Evidence for Exotic Mesons

from BNL-E852 and COMPASS

S. U. Chung

BNL[†] /Upton, NY, USA
Pusan National University,[α] Busan, Korea
and TU [‡] /Munich, Germany

Partly based on the results presented at:

The XIV$^{\mathrm{th}}$ International Conference on Hadron Spectroscopy, Munich, Germany (13–17 June 2011)

† Senior Scientist Emeritus
α Visiting Professor (part-time)
‡ Scientific Consultant (part-time) Excellence Cluster Universe at TU
Research Awardee (revisit: part-time) Alexander von Humboldt-Stiftung/Foundation
Visiting Professor (part-time) Institute for Advanced Studies (IAS) at TU

Plan of Talk

- Introduction:
  A brief overview of exotic mesons

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  Data taken from 1994 to 1998 at
  the BNL MultParticle Spectrometer (MPS)
  (Only a brief sketch — highly abbreviated)

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- Conclusions and Future Prospects
  Central Diffractive Production of Exotic Mesons (< 3 GeV)

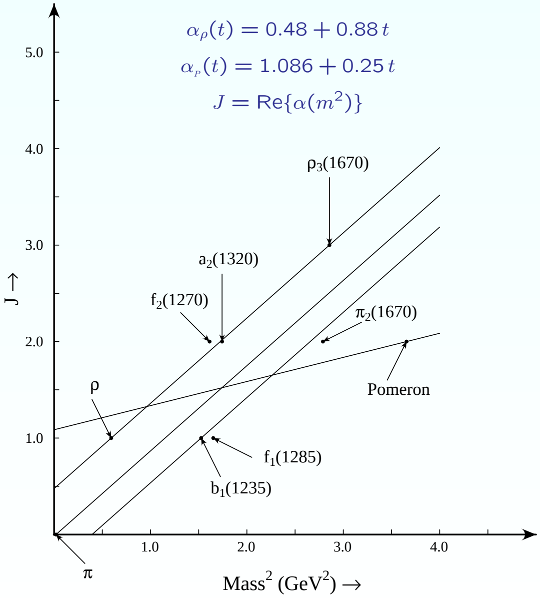
  at ALICE and STAR

Regge Trajectories

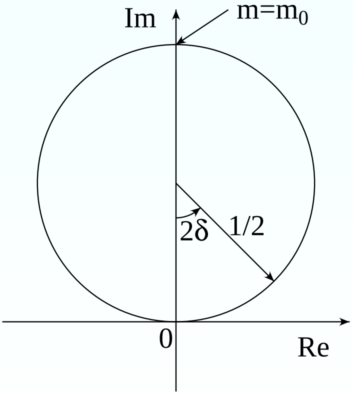
$$\alpha_\rho(t) = 0.48 + 0.88\,t$$

$$\alpha_{_P}(t) = 1.086 + 0.25\,t$$

$$J = \text{Re}\{\alpha(m^2)\}$$



Phase motion of a Breit-Wigner form

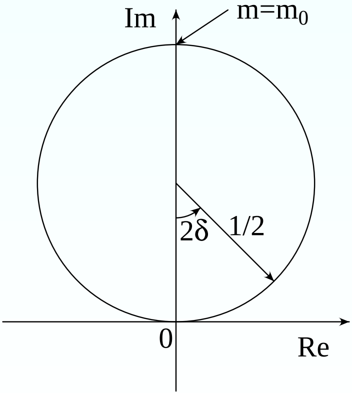


$$\Delta(m) = \frac{m_0\,\Gamma_0}{m_0^2 - m^2 - i\,m_0\,\Gamma_0}$$

$$= \mathrm{e}^{i\,\delta(m)}\,\sin\delta(m)$$

$$\cot\delta(m) = \frac{m_0^2 - m^2}{m_0\,\Gamma_0}$$

Phase motion of a Breit-Wigner form



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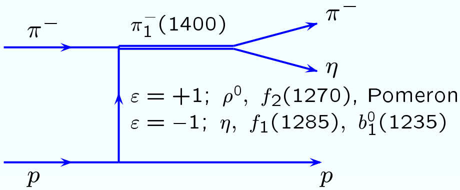
Interference effect:

$$A = 1 + \alpha, \quad \alpha \sim \pm 0.1$$

$$|A|^2 = 1 + 2\alpha + \alpha^2$$

Reggeon exchange:



$\varepsilon = +1$ Natural-parity exchange
$\varepsilon = -1$ Unnatural-parity exchange

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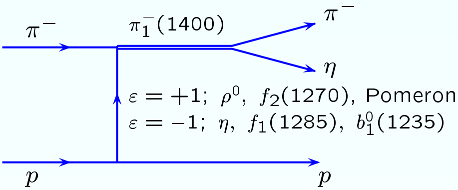

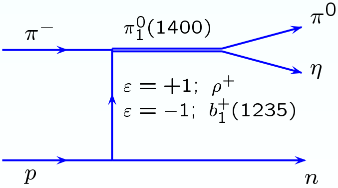

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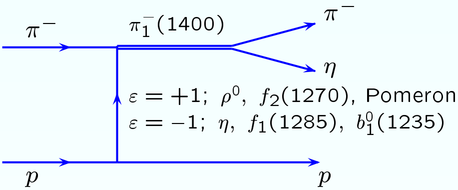
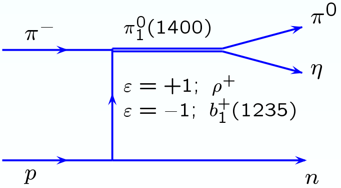


