Precision Hadron Spectroscopy at COMPASS
- Scalar Meson Sector -

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for the
COMPASS Collaboration

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Context: Strong Interaction

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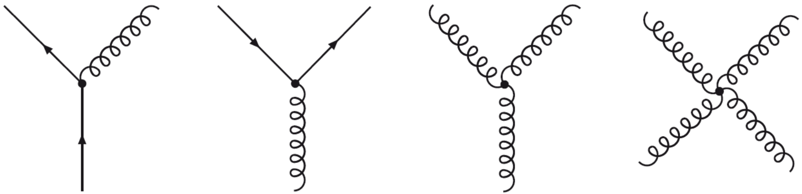
Quantum Chromodynamics (QCD)

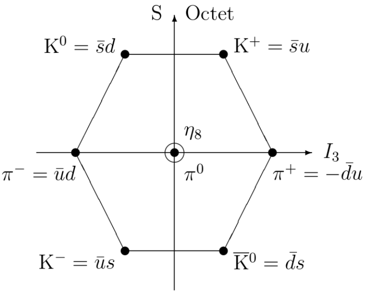
- Degrees of freedom: quarks and gluons
- Confinement: only colour-neutral objects can be observed
- Baryons (qqq, $\bar{q}\bar{q}\bar{q}$) and Mesons ($q\bar{q}$) as the relevant degrees of freedom
- Gluonic bound states predicted by many approximations (lightest: $J^{PC} = 0^{++}$).

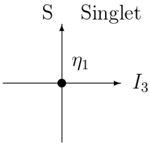


Where are the glueballs?

Light-Quark Meson Spectroscopy

- Flavour SU(3): Mesons are grouped in nonets (pseudoscalar, vector, ...)





Light-Quark Meson Spectroscopy

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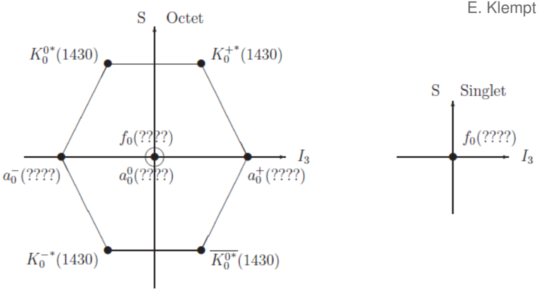
- Flavour SU(3): Mesons are grouped in nonets (pseudoscalar, vector, ...)
- Scalar isoscalar mesons ($I^G J^{PC} = 0^+ 0^{++}$):
  f_0(500), f_0(980), f_0(1370), f_0(1500), f_0(1710), ...

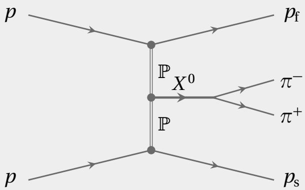
'ground state nonet of scalar mesons as most physicists in the field would agree upon'
E. Klempt [arXiv:hep-ex/0101031]



- **Super-numerous f_0 states** not at all understood by quark models
  $\Rightarrow$ Mixing with **Glueballs?**

Embedded Production

Central Production:



- Glue-rich environment (DPE)
- Long, controversial history

Embedded Production

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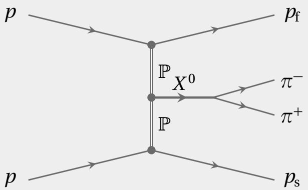

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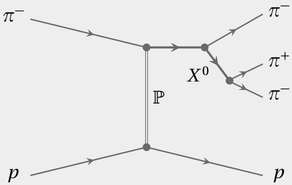
Diffractive Dissociation:



- Assumption of isobaric decay
- Novel extraction of 2π resonances

Embedded Production

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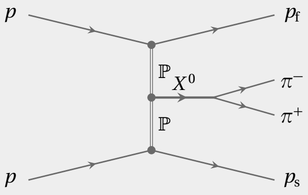
Central Production:



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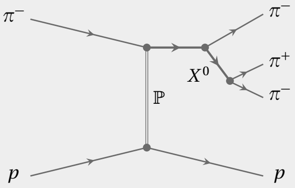


- Assumption of isobaric decay
- Novel extraction of 2π resonances

Experimental requirements:

