

Searching for the odderon in exclusive $pp \rightarrow pp\phi$ and $pp \rightarrow pp\phi\phi$ reactions at the LHC

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Searching for odderon (C = -1 partner of pomeron)

- First introduced in the framework of asymptotic theories
L. Łukaszuk and B. Nicolescu, Lett. Nuovo Cim. 8 (1973) 405
 - Predicted in QCD as a colorless 3-gluon bound state exchange
J. Kwieciński, M. Praszalowicz, 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 small 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, 7, and 13 TeV) for pp elastic scattering (TOTEM Coll., EPJC79 (2019) 785, EPJC80 (2020) 91)
→ provides evidence for the odderon exchange [see Ch. Royon talk]
 - It is of great importance to study possible odderon effects in other reactions than pp elastic scattering:
 - central J/Ψ production in high-energy pp and $p\bar{p}$ collisions
Schafer, Mankiewicz, Nachtmann, PLB272 (1991) 419
Bzdak et al. PRD75 (2007) 094023
 - photoproduction of $f_2(1270)$ and $a_2(1320)$,
exclusive neutral pseudoscalar mesons Berger, Donnachie, Dosch, Nachtmann, EPJC14 (2000) 673
 - photoproduction and electroproduction of heavy C = +1 quarkonia
 - observation of charge asymmetry in the $\pi^+ \pi^-$ production Ginzburg, Ivanov, Nikolaev, EPJC5 (2003) 02
 - ultraperipheral proton-ion and ion-ion collisions
Harland-Lang et al., PRD99 (2019) 034011
Goncalves et al., EPJC79 (2019) 408
McNulty et al., EPJC80 (2020) 288
 - Review on odderon physics: C. Ewerz, arXiv: 0306137
- I this talk I hope to show you that **CEP of ϕ and $\phi\phi$** offers good possibilities to **search for odderon effects** in proton-proton collisions at high energies.

Model for soft high-energy scattering: Tensor pomeron and vector odderon

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

- The main feature of the model is that the pomeron exchange ($C = +1$) is described as effective spin 2 exchange (symmetric rank 2 tensor):

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

$$\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}}t, \quad \alpha_{\mathbb{P}}(0) = 1.0808, \quad \alpha'_{\mathbb{P}} = 0.25 \text{ GeV}^{-2}$$

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

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

- The odderon exchange ($C = -1$) is described as effective vector exchange:

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

$$i\Gamma_{\mu}^{(\mathbb{O}pp)}(p', p) = -i3\beta_{\mathbb{O}pp} M_0 F_1((p' - p)^2) \gamma_{\mu}$$

where $\eta_{\mathbb{O}}$ is a parameter with value $\eta_{\mathbb{O}} = \pm 1$; $M_0 = 1 \text{ GeV}$ is inserted for dimensional reasons; $\alpha_{\mathbb{O}}(t)$ is the odderon trajectory $\alpha_{\mathbb{O}}(t) = \alpha_{\mathbb{O}}(0) + \alpha'_{\mathbb{O}}t$

$$F_1(t) = \frac{4m_p^2 - 2.79t}{(4m_p^2 - t)(1 - t/m_D^2)^2}, \quad m_D^2 = 0.71 \text{ GeV}^2$$

Applications

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

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

Photoproduction and low x DIS

Britzger, Ewerz, Glazov, Nachtmann, Schmitt, PRD100 (2019) 114007

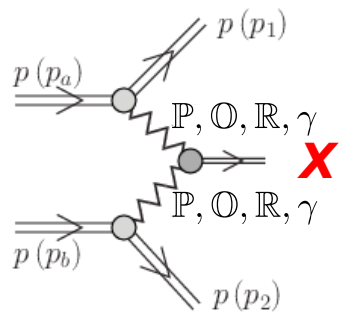
A “vector pomeron” cannot couple in the total photoabsorption cross section $\sigma_{\gamma p}$.

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

Ewerz, P.L., Nachtmann, 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.

Central Exclusive Production (CEP), $p p \rightarrow p p X$, *P.L., Nachtmann, Szczurek:*



X: η, η', f_0

ρ^0

$\pi^+ \pi^-, f_0, f_2 (\rightarrow \pi^+ \pi^-)$

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

ρ^0 with proton diss.

$p\bar{p}$

$K^+ K^-$

$f_1(1285)$

$K^{*0} \bar{K}^{*0}, f_2(1950)$

Ann. Phys. 344 (2014) 301

PRD91 (2015) 074023

PRD93 (2016) 054015, PRD101 (2020) 034008

PRD94 (2016) 034017

PRD95 (2017) 034036

PRD97 (2018) 094027

PRD98 (2018) 014001

P.L., Leutgeb, Nachtmann, Rebhan, Szczurek, PRD102 (2020) 114003

P.L., PRD103 (2021) 054039 ← see poster

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

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

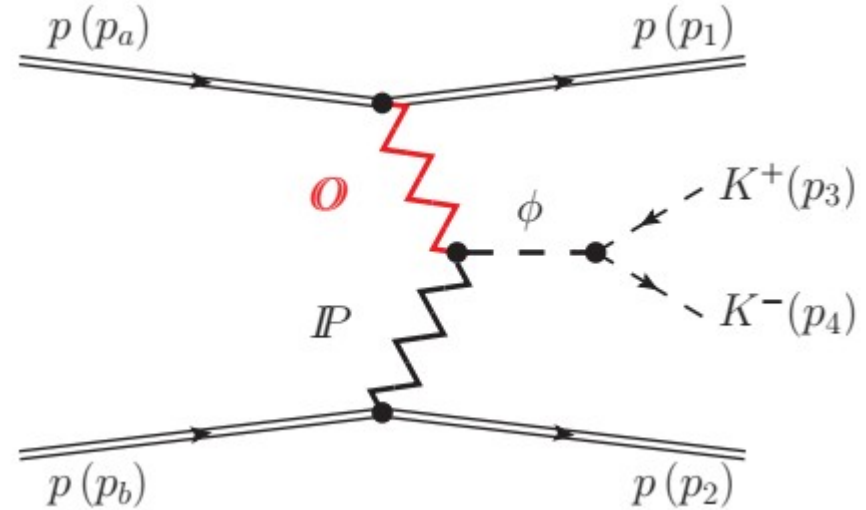
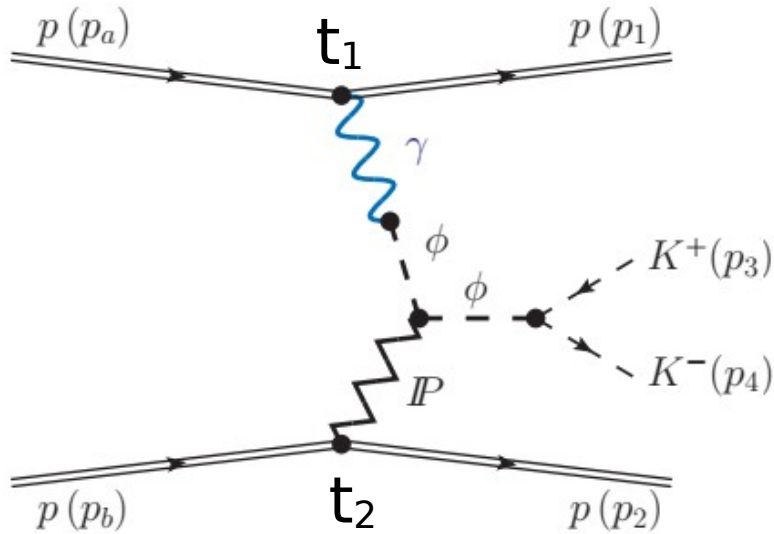
P.L., Nachtmann, Szczurek, PRD101 (2020) 094012 ← this talk

P.L., Nachtmann, Szczurek, PRD99 (2019) 094034 ← this talk

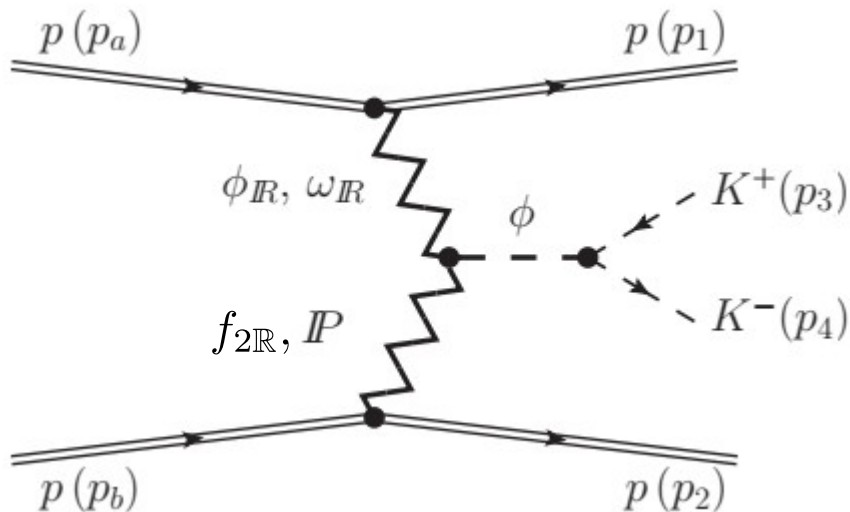
The reaction $pp \rightarrow pp (\phi \rightarrow K^+ K^-)$

In my talk I shall consider the exclusive processes at large c.m. energy \sqrt{s} but small momentum transfers $|t_1|, |t_2|$.

