Exclusive diffractive production of hadrons in pp collisions

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Plan

1) $pp \to pp\, \pi^+\pi^-$ reaction

- diffractive mechanism – dipion continuum, scalar and tensor resonances
- photoproduction mechanism – ρ^0 and non-resonant (Drell-Söding)

2) preliminary results on $pp \to pp\, K^+K^-$ and $pp \to pp\, p\bar{p}$

3) $pp \to p\, \rho^0\, (n\pi^+)$ reaction as a background to $pp \to p\, \rho^0\, p$ reaction

4) $pp \to pp\, \pi^+\pi^-\pi^+\pi^-$ via the intermediate σσ and ρρ states

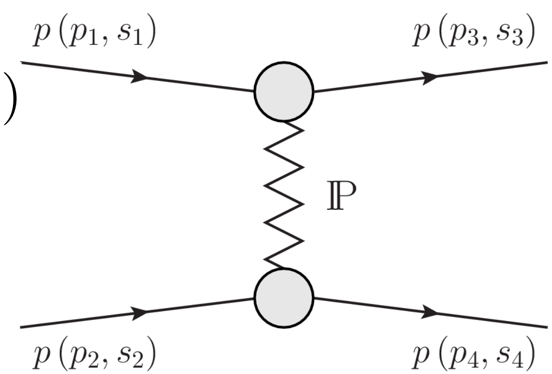
- Exclusive processes are very attractive for different experiments: COMPASS, HERA, STAR, CDF, ALICE, CMS, ATLAS, LHCb.
- Many aspects deserve to study: nature of soft pomeron, size of absorptive corrections, role of reggeon exchanges, dimeson invariant mass spectra, ...
- pQCD image of pomeron implies that DPE is a gluon-rich process → gluon bound states (glueballs) could be preferentially produced

The nature of soft pomeron

- C. Ewerz, M. Maniatis, O. Nachtmann, *A Model for Soft High-Energy Scattering: Tensor Pomeron and Vector Odderon*, Annals Phys. 342 (2014) 31
- C. Ewerz, P. L., O. Nachtmann, A. Szczurek, *Helicity in proton-proton elastic scattering and the spin structure of the pomeron,* Phys. Lett. B763 (2016) 382

We believe that the soft pomeron is best described as the effective exchange of a symmetric rank 2 tensor object, the tensor pomeron.

$$< 2s_3, 2s_4|\mathcal{T}|2s_1, 2s_2 >= (-i)\bar{u}(p_3, s_3) i\Gamma^{(\mathbb{P}_T pp)}_{\mu\nu}(p_3, p_1) u(p_1, s_1) \times i\Delta^{(\mathbb{P}_T)\mu\nu,\kappa\lambda}(s,t) \times \bar{u}(p_4, s_4) i\Gamma^{(\mathbb{P}_T pp)}_{\mu\nu}(p_4, p_2) u(p_2, s_2)$$



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

$$i\Gamma^{(\mathbb{P}_T pp)}_{\mu\nu}(p', p) = -i3\beta_{\mathbb{P}NN} F_1\left((p'-p)^2\right)\left\{\frac{1}{2}[\gamma_\mu(p'+p)_\nu + \gamma_\nu(p'+p)_\mu] - \frac{1}{4}g_{\mu\nu}(\not{p}' + \not{p})\right\}$$

$$\beta_{\mathbb{P}NN} = 1.87\ \mathrm{GeV}^{-1} \qquad F_1(t) = \frac{4m_p^2 - 2.79\,t}{(4m_p^2 - t)(1 - t/m_D^2)^2} \qquad m_D^2 = 0.71\ \mathrm{GeV}^2$$

$$\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}} t$$
$$\alpha_{\mathbb{P}}(0) = 1.0808$$
$$\alpha'_{\mathbb{P}} = 0.25\,\mathrm{GeV}^{-2}$$

- Comparison with experimental data on polarised high-energy *pp* elastic scattering [L. Adamczyk et al. (STAR Collaboration), Phys. Lett. B719 (2013) 62)]

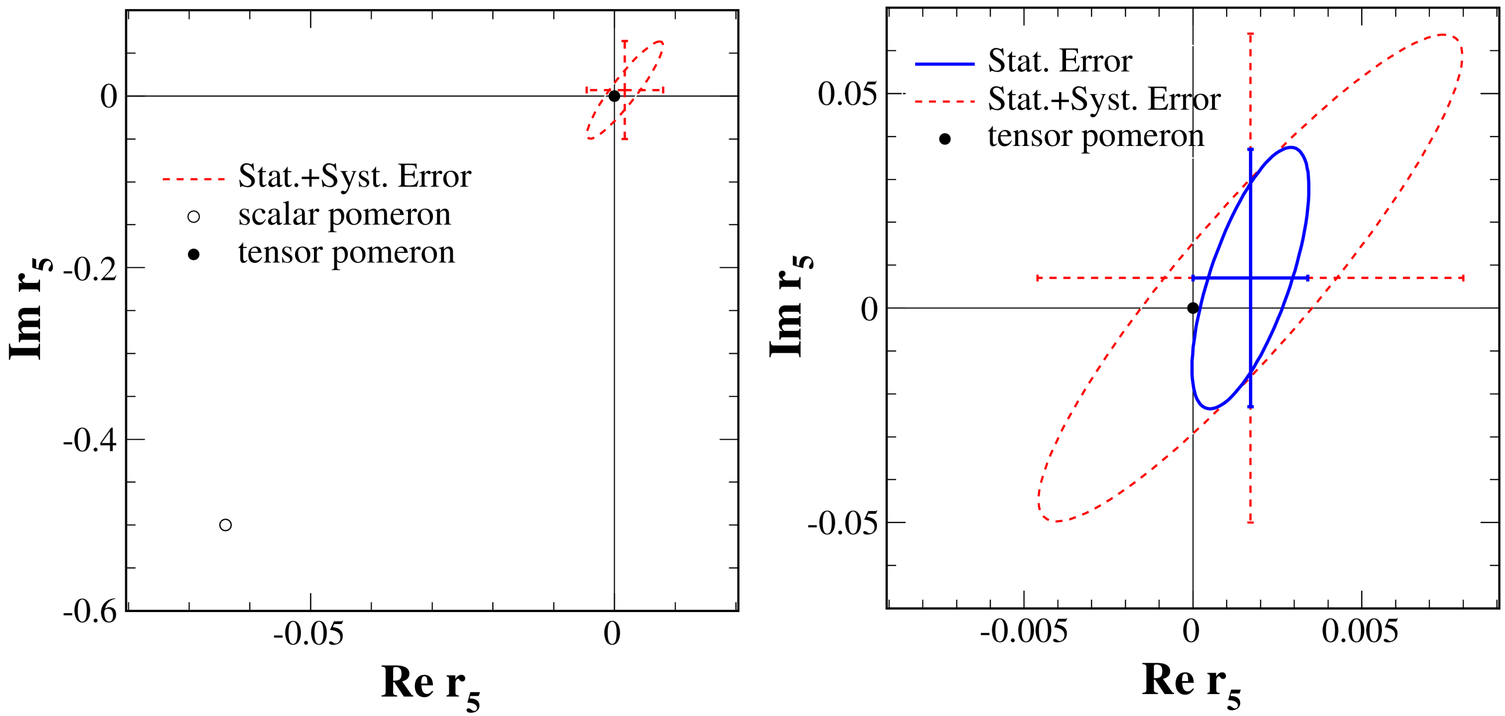
Ratio of single-flip to non-flip amplitudes:

$$r_5(s,t) = \frac{2m_p\,\phi_5(s,t)}{\sqrt{-t}\,\mathrm{Im}[\phi_1(s,t)+\phi_3(s,t)]}$$

$$\sqrt{s} = 200\ \mathrm{GeV}$$
$$0.003 \leqslant |t| \leqslant 0.035\ \mathrm{GeV}^2$$

$$r_5^{I\!P_T}(s,t) = -\frac{m_p^2}{s}\left[i + \tan\left(\frac{\pi}{2}(\alpha_{I\!P}(t)-1)\right)\right], \qquad r_5^{I\!P_T}(s,0) = (-0.28 - i2.20)\times 10^{-5}$$

$$r_5^{I\!P_S}(s,t) = -\frac{1}{2}\left[i + \tan\left(\frac{\pi}{2}(\alpha_{I\!P}(t)-1)\right)\right], \qquad r_5^{I\!P_S}(s,0) = -0.064 - i0.500$$

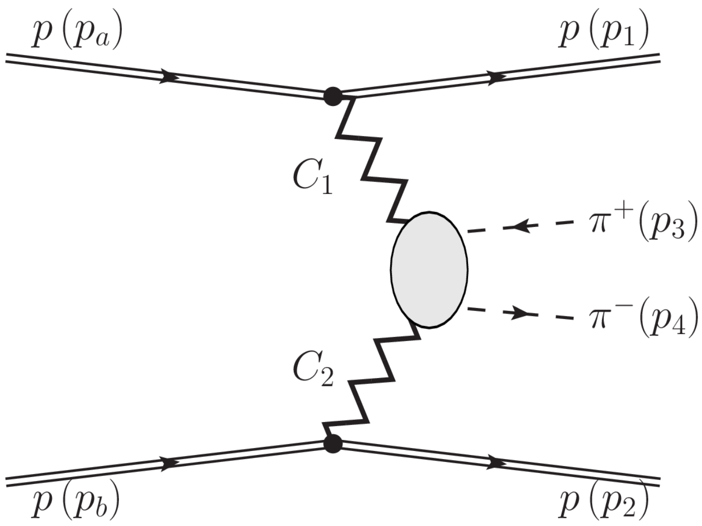


The tensor-pomeron result is compatible with the general rules of QFT and the STAR experimental result. see talk by Otto Nachtmann

Central exclusive production within tensor pomeron approach

- P. L., O. Nachtmann, A. Szczurek, *Exclusive central diffractive production of scalar and pseudoscalar mesons; tensorial vs. vectorial pomeron*, Annals Phys. 344 (2014) 301
- P. L, 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) 07402300
- P. L., O. Nachtmann, A. Szczurek, *Central exclusive diffractive production of the $\pi^+\pi^-$ continuum, scalar and tensor resonances in pp and $p\bar{p}$ scattering within the tensor Pomeron approach*, Phys. Rev. D93 (2016) 054015
- P. L., O. Nachtmann, A. Szczurek, *Exclusive diffractive production of $\pi^+\pi^-\pi^+\pi^-$ via the intermediate $\sigma\sigma$ and $\rho\rho$ states in proton-proton collisions within tensor Pomeron approach*, Phys. Rev. D94 (2016) 034017
- P. L., O. Nachtmann, A. Szczurek, *Central production of ρ^0 in pp collisions with single proton diffractive dissociation at the LHC*, Phys. Rev. D95 (2017) 034036

Dipion continuum production



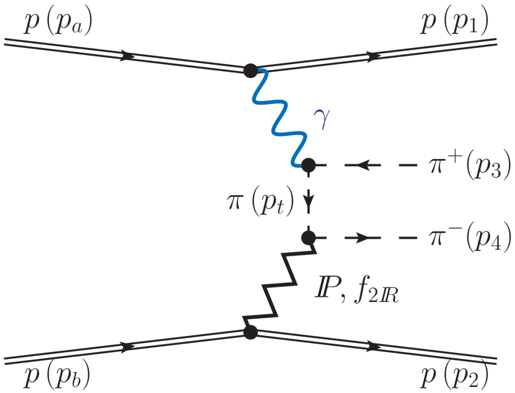
C = +1 exchanges ($I\!P$, $f_{2I\!R}$, $a_{2I\!R}$) are represented as rank-2 tensor
C = -1 exchanges (odderon (?), $\omega_{I\!R}$, $\rho_{I\!R}$) represented as vector

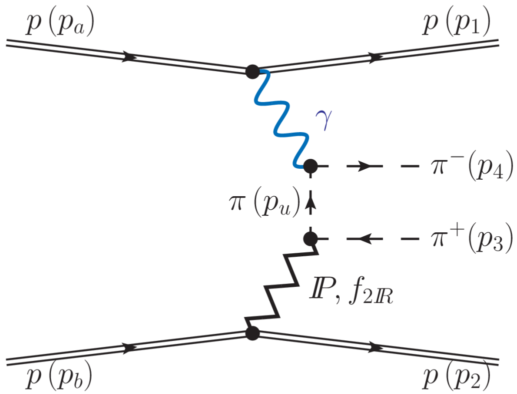
Exchange object	C	G
$I\!P$	1	1
$f_{2I\!R}$	1	1
$a_{2I\!R}$	1	-1
γ	-1	
$\mathbb{O}$	-1	-1
$\omega_{I\!R}$	-1	-1
$\rho_{I\!R}$	-1	1

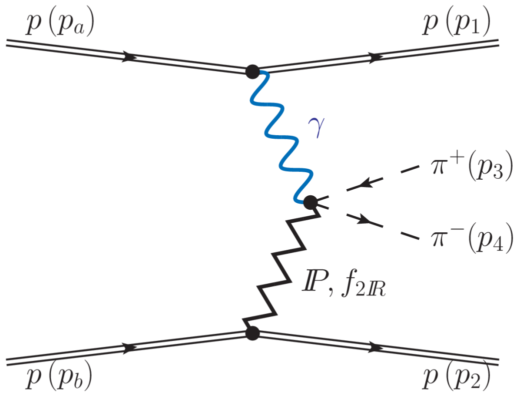
$$(C_1, C_2) = (1,1): \quad (I\!P + f_{2I\!R}, I\!P + f_{2I\!R})$$
$$(C_1, C_2) = (-1,-1): \quad (\rho_{I\!R} + \gamma, \rho_{I\!R} + \gamma)$$
$$(C_1, C_2) = (1,-1): \quad (I\!P + f_{2I\!R}, \rho_{I\!R} + \gamma)$$
$$(C_1, C_2) = (-1,1): \quad (\rho_{I\!R} + \gamma, I\!P + f_{2I\!R})$$

G parity invariance forbids the vertices:
$a_{2I\!R}\pi\pi$, $\omega_{I\!R}\pi\pi$, $\mathbb{O}\pi\pi$

for the cases involving the photon exchange one also has to take into account the diagrams involving the contact terms (gauge invariant version of the Drell-Söding mechanism)



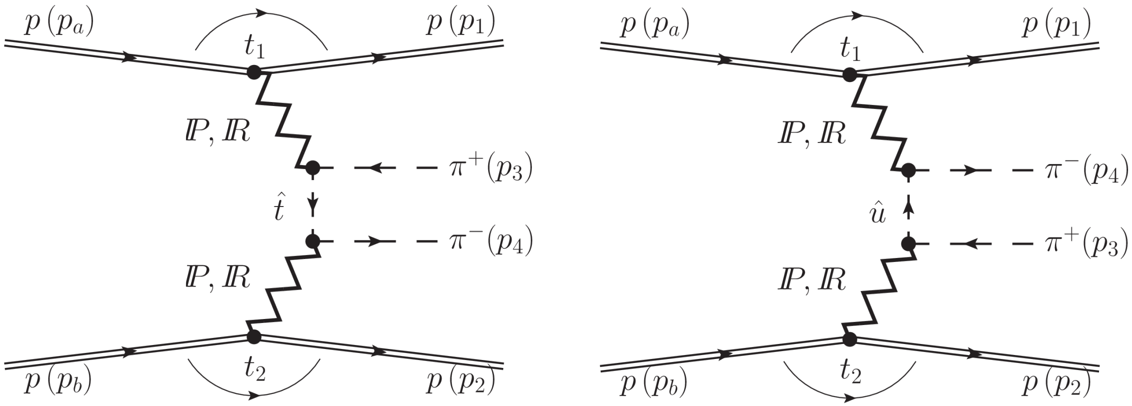




Diffractive dipion continuum production

$$\mathcal{M}^{\pi\pi-\mathrm{continuum}}_{pp\to pp\pi^+\pi^-} = \boxed{\mathcal{M}^{(I\!PI\!P\to\pi^+\pi^-)}} + \mathcal{M}^{(I\!P f_{2I\!R}\to\pi^+\pi^-)} + \mathcal{M}^{(f_{2I\!R} I\!P\to\pi^+\pi^-)} + \mathcal{M}^{(f_{2I\!R} f_{2I\!R}\to\pi^+\pi^-)}$$

$$\mathcal{M}^{(I\!PI\!P\to\pi^+\pi^-)} = \mathcal{M}^{(\hat{\mathrm{t}})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^+\pi^-} + \mathcal{M}^{(\hat{\mathrm{u}})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^+\pi^-}$$



in terms of effective tensor pomeron propagator, proton and pion vertex functions

$$\mathcal{M}^{(\hat{\mathrm{t}})} = (-i)\bar{u}(p_1,\lambda_1) i\Gamma^{(I\!Ppp)}_{\mu_1\nu_1}(p_1,p_a)u(p_a,\lambda_a)\, i\Delta^{(I\!P)\,\mu_1\nu_1,\alpha_1\beta_1}(s_{13},t_1)\, i\Gamma^{(I\!P\pi\pi)}_{\alpha_1\beta_1}(p_t,-p_3)$$
$$\times\, i\Delta^{(\pi)}(p_t)\, i\Gamma^{(I\!P\pi\pi)}_{\alpha_2\beta_2}(p_4,p_t)\, i\Delta^{(I\!P)\,\alpha_2\beta_2,\mu_2\nu_2}(s_{24},t_2)\, \bar{u}(p_2,\lambda_2) i\Gamma^{(I\!Ppp)}_{\mu_2\nu_2}(p_2,p_b)u(p_b,\lambda_b)$$

