Central Production of Two-Pseudoscalar Meson Systems at COMPASS

Alexander Austregesilo

PWA Meeting
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Jefferson Lab, Newport News, VA

Outline

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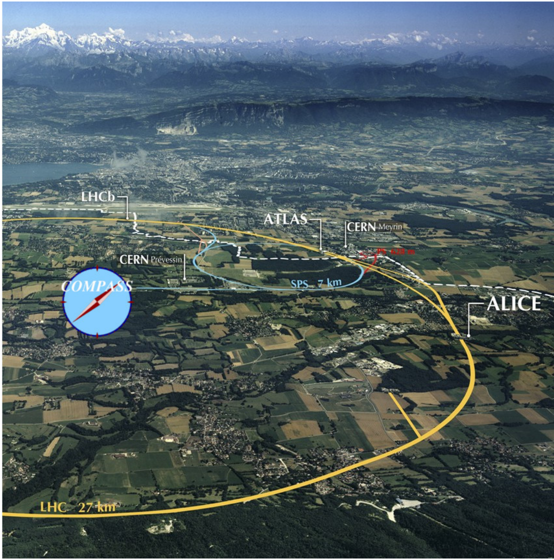
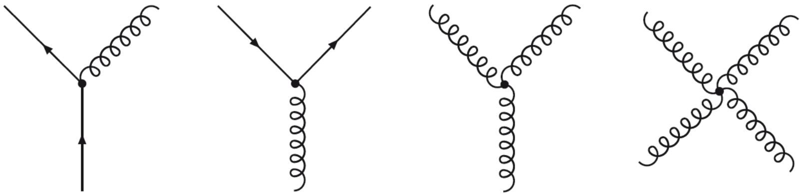
1. Light Scalar Mesons
2. Central Production
3. Partial-Wave Analysis
4. Interpretation
5. Final States with Strangeness



Context: Strong Interaction

Quantum ChromoDynamics (QCD)

- Degrees of freedom: quarks and gluons
- Confinement: only color-neutral objects can be observed
- Baryons (qqq, $\bar{q}\bar{q}\bar{q}$) and Mesons ($q\bar{q}$) as the relevant degrees of freedom



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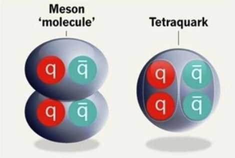
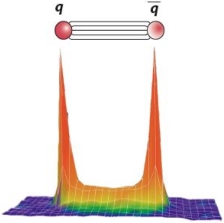
- Baryons (qqq, $\bar{q}\bar{q}\bar{q}$) and Mesons ($q\bar{q}$) as the relevant degrees of freedom
- Glueballs and other exotic hadrons predicted by many approximations

Multiquark



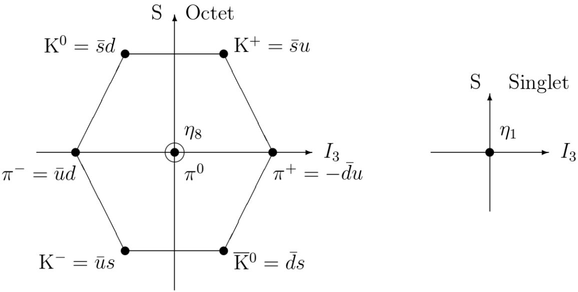
Hybrid Meson



Gell-Mann's Totalitarian Principle: Everything not forbidden is compulsory!

Light-Quark Meson Spectroscopy

- Flavor SU(3): Mesons are grouped into $3 \otimes 3 = 8 \oplus 1$ nonets



Light-Quark Meson Spectroscopy

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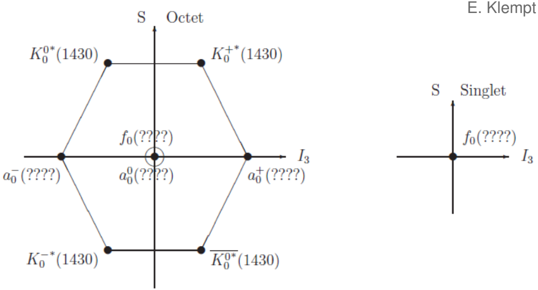
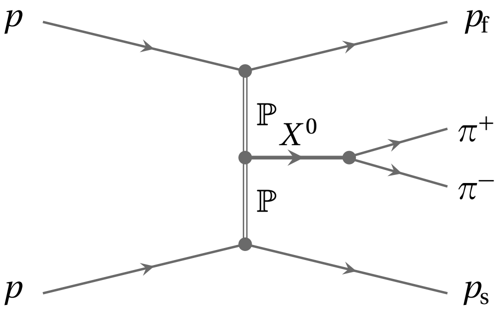
- Flavor SU(3): Mesons are grouped into $3 \otimes 3 = 8 \oplus 1$ nonets
- Scalar isoscalar mesons ($I^G J^{PC} = 0^+ 0^{++}$):
  f_0(500), f_0(980), f_0(1370), f_0(1500), f_0(1710), ...

