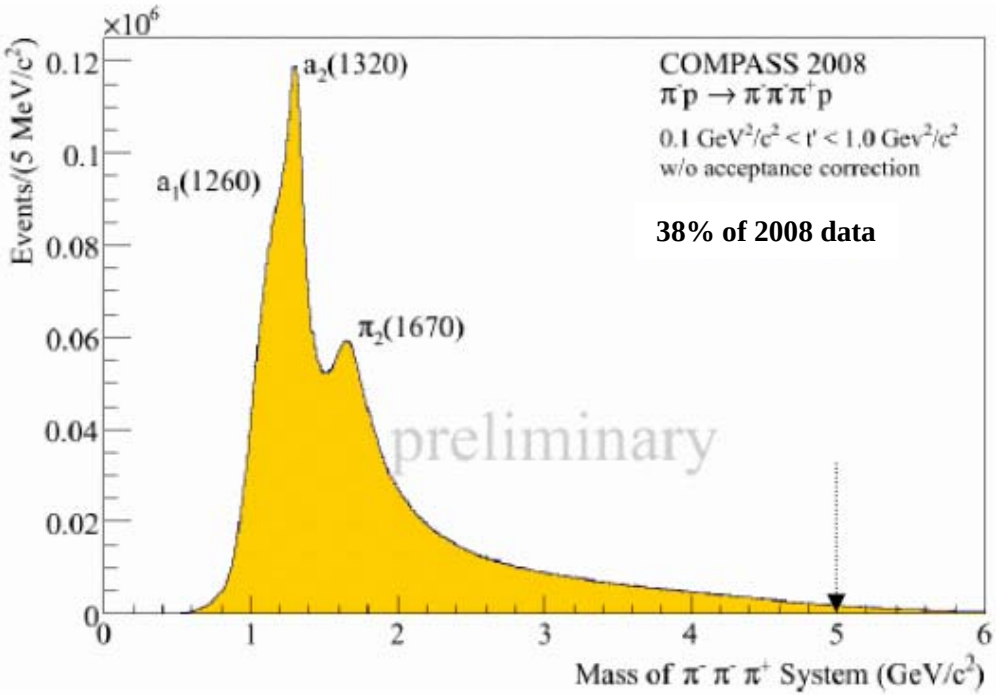
… and further decay channels:

- study of $\eta'\pi$, $\eta\pi$ decay channel via:
  - a) $\pi^-\,\mathbf{p} \longrightarrow \pi^-\eta\,\mathbf{p}$
  - b) $\pi^-\,\mathbf{p} \longrightarrow \pi^-\eta'\mathbf{p}$
- study of $f_1\pi$ decay channel via:
  - a) $\pi^-\,\mathbf{p} \longrightarrow K\bar{K}\pi\pi^-\,\mathbf{p}$ (two modes)

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

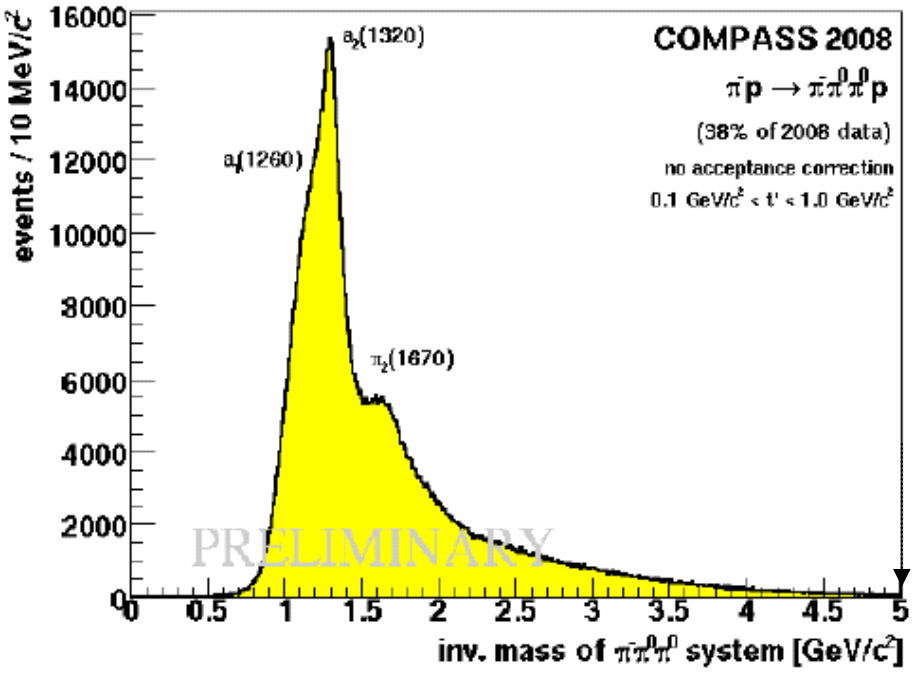
search for $\pi_1(1600)$

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



PWA: ~ 24M events

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



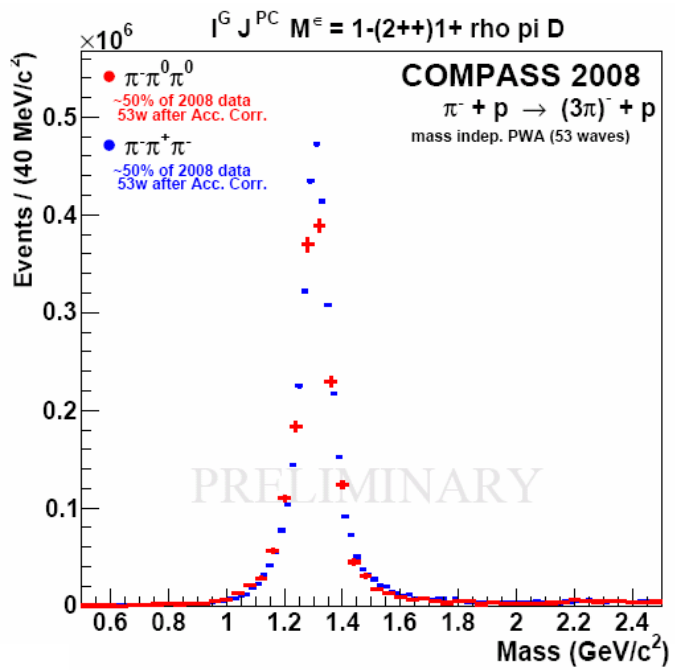
PWA: ~ 1M events

Comparison: Neutral vs. charged mode

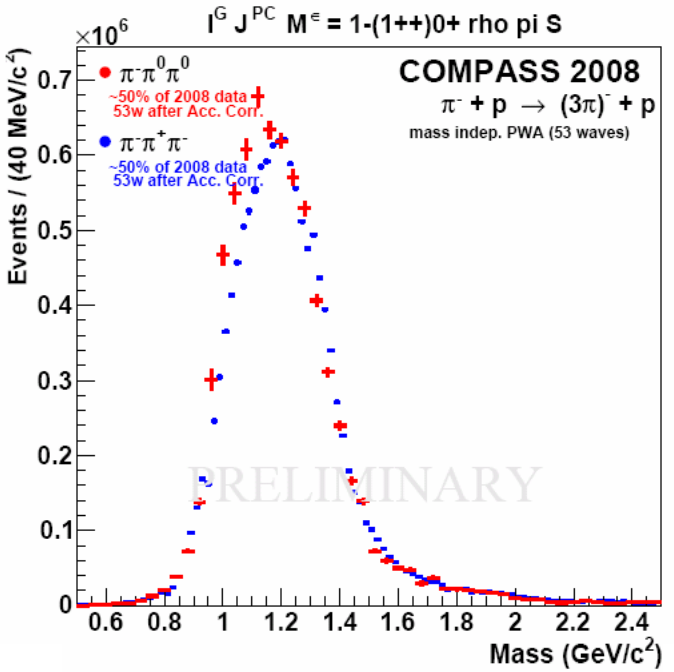
The 3 prominent resonances -- Consistency of isospin partners

search for $\pi_1(1600)$

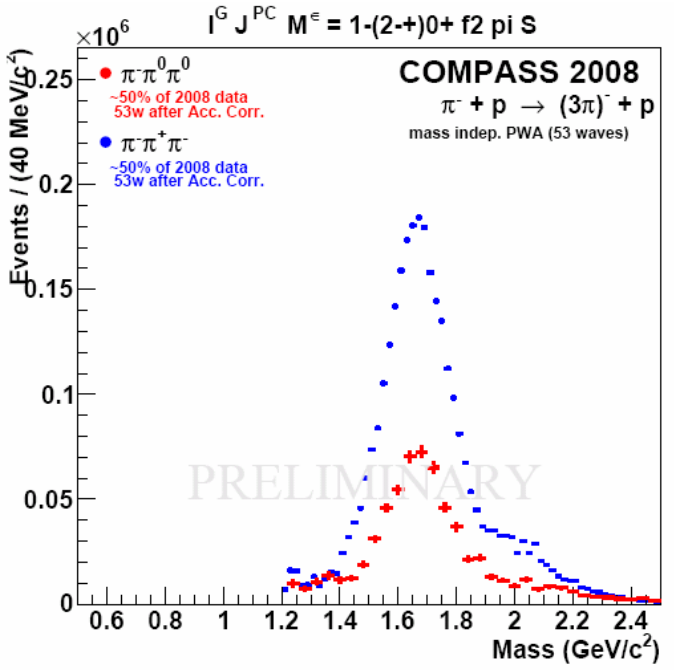
$a_2(1320) \rightarrow \rho\pi$



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



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

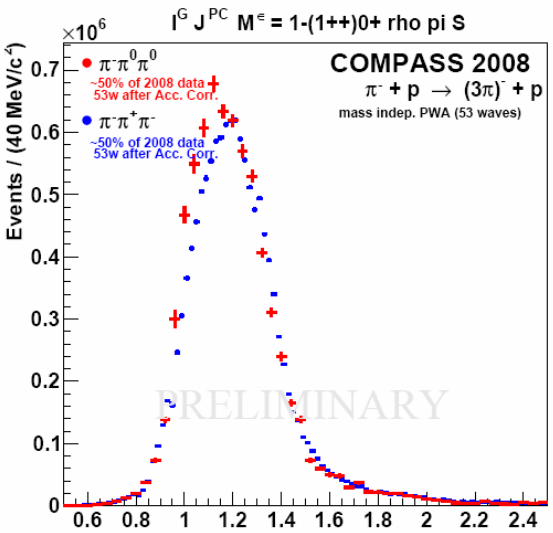


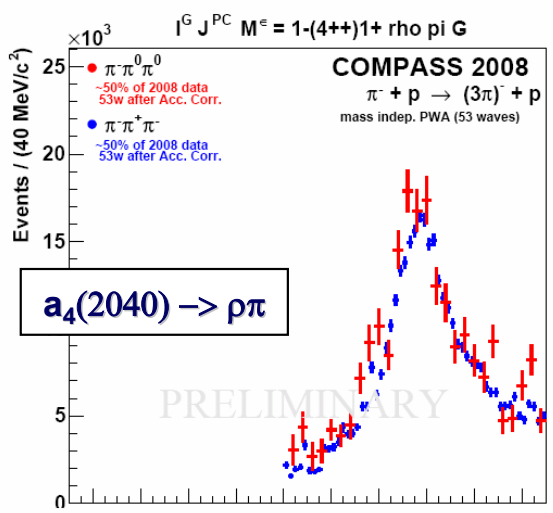
Isospin symmetry: neutral / charge mode

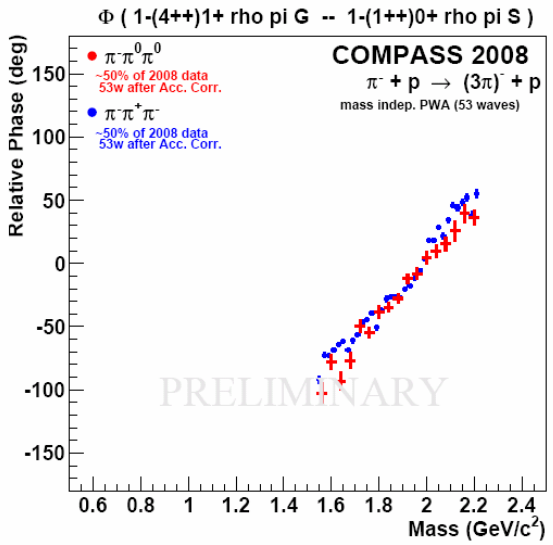
- X^- decaying into $\rho\,\pi$: 1/1 intensity expected *(isovector)*
- X^- decaying into $f_2\,\pi$: 1/2 intensity expected *(isoscalar)*

Comparison: Neutral vs. charged mode

Intensities and relative phase – very small & exotic wave

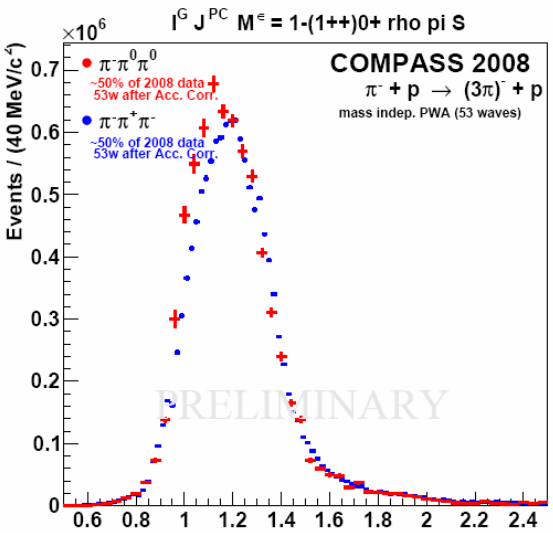


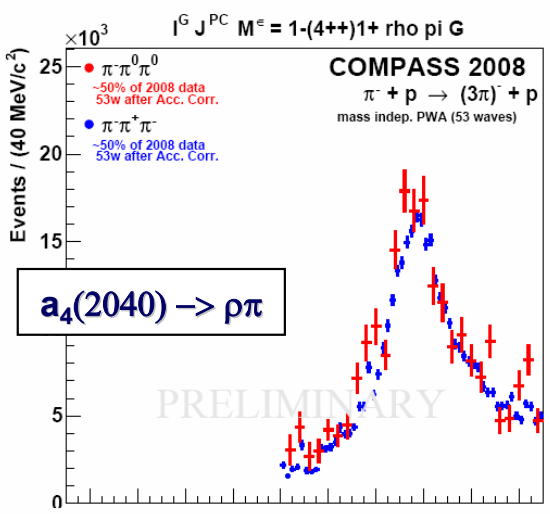


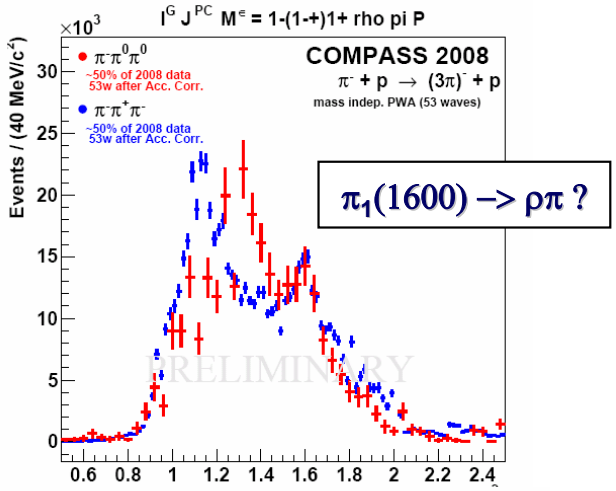


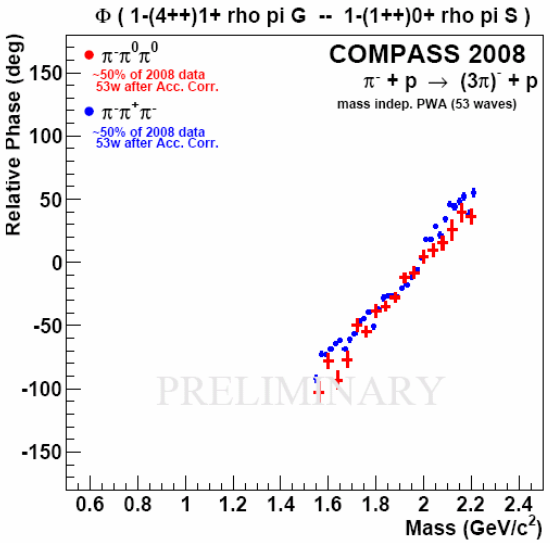
Comparison: Neutral vs. charged mode

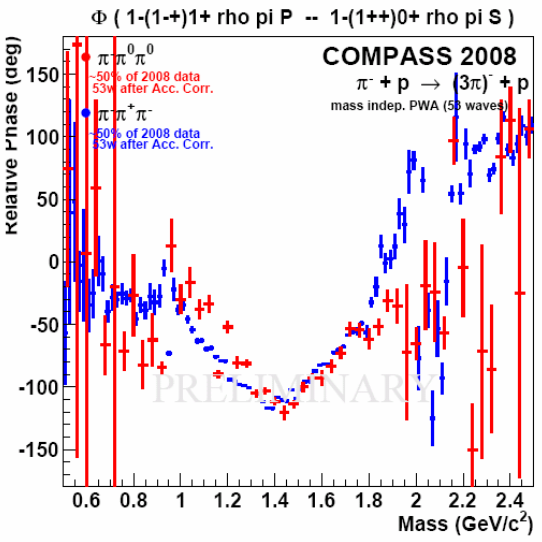
Intensities and relative phase – very small & exotic wave





