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

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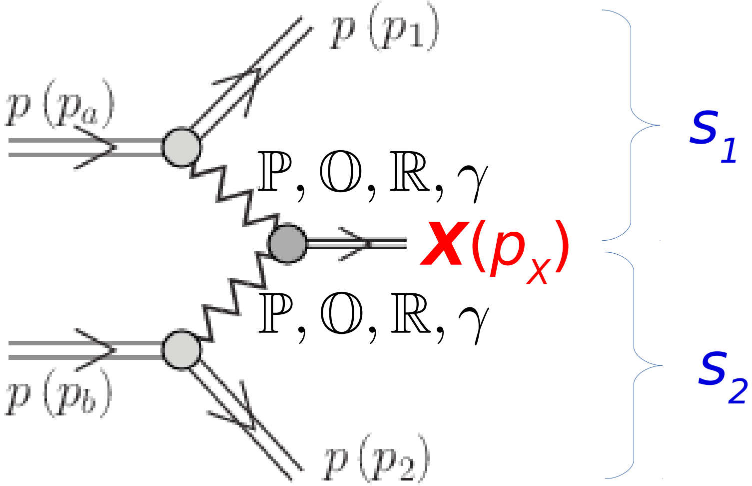
Searching for odderon (C = -1 partner of pomeron)

- First introduced in the framework of asymptotic theories
  L. Łukaszuk and B. Nicolescu, Lett. Nuovo Cim. 8 (1973) 405
- Predicted in QCD as a 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 $\sqrt{s} = 53\ \mathrm{GeV}$ (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 C. 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., arXiv:2002.05031
- Nice review on odderon physics: C. Ewerz, arXiv: 0306137

Central Exclusive Production (CEP)
in proton-proton collisions at high energies



$p\,(p_a) + p\,(p_b) \to p\,(p_1) + \boldsymbol{X}\,(p_X) + p\,(p_2)$

We require large rapidity gaps between
$p\,(p_1)$ and ***X***, $p\,(p_2)$ and ***X***.

Exchange objects:

- $\mathbb{P}$ (C = +1) pomeron, should dominate for large s_1, s_2
- $\mathbb{O}$ (C= -1) odderon
- $\mathbb{R}$: $f_{2\mathbb{R}}, a_{2\mathbb{R}}$ (C = +1)
  $\omega_{\mathbb{R}}, \rho_{\mathbb{R}}$ (C = -1)
  reggeons
- γ (C = -1) photon

I hope to show you that <u>CEP offers possibilities to study odderon effects</u>.

In my talk I shall consider the exclusive processes:

$p\,p \to p\,p\,(\phi \to K^+ K^-)$
$p\,p \to p\,p\,(\phi \to \mu^+ \mu^-)$
$p\,p \to p\,p\,K^+ K^- K^+ K^-$ (via intermediate $\phi\phi$ state)

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):

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

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

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

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

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

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

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

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

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

Applications

$\gamma\, p \to \pi^+ \pi^- p$ *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 $\sigma_{\gamma p}$.

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

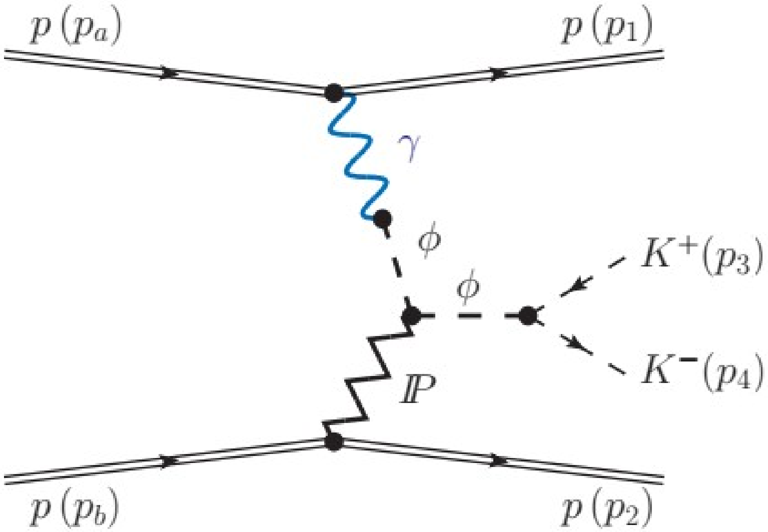
Ewerz, P.L., Nachtmann, Szczurek, PLB 763 (2016) 382

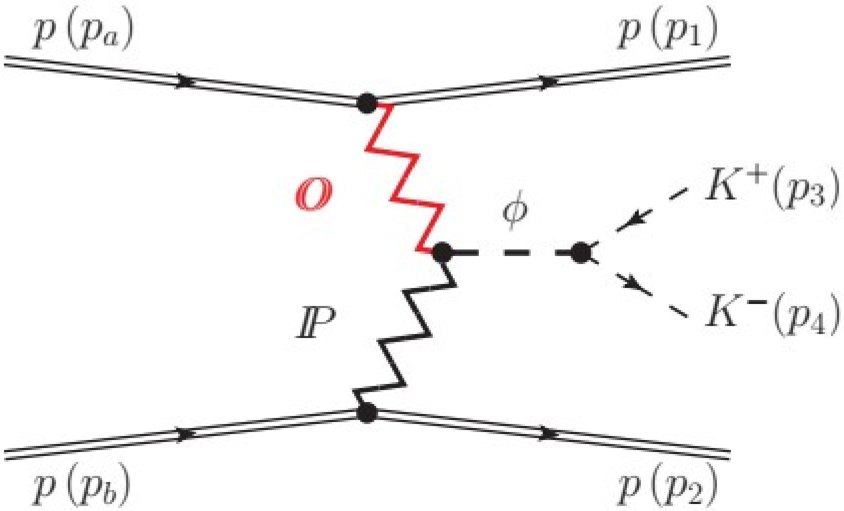
Studying the ratio r_5 of single-helicity-flip to non-flip amplitudes we found that the STAR data [L. Adamczyk *et al.*, PLB 719 (2013) 62] are consistent with the tensor pomeron model while they clearly exclude a scalar pomeron. Vector pomeron is in contradiction to the rules of QFT.

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

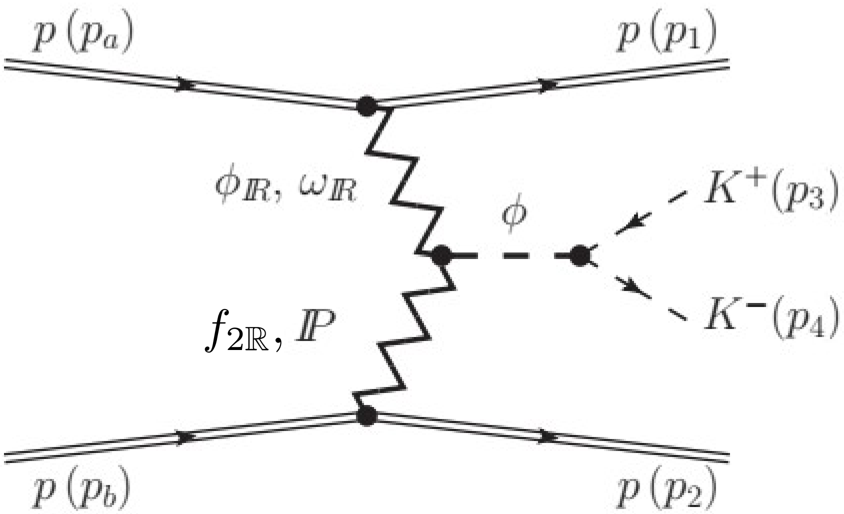
X: η, η', f_0	*Ann. Phys. 344 (2014) 301*
ρ^0	*PRD91 (2015) 074023*
$\pi^+ \pi^-$, f_0, f_2	*PRD93 (2016) 054015*
$\pi^+ \pi^- \pi^+ \pi^-$, $\rho^0 \rho^0$	*PRD94 (2016) 034017*
ρ^0 with proton diss.	*PRD95 (2017) 034036*
$p\bar{p}$	*PRD97 (2018) 094027*
$K^+ K^-$	*PRD98 (2018) 014001*
$K^+ K^- K^+ K^-$, $\phi\phi$	*PRD99 (2019) 094034* **← this talk**
$f_2 \to \pi^+ \pi^-$	*PRD101 (2020) 034008*
$\phi \to K^+ K^-$, $\mu^+ \mu^-$	*PRD101 (2020) 094012* **← this talk**
$f_1(1285)$, $f_1(1420)$ **← see O. Nachtmann talk**	

