Applications of the tensor pomeron model
to exclusive central diffractive meson production

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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, Ann. Phys. 344 (2014) 301

2. *The $\rho^0$ contribution to exclusive production of $\pi^+\pi^-$ pairs in proton-proton collisions*

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

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How is the nature of soft pomeron?

The Chew-Frautschi plots (the exchanges particles spin $J$ vs its squared mass $m_J^2$) shows that all possible exchanges form so called Regge trajectories

- In the Regge theory the $t$-channel Regge exchanges (IR) correspond to a sum of ordinary mesons with the same quantum numbers. $C = +1 (f_2, a_2)$ trajectories and $C = -1 (\omega, \rho)$ trajectories are all degenerate with intercept $\alpha(0) \approx 0.5$ (they contribute terms $\sim 1/\sqrt{s}$).
- The contributions from the isospin $l = 1$ exchanges $\rho_{IR}$ and $a_{2IR}$ are very much less than that those from $l = 0$ exchanges $f_{2IR}$ and $\omega_{IR}$.
- To generate a non-falling total cross section ($\sqrt{s} \rightarrow \infty, \sqrt{|t|} \lesssim 1 \text{ GeV}$) a new trajectory (Pomeranchuk trajectory) with the leading pole called the pomeron (IP) was postulated. It has $\alpha(0)$ slightly above 1 and the quantum numbers of the vacuum, that is $l = 0$ and $C = +1$.
- There is belief that the pomeron rather is associated with the exchange of family of glueballs.
- It is possible that there exists also an odderon, a $C = -1$ partner of the pomeron.

Collins, *An introduction to Regge theory and high energy physics*, CUP, 1977,
Donnachie, Dosch, Nachtmann and Landshoff, *Pomeron physics and QCD*, CUP, 2002,
Close, Donnachie, Shaw, *Electromagnetic interactions and hadronic structure*, CUP, 2007
Vector pomeron vs Tensor pomeron

\[ i \mathcal{M}^{pp \rightarrow pp}_{\bar{\lambda}_a \bar{\lambda}_b \rightarrow \bar{\lambda}_1 \bar{\lambda}_2} \left| \Gamma_V \right| \]

\[ \times \bar{u}(p_1, \bar{\lambda}_1) i \Gamma^{(ip_{pp})}_\mu (p_1, p_a) u(p_a, \bar{\lambda}_a) \]

\[ \times i \Delta^{(ip_{V})}_{\mu \nu} (s, t) \]

\[ \times \bar{u}(p_2, \bar{\lambda}_2) i \Gamma^{(ip_{pp})}_v (p_2, p_b) u(p_b, \bar{\lambda}_b) \]

\[ i \Gamma^{(ip_{pp})}_\mu (p', p) = -i 3 \beta_{IPNN} F_1 ((p' - p)^2) M_0 \gamma_i \]

\[ i \Delta^{(ip_{V})}_{\mu \nu} (s, t) = \frac{1}{M_0^2} g_{\mu \nu} (-is \alpha'_{ip}) a_{ip}(t)^{-1} \]

\[ s \gg 4m^2_P \]

\[ \frac{1}{2} \left[ \gamma_\mu (p' + p)_\nu + \gamma_\nu (p' + p)_\mu \right] - \frac{1}{4} g_{\mu \nu} (p' + p) \]

\[ i \Delta^{(ip_T)}_{\mu \nu, \kappa \lambda} (s, t) = \frac{1}{4s} \left( g_{\mu \kappa} g_{\nu \lambda} + g_{\mu \lambda} g_{\nu \kappa} - \frac{1}{2} g_{\mu \nu} g_{\kappa \lambda} \right) (-is \alpha'_{ip}) a_{ip}(t)^{-1} \]

\[ \delta_{\bar{\lambda}_1 \bar{\lambda}_a} \delta_{\bar{\lambda}_2 \bar{\lambda}_b} \leftarrow \text{Donnachie – Landshoff pomeron ansatz} \]

\[ \beta_{IPNN} = 1.87 \text{ GeV}^{-1}, \, M_0 = 1 \text{ GeV}, \, a_{ip}(t) = a_{ip}(0) + a'_{ip} t, \, a_{ip}(0) = 1.0808, \, a'_{ip} = 0.25 \text{ GeV}^{-2}, \, F_1(t) = \frac{4m^2_P - 2.79 t}{(4m^2_P - t)(1 - t/m_D^2)} \]

