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# Searching for odderon exchange in exclusive reactions with $\phi$ meson

Antoni Szczurek <sup>1,2</sup>,  
Piotr Lebiedowicz <sup>1</sup>, Otto Nachtmann <sup>3</sup>,

<sup>1</sup>Institute of Nuclear Physics PAN Kraków

<sup>2</sup>University of Rzeszów

<sup>3</sup>Institute für Theoretische Physik, Universität Heidelberg

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# Our works on central production

Our **recent** works on central production:

1. Production of  $\pi^+\pi^-$  pairs in  $pp \rightarrow pp\pi^+\pi^-$  reaction.
2. Production of  $K^+K^-$  pairs in  $pp \rightarrow ppK^+K^-$  reaction.
3. Production of two pairs of  $\pi^+\pi^-$  in  $pp \rightarrow pp\pi^+\pi^-\pi^+\pi^-$  reaction  
Three pomeron exchanges (!)
4. Production of  $\phi\phi$  final state  
 $pp \rightarrow ppK^+K^-K^+K^-$  reaction  
in quest for **blueballs** and **odderon exchange**.
5. Production of  $p\bar{p}$  pairs in  $pp \rightarrow pp(p\bar{p})$  reaction  
interesting spin effects for Regge-like reactions.
6. Exclusive production of  $J/\psi$  meson in  $pp \rightarrow ppJ/\psi$  and semiexclusive processes.
7. Production of  $e^+e^-$  or  $\mu^+\mu^-$  pairs via  $\gamma\gamma$  fusion **with photon transverse momenta**.
8. Production of  $W^+W^-$  pairs via  $\gamma\gamma$  fusion **with photon transverse momenta**.
9. Production of  $t\bar{t}$  pairs via  $\gamma\gamma$  fusion.

# Regge approach

- ▶ At higher energies  $\sqrt{s} > 2\text{-}3 \text{ GeV}$ , meson-exchange approach stops to work.
- ▶ Regge approach was proposed.  
Exchange of so-called **Regge trajectories**.
- ▶ In the past rather **two-body processes** were studied.  
An example is elastic scattering.
- ▶  $pp \rightarrow pp, p\bar{p} \rightarrow p\bar{p}$   
 $\pi^+ p \rightarrow \pi^+ p, \pi^- p \rightarrow \pi^- p$   
 $K^+ p \rightarrow K^+ p, K^- p \rightarrow K^- p$
- ▶ Several Regge trajectories are necessary to describe the two-body reactions:
  - (a) **leading trajectory** (trajectories):  
pomeron (**C=1**), odderon (**C=-1**) (**not clearly identified**)
  - (b) **subleading trajectories**:  
 $f_2 \gg a_2$  (**C=+1**),  $\omega \gg \rho$  (**C=-1**)
- ▶ One can understand total cross sections in the Regge picture.
- ▶ Extension of the Regge approach to  $2 \rightarrow 3, 2 \rightarrow 4$ , etc, processes **possible only now**. Not yet tested.
- ▶ Use coupling constants **extracted from the elastic scattering and total cross sections**.

## Tensor pomeron model

In our recent works all amplitudes are calculated assuming **tensor pomeron model** proposed by **Nachtmann et al.**, *Annals Phys.* 342 (2014) 31.

- ▶ It is often said that Pomeron has **vacuum quantum numbers**.
- ▶ This is true for **color** but not **spin** degrees of freedom.
- ▶ Often **vector pomeron** is used in practical calculations.
- ▶ **Vector pomeron** is inconsistent with **Field Theory**, and  $\gamma p \rightarrow \gamma p$  scattering (**A. Glazov** talk here)
- ▶ **Tensor pomeron** consistent with so called  **$r_5$  observable** measured in proton-proton elastic scattering by STAR  
*C. Ewerz, P. Lebiedowicz, O. Nachtmann and A. Szczurek*, *Phys. Lett.* **B763** (2016) 382.
- ▶ **Feynman rules** for exchanges of the soft objects have been proposed (**vertices, propagators**).
- ▶ We keep checking whether it works for different other processes.  
**So far yes!** Further tests are needed.
- ▶ Tensor pomeron, see also **Chung-I Tan et al.** and **E. Shuryak et**

# Tensor pomeron

The propagator of the tensor-pomeron exchange is written as:

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

and fulfils the following relations

$$\begin{aligned} \Delta_{\mu\nu,\kappa\lambda}^{(\mathbb{P})}(\mathbf{s}, t) &= \Delta_{\nu\mu,\kappa\lambda}^{(\mathbb{P})}(\mathbf{s}, t) = \Delta_{\mu\nu,\lambda\kappa}^{(\mathbb{P})}(\mathbf{s}, t) = \Delta_{\kappa\lambda,\mu\nu}^{(\mathbb{P})}(\mathbf{s}, t), \\ g^{\mu\nu} \Delta_{\mu\nu,\kappa\lambda}^{(\mathbb{P})}(\mathbf{s}, t) &= 0, \quad g^{\kappa\lambda} \Delta_{\mu\nu,\kappa\lambda}^{(\mathbb{P})}(\mathbf{s}, t) = 0. \end{aligned} \quad (2)$$

It gives by construction the same result for  $pp \rightarrow pp$  elastic scattering as [traditional Regge approach](#).

# Soft Odderon

- ▶  $C = -1$  partner of pomeron  
[Lukaszuk, Nicolescu](#), Lett. Nuovo Cim. **8**, 405 (1973)
- ▶ Does it exist ?, is it soft ?
- ▶ nice review on odderon physics:  
[C. Ewerz](#), hep-ph/0306137.
- ▶ new data for  $pp$  elastic scattering at  $\sqrt{s} = 2.76$  GeV of TOTEM collaboration:  
[Antchev et al. \[TOTEM collaboration\]](#), arXiv:1812.08610[hep-ex]  
suggestion of presence of odderon
- ▶ some last year analyses of [Nicolescu et al.](#)
- ▶ Here odderon in  $pp \rightarrow ppM$  and  $pp \rightarrow pph\bar{h}$ .
- ▶ In our tensorial approach odderon is a **vectorial exchange**.
- ▶ Odderon propagator:

$$i\Delta_{\mu\nu}^{(0)}(s, t) = -ig_{\mu\nu} \frac{\eta_0}{M_0^2} (-is\alpha'_0)^{\alpha_0(t)-1}, \quad (3)$$

$$\alpha_0(t) = \alpha_0(0) + \alpha'_0 t, \quad (4)$$

## Exclusive reactions

- ▶ Consider **exclusive** process  $pp \rightarrow ppM\bar{M}$   
( $pp \rightarrow ppR$  or even  $pp \rightarrow ppM\bar{M}M\bar{M}$ )
- ▶ Calculate (helicity-dependent) amplitude  $\mathcal{M}_{pp \rightarrow ppM\bar{M}}$
- ▶ Calculate differential cross sections:

$$d\sigma = \frac{1}{2s} |\mathcal{M}_{pp \rightarrow ppM\bar{M}}|^2 \quad (5)$$

$$\frac{d^3p_1}{(2\pi)^3 2E_1} \frac{d^3p_2}{(2\pi)^3 2E_2} \frac{d^3p_3}{(2\pi)^3 2E_3} \frac{d^3p_4}{(2\pi)^3 2E_4} \delta^4(p_a + p_b - p_1 - p_2 - p_3 - p_4) \quad (6)$$

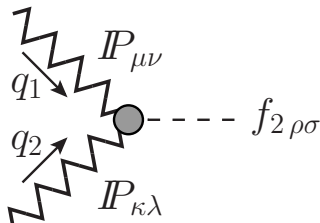
- ▶ In general **8-fold integration**.  
We have special choice of integration variables adjusted to CEP.
- ▶ Any differential distribution can be calculated
- ▶ Include **absorption effects**

# Resonances

## Scalar/pseudoscalar resonances:

*P. Lebiedowicz, O. Nachtmann and A. Szczurek, Ann. Phys. **344C** (2014) 301.*

## Tensor resonances:



*P. Lebiedowicz, O. Nachtmann and A. Szczurek, Phys. Rev. **D92** (2016) 054015.*

For **tensor meson** and **tensor pomerons** there are  
**7 possible couplings.**

We have tried different of them.



