# Exclusive meson pair production in proton-proton collisions

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# Introduction

The 4-body reactions $pp \to p\pi^+\pi^- p$ and $pp \to pK^+K^- p$
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 $\chi_c$ 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 $\chi_{cJ}$ 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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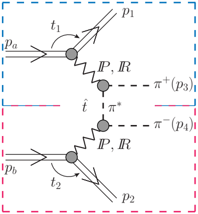
**Could other decay channels be used ?**

| 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

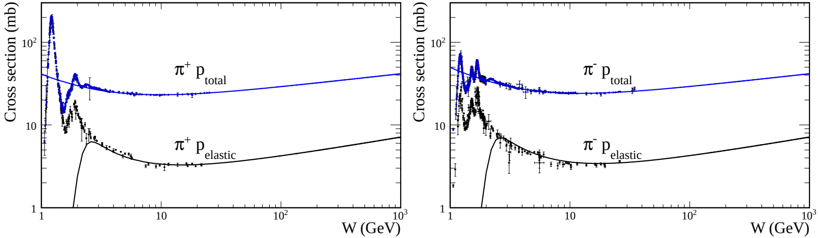
$$\mathcal{M}^{Born}_{pp\to pp\pi\pi} = M_{13}(s_{13},t_1)F_\pi(\hat{t})\frac{1}{\hat{t}-m_\pi^2}F_\pi(\hat{t})M_{24}(s_{24},t_2)$$
$$+ M_{14}(s_{14},t_1)F_\pi(\hat{u})\frac{1}{\hat{u}-m_\pi^2}F_\pi(\hat{u})M_{23}(s_{23},t_2), \qquad F_\pi(\hat{t}/\hat{u}) = \exp\left(\frac{\hat{t}/\hat{u}-m_\pi^2}{\Lambda^2_{off}}\right)$$

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

$$\mathcal{P}^\pi(\hat{t}/\hat{u},\hat{s}) = \frac{1+\exp(-i\pi\alpha_\pi(\hat{t}/\hat{u}))}{\sin\pi\alpha_\pi(\hat{t}/\hat{u})}\left(\frac{\hat{s}}{\hat{s}_0}\right)^{\alpha_\pi(\hat{t}/\hat{u})}\frac{\pi\alpha'_\pi}{2\Gamma(\alpha_\pi(\hat{t}/\hat{u})+1)}$$
$$\alpha_\pi(\hat{t}/\hat{u}) = \alpha'_\pi(\hat{t}/\hat{u}-m_\pi^2) \text{ with a slope } \alpha'_\pi = 0.7\ \text{GeV}^{-2}$$

functions of interpolation between meson and reggeon exchanges
$\beta_M(\hat{s}) = \exp\left(-(\hat{s}-4m_\pi^2)/\Lambda^2_{int}\right), \beta_R(\hat{s}) = 1-\beta_M(\hat{s})$

# $\pi p$ cross sections



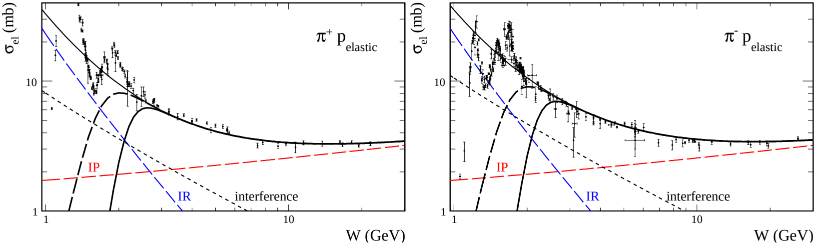

- Donnachie-Landshoff parametrization for total $\pi N$ cross section ($\sigma_{tot}^{\pi p} = C_i s^{\alpha_i(0)-1}$ , $i = IP, IR$):

$$\sigma_{tot}^{\pi^+ p}: \ 13.63 s^{0.0808} + 27.56 s^{-0.4525}$$
$$\sigma_{tot}^{\pi^- p}: \ 13.63 s^{0.0808} + 36.02 s^{-0.4525}$$