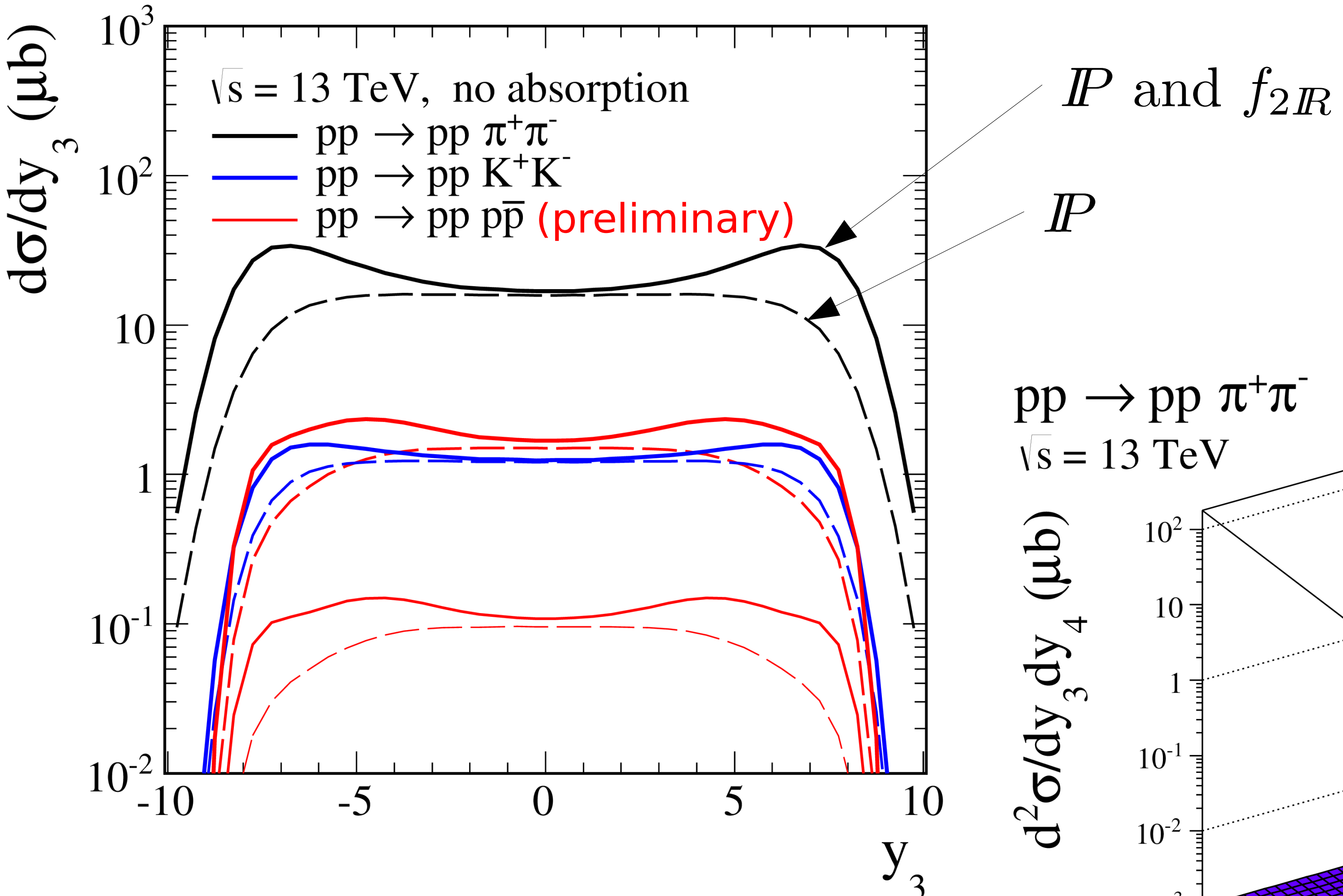
$$i\Gamma^{(I\!P\pi\pi)}_{\mu\nu}(k',k) = -i2\beta_{I\!P\pi\pi}\, F_M((k'-k)^2)\left[(k'+k)_\mu(k'+k)_\nu - \frac{1}{4}g_{\mu\nu}(k'+k)^2\right]$$

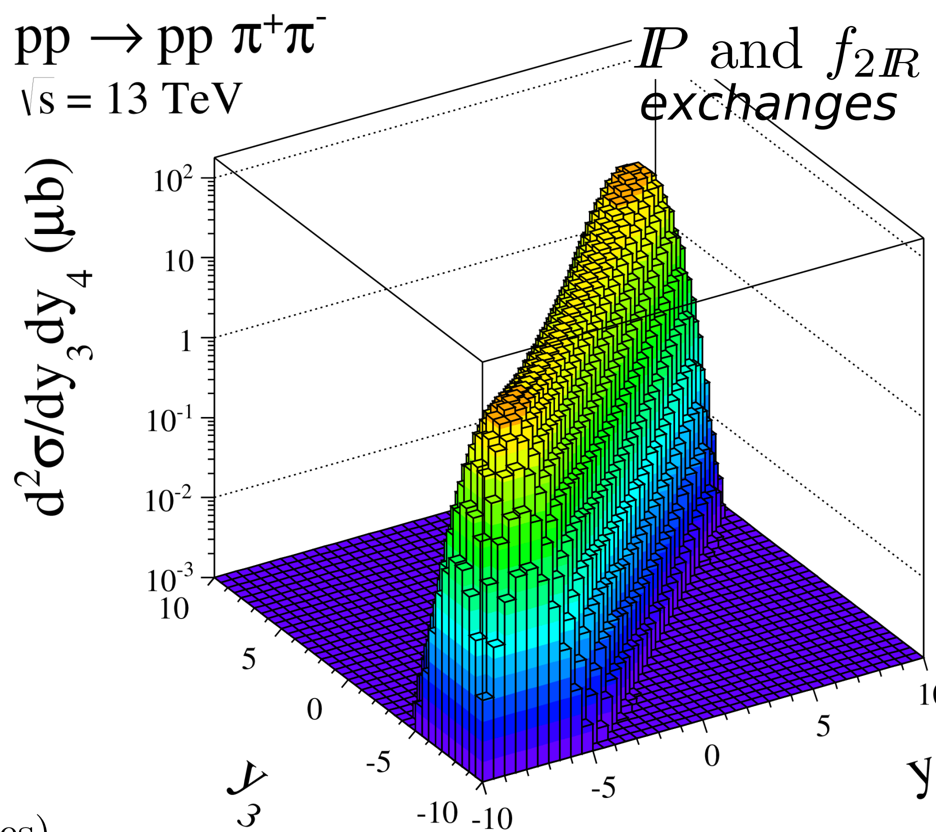
$$\beta_{I\!P\pi\pi} = 1.76\ \mathrm{GeV}^{-1}, \quad F_M(t) = \tfrac{1}{1-t/\Lambda_0^2}, \quad \Lambda_0^2 = 0.5\ \mathrm{GeV}^2$$

off-shell effects of intermediate pions

$$\mathrm{F}_\pi(\hat{t}) = \exp\left(\frac{\hat{t}-m_\pi^2}{\Lambda^2_{off,E}}\right), \qquad \mathrm{F}_\pi(\hat{t}) = \frac{\Lambda^2_{off,M}-m_\pi^2}{\Lambda^2_{off,M}-\hat{t}}; \qquad \mathrm{F}_\pi(m_\pi^2) = 1$$

Diffractive continuum mechanism





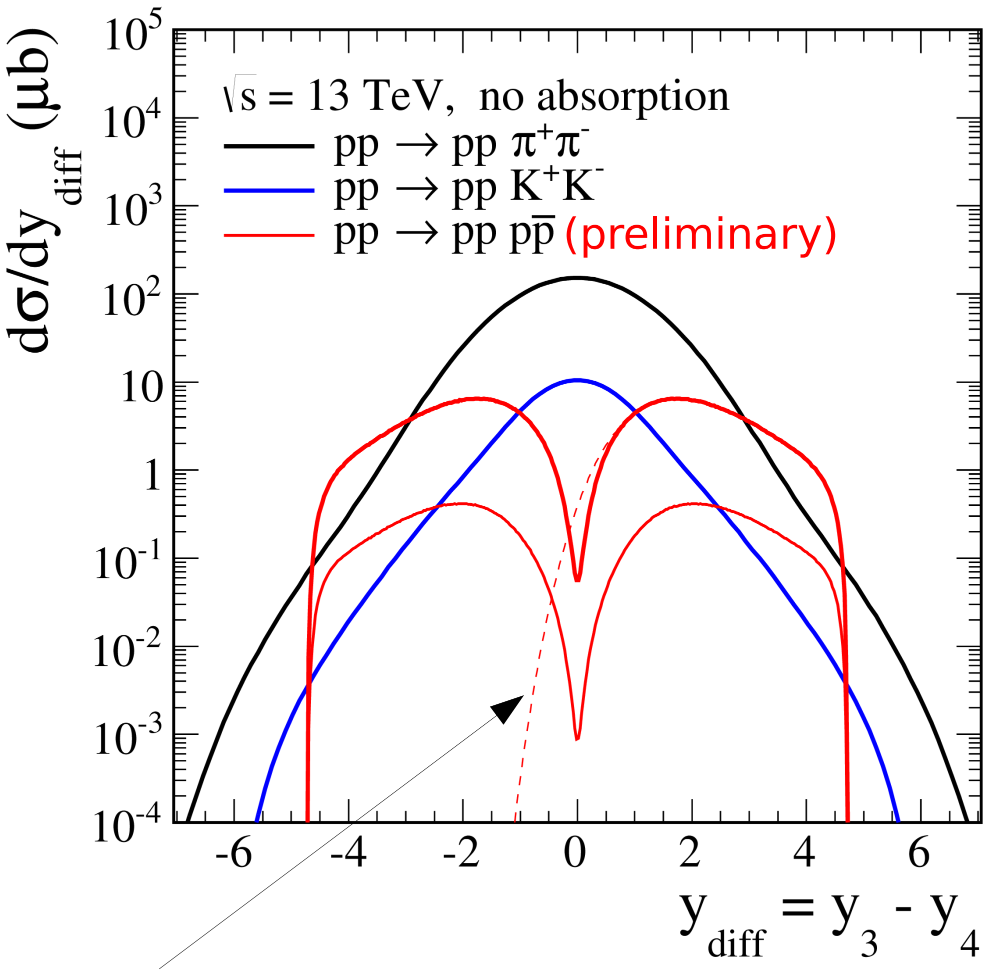
Results have been obtained for

$\Lambda^{(\pi)}_{off,E} = 1$ GeV(black lines)

$\Lambda^{(K)}_{off,E} = 1$ GeV(blue lines)

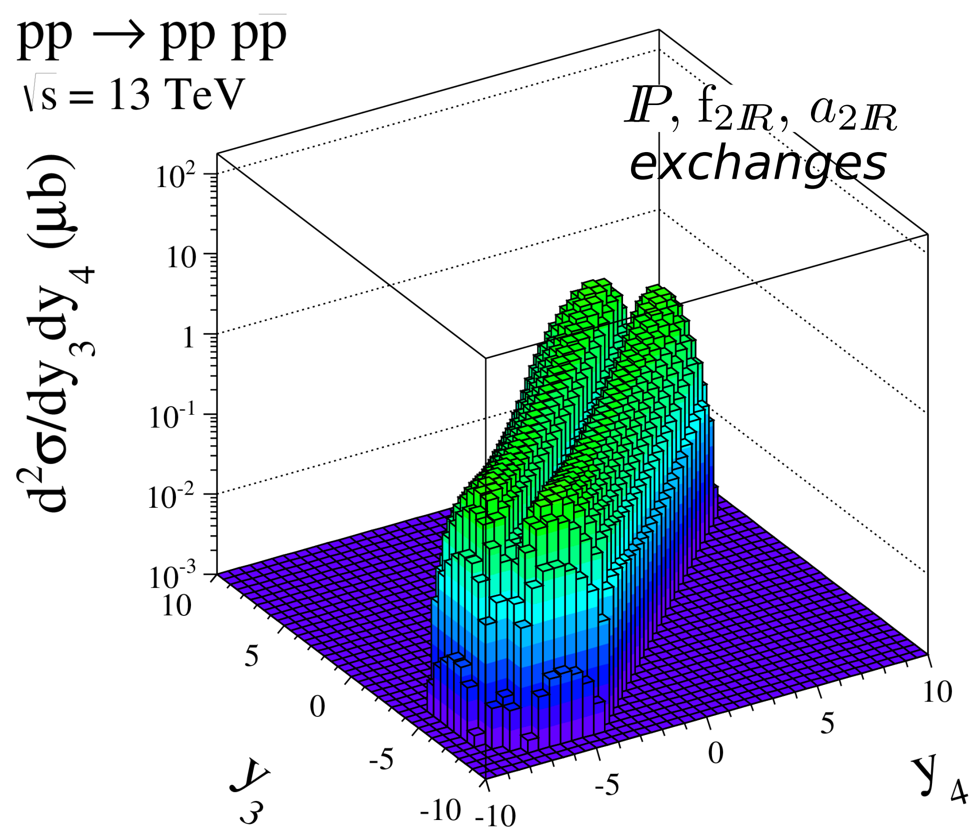
$\Lambda^{(p)}_{off,E} = 0.8$ GeV(lower red lines), 1 GeV(upper red lines)

Diffractive continuum mechanism

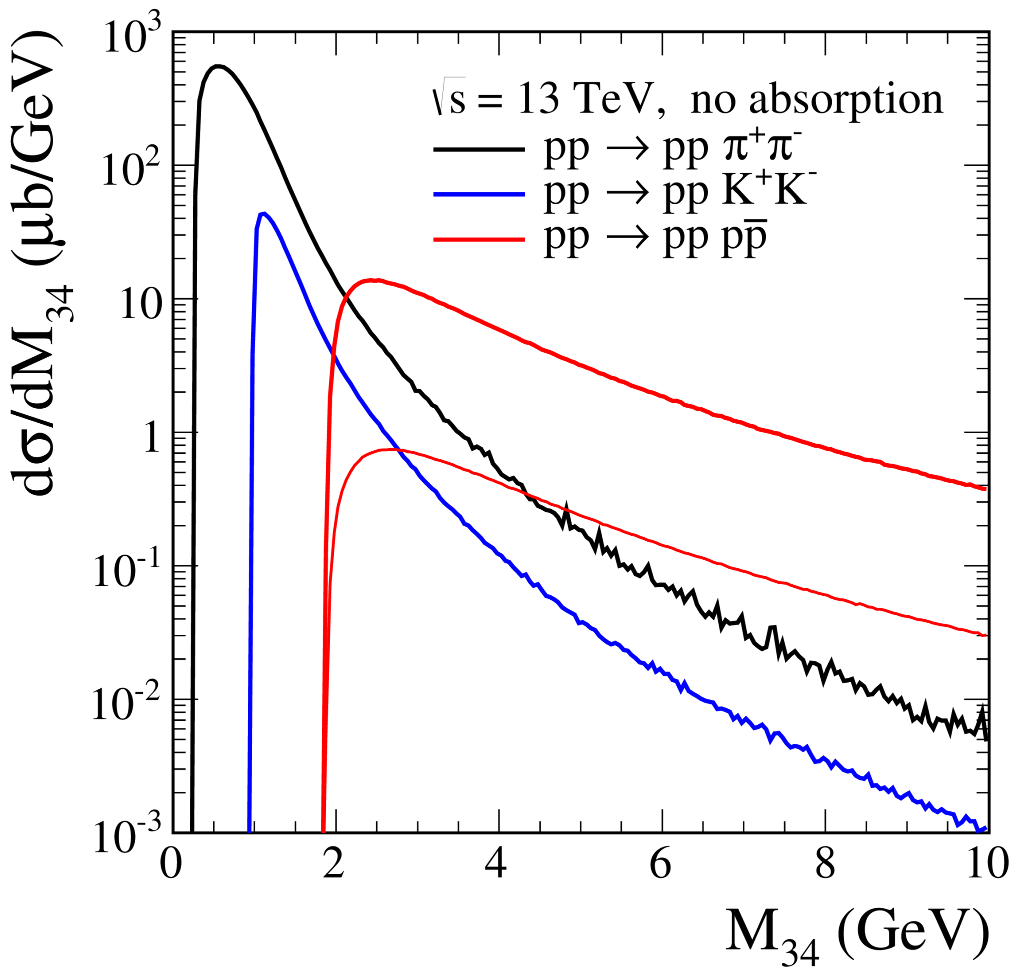


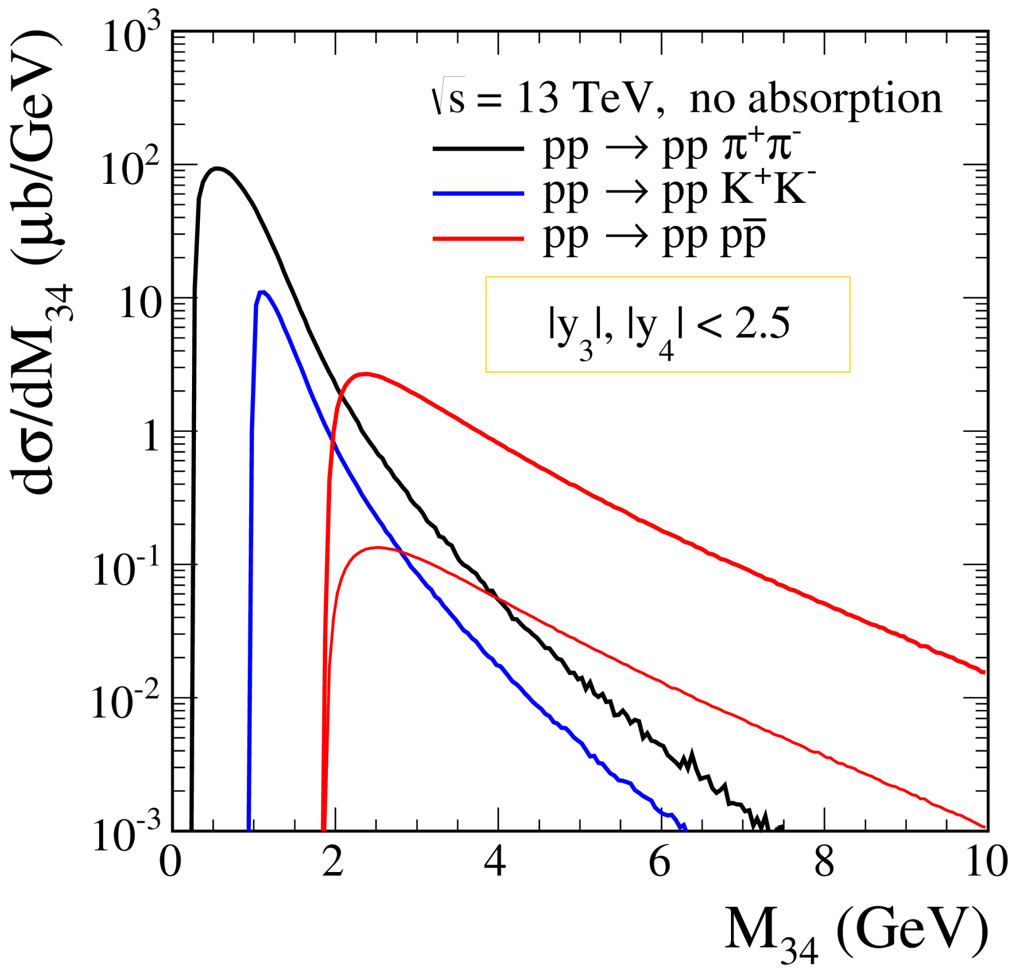
Only one diagram (t-diagram)

Interesting pattern for (y_3, y_4) distribution.