'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 understood by constituent quark models
  $\Rightarrow$ Mixing with **Glueballs?**

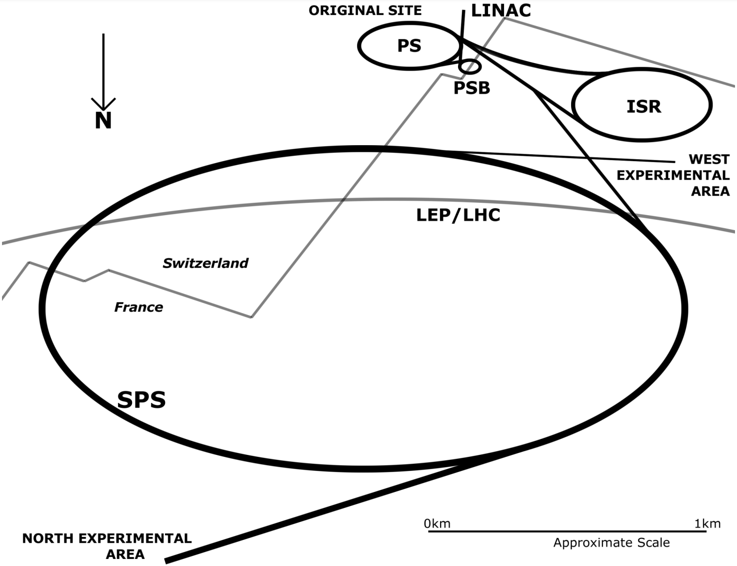
Central Production



$p\,p \rightarrow p_{fast}\,X\,p_{slow}$

- Proton beam impinging on proton target, both **stay intact** and are detected
- Double-Pomeron production of meson system (**gluon-rich environment**)
- Decay into two pseudoscalar mesons ($\boldsymbol{\pi^+\pi^-}$, $\pi^0\pi^0$, $\boldsymbol{K^+K^-}$, $\eta\,\eta$, ..)

Central Production at CERN



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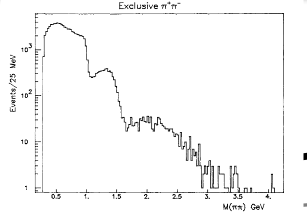

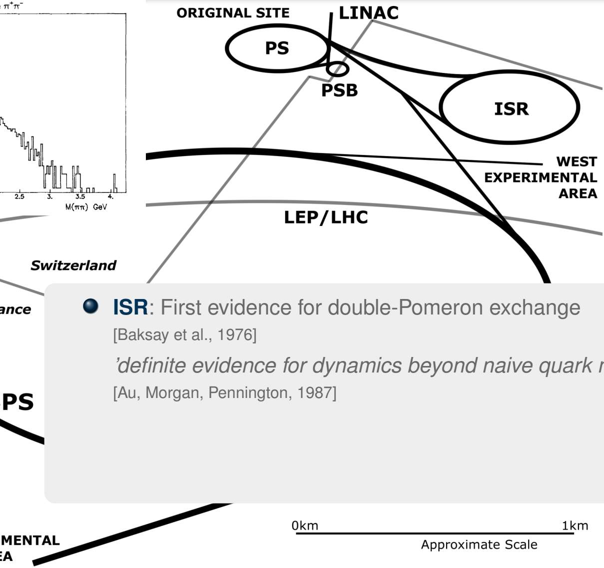

- **ISR**: First evidence for double-Pomeron exchange
  [Baksay et al., 1976]
  'definite evidence for dynamics beyond naive quark model'
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Central Production at CERN

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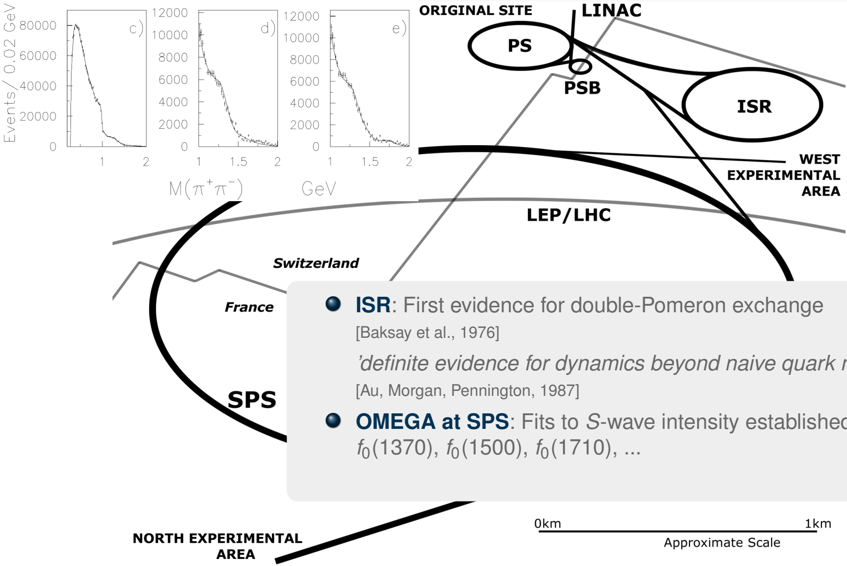