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





at high energies (LHC) we expect this reaction to be dominated by the processes



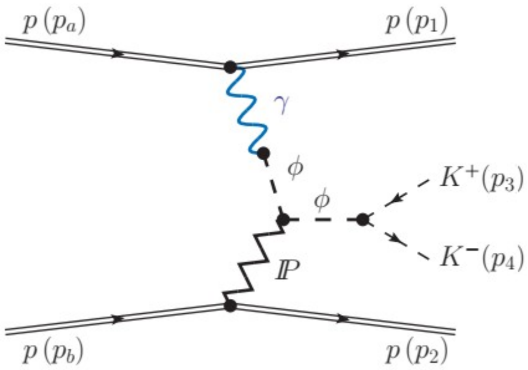
important at lower energies (WA102)

Photon-pomeron fusion

- 2 → 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

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

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

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

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

where $\beta_{I\!PNN} = 1.87\ \mathrm{GeV}^{-1}$

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

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

- For the $I\!P\phi\phi$ vertex we have (in analogy to $f_2\gamma\gamma$ vertex)

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

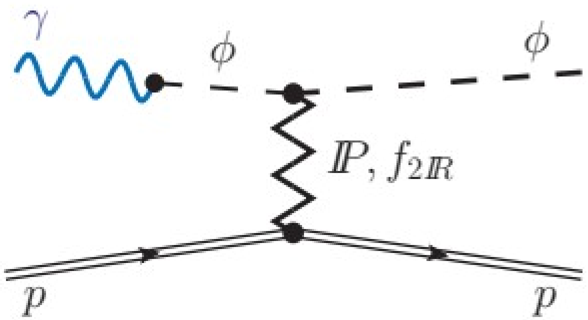
$$\Gamma^{(0)}_{\mu\nu\kappa\lambda}(k_1,k_2) = \left[(k_1\cdot k_2)g_{\mu\nu} - k_{2\mu}k_{1\nu}\right]\left[k_{1\kappa}k_{2\lambda} + k_{2\kappa}k_{1\lambda} - \frac{1}{2}(k_1\cdot k_2)g_{\kappa\lambda}\right]$$

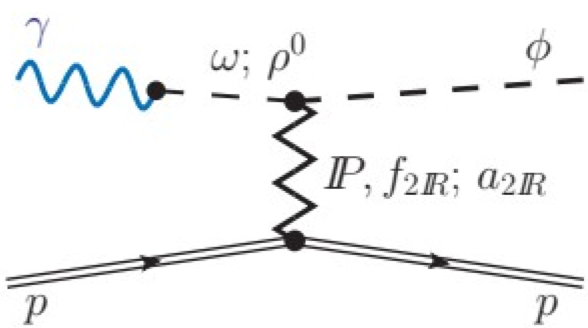
$$\begin{aligned}\Gamma^{(2)}_{\mu\nu\kappa\lambda}(k_1,k_2) = {} & (k_1\cdot k_2)(g_{\mu\kappa}g_{\nu\lambda} + g_{\mu\lambda}g_{\nu\kappa}) + g_{\mu\nu}(k_{1\kappa}k_{2\lambda} + k_{2\kappa}k_{1\lambda}) \\ & - k_{1\nu}k_{2\lambda}g_{\mu\kappa} - k_{1\nu}k_{2\kappa}g_{\mu\lambda} - k_{2\mu}k_{1\lambda}g_{\nu\kappa}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

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 $\gamma p \to \phi p$.

