

Short review of $pp \rightarrow ppX$ processes - prospects for LHC

Antoni Szczurek

Institute of Nuclear Physics (PAN), Cracow, Poland
Rzeszów University, Rzeszów, Poland

Results and prospects of forward physics at the LHC

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- $pp \rightarrow pp\gamma\gamma$
- $pp \rightarrow pp\gamma$
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- $pp \rightarrow pp\pi^+\pi^-$
- Conclusions

Introduction

- Most of the high energy processes concentrated on single particle distributions (in transverse momentum or (pseudo)rapidity)
- Exclusive a few body final states studied very rarely
- **QCD type processes – KMR mechanism**
 - $pp \rightarrow ppH$ (Higgs boson properties)
 - $pp \rightarrow pp\chi_c$
 - $pp \rightarrow ppb\bar{b}$ (Higgs background)
 - $pp \rightarrow ppgg$
 - $pp \rightarrow pp\gamma\gamma$
 - $pp \rightarrow ppMM$ (large invariant masses of mesons)
- **QED processes**
 - $pp \rightarrow pp\mu^+\mu^-$ (e.m. form factors)
 - $pp \rightarrow ppW^+W^-$ (gauge boson coupling)
 - $pp \rightarrow ppm\bar{m}$ (Dirac monopoles)



Introduction, continued

- QCD photoproduction of vector mesons

- $pp \rightarrow ppJ/\psi$ (search for odderon)
- $pp \rightarrow pp\Upsilon$
- $pp \rightarrow pp\rho(\omega, \phi)$
- $pp \rightarrow ppZ^0$

- Production of meson pairs

- $pp \rightarrow pp\pi^+\pi^-$ (search for glueballs)
- $pp \rightarrow ppK^+K^-$
- $pp \rightarrow nn\pi^+\pi^+$

mechanism of the reaction

diffractive excitation of resonances

glueballs (?)

large contribution to central diffraction cross section

low energy theorems ($gg \rightarrow \pi\pi$)

Introduction, continued

- Production of single pion

- $pp \rightarrow pp\pi^0$
- $pp \rightarrow pn\pi^+$

Large cross section

Large contribution to single diffraction cross section

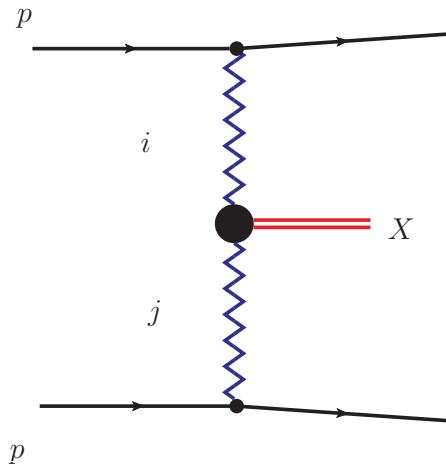
Contribution to large rapidity production (cosmic ray interactions)

- Diffractive excitation of single resonances

- $pp \rightarrow pp\gamma$

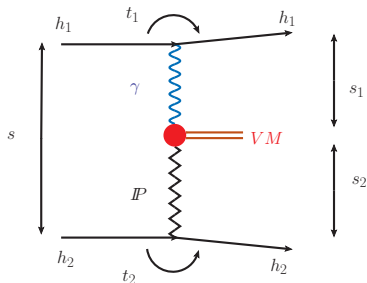


Central exclusive production



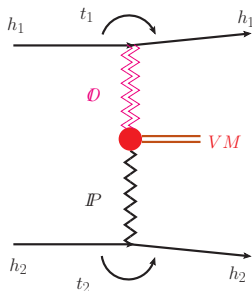
Exclusive Production of $J/\psi, \Upsilon$ in Hadronic Collision

Photoproduction



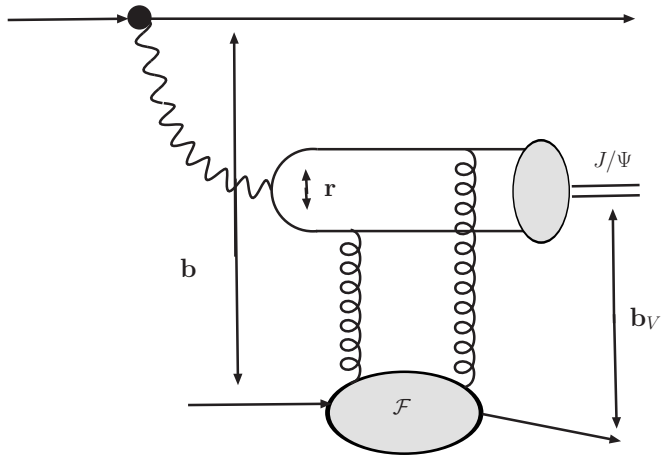
Khoze-Martin-Ryskin '02; Klein & Nystrand '04
cross section \sim nanobarns

