

workshop on central exclusive production at the LHC

## CEP of boson and fermion pairs

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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 glueballs 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**.
- ▶ **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 al.**

## Tensor pomeron

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

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

and fulfills the following relations

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

It gives by construction the same result for  $pp \rightarrow pp$  elastic scattering as traditional Regge approach.

# Exclusive reactions

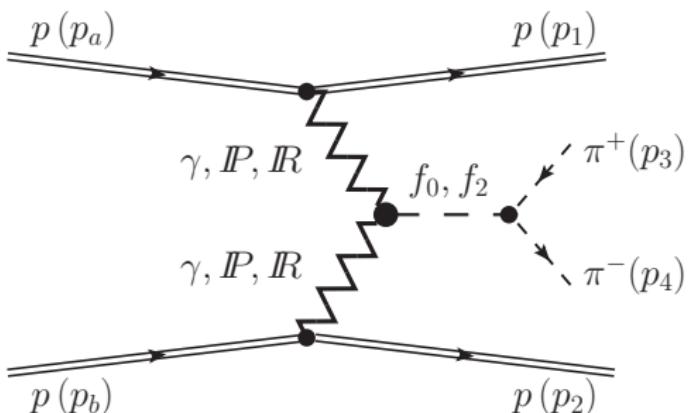
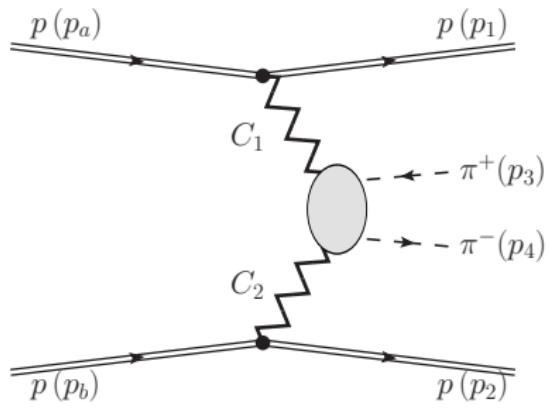
- ▶ Consider **exclusive** process  $pp \rightarrow pp\bar{M}\bar{M}$   
( $pp \rightarrow ppR$  or even  $pp \rightarrow pp\bar{M}\bar{M}M\bar{M}$ )
- ▶ Calculate (helicity-dependent) amplitude  $\mathcal{M}_{pp \rightarrow pp\bar{M}\bar{M}}$
- ▶ Calculate differential cross sections:

$$d\sigma = \frac{1}{2s} \overline{|\mathcal{M}_{pp \rightarrow pp\bar{M}\bar{M}}|^2} \quad (3)$$

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

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

$$pp \rightarrow pp\pi^+\pi^-$$



The **four-body** process amplitude written  
in terms of **two-body** Regge amplitudes

*Lebiedowicz, Szczurek, Phys. Rev. D81 (2010) 036003.*

$$pp \rightarrow pp\pi^+\pi^-$$

The full Born amplitude of  $\pi^+\pi^-$  production is a sum of continuum amplitude and the amplitudes through the s-channel resonances:

$$\mathcal{M}_{pp \rightarrow pp\pi^+\pi^-} = \mathcal{M}_{pp \rightarrow pp\pi^+\pi^-}^{\pi\pi-\text{continuum}} + \mathcal{M}_{pp \rightarrow pp\pi^+\pi^-}^{\pi\pi-\text{resonances}}. \quad (5)$$

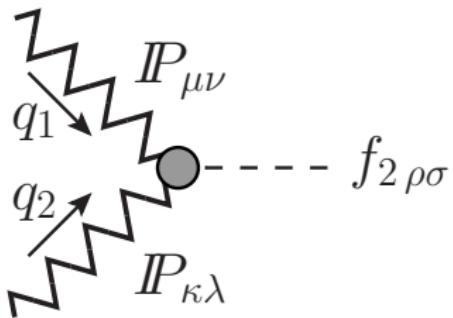
Absorption effects should be included in addition

# Resonances

Scalar/pseudoscalar resonances:

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

Tensor resonances:



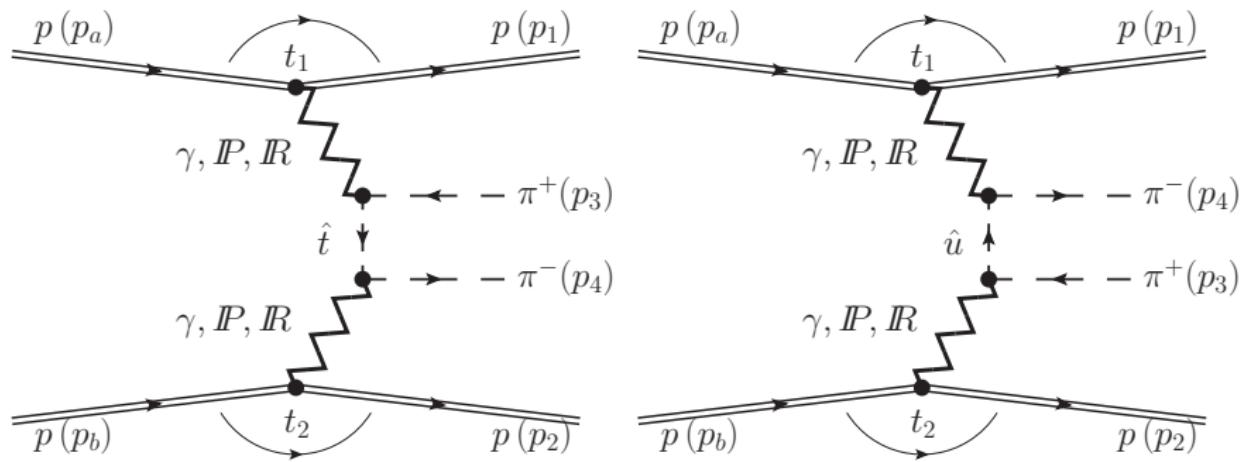
P. Lebiedowicz, O. Nachtmann and A. Szczurek, Phys. Rev. **D92** (2016) 054015.

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

We have tried different of them.

Only one (!) fits to experimental characteristics.

$$pp \rightarrow pp\pi^+\pi^-$$



The two (t- and u-channel) contributions must be added **coherently**.

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

$$pp \rightarrow pp\pi^+\pi^-$$

The **PP**-exchange amplitude can be written as

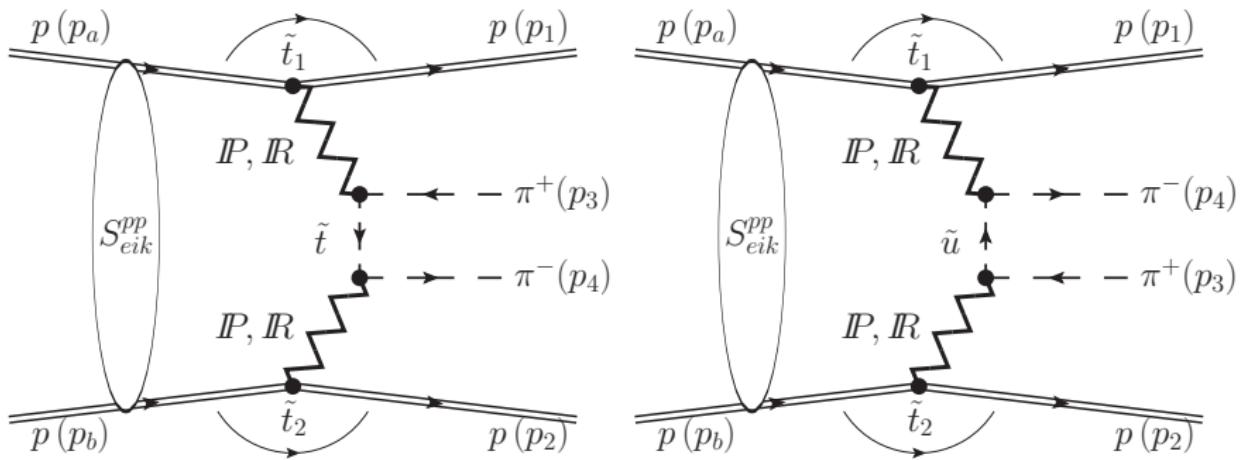
$$\mathcal{M}^{(\mathbf{PP} \rightarrow \pi^+ \pi^-)} = \mathcal{M}_{\lambda_a \lambda_b \rightarrow \lambda_1 \lambda_2 \pi^+ \pi^-}^{(\hat{t})} + \mathcal{M}_{\lambda_a \lambda_b \rightarrow \lambda_1 \lambda_2 \pi^+ \pi^-}^{(\hat{u})}, \quad (6)$$

where

$$\begin{aligned} \mathcal{M}_{\lambda_a \lambda_b \rightarrow \lambda_1 \lambda_2 \pi^+ \pi^-}^{(\hat{t})} &\simeq 3\beta_{\mathbf{PNN}} 2(p_1 + p_a)_{\mu_1} (p_1 + p_a)_{\nu_1} \delta_{\lambda_1 \lambda_a} F_1(t_1) F_M(t_1) \\ &\times 2\beta_{\mathbf{P}\pi\pi} (p_t - p_3)^{\mu_1} (p_t - p_3)^{\nu_1} \frac{1}{4s_{13}} (-is_{13}\alpha'_{\mathbf{P}})^{\alpha_{\mathbf{P}}(t_1)-1} \frac{[\hat{F}_{\pi}(p_t^2)]^2}{p_t^2 - m_{\pi}^2} \\ &\times 2\beta_{\mathbf{P}\pi\pi} (p_4 + p_t)^{\mu_2} (p_4 + p_t)^{\nu_2} \frac{1}{4s_{24}} (-is_{24}\alpha'_{\mathbf{P}})^{\alpha_{\mathbf{P}}(t_2)-1} \\ &\times 3\beta_{\mathbf{PNN}} 2(p_2 + p_b)_{\mu_2} (p_2 + p_b)_{\nu_2} \delta_{\lambda_2 \lambda_b} F_1(t_2) F_M(t_2), \end{aligned} \quad (7)$$

$$\begin{aligned} \mathcal{M}_{\lambda_a \lambda_b \rightarrow \lambda_1 \lambda_2 \pi^+ \pi^-}^{(\hat{u})} &\simeq 3\beta_{\mathbf{PNN}} 2(p_1 + p_a)_{\mu_1} (p_1 + p_a)_{\nu_1} \delta_{\lambda_1 \lambda_a} F_1(t_1) F_M(t_1) \\ &\times 2\beta_{\mathbf{P}\pi\pi} (p_4 + p_u)^{\mu_1} (p_4 + p_u)^{\nu_1} \frac{1}{4s_{14}} (-is_{14}\alpha'_{\mathbf{P}})^{\alpha_{\mathbf{P}}(t_1)-1} \frac{[\hat{F}_{\pi}(p_u^2)]^2}{p_u^2 - m_{\pi}^2} \\ &\times 2\beta_{\mathbf{P}\pi\pi} (p_u - p_3)^{\mu_2} (p_u - p_3)^{\nu_2} \frac{1}{4s_{23}} (-is_{23}\alpha'_{\mathbf{P}})^{\alpha_{\mathbf{P}}(t_2)-1} \\ &\times 3\beta_{\mathbf{PNN}} 2(p_2 + p_b)_{\mu_2} (p_2 + p_b)_{\nu_2} \delta_{\lambda_2 \lambda_b} F_1(t_2) F_M(t_2). \end{aligned} \quad (8)$$

# Absorption effects



Considerably lowers the cross section  
eikonal approximation  
kinematics dependent  $S_G$

# Absorption effects

The rescattering correction to the amplitude due to pp interaction:

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

This amplitude has to be added to the Born amplitude.  
It reduces cross section. The effective gap survival factor is then  
dependent on kinematics and collision energy.

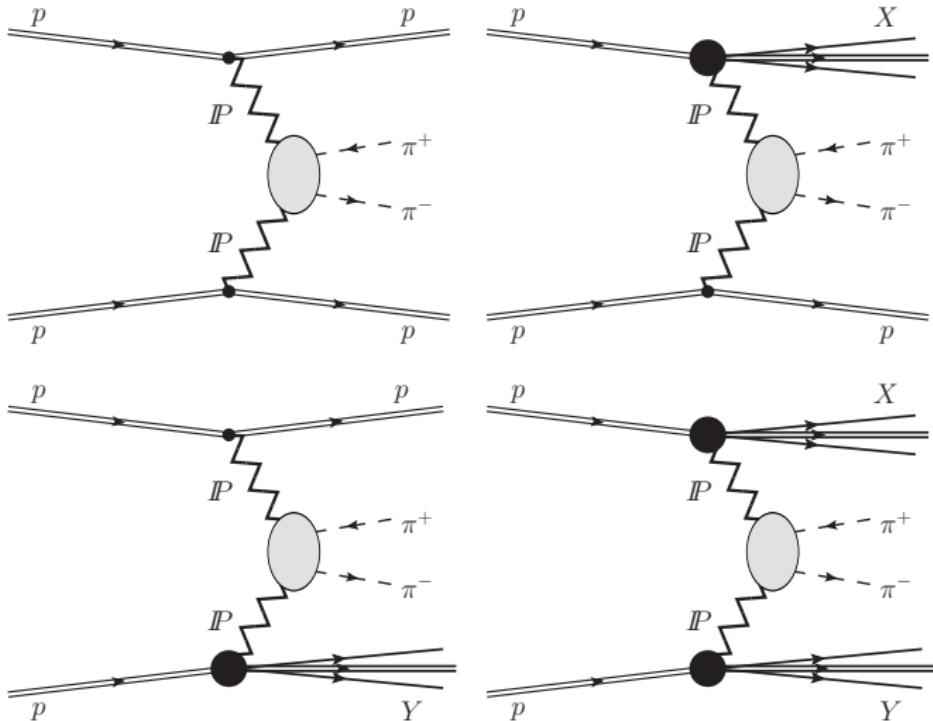
# Absorption effects

## Further corrections

$$\begin{aligned}\mathcal{M}_{pp \rightarrow pp\pi^+\pi^-}^{\pi p\text{-rescattering}} &\approx \frac{i}{16\pi^2 s_{14}} \int d^2 k_t \mathcal{M}_{pp \rightarrow pp\pi^+\pi^-}^{\text{Born}}(s, \tilde{t}_1, t_2, \tilde{t}_a) \mathcal{M}_{\pi^- p \rightarrow \pi^- p}^{\text{P-exchange}}(s_{14}, k_t) \\ &+ \frac{i}{16\pi^2 s_{13}} \int d^2 k_t \mathcal{M}_{pp \rightarrow pp\pi^+\pi^-}^{\text{Born}}(s, \tilde{t}_1, t_2, \tilde{u}_a) \mathcal{M}_{\pi^+ p \rightarrow \pi^+ p}^{\text{P-exchange}}(s_{13}, k_t) \\ &+ \frac{i}{16\pi^2 s_{23}} \int d^2 k_t \mathcal{M}_{pp \rightarrow pp\pi^+\pi^-}^{\text{Born}}(s, t_1, \tilde{t}_2, \tilde{t}_b) \mathcal{M}_{\pi^+ p \rightarrow \pi^+ p}^{\text{P-exchange}}(s_{23}, k_t) \\ &+ \frac{i}{16\pi^2 s_{24}} \int d^2 k_t \mathcal{M}_{pp \rightarrow pp\pi^+\pi^-}^{\text{Born}}(s, t_1, \tilde{t}_2, \tilde{u}_b) \mathcal{M}_{\pi^- p \rightarrow \pi^- p}^{\text{P-exchange}}(s_{24}, k_t)\end{aligned}$$

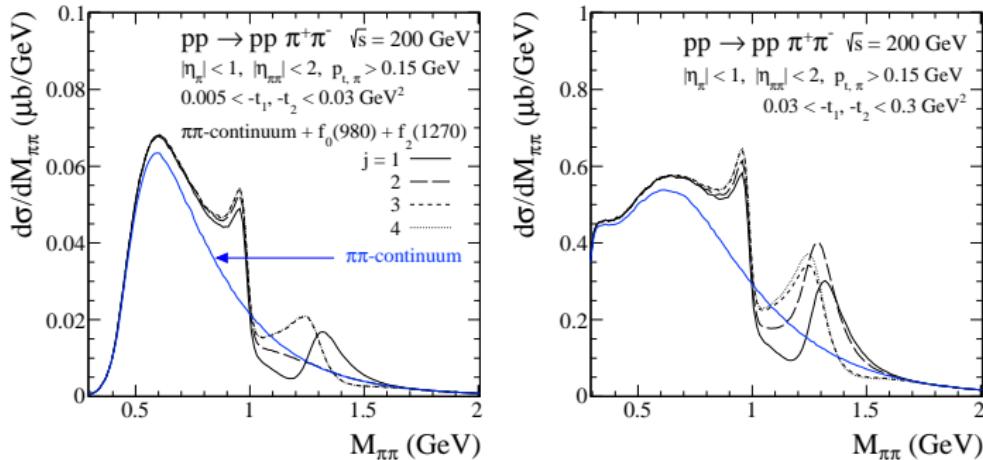
P. Lebiedowicz and A. Szczurek, “Revised model of absorption corrections for the  $pp \rightarrow pp\pi^+\pi^-$ ”, Phys. Rev. D92 (2015) 054001.