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

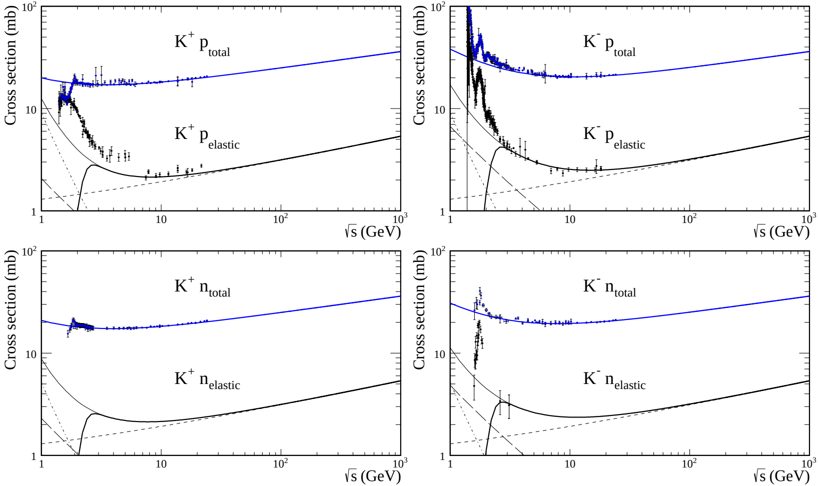
  the values of pomeron and reggeon couplings to $\pi p$:
  $C_{IP} = 13.63 mb$, $C_{f_2} = 31.79 mb$, $C_\rho = 4.23 mb$

# $\pi p$ elastic scattering




- nicely describes the $\pi p_{elastic}$ data for $\sqrt{s} > 2.5$ GeV with slope parameters $B(s) = B_i^{\pi p} + 2\alpha_i' \ln(\frac{s}{s_0})$: $B_{IP}^{\pi p} = 5.5$ GeV$^{-2}$ and $B_{IR}^{\pi p} = 4$ GeV$^{-2}$
- smooth cut-off correction factor $f_{cont}^{\pi N}(W) = \exp\left(\frac{W - W_{cut}}{a_{cut}}\right) / (1 + \exp\left(\frac{W - W_{cut}}{a_{cut}}\right))$ where $W_{cut} = 1.5$ GeV (dashed line) and 2 GeV (solid line), $a_{cut} = 0.2$ GeV
- model includes absorption effects in an effective way

# $Kp$ and $Kn$ cross sections

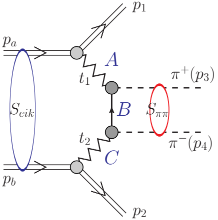



$$M_{K^{\pm}p}(s,0) = A_{I\!P}(s) + A_{f_2}(s) + A_{a_2}(s) \mp A_{\omega}(s) \mp A_{\rho}(s)$$
$$M_{K^{\pm}n}(s,0) = A_{I\!P}(s) + A_{f_2}(s) - A_{a_2}(s) \mp A_{\omega}(s) \pm A_{\rho}(s)$$

# 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.

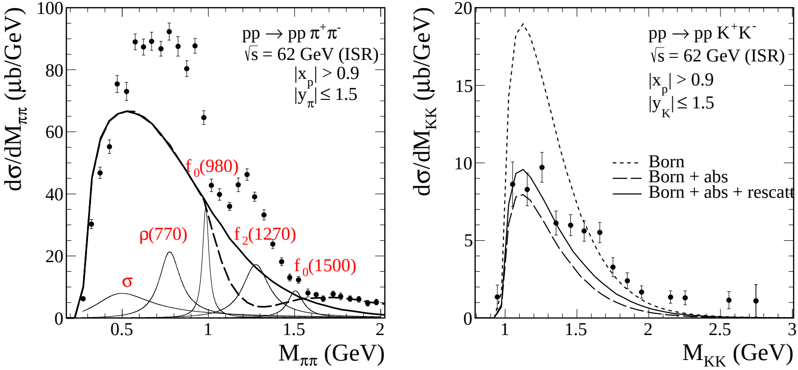
$$\frac{F_\pi^2(\hat{t})}{\hat{t}-m_\pi^2} \to \frac{i}{16\pi^2\hat{s}}\int d^2\kappa\,\frac{F_\pi^2(\hat{t}_1)}{\hat{t}_1-m_\pi^2}M_{\pi^+\pi^-\to\pi^+\pi^-}(\hat{s},\hat{t}_2)$$