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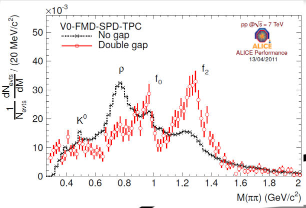
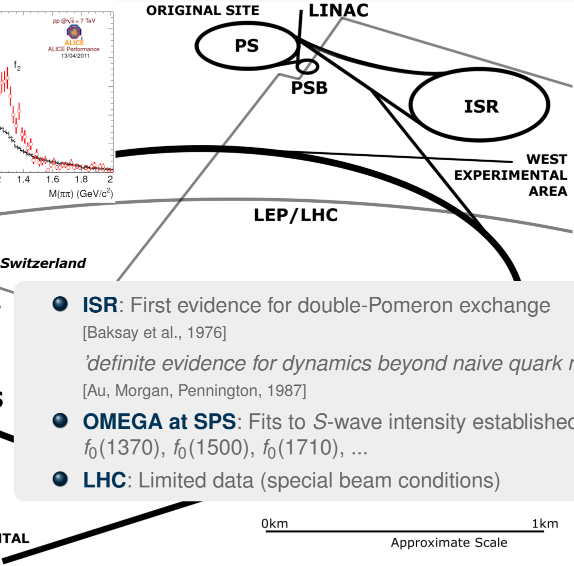
Central Production at CERN





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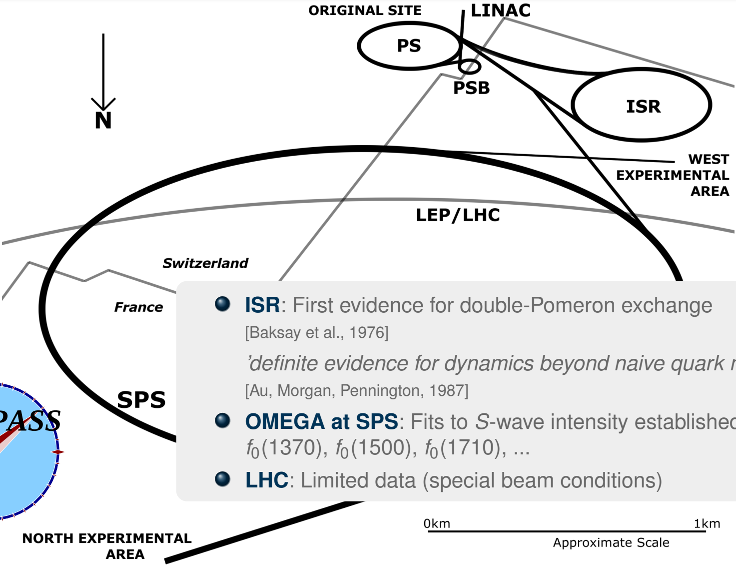

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The COMPASS Experiment

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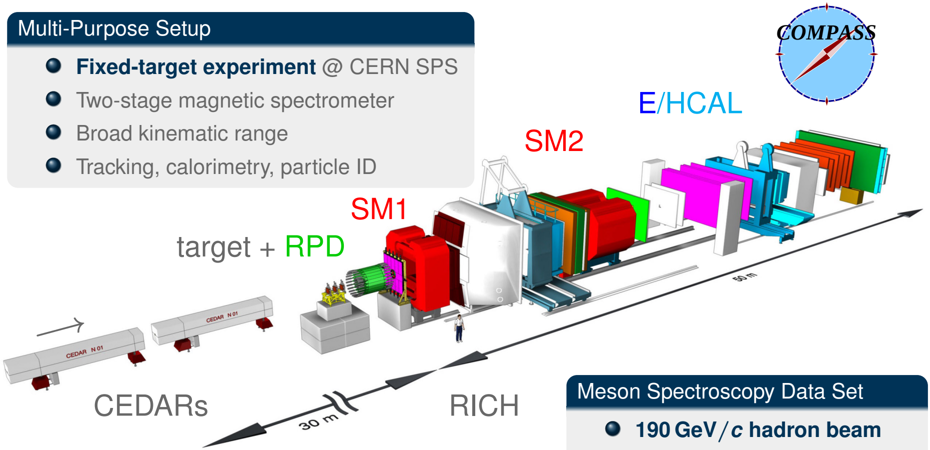
Multi-Purpose Setup

- **Fixed-target experiment** @ CERN SPS
- Two-stage magnetic spectrometer
- Broad kinematic range
- Tracking, calorimetry, particle ID



Meson Spectroscopy Data Set

- **190 GeV/c hadron beam**
- ($\boldsymbol{p}$, π^+, K^+) or (π^-, K^-, $\bar{p}$)
- Liquid **H_2 target**
- Trigger on recoil proton

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

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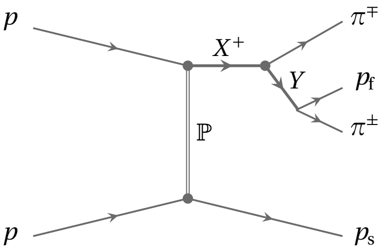

