Exclusive diffractive production of pion pairs and resonances in proton-proton collisions within tensor pomeron approach

Piotr Lebiedowicz

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

in collaboration with Otto Nachtmann and Antoni Szczurek

DIFFRACTION 2016

International Workshop on Diffraction in High-Energy Physics
2-8 September 2016, Acireale (Italy)

Plan

1) Diffractive mechanism of $\pi^+\pi^-$ production (continuum, scalar and tensor resonances)

2) Photoproduction mechanism (ρ^0 and non-resonant (Drell-Söding) contributions)

3) Diffractive production of $\pi^+\pi^-\pi^+\pi^-$ 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, *ρ^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

The nature of soft pomeron

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.

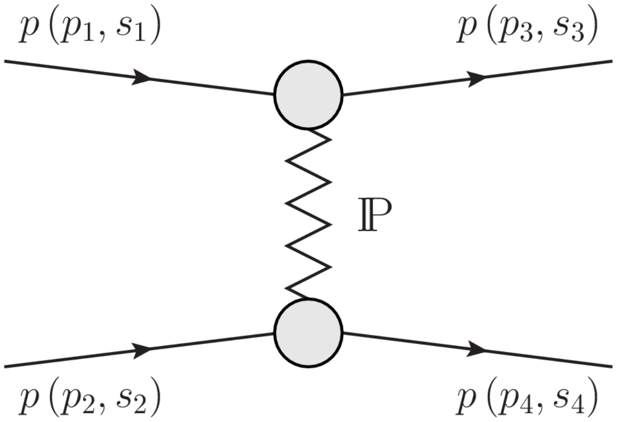
- However, a vector pomeron is widely used in the literature [Donnachie and Landshoff]
- In [C. Ewerz, M. Maniatis, O. Nachtmann, Annals Phys. 342 (2014) 31] it was proposed to describe the soft pomeron as an effective rank-2 symmetric tensor exchange.

  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.

pp elastic scattering

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

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

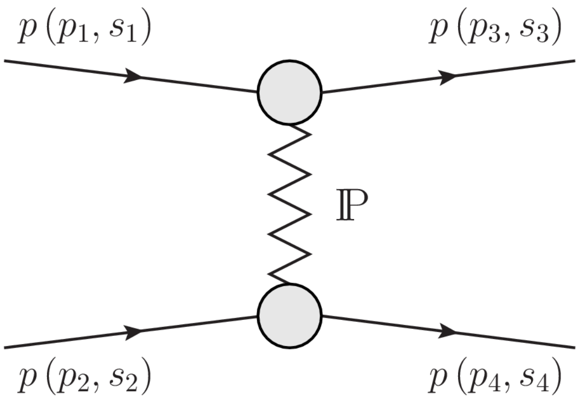
The amplitudes with no helicity flip are ϕ_1 and ϕ_3, with single flip ϕ_5, and with double flip ϕ_2 and ϕ_4.

The total cross section for unpolarised protons is

$$\sigma_{tot}(pp) = \frac{1}{s(s-4m_p^2)} \frac{1}{4} \sum_{s_1,s_2} \mathrm{Im} < 2s_3, 2s_4|\mathcal{T}|2s_1, 2s_2 >|_{t=0}$$
$$= \frac{1}{2\sqrt{s(s-4m_p^2)}} \mathrm{Im}\left[\phi_1(s,0) + \phi_3(s,0)\right]$$

Tensor and scalar pomeron ansatz

Tensor pomeron



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

$$< p(p', s')|J_{T\,\mu\nu}(0)|p(p, s) >= \bar{u}(p', s')\Gamma_{\mu\nu}^{((I\!P_T pp)}(p', p)u(p, s)$$

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

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

$$i\Gamma_{\mu\nu}^{(I\!P_T pp)}(p', p) = i\Gamma_{\mu\nu}^{(I\!P_T \bar{p}\bar{p})}(p', p) = -i3\beta_{I\!P NN}F_1\big((p'-p)^2\big)\left\{\frac{1}{2}[\gamma_\mu(p'+p)_\nu + \gamma_\nu(p'+p)_\mu] - \frac{1}{4}g_{\mu\nu}(\not{p}' + \not{p})\right\}$$

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

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

Scalar pomeron

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

$$i\Gamma_{\mu\nu}^{(I\!P_S pp)}(p', p) = i\Gamma_{\mu\nu}^{(I\!P_S \bar{p}\bar{p})}(p', p) = -i3\beta_{I\!P NN}M_0 F_1\big((p'-p)^2\big)$$

Vector pomeron ansatz

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

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

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

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.

Comparison with experiment

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

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

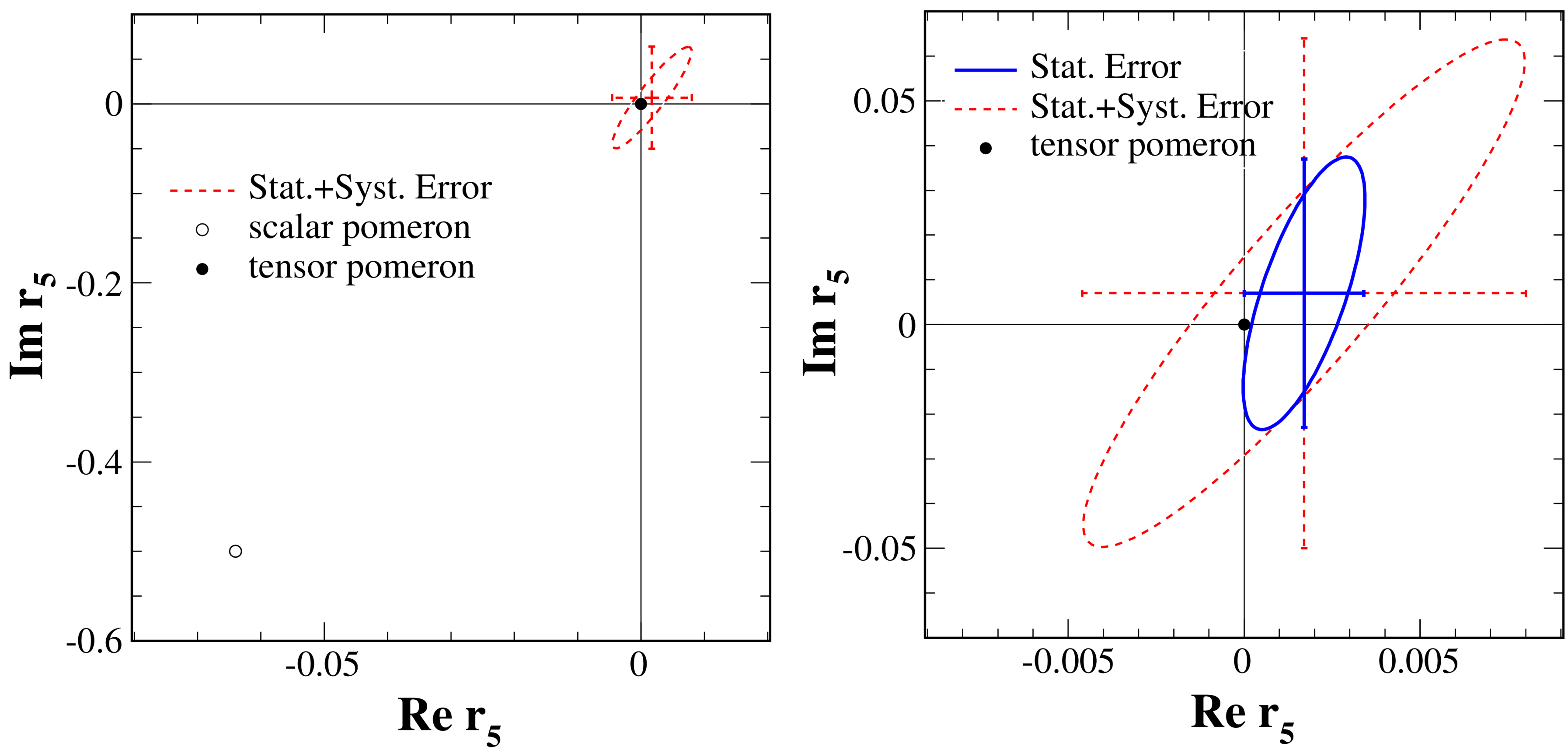
We find (arXiv:1606.08067) for the tensor and scalar pomeron cases

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

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

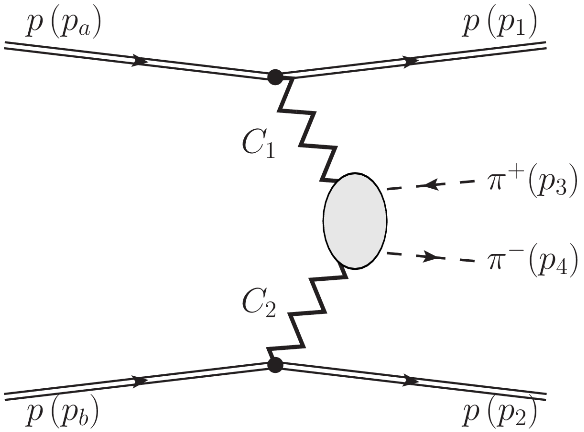
The measurement of r_5 is done for $0.003 \leqslant |t| \leqslant 0.035$ GeV^2 and no t-dependence of r_5 is observed in this range. Therefore, we can approximately set $t = 0$ and obtain with $\sqrt{s} = 200$ GeV

$$r_5^T(s,0) = (-0.28 - i2.20) \times 10^{-5}\,,$$
$$r_5^S(s,0) = -0.064 - i0.500\,.$$



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

Dipion continuum production



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

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

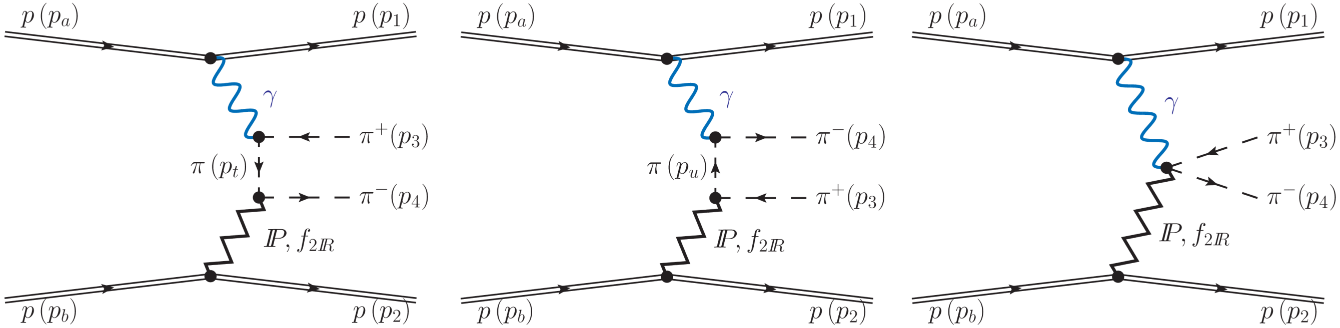
$$(C_1, C_2) = (1,1): \quad (I\!P + f_{2I\!R}, I\!P + f_{2I\!R})$$
$$(C_1, C_2) = (-1,-1): \quad (\rho_{I\!R} + \gamma, \rho_{I\!R} + \gamma)$$
$$(C_1, C_2) = (1,-1): \quad (I\!P + f_{2I\!R}, \rho_{I\!R} + \gamma)$$
$$(C_1, C_2) = (-1,1): \quad (\rho_{I\!R} + \gamma, I\!P + f_{2I\!R})$$

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

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



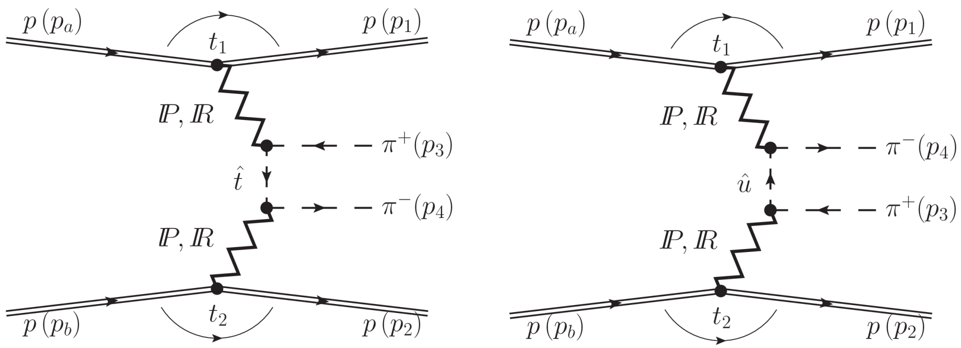
The inclusion of these diagrams is a gauge invariant version of the Drell-Söding mechanism.

