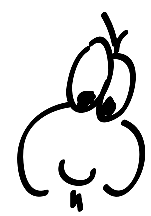
The Spin Structure of the Soft Pomeron



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ECT*-EMMI/GSI Workshop, Trento, Feb 27, 2017

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The spin structure of the soft pomeron

1 Introduction

2 Helicity amplitudes in pp elastic scattering

3 Tensor, vector or scalar pomeron?

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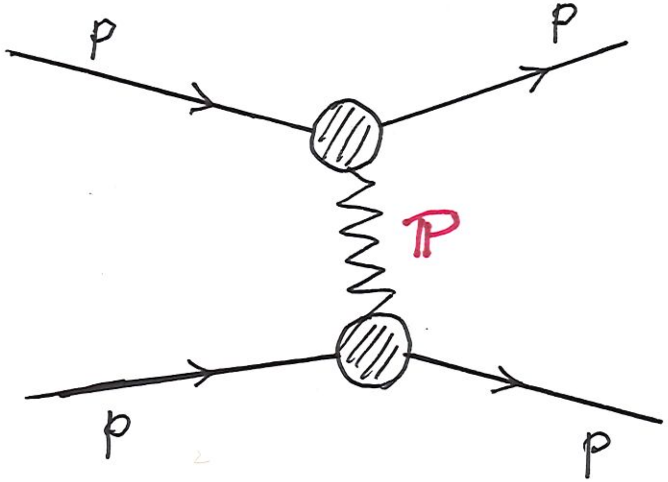
5 Conclusions and historical remarks

1 Introduction

In this talk we shall discuss the pomeron, mainly the soft one, whose exchange governes many high-energy reactions.

Examples:

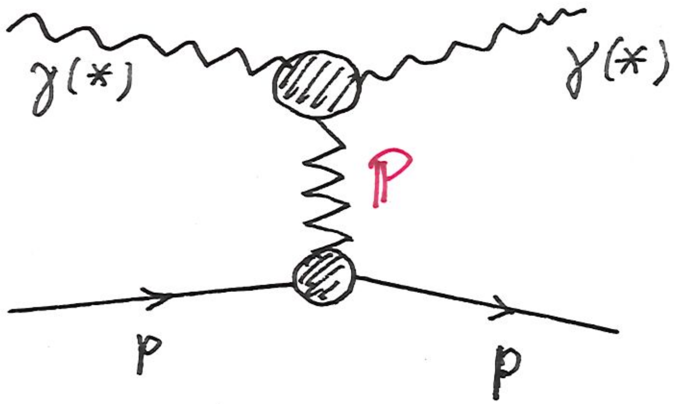
- $p\,p$ elastic scattering



- real and virtual Compton scattering,

$$\gamma^{(*)} + p \longrightarrow \gamma^{(*)} + p$$

$\Longrightarrow$ $\sigma_{tot}(\gamma, p)$ and structure functions of DIS

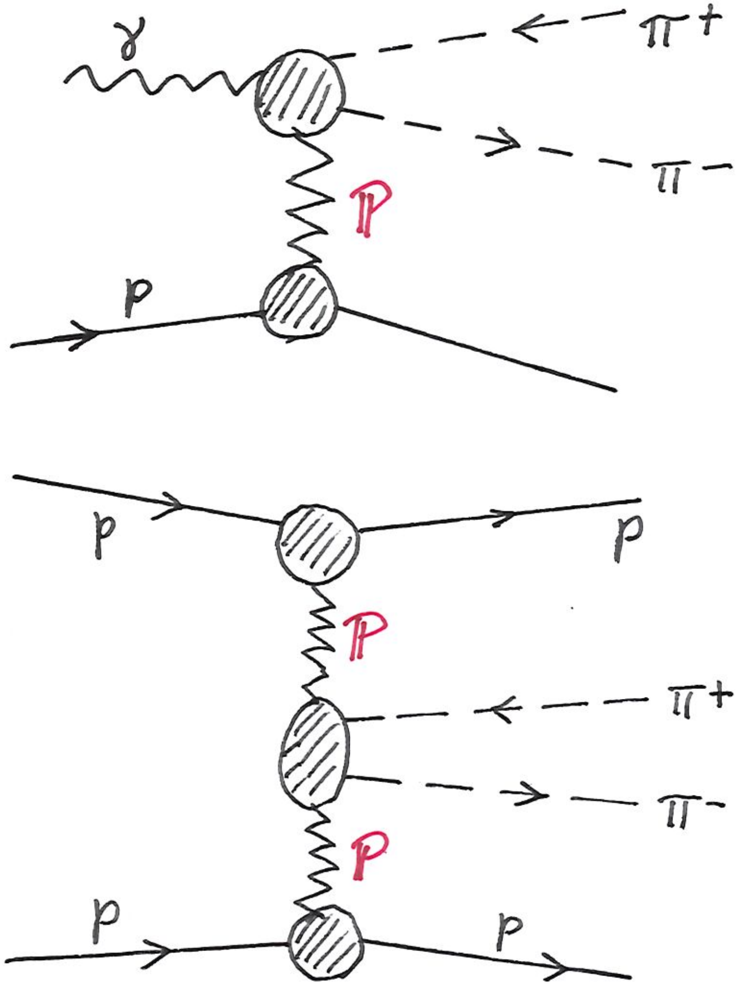


exclusive reactions

- $\gamma + p \longrightarrow \pi^+ + \pi^- + p$

  $p + p \longrightarrow p + \pi^+ + \pi^- + p$

Everybody draws such diagrams but the interpretation given to them can differ widely.



