Production of light mesons in central diffractive *pp* collisions

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Bound states in strongly coupled systems

The Galileo Galilei Institute for Theoretical Physics
Florence, Italy, 12-16 March, 2018

Plan

1) Introduction – Central Exclusive Production (CEP) in *pp* collisions

2) Model for high-energy soft reactions – Tensor pomeron approach

3) Examples of reactions

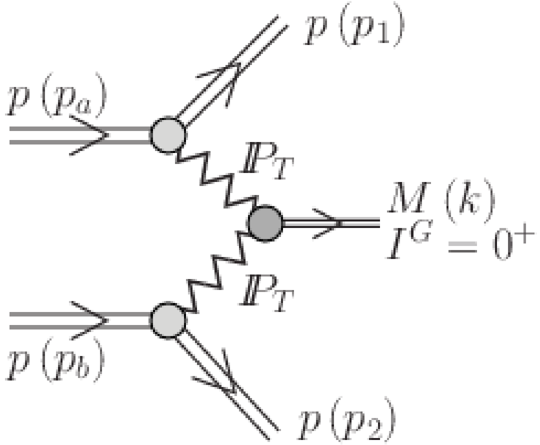
- $p\, p \to p\, p\, \pi^+ \pi^-$
    - diffractive mechanism – dipion continuum, scalar and tensor resonances
    - photoproduction mechanism – ρ^0 and non-resonant (Drell-Söding) contributions
- $p\, p \to p\, p\, K^+ K^-$
- $p\, p \to p\, p\, p\, \bar{p}$
- $p\, p \to p\, p\, \pi^+ \pi^- \pi^+ \pi^-$ (see appendix)

4) Conclusions

Central production of light mesons

- As predicted by Regge theory the diffractive cross section at high energy is dominated by double pomeron exchange (DPE)
- QCD image of pomeron implies that DPE is a gluon-rich process

  → gluonic bound states (glueballs) could be preferentially produced



J^{PC}	mesons
0^{-+}	η , $\eta'(958)$
0^{++}	$f_0(500)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$
1^{++}	$f_1(1285)$, $f_1(1420)$
2^{++}	$f_2(1270)$, $f_2'(1525)$, $f_2(1950)$
4^{++}	$f_4(2050)$

glueballs

- Such processes were studied extensively at CERN starting from the ISR experiments (AFS and ABCDHW groups), later at SPS by the WA76 and WA102 collaborations, and more recently by the COMPASS collaboration. The measurement of two charged pions in $p\bar{p}$ collisions was performed by the CDF collaboration at Tevatron.

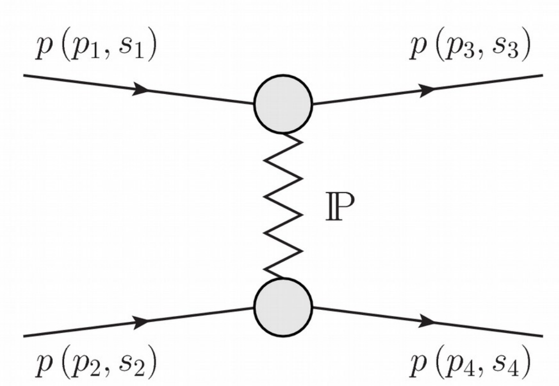
  Exclusive reactions are of particular interest since they can be studied in current experiments at the LHC by the ALICE, ATLAS+ALFA, CMS+TOTEM, and LHCb collaborations, as well as by the STAR collaboration at RHIC.

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, Annals Phys. 342 (2014) 31
The soft pomeron is described as <u>the effective exchange of a symmetric rank-two tensor object</u>, the tensor pomeron.



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

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

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

$$\beta_{I\!P NN} = 1.87\ \mathrm{GeV}^{-1}$$

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

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

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

Comparison with experiment

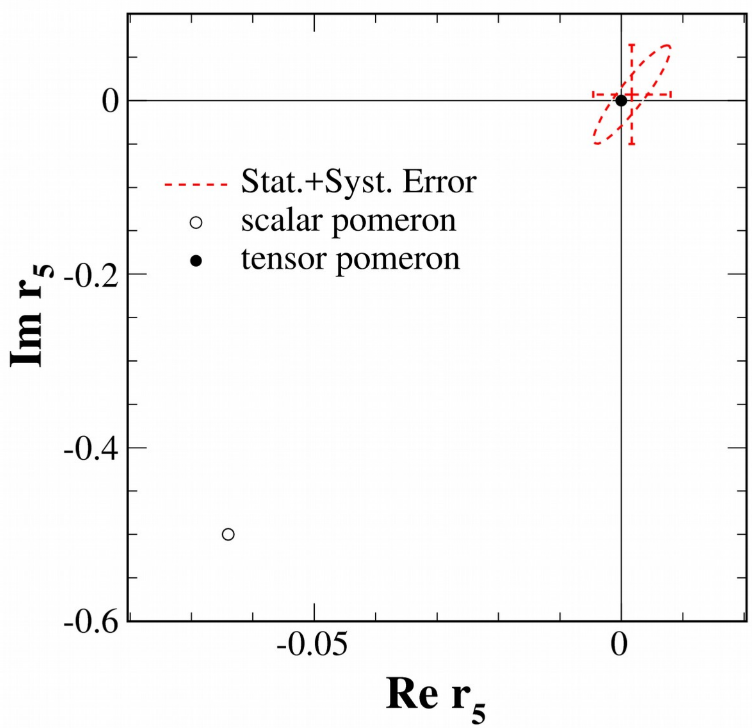
C. Ewerz, P. L., O. Nachtmann, A. Szczurek, *Helicity in proton-proton elastic scattering and the spin structure of the pomeron,* Phys. Lett. B763 (2016) 382

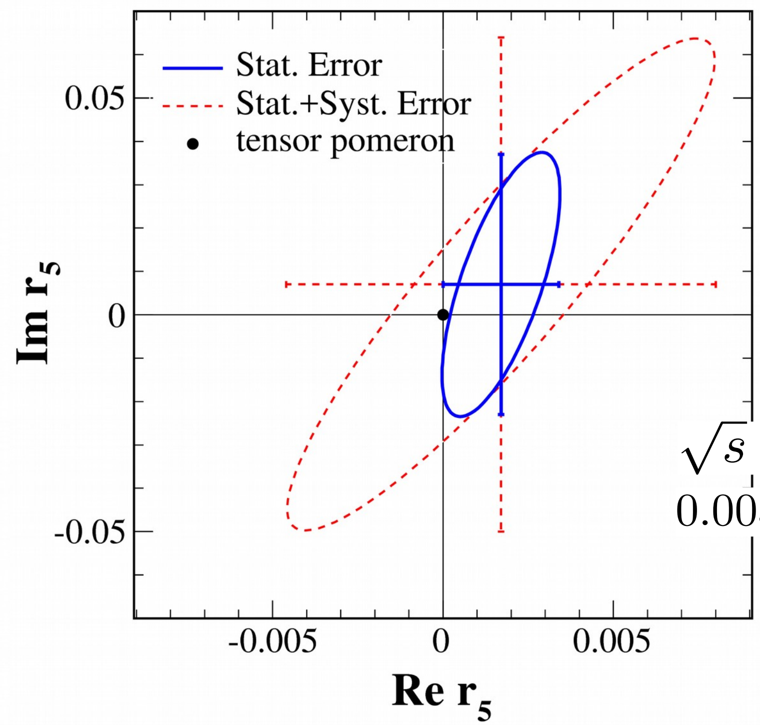
- Vector exchange has C = -1. It follows $\sigma_{tot}^{pp} = -\,\sigma_{tot}^{\bar{p}p}$

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



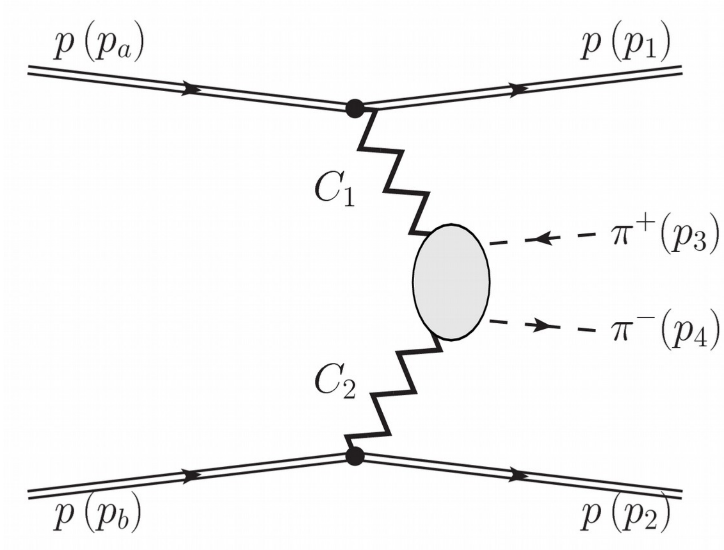


$\sqrt{s} = 200$ GeV

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

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

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



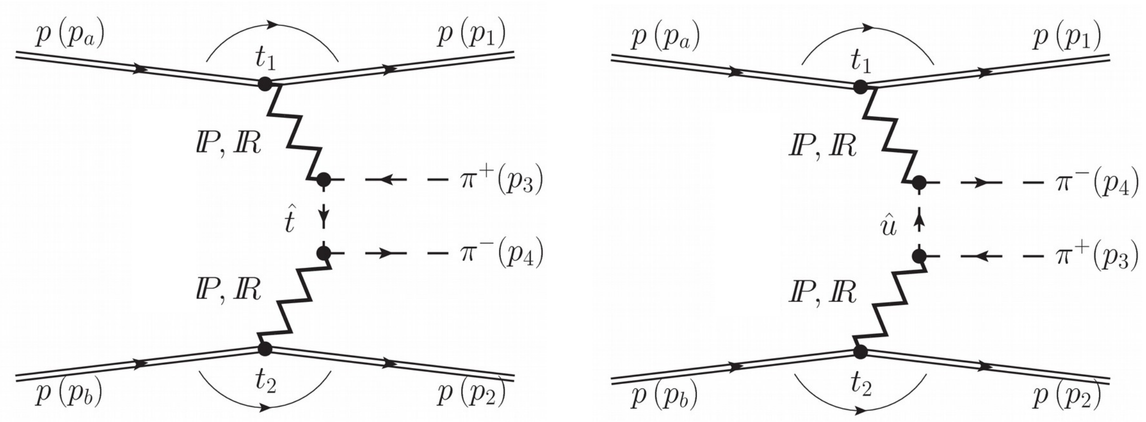
Exchange object	C	G
$I\!P$	1	1
$f_{2I\!R}$	1	1
$a_{2I\!R}$	1	-1
γ	-1	
$\mathbb{O}$	-1	-1
$\omega_{I\!R}$	-1	-1
$\rho_{I\!R}$	-1	1

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

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

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

Diffractive dipion continuum production



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

$$\mathcal{M}^{(I\!PI\!P\to\pi^+\pi^-)} = \mathcal{M}^{(\hat{\mathrm{t}})} + \mathcal{M}^{(\hat{\mathrm{u}})}$$

in terms of effective tensor pomeron propagator, *IPpp* and *IPππ* vertices

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

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

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

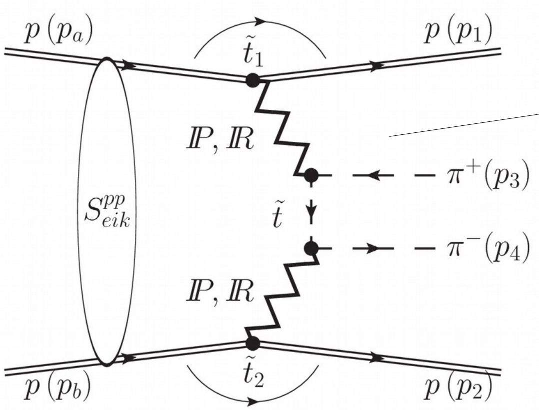
off-shell effects of intermediate pions

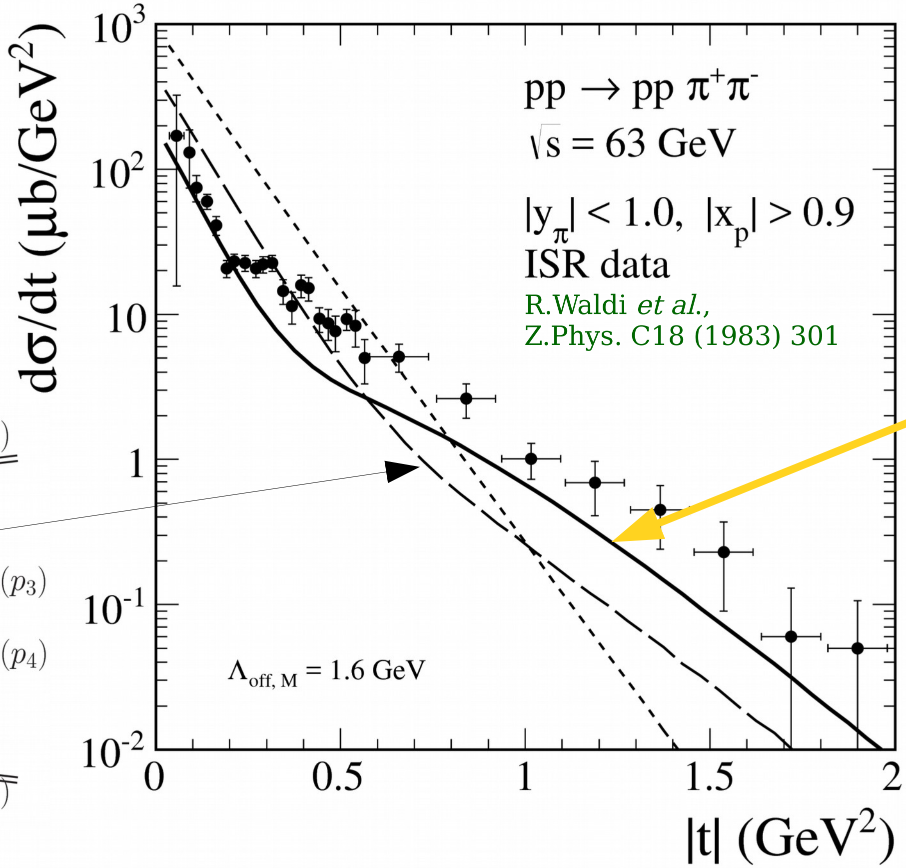
$$\mathrm{F}_\pi(\hat{t}) = \exp\left(\frac{\hat{t}-m_\pi^2}{\Lambda^2_{off,E}}\right), \qquad \mathrm{F}_\pi(\hat{t}) = \frac{\Lambda^2_{off,M}-m_\pi^2}{\Lambda^2_{off,M}-\hat{t}}; \qquad \mathrm{F}_\pi(m_\pi^2) = 1$$

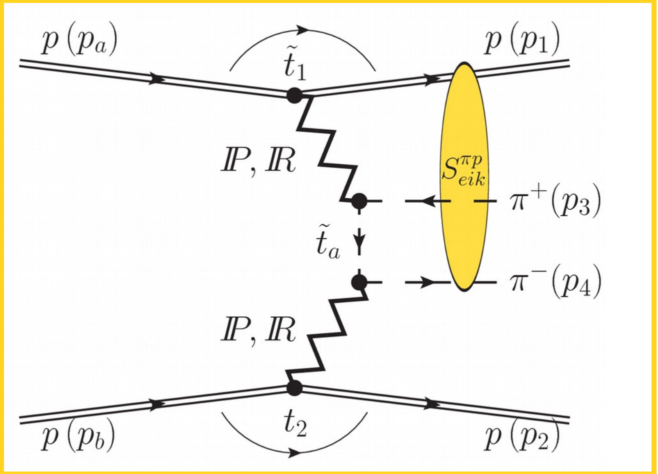
Absorption corrections

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

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







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

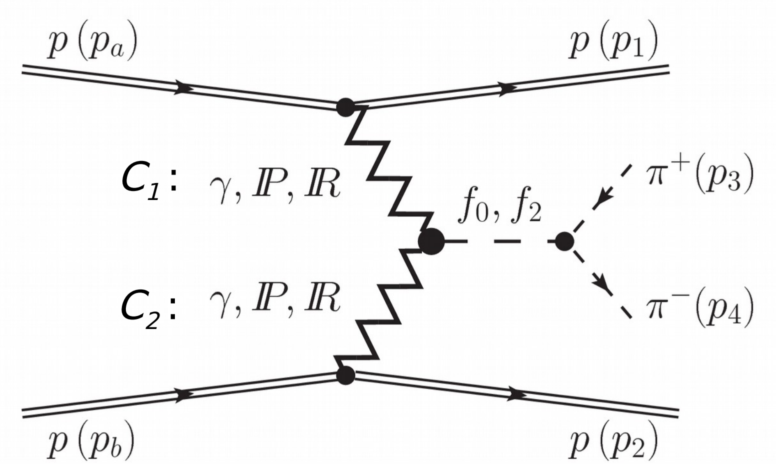
Such effect is quantified by gap survival probability factor < S²>
(ratio of absorbed-to-Born cross section)

$< S^2 > \simeq 0.1 - 0.2$ for diffractive processes at LHC
$< S^2 > \simeq 0.8 - 0.9$ for photoproduction at LHC

Absorption effects can be included effectively: $\frac{d\sigma^{absorbed}}{dM_{\pi\pi}} = \frac{d\sigma^{Born}}{dM_{\pi\pi}} \times < S^2 >$

Dipion resonant production

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



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^{++}, $f_4(2050)$	$(I\!P + f_{2I\!R}, I\!P + f_{2I\!R})$, $(a_{2I\!R}, a_{2I\!R})$, $(\mathbb{O} + \omega_{I\!R} + \gamma, \mathbb{O} + \omega_{I\!R} + \gamma)$, $(\rho_{I\!R}, \rho_{I\!R})$, $(\gamma, \rho_{I\!R})$, $(\rho_{I\!R}, \gamma)$

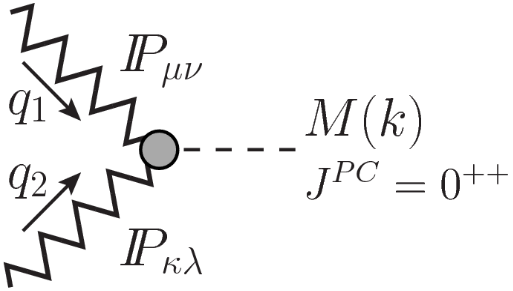
IP IP M couplings

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 “real tensor pomerons”.