- Versatile apparatus with various beams and broad kinematic acceptance
- Precise detection of multiple decay modes (h^+h^-, h^0h^0, $K\bar{K}$) in order to determine the nature of the produced resonances

The COMPASS Experiment

Beams from CERN SPS

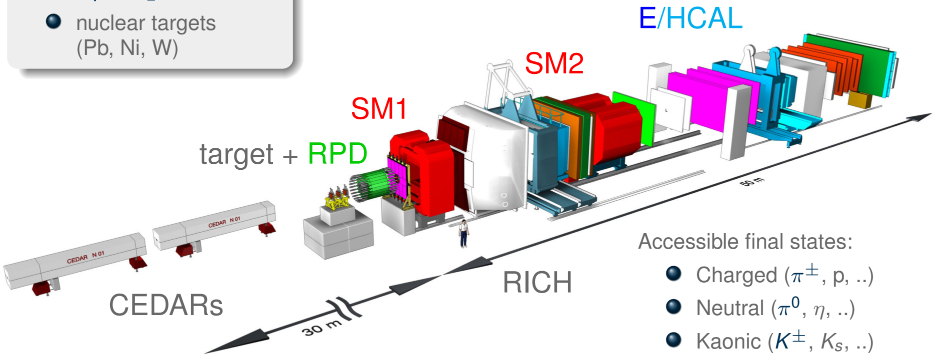
- 190 GeV$/c$ π^-, K^-
- 190 GeV$/c$ p, π^+, K^+

Targets

- liquid H_2
- nuclear targets (Pb, Ni, W)

Two-stage magnetic spectrometer

- Large angular acceptance
- Broad kinematic range
- Tracking, calorimetry, particle ID



Accessible final states:

- Charged ($\pi^\pm$, p, ..)
- Neutral (π^0, η, ..)
- Kaonic ($K^\pm$, K_s, ..)

COMPASS at CERN SPS

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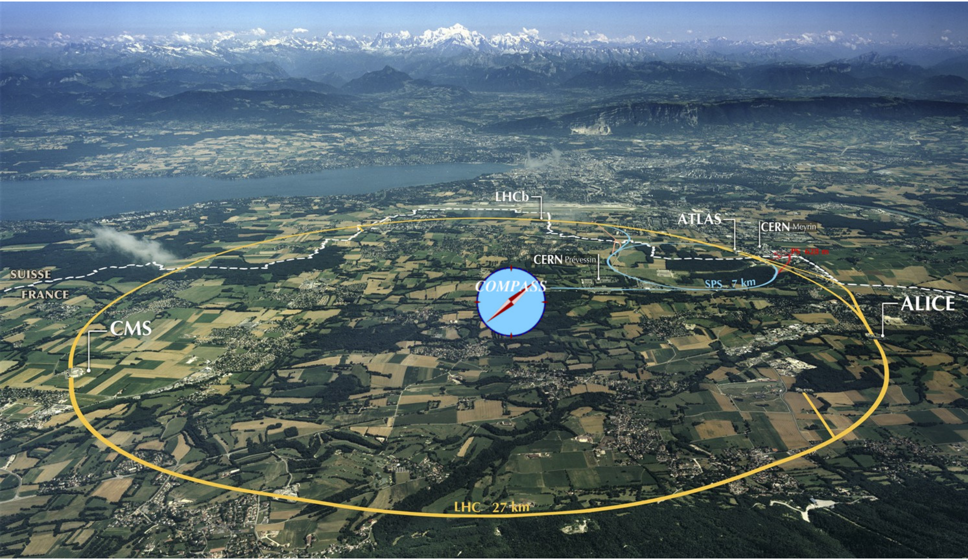

