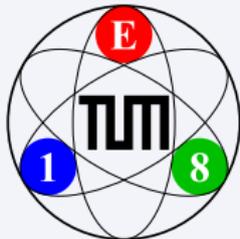


Hadron Spectroscopy with COMPASS

Boris Grube
for the COMPASS Collaboration

Physik-Department E18
Technische Universität München,
Garching, Germany

DPG Frühjahrstagung 2012
Mainz, 19.03.2012
Gruppenbericht HK 8.1



The COMPASS Physics Program

COmmon MUon and PROton APParatus for STRUCTure and SPECTROSCOPY

Goal

- Study **non-perturbative regime of QCD**
- Probe structure and dynamics of hadrons

Very low Q^2 :

chiral dynamics

- π and K em. polarizabilities
- $\pi\gamma^*$ reactions (Primakoff)

HK 23.1 J. M. Friedrich

Intermediate Q^2 :

spectroscopy

- Mass spectrum of hadrons
- Gluonic excitations

Large Q^2 :

nucleon structure

- Helicity, transversity PDFs
- Generalized PDFs

HK 23.2, 23.4, 23.6, 23.7, 61.2

Plenary Talk: **PV III** F. Nerling

- 1 The experimental setup
- 2 Search for spin-exotic mesons
 - PWA of $\pi^- \pi^+ \pi^-$ from π^- diffraction
 - PWA of $\pi^- \eta$ and $\pi^- \eta'$ from π^- diffraction
 - PWA of $\pi^- \pi^+ \pi^- \pi^+ \pi^-$ from π^- diffraction
- 3 Search for scalar glueballs
 - PWA of $\pi^+ \pi^-$ from central production

Outline

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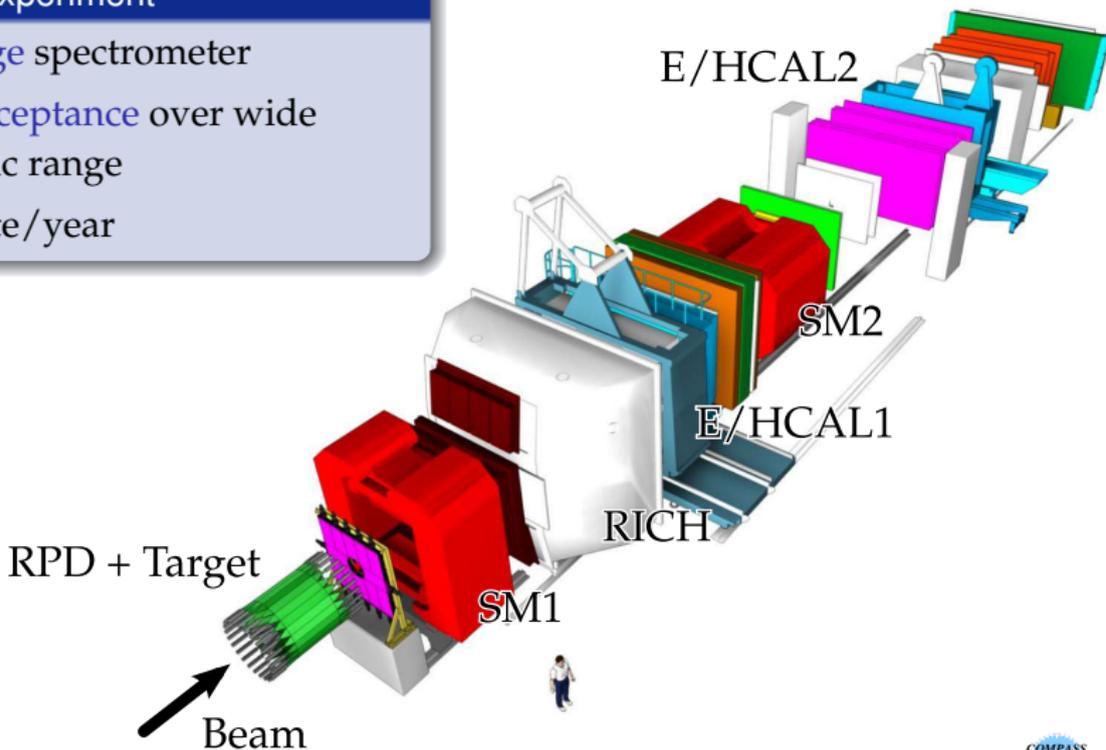
The COMPASS Experiment at the CERN SPS

Experimental Setup

NIM A 577, 455 (2007)

Fixed-target experiment

- Two-stage spectrometer
- Large acceptance over wide kinematic range
- > 1 PByte/year



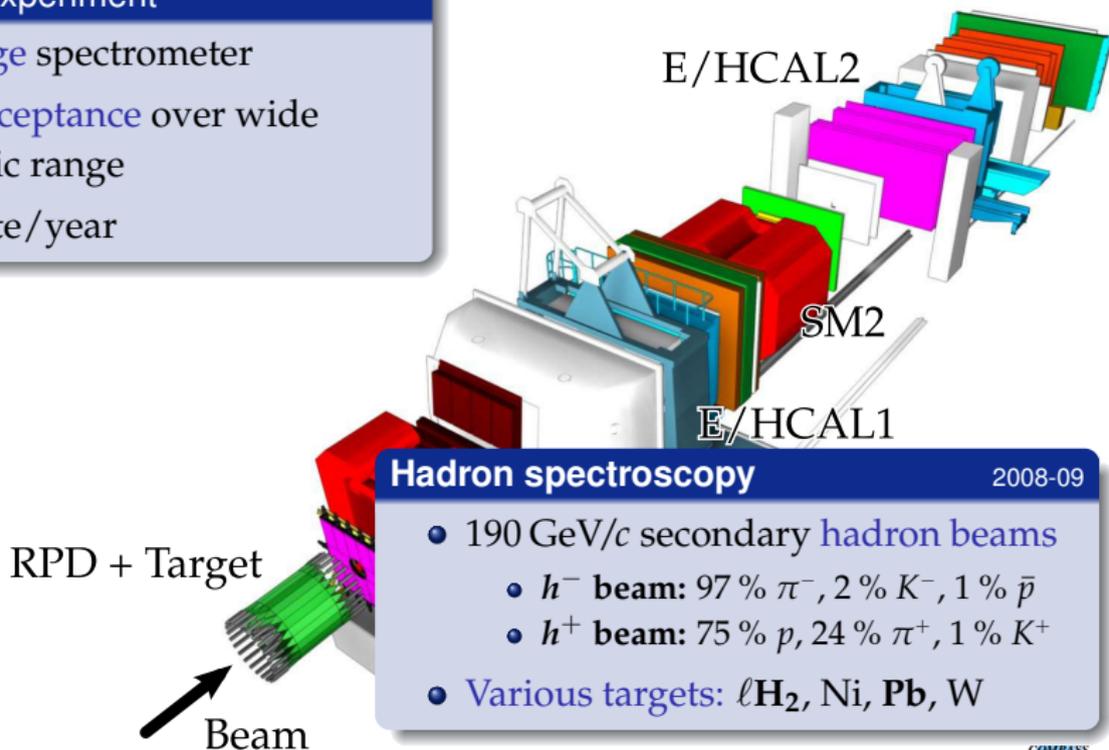
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Hadron spectroscopy

2008-09

- 190 GeV/c secondary hadron beams
 - h^- beam: 97 % π^- , 2 % K^- , 1 % \bar{p}
 - h^+ beam: 75 % p , 24 % π^+ , 1 % K^+
- Various targets: ℓ H₂, Ni, Pb, W