## Different $\mathbb{P}\mathbb{P} \rightarrow f_2$ couplings

$$i\Gamma_{\mu\nu,\kappa\lambda,\rho\sigma}^{(\mathbb{P}\mathbb{P}f_2)(1)} = 2i g_{\mathbb{P}\mathbb{P}f_2}^{(1)} M_0 R_{\mu\nu\mu_1\nu_1} R_{\kappa\lambda\alpha_1\lambda_1} R_{\rho\sigma\rho_1\sigma_1} g^{\nu_1\alpha_1} g^{\lambda_1\rho_1} g^{\sigma_1\mu_1}, \quad (7)$$

$$i\Gamma_{\mu\nu,\kappa\lambda,\rho\sigma}^{(\mathbb{P}\mathbb{P}f_2)(2)}(q_1, q_2) = -\frac{2i}{M_0} g_{\mathbb{P}\mathbb{P}f_2}^{(2)} \left( (q_1 \cdot q_2) R_{\mu\nu\rho_1\alpha} R_{\kappa\lambda\sigma_1}{}^\alpha - q_{1\rho_1} q_2^{\mu_1} R_{\mu\nu\mu_1\alpha} R_{\kappa\lambda\sigma_1}{}^\alpha \right. \\ \left. - q_1^{\mu_1} q_{2\sigma_1} R_{\mu\nu\rho_1\alpha} R_{\kappa\lambda\mu_1}{}^\alpha + q_{1\rho_1} q_{2\sigma_1} R_{\mu\nu\kappa\lambda} \right) R_{\rho_1\sigma_1} \quad (8)$$

$$i\Gamma_{\mu\nu,\kappa\lambda,\rho\sigma}^{(\mathbb{P}\mathbb{P}f_2)(3)}(q_1, q_2) = -\frac{2i}{M_0} g_{\mathbb{P}\mathbb{P}f_2}^{(3)} \left( (q_1 \cdot q_2) R_{\mu\nu\rho_1\alpha} R_{\kappa\lambda\sigma_1}{}^\alpha + q_{1\rho_1} q_2^{\mu_1} R_{\mu\nu\mu_1\alpha} R_{\kappa\lambda\sigma_1}{}^\alpha \right. \\ \left. + q_1^{\mu_1} q_{2\sigma_1} R_{\mu\nu\rho_1\alpha} R_{\kappa\lambda\mu_1}{}^\alpha + q_{1\rho_1} q_{2\sigma_1} R_{\mu\nu\kappa\lambda} \right) R_{\rho_1\sigma_1} \quad (9)$$

## Different $\mathbb{P}\mathbb{P} \rightarrow f_2$ couplings

$$i\Gamma_{\mu\nu,\kappa\lambda,\rho\sigma}^{(\mathbb{P}\mathbb{P}f_2)(4)}(q_1, q_2) = -\frac{i}{M_0} g_{\mathbb{P}\mathbb{P}f_2}^{(4)} \left( q_1^{\alpha_1} q_2^{\mu_1} R_{\mu\nu\mu_1\nu_1} R_{\kappa\lambda\alpha_1\lambda_1} + q_2^{\alpha_1} q_1^{\mu_1} R_{\mu\nu\alpha_1\lambda_1} R_{\kappa\lambda\mu_1\nu_1} \right) \quad (10)$$

$$i\Gamma_{\mu\nu,\kappa\lambda,\rho\sigma}^{(\mathbb{P}\mathbb{P}f_2)(5)}(q_1, q_2) = -\frac{2i}{M_0^3} g_{\mathbb{P}\mathbb{P}f_2}^{(5)} \left( q_1^{\mu_1} q_2^{\nu_1} R_{\mu\nu\nu_1\alpha} R_{\kappa\lambda\mu_1}{}^\alpha + q_1^{\nu_1} q_2^{\mu_1} R_{\mu\nu\mu_1\alpha} R_{\kappa\lambda\nu_1}{}^\alpha - 2(q_1 \cdot q_2) R_{\mu\nu\kappa\lambda} \right) q_{1\alpha_1} q_{2\lambda_1} R^{\alpha_1\lambda_1}{}_{\rho\sigma}, \quad (11)$$

$$i\Gamma_{\mu\nu,\kappa\lambda,\rho\sigma}^{(\mathbb{P}\mathbb{P}f_2)(6)}(q_1, q_2) = \frac{i}{M_0^3} g_{\mathbb{P}\mathbb{P}f_2}^{(6)} \left( q_1^{\alpha_1} q_1^{\lambda_1} q_2^{\mu_1} q_{2\rho_1} R_{\mu\nu\mu_1\nu_1} R_{\kappa\lambda\alpha_1\lambda_1} + q_2^{\alpha_1} q_2^{\lambda_1} q_1^{\mu_1} q_{1\rho_1} R_{\mu\nu\alpha_1\lambda_1} R_{\kappa\lambda\mu_1\nu_1} \right) R^{\nu_1\rho_1}{}_{\rho\sigma}, \quad (12)$$

$$i\Gamma_{\mu\nu,\kappa\lambda,\rho\sigma}^{(\mathbb{P}\mathbb{P}f_2)(7)}(q_1, q_2) = -\frac{2i}{M_0^5} g_{\mathbb{P}\mathbb{P}f_2}^{(7)} q_1^{\rho_1} q_1^{\alpha_1} q_1^{\lambda_1} q_2^{\sigma_1} q_2^{\mu_1} q_2^{\nu_1} R_{\mu\nu\mu_1\nu_1} R_{\kappa\lambda\alpha_1\lambda_1} R_{\rho\sigma\rho_1\sigma_1}, \quad (13)$$

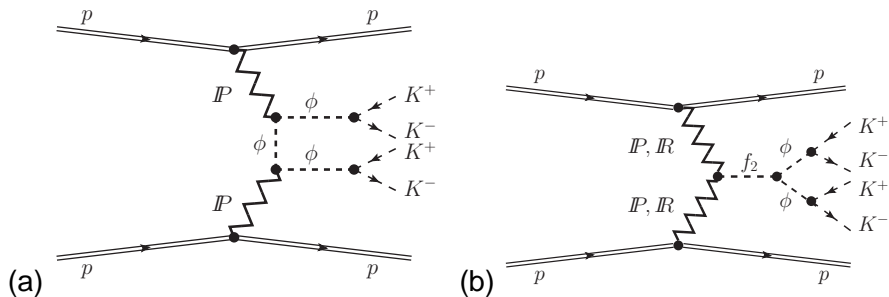
$$pp \rightarrow pp\phi\phi$$

- ▶ Observed by WA102, no theoretical interpretation
- ▶ Several mechanisms possible a priori
  - ▶ continuum (" $\phi$ " exchange, **reggeization (?)** )
  - ▶  $f_2(1950)$  (not yet, TTT coupling)
  - ▶  $f_2(2340)$  (TTT coupling)
  - ▶ **glueball candidate(s)**, below ( $f_0(1710)$ ) and above threshold
  - ▶  $\eta(2100)$ ,  $\eta(2225)$  and  $X(2500)$  observed in  $J/\psi \rightarrow \gamma\phi\phi$ .  
Are they produced in CEP ?
  - ▶ **Odderon exchange ?**

Our recent analysis:

Lebiedowicz, Nachtmann, Szczurek, arXiv.1901.11490,  
Phys. Rev. **D99** (2019) 094034.

$$pp \rightarrow pp\phi\phi$$



**Figure:** The “Born level” diagrams for double-pomeron/reggeon central exclusive  $\phi\phi$  production and their subsequent decays into  $K^+K^-K^+K^-$  in proton-proton collisions. In (a) we have the continuum  $\phi\phi$  production, in (b)  $\phi\phi$  production via an  $f_2$  resonance. Other resonances, e.g. of  $f_0$ - and  $\eta$ -type, can also contribute here.

## Some details of the calculation

- ▶ We write the amplitudes for continuum  $\phi$ -meson exchange (long formula).
- ▶ The formalism for  $\mathbb{P}\mathbb{P} \rightarrow f_2(2340)$  as previously for  $f_2(1270)$ .
- ▶  $f_2 \rightarrow \phi\phi$  decay (tensor  $\rightarrow$  vector+vector) in analogy to  $\gamma\gamma \rightarrow f_2(1270)$  (two active tensorial couplings).
- ▶ Blueball filter variable:

$$\mathbf{dP}_t = \mathbf{q}_{t,1} - \mathbf{q}_{t,2} = \mathbf{p}_{t,2} - \mathbf{p}_{t,1}, \quad dP_t = |\mathbf{dP}_t|, \quad (14)$$

$f_2 \rightarrow \phi\phi$  decay

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

$$i\Gamma_{\mu\nu\kappa\lambda}^{(f_2\phi\phi)}(p_3, p_4) = i\frac{2}{M_0^3}g'_{f_2\phi\phi}\Gamma_{\mu\nu\kappa\lambda}^{(0)}(p_3, p_4)F^{(f_2\phi\phi)}(p_{34}^2) - i\frac{1}{M_0}g''_{f_2\phi\phi}\Gamma_{\mu\nu\kappa\lambda}^{(2)}(p_3, p_4)F''^{(f_2\phi\phi)}(p_{34}^2), \quad (15)$$

with  $M_0 = 1$  GeV and dimensionless coupling constants  $g'_{f_2\phi\phi}$  and  $g''_{f_2\phi\phi}$  being free parameters.

