Photoproduction mechanisms to the $pp \to pp\, \pi^+\pi^-$ reaction

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Content

- Introduction
- Photoproduction mechanisms of $\pi^+\pi^-$ pairs in proton-proton collisions
- Results
- Conclusions

Based on:

P. Lebiedowicz, O. Nachtmann, A. Szczurek, *The ρ^0 and Drell-Söding contributions to central exclusive production of $\pi^+\pi^-$ pairs in proton-proton collisions at high energies*, arXiv:1412.3677

Related works:

- C. Ewerz, M. Maniatis, O. Nachtmann, *A Model for Soft High-Energy Scattering: Tensor Pomeron and Vector Odderon*, arXiv:1309.3478, Annals Phys. 342 (2014) 31
- A. Bolz, C. Ewerz, M. Maniatis, O. Nachtmann, M. Sauter, A. Schöning, *Photoproduction of $\pi^+\pi^-$ pairs in a model with tensor-pomeron and vector-odderon exchange*, arXiv:1409.8483
- P. Lebiedowicz, O. Nachtmann, A. Szczurek, *Exclusive central diffractive production of scalar and pseudoscalar mesons; tensorial vs. vectorial pomeron*, arXiv:1309.3913, Annals Phys. 344 (2014) 301

The soft pomeron model

C. Ewerz, M. Maniatis and O. Nachtmann, Annals Phys. 342 (2014) 31

Formulation of a Regge-type model (effective vertices and propagators respecting the standard *C* parity and crossing rules of QFT):
C = +1 exchanges (*IP*, f_{2IR}, a_{2IR}) represented as tensors,
C = -1 exchanges (odderon, ω_{IR}, ρ_{IR}) represented as vectors.

In QFT a tensor gives the same sign for the coupling of particles and antiparticles.

Example: *pp* elastic scattering via effective tensor pomeron exchange

$$i\Gamma_{\mu\nu}^{(\mathbb{P}_T pp)}(p',p) = i\Gamma_{\mu\nu}^{(\mathbb{P}_T \bar{p}\bar{p})}(p',p) = -i\,3\beta_{\mathbb{P}NN}\,F_1\left((p'-p)^2\right)\left\{\frac{1}{2}\left[\gamma_\mu(p'+p)_\nu + \gamma_\nu(p'+p)_\mu\right] - \frac{1}{4}g_{\mu\nu}(\not{p}'+\not{p})\right\}$$

$$i\Delta_{\mu\nu,\kappa\lambda}^{(\mathbb{P}_T)}(s,t) = \frac{1}{4s}\left(g_{\mu\kappa}g_{\nu\lambda} + g_{\mu\lambda}g_{\nu\kappa} - \frac{1}{2}g_{\mu\nu}g_{\kappa\lambda}\right)(-is\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1}$$

$$\beta_{\mathbb{P}NN} = 1.87\ \mathrm{GeV}^{-1}\,, \qquad \alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}}\,t\,, \qquad F_1(t) = \frac{4m_p^2 - 2.79\,t}{(4m_p^2 - t)(1 - t/m_D^2)^2}$$

$$\alpha_{\mathbb{P}}(0) = 1.0808,\ \alpha'_{\mathbb{P}} = 0.25\ \mathrm{GeV}^{-2}, \qquad m_D^2 = 0.71\ \mathrm{GeV}^2$$

Tensor pomeron gives, at high energies, the same results for the *pp* and $p\bar{p}$ elastic amplitudes as for the DL-pomeron ansatz (frequently called a '*C* = +1 photon')

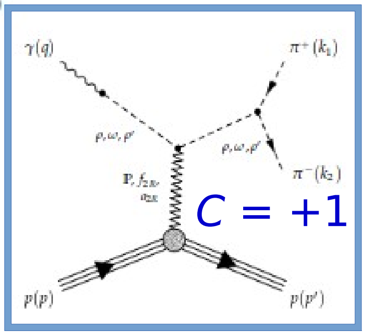
$$\mathcal{M}^{2\to 2}_{\lambda_a\lambda_b\to\lambda_1\lambda_2}(s,t) \xrightarrow{s\gg 4m_p^2} i\,2s\,\left[3\beta_{\mathbb{P}NN}\,F_1(t)\right]^2\,(-is\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1}\,\delta_{\lambda_1\lambda_a}\,\delta_{\lambda_2\lambda_b}$$

Photoproduction of $\pi^+\pi^-$ pairs

A. Bolz, C. Ewerz, M. Maniatis, O. Nachtmann, M. Sauter, A. Schöning, arXiv:1409.8483
Photoproduction of $\pi^+\pi^-$ pairs in a model with tensor-pomeron and vector-odderon exchange

Resonant contributions

(a)



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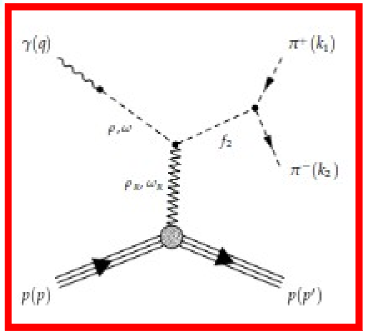
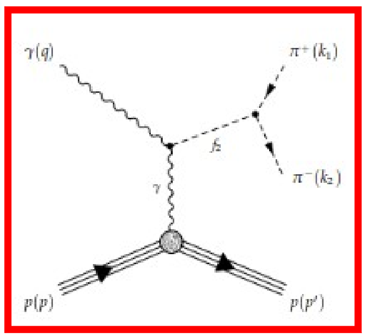


(c)



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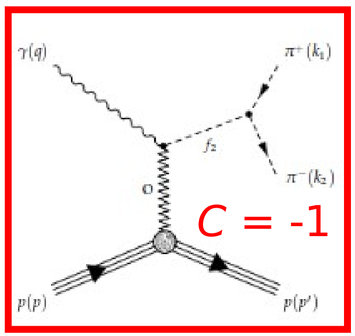
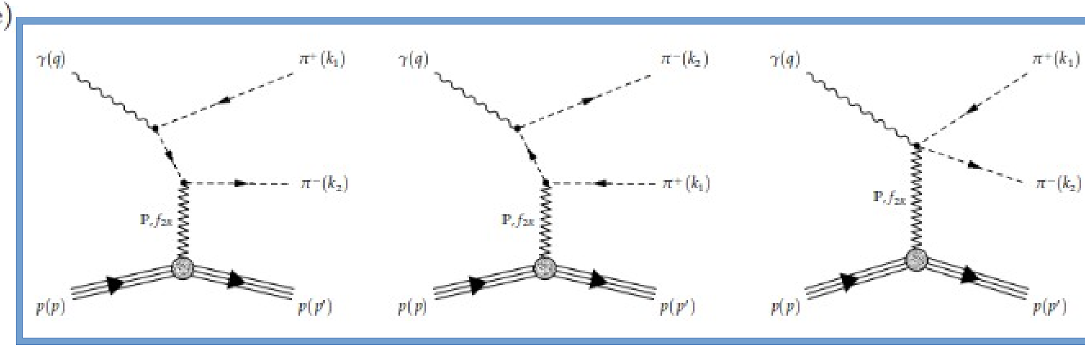
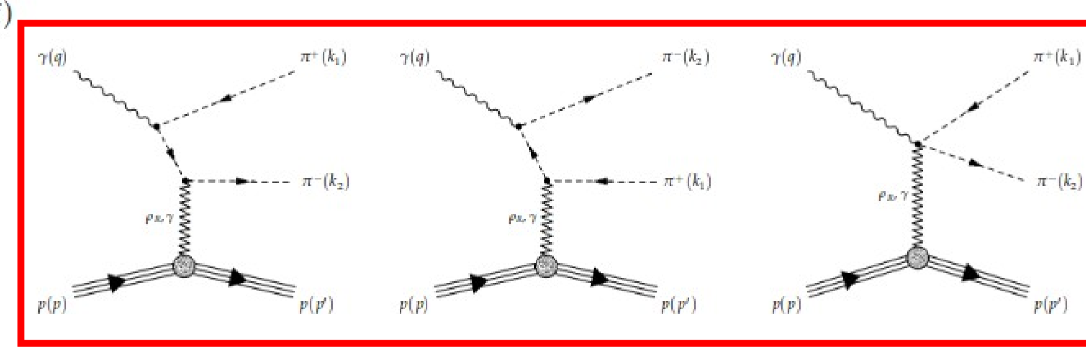


Non-resonant contributions

(e)



(f)

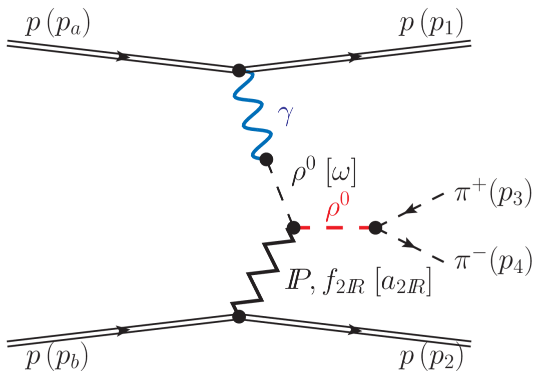


The interference of diagrams with exchange of $C = +1$ and $C = -1$ objects is signaled by charge asymmetry.

Significant charge asymmetry predicted around f_2-mass = 1.27 GeV:
Increase as a function of $|t|$ might indicate an odderon-effect.