# Non exclusive processes



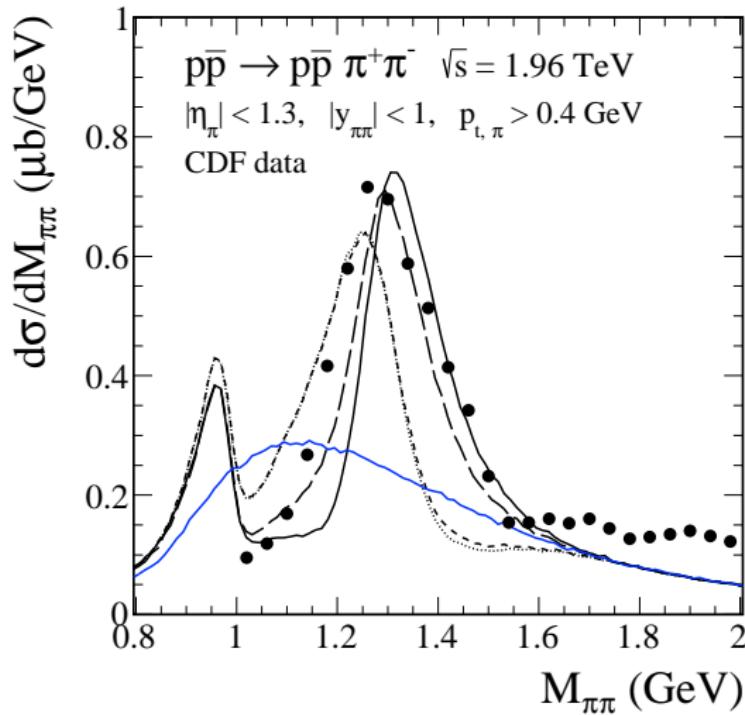
Very forward/backward emission of remnant particles  
Contribute when protons are not measured (!)

$$pp \rightarrow pp\pi^+\pi^-$$



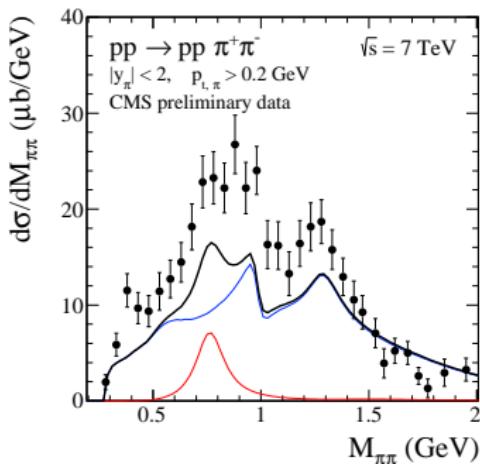
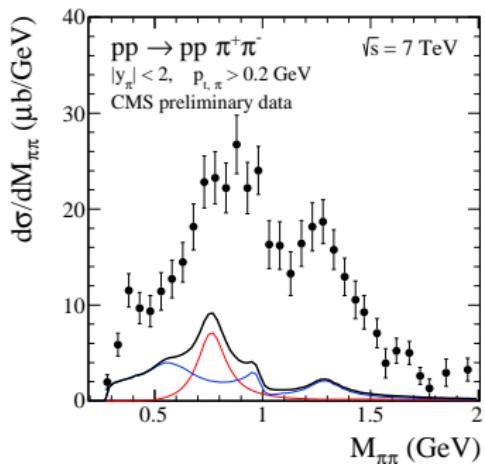
Interesting (**negative**) interference of  $f_0(980)$  and two-pion continuum.

$p\bar{p} \rightarrow p\bar{p} \pi^+ \pi^-$



Not completely exclusive data (protons not measured).

$pp \rightarrow pp\pi^+\pi^-$



The parameters fixed to the CDF data.

Warning: Preliminary CMS data

Dissociation contributions ?

$$pp \rightarrow f_2(\rightarrow \pi^+ \pi^-) pp$$

$$\begin{aligned} \mathcal{M}_{\lambda_a \lambda_b \rightarrow \lambda_1 \lambda_2 \pi^+ \pi^-}^{(\mathbf{P}\mathbf{P} \rightarrow f_2 \rightarrow \pi^+ \pi^-)} = & (-i) \bar{u}(p_1, \lambda_1) i\Gamma_{\mu_1 \nu_1}^{(\mathbf{P}pp)}(p_1, p_a) u(p_a, \lambda_a) i\Delta^{(\mathbf{P}) \mu_1 \nu_1, \alpha_1 \beta_1}(s_1, t_1) \\ & \times i\Gamma_{\alpha_1 \beta_1, \alpha_2 \beta_2, \rho \sigma}^{(\mathbf{P}\mathbf{P}f_2)}(q_1, q_2) i\Delta^{(f_2) \rho \sigma, \alpha \beta}(p_{34}) i\Gamma_{\alpha \beta}^{(f_2 \pi \pi)}(p_3, p_4) \\ & \times i\Delta^{(\mathbf{P}) \alpha_2 \beta_2, \mu_2 \nu_2}(s_2, t_2) \bar{u}(p_2, \lambda_2) i\Gamma_{\mu_2 \nu_2}^{(\mathbf{P}pp)}(p_2, p_b) u(p_b, \lambda_b). \end{aligned} \quad (11)$$

The main ingredient of the amplitude (11) is the pomeron-pomeron- $f_2$  vertex

$$i\Gamma_{\mu\nu, \kappa\lambda, \rho\sigma}^{(\mathbf{P}\mathbf{P}f_2)}(q_1, q_2) = \left( i\Gamma_{\mu\nu, \kappa\lambda, \rho\sigma}^{(\mathbf{P}\mathbf{P}f_2)(1)}|_{bare} + \sum_{j=2}^7 i\Gamma_{\mu\nu, \kappa\lambda, \rho\sigma}^{(\mathbf{P}\mathbf{P}f_2)(j)}(q_1, q_2)|_{bare} \right) \tilde{F}^{(\mathbf{P}\mathbf{P}f_2)}(q_1^2, q_2^2)$$

## Different $\mathbf{PP} \rightarrow f_2$ couplings

$$i\Gamma_{\mu\nu,\kappa\lambda,\rho\sigma}^{(\mathbf{PP}f_2)(1)} = 2i g_{\mathbf{PP}f_2}^{(1)} M_0 R_{\mu\nu\mu_1\nu_1} R_{\kappa\lambda\alpha_1\lambda_1} R_{\rho\sigma\rho_1\sigma_1} g^{\nu_1\alpha_1} g^{\lambda_1\rho_1} g^{\sigma_1\mu_1}, \quad (13)$$

$$\begin{aligned} i\Gamma_{\mu\nu,\kappa\lambda,\rho\sigma}^{(\mathbf{PP}f_2)(2)}(q_1, q_2) = & -\frac{2i}{M_0} g_{\mathbf{PP}f_2}^{(2)} \left( (q_1 \cdot q_2) R_{\mu\nu\rho_1\alpha} R_{\kappa\lambda\sigma_1}{}^\alpha - q_{1\rho_1} q_2^{\mu_1} R_{\mu\nu\mu_1\alpha} R_{\kappa\lambda\sigma_1}{}^\alpha \right. \\ & \left. - q_1^{\mu_1} q_{2\sigma_1} R_{\mu\nu\rho_1\alpha} R_{\kappa\lambda\mu_1}{}^\alpha + q_{1\rho_1} q_{2\sigma_1} R_{\mu\nu\kappa\lambda} \right) R_{\rho\sigma} \end{aligned} \quad (14)$$

$$\begin{aligned} i\Gamma_{\mu\nu,\kappa\lambda,\rho\sigma}^{(\mathbf{PP}f_2)(3)}(q_1, q_2) = & -\frac{2i}{M_0} g_{\mathbf{PP}f_2}^{(3)} \left( (q_1 \cdot q_2) R_{\mu\nu\rho_1\alpha} R_{\kappa\lambda\sigma_1}{}^\alpha + q_{1\rho_1} q_2^{\mu_1} R_{\mu\nu\mu_1\alpha} R_{\kappa\lambda\sigma_1}{}^\alpha \right. \\ & \left. + q_1^{\mu_1} q_{2\sigma_1} R_{\mu\nu\rho_1\alpha} R_{\kappa\lambda\mu_1}{}^\alpha + q_{1\rho_1} q_{2\sigma_1} R_{\mu\nu\kappa\lambda} \right) R_{\rho\sigma} \end{aligned} \quad (15)$$

## Different $\text{PP} \rightarrow f_2$ couplings

$$i\Gamma_{\mu\nu,\kappa\lambda,\rho\sigma}^{(\text{PP}f_2)(4)}(q_1, q_2) = -\frac{i}{M_0} g_{\text{PP}f_2}^{(4)} \left( q_1^{\alpha_1} q_2^{\mu_1} R_{\mu\nu\mu_1\nu_1} R_{\kappa\lambda\alpha_1\lambda_1} + q_2^{\alpha_1} q_1^{\mu_1} R_{\mu\nu\alpha_1\lambda_1} R_{\kappa\lambda\mu_1} \right) \quad (16)$$

$$i\Gamma_{\mu\nu,\kappa\lambda,\rho\sigma}^{(\text{PP}f_2)(5)}(q_1, q_2) = -\frac{2i}{M_0^3} g_{\text{PP}f_2}^{(5)} \left( q_1^{\mu_1} q_2^{\nu_1} R_{\mu\nu\nu_1\alpha} R_{\kappa\lambda\mu_1}{}^\alpha + q_1^{\nu_1} q_2^{\mu_1} R_{\mu\nu\mu_1\alpha} R_{\kappa\lambda\nu_1}{}^\alpha - 2 (q_1 \cdot q_2) R_{\mu\nu\kappa\lambda} \right) q_1^{\alpha_1} q_2^{\lambda_1} R^{\alpha_1\lambda_1}{}_{\rho\sigma}, \quad (17)$$

$$i\Gamma_{\mu\nu,\kappa\lambda,\rho\sigma}^{(\text{PP}f_2)(6)}(q_1, q_2) = \frac{i}{M_0^3} g_{\text{PP}f_2}^{(6)} \left( q_1^{\alpha_1} q_1^{\lambda_1} q_2^{\mu_1} q_2^{\rho_1} R_{\mu\nu\mu_1\nu_1} R_{\kappa\lambda\alpha_1\lambda_1} + q_2^{\alpha_1} q_2^{\lambda_1} q_1^{\mu_1} q_1^{\rho_1} R_{\mu\nu\alpha_1\lambda_1} R_{\kappa\lambda\mu_1\nu_1} \right) R^{\nu_1\rho_1}{}_{\rho\sigma}, \quad (18)$$

$$i\Gamma_{\mu\nu,\kappa\lambda,\rho\sigma}^{(\text{PP}f_2)(7)}(q_1, q_2) = -\frac{2i}{M_0^5} g_{\text{PP}f_2}^{(7)} q_1^{\rho_1} q_1^{\alpha_1} q_1^{\lambda_1} q_2^{\sigma_1} q_2^{\mu_1} q_2^{\nu_1} R_{\mu\nu\mu_1\nu_1} R_{\kappa\lambda\alpha_1\lambda_1} R_{\rho\sigma\rho_1\sigma_1}, \quad (19)$$

$$pp \rightarrow f_2(\rightarrow \pi^+ \pi^-) pp$$

Let us go to the  $f_2(1270)$  center of mass system.

We choose the **Collins-Soper basis** for the reaction with unit vectors defining the axes as follows:

$$\mathbf{e}_{1,CS} = \frac{\hat{\mathbf{p}}_a + \hat{\mathbf{p}}_b}{|\hat{\mathbf{p}}_a + \hat{\mathbf{p}}_b|}, \quad (20)$$

$$\mathbf{e}_{2,CS} = \frac{\hat{\mathbf{p}}_a \times \hat{\mathbf{p}}_b}{|\hat{\mathbf{p}}_a \times \hat{\mathbf{p}}_b|}, \quad (21)$$

$$\mathbf{e}_{3,CS} = \frac{\hat{\mathbf{p}}_a - \hat{\mathbf{p}}_b}{|\hat{\mathbf{p}}_a - \hat{\mathbf{p}}_b|}. \quad (22)$$

Here  $\hat{\mathbf{p}}_a = \mathbf{p}_1/|\mathbf{p}_1|$ ,  $\hat{\mathbf{p}}_b = \mathbf{p}_2/|\mathbf{p}_2|$ , where  $\mathbf{p}_1$ ,  $\mathbf{p}_2$  are the three-momenta of the initial protons in the  $\pi^+ \pi^-$  rest system.

P. Lebiedowicz, O. Nachtmann and A. Szczurek, arXiv:1901.07788.

# Angular distributions

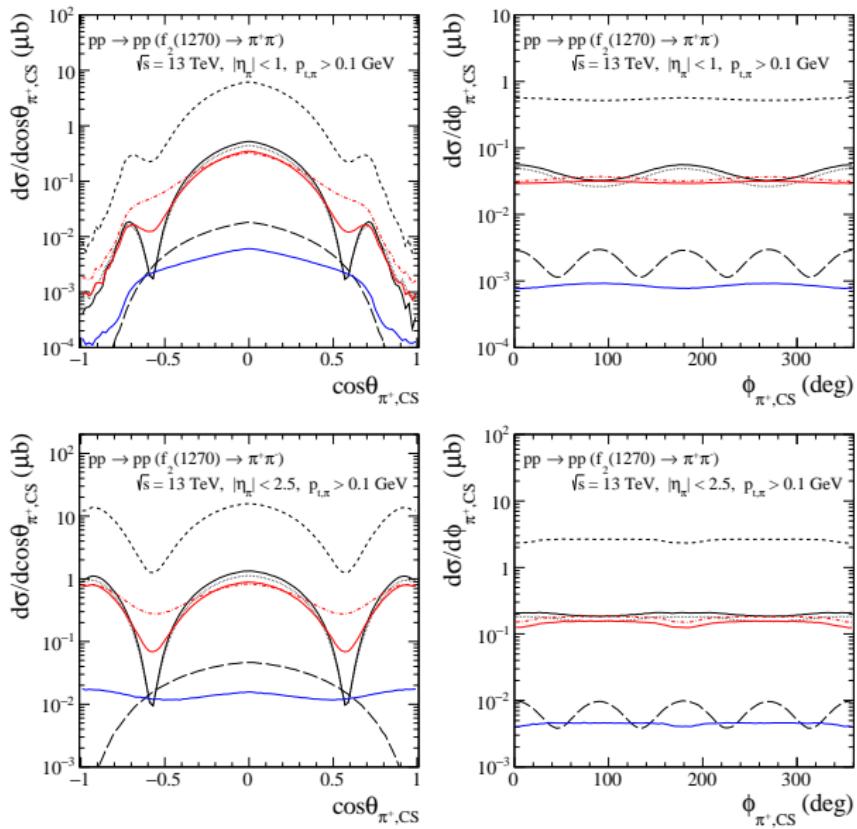
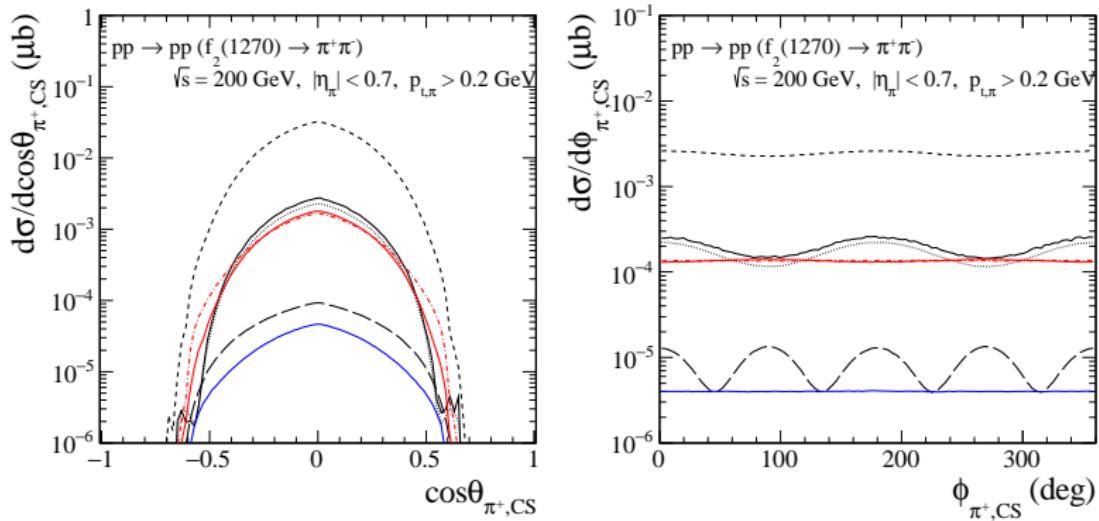


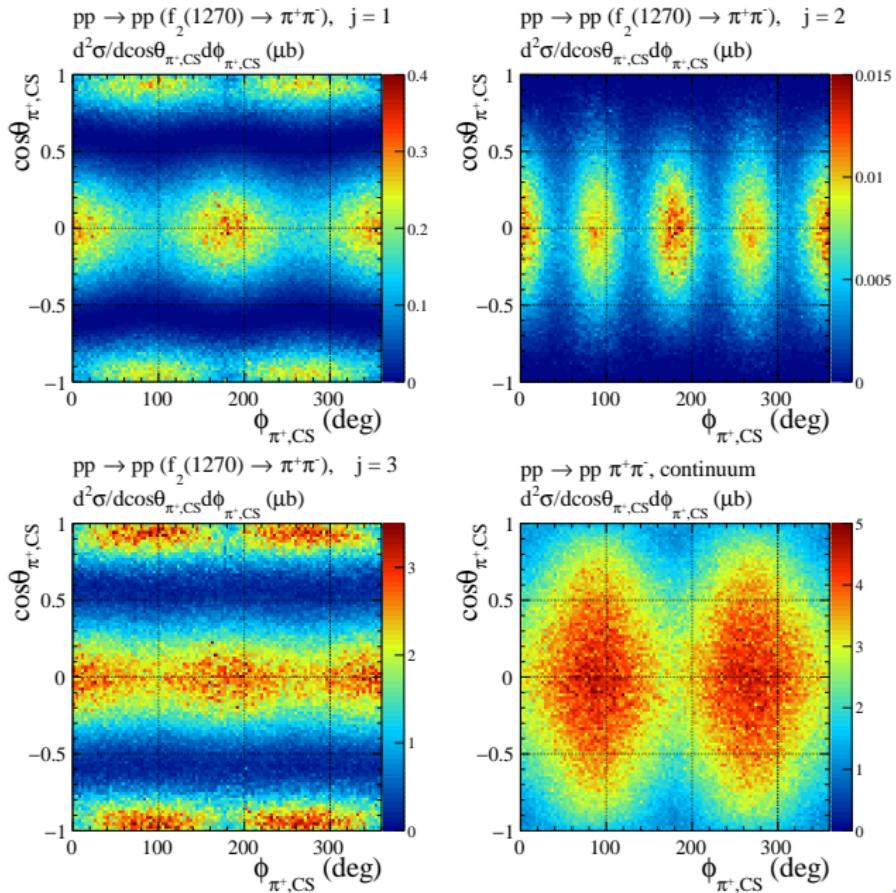
Figure: The distributions in  $\cos\theta_{\pi^+,CS}$  (the left panels) and in  $\phi_{\pi^+,CS}$  (the right panels) for the reaction  $pp \rightarrow pp(f_2^{(1270)} \rightarrow \pi^+\pi^-)$  at  $\sqrt{s} = 13$  TeV. The top row corresponds to the selection condition  $|p_{t,\pi}| < 1$  and  $p_{t,\pi} > 0.1$  GeV. The bottom row corresponds to the more relaxed selection condition  $|p_{t,\pi}| < 2.5$  and  $p_{t,\pi} > 0.1$  GeV. The distributions are plotted as  $d\sigma/d\cos\theta_{\pi^+,CS}$  (left panels) and  $d\sigma/d\phi_{\pi^+,CS}$  (right panels) in units of  $\mu\text{b}$ .