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

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

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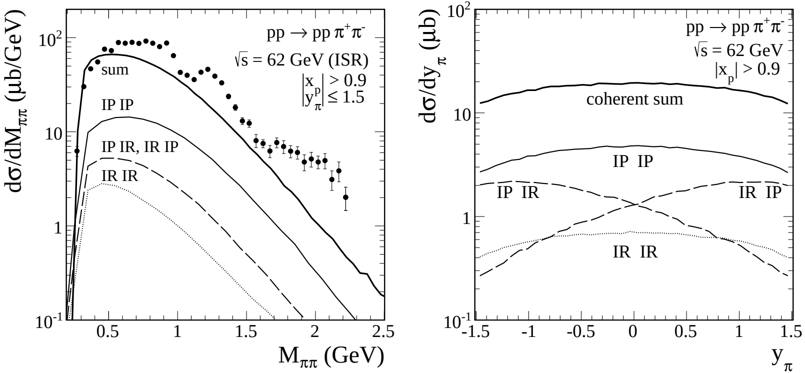


Decomposition of cross section in $M_{\pi\pi}$ and $y_\pi$
when all (upper line) and only some components in the amplitude are included

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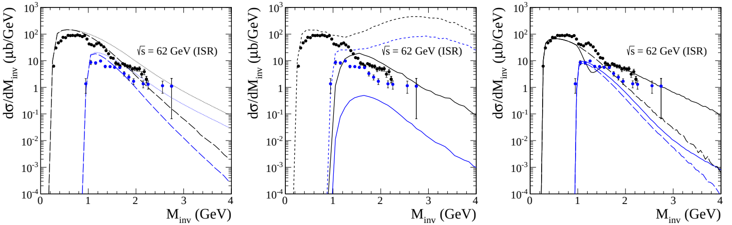



Black lines - $\pi^+\pi^-$ distributions, blue lines - $K^+K^-$ distributions.

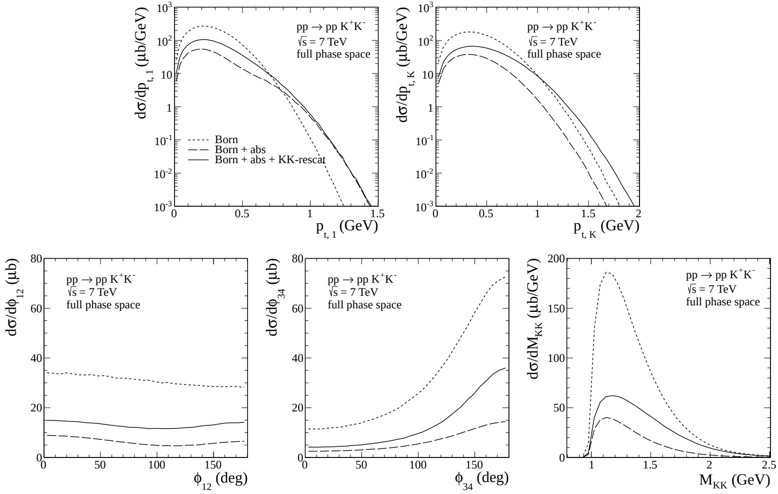
Left: born, mesonic propagator (dotted lines), mesonic + regge propagator (dashed lines).
We see that at $W = 4$ GeV, where secondary reggeons are small, we have a factor $(g_{IP}^{\pi\pi}/g_{IP}^{KK})^4 \approx 2$ suppression of cross section.