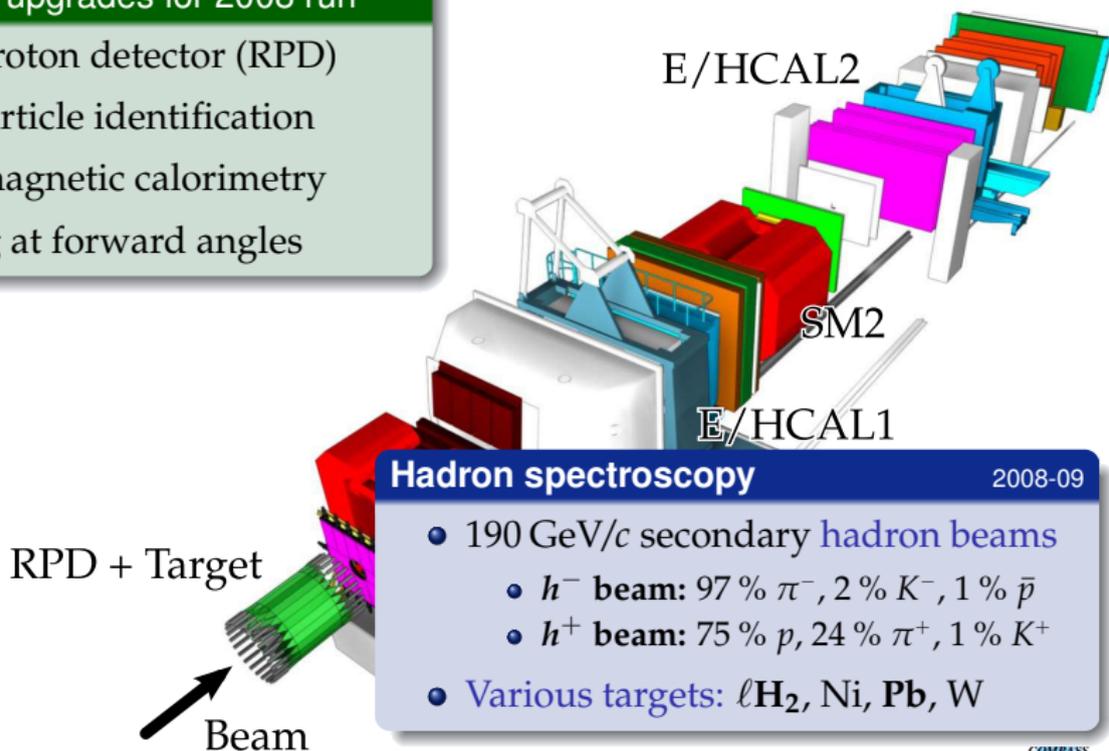
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Experimental Setup

NIM A 577, 455 (2007)

Spectrometer upgrades for 2008 run

- Recoil proton detector (RPD)
- Beam particle identification
- Electromagnetic calorimetry
- Tracking at forward angles



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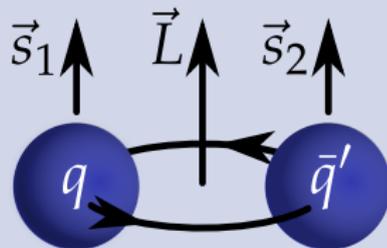
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Mesons in the Constituent Quark Model

Spin-parity rules for bound $q\bar{q}'$ system

- Quark spins couple to **total intrinsic spin**
 $S = 0$ (singlet) or 1 (triplet)
- Relative **orbital angular Momentum** \vec{L}
and total spin \vec{S} couple to
meson spin $\vec{J} = \vec{L} + \vec{S}$
- Parity $P = (-1)^{L+1}$
- Charge conjugation $C = (-1)^{L+S}$
- **Forbidden** J^{PC} : $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \dots$



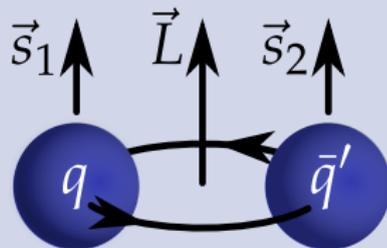
QCD allows for states beyond the CQM

- Hybrids $|q\bar{q}g\rangle$, glueballs $|gg\rangle$, multi-quark states $|q^2\bar{q}^2\rangle, \dots$
- **Physical mesons**: superposition of all allowed basis states
- **“Exotic” mesons** have quantum numbers forbidden for $|q\bar{q}\rangle$
 - Particularly interesting: J^{PC} -exotic states

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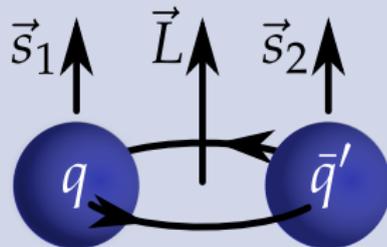
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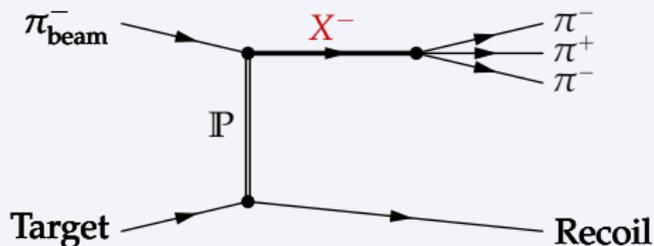
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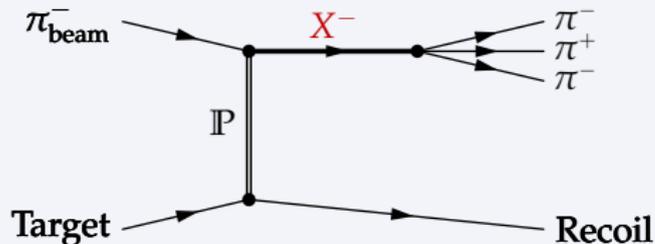
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Production of Hadrons in Diffractive Dissociation



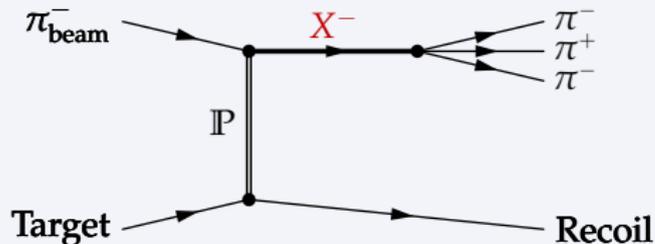
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- High \sqrt{s} and low t : Pomeron exchange dominates strong interactions
- Rich spectrum: large number of overlapping and interfering states
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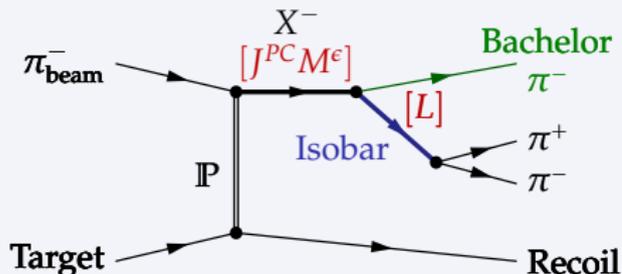
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Diffractive Dissociation of π^- into $\pi^- \pi^+ \pi^-$ Final State



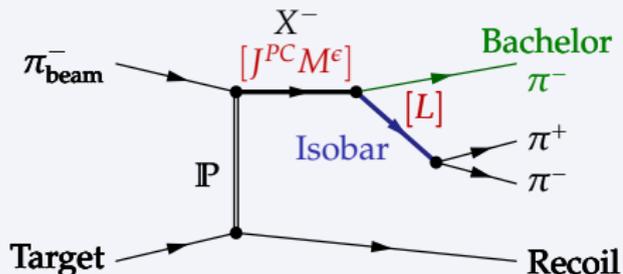
Isobar model: X^- decay is chain of successive two-body decays

- “Wave”: unique combination of **isobar** and quantum numbers
- Full wave specification (in reflectivity basis): $J^{PC} M^E [\text{isobar}] L$

