The Light-Meson Spectra from COMPASS and The Outlook for ALICE

S. U. CHUNG [†]
for the
COMPASS [‡] and ALICE [α] Collaborations

based on a talk by A. Austregesilo, TU/München,
at the LHCb Workshop, Rio de Janeiro, Brazil (July 2015)

PhD Thesis by A. Austregesilo, TU/München,
CERN-THESIS-2014-190 (21/10/2014)

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Outline

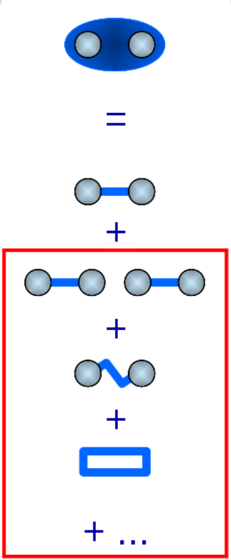
Light-Meson Spectroscopy

Partial-wave Analysis

COMPASS Summary

ALICE

Light-Meson Spectroscopy



$(q\bar{q})_0$

$(q\bar{q})(q\bar{q})$

$(q\bar{q})_8 g$

Hybrid

gg

Glueball

Constituent Quark Model (CQM)

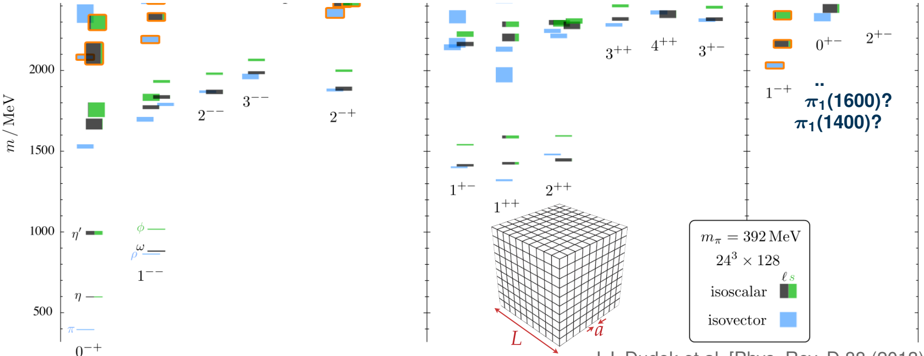
- Bound state of $q\bar{q}$
- Quantum numbers: $I^G(J^{PC})$

Light Meson Spectroscopy

- Many missing and disputed states
- Broad and overlapping resonances
- **Exotic quantum numbers (0^{--}, 0^{+-}, 1^{-+}, ...) forbidden by NR QM**

$\Rightarrow$ Study spectrum and properties (width, decay, ...) of mesons

Light Mesons on the Lattice



J.J. Dudek et al. [Phys. Rev. D 88 (2013)]

- Tremendous progress in recent years
- Excited states, spin-identified spectra
- Resonance parameters and decay modes not (yet) accessible
- Experimental results need to reach equivalent precision

Central Production

$p\,p \longrightarrow p_{\text{fast}}\,X\,p_{\text{slow}}$

- 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 ($\boldsymbol{\pi}^+\boldsymbol{\pi}^-$, $\pi^0\pi^0$, K^+K^-, $\eta\,\eta$, ..)
- 50×10^6 $\pi^+\pi^-$ events; 1.6×10^6 $\pi^0\pi^0$ events; 0.4×10^6 K^+K^- events

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**: ALICE (limited data so far)

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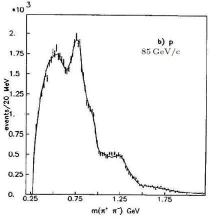
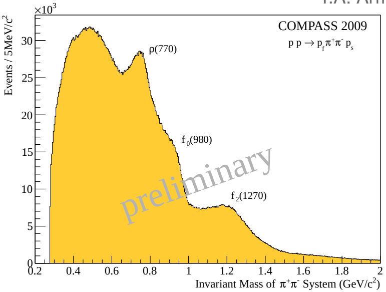
$\sqrt{s}$-Dependence

