Diffractive and exclusive production of light mesons in proton-proton collisions

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Contents

- Diffractive mechanism of $\pi^+\pi^-$ pairs production
- Photoproduction mechanisms (*ρ^0 and Drell-Söding contributions)*
- Results and predictions for different experiments

Based on:

P. Lebiedowicz, A. Szczurek, *Revised model of absorption corrections for the pp → pp $\pi^+\pi^-$ process*, arXiv:1504.0760, in print in Phys. Rev. D92

P. Lebiedowicz, O. Nachtmann, A. Szczurek, *ρ^0 and Drell-Söding contributions to central exclusive production of $\pi^+\pi^-$ pairs in proton-proton collisions at high energies*, Phys. Rev. D91 (2015) 7, 07402300

Related works:

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

A. Bolz, C. Ewerz, M. Maniatis, O. Nachtmann, M. Sauter, A. Schöning, JHEP 1501, 151 (2015)

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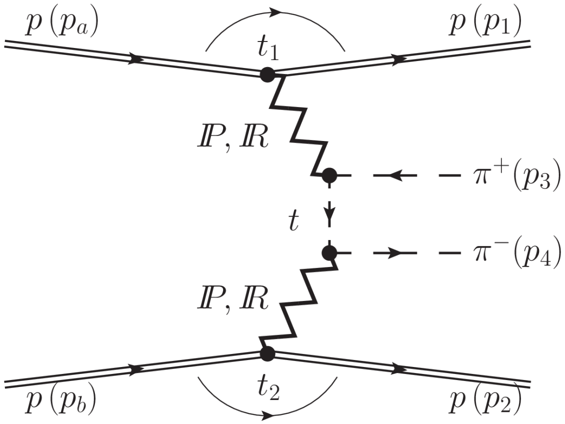
and by the START fellowship from the Foundation for Polish Science.

Diffractive mechanism



$$p(p_a,\lambda_a)+p(p_b,\lambda_b)\to p(p_1,\lambda_1)+\pi^+(p_3)+\pi^-(p_4)+p(p_2,\lambda_2)$$

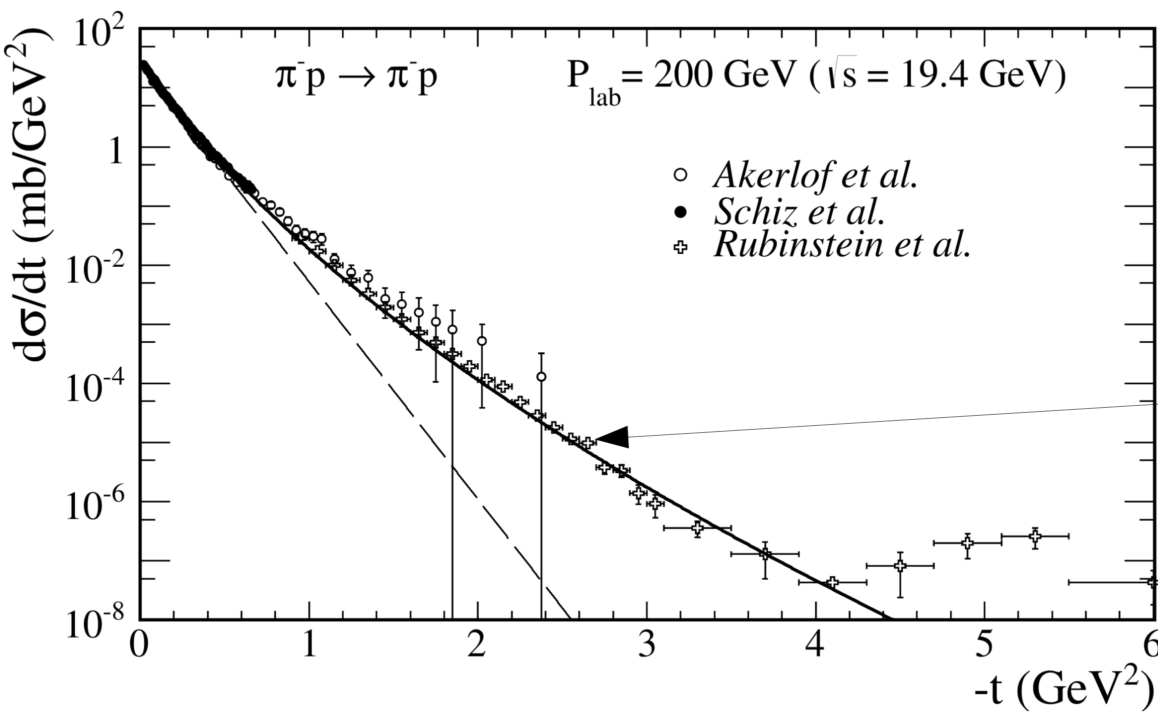
$$\mathcal{M}^{\rm Born}_{pp\to pp\pi^+\pi^-} = M_{13}(s_{13},t_1)\,\frac{F_\pi^2(t)}{t-m_\pi^2}\,M_{24}(s_{24},t_2) + [u-\text{channel}]$$

$$\begin{aligned} M_{ij}(s_{ij},t_i) &= i\,C_{I\!P}\,(s_{ij}/s_0)^{0.0808}\,\exp\left(B_{I\!P}\,t_i/2\right)\\ &\quad +\eta_{f_{2I\!R}}\,C_{f_{2I\!R}}\,(s_{ij}/s_0)^{0.5475}\,\exp\left(B_{f_{2I\!R}}\,t_i/2\right)\end{aligned}$$

form factors for the off-shell pions: $F_\pi(t)=\exp\left(\dfrac{t-m_\pi^2}{\Lambda^2_{off,E}}\right)$ or $F_\pi(t)=\dfrac{\Lambda^2_{off,M}-m_\pi^2}{\Lambda^2_{off,M}-t}$

$$\exp\left(B_{I\!P}\,t_i/2\right)\to \qquad f(t_i,s_{ij})=\exp\left(\mu^2 B_{I\!P}\right)\exp\left(-\mu^2 B_{I\!P}\sqrt{1-t_i/\mu^2}\right)$$

$$B_{I\!P}\equiv B(s_{ij})=B_0+2\alpha'_{I\!P}\ln\left(s_{ij}/s_0\right)$$

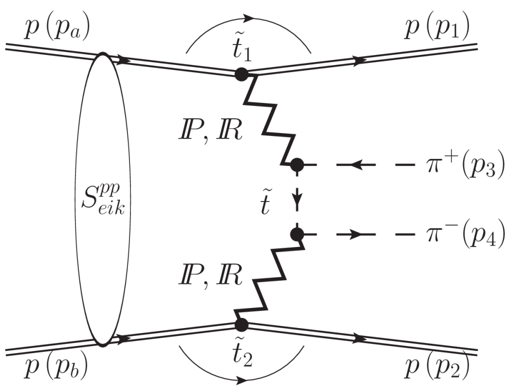


the 'stretched exponential' form coincides at low $|t|$ with the simple exponential form while at larger |t| a harder tail appears

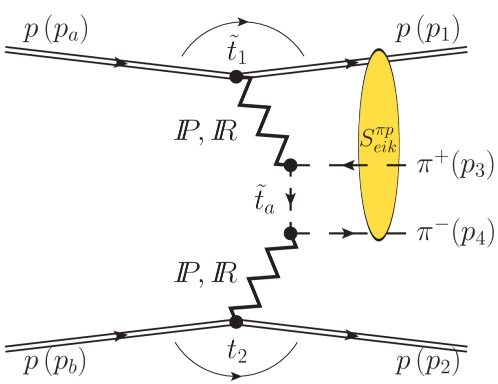
Absorption effects

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

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



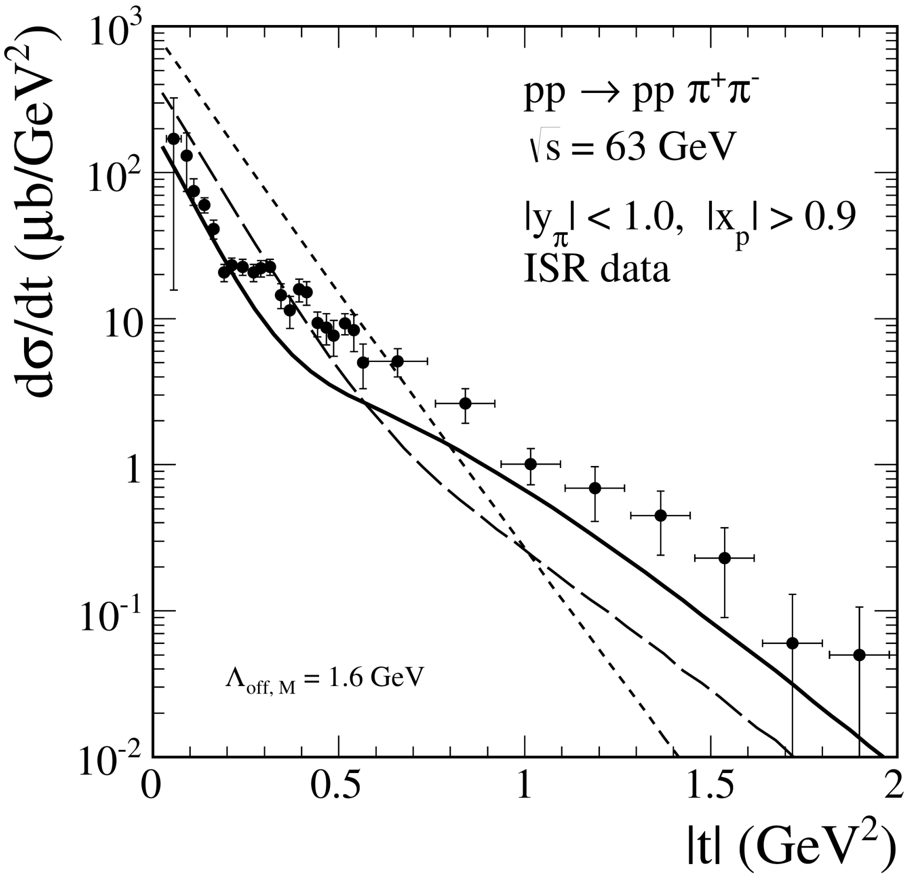
← absorption corrections due to *pp interactions* (ISI & FSI)

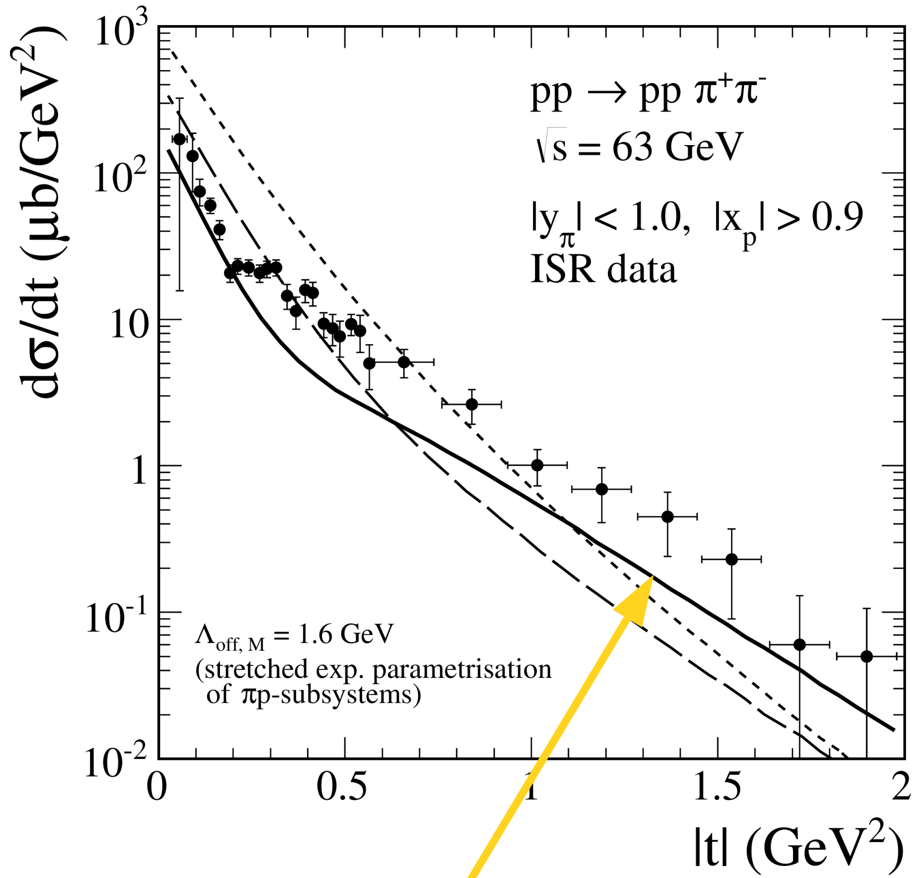


← new absorption corrections (*πp* FSI)

Ratio of full and Born cross sections $< S^2 >= \frac{\sigma^{Born\,+\,(NN-rescat.)+\,(\pi N-rescat.)}}{\sigma^{Born}}$