Fit model: $\sigma(m_X, \tau) = \sigma_0 \left| \sum_{\text{waves}} T_{\text{wave}}(m_X) A_{\text{wave}}(m_X, \tau) \right|^2$

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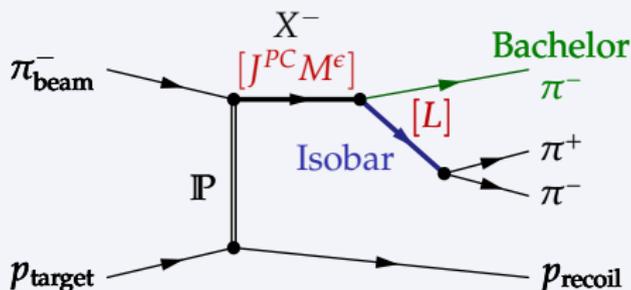
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PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$

HK 23.3 F. Haas



- 190 GeV/c negative hadron beam: 97 % π^- , 2 % K^- , 1 % \bar{p}
- Liquid hydrogen target
- Recoil proton measured by RPD
- Kinematic range $0.1 < t' < 1.0$ (GeV/c)²

PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$

HK 23.3 F. Haas

World's largest 3π data set: 96 M events

- Challenging analysis
 - Needs precise understanding of apparatus
 - Model deficiencies become visible

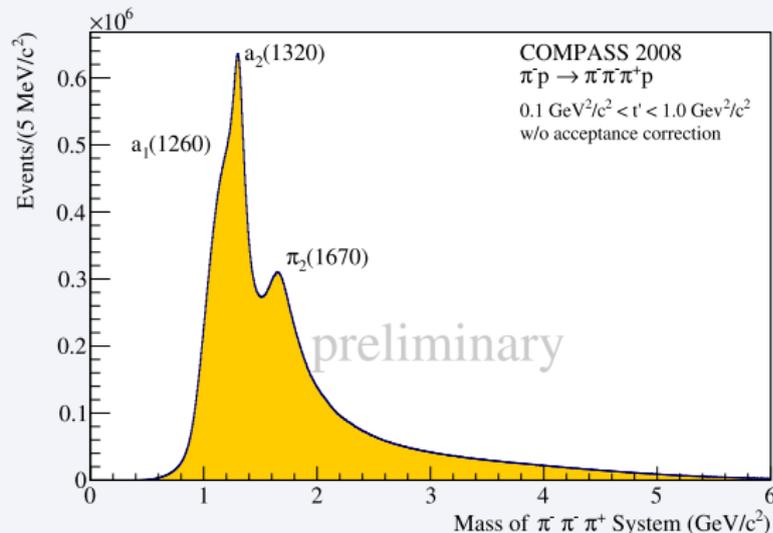
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$\pi^- \pi^+ \pi^-$ invariant mass distribution



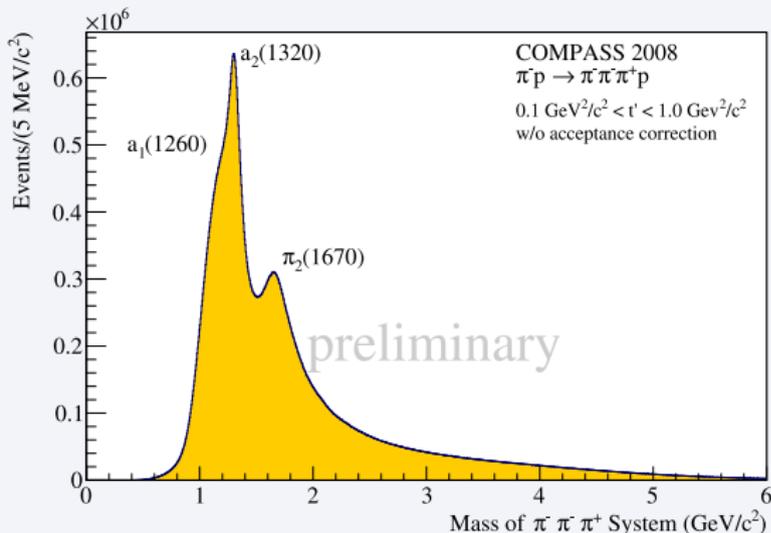
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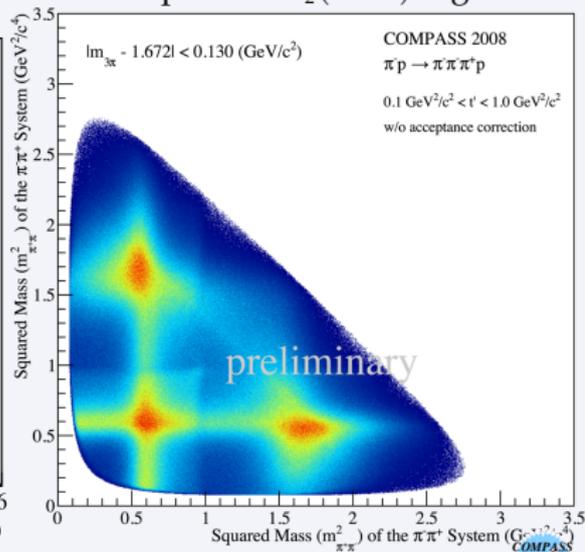
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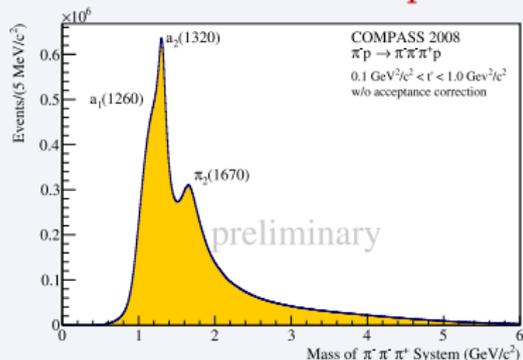
Dalitz plot for $\pi_2(1670)$ region



PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$

HK 23.3 F. Haas

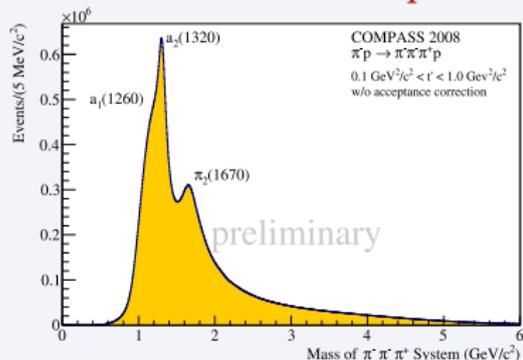
$\pi^- \pi^+ \pi^-$ invariant mass spectrum



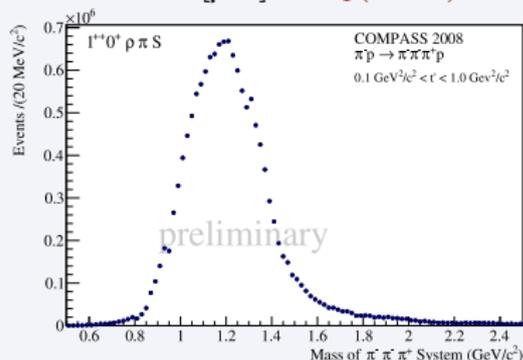
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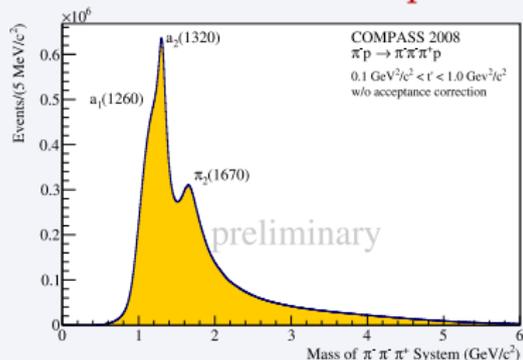
$1^{++} 0^+ [\rho\pi] S : a_1(1260)$



