The tensor pomeron model for diffractive processes

O. Nachtmann

Institut für Theoretische Physik
Universität Heidelberg

Outline

Based on the following common works:

- C. Ewerz, M. Maniatis, O. Nachtmann, Annals Phys. **342**, 31 (2014)
- P. Lebiedowicz, O. Nachtmann, A. Szczurek, Annals Phys. **344**, 301 (2014)
- A. Bolz, C. Ewerz, M. Maniatis, O. Nachtmann, M. Sauter, A. Schöning, JHEP **1501**, 151 (2015)
- P. Lebiedowicz, O. Nachtmann, A. Szczurek, Phys. Rev. **D91**, 7, 074023 (2015)

Introduction

Examples of high-energy soft reactions:

- elastic scattering

$$p + p \to p + p$$
$$\bar{p} + p \to \bar{p} + p$$
$$\pi + p \to \pi + p$$

- photoproduction

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

- central production

$$p + p \to p + \text{ meson } + p$$

$$\sqrt{s} \to \infty\,,\ \sqrt{|t|} \leq 1\,\text{GeV}$$

In QCD: neither pure short nor pure long distance regime, difficult to treat.

The physics of exchanges, regge regime. Exchange objects:

pomeron $\mathbb{P}$

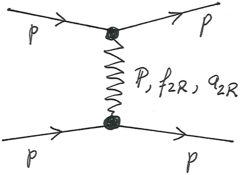
reggeons $f_{2R},\ a_{2R},\ \omega_R,\ \rho_R$

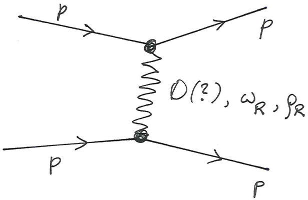
odderon (?) $\mathbb{O}$

- Our aim is to give simple rules, compatible with QFT, for calculating such exchange amplitudes.

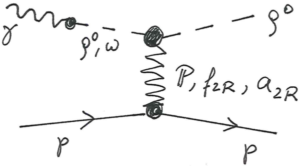
Examples:

- $p + p \longrightarrow p + p$





- $\gamma + p \longrightarrow \rho^0 + p$



We need a list of effective propagators and vertices:
$\mathbb{P}$ propagator, $\mathbb{P}pp$ vertex etc.

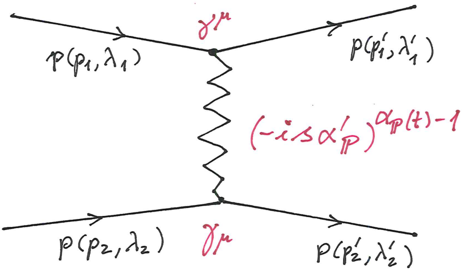
We tried to make a marriage between QFT and Regge theory.

Unexpected results:

- $\mathbb{P}$ as an effective rank-two tensor exchange.
- Relations between particle-particle-particle and reggeon-particle-particle vertices.
- Insight into the meaning of the vector-meson-dominance (VMD) relations.

The tensor pomeron

Example: pp and $\bar{p}p$ scattering
Starting point: standard Donnachie-Landshoff (DL) pomeron



effective vectorial exchange

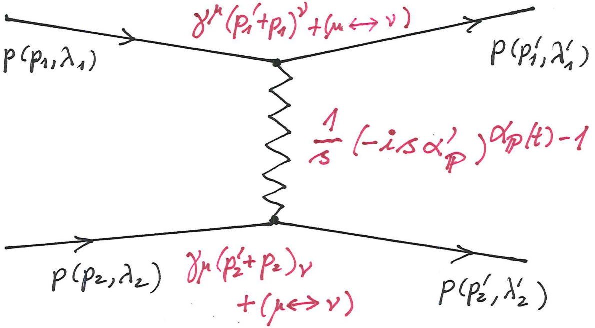
$$s = (p_1 + p_2)^2 \,, \; t = (p_1 - p_1')^2 \,, \; \alpha_{\mathbb{P}}(t) = 1 + \epsilon_{\mathbb{P}} + \alpha'_{\mathbb{P}} t$$

$$\epsilon_{\mathbb{P}} = 0.0808 \,, \; \alpha'_{\mathbb{P}} = 0.25 \text{ GeV}^{-2}$$

The DL pomeron is very successful, but there are problems. An effective vectorial exchange gives opposite sign for pp and $\bar{p}p$ amplitudes. But $\mathbb{P}$ exchange must give same sign.

