Exclusive central diffractive production of scalar, pseudoscalar and vector mesons

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  (1) Exclusive central diffractive production of scalar and pseudoscalar mesons

  P. Lebiedowicz, O. Nachtmann and A. Szczurek, Ann. Phys. 344 (2014) 301

  (2) Exclusive central diffractive production of vector ρ^0 meson

  P. Lebiedowicz, O. Nachtmann and A. Szczurek, in preparation

  The ρ^0 contribution to exclusive production of $\pi^+\pi^-$ pairs in pp collisions

- Conclusions

The soft pomeron model

For *pp* elastic scattering we get (T-matrix element):

effective vector pomeron exchange vs effective tensor pomeron exchange

$$\mathcal{M}^{pp\to pp}_{\lambda_a\lambda_b\to\lambda_1\lambda_2}|_{I\!P_V} = (-i)\bar{u}(p_1,\lambda_1) i\Gamma^{(I\!P_V pp)}_{\mu}(p_1,p_a) u(p_a,\lambda_a) \times i\Delta^{(I\!P_V)\,\mu\nu}(s,t) \times \bar{u}(p_2,\lambda_2) i\Gamma^{(I\!P_V pp)}_{\nu}(p_2,p_b) u(p_b,\lambda_b)$$

$$\mathcal{M}^{pp\to pp}_{\lambda_a\lambda_b\to\lambda_1\lambda_2}|_{I\!P_T} = (-i)\bar{u}(p_1,\lambda_1) i\Gamma^{(I\!P_T pp)}_{\mu_1\nu_1}(p_1,p_a) u(p_a,\lambda_a) \times i\Delta^{(I\!P_T)\,\mu_1\nu_1,\mu_2\nu_2}(s,t) \times \bar{u}(p_2,\lambda_2) i\Gamma^{(I\!P_T pp)}_{\mu_2\nu_2}(p_2,p_b) u(p_b,\lambda_b)$$

$$i\Gamma^{(I\!P_V pp)}_{\mu}(p',p) = -i\,3\beta_{I\!P NN}\,F_1\big((p'-p)^2\big)\,M_0\,\gamma_\mu$$

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

$$i\Gamma^{(I\!P_T pp)}_{\mu\nu}(p',p) = -i\,3\beta_{I\!P NN}\,F_1\big((p'-p)^2\big) \times \left\{\frac{1}{2}\left[\gamma_\mu(p'+p)_\nu + \gamma_\nu(p'+p)_\mu\right] - \frac{1}{4}g_{\mu\nu}(\not{p}'+\not{p})\right\}$$

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

The Donnachie – Landschoff pomeron
is frequently called a '*C* = +1 photon'
→ problems from the point of view of QFT

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

O. Nachtmann, High-energy soft reactions: A model with tensor pomeron and vector odderon, WE-Heraeus-Summerschool, Heidelberg, 2013

Effective *IP*$_T$ *pp* vertex and *IP*$_T$ propagator
respect the standard *C* parity and crossing rules of QFT

In QFT a second rank tensor - like for gravity - gives
the same sign for the coupling of particles and of antiparticles

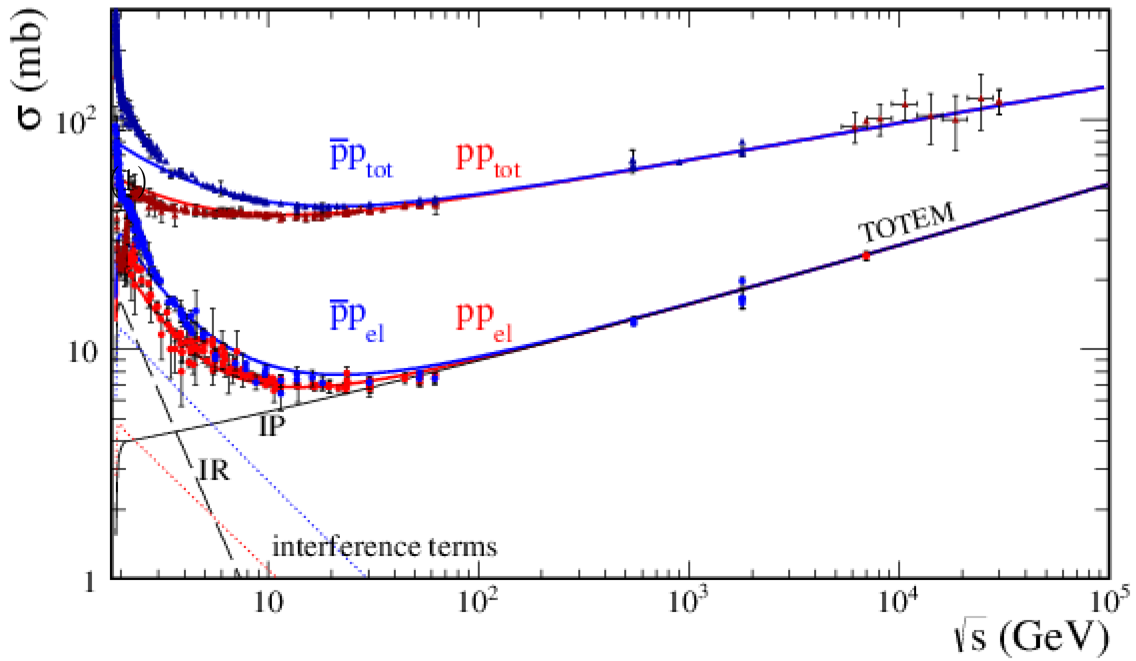
$$\beta_{I\!P NN} = 1.87\ \mathrm{GeV}^{-1}\,,\ M_0 = 1\ \mathrm{GeV}\,, \qquad \alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P}\,t\,, \qquad F_1(t) = \frac{4m_p^2 - 2.79\,t}{(4m_p^2 - t)(1 - t/m_D^2)^2}$$

$$\alpha_{I\!P}(0) = 1.0808,\ \alpha'_{I\!P} = 0.25\ \mathrm{GeV}^{-2}, \qquad m_D^2 = 0.71\ \mathrm{GeV}^2$$

Total and elastic scattering

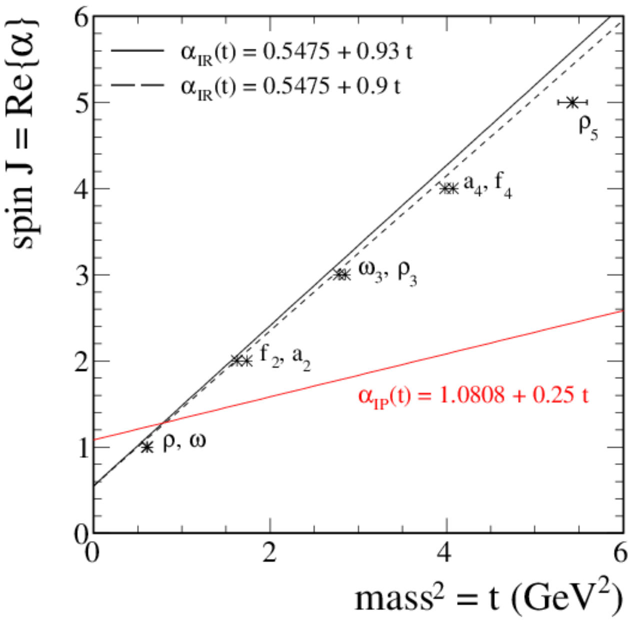
For high energies, we have
$\sigma_{tot}(s) \sim s^{-1}\,\mathrm{Im} M_{ab\to ab}(s,t=0)$

$$M_{pp\to pp}(s) = A_{I\!P}(s) + A_{f_2 I\!R}(s) + A_{a_2 I\!R}(s) - A_{\omega I\!R}(s) - A_{\rho I\!R}(s)$$
$$M_{\bar{p}p\to \bar{p}p}(s) = A_{I\!P}(s) + A_{f_2 I\!R}(s) + A_{a_2 I\!R}(s) + A_{\omega I\!R}(s) + A_{\rho I\!R}(s)$$



Tensor pomeron gives, at high energies, the same results for the *pp* and *p$\bar{p}$* elastic amplitudes as the standard DL pomeron

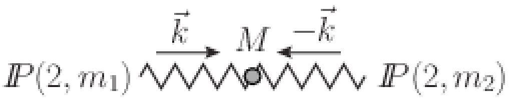
$$\mathcal{M}^{2\to2}_{\lambda_a\lambda_b\to\lambda_1\lambda_2}(s,t) \xrightarrow{s\gg 4m_p^2} i\,2s\,\left[3\beta_{I\!PNN}\,F_1(t)\right]^2\,(-is\alpha'_{I\!P})^{\alpha_{I\!P}(t)-1}\,\delta_{\lambda_1\lambda_a}\,\delta_{\lambda_2\lambda_b}$$



In the Regge theory the t-channel Regge exchanges (*IR*) form so-called linear Regge trajectories and correspond to a sum of ordinary mesons with the same quantum numbers (see the Chew-Frautschi plot); *C* = +1 (f_2, a_2) and *C* = -1 (ω, ρ) secondary trajectories are all degenerate with intercept ~0.5.

There is belief that the pomeron rather is associated with the exchange of family of glueballs.

$I\!P_V \, I\!P_V$ fusion vs $I\!P_T \, I\!P_T$ fusion



$I\!P_V I\!P_V \to M$

l	S	J	P
0	0	0	+
	2	2	
1	1	0, 1, 2	−
2	0	2	+
	2	0,1,2,3,4	
3	1	2,3,4	−
4	0	4	+
	2	2,3,4,5,6	

$I\!P_T I\!P_T \to M$

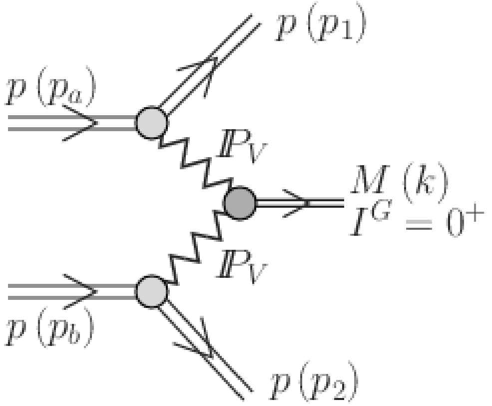
l	S	J	P
0	0	0	+
	2	2	
	4	4	
1	1	0, 1, 2	−
	3	2, 3, 4	
2	0	2	+
	2	0,1,2,3,4	
	4	2,3,4,5,6	
3	1	2,3,4	−
	3	0,1,2,3,4,5,6	
4	0	4	+
	2	2,3,4,5,6	
	4	0,1,2,3,4,5,6,7,8	

		$I\!P_V$		$I\!P_T$	
J^{PC}	meson M	l	S	l	S
0^{-+}	η	1	1	1	1
	$\eta'(958)$			3	3
0^{++}	$f_0(980)$	0	0	0	0
	$f_0(1370)$	2	2	2	2
	$f_0(1500)$			4	4
1^{++}	$f_1(1285)$	2	2	2	2
	$f_1(1420)$			4	4
2^{++}	$f_2(1270)$	0	2	0	2
	$f_2'(1525)$	2	0	2	0
		2	2	2	2
		4	2	2	4
				4	2
				4	4
4^{++}	$f_4(2050)$	2	2	0	4
		4	0	2	2
		4	2	2	4
				4	0
				4	2
				4	4

The values, for orbital angular momentum (l), total spin (S) of the two "pomeron particles", total angular momentum (J) and parity (P) of the state, respectively, possible in the annihilation reaction of two "pomeron particles" into a meson.

$$|l - S| \leqslant J \leqslant l + S, \qquad P = (-1)^l$$

Exclusive production of resonances via $I\!P_V\, I\!P_V$ fusion

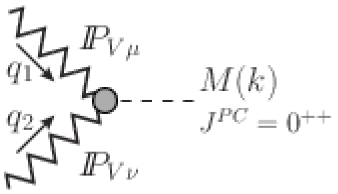


$$\mathcal{M}^{2\to 3}_{\lambda_a\lambda_b\to\lambda_1\lambda_2 M}\,|_{I\!P_V} = (-i)\bar{u}(p_1,\lambda_1)i\Gamma^{(I\!P_V pp)}_{\mu_1}(p_1,p_a)u(p_a,\lambda_a) \times i\Delta^{(I\!P_V)\,\mu_1\nu_1}(s_{13},t_1)\; i\Gamma^{(I\!P_V I\!P_V\to M)}_{\nu_1\nu_2}(q_1,q_2)\; i\Delta^{(I\!P_V)\,\nu_2\mu_2}(s_{23},t_2) \times\bar{u}(p_2,\lambda_2)i\Gamma^{(I\!P_V pp)}_{\mu_2}(p_2,p_b)u(p_b,\lambda_b)$$

$$i\Gamma^{(I\!P_V I\!P_V\to M)}_{\mu\nu}(q_1,q_2) = \left(i\Gamma'^{(I\!P_V I\!P_V\to M)}_{\mu\nu}\,|_{bare} + i\Gamma''^{(I\!P_V I\!P_V\to M)}_{\mu\nu}(q_1,q_2)\,|_{bare}\right) F_{I\!PI\!PM}(q_1^2,q_2^2)$$

$$F_{I\!PI\!PM}(t_1,t_2) = F_M(t_1)F_M(t_2)\,,\quad F_M(t) = F_\pi(t) = \frac{1}{1-t/\Lambda_0^2}\,,\quad \Lambda_0^2 = 0.5\ \mathrm{GeV}^2$$

The “bare” vertices were obtained from a covariant Lagrangians corresponding to the l and S values.