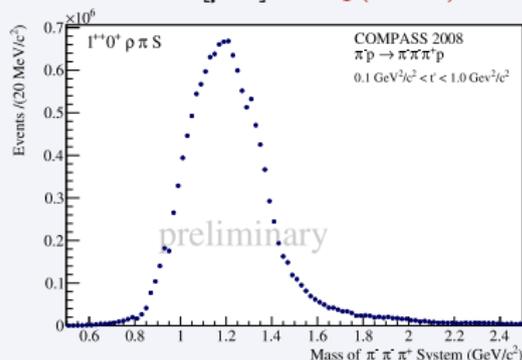
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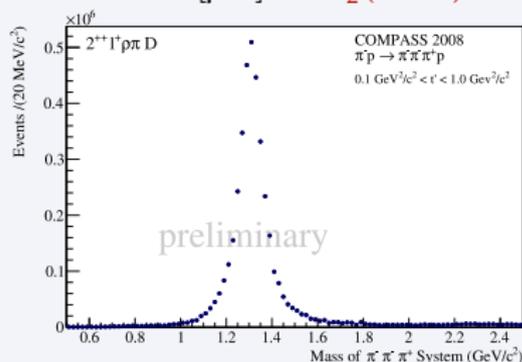
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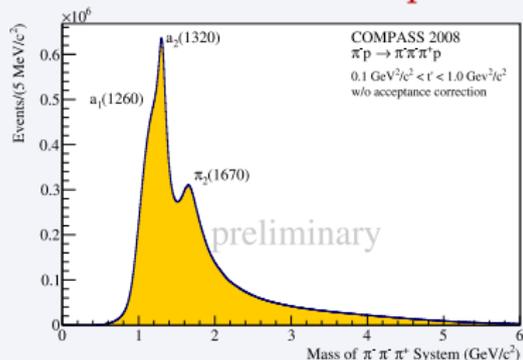
$2^{++} 1^+ [\rho\pi] D : a_2(1320)$



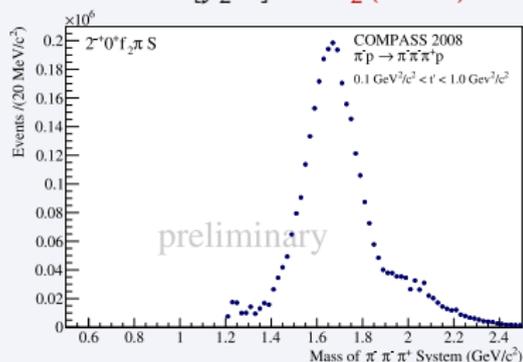
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HK 23.3 F. Haas

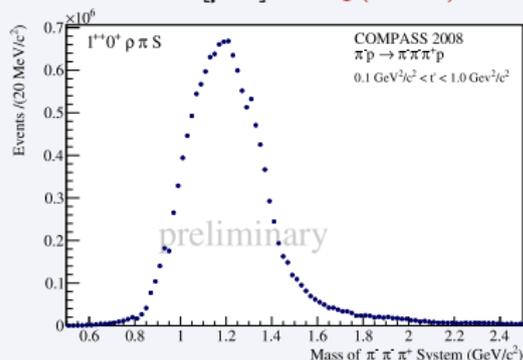
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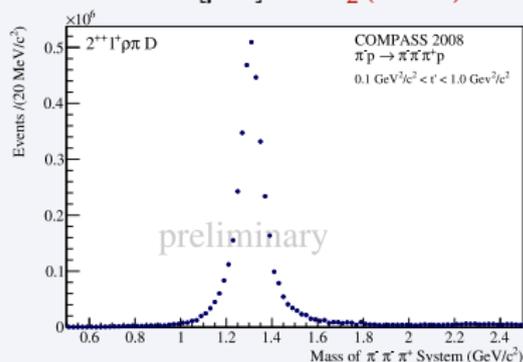
$2^-+ 0^+ [f_2 \pi] S : \pi_2(1670)$



$1^{++} 0^+ [\rho \pi] S : a_1(1260)$

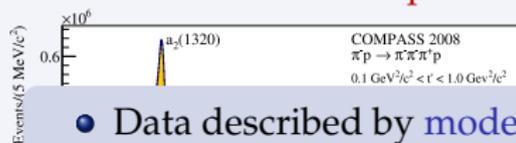


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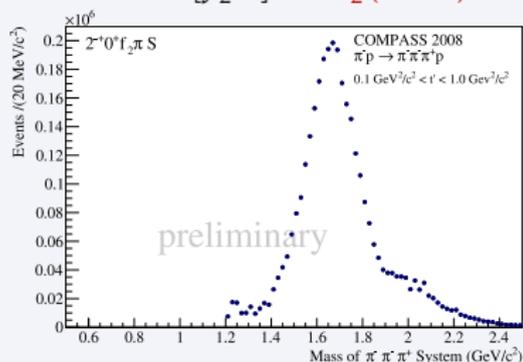
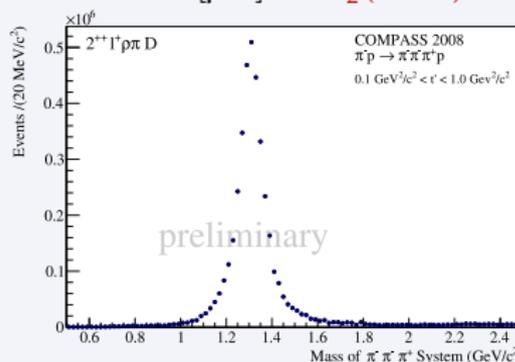
PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$

HK 23.3 F. Haas

 $\pi^- \pi^+ \pi^-$ invariant mass spectrum $1^{++} 0^+ [\rho\pi] S : a_1(1260)$ 

- Data described by model consisting of 52 waves + incoherent isotropic background

- Isobars: $(\pi\pi)_{S\text{-wave}}$, $f_0(980)$, $\rho(770)$, $f_2(1270)$, $f_0(1500)$ and $\rho_3(1690)$

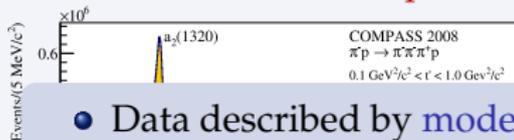
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HK 23.3 F. Haas

$\pi^- \pi^+ \pi^-$ invariant mass spectrum

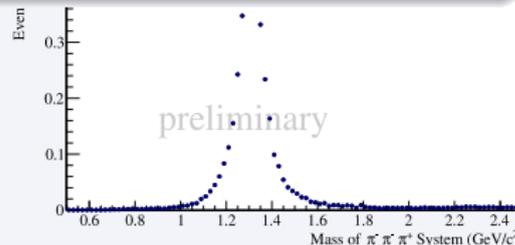
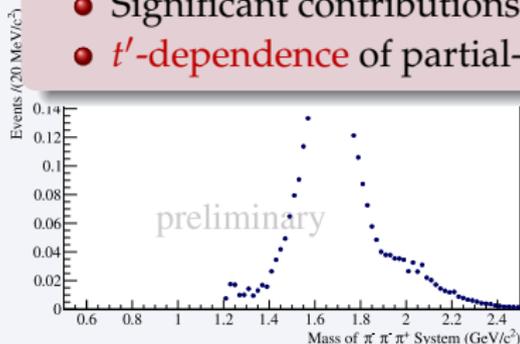
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- Data described by model consisting of 52 waves + incoherent isotropic background
- Isobars: $(\pi\pi)_{S\text{-wave}}, f_0(980), \rho(770), f_2(1270), f_0(1500)$ and $\rho_3(1690)$