Diffractive dipion continuum production

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

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

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

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

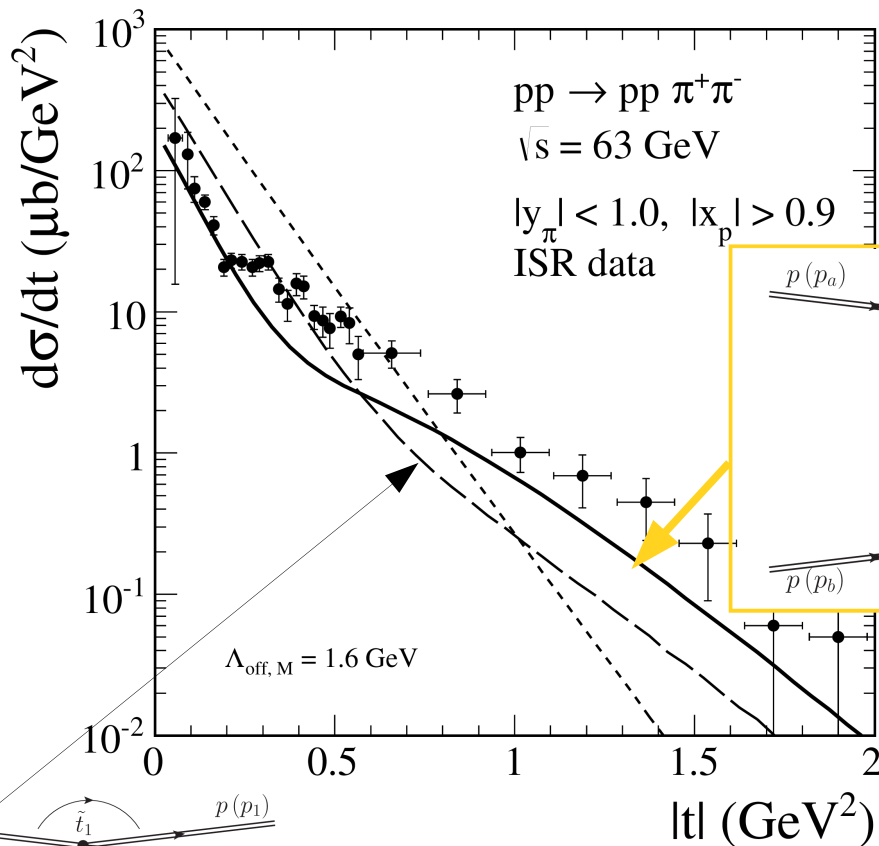
$$\times\, i\Delta^{(\pi)}(p_t)\; i\Gamma^{(I\!\!P\pi\pi)}_{\alpha_2\beta_2}(p_4,p_t)\,i\Delta^{(I\!\!P)\,\alpha_2\beta_2,\mu_2\nu_2}(s_{24},t_2)\,\bar{u}(p_2,\lambda_2)i\Gamma^{(I\!\!P pp)}_{\mu_2\nu_2}(p_2,p_b)u(p_b,\lambda_b)$$

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

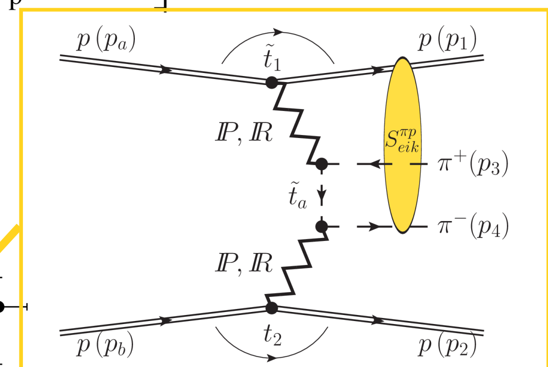
$$i\Gamma^{(I\!\!P\pi\pi)}_{\mu\nu}(k',k) = -i2\beta_{I\!\!P\pi\pi}\,F_M((k'-k)^2)\left[(k'+k)_\mu(k'+k)_\nu - \frac{1}{4}g_{\mu\nu}(k'+k)^2\right]$$

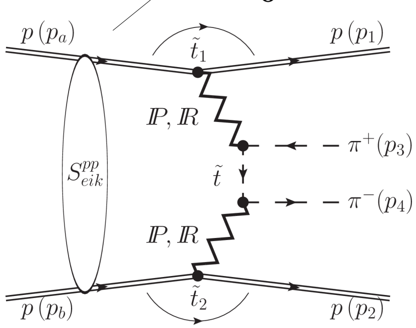
$$\beta_{I\!\!P\pi\pi} = 1.76\ \mathrm{GeV}^{-1}, \quad F_M(t) = \tfrac{1}{1-t/\Lambda_0^2}, \quad \Lambda_0^2 = 0.5\ \mathrm{GeV}^2$$

Absorption corrections, $\pi\pi$ continuum term



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





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

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

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

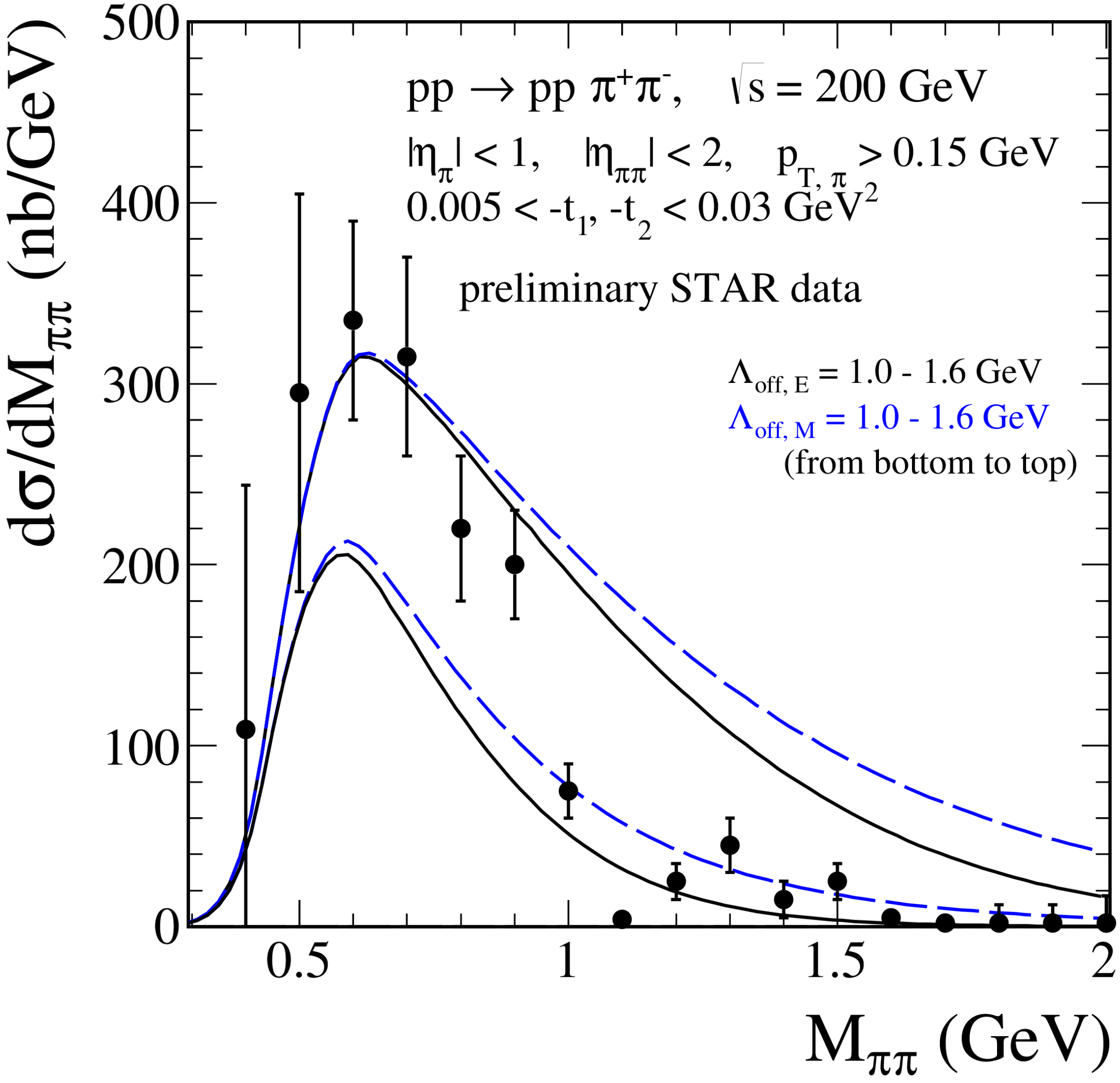
Off-shell pion form factor, $\pi\pi$ continuum term

preliminary STAR data: L. Adamczyk et al., Int.J.Mod.Phys. A29 no. 28, (2014) 1446010

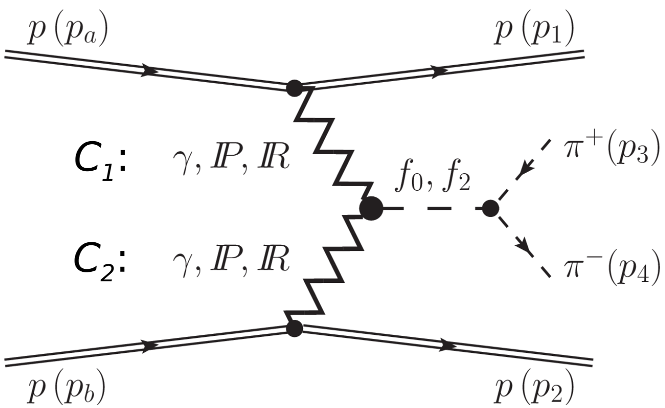
off-shell effects of the intermediate pions can be described by the form factors

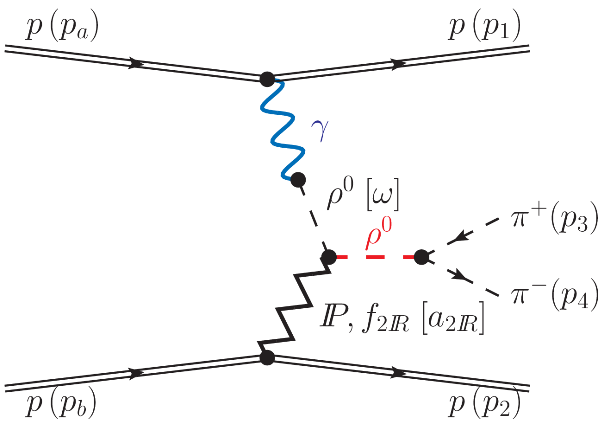
$$F_\pi(\hat{t}) = \exp\left(\frac{\hat{t} - m_\pi^2}{\Lambda_{off,E}^2}\right)$$

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



Dipion resonant production





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

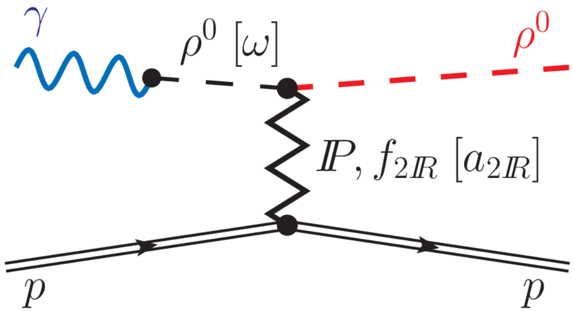
$I^G J^{PC}$, resonances	(C_1, C_2) production modes
0^+0^{++}, $f_0(500)$, $f_0(980)$, $f_0(1500)$, $f_0(1370)$, $f_0(1710)$ 0^+2^{++}, $f_2(1270)$, $f_2'(1525)$, $f_2(1950)$ 0^+4^{++}, $f_4(2050)$	$(I\!P + f_{2I\!R}, I\!P + f_{2I\!R})$, $(a_{2I\!R}, a_{2I\!R})$, $(\mathbb{O} + \omega_{I\!R} + \gamma,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