Comparison with ISR data

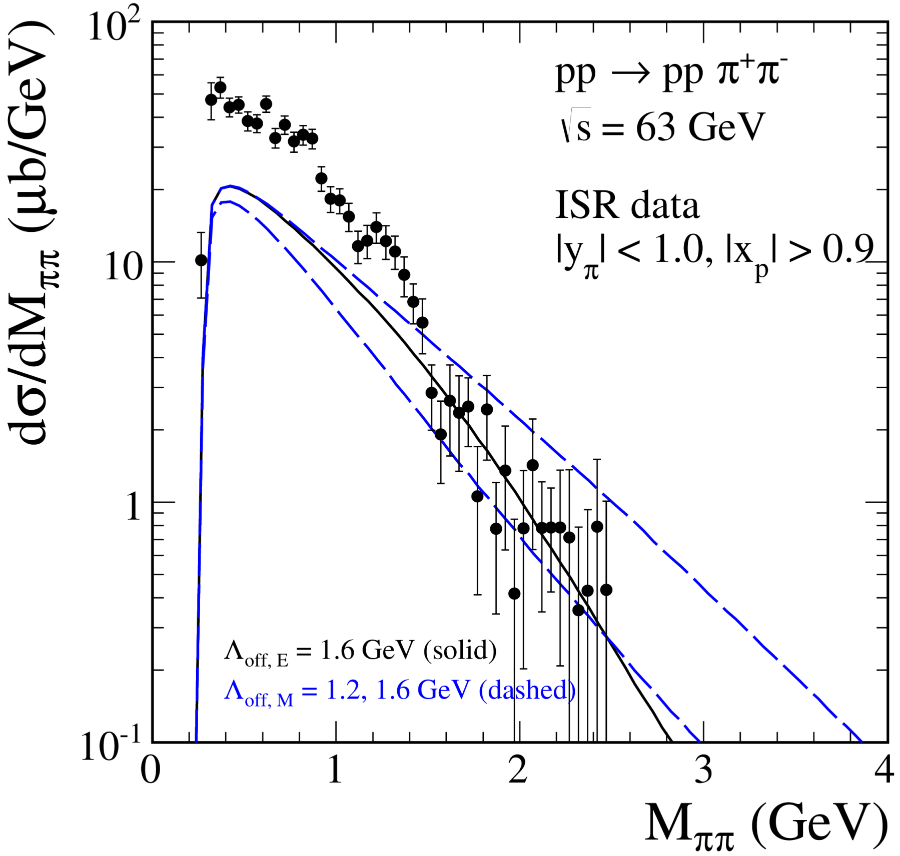


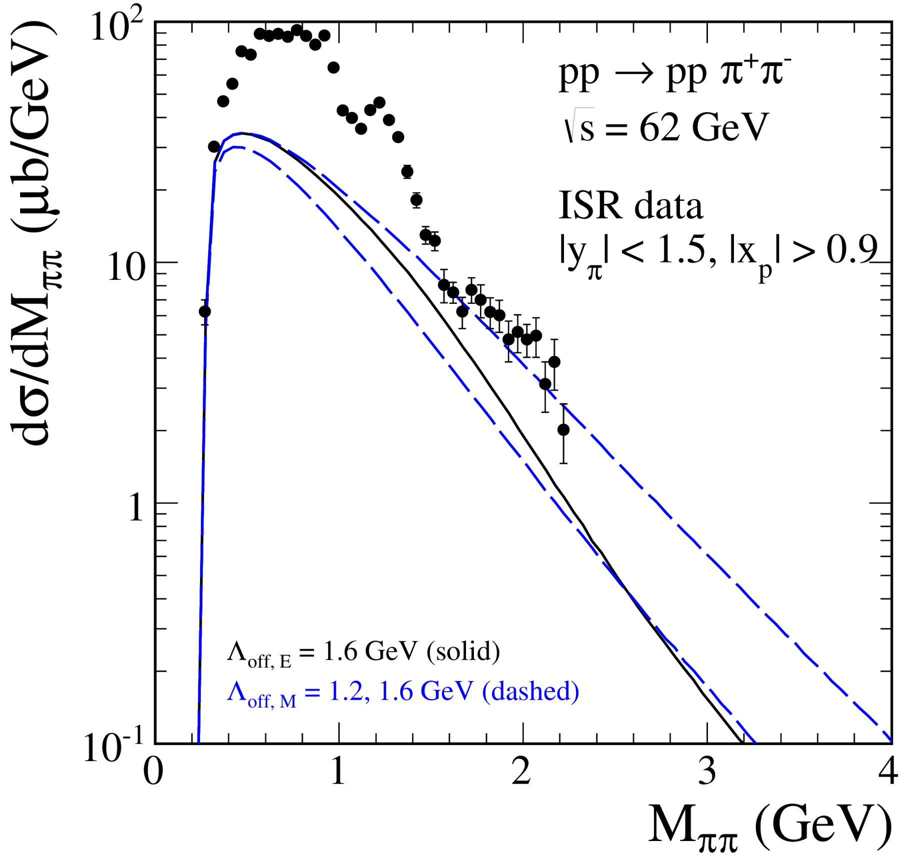


πp FSI effects enhancement cross section at large |t|

ISR data: R.Waldi, K. R. Schubert, and K. Winter, *Search for glueballs in a pomeron pomeron scattering experiment*, Z.Phys. C18 (1983) 301–306.

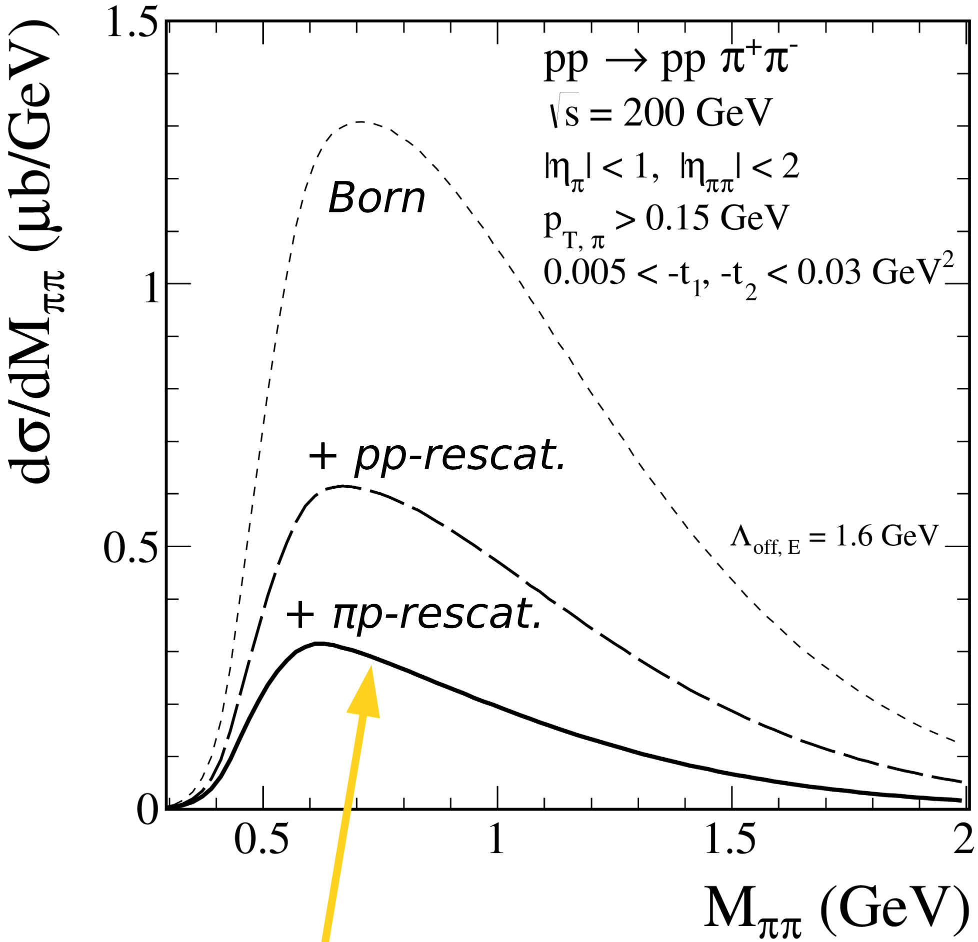
Comparison with ISR data

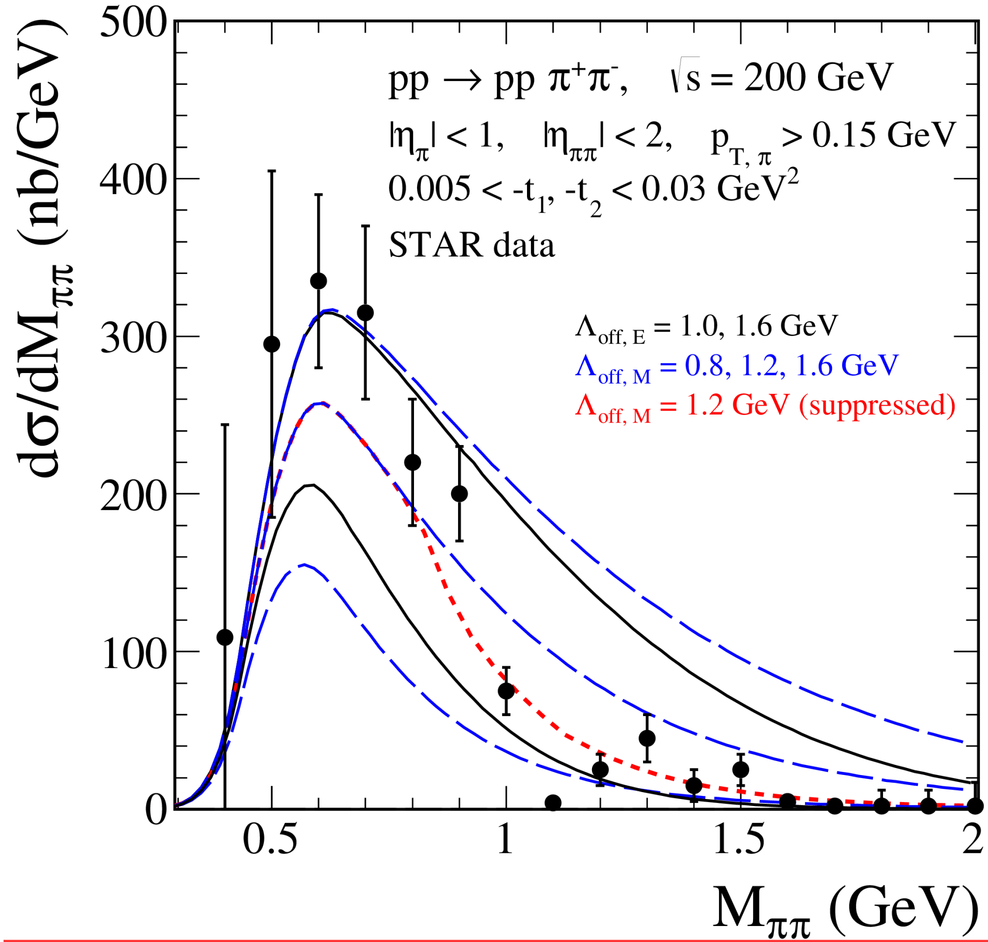




ISR data:
Left panel: R.Waldi, K. R. Schubert, and K. Winter, *Search for glueballs in a pomeron pomeron scattering experiment*, Z.Phys. C18 (1983) 301–306;
Right panel: A. Breakstone et al., (ABCDHW Collaboration), *The reaction Pomeron-Pomeron → $\pi^+\pi^-$ and an unusual production mechanism for the f2(1270)*, Z.Phys. C48 (1990) 569–576.

Comparison with STAR (preliminary) data





πp FSI effects further damping of the cross section by a factor of about 2

$$< S^2 > (M_{\pi\pi}) \simeq 0.2$$

a suppression factor:

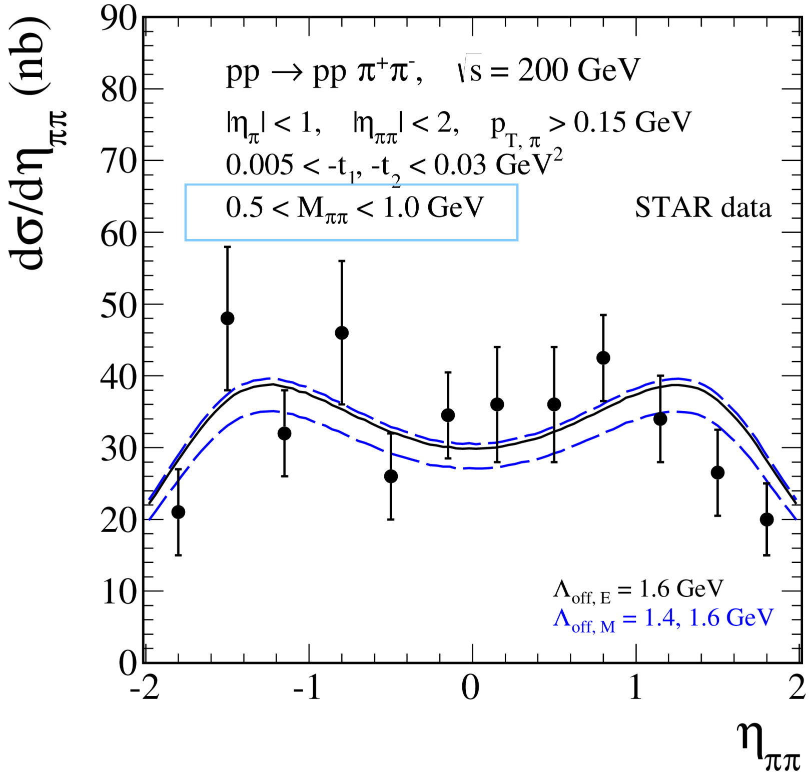
$$f(M_{\pi\pi}) = \exp(-c\ln(M_{\pi\pi}/M_0)) = (M_0/M_{\pi\pi})^c$$

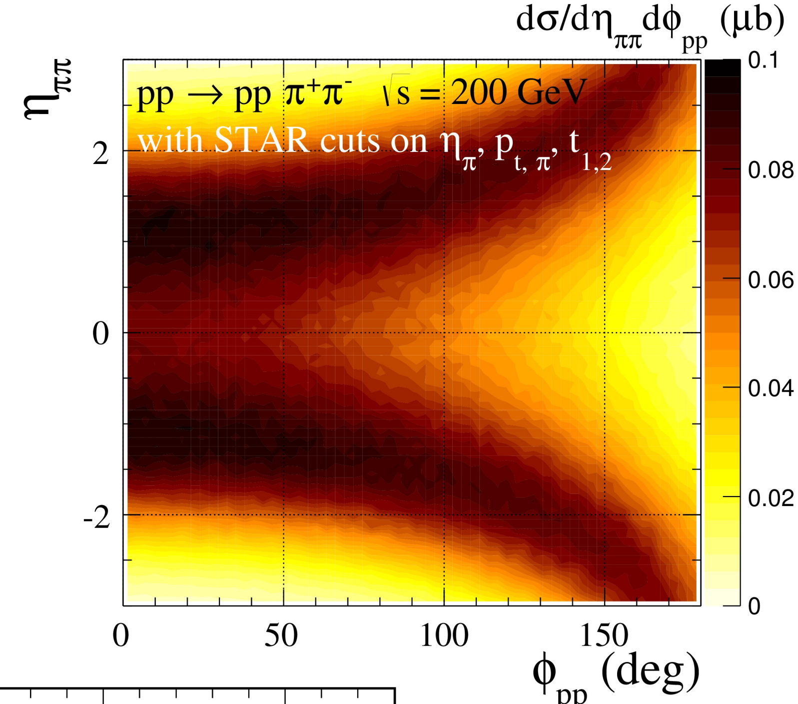
$$M_0 = 0.8 \text{ GeV}^2, \quad c = 0.5$$

