

Exclusive resonance production at the LHC

Rainer Schicker
(in coll. with R.Fiore, L.Jenkowszky)

Phys. Inst., Heidelberg

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Central production at hadron colliders

Dual resonance model Pomeron-Pomeron scattering

Nonlinear, complex meson Regge trajectories

Pomeron-Pomeron cross section

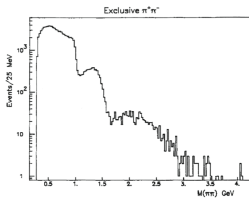
Pomeron distribution in the proton

Cross sections at hadron level

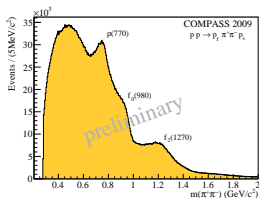
Conclusions, outlook

Central production at hadron colliders I

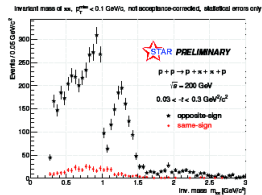
■ mass spectra of exclusive pion pairs in proton-proton collisions



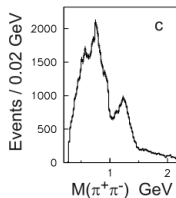
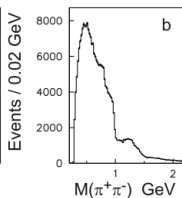
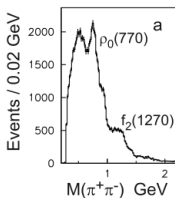
AFS at the ISR, $\sqrt{s}=63$ GeV



COMPASS at CERN, $\sqrt{s}=18.9$ GeV



STAR at RHIC, $\sqrt{s}=200$ GeV



OMEGA facility at SPS fixed target

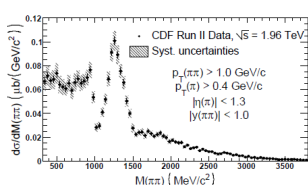
WA76, WA102

$\sqrt{s} = 12.7\text{-}29$ GeV

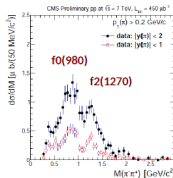
Fig. 2. The centrally produced $\pi^+\pi^-$ effective mass spectrum at $\sqrt{s} =$ a) 12.7 GeV and b) 29 GeV using a LL trigger and c) at 29 GeV from a LR trigger.

Central production at hadron colliders II

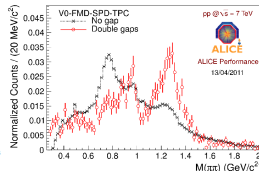
■ mass spectra of exclusive pion pairs in proton-proton collisions



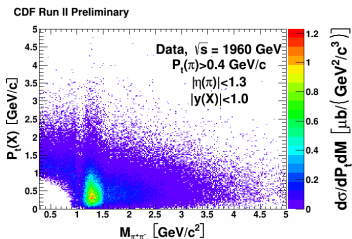
CDF at the TEVATRON, $\sqrt{s}=1960$ GeV



CMS at LHC
 $\sqrt{s}=7$ TeV



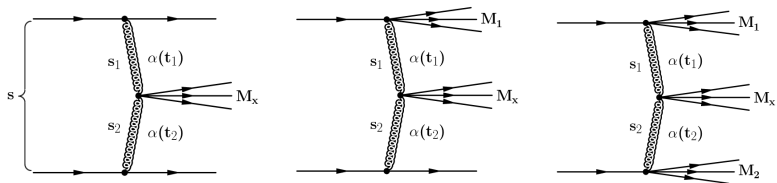
ALICE at LHC, $\sqrt{s}=7$ TeV



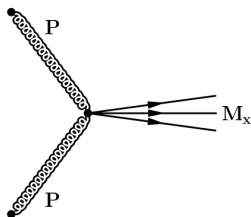
- event generator for resonance prod.
 - ▶ evaluation of acceptance
 - ▶ efficiency corrections
- for Partial-Wave Analysis
 - ▶ understand the $\rho(770)$, $f_0(980)$, $f_2(1270)$

Central production event topologies

■ central production with/without diffractive dissociation



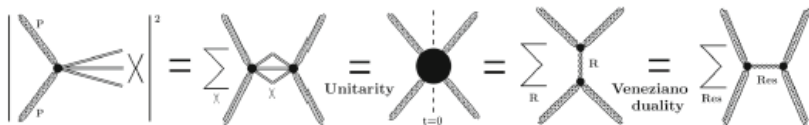
■ Pomeron-Pomeron-meson vertex in all three topologies