At high energies (LHC) the main diagrams contributing are:



At lower energies (WA102) the subleading processes are important:



Exchange objects:

\mathbb{P} ($C = +1$) pomeron

\mathbb{O} ($C = -1$) **odderon (?)**

$\mathbb{R} : f_{2\mathbb{R}}$ ($C = +1$)

$\omega_{\mathbb{R}}, \phi_{\mathbb{R}}$ ($C = -1$)

γ ($C = -1$) **photon**

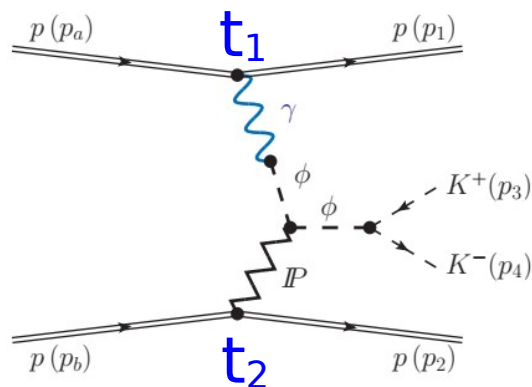
} reggeons

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

$$\begin{aligned} \mathcal{M}_{pp \rightarrow pp K^+ K^-}^{(\gamma \mathbb{P})} &= (-i) \bar{u}(p_1, \lambda_1) i \Gamma_{\mu}^{(\gamma pp)}(p_1, p_a) u(p_a, \lambda_a) \\ &\times i \Delta^{(\gamma) \mu \sigma}(q_1) i \Gamma_{\sigma \nu}^{(\gamma \rightarrow \phi)}(q_1) i \Delta^{(\phi) \nu \rho_1}(q_1) i \Gamma_{\rho_2 \rho_1 \alpha \beta}^{(\mathbb{P} \phi \phi)}(p_{34}, q_1) i \Delta^{(\phi) \rho_2 \kappa}(p_{34}) i \Gamma_{\kappa}^{(\phi K K)}(p_3, p_4) \\ &\times i \Delta^{(\mathbb{P}) \alpha \beta, \delta \eta}(s_2, t_2) \bar{u}(p_2, \lambda_2) i \Gamma_{\delta \eta}^{(\mathbb{P} pp)}(p_2, p_b) u(p_b, \lambda_b) \end{aligned}$$

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

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

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

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

$$\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}}t$$

$$\alpha_{\mathbb{P}}(0) = 1.0808, \quad \alpha'_{\mathbb{P}} = 0.25 \text{ GeV}^{-2}$$

- For the $\mathbb{P}\phi\phi$ vertex we have (in analogy to $f_2\gamma\gamma$ vertex)

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

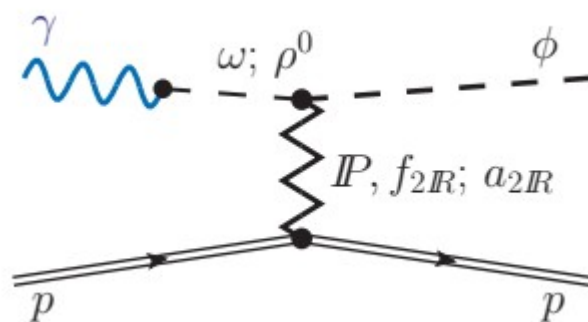
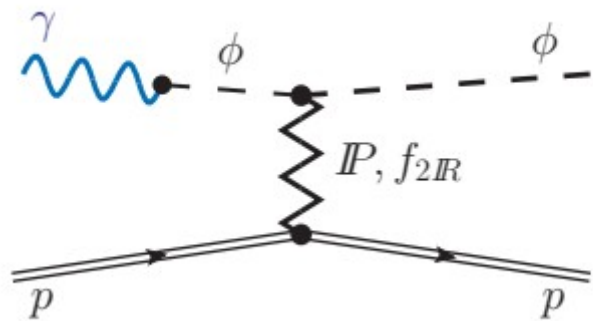
$$\Gamma_{\mu\nu\kappa\lambda}^{(0)}(k_1, k_2) = \left[(k_1 \cdot k_2)g_{\mu\nu} - k_{2\mu}k_{1\nu} \right] \left[k_{1\kappa}k_{2\lambda} + k_{2\kappa}k_{1\lambda} - \frac{1}{2}(k_1 \cdot k_2)g_{\kappa\lambda} \right]$$

$$\begin{aligned} \Gamma_{\mu\nu\kappa\lambda}^{(2)}(k_1, k_2) = & (k_1 \cdot k_2)(g_{\mu\kappa}g_{\nu\lambda} + g_{\mu\lambda}g_{\nu\kappa}) + g_{\mu\nu}(k_{1\kappa}k_{2\lambda} + k_{2\kappa}k_{1\lambda}) \\ & - k_{1\nu}k_{2\lambda}g_{\mu\kappa} - k_{1\nu}k_{2\kappa}g_{\mu\lambda} - k_{2\mu}k_{1\lambda}g_{\nu\kappa} - k_{2\mu}k_{1\kappa}g_{\nu\lambda} \\ & - [(k_1 \cdot k_2)g_{\mu\nu} - k_{2\mu}k_{1\nu}]g_{\kappa\lambda} \end{aligned}$$

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

The coupling parameters $a_{\mathbb{P}\phi\phi}$, $b_{\mathbb{P}\phi\phi}$ and the cut-off parameter $\Lambda_{0,\mathbb{P}\phi\phi}^2$ in $F_M(t) = \frac{1}{1-t/\Lambda_{0,\mathbb{P}\phi\phi}^2}$ are fixed from the process $\gamma p \rightarrow \phi p$.

• Photoproduction process

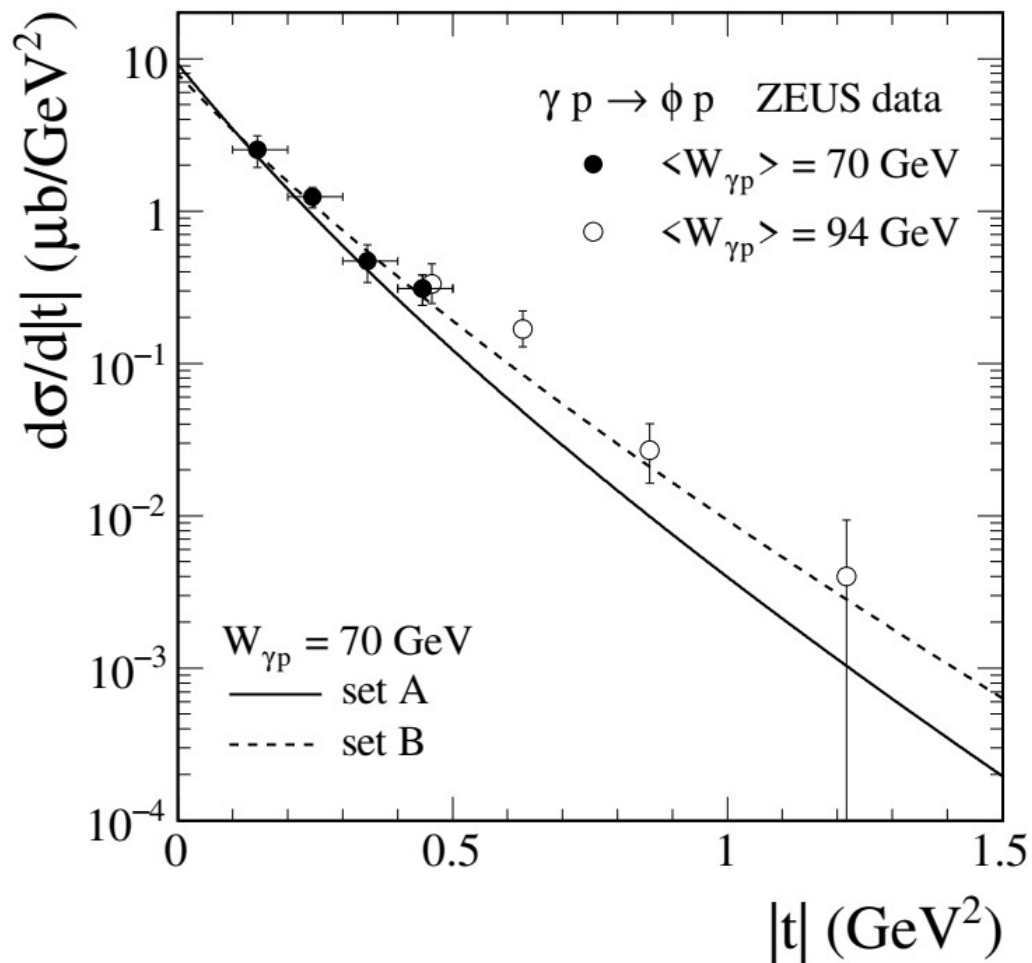
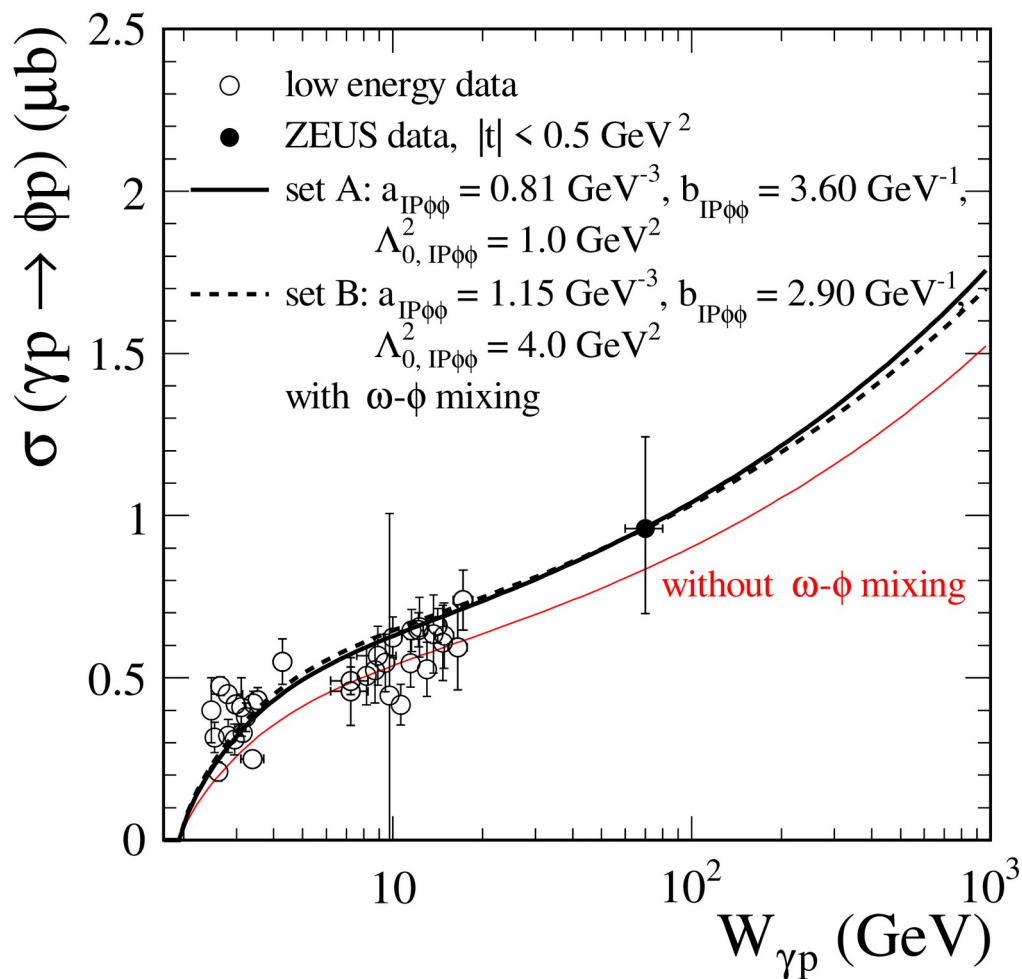