Odderon-Pomeron fusion

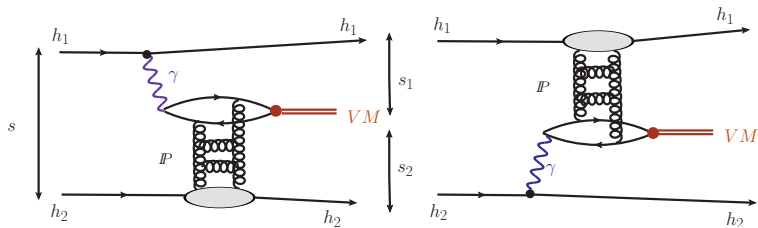


A. Schäfer, Mankiewicz & Nachtmann '91
cross section \sim 0.1 nanobarns

In QCD



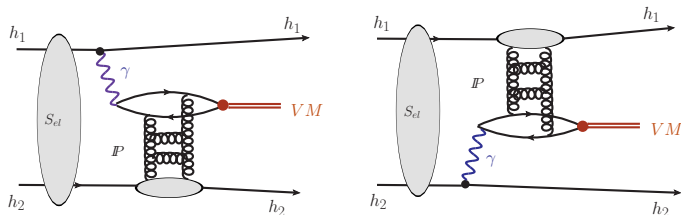
Exclusive Photoproduction in Hadronic Collisions



$$\begin{aligned}
 M(\mathbf{p}_1, \mathbf{p}_2) &= e_1 \frac{2}{z_1} \frac{\mathbf{p}_1}{t_1} \mathcal{F}_{\hat{n}'_1 \hat{n}_1}(\mathbf{p}_1, t_1) \mathcal{M}_{\gamma^* h_2 \rightarrow V h_2}(s_2, t_2, Q_2^2) \\
 &+ e_2 \frac{2}{z_2} \frac{\mathbf{p}_2}{t_2} \mathcal{F}_{\hat{n}'_2 \hat{n}_2}(\mathbf{p}_2, t_2) \mathcal{M}_{\gamma^* h_1 \rightarrow V h_1}(s_1, t_1, Q_2^2).
 \end{aligned}$$



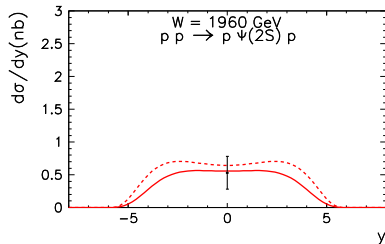
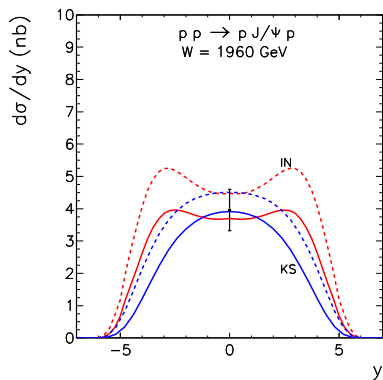
Absorption corrections



$$M(\mathbf{p}_1, \mathbf{p}_2) = \int \frac{d^2\mathbf{k}}{(2\pi)^2} S_{el}(\mathbf{k}) M^{(0)}(\mathbf{p}_1 - \mathbf{k}, \mathbf{p}_2 + \mathbf{k})$$

- Absorptive corrections depend on elastic $h_1 h_2$ amplitude
→ taken from data.
- photon pole → peripheral interactions → Absorption at 20%–level.

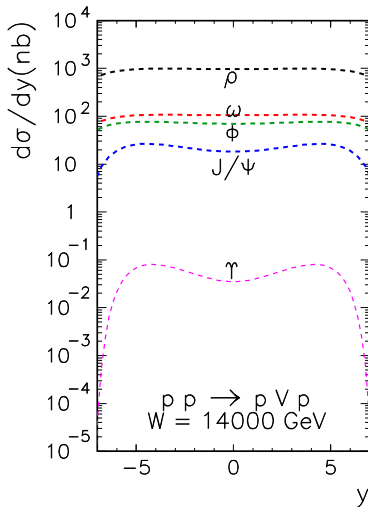
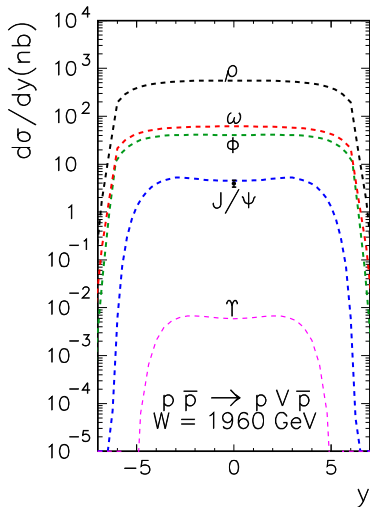
Rapidity spectra at Tevatron