- amplitude
Pomeron-Pomeron \rightarrow meson
- cross section
Pomeron-Pomeron \rightarrow meson

Dual resonance model of Pomeron-Pomeron scattering

- many overlapping resonances at low masses $M < 3 \text{ GeV}/c^2$
- transition into continuum
- Dual Amplitude with Mandelstam Analyticity (DAMA)



- DAMA requires the use of nonlinear, complex Regge traject.
- resonance widths are provided by imaginary part of DAMA
- direct-channel pole decomposition relevant for central prod.

$$A(M_X^2, t) = a \sum_{i=f,P} \sum_J \frac{[f_i(t)]^{J+2}}{J - \alpha_i(M_X^2)}. \quad (1)$$

Nonlinear, complex meson trajectories

- real and imaginary part of trajectory are connected by dispersion relation

$$\Re \alpha(s) = \alpha(0) + \frac{s}{\pi} PV \int_0^\infty ds' \frac{\Im m \alpha(s')}{s'(s' - s)}. \quad (2)$$

- imaginary part is related to the decay width

$$\Gamma(M_R) = \frac{\Im m \alpha(M_R^2)}{\alpha' M_R}. \quad (3)$$

- imaginary part chosen as sum of single threshold terms

$$\Im m \alpha(s) = \sum_n c_n (s - s_n)^{1/2} \left(\frac{s - s_n}{s} \right)^{|\Re \alpha(s_n)|} \theta(s - s_n). \quad (4)$$

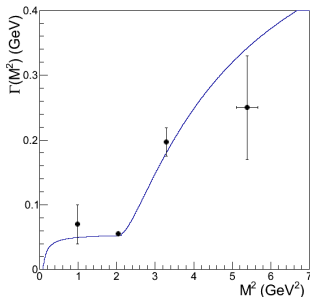
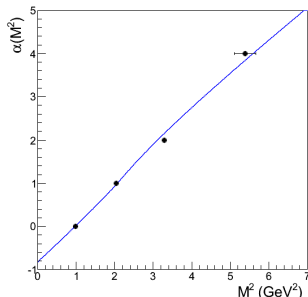
- imaginary part of trajectory shown in Eq.(4) has correct threshold and asymptotic behaviour
- c_n are expansion coefficients

Two f-trajectories

- use the following f-resonances for fitting two f-trajectories

	$I^G J^{PC}$	Traj.	M (GeV)	Γ (GeV)
$f_0(980)$	$0^+ 0^{++}$	f_1	0.990 ± 0.020	0.070 ± 0.030
$f_1(1420)$	$0^+ 1^{++}$	f_1	1.426 ± 0.001	0.055 ± 0.003
$f_2(1810)$	$0^+ 2^{++}$	f_1	1.815 ± 0.012	0.197 ± 0.022
$f_4(2300)$	$0^+ 4^{++}$	f_1	2.320 ± 0.060	0.250 ± 0.080
$f_2(1270)$	$0^+ 2^{++}$	f_2	1.275 ± 0.001	0.185 ± 0.003
$f_4(2050)$	$0^+ 4^{++}$	f_2	2.018 ± 0.011	0.237 ± 0.018
$f_6(2510)$	$0^+ 6^{++}$	f_2	2.469 ± 0.029	0.283 ± 0.040

f_1 traj.

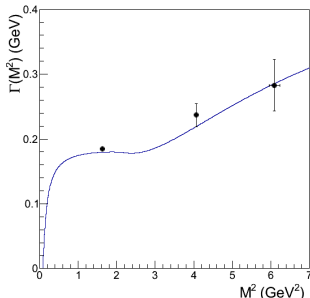
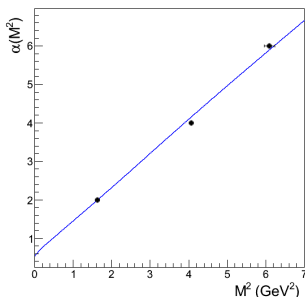


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f_2 traj.



The Pomeron trajectory

- the following parameterisation is used

$$\alpha_P(M^2) = \frac{1 + \varepsilon + \alpha' M^2}{1 - c\sqrt{s_0 - M^2}} \quad (5)$$

$\varepsilon = 0.08$, $\alpha' = 0.25 \text{ GeV}^{-2}$, $c = \alpha' / 10 = 0.025$,
 s_0 the two pion thresh. $s_0 = 4m_\pi^2$.

