1) Introduction
   Central Exclusive Production (CEP) in $pp$ collisions
2) Tensor-pomeron and vector-odderon approach
3) Recent results
   - $pp \rightarrow pp$ ($\phi \rightarrow K^+ K^-$)
   - $pp \rightarrow pp$ ($\phi \rightarrow \mu^+ \mu^-$)
   - $pp \rightarrow pp K^+ K^- K^+ K^-$ (via intermediate $\phi\phi$ state)
4) Conclusions
Central Exclusive Production (CEP) in proton-proton collisions at high energies

\[ p \ (p_a) + p \ (p_b) \rightarrow p \ (p_1) + X \ (p_X) + p \ (p_2) \]

\( X \) may be a single particle, a group of particles, jets, etc. We require large rapidity gaps between \( p \ (p_1) \) and \( X \), \( p \ (p_2) \) and \( X \).

Exchange objects:
- \( P \ (C = +1) \) pomeron, should dominate for large \( s_1, s_2 \)
- \( O \ (C = -1) \) odderon
- \( R : f_{2R}, a_{2R} \ (C = +1) \)
- \( \omega_R, \rho_R \ (C = -1) \)
- \( \gamma \ (C = -1) \) photon

\[ \begin{align*}
S_1 & \Rightarrow p, O, R, \gamma \\
S_2 & \Rightarrow p, O, R, \gamma
\end{align*} \]
What can we hope to learn from CEP?

- (1) Properties and the coupling of the exchange objects *pomeron* (IP), *odderon* (O), *reggeon* (IR), *photon* (γ) to the external protons and to the system X. Here IP, IR, γ are well established. But what is the spin structure of the pomeron IP? Does the “elusive odderon” exist? I hope to show you that CEP offers possibilities to study odderon effects.

- Properties of the system X
  - (2) Search for and characterisation of resonances, e.g. glueballs (gluonic bound states)
  - Higgs particle, electroweak physics, physics beyond the SM, etc.

  In my talk I shall consider mainly hadronic system X: φ, φφ

- From the theory point of view the topics (1) - (2) are, mainly nonperturbative, QCD problems.

We have to resort to model:
“A model for soft high-energy scattering: Tensor pomeron and vector odderon”, C. Ewerz, M. Maniatis, O. Nachtmann, Ann. Phys. 342 (2014) 31
Applications of the tensor-pomeron model

$\gamma p \rightarrow \pi^+ \pi^- p$  Bolz, Ewerz, Maniatis, Nachtmann, Sauter, Schöning, JHEP 01 (2015) 151

There will be interference between $\gamma p \rightarrow (\rho^0 \rightarrow \pi^+ \pi^-) p$ (pomeron exchange) and $\gamma p \rightarrow (f_2(1270) \rightarrow \pi^+ \pi^-) p$ (odderon exchange) processes and as a consequence $\pi^+\pi^-$ charge asymmetries.

Helicity in proton-proton elastic scattering and the spin structure of the pomeron

C. Ewerz, P. L., O. Nachtmann, A. Szczurek, PLB 763 (2016) 382

Studying the ratio $r_5$ of single-helicity-flip to non-flip amplitudes we found that the STAR data [L. Adamczyk et al., PLB 719 (2013) 62] are consistent with the tensor pomeron model while they clearly exclude a scalar pomeron. Vector pomeron is in contradiction to the rules of QFT.

CEP, $p p \rightarrow p p X$, P.L., Nachtmann, Szczurek:

$X$: $\eta, \eta', f_0$

$\rho^0$

$\pi^+ \pi^-, f_0, f_2$

$\pi^+ \pi^- \pi^+ \pi^-, \rho^0 \rho^0$

$\rho^0$ with proton diss.

$K^+ K^-$

$\rho \rho$

$K^+ K^- K^+, \phi\phi$

$f_2 \rightarrow \pi^+ \pi^-$

$\phi \rightarrow K^+ K^-, \mu^+ \mu^-$

Ann. Phys. 344 (2014) 301

PRD91 (2015) 074023

PRD93 (2016) 054015

PRD94 (2016) 034017

PRD95 (2017) 034036

PRD98 (2018) 014001

PRD97 (2018) 094027

PRD99 (2019) 094034

arXiv:1901.07788 [hep-ph]

arXiv:1911.01909 [hep-ph]

Photoproduction and low $x$ DIS  Britzger, Ewerz, Glazov, Nachtmann, Schmitt, PRD100 (2019) 114007
Searching for odderon

- **Odderon (C = -1 partner of pomeron)** was first introduced in the framework of asymptotic theories, L. Łukaszuk and B. Nicolescu, Lett. Nuovo Cim. 8 (1973) 405

- Predicted in QCD as a colourless 3-gluon bound state exchange: J. Kwieciński, M. Praszałowicz, PLB94 (1980) 413
  J. Bartels, Nucl. Phys. B175 (1980) 365
  J. Bartels, L. N. Lipatov, G. P. Vacca, PLB477 (2000) 178

- A hint of the odderon was seen in ISR results (PRL54 (1985) 2180) as a very significant difference between the differential cross sections of elastic $pp$ and $p\bar{p}$ scattering in the diffractive dip region at $\sqrt{s} = 53$ GeV (but non-negligible contribution from reggeons !)

- The D0 observation of a very shallow dip in $p\bar{p}$ (at 1.96 TeV) (PRD86 (2012) 012009) compared to very pronounced dip measured by TOTEM (at 2.76 TeV, 7 TeV, 13 TeV) for $pp$ elastic scattering (EPJC79 (2019) 785, and arXiv:1812.08610)
  → provides evidence for the odderon exchange

- It is of great importance to study possible odderon effects in other reactions than $pp$ elastic scattering:
  → central $J/\Psi$ production in high-energy $pp$ and $p\bar{p}$ collisions: Schafer, Mankiewicz, Nachtmann, PLB272 (1991) 419
  Bzdak et al. PRD75 (2007) 094023
  Berger, Donnachie, Dosch, Nachtmann, EPJC14 (2000) 673
  → photoproduction of $f_2(1270)$ and $a_2(1320)$, exclusive neutral pseudoscalar mesons
  → photoproduction and electroproduction of heavy C = +1 quarkonia
  → observation of charge asymmetry in the $\pi^+ \pi^-$ production
  → ultraperipheral proton-ion collisions: Ginzburg, Ivanov, Nikolaev, EPJC5 (2003) 02
  Harland-Lang et al., PRD99 (2019) 034011
  Goncalves et al., EPJC79 (2019) 408

- Nice review on odderon physics: C. Ewerz, arXiv: 0306137
The reaction $pp \rightarrow pp (\phi \rightarrow K^+ K^-)$ at high energies (LHC) we expect this reaction to be dominated by the processes important at lower energies.
Photon-pomeron fusion

- 2 → 4 exclusive reaction

\[ p(p_a, \lambda_a) + p(p_b, \lambda_b) \rightarrow p(p_1, \lambda_1) + [\phi(p_{34}) \rightarrow K^+(p_3) + K^-(p_4)] + p(p_2, \lambda_2) \]

where \( p_{a,b}, p_{1,2} \) and \( \lambda_{a,b}, \lambda_{1,2} = \pm \frac{1}{2} \) denote the four-momenta and helicities of the protons and \( p_{3,4} \) denote the four-momenta of the \( K \) mesons, respectively.

