Exclusive diffractive production of $\pi^+\pi^-$ continuum and resonances within tensor pomeron approach

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Contents

1) Diffractive mechanism of $\pi^+\pi^-$ production (continuum and resonances)
2) Photoproduction mechanism (ρ^0 and Drell-Söding contributions)
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4) Results for present and future experiments

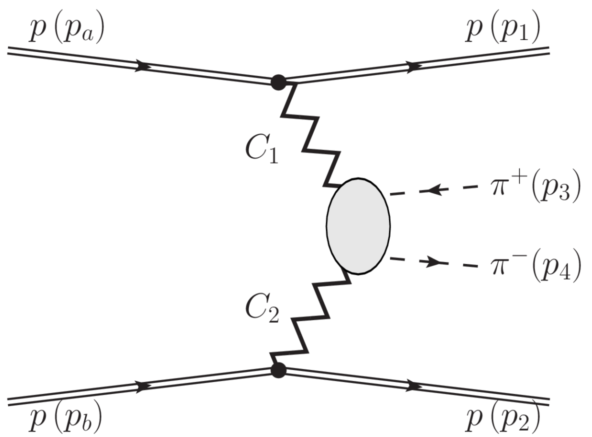
Based on:

- 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
- C. Ewerz, M. Maniatis, O. Nachtmann, *A Model for Soft High-Energy Scattering: Tensor Pomeron and Vector Odderon,* arXiv:1309.3478, Annals Phys. 342 (2014) 31
- 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

Related work:

- 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 → pp $\pi^+\pi^-$ process*, arXiv:1504.07560, Phys. Rev. D92 (2015) 054001

Dipion continuum production



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

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

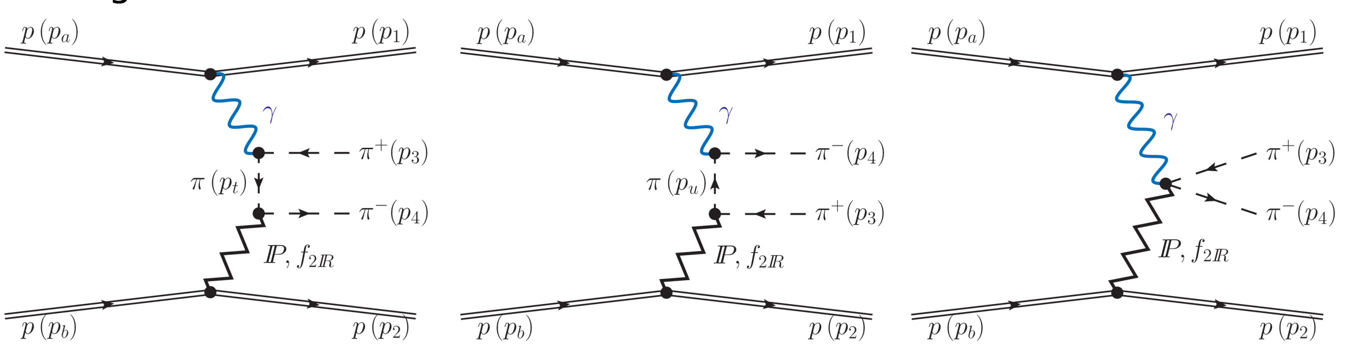
C = +1 exchanges ($I\!P$, $f_{2I\!R}$, $a_{2I\!R}$) are represented as rank-two-tensor
C = -1 exchanges (odderon (?), $\omega_{I\!R}$, $\rho_{I\!R}$) represented as vector

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

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



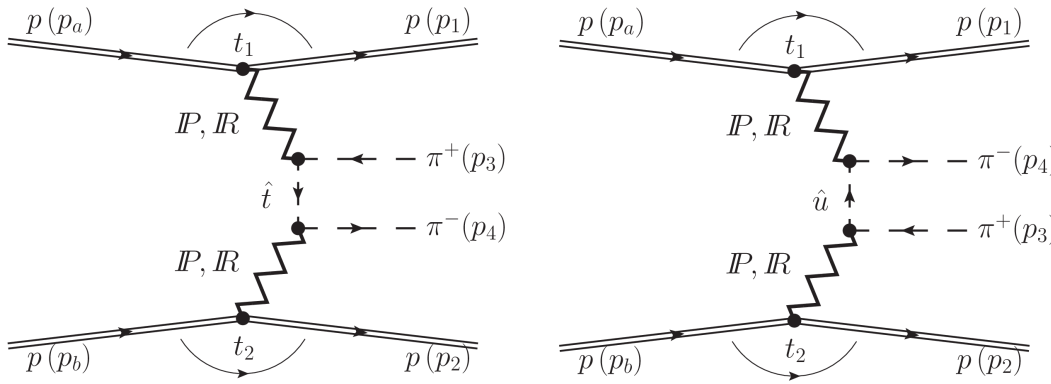
The inclusion of these diagrams is a gauge invariant version of the Drell-Söding mechanism.

Diffractive dipion continuum production

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

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

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



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

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

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

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

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

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

$I\!P$ propagator and vertex functions

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

The propagator of the tensor-pomeron exchange is written as

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

with the standard linear trajectory $\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P}t$.

The coupling of tensor pomeron to protons (antiprotons) and pions are

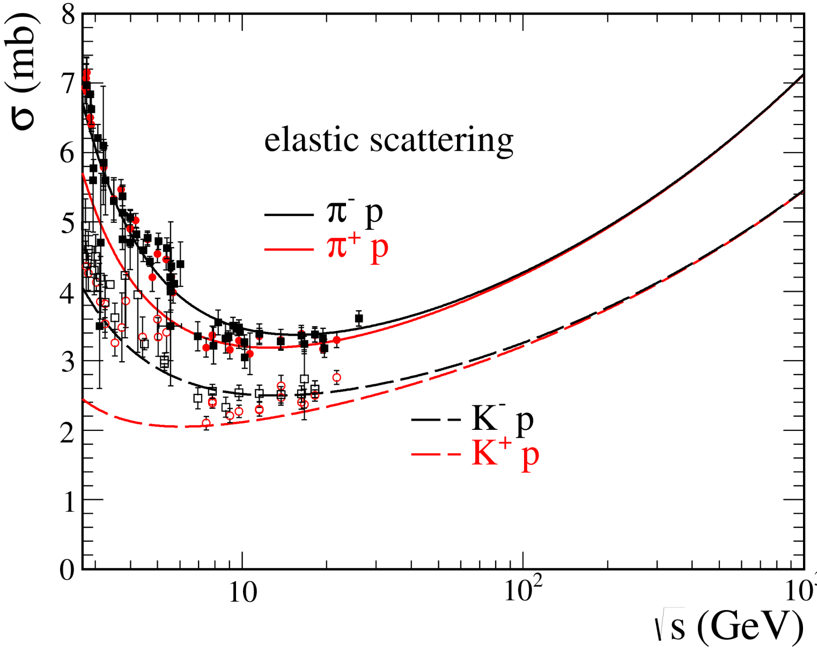
$$i\Gamma^{(I\!Ppp)}_{\mu\nu}(p',p) = -i3\beta_{I\!PNN}F_1\left((p'-p)^2\right)\left\{\frac{1}{2}[\gamma_\mu(p'+p)_\nu + \gamma_\nu(p'+p)_\mu] - \frac{1}{4}g_{\mu\nu}(\not{p}'+\not{p})\right\},$$

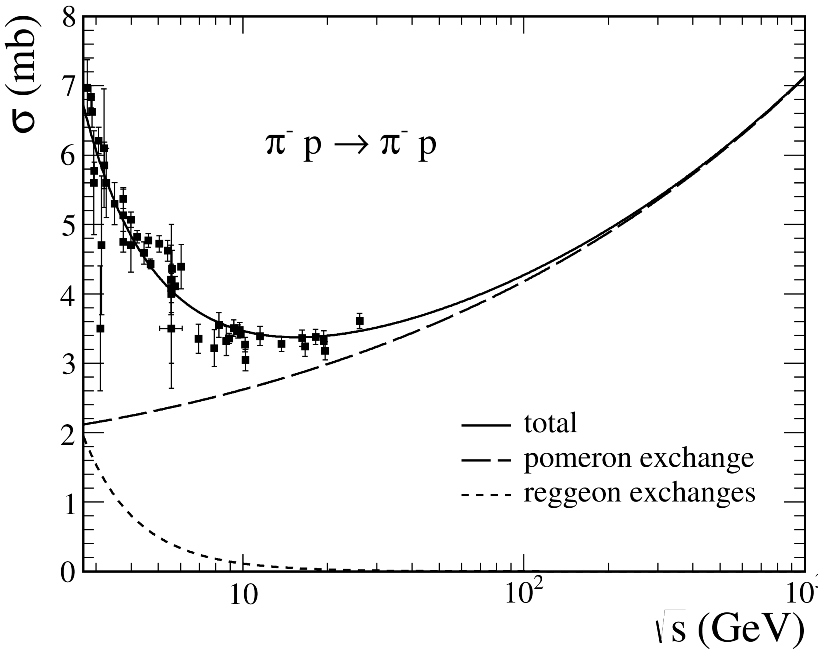
$$i\Gamma^{(I\!P\pi\pi)}_{\mu\nu}(k',k) = -i2\beta_{I\!P\pi\pi}\,F_M((k'-k)^2)\left[(k'+k)_\mu(k'+k)_\nu - \frac{1}{4}g_{\mu\nu}(k'+k)^2\right],$$

where $\beta_{I\!PNN} = 1.87\ \mathrm{GeV}^{-1}$, $\beta_{I\!P\pi\pi} = 1.76\ \mathrm{GeV}^{-1}$

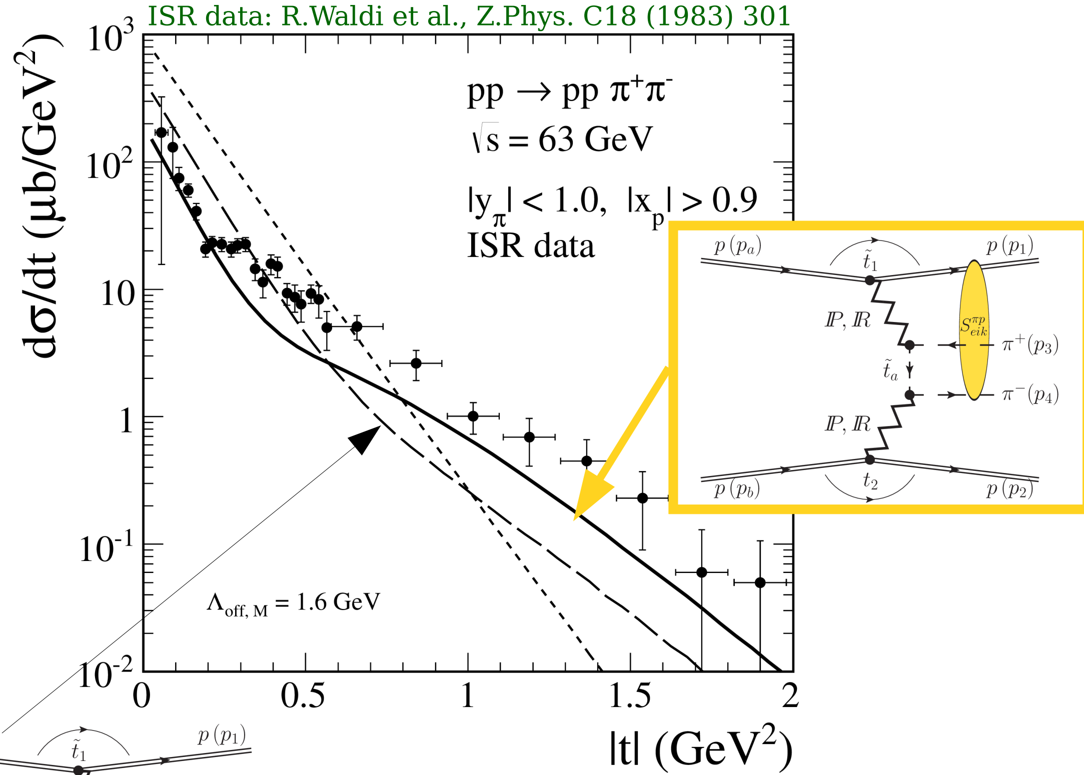
$$F_1(t) = \frac{4m_p^2 - 2.79\,t}{(4m_p^2 - t)(1 - t/m_D^2)^2}, \qquad F_M(t) = \frac{1}{1 - t/\Lambda_0^2},$$

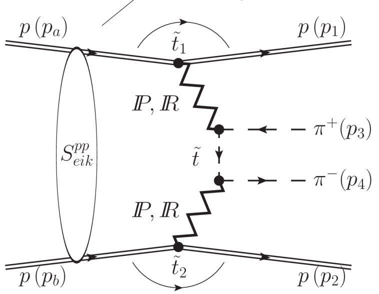
where m_p is the proton mass and $m_D^2 = 0.71\ \mathrm{GeV}^2$ is the dipole mass squared and $\Lambda_0^2 = 0.5\ \mathrm{GeV}^2$.