Notation: $J^{PC} M^{\varepsilon}\ R_1 \left[\begin{smallmatrix} L \\ S \end{smallmatrix}\right] R_2$

$J^{PC} M^{\varepsilon}\ R_1[L]\pi$

$J^{PC} M^{\varepsilon}\ R_1\pi\ L$



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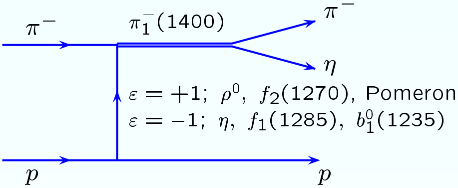

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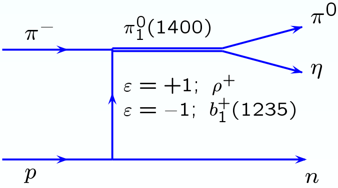
$J^{PC} M^{\varepsilon}\ R_1 [L] \pi$

$J^{PC} M^{\varepsilon}\ R_1 \pi\ L$

If $S_1 = S_2 = 0$: L_a where $a = (M,\ \varepsilon)$
L_0 (ε fixed) or L_ε ($M = 1$ assumed)



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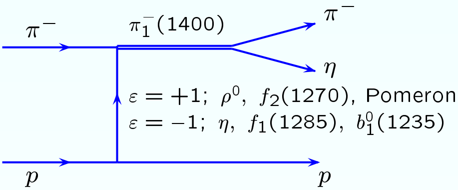

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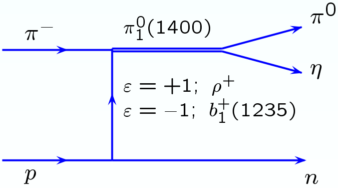

$1^{-+}1^{+}\ \eta \left[{P \atop 0}\right] \pi \rightarrow P_+$

$2^{++}1^{+}\ \eta \left[{D \atop 0}\right] \pi \rightarrow D_+$

$1^{-+}0^{-}\ \eta \left[{P \atop 0}\right] \pi \rightarrow P_0$

$1^{-+}1^{-}\ \eta \left[{P \atop 0}\right] \pi \rightarrow P_-$

$2^{++}0^{-}\ \eta \left[{D \atop 0}\right] \pi \rightarrow D_0$

$2^{++}1^{-}\ \eta \left[{D \atop 0}\right] \pi \rightarrow D_-$

Definition: Exotic Mesons

- Conventional $q\bar{q}$ mesons
  $\vec{J} = \vec{L} + \vec{S}$, $P = (-)^{L+1}$, $C = (-)^{L+S}$;
  Forbidden $J^{PC} = \boxed{0^{--}}$, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, etc.

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- Exotic mesons:
  $n\bar{n} + g$, $n = \{u, d\}$, mass ~ 1.9 GeV with $J^{PC} = 1^{-+}$ at the lightest meson
  $n\bar{n} + n\bar{n}$; 4-quark (tetra-) exotics

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- Notation for Exotic Mesons: The key determinant is $\{PC\}$, e.g.

$I^G(J^{PC})$	$1^-(0^{-+})$	$0^+(0^{-+})$	$1^-(1^{-+})$	$0^+(1^{-+})$
Name	π	η	$\pi_1(1400)$	$\eta_1(1400?)$

$I^G(J^{PC})$	$1^+(1^{+-})$	$0^-(1^{+-})$	$1^+(2^{+-})$	$0^-(2^{+-})$
Name	$b_1(1235)$	$h_1(1170)$	$b_2(1900?)$	$h_2(1900?)$

Exotic Mesons:

BNL-E852

Reaction: $\pi^- p \to \eta\pi^- p$ at 18 GeV$/c$, $\eta \to \gamma\gamma$, $\sigma(\eta \to \gamma\gamma) \sim 30$ MeV

$\sim 47\,200$ events (Triggered on Recoil protons)

$t' = |t| - |t|_{\min} \geq 0$ and hence $t' = |t'|$

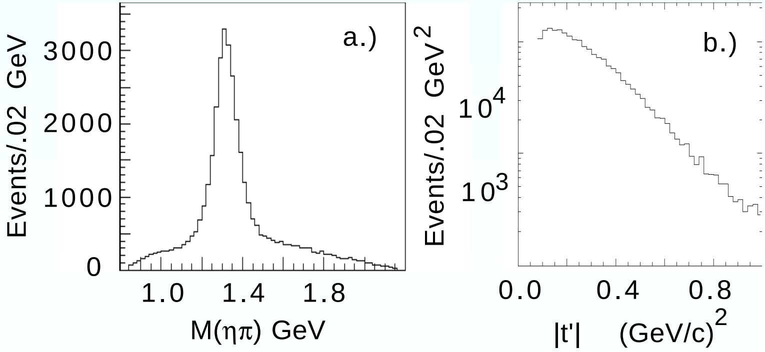

Figure 1

Exotic Meson: $\pi_1^-(1400) \to \eta\pi^-$ BNL-E852

Reaction: $\pi^- p \to \eta\pi^- p$ at 18 GeV/c, $\eta \to \gamma\gamma$
$\sim$ 47 200 events

