Results for central exclusive production in pp collisions within tensor pomeron approach

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ECT Trento Workshop*

QCD challenges in pp, pA and AA collisions at high energies
27 Feb - 3 Mar 2017

Plan

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

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

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

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

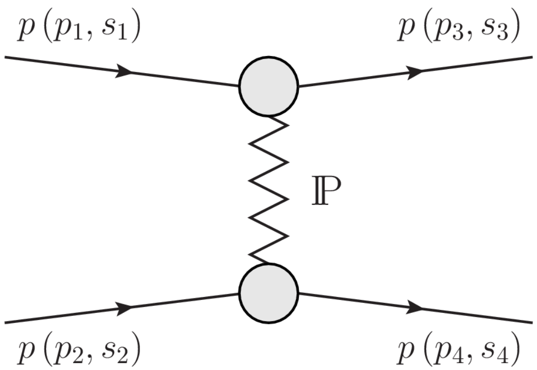
Motivation

- Exclusive processes are attractive for different experiments:
  COMPASS, STAR, CDF, ALICE, CMS, ATLAS, LHCb.
- Many aspects deserve to study:
  - nature of soft pomeron
  - mechanism of resonant and non-resonant production
    - size of absorptive corrections
    - role of reggeon exchanges
    - two-pion and four-pion invariant mass spectra, ...
- pQCD image of pomeron implies that DPE is a gluon-rich process
  → gluon bound states (glueballs) could be preferentially produced
- Exotic mesons in DPE and photon-pomeron processes (see talk by Suh-Urk Chung)

The nature of soft pomeron

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

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



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

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

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

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

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

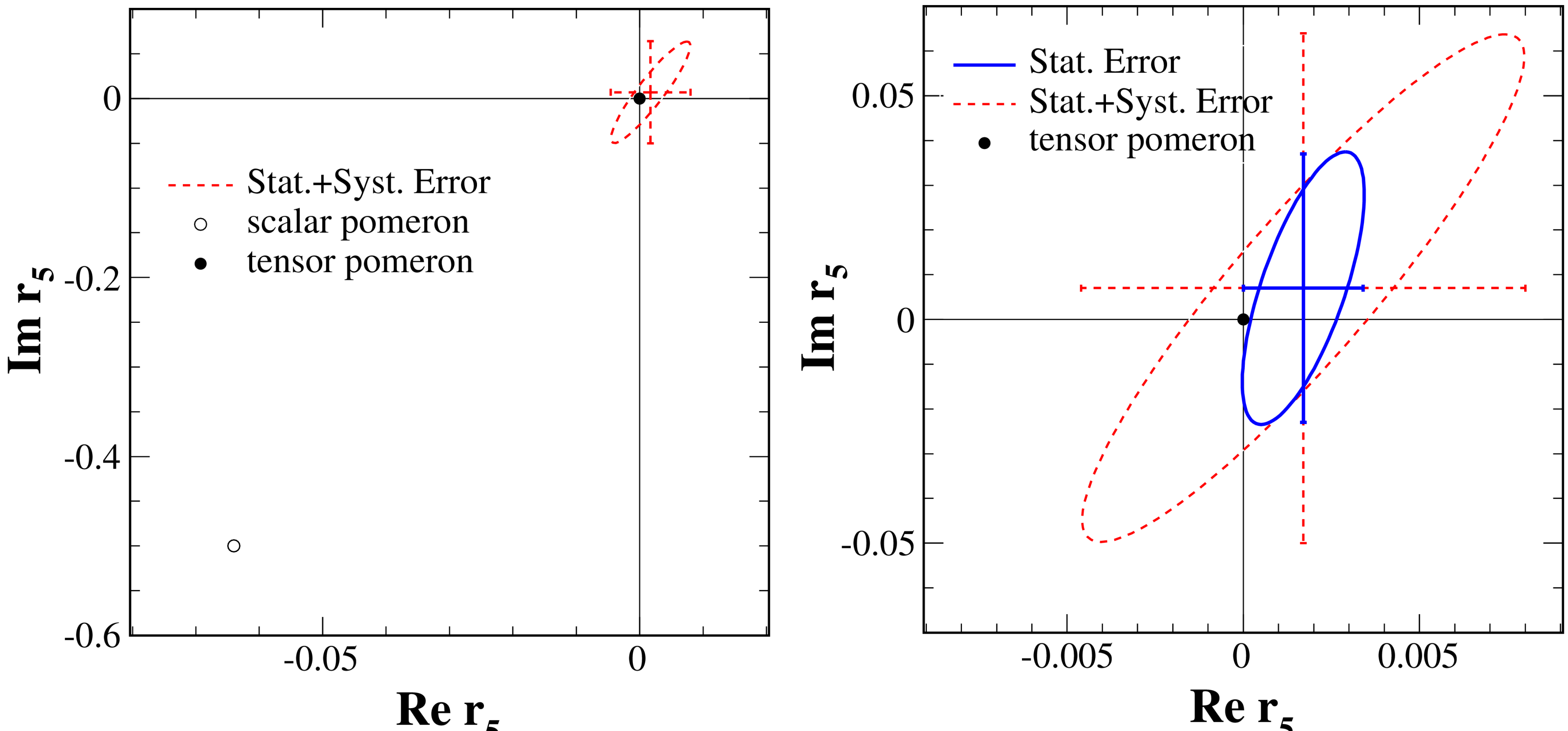
- Comparison with experimental data on polarised high-energy *pp* elastic scattering [L. Adamczyk et al. (STAR Collaboration), Phys. Lett. B719 (2013) 62)]

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

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

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

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



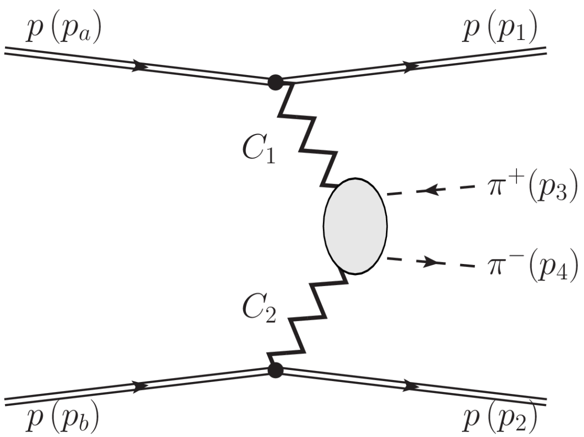
The tensor-pomeron result is compatible with the general rules of QFT and the STAR experimental result.

see talk by Carlo Ewerz

Central exclusive production of mesons

- P. L., 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. L, O. Nachtmann, A. Szczurek, *ρ^0 and Drell-Söding contributions to central exclusive production of $\pi^+\pi^-$ pairs in proton-proton collisions at high energies*, arXiv:1412.3677, Phys. Rev. D91 (2015) 07402300
- P. L., O. Nachtmann, A. Szczurek, *Central exclusive diffractive production of the $\pi^+\pi^-$ continuum, scalar and tensor resonances in pp and $p\bar{p}$ scattering within the tensor Pomeron approach*, arXiv:1601.04537, Phys. Rev. D93 (2016) 054015
- P. L., O. Nachtmann, A. Szczurek, *Exclusive diffractive production of $\pi^+\pi^-\pi^+\pi^-$ via the intermediate $\sigma\sigma$ and $\rho\rho$ states in proton-proton collisions within tensor Pomeron approach*, arXiv:1606.05126, Phys. Rev. D94 (2016) 034017
- P. L., O. Nachtmann, A. Szczurek, *Central production of ρ^0 in pp collisions with single proton diffractive dissociation at the LHC*, arXiv: 1612.06294, Phys. Rev. D95 (2017) 034036

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

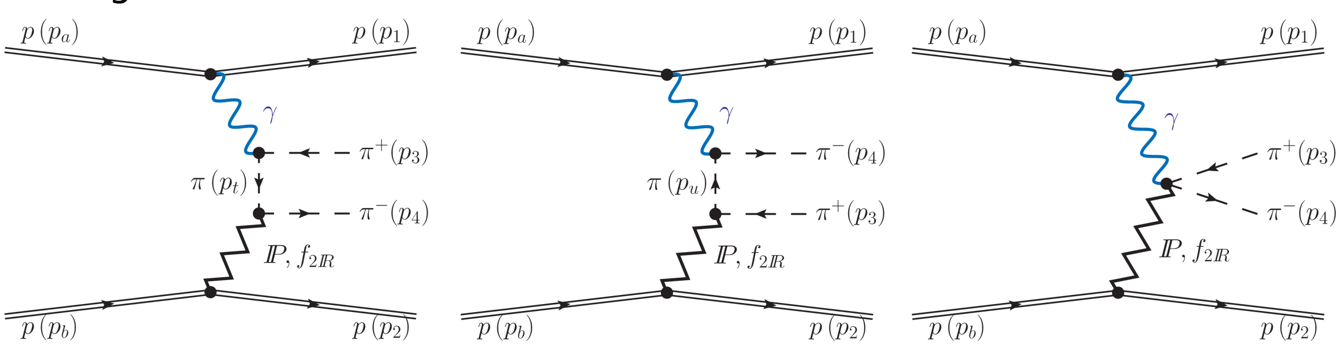
$$(C_1, C_2) = (1,1): \quad (I\!P + f_{2I\!R}, I\!P + f_{2I\!R})$$
$$(C_1, C_2) = (-1,-1): \quad (\rho_{I\!R} + \gamma, \rho_{I\!R} + \gamma)$$
$$(C_1, C_2) = (1,-1): \quad (I\!P + f_{2I\!R}, \rho_{I\!R} + \gamma)$$
$$(C_1, C_2) = (-1,1): \quad (\rho_{I\!R} + \gamma, I\!P + f_{2I\!R})$$

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

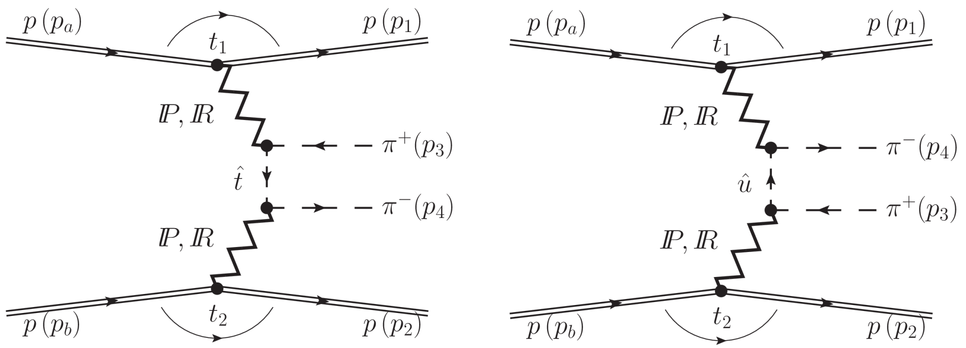
The full amplitude of dipion production is a sum of continuum and resonances amplitudes:

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

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

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

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



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

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

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

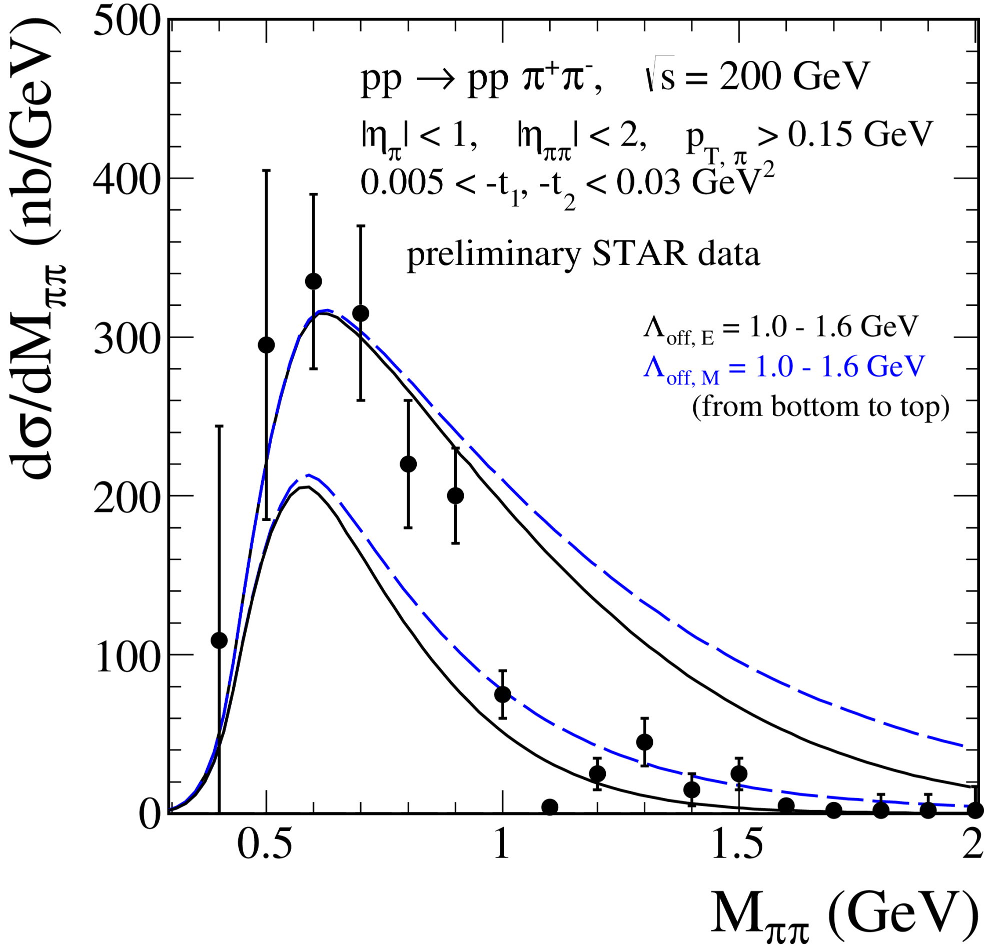
in terms of effective tensor pomeron propagator, proton and pion vertex functions

