Partial-Wave Analysis of Centrally Produced Two-Pseudoscalar Final States in $pp$ Reactions at COMPASS

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Introduction

Partial-Wave Analysis in Mass Bins

Mass-Dependent Parametrisation

Conclusion and Outlook
The COMPASS Experiment

Multi-Purpose Setup

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

Data Set

- 190 GeV/c proton beam
- Liquid H₂ target
- Trigger on recoil proton
Central Exclusive Production

Proton beam impinging on liquid hydrogen target

Double-Pomeron Exchange as glue-rich environment

⇒ Production of non-\(q\bar{q}\)-mesons (Glue Balls, Hybrids) at central rapidities
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- Decay into two-pseudoscalar final state ($\pi^+\pi^−$, $\pi^0\pi^0$, $K^+K^−$, $\eta\eta$, ..)
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Proton beam impinging on liquid hydrogen target
Double-Pomeron Exchange as glue-rich environment
⇒ Production of non-\textit{q}\bar{\textit{q}}-mesons (Glue Balls, Hybrids) at central rapidities
Decay into two-pseudoscalar final state (\pi^+\pi^-, \pi^0\pi^0, K^+K^-, \eta\eta, ..)
Rapidity gap between \textit{p}_s and the central system \textit{X} introduced by the principal trigger
\( \sqrt{s} = 12.7 \text{ GeV}/c^2 \)

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

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

- 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

T.A. Armstrong et al. [Z. Phys. C51 (1991)]
Two-Body Partial-Wave Analysis in Mass Bins
**Partial-Wave Analysis**

**Assumption:** collision of two space-like exchange particles ($P, R$)

Decay fully described by $M(\pi^+\pi^-)$, $\cos(\theta)$ and $\phi$
**Partial-Wave Analysis**

**Assumption:** collision of two space-like exchange particles ($P, R$)

- Decay fully described by $M(\pi^+\pi^-), \cos(\theta)$ and $\phi$
- Fit complex production amplitudes in mass bins to match spin contributions and interference pattern

\[ X \rightarrow \pi^+\pi^- \]

\[ \ell = 0 \]

\[ \ell = 1 \]

\[ \ell = 2 \]

\[ m = 0 \]

\[ m = 1 \]

\[ m = 2 \]

\[ \cos(m\phi) \ P_\ell^m(\cos \theta) \]
Partial-Wave Decomposition

Expand intensity $I(\theta, \phi)$ in terms of partial-waves for narrow mass bins:

$$I(\theta, \phi) = \sum_\varepsilon \left| \sum_{\ell m} T_{\varepsilon \ell m} Y^\varepsilon_{\ell m}(\theta, \phi) \right|^2$$

- Complex transition amplitudes $T_{\varepsilon \ell m}$, no assumption on mass-dependence
- Spectroscopic notation: $\ell^\varepsilon_m$
- Significant contributions only from $\ell = S, P, D, m \leq 1$

$\Rightarrow$ Maximum Likelihood Fit in Mass Bins

$$\ln L = \sum_{i=1}^N \ln I(\theta_i, \phi_i) - \int d\Omega I(\theta, \phi) \eta(\theta, \phi)$$

- the normalisation integral is evaluated by a phase-space Monte Carlo sample
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

⇒ 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!

A. Austregesilo (aaust@cern.ch) — PWA of Centrally Produced Two-Pseudoscalar System at COMPASS
Mass-Dependent Parametrisation of $K^+K^-$-System
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
**S₀-Wave**
- Relativistic Breit-Wigner parametrisation: \( f_0(1370), f_0(1500), f_0(1710) \)

**D₀-Wave**
- Relativistic Breit-Wigner parametrisation: \( f_2(1270), f'_2(1525) \)

**Non-Resonant Contribution**
- Phase space factor \( q^\ell \cdot \sqrt{\frac{q}{m^2}} \) with breakup momentum \( q \)
- Exponential background \( \exp(-\alpha q - \beta q^2) \) with fit parameters \( \alpha, \beta \)
**Parametrisation**

**S\textsubscript{0}-Wave**
- Relativistic Breit-Wigner parametrisation: \( f_0(1370), f_0(1500), f_0(1710) \)

**D\textsubscript{0}-Wave**
- Relativistic Breit-Wigner parametrisation: \( f_2(1270), f'_2(1525) \)

**Non-Resonant Contribution**
- Phase space factor \( q^\ell \cdot \sqrt{\frac{q}{m^2}} \) with breakup momentum \( q \)
- Exponential background \( \exp(-\alpha q - \beta q^2) \) with fit parameters \( \alpha, \beta \)