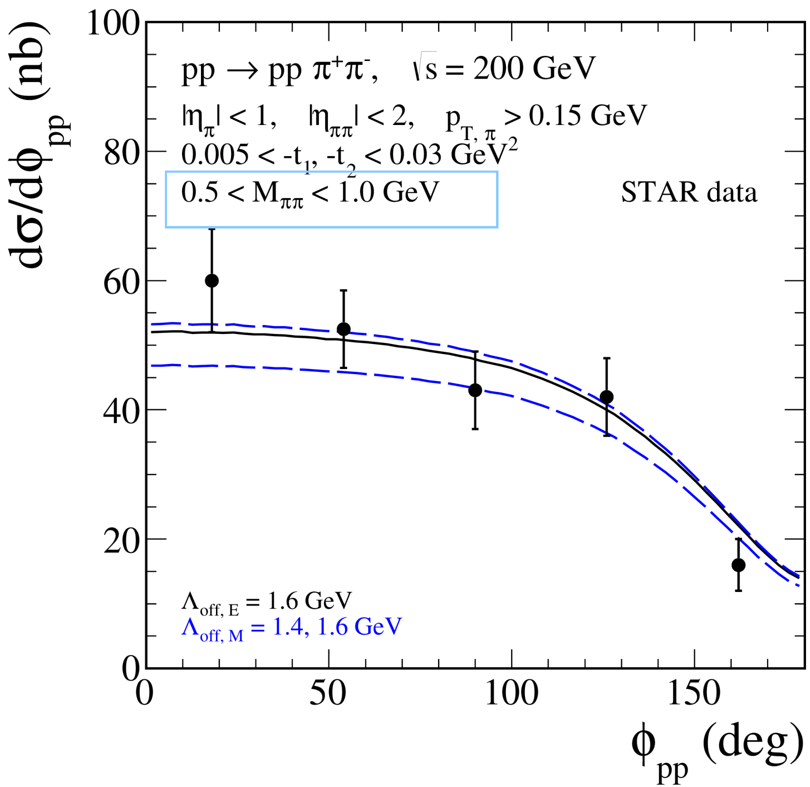
see Harland-Lang, Khoze, Ryskin, Eur.Phys.J. C74 (2014) 2848

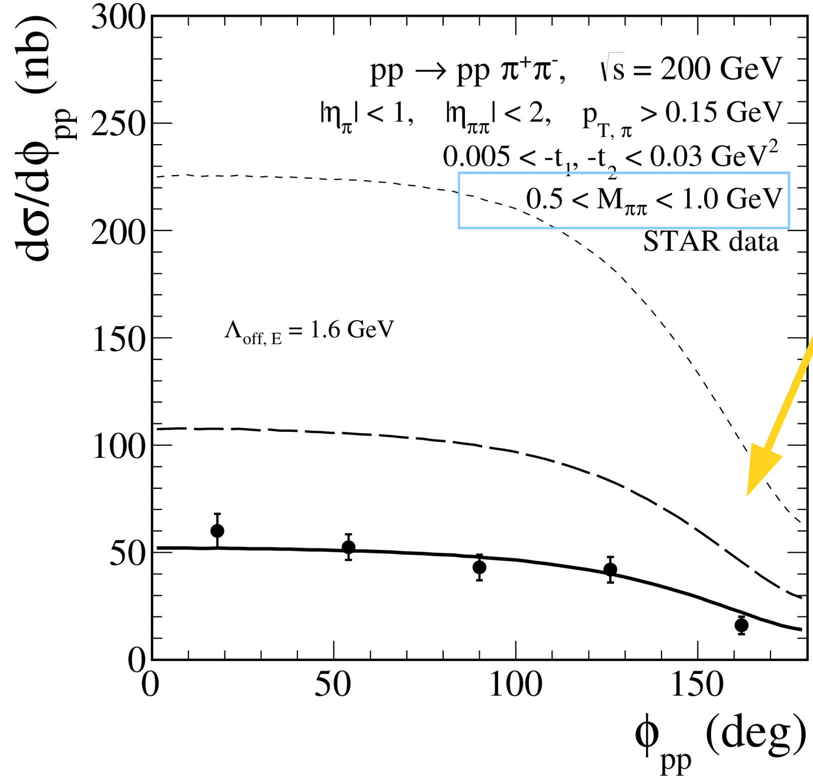
STAR data: L. Adamczyk, W. Guryn, and J. Turnau, *Central exclusive production at RHIC*, Int.J.Mod.Phys. A29 no. 28, (2014) 1446010, arXiv:1410.5752 [hep-ex].

Comparison with STAR data



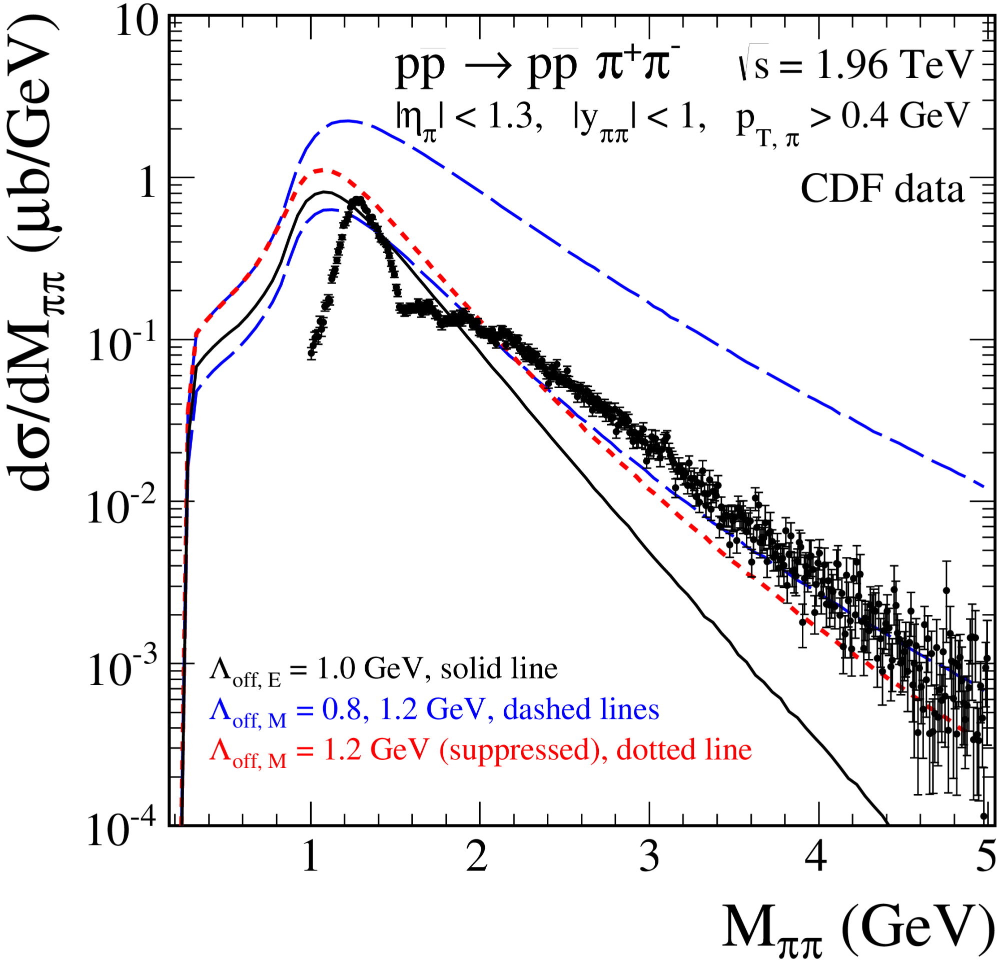


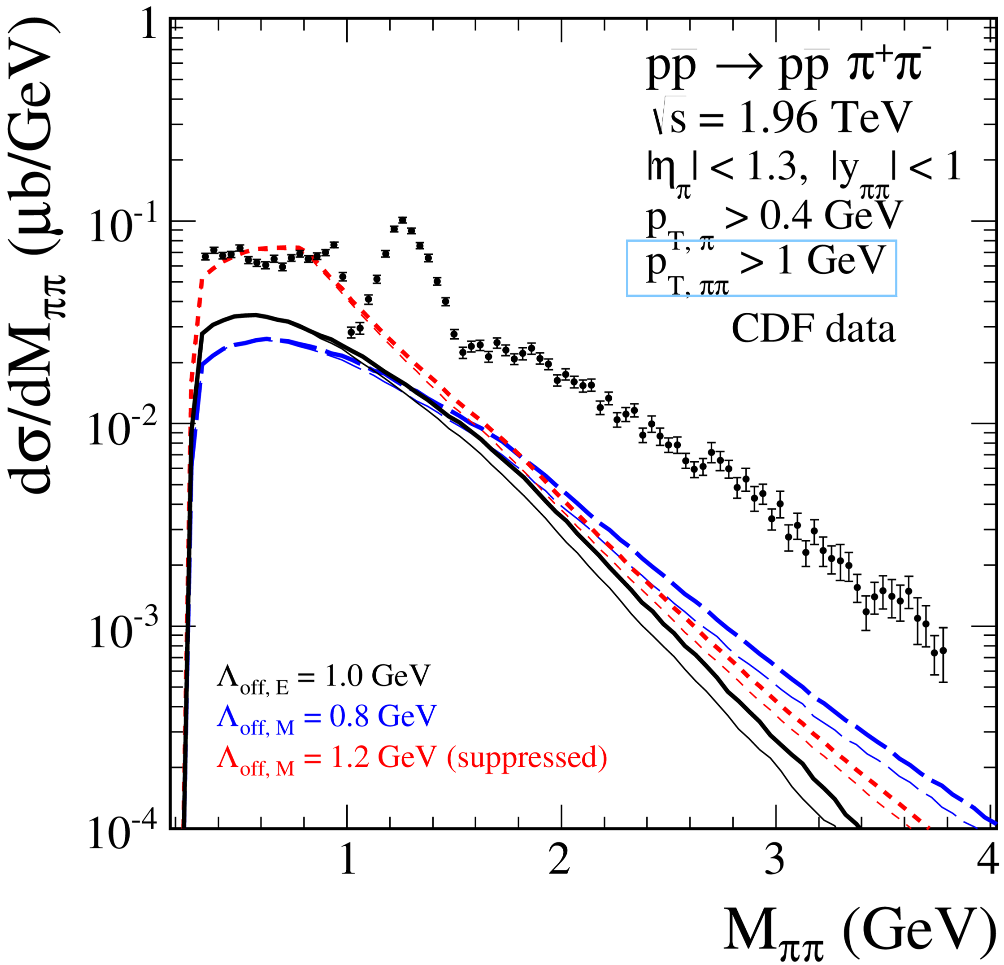




The decrease of azimuthal distribution at $\varphi \approx \pi$ is due to the condition $|\eta_{\pi\pi}| < 2$

Comparison with CDF data



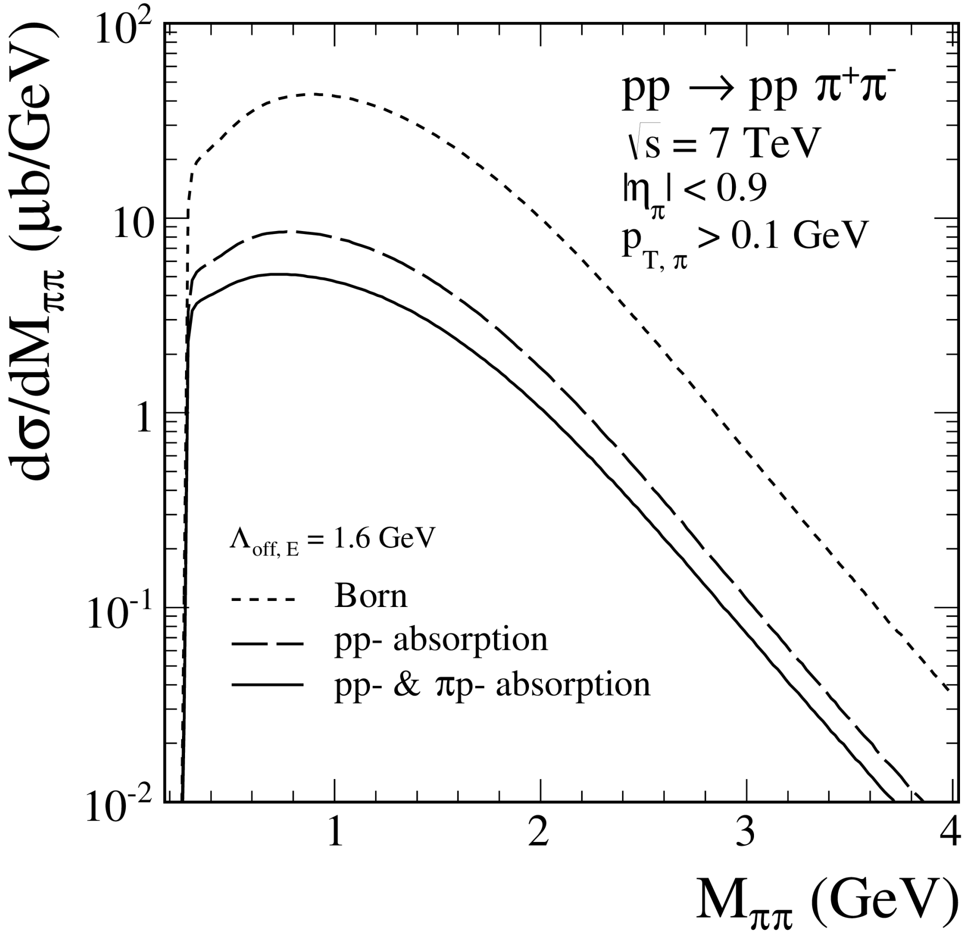


- (right panel) our model results are much below the CDF data which could be due to a contamination of non-exclusive processes
- effect of 'stretched exponential' parametrization is small (see thin vs. thick lines)

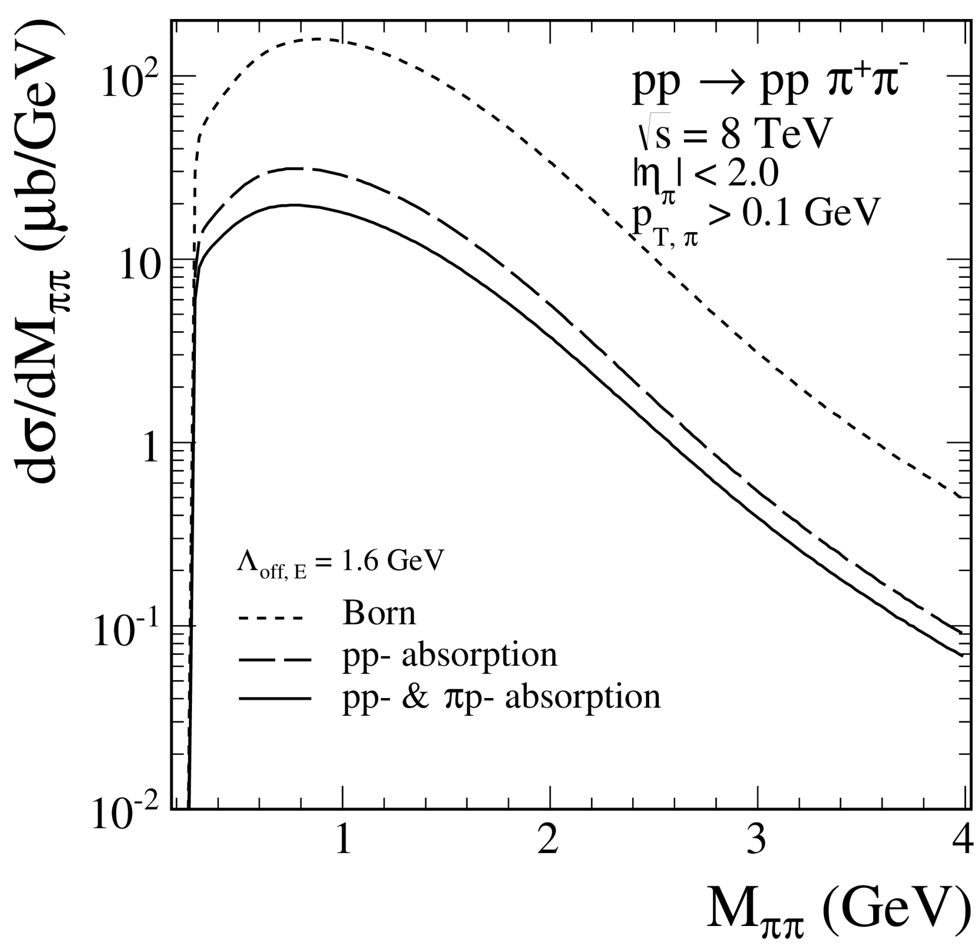
CDF data: T. A. Aaltonen et al., (CDF Collaboration), *Measurement of central exclusive $\pi^+\pi^-$ production in $p\bar{p}$ collisions at $\sqrt{s}$ = 0.9 and 1.96 TeV at CDF*, Phys.Rev. D91 no. 9, (2015) 091101, arXiv:1502.01391 [hep-ex]

