Exclusive production of resonances in proton-proton collisions at high energies

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

Phys. Inst., Heidelberg

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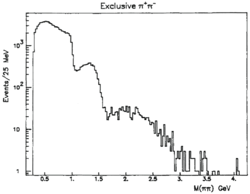
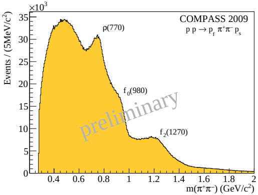
Central production at hadron colliders I

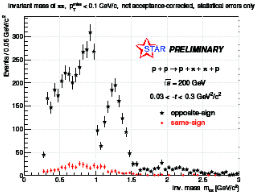
- mass spectra of exclusive pion pairs in proton-proton collisions



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



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



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

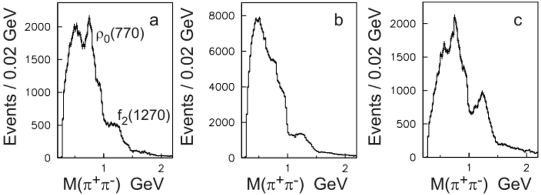


Fig. 2. The centrally produced $\pi^+\pi^-$ effective mass spectrum at $\sqrt{s}$ = a) 12.7 GeV and b) 29 GeV using a LL trigger and c) at 29 GeV from a LR trigger.

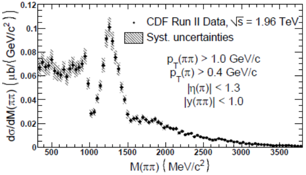
OMEGA facility at SPS fixed target

WA76, WA102

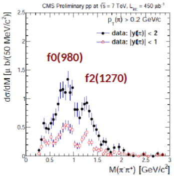
$\sqrt{s}$ = 12.7-29 GeV

Central production at hadron colliders II

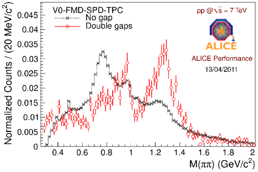
- mass spectra of exclusive pion pairs in proton-proton collisions



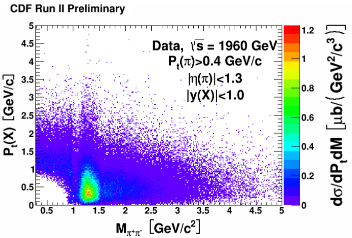
CDF at the TEVATRON, $\sqrt{s}$=1960 GeV



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



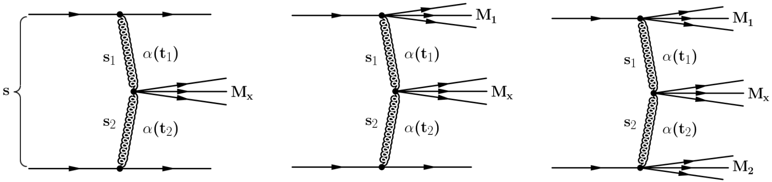
ALICE at LHC, $\sqrt{s}$=7 TeV



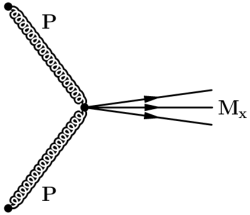
- event generator for resonance prod.
  - evaluation of acceptance
  - efficiency corrections
- for Partial-Wave Analysis
  - understand the $\rho(770)$, $f_0(980)$, $f_2(1270)$

Central production event topologies

- central production with/without diffractive dissociation



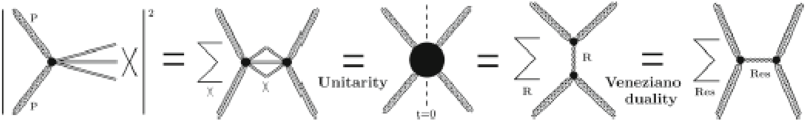
- Pomeron-Pomeron-meson vertex in all three topologies



- 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 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.