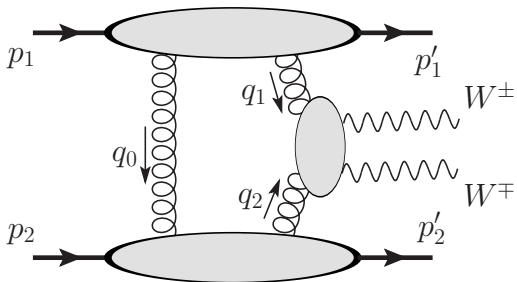
- CDF collaboration, T. Aaltonen et al. Phys. Rev. Lett. 102 (2009)
- W. Schäfer & A. Szczurek Phys. Rev. D76 (2007).
- calculations by A. Cisek, PhD thesis (2012),



Rapidity spectra at Tevatron/LHC energies



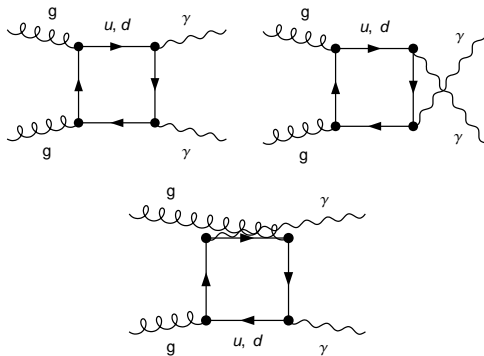
$pp \rightarrow pp\gamma\gamma$

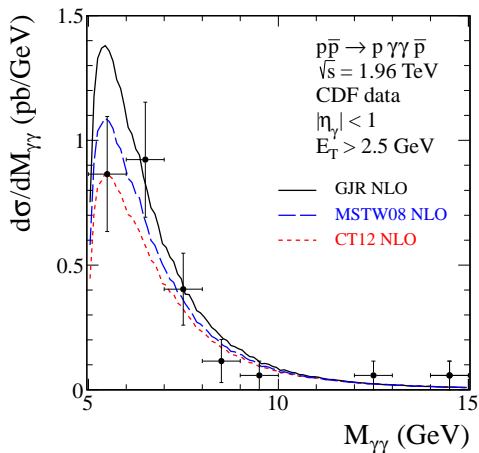


Lebiedowicz, Pasechnik, Szczurek

Nucl. Phys. **B867** (2013) 61.

$pp \rightarrow pp\gamma\gamma$

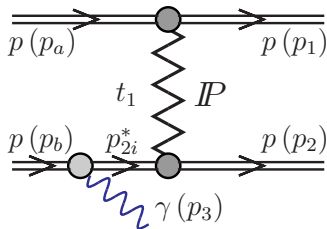
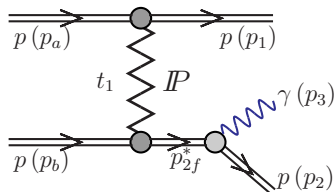
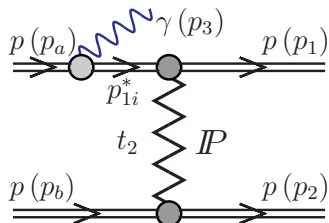
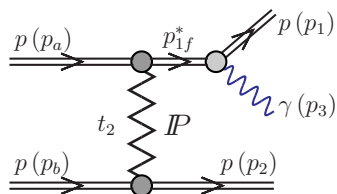




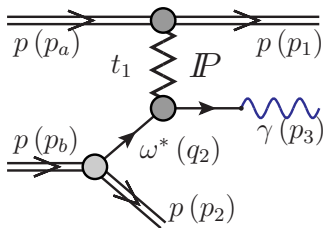
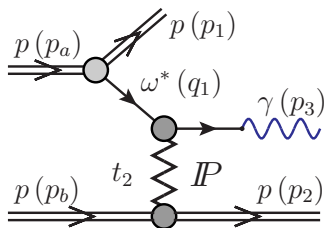
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Classical bremsstrahlung



Vector meson rescattering (new)



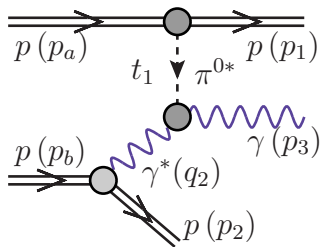
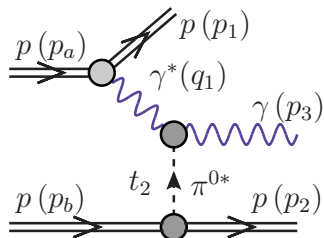
Vector meson is off-mass shell.

Similar diagrams for ρ^0 meson.

The diagrams for ω and ρ^0 interfere.