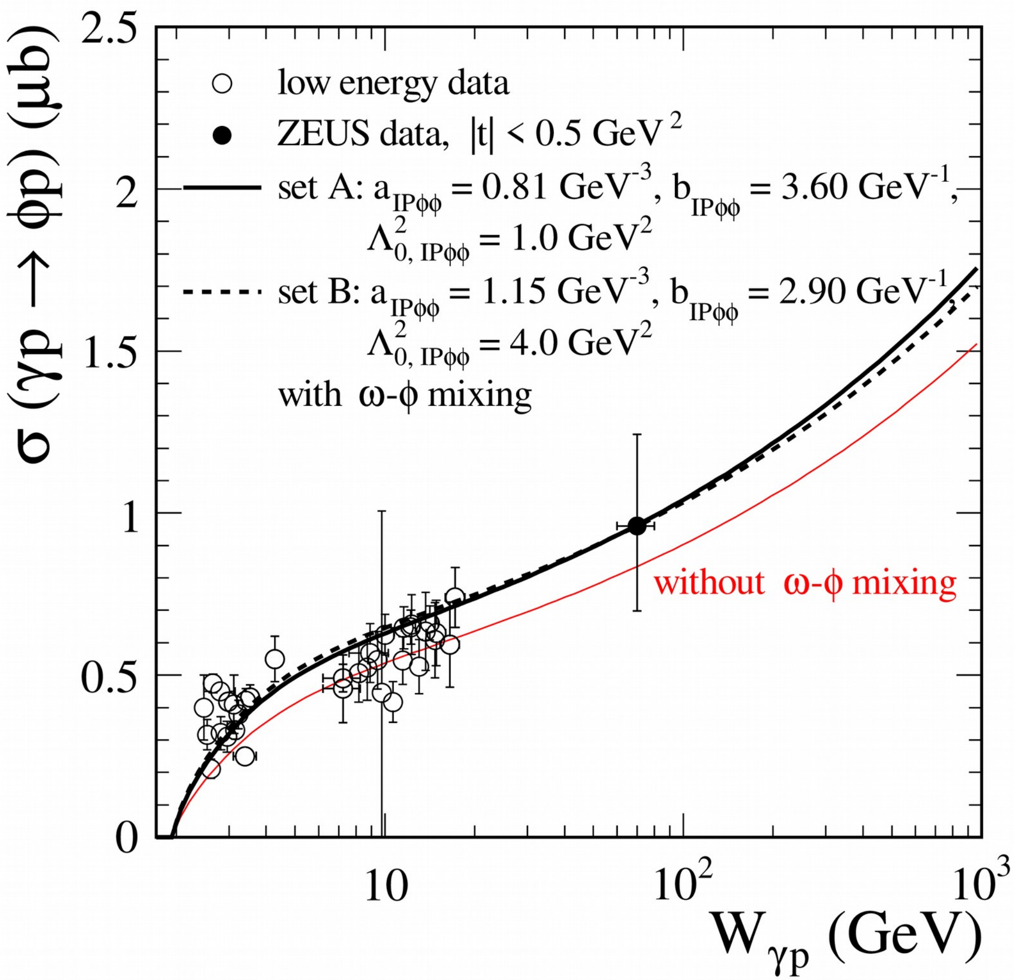
- Photoproduction process

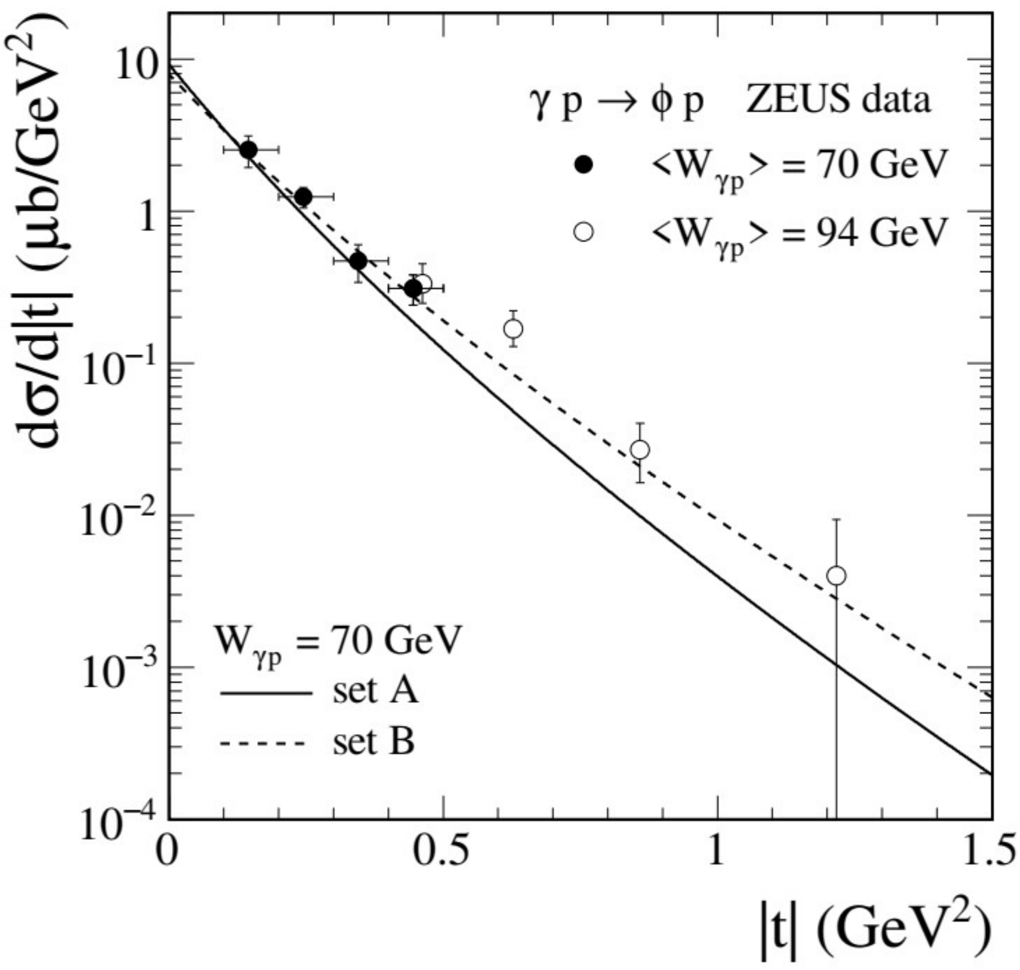




ω-ϕ mixing effect included

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

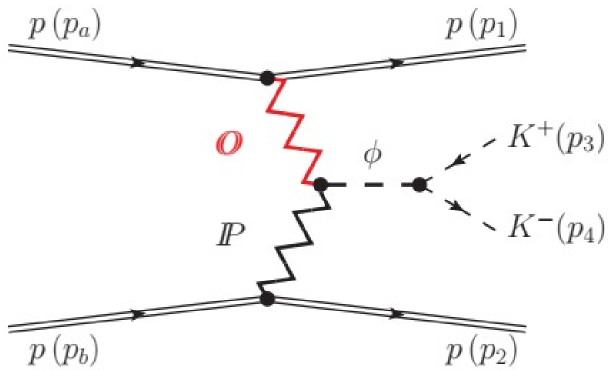




Odderon-pomeron fusion

Born-level amplitude:

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



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:

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

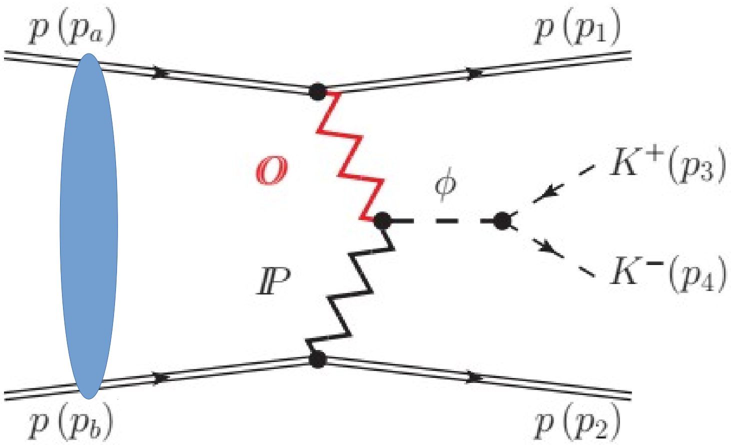
$$\beta_{\mathbb{O}pp} = 0.1\times\beta_{\mathbb{P}NN} \simeq 0.18\ \mathrm{GeV}^{-1}$$

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

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

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

Absorption effects



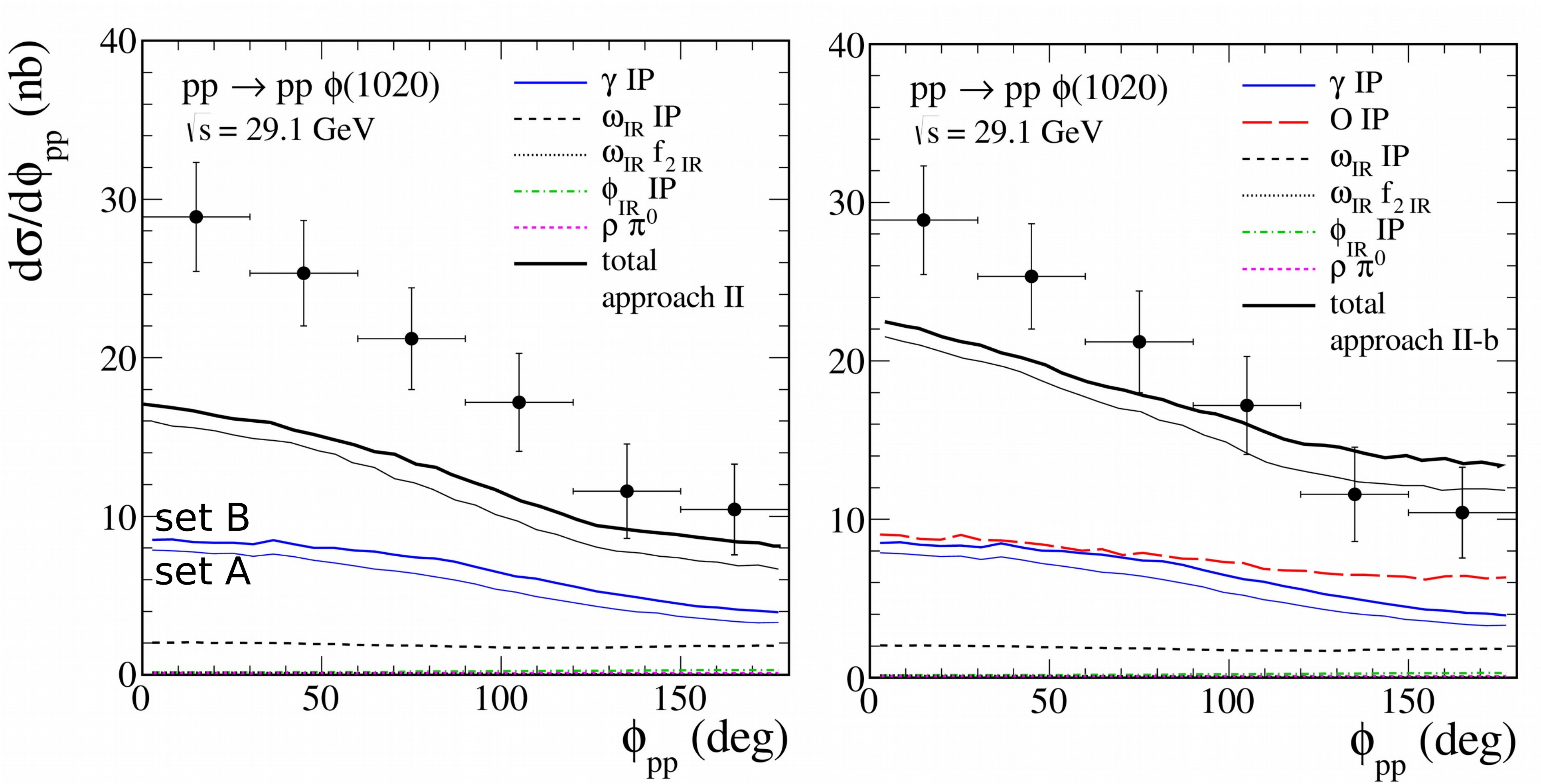
$$\mathcal{M} = \mathcal{M}^{Born} + \mathcal{M}^{pp-rescattering}$$

