Single and double ϕ production in *pp* collisions at the LHC: the role of odderon exchange

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Low-x 2021

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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. 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 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, 8, and 13 TeV) for *pp* elastic scattering (TOTEM Collaboration, EPJC79 (2019) 785, EPJC80 (2020) 91, TOTEM and D0, PRL127 (2021) 062003) → provides evidence for the odderon exchange

- It is of great importance to study possible odderon effects in other reactions:

  → central ϕ production in high-energy *pp* and $p\bar{p}$ collisions   Schäfer, Mankiewicz, Nachtmann, PLB272 (1991) 419
  → exclusive J/ψ and Υ hadroproduction   Bzdak, Motyka, Szymanowski, Cudell, 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 the LHC

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

C. Ewerz, M. Maniatis, O. Nachtmann, Ann. Phys. 342 (2014) 31
based on O. Nachtmann, Ann. Phys. 209 (1991) 436

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

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

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

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

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

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

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

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

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

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

Applications

γ p → π⁺ π⁻ p *Bolz, Ewerz, Maniatis, Nachtmann, Sauter, Schöning, JHEP 01 (2015) 151*

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

Photoproduction and low *x* DIS

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

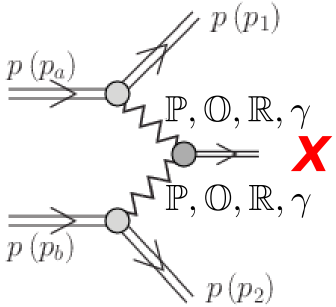
A "vector pomeron" cannot couple in the total photoabsorption cross section and in the structure functions of DIS.

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.

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



X: η, η', f_0	*Ann. Phys. 344 (2014) 301*
ρ^0	*PRD91 (2015) 074023*
$\pi^+\pi^-$, f_0, f_2 ($\to \pi^+\pi^-$)	*PRD93 (2016) 054015, PRD101 (2020) 034008*
$\pi^+\pi^-\pi^+\pi^-$, $\rho^0\rho^0$	*PRD94 (2016) 034017*
ρ^0 with proton diss.	*PRD95 (2017) 034036*
$p\bar{p}$	*PRD97 (2018) 094027*
K^+K^-	*PRD98 (2018) 014001*
$f_1(1285)$	*P.L., Leutgeb, Nachtmann, Rebhan, Szczurek, PRD102 (2020) 114003*
$K^{*0}\bar{K}^{*0}$, $f_2(1950)$	*P.L., PRD103 (2021) 054039*

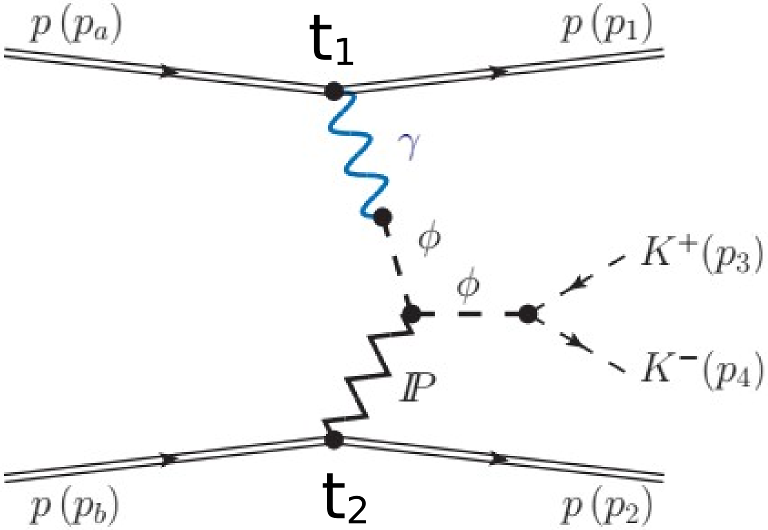
$\phi \to K^+K^-$, $\mu^+\mu^-$ *P.L., Nachtmann, Szczurek, PRD101 (2020) 094012* ← this talk

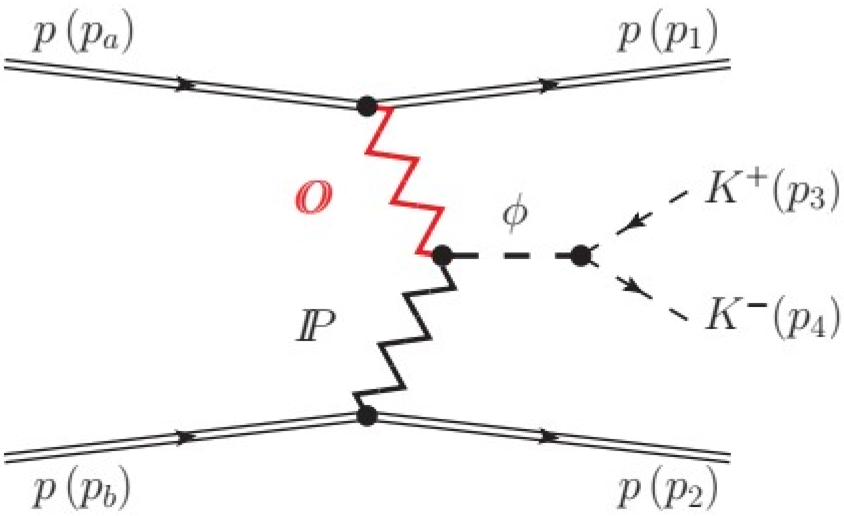
$\phi\phi \to K^+K^-K^+K^-$ *P.L., Nachtmann, Szczurek, PRD99 (2019) 094034* ← this talk

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

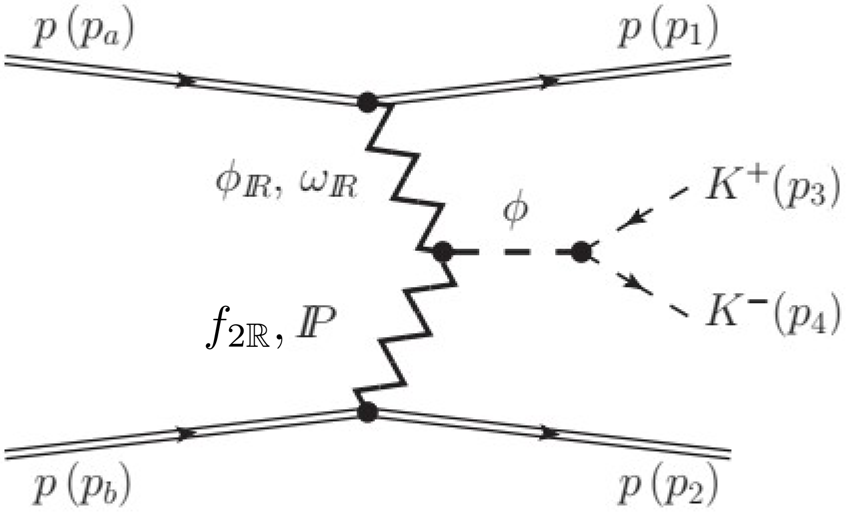
In my talk I shall consider the exclusive processes at large c.m. energy $\sqrt{s}$ but small momentum transfers $|t_1|$, $|t_2|$.

