Diffractive and photoproduction mechanisms in the $pp \to pp\pi^+\pi^-$ process

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Diffractive and electromagnetic processes at high energies

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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
- Conclusions

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. D

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

P. Lebiedowicz, O. Nachtmann, A. Szczurek, *Exclusive central diffractive production of scalar and pseudoscalar mesons; tensorial vs. vectorial pomeron*, Annals Phys. 344 (2014) 301

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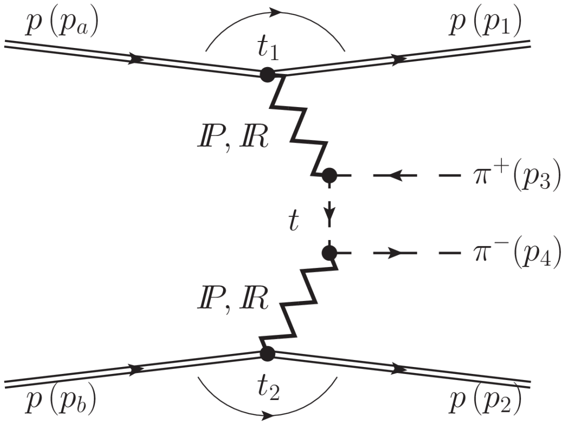
Diffractive mechanism



Dominant *IPIP* contribution have *C* = +1 and I = 0 of the produced $\pi^+\pi^-$ pairs

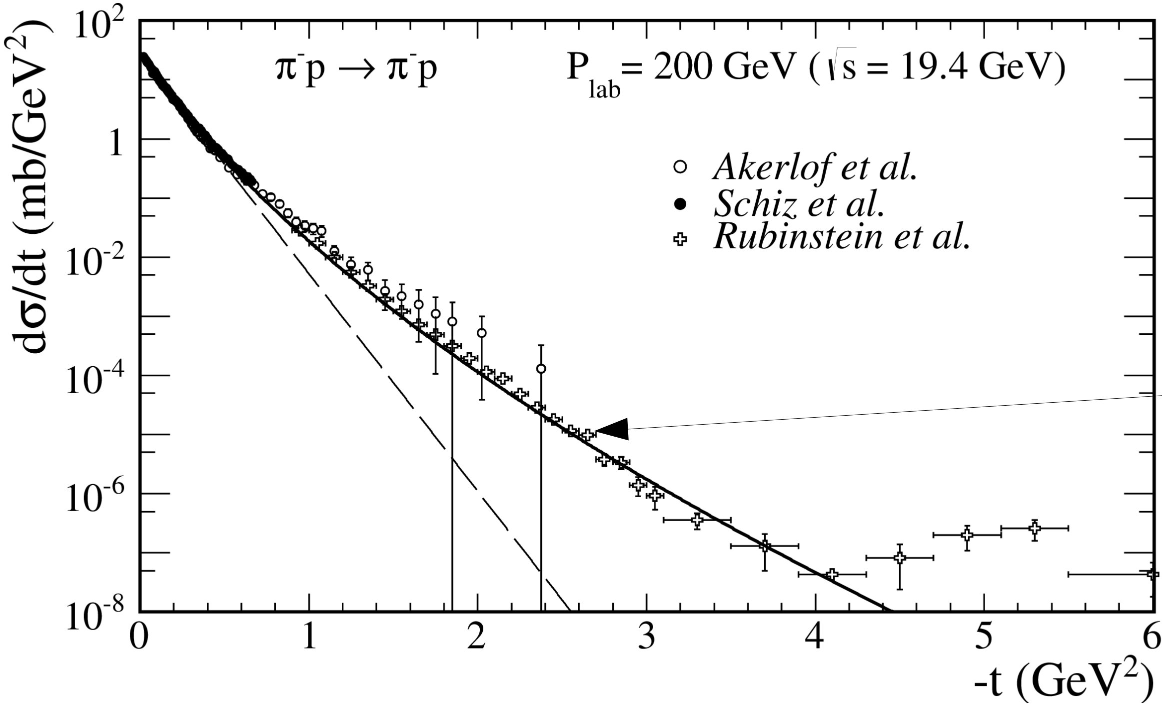
$$\mathcal{M}^{\rm Born}_{pp\to pp\pi^+\pi^-} = M_{13}(s_{13},t_1)\,\frac{F_\pi^2(t)}{t-m_\pi^2}\,M_{24}(s_{24},t_2) + [u-\text{channel}]$$

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

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

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

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

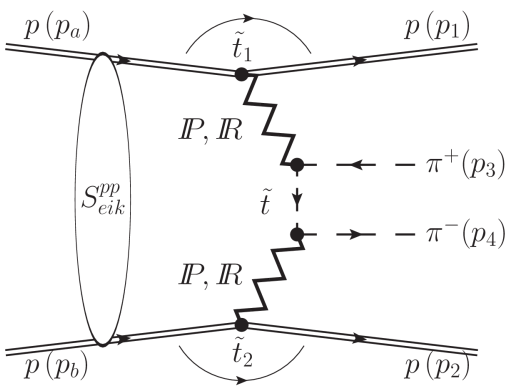


the 'stretched exponential' form coincides at low |*t*| with the simple exponential form while at larger |t| a harder tail appears

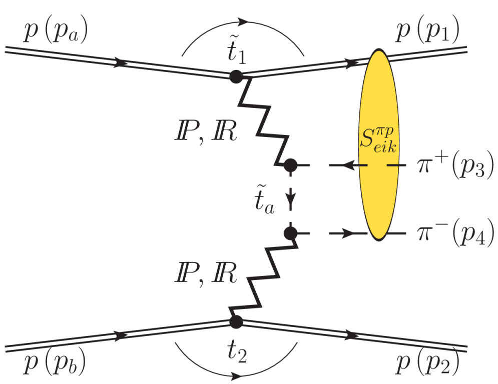
Absorption effects

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

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



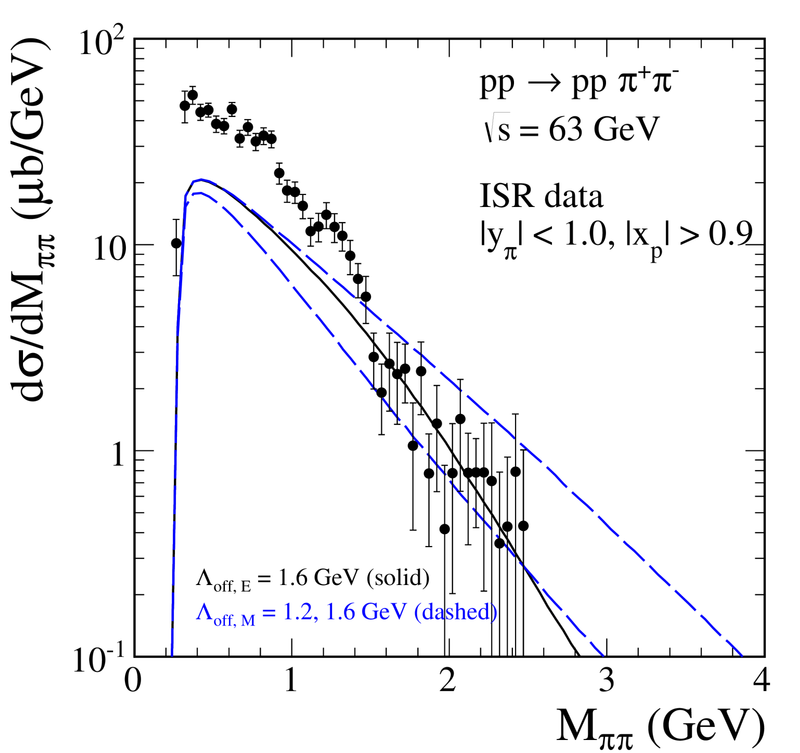
← absorption corrections due to *pp interactions* (ISI & FSI)



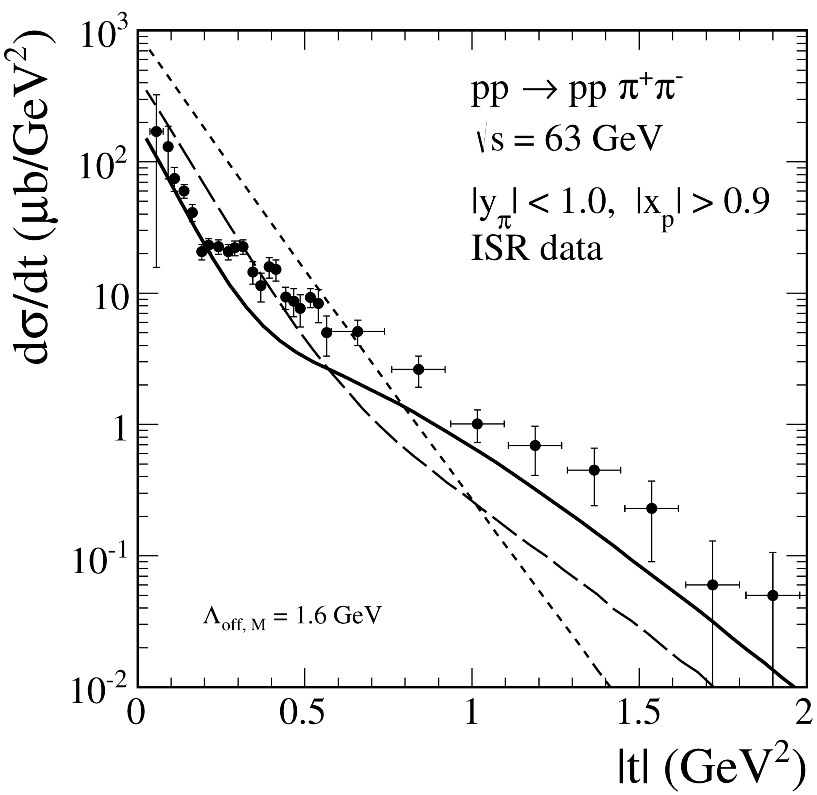
← new absorption corrections (*πp* FSI)

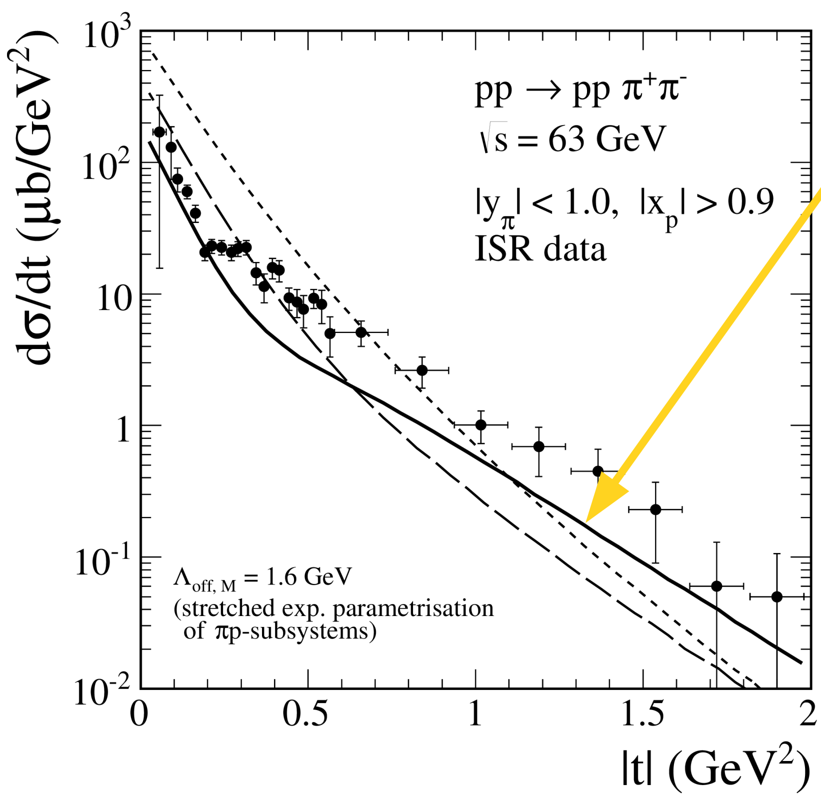
Ratio of full and Born cross sections $< S^2 > = \frac{\sigma^{Born + (NN-rescat.) + (\pi N-rescat.)}}{\sigma^{Born}}$

Comparison with ISR data



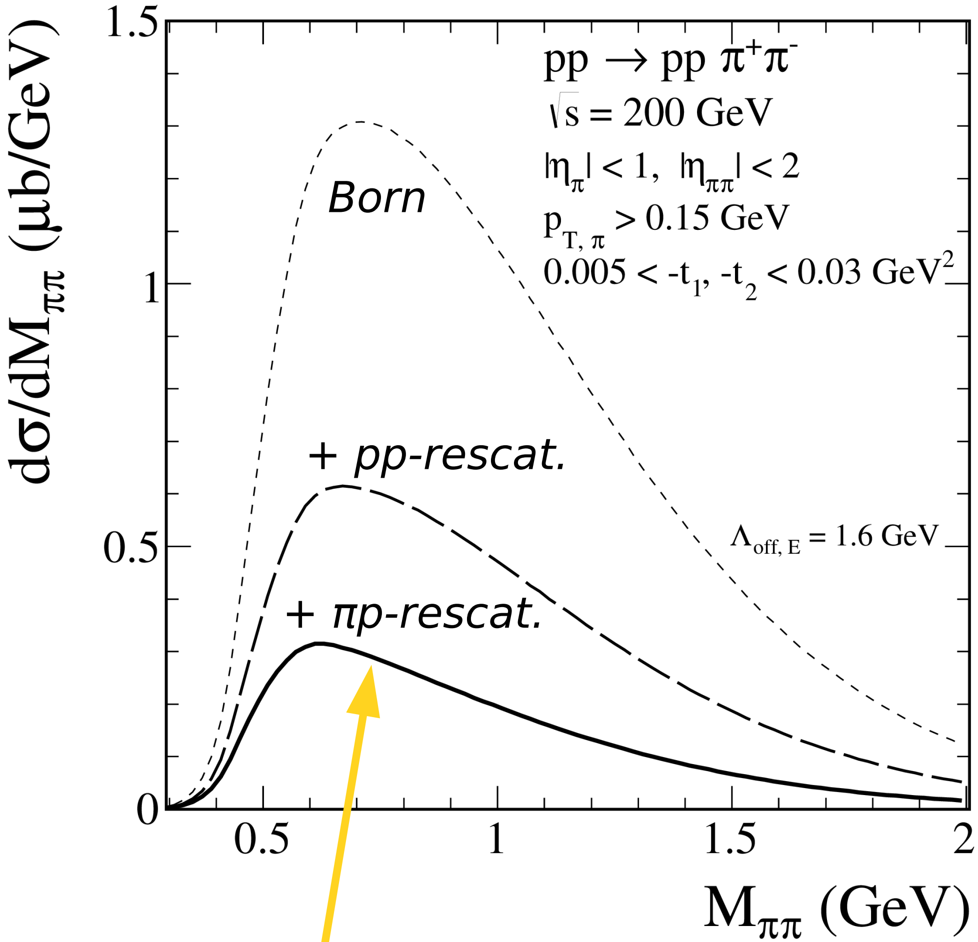
ISR data: R.Waldi, K. R. Schubert, and K. Winter, *Search for glueballs in a pomeron pomeron scattering experiment*, Z.Phys. C18 (1983) 301–306.