Predictions for the LHC

ALICE



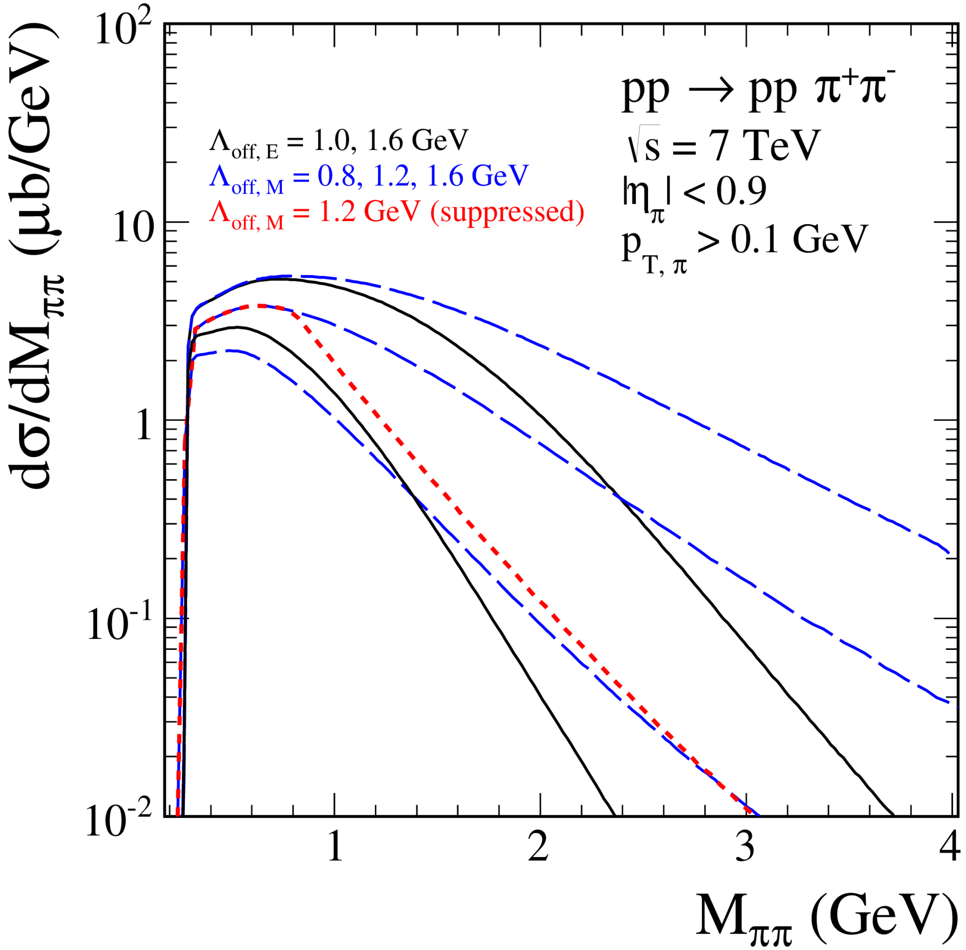
CMS+TOTEM, ATLAS+ALFA



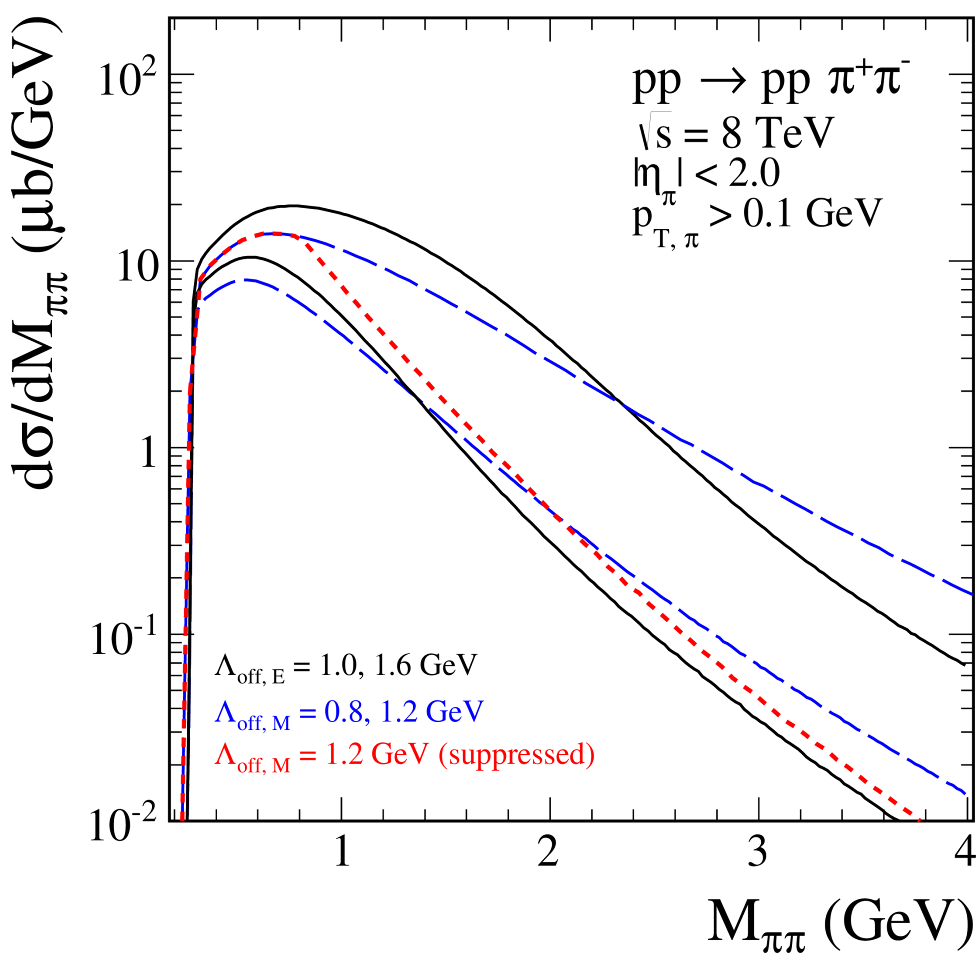
$$< S^2(M_{\pi\pi}) > \simeq 0.1$$

Predictions for the LHC

ALICE

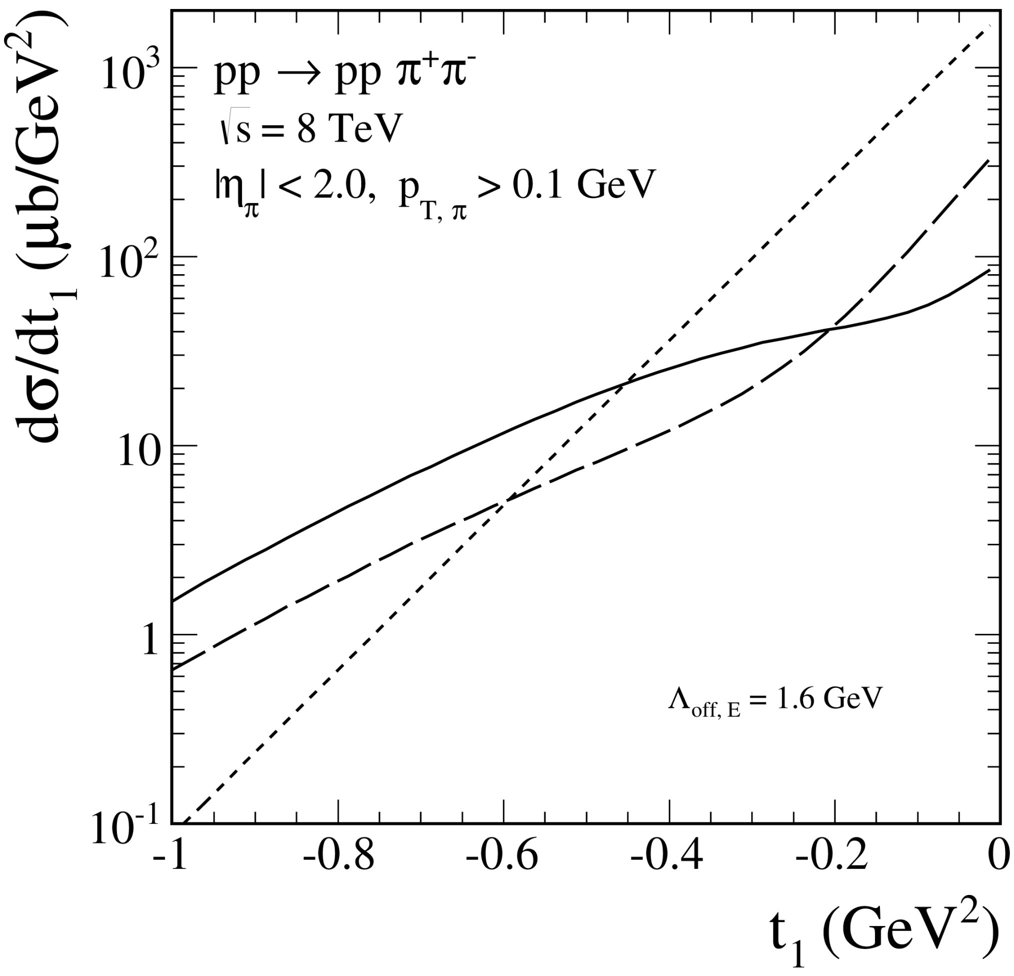


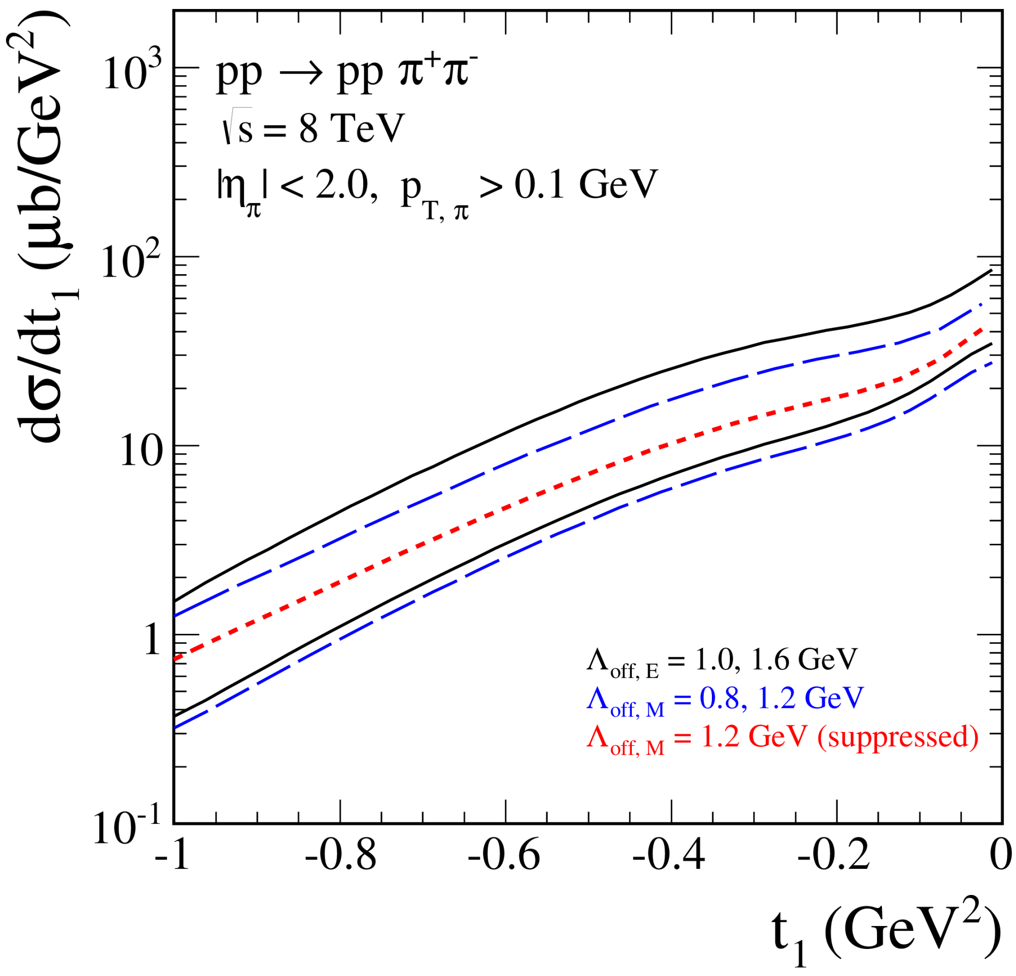
CMS+TOTEM, ATLAS+ALFA



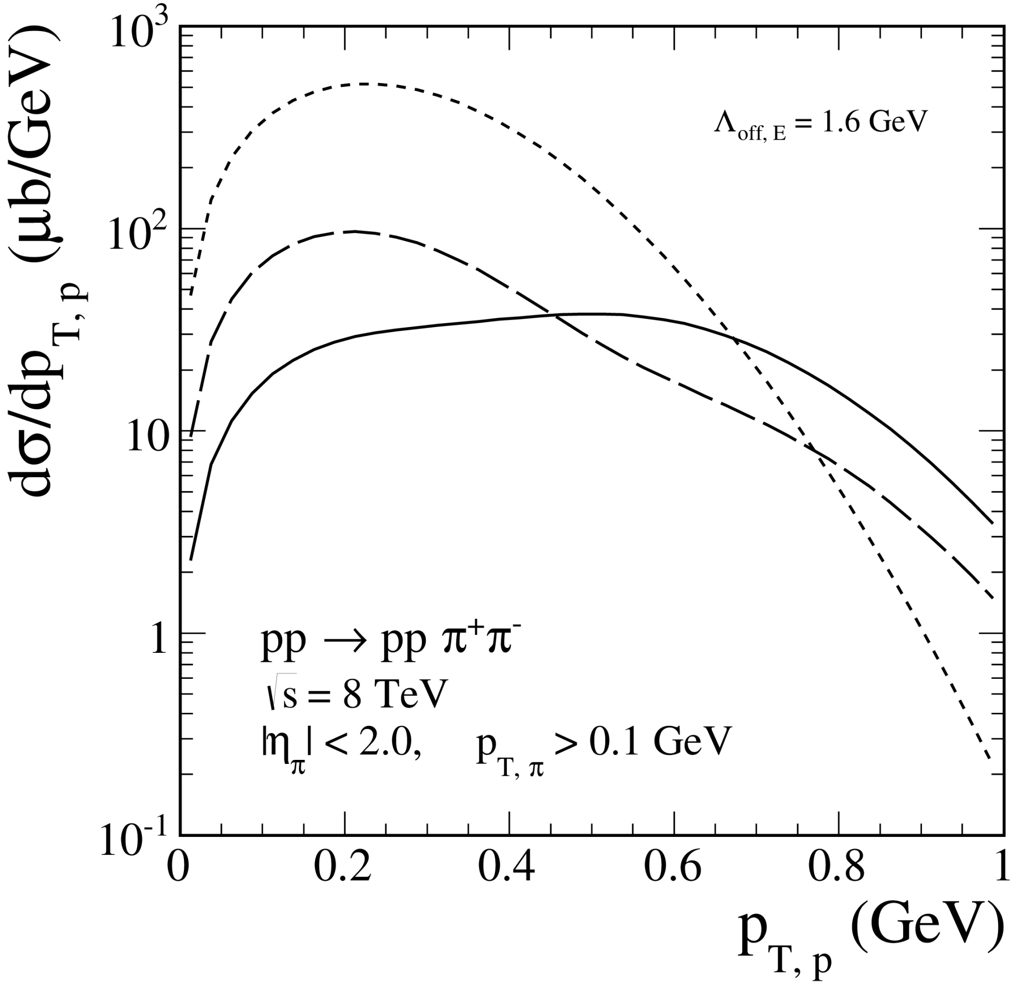
pp- and *πp*- absorption effects included