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

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

These corrections (called as soft survival factor, $\langle S^2 \rangle$) plays a crucial role, reduce the value of cross section and change, e.g., the ϕ_{pp} dependence

Comparison with WA102 data

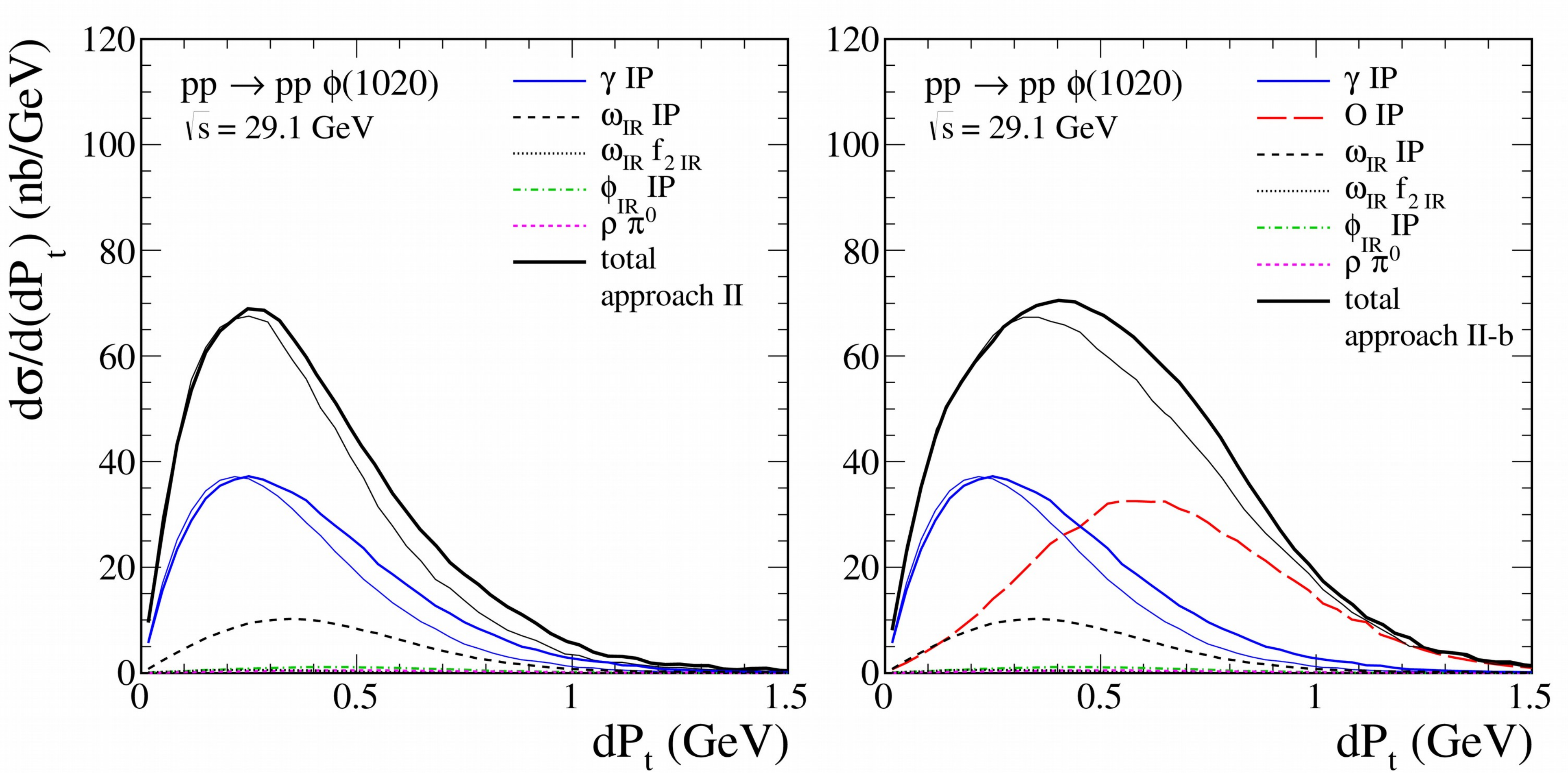


- WA102 data from PLB489 (2000) 29, $\sigma_{\text{exp.}} = (60 \pm 21)\,\text{nb}$
- Different fusion processes were considered. Large interference effects. The ϕ_{pp} distribution allow us to determine the respective coupling constants

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

- 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 hadronic diffractive terms

Comparison with WA102 data



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

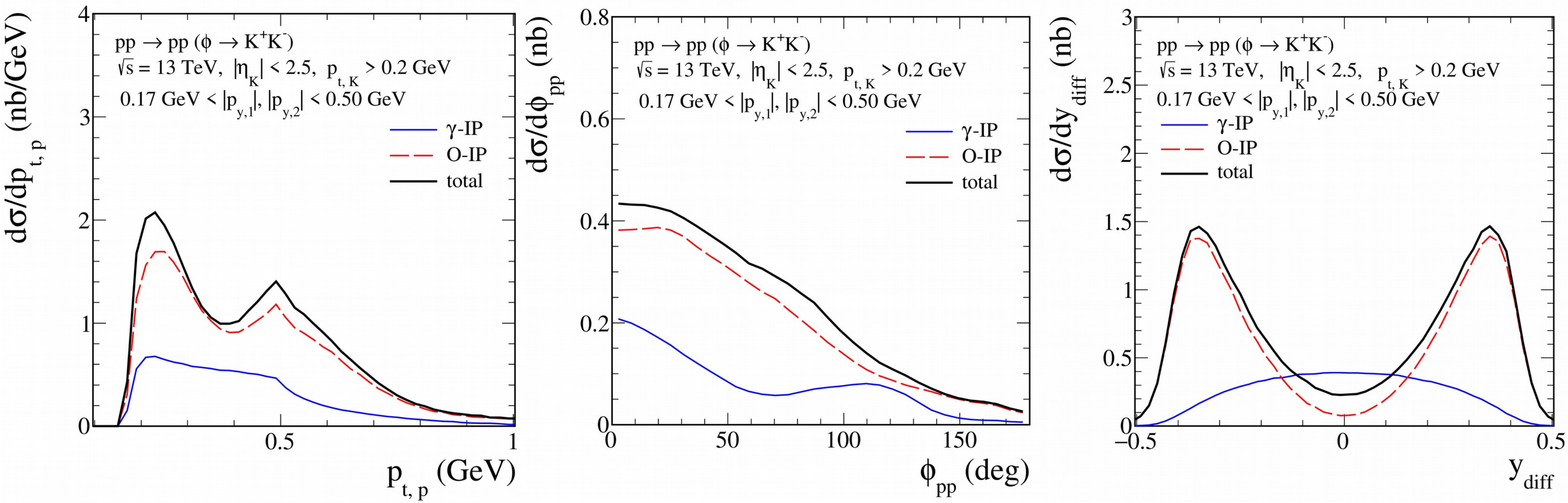
$$R = \frac{d\sigma/d(\mathrm{dP_t} \leqslant 0.2\ \mathrm{GeV})}{d\sigma/d(\mathrm{dP_t} \geqslant 0.5\ \mathrm{GeV})}$$

