$pp \to ppM$ reactions at high energies

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1. *Exclusive central diffractive production of scalar and pseudoscalar mesons; tensorial vs. vectorial pomeron*

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

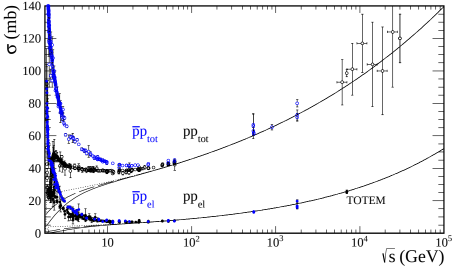
2. *Exclusive* $pp \to pp\pi^0$ *reaction at high energies*

- π^0-bremsstrahlung mechanisms (Drell-Hiida-Deck)
- $\gamma\gamma$ and $\gamma\omega$ $(\omega\gamma)$ exchanges
- $\gamma\mathcal{O}$ $(\mathcal{O}\gamma)$ exchanges

P. Lebiedowicz and A. Szczurek, Phys. Rev. D87 (2013) 074037

Results and Conclusions

Elastic scattering



$$i\mathcal{M}^{2\to 2}_{\lambda_a\lambda_b\to\lambda_1\lambda_2}\,|_{I\!P_V} = \bar{u}(p_1,\lambda_1)\, i\Gamma^{(I\!P_V pp)}_{\mu}(p_1,p_a)\, u(p_a,\lambda_a) \times i\Delta^{(I\!P_V)\,\mu\nu}(s,t) \times \bar{u}(p_2,\lambda_2)\, i\Gamma^{(I\!P_V pp)}_{\nu}(p_2,p_b)\, u(p_b,\lambda_b)$$

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

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

$$i\mathcal{M}^{2\to 2}_{\lambda_a\lambda_b\to\lambda_1\lambda_2}\,|_{I\!P_T} = \bar{u}(p_1,\lambda_1)\, i\Gamma^{(I\!P_T pp)}_{\mu_1\nu_1}(p_1,p_a)\, u(p_a,\lambda_a) \times i\Delta^{(I\!P_T)\,\mu_1\nu_1,\mu_2\nu_2}(s,t) \times \bar{u}(p_2,\lambda_2)\, i\Gamma^{(I\!P_T pp)}_{\mu_2\nu_2}(p_2,p_b)\, u(p_b,\lambda_b)$$

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

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

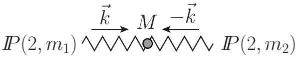
$$\xrightarrow{s\gg 4m_p^2}\; i\,2s\,\left[3\beta_{I\!PNN}\, F_1(t)\right]^2 \left(-is\alpha'_{I\!P}\right)^{\alpha_{I\!P}(t)-1}\; \delta_{\lambda_1\lambda_a}\,\delta_{\lambda_2\lambda_b}$$

$\beta_{I\!PNN} = 1.87\ \mathrm{GeV}^{-1}$, $M_0 = 1\ \mathrm{GeV}$, $\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P}\, t$, $\alpha_{I\!P}(0) = 1.0808$, $\alpha'_{I\!P} = 0.25\ \mathrm{GeV}^{-2}$, $F_1(t) = \dfrac{4m_p^2 - 2.79\,t}{(4m_p^2 - t)(1 - t/m_D^2)^2}$

see C. Ewerz, M. Maniatis and O. Nachtmann, a paper in preparation

What are the possible values of spin J and parity P for meson?

see O. Nachtmann talk



The values of l, S, J, and P possible in the annihilation of two ``vector-pomeron particles'' into a meson 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	

The values of l, S, J, and P possible in the annihilation of two ``spin 2 pomeron particles''.

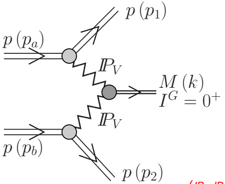
l	S	J	P
0	0	0	+
	2	2	
	4	4	
1	1	0, 1, 2	−
	3	2, 3, 4	
2	0	2	+
	2	0,1,2,3,4	
	4	2,3,4,5,6	
3	1	2,3,4	−
	3	0,1,2,3,4,5,6	
4	0	4	+
	2	2,3,4,5,6	
	4	0,1,2,3,4,5,6,7,8	

		$I\!P_V$		$I\!P_T$	
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

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

The continuation of the table for $l > 4$ is straightforward.

In general, different couplings with different l and S of two ``pomeron particles'' are possible.



$$\langle p(p_1,\lambda_1), p(p_2,\lambda_2), M(k) \,|\, \mathcal{T} \,|\, p(p_a,\lambda_a), p(p_b,\lambda_b)\rangle \,|_{I\!P_V} \equiv$$

$$\mathcal{M}^{2\to3}_{\lambda_a\lambda_b\to\lambda_1\lambda_2 M}\,|_{I\!P_V} = (-i)\bar{u}(p_1,\lambda_1) i\Gamma^{(I\!P_V pp)}_{\mu_1}(p_1,p_a) u(p_a,\lambda_a)$$
$$\times\, i\Delta^{(I\!P_V)\,\mu_1\nu_1}(s_{13},t_1)\;\; i\Gamma^{(I\!P_V I\!P_V\to M)}_{\nu_1\nu_2}(q_1,q_2)\;\; i\Delta^{(I\!P_V)\,\nu_2\mu_2}(s_{23},t_2)$$
$$\times\, \bar{u}(p_2,\lambda_2) i\Gamma^{(I\!P_V pp)}_{\mu_2}(p_2,p_b) u(p_b,\lambda_b)$$

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

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

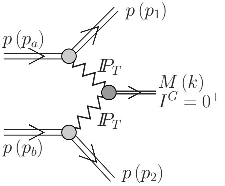
$$i\Gamma'^{(I\!P_V I\!P_V\to M)}_{\mu\nu}\,|_{bare} = i\, g'_{I\!P_V I\!P_V M}\, M_0\, 2g_{\mu\nu}$$

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

$$i\Gamma'^{(I\!P_V I\!P_V\to \tilde{M})}_{\mu\nu}(q_1,q_2)\,|_{bare} = i\,\frac{g'_{I\!P_V I\!P_V \tilde{M}}}{2M_0}\,\varepsilon_{\mu\nu\rho\sigma} q_1^\rho q_2^\sigma$$

The dimensionless coupling constants for scalar mesons $g'_{I\!P_V I\!P_V M}$ ($(l,S) = (0,0)$ term), $g''_{I\!P_V I\!P_V M}$ ($(l,S) = (2,2)$ term) and for pseudoscalar mesons $g'_{I\!P_V I\!P_V \tilde{M}}$ ($(l,S) = (1,1)$ term) can be fixed from the meson production data.