ω - ϕ mixing effect included

$$b_{\mathbb{P}\omega\phi} = -b_{\mathbb{P}\omega\omega} \tan(\Delta\theta_V)$$

$$b_{\mathbb{P}\omega\omega} = 7.04 \text{ GeV}^{-1}$$

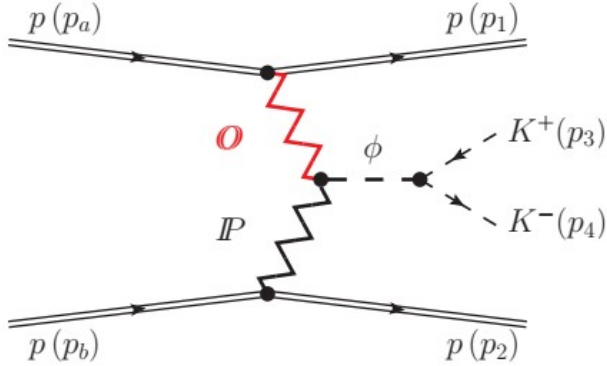
$$\Delta\theta_V = 3.7^\circ$$



Odderon-pomeron fusion

- Born-level amplitude:

$$\begin{aligned} \mathcal{M}_{pp \rightarrow pp K^+ K^-}^{(\mathbb{O}\mathbb{P})} &= (-i) \bar{u}(p_1, \lambda_1) i\Gamma_{\mu}^{(\mathbb{O}pp)}(p_1, p_a) u(p_a, \lambda_a) \\ &\times i\Delta^{(\mathbb{O}) \mu\rho_1}(s_1, t_1) i\Gamma_{\rho_1\rho_2\alpha\beta}^{(\mathbb{P}\mathbb{O}\phi)}(-q_1, p_{34}) i\Delta^{(\phi) \rho_2\kappa}(p_{34}) i\Gamma_{\kappa}^{(\phi KK)}(p_3, p_4) \\ &\times i\Delta^{(\mathbb{P}) \alpha\beta, \delta\eta}(s_2, t_2) \bar{u}(p_2, \lambda_2) i\Gamma_{\delta\eta}^{(\mathbb{P}pp)}(p_2, p_b) u(p_b, \lambda_b) \end{aligned}$$



Effective propagator of C = -1 odderon and the Opp vertex

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

$$i\Gamma_{\mu}^{(\mathbb{O}pp)}(p', p) = -i3\beta_{\mathbb{O}pp} M_0 F_1((p' - p)^2) \gamma_{\mu}$$

In our calculations we shall choose as default values:

$$\alpha_{\mathbb{O}}(0) = 1.05, \quad \alpha'_{\mathbb{O}} = 0.25 \text{ GeV}^{-2}, \quad \eta_{\mathbb{O}} = -1$$

$$\beta_{\mathbb{O}pp} = 0.1 \times \beta_{\mathbb{P}NN} \simeq 0.18 \text{ GeV}^{-1}$$

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

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

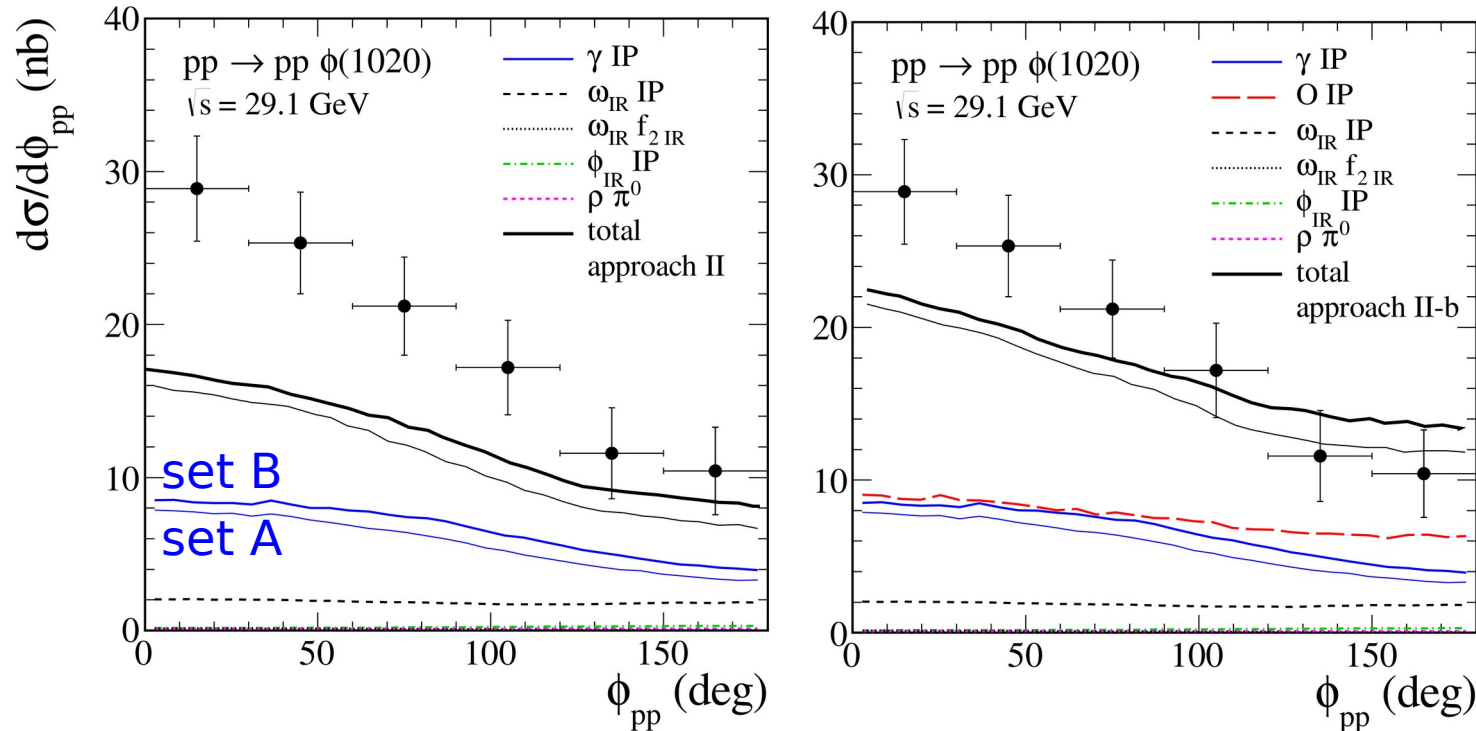
The coupling parameters $a_{\mathbb{P}\mathbb{O}\phi}$, $b_{\mathbb{P}\mathbb{O}\phi}$ and the cut-off parameter $\Lambda_{0, \mathbb{P}\mathbb{O}\phi}^2$ in $F_M(t)$ could be adjusted to experimental data.

- Absorption effects: $\mathcal{M} = \mathcal{M}^{Born} + \mathcal{M}^{pp-rescattering}$

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

here \vec{k}_{\perp} is the transverse momentum carried around the loop

Comparison with WA102 data



- Distributions in ϕ_{pp} the azimuthal angle between the outgoing protons.

Comparison of the model with the WA102 data on ϕ meson CEP:

(left) without an odderon contribution, (right) with an odderon contribution.

The total cross section is $\sigma_{\text{exp}} = (60 \pm 21) \text{ nb}$ [A. Kirk, PLB489 (2000) 29].

Different fusion processes were considered \rightarrow large interference effects.

The WA102 data support the existence of odderon exchange !