Properties of the pomeron:

vacuum internal quantum numbers:

charge	$Q = 0$
colour charge	$Q_c = 0$
isospin	$I = 0$
charge conjugation	$C = 1$

spin structure? We believe that the pomeron is best described as the effective exchange of a symmetric rank 2 tensor object, the tensor pomeron.

We shall show that the STAR experiment on pp elastic scattering with spin gives decisive evidence for this view.

References:

Ewerz, Maniatis, O.N., Ann. Phys. 342 (2014) 31

Lebiedowicz, O.N., Szczurek, Ann. Phys. 344 (2014) 301

Bolz, Ewerz, Maniatis, O.N., Sauter, Schöning, JHEP 1501 (2015) 151

Lebiedowicz, O.N., Szczurek, PR D91 (2015) 074023

PR D93 (2016) 054015

PR D94 (2016) 034017

arXiv: 1612.06294

Ewerz, Lebiedowicz, O.N., Szczurek, PL B763 (2016) 382

2 Helicity amplitudes in pp elastic scattering

$$p(p_1, s_1) + p(p_2, s_2) \longrightarrow p(p_3, s_3) + p(p_4, s_4)$$

$s_j \in \{+1/2, -1/2\}$, helicity indices

kinematic variables:

$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$

$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$

$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$

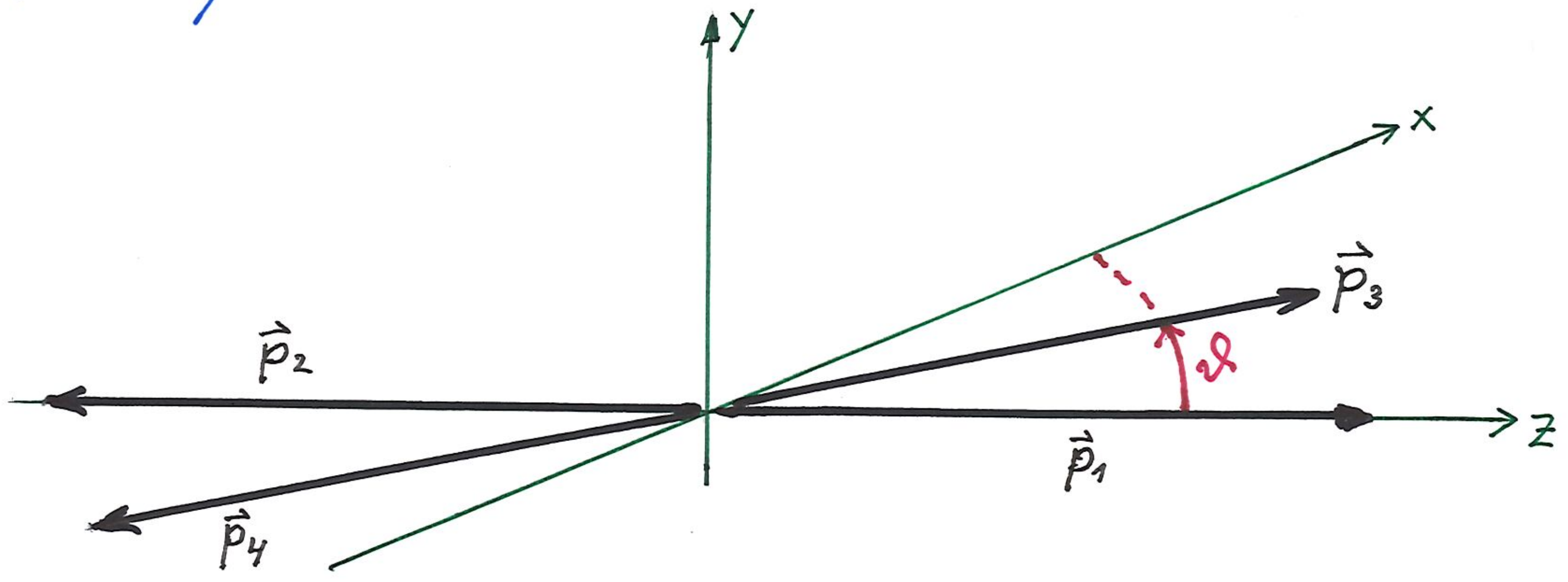
There are $2^4 = 16$ helicity amplitudes.

General analysis of the reaction:

Goldberger et al., PR 120 (1960) 2250

Buttimore et al., PR D18 (1978) 694; PR D59 (1999) 114010

c.m. Coordinate system



Definition of the helicity states $|p(p_1, s_1)\rangle$, $|p(\vec{p}_2, s_2)\rangle$ and corresponding Dirac spinors:

$$u_{s_j}(p_j) = \sqrt{p_j^0 + m_p} \begin{pmatrix} \chi^{(j)}_{s_j} \\ \dfrac{\vec{\sigma}\vec{p}_j}{p_j^0 + m_p} \chi^{(j)}_{s_j} \end{pmatrix}, \qquad \chi^{(1)}_{1/2} = \chi^{(2)}_{-1/2} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$\chi^{(1)}_{-1/2} = \chi^{(2)}_{1/2} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$j = 1, 2$

Consider $\mathcal{U}_2(\vartheta)$, a rotation by ϑ around the positive y axis.
We define the helicity states $|p(p_3, s_3)\rangle$, $|p(p_4, s_4)\rangle$ by

$$|p(p_3, s_3)\rangle = \mathcal{U}_2(\vartheta)\,|p(p_1, s_3)\rangle\,,$$

$$|p(p_4, s_4)\rangle = \mathcal{U}_2(\vartheta)\,|p(p_2, s_4)\rangle.$$

This fixes all phases of the states.