In other words: $\mathbb{P}$ exchange has charge conjugation $C = +1$ and not $C = -1$ as a vectorial exchange. Cure “by hand” changing signs of certain amplitudes? Difficult to impossible for more complicated reactions!

Our solution: $\mathbb{P}$ as an effective tensor exchange



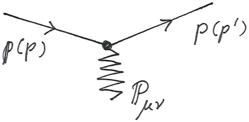
A tensor, like in gravity, couples equally to particles and antiparticles.

At high energies we get, with suitable coupling factors,

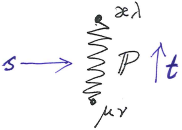
$$\begin{aligned}
&\langle p(1'), p(2')|T|p(1), p(2)\rangle|_{\mathbb{P}} = \\
&\langle \bar{p}(1'), p(2')|T|\bar{p}(1), p(2)\rangle|_{\mathbb{P}} = \\
&\qquad i\left[3\beta_{\mathbb{P}NN}F_1(t)\right]^2(-is\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1}2s\,\delta_{\lambda'_1\lambda_1}\delta_{\lambda'_2\lambda_2} \\
&\beta_{\mathbb{P}NN} = 1.87\ \text{GeV}^{-1}\ ,\ F_1(t)\ \text{form factor}
\end{aligned}$$

This is the same result as for the DL pomeron. But now the relative sign between pp and $\bar{p}p$ is correct automatically.

- Effective $\mathbb{P}NN$ vertex and $\mathbb{P}$ propagator:



$$-i\,3\beta_{\mathbb{P}NN}\,F_1(t)\left[\frac{1}{2}\gamma_\mu(p'+p)_\nu+\frac{1}{2}\gamma_\nu(p'+p)_\mu-\frac{1}{4}g_{\mu\nu}(\not{p}'+\not{p})\right]$$



$$\frac{1}{4s}\left(-is\alpha'_{\mathbb{P}}\right)^{(\alpha_{\mathbb{P}}(t)-1)}\left[g_{\mu\kappa}g_{\nu\lambda}+g_{\mu\lambda}g_{\nu\kappa}-\frac{1}{2}g_{\mu\nu}g_{\kappa\lambda}\right]$$

Tensor pomeron $\mathbb{P}_{\mu\nu}=\mathbb{P}_{\nu\mu}\,,\ \mathbb{P}^{\mu}_{\mu}=0.$

Effective propagators and vertices for $C = 1$ & $C = -1$ exchanges

Our aim: give a list of propagators & vertices.
If you want to calculate the amplitude for a specific process, e.g.

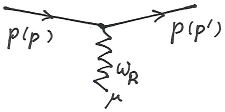
$$\gamma + p \to \rho^0 + p$$

proceed as follows:

- draw the relevant diagrams
- combine propagators and vertices
- get a result fitting the data perfectly!?

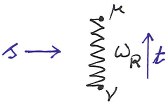
Some highlights from our list:

- all $C = 1$ exchanges, $\mathbb{P}$, f_{2R}, a_{2R}, are represented as rank-two-tensor exchanges.
- all $C = -1$ exchanges, $\mathbb{O}$ (?), ω_R, ρ_R, are represented as vectorial exchanges. Example: ω_R



$$-i g_{\omega_R pp} F_1[(p'-p)^2] \gamma_\mu$$

$$g_{\omega_R pp} = 8.65, \quad M_- = 1.41 \text{ GeV}$$



$$i g_{\mu\nu} (M_-)^{-2} (-is\alpha'_{R_-})^{\alpha_{R_-}(t)-1}$$

$$\alpha_{R_-}(t) = 0.55 + \alpha'_{R_-} t, \quad \alpha'_{R_-} = 0.9 \text{ GeV}^{-2},$$