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

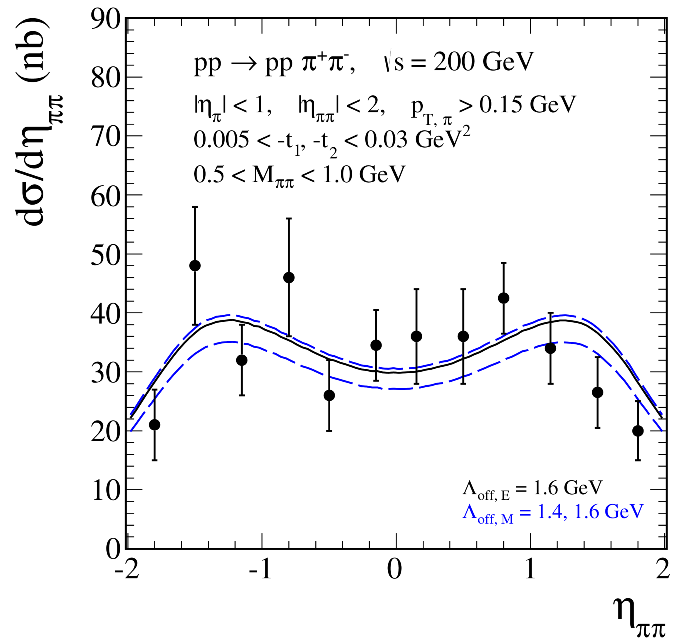
$$i\Gamma^{(I\!P\pi\pi)}_{\mu\nu}(k',k) = -i2\beta_{I\!P\pi\pi}\, F_M((k'-k)^2)\left[(k'+k)_\mu(k'+k)_\nu - \frac{1}{4}g_{\mu\nu}(k'+k)^2\right]$$

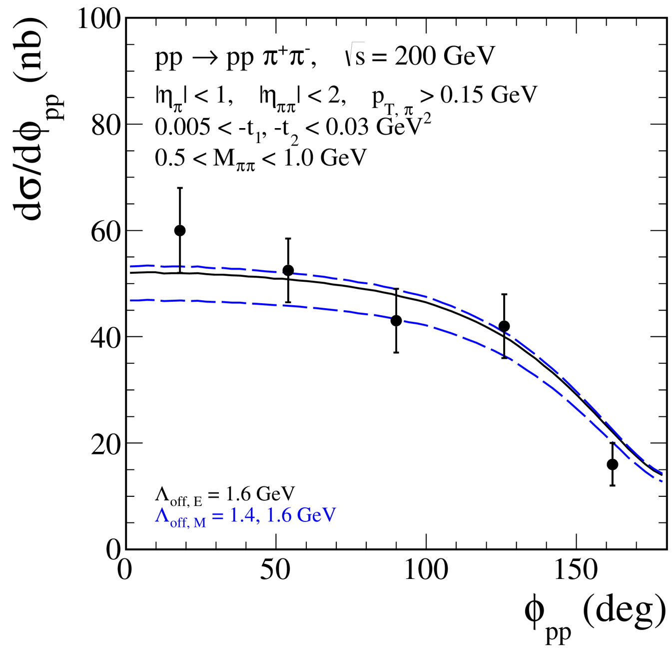
$$\beta_{I\!P\pi\pi} = 1.76\ \mathrm{GeV}^{-1}, \quad F_M(t) = \frac{1}{1-t/\Lambda_0^2}, \quad \Lambda_0^2 = 0.5\ \mathrm{GeV}^2$$

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



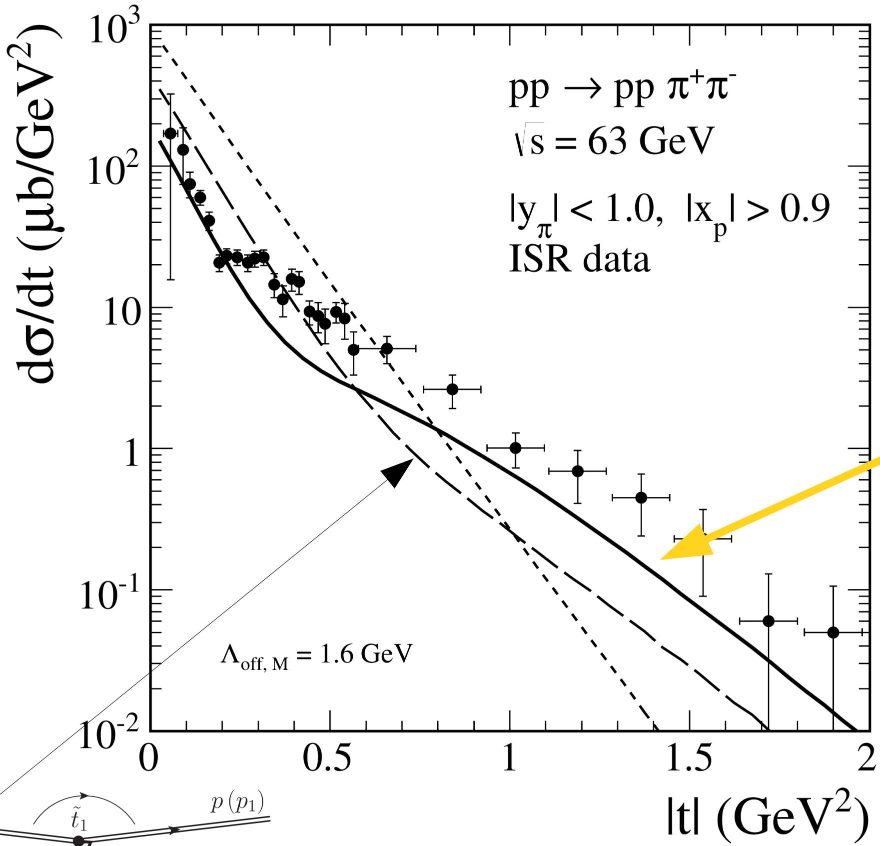


off-shell effects of the intermediate pions can be described by the form factors

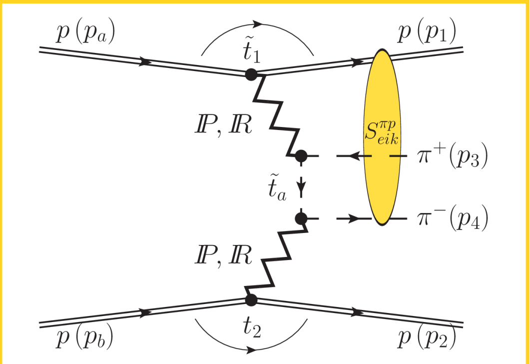
$$F_\pi(\hat{t}) = \exp\left(\frac{\hat{t} - m_\pi^2}{\Lambda_{off,E}^2}\right)$$

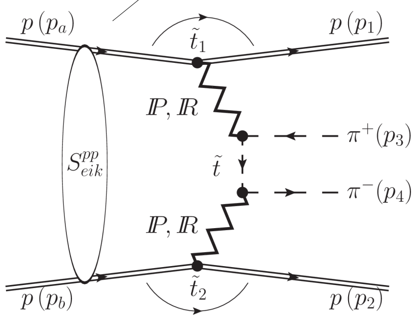
$$F_\pi(\hat{t}) = \frac{\Lambda_{off,M}^2 - m_\pi^2}{\Lambda_{off,M}^2 - \hat{t}}$$

Absorption corrections, ππ continuum term



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





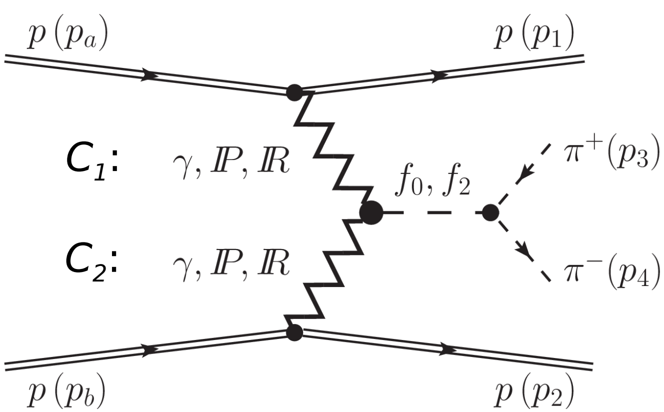
new absorption corrections (πN FSI) damping of the cross section by a factor of about 2 and give further enhancement at large |t|

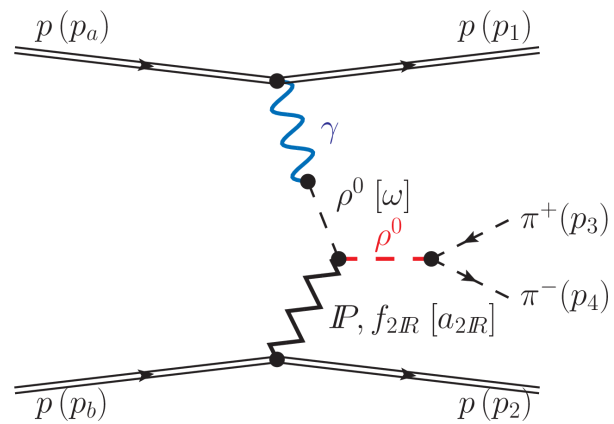
see P. L., A. Szczurek, Phys. Rev. D92 (2015) 054001

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

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

Dipion resonant production





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

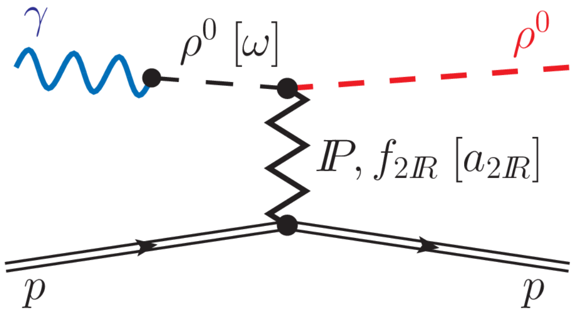
$I^G J^{PC}$, resonances	(C_1, C_2) production modes
0^+0^{++}, $f_0(500)$, $f_0(980)$, $f_0(1500)$, $f_0(1370)$, $f_0(1710)$ 0^+2^{++}, $f_2(1270)$, $f_2'(1525)$, $f_2(1950)$ 0^+4^{++}, $f_4(2050)$	$\{(I\!P + f_{2I\!R}, I\!P + f_{2I\!R}), (a_{2I\!R}, a_{2I\!R}),$ $(\mathbb{O} + \omega_{I\!R} + \gamma,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

At high energies, we shall concentrate on the dominant (C_1, C_2) contributions:

$(I\!P + f_{2I\!R}, I\!P + f_{2I\!R})$ for purely diffractive mechanism;

$(\gamma, I\!P + f_{2I\!R}), (I\!P + f_{2I\!R}, \gamma)$ for photoproduction mechanism.

Photoproduction of ρ^0 meson



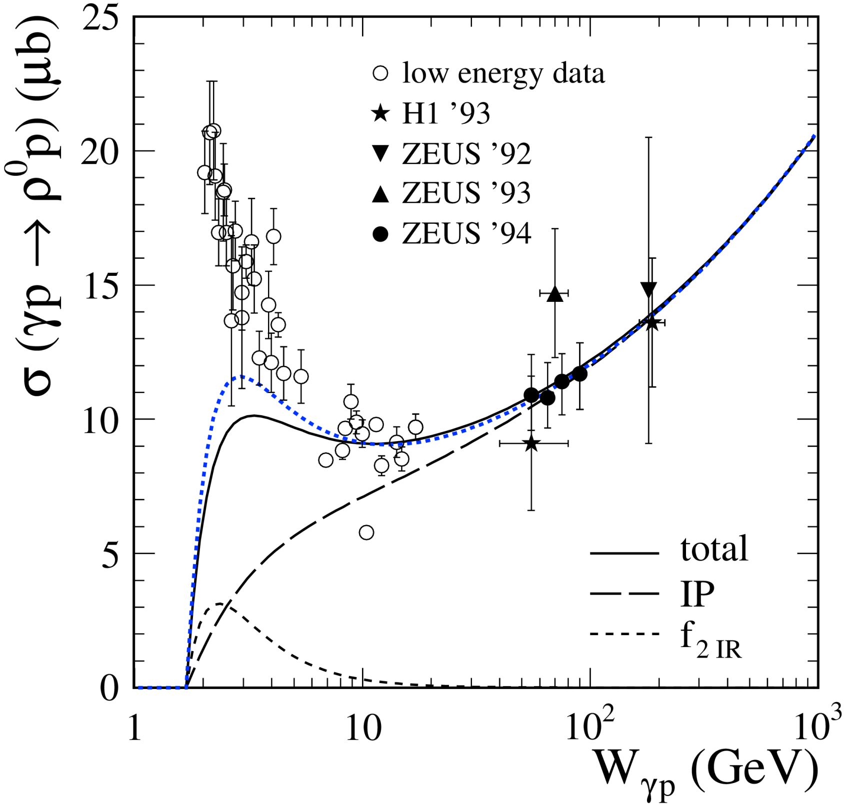
$$\mathcal{M}_{\lambda_\gamma \lambda_b \to \lambda_\rho \lambda_2}(s,t) \cong \quad ie\frac{m_\rho^2}{\gamma_\rho}\,\Delta_T^{(\rho)}(0)\,(\epsilon^{(\rho)\,\mu})^* \epsilon^{(\gamma)\,\nu} V_{\mu\nu\kappa\lambda}(s,t,q,p_\rho)$$
$$\times 2(p_2+p_b)^\kappa (p_2+p_b)^\lambda\,\delta_{\lambda_2 \lambda_b}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

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

(see the blue dotted line)

