Soft QCD in exclusive reactions at high energies

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Plan

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

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

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

- P. L., O. Nachtmann, A. Szczurek, *Exclusive central diffractive production of scalar and pseudoscalar mesons; tensorial vs. vectorial pomeron*, Annals Phys. 344 (2014) 301
- P. L, O. Nachtmann, A. Szczurek, *ρ^0 and Drell-Söding contributions to central exclusive production of $\pi^+\pi^-$ pairs in proton-proton collisions at high energies*, Phys. Rev. D91 (2015) 07402300
- P. L., O. Nachtmann, A. Szczurek, *Central exclusive diffractive production of the $\pi^+\pi^-$ continuum, scalar and tensor resonances in pp and $p\bar{p}$ scattering within the tensor Pomeron approach*, Phys. Rev. D93 (2016) 054015
- P. L., O. Nachtmann, A. Szczurek, *Exclusive diffractive production of $\pi^+\pi^-\pi^+\pi^-$ via the intermediate σσ and ρρ states in proton-proton collisions within tensor Pomeron approach*, Phys. Rev. D94 (2016) 034017
- P. L., O. Nachtmann, A. Szczurek, *Central production of ρ^0 in pp collisions with single proton diffractive dissociation at the LHC*, Phys. Rev. D95 (2017) 034036

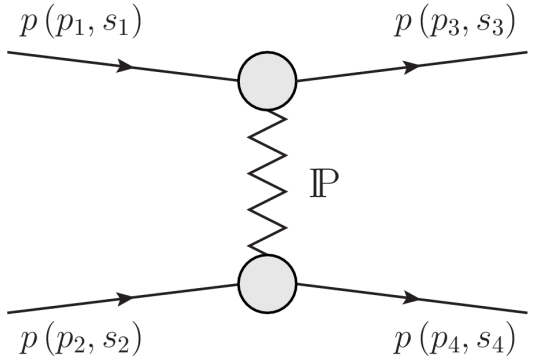
The nature of soft pomeron

High-energy *pp* elastic scattering is dominated by pomeron exchange.
The pomeron has vacuum internal quantum numbers: $Q = Q_c = I = 0$, $C = +1$.
Spin structure ?

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

The soft pomeron is described as the effective exchange of a symmetric rank-two tensor object, the tensor pomeron.

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



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

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

$3 \times \beta_{I\!PNN} = 3 \times 1.87\ \mathrm{GeV}^{-1}$

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

$\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P}t$

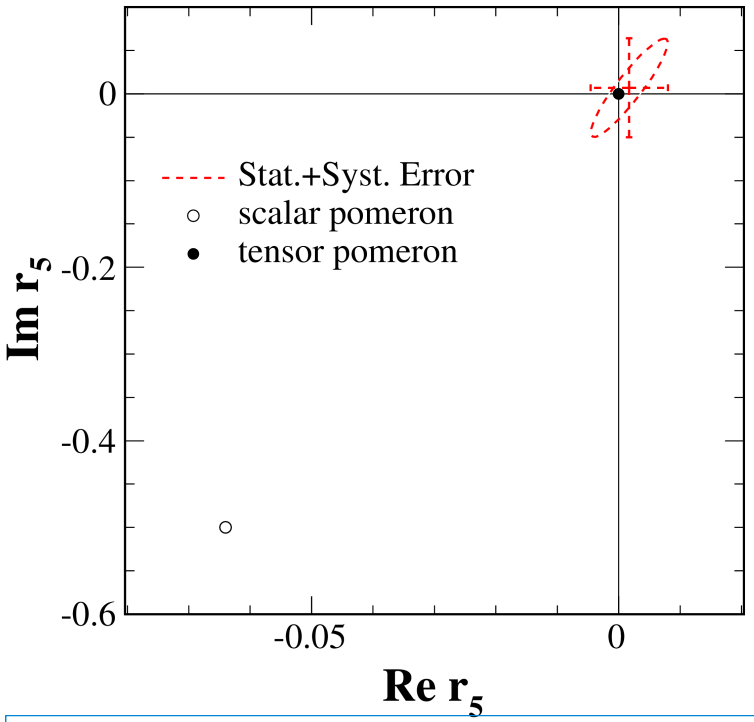
$\alpha_{I\!P}(0) = 1.0808, \qquad \alpha'_{I\!P} = 0.25\,\mathrm{GeV}^{-2}$

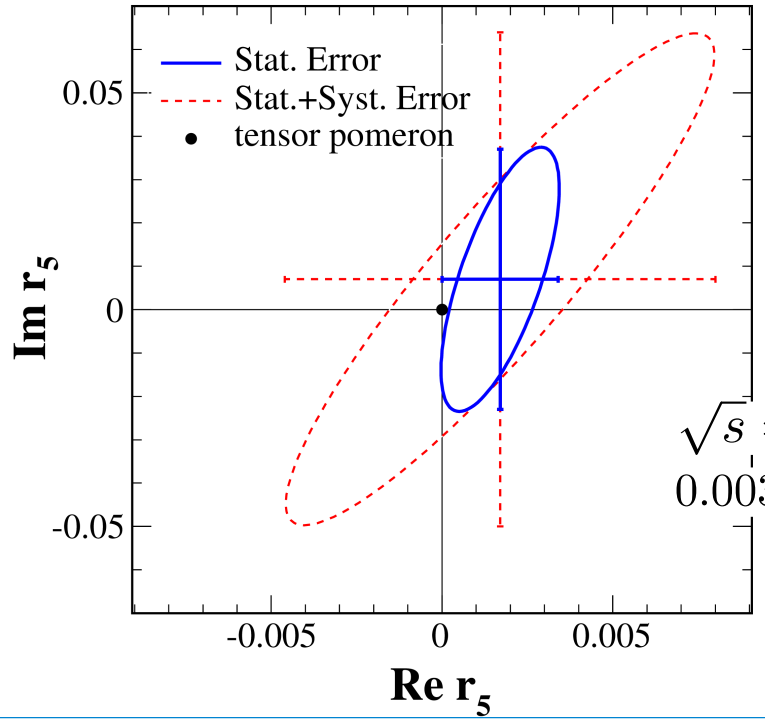
Comparison with experiment

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

- Vector exchange has C = -1. It follows $\sigma_{tot}^{pp} = -\sigma_{tot}^{\bar{p}p}$
- We are left with $I\!P_T$ and $I\!P_S$ (both correspond to C=+1 exchanges)
- To decide between them we turn to the STAR experiment (Phys. Lett. B719 (2013)) which measured the single spin asymmetry in polarised *pp* elastic scattering.

Ratio of single-flip to non-flip amplitudes $r_5(s,t) = \dfrac{2m_p\,\phi_5(s,t)}{\sqrt{-t}\,\mathrm{Im}[\phi_1(s,t)+\phi_3(s,t)]}$



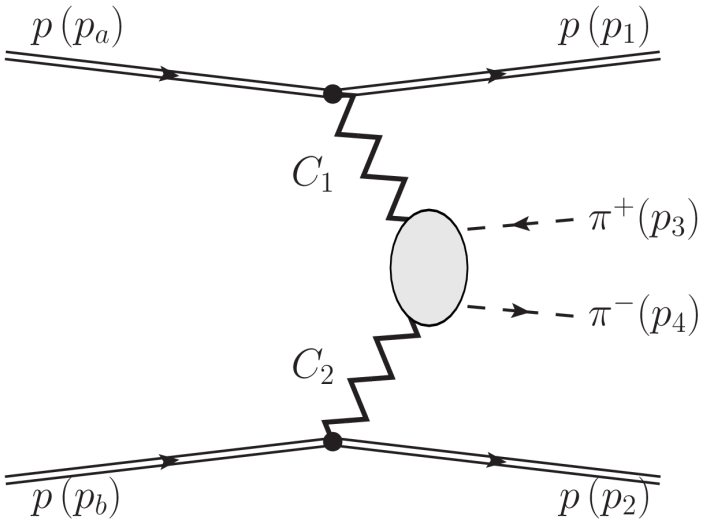


$\sqrt{s} = 200$ GeV

$0.003 \leqslant |t| \leqslant 0.035$ GeV^2

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

Dipion continuum production

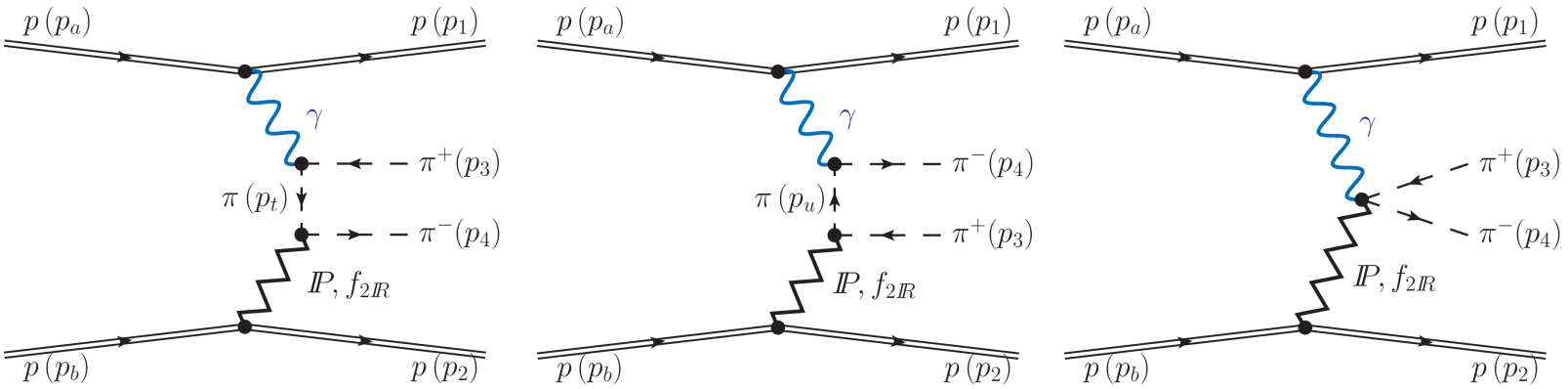


C = +1 exchanges (*IP*, f_{2IR}, a_{2IR}) are represented as rank-two tensor
C = -1 exchanges (odderon (?), ω_{IR}, ρ_{IR}) are represented as vector

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

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

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

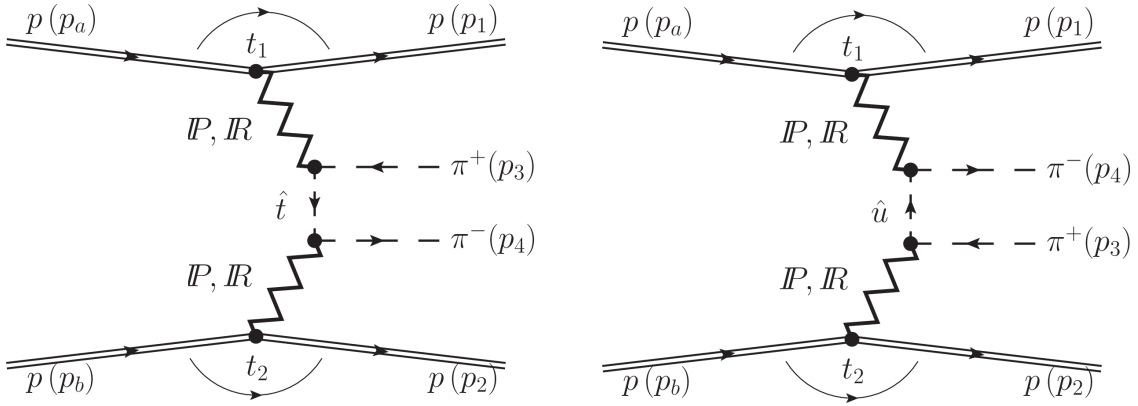


gauge invariant version of the Drell-Söding mechanism

Diffractive dipion continuum production

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

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



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

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

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

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

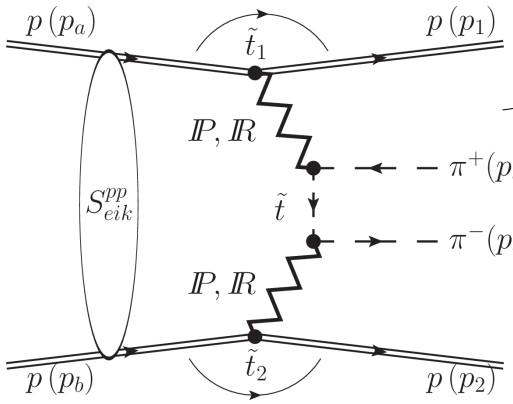
off-shell effects of intermediate pions

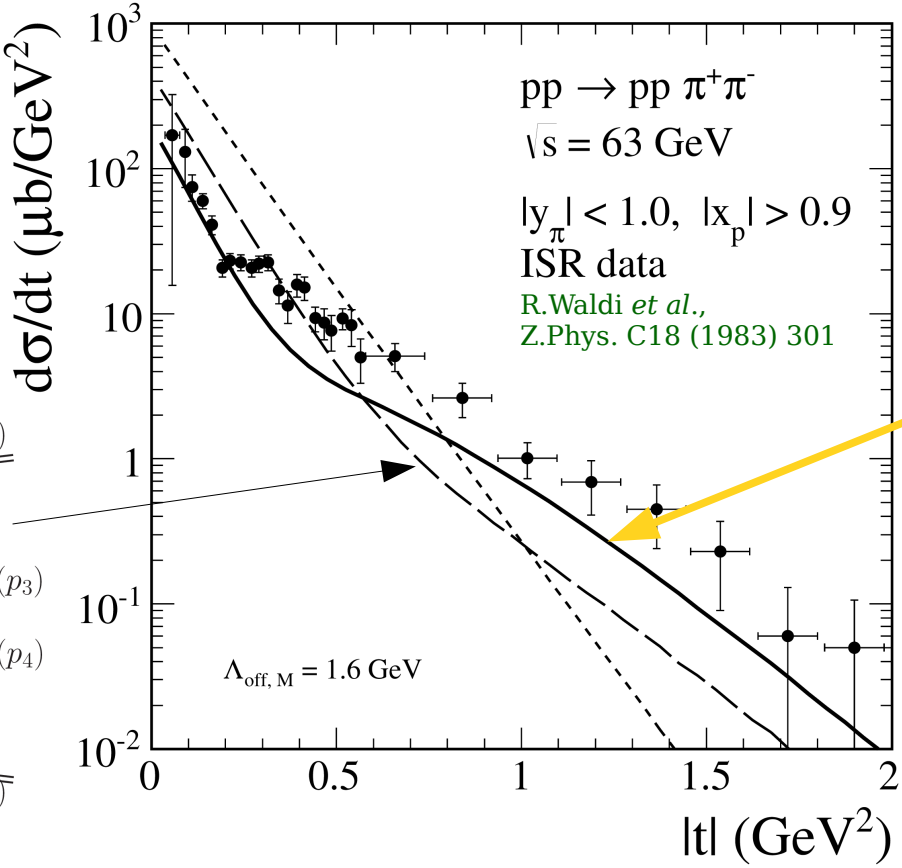
$$\text{F}_\pi(\hat{t}) = \exp\left(\frac{\hat{t}-m_\pi^2}{\Lambda^2_{off,E}}\right), \qquad \text{F}_\pi(\hat{t}) = \frac{\Lambda^2_{off,M}-m_\pi^2}{\Lambda^2_{off,M}-\hat{t}}; \qquad \text{F}_\pi(m_\pi^2) = 1$$

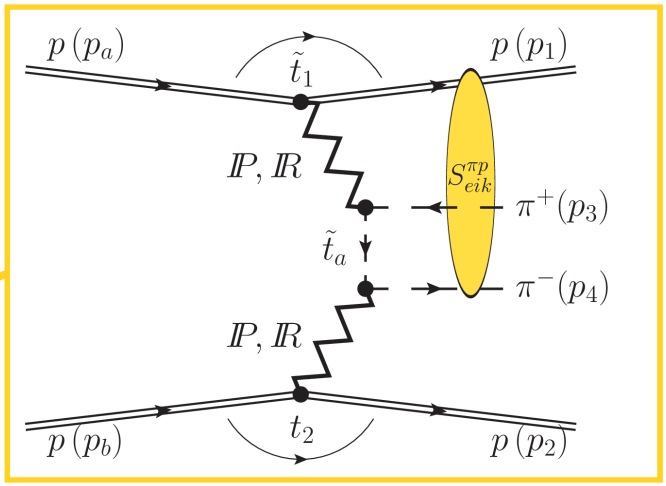
Absorption corrections

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

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







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

Absorption effects can be included effectively:

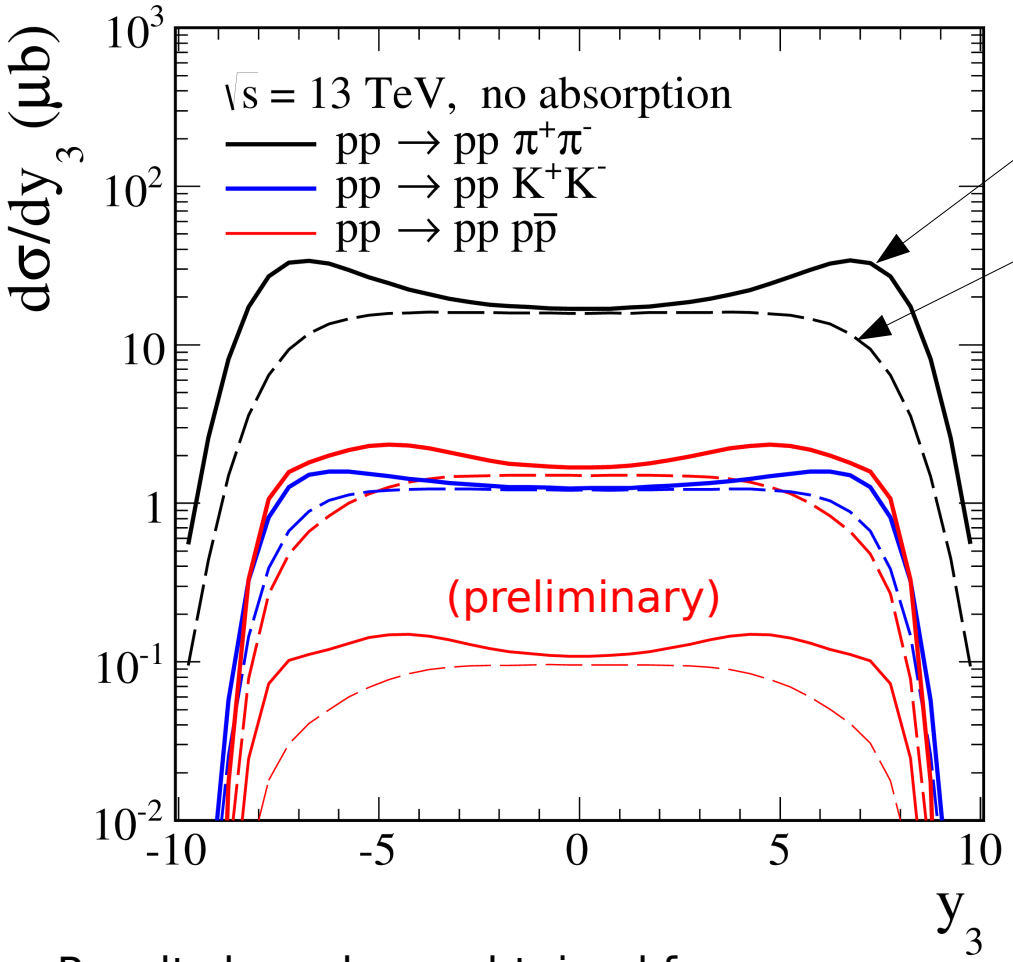
$$\frac{d\sigma^{absorbed}}{dM_{\pi\pi}} = \frac{d\sigma^{Born}}{dM_{\pi\pi}} \times < S^2 >$$

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

$< S^2 > \simeq 0.1 - 0.2$ for diffractive processes at LHC

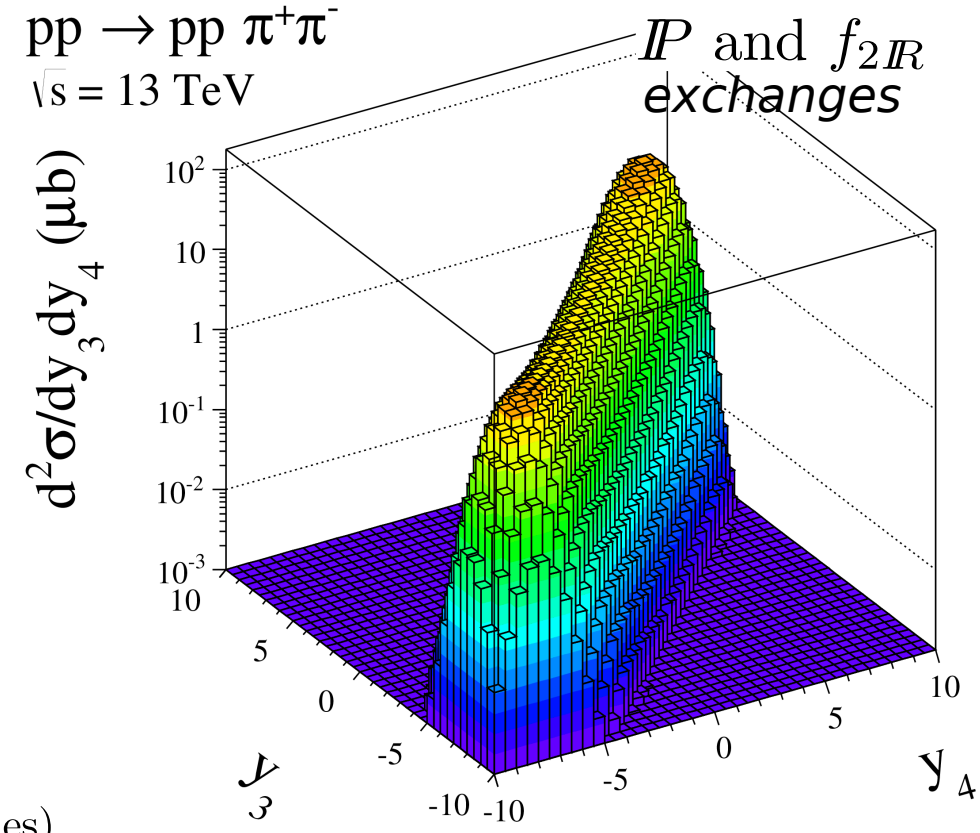
$< S^2 > \simeq 0.8 - 0.9$ for photoproduction at LHC

Diffractive continuum mechanism



$I\!P$ and $f_{2I\!R}$

$I\!P$



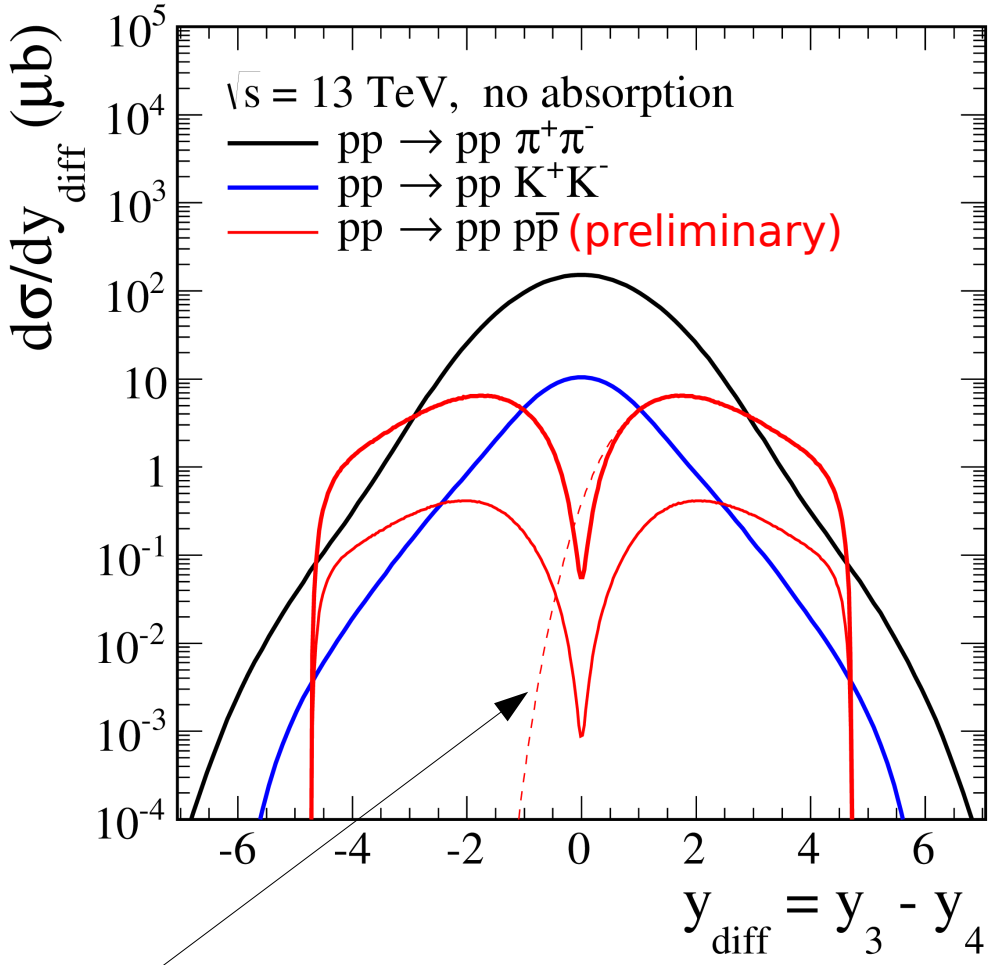
Results have been obtained for

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

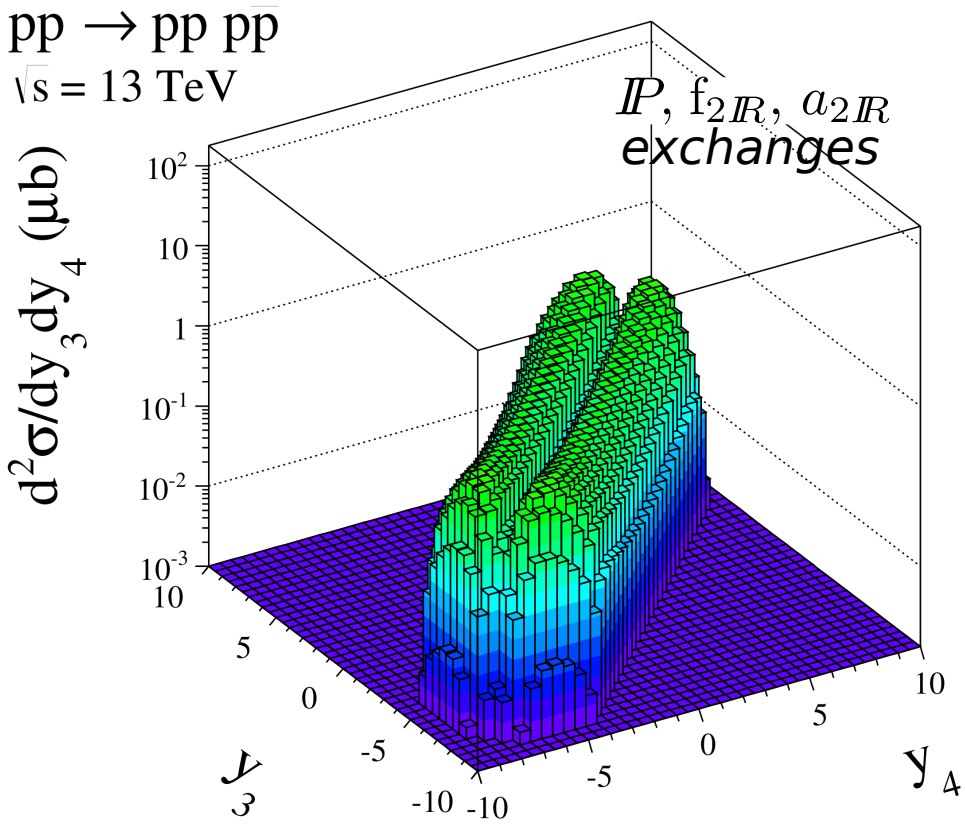
$\Lambda^{(K)}_{off,E} = 1$ GeV(blue lines)

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

Diffractive continuum mechanism

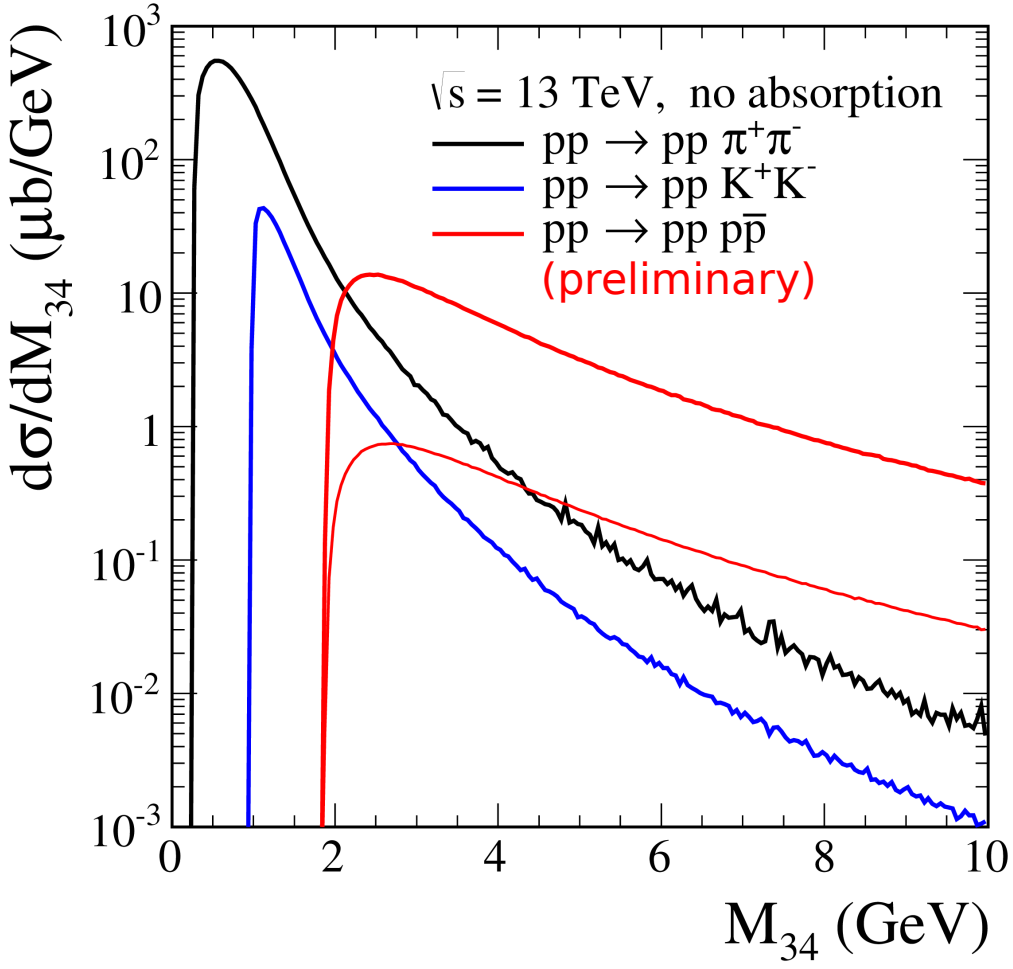


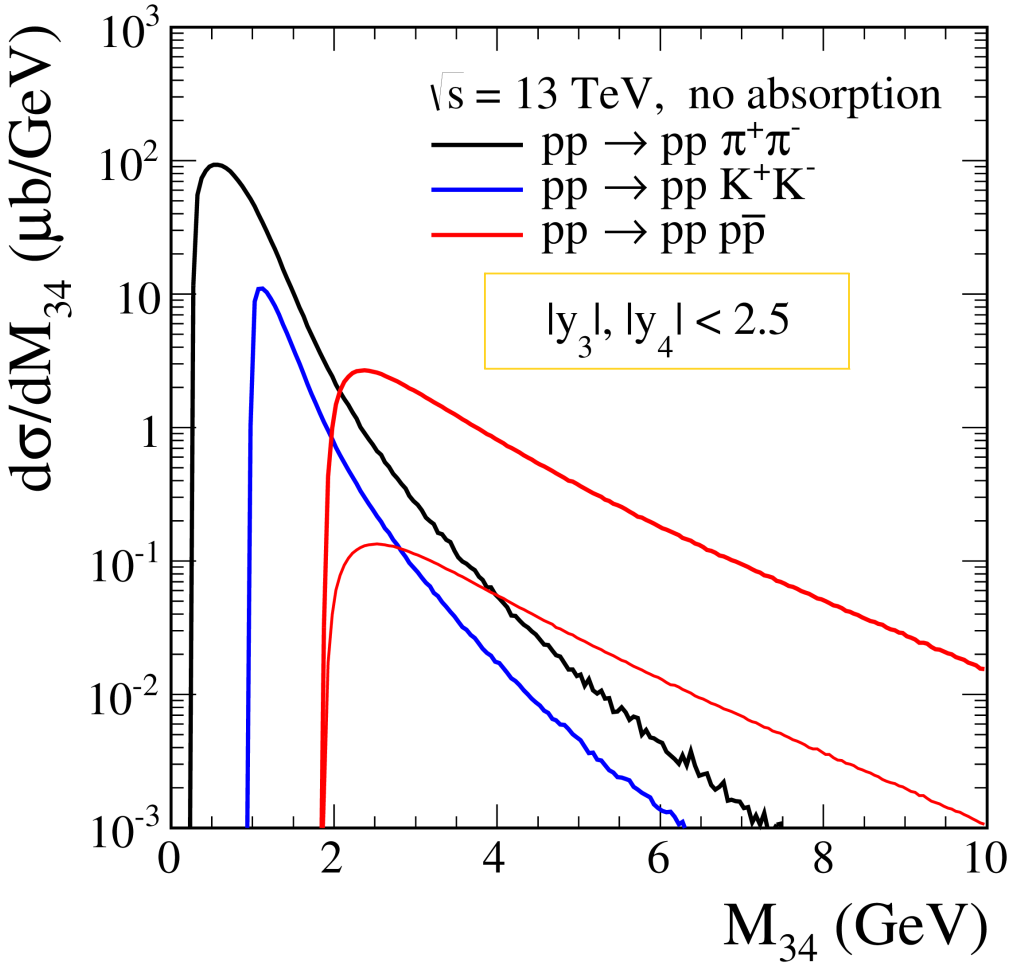
only one diagram (t-diagram)



One can observe that the dip extends over a whole diagonal in (y3, y4) space.