Notation:

$$\langle p(p_3, s_3), p(p_4, s_4)|T|p(p_1, s_1), p(p_2, s_2)\rangle$$

$$\equiv \langle 2s_3, 2s_4 | T | 2s_1, 2s_2\rangle$$

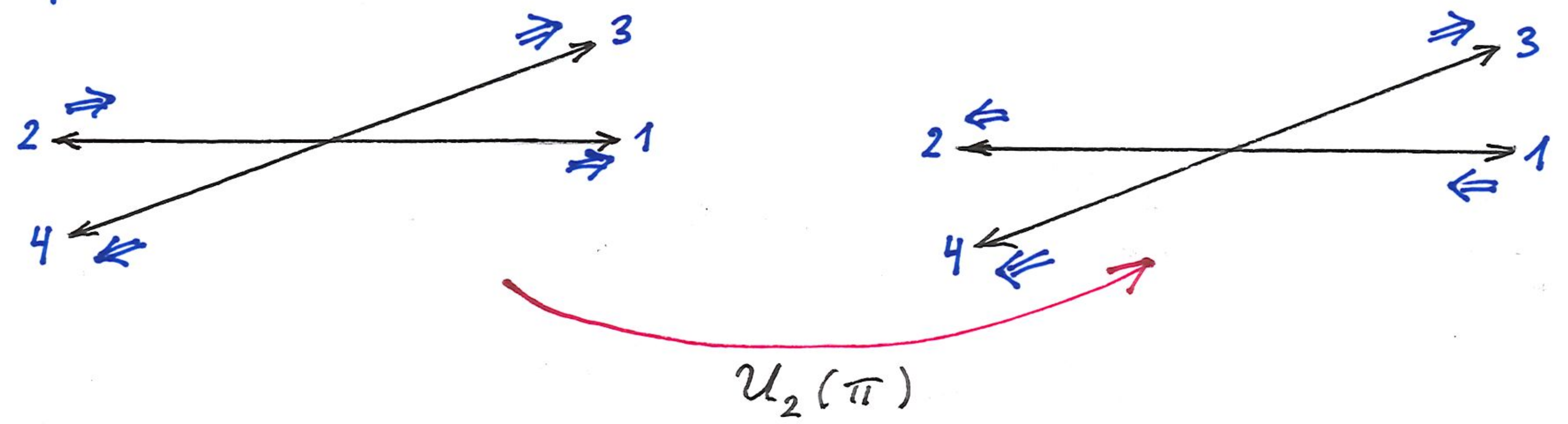
Symmetries of the reaction:

$\mathcal{U}_2(\pi)$ rotation by π around the positive y axis

$\mathcal{U}(\mathcal{P})$ parity transformation

$\mathcal{U}_3(\pi)\,\mathcal{U}_2(-\vartheta)\,V(T)$ time reversal (antiunitary) followed by rotation by $-\vartheta$ around pos. y axis followed by rotation by π around pos. z axis

Example:



$$\langle + + | T | + - \rangle = - \langle + + | T | - + \rangle$$

	$\mathcal{U}_2(\pi)$	$\mathcal{U}(P)$	$\mathcal{U}_{32}(\pi,-\vartheta)\, V(T)$	
$\langle ++\|T\|++\rangle$	$\langle ++\|T\|++\rangle$	$\langle --\|T\|--\rangle$	$\langle ++\|J\|++\rangle$	ϕ_1
$\langle ++\|T\|+-\rangle$	$-\langle ++\|T\|-+\rangle$	$\langle --\|T\|+-\rangle$	$\langle -+\|J\|++\rangle$	ϕ_5
$\langle ++\|T\|-+\rangle$	$-\langle ++\|T\|+-\rangle$	$\langle --\|T\|-+\rangle$	$\langle +-\|J\|++\rangle$	$-\phi_5$
$\langle ++\|T\|--\rangle$	$\langle ++\|T\|--\rangle$	$\langle --\|T\|++\rangle$	$\langle --\|J\|++\rangle$	ϕ_2
$\langle +-\|T\|++\rangle$	$-\langle -+\|T\|++\rangle$	$\langle +-\|T\|--\rangle$	$\langle ++\|J\|-+\rangle$	$-\phi_5$
$\langle +-\|T\|+-\rangle$	$\langle -+\|T\|-+\rangle$	$\langle +-\|T\|+-\rangle$	$\langle -+\|J\|-+\rangle$	ϕ_3
$\langle +-\|T\|-+\rangle$	$\langle -+\|T\|+-\rangle$	$\langle +-\|T\|-+\rangle$	$\langle +-\|J\|-+\rangle$	ϕ_4
$\langle +-\|T\|--\rangle$	$-\langle -+\|T\|--\rangle$	$\langle +-\|T\|++\rangle$	$\langle --\|J\|-+\rangle$	$-\phi_5$
$\langle -+\|T\|++\rangle$	$-\langle +-\|T\|++\rangle$	$\langle -+\|T\|--\rangle$	$\langle ++\|J\|+-\rangle$	$+\phi_5$
$\langle -+\|T\|+-\rangle$	$-\langle +-\|T\|-+\rangle$	$\langle -+\|T\|+-\rangle$	$\langle -+\|J\|+-\rangle$	ϕ_4
$\langle -+\|T\|-+\rangle$	$\langle +-\|T\|+-\rangle$	$\langle -+\|T\|-+\rangle$	$\langle +-\|J\|+-\rangle$	ϕ_3
$\langle -+\|T\|--\rangle$	$-\langle +-\|T\|--\rangle$	$\langle -+\|T\|++\rangle$	$\langle --\|J\|+-\rangle$	$+\phi_5$
$\langle --\|T\|++\rangle$	$\langle --\|T\|++\rangle$	$\langle ++\|T\|--\rangle$	$\langle ++\|T\|--\rangle$	ϕ_2
$\langle --\|T\|+-\rangle$	$-\langle --\|T\|-+\rangle$	$\langle ++\|T\|+-\rangle$	$\langle -+\|J\|--\rangle$	ϕ_5
$\langle --\|T\|-+\rangle$	$-\langle --\|T\|+-\rangle$	$\langle ++\|T\|-+\rangle$	$\langle +-\|J\|--\rangle$	$-\phi_5$
$\langle --\|T\|--\rangle$	$\langle --\|T\|--\rangle$	$\langle ++\|T\|++\rangle$	$\langle --\|J\|--\rangle$	ϕ_1

five independent amplitudes:

helicity:

$\phi_1(s,t) = \langle ++|T|++\rangle$ non flip

$\phi_2(s,t) = \langle ++|T|--\rangle$ double flip

$\phi_3(s,t) = \langle +-|T|+-\rangle$ non flip

$\phi_4(s,t) = \langle +-|T|-+\rangle$ double flip

$\phi_5(s,t) = \langle ++|T|+-\rangle$ single flip

$$\sigma_{tot}(p,p) = \frac{1}{4\sqrt{s(s-4m_p^2)}} \sum_{s_1,s_2} \mathrm{Im} \langle 2s_1, 2s_2 | T | 2s_1, 2s_2 \rangle \Big|_{t=0}$$

$$= \frac{1}{2\sqrt{s(s-4m_p^2)}} \mathrm{Im} \left[\phi_1(s,0) + \phi_3(s,0) \right]$$

3 Tensor, vector, or scalar pomeron?

These are the three hypotheses we want to test.

We choose our ansätze for the effective $\mathbb{P}$ propagators and $\mathbb{P}pp$ couplings such that at high energies the non-flip amplitudes ϕ_1 and ϕ_3 are the same for all three cases. This gives the same $\sigma_{tot}(p,p)$.

The Donnachie-Landshoff (DL) model treats the pomeron as effective vector exchange and gives a phenomenologically successful fit to $\sigma_{tot}(p,p)$ and $d\sigma/dt$.

Our ansätze are chosen such that ϕ_1 and ϕ_3 are as in the DL model.

Tensor pomeron

Here we describe the pomeron by a symmetric, traceless, tensor field of rank 2

$$\mathbb{P}_T^{\mu\nu}(x) = \mathbb{P}_T^{\nu\mu}(x) \,, \qquad \mathbb{P}_T^{\mu\nu}(x)\, g_{\mu\nu} = 0$$

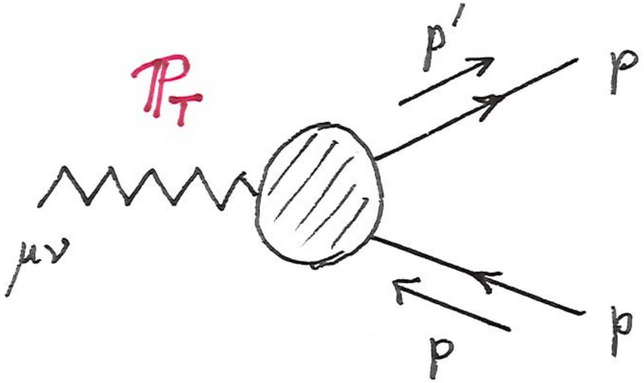
$\mathbb{P} p p$ coupling:

$$\mathcal{L}'_T(x) = J_{T\mu\nu}(x)\, \mathbb{P}_T^{\mu\nu}(x) \,,$$

$$J_{T\mu\nu}(x) = -3\beta_{\mathbb{P}NN} \frac{i}{2} \bar{\psi}_p(x) \left[\gamma_\mu \overleftrightarrow{\partial}_\nu + \gamma_\nu \overleftrightarrow{\partial}_\mu - \frac{1}{2} g_{\mu\nu} \gamma^\lambda \overleftrightarrow{\partial}_\lambda \right] \psi_p(x)$$

$$3\beta_{\mathbb{P}NN} = 3 \times 1.87 \text{ GeV}^{-1}$$

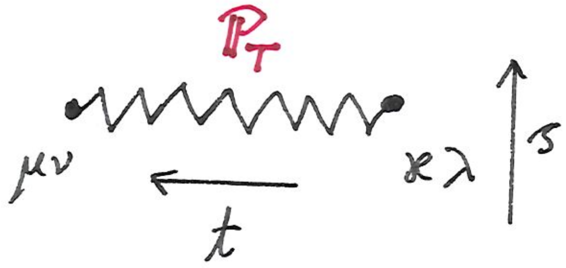
$\psi_p(x)$ proton field operator



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

$F_1(t)$: form factor, $F_1(0) = 1$.

$\mathbb{P}_T$ propagator:



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

$$\alpha_{\mathbb{P}}(t) = 1 + \varepsilon_{\mathbb{P}} + \alpha'_{\mathbb{P}}t$$ linear pomeron trajectory

$$\varepsilon_{\mathbb{P}} = 0.0808\,,$$

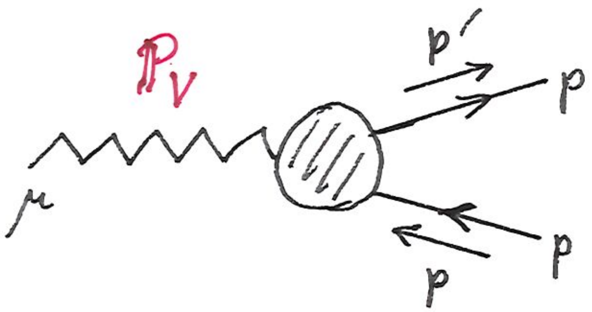
$$\alpha'_{\mathbb{P}} = 0.25\ \mathrm{GeV}^{-2}$$