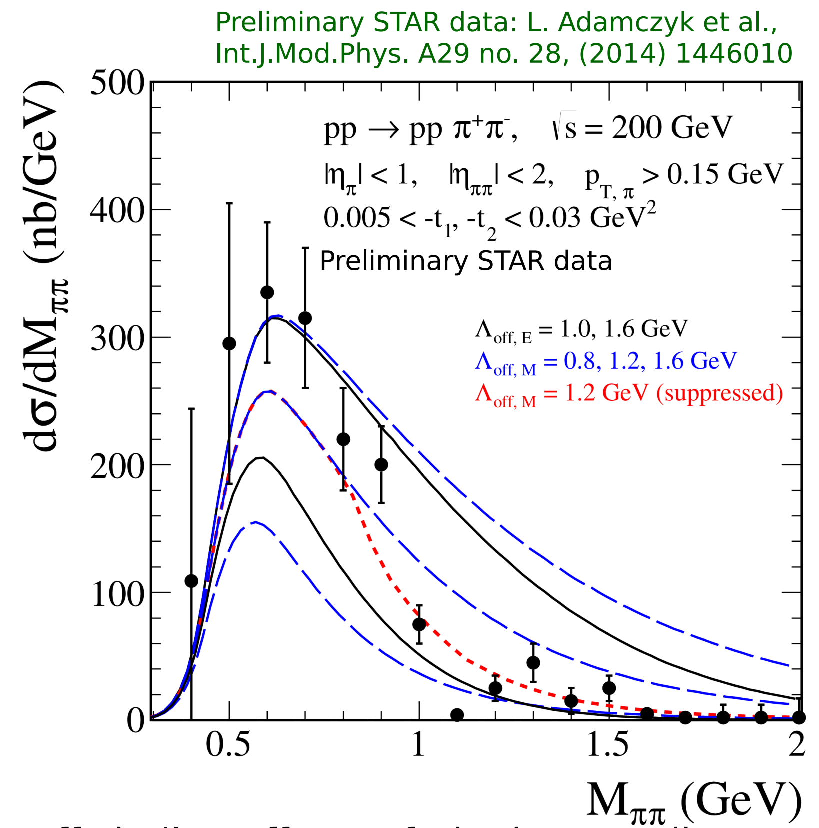
Absorption effects, off-shell pion form factor





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



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

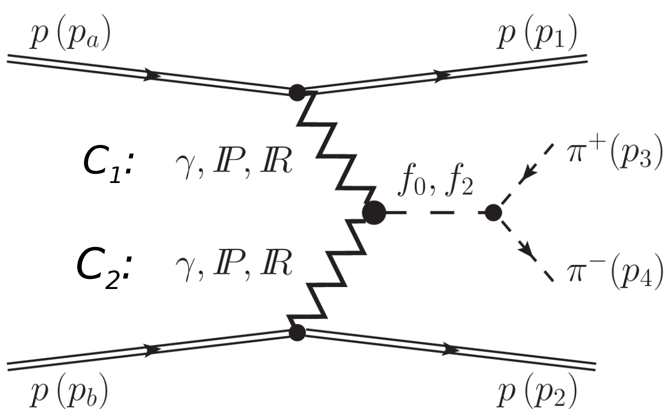
$$F_\pi(\hat{t}) = \exp\left(\frac{\hat{t} - m_\pi^2}{\Lambda_{off,E}^2}\right)$$

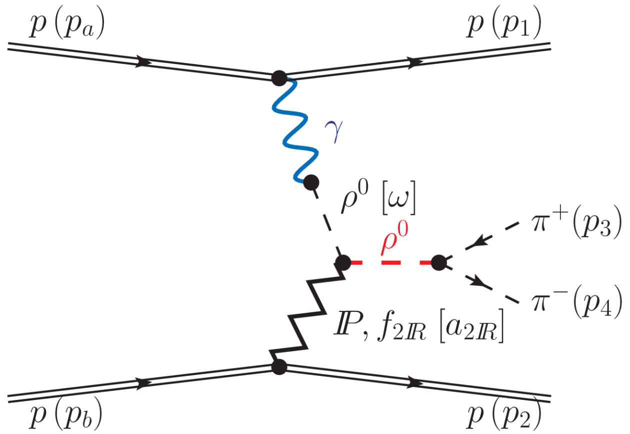
$$F_\pi(\hat{t}) = \frac{\Lambda_{off,M}^2 - m_\pi^2}{\Lambda_{off,M}^2 - \hat{t}}$$

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

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

Dipion resonant production



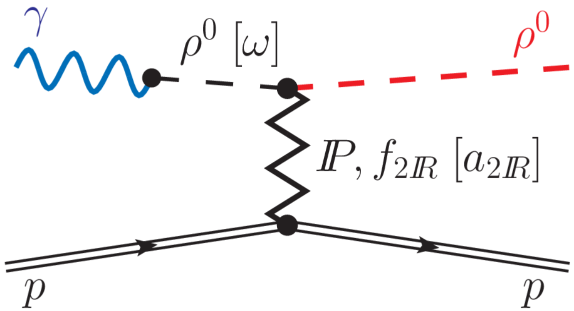


In general, many exchanges are possible in the dipion resonance production process.

$I^G J^{PC}$, 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^{++}, $f_4(2050)$	$\left\{ \begin{array}{c} (I\!P + f_{2I\!R}, I\!P + f_{2I\!R}),\ (a_{2I\!R}, a_{2I\!R}), \\ (\mathbb{O} + \omega_{I\!R} + \gamma, \mathbb{O} + \omega_{I\!R} + \gamma),\ (\rho_{I\!R}, \rho_{I\!R}), \\ (\gamma, \rho_{I\!R}),\ (\rho_{I\!R}, \gamma) \end{array} \right\}$
1^+1^{--}, $\rho(770)$, $\rho(1450)$, $\rho(1700)$ 1^+3^{--}, $\rho_3(1690)$	$\left\{ \begin{array}{c} (\gamma + \rho_{I\!R}, I\!P + f_{2I\!R}),\ (I\!P + f_{2I\!R}, \gamma + \rho_{I\!R}), \\ (\mathbb{O} + \omega_{I\!R}, a_{2I\!R}),\ (a_{2I\!R}, \mathbb{O} + \omega_{I\!R}) \end{array} \right\}$

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

Photoproduction of ρ^0 meson

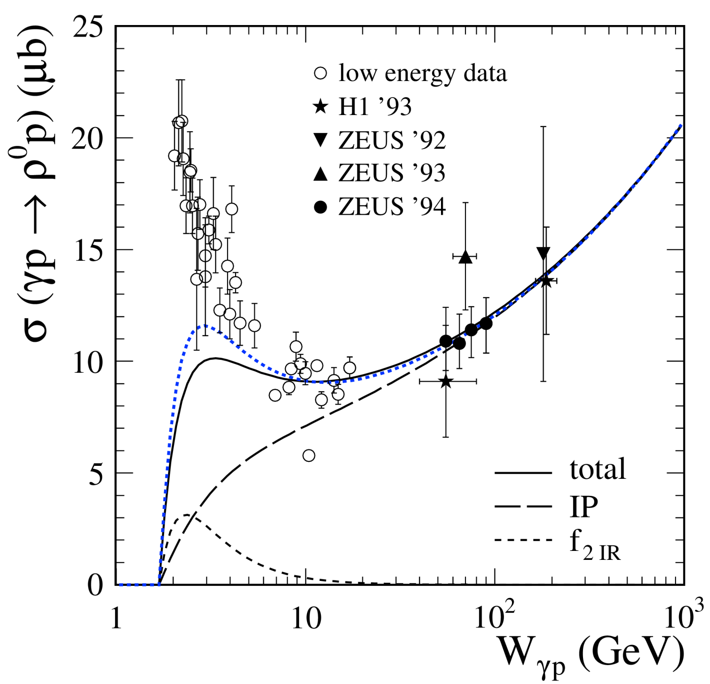


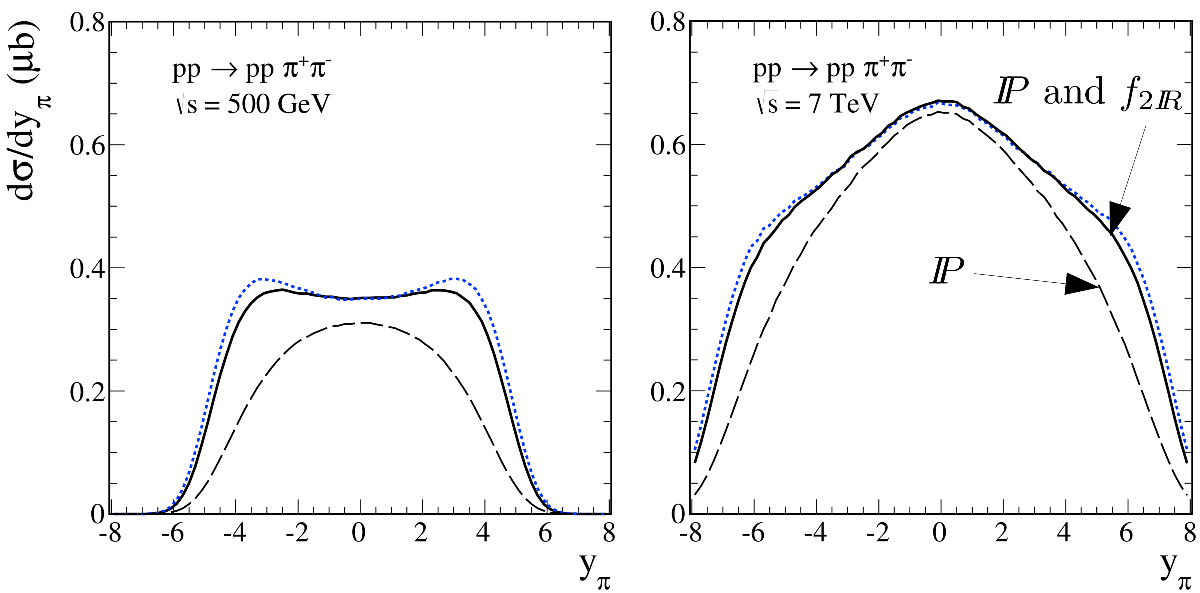
$$\mathcal{M}_{\lambda_\gamma \lambda_b \to \lambda_\rho \lambda_2}(s,t) \cong ie \frac{m_\rho^2}{\gamma_\rho} \Delta_T^{(\rho)}(0) \, (\epsilon^{(\rho)\,\mu})^* \epsilon^{(\gamma)\,\nu} V_{\mu\nu\kappa\lambda}(s,t,q,p_\rho)$$
$$\times 2(p_2+p_b)^\kappa (p_2+p_b)^\lambda \, \delta_{\lambda_2 \lambda_b}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