Exclusive production of resonances via $I\!P_T I\!P_T$ fusion



$$\langle p(p_1,\lambda_1),p(p_2,\lambda_2),M(k)\,|\,\mathcal{T}\,|\,p(p_a,\lambda_a),p(p_b,\lambda_b)\rangle\,|_{I\!P_T}\equiv$$

$$\mathcal{M}^{2\to3}_{\lambda_a\lambda_b\to\lambda_1\lambda_2 M}\,|_{I\!P_T} = (-i)\bar{u}(p_1,\lambda_1)i\Gamma^{(I\!P_T pp)}_{\mu_1\nu_1}(p_1,p_a)u(p_a,\lambda_a)$$

$$\times i\Delta^{(I\!P_T)\,\mu_1\nu_1,\kappa_1\lambda_1}(s_{13},t_1)\;\; i\Gamma^{(I\!P_T I\!P_T\to M)}_{\kappa_1\lambda_1,\kappa_2\lambda_2}(q_1,q_2)\;\; i\Delta^{(I\!P_T)\,\kappa_2\lambda_2,\mu_2\nu_2}(s_{23},t_2)$$

$$\times\bar{u}(p_2,\lambda_2)i\Gamma^{(I\!P_T pp)}_{\mu_2\nu_2}(p_2,p_b)u(p_b,\lambda_b)$$

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

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

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

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

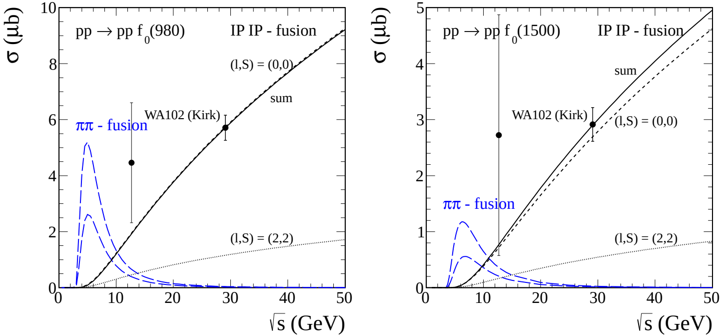
$$i\Gamma''^{(I\!P_T I\!P_T\to \tilde{M})}_{\mu\nu,\kappa\lambda}(q_1,q_2)\,|_{bare} = i\,\frac{g''_{I\!P_T I\!P_T \tilde{M}}}{M_0^3}\{\varepsilon_{\nu\lambda\rho\sigma}[q_{1\kappa}q_{2\mu} - (q_1q_2)g_{\mu\kappa}] + \varepsilon_{\mu\lambda\rho\sigma}[q_{1\kappa}q_{2\nu} - (q_1q_2)g_{\nu\kappa}]$$

$$+\varepsilon_{\nu\kappa\rho\sigma}[q_{1\lambda}q_{2\mu} - (q_1q_2)g_{\mu\lambda}] + \varepsilon_{\mu\kappa\rho\sigma}[q_{1\lambda}q_{2\nu} - (q_1q_2)g_{\nu\lambda}]\}(q_1-q_2)^{\rho}k^{\sigma}$$

The coupling constants for scalar mesons $g'_{I\!P_T I\!P_T M}$ ($(l,S)=(0,0)$ term), $g''_{I\!P_T I\!P_T M}$ ($(l,S)=(2,2)$ term) and for pseudoscalar mesons $g'_{I\!P_T I\!P_T \tilde{M}}$ ($(l,S)=(1,1)$ term), $g''_{I\!P_T I\!P_T \tilde{M}}$ ($(l,S)=(3,3)$ term) can be fixed from the meson production data.

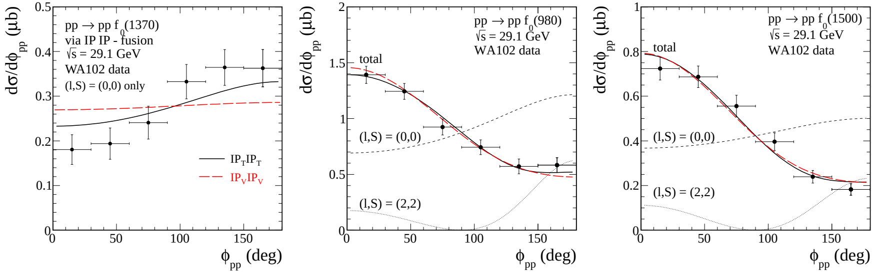
Experimental results for total cross sections of scalar mesons in *pp* collisions at $\sqrt{s} = 29.1$ GeV (WA102)
A. Kirk, Phys. Lett. B489 (2000) 29

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



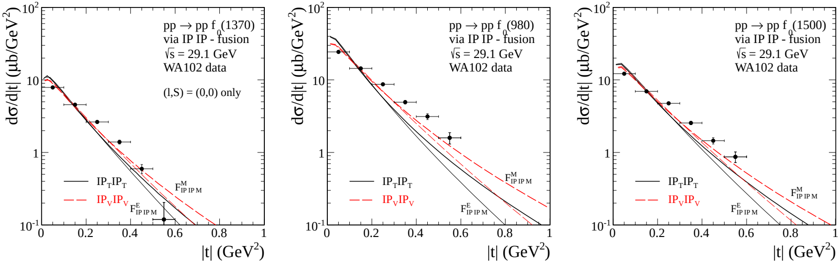
Distribution in azimuthal angle between outgoing protons

Our results and the WA102 experimental distributions have been normalized to the mean value of the total cross section given by Kirk.



- The preference of the $f_0(1370)$ for the $\phi_{pp} \approx \pi$ domain in contrast to the enigmatic $f_0(980)$ and $f_0(1500)$.
- 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.

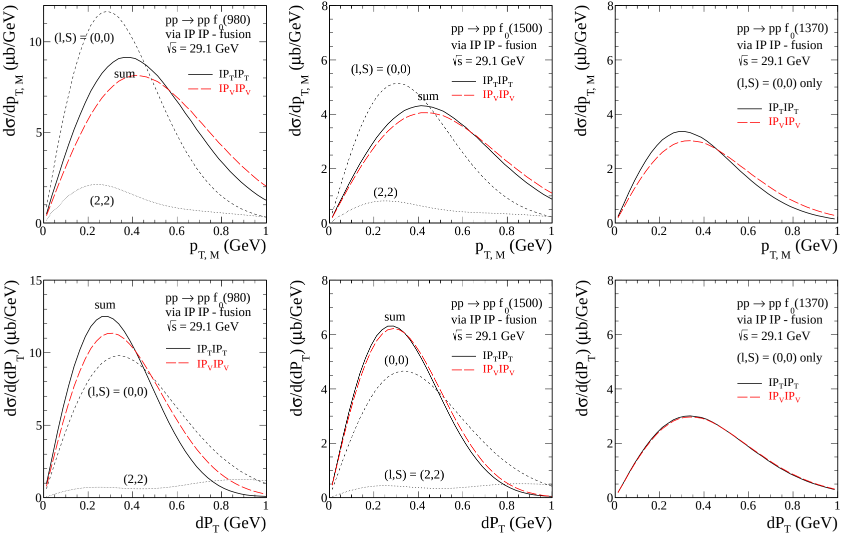
Vertex	$(0, 0)$ term	$(2, 2)$ term
$IP_T IP_T f_0(980)$	0.79	4
$IP_V IP_V f_0(980)$	0.27	0.8
$IP_T IP_T f_0(1500)$	1.22	6
$IP_V IP_V f_0(1500)$	0.21	0.73
$IP_T IP_T f_0(1370)$	0.81	--
$IP_V IP_V f_0(1370)$	0.17	--