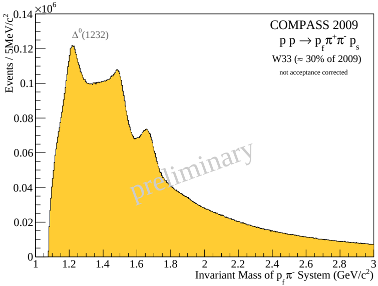

- Baryon resonances in $p_f\pi^\pm$ subsystems
  → **Diffractive dissociation** of the beam proton as dominant process

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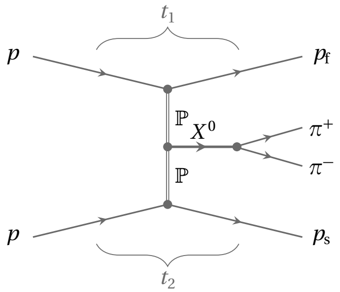

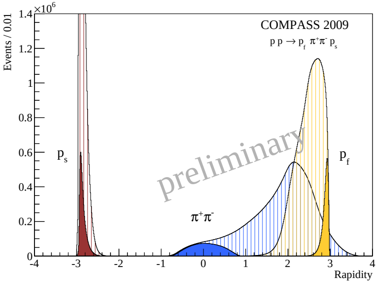

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- **Kinematic separation** between p_f and $\pi^\pm$
- Separation between p_s and $\pi^\pm$ by trigger on recoil proton p_s

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

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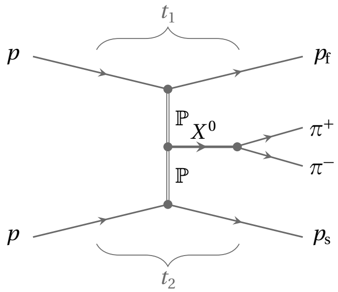
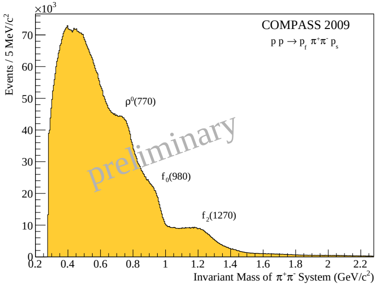
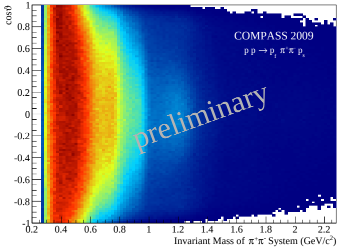


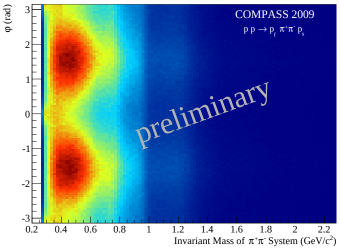


- Baryon resonances in $p_{\mathrm{f}}\pi^{\pm}$ subsystems
  $\rightarrow$ **Diffractive dissociation** of the beam proton as dominant process
- **Kinematic separation** between p_{f} and $\pi^{\pm}$
- Separation between p_{s} and $\pi^{\pm}$ by trigger on recoil proton p_{s}
- $\rho(770)$ production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

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

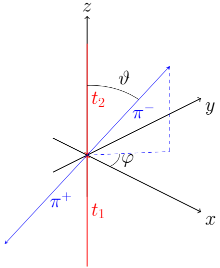
Partial-Wave Analysis



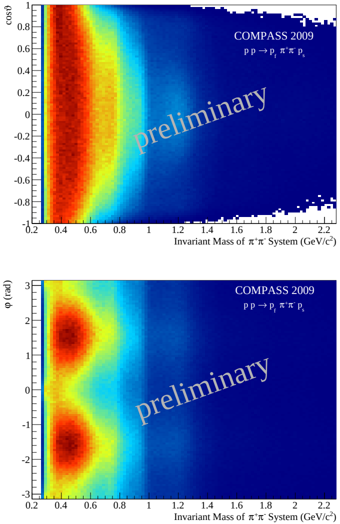


$X^0 \to \pi^+\pi^-$

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

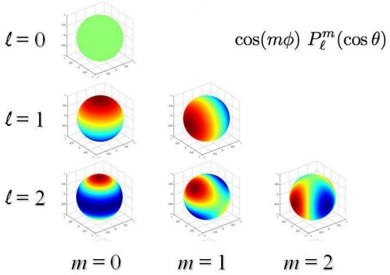


Partial-Wave Analysis



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

- **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



Construction of Wave-Set

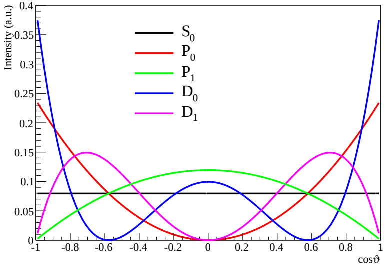
Strong Interaction Conserves Parity

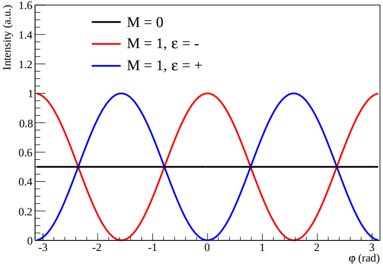
- Eigenstates of **reflectivity ϵ**, waves with opposite ϵ do not interfere

$$Y_M^{\epsilon L}(\theta, \phi) = c(M)\left[Y_M^L(\theta, \phi) - \epsilon(-1)^m Y_{-M}^L(\theta, \phi)\right], \quad M \geq 0$$