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*

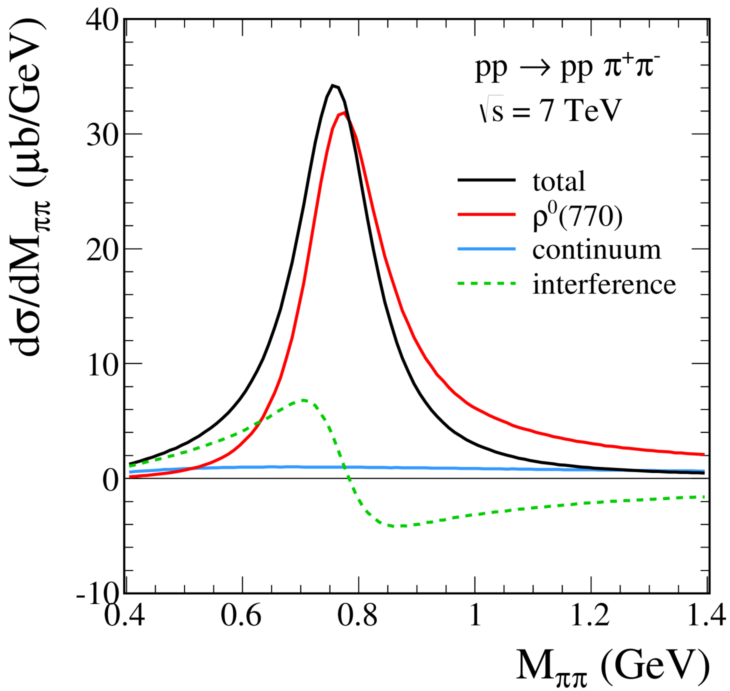


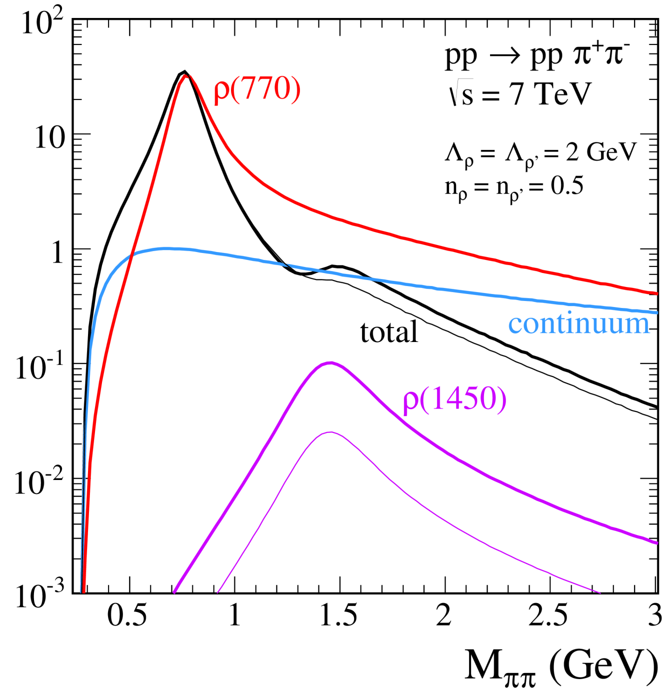


The coupling constants *IP/IR-ρ-ρ* have been estimated from parametrization
of total cross sections for *πp* scattering assuming $\sigma_{tot}(\rho^0(\lambda_\rho = \pm 1), p) = \frac{1}{2}\left[\sigma_{tot}(\pi^+,p) + \sigma_{tot}(\pi^-,p)\right]$

ρ^0 and $\pi^+\pi^-$ continuum

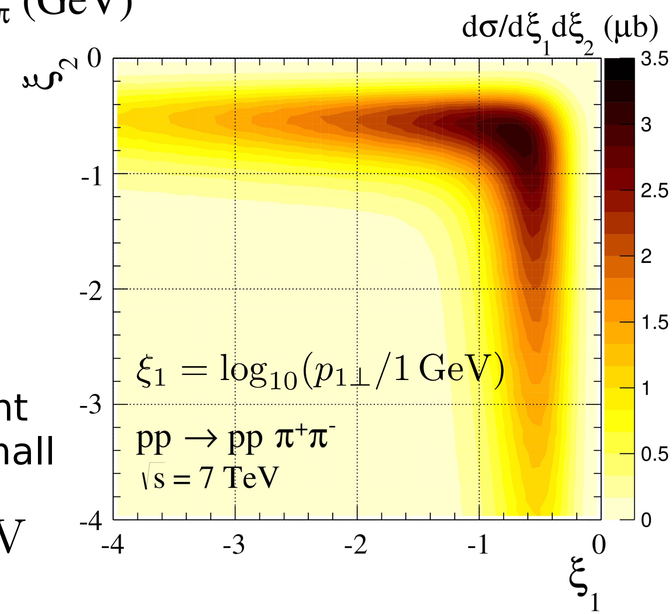
The non-resonant (Drell-Söding) contribution interfere with resonant $\rho(770)$ contribution
→ skewing of ρ^0 line shape.





Here we take a relatively hard form factor for the resonant contribution:

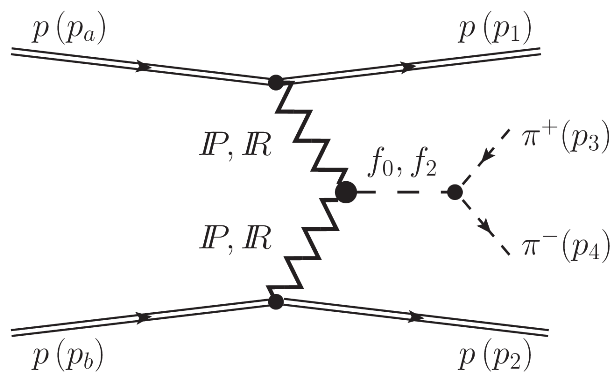
$$\tilde{F}^{(\rho)}(k^2) = \left[1 + \frac{k^2(k^2 - m_\rho^2)}{\Lambda_\rho^4}\right]^{-n_\rho}$$



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 momentum transfer $|t|$.

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

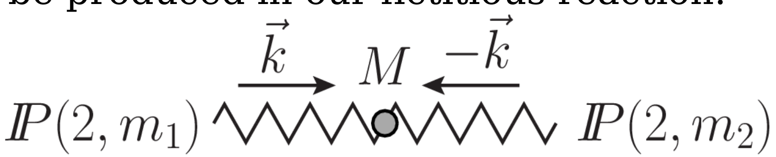
Pomeron-pomeron-meson coupling



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:



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.

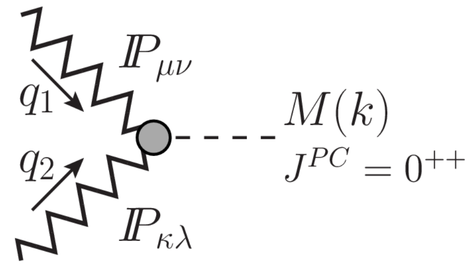
l	S	J	P
0	0	0	+
	2	2	
	4	4	
1	1	0, 1, 2	−
	3	2, 3, 4	
2	0	2	+
	2	0,1,2,3,4	
	4	2,3,4,5,6	
3	1	2,3,4	−
	3	0,1,2,3,4,5,6	
4	0	4	+
	2	2,3,4,5,6	
	4	0,1,2,3,4,5,6,7,8	
5	1	4.5.6	−
	3	2,3,4,5,6,7,8	
6	0	6	+
	2	4,5,6,7,8	
	4	2,3,4,5,6,7,8,9,10	

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).

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

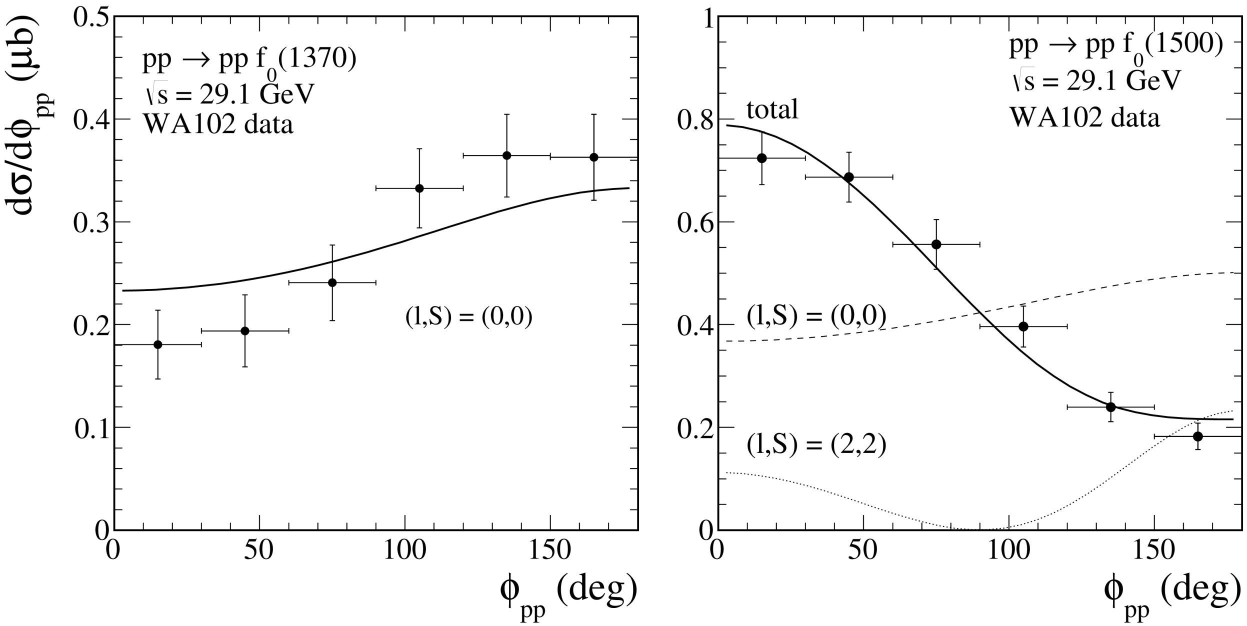
Scalar mesons

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



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

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



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

(proposed by F. Close)

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

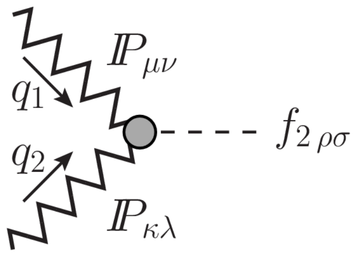
- $f_0(1370)$ peaks as $\phi_{pp} \to \pi$ whereas the $f_0(980)$, $f_0(1500)$, $f_0(1710)$ peak at $\phi_{pp} \to 0$
- $f_0(1500)$ and $f_0(1710)$ which could have a large 'gluonic component' have a large value for the *dPt* ratio

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:

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



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

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

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

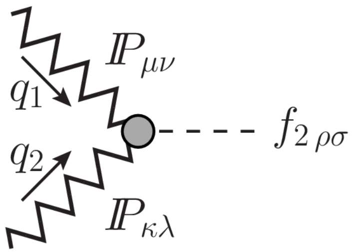
where $\hat{g}_{\mu\nu} = -g_{\mu\nu} + p_{34\mu}p_{34\nu}/p_{34}^2$ and $\Delta^{(f_2)}_{\nu\mu,\kappa\lambda}(p_{34}) = \Delta^{(f_2)}_{\mu\nu,\lambda\kappa}(p_{34}) = \Delta^{(f_2)}_{\kappa\lambda,\mu\nu}(p_{34})$, $g^{\kappa\lambda}\Delta^{(f_2)}_{\mu\nu,\kappa\lambda}(p_{34}) = 0$.