Resonant ρ^0 production in pp collisions

Dominant resonant contribution comes via $C = +1$ exchanges ($I\!P$, $f_{2I\!R}$)



$$\mathcal{M}^{Born}_{pp\to pp\pi^+\pi^-} = \mathcal{M}^{\gamma I\!P} + \mathcal{M}^{I\!P\gamma} + \mathcal{M}^{\gamma f_{2I\!R}} + \mathcal{M}^{f_{2I\!R}\gamma}$$

$$\begin{aligned}\mathcal{M}^{(\gamma I\!P)}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^+\pi^-} = {} & (-i)\bar{u}(p_1,\lambda_1) i\Gamma^{(\gamma pp)}_{\mu}(p_1,p_a) u(p_a,\lambda_a) \\ & \times i\Delta^{(\gamma)\,\mu\sigma}(q_1)\, i\Gamma^{(\gamma\to\rho)}_{\sigma\nu}(q_1)\, i\Delta^{(\rho)\,\nu\rho_1}(q_1)\, i\Delta^{(\rho)\,\rho_2\kappa}(p_{34})\, i\Gamma^{(\rho\pi\pi)}_{\kappa}(p_3,p_4) \\ & \times i\Gamma^{(I\!P\rho\rho)}_{\rho_2\rho_1\alpha\beta}(p_{34},q_1)\, i\Delta^{(I\!P)\,\alpha\beta,\delta\eta}(s_2,t_2)\, \bar{u}(p_2,\lambda_2) i\Gamma^{(I\!P pp)}_{\delta\eta}(p_2,p_b) u(p_b,\lambda_b)\end{aligned}$$

$$\tilde{F}^{(\rho)}(k^2) = \left[1 + \frac{k^2(k^2-m_\rho^2)}{\Lambda_\rho^4}\right]^{-n_\rho}$$

$$\begin{aligned}\mathcal{M}^{(\gamma I\!P + \gamma f_{2I\!R})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^+\pi^-} \simeq {} & ie(p_1+p_a)^{\mu} F_1(t_1)\delta_{\lambda_1\lambda_a} \\ & \times e\frac{m_\rho^2}{\gamma_\rho}\frac{1}{t_1}\,\Delta^{(\rho)}_{\mu\rho_1}(q_1)\,\Delta^{(\rho)}_{\rho_2\kappa}(p_{34})\,\frac{g_{\rho\pi\pi}}{2}(p_3-p_4)^{\kappa}\,\tilde{F}^{(\rho)}(q_1^2)\tilde{F}^{(\rho)}(p_{34}^2) \\ & \times V^{\rho_2\rho_1\alpha\beta}(s_2,t_2,q_1,p_{34}) F_M(t_2)\, 2(p_2+p_b)_{\alpha}(p_2+p_b)_{\beta} F_1(t_2)\delta_{\lambda_2\lambda_b}\end{aligned}$$

$$\begin{aligned}V_{\mu\nu\kappa\lambda}(s,t,q,p_{34}) = {} & \frac{1}{4s}\Big\{2\Gamma^{(0)}_{\mu\nu\kappa\lambda}(p_{34},-q)\left[3\beta_{I\!PNN}\, a_{I\!P\rho\rho}(-is\alpha'_{I\!P})^{\alpha_{I\!P}(t)-1} + M_0^{-1} g_{f_{2I\!R}pp}\, a_{f_{2I\!R}\rho\rho}(-is\alpha'_{I\!R_+})^{\alpha_{I\!R_+}(t)-1}\right] \\ & -\Gamma^{(2)}_{\mu\nu\kappa\lambda}(p_{34},-q)\left[3\beta_{I\!PNN}\, b_{I\!P\rho\rho}(-is\alpha'_{I\!P})^{\alpha_{I\!P}(t)-1} + M_0^{-1} g_{f_{2I\!R}pp}\, b_{f_{2I\!R}\rho\rho}(-is\alpha'_{I\!R_+})^{\alpha_{I\!R_+}(t)-1}\right]\Big\}\end{aligned}$$

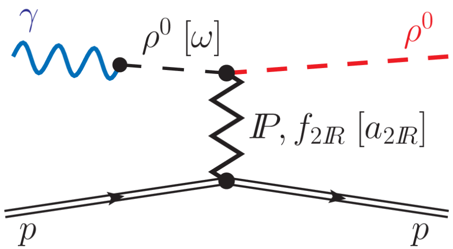
rank-four tensor functions: *C. Ewerz, M. Maniatis and O. Nachtmann, Ann. Phys. 342 (2014) 31*

The coupling constants in the *IPρρ and* f_{2IR}*ρρ* vertices have been estimated from the parametrization of total cross sections for pion-proton scattering assuming $\sigma_{tot}(\rho^0(\epsilon^{(\lambda_\rho=\pm1)}),p) = \frac{1}{2}\left[\sigma_{tot}(\pi^+,p) + \sigma_{tot}(\pi^-,p)\right]$ and are expected to approximately fulfil the relations:

$$2m_\rho^2\, a_{I\!P\rho\rho} + b_{I\!P\rho\rho} = 4\beta_{I\!P\pi\pi} = 7.04\ \mathrm{GeV}^{-1}$$

$$2m_\rho^2\, a_{f_{2I\!R}\rho\rho} + b_{f_{2I\!R}\rho\rho} = M_0^{-1} g_{f_{2I\!R}\pi\pi} = 9.30\ \mathrm{GeV}^{-1} \qquad M_0 = 1\ \mathrm{GeV}$$

Photoproduction of ρ^0 meson



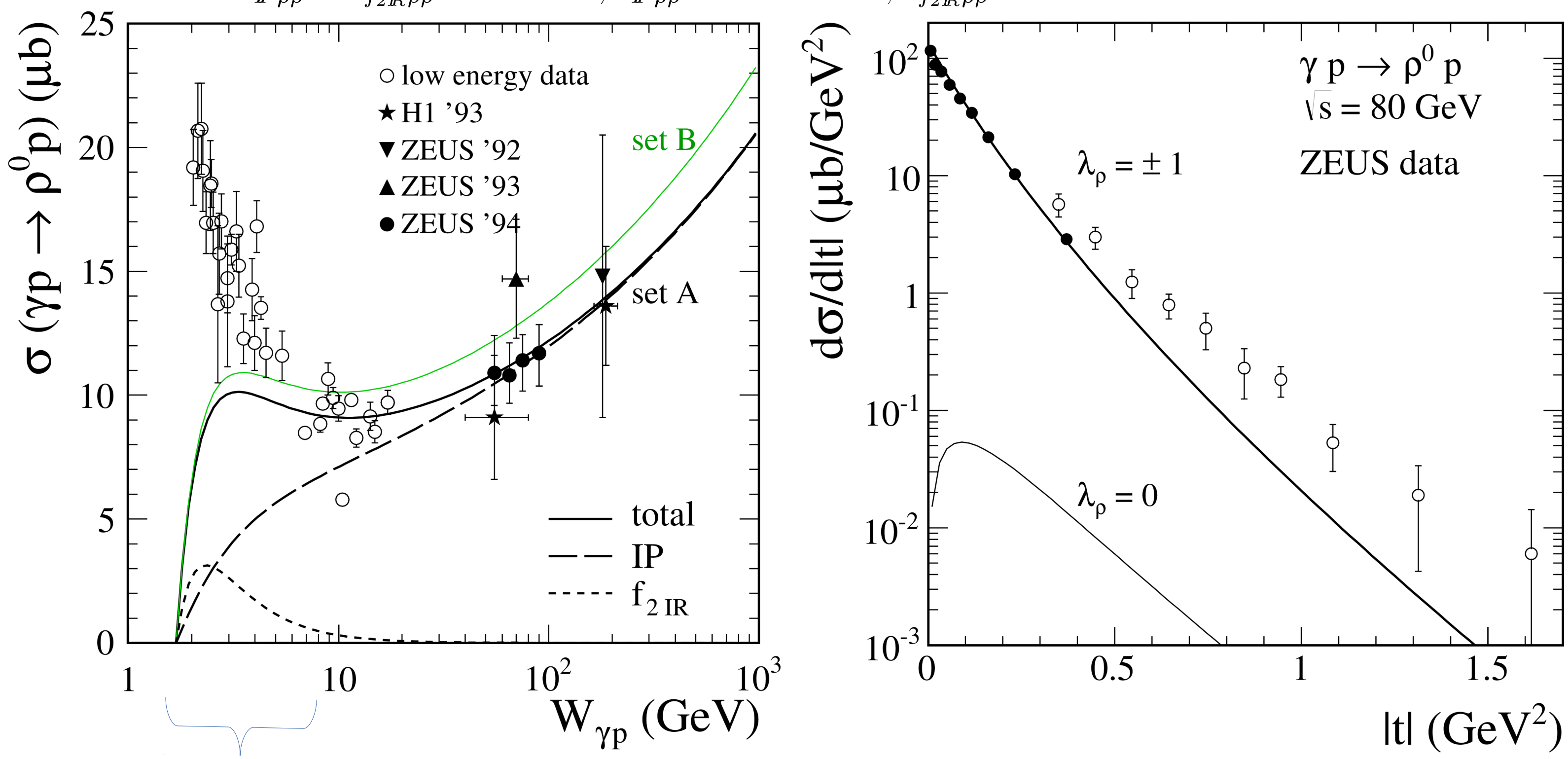
$$\mathcal{M}_{\lambda_\gamma \lambda_b \to \lambda_\rho \lambda_2}(s,t) \cong \; ie\frac{m_\rho^2}{\gamma_\rho}\,\Delta_T^{(\rho)}(0)\,(\epsilon^{(\rho)\,\mu})^*\epsilon^{(\gamma)\,\nu} V_{\mu\nu\kappa\lambda}(s,t,q,p_\rho)$$
$$\times 2(p_2+p_b)^\kappa (p_2+p_b)^\lambda\,\delta_{\lambda_2\lambda_b} F_1(t) F_M(t)$$