Vector pomeron (DL pomeron)

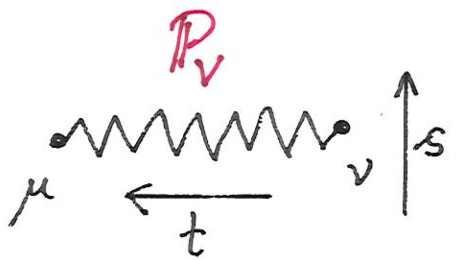
Here the pomeron is described by a vector field $\mathbb{P}_V^{\mu}(x)$.

$$\mathcal{L}'_V(x) = J_{V\mu}(x)\, \mathbb{P}_V^{\mu}(x)\,,$$

$$J_{V\mu}(x) = -3\beta_{\mathbb{P}NN} M_0\, \bar{\psi}_p(x)\, \gamma_\mu\, \psi_p(x)\,, \quad M_0 \equiv 1\ \mathrm{GeV}$$



$$i\Gamma_\mu^{(\mathbb{P}_V pp)}(p',p) = -i\, 3\beta_{\mathbb{P}NN} M_0\, F_1\left[(p'-p)^2\right] \gamma_\mu$$



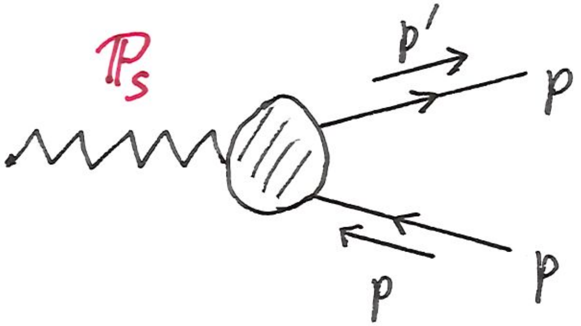
$$i\Delta_{\mu\nu}^{(\mathbb{P}_V)}(s,t) = \frac{1}{M_0^2}\, g_{\mu\nu}\, (-is\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1}$$

Scalar pomeron

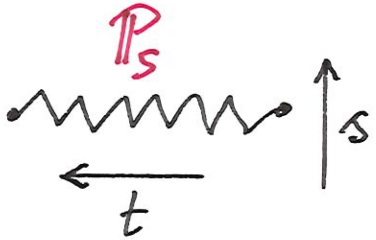
Here the pomeron is described by a scalar field $\mathbb{P}_S(x)$.

$$\mathcal{L}'_S(x) = J_S(x)\, \mathbb{P}_S(x)$$

$$J_S(x) = -3\beta_{\mathbb{P}NN} M_0\, \bar{\psi}_p(x)\, \psi_p(x)$$

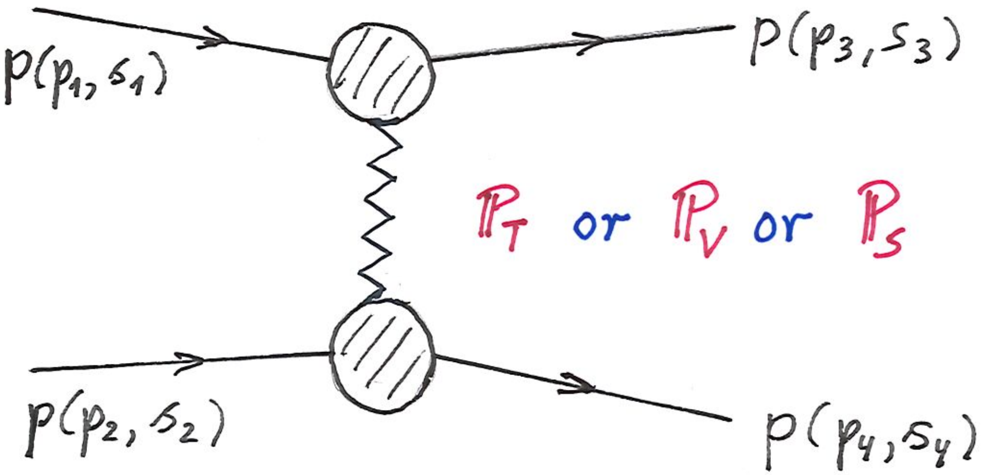


$$i\Gamma^{(\mathbb{P}_S pp)}(p',p) = -i\, 3\beta_{\mathbb{P}NN} M_0\, F_1\left[(p'-p)^2\right]$$



$$i\Delta^{(\mathbb{P}_S)}(s,t) = \frac{s}{2m_p^2 M_0^2}\left(-is\alpha'_{\mathbb{P}}\right)^{\alpha_{\mathbb{P}}(t)-1}$$

Calculation of the amplitudes $\phi_j(s,t)$:



reduced amplitudes:

$$\hat{\phi}_j(s,t) = \phi_j(s,t) \,/\, \mathcal{F}(s,t) \qquad j = 1, \dots, 5$$

$$\mathcal{F}(s,t) = i \left[3 \beta_{\mathbb{P}NN} F_1(t) \right]^2 \frac{1}{4s} \left(-i s \alpha'_{\mathbb{P}} \right)^{\alpha_{\mathbb{P}}(t)-1}$$

pomeron ansatz			
	tensor	vector	scalar
$\hat{\Phi}_1(s,t)$	$8s^2$	$8s^2$	$8s^2$
$\hat{\Phi}_2(s,t)$	$10\,m_p^2\,t$	$16\,m_p^2\,t$	$2s^2t/m_p^2$
$\hat{\Phi}_3(s,t)$	$8s^2$	$8s^2$	$8s^2$
$\hat{\Phi}_4(s,t)$	$-10\,m_p^2\,t$	$-16\,m_p^2\,t$	$-2s^2t/m_p^2$
$\hat{\Phi}_5(s,t)$	$-8s\,m_p\sqrt{-t}$	$-8s\,m_p\sqrt{-t}$	$-4s^2\sqrt{-t}/m_p$

$$s \gg m_p^2\,,\ |t|$$

4 Comparison with experiment

total cross section:

$$\sigma_{tot}(p,p) = \frac{1}{2s} \operatorname{Im}\left[\phi_1(s,0) + \phi_3(s,0)\right]$$

