# Recent results on central exclusive production of pions in pp collisions

## Piotr Lebiedowicz

Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland

in collaboration with Otto Nachtmann and Antoni Szczurek

*ECT\* Trento Workshop*

*QCD at LHC: forward physics and UPC collisions of heavy ions*
*26-30 September 2016*

1) *pp* elastic scattering (tensor pomeron ansatz)

2) $pp \to pp\pi^+\pi^-$ reaction

- diffractive mechanism [continuum, scalar and tensor resonances]

- photoproduction mechanism [$\rho^0 \to \pi^+\pi^-$ and non-resonant (Drell-Söding)]

- $pp \to pn\rho^0\pi^+$ reaction as a background to $pp \to pp\rho^0$ reaction

3) $pp \to pp\ \pi^+\pi^-\pi^+\pi^-$ (diffractive mechanism via the intermediate $\sigma\sigma$ and $\rho\rho$ states)

- P. Lebiedowicz, O. Nachtmann, A. Szczurek, *Exclusive central diffractive production of scalar and pseudoscalar mesons; tensorial vs. vectorial pomeron*, arXiv:1309.3913, Annals Phys. 344 (2014) 301

- P. Lebiedowicz, O. Nachtmann, A. Szczurek, *$\rho^0$ and Drell-Söding contributions to central exclusive production of $\pi^+\pi^-$ pairs in proton-proton collisions at high energies*, arXiv:1412.3677, Phys. Rev. D91 (2015) 07402300

- P. Lebiedowicz, 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*, arXiv:1601.04537, Phys. Rev. D93 (2016) 054015

- P. Lebiedowicz, 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*, arXiv:1606.05126, Phys. Rev. D94 (2016) 034017

High-energy small-angle hadron-hadron scattering is dominated by the exchange of the soft pomeron. It is clear that it has vacuum internal quantum numbers.

What is much less clear is the spin structure of the soft pomeron.

- In [C. Ewerz, M. Maniatis, O. Nachtmann, Annals Phys. 342 (2014) 31] it was proposed to describe the soft pomeron as an effective rank-2 symmetric tensor exchange.

  There, the all reggeon exchanges with C = +1 (C = -1) were described as effective tensor (vector) exchanges and a large number of the couplings of these objects to hadrons were determined from experimental data.

- In [C. Ewerz, P. Lebiedowicz, O. Nachtmann, A. Szczurek, *Helicity in proton-proton elastic scattering and the spin structure of the pomeron,* arXiv:1606.08067] we have confronted three hypotheses for the soft pomeron – tensor, vector, and scalar – with experimental data on polarised high-energy *pp* elastic scattering from the STAR collaboration.

There are 16 helicity amplitudes defined as the $\mathcal{T}$-matrix elements

$$< p(p_3, s_3), p(p_4, s_4)|\mathcal{T}|p(p_1, s_1), p(p_2, s_2) > \equiv < 2s_3, 2s_4|\mathcal{T}|2s_1, 2s_2 >$$
$$s_j \in \{1/2, -1/2\}, \quad j = 1, ..., 4 \,.$$

and only five are independent

$$\phi_1(s, t) = < + + |\mathcal{T}| + + > \,,$$
$$\phi_2(s, t) = < + + |\mathcal{T}| - - > \,,$$
$$\phi_3(s, t) = < + - |\mathcal{T}| + - > \,,$$
$$\phi_4(s, t) = < + - |\mathcal{T}| - + > \,,$$
$$\phi_5(s, t) = < + + |\mathcal{T}| + - > \,.$$

$p\,(p_1, s_1)$ $\qquad$ $p\,(p_3, s_3)$

$\mathbb{P}$

$p\,(p_2, s_2)$ $\qquad$ $p\,(p_4, s_4)$
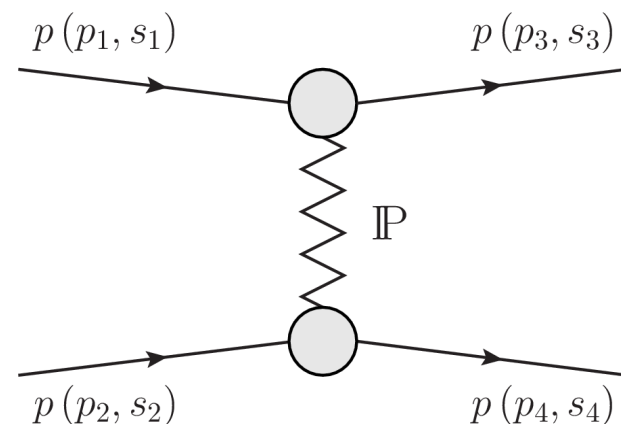
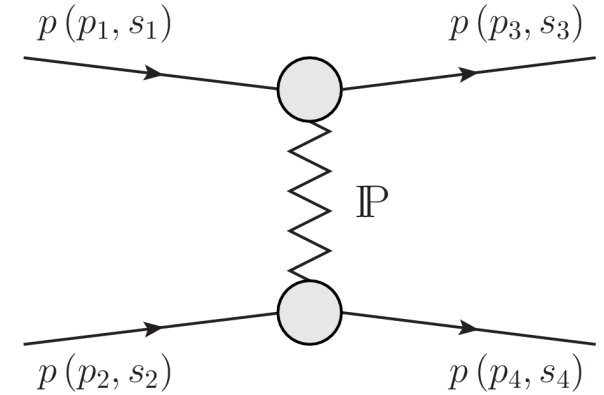The amplitudes with no helicity flip are $\phi_1$ and $\phi_3$, with single flip $\phi_5$, and with double flip $\phi_2$ and $\phi_4$.

The total cross section for unpolarised protons is

$$\sigma_{tot}(pp) = \frac{1}{s(s - 4m_p^2)} \frac{1}{4} \sum_{s_1, s_2} \text{Im} < 2s_3, 2s_4|\mathcal{T}|2s_1, 2s_2 >|_{t=0}$$

$$= \frac{1}{2\sqrt{s(s - 4m_p^2)}} \text{Im}\left[\phi_1(s, 0) + \phi_3(s, 0)\right]$$

3

## Tensor pomeron

$$i < 2s_3, 2s_4 | \mathcal{T} | 2s_1, 2s_2 >= i < p(p_3, s_3) | J_{T\,\mu\nu}(0) | p(p_1, s_1) >$$
$$\times i\Delta^{(\mathbb{P}_T)\mu\nu,\kappa\lambda}(s, t)$$
$$\times i < p(p_4, s_4) | J_{T\,\kappa\lambda}(0) | p(p_2, s_2) >$$

$$< p(p', s') | J_{T\,\mu\nu}(0) | p(p, s) >= \bar{u}(p', s')\Gamma^{((\mathbb{P}_T pp)}_{\mu\nu}(p', p) u(p, s)$$



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

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

$$i\Gamma^{(\mathbb{P}_T pp)}_{\mu\nu}(p', p) = i\Gamma^{(\mathbb{P}_T \bar{p}\bar{p})}_{\mu\nu}(p', p) = -i3\beta_{\mathbb{P}NN}F_1\big((p'-p)^2\big)\left\{\frac{1}{2}[\gamma_\mu(p'+p)_\nu + \gamma_\nu(p'+p)_\mu] - \frac{1}{4}g_{\mu\nu}(p\!\!\!/' + p\!\!\!/)\right\}$$

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

$$\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}}t,$$
$$\alpha_{\mathbb{P}}(0) = 1 + \epsilon_{\mathbb{P}},$$
$$\epsilon_{\mathbb{P}} = 0.0808,$$
$$\alpha'_{\mathbb{P}} = 0.25\,\text{GeV}^{-2}$$

## Scalar pomeron

$$i\Delta^{(\mathbb{P}_S)}(s, t) = \frac{s}{2m_p^2 M_0^2}(-is\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1}$$

$$i\Gamma^{(\mathbb{P}_S pp)}_{\mu\nu}(p', p) = i\Gamma^{(\mathbb{P}_S \bar{p}\bar{p})}_{\mu\nu}(p', p) = -i3\beta_{\mathbb{P}NN}M_0 F_1\big((p'-p)^2\big)$$

The corresponding $I\!\!P_V pp$ vertex and $I\!\!P_V$ propagator are

$$i\Gamma_{\mu}^{(I\!\!P_V pp)}(p',p) = -i\,3\beta_{I\!\!PNN}F_1[(p'-p)^2]\,\gamma_{\mu}$$

$$i\Delta_{\mu\nu}^{(I\!\!P_V)}(s,t) = \frac{1}{M_0^2}g_{\mu\nu}\,(-is\alpha'_{I\!\!P})^{\alpha_{I\!\!P}(t)-1}$$

where $M_0 \equiv 1$ GeV is introduced for dimensional reasons.

A charge-conjugation transformation $C$ gives

$$< \bar{p}(p_3,s_3)|J_{V\,\mu}(0)|\bar{p}(p_1,s_1) >= - < p(p_3,s_3)|J_{V\,\mu}(0)|p(p_1,s_1) > .$$

Thus, we get for a vector pomeron

$$< \bar{p}(p_3,s_3),p(p_4,s_4)|\mathcal{T}|\bar{p}(p_1,s_1),p(p_2,s_2) >= - < p(p_3,s_3),p(p_4,s_4)|\mathcal{T}|p(p_1,s_1),p(p_2,s_2) >$$

$$\sigma_{tot}(\bar{p}p) = -\sigma_{tot}(pp)\,.$$

Clearly, this result does not make sense for a non-vanishing cross section and would contradict the rules of QFT.

In order to discriminate between the tensor and scalar pomeron cases we turn to data from the STAR experiment at RHIC [L. Adamczyk et al. (STAR Collaboration), Phys. Lett. B719 (2013) 62)].

There, a measurement of the ratio of single-flip to non-flip amplitudes was performed. The relevant quantity is

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

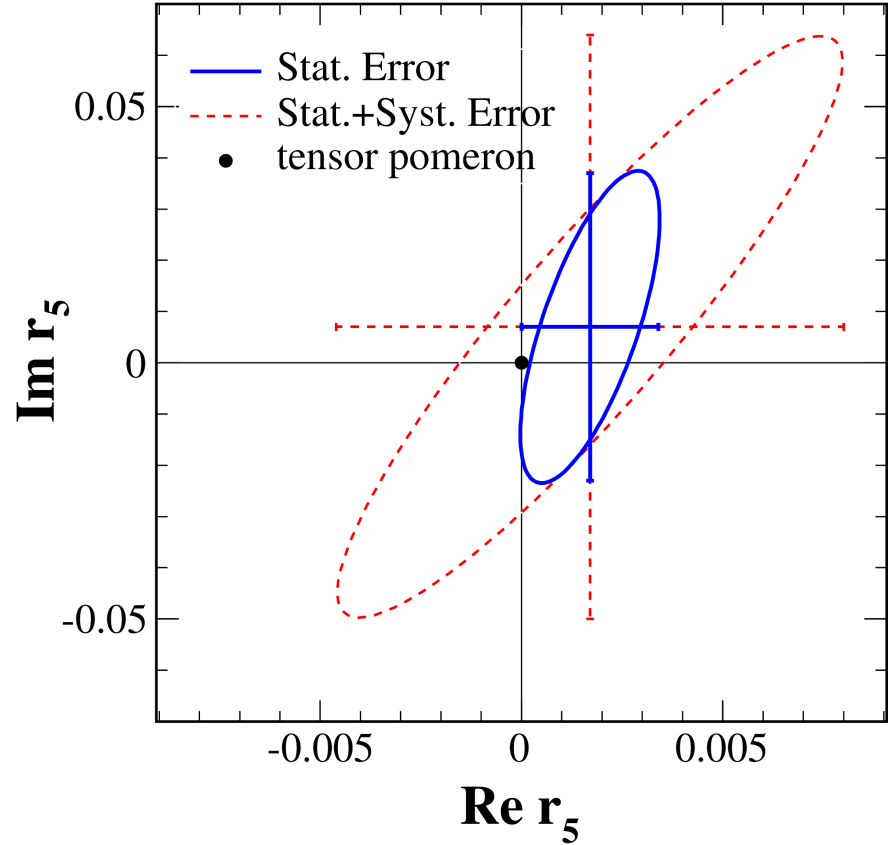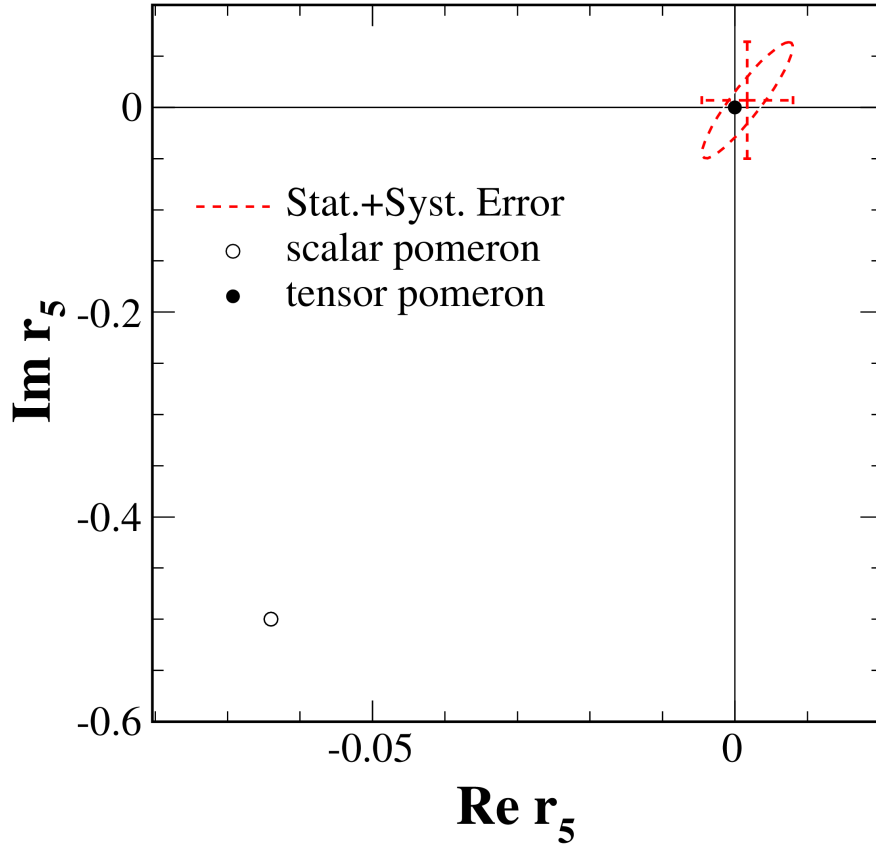We find for the tensor and scalar pomeron cases (arXiv:1606.08067)

$$r_5^T(s,t) = -\frac{m_p^2}{s}\left[i + \tan\left(\frac{\pi}{2}(\alpha(t)-1)\right)\right],$$

$$r_5^S(s,t) = -\frac{1}{2}\left[i + \tan\left(\frac{\pi}{2}(\alpha(t)-1)\right)\right].$$

The measurement of $r_5$ is done for $0.003 \leqslant |t| \leqslant 0.035$ GeV$^2$ and no $t$-dependence of $r_5$ is observed in this range. Therefore, we can approximately set $t = 0$ and obtain with $\sqrt{s} = 200$ GeV
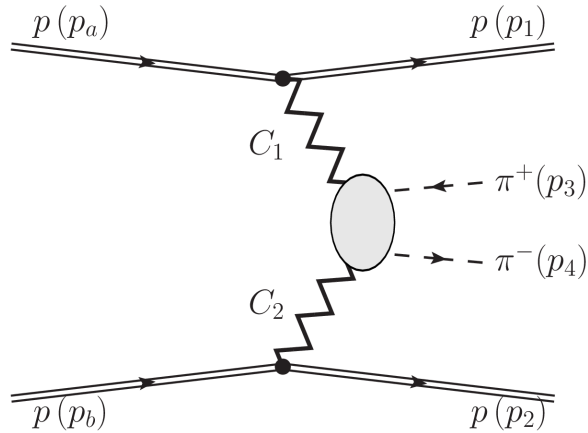
$$r_5^T(s,0) = (-0.28 - i2.20) \times 10^{-5}\,,$$
$$r_5^S(s,0) = -0.064 - i0.500\,.$$



The tensor-pomeron result is compatible with the experiment whereas the scalar-pomeron result is far outside the experimental error ellipse.