$$F_M(t) = \frac{1}{1-t/\Lambda_0^2}$$
$$\Lambda_0^2 = 0.5\ GeV^2$$

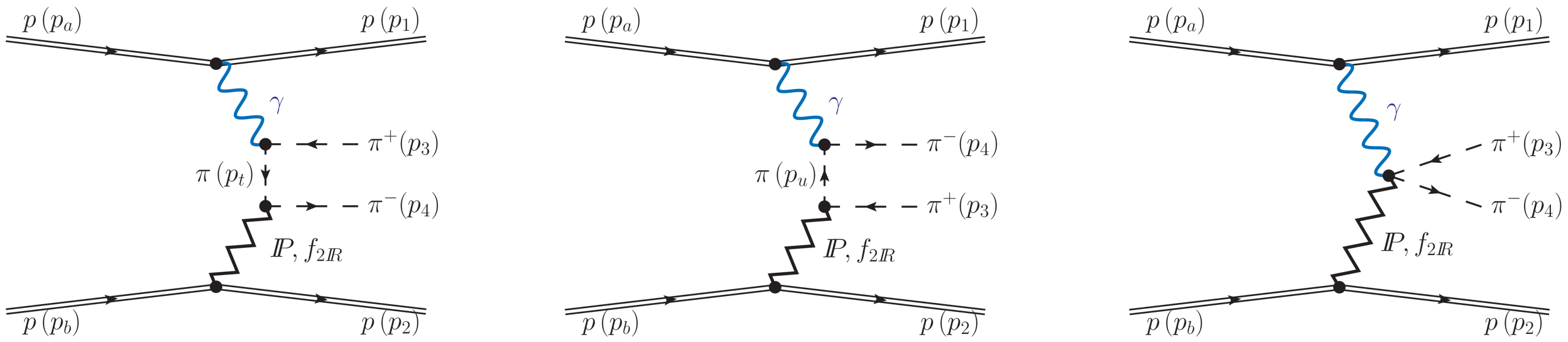
$$V_{\mu\nu\kappa\lambda}(s,t,q,p_\rho) = \frac{1}{4s}\Big\{ 2\Gamma^{(0)}_{\mu\nu\kappa\lambda}(p_\rho,-q)\left[3\beta_{I\!PNN}\, a_{I\!P\rho\rho}(-is\alpha'_{I\!P})^{\alpha_{I\!P}(t)-1} + M_0^{-1} g_{f_{2I\!R}pp}\, a_{f_{2I\!R}\rho\rho}(-is\alpha'_{I\!R_+})^{\alpha_{I\!R_+}(t)-1}\right]$$
$$-\Gamma^{(2)}_{\mu\nu\kappa\lambda}(p_\rho,-q)\left[3\beta_{I\!PNN}\, b_{I\!P\rho\rho}(-is\alpha'_{I\!P})^{\alpha_{I\!P}(t)-1} + M_0^{-1} g_{f_{2I\!R}pp}\, b_{f_{2I\!R}\rho\rho}(-is\alpha'_{I\!R_+})^{\alpha_{I\!R_+}(t)-1}\right]\Big\}$$

set A : $a_{I\!P\rho\rho} = 0.7\ \text{GeV}^{-3}$, $a_{f_{2I\!R}\rho\rho} = 0\ \text{GeV}^{-3}$, $b_{I\!P\rho\rho} = 6.2\ \text{GeV}^{-1}$, $b_{f_{2I\!R}\rho\rho} = 9.3\ \text{GeV}^{-1}$

set B : $a_{I\!P\rho\rho} = a_{f_{2I\!R}\rho\rho} = 0\ \text{GeV}^{-3}$, $b_{I\!P\rho\rho} = 7.04\ \text{GeV}^{-1}$, $b_{f_{2I\!R}\rho\rho} = 9.3\ \text{GeV}^{-1}$



No agreement expected at very low $W_{\gamma p}$ values



The inclusion of these diagrams is a gauge invariant version of the Drell-Söding mechanism.
The non-resonant production interfere with resonant ρ production.

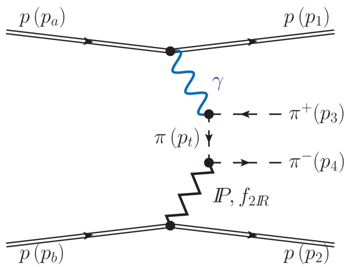
Set of vertices respecting QFT rules, arXiv:1409.8483 (O. Nachtmann *et al.*)

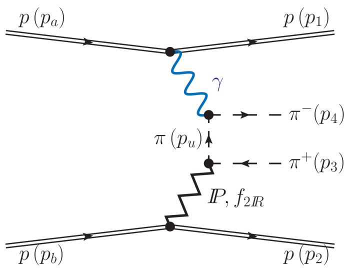
$$i\Gamma^{(I\!P\pi\pi)}_{\alpha\beta}(k',k) = -i2\beta_{I\!P\pi\pi}\left[(k'+k)_\alpha(k'+k)_\beta - \frac{1}{4}g_{\alpha\beta}(k'+k)^2\right] F_M((k'-k)^2)$$

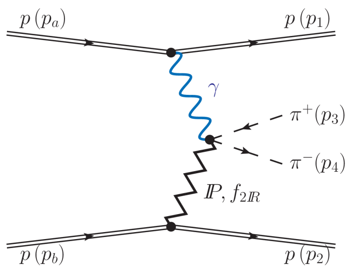
$$i\Gamma^{(\gamma\pi\pi)}_{\nu}(k',k) = ie(k'+k)_\nu\, F_M((k'-k)^2)$$

$$i\Gamma^{(I\!P\gamma\pi\pi)}_{\nu,\alpha\beta}(q,k',k) = -ie2\beta_{I\!P\pi\pi}\left[2g_{\alpha\nu}(k'+k)_\beta + 2g_{\beta\nu}(k'+k)_\alpha - g_{\alpha\beta}(k'+k)_\nu\right] F_M(q^2)\, F_M((k'-q-k)^2)$$

Non-resonant $\pi^+\pi^-$ production







In the high-energy approximation we can write for tensor-pomeron exchange

$$\mathcal{M}^{(a)}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^+\pi^-} \simeq ie^2(p_1+p_a)^\mu\,\delta_{\lambda_1\lambda_a}\,F_1(t_1)F_M(t_1)\frac{1}{t_1}(p_t-p_3)_\mu\frac{1}{p_t^2-m_\pi^2}$$
$$\times 2\beta_{I\!P\pi\pi}\,(p_4+p_t)^\alpha(p_4+p_t)^\beta\,\frac{1}{4s_{234}}(-is_{234}\alpha'_{I\!P})^{\alpha_{I\!P}(t_2)-1}$$
$$\times 3\beta_{I\!PNN}\,2(p_2+p_b)_\alpha(p_2+p_b)_\beta\,\delta_{\lambda_2\lambda_b}\,F_1(t_2)F_M(t_2)$$

$$\mathcal{M}^{(b)}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^+\pi^-} \simeq ie^2(p_1+p_a)^\mu\,\delta_{\lambda_1\lambda_a}\,F_1(t_1)F_M(t_1)\frac{1}{t_1}(p_4+p_u)_\mu\frac{1}{p_u^2-m_\pi^2}$$
$$\times 2\beta_{I\!P\pi\pi}\,(p_u-p_3)^\alpha(p_u-p_3)^\beta\,\frac{1}{4s_{234}}(-is_{234}\alpha'_{I\!P})^{\alpha_{I\!P}(t_2)-1}$$
$$\times 3\beta_{I\!PNN}\,2(p_2+p_b)_\alpha(p_2+p_b)_\beta\,\delta_{\lambda_2\lambda_b}\,F_1(t_2)F_M(t_2)$$

$$\mathcal{M}^{(c)}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^+\pi^-} \simeq -ie^2(p_1+p_a)^\nu\,\delta_{\lambda_1\lambda_a}\,\frac{1}{t_1}F_1(t_1)F_M(t_1)$$
$$\times 2\beta_{I\!P\pi\pi}\,[2g_{\alpha\nu}(p_4-p_3)_\beta+2g_{\beta\nu}(p_4-p_3)_\alpha]\,\frac{1}{4s_{234}}(-is_{234}\alpha'_{I\!P})^{\alpha_{I\!P}(t_2)-1}$$
$$\times 3\beta_{I\!PNN}\,2(p_2+p_b)^\alpha(p_2+p_b)^\beta\,\delta_{\lambda_2\lambda_b}\,F_1(t_2)F_M(t_2)$$