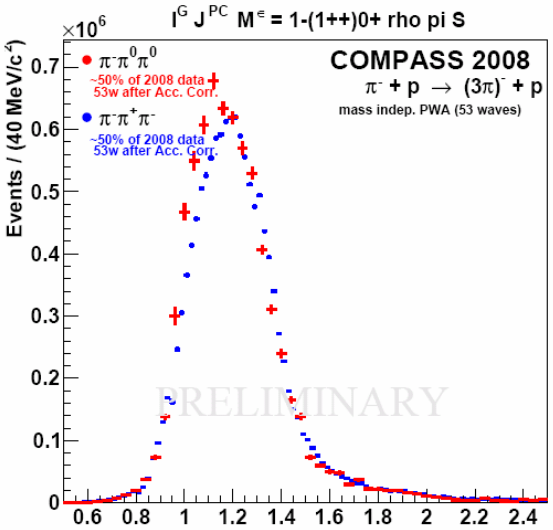


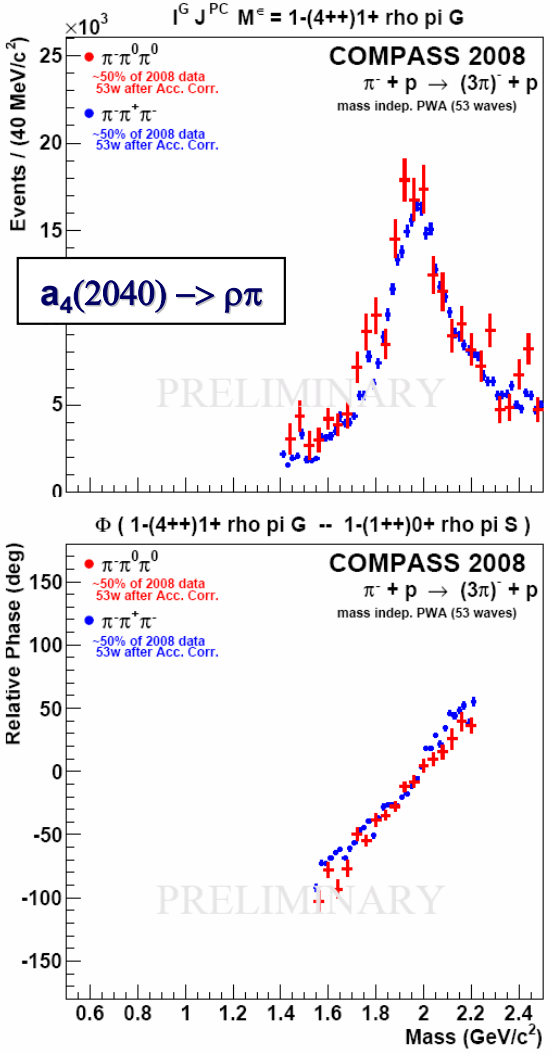


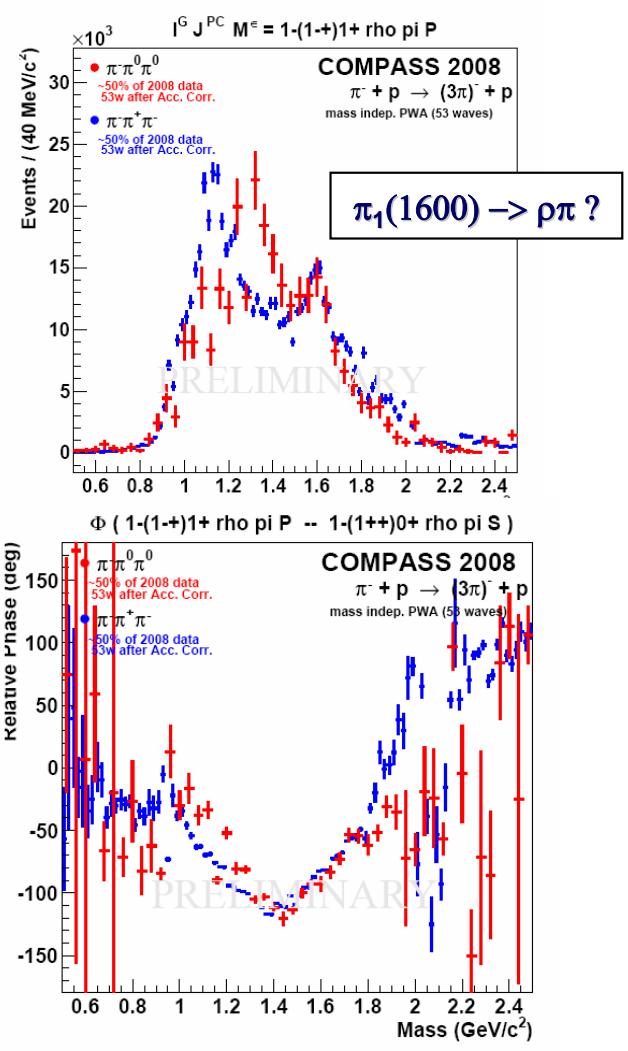


Comparison: Neutral vs. charged mode

Intensities and relative phase – very small & exotic wave







$\pi_1(1600) \rightarrow \rho\pi$?

Before any strong conclusion:

- More systematic studies
- Mass-dependent fit

Study of the exotic 1^{-+} wave
-- different decay channels …

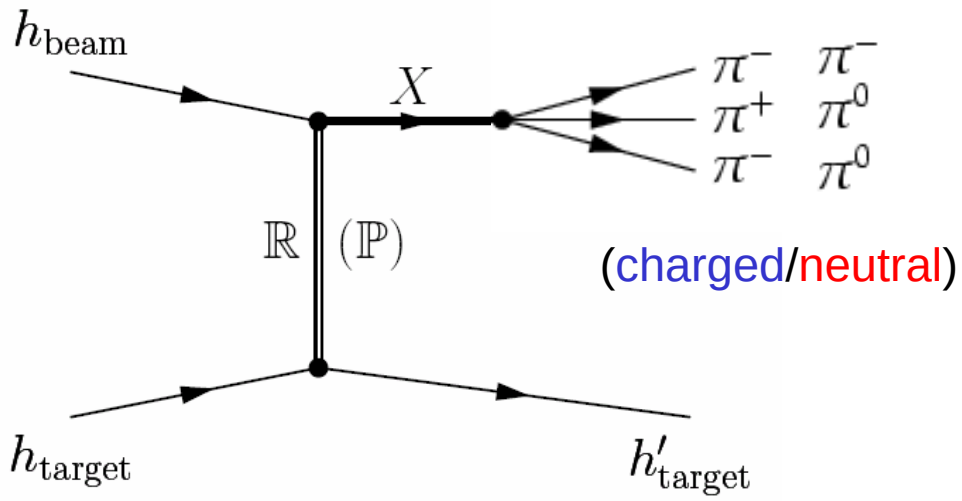
Hybrid candidates (1.3 - 2.2 GeV/c²):

lightest hybrid predicted: exotic $J^{PC} = 1^{-+}$

- $\pi_1(1400)$: VES, E852, Crystal Barrel –> $\eta\pi$
- $\pi_1(1600)$: 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

→ *access to all decay channels, spin-exotics were reported in so far ..*



COMPASS (2008/09 data), lets focus on:

- 190 GeV π^- beam *(proton target)*

- study of $\rho\pi$ decay channel via:
  - a) $\pi^- p \longrightarrow \pi^-\pi^+\pi^- p$ (charged mode)
  - b) $\pi^- p \longrightarrow \pi^-\pi^0\pi^0 p$ (neutral mode)

… and further decay channels:

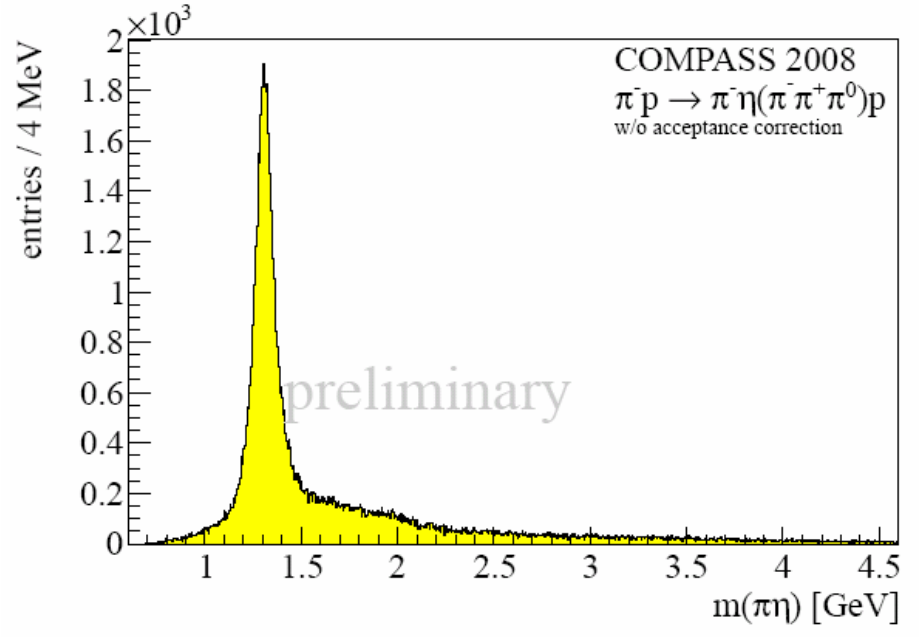
- study of $\eta'\pi$, $\eta\pi$ decay channel via:
  - a) $\pi^- p \longrightarrow \pi^-\eta p$
  - b) $\pi^- p \longrightarrow \pi^-\eta' p$

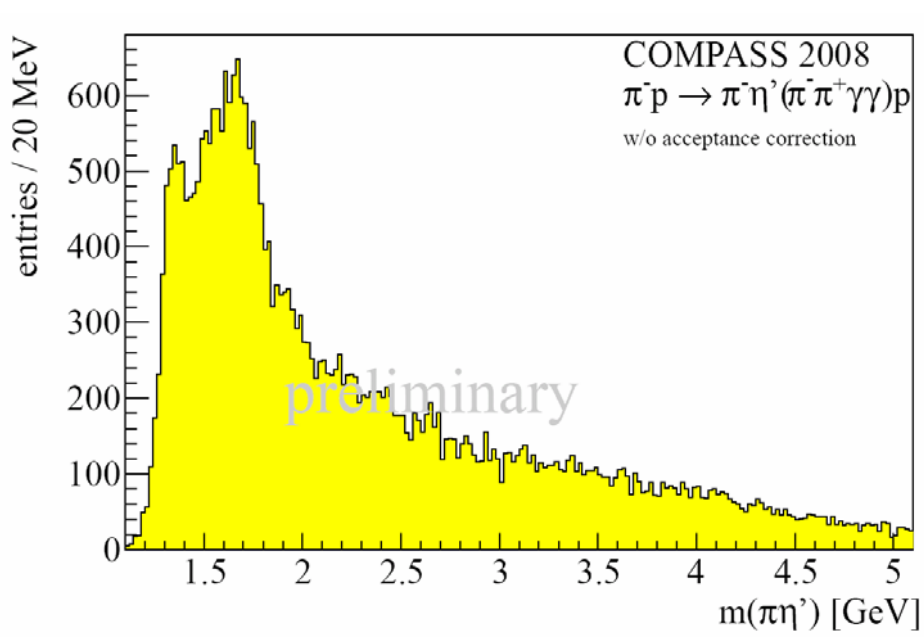
- study of $f_1\pi$ decay channel via:
  - a) $\pi^- p \longrightarrow K\bar{K}\pi\pi^- p$ (two modes)

Different channel for the search: π^-+p –> π^- η/η' + p

search for $\pi_1(1600)$

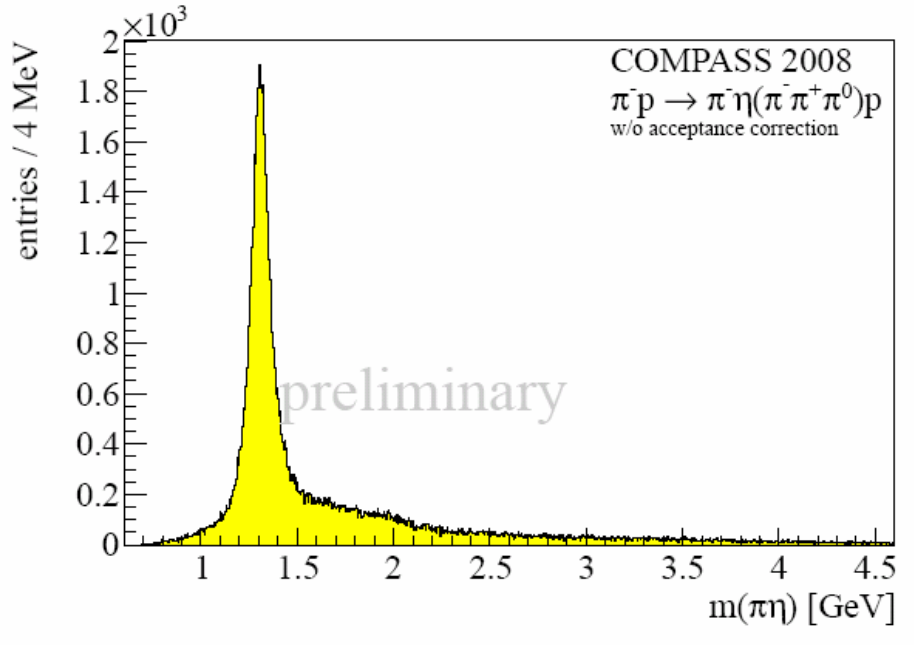
- η reconstructed from η –> $\pi^+\pi^-\pi^0$
- η' reconstructed from η' –> $\pi^+\pi^-\eta$, with η –> $\gamma\gamma$





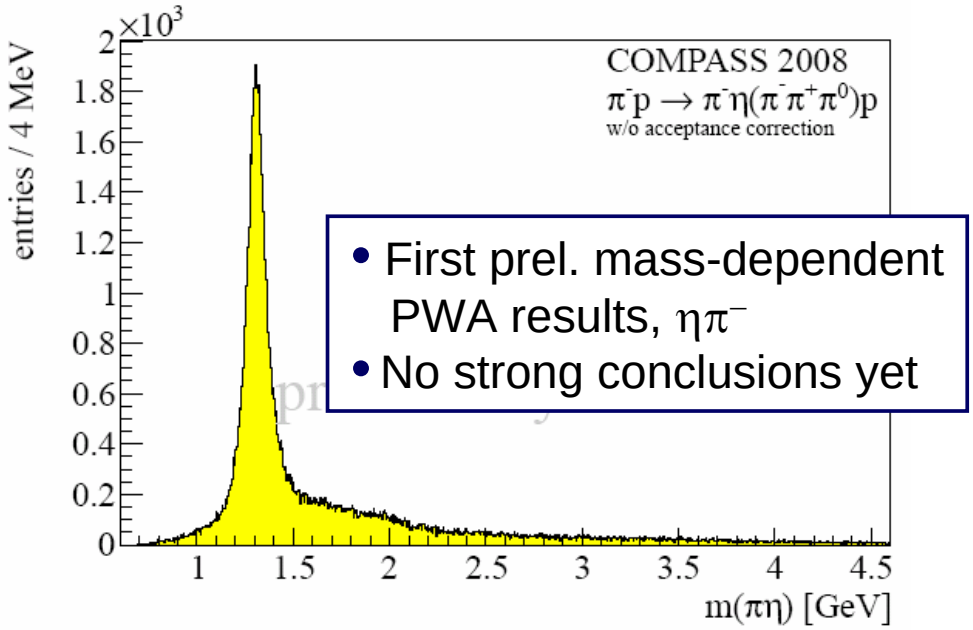
Different channel for the search: $\pi^- + p \rightarrow \pi^- \eta + p$

search for $\pi_1(1600)$

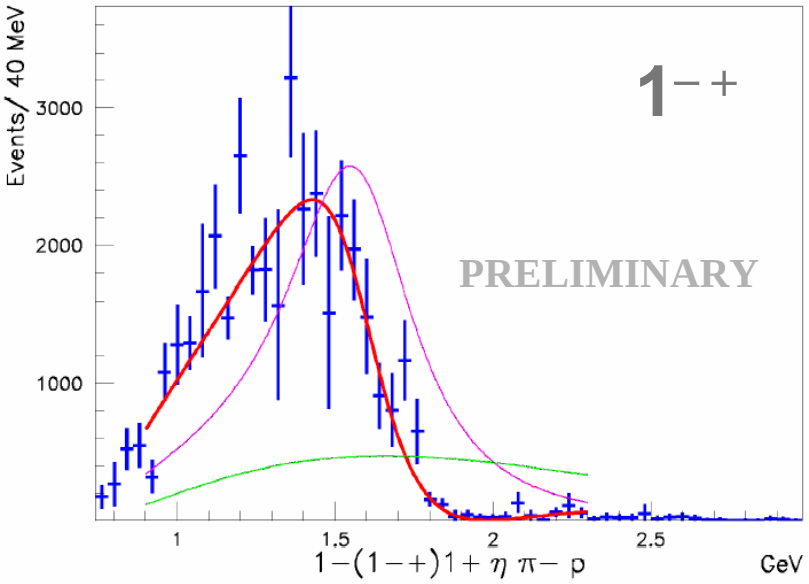


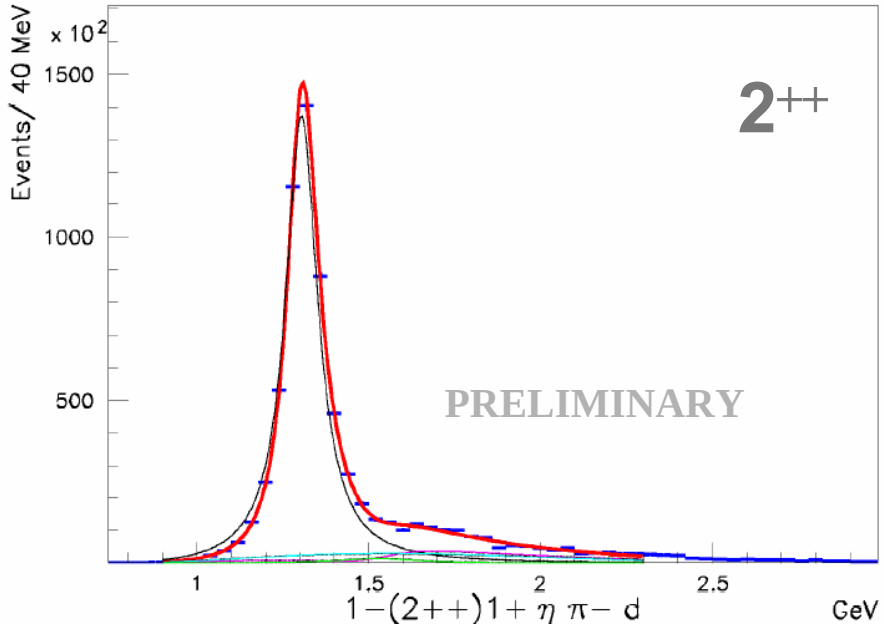
Different channel for the search: $\pi^-+p \rightarrow \pi^-\eta + p$