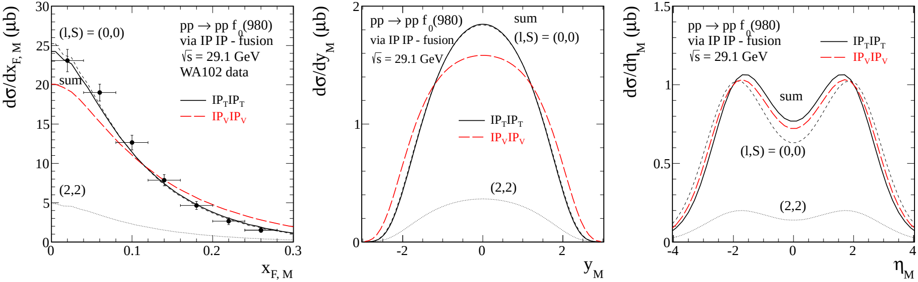
$$F^M_{IPIPM}(t_1, t_2) = F_M(t_1) F_M(t_2)\,, \quad F_M(t) = F_\pi(t) = \frac{1}{1 - t/\Lambda_0^2}\,, \quad \Lambda_0^2 = 0.5 \text{ GeV}^2$$

$$F^E_{IPIPM}(t_1, t_2) = \exp\left(\frac{t_1 + t_2}{\Lambda_E^2}\right)\,, \quad \Lambda_E^2 = 0.64 \text{ GeV}^2$$

$p_{\perp,M}$ and $dP_\perp = |d\vec{P}_\perp| = |\vec{q}_{1\perp} - \vec{q}_{2\perp}| = |\vec{p}_{2\perp} - \vec{p}_{1\perp}|$

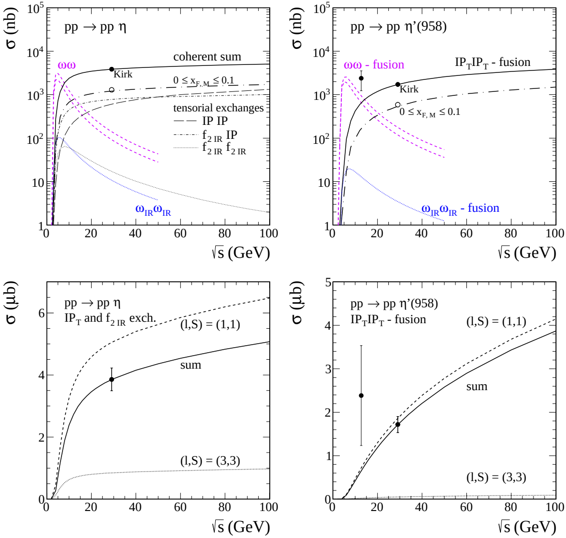


$x_{F,M}$, y_M, and η_M distributions



Pseudoscalar mesons

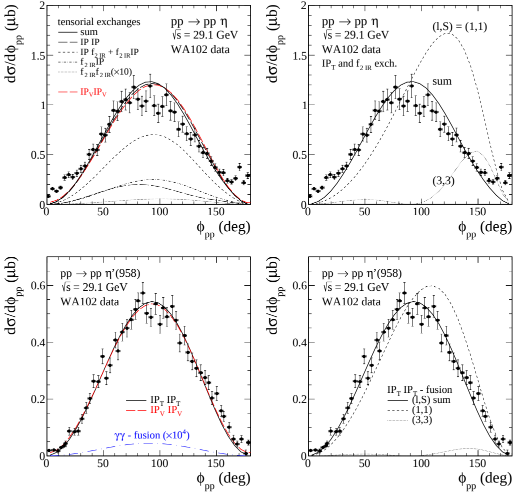
For η production we included subleading exchanges (reggeon-pomeron, pomeron-reggeon, and reggeon-reggeon) which improve the agreement with experimental data.



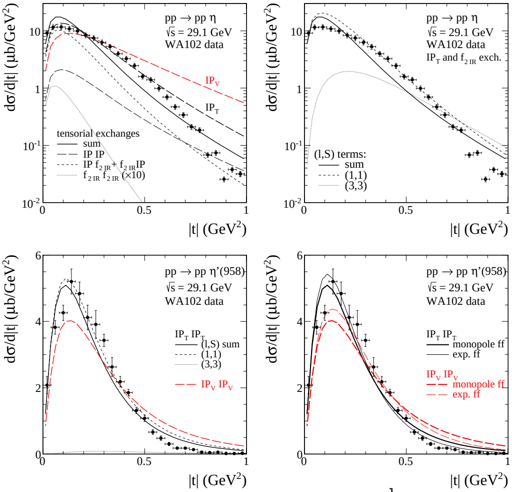
$\sigma(\eta) = 3.86 \pm 0.37\ \mu$b, $\sigma(\eta') = 1.72 \pm 0.18\ \mu$b from A. Kirk, Phys. Lett. **B489** (2000) 29

ϕ_{pp} distribution

Our results and the WA102 experimental distributions have been normalized to the mean value of the total cross section given by Kirk.



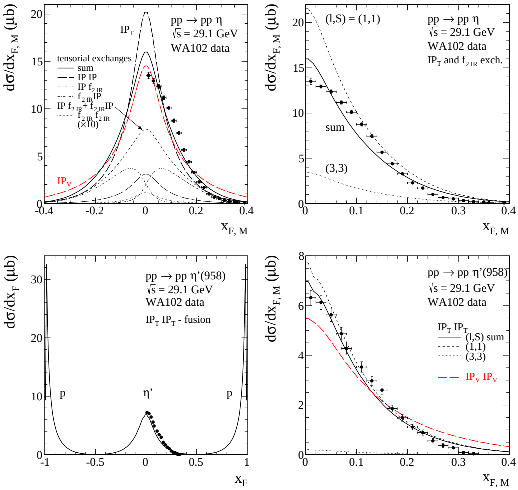
t distribution



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

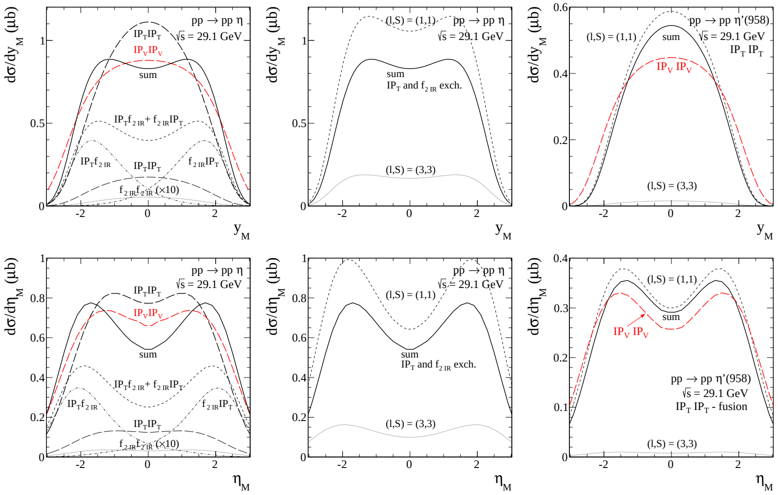
$$F^{E}_{IPIPM}(t_1, t_2) = \exp\left(\frac{t_1 + t_2}{\Lambda_E^2}\right)\,, \quad \Lambda_E^2 = 0.64\ \mathrm{GeV}^2$$

$x_{F,M}$ distribution

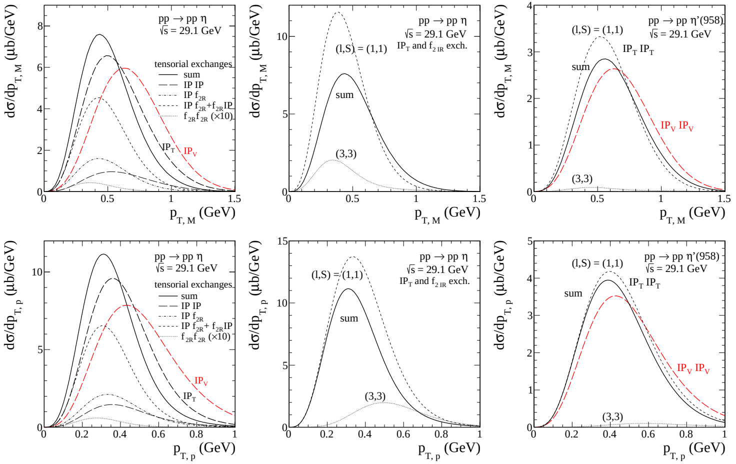


- The meson distribution peaks at $x_F = 0$ and the protons at $x_F \to \pm 1$.
- The enhancement of the η distribution at larger values of $x_{F,M}$ can be explained by $f_{2IR}IP$ and IPf_{2IR} exchanges.
- Production of η' seems to be less affected by contributions from subleading exchanges.