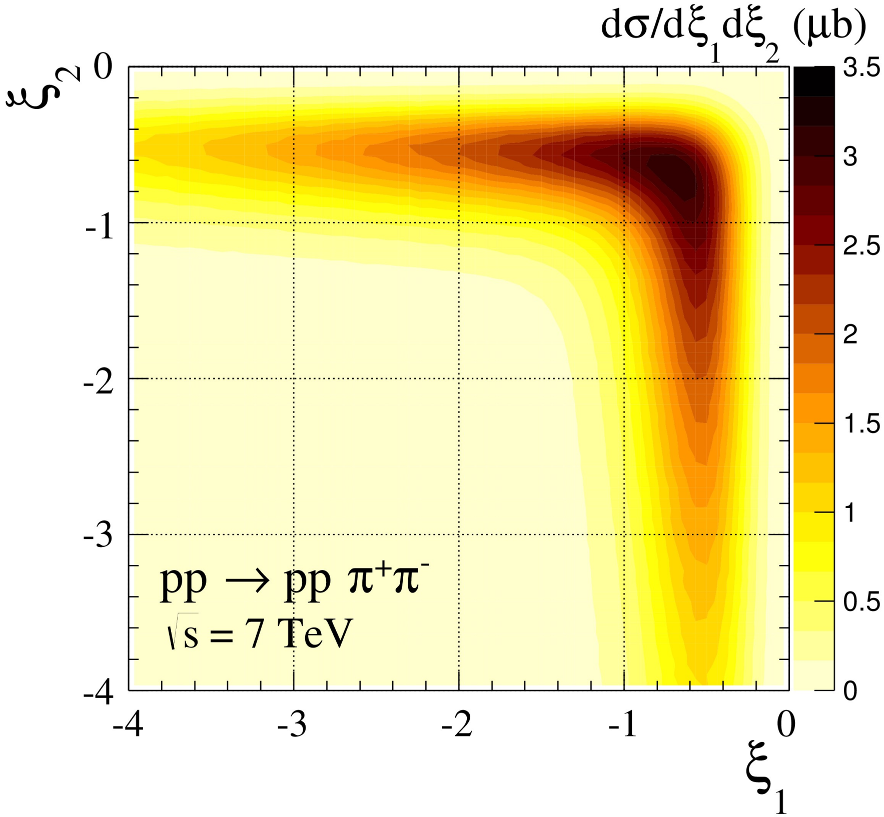
Gauge invariance of our expressions can be checked explicitly. As it should be we find: $\{\mathcal{M}^{(a)}+\mathcal{M}^{(b)}+\mathcal{M}^{(c)}\}|_{p_1+p_a\to q_1}=0$

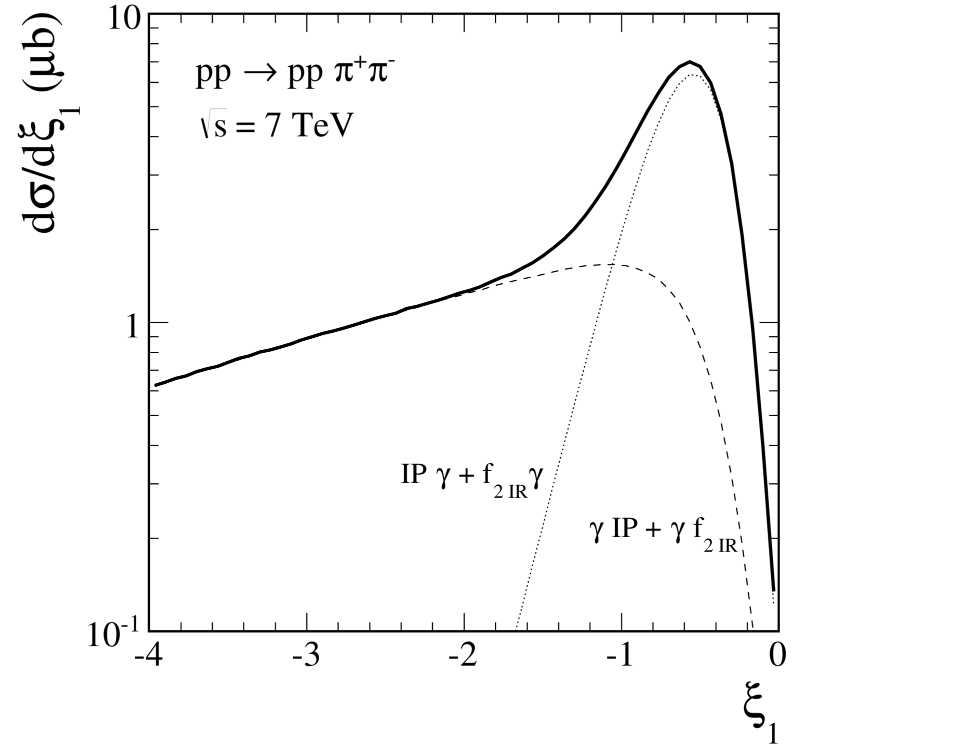
A possible way to include form factors for the inner subprocesses (in order to maintain gauge invariance):

$$\mathcal{M}^{(\gamma I\!P)}=(\mathcal{M}^{(a)}+\mathcal{M}^{(b)}+\mathcal{M}^{(c)})\,F(p_t^2,p_u^2,p_{34}^2)$$

$$F(p_t^2,p_u^2,p_{34}^2)=\frac{F^2(p_t^2)+F^2(p_u^2)}{1+F^2(-p_{34}^2)}\,, \qquad F(p^2)=\frac{\Lambda_\pi^2-m_\pi^2}{\Lambda_\pi^2-p^2}$$

ξ distribution



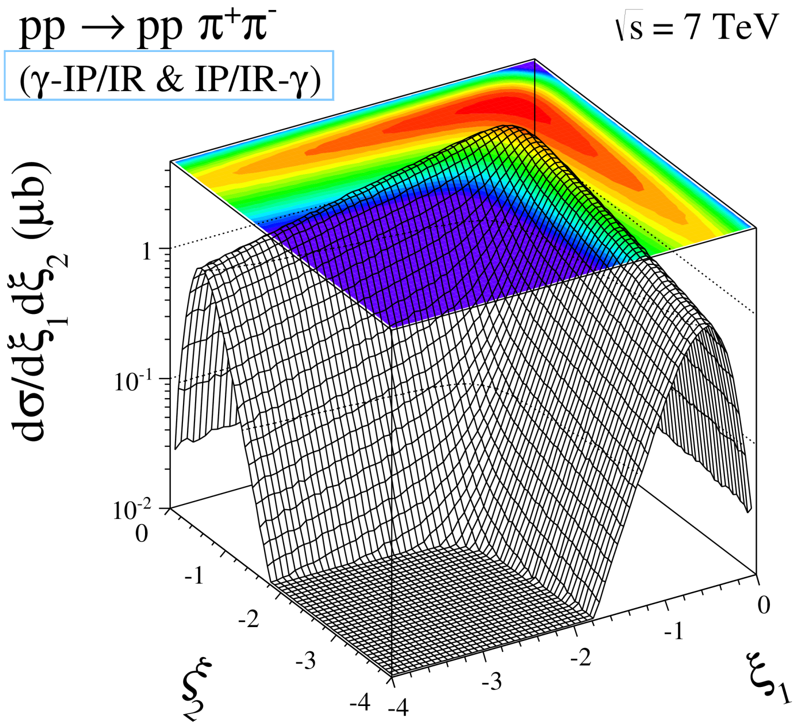


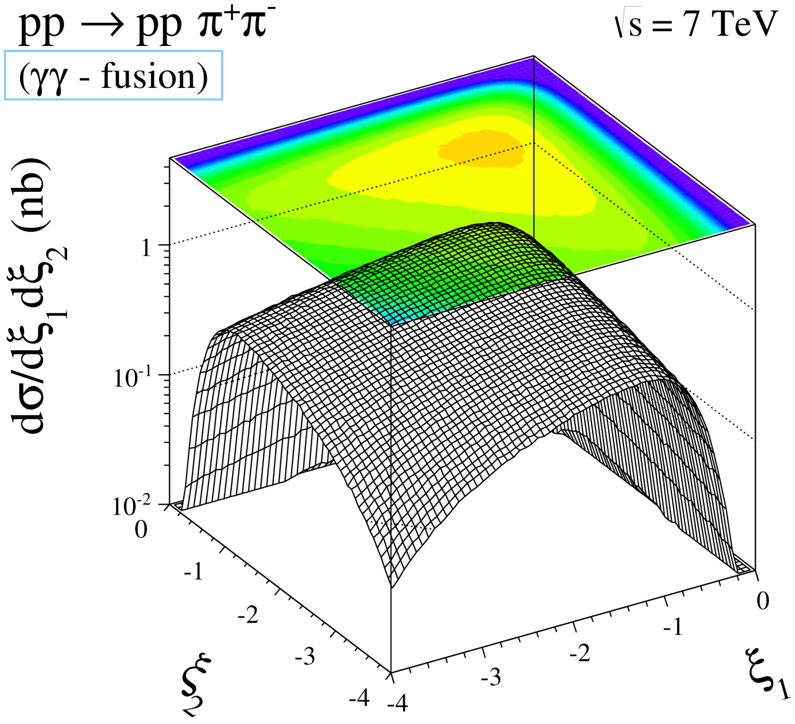
$\xi_1 = \log_{10}(p_{1\perp}/1\,\mathrm{GeV})$ For example $\xi_1 = -1$ means $p_{1\perp} = 0.1$ GeV.

Here we include both the resonant and non-resonant contributions.

Due to the photon propagators occurring in the diagrams we expect the photon induced processes to be most important when at least one of the protons is undergoing only a very small momentum transfer.