- The ratio was also measured:

$$R = \frac{d\sigma/d(dP_t \leq 0.2 \text{ GeV})}{d\sigma/d(dP_t \geq 0.5 \text{ GeV})}$$

WA102 experiment: $R_{\text{exp}} = 0.18 \pm 0.07$

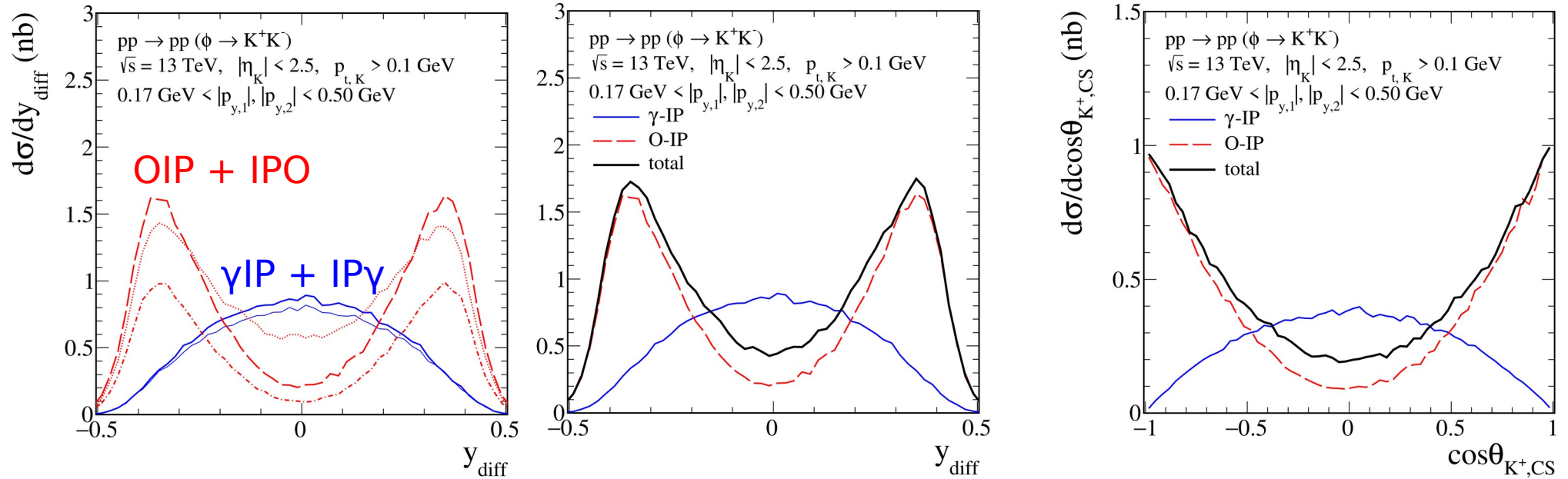
$R_{\text{th}} = 0.71$ (no odderon), $R_{\text{th}} = 0.27$ (with odderon)

$$dP_t = |d\mathbf{P}_t|, \quad d\mathbf{P}_t = \mathbf{q}_{t,1} - \mathbf{q}_{t,2} = \mathbf{p}_{t,2} - \mathbf{p}_{t,1}$$

The WA102 data allow us to determine the model parameters:

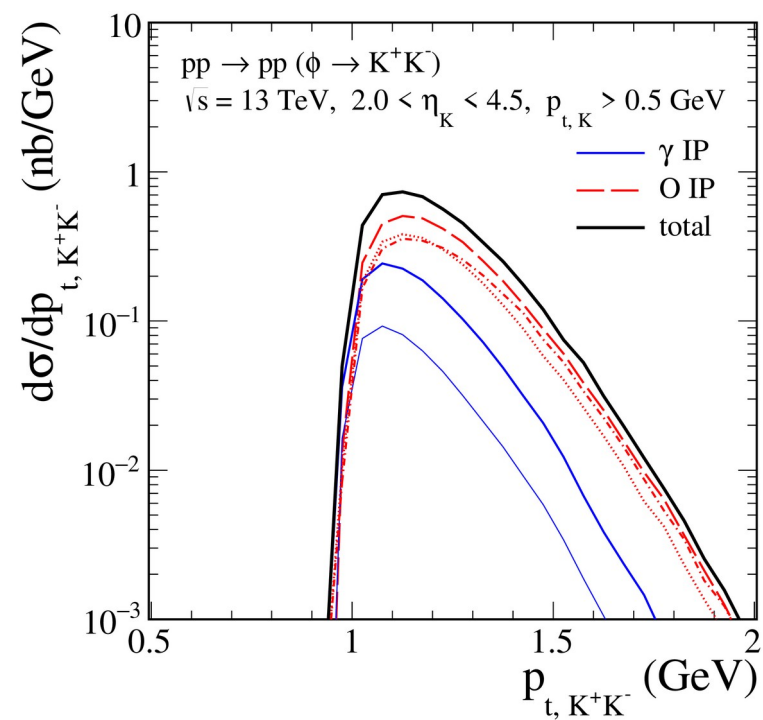
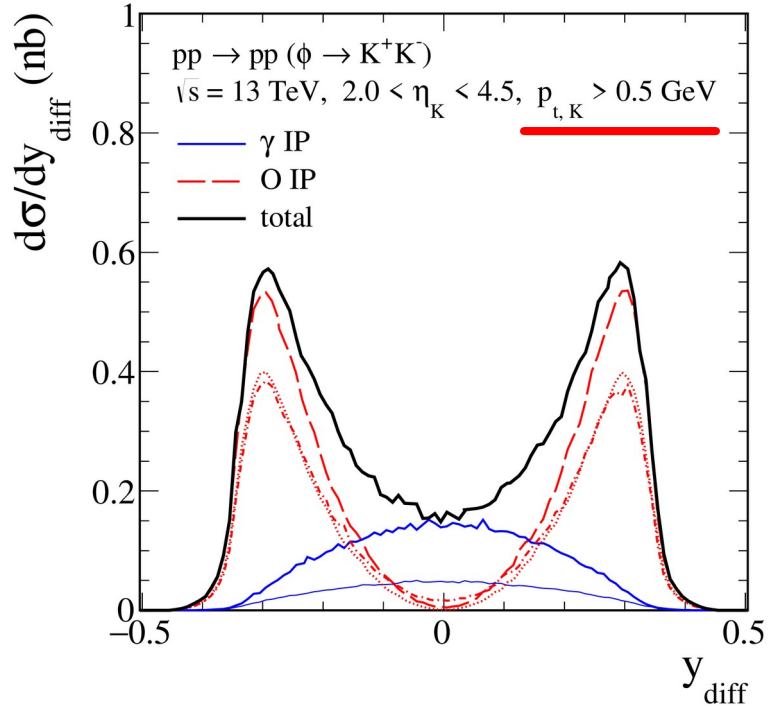
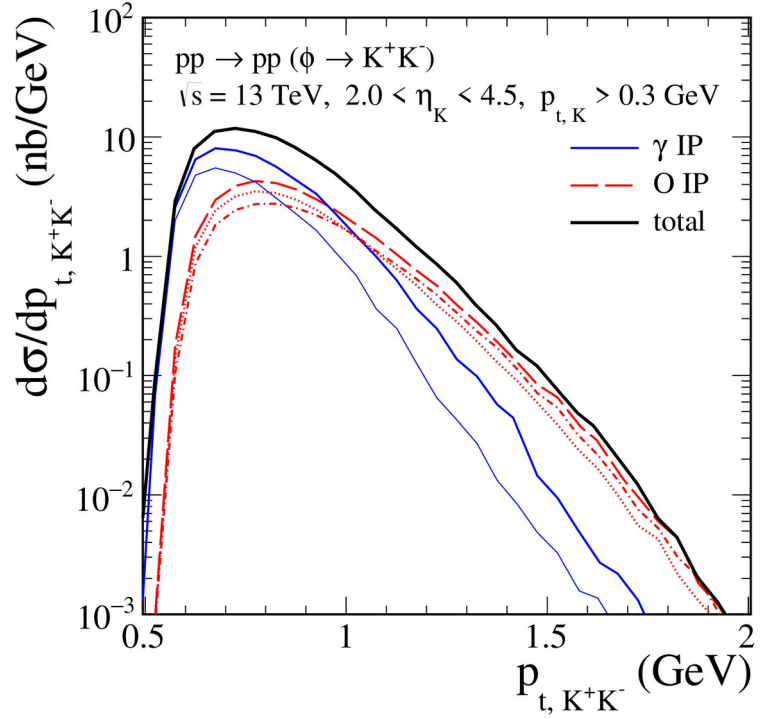
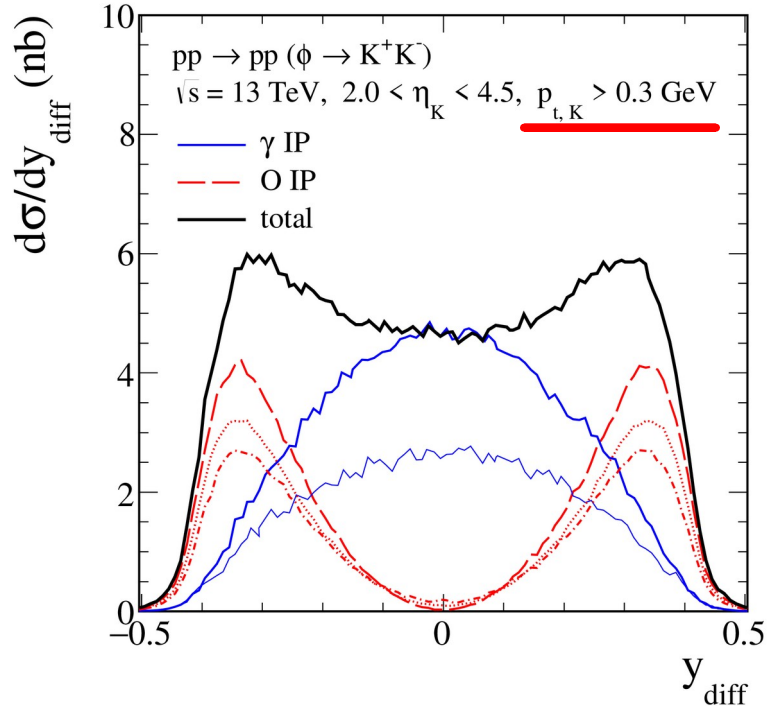
$$a_{\mathbb{P}\mathbb{O}\phi} = -0.8 \text{ GeV}^{-3}, \quad b_{\mathbb{P}\mathbb{O}\phi} = 1.6 \text{ GeV}^{-1}, \quad \Lambda_{0,\mathbb{P}\mathbb{O}\phi}^2 = 0.5 \text{ GeV}^2$$