Diffractive continuum mechanism





Results have been obtained for

$\Lambda^{(\pi)}_{off,E} = 1$ GeV(black line)

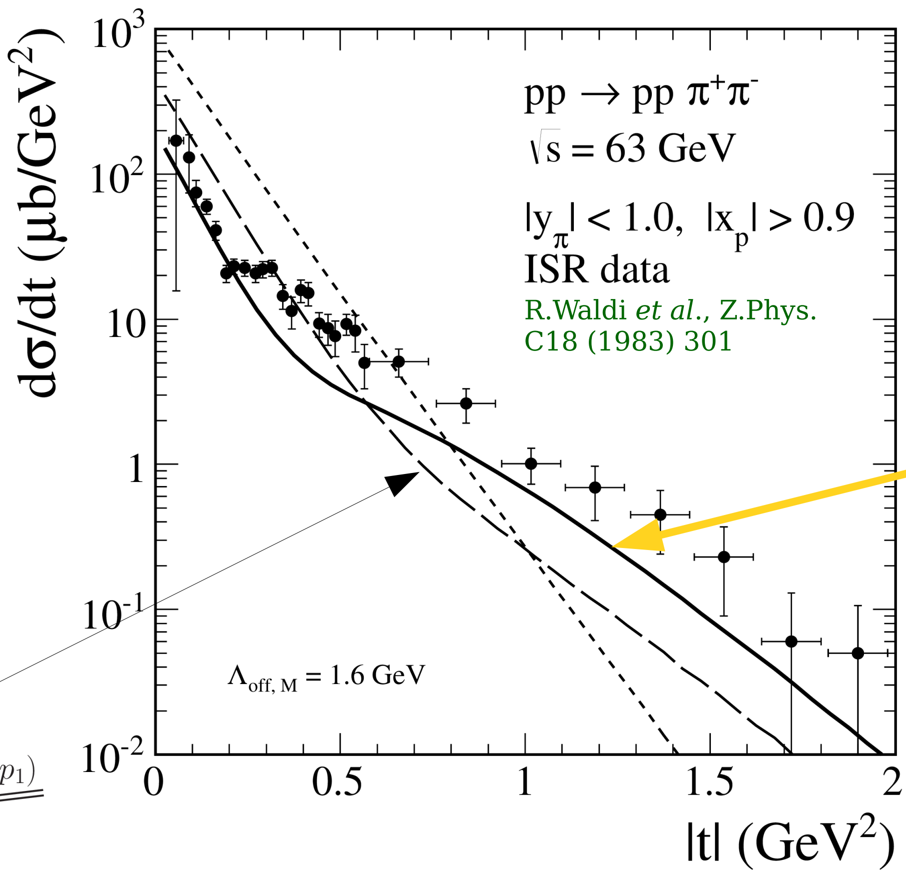
$\Lambda^{(K)}_{off,E} = 1$ GeV(blue line)

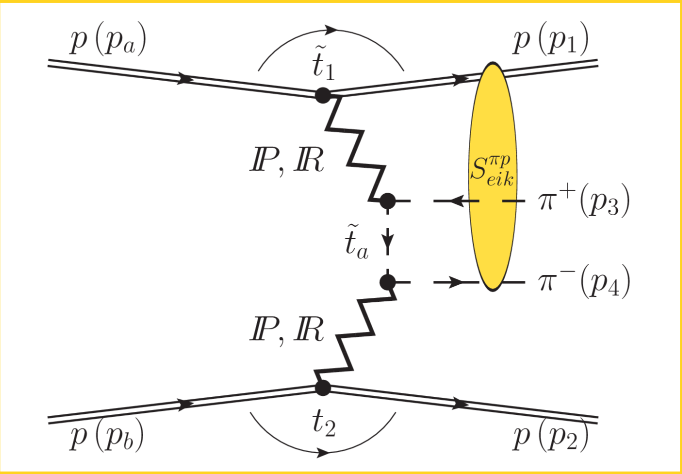
$\Lambda^{(p)}_{off,E} = 1$ GeV(upper red line), 0.8 GeV(lower red line)

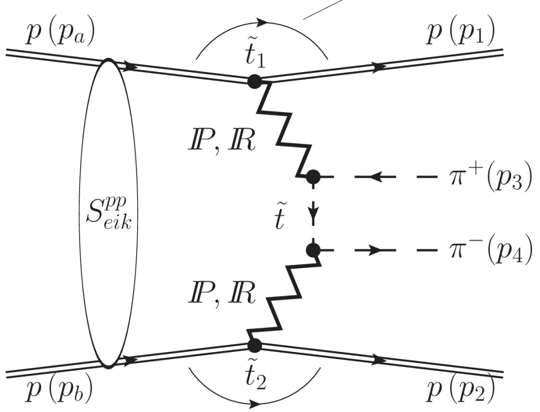
Absorption corrections; $\pi\pi$ continuum term

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

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





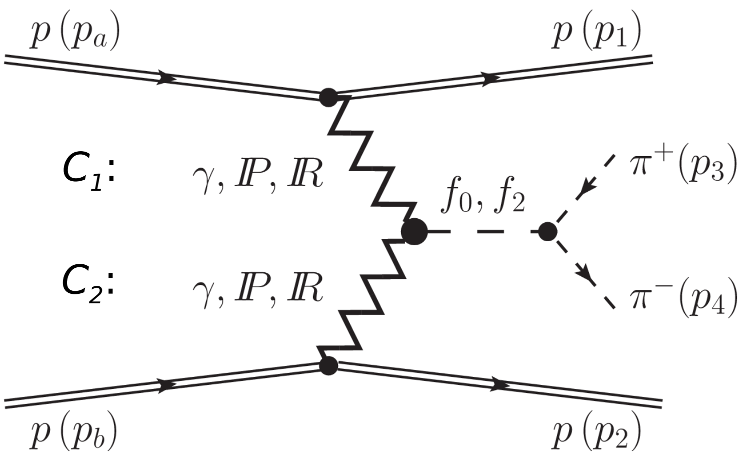


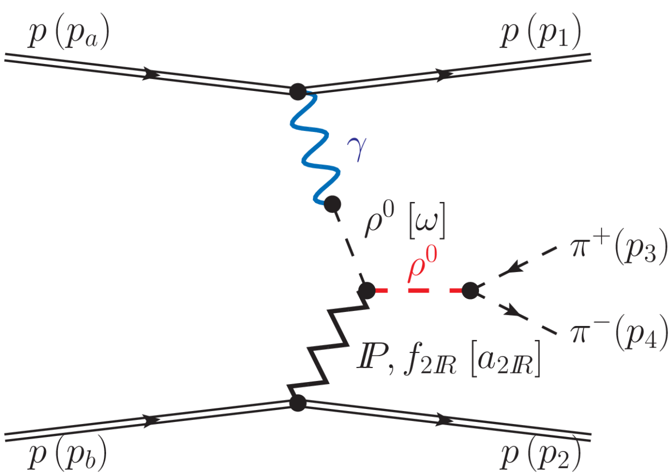
new absorption corrections (πN FSI) damping of the cross section by a factor of about 2 and give further enhancement at large |t|

see P. L., A. Szczurek, Phys. Rev. D92 (2015) 054001

Dipion resonant production

$$\mathcal{M}_{pp\to pp\pi^+\pi^-} = \mathcal{M}^{\pi\pi-\text{continuum}}_{pp\to pp\pi^+\pi^-} + \boxed{\mathcal{M}^{\pi\pi-\text{resonances}}_{pp\to pp\pi^+\pi^-}}$$



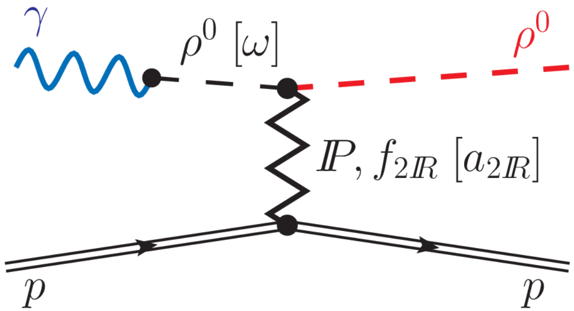


In general, many exchanges are possible in the dipion resonance production process.

$I^G J^{PC}$, resonances	(C_1, C_2) production modes
0^+0^{++}, $f_0(500)$, $f_0(980)$, $f_0(1500)$, $f_0(1370)$, $f_0(1710)$ 0^+2^{++}, $f_2(1270)$, $f_2'(1525)$, $f_2(1950)$ 0^+4^{++}, $f_4(2050)$	$\{(I\!\!P + f_{2I\!\!R}, I\!\!P + f_{2I\!\!R}), (a_{2I\!\!R}, a_{2I\!\!R}),$ $(\mathbb{O} + \omega_{I\!\!R} + \gamma, \mathbb{O} + \omega_{I\!\!R} + \gamma), (\rho_{I\!\!R}, \rho_{I\!\!R}),$ $(\gamma, \rho_{I\!\!R}), (\rho_{I\!\!R}, \gamma)\}$
1^+1^{--}, $\rho(770)$, $\rho(1450)$, $\rho(1700)$ 1^+3^{--}, $\rho_3(1690)$	$\{(\gamma + \rho_{I\!\!R}, I\!\!P + f_{2I\!\!R}), (I\!\!P + f_{2I\!\!R}, \gamma + \rho_{I\!\!R}),$ $(\mathbb{O} + \omega_{I\!\!R}, a_{2I\!\!R}), (a_{2I\!\!R}, \mathbb{O} + \omega_{I\!\!R})\}$

At high energies, we shall concentrate on the dominant (C_1, C_2) contributions:
$(I\!\!P + f_{2I\!\!R}, I\!\!P + f_{2I\!\!R})$ for purely diffractive mechanism;
$(\gamma, I\!\!P + f_{2I\!\!R})$, $(I\!\!P + f_{2I\!\!R}, \gamma)$ for photoproduction mechanism.

Photoproduction of ρ^0 meson



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

$$\times 2(p_2+p_b)^\kappa (p_2+p_b)^\lambda\,\delta_{\lambda_2\lambda_b} F_1(t) F_M(t)$$

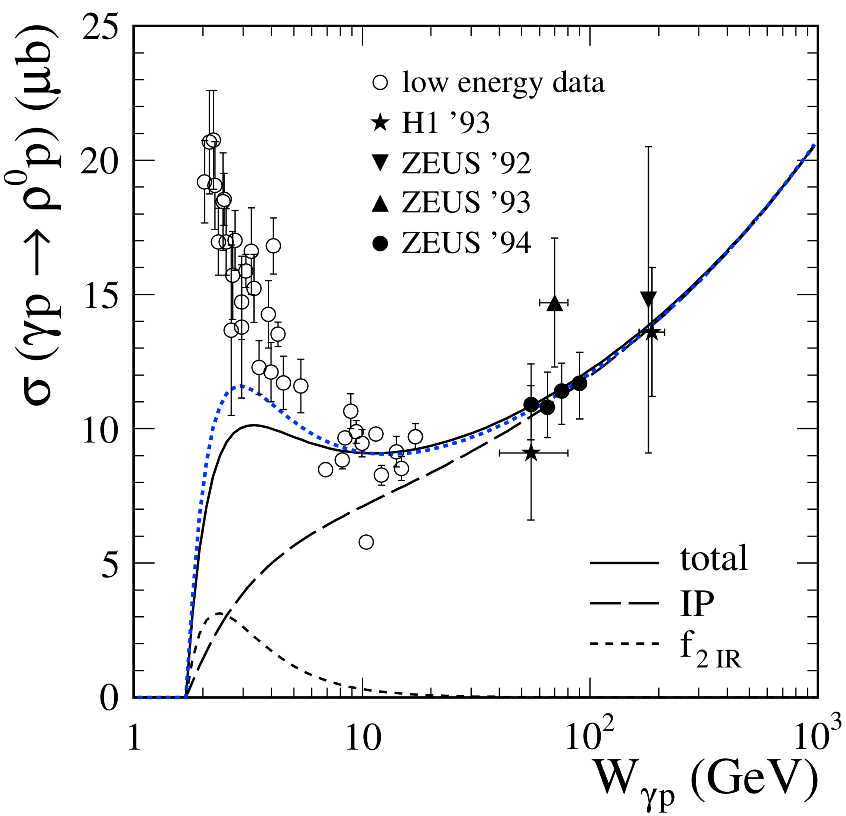
alternatively, $F_1(t)F_M(t) \to$ factorised form $F_{\rho p}^{(P/R)}(t) = \exp\left(\frac{B_{\rho p}^{(P/R)} t}{2}\right)$

(see the blue dotted line)

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

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

tensorial functions: *C. Ewerz, M. Maniatis and O. Nachtmann, Ann. Phys. 342 (2014) 31*



The coupling constants *IP/IR-ρ-ρ* have been estimated from parametrization of total cross sections for *πp* scattering assuming

$$\sigma_{tot}(\rho^0(\lambda_\rho=\pm1),p) = \tfrac{1}{2}\left[\sigma_{tot}(\pi^+,p)+\sigma_{tot}(\pi^-,p)\right]$$

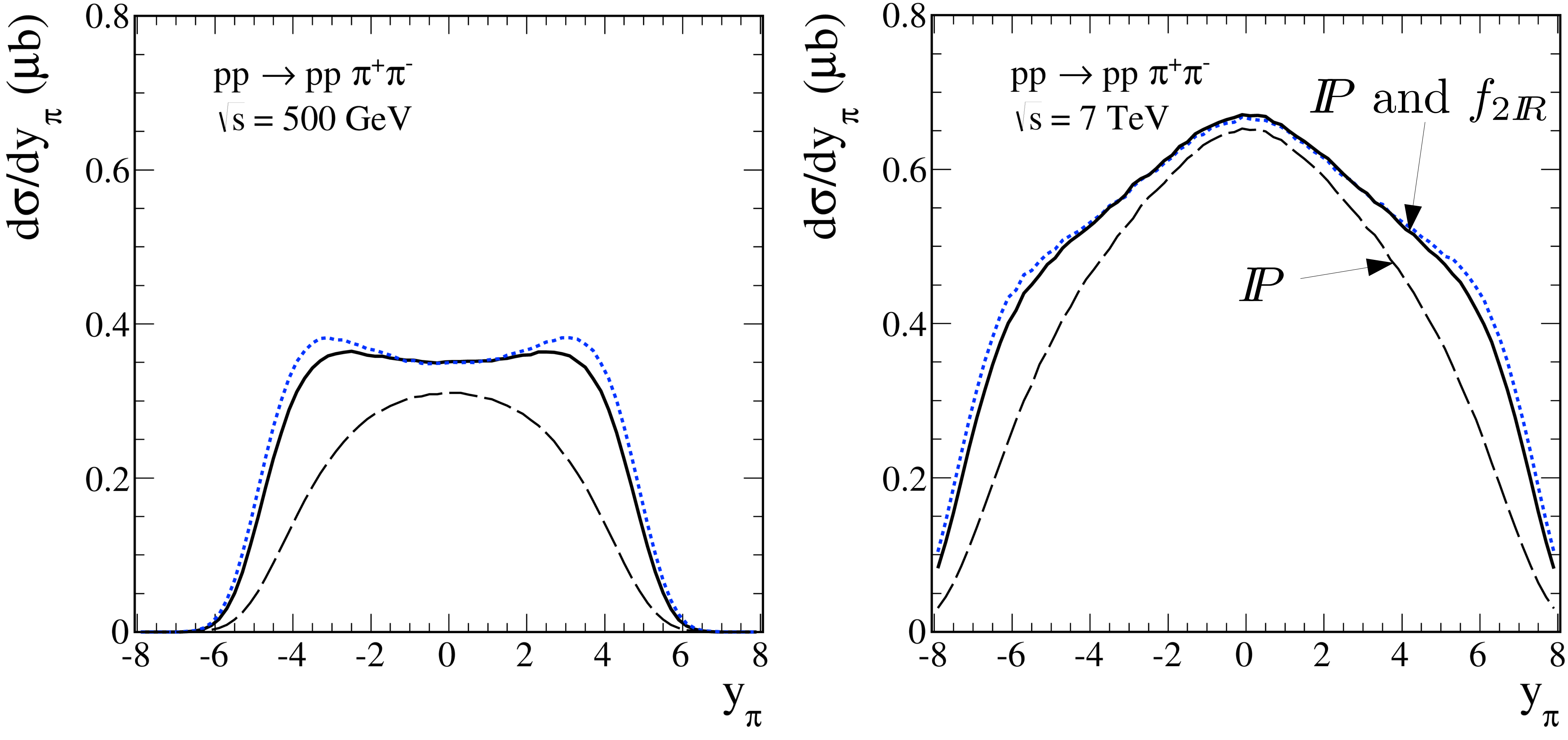
and are expected to approximately fulfill:

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

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

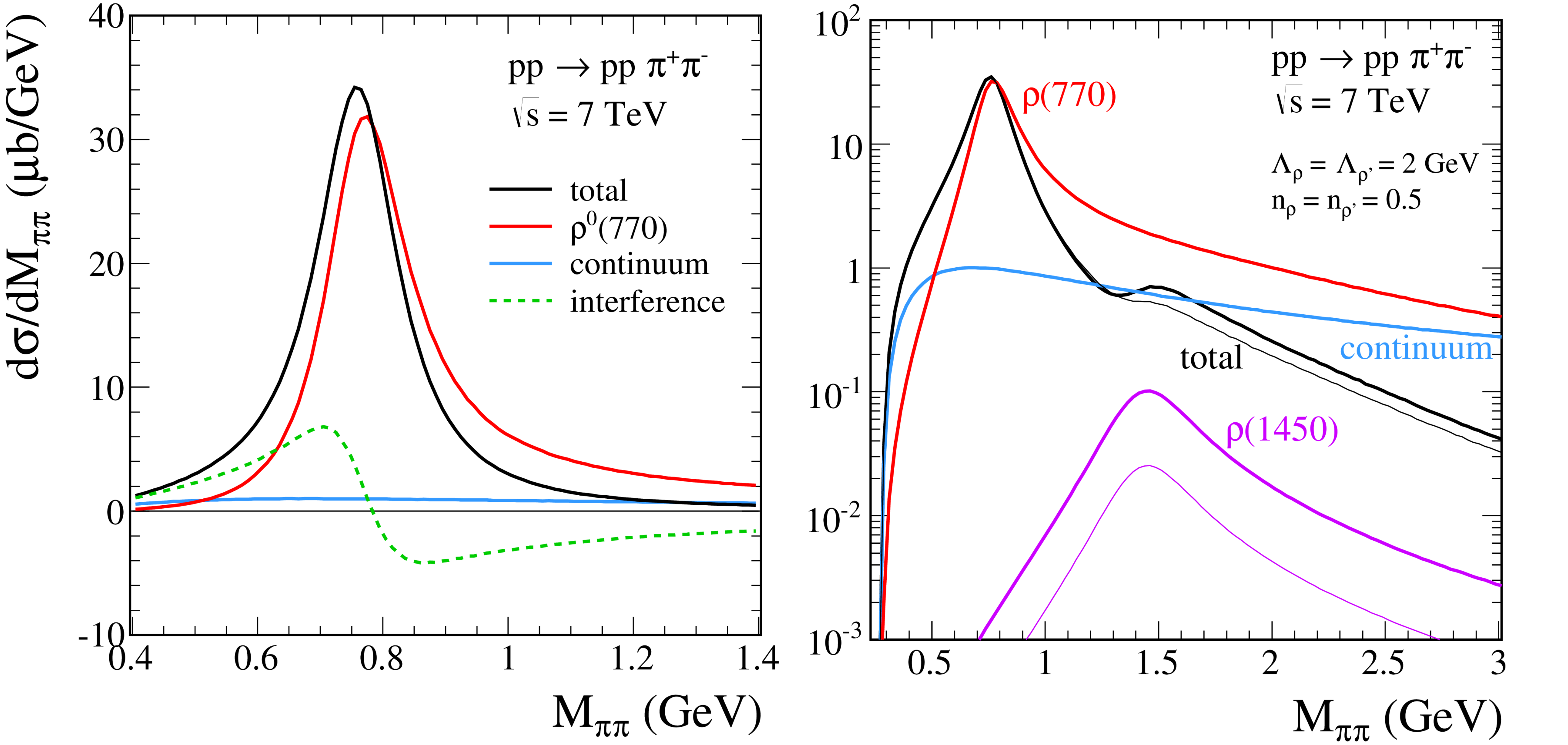
$$M_0 = 1\ \mathrm{GeV}$$

Photoproduction mechanism: ρ^0 and $\pi^+\pi^-$ continuum



The f2 reggeon exchange included in the amplitude contributes mainly at backward and forward pion rapidities. Its contribution is non-negligible even at the LHC.