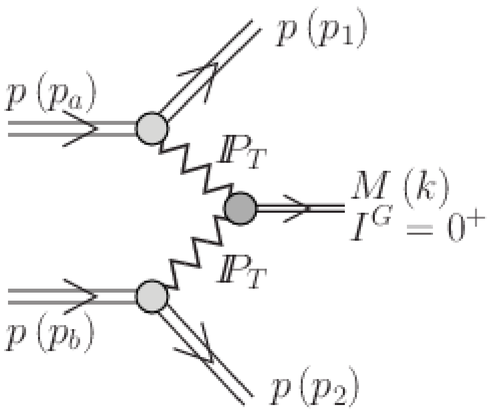
$$J^{PC} = 0^{++}:\quad i\Gamma'^{(I\!P_V I\!P_V\to M)}_{\mu\nu}\,|_{bare} = i\,g'_{I\!P_V I\!P_V M}\,M_0\,2g_{\mu\nu} \quad \Leftarrow (l,S) = (0,0)\ term$$

$$i\Gamma''^{(I\!P_V I\!P_V\to M)}_{\mu\nu}(q_1,q_2)\,|_{bare} = \frac{2i\,g''_{I\!P_V I\!P_V M}}{M_0}\left[q_{2\mu}q_{1\nu} - (q_1q_2)g_{\mu\nu}\right] \quad \Leftarrow (l,S) = (2,2)\ term$$

$$J^{PC} = 0^{-+}:\quad i\Gamma'^{(I\!P_V I\!P_V\to \tilde{M})}_{\mu\nu}(q_1,q_2)\,|_{bare} = i\,\frac{g'_{I\!P_V I\!P_V \tilde{M}}}{2M_0}\,\varepsilon_{\mu\nu\rho\sigma}q_1^\rho q_2^\sigma \quad \Leftarrow (l,S) = (1,1)\ term$$

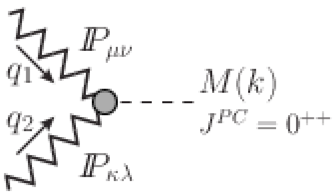
The dimensionless coupling constants $g_{IP\,IP\,M}$ can be fixed from the meson production data.

Exclusive production of resonances via $IP_T\, IP_T$ fusion



$$\mathcal{M}^{2\to 3}_{\lambda_a\lambda_b\to\lambda_1\lambda_2 M}\,|_{I\!P_T} = (-i)\bar{u}(p_1,\lambda_1)i\Gamma^{(I\!P_T pp)}_{\mu_1\nu_1}(p_1,p_a)u(p_a,\lambda_a)$$
$$\times i\Delta^{(I\!P_T)\,\mu_1\nu_1,\kappa_1\lambda_1}(s_{13},t_1)\;\; i\Gamma^{(I\!P_T I\!P_T\to M)}_{\kappa_1\lambda_1,\kappa_2\lambda_2}(q_1,q_2)\;\; i\Delta^{(I\!P_T)\,\kappa_2\lambda_2,\mu_2\nu_2}(s_{23},t_2)$$
$$\times\bar{u}(p_2,\lambda_2)i\Gamma^{(I\!P_T pp)}_{\mu_2\nu_2}(p_2,p_b)u(p_b,\lambda_b)$$

$$i\Gamma^{(I\!P_T I\!P_T\to M)}_{\mu\nu,\kappa\lambda}(q_1,q_2) = \left(i\Gamma'^{(I\!P_T I\!P_T\to M)}_{\mu\nu,\kappa\lambda}\,|_{bare} + i\Gamma''^{(I\!P_T I\!P_T\to M)}_{\mu\nu,\kappa\lambda}(q_1,q_2)\,|_{bare}\right) F_{I\!P I\!P M}(q_1^2,q_2^2)$$



$$\mathrm{J}^{PC} = 0^{++}:\; i\Gamma'^{(I\!P_T I\!P_T\to M)}_{\mu\nu,\kappa\lambda}\,|_{bare} = i\,g'_{I\!P_T I\!P_T M}\,M_0\left(g_{\mu\kappa}g_{\nu\lambda} + g_{\mu\lambda}g_{\nu\kappa} - \frac{1}{2}g_{\mu\nu}g_{\kappa\lambda}\right) \quad \Leftarrow (l,S) = (0,0)\ term$$

$$i\Gamma''^{(I\!P_T I\!P_T\to M)}_{\mu\nu,\kappa\lambda}(q_1,q_2)\,|_{bare} = \frac{i\,g''_{I\!P_T I\!P_T M}}{2M_0}\left[q_{1\kappa}q_{2\mu}g_{\nu\lambda} + q_{1\kappa}q_{2\nu}g_{\mu\lambda} + q_{1\lambda}q_{2\mu}g_{\nu\kappa} + q_{1\lambda}q_{2\nu}g_{\mu\kappa} - 2(q_1q_2)(g_{\mu\kappa}g_{\nu\lambda} + g_{\nu\kappa}g_{\mu\lambda})\right] \quad \Leftarrow (2,2)$$

$$\mathrm{J}^{PC} = 0^{-+}:\; i\Gamma'^{(I\!P_T I\!P_T\to \tilde{M})}_{\mu\nu,\kappa\lambda}(q_1,q_2)\,|_{bare} = i\,\frac{g'_{I\!P_T I\!P_T \tilde{M}}}{2M_0}\left(g_{\mu\kappa}\varepsilon_{\nu\lambda\rho\sigma} + g_{\nu\kappa}\varepsilon_{\mu\lambda\rho\sigma} + g_{\mu\lambda}\varepsilon_{\nu\kappa\rho\sigma} + g_{\nu\lambda}\varepsilon_{\mu\kappa\rho\sigma}\right)(q_1-q_2)^\rho k^\sigma \quad \Leftarrow (1,1)$$

$$i\Gamma''^{(I\!P_T I\!P_T\to \tilde{M})}_{\mu\nu,\kappa\lambda}(q_1,q_2)\,|_{bare} = i\,\frac{g''_{I\!P_T I\!P_T \tilde{M}}}{M_0^3}\{\varepsilon_{\nu\lambda\rho\sigma}[q_{1\kappa}q_{2\mu} - (q_1q_2)g_{\mu\kappa}] + \varepsilon_{\mu\lambda\rho\sigma}[q_{1\kappa}q_{2\nu} - (q_1q_2)g_{\nu\kappa}]$$
$$+\varepsilon_{\nu\kappa\rho\sigma}[q_{1\lambda}q_{2\mu} - (q_1q_2)g_{\mu\lambda}] + \varepsilon_{\mu\kappa\rho\sigma}[q_{1\lambda}q_{2\nu} - (q_1q_2)g_{\nu\lambda}]\}(q_1-q_2)^\rho k^\sigma \quad \Leftarrow (3,3)$$

$I\!P_V\, I\!P_V$ fusion vs $I\!P_T\, I\!P_T$ fusion

We shall now consider the high-energy small-angle limit for both the tensorial and vectorial pomeron fusion reactions giving the mesons M and $\tilde{M}$.

$$|t_1|, |t_2| \ll m_p^2\,, \quad m_M^2 \ll s\,, \quad \xi_1, \xi_2 = \mathcal{O}(m_M/\sqrt{s})$$

$$\xi_1 \cong \frac{s_{23}}{s}\,, \quad \xi_2 \cong \frac{s_{13}}{s}\,, \quad m_M^2 \cong s\xi_1\xi_2 = \frac{s_{13}s_{23}}{s}\,, \quad t_1 \cong -\vec{q}_{1\perp}^{\,2}\,, \quad t_2 \cong -\vec{q}_{2\perp}^{\,2}\,;$$

$$\Bigg\} \quad s_{13}, s_{23} = \mathcal{O}(m_M\sqrt{s})$$

$$\bar{u}(p_1,\lambda_1)\gamma^\mu u(p_a,\lambda_a) \cong (p_1+p_a)^\mu \delta_{\lambda_1\lambda_a}$$

$$\bar{u}(p_2,\lambda_2)\gamma^\mu u(p_b,\lambda_b) \cong (p_2+p_b)^\mu \delta_{\lambda_2\lambda_b}$$

$$\begin{aligned}
\mathcal{M}^{2\to 3}_{\lambda_a\lambda_b\to\lambda_1\lambda_2 M}\,|_{I\!P_T I\!P_T} \;\cong\;& -2s\,(3\beta_{I\!P NN})^2\, F_1(t_1)\, F_1(t_2)\, F_{I\!P I\!P M}(t_1,t_2) \\
&\times \frac{M_0}{m_M^2}\Big(g'_{I\!P_T I\!P_T M} + g''_{I\!P_T I\!P_T M}\,\frac{1}{M_0^2}\,|\vec{p}_{1\perp}||\vec{p}_{2\perp}|\cos\phi_{pp}\Big) \\
&\times (-is_{13}\alpha'_{I\!P})^{\alpha_{I\!P}(t_1)-1}\;(-is_{23}\alpha'_{I\!P})^{\alpha_{I\!P}(t_2)-1} \\
&\times \delta_{\lambda_1\lambda_a}\delta_{\lambda_2\lambda_b} \qquad (1)
\end{aligned}$$

$$\begin{aligned}
\mathcal{M}^{2\to 3}_{\lambda_a\lambda_b\to\lambda_1\lambda_2 \tilde{M}}\,|_{I\!P_T I\!P_T} \;\cong\;& -2s\,(3\beta_{I\!P NN})^2\, F_1(t_1)\, F_1(t_2)\, F_{I\!P I\!P \tilde{M}}(t_1,t_2) \\
&\times \frac{2}{m_{\tilde{M}}^2 M_0}|\vec{p}_{1\perp}||\vec{p}_{2\perp}|\sin\phi_{pp}\Big(g'_{I\!P_T I\!P_T \tilde{M}} + g''_{I\!P_T I\!P_T \tilde{M}}\,\frac{2}{M_0^2}|\vec{p}_{1\perp}||\vec{p}_{2\perp}|\cos\phi_{pp}\Big) \\
&\times (-is_{13}\alpha'_{I\!P})^{\alpha_{I\!P}(t_1)-1}\;(-is_{23}\alpha'_{I\!P})^{\alpha_{I\!P}(t_2)-1} \\
&\times \delta_{\lambda_1\lambda_a}\delta_{\lambda_2\lambda_b} \qquad (2)
\end{aligned}$$

For the vectorial pomeron we get in this limit the expressions (1) and (2), respectively, but with the replacements:

$$g'_{I\!P_T I\!P_T M} \to \frac{2m_M^2}{M_0^2}\, g'_{I\!P_V I\!P_V M}\,, \quad g''_{I\!P_T I\!P_T M} \to \frac{2m_M^2}{M_0^2}\, g''_{I\!P_V I\!P_V M}\,,$$

