

New Insights on Spectroscopy and Properties of light hadrons with COMPASS

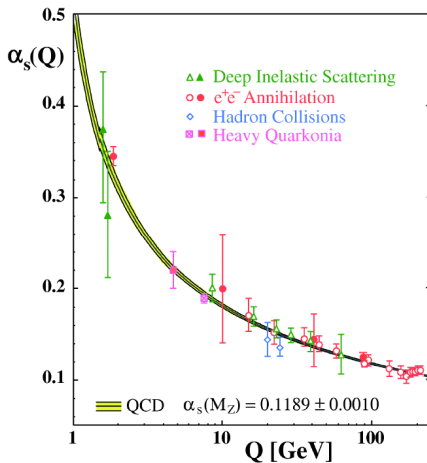
Florian Haas

Physik Department E18 - Technische Universität München
for the COMPASS Collaboration

XIth Quark Confinement and the Hadron Spectrum

supported by:
Maier-Leibnitz-Labor der TU und LMU München,
Cluster of Excellence: Origin and Structure of the Universe, BMBF



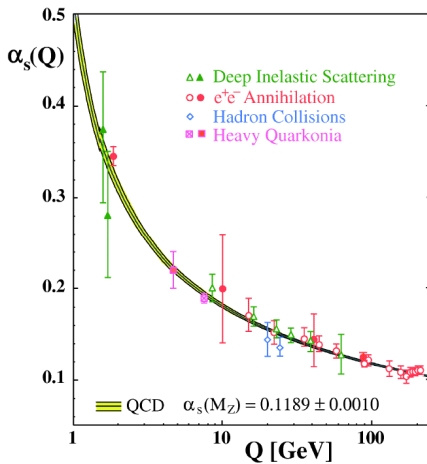


- Confinement
- Hadrons relevant DOF

- Asymptotic Freedom
- Quarks & Gluons relevant DOF
- Perturbative QCD
- Hadronization, Jets

S. Bethke

[arXiv:hep-ex/0606035v2]

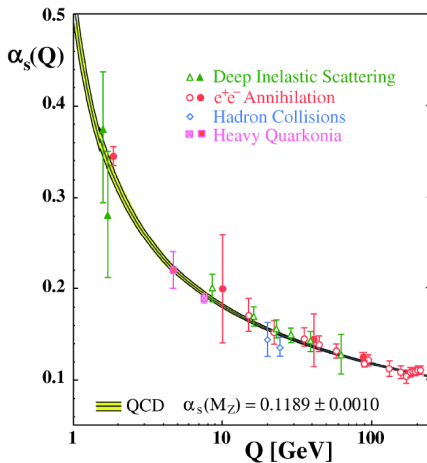


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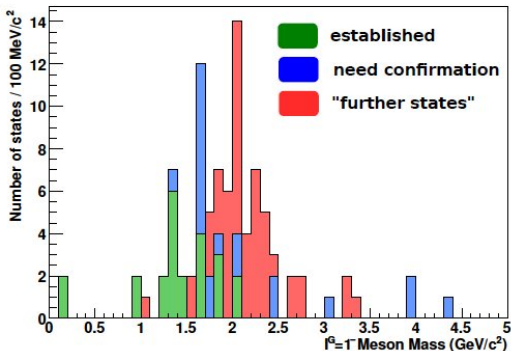
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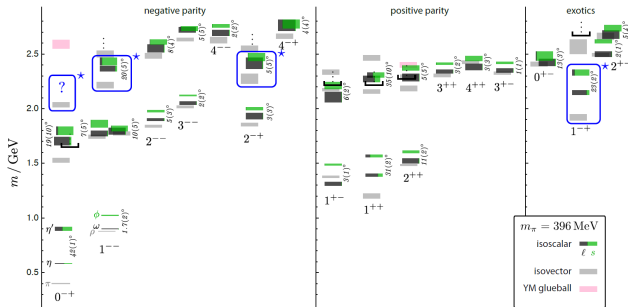


- Confinement
- Hadrons relevant DOF
- Dynamics of excited states?
- Models and theories
 - Quark model
 - Bag model
 - Flux tube model
 - χ_{PT} for slow pions
 - Lattice QCD





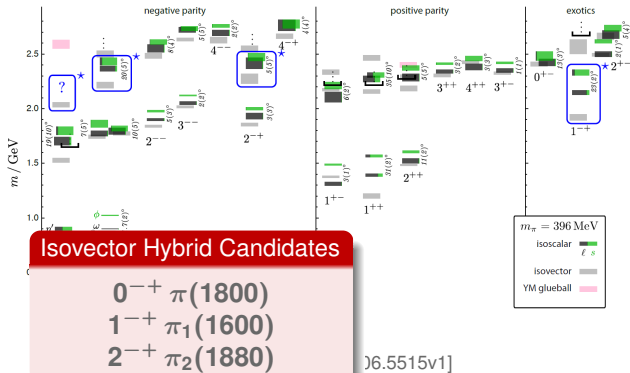
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Dudek et al. [arXiv:1106.5515v1]



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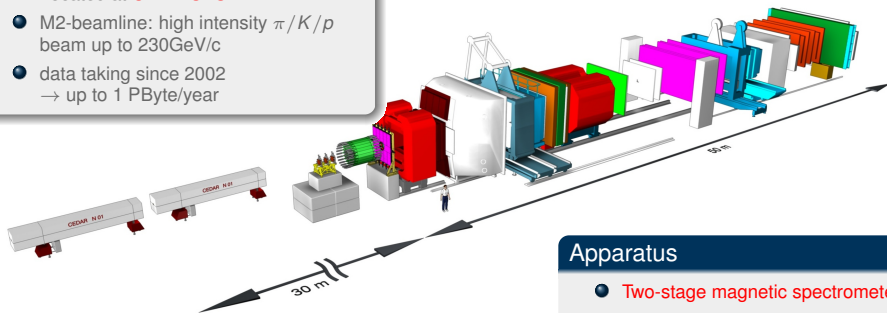


The COMPASS Hadron Setup

Spectrometer and Hadron Beam

Overview

- **CO**mmun **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy ¹
- Located at **CERN SPS**
- M2-beamline: high intensity $\pi/K/p$ beam up to 230GeV/c
- data taking since 2002
→ up to 1 PByte/year



Apparatus

- **Two-stage magnetic spectrometer**
- Large acceptance charged tracking
- Calorimetry (ECAL/HCAL)
- Kaon PID (CEDARs/RICH)

¹ [Nucl. Instr. and Meth. A 577 (2007) 455]