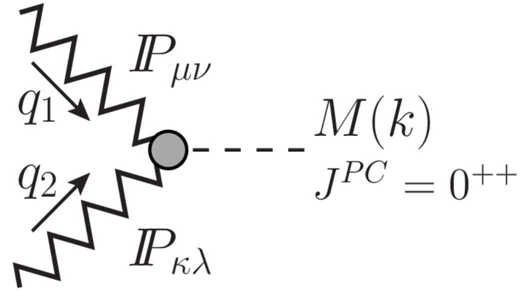
Photoproduction mechanism: ρ^0 and $\pi^+\pi^-$ continuum



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

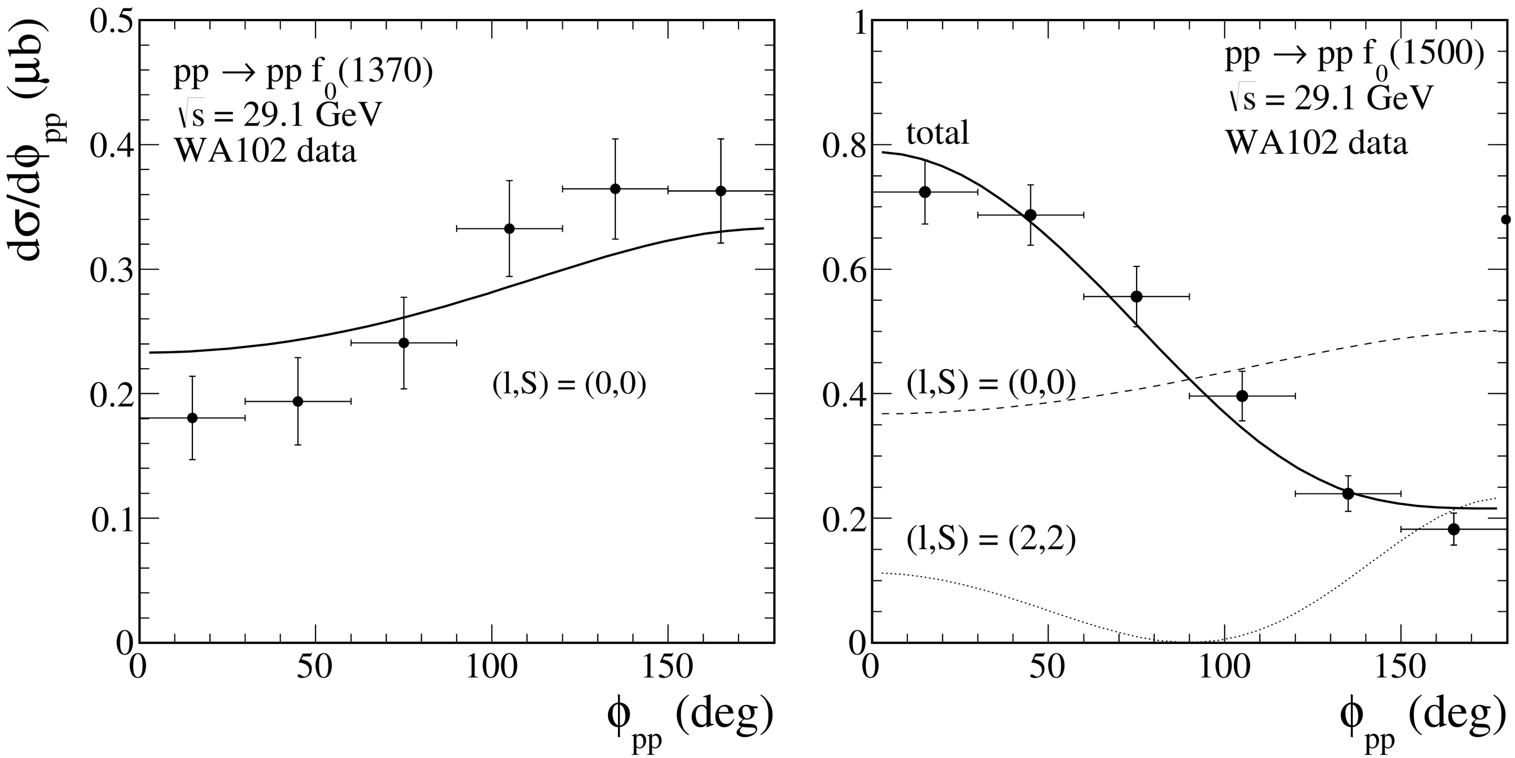
Diffractive mechanism: scalar resonances

For a scalar mesons the "bare" tensorial *IP-IP-M* vertices corresponding to (l,S) = (0,0) and (2,2) terms are



$$i\Gamma'^{(\mathbb{P}\mathbb{P}\to M)}_{\mu\nu,\kappa\lambda} = i\, g'_{\mathbb{P}\mathbb{P}M}\, M_0 \left(g_{\mu\kappa} g_{\nu\lambda} + g_{\mu\lambda} g_{\nu\kappa} - \frac{1}{2} g_{\mu\nu} g_{\kappa\lambda} \right)$$

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



$f_0(1370)$ peaks as $\phi_{pp} \to \pi$

$f_0(980)$, $f_0(1500)$, $f_0(1710)$ peak at $\phi_{pp} \to 0$

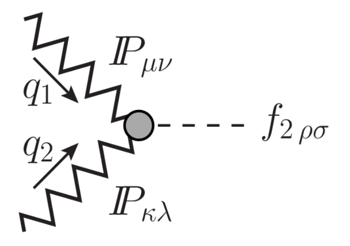
Our results and WA102 data have been normalized to the mean value of the total cross section given by A. Kirk, Phys. Lett. B489 (2000) 29.

In most cases one has to add coherently amplitudes for two lowest (l, S) couplings.

Diffractive mechanism: $f_2(1270)$

The amplitude for the process $pp \to pp\,(f_2 \to \pi^+\pi^-)$ via $I\!P I\!P$ fusion:

$$\mathcal{M}^{(I\!P I\!P \to f_2 \to \pi^+\pi^-)}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^+\pi^-} = (-i)\,\bar{u}(p_1,\lambda_1) i\Gamma^{(I\!P pp)}_{\mu_1\nu_1}(p_1,p_a) u(p_a,\lambda_a)\; i\Delta^{(I\!P)\,\mu_1\nu_1,\alpha_1\beta_1}(s_1,t_1)$$
$$\times\, i\Gamma^{(I\!P I\!P f_2)}_{\alpha_1\beta_1,\alpha_2\beta_2,\rho\sigma}(q_1,q_2)\; i\Delta^{(f_2)\,\rho\sigma,\alpha\beta}(p_{34})\; i\Gamma^{(f_2\pi\pi)}_{\alpha\beta}(p_3,p_4)$$
$$\times\, i\Delta^{(I\!P)\,\alpha_2\beta_2,\mu_2\nu_2}(s_2,t_2)\; \bar{u}(p_2,\lambda_2) i\Gamma^{(I\!P pp)}_{\mu_2\nu_2}(p_2,p_b) u(p_b,\lambda_b)\,,$$



$$i\Gamma^{(I\!P I\!P f_2)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = \left(i\Gamma^{(I\!P I\!P f_2)(1)}_{\mu\nu,\kappa\lambda,\rho\sigma}\,|_{bare} + \sum_{j=2}^{7} i\Gamma^{(I\!P I\!P f_2)(j)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2)\,|_{bare} \right) \tilde{F}^{(I\!P I\!P f_2)}(q_1^2,q_2^2,p_{34}^2)\,.$$

Here $p_{34} = q_1 + q_2$ and the form factor $\tilde{F}^{(I\!P I\!P f_2)} = F_M(q_1^2) F_M(q_2^2) F^{(I\!P I\!P f_2)}(p_{34}^2)$.

$$i\Delta^{(f_2)}_{\mu\nu,\kappa\lambda}(p_{34}) = \frac{i}{p_{34}^2 - m_{f_2}^2 + i m_{f_2}\Gamma_{f_2}} \left[\frac{1}{2}(\hat{g}_{\mu\kappa}\hat{g}_{\nu\lambda} + \hat{g}_{\mu\lambda}\hat{g}_{\nu\kappa}) - \frac{1}{3}\hat{g}_{\mu\nu}\hat{g}_{\kappa\lambda} \right],$$

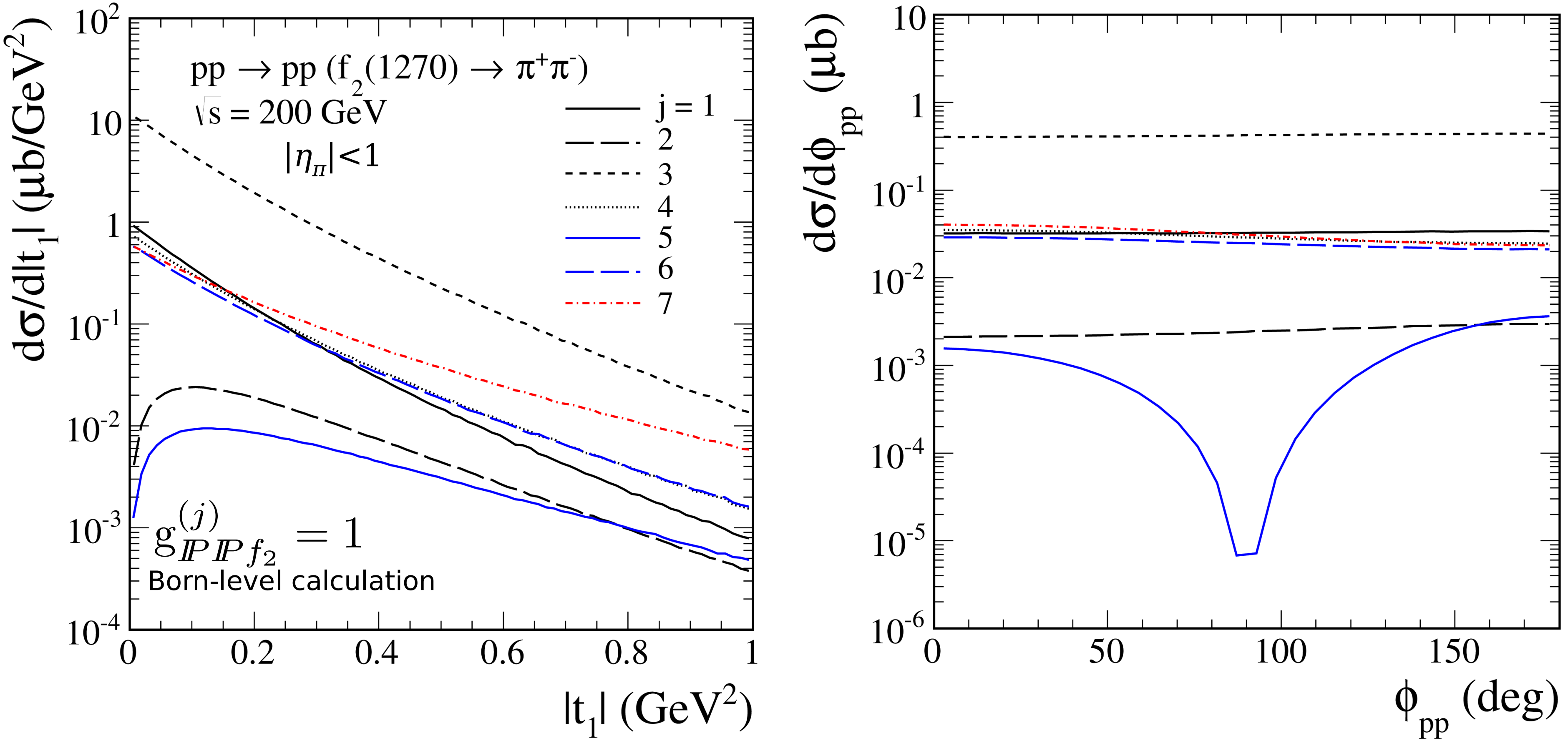
where $\hat{g}_{\mu\nu} = -g_{\mu\nu} + p_{34\mu}p_{34\nu}/p_{34}^2$ and $\Delta^{(f_2)}_{\nu\mu,\kappa\lambda}(p_{34}) = \Delta^{(f_2)}_{\mu\nu,\lambda\kappa}(p_{34}) = \Delta^{(f_2)}_{\kappa\lambda,\mu\nu}(p_{34})$, $\quad g^{\kappa\lambda}\Delta^{(f_2)}_{\mu\nu,\kappa\lambda}(p_{34}) = 0$.

$$i\Gamma^{(f_2\pi\pi)}_{\mu\nu}(p_3,p_4) = -i\,\frac{g_{f_2\pi\pi}}{2M_0} \left[(p_3-p_4)_\mu (p_3-p_4)_\nu - \frac{1}{4} g_{\mu\nu}(p_3-p_4)^2 \right] F^{(f_2\pi\pi)}(p_{34}^2)\,,$$

where $g_{f_2\pi\pi} = 9.26$ was obtained from the corresponding partial decay width.

We assume that $F^{(f_2\pi\pi)}(p_{34}^2) = F^{(I\!P I\!P f_2)}(p_{34}^2) = \exp\left(\frac{-(p_{34}^2 - m_{f_2}^2)^2}{\Lambda_{f_2}^4} \right)$, $\Lambda_{f_2} = 1$ GeV.

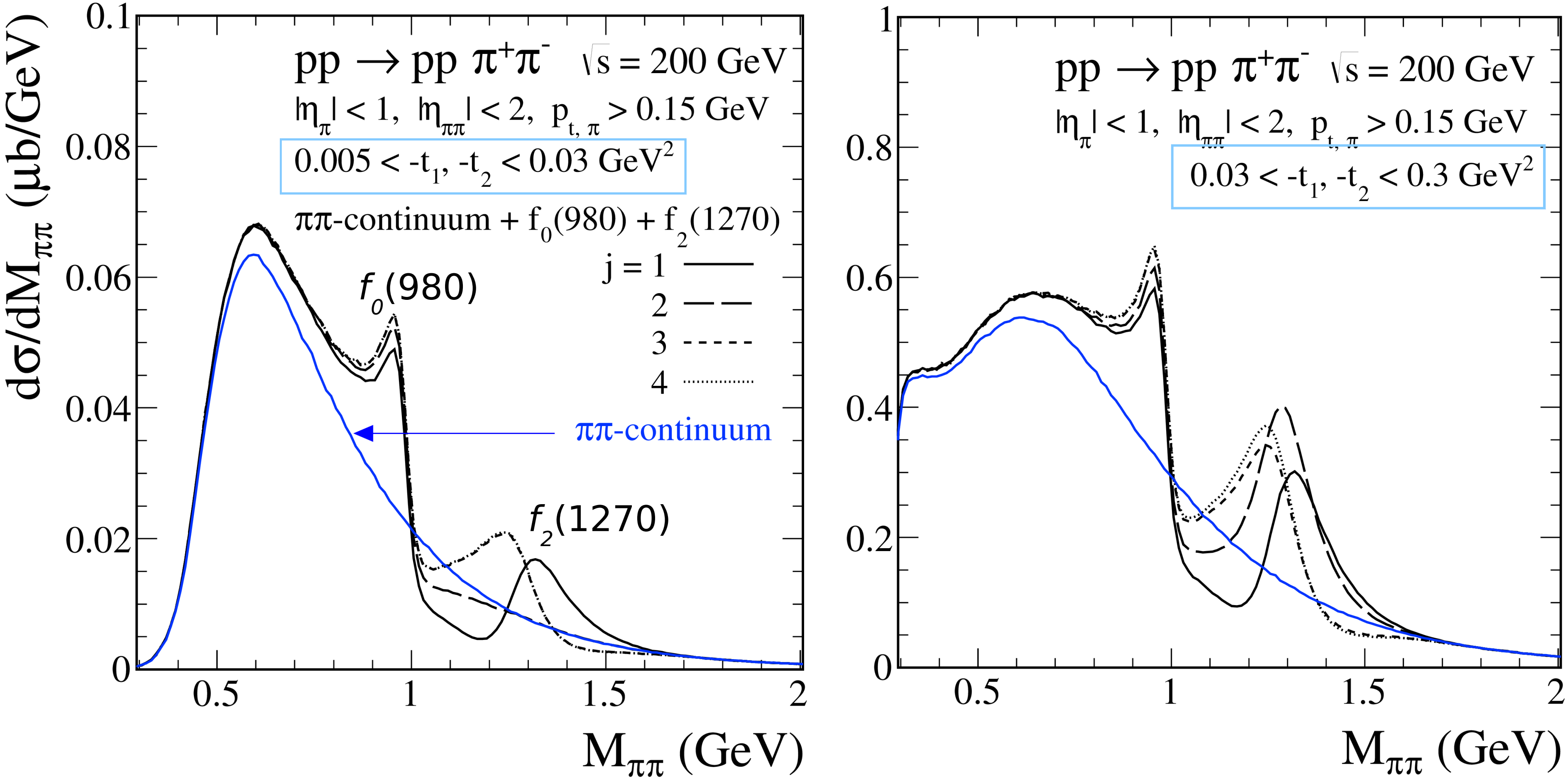
Diffractive mechanism: tensor resonance



We can associate the couplings j = 1, …, 7 with the following (l,S) values:
(0,2), (2,0) – (2,2), (2,0) + (2,2), (2,4), (4,2), (4,4), (6,4), respectively.

j = 2 coupling is in agreement with experimental observations (WA102, COMPASS, ISR)
→ f_2(1270) peaks at ϕ_{pp}~180^o and is most prominently observed at large |t|

Diffractive mechanism: tensor resonance

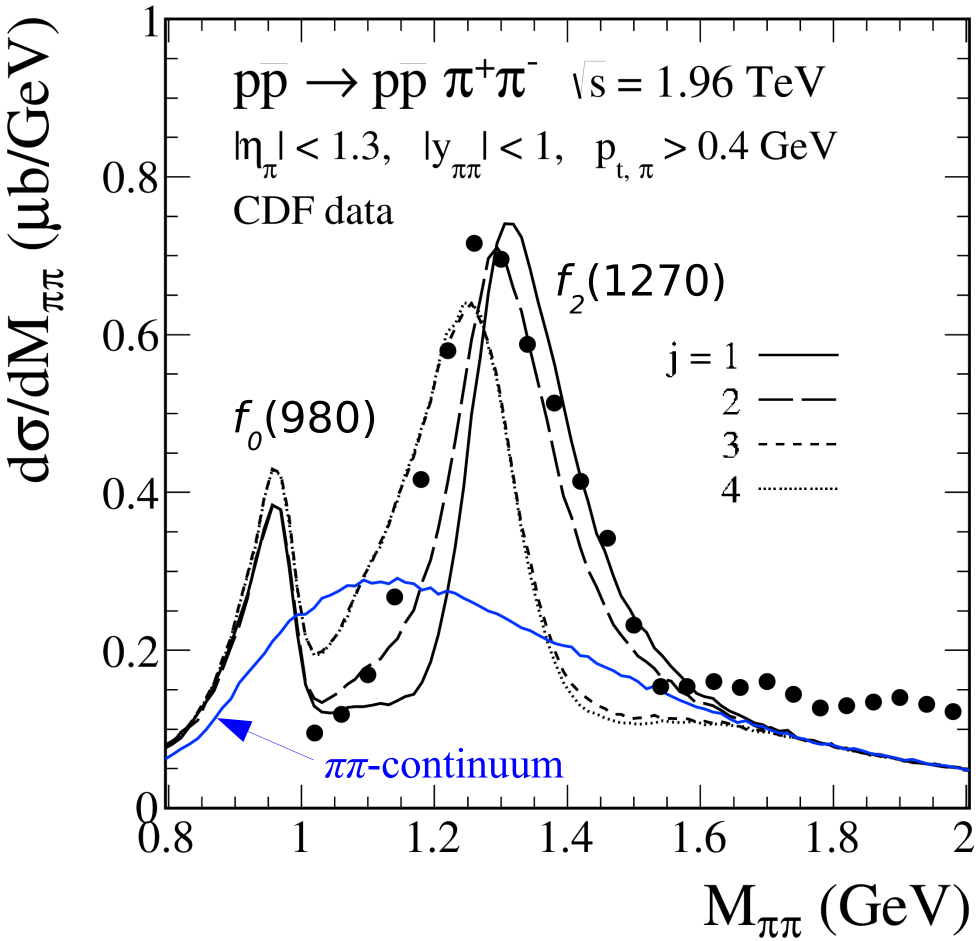


Different couplings generate different interference pattern. The relative contribution of the resonant $f_2(1270)$ and dipion continuum strongly depends on the cut on $|t|$

→ this may explain some controversial observation made by the ISR groups (AFS, ABCDHW).