Effective \( IP_T pp \) vertex and \( IP_T \) propagator compatible with QFT rules!

see C. Ewerz, M. Maniatis and O. Nachtmann, Ann. Phys. 342 (2014) 31, O. Nachtmann, a talk High-energy soft reactions: A model with tensor pomeron and vector odderon, WE-Heraeus-Summerschool, Heidelberg, 2013
Exclusive production of resonances via $IP_V/\bar{IP}_V$ fusion

\[ \langle p(p_1, \bar{p}_1), p(p_2, \bar{p}_2), M(k) \mid T \mid p(p_a, \bar{p}_a), p(p_b, \bar{p}_b) \rangle \mid_{IP_V} \equiv \]

\[ \mathcal{M}^{2 \rightarrow 3}_{\bar{p}_a\bar{p}_b \rightarrow \bar{p}_1\bar{p}_2 M} \mid_{IP_V} = (-i)\bar{u}(p_1, \bar{p}_1)i\Gamma_{\mu_1}^{(IP_V pp)}(p_1, p_a)u(p_a, \bar{p}_a) \]

\[ \times i\Delta^{(IP_V)}_{\mu_1\nu_1}(s_{13}, t_1) i\Gamma_{\nu_1\nu_2}^{(IP_V \rightarrow M)}(q_1, q_2) i\Delta^{(IP_V)}_{\nu_2\mu_2}(s_{23}, t_2) \]

\[ \times \bar{u}(p_2, \bar{p}_2)i\Gamma_{\mu_2}^{(IP_V pp)}(p_2, p_b)u(p_b, \bar{p}_b) \]

\[ i\Gamma_{\mu\nu}^{(IP_V/IP_V \rightarrow M)}(q_1, q_2) = \left( i\Gamma_{\mu\nu}^{(IP_V/IP_V \rightarrow M)} \mid_{bare} + i\Gamma_{\mu\nu}^{(IP_V/IP_V \rightarrow M)}(q_1, q_2) \mid_{bare} \right) F_{IPPM}(q_1^2, q_2^2) \]

\[ J^{PC} = 0^{++} : \quad i\Gamma_{\mu\nu}^{(IP_V/IP_V \rightarrow M)} \mid_{bare} = i g'_{\mu\nu}^{IP_V/IP_V M} M_0 \frac{g_{\mu\nu}}{2} \left( \bar{u}(l, S) = (0, 0) \right) \text{ term} \]

\[ i\Gamma_{\mu\nu}^{(IP_V/IP_V \rightarrow M)}(q_1, q_2) \mid_{bare} = \frac{2i g'_{\mu\nu}^{IP_V/IP_V M}}{M_0} [q_2 \mu q_1 \nu - (q_1 q_2) g_{\mu\nu}] \left( \bar{u}(l, S) = (2, 2) \right) \text{ term} \]

\[ J^{PC} = 0^{--} : \quad i\Gamma_{\mu\nu}^{(IP_V/IP_V \rightarrow \bar{M})}(q_1, q_2) \mid_{bare} = i \frac{g'_{\mu\nu}^{IP_V/IP_V \bar{M}}}{2M_0} \epsilon_{\mu
u\rho\sigma} q_1^\rho q_2^\sigma \left( \bar{u}(l, S) = (1, 1) \right) \text{ term} \]

The dimensionless coupling constants for scalar mesons $g'_{\mu\nu}^{IP_V/IP_V M}, g''_{\mu\nu}^{IP_V/IP_V M}$ and for pseudoscalar mesons $g'_{\mu\nu}^{IP_V/IP_V \bar{M}}$ can be fixed from the meson production data.

\[ F_{IPPM}^M(t_1, t_2) = F_M(t_1)F_M(t_2), \quad F_M(t) = F_\pi(t) = \frac{1}{1 - t/\Lambda_0^2}, \quad \Lambda_0^2 = 0.5 \text{ GeV}^2 \]
Exclusive production of resonances via $IP_T IP_T$ fusion