Naturality

- ϵ coincides with exchanged **naturality η** for reaction with pion beam
- For central production, natural transfers ($J^P = 0^+, 1^-, 2^+, \ldots$) correspond to $\epsilon = -1$





Partial-Wave Decomposition

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

$$I(\vartheta, \varphi) = \sum_{\varepsilon} \left| \sum_{LM} T^{\varepsilon}_{LM} Y^{\varepsilon L}_{M}(\vartheta, \varphi) \right|^2$$

- **Complex-valued transition amplitudes T^{ε}_{LM}**, no assumption on mass-dependence
- Quantum-mechanical interference between amplitudes with same $|\mathrm{i}\rangle$ and $|\mathrm{f}\rangle$
- Explicit incoherent sum over the **reflectivities ε** (parity conservation)
- Significant contributions only from $L = S, P, D$ and $M \leq 1$

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

Extended Maximum-Likelihood Fit

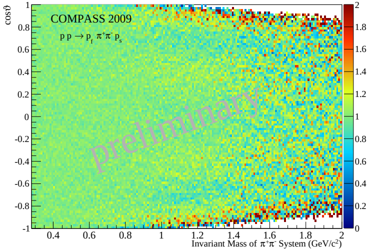
$$I(\vartheta, \varphi) = \sum_{\varepsilon} \left| \sum_{LM} T^{\varepsilon}_{LM} Y^{\varepsilon L}_{M}(\vartheta, \varphi) \right|^2$$

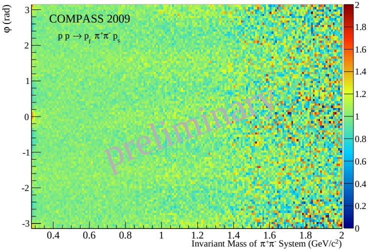
Maximize likelihood function

$$\ln L = \sum_{i=1}^{N} \ln I(\vartheta_i, \varphi_i) - \int d\Omega\, I(\vartheta, \varphi)\, \eta(\vartheta, \varphi)$$

- by choosing T^{ε}_{LM} such that the intensity fits the observed N events
- **Normalisation integral** evaluated by a phase-space Monte Carlo sample
- with the **acceptance** $\boldsymbol{\eta(\vartheta, \varphi)}$

Evaluation of the Fit Quality





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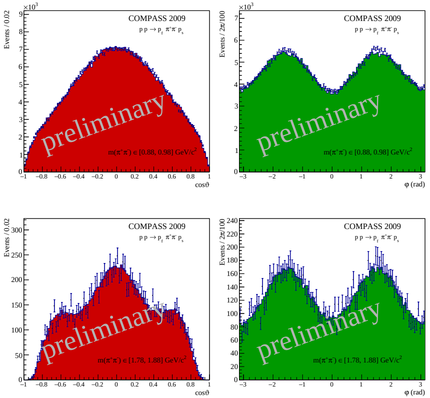

Ambiguities in the $\pi^+\pi^-$ System

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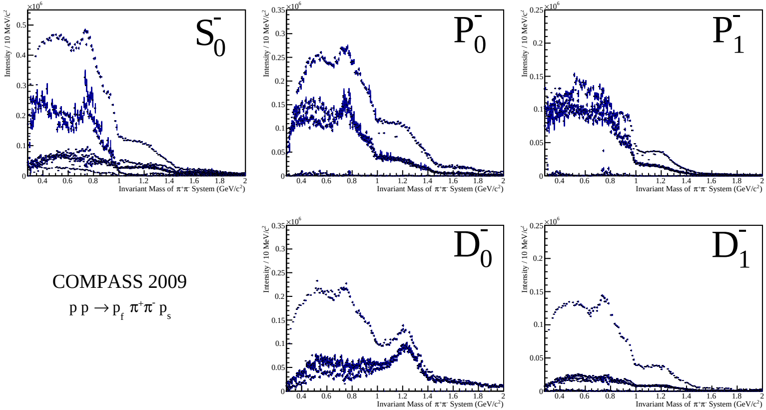

