Diffractive and Coulomb Dissociation of pions into three charged pions at low momentum transfer at COMPASS

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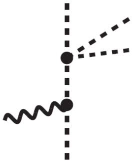
Outline

Meson Spectroscopy at Low Momentum Transfer

Motivation for Analysis

Meson spectrum at low momentum transfer

- Two production mechanisms
- $a_2(1320)$ resonance in detail:
  - in photon-pion process $\longrightarrow \Gamma(a_2(1320) \longrightarrow \pi\gamma)$
  - in diffractive (pomeron) production
  - interference effect
- More radiative couplings (heavier mesons?)
- Test of ChPT at low masses (chiral diagrams)



chiral contribution to 3π production in $\pi\gamma$ scattering

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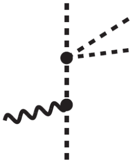


chiral contribution to 3π production in $\pi\gamma$ scattering

Challenges and Opportunities in the light (u,d) Quark Sector

- High density of states; broad, overlapping states
- Exploit interference effects $\rightarrow$ phase motion
- Requires high statistics, complete PS coverage

$\rightarrow$ **COMPASS can contribute significantly in the low mass region**

COMPASS 2004 Pilot Hadron Run

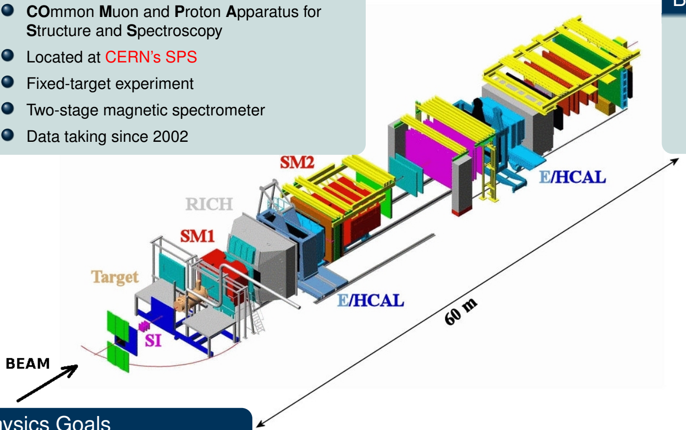
Experimental Setup

Overview

- **CO**mmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy
- Located at CERN's SPS
- Fixed-target experiment
- Two-stage magnetic spectrometer
- Data taking since 2002

Second./Tert. SPS Beams

- Muons: $4{\cdot}10^{7}s^{-1}$
- Hadrons: up to $2{\cdot}10^{7}s^{-1}$
- E: 100-250 GeV



Physics Goals

- Nucleon spin structure
- Hadron spectroscopy

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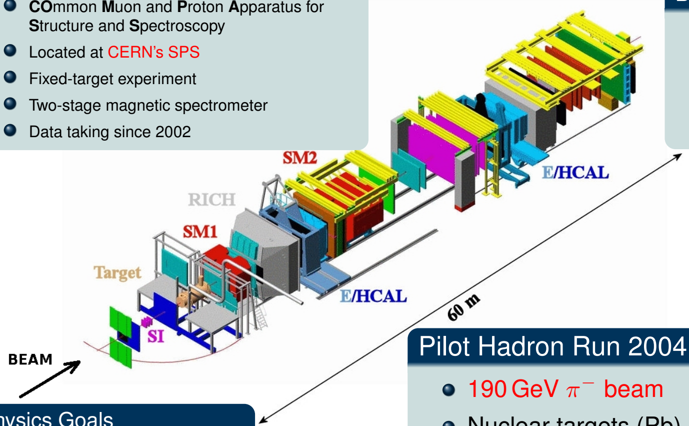