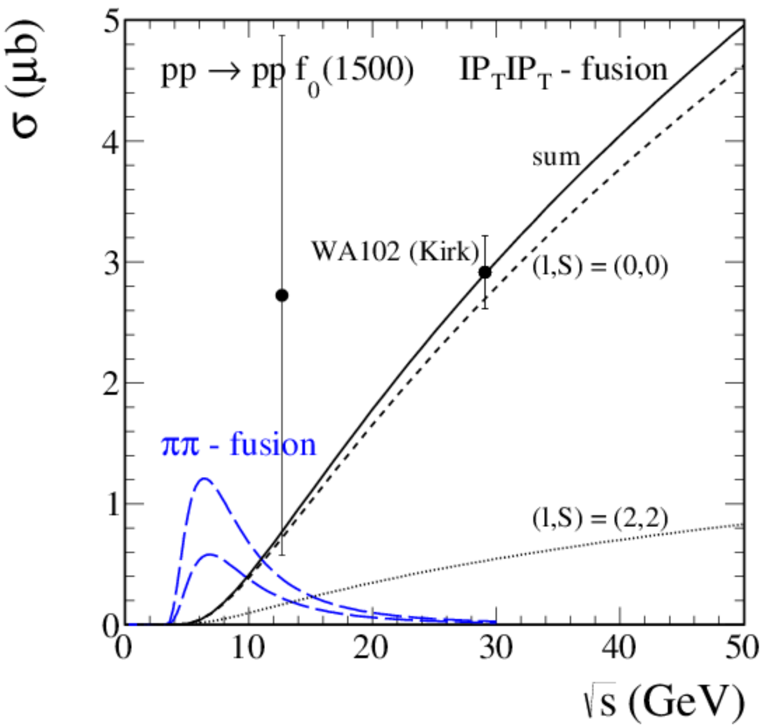
$$g'_{I\!P_T I\!P_T \tilde{M}} \to \frac{m_{\tilde{M}}^2}{4M_0^2}\, g'_{I\!P_V I\!P_V \tilde{M}}\,, \quad g''_{I\!P_T I\!P_T \tilde{M}} \to 0$$

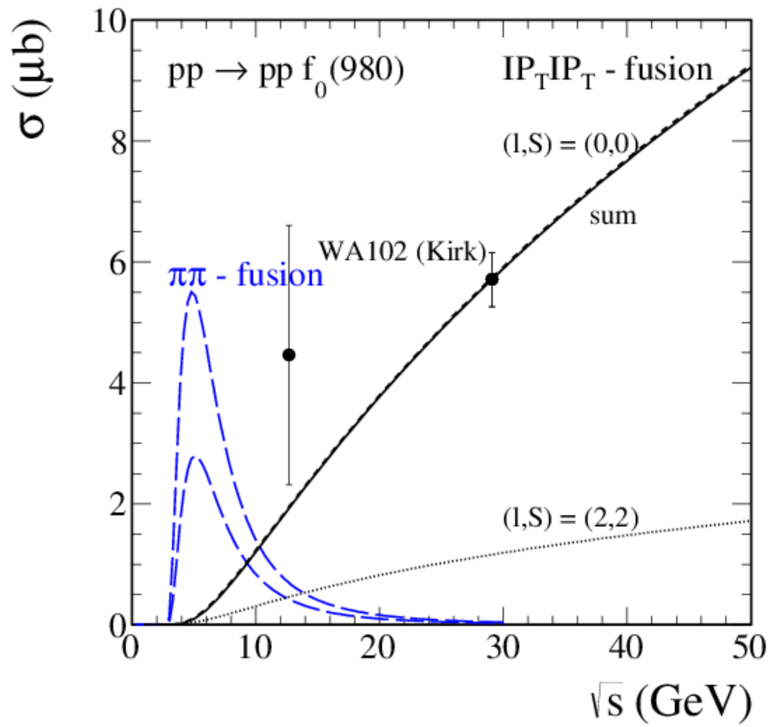
We see that for the vectorial pomeron the term $\propto \cos\phi_{pp}\sin\phi_{pp}$ in (2) is absent.

Experimental results (WA102) for total cross sections of scalar mesons in *pp* collisions (29.1 GeV)

A. Kirk, Phys. Lett. B489 (2000) 29

	$f_0(980)$	$f_0(1370)$	$f_0(1500)$	$f_0(1710)$	$f_0(2000)$
$\sigma(\mu b)$	5.71 ± 0.45	1.75 ± 0.58	2.91 ± 0.30	0.25 ± 0.07	3.14 ± 0.48

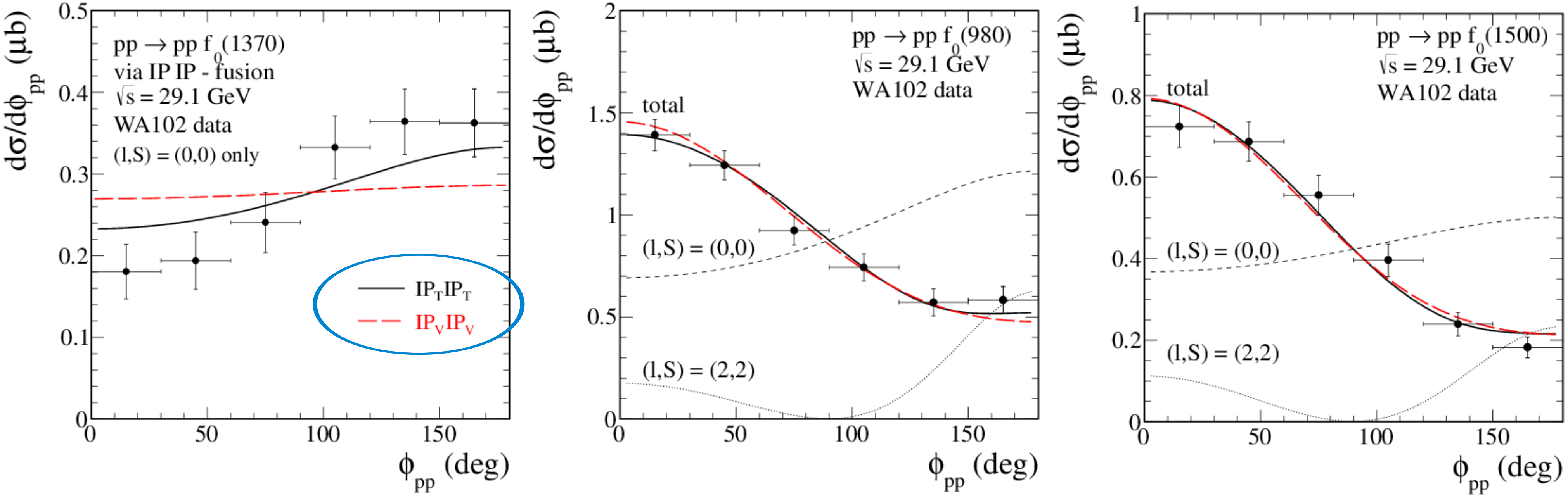




$\pi\pi$ - fusion mechanism → *A. Szczurek and P. L., Nucl. Phys. A826 (2009) 101, arXiv:0906.0286*

$J^{PC} = 0^{++}$ ϕ_{pp} distribution

Our results and the WA102 exp. distributions have been normalized to the value of total cross sections given by Kirk.

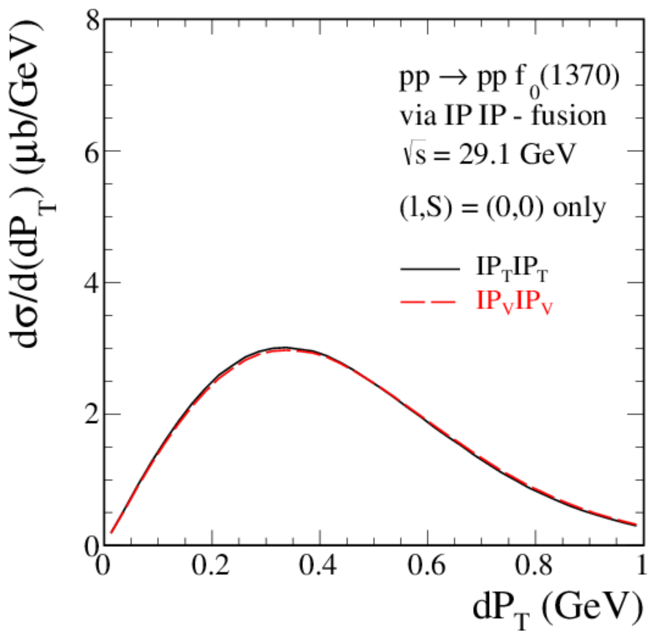


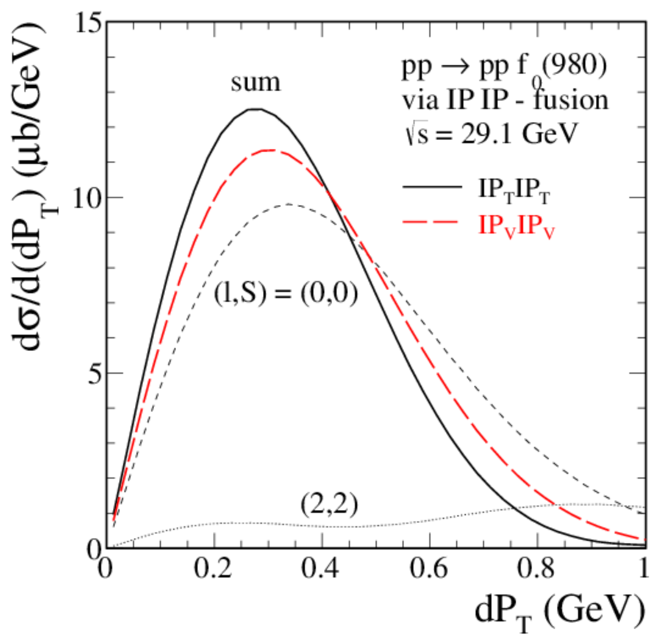
For $f_0(1370)$ the tensorial pomeron with the $(l, S) = (0, 0)$ coupling alone already describes data.
The vectorial pomeron term is disfavoured here.

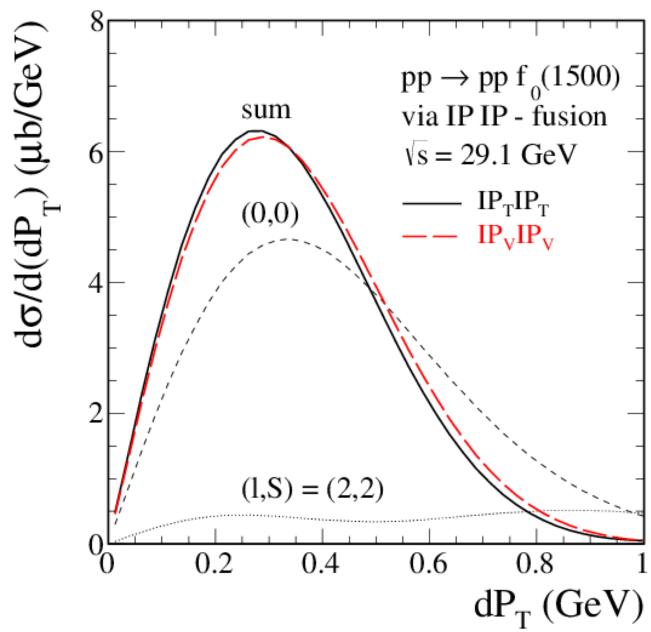
dP_T distribution

The "glueball fillter" variable $\mathrm{dP}_\perp = |d\vec{P}_\perp| = |\vec{q}_{1\perp} - \vec{q}_{2\perp}| = |\vec{p}_{2\perp} - \vec{p}_{1\perp}|$

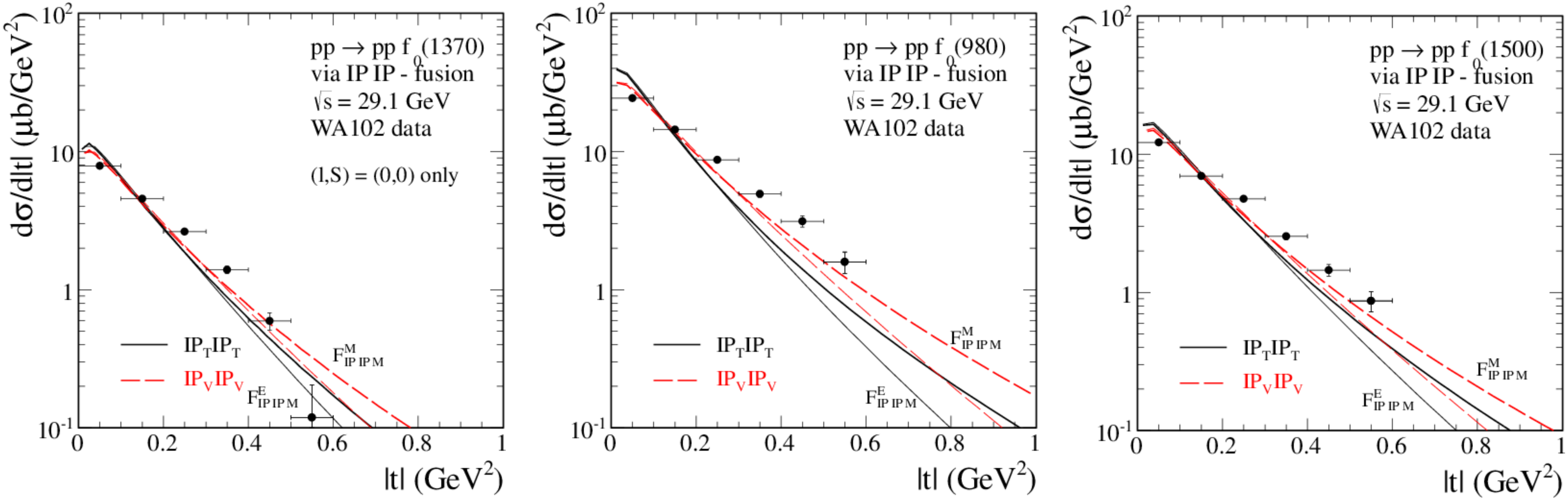
F. E. Close and A. Kirk, Phys. Lett. B397 (1997) 333