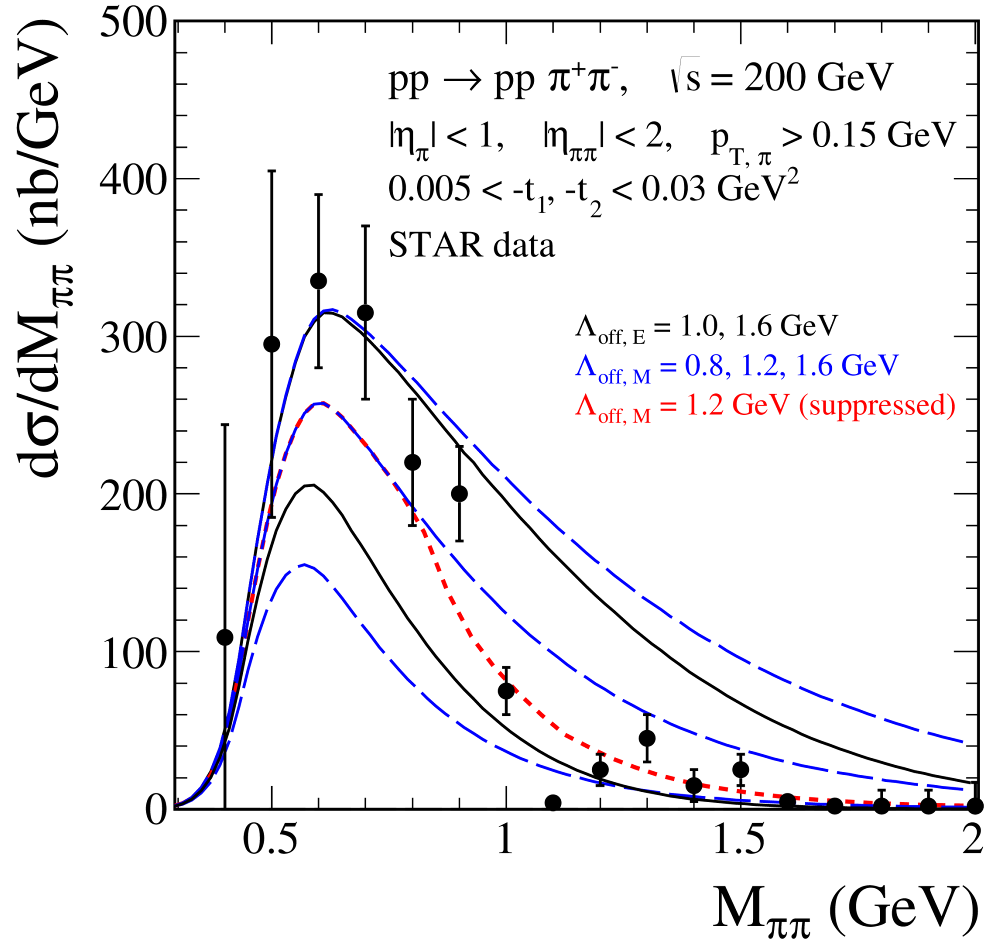




πp FSI effects enhancement cross section at large |t|

Comparison with STAR data





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

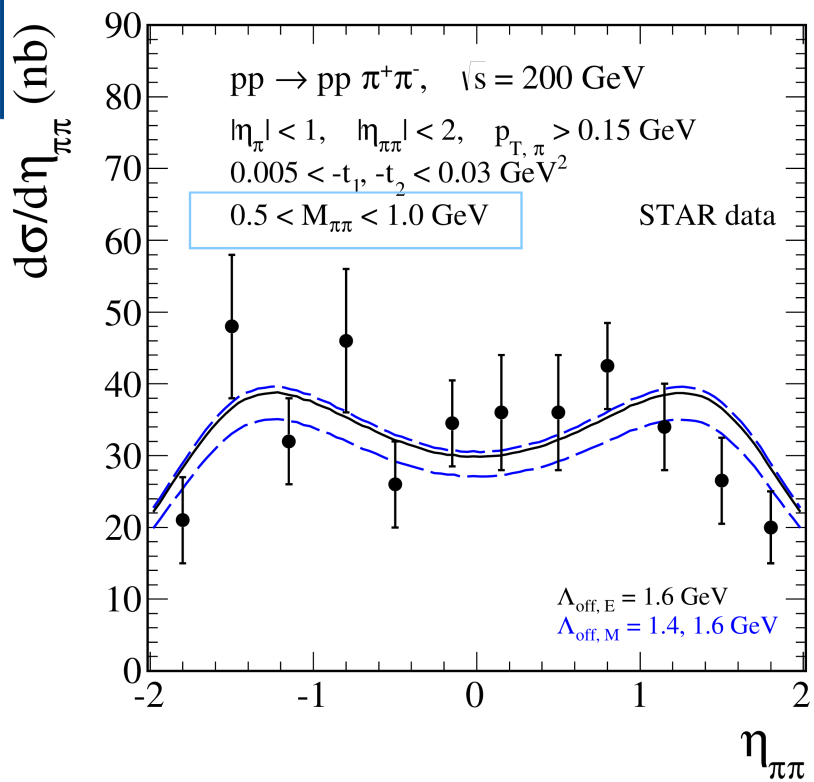
$$< S^2 > (M_{\pi\pi}) \simeq 0.2$$

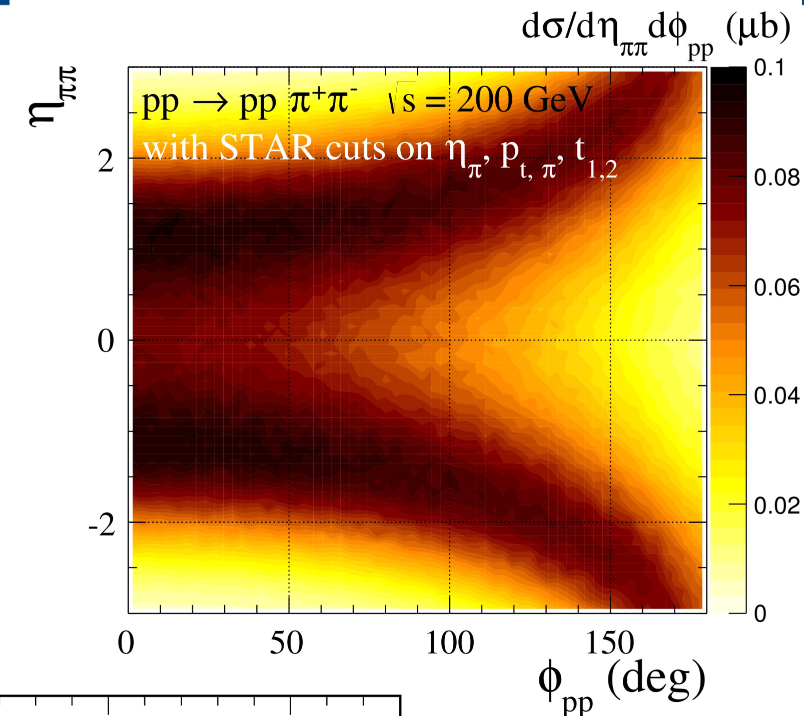
a suppression factor:

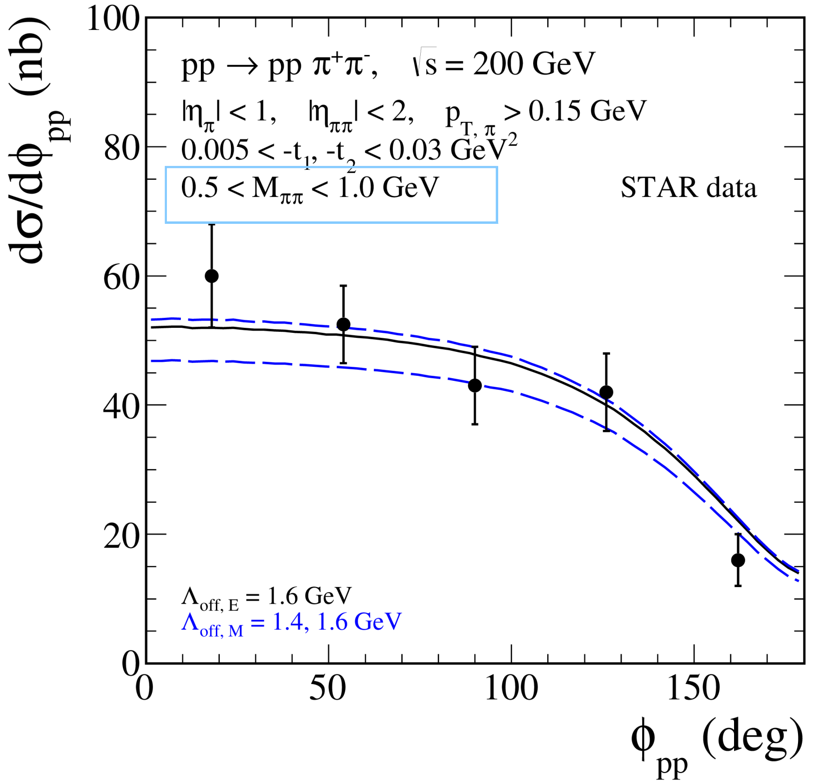
$$f(M_{\pi\pi}) = \exp(-c \ln(M_{\pi\pi}/M_0)) = (M_0/M_{\pi\pi})^c$$
$$M_0 = 0.8 \text{ GeV}^2, \quad \text{c}= 0.5$$

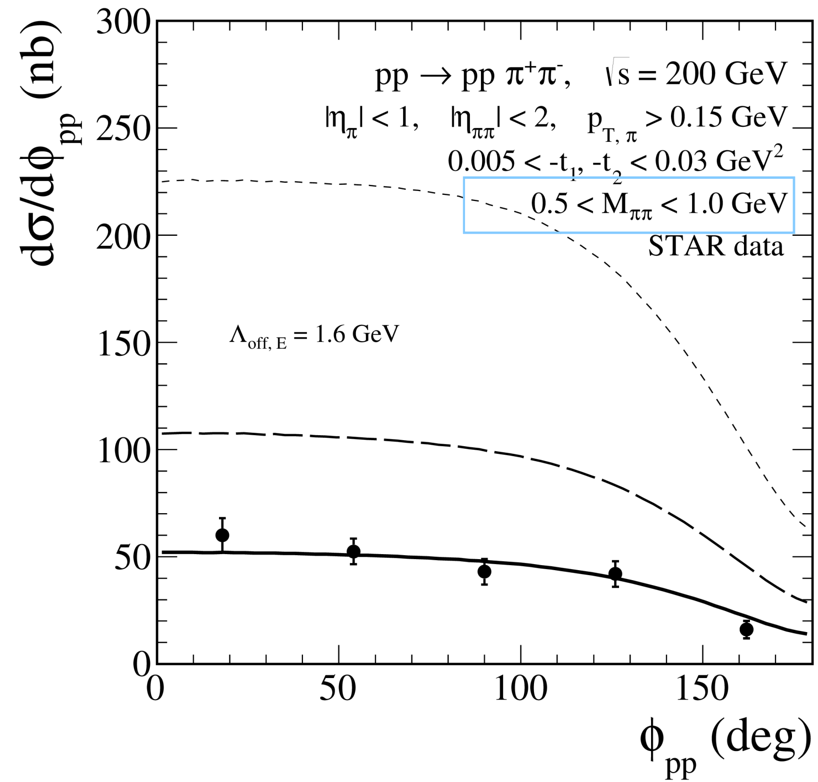
STAR data: L. Adamczyk, W. Guryn, and J. Turnau, *Central exclusive production at RHIC*, Int.J.Mod.Phys. A29 no. 28, (2014) 1446010, arXiv:1410.5752 [hep-ex].

Comparison with STAR data



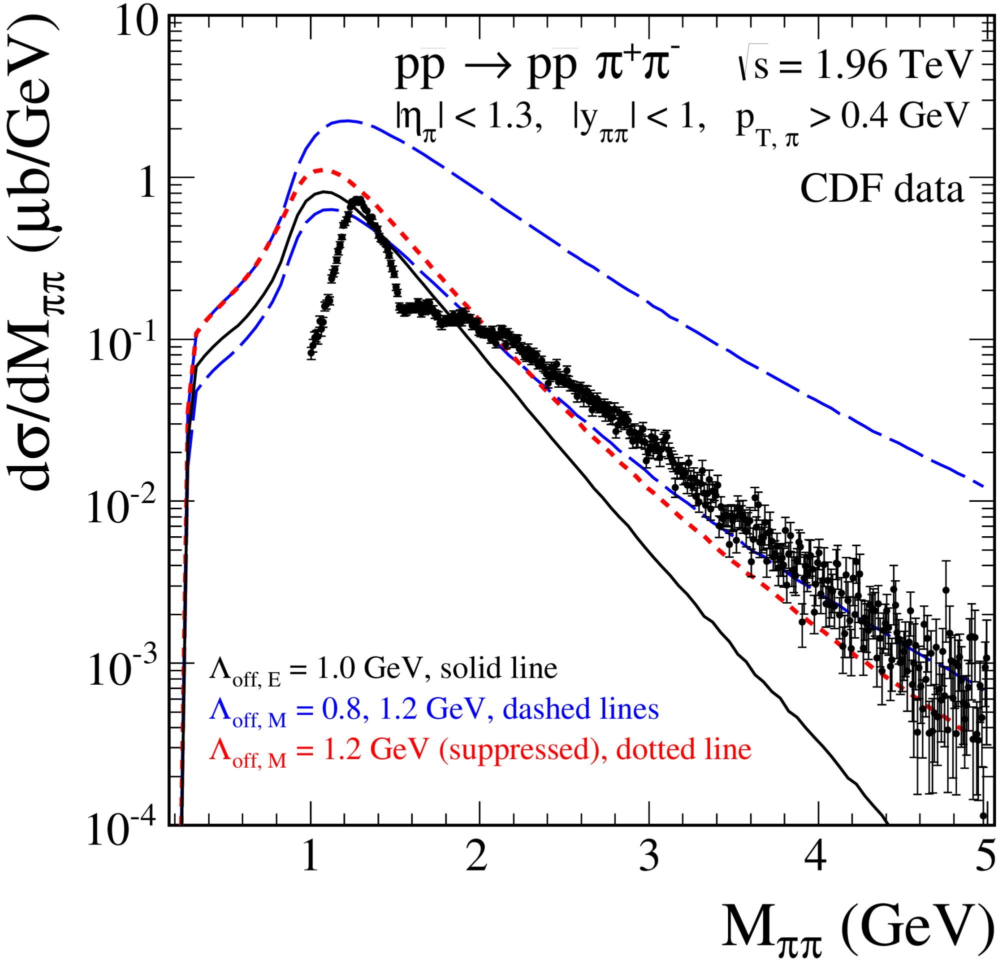


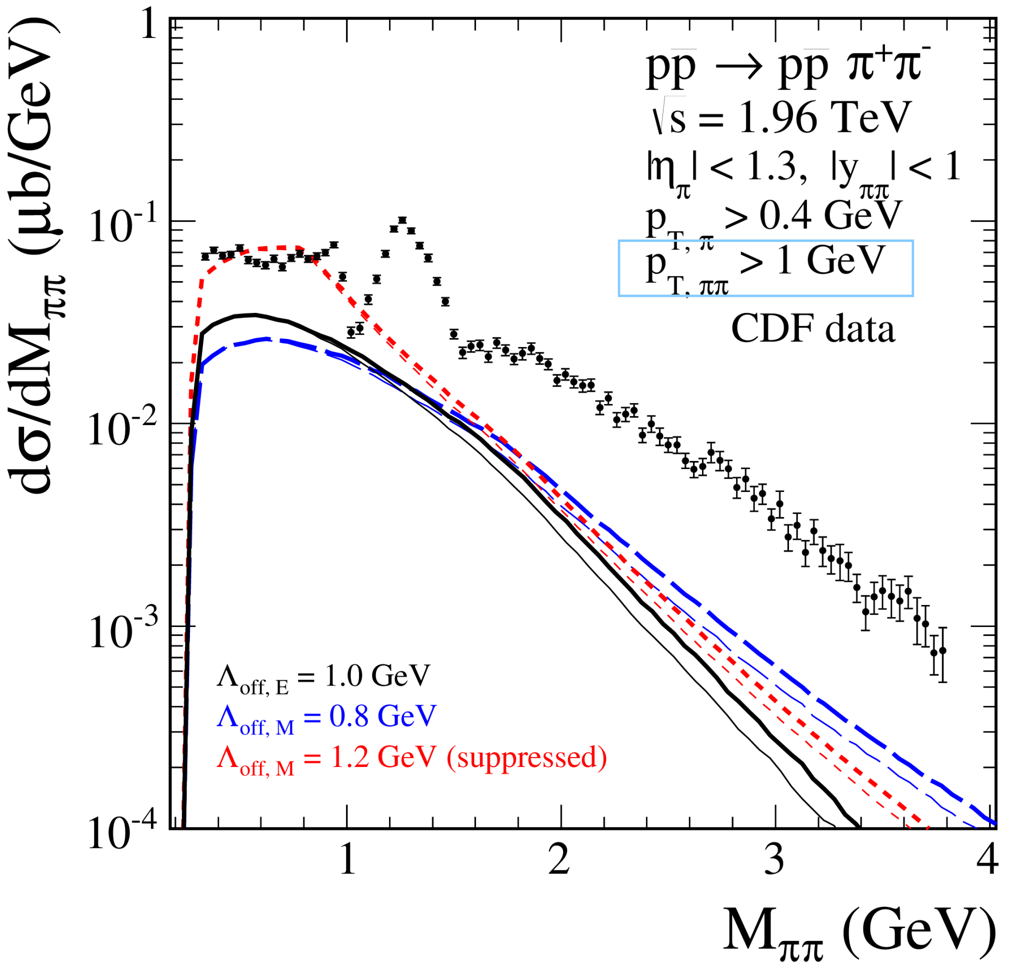




The decrease of azimuthal distribution at $\varphi \approx \pi$ is due to the condition $|\eta_{\pi\pi}| < 2$