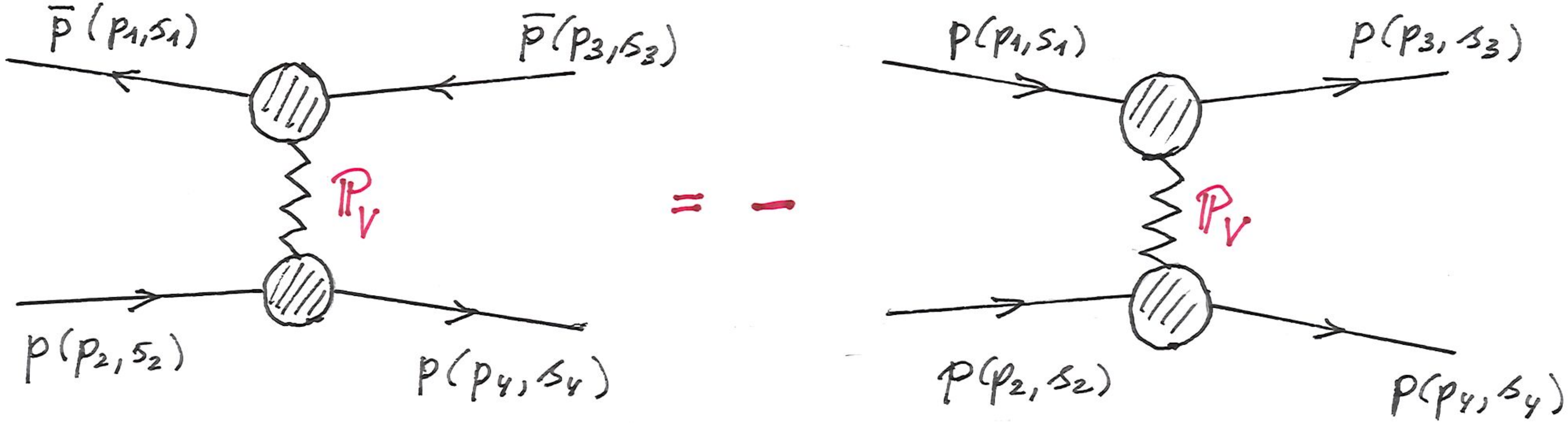
$$= 2\left(3\beta_{\mathbb{P}NN}\right)^2 \cos\left(\frac{\pi}{2}\epsilon_{\mathbb{P}}\right)\left(s\alpha'_{\mathbb{P}}\right)^{\epsilon_{\mathbb{P}}}$$

This is the standard result of the DL model:

σ_{tot} rises with a small power, $\epsilon_{\mathbb{P}} = 0.0808$, of s.

By construction we have the same result for our tensor, vector, and scalar pomeron.

Problems with the vector pomeron:



The minus sign for $\bar{p}p$ versus pp has the same origin as for $e^+ e^-$ versus $e^- e^-$ scattering in the one-photon exchange approximation. Vector exchange has $C = -1$.

It follows

$$\sigma_{tot}(\bar{p}, p)^{\mathbb{P}_V} = - \sigma_{tot}(p, p)^{\mathbb{P}_V}$$

In our opinion a vector pomeron $\mathbb{P}_V$ is not a viable option.

We are left with $\mathbb{P}_T$ and $\mathbb{P}_S$. Both correspond to charge conjugation $C = +1$ exchanges:

$$\langle \bar{p}, p | T | \bar{p}, p \rangle^{\mathbb{P}_T} = \langle p, p | T | p, p \rangle^{\mathbb{P}_T}$$

$$\langle \bar{p}, p | T | \bar{p}, p \rangle^{\mathbb{P}_S} = \langle p, p | T | p, p \rangle^{\mathbb{P}_S}$$

Remember gravity, also a tensor exchange, which gives the same attraction for $\bar{p}p$ and pp.

To decide between $\mathbb{P}_T$ and $\mathbb{P}_S$ we turn to the STAR experiment (PL B 719 (2013) 62) which measured the single spin asymmetry A_N in polarised pp elastic scattering at $\sqrt{s} = 200$ GeV.