Physics Goals

- Nucleon spin structure
- Hadron spectroscopy

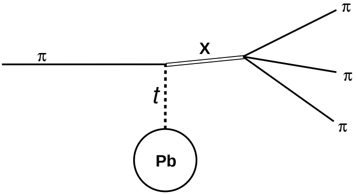
Pilot Hadron Run 2004

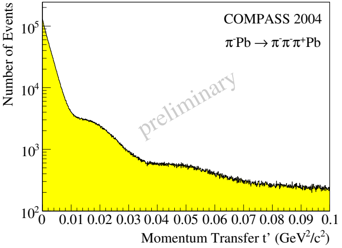
- 190 GeV π^- beam
- Nuclear targets (Pb)
- Tracking: Silicons for vertexing
- Trigger: Multiplicity trigger, ECAL trigger

Diffractive and Coulomb Production of Mesons

- Diffraction: target particle remains intact
  $\rightarrow$ low momentum transfer
  $I = 0$ Reggeon t-channel exchange
- Primakoff: photon exchange
  contribution at smallest momentum transfer

- Dissociation: beam pion is excited to a resonance X^-, which subsequently decays
  $\Rightarrow$ e. g. $\pi^- Pb \rightarrow X^- Pb \rightarrow \pi^- \pi^- \pi^+ Pb$





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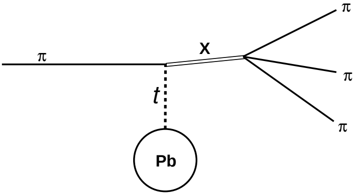

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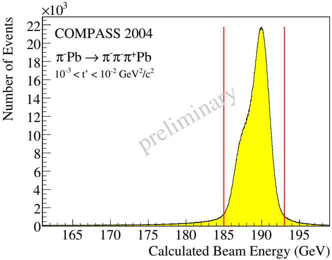
- Exclusive 3π final state events
- COMPASS 2004 (few days of data taking):
  - $\sim$ 4 000 000 3π events

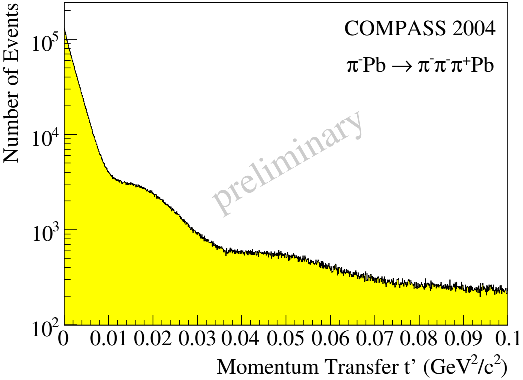


3π Data Sample (2004)

Momentum Transfer

Momentum transfer to target:

$$-t = -(p_{\text{beam}} - p_{(\pi^-\pi^-\pi^+)})^2 \quad \Rightarrow t' = |t| - |t|_{\text{min}}$$



with

$$|t|_{\text{min}} = \frac{(m_{3\pi}^2 - m_\pi^2)^2}{4|\vec{p}_{\text{beam}}|_{\text{lab}}^2}$$

Diffraction pattern:
Pb nucleus acts like "black disc" in optics

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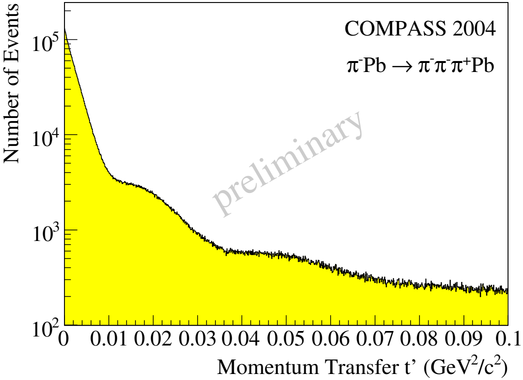

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Diffraction pattern: Pb nucleus acts like "black disc" in optics