Central: born, $\pi\pi$- and $KK$-rescat. contribution with smooth cut correction factor $S_{thr}(\hat{s})$ (solid lines).
We see 2 orders of magnitude difference between the $\pi\pi$ and $KK$ cross sections $\rightarrow$ role of formfactors !

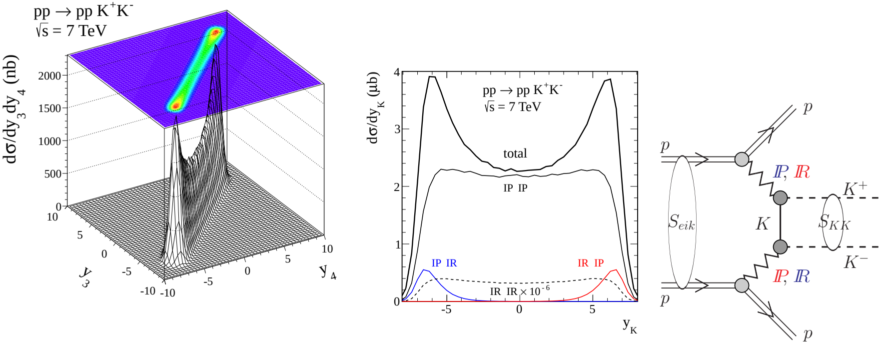
$$S_{thr}(\hat{s}) = \begin{cases} 0, & \hat{s} \leqslant \hat{s}_{thr} = 4m_K^2, \\ 1 - \exp(-(\hat{s} - \hat{s}_{thr})/\Delta\hat{s}), & \hat{s} > \hat{s}_{thr} = 4m_K^2, \quad \Delta\hat{s} = 9 \text{ GeV}^2 \end{cases}$$

Right: born+abs (dashed lines), born+abs+rescat (solid lines) with cut correction factor $fthr(s)$ for $\pi^+\pi^-$-rescat. contribution.
At $KK$-rescat. contribution we included also vector meson exchanges.

# Differential cross section at $\sqrt{s} = 7$ TeV

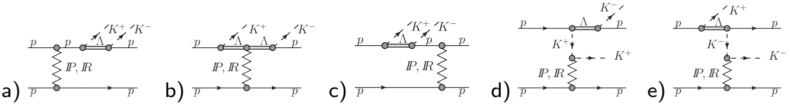


# Differential cross section in rapidity space at $\sqrt{s} = 7$ TeV

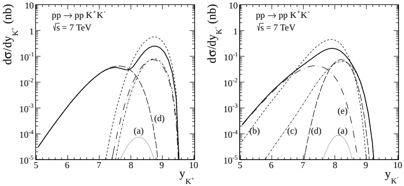


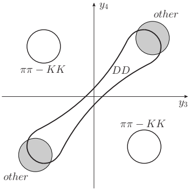

Center panel: Decomposition of cross section in ($y_K = y_3 \cong y_4$)
when all (upper line) and only some components in the amplitude are included
($IP \otimes IR$ and $IR \otimes IP$ peaks at backward and forward $y_K$)

# Other diffractive processes

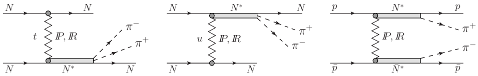


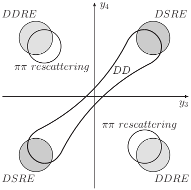

(+ diagrams with emission of kaons from second proton line)




$K^+K^-$ production

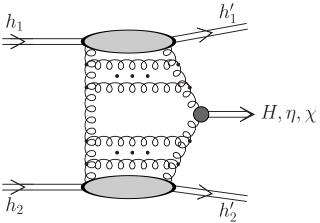



$\pi^+\pi^-$ production

(DSRE and DDRE)

# Diffractive QCD mechanism




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

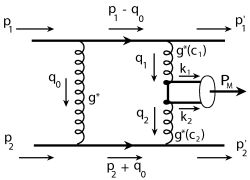
  V.A. Khoze, A.D. Martin and M.G. Ryskin, Phys. Lett **B401** (1997) 330; Eur. Phys. J. **C23** (2002) 311
  A.B. Kaidalov, V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. **C23** (2003) 387; **C33** (2004) 261

