New Insights on Spectroscopy and Properties of light hadrons with COMPASS

Florian Haas

Physik Department E18 - Technische Universität München
for the COMPASS Collaboration

Annual Meeting of the GDR PH-QCD ”Annihilation and Scattering” Group
Recent Highlights in Hadron Structure

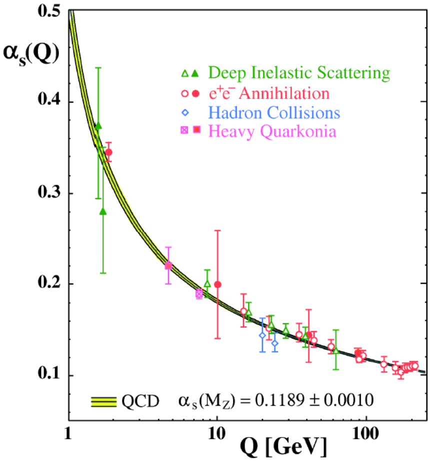
supported by:
Maier-Leibnitz-Labor der TU und LMU München,

Cluster of Excellence: Origin and Structure of the Universe, BMBF

From QCD to Hadron Physics

Technische Universität München

- Confinement
- Hadrons relevant DOF



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

S. Bethke

[arXiv:hep-ex/0606035v2]

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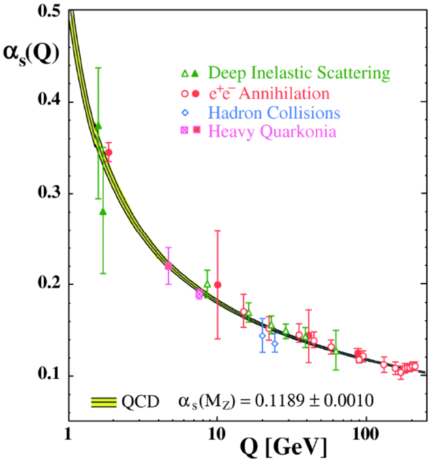

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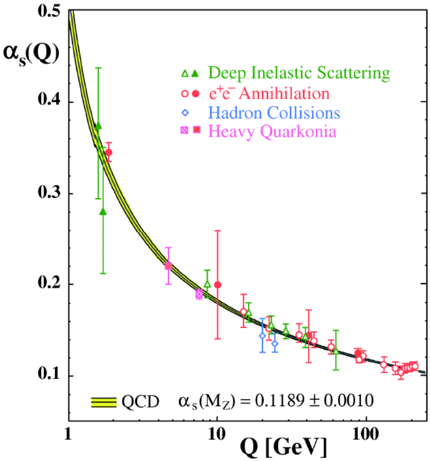

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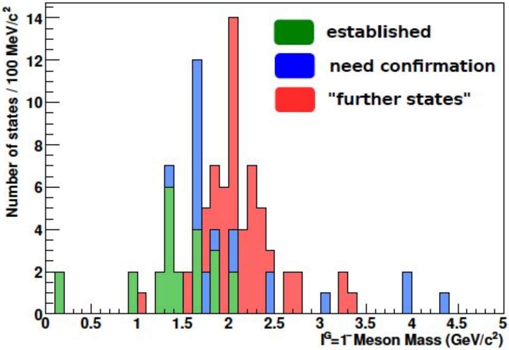
- Dynamics of excited states?
- Models and theories
  - Quark model
  - Bag model
  - Flux tube model
  - χ_{PT} for slow pions
  - Lattice QCD



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Dudek et al. [arXiv:1106.5515v1]

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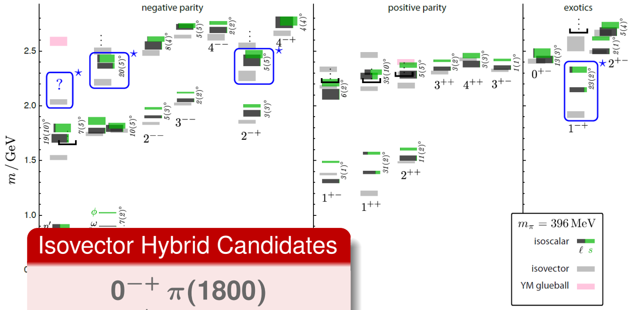

Isovector Hybrid Candidates

0^{-+} $\pi(1800)$
1^{-+} $\pi_1(1600)$
2^{-+} $\pi_2(1880)$

)6.5515v1]

The COMPASS Hadron Setup

Spectrometer and Hadron Beam

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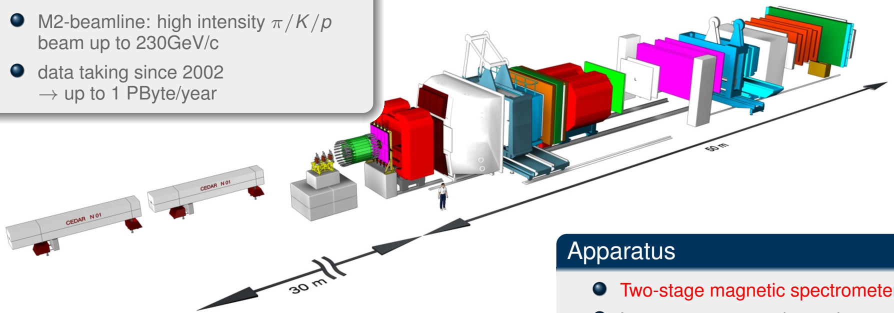
Overview

- **CO**mmon **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 $\rightarrow$ 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

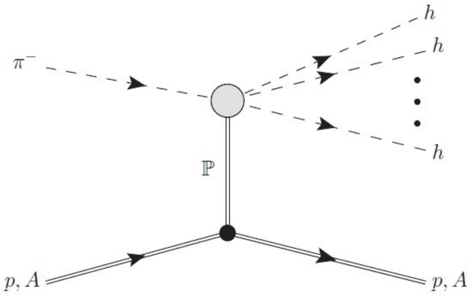
Tests of Chiral Dynamics

- 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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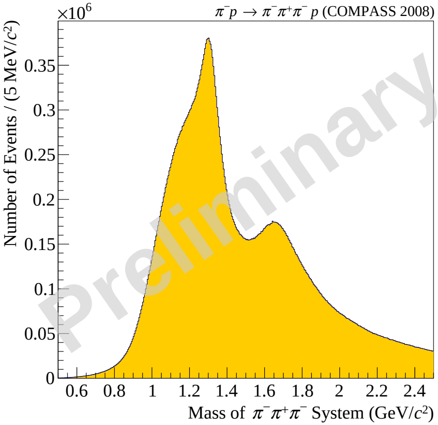
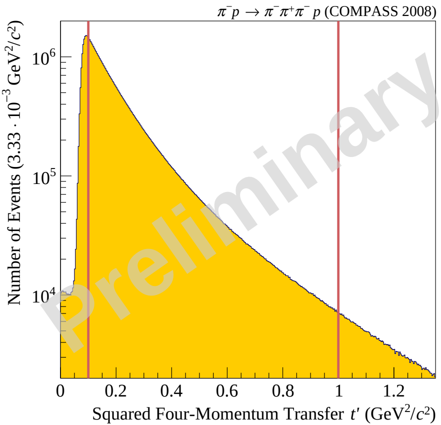
- 190 GeV/c hadron beam $\rightarrow$ $96\%\pi^-, 3.5\%K^-, 0.5\%\bar{p}$
- 40cm liquid hydrogen target
- $0.1\text{GeV}^2/\text{c}^2 < t' < 1.0\text{GeV}^2/\text{c}^2$
- $\sim$50M exclusive events (2008)