- "Low t'": $10^{-3}\,(\text{GeV}/c)^2 < t' < 10^{-2}\,(\text{GeV}/c)^2$ $\sim$ 2 000 000 events
- "Primakoff region": $t' < 10^{-3}\,(\text{GeV}/c)^2$ $\sim$ 1 000 000 events

Primakoff contribution at $t' < 10^{-3}\,(\mathrm{GeV}/c)^2$

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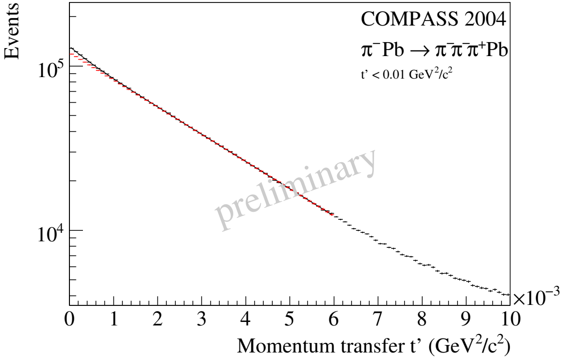
Primakoff: $\sigma(t') \propto e^{-b_{\mathrm{Prim}} t'}$, $b_{\mathrm{Prim}} \approx 2000\,(\mathrm{GeV}/c)^{-2}$ (mainly resolution)

Diffractive: $\sigma(t') \propto e^{-b_{\mathrm{diff}} t'}$, $b_{\mathrm{diff}} \approx 400\,(\mathrm{GeV}/c)^{-2}$ for lead target

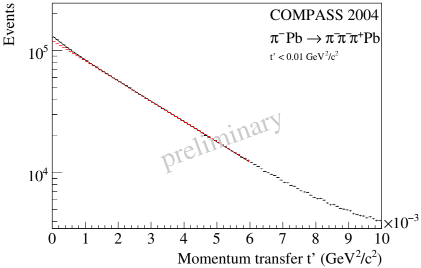


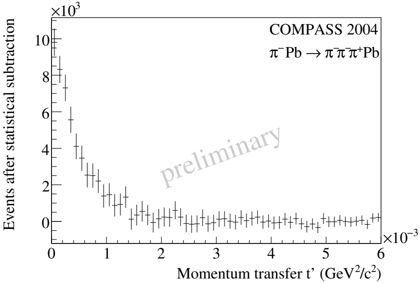
(Mass) spectrum of this Primakoff contribution?

$\Rightarrow$ Statistical subtraction of diffractive background (for bins of $m_{3\pi}$)

Basic features of the statistical subtraction

- Fit of t' spectrum with sum of both exponentials for $0 < t' < 0.006\,(\mathrm{GeV}/c)^2$ $(0.5 < m_{3\pi} < 2.5\,\mathrm{GeV}/c^2)$
- Subtraction of "diffractive" exponent from t' spectrum



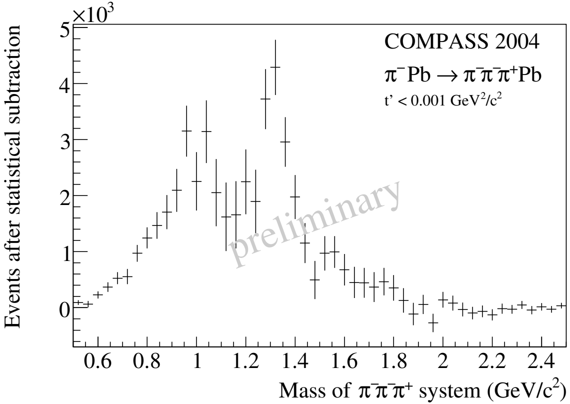


- Fit and subtraction in 3π mass bins:
  - $b_{\mathrm{Prim}} = 2050\,(\mathrm{GeV}/c)^{-2}$ fixed
  - b_{diff} as fit parameter

Primakoff contribution

Mass spectrum from statistical subtraction

- Statistical subtraction separately in 40 MeV$/c^2$ mass bins
- Integrate Primakoff contribution of the t' spectra for $t' < 10^{-3}\,(\mathrm{GeV}/c)^2$