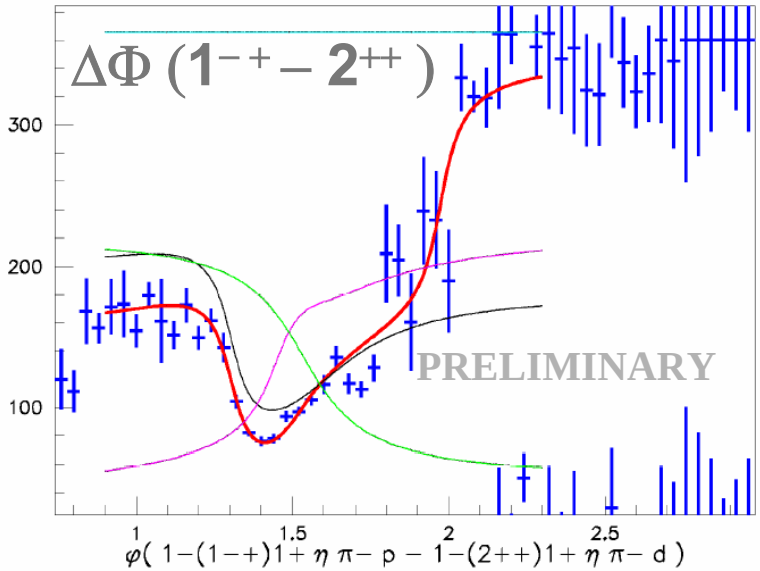
search for $\pi_1(1600)$



- First prel. mass-dependent PWA results, $\eta\pi^-$
- No strong conclusions yet

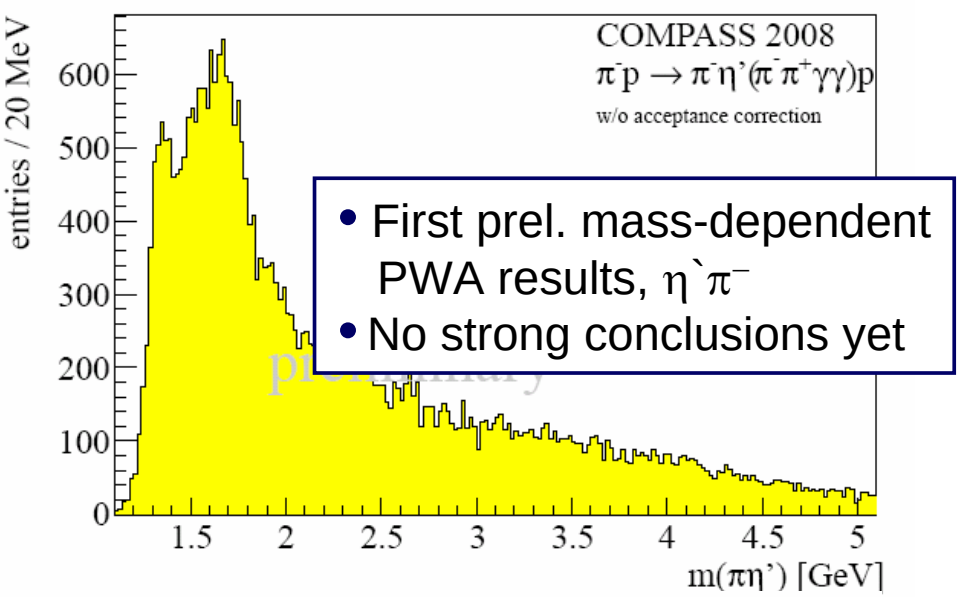




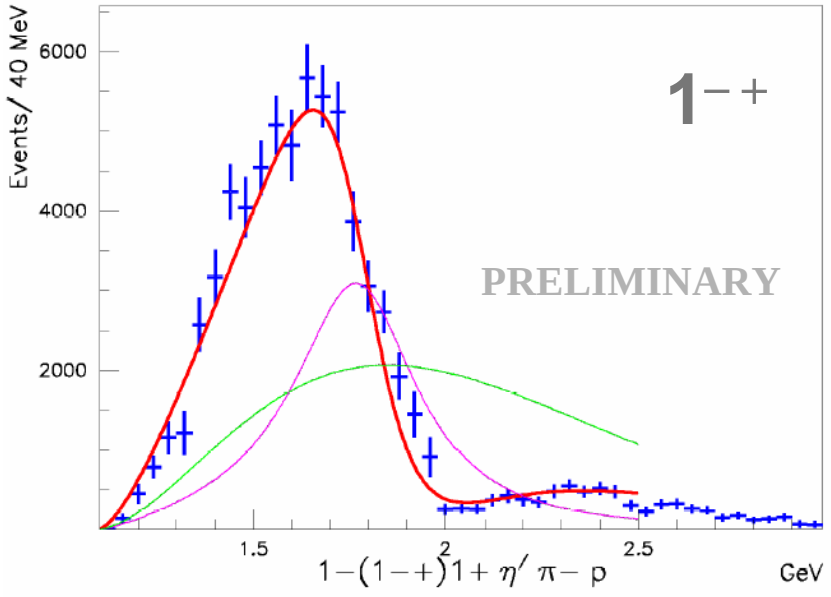


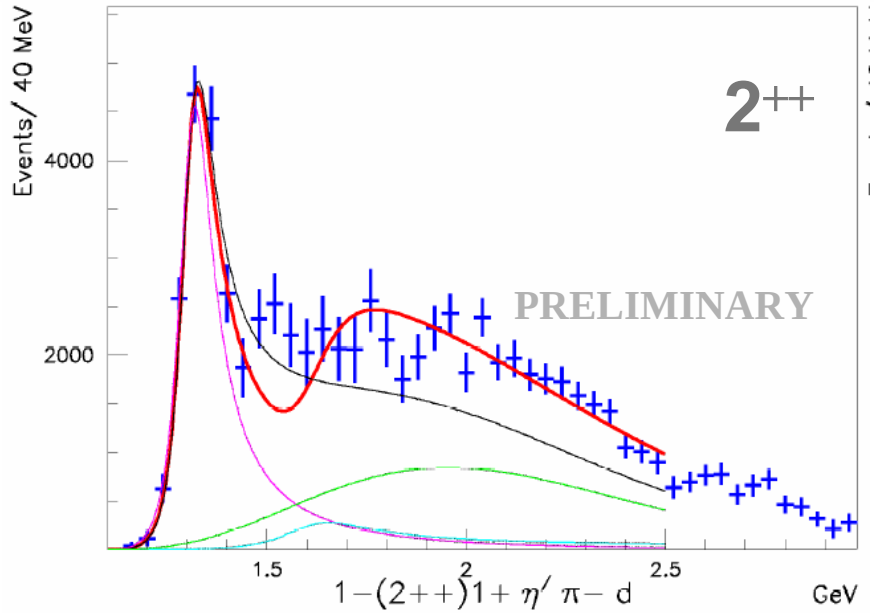
Different channel for the search: $\pi^- + p \rightarrow \pi^- \eta' + p$

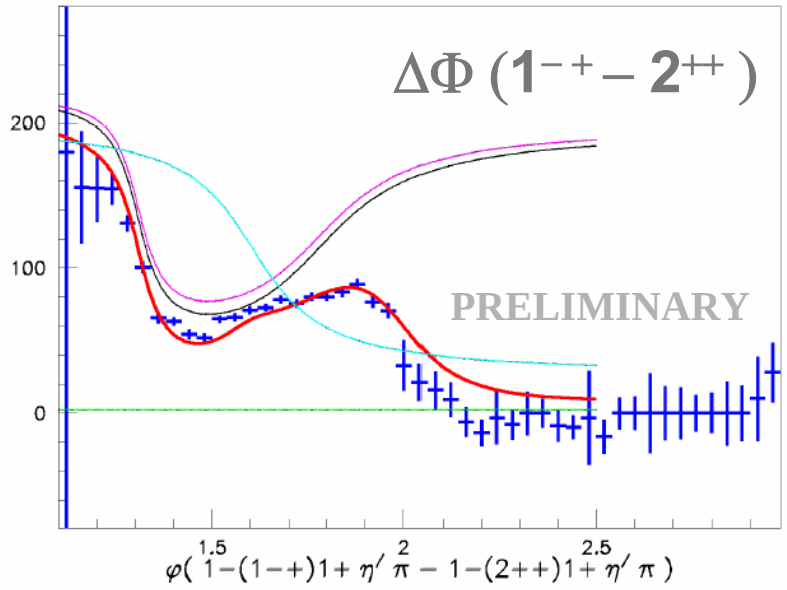
search for $\pi_1(1600)$



- First prel. mass-dependent PWA results, $\eta'\pi^-$
- No strong conclusions yet





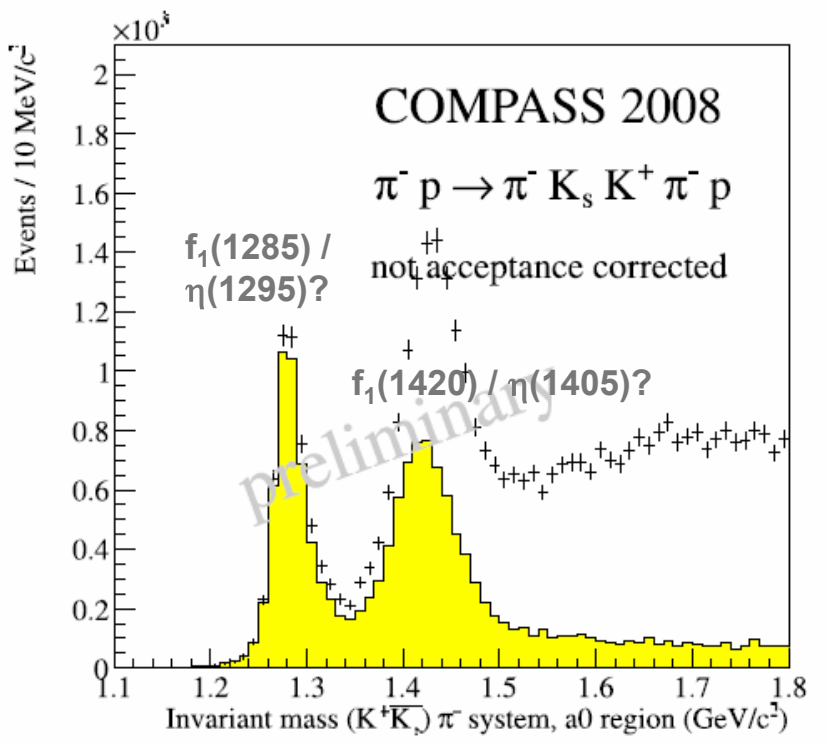


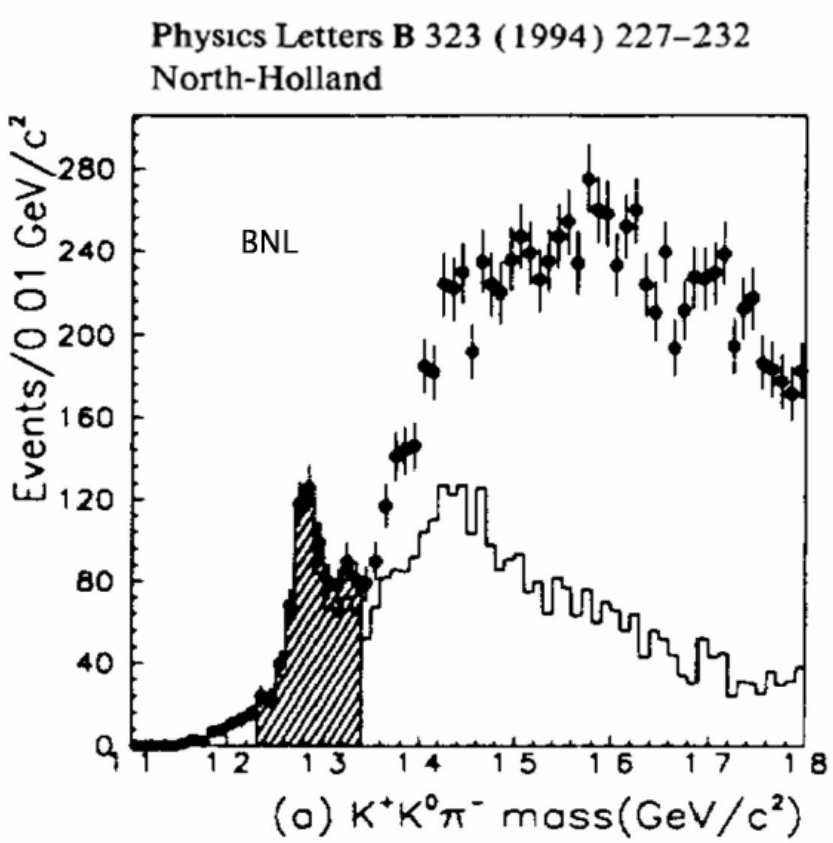
Different channel for the search: First studies of $K\bar{K}\pi\pi$ final states

Physics channel: $\pi^- p \rightarrow K\bar{K}\,\pi\,\pi^-\,p$ (two modes)
Motivation: Search for diffr. X^- coupling to $s\bar{s}$ final states
First preliminary PWA started: $\overline{K^0}\,K^+\,\pi^-\,\pi^-$

search for $\pi_1(1600)$, $\pi_1(2000)$

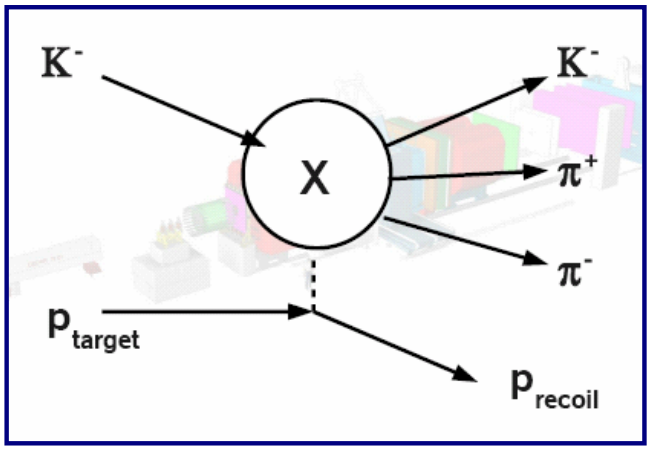
$(K\bar{K}\pi)^0$ subsystem:

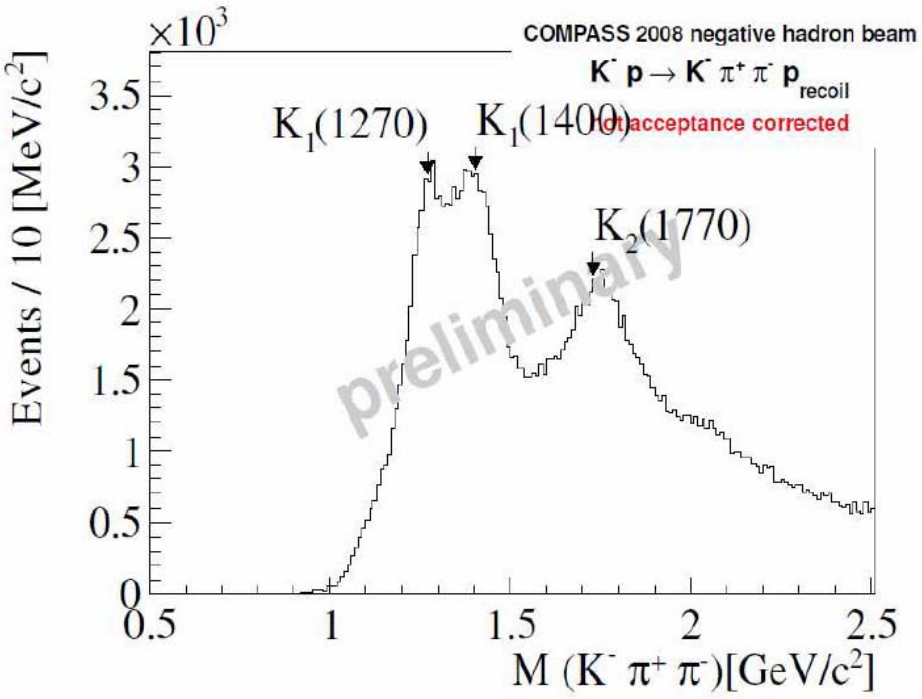




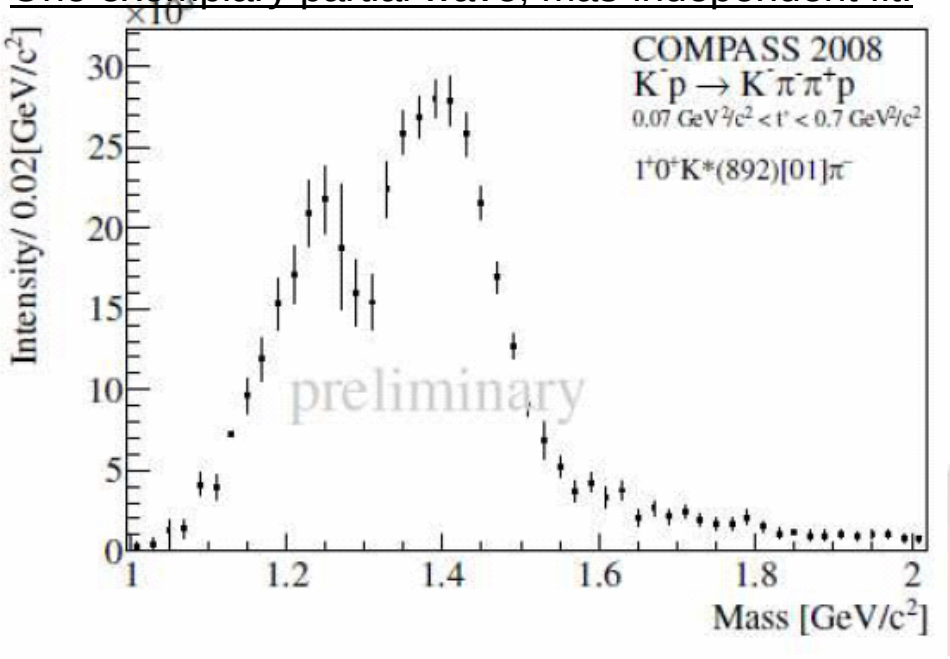
Statistics: 2008 data => ~ factor 10 w.r.t. BNL (~20 for 2008/09)

Physics with the kaon beam: Kaon diffraction





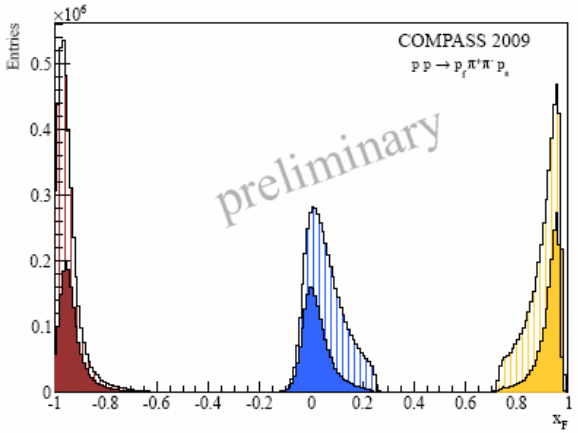
One exemplary partial wave, mas-independent fit:



- Statistics ~5 more than WA03
- Several states need confirmation,
  → *e.g. the K(1460)*
- Kaon physics will be an interesting option for future measurements!