Light-Meson Spectroscopy

$\pi^- \pi^- \pi^+$ and $\pi^- \pi^0 \pi^0$

$\eta \pi^-$ and $\eta' \pi^-$

Status of the $J^{PC} = 1^{-+}$ Spin Exotic Partial Wave

$\pi\pi$ Production at Central Rapidities

Tests of Chiral Dynamics

3π Primakoff Production

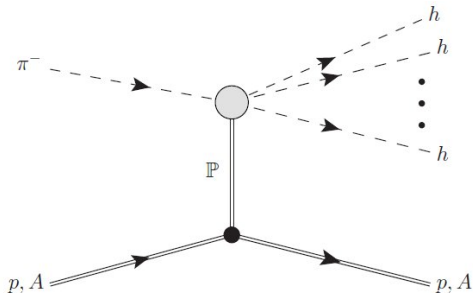
Pion Polarizability



Light-Meson Spectroscopy

Isovector Mesons

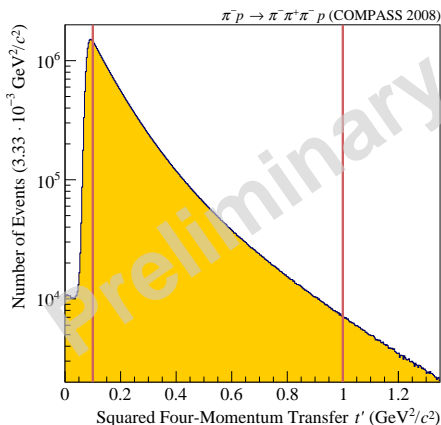
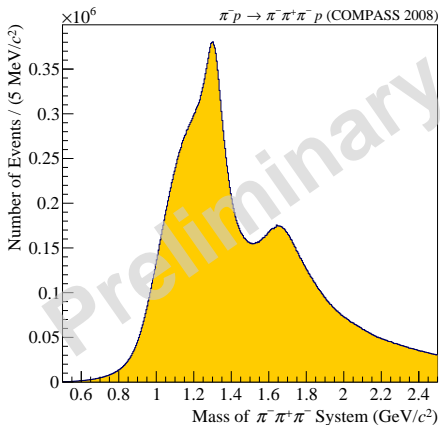
Diffractive Pion Dissociation





Diffractive Dissociation into $\pi^- \pi^+ \pi^-$

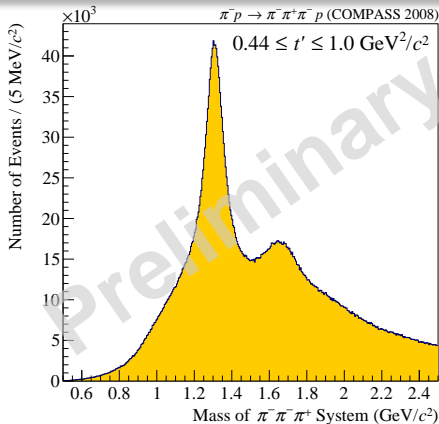
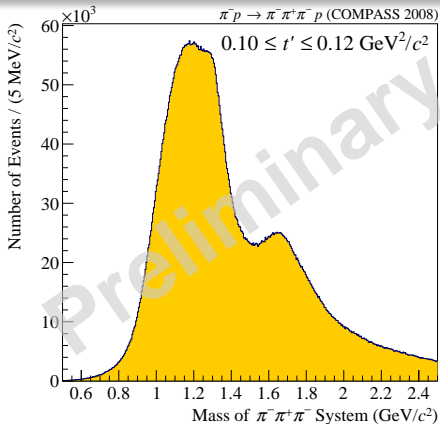
relevant kinematic distributions





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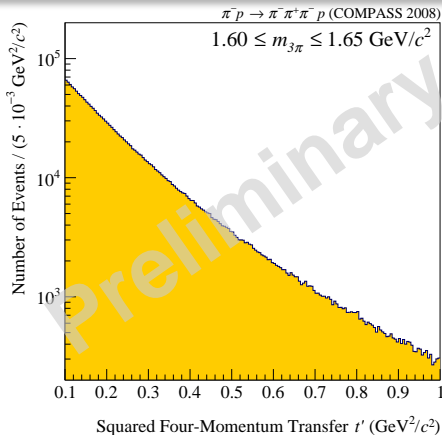
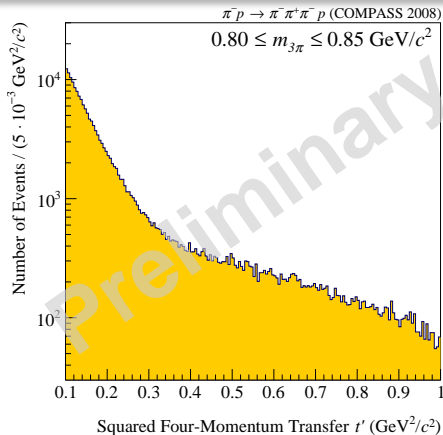


The invariant mass of the final state depends on squared four-momentum transfer t



Diffractive Dissociation into $\pi^- \pi^+ \pi^-$

relevant kinematic distributions

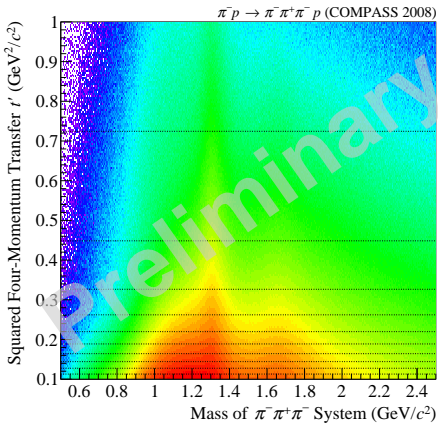


The squared four-momentum transfer t depends on the invariant mass of the final state



Diffractive Dissociation into $\pi^- \pi^+ \pi^-$

relevant kinematic distributions



Ansatz: Split data into small bins of t and $m_{3\pi}$



Partial Wave Analysis - Formalism

Step One: Decomposition in Spin-Parity States

Spin-Parity Decomposition for each bin of t and $m_{3\pi}$ (2D)

Assumption 1: Partial waves that contribute to the same final state are fully coherent.

$$\mathcal{I}(\tau) \sim \left| \sum_i \psi_i \right|^2$$

- T_i : Transition amplitude $\in \mathbb{C}$ (unknown, contains information on intensity and phases)
- ψ_i : Decay amplitude $\in \mathbb{C}$ (calculable, based on a set of kinematical distributions τ)
- i : partial waves $J^{PC} M^E \xi \pi L$ e.g. 3π : 87 waves up to spin 6 + one incoherent isotropic wave



Partial Wave Analysis - Formalism

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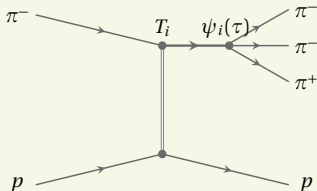
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Production and Decay