Predictions for the $pp \rightarrow pp K^+K^-$ reaction (ATLAS-ALFA)



- Now we extrapolate to LHC energies. Can we distinguish γ and **odderon (O)** exchange?
- **Odderon exchange** gives ϕ mesons with larger p_t than γ exchange
- Due to the ALFA cuts on the leading protons the photoproduction term is strongly suppressed. For the ATLAS-ALFA experimental cuts the absorption effects lead to a large damping of the cross section for both terms. This effect could be verified in experiments at the LHC (ATLAS-ALFA, CMS-TOTEM) when both protons are measured
- Interesting distribution in $y_{\text{diff}} = y_{K^+} - y_{K^-}$. Different behaviour is seen for γ IP and **OIP** contributions. **Odderon exchange gives ϕ mesons** with preferential **longitudinal polarisation** in beam direction, **γ exchange produces preferentially transversely polarised ϕ 's**. These polarisation difference can be seen in the decay $\phi \rightarrow K^+K^-$ (angular distributions in the Collins-Soper frame)

Predictions for the $pp \rightarrow pp K^+K^-$ reaction (LHCb)

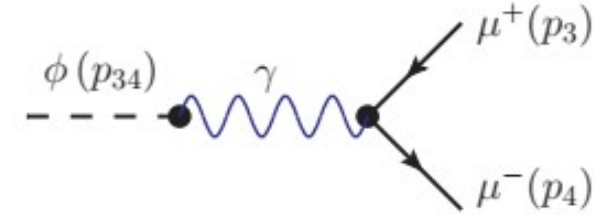


The reaction $pp \rightarrow pp \mu^+ \mu^-$

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

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

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



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

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

From the experimental values (PDG)

$$m_{\phi} = (1019.461 \pm 0.016) \text{ MeV},$$

$$\Gamma(\phi \rightarrow \mu^+ \mu^-) / \Gamma_{\phi} = (2.86 \pm 0.19) \times 10^{-4},$$

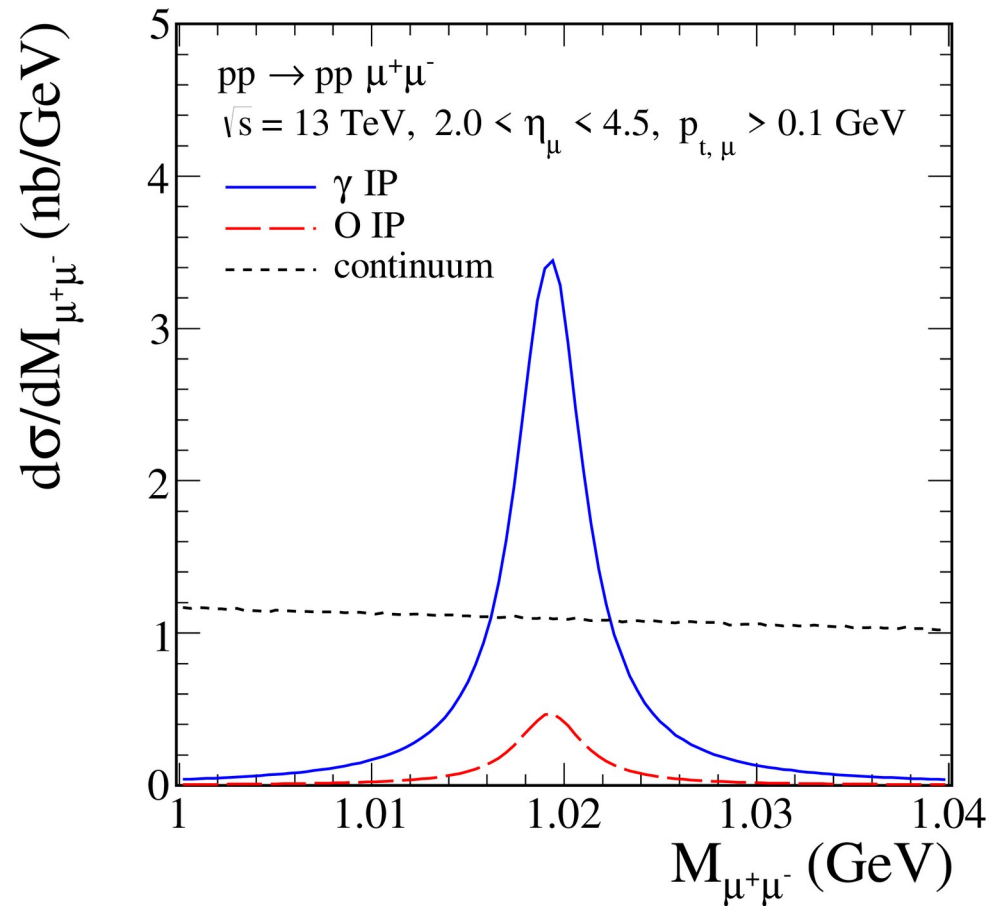
$$\Gamma_{\phi} = (4.249 \pm 0.013) \text{ MeV}$$

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

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

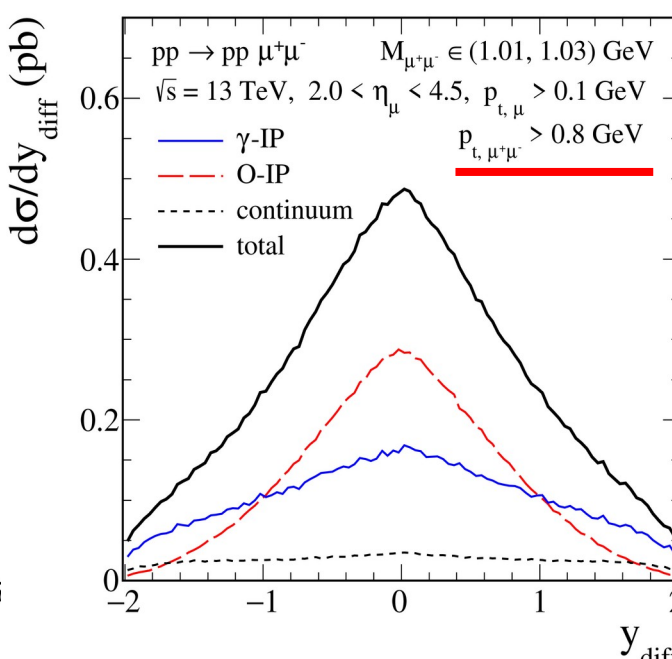
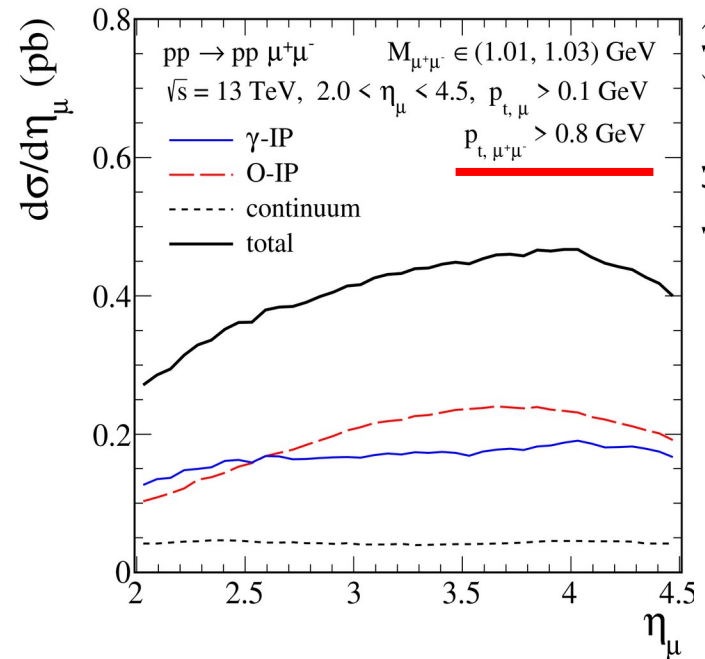
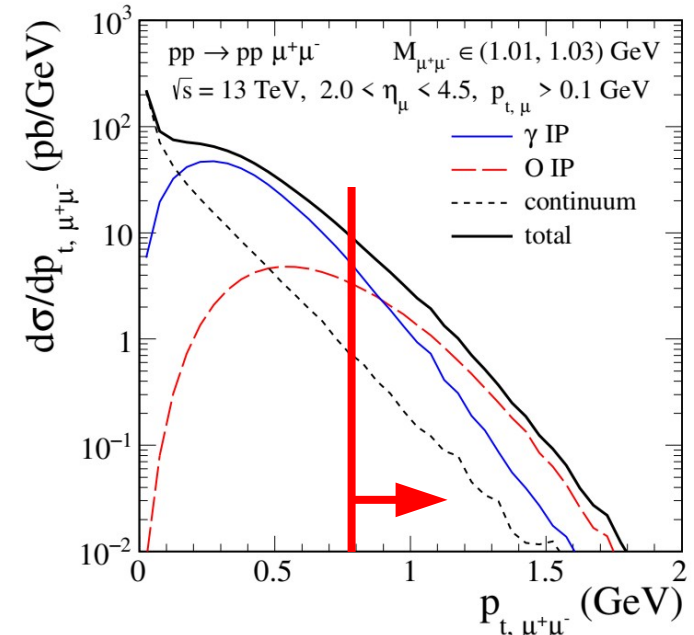
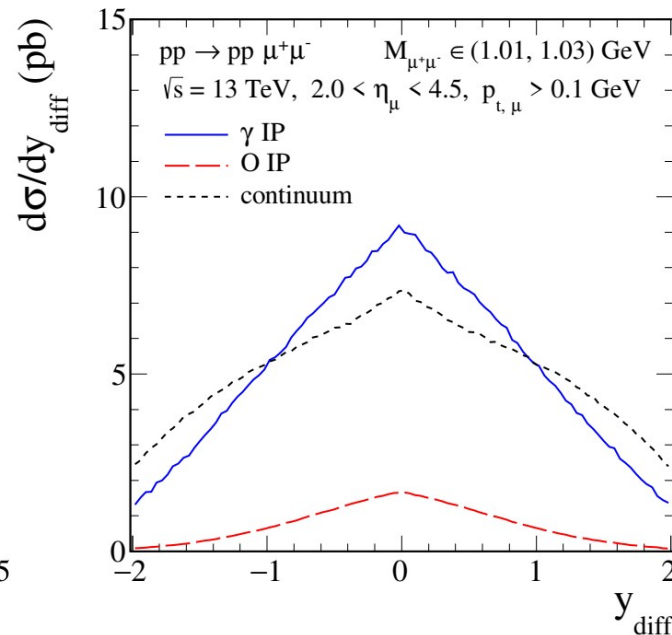
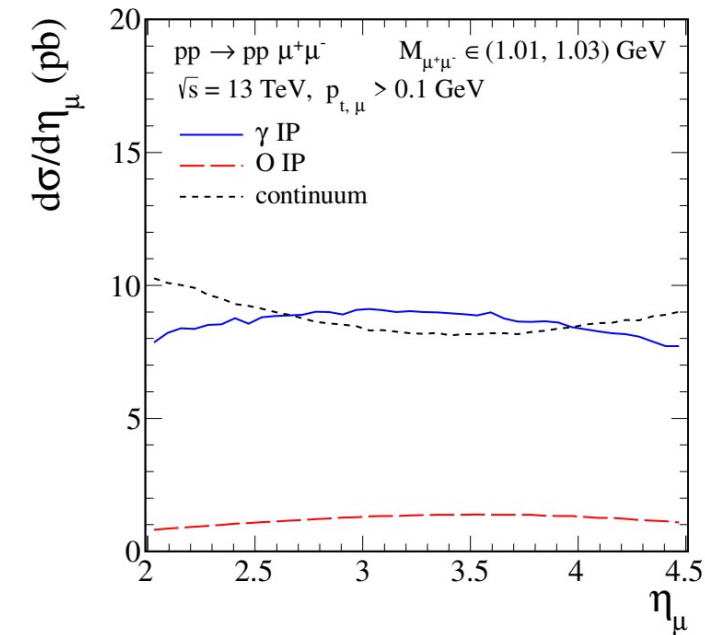
$$g_{\phi \mu^+ \mu^-} = (6.92 \pm 0.08) \times 10^{-3}$$