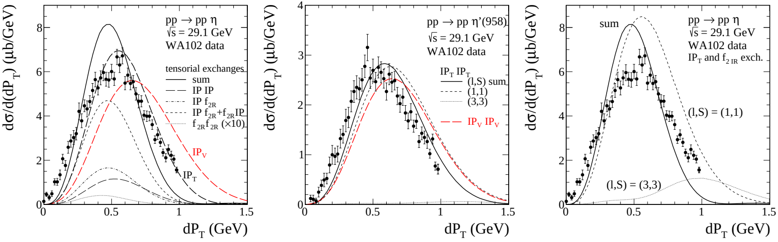
y_M and η_M distributions

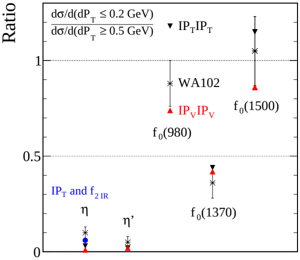


$p_{\perp,M}$ and $p_{\perp,p}$ distributions



$dP_\perp$ distribution

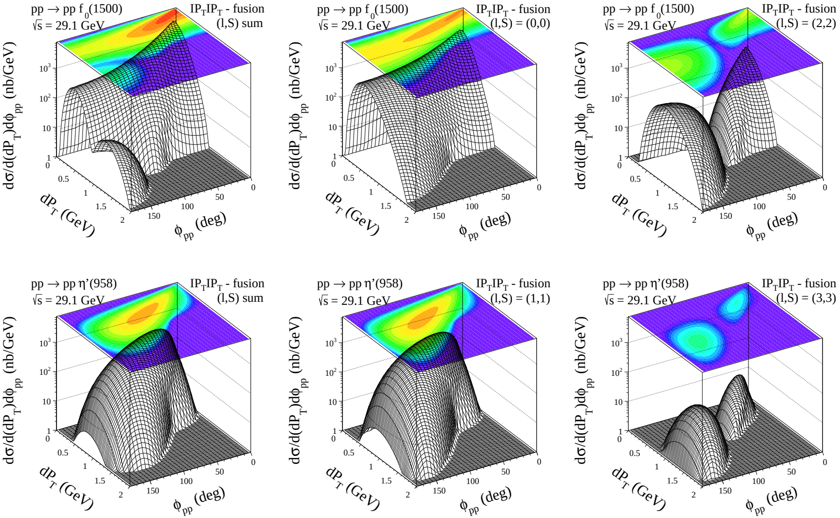




The ratio of mesons production at small $dP_\perp$ to large $dP_\perp$ for two models has been compared with the experimental results from A. Kirk, Phys. Lett. B489 (2000) 29.

It can be observed that scalar mesons which could have a large 'gluonic component' have a large value for this ratio.

$(dP_\perp, \phi_{pp})$ distribution



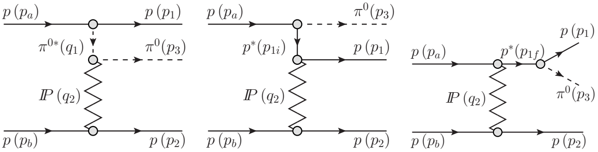
The $dP_\perp$ and ϕ_{pp} effects are understood as being due to the fact that in general more than one coupling structure *IPIPM* is possible.

It remains a challenge for theory to predict these coupling structure from calculations in the framework of QCD.

Conclusions

- The tensorial pomeron $I\!P_T$ can equally well describe existing experimental data on the exclusive meson production as the less theoretically justified vectorial pomeron $I\!P_V$ frequently used in the literature.
- In most cases 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.
- 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 $I\!P_T$, a term which is not possible for the $I\!P_V$.
- Future experimental data on exclusive meson production at high energies should thus provide good information on the spin structure of the soft pomeron and on its couplings to the nucleon and the mesons.
- To-do list
    - A consistent model of the resonances decaying e.g. into the $\pi\pi$ channel and the non-resonant background. The interference of the resonance signals with the $\pi\pi$ continuum.
    - The central production of other mesons like the $f_2(1270)$.
    - To extend the studies of central meson production in diffractive processes to higher energies, where the dominance of the $I\!P$ exchange can be better justified.
    - Absorption effects may also change the shapes of t_1/t_2, ϕ_{pp}, etc. distributions. The deviation from ``bare'' distributions probably is more significant at high energies where the absorptive corrections should be more important.

$pp \to pp\pi^0$, diffractive bremsstrahlung mechanisms



$$\begin{aligned}
\mathcal{M}^{(\pi-\text{exchange})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^0} &= \bar{u}(p_1,\lambda_1)i\gamma_5 u(p_a,\lambda_a)\, S_\pi(t_1)\, g_{\pi NN}\, F_{\pi^* NN}(t_1) F_{\mathbb{P}\pi^*\pi}(t_1) \\
&\times \left(A_P^{\pi N}(s_{23},t_2) + A_R^{\pi N}(s_{23},t_2)\right)\ /(2s_{23}) \\
&\times (q_1+p_3)_\mu\, \bar{u}(p_2,\lambda_2)\gamma^\mu u(p_b,\lambda_b) \\
\mathcal{M}^{(p-\text{exchange})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^0} &= g_{\pi NN}\, \bar{u}(p_1,\lambda_1)\gamma^\mu S_N(p_{1i}^2) i\gamma_5 u(p_a,\lambda_a)\, F_{\pi NN^*}(p_{1i}^2)\, F_{\mathbb{P}N^*N}(p_{1i}^2)\, \mathcal{F}_{N^*}(s_{13},t_1) \\
&\times \left(A_P^{NN}(s_{12},t_2) + A_R^{NN}(s_{12},t_2)\right)\ /(2s_{12}) \\
&\times \bar{u}(p_2,\lambda_2)\gamma_\mu u(p_b,\lambda_b) \\
\mathcal{M}^{(\text{direct production})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^0} &= g_{\pi NN}\, \bar{u}(p_1,\lambda_1) i\gamma_5 S_N(p_{1f}^2)\gamma^\mu u(p_a,\lambda_a)\, F_{\pi N^* N}(p_{1f}^2)\, F_{\mathbb{P}NN^*}(p_{1f}^2) \\
&\times \left(A_P^{NN}(s,t_2) + A_R^{NN}(s,t_2)\right)\ /(2s) \\
&\times \bar{u}(p_2,\lambda_2)\gamma_\mu u(p_b,\lambda_b)
\end{aligned}$$