**Two free couplings**

will be discussed in the following.

## $\phi$ -exchange reggeization

$$\Delta_{\rho_1 \rho_2}^{(\phi)}(\hat{p}) \rightarrow \Delta_{\rho_1 \rho_2}^{(\phi)}(\hat{p}) \left( \exp(i\phi(s_{34})) \frac{s_{34}}{s_0} \right)^{\alpha_\phi(\hat{p}^2)-1}, \quad (16)$$

where we take  $s_0 = 4m_\phi^2$  and  $\alpha_\phi(\hat{p}^2) = \alpha_\phi(0) + \alpha'_\phi \hat{p}^2$  with  $\alpha_\phi(0) = 0.1$  from **Collins book** and  $\alpha'_\phi = 0.9 \text{ GeV}^{-2}$ .

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

$$\phi(s_{34}) = \frac{\pi}{2} \exp\left(\frac{s_0 - s_{34}}{s_0}\right) - \frac{\pi}{2} \quad (17)$$

which role is to interpolate between **meson physics** close to the  $\phi\phi$  threshold,  $s_{34} = 4m_\phi^2$ , and **Regge physics** at high energies.

## Another reggeization procedure

Regge formalism applies when  $\hat{t}, \hat{u} \ll s_{34}$ .

At the threshold ( $M_{\phi\phi} \sim 2m_\phi$ )  $\hat{t}$  and  $\hat{u}$  are not very small.

**Another idea:** At  $Y_{\text{diff}} = 0$  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  $\phi$  meson propagator, and of **high**  $Y_{\text{diff}}$  where we use the reggeized form:

$$\begin{aligned} & \Delta_{\rho_1\rho_2}^{(\phi)}(\hat{p}) \rightarrow \Delta_{\rho_1\rho_2}^{(\phi)}(\hat{p}) F(Y_{\text{diff}}) \\ & + \Delta_{\rho_1\rho_2}^{(\phi)}(\hat{p}) [1 - F(Y_{\text{diff}})] \left( \exp(i\phi(s_{34})) \frac{s_{34}}{s_0} \right)^{\alpha_\phi(\hat{p}^2)-1} . \end{aligned} \quad (18)$$

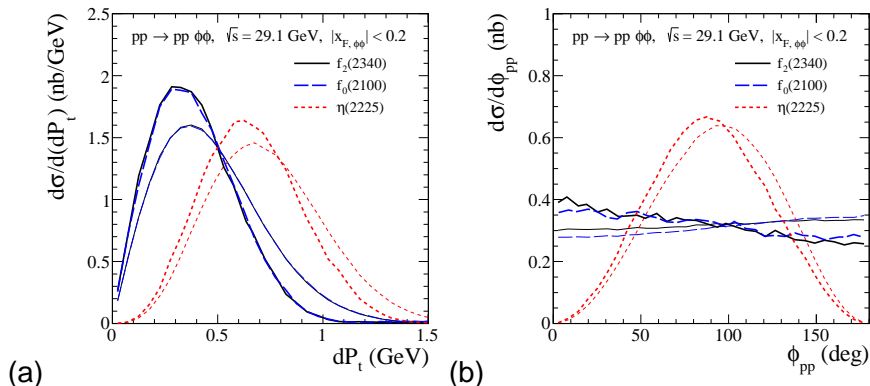
We use a simple function:

$$F(Y_{\text{diff}}) = \exp(-c_y |Y_{\text{diff}}|) . \quad (19)$$

For  $c_y > 2$  the two procedures give similar results for  $\frac{d\sigma}{dM_{\phi\phi}}$  above 4-5 GeV.

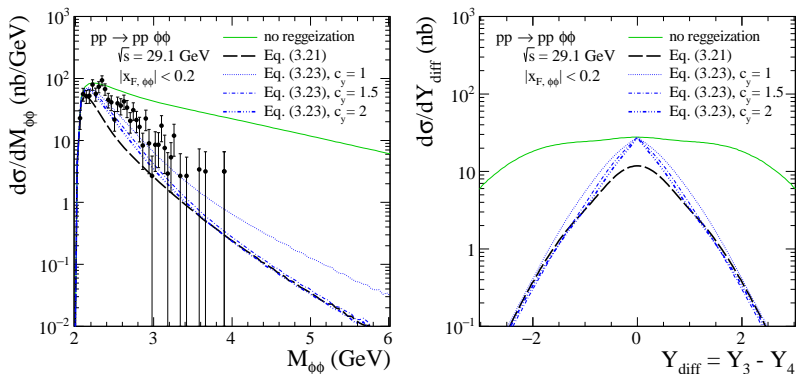


# $pp \rightarrow pp\phi\phi$ , WA102 data, spin dependence



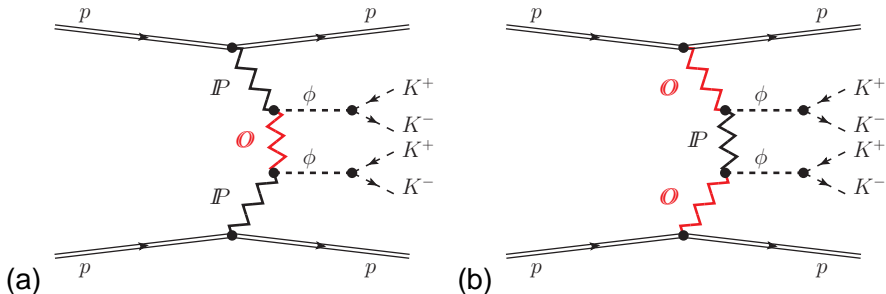
**Figure:** The distribution in  $dP_t$  (14) and in  $\phi_{pp}$  for the central exclusive  $\phi\phi$  production at  $\sqrt{s} = 29.1$  GeV and  $|x_{F,\phi\phi}| \leq 0.2$ . The results for **scalar, pseudoscalar and tensor resonances** without (the thin lines) and with (the thick lines) absorptive corrections are shown. Because here we are interested only in the shape of the distributions we normalised the differential distributions arbitrarily to 1 nb.

# $pp \rightarrow pp\phi\phi$ , WA102 data



**Figure:** The distributions in  $\phi\phi$  invariant mass (the left panel) and in  $Y_{\text{diff}}$ , the rapidity distance between the two  $\phi$  mesons, (the right panel) for the  $\phi$ -exchange continuum contribution. The calculations were done for  $\sqrt{s} = 29.1$  GeV and  $|x_{F,\phi\phi}| \leq 0.2$ . In the left panel we show the WA102 experimental data normalised to  $\sigma_{\text{exp}}^{(\phi\phi)} = 41$  nb. The green solid line corresponds to the **non-reggeized contribution**. The results for two prescriptions of reggeization are shown by the black and blue lines,

# Continuum with odderon exchange



**Figure:** The Born level diagrams for diffractive production of a  $\phi$ -meson pair with one and two odderon exchanges.