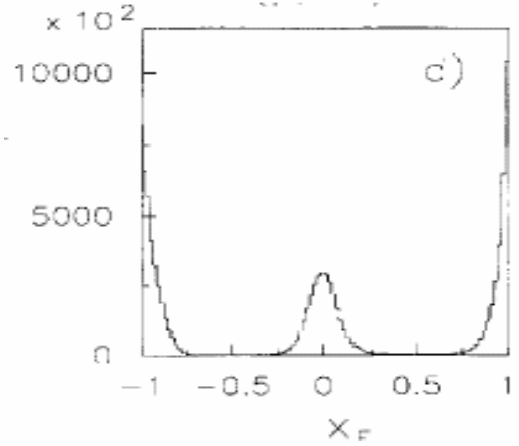
First studies of Central Production of $(\pi\pi)^0$

COMPASS

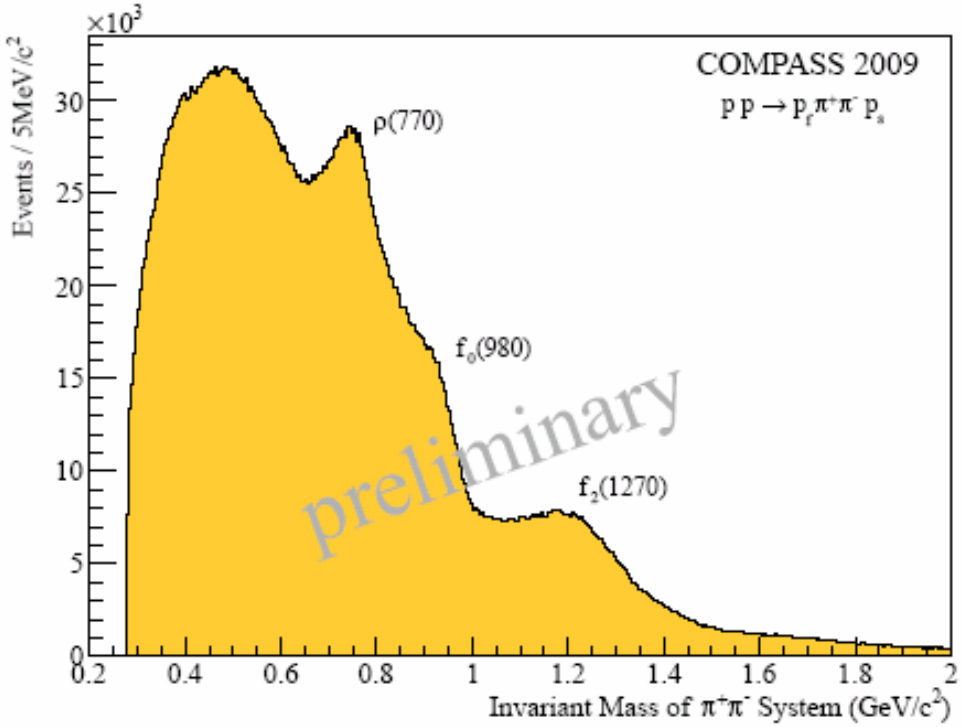


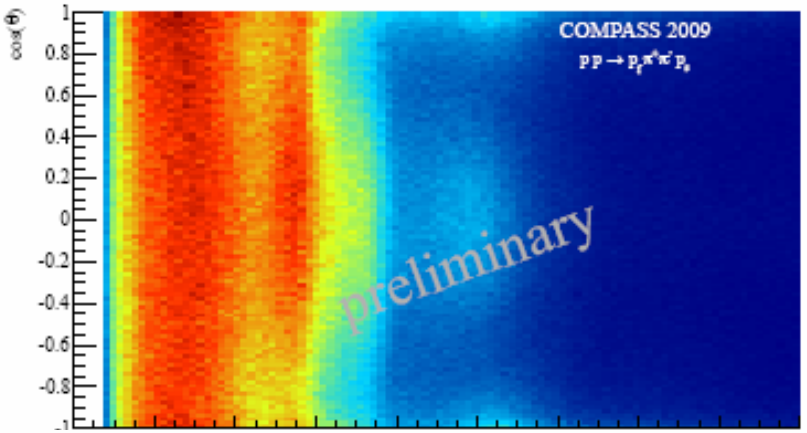
WA102

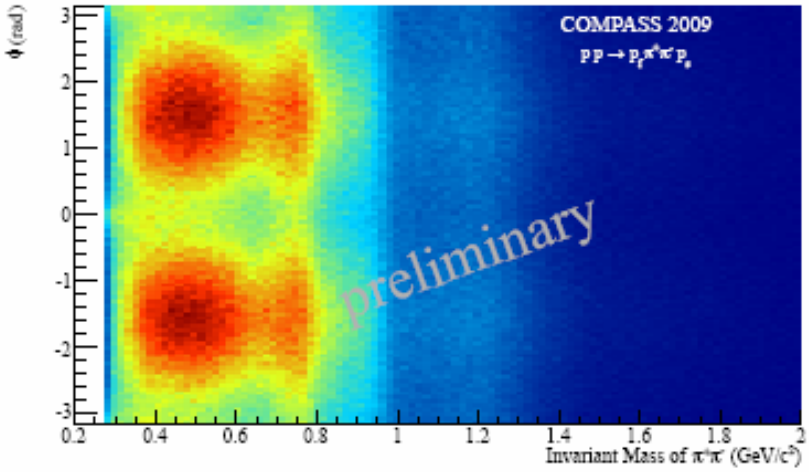
[Barberis et al. PL B 453 (1999)]



Search for resonances, CP

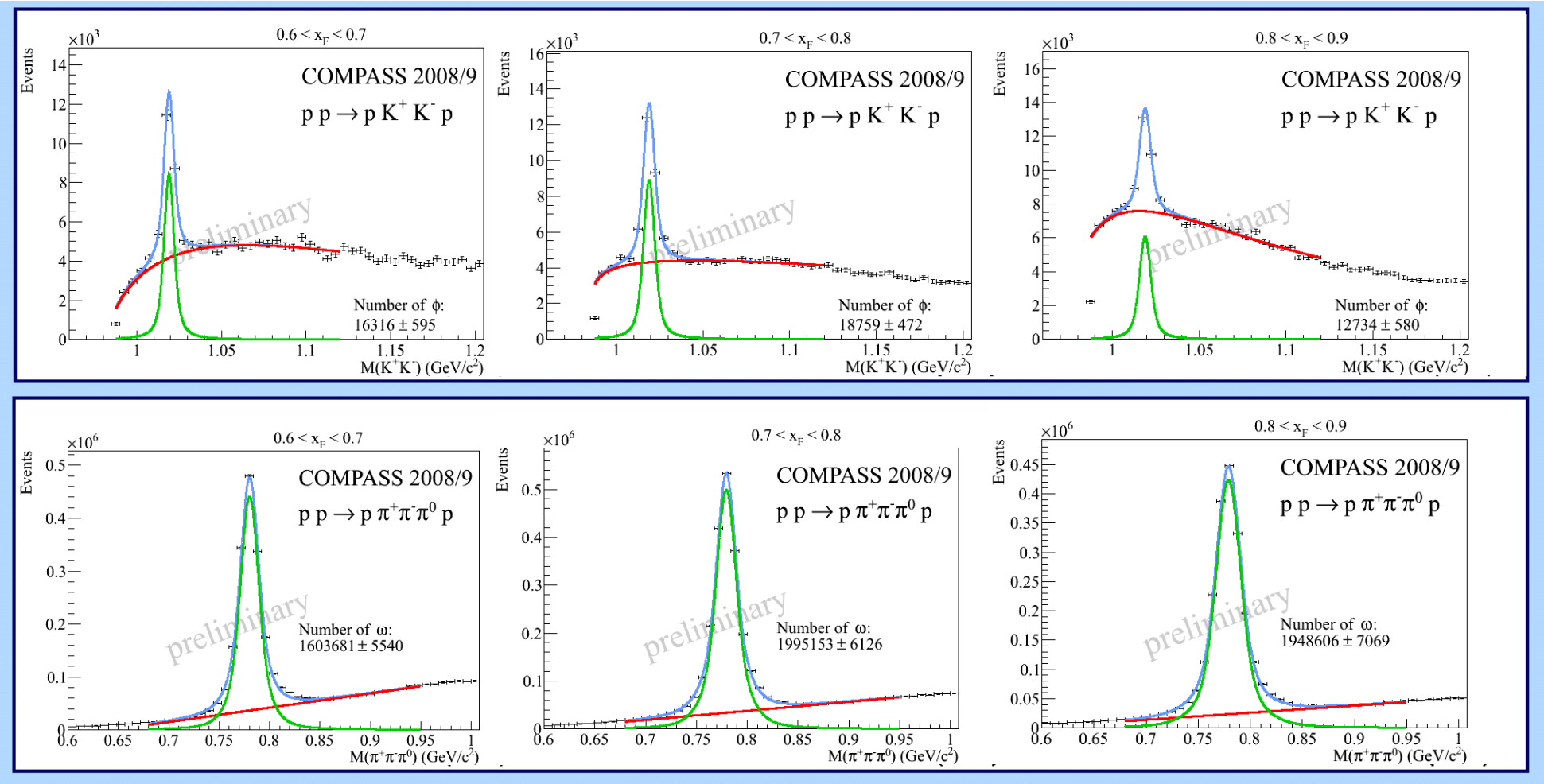






Test of OZI violation

- Comparison of differential cross sections in ω and ϕ production *(with respect to x_F, in pp reactions)*



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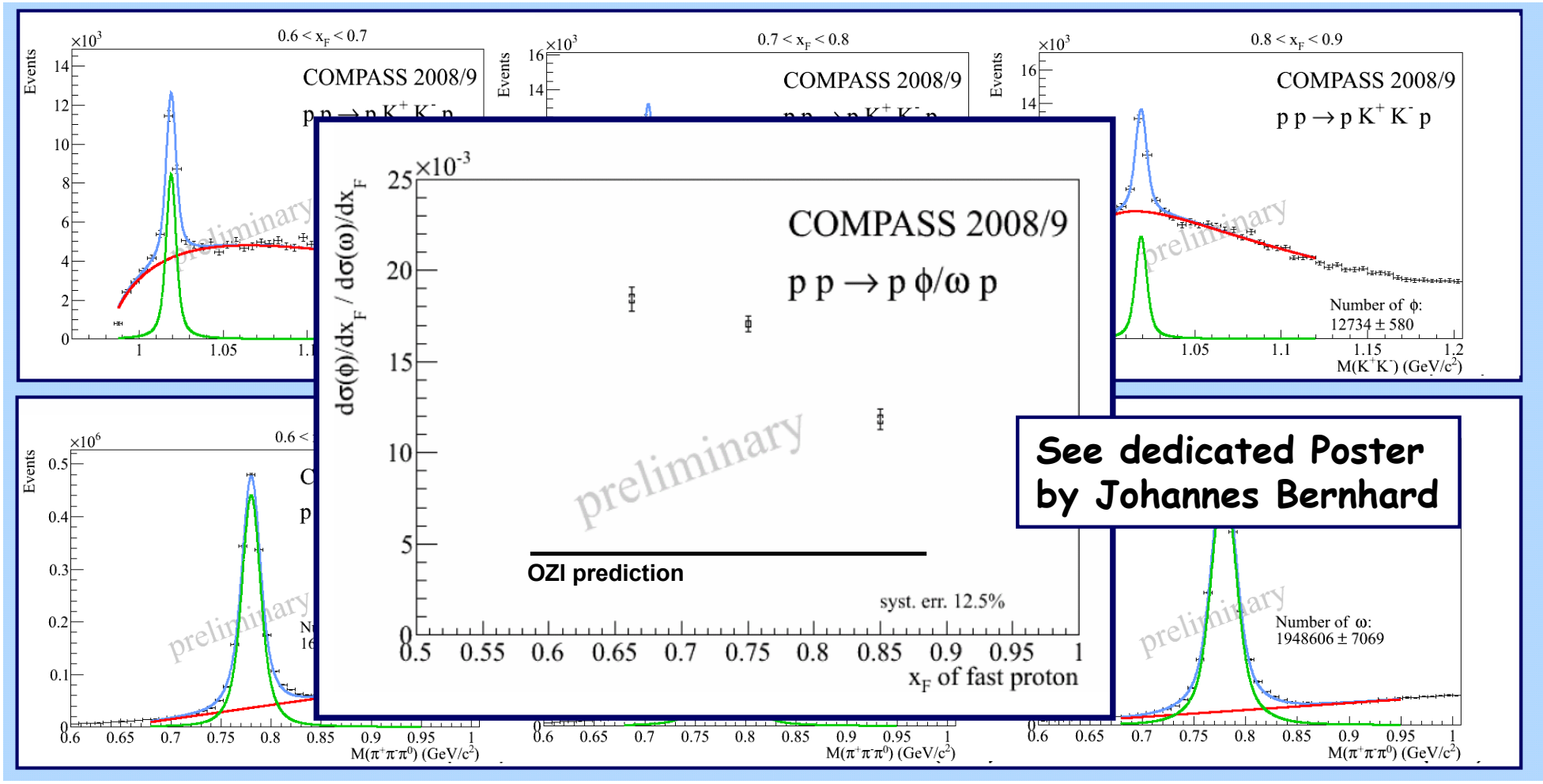
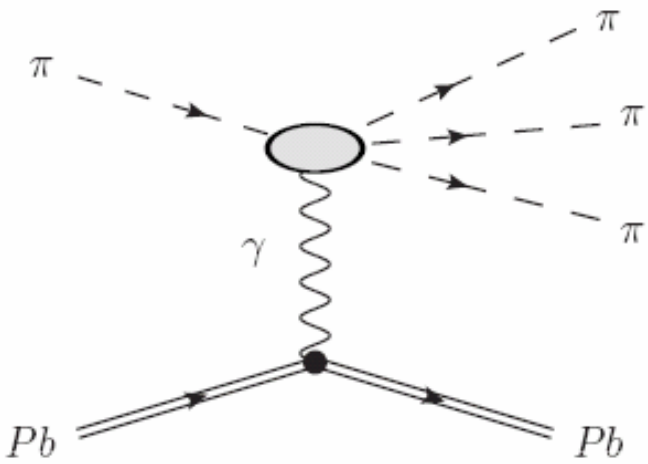
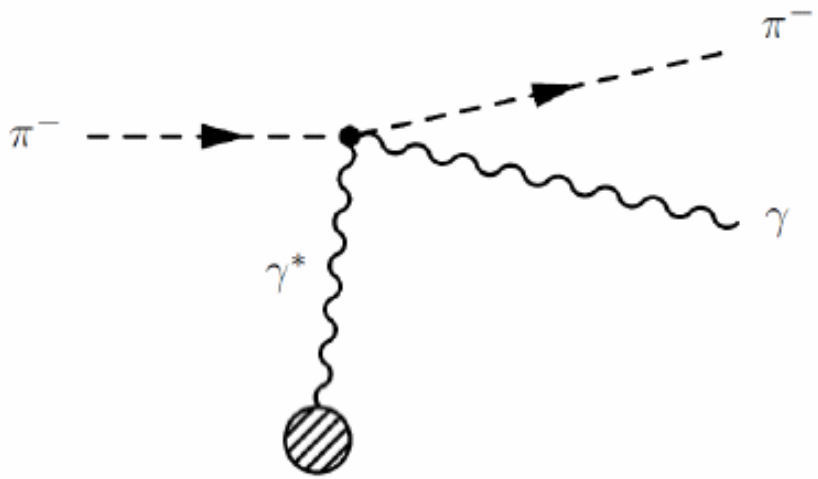


Test of Chiral dynamics
(low t' in Coulomb region)

Go to very low Q^2:



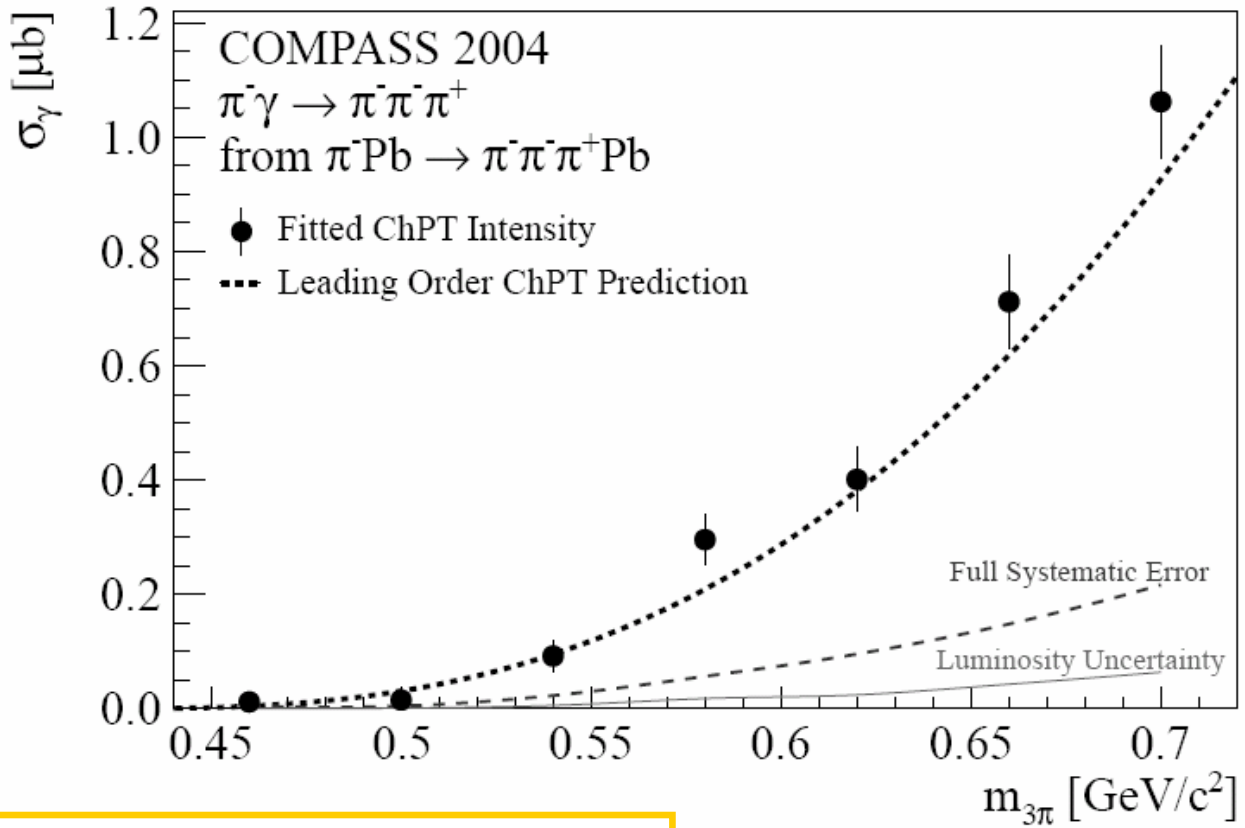


Measurement of Chiral dynamics in 3π final states
(low t' in Coulomb region)