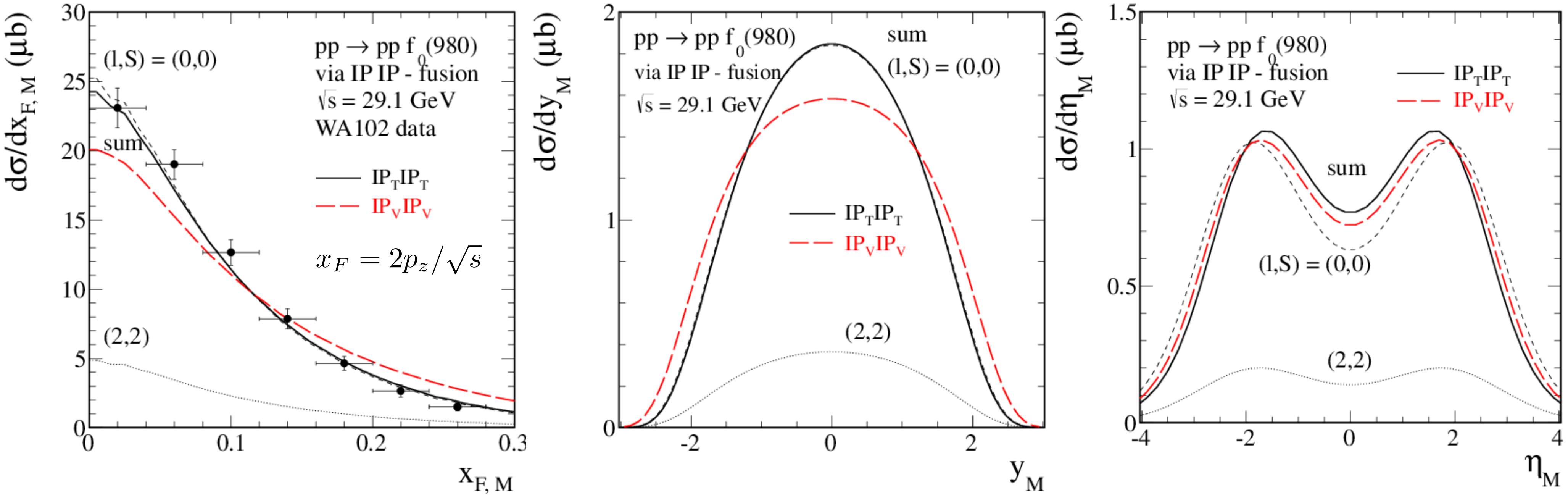
$J^{PC} = 0^{++}$ t distribution



$$F^{M}_{I\!PI\!PM}(t_1,t_2) = F_M(t_1)F_M(t_2)\,, \quad F_M(t) = F_\pi(t) = \frac{1}{1-t/\Lambda_0^2}\,, \quad \Lambda_0^2 = 0.5~\mathrm{GeV}^2$$

$$F^{E}_{I\!PI\!PM}(t_1,t_2) = \exp\left(\frac{t_1+t_2}{\Lambda_E^2}\right)\,, \quad \Lambda_E^2 = 0.64~\mathrm{GeV}^2$$

$J^{PC} = 0^{++}$ $x_{F,M}$, y_M and η_M distributions



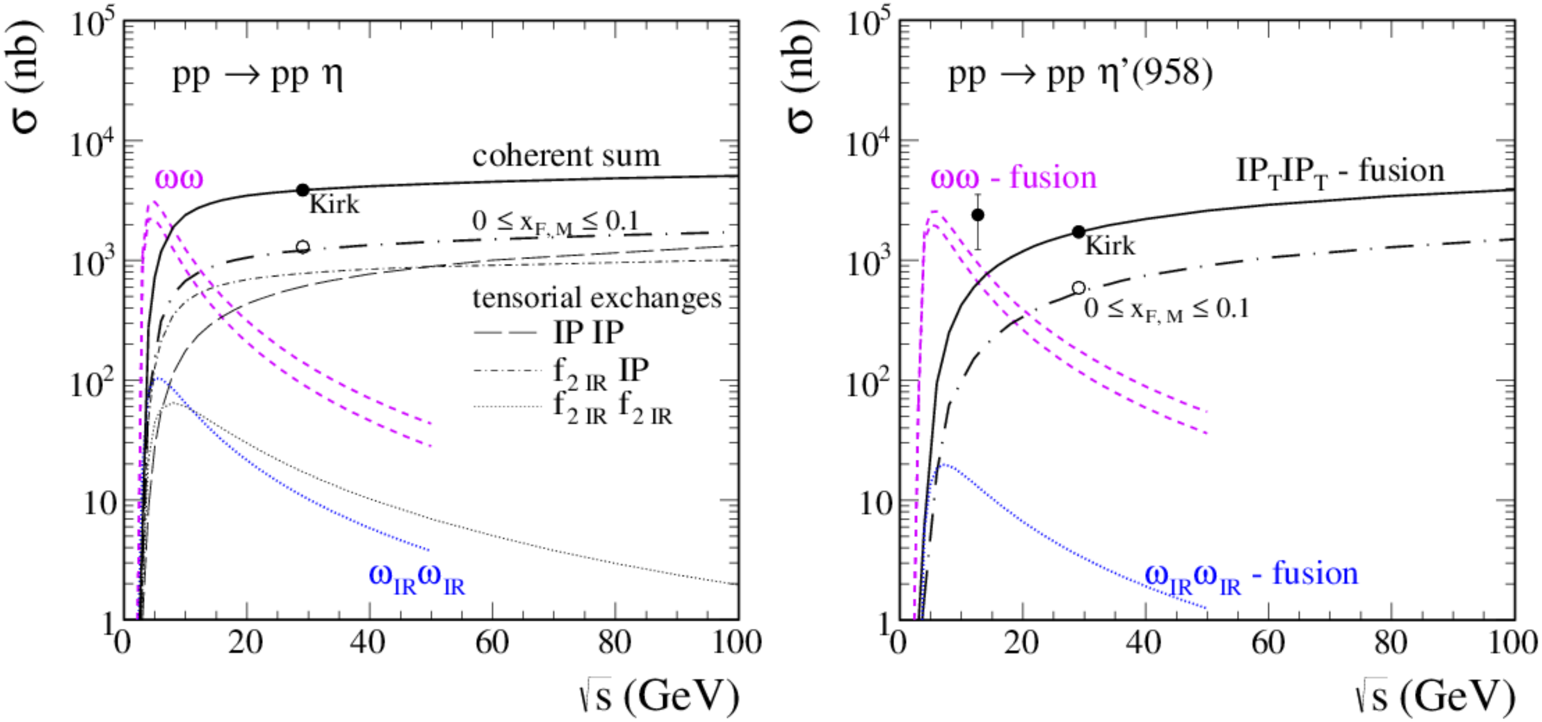
The dip in the η_M distribution for $|\eta_M| \to 0$ is a kinematic effect.

Cross section

Exp. results (WA102) for total cross sections of pseudoscalar mesons in *pp* collisions (29.1 GeV)

A. Kirk, Phys. Lett. B489 (2000) 29

$$\sigma(\eta) = 3.86 \pm 0.37\ \mu\text{b}$$
$$\sigma(\eta') = 1.72 \pm 0.18\ \mu\text{b}$$

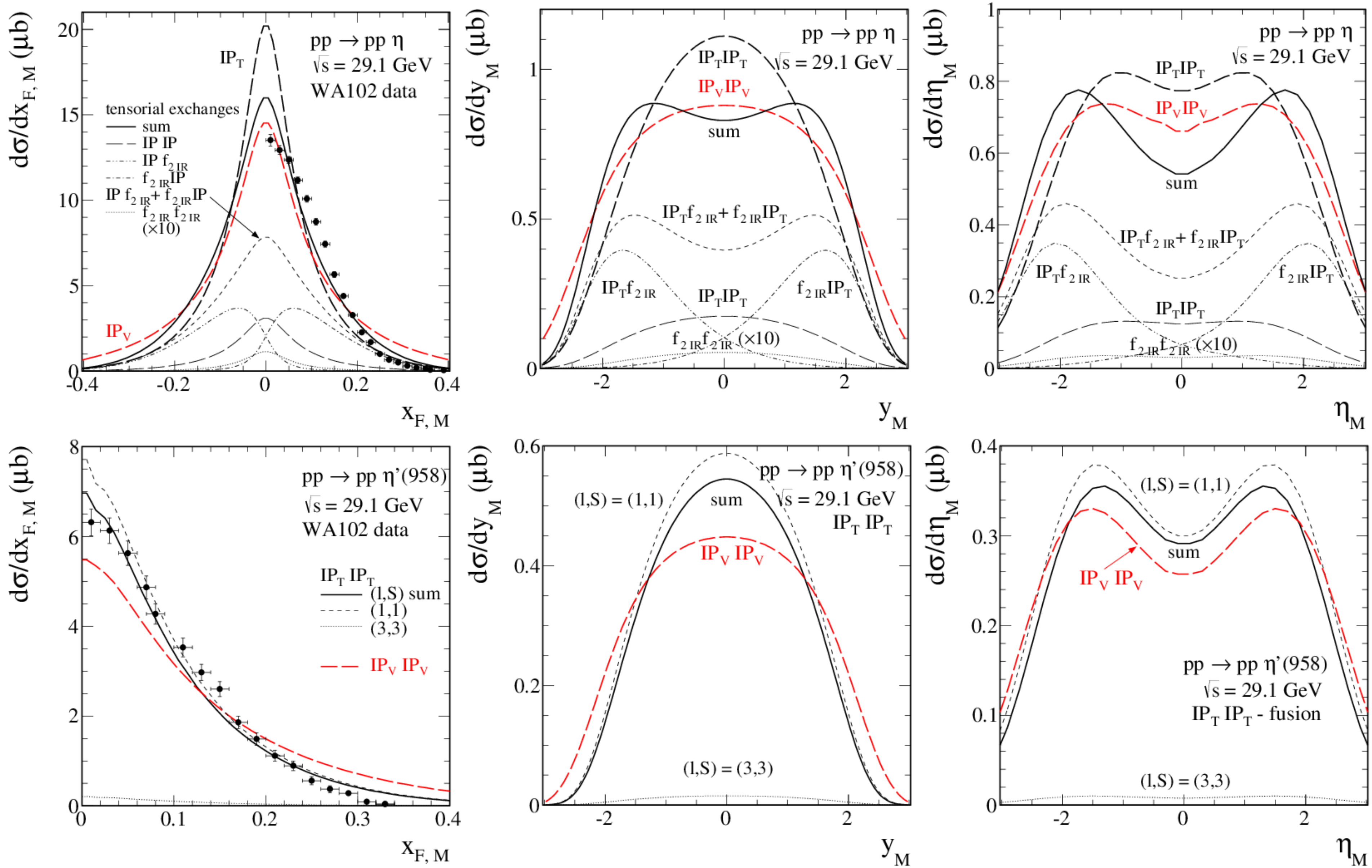


For η production we included subleading exchanges (reggeon-pomeron, pomeron-reggeon, and reggeon-reggeon) which improve the agreement with experimental data.

Production of η' seems to be less affected by contributions from subleading exchanges.

