

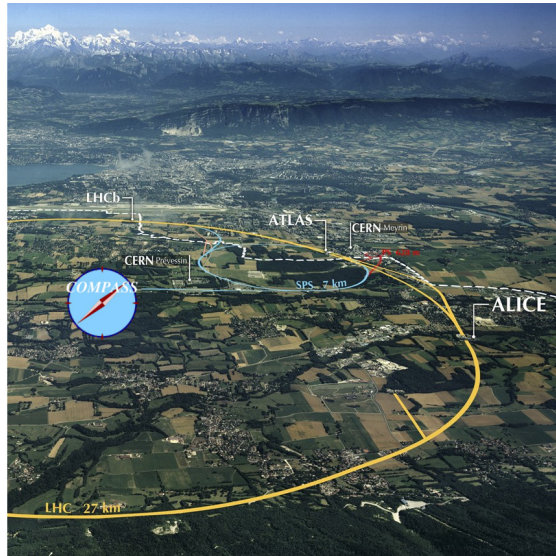
Central Production of Two-Pseudoscalar Meson Systems at COMPASS

Alexander Austregesilo

PWA Meeting
February 27th, 2017
Jefferson Lab, Newport News, VA



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

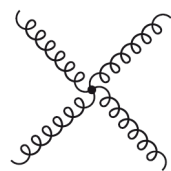
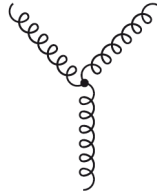
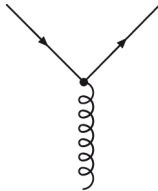
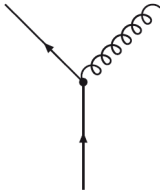




Context: Strong Interaction

Quantum ChromoDynamics (QCD)

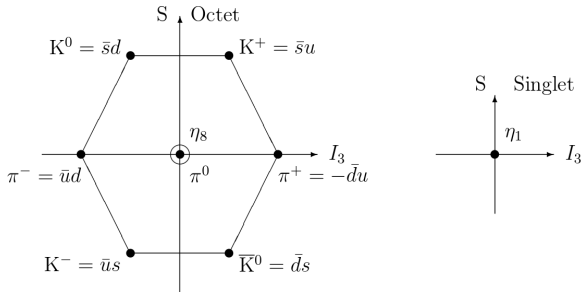
- Degrees of freedom: quarks and gluons
- Confinement: only color-neutral objects can be observed
- Baryons (qqq , $\bar{q}\bar{q}\bar{q}$) and Mesons ($q\bar{q}$) as the relevant degrees of freedom





Light-Quark Meson Spectroscopy

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

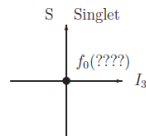
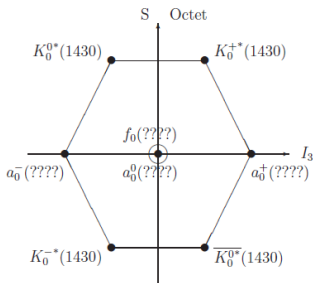