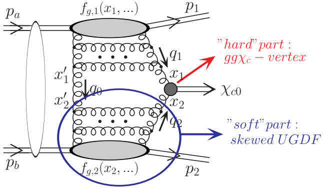
- to apply KKMR QCD mechanism to heavy quarkonia production ($H \to \chi_c$)

  R.S. Pasechnik, A. Szczurek and O.V. Teryaev, Phys. Rev. **D78** (2008) 014007 ($\chi_{c0}$ meson)
  R.S. Pasechnik, A. Szczurek and O.V. Teryaev, Phys. Lett. **B680** (2009) 62 ($\chi_{c1}$ meson)
  R.S. Pasechnik, A. Szczurek and O.V. Teryaev, Phys. Rev. **D81** (2010) 034024 ($\chi_{c2}$ 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 $pp \to pp\chi_{c0}$




decomposition of gluon momenta

$q_{1,2} = x_{1,2}p_{1,2} + q_{1/2_\perp}$, $0 < x_{1,2} < 1$

$q_0 = x'_1 p_1 + x'_2 p_2 + q_{0_\perp} \approx q_{0_\perp}$, $x'_1 \sim x'_2 = x' \ll x_{1,2}$

$$\mathcal{M}^{Born}_{pp\to pp\chi_c} \sim \Im \int d^2 q_{0,t}\, V(\mathbf{q}_{1,t}, \mathbf{q}_{2,t}) \frac{f^{off}_{g,1}(x_1, x'_1, q^2_{0,t}, q^2_{1,t}, t_1) f^{off}_{g,2}(x_2, x'_2, q^2_{0,t}, q^2_{2,t}, t_2)}{q^2_{0,t}\, q^2_{1,t}\, q^2_{2,t}}$$

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

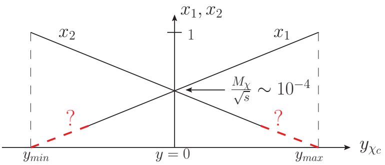
gg $\to \chi_{c0}$ vertex [Pasechnik, Szczurek and Teryaev] where active gluon virtualities (transverse momenta) are explicitly taken into account, $g_s^2 = 4\pi\alpha_s(M^2_\chi)$ - Shirkov-Solovtsov, $\mathcal{R}'_{\chi_{cJ}}(0) = \sqrt{0.075}$ GeV$^{5/2}$, $K_{NLO} \simeq 1.68$

# KMR UGDF

two gluon kinematics → one gluon "effective" kinematics with $Q^2_{1/2,t} = \min(q^2_{0,t}, q^2_{1/2,t})$

$$f_g^{KMR}(x, x', Q_t^2, \mu^2; t) = R_g \frac{\partial}{\partial \ln q_t^2}\left[xg(x, q_t^2)\sqrt{T_g(q_t^2, \mu^2)}\right]_{q_t^2 = Q_t^2} F(t)$$

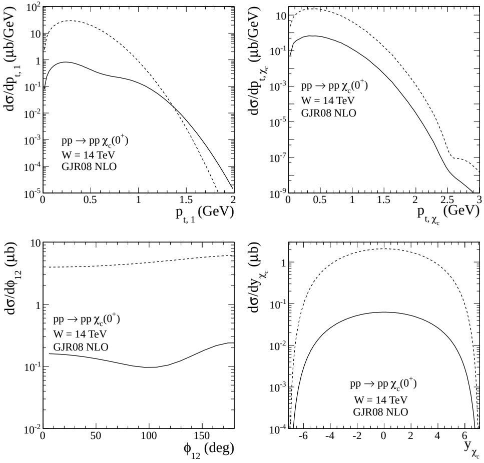
- $R_g$: *accounts for skewed effect*
- $xg(x, q_t^2)$: *integrated density, defined at $Q_t > Q_0$*
- $T_g(q_t^2, \mu^2)$: *Sudakov f.f. (ensures the purity of rapidity gaps)*
- $F(t)$: *effective f.f. $F(t) = \exp(bt/2)$, $b = 4\,GeV^{-2}$*