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) } reggeons

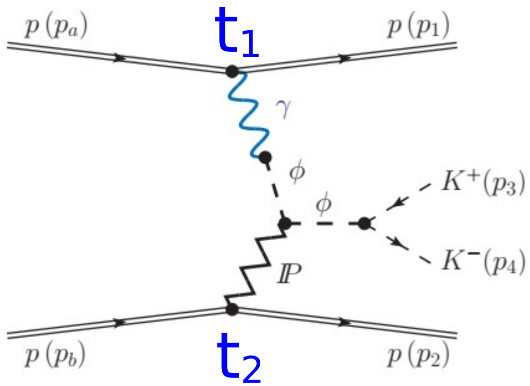
γ (C = -1) photon

Photon-pomeron fusion

- $2 \to 4$ exclusive reaction

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

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

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

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

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

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

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

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

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

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

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

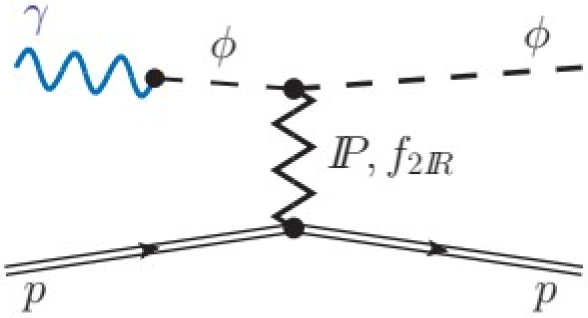
$$\Gamma^{(0)}_{\mu\nu\kappa\lambda}(k_1,k_2) = \left[(k_1\cdot k_2)g_{\mu\nu} - k_{2\mu}k_{1\nu}\right]\left[k_{1\kappa}k_{2\lambda} + k_{2\kappa}k_{1\lambda} - \frac{1}{2}(k_1\cdot k_2)g_{\kappa\lambda}\right]$$

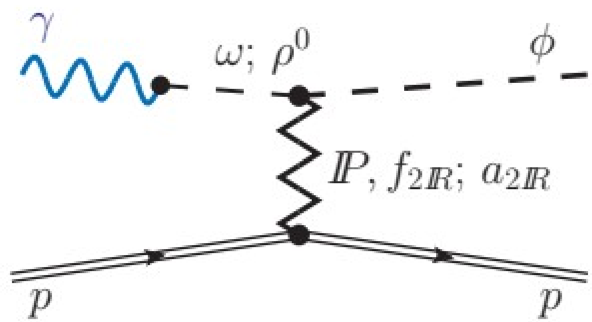
$$\begin{aligned}\Gamma^{(2)}_{\mu\nu\kappa\lambda}(k_1,k_2) = {} & (k_1\cdot k_2)(g_{\mu\kappa}g_{\nu\lambda} + g_{\mu\lambda}g_{\nu\kappa}) + g_{\mu\nu}(k_{1\kappa}k_{2\lambda} + k_{2\kappa}k_{1\lambda}) \\ & - k_{1\nu}k_{2\lambda}g_{\mu\kappa} - k_{1\nu}k_{2\kappa}g_{\mu\lambda} - k_{2\mu}k_{1\lambda}g_{\nu\kappa}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

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 $\Lambda^2_{0,\,\mathbb{P}\phi\phi}$ in $F_M(t) = \frac{1}{1-t/\Lambda^2_{0,\mathbb{P}\phi\phi}}$ are fixed from the process $\gamma p \to \phi p$.