The $f_0(500)$ resonance

- exclusive pion pair mass distribution at COMPASS shows broad continuum at $m_{\pi^+\pi^-} < 1 \text{ GeV}/c^2$
- this mass range attributed to $f_0(500)$ resonance
- at hadron colliders, this mass range is seriously suffering from missing acceptance for pairs of low transverse momentum
- $f_0(500)$ is of prime importance for understanding of
 - ▶ attractive part of nucleon-nucleon interaction
 - ▶ spontaneous breaking of chiral symmetry
- parameterised by Breit-Wigner form

$$A(M^2) = a \frac{-M_0\Gamma}{M^2 - M_0^2 + iM_0\Gamma} \quad (6)$$

The Pomeron-Pomeron cross section

- the Pomeron-Pomeron cross section derived from imaginary part of trajectories ($f_1, f_2, Pomeron$) by the optical theorem

$$\sigma_t^{PP}(M^2) = \Im A(M^2, t=0) = \sum_{i=f,P} \sum_J \frac{[f_i(0)]^{J+2} \Im \alpha_i(M^2)}{(J - \Re \alpha_i(M^2))^2 + (\Im \alpha_i(M^2))^2}. \quad (7)$$

- the $f_0(500)$ resonance contributes to the cross section

$$\sigma_{f_0(500)}^{PP}(M^2) = a \sqrt{1 - \frac{4 m_\pi^2}{M^2}} \frac{M_0^2 \Gamma^2}{(M^2 - M_0^2)^2 + M_0^2 \Gamma^2}, \quad (8)$$

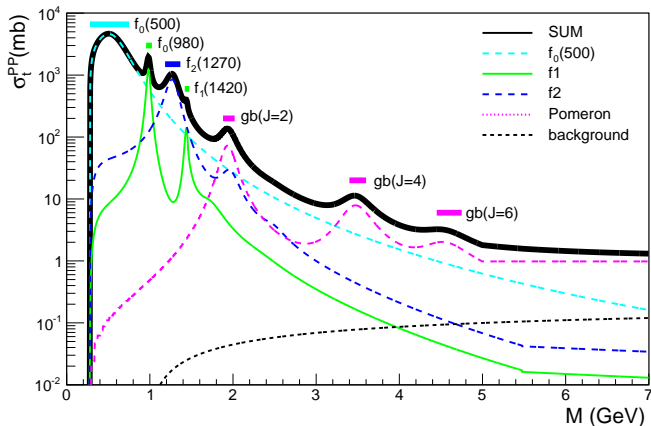
with the resonance mass of $M_0 = (0.40-0.55)$ GeV and a width $\Gamma = (0.40-0.70)$ GeV

- background term

$$\sigma_{backgr.}^{PP}(M^2) = c * (0.1 + \log(M^2)) \text{ mb}, \quad (9)$$

The Pomeron-Pomeron cross section

- contributions of the $f_0(500)$, f_1 , f_2 and Pomeron trajectory, and the background
- R.Fiore et al., Eur.Phys.J.C76 (2016) no.1., 38.



Cross section at hadron level

- differential cross section $d\sigma = \frac{|\mathcal{M}|^2}{\text{flux}} dQ$
 \mathcal{M} = inv. amplitude,
 dQ = Lorentz-invariant phase space
 flux = flux factor
- $|\mathcal{M}|^2 dQ = \text{flux}_{\text{prot}} d\sigma_{\text{prot}} = \text{flux}_{\text{Pom}} F_{\text{prot}}^{\text{Pom}} d\sigma_{\text{Pom}}$
- $F_{\text{prot}}^{\text{Pom}}$ = "Distribution of pomerons in the proton"
- $d\sigma_{\text{prot}} = \frac{\text{flux}_{\text{Pom}}}{\text{flux}_{\text{prot}}} F_{\text{prot}}^{\text{Pom}} d\sigma_{\text{Pom}}$
- flux factor for collinear two-body collision of A and B:
 $\text{flux} = 4 \cdot ((p_A \cdot p_B)^2 - m_A^2 m_B^2)^{1/2}$