$1^{-+}1^+ \, \eta \left[{P \atop 0}\right] \pi \to P_+$

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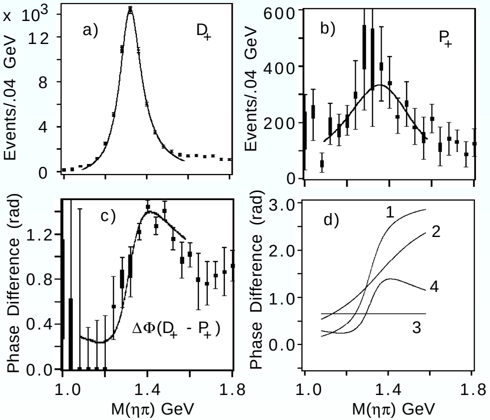

Figure 3

$$\begin{cases} M(P_+) = 1370 \pm 16 \, {+50 \atop -30} \\ \Gamma(P_+) = 385 \pm 40 \, {+\ 65 \atop -105} \end{cases}$$

PRL 79, 1630 (1997)
PRD 60, 092001 (1999)

S. U. Chung,
PRD 56, 7299 (1997)

- A (P-wave $\pi\eta_8$) system [the $\pi_1(1400)$ in $I^G(J^{PC}) = 1^-(1^{-+})$] must be in a flavor representation of $\{10 \oplus \overline{10}\}$:

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S. U. Chung, E. Klempt, and J. K. Körner, Eur. Phys. J. A. 15, 539 (2002)

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Internal Structure for Exotics $\pi_1(1400) \to \eta\pi$:

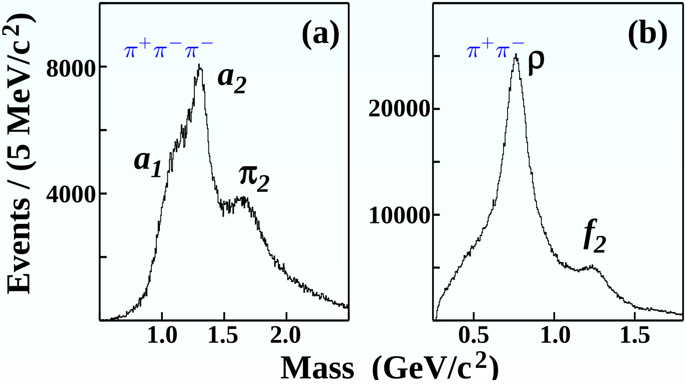
flavor $10 \oplus \overline{10}$	$(q\bar{q})_8 \otimes (q\bar{q})_8$	$(qq)_{\bar{3}} \otimes (\bar{q}\bar{q})_{\bar{6}}$ $(qq)_6 \otimes (\bar{q}\bar{q})_3$
color singlet	$(q\bar{q})_8 \otimes (q\bar{q})_8$ $(q\bar{q})_1 \otimes (q\bar{q})_1$	$(qq)_{\bar{3}} \otimes (\bar{q}\bar{q})_3$ $(qq)_6 \otimes (\bar{q}\bar{q})_{\bar{6}}$

$q = \{u, d, s\}$

Exotic Meson: $\rho^0(770)\pi^-$

BNL-E852

Reaction: $\pi^- p \rightarrow \pi^+\pi^-\pi^- p$ at 18 GeV/c
$\sim$ 250 000 events



Exotic Meson: $\pi_1^-(1600) \to \rho^0(770)\pi^-$, $\rho^0(770) \to \pi^+\pi^-$

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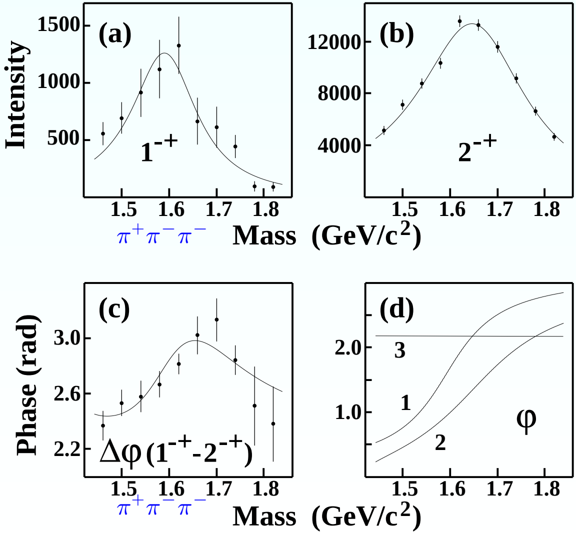
Partial waves: $1^{-+}1^+\rho(770)[P]\pi$, $2^{-+}0^+f_2(1270)[S]\pi$