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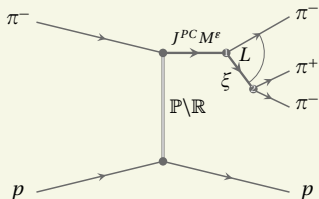
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Isobar Model





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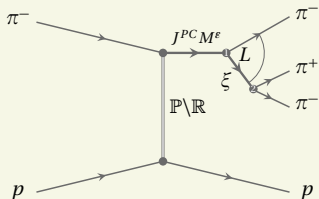
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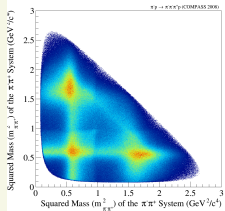
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Isobar Model



Dalitz Plot $\pi_2(1670)$ region





Partial Wave Analysis - Formalism

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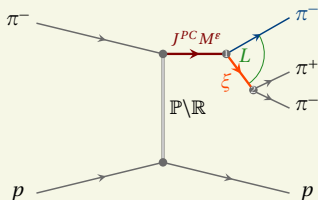
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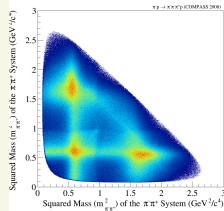
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Extraction of Resonance Parameters for t' and m

- Use full information of the spin density matrix elements $T_i T_j^*(m_x, t')$
 - Intensities
 - Phases
- Parametrise the spin density matrix
 - Breit-Wigner forms
 - t' -dependent non-resonant contributions
- χ^2 fit of the spin-density submatrix



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Partial-wave analysis of

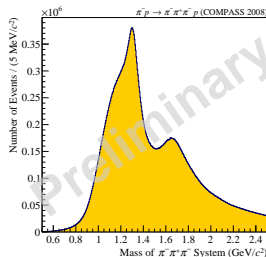
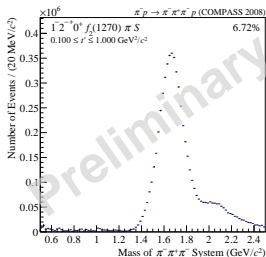
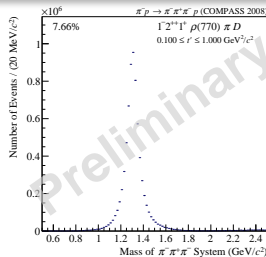
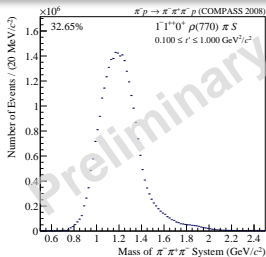
$$\pi^- + p \rightarrow \pi^- \pi^- \pi^+ + p$$

$$\pi^- + p \rightarrow \pi^- \pi^0 \pi^0 + p$$



$\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ (2008)

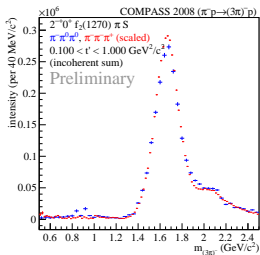
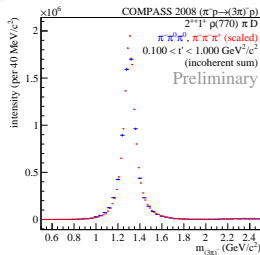
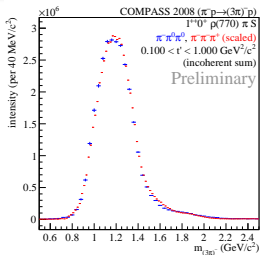
Intensities of dominant J^{PC} states





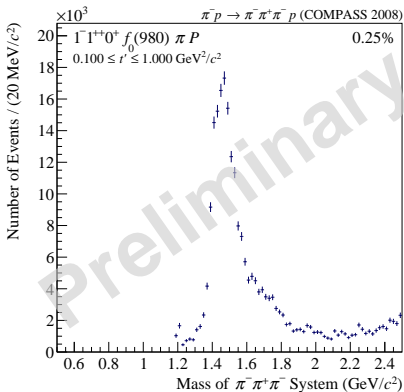
$\pi^- p \rightarrow (3\pi)^- p$ (2008)

Intensities of dominant J^{PC} states



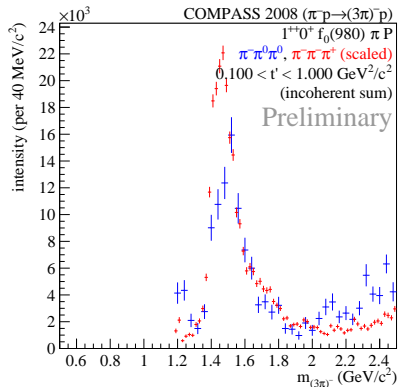
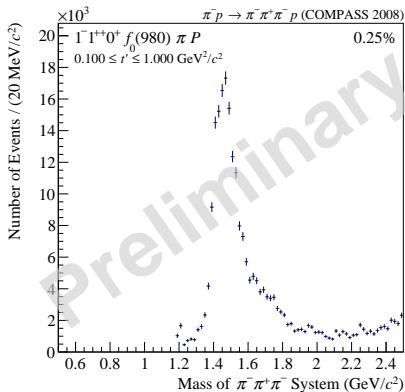


A new Axialvector Resonance?

 $1^{++}0^+ f_0(980)\pi P$




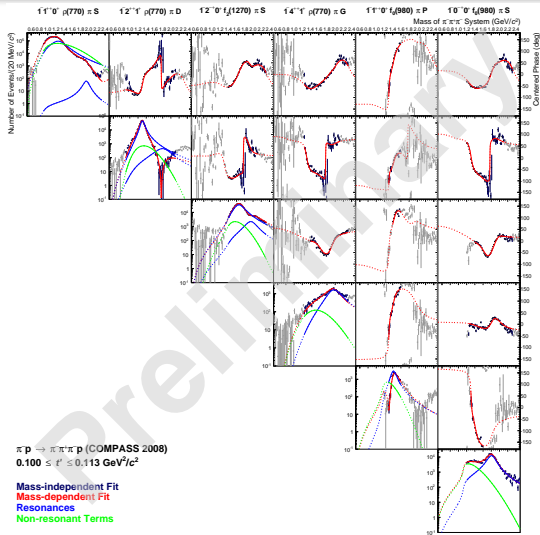
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Extraction of Resonance Parameters