Ewerz-Maniatis-Nachtmann model: Regge-type model respecting the rules of QFT to describe high-energy soft reactions

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

$$(C_1, C_2) = (1, 1): \quad (IP + f_{2IR}, IP + f_{2IR})$$
$$(C_1, C_2) = (-1, -1): \quad (\rho_{IR} + \gamma, \rho_{IR} + \gamma)$$
$$(C_1, C_2) = (1, -1): \quad (IP + f_{2IR}, \rho_{IR} + \gamma)$$
$$(C_1, C_2) = (-1, 1): \quad (\rho_{IR} + \gamma, IP + f_{2IR})$$

| Exchange object | $C$ | $G$ |
|:---:|:---:|:---:|
| $IP$ | 1 | 1 |
| $f_{2IR}$ | 1 | 1 |
| $a_{2IR}$ | 1 | -1 |
| $\gamma$ | -1 | |
| $\mathbb{O}$ | -1 | -1 |
| $\omega_{IR}$ | -1 | -1 |
| $\rho_{IR}$ | -1 | 1 |

$G$ parity invariance forbids the vertices:

$$a_{2IR}\pi\pi, \ \omega_{IR}\pi\pi, \ \mathbb{O}\pi\pi$$

for the cases involving the photon exchange one also has to take into account the diagrams involving the contact terms
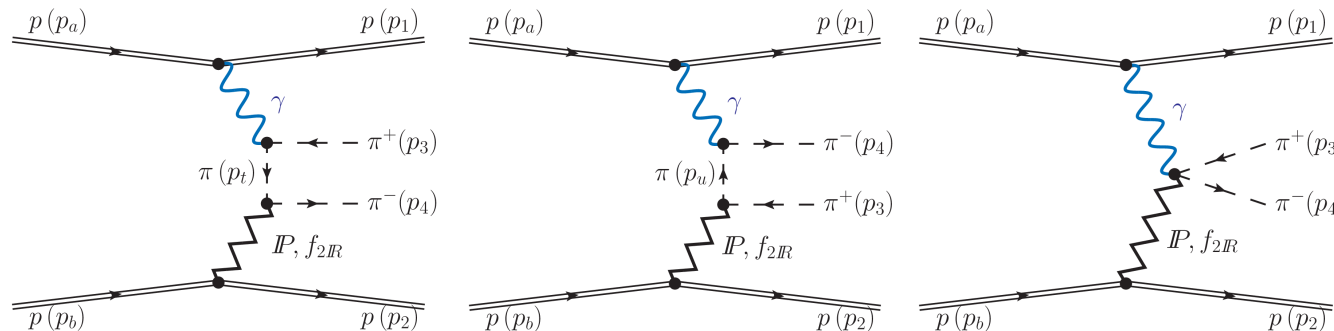


The inclusion of these diagrams is a gauge invariant version of the Drell-Söding mechanism.

The full amplitude of dipion production is a sum of continuum and resonances amplitudes:

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

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

The *IP IP* - exchange amplitude can be written as

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



$$\mathcal{M}^{(\hat{t})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^+\pi^-} =$$

$$(-i)\bar{u}(p_1,\lambda_1) i\Gamma^{(I\!P pp)}_{\mu_1\nu_1}(p_1,p_a) u(p_a,\lambda_a)\, i\Delta^{(I\!P)\,\mu_1\nu_1,\alpha_1\beta_1}(s_{13},t_1)\, i\Gamma^{(I\!P\pi\pi)}_{\alpha_1\beta_1}(p_t,-p_3)$$

$$\times\, i\Delta^{(\pi)}(p_t)\, i\Gamma^{(I\!P\pi\pi)}_{\alpha_2\beta_2}(p_4,p_t)\, i\Delta^{(I\!P)\,\alpha_2\beta_2,\mu_2\nu_2}(s_{24},t_2)\, \bar{u}(p_2,\lambda_2) i\Gamma^{(I\!P pp)}_{\mu_2\nu_2}(p_2,p_b) u(p_b,\lambda_b)$$

in terms of effective tensor pomeron propagator, proton and pion vertex functions
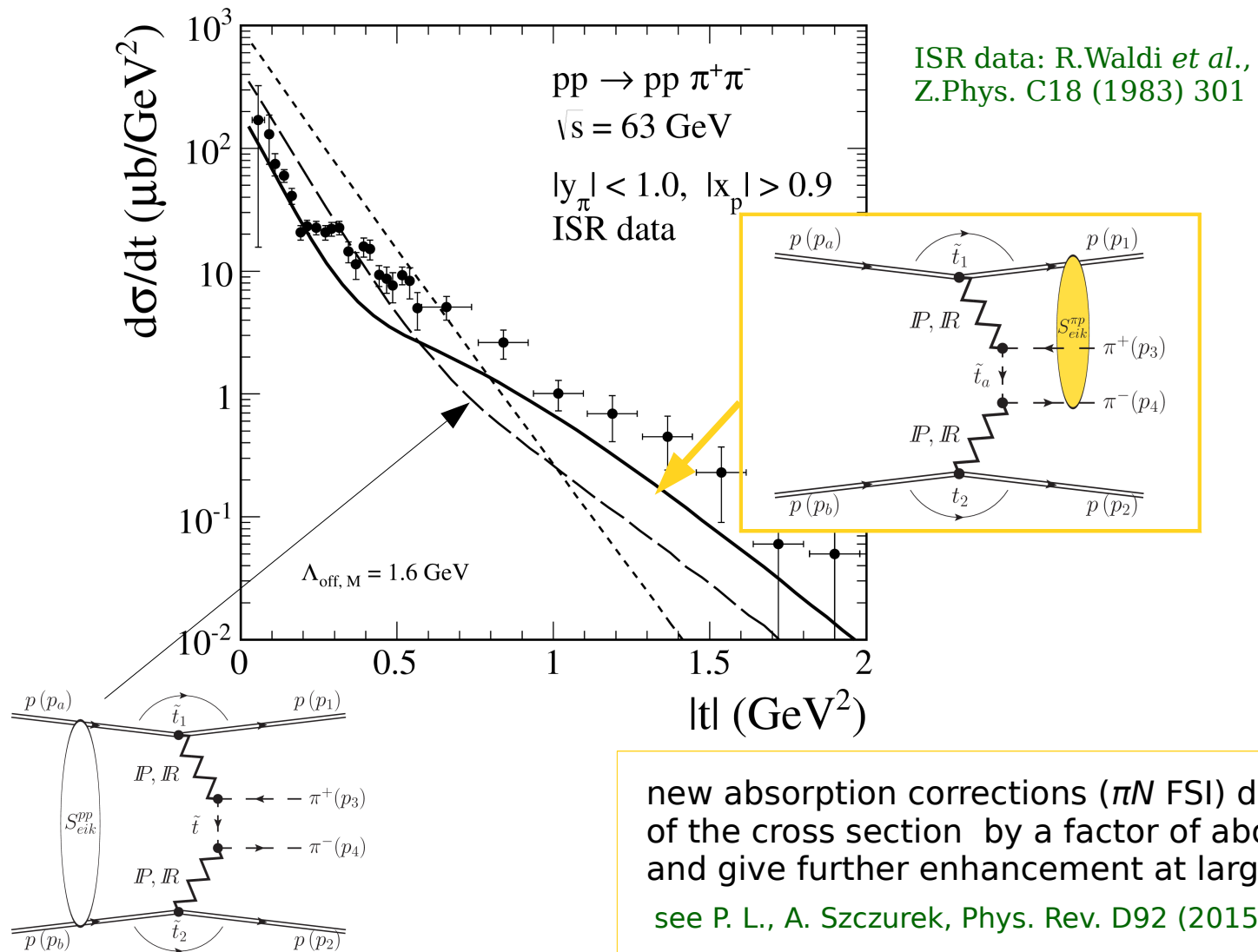see C. Ewerz, M. Maniatis, O. Nachtmann, Annals Phys. 342 (2014) 31

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

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

ISR data: R.Waldi *et al.*, Z.Phys. C18 (1983) 301

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

$\sqrt{s} = 63$ GeV

$|y_\pi| < 1.0, \quad |x_p| > 0.9$
ISR data

$\Lambda_{\text{off, M}} = 1.6$ GeV

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

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

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

10

$pp \rightarrow pp\ \pi^{+}\pi^{-}, \quad \sqrt{s} = 200$ GeV

$|\eta_{\pi}| < 1, \quad |\eta_{\pi\pi}| < 2, \quad p_{T,\pi} > 0.15$ GeV
$0.005 < -t_1, -t_2 < 0.03$ GeV$^2$

preliminary STAR data

$\Lambda_{off,E} = 1.0 - 1.6$ GeV
$\Lambda_{off,M} = 1.0 - 1.6$ GeV
(from bottom to top)

$pp \rightarrow pp\ \pi^{+}\pi^{-}, \quad \sqrt{s} = 200$ GeV

$|\eta_{\pi}| < 1, \quad |\eta_{\pi\pi}| < 2, \quad p_{T,\pi} > 0.15$ GeV
$0.005 < -t_1, -t_2 < 0.03$ GeV$^2$
$0.5 < M_{\pi\pi} < 1.0$ GeV

$\Lambda_{off,E} = 1.6$ GeV
$\Lambda_{off,M} = 1.4, 1.6$ GeV

$pp \rightarrow pp\ \pi^{+}\pi^{-}, \quad \sqrt{s} = 200$ GeV

$|\eta_{\pi}| < 1, \quad |\eta_{\pi\pi}| < 2, \quad p_{T,\pi} > 0.15$ GeV
$0.005 < -t_1, -t_2 < 0.03$ GeV$^2$
$0.5 < M_{\pi\pi} < 1.0$ GeV

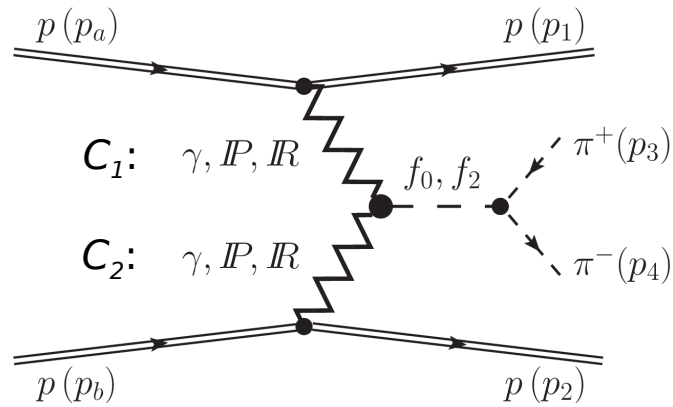$\Lambda_{off,E} = 1.6$ GeV
$\Lambda_{off,M} = 1.4, 1.6$ GeV

off-shell effects of the intermediate pions
can be described by the form factors

$$F_{\pi}(\hat{t}) = \exp\left(\frac{\hat{t} - m_{\pi}^2}{\Lambda_{off,E}^2}\right)$$

$$F_{\pi}(\hat{t}) = \frac{\Lambda_{off,M}^2 - m_{\pi}^2}{\Lambda_{off,M}^2 - \hat{t}}$$

11

$p\,(p_a)$    $p\,(p_1)$

$C_1:$  $\gamma, I\!\!P, I\!\!R$

$f_0, f_2$  $\pi^+(p_3)$

$C_2:$  $\gamma, I\!\!P, I\!\!R$

$\pi^-(p_4)$

$p\,(p_b)$    $p\,(p_2)$

$p\,(p_a)$    $p\,(p_1)$

$\gamma$

$\rho^0\,[\omega]$

$\rho^0$  $\pi^+(p_3)$

$\pi^-(p_4)$

$I\!\!P, f_{2I\!\!R}\,[a_{2I\!\!R}]$

$p\,(p_b)$    $p\,(p_2)$
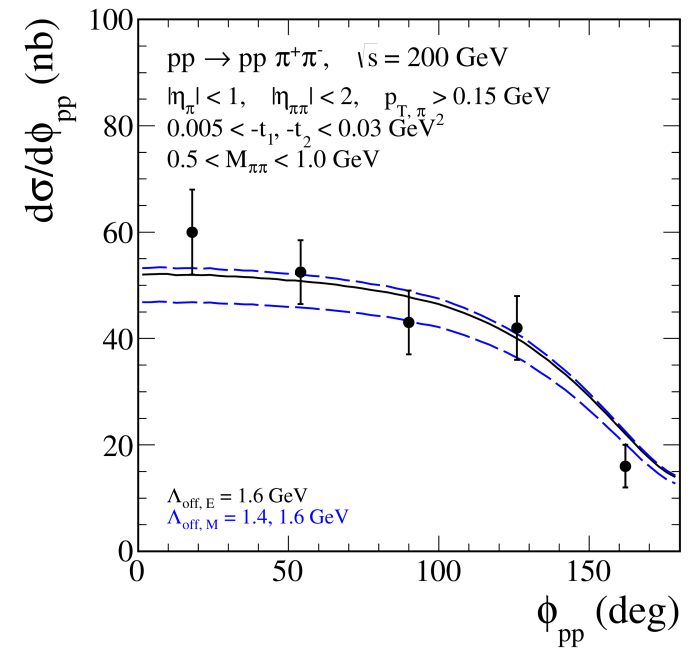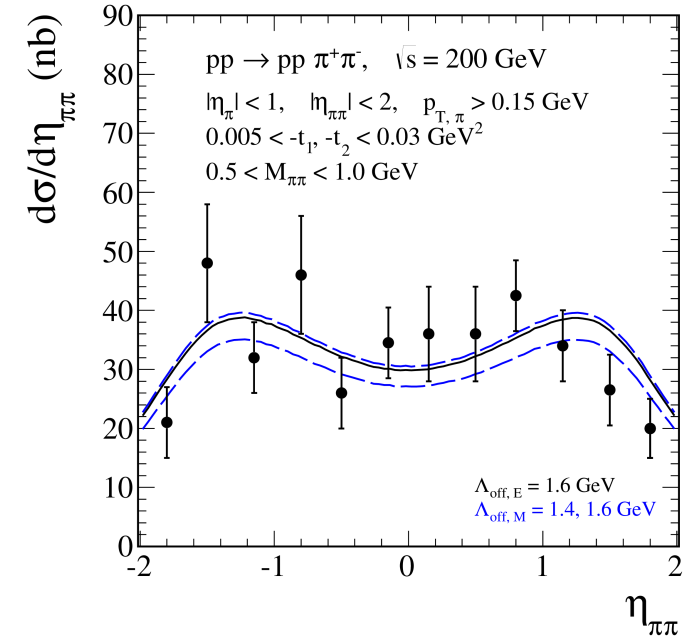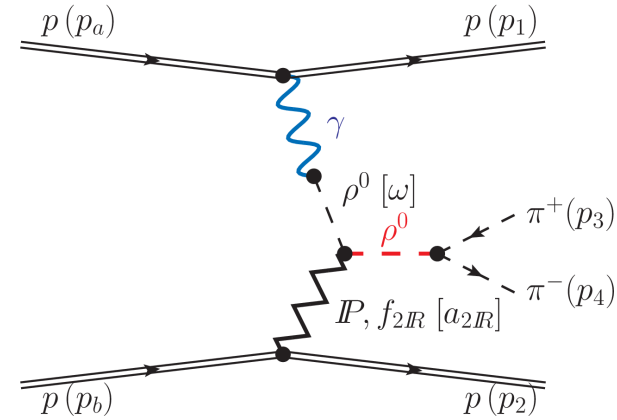
In general, many exchanges are possible in the dipion resonance production process.

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

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;

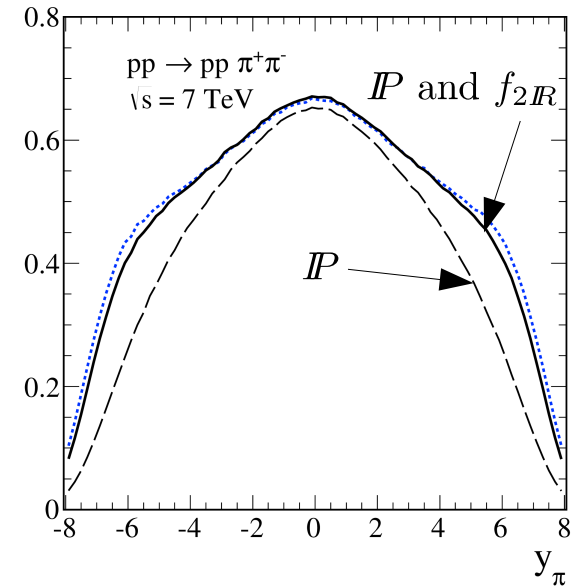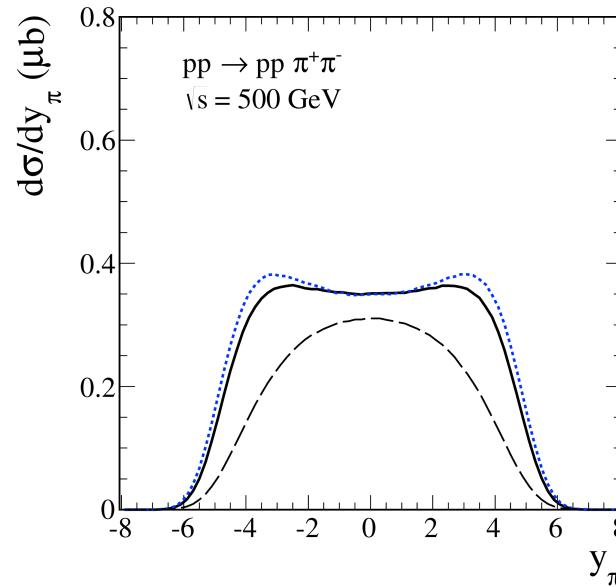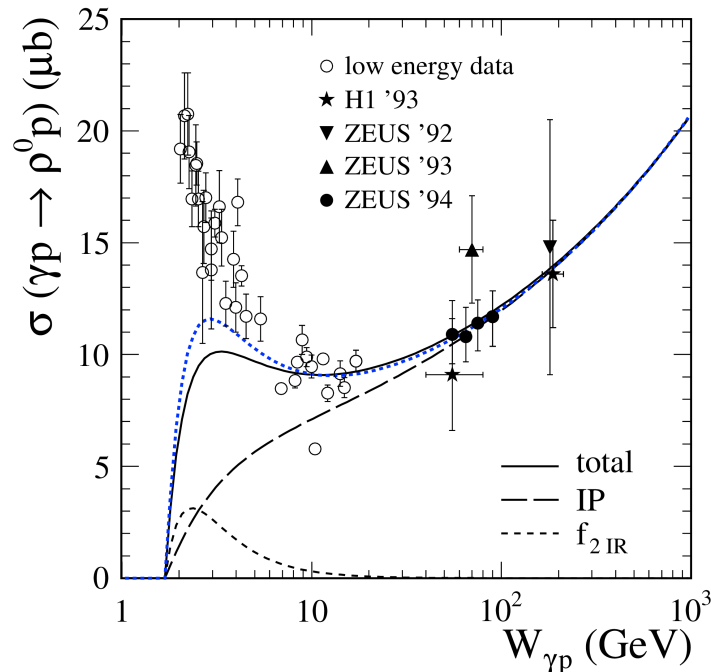$(\gamma, I\!\!P + f_{2I\!\!R}), (I\!\!P + f_{2I\!\!R}, \gamma)$ for photoproduction mechanism.
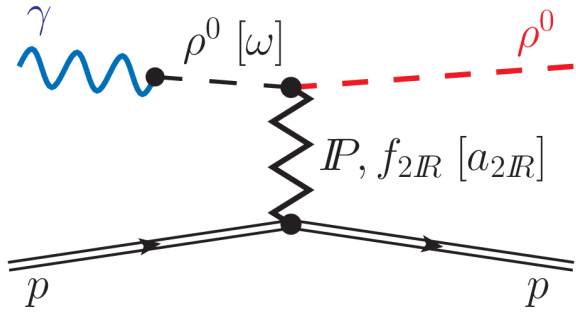
$$\mathcal{M}_{\lambda_\gamma \lambda_b \to \lambda_\rho \lambda_2}(s,t) \cong \quad ie\frac{m_\rho^2}{\gamma_\rho}\Delta_T^{(\rho)}(0)\,(\epsilon^{(\rho)\,\mu})^*\epsilon^{(\gamma)\,\nu}V_{\mu\nu\kappa\lambda}(s,t,q,p_\rho)$$