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

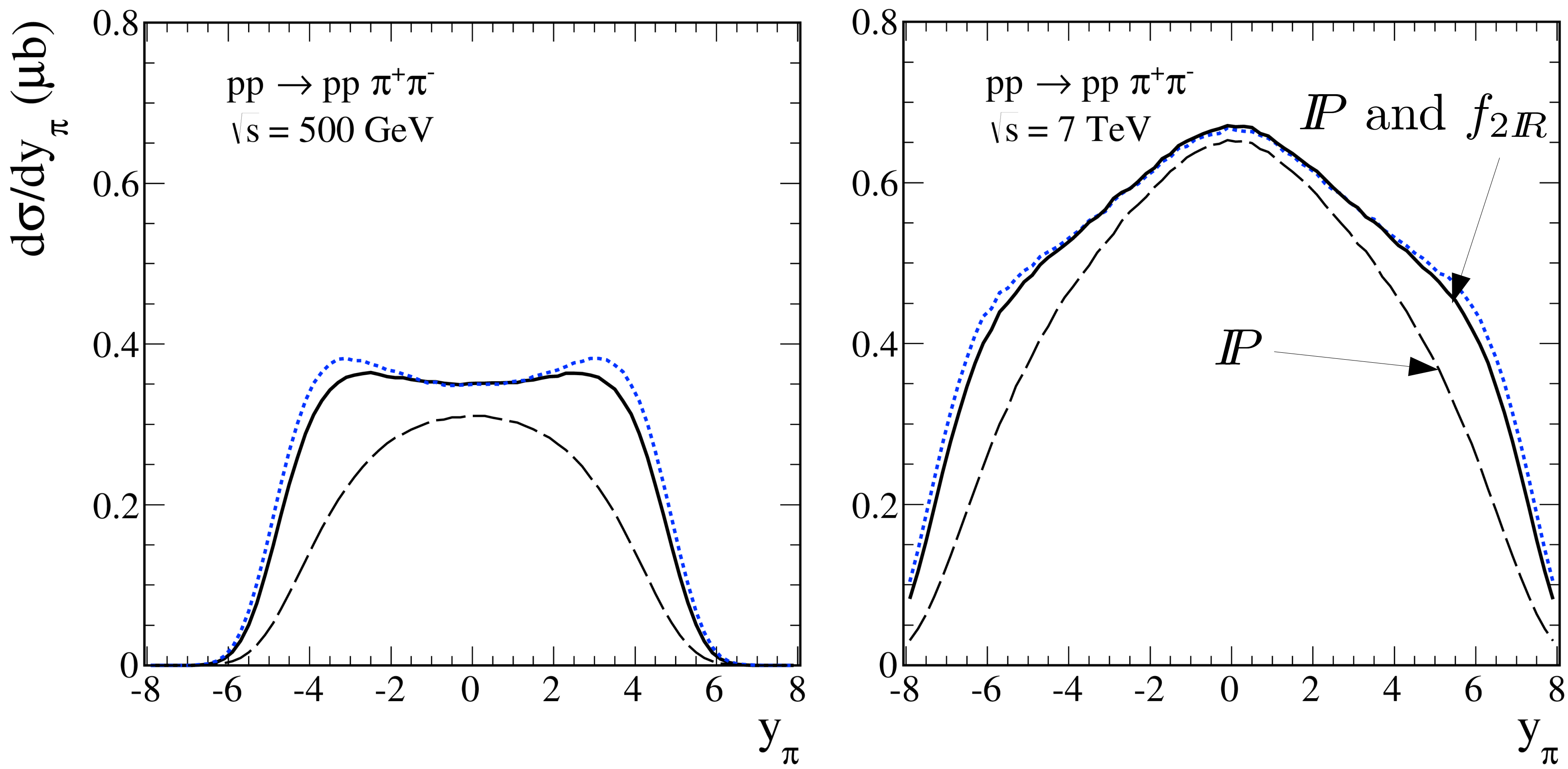
tensorial functions: *C. Ewerz, M. Maniatis and O. Nachtmann, Ann. Phys. 342 (2014) 31*



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

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

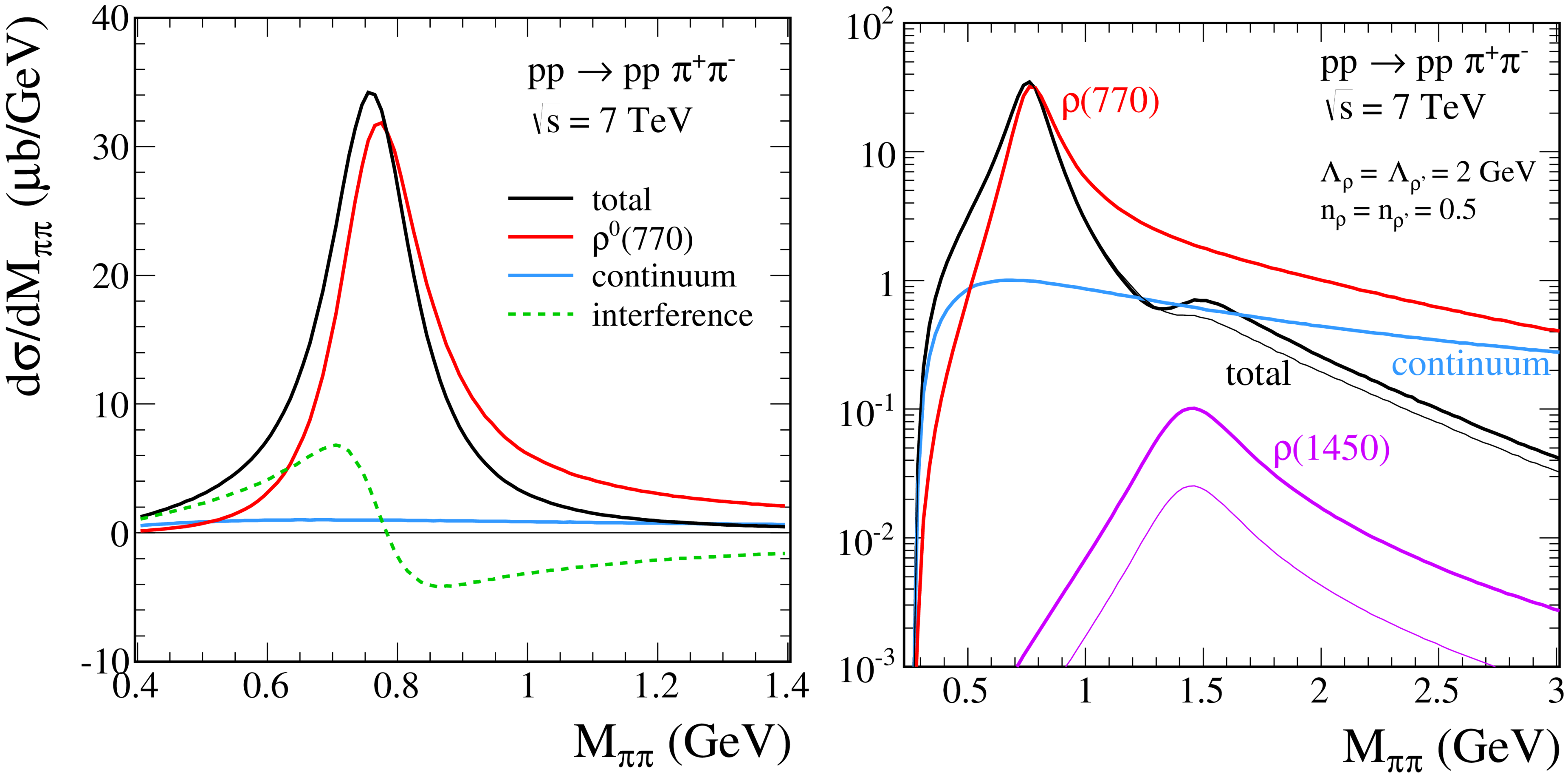
Photoproduction mechanism: ρ^0 and $\pi^+\pi^-$ continuum



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

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

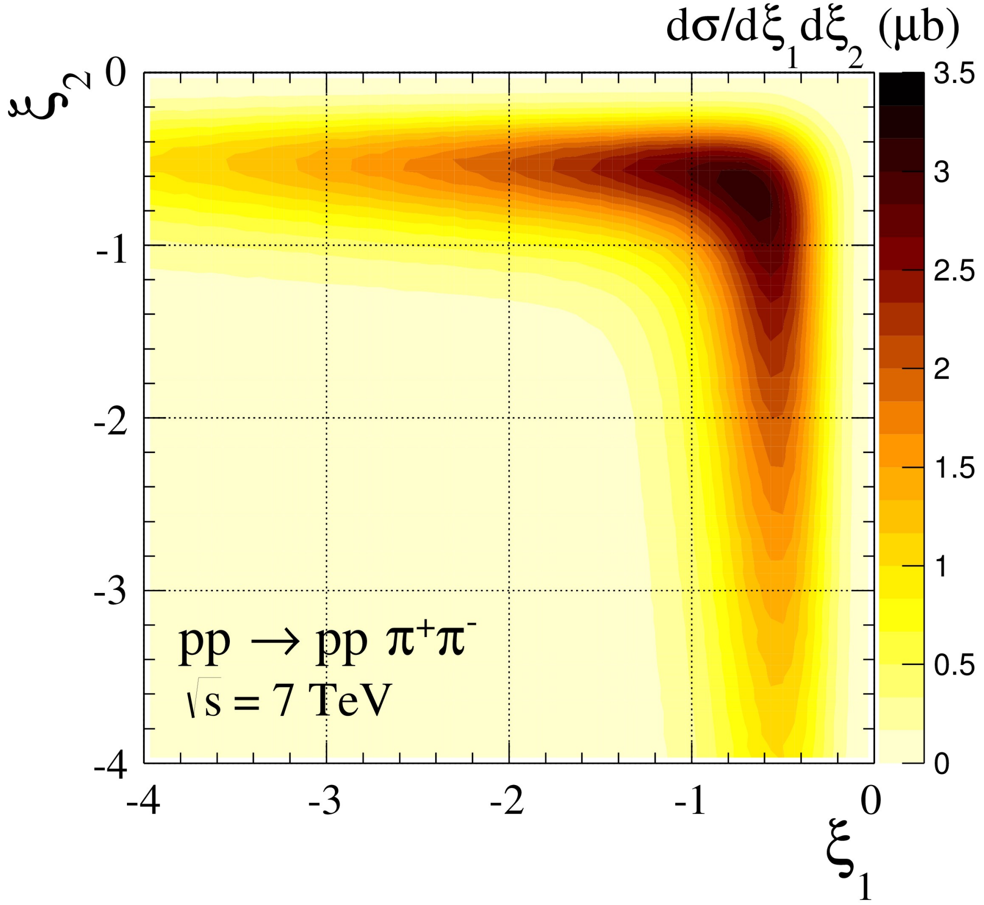
The non-resonant (Drell-Söding) contribution interferes with resonant $\rho(770)$ contribution
→ skewing of ρ^0 line shape.



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

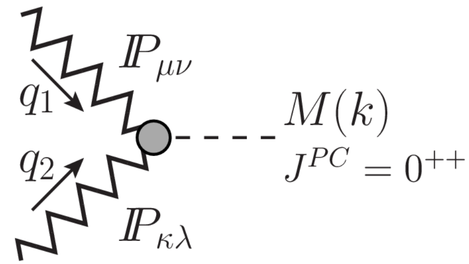
$\xi_1 = \log_{10}(p_{1\perp}/1\,\mathrm{GeV})$

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



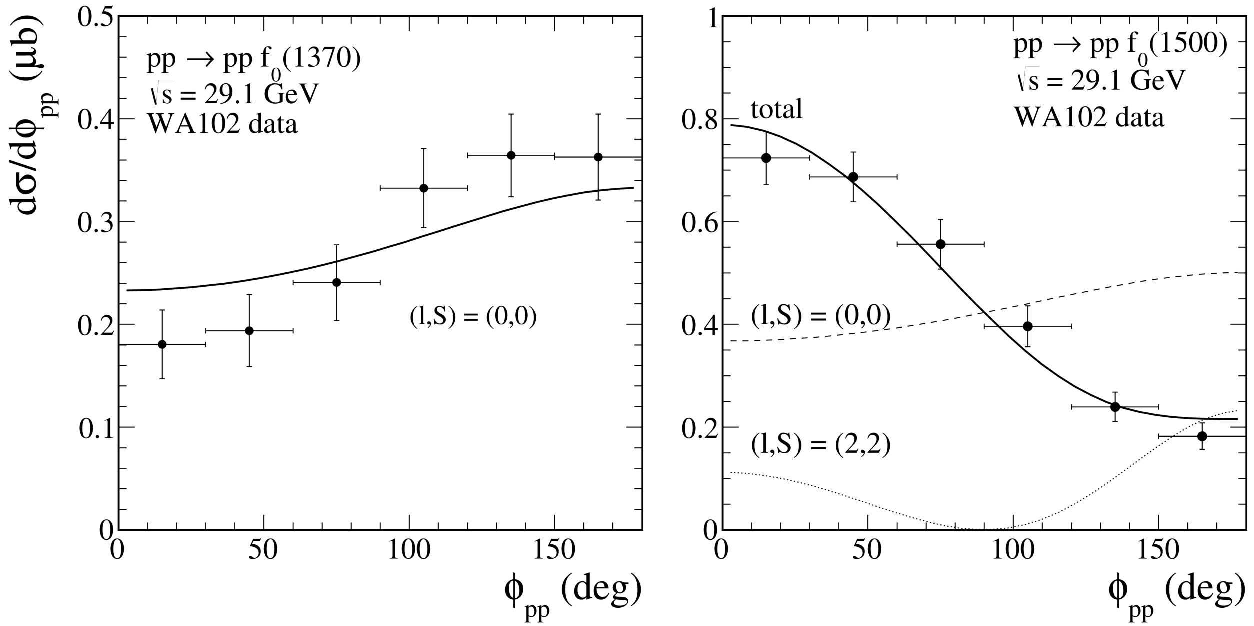
Diffractive mechanism: scalar resonances

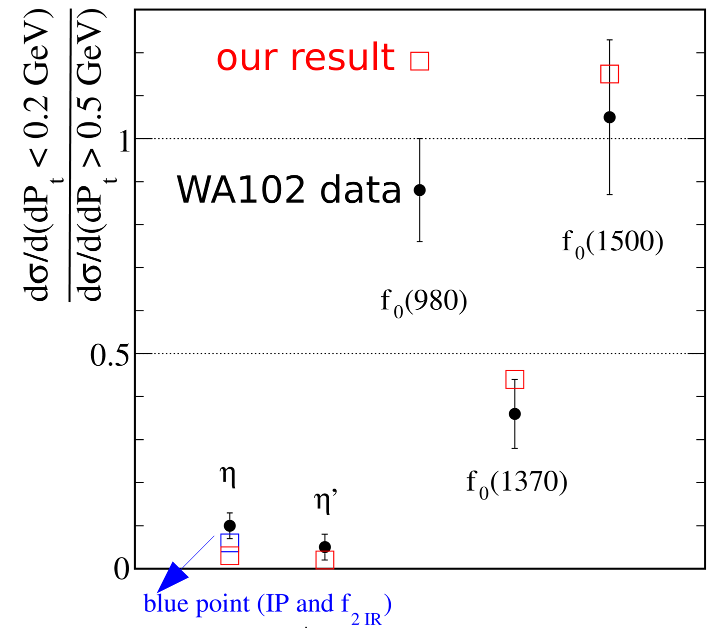
For a scalar mesons the "bare" tensorial *IP-IP-M* vertices corresponding to (l,S) = (0,0) and (2,2) terms are