\[
\langle p(p_1, \tilde{p}_1), p(p_2, \tilde{p}_2), M(k) | T | p(p_a, \tilde{p}_a), p(p_b, \tilde{p}_b) \rangle |_{IP_T} \equiv \mathcal{M}^2_{\tilde{x}\tilde{y} \rightarrow z = 0}^{2 \rightarrow 3} \mathcal{M}^{G}_{\tilde{x} \tilde{y} \rightarrow z = 0, M(k)} |_{IP_T} = (-i)\tilde{u}(p_1, \tilde{p}_1) i\Gamma^{(IP_T PP)}_{\mu_1 \nu_1}(p_1, p_a) u(p_a, \tilde{p}_a) \\
\times i\Delta^{(IP_T)}_{\mu_1 \nu_1, \lambda_1 \tilde{p}_1}(s_1, t_1) i\Gamma^{(IP_T IP_T \rightarrow M)}_{\kappa_1 \lambda_1, \kappa_2 \tilde{p}_2}(q_1, q_2) i\Delta^{(IP_T)}_{\kappa_2 \tilde{p}_2, \mu_2 \nu_2}(s_2, t_2) \\
\times \tilde{u}(p_2, \tilde{p}_2) i\Gamma^{(IP_T PP)}_{\mu_2 \nu_2}(p_2, p_b) u(p_b, \tilde{p}_b)
\]

\[
i\Gamma^{(IP_T IP_T \rightarrow M)}_{\mu \nu, \lambda \tilde{\lambda}}(q_1, q_2) = \left( i\Gamma^{(IP_T IP_T \rightarrow M)}_{\mu \nu, \lambda \tilde{\lambda}} |_{bare} + i\Gamma^{(IP_T IP_T \rightarrow M)}_{\mu \nu, \lambda \tilde{\lambda}}(q_1, q_2) |_{bare} \right) F_{\text{IPTPM}}(q_1, q_2)
\]

\[
J^{PC} = 0^{++}:
\]

\[
i\Gamma^{(IP_T IP_T \rightarrow M)}_{\mu \nu, \lambda \tilde{\lambda}} |_{bare} = i \left( g'_{IP_T IP_T M} M_0 \left( g_{\mu \nu} g_{\lambda \tilde{\lambda}} + g_{\mu \tilde{\lambda}} g_{\nu \lambda} - \frac{1}{2} g_{\mu \nu} g_{\lambda \tilde{\lambda}} \right) \right) \leftrightarrow (1, 1) \text{ term}
\]

\[
i\Gamma^{(IP_T IP_T \rightarrow M)}_{\mu \nu, \lambda \tilde{\lambda}}(q_1, q_2) |_{bare} = i \left( g'_{IP_T IP_T M} \frac{M_0}{2M_0} \left[ q_{1 \lambda} q_{2 \mu} g_{\nu \tilde{\lambda}} + q_{1 \lambda} q_{2 \nu} g_{\mu \tilde{\lambda}} + q_{1 \tilde{\lambda}} q_{2 \mu} g_{\nu \lambda} + q_1 q_2 g_{\mu \nu} - 2(q_1 q_2) (g_{\mu \nu} g_{\lambda \tilde{\lambda}} + g_{\mu \tilde{\lambda}} g_{\nu \lambda}) \right] \right) \left( q_1 - q_2 \right)^\rho k^\sigma \leftrightarrow (2, 2)
\]

\[
J^{PC} = 0^{-+}:
\]

\[
i\Gamma^{(IP_T IP_T \rightarrow M)}_{\mu \nu, \lambda \tilde{\lambda}}(q_1, q_2) |_{bare} = i \left( g'_{IP_T IP_T M} \frac{M_0}{2M_0} \left( g_{\mu \nu} \epsilon_{\nu \tilde{\lambda} \rho \sigma} + g_{\nu \lambda} \epsilon_{\lambda \tilde{\lambda} \rho \sigma} + g_{\mu \tilde{\lambda}} \epsilon_{\mu \nu \rho \sigma} + g_{\nu \tilde{\lambda}} \epsilon_{\nu \lambda \rho \sigma} \right) (q_1 - q_2)^\rho k^\sigma \right) \leftrightarrow (1, 1)
\]

\[
i\Gamma^{(IP_T IP_T \rightarrow M)}_{\mu \nu, \lambda \tilde{\lambda}}(q_1, q_2) |_{bare} = i \left( g'_{IP_T IP_T M} \frac{M_0}{M_0} \left\{ \epsilon_{\nu \tilde{\lambda} \rho \sigma} [q_{1 \lambda} q_{2 \mu} - (q_1 q_2) g_{\nu \lambda}] + \epsilon_{\mu \tilde{\lambda} \rho \sigma} [q_{1 \lambda} q_{2 \nu} - (q_1 q_2) g_{\nu \lambda}] \\
+ \epsilon_{\nu \lambda \rho \sigma} [q_{1 \tilde{\lambda}} q_{2 \mu} - (q_1 q_2) g_{\mu \tilde{\lambda}}] + \epsilon_{\mu \lambda \rho \sigma} [q_{1 \tilde{\lambda}} q_{2 \nu} - (q_1 q_2) g_{\nu \lambda}] \right\} \right) (q_1 - q_2)^\rho k^\sigma \leftrightarrow (3, 3)
\]
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