- Kinematic variables

\[ p_{34} = p_3 + p_4, \quad q_1 = p_a - p_1, \quad q_2 = p_b - p_2, \]
\[ s = (p_a + p_b)^2 = (p_1 + p_2 + p_{34})^2, \]
\[ t_1 = q_1^2, \quad t_2 = q_2^2, \]
\[ s_1 = (p_1 + p_{34})^2, \quad s_2 = (p_2 + p_{34})^2 \]

- Born-level amplitude

\[ \mathcal{M}_{pp \to ppK^+K^-}^{(\gamma P)} = (-i)\bar{u}(p_1, \lambda_1)i\Gamma_{\mu}^{(\gamma pp)}(p_1, p_a)u(p_a, \lambda_a) \times i\Delta^{(\gamma)\mu\nu}(q_1)i\Gamma^{(\gamma \rightarrow \phi)}(q_1)i\Delta^{(\phi)\nu\rho_1}(q_1)\Gamma_{\rho_2\rho_1\alpha\beta}(p_{34}, q_1)i\Delta^{(\phi)\rho_2\kappa}(p_{34})i\Gamma_{\kappa}(\phi K K)(p_3, p_4) \times i\Delta^{(P)\alpha\beta\delta\eta}(s_2, t_2)\bar{u}(p_2, \lambda_2)i\Gamma^{(PP)}_{\delta\eta}(p_2, p_b)u(p_b, \lambda_b) \]

Model is formulated in terms of effective propagators and vertices. The vertices are derived from Lagrangians for the couplings. Inclusion of photons is straightforward and gauge invariance is guaranteed. The Regge factors are incorporated in the effective propagators.
**Effective propagator and proton vertex function for the tensor pomeron**

\[
i\Delta_{\mu\nu,\kappa\lambda}^{(IP)}(s, t) = \frac{1}{4s} \left( g_{\mu\kappa}g_{\nu\lambda} + g_{\mu\lambda}g_{\nu\kappa} - \frac{1}{2}g_{\mu\nu}g_{\kappa\lambda} \right) (-i\sigma\alpha'_{IP})^{-1} 
\]

\[
i\Gamma_{\mu\nu}^{(IP pp)}(p', p) = -i3\beta_{IP NN} F_1(t) \left\{ \frac{1}{2} [\gamma_{\mu}(p' + p)_\nu + \gamma_{\nu}(p' + p)_\mu] - \frac{1}{4}g_{\mu\nu}(p' + p) \right\}
\]

where \( \beta_{IP NN} = 1.87 \text{ GeV}^{-1} \)

\[
\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP} t \\
\alpha_{IP}(0) = 1.0808, \quad \alpha'_{IP} = 0.25 \text{ GeV}^{-2}
\]

**For the \( IP\phi\phi \) vertex we have (in analogy to \( f_2\gamma\gamma \) vertex)**

\[
i\Gamma_{\mu\nu,\kappa\lambda}^{(IP\phi\phi)}(k', k) = i F_M((k' - k)^2) \left[ 2\alpha_{IP\phi\phi} \Gamma_{\mu\nu,\kappa\lambda}^{(0)}(k', -k) - b_{IP\phi\phi} \Gamma_{\mu\nu,\kappa\lambda}^{(2)}(k', -k) \right]
\]

\[
\Gamma_{\mu\nu,\kappa\lambda}^{(0)}(k_1, k_2) = \left[ (k_1 \cdot k_2) g_{\mu\nu} - k_2\mu k_1\nu \right] \left[ k_1\kappa k_2\lambda + k_2\kappa k_1\lambda - \frac{1}{2} (k_1 \cdot k_2) g_{\kappa\lambda} \right]
\]

\[
\Gamma_{\mu\nu,\kappa\lambda}^{(2)}(k_1, k_2) = (k_1 \cdot k_2) (g_{\mu\kappa}g_{\nu\lambda} + g_{\mu\lambda}g_{\nu\kappa}) + g_{\mu\nu} (k_1\kappa k_2\lambda + k_2\kappa k_1\lambda)
\]

\[
- k_1\nu k_2\lambda g_{\mu\kappa} - k_1\kappa k_2\nu g_{\lambda\mu} - k_2\kappa k_1\nu g_{\mu\kappa} - k_2\mu k_1\kappa g_{\nu\lambda}
\]

\[
- [(k_1 \cdot k_2) g_{\mu\nu} - k_2\nu k_1\mu g_{\kappa\lambda}]
\]

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

**We take**

\[
F_1(t) = \frac{4m_p^2 - 2.79 t}{(4m_p^2 - t)(1 - t/m_D^2)^2}, \quad F_M(t) = \frac{1}{1 - t/\Lambda_{0,IP\phi\phi}^2}
\]
- Photoproduction process

\[ \gamma p \rightarrow \phi p \]

**ω-φ mixing effect**

\[ b_{P\omega\phi} = -b_{P\omega\omega} \tan(\Delta \theta_V) \]

\[ b_{P\omega\omega} = 7.04 \text{ GeV}^{-1} \]

\[ \Delta \theta_V = 3.7^\circ \]

\[ \sigma(\gamma p \rightarrow \phi p) \text{ (mb)} \]

- Low energy data
- ZEUS data, \(|t| < 0.5 \text{ GeV}^2\)

**Set A:**

\[ a_{IP\phi} = 0.81 \text{ GeV}^{-1}, \quad b_{IP\phi} = 3.60 \text{ GeV}^{-1}, \quad \Lambda_{0, IP\phi} = 1.0 \text{ GeV}^2 \]

**Set B:**

\[ a_{IP\phi} = 1.15 \text{ GeV}^{-1}, \quad b_{IP\phi} = 2.90 \text{ GeV}^{-1}, \quad \Lambda_{0, IP\phi} = 4.0 \text{ GeV}^2 \]

with ω-φ mixing

\[ d\sigma/dt \text{ (mb/GeV}^2\text{)} \]

\[ W_{\gamma p} = 70 \text{ GeV} \]

- ZEUS data

**Set A**

\[ <W_{\gamma p}> = 70 \text{ GeV} \]