Mass spectrum from statistical subtraction

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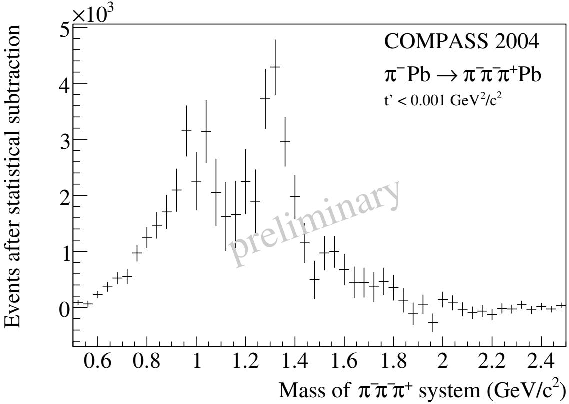


Selex, Phys. Lett. B 521(2001), 171-180

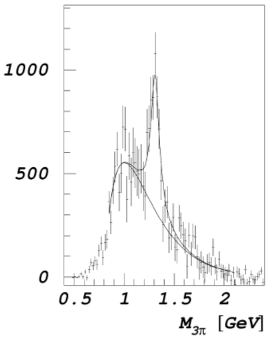
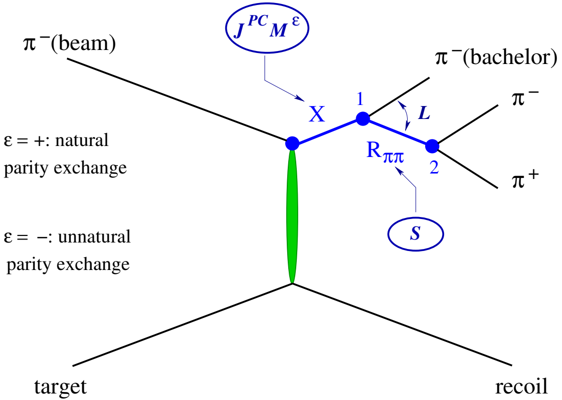


Fig. 3. $M_{3\pi}$ mass distribution for the Cu target after subtraction of diffractive background. The curve shows fit with a sum of pure Coulomb contribution and smooth background.

Partial Wave Analysis Formalism

Isobar Model

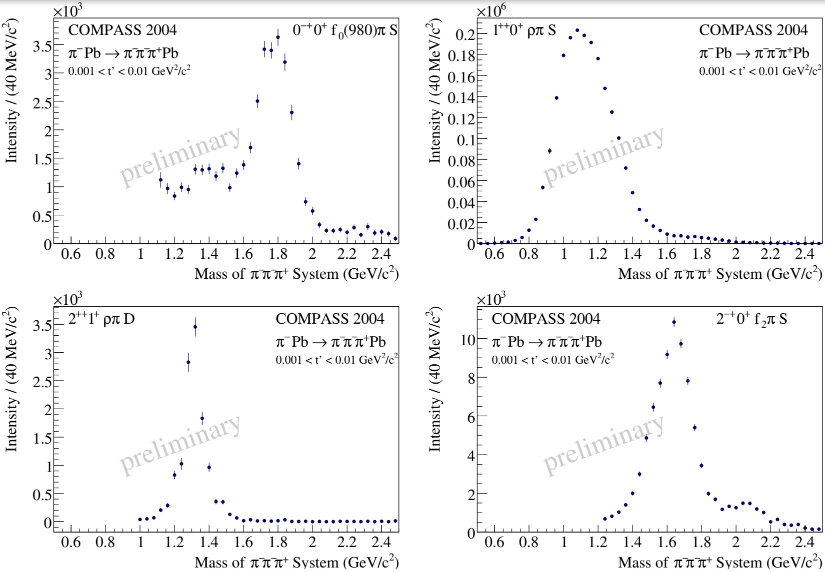


- Isobar model: Intermediate 2-particle decays
- Partial wave in reflectivity basis: $J^{PC}M^{\epsilon}[isobar]L$