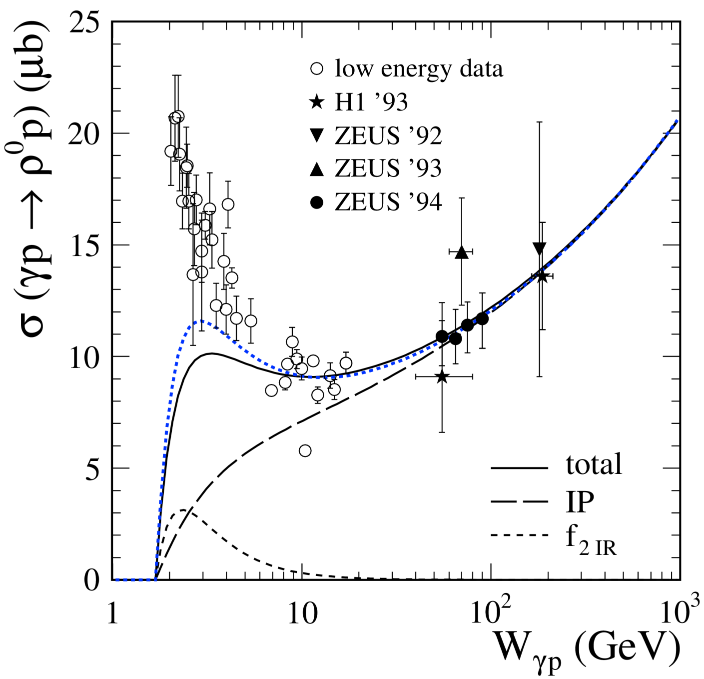


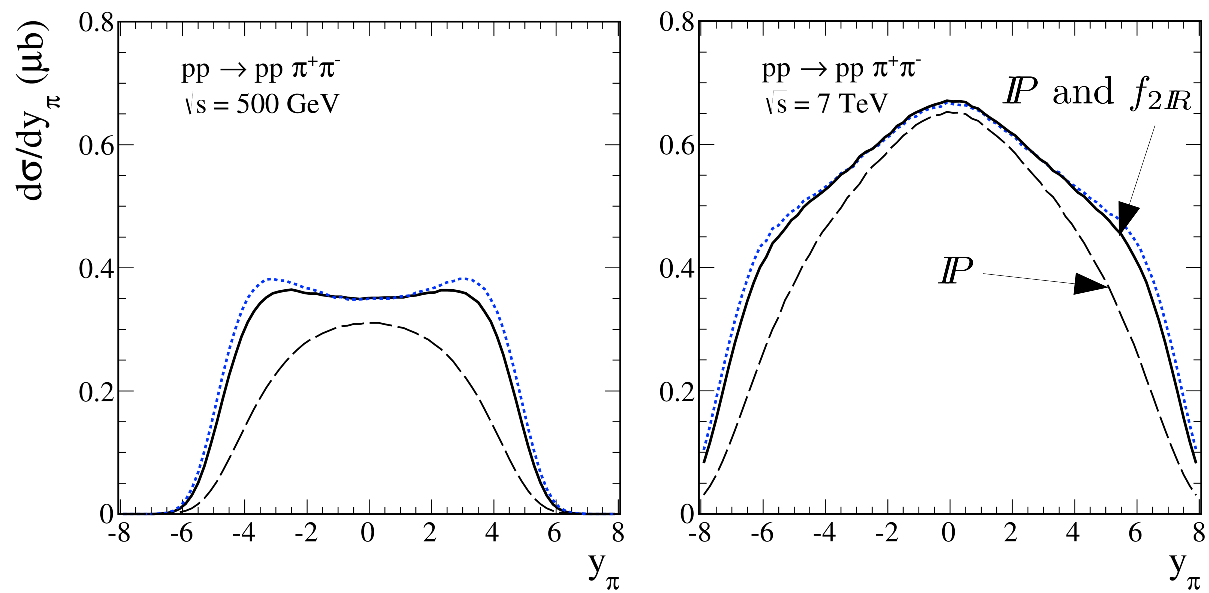
$$\mathcal{M}_{\lambda_\gamma\lambda_b\to\lambda_\rho\lambda_2}(s,t) \cong ie\frac{m_\rho^2}{\gamma_\rho}\,\Delta_T^{(\rho)}(0)\,(\epsilon^{(\rho)\,\mu})^*\epsilon^{(\gamma)\,\nu}V_{\mu\nu\kappa\lambda}(s,t,q,p_\rho) \times 2(p_2+p_b)^\kappa(p_2+p_b)^\lambda\,\delta_{\lambda_2\lambda_b}F_1(t)F_M(t)$$

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*

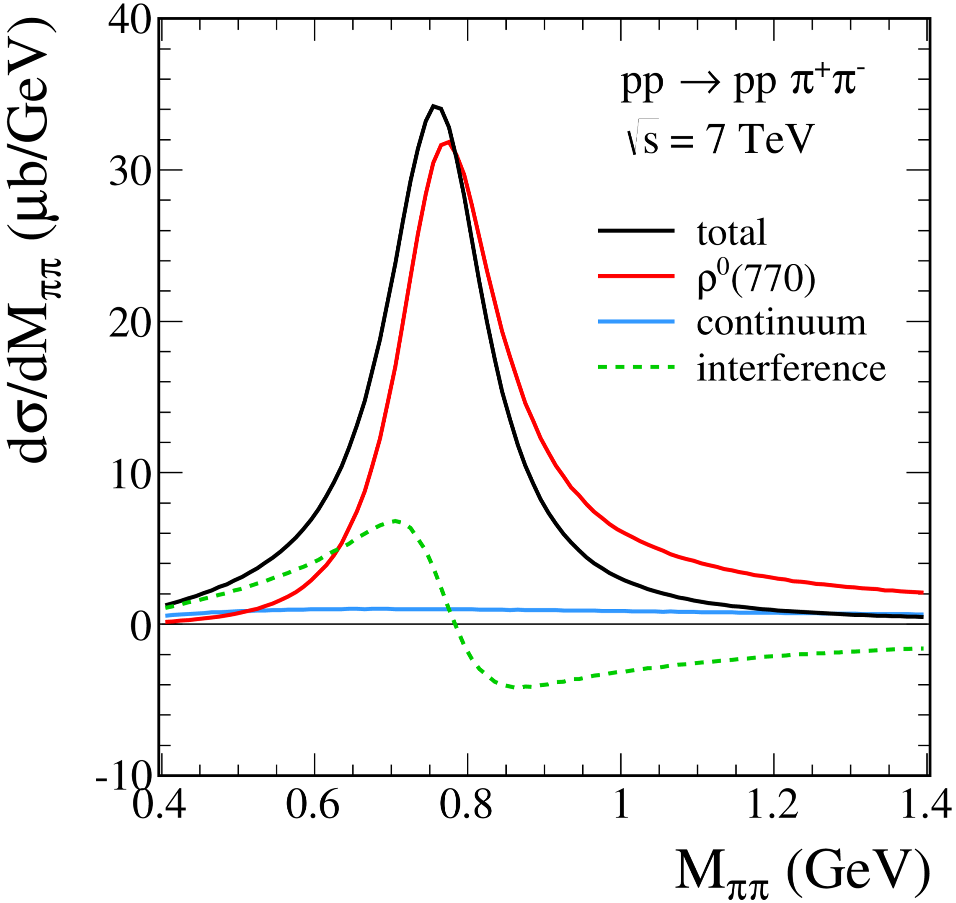


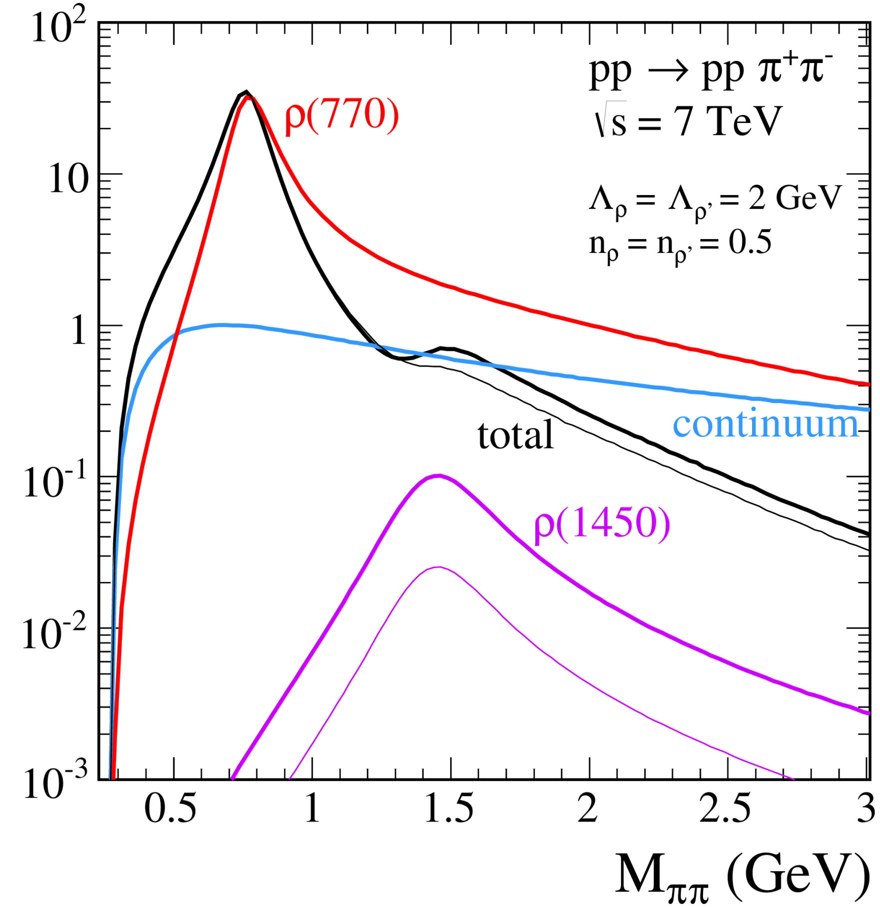


The coupling constants *IP/IR-ρ-ρ* have been estimated from parametrization of total cross sections for *πp* scattering assuming $\sigma_{tot}(\rho^0(\lambda_\rho=\pm1),p) = \frac{1}{2}\left[\sigma_{tot}(\pi^+,p)+\sigma_{tot}(\pi^-,p)\right]$

ρ^0 and $\pi^+\pi^-$ continuum

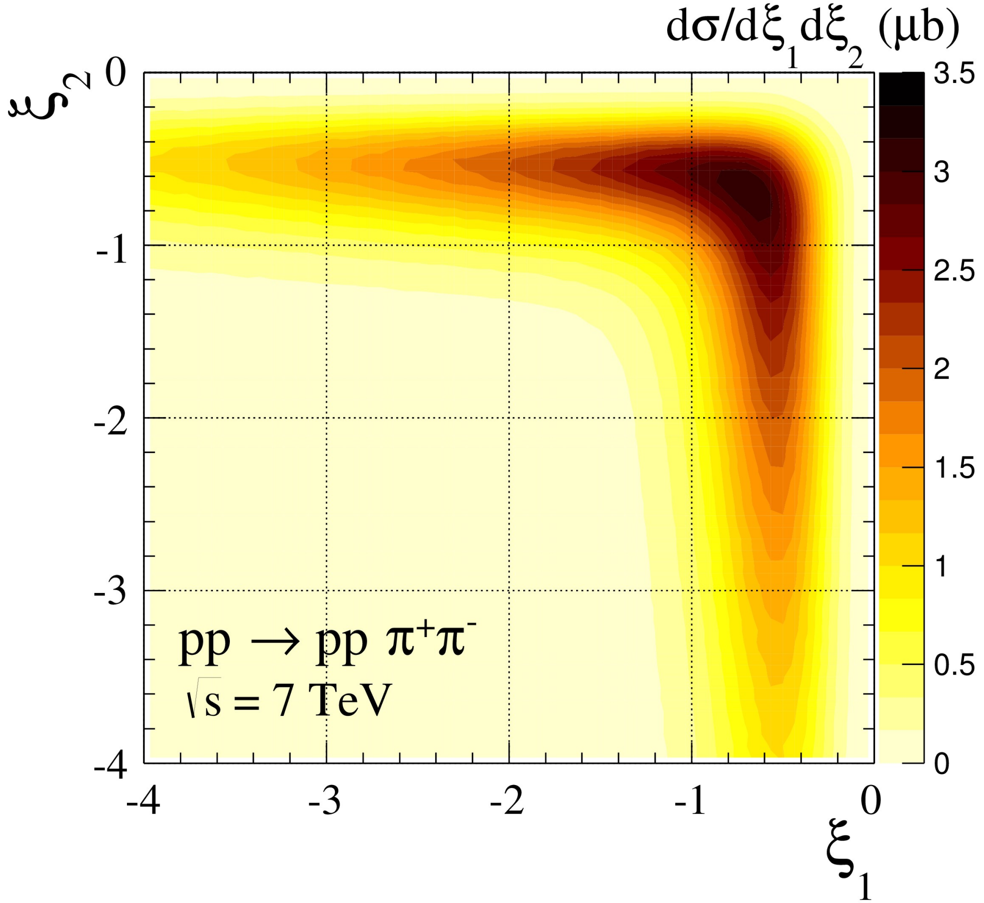
The non-resonant (Drell-Söding) contribution interfere with resonant $\rho(770)$ contribution → skewing of ρ^0 line shape.