# Angular distributions

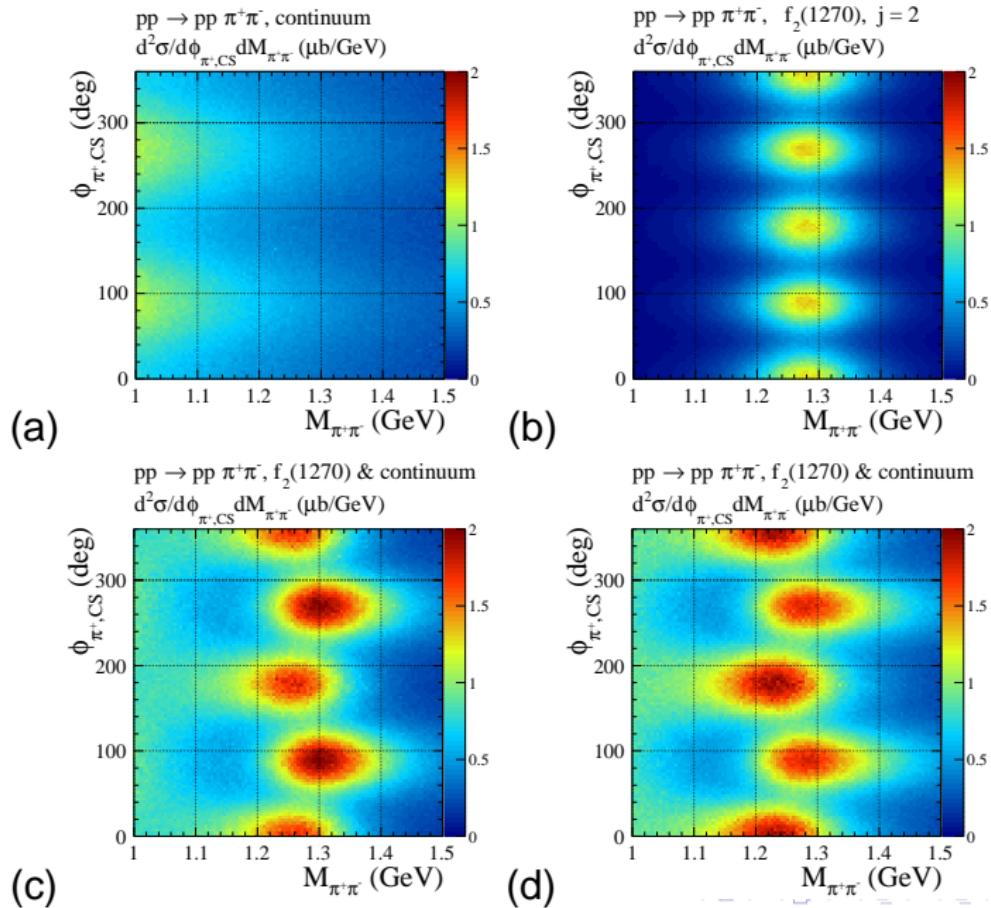


**Figure:** The same but for  $\sqrt{s} = 200 \text{ GeV}$  and the STAR experimental cuts:  $|\eta_\pi| < 0.7$ ,  $p_{t,\pi} > 0.2 \text{ GeV}$ , and with extra cuts on the leading protons of  $(p_{x,p} + 0.3 \text{ GeV})^2 + p_{y,p}^2 < 0.25 \text{ GeV}^2$ ,  $0.2 \text{ GeV} < |p_{y,p}| < 0.4 \text{ GeV}$ ,  $p_{x,p} > -0.2 \text{ GeV}$ .

# Angular distributions



# Angular distributions



# Angular distributions

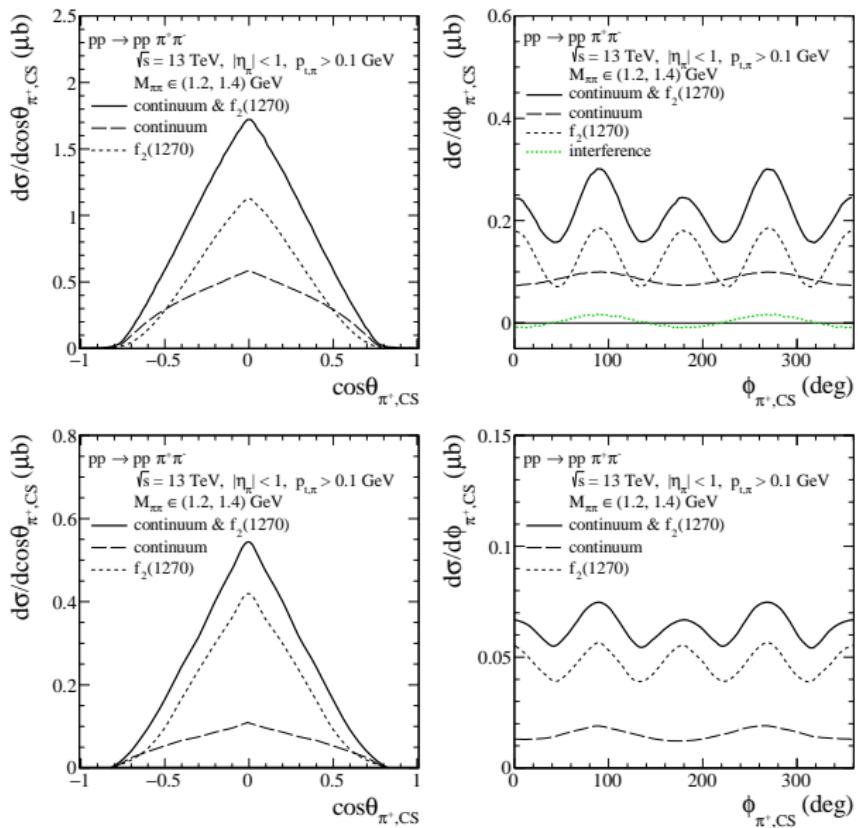
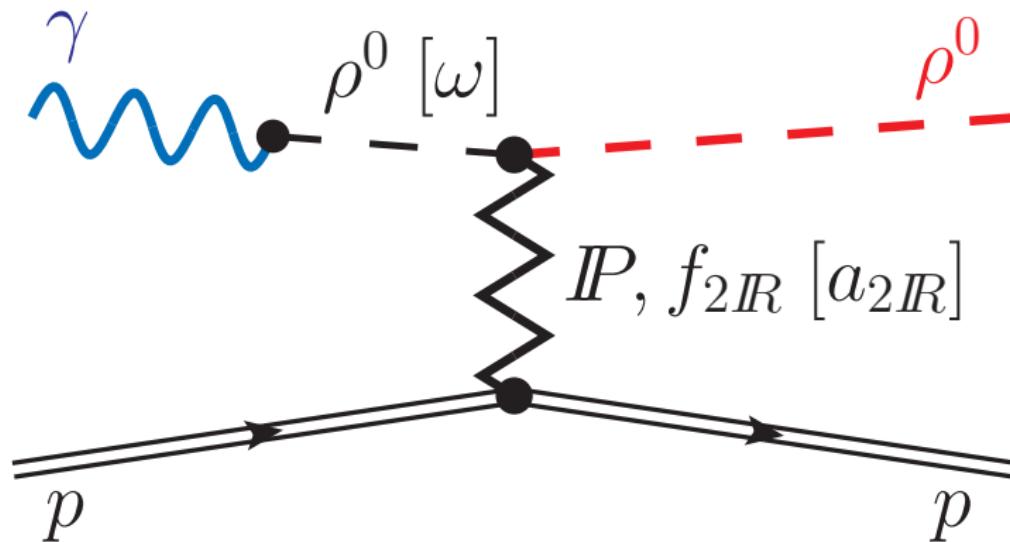


Figure: The distributions in  $\cos \theta_{\pi^+,CS}$  (the left panels) and in  $\phi_{\pi^+,CS}$  (the right panels) for  $pp \rightarrow pp \pi^+ \pi^-$  at  $\sqrt{s} = 13 \text{ TeV}$ . The distributions are shown for different contributions: continuum (dashed line), continuum &  $f_2(1270)$  (solid line), and  $f_2(1270)$  (dotted line). The interference term (dotted line) is small and mostly negligible.

# Photoproduction at HERA

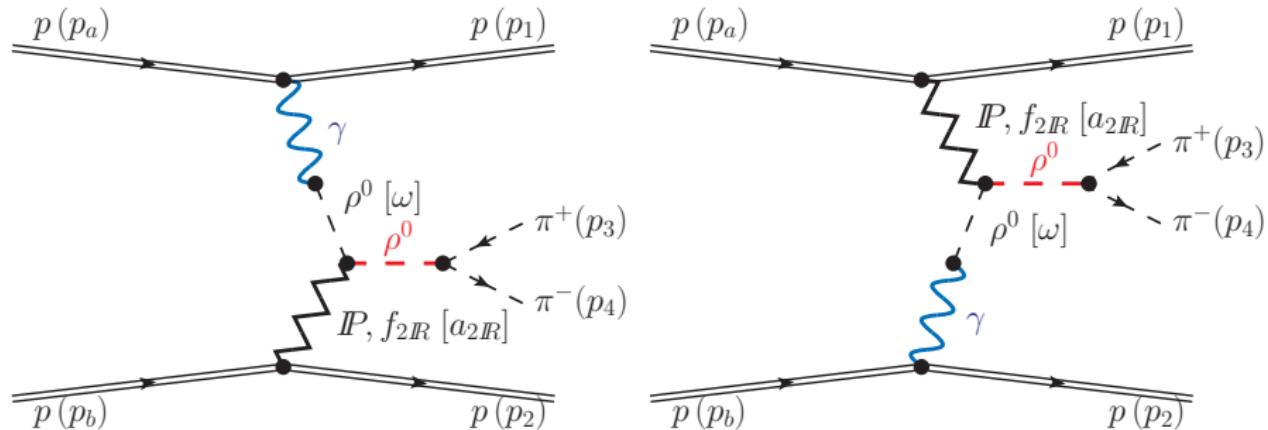
VDM (vector dominance model) mechanism:



Can be inserted to  $pp$  collisions.

$$pp \rightarrow pp\pi^+\pi^-$$

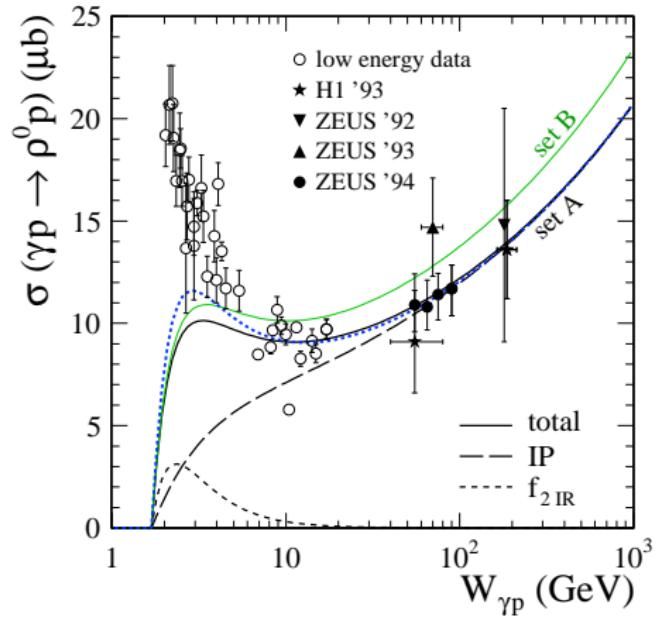
photon induced production of  $\rho^0$  resonances



Dominant photoproduction mechanism in the  $\pi^+\pi^-$  channel.

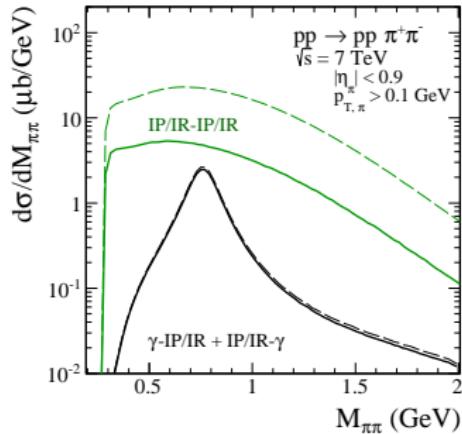
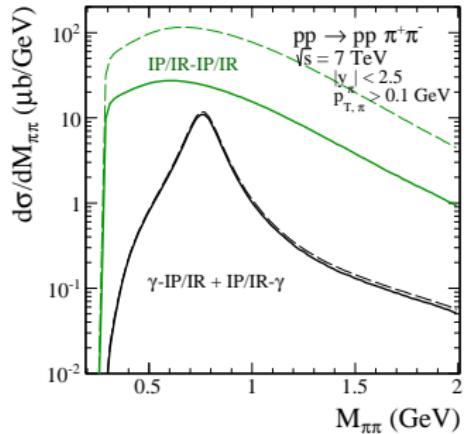
P.Lebiedowicz, O. Nachtmann and A. Szczurek, Phys. Rev. D91 (2015) 074023.

# HERA data



No freedom for  $2 \rightarrow 4$   $pp \rightarrow pp\rho^0$  processes.

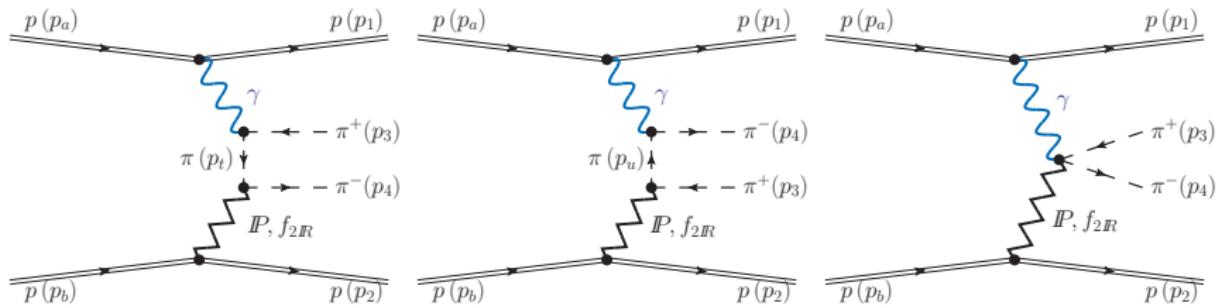
$pp \rightarrow pp\pi^+\pi^-$



with absorption effects included

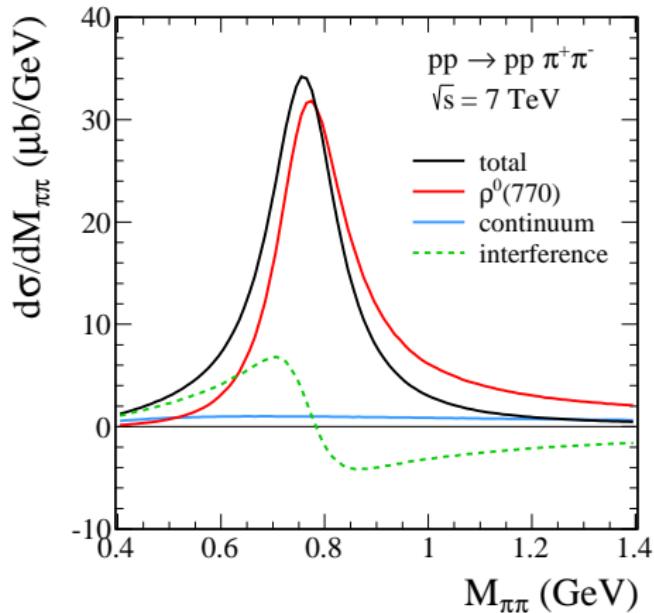
$$pp \rightarrow pp\pi^+\pi^-$$

photon induced diffractive continuum



So-called **Söding mechanism**.