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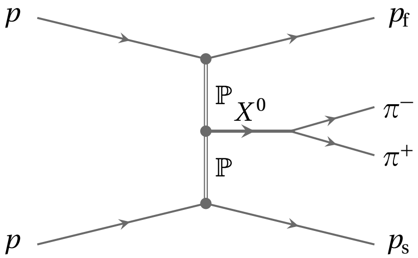
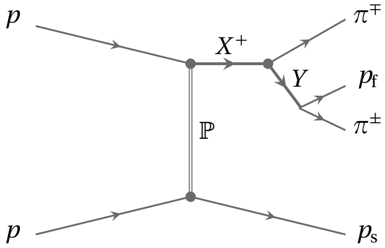
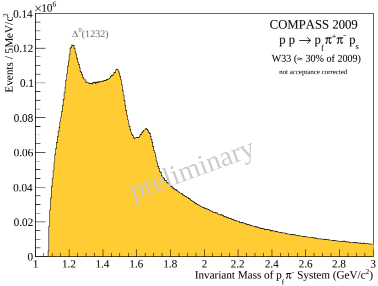
Central Production of Two-Pseudoscalar Final States



Central Production of $\pi^+\pi^-$ System





- Baryon resonances in $p_f\pi^\pm$ subsystems
  $\rightarrow$ **Diffractive dissociation** of the beam proton as dominant process

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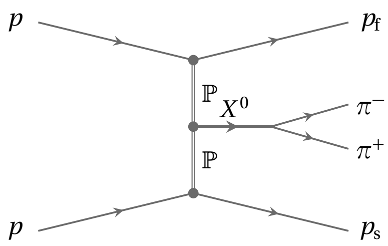

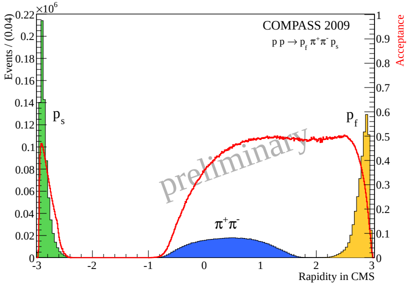

- Baryon resonances in $p_f\pi^\pm$ subsystems
  $\rightarrow$ **Diffractive dissociation** of the beam proton as dominant process
- **Kinematic separation** between p_f and $\pi^\pm$
- Separation between p_s and $\pi^\pm$ by trigger on recoil proton p_s

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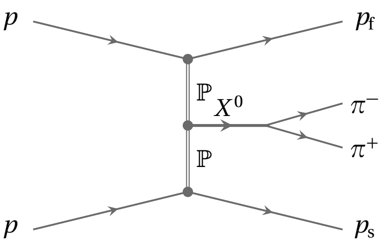
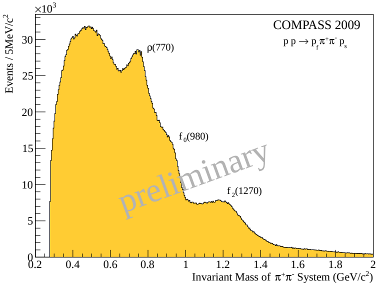
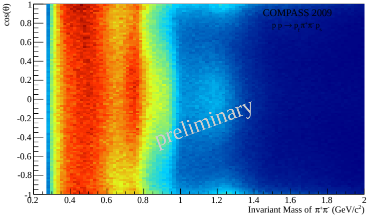


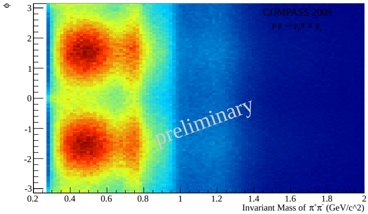


- Baryon resonances in $p_f\pi^\pm$ subsystems
  $\rightarrow$ **Diffractive dissociation** of the beam proton as dominant process
- **Kinematic separation** between p_f and $\pi^\pm$
- Separation between p_s and $\pi^\pm$ by trigger on recoil proton p_s
- $\rho(770)$ production $\rightarrow$ kinematic selection cannot isolate pure DPE sample

$\Rightarrow$ **Two-Body Partial-Wave Analysis (PWA)**

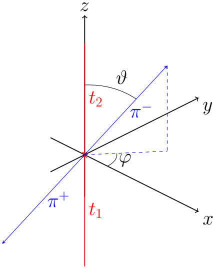
Partial-Wave Analysis



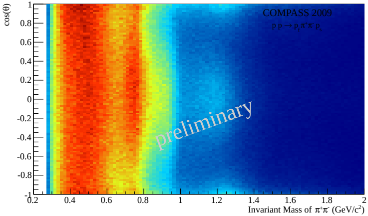


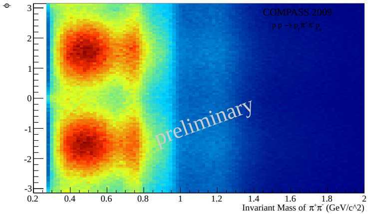
$X^0 \to \pi^+\pi^-$

- **Assumption:** collision of two space-like exchange particles
- Decay of X^0 fully described by $M(\pi^+\pi^-)$, $\cos\vartheta$ and φ