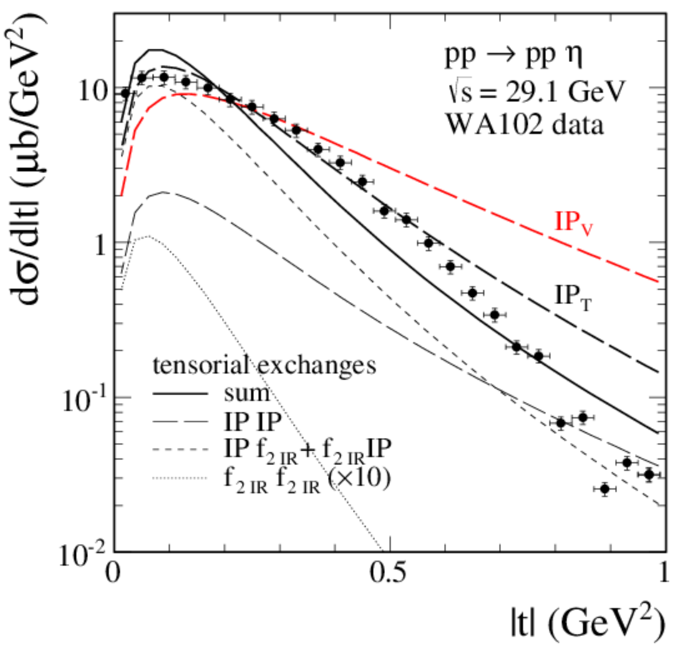
$J^{PC} = 0^{-+}$ $x_{F,M}$, y_M and η_M distributions

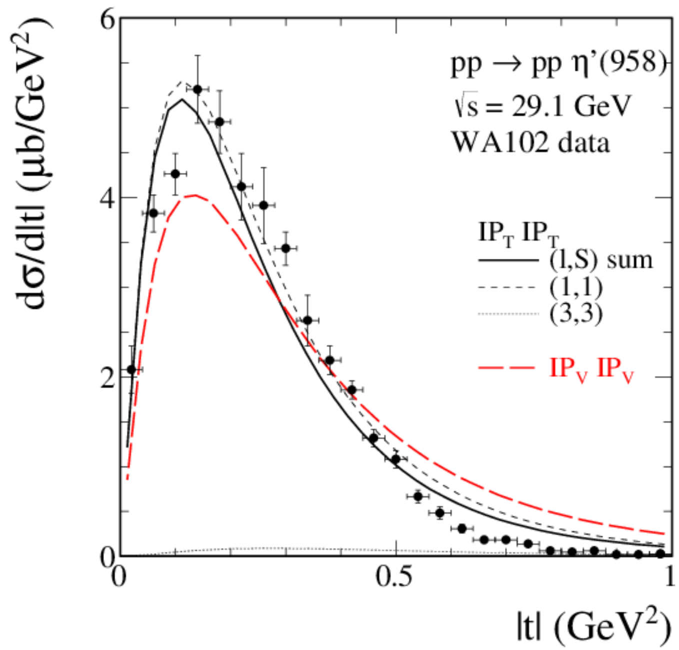
Our results and the WA102 exp. distributions have been normalized to the value of total cross sections given by Kirk.



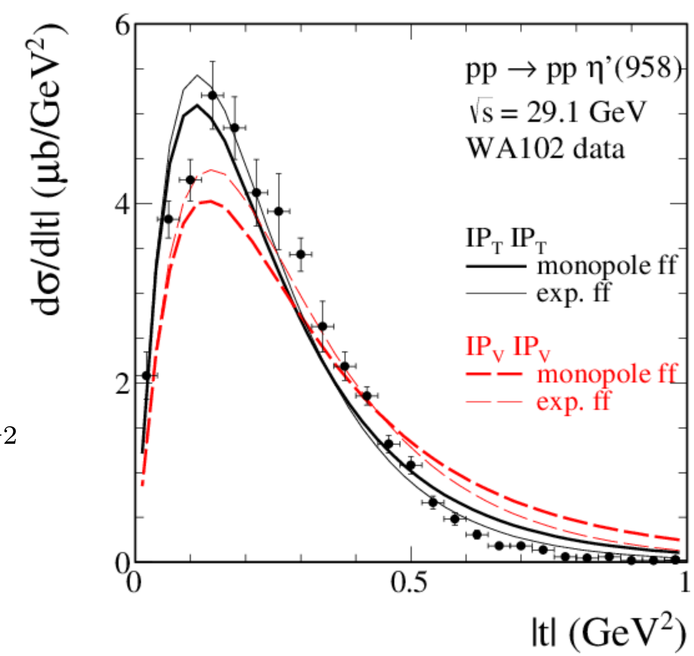
For η meson the enhancement of distributions at larger values of $x_{F,M}$ or y_M can be explained by the pomeron-reggeon exchanges

$J^{PC} = 0^{-+}$ t distribution





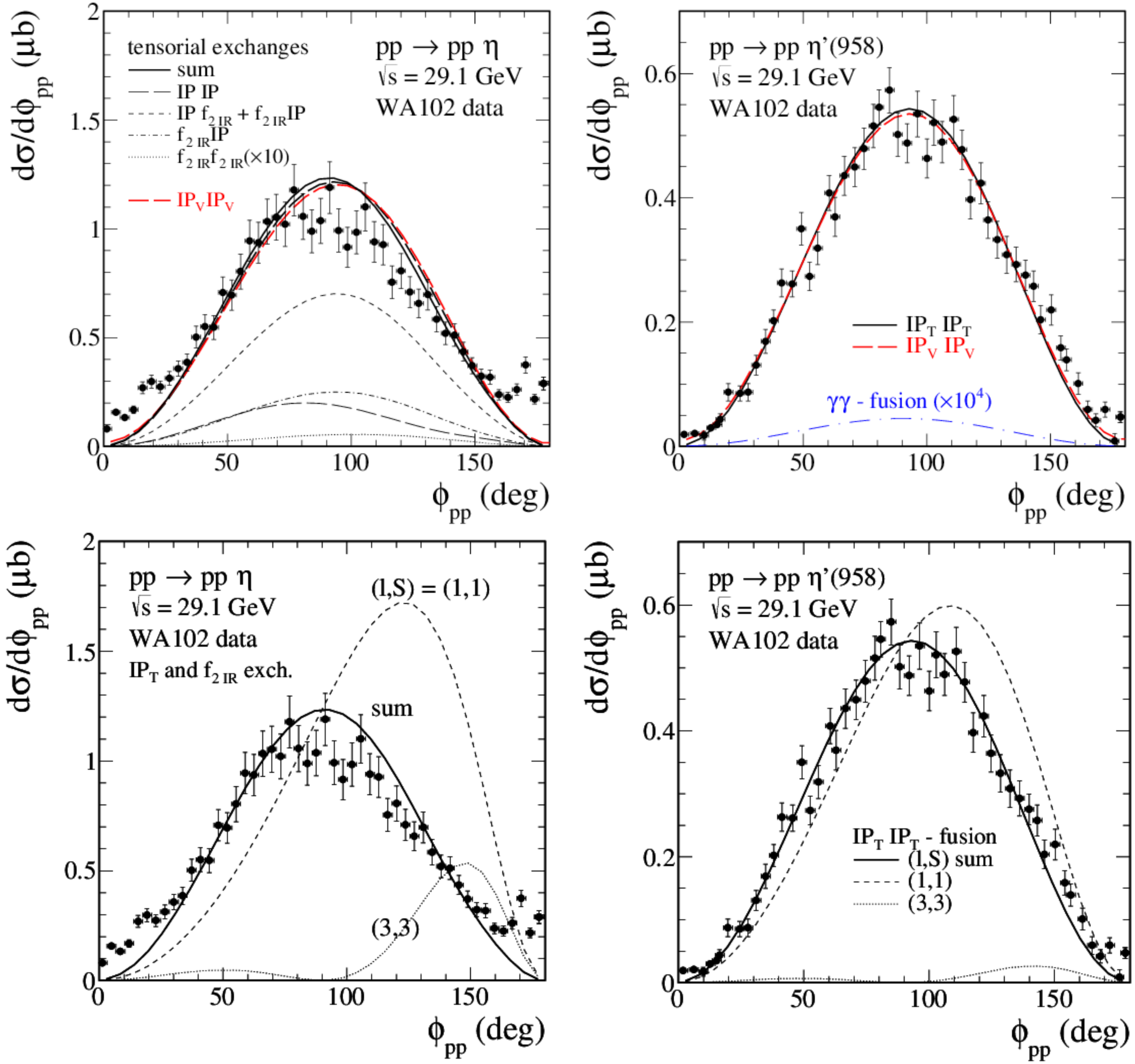
The vectorial pomeron term is disfavoured here.



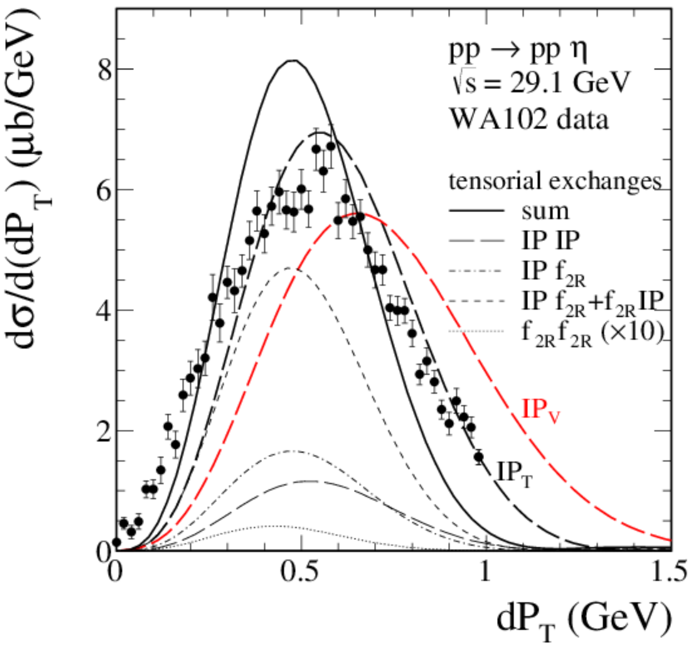
$$F^{M}_{I\!PI\!PM}(t_1,t_2) = F_M(t_1)F_M(t_2)\,, \quad F_M(t) = F_\pi(t) = \frac{1}{1-t/\Lambda_0^2}\,, \quad \Lambda_0^2 = 0.5\ \mathrm{GeV}^2$$

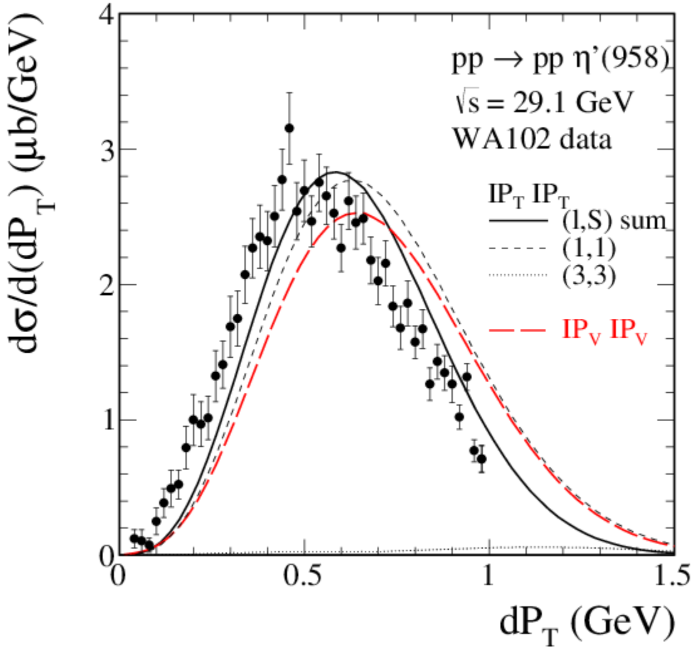
$$F^{E}_{I\!PI\!PM}(t_1,t_2) = \exp\left(\frac{t_1+t_2}{\Lambda_E^2}\right)\,, \quad \Lambda_E^2 = 0.64\ \mathrm{GeV}^2$$