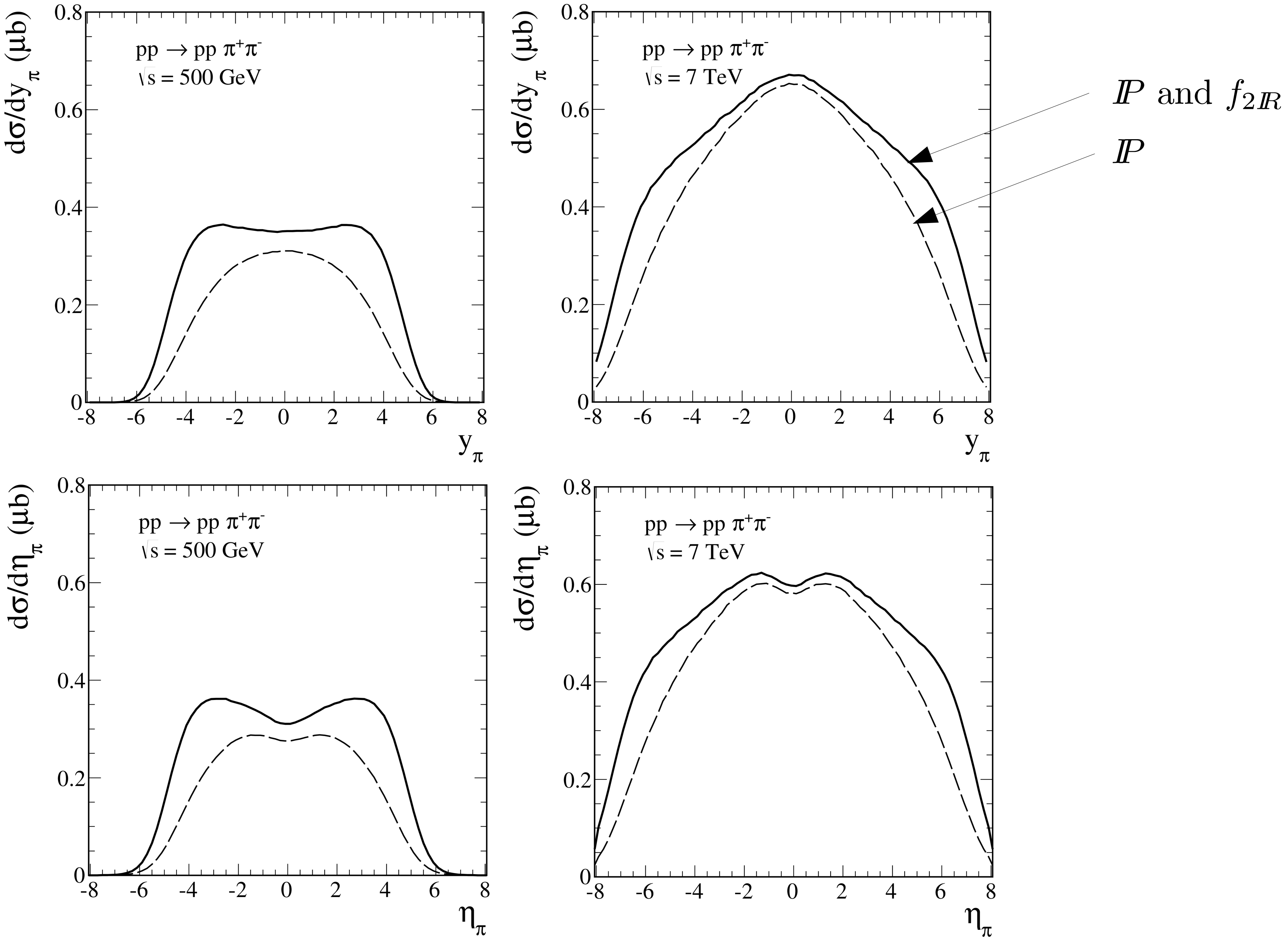
(ξ_1, ξ_2) distribution



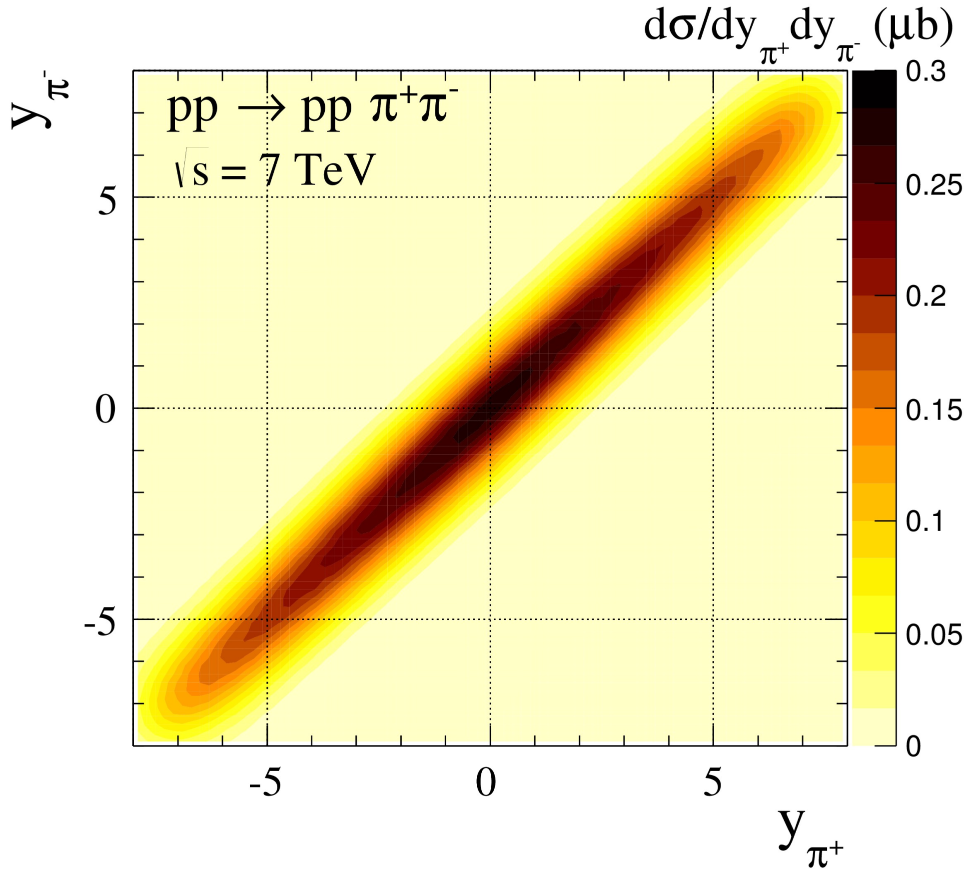


The photon-pomeron/f_{2R} contributions are expected to be the dominant ones for highly peripheral *pp* collisions. Experimentally such collision could be selected by requiring only a very small deflection angle for one of the outgoing protons.

y_π and η_π distributions

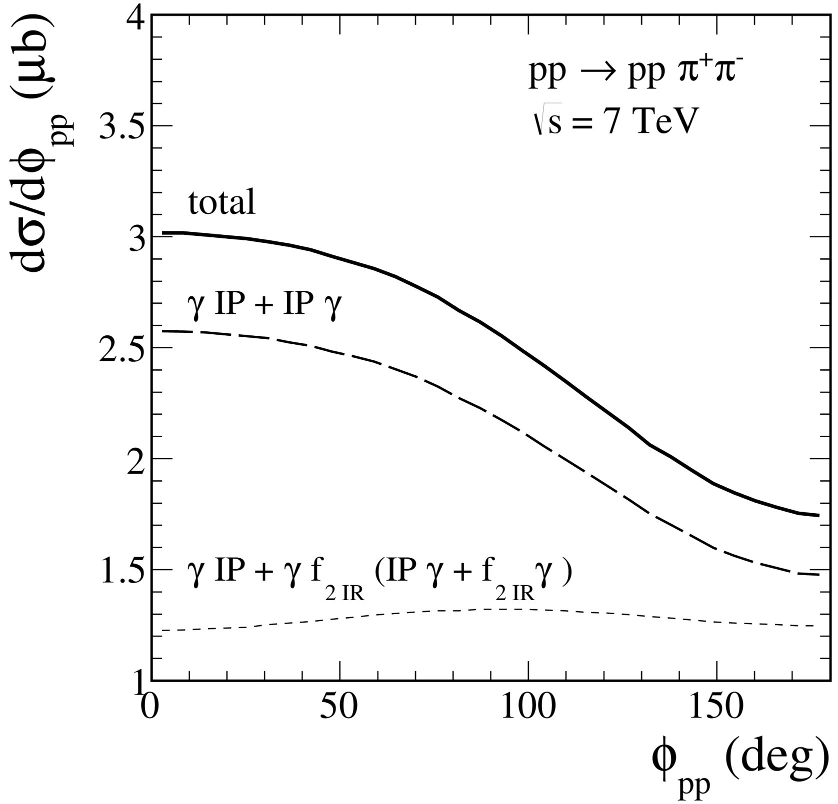


Correlation between y_{π^+} and y_{π^-}



The rapidities of the two pions are strongly correlated and $y_{\pi+} \approx y_{\pi-}$.
This is similar characteristic as for the double pomeron/reggeon exchanges in the fully diffractive mechanism *P. L. and A. Szczurek, Phys. Rev. D81 (2010) 036003*.