at $\sqrt{s} = 14$ TeV

- "hard" scale $\mu^2 = M_\chi^2$
- we use GRV NLO and GJR NLO collinear gluon distributions ($Q_t^2 > 0.5$ GeV$^2$)
- skewed KMR UGDFs does not explicitly depend on $x'$, assuming $x' \ll x \ll 1$;
- in terms of the meson rapidity
  $sx_1x_2 = M_\chi^2 + |\mathbf{P}_\perp|^2 \equiv M_\perp^2$
  $x_{1,2} = \frac{M_\perp}{\sqrt{s}} exp(\pm y)$

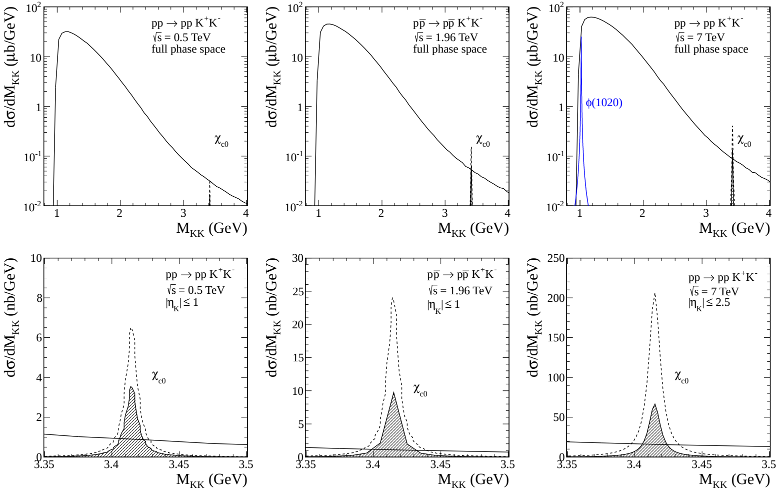
# Differential cross sections for the $pp \to pp\chi_{c0}$ reaction




at $\sqrt{s} = 14$ TeV

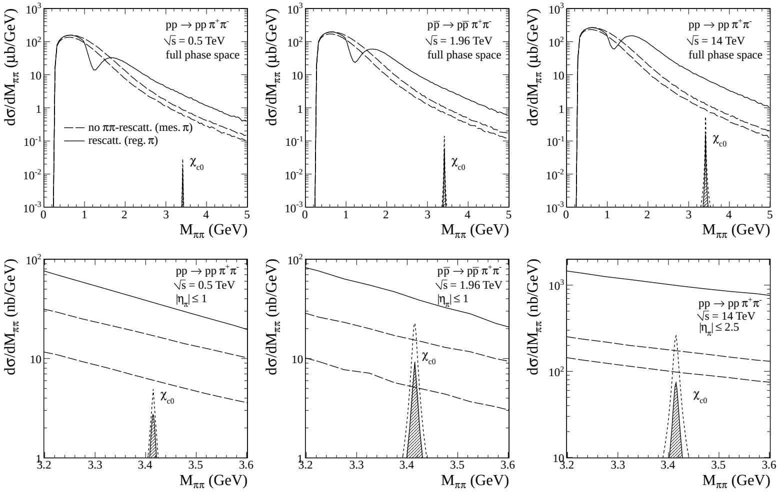
without (upper lines) and with (lower lines) absorption effects