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

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





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

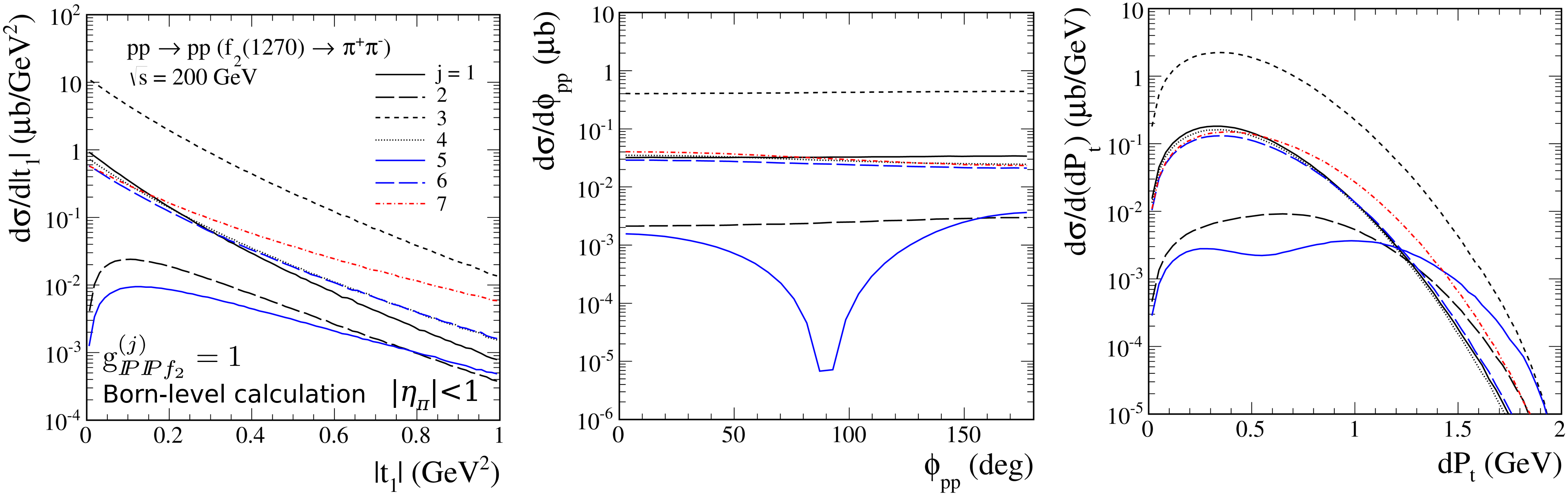
(proposed by F. Close)

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

Diffractive mechanism: tensor resonance



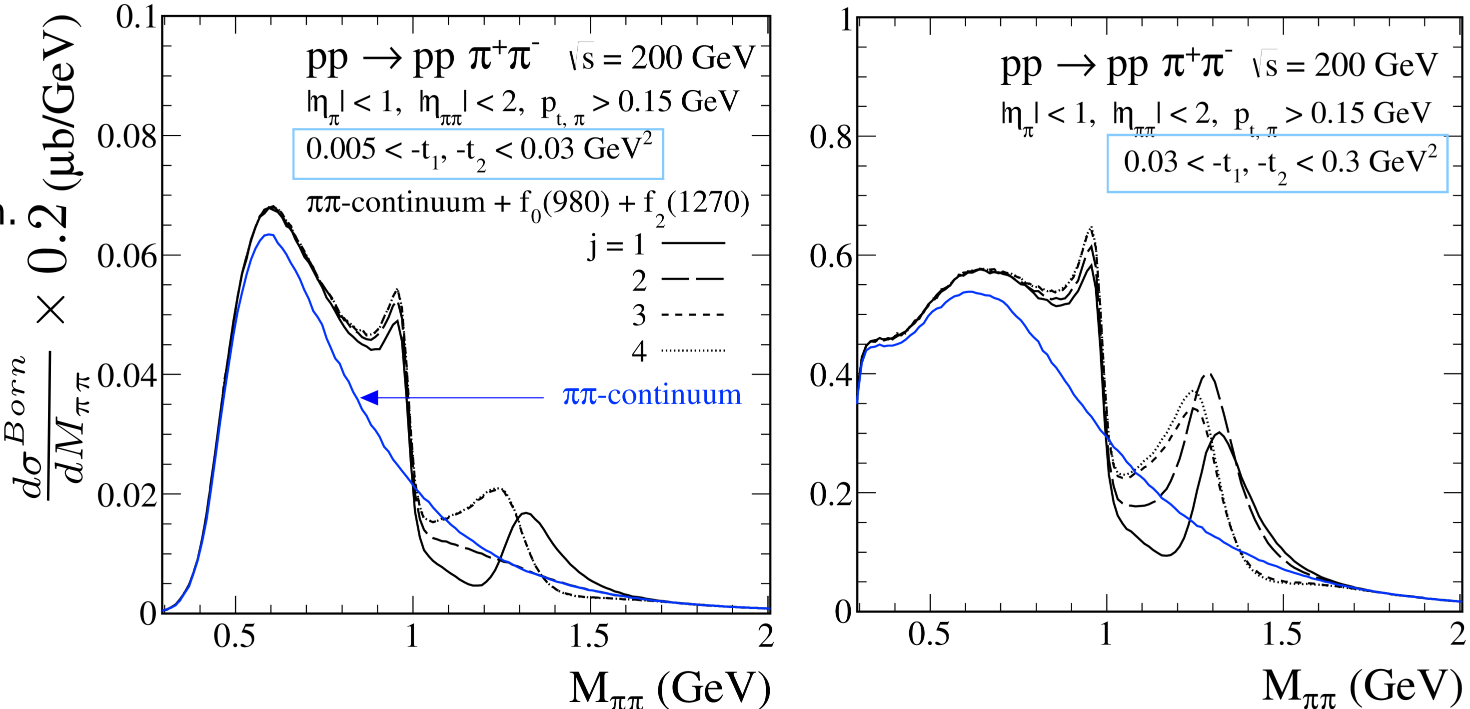
j = 2 coupling is in agreement with experimental observations (WA102, COMPASS, ISR)

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

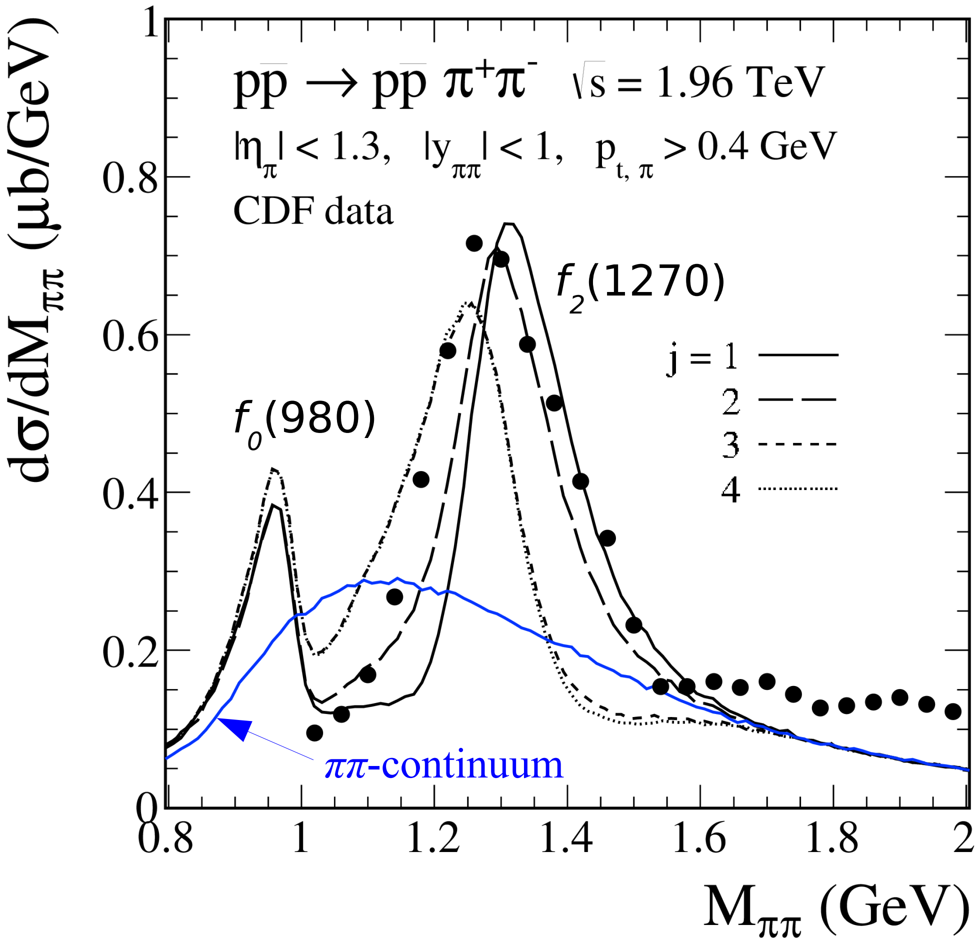
Different couplings generate different interference pattern.

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 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.

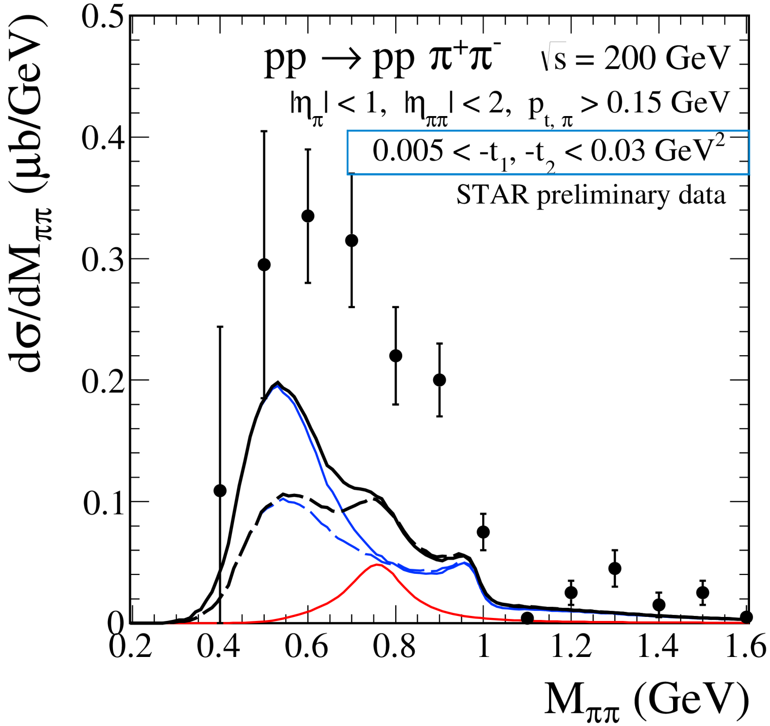
We take the monopole form for off-shell pion form factors with $\Lambda_{off,M}$ = 0.7 GeV.

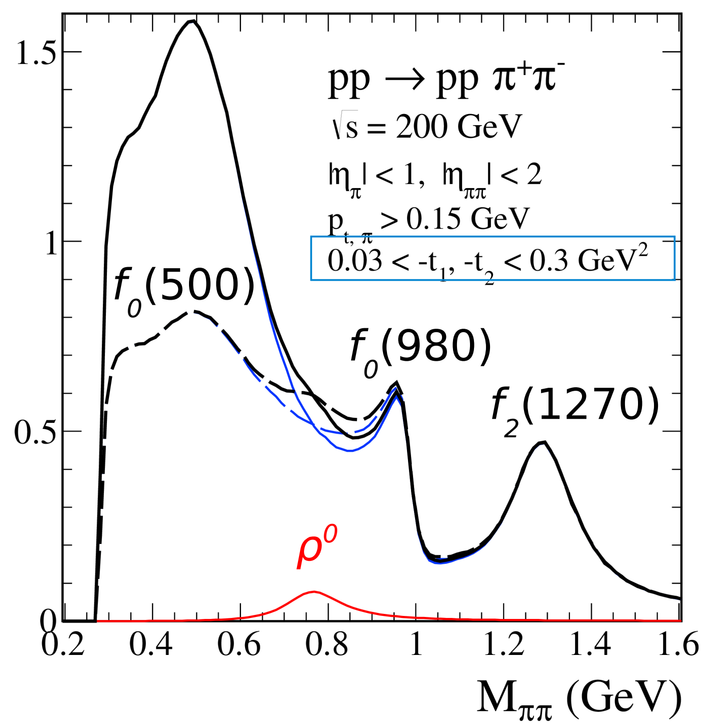
Absorption effects were included effectively:

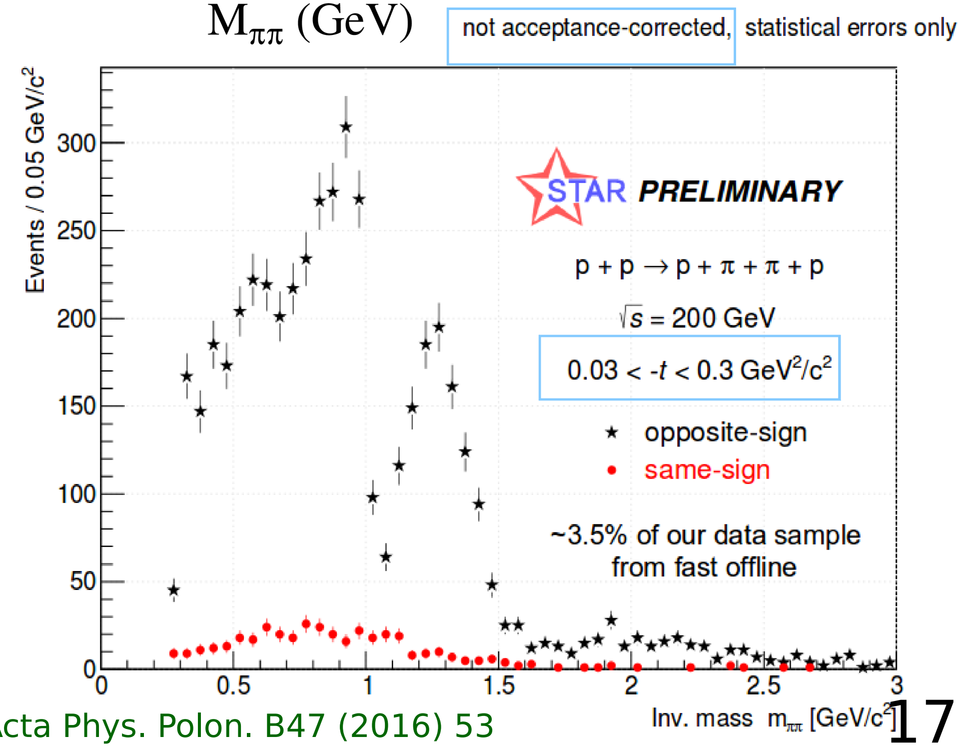
$$\frac{d\sigma^{Born}}{dM_{\pi\pi}} \times < S^2 >$$