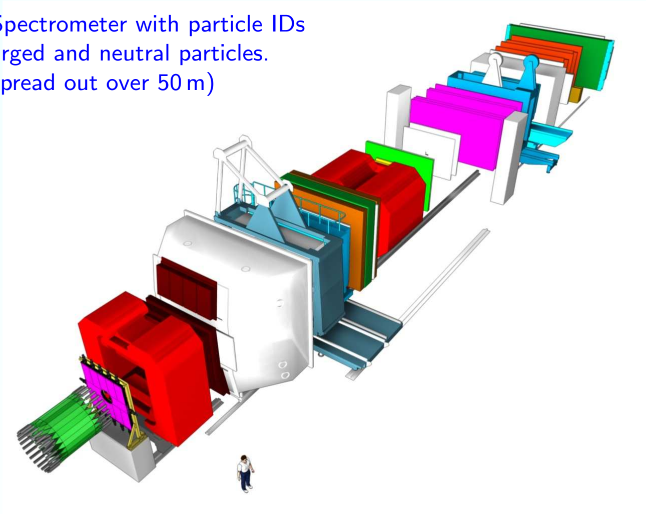
$1^{-+}1^+\ \rho\left[{P \atop 1}\right]\pi$

$2^{++}0^+\ f_2\left[{S \atop 2}\right]\pi$

$$\left\{ \begin{array}{l} M = 1593 \pm 8 \,{}^{+\ 29}_{-\ 47} \\ \Gamma = 168 \pm 20 \,{}^{+150}_{-\ 12} \end{array} \right.$$

PRL 81, 5760 (1998)
PRD 65, 072001 (2002)

Two-stage Spectrometer with particle IDs
for both charged and neutral particles.
(Detectors spread out over 50 m)



COMPASS: P. Abbon, *et al.*, NIM A577, 455 (2007)

Hadron Physics Program of COMPASS

- Data-taking runs:

  μ^+ beams at 160 GeV/c in 2002–2004
  π^- beams at 190 GeV/c in 2004 (two weeks)
  μ^+ beams at 160 GeV/c in 2006–2007
  Hadron$^\pm$ beams at 190 GeV/c in 2008–2009
  μ^+ beams at 160 GeV/c in 2010
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- Pilot hadron run in 2004 with 190 GeV/c π^- beam at 10^6/s on Pb, Cu and C targets

  An example: $\boxed{\pi^- + \mathrm{Pb} \to (\pi^+\pi^-\pi^-) + \mathrm{Pb}}$ Statistics: $\simeq 500\,000$ events

  Exclusive events at low t
  A New Evidence for a $J^{PC} = 1^{-+}$ exotic meson: PRL 104, 241803 (2010)

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- Runs with a Recoil-Proton Detector (RPD) in 2008–2009

  An example: $\boxed{\pi^- + p \to (\pi^+\pi^-\pi^-) + p}$

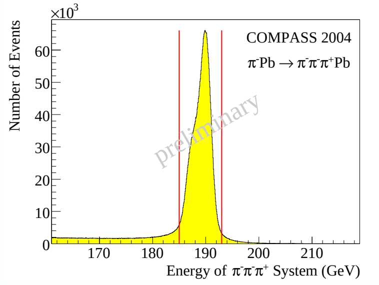
  2008 Statistics: $\simeq$ 100 000 000 events ($\simeq$ 400 times BNL data)

  Exclusive events at low t
  Search for $J^{PC} = 0^{\pm -}, 1^{-+}, 2^{+-}, 3^{-+}\ldots$ exotic mesons

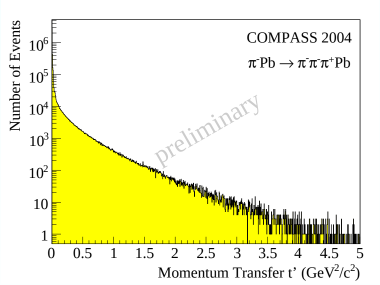
COMPASS:

Reaction: $\pi^- + \mathrm{Pb} \to \pi^+\pi^-\pi^- + \mathrm{Pb}$ at 190 GeV/c
$\sim$ 420 000 events

E(Beam)



t' Distribution



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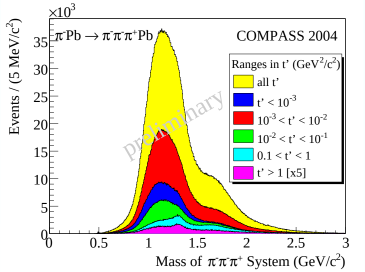
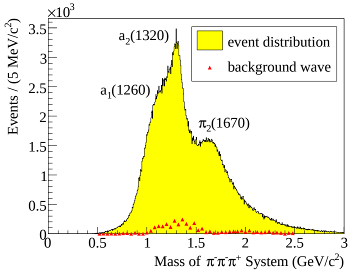
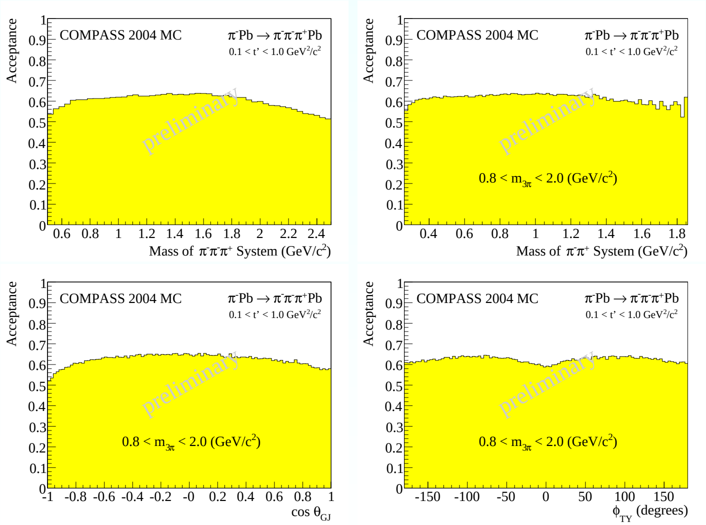
t' all