**No coupling to protons in diagram (a).**

# Odderon exchange

Our ansatz for the effective propagator of  $C = -1$  odderon follows Ewerz et al.

$$i\Delta_{\mu\nu}^{(\odot)}(s, t) = -ig_{\mu\nu} \frac{\eta_{\odot}}{M_{\odot}^2} (s\alpha'_{\odot})^{\alpha_{\odot}(t)-1}, \quad (20)$$

$$\alpha_{\odot}(t) = \alpha_{\odot}(0) + \alpha'_{\odot} t, \quad (21)$$

where in (20) we have  $M_{\odot}^{-2} = 1 \text{ (GeV)}^{-2}$  for dimensional reasons. Further more, we shall assume representative values for the odderon parameters

$$\eta_{\odot} = -1, \quad \alpha_{\odot}(0) = 1.05, \quad \alpha'_{\odot} = 0.25 \text{ GeV}^{-2}. \quad (22)$$

For the  $\mathbb{P}\mathbb{O}\phi$  vertex we use an ansatz analogous to the  $\mathbb{P}\rho\rho$  vertex. We get then, orienting the momenta of the  $\odot$  and the  $\phi$  outwards, the following formula:

$$i\Gamma_{\mu\nu\kappa\lambda}^{(\mathbb{P}\mathbb{O}\phi)}(k', k) = iF^{(\mathbb{P}\mathbb{O}\phi)}((k+k')^2, k'^2, k^2) \left[ 2 a_{\mathbb{P}\mathbb{O}\phi} \Gamma_{\mu\nu\kappa\lambda}^{(0)}(k', k) - b_{\mathbb{P}\mathbb{O}\phi} \Gamma_{\mu\nu\kappa\lambda}^{(2)}(k', k) \right]. \quad (23)$$

## Odderon exchange

Here  $k', \mu$  and  $k, \nu$  are momentum and vector index of the odderon and the  $\phi$ , respectively,  $a_{\mathbb{P}\mathbb{O}\phi}$  and  $b_{\mathbb{P}\mathbb{O}\phi}$  are coupling constants and  $F^{(\mathbb{P}\mathbb{O}\phi)}(k^2, k'^2, (k+k')^2)$  is a form factor. In practical calculations we take the **factorized form** for the  $\mathbb{P}\mathbb{O}\phi$  form factor

$$F^{(\mathbb{P}\mathbb{O}\phi)}((k+k')^2, k'^2, k^2) = F((k+k')^2) F(k'^2) F^{(\mathbb{P}\mathbb{O}\phi)}(k^2), \quad (24)$$

where we adopt the monopole form

$$F(k^2) = \frac{1}{1 - k^2/\Lambda^2} \quad (25)$$

and  $F^{(\mathbb{P}\mathbb{O}\phi)}(k^2)$  is a form factor normalised to  $F^{(\mathbb{P}\mathbb{O}\phi)}(m_\phi^2) = 1$ . The coupling parameters  $a_{\mathbb{P}\mathbb{O}\phi}$ ,  $b_{\mathbb{P}\mathbb{O}\phi}$  in (23) and the cut-off parameter  $\Lambda^2$  in the form factor can be adjusted to experimental data.

# Continuum with photon exchange

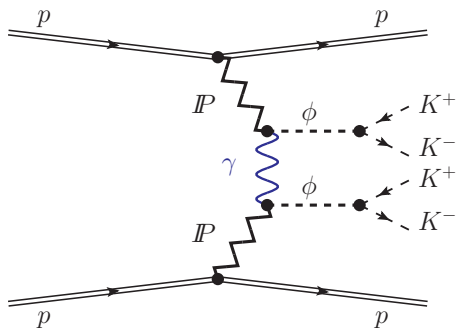
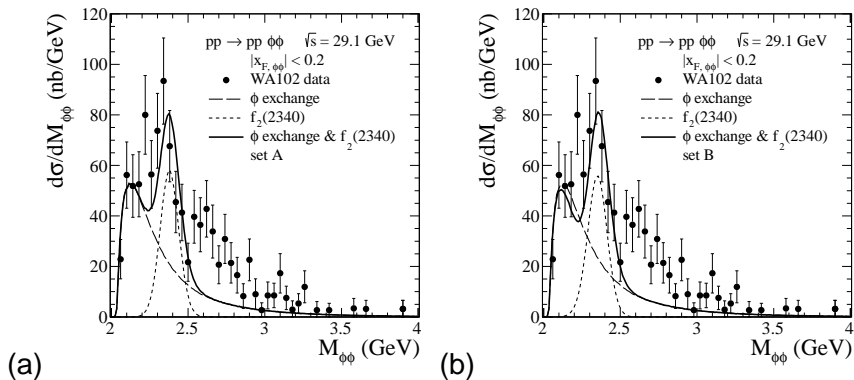


Figure: The “Born level” diagram for diffractive production of a  $\phi$ -meson pair with an intermediate photon exchange.

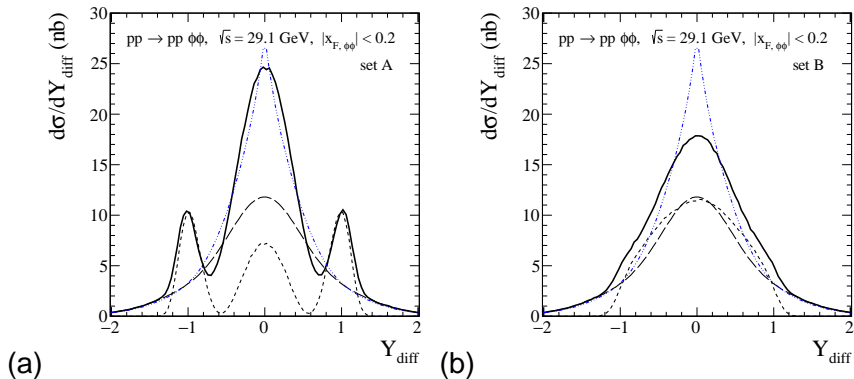
This turned out to be small

# Invariant mass distribution, $\phi$ exchange + $f_2(2340)$



**Figure:** Invariant mass distributions for the central  $\phi\phi$  system compared to the WA102 data at  $\sqrt{s} = 29.1$  GeV and  $|x_{F,\phi\phi}| \leq 0.2$ . The data points have been normalized to the total cross section  $\sigma_{exp}^{(\phi\phi)} = 41$  nb. We show results for **two different  $f_2 \rightarrow \phi\phi$  couplings** set A, (panel (a)) or set B (panel (b))) The long-dashed line corresponds to the reggeized  $\phi$ -exchange contribution while the short-dashed line corresponds to the  $f_2(2340)$  resonance term. The solid line represents the coherent sum of both contributions. The absorption effects were included here

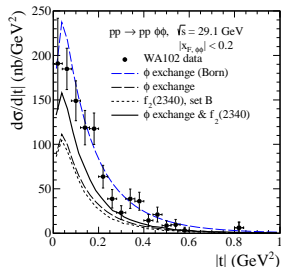
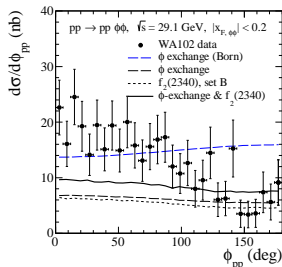
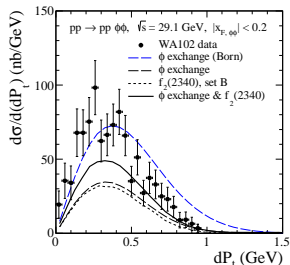
# Distribution in $Y_{\text{diff}}$ , $\phi$ exchange + $f_2(2340)$



**Figure:** The distribution in rapidity distance between two centrally produced  $\phi(1020)$  mesons  $Y_{\text{diff}} = Y_3 - Y_4$  at  $\sqrt{s} = 29.1$  GeV and for  $|x_{F,\phi\phi}| \leq 0.2$ . for **two different  $f_2 \rightarrow \phi\phi$  couplings**. **No clear dependence on  $\mathbb{P}\mathbb{P} \rightarrow f_2(2340)$  coupling**. The absorption effects were included here.

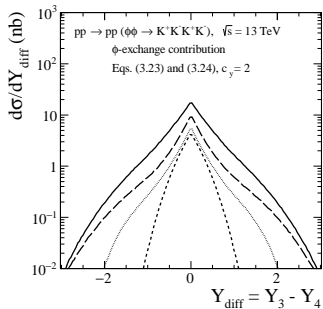
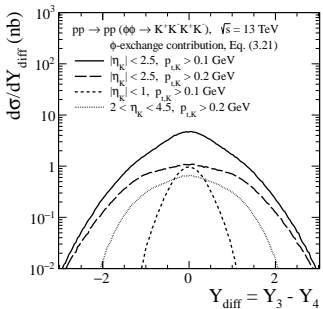
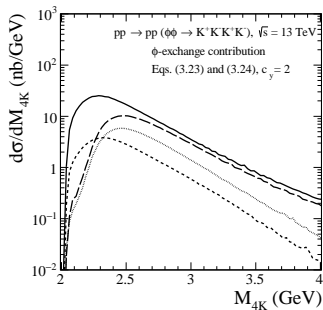
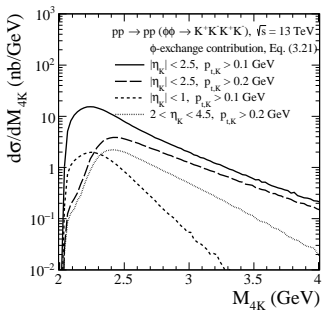


# WA102, some other distributions

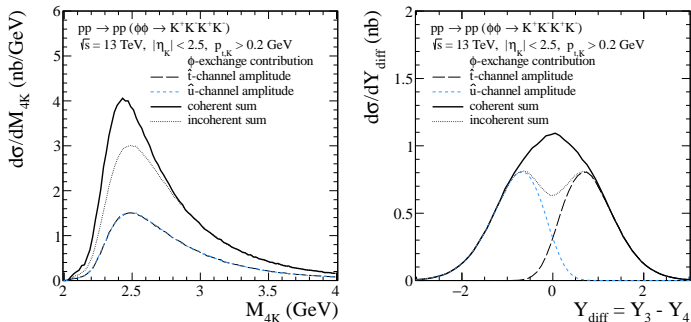


$f_2(2340)$  and  $\phi$  exchange  
second choice of the  $f_2 \rightarrow \phi\phi$  coupling  
Something is still missing ?

