Exclusive production of meson pairs and resonances in proton-proton collisions

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Introduction

The 4-body reactions $pp \to p\,\pi^+\pi^-\,p$ and $pp \to p\,K^+K^-\,p$
constitutes an irreducible background to 3-body processes $pp \to p\,M\,p$,
where *e.g.* $M = \sigma, \rho^0, f_0(980), \phi, f_2(1270), f_0(1500), f_2'(1525), \chi_{c0}$, glueball
$\to$ these resonances are seen (or will be seen) "on" the $\pi\pi$ and/or KK continuum

Measurement of χ_c at Tevatron (CDF Collaboration)

$$\chi_c \to J/\psi(\to \mu^+\mu^-) + \gamma, \quad \frac{d\sigma_{\chi_c}}{dy}|_{y=0} = (76 \pm 14)\ \text{nb}$$

[T. Aaltonen *et al.*, Phys. Rev. Lett. **102** (2009) 242001]

$M(J/\psi\gamma)$ resolution does not allow a seperation of the different χ_{cJ} states!

Channel	$\mathcal{B}(\chi_{c0})$	$\mathcal{B}(\chi_{c1})$	$\mathcal{B}(\chi_{c2})$
$J/\psi\gamma$	$(1.16 \pm 0.08)\%$	$(34.4 \pm 1.5)\%$	$(19.5 \pm 0.8)\%$

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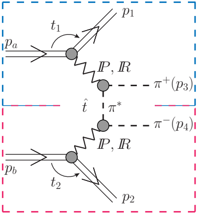
but $\sigma(\chi_{c0})$ obtained within the k_t-factorization is much bigger than for χ_{c1} and χ_{c2}
Could other decay channels be used ?

Channel	$\mathcal{B}(\chi_{c0})$	$\mathcal{B}(\chi_{c1})$	$\mathcal{B}(\chi_{c2})$
$\pi^+\pi^-$	$(0.56 \pm 0.03)\%$	$-$	$(0.16 \pm 0.01)\%$
K^+K^-	$(0.610 \pm 0.035)\%$	$-$	$(0.109 \pm 0.008)\%$
$p\bar{p}$	$(0.0228 \pm 0.0013)\%$	$(0.0073 \pm 0.0004)\%$	$(0.0072 \pm 0.0004)\%$
$\pi^+\pi^-\pi^+\pi^-$	$(2.27 \pm 0.19)\%$	$(0.76 \pm 0.26)\%$	$(1.11 \pm 0.11)\%$
$\pi^+\pi^-K^+K^-$	$(1.80 \pm 0.15)\%$	$(0.45 \pm 0.10)\%$	$(0.92 \pm 0.11)\%$

Diffractive amplitude for $\pi^+\pi^-$ continuum



$+$ crossed diagram $(3 \leftrightarrow 4)$

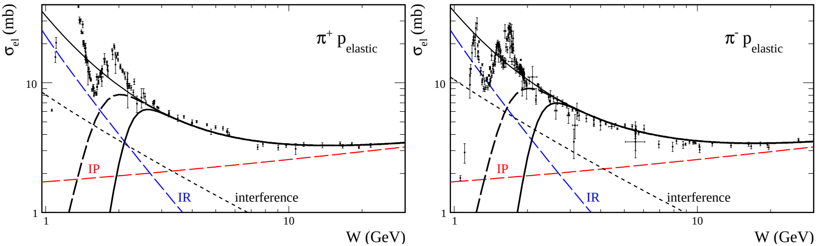
P. Lebiedowicz and A. Szczurek, Phys. Rev. **D81** (2010) 036003

$$\mathcal{M}^{Born}_{pp\to pp\pi\pi} = M_{13}(s_{13}, t_1) F_\pi(\hat{t}) \frac{1}{\hat{t} - m_\pi^2} F_\pi(\hat{t}) M_{24}(s_{24}, t_2)$$

$$+ \quad M_{14}(s_{14}, t_1) F_\pi(\hat{u}) \frac{1}{\hat{u} - m_\pi^2} F_\pi(\hat{u}) M_{23}(s_{23}, t_2), \qquad F_\pi(\hat{t}/\hat{u}) = \exp\left(\frac{\hat{t}/\hat{u} - m_\pi^2}{\Lambda^2_{off}}\right)$$

we propose to use a generalized propagator: $\frac{1}{\hat{t}/\hat{u} - m_\pi^2} \to \beta_M(\hat{s}) \frac{1}{\hat{t}/\hat{u} - m_\pi^2} + \beta_R(\hat{s}) \mathcal{P}^\pi(\hat{t}/\hat{u}, \hat{s})$

πp cross sections



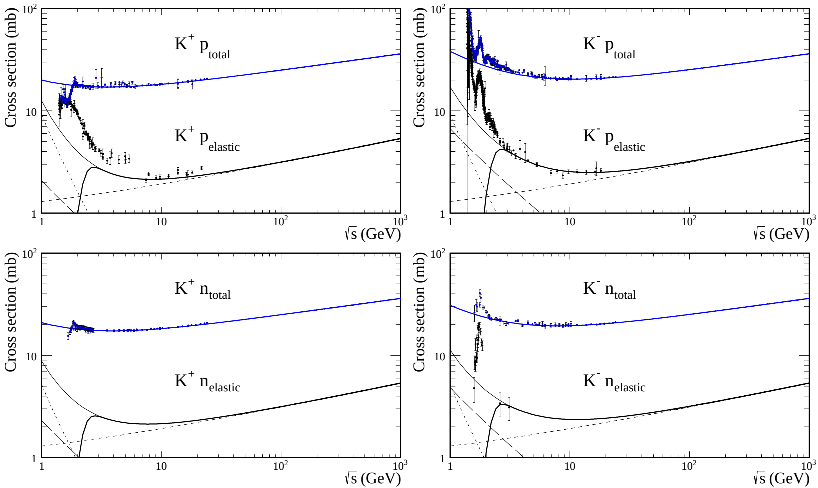
- Donnachie-Landshoff parametrization for total πN cross section ($\sigma_{tot}^{\pi p} = C_i s^{\alpha_i(0)-1}$, $i = IP,\ IR$):