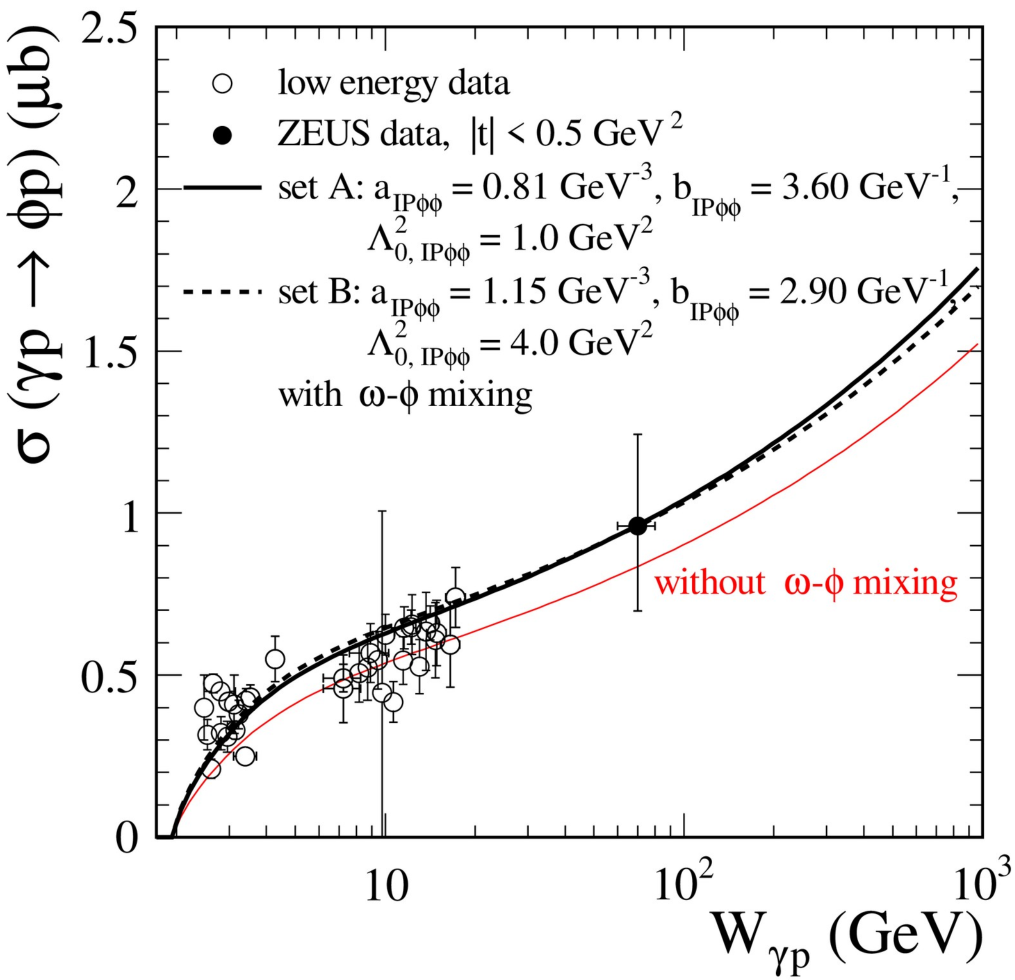
- Photoproduction process

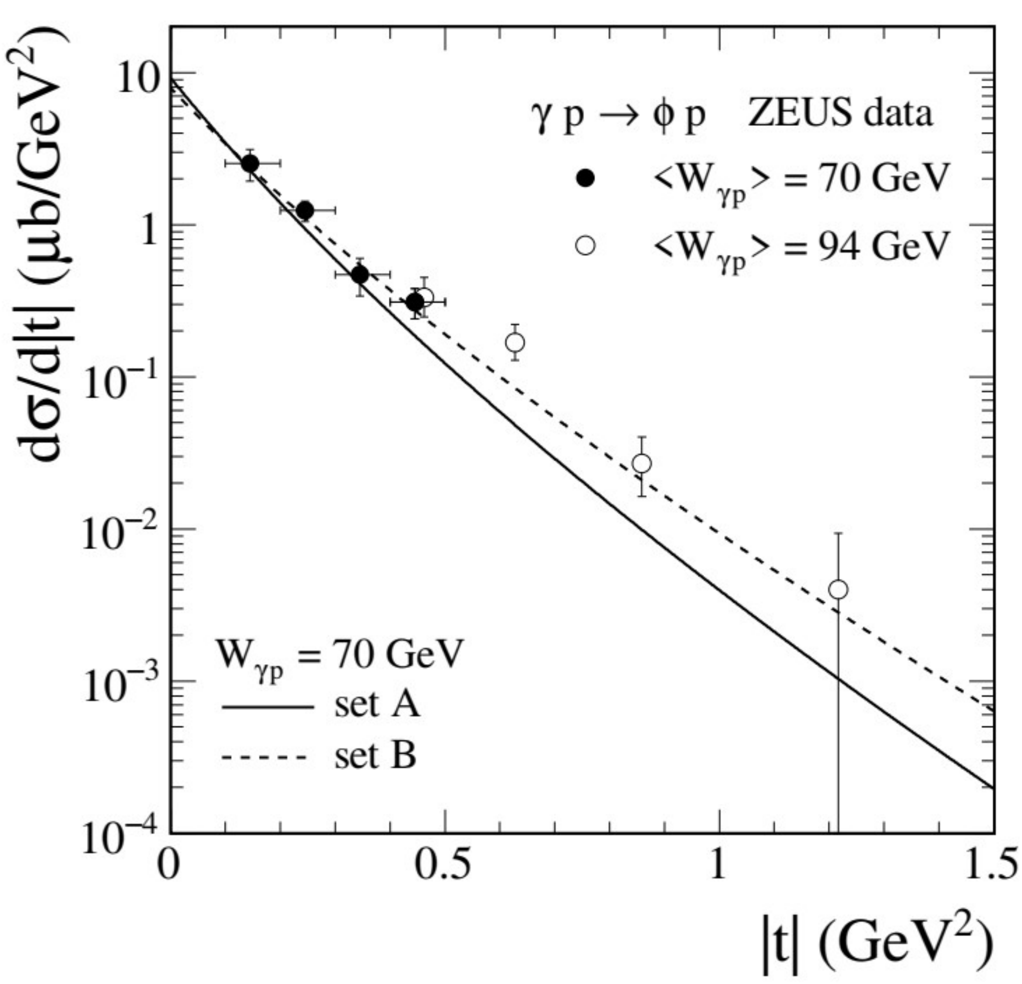




ω-ϕ mixing effect included

$$b_{\mathbb{P}\omega\phi} = -b_{\mathbb{P}\omega\omega}\tan(\Delta\theta_V)$$
$$b_{\mathbb{P}\omega\omega} = 7.04\ \mathrm{GeV}^{-1}$$
$$\Delta\theta_V = 3.7^o$$

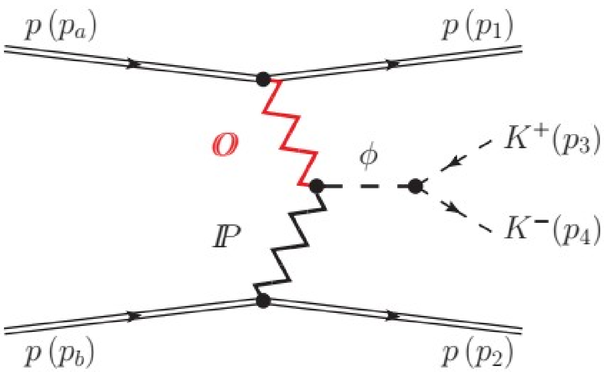




Odderon-pomeron fusion

- Born-level amplitude:

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



Effective propagator of C = -1 odderon and the O*pp* vertex

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

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

In our calculations we shall choose as default values:

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

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

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

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

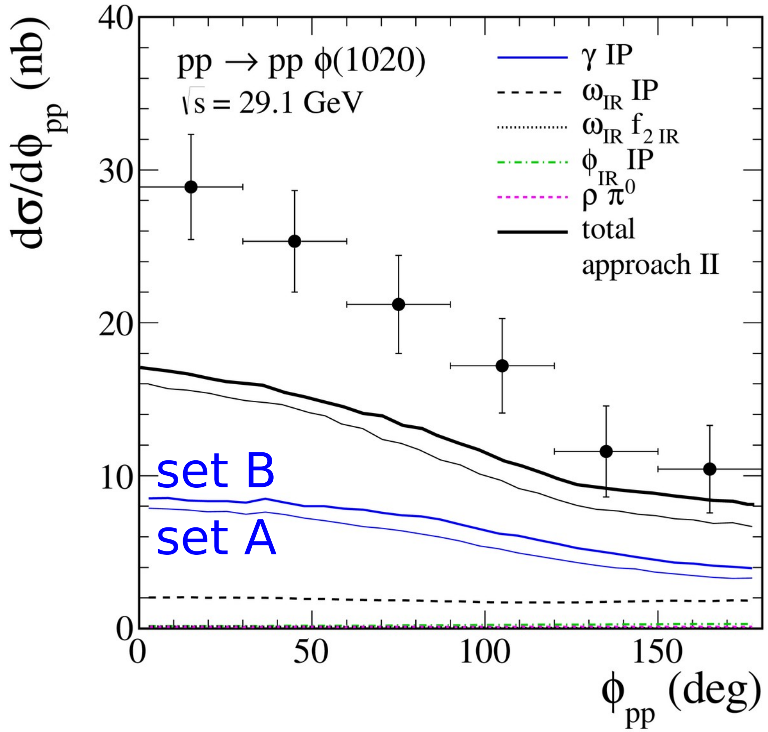
The coupling parameters $a_{\mathbb{P}\mathbb{O}\phi}$, $b_{\mathbb{P}\mathbb{O}\phi}$ and the cut-off parameter $\Lambda^2_{0,\,\mathbb{P}\mathbb{O}\phi}$ in $F_M(t)$ could be adjusted to experimental data.

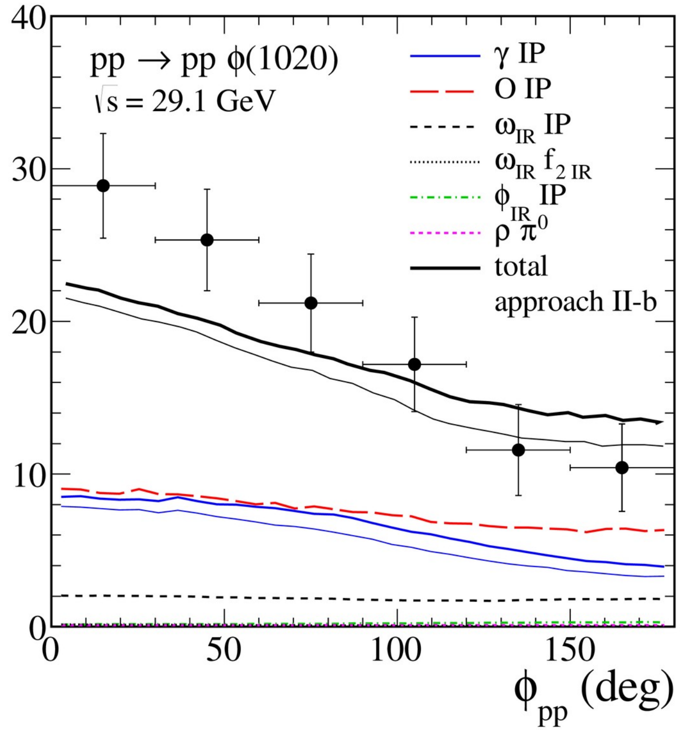
- Absorption effects: $\mathcal{M} = \mathcal{M}^{Born} + \mathcal{M}^{pp-rescattering}$

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

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 $\sigma_{\rm exp} = (60 \pm 21)\,{\rm nb}$ [A. Kirk, PLB489 (2000) 29].
  Different fusion processes were considered → large interference effects.
  The WA102 data support the existence of odderon exchange !
- The ratio was also measured:

$$R = \frac{d\sigma/d({\rm dP_t} \leqslant 0.2\ {\rm GeV})}{d\sigma/d({\rm dP_t} \geqslant 0.5\ {\rm GeV})}$$