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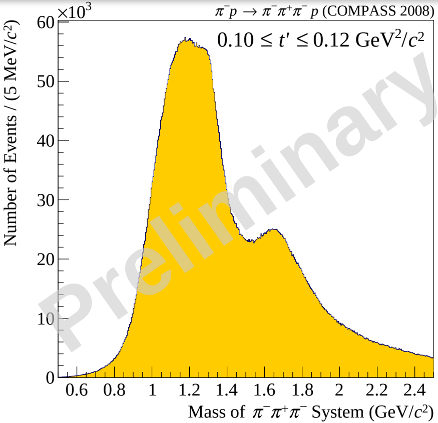

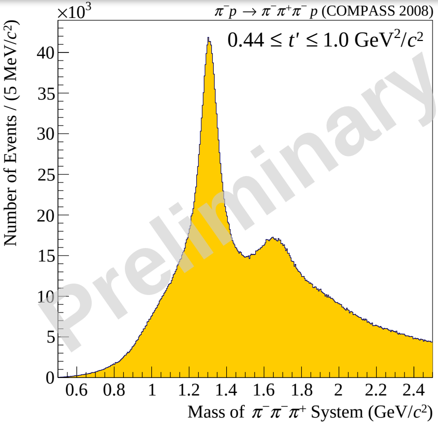

The invariant mass of the final state depends on squarred four-momentum transfer t

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

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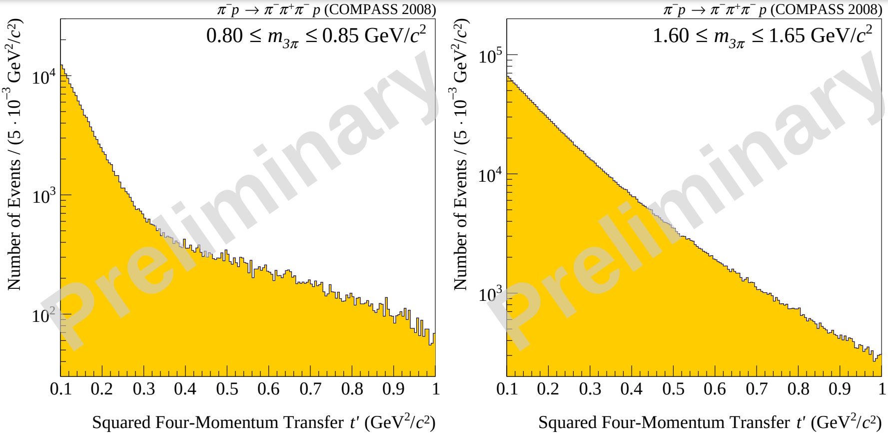

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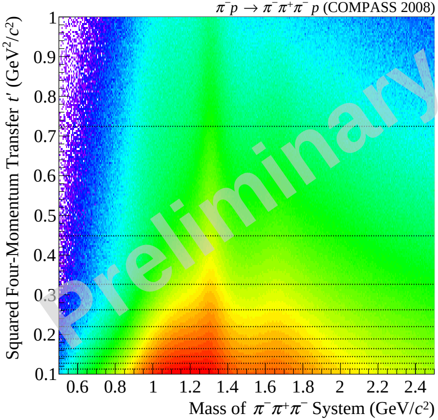

Ansatz: Split data into small bins of t and $m_{3\pi}$

Partial Wave Analysis - Formalism

Step One: Decomposition in Spin-Parity States

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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 $J^{PC} M^{\varepsilon} \xi \pi L$ e.g. 3π: 87 waves up to spin 6 + one incoherent isotropic wave

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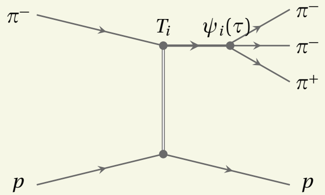
Production and Decay



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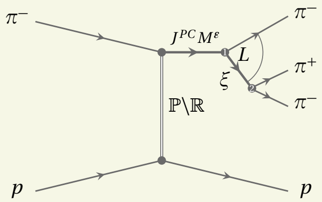
Isobar Model



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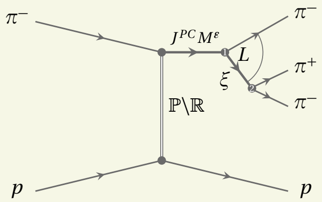
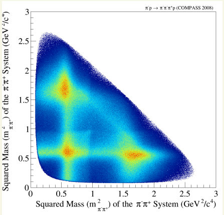


Dalitz Plot $\pi_2(1670)$ region



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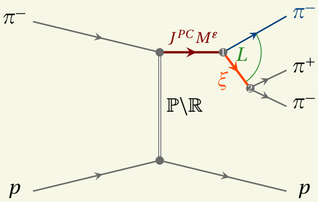

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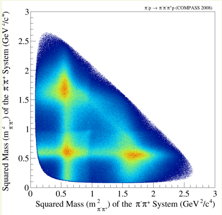

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Extraction of Resonance Parameters for t' and m

- 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

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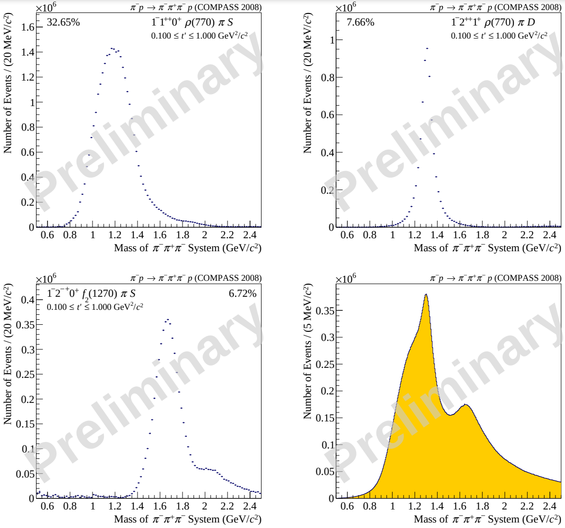