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

Nonlinear, complex meson trajectories

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

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

- imaginary part is related to the decay width

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

- imaginary part chosen as sum of single threshold terms

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

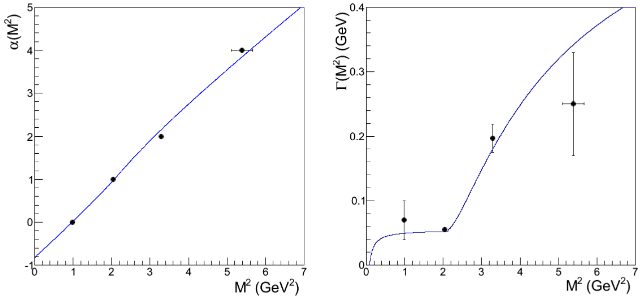
- imaginary part of trajectory shown in Eq.(4) has correct threshold and asymptotic behaviour
- c_n are expansion coefficients

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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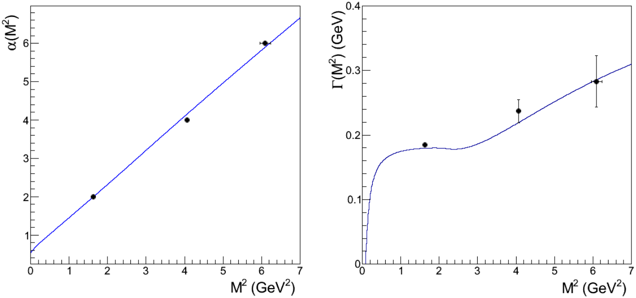
f_2 traj.



The Pomeron trajectory

- the following parameterisation is used

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

$\varepsilon = 0.08$, $\alpha^{'} = 0.25$ 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 $m_{\pi^+\pi^-} < 1$ 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 tranverse 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

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

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

$$\sigma_t^{PP}(M^2) \;=\; \Im m\, A(M^2, t=0) \;=$$

$$\sum_{i=f,P} \sum_J \frac{[f_i(0)]^{J+2}\, \Im m\, \alpha_i(M^2)}{(J - \Re e\, \alpha_i(M^2))^2 + (\Im m\, \alpha_i(M^2))^2}. \tag{7}$$

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

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

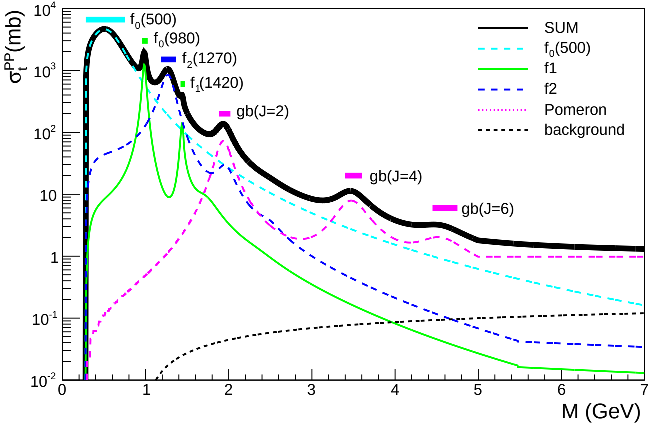
with the resonance mass of $M_0 = (0.40\text{–}0.55)$ GeV and a width $\Gamma = (0.40\text{–}0.70)$ GeV

- background term

$$\sigma^{PP}_{backgr.}(M^2) = c * (0.1 + \log(M^2))\ \mathrm{mb}, \tag{9}$$

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

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. $\alpha(t){=}1.{+}\varepsilon{+}\alpha^{'}t$, $\varepsilon \sim 0.085, \alpha^{'}{=}0.25$ GeV^{-2}

Resonance cross section at hadron level

$$\sigma_{pp} = \iiiint\!\!\iint \frac{flux_P}{flux_p} \cdot F^P_{p_A}(t_A, \xi_A, \phi_A) F^P_{p_B}(t_B, \xi_B, \phi_B) \sigma_{PP}(M_x, t_{A,B}) dt_A d\xi_A d\phi_A dt_B d\xi_B d\phi_B \tag{10}$$