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

$R = 0.71$ (no odderon), $R = 0.27$ (with odderon)

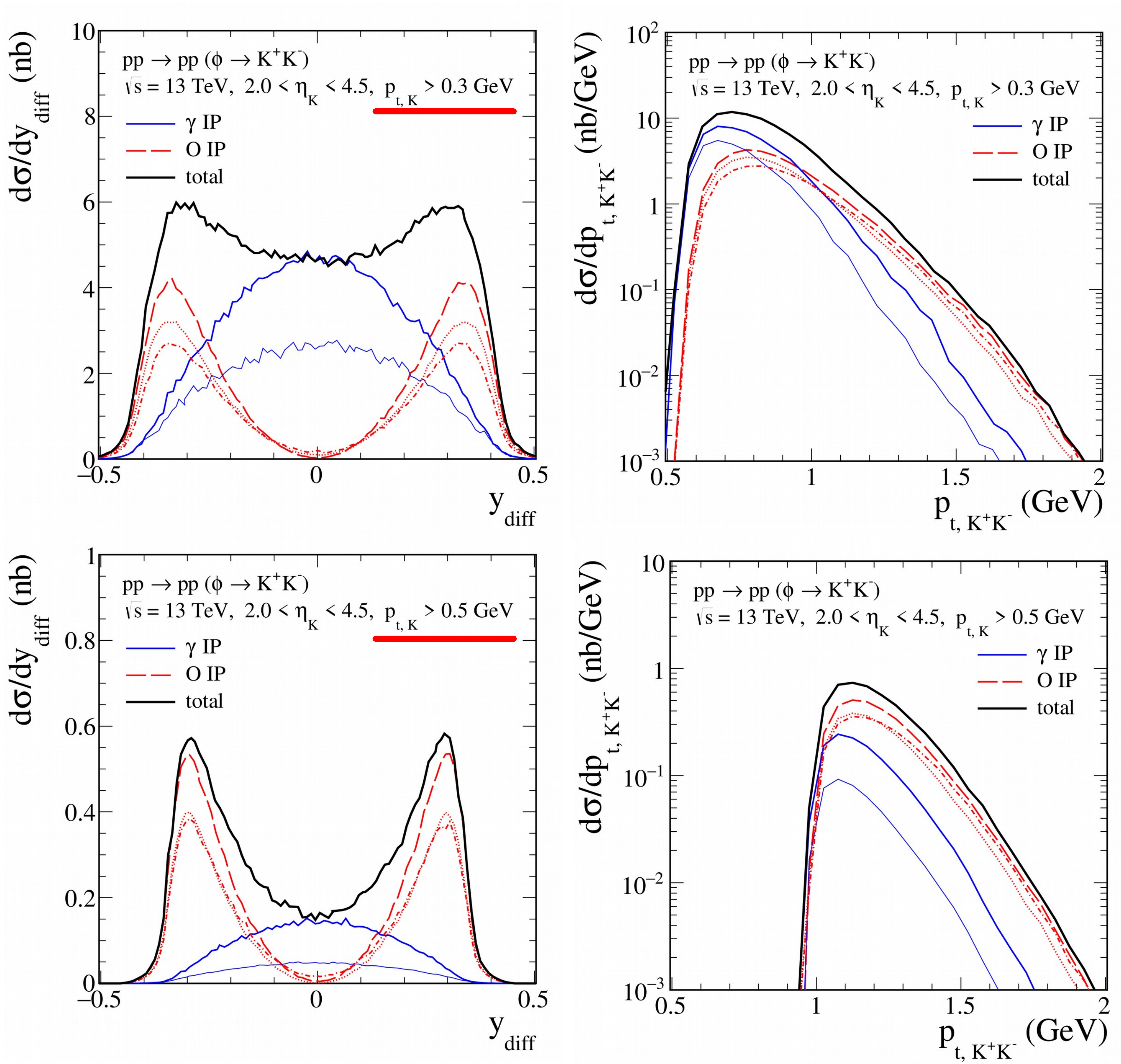
- We find that two couplings $a_{I\!P\mathbb{O}\phi}$ and $b_{I\!P\mathbb{O}\phi}$ are needed to describe ϕ_{pp} and dP_t
- The WA102 data support the existence of odderon exchange !
- It would be very useful to measure the outgoing protons at the LHC

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



- Different behaviour is seen for γIP and OIP contributions.
- Due to the ALFA cuts on the leading protons the photoproduction term is strongly suppressed
- 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 experiments at the LHC (ATLAS-ALFA, CMS-TOTEM) when both protons are measured.
- 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 IPOϕ vertex → minimum at $y_{diff} = y_3 - y_4 = 0$

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

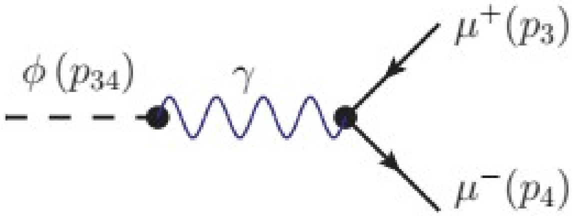


The reaction $pp \to pp\,\mu^+\mu^-$

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 $i\Gamma_\kappa^{(\phi KK)}(p_3, p_4)$ 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 $\phi \to \gamma \to \mu^+\mu^-$ 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)