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

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)

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

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

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



The coupling constants *IP/IR-$\rho$-$\rho$* have been estimated from parametrization
of total cross sections for $\pi p$ scattering assuming $\sigma_{tot}(\rho^0(\lambda_\rho=\pm1),p)=\frac{1}{2}\left[\sigma_{tot}(\pi^+,p)+\sigma_{tot}(\pi^-,p)\right]$
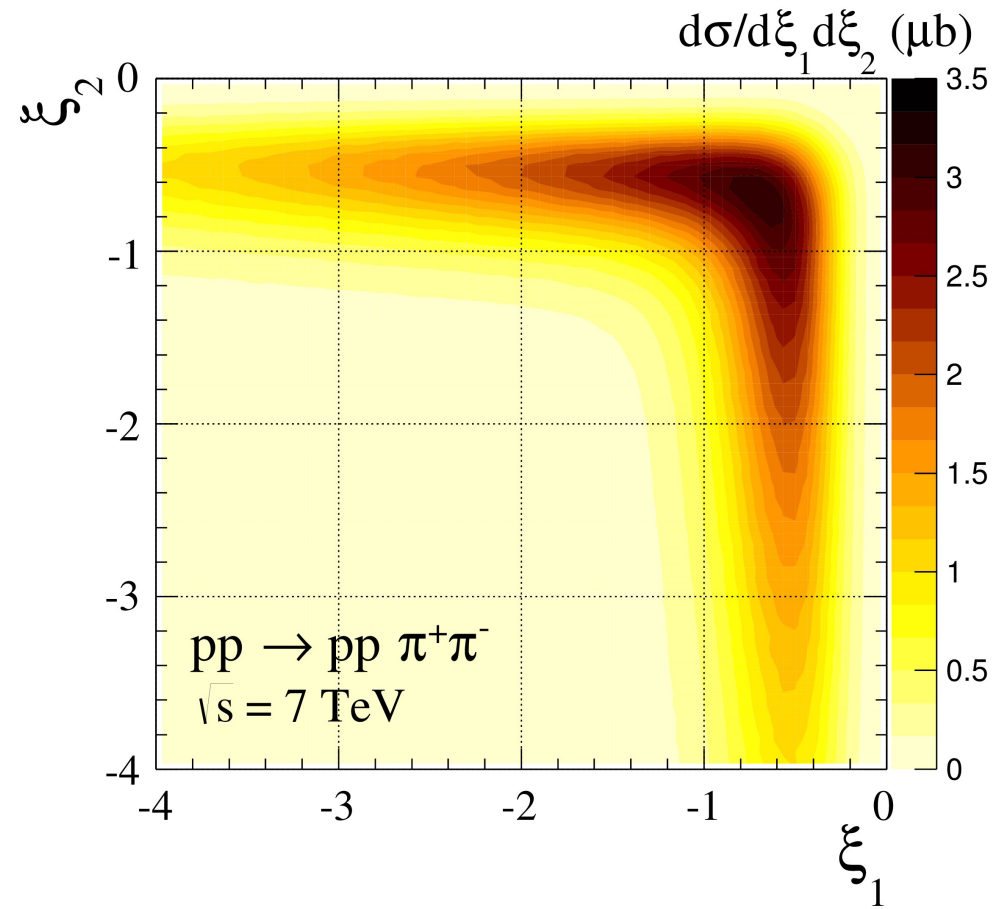
The non-resonant (Drell-Söding) contribution interfere with resonant $\rho(770)$ contribution → skewing of $\rho^0$ line shape.
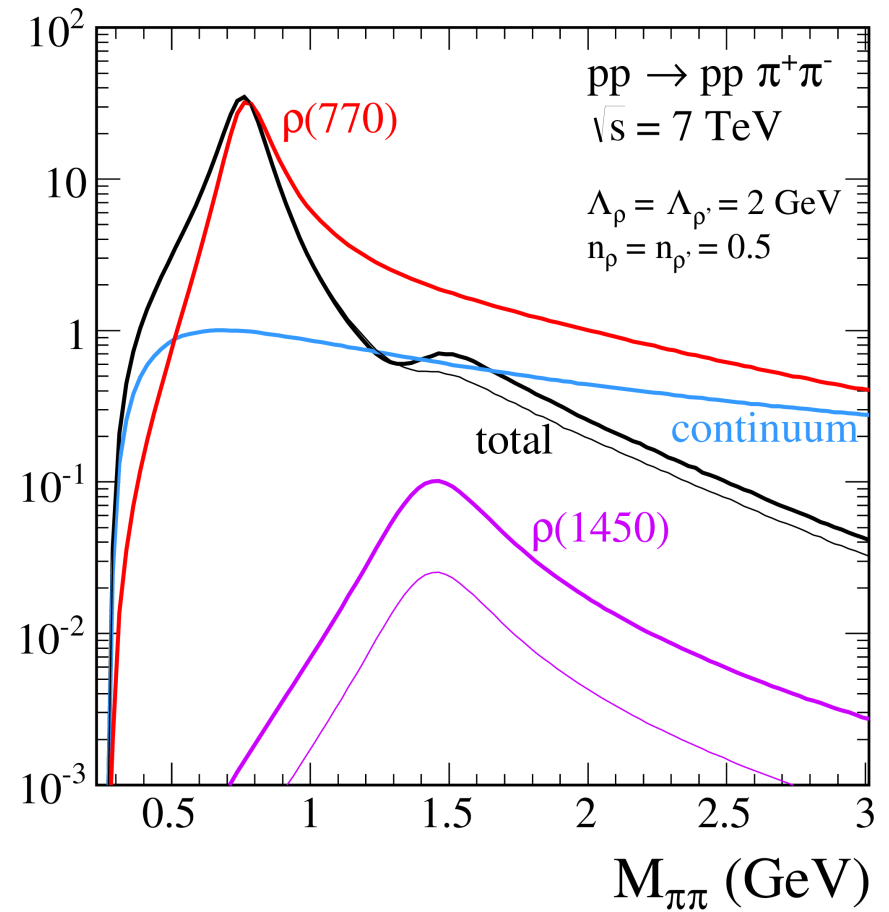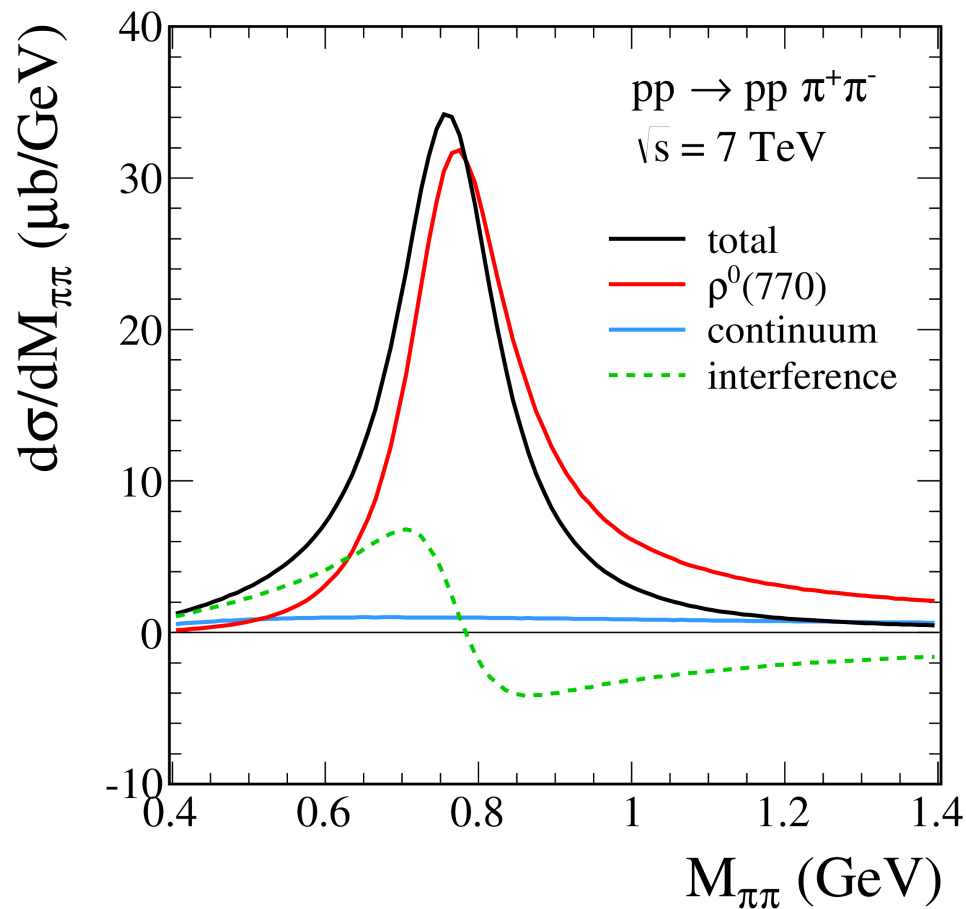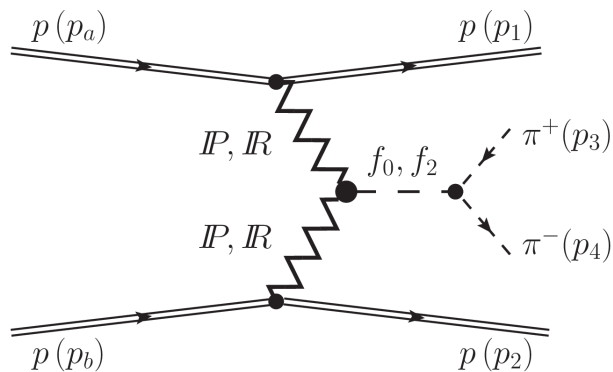
# $\rho^0$ and $\pi^+\pi^-$ continuum

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

$$\xi_1 = -1 \text{ means } p_{1\perp} = 0.1 \text{ GeV}$$



We expect the photon induced processes to be most important when <u>at least one</u> of the protons is undergoing only a very small |t|.

The values, for orbital angular momentum $l$, total spin $S$, total angular momentum $J$, and parity $P$, possible in the annihilation of two "spin 2 pomeron particles". We have $S \in \{0, 1, 2, 3, 4\}$, $P = (-1)^l$, $|l - S| \leqslant J \leqslant l + S$, and Bose symmetry requires $l - S$ to be even.

$M$ must have isospin and $G$ parity $I^G = 0^+$ and charge conjugation $C = +1$

In table we list the values of $J$ and $P$ of mesons which can be produced in our fictitious reaction:

$$\xrightarrow{\vec{k}} M \xleftarrow{-\vec{k}}$$
$$\mathbb{P}(2, m_1) \text{\Large\char"27F} M \text{\Large\char"27F} \mathbb{P}(2, m_2)$$
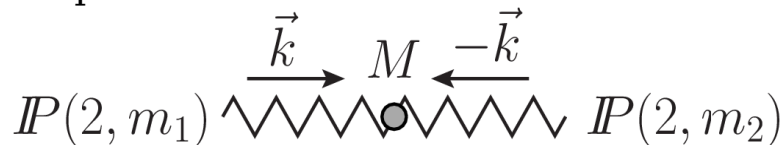
For each value of $l$, $S$, $J$, and $P$ we can construct a covariant Lagrangian density $\mathcal{L}'$ coupling (the field operator for the meson $M$ to the pomeron fields) and the vertex corresponding to the $l$ and $S$.

| $l$ | $S$ | $J$ | $P$ |
|---|---|---|---|
| 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 $(0,2)$.

# Scalar mesons

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

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

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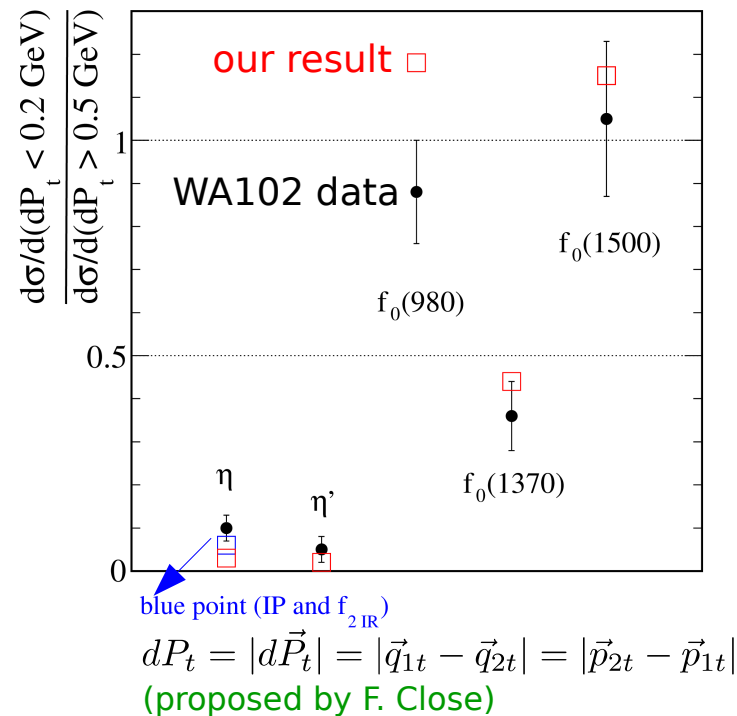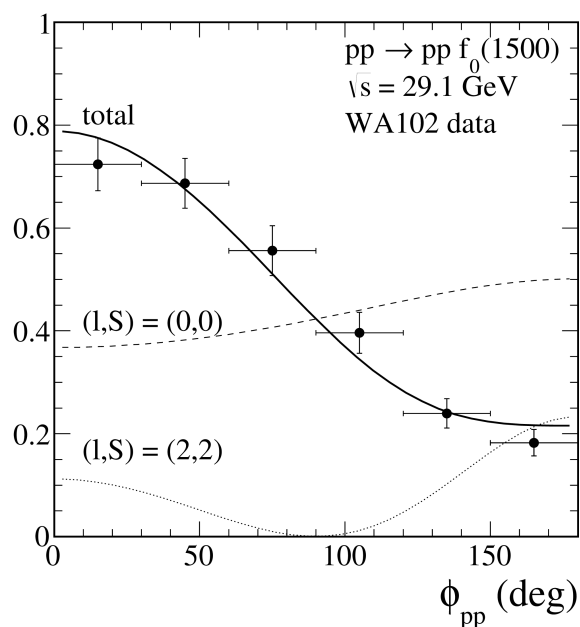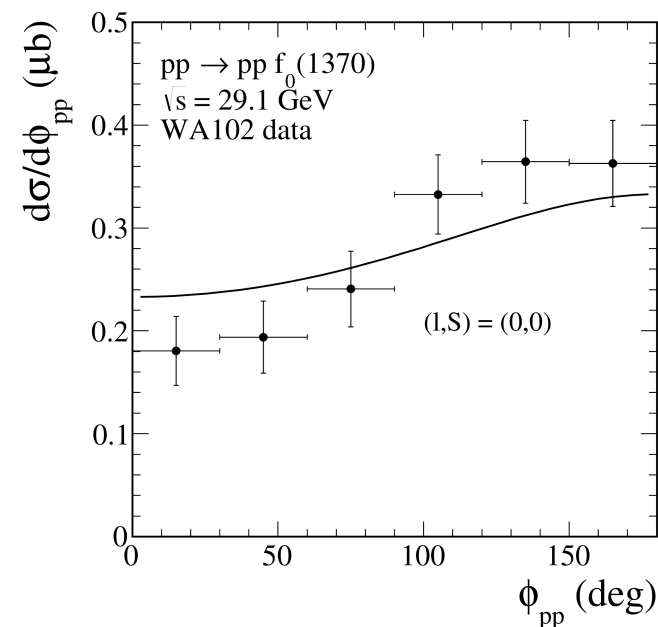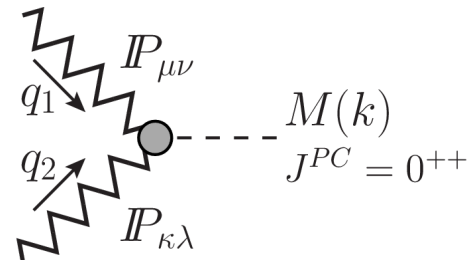