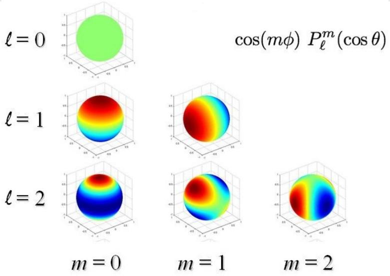
Partial-Wave Analysis





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

- **Assumption:** collision of two space-like exchange particles
- Decay of X^0 fully described by $M(\pi^+\pi^-)$, $\cos\vartheta$ and φ
- Decompose into complex-valued amplitudes (spherical harmonics) with definite spin and parity



Partial-Wave Decomposition

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Expand intensity $I(\vartheta, \varphi)$ into partial-wave amplitudes in narrow mass bins ($10\,\mathrm{MeV}/c^2$):

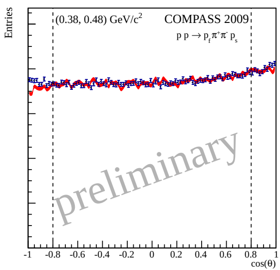
$$I(\vartheta, \varphi) = \left| \sum_{LM} T_{LM} Y_M^L(\vartheta, \varphi) \right|^2$$

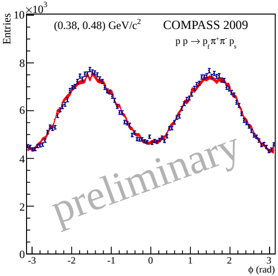
- Quantum-mechanical interference between amplitudes with same $|\mathrm{i}\rangle$ and $|\mathrm{f}\rangle$
- Complex-valued transition amplitudes T_{LM}, no assumption on mass-dependence
- Significant contributions only from $L = S, P, D$ and $M \leq 1$

$\Rightarrow$ **Maximum Likelihood Fit in Mass Bins**

Evaluation of the Fit Quality

$$I(\vartheta, \varphi) = \left| \sum_{LM} T_{LM} Y_M^L(\vartheta, \varphi) \right|^2$$





- Angular distributions are reproduced by MC sample weighted with fit results (red)
- Physical observables: **intensities** $|T_{LM}|^2$ and **relative phases** ($\rightarrow$ Model)

Model Parametrisation

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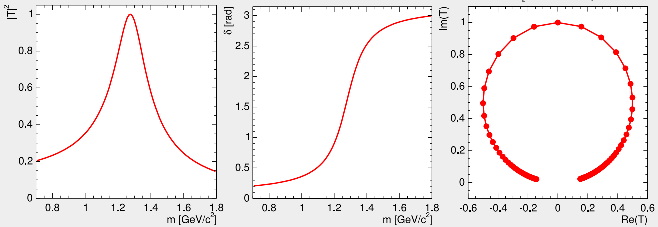
Resonance: Relativistic Breit-Wigner Function

[K. Peters, arXiv:hep-ph/0412069]



$\mathcal{R}_{\text{dyn}}(m) = \frac{m_0\sqrt{\Gamma_0}\sqrt{\Gamma(m;L)}}{m_0^2 - m^2 - i m_0 \Gamma(m;L)}$ with the **parameters m_0, Γ_0** and the dynamical width $\Gamma(m, L)$

Non-Resonant Contribution: Phase Space with Exponential Damping

$\mathcal{N}(m) = \left(\frac{q}{m}\right)^L \cdot \sqrt{\frac{q}{m}} \cdot \exp(-\alpha q^2)$ with breakup momentum q and **parameter α**