For each value of l, S, J, and P we can construct a covariant Lagrangian density coupling L' 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.

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).



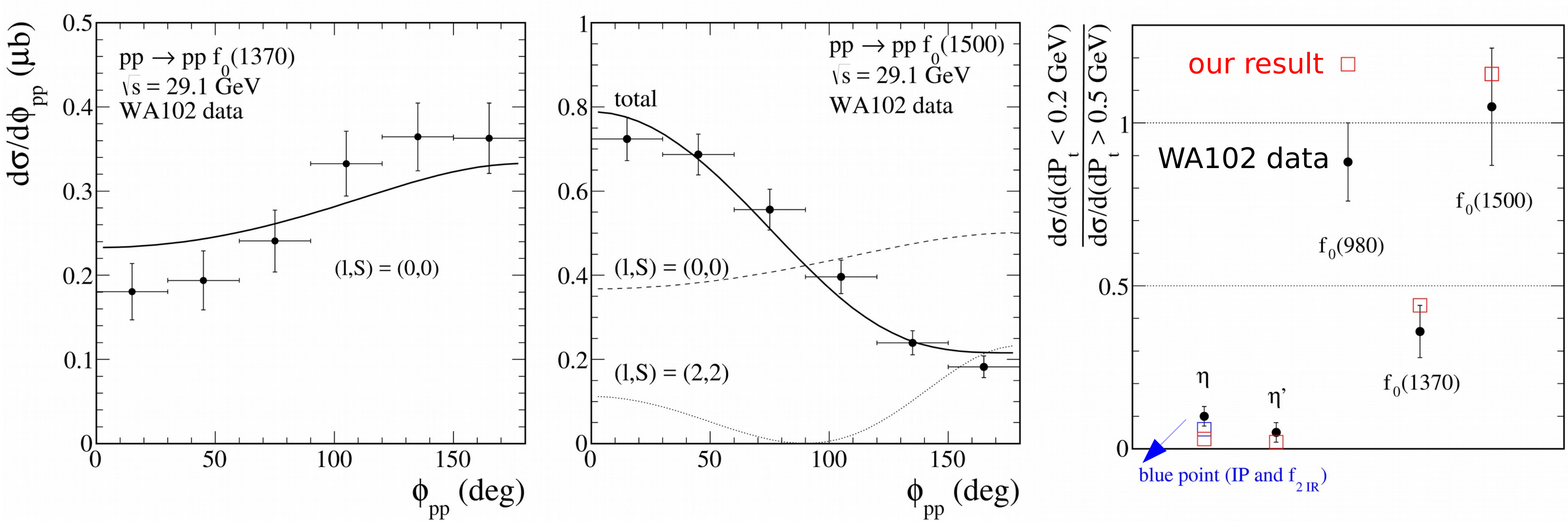
For a scalar mesons the “bare” tensorial *IP-IP-M* vertices corresponding to (l,S) = (0,0) and (2,2) terms are

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	

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

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

Diffractive mechanism: scalar resonances



- 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

- There is an important qualitative difference in the ϕ_{pp} distribution:
  $f_0(1370)$ peaks as $\phi_{pp} \to \pi$
  $f_0(980)$, $f_0(1500)$, $f_0(1710)$ peak at $\phi_{pp} \to 0$ and both (l, S) contributions are necessary

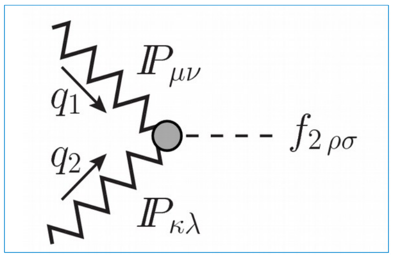
- $f_0(1500)$ and $f_0(1710)$ which could have a large 'gluonic component' have a large value of dPt ratio → 'glueballs' are produced predominantly at small dP_t

$$dP_t = |d\vec{P}_t| = |\vec{q}_{1t} - \vec{q}_{2t}| = |\vec{p}_{2t} - \vec{p}_{1t}|$$ ("glueball filter variable" proposed by F. Close)

Diffractive mechanism: tensor resonances

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

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



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

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

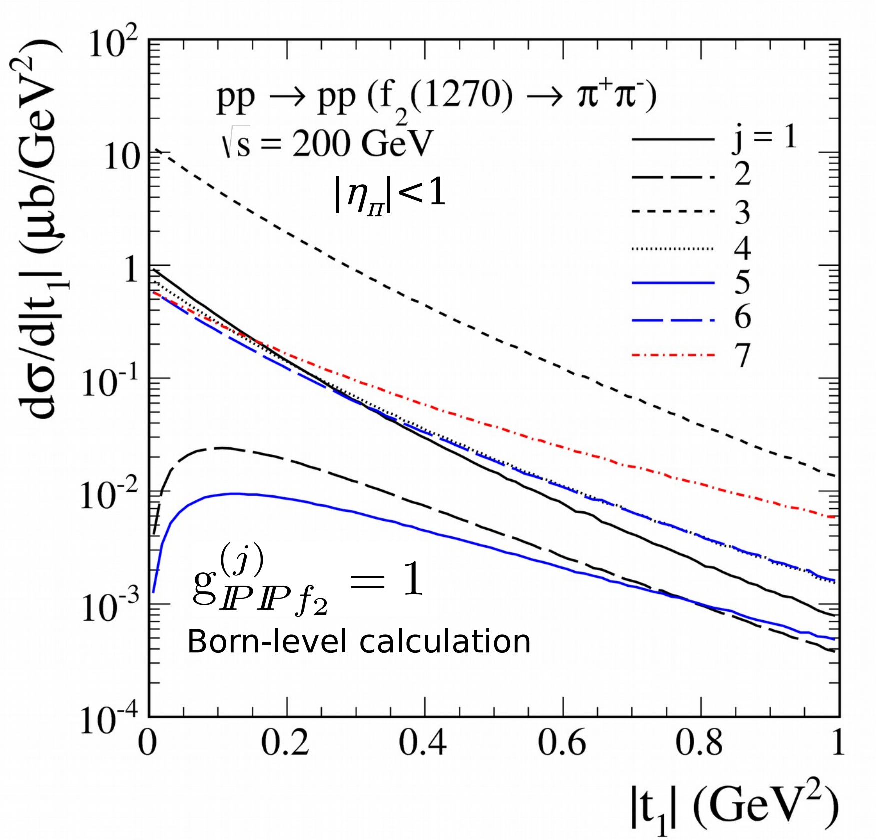
$$i\Delta^{(f_2)}_{\mu\nu,\kappa\lambda}(p_{34}) = \frac{i}{p_{34}^2 - m_{f_2}^2 + i m_{f_2}\Gamma_{f_2}} \left[\frac{1}{2}(\hat{g}_{\mu\kappa}\hat{g}_{\nu\lambda} + \hat{g}_{\mu\lambda}\hat{g}_{\nu\kappa}) - \frac{1}{3}\hat{g}_{\mu\nu}\hat{g}_{\kappa\lambda} \right],$$

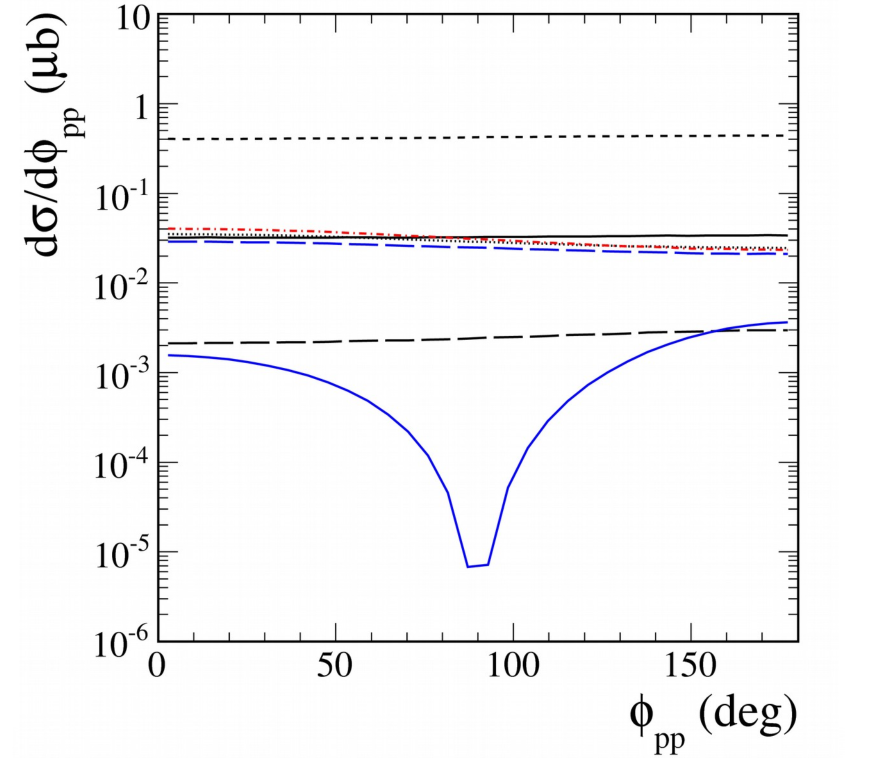
where $\hat{g}_{\mu\nu} = -g_{\mu\nu} + p_{34\mu}p_{34\nu}/p_{34}^2$ and $\Delta^{(f_2)}_{\nu\mu,\kappa\lambda}(p_{34}) = \Delta^{(f_2)}_{\mu\nu,\lambda\kappa}(p_{34}) = \Delta^{(f_2)}_{\kappa\lambda,\mu\nu}(p_{34})$,

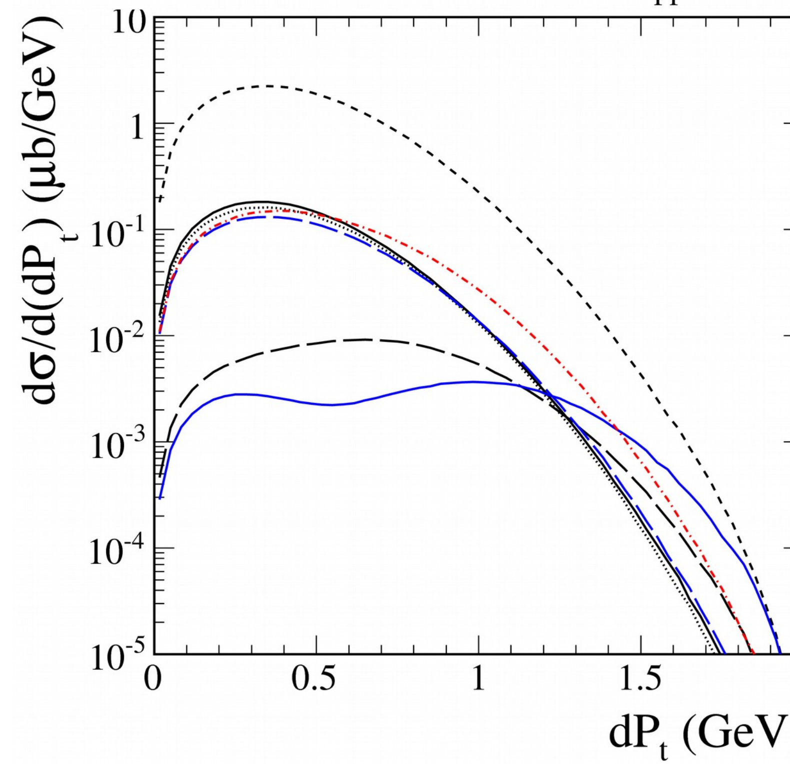
$$g^{\mu\nu}\Delta^{(f_2)}_{\mu\nu,\kappa\lambda}(p_{34}) = 0,\; g^{\kappa\lambda}\Delta^{(f_2)}_{\mu\nu,\kappa\lambda}(p_{34}) = 0.$$

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

$f_2(1270)$ resonance





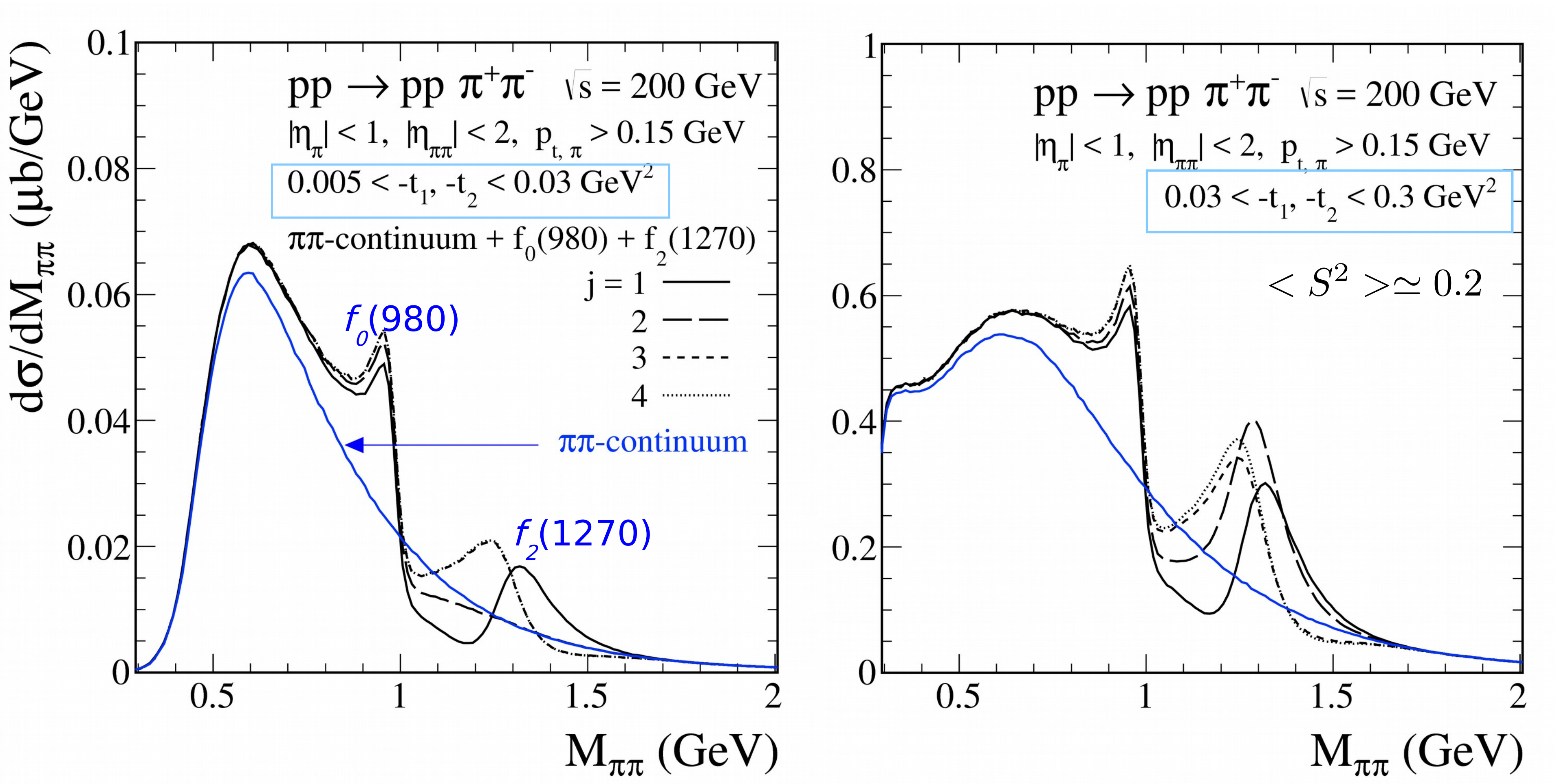


j = 2 coupling is in agreement with experimental observations (WA102, COMPASS, ISR)