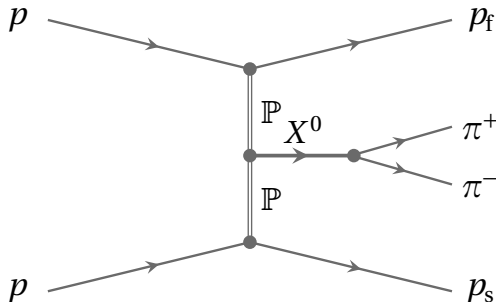
Light-Quark Meson Spectroscopy

- 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?**

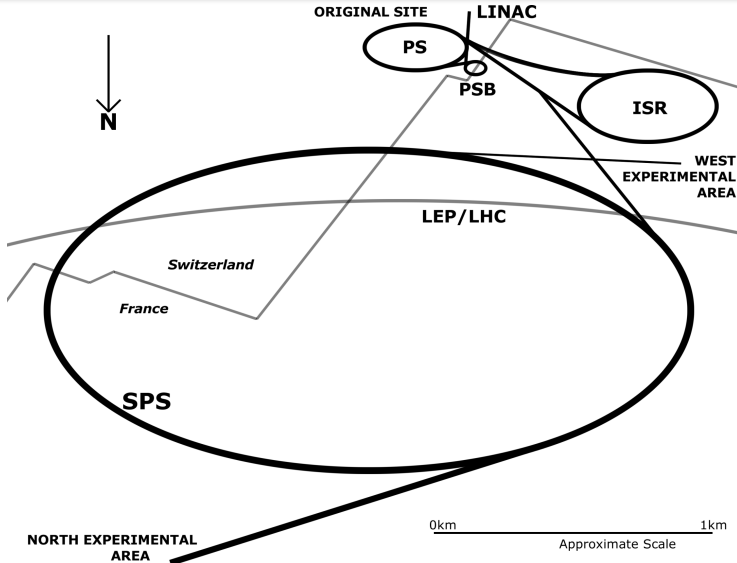


$$pp \rightarrow p_{\text{fast}} X p_{\text{slow}}$$

- 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 ($\pi^+ \pi^-$, $\pi^0 \pi^0$, $K^+ K^-$, $\eta \eta$, ..)



Central Production at CERN

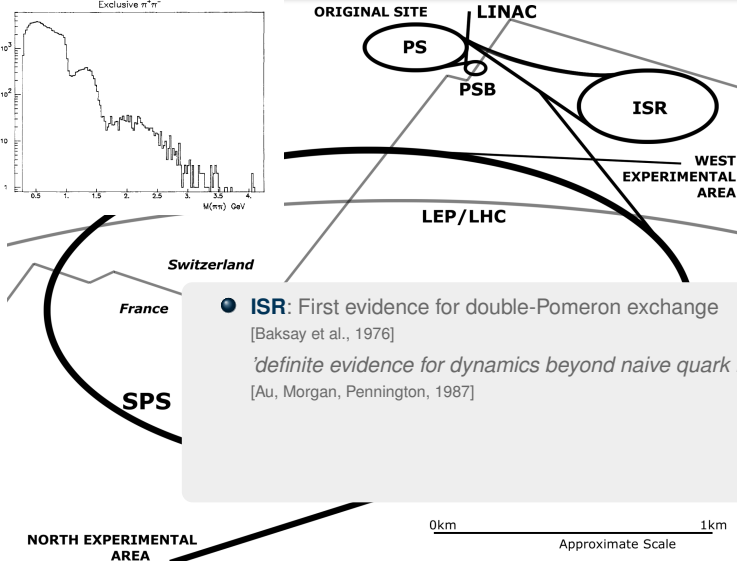
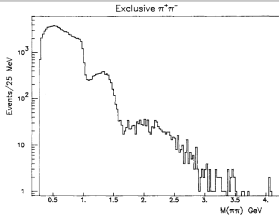




Central Production at CERN



Technische Universität München



- **ISR:** First evidence for double-Pomeron exchange

[Baksay et al., 1976]

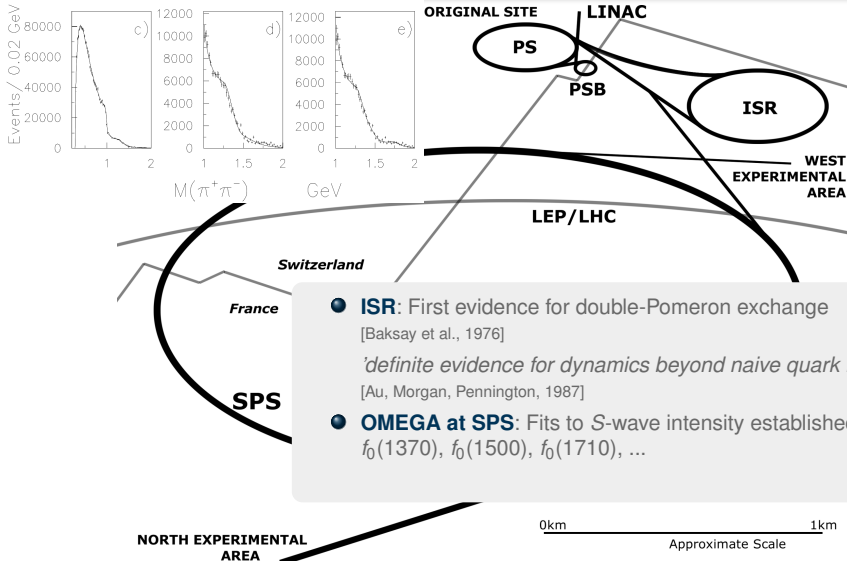
'definite evidence for dynamics beyond naive quark model'

[Au, Morgan, Pennington, 1987]