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

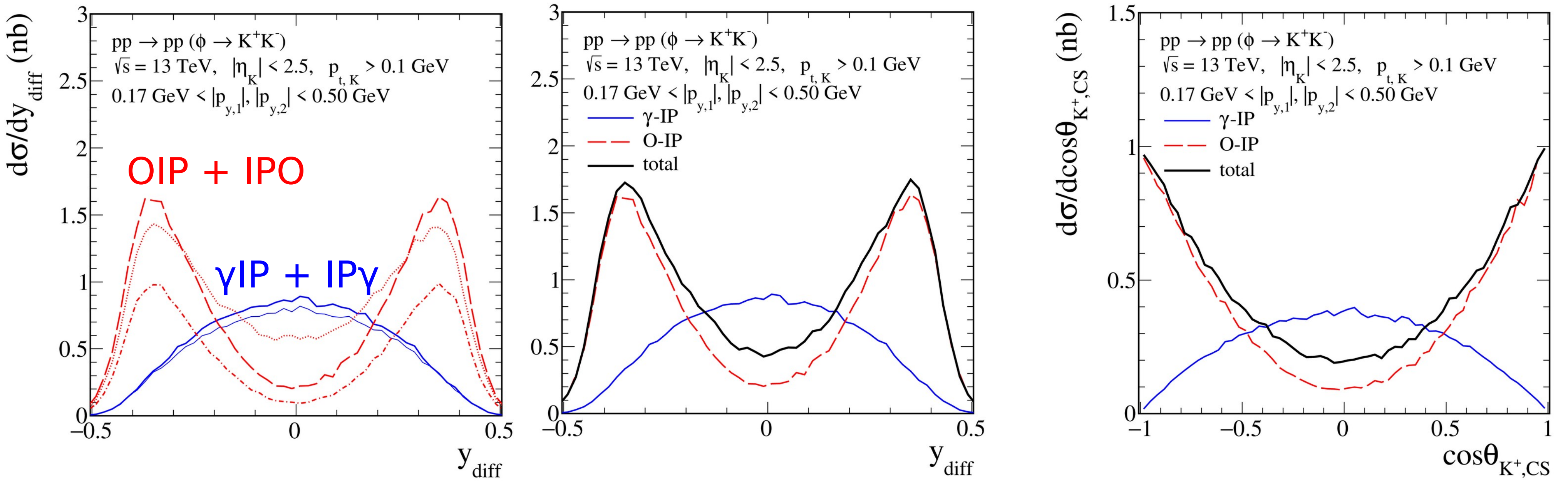
$R_{\rm th} = 0.71$ (no odderon), $R_{\rm th} = 0.27$ (with odderon)

$${\rm dP_t} = |\boldsymbol{dP_t}|, \quad \boldsymbol{dP_t} = \boldsymbol{q_{t,1}} - \boldsymbol{q_{t,2}} = \boldsymbol{p_{t,2}} - \boldsymbol{p_{t,1}}$$

The WA102 data allow us to determine the model parameters:

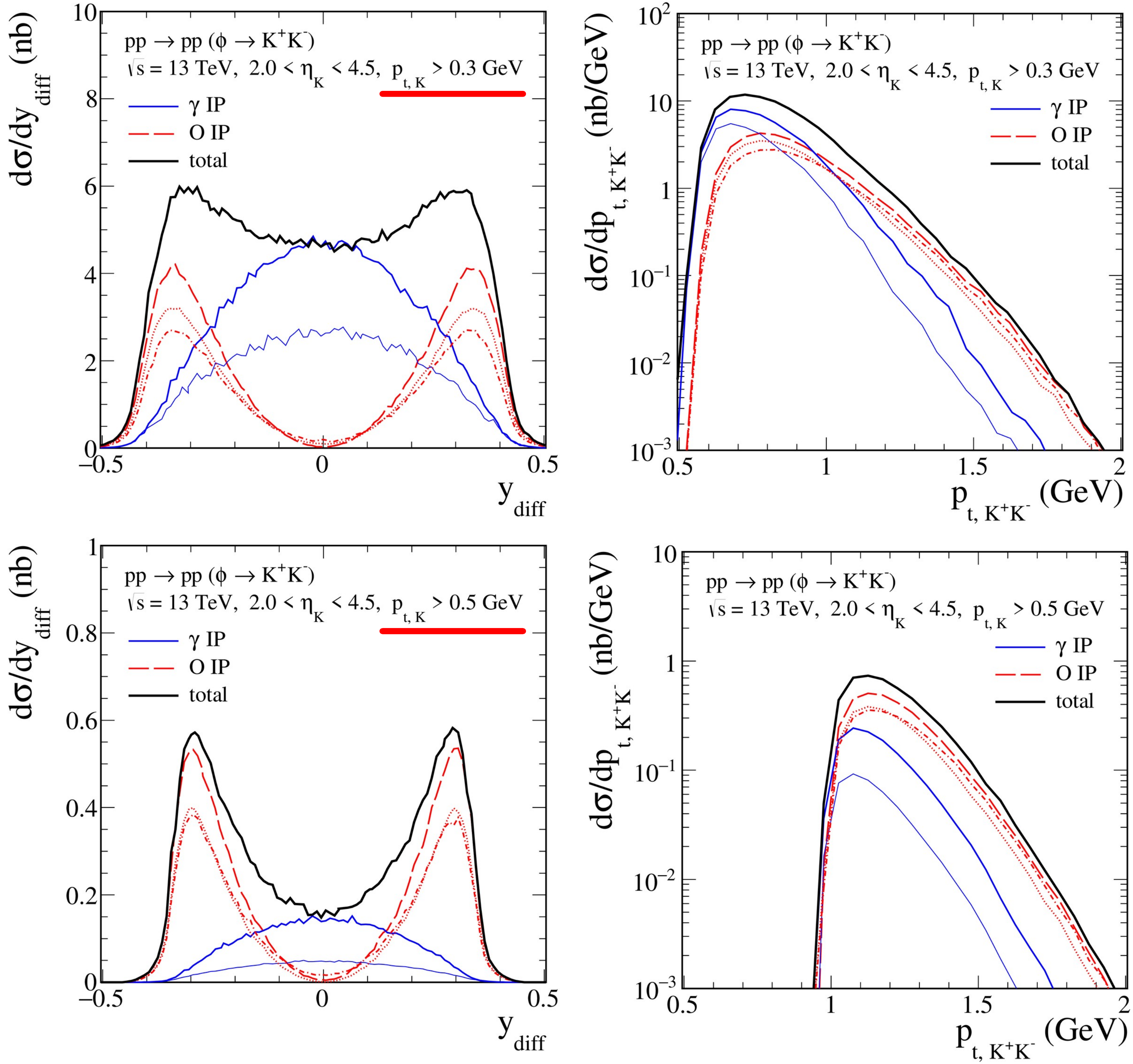
$$a_{\mathbb{P}\mathbb{O}\phi} = -0.8\ {\rm GeV}^{-3}, \quad b_{\mathbb{P}\mathbb{O}\phi} = 1.6\ {\rm GeV}^{-1}, \quad \Lambda^2_{0,\,\mathbb{P}\mathbb{O}\phi} = 0.5\,{\rm GeV}^2$$

Predictions for the *pp* → *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 $y_{diff} = y_{K+} - y_{K-}$. Different behaviour is seen for γIP 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 $\phi \to K^+K^-$ (angular distributions in the Collins-Soper frame)

Predictions for the *pp* → *pp* K^+K^- reaction (LHCb)

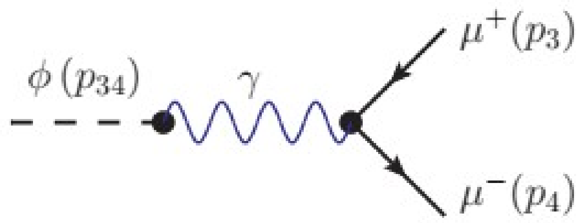


The reaction $pp \to pp\,\mu^+\mu^-$

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

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

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



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

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

From the experimental values (PDG)