$0.1 < t' < 1.0 \quad (\mathrm{GeV}/c)^2$



COMPASS acceptance: $0.1 < t' < 1.0\ (\mathrm{GeV}/c)^2$



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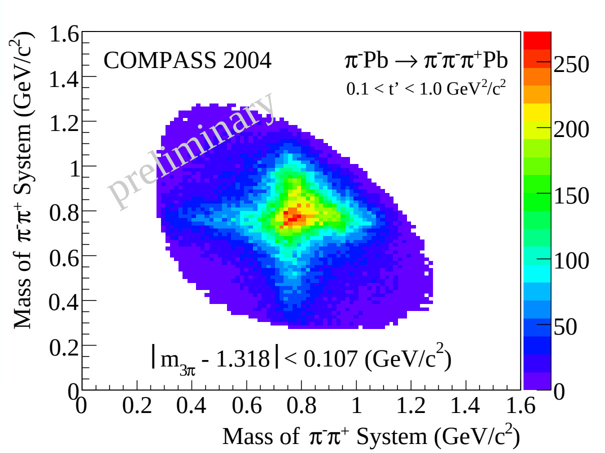
$(1.318 - 0.107)\ \mathrm{GeV} < M(3\pi) < (1.318 + 0.107)\ \mathrm{GeV}$



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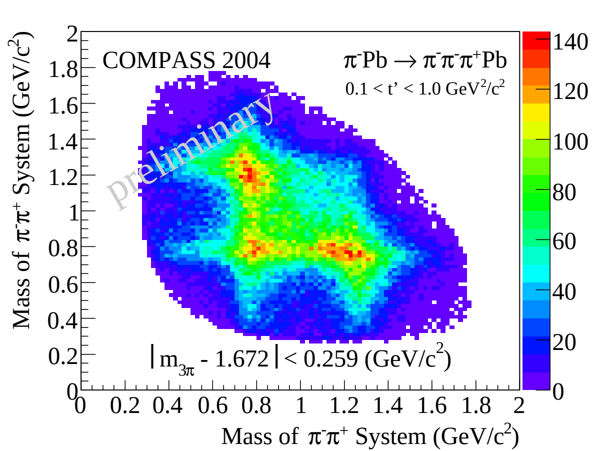
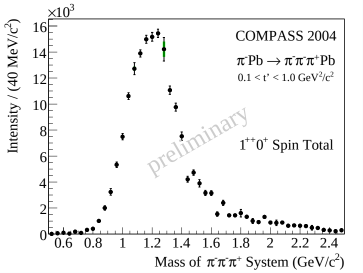
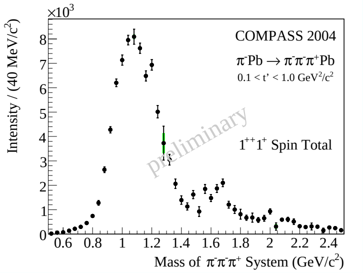
$\sim$ 420 000 events

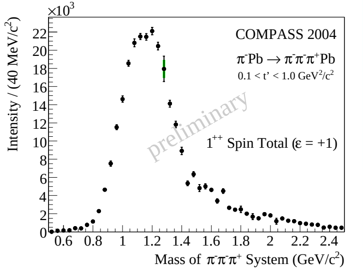
$(1.672 - 0.259)\ \mathrm{GeV} < M(3\pi) < (1.672 + 0.259)\ \mathrm{GeV}$