Absorption effects were included effectively: $\frac{d\sigma^{Born}}{dM_{\pi\pi}} \times < S^2 > , \quad < S^2 > \simeq 0.2$

Comparison with CDF data



CDF data: T. A. Aaltonen et al., (CDF Collaboration), Phys.Rev. D91 (2015) 091101.

Events with two oppositely charged particles, assumed to be pions, and no other particles detected in $|\eta| < 5.9$.

(no proton tagging → rapidity gap method)

The visible structure attributed to f_0 and $f_2(1270)$ mesons which interfere with the continuum.

We assume that the peak in the region 1.2 – 1.4 GeV corresponds mainly to the $f_2(1270)$ resonance.
We have adjusted the j = 1,..,4 couplings to get the same cross section in the region 1.0 – 1.4 GeV.

There may also be a contribution from $f_0(1370)$, $f_0(1500)$, and $f_0(1710)$.

For CDF conditions, the f_2-to-background ratio is about a factor of 2.

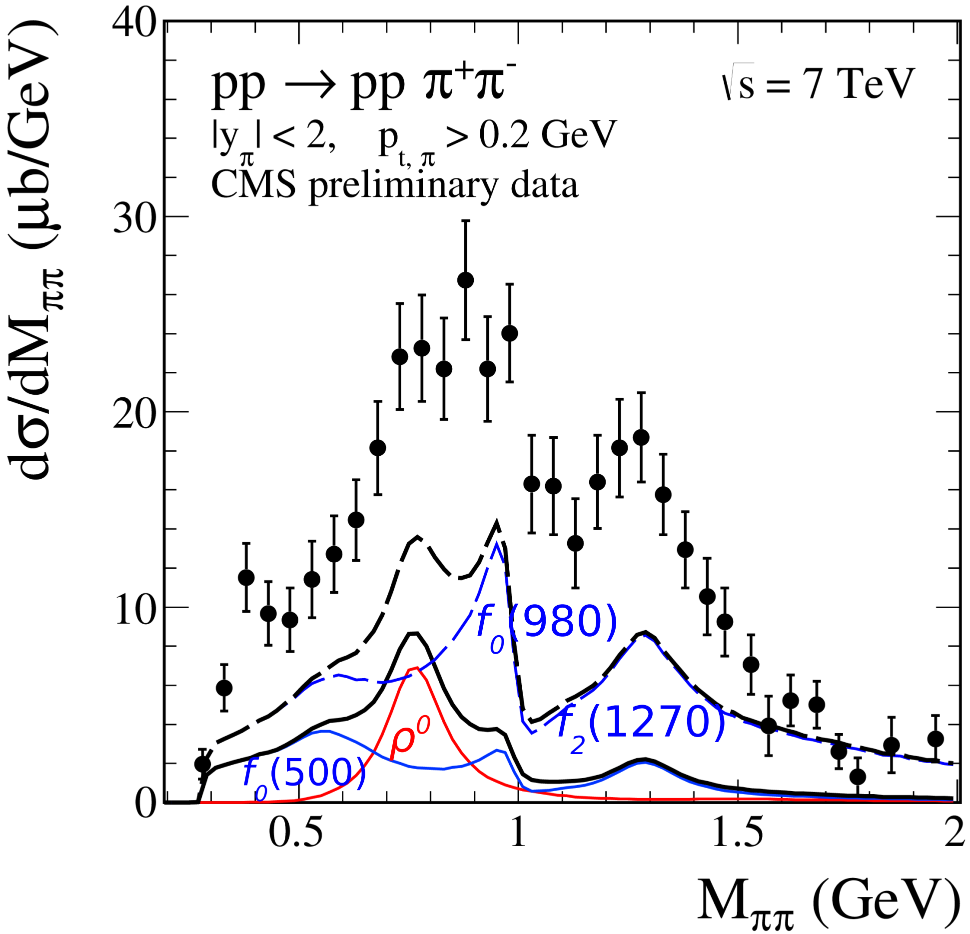
We take the monopole form for off-shell pion form factors with $\Lambda_{off,M}$ = 0.7 GeV.

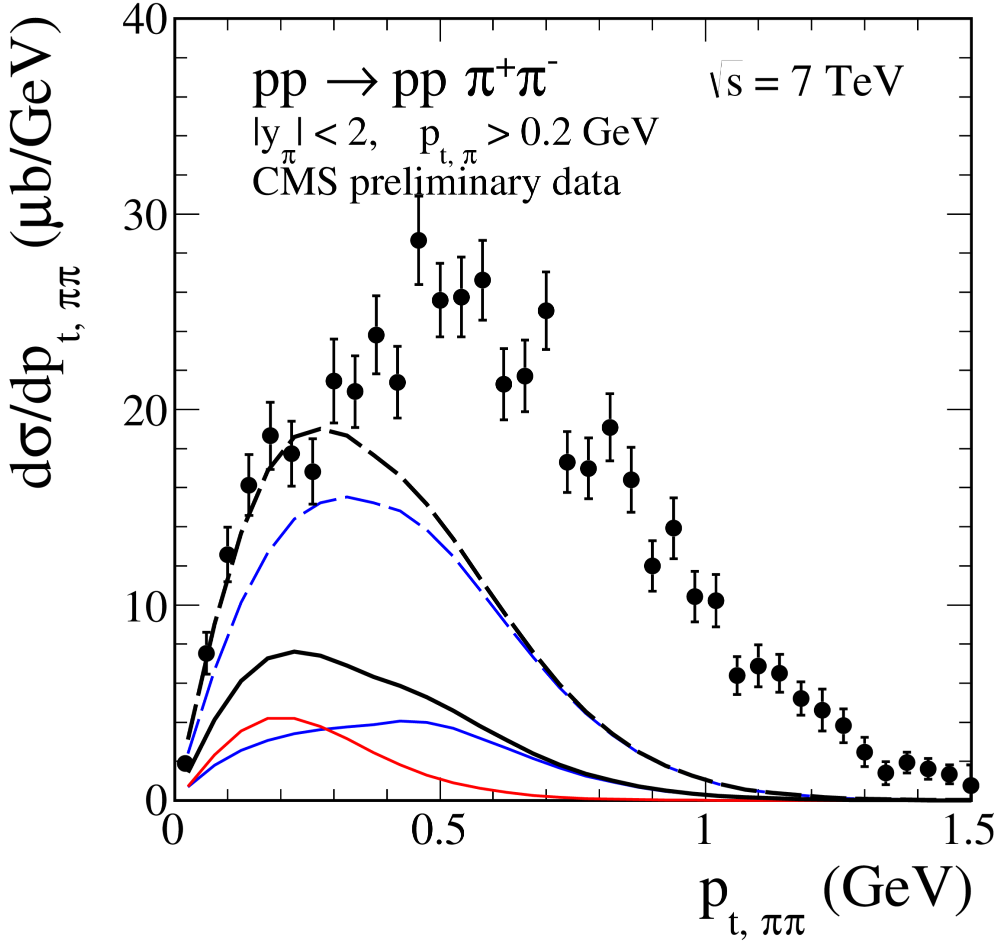
Absorption effects were included effectively:

$$\frac{d\sigma^{Born}}{dM_{\pi\pi}} \times < S^2 >$$

$< S^2 > \simeq 0.1$
ratio of full (absorbed)-to-Born cross section

Comparison with CMS preliminary data





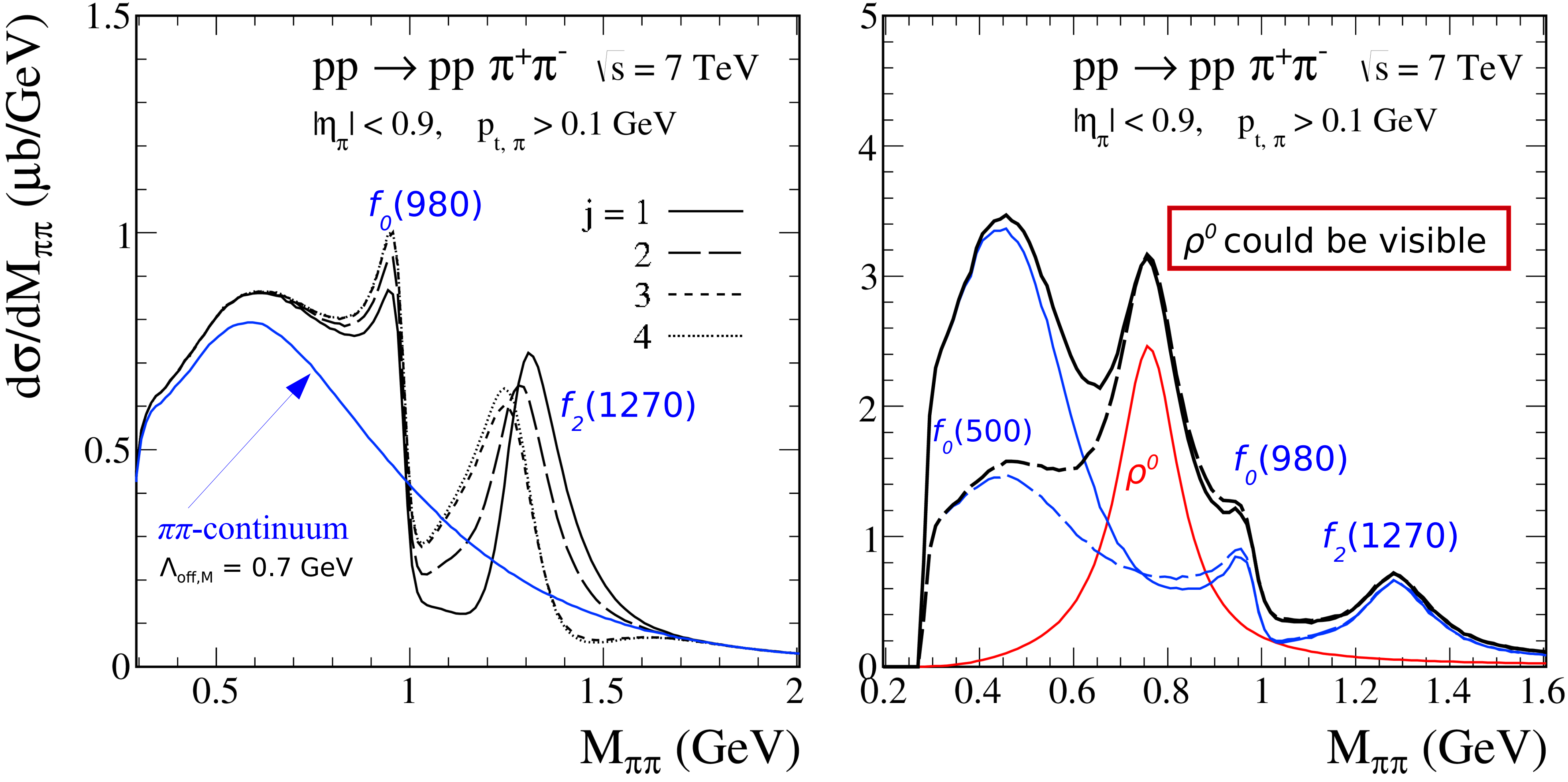
In diff. continuum term: (solid blue line) $\Lambda_{off,M}$ = 0.7 GeV (the same couplings as for CDF predictions)
(dashed blue line) $\Lambda_{off,M}$ = 1.2 GeV, and enhanced *f0*(980) and *f2* couplings

Our model results are much below the CMS preliminary data (CMS-PAS-FSQ-12-004) which could be due to a contamination of non-exclusive processes (one or both protons undergoing dissociation).

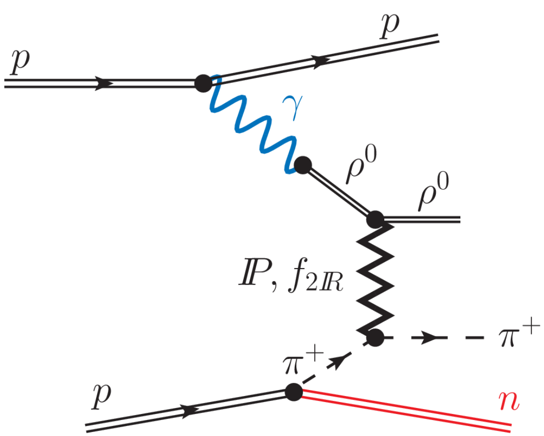
$< S^2 > \simeq 0.1$ for the diffractive contribution
$< S^2 > \simeq 0.9$ for the photon-IP/IR contribution

ρ^0 could be visible

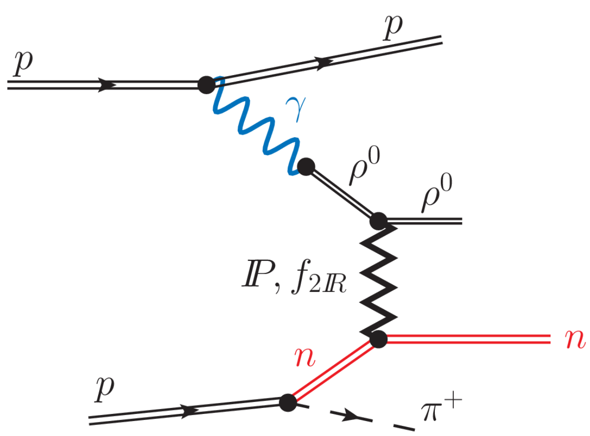
Predictions for ALICE



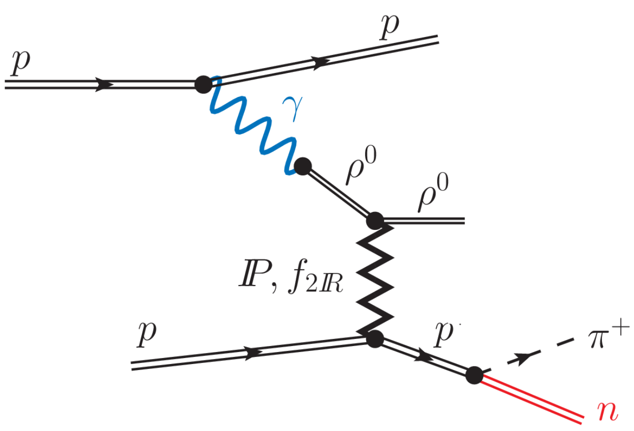
$pp \to pn\rho^0\pi^+$



pion exchange



neutron exchange

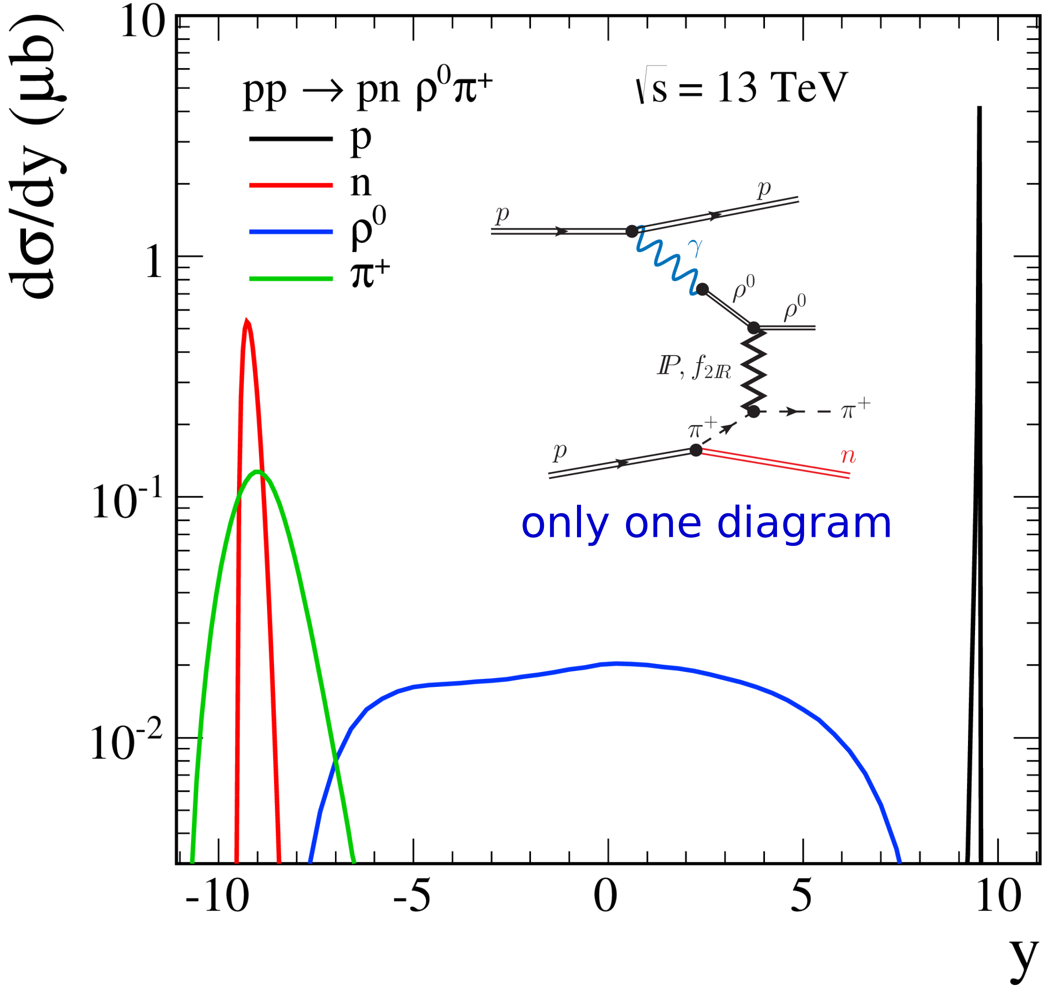


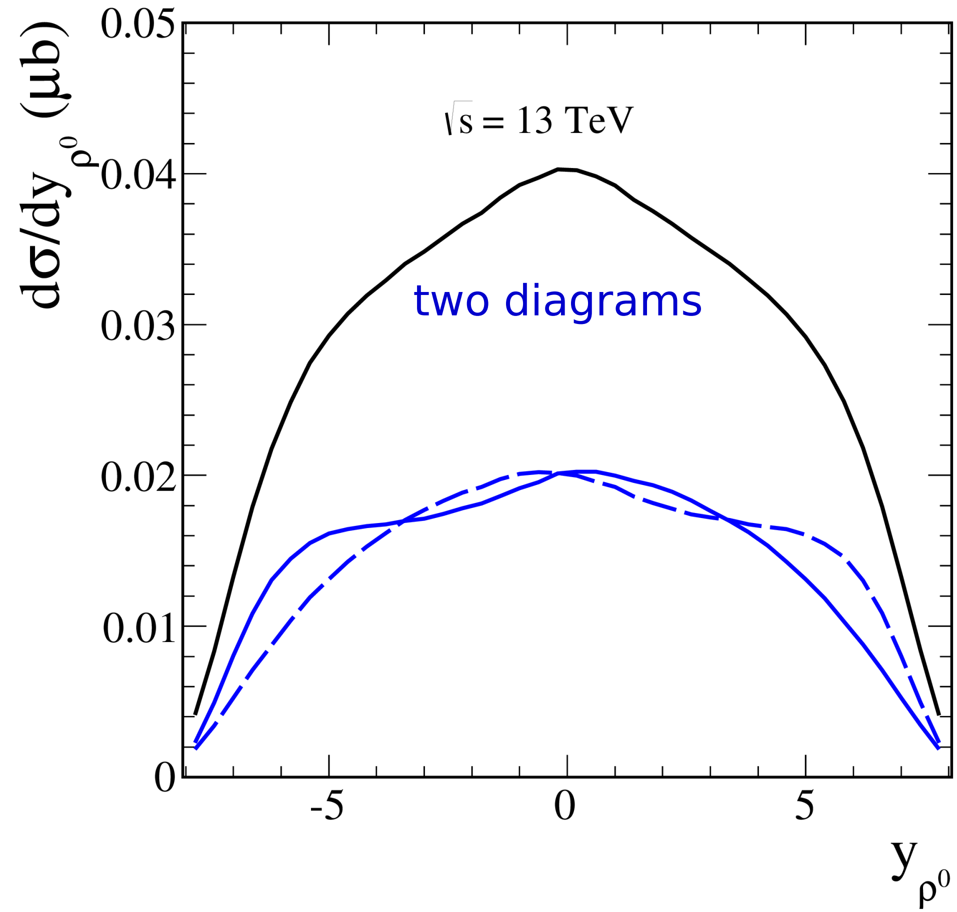
direct production

- Motivated by the study of diffractive π^0-strahlung in $pp \to pp\pi^0$ process (Drell-Hiida-Deck model) we consider here only contributions related to the diffractive $p \to \pi N$ transition.
  At large s and small $|t|$ in p-n vertex the pion exchange contribution dominates.
  see P. L., A. Szczurek, Phys. Rev. D87 (2013) 074037
- There are also resonance contributions due to diffractive excitation of resonances, N^* states, and their subsequent decays into the πN channel.
  see L. Jenkovszky. et al., Phys. Atom. Nucl. 77, Phys. Rev. D83 (2011) 056014
- The $pp \to pN\rho^0\pi$ processes constitutes inelastic (non-exclusive) background to the $pp \to pp\rho^0$ reaction in the case when final state protons are not measured and only rapidity gap conditions are checked experimentally.
- The $pp \to pn\rho^0\pi^+$ reaction was discussed in the dipole saturation-inspired approach
  V.P. Goncalves *et al.*, Phys. Rev. D94 (2016) 014009

$pp \to pn\rho^0\pi^+$

We have estimated first predictions within the tensor pomeron framework.
We take into account only diagram with the pion exchange.
No absorption effects were included.