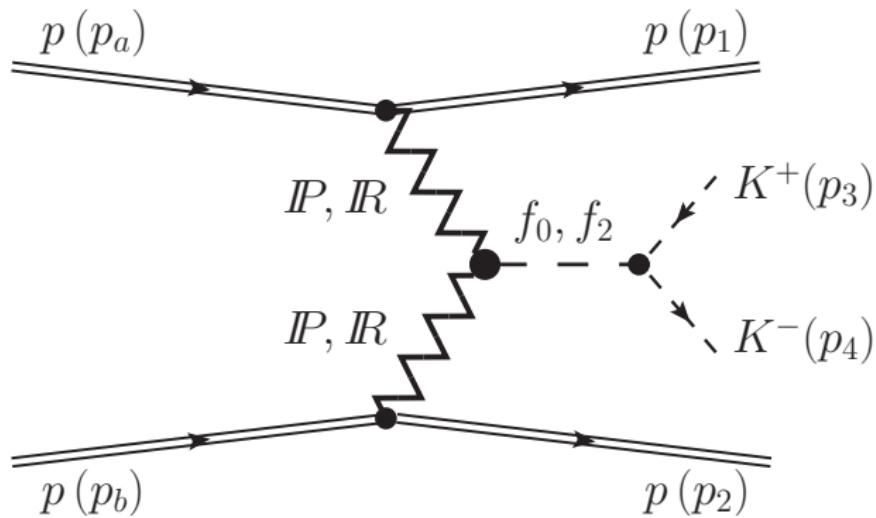
# Interference effect



Modification of the spectral shape (**skewness**).

$$pp \rightarrow ppK^+K^-$$

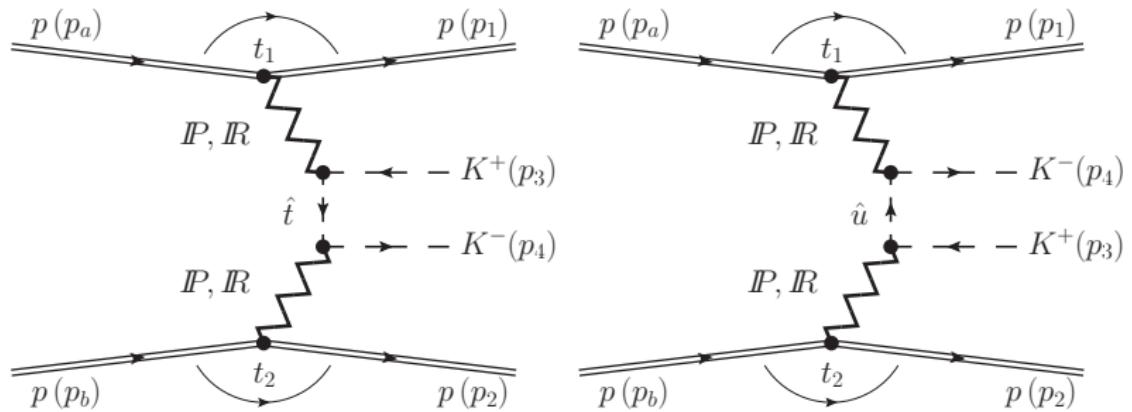
Purely diffractive resonance mechanisms:



P. Lebiedowicz, O. Nachtmann and A. Szczurek, arXiv:1804.04706,  
Phys. Rev. D98 (2018) 014016

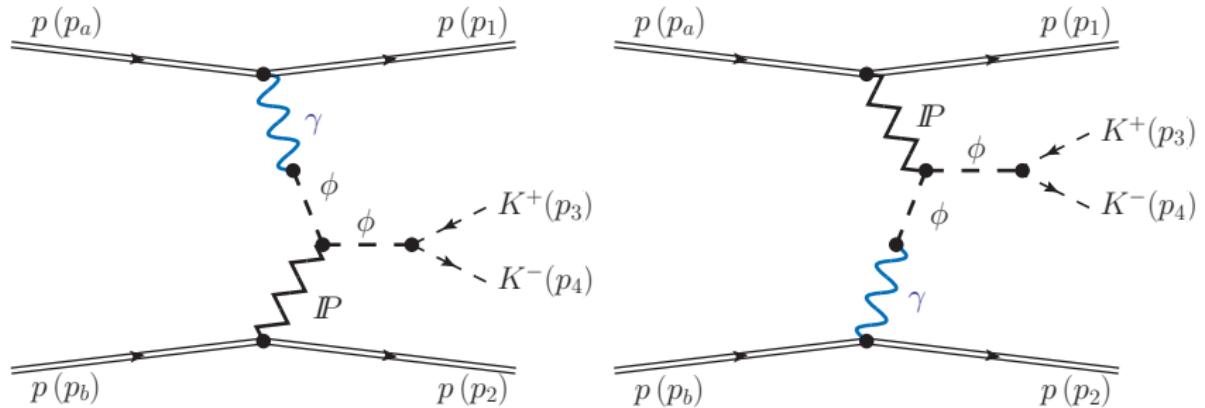
$$pp \rightarrow ppK^+K^-$$

Purely diffractive continuum mechanism:



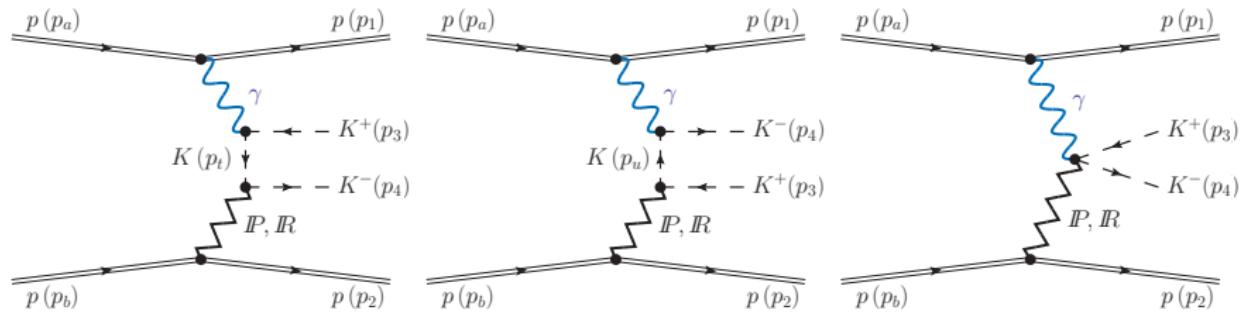
$$pp \rightarrow ppK^+K^-$$

Diffractive photoproduction resonance mechanism:

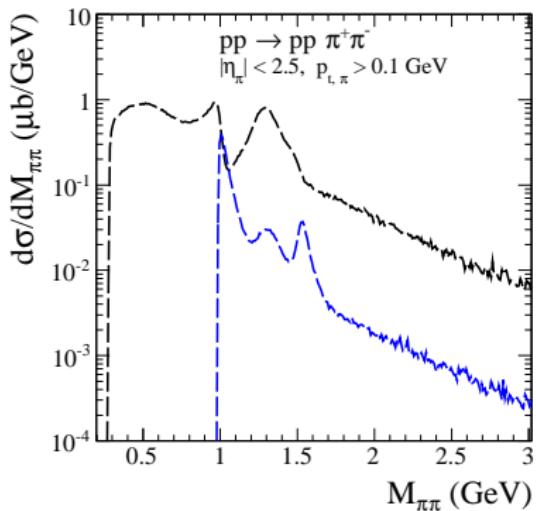
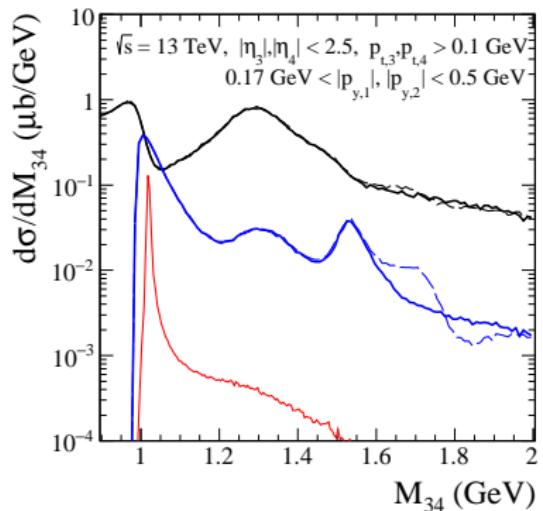


$$pp \rightarrow ppK^+K^-$$

Diffractive photoproduction continuum mechanism:

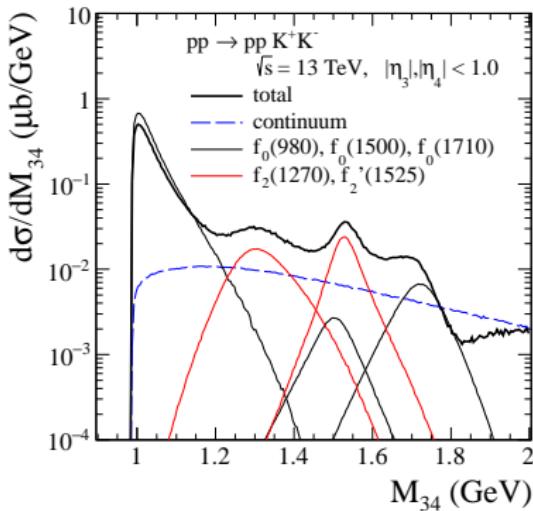


# Results for CMS



CMS rapidity acceptance

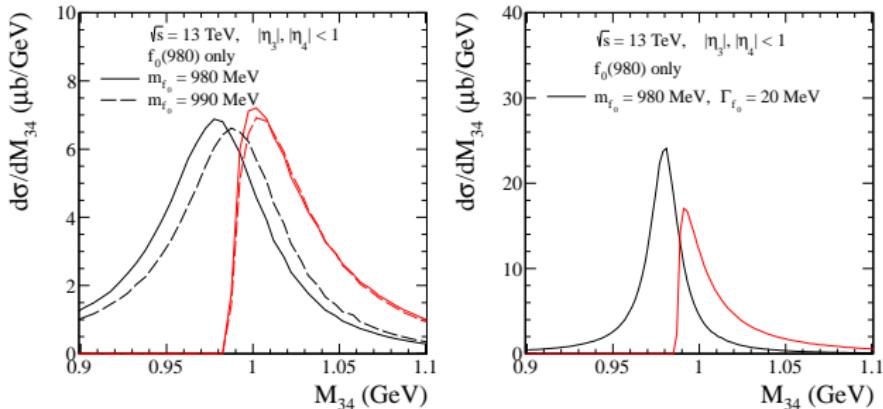
# Resonance decomposition



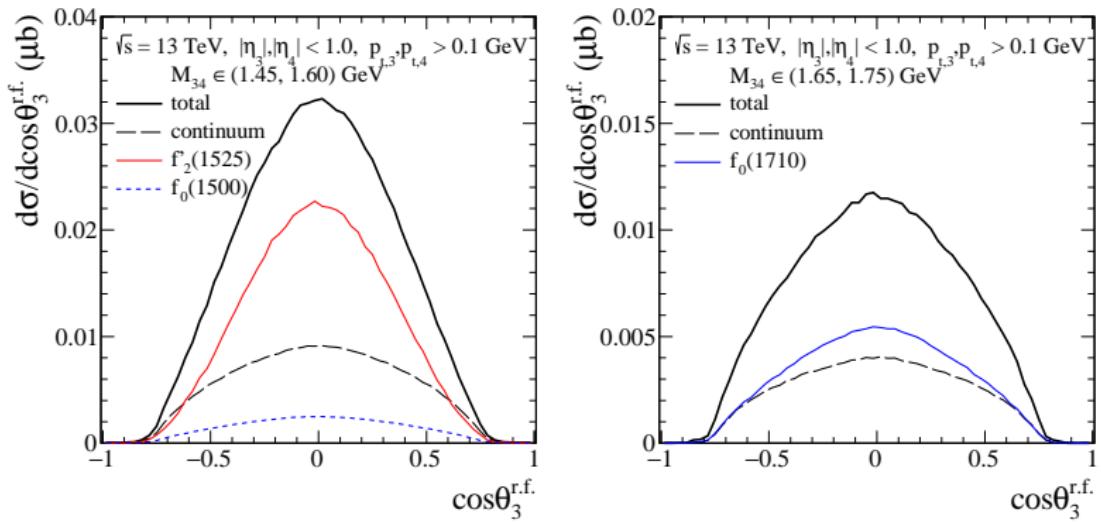
Really many resonances may participate.

Parameters fixed by detailed knowledge of different reactions.

# $f_0(980)$ line shape



# Angular distribution in the KK rest frame ( $f_0(1500)$ and $f_0(1710)$ )

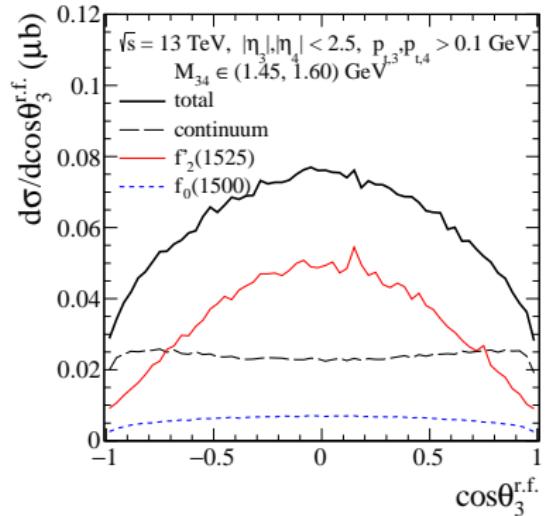


Not too instructive!

Too small range of rapidity?

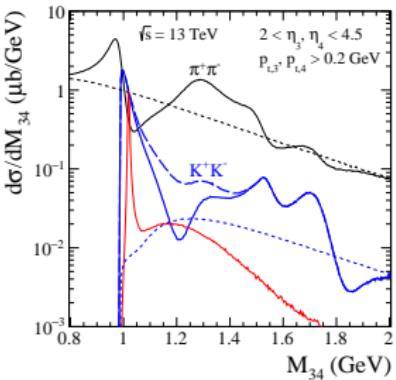
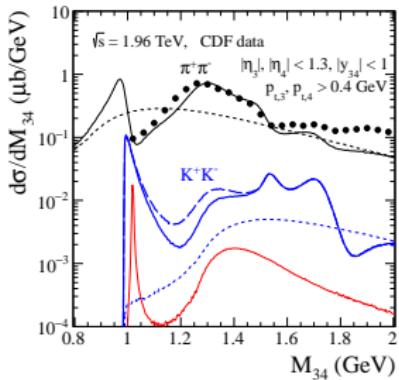
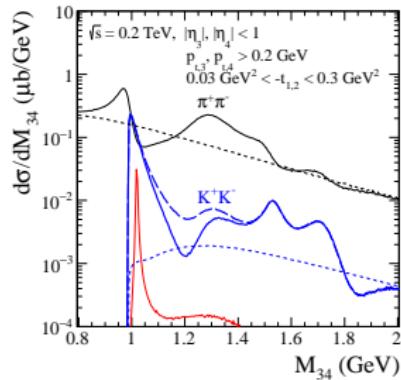
Can CMS measured such distributions?

# Angular distribution in the KK rest frame



CMS range of rapidities

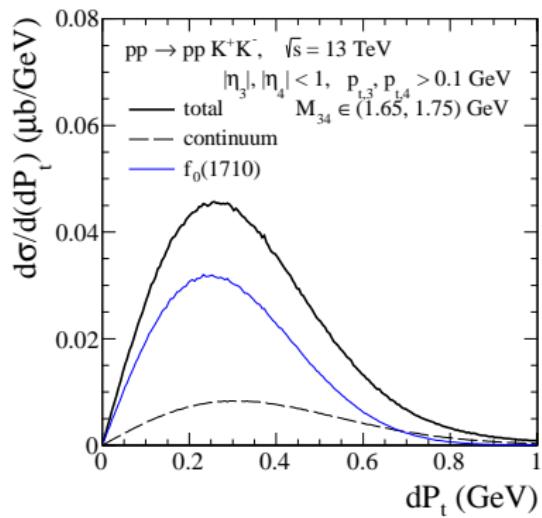
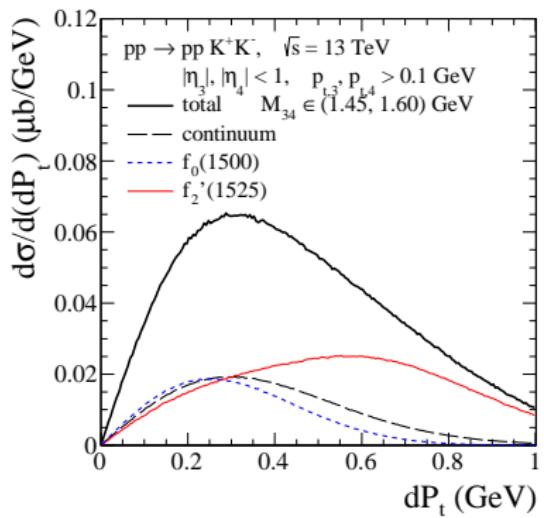
# Predictions for different experiments



Can one observe  $\phi$  meson ?