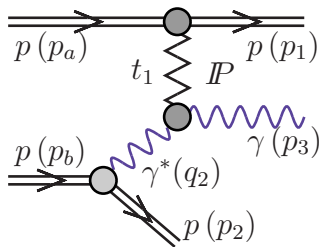
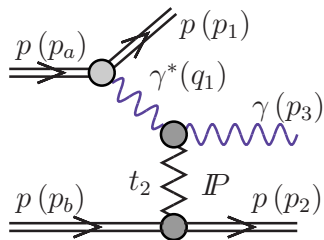


Pion cloud contribution (new)



Anomalous coupling, but off-shell pion

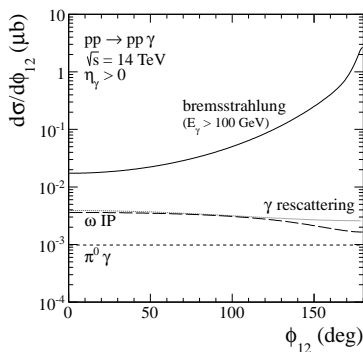
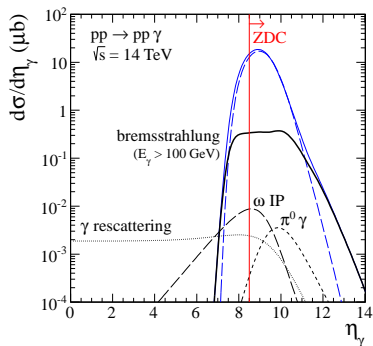
Photon rescattering (new)



photon-proton quasi-elastic scattering



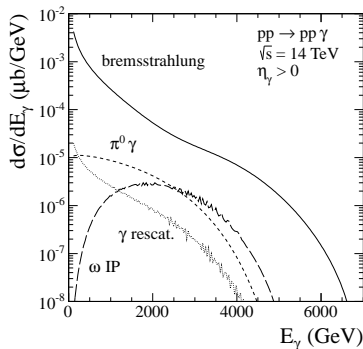
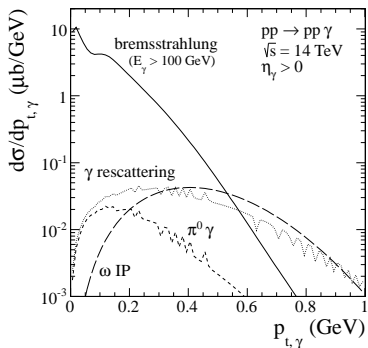
Differential distributions, page 1



Most of the mechanisms at large (pseudo)rapidities
Only photon elastic rescattering at midrapidities