→ $f_2(1270)$ peaks at $\phi_{pp} \sim 180^o$ and is most prominently observed at large $|t|$

→ suppressed as $dP_t \to 0$ (undisputed $q\bar{q}$ state)

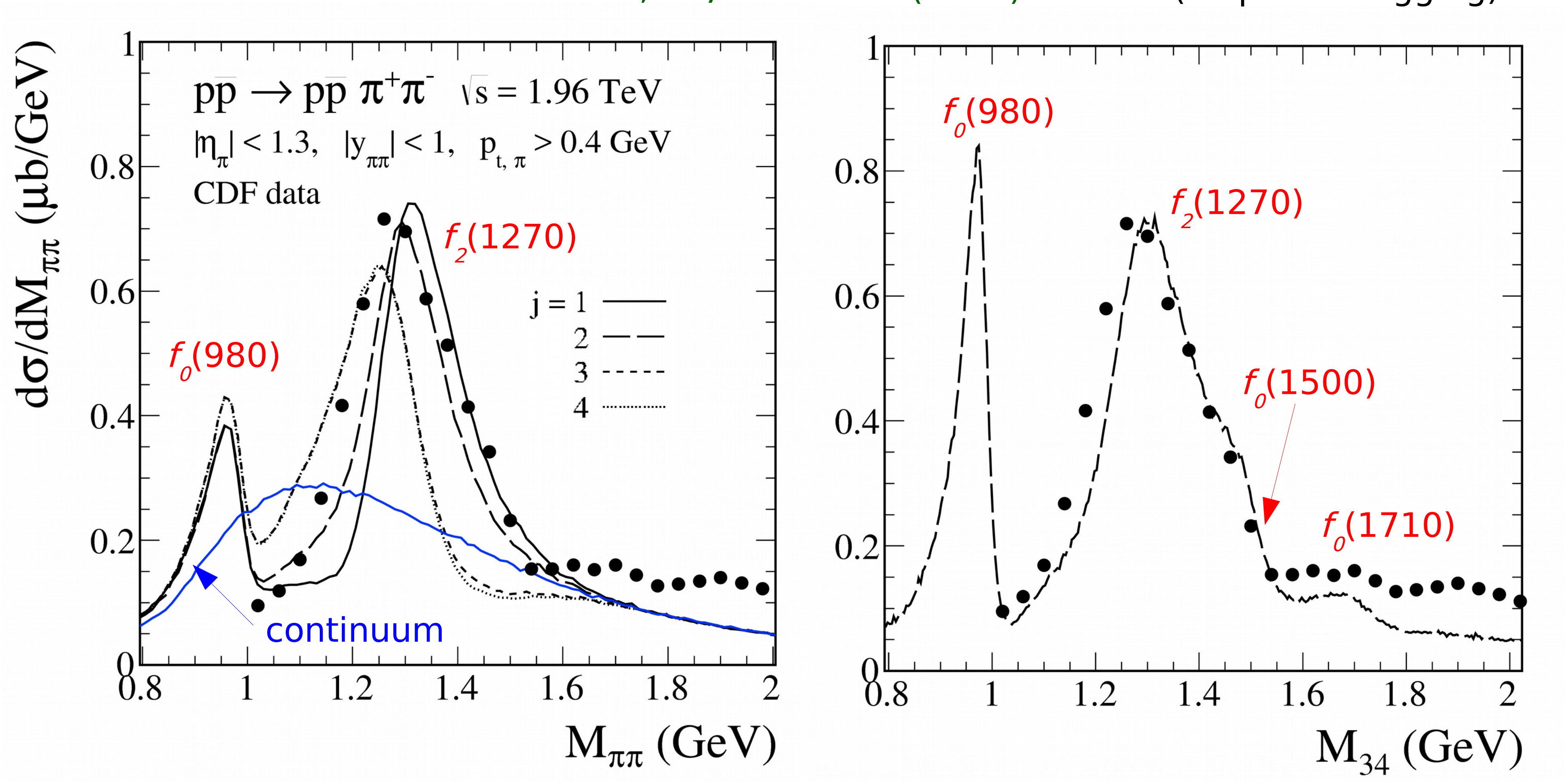
Diffractive mechanism: tensor resonance



- Interesting interference of $f_0(980)$ and two-pion continuum
- Different *IP IP* f_2 - couplings generate different interference pattern
- The relative contribution of the resonant $f_2(1270)$ and continuum strongly depends on the cut on $|t|$ → this may explain some observation made by the ISR collaborations

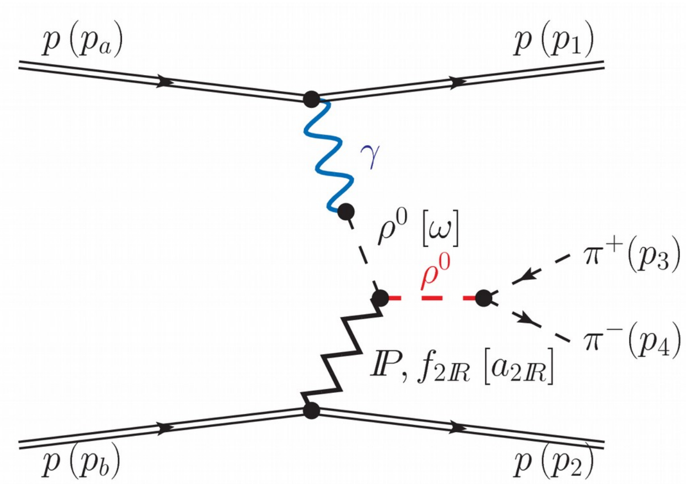
Comparison with CDF data

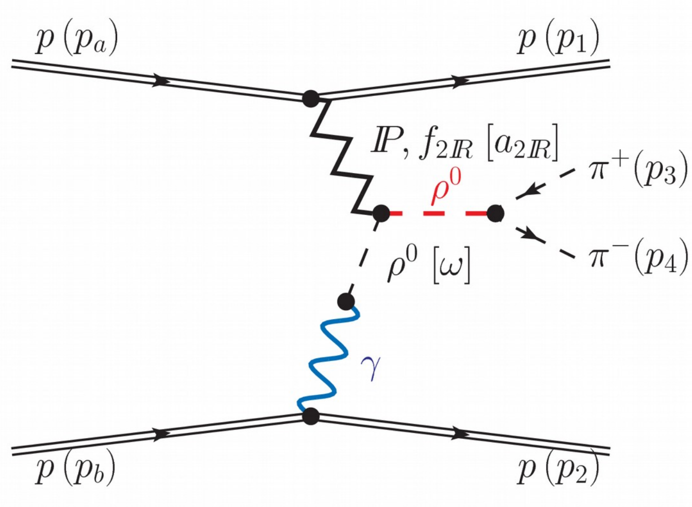
CDF data: T. A. Aaltonen et al., Phys.Rev. D91 (2015) 091101 (no proton tagging)



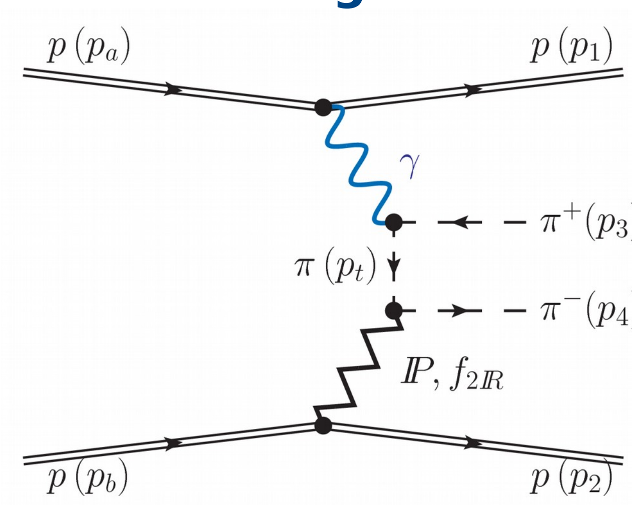
- The visible structure attributed to f_0 and $f_2(1270)$ mesons which interfere with the continuum
- We take the monopole form for off-shell pion form factors with $\Lambda_{\mathrm{off},M}$ = 0.7 GeV.
- Absorption effects were included: $\frac{d\sigma}{dM_{\pi\pi}} = \frac{d\sigma^{Born}}{dM_{\pi\pi}} \times < S^2 >, \qquad < S^2 >= 0.1$

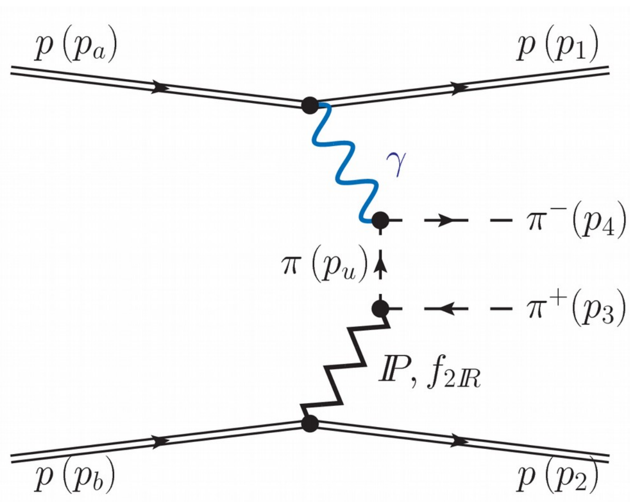
Diffractive photoproduction of $\pi^+\pi^-$ pairs

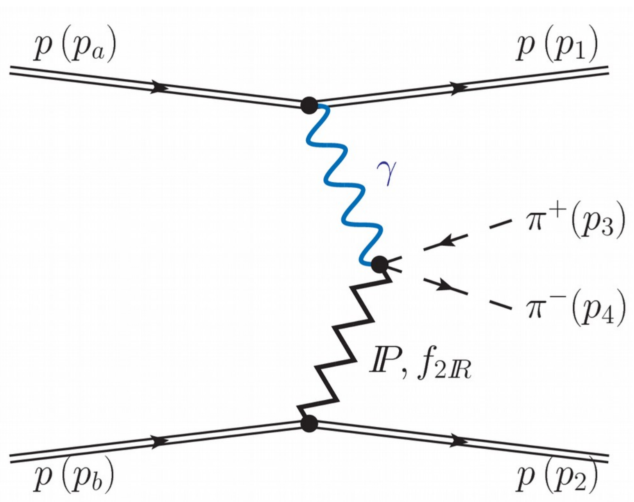




Drell-Söding mechanism

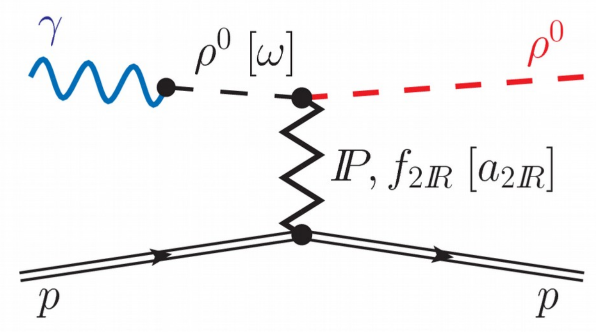






There are also 3 additional diagrams (*IP* γ – fusion)

Photoproduction of ρ^0 meson

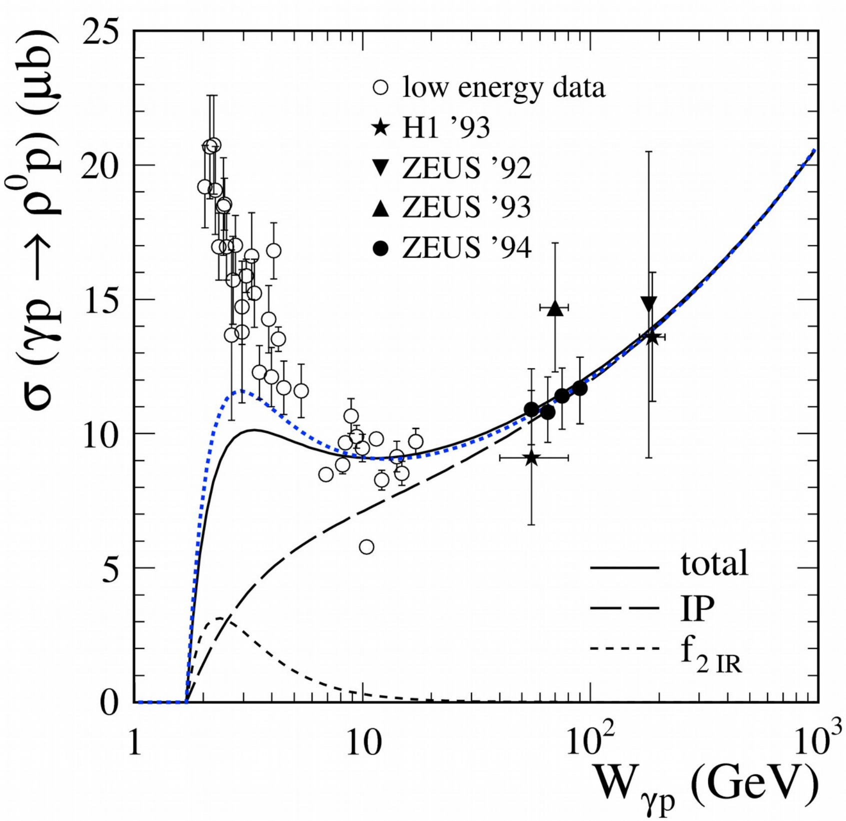


$$\mathcal{M}_{\lambda_\gamma \lambda_b \to \lambda_\rho \lambda_2}(s,t) \cong \quad ie\frac{m_\rho^2}{\gamma_\rho}\Delta_T^{(\rho)}(0)\,(\epsilon^{(\rho)\,\mu})^*\epsilon^{(\gamma)\,\nu} V_{\mu\nu\kappa\lambda}(s,t,q,p_\rho)$$
$$\times 2(p_2+p_b)^\kappa (p_2+p_b)^\lambda\, \delta_{\lambda_2\lambda_b}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

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)