**In total: 27 parameters**
(to fit 438 points)
Intensities and Phase

- **Intensity of S0 wave**
  - COMPASS 2009
  - $pp \rightarrow pK^+K^- p_s$

- **arg($S0 / D0$)**
  - COMPASS 2009
  - $pp \rightarrow pK^+K^- p_s$

- **Intensity of D0 wave**
  - COMPASS 2009
  - $pp \rightarrow pK^+K^- p_s$

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

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Intensities and Phase

- BW contributions
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Summary

- Order-of-magnitude **larger sample** than previous experiments (for charged channels)
- **Acceptance corrected PWA** with unprecedented precision
- Simplistic **mass-dependent parametrisation** can describe the $K^+K^-$ fit
- Breit-Wigner parameters mostly consistent with **PDG values**
Conclusion

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Outlook
- **Unitary models** ($K$-matrix, ..)
- **Combined fit** of all available channels ($\pi^+\pi^-, K^+K^-, K_SK_S, \pi^0\pi^0, \eta\eta, ...$)
- Extract **resonance parameters** in the scalar sector
- Information about the **composition** of supernumerous resonances
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Thank you for your attention!
Kinematic Selection

- $M(p_π) > 1.5 \text{ GeV}/c^2$
Kinematic Selection

- $x_F(p_f) > 0.9$

COMPASS 2009

$p p \rightarrow p_1^+ p_1^- p_f$

$M(p\pi) > 1.5/2.0$ GeV/$c^2$

Entries

$p_f$

$p_s$

$\pi^+\pi^-$

Feynman $x_f$

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Kinematic Selection

\[ \frac{M}{p} > 1.5 \text{ GeV} / c^2 \]

\[ x \cdot F(p_f) > .9 \]

\[ |y(\pi)| < 1 \]

\[ Z_A = \ln \left( \frac{s}{s_1} \right) \]

\[ Z_B = \ln \left( \frac{s}{s_2} \right) \]


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Kinematic Selection

\[ p \rightarrow t_1 \rightarrow p_{\text{fast}} \]

\[ p_{\text{target}} \rightarrow t_2 \rightarrow p_{\text{slow}} \]

- \( |y(\pi)| < 1 \)
- DD: double diffraction (= central production)
- DSRE: diffractive single resonance excitation

P. Lebiedowicz and A. Szczurek, [Phys. Rev. D 81 (2010)]
**Kinematic Selection**

- $M(p\pi) > 1.5 \text{ GeV}/c^2$
- $x_F(p_f) > 0.9$
- $Z_{A,B} > 2.3$
- $|y(\pi)| < 1$
- ...

**Large overlap of the cuts, weak dependence of the results**

(CEP sample by all definitions, but not pure DPE!)
Glueball Filter


\[ dP_T \leq 0.2 \text{ GeV/c} \]  \[ 0.2 \leq dP_T < 0.5 \text{ GeV/c} \]  \[ dP_T \geq 0.5 \text{ GeV/c} \]

- \( dP_T = |\vec{p}_{T_1} - \vec{p}_{T_2}| \) in \( pp \) centre-of-mass
- Only scalar signals remain for small \( dP_T \)
Maximise likelihood function

\[ \ln L = \sum_{i=1}^{N} \ln I(\theta_i, \phi_i) - \int d\Omega I(\theta, \phi) \eta(\theta, \phi) \]

- by choosing \( T_{\epsilon \ell m} \) such that the intensity fits the observed \( N \) events
- the normalisation integral is evaluated by a phase-space Monte Carlo sample
- with the acceptance \( \eta(\theta, \phi) \)
Through variable transformation \( u = \tan(\theta/2) \), angular distribution for this wave set can be written as a function of \( |G(u)|^2 \) with

\[
G(u) = a_4 u^4 - a_3 u^3 + a_2 u^2 - a_1 u + a_0
\]

where coefficients \( a_i \) are functions of amplitudes.

- or with in terms of 4 complex roots \( u_i \) ('Barrelet zeros')

\[
G(u) = a_4 (u - u_1)(u - u_2)(u - u_3)(u - u_4)
\]

- Laguerre's method to find polynomial roots numerically

- Complex conjugation of one/more of these roots result in the same measured angular distribution

\[\rightarrow 8 \text{ different ambiguous solutions} \] (same likelihood per definition!)

Techniques of amplitude analysis for two-pseudoscalar systems
Evaluation of Fit with Weighted MC

Blue: data, red: weighted MC

Preliminary

COMPASS 2009

pp → pK+K−p

pp → pK+K−p

Blue: data, red: weighted MC
Evaluation of Fit with Weighted MC

Blue: data, red: weighted MC
Blue: data, red: weighted MC
Blue: data, red: weighted MC

Peaking distribution for $|\cos(\theta)| > 0.9$ for masses above 2 GeV/$c^2$ cannot be described by fit (limited wave set)

Signature of diffractive dissociation background