|         | $f_0(980)$ | $f_0(1370)$ | $f_0(1500)$ | $f_0(1710)$ | $f_0(2000)$ |
|---------|------------|-------------|-------------|-------------|-------------|
| $\sigma(\mu b)$ | $5.71 \pm 0.45$ | $1.75 \pm 0.58$ | $2.91 \pm 0.30$ | $0.25 \pm 0.07$ | $3.14 \pm 0.48$ |
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.
$0^{++}$, $t$ distribution

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

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

$pp \rightarrow pp f_1(1370)$ via IP IP - fusion
$\sqrt{s} = 29.1$ GeV
WA102 data

$(l,S) = (0,0)$ only

$pp \rightarrow pp f_1(980)$ via IP IP - fusion
$\sqrt{s} = 29.1$ GeV
WA102 data

$pp \rightarrow pp f_1(1500)$ via IP IP - fusion
$\sqrt{s} = 29.1$ GeV
WA102 data
The meson distribution peaks at $x_{F,M} = 0$ and the protons at $x_{F,p} \to \pm 1$, $x_F = 2p_z / \sqrt{s}$
Pseudoscalar mesons ($J^{PC} = 0^{-+}$)

For $\eta$ 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
Our results and the WA102 exp. distributions have been normalized to the value of total cross sections given by Kirk.
$0^{-+}$, $t$ distribution

$$F_{IPIPM}^M(t_1, t_2) = F_M(t_1) F_M(t_2), \quad F_M(t) = F_\pi(t) = \frac{1}{1 - t/\Lambda^2_0}, \quad \Lambda^2_0 = 0.5 \text{ GeV}^2$$

$$F_{IPIPM}^E(t_1, t_2) = \exp \left( \frac{t_1 + t_2}{\Lambda^2_E} \right), \quad \Lambda^2_E = 0.64 \text{ GeV}^2$$
The enhancement of the $\eta$ distribution at larger values of $x_{F,M}$ can be explained by the $f_{2IR}IP$ and $IPf_{2IR}$ exchanges.

Production of $\eta'$ seems to be less affected by contributions from subleading exchanges.
0−, $y_M$ and $\eta_M$ distributions

\[\begin{align*}
\text{(l,S)} &= (1,1) \\
\text{(l,S)} &= (3,3) \\
\text{sum} \\
\end{align*}\]
$0^{--}$, $p_{\perp,M}$ and $p_{\perp,p}$ distributions

$$\sigma(p_{T,M}(\text{GeV}) \rightarrow p_{T,p}(\text{GeV})$$

$pp \rightarrow pp \eta_{r} \quad \mathbf{f} = 29.1 \text{ GeV}$

$IP_{T}IP_{T}$ and $f_{2 \text{IR}}$ exch.

$(l,S) = (1,1)$

$(l,S) = (3,3)$

$IP_{T}IP_{T}$

$IP_{V}IP_{V}$

$pp \rightarrow pp \eta'(958)$

$\mathbf{f} = 29.1 \text{ GeV}$

$\eta_{pp} \rightarrow pp = 29.1 \text{ GeVs}$

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

The $dP_\perp$ and $\phi_{pp}$ effects → in general more than one coupling structure $IPIPM$ is possible.

Challenge for theory to predict these coupling structure from calculations in the framework of QCD.
\( \rho^0 \) contribution to central exclusive production of \( \pi^+ \pi^- \) pairs

\[
M^{(P-\text{wave})} = M_{\gamma p}^\gamma + M_{\gamma 2IR}^\gamma + M_{\gamma 2IR}^\gamma
\]

\[
M_{\rho_\alpha \rho_\beta \rightarrow \rho_1 \rho_2} = \bar{u}(p_1, \rho_1) i\Gamma_{\mu}^{\gamma pp}(p_1, \rho_0) u(\rho_0, \rho_\alpha)
\]

\[
\times i\Delta(\gamma)_{\mu\alpha}(q_1) i\Gamma_{\alpha\nu}^{\gamma \rho}(q_1) i\Delta(\rho)_{\nu\alpha}(q_1) i\Delta(\rho)_{\rho_2 \kappa}(p_34) i\Gamma_{\kappa\pi\pi}^\rho(p_3, p_4)
\]