- inclusion of photons using vector meson dominance, VMD

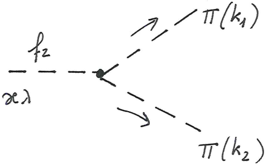
$$-ie\,\frac{m_V^2}{\gamma_V}\,g_{\mu\nu} \qquad V = \rho^0, \omega, \phi$$

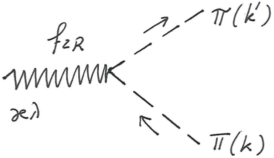
No gauge invariance problems using our QFT vertices!

- relations between particle-particle-particle and reggeon-particle-particle vertices.

Example:

$$f_2\pi\pi \qquad f_{2R}\pi\pi$$





$$-i\,\frac{g_{f_2\pi\pi}}{2M_0}\Big[(k_1-k_2)_\kappa(k_1-k_2)_\lambda - \frac{1}{4}g_{\kappa\lambda}(k_1-k_2)^2\Big]$$

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

$g_{f_2\pi\pi} = 9.26 \pm 0.15$

from $\Gamma(f_2 \to \pi\pi)$

$$-i\,\frac{g_{f_{2R}\pi\pi}}{2M_0}F_M\big[(k'-k)^2\big]\Big[(k'+k)_\kappa(k'+k)_\lambda - \frac{1}{4}g_{\kappa\lambda}(k'+k)^2\Big]$$

$g_{f_{2R}\pi\pi} = 9.30$

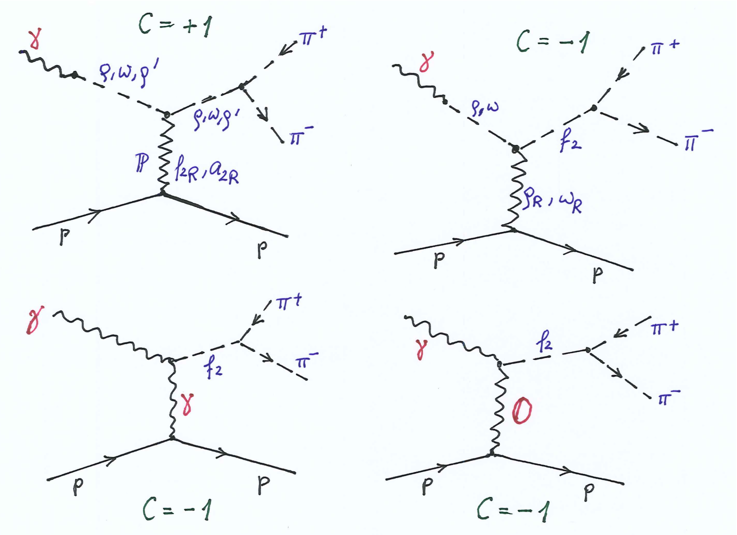
from $\sigma_{\text{tot}}(\pi^\pm p)$

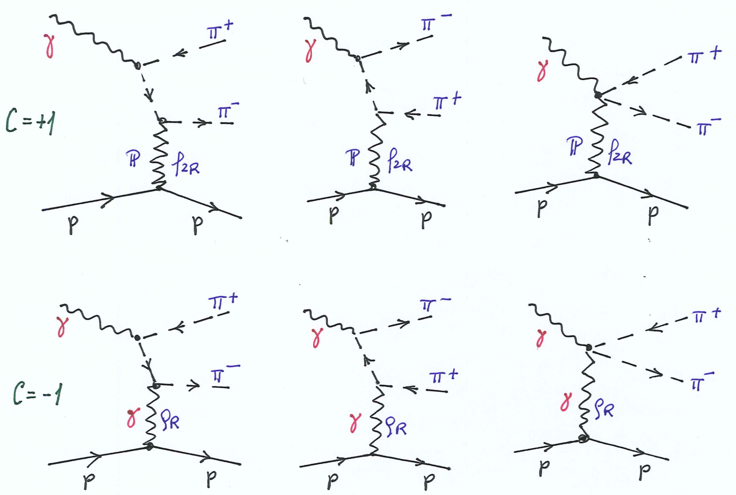
Photoproduction of $\pi^+\pi^-$ pairs

$$\gamma(q) + p(p) \to \pi^+(k_1) + \pi^-(k_2) + p(p')$$

Many exchanges, both with $C = +1$ and $C = -1$, contribute.