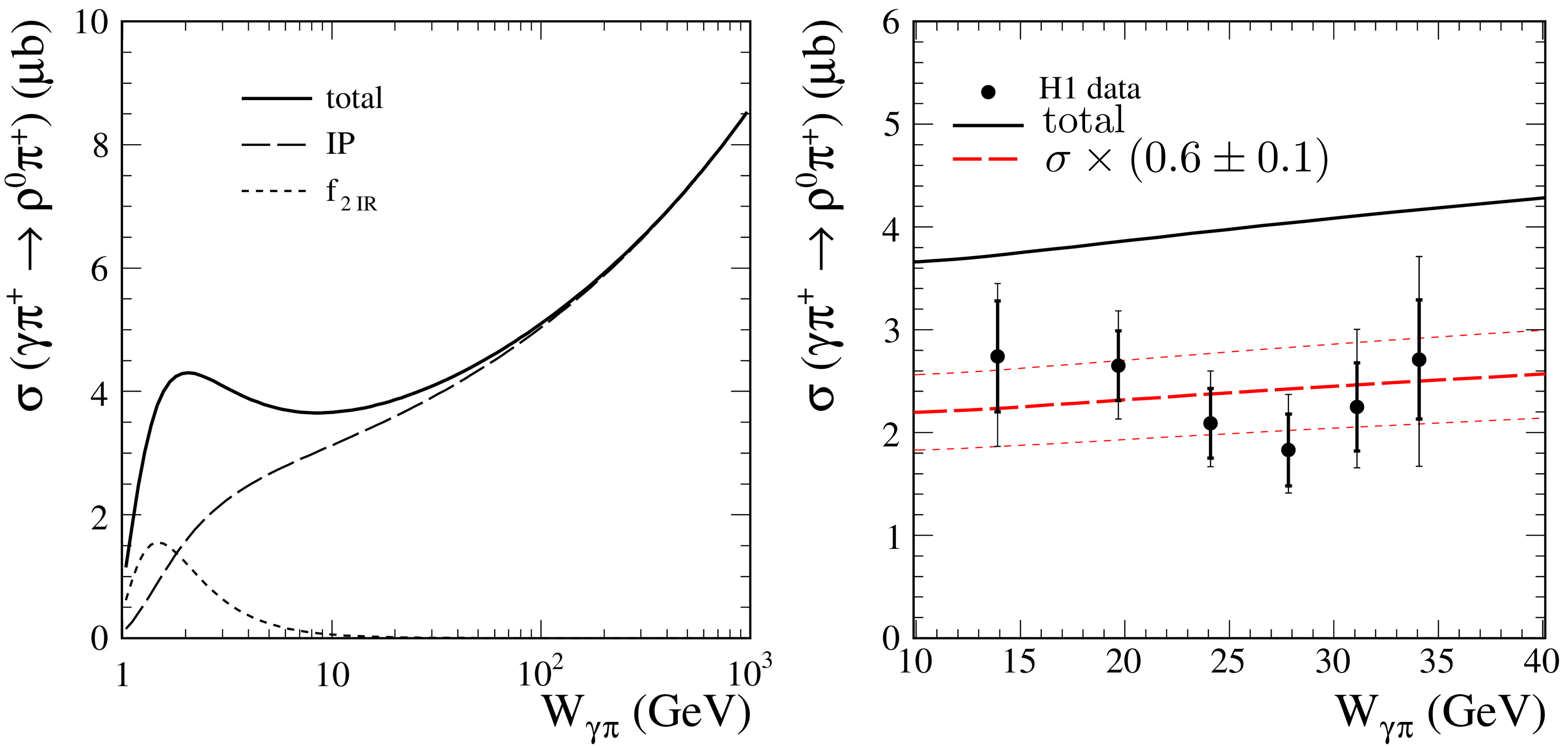




Due to specificity of the reaction the corresponding amplitudes do not interfere as some of the particles in the final state are emitted in different hemispheres (exclusively forward or backward) for the two amplitudes (mechanisms).

$\gamma\pi^+ \to \rho^0\pi^+$

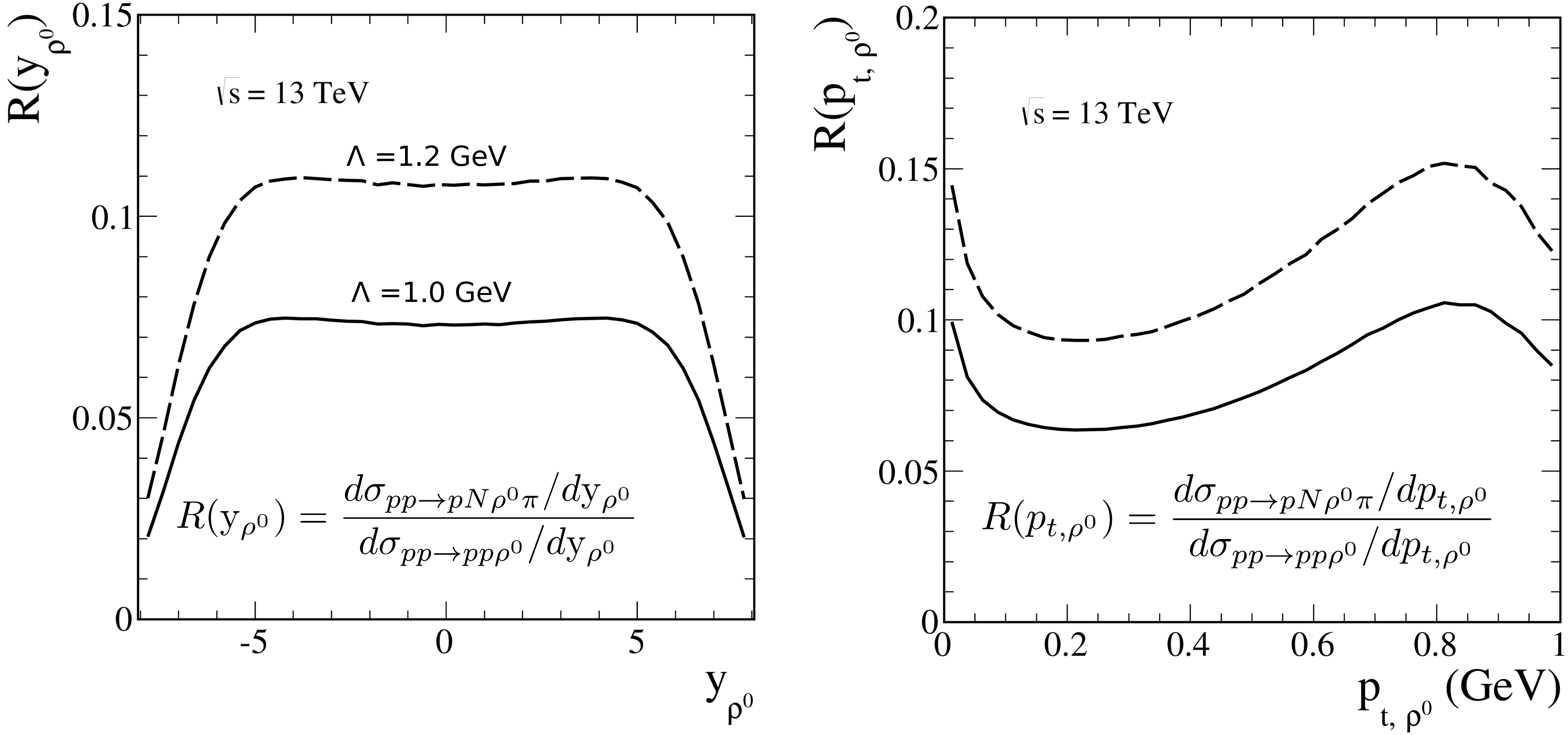
- The $\gamma p \to \rho^0 n\pi^+$ process was studied recently at HERA
  V. Andreev *et al.* (H1 Collaboration), Eur. Phys. J C76 (2016) 41
  (see talk by Jan Olsson)



- From a measurement of $pp \to pN\rho^0\pi$ one would be able to extract the cross section, total and differential, for $\gamma\pi \to \rho^0\pi$.

  For the LHC one could cover a much broader range of *W_{γπ}* but the experimental extraction of the $\gamma\pi \to \rho^0\pi$ cross sections is certainly not easy.

How large are discussed "inelastic" processes $pp \to pn\rho^0\pi^+$ and $pp \to pp\rho^0\pi^0$ compared to "elastic" $pp \to pp\rho^0$ process ?



- the ratio of integrated cross sections

$$\sigma_{inel}/\sigma_{el} \approx (3/2 \times 0.46\,\mu b)/10.32\,\mu b \approx 0.07 \quad \text{for } \Lambda = 1 \text{ GeV}$$

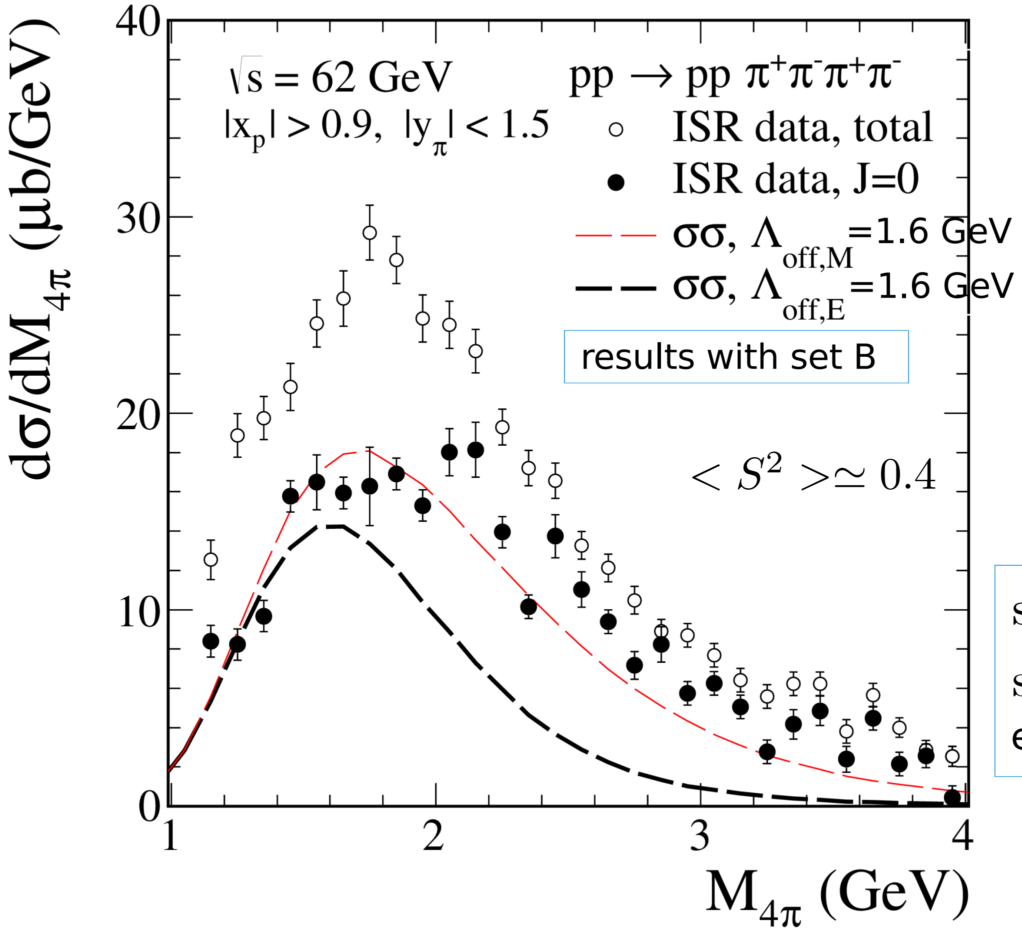
$$\sigma_{inel}/\sigma_{el} \approx 1.02\,\mu b/10.32\,\mu b \approx 0.1 \quad \text{for } \Lambda = 1.2 \text{ GeV}$$

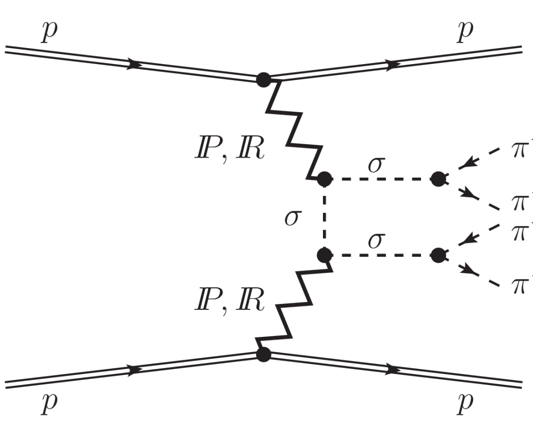
- almost no dependence on rapidity (except of the edges of the phase space)
- interesting pattern for the ratio of transverse momentum

Diffractive production of $\pi^+\pi^-\pi^+\pi^-$ in *pp* collisions

$$\sigma_{2\to6} = \int_{2m_\pi}^{\max\{m_{X_3}\}} \int_{2m_\pi}^{\max\{m_{X_4}\}} \sigma_{2\to4}(..., m_{X_3}, m_{X_4})\, f_M(m_{X_3})\, f_M(m_{X_4})\, dm_{X_3}\, dm_{X_4}$$

with the spectral functions of meson $f_M(m_{X_i}) = A_N \left(1 - \frac{4m_\pi^2}{m_{X_i}^2}\right)^{n/2} \frac{\frac{2}{\pi} m_M^2 \Gamma_{M,tot}}{(m_{X_i}^2 - m_M^2)^2 + m_M^2 \Gamma_{M,tot}^2}$





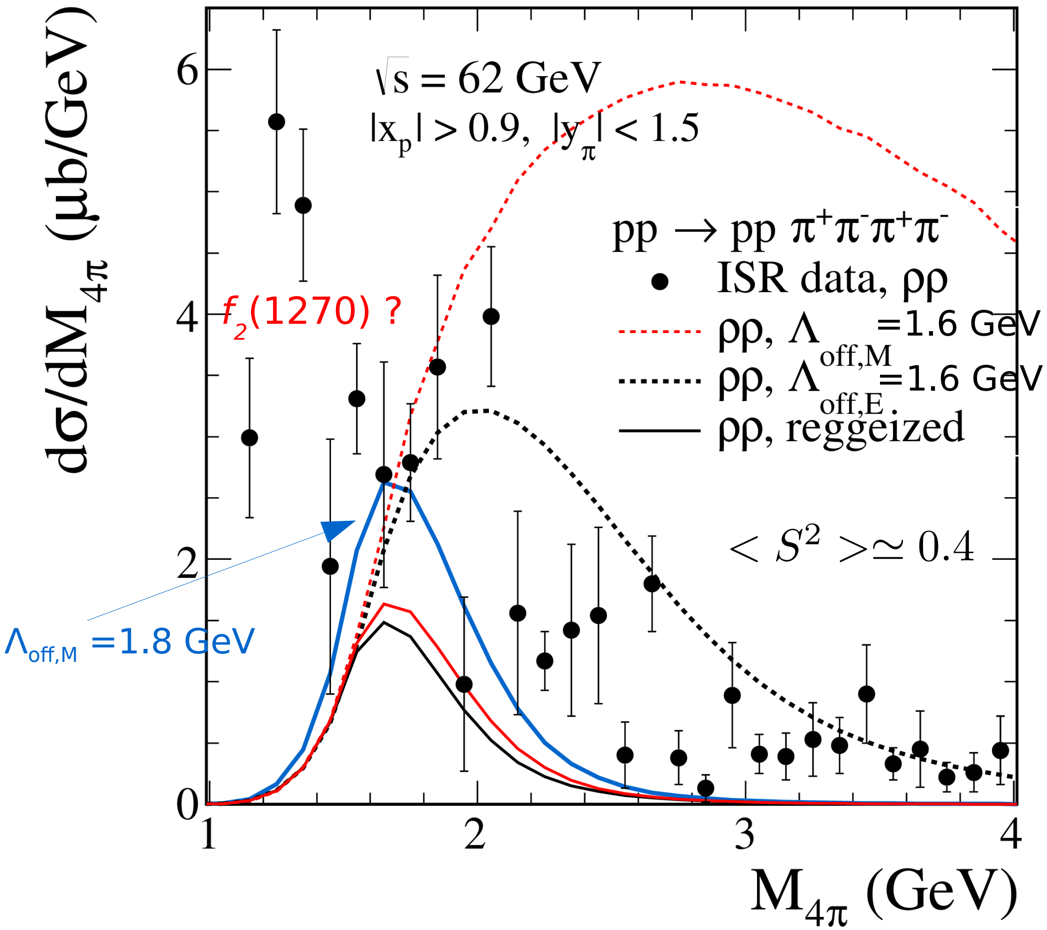
set A : $\beta_{I\!P\sigma\sigma} = 2\beta_{I\!P\pi\pi}$, $g_{f_{2I\!R}\sigma\sigma} = g_{f_{2I\!R}\pi\pi}$

set B : $\beta_{I\!P\sigma\sigma} = 2 \times (2\beta_{I\!P\pi\pi})$, $g_{f_{2I\!R}\sigma\sigma} = 2 \times g_{f_{2I\!R}\pi\pi}$

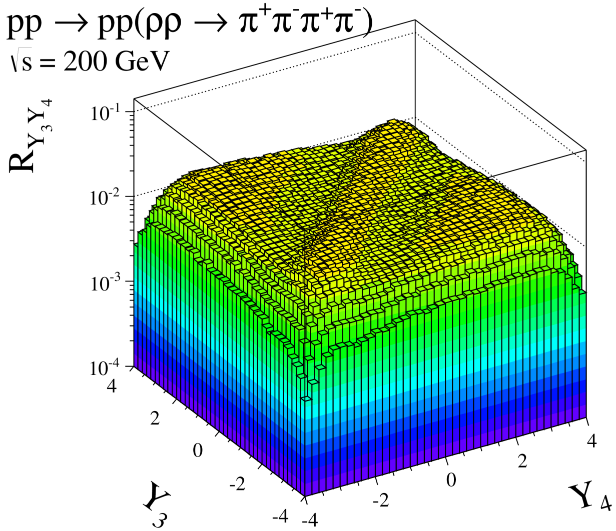
enhanced coupling constants

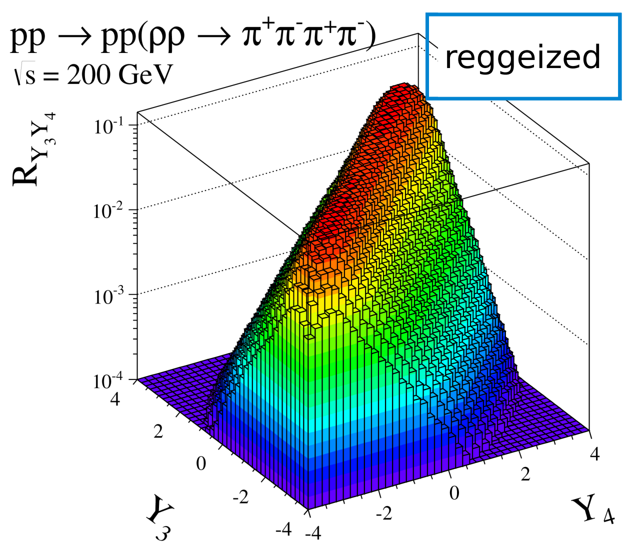
The 4π ISR data contains a large $\rho^0\pi^+\pi^-$ component with an enhancement in the J =2 term interpreted by ABCDHW Collaboration as a f_2(1720) state.