Comparison with CDF data

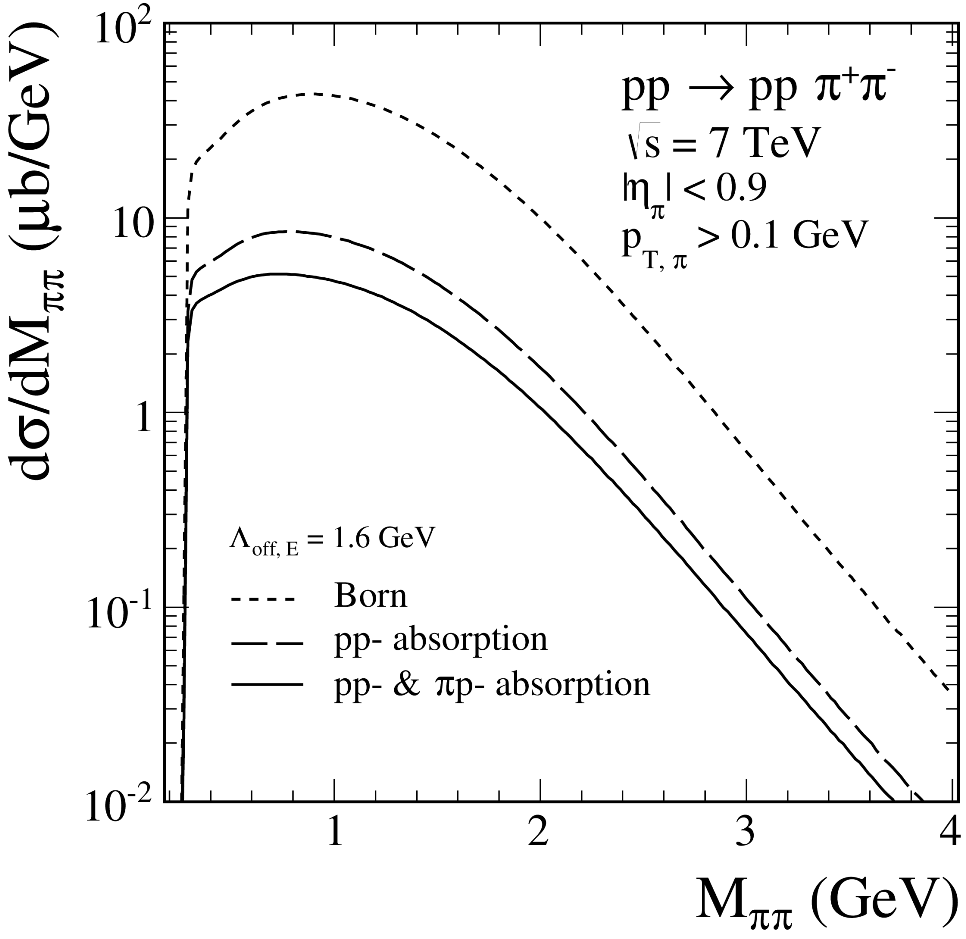




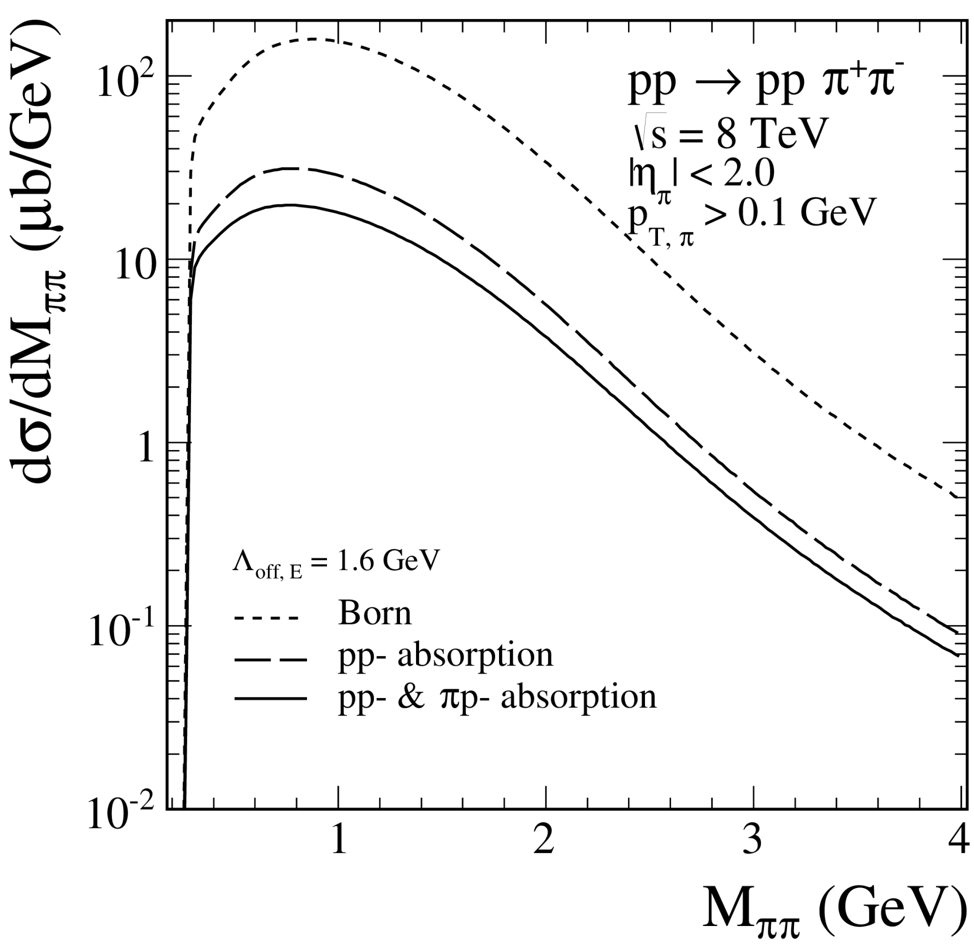
- (right panel) model results are much below the CDF data which could be due to a contamination of non-exclusive processes and/or the perturbative mechanism
- effect of 'stretched exponential' parametrization is small (see thin vs. thick lines)

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].