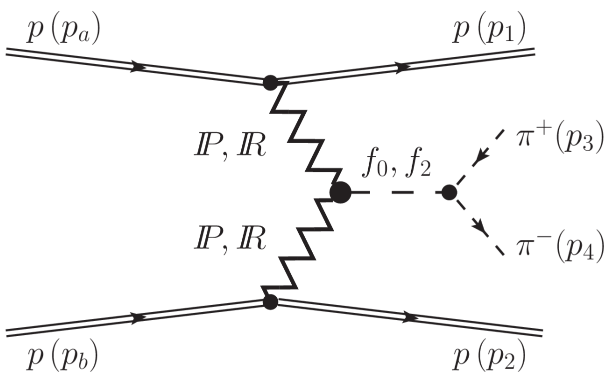
ρ^0 and $\pi^+\pi^-$ continuum

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



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 $|t|$.

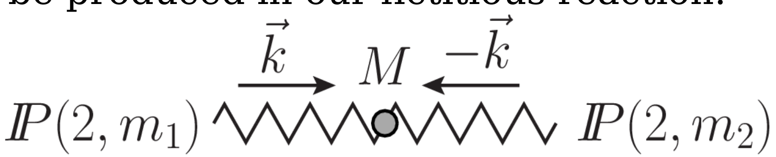
Pomeron-pomeron-meson couplings



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:



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	

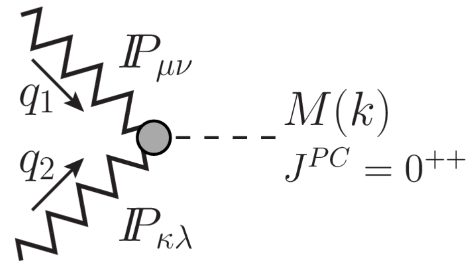
For each value of l, S, J, and P we can construct a covariant Lagrangian density $\mathcal{L}'$ coupling (the field operator for the meson M to the pomeron fields) and the vertex corresponding to the l and S.

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

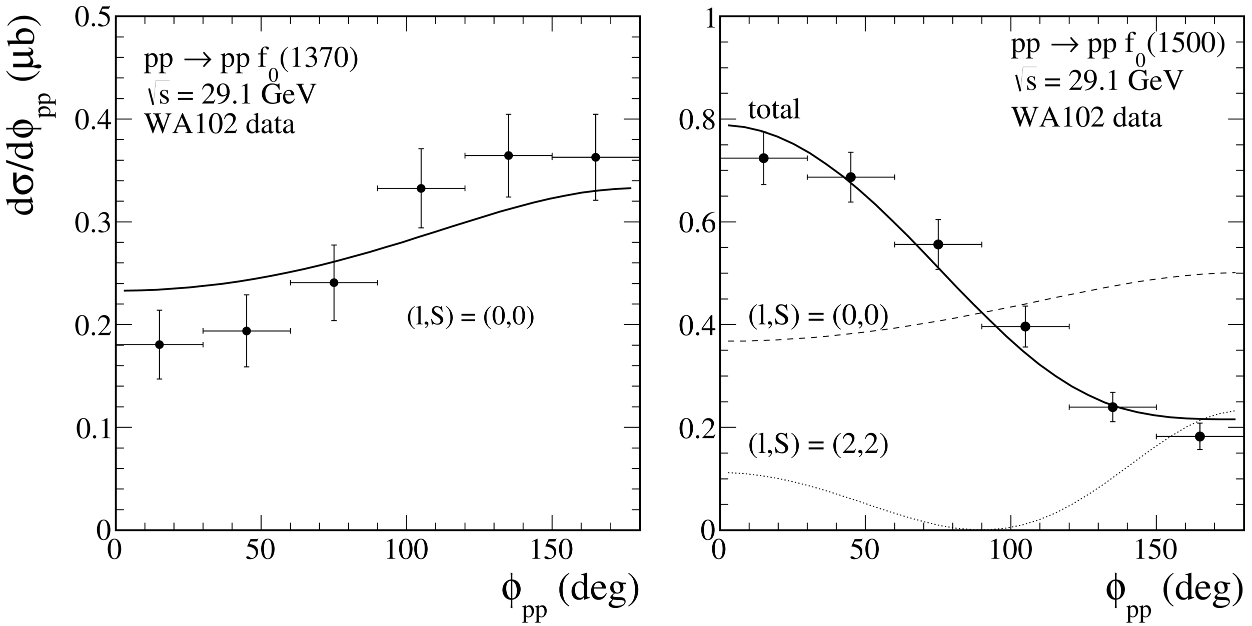
Scalar mesons

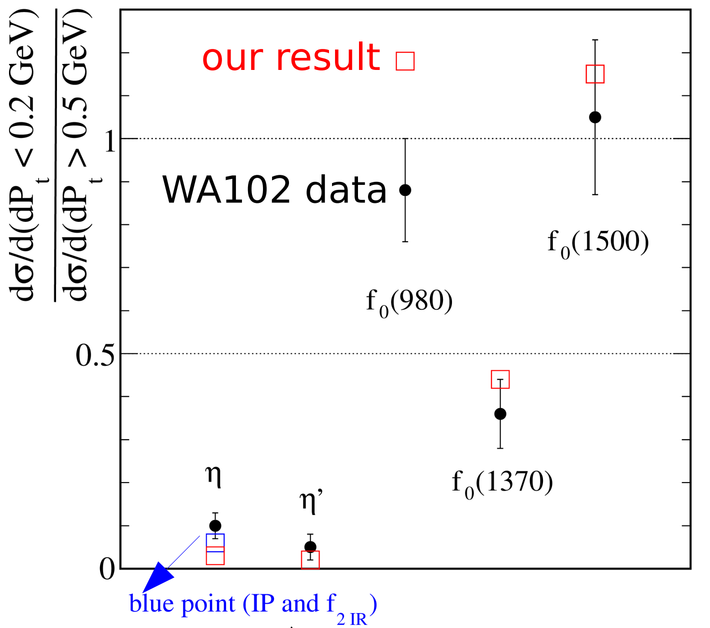
For a scalar mesons the "bare" tensorial *IP-IP-M* vertices corresponding to (l,S) = (0,0) and (2,2) terms are



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

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





$$dP_t = |d\vec{P}_t| = |\vec{q}_{1t} - \vec{q}_{2t}| = |\vec{p}_{2t} - \vec{p}_{1t}|$$

(proposed by F. Close)

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.

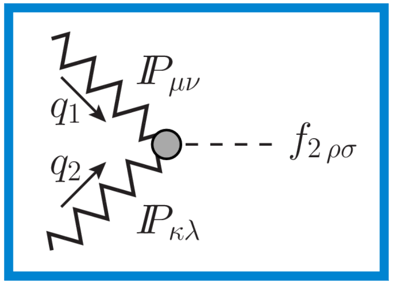
- $f_0(1370)$ peaks as $\phi_{pp} \to \pi$ whereas the $f_0(980)$, $f_0(1500)$, $f_0(1710)$ peak at $\phi_{pp} \to 0$
- $f_0(1500)$ and $f_0(1710)$ which could have a large 'gluonic component' have a large value of dP_t ratio

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

$f_2(1270)$ meson

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 $\Delta^{(f_2)}_{\nu\mu,\kappa\lambda}(p_{34}) = \Delta^{(f_2)}_{\mu\nu,\lambda\kappa}(p_{34}) = \Delta^{(f_2)}_{\kappa\lambda,\mu\nu}(p_{34})$, $\quad g^{\kappa\lambda}\Delta^{(f_2)}_{\mu\nu,\kappa\lambda}(p_{34}) = 0$.

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

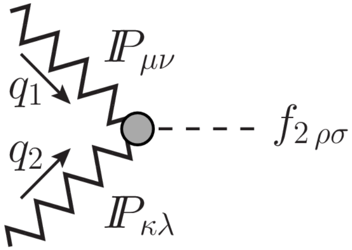
where $g_{f_2\pi\pi} = 9.26$ was obtained from the corresponding partial decay width.

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

IP-IP-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

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



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

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

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

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

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

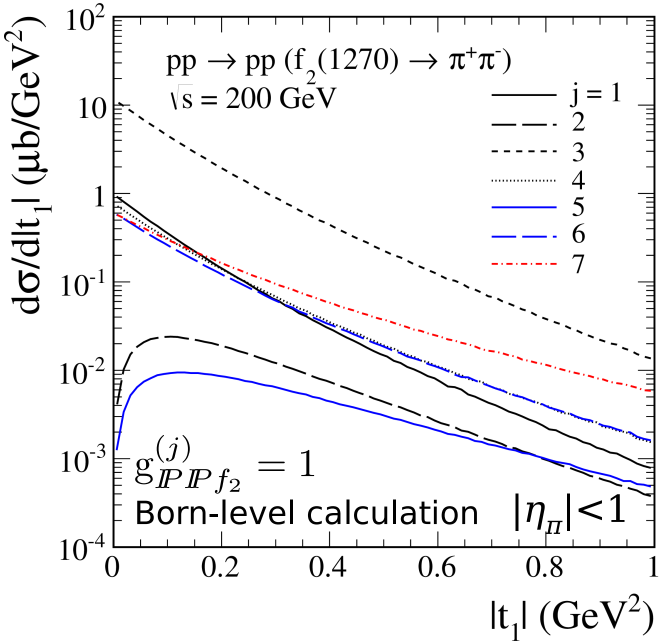
$$i\Gamma^{(\mathbb{P}\mathbb{P}f_2)(6)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = \frac{i}{M_0^3}\, g^{(6)}_{\mathbb{P}\mathbb{P}f_2} \Big(q_1^{\alpha_1}\, q_1^{\lambda_1}\, q_2^{\mu_1}\, q_{2\rho_1}\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1} + q_2^{\alpha_1}\, q_2^{\lambda_1}\,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

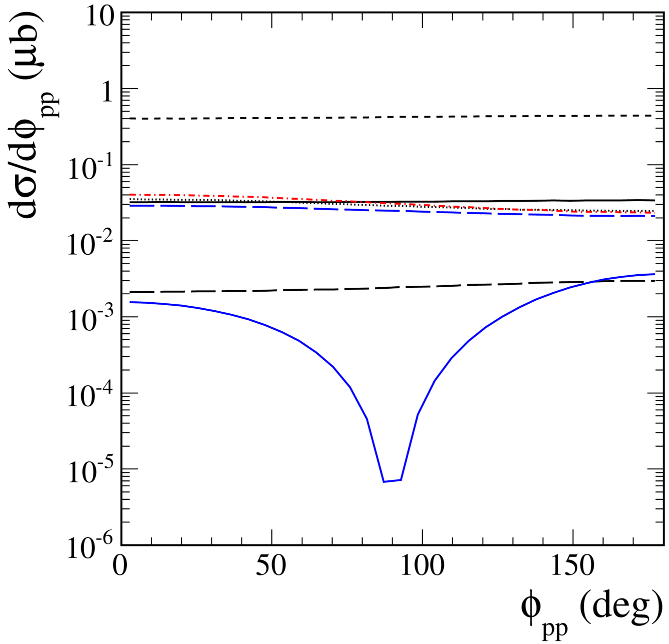
$$i\Gamma^{(\mathbb{P}\mathbb{P}f_2)(7)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{2i}{M_0^5}\, g^{(7)}_{\mathbb{P}\mathbb{P}f_2}\, q_1^{\rho_1}\, q_1^{\alpha_1}\, q_1^{\lambda_1}\, q_2^{\sigma_1}\, q_2^{\mu_1}\, q_2^{\nu_1}\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1}\, R_{\rho\sigma\rho_1\sigma_1}$$

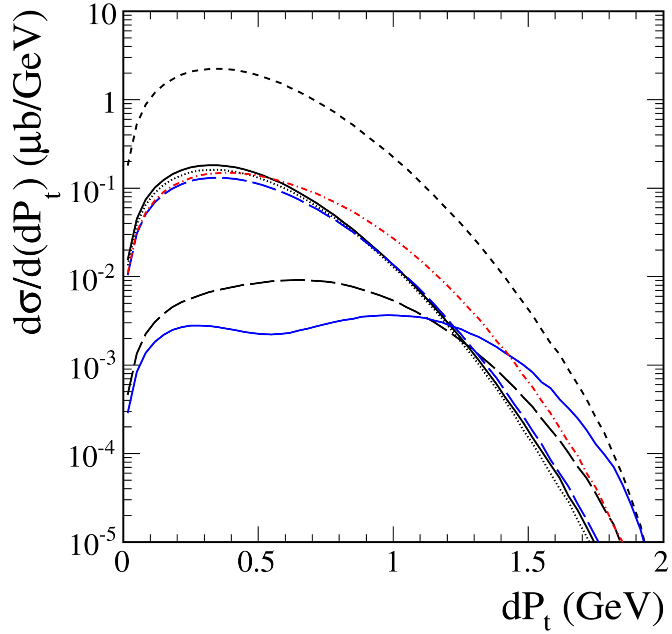
We can associate the couplings j = 1, …, 7 with the following (l,S) values:
(0,2), (2,0) – (2,2), (2,0) + (2,2), (2,4), (4,2), (4,4), (6,4), respectively.