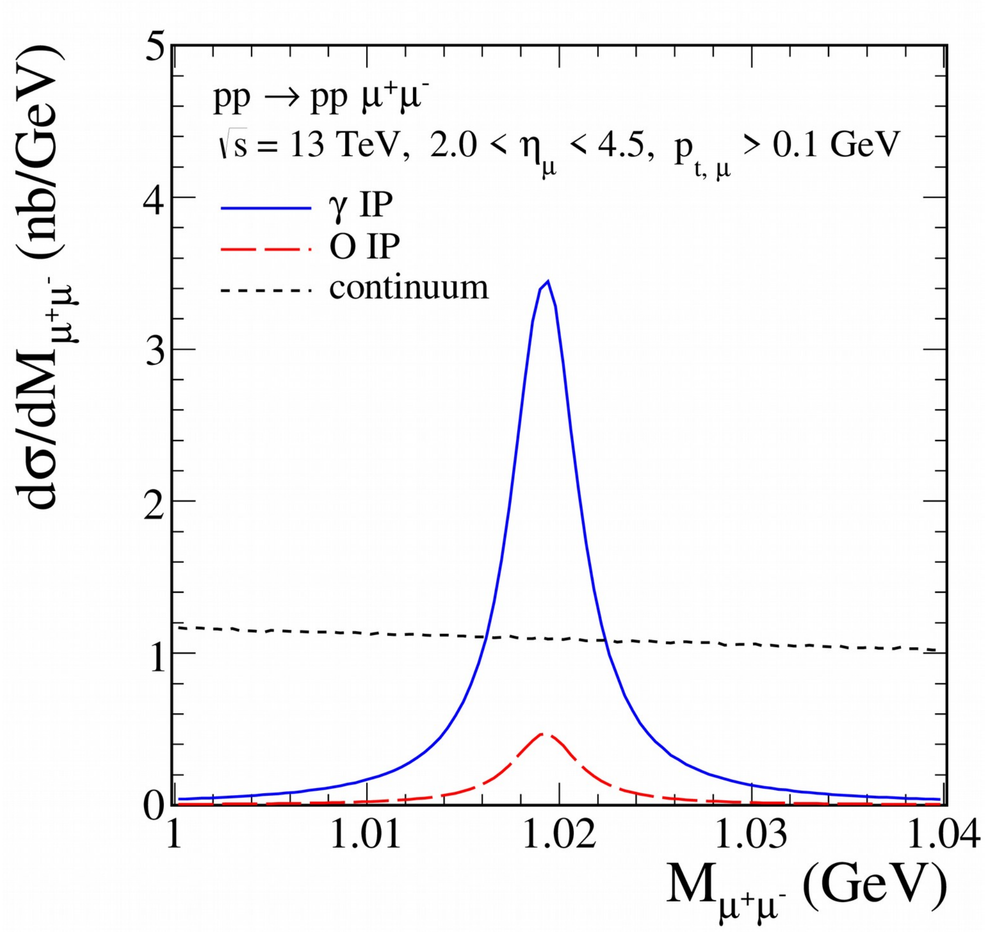
$$m_\phi = (1019.461 \pm 0.016)\ \text{MeV}\,,$$
$$\Gamma(\phi \to \mu^+\mu^-)/\Gamma_\phi = (2.86 \pm 0.19) \times 10^{-4}\,,$$
$$\Gamma_\phi = (4.249 \pm 0.013)\ \text{MeV}$$

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

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

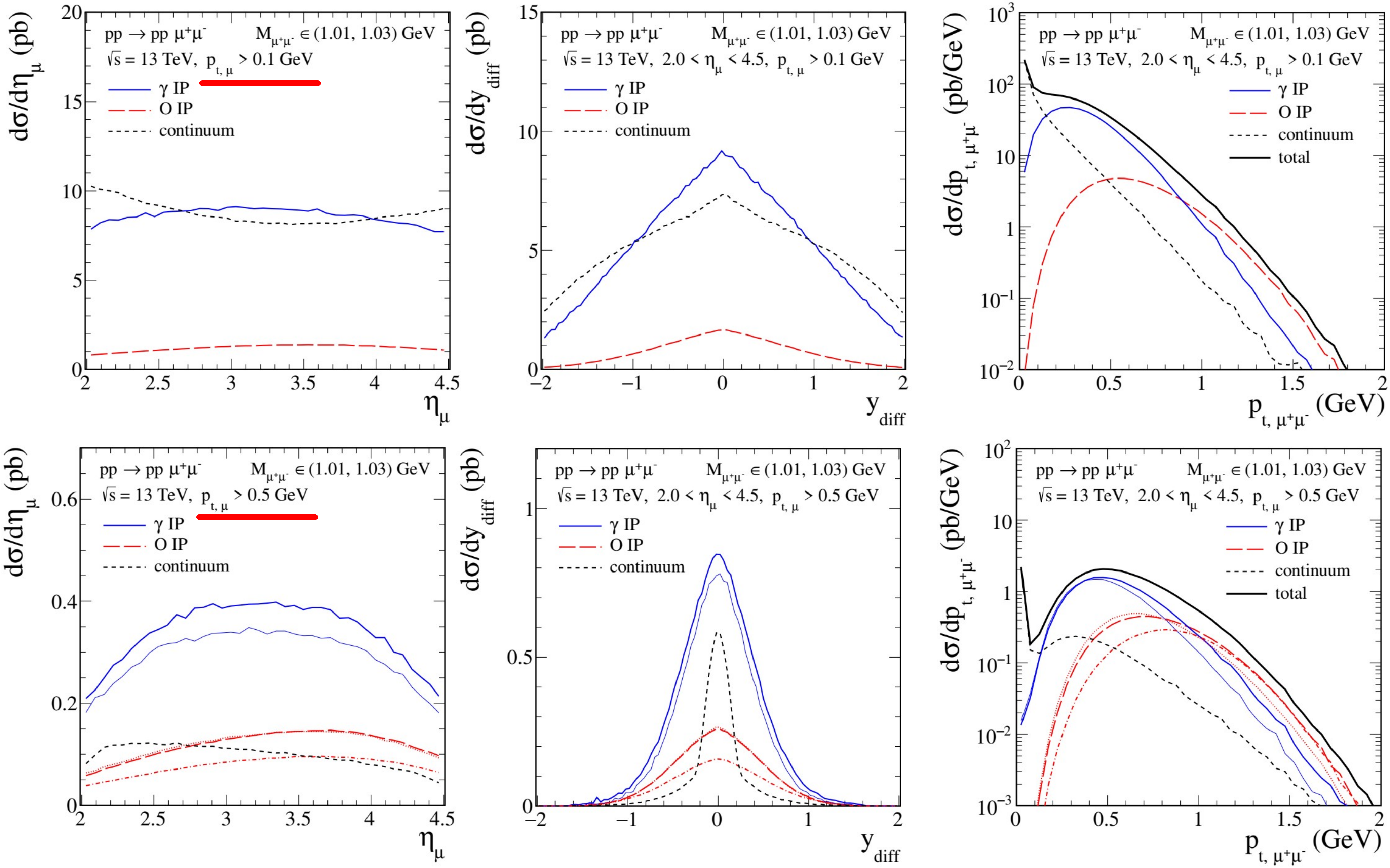
$$g_{\phi\mu^+\mu^-} = (6.92 \pm 0.08) \times 10^{-3}$$

Predictions for the *pp* → *pp* *μ*⁺*μ*⁻ reaction (LHCb)



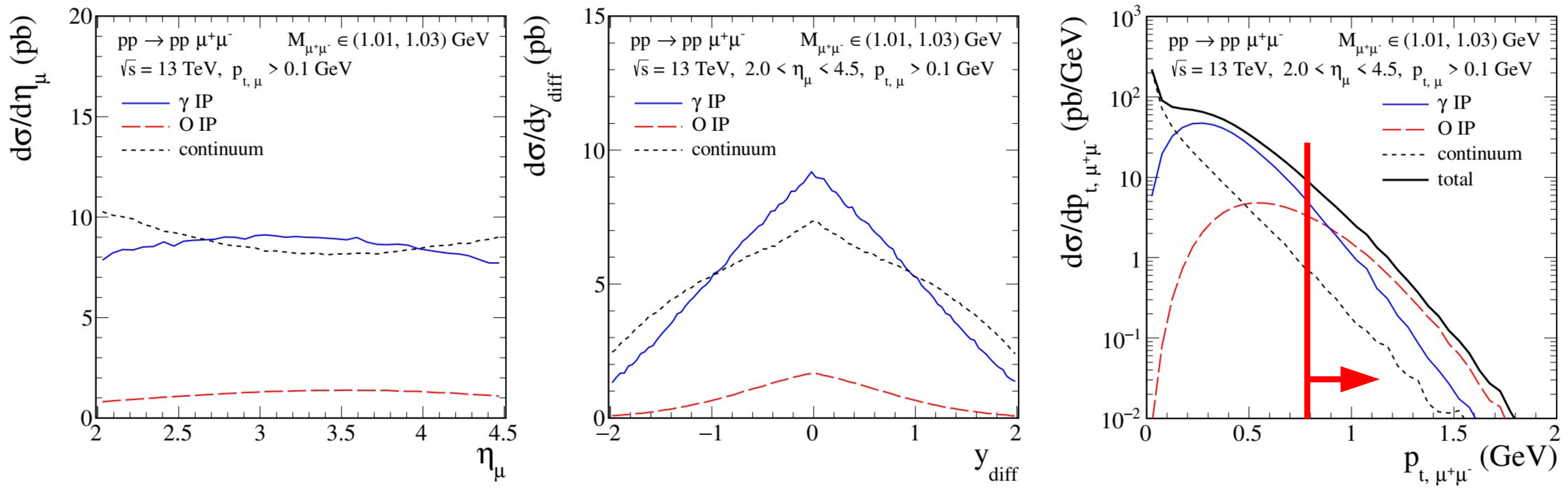
We show the contributions from the $\gamma\mathbb{P}$- and $\mathbb{O}\mathbb{P}$-fusion processes and the continuum $\gamma\gamma \to \mu^+\mu^-$ term.