# Glueball filter variable distribution

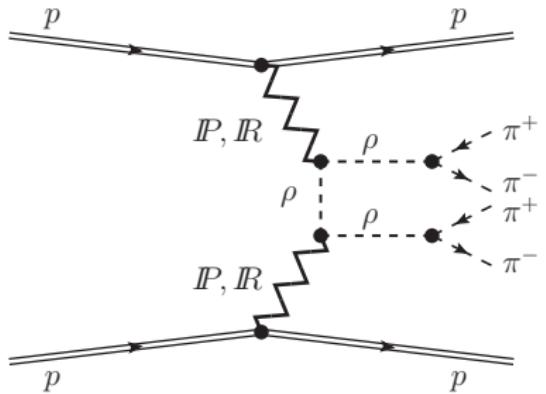
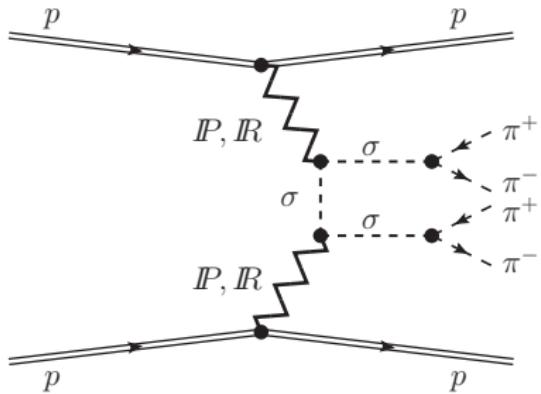
$$d\mathbf{P}_t = \mathbf{q}_{t,1} - \mathbf{q}_{t,2} = \mathbf{p}_{t,2} - \mathbf{p}_{t,1}, \quad dP_t = |\mathbf{dP}_t|. \quad (23)$$



Some difference between continuum and resonances

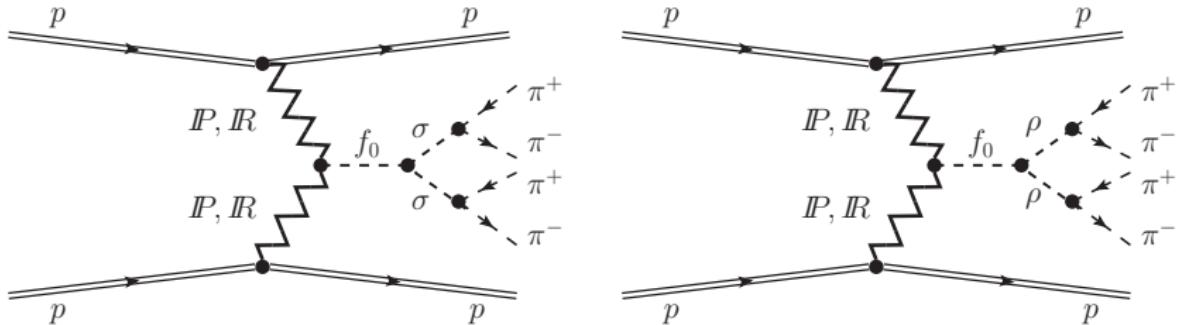
$$pp \rightarrow pp\pi^+\pi^-\pi^+\pi^-$$

Double resonance production:



$$pp \rightarrow pp\pi^+\pi^-\pi^+\pi^-$$

### Single resonance production:



- ▶ Contribution to mechanism of diffractive production of resonances  
 $(f_2(1270), f_1(1285), f_0(1500), f_0(1710), f_2(1950))$
- ▶ Contribution to decays and branching fractions.

$$pp \rightarrow pp\sigma\sigma$$

The amplitude for this process can be written as the following sum:

$$\mathcal{M}_{pp \rightarrow pp\sigma\sigma}^{(\sigma-\text{exchange})} = \mathcal{M}^{(\mathbf{P}\mathbf{P} \rightarrow \sigma\sigma)} + \mathcal{M}^{(\mathbf{P}f_{2R} \rightarrow \sigma\sigma)} + \mathcal{M}^{(f_{2R}\mathbf{P} \rightarrow \sigma\sigma)} + \mathcal{M}^{(f_{2R}f_{2R} \rightarrow \sigma\sigma)} \quad (24)$$

For instance, the **PP**-exchange amplitude can be written as

$$\mathcal{M}^{(\mathbf{P}\mathbf{P} \rightarrow \sigma\sigma)} = \mathcal{M}_{\lambda_a \lambda_b \rightarrow \lambda_1 \lambda_2 \sigma\sigma}^{(\hat{t})} + \mathcal{M}_{\lambda_a \lambda_b \rightarrow \lambda_1 \lambda_2 \sigma\sigma}^{(\hat{u})} \quad (25)$$

with the  $\hat{t}$ - and  $\hat{u}$ -channel amplitudes

$$\begin{aligned} \mathcal{M}_{\lambda_a \lambda_b \rightarrow \lambda_1 \lambda_2 \sigma\sigma}^{(\hat{t})} = & (-i) \bar{u}(p_1, \lambda_1) i\Gamma_{\mu_1 \nu_1}^{(\mathbf{P}pp)}(p_1, p_a) u(p_a, \lambda_a) i\Delta^{(\mathbf{P}) \mu_1 \nu_1, \alpha_1 \beta_1}(s_{13}, t_1) i\Gamma_{\alpha_1 \beta_1}^{(\mathbf{P}\sigma\sigma)}(p_t, -p_3) i\Delta^{(\sigma)}(p_t) \\ & \times i\Gamma_{\alpha_2 \beta_2}^{(\mathbf{P}\sigma\sigma)}(p_4, p_t) i\Delta^{(\mathbf{P}) \alpha_2 \beta_2, \mu_2 \nu_2}(s_{24}, t_2) \bar{u}(p_2, \lambda_2) i\Gamma_{\mu_2 \nu_2}^{(\mathbf{P}pp)}(p_2, p_b) u(p_b, \lambda_b), \end{aligned} \quad (26)$$

$$\begin{aligned} \mathcal{M}_{\lambda_a \lambda_b \rightarrow \lambda_1 \lambda_2 \sigma\sigma}^{(\hat{u})} = & (-i) \bar{u}(p_1, \lambda_1) i\Gamma_{\mu_1 \nu_1}^{(\mathbf{P}pp)}(p_1, p_a) u(p_a, \lambda_a) i\Delta^{(\mathbf{P}) \mu_1 \nu_1, \alpha_1 \beta_1}(s_{14}, t_1) i\Gamma_{\alpha_1 \beta_1}^{(\mathbf{P}\sigma\sigma)}(p_4, p_u) i\Delta^{(\sigma)}(p_u) \\ & \times i\Gamma_{\alpha_2 \beta_2}^{(\mathbf{P}\sigma\sigma)}(p_u, -p_3) i\Delta^{(\mathbf{P}) \alpha_2 \beta_2, \mu_2 \nu_2}(s_{23}, t_2) \bar{u}(p_2, \lambda_2) i\Gamma_{\mu_2 \nu_2}^{(\mathbf{P}pp)}(p_2, p_b) u(p_b, \lambda_b). \end{aligned} \quad (27)$$

$$pp \rightarrow pp\rho^0\rho^0$$

We write the amplitude as

$$\mathcal{M}_{\lambda_a\lambda_b \rightarrow \lambda_1\lambda_2\rho\rho} = \left(\epsilon_{\rho_3}^{(\rho)}(\lambda_3)\right)^* \left(\epsilon_{\rho_4}^{(\rho)}(\lambda_4)\right)^* \mathcal{M}_{\lambda_a\lambda_b \rightarrow \lambda_1\lambda_2\rho\rho}^{\rho_3\rho_4}, \quad (28)$$

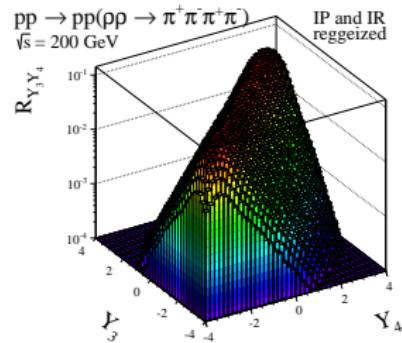
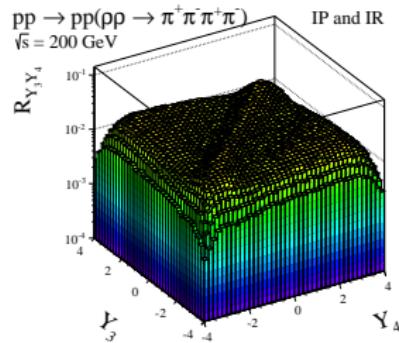
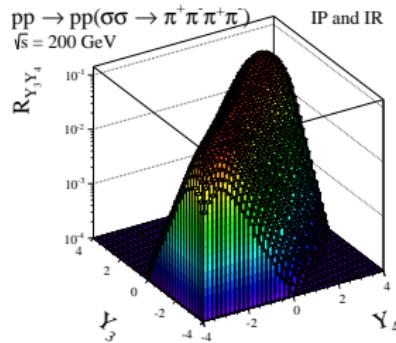
where  $\epsilon_{\rho}^{(\rho)}(\lambda)$  are the polarisation vectors of the  $\rho$  meson.

$$\begin{aligned} \mathcal{M}_{\lambda_a\lambda_b \rightarrow \lambda_1\lambda_2\rho\rho}^{(\rho\text{-exchange})\rho_3\rho_4} &\simeq 2(p_1 + p_a)_{\mu_1}(p_1 + p_a)_{\nu_1} \delta_{\lambda_1\lambda_a} F_1(t_1) F_M(t_1) \\ &\times \left\{ V^{\rho_3\rho_1\mu_1\nu_1}(s_{13}, t_1, p_t, p_3) \Delta_{\rho_1\rho_2}^{(\rho)}(p_t) V^{\rho_4\rho_2\mu_2\nu_2}(s_{24}, t_2, -p_t, p_4) \left[ \hat{F}_\rho(p_t^2) \right]^2 \right. \\ &+ V^{\rho_4\rho_1\mu_1\nu_1}(s_{14}, t_1, -p_u, p_4) \Delta_{\rho_1\rho_2}^{(\rho)}(p_u) V^{\rho_3\rho_2\mu_2\nu_2}(s_{23}, t_2, p_u, p_3) \left[ \hat{F}_\rho(p_u^2) \right]^2 \left. \right\} \\ &\times 2(p_2 + p_b)_{\mu_2}(p_2 + p_b)_{\nu_2} \delta_{\lambda_2\lambda_b} F_1(t_2) F_M(t_2), \end{aligned} \quad (29)$$

where  $V_{\mu\nu\kappa\lambda}$  reads as

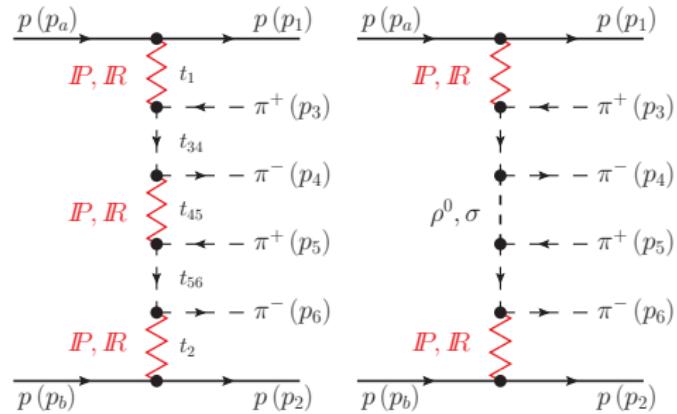
$$\begin{aligned} V_{\mu\nu\kappa\lambda}(s, t, k_2, k_1) &= 2\Gamma_{\mu\nu\kappa\lambda}^{(0)}(k_1, k_2) \frac{1}{4s} \left[ 3\beta_{\mathbf{P}NN} a_{\mathbf{P}\rho\rho} (-is\alpha'_{\mathbf{P}})^{\alpha_{\mathbf{P}}(t)-1} \right. \\ &\quad \left. + \frac{1}{M_0} g_{f_2\mathbf{R}\rho\rho} a_{f_2\mathbf{R}\rho\rho} (-is\alpha'_{f_2\mathbf{R}})^{\alpha_{f_2\mathbf{R}}(t)-1} \right] \\ &- \Gamma_{\mu\nu\kappa\lambda}^{(2)}(k_1, k_2) \frac{1}{4s} \left[ 3\beta_{\mathbf{P}NN} b_{\mathbf{P}\rho\rho} (-is\alpha'_{\mathbf{P}})^{\alpha_{\mathbf{P}}(t)-1} \right. \\ &\quad \left. + \frac{1}{M_0} g_{f_2\mathbf{R}\rho\rho} b_{f_2\mathbf{R}\rho\rho} (-is\alpha'_{f_2\mathbf{R}})^{\alpha_{f_2\mathbf{R}}(t)-1} \right]. \end{aligned} \quad (30)$$

# $\sigma\sigma$ and $\rho^0\rho^0$ production



$$\sqrt{s} = 200 \text{ GeV}$$

$$pp \rightarrow pp\pi^+\pi^-\pi^+\pi^-$$



Only the first type of diagrams was included

R. Kycia, P. Lebiedowicz, A. Szczurek and J. Turnau,  
Phys. Rev. D95 (2017) 094020.

$$pp \rightarrow pp\pi^+\pi^-\pi^+\pi^-$$

$$\begin{aligned}\mathcal{M} = & \frac{1}{2} (\mathcal{M}_{\{3456\}} + \mathcal{M}_{\{5436\}} + \mathcal{M}_{\{3654\}} + \mathcal{M}_{\{5634\}}) \\ & + \frac{1}{2} (\mathcal{M}_{\{4356\}} + \mathcal{M}_{\{4536\}} + \mathcal{M}_{\{6354\}} + \mathcal{M}_{\{6534\}}) \\ & + \frac{1}{2} (\mathcal{M}_{\{3465\}} + \mathcal{M}_{\{5463\}} + \mathcal{M}_{\{3645\}} + \mathcal{M}_{\{5643\}}) \\ & + \frac{1}{2} (\mathcal{M}_{\{4365\}} + \mathcal{M}_{\{4563\}} + \mathcal{M}_{\{6345\}} + \mathcal{M}_{\{6543\}}),\end{aligned}\tag{31}$$

$$pp \rightarrow pp\pi^+\pi^-\pi^+\pi^-$$

$$\mathcal{M}_{\{3456\}} = A_{\pi p}(s_{13}, t_1) \frac{F_\pi(t_{34})}{t_{34} - m_\pi^2} A_{\pi\pi}(s_{45}, t_{45}) \frac{F_\pi(t_{56})}{t_{56} - m_\pi^2} A_{\pi p}(s_{26}, t_2), \quad (32)$$

$$\mathcal{M}_{\{4356\}} = A_{\pi p}(s_{14}, t_1) \frac{F_\pi(t_{43})}{t_{43} - m_\pi^2} A_{\pi\pi}(s_{35}, t_{35}) \frac{F_\pi(t_{56})}{t_{56} - m_\pi^2} A_{\pi p}(s_{26}, t_2), \quad (33)$$

$$\mathcal{M}_{\{3465\}} = A_{\pi p}(s_{13}, t_1) \frac{F_\pi(t_{34})}{t_{34} - m_\pi^2} A_{\pi\pi}(s_{46}, t_{46}) \frac{F_\pi(t_{65})}{t_{65} - m_\pi^2} A_{\pi p}(s_{25}, t_2), \quad (34)$$

$$\mathcal{M}_{\{4365\}} = A_{\pi p}(s_{14}, t_1) \frac{F_\pi(t_{43})}{t_{43} - m_\pi^2} A_{\pi\pi}(s_{36}, t_{36}) \frac{F_\pi(t_{65})}{t_{65} - m_\pi^2} A_{\pi p}(s_{25}, t_2). \quad (35)$$

$$pp \rightarrow pp\pi^+\pi^-\pi^+\pi^-$$

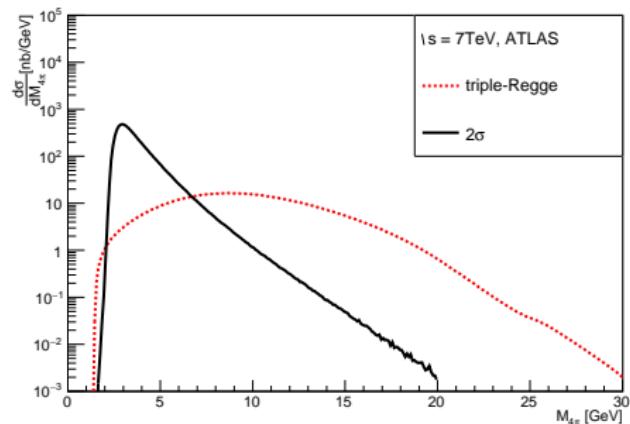
The subprocess amplitudes with the Regge exchanges are given as

$$A_{\pi p}(s, t) = \sum_{j=\mathbf{P}, f_2 \mathbf{R}} \eta_j s C_{\pi p}^j \left( \frac{s}{s_0} \right)^{\alpha_j(t)-1} F_{\pi p}^j(t), \quad (36)$$

$$A_{\pi\pi}(s, t) = \sum_{j=\mathbf{P}, f_2 \mathbf{R}} \eta_j s C_{\pi\pi}^j \left( \frac{s}{s_0} \right)^{\alpha_j(t)-1} F_{\pi\pi}^j(t), \quad (37)$$

where the signature factors are  $\eta_{\mathbf{P}} = i$  and  $\eta_{f_2 \mathbf{R}} = i - 0.86$ .

$$pp \rightarrow pp\pi^+\pi^-\pi^+\pi^-$$



Large  $4\pi$  invariant masses

Good measurement for CMS (!)