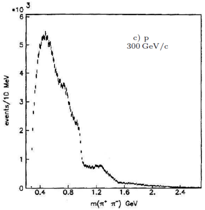
Study of the centrally produced $\pi\pi$ and $K\bar{K}$ systems at 85 and 300 GeV/c
T.A. Armstrong et al. [Z. Phys. C51 (1991)]



$\sqrt{s} = 12.7\,\text{GeV}/c^2$
(WA76)



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



$\sqrt{s} = 23.7\,\text{GeV}/c^2$
(WA91)

- 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

Introduction to Ambiguities:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}z} = \left| f_2(z) \right|^2 \quad \text{for} \quad \text{a complex amplitude } f_2(z)$$

where

$$f_2(z) = a\,z^2 + b\,z + c$$
$$= a(x - x_1)\,(x - x_2), \quad x_1,\, x_2 = \text{complex}$$

Note we obtain different functions for

$$(x_1,\, x_2)$$

Ambiguities

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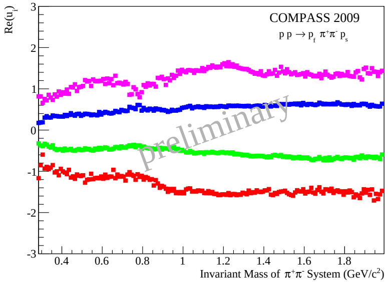
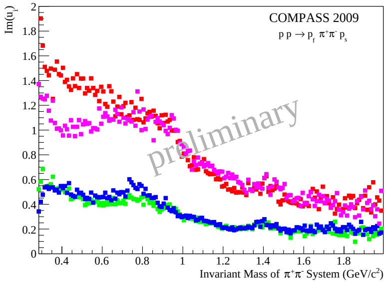
- 8 mathematically ambiguous solutions result in the same angular distribution
- Analytical computation via method of **Barrelet Zeros**

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

⇒ 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)

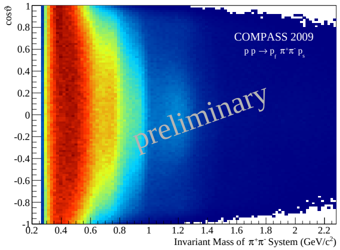
$\pi^0\pi^0$ System

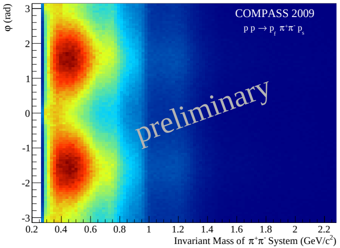
- Identical particles, only even waves allowed
- Reduces number of ambiguities to 2

Combination of $\pi\pi$ Systems

- Consistent picture of the reaction, measured with different parts of experimental setup

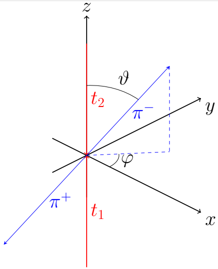
Partial-Wave Analysis





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

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



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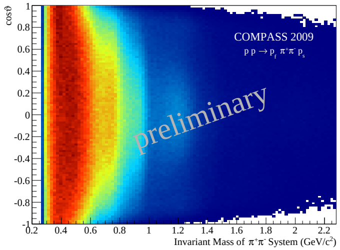

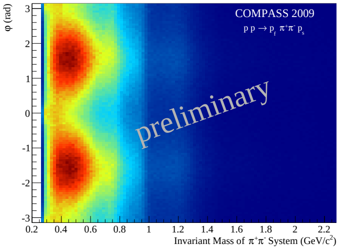

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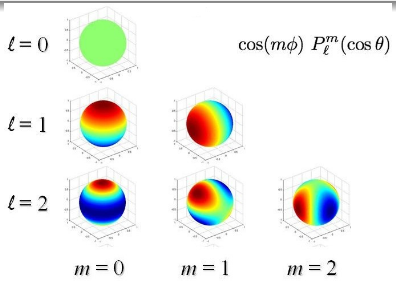
- Decompose into complex-valued amplitudes (spherical harmonics) with definite spin and parity