Predictions for the $pp \rightarrow pp \mu^+ \mu^-$ reaction (LHCb)



We show the contributions from the $\gamma\mathbb{P}$ - and $\mathbb{O}\mathbb{P}$ -fusion processes and the continuum $\gamma\gamma \rightarrow \mu^+ \mu^-$ term.

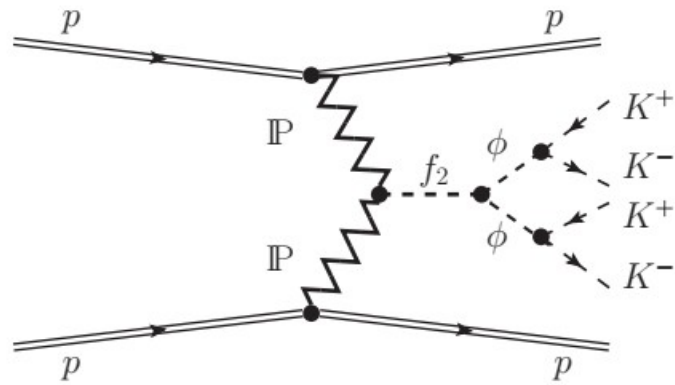
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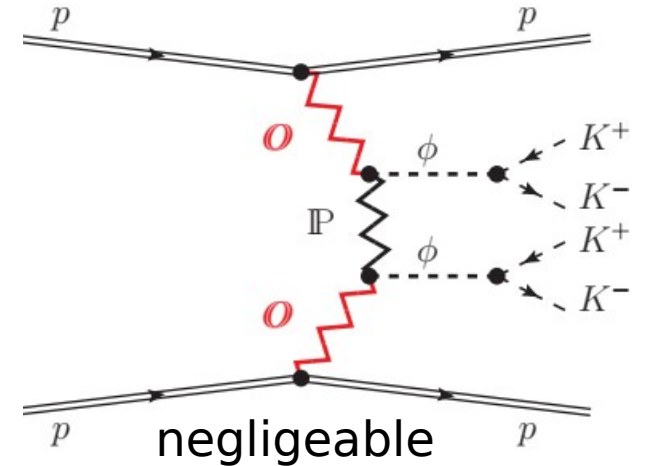
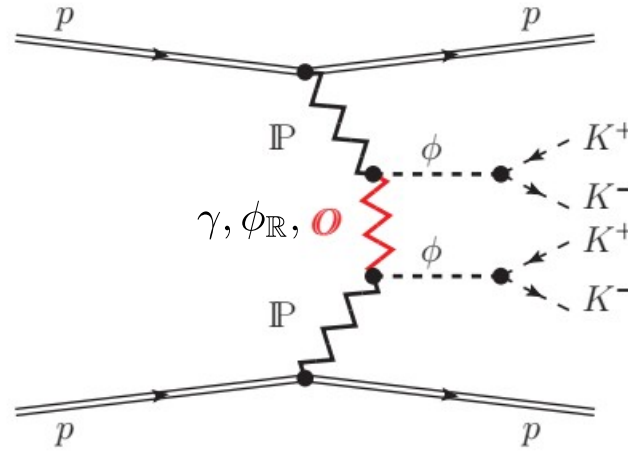
- $p_{t, \mu^+ \mu^-} > 0.8$ GeV cut can be helpful to reduce the $\gamma\gamma \rightarrow \mu^+ \mu^-$ continuum and γ IP-fusion contributions
- In this case the absolute normalization of the cross section or detailed studies of shape of distributions should provide a hint whether one observes the odderon effects

The reaction $pp \rightarrow pp(\phi\phi \rightarrow K+K-K+K-)$

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



$f_2(2340)$ resonance;
“tensor glueball production”



Some modifications are needed to simulate $2 \rightarrow 6$ reaction
(e.g. smearing of ϕ masses due to their resonance distribution)

$$\sigma_{2 \rightarrow 6} = [\mathcal{B}(\phi \rightarrow K^+ K^-)]^2 \int_{2m_K} \int_{2m_K} \sigma_{2 \rightarrow 4}(\dots, m_{X_3}, m_{X_4}) f_\phi(m_{X_3}) f_\phi(m_{X_4}) dm_{X_3} dm_{X_4}$$

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

Contributions:

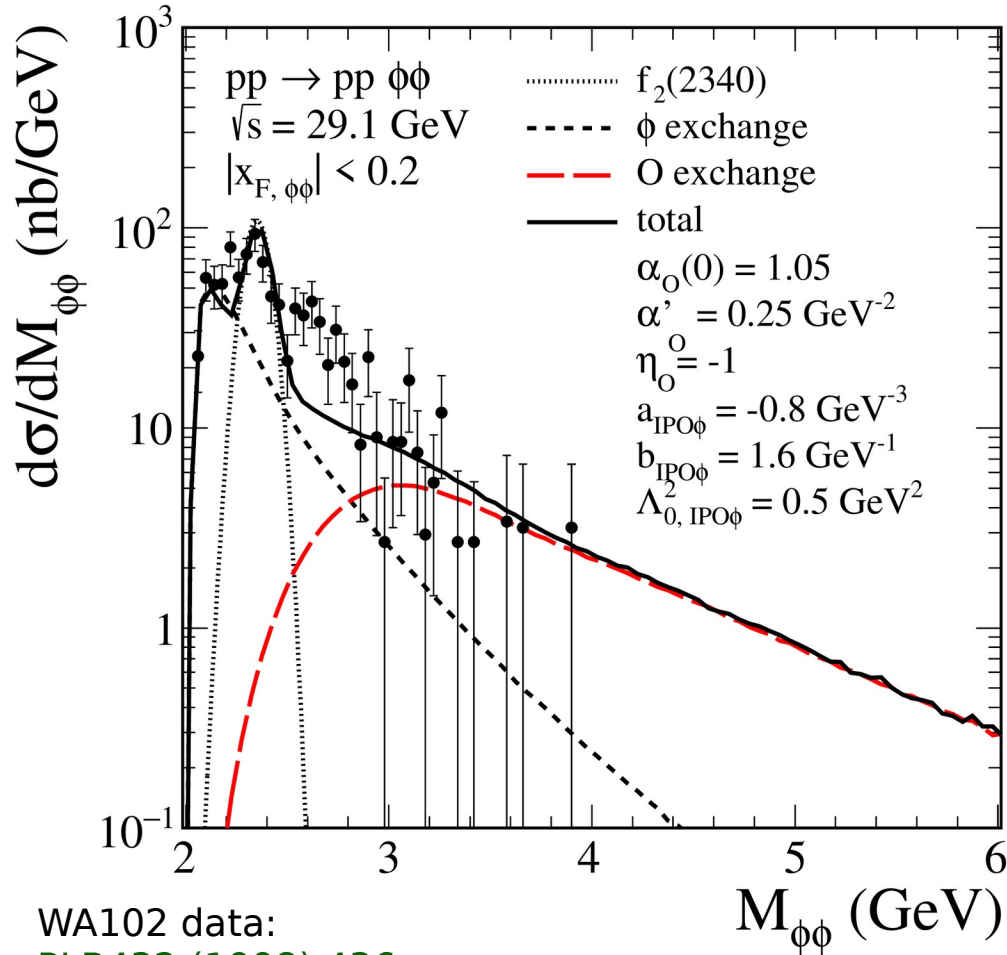
γ : negligeable

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

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

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

Comparison with WA102

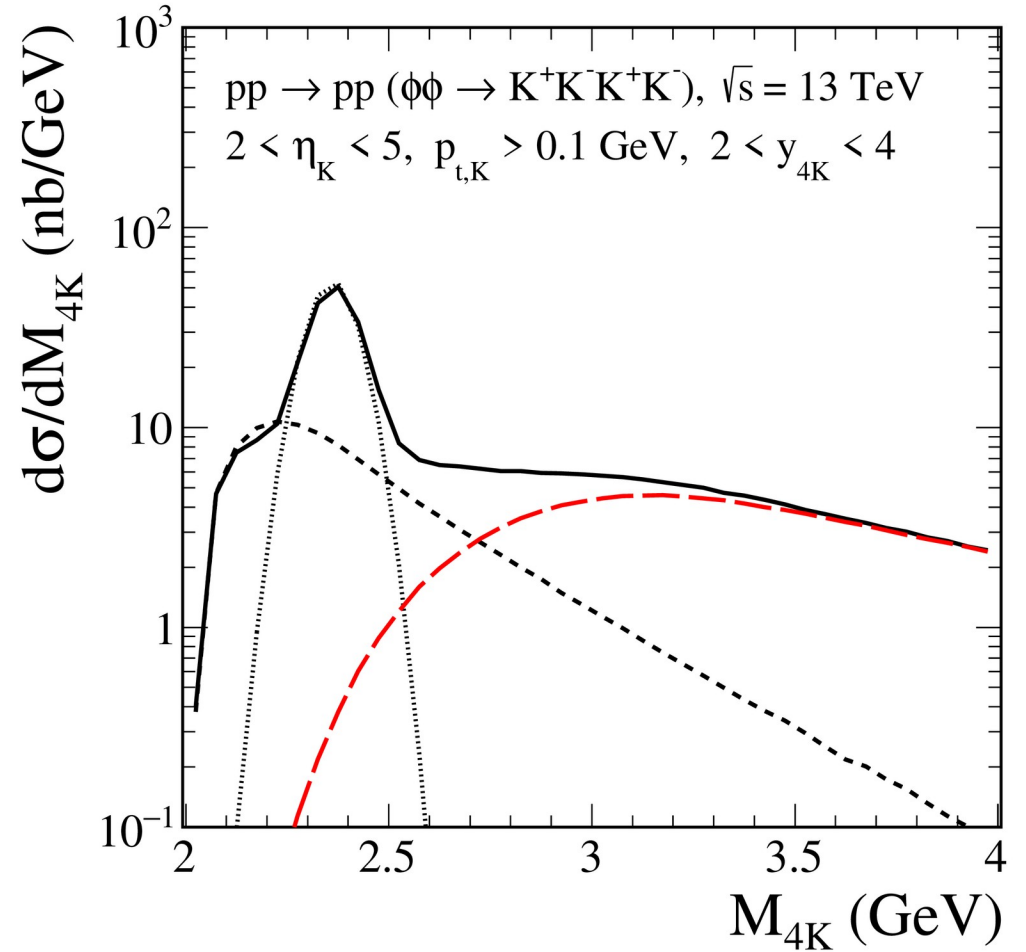


WA102 data:

PLB432 (1998) 436

PLB489 (2000) 29

Predictions for LHCb



The small intercept of the ϕ reggeon exchange, $\alpha_\phi(0) = 0.1$ makes the ϕ -exchange contribution steeply falling with increasing M_{4K} (and also $|Y_{\text{diff}}|$). Therefore, an odderon with an intercept $\alpha_O(0) \approx 1$ should be clearly visible in these distributions if $\mathbb{P}\mathbb{O}\phi$ coupling is of reasonable size.

Conclusions

I have shown you some applications of the **tensor-pomeron and vector-odderon model** [C. Ewerz, M. Maniatis, O. Nachtmann, *Ann. Phys.* 342 (2014) 31] to CEP.

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

$pp \rightarrow pp \phi (\rightarrow K^+K^-, \mu^+\mu^-)$ [P. L., O. Nachtmann, A. Szczurek, *PRD101* (2020) 094012]

- WA102 data give an indication for odderon-exchange contribution
- **We have given predictions for experiments at the LHC.**
We have presented distributions ($pp \rightarrow pp K^+K^-$) which are sensitive to the odderon exchange ($p_{t,K+K'}, y_{\text{diff}}$ rapidity distance between the K^+ and K^- , $\cos\theta_{K^+,CS}$)
- To observe a sizeable deviation from photoproduction (in $pp \rightarrow pp \mu^+\mu^-$) a $p_{t,\mu^+\mu^-} > 0.8$ GeV cut on transverse momentum of the $\mu^+\mu^-$ pair seems necessary

$pp \rightarrow pp \phi\phi (\rightarrow K^+K^-K^+K^-)$ [P. L., O. Nachtmann, A. Szczurek, *PRD99* (2019) 094034]

- The $\phi\phi$ invariant mass distribution has a rich structure
→ resonances at low $M_{\phi\phi}$ and continuum terms at higher $M_{\phi\phi}$
- **The odderon-exchange contribution should be distinguishable from other contributions in the region of large four-kaon invariant masses** (large y distance between the ϕ mesons)

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

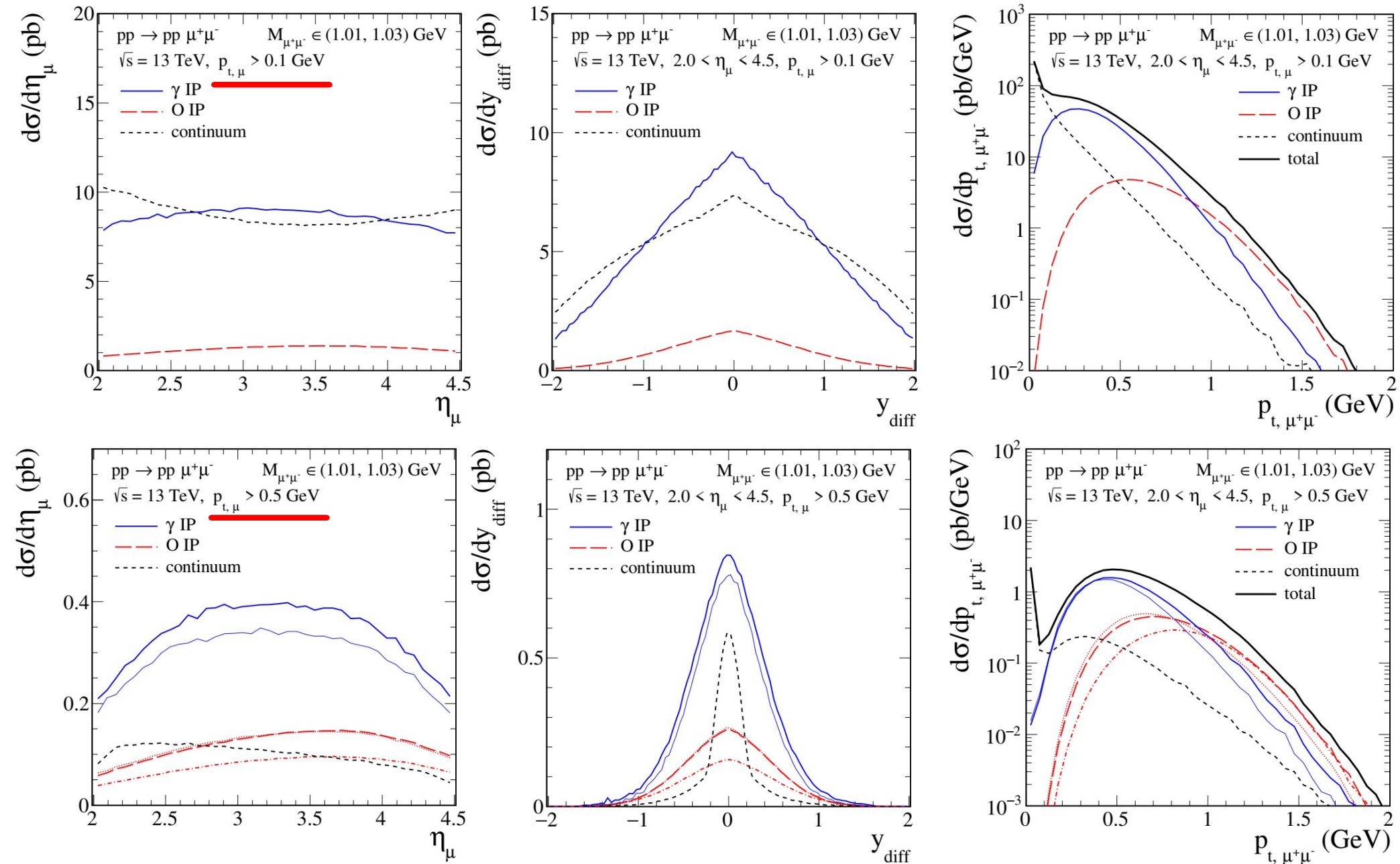
We are looking forward to first experimental results on CEP of ϕ and $\phi\phi$ at the LHC. Comparison with 'exclusive' data should be very valuable for clarifying the status of odderon.