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

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

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

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



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

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

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

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

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

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

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

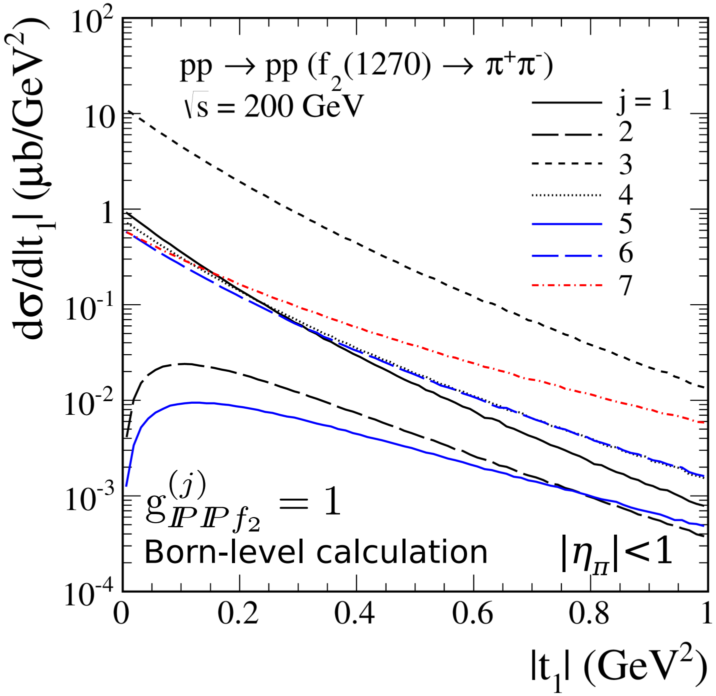
$$i\Gamma^{(I\!PI\!Pf_2)(6)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = \frac{i}{M_0^3}\, g^{(6)}_{I\!PI\!Pf_2} \Big(q_1^{\alpha_1}\, q_1^{\lambda_1}\, q_2^{\mu_1}\, q_{2\rho_1}\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1} + q_2^{\alpha_1}\, q_2^{\lambda_1}\, q_1^{\mu_1}\, q_{1\rho_1}\,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

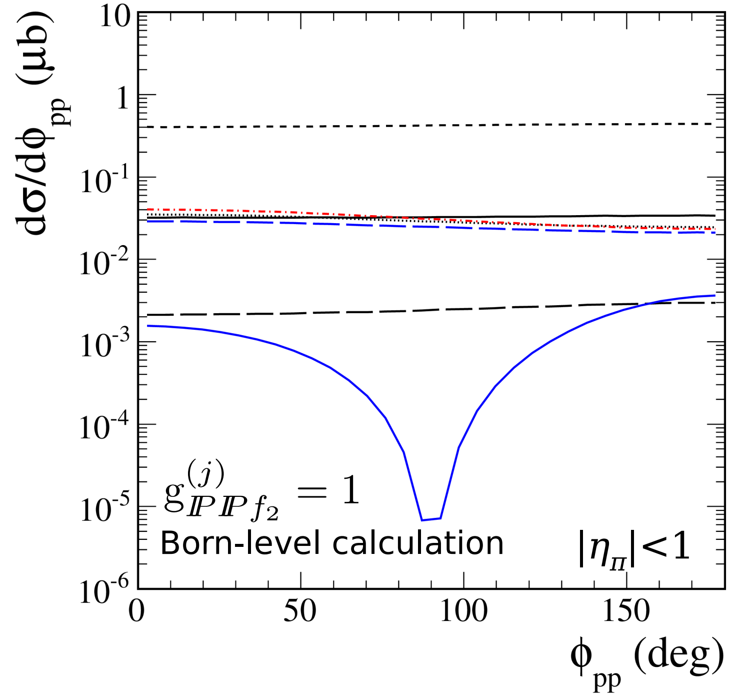
$$i\Gamma^{(I\!PI\!Pf_2)(7)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{2i}{M_0^5}\, g^{(7)}_{I\!PI\!Pf_2}\, q_1^{\rho_1}\, q_1^{\alpha_1}\, q_1^{\lambda_1}\, q_2^{\sigma_1}\, q_2^{\mu_1}\, q_2^{\nu_1}\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1}\, R_{\rho\sigma\rho_1\sigma_1}$$

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

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

Choice of *IP-IP-f₂(1270)* coupling





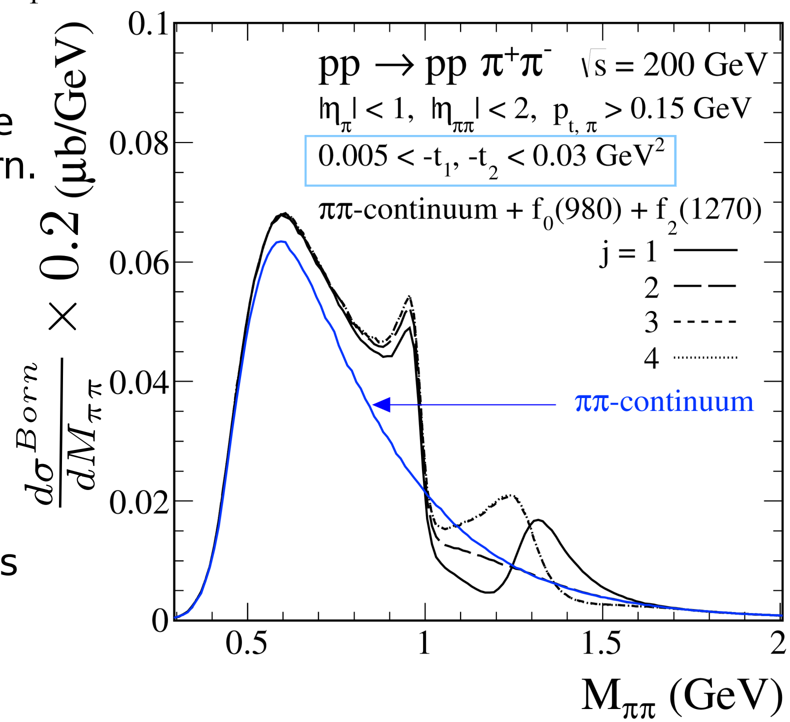
Our choice of coupling (j=2) is in agreement with exp. observations (WA102, ISR)

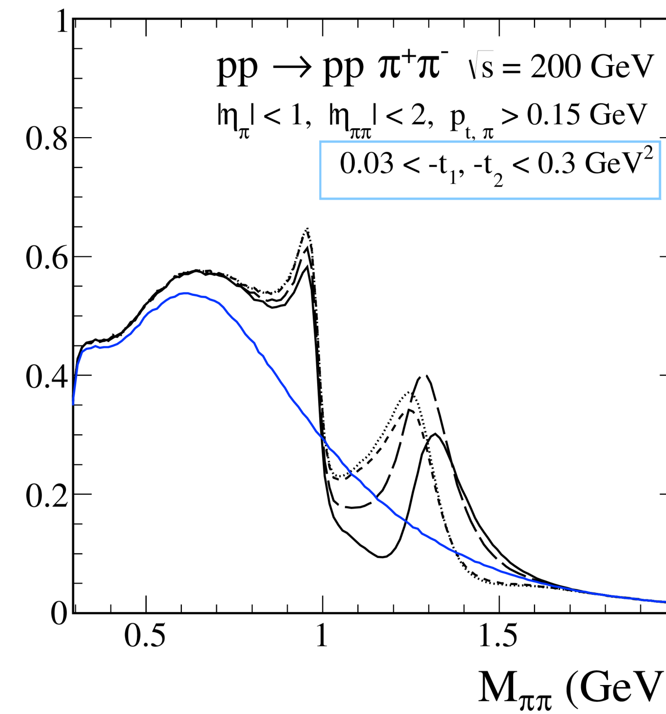
$f_2(1270)$ peaks at $\phi_{pp} \to \pi$

Different couplings generate different interference pattern.

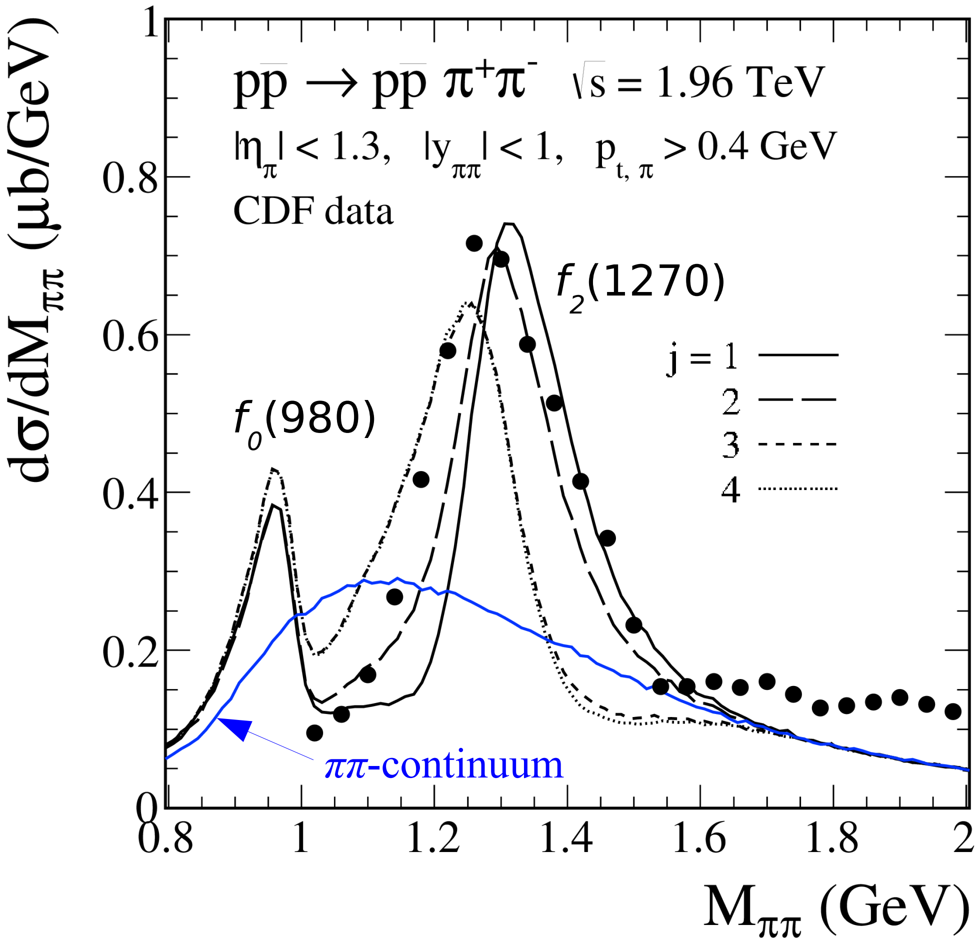
The relative contribution of the resonant $f_2(1270)$ and dipion continuum strongly depends on the cut on $|t|$