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



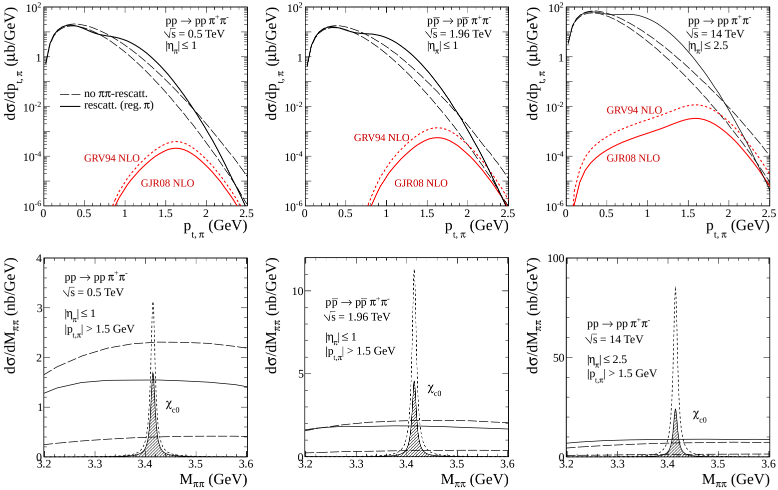

$$\frac{d\sigma_{\chi_{c0}}}{dM_{KK}} = \mathcal{B}(\chi_{c0} \to K^+K^-)\, \sigma_{pp\to pp\chi_{c0}}\; 2M_{KK}\, \frac{1}{K}\, \frac{M_{KK}\Gamma}{(M_{KK}^2 - M^2)^2 + (M_{KK}\Gamma)^2}$$

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



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

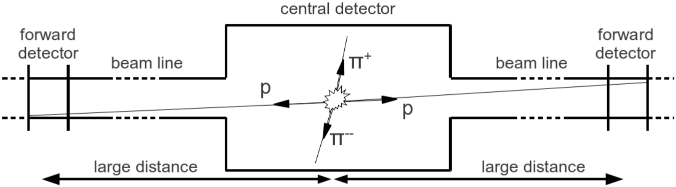
Pions from $\chi_{c0}$ decay are placed at slighty larger $p_t$



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

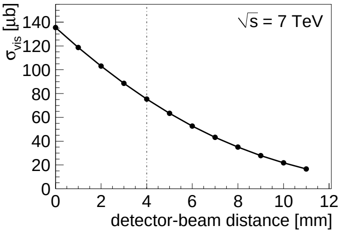
**R. Staszewski, P. Lebiedowicz, M. Trzebiński, J. Chwastowski, A. Szczurek, Acta Phys. Polon. B 42 (2011) 1861**

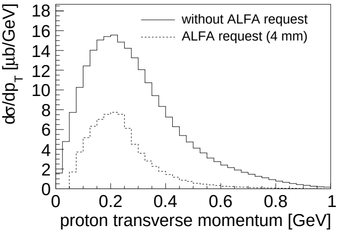
Huge total cross-section for $pp \to pp\pi^+\pi^-$: more than 200 $\mu b$ for $\sqrt{s} = 7$ TeV
(see P. Lebiedowicz, A. Szczurek, Phys. Rev. **D81** (2010) 036003)




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.

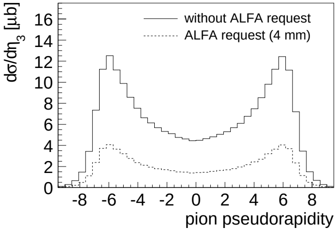
# Exclusive $\pi^+\pi^-$ Production at the LHC with Forward Proton Tagging