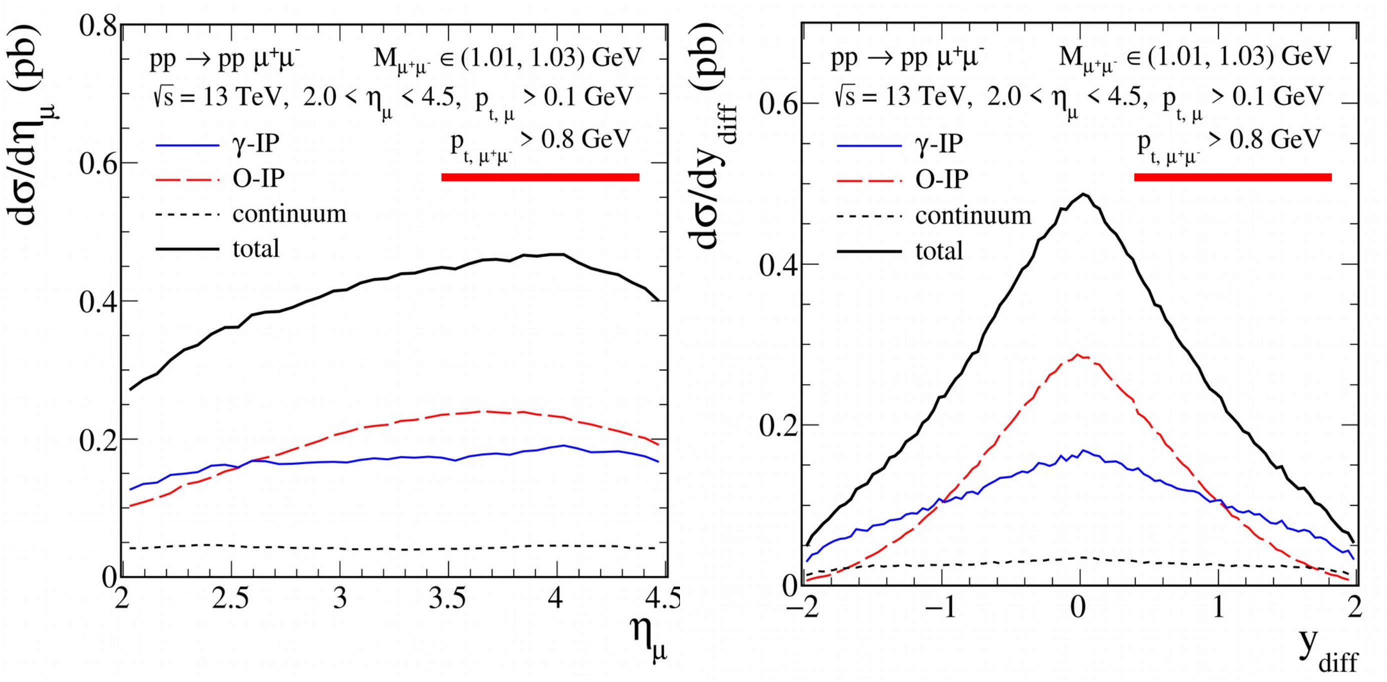
Predictions for the *pp* → *pp* $\mu^+\mu^-$ reaction (LHCb)



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

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

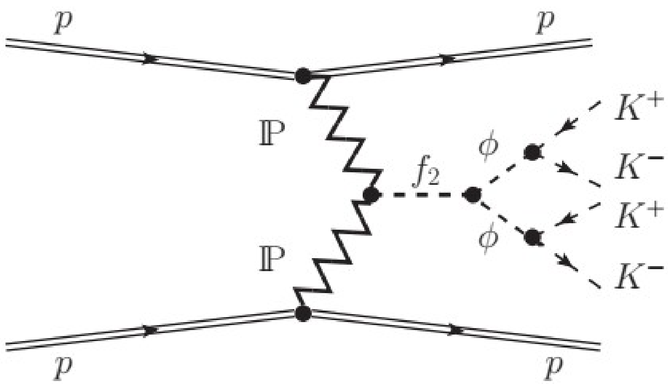




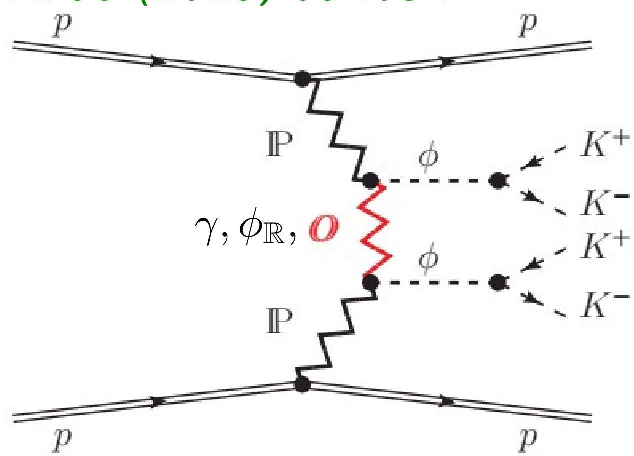
- $p_{t,\mu+\mu-}$ > 0.8 GeV cut can be helpful to reduce the γγ → $\mu^+\mu^-$ continuum and γ IP-fusion contribution
- In this case the absolute normalization of the cross section or detailed studies of shapes of distributions should provide a hint whether one observes the O effect

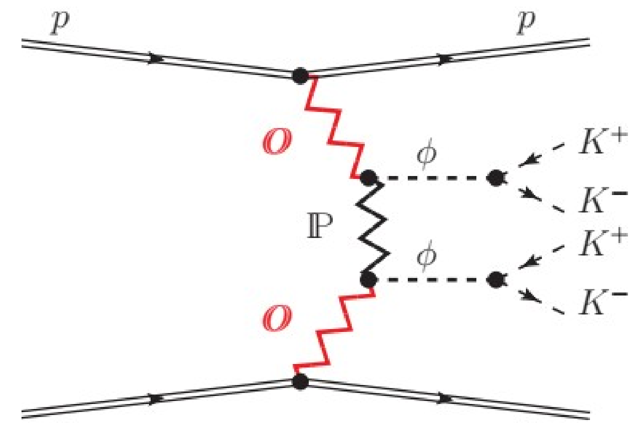
The reaction *pp* → *pp*($\phi\phi$ → *K*+*K*-*K*+*K*-)

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:

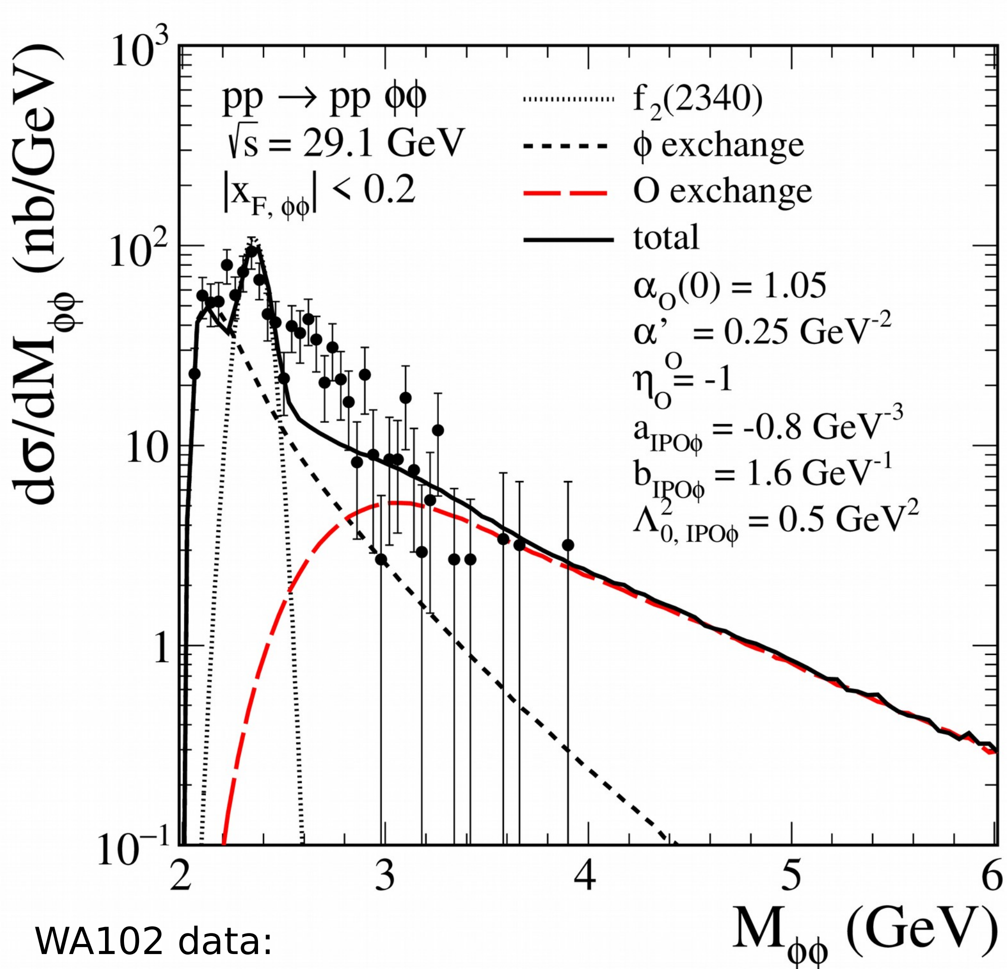
$$\gamma : \quad \text{negligeable}$$

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

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

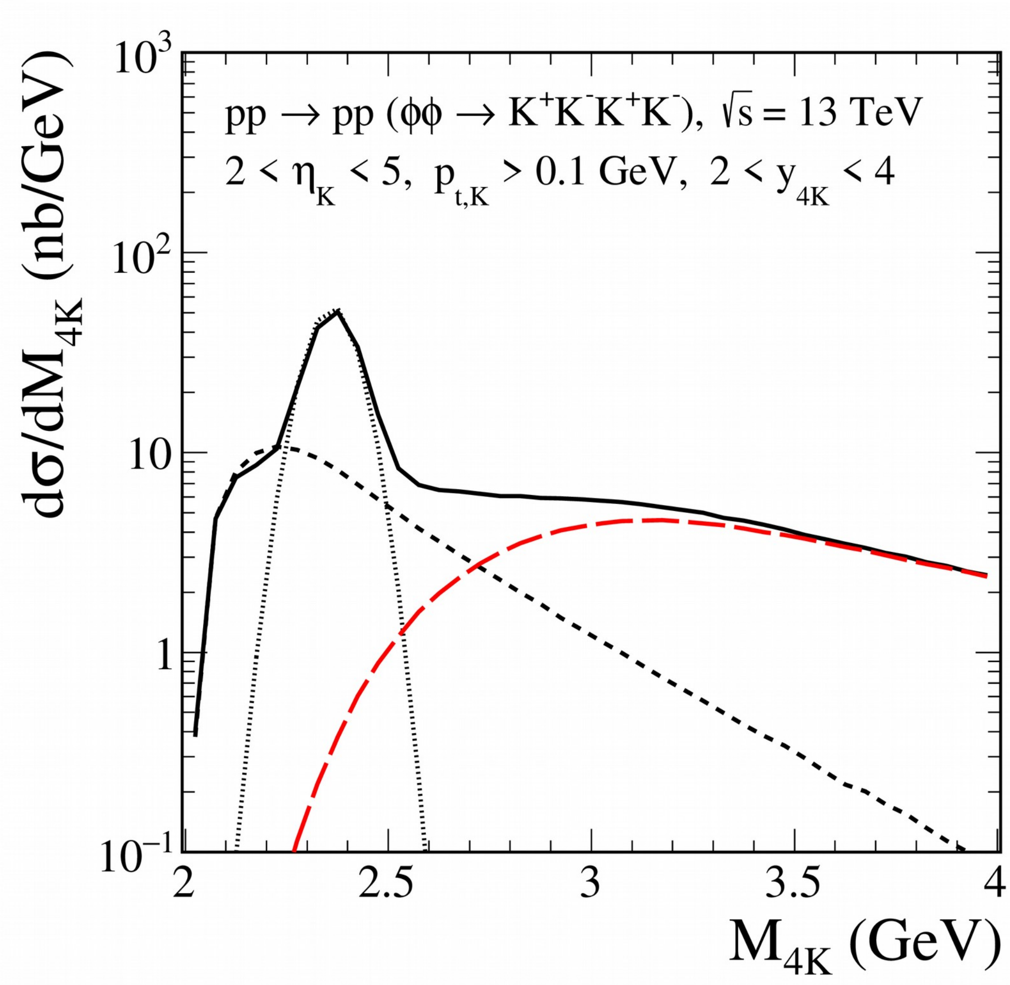
If $\alpha_{\mathbb{O}}(0) \approx 1.0$, then $\mathbb{O}$ exchange will win for large $M_{\phi\phi}$.

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

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 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.

$pp \to pp\ \phi$

- 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^+ and K^-)
- 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

$pp \to pp\ \phi\phi$

- The $\phi\phi$ invariant mass distribution has a rich structure (resonances at low $M_{\phi\phi}$, continuum terms at higher $M_{\phi\phi}$, 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 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 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.

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.

pp → pp K⁺K⁻

Cuts	Contributions	$\sigma^{(\mathrm{Born})}$ (nb)	$\sigma^{(\mathrm{full})}$ (nb)	$\langle S^2 \rangle$
$\lvert\eta_K\rvert < 2.5$, $p_{t,K} > 0.1$ 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	
$\lvert\eta_K\rvert < 2.5$, $p_{t,K} > 0.2$ 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
	$\mathbb{O}\mathbb{P}$ 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 → pp μ⁺μ⁻

Cuts	Contributions	$\sigma^{(\mathrm{Born})}$ (nb)	$\sigma^{(\mathrm{full})}$ (nb)	$\langle S^2 \rangle$
$2.0 < \eta_\mu < 4.5$, $p_{t,\mu} > 0.1$ 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}	