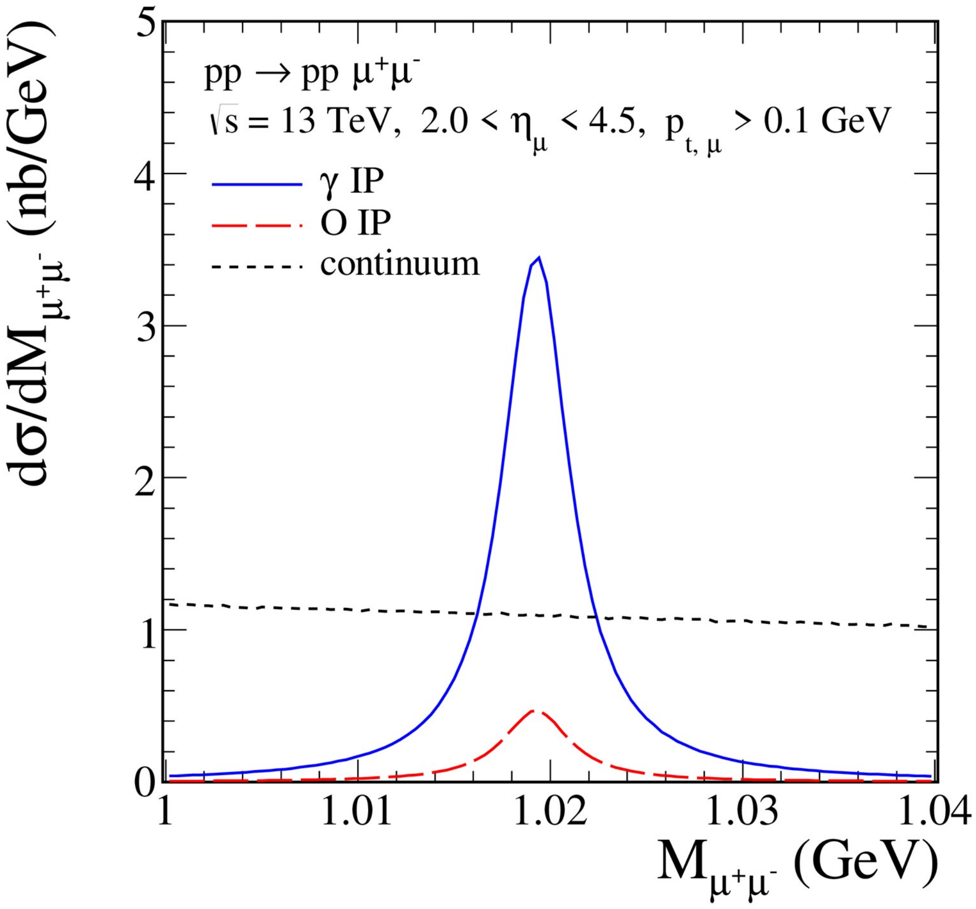
$$\begin{aligned} m_\phi &= (1019.461 \pm 0.016)\ \mathrm{MeV}\,, \\ \Gamma(\phi \to \mu^+\mu^-)/\Gamma_\phi &= (2.86 \pm 0.19) \times 10^{-4}\,, \\ \Gamma_\phi &= (4.249 \pm 0.013)\ \mathrm{MeV} \end{aligned}$$

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

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

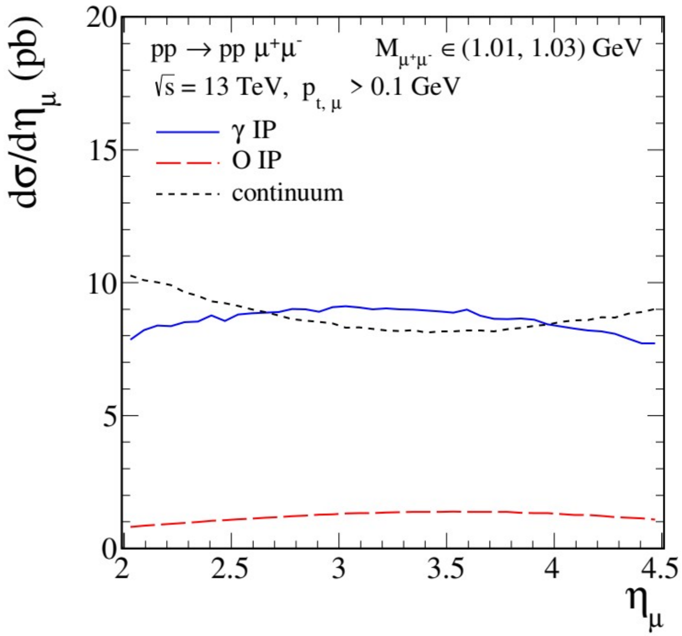
$$g_{\phi\mu^+\mu^-} = (6.92 \pm 0.08) \times 10^{-3}$$

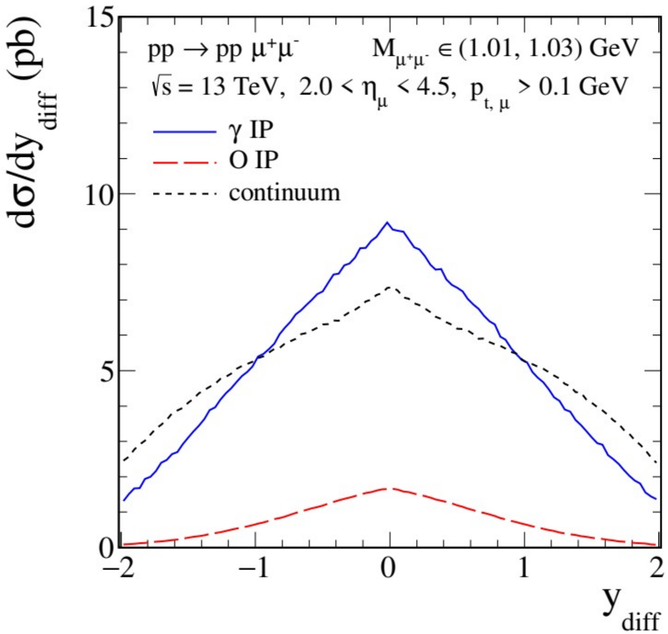
Predictions for the *pp* → *pp* $\mu^+\mu^-$ reaction (LHCb)