Intensity distributions for 30 fit attempts with random starting values

Ambiguities in the $\pi^+\pi^-$ System

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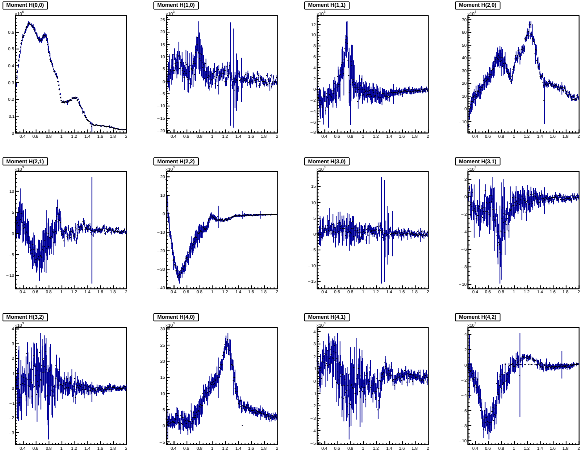

Unique decomposition into moments

Ambiguities in the $\pi^+\pi^-$ System

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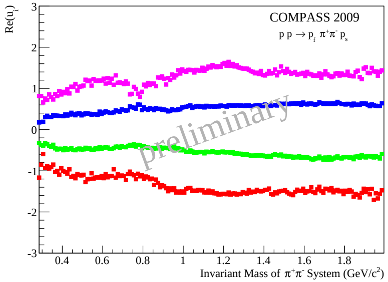
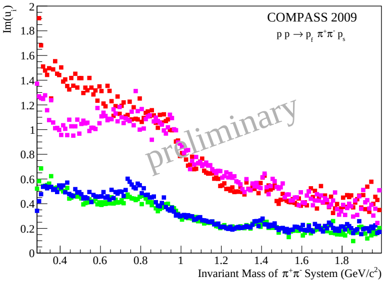
- 8 mathematically ambiguous solutions result in the same angular distribution
- Analytical computation via method of **Barrelet Zeros**

S.-U. Chung, [Phys. Rev. D 56 (1997), 7299]

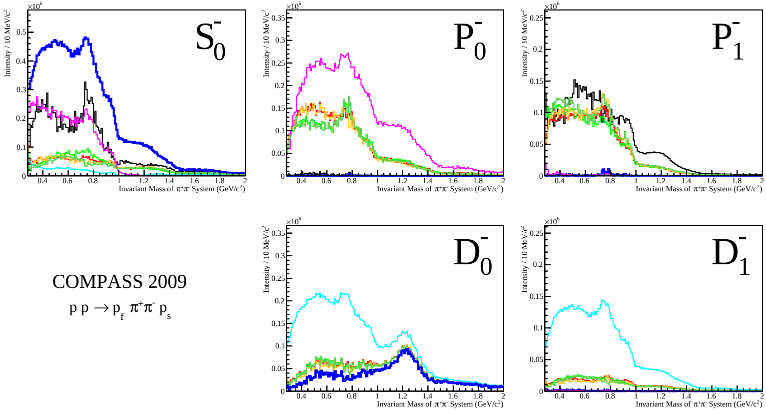




- Real (left) and imaginary (right) part of polynomial roots
- Well separated, imaginary parts do not cross the real axis

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

Ambiguities in the $\pi^+\pi^-$ System



Intensity distributions for 8 solutions computed with the results of one single fit

$\pi^+\pi^-$ System: Physical Solution

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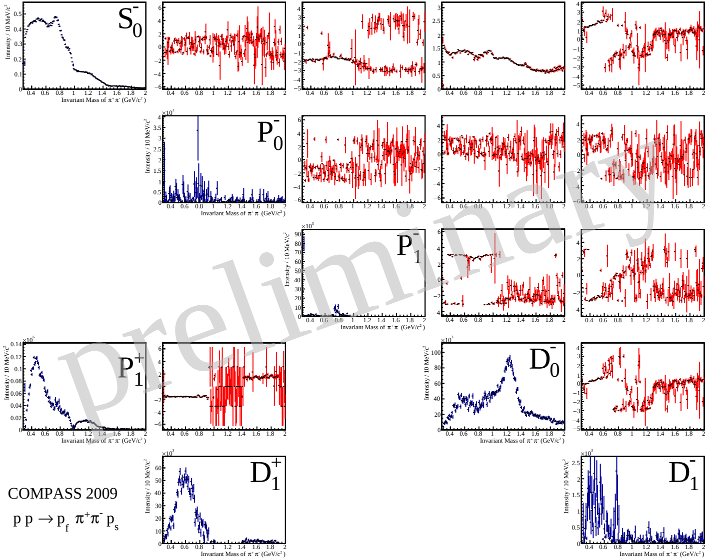

$\pi\pi$ System: Physical Solution

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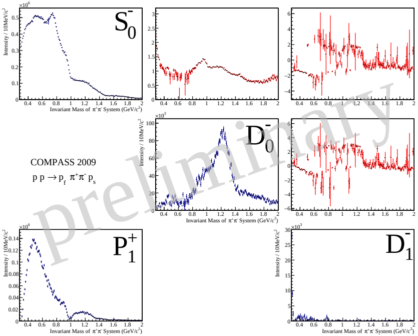
$\pi^+\pi^-$