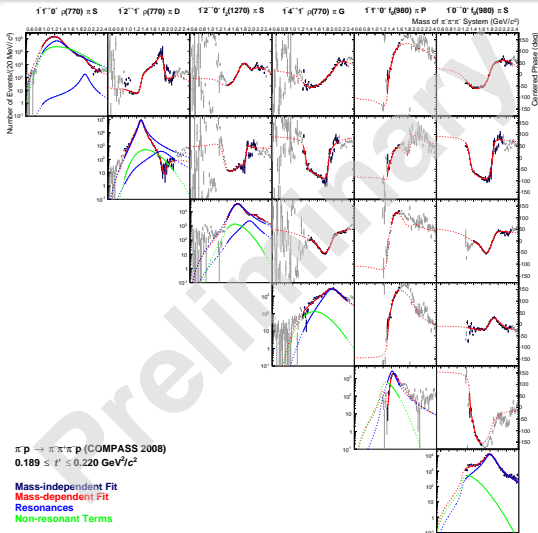
simultaneous fit of 6 partial waves in 11 t' bins





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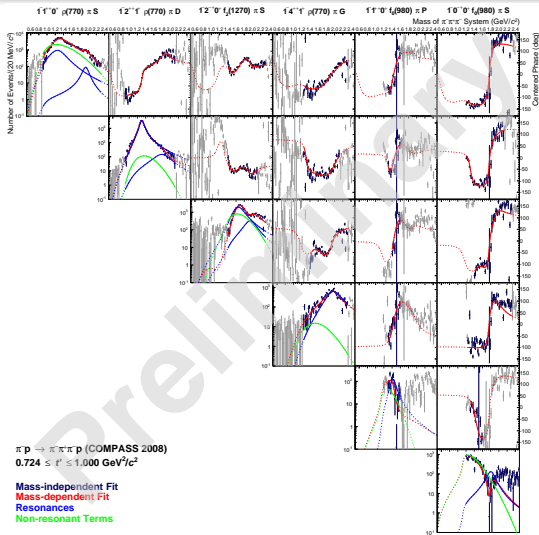
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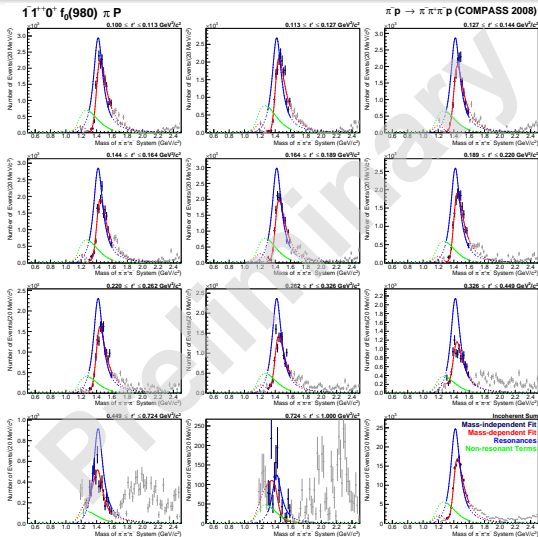
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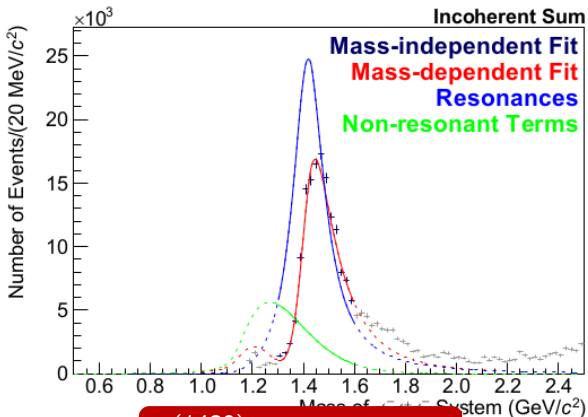
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The $a_1(1420)$



$a_1(1420)$

$M = 1412 - 1422 \text{ MeV}/c^2$

$\Gamma = 130 - 150 \text{ MeV}/c^2$



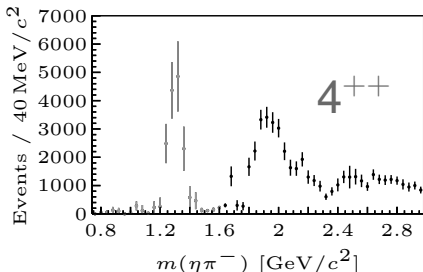
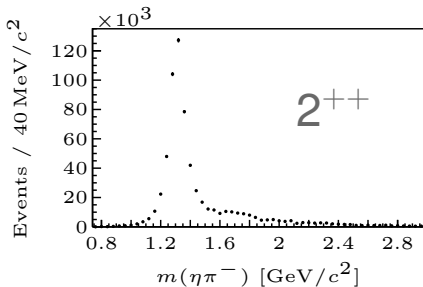
Partial-wave analysis of

$$\pi^- + p \rightarrow \eta\pi + p$$

$$\pi^- + p \rightarrow \eta'\pi + p$$



$$\pi^- + p \rightarrow \eta\pi + p \quad (2008)$$

 $D_+^- \text{ vs } G_+^- \text{-wave}$


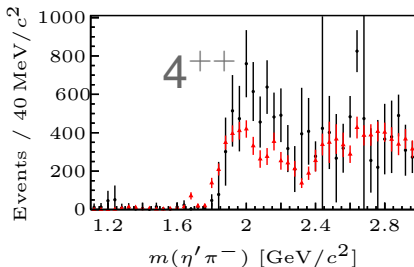
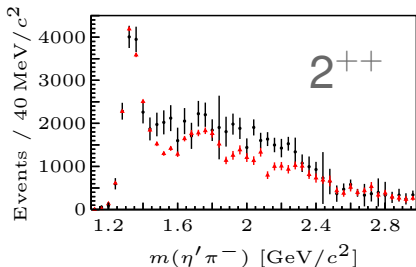
CERN Preprint CERN-PH-EP-2014-204

subm. to PLB



$$\pi^- + p \rightarrow \eta' \pi + p \quad (2008)$$

Comparison $\pi^- + p \rightarrow \eta' \pi + p$ vs $\pi^- + p \rightarrow \eta \pi + p$ (2008)

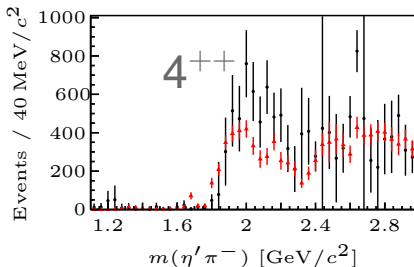
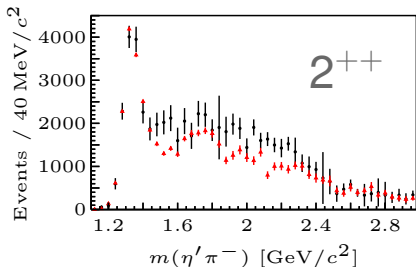


Scaling of $\eta\pi$: Adjustment for branching and phase space



$$\pi^- + p \rightarrow \eta' \pi + p \quad (2008)$$

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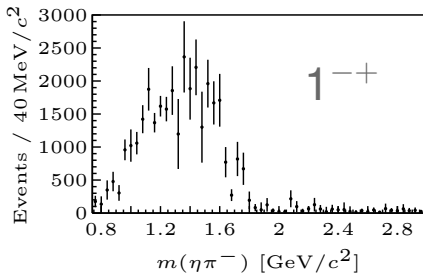


Scaling of $\eta\pi$: Adjustment for branching and phase space

Even- L waves have very similar intensity distributions in $\eta\pi$ and $\eta'\pi$ (after correction for phase-space effects) over the whole mass range.