ALICE has too narrow range of rapidities and cannot see it.

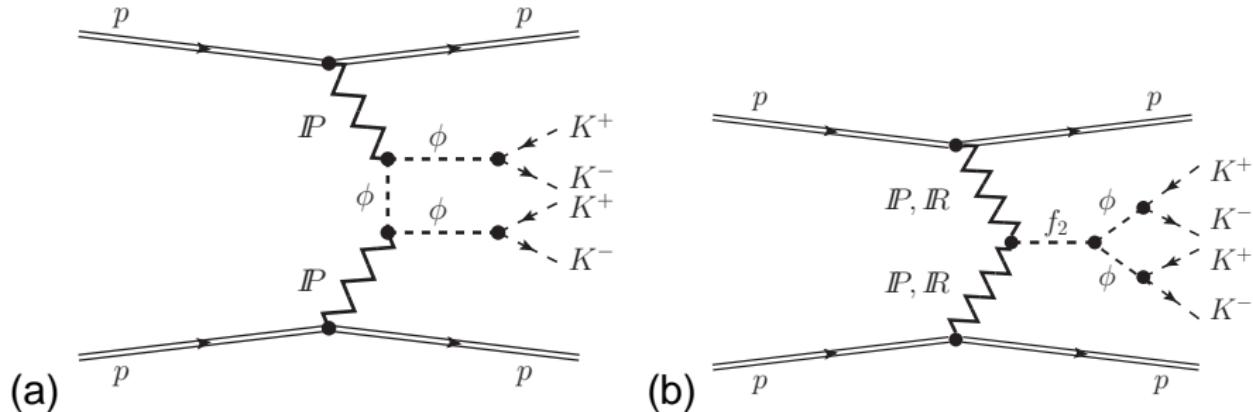
$$pp \rightarrow pp\phi\phi$$

- ▶ 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 ?

Our recent analysis:

Lebiedowicz, Nachtmann, Szczurek, arXiv.1901.11490.

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



**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

- ▶ Reggeization of the  $\phi$ -meson exchange:

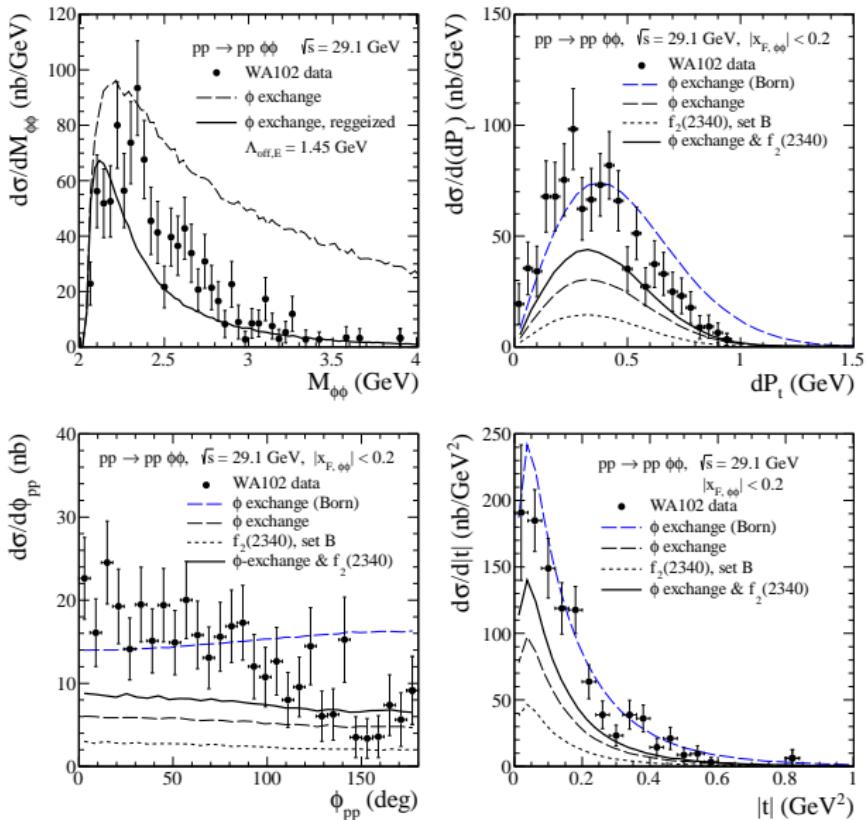
$$\Delta_{\rho_1\rho_2}^{(\phi)}(\hat{p}) \rightarrow \Delta_{\rho_1\rho_2}^{(\phi)}(\hat{p}) \left( \frac{s_{34}}{s_0} \right)^{\alpha_\phi(\hat{p}^2)-1}, \quad (38)$$

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  $\alpha'_\phi = 0.9 \text{ GeV}^{-2}$ .

- ▶ The formalism for  $\text{PP} \rightarrow f_2(2340)$  as previously for  $f_2(1270)$ .
- ▶ Glueball filter variable:

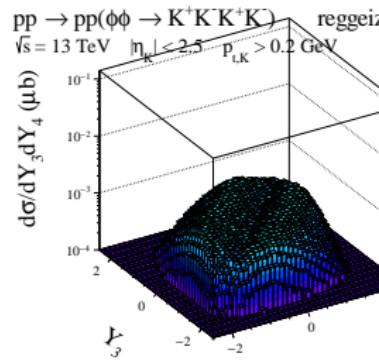
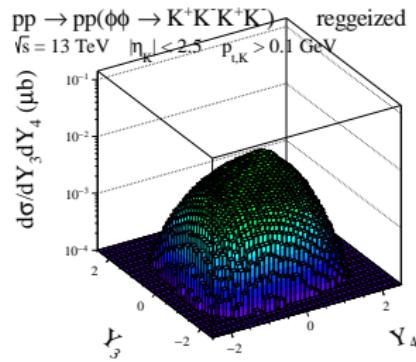
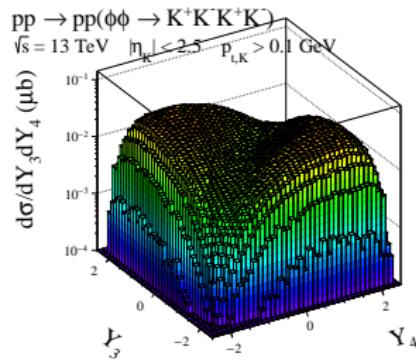
$$\mathbf{dP}_t = \mathbf{q}_{t,1} - \mathbf{q}_{t,2} = \mathbf{p}_{t,2} - \mathbf{p}_{t,1}, \quad dP_t = |\mathbf{dP}_t|, \quad (39)$$

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

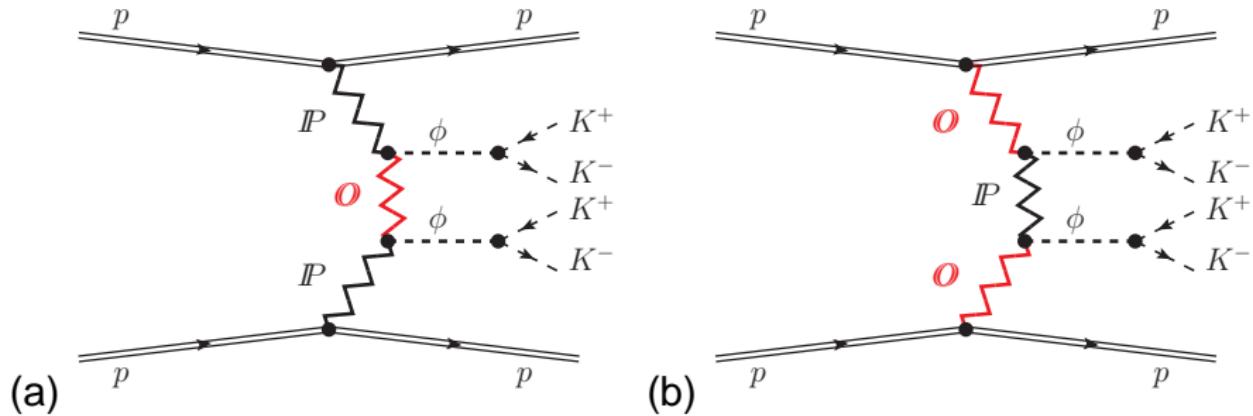


## Not yet perfect

# $pp \rightarrow pp\phi\phi$ , predictions for the LHC



# Continuum with odderon exchange



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

# Odderon exchange

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

$$i\Delta_{\mu\nu}^{(\mathbb{O})}(s, t) = -ig_{\mu\nu} \frac{\eta_{\mathbb{O}}}{M_0^2} (-is\alpha'_{\mathbb{O}})^{\alpha_{\mathbb{O}}(t)-1}, \quad (40)$$

$$\alpha_{\mathbb{O}}(t) = \alpha_{\mathbb{O}}(0) + \alpha'_{\mathbb{O}} t, \quad (41)$$

where in (40) we have  $M_0^{-2} = 1 \text{ (GeV)}^{-2}$  for dimensional reasons. Further more, we shall assume representative values for the odderon parameters

$$\eta_{\mathbb{O}} = -1, \quad \alpha_{\mathbb{O}}(0) = 1.05, \quad \alpha'_{\mathbb{O}} = 0.25 \text{ GeV}^{-2}. \quad (42)$$

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

$$i\Gamma_{\mu\nu\kappa\lambda}^{(\mathbf{P}\mathbb{O}\phi)}(k', k) = iF^{(\mathbf{P}\mathbb{O}\phi)}((k+k')^2, k'^2, k^2) \left[ 2a_{\mathbf{P}\mathbb{O}\phi} \Gamma_{\mu\nu\kappa\lambda}^{(0)}(k', k) - b_{\mathbf{P}\mathbb{O}\phi} \Gamma_{\mu\nu\kappa\lambda}^{(2)}(k', k) \right]. \quad (43)$$

## Odderon exchange

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

$$F^{(\text{PO}\phi)}((k + k')^2, k'^2, k^2) = F((k + k')^2) F(k'^2) F^{(\text{PO}\phi)}(k^2), \quad (44)$$

where we adopt the monopole form

$$F(k^2) = \frac{1}{1 - k^2/\Lambda^2} \quad (45)$$

and  $F^{(\text{PO}\phi)}(k^2)$  is a form factor normalised to  $F^{(\text{PO}\phi)}(m_\phi^2) = 1$ . The coupling parameters  $a_{\text{PO}\phi}$ ,  $b_{\text{PO}\phi}$  in (43) and the cut-off parameter  $\Lambda^2$  in the form factor can be adjusted to experimental data.

# Continuum with photon exchange

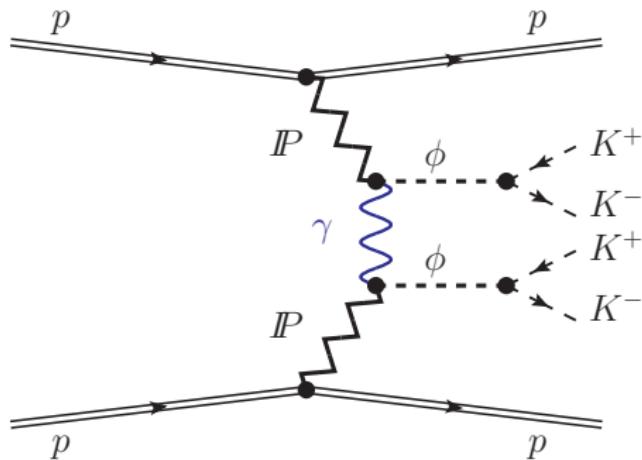
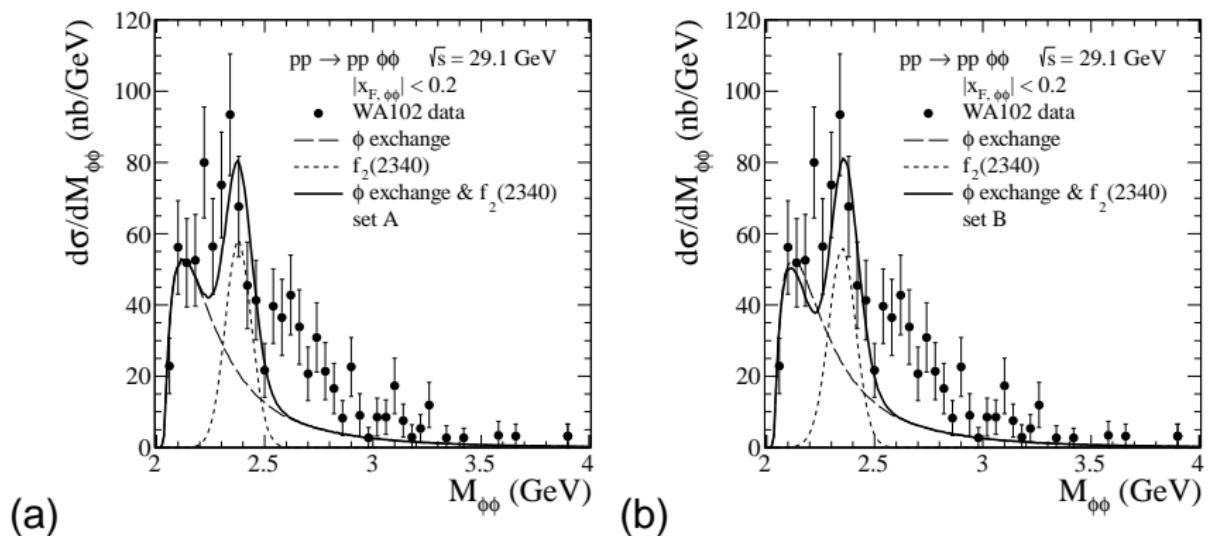


Figure: The “Born level” diagram for diffractive production of a  $\phi$ -meson pair with an intermediate photon exchange.

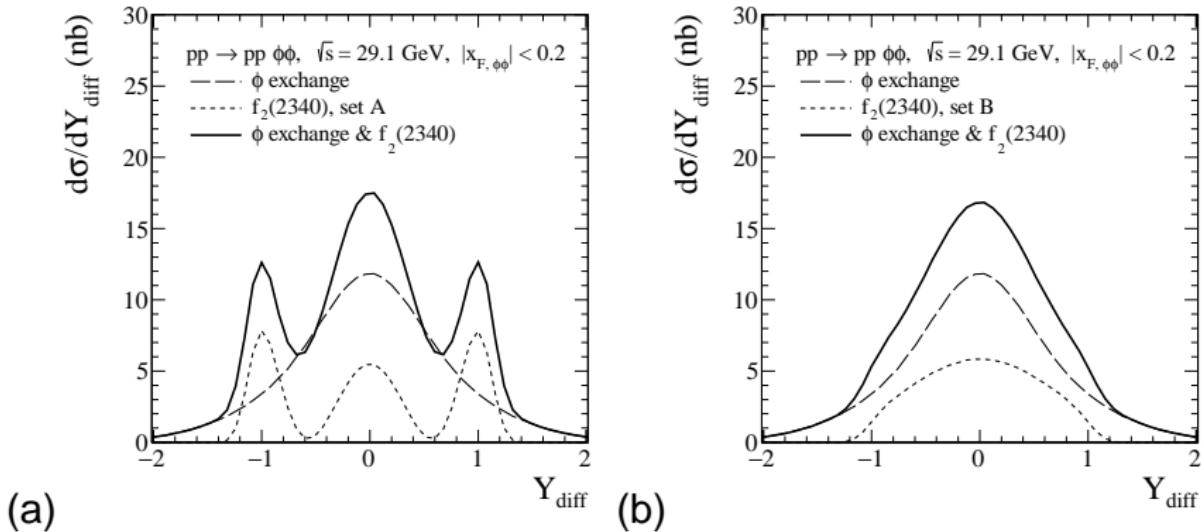
This turned out to be small

# Invariant mass distribution



**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 sets of the parameters from a table in our recent paper, the set A [see the panel (a)] and the set B [see the 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