- Mass-independent PWA (40 MeV/c^2 mass bins): 38 waves
  Fit of angular dependence of partial waves, interferences
- Mass-dependent χ^2-fit

PWA of data with low t'

Intensity of selected waves: $0^{-+}0^{+} f_0(980)\pi S$, $1^{++}0^{+} \rho\pi S$, $2^{++}1^{+} \rho\pi D$, $2^{-+}0^{+} f_2(1270)\pi S$



Spin Totals for $t' < 10^{-3}\,(\mathrm{GeV}/c)^2$

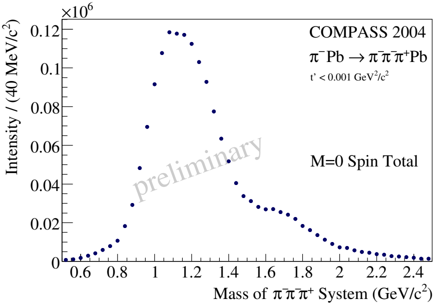
"Spin Totals": Sum of all contributions for given M (i.e. z-projection of J)

t'-dependent amplitudes:

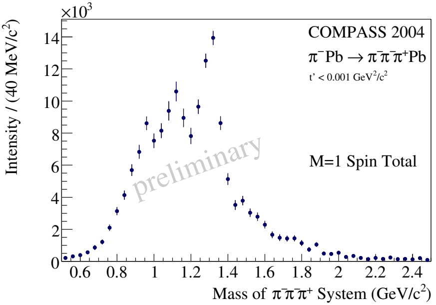
Primakoff production: M=1: $\sigma(t') \propto e^{-b_{\mathrm{Prim}} t'}$ $\longrightarrow$ arises at $t' \approx 0$ (resoluted shape!)

Diffractive production: M=0: $\sigma(t') \propto e^{-b_{\mathrm{diff}}(m) t'}$

M=1: $\sigma(t') \propto t' e^{-b_{\mathrm{diff}}(m) t'}$ $\longrightarrow$ vanishes for $t' \approx 0$

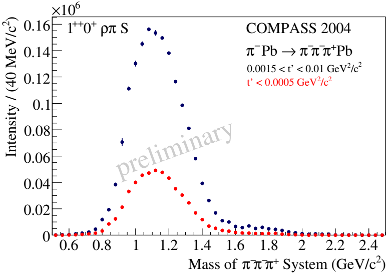


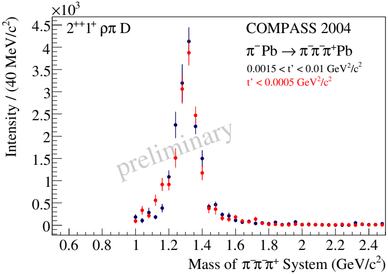
M=0

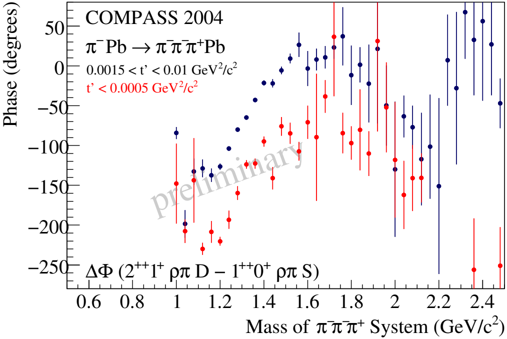


M=1

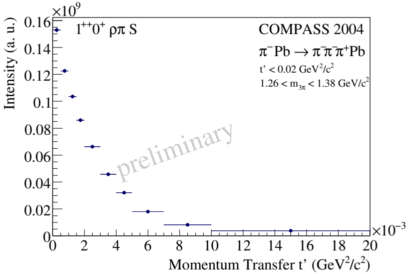
Production Phase $a_2 - a_1$ for separated t' regions