The experiment is done at very small $|t|$,

$$0.003 \leq |t| \leq 0.035 \text{ GeV}^2,$$

that is, in the Coulomb-nuclear interference region. This allows to extract real and imaginary part of the single-flip amplitude $\phi_5(s,t)$. Quoted is

$$r_5(s,t) = \frac{2 m_p \, \phi_5(s,t)}{\sqrt{-t}\; \mathrm{Im}\left[\phi_1(s,t) + \phi_3(s,t)\right]}$$

We get for the tensor pomeron

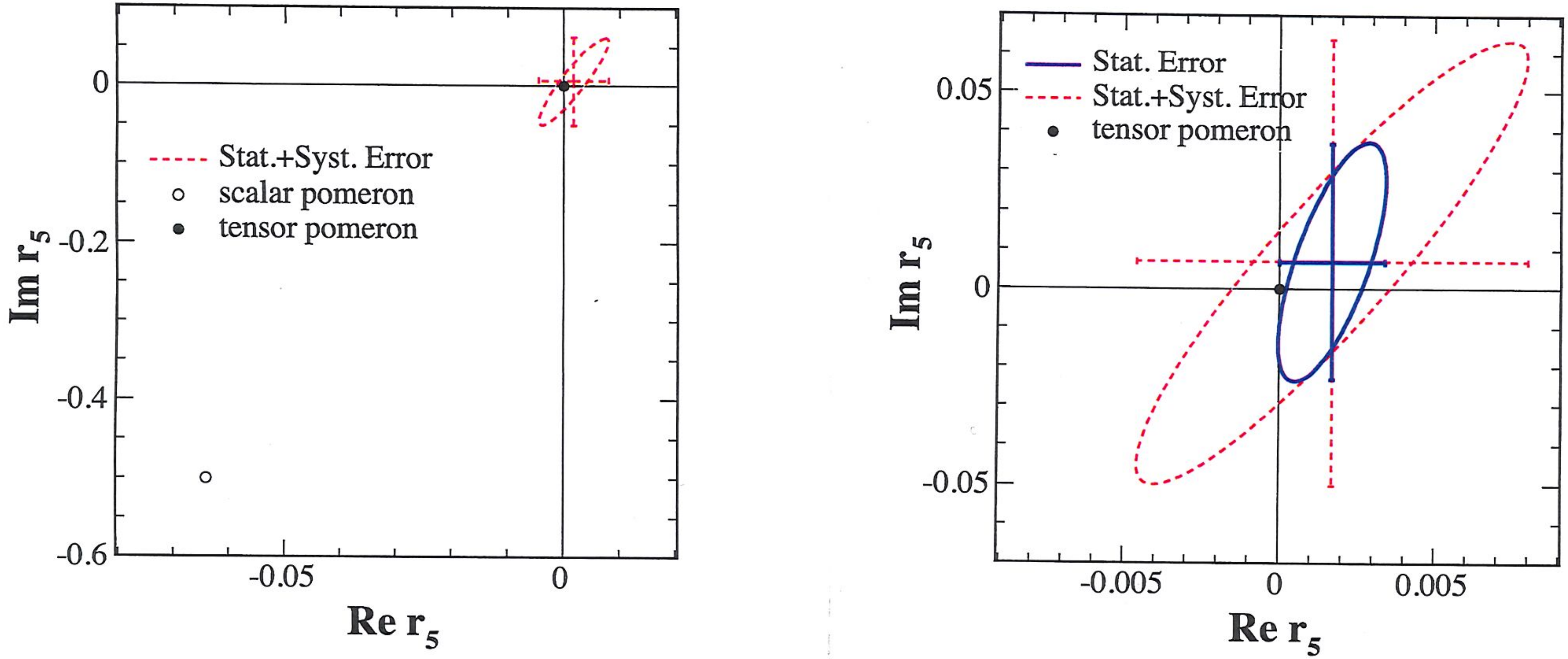
$$r_5^{\mathbb{P}_T}(s,t) = -\frac{m_p^2}{s}\left[i + \tan\left(\frac{\pi}{2}\left(\alpha_{\mathbb{P}}(t)-1\right)\right)\right]$$

$$r_5^{\mathbb{P}_T}(s,0)\Big|_{s=(200\,\mathrm{GeV})^2} = (-0.28 - i\,2.20)\times 10^{-5}$$

and for the scalar pomeron

$$r_5^{\mathbb{P}_S}(s,t) = -\frac{1}{2}\left[i + \tan\left(\frac{\pi}{2}\left(\alpha_{\mathbb{P}}(t)-1\right)\right)\right]$$

$$r_5^{\mathbb{P}_S}(s,0)\Big|_{s=(200\,\mathrm{GeV})^2} = -0.064 - i\,0.500$$



Experiment : STAR

Theory : Ewerz, Lebiedowicz, O.N., Szczurek

5 Conclusions and historical remarks

From our three ansätze for the pomeron, tensor, vector, or scalar, only the tensor pomeron is compatible with the general rules of QFT and the STAR experimental result.

History: attempts to relate the pomeron to tensors were already made in the 1960s and 1970s

Freund, PL 2 (1962) 136, NC A 5 (1971) 9

Carlitz et al. PRL 26 (1971) 1515

But these attempts were abandoned with the advent of QCD

The pomeron as a gluonic object in QCD perturbation theory:

Low, PR D 12 (1975) 163

Nussinov PRL 34 (1975) 1286

Kuraev, Lipatov, Fadin Zh. Eksp. Teor. Fiz. 72 (1977) 377

Balitsky, Lipatov, Yad. Fiz. 28 (1978) 1597

⋮

Phenomenological vector pomeron:

Donnachie, Landshoff, NP B 231 (1984) 189, B267 (1986) 690

⋮

Pomeron in soft reactions and nonperturbative QCD:

Landshoff, O.N., Z. Phys. C 35 (1987) 405: abelian toy model

O. N. Ann. Phys. 209 (1991) 436: functional integral techniques

In the latter paper we could show that the pomeron could be understood as the coherent sum of elementary exchanges of spin $2 + 4 + 6 + \dots$

The same applies to our tensor pomeron (Ewerz et al. (2014)), thus giving it good backing in QCD.