- Our aim: construct a model amplitude allowing to calculate all distributions including asymmetries due to $C = +1$ and $C = -1$ exchanges.
- The reaction can be studied e.g. with HERA data and may be used to look for odderon effects


C = +1
γ
ρ, ω, ρ'
ρ, ω, ρ'
π+
π−
P
f2R, a2R
p
p
C = −1
γ
ρ, ω
f2
π+
π−
ρR, ωR
p
p
γ
f2
π+
π−
γ
p
p
C = −1
γ
f2
π+
π−
O
p
p
C = −1


C=+1
C=-1

There are many diagrams. It is essential to have a model where charge conjugation properties and gauge invariance are automatically correct.

We can calculate all distributions and asymmetries in our model with parameters to be fixed by experiment.

Examples as given in JHEP **1501**, 151 (2015)

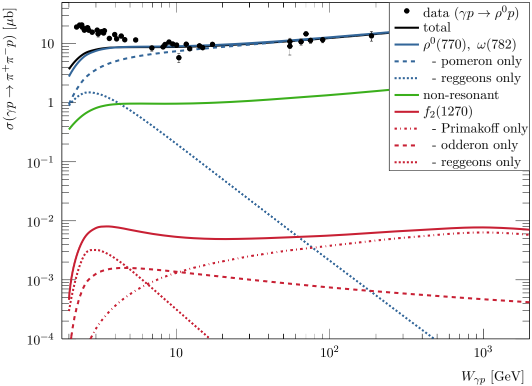


Figure 3. The total cross section $\sigma\,(\gamma p \to \pi^+\pi^- p)$ as a function of the center-of-mass energy $W_{\gamma p}$. The cross section is integrated over $2m_\pi \leq m_{\pi^+\pi^-} \leq 1.5\,\text{GeV}$ and $-1\,\text{GeV}^2 \leq t \leq 0$. The full model and individual contributions from vector meson production, non-resonant processes, and f_2 production are shown. The reggeon contributions comprise f_{2R} and a_{2R} in case of vector meson, and ρ_R and ω_R in case of f_2 production. High energy data for $\sigma\,(\gamma p \to \rho^0 p)$ from H1 [17] and ZEUS [16, 18] at HERA as well as fixed target data, referenced in [18], are shown for illustration.

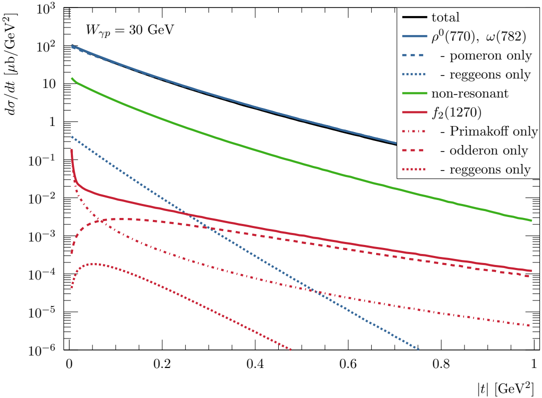


Figure 4. The differential cross section $d\sigma/dt\,(\gamma p \to \pi^+\pi^- p)$ as function of $|t|$. The cross section is integrated over the range $2m_\pi \leq m_{\pi^+\pi^-} \leq 1.5\,\text{GeV}$ and given for fixed $W_{\gamma p} = 30\,\text{GeV}$. In addition to the full model results also contributions from the main diagrams are shown, see figure 3 for explanations.