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





Comparison with CDF data



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

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

(no proton tagging → rapidity gap method)

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

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

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

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

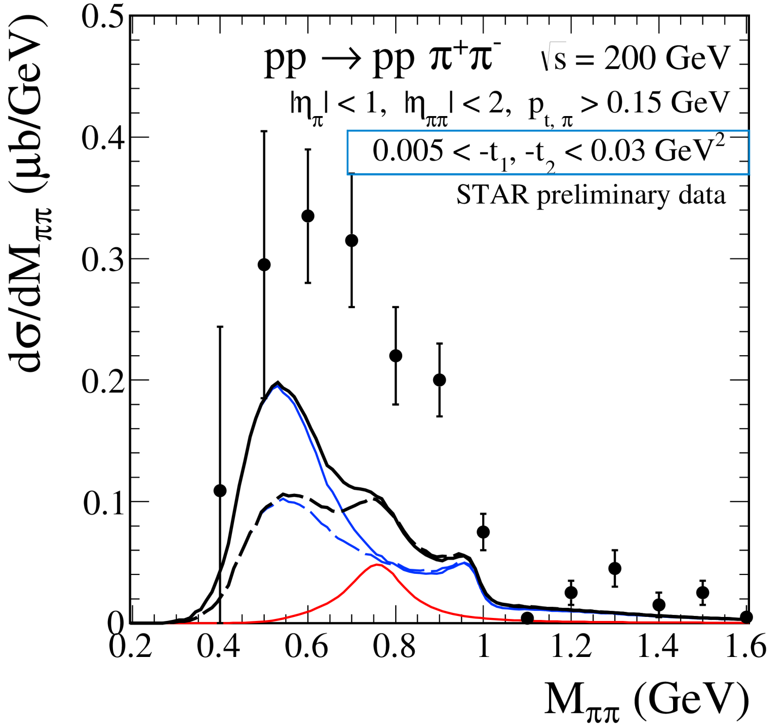
We take the monopole form for off-shell pion form factors with $\Lambda_{off,M}$ = 0.7 GeV.

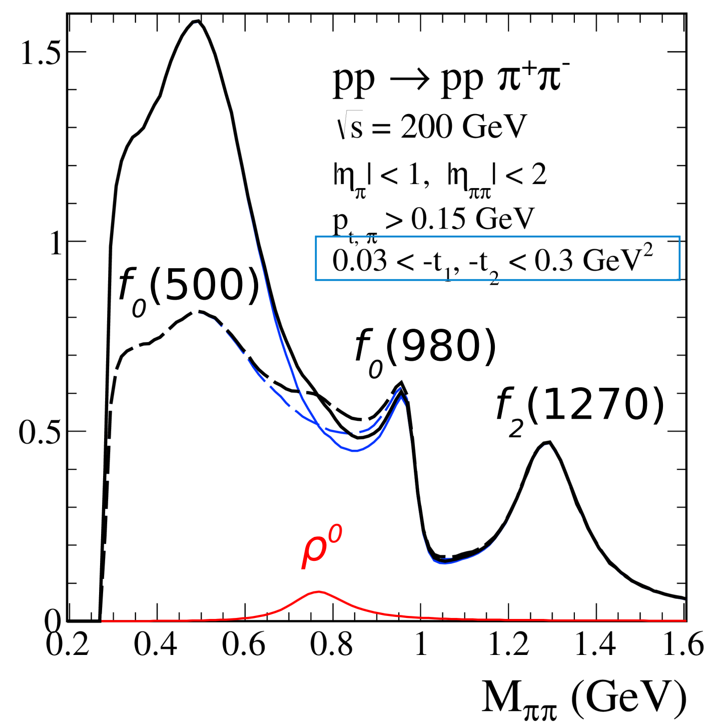
Absorption effects were included effectively:

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

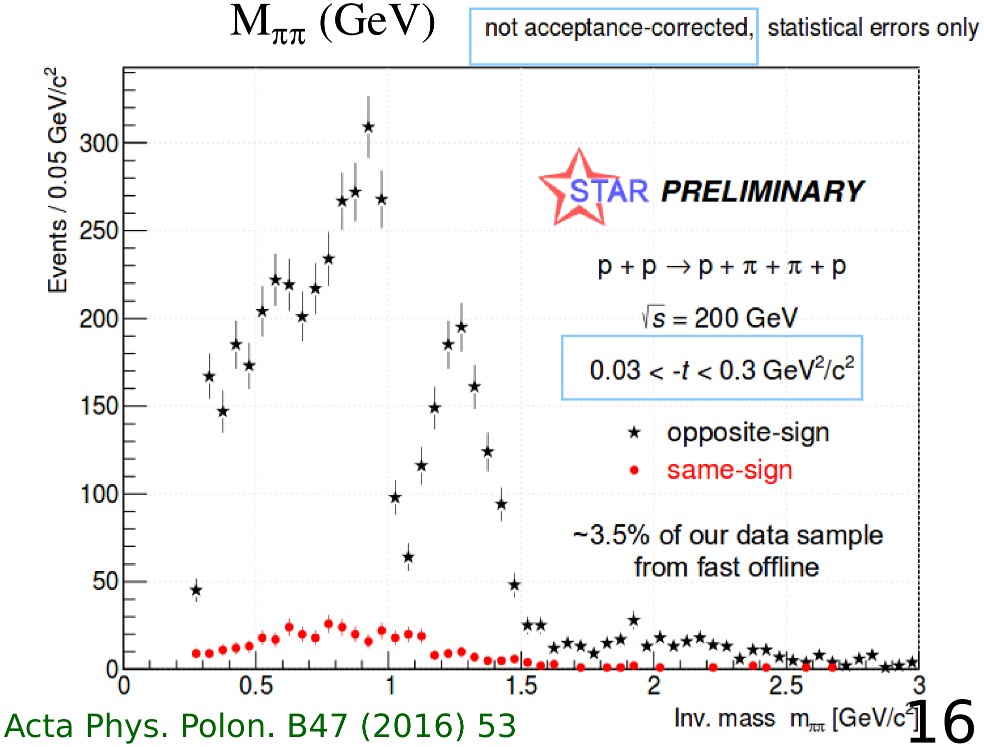
$< S^2 > \simeq 0.1$
ratio of full (absorbed)-to-Born cross section