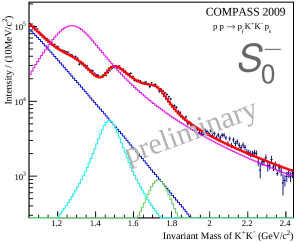
- Sum with complex-valued coefficient (**strength + phase**) for each component

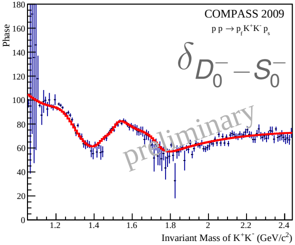
Mass-Dependence of K^+K^-

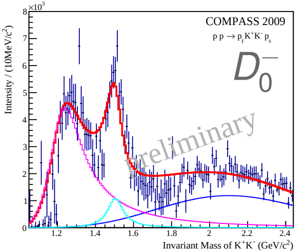
$f_0(1370)$

$f_0(1500)$

$f_0(1710)$





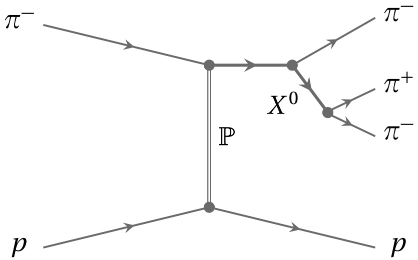


$f_2(1270)$

$f_2'(1525)$

- BW contributions
- non-resonant contribution
- **coherent sum**

Extraction of $(\pi\pi)_S$-Wave from Diffractive Dissociation of Pion Beam into 3-Pion Final States



3-Pion Final States

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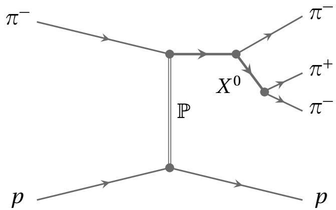
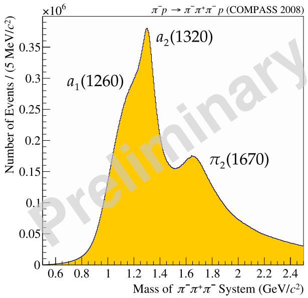
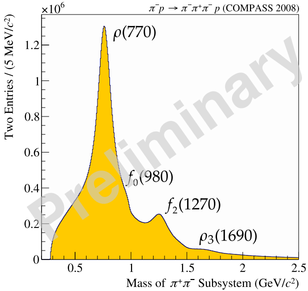


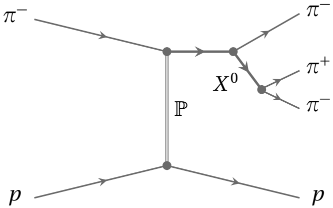
$\pi^- p \to \pi^- \pi^+ \pi^- p$

- 190 GeV/c π^- on lH_2 target
- $\approx$ 50M exclusive events
  $\to$ **unprecedented precision**
- Squared 4-momentum transfer
  $0.1 < t' < 1 (\text{GeV}/c)^2$



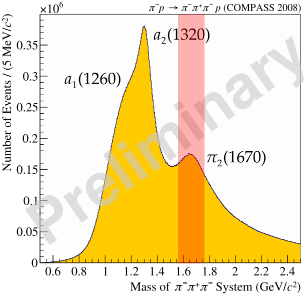


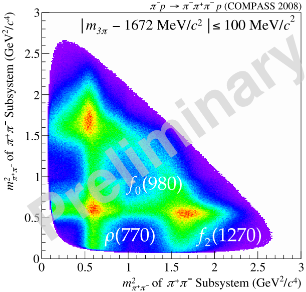
3-Pion Final States



$\pi^- p \to \pi^- \pi^+ \pi^- p$

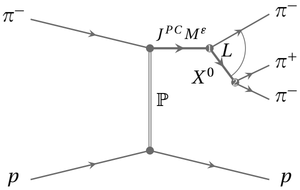
- Sequential 2-body decays
- Isobar Model: intermediate $\pi^+\pi^-$ resonance
- **Previously:** isobar with **fixed** parametrisation