\[
\times i\Gamma_{\rho_1\rho_2 \alpha\beta}^{\gamma pp}(q_1, p_34) i\Delta^{(IP\rho p)}(s_2, t_2) \bar{u}(p_2, \rho_2) i\Gamma_{\delta\pi\pi}^{\gamma pp}(p_2, \rho_0) u(\rho_0, \rho_\beta)
\]

\[
M_{\rho_\alpha \rho_\beta \rightarrow \rho_1 \rho_2} \approx \pm e(p_1 + p_\alpha)^\mu F_1(t_1) \delta_{\rho_1 \rho_\alpha}
\]

\[
\times e \frac{m_\rho^2}{\gamma_\rho} \Delta(\rho)_{\mu\rho}(q_1) \Delta(\rho)_{\rho_2 \kappa}(p_34) \frac{g_{\rho\pi\pi}}{2} (p_3 - p_4)^\kappa F_{\rho\pi\pi}(s_34) F_{\rho\pi\pi}(s_34)
\]

\[
\times \sqrt{\rho_{1\rho_2 \alpha\beta}}(s_2, t_2) 2(p_2 + p_\beta) \delta F_M(t_2) F_1(t_2) \delta_{\rho_2 \rho_\beta}
\]
Photoproduction of $\rho^0$ meson

$$\mathcal{M}_{\gamma p \rightarrow \rho_0 p_2}(s, t) \cong c^{(\gamma \rightarrow \rho)} (\Delta_T^{(\rho)})^{-1} e^\mu_\gamma (e^\nu_\rho)^* V_{\mu \nu \kappa \lambda} (s, t)(p_2 + p_b)^\kappa (p_2 + p_b)^\lambda 2 \delta_{\rho_2 \rho_b} F_1(t) F_M(t)$$

where $c^{(\gamma \rightarrow \rho)} = -i e m_p / \gamma_p$, $4\pi / \gamma_p^2 = 0.496$, $\Delta_T^{(\rho)} = -m_\rho^2 + i m_\rho \Gamma_{\rho, \text{tot}}$

$$V_{\mu \nu \kappa \lambda} (s, t) = \frac{1}{4s} \left\{ \Gamma^{(0)}_{\mu \nu \kappa \lambda} (-p_\gamma, p_\rho) \left[ 6 \beta_{\text{IPNN}} a_{\rho \rho \rho \rho} (-i s a'_{\rho \rho}) \alpha_{\text{IP}}(t)^{-1} + 2 M_0^{-1} g_{\text{2IR} \rho \rho} \alpha_{\text{2IR} \rho \rho} (-i s a'_{\text{2IR}}) \alpha_{\text{2IR} +}(t)^{-1} \right] \\
- \Gamma^{(2)}_{\mu \nu \kappa \lambda} (-p_\gamma, p_\rho) \left[ 3 \beta_{\text{IPNN}} b_{\rho \rho \rho \rho} (-i s a'_{\rho \rho}) \alpha_{\text{IP}}(t)^{-1} + M_0^{-1} g_{\text{2IR} \rho \rho} b_{\text{2IR} \rho \rho} (-i s a'_{\text{2IR}}) \alpha_{\text{2IR} +}(t)^{-1} \right] \right\}$$

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

![Graph](image-url)
$\xi_1 = \log_{10}(p_{1\perp}/1\text{ GeV})$ distribution

\begin{align*}
\text{pp } &\rightarrow \text{pp } (\rho^0 \rightarrow \pi^+\pi^-) \\
\sqrt{s} &= 200 \text{ GeV}
\end{align*}

\begin{align*}
\text{pp } &\rightarrow \text{pp } (\rho^0 \rightarrow \pi^+\pi^-) \\
\sqrt{s} &= 7 \text{ TeV}
\end{align*}
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 see P. L. and A. Szczurek, Phys. Rev. D81 (2010) 036003.
The effect of $\phi_{pp}$ deviation from a constant is due to interference of $\gamma$-IP and IP-$\gamma$ amplitudes. Similar effect was discussed first in W. Schafer and A. Szczurek, Phys. Rev. D76 (2007) 094014 for the exclusive production of $J/\psi$ meson; see A. Cisek talk.
$M_{\pi\pi}$ and $p_{\perp,\pi}$ distributions

$\sigma_{pp\rightarrow pp(\rho^0 \rightarrow \pi^+ \pi^-)}$ in $\mu b$ (Born approximation)

| $\sqrt{s}$, TeV | cuts | IP and $f_{2IR}$ | IP |
|----------------|------|-----------------|----|
|                |      | set A           | 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)   | | 0.032 (0.038)   | 0.026 |
| 0.5 (STAR II)  | | 0.004 (0.004)   | 0.004 |
| 7 (CMS)        | | 4.14 (4.11)     | 4.02 |
| 7 (ALICE)      | | 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.