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

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

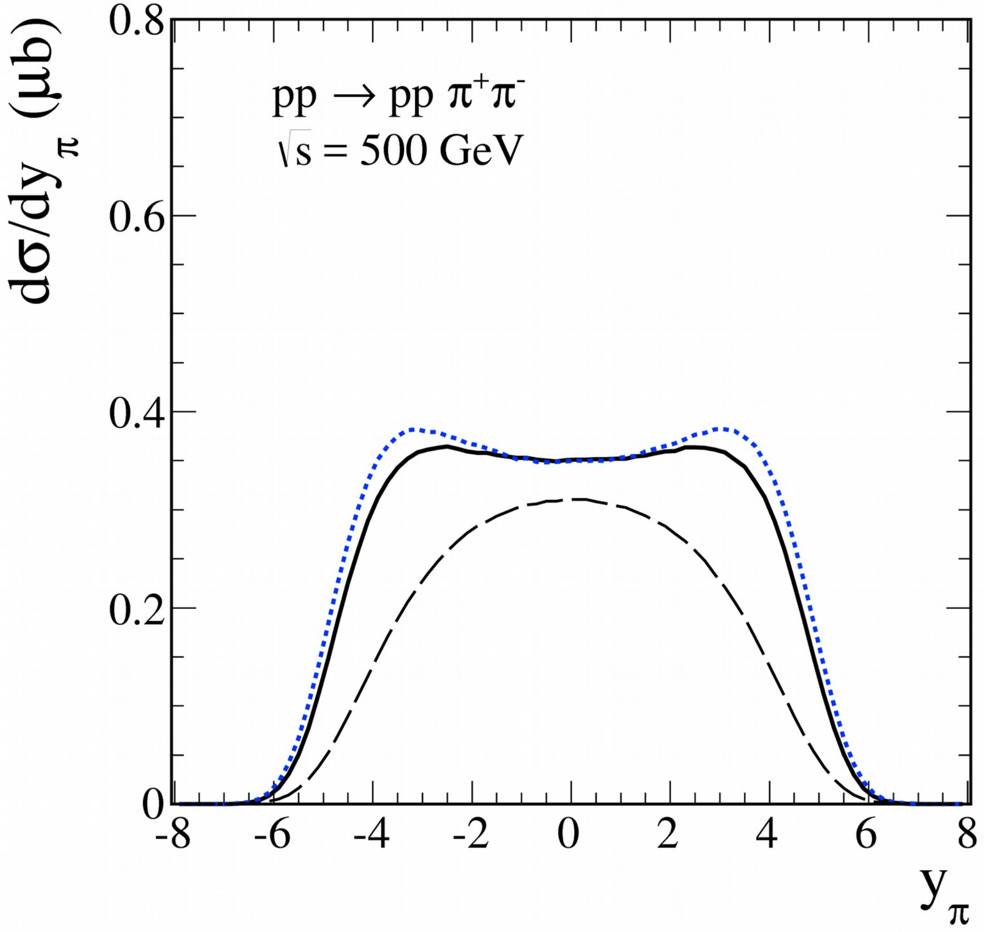
$$\sigma_{tot}(\rho^0(\lambda_\rho=\pm 1),p) = \tfrac{1}{2}\left[\sigma_{tot}(\pi^+,p)+\sigma_{tot}(\pi^-,p)\right]$$

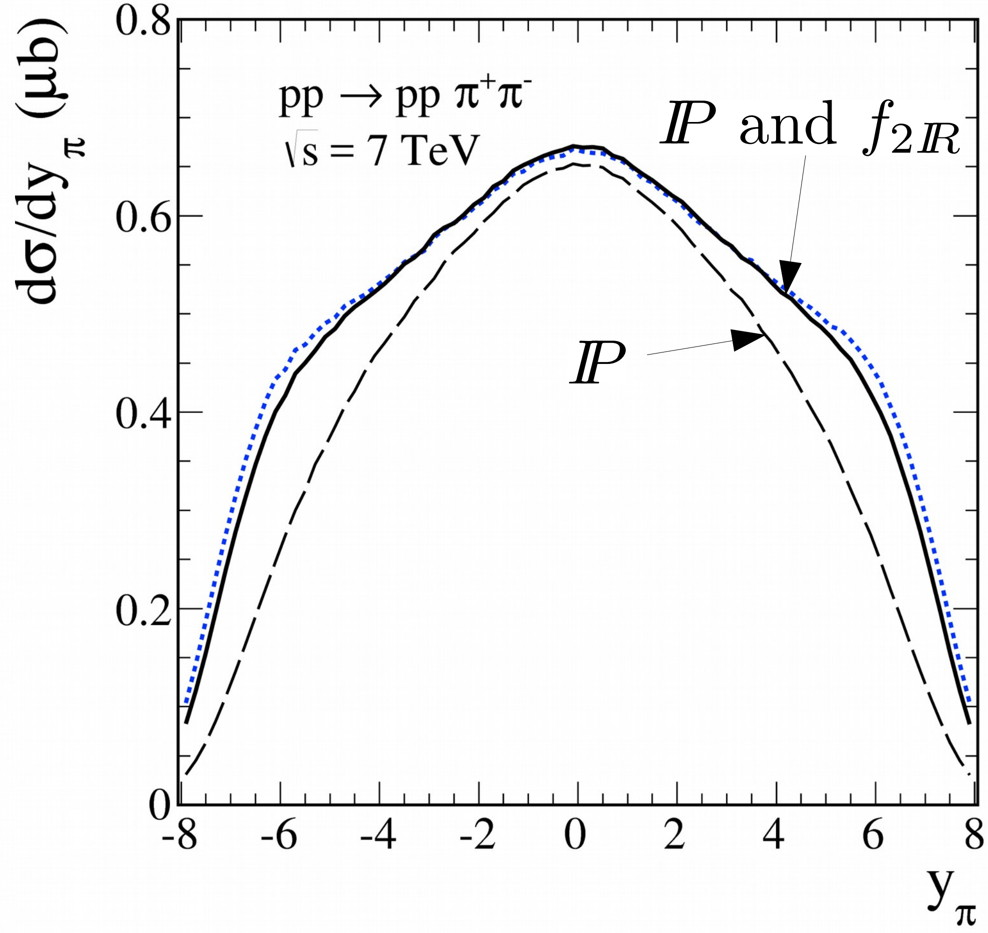
and are expected to approximately fulfill:

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

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

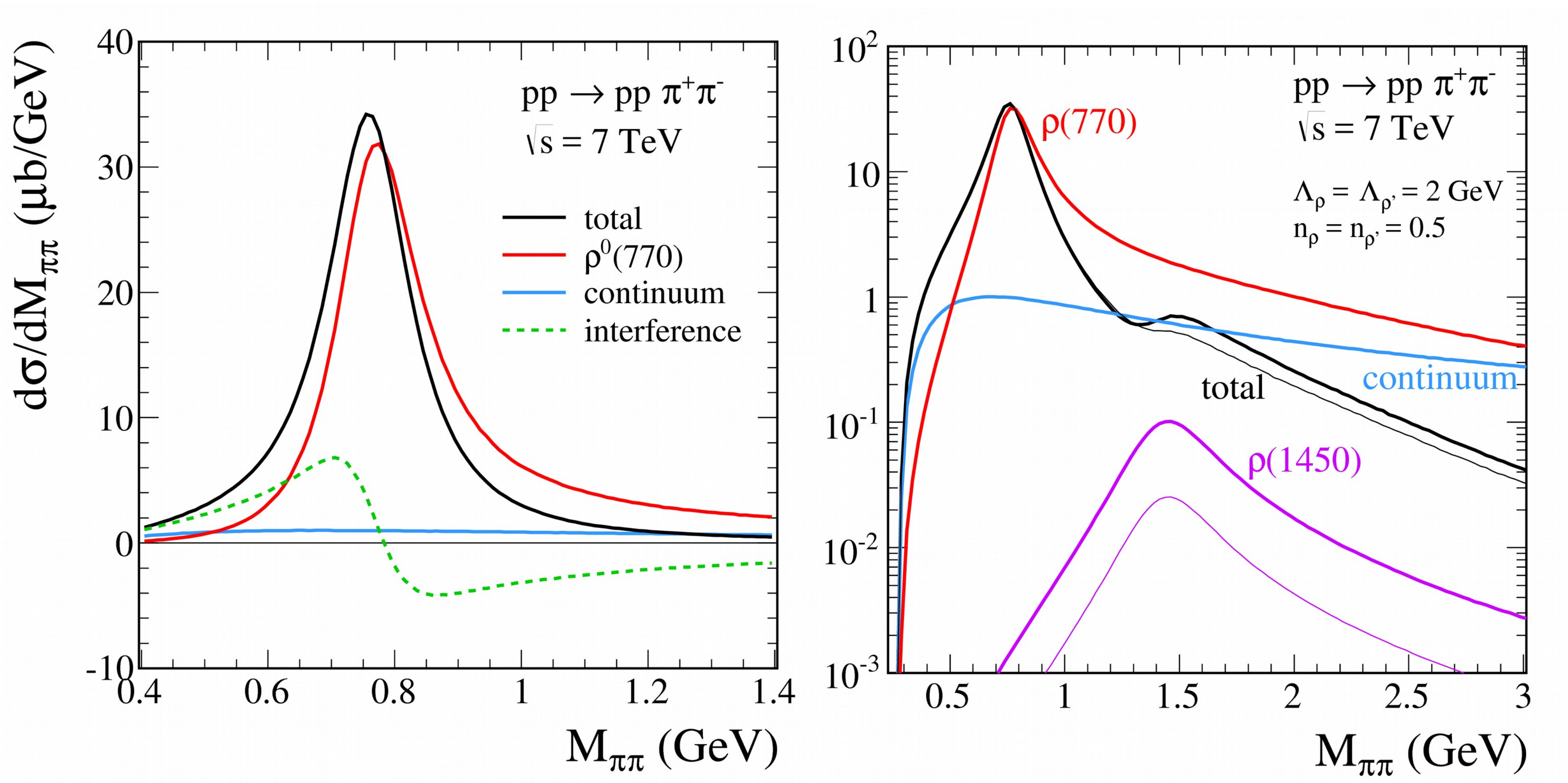
ρ^0 and $\pi^+\pi^-$ continuum





The f_2 - reggeon exchange included in the amplitude contributes mainly at backward and forward pion rapidities. Its contribution is non-negligible even at the LHC.

ρ^0 and $\pi^+\pi^-$ continuum



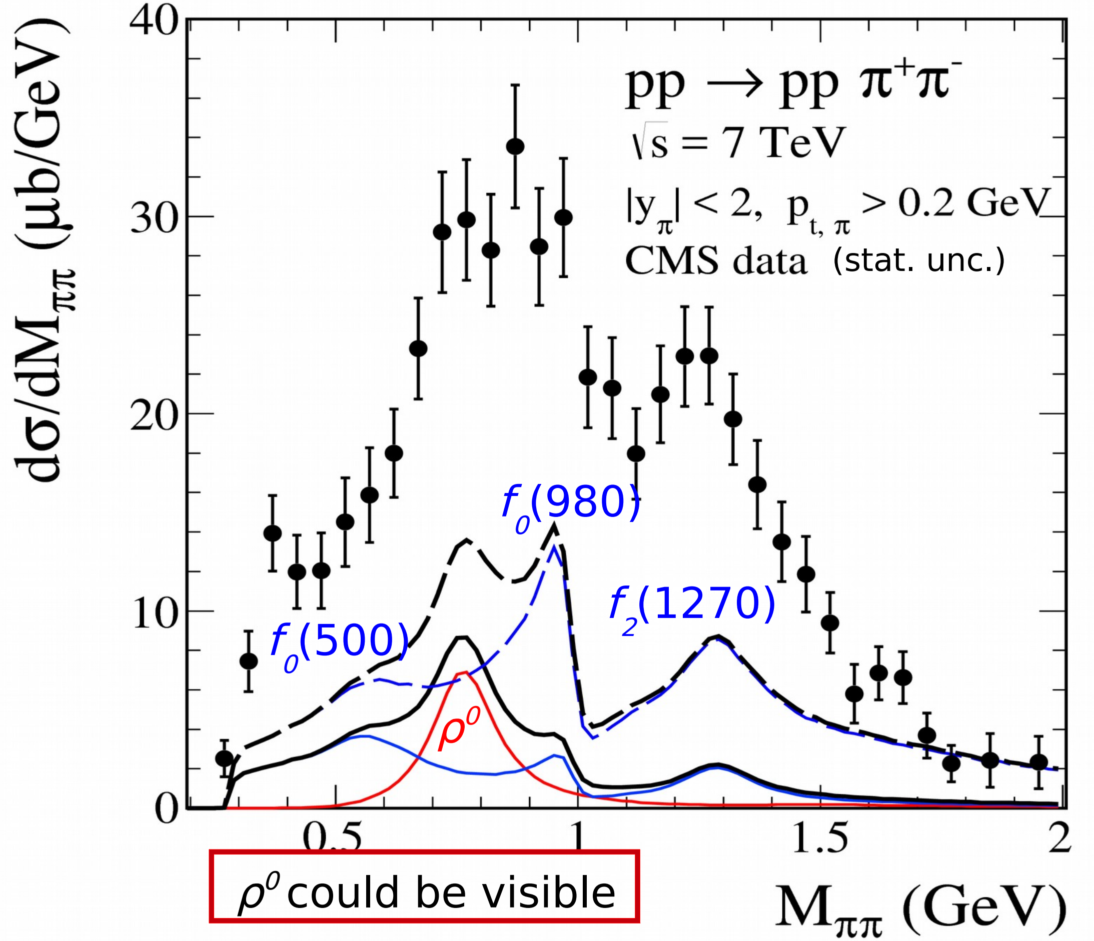
The non-resonant (Drell-Söding) contribution interferes with resonant ρ^0 contribution
→ skewing of ρ^0 line shape

The skewing effect was discussed in context of $\gamma p \to \pi^+ \pi^- p$ reaction, e.g. see

A. Szczurek and A. Szczepaniak, PRD 71 (2005) 054005

A. Bolz et al., JHEP 1501 (2015) 151 (within tensor-pomeron model)

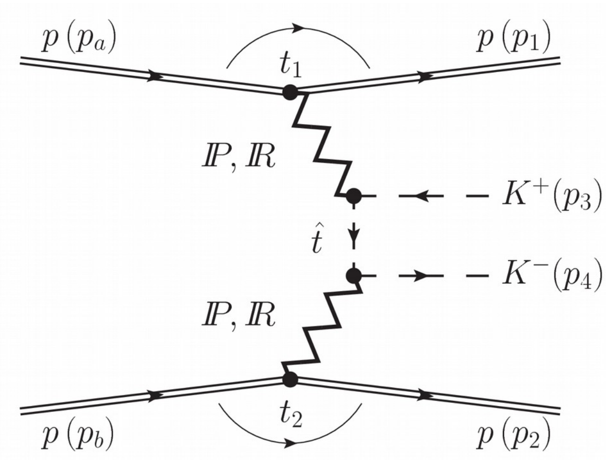
Comparison with CMS 'preliminary' data

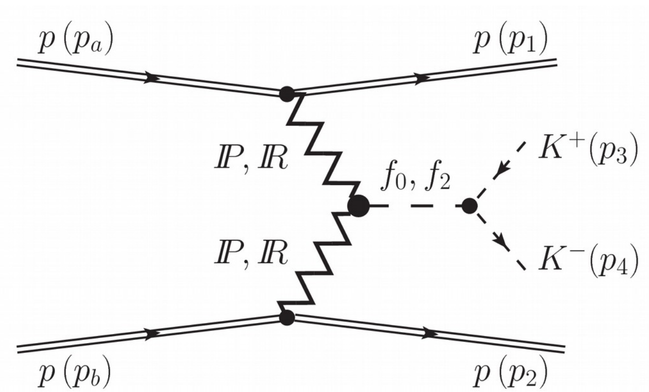


- Our model results (the same couplings as for CDF predictions, $< S^2 > = 0.1$) are much below the CMS data (CMS-FSQ-12-004) which could be due to contamination of non-exclusive processes (one or both protons undergoing dissociation).
- Purely exclusive data expected from STAR, CMS+TOTEM and ATLAS+ALFA should provide interesting information on the lightest glueballs and other mesons.