$+$
$(\pi\pi)_S$, $f_0(1500)$

Partial-Wave Analysis

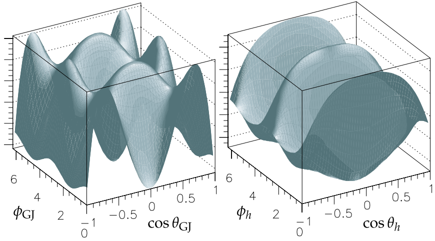


Decay Amplitude in Isobar Model

Partial wave : unique combination of $J^{PC}M^{\varepsilon}X^0\pi L$

Resonance decay
$X^-(2^{-+}) \to f_2(1270)\pi^-$

Isobar decay
$f_2(1270) \to \pi^+\pi^-$

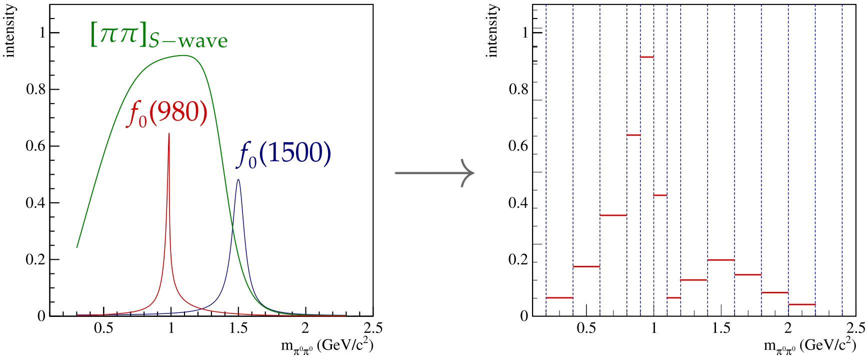


Example: angular distribution for $2^{-+}1^+\ f_2(1270)\pi D$ [Dzierba et al., PRD73 (2006)]

$(\pi\pi)_S$-Wave Extraction from 3π

Novel analysis method

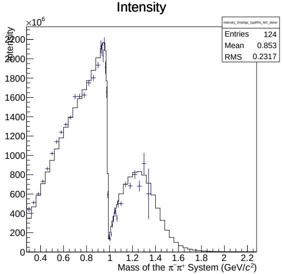
- $J^{PC} = 0^{++}$ isobar amplitudes $\longrightarrow$ piece-wise constant amplitude in $M_{\pi\pi}$ bins
- Extract $J^{PC} = 0^{++}$ isobar amplitude from data as a function of $M_{3\pi}$
- Drastic reduction of model bias, but significant increase in number of parameters

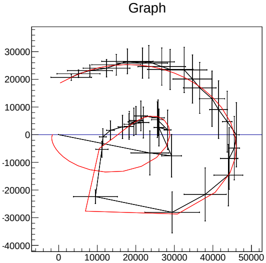


Monte-Carlo Studies

Evaluation of Novel Method

- MC sample with isobaric shapes
- One exemplary 3π mass bin
- One fixed wave as reference necessary
- Good reproduction of isobar shapes





Data: $0^{-+}0^{+}(\pi\pi)_s\,\pi S$

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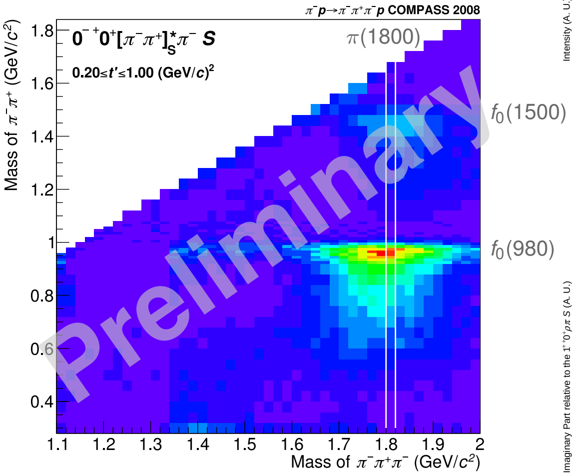