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

Choice of *IP-IP-f_2(1270)* coupling







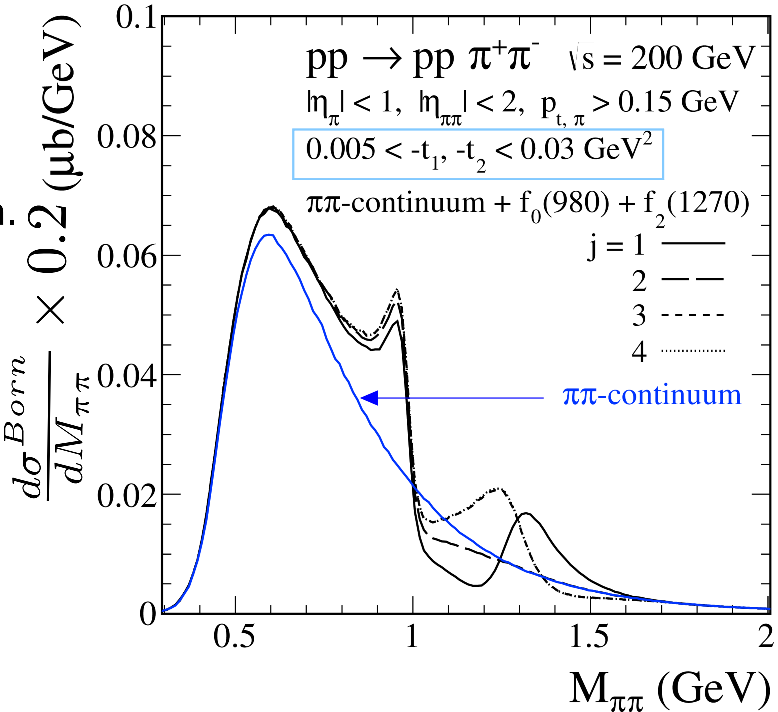
j = 2 coupling is in agreement with experimental observations (WA102, COMPASS, ISR)

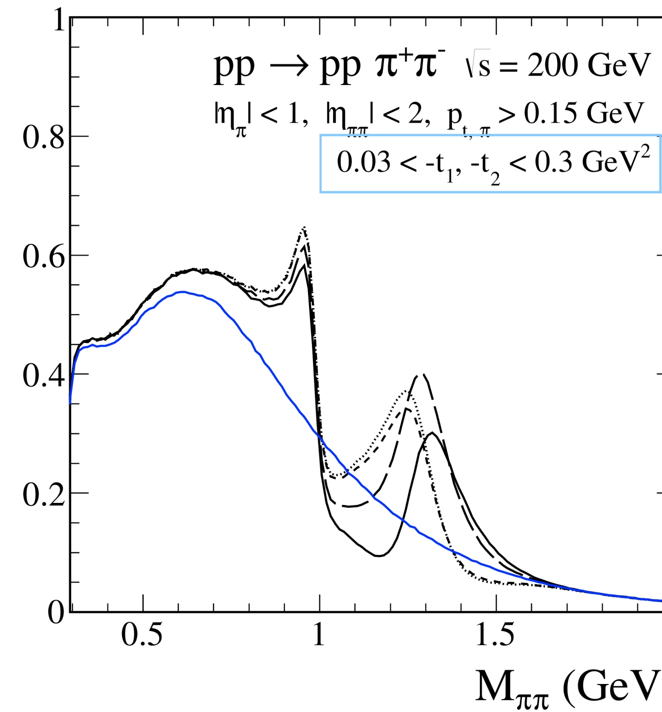
→ f_2(1270) peaks at ϕ_{pp}~180° and is most prominently observed at large |*t*| and is suppressed as dP_t → 0 (undisputed $q\bar{q}$ state)

Different couplings generate different interference pattern.

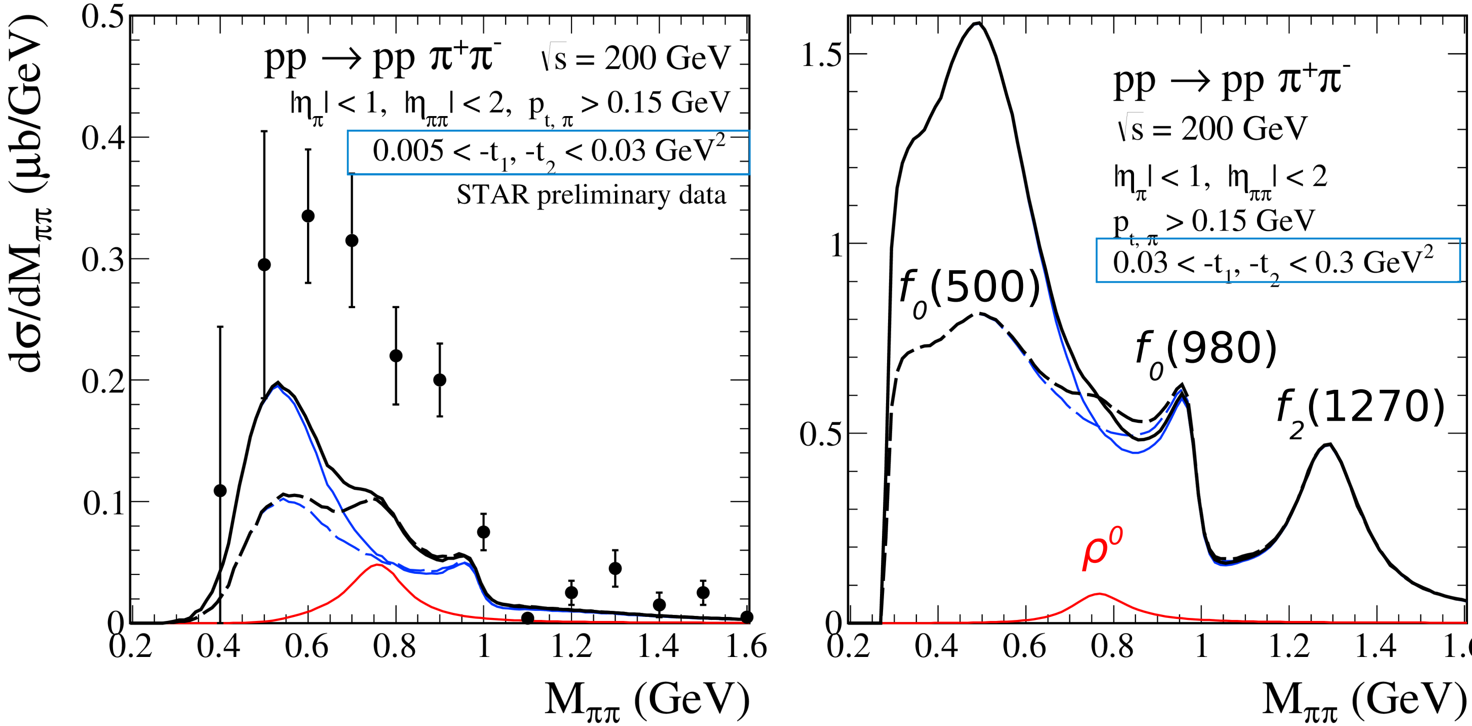
The relative contribution of the resonant f_2(1270) and dipion continuum strongly depends on the cut on |*t*|

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



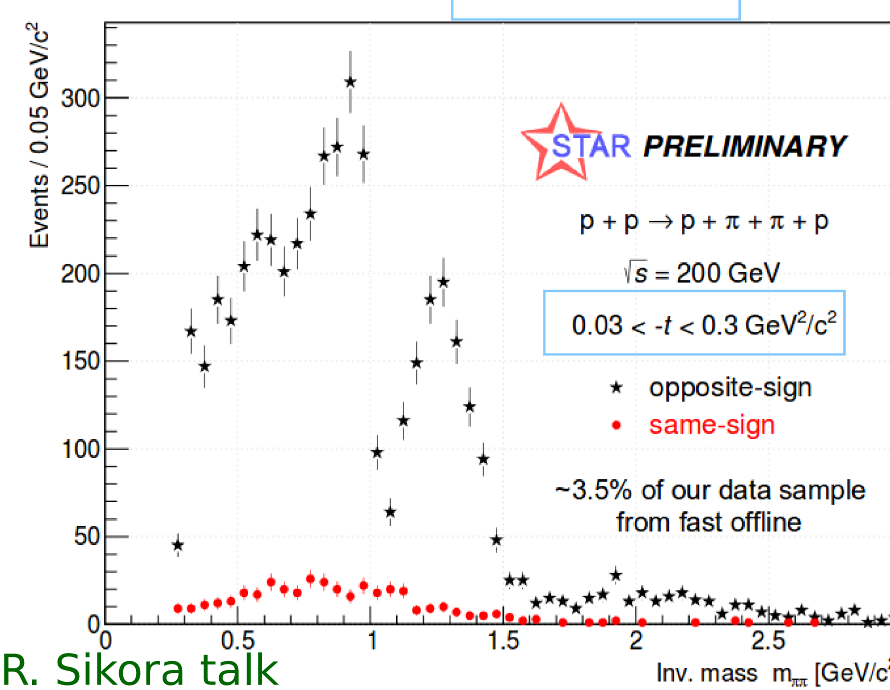


Comparison with STAR preliminary data



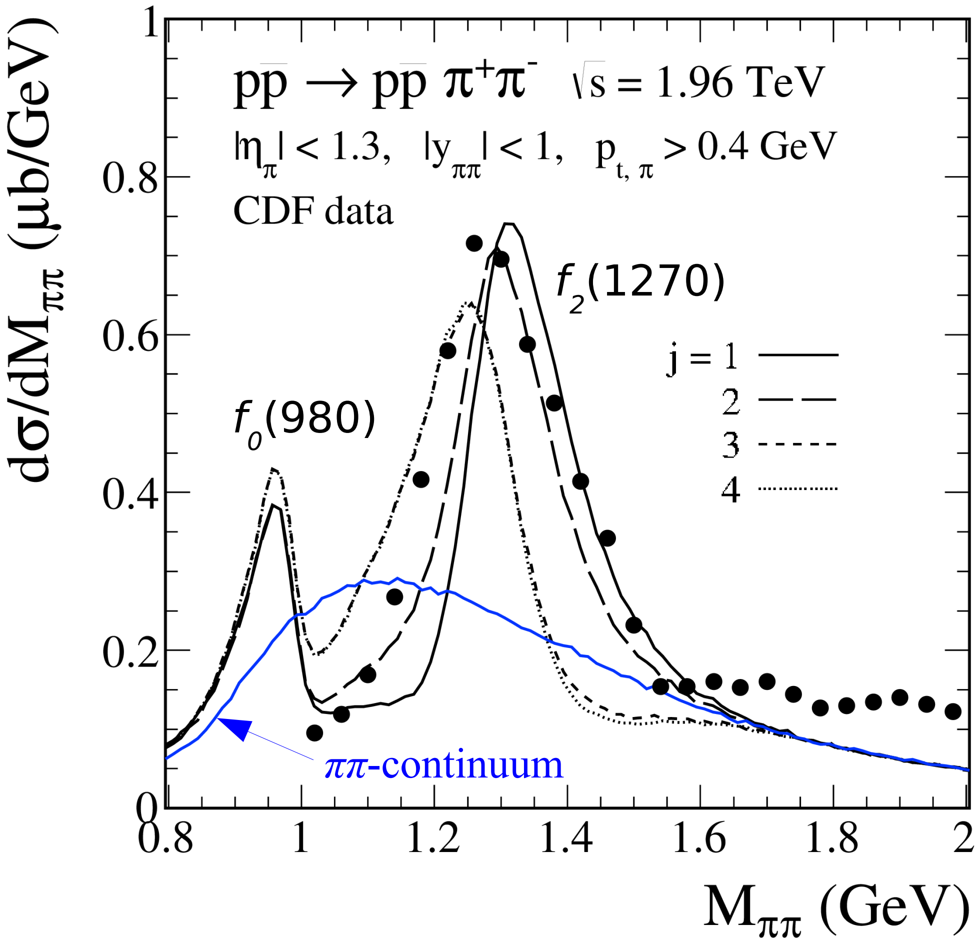
- Blue lines (diffractive term), red line (ρ^0 term), black lines (complete result)
- In calculation of f_2 term only one of the *IP-IP-*f_2 couplings (j=2) was taken
- At $M_{\pi\pi}$ < 1 GeV also other processes may be important → $\pi\pi$ FSI effect ($f_0(500)$ meson)
- Absorption effects were included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

not acceptance-corrected, statistical errors only



STAR preliminary data: R. Sikora talk

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.