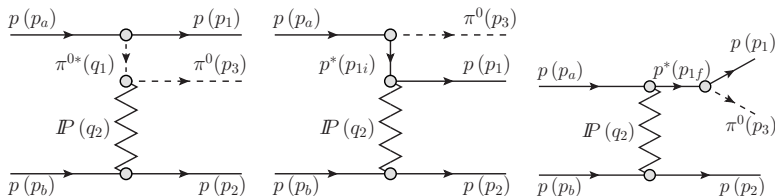
Differential distributions, page 2



Large energy photons, ZDC



$pp \rightarrow pp\pi^0$, mechanisms

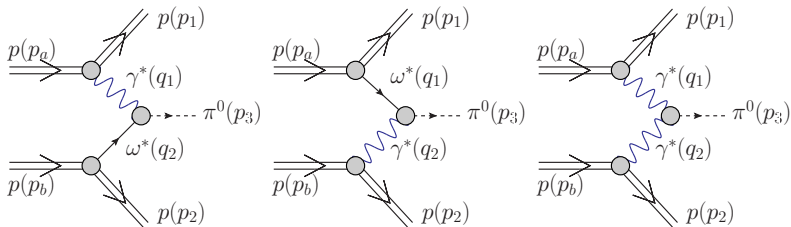


$pp \rightarrow pn\pi^+$ studied at low energies

3 diagrams: Drell-Hiida-Deck model



$pp \rightarrow pp\pi^0$, new mechanisms



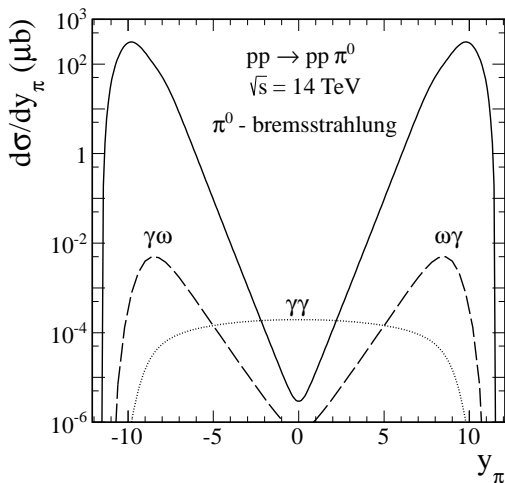
strong coupling of omega to nucleon

$\gamma^* \gamma^* \pi^0$ anomalous coupling

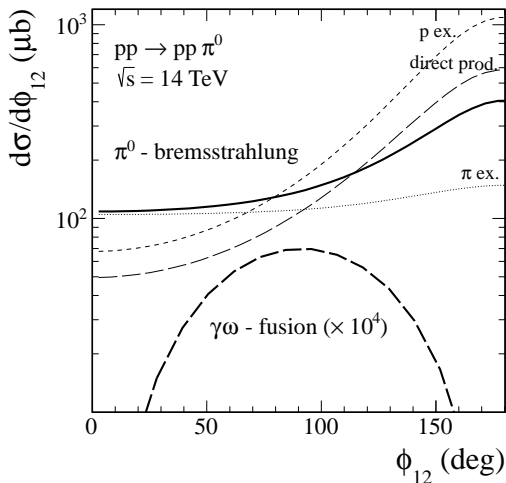
The strength fixed from $\pi^0 \rightarrow \gamma\gamma$.



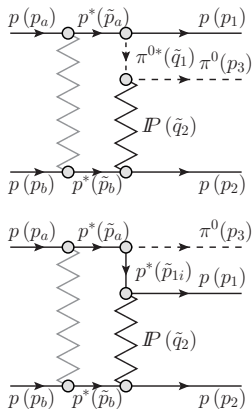
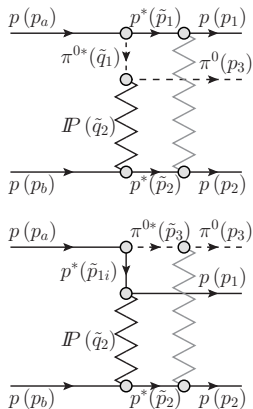
$pp \rightarrow pp\pi^0$, contributions



$pp \rightarrow pp\pi^0$, contributions



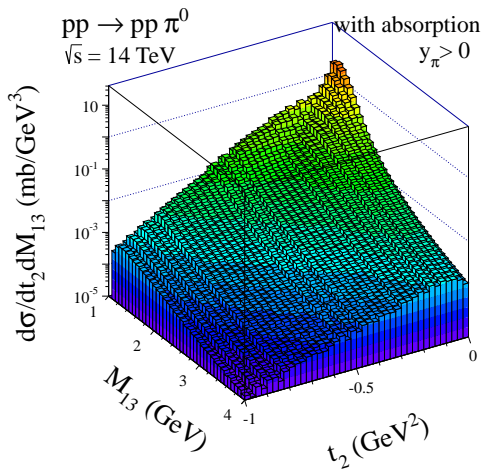
$pp \rightarrow pp\pi^0$, absorption effects



calculation in progress

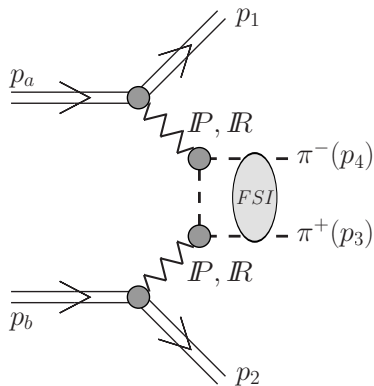
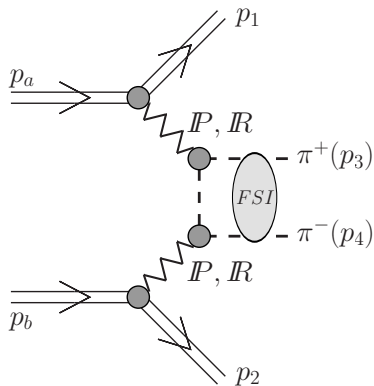


$pp \rightarrow pp\pi^0$, first results with absorption



mass-dependent slope

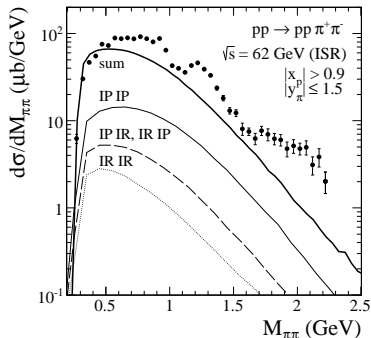
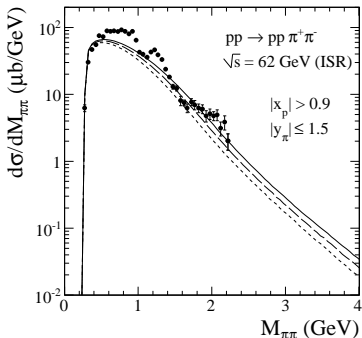
$$pp \rightarrow pp\pi^+\pi^-$$