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

Comparison with STAR preliminary data



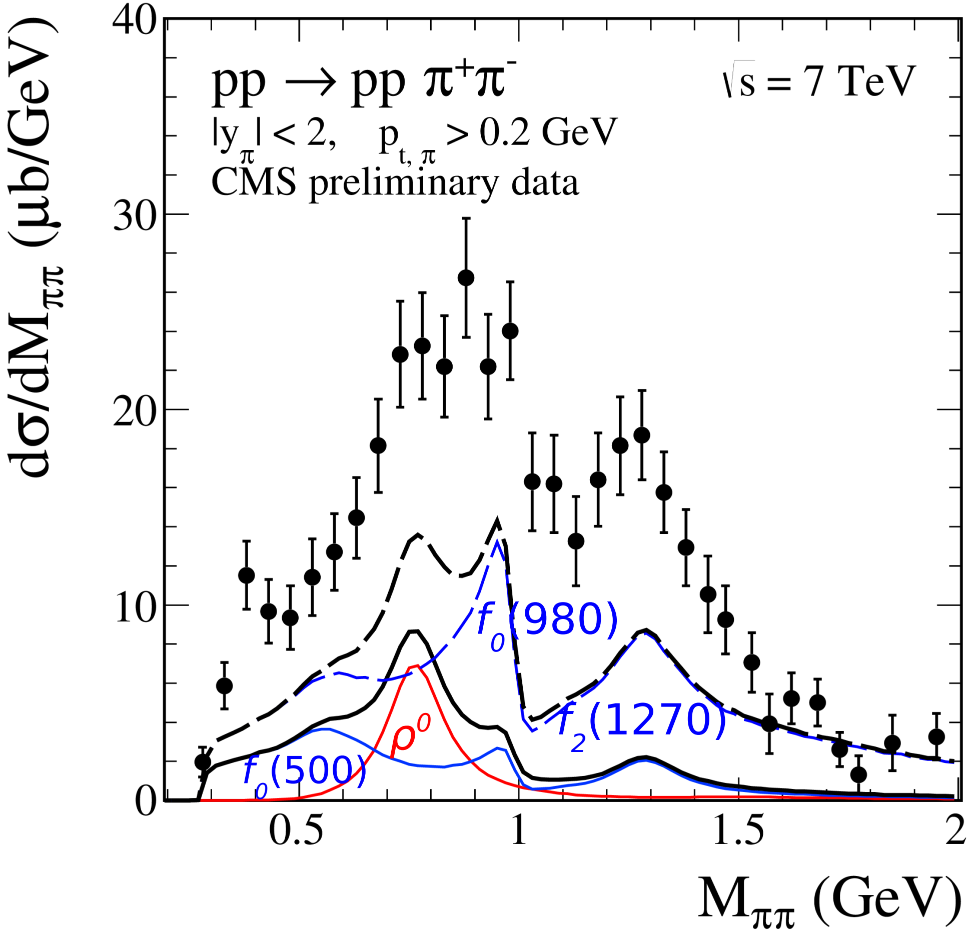


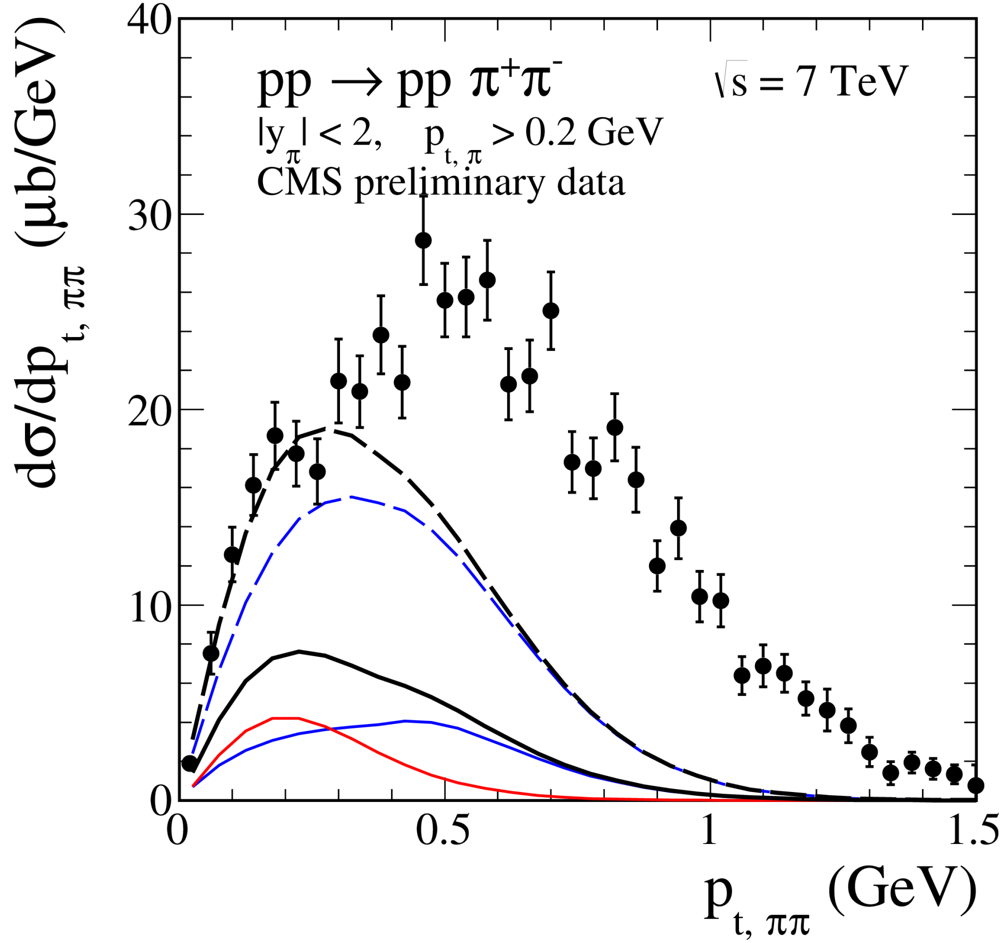


- Blue lines (diffractive term), red line (ρ^0 term), black lines (complete result)
- In calculation of f_2 term only one of the *IP-IP-f_2* couplings (j=2) was taken
- At $M_{\pi\pi} < 1$ GeV also other processes may be important → $\pi\pi$ FSI effect ($f_0(500)$ meson)
- Absorption effects were included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

Comparison with CMS preliminary data





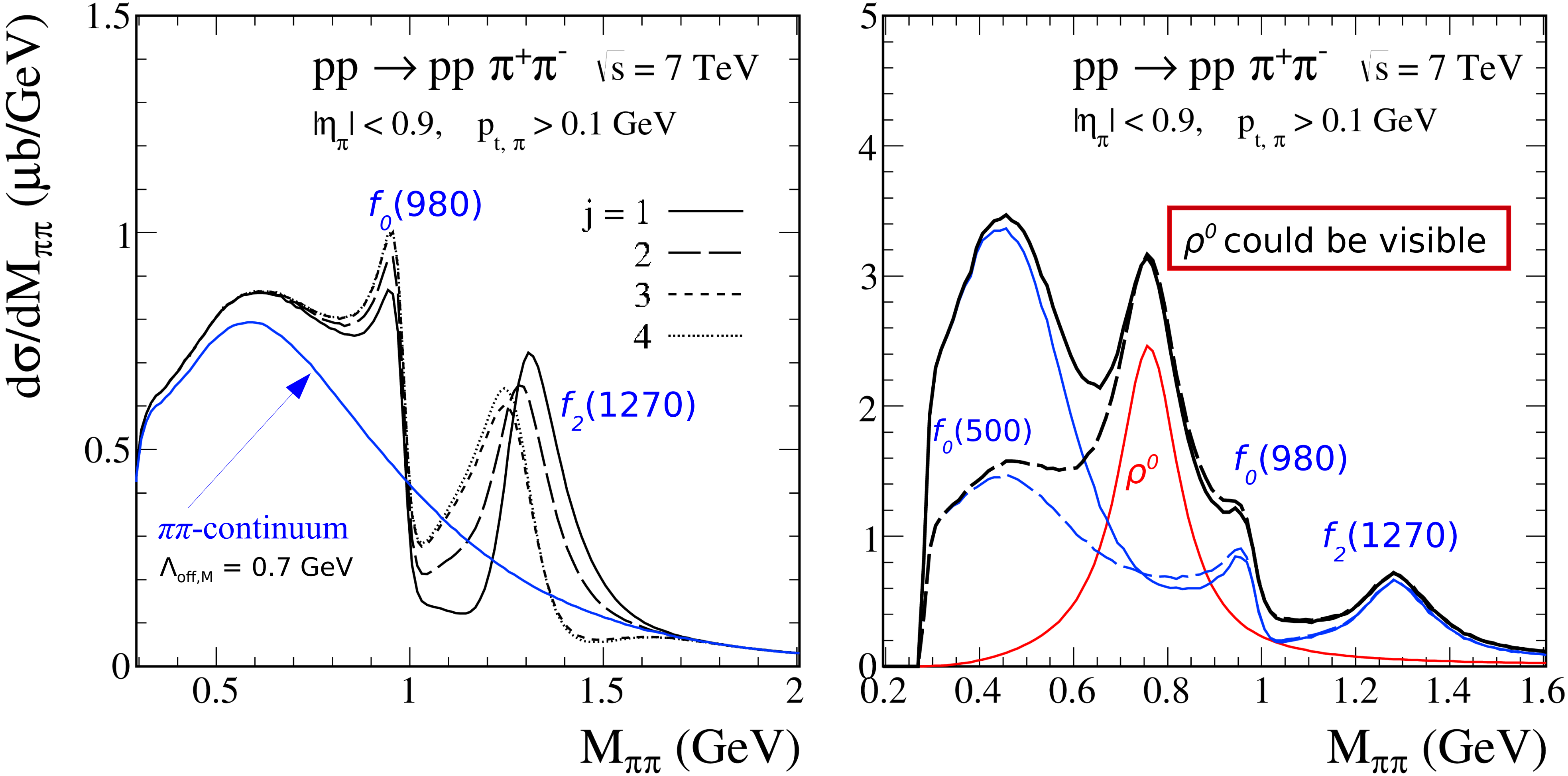
In diff. continuum term: (solid blue line) $\Lambda_{off,M}$ = 0.7 GeV (the same couplings as for CDF predictions)
(dashed blue line) $\Lambda_{off,M}$ = 1.2 GeV, with enhanced *f0*(980) and *f2* couplings

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

Predictions for ALICE

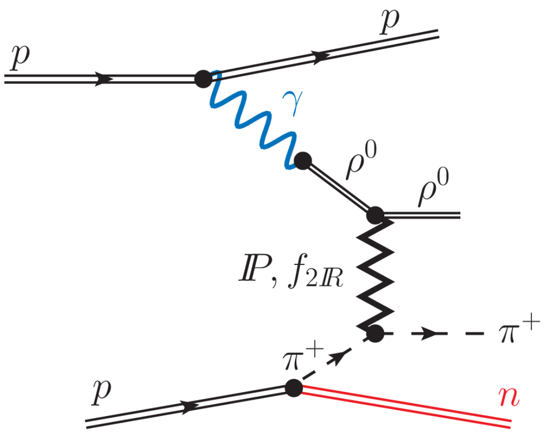


Different *IP-IP-f_2* couplings generate different interference pattern.