$\pi^- p \to (3\pi)^- p$ (2008)
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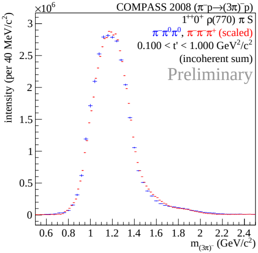
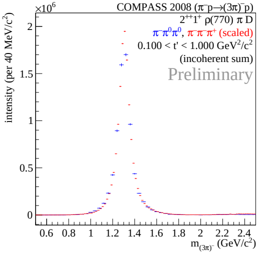
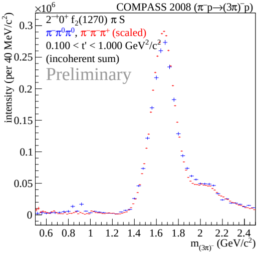
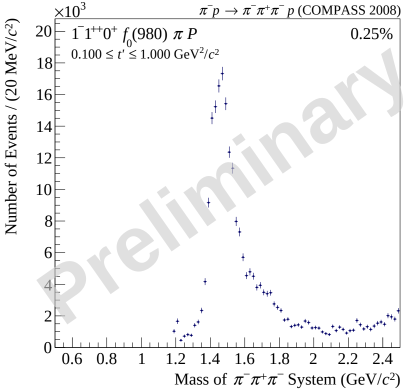






A new Axialvector Resonance?

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



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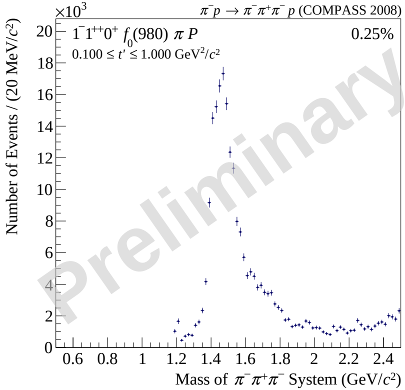
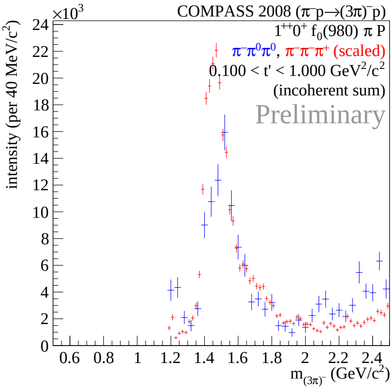
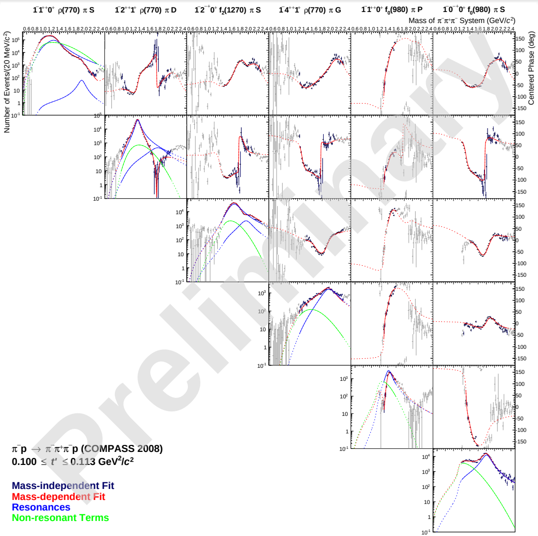




Extraction of Resonance Parameters

simultaneous fit of 6 partial waves in 11 t' bins



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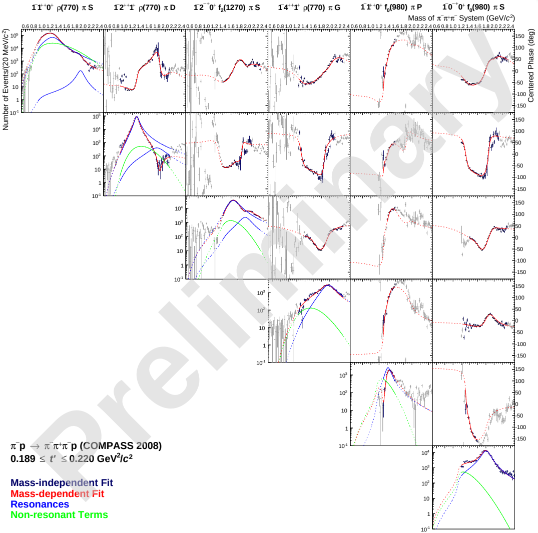

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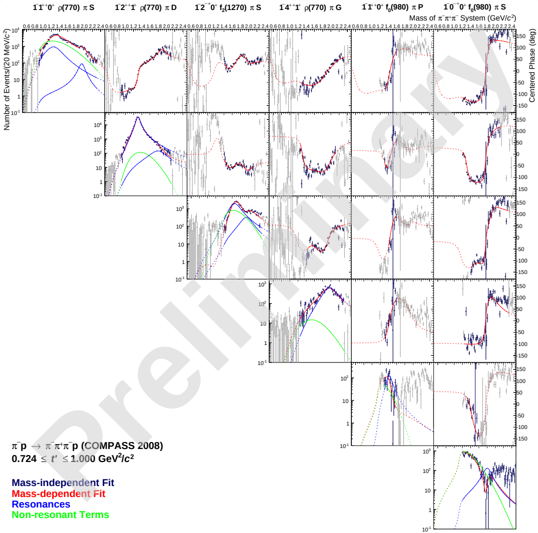

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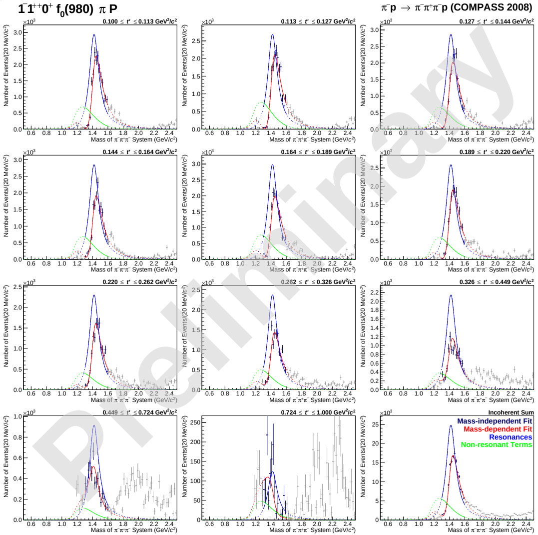