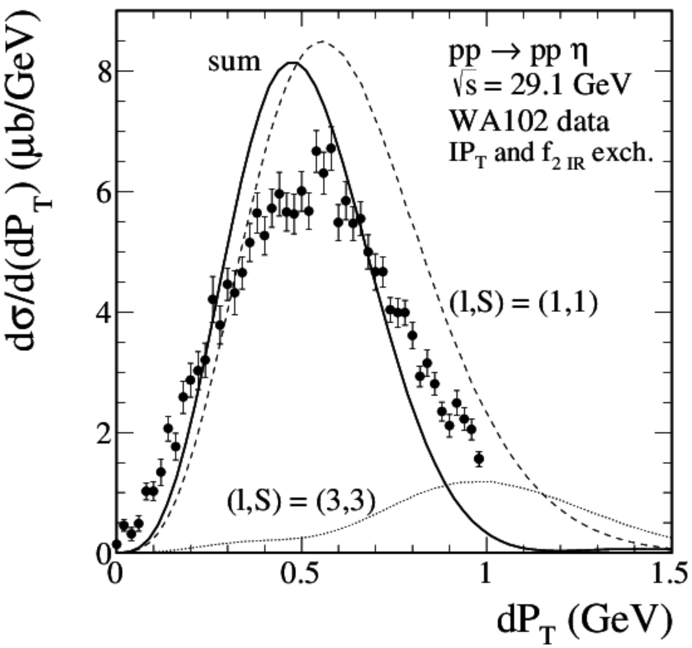
$J^{PC} = 0^{-+}$ ϕ_{pp} distribution



$J^{PC} = 0^{-+}$ dP_T distribution

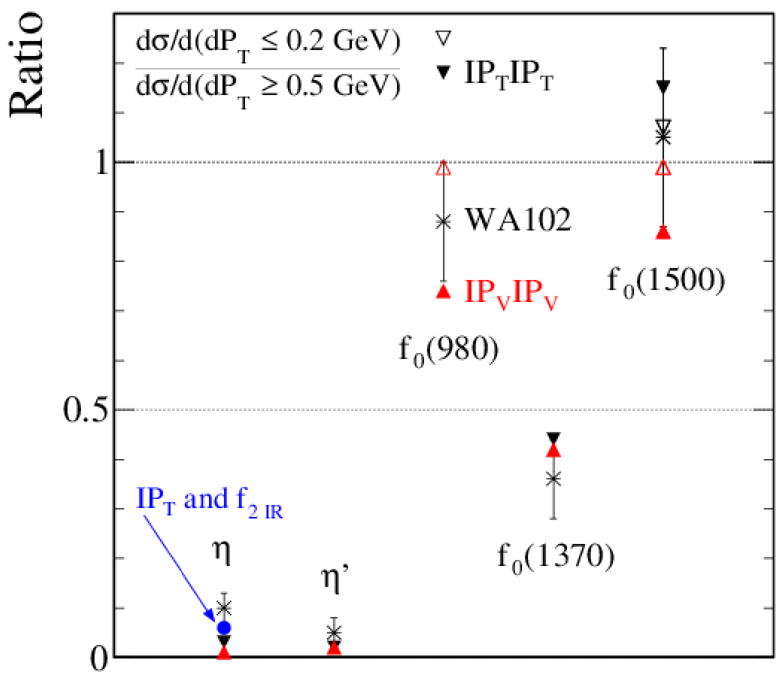






$$\mathrm{dP}_\perp = |d\vec{P}_\perp| = |\vec{q}_{1\perp} - \vec{q}_{2\perp}| = |\vec{p}_{2\perp} - \vec{p}_{1\perp}|$$

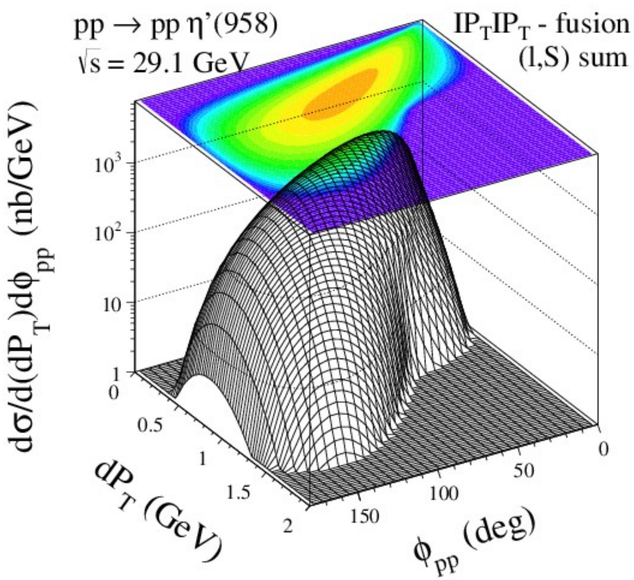
$J^{PC} = 0^{++}$ and 0^{-+} (dP_T, ϕ_{pp}) distributions

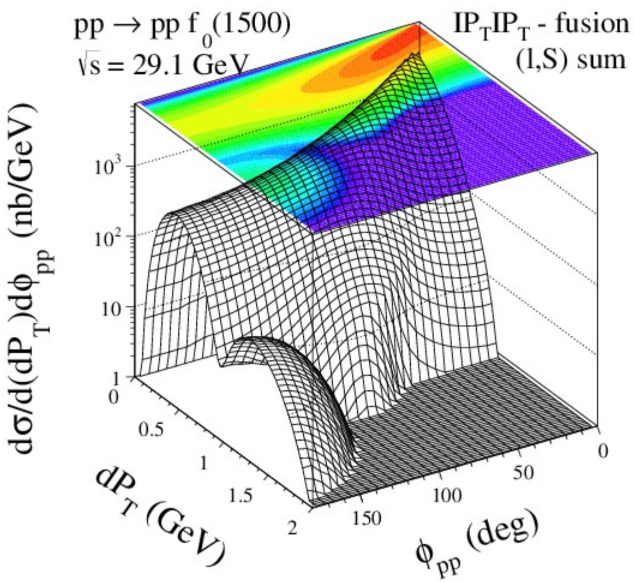


The ratio of mesons production at small $dP_\perp$ to large $dP_\perp$ for two models has been compared with the exp. results from A. Kirk, Phys. Lett. B489 (2000) 29.

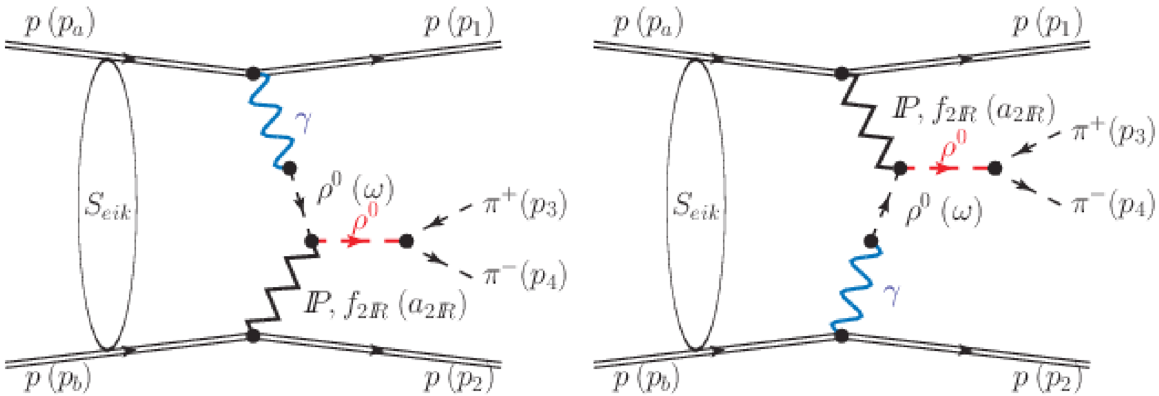
It was observed that all undisputed $q\bar{q}$ states (η, η', $f_1(1285)$ etc.) are suppressed as $dP_\perp \to 0$, whereas the glueball candidates (e.g. $f_0(1500)$, $f_2(1950)$) are prominent.

The $dP_\perp$ and ϕ_{pp} effects
→ in general more than one coupling structure *IP IP M* is possible.





The ρ^0 contribution to CEP of $\pi^+\pi^-$ pairs in pp collisions



$$\mathcal{M}^{(P-\text{wave})} = \mathcal{M}^{\gamma I\!P} + \mathcal{M}^{I\!P\gamma} + \mathcal{M}^{\gamma f_{2I\!R}} + \mathcal{M}^{f_{2I\!R}\gamma}$$

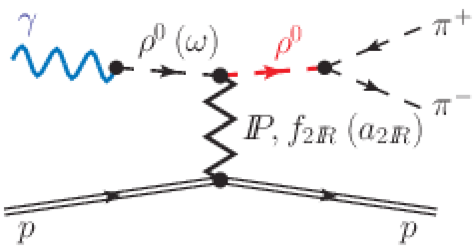
in the Born approximation

$$\mathcal{M}^{\gamma I\!P}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^+\pi^-} = \bar{u}(p_1,\lambda_1) i\Gamma^{(\gamma pp)}_{\mu}(p_1,p_a)u(p_a,\lambda_a)\; i\Delta^{(\gamma)\,\mu\sigma}(q_1)\, i\Gamma^{(\gamma\to\rho)}_{\sigma\nu}(q_1)\; i\Delta^{(\rho)\,\nu\rho_1}(q_1)\, i\Delta^{(\rho)\,\rho_2\kappa}(p_{34})\, i\Gamma^{(\rho\pi\pi)}_{\kappa}(p_3,p_4)$$
$$\times i\Gamma^{(I\!P\rho\rho)}_{\rho_1\rho_2\alpha\beta}(-q_1,-p_{34})\, i\Delta^{(I\!P)\,\alpha\beta\delta\eta}(s_2,t_2)\, \bar{u}(p_2,\lambda_2) i\Gamma^{(I\!P pp)}_{\delta\eta}(p_2,p_b)u(p_b,\lambda_b)$$

$$\mathcal{M}^{\gamma I\!P,\,\gamma f_{2I\!R}}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^+\pi^-} \cong \pm e(p_1+p_a)^{\mu}F_1(t_1)\delta_{\lambda_1\lambda_a}$$
$$\times e\frac{m_\rho^2}{\gamma_\rho}\frac{1}{t_1}\,\Delta^{(\rho)}_{\mu\rho_1}(q_1)\,\Delta^{(\rho)}_{\rho_2\kappa}(p_{34})\,\frac{g_{\rho\pi\pi}}{2}(p_3-p_4)^{\kappa}\,F_{\rho\pi\pi}(s_{34})F_{\rho\pi\pi}(s_{34})$$
$$\times V^{\rho_1\rho_2\alpha\beta}(s_2,t_2)\,2(p_2+p_b)_\alpha(p_2+p_b)_\beta F_M(t_2)F_1(t_2)\delta_{\lambda_2\lambda_b}$$

where the decay vertex for $\rho\to\pi^+\pi^-$ is well known and the coupling constant is $g_{\rho\pi\pi} = 11.51$

Photoproduction of ρ^0 meson



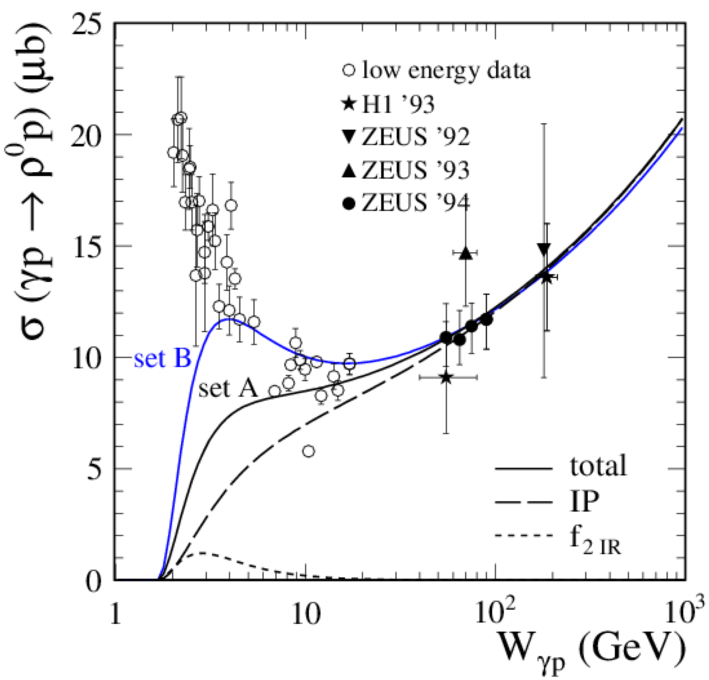
$$\mathcal{M}^{\gamma p \to \rho^0 p}_{\lambda_\gamma \lambda_b \to \lambda_\rho \lambda_2}(s,t) \cong c^{(\gamma\to\rho)} \, (\Delta_T^{(\rho)})^{-1} \, \epsilon^{\mu}_{\gamma} (\epsilon^{\nu}_{\rho})^{*} V_{\mu\nu\kappa\lambda}(s,t) (p_2+p_b)^{\kappa} (p_2+p_b)^{\lambda} \, 2\delta_{\lambda_2 \lambda_b} F_1(t) F_M(t)$$