# Distribution in $Y_{\text{diff}}$

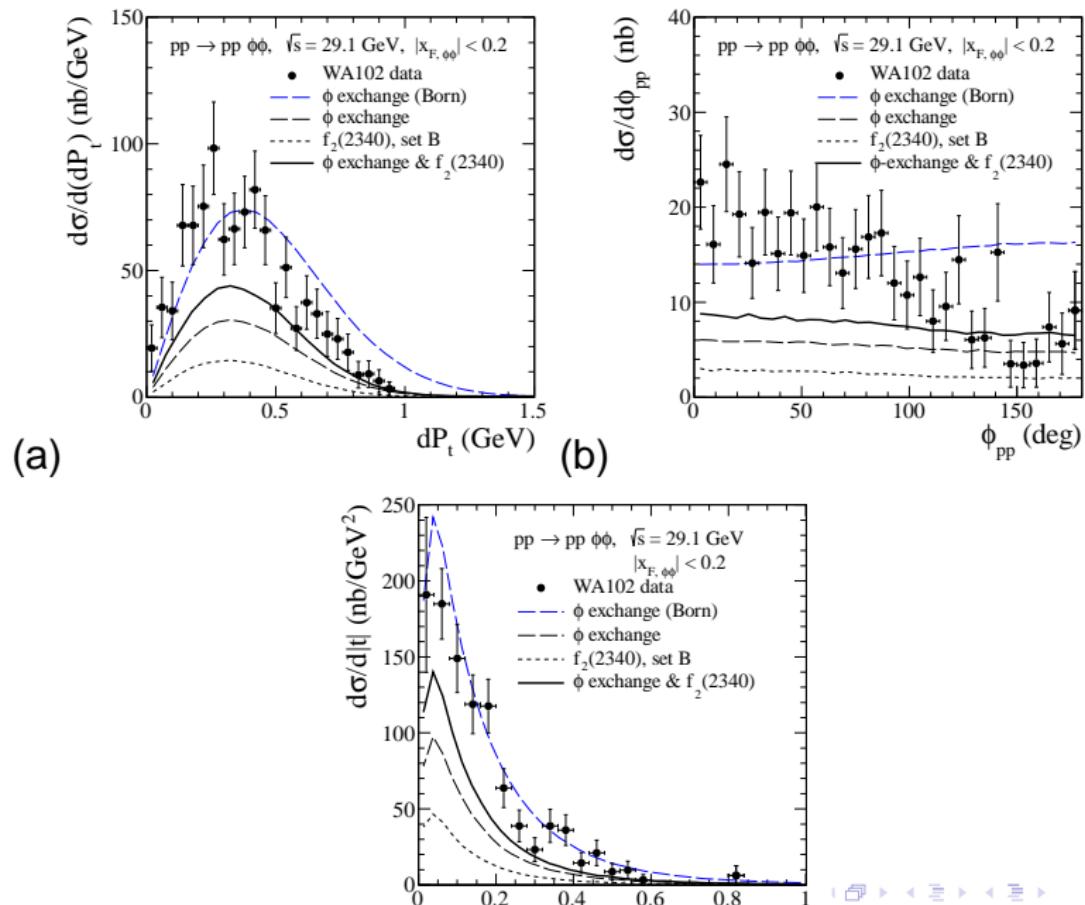


(a)

(b)

**Figure:** The distribution in rapidity distance between two centrally produced  $\phi(1020)$  mesons  $Y_{\text{diff}} = Y_3 - Y_4$  at  $\sqrt{s} = 29.1 \text{ GeV}$  and for  $|x_{F, \phi\phi}| \leq 0.2$ . Here we show results for the two sets, A and B, of the parameters from the table. The absorption effects were included here.

# Some other distributions



# Predictions for LHC

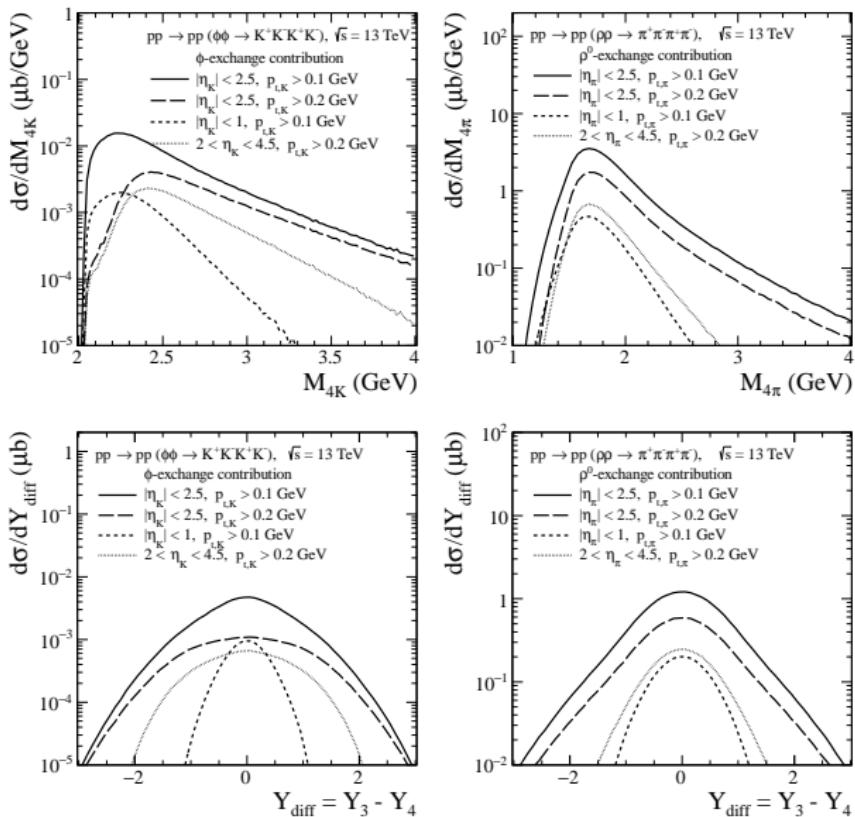
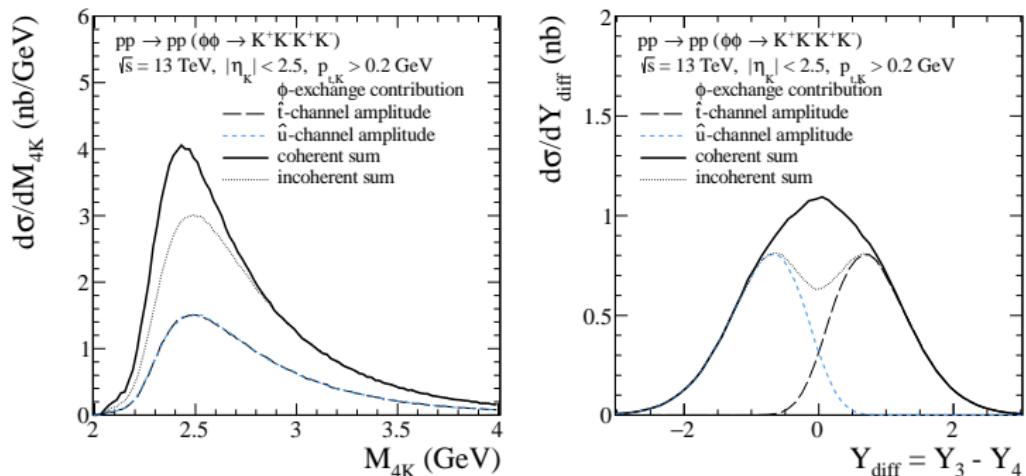


Figure: Differential cross sections as the function of the four-kaon/pion

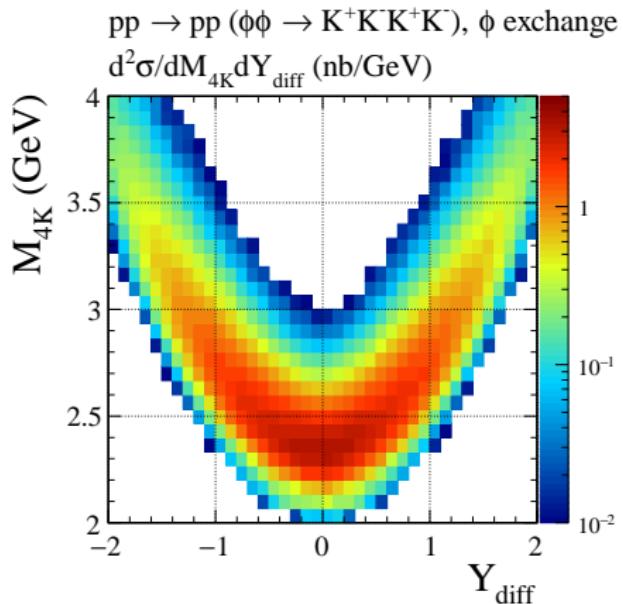


# Predictions for LHC



**Figure:** Differential cross sections as the function of the four-kaon invariant mass (the left panel) and as the function of  $Y_{\text{diff}}$  (the right panel) for 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 individual  $\hat{t}$  and  $\hat{u}$  terms, respectively. The absorption effects are included here.

# Predictions for LHC



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

# Odderon exchange

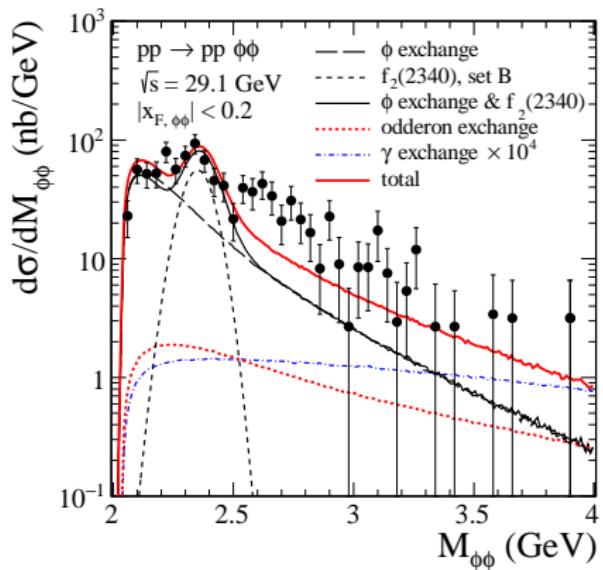
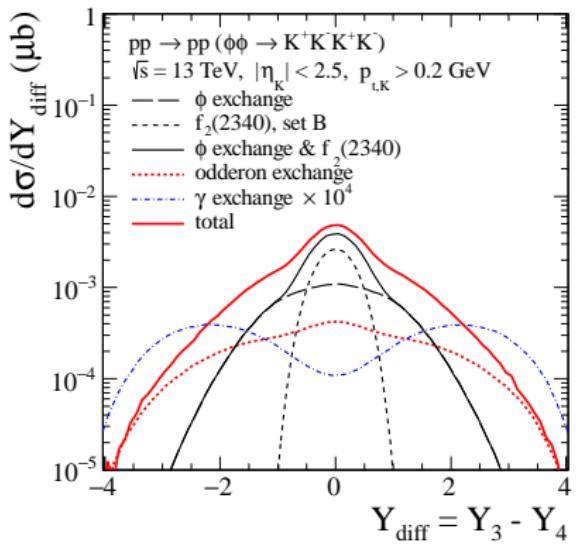
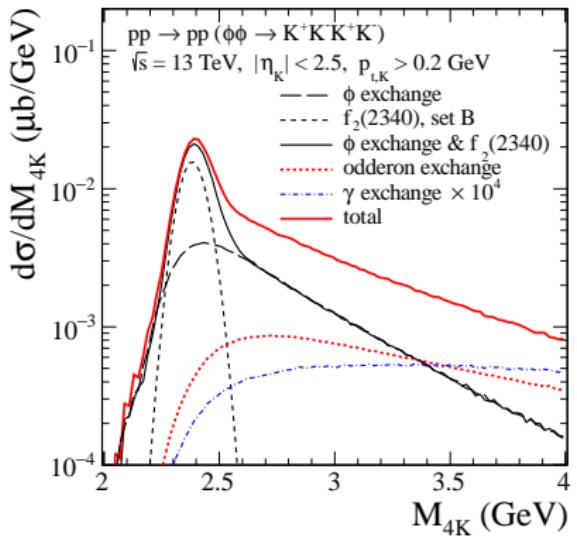


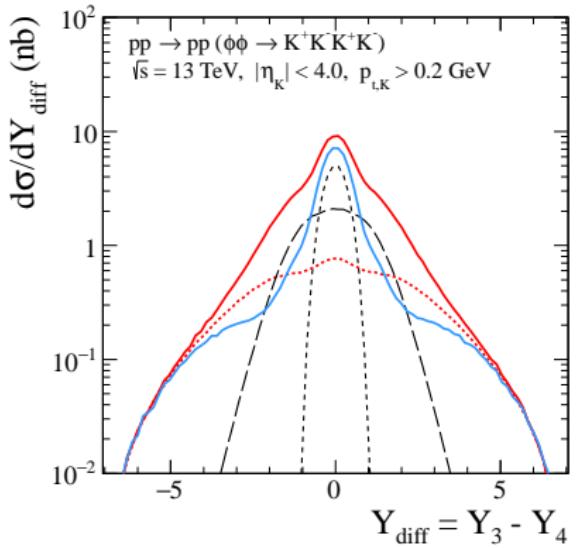
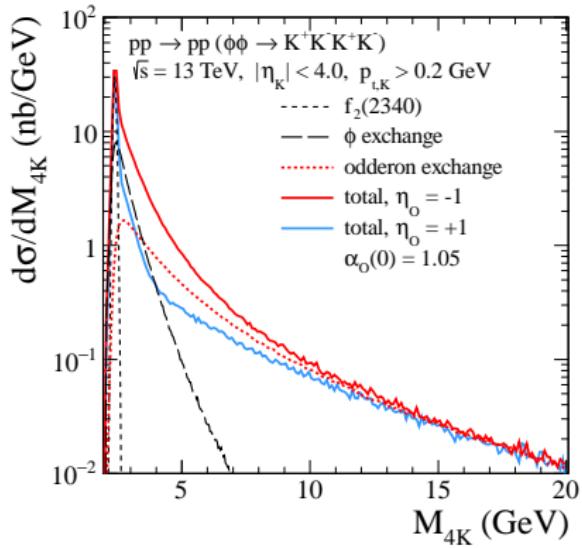
Figure: Invariant mass distributions for the central production of  $\phi\phi$  at  $\sqrt{s} = 29.1 \text{ GeV}$  and  $|x_{F,\phi\phi}| \leq 0.2$  together with the WA102 data. In the calculations the parameter set B of the table has been used. The black long-dashed line corresponds to the  $\phi$ -exchange contribution and the black dashed line corresponds to the  $f_2(2340)$  contribution. The black solid line represents a coherent sum of  $\phi$ -exchange and  $f_2(2340)$  terms. The red dotted line corresponds to the odderon exchange contribution. The blue dash-dotted line corresponds to the  $\gamma$ -exchange contribution.

# Odderon exchange

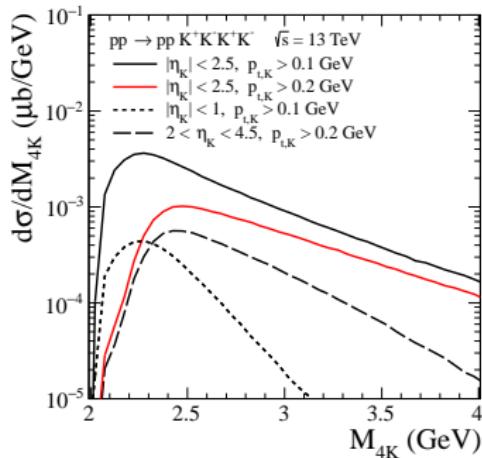
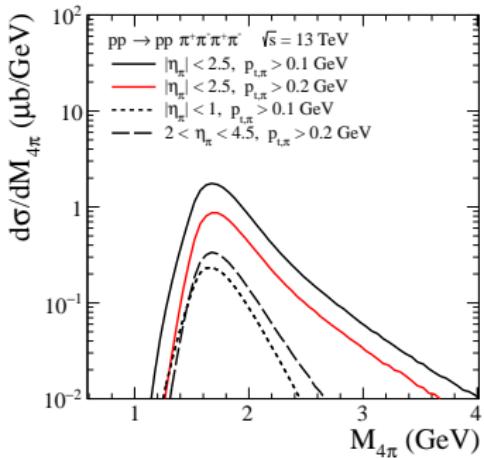


**Figure:** The distributions in  $M_{4K}$  (the left panel) and in  $Y_{\text{diff}}$  (the right panel) for the  $pp \rightarrow pp(\phi\phi \rightarrow K^+K^-K^+K^-)$  reaction calculated for  $\sqrt{s} = 13 \text{ TeV}$  and  $|\eta_K| < 2.5$ ,  $p_{t,K} > 0.2 \text{ GeV}$ . The absorption effects are included in the calculations.