Specific tests for the spin structure of the pomeron have been proposed in

Arens, Diehl, Landshoff, O.N. Z. Phys. C74 (1997) 651 for diffractive deep inelastic lepton-nucleon scattering;

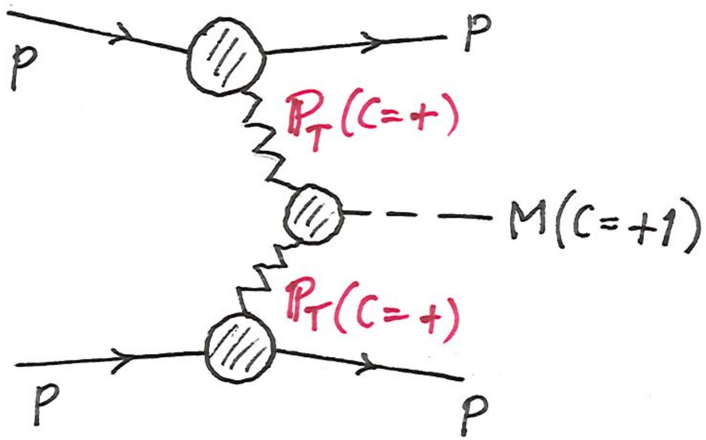
Close, Schuler, PL B458 (1999) 127, B464 (1999) 279 for central exclusive meson production:

$$p + p \longrightarrow p + \text{meson} + p.$$

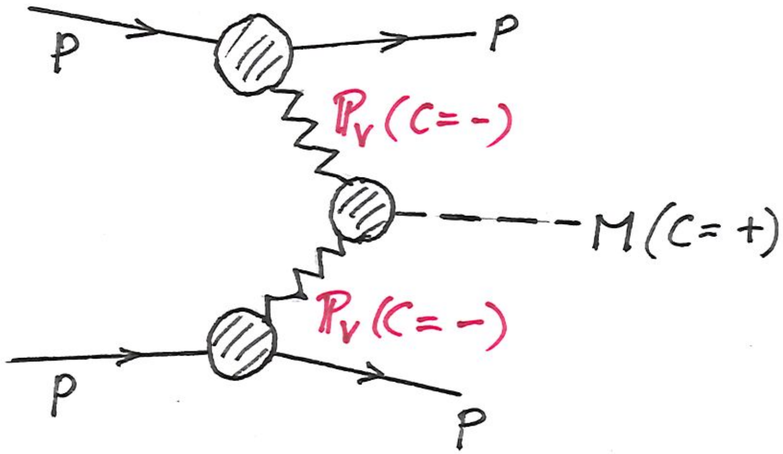
Close and Schuler claim to find evidence that the pomeron transforms as a non-conserved vector current. As we have seen we cannot support such a picture. What is the explanation of this discrepancy?

For central exclusive meson production with double pomeron exchange we have

with the tensor pomeron



with a vector pomeron (Close, Schuler)

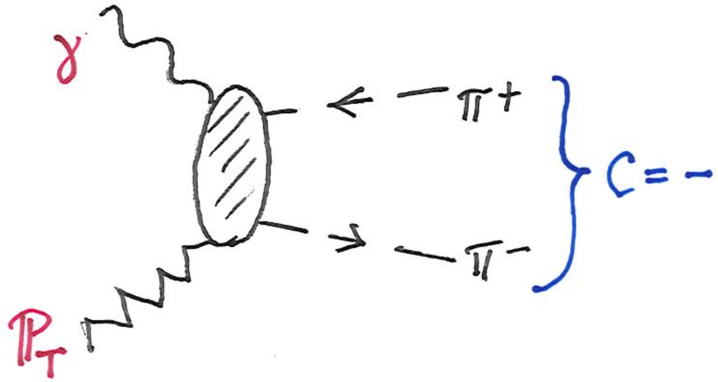


Here we find no drastic differences between $\mathbb{P}_T$ and $\mathbb{P}_V$ (Lebiedowic, O.N., Szczurek, Ann. Phys. (2014)).

But drastic differences turn up if in the middle we have, e.g., gamma-pomeron fusion.

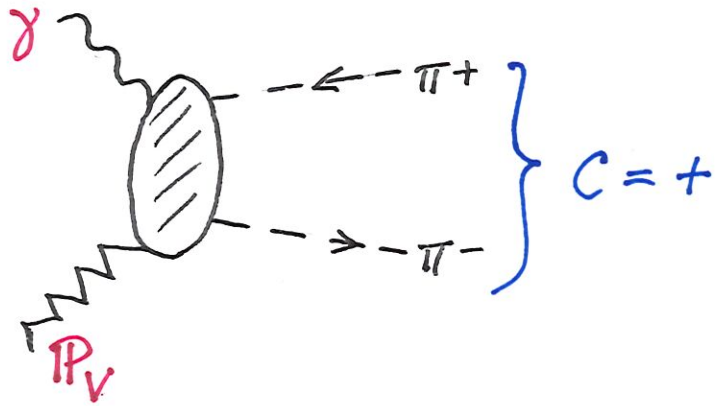
Example: $\gamma + \mathbb{P} \longrightarrow \pi^+ + \pi^-$

tensor pomeron



$\pi^+\pi^-$ in antisymmetric state

vector pomeron



$\pi^+\pi^-$ in symmetric state

This gives a further clear evidence against a vector nature of the pomeron.

Investigations of the pomeron using the methods of AdS / CFT correspondence also prefer a tensor nature of the pomeron:

Domokos, Harvey, Mann, PR D 80 (2009) 126015

Iatrakis, Ramamurti, Shuryak, PR D 94 (2016) 045005

Summary

For the reactions investigated so far the tensor pomeron model works well.

The tensor pomeron gets backing from QCD and AdS / CFT studies.

It will be interesting to see if the tensor pomeron concept is useful also when going from soft to hard reactions, e.g., DIS, exclusive J/ψ production,...

Thank you for your attention