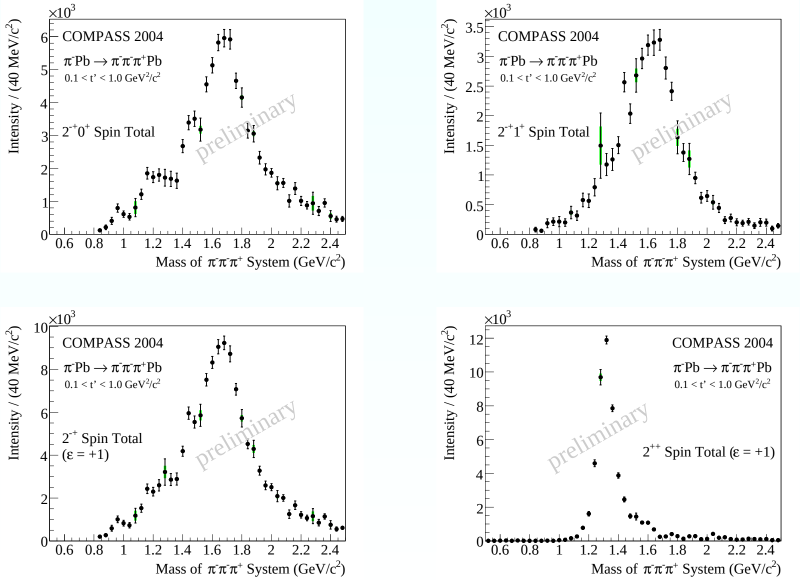
COMPASS: $J^{PC} = 1^{++}$





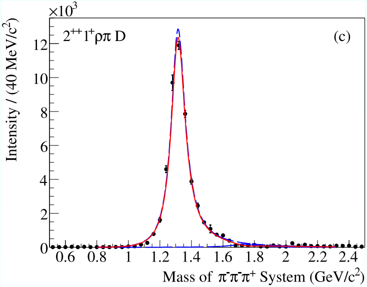


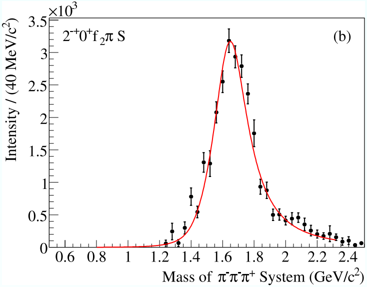
COMPASS: $J^{PC} = 2^{-+}$ and 2^{++}

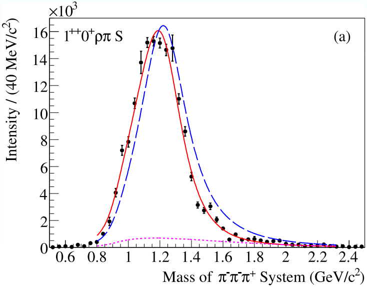


COMPASS: mass-dependent fit

$J^{PC} = 2^{++}\,1^{+}\ \rho[D]\pi$, $J^{PC} = 2^{-+}\,0^{+}\ f_2[S]\pi$ **and** $J^{PC} = 1^{++}\,0^{+}\ \rho[S]\pi$

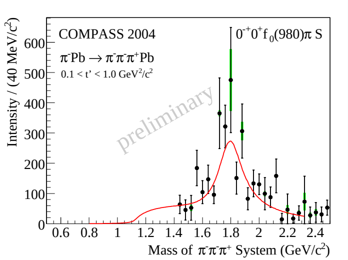


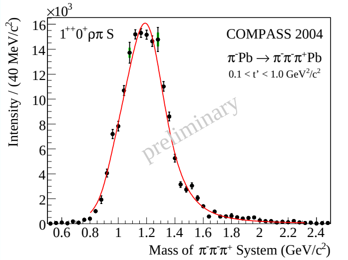


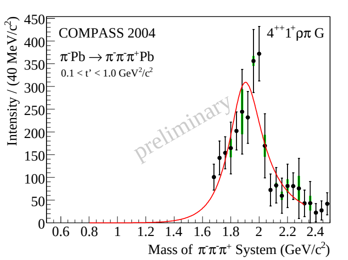


COMPASS: mass-dependent fit

$J^{PC} = 0^{-+}\,0^{+}\ f_0(980)[D]\pi$, $J^{PC} = 1^{++}\,0^{+}\ \rho[S]\pi$ and $J^{PC} = 4^{++}\,1^{+}\ \rho[G]\pi$





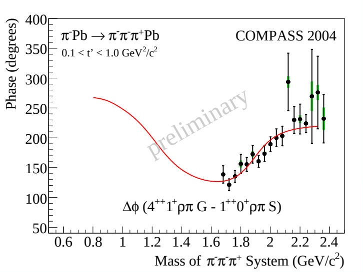


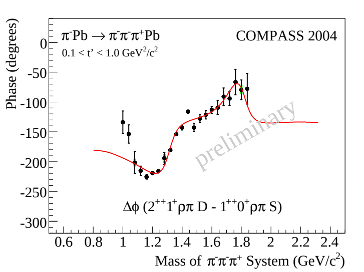
COMPASS: mass-dependent fit

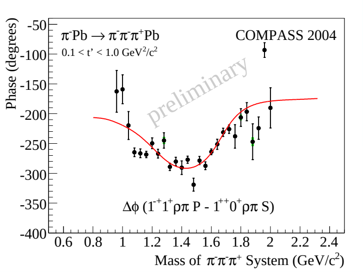
$\Delta\Phi(4^{++}\,1^{+}\ \rho[G]\pi\ \ominus\ 1^{++}\,0^{+}\ \rho[S]\pi)$

$\Delta\Phi(2^{-+}\,1^{+}\ \rho[D]\pi\ \ominus\ 1^{++}\,0^{+}\ \rho[S]\pi)$

$\Delta\Phi(1^{-+}\,1^{+}\ \rho[P]\pi\ \ominus\ 1^{++}\,0^{+}\ \rho[S]\pi)$







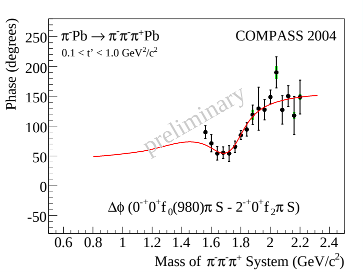
COMPASS: **mass-dependent fit**

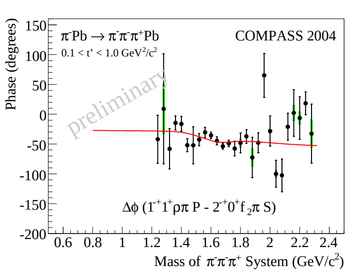
$\Delta\Phi(0^{-+}\,0^{+}\ f_0(980)[S]\pi\ \ominus\ 2^{-+}\,0^{+}\ f_2[S]\pi)$