ALICE



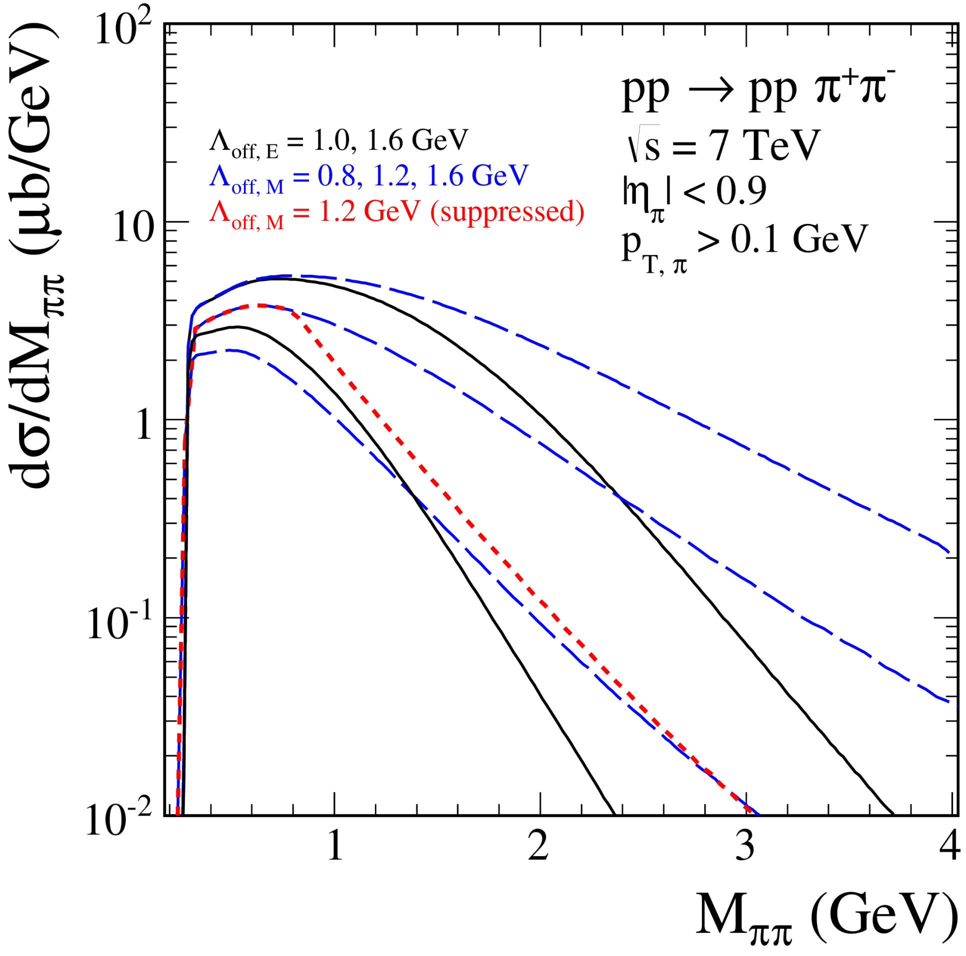
CMS+TOTEM, ATLAS+ALFA



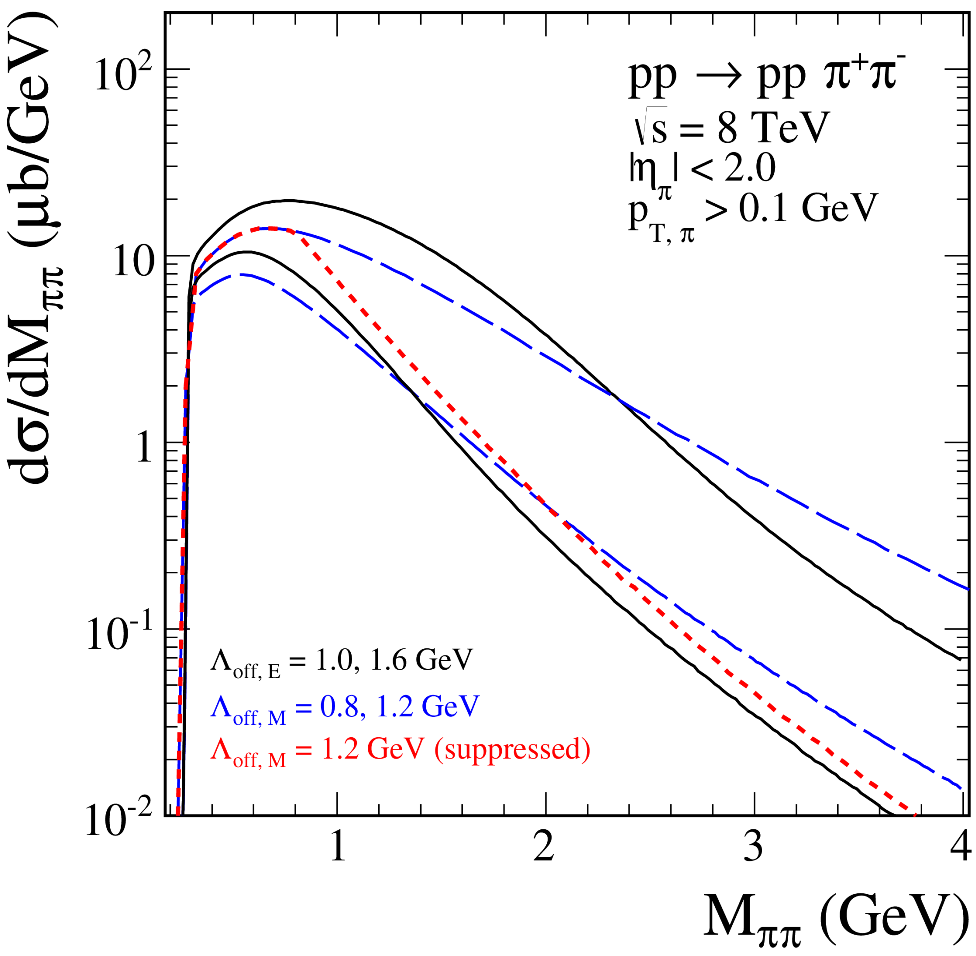
$$< S^2(M_{\pi\pi}) > \simeq 0.1$$

Predictions for the LHC

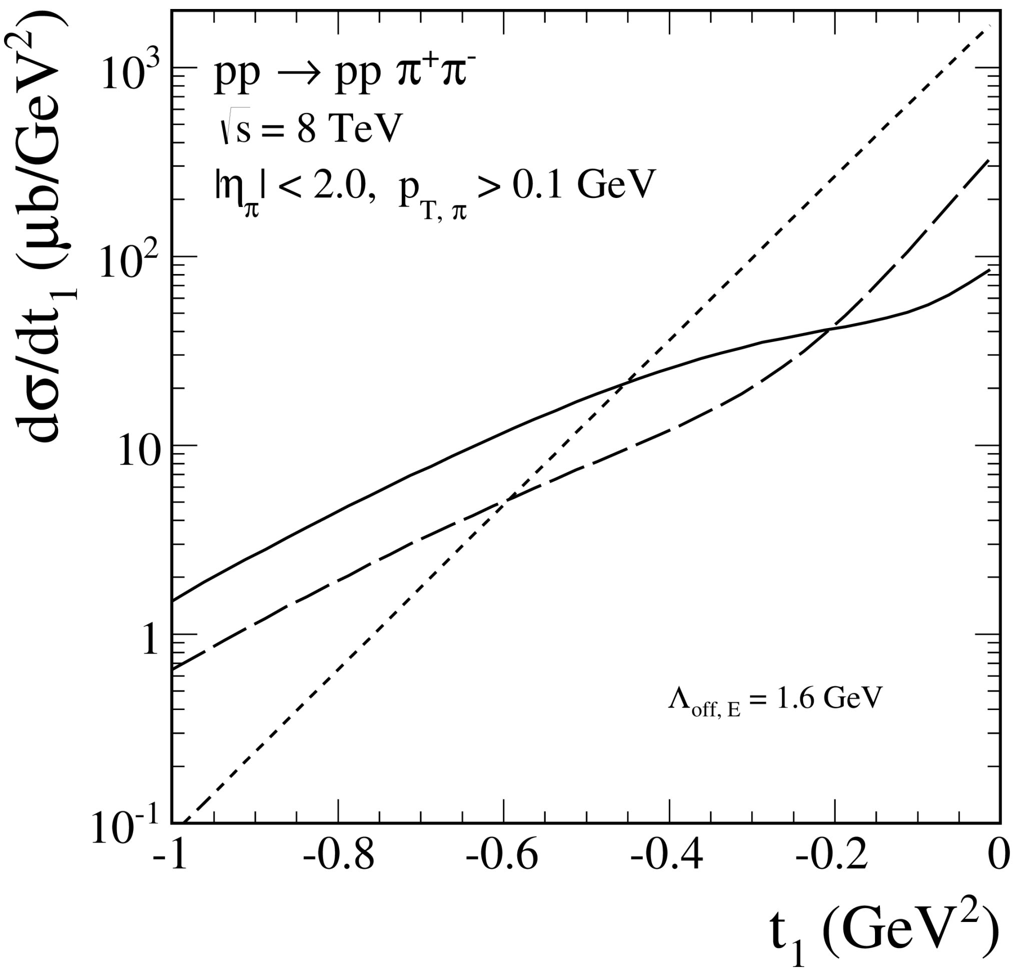
ALICE

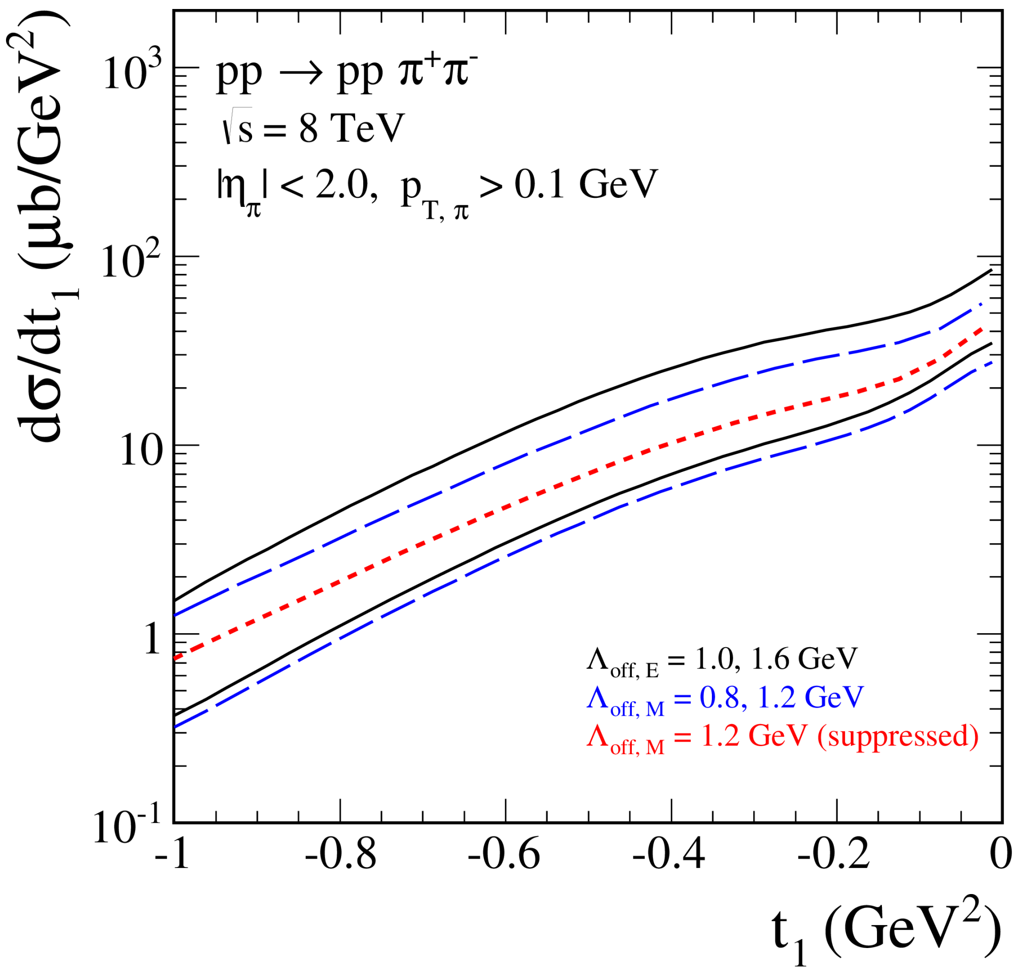


CMS+TOTEM, ATLAS+ALFA

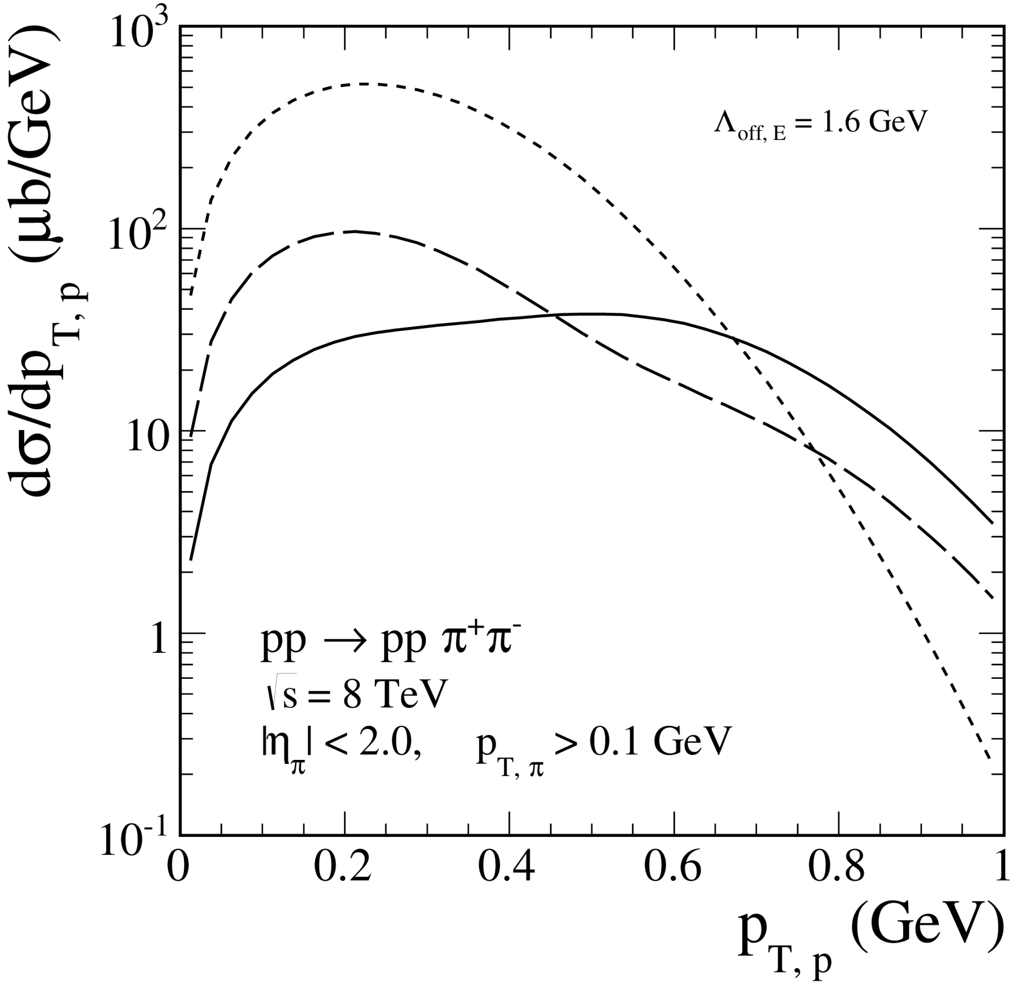


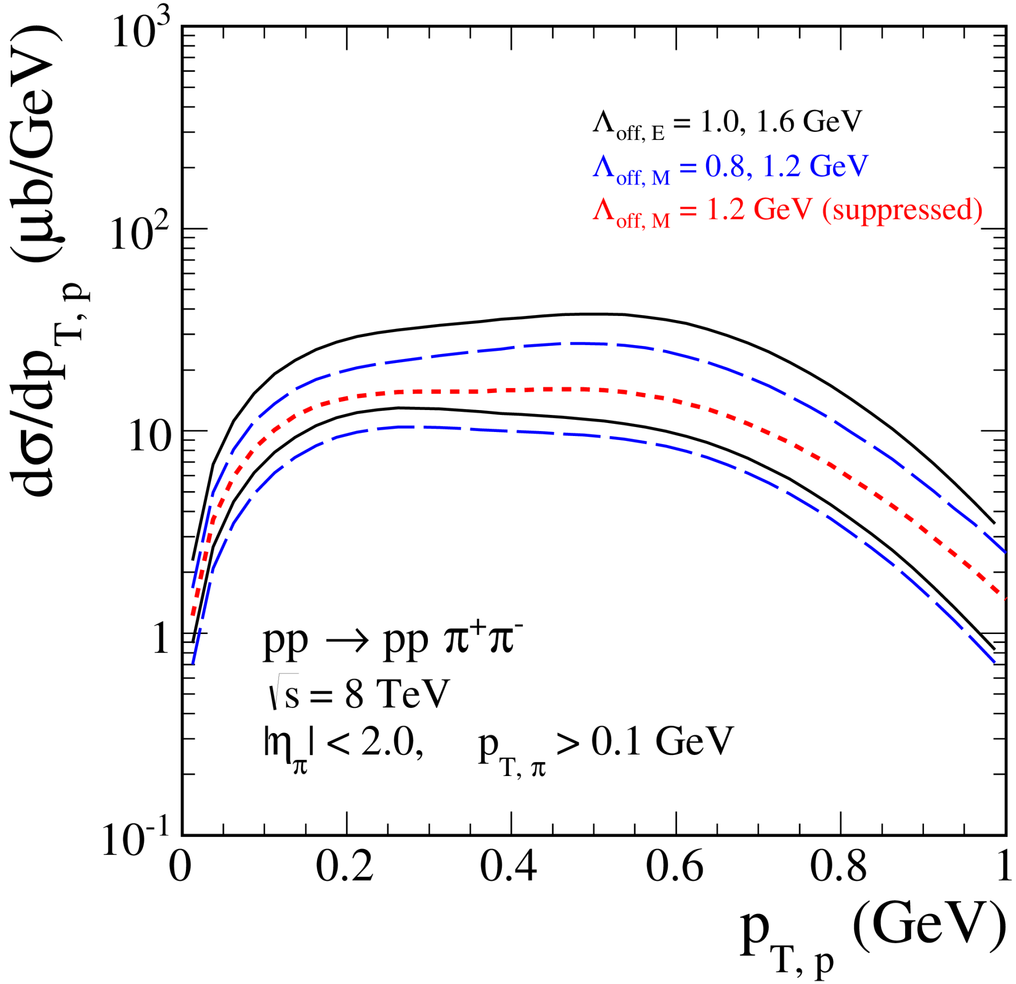
Predictions for CMS+TOTEM, ATLAS+ALFA



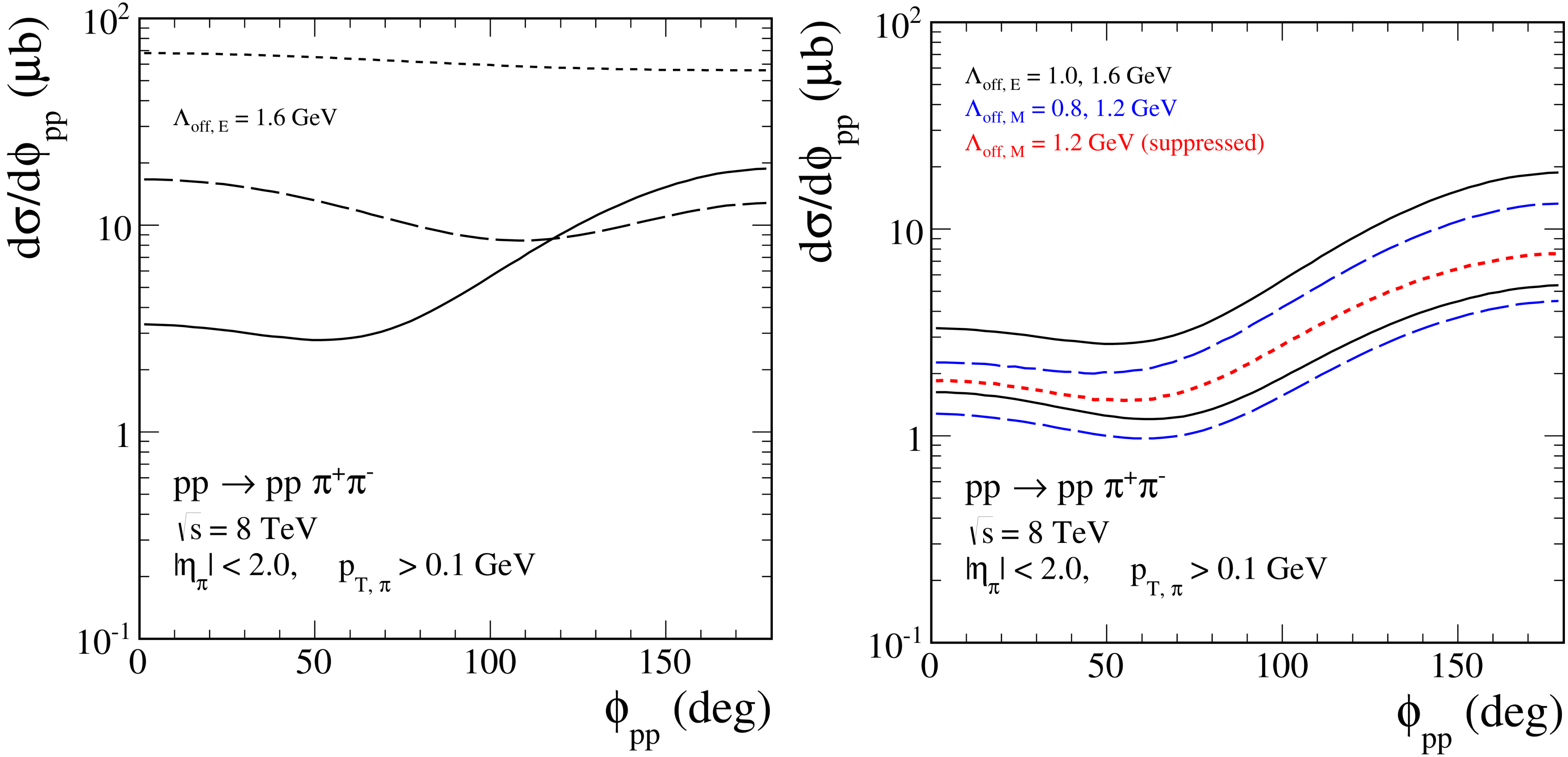


Predictions for CMS+TOTEM, ATLAS+ALFA

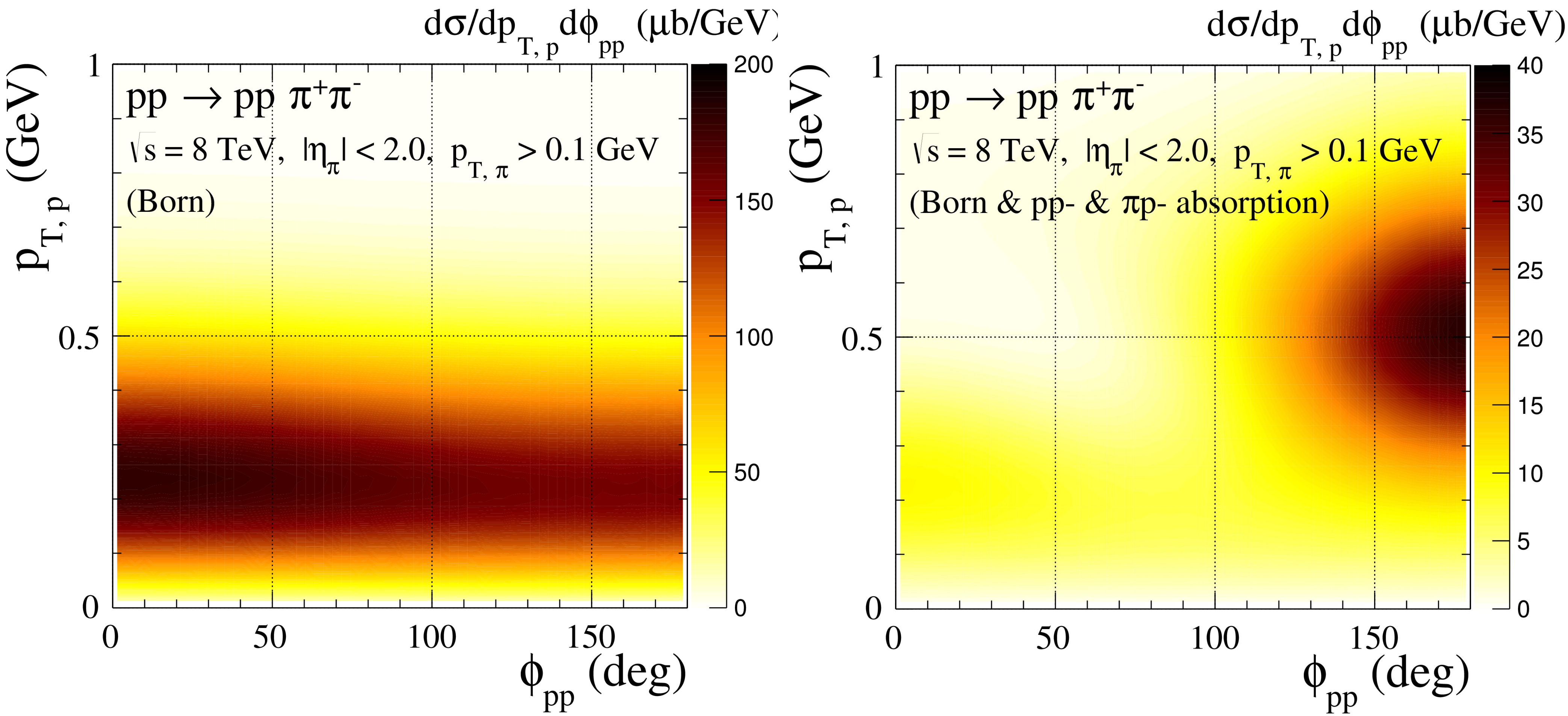




Predictions for CMS+TOTEM, ATLAS+ALFA



Predictions for CMS+TOTEM, ATLAS+ALFA



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

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 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

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

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

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

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

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

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

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')

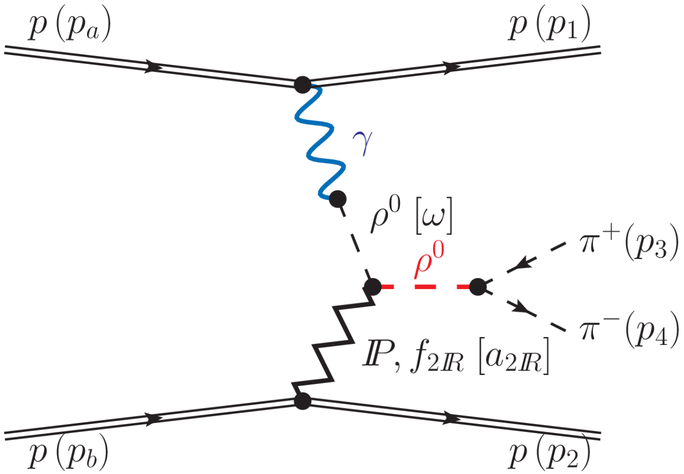
$$\mathcal{M}^{2\to 2}_{\lambda_a\lambda_b\to\lambda_1\lambda_2}(s,t) \xrightarrow{s \gg 4m_p^2} i\,2s\ \left[3\beta_{I\!PNN}\,F_1(t)\right]^2\ (-is\alpha'_{I\!P})^{\alpha_{I\!P}(t)-1}\ \delta_{\lambda_1\lambda_a}\,\delta_{\lambda_2\lambda_b}$$

But with tensor pomeron (effective spin 2 exchange) it is much more natural to write down effective vertices of all kinds which respect the rules of QFT.