Go to very low Q^2:

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

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



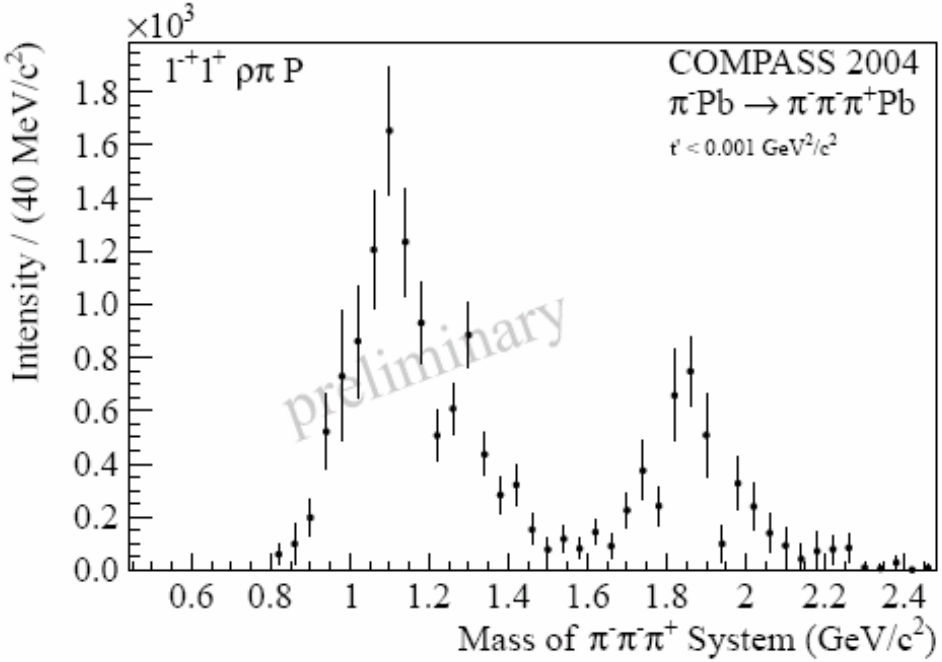
First measurement of cross-section in this range:

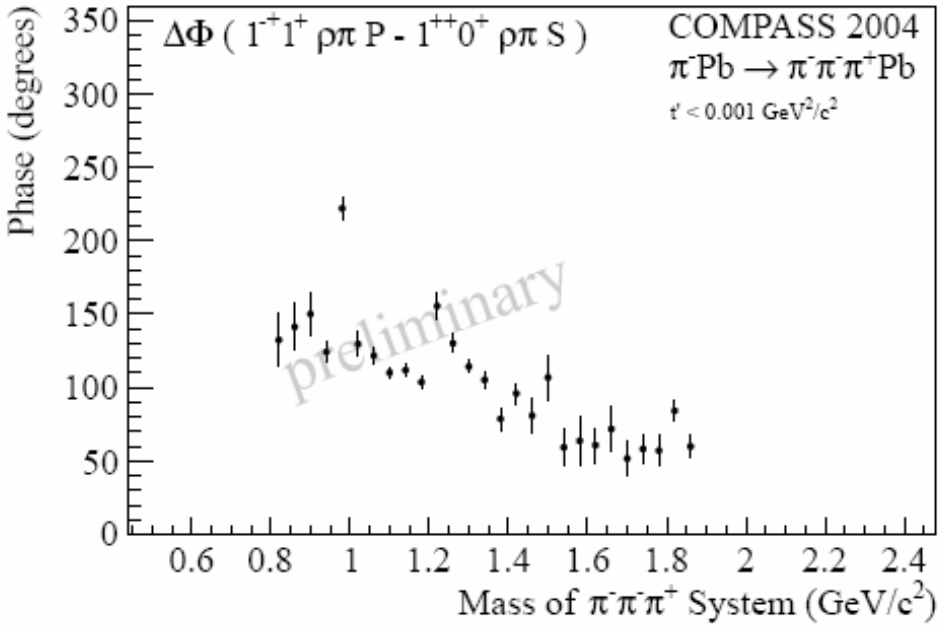
Reaction $\pi^- Pb \to \pi^-\pi^-\pi^+ Pb$

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

Measurement of Chiral dynamics in 3π final states
(low t′ in Coulomb region)

Go to very low Q^2:





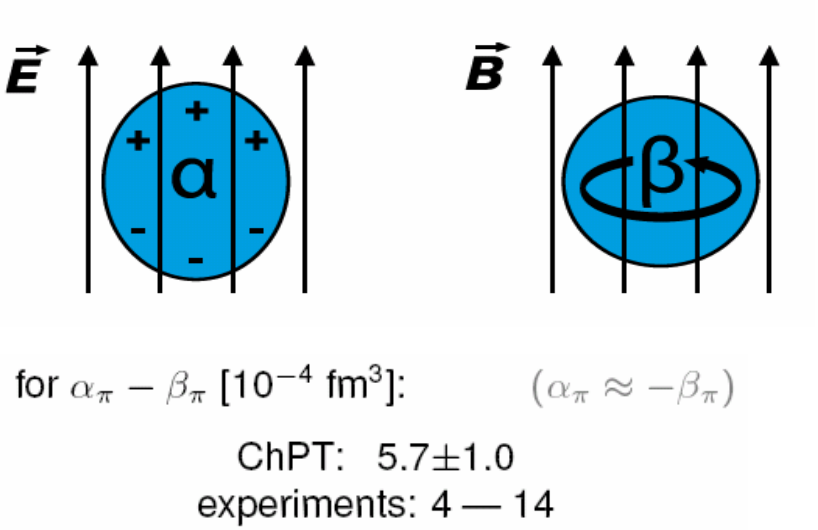
Spin exotics in photo production:

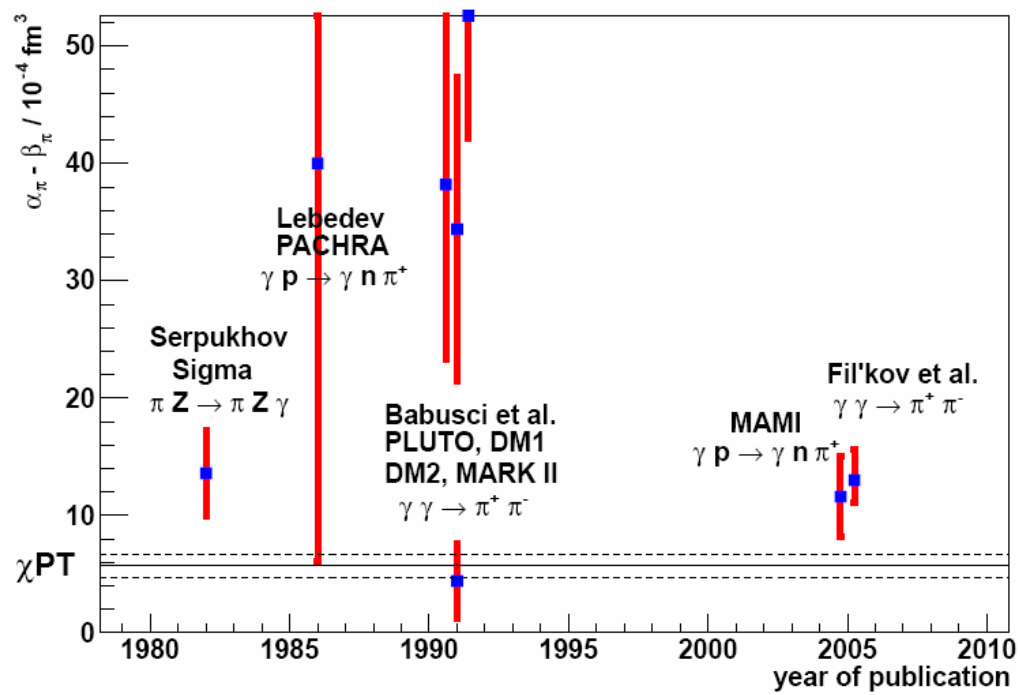
- **no evidence for the $\pi_1(1600)$ in Primakoff production**
- **inline with results from CLAS/JLab** [hep-ex/1108.6112]

Outlook: Measurements of Primakoff reactions

(low t′ in Coulomb region)

- **Measurement of fundamental pion / kaon polarisibility**
- **Dedicated run in 2012** (data taking started)
  => experimentally demanding, systematics precisely to be controlled





- **Uncertainty on $\alpha_\pi - \beta_\pi$: ±0.66** (ChPT: 5.7)
- **First measurement of polarisibility as sum $\alpha_\pi + \beta_\pi$ at expected uncertainty of ±0.025** (ChPT: 0.16)

Summary & conclusions

- **COMPASS: High potential for Hadron spectroscopy**
  - ✓ **2008/09: Very high statistics taken** *(hadron beams, proton & nuclear targets)*
  - ✓ **COMPASS measures Neutral & Charged channels**
  - ✓ **All relevant channels for spin-exotic search feasible**

  => and many other analysis topics (OZI, ChPT, Baryon spectroscopy …)

Not discussed:
Further channels in meson spectroscopy ($p\pi \rightarrow 5\pi\, p$, $p\pi \rightarrow K^+K^-\pi\, p$, ...)
Baryon spectroscopy

- **COMPASS-II (outlook)**
  - **Primakoff** *(polarisibilities) → 2012 run, ongoing*
  - **Drell Yan** *(fundamental check of Sievers fctn.) → 2014 data taking*
  - **GPDs** *(2D → 3D picture of the nucleon) → 2015/16 data taking*

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  => and many other analysis topics (OZI, ChPT, Baryon spectroscopy …)

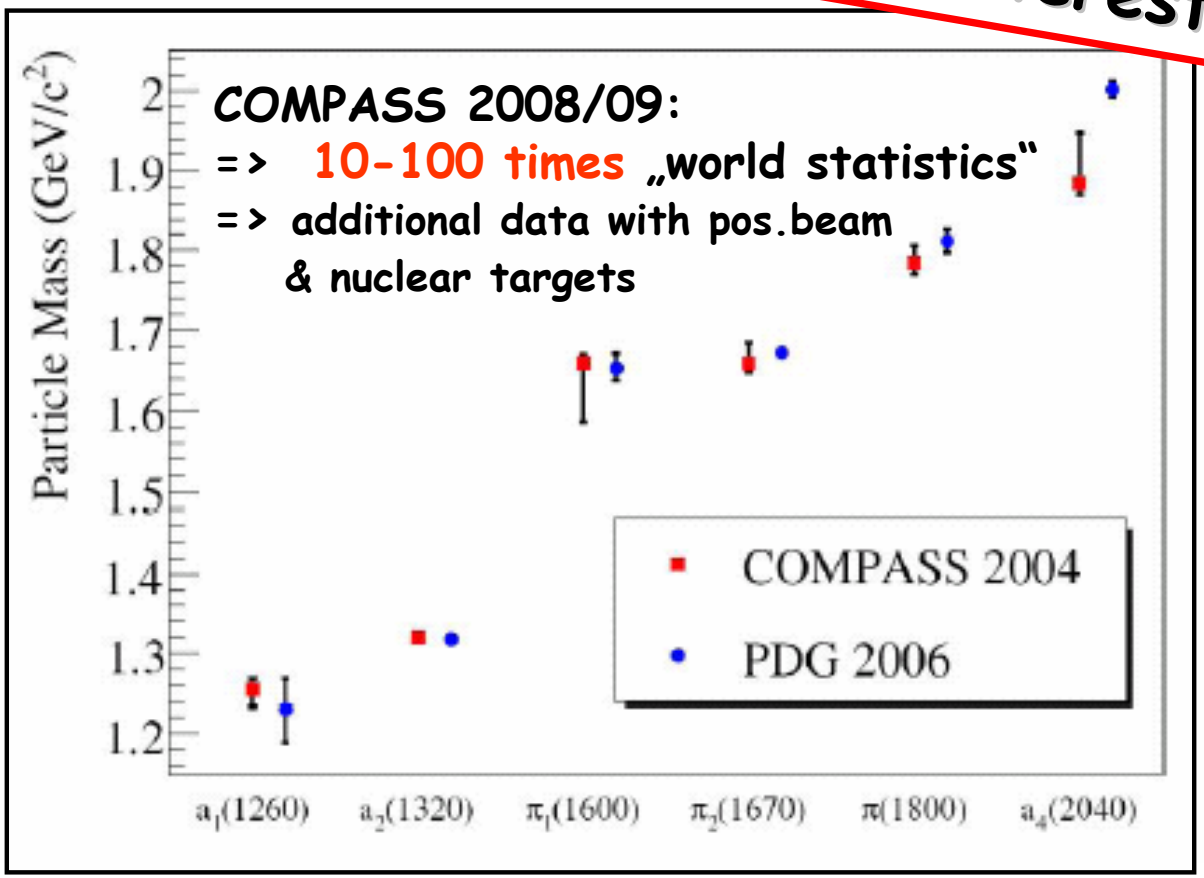
Not discussed:
Further channels in meson spectroscopy ($p\pi \rightarrow 5\pi\, p$, $p\pi \rightarrow K^+K^-\pi\, p$, ...)
Baryon spectroscopy

Advertisment: 2 dedicated Poster
-> Test of OZI violation by J.Bernhard
-> 3π neutral vs. charged by F.Nerling

- **COMPASS-II (outlook)**
  - **Primakoff** *(polarisibilities)* → *2012 run, ongoing*
  - **Drell Yan** *(fundamental check of Sievers fctn.)* → *2014 data taking*
  - **GPDs** *(2D → 3D picture of the nucleon)* → *2015/16 data taking*

Summary & conclusions

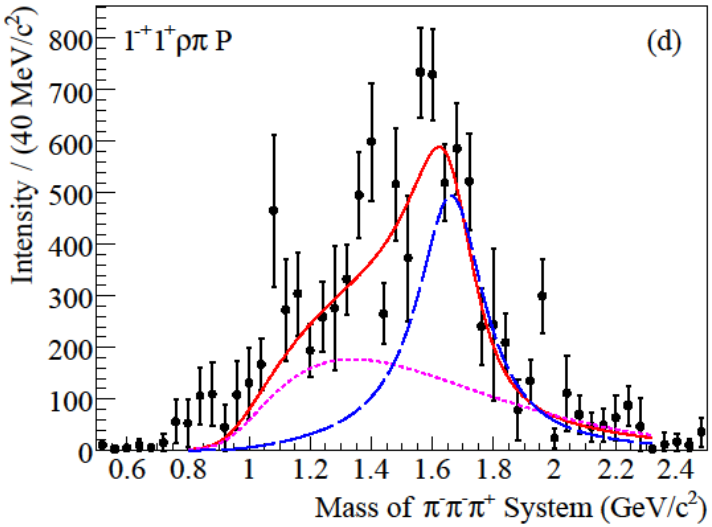
Stay tuned for more interesting COMPASS results …

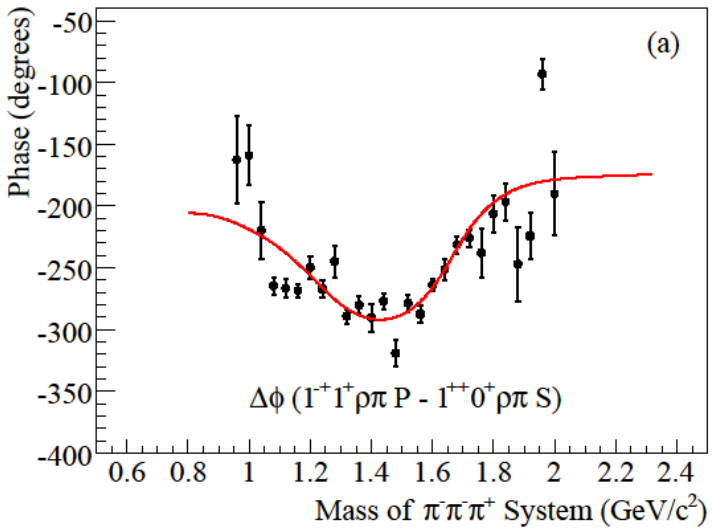


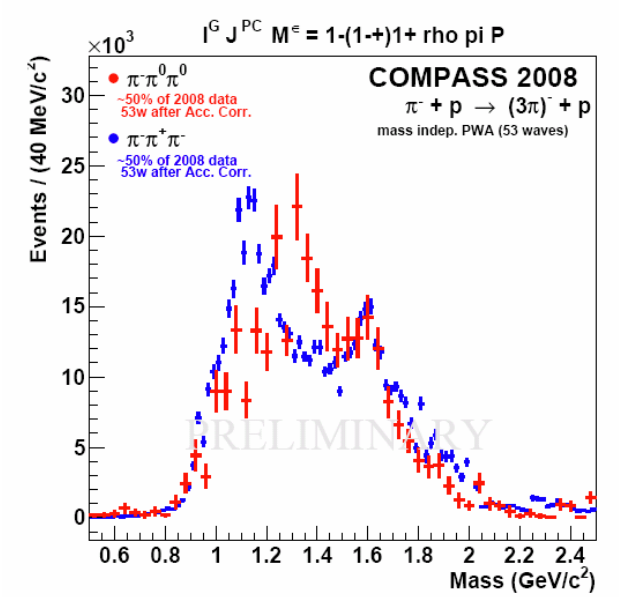
THANK YOU !!!