$\Delta\Phi(1^{-+}\,1^{+}\ \rho[P]\pi\ \ominus\ 2^{-+}\,0^{+}\ f_2[S]\pi)$

Reaction: $\pi^- + \mathrm{Pb} \to \pi^+\pi^-\pi^- + \mathrm{Pb}$ at 190 GeV/c

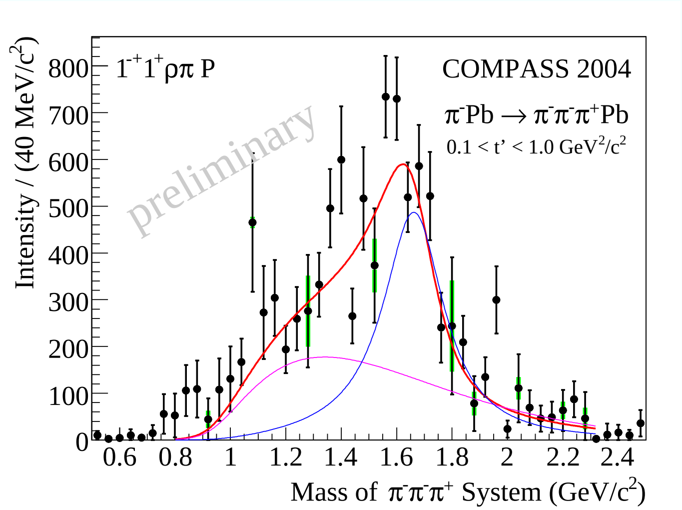
$\sim$ 420 000 events





COMPASS: Evidence for $J^{PC} = 1^{-+}$ $\pi_1(1600)$

Reaction: $\pi^- + \mathrm{Pb} \to \pi^+\pi^-\pi^- + \mathrm{Pb}$ at 190 GeV/c
$\sim$ 420 000 events

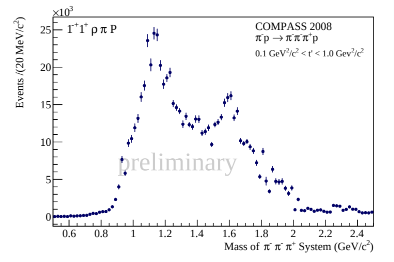


COMPASS: New Evidence for $J^{PC} = 1^{-+}$ $\pi_1(1600)$

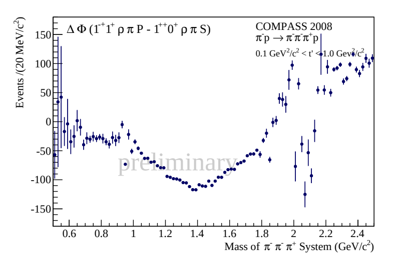
Reaction: $\pi^- + p \rightarrow \pi^+\pi^-\pi^- + p$ at 190 GeV/c

$\sim$ 96 000 000 events in $0.1 < t' < 1.0$ $(\mathrm{GeV}/c)^2$

$1^{-+}1^+\rho\pi\ P$



$\Delta\Phi(1^{-+}1^+\rho\pi\ P) - (1^{++}0^+\rho\pi\ S)$



COMPASS:

Resonance masses, total widths, and intensities for the specified decay channel of the six waves included in the mass-dependent fit to the data.
The first uncertainty corresponds to the statistical error,
the asymmetric second one to the systematic error.

Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	Intensity (%)	Channel $J^{PC} M^{\epsilon} \mathrm{R}^{\mathrm{a}}$ 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

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Experiments	M (MeV)	Γ (MeV)	Decay
BNL ($\pi^- p$ at 18 GeV/c)	$1593 \pm 8\ ^{+20}_{-47}$	$168 \pm 20\ ^{+150}_{-12}$	$\rho\pi$

First MC Results (Preliminary) on ALICE

Jeewon SEO, Sun-Kun OH
Konkuk University, Seoul, Korea

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- First Study

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Konkuk University, Seoul, Korea

$$\mathrm{Pb} + \mathrm{Pb} \to \mathrm{Pb} + X^0 + \mathrm{Pb} \quad \text{at} \quad \sqrt{s_{NN}} = 2.75\ \mathrm{TeV}$$

$$X^0 \to \pi^+\pi^-\pi^+\pi^-$$

Dominant Production Mechanism:

Photon-Pomeron Fusion Process $\longrightarrow$ $C = -1$ for X^0 (or $I^G = 1^+$)
ALICE Acceptance $\simeq 4.3\,\%$ for $(-6.0 < y < +6.0)$ generated
$(-1.0 < y < +1.0)$ accepted

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- Second Study (under way)

$$p + p \to p + X^0 + p \quad \text{at} \quad \sqrt{s} = 7.0\ \mathrm{TeV}$$
$$X^0 \to \pi^+\pi^-\pi^+\pi^-$$

Dominant Production Mechanism:

Double-Pomeron Exchange Process $\longrightarrow$ $C = +1$ for X^0 (or $I^G = 0^+$)