The $a_1(1420)$

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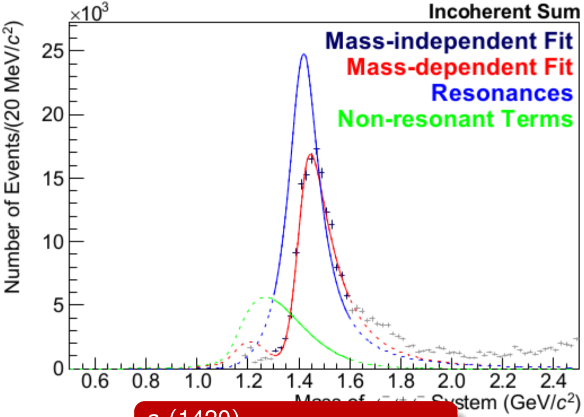


$a_1(1420)$

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

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

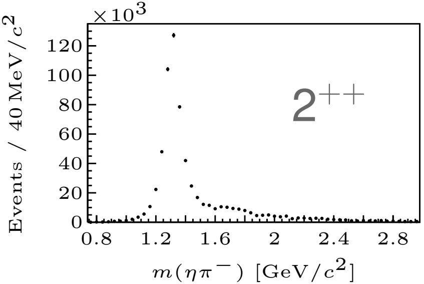
Partial-wave analysis of

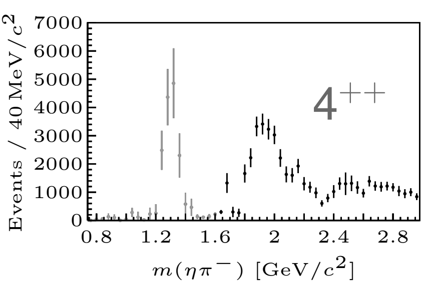
$$\pi^- + p \rightarrow \eta\pi + p$$

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

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

D_+- vs G_+-wave

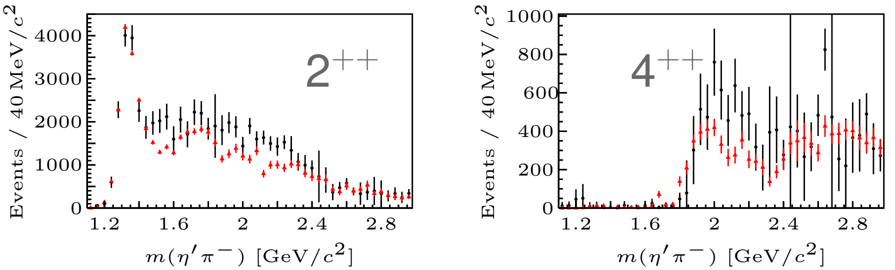




CERN Preprint CERN-PH-EP-2014-204 subm. to PLB

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

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



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

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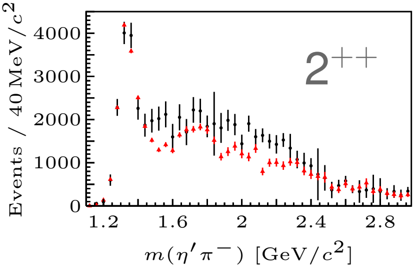

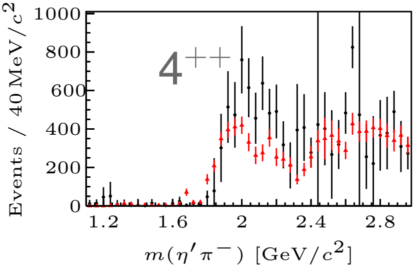

Scaling of $\eta\pi$: Adjustment for branching and phase space

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.

$\pi^- + p \to \eta\pi + p$ (2008)

P_+-wave

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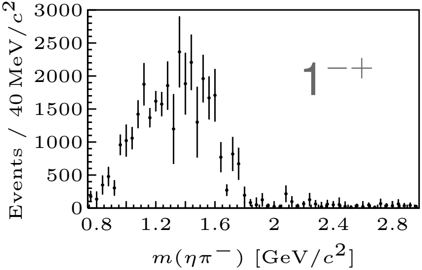
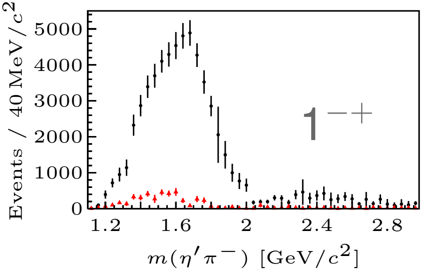


$\pi^- + p \to \eta'\pi + p$ (2008)

Comparison $\pi^- + p \to \eta'\pi + p$ vs $\pi^- + p \to \eta\pi + p$ (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

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

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

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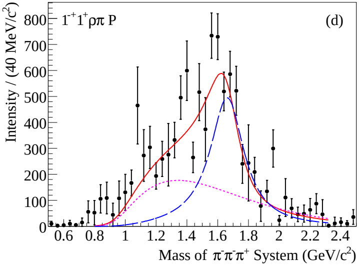
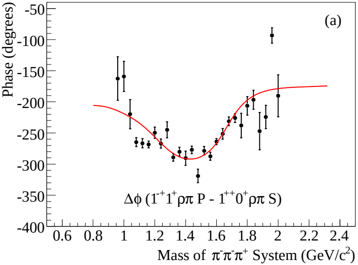
Exotic Signatures

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

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



[PRL **104** (2010) 241803]



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

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

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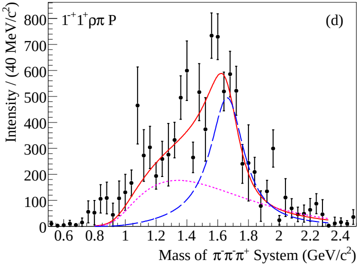


[PRL **104** (2010) 241803]

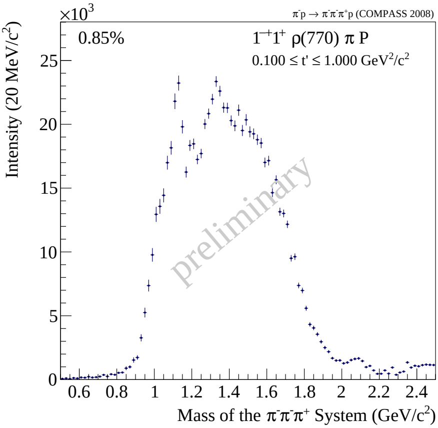
Spin Exotic $\pi_1(1600)$

- Significant 1^{-+} amplitude consistent with resonance at $\sim 1.7\,\mathrm{GeV}/c^2$
- No leakage observed ($< 5\%$)
- BW for $\pi_1(1600)$ + background:
  $M = (1.660 \pm 0.010\,^{+0.000}_{-0.064})\,\mathrm{GeV}/c^2$
  $\Gamma = (0.269 \pm 0.021\,^{+0.042}_{-0.064})\,\mathrm{GeV}/c^2$