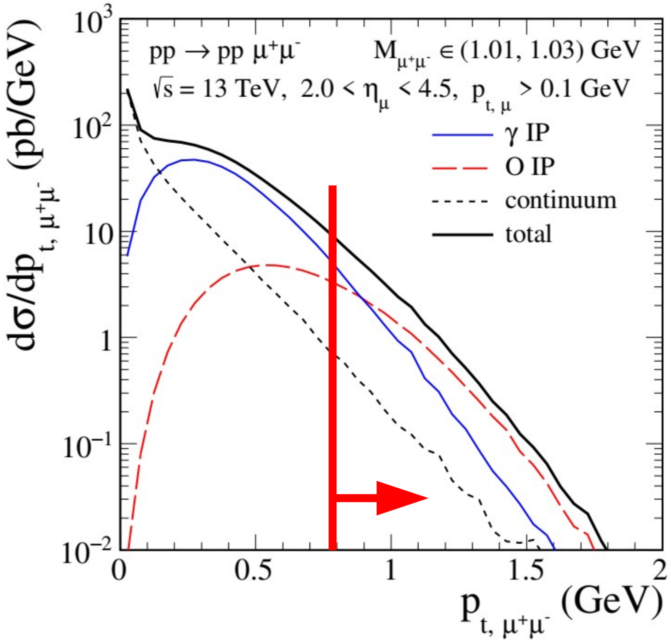


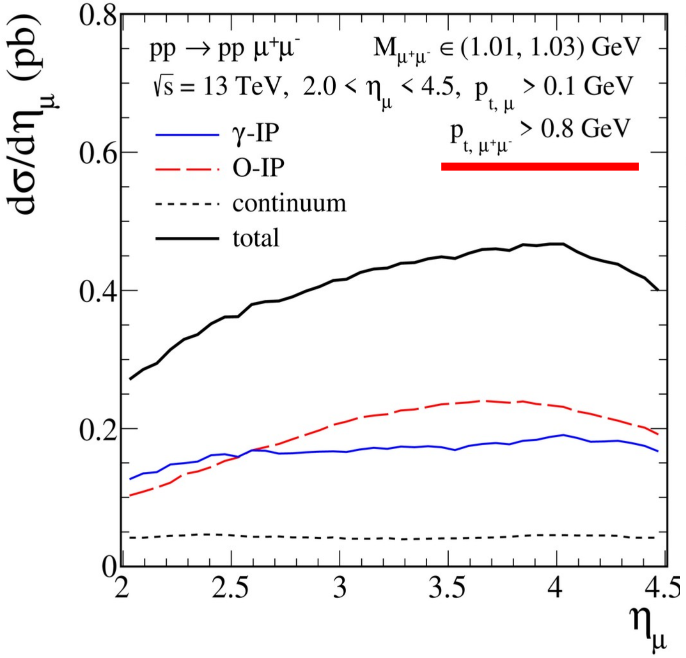
We show the contributions from the $\gamma\mathbb{P}$- and $\mathbb{OP}$-fusion processes and the continuum $\gamma\gamma \to \mu^+\mu^-$ term.

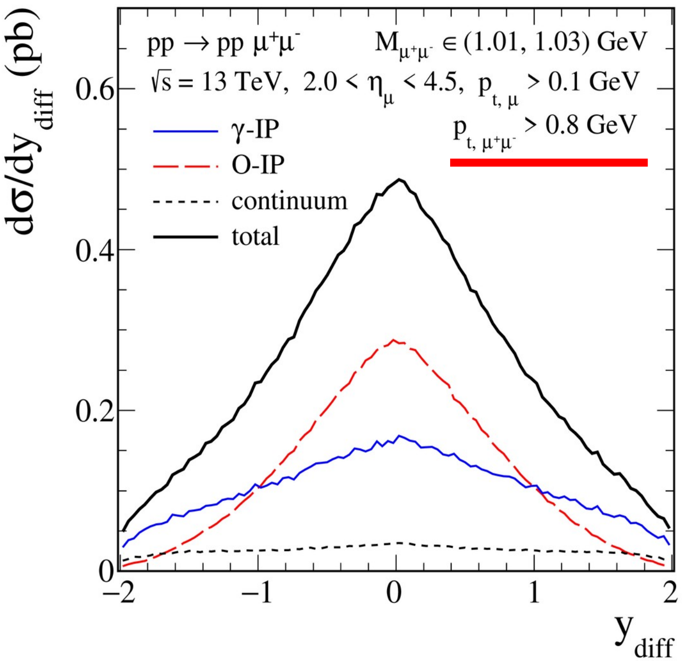
Predictions for the *pp* → *pp* $\mu^+\mu^-$ reaction (LHCb)







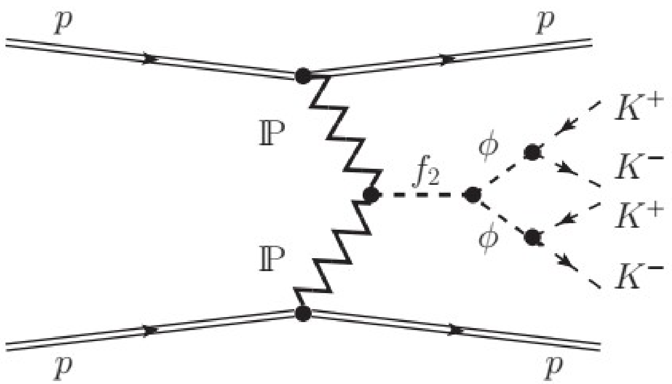




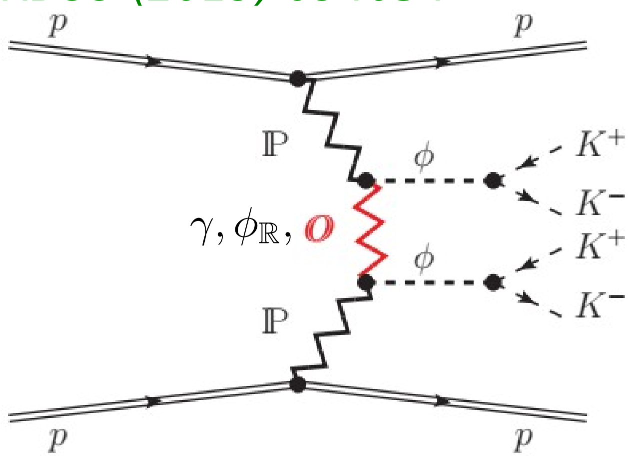
- $p_{t,\mu+\mu-} > 0.8$ GeV cut can be helpful to reduce the $\gamma\gamma \to \mu^+\mu^-$ continuum and γ IP-fusion contributions
- In this case the absolute normalization of the cross section or detailed studies of shape of distributions should provide a hint whether one observes the odderon effects

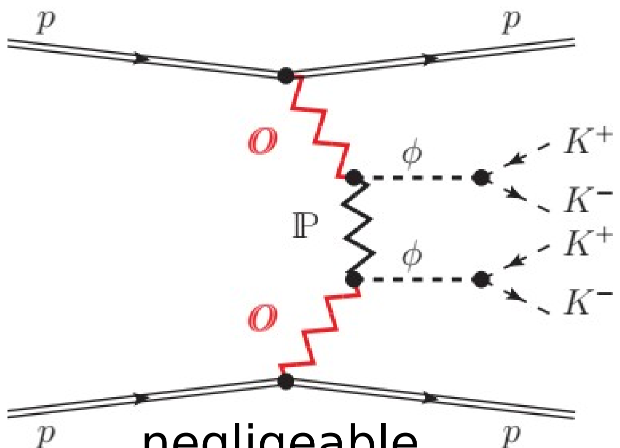
The reaction $pp \to pp(\phi\phi \to K^+K^-K^+K^-)$