(see Otto Nachtmann talk)

Resonant ρ^0 production

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



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

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

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

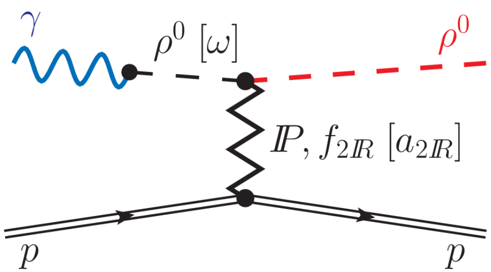
$$V_{\mu\nu\kappa\lambda}(s,t,q,p_{34}) = \frac{1}{4s}\Big\{2\Gamma^{(0)}_{\mu\nu\kappa\lambda}(p_{34},-q)\left[3\beta_{I\!PNN}\,a_{I\!P\rho\rho}(-is\alpha'_{I\!P})^{\alpha_{I\!P}(t)-1} + M_0^{-1}g_{f_{2I\!R}pp}\,a_{f_{2I\!R}\rho\rho}(-is\alpha'_{I\!R_+})^{\alpha_{I\!R_+}(t)-1}\right]$$
$$-\Gamma^{(2)}_{\mu\nu\kappa\lambda}(p_{34},-q)\left[3\beta_{I\!PNN}\,b_{I\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

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

The coupling constants in the *$I\!P\rho\rho$ and $f_{2I\!R}\rho\rho$* vertices have been estimated from the parametrization of otal 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:

$$2m_\rho^2\,a_{I\!P\rho\rho} + b_{I\!P\rho\rho} = 4\beta_{I\!P\pi\pi} = 7.04\ \text{GeV}^{-1}$$
$$2m_\rho^2\,a_{f_{2I\!R}\rho\rho} + b_{f_{2I\!R}\rho\rho} = M_0^{-1}g_{f_{2I\!R}\pi\pi} = 9.30\ \text{GeV}^{-1} \qquad M_0 = 1\ \text{GeV}$$

Photoproduction of ρ^0 meson



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

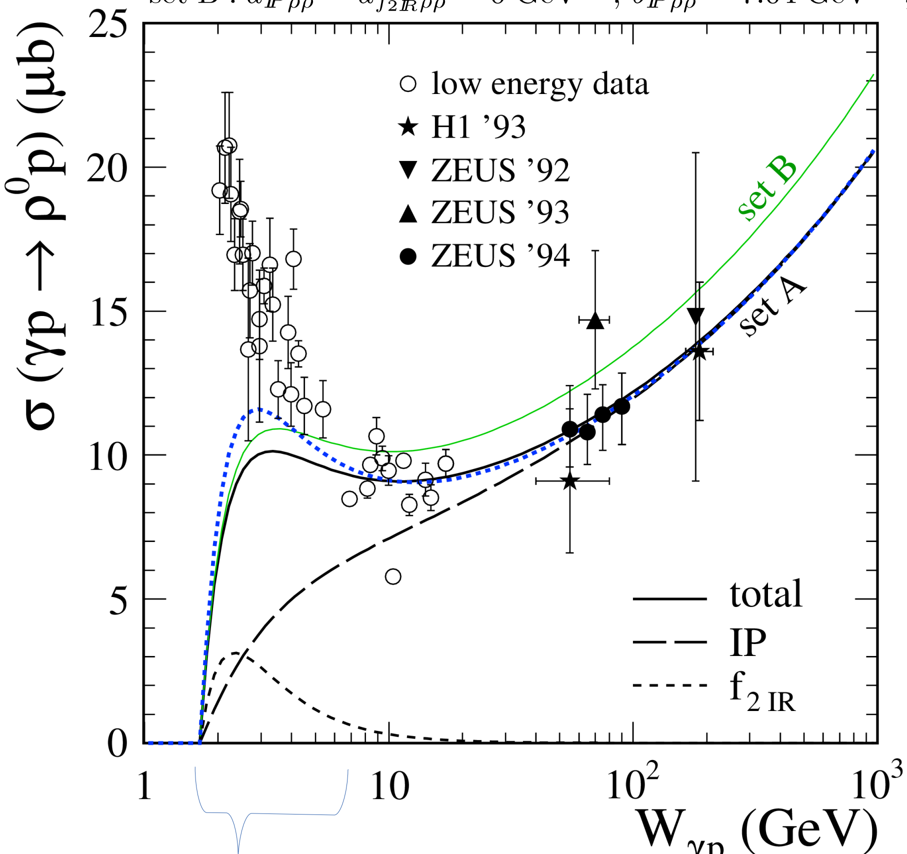
$$F_M(t) = \frac{1}{1 - t/\Lambda_0^2}$$
$$\Lambda_0^2 = 0.5\ GeV^2$$

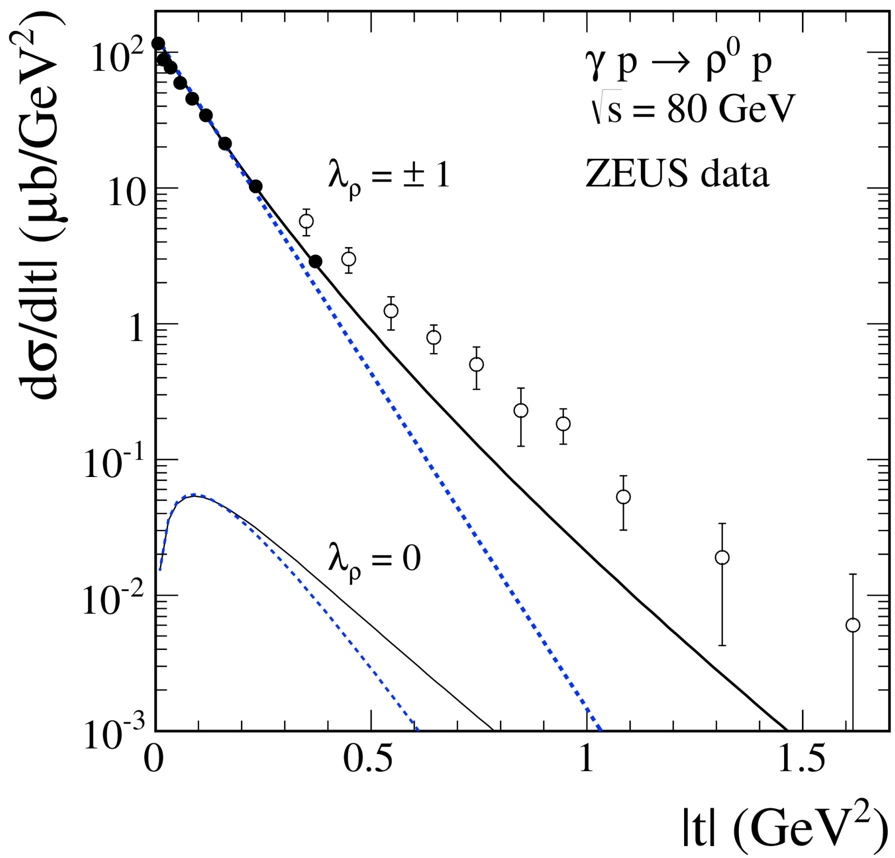
alternatively, $F_1(t)F_M(t) \to$ factorised form $F_{\rho p}^{(P/R)}(t) = \exp\left(\frac{B_{\rho p}^{(P/R)} t}{2}\right)$

see blue dotted lines

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

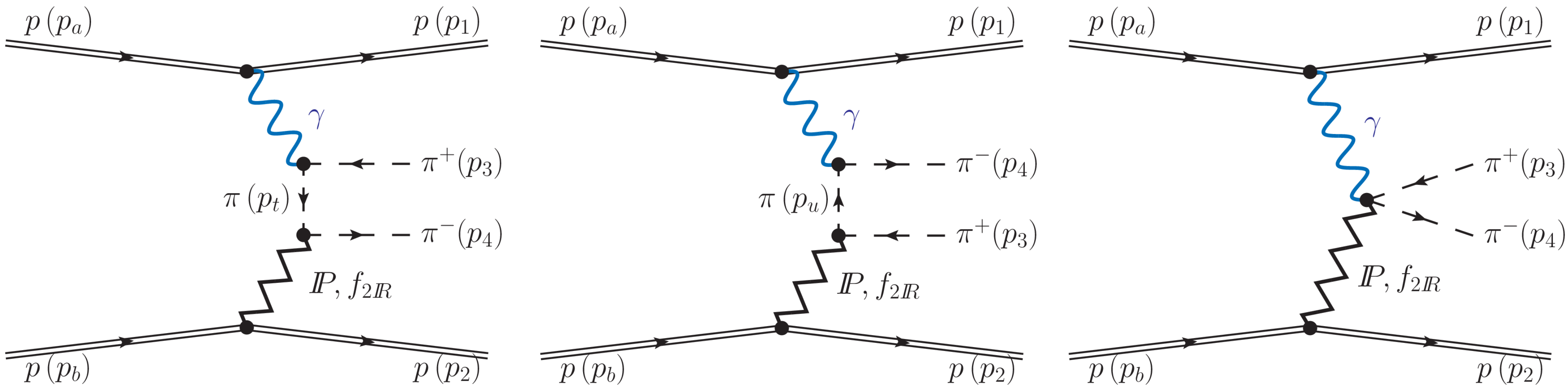
set B : $a_{I\!P\rho\rho} = a_{f_{2I\!R}\rho\rho} = 0\ \mathrm{GeV}^{-3}$, $b_{I\!P\rho\rho} = 7.04\ \mathrm{GeV}^{-1}$, $b_{f_{2I\!R}\rho\rho} = 9.3\ \mathrm{GeV}^{-1}$





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.

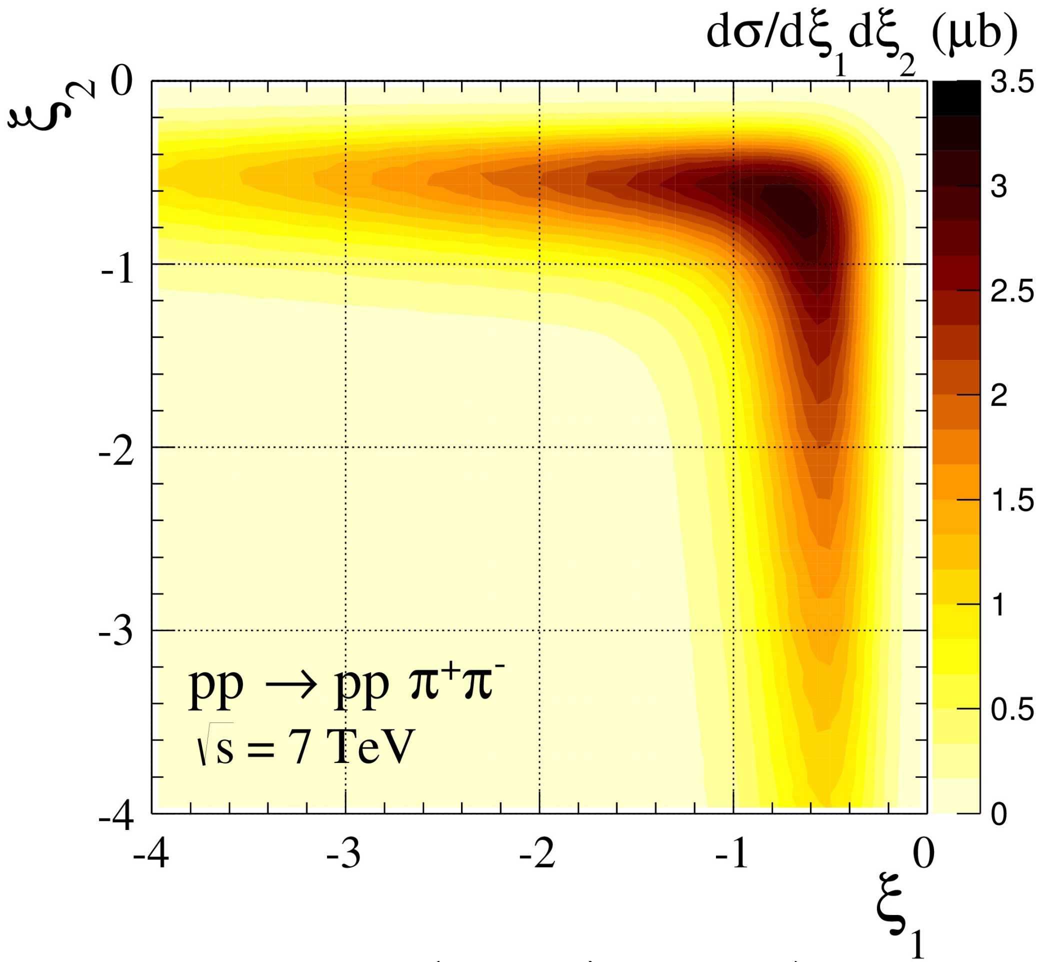
Set of vertices respecting QFT rules (O. Nachtmann *et al.*, *JHEP 1501 (2015) 151*)

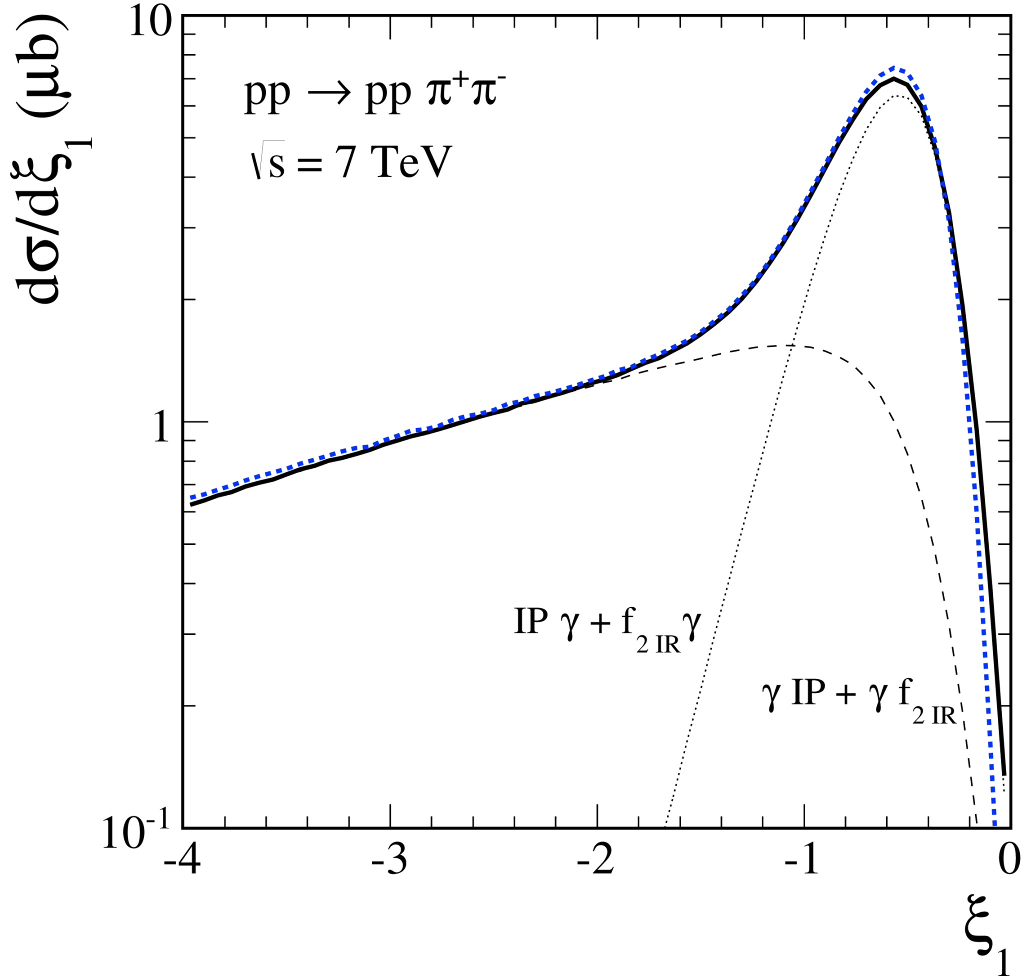
$$i\Gamma^{(I\!P\pi\pi)}_{\alpha\beta}(k',k) = -i2\beta_{I\!P\pi\pi}\left[(k'+k)_\alpha(k'+k)_\beta - \frac{1}{4}g_{\alpha\beta}(k'+k)^2\right] F_M((k'-k)^2)$$