Comparison with STAR preliminary data





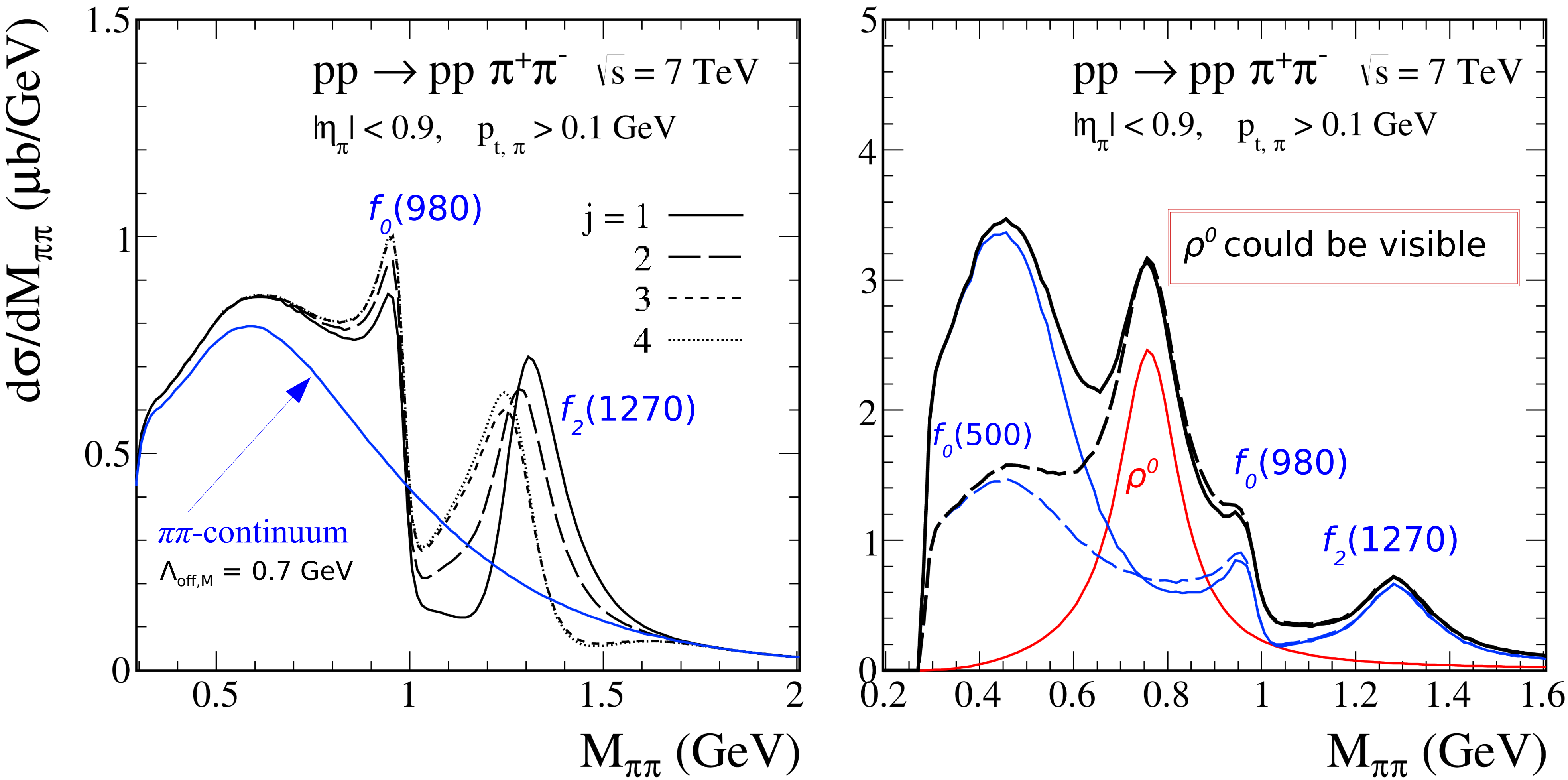
see W. Guryn talk



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

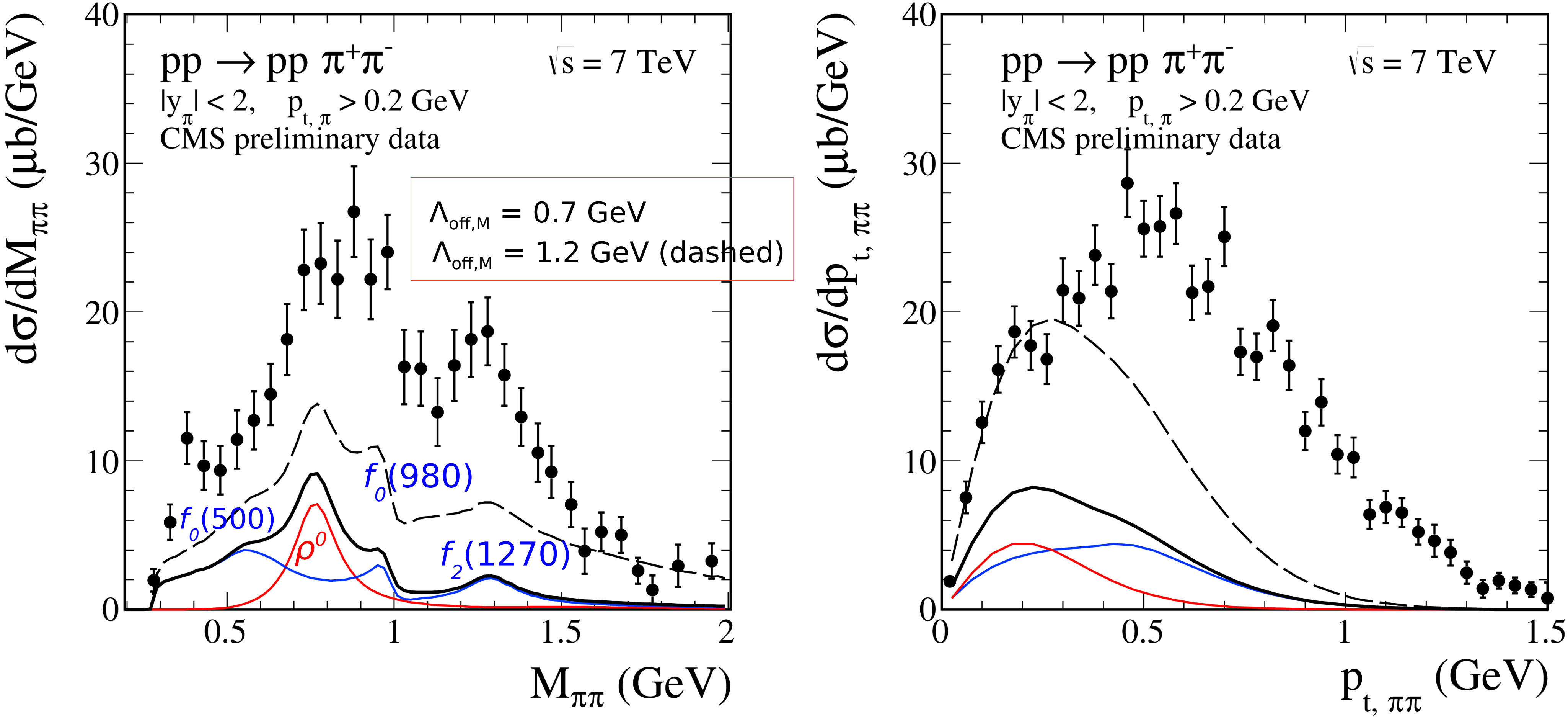
STAR preliminary data for small |t|: L.Adamczyk, W.Guryn, J.Turnau, Int.J.Mod.Phys. A29 no. 28, (2014) 1446010; for larger |t|: W. Guryn, Acta Phys. Polon. B47 (2016) 53

Predictions for ALICE



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

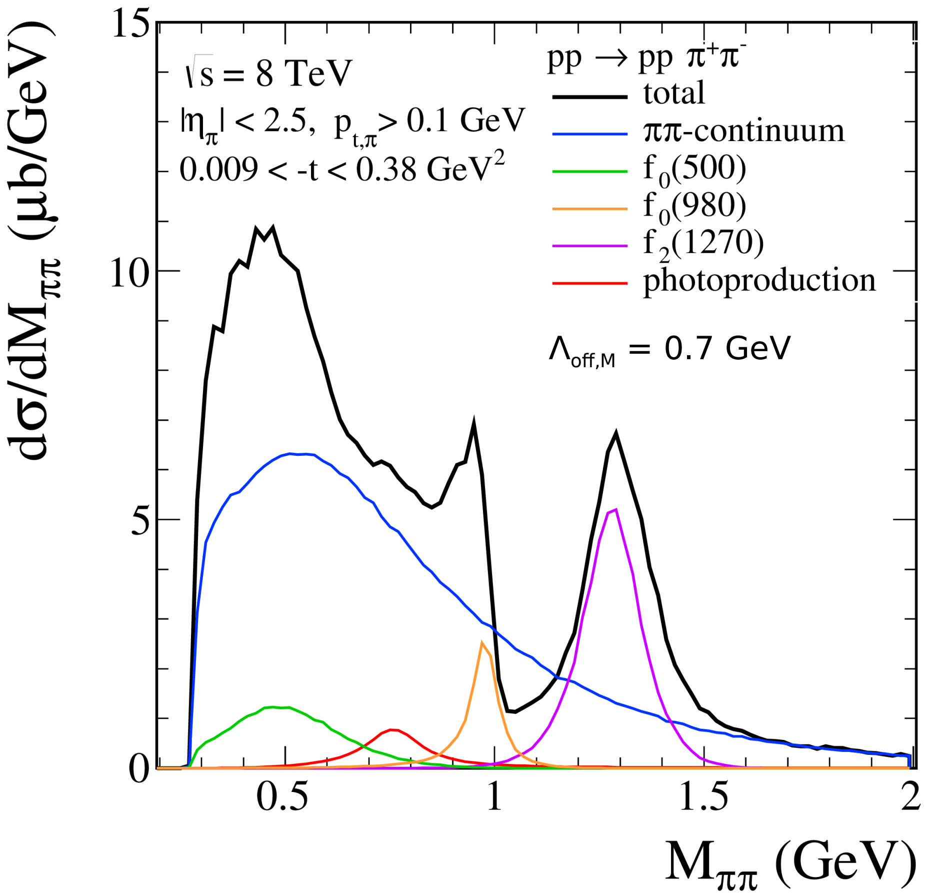
Comparison with CMS preliminary data



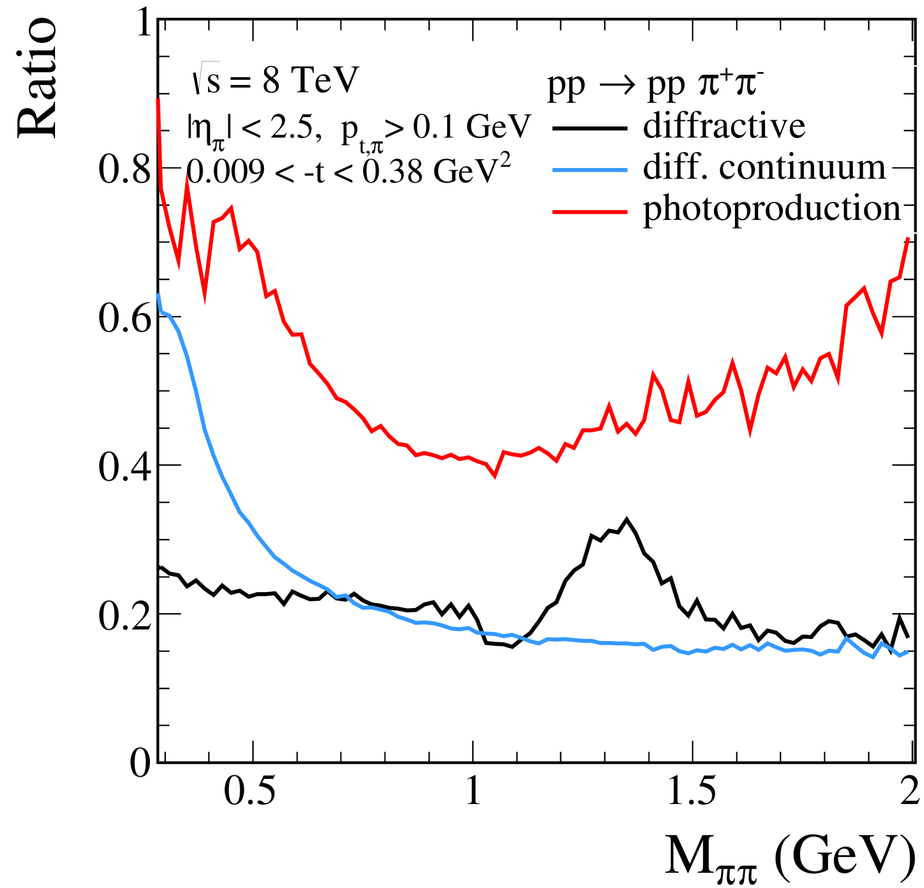
- our model results are much below the CMS data which could be due to a contamination of non-exclusive processes (one or both protons undergoing dissociation)
- we observe that the ρ^0 photoproduction term could be visible

CMS preliminary data: CMS-PAS-FSQ-12-004

Predictions for ATLAS+ALFA



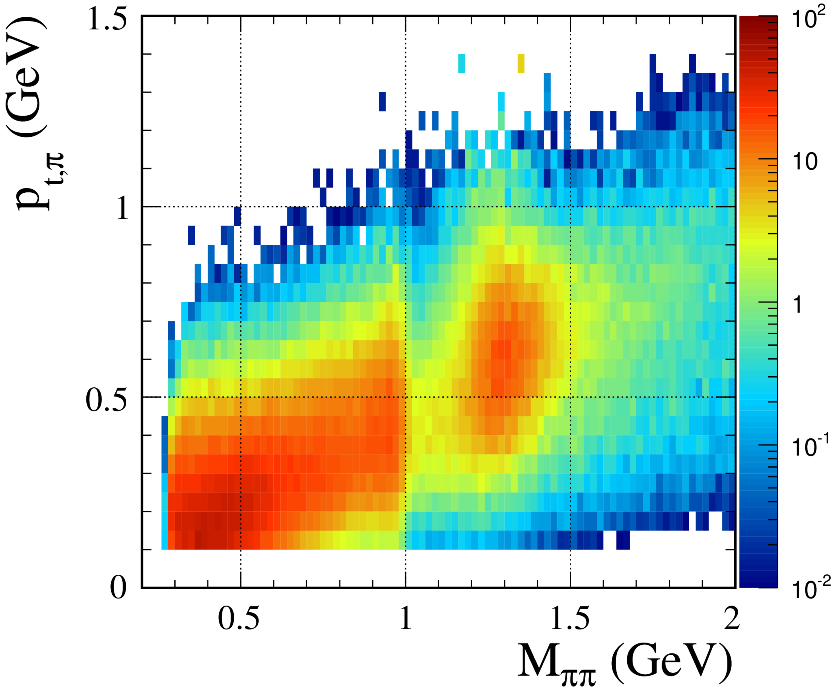
ratio of full (absorbed)-to-Born cross section