Understanding of small waves is work in progress

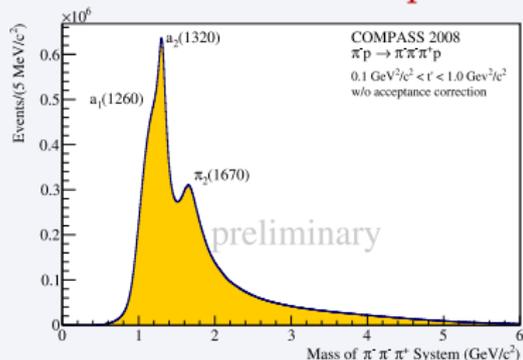
- Significant contributions from Deck-like processes
- t' -dependence of partial-wave amplitudes important



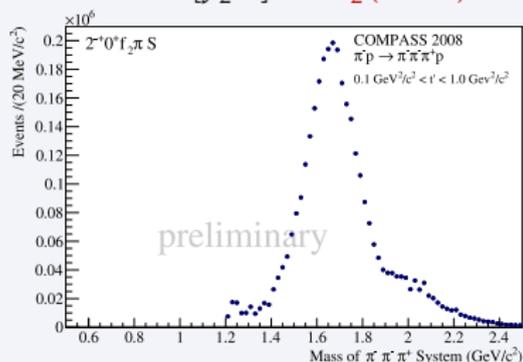
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HK 23.3 F. Haas

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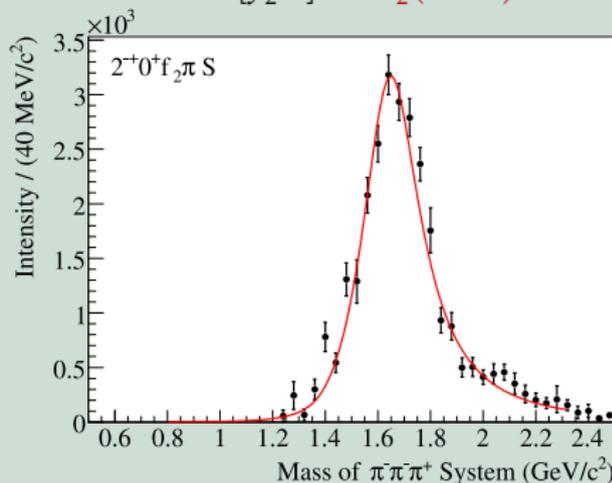
$2^-+ 0^+ [f_2 \pi] S : \pi_2(1670)$



200x data from pilot-run

PRL 104 (2010) 241803

$2^-+ 0^+ [f_2 \pi] S : \pi_2(1670)$



- 420 000 events
- Pb target

Mass of $\pi^- \pi^+ \pi^-$ System (GeV/c^2) COMPASS

Hadron Spectroscopy with

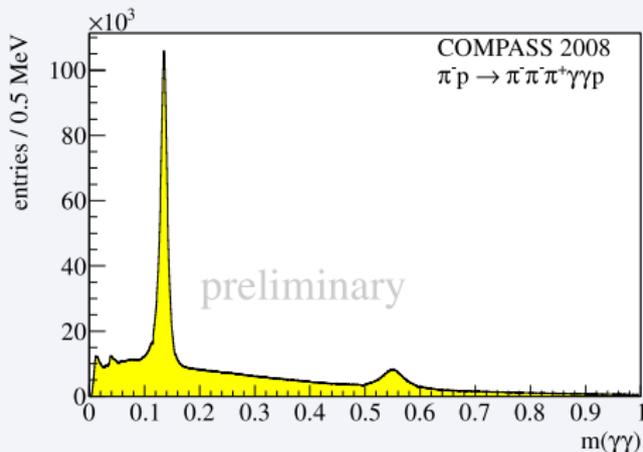
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HK 8.2 T. Schlüter

Selection of exclusive events with 3 charged tracks + 2 photons

- η reconstructed from $\eta \rightarrow \pi^+ \pi^- \pi^0$
- η' reconstructed via $\pi^+ \pi^- \eta$ decay with $\eta \rightarrow \gamma \gamma$

$\gamma\gamma$ mass distribution



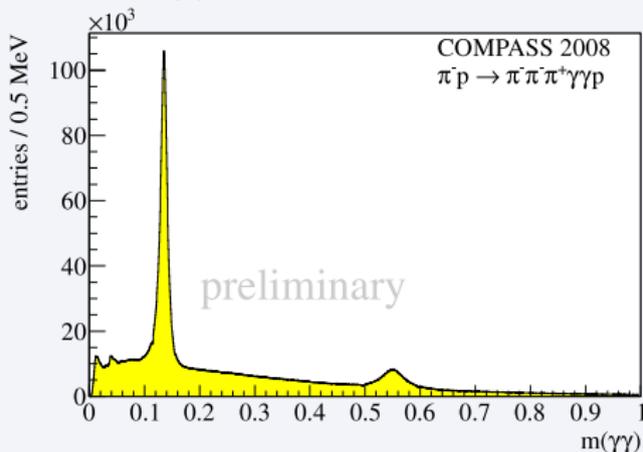
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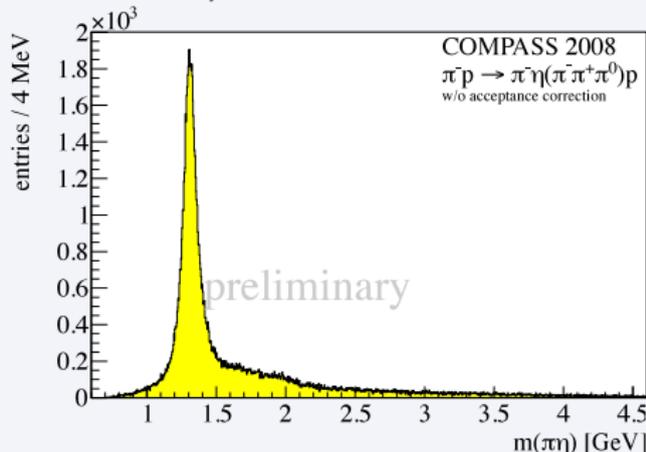
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$\pi^- \eta$ mass distribution



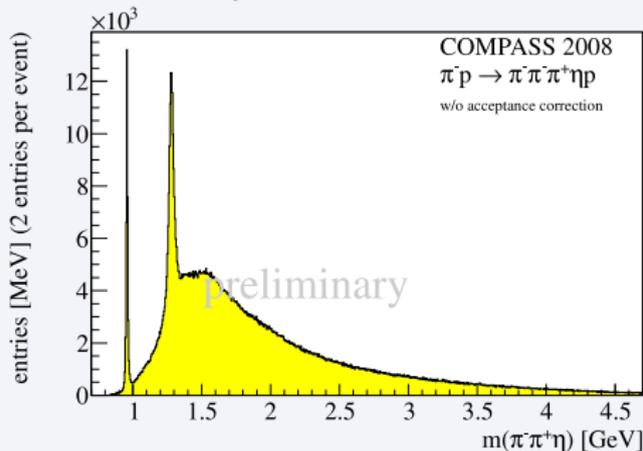
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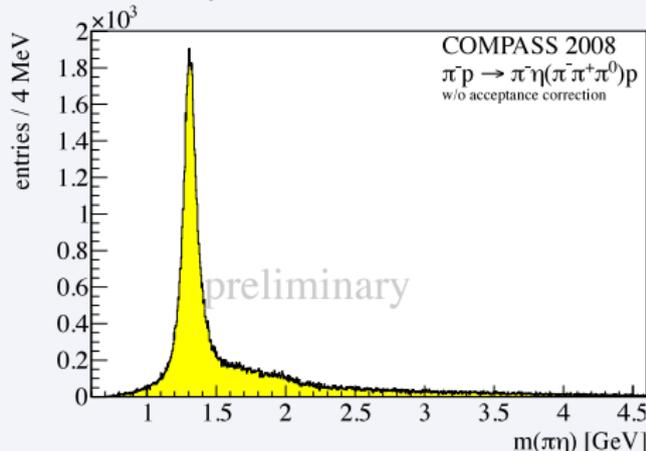
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$\pi^- \eta$ mass distribution