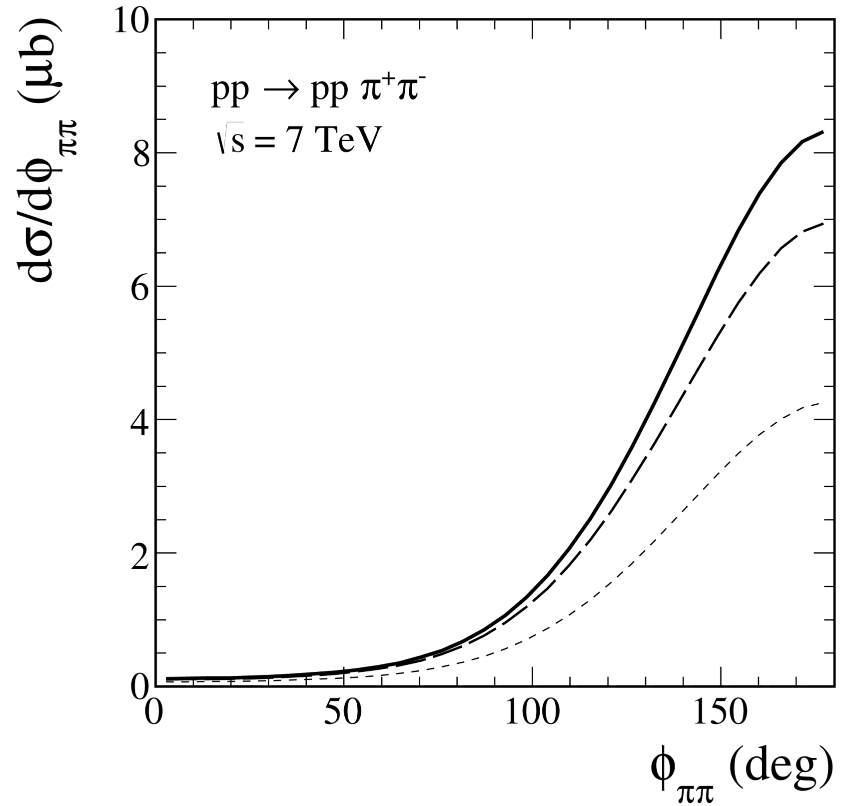
ϕ_{pp} and $\phi_{\pi\pi}$ distributions



The effect of ϕ_{pp} deviation from a constant is due to interference of *γ-IP* and *IP-γ* amplitudes.

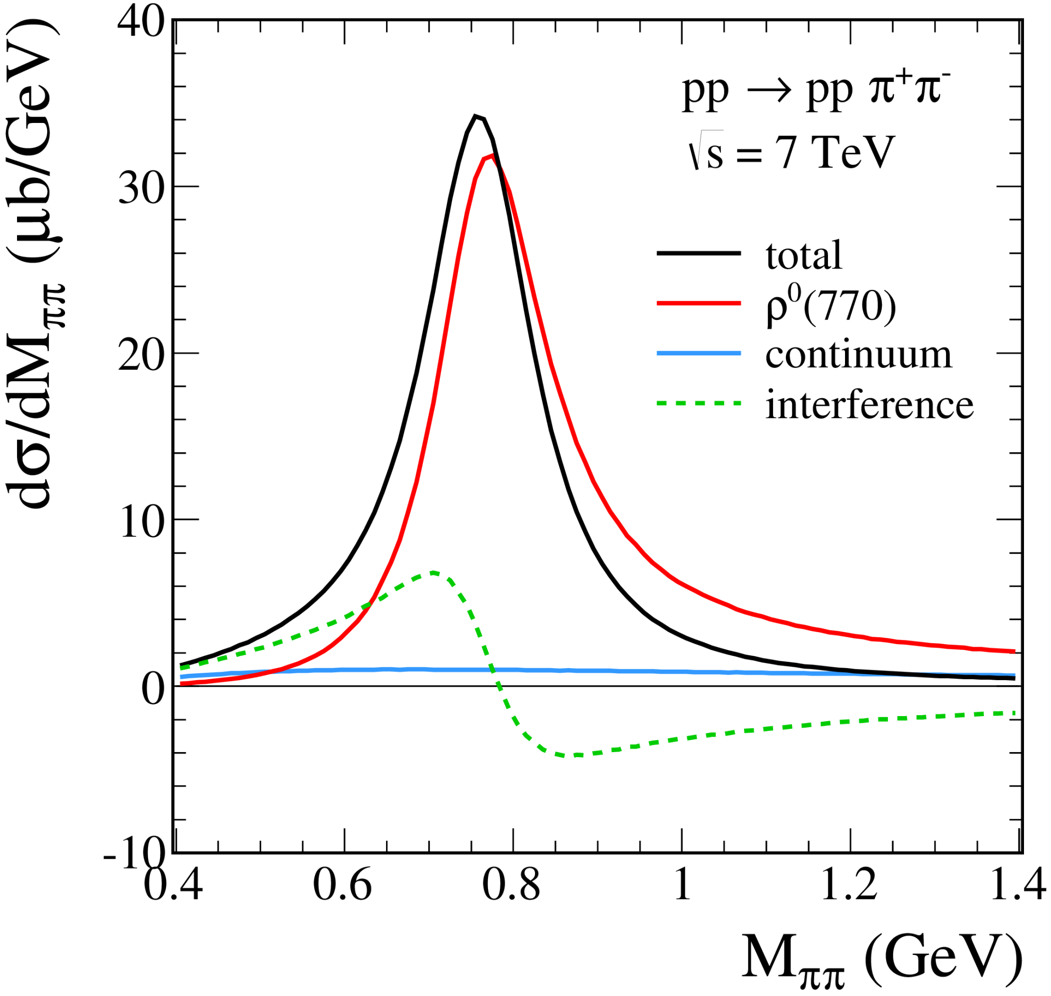
Similar effect was discussed for the exclusive production of *J/ψ* meson
W. Schäfer and A. Szczurek, Phys. Rev. D76 (2007) 094014.

The absorption effects lead to extra decorrelation in azimuth compared to the Born-level results presented here.



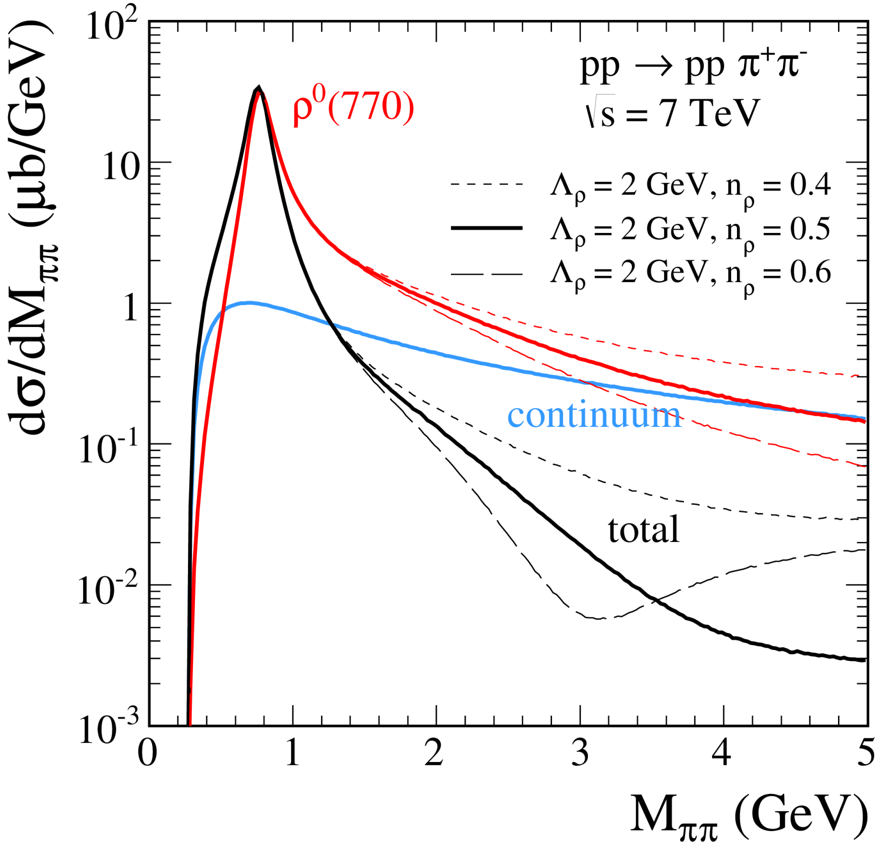
The measurement of forward/backward protons is crucial in better understanding of the mechanism reaction
R. Staszewski, P.L., M. Trzebiński, J. Chwastowski, A. Szczurek, Acta Phys. Polon. B42 (2011) 1861 *(ATLAS + ALFA)*

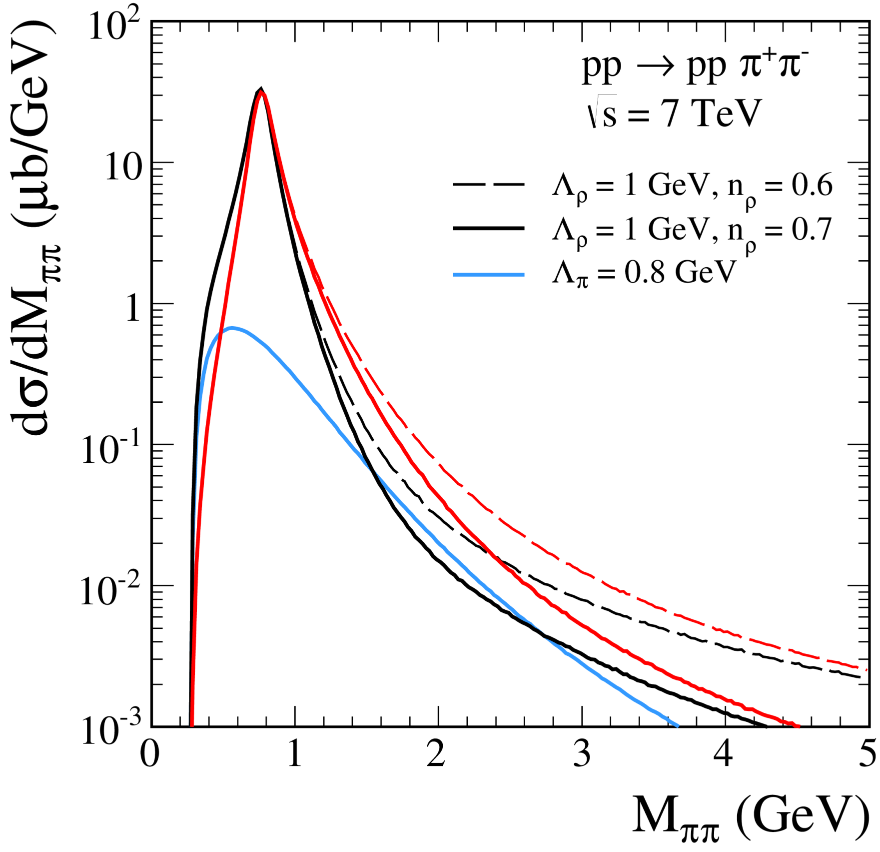
$M_{\pi\pi}$ distribution



The non-resonant contribution interfere with resonant ρ^0 contribution
→ skewing of ρ^0 line shape.