Drell-Hiida-Deck model

see $pp \to pp\omega$ [a] and $pp \to pp\gamma$ [b] processes

[a] A. Cisek, P. L., W. Schäfer and A. Szczurek, Phys. Rev. D83 (2011) 114004

[b] P. L. and A. Szczurek, Phys.Rev. D87 (2013) 114013

$pp \to pp\pi^0$, diffractive bremsstrahlung mechanisms

- The energy dependence of the elastic scattering $A(s,t)$ was parametrized in the Regge-like form with pomeron ($i = \mathbb{P}$) and reggeon ($i = \mathbb{R} = f_2, \rho, a_2, \omega$) exchanges

$$A_i^{el}(s,t) = \eta_i \, C_i \, s \left(\frac{s}{s_0}\right)^{\alpha_i(t)-1} \exp\left(\frac{B_i^{el} t}{2}\right)$$

the effective slope of the elastic differential cross section $B(s) = B_i^{el} + 2\alpha_i' \ln\left(s/s_0\right)$
where we use the scale parameter $s_0 = 1$ GeV^2
$B_{\mathbb{P}}^{NN} = 9$ GeV^{-2}, $B_{\mathbb{P}}^{\pi N} = 5.5$ GeV^{-2}, $B_{\mathbb{R}}^{NN} = 6$ GeV^{-2}, $B_{\mathbb{R}}^{\pi N} = 4$ GeV^{-2}
C_i, η_i and $\alpha_i(t) = \alpha_i(0) + \alpha_i' \, t$ from Donnachie-Landshoff analysis of the total NN and πN cross sections and the optical theorem $\sigma^{tot}(s) \cong 1/s \, \mathrm{Im} A^{el}(s, t=0)$
see P. L. and A. Szczurek, Phys. Rev. D81 (2010) 036003

- off-shell nucleon

$$F(p^2) = \frac{\Lambda_N^4}{(p^2 - m_p^2)^2 + \Lambda_N^4}$$

off-shell pion

$$F(t) = \exp\left(\frac{t - m_\pi^2}{\Lambda_\pi^2}\right)$$

- We use a generalized pion propagator

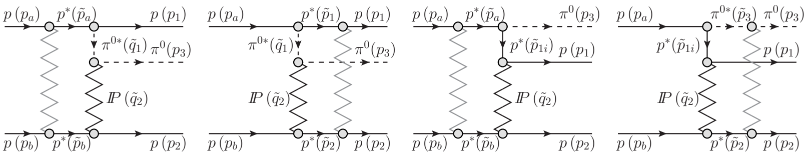
$$S_\pi(t) \to \beta_M(s) S_\pi(t) + \beta_R(s) \mathcal{P}^\pi(t,s)$$

where the pion Regge propagator gives a suppression for large values of t

$$\mathcal{P}^\pi(t,s) = \frac{\pi \alpha_\pi'}{2\Gamma(\alpha_\pi(t)+1)} \frac{1 + \exp(-i\pi\alpha_\pi(t))}{\sin(\pi\alpha_\pi(t))} \left(\frac{s}{s_0}\right)^{\alpha_\pi(t)}$$

- We improve the ρ-exchange amplitude to reproduce the high-energy Regge dependence: $\mathcal{F}_{N^*}(s_{13}, t_1)$

$pp \to pp\pi^0$, absorption effects



$$\mathcal{M}_{\rm abs}(-\boldsymbol{p}_{1\perp},-\boldsymbol{p}_{2\perp}) = \mathcal{M}(-\boldsymbol{p}_{1\perp},-\boldsymbol{p}_{2\perp}) - \delta\mathcal{M}(-\boldsymbol{p}_{1\perp},-\boldsymbol{p}_{2\perp})$$

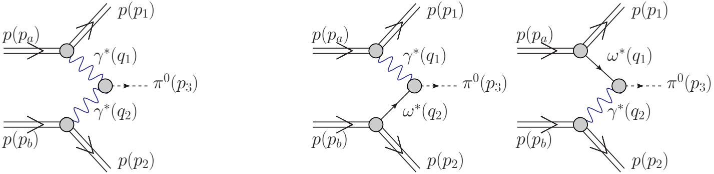
$\delta\mathcal{M}$ for the diagrams with "initial-state" absorption is the sum of convolution integral

$$\delta\mathcal{M}^{\rm initial\ state\ abs}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^0}(-\boldsymbol{p}_{1\perp},-\boldsymbol{p}_{2\perp}) = \frac{i}{8\pi^2 s}\int d^2k_\perp\, A^{NN}_{\lambda_a\lambda_b\to\lambda'_a\lambda'_b}(s,\boldsymbol{k}_\perp)\Big[\mathcal{M}^{(\pi-{\rm exchange})}_{\lambda'_a\lambda'_b\to\lambda_1\lambda_2\pi^0}(-\tilde{\boldsymbol{p}}_{1\perp},-\tilde{\boldsymbol{p}}_{2\perp}) + \mathcal{M}^{(p-{\rm exchange})}_{\lambda'_a\lambda'_b\to\lambda_1\lambda_2\pi^0}(-\tilde{\boldsymbol{p}}_{1\perp}$$

and in the case of diagrams with "final-state" absorption we have

$$\begin{aligned}\delta\mathcal{M}^{\rm final\ state\ abs}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^0}(-\boldsymbol{p}_{1\perp},-\boldsymbol{p}_{2\perp}) \quad = \quad & \frac{i}{8\pi^2}\int d^2k_\perp \frac{1}{s_{12}}\mathcal{M}^{(\pi-{\rm exchange})}_{\lambda_a\lambda_b\to\lambda'_1\lambda'_2\pi^0}(-\tilde{\boldsymbol{p}}_{1\perp},-\tilde{\boldsymbol{p}}_{2\perp})\, A^{NN}_{\lambda'_1\lambda'_2\to\lambda_1\lambda_2}(s_{12},\boldsymbol{k}_\perp) \\ & + \frac{i}{8\pi^2}\int d^2k_\perp \frac{1}{s_{23}}\mathcal{M}^{(p-{\rm exchange})}_{\lambda_a\lambda_b\to\lambda_1\lambda'_2\pi^0}(-\tilde{\boldsymbol{p}}_{1\perp},-\tilde{\boldsymbol{p}}_{2\perp})\, A^{\pi N}_{\lambda'_2\to\lambda_2}(s_{23},\boldsymbol{k}_\perp)\end{aligned}$$

where $-\tilde{\boldsymbol{p}}_{1\perp} = -\boldsymbol{p}_{1\perp} + \boldsymbol{k}_\perp, -\tilde{\boldsymbol{p}}_{2\perp} = -\boldsymbol{p}_{2\perp} - \boldsymbol{k}_\perp$ and $\boldsymbol{k}_\perp$ is the momentum transfer