ISR data: A. Breakstone *et al.* (ABCDHW Collaboration), Z. Phys. C58 (1993) 251



$$R_{Y_3 Y_4} = \frac{d^2\sigma}{dY_3 dY_4} \Big/ \int dY_3 dY_4 \frac{d^2\sigma}{dY_3 dY_4}$$





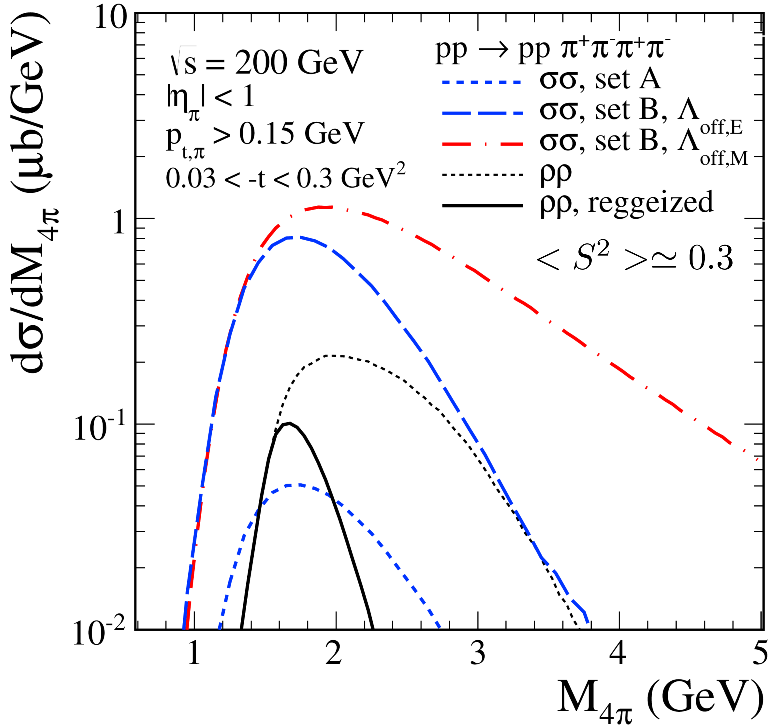
- reggeization effect

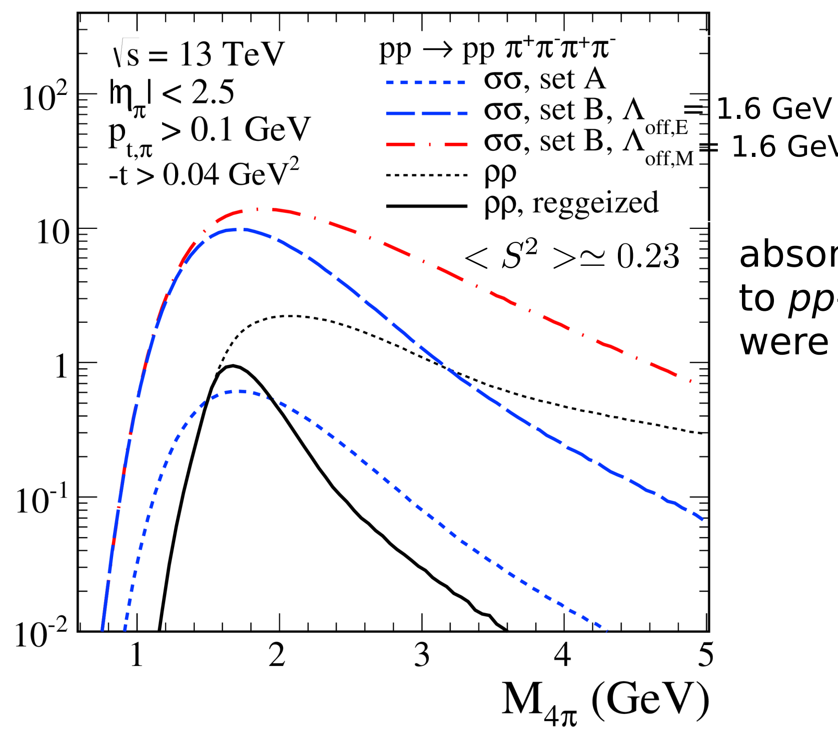
$$\Delta^{(\rho)}_{\rho_1\rho_2}(p) \to \Delta^{(\rho)}_{\rho_1\rho_2}(p)\,(s_{34}/s_0)^{\alpha_\rho(p^2)-1}, \quad s_0 = 4m_\rho^2$$

becomes crucial when the separation in rapidity between two ρ mesons increases $|Y_3 - Y_4| > 0$

see also discussion in
L.A. Harland-Lang, V.A. Khoze, M.G. Ryskin, Eur. Phys. J. C74 (2014) 2848

Cross sections (in μb) for $pp \to pp\,\pi^+\pi^-\pi^+\pi^-$





absorption effects due to *pp*-rescattering were included

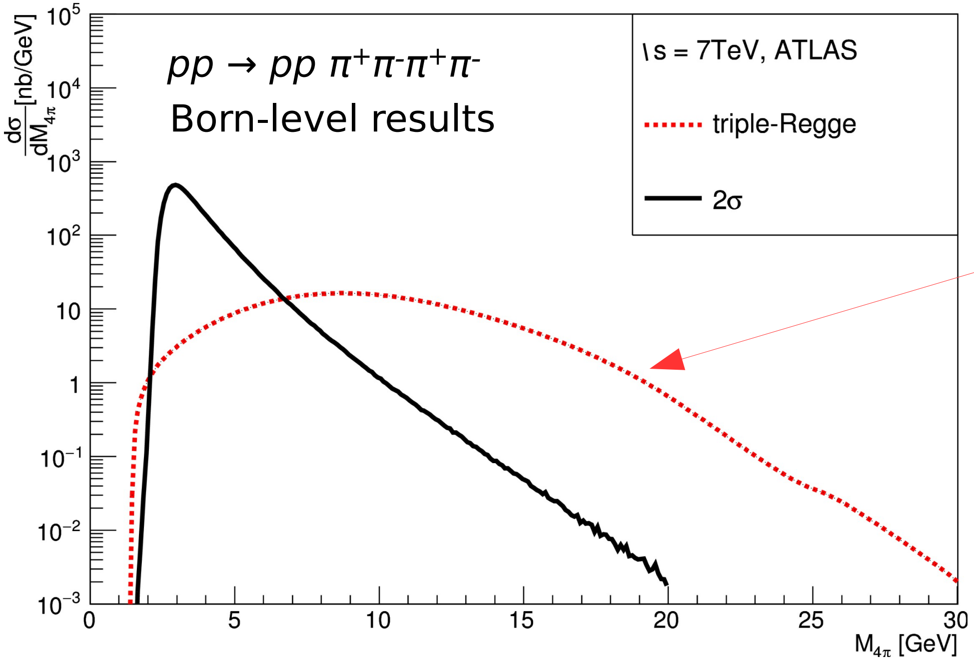
		"Born level" cross sections in μb	
$\sqrt{s}$, TeV	Cuts	$\sigma\sigma$ (set B)	$\rho\rho$
0.2	$\|\eta_\pi\| < 1$, $p_{t,\pi} > 0.15$ GeV, $0.03 < -t < 0.3$ GeV^2	2.94	0.88 (0.17)
7	$\|\eta_\pi\| < 0.9$, $p_{t,\pi} > 0.1$ GeV	10.40	2.79 (0.53)
7	$\|y_\pi\| < 2$, $p_{t,\pi} > 0.2$ GeV	34.88	17.94 (2.20)
13	$\|\eta_\pi\| < 1$, $p_{t,\pi} > 0.1$ GeV	16.18	3.56 (0.72)
13	$\|\eta_\pi\| < 2.5$, $p_{t,\pi} > 0.1$ GeV	120.06	45.58 (6.21)
13	$\|\eta_\pi\| < 2.5$, $p_{t,\pi} > 0.1$ GeV, $-t > 0.04$ GeV^2	47.52	18.08 (2.44)

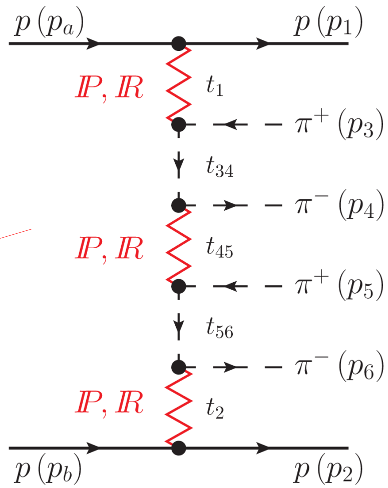
Table: Born cross sections in *μb.* The *σσ* contribution was calculated with the enhanced (set B) couplings while the *ρρ* contribution without and with (in the parentheses) inclusion of *ρ* meson reggeization.

Predicted cross section can be obtained by multiplying the Born cross section by the gap survival factor: 0.3 (STAR), 0.21 (7 TeV), 0.19 (13 TeV), 0.23 (13 TeV, with cuts on $|t|$).

See P. L., O. Nachtmann, A. Szczurek, arXiv:1606.05126, Phys. Rev. D94 (2016) 034017

Triple Regge exchange mechanism of 4π continuum





R. Kycia, P. L., A. Szczurek and J. Turnau,
Phys. Rev. D95 (2017) 094020

- Calculation of triple Regge exchange mechanism is performed with GenEx MC.
- Large cross section is found at the LHC (1-5 *μb,* whole phase space, with absorption effects of order of 0.1)
- Large M_{4π} are populated compared to other mechanisms (production of *σσ, ρρ pairs*).

We consider the case of ATLAS and ALICE cuts.
The ATLAS (or CMS) has better chances to identify the triple-Regge exchange processes.

For |y_{π}| < 2.5,   p_{t, π} > 0.5 GeV and at c.m energies of 7 - 13 TeV, we obtained σ = 141 – 154 nb, respectively, neglecting absorption effects.

Conclusions

- The tensor-pomeron model (Ewerz-Maniatis-Nachtmann) was applied to many reactions.
  The amplitudes are formulated in terms of effective vertices and propagators respecting the standard crossing and charge conjugation relations of QFT.
  For the reactions investigated so far the tensor pomeron model works well.

- We have given a consistence treatment of the $\pi^+\pi^-$ continuum and resonance production in proton-(anti)proton collisions.

  The distribution in dipion invariant mass shows a rich pattern of structure that depends on the cuts used in a particular experiment. We find that the relative contribution of the $f_2(1270)$ and $\pi\pi$-continuum strongly depends on the cut on $|t|$ which may explain some controversial observation made by the ISR groups.
  By assuming dominance of one *of the IP-IP-*f_2 couplings (j=2) we can get only a rough description of the recent CDF and preliminary STAR data.

  Disagreement with the preliminary CMS data could be due to a large dissociation contribution.
  Purely exclusive data expected from STAR, CMS+TOTEM and ATLAS+ALFA will allow us to draw definite conclusions.

- We have estimated the cross sections for the process $pp \to pp\ \pi^+\pi^-\pi^+\pi^-$ via intermediate $\sigma\sigma$ and $\rho\rho$ states.
  We compared our results with the ISR data. A measurable cross section of few μb was obtained including the exp. cuts relevant for LHC experiments.

- The proton excitation processes $pp \to pN\rho^0\pi$ constitute an important inelastic (non-exclusive) background to the $pp \to pp\rho^0$ reaction. The ratio of integrated cross sections is of the order of 7-10%.
  While it weakly depends on ρ^0 rapidity we predict an interesting pattern in transverse momentum.
  The reaction $pp \to pn\rho^0\pi^+$ may be a prototype for the reaction $pp \to pnJ/\psi\pi^+$.

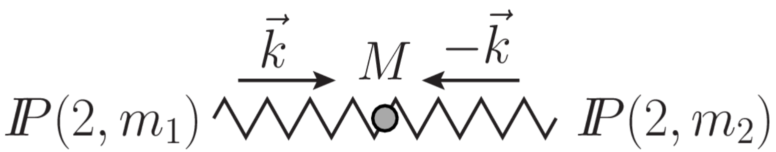
- In progress: MC generator for the soft reactions within tensor pomeron model (talk by M. Trzebiński).

Extra slides

Pomeron-pomeron-meson couplings

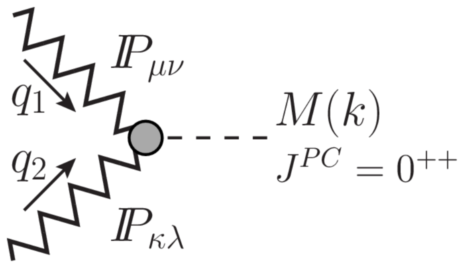
l – orbital angular momentum
S – total spin, we have $S \in \{0, 1, 2, 3, 4\}$
J – total angular momentum (spin of the produced meson)
P – parity of meson
and Bose symmetry requires $l - S$ to be even

In table we list the values of J and P of mesons which can be produced in our fictitious reaction (annihilation of two "spin 2 pomeron particles"):



For each value of l, S, J, and P we can construct a covariant Lagrangian density $\mathcal{L}'$ coupling the field operator for the meson M to the pomeron fields

and then we can obtain the "bare" vertices corresponding to the l and S.



l	S	$\lvert l-S \rvert \leqslant J \leqslant l+S$	$P = (-1)^l$
0	0	0	+
	2	2	
	4	4	
1	1	0, 1, 2	−
	3	2, 3, 4	
2	0	2	+
	2	0,1,2,3,4	
	4	2,3,4,5,6	
3	1	2,3,4	−
	3	0,1,2,3,4,5,6	
4	0	4	+
	2	2,3,4,5,6	
	4	0,1,2,3,4,5,6,7,8	
5	1	4.5.6	−
	3	2,3,4,5,6,7,8	
6	0	6	+
	2	4,5,6,7,8	
	4	2,3,4,5,6,7,8,9,10	

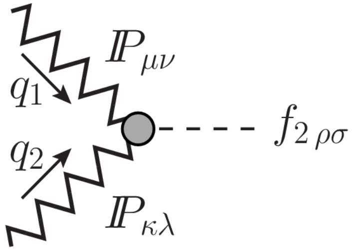
The lowest (l,S) term for a scalar meson $J^{PC} = 0^{++}$ is (0,0) while for a tensor meson $J^{PC} = 2^{++}$ is (0,2).

see P. L, O. Nachtmann, A. Szczurek, Annals Phys. 344 (2014) 301

$I\!P$-$I\!P$-f_2 couplings

In order to write the corresponding formulae of vertices in a compact and convenient form we find it useful to define the tensor

$$R_{\mu\nu\kappa\lambda} = \frac{1}{2} g_{\mu\kappa} g_{\nu\lambda} + \frac{1}{2} g_{\mu\lambda} g_{\nu\kappa} - \frac{1}{4} g_{\mu\nu} g_{\kappa\lambda}$$



$$i\Gamma^{(I\!PI\!Pf_2)(1)}_{\mu\nu,\kappa\lambda,\rho\sigma} = 2i\, g^{(1)}_{I\!PI\!Pf_2} M_0\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1}\, R_{\rho\sigma\rho_1\sigma_1}\, g^{\nu_1\alpha_1}\, g^{\lambda_1\rho_1}\, g^{\sigma_1\mu_1}$$

$$i\Gamma^{(I\!PI\!Pf_2)(2)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{2i}{M_0}\, g^{(2)}_{I\!PI\!Pf_2} \Big((q_1\cdot q_2)\, R_{\mu\nu\rho_1\alpha}\, R_{\kappa\lambda\sigma_1}{}^{\alpha} - q_{1\rho_1}\, q_2^{\mu_1}\, R_{\mu\nu\mu_1\alpha}\, R_{\kappa\lambda\sigma_1}{}^{\alpha} - q_1^{\mu_1}\, q_{2\sigma_1}\, R_{\mu\nu\rho_1\alpha}\, R_{\kappa\lambda\mu_1}{}^{\alpha} + q_{1\rho_1}\, q_{2\sigma_1}\, R_{\mu\nu\kappa\lambda} \Big) R_{\rho\sigma}{}^{\rho_1\sigma_1}$$

$$i\Gamma^{(I\!PI\!Pf_2)(3)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{2i}{M_0}\, g^{(3)}_{I\!PI\!Pf_2} \Big((q_1\cdot q_2)\, R_{\mu\nu\rho_1\alpha}\, R_{\kappa\lambda\sigma_1}{}^{\alpha} + q_{1\rho_1}\, q_2^{\mu_1}\, R_{\mu\nu\mu_1\alpha}\, R_{\kappa\lambda\sigma_1}{}^{\alpha} + q_1^{\mu_1}\, q_{2\sigma_1}\, R_{\mu\nu\rho_1\alpha}\, R_{\kappa\lambda\mu_1}{}^{\alpha} + q_{1\rho_1}\, q_{2\sigma_1}\, R_{\mu\nu\kappa\lambda} \Big) R_{\rho\sigma}{}^{\rho_1\sigma_1}$$

$$i\Gamma^{(I\!PI\!Pf_2)(4)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{i}{M_0}\, g^{(4)}_{I\!PI\!Pf_2} \Big(q_1^{\alpha_1}\, q_2^{\mu_1}\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1} + q_2^{\alpha_1}\, q_1^{\mu_1}\, R_{\mu\nu\alpha_1\lambda_1}\, R_{\kappa\lambda\mu_1\nu_1} \Big) R^{\nu_1\lambda_1}{}_{\rho\sigma}$$

$$i\Gamma^{(I\!PI\!Pf_2)(5)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{2i}{M_0^3}\, g^{(5)}_{I\!PI\!Pf_2} \Big(q_1^{\mu_1}\, q_2^{\nu_1}\, R_{\mu\nu\nu_1\alpha}\, R_{\kappa\lambda\mu_1}{}^{\alpha} + q_1^{\nu_1}\, q_2^{\mu_1}\, R_{\mu\nu\mu_1\alpha}\, R_{\kappa\lambda\nu_1}{}^{\alpha} - 2(q_1\cdot q_2)\, R_{\mu\nu\kappa\lambda} \Big) q_{1\alpha_1}\, q_{2\lambda_1}\, R^{\alpha_1\lambda_1}{}_{\rho\sigma}$$