$M_{\pi\pi}$ distribution

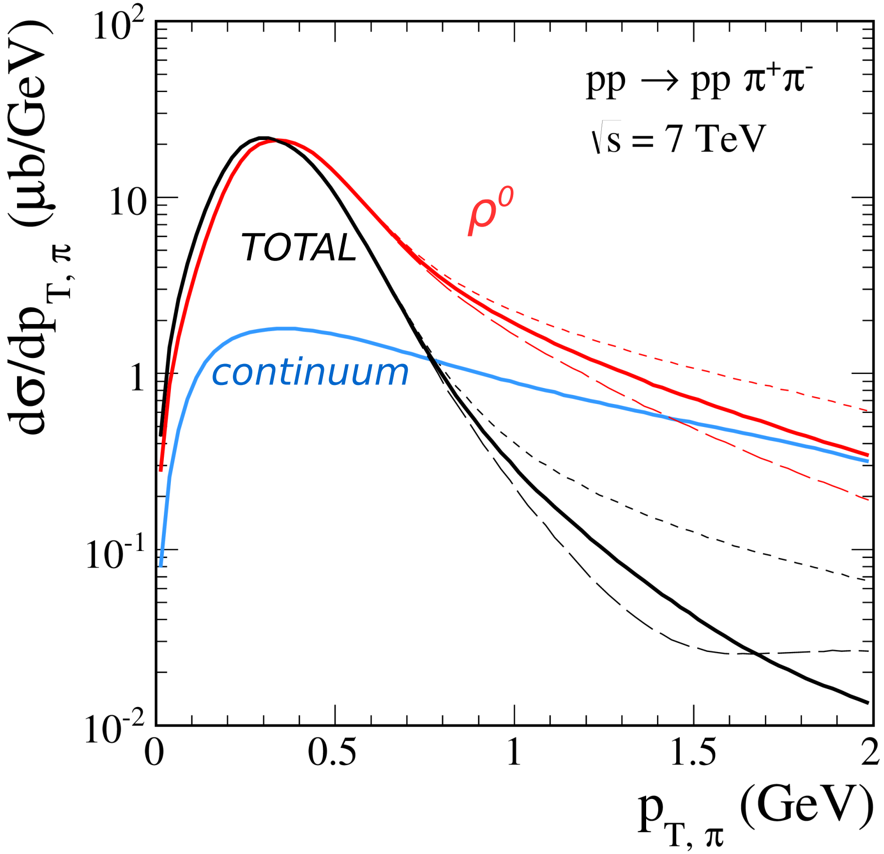




Here we take a relatively hard form factors for the resonant contribution and no form factors for the inner processes for the non-resonant contribution.

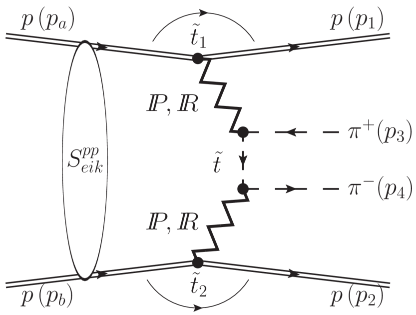
Results with softer form factors and including monopole-like form factors for the inner processes.

$p_{\perp\pi}$ distribution



$\mathrm{p}_{\perp,\pi^+}$ or $p_{\perp,\pi^-}$

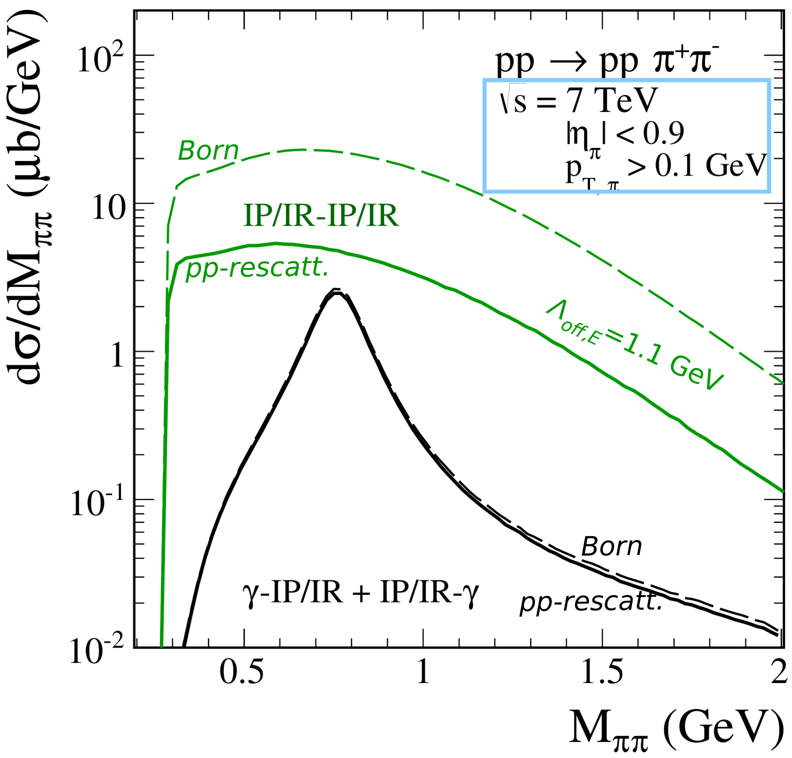
At small $p_{\perp,\pi}$ the resonance contribution is the dominant one. At higher $p_{\perp,\pi}$ our calculation gives a strong cancellation between the resonant and the non-resonant terms.

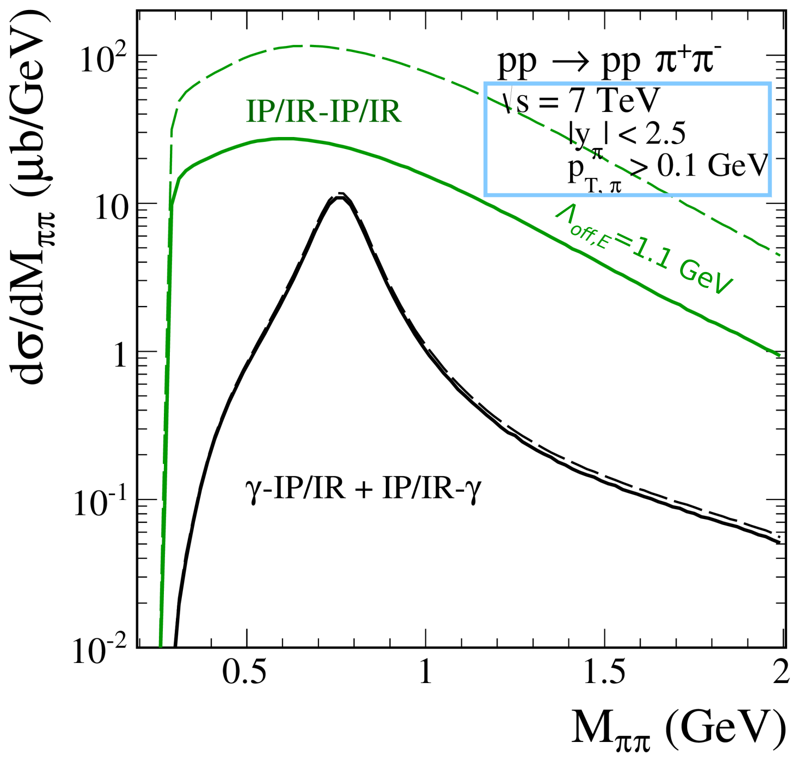


IP/IR-IP/IR mechanism

$$\mathcal{M}_{pp\to pp\pi^+\pi^-} = \mathcal{M}^{Born}_{pp\to pp\pi^+\pi^-} + \mathcal{M}^{pp-rescattering}_{pp\to pp\pi^+\pi^-}$$

$$\mathcal{M}^{pp-rescattering}_{pp\to pp\pi^+\pi^-}(s,\vec{p}_{1\perp},\vec{p}_{2\perp}) = \frac{i}{8\pi^2 s}\int d^2\vec{k}_\perp \mathcal{M}_{pp\to pp}(s,-\vec{k}^2_\perp)\mathcal{M}^{Born}_{pp\to pp\pi^+\pi^-}(s,\vec{p}_{1\perp}-\vec{k}_\perp,\vec{p}_{2\perp}+\vec{k}_\perp)$$