**Set B**

\[ <W_{\gamma p}> = 94 \text{ GeV} \]
Odderon-pomeron fusion

Born-level amplitude:

\[
M^{(\mathcal{OP})}_{pp \rightarrow ppK^+K^-} = (-i)\bar{u}(p_1, \lambda_1)i\Gamma^{(\mathcal{OP})}_\mu(p_1, p_a)u(p_a, \lambda_a) \\
\times i\Delta^{(\mathcal{O})}_\mu\nu(s_1, t_1) i\Gamma^{(\mathcal{FP})}_{\rho_1\rho_2\alpha\beta}(−q_1, p_{34})i\Delta^{(\phi)}_{\rho_2\kappa}(p_{34})i\Gamma^{(\phiKK)}_\kappa(p_3, p_4) \\
\times i\Delta^{(\mathcal{P})}_{\alpha\beta,\delta\eta}(s_2, t_2) \bar{u}(p_2, \lambda_2)i\Gamma^{(\mathcal{PP})}_{\delta\eta}(p_2, p_b)u(p_b, \lambda_b)
\]

Effective propagator of \(C = -1\) odderon and the \(\mathcal{OP}\) vertex

\[
i\Delta^{(\mathcal{O})}_{\mu\nu}(s, t) = -ig_{\mu\nu}\frac{\eta_\mathcal{O}}{M_0^2}(-is\alpha'_\mathcal{O})^{\alpha_\mathcal{O}(t)−1}
\]

\[
i\Gamma^{(\mathcal{OP})}_\mu(p', p) = -i3\beta_{\mathcal{OP}} M_0 F_1((p' − p)^2)\gamma_\mu
\]

where \(\eta_\mathcal{O}\) is a parameter with value \(\eta_\mathcal{O} = ±1\); \(M_0 = 1\) GeV is inserted for dimensional reasons; \(\alpha_\mathcal{O}(t)\) is the odderon trajectory, assumed to be linear in \(t\):

\[
\alpha_\mathcal{O}(t) = \alpha_\mathcal{O}(0) + \alpha'_\mathcal{O} t
\]

The odderon parameters are not yet known from experiment.

In our calculations we shall choose as default values

\[
\alpha_\mathcal{O}(0) = 1.05 , \ \alpha'_\mathcal{O} = 0.25 \text{ GeV}^{-2} , \ \eta_\mathcal{O} = -1 , \ \beta_{\mathcal{OP}} = 0.1 \times \beta_{\mathcal{PNN}} \simeq 0.18 \text{ GeV}^{-1}
\]
For the $\mathbb{P}\phi\phi$ vertex we use an ansatz analogous to the $\mathbb{P}\phi\phi$ vertex:

\[
\begin{align*}
  i \Gamma^{(\mathbb{P}\phi\phi)}_{\rho_1 \rho_2 \alpha \beta}(-q_1, p_{34}) &= i \left[ 2 \, a_{\mathbb{P}\phi\phi} \, \Gamma^{(0)}_{\rho_2 \rho_1 \alpha \beta}(p_{34}, -q_1) - b_{\mathbb{P}\phi\phi} \, \Gamma^{(2)}_{\rho_2 \rho_1 \alpha \beta}(p_{34}, -q_1) \right] \\
  &\times F_M(q_2^2) \, F_M(q_1^2) \, F^{(\phi)}(p_{34}^2)
\end{align*}
\]

The coupling parameters $a_{\mathbb{P}\phi\phi}, b_{\mathbb{P}\phi\phi}$ and the cut-off parameter $\Lambda^2_{0, \mathbb{P}\phi\phi}$ in $F_M(t) = \frac{1}{1 - t/\Lambda^2_{0, \mathbb{P}\phi\phi}}$ could be adjusted to experimental data.

Absorption effects should be included:

\[
\mathcal{M} = \mathcal{M}^{\text{Born}} + \mathcal{M}^{\text{pp-rescattering}}
\]

\[
\mathcal{M}^{\text{pp-rescattering}}(s, \vec{p}_{1\perp}, \vec{p}_{2\perp}) = \frac{i}{8\pi^2 s} \int d^2 \vec{k}_\perp \mathcal{M}^{\text{Born}}(s, \vec{p}_{1\perp} - \vec{k}_\perp, \vec{p}_{2\perp} + \vec{k}_\perp) \mathcal{M}^{\text{pp-exch.}}_{\text{pp\to pp}}(s, -\vec{k}_\perp^2)
\]

here $\vec{k}_\perp$ is the transverse momentum carried around the loop.
Comparison with WA102 data

- WA102 data from PLB489 (2000) 29, \( \sigma_{\text{exp}} = (60 \pm 21) \text{ nb} \)
- Different fusion processes were considered. Large interference effects. The \( \phi_{pp} \) distribution allow us to determine the respective coupling constants
  \[ a_{\text{P}\Phi} = -0.8 \text{ GeV}^{-3} , \quad b_{\text{P}\Phi} = 1.6 \text{ GeV}^{-1} , \quad \Lambda_0^{2,\text{P}\Phi} = 0.5 \text{ GeV}^2 \]
- We obtain the gap survival factor \( \langle S^2 \rangle = 0.8 \) for the photoproduction term and \( \langle S^2 \rangle = 0.4 \) for the diffractive contributions
Comparison with WA102 data

- We find that two couplings are needed.
- The WA102 data support the existence of odderon exchange!
- It would be very useful to measure the outgoing protons at the LHC

\[
\frac{d\sigma}{dP_t} = |dP_t|, \quad dP_t = q_{t,1} - q_{t,2} = p_{t,2} - p_{t,1}
\]

\[
R = \frac{d\sigma/d(dP_t \leq 0.2 \text{ GeV})}{d\sigma/d(dP_t \geq 0.5 \text{ GeV})} \quad R_{WA102} = 0.18 \pm 0.07 \quad \text{[from PLB489 (2000) 29]}
\]

\[
R = 0.71 \text{ (no odderon)}, \quad R = 0.27 \text{ (with odderon)}
\]

- We find that two couplings \(a_{IP\phi}\) and \(b_{IP\phi}\) are needed.
- The WA102 data support the existence of odderon exchange!
- It would be very useful to measure the outgoing protons at the LHC.
Predictions for the $pp \rightarrow pp K^+K^-$ reaction

- Shown are the results for two diagrams separately and their coherent sum (total).
- The interference effects between the two diagrams is clearly visible, especially for the O IP-fusion mechanism.
- Due to the photon exchange the protons are scattered only at small angles and the $\gamma P$ distribution has a singularity for $|t_1| \to 0$. Of course, $t_1 = 0$ cannot be reached here from kinematics. In contrast, the O IP distribution shows a dip for $|t_1| \to 0$. 

Equation: $pp \rightarrow pp (\phi \rightarrow K^+K^-)$

$\sqrt{s} = 13$ TeV, $|\eta_K| < 2.5$, $p_{t,K} > 0.1$ GeV

No absorption
Results within (Born) and with (thick lines) absorption effects are shown. For the ATLAS-ALFA kinematics the absorption effects lead to a large damping of the cross section both for the purely diffractive and for the photoproduction mechanisms.