Diffractive continuum mechanism





Results have been obtained for

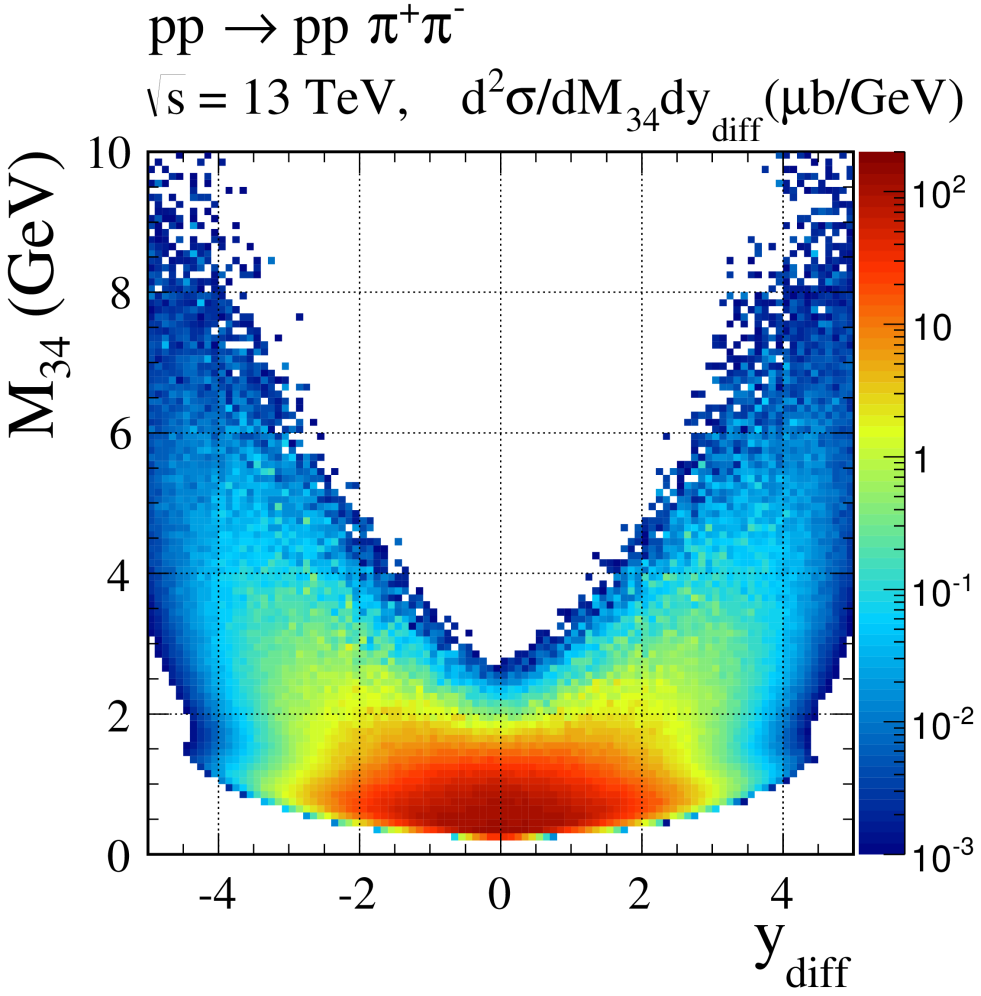
$\Lambda^{(\pi)}_{off,E} = 1$ GeV(black line)

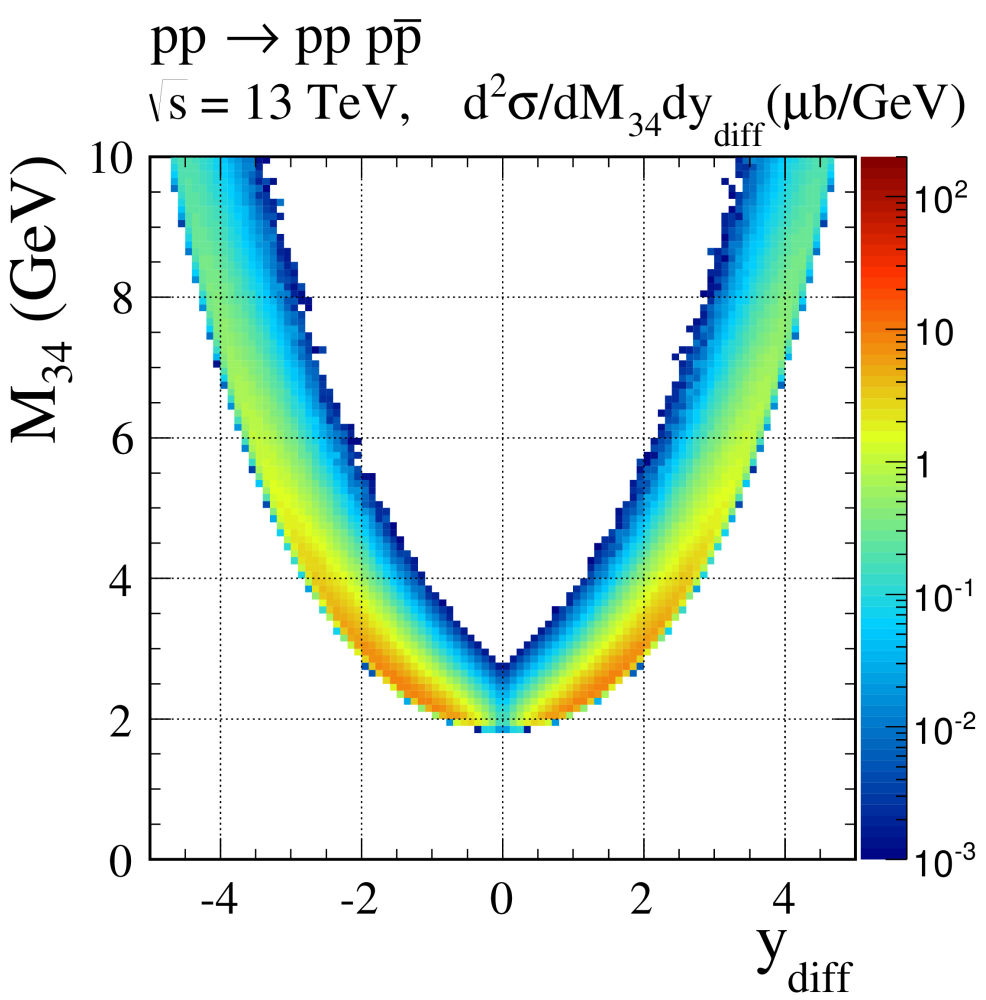
$\Lambda^{(K)}_{off,E} = 1$ GeV(blue line)

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

We predict also less steep dependence of *pp* invariant mass distribution than for the dimeson pairs.

Diffractive continuum mechanism



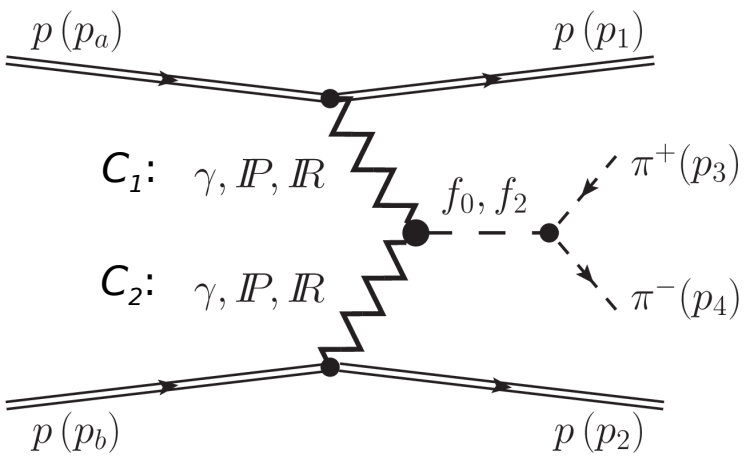


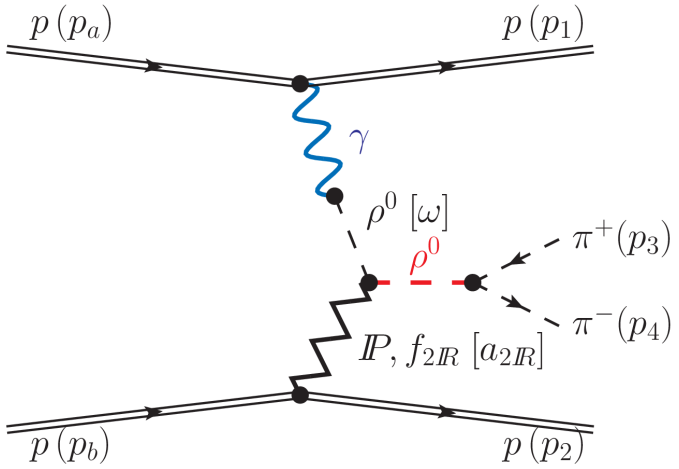
One can observe characteristic ridge at the edge of the (M_{34}, y_{diff}) space.
The interior is then free of the diffractive continuum.

Any experimentally observed distortions from the present predictions may therefore signal a presence of resonances.
Then possible identification of $p\bar{p}$ resonances should be easier.

Dipion resonant production

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





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

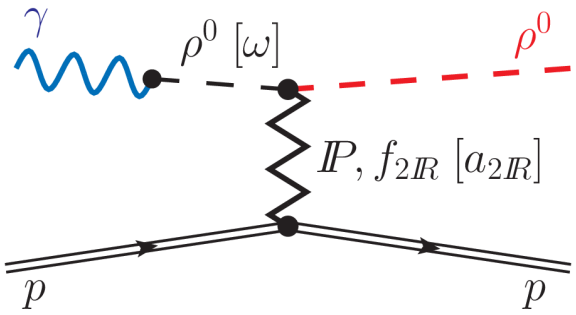
$I^G J^{PC}$, resonances	(C_1, C_2) production modes
0^+0^{++}, $f_0(500)$, $f_0(980)$, $f_0(1500)$, $f_0(1370)$, $f_0(1710)$ 0^+2^{++}, $f_2(1270)$, $f_2'(1525)$, $f_2(1950)$ 0^+4^{++}, $f_4(2050)$	$(I\!P + f_{2I\!R}, I\!P + f_{2I\!R})$, $(a_{2I\!R}, a_{2I\!R})$, $(\mathbb{O} + \omega_{I\!R} + \gamma,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

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

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

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

Photoproduction of ρ^0 meson

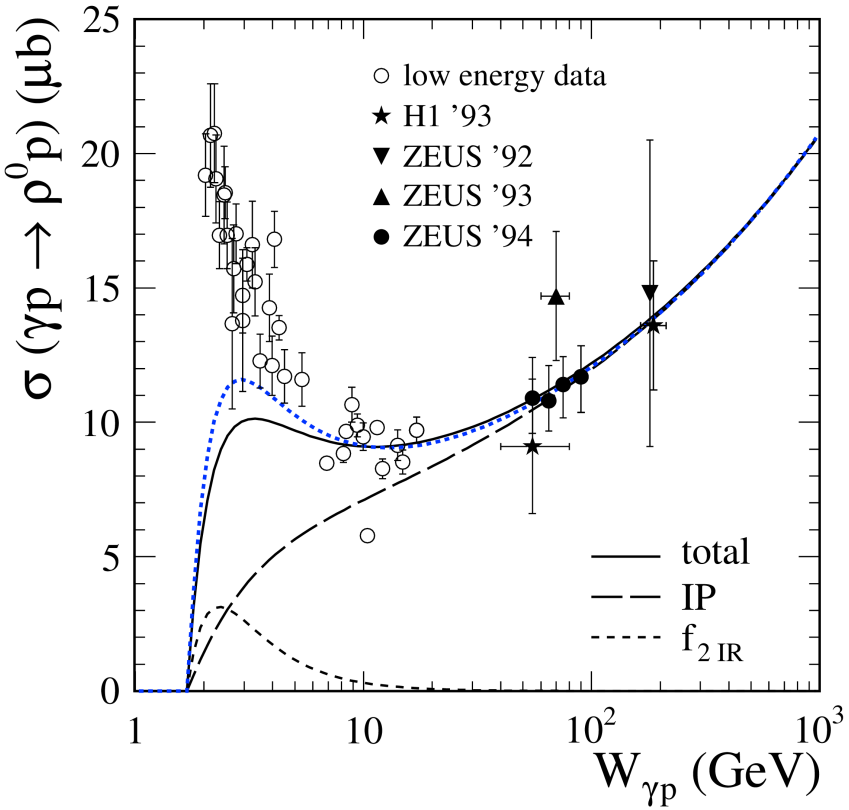


$$\mathcal{M}_{\lambda_\gamma\lambda_b\to\lambda_\rho\lambda_2}(s,t) \cong ie\frac{m_\rho^2}{\gamma_\rho}\,\Delta_T^{(\rho)}(0)\,(\epsilon^{(\rho)\,\mu})^*\epsilon^{(\gamma)\,\nu}V_{\mu\nu\kappa\lambda}(s,t,q,p_\rho)$$
$$\times 2(p_2+p_b)^\kappa(p_2+p_b)^\lambda\,\delta_{\lambda_2\lambda_b}F_1(t)F_M(t)$$

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

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

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



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

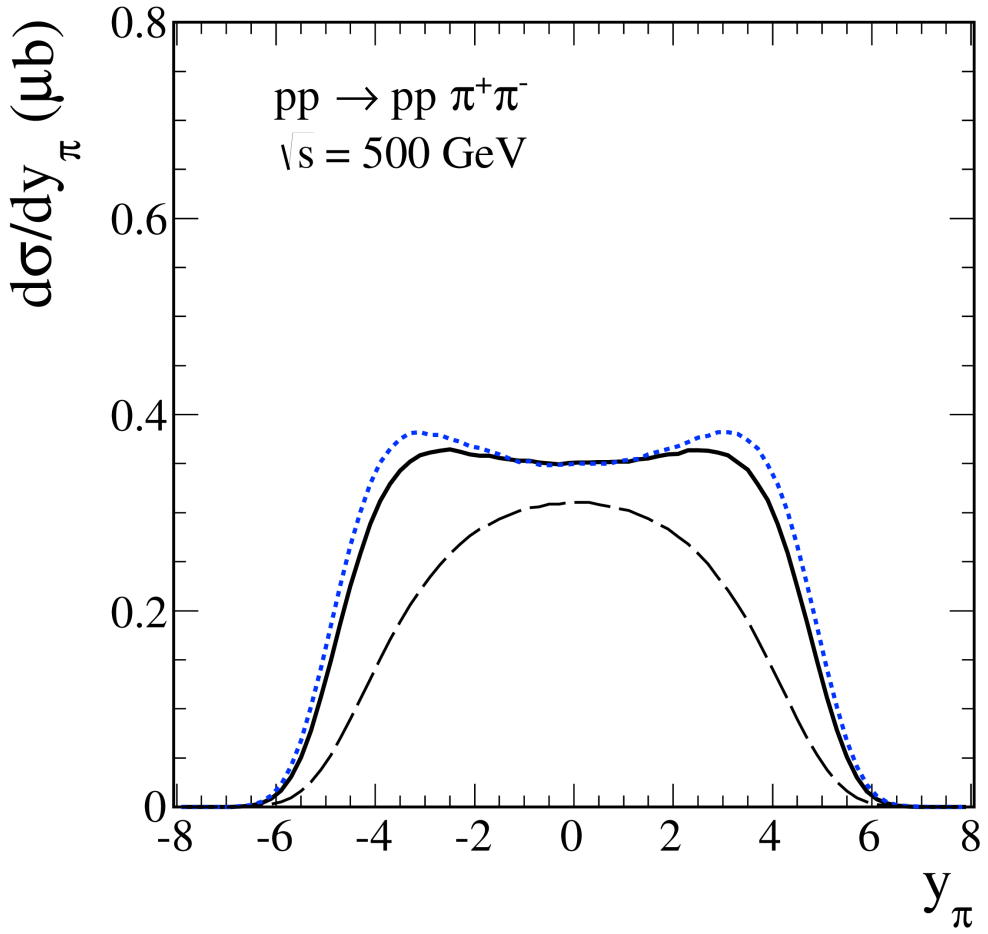
$$\sigma_{tot}(\rho^0(\lambda_\rho=\pm1),p) = \tfrac{1}{2}\left[\sigma_{tot}(\pi^+,p)+\sigma_{tot}(\pi^-,p)\right]$$