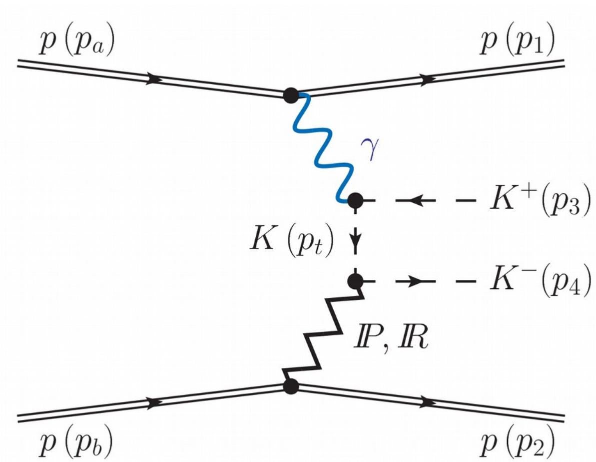
$pp \to pp\, K^+K^-$

Purely diffractive continuum and resonance mechanisms:

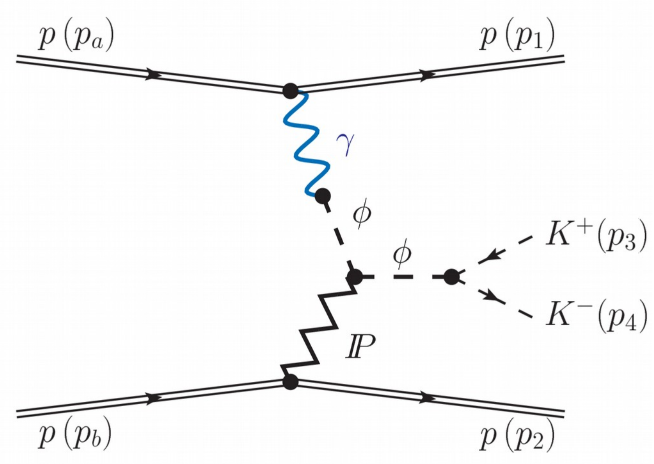




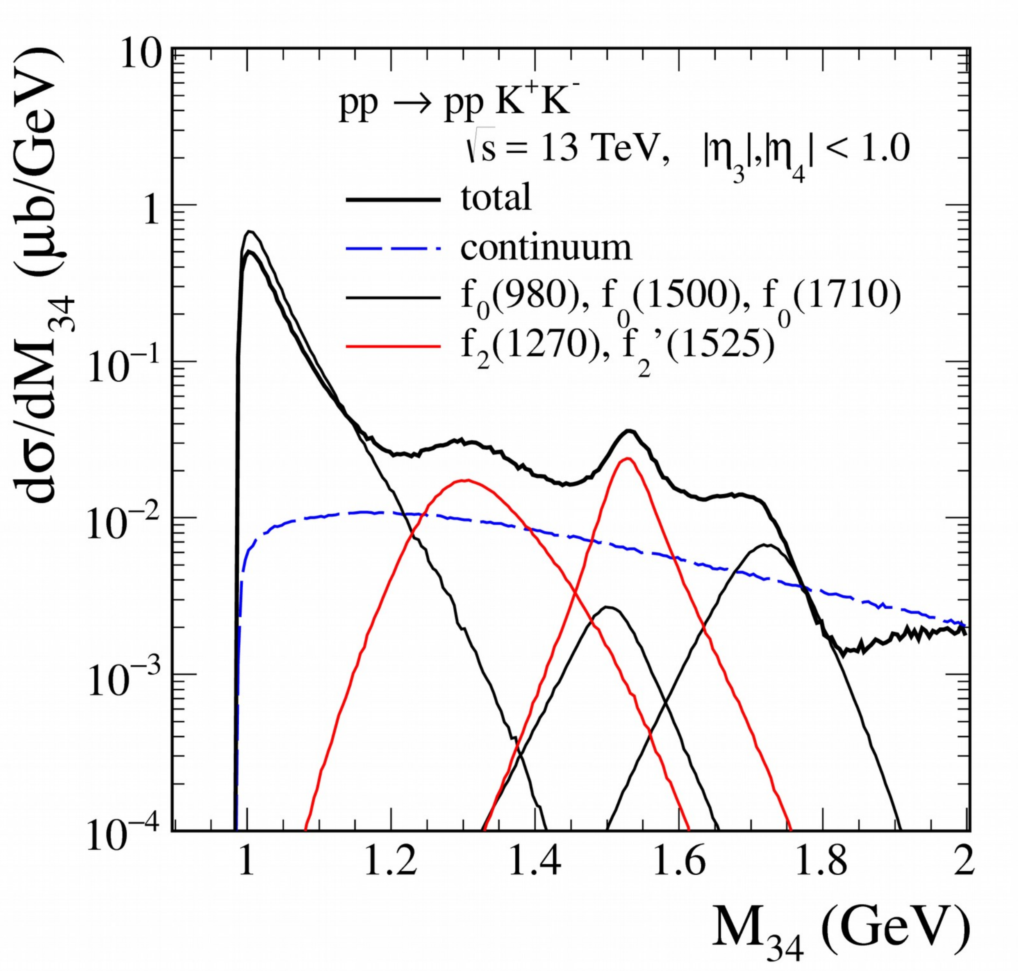
Diffractive photoproduction mechanisms:



(Drell-Söding mechanism)

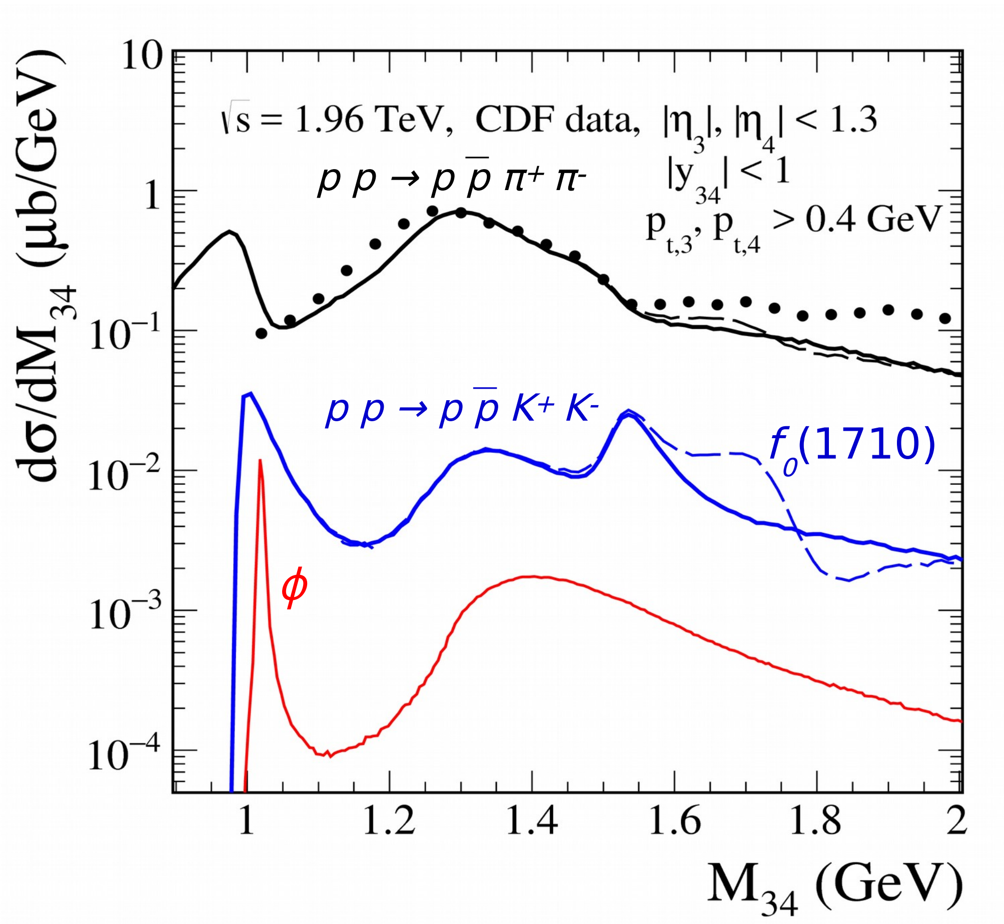


$pp \to pp\, K^+K^-$



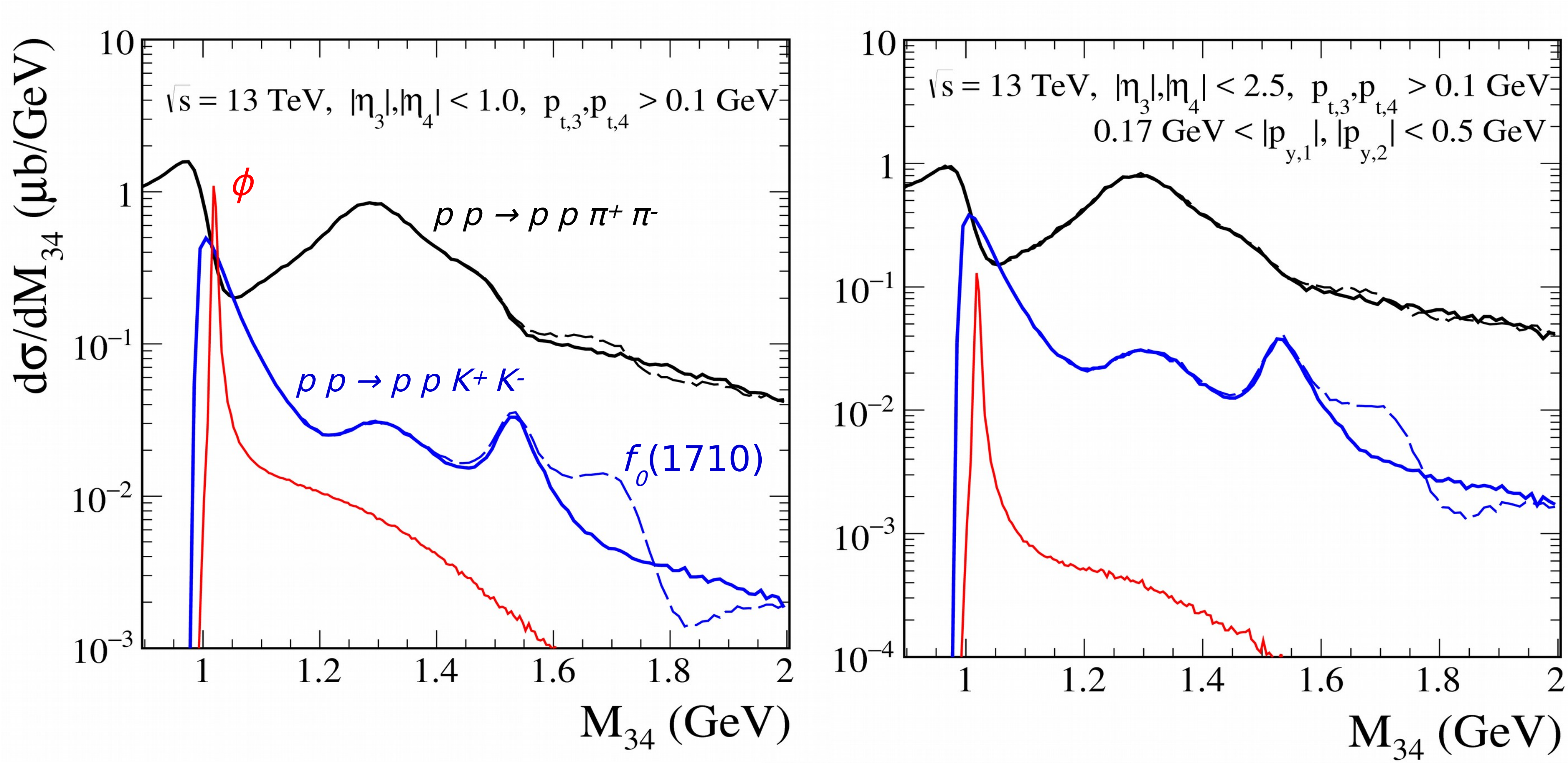
- Many resonances may participate.
- Parameters fixed by detailed knowledge of different reactions

$pp \to pp\, K^+K^-$



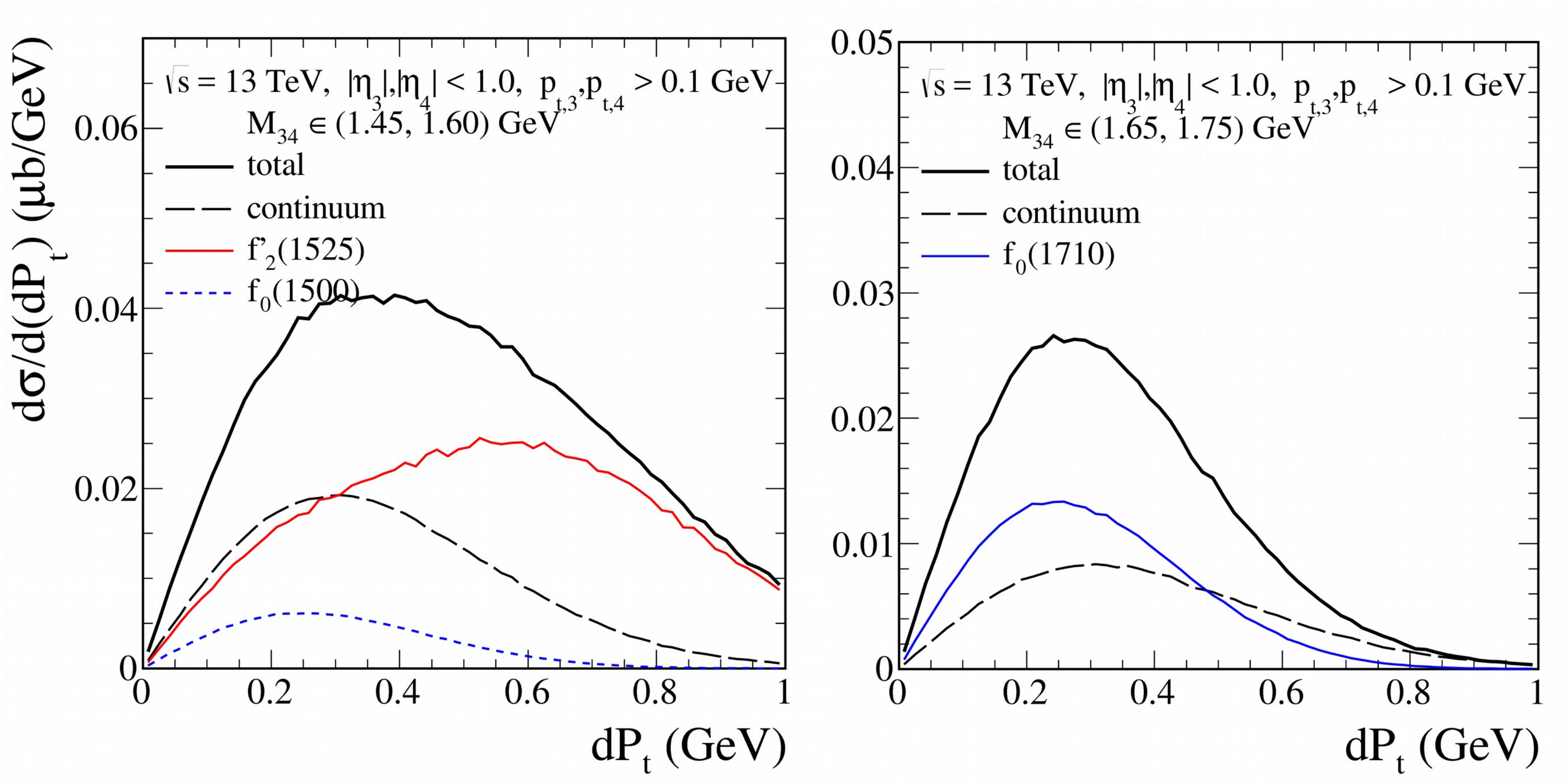
Limited CDF acceptance, in particular $p_t > 0.4$ GeV condition on centrally produced K^+ and K^- mesons, causes a reduction of cross section in low-mass region M_{KK} (clearly visible minimum for the photoproduction term).

$pp \to pp\, K^+K^-$



We expect that one could observe the ϕ resonance term, especially when no restrictions on the leading protons are included (ALICE, CMS, LHCb).