This effect could be verified in future experiments when both protons are measured, e.g. by the ATLAS-ALFA and CMS-TOTEM experimental groups.
Predictions for the $pp \to pp K^+K^-$ reaction (ATLAS + ALFA)

- (left) For the OIP-fusion process the complete result indicates a large (destructive) interference effect of the two type of couplings, $a$ and $b$, in the IPO $\phi$ vertex → minimum at $y_{\text{diff}} = y_3 - y_4 = 0$

- (right) Different behaviour is seen for γlP and OIP contributions. The results for different choices of parameters are shown: the red dash-dotted line, the long-dashed line, and the dotted line correspond to $(a \ [\text{GeV}^{-3}], b \ [\text{GeV}^{-1}]) = (-0.8, 1.0), (-0.8, 1.6), \text{and} (-0.6, 1.6)$, respectively.
Predictions for the \( pp \rightarrow pp K^+K^- \) reaction (LHCb)
The reaction $pp \rightarrow pp \mu^+\mu^-$

The amplitudes for the $pp \rightarrow pp\mu^+\mu^-$ reaction through $\phi$ resonance production can be obtained from the $pp \rightarrow ppK^+K^-$ amplitudes with $i\Gamma_{\kappa}^{(\phi KK)}(p_3,p_4)$ replaced by $\bar{u}(p_4,\lambda_4)i\Gamma_{\kappa}^{(\phi\mu\mu)}(p_3,p_4)v(p_3,\lambda_3)$.

Here we describe the transition $\phi \rightarrow \gamma \rightarrow \mu^+\mu^-$ by an effective vertex:

$$i\Gamma_{\kappa}^{(\phi\mu\mu)}(p_3,p_4) = i g_{\phi\mu^+\mu^-}\gamma_{\kappa}$$

The decay rate $\phi \rightarrow \mu^+\mu^-$ is calculated from the diagram

$$\Gamma(\phi \rightarrow \mu^+\mu^-) = \frac{1}{12\pi} |g_{\phi\rightarrow \mu^+\mu^-}|^2 m_\phi \left(1 + \frac{2m_\mu^2}{m_\phi^2}\right) \left(1 - \frac{4m_\mu^2}{m_\phi^2}\right)^{1/2}$$

From the experimental values (PDG)

$$m_\phi = (1019.461 \pm 0.016) \text{ MeV},$$
$$\Gamma(\phi \rightarrow \mu^+\mu^-)/\Gamma_\phi = (2.86 \pm 0.19) \times 10^{-4},$$
$$\Gamma_\phi = (4.249 \pm 0.013) \text{ MeV}$$

we get $g_{\phi^+\mu^-} = (6.71 \pm 0.22) \times 10^{-3}$

Using VMD model we get $g_{\phi^+\mu^-} = -e^2 \frac{1}{\gamma_\phi}, \quad \gamma_\phi < 0, \quad 4\pi/\gamma_\phi^2 = 0.0716 \pm 0.0017$

$$g_{\phi^+\mu^-} = (6.92 \pm 0.08) \times 10^{-3}$$
We show the contributions from the $\gamma P$- and $\Omega P$-fusion processes and the continuum $\gamma\gamma \rightarrow \mu^+\mu^-$ term.
Predictions for the $pp \rightarrow pp \mu^+\mu^-$ reaction (LHCb)

- $p_{t,\mu^+\mu^-} > 0.8$ GeV cut can be helpful to reduce the $\gamma\gamma \rightarrow \mu^+\mu^-$ continuum and $\gamma$ IP-fusion contribution
The $\mu^+\mu^-$ channel seems to be less promising in identifying the odderon exchange. In this case the absolute normalization of the cross section or detailed studies of shapes of distributions should provide a hint whether one observes the O effect.
Predictions for the $pp \rightarrow pp \mu^+\mu^-$ reaction (LHCb)

- The calculations were done for $\sqrt{s} = 13$ TeV and with cuts on $2.0 < \eta_\mu < 4.5$, $p_{t,\mu} > 0.1$ GeV, and $p_{t,\mu^+\mu^-} > 0.8$ GeV.
- The O-exchange contribution shows an enhancement at $\eta_{\mu^+} \sim \eta_{\mu^-} > 4$.
## Cross sections in nb

Table 1: The integrated cross sections in nb for the CEP of single φ mesons in \( pp \) collisions with the subsequent decays \( \phi \to K^+K^- \) or \( \phi \to \mu^+\mu^- \). The results have been calculated for \( \sqrt{s} = 13 \text{ TeV} \) in the dikaon/dimuon invariant mass region \( M_{34} \in (1.01, 1.03) \text{ GeV} \) and for some typical experimental cuts. The ratios of full and Born cross sections \( \langle S^2 \rangle \) (the gap survival factors) are shown.