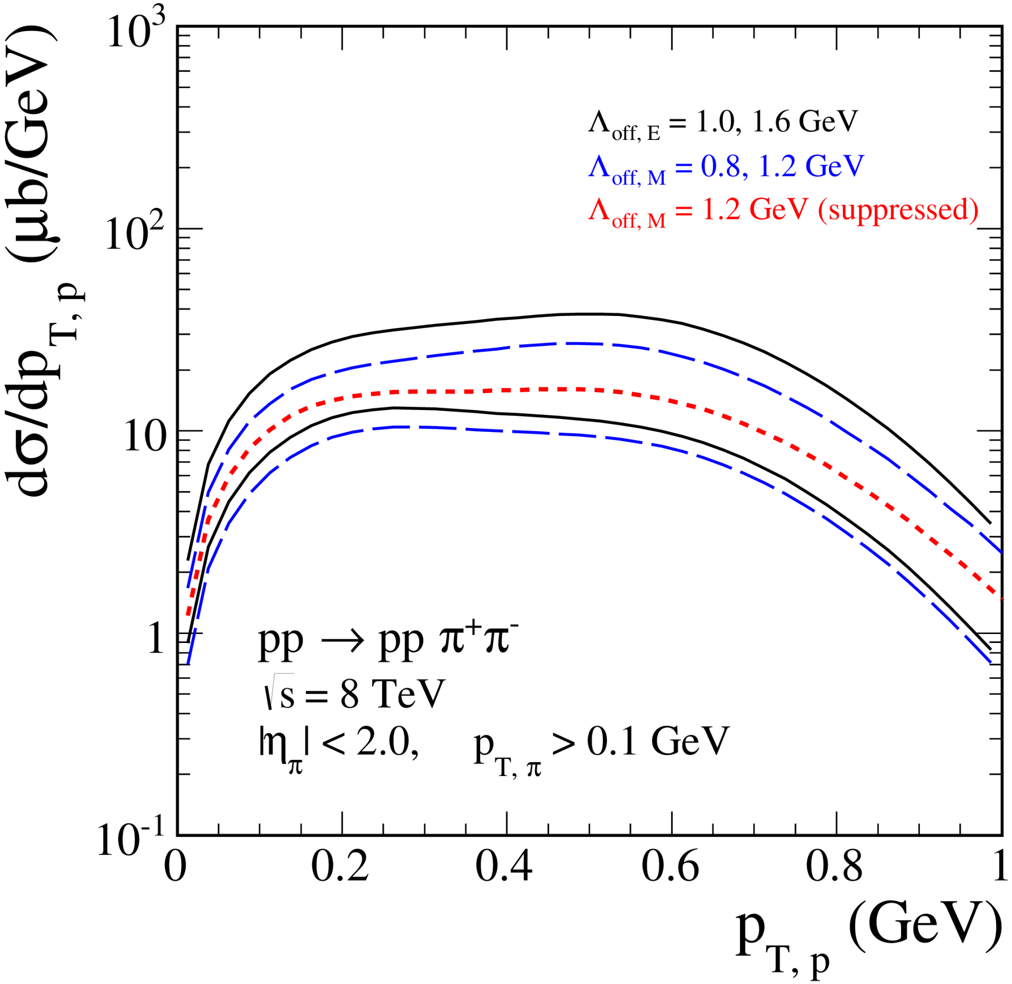
Predictions for CMS+TOTEM, ATLAS+ALFA



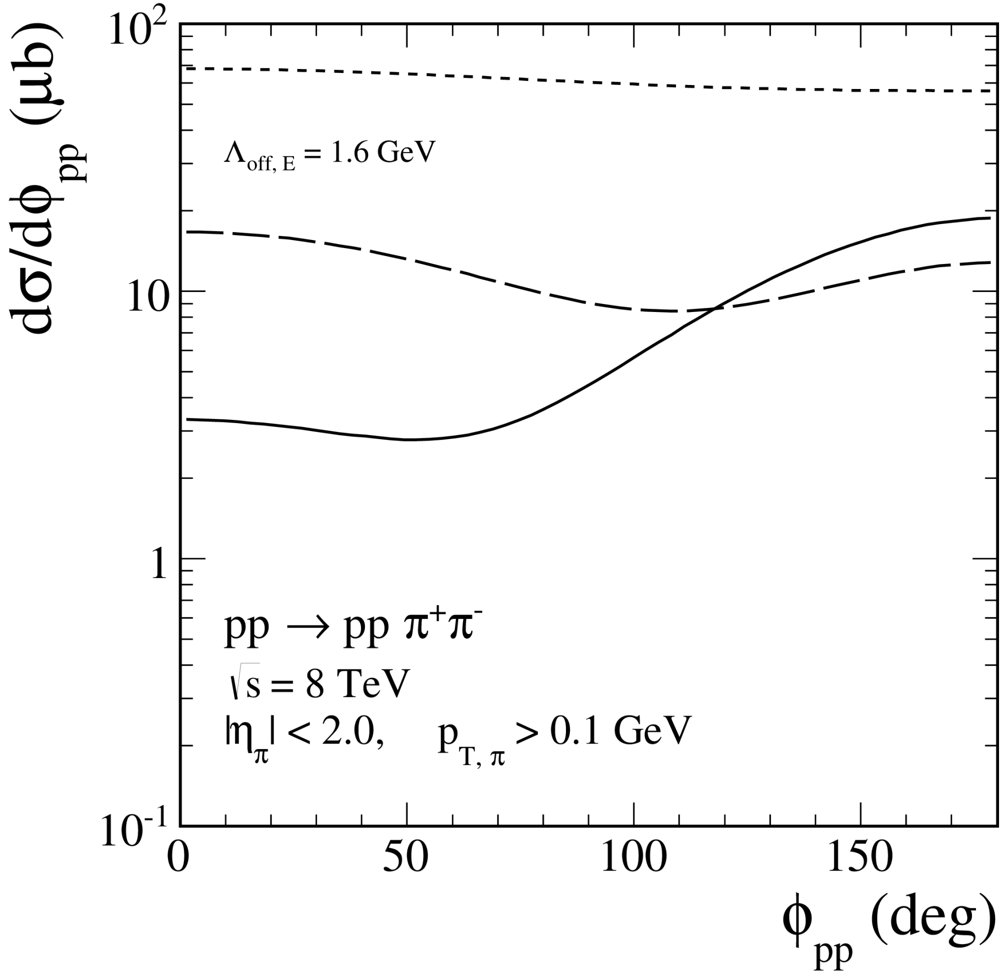


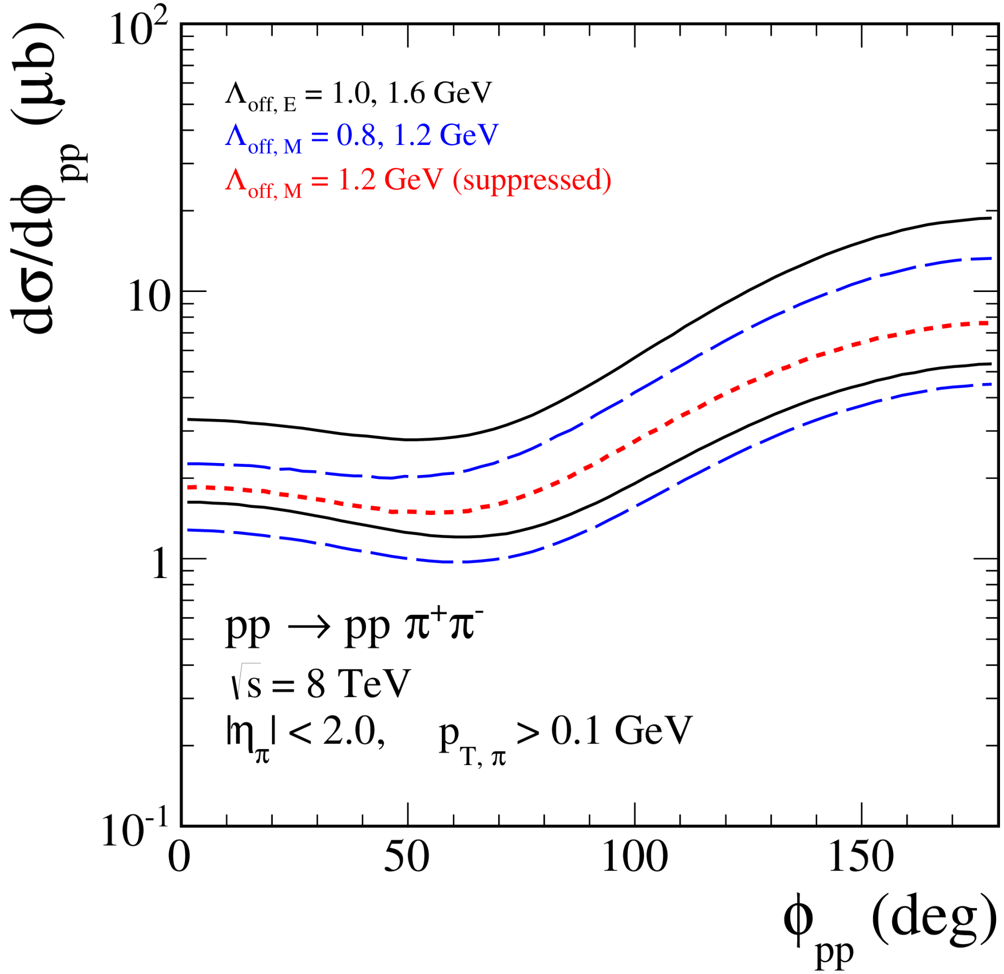
Predictions for CMS+TOTEM, ATLAS+ALFA



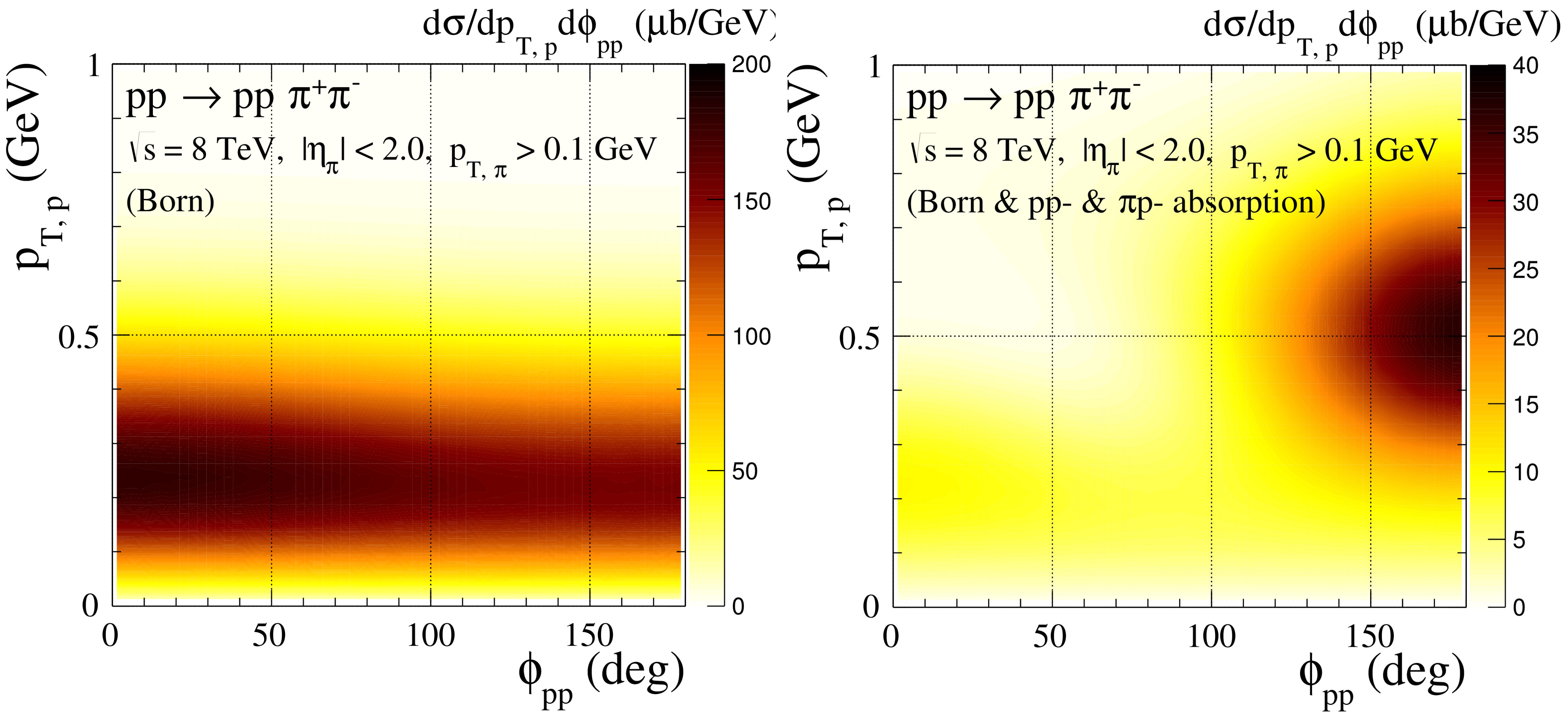


Predictions for CMS+TOTEM, ATLAS+ALFA





Predictions for CMS+TOTEM, ATLAS+ALFA



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

Cross sections (in μb) for diffractive contribution

$\sqrt{s}$ (TeV):	0.2 (STAR)	1.96 (CDF)	7 (ALICE)	8 (CMS)	13 (CMS)
$\Lambda_{off,E} = 1.6$ GeV	0.23	3.69	6.57	23.92	28.64
$\Lambda_{off,E} = 1.0$ GeV	0.09	0.63	2.16	7.88	8.98
$\Lambda_{off,M} = 1.6$ GeV	0.26	6.45	9.12	33.60	40.92
$\Lambda_{off,M} = 1.2$ GeV	0.17 (0.13) [1]	2.48 (0.90)	4.65 (3.00)	17.14 (10.83)	20.65 (12.71)
$\Lambda_{off,M} = 0.8$ GeV	0.07	0.58	1.74	6.48	7.45

The integrated cross sections in μb for the central exclusive $\pi^+\pi^-$ production via the double-pomeron/$f_{2I\!R}$ exchange mechanism including the NN and πN absorption effects. The results with cuts for different experiments and for the different values of the off-shell-pion form-factor parameters are shown.