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

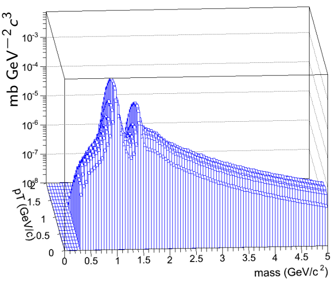
$$\sigma_{pp} = \iiiint\!\!\int \frac{flux_P}{flux_p} \cdot \tilde{F}^P_{p_A} \tilde{F}^P_{p_B} \frac{p_{T,x} dp_{T,x}}{\sqrt{F^2 - (p^2_{T,x} - G)^2}} \frac{\sigma_{PP}(M_x, u_+, u_-) M_x J dM_x du_+ du_- dv_-}{\sqrt{H^2 - (\frac{p^2_{T,x} + M^2_x}{2\gamma^2})}}$$

$$\frac{d\sigma_{pp}}{dM_x dp_{T,x}} = \iiint \frac{flux_P}{flux_p} \cdot \tilde{F}^P_{p_A} \tilde{F}^P_{p_B} \frac{p_{T,x}}{\sqrt{F^2 - (p^2_{T,x} - G)^2}} \frac{\sigma_{PP}(M_x, u_+, u_-) M_x J du_+ du_- dv_-}{\sqrt{H^2 - (\frac{p^2_{T,x} + M^2_x}{2\gamma^2})}}$$

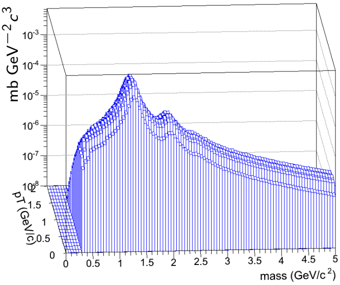
$$F = F(u_+, u_-, v_-), \quad G = G(u_+, u_-, v_-), \quad H = H(u_+, u_-, v_-)$$

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 $\xi_{A,B} < 10^{-3}, |t_{A,B}| < 1.5$ GeV^2.

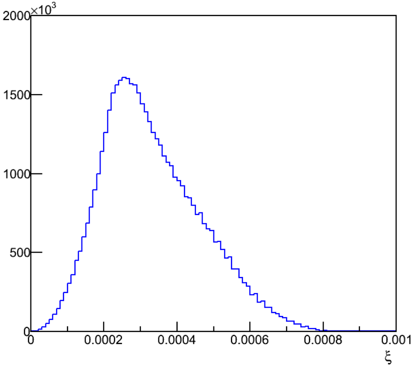


$\frac{d\sigma(pp \to ppf_0(980))}{dM_x dp_{T,x} dy}$



$\frac{d\sigma(pp \to ppf_2(1270))}{dM_x dp_{T,x} dy}$

Fractional longitudinal momentum loss



Fract. longitudinal momentum loss ξ in $\frac{d\sigma(pp \to ppf_0(980))}{dy}|_{y=0}$

Conclusions and outlook

- Model presented for Pomeron-Pomeron cross section in resonance region M $<$ 5 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

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

- imaginary part chosen as sum of single threshold terms

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

- real part of trajectory given by

$$\Re e\, \alpha(s) = \alpha(0) + \frac{s}{\sqrt{\pi}} \sum_n c_n \frac{\Gamma(\lambda_n + 3/2)}{\Gamma(\lambda_n + 2)\sqrt{s_n}}\, {}_2F_1(1, 1/2; \lambda_n + 2; \frac{s}{s_n}) \theta(s_n - s)$$

$$+ \frac{2}{\sqrt{\pi}} \sum_n c_n \frac{\Gamma(\lambda_n + 3/2)}{\Gamma(\lambda_n + 1)} \sqrt{s_n}\, {}_2F_1(-\lambda_n, 1; 3/2; \frac{s_n}{s}) \theta(s - s_n). \tag{13}$$

Lorentz-invariant phase space

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

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

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

with J = Jacobian determinant of the transformation

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

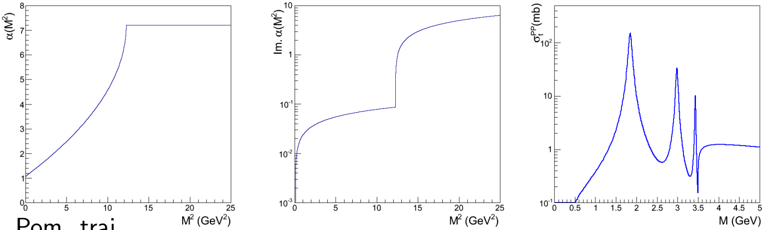
The Pomeron trajectory I

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

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

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

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



Pom. traj.

The Pomeron trajectory II

- Pomeron trajectory parameterised as

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

with resulting cross section

Pom. traj.