0km 1km
Approximate Scale

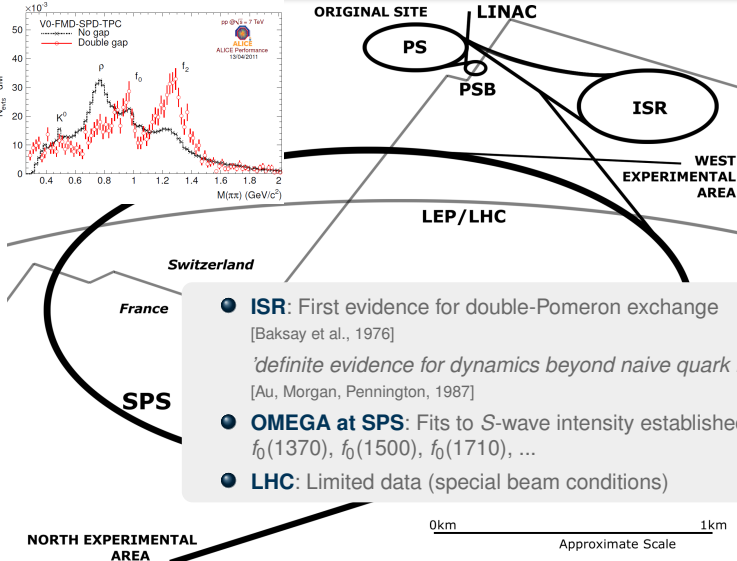
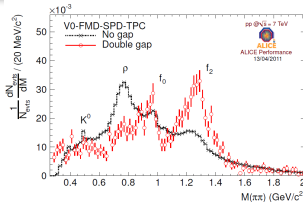


Central Production at CERN





Central Production at CERN



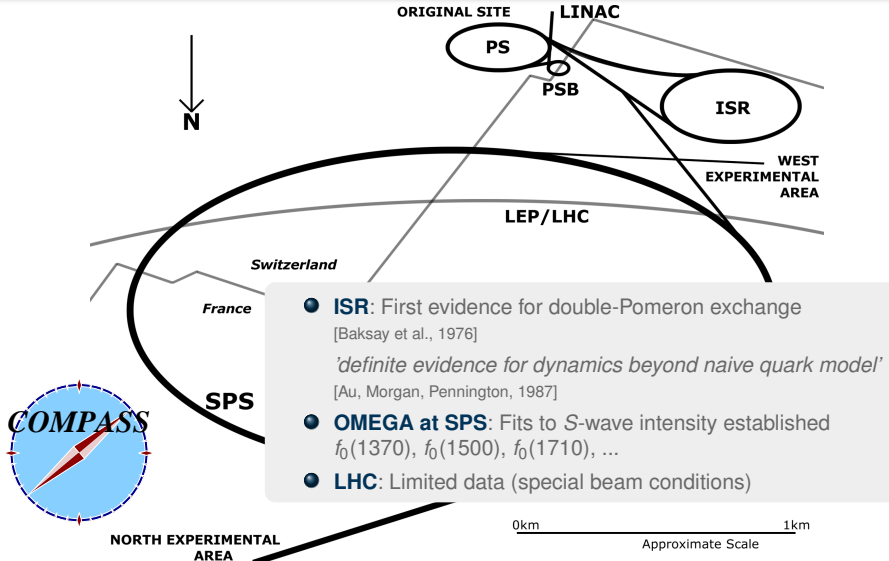
- **ISR:** First evidence for double-Pomeron exchange [Baksay et al., 1976]
'definite evidence for dynamics beyond naive quark model' [Au, Morgan, Pennington, 1987]
- **OMEGA at SPS:** Fits to S -wave intensity established $f_0(1370)$, $f_0(1500)$, $f_0(1710)$, ...
- **LHC:** Limited data (special beam conditions)



Central Production at CERN



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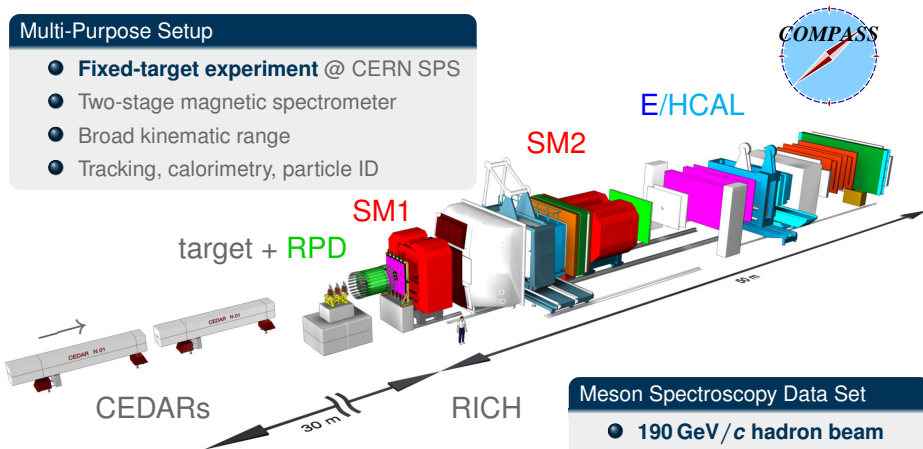