Pomeron distribution in the proton

- "Distribution of pomerons in the proton" = $F_p^P(t, \xi)$
A.Donnachie, P.V.Landshoff, Nucl. Phys. B303 (1988) 634.
 - ▶ t = 4-momentum transfer to the proton (Mandelstam t)
 - ▶ ξ = fractional long. momentum loss of proton = $1-x_F$
- Pomeron couples to quarks rather like a $C = +1$ isoscalar photon
- $F_p^P(t, \xi) = \frac{9\beta_0^2}{4\pi^2} [F_1(t)]^2 \xi^{1-2\alpha(t)}$, integrated over azimuth
- $F_1(t)$ elastic form factor
- Pomeron traj. $\alpha(t) = 1. + \varepsilon + \alpha' t$, $\varepsilon \sim 0.085$, $\alpha' = 0.25 \text{ GeV}^{-2}$

Resonance cross section at hadron level

$$\sigma_{PP} = \iiint \frac{\text{flux}_P}{\text{flux}_P} \cdot F_{PA}^P(t_A, \xi_A, \phi_A) F_{PB}^P(t_B, \xi_B, \phi_B) \sigma_{PP}(M_x, t_{A,B}) dt_A d\xi_A d\phi_A dt_B d\xi_B d\phi_B \quad (10)$$

kinematic transformation ($\Delta\phi = \phi_A - \phi_B$):

$(t_A, \xi_A, t_B, \xi_B, \Delta\phi) \rightarrow u_+, u_-, v_-, M_x, p_{T,x}$

M_x : mass of central system, $p_{T,x}$: trans. mom. of central system

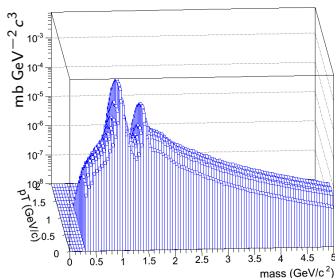
$$\sigma_{PP} = \iiint \frac{\text{flux}_P}{\text{flux}_P} \cdot \tilde{F}_{PA}^P \tilde{F}_{PB}^P \frac{p_{T,x} dp_{T,x}}{\sqrt{F^2 - (p_{T,x}^2 - G)^2}} \frac{\sigma_{PP}(M_x, u_+, u_-) M_x J dM_x du_+ du_- dv_-}{\sqrt{H^2 - \left(\frac{p_{T,x}^2 + M_x^2}{2\gamma^2}\right)}}$$

$$\frac{d\sigma_{PP}}{dM_x dp_{T,x}} = \iiint \frac{\text{flux}_P}{\text{flux}_P} \cdot \tilde{F}_{PA}^P \tilde{F}_{PB}^P \frac{p_{T,x}}{\sqrt{F^2 - (p_{T,x}^2 - G)^2}} \frac{\sigma_{PP}(M_x, u_+, u_-) M_x J du_+ du_- dv_-}{\sqrt{H^2 - \left(\frac{p_{T,x}^2 + M_x^2}{2\gamma^2}\right)}}$$

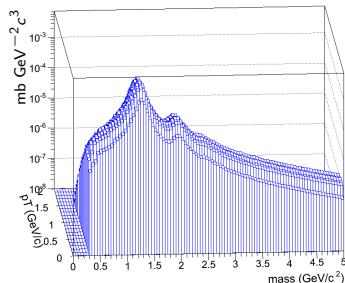
$$F = F(u_+, u_-, v_-), \quad G = G(u_+, u_-, v_-), \quad H = H(u_+, u_-, v_-)$$

Differential hadronic cross sections

- QCD motivated t-dependence of PP cross section $\propto \frac{1}{\sqrt{t_A \cdot t_B}}$
- convolute PP cross section with DL PP-dist. to get $\frac{d\sigma}{dM_x dp_{T,x}}$
- integration range $\xi_{A,B} < 10^{-3}$, $|t_{A,B}| < 1.5 \text{ GeV}^2$.

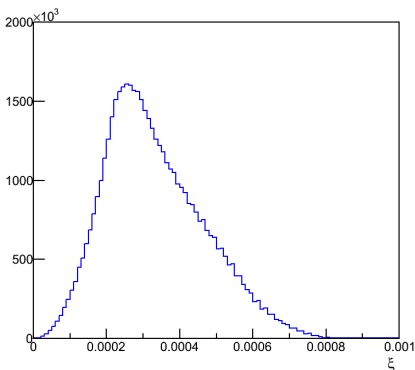


$$\frac{d\sigma(pp \rightarrow pp f_0(980))}{dM_x dp_{T,x} dy}$$



$$\frac{d\sigma(pp \rightarrow pp f_2(1270))}{dM_x dp_{T,x} dy}$$

Fractional longitudinal momentum loss



Fract. longitudinal momentum loss ξ in $\left. \frac{d\sigma(pp \rightarrow pp f_0(980))}{dy} \right|_{y=0}$

Conclusions and outlook

- Model presented for Pomeron-Pomeron cross section in resonance region $M < 5 \text{ GeV}$.
- Cross section at hadron level derived by convoluting Pomeron-Pomeron cross section with Pomeron distribution and scaling by Pomeron/proton flux.
- Cross section at hadron level calculable for event topologies of single/double diffractive dissociation (work in progress).
- Model can be extended to lower energies where Reggeon exchanges contribute.
- To do: absorptive corrections, multi Pomeron exchanges.