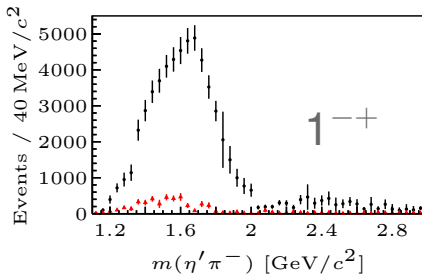
$$\pi^- + p \rightarrow \eta\pi + p \quad (2008)$$

 $P_{+}\text{-wave}$ 



$$\pi^- + p \rightarrow \eta' \pi + p \quad (2008)$$

Comparison $\pi^- + p \rightarrow \eta' \pi + p$ vs $\pi^- + p \rightarrow \eta \pi + p$ (2008)



Odd- L waves, in particular the P wave, are suppressed in $\eta\pi$ by a factor 5 to 10, again over the whole mass range.



Status of the $J^{PC} = 1^{-+}$ Spin Exotic Partial Wave



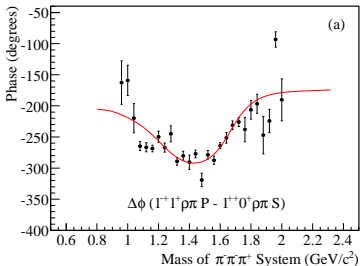
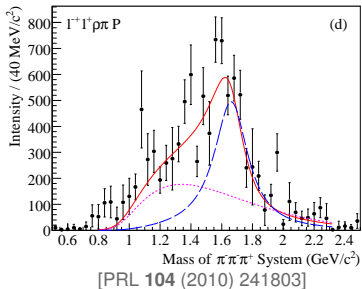
$$\pi^- Pb \rightarrow \pi^- \pi^+ \pi^- Pb \quad (2004)$$

The spin exotic $J^{PC} = 1^{-+} \rho\pi$ *P*-wave

Exotic Signatures

- Isospin exotics: “forbidden” decays
- **Spin exotics:** $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-} \dots$ forbidden in $q\bar{q}$
- Proof of existence \rightarrow strong hint for physics beyond the quark model

COMPASS (2004): $\pi^- Pb \rightarrow \pi^- \pi^+ \pi^- Pb$ $\sim 400\,000$ events





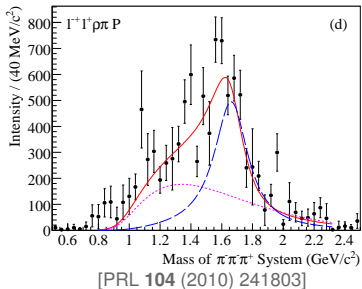
$\pi^- Pb \rightarrow \pi^- \pi^+ \pi^- Pb$ (2004)

The spin exotic $J^{PC} = 1^{-+} \rho\pi$ *P*-wave

Exotic Signatures

- Isospin exotics: “forbidden” decays
- **Spin exotics:** $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-} \dots$ forbidden in $q\bar{q}$
- Proof of existence \rightarrow strong hint for physics beyond the quark model

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Spin Exotic $\pi_1(1600)$

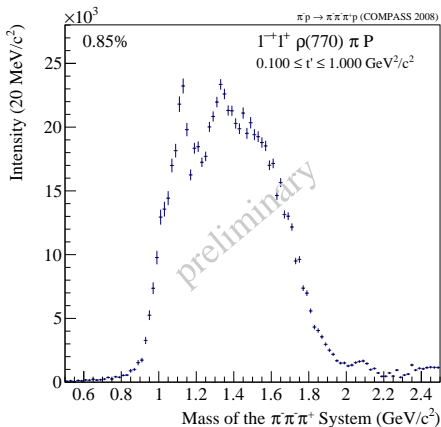
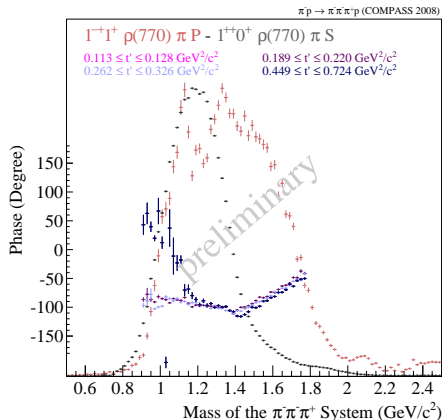
- Significant 1^{-+} amplitude consistent with resonance at ~ 1.7 GeV/c²
- No leakage observed ($< 5\%$)
- BW for $\pi_1(1600)$ + background:
 $M = (1.660 \pm 0.010^{+0.000}_{-0.064})$ GeV/c²
 $\Gamma = (0.269 \pm 0.021^{+0.042}_{-0.064})$ GeV/c²



$$\pi^- p \rightarrow \pi^- \pi^+ \pi^- p \quad (2008)$$

The spin exotic $J^{PC} = 1^{-+} \rho\pi$ P-wave

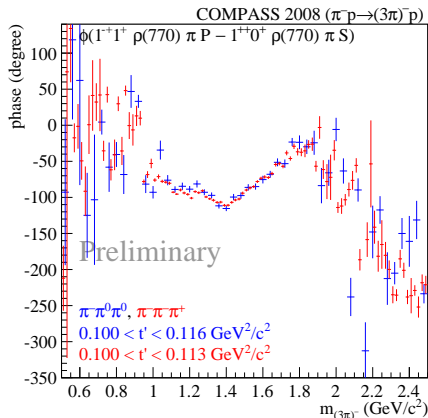
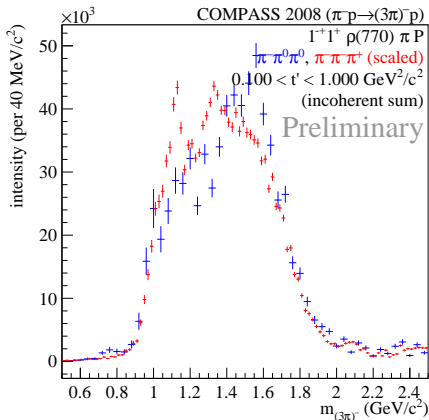
Intensity