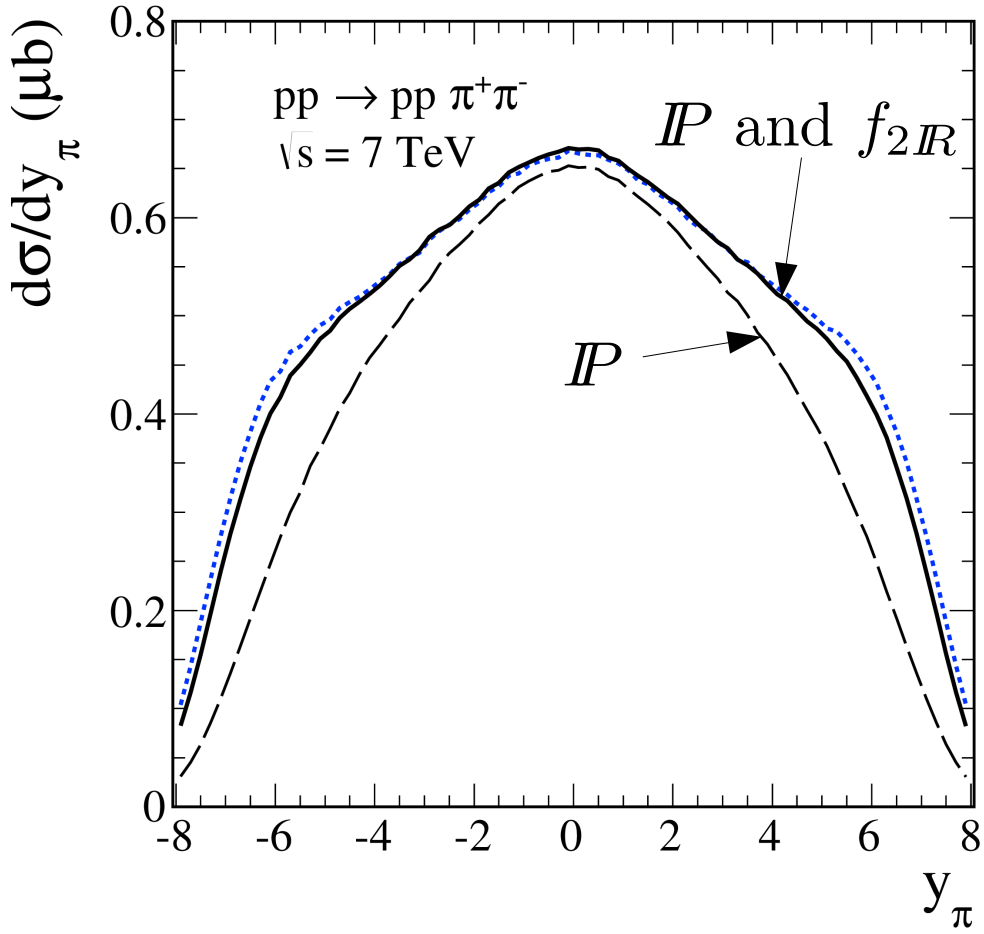
and are expected to approximately fulfill:

$$2m_\rho^2\,a_{I\!P\rho\rho} + b_{I\!P\rho\rho} = 4\beta_{I\!P\pi\pi} = 7.04\ \text{GeV}^{-1}$$
$$2m_\rho^2\,a_{f_{2I\!R}\rho\rho} + b_{f_{2I\!R}\rho\rho} = M_0^{-1}g_{f_{2I\!R}\pi\pi} = 9.30\ \text{GeV}^{-1}$$

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

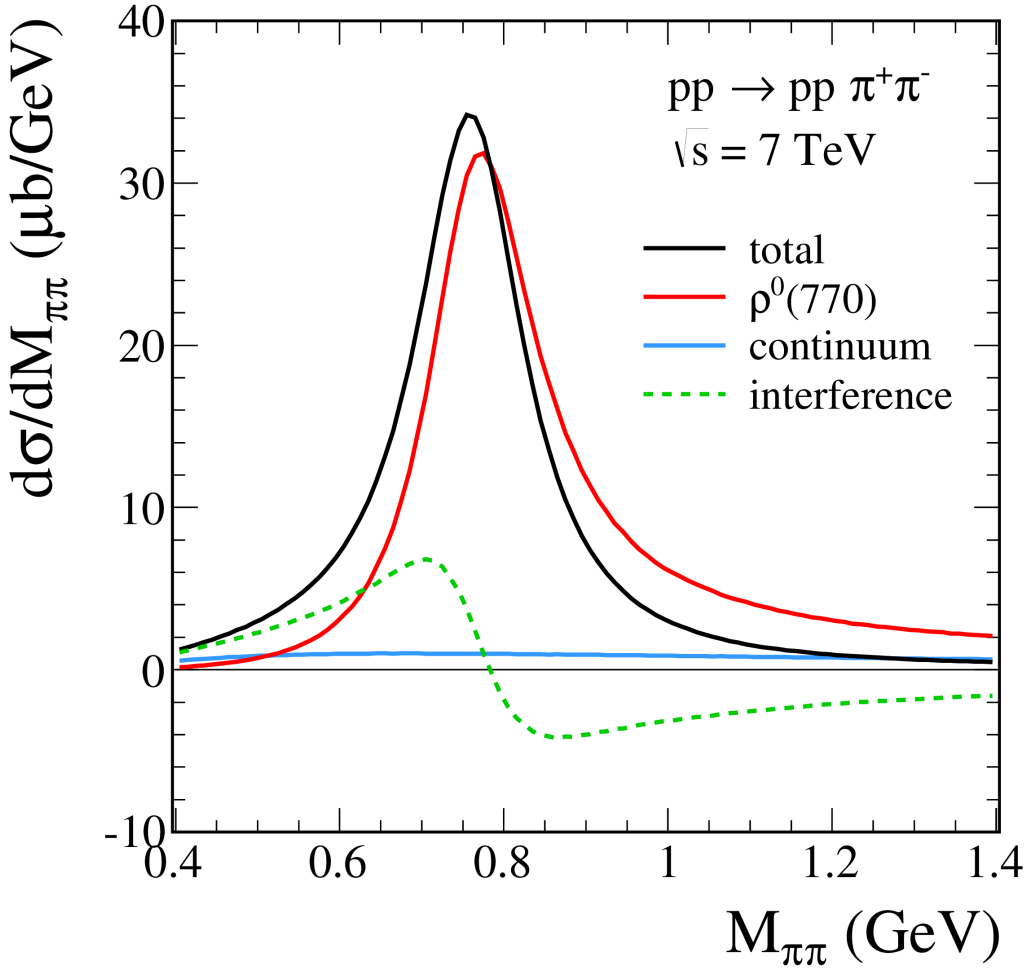
Photoproduction mechanism: ρ^0 and $\pi^+\pi^-$ continuum

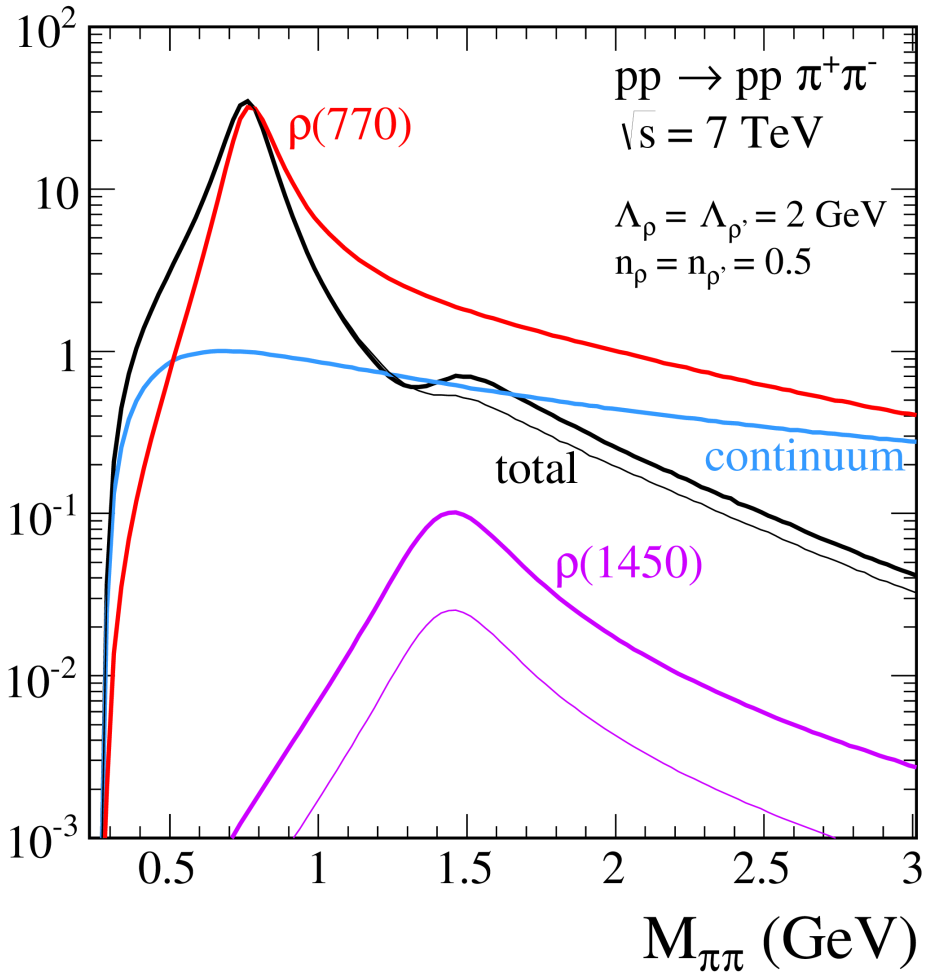




The f2 reggeon exchange included in the amplitude contributes mainly at backward and forward pion rapidities. Its contribution is non-negligible even at the LHC.

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

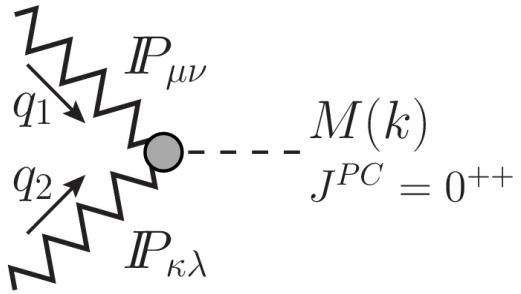




The non-resonant (Drell-Söding) contribution interferes with resonant ρ contributions
→ skewing of ρ^0 line shape.

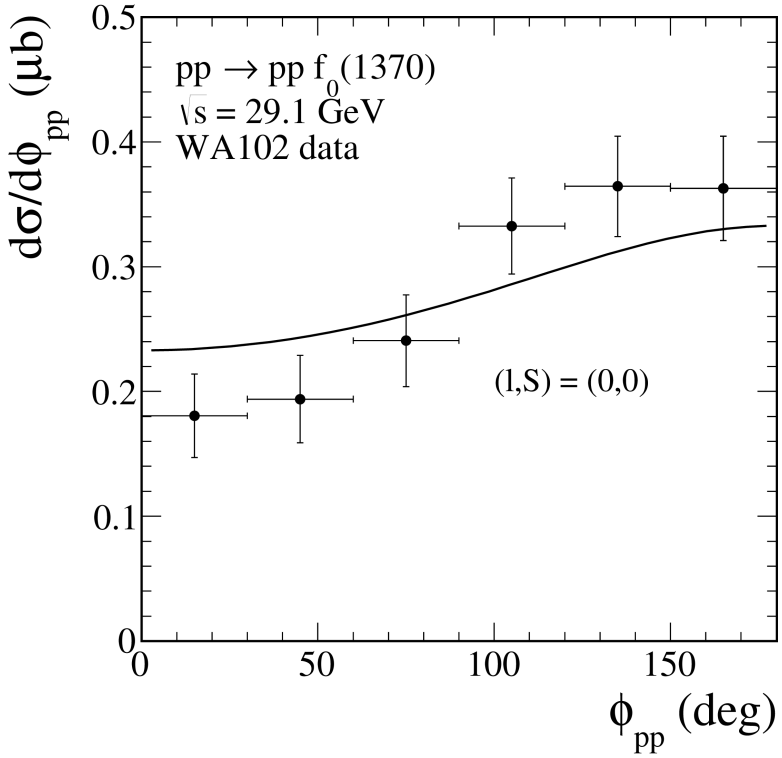
Diffractive mechanism: scalar resonances

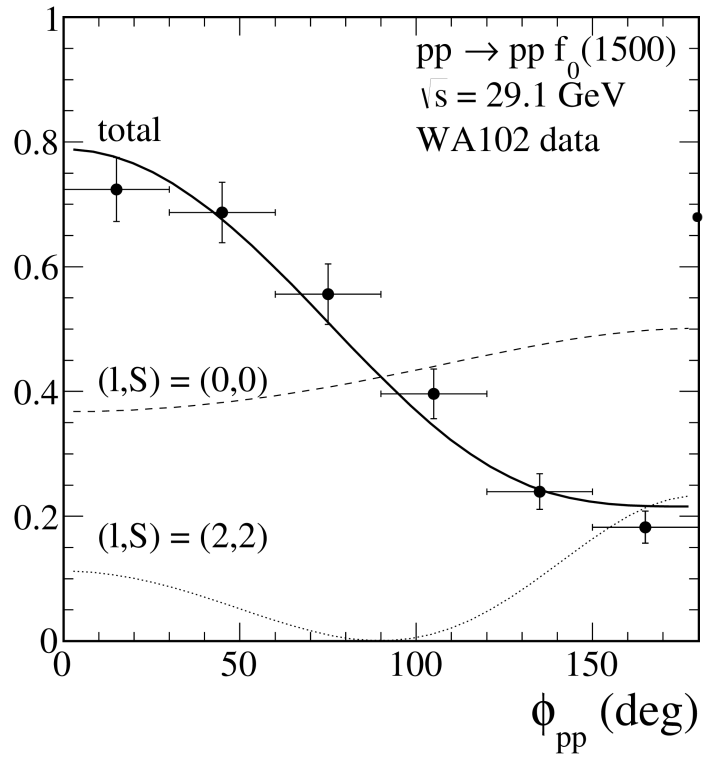
For a scalar mesons the "bare" tensorial *IP-IP-M* vertices corresponding to (l,S) = (0,0) and (2,2) terms are



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

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





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

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

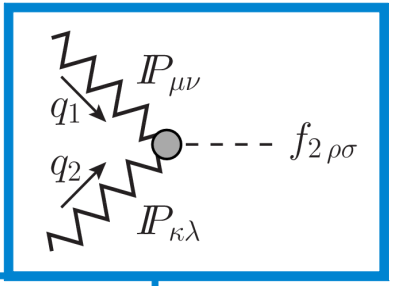
Our results and WA102 data have been normalized to the mean value of the total cross section given by A. Kirk, Phys. Lett. B489 (2000) 29.

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

Diffractive mechanism: $f_2(1270)$

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

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



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

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

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

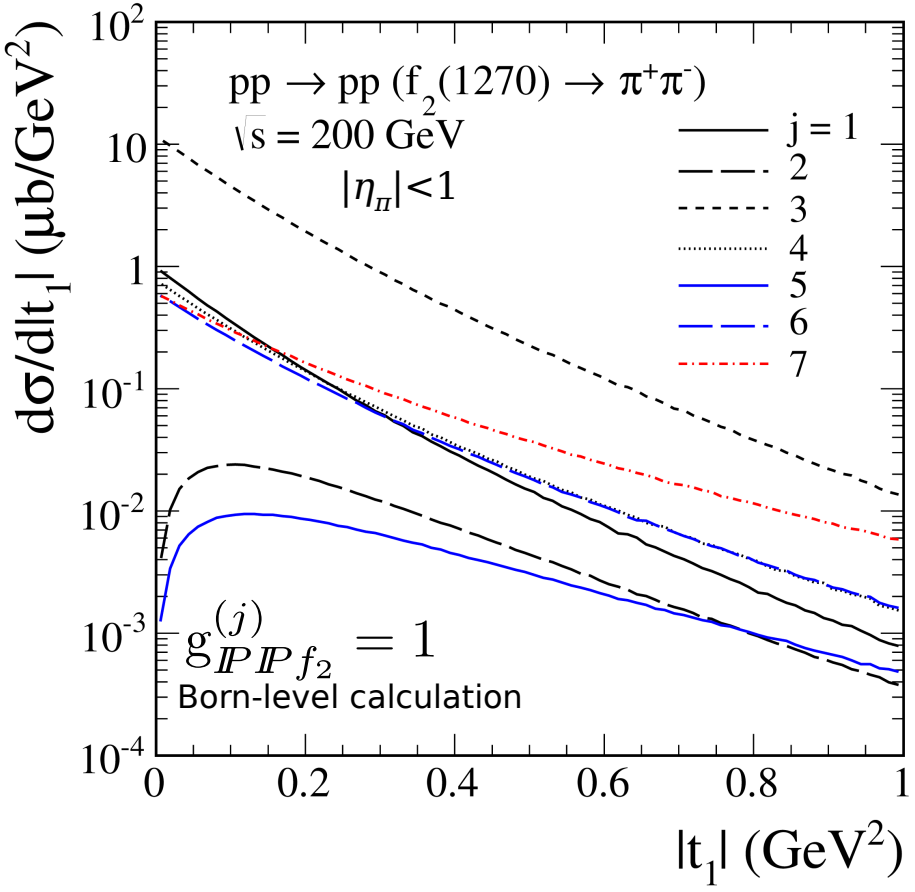
where $\hat{g}_{\mu\nu} = -g_{\mu\nu} + p_{34\mu}p_{34\nu}/p_{34}^2$ and $\Delta^{(f_2)}_{\nu\mu,\kappa\lambda}(p_{34}) = \Delta^{(f_2)}_{\mu\nu,\lambda\kappa}(p_{34}) = \Delta^{(f_2)}_{\kappa\lambda,\mu\nu}(p_{34})$, $\quad g^{\kappa\lambda}\Delta^{(f_2)}_{\mu\nu,\kappa\lambda}(p_{34}) = 0.$