  $\sigma_{tot}^{\pi^+ p}$: $13.63 s^{0.0808} + 27.56 s^{-0.4525}$ $\sigma_{tot}^{\pi^- p}$: $13.63 s^{0.0808} + 36.02 s^{-0.4525}$
- The optical theorem: $\sigma_{tot}^{\pi p} \simeq \frac{1}{s} Im M_{el}^{\pi p}(s, t=0)$ (when s is large)
- $M_{\pi^\pm p}(s,0) = A_{IP}(s) + A_{f_2}(s) \mp A_\rho(s)$
- $$M_{\pi p \to \pi p}(s,t) = \eta_i\ s\ C_i \left(\frac{s}{s_0}\right)^{\alpha_i(t)-1} \exp\left(\frac{B_i^{\pi p}}{2}\ t\right)$$

  the values of pomeron and reggeon couplings to πp:

  $C_{IP} = 13.63 mb$, $C_{f_2} = 31.79 mb$, $C_\rho = 4.23 mb$
- nicely describes the $\pi p_{elastic}$ data for $\sqrt{s} > 2.5$ GeV with slope parameters $B(s) = B_i^{\pi p} + 2\alpha_i' \ln(\frac{s}{s_0})$: $B_{IP}^{\pi p} = 5.5\ \text{GeV}^{-2}$ and $B_{IR}^{\pi p} = 4\ \text{GeV}^{-2}$

Kp and Kn cross sections

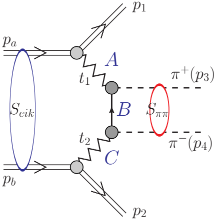


$$M_{K^\pm p}(s,0) = A_{IP}(s) + A_{f_2}(s) + A_{a_2}(s) \mp A_{\omega}(s) \mp A_{\rho}(s)$$
$$M_{K^\pm n}(s,0) = A_{IP}(s) + A_{f_2}(s) - A_{a_2}(s) \mp A_{\omega}(s) \pm A_{\rho}(s)$$

Absorption corrections

$$\mathcal{M}^{full}_{pp\to pp\pi\pi} = \mathcal{M}^{Born} + \mathcal{M}^{pp-rescatt.} + \mathcal{M}^{\pi\pi-rescatt.}$$

$$\mathcal{M}^{Born} = M_{13}(s_{13}, t_1)\frac{F_\pi^2(\hat{t})}{\hat{t}-m_\pi^2} M_{24}(s_{24}, t_2) + M_{14}(s_{14}, t_1)\frac{F_\pi^2(\hat{u})}{\hat{u}-m_\pi^2} M_{23}(s_{23}, t_2)$$



$$\mathcal{M}^{pp-rescatt.} = \frac{i}{8\pi^2 s}\int d^2\mathbf{k}_t M^{el}_{NN}(s, k_t^2)\mathcal{M}^{Born}(\mathbf{p}^*_{a,t} - \mathbf{p}_{1,t}, \mathbf{p}^*_{b,t} - \mathbf{p}_{2,t})$$

where $p_a^* = p_a - k_t$ and $p_b^* = p_b + k_t$ with momentum transfer k_t

$$M^{el}_{NN}(s, k_t^2) = M_0(s)\,\exp(-Bk_t^2/2)$$

from optical theorem: $\mathrm{Im}\, M_0(s, t = 0) = s\sigma_{tot}(s)$

$$B(s) = B^{NN}_{IP} + 2\alpha'_{IP}\ln(\frac{s}{s_0})$$

where $s_0 = 1$ GeV^2, $\alpha'_{IP} = 0.25$ GeV^{-2}, $B^{NN}_{IP} = 9$ GeV^{-2}

$\pi\pi$-rescatt.

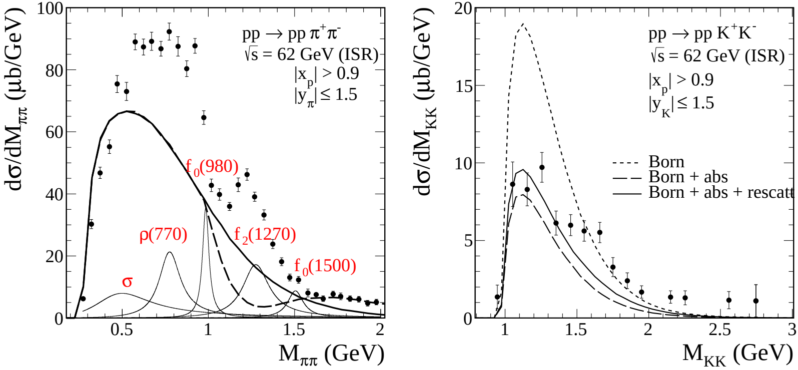
$$\frac{F_\pi^2(\hat{t})}{\hat{t}-m_\pi^2} \to \frac{i}{16\pi^2\hat{s}}\int d^2\kappa \frac{F_\pi^2(\hat{t}_1)}{\hat{t}_1-m_\pi^2} M_{\pi^+\pi^-\to\pi^+\pi^-}(\hat{s}, \hat{t}_2)$$

$$\frac{F_\pi^2(\hat{u})}{\hat{u}-m_\pi^2} \to \frac{i}{16\pi^2\hat{s}}\int d^2\kappa \frac{F_\pi^2(\hat{u}_1)}{\hat{u}_1-m_\pi^2} M_{\pi^-\pi^+\to\pi^-\pi^+}(\hat{s}, \hat{u}_2)$$