The COMPASS Experiment

Multi-Purpose Setup

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

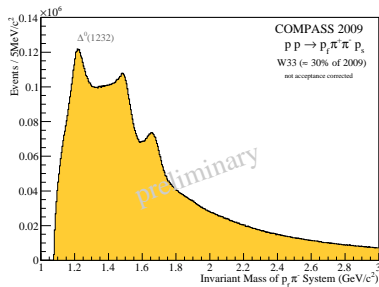
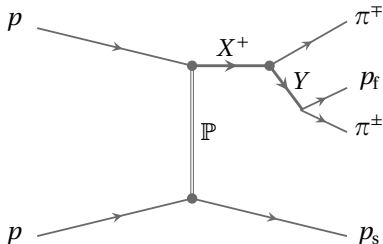


Meson Spectroscopy Data Set

- **190 GeV/c hadron beam**
- (p, π^+, K^+) or (π^-, K^-, \bar{p})
- Liquid **H₂** target
- Trigger on recoil proton



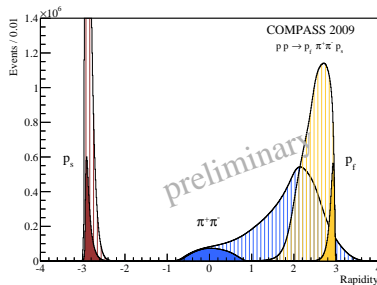
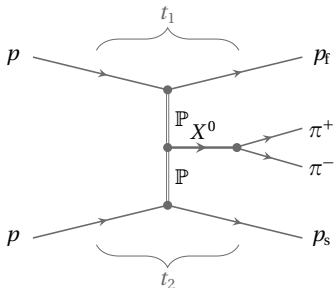
Central Production of $\pi^+\pi^-$ System



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



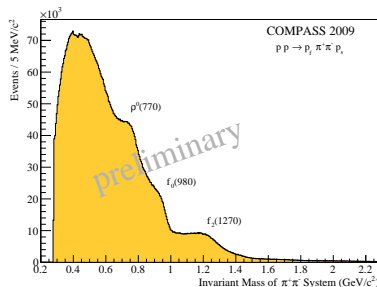
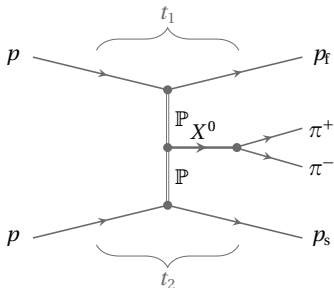
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Central Production of $\pi^+\pi^-$ System

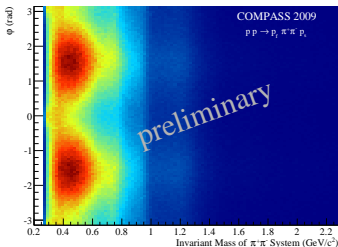
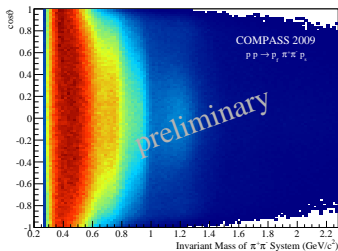


- Baryon resonances in $p_f \pi^\pm$ subsystems
 \rightarrow **Diffraction dissociation** of the beam proton as dominant process
- **Kinematic separation** between p_f and π^\pm
- Separation between p_s and π^\pm by trigger on recoil proton p_s
- $\rho(770)$ production \rightarrow kinematic selection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

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

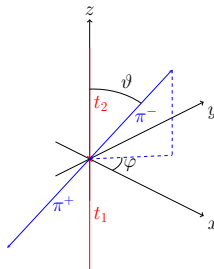


Partial-Wave Analysis



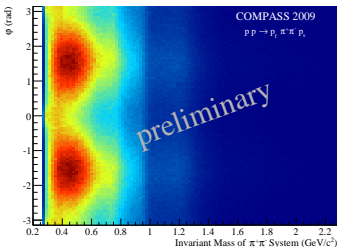
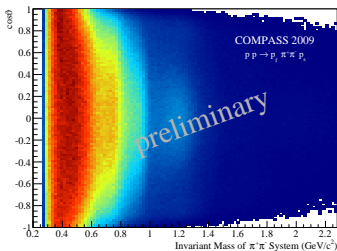
$$X^0 \rightarrow \pi^+ \pi^-$$