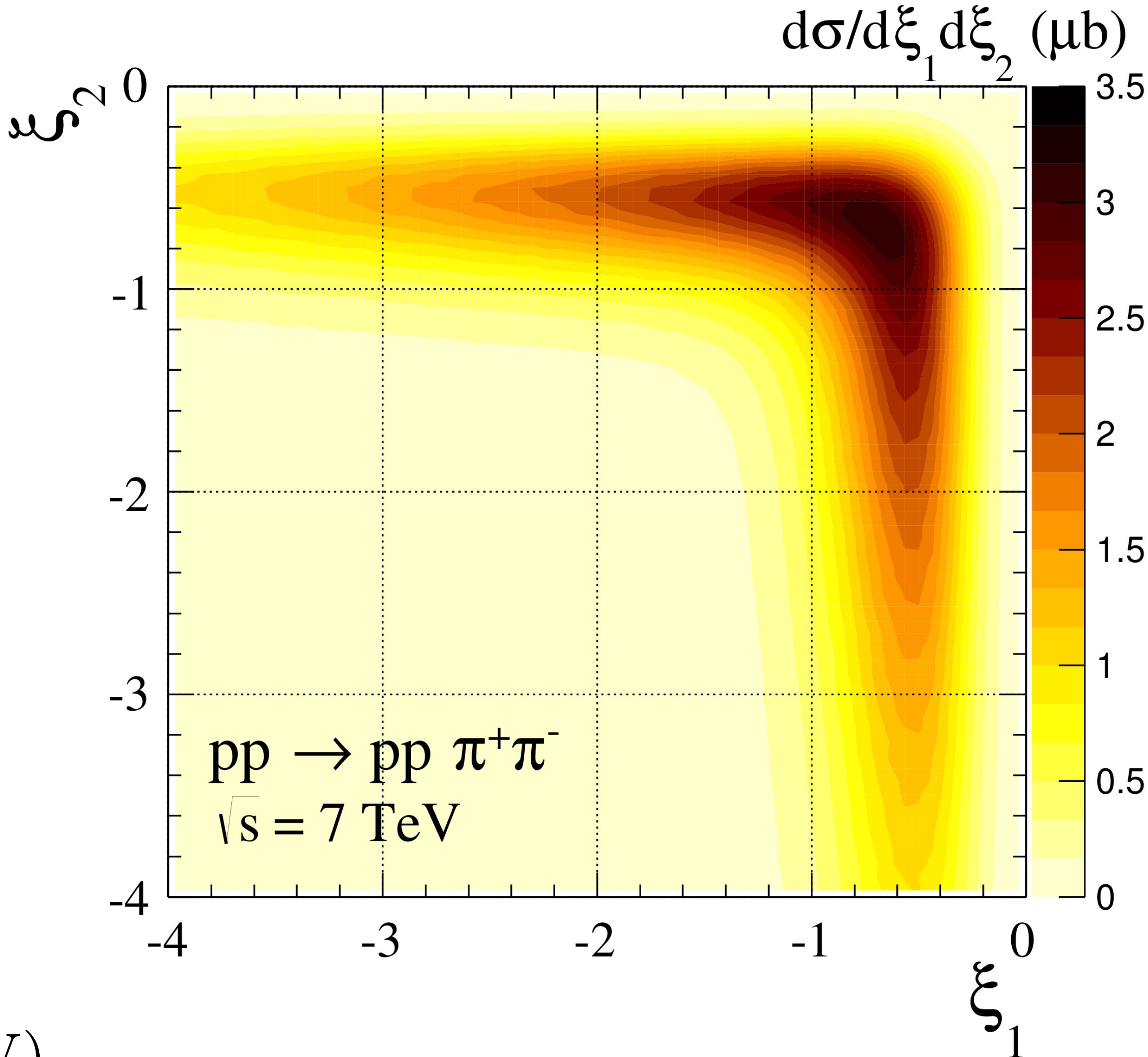
$$i\Gamma^{(I\!PI\!Pf_2)(6)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = \frac{i}{M_0^3}\, g^{(6)}_{I\!PI\!Pf_2} \Big(q_1^{\alpha_1}\, q_1^{\lambda_1}\, q_2^{\mu_1}\, q_{2\rho_1}\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1} + q_2^{\alpha_1}\, q_2^{\lambda_1}\, q_1^{\mu_1}\, q_{1\rho_1}\, R_{\mu\nu\alpha_1\lambda_1}\, R_{\kappa\lambda\mu_1\nu_1} \Big) R^{\nu_1\rho_1}{}_{\rho\sigma}$$

$$i\Gamma^{(I\!PI\!Pf_2)(7)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{2i}{M_0^5}\, g^{(7)}_{I\!PI\!Pf_2}\, q_1^{\rho_1}\, q_1^{\alpha_1}\, q_1^{\lambda_1}\, q_2^{\sigma_1}\, q_2^{\mu_1}\, q_2^{\nu_1}\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1}\, R_{\rho\sigma\rho_1\sigma_1}$$

We can associate the couplings j = 1, …, 7 with the following (l,S) values:
(0,2), (2,0) – (2,2), (2,0) + (2,2), (2,4), (4,2), (4,4), (6,4), respectively.

see P. L., O. Nachtmann, A. Szczurek, arXiv:1601.04537, Phys. Rev. D93 (2016) 054015

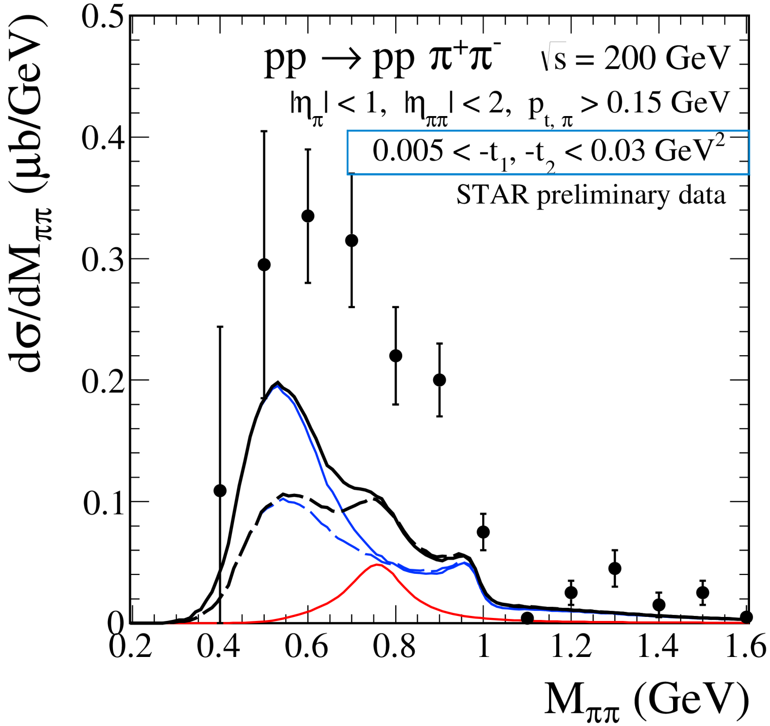
Photoproduction mechanism: ρ^0 and $\pi^+\pi^-$ continuum

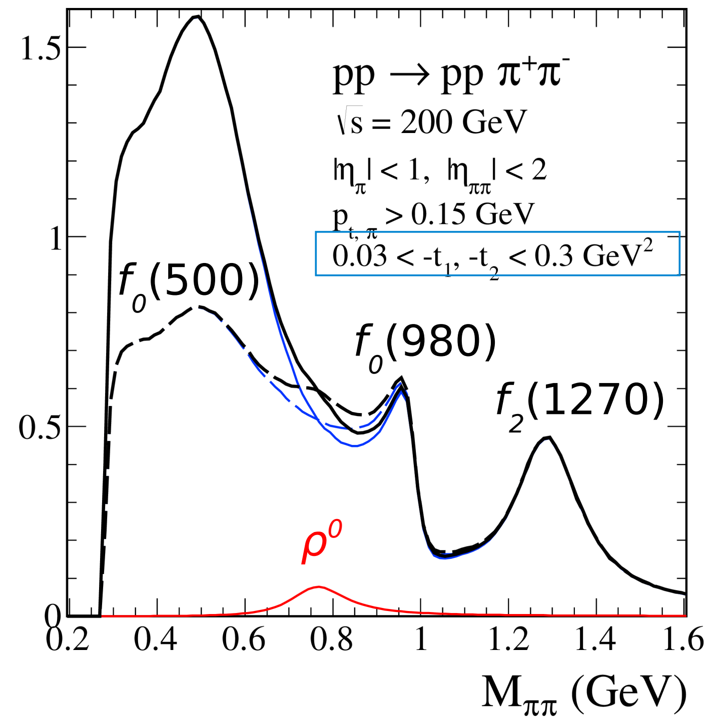


$$\xi_1 = \log_{10}(p_{1\perp}/1\,\mathrm{GeV})$$

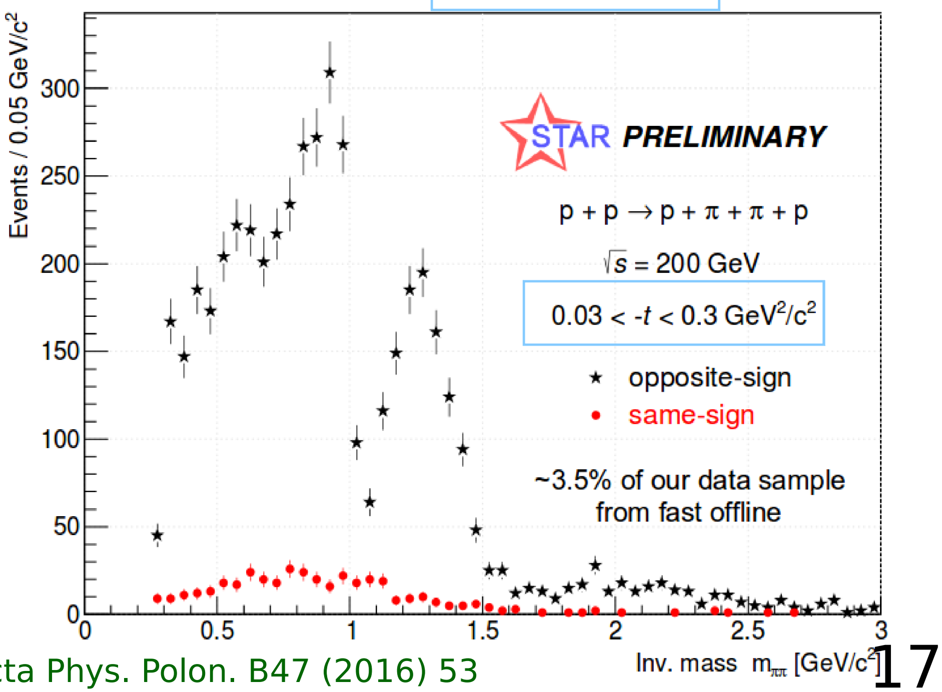
$$\xi_1 = -1 \;(\text{means } p_{1\perp} = 0.1\;\mathrm{GeV})$$

Comparison with STAR preliminary data





not acceptance-corrected, statistical errors only

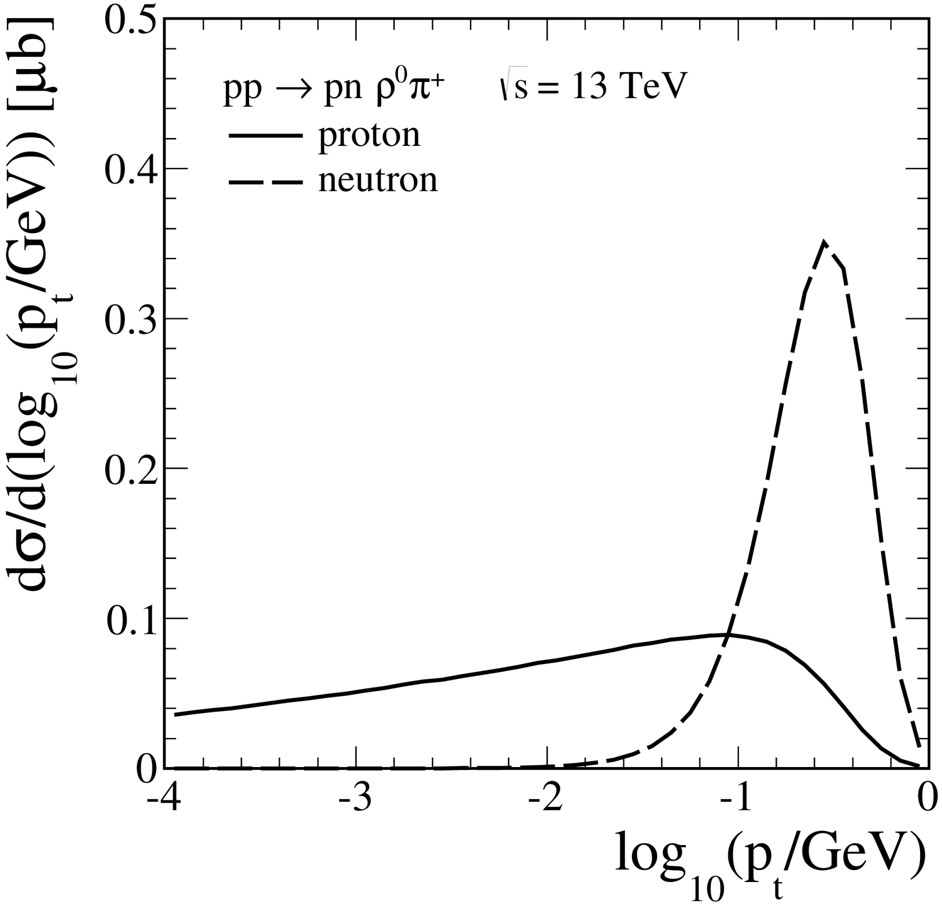


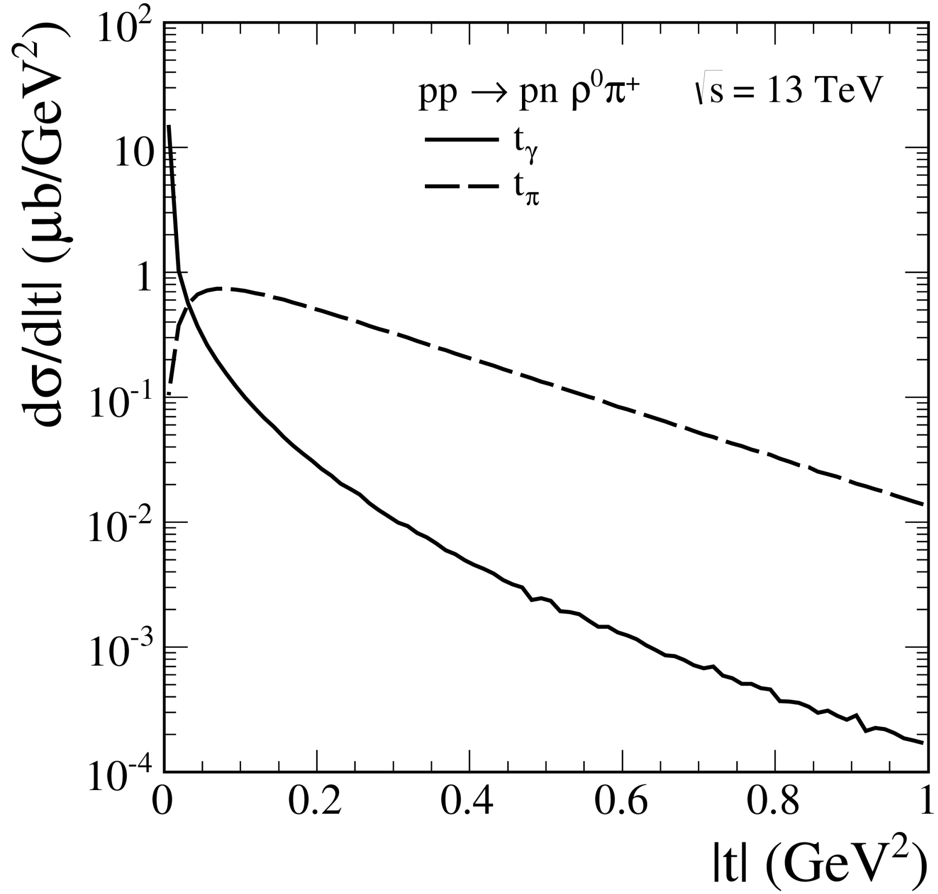
- Blue lines (diffractive term), red line (ρ^0 term), black lines (complete result)
- In calculation of f_2 term only one of the *IP-IP-f_2* couplings (j=2) was taken
- At $M_{\pi\pi} < 1$ GeV also other processes may be important → $\pi\pi$ FSI effect ($f_0(500)$ meson)
- Absorption effects were included effectively:
  $< S^2 > \simeq 0.2$ for the diffractive contribution
  $< S^2 > \simeq 0.9$ for the photon-IP/IR contribution

STAR preliminary data for small |t|: L.Adamczyk, W.Guryn, J.Turnau, Int.J.Mod.Phys. A29 no. 28, (2014) 1446010; for larger |t|: W. Guryn, Acta Phys. Polon. B47 (2016) 53

$pp \to pn\rho^0\pi^+$

We take into account only pion exchange contribution (results for only one diagram).
No absorption effects were included.





Related works:

- P. Lebiedowicz, R. Pasechnik, A. Szczurek, *Measurement of exclusive production of χ_{c0} scalar meson in proton-(anti)proton collisions via $\chi_{c0} \to \pi^+\pi^-$ decay*, arXiv:1103.5642, Phys. Lett. B701 (2011) 434

- R. Staszewski, P. Lebiedowicz, M. Trzebiński, J. Chwastowski, A. Szczurek, *Exclusive $\pi^+\pi^-$ Production at the LHC with Forward Proton Tagging*, arXiv: 1104.3568, Acta Phys. Polon. B42 (2011) 1861

- L.A. Harland-Lang, V.A. Khoze, M.G. Ryskin, *Modelling exclusive meson pair production at hadron colliders*, arXiv:1312.4553, Eur. Phys. J. C74 (2014) 2848

- 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, JHEP 1501 (2015) 151

- P. Lebiedowicz, A. Szczurek, *Revised model of absorption corrections for the $pp \to pp\ \pi^+\pi^-$ process*, arXiv:1504.07560, Phys. Rev. D92 (2015) 054001

- R. Fiore, L. Jenkovszky, R. Schicker, *Resonance production in Pomeron-Pomeron collisions at the LHC*, arXiv:1512.04977, Eur. Phys. J. C76 (2016) 38

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