[1] The numbers in the parentheses show the resulting cross sections multiplying the amplitude by the suppressed factor $f(M_{\pi\pi})$.

STAR cuts: $|\eta_\pi| < 1.0$, $|\eta_{\pi\pi}| < 2.0$, $p_{\perp,\pi} > 0.15$ GeV, $0.005 < -t_1, -t_2 < 0.03$ GeV^2

CDF cuts: $|\eta_\pi| < 1.3$, $|y_{\pi\pi}| < 1$, $p_{t,\pi} > 0.4$ GeV

ALICE cuts: $|\eta_\pi| < 0.9$, $p_{\perp,\pi} > 0.1$ GeV

CMS cuts: $|\eta_\pi| < 2.0$, $p_{\perp,\pi} > 0.1$ GeV

Tensor pomeron model

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

Regge-type model with effective vertices and propagators respecting the standard *C* parity and crossing rules of QFT:
C = +1 exchanges ($I\!P$, $f_{2I\!R}$, $a_{2I\!R}$) are represented as rank-two-tensor exchanges,
C = -1 exchanges (odderon, $\omega_{I\!R}$, $\rho_{I\!R}$) are represented as vectorial exchanges.

Example: *pp* elastic scattering via effective <u>tensor pomeron</u> exchange

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

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

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

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

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

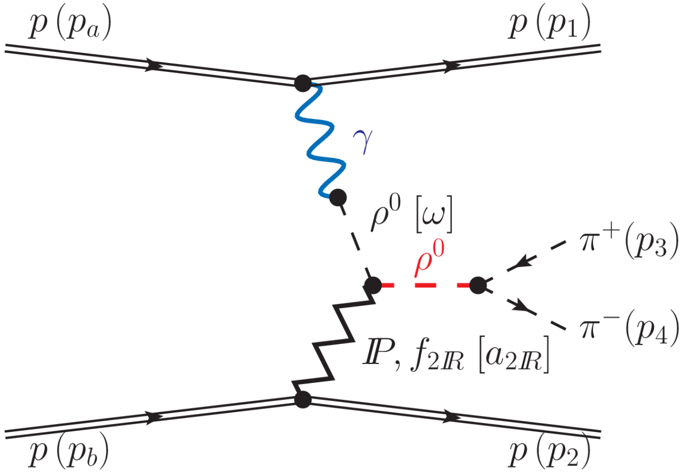
Tensor pomeron gives, at high energies, the same results for the *pp* and $p\bar{p}$ elastic amplitudes as for standard Donnachie-Landshoff (DL) pomeron (frequently called a '*C* = +1 photon').

The DL pomeron is very succesful, but there are problems. An effective vectorial exchange gives opposite sign for *pp* and $p\bar{p}$ amplitudes. But *IP* exchange must give same sign.
In the other words: *IP* exchange has charge conjugation *C* = +1.

A tensor couples equally to particles and antiparticles and the relative sign between *pp* and $p\bar{p}$ is correct automatically.

Resonant ρ^0 production

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



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

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

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

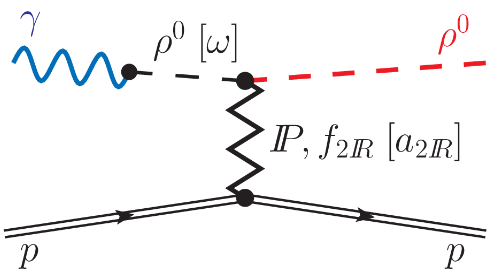
$$V_{\mu\nu\kappa\lambda}(s,t,q,p_{34}) = \frac{1}{4s}\Big\{2\Gamma^{(0)}_{\mu\nu\kappa\lambda}(p_{34},-q)\left[3\beta_{I\!PNN}\,a_{I\!P\rho\rho}(-is\alpha'_{I\!P})^{\alpha_{I\!P}(t)-1} + M_0^{-1}g_{f_{2I\!R}pp}\,a_{f_{2I\!R}\rho\rho}(-is\alpha'_{I\!R_+})^{\alpha_{I\!R_+}(t)-1}\right]$$
$$-\Gamma^{(2)}_{\mu\nu\kappa\lambda}(p_{34},-q)\left[3\beta_{I\!PNN}\,b_{I\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

tensorial 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 fulfill 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



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

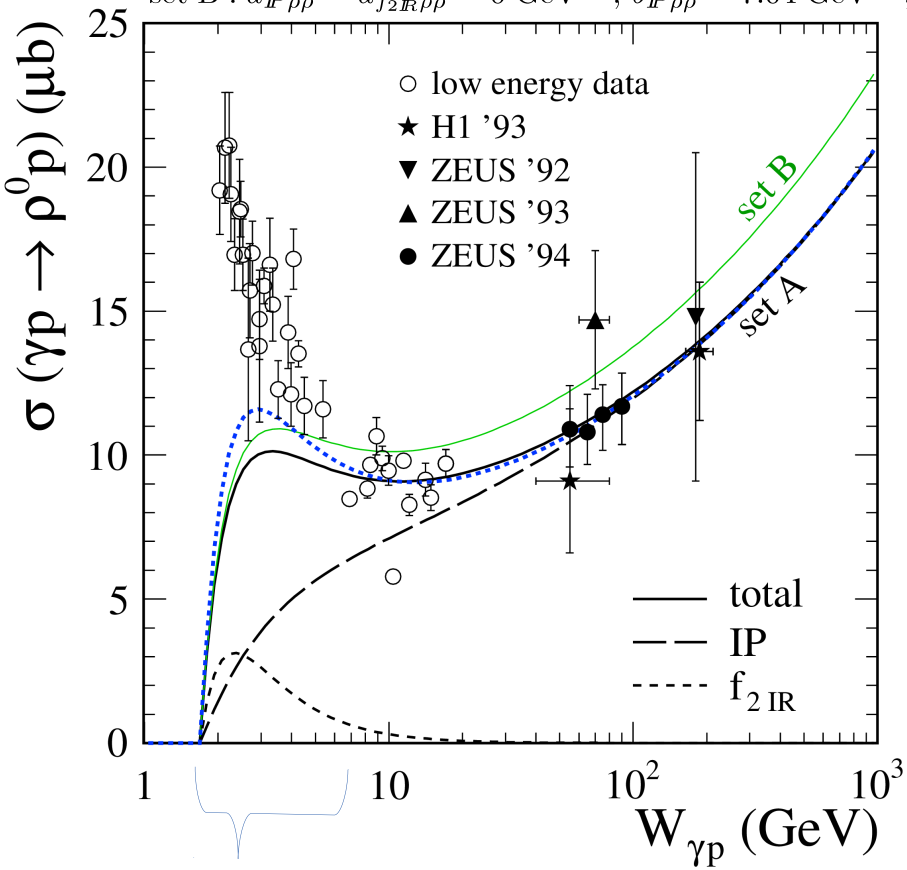
$$F_M(t) = \frac{1}{1 - t/\Lambda_0^2}$$
$$\Lambda_0^2 = 0.5\ GeV^2$$

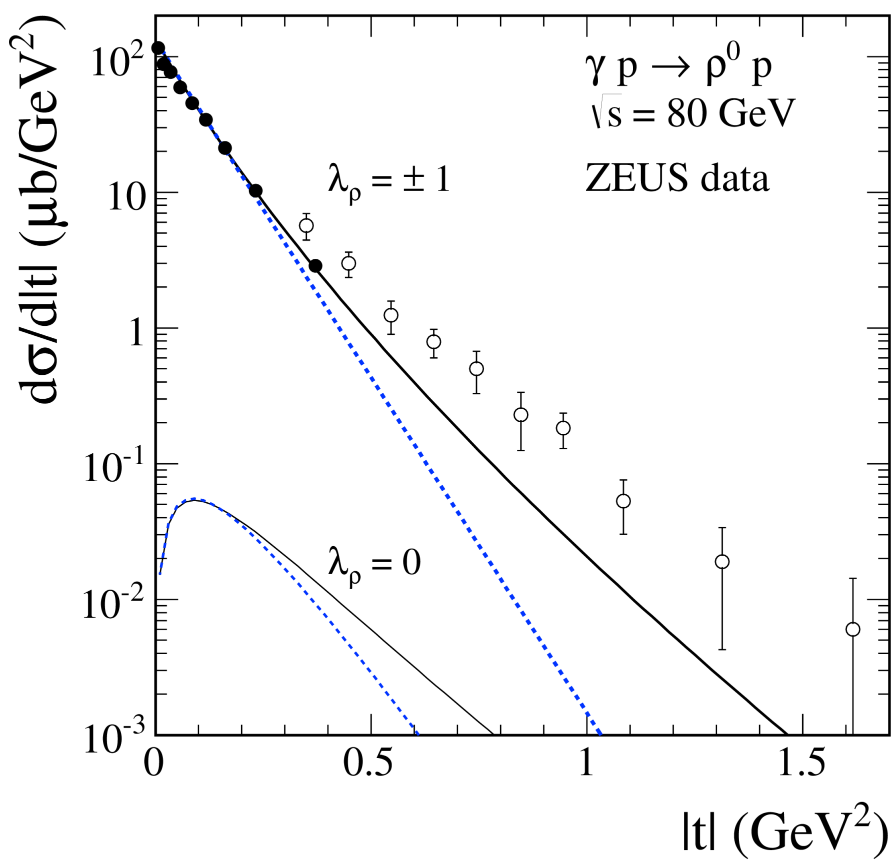
alternatively, $F_1(t)F_M(t) \to$ factorised form $F_{\rho p}^{(P/R)}(t) = \exp\left(\frac{B_{\rho p}^{(P/R)}t}{2}\right)$

(see blue dotted lines)

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

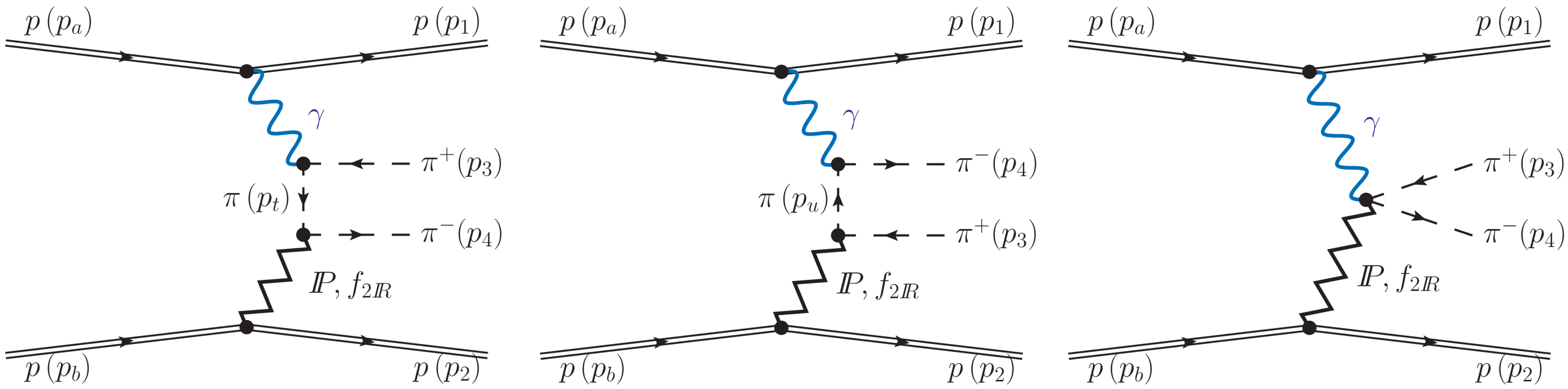
set B : $a_{I\!P\rho\rho} = a_{f_{2I\!R}\rho\rho} = 0\ \text{GeV}^{-3}$, $b_{I\!P\rho\rho} = 7.04\ \text{GeV}^{-1}$, $b_{f_{2I\!R}\rho\rho} = 9.3\ \text{GeV}^{-1}$





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

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



The inclusion of these diagrams is a gauge invariant version of the Drell-Söding mechanism.