Regge-type interaction: $M^{Regge}_{\pi\pi\to\pi\pi}(\hat{s}, \hat{t}/\hat{u}) = \eta_i\,\hat{s}\,C_i^{\pi\pi}\left(\frac{\hat{s}}{\hat{s}_0}\right)^{\alpha_i(\hat{t}/\hat{u})-1}\exp\left(\frac{B_i^{\pi\pi}}{2}\,\hat{t}/\hat{u}\right)$,

where $C_i^{\pi\pi} = \frac{(C_i^{\pi N})^2}{C_i^{NN}}$, $\quad i = IP, f_2, \rho$

Our model of continuum vs ISR data



data from A. Breakstone *et al.* (ABCDHW Collaboration), Z. Phys. **C48** (1990) 569; **C42** (1989) 387

exp. cross sections: $\sigma_{pp\to pp\pi^+\pi^-} = (79 \pm 13)\ \mu$b and $\sigma_{pp\to ppK^+K^-} = (6.5 \pm 1.7)\ \mu$b

where in $\mathcal{M}^{KK-rescatt.}$ we have $M_{KK\to KK} = \beta_M(\hat{s})M^{\rho,\omega,\phi-meson\ exch.} + \beta_R(\hat{s})M^{Regge}$

with $\beta_M(\hat{s}) = \exp(-(\hat{s}-4m_K^2)/\Delta\hat{s})$, $\quad \beta_R(\hat{s}) = 1-\beta_M(\hat{s})$, $\quad \Delta\hat{s} = 9$ GeV^2

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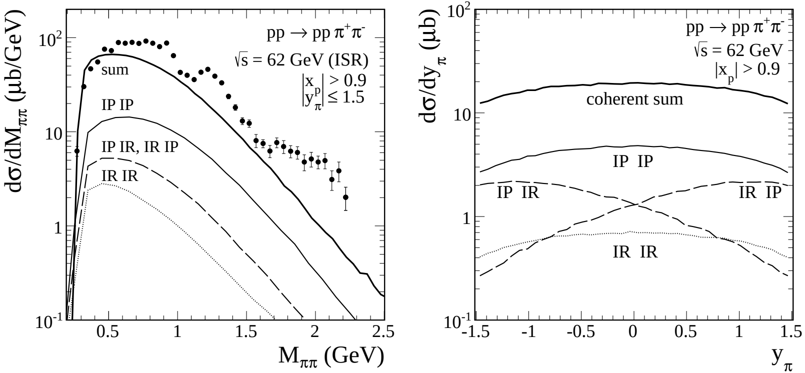
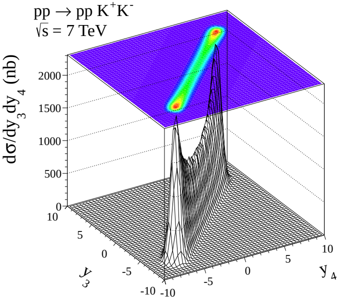
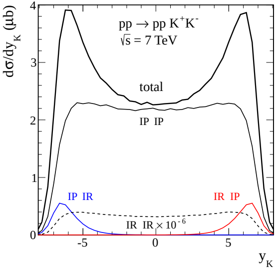
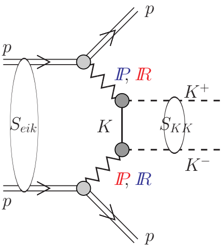


Decomposition of cross section in $M_{\pi\pi}$ and y_π
when all (upper line) and only some components in the amplitude are included

Differential cross section in rapidity space at $\sqrt{s} = 7$ TeV

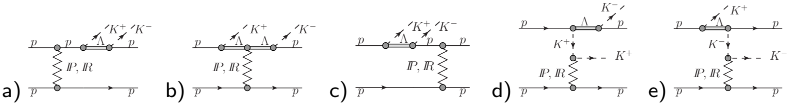




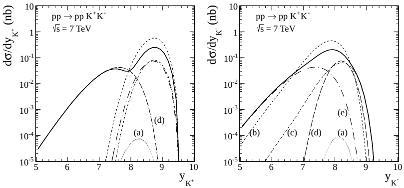


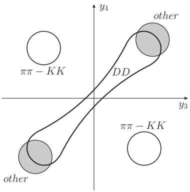
Center panel: Decomposition of cross section in ($y_K = y_3 \cong y_4$)
when all (upper line) and only some components in the amplitude are included
($IP \otimes IR$ and $IR \otimes IP$ peaks at backward and forward y_K)

Other diffractive processes

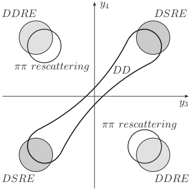


(+ diagrams with emission of kaons from second proton line)