# Predictions for LHC, $\phi$ exchange only

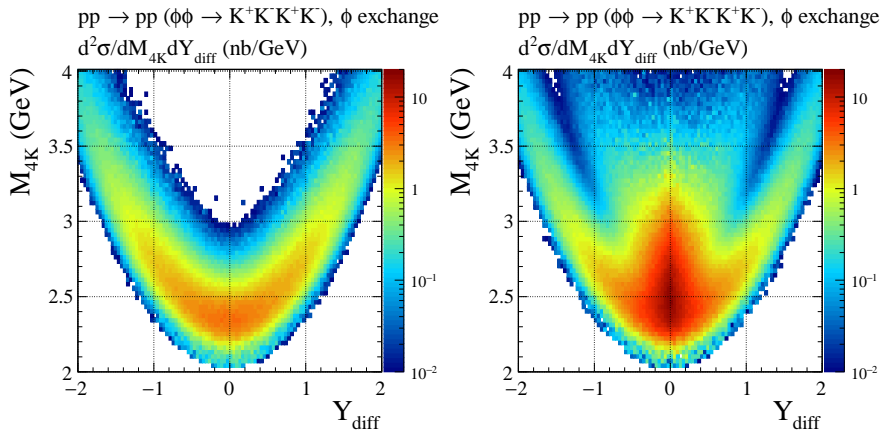


# Predictions for LHC, $\phi$ exchange only



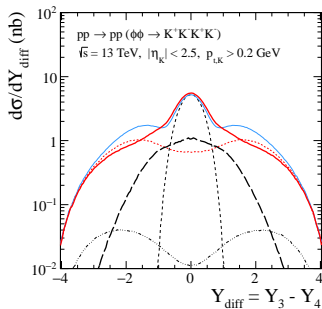
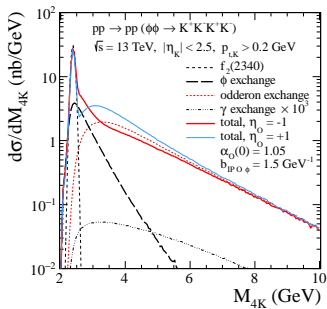
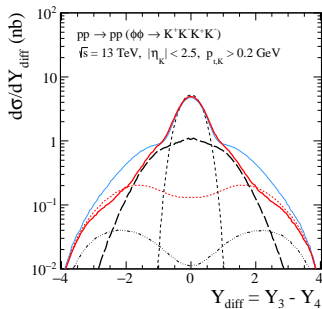
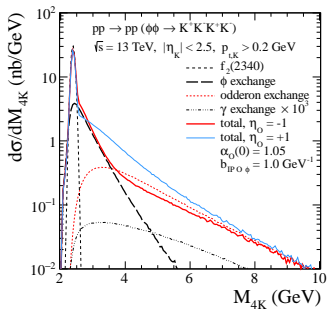
**Figure:** The  $pp \rightarrow pp(\phi\phi \rightarrow K^+K^-K^+K^-)$  reaction calculated for  $\sqrt{s} = 13 \text{ TeV}$  and  $|\eta_K| < 2.5, p_{t,K} > 0.2 \text{ GeV}$ . The results for the  $\phi(1020)$ -exchange contribution are presented. The black solid line correspond to the coherent sum of the  $\hat{t}$ - and  $\hat{u}$ -channel amplitudes. Their incoherent sum is shown by the dotted line for comparison. The black long-dashed and blue dashed line correspond to the results for the  $\hat{t}$  and  $\hat{u}$  terms, respectively. The absorption effects are included here.

# Predictions for LHC, $\phi$ -exchange

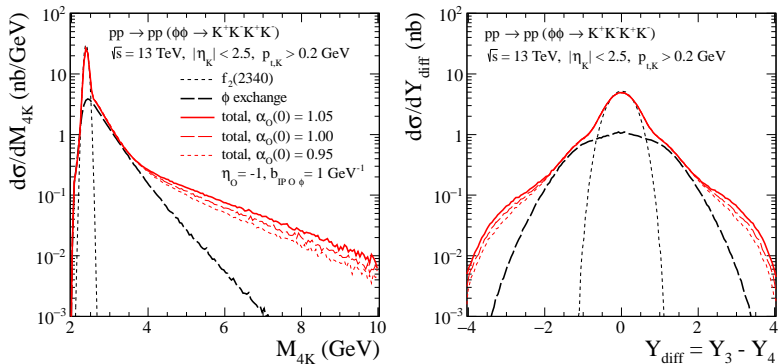


**Figure:** The two-dimensional distribution in  $(Y_{diff}, M_{4K})$  for the diffractive continuum four-kaon production for  $\sqrt{s} = 13$  TeV and  $|\eta_K| < 2.5$ ,  $p_{t,K} > 0.2$  GeV. **Two different reggeization methods.** The absorption effects are included here.

# Odderon exchange at the LHC

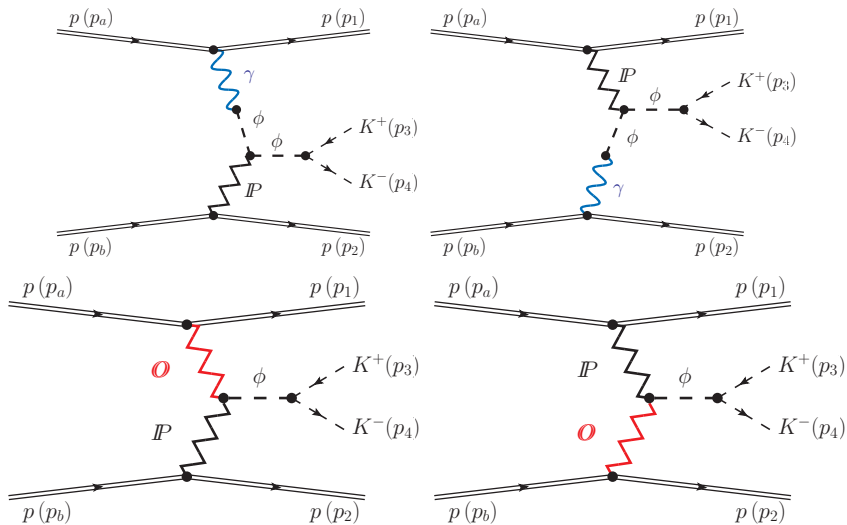


# Odderon at the LHC



**Figure:** The complete results for  $\sqrt{s} = 13 \text{ TeV}$  and  $|\eta_K| < 2.5$ ,  $p_{t,K} > 0.2 \text{ GeV}$  are shown. Here we show results for  $\eta_0 = -1$  and for various values of the odderon intercept  $\alpha_0(0)$ . Here we take  $a_{\text{PPO}\phi} = 0$  and  $b_{\text{PPO}\phi} = 1 \text{ GeV}^{-1}$ . **Odderon could be visible for  $M_{\phi\phi} > 6 \text{ GeV}$  and/or for  $Y_{\text{diff}} > 3$ .**