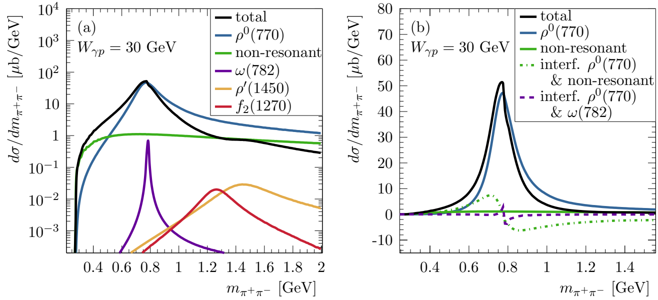


Figure 5. Differential cross sections $d\sigma/dm_{\pi^+\pi^-}$ $(\gamma p \to \pi^+\pi^- p)$ as function of $m_{\pi^+\pi^-}$ for fixed $W_{\gamma p} = 30\,\text{GeV}$ and integrated over the range $-1\,\text{GeV}^2 \le t \le 0$. (a) The full model, non-resonant contributions and the contributions from the resonances $\rho^0(770)$, $\omega(782)$, $f_2(1270)$ and $\rho'(1450)$ are shown. (b) Dominant contributions in the ρ mass region including the leading interferences of $\rho^0(770)$ with the non-resonant $\pi^+\pi^-$ production and the $\omega(782)$ meson are shown.

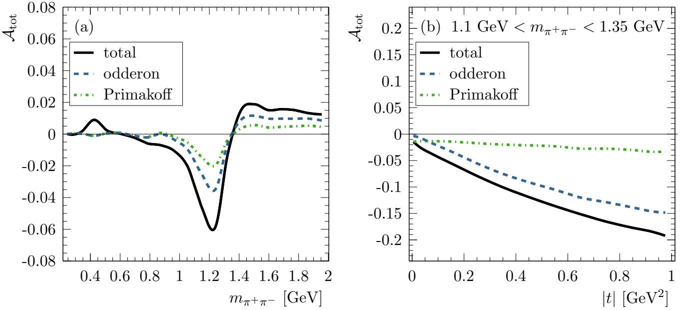


Figure 7. Total charge asymmetry $\mathcal{A}_{\rm tot}$ (3.4) in the proton-Jackson system as function of the (a) invariant mass of the $\pi^+\pi^-$ system and (b) squared momentum transfer t. The asymmetries are presented for fixed $W_{\gamma p} = 30\,\text{GeV}$ and (a) integrated over the range $-1\,\text{GeV}^2 \leq t \leq 0$ and (b) integrated over the range $1.1\,\text{GeV} < m_{\pi^+\pi^-} < 1.35\,\text{GeV}$. The individual contributions to the asymmetries from photon (Primakoff) and odderon exchange are shown by the green dashed-dotted and blue dashed lines, respectively.

Conclusions

- We outlined a model for high-energy soft reactions based on QFT plus elements of Regge theory. We give a list of propagators and vertices.
- $C = +1$ exchanges, $\mathbb{P}, f_{2R}, a_{2R}$, are represented as tensors of rank 2.
- $C = -1$ exchanges, $\mathbb{O}(?), \omega_R, \rho_R$, are represented as vectors.
- Comparisons with data would be most welcome:
  ISR, UA1, UA2, FNAL, HERA, LHC, COMPASS, RHIC

- The model allows to calculate cross sections and distributions of soft reactions in terms of just a few coupling parameters.
- Central production: result available for

$$p + p \to p + M + p \,, \quad M = 0^{++} \text{ and } 0^{-+} \text{ mesons}$$
$$\text{scalars } (0^{++}) : f_0(980),\; f_0(1370),\; f_0(1500),$$
$$\text{pseudoscalars } (0^{-+}) : \;\eta\,,\; \eta'(958).$$
$$p + p \to p + \pi^+ + \pi^- + p, \quad \text{“photoproduction''contribution}$$