Double-pomeron exchanges searched for in 1970's



$pp \rightarrow \pi^+ \pi^-$ at ISR

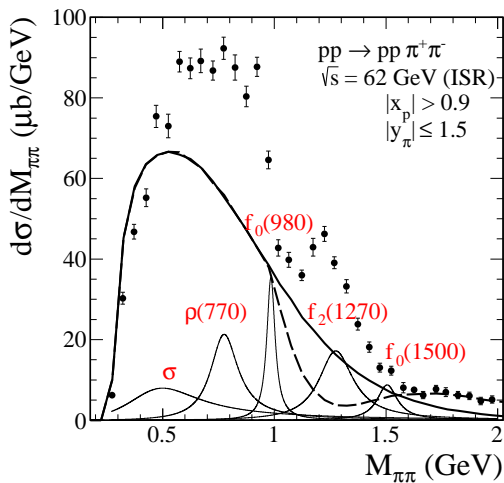


Large contribution of non-DPE even at $\sqrt{s} = 62$ GeV.

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



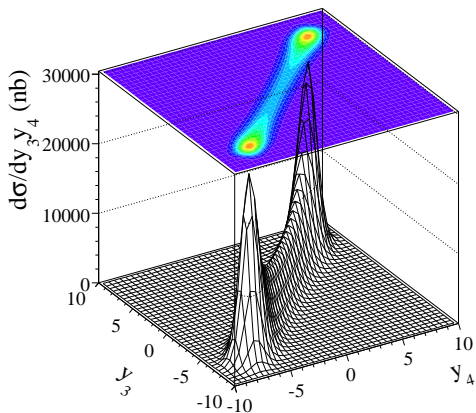
Resonance contributions



Waiting for consistent inclusion of continuum and resonances

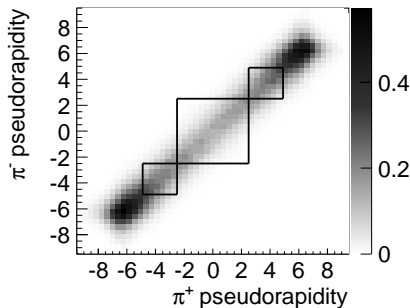
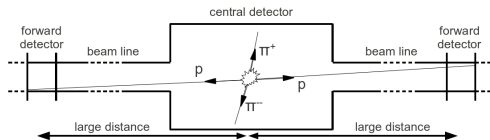


$\gamma(\pi^+) \times \gamma(\pi^-)$ correlations



We predict funny camel-like shape

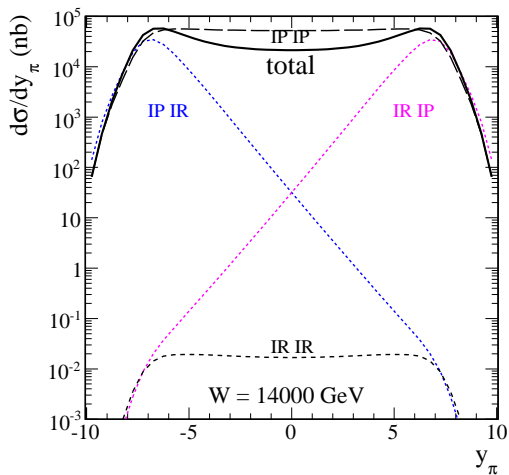
A measurement with ALFA@ATLAS



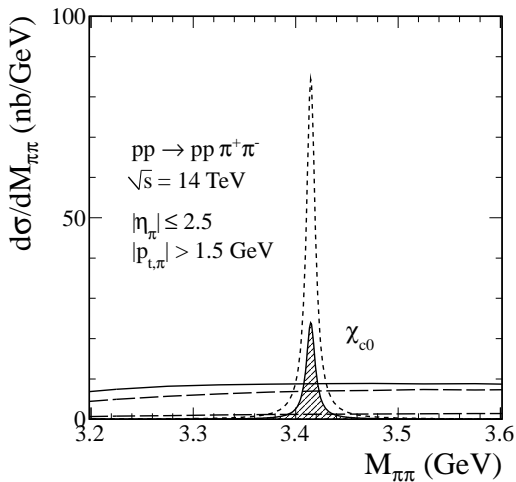
R. Staszewski, P. Lebiedowicz, M. Trzebiński, J. Chwastowski and A. Szczurek. Acta Phys. Polon. **B42** (2011) 181.