# Return to $pp \rightarrow pp\phi$



Odderon exchange contribution modifies the the photon-exchange contribution

# Photoproduction process

$$\begin{aligned}
 \mathcal{M}_{\lambda_a \lambda_b \rightarrow \lambda_1 \lambda_2 K^+ K^-}^{(\gamma \mathbb{P})} &= (-i) \bar{u}(p_1, \lambda_1) i \Gamma_{\mu}^{(\gamma \mathbb{P})}(p_1, p_a) u(p_a, \lambda_a) \\
 &\times i \Delta^{(\gamma)} \mu_{\sigma} (q_1) i \Gamma_{\sigma \nu}^{(\gamma \rightarrow \phi)}(q_1) i \Delta^{(\phi)} \nu \rho_1 (q_1) i \Gamma_{\rho_2 \rho_1 \alpha \beta}^{(\mathbb{P} \phi \phi)}(p_{34}, q_1) i \Delta^{(\phi)} \rho_2 \kappa (p_{34}) i \Gamma_{\kappa}^{(\phi K K)}(p_3, p_4) \\
 &\times i \Delta^{(\mathbb{P})} \alpha \beta, \delta \eta (s_2, t_2) \bar{u}(p_2, \lambda_2) i \Gamma_{\delta \eta}^{(\mathbb{P} \mathbb{P})}(p_2, p_b) u(p_b, \lambda_b).
 \end{aligned} \tag{26}$$

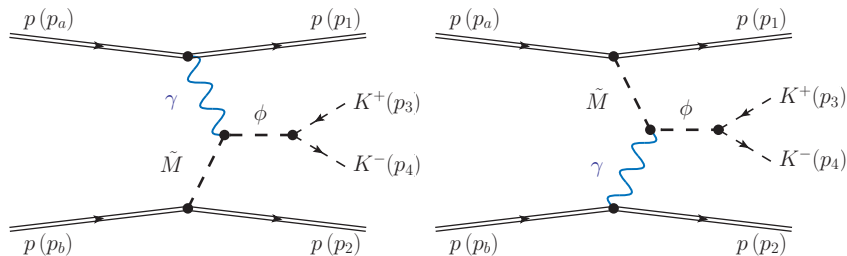
$$\begin{aligned}
 \mathcal{M}_{\lambda_a \lambda_b \rightarrow \lambda_1 \lambda_2 K^+ K^-}^{(\gamma \mathbb{P})} &= -i e^2 \bar{u}(p_1, \lambda_1) \left[ \gamma^{\alpha} F_1(t_1) + \frac{i}{2m_p} \sigma^{\alpha \alpha'} (p_1 - p_a)_{\alpha'} F_2(t_1) \right] u(p_a, \lambda_a) \\
 &\times \frac{1}{t_1} \frac{(-m_{\phi}^2)}{t_1 - m_{\phi}^2} \frac{1}{\gamma_{\phi}} \Delta_T^{(\phi)}(p_{34}^2) \frac{g_{\phi K^+ K^-}}{2} (p_3 - p_4)^{\beta} F^{(\phi K K)}(p_{34}^2) \\
 &\times \left[ 2a_{\mathbb{P} \phi \phi} \Gamma_{\alpha \beta \kappa \lambda}^{(0)}(p_{34}, -q_1) - b_{\mathbb{P} \phi \phi} \Gamma_{\alpha \beta \kappa \lambda}^{(2)}(p_{34}, -q_1) \right] \check{F}^{(\phi)}(t_1) \check{F}^{(\phi)}(p_{34}^2) F_M(t_2) \\
 &\times \frac{1}{2s_2} \left( -i s_2 \alpha'_{\mathbb{P}} \right)^{\alpha \mathbb{P}(t_2) - 1} 3\beta_{\mathbb{P} N N} F_1(t_2) \bar{u}(p_2, \lambda_2) \left[ \gamma^{\kappa} (p_2 + p_b)^{\lambda} \right] u(p_b, \lambda_b).
 \end{aligned} \tag{27}$$



# Pomeron-odderon fusion

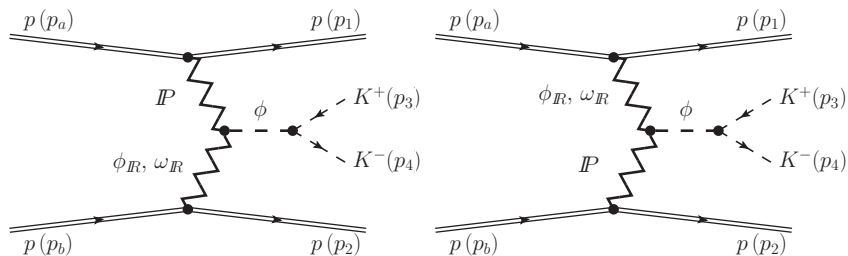
$$\begin{aligned} \mathcal{M}_{\lambda_a \lambda_b \rightarrow \lambda_1 \lambda_2 K^+ K^-}^{(\mathbb{O}\mathbb{P})} &= (-i) \bar{u}(p_1, \lambda_1) i\Gamma_{\mu}^{(\mathbb{O}pp)}(p_1, p_a) u(p_a, \lambda_a) \\ &\times i\Delta^{(\mathbb{O})\mu\rho_1}(q_1) i\Gamma_{\rho_2\rho_1\alpha\beta}^{(\mathbb{P}\mathbb{O}\phi)}(p_{34}, q_1) i\Delta^{(\phi)\rho_2\kappa}(p_{34}) i\Gamma_{\kappa}^{(\phi KK)}(p_3, p_4) \\ &\times i\Delta^{(\mathbb{P})\alpha\beta,\delta\eta}(s_2, t_2) \bar{u}(p_2, \lambda_2) i\Gamma_{\delta\eta}^{(\mathbb{P}pp)}(p_2, p_b) u(p_b, \lambda_b). \quad (28) \end{aligned}$$

## Other mechanisms for low/intermediate energies



At low energies, as WA102, also **pseudoscalar** meson exchanges

# Other mechanisms for low/intermediate energies



New diagrams due to  $\omega - \phi$  mixing

At present we think that:

$\omega$  exchange is larger than  $\phi$  exchange.

## Other mechanisms for low/intermediate energies - comments

- ▶  $\pi^0 \rho^0 \rightarrow \phi$  and  $\rho^0 \pi^0 \rightarrow \phi$  fusion  
reggeization of  $\rho^0$  very important,  
spin-flip dominance of  $\rho^0$  exchange  
 $\phi \rightarrow \rho^0 \pi^0$  is known.
- ▶  $\phi \mathbb{P} \rightarrow \phi$  and  $\mathbb{P} \phi \rightarrow \phi$  fusion  
reggeization of  $\phi$  was already discussed,  $g_{\phi pp}$  is known (not very precisely) from low energies.
- ▶  $\omega \mathbb{P} \rightarrow \phi$  and  $\mathbb{P} \omega \rightarrow \phi$  fusion  
Off-diagonal  $\omega \rightarrow \phi$  transition – mixing of  $\phi$  and  $\omega$ .  
Mixing small but  $\omega$  strongly couples to proton.
- ▶  $\eta \omega$  and  $\omega \eta$  reggeization of  $\omega$

# $pp \rightarrow pp\phi$ , WA102 data, preliminary solution

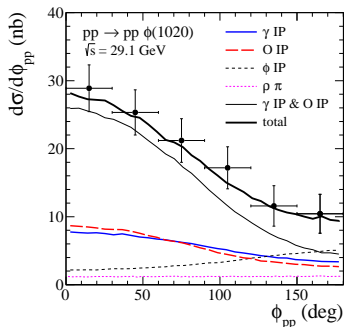


Figure: Azimuthal angle correlations between protons.

$$g_{Opp} = \frac{1}{10} g_{Ppp} \text{ (educated guess, TOTEM)}$$

strong interference of  $\gamma P$  and  $O P$

# Other distributions for WA102, preliminary solution

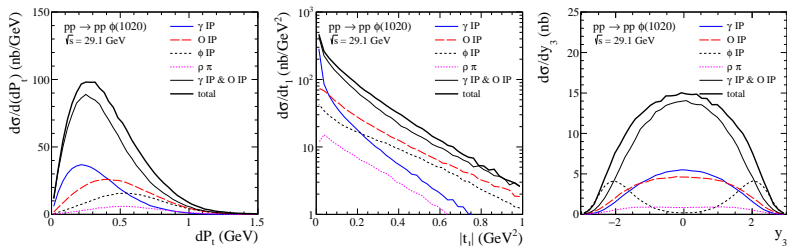


Figure: These distributions were not measured.

$pp \rightarrow pp\phi$ , at low energy

$W_{\gamma p}$  are not too large

But we rather control the photoproduction cross section

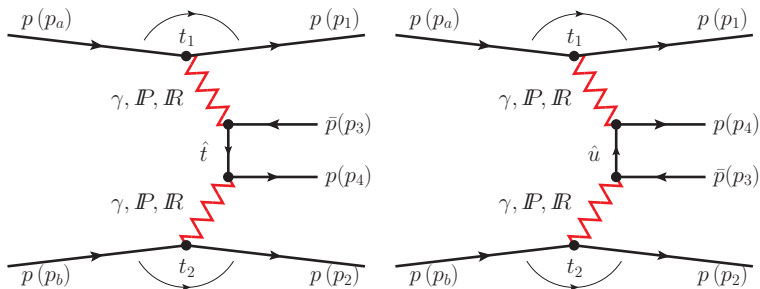
LHCb will measure the data for  $pp \rightarrow pp\phi$ .