Phase motion vs $1^{++} \rho\pi$ S-wave



Comparison $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ vs $\pi^- p \rightarrow \pi^- \pi^0 \pi^0 p$ (2008)

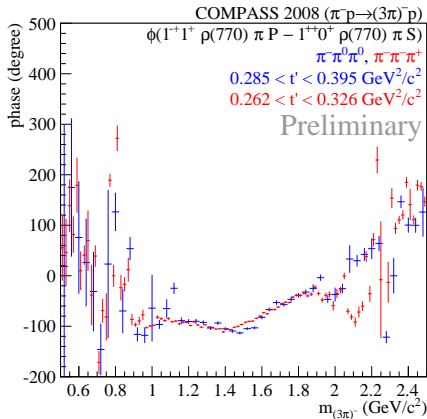
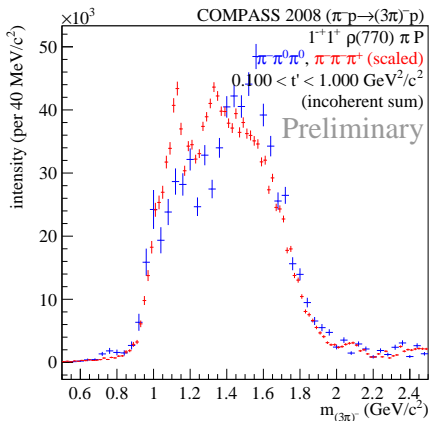
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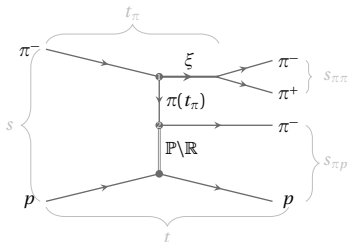




Non-Resonant Production

The Deck Effect

- Additional production mechanism for the same final state \rightarrow non-resonant contribution
- An incident beam pion dissociates into a ρ or f_2 and a virtual π . The virtual π scatters diffractively from the target proton (via Pomeron) into a real state.



- Amplitude parametrisation:

$$\Psi(M_{\pi\pi}, t_\pi, t) = \frac{A_{\pi\pi}(M_{\pi\pi}, t_\pi)A_{\pi\rho}(s_{\pi\rho}, t)}{m_\pi^2 - t_\pi}$$

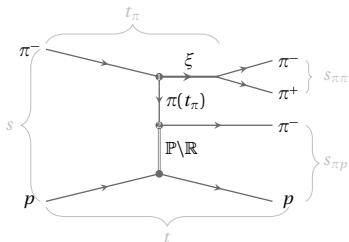
- $A_{\pi\pi}$ scattering amplitude through the ρ or/and f_2
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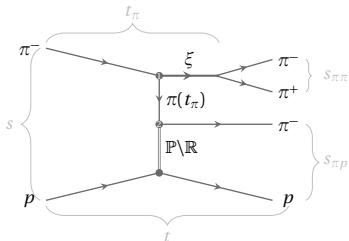
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Studies of the Deck Contribution to the Data

Procedure

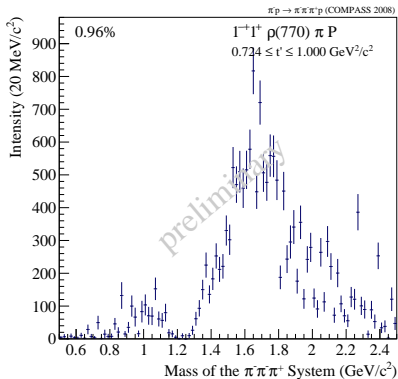
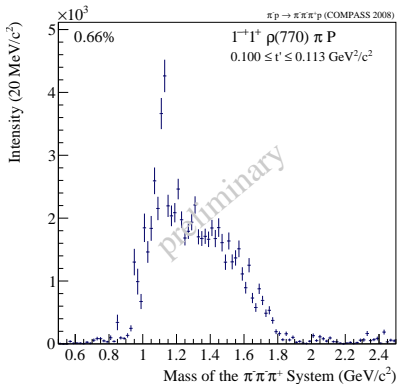


- Generate MC data distributed according to Deck amplitude
- Fit this data with the same model in bins of t' and $m_{3\pi}$
- Investigate the contributions of the Deck intensity in the single waves
- Caveat: interference of the simulated Deck amplitude with diffractive production not taken into account



$\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$ (2008)

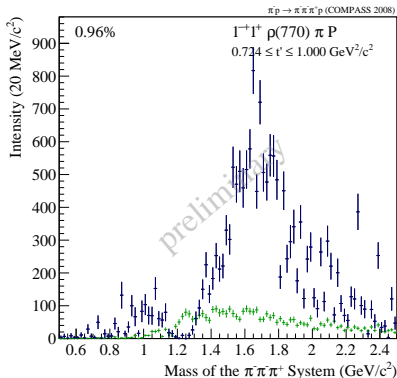
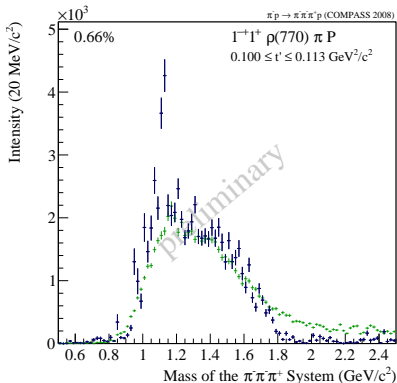
selected t' bins



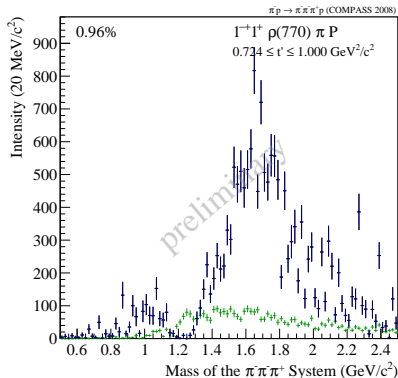
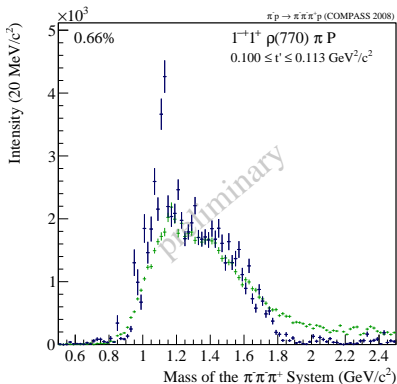


$$\pi^- p \rightarrow \pi^- \pi^+ \pi^- p \quad (2008)$$

selected t' bins, Deck overlaid



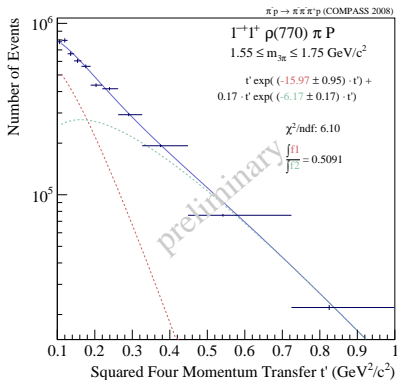


$$\pi^- p \rightarrow \pi^- \pi^+ \pi^- p \quad (2008)$$
selected t' bins, Deck overlaidDeck contribution suppressed at larger t'