| Cuts | Contributions | \( \sigma^{(\text{Born})} \) (nb) | \( \sigma^{(\text{full})} \) (nb) | \( \langle S^2 \rangle \) |
|------|--------------|----------------|----------------|--------|
| \( |\eta_K| < 2.5, p_{t,K} > 0.1 \text{ GeV} \) | \( \gamma^P \) fusion | 60.07 | 55.09 | 0.9 |
| \( \gamma^P \) and \( \Omega^P \) fusion | 21.40 | 6.44 | 0.3 |
| \( |\eta_K| < 2.5, p_{t,K} > 0.1 \text{ GeV}, \) \( 0.17 \text{ GeV} < |p_{y,1}|, |p_{y,2}| < 0.5 \text{ GeV} \) | \( \gamma^P \) fusion | 1.77 | 0.52 | 0.3 |
| \( \gamma^P \) and \( \Omega^P \) fusion | 2.91 | 0.79 | 0.3 |
| \( 2.0 < \eta_K < 4.5, p_{t,K} > 0.1 \text{ GeV} \) | \( \gamma^P \) fusion | 43.18 | 40.07 | 0.9 |
| \( \Omega^P \) fusion | 16.73 | 4.70 | 0.3 |
| \( \gamma^P \) and \( \Omega^P \) fusion | 3.09 | 1.64 | 0.3 |
| \( 2.0 < \eta_K < 4.5, p_{t,K} > 0.3 \text{ GeV} \) | \( \gamma^P \) fusion | 3.09 | 2.57 | 0.8 |
| \( \Omega^P \) fusion | 6.57 | 1.64 | 0.3 |
| \( \gamma^P \) and \( \Omega^P \) fusion | 0.93 \times 10^{-1} | 0.66 \times 10^{-1} | 0.7 |
| \( 2.0 < \eta_K < 4.5, p_{t,K} > 0.5 \text{ GeV} \) | \( \gamma^P \) fusion | 0.93 \times 10^{-1} | 0.66 \times 10^{-1} | 0.7 |
| \( \Omega^P \) fusion | 0.88 | 0.16 | 0.2 |
| \( \gamma^P \) and \( \Omega^P \) fusion | 0.93 \times 10^{-1} | 0.66 \times 10^{-1} | 0.7 |
| \( 2.0 < \eta_\mu < 4.5, p_{t,\mu} > 0.1 \text{ GeV} \) | \( \gamma^P \) fusion | 23.93 \times 10^{-3} | 20.96 \times 10^{-3} | 0.9 |
| \( \Omega^P \) fusion | 10.06 \times 10^{-3} | 3.02 \times 10^{-3} | 0.3 |
| \( \gamma^P \) and \( \Omega^P \) fusion | 23.93 \times 10^{-3} | 20.96 \times 10^{-3} | 0.9 |
| \( 2.0 < \eta_\mu < 4.5, p_{t,\mu} > 0.5 \text{ GeV} \) | \( \gamma^P \) fusion | 1.21 \times 10^{-3} | 0.85 \times 10^{-3} | 0.7 |
| \( \Omega^P \) fusion | 1.49 \times 10^{-3} | 0.45 \times 10^{-3} | 0.2 |
| \( \gamma^P \) and \( \Omega^P \) fusion | 1.21 \times 10^{-3} | 0.85 \times 10^{-3} | 0.7 |
| \( 2.0 < \eta_\mu < 4.5, p_{t,\mu} > 0.1 \text{ GeV}, \) \( p_{t,\mu+\mu^-} > 0.8 \text{ GeV} \) | \( \gamma^P \) fusion | 0.70 \times 10^{-3} | 0.41 \times 10^{-3} | 0.6 |
| \( \Omega^P \) fusion | 2.46 \times 10^{-3} | 0.51 \times 10^{-3} | 0.2 |
| \( \gamma^P \) and \( \Omega^P \) fusion | 0.70 \times 10^{-3} | 0.41 \times 10^{-3} | 0.6 |
The reaction $pp \rightarrow pp \, \phi\phi$

P.L., O. Nachtmann, A. Szczurek, PRD99 (2019) 094034

- At high energies we expect this reaction to be dominated by the IPIP fusion processes
- We can expect resonances at low $M_{\phi\phi}$ and Regge $C = -1$ exchanges at high $M_{\phi\phi}$

Contributions

$\gamma$: negligible

$\phi_R$: $\propto (M_{\phi\phi}^2)^{\alpha_\phi(\hat{t})^{-1}}$, $\alpha_\phi(\hat{t}) = 0.1 + 0.9 \, \hat{t}$

$\Box$: $\propto (M_{\phi\phi}^2)^{\alpha_\Box(\hat{t})^{-1}}$, $\alpha_\Box(0) \approx 1.0$

If $\alpha_\Box(0) \approx 1.0$, then $\Box$ exchange will win for large $M_{\phi\phi}$. 

e.g. $f_2(2340)$ resonance, tensor glueball production
Comparison with WA102 data and predictions for LHCb

The small intercept of the $\phi$ reggeon exchange, $\alpha_\phi(0) = 0.1$ makes the $\phi$-exchange contribution steeply falling with increasing $M_{4K}$ and $|Y_{\text{diff}}|$. Therefore, an odderon with an intercept $\alpha_\square(0) \approx 1$ should be clearly visible in these distributions.
Conclusions

- I have shown you some applications of the tensor-pomeron and vector-odderon model to CEP. It is effective model where some parameters have to be determined from experiment. All amplitudes are formulated in terms of effective propagators and vertices for the exchanged objects respecting the standard crossing and charge conjugation relations of QFT and the power-law ansätze from the Regge model.

\[ pp \rightarrow pp \phi \]
- WA102 data give an indication for odderon-exchange contribution
- We have presented distributions which are sensitive to the O-exchange contributions \((p_{t,K+K}, y_{diff} \) rapidity distance between the \( K \) mesons)
- To observe a sizeable deviation from photoproduction a \( p_{t,\mu^+\mu^-} > 0.8 \) GeV cut on transverse momentum of the \( \mu^+\mu^- \) pair seems necessary

\[ pp \rightarrow pp \phi\phi \]
- The \( \phi\phi \) invariant mass distribution has a rich structure (continuum, resonances, interference effects)
- The O-exchange contribution should be distinguishable from other contributions in the region of large four-kaon invariant masses and for large rapidity distance between the \( \phi \) mesons (“three-gap events”)

- In principle CEP of \( \phi \) and \( \phi\phi \) offers the possibility to determine the IPO\( \phi \) coupling (at least, to derive an upper limit on the odderon contribution).

- We are looking forward to many checks of the model in CEP at the LHC. Comparison with ‘exclusive’ data expected from LHC experiments should be very valuable for clarifying the status of the odderon.
Some modifications are needed to simulate $2 \rightarrow 6$ reaction (e.g. smearing of $\phi$ masses due to their resonance distribution)

$$\sigma_{2\rightarrow6} = [\mathcal{B}(\phi \rightarrow K^+K^-)]^2 \int_{2m_K} \int_{2m_K} \sigma_{2\rightarrow4}(\ldots, m_{X_3}, m_{X_4}) f_\phi(m_{X_3}) f_\phi(m_{X_4}) \, dm_{X_3} \, dm_{X_4}$$

with the branching fraction $\mathcal{B}(\phi(1020) \rightarrow K^+K^-) = 0.492$ [PDG] and the spectral function of $\phi$ meson:

$$f_\phi(m_{X_i}) = C_\phi \left(1 - \frac{4m_K^2}{m_{X_i}^2}\right)^{3/2} \frac{\frac{2}{\pi}m_\phi^2\Gamma_\phi}{(m_{X_i}^2 - m_\phi^2)^2 + m_\phi^2\Gamma_\phi^2}$$

$C_\phi$ is found from the condition $\int_{2m_K}^\infty f_\phi(m_{X_i}) \, dm_{X_i} = 1$

Any differential distribution can be calculated.