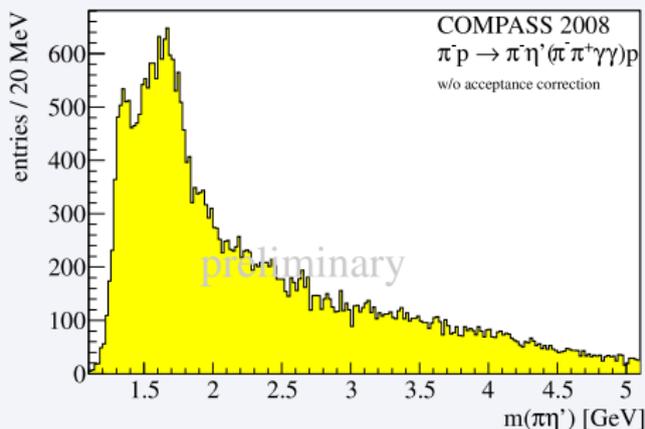
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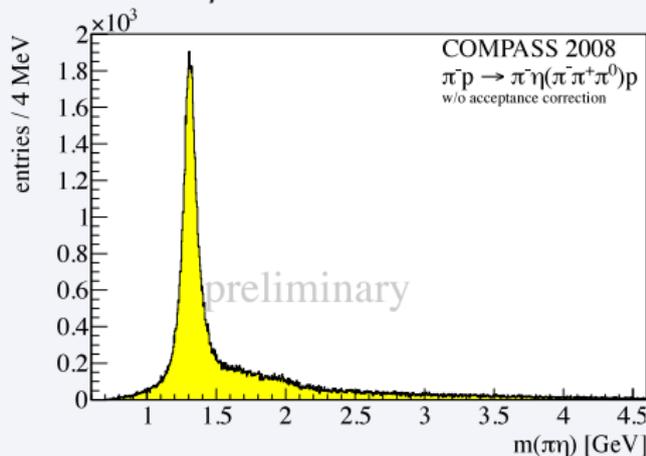
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$\pi^- \eta'$ mass distribution

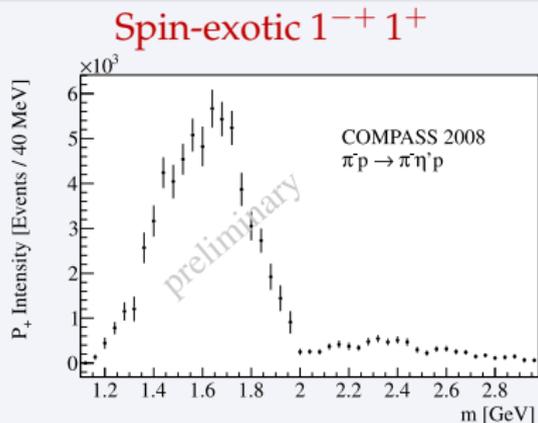


$\pi^- \eta$ mass distribution



PWA of $\pi^- p \rightarrow \pi^- \eta' p$

HK 8.2 T. Schlüter

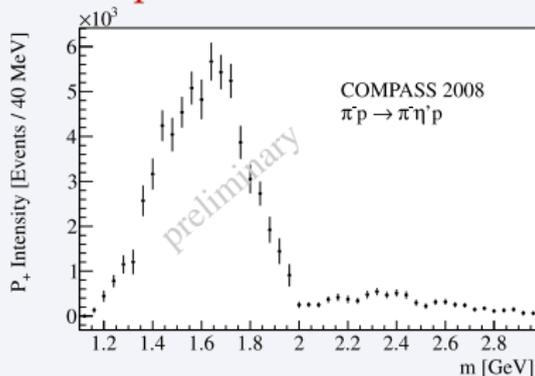


- $1^{-+} 1^{+}$ is dominant wave
- Slight phase motion w.r.t. $2^{++} 1^{+}$

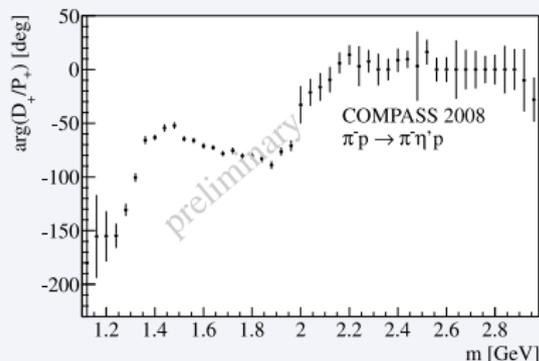
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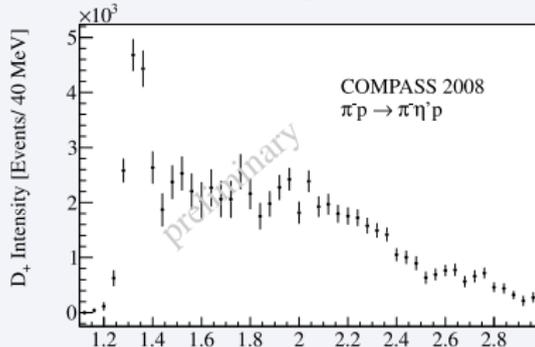
Spin-exotic $1^{-+} 1^{+}$



$2^{++} 1^{+} - 1^{-+} 1^{+}$



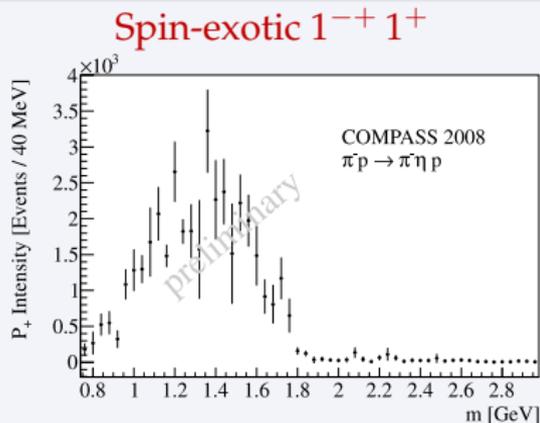
$2^{++} 1^{+} : a_2(1320)$



- $1^{-+} 1^{+}$ is dominant wave
- Slight phase motion w.r.t. $2^{++} 1^{+}$

PWA of $\pi^- p \rightarrow \pi^- \eta p$

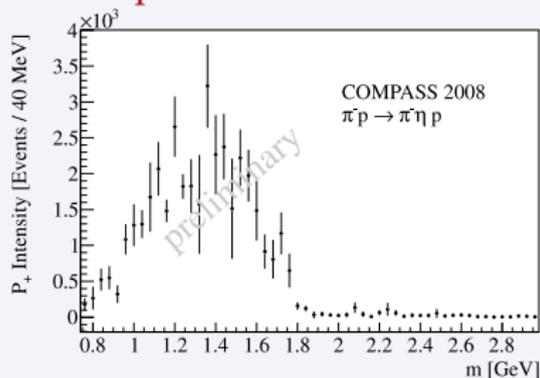
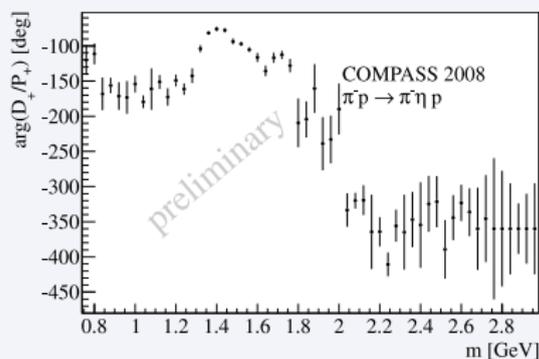
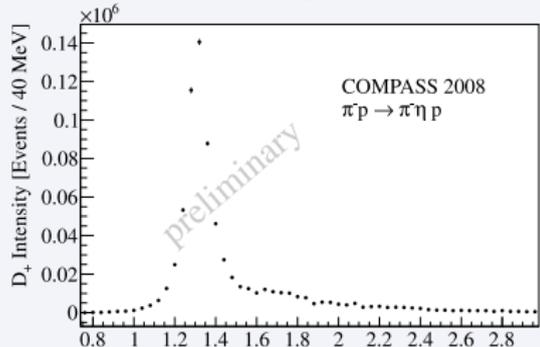
HK 8.2 T. Schlüter