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



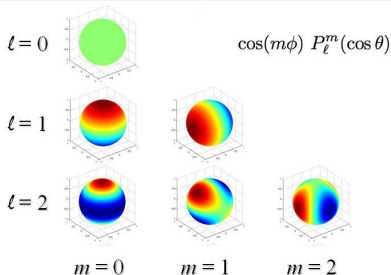


Partial-Wave Analysis



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

- **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

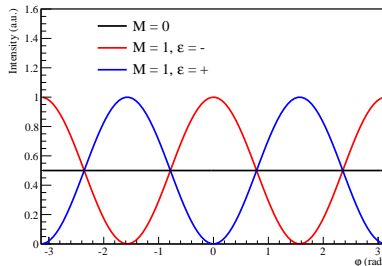
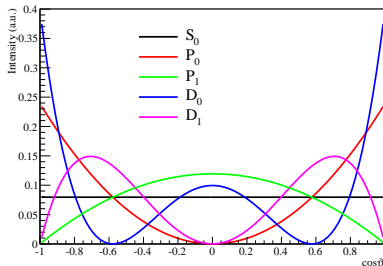
Strong Interaction Conserves Parity

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

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

Naturality

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





Partial-Wave Decomposition

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

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

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

⇒ **Extended Maximum-Likelihood Fit in Mass Bins**



Extended Maximum-Likelihood Fit

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

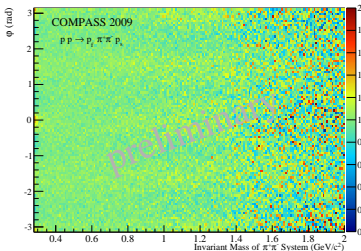
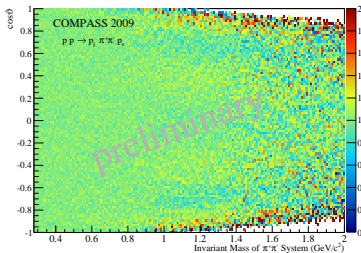
Maximize likelihood function

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

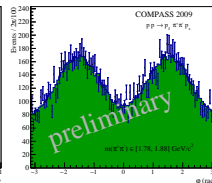
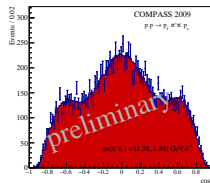
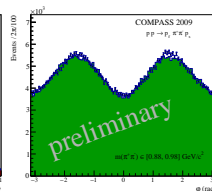
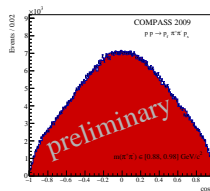
- by choosing T_{LM}^{ε} such that the intensity fits the observed N events
- **Normalisation integral** evaluated by a phase-space Monte Carlo sample
- with the **acceptance** $\eta(\vartheta, \varphi)$



Evaluation of the Fit Quality

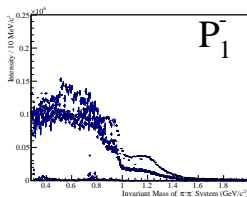
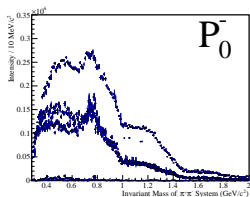
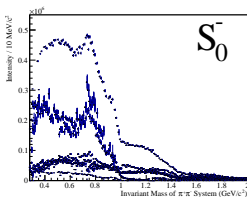


$$I(\vartheta, \varphi) = \sum_{\varepsilon} \left| \sum_{LM} T_{LM}^{\varepsilon} Y_M^{\varepsilon L}(\vartheta, \varphi) \right|^2$$

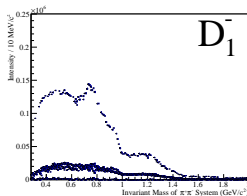
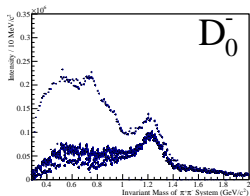