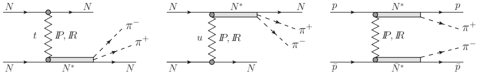




K^+K^- production

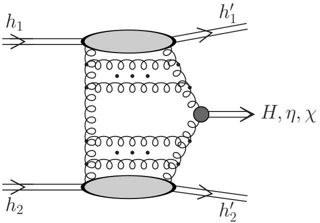


$\pi^+\pi^-$ production



(DSRE and DDRE)

Diffractive QCD mechanism



- QCD mechanism proposed by Kaidalov, Khoze, Martin, Ryskin (KKMR approach)

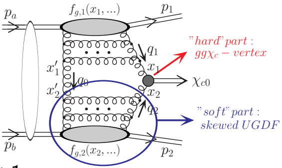
  V.A. Khoze, A.D. Martin and M.G. Ryskin, Phys. Lett **B401** (1997) 330; Eur. Phys. J. **C23** (2002) 311
  A.B. Kaidalov, V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. **C23** (2003) 387; **C33** (2004) 261

- to apply KKMR QCD mechanism to heavy quarkonia production ($H \to \chi_c$)

  R.S. Pasechnik, A. Szczurek and O.V. Teryaev, Phys. Rev. **D78** (2008) 014007 (χ_{c0} meson)
  R.S. Pasechnik, A. Szczurek and O.V. Teryaev, Phys. Lett. **B680** (2009) 62 (χ_{c1} meson)
  R.S. Pasechnik, A. Szczurek and O.V. Teryaev, Phys. Rev. **D81** (2010) 034024 (χ_{c2} meson)
  L.A. Harland-Lang, V.A. Khoze, M.G. Ryskin and W.J. Stirling, Eur. Phys. J. **C65** (2010) 433
  L.A. Harland-Lang, V.A. Khoze, M.G. Ryskin and W.J. Stirling, Eur. Phys. J. **C71** (2011) 1545

- It is interesting to test KKMR approach for diffractive light mesons production at high energies – a good probe of nonperturbative dynamics of partons described by UGDFs.

Amplitude for exclusive process $pp \to pp\chi_{c0}$



$q_{1,2} = x_{1,2}p_{1,2} + q_{1/2_\perp}$, $0 < x_{1,2} < 1$
$q_0 = x_1' p_1 + x_2' p_2 + q_{0_\perp} \approx q_{0_\perp}$, $x_1' \sim x_2' = x' \ll x_{1,2}$

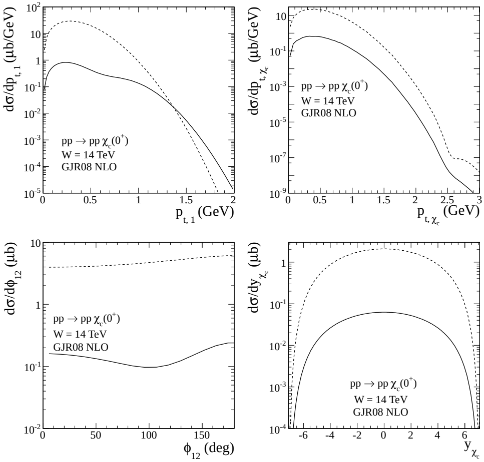
$$\mathcal{M}^{Born}_{pp\to pp\chi_c} \sim \Im \int d^2 q_{0,t}\, V(\mathbf{q}_{1,t},\mathbf{q}_{2,t}) \frac{f^{off}_{g,1}(x_1, x_1', q^2_{0,t}, q^2_{1,t}, t_1) f^{off}_{g,2}(x_2, x_2', q^2_{0,t}, q^2_{2,t}, t_2)}{q^2_{0,t}\, q^2_{1,t}\, q^2_{2,t}}$$

$gg \to \chi_{c0}$ vertex (Pasechnik, Szczurek and Teryaev)

$$V(\mathbf{q}_{1,t},\mathbf{q}_{2,t}) = K_{NLO} \frac{8 i g_s^2}{M_\chi} \frac{\mathcal{R}'(0)}{\sqrt{\pi M_\chi N_c}} \frac{3M_\chi^2 \mathbf{q}_{1,t}\mathbf{q}_{2,t} - 2\mathbf{q}^2_{1,t}\mathbf{q}^2_{2,t} - (\mathbf{q}_{1,t}\mathbf{q}_{2,t})(\mathbf{q}^2_{1,t} + \mathbf{q}^2_{2,t})}{(M_\chi^2 + \mathbf{q}^2_{1,t} + \mathbf{q}^2_{2,t})^2}$$

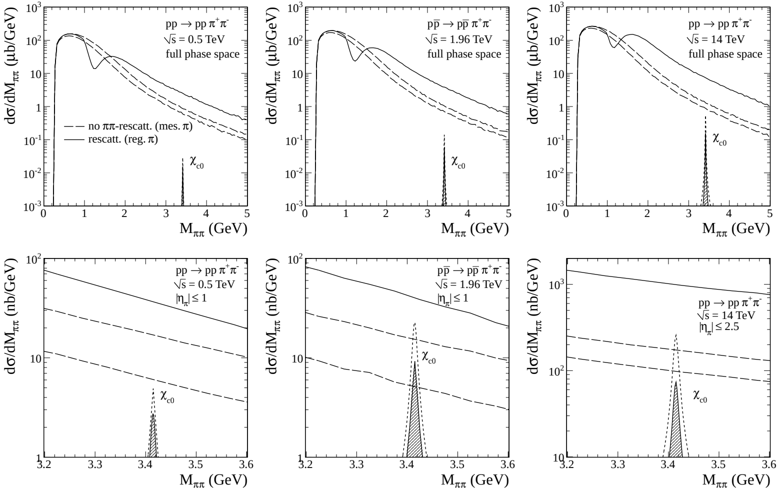
- off-shell effects included
- KMR UGDF (see V. Khoze talk)