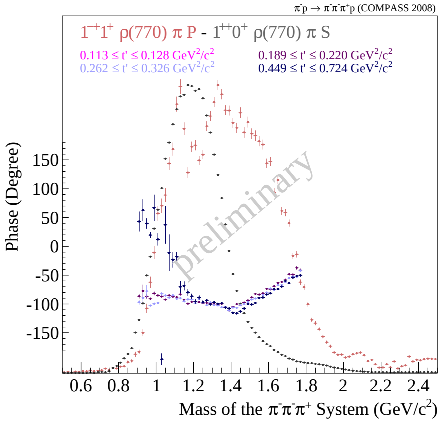
$\pi^- p \to \pi^- \pi^+ \pi^- p$ (2008)

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

Intensity

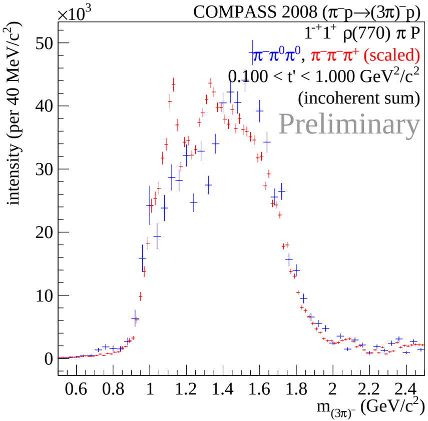


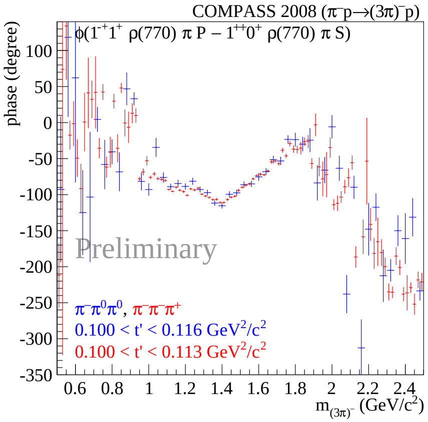
Phase motion vs $1^{++} \rho\pi$ *S*-wave



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

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





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

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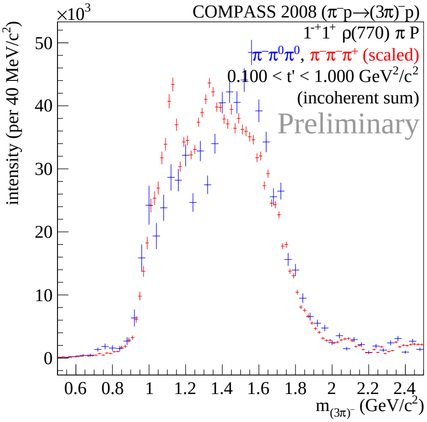
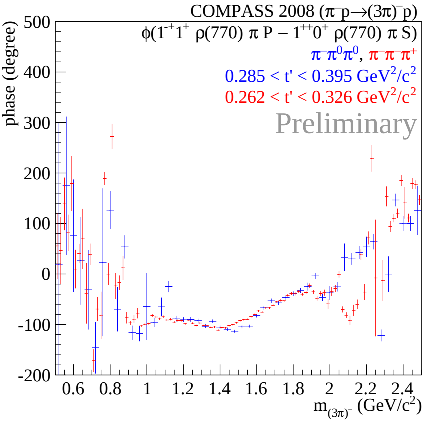
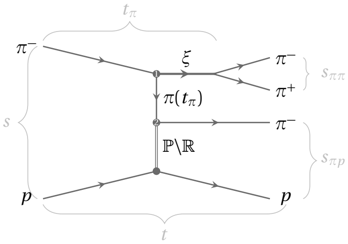




Non-Resonant Production

The Deck Effect

- Additional production mechanism for the same final state → 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:

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

  - $A_{\pi\pi}$ scattering amplitude through the ρ or/and f_2
  - $A_{\pi p}$ $\pi^- p$ elastic scattering amplitude

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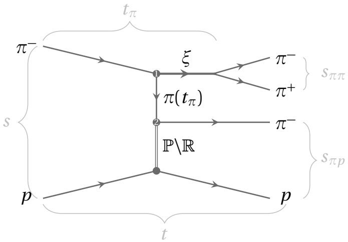

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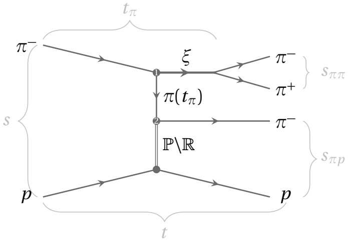

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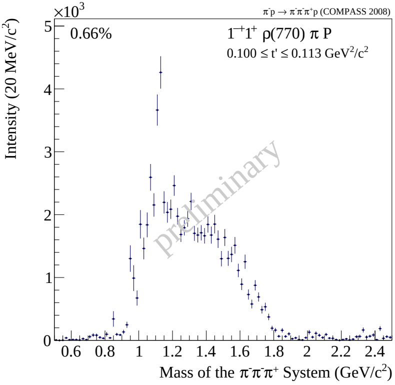
Studies of the Deck Contribution to the Data

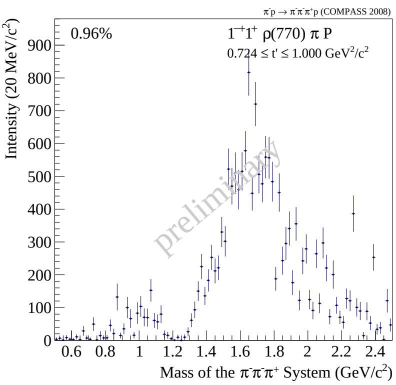
Procedure

- 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





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

selected t' bins, Deck overlaid

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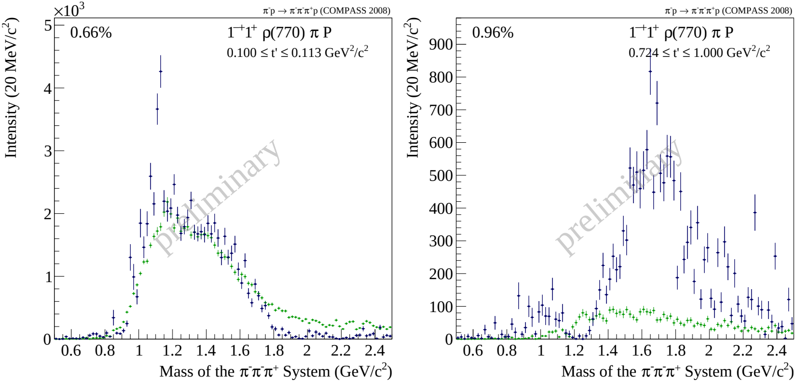