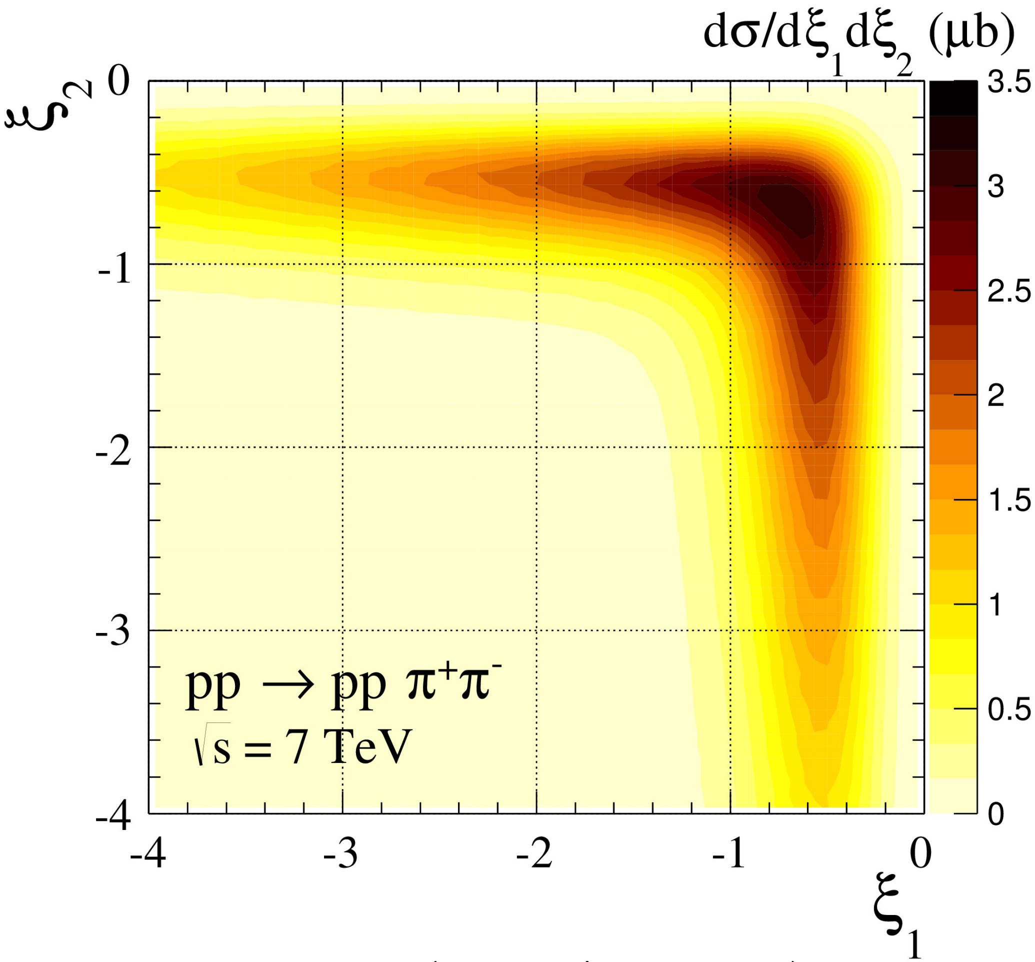
Set of vertices respecting QFT rules (O. Nachtmann *et al.*, *JHEP 1501 (2015) 151*)

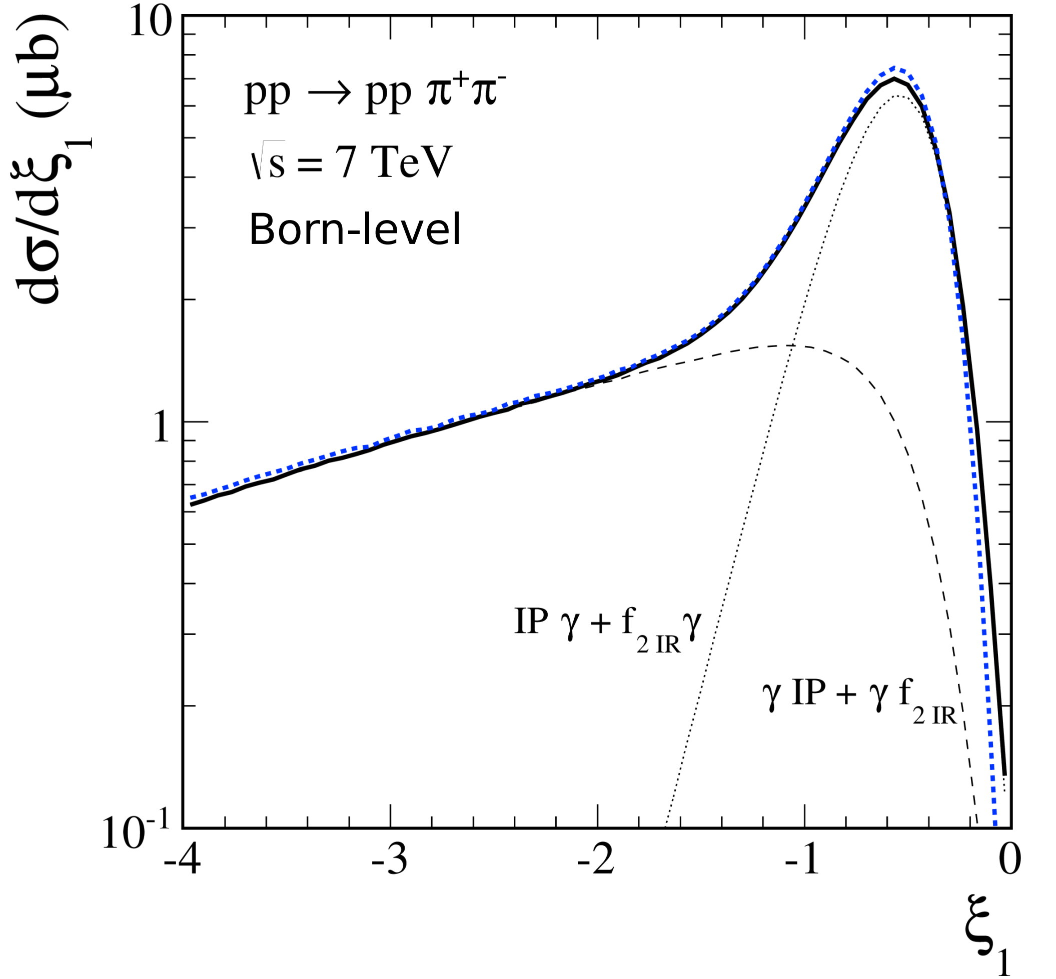
$$i\Gamma^{(I\!P\pi\pi)}_{\alpha\beta}(k',k) = -i2\beta_{I\!P\pi\pi}\left[(k'+k)_\alpha(k'+k)_\beta - \frac{1}{4}g_{\alpha\beta}(k'+k)^2\right] F_M((k'-k)^2)$$

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

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

ξ distribution

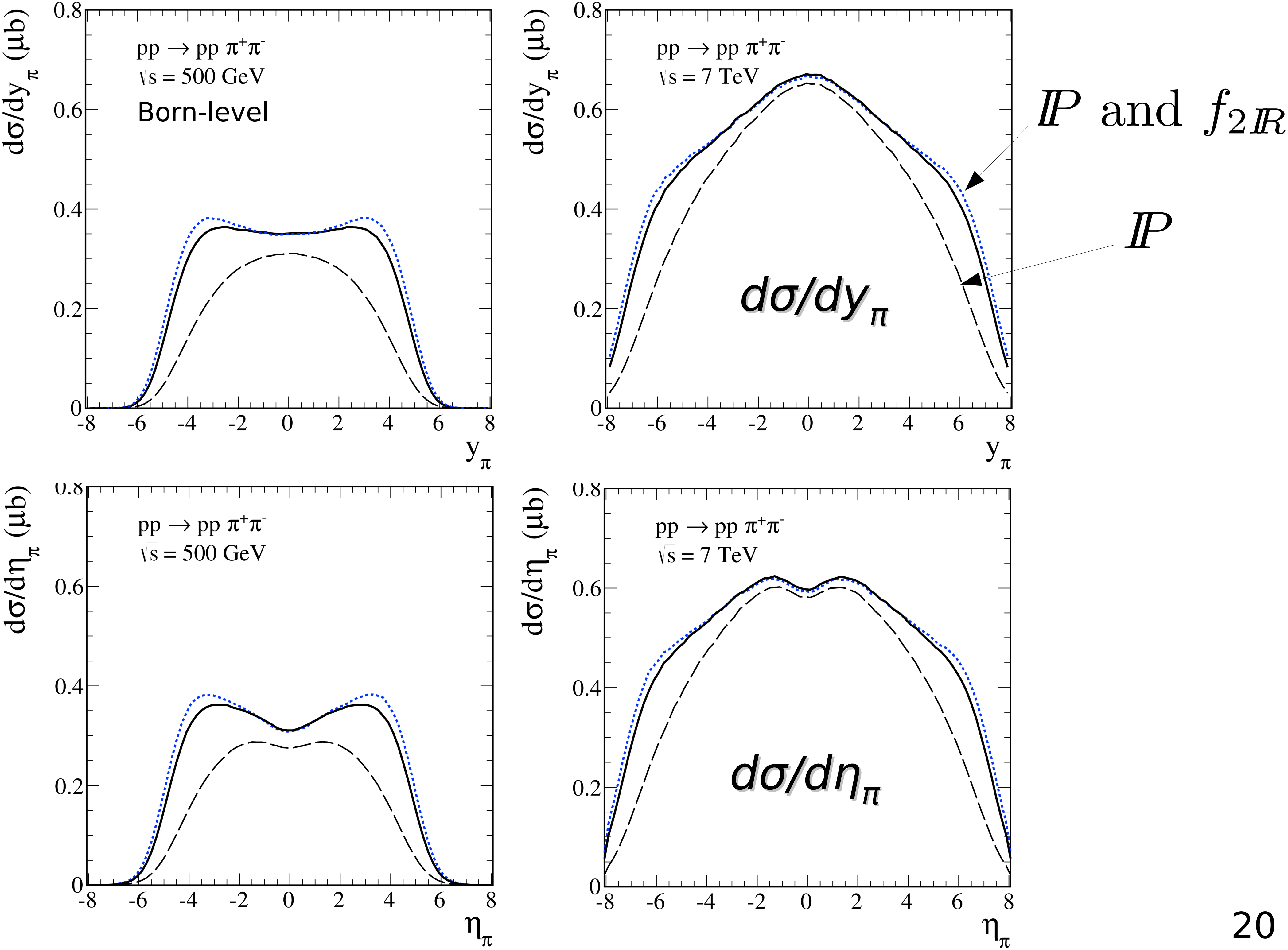




$$\xi_1 = \log_{10}(p_{1\perp}/1\,\mathrm{GeV})$$

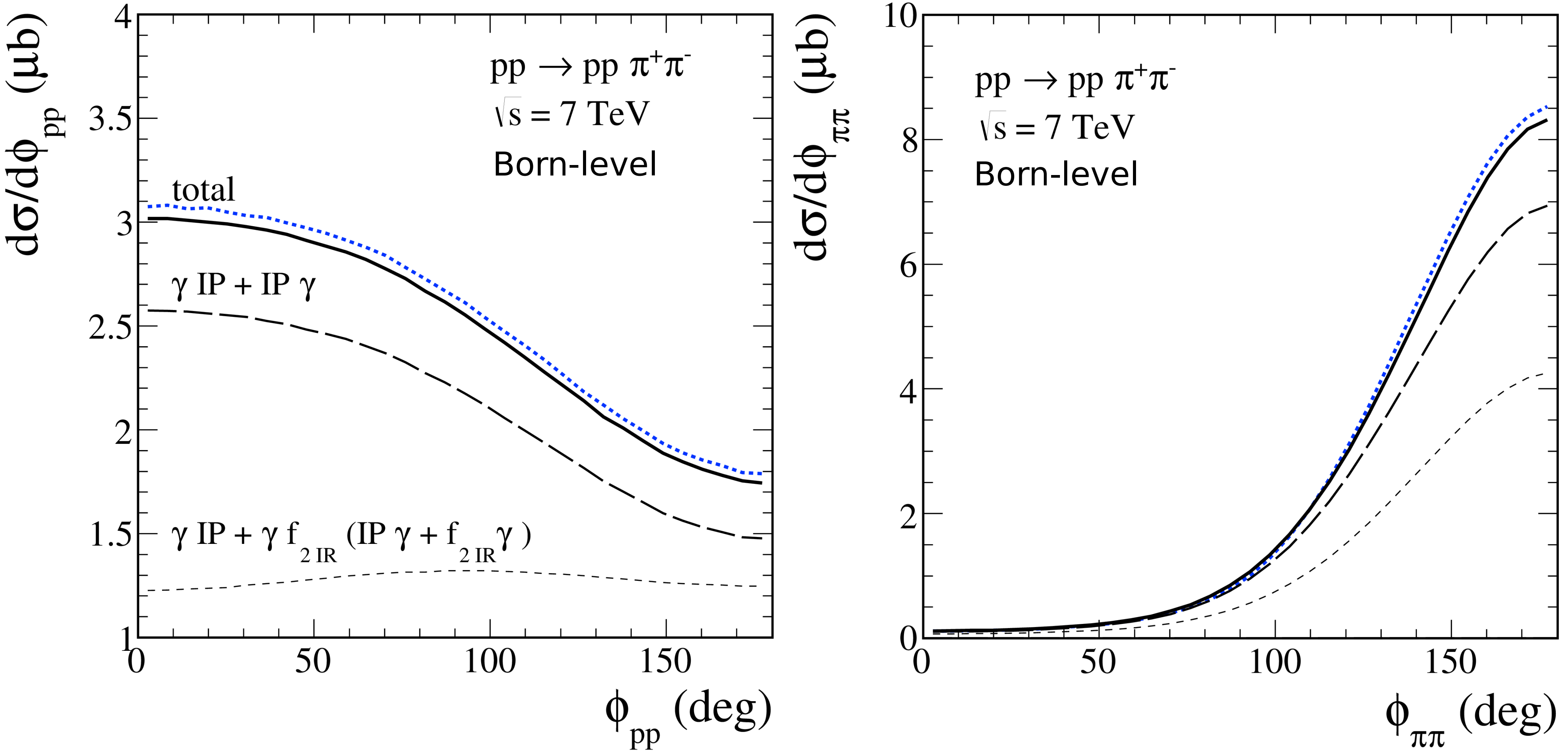
For example $\xi_1 = -1$ means $p_{1\perp} = 0.1$ GeV.