$$\mathcal{M}^{\gamma\gamma-\text{exchange}}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^0} = e\,\bar{u}(p_1,\lambda_1)\gamma^\mu u(p_a,\lambda_a)\,F_1(t_1)$$
$$\times\ \frac{g_{\mu\mu'}}{t_1}\,(-i)\,e^2\,\epsilon^{\mu'\nu'\rho\sigma}\,q_{1,\rho}q_{2,\sigma}\,F_{\gamma^*\gamma^*\to\pi^0}(t_1,t_2)\,\frac{g_{\nu\nu'}}{t_2}$$
$$\times\ e\,\bar{u}(p_2,\lambda_2)\gamma^\nu u(p_b,\lambda_b)\,F_1(t_2)$$
$$\mathcal{M}^{\gamma\omega-\text{exchange}}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^0} = e\,\bar{u}(p_1,\lambda_1)\gamma^\mu u(p_a,\lambda_a)\,F_1(t_1)$$
$$\times\ \frac{g_{\mu\mu'}}{t_1}\,(-i)\,g_{\gamma\omega\pi^0}\,\epsilon^{\mu'\nu'\rho\sigma}\,q_{1,\rho}q_{2,\sigma}\,F_{\gamma^*\omega^*\to\pi^0}(t_1,t_2)\,\frac{-g_{\nu\nu'}+q_\nu q_{\nu'}/m_\omega^2}{t_2-m_\omega^2}$$
$$\times\ g_{\omega NN}\,\bar{u}(p_2,\lambda_2)\gamma^\nu u(p_b,\lambda_b)\,F_{\omega NN}(t_2)\,\mathcal{F}_\omega(s_{23},t_2)$$

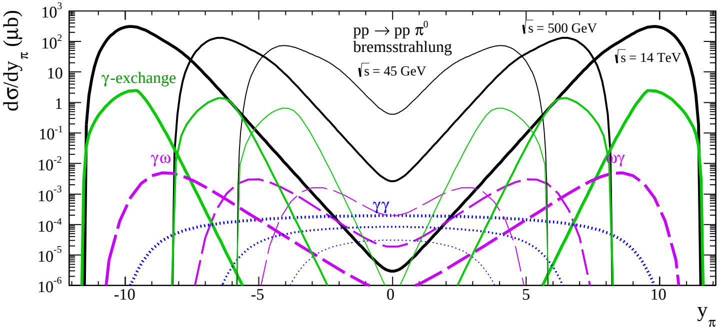
$\gamma^*\gamma^*\pi^0$ anomalous coupling, the strenght fixed from $\pi^0 \to \gamma\gamma$,
on-shell normalization $F_{\gamma^*\gamma^*\to\pi^0}(t_1,t_2) = \frac{N_c}{12\pi^2 f_\pi}(1-t_1/m_\rho^2)(1-t_2/m_\rho^2)$

strong coupling of omega to nucleon, $g^2_{\omega NN}/4\pi = 10$

$F_{\omega NN}(t) = \exp\left(\frac{t-m_\omega^2}{\Lambda^2_{\omega NN}}\right)$, $\Lambda_{\omega NN} = 1$ GeV and $g_{\omega\pi^0\gamma} \simeq 0.7\ \text{GeV}^{-1}$ obtained from the ω partial decay width

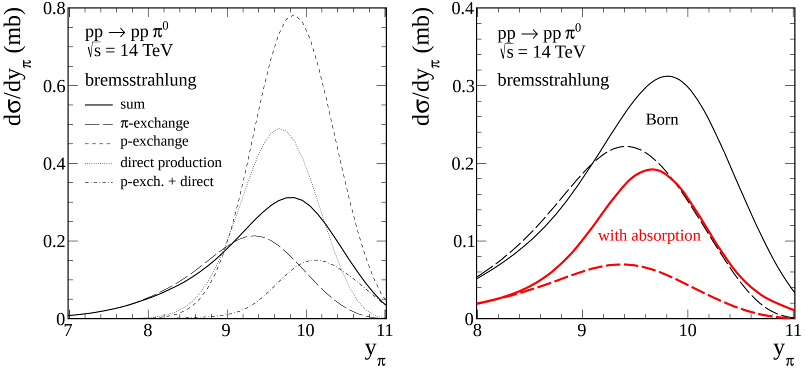
$F_{\gamma^*\omega^*\to\pi^0}(t_1,t_2) = \frac{m_\rho^2}{m_\rho^2-t_1}\exp\left(\frac{t_2-m_\omega^2}{\Lambda^2_{\omega\pi\gamma}}\right)$, $\Lambda_{\omega\pi\gamma} = 0.8$ GeV as found from the fit to the $\gamma p \to \omega p$ exp. data

Rapidity distribution of π^0



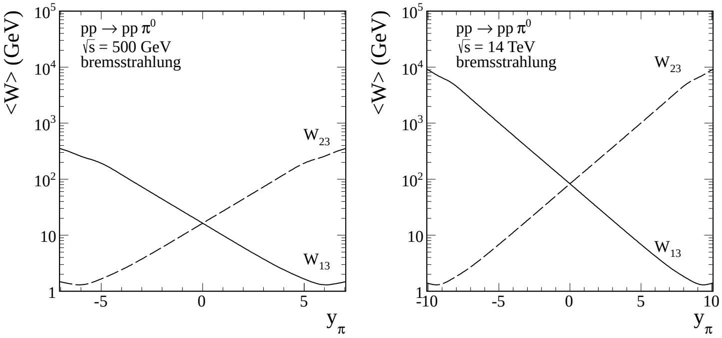
- π^0-**bremsstrahlung** contributions (both ***P*** and γ exchanges) and $\omega\gamma$ $(\gamma\omega)$ exchanges peaks at forward (backward) region of rapidity, respectively
- $\omega\gamma$ $(\gamma\omega)$ exchanges are small at $y \sim 0$ due to ω reggezation
- $\gamma\gamma$ fusion contributes at midrapidity
- we have used $\Lambda_N = \Lambda_\pi = 1$ GeV
- neutral pions could be measured by ZDCs at $|\eta_{\pi^0}| > 8 - 9$

Rapidity distribution of π^0



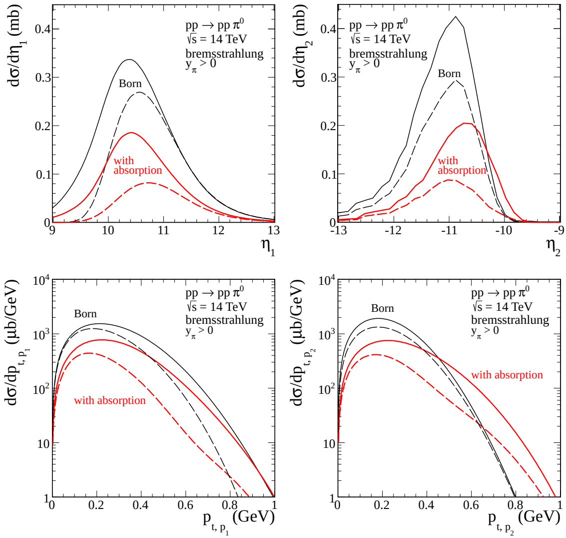
- individual π^0-bremsstrahlung contributions to the Born cross section — large cancellation between initial (p-exchange) and final state radiation (direct production)
- absorption effects included
- uncertainties of form factors: solid lines ($\Lambda_N = \Lambda_\pi = 1$ GeV), dashed lines ($\Lambda_N = 0.6$ GeV and $\Lambda_\pi = 1$ GeV)