- $1^-+ 1^+$ much smaller
- $2^{++} 1^+$ is dominant wave
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HK 8.2 T. Schlüter

Spin-exotic $1^{-+} 1^{+}$  $1^{-+} 1^{+} - 2^{++} 1^{+}$  $2^{++} 1^{+} : a_2(1320)$ 

- $1^{-+} 1^{+}$ much smaller
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PWA of $\pi^- p \rightarrow \pi^- \eta p$ and $\pi^- \eta' p$

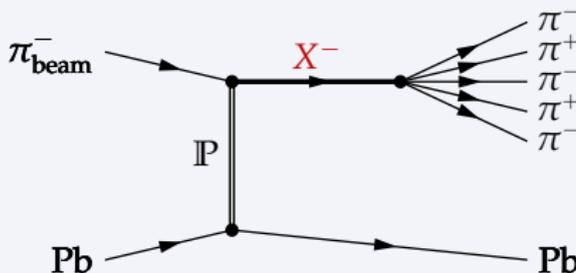
HK 8.2 T. Schlüter

Work in progress

- Resonance interpretation of $1^{-+} 1^{+}$ requires **understanding of resonance structure of $2^{++} 1^{+}$ wave**
- **First mass-dependent fits** (HK 8.2 T. Schlüter)
- **Final goal: combined analysis** of both channels

PWA of $\pi^- \text{Pb} \rightarrow \pi^- \pi^+ \pi^- \pi^+ \pi^- \text{Pb}$

HK 8.4 S. Neubert



First mass-dependent analysis of this channel

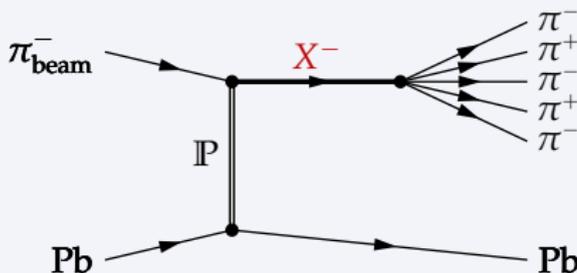
- **Light-meson frontier:** access to mesonic states in $2 \text{ GeV}/c^2$ region
- Little information from previous experiments

Data from pilot run

- Pb target
- Recoil not measured
- Kinematic range $t' < 5 \cdot 10^{-3} (\text{GeV}/c)^2$

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Fit model

- Complicated isobar structure
 - Large number of possible waves
 - Data exhibit no dominant waves
- Exploration of model space using evolutionary algorithm based on goodness-of-fit criterion
 - 284 waves tested
 - Also provides estimate for systematic uncertainty from fit model
- Best model: 31 waves + incoherent isotropic background
- Isobars
 - $(2\pi)^0$ isobars: $(\pi\pi)_{S\text{-wave}}, \rho(770)$
 - $(3\pi)^\pm$ isobars: $a_1(1260), a_2(1320)$
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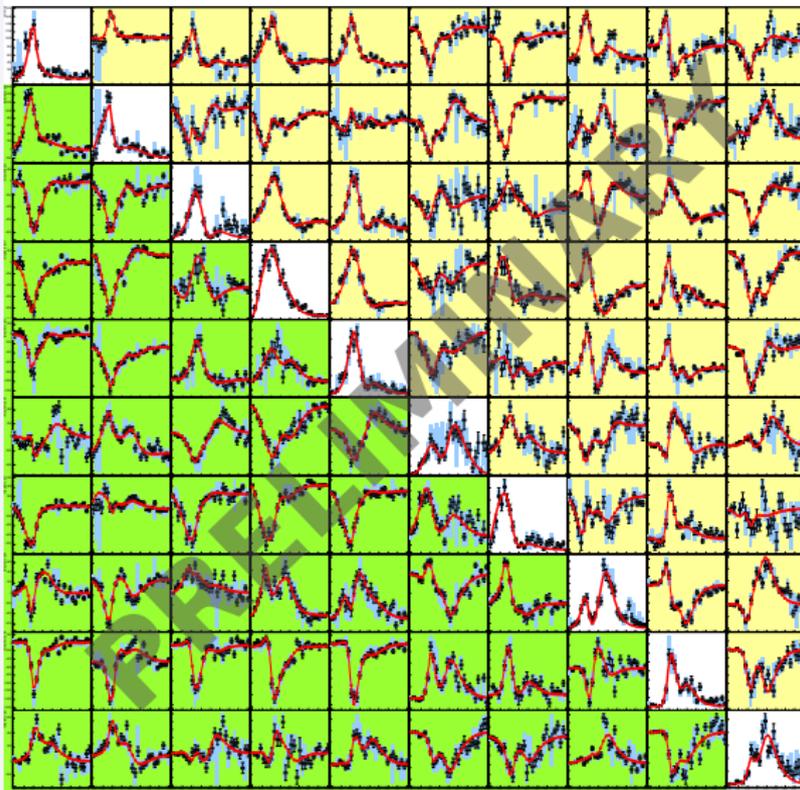
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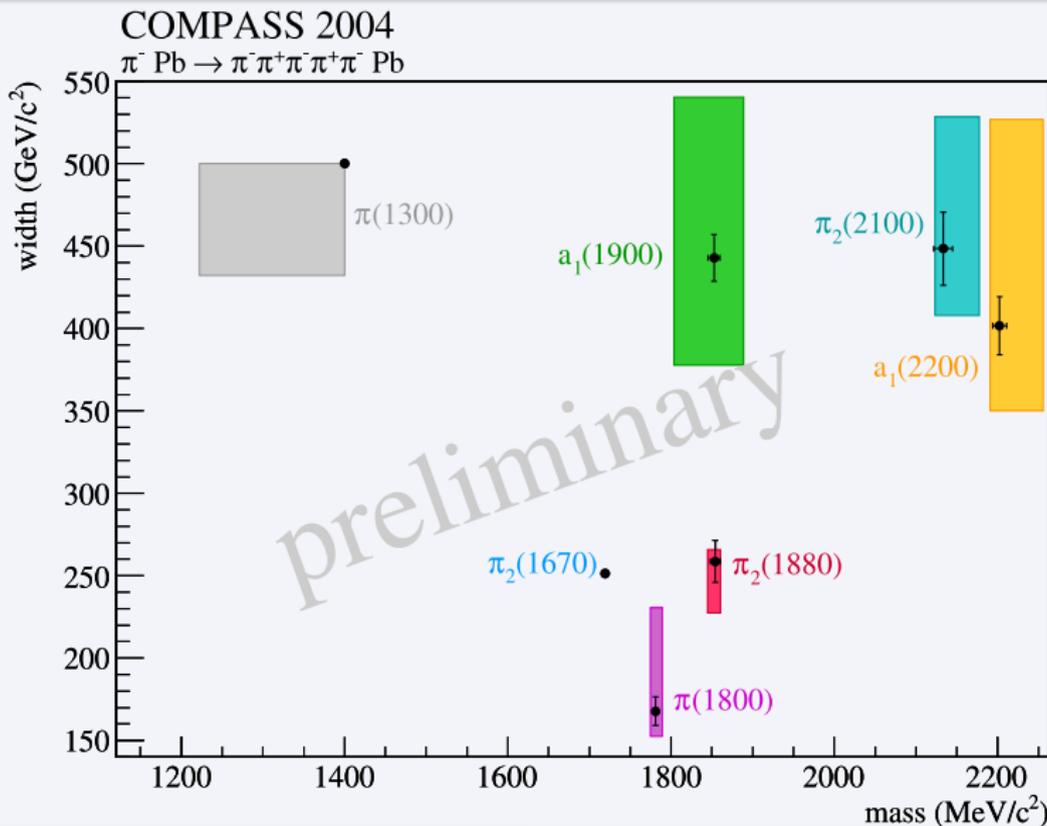
PWA of $\pi^- \text{Pb} \rightarrow \pi^- \pi^+ \pi^- \pi^+ \pi^- \text{Pb}$