Our results and WA102 data have been normalized to the mean value of the total cross section given by A. Kirk, Phys. Lett. B489 (2000) 29.
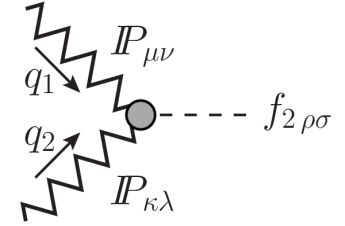
- $f_0(1370)$ peaks as $\phi_{pp} \to \pi$ whereas the $f_0(980)$, $f_0(1500)$, $f_0(1710)$ peak at $\phi_{pp} \to 0$
- $f_0(1500)$ and $f_0(1710)$ which could have a large 'gluonic component' have a large value of $dP_t$ ratio

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

17

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

$$\mathcal{M}^{(I\!P I\!P \to f_2 \to \pi^+\pi^-)}_{\lambda_a \lambda_b \to \lambda_1 \lambda_2 \pi^+ \pi^-} = (-i)\, \bar{u}(p_1, \lambda_1) i\Gamma^{(I\!P pp)}_{\mu_1 \nu_1}(p_1, p_a) u(p_a, \lambda_a)\, i\Delta^{(I\!P)\,\mu_1 \nu_1, \alpha_1 \beta_1}(s_1, t_1)$$

$$\times\, i\Gamma^{(I\!P I\!P f_2)}_{\alpha_1 \beta_1, \alpha_2 \beta_2, \rho\sigma}(q_1, q_2)\, i\Delta^{(f_2)\,\rho\sigma, \alpha\beta}(p_{34})\, i\Gamma^{(f_2 \pi\pi)}_{\alpha\beta}(p_3, p_4)$$

$$\times\, i\Delta^{(I\!P)\,\alpha_2 \beta_2, \mu_2 \nu_2}(s_2, t_2)\, \bar{u}(p_2, \lambda_2) i\Gamma^{(I\!P pp)}_{\mu_2 \nu_2}(p_2, p_b) u(p_b, \lambda_b)\,,$$



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

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

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

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

$$i\Gamma^{(f_2 \pi\pi)}_{\mu\nu}(p_3, p_4) = -i\,\frac{g_{f_2 \pi\pi}}{2M_0} \left[ (p_3 - p_4)_\mu (p_3 - p_4)_\nu - \frac{1}{4}g_{\mu\nu}(p_3 - p_4)^2 \right] F^{(f_2 \pi\pi)}(p_{34}^2)\,,$$
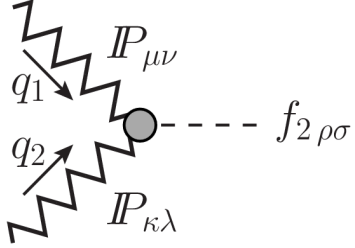
where $g_{f_2 \pi\pi} = 9.26$ was obtained from the corresponding partial decay width.

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

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

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



$$i\Gamma^{(\mathbb{P}\mathbb{P}f_2)(1)}_{\mu\nu,\kappa\lambda,\rho\sigma} = 2i\, g^{(1)}_{\mathbb{P}\mathbb{P}f_2} M_0\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1}\, R_{\rho\sigma\rho_1\sigma_1}\, g^{\nu_1\alpha_1}\, g^{\lambda_1\rho_1}\, g^{\sigma_1\mu_1}$$

$$i\Gamma^{(\mathbb{P}\mathbb{P}f_2)(2)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{2i}{M_0}\, g^{(2)}_{\mathbb{P}\mathbb{P}f_2}\Big((q_1\cdot q_2)\, R_{\mu\nu\rho_1\alpha}\, R_{\kappa\lambda\sigma_1}{}^{\alpha} - q_{1\rho_1}\, q_2^{\mu_1}\, R_{\mu\nu\mu_1\alpha}\, R_{\kappa\lambda\sigma_1}{}^{\alpha}$$
$$- q_1^{\mu_1}\, q_{2\sigma_1}\, R_{\mu\nu\rho_1\alpha}\, R_{\kappa\lambda\mu_1}{}^{\alpha} + q_{1\rho_1}\, q_{2\sigma_1}\, R_{\mu\nu\kappa\lambda}\Big) R_{\rho\sigma}{}^{\rho_1\sigma_1}$$

$$i\Gamma^{(\mathbb{P}\mathbb{P}f_2)(3)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{2i}{M_0}\, g^{(3)}_{\mathbb{P}\mathbb{P}f_2}\Big((q_1\cdot q_2)\, R_{\mu\nu\rho_1\alpha}\, R_{\kappa\lambda\sigma_1}{}^{\alpha} + q_{1\rho_1}\, q_2^{\mu_1}\, R_{\mu\nu\mu_1\alpha}\, R_{\kappa\lambda\sigma_1}{}^{\alpha}$$
$$+ q_1^{\mu_1}\, q_{2\sigma_1}\, R_{\mu\nu\rho_1\alpha}\, R_{\kappa\lambda\mu_1}{}^{\alpha} + q_{1\rho_1}\, q_{2\sigma_1}\, R_{\mu\nu\kappa\lambda}\Big) R_{\rho\sigma}{}^{\rho_1\sigma_1}$$

$$i\Gamma^{(\mathbb{P}\mathbb{P}f_2)(4)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{i}{M_0}\, g^{(4)}_{\mathbb{P}\mathbb{P}f_2}\Big(q_1^{\alpha_1}\, q_2^{\mu_1}\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1} + q_2^{\alpha_1}\, q_1^{\mu_1}\, R_{\mu\nu\alpha_1\lambda_1}\, R_{\kappa\lambda\mu_1\nu_1}\Big) R^{\nu_1\lambda_1}{}_{\rho\sigma}$$
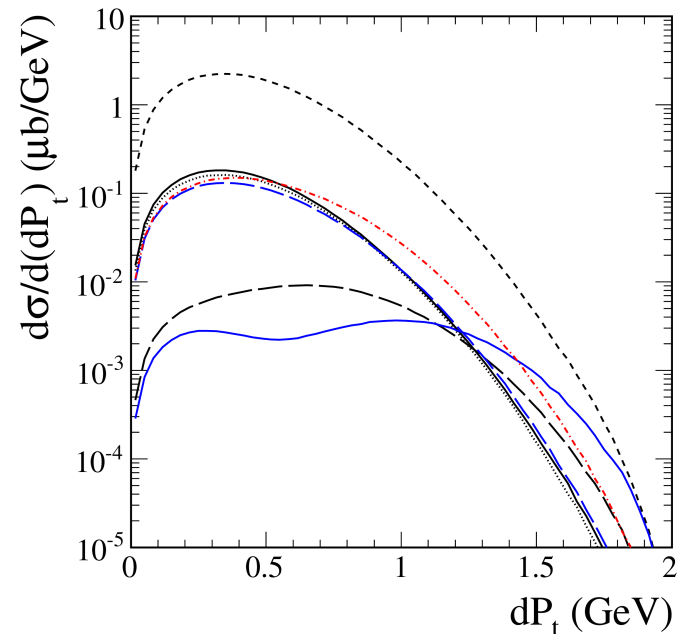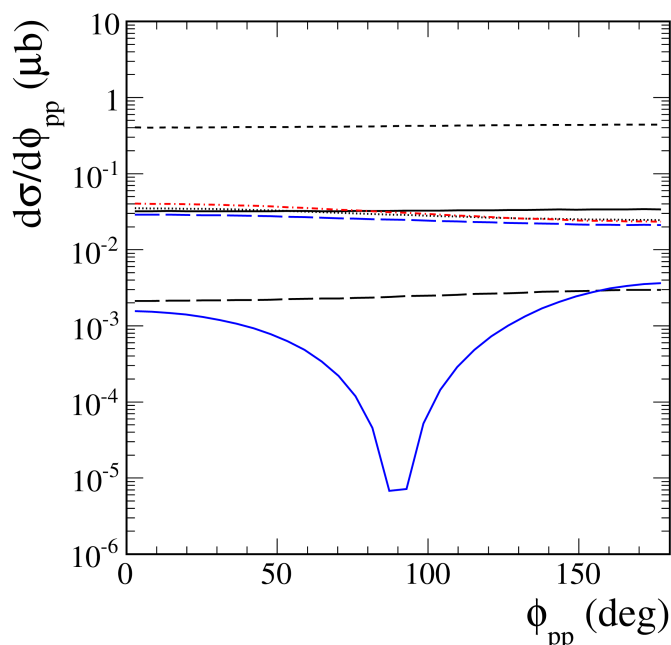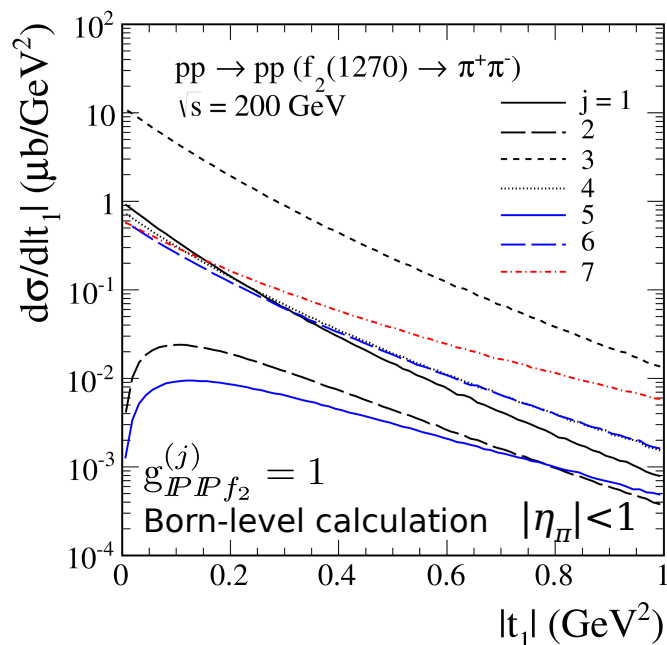
$$i\Gamma^{(\mathbb{P}\mathbb{P}f_2)(5)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{2i}{M_0^3}\, g^{(5)}_{\mathbb{P}\mathbb{P}f_2}\Big(q_1^{\mu_1}\, q_2^{\nu_1}\, R_{\mu\nu\nu_1\alpha}\, R_{\kappa\lambda\mu_1}{}^{\alpha} + q_1^{\nu_1}\, q_2^{\mu_1}\, R_{\mu\nu\mu_1\alpha}\, R_{\kappa\lambda\nu_1}{}^{\alpha}$$
$$- 2(q_1\cdot q_2)\, R_{\mu\nu\kappa\lambda}\Big) q_{1\alpha_1}\, q_{2\lambda_1}\, R^{\alpha_1\lambda_1}{}_{\rho\sigma}$$

$$i\Gamma^{(\mathbb{P}\mathbb{P}f_2)(6)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = \frac{i}{M_0^3}\, g^{(6)}_{\mathbb{P}\mathbb{P}f_2}\Big(q_1^{\alpha_1}\, q_1^{\lambda_1}\, q_2^{\mu_1}\, q_{2\rho_1}\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1}$$
$$+ q_2^{\alpha_1}\, q_2^{\lambda_1}\, q_1^{\mu_1}\, q_{1\rho_1}\, R_{\mu\nu\alpha_1\lambda_1}\, R_{\kappa\lambda\mu_1\nu_1}\Big) R^{\nu_1\rho_1}{}_{\rho\sigma}$$

$$i\Gamma^{(\mathbb{P}\mathbb{P}f_2)(7)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{2i}{M_0^5}\, g^{(7)}_{\mathbb{P}\mathbb{P}f_2}\, q_1^{\rho_1}\, q_1^{\alpha_1}\, q_1^{\lambda_1}\, q_2^{\sigma_1}\, q_2^{\mu_1}\, q_2^{\nu_1}\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1}\, R_{\rho\sigma\rho_1\sigma_1}$$

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.

19

$pp \rightarrow pp$ ($f_2$(1270) $\rightarrow \pi^+\pi^-$)

$\sqrt{s}$ = 200 GeV

j = 1
2
3
4
5
6
7

$g^{(j)}_{IP\,IP\,f_2} = 1$

Born-level calculation $|\eta_\pi| < 1$
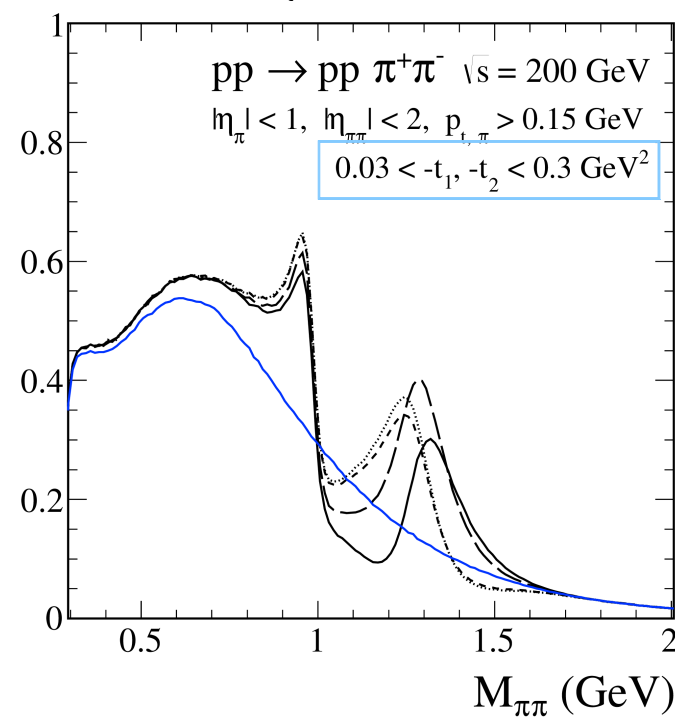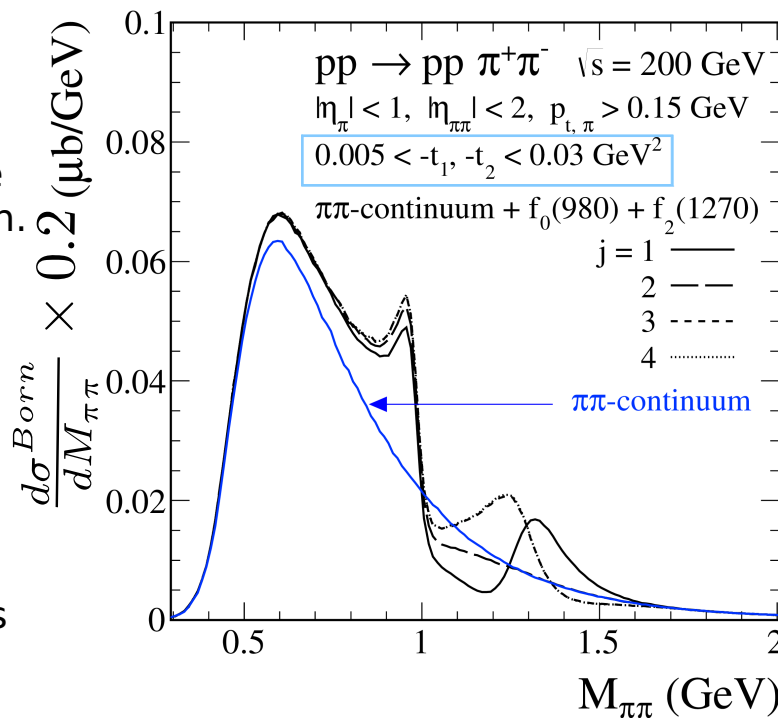
j = 2 coupling is in agreement with experimental observations (WA102, COMPASS, ISR)

→ $f_2$(1270) peaks at $\phi_{pp} \sim 180^o$ and is most prominently observed at large $|t|$ and is suppressed as $dP_t \rightarrow 0$ (undisputed $q\bar{q}$ state)
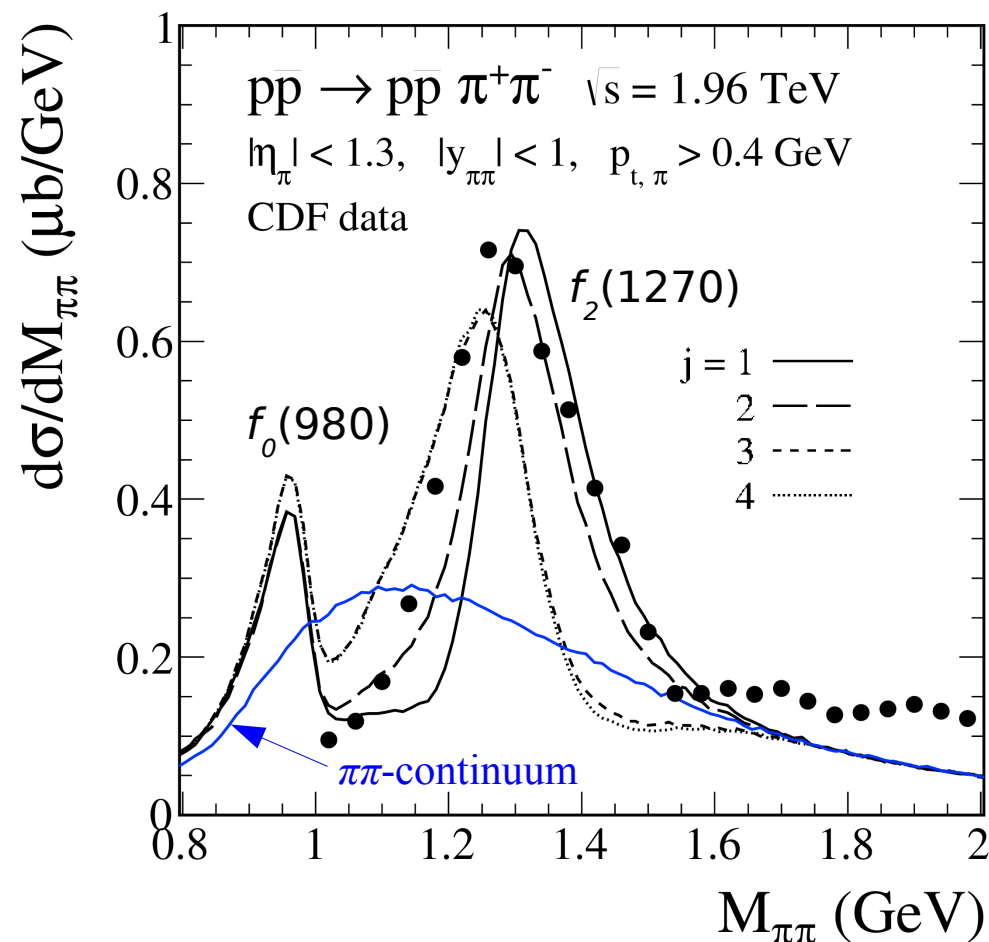
Different couplings generate different interference pattern.