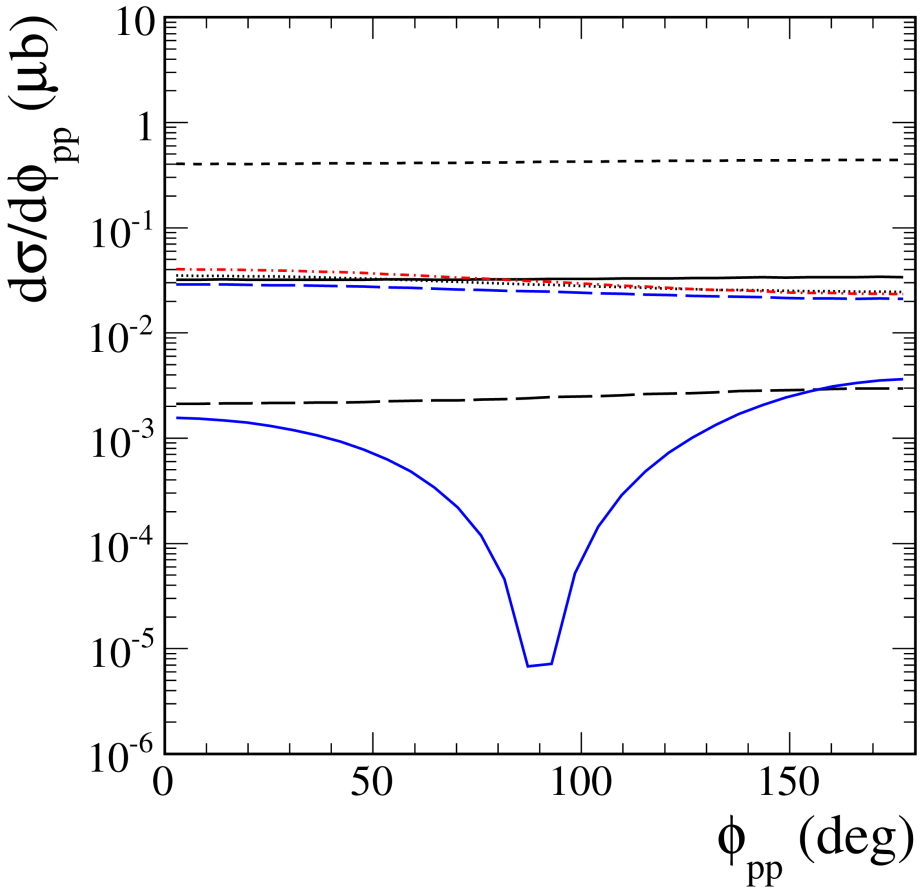
$$i\Gamma^{(f_2\pi\pi)}_{\mu\nu}(p_3,p_4) = -i\,\frac{g_{f_2\pi\pi}}{2M_0} \left[(p_3-p_4)_\mu (p_3-p_4)_\nu - \frac{1}{4} g_{\mu\nu}(p_3-p_4)^2 \right] F^{(f_2\pi\pi)}(p_{34}^2)\,,$$

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.

Diffractive mechanism: tensor resonance

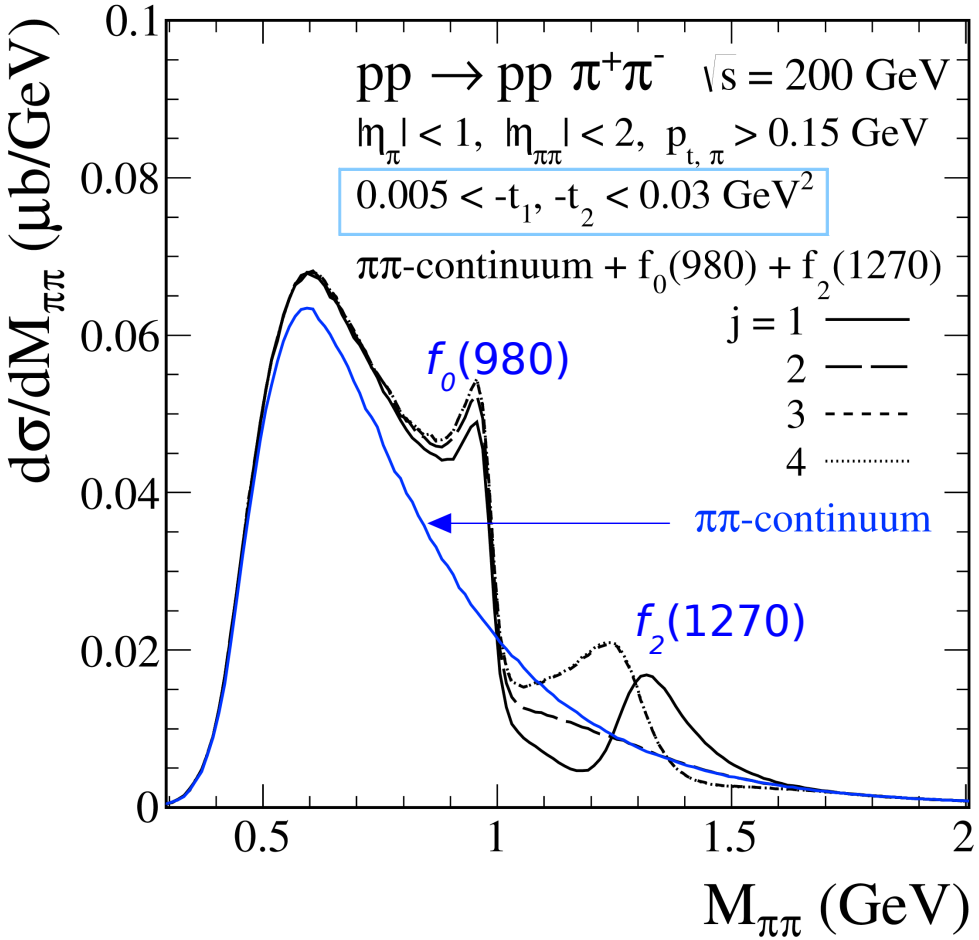


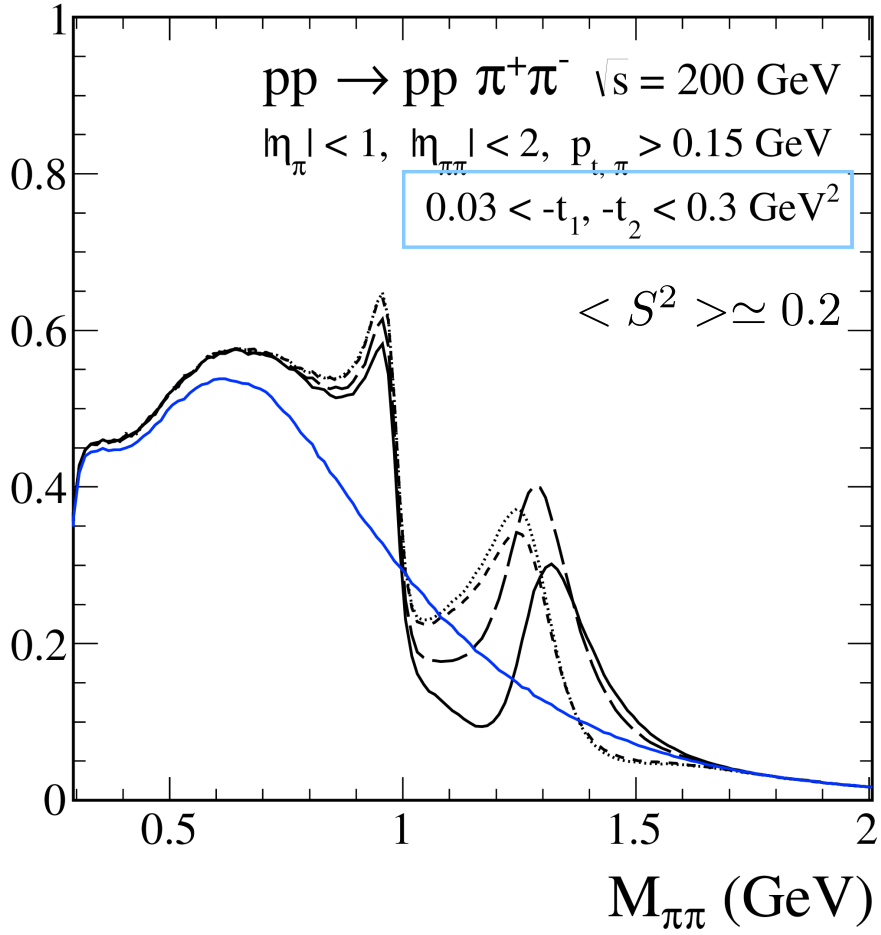


We can associate the couplings j = 1, ..., 7 with the following (l,S) values:
(0,2), (2,0) – (2,2), (2,0) + (2,2), (2,4), (4,2), (4,4), (6,4), respectively.

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

Diffractive mechanism: tensor resonance

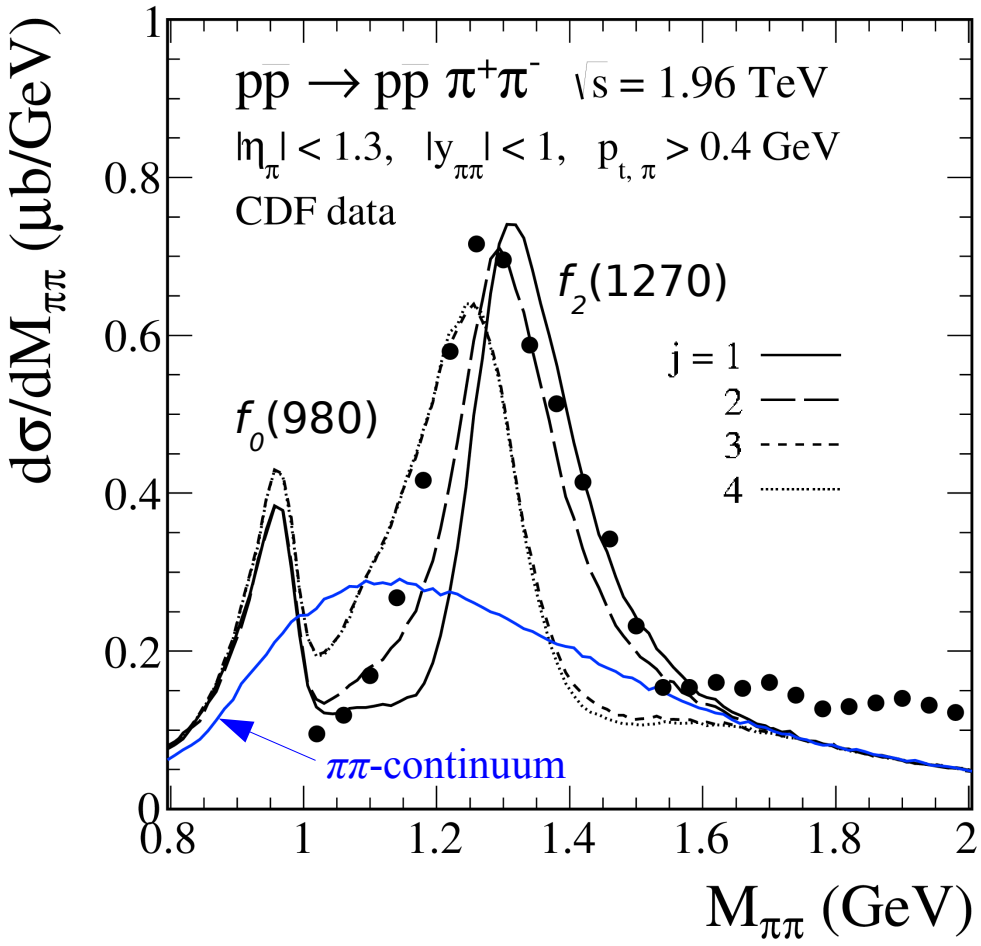




Different couplings generate different interference pattern. The relative contribution of the resonant $f_2(1270)$ and dipion continuum strongly depends on the cut on $|t|$

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

Comparison with CDF data



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:

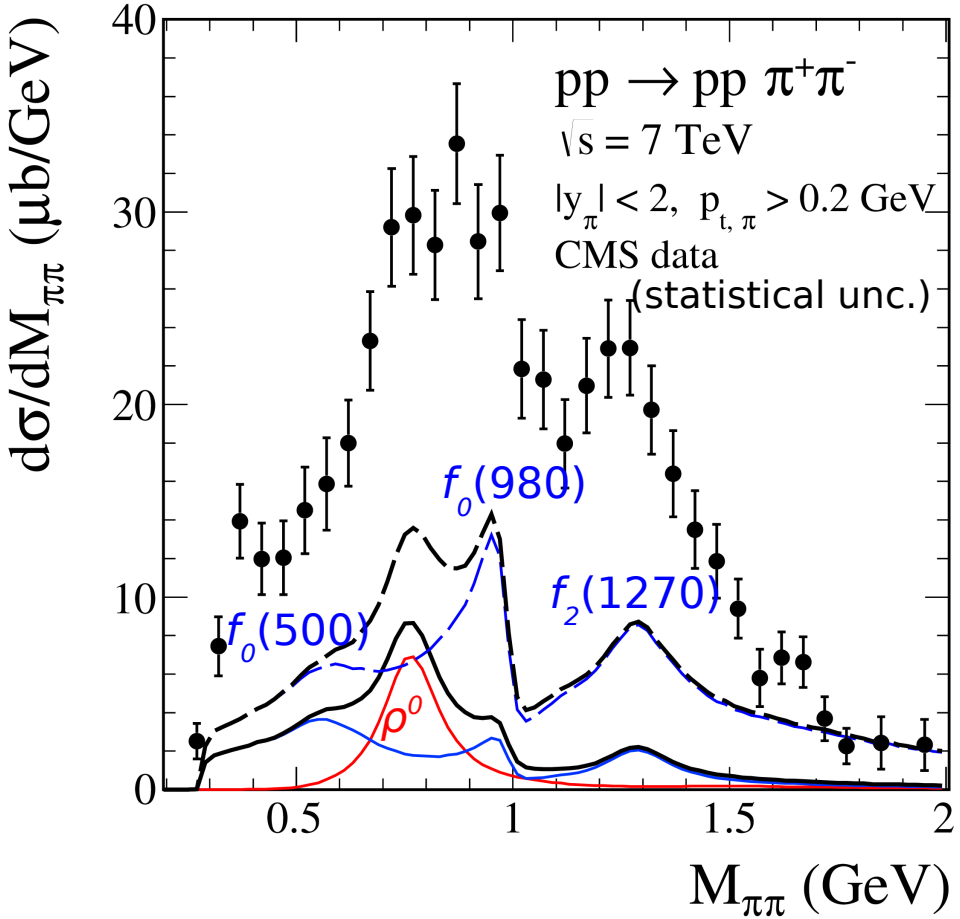
$$\frac{d\sigma}{dM_{\pi\pi}} = \frac{d\sigma^{Born}}{dM_{\pi\pi}} \times < S^2 >, \qquad < S^2 >= 0.1$$

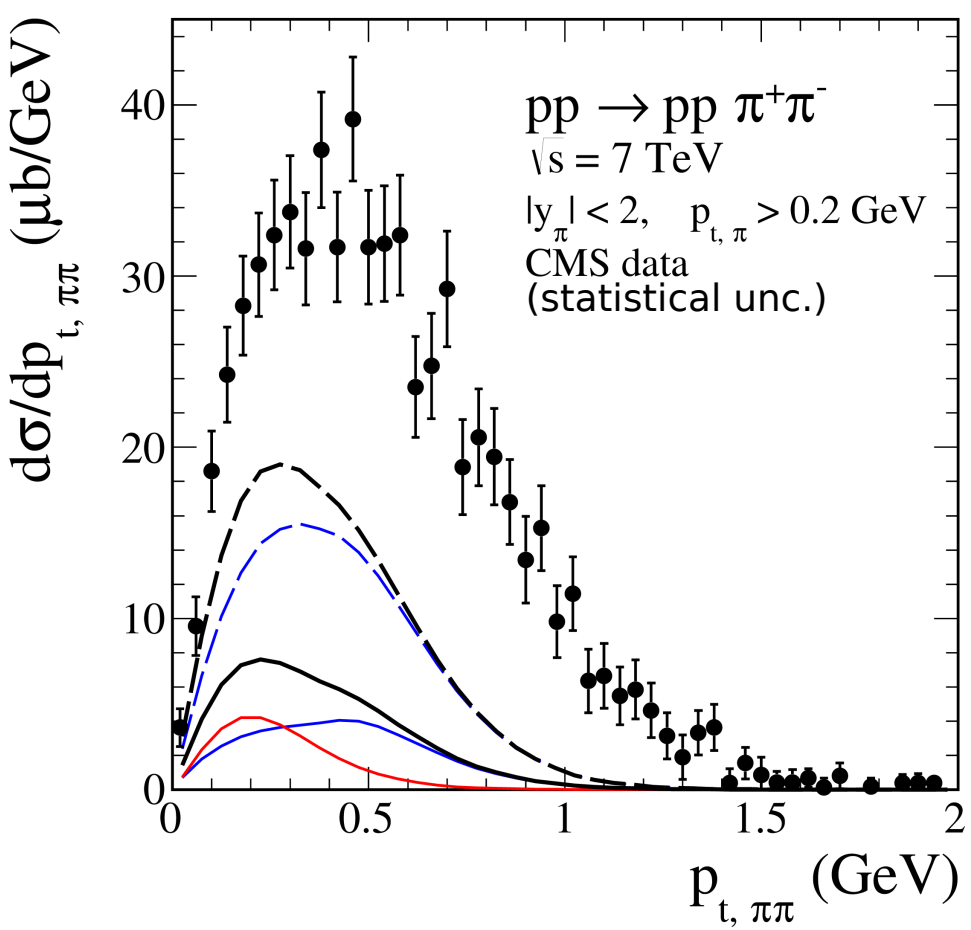
Events with two oppositely charged particles, assumed to be pions, and no other particles detected in $|\eta| < 5.9$.