Identify deviations from photoproduction.

Do we know photoproduction (saturation effects)?

$$pp \rightarrow ppp\bar{p}$$

### The continuum (nonresonance) contribution



We do Feynman-diagram calculations with well fixed rules (!)



## Possible exchanges

$$(C_1, C_2) = (1, 1) : (\mathbb{P} + \mathbb{R}_+, \mathbb{P} + \mathbb{R}_+); \quad (29)$$

$$(C_1, C_2) = (-1, -1) : (\mathbb{O} + \mathbb{R}_- + \gamma, \mathbb{O} + \mathbb{R}_- + \gamma); \quad (30)$$

$$(C_1, C_2) = (1, -1) : (\mathbb{P} + \mathbb{R}_+, \mathbb{O} + \mathbb{R}_- + \gamma); \quad (31)$$

$$(C_1, C_2) = (-1, 1) : (\mathbb{O} + \mathbb{R}_- + \gamma, \mathbb{P} + \mathbb{R}_+). \quad (32)$$

$$pp \rightarrow ppp\bar{p}$$

The full amplitude for  $p\bar{p}$  production is a sum of continuum amplitude and the amplitudes with the s-channel resonances:

$$\mathcal{M}_{pp \rightarrow ppp\bar{p}} = \mathcal{M}_{pp \rightarrow ppp\bar{p}}^{p\bar{p}\text{-continuum}} + \mathcal{M}_{pp \rightarrow ppp\bar{p}}^{p\bar{p}\text{-resonances}}. \quad (33)$$

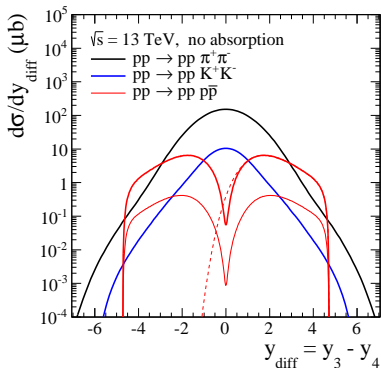
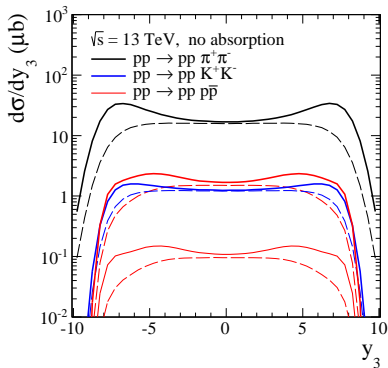
No  $p\bar{p}$  resonances are known (to us) except of  $\eta_c$  and  $\chi_c(0)$  mesons (see PDG).

$$pp \rightarrow ppp\bar{p}$$

$$\begin{aligned}
 \mathcal{M}_{\lambda_a \lambda_b \rightarrow \lambda_1 \lambda_2 \lambda_3 \lambda_4}^{(\mathbb{P}\mathbb{P} \rightarrow \bar{p}p)} &= (-i) \bar{u}(p_1, \lambda_1) i\Gamma_{\mu_1 \nu_1}^{(\mathbb{P}pp)}(p_1, p_a) u(p_a, \lambda_a) i\Delta^{(\mathbb{P}) \mu_1 \nu_1, \alpha_1 \beta_1}(s_{13}, t_1) \\
 &\times \bar{u}(p_4, \lambda_4) [i\Gamma_{\alpha_2 \beta_2}^{(\mathbb{P}pp)}(p_4, p_t) i\Delta^{(p)}(p_t) i\Gamma_{\alpha_1 \beta_1}^{(\mathbb{P}pp)}(p_t, -p_3) \\
 &\quad + i\Gamma_{\alpha_1 \beta_1}^{(\mathbb{P}pp)}(p_4, p_u) i\Delta^{(p)}(p_u) i\Gamma_{\alpha_2 \beta_2}^{(\mathbb{P}pp)}(p_u, -p_3)] v(p_3, \lambda_3) \\
 &\times i\Delta^{(\mathbb{P}) \alpha_2 \beta_2, \mu_2 \nu_2}(s_{24}, t_2) \bar{u}(p_2, \lambda_2) i\Gamma_{\mu_2 \nu_2}^{(\mathbb{P}pp)}(p_2, p_b) u(p_b, \lambda_b).
 \end{aligned}
 \tag{34}$$

No absorption effects.

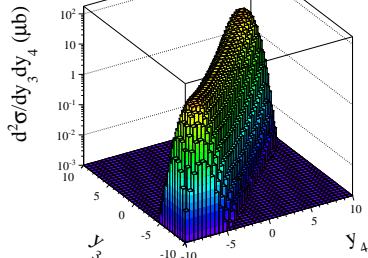
$pp \rightarrow ppp\bar{p}$



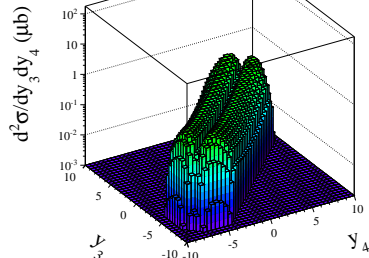
Surprising effect of the dip at  $y_{\text{diff}} = 0$ .  
New effect for spin-1/2 particles  
Good separation of  $t$  and  $u$  contributions.

# $y_3xy_4$ space

$pp \rightarrow pp \pi^+\pi^-$   
 $\sqrt{s} = 13 \text{ TeV}$

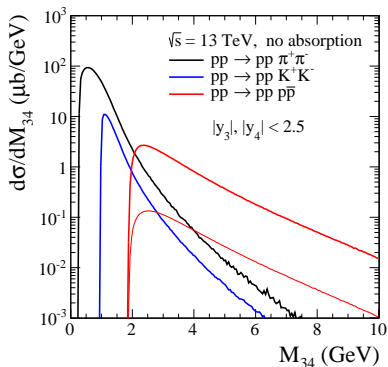
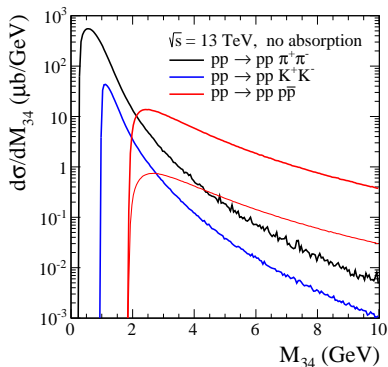


$pp \rightarrow pp p\bar{p}$   
 $\sqrt{s} = 13 \text{ TeV}$



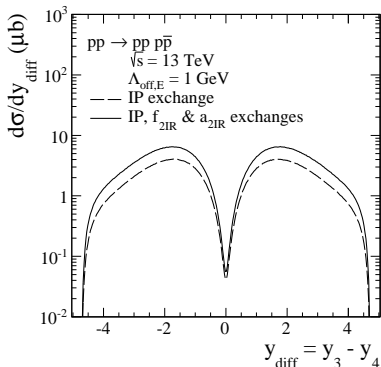
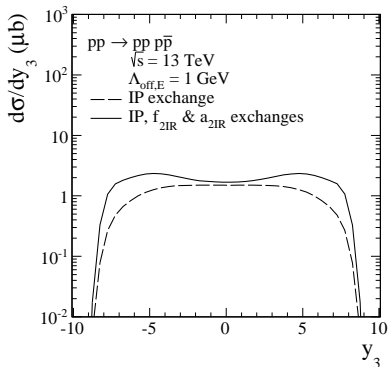
Completely different character.  
The dip is everywhere on the diagonal  
(ATLAS can do it, ALICE not really).

# $M_{p\bar{p}}$ -distribution



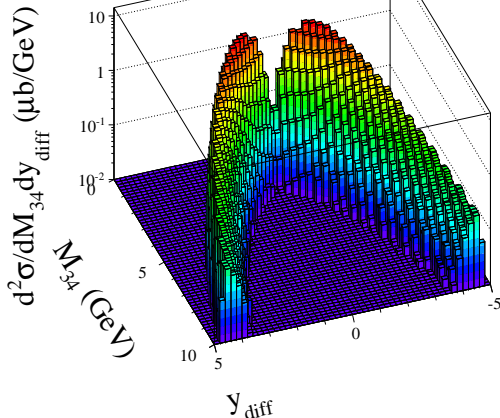
Different slope for pairs of pseudoscalar and for spin-1/2 hadrons.  
We explicitly include spin degrees of freedom in the Regge calculus.