HK 8.4 S. Neubert



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Proof of Principle: First mass-dependent full five-body PWA

- Rather **simplistic fit model**
 - Spin-density sub-matrix of **10 waves** described using **7 resonances** + background terms
 - Parameterization by sum of **relativistic constant-width Breit-Wigners**
 - Mixing and coupled-channel effects neglected
 - Multi-peripheral processes (Deck-effect) not taken into account
- **Good description of data**

Work in progress

- **Much more data on tape**
 - Proton target, kinematic range $0.1 < t' < 1$ (GeV/c)²
- **Improvement of fit models**

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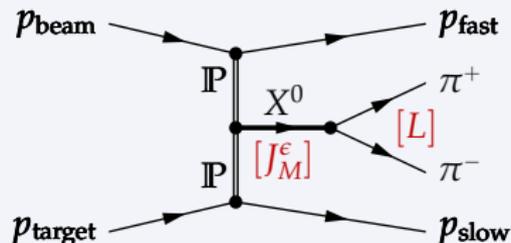
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Outline

- 1 The experimental setup
- 2 Search for spin-exotic mesons
 - PWA of $\pi^-\pi^+\pi^-$ from π^- diffraction
 - PWA of $\pi^-\eta$ and $\pi^-\eta'$ from π^- diffraction
 - PWA of $\pi^-\pi^+\pi^-\pi^+\pi^-$ from π^- diffraction
- 3 Search for scalar glueballs
 - PWA of $\pi^+\pi^-$ from central production

PWA of $p p \rightarrow p_{\text{fast}} \pi^+ \pi^- p_{\text{slow}}$

HK 22.3 A. Austregesilo

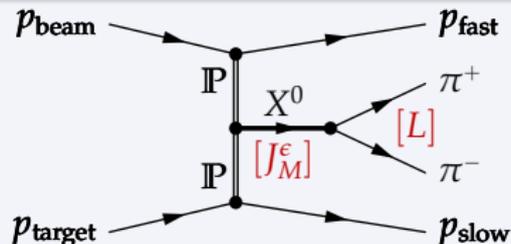


Search for glueballs

- Mesonic state with no valence quarks
- Lattice QCD simulations predict lightest glueball to be scalars
 - Strong mixing with conventional scalar mesons expected
 - Difficult to disentangle
- Pomeron-Pomeron processes well-suited to study scalar mesons

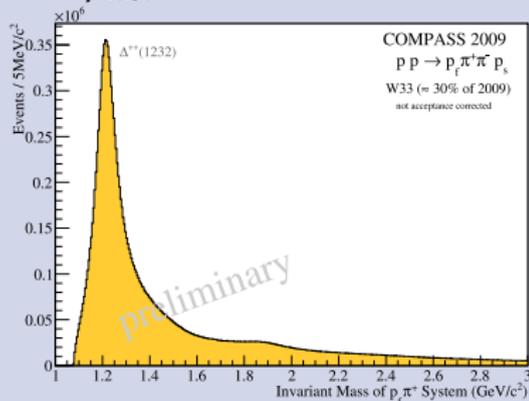
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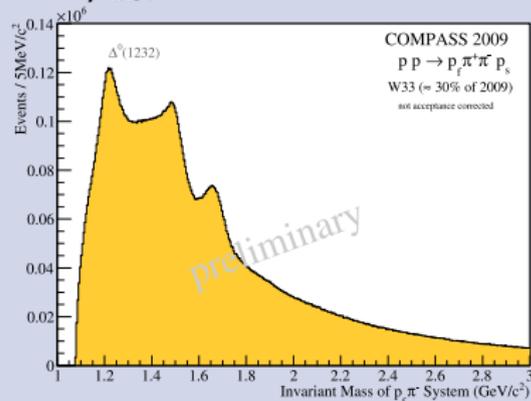


Selection of central events: cut $m(p_{\text{fast}}\pi^\pm), m(p_{\text{slow}}\pi^\pm) > 1.5 \text{ GeV}/c^2$

$p_{\text{fast}}\pi^+$ invariant mass

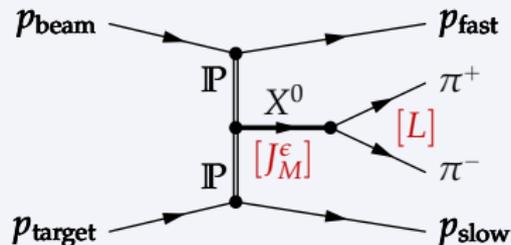


$p_{\text{fast}}\pi^-$ invariant mass



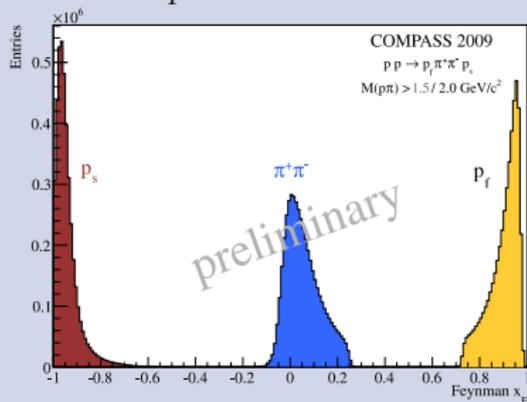
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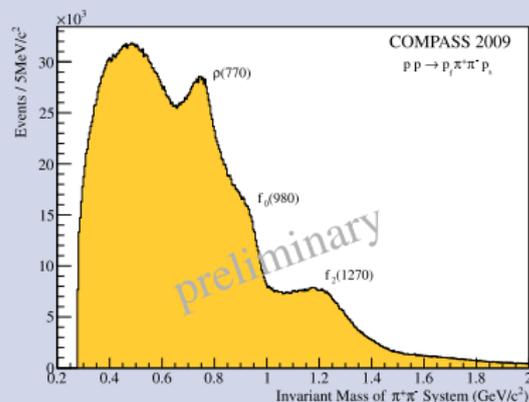


Selected central events

x_F distribution



$\pi^+\pi^-$ invariant mass



PWA of $p p \rightarrow p_{\text{fast}} \pi^+ \pi^- p_{\text{slow}}$

Proof of concept

- Analysis similar to previous experiments (WA102)
 - Comparable results
- Simplistic fit model
 - Angular information of the two proton scattering planes not taken into account
- 8 different mathematically ambiguous solutions
 - Additional constraints needed to select physical solution
- Next step: mass-dependent fit

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Conclusions and Outlook

COMPASS has acquired world's largest data sets for many channels

- Main focus on search for J^{PC} -exotic mesons
 - Pilot run: significant $J^{PC} = 1^{-+}$ signal consistent with $\pi_1(1600)$ seen in $\pi^- \pi^+ \pi^-$ data on Pb target PRL 104 (2010) 241803
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