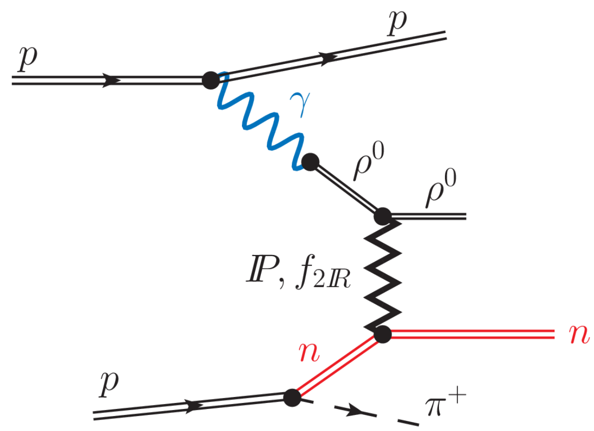
$< S^2 > \simeq 0.1$ for the diffractive contribution

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

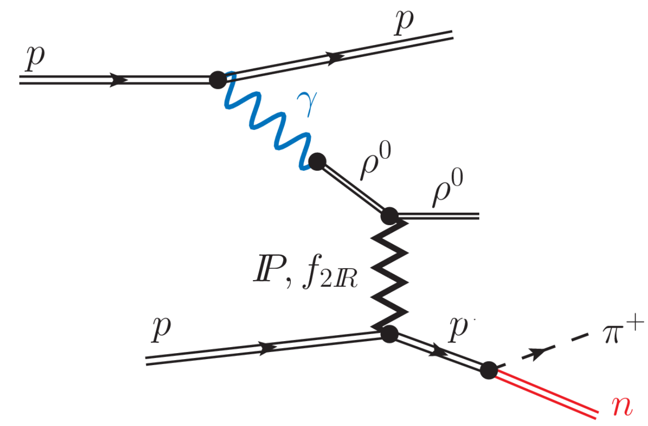
$pp \to pn\rho^0\pi^+$



pion exchange



neutron exchange



direct production

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

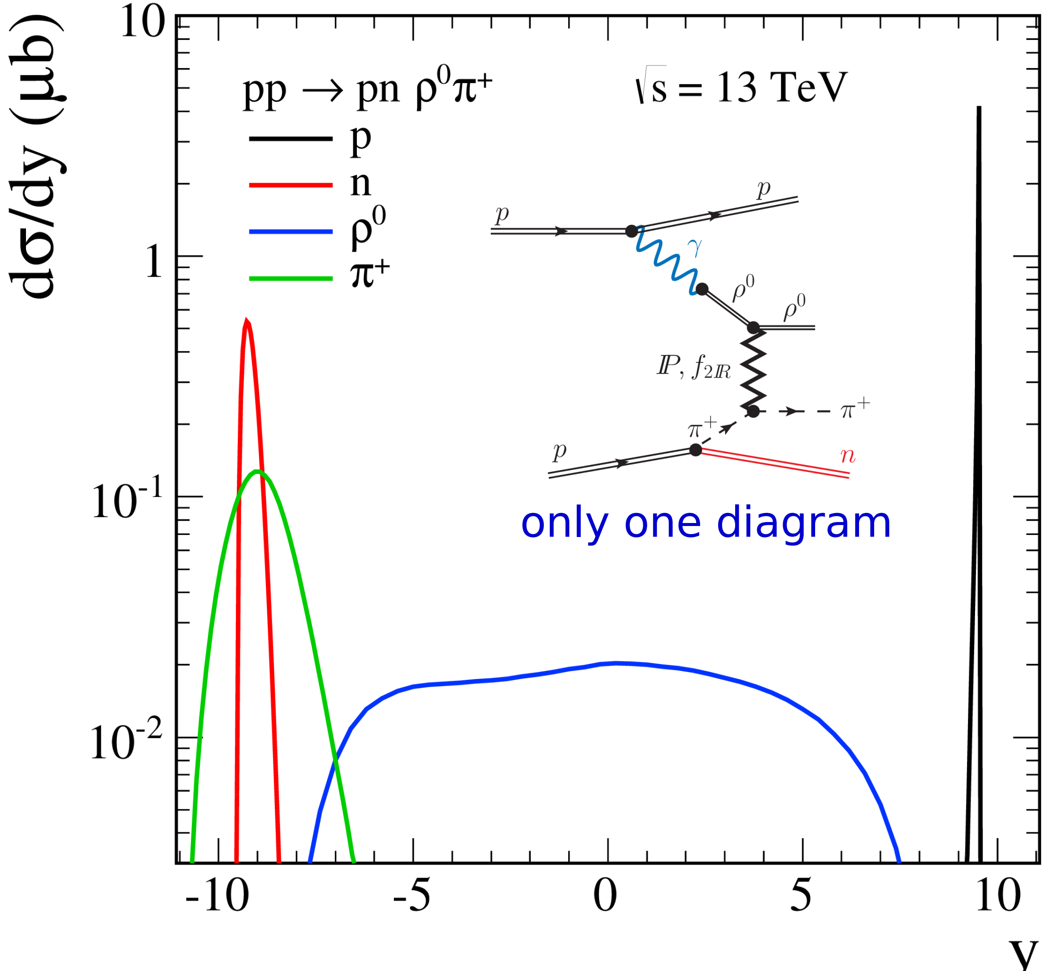
- There are also resonance contributions due to diffractive excitation of resonances, N^* states, and their subsequent decays into the πN channel.
  see L. Jenkovszky. et al., Phys. Atom. Nucl. 77, Phys. Rev. D83 (2011) 056014

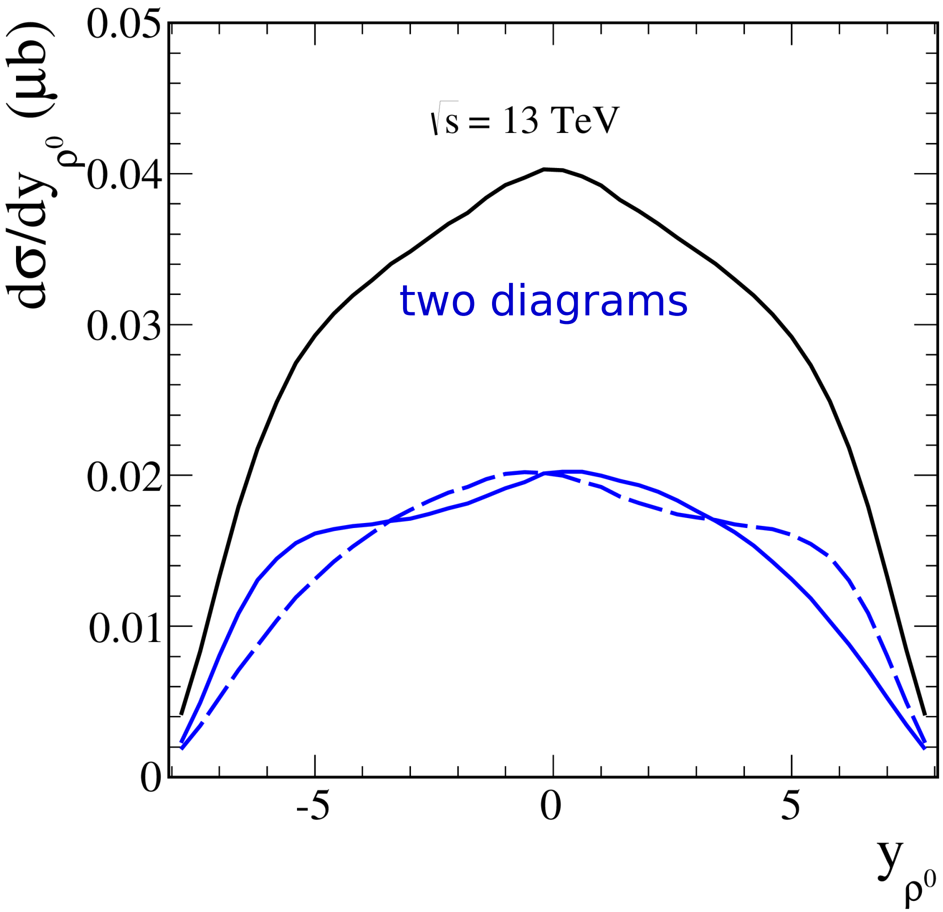
- The $pp \to pN\rho^0\pi$ processes constitutes inelastic (non-exclusive) background to the $pp \to pp\rho^0$ reaction in the case when final state protons are not measured and only rapidity gap conditions are checked experimentally.

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

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

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

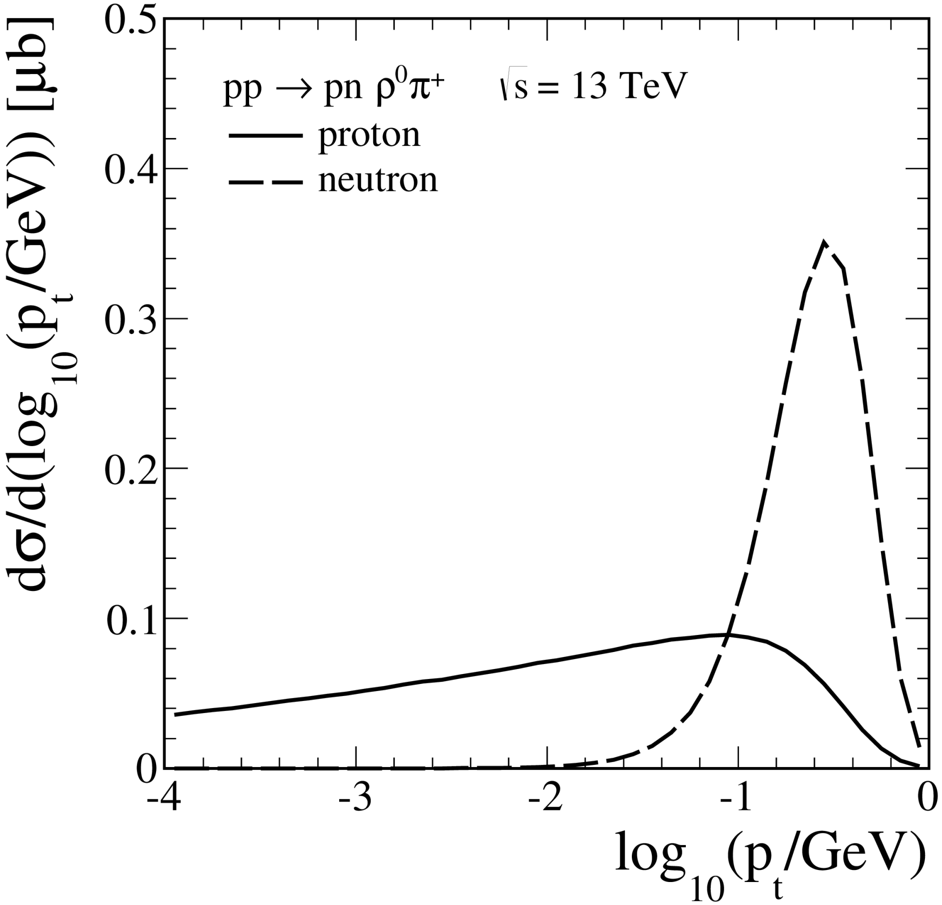


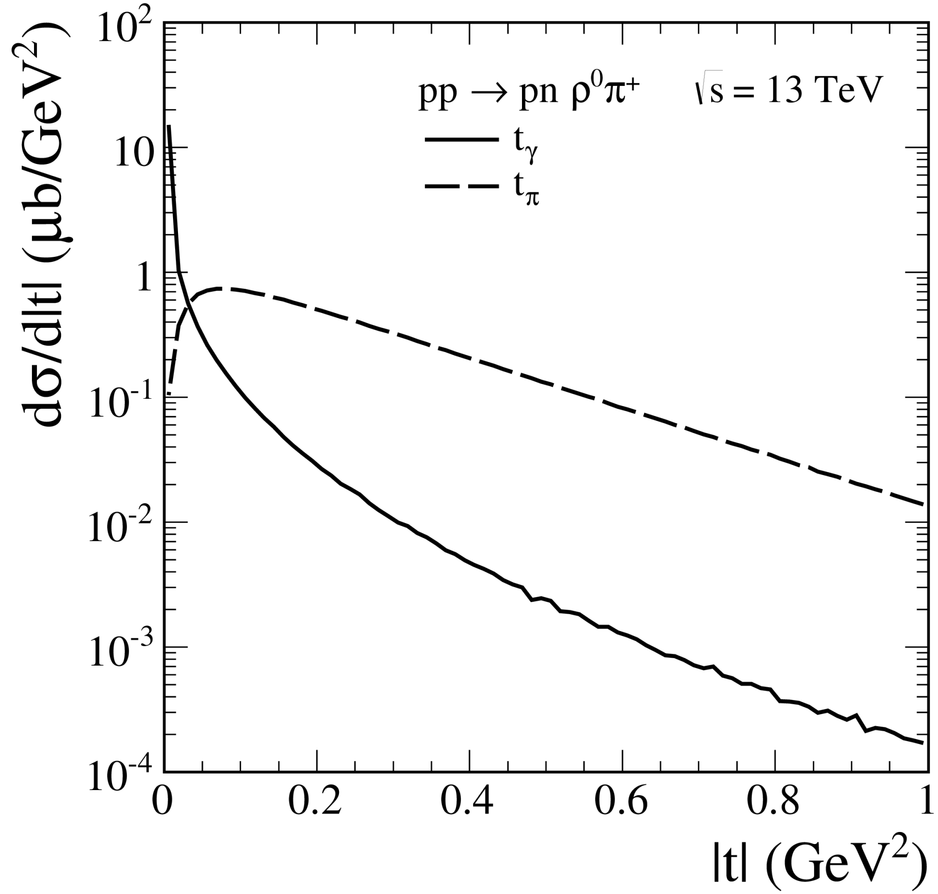


Due to specificity of the reaction the corresponding amplitudes do not interfere as some of the particles in the final state are emitted in different hemispheres (exclusively forward or backward) for the two amplitudes (mechanisms).