# Role of subleading reggeons



Even at  $\sqrt{s} = 13$  TeV a sizeable effect of subleading reggeons.

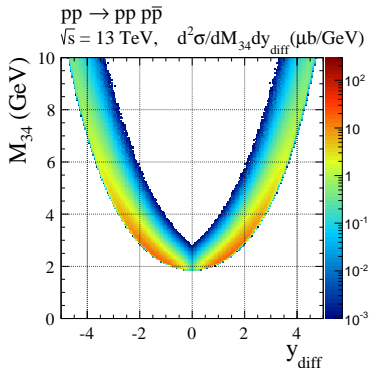
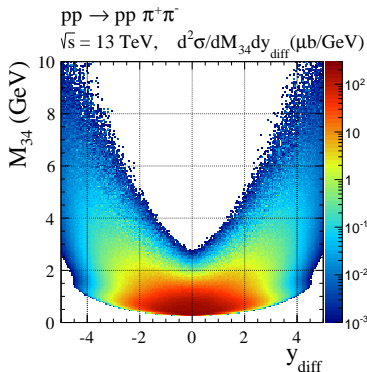
$pp \rightarrow pp \bar{p}$   
 $\sqrt{s} = 13 \text{ TeV}$



Region inside of the ridge seems promising  
in searches for resonances

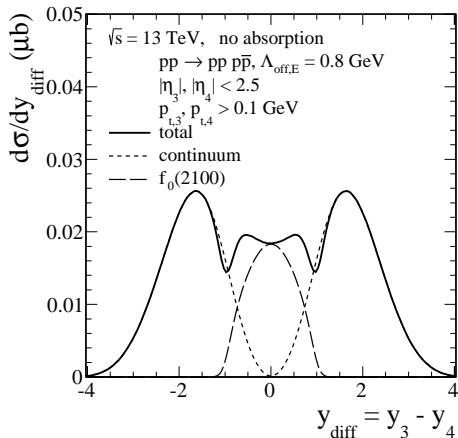


# $\pi^+\pi^-$ versus $p\bar{p}$ production



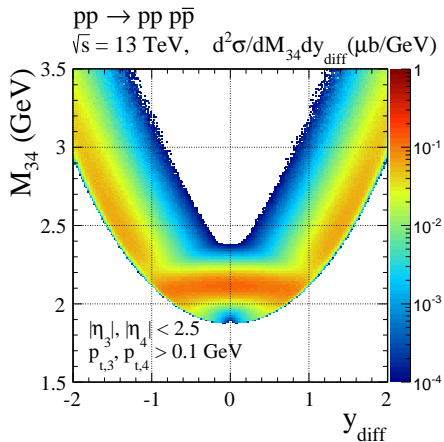
Different situation for  $\pi^+\pi^-$  and  $p\bar{p}$

# Potential role of resonances with $M \sim 2$ GeV



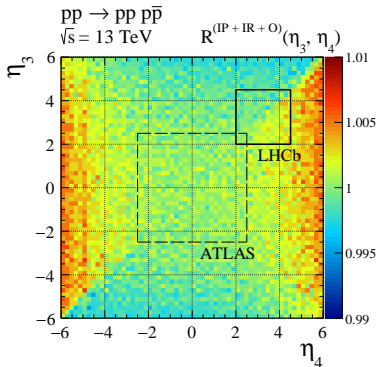
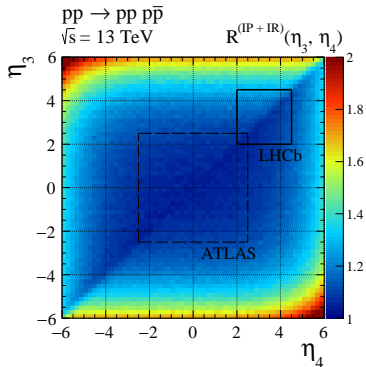
resonances may destroy the dip

# Potential role of resonances with $M \sim 2$ GeV



resonances may destroy (close) the gorge

# Role of ingredients, ratios



first: role of **subleading reggeons**  
second: role of **odderon**

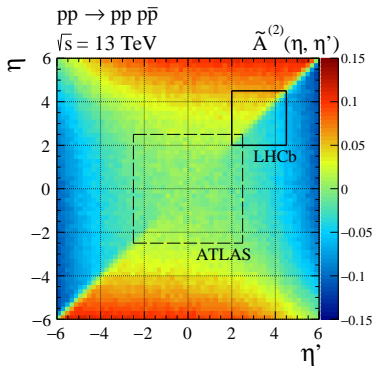
## Asymmetry between central $p$ and $\bar{p}$

In two dimensions (e.g.  $\eta_1, \eta_2$ ) we can define the asymmetry:

$$\tilde{A}^{(2)}(\eta, \eta') = \frac{\frac{d^2\sigma}{d\eta_3 d\eta_4}(\eta, \eta') - \frac{d^2\sigma}{d\eta_3 d\eta_4}(\eta', \eta)}{\frac{d^2\sigma}{d\eta_3 d\eta_4}(\eta, \eta') + \frac{d^2\sigma}{d\eta_3 d\eta_4}(\eta', \eta)}. \quad (35)$$

# Asymmetry between central $p$ and $\bar{p}$

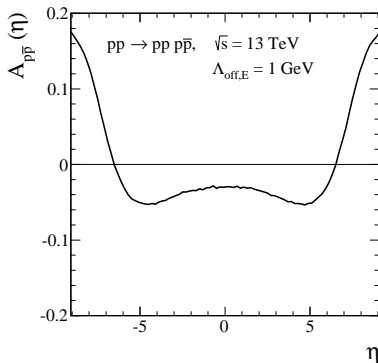
$$A = \frac{\sigma(p) - \sigma(\bar{p})}{\sigma(p) + \sigma(\bar{p})} \quad (36)$$



Clear asymmetry

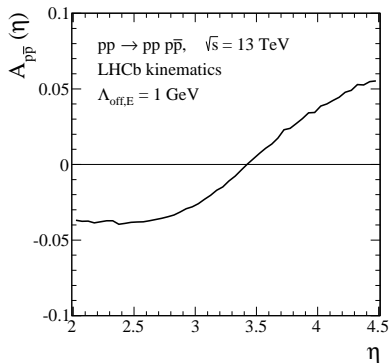
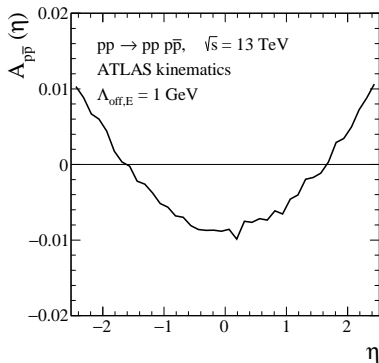
# Asymmetry between central $p$ and $\bar{p}$

Projection on one-dimension  
(full phase space)



# Asymmetry between central $p$ and $\bar{p}$

## Projection on one-dimension (experimental cuts)





# Conclusions

- ▶ The Regge phenomenology was extended to  $2 \rightarrow 3$ ,  $2 \rightarrow 4$  and  $2 \rightarrow 6$  exclusive processes.
- ▶ The tensor pomeron/reggeon model was applied to many reactions.
- ▶ At lower energies tensor/vector reggeons.
- ▶ Three reactions ( $pp \rightarrow pp\phi\phi$ ,  $pp \rightarrow pp\phi$  and  $pp \rightarrow ppp\bar{p}$ ) have been studied in the context of identifying odderon exchange.
- ▶  $pp \rightarrow pp\phi\phi$  seems promising as here the odderon does not couple to protons. An upper limit for the odderon exchange has been established based on the WA102 data.
- ▶ This upper limit for the  $\mathbb{P}\mathbb{O} \rightarrow \phi$  coupling was used for the  $pp \rightarrow pp\phi$  reaction, together with the TOTEM estimate. The WA102 data support the existence of odderon exchange.
- ▶ Special asymmetries for centrally produced  $p\bar{p}$  system have been proposed to identify  $C = -1$  exchanges. The asymmetry caused by subleading reggeon exchanges is probably larger than that for the odderon exchange.