(no proton tagging → rapidity gap method)

CDF data: T. A. Aaltonen et al., Phys.Rev. D91 (2015) 091101
→ see talk by Ch. Mesropian

Comparison with CMS preliminary data





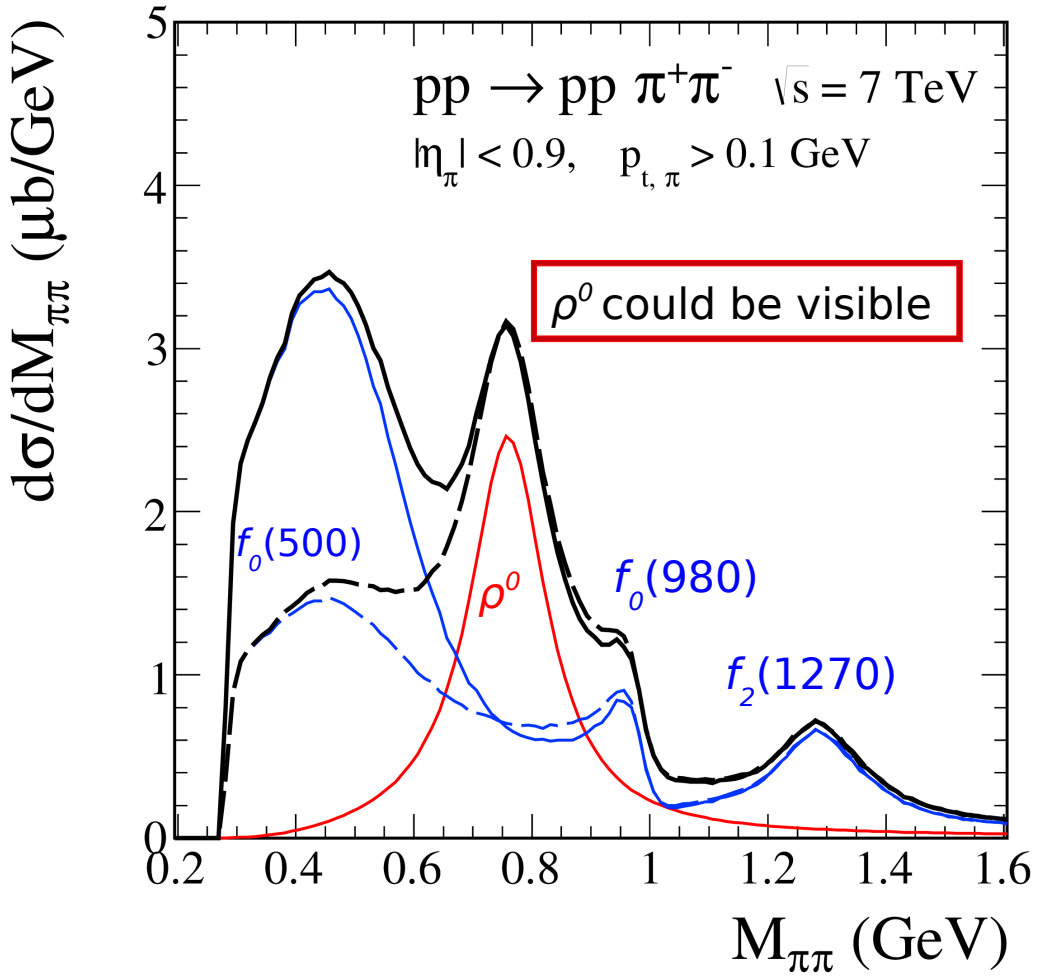
In diff. continuum term: (solid blue line) $\Lambda_{off,M}$ = 0.7 GeV (the same couplings as for CDF predictions)
(dashed blue line) $\Lambda_{off,M}$ = 1.2 GeV, and enhanced *f0*(980) and *f2* couplings

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

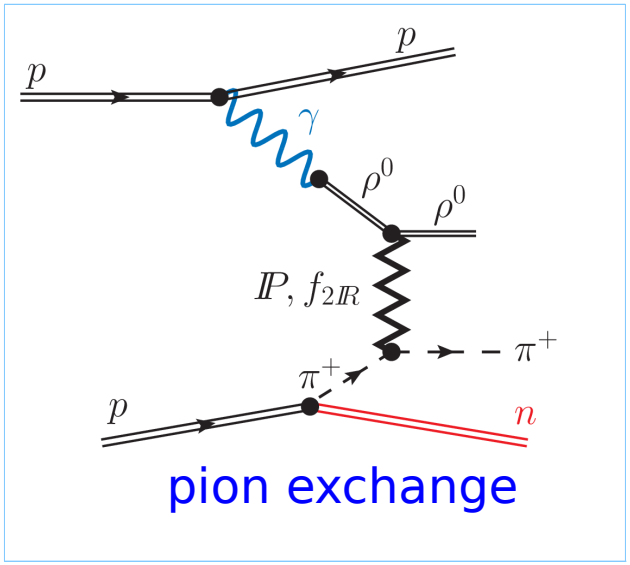
$< S^2 > \simeq 0.1$ for the diffractive contribution
$< S^2 > \simeq 0.9$ for the photon-IP/IR contribution

ρ^0 could be visible

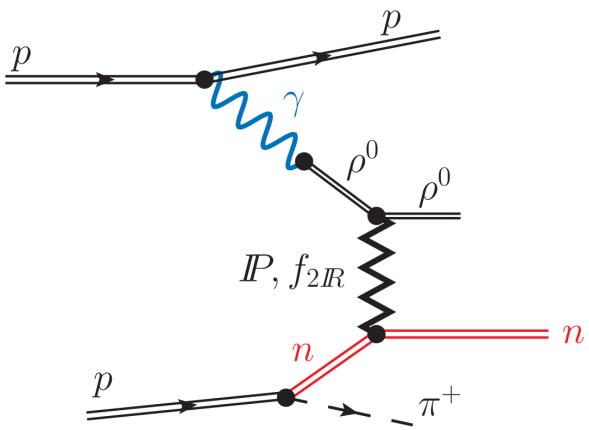
Predictions for ALICE



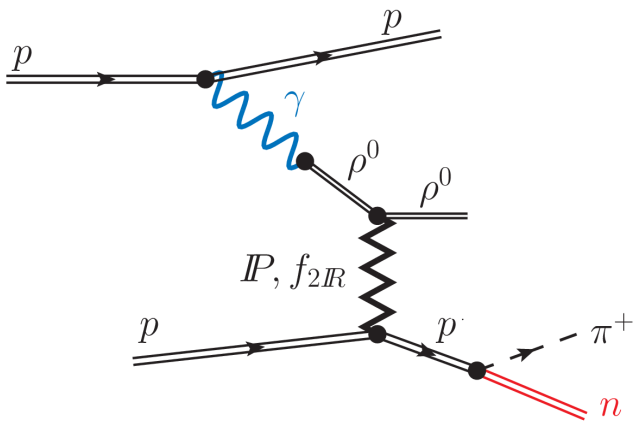
$pp \to p\,\rho^0\,(\pi^+ n)$



pion exchange



neutron exchange



direct production

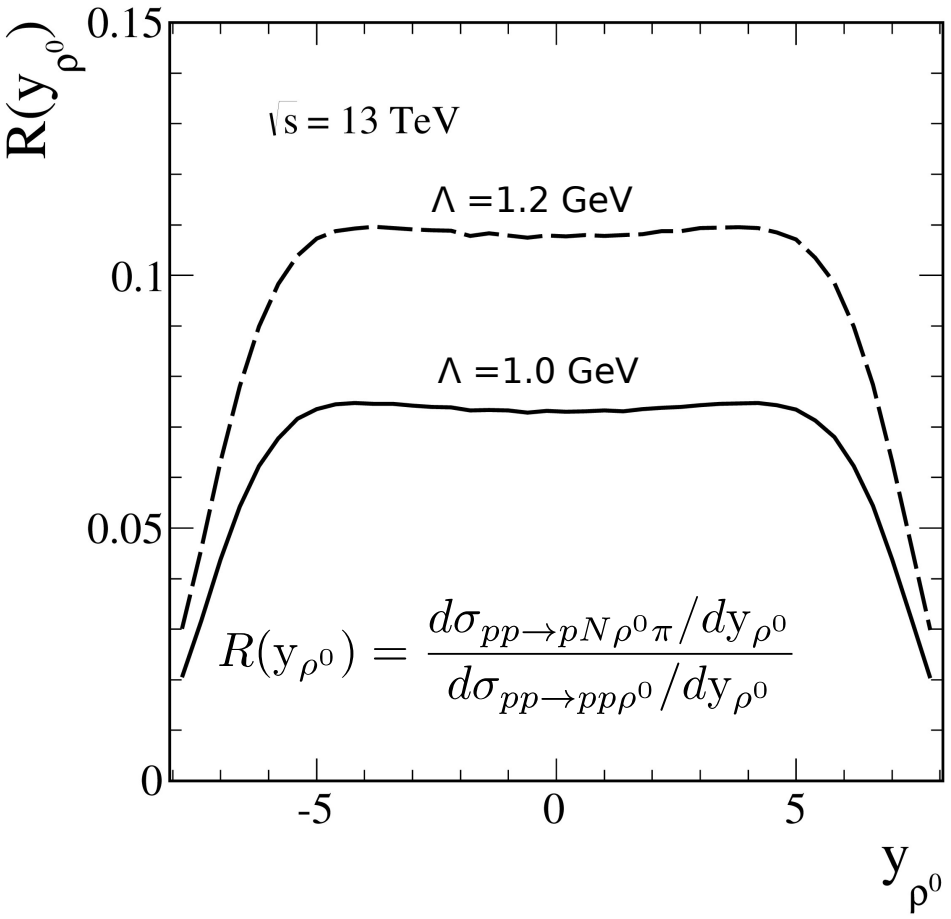
- Motivated by the study of diffractive π^0-strahlung in $pp \to pp\pi^0$ process (Drell-Hiida-Deck model) we consider here only contributions related to the diffractive $p \to \pi N$ transition.
  At large s and small $|t|$ in p-n vertex the pion exchange contribution dominates.
  see P. L., A. Szczurek,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

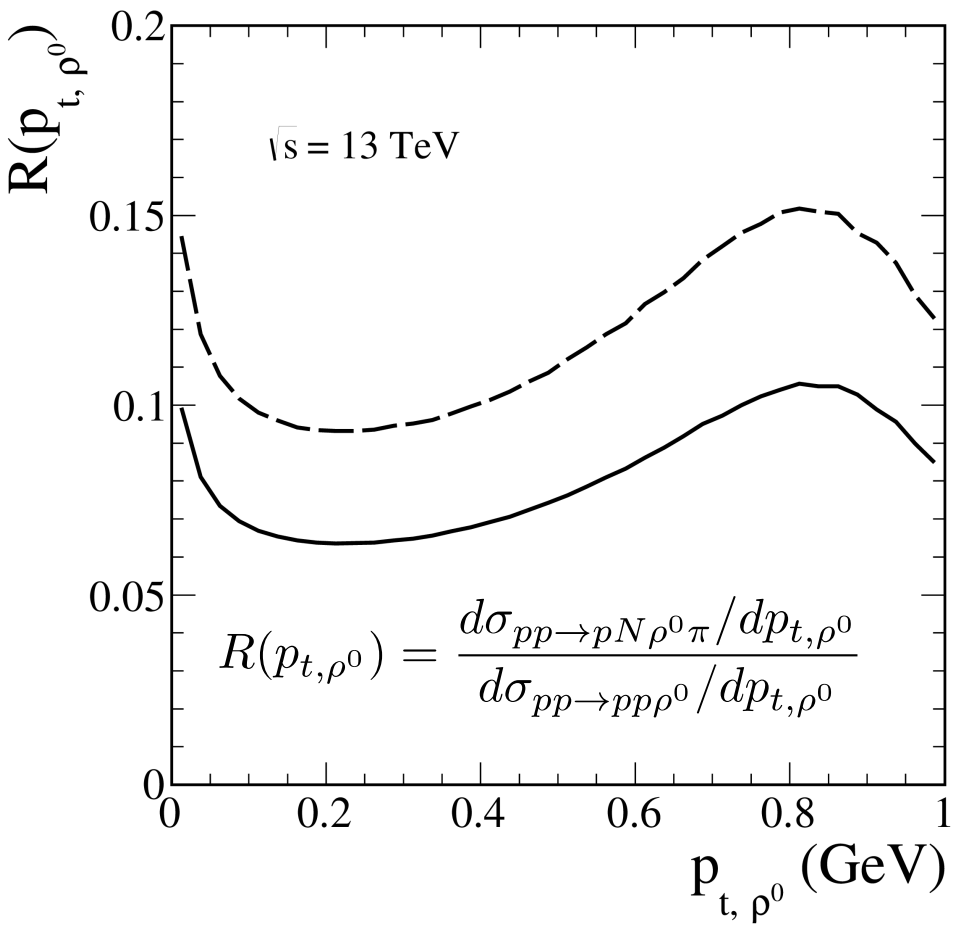
- There are also resonance contributions due to diffractive excitation of resonances, N^* states, and their subsequent decays into the πN channel.
  see L. Jenkovszky. et al., Phys. Atom. Nucl. 77, Phys. Rev. D83 (2011) 056014

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

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 single proton diffractive dissociation in the *$pp \to p\rho^0\pi N$ processes* constitute an important inelastic (non-exclusive) background (~7-10%) to the reference (exclusive) *$pp \to p\rho^0 p$* process at LHC energies.