Backup

Nonlinear, complex meson trajectories

- real and imag. part of traj. are related by dispersion relation

$$\Re \alpha(s) = \alpha(0) + \frac{s}{\pi} PV \int_0^\infty ds' \frac{\Im m \alpha(s')}{s'(s' - s)}. \quad (11)$$

- imaginary part chosen as sum of single threshold terms

$$\Im m \alpha(s) = \sum_n c_n (s - s_n)^{1/2} \left(\frac{s - s_n}{s} \right)^{|\Re \alpha(s_n)|} \theta(s - s_n). \quad (12)$$

- real part of trajectory given by

$$\begin{aligned} \Re \alpha(s) = & \alpha(0) + \frac{s}{\sqrt{\pi}} \sum_n c_n \frac{\Gamma(\lambda_n + 3/2)}{\Gamma(\lambda_n + 2) \sqrt{s_n}} {}_2F_1\left(1, 1/2; \lambda_n + 2; \frac{s}{s_n}\right) \theta(s_n - s) \\ & + \frac{2}{\sqrt{\pi}} \sum_n c_n \frac{\Gamma(\lambda_n + 3/2)}{\Gamma(\lambda_n + 1)} \sqrt{s_n} {}_2F_1\left(-\lambda_n, 1; 3/2; \frac{s_n}{s}\right) \theta(s - s_n). \end{aligned} \quad (13)$$

Lorentz-invariant phase space

- $2 \rightarrow 3$ body reaction: $A + B \rightarrow 1 + 2 + X$
- Lorentz-invariant three-particle phase space:

$$\frac{d^3\vec{P}_1}{(2\pi)^3 2E_1} \frac{d^3\vec{P}_2}{(2\pi)^3 2E_2} d^4P_X (2\pi)^4 \delta^4(P_A + P_B - P_1 - P_2 - P_X)$$

$$= J \cdot dt_A d\xi_A d\phi_A dt_B d\xi_B d\phi_B \quad (14)$$

with $J =$ Jacobian determinant of the transformation

$$(\vec{P}_1, \vec{P}_2, P_X)(2\pi)^4 \delta^4(P_A + P_B - P_1 - P_2 - P_X) \rightarrow (t_A, \xi_A, \phi_A, t_B, \xi_B, \phi_B)$$

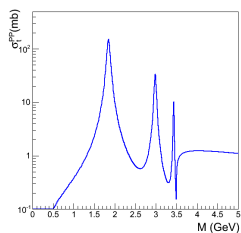
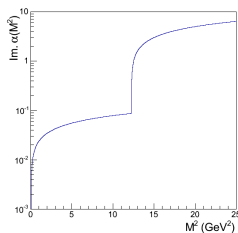
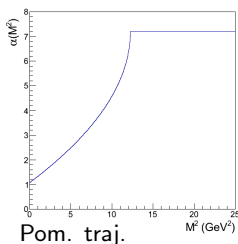
The Pomeron trajectory I

$$\alpha_P(M^2) = 1. + \varepsilon + \alpha' M^2 - c\sqrt{s_0 - M^2}, \quad (15)$$

Linear term in Eq. 14 is replaced by heavy threshold mimicking linear behaviour in mass region $M < 5$ GeV.

$$\alpha_P(M^2) = \alpha_0 + \alpha_1 \left(2m_\pi - \sqrt{4m_\pi^2 - M^2} \right) + \alpha_2 \left(\sqrt{M_H^2} - \sqrt{M_H^2 - M^2} \right) \quad (16)$$

with M_H an effective threshold set at $M_H = 3.5$ GeV



The Pomeron trajectory II

- Pomeron trajectory parameterised as

$$\alpha_P(M^2) = \frac{1 + \varepsilon + \alpha' M^2}{1 - c\sqrt{s_0 - M^2}} \quad (17)$$

with resulting cross section