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

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

ξ distribution



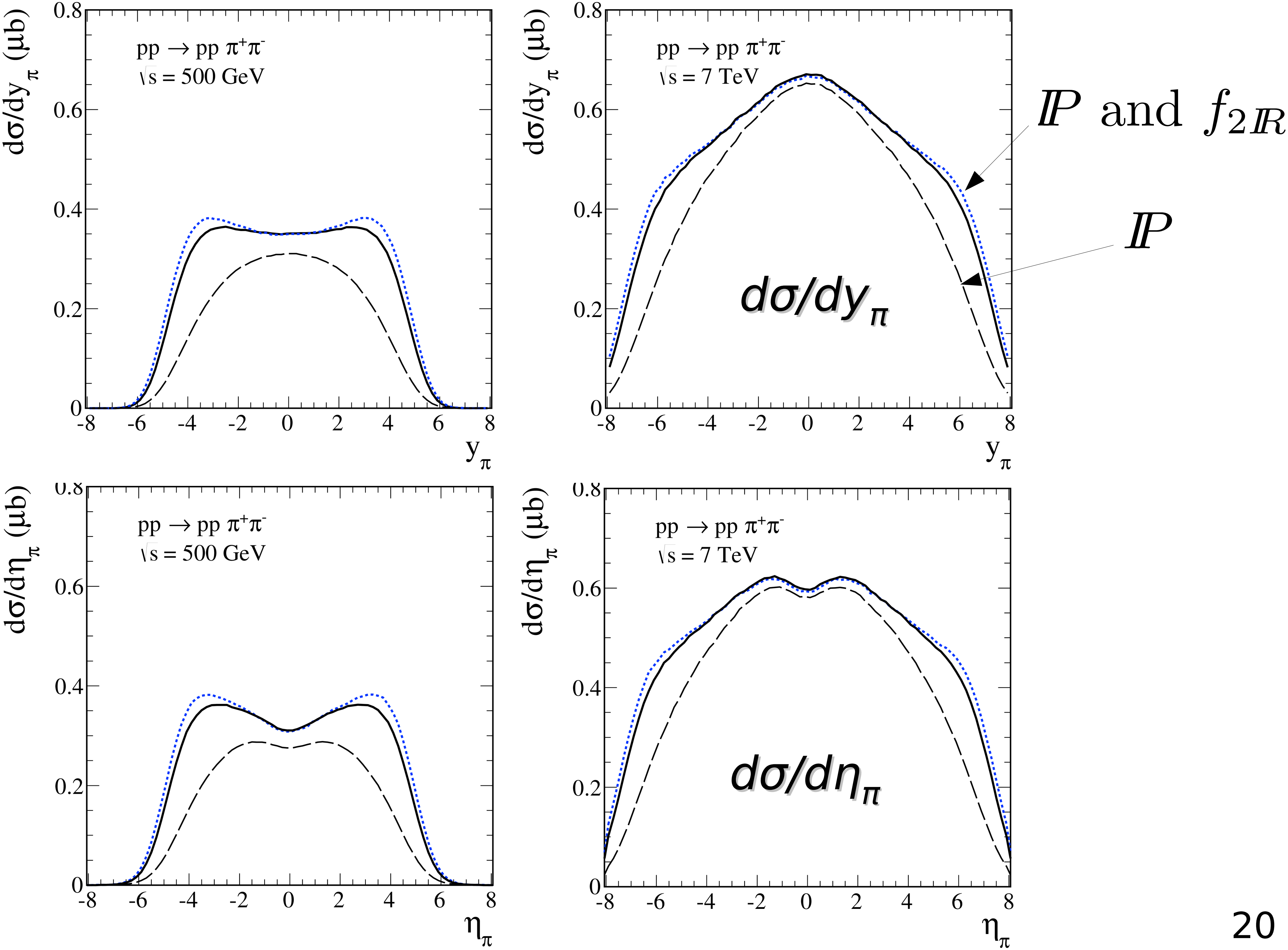


$$\xi_1 = \log_{10}(p_{1\perp}/1\,\mathrm{GeV})$$

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

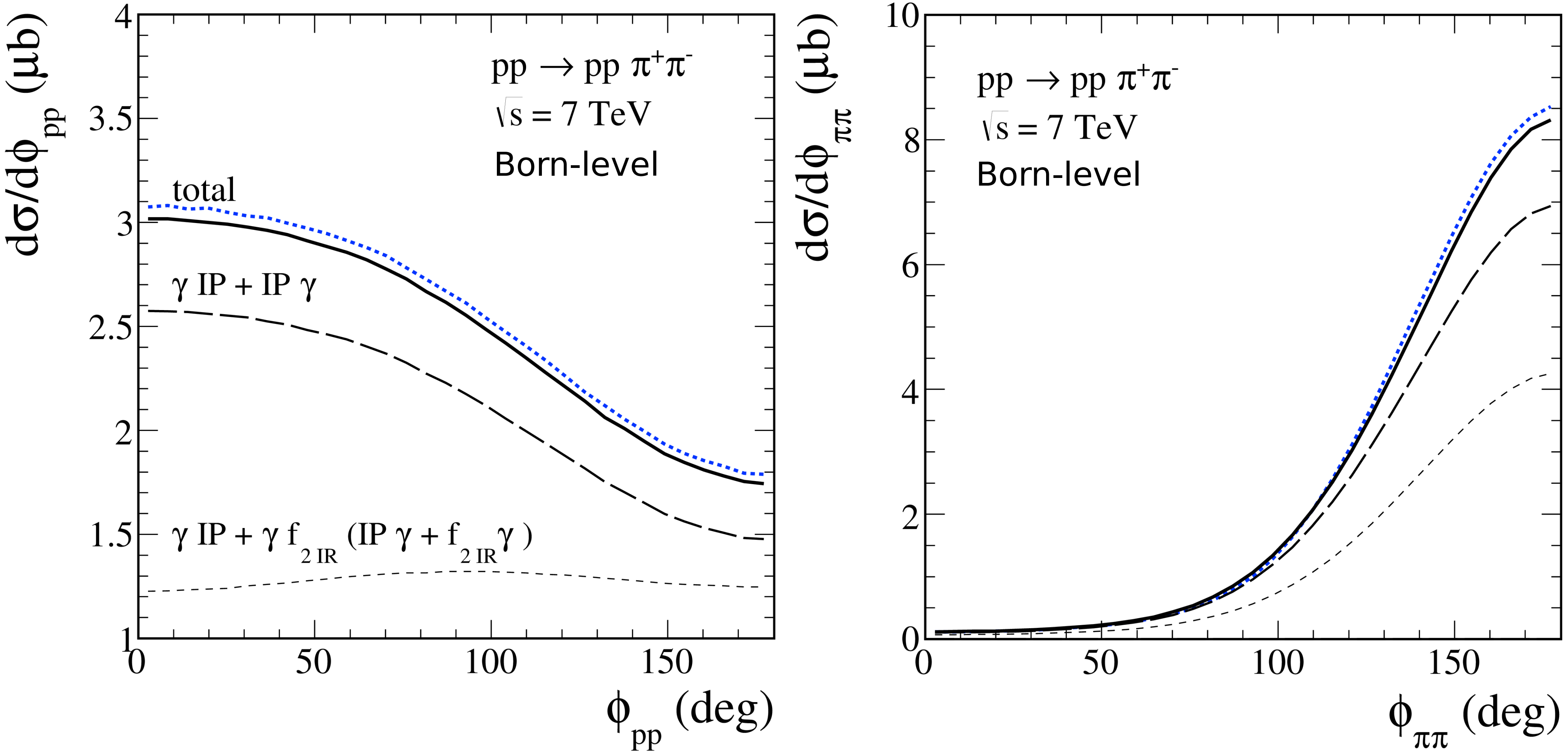
Due to the photon propagators occurring in the diagrams we expect the photon induced processes to be most important when at least one of the protons is undergoing only a very small momentum transfer.

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



pp → pp π⁺π⁻
√s = 500 GeV
pp → pp π⁺π⁻
√s = 7 TeV
$I\!P$ and $f_{2 I\!R}$
$I\!P$
dσ/dy_π
dσ/dη_π
dσ/dy_π (μb)
y_π
dσ/dη_π (μb)
η_π

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



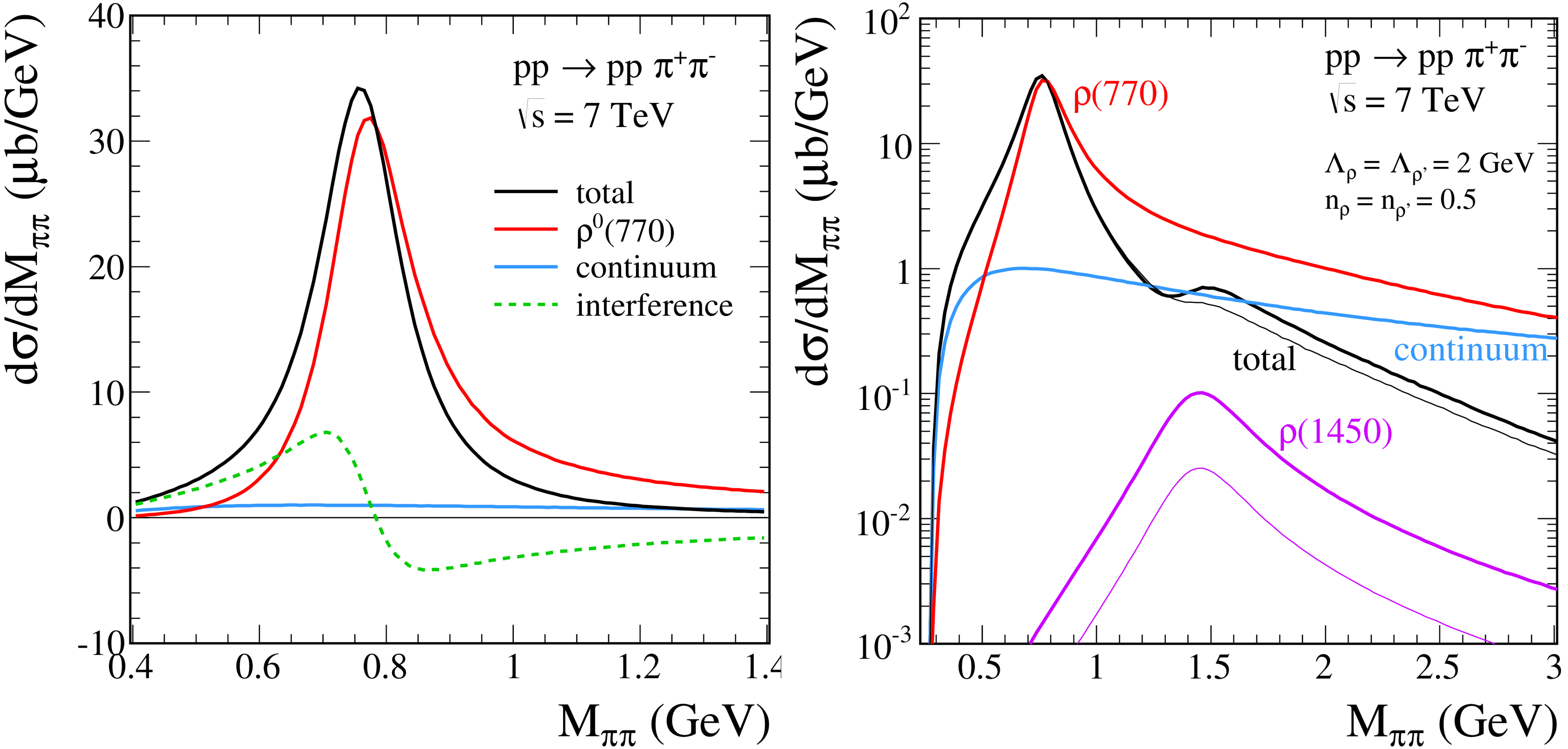
The effect of ϕ_{pp} deviation from a constant is due to interference of *γ-IP* and *IP-γ* amplitudes (see *W. Schäfer and A. Szczurek, Phys. Rev. D76 (2007) 094014* for the exclusive production of J/ψ meson).

- 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

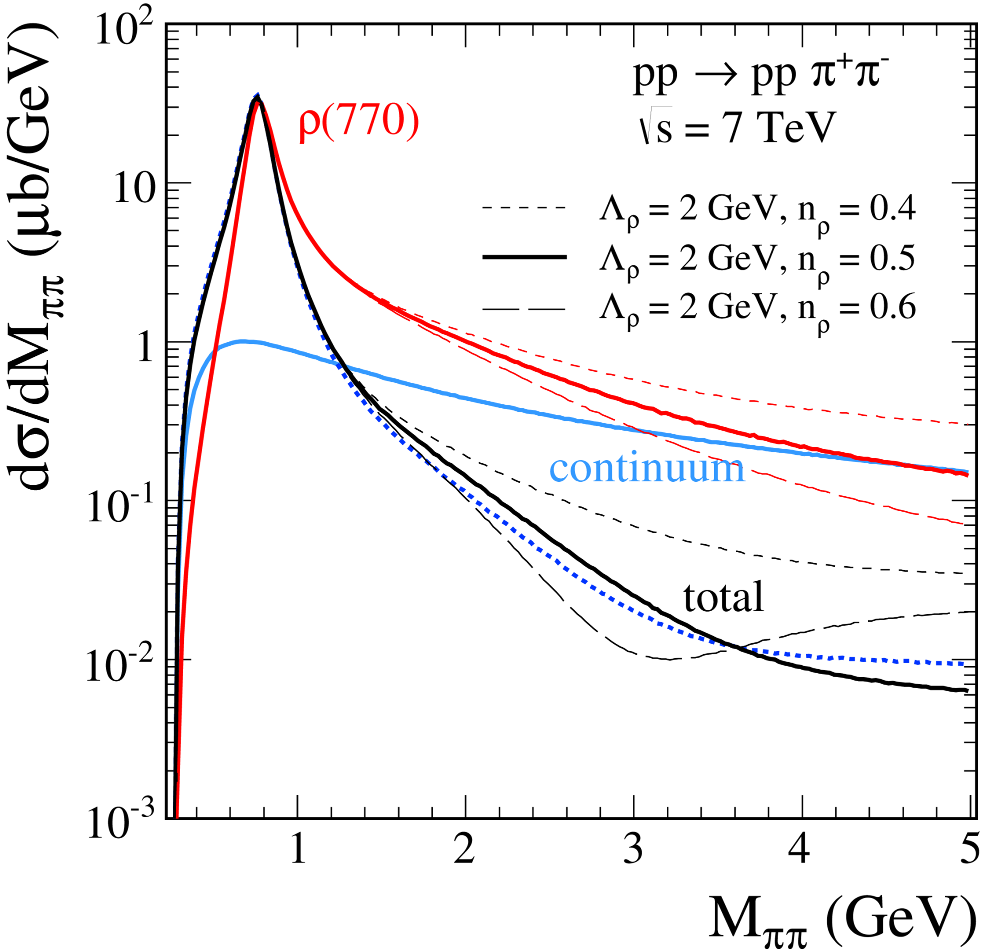
$M_{\pi\pi}$ distribution

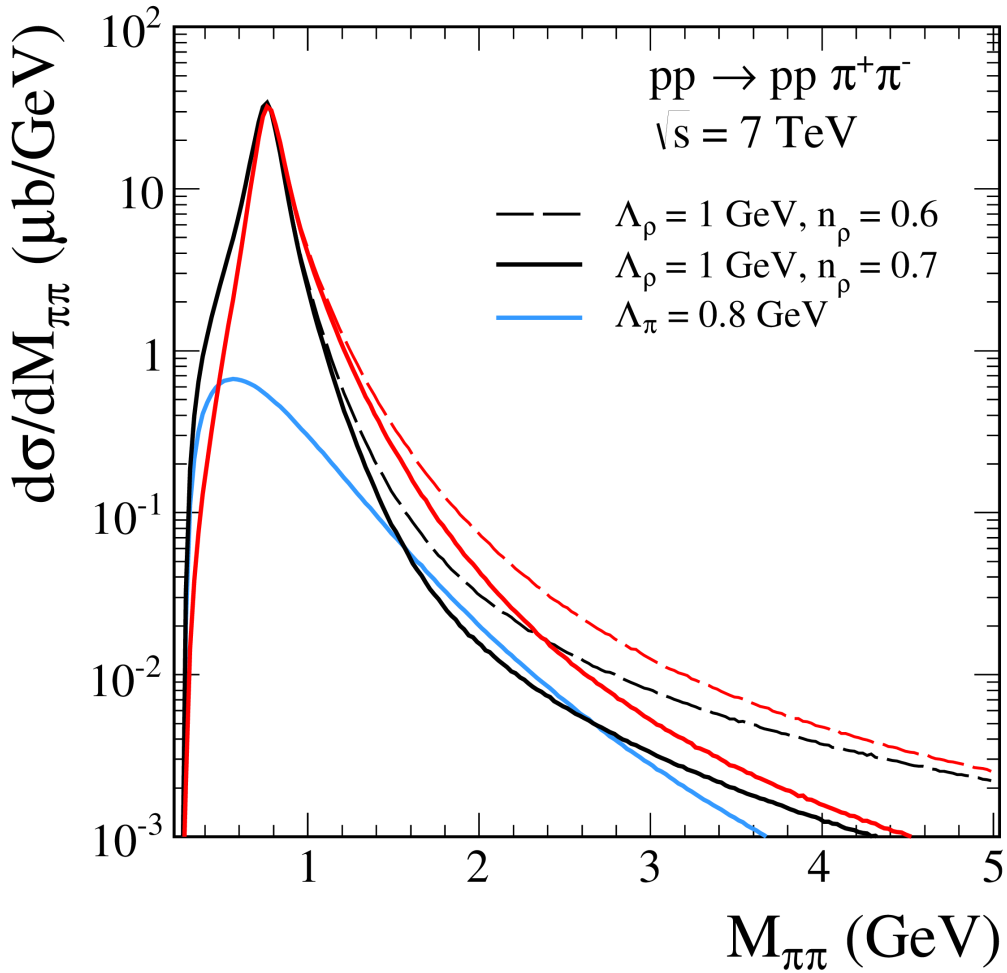


The non-resonant (Drell-Söding) contribution interfere with resonant ρ^0 contribution → skewing of ρ^0 line shape.

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

$M_{\pi\pi}$ distribution



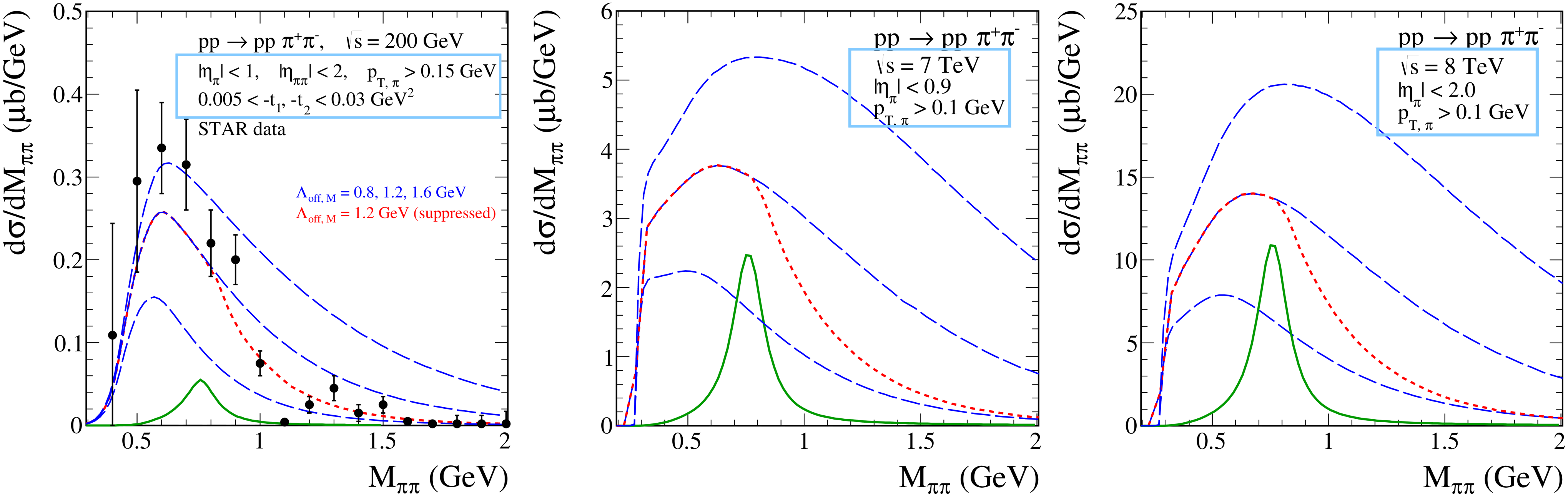


At higher $p_{t,\pi}$ our calculation gives a strong cancellation between the resonant and the non-resonant terms

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

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

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



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

Conclusions

- Central exclusive production of pion pairs 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.