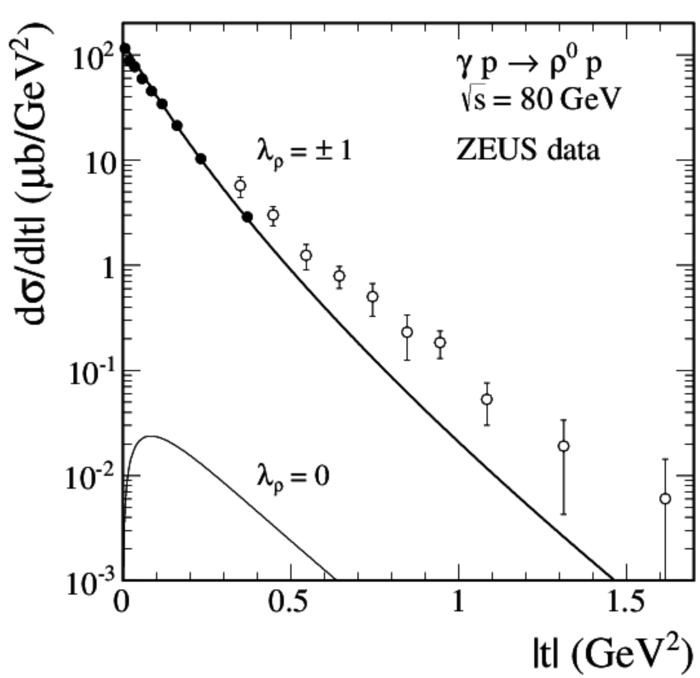
where $c^{(\gamma\to\rho)} = -iem_\rho^2/\gamma_\rho$, $4\pi/\gamma_\rho^2 = 0.496$, $\Delta_T^{(\rho)} = -m_\rho^2 + i m_\rho \Gamma_{\rho,tot}$

$g_{f_{2\mathbb{R}}pp} = 11.04$

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

where two rank-four tensor functions: *C. Ewerz, M. Maniatis and O. Nachtmann, Ann. Phys. 342 (2014) 31*

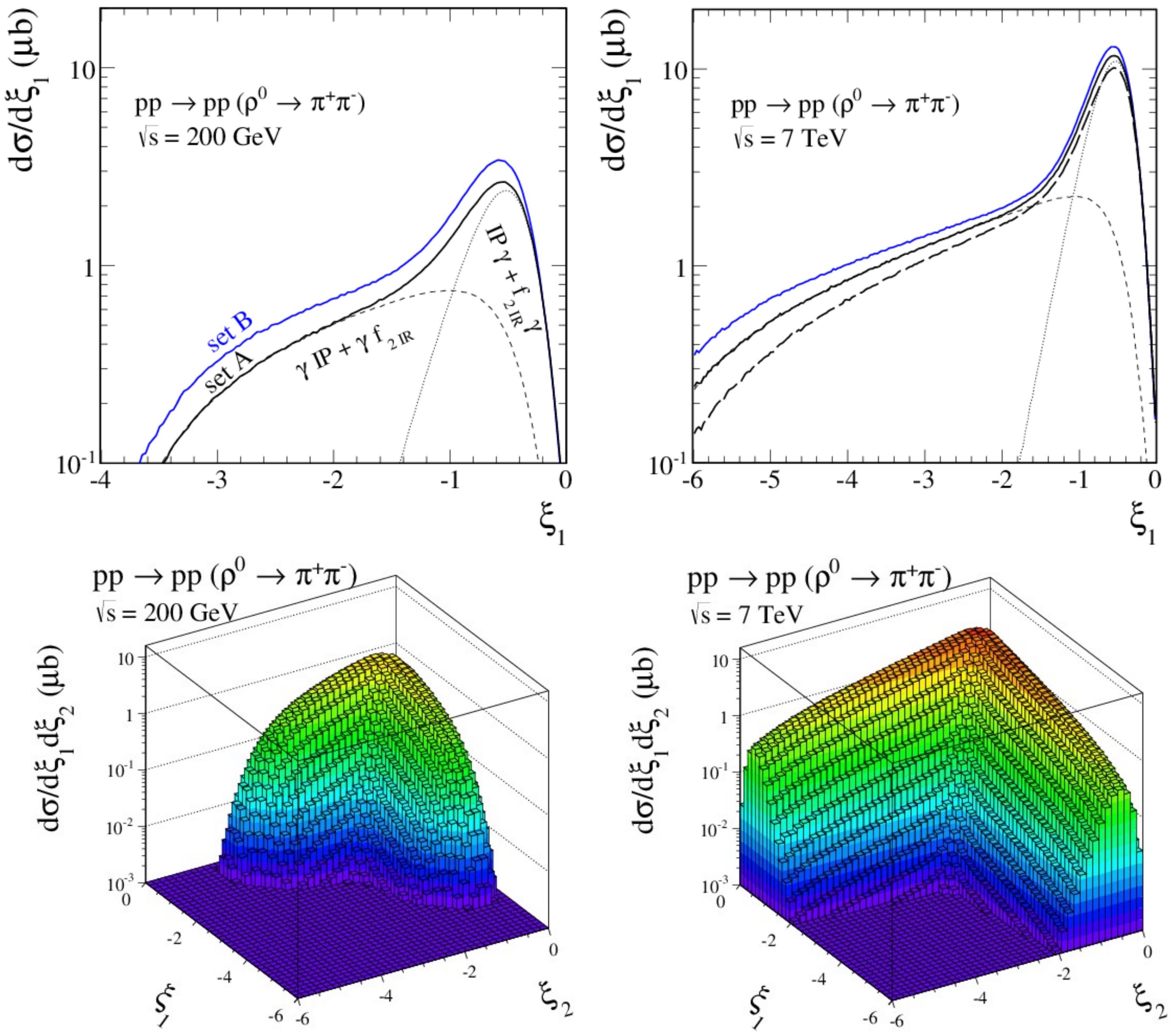




set A : $a_{\mathbb{P}\rho\rho} = 0.45$ GeV^{-3}, $a_{f_{2\mathbb{R}}\rho\rho} = 2.91$ GeV^{-3}, $b_{\mathbb{P}\rho\rho} = 6.50$ GeV^{-1}, $b_{f_{2\mathbb{R}}\rho\rho} = 5.80$ GeV^{-1} (default values)

set B : $a_{\mathbb{P}\rho\rho} = a_{f_{2\mathbb{R}}\rho\rho} = 0$ GeV^{-3}, $b_{\mathbb{P}\rho\rho} = 6.70$ GeV^{-1}, $b_{f_{2\mathbb{R}}\rho\rho} = 14.50$ GeV^{-1}

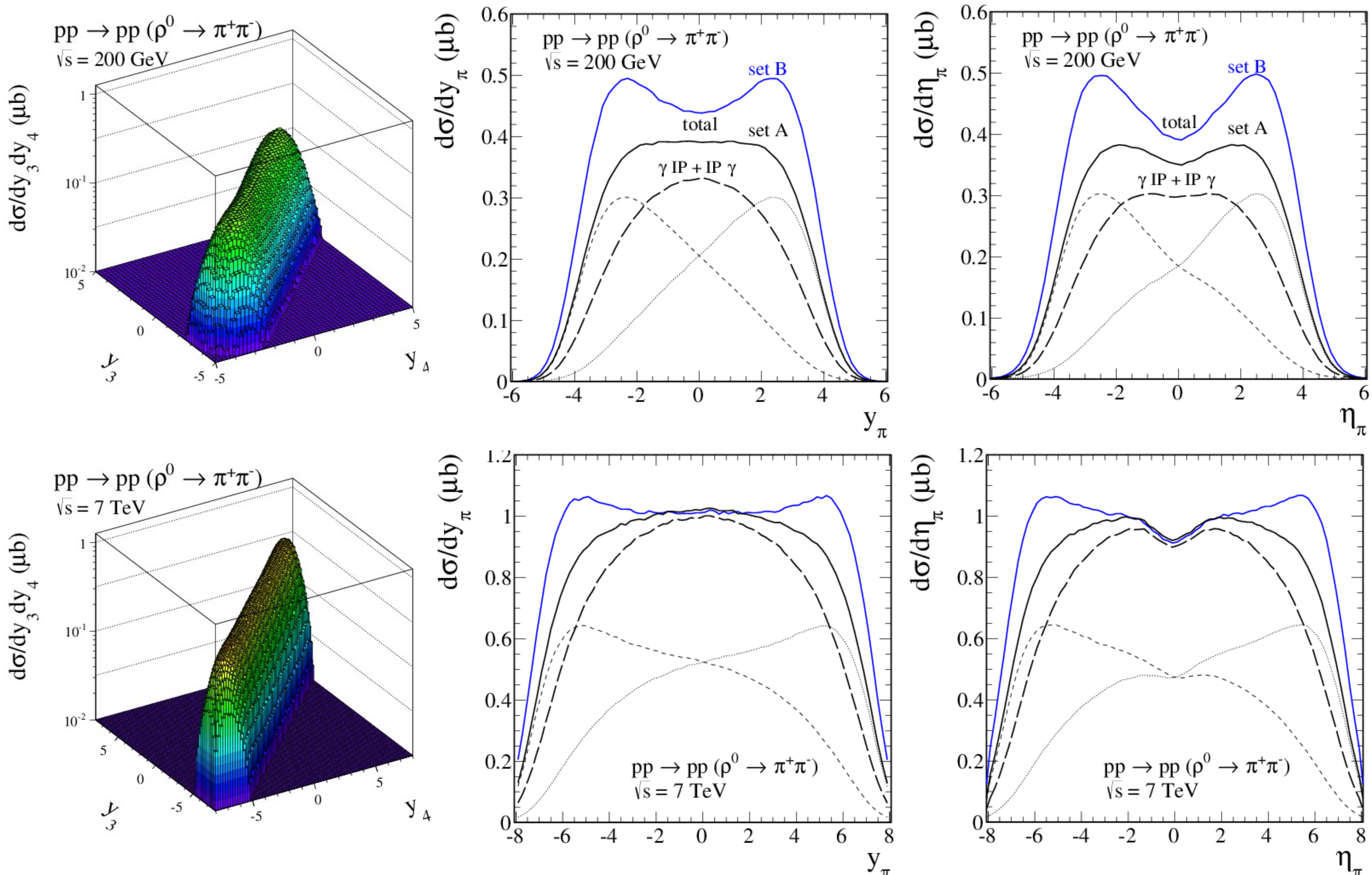
ξ distribution



ξ is auxiliary variable:

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

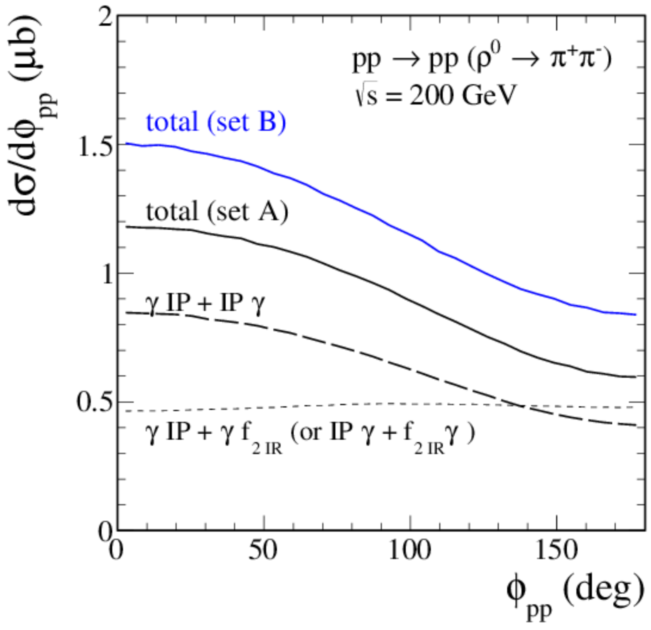
y_π and η_π distributions

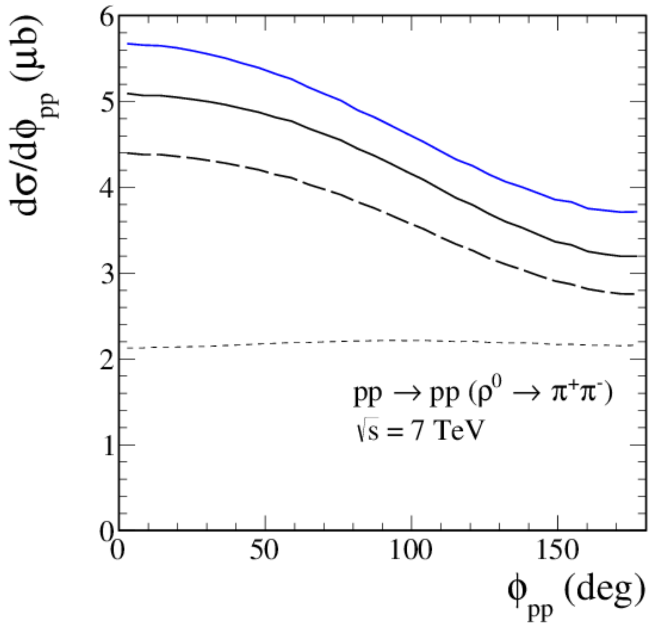


The rapidities of the two pions are strongly correlated and $y_{\pi+} \approx y_{\pi-}$.