Partial-Wave Decomposition

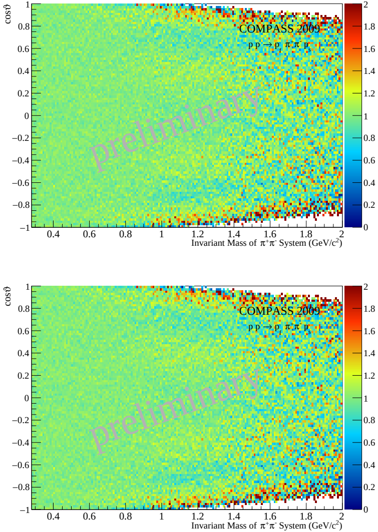
Expand intensity $I(\vartheta, \varphi)$ into partial-wave amplitudes in narrow mass bins ($10\,\mathrm{MeV}/c^2$):

$$I(\vartheta, \varphi) = \sum \left| \sum_{LM} T_{LM} Y^L_M(\vartheta, \varphi) \right|^2$$

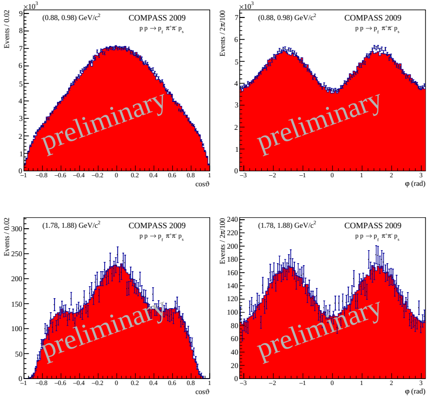
- Quantum-mechanical interference between amplitudes with same $|\mathrm{i}\rangle$ and $|\mathrm{f}\rangle$
- **Complex-valued transition amplitudes T_{LM}**, no assumption on mass-dependence
- Significant contributions only from $L = S, P, D$ and $M \leq 1$

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

Evaluation of the Fit Quality



$$I(\vartheta, \varphi) = \sum \left| \sum_{LM} T_{LM} Y^L_M(\vartheta, \varphi) \right|^2$$



Fit to the $\pi\pi$ System: Physical Solution

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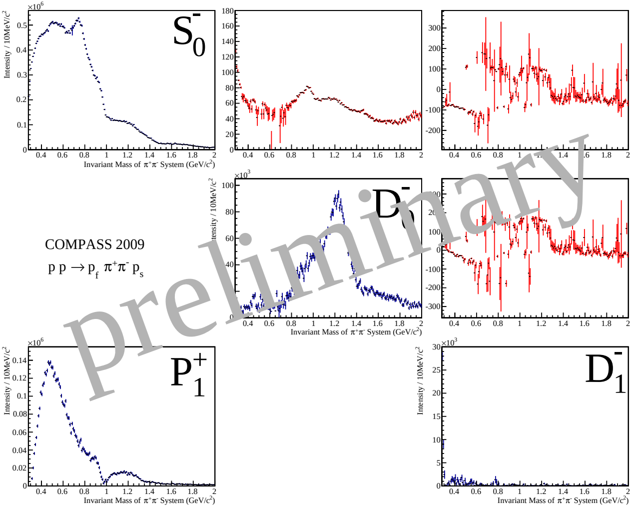
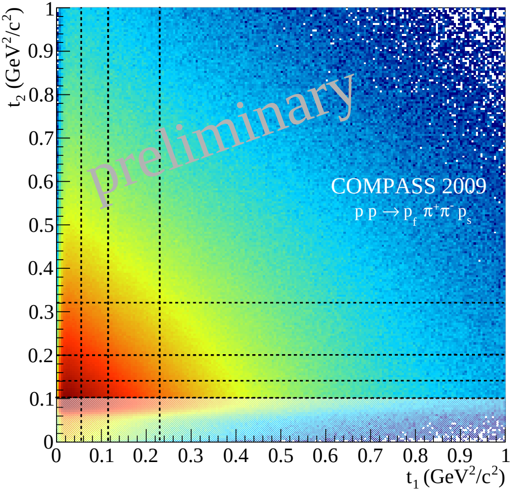
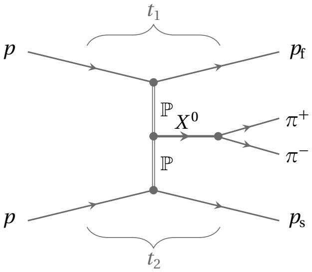