Ambiguities in the $\pi^+\pi^-$ System



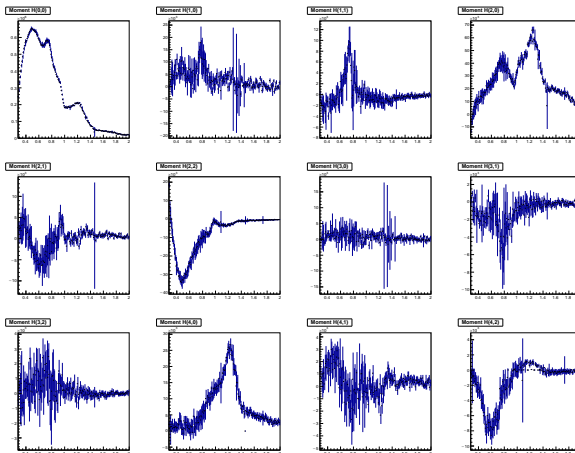
COMPASS 2009

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

Intensity distributions for 30 fit attempts with random starting values



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



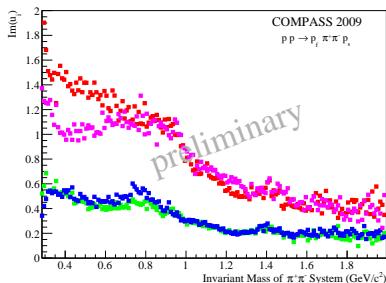
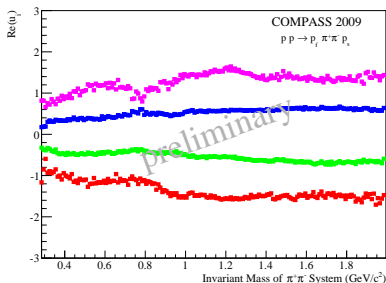
Unique decomposition into moments



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

- 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]

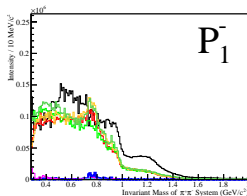
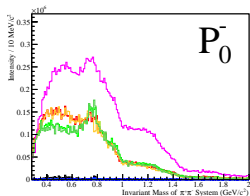
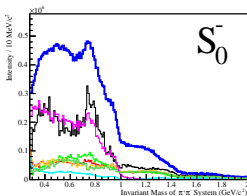


- Real (left) and imaginary (right) part of polynomial roots
- Well separated, imaginary parts do not cross the real axis

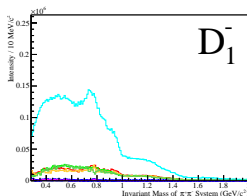
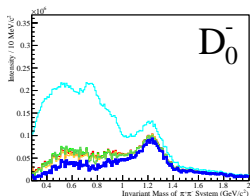
⇒ Solutions can be uniquely identified and linked from mass bin to mass bin