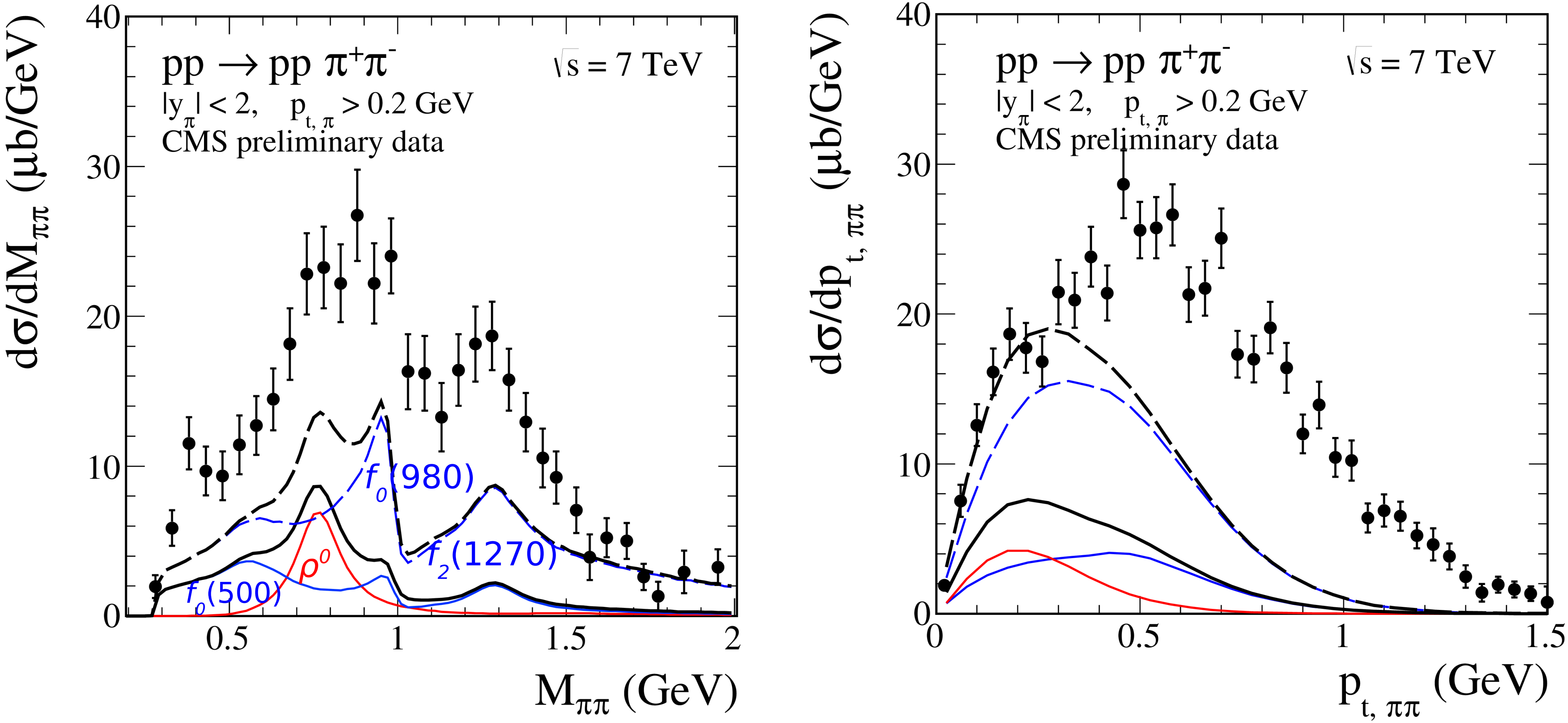
Absorption effects were included effectively:

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

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

see M. Albrow talk

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, with 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).

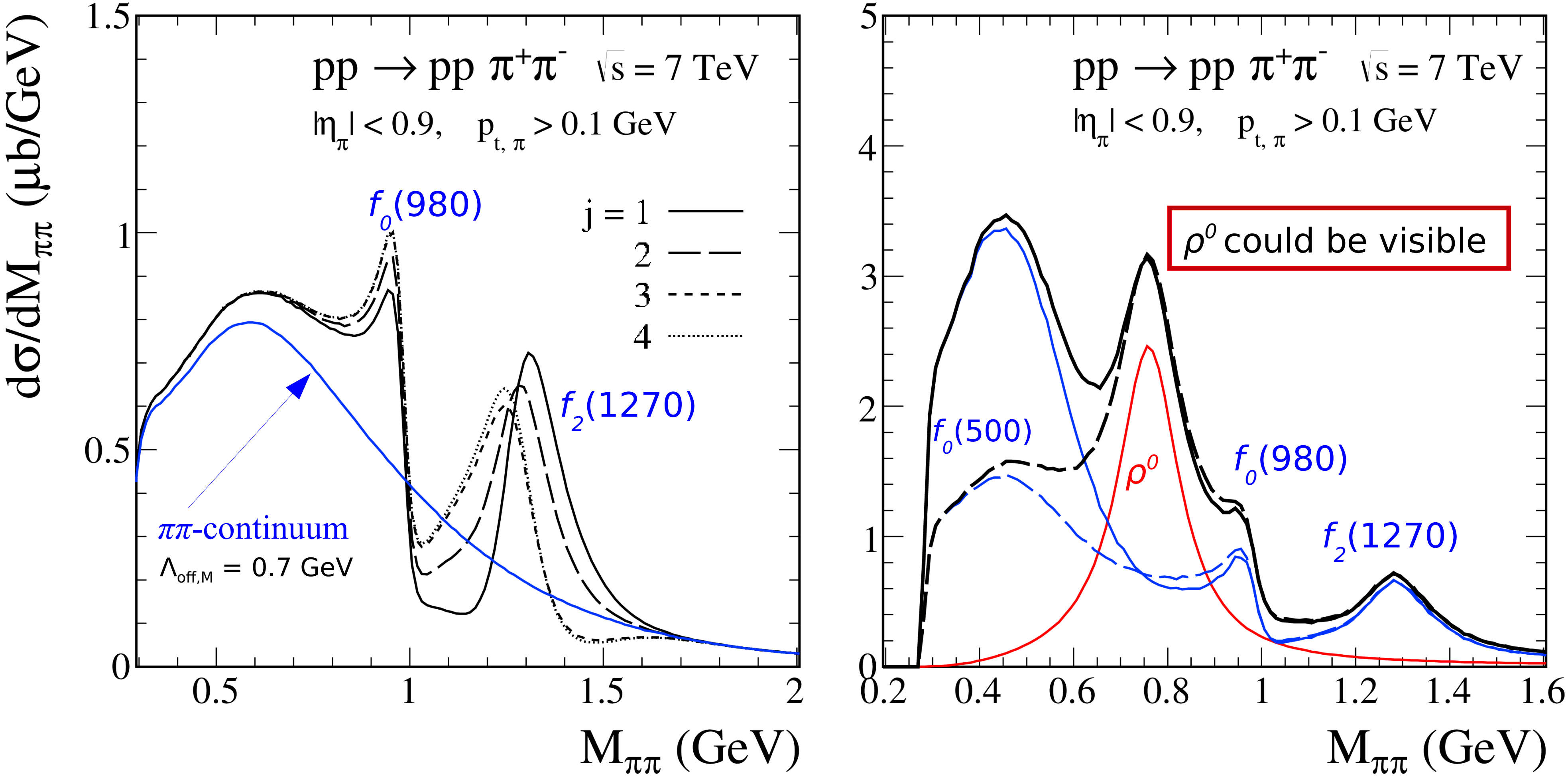
$< S^2 > \simeq 0.1$ for the diffractive contribution

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

ρ^0 could be visible

see M. Khakzad talk

Predictions for ALICE



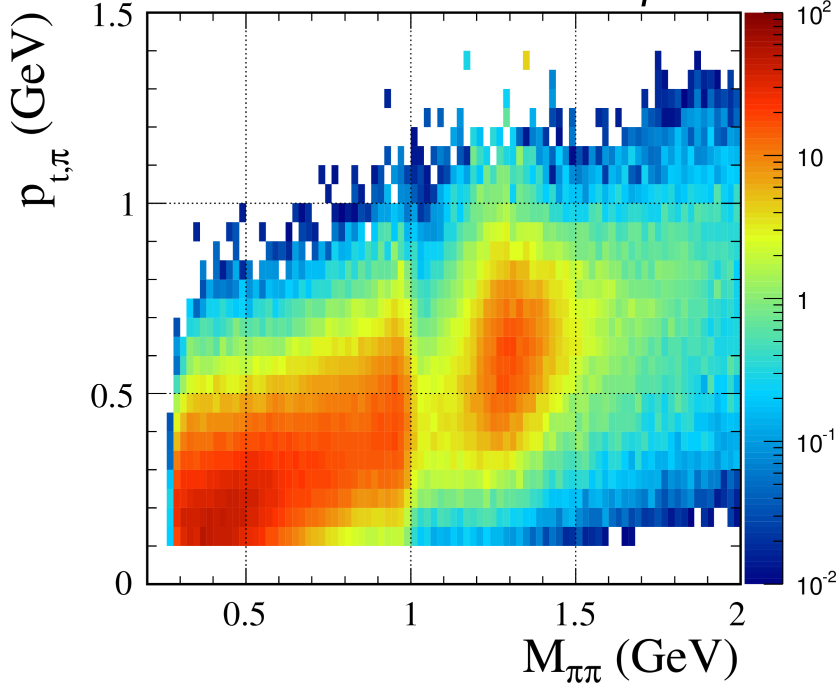
Different *IP-IP-f*$_2$ couplings generate different interference pattern.

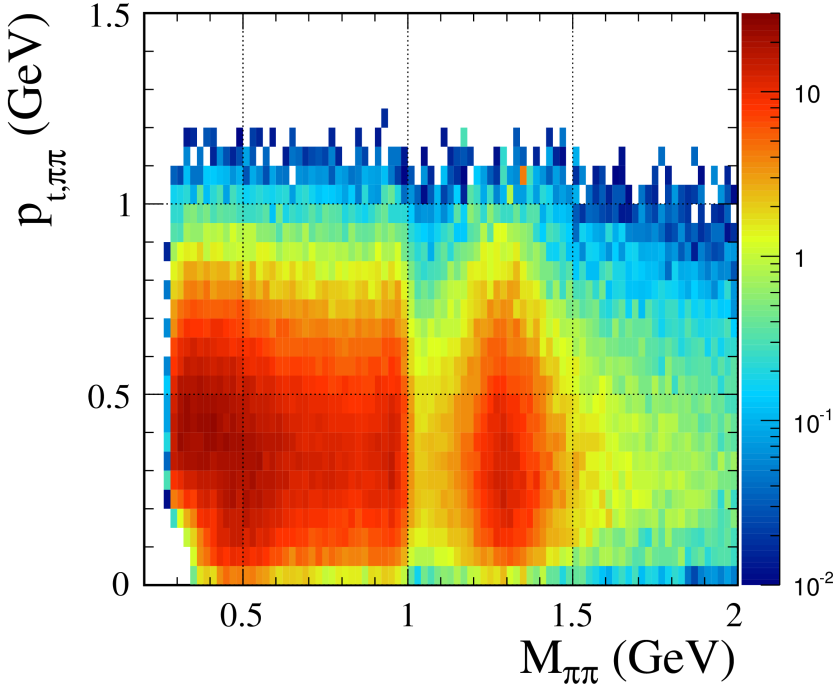
$< S^2 > \simeq 0.1$ for the diffractive contribution

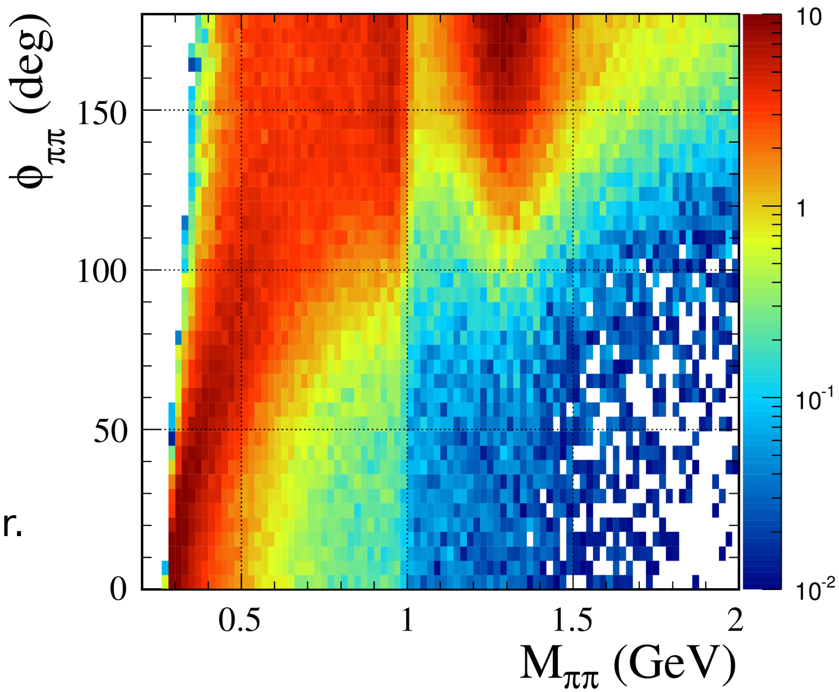
$< S^2 > \simeq 0.9$ for the photon-IP/IR contribution