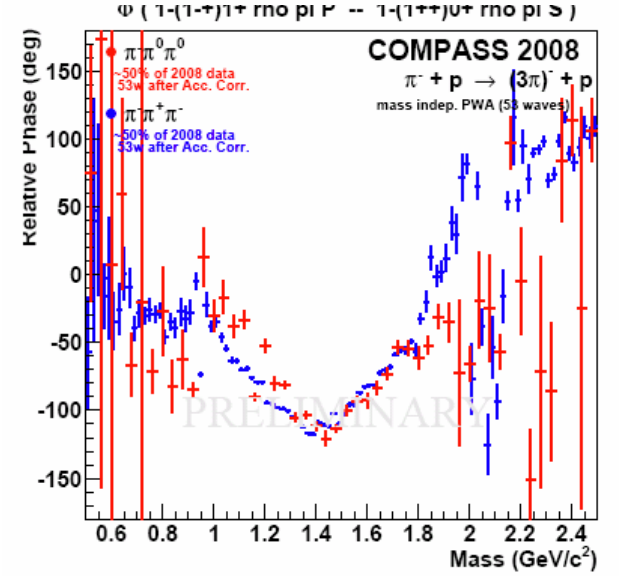
Additional material

Exotic signal – 2004 vs 2008 data



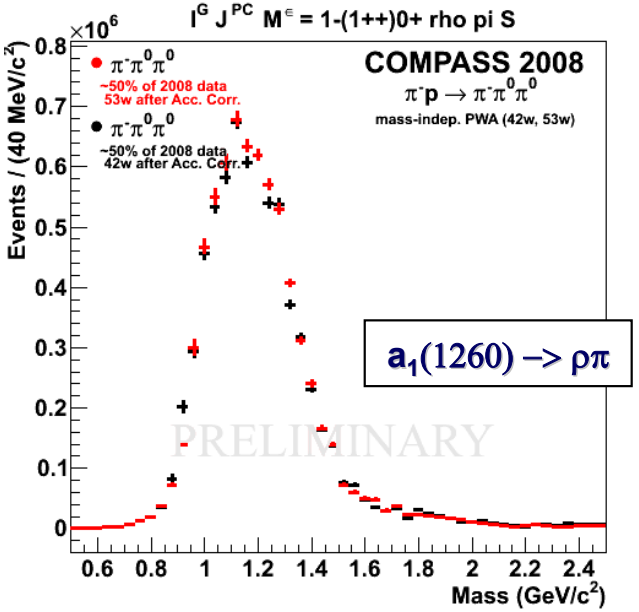


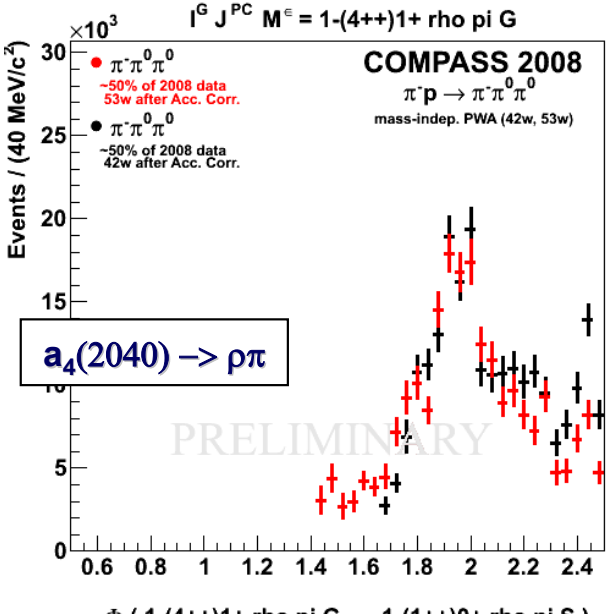


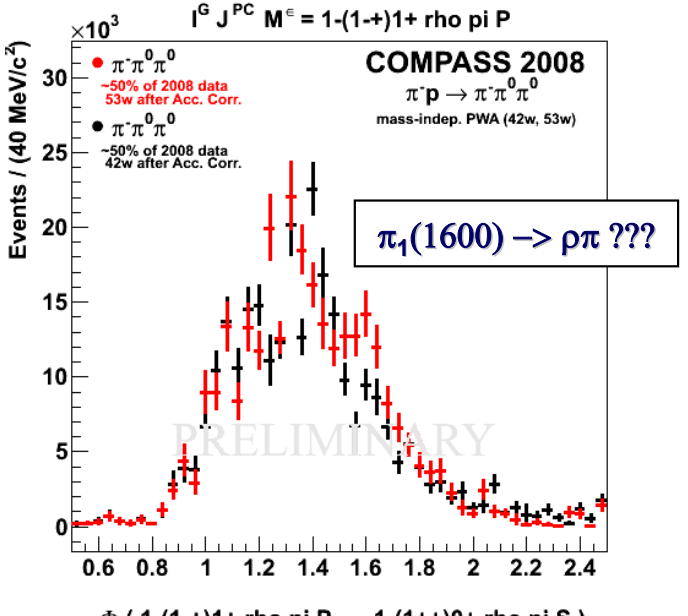


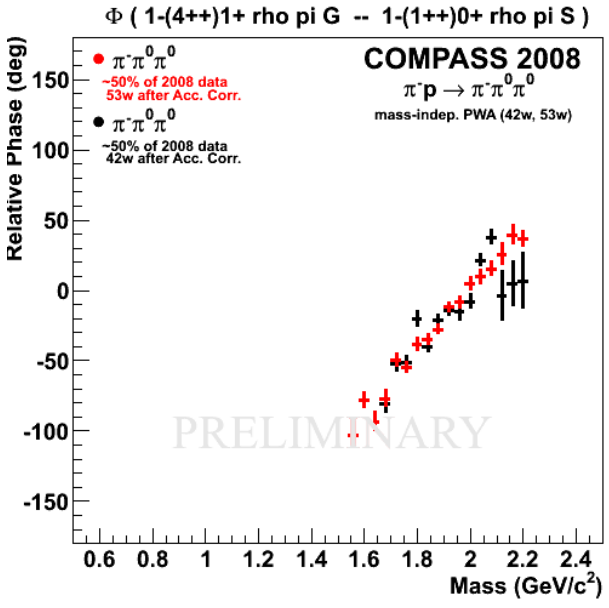
Selected partial waves & phases

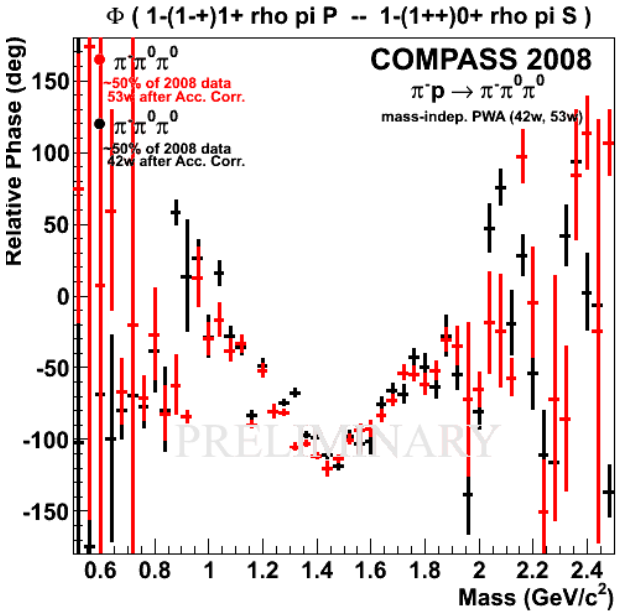
3π diffractive -- Neutral mode: 42 vs. 53 waves (norm. ρπ totals)







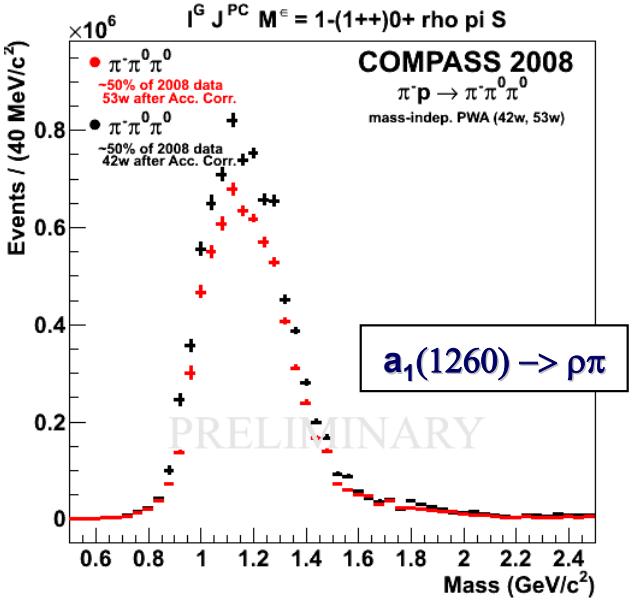


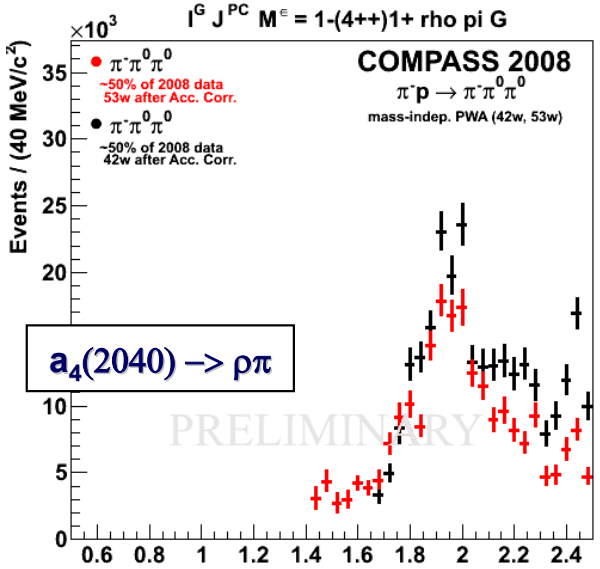


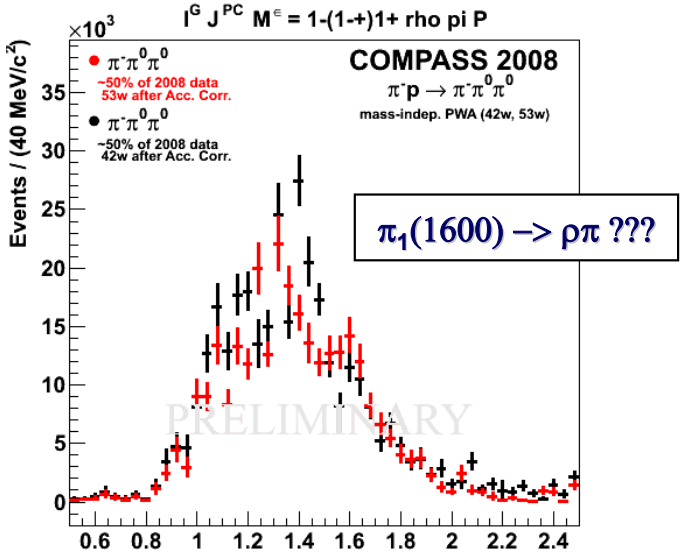
No change in observed resonances, objects with increased wave-set !

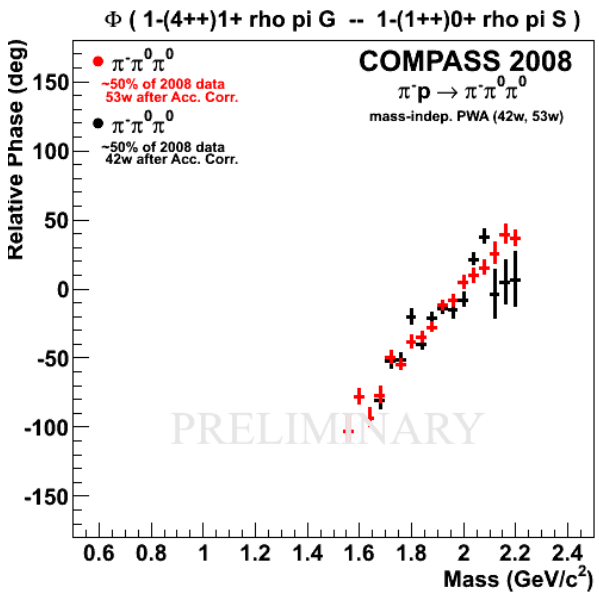
Selected partial waves & phases

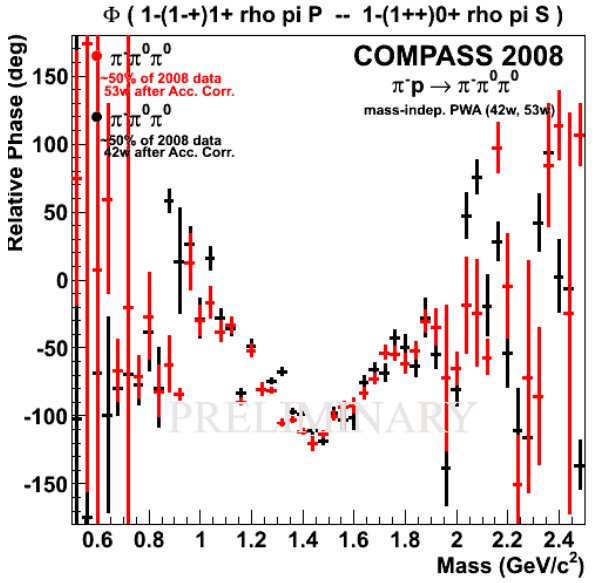
3π diffractive -- Neutral mode: 42 vs. 53 waves









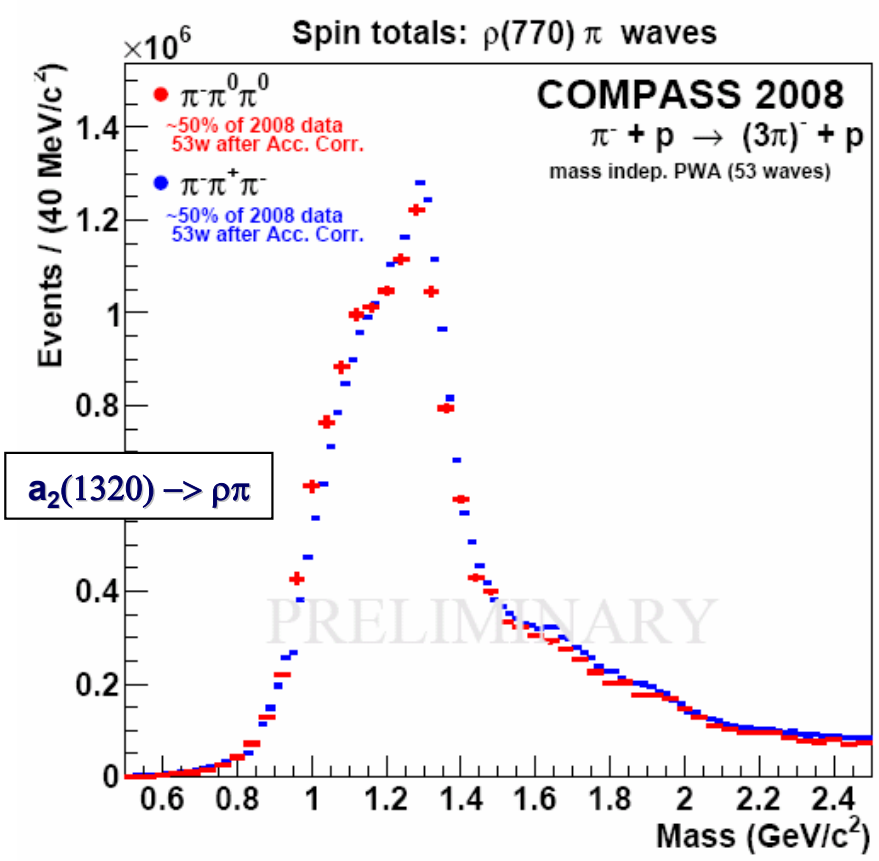


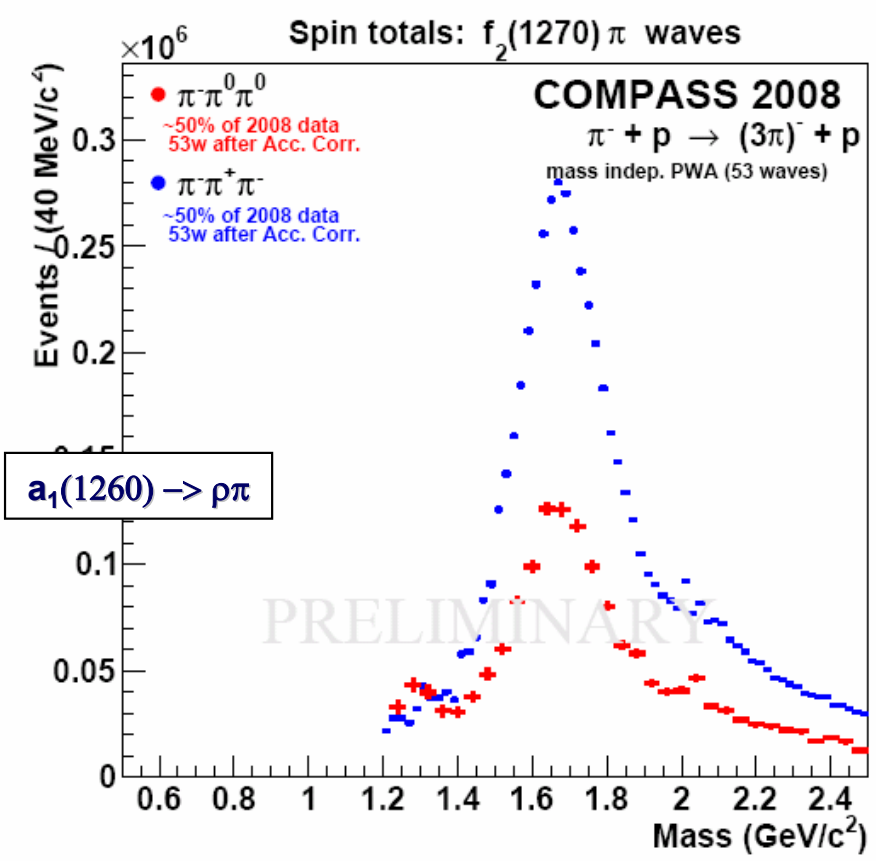
No change in observed resonances, objects with increased wave-set !