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



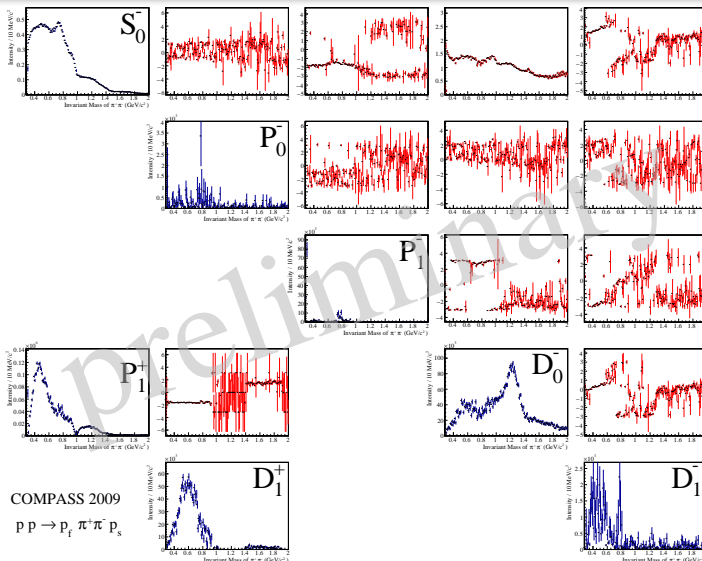
COMPASS 2009

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

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



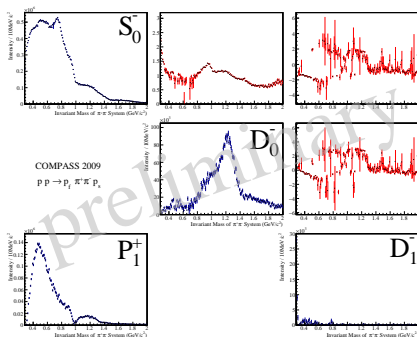
$\pi^+\pi^-$ System: Physical Solution





$\pi\pi$ System: Physical Solution

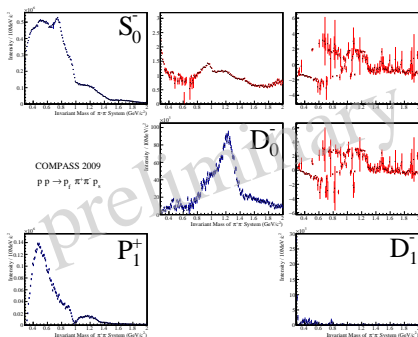
$$\pi^+\pi^-$$



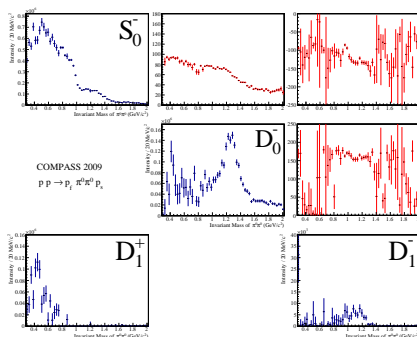


$\pi\pi$ System: Physical Solution

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



$$\pi^0\pi^0$$





Ambiguities in the $\pi\pi$ Systems

$\pi^+\pi^-$ 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

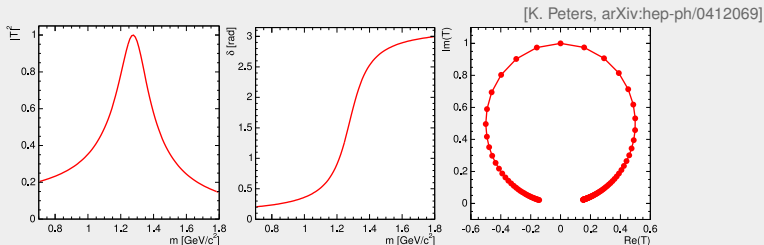
- Identical particles, only even waves allowed
- Reduces number of ambiguities to 2

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



Resonance: Relativistic Breit-Wigner Function



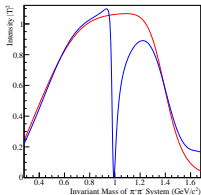
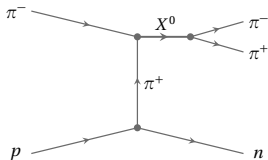
Non-Resonant Contribution

Phase-space with exponential damping (phenomenological)

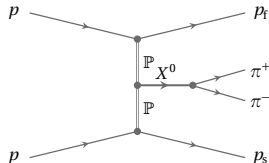
- Sum with complex-valued coefficient (**strength + phase**) for each component



Unitarity Constraints

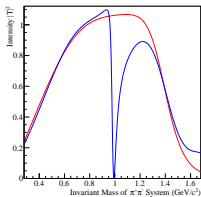
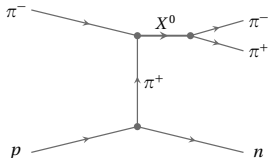


- **Watson theorem** relates phase of prod. processes
- M solution from
Au, Morgan, Pennington
Phys. Rev. D 35 (1987) 1633
- $\pi\pi$ ampl. vanishes near threshold (Adler zero)



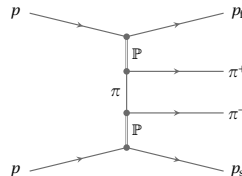


Unitarity Constraints



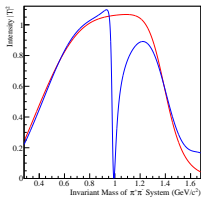
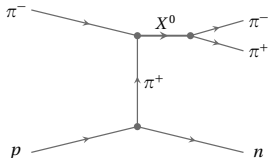
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$$\mathbb{T}_{\text{red}} = \frac{\mathbb{T}}{s - s_0}$$



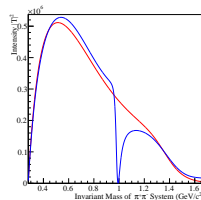
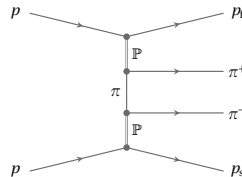