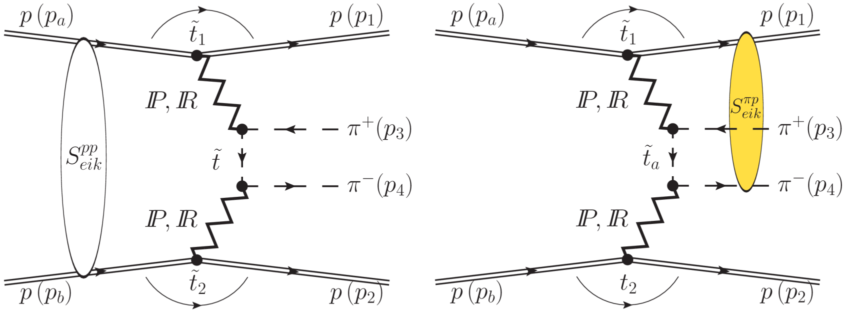


ratio of full and Born cross sections $< S^2(M_{\pi\pi}) >= \frac{d\sigma^{Born+pp-rescattering}/dM_{\pi\pi}}{d\sigma^{Born}/dM_{\pi\pi}}$

$< S^2 > \simeq 0.9$ for the photon-pomeron/reggeon contribution
and $< S^2 > \simeq 0.2$ for the double-pomeron/reggeon contribution

We observe that at midrapidities the photoproduction term could be visible in experiments.

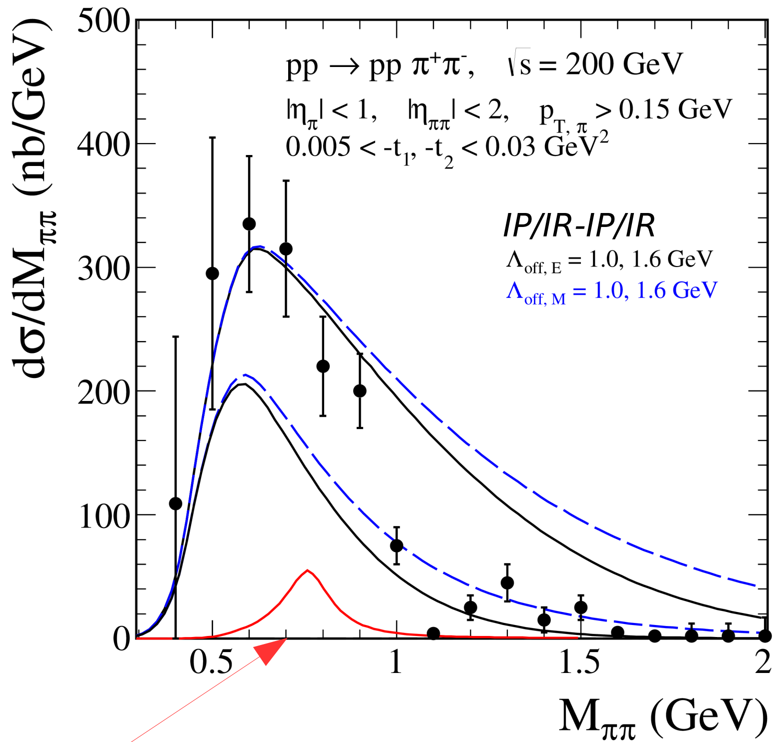
IP/IR-IP/IR mechanism

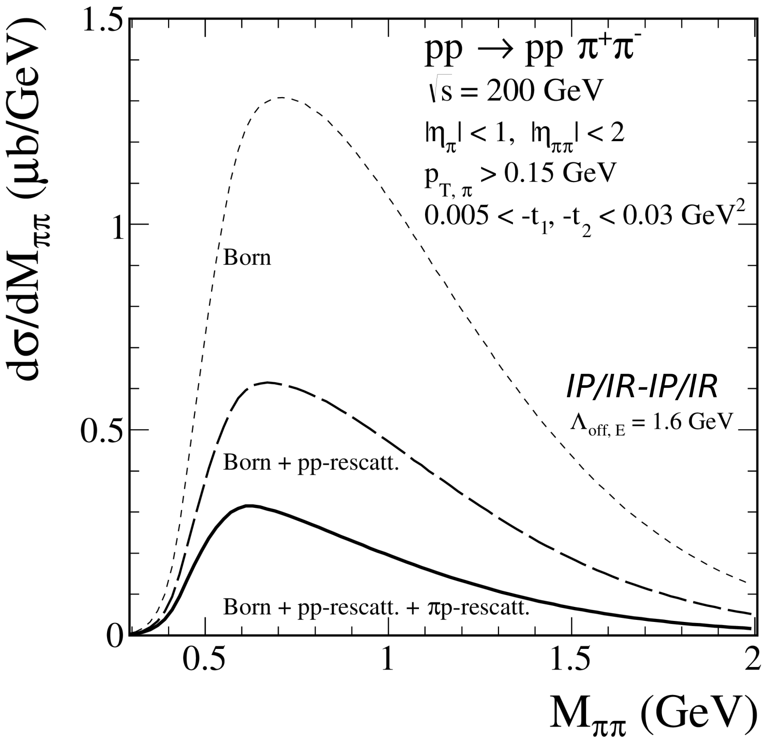


$$\mathcal{M}_{pp\to pp\pi^+\pi^-} = \mathcal{M}^{Born}_{pp\to pp\pi^+\pi^-} + \mathcal{M}^{pp-rescattering}_{pp\to pp\pi^+\pi^-} + \mathcal{M}^{\pi p-rescattering}_{pp\to pp\pi^+\pi^-}$$

damping of the cross section by a factor of about 2

see A. Szczurek talk





photoproduction contribution

STAR data → L. Adamczyk, W. Guryn, J. Turnau, *Central exclusive production at RHIC*, arXiv:1410.5752

σ = 133±8(stat.)±12(syst.) nb *see also J. Turnau talk*

Cross sections

σ in μb

$\sqrt{s}$, TeV	$I\!P$ and $f_{2 I\!R}$	$I\!P$
0.2	2.22	1.36
0.5	3.38	2.31
1.96	5.77	4.51
7	7.80	6.64
0.2 (STAR cuts)	0.011	0.008
7 (ALICE cuts)	0.59	0.58
7 (CMS cuts)	2.61	2.53

Table 1: The integrated cross sections in μb for the central exclusive $\pi^+\pi^-$ production via the photoproduction mechanism for $2m_\pi \leqslant M_{\pi\pi} \leqslant 1.5$ GeV. In the calculations for the last three lines the following cuts were imposed: $|\eta_\pi| < 1.0$, $|\eta_{\pi\pi}| < 2.0$, $p_{\perp,\pi} > 0.15$ GeV, $0.005 < -t_1, -t_2 < 0.03$ GeV^2 at $\sqrt{s} = 200$ GeV (STAR cuts) while at the LHC energies $|y_\pi| < 2.5$, $p_{\perp,\pi} > 0.1$ GeV (CMS cuts) and $|\eta_\pi| < 0.9$, $p_{\perp,\pi} > 0.1$ GeV (ALICE cuts).

Conclusions and Outlook

- We have made first estimates of central exclusive photoproduction mechanisms to the $pp \to pp\pi^+\pi^-$ reaction. Due to the photon propagators occurring in these diagrams we expect these processes to be most important when at least one of the protons is undergoing only a very small momentum transfer.

  The photoproduction contribution constitutes about 10% of the double *IP*/*IR* contribution (strongly depending on the invariant mass of the two-pion system).

  Similar characteristic of rapidity and $p_{\perp,\pi}$ distributions, but different dependence on $p_{\perp,p}$ and ϕ_{pp}. Rapidities distribution of the two pions are strongly correlated and $y(\pi^+) \approx y(\pi^-)$.

  One could separate the space in azimuthal angle into two regions: $\phi_{pp} < \pi/2$ and $\phi_{pp} > \pi/2$. The photoproduction contribution in the first region should be strongly enhanced for *pp*-collisions. Also a cut on $\phi_{\pi\pi}$ could help to enhance the photoptroduction contribution.

- The absorptive corrections for photon induced $pp \to pp\pi^+\pi^-$ reaction lead to about 10% reduction of the cross section. In the case of central exclusive production of heavier vector mesons the effect is even larger (see e.g. the exclusive production of J/ψ meson: Cisek, Schafer, Szczurek, arXiv:1405.2253).

- Our study shows the potential of exclusive reactions for testing the nature of the soft pomeron. Future experimental data (COMPASS, STAR RHIC, CDF Tevatron, ALICE, CMS, ATLAS, LHCb etc.) on exclusive meson production should thus provide good information on the spin structure of the soft pomeron and on its couplings to the nucleon and the mesons.

- In progress: a consistent model of the tensor resonances decaying into the $\pi\pi/KK$ channels and the non-resonant background. Interference effects between resonant and non-resonant contributions.

- Closely related to the reaction $pp \to pp\pi^+\pi^-$ discussed here are the reactions of central $\pi^+\pi^-$ production in ultra-peripheral nucleon-nucleus ($pA \to pA\pi^+\pi^-$) and nucleus-nucleus ($AA \to AA\pi^+\pi^-$) collisions. The application of tensor pomeron concept to collisions involving nuclei is an interesting problem.