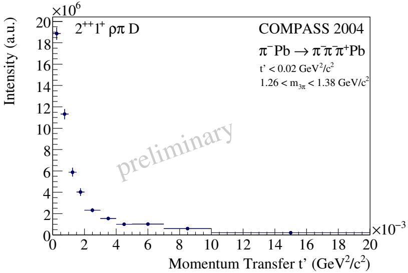


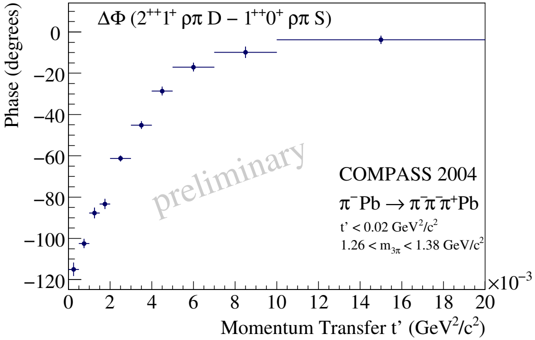




Phase $a_2 - a_1$ in detail: t' dependence







Theory: Phase a_2(strong+Coulomb)-a_1(strong)

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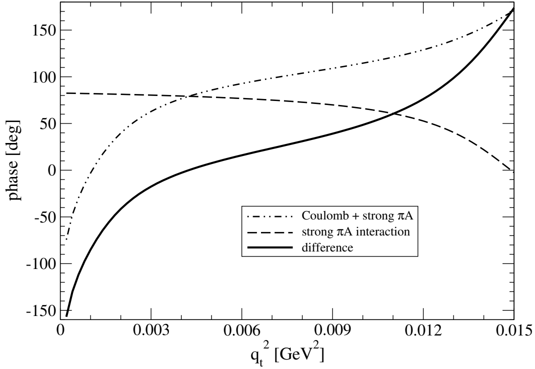

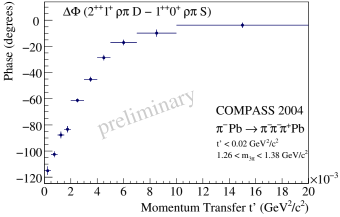

Glauber modell

G. Fäldt and U. Tengblad, Phys. Rev. C79, 014607 (2009)

Plot: N. Kaiser (TU München)

⇒ indicates confirmation of interference Coulumb-interaction - strong interaction
⇒ detailed studies of the nature of resonances

Summary and Outlook

- COMPASS 2004 hadron run (few days) using a 190 GeV π^- beam
- $\pi^- Pb \rightarrow \pi^-\pi^-\pi^+ Pb$ at (very) low momentum transfer
- Extraction of photo-produced contribution
- PWA in mass bins and t' bins
- Production phase of $a_2(1320)$ dependent on t' shows interference of contributions from Coulomb and strong interaction

Further Analysis of 3π data at low momentum transfer:

- Mass-dependent PWA:
  Proper incorporation of Deck effect,
  Test of chiral diagrams in threshold mass region
- Comparison with hydrogen, lead and nickel data (2009, extended spectrometer)

BACKUP: 3π Data Sample (2004)