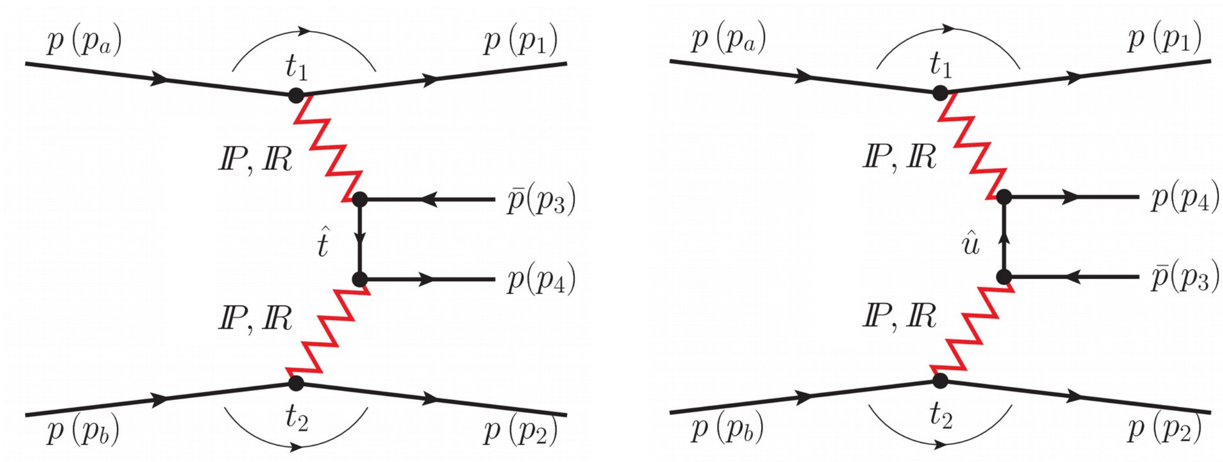
$pp \to pp\, K^+K^-$



- "Glueball filter variable" distributions in two K^+K^- invariant mass windows

  dPt → difference in the transverse momentum vectors between two exchange pomerons

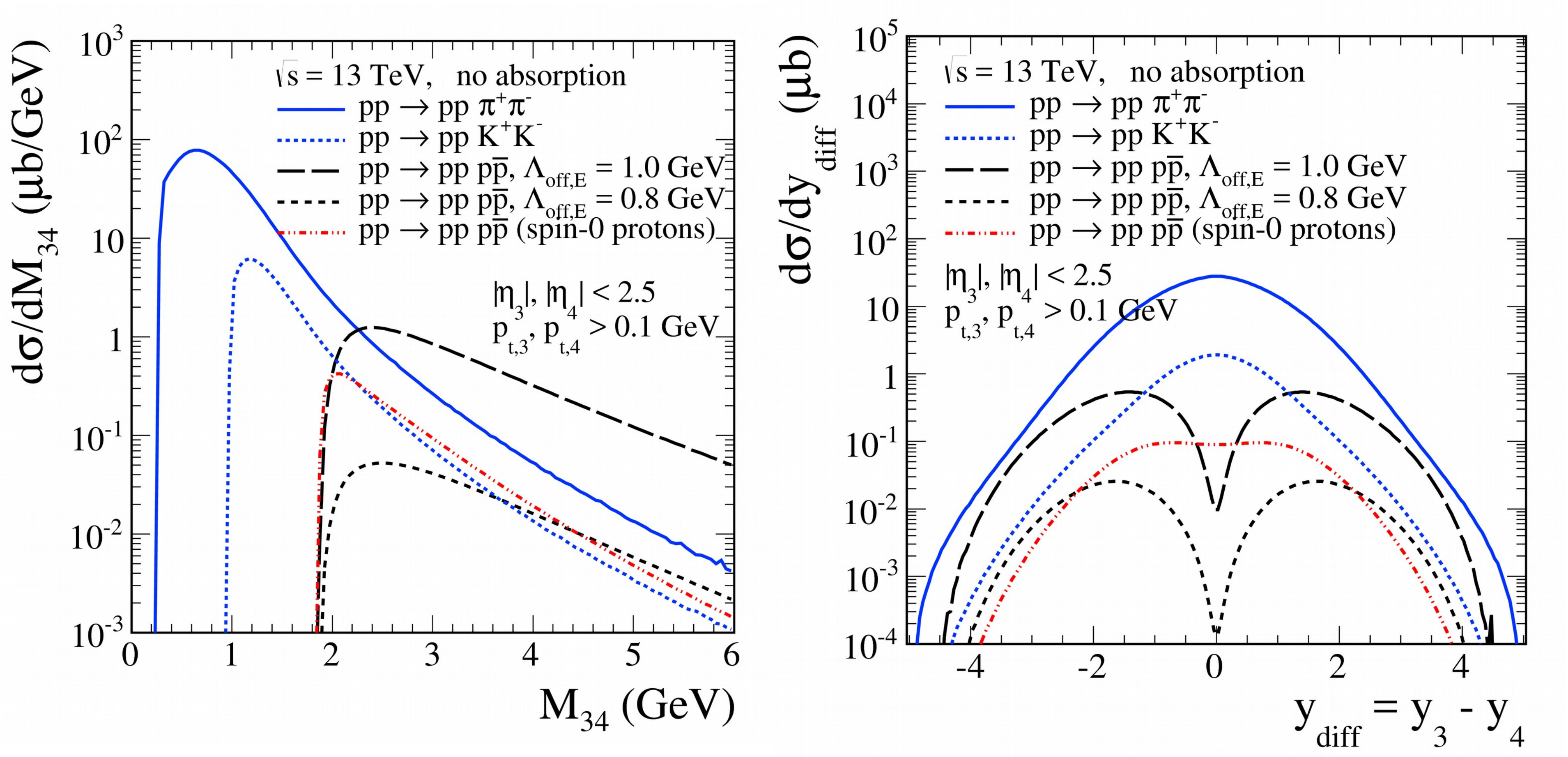
- We see that the maximum for the $q\bar{q}$ state $f'_2(1525)$ is around of dPt = 0.6 GeV.
  For the scalar glueball candidates $f_0(1500)$ and $f_0(1710)$ the maximum is around 0.25 GeV.



In high-energy approximation we can write $I\!P I\!P$-exchange amplitude as

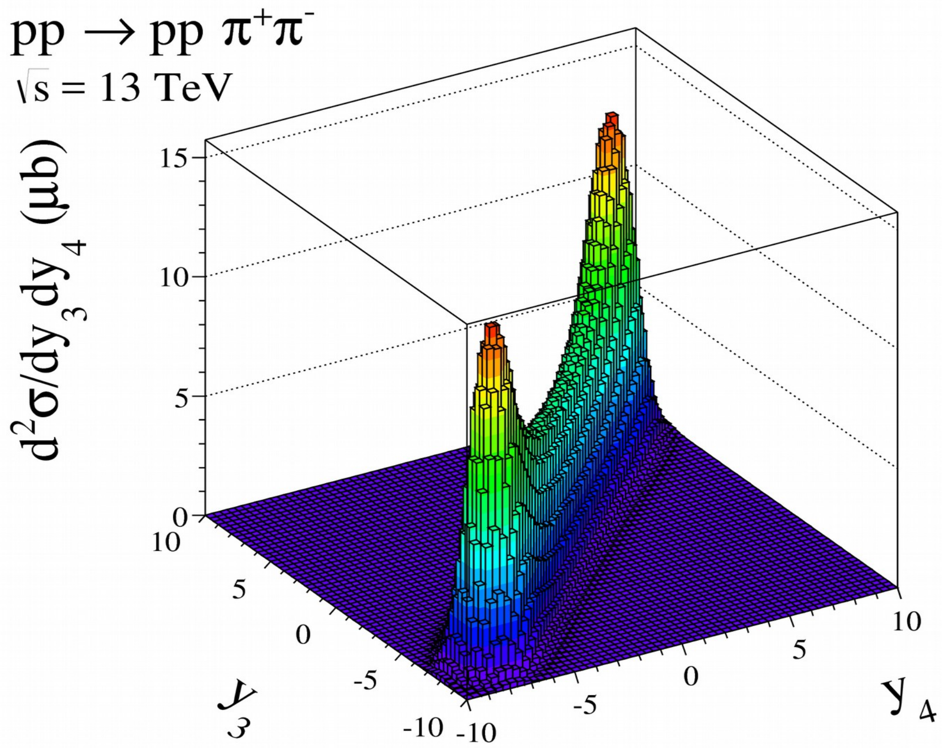
$$
\begin{aligned}
\mathcal{M}^{(I\!P I\!P \to p\bar{p})}_{\lambda_a \lambda_b \to \lambda_1 \lambda_2 \lambda_3 \lambda_4} \simeq\; & (3\beta_{I\!P NN})^2\, 2(p_1 + p_a)_{\mu_1} (p_1 + p_a)_{\nu_1}\, \delta_{\lambda_1 \lambda_a}\, [F_1(t_1)]^2 \\
& \times \bar{u}(p_4, \lambda_4) [\gamma^{\mu_2} (p_4 + p_t)^{\nu_2}\, \frac{1}{4 s_{13}} (-i s_{13} \alpha'_{I\!P})^{\alpha_{I\!P}(t_1) - 1}\, \frac{[\hat{F}_p(p_t^2)]^2}{\not{p}_t - m_p} \\
& \times \gamma^{\mu_1} (p_t - p_3)^{\nu_1}\, \frac{1}{4 s_{24}} (-i s_{24} \alpha'_{I\!P})^{\alpha_{I\!P}(t_2) - 1} \\
& \quad + \gamma^{\mu_1} (p_4 + p_u)^{\nu_1}\, \frac{1}{4 s_{14}} (-i s_{14} \alpha'_{I\!P})^{\alpha_{I\!P}(t_1) - 1}\, \frac{[\hat{F}_p(p_u^2)]^2}{\not{p}_u - m_p} \\
& \times \gamma^{\mu_2} (p_u - p_3)^{\nu_2}\, \frac{1}{4 s_{23}} (-i s_{23} \alpha'_{I\!P})^{\alpha_{I\!P}(t_2) - 1}]\, v(p_3, \lambda_3) \\
& \times (3\beta_{I\!P NN})^2\, 2(p_2 + p_b)_{\mu_2} (p_2 + p_b)_{\nu_2}\, \delta_{\lambda_2 \lambda_b}\, [F_1(t_2)]^2
\end{aligned}
$$

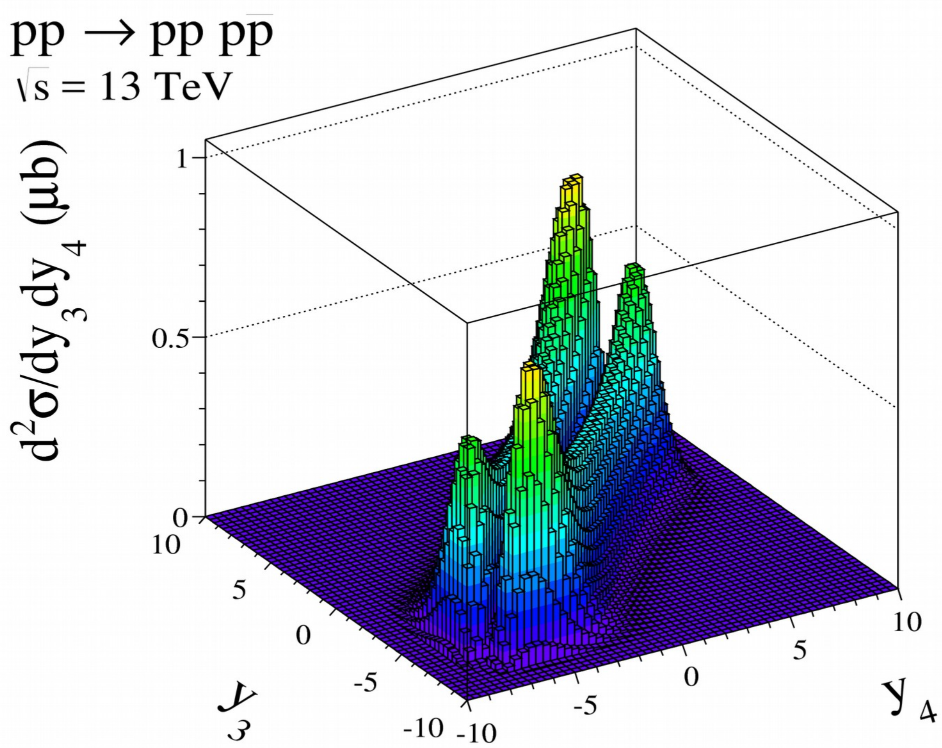
$pp \to pp\, p\bar{p}$



- We predict less steep dependence of $p\bar{p}$ invariant mass distribution than for the pseudoscalar meson pairs
- Surprising effect of the dip at rapidity difference

$pp \to pp\, p\bar{p}$

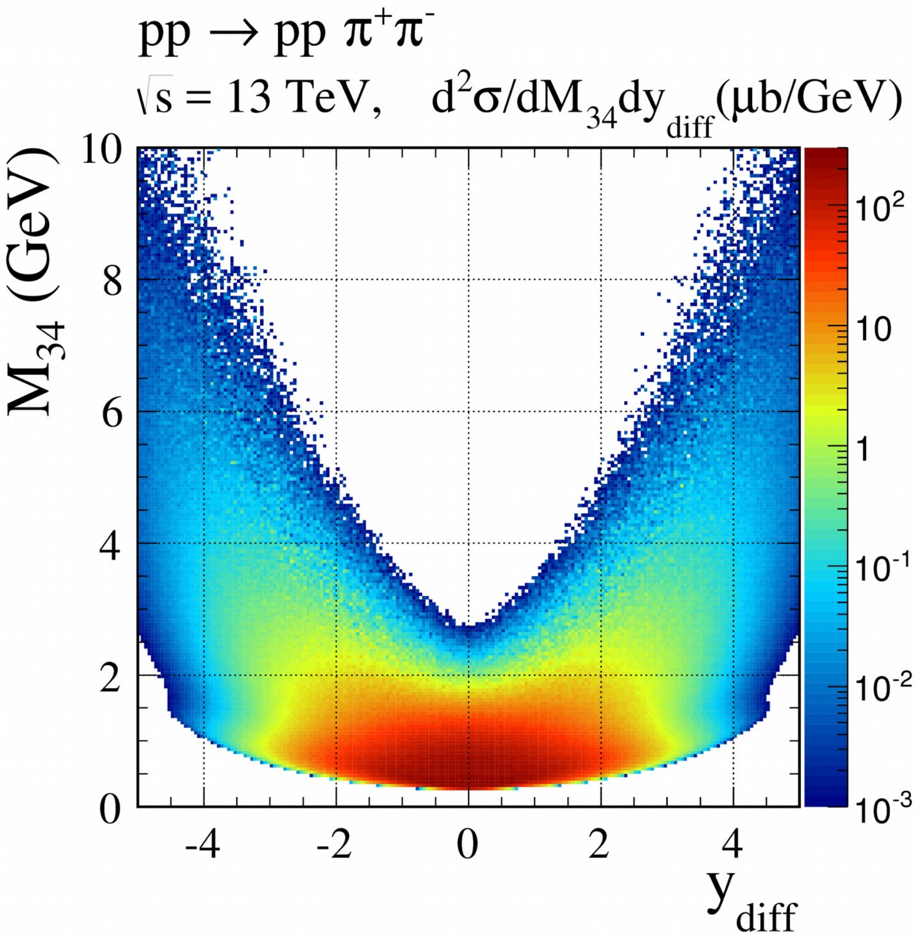


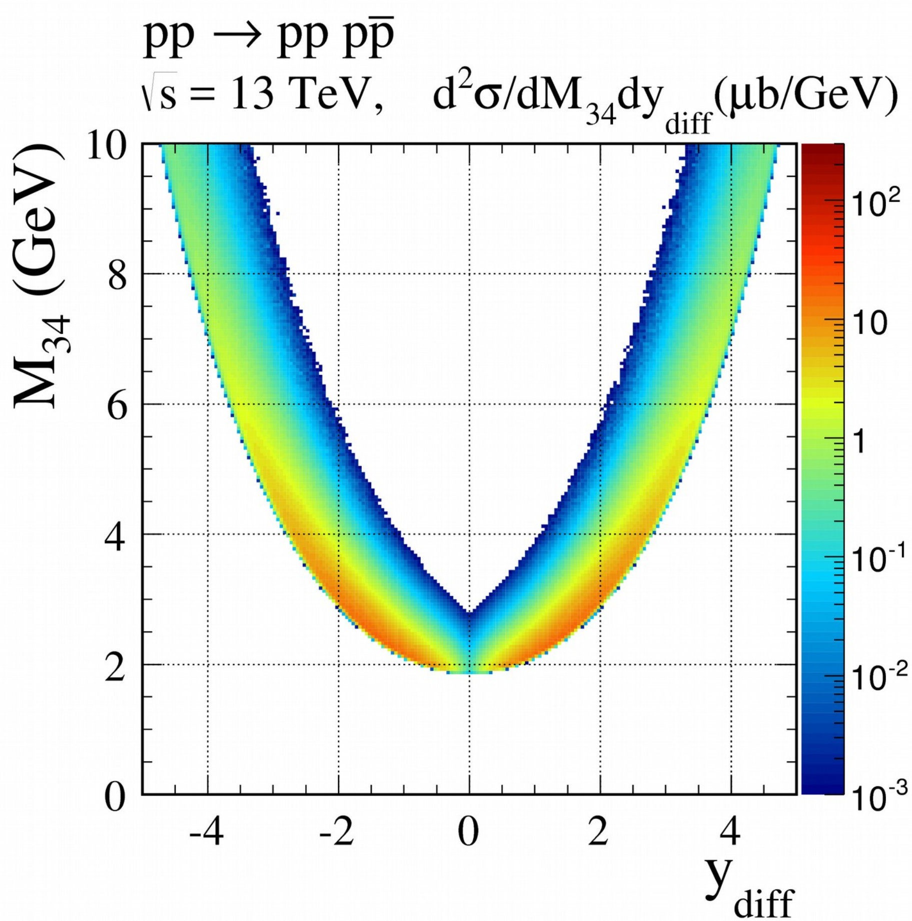


- Even at LHC energies a sizeable effect of subleading reggeons

- Dip extends over a whole diagonal in (y3, y4) space
- Good seperation of t- and u-channel contribiutions