Cross sections in nb for CEP of single ϕ in pp collisions

Table 1: The integrated cross sections in nb for the CEP of single ϕ mesons in pp collisions with the subsequent decays $\phi \rightarrow K^+K^-$ or $\phi \rightarrow \mu^+\mu^-$. The results have been calculated for $\sqrt{s} = 13$ TeV in the dikaon/dimuon invariant mass region $M_{34} \in (1.01, 1.03)$ 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.

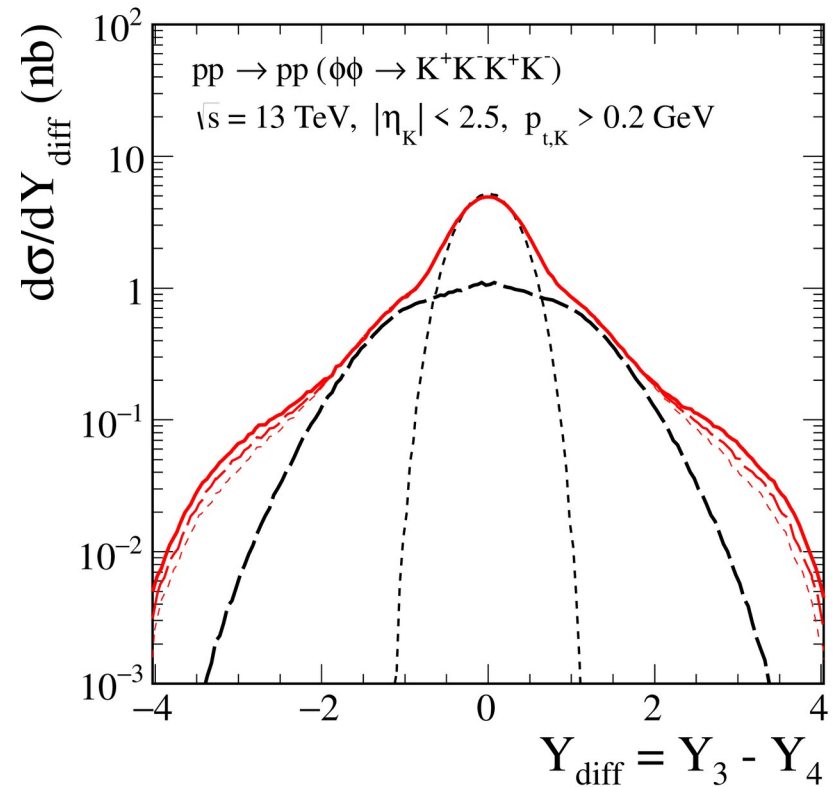
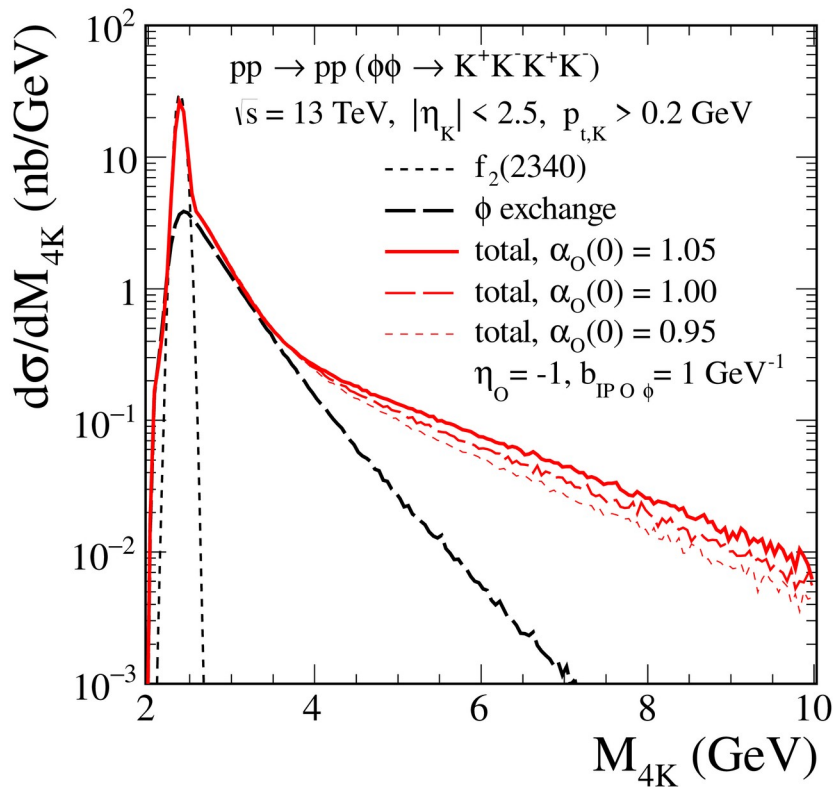
Cuts	Contributions	$\sigma^{(\text{Born})}$ (nb)	$\sigma^{(\text{full})}$ (nb)	$\langle S^2 \rangle$
$pp \rightarrow pp K^+K^-$ $ \eta_K < 2.5, p_{t,K} > 0.1$ GeV	$\gamma\mathbb{P}$ fusion	60.07	55.09	0.9
	$\mathbb{O}\mathbb{P}$ fusion	21.40	6.44	0.3
	$\gamma\mathbb{P}$ and $\mathbb{O}\mathbb{P}$		58.58	
$ \eta_K < 2.5, p_{t,K} > 0.2$ GeV, 0.17 GeV $< p_{y,1} , p_{y,2} < 0.5$ GeV	$\gamma\mathbb{P}$ fusion	1.07	0.24	0.2
	$\mathbb{O}\mathbb{P}$ fusion	2.10	0.61	0.3
	$\gamma\mathbb{P}$ and $\mathbb{O}\mathbb{P}$		0.70	
$2.0 < \eta_K < 4.5, p_{t,K} > 0.1$ GeV	$\gamma\mathbb{P}$ fusion	43.18	40.07	0.9
	$\mathbb{O}\mathbb{P}$ fusion	16.73	4.70	0.3
	$\gamma\mathbb{P}$ and $\mathbb{O}\mathbb{P}$		43.28	
$2.0 < \eta_K < 4.5, p_{t,K} > 0.3$ GeV	$\gamma\mathbb{P}$ fusion	3.09	2.57	0.8
	$\mathbb{O}\mathbb{P}$ fusion	6.57	1.64	0.3
	$\gamma\mathbb{P}$ and $\mathbb{O}\mathbb{P}$		4.24	
$2.0 < \eta_K < 4.5, p_{t,K} > 0.5$ GeV	$\gamma\mathbb{P}$ fusion	0.93×10^{-1}	0.66×10^{-1}	0.7
	$\mathbb{O}\mathbb{P}$ fusion	0.88	0.16	0.2
	$\gamma\mathbb{P}$ and $\mathbb{O}\mathbb{P}$		0.24	
$pp \rightarrow pp \mu^+\mu^-$ $2.0 < \eta_\mu < 4.5, p_{t,\mu} > 0.1$ GeV	$\gamma\mathbb{P}$ fusion	23.93×10^{-3}	20.96×10^{-3}	0.9
	$\mathbb{O}\mathbb{P}$ fusion	10.06×10^{-3}	3.02×10^{-3}	0.3
	$\gamma\mathbb{P}$ and $\mathbb{O}\mathbb{P}$		21.64×10^{-3}	
$2.0 < \eta_\mu < 4.5, p_{t,\mu} > 0.5$ GeV	$\gamma\mathbb{P}$ fusion	1.21×10^{-3}	0.85×10^{-3}	0.7
	$\mathbb{O}\mathbb{P}$ fusion	1.49×10^{-3}	0.45×10^{-3}	0.2
	$\gamma\mathbb{P}$ and $\mathbb{O}\mathbb{P}$		1.07×10^{-3}	
$2.0 < \eta_\mu < 4.5, p_{t,\mu} > 0.1$ GeV, $p_{t,\mu^+\mu^-} > 0.8$ GeV	$\gamma\mathbb{P}$ fusion	0.70×10^{-3}	0.41×10^{-3}	0.6
	$\mathbb{O}\mathbb{P}$ fusion	2.46×10^{-3}	0.51×10^{-3}	0.2
	$\gamma\mathbb{P}$ and $\mathbb{O}\mathbb{P}$		0.91×10^{-3}	

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- **Larger $p_{t, \mu}$** (bottom panels) can be helpful to reduce the $\gamma\gamma \rightarrow \mu^+\mu^-$ continuum

The reaction $pp \rightarrow pp(\phi\phi \rightarrow K+K-K+K-)$



[PRD99 (2019) 094034]

The odderon-exchange contribution should be distinguishable from other contributions in the region of large four-kaon invariant masses and large rapidity (Y) distance between the ϕ mesons.

If an odderon exchange is seen, then these distributions will reveal the intercept of the odderon trajectory.