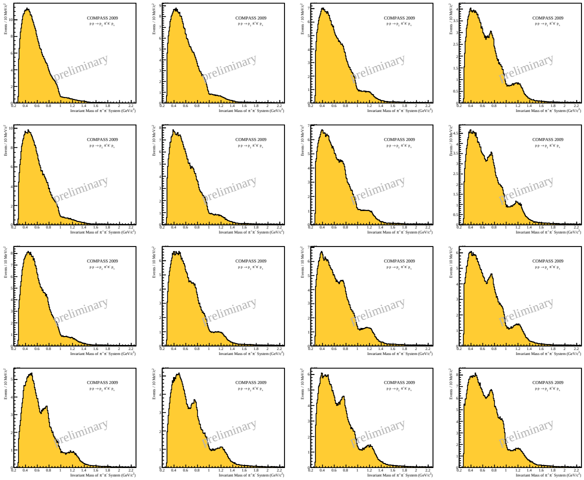
t-Dependent Analysis

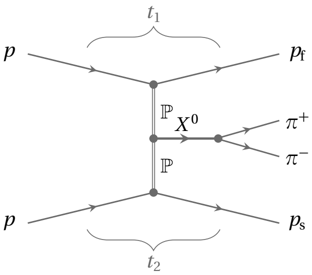




- Disregarded $t_2 < 0.1\ \text{GeV}^2/c^2$ due to trigger inefficiency
- 4×4 bins with approximately equal #events ($\approx 3 \cdot 10^5$)
- Not symmetric in $t_{1/2}$!

t-Dependent Analysis





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Fit to the $\pi\pi$ System:

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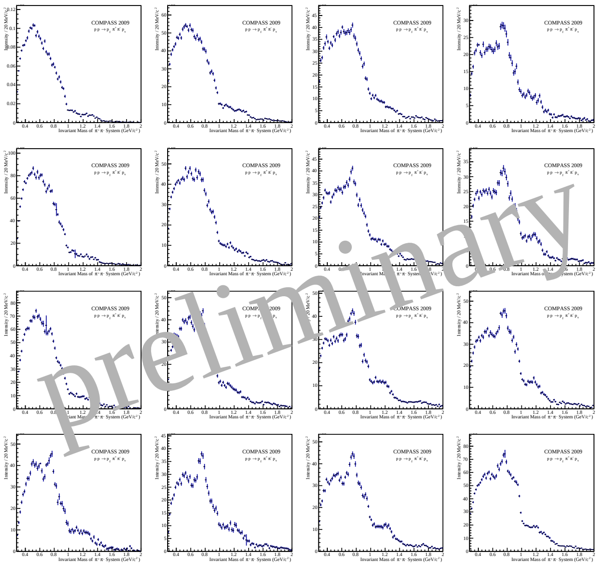
$t_1 \Rightarrow$

t_2 $\Downarrow$

S_0^-



Fit to the $\pi\pi$ System:

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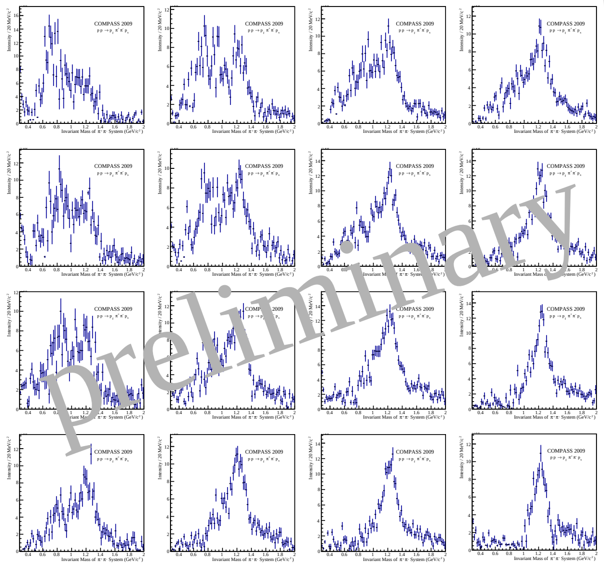
$t_1 \Rightarrow$

t_2

$\Downarrow$

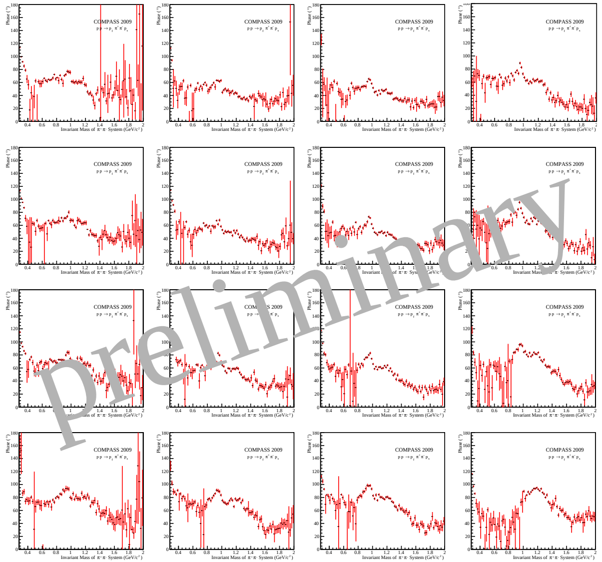
D_0^-



Fit to the $\pi\pi$ System:

$t_1 \Rightarrow$ $S_0^- - D_0^-$

t_2 $\Downarrow$



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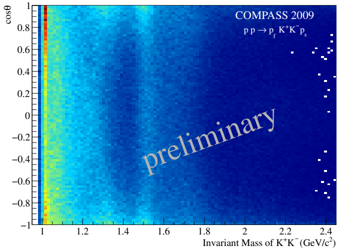
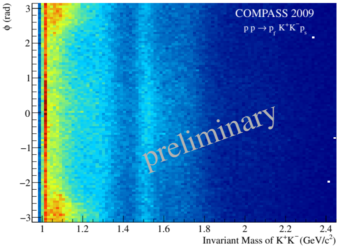
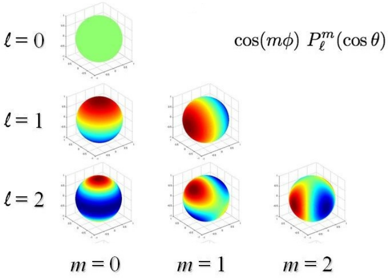