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 exp. groups (AFS, ABCDHW)



$pp \rightarrow pp\ \pi^+\pi^-$ $\sqrt{s}$ = 200 GeV

$|\eta_\pi| < 1,\ |\eta_{\pi\pi}| < 2,\ p_{t,\pi} > 0.15$ GeV

$0.005 < -t_1, -t_2 < 0.03$ GeV$^2$

$\pi\pi$-continuum + $f_0$(980) + $f_2$(1270)

j = 1
2
3
4

$\pi\pi$-continuum

$pp \rightarrow pp\ \pi^+\pi^-$ $\sqrt{s}$ = 200 GeV

$|\eta_\pi| < 1,\ |\eta_{\pi\pi}| < 2,\ p_{t,\pi} > 0.15$ GeV

$0.03 < -t_1, -t_2 < 0.3$ GeV$^2$

20

$$pp \to pp\,\pi^+\pi^- \quad \sqrt{s} = 1.96 \text{ TeV}$$

$|\eta_\pi| < 1.3, \quad |y_{\pi\pi}| < 1, \quad p_{t,\pi} > 0.4 \text{ GeV}$

CDF data

$f_2(1270)$

$f_0(980)$

$j = 1$ ———
$2$ — —
$3$ - - - - -
$4$ ·········

$\pi\pi$-continuum

$M_{\pi\pi}$ (GeV)

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.

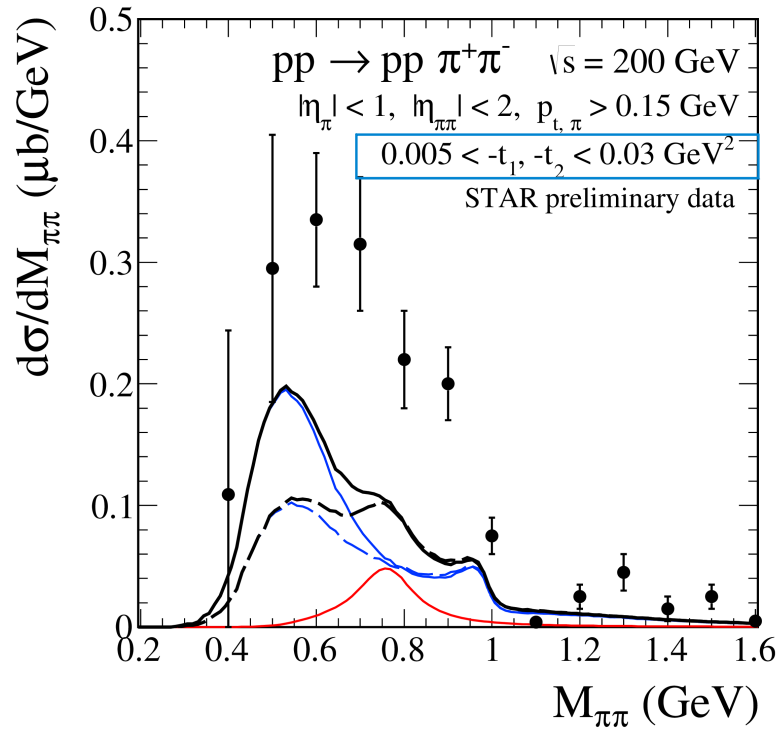We take the monopole form for off-shell pion form factors with $\Lambda_{\text{off,M}} = 0.7$ GeV.

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
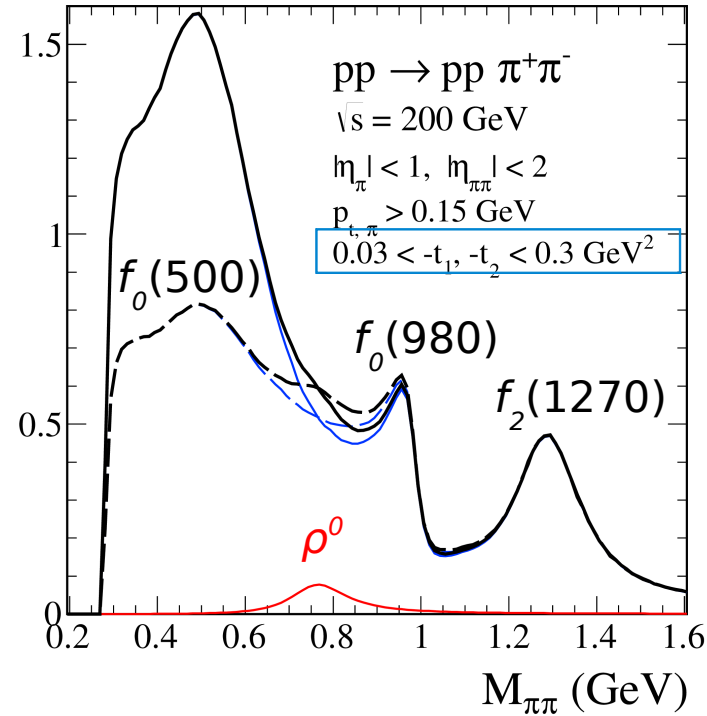
- Blue lines (diffractive term), red line ($\rho^0$ term), black lines (complete result)

- In calculation of $f_2$ term only one of the $IP\text{-}IP\text{-}f_2$ 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
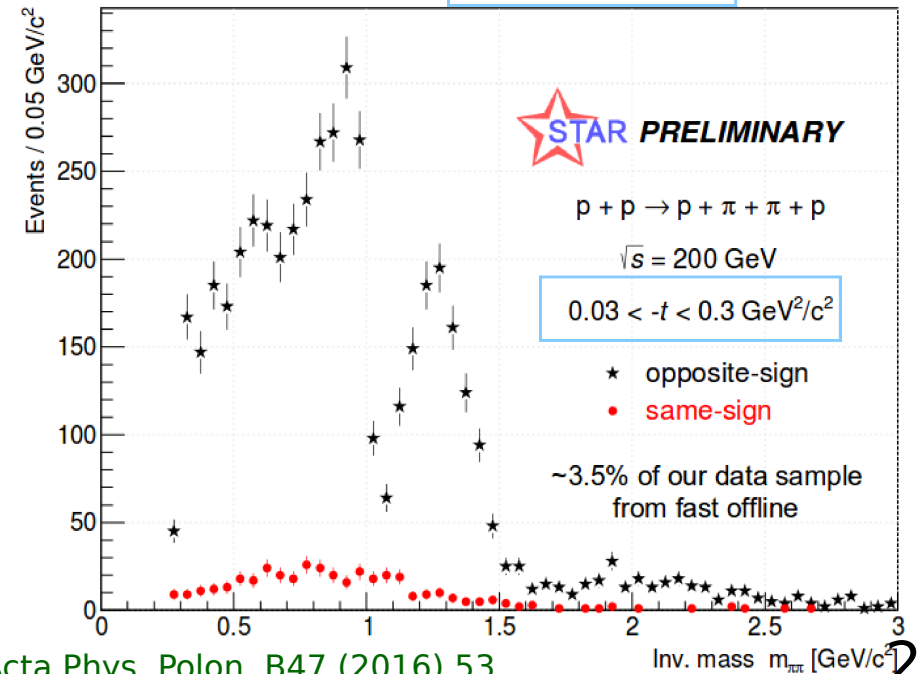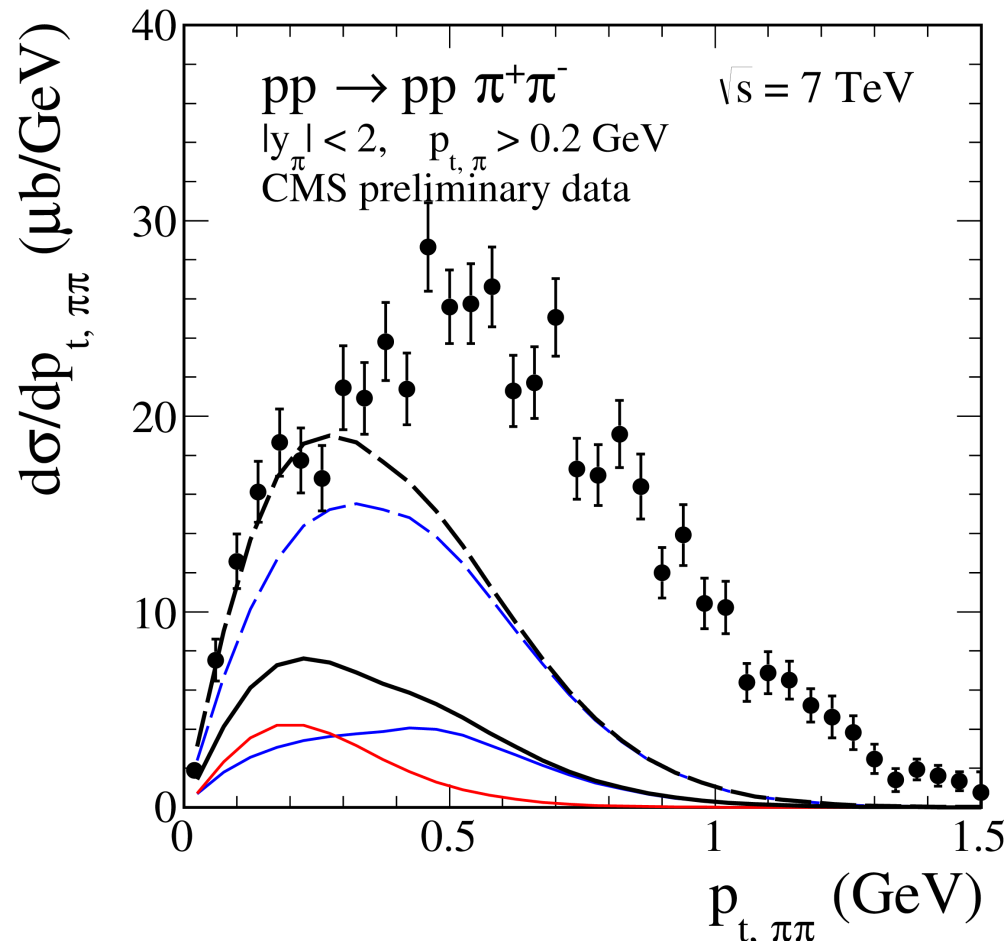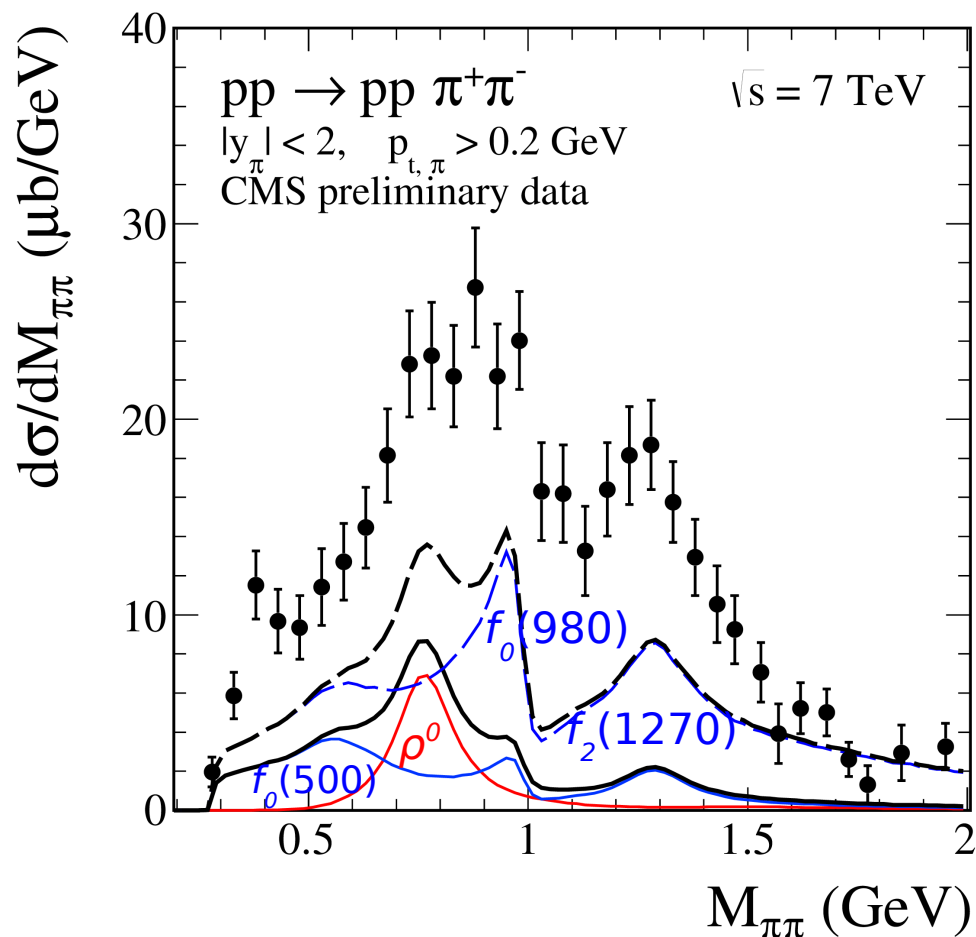
In diff. continuum term: (solid blue line) $\Lambda_{off,M}$ = 0.7 GeV (the same couplings as for CDF predictions)
(dashed blue line) $\Lambda_{off,M}$ = 1.2 GeV, with enhanced $f0(980)$ and $f2$ couplings