$\pi\pi$ System: Physical Solution

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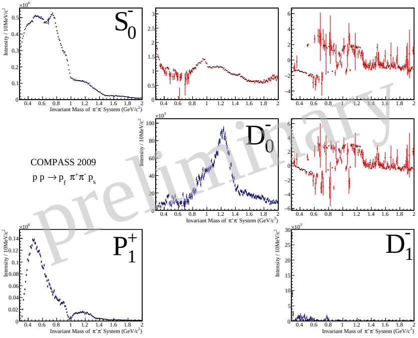
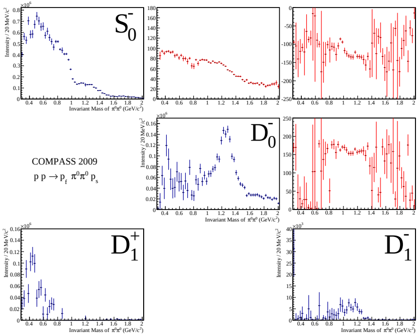
$\pi^+\pi^-$	$\pi^0\pi^0$





Ambiguities in the $\pi\pi$ Systems

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$\pi^+\pi^-$ System

- 8 different solutions can be calculated analytically from the result of one fit
- Differentiation requires additional input
  (e.g. behavior at threshold, physics content)

$\pi^0\pi^0$ System

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

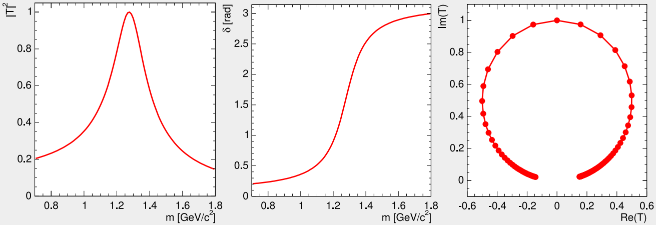
Combination of $\pi\pi$ Systems

- Consistent picture of the reaction
- Measured with different parts of experimental setup
- $\rho(770)$ signal cannot be described by this model, different production mechanism
- Interpretation with mass dependent parameterization

Model-Dependent Parameterization

Resonance: Relativistic Breit-Wigner Function

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

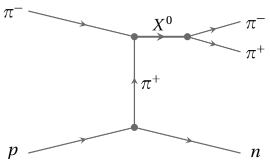


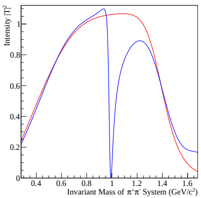
Non-Resonant Contribution

Phase-space with exponential damping (phenomenological)

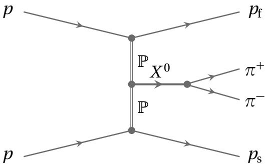
- Sum with complex-valued coefficient (**strength + phase**) for each component

Unitarity Constraints





- **Watson theorem** relates phase of prod. processes
- M solution from
  Au, Morgan, Pennington
  Phys. Rev. D 35 (1987) 1633
- $\pi\pi$ ampl. vanishes near threshold (Adler zero)



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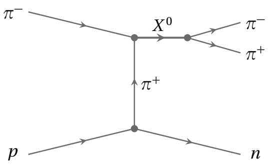

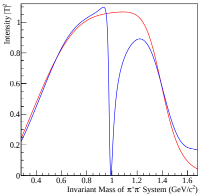

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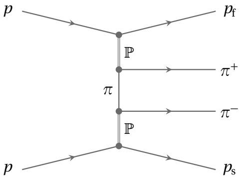

Unitarity Constraints

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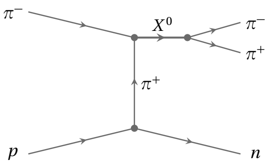

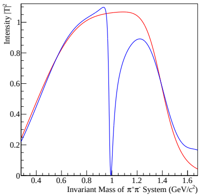

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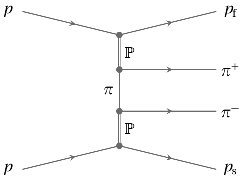
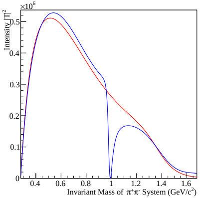
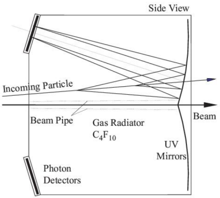
$$\mathbb{T}_{\text{red}} = \frac{\mathbb{T}}{s - s_0}$$

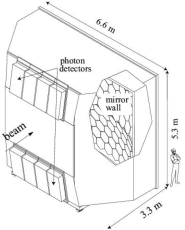




- **Constrain** masses below 1 GeV/c with $\pi\pi$ scattering data
- First fit of S-wave amplitude **with interference** to D-wave
- Interpretation with mass dependent parameterization