$\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$ (2008)

t' -Dependence in $1550 \leq m_{3\pi} \leq 1750$ MeV/ c^2

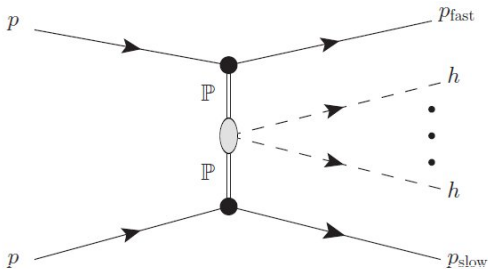


Analysis of t' -dependencies necessary in order to understand the underlying production processes.



Isoscalar Scalar Mesons

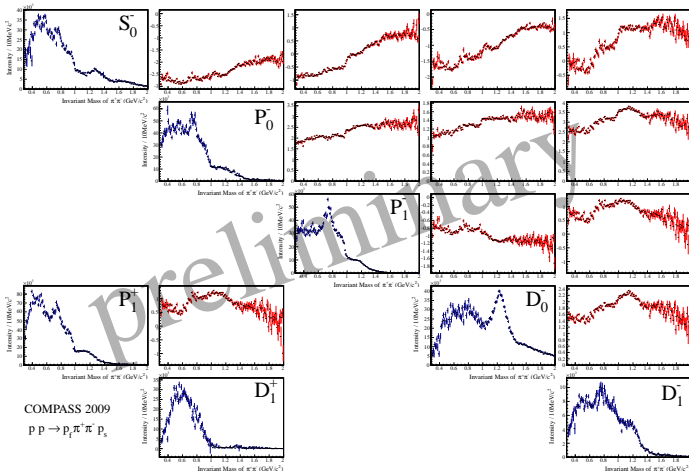
Meson Production at Central Rapidities in pp Scattering





$$pp \rightarrow p_{\text{fast}} \pi^+ \pi^- + p_{\text{slow}}$$

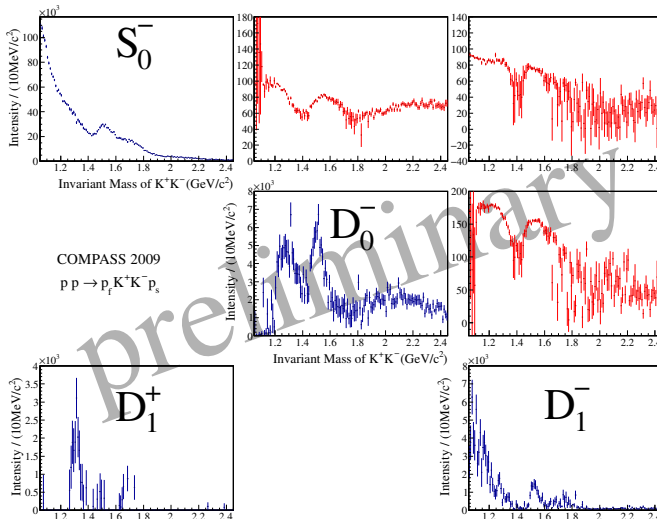
Amplitude Analysis of $\pi^+ \pi^-$ System – Physical Solution after Disambiguation





$$pp \rightarrow p_{\text{fast}} K^+ K^- + p_{\text{slow}}$$

Amplitude Analysis of $K^+ K^-$ System – Physical Solution after Disambiguation

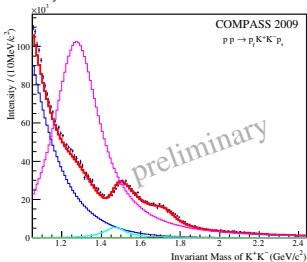




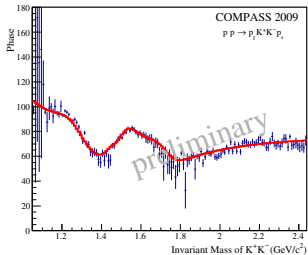
$$pp \rightarrow p_{\text{fast}} K^+ K^- + p_{\text{slow}}$$

Amplitude Analysis of $K^+ K^-$ System – Fit of the Mass Dependence

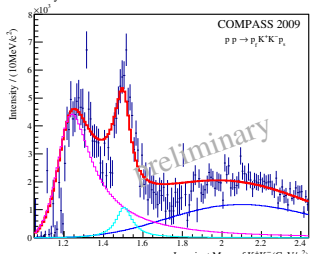
Intensity of S0 wave



Phase(S0 - D0)

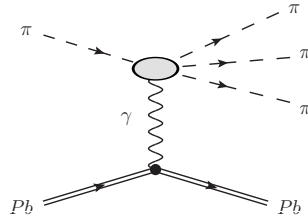
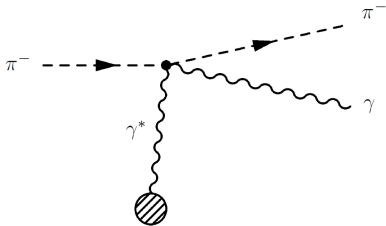


Intensity of D0 wave





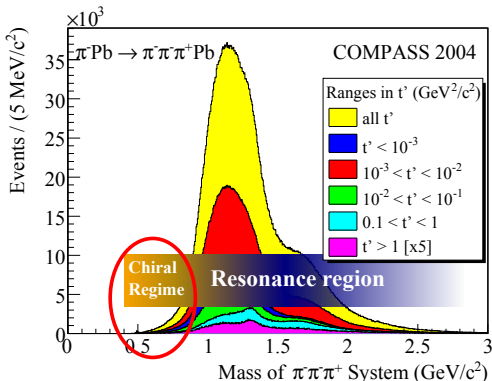
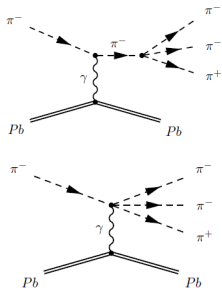
Tests of Chiral Dynamics



see Talk of J. Friedrich, Parallel II, B4

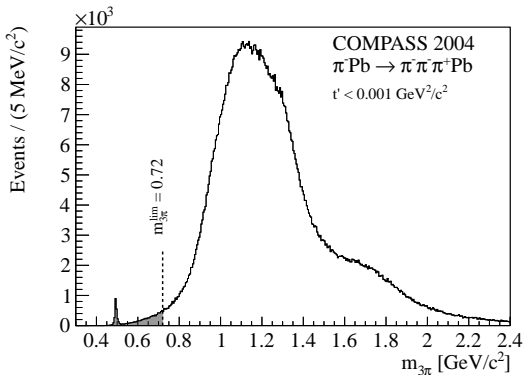
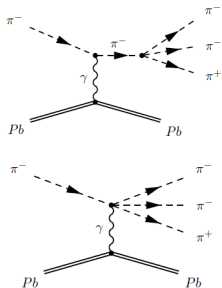