To include experimental cuts on produced kaons we perform the decays of $\phi$ mesons isotropically in the $\phi$ rest frames and then use relativistic transformations to the overall c.m. frame.
We consider the $2 \to 4$ exclusive reaction:

$$p(p_a, \lambda_a) + p(p_b, \lambda_b) \to p(p_1, \lambda_1) + \phi(p_3, \lambda_3) + \phi(p_4, \lambda_4) + p(p_2, \lambda_2)$$

The Born-level amplitude (\textit{\phi-exchange continuum}) can be written as the sum

$$\mathcal{M}^{(\phi\text{-exchange})}_{\lambda_a \lambda_b \to \lambda_1 \lambda_2 \phi \phi} \rho_3 \rho_4 = \mathcal{M}^{(\hat{t})}_{\lambda_a \lambda_b \to \lambda_1 \lambda_2 \phi \phi} \rho_3 \rho_4 + \mathcal{M}^{(\hat{u})}_{\lambda_a \lambda_b \to \lambda_1 \lambda_2 \phi \phi} \rho_3 \rho_4$$

with the $\hat{t}$-channel amplitude:

$$\mathcal{M}^{(\hat{t})}_{\lambda_a \lambda_b \to \lambda_1 \lambda_2 \phi \phi} \rho_3 \rho_4 = (-i) \bar{u}(p_1, \lambda_1) i \Gamma^{(IP)^{pp}}_{\mu_1 \nu_1}(p_1, p_a) u(p_a, \lambda_a) i \Delta^{(IP)}_{\mu_1 \nu_1, \alpha_1 \beta_1}(s_{13}, t_1)$$

$$\times i \Gamma^{(IP)^{\phi \phi}}_{\rho_1 \rho_3 \alpha_1 \beta_1}(\hat{p}_t, -p_3) i \Delta^{(\phi)}_{\rho_1 \rho_2}(\hat{p}_t) i \Gamma^{(IP)^{\phi \phi}}_{\rho_4 \rho_2 \alpha_2 \beta_2}(p_4, \hat{p}_t)$$

$$\times i \Delta^{(IP)}_{\alpha_2 \beta_2, \mu_2 \nu_2}(s_{24}, t_2) \bar{u}(p_2, \lambda_2) i \Gamma^{(IP)^{pp}}_{\mu_2 \nu_2}(p_2, p_b) u(p_b, \lambda_b)$$

where $\hat{p}_t = p_a - p_1 - p_3$, $s_{ij} = (p_i + p_j)^2$, $t_1 = (p_1 - p_a)^2$, $t_2 = (p_2 - p_b)^2$

Absorptive corrections should be included:

$$\mathcal{M}_{pp \to pp\phi\phi} = \mathcal{M}_{pp \to pp\phi\phi}^{\text{Born}} + \mathcal{M}_{pp \to pp\phi\phi}^{\text{pp-rescattering}}$$
In the high-energy approximation we can write

\[ M_{\lambda a \lambda b \rightarrow \lambda_1 \lambda_2 \phi \phi}^{(\phi-\text{exchange}) \rho_3 \rho_4} = 2(p_1 + p_a)_{\mu_1} (p_1 + p_a)_{\nu_1} \delta_{\lambda_1 \lambda_a} F_1(t_1) F_M(t_1) \]

\[ \times \left\{ V^{\rho_3 \rho_1 \mu_1 \nu_1} (s_{13}, t_1, \hat{p}_t, p_3) \Delta_{\rho_1 \rho_2}^{(\phi)} (\hat{p}_t) V^{\rho_4 \rho_2 \mu_2 \nu_2} (s_{24}, t_2, -\hat{p}_t, p_4) \left[ \hat{F}_\phi (\hat{p}_t^2) \right]^2 \right\} \]

\[ + V^{\rho_4 \rho_1 \mu_1 \nu_1} (s_{14}, t_1, -\hat{p}_u, p_4) \Delta_{\rho_1 \rho_2}^{(\phi)} (\hat{p}_u) V^{\rho_3 \rho_2 \mu_2 \nu_2} (s_{23}, t_2, \hat{p}_u, p_3) \left[ \hat{F}_\phi (\hat{p}_u^2) \right]^2 \}

\times 2(p_2 + p_b)_{\mu_2} (p_2 + p_b)_{\nu_2} \delta_{\lambda_2 \lambda_b} F_1(t_2) F_M(t_2) \]

where

\[ V_{\mu \nu \kappa \lambda} (s, t, k_2, k_1) = \frac{1}{4s} 3 \beta_{IPNN} (-i s \alpha'_{IP})^{\alpha P(t)-1} \left[ 2a_{IP \phi \phi} \Gamma_{\mu \nu \kappa \lambda}^{(0)} (k_1, k_2) - b_{IP \phi \phi} \Gamma_{\mu \nu \kappa \lambda}^{(2)} (k_1, k_2) \right]. \]

The amplitude contains a form factor taking into account the off-shell dependences of the intermediate \( \phi \)-mesons

\[ \hat{F}_\phi (\hat{p}^2) = \exp \left( \frac{\hat{p}^2 - m_\phi^2}{\Lambda_{off,E}^2} \right) \]

where the cut-off parameter \( \Lambda_{off,E} \) could be adjusted to experimental data.
We should take into account the fact that the exchanged intermediate object is not a simple spin-1 particle ($\phi$ meson) but may correspond to a Regge exchange, that is, the reggeization of the intermediate $\phi$ meson is necessary.

\[
\Delta_{\rho_1\rho_2}^{(\phi)}(\hat{p}) \rightarrow \Delta_{\rho_1\rho_2}^{(\phi)}(\hat{p}) \left( \exp(i\phi(s_{34})) \frac{s_{34}}{s_{\text{thr}}} \right)^{\alpha_{\phi}(\hat{p}^2)-1}
\]

where $s_{34} = (p_3 + p_4)^2 = M_{\phi\phi}^2$, $s_{\text{thr}} = 4m_{\phi}^2$

We assume for the $\phi$ Regge trajectory (from Collins book)

\[
\alpha_{\phi}(\hat{p}^2) = \alpha_{\phi}(0) + \alpha'_{\phi} \hat{p}^2
\]

\[
\alpha_{\phi}(0) = 0.1, \quad \alpha'_{\phi} = 0.9 \text{ GeV}^{-2}
\]

In order to have the correct phase behaviour we introduced the function $\exp(i\phi(s_{34}))$ with

\[
\phi(s_{34}) = \frac{\pi}{2} \exp \left( \frac{s_{\text{thr}} - s_{34}}{s_{\text{thr}}} \right) - \frac{\pi}{2}
\]

This procedure of reggeization assures agreement with mesonic physics in the $\phi\phi$ system close to threshold, $s_{34} = 4m_{\phi}^2$ (no suppression), and it gives the Regge behaviour at large $s_{34}$.
Regge formalism applies when $|\hat{P}_t^2|, |\hat{P}_u^2| \ll s_{34}$

At the threshold ($M_{\phi\phi} = 2m_{\phi}$) both $|\hat{P}_t^2|$ and $|\hat{P}_u^2|$ are not very small

Another idea of reggeization:
At $Y_{\text{diff}} = Y_3 - Y_4 = 0$ (i.e. for $|\hat{P}^2| \sim s_{34}$) reproduce meson physics, suggested by Harland-Lang, Khoze, Ryskin

We propose a formula for the $\phi$ propagator which interpolates between the regions of low $Y_{\text{diff}}$, where we use the standard $\phi$ propagator, and of high $Y_{\text{diff}}$ where we use the reggeized form:

$$\Delta^{(\phi)}_{\rho_1 \rho_2} (\hat{p}) \to \Delta^{(\phi)}_{\rho_1 \rho_2} (\hat{p}) F(Y_{\text{diff}}) + \Delta^{(\phi)}_{\rho_1 \rho_2} (\hat{p}) [1 - F(Y_{\text{diff}})] \left( \exp(i\phi(s_{34})) \frac{s_{34}}{s_{\text{thr}}} \right)^{\alpha_{\phi}(\hat{p}^2)-1}$$

with a simple function

$$F(Y_{\text{diff}}) = \exp (-c_y |Y_{\text{diff}}|)$$

Here $c_y$ is an unknown parameter which measures how fast one approaches to the Regge regime.
The distributions in $\phi\phi$ invariant mass and in $Y_{\text{diff}}$, the rapidity distance between the two $\phi\phi$ mesons, for the $\phi$-exchange continuum contribution.