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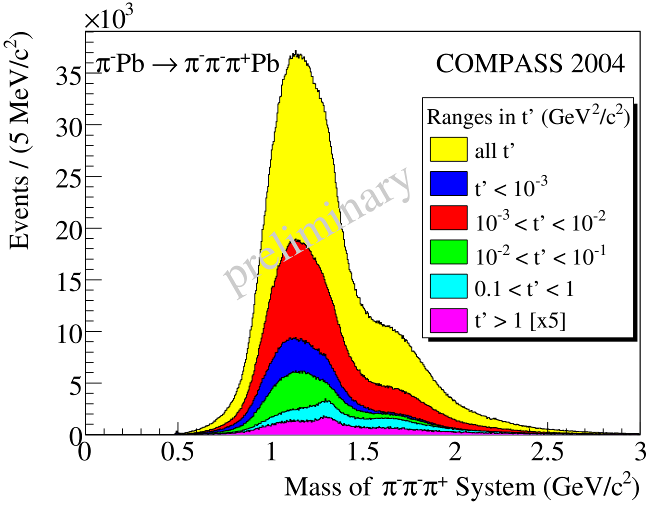
$\pi^-\pi^-\pi^+$ mass distribution

Different t' ranges:



BACKUP: Partial Wave Analysis Formalism

- Mass-independent PWA (narrow mass bins):

$$\sigma_{\mathrm{indep}}(\tau, m, t') = \sum_{\epsilon=\pm 1} \sum_{r=1}^{N_r} \left| \sum_i T_{ir}^{\epsilon} f_i^{\epsilon}(t') \psi_i^{\epsilon}(\tau, m) \Big/ \sqrt{\int |f_i^{\epsilon}(t')|^2 \mathrm{d}t'} \sqrt{\int |\psi_i^{\epsilon}(\tau', m)|^2 \mathrm{d}\tau'} \right|^2$$

  - Production strenght assumed constant in single bins
  - Decay amplitudes $\psi_i^{\epsilon}(\tau, m)$, with t' dependence $f_i^{\epsilon}(t')$
  - Production amplitudes T_{ir}^{ϵ} $\longrightarrow$ Extended log-likelihood fit
  - Acceptance corrections included

- Spin-density matrix: $\rho_{ij}^{\epsilon} = \sum_r T_{ir}^{\epsilon} T_{jr}^{\epsilon *}$

$\longrightarrow$ Physical parameters:

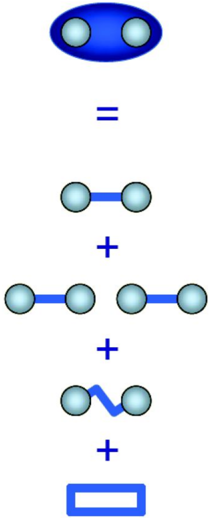
$$\mathrm{Intens}_i^{\epsilon} = \rho_{ii}^{\epsilon},$$

relative phase Φ_{ij}^{e}

$$\mathrm{Coh}\ _{i,j}^{\epsilon} = \sqrt{(\ \mathrm{Re}\ \rho_{ij}^{\epsilon})^2 + (\ \mathrm{Im}\ \rho_{ij}^{\epsilon})^2} \Big/ \sqrt{\rho_{ii}^{\epsilon} \rho_{jj}^{\epsilon}}$$

- Mass-dependent χ^2-fit (not presented here):
  - X parameterized by Breit-Wigner (BW) functions
  - Background can be added

BACKUP: Mesons and Spin-Exotic States



Constituent Quark Model

- Color-neutral $q\bar{q}$ systems
- Quantum numbers $I^G J^{PC}$
- $P = (-1)^{L+1}$ $\quad C = (-1)^{L+S}$ $\quad G = (-1)^{I+L+S}$
- J^{PC} Multiplets: $0^{++}, 0^{-+}, 1^{--}, 1^{+-}, 1^{++}, 2^{++}, \ldots$
- Forbidden: $0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$

QCD: Additional color-neutral objects

- Tetraquarks $(q\bar{q})(q\bar{q})$
- Hybrids $(q\bar{q})g$ $\quad (\pi_1(1400), \pi_1(1600))$
- Glueballs gg $\quad (f_0(1500))$

Spin Exotic States

- J^{PC} forbidden $\Rightarrow$ cannot be a $q\bar{q}$ state
- No mixing with quark model states

$\Rightarrow$ **COMPASS**