HK 8.3

Two sets of partial wave totals

3π diffractive -- Neutral vs. Charged mode: 53 waves





Isospin symmetry: neutral / charge mode

- X^- decaying into ρ π: 1/1 intensity expected
- X^- decaying into f_2 π: 1/2 intensity expected

Data follows isospin symmetry:

- throughout full wave-set
- main & small waves, *prev./next slides*

First comparison: Neutral vs. charged mode

simple isospin symmetry check

Isospin symmetry: neutral / charged mode

- X^- decaying into $\rho\,\pi$: 1/1 intensity expected
- X^- decaying into $f_2\,\pi$: 1/2 intensity expected

General: Branching not entirely determined by Clebsch-Gordon coeff.,
but also Bose-Symmetrisation with the bachelor π:

=> *no effect for resonances decaying into* $\rho\pi$ (same effect)

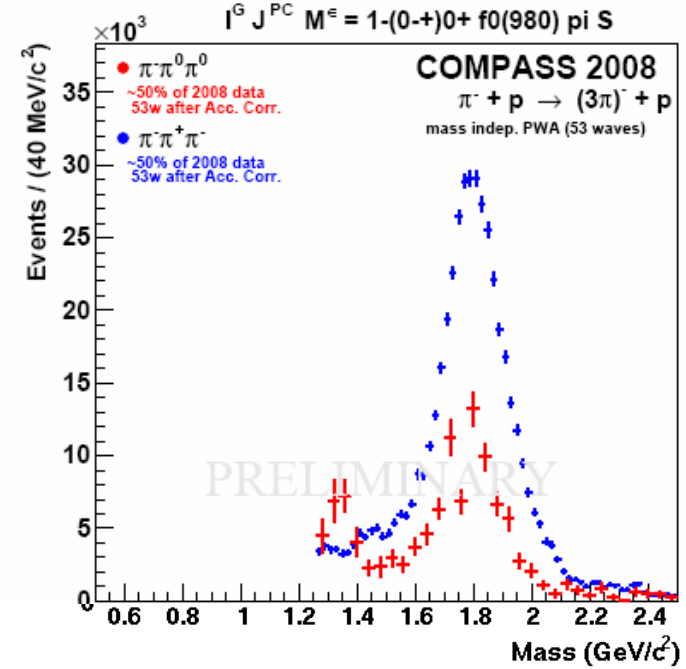
=> *BR might differ for resonances going to* $f_{0,2}\pi$

Checked by calculation:

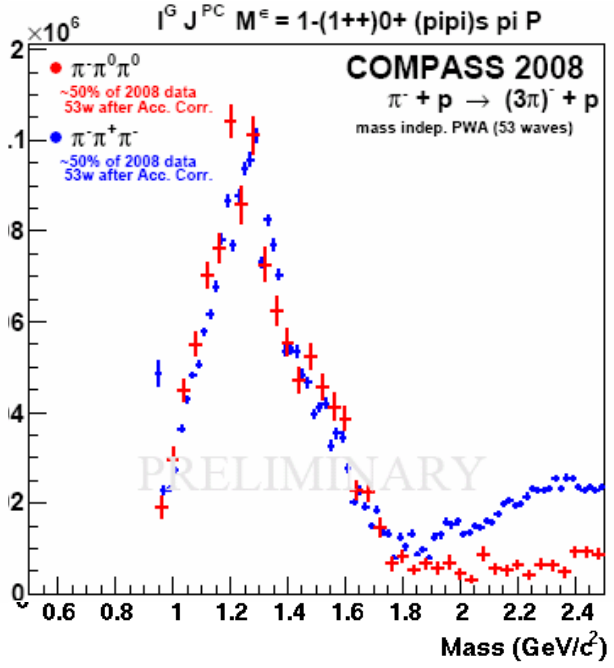
$BR = N(\pi^-\pi^0\pi^0)/N(\pi^-\pi^-\pi^+)$	
Expected from isobar model amplitude calculations	Found in data (Figs. 18, 20, 25)
$BR(\ 0^{-+} f_0(1400)\pi\ S) = 0.29$ (at 1.8 GeV)	0.25 (at 1.8 GeV)
$BR(\ 0^{-+} f_0(980)\pi\ S) = 0.44$ (at 1.8 GeV)	0.46 (at 1.8 GeV)
$BR(\ 1^{++} f_0(1400)\pi\ P) = 0.80$ (at 1.3 GeV)	0.87 (at 1.2 GeV)
$BR(\ 2^{-+} f_2(1270)\pi\ S) = 0.50$ (at 1.67 GeV)	0.40 (at 1.67 GeV)

Selected partial waves
isospin symmetry check ctd.

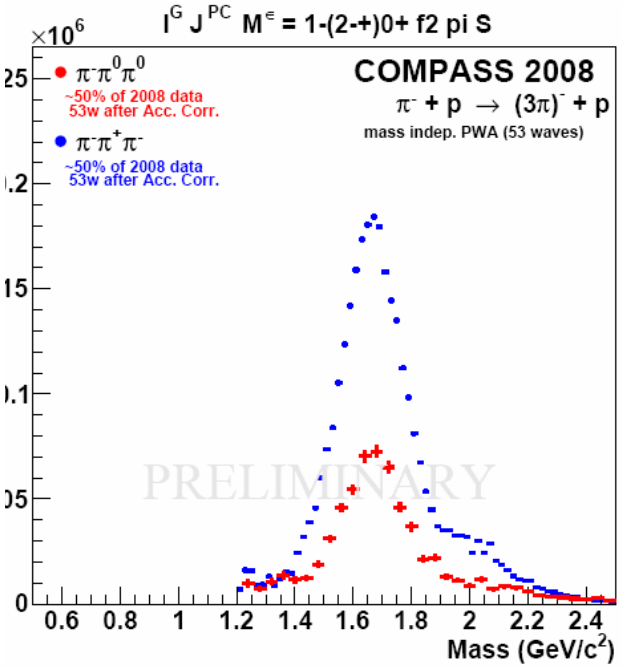
$\pi(1800) \rightarrow \rho\pi$



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



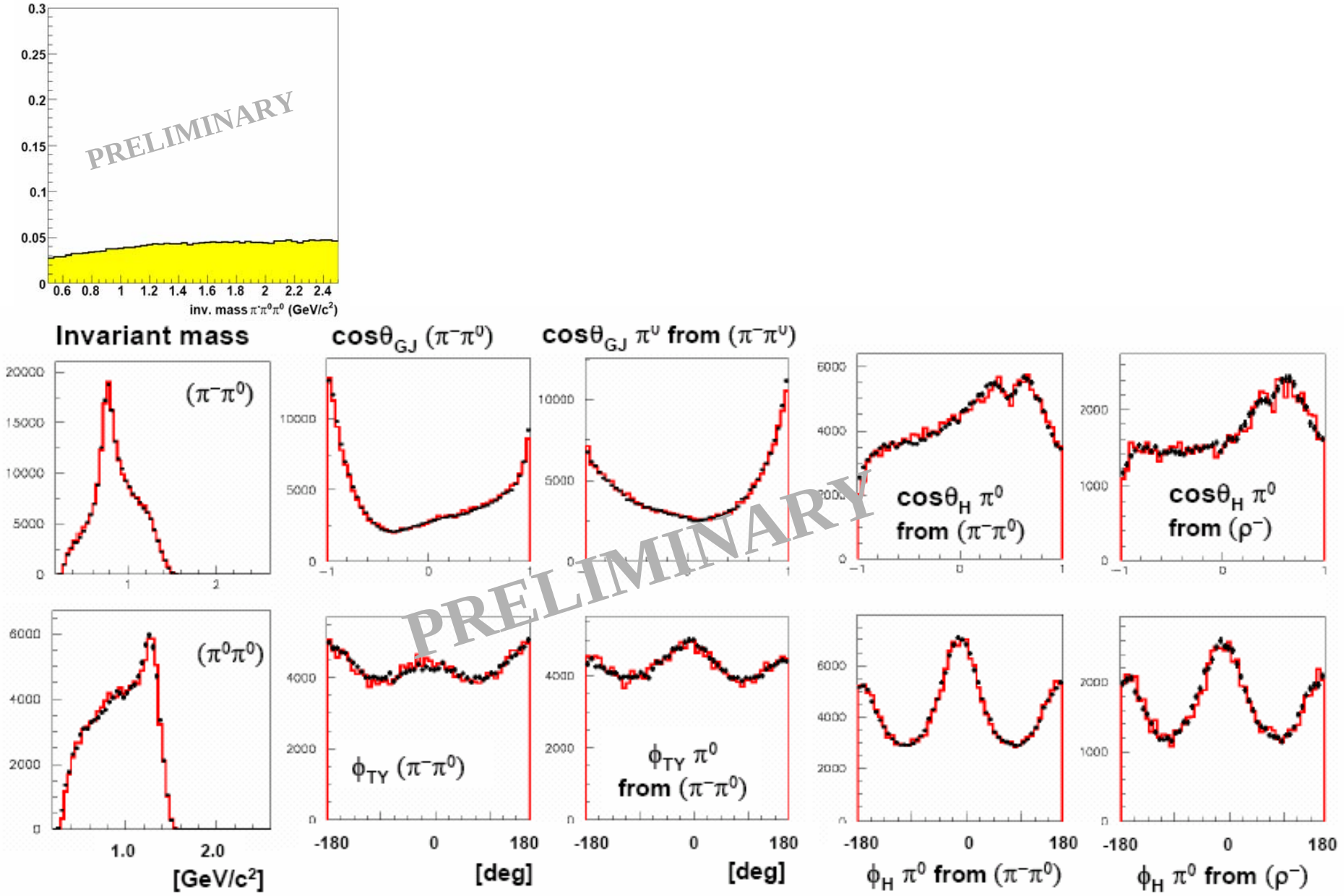
$\pi_2(1670) \rightarrow f_2\ \pi$



$BR = N(\pi^-\pi^0\pi^0)/N(\pi^-\pi^-\pi^+)$	
Expected from isobar model amplitude calculations	Found in data (Figs. 18, 20, 25)
BR($0^{-+} f_0(1400)\pi\ S$) = 0.29 (at 1.8 GeV)	0.25 (at 1.8 GeV)
BR($0^{-+} f_0(980)\pi\ S$) = 0.44 (at 1.8 GeV)	0.46 (at 1.8 GeV)
BR($1^{++} f_0(1400)\pi\ P$) = 0.80 (at 1.3 GeV)	0.87 (at 1.2 GeV)
BR($2^{-+} f_2(1270)\pi\ S$) = 0.50 (at 1.67 GeV)	0.40 (at 1.67 GeV)

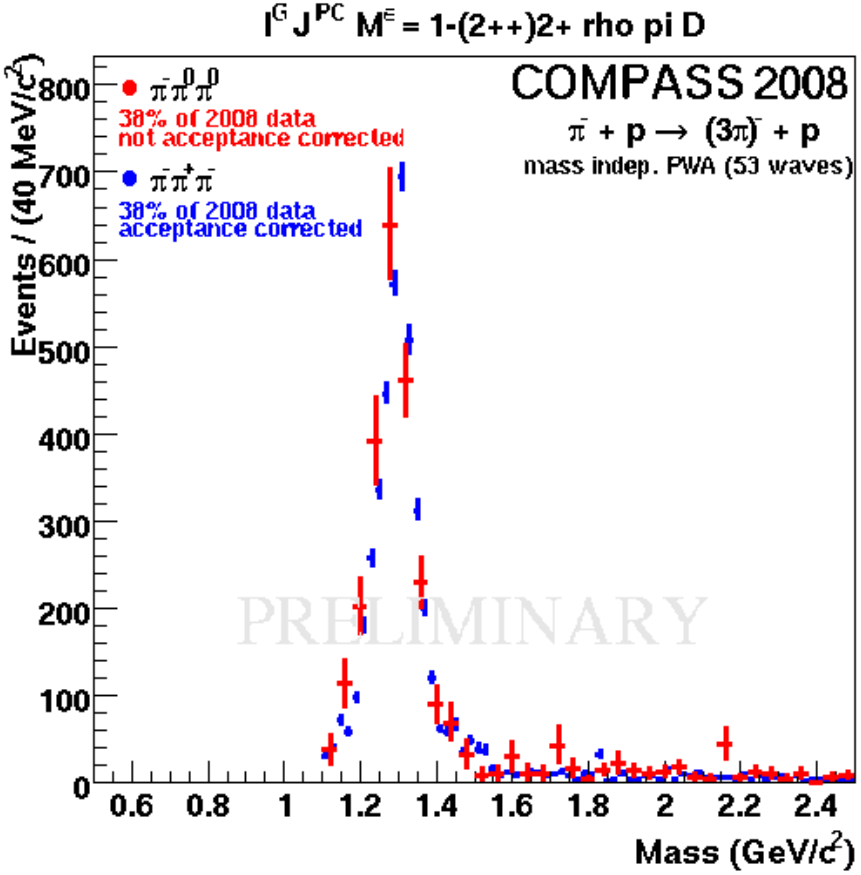
in fair agreement with the data

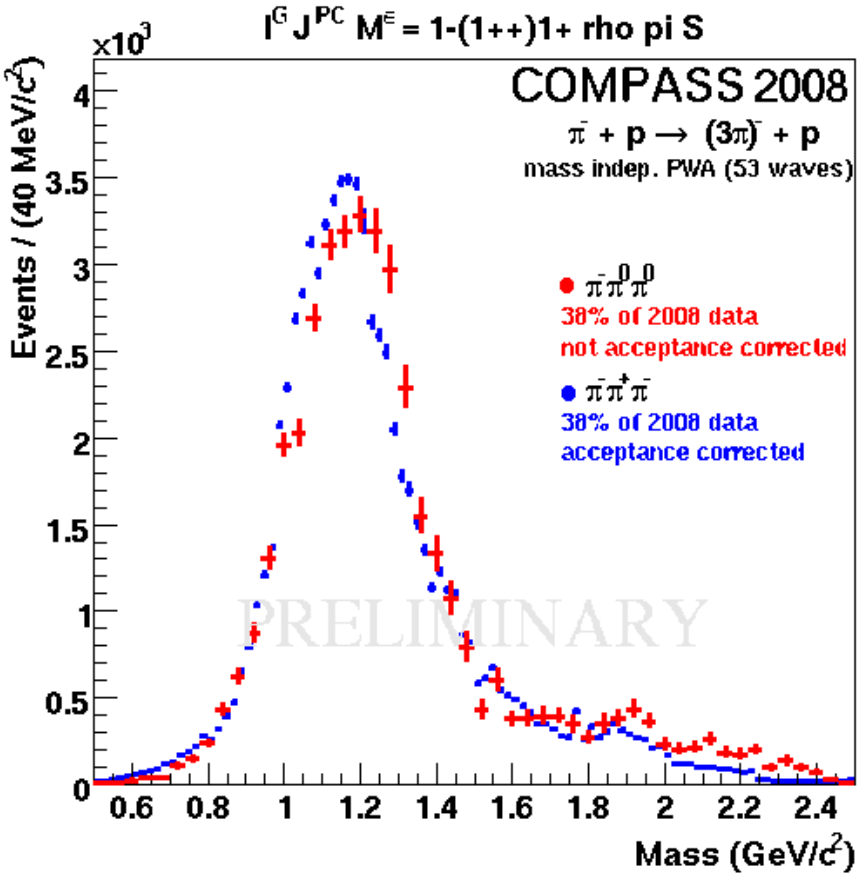
Comparison of real data and MC prediction
-- 5 variables describing 3 body decay



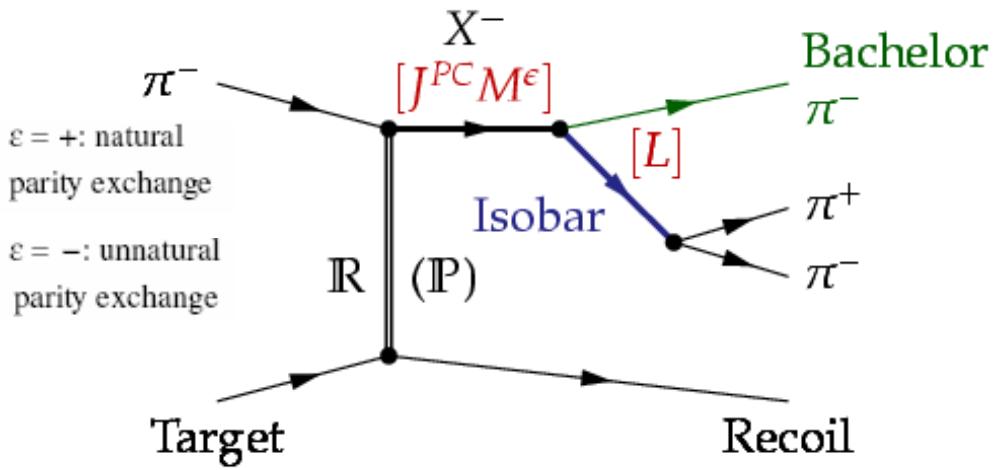
Selected partial waves
isospin symmetry check ctd.