Differential cross sections for the $pp \to pp\chi_{c0}$ reaction



$\sqrt{s} = 14$ TeV, without (dotted lines) and with (solid lines) absorption effects

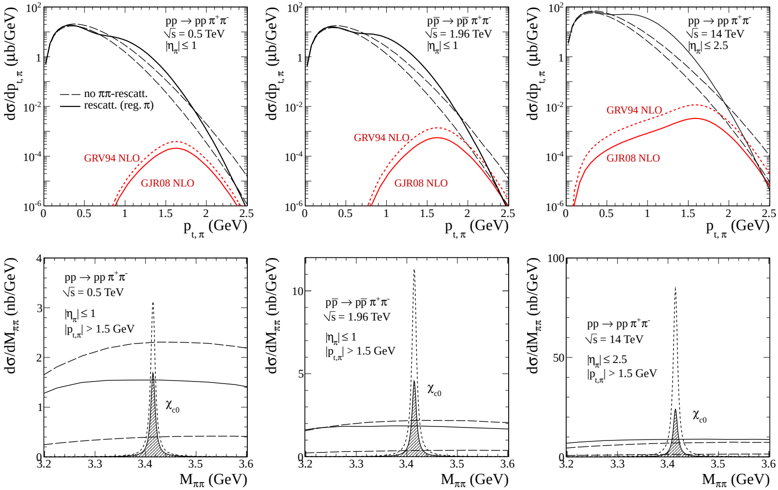
$M_{\pi^+\pi^-}$ distribution at $\sqrt{s} = 0.5, 1.96, 14$ TeV



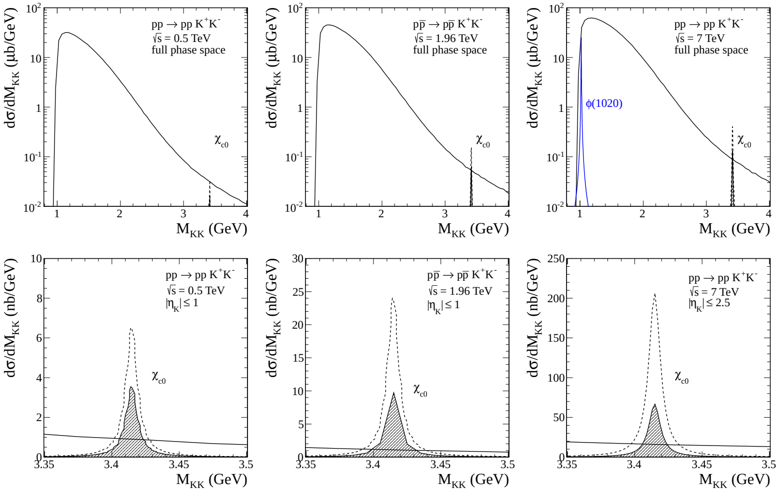
$$\frac{d\sigma_{\chi_{c0}}}{dM_{\pi\pi}} = \mathcal{B}(\chi_{c0} \to \pi^+\pi^-)\, \sigma_{pp\to pp\chi_{c0}}\, 2M_{\pi\pi}\, \frac{1}{\pi}\, \frac{M_{\pi\pi}\Gamma}{(M_{\pi\pi}^2 - M^2)^2 + (M_{\pi\pi}\Gamma)^2}$$

$p_{t,\pi}$ and $M_{\pi^+\pi^-}$ distributions at $\sqrt{s} = 0.5, 1.96, 14$ TeV

Pions from χ_{c0} decay are placed at slighty larger p_t



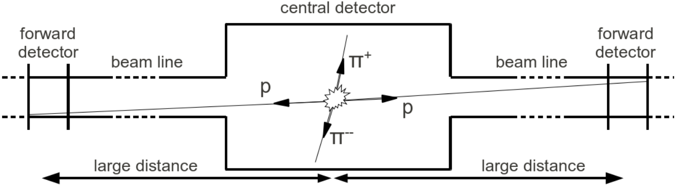
$M_{K^+K^-}$ distribution at $\sqrt{s} = 0.5, 1.96, 7$ TeV



Exclusive $\pi^+\pi^-$ Production at the LHC with Forward Proton Tagging

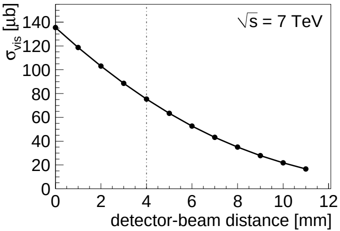
R. Staszewski, P. Lebiedowicz, M. Trzebiński, J. Chwastowski, A. Szczurek,
Acta Phys. Polon. **B 42** (2011) 1861

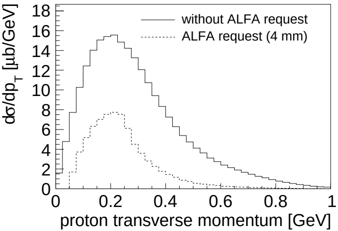
Huge total cross-section for $pp \to pp\pi^+\pi^-$: more than 200 μb for $\sqrt{s} = 7$ TeV
(see P. Lebiedowicz, A. Szczurek, Phys. Rev. **D81** (2010) 036003)



Pions detected in the ATLAS detector (tracker or calorimeter).
Protons tagged in the ALFA stations ($\sim$ 240 m far from IP).
Calculations done for $\beta^* = 90$ m LHC optics, $\sqrt{s} = 7$ TeV.