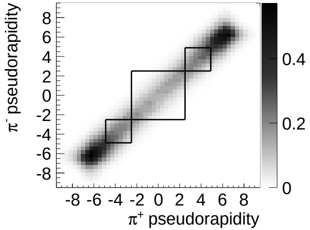


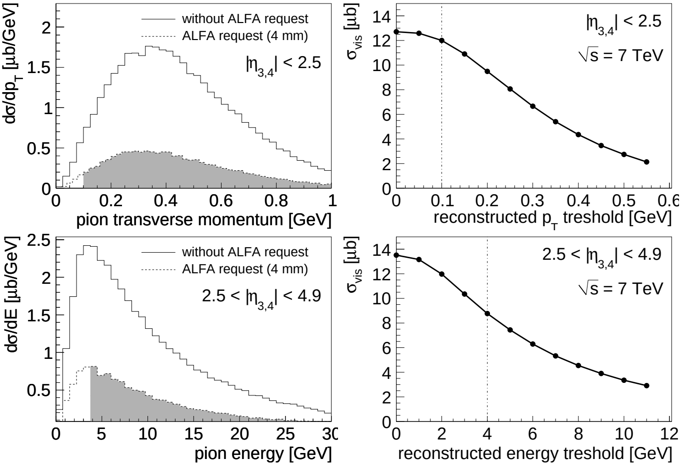

Left: Cross section visible in the ALFA detectors (both protons tagged) as a function of the distance between the detectors and the beam centre. Distance of 4mm corresponds to 75 $\mu b$ of cross-section visible in the ALFA detectors.
Right: The proton $p_t$ distribution; the dotted line marks the distribution 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

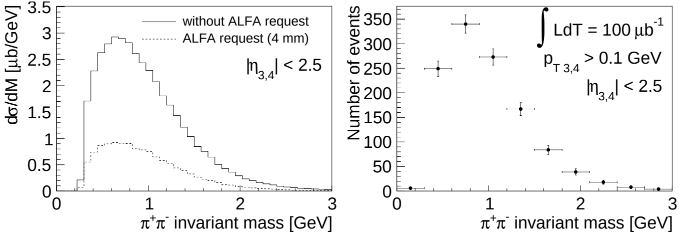



The grey area and the vertical dash-dotted line marks the lower boundary of the region accessible by ATLAS.

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

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

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




Right: Possible measurement of the $\pi^+\pi^-$ invariant mass distribution for L $= 100\ \mu$b$^{-1}$ (luminosity: $10^{27}$ cm$^{-2}$s$^{-1}$, data collecting time: 30h). Only the statistical errors are plotted.

With enough statistic it should be possible to see:
$f_2(1270)$, glueball candidates (*e.g.* $f_0(1500)$), charmonia (*e.g.* $\chi_{c0}$).

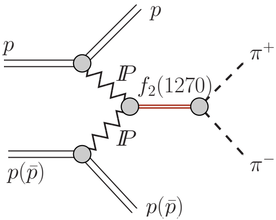
$\rightarrow$ Measurements of exclusive $\pi^+\pi^-$ is possible!
$\rightarrow$ It requires ALFA triger and low-$p_t$ tracking.

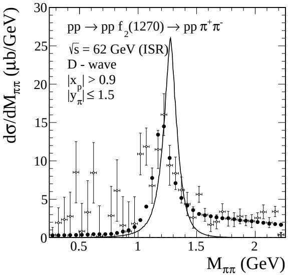
$\rightarrow$ Similar production of $K^+K^-$ and $p\bar{p}$

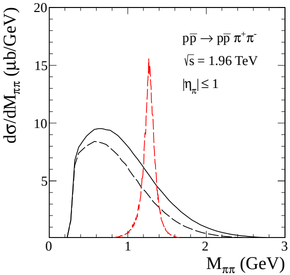
# $f_2(1270)$ production in the reaction: $pp \to$ (tensor $I\!P$) (tensor $I\!P$) $\to pp\pi^+\pi^-$

see O. Nachtmann talk "A model for high-energy soft reactions", ECT* Trento, Exclusive and diffractive processes in high energy proton-proton and nucleus-nucleus collisions, February 27 - March 2, 2012

preliminary results:




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

see talk M. Żurek

# Conclusions

- Difficulty to seperate $\chi_c(0^+)$, $\chi_c(1^+)$, $\chi_c(2^+)$ in the $J/\psi\gamma$ channel
- 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)
- $\chi_c$ amplitudes can be written in terms of off-diagonal UGDF's
- Several differential distributions for $pp \rightarrow pp\chi_{c0}$, $pp\pi^+\pi^-$, $ppK^+K^-$ processes including absorptive corrections are calculated
- With enough statistic it should be possible to see in $M_{\pi\pi}$:
  $f_2(1270)$, glueball candidates, charmonia ( e.g. $\chi_c(0^+)$)
- Influence of kinematical cuts on the S/B ratio has been investigated