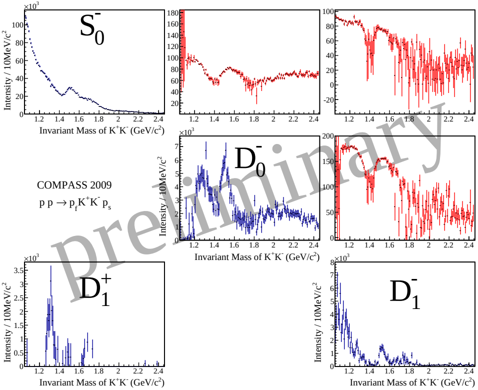


$X \to K^+K^-$

- **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



Fit to the 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

Mass-Dependence of K^+K^-

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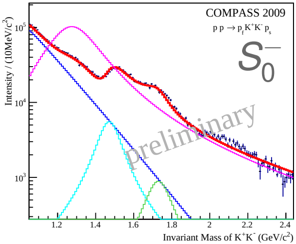
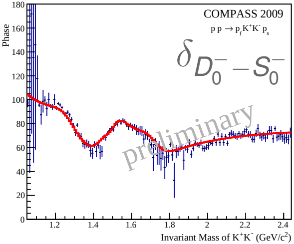
$f_0(1370)$

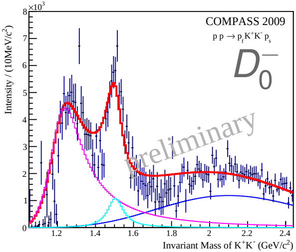
$f_0(1500)$

$f_0(1710)$





BW contributions
non-resonant contribution
coherent sum



$f_2(1270)$

$f_2'(1525)$

Interference of S and D

distinguish resonances from non-resonant contribution

COMPASS Summary

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

$I^G(J^{PC})$ (R1/2) [a]	ℓ [b]	$I^G(J^{PC})$ (R2/1) [a]	$I^G(J^{PC})$ (Final State) [c]
$\rho\ 1^+(1^{--})$	0	$\mathbb{P}\ 0^+(2^{++})$	$\pi\pi \to 1^+(1^{--},\ 3^{--})$
	0		$4\pi \to 1^+(1^{+-},\ 2^{+-},\ 3^{+-})$
	1		$\ell = 1$ does not couple to $\pi\pi$
	1		$4\pi \to 1^+(0^{+-},\ 1^{+-},\ 2^{+-},\ 3^{+-},\ 4^{+-})$
$\mathbb{P}\ 0^+(2^{++})$	0	$\mathbb{P}\ 0^+(2^{++})$	$\pi\pi \to 0^+(0^{++}, 2^{++}, 4^{++})$
	0		$4\pi \to 0^+(0^{++},\ 1^{++},\ 2^{++},\ 3^{++},\ 4^{++})$
	1		$\ell = 1$ does not couple to $\pi\pi$
	1		$4\pi \to 0^+(0^{-+},\ 1^{-+},\ 2^{-+},\ 3^{-+},\ 4^{-+},\ 5^{-+})$
$b_1(1235)$ $1^+(1^{+-})$	0	$\mathbb{P}$ $0^+(2^{++})$	$\ell = 0$ does not couple to $\pi\pi$
	0		$4\pi \to 1^+(1^{+-},\ 2^{+-},\ 3^{+-})$
	1		$\pi\pi \to 1^+(1^{--},\ 3^{--})$
	1		$4\pi \to 1^+(\boxed{0^{--}},\ 1^{--},\ 3^{--},\ 4^{--})$

Regge-domain formula for $a + b \to 1 + 3 + 2$:

$$\boxed{s_{13}\, s_{23} = s\, w_3^2} \text{ where } \sqrt{s_{13}} = \sqrt{s_{23}} \text{ and } w_3 = 2.0 \text{ GeV.}$$

$$\boxed{R = \sigma_{\rm tot}[\rho(770)]/\sigma_{\rm tot}(\text{Pomeron})}$$

Experiment	Beam	Target Beam	$p_{\rm beam}$ (GeV/c)	$\sqrt{s}$ (GeV)	R (%)	$\sqrt{s_{13}}$ (GeV)
COMPASS[b]	p	p	190	18.9	2.9	6.15
ALICE[e]	p	p	$3\,500 \times 3\,500$	$7\,000$	2.5×10^{-3}	118

[b] A. Austregesilo, (The COMPASS Collaboration), Blois 2013.
[e] Taesoo Kim/Yonsei Univeristy, Seoul, Korea (not released).