- The green solid line corresponds to the non-reggeized contribution. The results for the two prescription of reggeization are shown by the black and blue lines.
- The absorption effects ($pp$ nonperturbative interactions) calculated at the amplitude level are included.
Now we consider the amplitude through s-channel $f_2$ meson exchange

$$M_{\lambda_a \lambda_b \rightarrow \lambda_1 \lambda_2 \phi \phi} = (-i) \bar{u}(p_1, \lambda_1) i \Gamma_{\mu_1 \nu_1}^{(PP)} (p_1, p_a) u(p_a, \lambda_a) \, i \Delta^{(P)}_{\mu_1 \nu_1, \alpha_1 \beta_1} (s_1, t_1)$$
$$\times i \Gamma_{\alpha_1 \beta_1, \alpha_2 \beta_2, \rho \sigma}^{(PP \, f_2)} (q_1, q_2) \, i \Delta^{(f_2)}_{\rho \sigma, \alpha \beta} (p_{34}) \, i \Gamma_{\alpha \beta \rho \sigma}^{(f_2 \phi \phi)} (p_3, p_4)$$
$$\times i \Delta^{(P)}_{\alpha_2 \beta_2, \mu_2 \nu_2} (s_2, t_2) \, \bar{u}(p_2, \lambda_2) i \Gamma_{\mu_2 \nu_2}^{(PP \, \phi \phi)} (p_2, p_b) u(p_b, \lambda_b)$$

where $s_1 = (p_1 + p_3 + p_4)^2$, $s_2 = (p_2 + p_3 + p_4)^2$, $q_1 = p_a - p_1$, $q_2 = p_b - p_2$, $t_1 = q_1^2$, $t_2 = q_2^2$, and $p_{34} = q_1 + q_2 = p_3 + p_4$.

The $IP IP$ $f_2$ vertex, including a form factor, can be written as

$$i \Gamma^{(PP \, f_2)}_{\mu \nu, \kappa \lambda, \rho \sigma} (q_1, q_2) = \left( i \Gamma^{(PP \, f_2)}_{\mu \nu, \kappa \lambda, \rho \sigma}^{(1)} \bigg| \text{bare} + \sum_{j=2}^{7} i \Gamma^{(PP \, f_2)}_{\mu \nu, \kappa \lambda, \rho \sigma}^{(j)} (q_1, q_2) \bigg| \text{bare} \right) F^{(PP \, f_2)} (q_1^2, q_2^2, p_{34}^2)$$

$$i \Gamma^{(PP \, f_2)}_{\mu \nu, \kappa \lambda, \rho \sigma}^{(1)} = 2i \, g^{(1)}_{IP IP \, f_2} M_0 \, R_{\mu \nu \mu_1 \nu_1} R_{\kappa \lambda \alpha_1 \lambda_1} R_{\rho \sigma \rho_1 \sigma_1} g^{\nu_1 \alpha_1} g^{\lambda_1 \rho_1} g^{\sigma_1 \mu_1} \frac{1}{2} g_{\mu \kappa} g_{\nu \lambda} + \frac{1}{2} g_{\mu \lambda} g_{\nu \kappa} - \frac{1}{4} g_{\mu \nu} g_{\kappa \lambda}$$

For the $f_2 \phi \phi$ vertex we take (in analogy to $f_2 \gamma \gamma$ vertex)

$$i \Gamma^{(f_2 \phi \phi)}_{\mu \nu \kappa \lambda} (p_3, p_4) = \frac{2}{M_0^3} g'_{f_2 \phi \phi} \Gamma^{(0)}_{\mu \nu \kappa \lambda} (p_3, p_4) F'(f_2 \phi \phi) (p_{34}^2)$$
$$-i \frac{1}{M_0} g''_{f_2 \phi \phi} \Gamma^{(2)}_{\mu \nu \kappa \lambda} (p_3, p_4) F''(f_2 \phi \phi) (p_{34}^2)$$
The nature of these resonances is not understood at present and a tensor glueball has still not been clearly identified. According to lattice-QCD simulations, the lightest tensor glueball has a mass between 2.2 and 2.4 GeV.
The distribution in $dP_t$ and in $\phi_{pp}$ for the central exclusive $\phi\phi$ production at $\sqrt{s} = 29.1$ GeV and $|x_{F,\phi\phi}| \leq 0.2$. The results for scalar, pseudoscalar and tensor resonances without (the thin lines) and with (the thick lines) absorptive corrections are shown. Because here we are interested only in the shape of the distributions we normalised the differential distributions arbitrarily to 1 nb for both cases, with and without absorption corrections.
We show results for two sets of parameters: set A (left panel) and set B (right panel).

The interference of the continuum and resonance contributions depends on subtle details (choice of the couplings for resonant term, reggeization).

\[ g^{(1)}_{\bar{IP}IP} f_2 g'_{f_2 \phi} \neq 0 \quad \text{and} \quad g^{(1)}_{\bar{IP}IP} f_2 g''_{f_2 \phi} \neq 0 \]
We have checked that the shapes of $Y_{\text{diff}}$ distributions do not depend significantly on the choice of the IP IP $f_2$ vertex coupling.

The distribution in $Y_{\text{diff}}$ can be used to determine the $f_2(2340) \rightarrow \phi \phi$ coupling using results expected from LHC measurements, in particular, if they cover a wider range of rapidities.
Quite a different pattern can be seen for the Born case and for the case with absorption. The ratio of full and Born cross sections is \(<S^2> \sim 0.4\) (WA102 kinematics).

- Glueball candidates should be prominent for \(dP_t \to 0\).
The ratio of full and Born cross sections is $S_g \sim 0.2$ (LHC kinematics).