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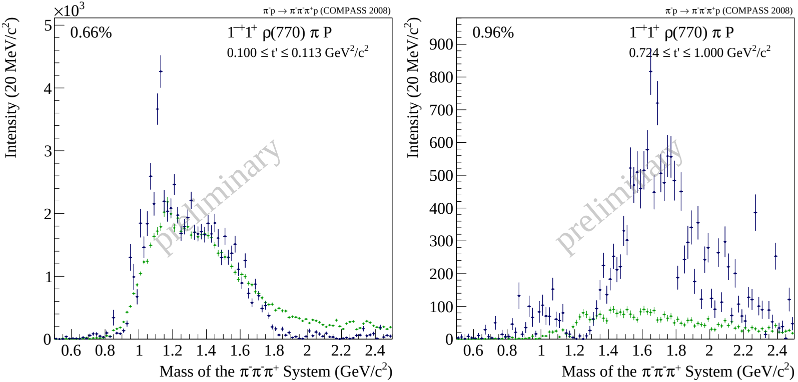
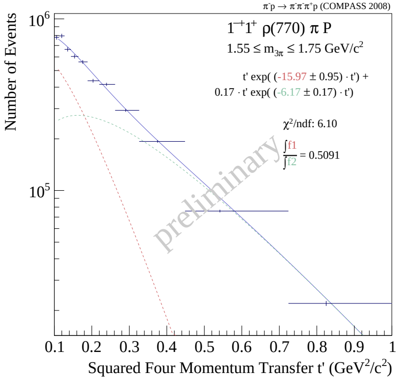


Deck contribution suppressed at larger t'

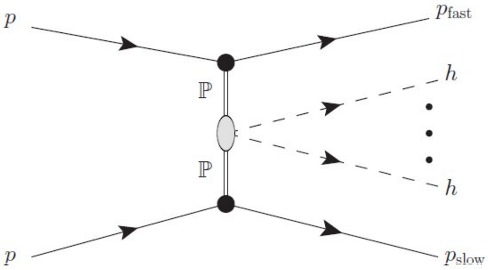
$\pi^- p \to \pi^-\pi^+\pi^- p$ (2008)

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



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

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

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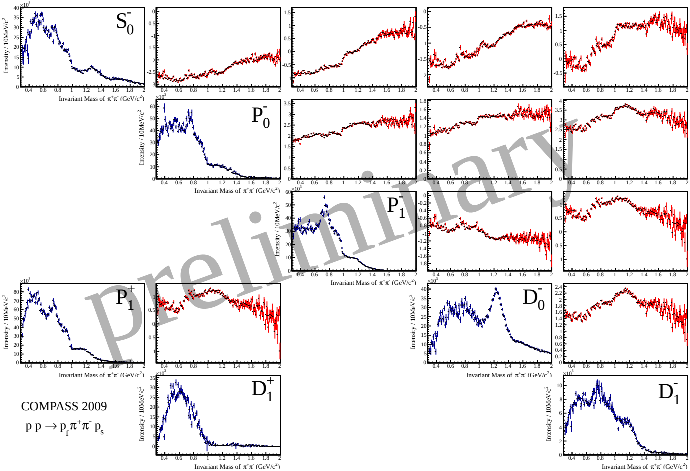
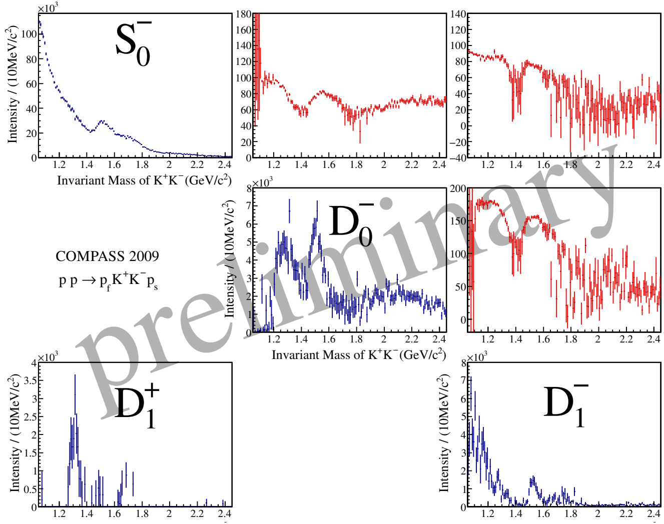


$pp \to p_{\text{fast}} K^+ K^- + p_{\text{slow}}$

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



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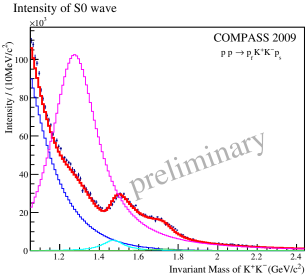
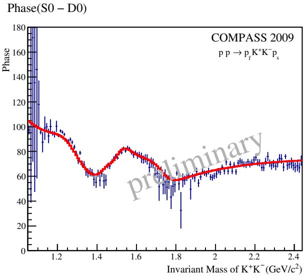
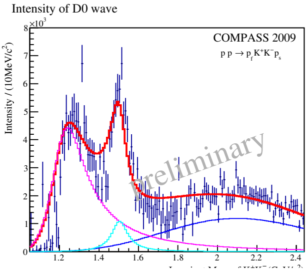
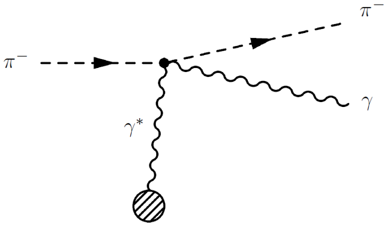
Amplitude Analysis of K^+K^- System – Fit of the Mass Dependence

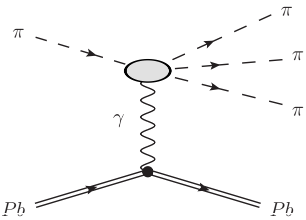






Tests of Chiral Dynamics





Primakoff 3π Spectral Function from χPT

PRL 108, 192001 (2012)

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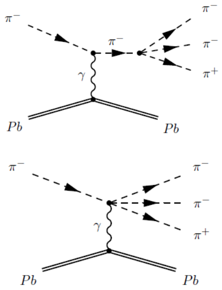
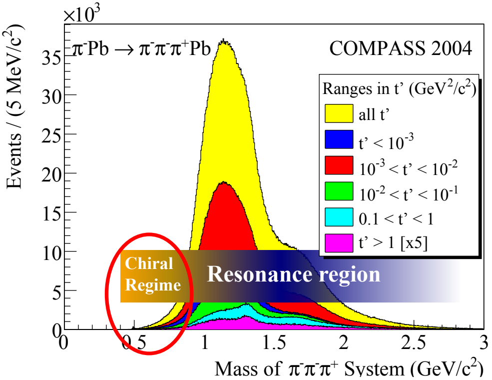
- Chiral regime (low masses, $t' < 0.001(\text{GeV}/c)^2$) $\rightarrow$ fraction of final state events photoproduced
- Heavy nucleus acts as a quasi-real photon source
- Analysis ansatz: χPT amplitude included in PWA
- $\Rightarrow \gamma\pi^- \rightarrow \pi^-\pi^+\pi^-$ absolute cross section