$\langle W_{ij} \rangle \, (y_{\pi^0})$ distribution



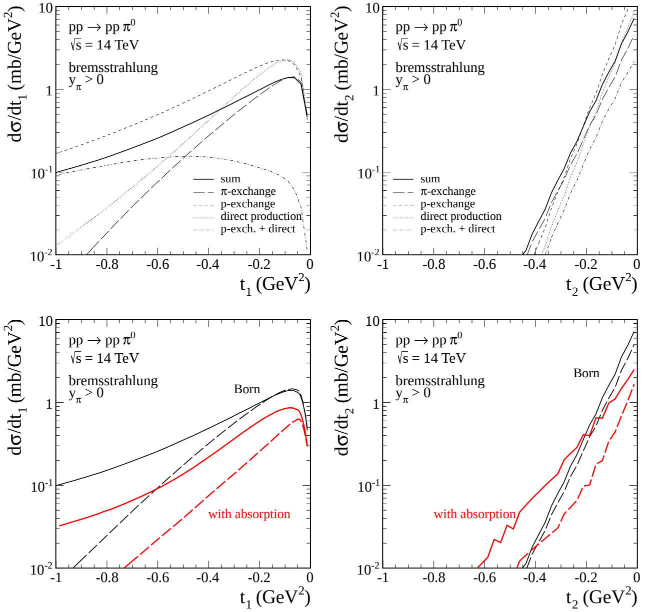
- diffractive excitation of nucleon resonances
  — when the energy in πN subsystem $W_{ij} \in \mathrm{R}$ (the nucleon resonance domain)
- only some nucleon resonances can be excited diffractively
  see L. Jenkovszky, O. Kuprash, R. Orava and A. Salii, *Low missing mass, single- and double diffraction dissociation at the LHC*, arXiv:1211.5841
- one way to introduce resonances in DHD model is to include them as intermediate states in the direct production

η_p and $p_{\perp,p}$ distributions for $y_{\pi^0} > 0$ at $\sqrt{s} = 14$ TeV

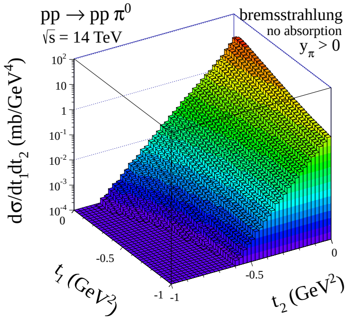


- protons could be measured by ALFA (ATLAS) or TOTEM (CMS) detectors
- absorption causes a transverse momentum dependent damping of the cross section at small $p_{\perp,p}$ and an enhancement at large $p_{\perp,p}$

t distribution for $y_{\pi^0} > 0$ at $\sqrt{s} = 14$ TeV

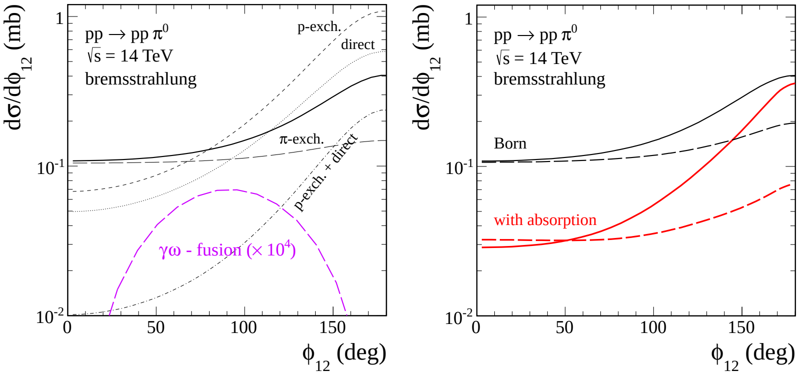


(t_1, t_2) distribution for $y_{\pi^0} > 0$ at $\sqrt{s} = 14$ TeV



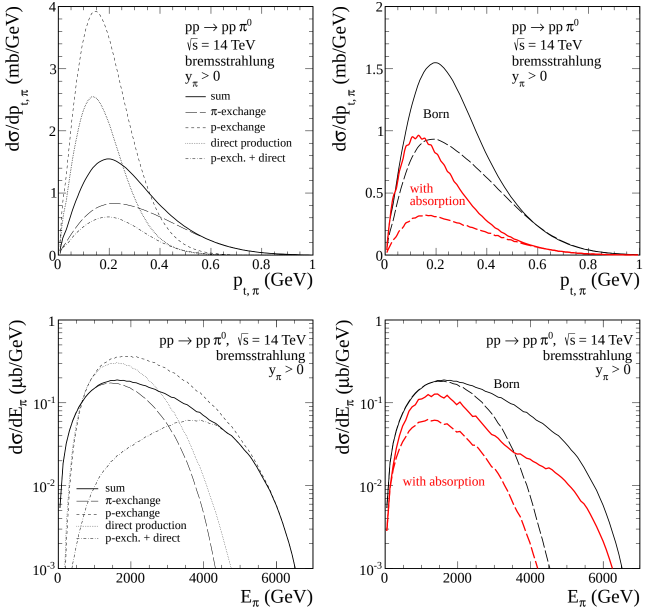
- distributions in t_1 or t_2 are different because we have limited to the case of $y_{\pi^0} > 0$

Distribution in azimuthal angle between outgoing protons for $y_{\pi^0} > 0$ at $\sqrt{s} = 14$ TeV

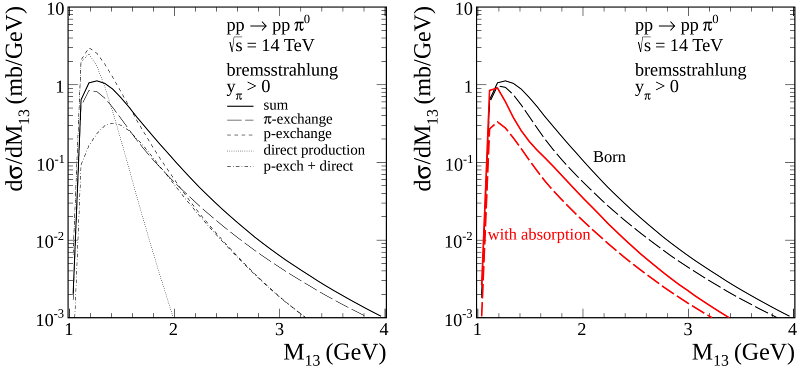


- π^0-bremsstrahlung contribution is peaked at back-to-back configuration ($\phi_{12} = \pi$)
- convenient way to fix relative contribution of different diagrams

$p_{\perp,\pi^0}$ and E_{π^0} distributions for $y_{\pi^0} > 0$ at $\sqrt{s} = 14$ TeV

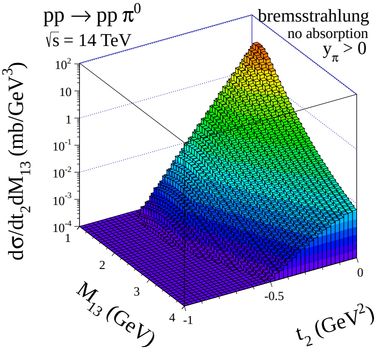


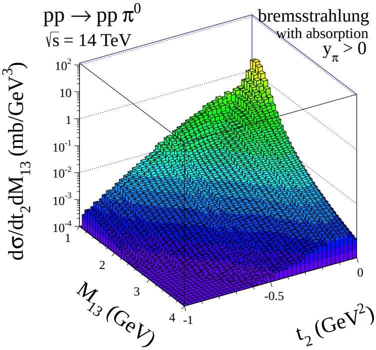
Distribution in proton-pion invariant mass M_{13} for $y_{\pi^0} > 0$ at $\sqrt{s} = 14$ TeV