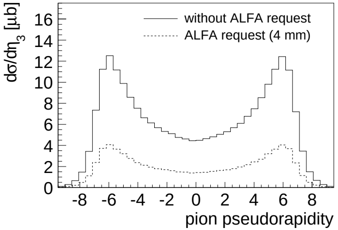
Exclusive $\pi^+\pi^-$ Production at the LHC with Forward Proton Tagging

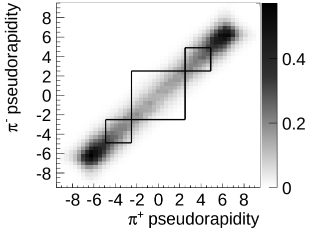




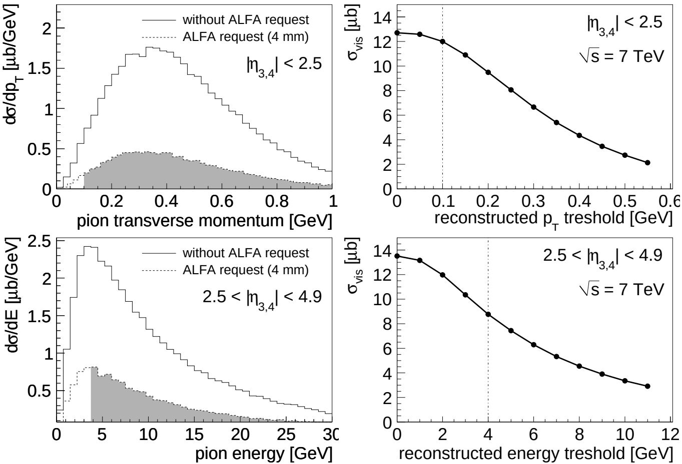
Left: Cross section visible in the ALFA detectors (both protons tagged) as a function of the distance between the detectors and the beam centre. Distance of 4mm corresponds to 75 μb of cross-section visible in the ALFA detectors.
Right: The proton p_t distribution; the dotted line marks the distribution for the events with both protons tagged by ALFA detectors positioned at 4 mm.

Most of outgoing protons are in ALFA acceptance region!





Exclusive $\pi^+\pi^-$ Production at the LHC with Forward Proton Tagging



The grey area and the vertical dash-dotted line marks the lower boundary of the region accessible by ATLAS.

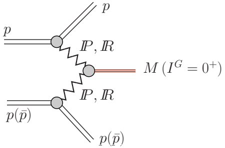
Clearly, the cross section falls very steeply with increasing thresholds values.

Measurements of exclusive $\pi^+\pi^-$ is possible!

$\sigma_{vis} = 21\mu b$ (with detector-beam distance 4 mm and $p_{t,\pi} = 0.1$ GeV, $E_\pi = 4$ GeV)

Exclusive production of resonances

$pp \to$ (tensor IP) (tensor IP) $\to p\,M\,p$



J^P	mesons
0^-	η, $\eta'(958)$
0^+	$f_0(600)$, $f_0(980)$, $f_0(1500)$
1^+	$f_1(1285)$, $f_1(1420)$
2^+	$f_2(1270)$, $f_2'(1525)$

O. Nachtmann talk "A model for high-energy soft reactions", ECT* Trento , February 2012

$$\begin{aligned}\mathcal{M}^{2\to3}_{\lambda_a\lambda_b\to\lambda_1\lambda_2 0^\pm} \;=\; & (3\beta_{PNN})^2\, F_1(t_1)\, F_1(t_2)\, F^M_{PPM}(t_1,t_2) \\ & \times \bar{u}(p_1,\lambda_1) i\Gamma^{(PNN)}_{\mu_1\nu_1} u(p_a,\lambda_a) \\ & \times i\Delta^{\mu_1\nu_1,\kappa_1\lambda_1}_{(P)} \quad i\Gamma^{(PP\to M)}_{\kappa_1\lambda_1,\kappa_2\lambda_2} \quad i\Delta^{\mu_2\nu_2,\kappa_2\lambda_2}_{(P)} \\ & \times \bar{u}(p_2,\lambda_2) i\Gamma^{(PNN)}_{\mu_2\nu_2} u(p_b,\lambda_b)\end{aligned}$$

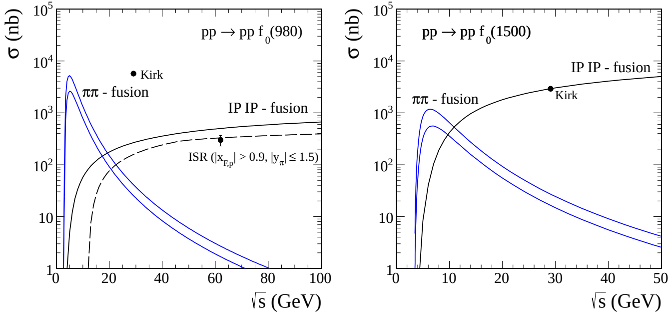
$$i\Gamma^{(PP\to 0^+)}_{\mu\nu,\kappa\lambda} = -i\, g_{PPM}\, M_0 \left(g_{\mu\kappa} g_{\nu\lambda} + g_{\mu\lambda} g_{\nu\kappa} - \frac{1}{2} g_{\mu\nu} g_{\kappa\lambda} \right)$$

$$i\Gamma^{(PP\to 0^-)}_{\mu\nu,\kappa\lambda} = -i\, \frac{g_{PPM}}{2M_0} \left(g_{\mu\kappa}\varepsilon_{\nu\lambda\rho\sigma} + g_{\nu\kappa}\varepsilon_{\mu\lambda\rho\sigma} + g_{\mu\lambda}\varepsilon_{\nu\kappa\rho\sigma} + g_{\nu\lambda}\varepsilon_{\mu\kappa\rho\sigma} \right) (q_1 - q_2)^\rho (q_1 + q_2)^\sigma$$