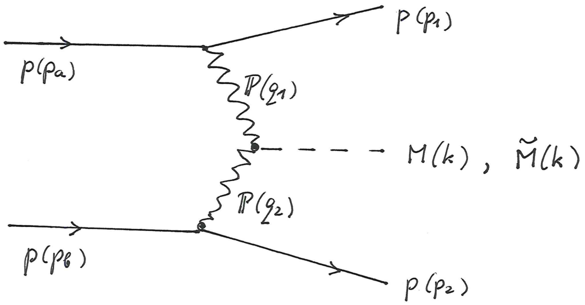
- diffractive dissociation:

$$p + p \to p + X : \quad \text{work in progress,}$$

- DIS

$$\gamma^* + p \to \gamma^* + p : \quad \text{work in progress.}$$

Central production of 0^{++} meson M and 0^{-+} mesons $\tilde{M}$



$$M = f_0(980),\ f_0(1370),\ f_0(1500)$$

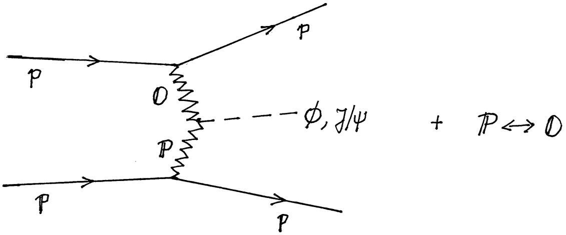
$$\tilde{M} = \eta, \eta'(958)$$

effective coupling Lagrangians ($M_0 \equiv 1$ GeV)

$$\mathcal{L}_{\mathbb{P}\mathbb{P}M} = M_0 g'_{\mathbb{P}\mathbb{P}M} \mathbb{P}_{\mu\nu}(x) \mathbb{P}^{\mu\nu}(x) \chi_M(x) + \frac{1}{2M_0} g''_{\mathbb{P}\mathbb{P}M} \left[\partial^\mu \mathbb{P}^{\nu\rho}(x) - \partial^\nu \mathbb{P}^{\mu\rho}(x)\right] \left[\partial_\mu \mathbb{P}_{\nu\rho}(x) - \partial_\nu \mathbb{P}_{\mu\rho}(x)\right] \chi_M(x)$$

$$\mathcal{L}_{\mathbb{P}\mathbb{P}\tilde{M}} = -\frac{2}{M_0} g'_{\mathbb{P}\mathbb{P}\tilde{M}} \left[\partial_\rho \mathbb{P}_{\mu\nu}(x)\right] \left[\partial_\sigma \mathbb{P}_{\kappa\lambda}(x)\right] g^{\mu\kappa} \epsilon^{\nu\lambda\rho\sigma} \chi_{\tilde{M}}(x) - \frac{1}{M_0^3} g''_{\mathbb{P}\mathbb{P}\tilde{M}} \epsilon^{\mu_1\mu_2\nu_1\nu_2} \left[\partial_{\mu_1} \chi_{\tilde{M}}(x)\right] \left[\partial_{\mu_3} \mathbb{P}_{\mu_4\nu_1}(x) - \partial_{\mu_4} \mathbb{P}_{\mu_3\nu_1}(x)\right] \overleftrightarrow{\partial}_{\mu_2} \left[\partial^{\mu_3} \mathbb{P}^{\mu_4}_{\nu_2}(x) - \partial^{\mu_4} \mathbb{P}^{\mu_3}_{\nu_2}(x)\right]$$

- Fits to data from WA102, $\sqrt{s} = 29.1$ GeV, have been made and are O.K., determine coupling parameters.
- Do the same coupling parameters fit LHC data at $\sqrt{s} = 1$ to 13 TeV?
  Absorption effects, gap survival factors?
- Which distributions are accessible at LHC?
- Central production of ϕ and J/ψ and odderon search:



- Open problems:

  - Absorption
  - Inclusion of strange particles?
  - Form factors?
  - Closer connection with QCD?
  - General comparison of the model with data on soft high-energy reactions.