- The diffractive non-resonant background contributes at small $\pi^0 p$ invariant mass and could be therefore misinterpreted as the Roper resonance $N^*(1440)$
- π^0-bremsstrahlung gives a sizable contribution to the low mass ($M_X > m_p + m_{\pi^0}$) single diffractive cross section

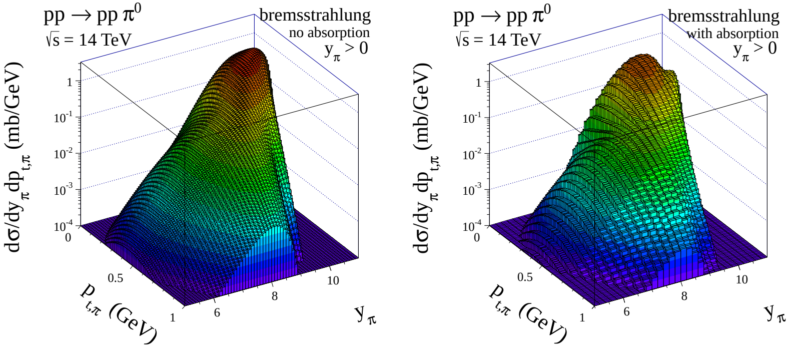
Distribution in (t_2, M_{13}) for $y_{\pi^0} > 0$ at $\sqrt{s} = 14$ TeV





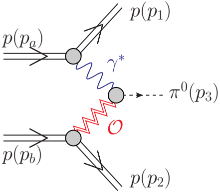
- strong dependence of slope in t on the mass of the supplementary excited $p\pi^0$ system — similar effect was observed at ISR energies
- large contribution comes from the π-exchange component while the baryon exchange terms are suppressed due to amplitude cancellations
- absorptive effects could be partially responsible for the irregular structure in space (t_2, M_{13}) at small $|t_2|$ and $M_{13} \sim 1.3$ GeV

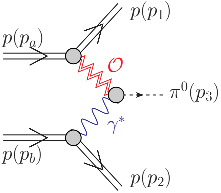
Distribution in $(y_{\pi^0}, p_{\perp,\pi^0})$ for $y_{\pi^0} > 0$ at $\sqrt{s} = 14$ TeV



- sizable correlations is partially due to interference of different components (amplitudes)

$\gamma\mathcal{O}$ and $\mathcal{O}\gamma$ exchanges





Equivalent Photon Approximation

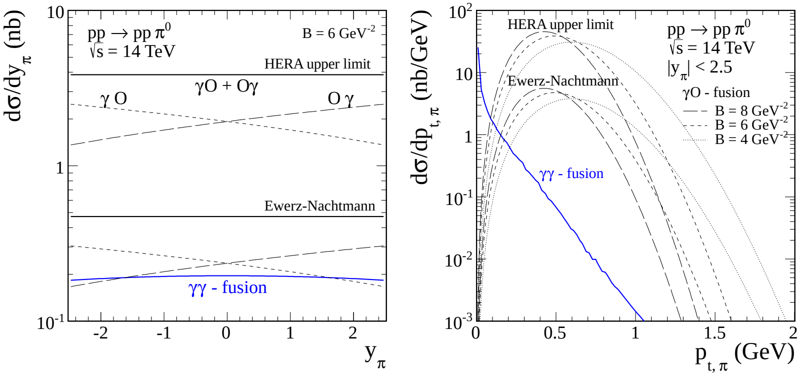
$$\frac{d\sigma}{dy dp_\perp^2} = z_1 f(z_1) \frac{d\sigma_{\gamma p \to \pi^0 p}}{dt_2}(s_{23}, t_2 \approx -p_\perp^2) + z_2 f(z_2) \frac{d\sigma_{\gamma p \to \pi^0 p}}{dt_1}(s_{13}, t_1 \approx -p_\perp^2)$$

$f(z)$ is an elastic photon flux in the proton, $z_{1/2} = \frac{m_\perp}{\sqrt{s}} \exp(\pm y)$, $m_\perp = \sqrt{m_\pi^2 + p_\perp^2}$

$$\frac{d\sigma_{\gamma p \to \pi^0 p}}{dt} = -B^2 t \exp(Bt) \sigma_{\gamma p \to \pi^0 p}$$

- $d\sigma_{\gamma p \to \pi^0 p}/dt$ vanishes at $t = 0$ which is due to helicity flip in the $\gamma \to \pi^0$ transition
- The slope parameter can be expected to be typically as for other soft processes
- At LHC and at $y = 0$ typical energies in the γp subsystems are similar as at HERA

Pion rapidity and $p_{\perp,\pi^0}$ distributions at $\sqrt{s} = 14$ TeV



- We show predictions for two different estimates of the $\gamma p \to \pi^0 p$ cross section (energy independent): $\sigma_{\gamma p \to \pi^0 p}^{HERA\ upper\ limit} = 49$ nb [a] and $\sigma_{\gamma p \to \pi^0 p}^{Ewerz-Nachtmann} = 6$ nb [b]

  [a] H1 Collaboration (C. Adloff *et al.*), Phys. Lett. B544 (2002) 35

  [b] A. Donnachie, H.G. Dosch and O. Nachtmann, Eur. Phys. J C45 (2006) 771, C. Ewerz and O. Nachtmann, Eur. Phys. J. C49 (2007) 685

- One can expect potential deviation from $\gamma\gamma$ contribution at $p_{\perp,\pi^0} \sim 0.5$ GeV as signal of odderon exchange

Conclusions

- Large cross sections of the order of mb are predicted for the $pp \to pp\pi^0$ reaction

Model (for $y_{\pi^0} > 0$)	$\sqrt{s} = 45$ GeV	$\sqrt{s} = 500$ GeV	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 14$ TeV
No absorption	$103 - 146\ \mu b$	$177 - 251\ \mu b$	$337 - 481\ \mu b$	$402 - 575\ \mu b$
Absorption in initial state	$46 - 76\ \mu b$	$62 - 125\ \mu b$	$85 - 273\ \mu b$	$94 - 357\ \mu b$
Absorption in final state	$60 - 91\ \mu b$	$84 - 139\ \mu b$	$118 - 244\ \mu b$	$128 - 290\ \mu b$

lower limit ($\Lambda_N = 0.6$ GeV, $\Lambda_\pi = 1$ GeV) — upper limit ($\Lambda_N = \Lambda_\pi = 1$ GeV)

— absorptive effects lower the cross section by a factor 2 to 3

- Large contribution to single diffraction cross section

$$\sigma_{SD}^{DHD} = 3\ \sigma_{pp\to pp\pi^0}^{DHD}$$

- Monte Carlo generators do not include it
- Diffractive excitation of single resonances

$$\sigma_{pp\to pp\pi^0}^{N^*} = \sigma_{SD}^{N^*} \times BR(N^* \to N\pi) \times \frac{1}{3} \qquad \textit{where } BR(N^* \to N\pi) \approx 65\%$$

- Contribution to large rapidity production (cosmic ray interactions)

  — very energetic photons ($\sim 0.5 - 2$ TeV)
- Searches for odderon exchange

  $\sigma_{pp\to pp\pi^0} < 20$ nb (at $\sqrt{s} = 14$ TeV and $|y_{\pi^0}| < 2.5$)