The coupling constants g_{PPM} have been fitted to exp. data

$J^P = 0^+$

preliminary results (Lebiedowicz, Nachtmann, Szczurek)



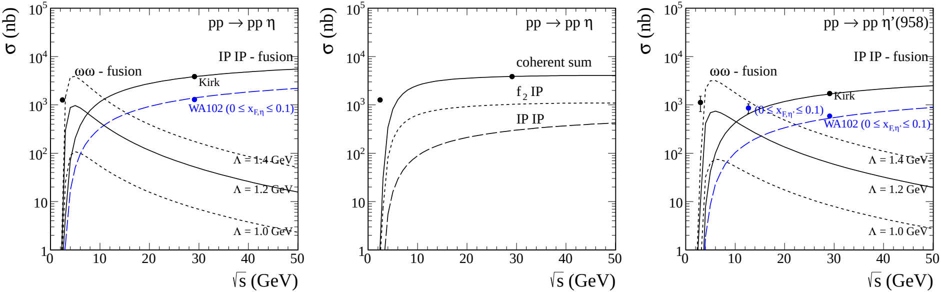
COMPASS could help in understanding this situation !

At low energy the $\pi\pi$-fusion dominates,
$F(t) = \frac{\Lambda^2 - m_M^2}{\Lambda^2 - t}$, where $\Lambda = 0.8$ GeV (bottom line) and $\Lambda = 1.2$ GeV (upper line)
(see A. Szczurek and P. Lebiedowicz, Nucl. Phys. **A826** (2009) 101).

data from: A. Kirk, Phys. Lett. **B489** (2000) 29; A. Breakstone *et al.* (ABCDHW Collaboration), Z. Phys. **C48** (1990) 569.

$J^P = 0^-$

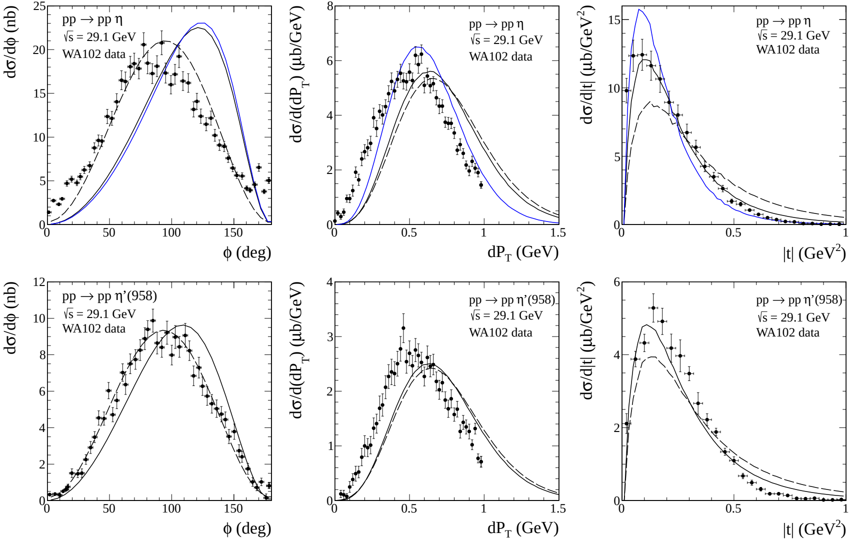
preliminary results (Lebiedowicz, Nachtmann, Szczurek)



At lower energies we expect large $\omega\omega$-exchange contribution due to large $g_{NN\omega}$.
We use here $F(t) = \exp\left(t - m_M^2/\Lambda^2\right)$ from $\Lambda = 1.0$ GeV (bottom line) to 1.4 GeV (upper line).

data from: WA102 (D. Barberis *et al.*), Phys. Lett. **B427** (1998) 398; **B467** (1999) 165; A. Kirk, Phys. Lett. **B489** (2000) 29.

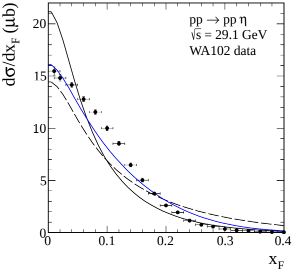
tensor IP (black solid line), tensor IP + f_2 (blue solid line), vector IP (dashed line)

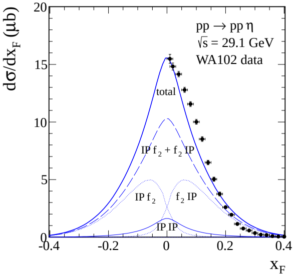


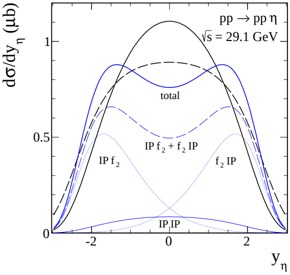
$$dP_{\perp} = \mathbf{q}_{1\perp} - \mathbf{q}_{2\perp}$$ (see Close and Schuler)

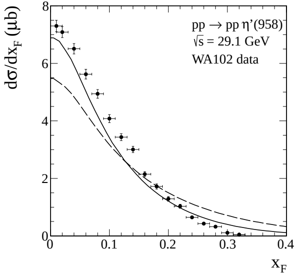
data from: WA102 Collaboration (D. Barberis *et al.*), Phys. Lett. **B427** (1998) 398; A. Kirk, Phys. Lett. **B489** (2000) 29.