- Chiral regime (low masses, $t' < 0.001(\text{GeV}/c)^2$)
→ fraction of final state events photoproduced
- Heavy nucleus acts as a quasi-real photon source
- Analysis ansatz: χ PT amplitude included in PWA
- ⇒ $\gamma\pi^- \rightarrow \pi^-\pi^+\pi^-$ absolute cross section



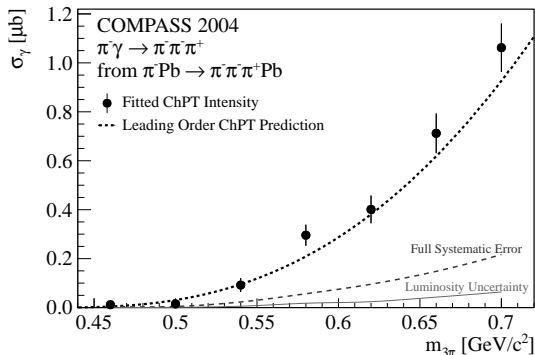
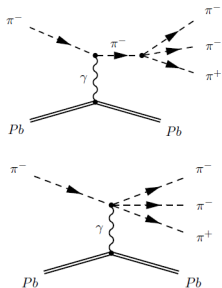


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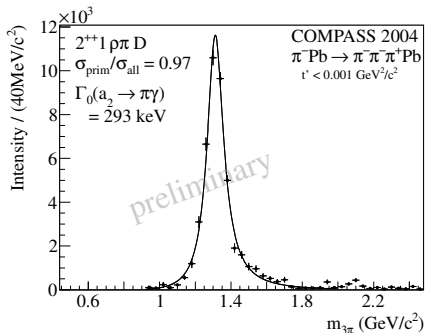




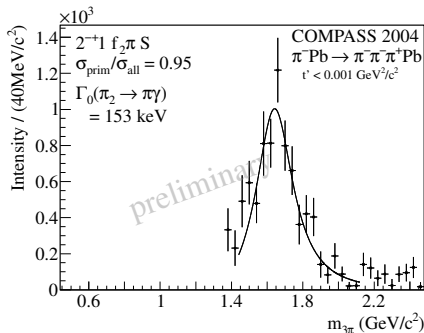
Radiative Coupling of $a_2(1320)$ and $\pi_2(1670)$

Technische Universität München

EPJ A50 (2014) 79



$$\Gamma_0(a_2(1320) \rightarrow \gamma\pi) M2$$

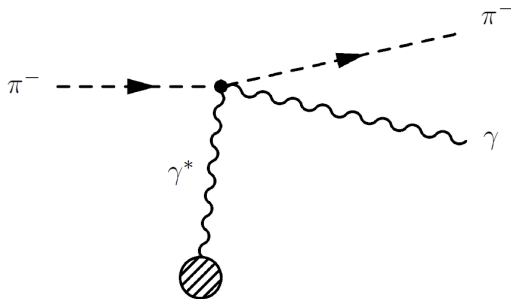


$$\Gamma_0(\pi_2(1670) \rightarrow \gamma\pi) E2$$



Pion Polarizability

in Primakoff–Compton Scattering



Primakoff Compton Reaction

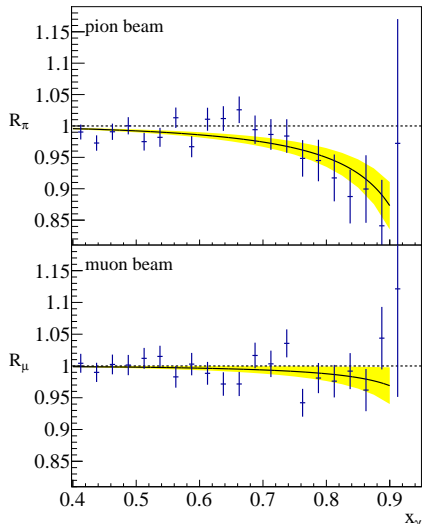
$$\gamma^{(*)} \pi \rightarrow \pi \gamma$$

tiny extrapolation $\gamma^* \rightarrow \gamma \quad \mathcal{O}(10^{-3} m_\pi^2)$



Pion Polarizability

Fit to Muon and Pion Data, CERN-PH-EP-2014-109, subm. to PRL





Conclusions

- COMPASS 2008/2009: **large data sets** in
 - diffractive $\pi^-/K^-/p$ dissociation (up to 2 orders of magnitude improvement)
- Meson Spectroscopy
 - $\pi^-\pi^+\pi^-$, $\pi^-\pi^0\pi^0$, $\eta\pi^-$, $\eta'\pi^-$, $K^-\pi^+\pi^-$, 5π , $\pi^-\pi_{\text{isobar}}^+$
 - Central production in pp and πp
- Baryon Spectroscopy
 - $p\pi^0$, $p\pi^+\pi^-$, pK^+K^- , $p\omega$, ...
- **Chiral dynamics:**
 - 3π -amplitude
 - Pion polarizability
- Spin alignment and violation of the OZI rule



Outlook – Deisobared Fit of the $\pi^- \pi^+ \pi^-$ Final State

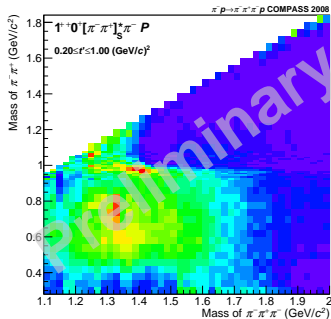
Idea: Reducing the model systematics by a simultaneous fit of the 2π subsystem and the 3π final state



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Example: 1^{++} partial waves decaying via scalar isobars

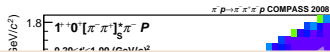




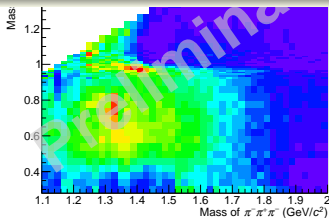
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see Talk of D. Ryabchikov, Parallel II, B7





Deck-like Monte Carlo Kinematic Distributions