Absorption effect leads to significant modification of these distributions.
Table 1: The integrated cross sections in nb for the $pp \rightarrow pp(4K)$ reaction. The absorption effects are included here.

| $\sqrt{s}$, TeV | Cuts                                      | Total | $\phi$ exchange | $f_2(2340)$ (set B) |
|-----------------|-------------------------------------------|-------|------------------|---------------------|
| 13              | $|\eta_K| < 1, p_{t,K} > 0.1$ GeV               | 2.11  | 0.83             | 2.00                |
| 13              | $|\eta_K| < 2.5, p_{t,K} > 0.1$ GeV            | 16.16 | 8.30             | 12.80               |
| 13              | $|\eta_K| < 2.5, p_{t,K} > 0.2$ GeV           | 5.75  | 2.67             | 4.47                |
| 13              | $2 < \eta_K < 4.5, p_{t,K} > 0.2$ GeV    | 3.06  | 1.26             | 2.62                |
Continuum with odderon exchange

- The amplitude as for $\phi$-exchange contribution, but we have to make:

$$i\Delta_{\mu\nu}^{(\phi)}(\hat{p}) \to i\Delta_{\mu\nu}^{(\ominus)}(s_{34}, \hat{p}^2)$$

$$i\Gamma_{\mu\nu\kappa\lambda}^{(\mathbb{P}\phi\phi)}(k', k) \to i\Gamma_{\mu\nu\kappa\lambda}^{(\mathbb{P}\ominus\phi)}(k', k)$$

- For the $\mathbb{P}\ominus\phi$ vertex we use an ansatz analogous to $\mathbb{P}\phi\phi$ vertex:

$$i\Gamma_{\mu\nu\kappa\lambda}^{(\mathbb{P}\ominus\phi)}(k', k) = iF^{(\mathbb{P}\ominus\phi)}((k + k')^2, k'r^2, k^2) \left[ 2 a_{\mathbb{P}\ominus\phi} \Gamma_{\mu\nu\kappa\lambda}^{(0)}(k', k) - b_{\mathbb{P}\ominus\phi} \Gamma_{\mu\nu\kappa\lambda}^{(2)}(k', k) \right]$$

In practical calculations we take the factorized form for the $\mathbb{P}\ominus\phi$ form factor

$$F^{(\mathbb{P}\ominus\phi)}((k + k')^2, k'r^2, k^2) = F((k + k')^2) F(k'r^2) F^{(\mathbb{P}\phi\phi)}(k^2),$$

$$F(k^2) = \frac{1}{1 - k^2/\Lambda_{\text{odd}}^2}, \quad F^{(\mathbb{P}\ominus\phi)}(0, 0, m_\phi^2) = 1$$
The small intercept of the $\phi$ reggeon exchange, $\alpha_\phi(0) = 0.1$ makes the $\phi$-exchange contribution steeply falling with increasing $M_{4K}$ and $|Y_{\text{diff}}|$. Therefore, an odderon with an intercept $\alpha_{\otimes}(0) \approx 1$ should be clearly visible in these distributions.
Tensor-Pomeron model for high-energy soft reactions

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

The main feature of the model is that the Pomeron exchange is described as effective exchange of a symmetric rank 2 tensor:

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

\[ \alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP}t, \quad \alpha_{IP}(0) = 1.0808, \quad \alpha'_{IP} = 0.25 \text{ GeV}^{-2} \]

\[ i\Gamma_{\mu\nu}^{(IP pp)}(p', p) = -i3\beta_{IP NN} F_1 \left( (p' - p)^2 \right) \left\{ \frac{1}{2} [\gamma_{\mu}(p' + p)_{\nu} + \gamma_{\nu}(p' + p)_{\mu}] - \frac{1}{4} g_{\mu\nu}(p' + p) \right\} \]

\[ \beta_{IP NN} = 1.87 \text{ GeV}^{-1} \]

**pp elastic scattering (helicity amplitudes)**

\[ \langle 2s_3, 2s_4 | T | 2s_1, 2s_2 \rangle = (-i)\bar{u}(p_3, s_3) i\Gamma_{\mu\nu}^{(IP pp)}(p_3, p_1) u(p_1, s_1) \]

\[ \times i\Delta_{\mu\nu,\kappa\lambda}^{(IP)}(s, t) \]

\[ \times \bar{u}(p_4, s_4) i\Gamma_{\kappa\lambda}^{(IP pp)}(p_4, p_2) u(p_2, s_2) \]

Only 5 out of 16 helicity amplitudes are independent, e.g.

\[ \phi_1(s, t) = \langle ++ | T | ++ \rangle \]

\[ \phi_3(s, t) = \langle + - | T | + - \rangle \quad \text{helicity-conserving amplitudes} \]

\[ \phi_5(s, t) = \langle ++ | T | + - \rangle \quad \text{single-helicity-flip amplitude} \]
**Tensor, vector, or scalar Pomeron?**

C. Ewerz, P. L., O. Nachtmann, A. Szczurek, *Helicity in proton-proton elastic scattering and the spin structure of the pomeron*, PLB 763 (2016) 382

We choose our ansätze for three the effective $IP$ propagators and $IPpp$ couplings such that at high energies the $\phi_1$ and $\phi_3$ are the same for all three cases. This gives the same $\sigma_{tot}^{pp}$. The Donnachie-Landshoff (DL) model treats the Pomeron as effective vector exchange and gives a phenomenologically successful fit to $\sigma_{tot}^{pp}$ and $d\sigma/dt$.

Our ansätze are chosen such that $\phi_1$ and $\phi_3$ are as in the DL model.

- **Vector exchange $IP_V$** has $C = -1$ than $\sigma_{tot}^{pp} = - \sigma_{tot}^{\bar{p}p}$ (not a viable option).

- **We are left with $IP_T$ and $IP_S$** (both correspond to $C=+1$ exchanges)

To decide between them we turn to the STAR experiment [PLB 719 (2013)] which measured the single spin asymmetry $A_N$ in polarised $pp$ elastic scattering.

\[
\sqrt{s} = 200 \text{ GeV} \quad 0.003 \leq |t| \leq 0.035 \text{ GeV}^2
\]

\[
r_5(s, t) = \frac{2m_p \phi_5(s,t)}{\sqrt{-t} \text{ Im}[\phi_1(s,t)+\phi_3(s,t)]}
\]

\[
r_5^{IP_T}(s, t) = - \frac{m_p^2}{s} \left[ i + \tan \left( \frac{\pi}{2} \alpha_T(t) - 1 \right) \right]
\]

\[
r_5^{IP_T}(s, 0) = (-0.28 - i2.20) \times 10^{-5}
\]

\[
r_5^{IP_S}(s, t) = - \frac{1}{2} \left[ i + \tan \left( \frac{\pi}{2} \alpha_P(t) - 1 \right) \right]
\]

\[
r_5^{IP_S}(s, 0) = -0.064 - i0.500 \quad \text{Very far from data!}
\]

Only the tensor-Pomeron is compatible with the general rules of QFT and the STAR experimental result.