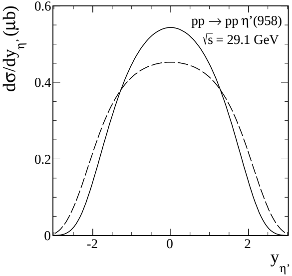
tensor IP (black solid line), tensor IP + f_2 (blue solid line), vector IP (dashed line)







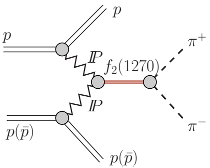


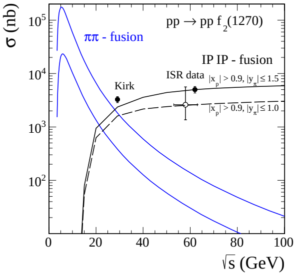


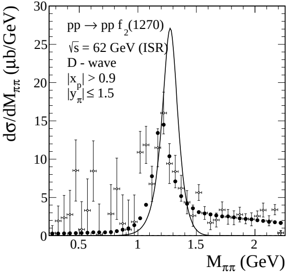
data from: WA102 Collaboration (D. Barberis *et al.*), Phys. Lett. **B427** (1998) 398; A. Kirk, Phys. Lett. **B489** (2000) 29.

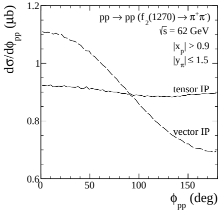
$f_2(1270)$ production: $pp \to$ (tensor $I\!P$) (tensor $I\!P$) $\to p\, \pi^+ \pi^-\, p$

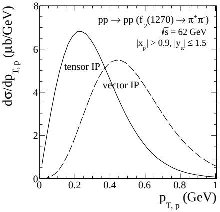
preliminary results (Lebiedowicz, Nachtmann, Szczurek)







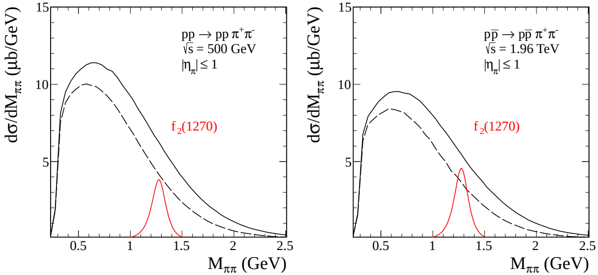




data from: A. Kirk, Phys. Lett. **B489** (2000) 29; A. Breakstone *et al.* (ABCDHW Collaboration), Z. Phys. **C48** (1990) 569; R. Waldi *et al.*, Z. Phys. **C18** (1983) 301.

$f_2(1270)$ production: $pp \to$ (tensor IP) (tensor IP) $\to p\,\pi^+\pi^-\,p$

preliminary results (without cuts on $p_{\perp,\pi}$)



In principle, the resonance and continuum contributions can be added coherently together leading to the distortion of the $f_2(1270)$ line shape as observe for the $\gamma\gamma \to f_2(1270) \to \pi^+\pi^-$ (see A. Szczurek and J. Speth, Nucl. Phys. **A728** (2003) 182).

work in progress

see also talks: L. Adamczyk, M. Albrow

Conclusions

- Difficulty to seperate $\chi_c(0^+)$, $\chi_c(1^+)$, $\chi_c(2^+)$ in the $J/\psi\gamma$ channel
  $\rightarrow$ possible in the $\pi^+\pi^-$, K^+K^- channels (at RHIC, Tevatron and LHC)
  $\rightarrow$ $pp\chi_{c0}$ grows much faster with $\sqrt{s}$ than $pp\pi^+\pi^-$, ppK^+K^-

  P. Lebiedowicz, R. Pasechnik and A. Szczurek, Phys. Lett. **B701**, 434 (2011)

  P. Lebiedowicz and A. Szczurek, Phys. Rev. **D85**, 014026 (2012)

- χ_c amplitudes can be written in terms of off-diagonal UGDF's
- Several differential distributions for $pp \to pp\chi_{c0}$, $pp\pi^+\pi^-$, ppK^+K^- processes including absorptive corrections are calculated
  $\rightarrow$ influence of kinematical cuts on the S/B ratio has been investigated
- With enough statistic it should be possible to see resonance states in $M_{\pi\pi}$, e.g. $f_2(1270)$, glueball candidates ($f_0(1500)$), charmonia ($\chi_c(0^+)$)
- We have found that tensorial Pomeron (O. Nachtmann) may equally well describe experimental data on exclusive meson production as the vectorial Pomeron used in the literature. The present experimental data do not allow to clearly distinguish between the two models. Future experimental data on exclusive meson production at higher energies may give a better answer on the spin structure of the Pomeron and its coupling to the nucleon and mesons