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



$f_2(2340)$ resonance;
"tensor glueball production"





negligeable

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

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

- 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:

$$\gamma : \quad \text{negligeable}$$

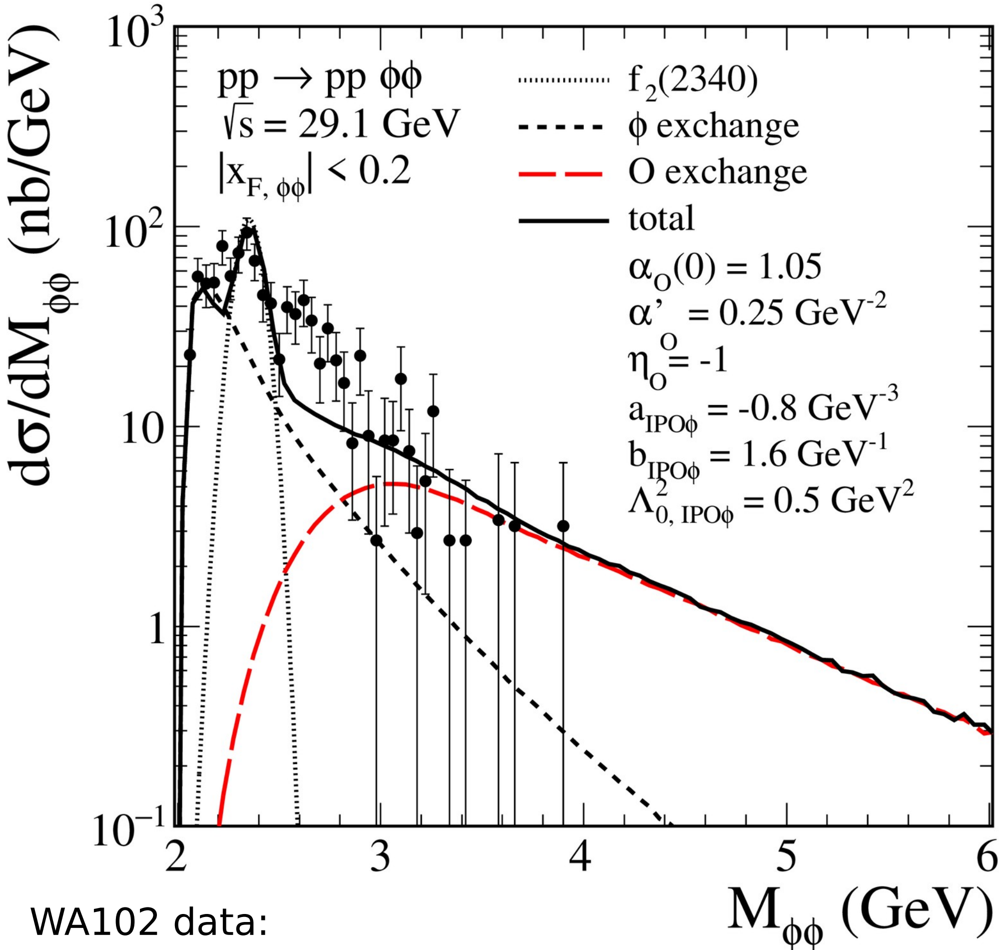
$$\phi_{\mathbb{R}} : \quad \propto \left(M_{\phi\phi}^2\right)^{\alpha_\phi(\hat{t})-1}, \; \alpha_\phi(\hat{t}) = 0.1 + 0.9\,\hat{t}$$

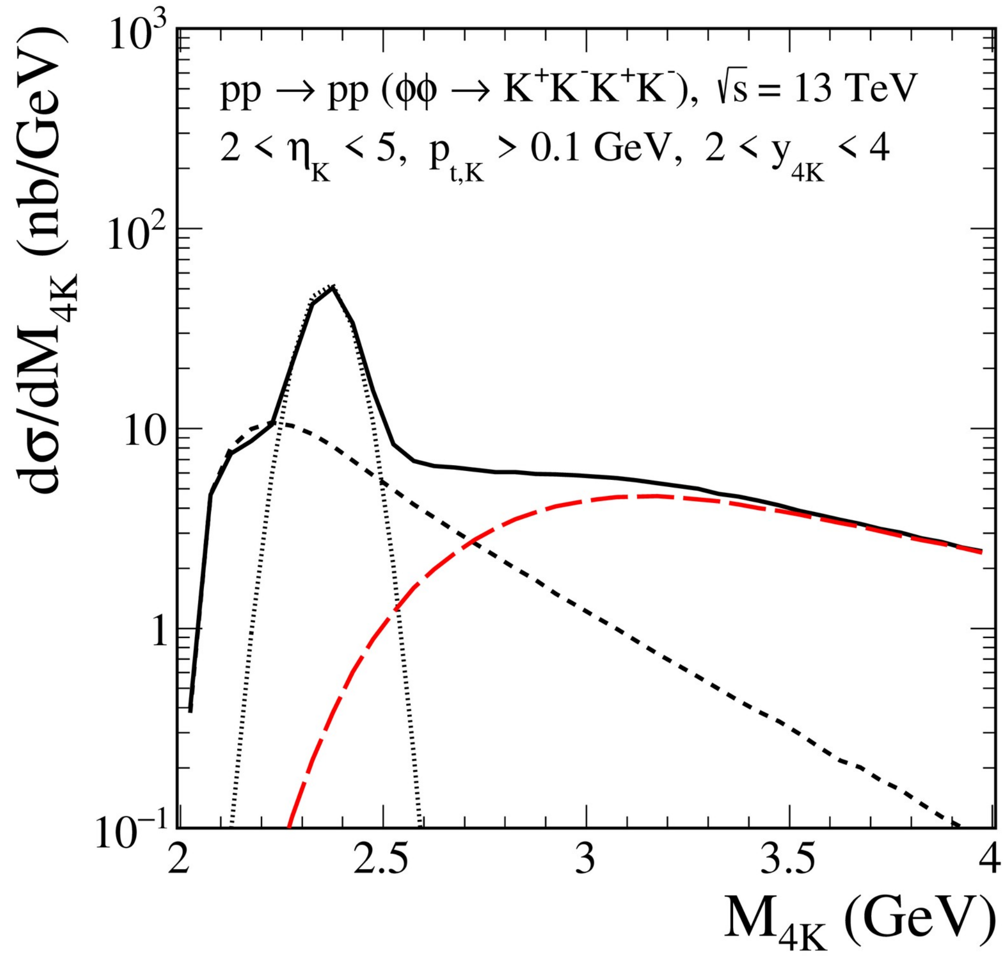
$$\mathbb{O} : \quad \propto \left(M_{\phi\phi}^2\right)^{\alpha_{\mathbb{O}}(\hat{t})-1}, \; \alpha_{\mathbb{O}}(0) \approx 1.0 \quad ?$$

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

Comparison with WA102

Predictions for LHCb





WA102 data:
PLB432 (1998) 436
PLB489 (2000) 29

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 $|Y_{\rm diff}|$). Therefore, an odderon with an intercept $\alpha_{\mathbb{O}}(0) \approx 1$ should be clearly visible in these distributions if $\mathbb{P}\mathbb{O}\phi$ coupling is of resonable 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.

$pp \to pp\, \phi$ $(\to K^+K^-,\ \mu^+\mu^-)$ [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 ($pp \to pp\, K^+K^-$) which are sensitive to the odderon exchange ($p_{t,K+K-}$, y_{diff} rapidity distance between the K^+ and K^-, $\cos\theta_{K+,CS}$)
- To observe a sizeable deviation from photoproduction (in $pp \to pp\, \mu^+\mu^-$) $p_{t,\mu+\mu-} > 0.8$ GeV cut on transverse momentum of the $\mu^+\mu^-$ pair seems necessary

$pp \to pp\, \phi\phi$ $(\to K^+K^-K^+K^-)$ [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 IPOϕ coupling (at least, to derive an upper limit on the odderon contribution).