Reggeons at high energies



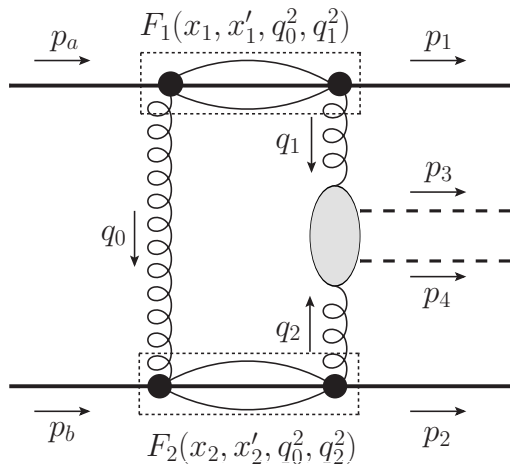
$$\chi_c(0) \rightarrow \pi^+ \pi^-$$



Difficult in $\chi_c(J^+) \rightarrow J/\psi \gamma$ channel

$gg \rightarrow \pi\pi$ nonperturbative coupling

competitive mechanism:



UGDF in nonperturbative region

Conclusions

- Extremely **large span of rapidities** at the LHC
- Different processes could be measured in **unexplored region of energies**.
- Testing photoproduction at much larger energies than at HERA.
- Searches for **odderon** possible in exclusive vector meson production.
- Searches for **glueballs** possible in exclusive production of $\pi^+\pi^-$ or K^+K^- pairs.
- Many exclusive channels contribute to **single diffraction** ($pp \rightarrow pp\pi^0$) or **central diffraction** ($pp \rightarrow pp\pi\pi$) cross section.
- Many interesting nonperturbative effects:
 - **low energy phenomena** at high energies.
 - testing the **nature of the pomeron** (e.g. its spin structure)



List of our publications on the subjects discussed here

$pp \rightarrow ppH$ and $pp \rightarrow ppb\bar{b}$

- R. Maciuła, R.S. Pasechnik and A. Szczurek, "Exclusive double-diffractive production of open charm in proton-proton and proton-antiproton collisions", Phys. Lett. **B685** (2010) 165.
- R. Maciuła, R. Pasechnik and A. Szczurek, "Exclusive $b\bar{b}$ pair production and irreducible background to the exclusive Higgs boson production", Phys. Rev. **D82** (2010) 114011.
- R. Maciuła, R. Pasechnik and A. Szczurek, "Central exclusive quark-antiquark dijet and Standard Model Higgs boson production in proton-(anti)proton collisions", Phys. Rev. **D83** (2011) 114034.
- R. Maciuła, R. Pasechnik and A. Szczurek, "New contributions to central exclusive production of dijets in proton-(anti)proton collisions", Phys. Rev. **D84** (2011) 114014.
- P. Lebiedowicz, R. Pasechnik and A. Szczurek, "Diffractive pQCD mechanism of exclusive production of W^+W^- pairs in proton-proton collisions", Nucl. Phys. **B867** (2013) 61.



List of our publications on the subjects discussed here

$pp \rightarrow pp\chi_c$

- R.S. Pasechnik, A. Szczurek and O.V. Teryaev, "Central exclusive production of the scalar χ_c meson at the Fermilab Tevatron, BNL RHIC, and CERN LHC energies", Phys. Rev. **D78** (2008) 014007.
- R.S. Pasechnik, A. Szczurek and O.V. Teryaev, "Elastic double diffractive production of axial-vector $\chi_c(1^{++})$ mesons and the Landau-Yang theorem", Phys. Lett. **B680** (2009) 62.
- R. Pasechnik, A. Szczurek and O. Teryaev, "Polarization effects in the central exclusive χ_c production and the J/Ψ angular distributions", Phys. Rev. **D83**, 074017 (2011).
- P. Lebiedowicz, R. Pasechnik and A. Szczurek, "Measurement of exclusive production of scalar χ_{c0} meson in proton-(anti)proton collisions via $\chi_{c0} \rightarrow \pi^+\pi^-$ decay", Phys. Lett. **B701** (2011) 434.



List of our publications on the subjects discussed here

$pp \rightarrow ppM, M$ – light scalar or pseudoscalar meson

- A. Szczurek, R.S. Pasechnik and O.V. Teryaev, “ $pp \rightarrow pp\eta'$ reaction at high energies”, Phys. Rev. **D75** (2007) 054021.
- A. Szczurek and P. Lebiedowicz, "Exclusive scalar $f_0(1500)$ meson production for energy ranges available at the GSI Facility for Antiproton and Ion Research (GSI-FAIR) and at the Japan Proton Accelerator Research Complex (J-PARC), Nucl. Phys. **A826** (2009) 101.
- P. Lebiedowicz and A. Szczurek, a paper in preparation.
- P. Lebiedowicz, O. Nachtman and A. Szczurek, a paper in preparation.