$pp \to pp\, p\bar{p}$





- Different situation for $\pi^+\pi^-$ and $p\bar{p}$
- Region inside of the ridge seems promising in searches for $p\bar{p}$ resonances
- Any experimentally observed distortions from our predictions may therefore signal a presence of resonances
- No $p\bar{p}$ resonances are known (to us) except of η_c and χ_c mesons (see PDG)

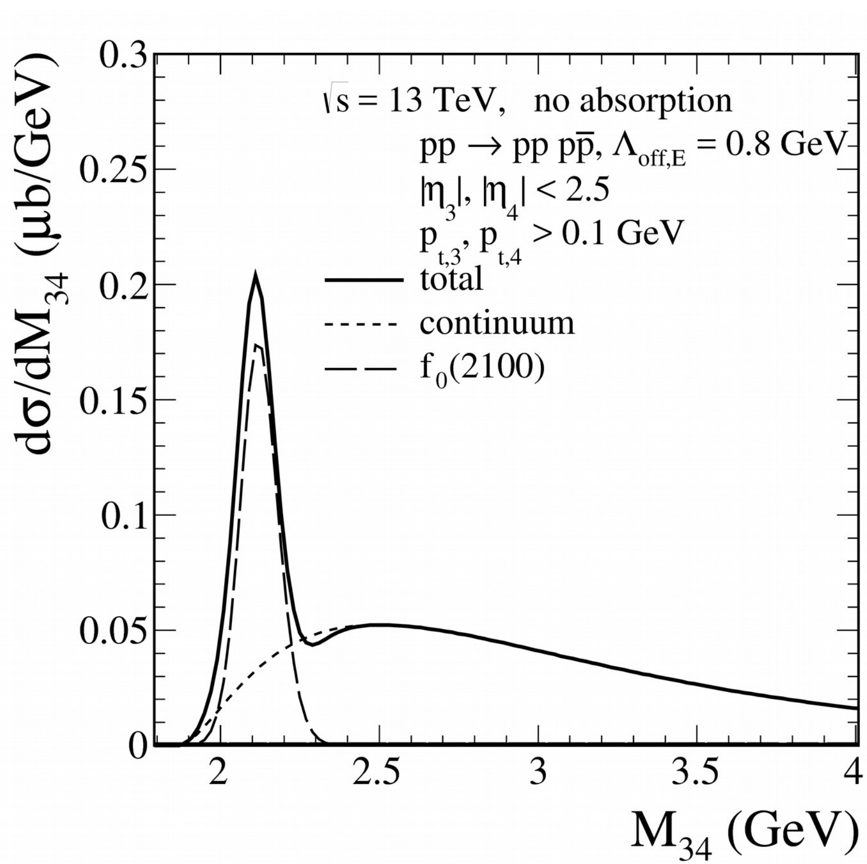
$pp \to pp\, p\bar{p}$

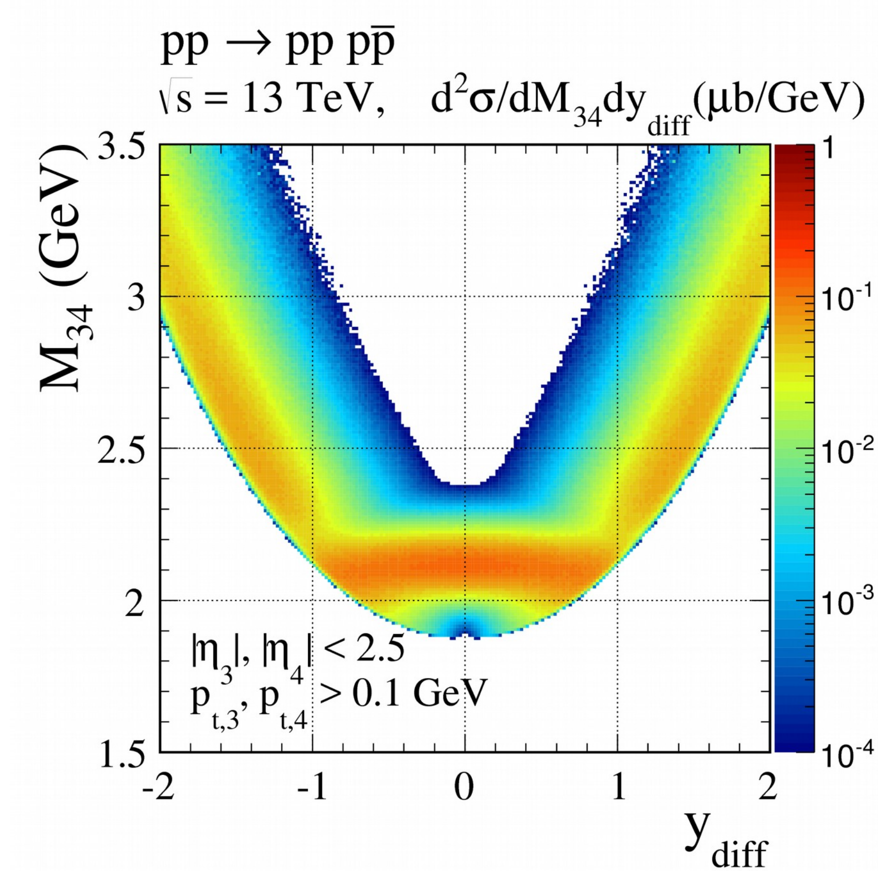
→ Bound states of a baryon and an antibaryon have been predicted, but have remained elusive

→ The $f_0(2100)$ was observed in $p\bar{p} \to \eta\eta$ reaction (PWA of Crystal Barell data, Anisovich *et al.*).
It may be considered as a second scalar glueball, probably mixed with $q\bar{q}$ states.

→ Lattice calculations predict for the tensor glueball a mass of about 2300 MeV.
Narrow state $f_2(2220)$, also known as $\xi(2220)$, was seen in J/ψ radiative decay (MARK III, BES)

→ Also other explanations are possible, such as the proton-antiproton FSI.





Conclusions

- We have given a consistence treatment of the production of $\pi^+\pi^-$ / K^+K^- continuum and resonances in proton-proton collisions using the tensor-pomeron model.

  The amplitudes are formulated in terms of effective vertices and propagators respecting the standard crossing and charge conjugation relations of QFT.

- 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 CMS data due to large proton-dissociation contribution.

  Purely exclusive data expected from STAR, CMS+TOTEM and ATLAS+ALFA should provide interesting information on the lightest glueballs and scalar/tensor mesons.

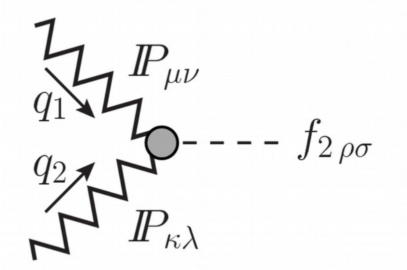
- First attempt in computing cross sections for the $pp \to pp\, p\bar{p}$ reaction.
  $\pi^+\pi^-$ and $p\bar{p}$ continua production have quite different characteristics ($d\sigma/dM$ and $d\sigma/dy_{diff}$).

- In progress:
  $pp \to pp\, \pi^+\pi^-\pi^+\pi^-$ process via intermediate $\sigma\sigma$ and $\rho\rho$ states (see extra slides),
  and via single scalar/ tensor resonance, $pp \to pp\, K^+K^-K^+K^-$ process via vector-vector states.

Extra slides

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



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

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

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

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

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

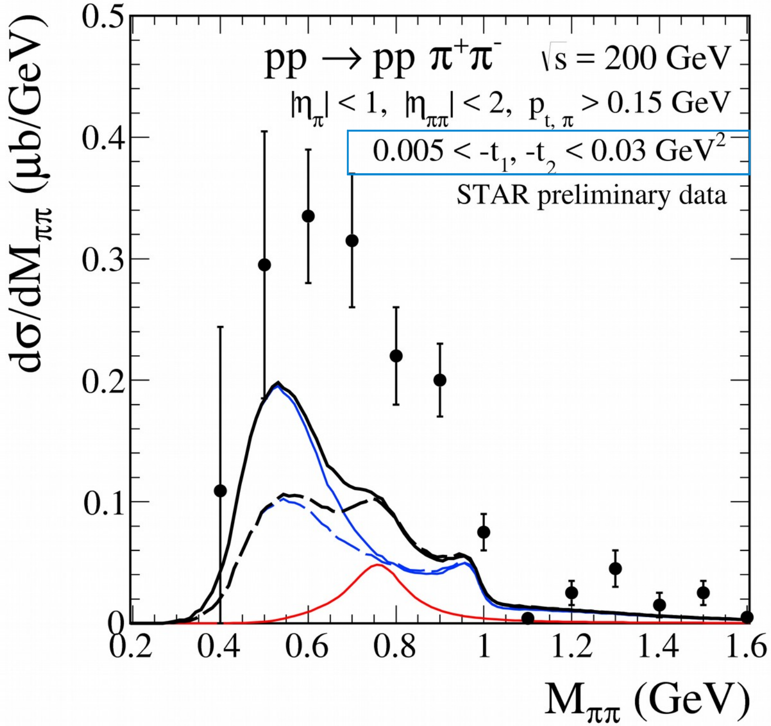
$$i\Gamma^{(\mathbb{P}\mathbb{P}f_2)(6)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = \frac{i}{M_0^3}\, g^{(6)}_{\mathbb{P}\mathbb{P}f_2} \Big(q_1^{\alpha_1}\, q_1^{\lambda_1}\, q_2^{\mu_1}\, q_{2\rho_1}\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1} + q_2^{\alpha_1}\, q_2^{\lambda_1}\,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

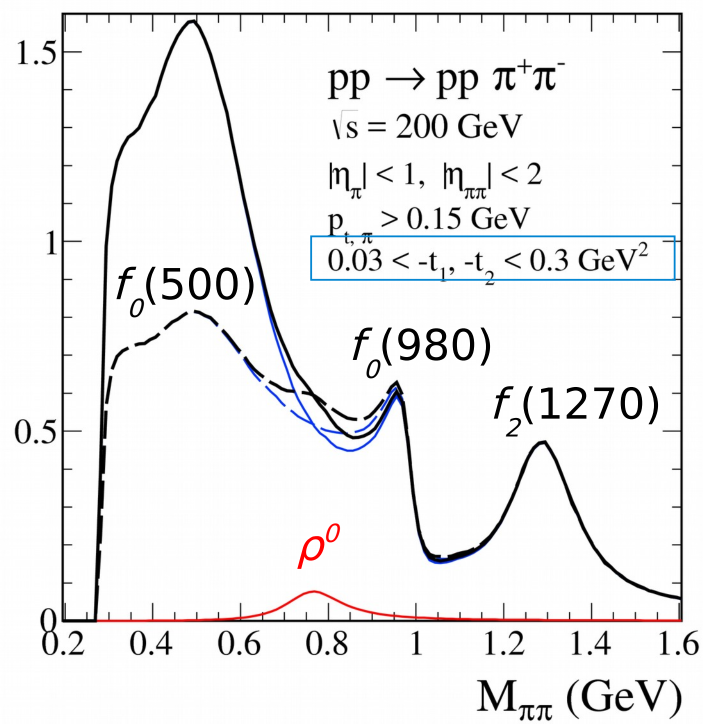
$$i\Gamma^{(\mathbb{P}\mathbb{P}f_2)(7)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{2i}{M_0^5}\, g^{(7)}_{\mathbb{P}\mathbb{P}f_2}\, q_1^{\rho_1}\, q_1^{\alpha_1}\, q_1^{\lambda_1}\, q_2^{\sigma_1}\, q_2^{\mu_1}\, q_2^{\nu_1}\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1}\, R_{\rho\sigma\rho_1\sigma_1}$$

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

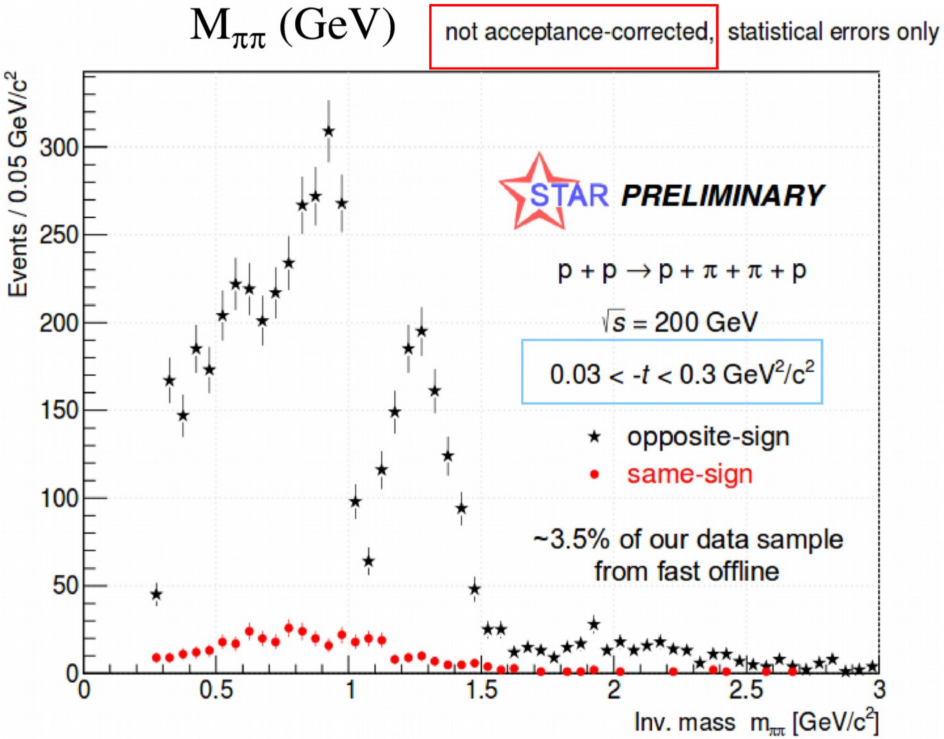
see P. L., O. Nachtmann, A. Szczurek, arXiv:1601.04537, Phys. Rev. D93 (2016) 054015

Comparison with STAR preliminary data





- Blue lines (diffractive term)
  red line (ρ^0 term)
  black lines (complete result)
- For f_2 term only (j=2) *IP-IP-f_2* coupling was taken
- At $M_{\pi\pi}$ < 1 GeV also other processes may be important
  → $\pi\pi$ FSI effect (f_0(500) meson) [Au, Morgan, Pennington]