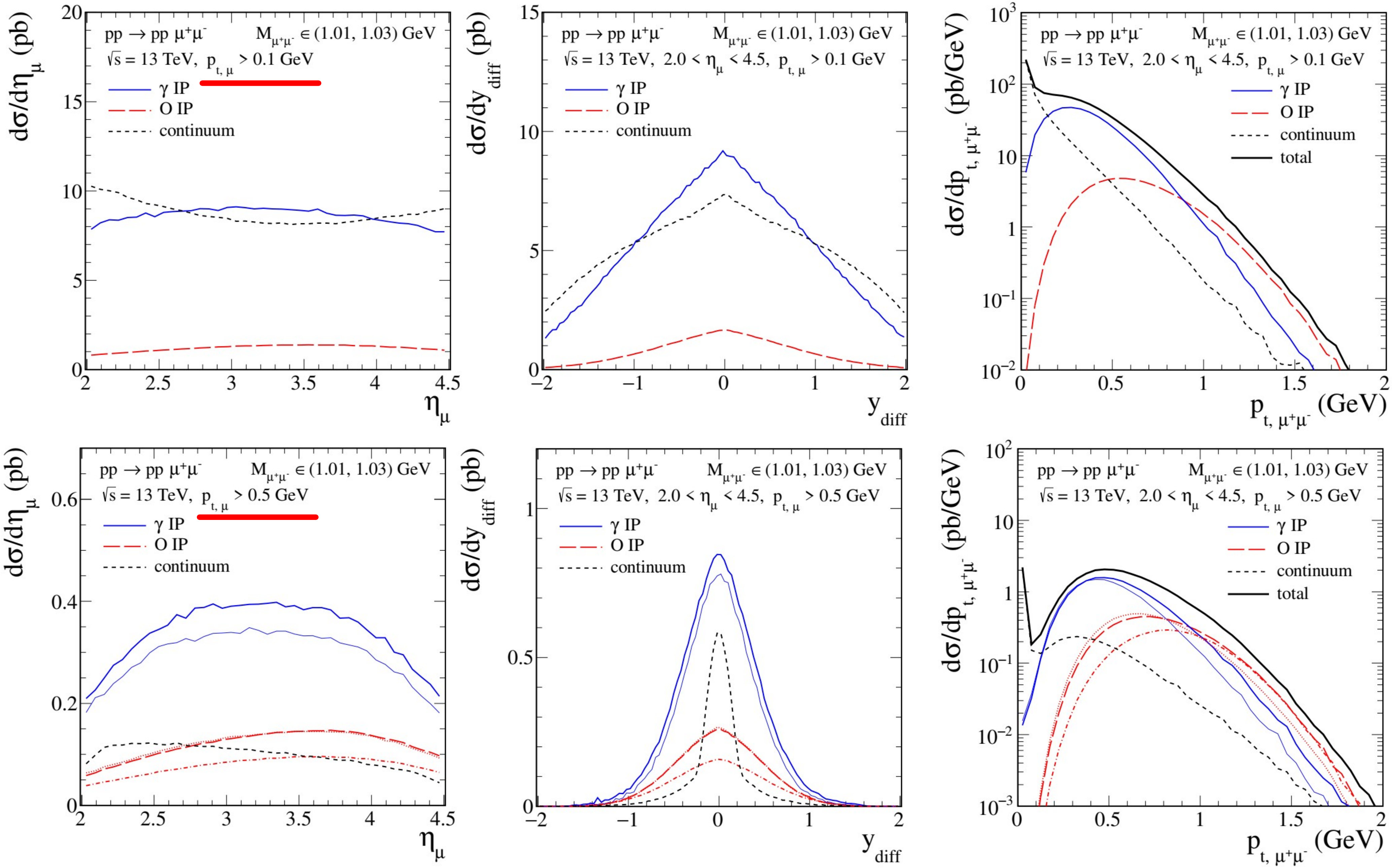
We are looking forward to first experimental results on CEP of ϕ and $\phi\phi$ at the LHC.
Comparison with ‘exclusive’ data should be very valuable for clarifying the role of odderon.

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 $\phi \to K^+K^-$ or $\phi \to \mu^+\mu^-$. 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.

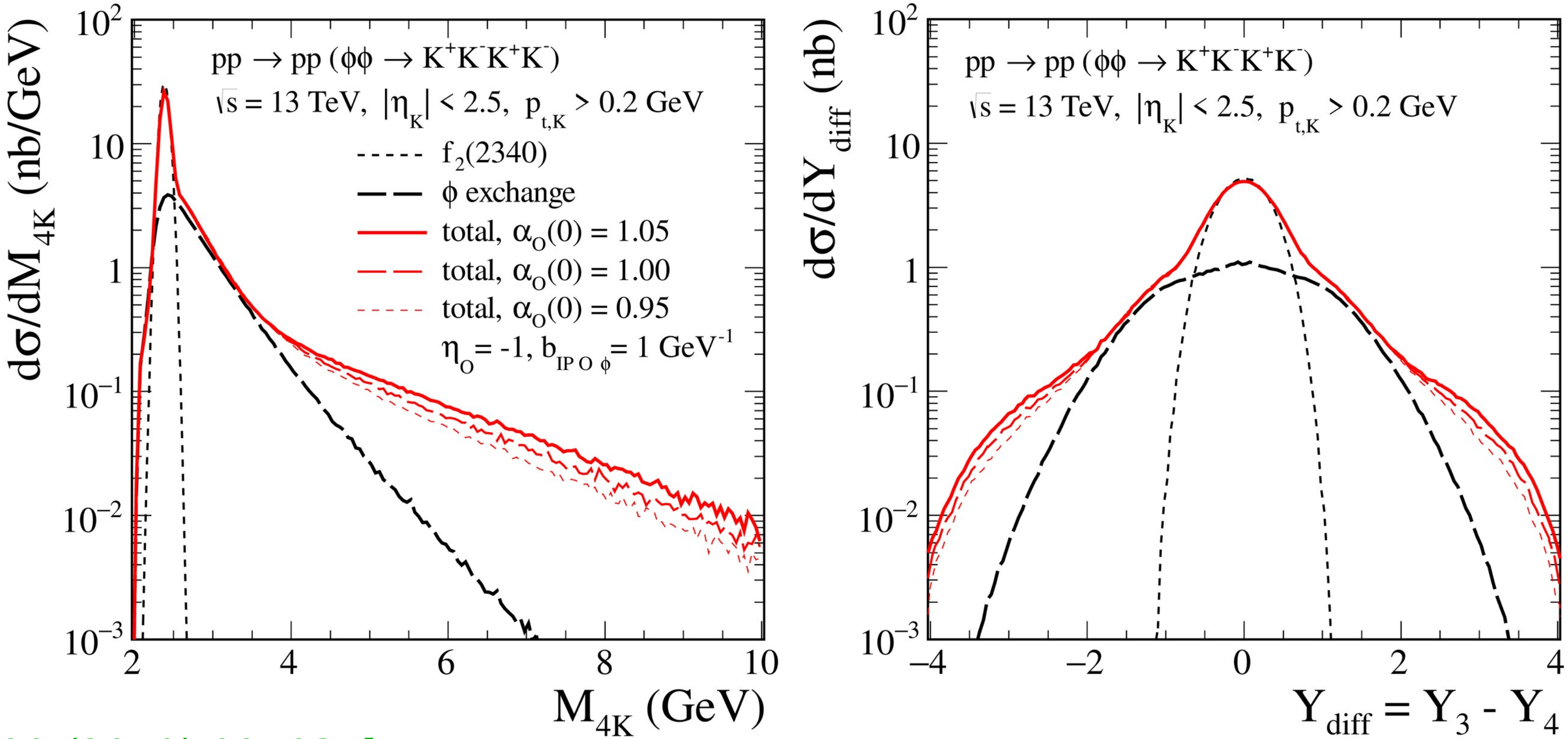
Process	Cuts	Contributions	$\sigma^{(\mathrm{Born})}$ (nb)	$\sigma^{(\mathrm{full})}$ (nb)	$\langle S^2 \rangle$
$pp \to pp\, K^+K^-$	$\lvert\eta_K\rvert < 2.5$, $p_{t,K} > 0.1$ GeV	$\gamma\mathbb{P}$ fusion	60.07	55.09	0.9
		$\mathbb{OP}$ fusion	21.40	6.44	0.3
		$\gamma\mathbb{P}$ and $\mathbb{OP}$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

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



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

The reaction *pp* → *pp*(*ϕϕ* → *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.