Unitarity Constraints



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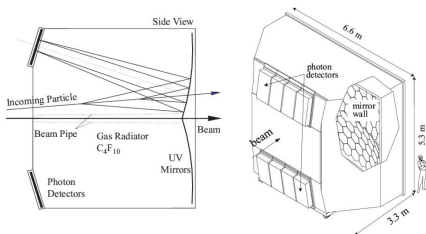
$$\mathbb{T}_{\text{red}} = \frac{\mathbb{T}}{s - s_0}$$



- **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

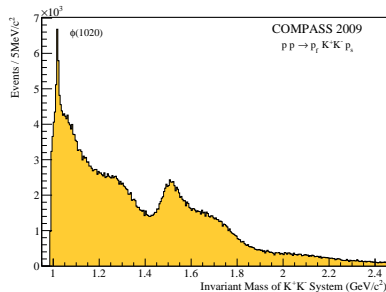
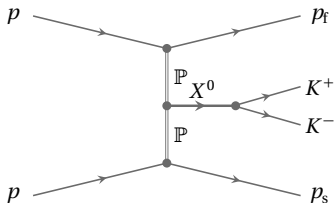


Selection of Kaons



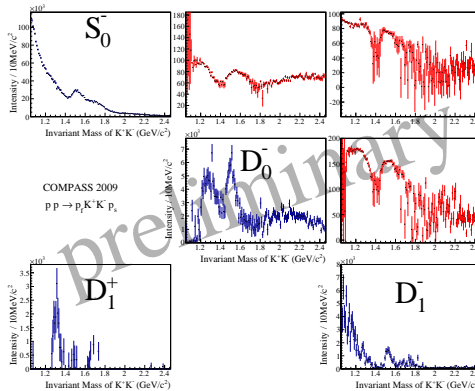
COMPASS RICH Detector

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





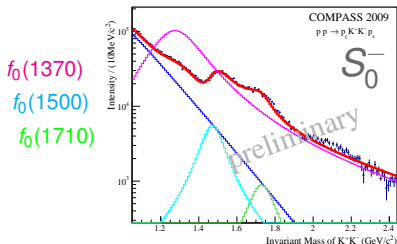
Fit to the K^+K^- System



- 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



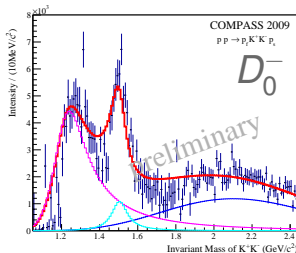
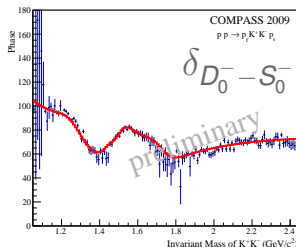
Mass-Dependence of $K^+ K^-$



BW contributions
non-resonant contribution
coherent sum

Interference of S and D

Distinguishes resonances from
non-resonant contribution





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 ambiguities resolved
 - Interference of S - and D -waves helps to identify resonant components
- **Consistent picture of scalar sector** through combination of different approaches

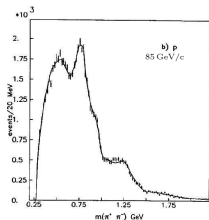


Backup Slides

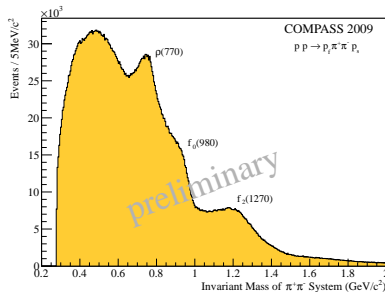


\sqrt{s} -Dependence

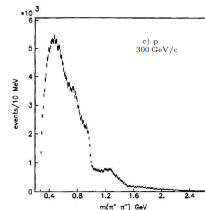
T.A. Armstrong et al. [Z. Phys. C51 (1991)]



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



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

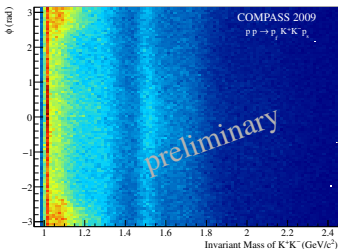
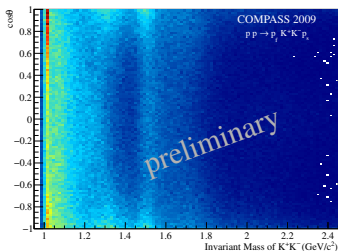


$$\sqrt{s} = 23.7 \text{ GeV}/c^2$$

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



PWA of K^+K^- System



$$X \rightarrow K^+K^-$$

- **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