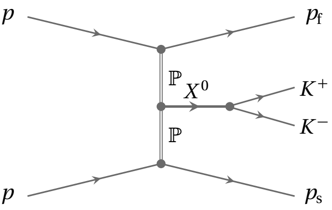
Selection of Kaons

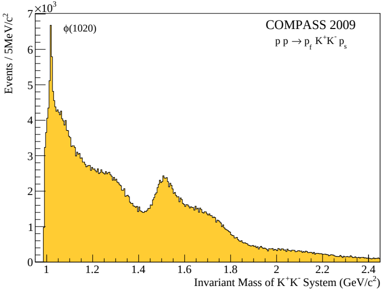




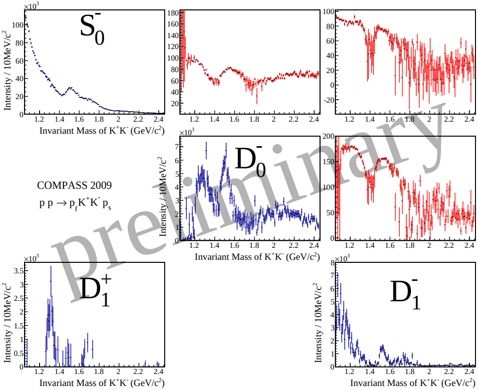
COMPASS RICH Detector

- K identification with $[10, 50]\,\mathrm{GeV}/c$
- Large sample with visible structures
- Production of $\phi(1020)$
  $\Rightarrow$ not pure DPE





Fit to the K^+K^- System



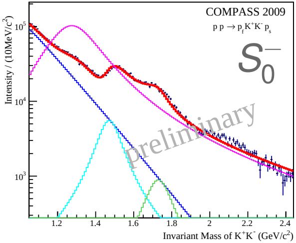
- Similar partial-wave analysis to $\pi^+\pi^-$-system
- Odd waves do not play a significant role above the $\phi(1020)$-mass
  $\Rightarrow$ Reduction of ambiguities

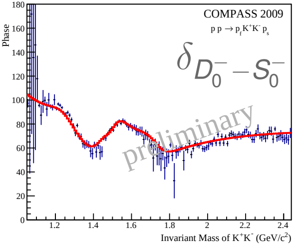
Mass-Dependence of K^+K^-

$f_0(1370)$

$f_0(1500)$

$f_0(1710)$

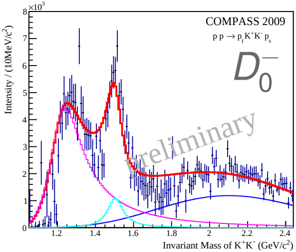




BW contributions

non-resonant contribution

coherent sum



$f_2(1270)$

$f_2'(1525)$

Interference of *S* and *D*

Distinguishes resonances from non-resonant contribution

Summary

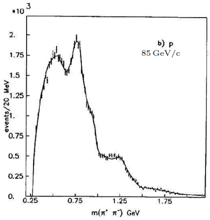
COMPASS is a unique experiment to study
Light Mesons in Central Production

- **Large samples** of **precision data** for many final states
- **Novel analysis schemes** provide insight in hadron dynamics
  - Mathematical ambuiguities resolved
  - Interference of *S*- and *D*-waves helps to identify resonant components
- **Consistent picture of scalar sector** through combination of different approaches

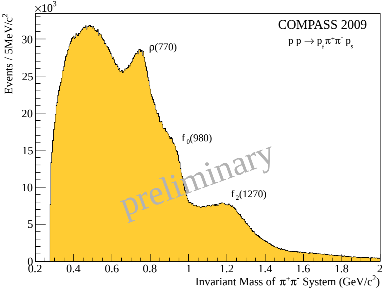
Backup Slides

$\sqrt{s}$-Dependence

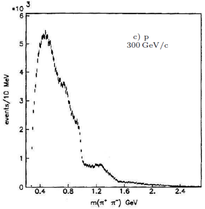
T.A. Armstrong et al. [Z. Phys. C51 (1991)]



$\sqrt{s} = 12.7\,\mathrm{GeV}/c^2$



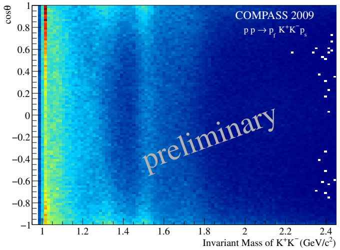
$\sqrt{s} = 18.9\,\mathrm{GeV}/c^2$

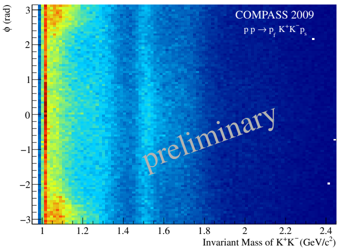


$\sqrt{s} = 23.7\,\mathrm{GeV}/c^2$

- Production of $\rho(770)$ disappears rapidly with increasing $\sqrt{s}$
- Low-mass enhancement and $f_0(980)$ remain practically unchanged
  $\rightarrow$ characteristic for s-independent Pomeron-Pomeron scattering
- Kinematic selection cannot single out pure DPE sample

PWA of K^+K^- System





$X \to K^+K^-$

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