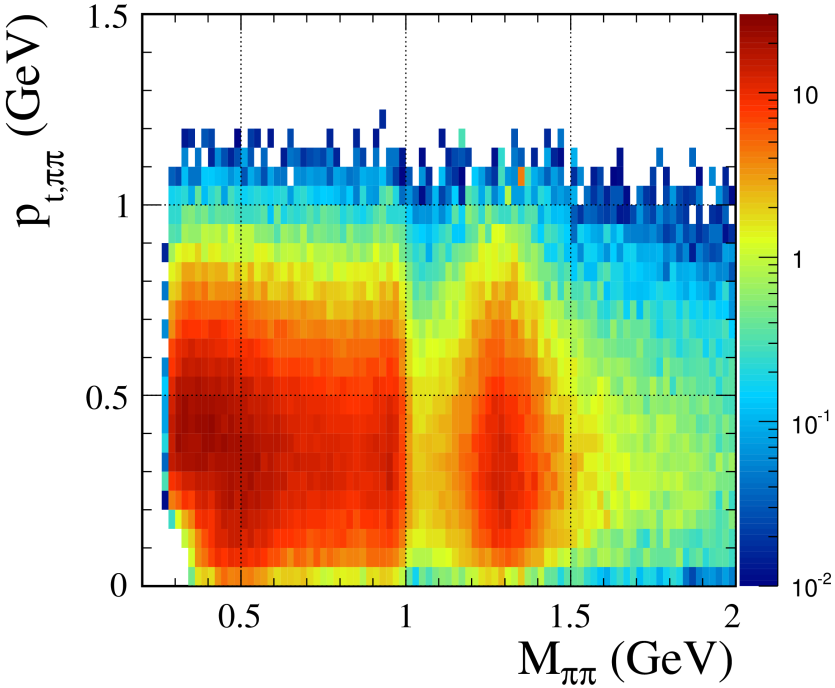


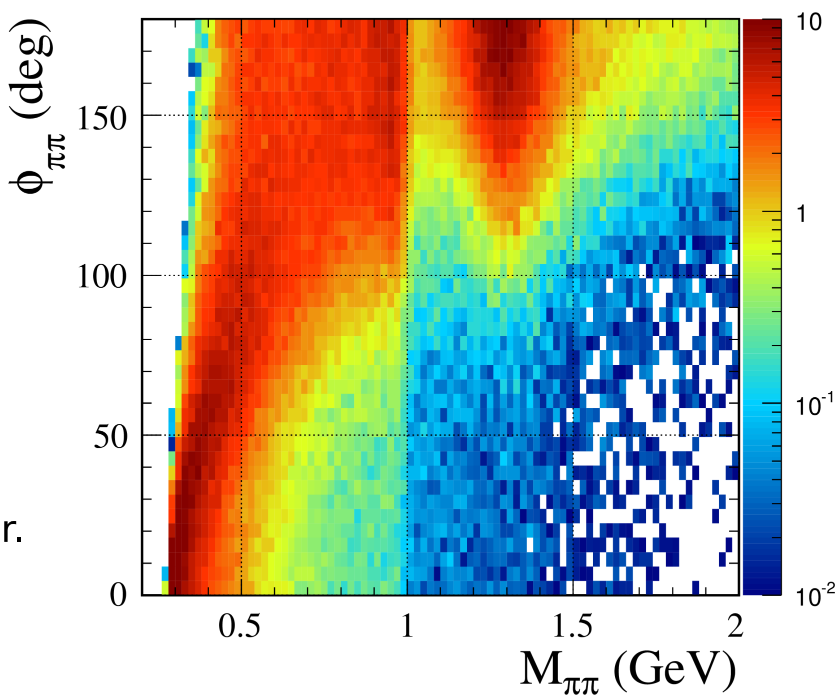
Here the absorption effects due to *pp*-rescattering only were included.

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

Predictions for ATLAS+ALFA

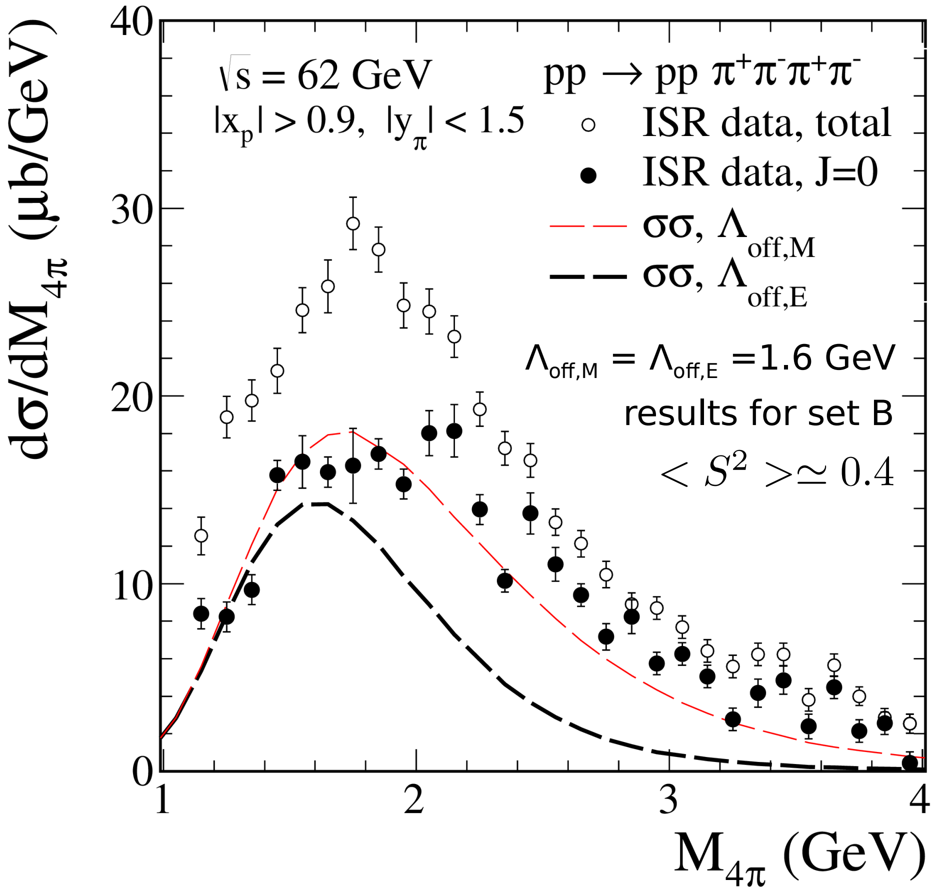


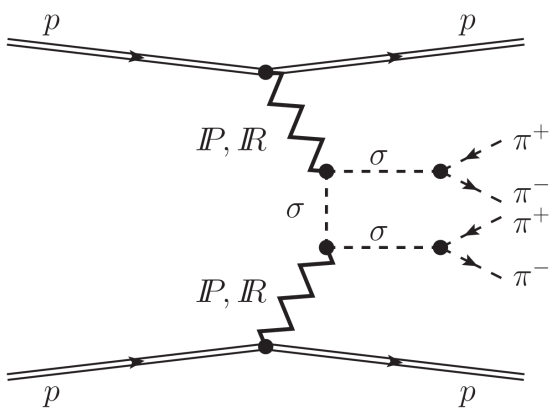




The cuts on pion transverse momenta,
on transverse momentum of pion pair,
or on $\phi_{\pi\pi}$ may play the role of a $\pi^+\pi^-$ resonance filter.

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





Two sets of the coupling constants:

$$\text{set A}: \ \beta_{I\!P\sigma\sigma} = 2\beta_{I\!P\pi\pi}\,,\ g_{f_2 I\!R\sigma\sigma} = g_{f_2 I\!R\pi\pi}$$

$$\boxed{\text{set B}: \ \beta_{I\!P\sigma\sigma} = 4\beta_{I\!P\pi\pi}\,,\ g_{f_2 I\!R\sigma\sigma} = 2g_{f_2 I\!R\pi\pi}}$$

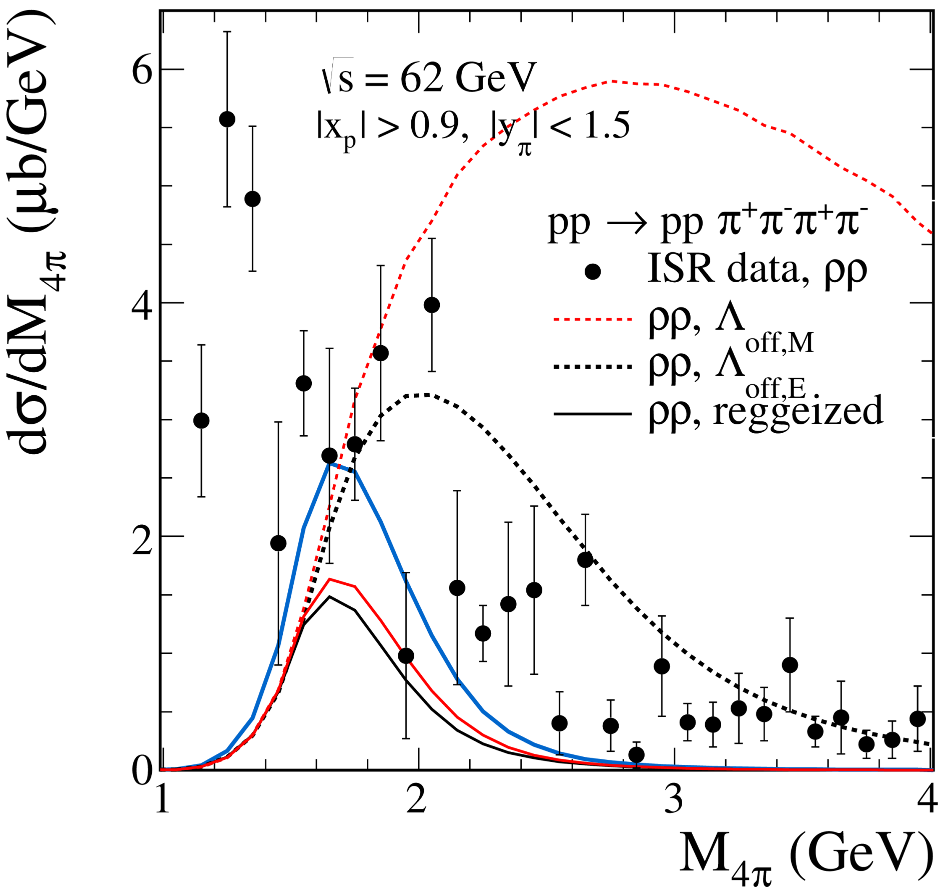
$$\sigma_{2\to6} = \int_{2m_\pi}^{\max\{m_{X_3}\}} \int_{2m_\pi}^{\max\{m_{X_4}\}} \sigma_{2\to4}(..., m_{X_3}, m_{X_4})\, f_M(m_{X_3})\, f_M(m_{X_4})\, dm_{X_3}\, dm_{X_4}$$

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

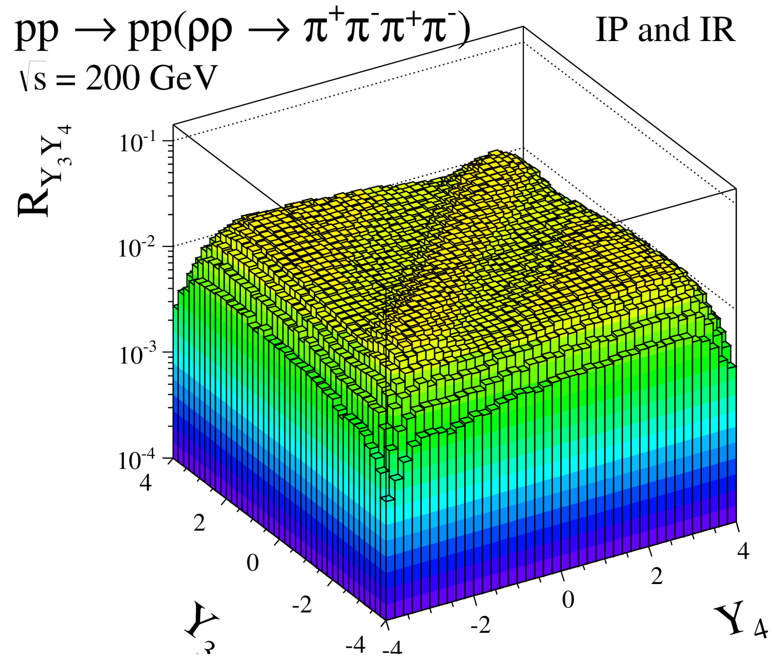
The 4π ISR data contains a large $\rho^0\pi^+\pi^-$ component with an enhancement in the J =2 term which was interpreted as a $f_2(1720)$ state.