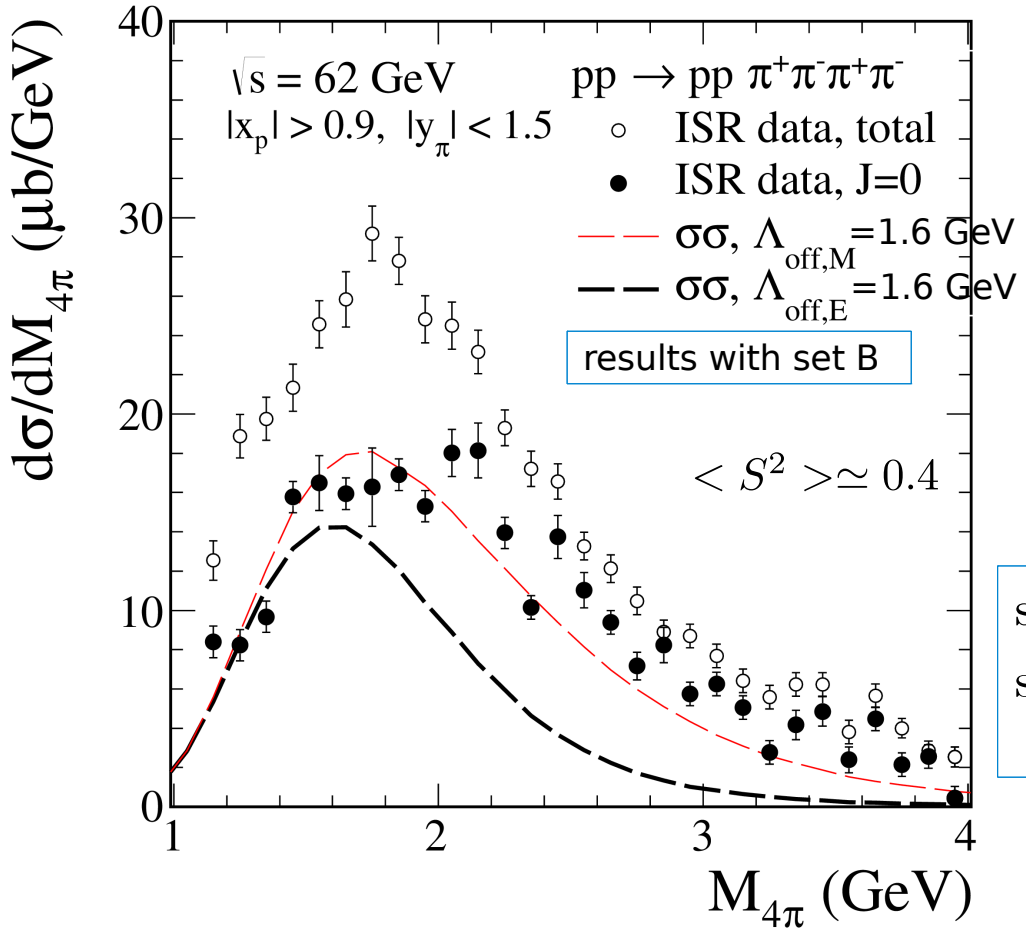
$\sigma_{inel}/\sigma_{el} \approx (3/2 \times 0.46\,\mu b)/10.32\,\mu b \approx 0.07$ for Λ =1 GeV

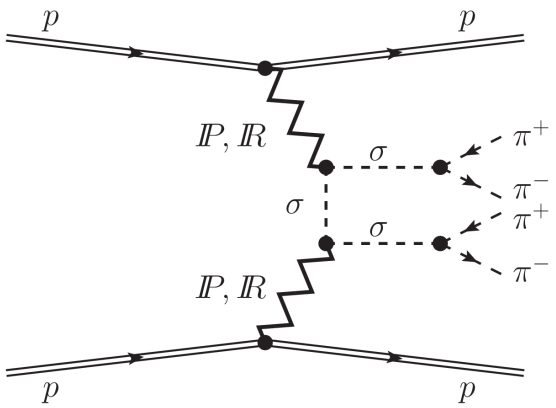
$\sigma_{inel}/\sigma_{el} \approx 1.02\,\mu b/10.32\,\mu b \approx 0.1$ for Λ =1.2 GeV

Diffractive production of $\pi^+\pi^-\pi^+\pi^-$

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

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





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

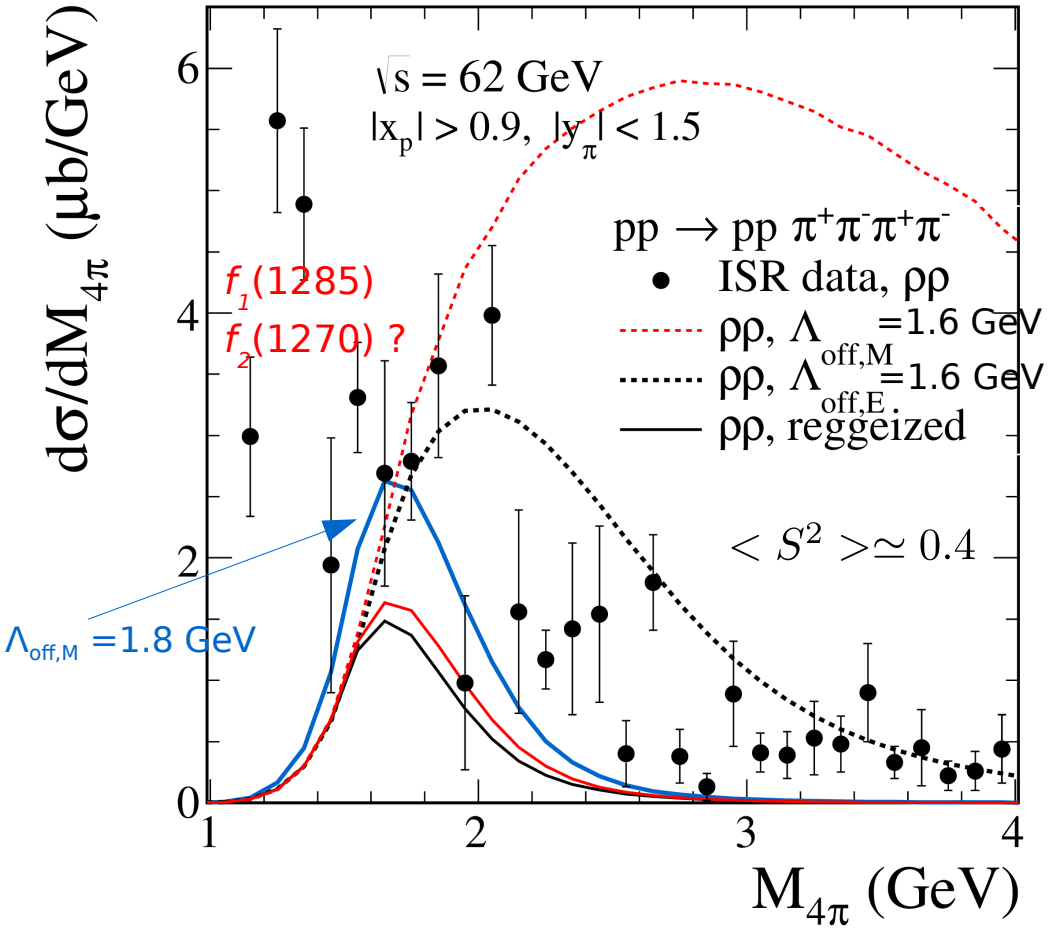
set B : $\beta_{I\!P\sigma\sigma} = 2 \times (2\beta_{I\!P\pi\pi})$, $g_{f_{2I\!R}\sigma\sigma} = 2 \times g_{f_{2I\!R}\pi\pi}$

enhanced coupling constants

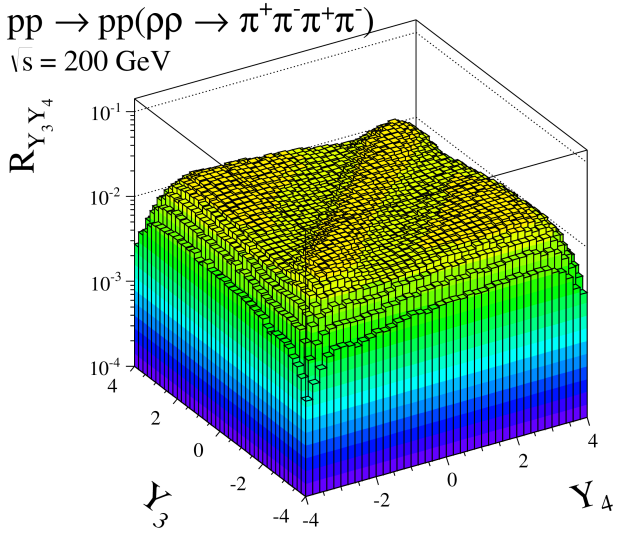
The 4π ISR data contains a large $\rho^0\pi^+\pi^-$ component with an enhancement in the J =2 term interpreted by ABCDHW Collaboration as a $f_2(1720)$ state.

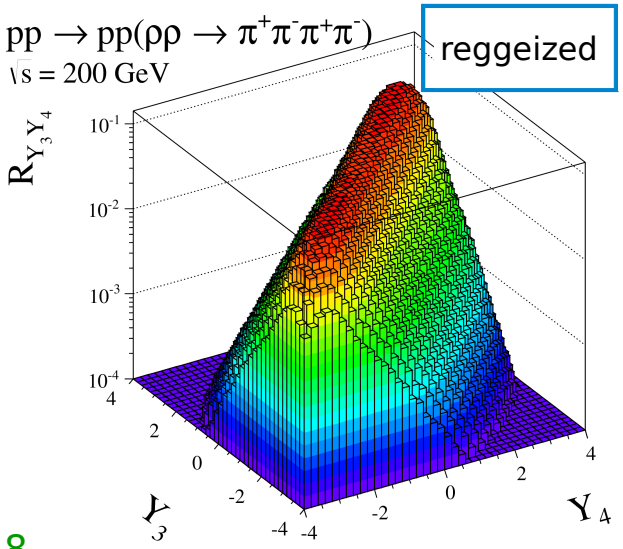
ISR data: A. Breakstone *et al*. (ABCDHW Collaboration), Z. Phys. C58 (1993) 251

4π production (ρρ contribution)



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





- reggeization effect

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

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

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

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

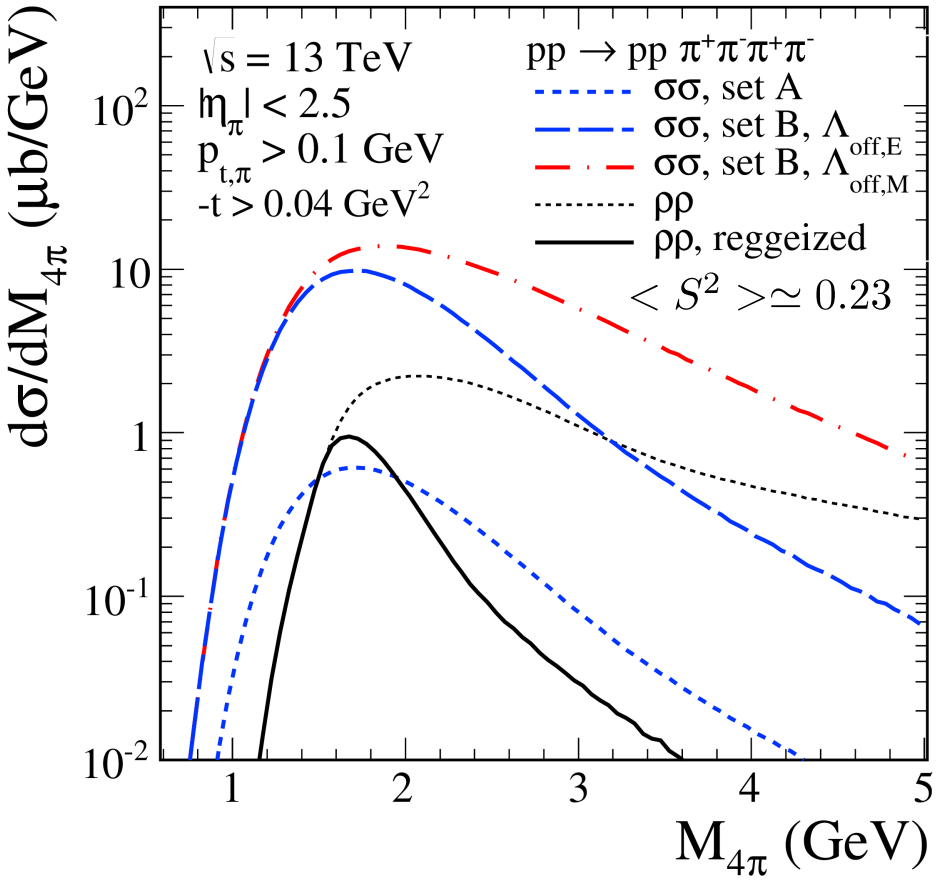
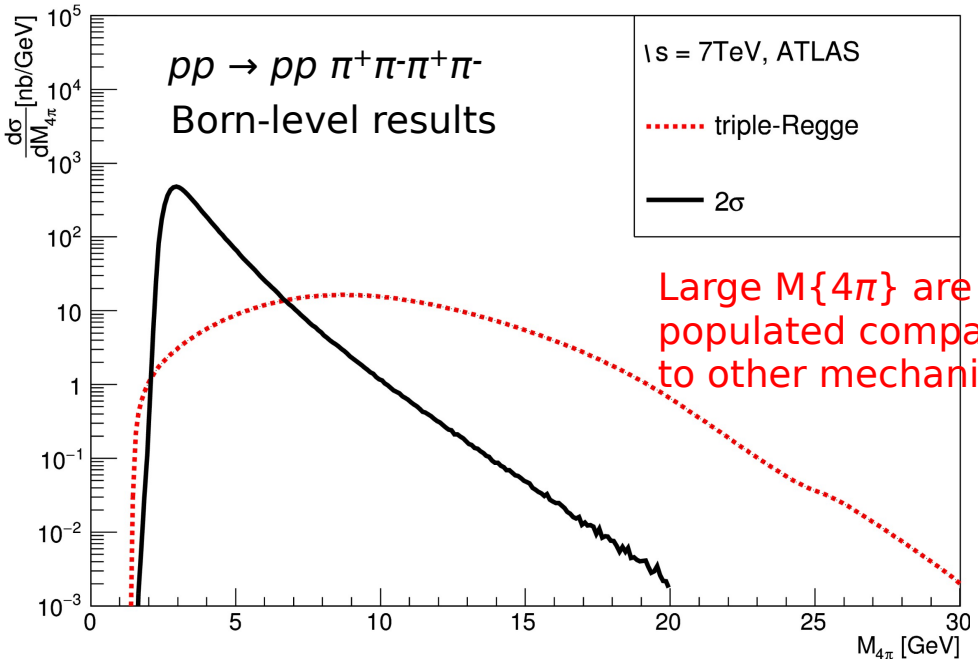


Table: Born cross sections in *μb*.
The *σσ* contribution was calculated with the enhanced (set B) couplings.
Results for the *ρρ* contribution without and with (in the parentheses) inclusion of *ρ*-reggeization.

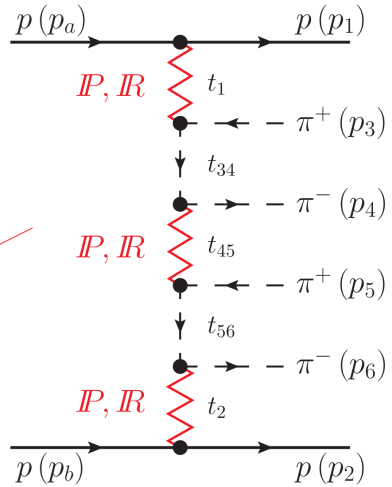
Predicted cross section can be obtained by multiplying the Born cross section by the gap survival factor:
0.3 (STAR), 0.21 (7 TeV),
0.19 (13 TeV), 0.23 (13 TeV, with cuts on $|t|$).

		"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)

Triple Regge exchange mechanism of 4π continuum



Large M{4π} are populated compared to other mechanisms



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

- Calculation of triple Regge exchange mechanism is performed with GenEx MC.
- Large cross section is found at the LHC (1-5 *μb,* whole phase space, with absorption effects of order of 0.1)
- We consider the case of ATLAS and ALICE cuts.
  The ATLAS (or CMS) has better chances to identify the triple-Regge exchange processes.

→ see talk by R. Kycia

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

Conclusions

- The tensor-pomeron model was applied to many reactions.
  The amplitudes are formulated in terms of effective vertices and propagators respecting the standard crossing and charge conjugation relations of QFT.

- 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. → see poster by R. Sikora

- The single proton diffractive dissociation in the *$pp \to p\rho^0\pi N$ processes* constitute an important inelastic (non-exclusive) background (~7-10%) to the reference (exclusive) $pp \to p\rho^0 p$ process at LHC energies.

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

- In progress: GenEx MC generator for soft reactions within tensor pomeron approach

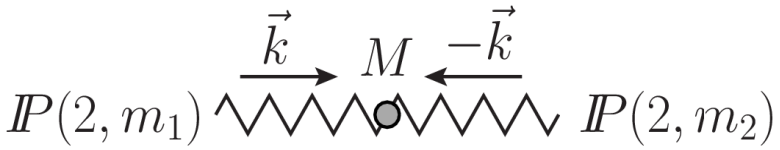
  → see talk by P. Erland and poster by R. Kycia

Extra slides

Pomeron-pomeron-meson couplings

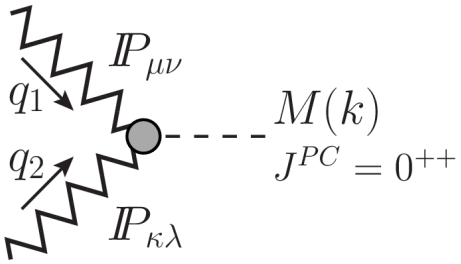
l – orbital angular momentum
S – total spin, we have $S \in \{0, 1, 2, 3, 4\}$
J – total angular momentum (spin of the produced meson)
P – parity of meson
and Bose symmetry requires $l - S$ to be even

In table we list the values of J and P of mesons which can be produced in annihilation of two "spin 2 pomeron particles"



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

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



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

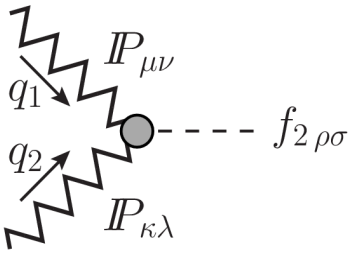
The lowest (l,S) term for a scalar meson $J^{PC} = 0^{++}$ is (0,0) while for a tensor meson $J^{PC} = 2^{++}$ is (0,2).