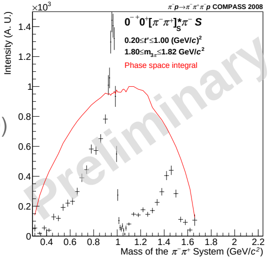

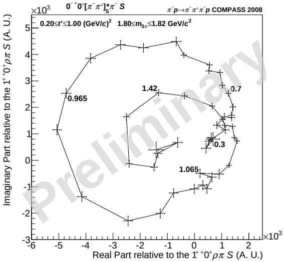

Next step: physical model for $(\pi\pi)_s$ amplitudes

$\Rightarrow$ **Extraction of scalar resonances**

Conclusion

COMPASS is a unique experiment to study
light-quark hadron spectroscopy

- **Large samples** and **precision data** outperform previous experiments
- **Novel analysis schemes** provide insight in hadron dynamics
- **Consistent picture of scalar sector** through combination of different approaches

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- Similar phenomena in different mass regimes
  $\rightarrow$ resonances, reflections, threshold effects, non-resonant production, ...
- Synergy with heavy meson decay and *CP*-violation analyses

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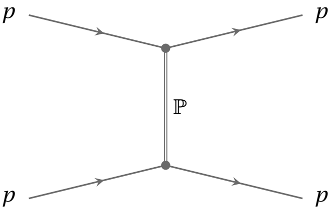
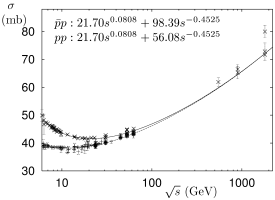
Thank you for your attention!

Backup Slides

Regge Theory



S. Donnachie et al. (2002)



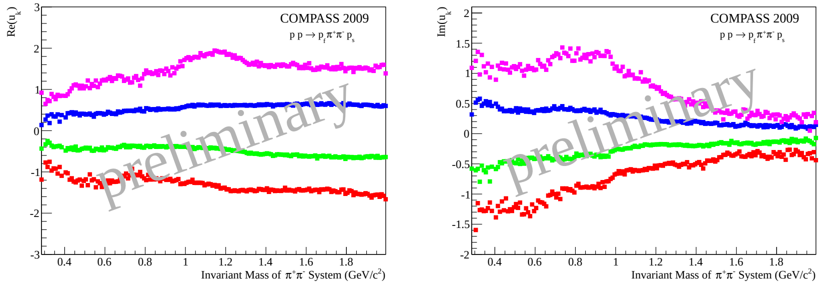
Phenomenological Theory of Hadron Scattering

- Postulation of Pomeron $\mathbb{P}$ necessary for scattering above $\sqrt{s} \approx 10\,\mathrm{GeV}$
- **Which observed particles, if any, correspond to the Pomeron?**

How does Regge theory emerge from QCD at long distances?

Ambiguities

- 8 mathematically ambiguous solutions result in the same angular distribution
- Analytical computation via method of Barrelet Zeros



- Real (left) and imaginary (right) part of polynomial roots
- Well separated, imaginary parts do not cross the real axis

$\Rightarrow$ Solutions can be uniquely identified and linked from mass bin to mass bin

Ambiguities in the $\pi\pi$ Systems

$\pi^+\pi^-$ System

- 8 different solutions can be calculated analytically
- Differentiation requires additional input
  (e.g. behaviour at threshold, physics content)

$\pi^0\pi^0$ System

- Identical particles, only even waves allowed
- Reduces number of ambiguities to 2

Combination of $\pi\pi$ Systems

- Consistent picture of the reaction, measured with different parts of experimental setup
- Interpretation with mass dependent parametrisation under way!

Fit to the K^+K^- System

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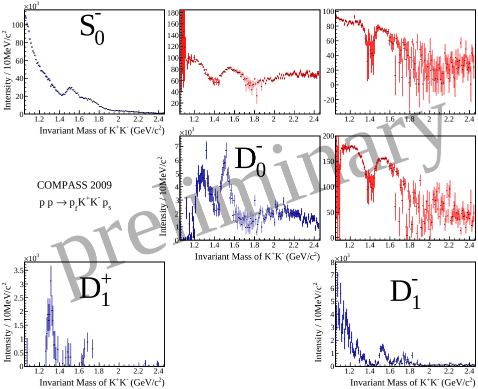

- Similar partial-wave analysis of K^+K^--system
- Odd waves do not play a significant role above the $\phi(1020)$-mass
  $\Rightarrow$ Reduction of ambiguities