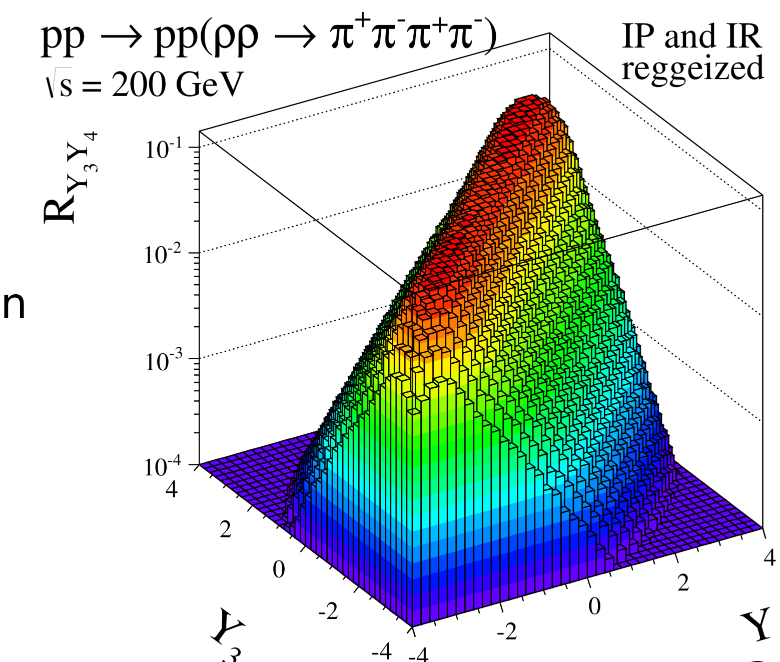
ISR data: A. Breakstone *et al*. (ABCDHW Collaboration), Z. Phys. C58 (1993) 251

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



$$R_{Y_3Y_4} = \frac{d^2\sigma}{dY_3dY_4} \Big/ \int dY_3dY_4 \frac{d^2\sigma}{dY_3dY_4}$$



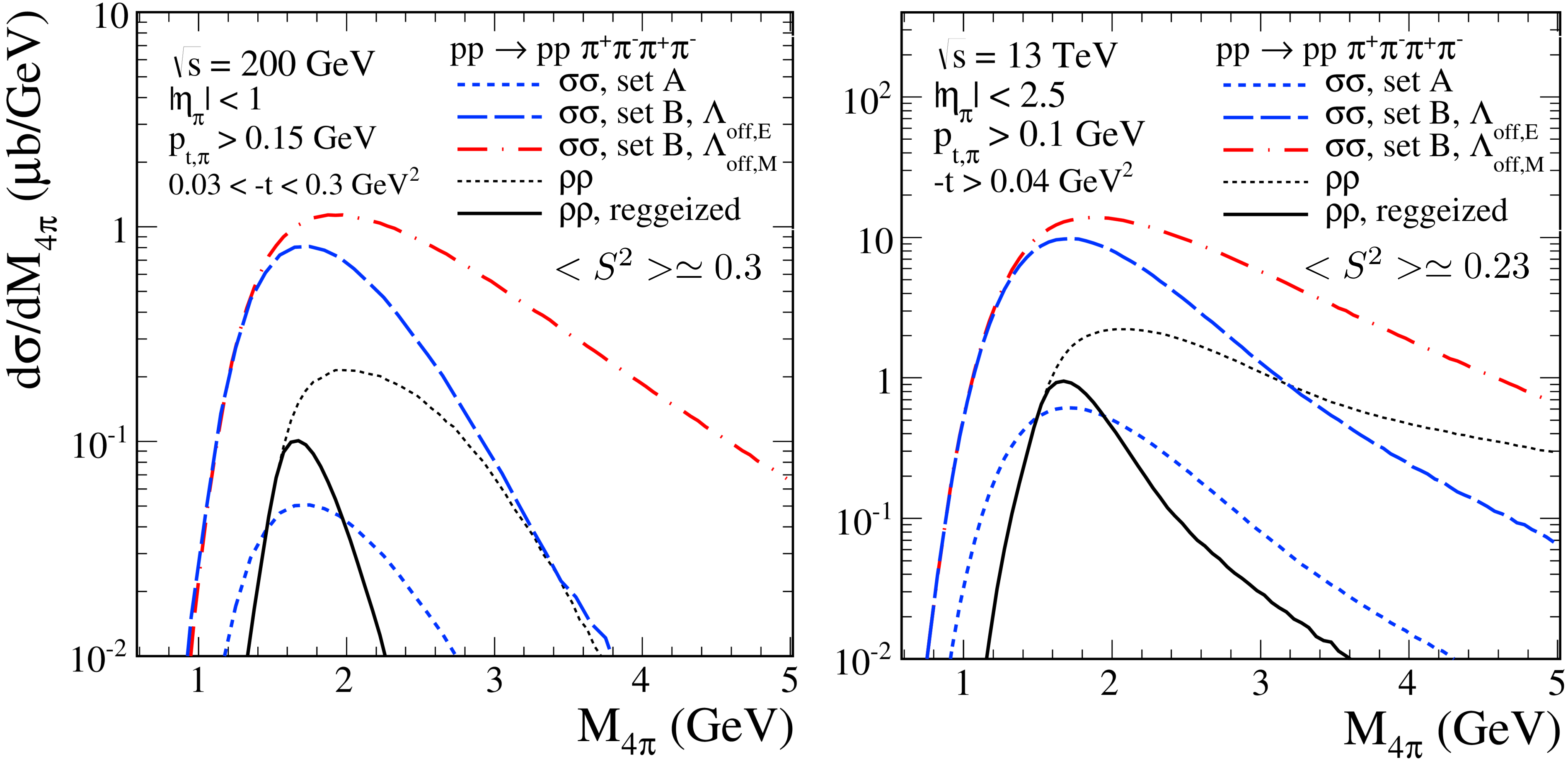


- reggeization effect becomes crucial when the separation in rapidity between the two ρ mesons increases

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

For the central exclusive production of $\rho\rho$ pairs see also poster by R. Kycia and J. Turnau.

Predictions for STAR and ATLAS



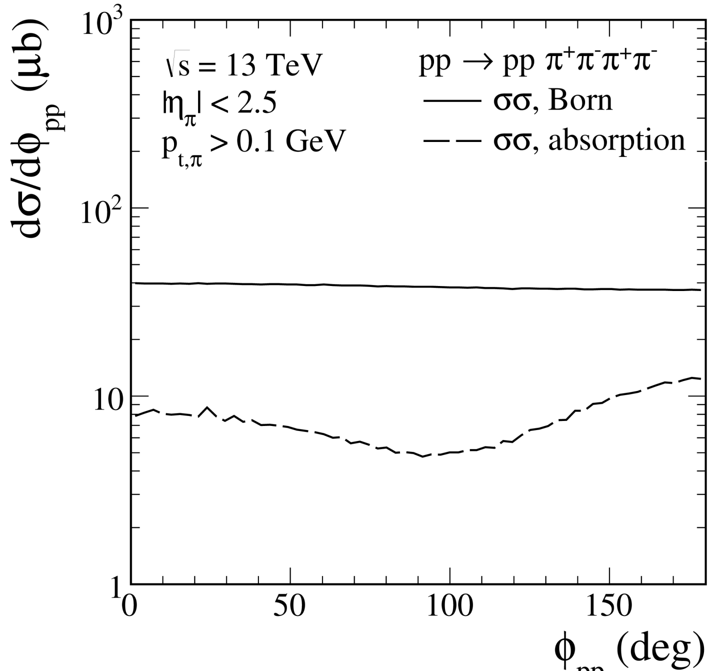
Absorption effects due to *pp*-rescattering were included.

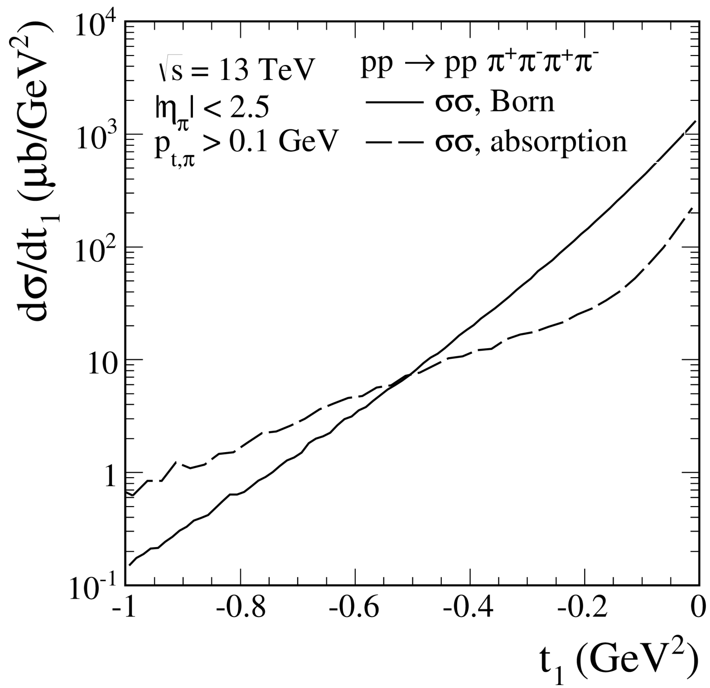
Cross sections (in μb) for $pp \to pp\ \pi^+\pi^-\pi^+\pi^-$

		"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 $\Lambda_{\mathrm{off,E}}$ = 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 $|t|$).





Summary and Conclusions

- The tensor-pomeron model (Ewerz-Maniatis-Nachtmann) was applied to many *pp* → *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. Central exclusive production of light mesons shows the potential for testing the nature of the soft pomeron and on its couplings to the hadrons.

- The $pp \to pp\pi^+\pi^-$ process is an attractive for different exp.: COMPASS, STAR, CDF, ALICE, CMS, ATLAS, LHCb.

- We have given a consistence treatment of the $\pi^+\pi^-$ continuum and resonance production.
  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.
  Only 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 resonant $f_2(1270)$ and dipion continuum strongly depends on the cut on proton p_t (or four-momentum transfer squared) which may explain some controversial observation made by the ISR groups (AFS, ABCDHW) in the past.
  We suggest some experimental cuts which may play the role of a $\pi\pi$ resonance filter
  (e.g., cuts on azimuthal angle between outgoing pions, transverse momenta of pions).

- 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.

- We have estimated the necleon-nucleon and pion-nucleon absorption corrections to diffractive double pomeron/reggeon contribution. For photon induced contributions the absorption lead to about 10% reduction of the cross section. The effect depends on the t region in which is considered.
  The measurement of protons is crucial in better understanding of mechanism reaction (absorption effects).