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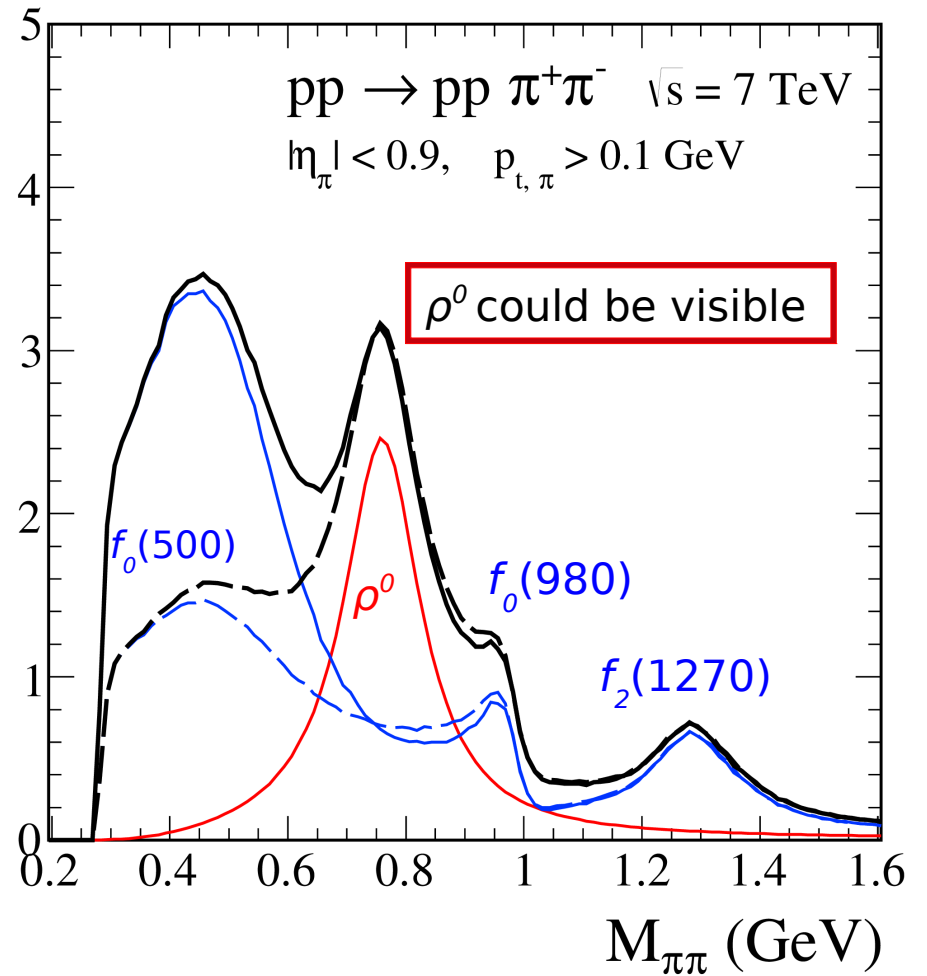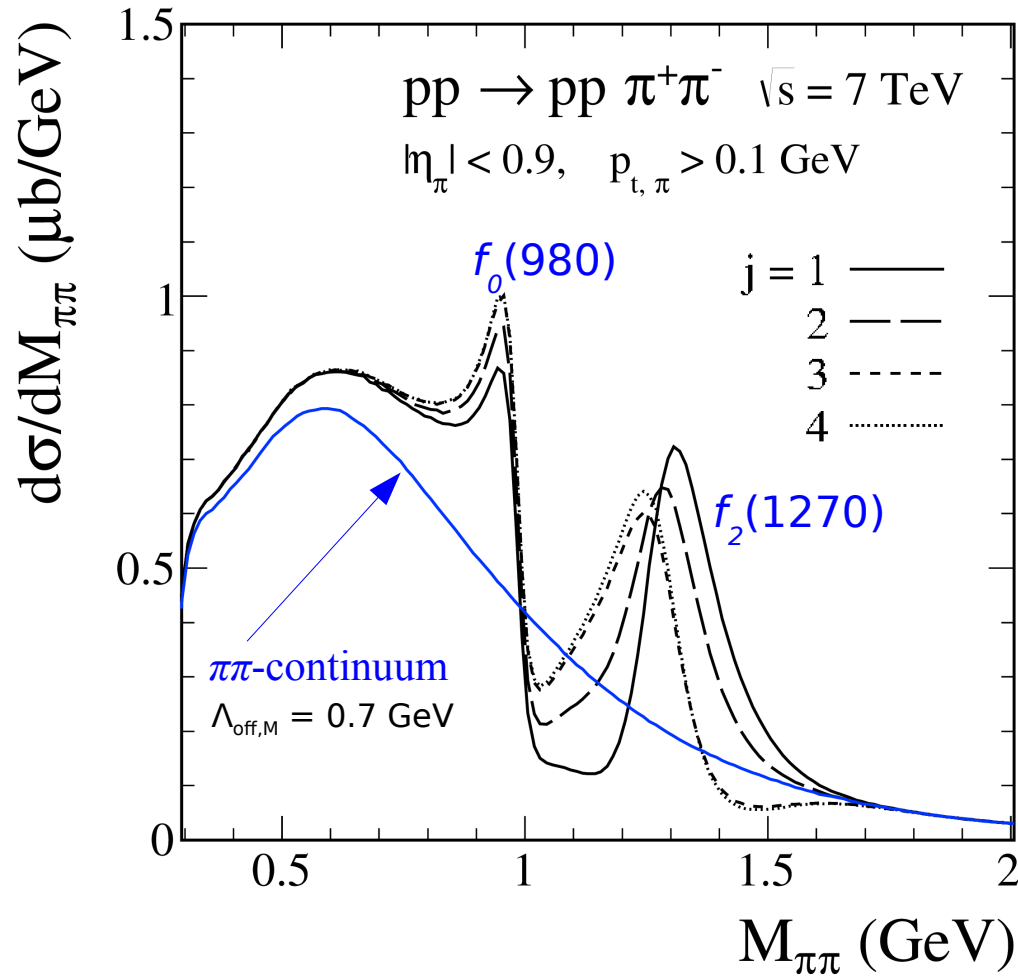
Our model results are much below the CMS preliminary data (CMS-PAS-FSQ-12-004) which could be due to a contamination of non-exclusive processes (one or both protons undergoing dissociation).

$< S^2 > \simeq 0.1$ for the diffractive contribution

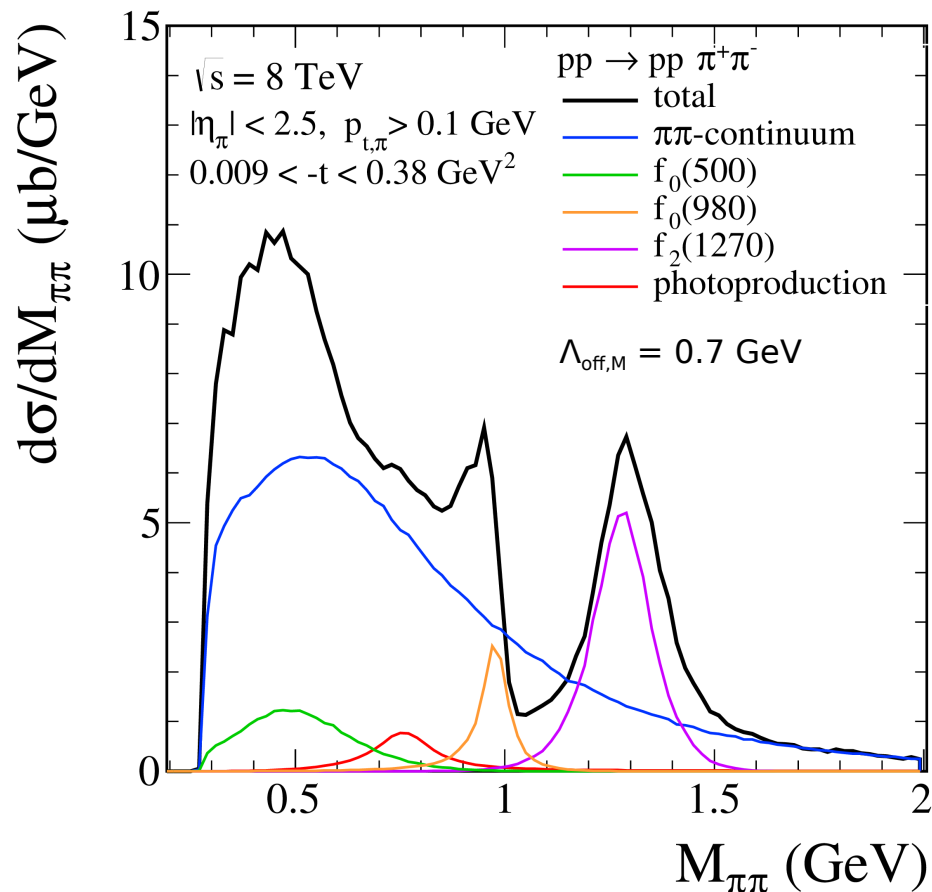$< S^2 > \simeq 0.9$ for the photon-IP/IR contribution    $\rho^0$ could be visible

23

Different *IP-IP-f$_2$* couplings generate different interference pattern.

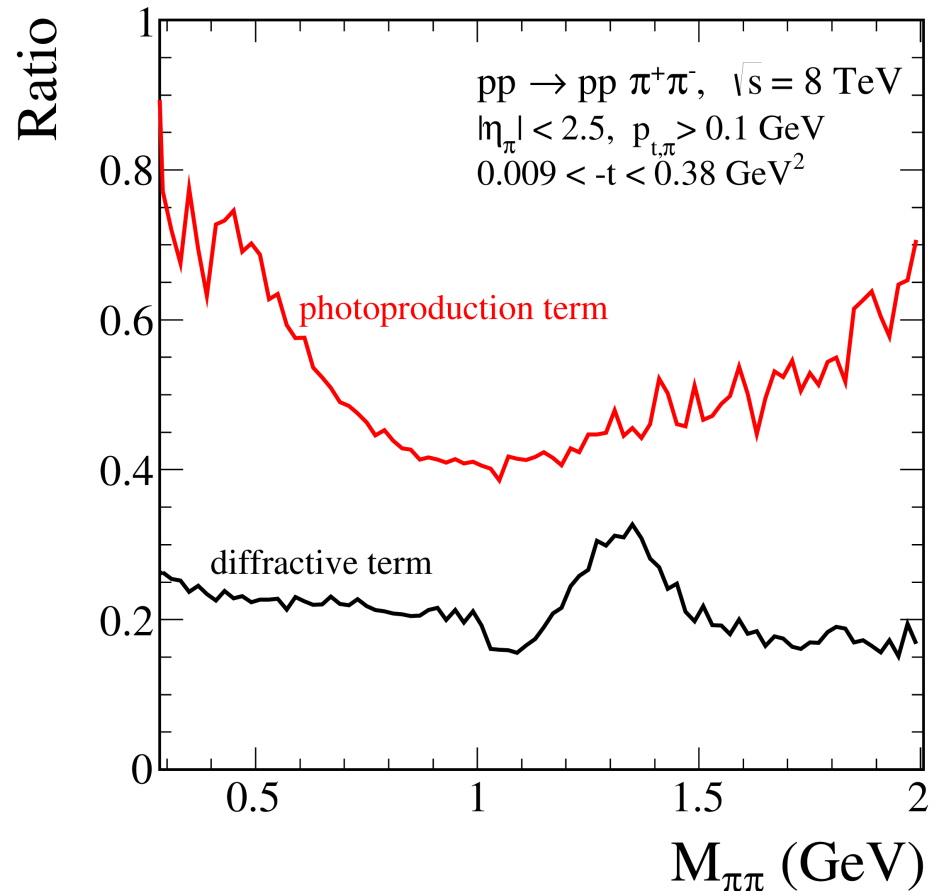$< S^2 > \simeq 0.1$ for the diffractive contribution

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

Ratio of full (absorbed)-to-Born cross section



Here we take the absorption corrections due to *pp*-rescattering only.
The absorption effect depends on the *t* region in which is considered.

Cross sections: at  8 TeV (7.09 – 14.11) µb,
at 13 TeV (7.35 – 14.57) µb,
for two off-shell pion form factor parameters $\Lambda_{off,M}$ = (0.7 – 1.0) GeV, respectively.

See also: R. Staszewski, P. L., M. Trzebiński, J. Chwastowski, A. Szczurek, *Exclusive π⁺π⁻ Production at the LHC with Forward Proton Tagging*, arXiv: 1104.3568, Acta Phys. Polon. B42 (2011) 1861

2dim diff. cross sections in $\mu b$
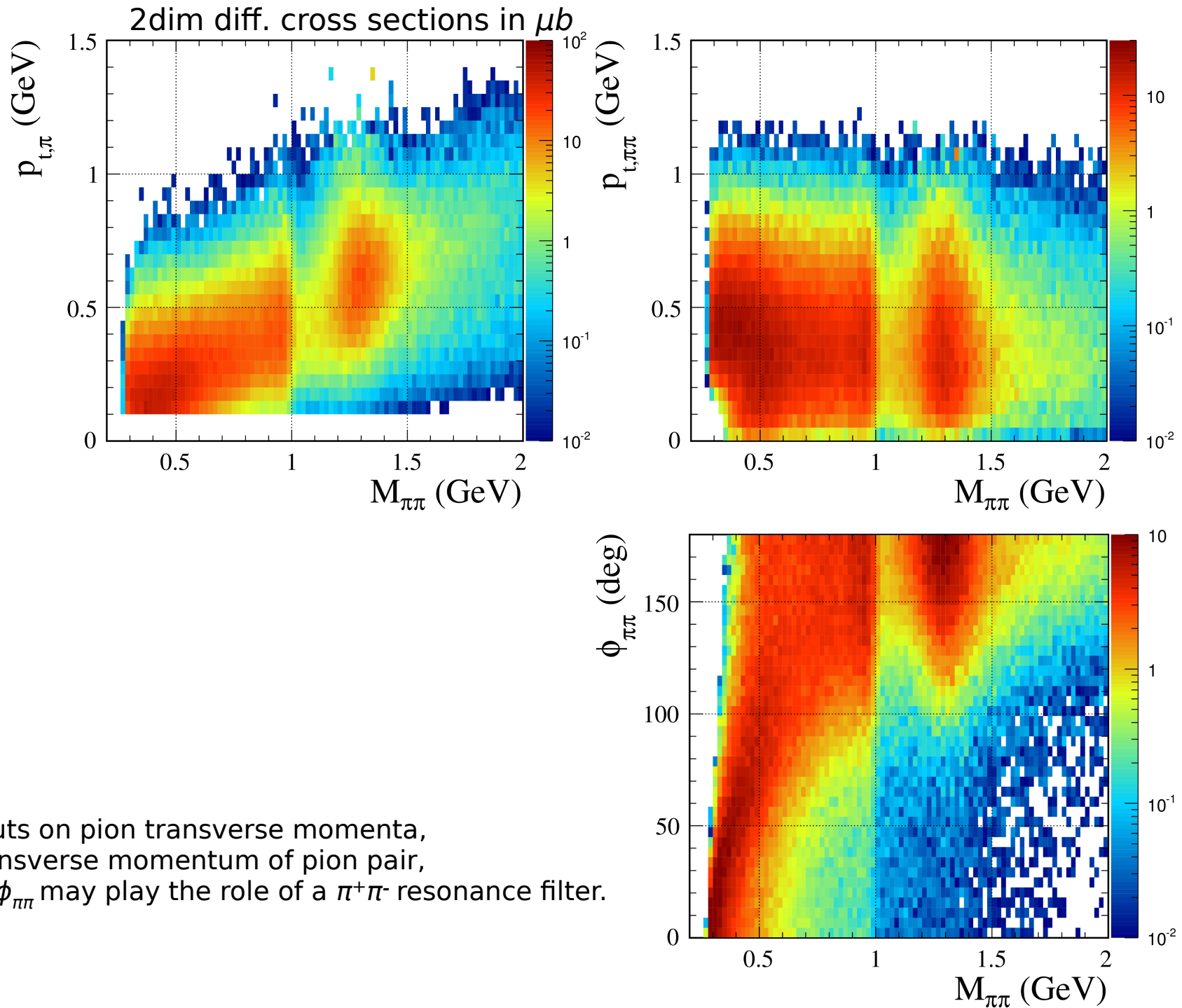
The cuts on pion transverse momenta,
on transverse momentum of pion pair,
or on $\phi_{\pi\pi}$ may play the role of a $\pi^+\pi^-$ resonance filter.

26

pion exchange          neutron exchange          direct production
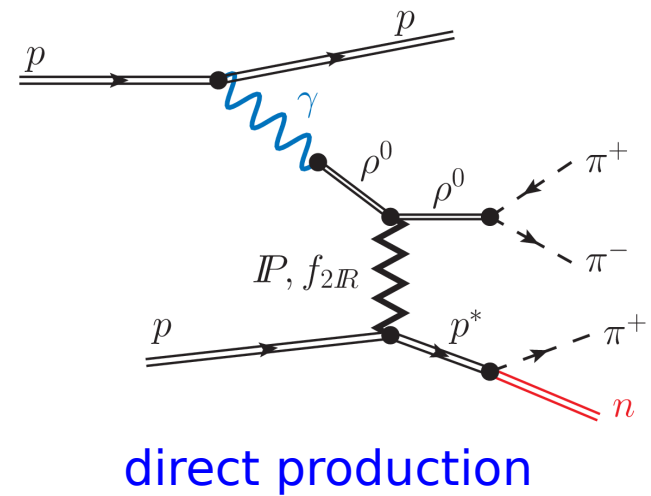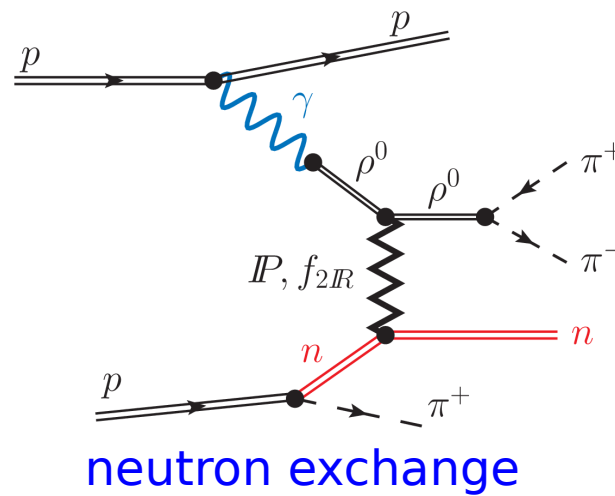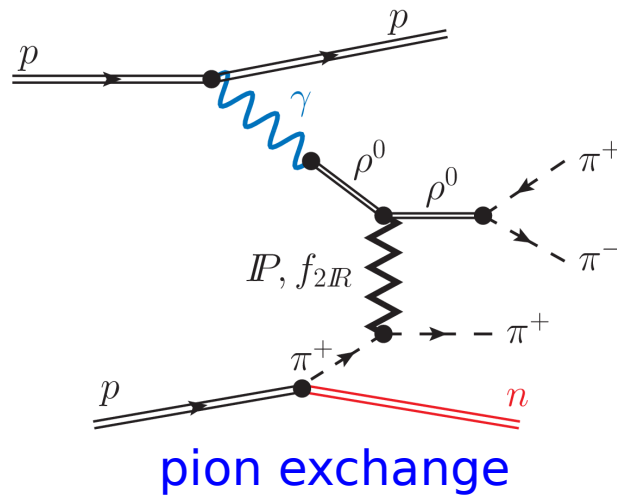
- Motivated by the study of diffractive $\pi^0$-strahlung in $pp \to pp\pi^0$ process (Drell-Hiida-Deck model) we consider here only contributions related to the diffractive $p \to \pi N$ transition.
  At large $s$ and small $|t|$ in $p$-$n$ vertex the pion exchange contribution dominates.
  P. L., A. Szczurek, Phys. Rev. D87 (2013) 074037

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

- The $pp \to pn\rho^0\pi^+$ reaction was discussed recently in the dipole saturation-inspired approach
  V.P. Goncalves $et\ al.$, Phys. Rev. D94 (2016) 014009