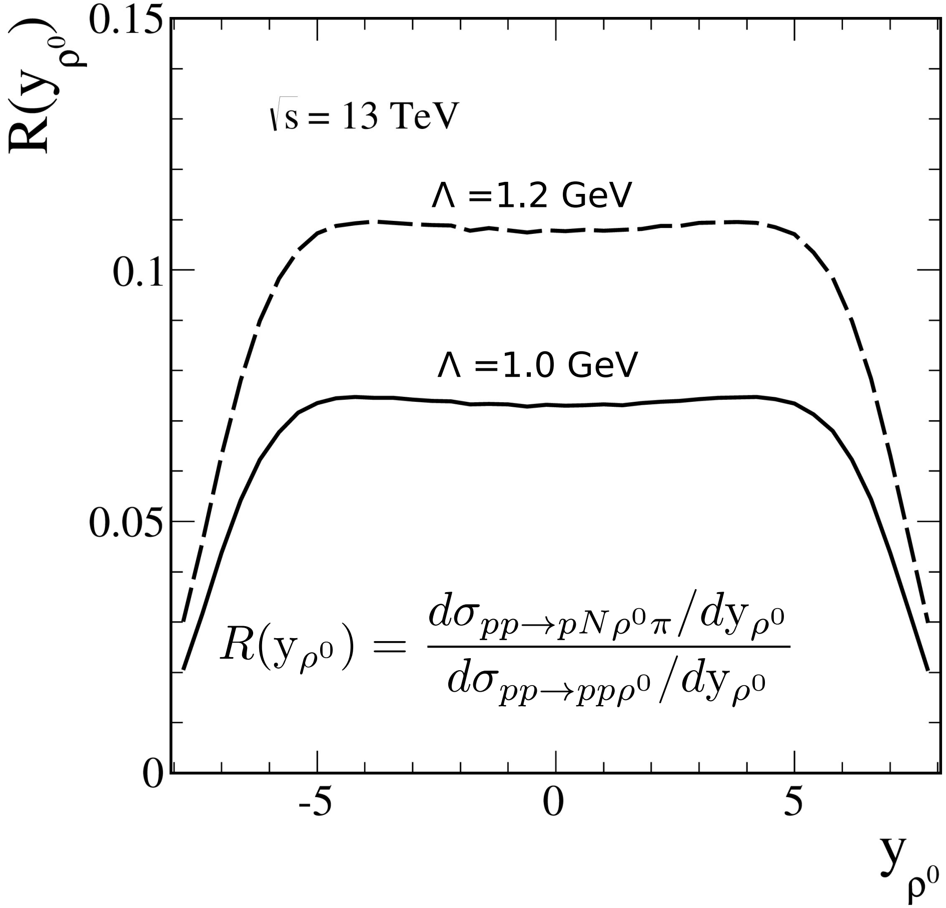
$pp \to pn\rho^0\pi^+$

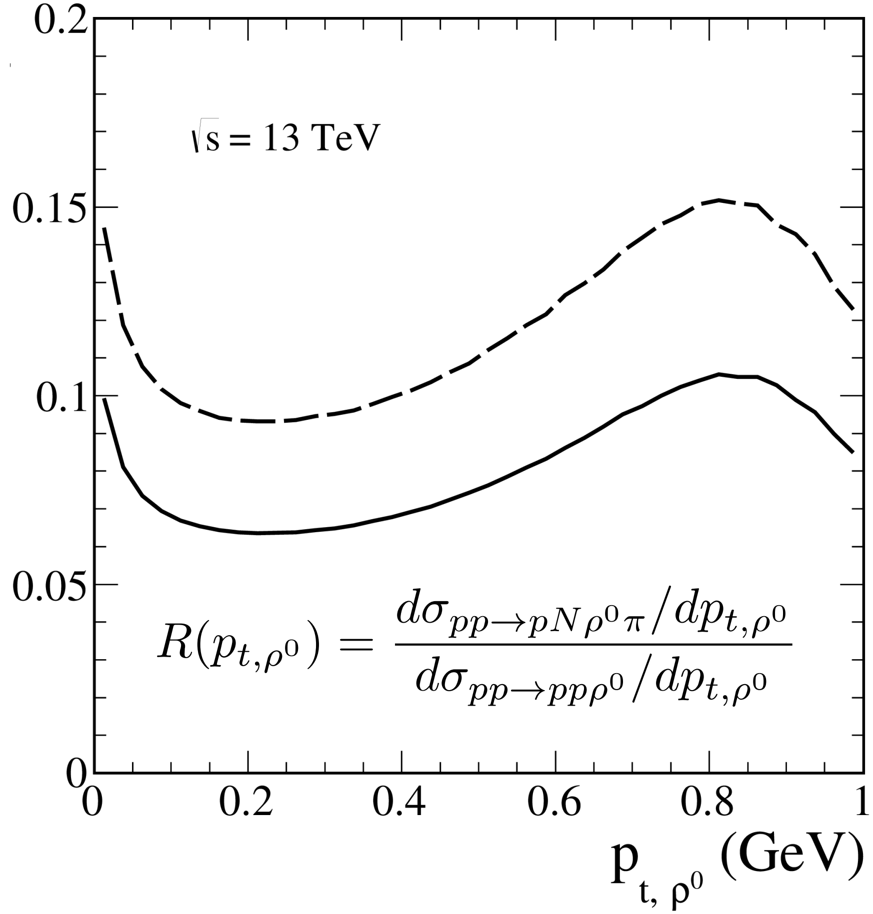
We take into account only pion exchange contribution (results for only one diagram).
No absorption effects were included.





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





- the ratio of integrated cross sections

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

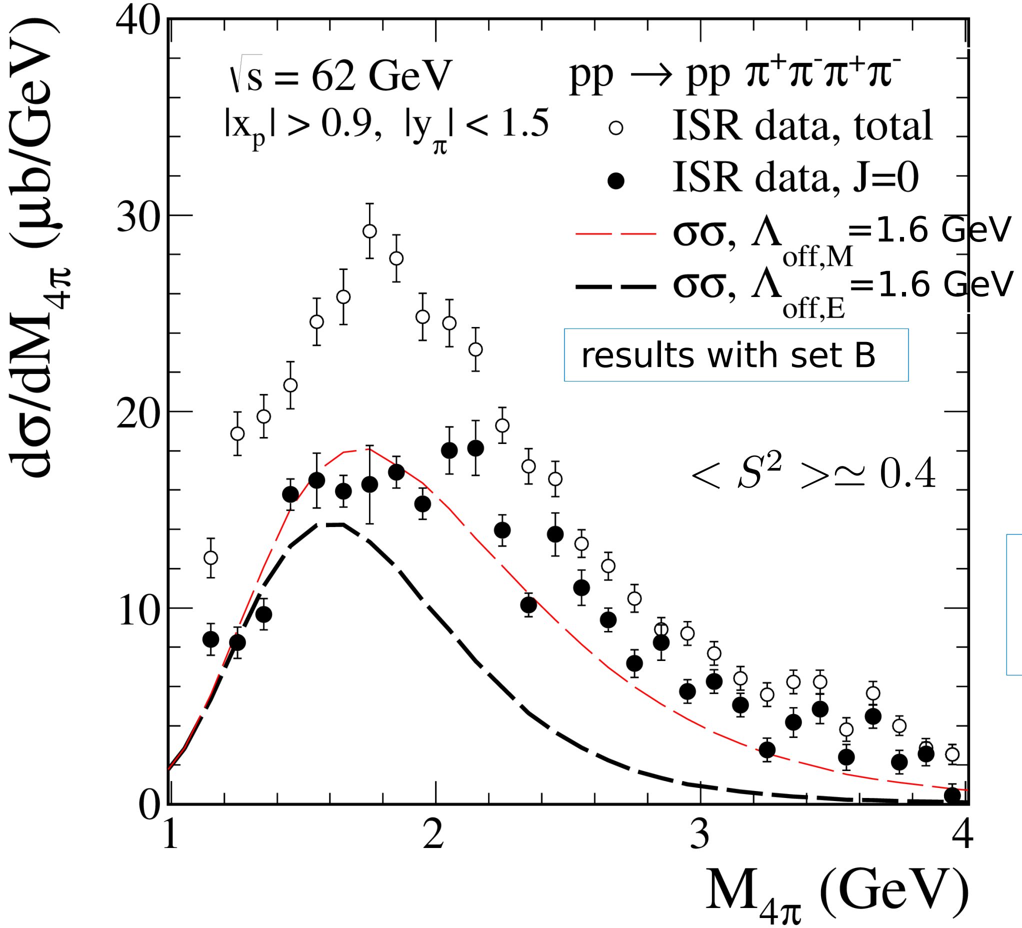
$$\sigma_{inel}/\sigma_{el} \approx 1.02\,\mu b/10.32\,\mu b \approx 0.1 \quad \text{for } \Lambda = 1.2 \text{ GeV}$$

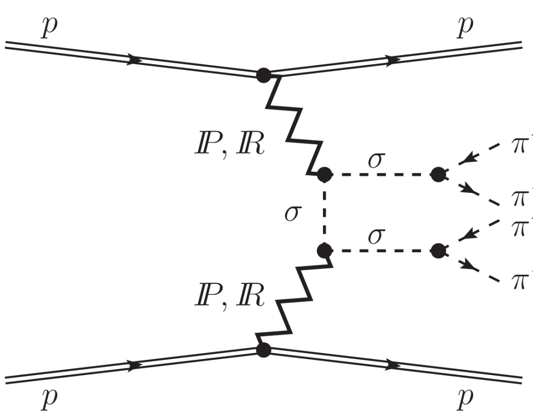
- almost no dependence on rapidity (except of the edges of the phase space)
- interesting pattern for the ratio of transverse momentum

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

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

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



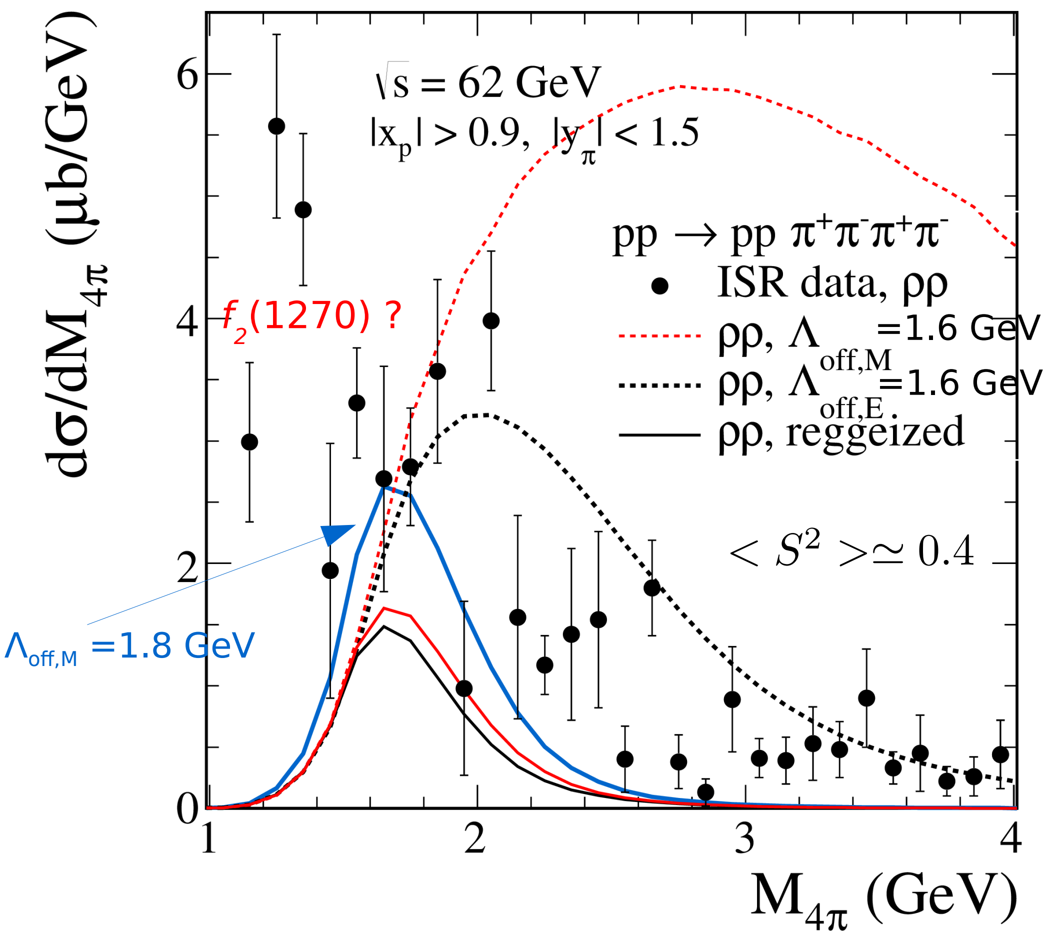


set B : $\beta_{I\!P\sigma\sigma} = 2 \times (2\beta_{I\!P\pi\pi})\,,\ g_{f_2 I\!R\sigma\sigma} = 2 \times g_{f_2 I\!R\pi\pi}$
enhanced coupling constants

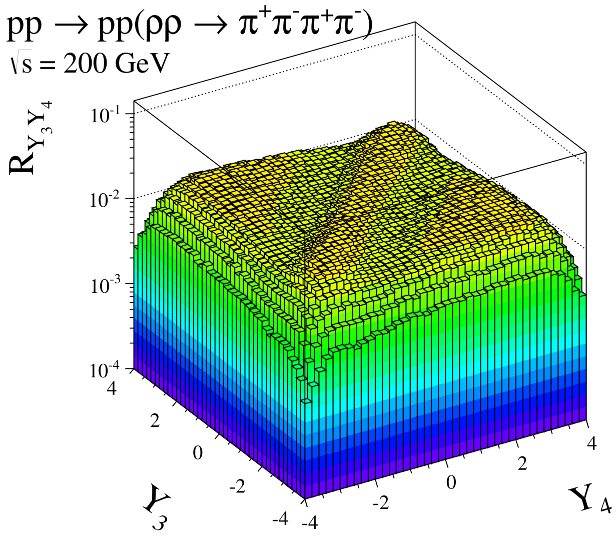
The 4π ISR data contains a large $\rho^0\pi^+\pi^-$ component with an enhancement in the J =2 term interpreted by ABCDHW Collaboration as a $f_2(1720)$ state.