Predictions for ATLAS+ALFA

2dim cross section in μb





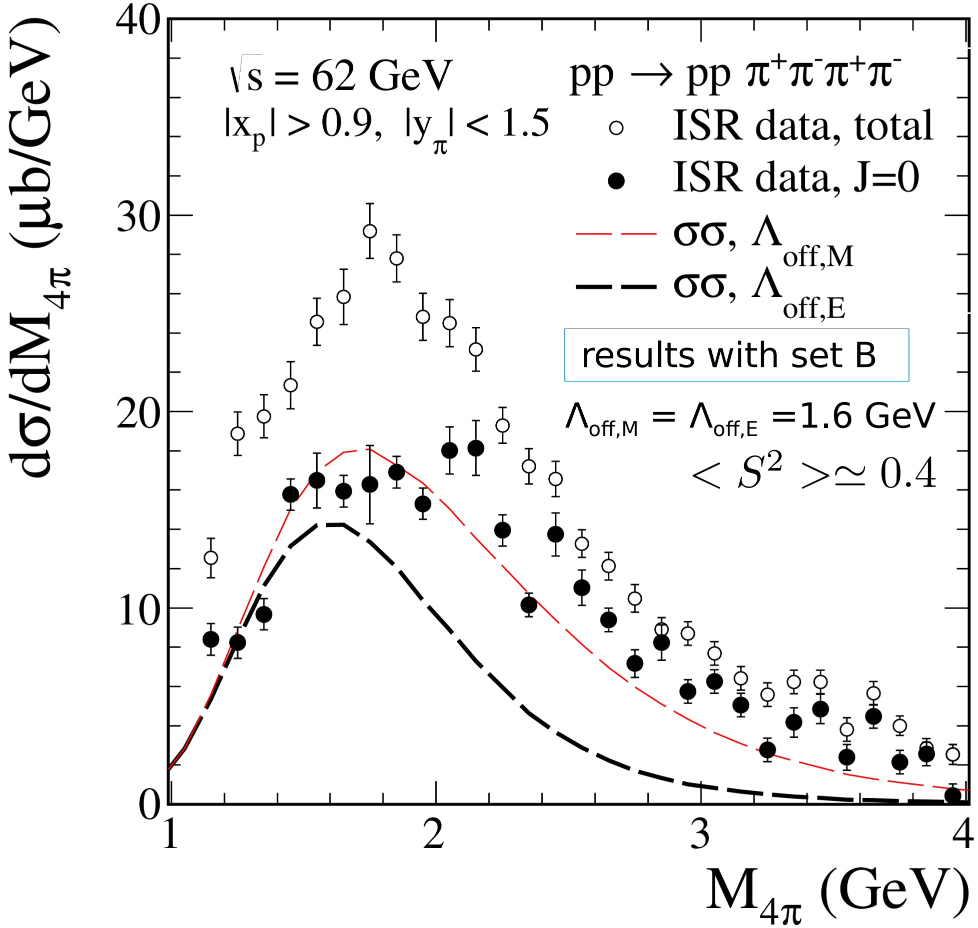


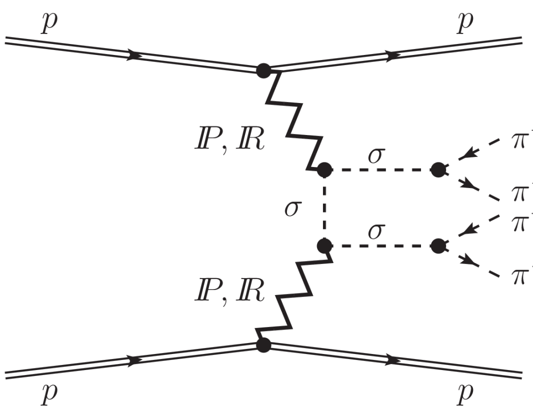
The cuts on pion transverse momenta,
on transverse momentum of pion pair,
or on $\phi_{\pi\pi}$ may play the role of a $\pi^+\pi^-$ resonance filter.

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

$$\sigma_{2\to 6} = \int_{2m_\pi}^{\max\{m_{X_3}\}} \int_{2m_\pi}^{\max\{m_{X_4}\}} \sigma_{2\to 4}(..., m_{X_3}, m_{X_4})\, f_M(m_{X_3})\, f_M(m_{X_4})\, dm_{X_3}\, dm_{X_4}$$

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





as for dipion continuum

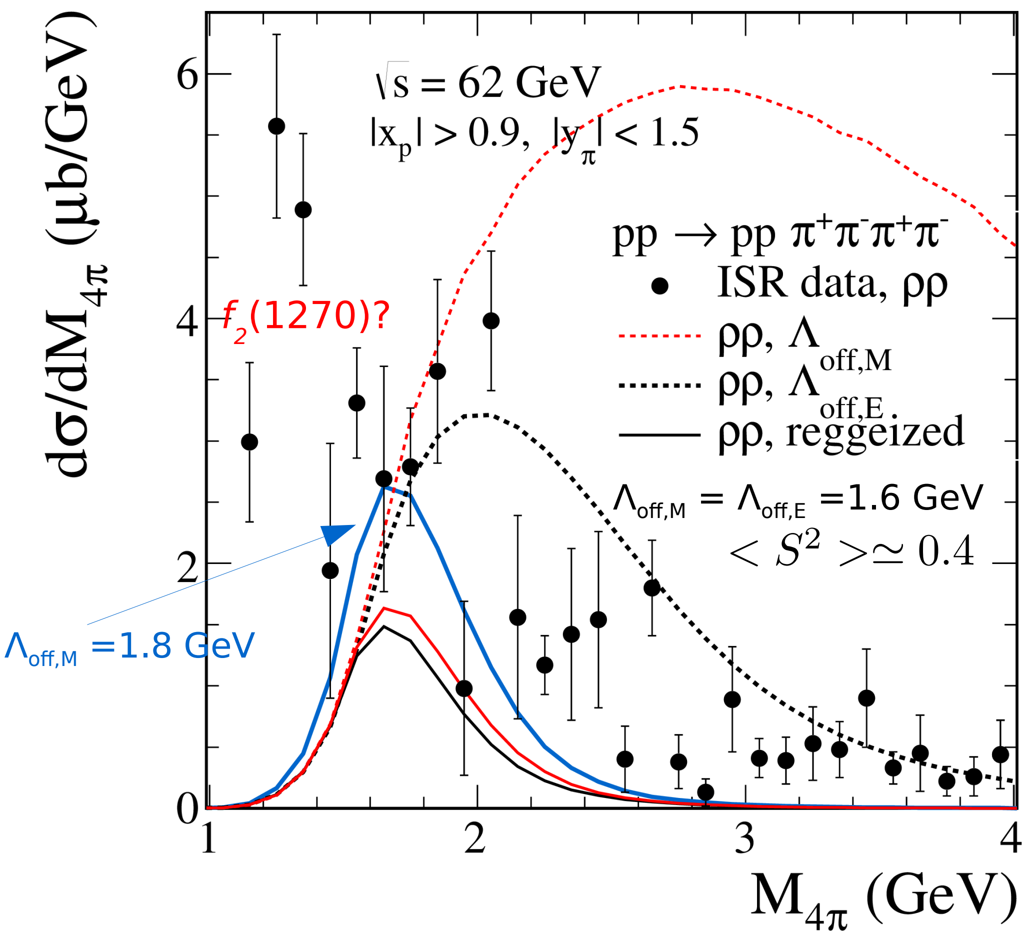
set A : $\beta_{I\!P\sigma\sigma} = 2\beta_{I\!P\pi\pi}$, $g_{f_{2I\!R}\sigma\sigma} = g_{f_{2I\!R}\pi\pi}$

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

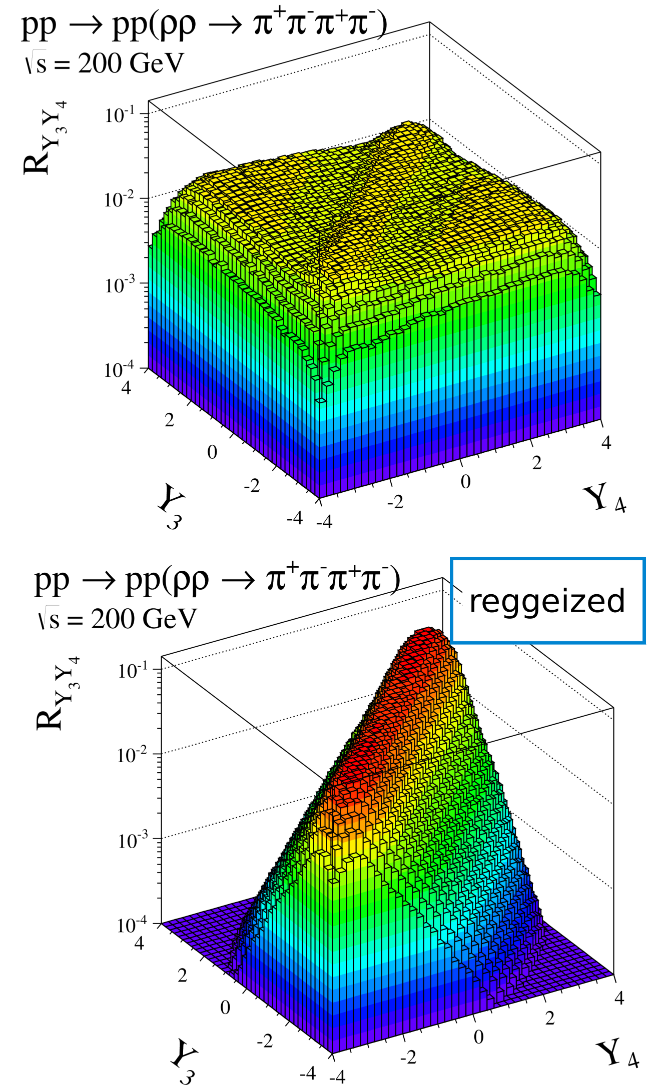
The 4*π* ISR data contains a large $\rho^0\pi^+\pi^-$ component with an enhancement in the J =2 term interpreted by ABCDHW Collaboration as a f_2(1720) state.