- We have made first estimates the pion-nucleon absorption corrections to diffractive double pomeron/reggeon contribution.

- Central exclusive photoproduction mechanisms to the $pp \to pp\pi^+\pi^-$ reaction have been considered. We expect that the ρ^0 contribution is the main source of P wave in the $\pi^+\pi^-$ channel in contrast to even waves populated in double-pomeron/reggeon processes. Similar characteristic of y_π and $p_{\perp,\pi}$ distributions, but different dependence on $p_{\perp,p}$ and ϕ_{pp}.

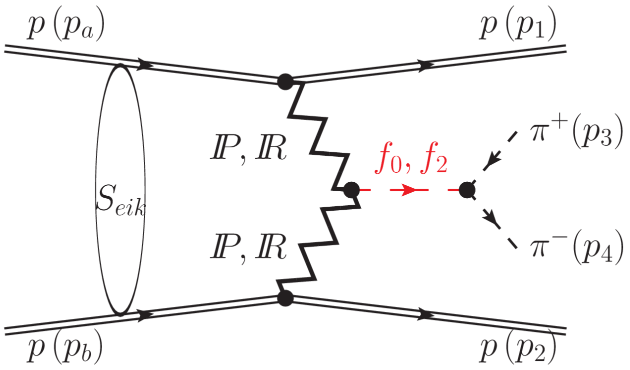
- The $pp \to pp\pi^+\pi^-$ process is an attractive for different experimental groups (COMPASS, STAR, CDF, ALICE, CMS+TOTEM, ATLAS+ALFA, LHCb). Future experimental data on exclusive meson production should provide more information for both diffractive and photoproduction mechanisms.

- In progress → a consistent model of the resonances decaying into the $\pi\pi/KK$ channels and the non-resonant background.

  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 (*see Mariola talk*).

Backup

Resonant $f_0(980)$ production

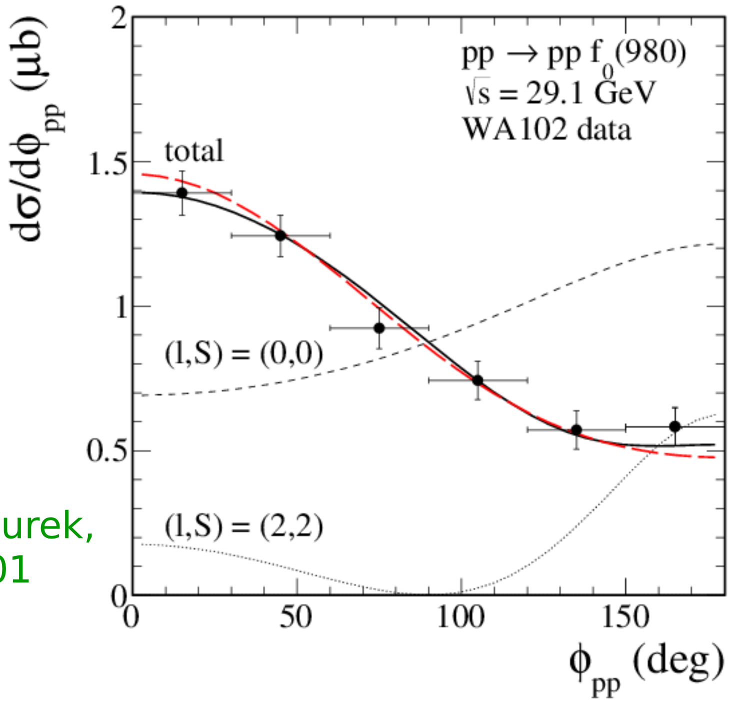


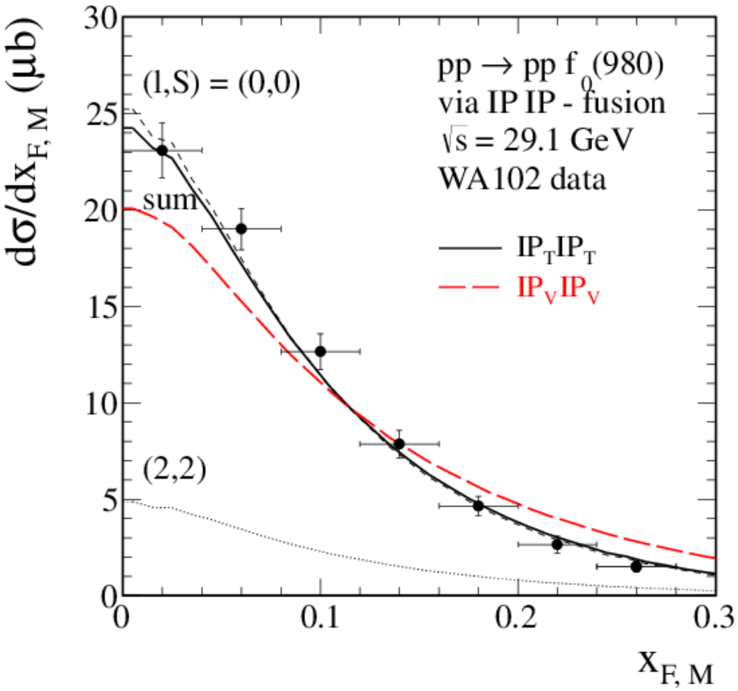
In most cases ($J^{PC} = 0^{++}, 0^{-+}$) one has to add coherently amplitudes for two lowest *(l, S)* couplings.

The corresponding coupling constants are not known and have been fitted to existing experimental data.

$$(l,S) = (0,0)\ term: i\Gamma'^{(I\!P_T I\!P_T \to M)}_{\mu\nu,\kappa\lambda} = i\, g'_{I\!P_T I\!P_T M}\, M_0 \left(g_{\mu\kappa} g_{\nu\lambda} + g_{\mu\lambda} g_{\nu\kappa} - \frac{1}{2} g_{\mu\nu} g_{\kappa\lambda} \right)$$

$$(2,2)\ term: i\Gamma''^{(I\!P_T I\!P_T \to M)}_{\mu\nu,\kappa\lambda}(q_1, q_2) = \frac{i\, g''_{I\!P_T I\!P_T M}}{2M_0} \left[q_{1\kappa} q_{2\mu} g_{\nu\lambda} + q_{1\kappa} q_{2\nu} g_{\mu\lambda} + q_{1\lambda} q_{2\mu} g_{\nu\kappa} + q_{1\lambda} q_{2\nu} g_{\mu\kappa} - 2(q_1 q_2)(g_{\mu\kappa} g_{\nu\lambda} + g_{\nu\kappa} g_{\mu\lambda}) \right]$$





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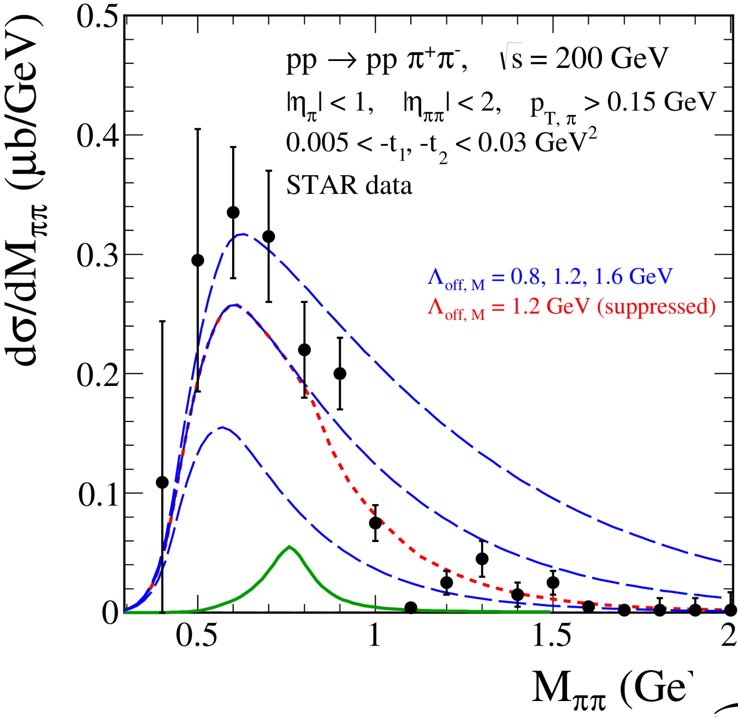
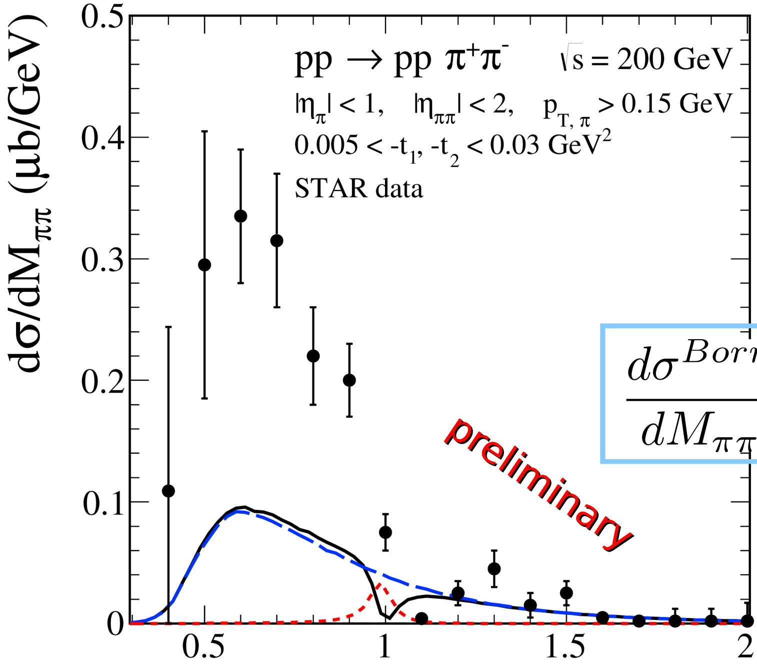
$M_{\pi\pi}$ distribution



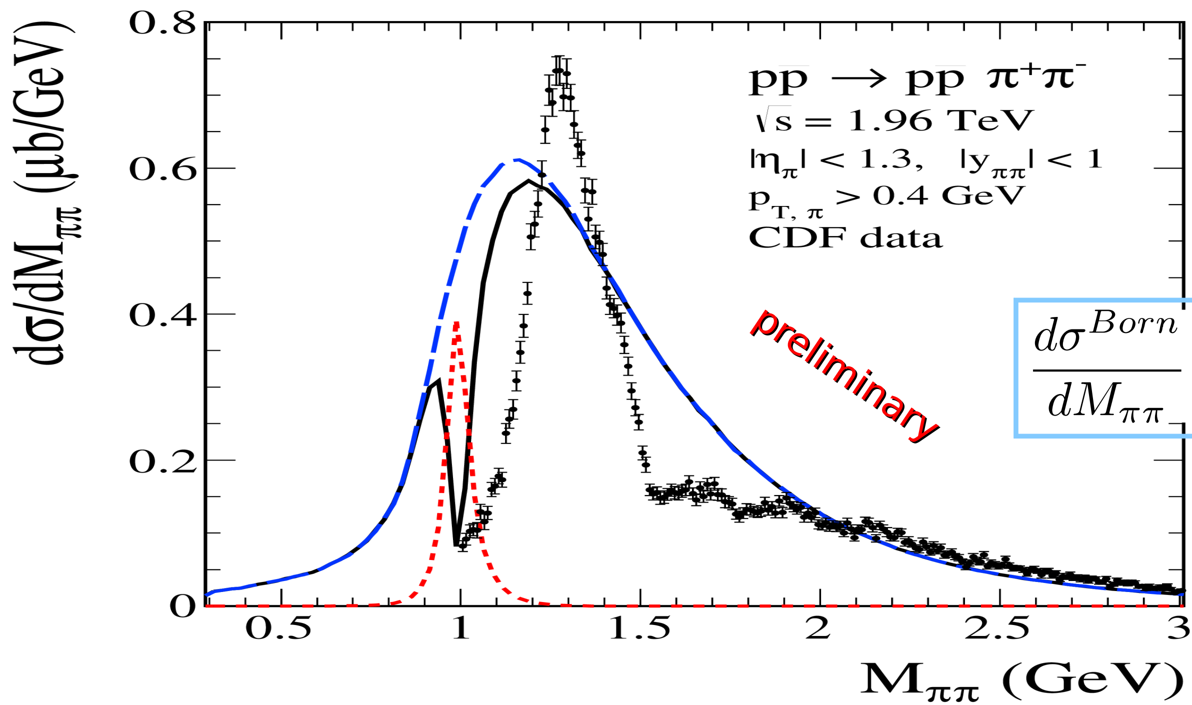


$$< S^2(M_{\pi\pi}) > \simeq 0.2$$

$$\frac{d\sigma^{Born}}{dM_{\pi\pi}} \times 0.2$$

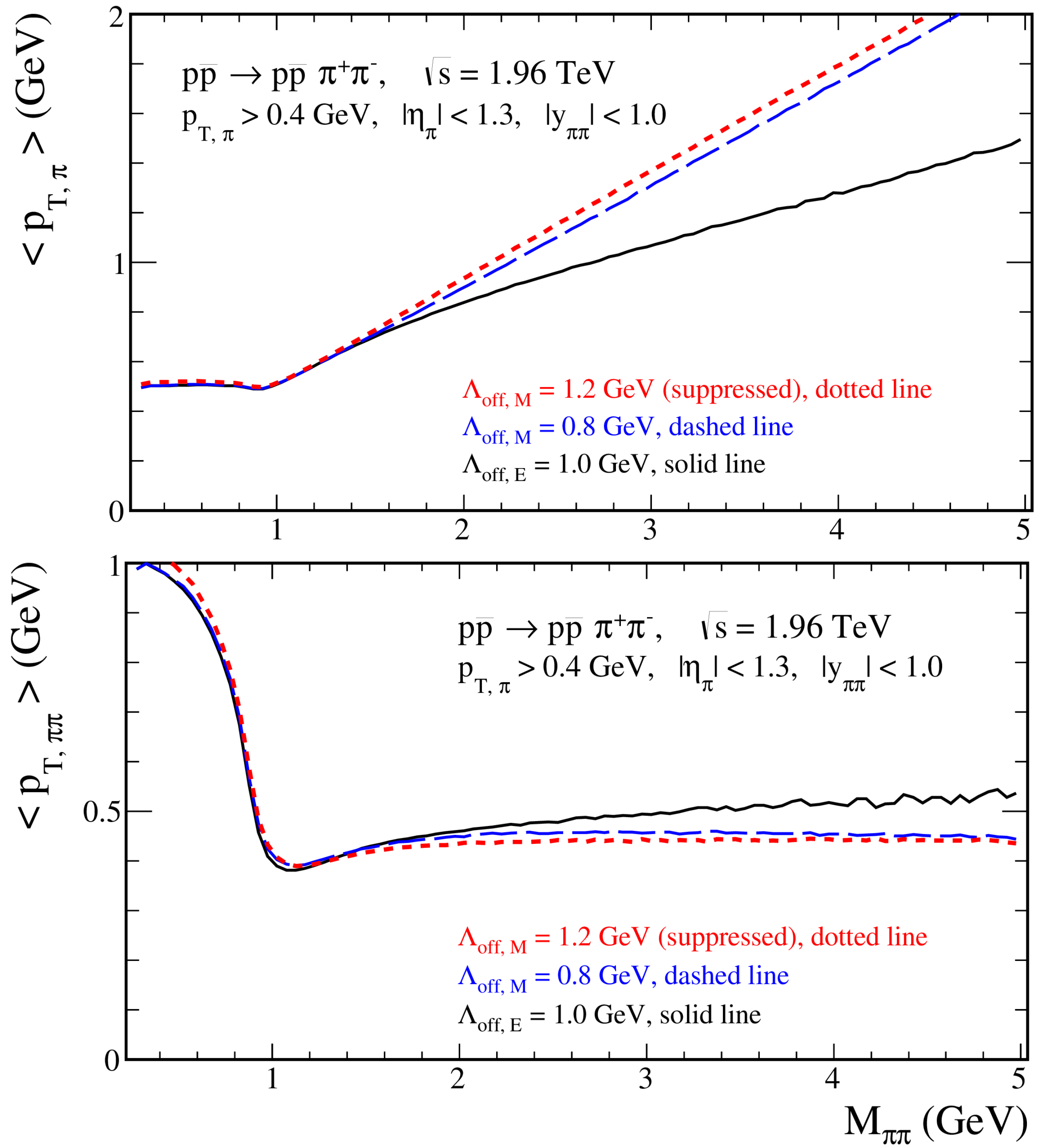
low-energy $\pi^+\pi^-$ FSI effects (enhancement of low *Mππ* region, relevant for STAR data)

interference of resonances and continuum (may depend on *t1* and *t2* that are very different for both experiments)



$$\frac{d\sigma^{Born}}{dM_{\pi\pi}} \times 0.1$$

Predictions for CDF



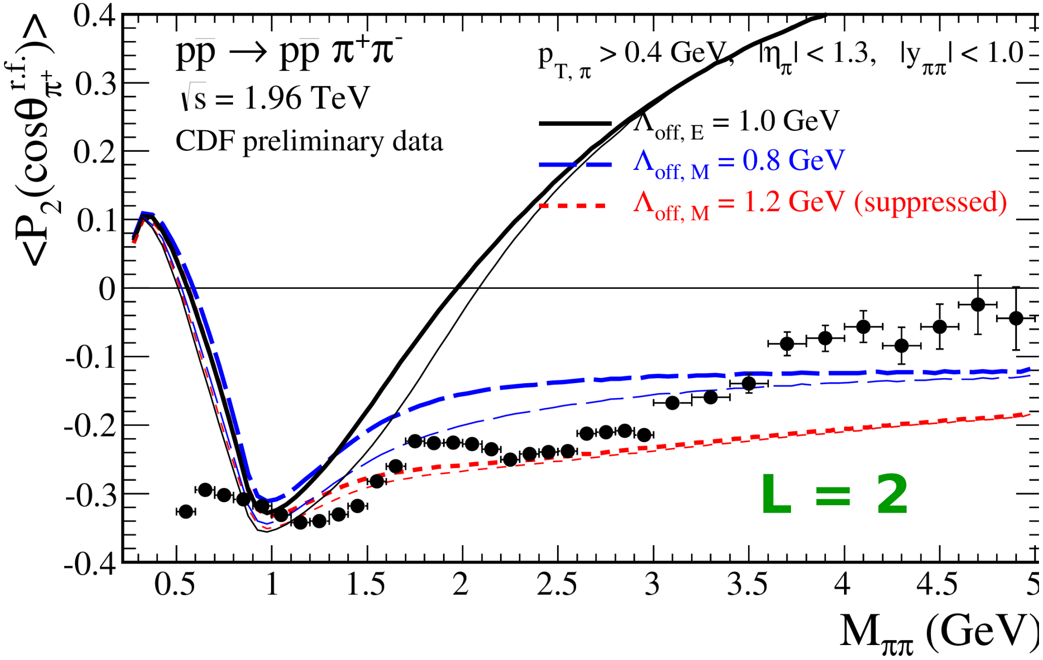
Our calculation shows a rise of the average pion transverse momentum with dipion invariant mass. A dependence on the form of the form factor is clearly seen.