See also the talk of Mike Albrow for his work at FermiLab

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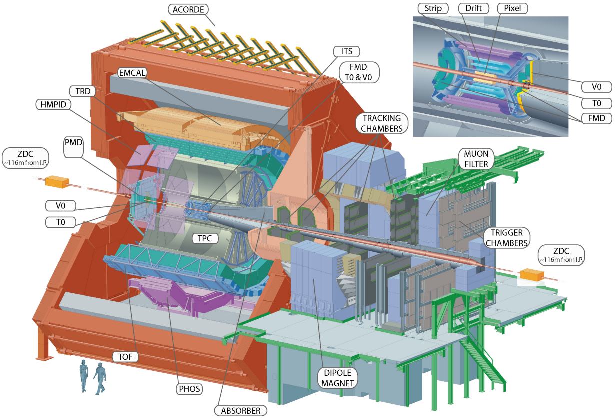
ALICE

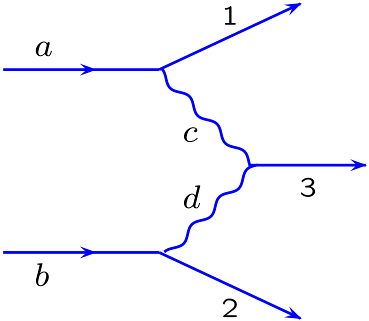


Nuclear Instruments and Methods in Physics Research A 766 (2014): pages 19 — 21; pages 259 — 262; pages 288 — 291; pages 292 — 295

Int. J. Mod. Phys. A 29 (2014) 1430044

$$a + b \rightarrow 1 + 3 + 2$$

$$a + b \to 1 + 3 + 2$$



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ALICE

- Introduction:

  $pp \to p + (\pi^+\pi^-) + p$ at 7 TeV 46,000 events (2010 data)

  Taesoo Kim
  Yonsei University, Seoul, Korea

  $pp \to p + (\pi^+\pi^-) + p$ at 13–14 TeV (More data from 2015 and beyond)

- No Roman pots for ALICE

  Assume equal momentum transfers, i.e. $-t_c = -t_d$, with exponential distributions and *fix* the one unknown parameter so as to maximize the probability of observation.
  Now, in fact, we have all the momenta for $a + b \to 1 + 3 + 2$
  ALICELet $\vec{\kappa}$ be the 2-dimensional vector perpendicualr to the beam axis and set

$$-t_c = \boldsymbol{\kappa}_1^2 \quad \text{and} \quad -t_d = \boldsymbol{\kappa}_2^2$$

$$\vec{\boldsymbol{\kappa}}_1 = -\frac{1}{2}\,\vec{\boldsymbol{\kappa}}_3, \quad \vec{\boldsymbol{\kappa}}_2 = -\frac{1}{2}\,\vec{\boldsymbol{\kappa}}_3 \quad \text{and} \quad \vec{\boldsymbol{\kappa}}_1 + \vec{\boldsymbol{\kappa}}_2 + \vec{\boldsymbol{\kappa}}_3 = 0$$

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ALICE

- Since we have all the momenta in the problem, we can reliably choose the quantization axis to be the exchange axis in the 3RF; this is the proper quantization axis and the correct rest-frame (RF) for double-Pomeron exchange processes.
- Events with double-gap topology are contained in the data sample taken with a minimum bias trigger. Double-gap events can hence be analyzed offline from the minimum bias data sample.
- Work is ongoing in ALICE to test the implementation of a hardware double-gap trigger at L0 level. This trigger requires minimum activity in the SPD (Silicon Pixel Detector) in the central barrel, and no activity in the detectors V0 (A and C) and AD (A and C).

Thank you for your attention