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.



pp → pp $\pi^+\pi^-$
$\sqrt{s}$ = 500 GeV
Born-level
pp → pp $\pi^+\pi^-$
$\sqrt{s}$ = 7 TeV
$I\!P$ and $f_{2I\!R}$
$I\!P$
$d\sigma/dy_\pi$
pp → pp $\pi^+\pi^-$
$\sqrt{s}$ = 500 GeV
pp → pp $\pi^+\pi^-$
$\sqrt{s}$ = 7 TeV
$d\sigma/d\eta_\pi$
$d\sigma/dy_\pi$ (μb)
y_π
$d\sigma/d\eta_\pi$ (μb)
η_π

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



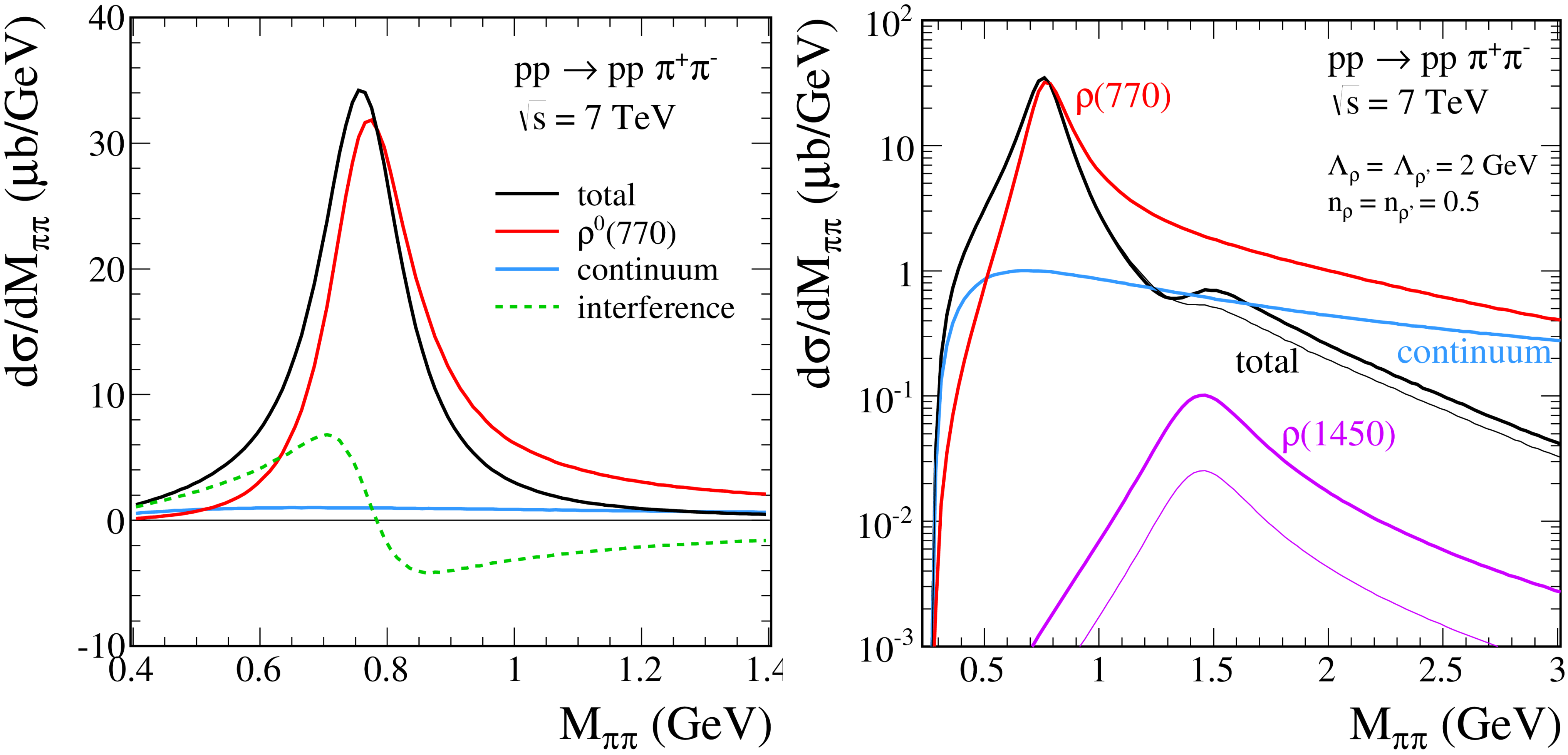
The effect of ϕ_{pp} deviation from a constant is due to interference of *γ-IP* and *IP-γ* amplitudes (see *W. Schäfer and A. Szczurek, Phys. Rev. D76 (2007) 094014* for the exclusive production of J/ψ meson).

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

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

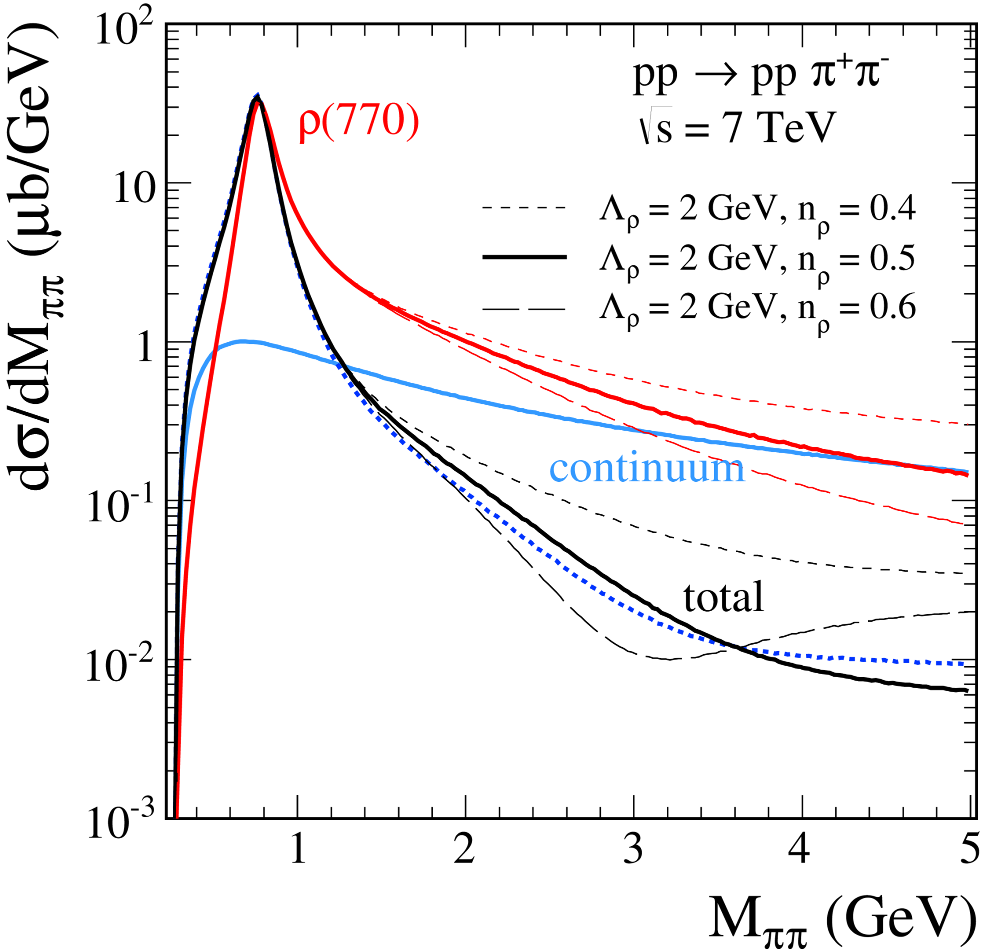
$M_{\pi\pi}$ distribution

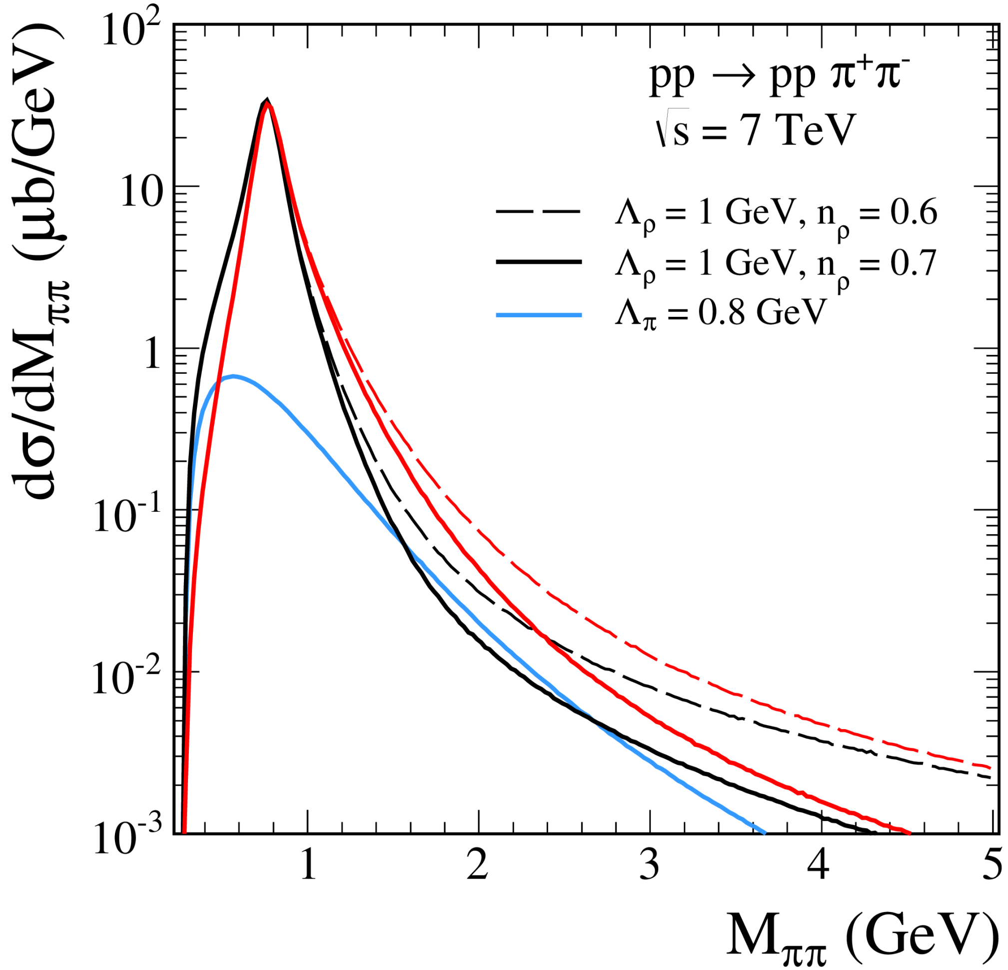


The non-resonant (Drell-Söding) contribution interfere with resonant ρ^0 contribution → skewing of ρ^0 line shape.

Here we take a relatively hard form factors for the resonant contribution
and no form factors for the inner $\gamma IP \to \pi^+\pi^-$ processes for the non-resonant contribution.

$M_{\pi\pi}$ distribution





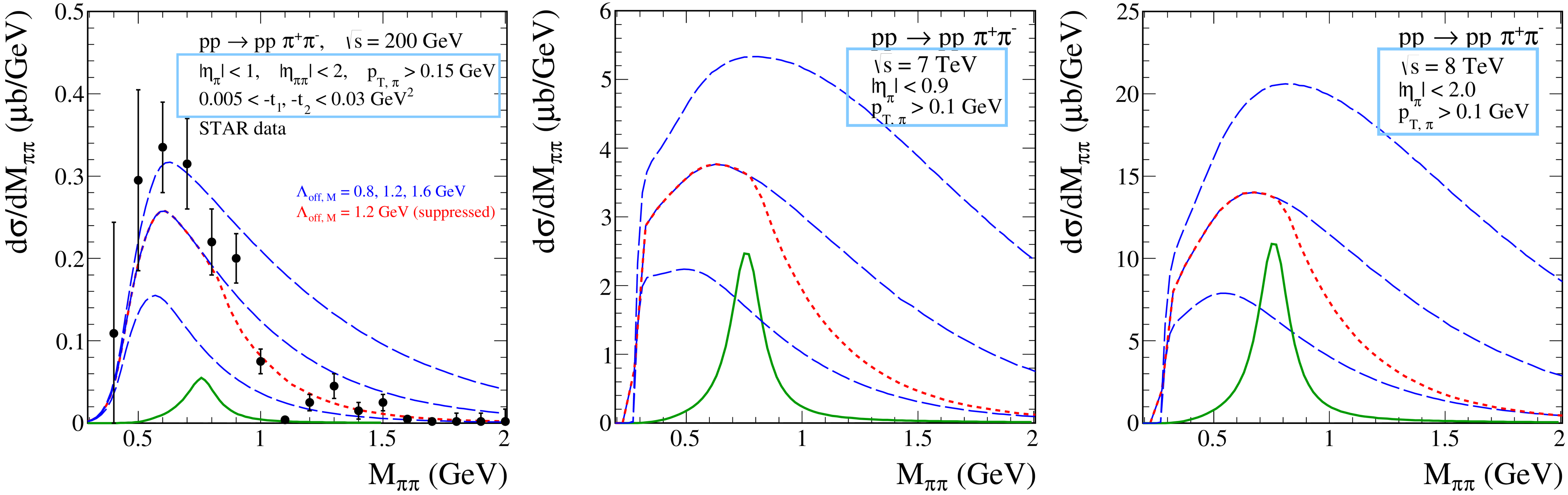
At higher $p_{t,\pi}$ our calculation gives a strong cancellation between the resonant and the non-resonant terms

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

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

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

Summary



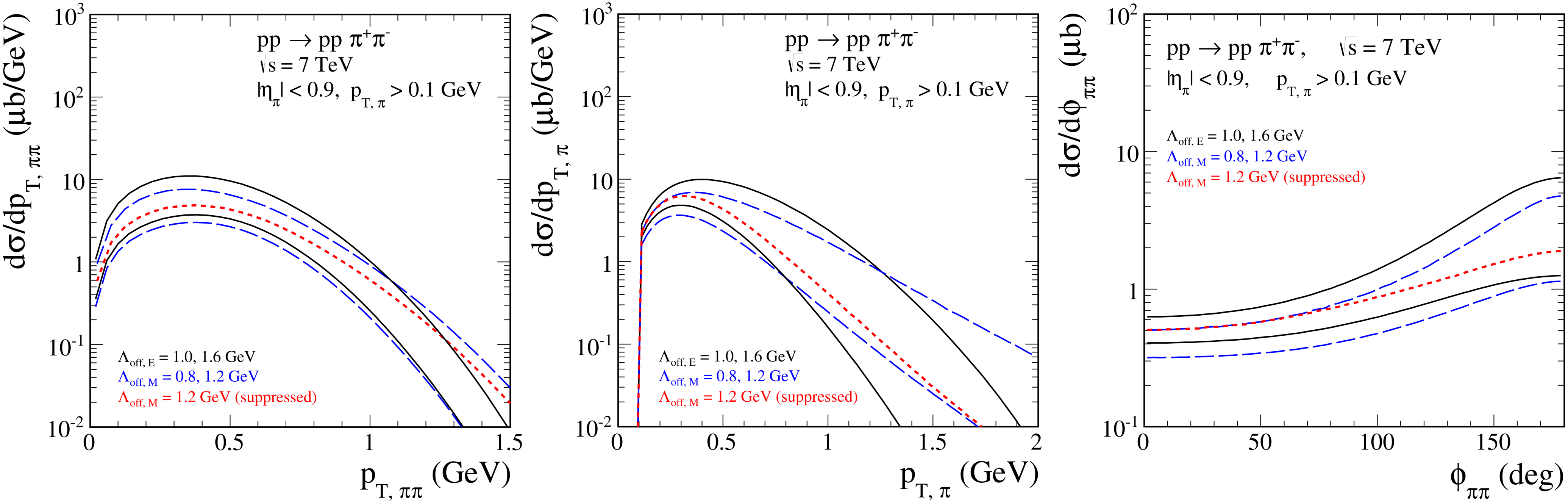
We observe that at midrapidities the photoproduction term could be visible in LHC experiments.

- The $pp \to pp\pi^+\pi^-$ process is an attractive for different experimental groups (COMPASS, STAR (R. Sikora talk), CDF, ALICE, CMS+TOTEM, ATLAS+ALFA, LHCb).
  Future experimental data on exclusive meson production should provide more information for both diffractive and photoproduction mechanisms.

- Exclusive production of light mesons shows the potential for testing the nature of the soft pomeron and on its couplings to the nucleon and the mesons, the interference effects between resonant and non-resonant contributions, absorption corrections, form factors.

Backup

Predictions for ALICE



pp- and *πp*- absorption effects included