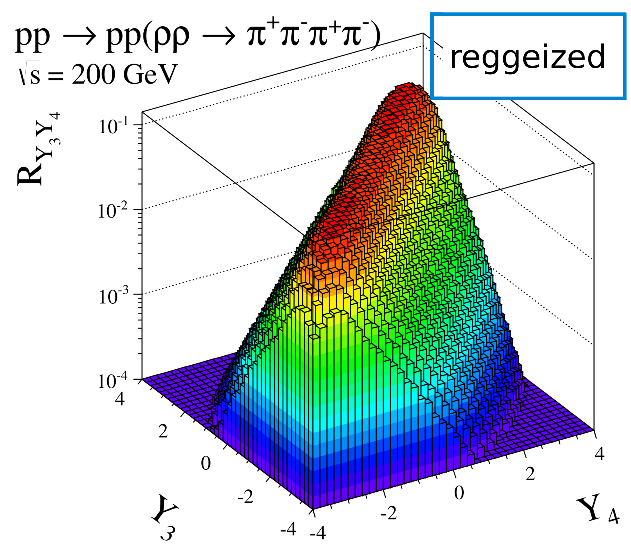
ISR data: A. Breakstone *et al*. (ABCDHW Collaboration), Z. Phys. C58 (1993) 251

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



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





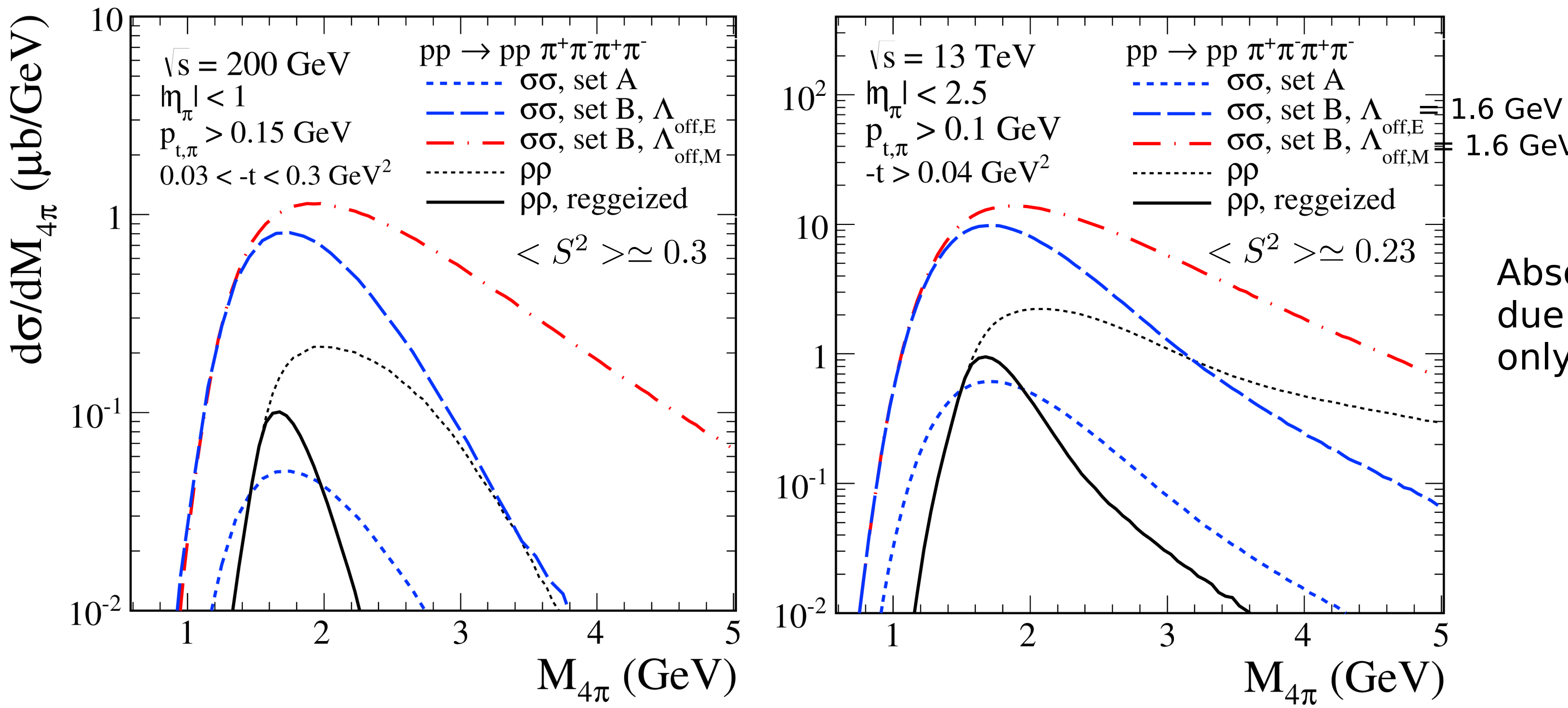
- reggeization effect

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

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

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

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



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

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

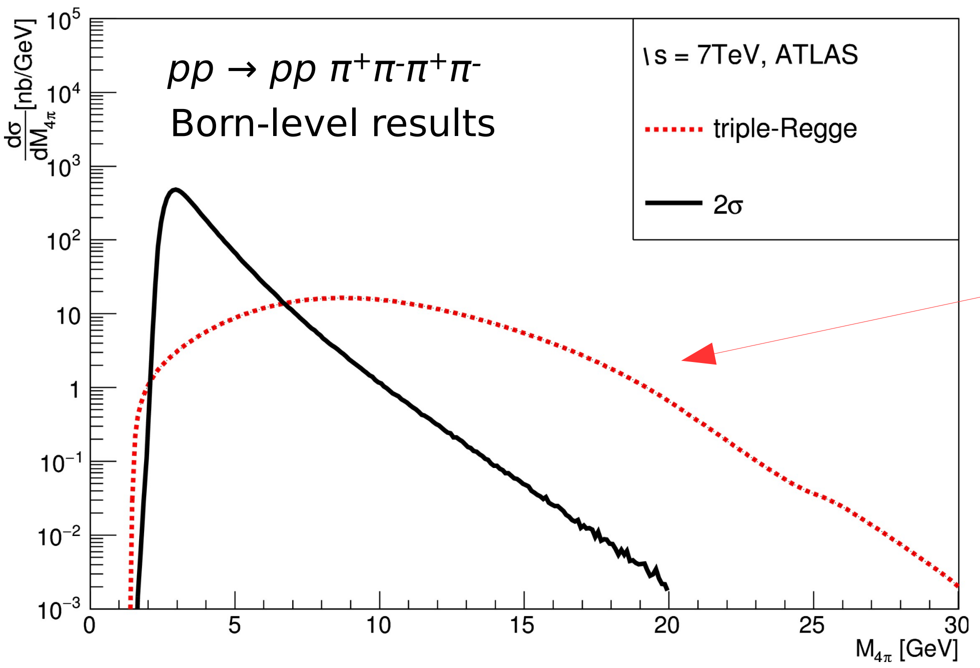
Table: Born cross sections in *μb.* The *σσ* contribution was calculated with the enhanced (set B) couplings while the *ρρ* contribution without and with (in the parentheses) inclusion of *ρ* meson reggeization.

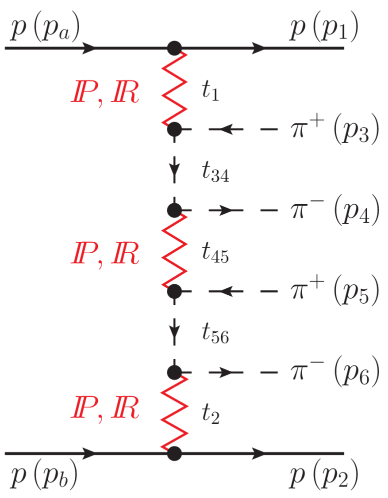
Predicted cross section can be obtained by multiplying the Born cross section by the gap survival factor: 0.3 (STAR), 0.21 (7 TeV), 0.19 (13 TeV), 0.23 (13 TeV, with cuts on $|t|$).

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

Triple Regge exchange mechanism of 4π continuum

R. Kycia, P. L., A. Szczurek and J. Turnau, arXiv:1702.07572





see talk by R. Kycia

- Calculation of triple Regge exchange mechanism is performed with the help of GenEx MC code.

- Large cross section is found at the LHC (1-5 *μb,* whole phase space, with absorption effects of order of 0.1)

  For the ATLAS cuts $|t_{1}|, |t_{2}| < 1$ GeV^2, $|y_{\pi}| < 2.5$, $p_{t,\pi} > 0.5$ GeV
  and c.m energies of 7 - 13 TeV, we obtained σ = 141 – 154 nb, respectively, neglecting absorption effects.

- Relatively large $M_{4\pi}$ are populated compared to other mechanisms (production of *σσ, ρρ pairs*).
  The ATLAS (or CMS) has better chances to identify the triple-Regge exchange processes.

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.

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

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

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

- We have estimated the cross sections for the process $pp \to pp\, \pi^+\pi^-\pi^+\pi^-$ via intermediate $\sigma\sigma$ and $\rho\rho$ states. We compared our results with the ISR data. A measurable cross section of few μb was obtained including the exp. cuts relevant for LHC experiments.
  In progress: Other mechanism in the context of 4π production (e.g. triple Regge continuum, resonances).

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

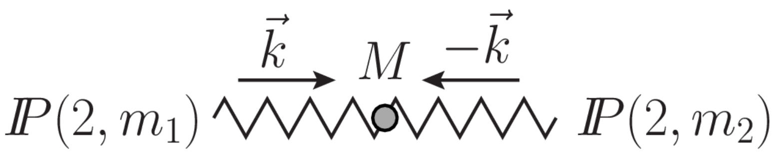
- In progress: MC generator for the soft reactions (2 → 4 and 2 → 6) within tensor pomeron approach (talk by Maciek Trzebiński).

Extra slides

Pomeron-pomeron-meson couplings

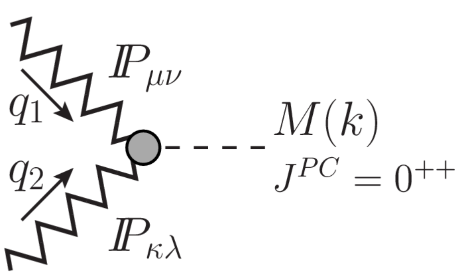
l – orbital angular momentum
S – total spin, we have $S \in \{0, 1, 2, 3, 4\}$
J – total angular momentum (spin of the produced meson)
P – parity of meson
and Bose symmetry requires $l - S$ to be even

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



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

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



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

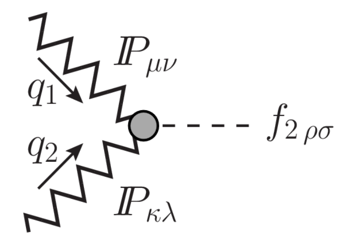
The lowest (l,S) term for a scalar meson $J^{PC} = 0^{++}$ is (0,0) while for a tensor meson $J^{PC} = 2^{++}$ is (0,2).

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

$f_2(1270)$ 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 $\Delta^{(f_2)}_{\nu\mu,\kappa\lambda}(p_{34}) = \Delta^{(f_2)}_{\mu\nu,\lambda\kappa}(p_{34}) = \Delta^{(f_2)}_{\kappa\lambda,\mu\nu}(p_{34})$, $\quad g^{\kappa\lambda}\Delta^{(f_2)}_{\mu\nu,\kappa\lambda}(p_{34}) = 0$.

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

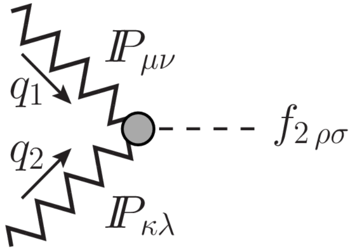
where $g_{f_2\pi\pi} = 9.26$ was obtained from the corresponding partial decay width.

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

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



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

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

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

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

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

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

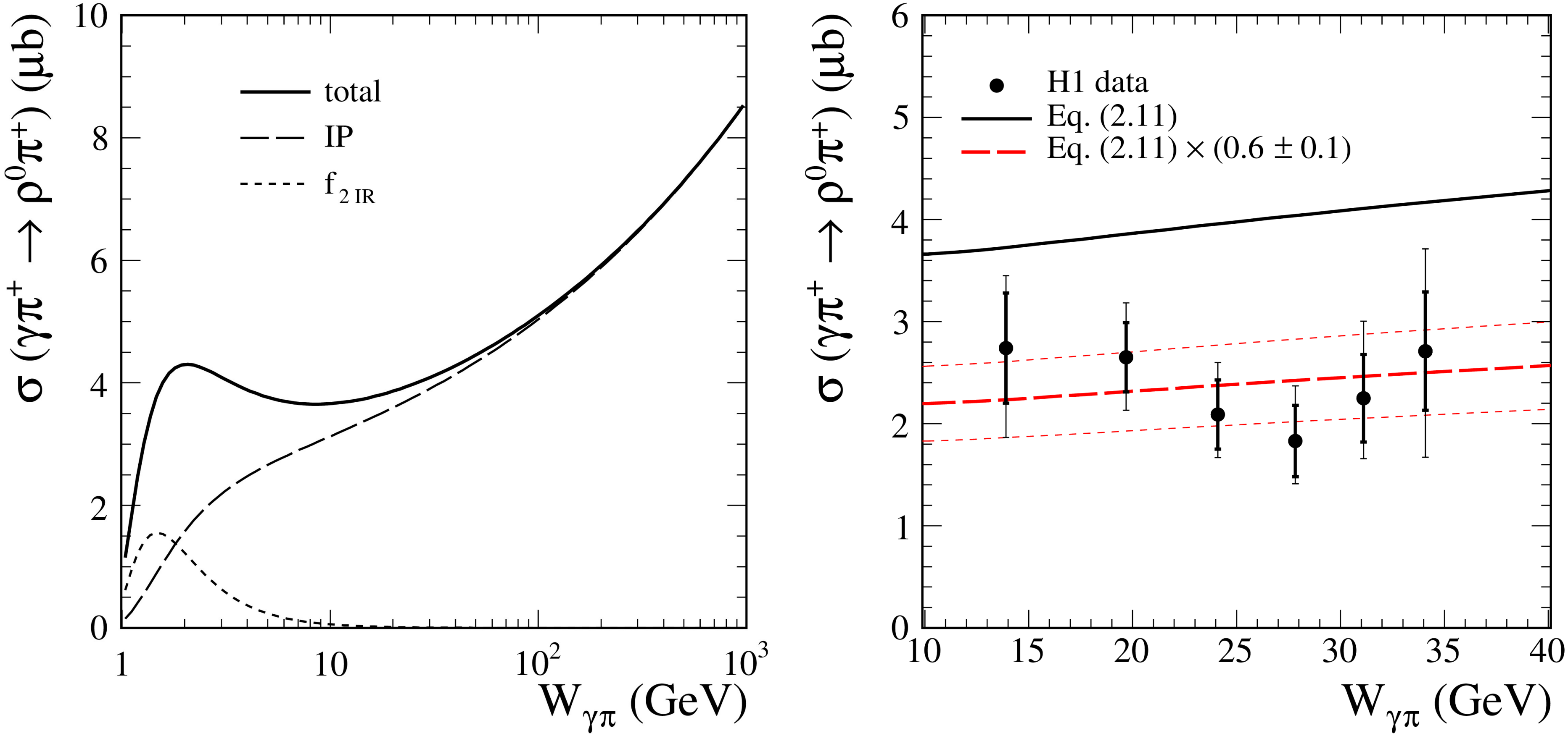
$$i\Gamma^{(\mathbb{P}\mathbb{P}f_2)(7)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{2i}{M_0^5}\, g^{(7)}_{\mathbb{P}\mathbb{P}f_2}\, q_1^{\rho_1}\, q_1^{\alpha_1}\, q_1^{\lambda_1}\, q_2^{\sigma_1}\, q_2^{\mu_1}\, q_2^{\nu_1}\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1}\, R_{\rho\sigma\rho_1\sigma_1}$$

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

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

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



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

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

Related works:

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

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

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

- A. Bolz, C. Ewerz, M. Maniatis, O. Nachtmann, M. Sauter, A. Schöning, *Photoproduction of $\pi^+\pi^-$ pairs in a model with tensor-pomeron and vector-odderon exchange,* arXiv:1409.8483, JHEP 1501 (2015) 151

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

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

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