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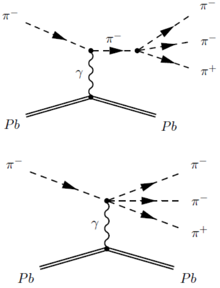

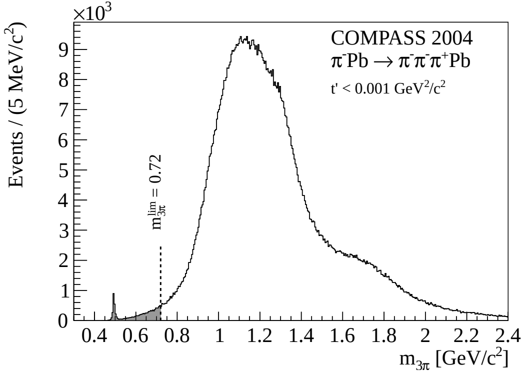

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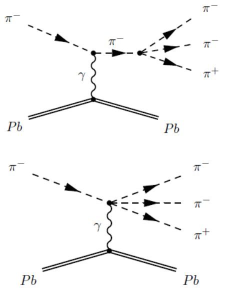
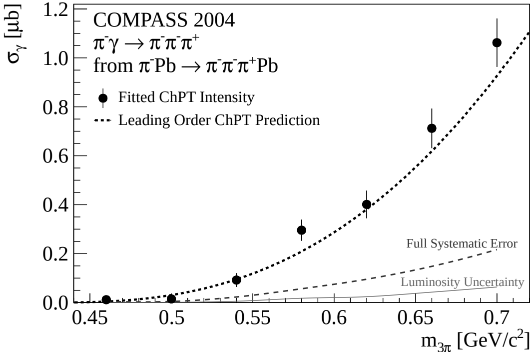
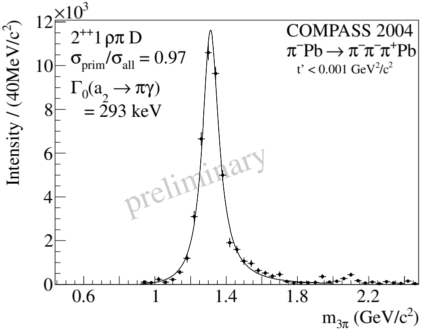
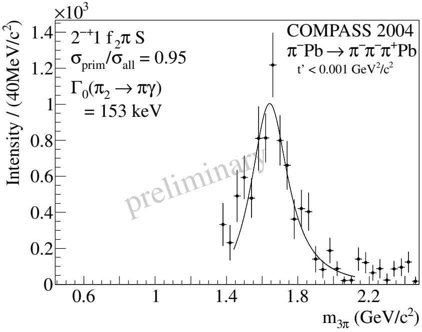




Radiative Coupling of $a_2(1320)$ and $\pi_2(1670)$

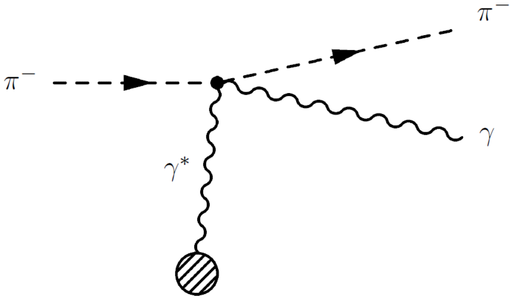
EPJ A50 (2014) 79





$\Gamma_0(a_2(1320) \to \gamma\pi)M2$ $\Gamma_0(\pi_2(1670) \to \gamma\pi)E2$

Pion Polarizability
in Primakoff–Compton Scattering



Primakoff Compton Reaction

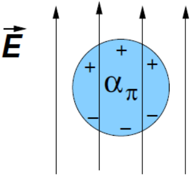
$$\gamma^{(*)}\pi \to \pi\gamma$$

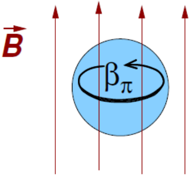
tiny extrapolation $\gamma^* \to \gamma$ $\mathcal{O}(10^{-3} m_\pi^2)$

Pion Polarizability

$$\pi + \gamma \to \pi + \gamma$$

Compton cross-section contains information about e.m. polarizability (as deviation from the expectation for a pointlike particle)





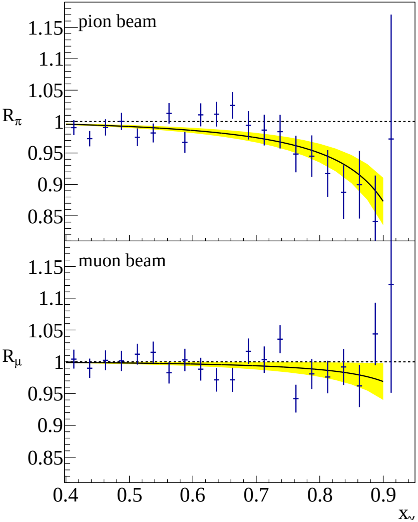
χPT (2-loop) prediction by χPT: $2\alpha_\pi = \alpha_\pi - \beta_\pi = (5.7 \pm 1.0)10^{-4}$ fm^3 but contradicts experimental observations (4 - 14)

Measurement :

- COMPASS: use pion and muon beam
- Experimentally demanding, systematics precisely to be controlled
- Assumption: $\alpha_\pi = -\beta_\pi$

Pion Polarizability

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



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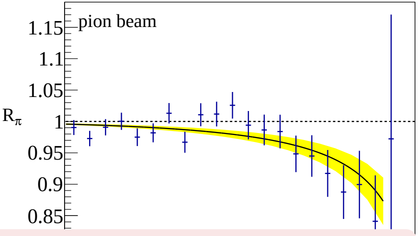
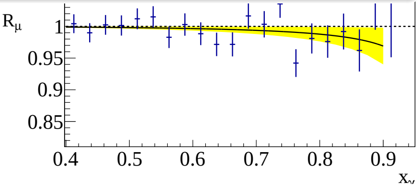


- $\alpha_\pi = (2.0 \pm 0.6_{\text{stat.}} \pm 0.7_{\text{sys.}}) \times 10^{-4}\ \text{fm}^3$
- $\alpha_\mu = (0.5 \pm 0.5_{\text{stat.}}) \times 10^{-4}\ \text{fm}^3$