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

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

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

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



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

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

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

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

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

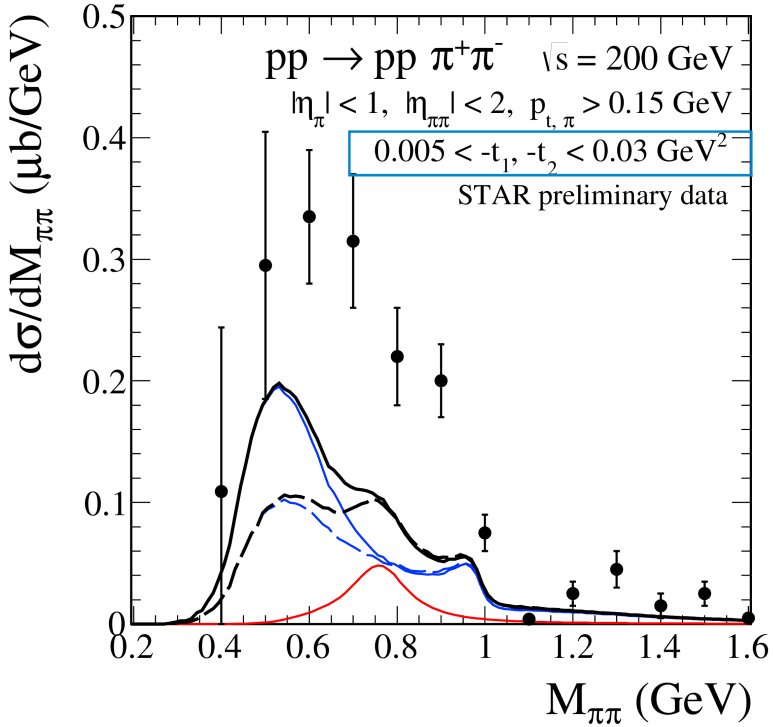
$$i\Gamma^{(I\!P I\!P f_2)(6)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = \frac{i}{M_0^3}\, g^{(6)}_{I\!P I\!P f_2} \Big(q_1^{\alpha_1}\, q_1^{\lambda_1}\, q_2^{\mu_1}\, q_{2\rho_1}\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1} + q_2^{\alpha_1}\, q_2^{\lambda_1}\, q_1^{\mu_1}\, q_{1\rho_1}\,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

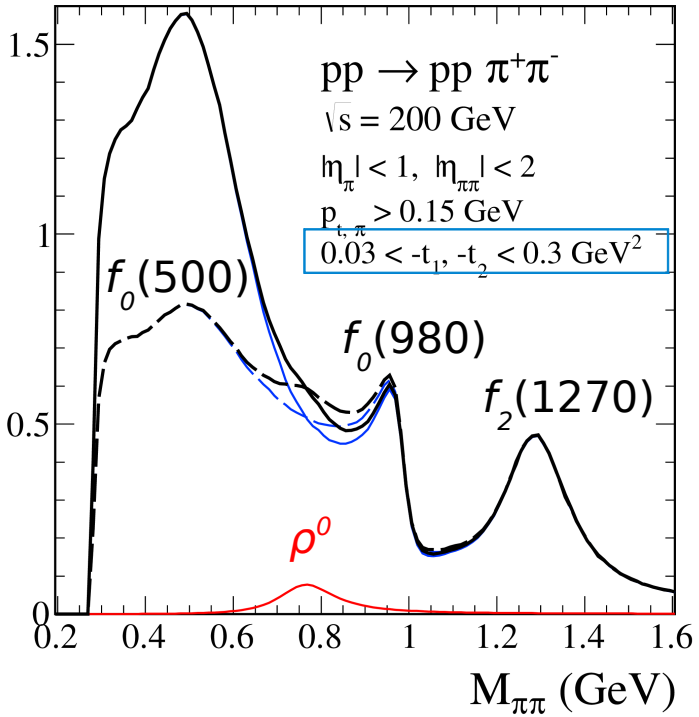
$$i\Gamma^{(I\!P I\!P f_2)(7)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{2i}{M_0^5}\, g^{(7)}_{I\!P I\!P f_2}\, q_1^{\rho_1}\, q_1^{\alpha_1}\, q_1^{\lambda_1}\, q_2^{\sigma_1}\, q_2^{\mu_1}\, q_2^{\nu_1}\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1}\, R_{\rho\sigma\rho_1\sigma_1}$$

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

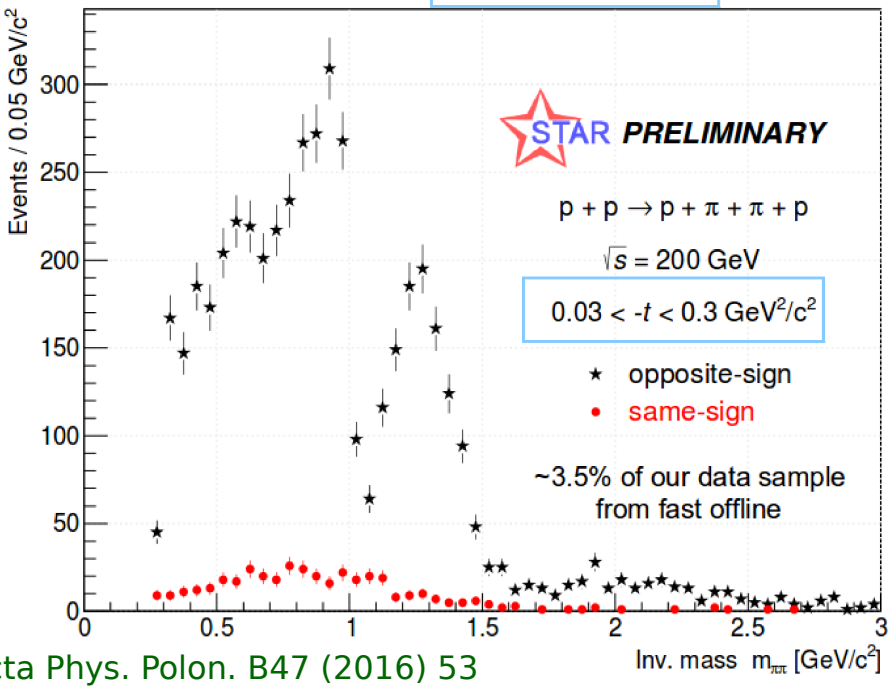
Comparison with STAR preliminary data





not acceptance-corrected, statistical errors only

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

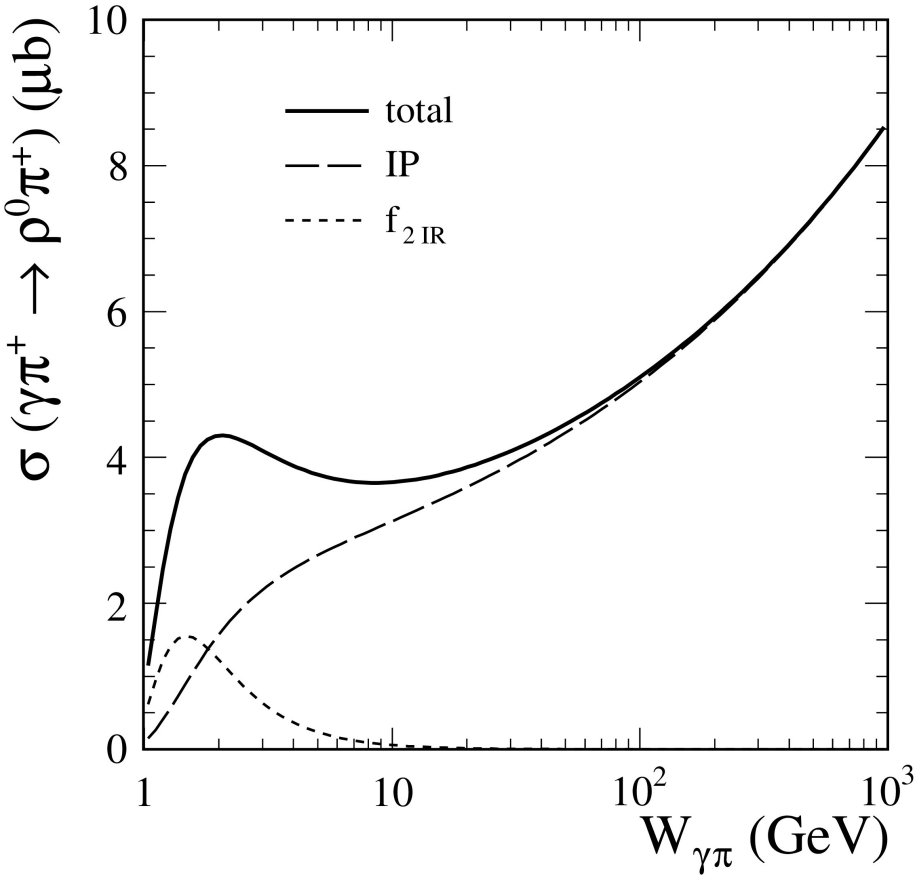


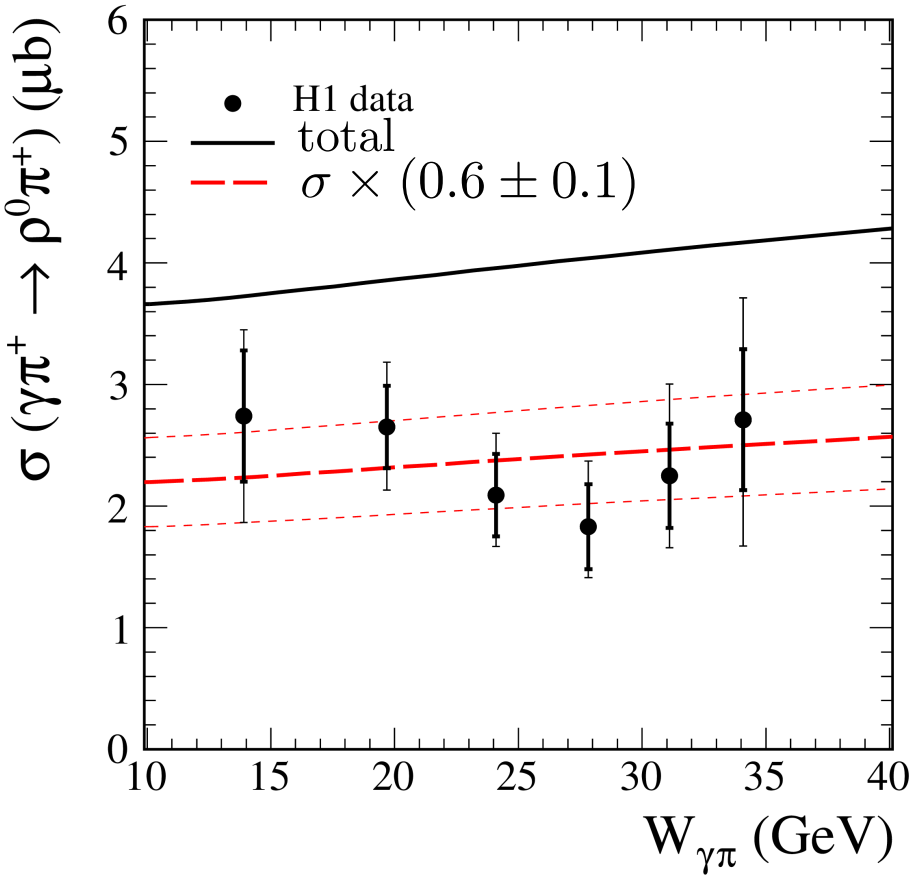
STAR preliminary data for small |t|: L.Adamczyk, W.Guryn, J.Turnau, Int.J.Mod.Phys. A29 no. 28, (2014) 1446010; for larger |t|: W. Guryn, Acta Phys. Polon. B47 (2016) 53

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

- 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



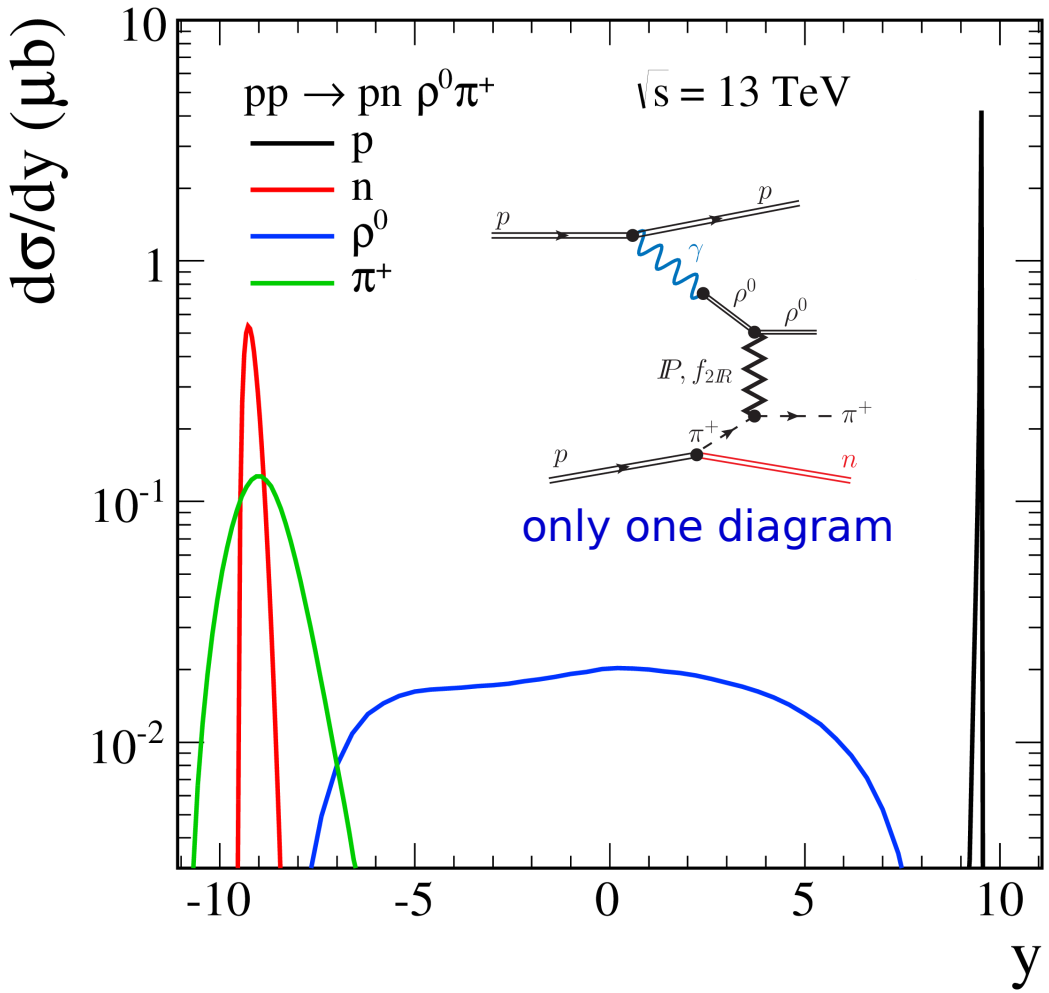


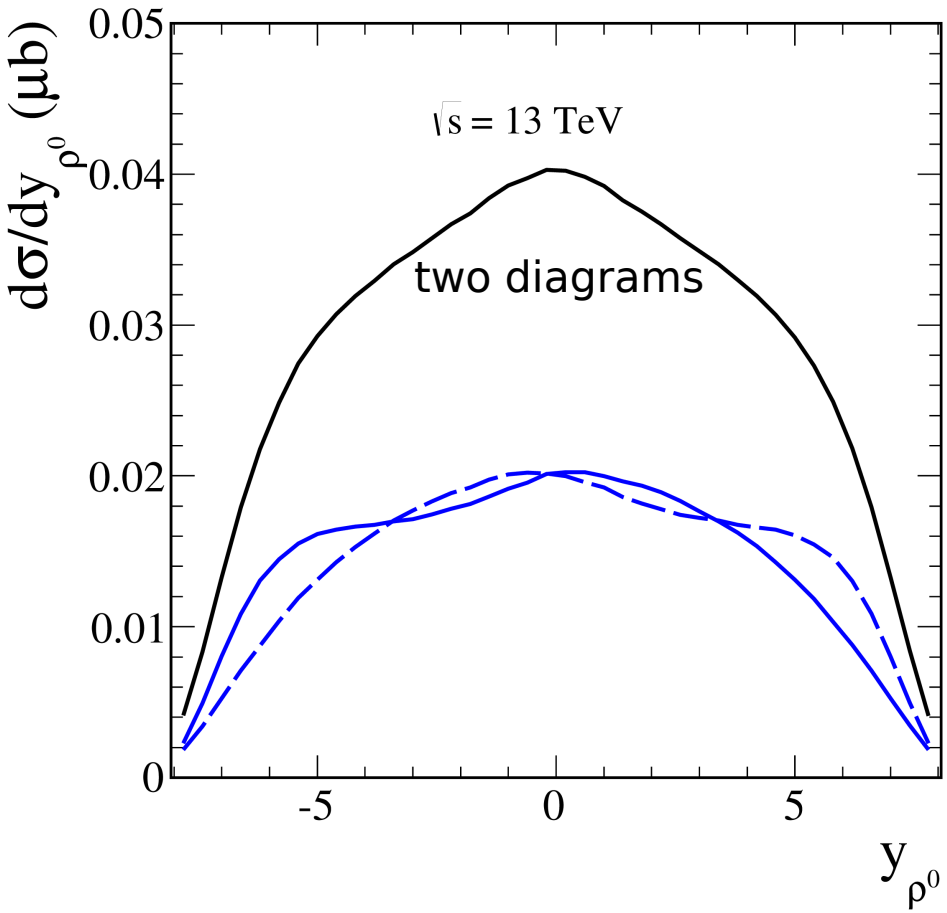
- From a measurement of $pp \to p\ \rho^0\ \pi N$ one would be able to extract the cross section, total and differential, for $\gamma\pi \to \rho^0\pi$.

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

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

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).

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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