27

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

We have estimated first predictions within the (soft) tensor pomeron framework.
We take into account only pion exchange contribution.
No absorption effects were included.
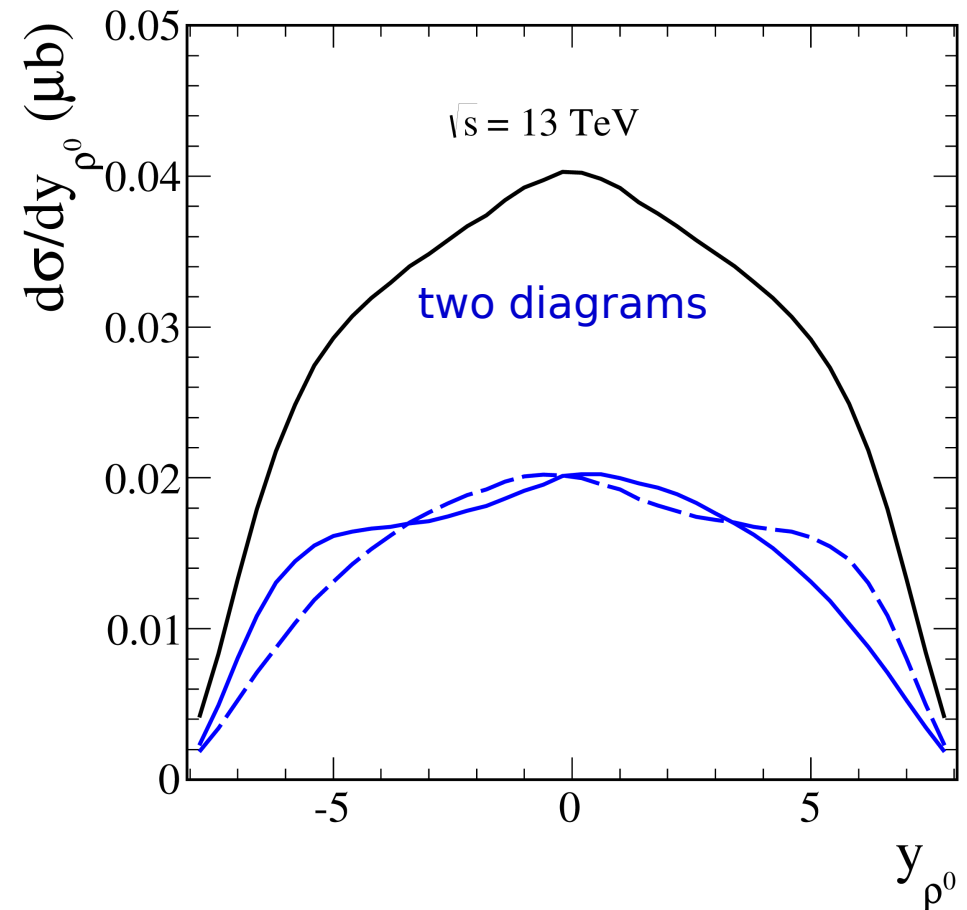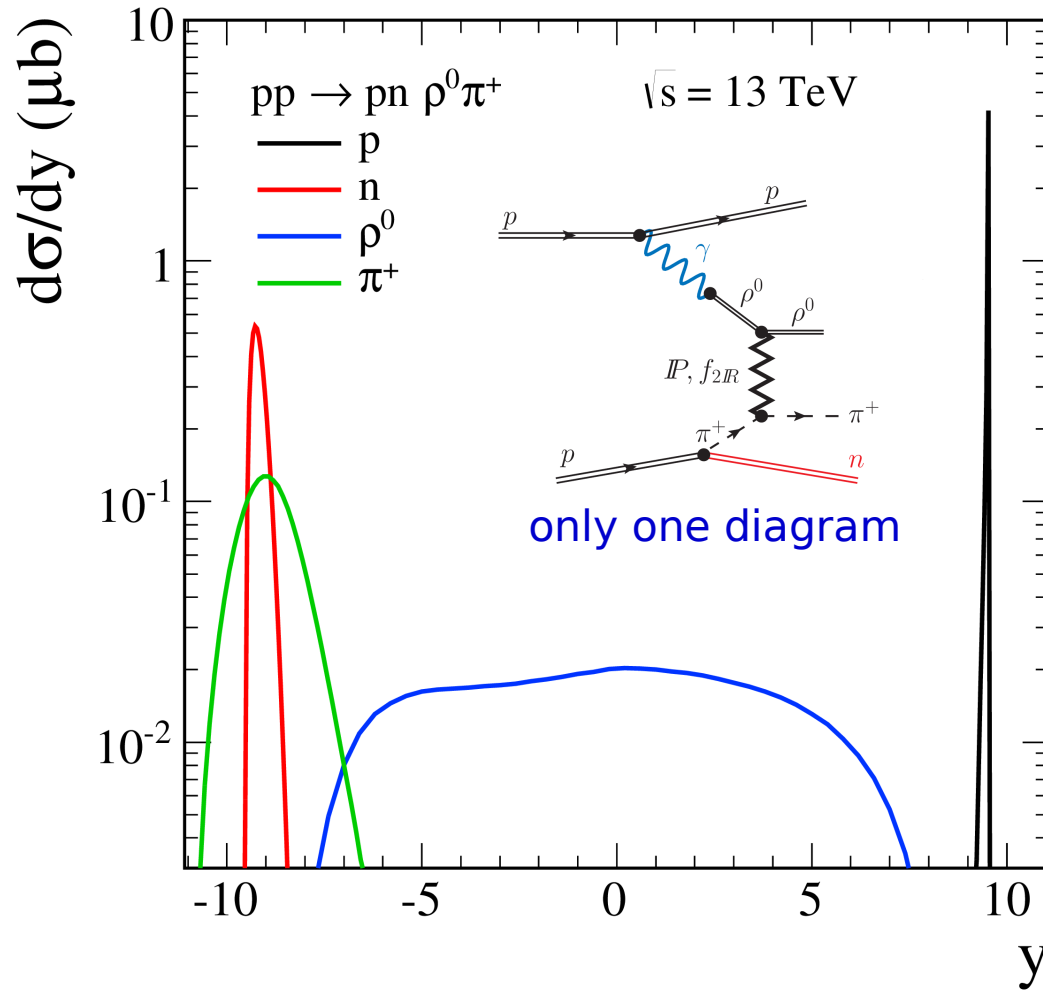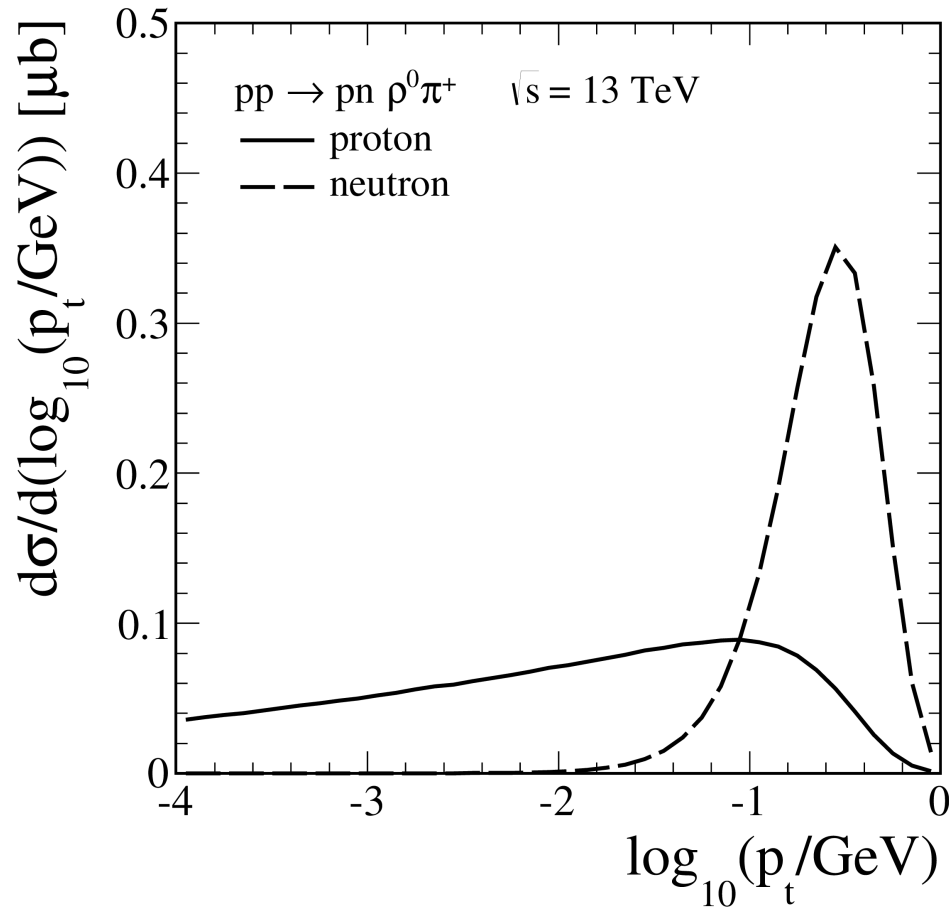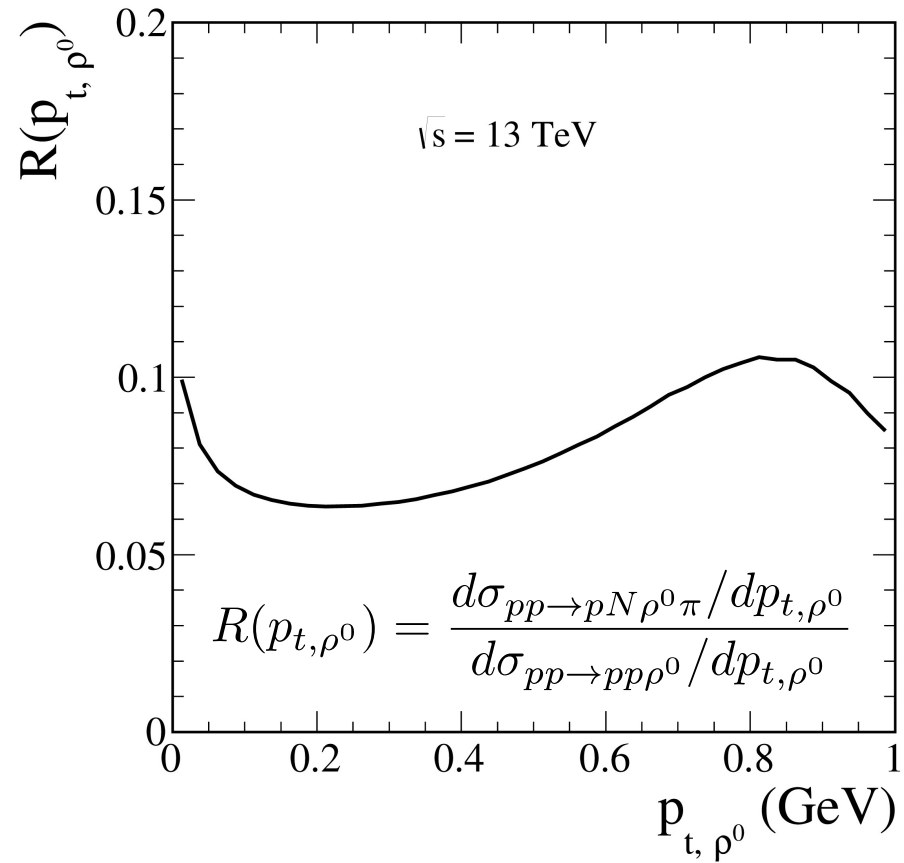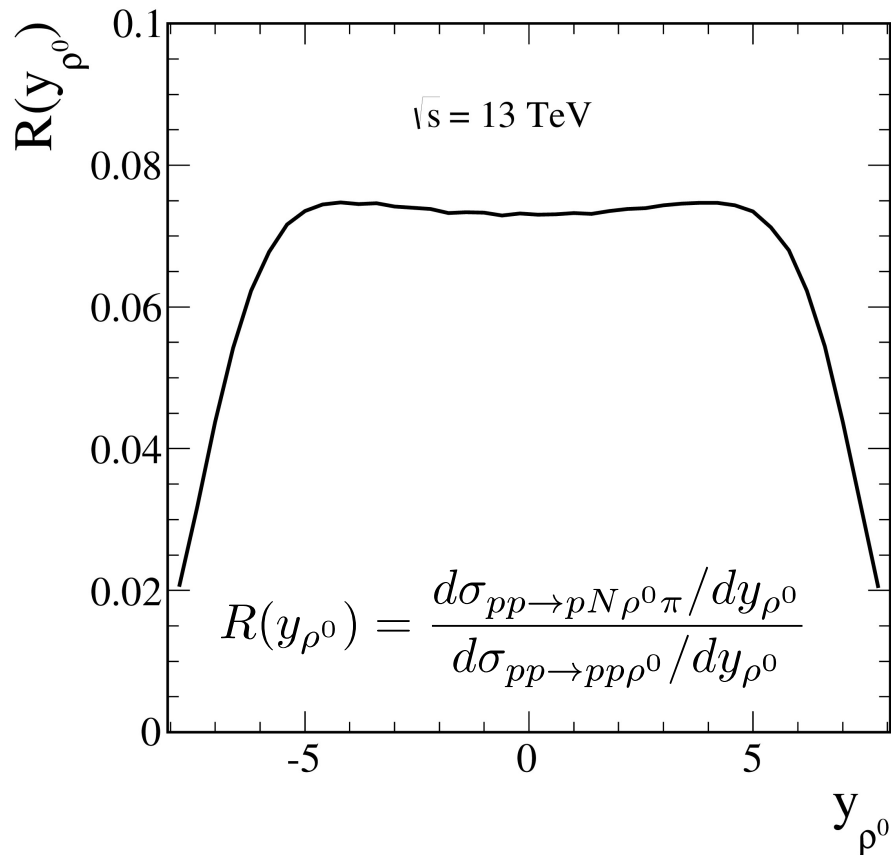


Due to specificity of the reaction the corresponding amplitudes do not interfere as some of the particles in the final state are emitted in different hemispheres (exclusively forward or backward) for the two amplitudes (mechanisms).

# $pp \rightarrow pn\rho^0\pi^+$

We take into account only pion exchange contribution (results for only one diagram).
No absorption effects were included.
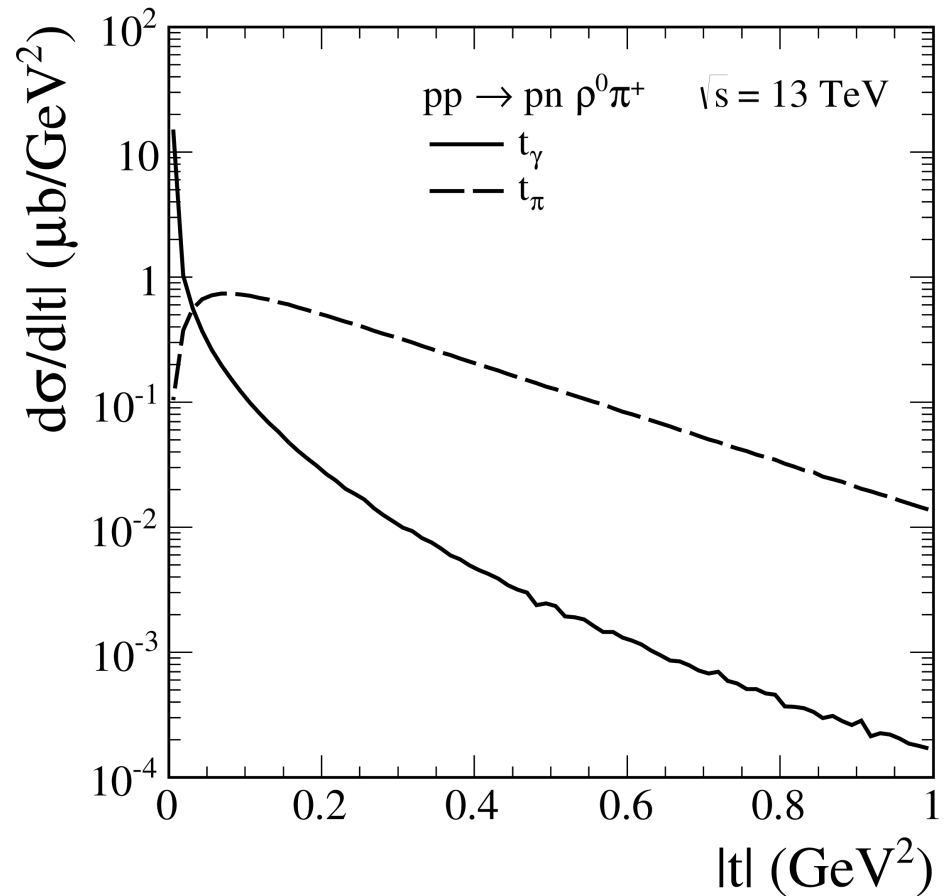
## How large are discussed "inelastic" processes $pp \to pn\rho^0\pi^+$ and $pp \to pp\rho^0\pi^0$ compared to "elastic" (exclusive) $pp \to pp\rho^0$ process ?



$$R(y_{\rho^0}) = \frac{d\sigma_{pp \to pN\rho^0\pi}/dy_{\rho^0}}{d\sigma_{pp \to pp\rho^0}/dy_{\rho^0}}$$

$$R(p_{t,\rho^0}) = \frac{d\sigma_{pp \to pN\rho^0\pi}/dp_{t,\rho^0}}{d\sigma_{pp \to pp\rho^0}/dp_{t,\rho^0}}$$