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

4π production ($\rho\rho$ contribution)



$$R_{Y_3Y_4} = \frac{d^2\sigma}{dY_3 dY_4} / \int dY_3 dY_4 \frac{d^2\sigma}{dY_3 dY_4}$$



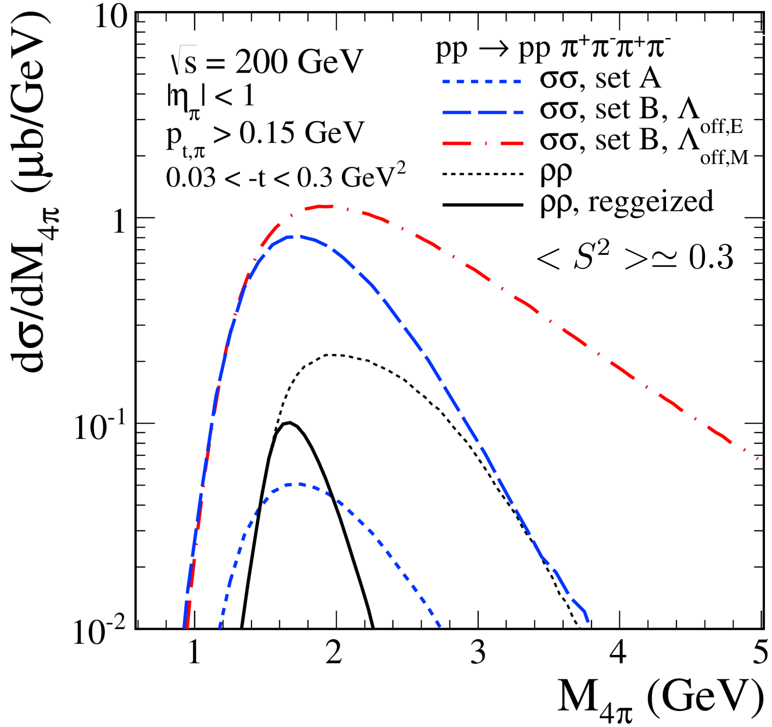
- reggeization effect

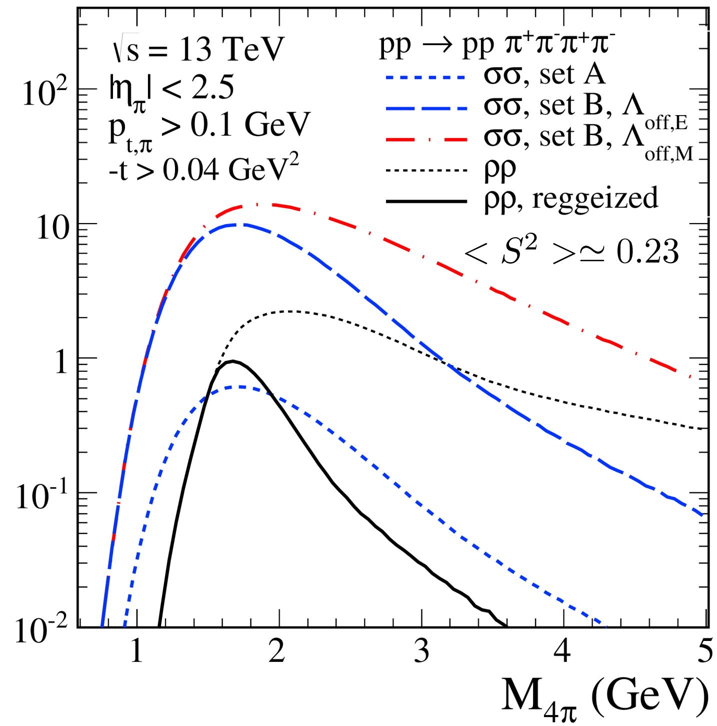
$$\Delta^{(\rho)}_{\rho_1\rho_2}(p) \to \Delta^{(\rho)}_{\rho_1\rho_2}(p) \left(\frac{s_{34}}{s_0}\right)^{\alpha_\rho(p^2)-1}, \quad s_0 = 4m_\rho^2$$

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, arXiv:1312.4553, Eur. Phys. J. C74 (2014) 2848

First predictions for RHIC and LHC (ATLAS+ALFA)





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

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

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

Conclusions

- 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 while they clearly exclude a scalar pomeron. We have further argued that a vector pomeron assumption is in contradiction to the rules of QFT. We therefore conclude that the tensor pomeron is the only viable option (for soft pomeron).

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

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

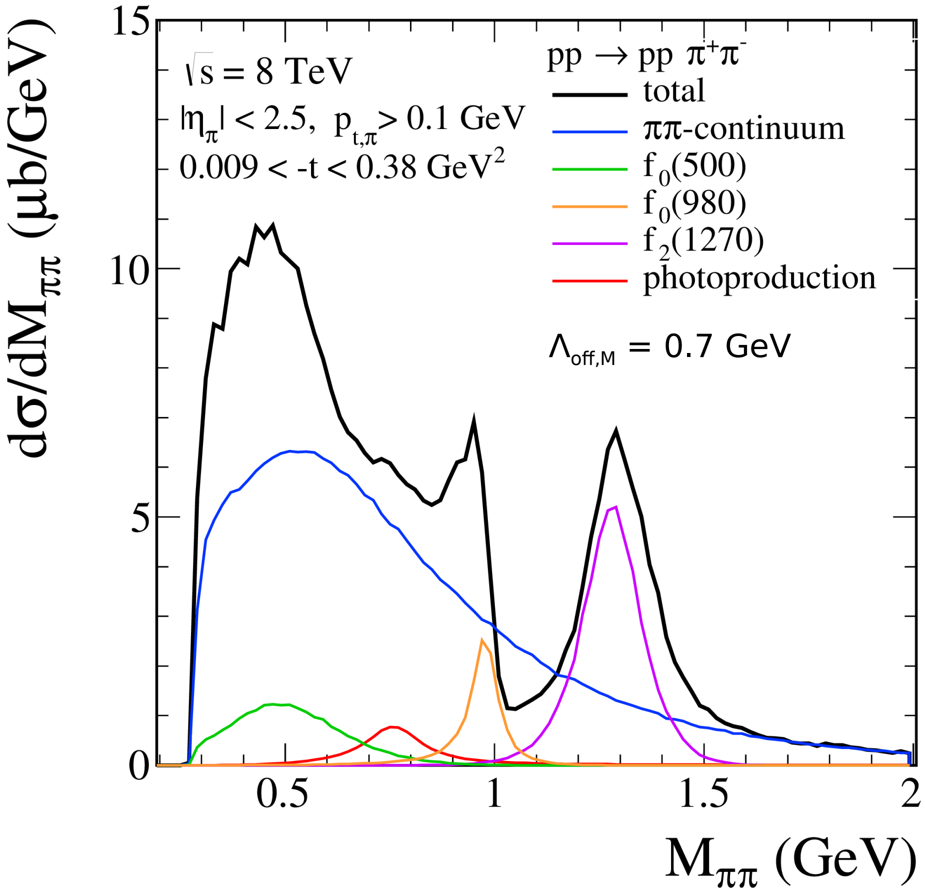
- The distribution in dipion invariant mass shows a rich pattern of structure that depends on the cuts used in a particular experiment. We find that the relative contribution of the $f_2(1270)$ and $\pi\pi$-continuum strongly depends on the cut on $|t|$ which may explain some controversial observation made by the ISR groups.

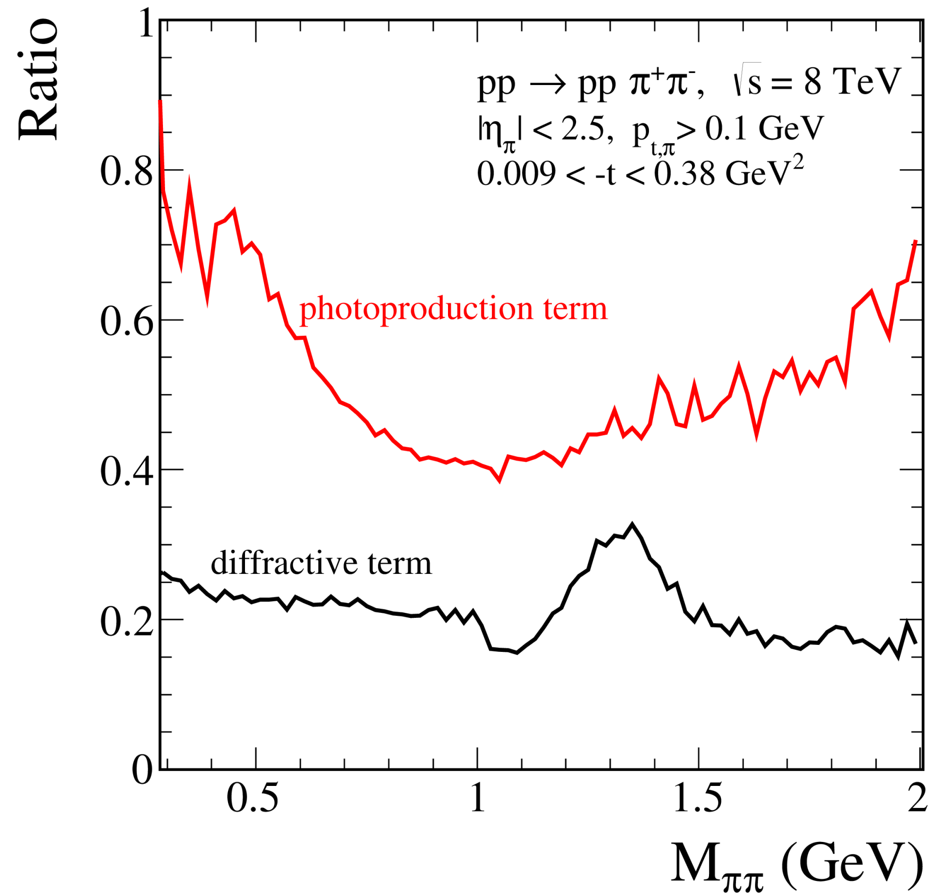
- We have estimated first predictions of the cross sections for the process $pp \to pp\ \pi^+\pi^-\pi^+\pi^-$ via intermediate $\sigma\sigma$ and $\rho\rho$ states. We compared our results with the ISR data. A measurable cross section of few μb was obtained including the exp. cuts relevant for LHC experiments.

Extra slides

Predictions for ATLAS+ALFA

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.

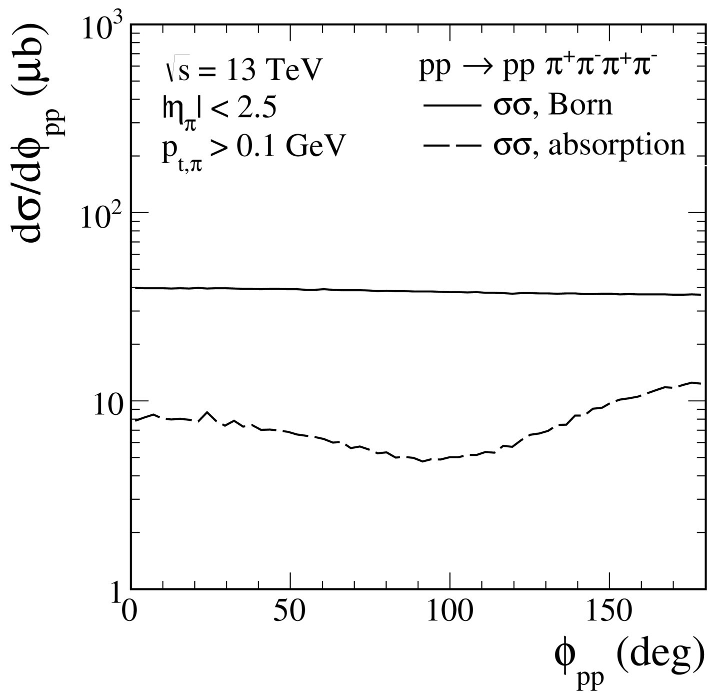
Cross sections: at 8 TeV (7.09 – 14.11) μb,
at 13 TeV (7.35 – 14.57) μb,
for two off-shell pion form factor parameters $\Lambda_{off,M}$ = (0.7 – 1.0) GeV, respectively.

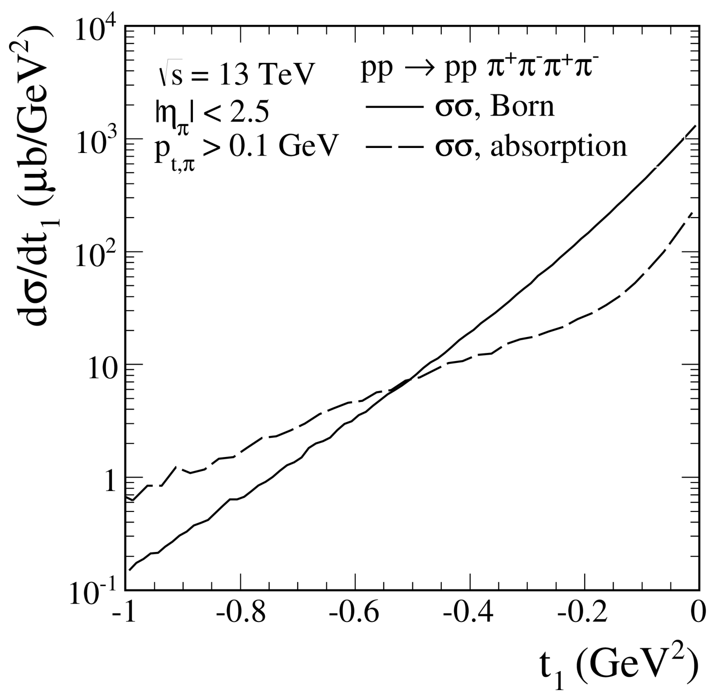
Cross sections (in μb) for $pp \to pp\ \pi^+\pi^-\pi^+\pi^-$

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

The $\sigma\sigma$ contribution was calculated using the enhanced coupling constants (set B) while the $\rho\rho$ contribution without and with (in the parentheses) the inclusion of ρ meson reggeization. Here the exponential off-shell meson form factor with $\Lambda_{off,E}$ = 1.6 GeV was used.

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





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

Acknowlegments

This work was supported by the Polish MNiSW grant No. IP2014 025173 (Iuventus Plus) and the Polish National Science Centre grants: 2014/15/B/ST2/02528 (OPUS) and 2015/17/D/ST2/03530 (SONATA).