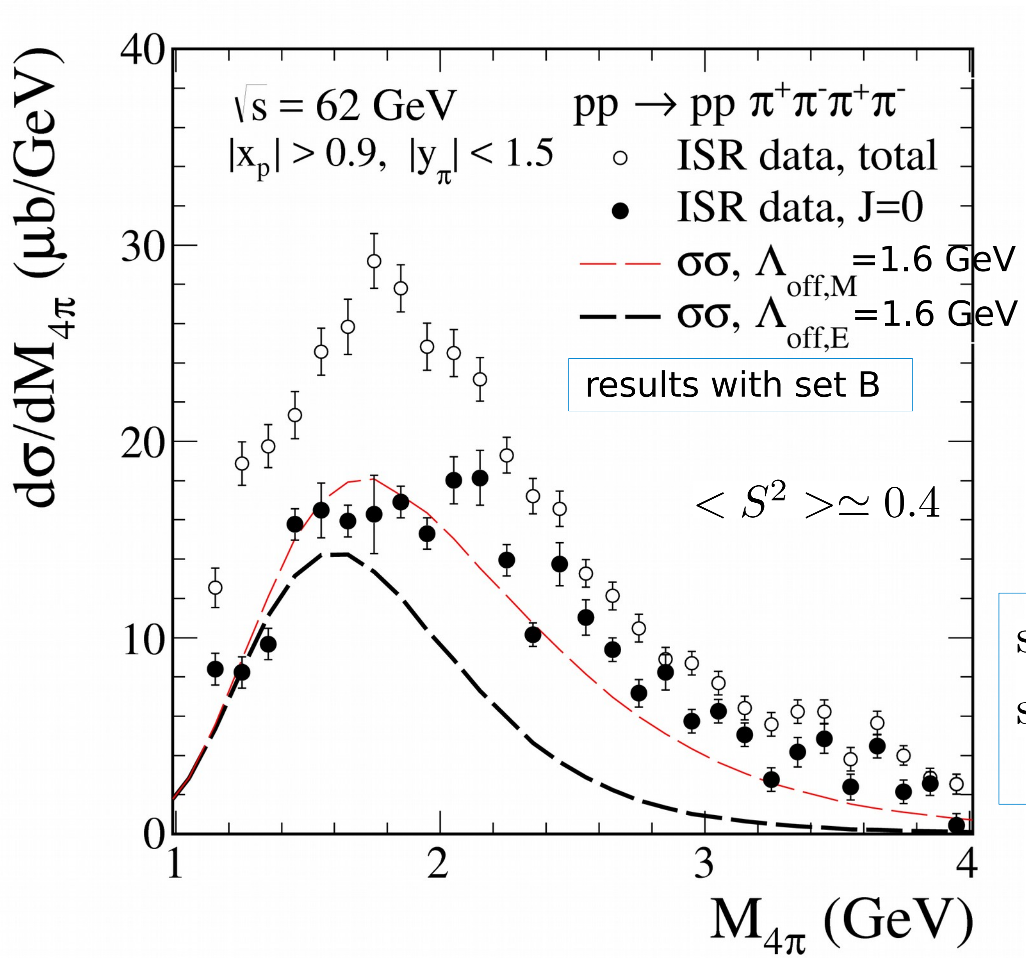


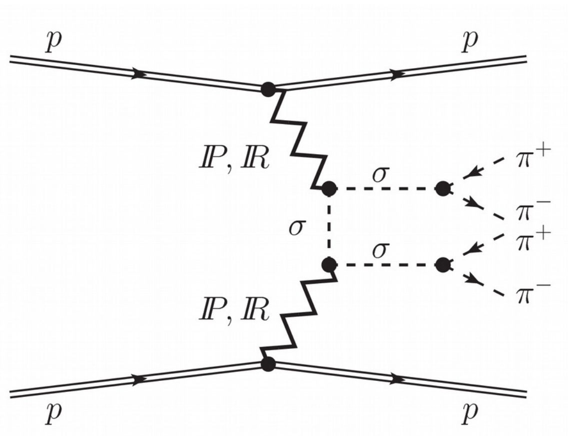
STAR preliminary data
for small |t| region: L.Adamczyk, W.Guryn, J.Turnau, Int.J.Mod.Phys. A29 (2014) 1446010
for larger |t|: W.Guryn, Acta Phys. Polon. B47 (2016) 53

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

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

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





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

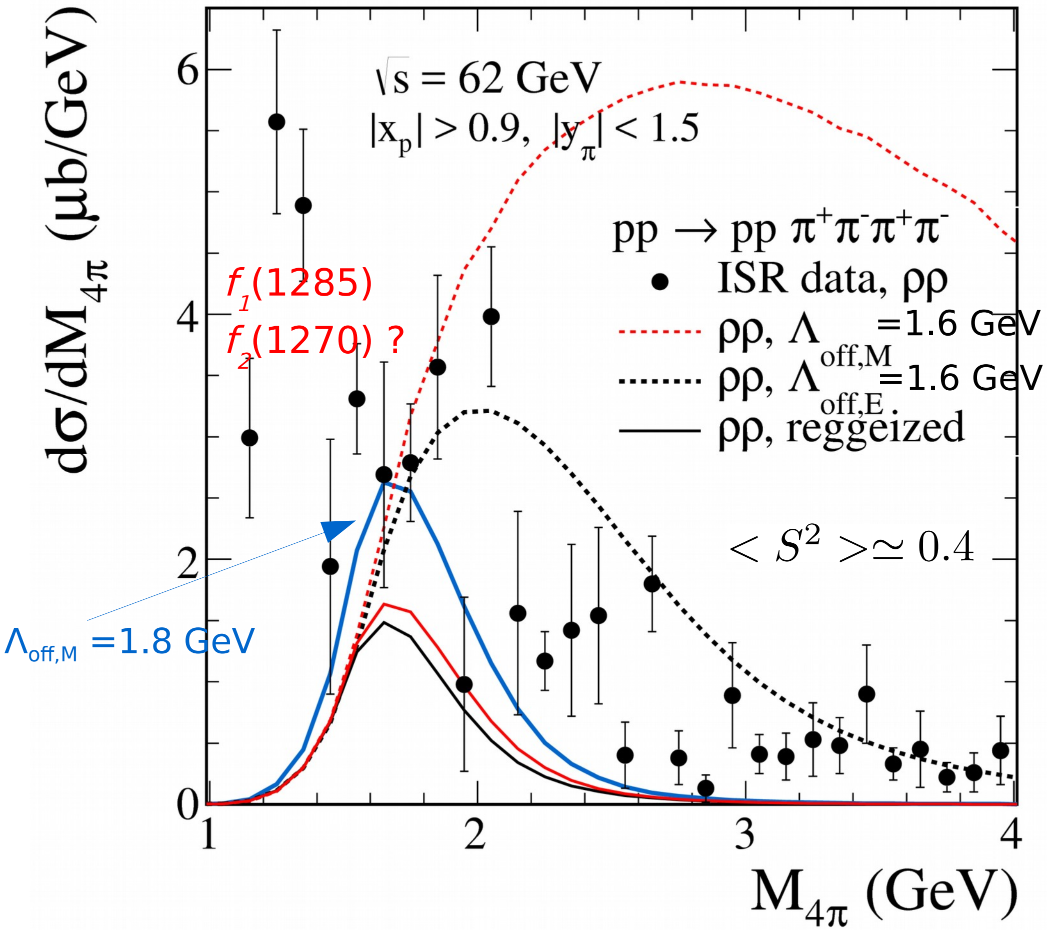
set B : $\beta_{I\!P\sigma\sigma} = 2\times(2\beta_{I\!P\pi\pi})\,,\ g_{f_2 I\!R\sigma\sigma} = 2\times g_{f_2 I\!R\pi\pi}$

enhanced coupling constants

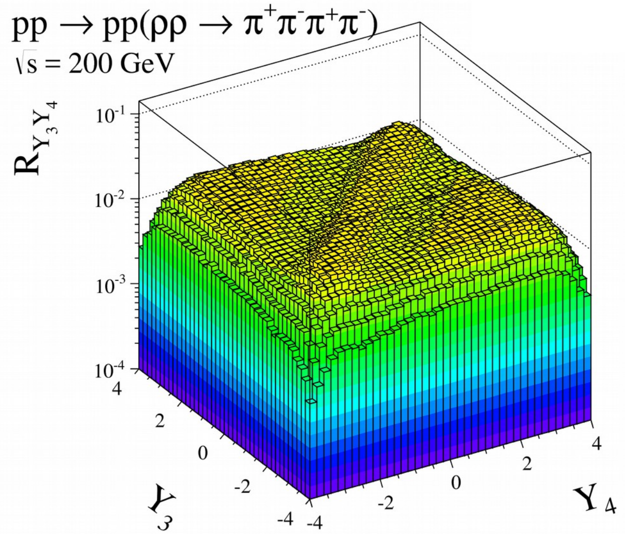
The 4π ISR data contains a large $\rho^0\pi^+\pi^-$ component with an enhancement in the J =2 term interpreted by ABCDHW Collaboration as a $f_2(1720)$ state.

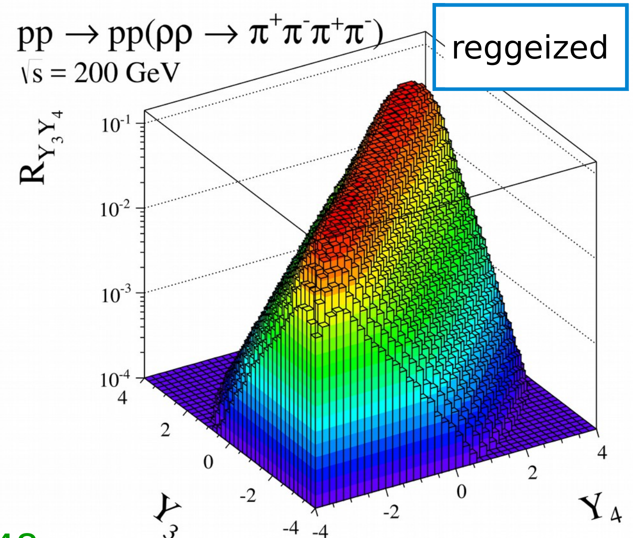
ISR data: A. Breakstone *et al*. (ABCDHW Collaboration), Z. Phys. C58 (1993) 251

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



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





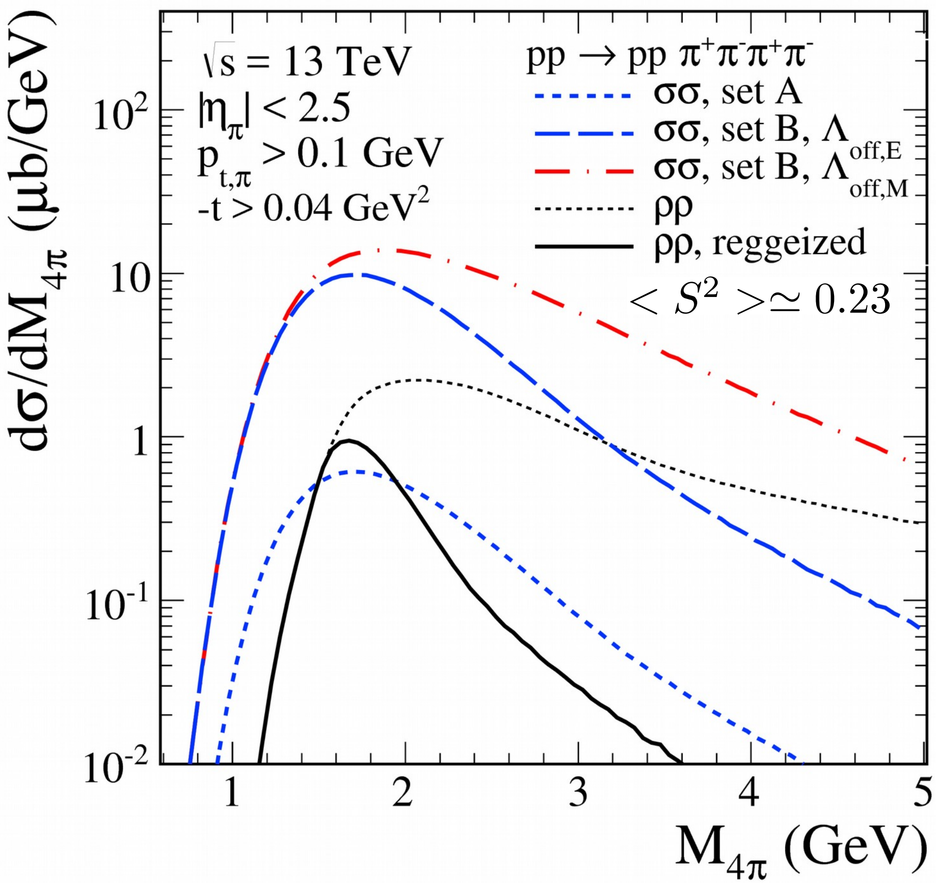
- reggeization effect

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

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



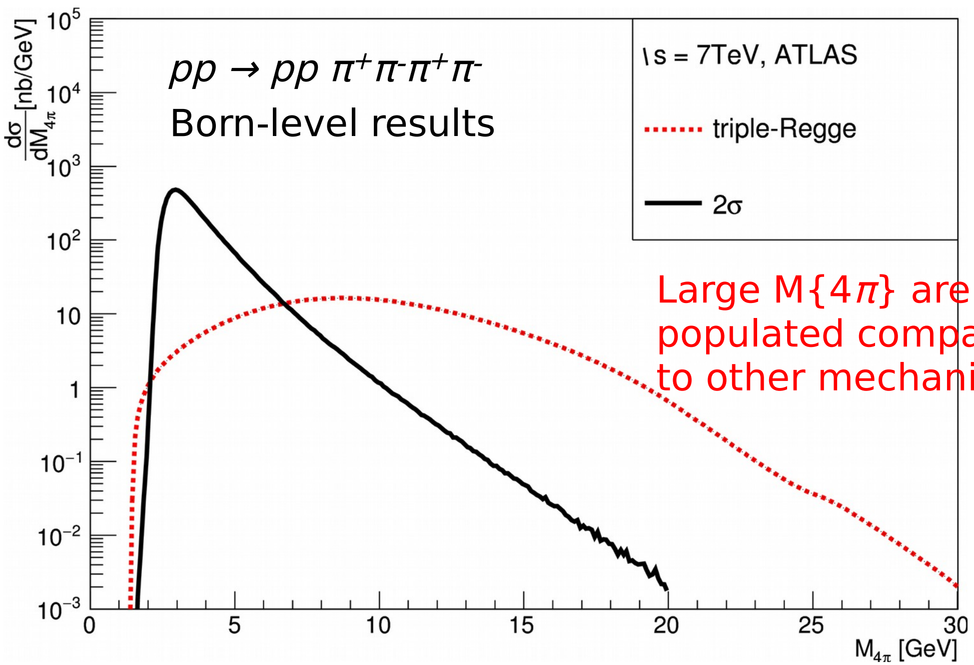
P. L., O. Nachtmann, A. Szczurek,
Phys. Rev. D94 (2016) 034017

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

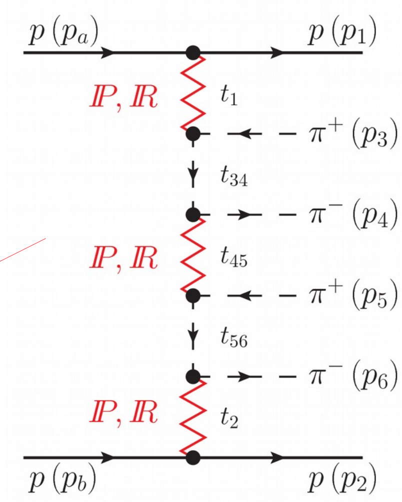
Predicted cross section can be obtained by multiplying the Born cross section by the gap survival factor:
0.3 (STAR), 0.21 (7 TeV),
0.19 (13 TeV), 0.23 (13 TeV, with cuts on $|t|$).

		"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.

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.

CEP in *pp* collisions

- P. L., O. Nachtmann, A. Szczurek, *Exclusive central diffractive production of scalar and pseudoscalar mesons; tensorial vs. vectorial pomeron*, Annals Phys. 344 (2014) 301
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- 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*, Phys. Rev. D94 (2016) 034017
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