- 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.

- Our study certainly shows the potential of \( pp \rightarrow pMp \) 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 \( \phi_{pp} \) may contain, for the \( IP_T \), a term which is not possible for the \( IP_V \).

- We have made estimates of the central exclusive \( \rho^0 \) meson production to the \( pp \rightarrow pp\pi^+ \pi^- \) reaction. The \( \rho^0 \) contribution constitutes 10-20\% of the double pomeron/reggeon exchange contribution calculated in a simple Regge-like model. Similar characteristic of rapidity and \( p_{\perp,\pi} \) distributions, but different dependence on \( p_{\perp,p} \) and \( \phi_{pp} \). This could be used to separate the \( \rho^0 \) contribution (should be strongly enhanced at \( \phi_{pp} < 90^0 \)).

- 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

- 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.
  A consistent model of the resonances decaying into the \( \pi\pi \) channel (other mesons like \( f_2(1270) \)) and the non-resonant background. The interference of the resonance signals with the \( \pi\pi \) continuum.

- Absorption effects may also change the shapes of \( t_1/t_2, \phi_{pp} \), etc. distributions. The deviation from "bare" distributions probably is more significant at high energies where the absorptive corrections should be more important.
Backup, other mechanisms to $pp \rightarrow pp\pi^+\pi^-$ reaction

The measurement of forward/backward protons is crucial in better understanding of the mechanism of $pp \rightarrow pp\pi^+\pi^-$ reaction:

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

$\pi^+ + (p_3)\pi^- + (p_4)$

Seik $p(p_a)\pi^+(p_3)\pi^-(p_4)$

I P, I R

P. L. and A. Szczurek, Phys. Rev. D81 (2010) 036003 ($pp \rightarrow pp\pi^+\pi^-$)

P. L., R. Pasechnik and A. Szczurek, Phys. Lett. B701 (2011) 434 ($pp \rightarrow pp(\chi_{c0} \rightarrow \pi^+\pi^-)$)

P. L. and A. Szczurek, Phys. Rev. D85 (2012) 014026 ($pp \rightarrow ppK^+\bar{K}^-$)

At smaller $\sqrt{s}$ are important the non-central (bremsstrahlung) mechanisms while at higher $\sqrt{s}$ contribute at very forward/backward rapidities

Similar processes was discussed in $pp$ and/or $p\bar{p}$ collisions at high energies:

A. Cisek, P. L., W. Schafer and A. Szczurek, Phys. Rev. D83 (2011) 114004 ($pp \rightarrow pp\pi^0$)

P. L. and A. Szczurek, Phys. Rev. D87 (2013) 074037 ($pp \rightarrow pp\omega$)

P. L. and A. Szczurek, Phys. Rev. D87 (2013) 114004 ($pp \rightarrow pp\gamma$)
What are the possible values of spin $J$ and parity $P$ for meson?

The values of $I$, $S$, and $J$, $P$ of orbital angular momentum, total spin of the two "vector-pomeron particles", and total angular momentum, parity of the state, respectively, possible in the annihilation reaction $IP_V IP_V \rightarrow M$.

The values of $I$, $S$, $J$, and $P$ possible in the annihilation of two "spin 2 pomeron particles" ($IP_T IP_T \rightarrow M$):

\[
\begin{array}{c|c|c|c|c}
\hline
I & S & J & P \\
\hline
0 & 0 & 0 & + \\
2 & 2 & & \\
4 & 4 & & \\
1 & 1 & 0, 1, 2 & - \\
2 & 0 & 2 & + \\
2 & 0,1,2,3,4 & & \\
3 & 1 & 2,3,4 & - \\
3 & 1 & 0,1,2,3,4,5,6 & \\
4 & 0 & 4 & + \\
2 & 2,3,4,5,6 & & \\
\hline
\end{array}
\]

$P = (-1)^I, \ |I - S| \leq J \leq I + S$

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

In general, different couplings with different $I$ and $S$ of two "pomeron particles" are possible.