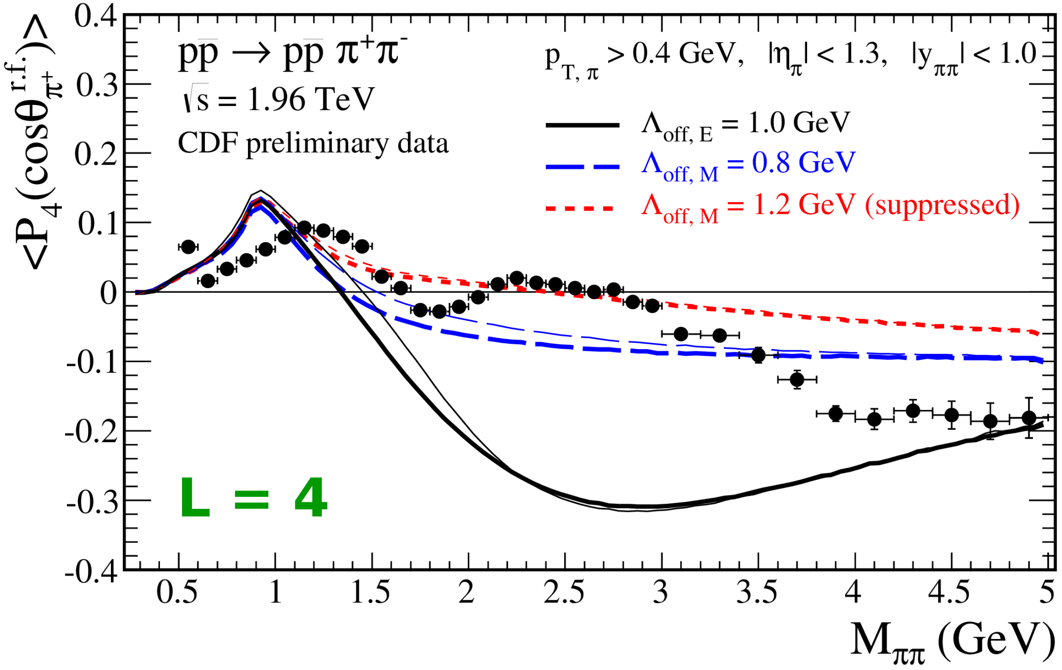
The average transverse momentum of the dipion pair is almost independent of the form of the form factor and a parameter of the form factor.

This can be understood from momentum conservation. The transverse momentum of the dipion system must be balanced by the transverse momenta of protons.

Comparison with CDF preliminary data

Another observable which can be very sensitive to the choice of off-shell pion form factors are the Legendre polynomials $< P_{L_{even}}(\cos\theta_{\pi^+}^{r.f.}) > (M_{\pi\pi})$ distributions, where $cos\theta_{\pi^+}^{r.f.}$ is the angle of the π^+ meson with respect to the beam axis, in the $\pi^+\pi^-$ rest frame.



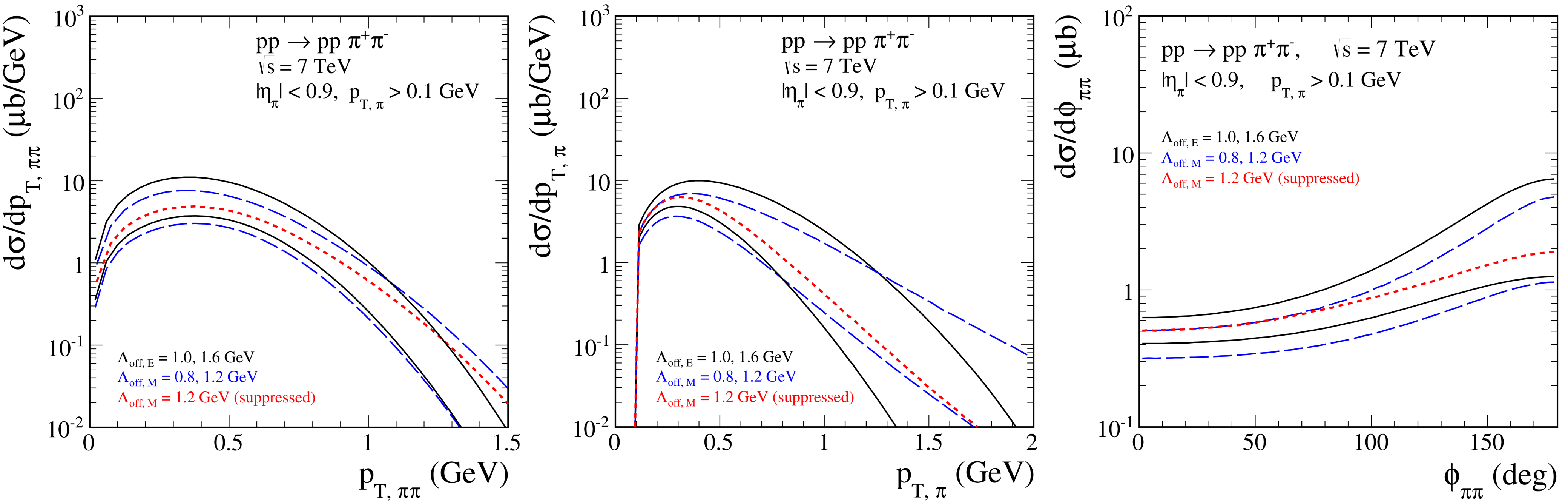


$< P_L >$ distributions are almost unaffected by the absorption effects; see the thin lines (without) and thick lines (with the absorption corrections)

the CDF data strongly support our predictions calculated with the monopole form factors

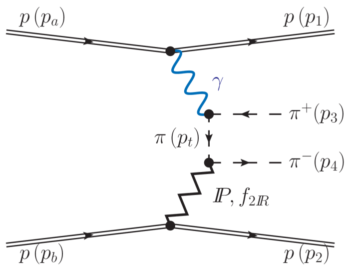
CDF preliminary data: M. Albrow, J. Lewis, M. Zurek, A. Swiech, D. Lontkovskyi, I. Makarenko, and J. S.Wilson. The public note is available at http://www-cdf.fnal.gov/physics/new/qcd/GXG_14/webpage/

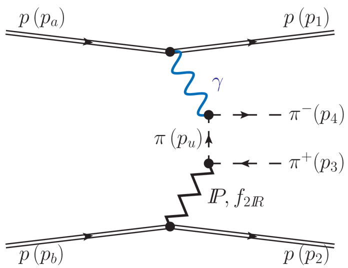
Predictions for ALICE

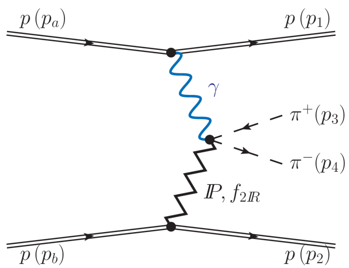


Non-resonant $\pi^+\pi^-$ production

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







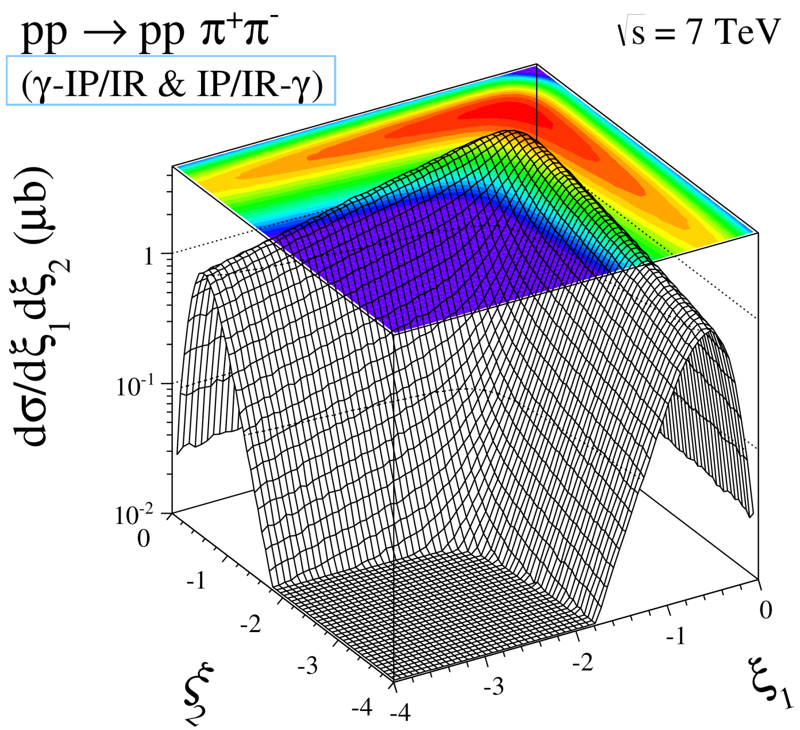
$$\begin{aligned}
\mathcal{M}^{(a)}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^+\pi^-} \simeq\; & ie^2(p_1+p_a)^\mu\,\delta_{\lambda_1\lambda_a}\,F_1(t_1)F_M(t_1)\frac{1}{t_1}(p_t-p_3)_\mu\frac{1}{p_t^2-m_\pi^2}\\
&\times 2\beta_{I\!P\pi\pi}\,(p_4+p_t)^\alpha(p_4+p_t)^\beta\,\frac{1}{4s_{234}}(-is_{234}\alpha'_{I\!P})^{\alpha_{I\!P}(t_2)-1}\\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

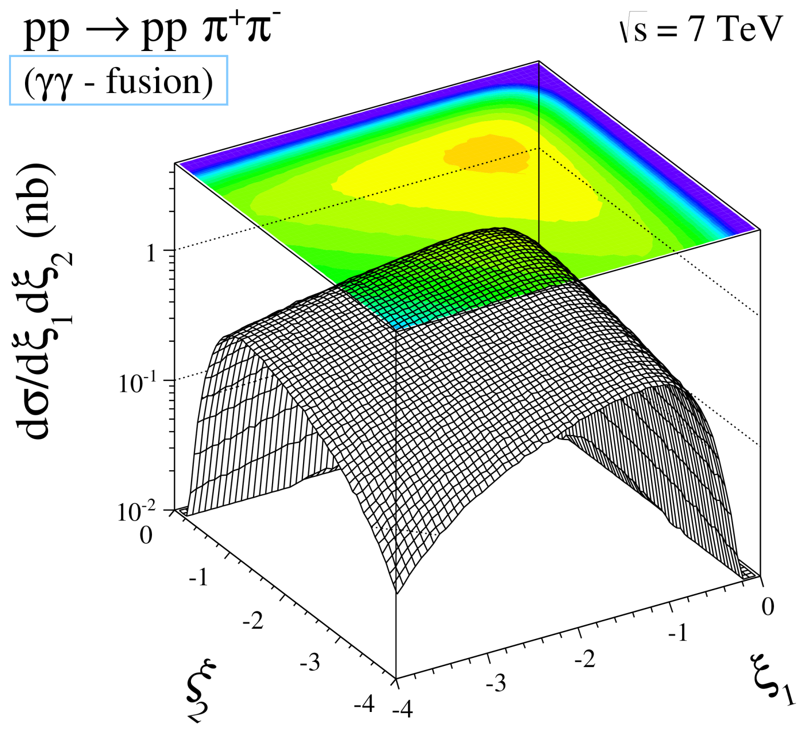
$$\begin{aligned}
\mathcal{M}^{(b)}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^+\pi^-} \simeq\; & ie^2(p_1+p_a)^\mu\,\delta_{\lambda_1\lambda_a}\,F_1(t_1)F_M(t_1)\frac{1}{t_1}(p_4+p_u)_\mu\frac{1}{p_u^2-m_\pi^2}\\
&\times 2\beta_{I\!P\pi\pi}\,(p_u-p_3)^\alpha(p_u-p_3)^\beta\,\frac{1}{4s_{234}}(-is_{234}\alpha'_{I\!P})^{\alpha_{I\!P}(t_2)-1}\\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

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

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

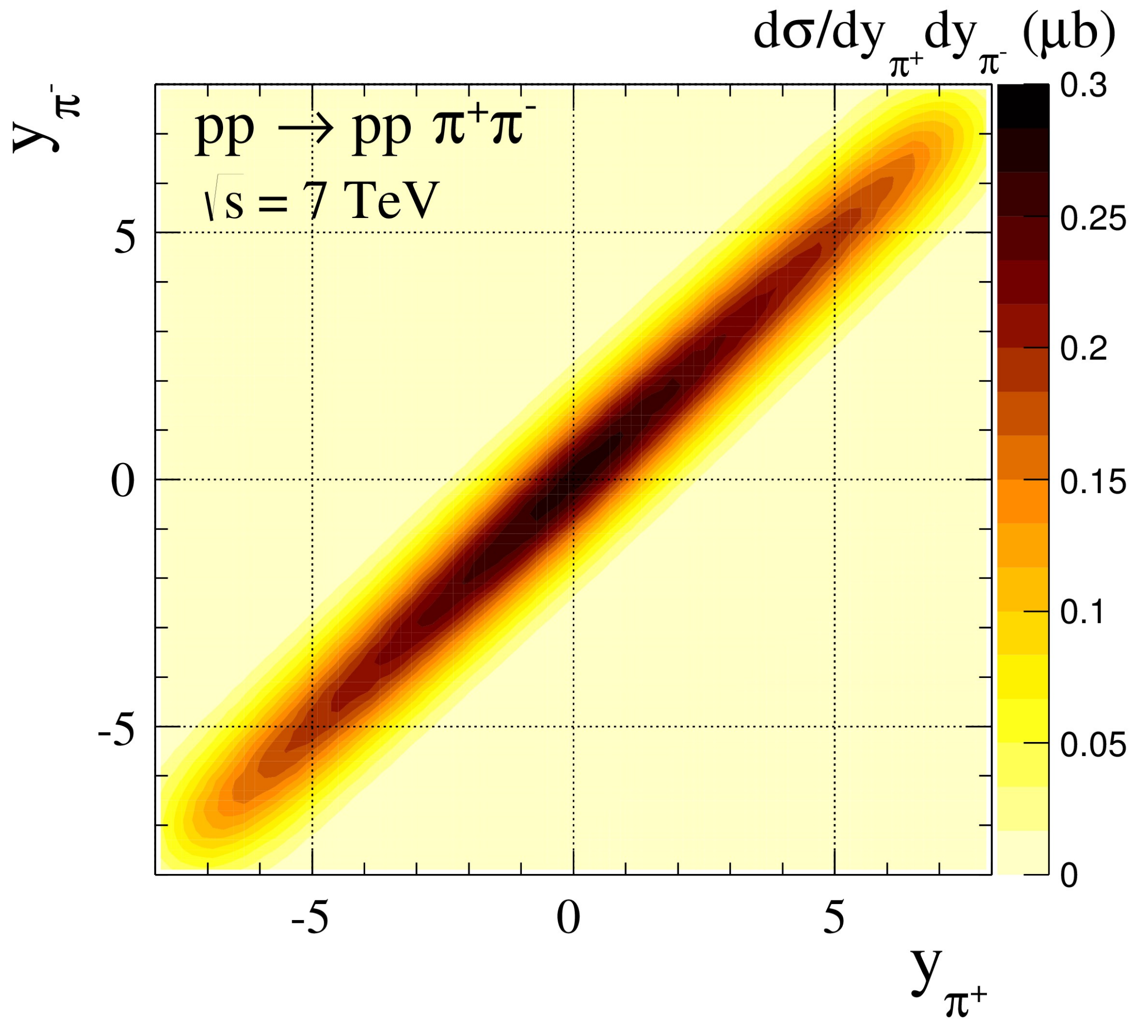
(ξ_1, ξ_2) distribution





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.

Photoproduction mechanism: *pp → pp (ρ^0 → π^+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)