Conclusions and Outlook

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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, $\pi^-\pi^+_{\mathrm{isobar}}$
  - Central production in pp and πp
- Baryon Spectroscopy
  - $p\pi^0, p\pi^+\pi^-, pK^+K^-, p\omega, \ldots$
- Chiral dynamics:
  - 3π–amplitude
  - Pion polarizability
- Spin alignment and violation of the OZI rule

Conclusions and Outlook

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

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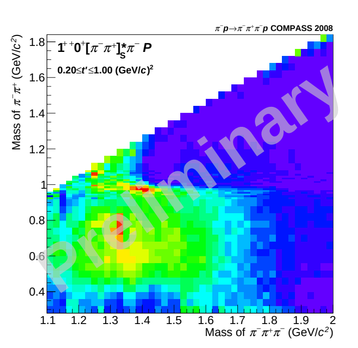
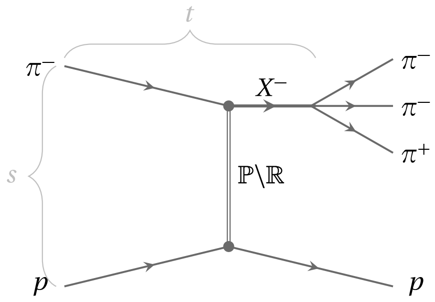
Example: 1^{++} partial waves decaying via scalar isobars



The Name of the Game
Diffractive Dissociation

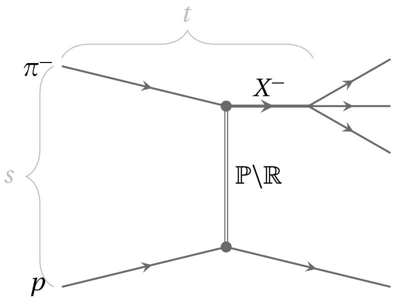


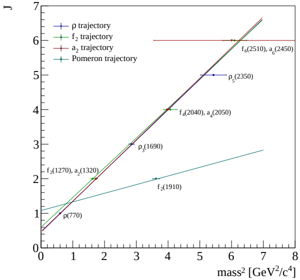
$$A(s,t) \sim g_{\lambda_a \lambda_c}(t) \left(\frac{s}{m^2}\right)^{\alpha(t)} \frac{S + exp(-i\pi\alpha(t))}{2 sin \pi\alpha(t)} g_{\lambda_b \lambda_d}(t)$$

- at COMPASS: s is fixed
- t is the running variable in order to describe diffraction

The Name of the Game

Diffractive Dissociation





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Decay Amplitudes and Isobar Parametrizations

2-body Decay Amplitude

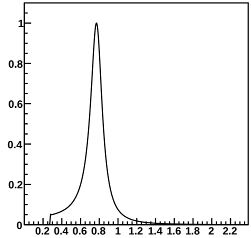
$$A(\tau) = \sum_{\lambda} D^J_{M,\lambda}(\phi, \theta, 0) f_\lambda(m, m_1, m_2)$$

$$f_\lambda(m, m_1, m_2) = \underbrace{\sqrt{2l+1}}_{\text{normalization}} \underbrace{(I_1 I_{1z} I_2 I_{2z} | I I_z)(l 0 s \lambda | J \lambda)(s_1 \lambda_1 s_2 - \lambda_2 | s \lambda)}_{\text{Clebsch-Gordon coeff.}} \underbrace{F_l \Delta(m)}_{\text{dyn. func.}}$$

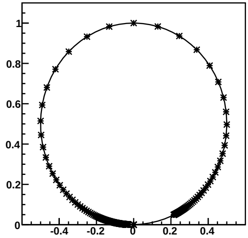
- Rotation functions $D^J_{M,\lambda}(\phi, \theta, 0)$, describing the angular part
- Clebsch-Gordan coefficients:
  - $(I_1 I_{1z} I_2 I_{2z} | I I_z)$: Isospin coupling
  - $(l 0 s \lambda | J \lambda)$: $l - s-$coupling
  - $(s_1 \lambda_1 s_2 - \lambda_2 | s \lambda)$: spin coupling
- F_l: Angular momentum barrier factors
- $\Delta(m)$: Dynamic description of the mother state. Parametrized by:
  - Breit-Wigner forms
  - fit to the data

How to parametrize the Isobar Resonances?

intensity of simple_rho_BW



Argand plot of simple_rho_BW

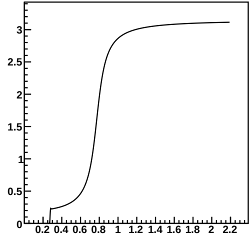


$$\Delta\ m = \frac{m_0\tau_0}{m_0^2 - m^2 - i m_0\tau_0}$$

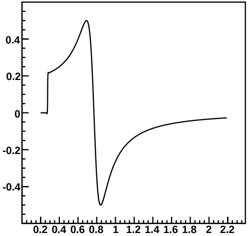
$$\text{RE:}\ \frac{m_0\tau_0(m_0^2 - m^2)}{(m_0^2 - m^2)^2 + (m_0\tau_0)^2}$$

$$\text{IM:}\ \frac{m_0\tau_0(m_0\tau_0)}{(m_0^2 - m^2)^2 + (m_0\tau_0)^2}$$

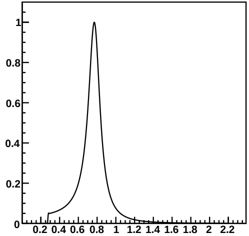
phase of simple_rho_BW



real part of simple_rho_BW

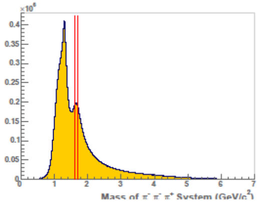


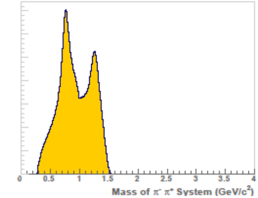
imaginary part of simple_rho_BW

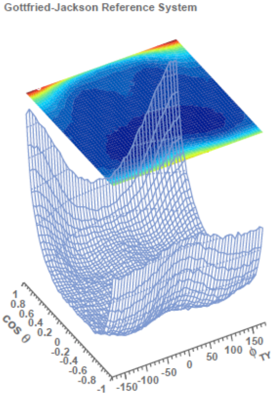


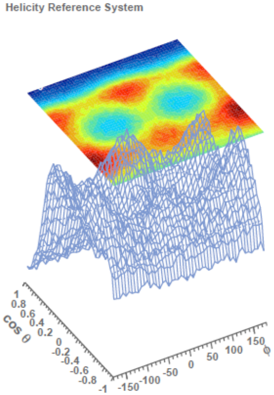
Kinematics of a 3π Decay

Technische Universität München









Deck-like Monte Carlo
Kinematic Distributions