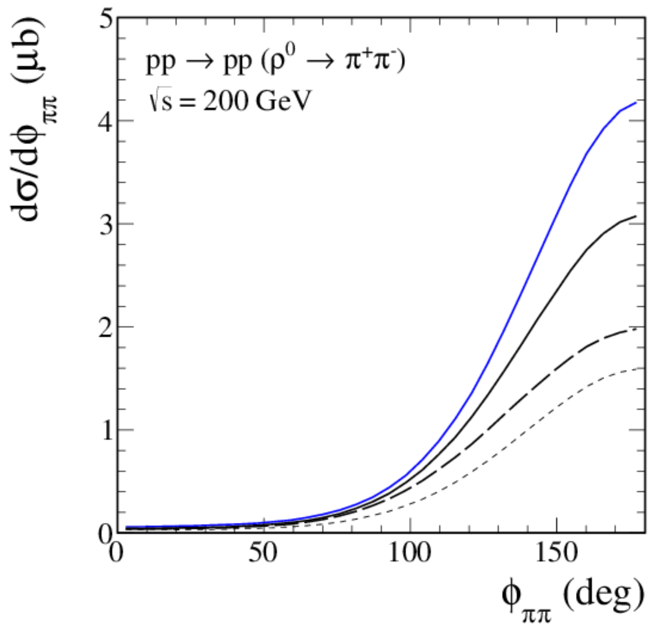
This is similar characteristic as for the double pomeron/reggeon exchanges in the fully diffractive mechanism *P. L. and A. Szczurek, Phys. Rev. D81 (2010) 036003*.

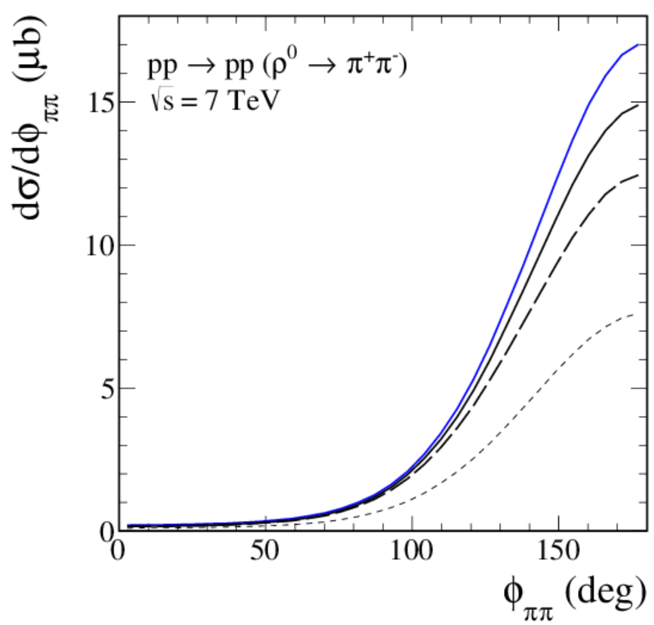
ϕ_{pp} and $\phi_{\pi\pi}$ distributions



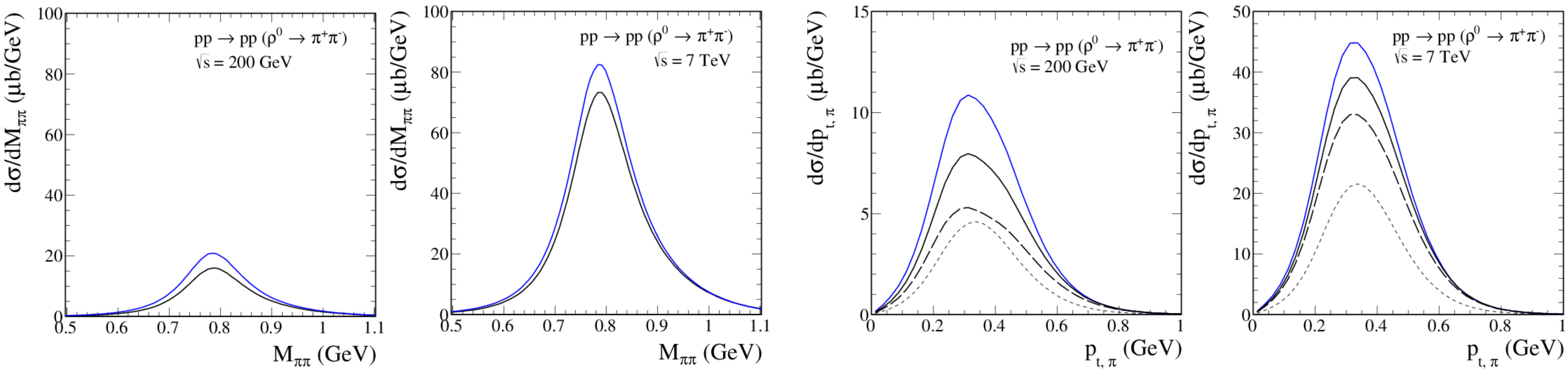


The effect of ϕ_{pp} deviation from a constant is due to interference of *γ-IP* and *IP-γ* amplitudes. Similar effect was discussed in *W. Schäfer and A. Szczurek, Phys. Rev. D76 (2007) 094014* for the exclusive production of *J/ψ* meson.





$M_{\pi\pi}$ and $p_{\perp\pi}$ distributions



$\sigma_{pp\to pp(\rho^0\to\pi^+\pi^-)}$ in μb

$\sqrt{s}$, TeV	cuts	$I\!P$ and $f_{2I\!R}$ set A (set B)	$I\!P$ set A
0.2	–	2.88 (3.73)	2.03
0.5	–	4.67 (5.79)	3.52
1.96	–	8.48 (9.97)	6.88
7	–	13.28 (14.85)	11.45
0.2 (STAR I)	$\lvert\eta_{\pi^\pm}\rvert < 1$, $p_{\perp,\pi^\pm} > 0.15$ GeV, $0.003 < -t_{1,2} < 0.035$ GeV^2	0.032 (0.038)	0.026
0.5 (STAR II)	$\lvert\eta_{\pi^\pm}\rvert < 1$, $p_{\perp,\pi^\pm} > 0.15$ GeV, $0.1 < -t_{1,2} < 1.5$ GeV^2	0.004 (0.004)	0.004
7 (CMS)	$\lvert y_{\pi^\pm}\rvert < 2.5$, $p_{\perp,\pi^\pm} > 0.1$ GeV	4.14 (4.11)	4.02
7 (ALICE)	$\lvert\eta_{\pi^\pm}\rvert < 0.9$, $p_{\perp,\pi^\pm} > 0.1$ GeV	0.91 (0.89)	0.89

Conclusions

- The tensorial pomeron IP_T can equally well describe existing experimental data on the exclusive meson production as the less theoretically justified vectorial pomeron IP_V frequently used in the literature.

- Our study certainly shows the potential of $pp \to pMp$ reactions for testing the nature of the soft pomeron.
  Pseudoscalar meson production could be of particular interest in this respect since
  there the distribution in ϕ_{pp} may contain, for the IP_T, a term which is not possible for the IP_V .
  In most cases ($J^{PC} = 0^{++}, 0^{-+}$) one has to add coherently amplitudes for two lowest (l, S) couplings.
  The corresponding coupling constants are not known and have been fitted to existing experimental data.

- We have made first estimates of central exclusive ρ^0 meson production in the $pp \to pp\pi^+\pi^-$ reaction.
  The ρ^0 contribution cnstitutes 10-20 % of the double pomeron/regggeon contribution
  calculated in a simple Regge model. Similar characteristic of rapidity and $p_{\perp,\pi}$ distributions,
  but different dependence on $p_{\perp,p}$ and ϕ_{pp}.

- Future experimental data (COMPASS, STAR RHIC, CDF Tevatron, ALICE, CMS, ATLAS, etc.)
  on exclusive meson production should thus provide good information on the spin structure
  of the soft pomeron and on its couplings to the nucleon and the mesons.
  see R. Schicker and M. Żurek talks

To-do list

- To extend the studies of central meson production in diffractive processes to higher energies, where the dominance of the *IP* exchange can be better justified.
  The deviation from ‘‘bare’’ distributions is more significant at high energies, where the absorptive corrections should be more important.
- A consistent model of the resonances decaying into the $\pi\pi/KK$ channels (other mesons like $f_2(1270)$) and the non-resonant background. The interference of the resonance signals with the $\pi\pi/KK$ continuum.
- Other mechanisms → see backup slide.

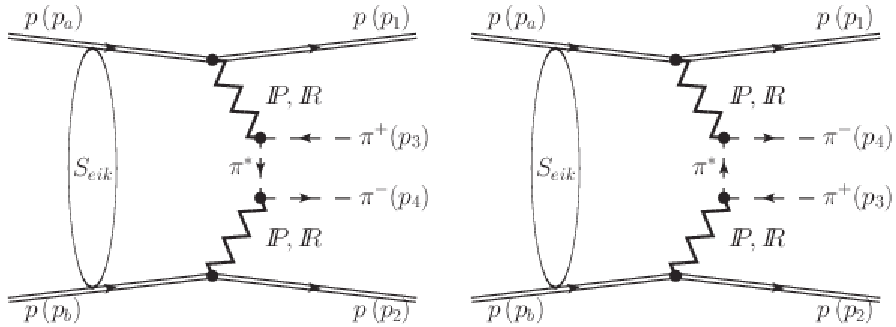
Other mechanisms to $pp \to pp\pi^+\pi^-$ reaction

The measurement of forward/backward protons is crucial in better understanding of the mechanism reaction

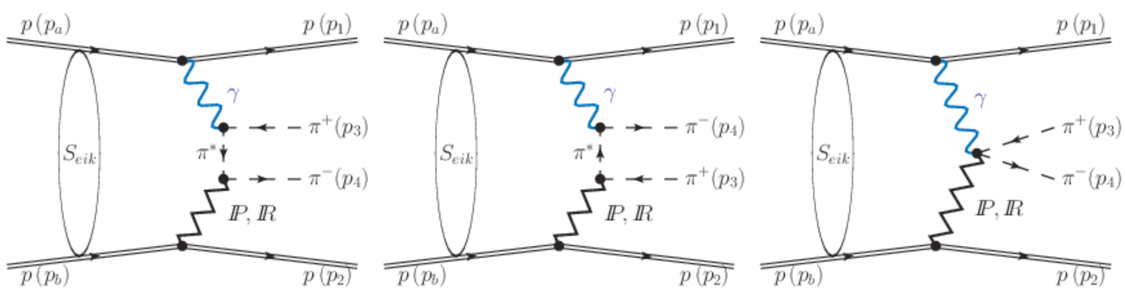
R. Staszewski, P.L., M. Trzebiński, J. Chwastowski, A. Szczurek, Acta Phys. Polon. B42 (2011) 1861) *(ATLAS + ALFA)*

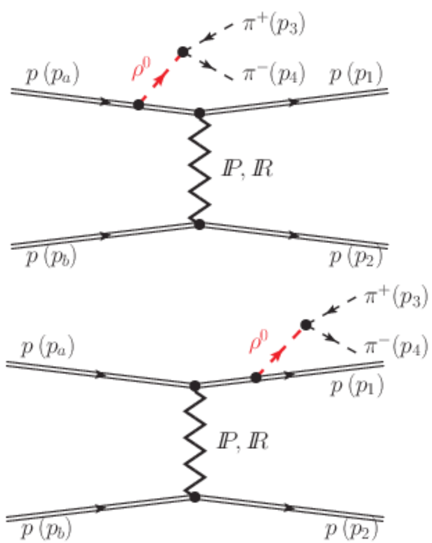
- *(background for scalar and tensor resonances)*

  P. L. and A. Szczurek, Phys. Rev. D81 (2010) 036003 *($pp \to pp\pi^+\pi^-$)*
  P. L., R. Pasechnik and A. Szczurek, Phys. Lett. B701 (2011) 434 *($pp \to pp(\chi_{c0} \to \pi^+\pi^-)$)*
  P. L. and A. Szczurek, Phys. Rev. D85 (2012) 014026 *($pp \to ppK^+K^-$)*



- *(background for ρ^0 resonance)*





A similar bremsstrahlung processes were discussed in pp and/or $p\bar{p}$ collisions at high energies

A. Cisek, P. L., W. Schäfer and A. Szczurek, Phys. Rev. D83 (2011) 114004 *($pp \to pp\pi^0$),*
P. L. and A. Szczurek, Phys. Rev. D87 (2013) 074037 *($pp \to pp\omega$), Phys. Rev. D87 (2013) 114004* *($pp \to pp\gamma$)*