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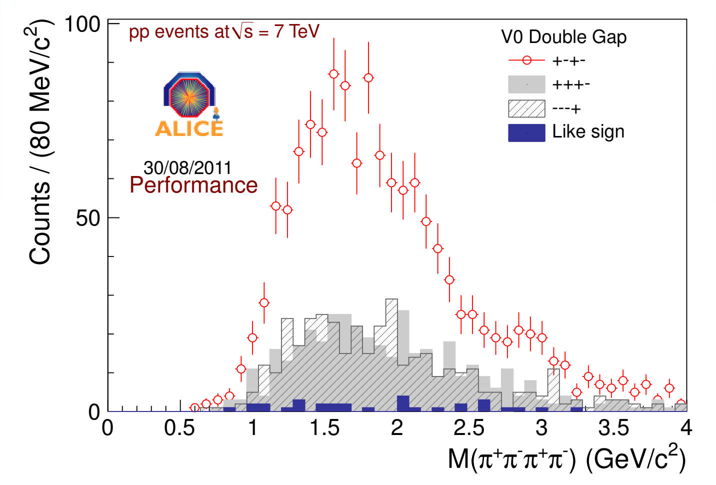
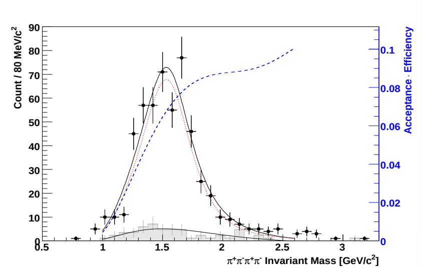
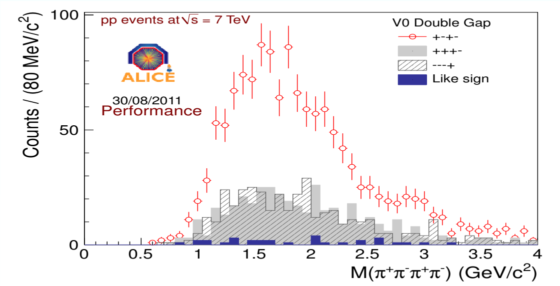
- Further study (under way): $X^0 \to (K\bar{K}\pi)^0$ or $X^0 \to (K\bar{K}\pi\pi)^0$


pp events at √s = 7 TeV
30/08/2011
Performance
ALICE
V0 Double Gap
+-+-
+++-
---+
Like sign
Counts / (80 MeV/c^2)
100
50
0
0.5
1
1.5
2
2.5
3
3.5
4
M($\pi^+\pi^-\pi^+\pi^-$) (GeV/c^2)

Compare the two figures from STAR and ALICE:





ALICE data shows wider distribution of events than STAR data.

Both show a peak at $\simeq$ 1.5 GeV, but there seems to be an additonal peak at $\simeq$ 2.0 GeV in the ALICE data, not present in the STAR data.

Conclusions and Future Prospects I

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     $\rightarrow \eta\pi$

     $\not\rightarrow \eta'\pi, \ \rho\pi, \ f_1(1285)\pi, \ b_1(1235)\pi$

     $\Rightarrow$ If $10 \oplus \overline{10}$, then predict

     no $\eta_1(1400)$ partner but $\rho(1400)$

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3. $\pi_1(2000)$: $M \sim 2000$ MeV, $\Gamma \sim 300$ MeV (Not covered today)
   $\rightarrow f_1(1285)\pi,\ b_1(1235)\pi$:

   $\diamond$ Constituents: $(n\bar{n}) + \text{gluon}$?

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Conclusions and Future Prospects II

Recent Results and Future Plans at COMPASS:

- Diffractive Dissociations $\pi^-(190\ \mathrm{GeV}/c) \to \pi^+\pi^-\pi^-$ on Pb and proton targets. The exotic meson $J^{PC} = 1^{-+}$ $\pi_1(1600) \to \rho\pi$ clearly seen both data samples,

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- The data from the proton target is currently under intense study by F. Hass/TUM (for his Ph.D. thesis) and by Dima Ryabchikov/IHEP, Protvino—currently at TUM.
- From a study of the partial waves on different t' bins, they have found that the partial waves have the t' dependence

$$A \propto (t')^{|M|} \exp[-(b \cdot t')/2]$$

where M is the spin projection of a partial wave, and the slope parameter b is *different for each partial wave* and is a function of the 3π mass.

Conclusions and Future Prospects II

Recent Results and Future Plans at COMPASS:

- Diffractive Dissociations $\pi^-(190\ \mathrm{GeV}/c) \to \pi^+\pi^-\pi^-$ on Pb and proton targets. The exotic meson $J^{PC} = 1^{-+}$ $\pi_1(1600) \to \rho\pi$ clearly seen both data samples,
- The data from the proton target is currently under intense study by F. Hass/TUM (for his Ph.D. thesis) and by Dima Ryabchikov/IHEP, Protvino—currently at TUM.
- From a study of the partial waves on different t' bins, they have found that the partial waves have the t' dependence

$$A \propto (t')^{|M|} \exp[-(b \cdot t')/2]$$

where M is the spin projection of a partial wave, and the slope parameter b is *different for each partial wave* and is a function of the 3π mass.

- The results of this analysis to be made public soon.

Conclusions and Future Prospects III

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- The exotic J^{PC}'s for X^0 are

$$1^{-+},\ 3^{-+},\ 5^{-+},\text{etc. for } \mathbb{P}+\mathbb{P}$$

$$2^{+-},\ 4^{+-},\ 6^{+-},\text{etc. for } \gamma+\mathbb{P}$$