- the ratio of integrated cross sections $\sigma_{2\to4}/\sigma_{2\to3} \approx 0.7\,\mu b / 10.3\,\mu b \approx 0.07$
- almost no dependence on rapidity (except of the edges of the phase space)
- an interesting pattern for the ratio of transverse momentum
- $pp \to pn\rho^0\pi^+$ reaction may be a prototype for the $pp \to pn\,J/\Psi\pi^+$ reaction

30

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

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



$\sqrt{s} = 62$ GeV $\qquad$ pp $\to$ pp $\pi^+\pi^-\pi^+\pi^-$

$|x_p| > 0.9, \quad |y_\pi| < 1.5$

- ○ ISR data, total
- ● ISR data, J=0
- --- $\sigma\sigma, \Lambda_{off,M}$
- -- $\sigma\sigma, \Lambda_{off,E}$

results with set B

$\Lambda_{off,M} = \Lambda_{off,E} = 1.6$ GeV

$< S^2 > \simeq 0.4$
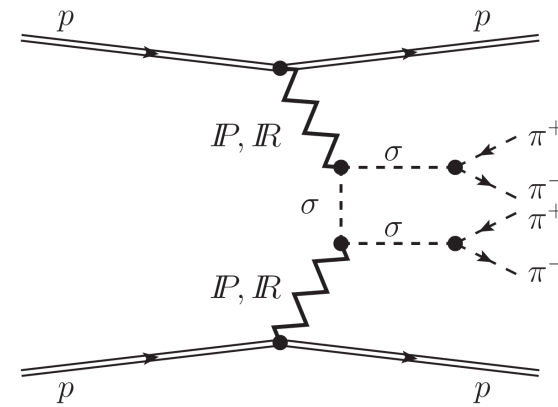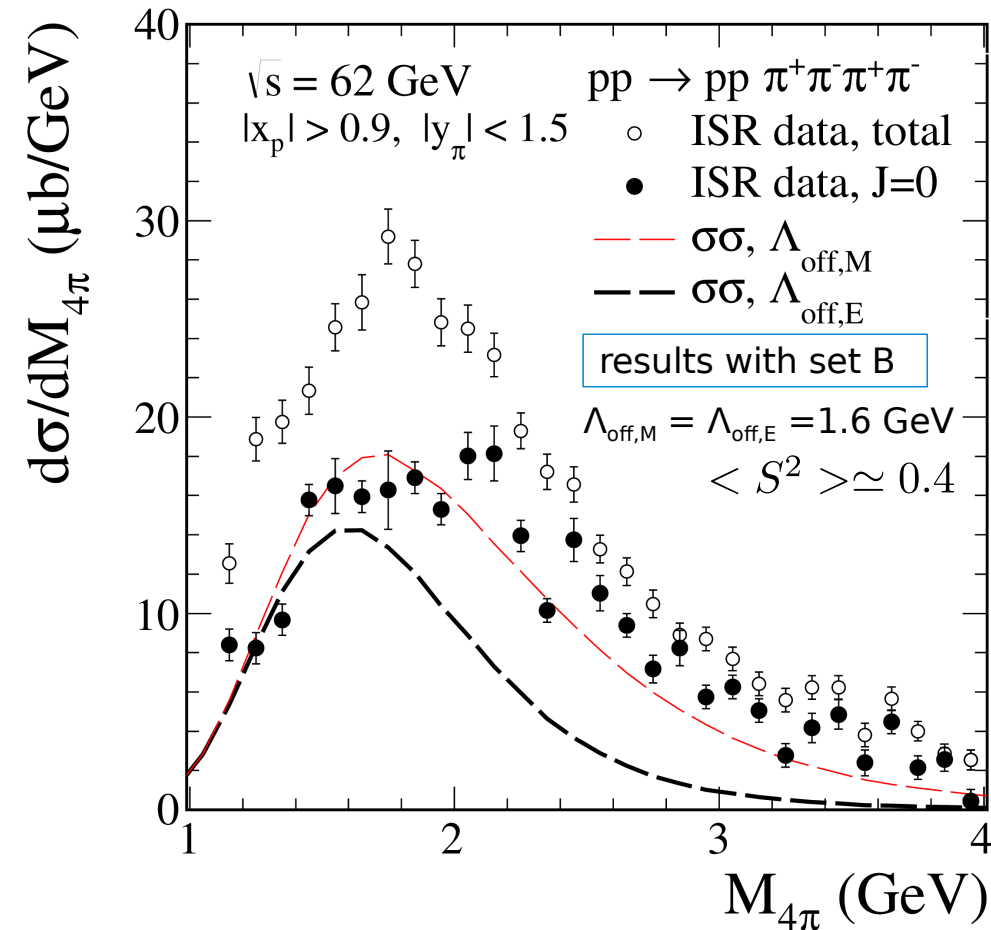


as for dipion continuum

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 : $\beta_{I\!P\sigma\sigma} = 4\beta_{I\!P\pi\pi}$ , $g_{f_2I\!R\sigma\sigma} = 2g_{f_2I\!R\pi\pi}$

enhanced coupling constants

The $4\pi$ 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
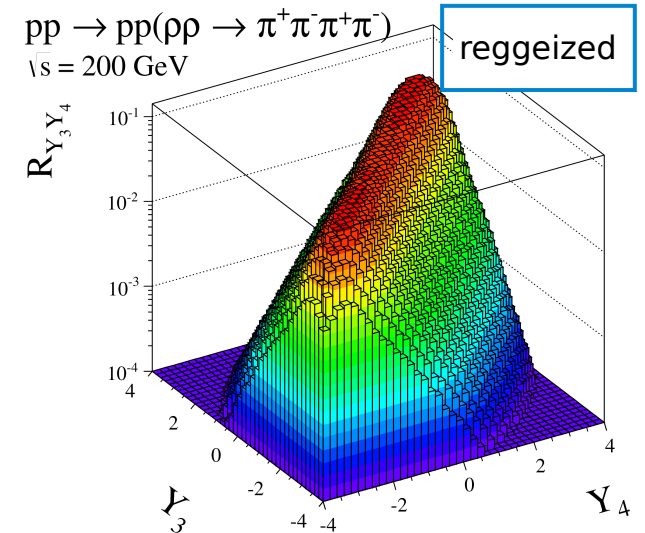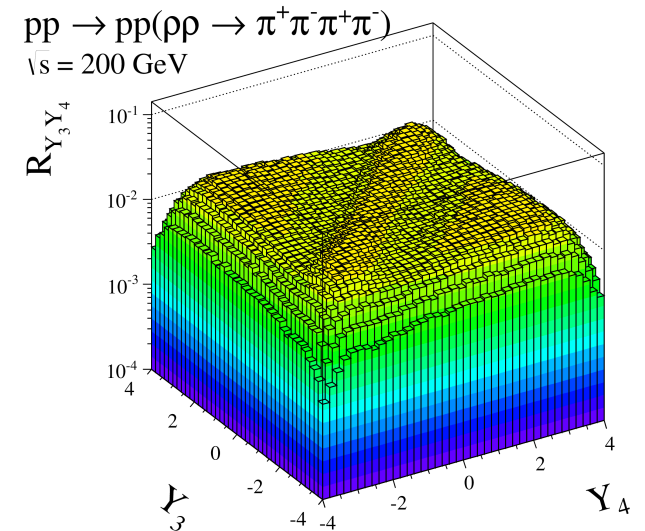
# 4π production (ρρ contribution)



$\sqrt{s} = 62$ GeV
$|x_p| > 0.9$, $|y_\pi| < 1.5$

$f_2(1270)$?

pp → pp π⁺π⁻π⁺π⁻
- ISR data, ρρ
- - - ρρ, $\Lambda_{off,M}$
- · · · ρρ, $\Lambda_{off,E}$
- — ρρ, reggeized

$\Lambda_{off,M} = \Lambda_{off,E} = 1.6$ GeV
$< S^2 > \simeq 0.4$

$\Lambda_{off,M} = 1.8$ GeV

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

pp → pp(ρρ → π⁺π⁻π⁺π⁻)
$\sqrt{s} = 200$ GeV

pp → pp(ρρ → π⁺π⁻π⁺π⁻)
$\sqrt{s} = 200$ GeV
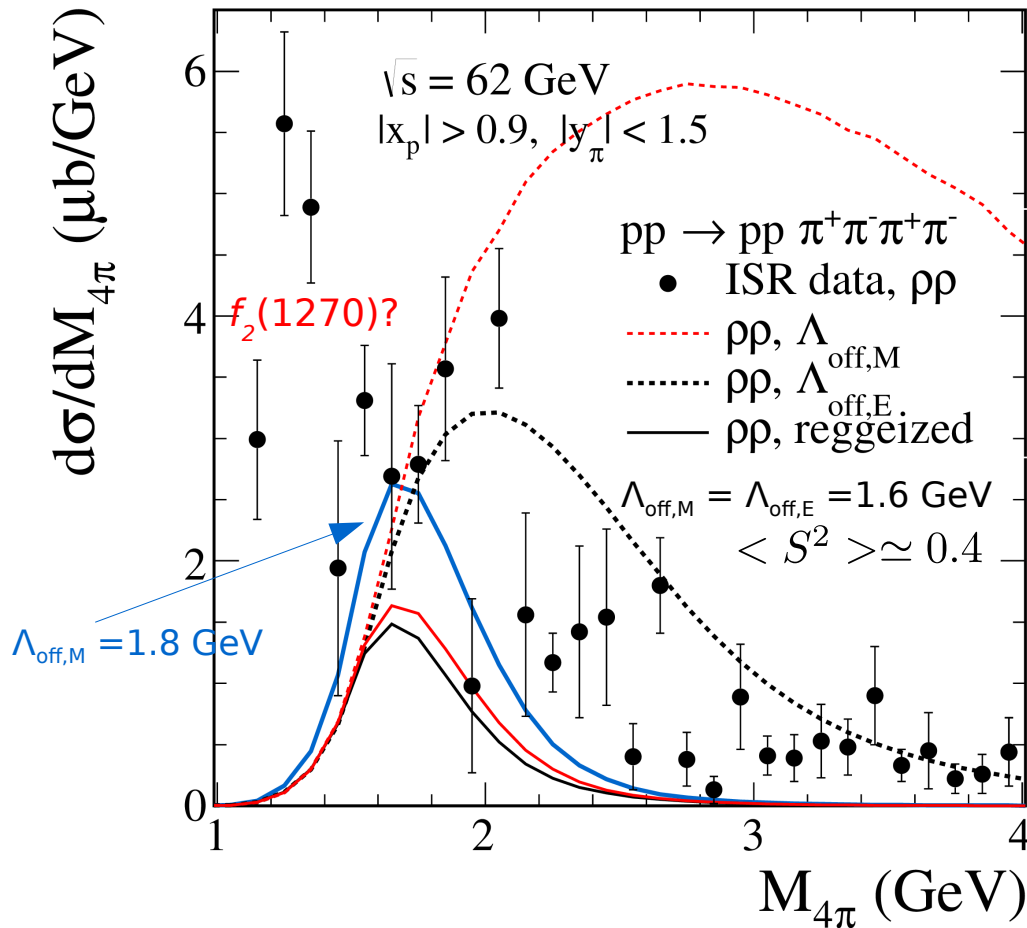
reggeized

- reggeization effect

$$\Delta^{(\rho)}_{\rho_1 \rho_2}(p) \rightarrow \Delta^{(\rho)}_{\rho_1 \rho_2}(p) \left( \frac{s_{34}}{s_0} \right)^{\alpha_\rho(p^2)-1}, \qquad s_0 = 4m_\rho^2$$

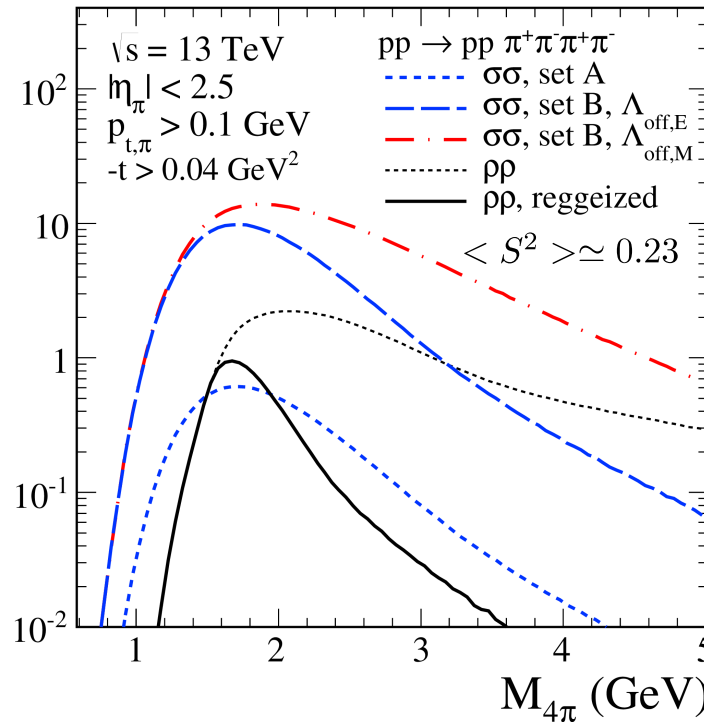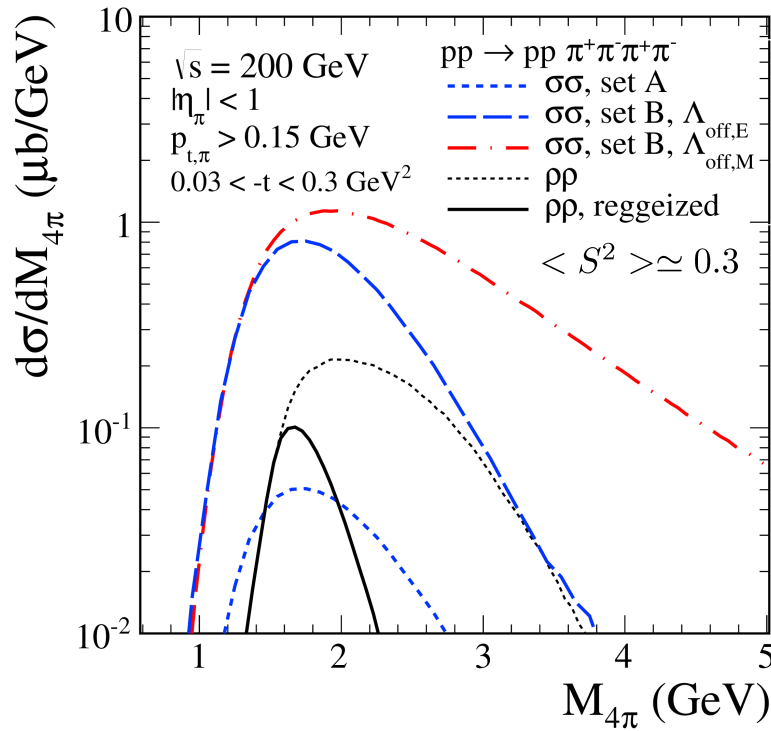becomes crucial when the separation in rapidity between two ρ mesons increases $|Y_3 - Y_4| > 0$

see also discussion in
L.A. Harland-Lang, V.A. Khoze, M.G. Ryskin, arXiv:1312.4553, Eur. Phys. J. C74 (2014) 2848

Absorption effects due to *pp*-rescattering were included.

Here $\Lambda_{off,E}$ = 1.6 GeV.

| $\sqrt{s}$, TeV | Cuts | "Born level" cross sections in $\mu b$ | |
|---|---|---|---|
| | | $\sigma\sigma$ (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 $\mu b$. The $\sigma\sigma$ contribution was calculated with the enhanced (set B) couplings while the $\rho\rho$ contribution without and with (in the parentheses) inclusion of $\rho$ 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 $|t|$).

# Conclusions

- The tensor-pomeron model (Ewerz-Maniatis-Nachtmann) was applied to many $pp \rightarrow pp$ *meson(s)* reactions. The amplitudes are formulated in terms of effective vertices and propagators respecting the standard crossing and charge conjugation relations of QFT.

- Studying the ratio $r_5$ of single-helicity-flip to non-flip amplitudes in polarised high-energy $pp$ elastic scattering we found that the STAR data are consistent with a tensor pomeron approach while they clearly exclude a scalar pomeron.

- We have given a consistence treatment of the $\pi^+\pi^-$ continuum and resonance production in proton-(anti)proton collisions. The $pp \rightarrow pp\pi^+\pi^-$ process is an attractive for different exp.: COMPASS, STAR, CDF, ALICE, CMS, ATLAS, LHCb. We include $f_0(500)$, $f_0(980)$, $f_2(1270)$ and $\rho^0$ contributions which interfere with the continuum. 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. The model parameters have been adjusted to HERA and CDF data and then used for the predictions for STAR, ALICE, and CMS experiments. Disagreement with the preliminary CMS data could be due to a large dissociation contribution. Purely exclusive data expected from CMS+TOTEM and ATLAS+ALFA will allow us to draw definite conclusions.

- 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.

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

- We have discussed $pp \rightarrow pN\rho^0\pi$ processes in the context of background to the $pp \rightarrow pp\rho^0$ reaction. The ratio of integrated cross sections is of the order of 7%. While it weakly depends on $\rho^0$ rapidity we predict an interesting pattern in transverse momentum.

- In progress: MC generator for the soft reactions $pp \rightarrow pp\pi^+\pi^-$ and $pp \rightarrow ppK^+K^-$ within tensor pomeron approach (see talk by Paula Erland), analysis of other mechanisms in the context of $4\pi$ production

*Related works:*

- P. Lebiedowicz, R. Pasechnik, A. Szczurek, *Measurement of exclusive production of $\chi_{c0}$ 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

# Acknowlegments