$a_2(1320)$ (M=2) –> ρπ





PWA using isobar model



X^- decay described using isobar model:

- Intermediate di-pion resonance (isobar)
  - *Spin S and rel. orbital angular momentum L w.r.t bachelor π^-*
  - *L+S couple to J*
- Partial waves (reflectivity basis): $J^{PC}\ M^{\varepsilon}$ [isobar] L

Partial wave analysis:

- **program:** Illinois/Protvino/Munich (D.Ryabchikov) software (IHEP/VES, TUM/COMPASS)
- **Isobars:** *$(\pi\pi)_S$ [broad $f_0(600)$+$f_0(1370)$], $f_0(980)$, $\rho(770)$, $f_2(1270)$, $\rho_3(1690)$*
- **Acceptance:** corrections (included via normalisation integrals)

Step 1) Mass independent PWA: (40MeV/c² bins, 53 partial waves)

$$\sigma_{indep}(\tau, m, t') = \sum_{\epsilon=\pm1} \sum_{r=1}^{N_r} \left| \sum_i T^{\epsilon}_{ir} f^{\epsilon}_i(t') \psi^{\epsilon}_i(\tau, m) / \sqrt{\int \left|\psi^{\epsilon}_i(\tau', m)\right|^2 d\tau'} \right|^2$$

- Production amplitudes $T^{\epsilon}_{ir} \rightarrow$ extended maximum likelihood fit
- Decay amplitudes $\psi^{\epsilon}_i(\tau, m)$ (Zemach tensors, D functions)

Waveset used for the PWA

$J^{PC}M^{\epsilon}$	L	Isobar π	Treshold (GeV/c^2)
$0^{-+}0^{+}$	S	$f_0(980)\pi$	1.25
$0^{-+}0^{+}$	S	$(\pi\pi)_s\pi$	-
$0^{-+}0^{+}$	P	$\rho\pi$	-
$1^{-+}1^{+}$	P	$\rho\pi$	-
$1^{++}0^{+}$	S	$\rho\pi$	-
$1^{++}0^{+}$	P	$f_2\pi$	1.20
$1^{++}0^{+}$	P	$(\pi\pi)_s\pi$	0.94
$1^{++}0^{+}$	D	$\rho\pi$	1.30
$1^{++}1^{+}$	S	$\rho\pi$	-
$1^{++}1^{+}$	P	$f_2\pi$	1.40
$1^{++}1^{+}$	P	$(\pi\pi)_s\pi$	1.20
$1^{++}1^{+}$	D	$\rho\pi$	1.40
$2^{-+}0^{+}$	S	$f_2\pi$	1.20
$2^{-+}0^{+}$	P	$\rho\pi$	0.80
$2^{-+}0^{+}$	D	$(\pi\pi)_s\pi$	0.80
$2^{-+}0^{+}$	D	$f_2\pi$	1.50
$2^{-+}0^{+}$	F	$\rho\pi$	1.20
$2^{-+}1^{+}$	S	$f_2\pi$	1.20
$2^{-+}1^{+}$	P	$\rho\pi$	0.80
$2^{-+}1^{+}$	D	$(\pi\pi)_s\pi$	1.20
$2^{-+}1^{+}$	D	$f_2\pi$	1.50
$2^{-+}1^{+}$	F	$\rho\pi$	1.20
$2^{++}1^{+}$	P	$f_2\pi$	1.20
$2^{++}1^{+}$	D	$\rho\pi$	-
$3^{++}0^{+}$	S	$\rho_3\pi$	1.76
$3^{++}0^{+}$	P	$f_2\pi$	1.20
$3^{++}0^{+}$	D	$\rho\pi$	1.20
$3^{++}1^{+}$	S	$\rho_3\pi$	1.76
$3^{++}1^{+}$	P	$f_2\pi$	1.20
$3^{++}1^{+}$	D	$\rho\pi$	1.50
$4^{-+}0^{+}$	F	$\rho\pi$	1.00
$4^{-+}1^{+}$	F	$\rho\pi$	1.20
$4^{++}1^{+}$	F	$f_2\pi$	1.60
$4^{++}1^{+}$	G	$\rho\pi$	1.40
$1^{-+}0^{-}$	P	$\rho\pi$	-
$1^{-+}1^{-}$	P	$\rho\pi$	-
$1^{++}1^{-}$	S	$\rho\pi$	-
$2^{-+}1^{-}$	S	$f_2\pi$	1.20
$2^{++}0^{-}$	P	$f_2\pi$	1.30
$2^{++}0^{-}$	D	$\rho\pi$	-
$2^{++}1^{-}$	P	$f_2\pi$	1.30
FLAT			

Table 5: List of the 42 waves used for the mass independent PWA

Updated PWA model: 53waves

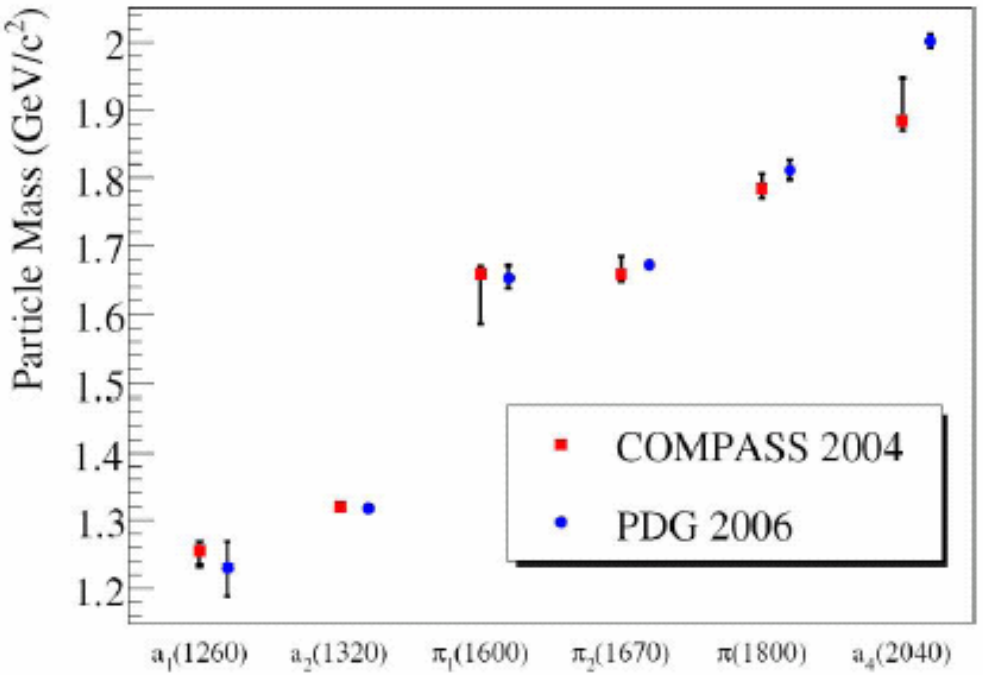
$J^{PC}M^{\epsilon}$	L	Isobar π	Treshold (GeV/c^2
$0^{-+}0^{+}$	S	$f_0(980)\pi$	1.25
$0^{-+}0^{+}$	S	$(\pi\pi)_s\pi$	-
$0^{-+}0^{+}$	P	$\rho\pi$	-
$1^{-+}1^{+}$	P	$\rho\pi$	-
$1^{++}0^{+}$	S	$\rho\pi$	-
$1^{++}0^{+}$	P	$f_2\pi$	1.20
$1^{++}0^{+}$	P	$(\pi\pi)_s\pi$	0.94
$1^{++}0^{+}$	D	$\rho\pi$	1.30
$1^{++}1^{+}$	S	$\rho\pi$	-
$1^{++}1^{+}$	P	$f_2\pi$	1.40
$1^{++}1^{+}$	P	$(\pi\pi)_s\pi$	1.20
$1^{++}1^{+}$	D	$\rho\pi$	1.40
$2^{-+}0^{+}$	S	$f_2\pi$	1.20
$2^{-+}0^{+}$	P	$\rho\pi$	0.80
$2^{-+}0^{+}$	D	$(\pi\pi)_s\pi$	0.80
$2^{-+}0^{+}$	D	$f_2\pi$	1.50
$2^{-+}0^{+}$	F	$\rho\pi$	1.20
$2^{-+}1^{+}$	S	$f_2\pi$	1.20
$2^{-+}1^{+}$	P	$\rho\pi$	0.80
$2^{-+}1^{+}$	D	$(\pi\pi)_s\pi$	1.20
$2^{-+}1^{+}$	D	$f_2\pi$	1.50
$2^{-+}1^{+}$	F	$\rho\pi$	1.20
$2^{++}1^{+}$	P	$f_2\pi$	1.20
$2^{++}1^{+}$	D	$\rho\pi$	-
$3^{++}0^{+}$	S	$\rho_3\pi$	1.76
$3^{++}0^{+}$	P	$f_2\pi$	1.20
$3^{++}0^{+}$	D	$\rho\pi$	1.20
$3^{++}1^{+}$	S	$\rho_3\pi$	1.76
$3^{++}1^{+}$	P	$f_2\pi$	1.20
$3^{++}1^{+}$	D	$\rho\pi$	1.50
$4^{-+}0^{+}$	F	$\rho\pi$	1.00
$4^{-+}1^{+}$	F	$\rho\pi$	1.20
$4^{++}1^{+}$	F	$f_2\pi$	1.60
$4^{++}1^{+}$	G	$\rho\pi$	1.40
$1^{-+}0^{-}$	P	$\rho\pi$	-
$1^{-+}1^{-}$	P	$\rho\pi$	-
$1^{++}1^{-}$	S	$\rho\pi$	-
$2^{-+}1^{-}$	S	$f_2\pi$	1.20
$2^{++}0^{-}$	P	$f_2\pi$	1.30
$2^{++}0^{-}$	D	$\rho\pi$	-
$2^{++}1^{-}$	P	$f_2\pi$	1.30
FLAT			

Table 5: List of the 42 waves used for the mass independent PWA.(**Table for Release**)

42 waveset extended by 11 waves:

```
1-(0-+)0+ f0(1500) pi S
1-(2++)2+ rho pi D
1-(2-+)2+ f2 pi S
1-(5++)0+ rho pi G
1-(6-+)0+ rho pi H
1-(0-+)0+ f2 pi D
1-(1-+)1+ f2 pi D
1-(2-+)0+ rho3 pi P
1-(3++)0+ f0(1400) pi F
1-(1++)0+ f0(980) pi P
1-(2-+)0+ f0(980) pi D
```

Fitted resonances (2004 data)

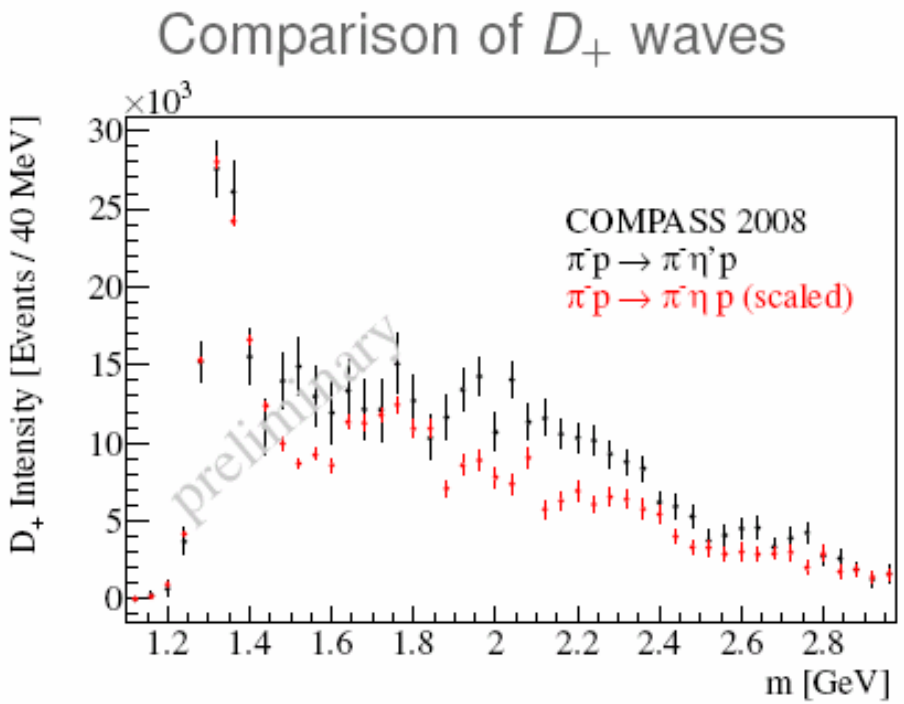


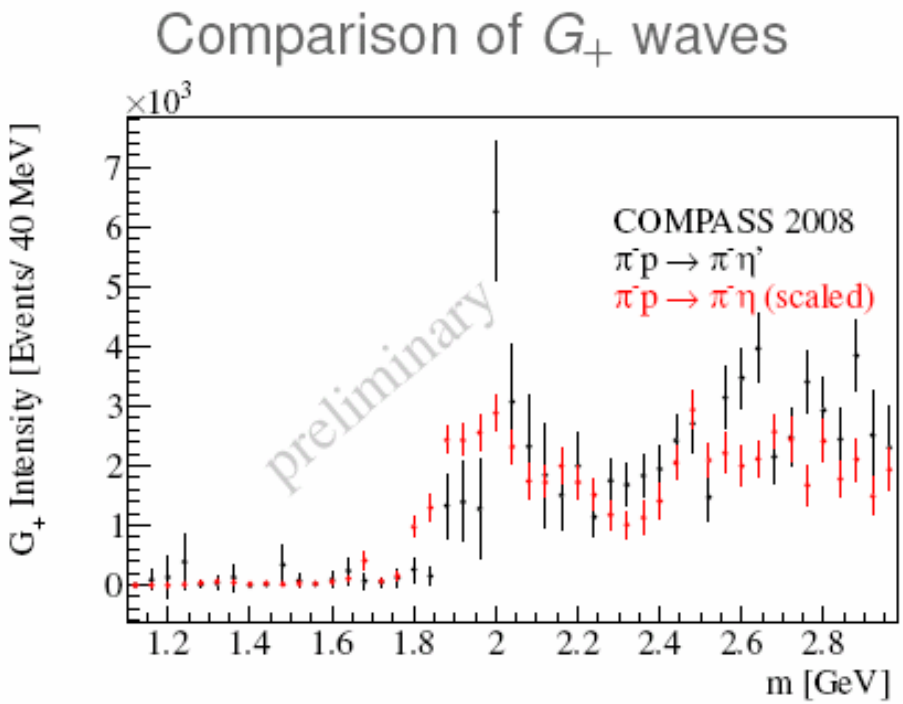
Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	Intensity (%)	Channel $J^{PC}M^{\epsilon}[\mathrm{isobar}]L$
$a_1(1260)$	$1255 \pm 6^{+7}_{-17}$	$367 \pm 9^{+28}_{-25}$	$67 \pm 3^{+4}_{-20}$	$1^{++}0^{+}\ \rho\pi\ S$
$a_2(1320)$	$1321 \pm 1^{+0}_{-7}$	$110 \pm 2^{+2}_{-15}$	$19.2 \pm 0.6^{+0.3}_{-2.2}$	$2^{++}1^{+}\ \rho\pi\ D$
$\pi_1(1600)$	$1660 \pm 10^{+0}_{-64}$	$269 \pm 21^{+42}_{-64}$	$1.7 \pm 0.2^{+0.9}_{-0.1}$	$1^{-+}1^{+}\ \rho\pi\ P$
$\pi_2(1670)$	$1658 \pm 3^{+24}_{-8}$	$271 \pm 9^{+22}_{-24}$	$10.0 \pm 0.4^{+0.7}_{-0.7}$	$2^{-+}0^{+}\ f_2\pi\ S$
$\pi(1800)$	$1785 \pm 9^{+12}_{-6}$	$208 \pm 22^{+21}_{-37}$	$0.8 \pm 0.1^{+0.3}_{-0.1}$	$0^{-+}0^{+}\ f_0\pi\ S$
$a_4(2040)$	$1885 \pm 13^{+50}_{-2}$	$294 \pm 25^{+46}_{-19}$	$1.0 \pm 0.3^{+0.1}_{-0.1}$	$4^{++}1^{+}\ \rho\pi\ G$

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

- η **reconstructed from** $\eta \rightarrow \pi^+\pi^-\pi^0$
- η' **reconstructed from** $\eta' \rightarrow \pi^+\pi^-\eta$, **with** $\eta \rightarrow \gamma\gamma$

search for $\pi_1(1600)$



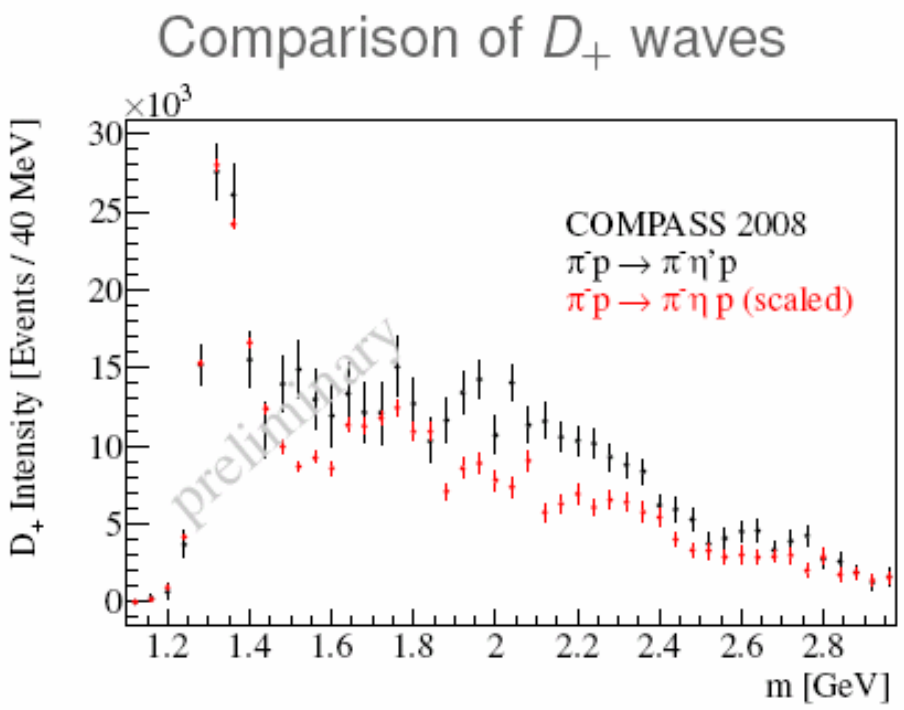


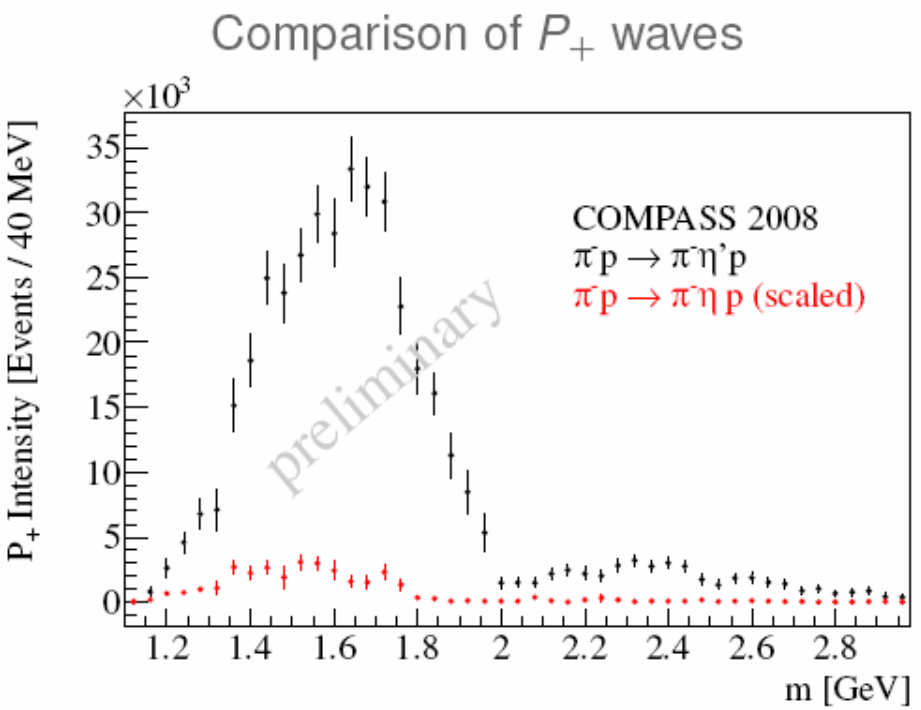
Normalised to compensate for BR and PSP

Different channel for the search: π^-+p –> π^- η/η' + p

- η **reconstructed from** $\eta \rightarrow \pi^+\pi^-\pi^0$
- η' **reconstructed from** $\eta' \rightarrow \pi^+\pi^-\eta$, **with** $\eta \rightarrow \gamma\gamma$

search for $\pi_1(1600)$





Normailsed to compensate for BR and PSP