List of our publications on the subjects discussed here

$pp \rightarrow ppV$, V -vector meson, photon, Z^0

- W. Schäfer and A. Szczurek, "Exclusive photoproduction of J/Ψ in proton-proton and proton-antiproton scattering", Phys. Rev. **D76** (2007) 094014.
- A. Rybarska, W. Schäfer and A. Szczurek, "Exclusive photoproduction of Υ : From HERA to Tevatron", Phys. Lett. **B668** (2008) 126.
- A. Cisek, W. Schäfer and A. Szczurek, "Production of Z^0 bosons with rapidity gaps: Exclusive photoproduction in γp and pp collisions and inclusive double diffractive Z^0 's", Phys. Rev. **D80** (2009) 074013.
- A. Cisek, W. Schäfer and A. Szczurek, "Exclusive photoproduction of ϕ meson in $\gamma p \rightarrow \phi p$ and $pp \rightarrow \phi p$ reactions", Phys. Lett. **B690** (2010) 168.
- A. Cisek, P. Lebiedowicz, W. Schäfer and A. Szczurek, "Exclusive production of ω meson in proton-proton collisions at high energies", Phys. Rev. **D83** (2011) 114004.
- G. Kubasiak and A. Szczurek, "Inclusive and exclusive diffractive production of dilepton pairs in proton-proton collisions at high energies", Phys. Rev. **D84** (2011) 014005.
- P. Lebiedowicz and A. Szczurek, "Exclusive diffractive photon bremsstrahlung at the LHC", a paper in preparation, February 2013.



List of our publications on the subjects discussed here

$pp \rightarrow pp\pi^+\pi^-$ and similar reactions

- P. Lebiedowicz, A. Szczurek and R. Kamiński, "Low-energy pion-pion scattering in the $pp \rightarrow pp\pi^+\pi^-$ and $p\bar{p} \rightarrow pp\pi^+\pi^-$ reactions", Phys. Lett. **B680** (2009) 459.
- P. Lebiedowicz and A. Szczurek, "Exclusive $pp \rightarrow pp\pi^+\pi^-$ reaction: From the threshold to LHC", Phys. Rev. **D81** (2010) 036003.
- P. Lebiedowicz and A. Szczurek, "Exclusive $pp \rightarrow nn\pi^+\pi^+$ reaction at LHC and RHIC", Phys. Rev. **D83** (2011) 076002.
- R. Staszewski, P. Lebiedowicz, M. Trzebiński, J. Chwastowski and A. Szczurek, "Exclusive $\pi^+\pi^-$ production at the LHC with Forward Proton Tagging", Acta Phys. Polon, **B42** (2011) 181.
- P. Lebiedowicz and A. Szczurek, " $pp \rightarrow ppK^+K^-$ reaction at high energies", Phys. Rev. **D85** (2012) 014026.
- N. Kochelev, N. Korchagin, W. Schäfer and A. Szczurek, a paper in preparation.

List of our publications on the subjects discussed here

AA \rightarrow AAX₁X₂ and similar reactions

- M. Kłusek, W. Schäfer and A. Szczurek, "Exclusive production of $\rho^0\rho^0$ pairs in $\gamma\gamma$ collisions at RHIC", Phys. Lett. **B674** (2009) 92.
- M. Kłusek-Gawenda and A. Szczurek, "Exclusive muon-pair production in ultrarelativistic heavy-ion collisions - realistic nucleus charge form factor and differential distributions", Phys. Rev. **C82** (2010) 014904.
- M. Kłusek-Gawenda, A. Szczurek, M. Machado and V. Serbo, "Double – photon exclusive processes with heavy quark – heavy antiquark pairs in high-energy Pb-Pb collisions at LHC", Phys. Rev. **C83** (2011) 024903.
- M. Łuszczak and A. Szczurek, "Exclusive $D\bar{D}$ meson pair production in peripheral ultrarelativistic heavy ion collisions", Phys. Lett. **B700** (2011) 116.
- M. Kłusek-Gawenda and A. Szczurek, "Exclusive production of large invariant mass pion pairs in ultrarelativistic heavy ion collisions", Phys. Lett. **B700** (2011) 322 .
- A. Cisek, W. Schäfer and A. Szczurek, "Exclusive coherent production of heavy vector mesons in nucleus-nucleus collisions at energies available at the CERN Large Hadron Collider", Phys. Rev. **C86** (2012) 014905.
- S. Baranov, A. Cisek, M. Kłusek-Gawenda, W. Schäfer and A. Szczurek, "The $\gamma\gamma \rightarrow J/\psi J/\psi$ reaction and the $J/\psi J/\psi$ pair production in exclusive ultraperipheral ultrarelativistic heavy ion collisions", Xarxiv:1208.5917, in print in EPJC.
- M. Kłusek-Gawenda and A. Szczurek, " $\pi^+\pi^-$ and $\pi^0\pi^0$ pair production in photon-photon and in peripheral ultrarelativistic heavy ion collisions", a paper in preparation.