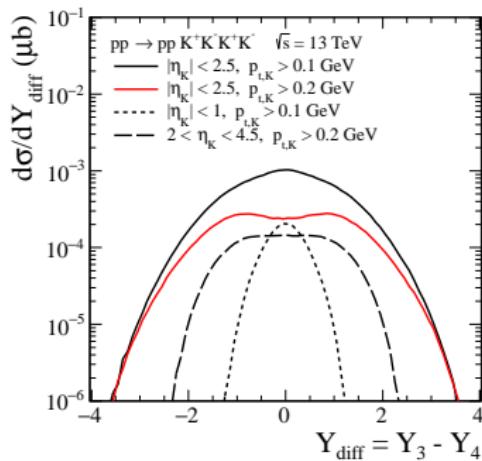
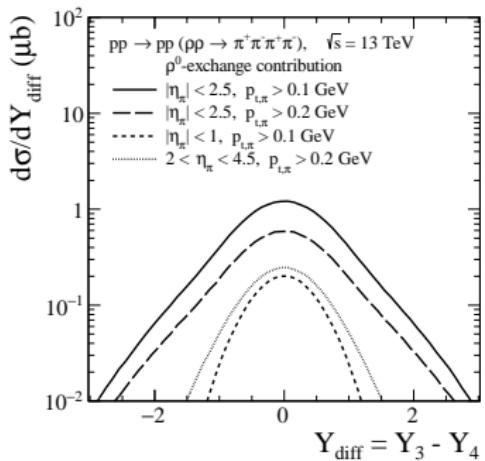
# Broder range of rapidity



# Predictions for the LHC

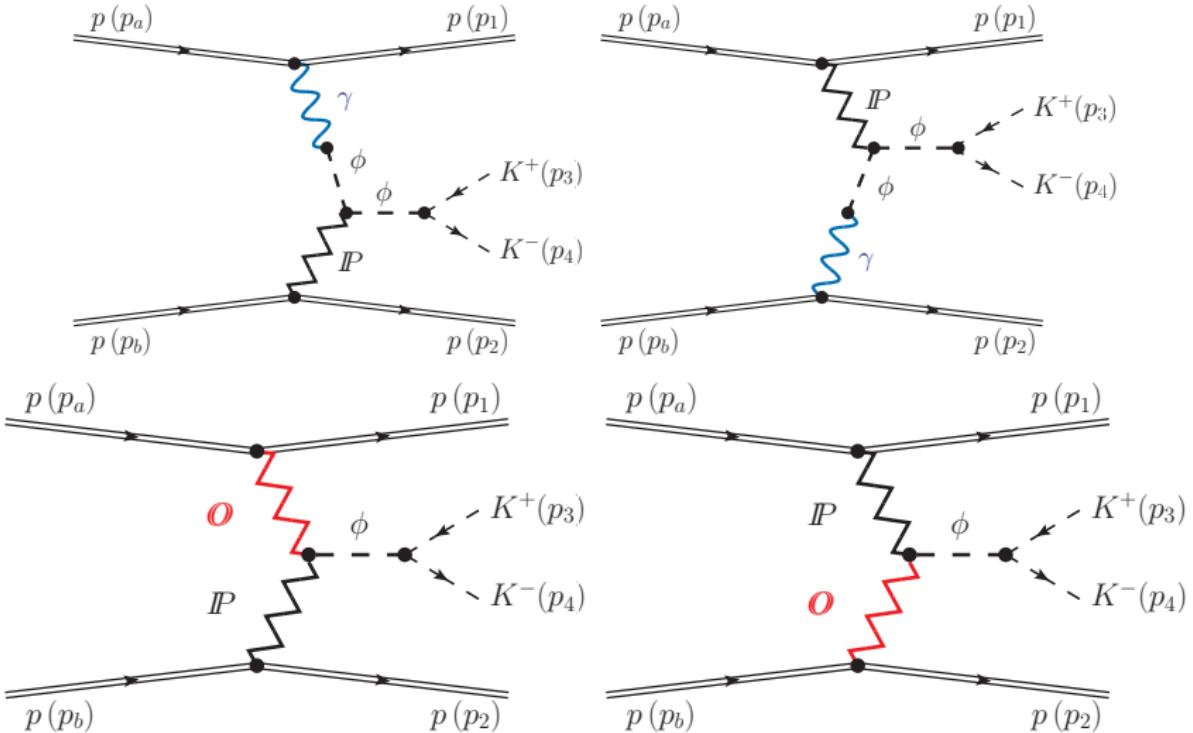


# Predictions for the LHC



One should return to the topic once the data at the LHC are available  
**CMS and LHCb data analysis in progress**

## Return to $pp \rightarrow pp\phi$



## Odderon exchange contribution modifies the photon-exchange contribution

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

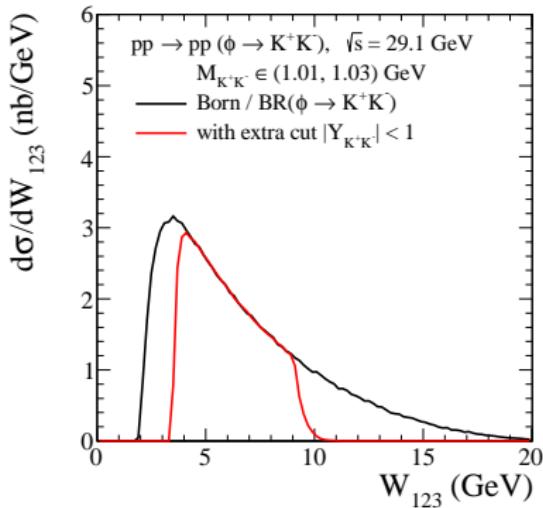


Figure: Photoproduction mechanism.

$W_{\gamma p}$  are relatively small

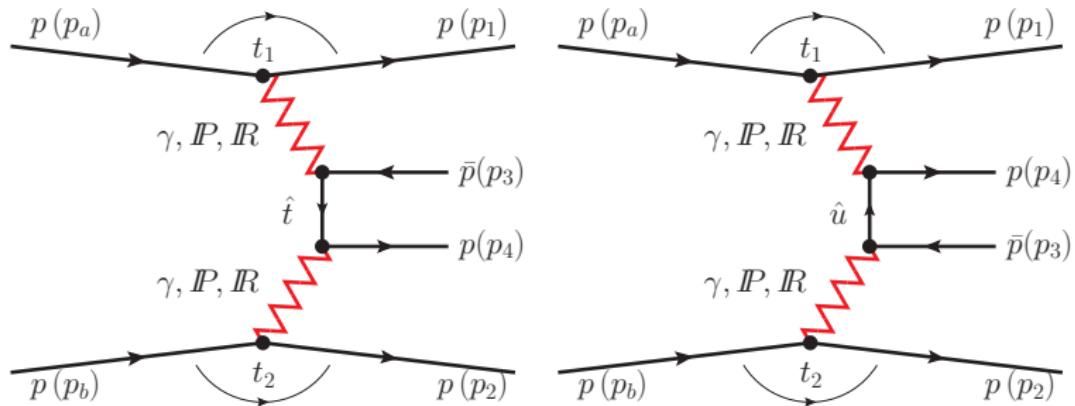
But we rather control the photoproduction cross section

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

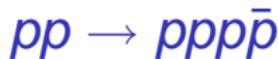
Identify deviations from photoproduction.

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

### The continuum (nonresonance) contribution



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



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

$$\mathcal{M}_{pp \rightarrow p\bar{p}p\bar{p}} = \mathcal{M}_{pp \rightarrow p\bar{p}p\bar{p}}^{p\bar{p}-\text{continuum}} + \mathcal{M}_{pp \rightarrow p\bar{p}p\bar{p}}^{p\bar{p}-\text{resonances}}. \quad (46)$$

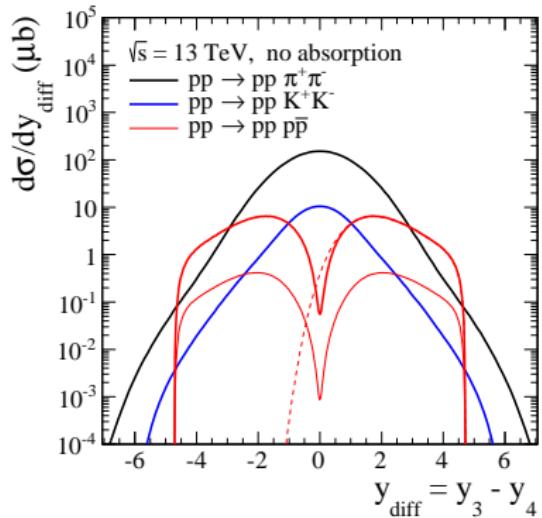
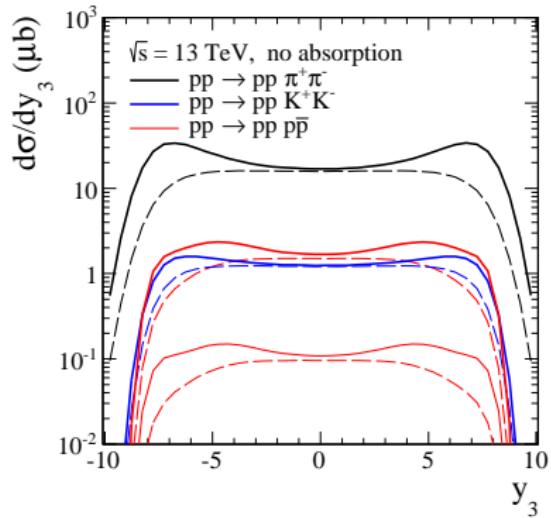
No  $p\bar{p}$  resonances are known (to us) except of  $\eta_c$  and  $\chi_c(0)$  mesons (see PDG).

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

$$\begin{aligned} \mathcal{M}_{\lambda_a \lambda_b \rightarrow \lambda_1 \lambda_2 \lambda_3 \lambda_4}^{(\mathbf{P} \mathbf{P} \rightarrow \bar{p} p)} &= (-i) \bar{u}(p_1, \lambda_1) i\Gamma_{\mu_1 \nu_1}^{(\mathbf{P} pp)}(p_1, p_a) u(p_a, \lambda_a) i\Delta^{(\mathbf{P}) \mu_1 \nu_1, \alpha_1 \beta_1}(s_{13}, t_1) \\ &\times \bar{u}(p_4, \lambda_4) [i\Gamma_{\alpha_2 \beta_2}^{(\mathbf{P} pp)}(p_4, p_t) i\Delta^{(p)}(p_t) i\Gamma_{\alpha_1 \beta_1}^{(\mathbf{P} pp)}(p_t, -p_3) \\ &+ i\Gamma_{\alpha_1 \beta_1}^{(\mathbf{P} pp)}(p_4, p_u) i\Delta^{(p)}(p_u) i\Gamma_{\alpha_2 \beta_2}^{(\mathbf{P} pp)}(p_u, -p_3)] v(p_3, \lambda_3) \\ &\times i\Delta^{(\mathbf{P}) \alpha_2 \beta_2, \mu_2 \nu_2}(s_{24}, t_2) \bar{u}(p_2, \lambda_2) i\Gamma_{\mu_2 \nu_2}^{(\mathbf{P} pp)}(p_2, p_b) u(p_b, \lambda_b). \end{aligned} \tag{47}$$

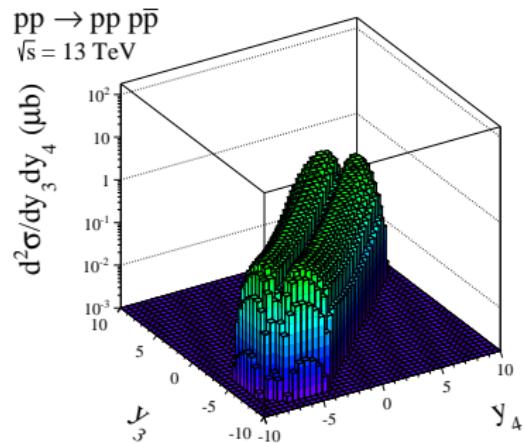
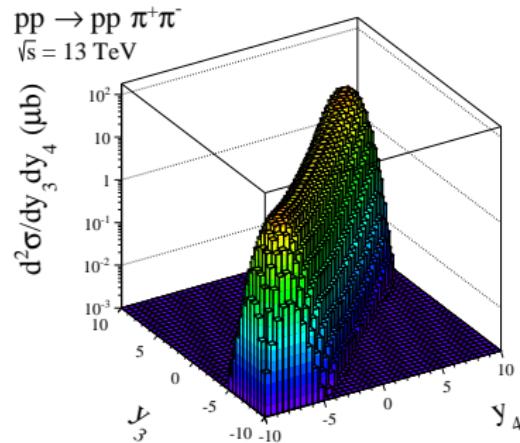
No absorption effects.

$pp \rightarrow ppp\bar{p}$



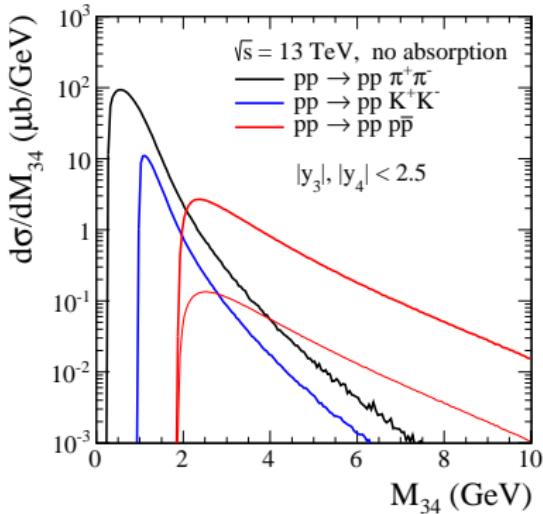
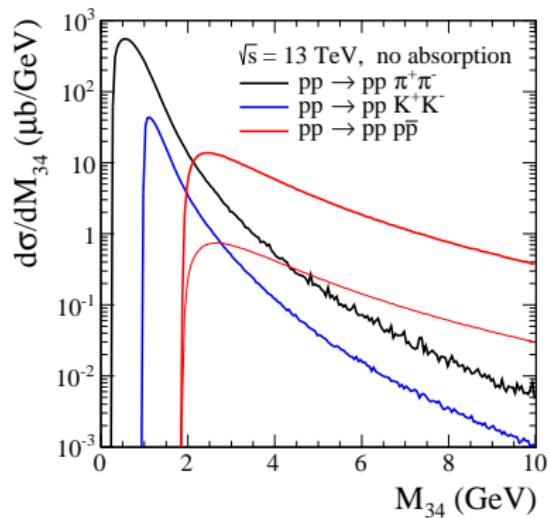
Surprising effect of the dip at  $y_{\text{diff}} = 0$ .  
New effect for spin-1/2 particles  
Good separation of  $t$  and  $u$  contributions.

# $y_3$ $y_4$ space



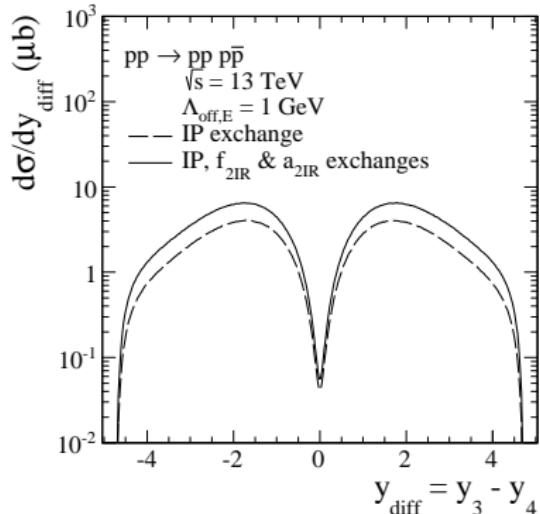
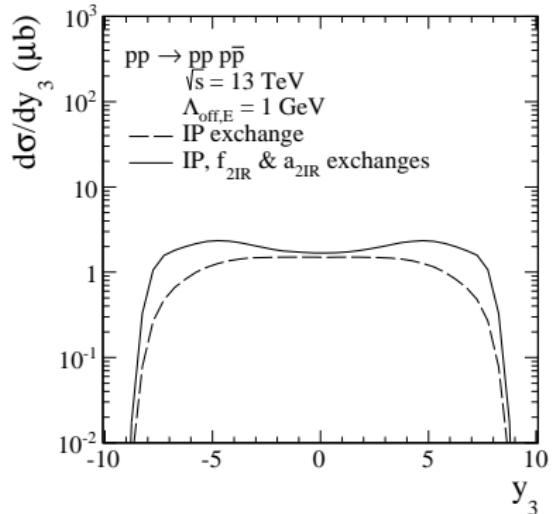
Completely different character.  
The dip is everywhere on the diagonal  
**(ATLAS can do it, ALICE not really).**

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



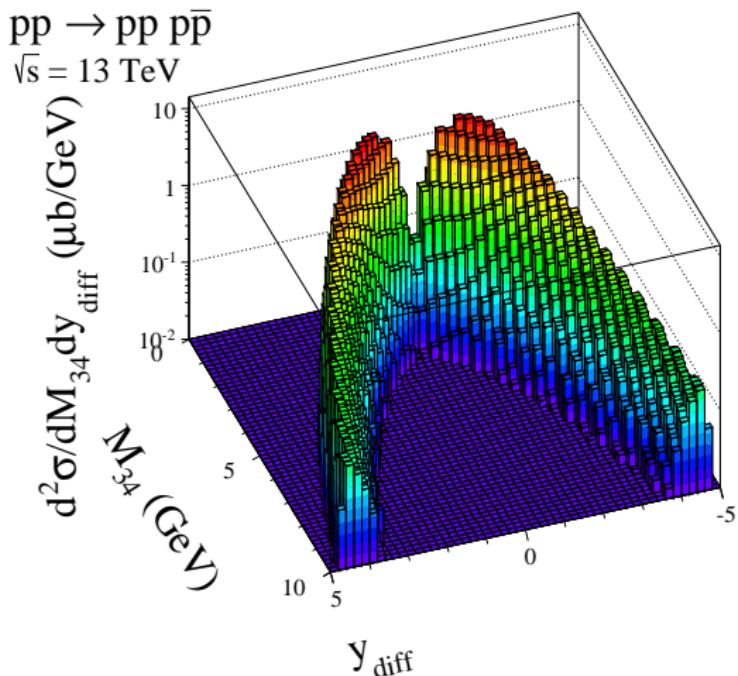
Different slope for pairs of pseudoscalar and for spin-1/2 hadrons.  
We explicitly include spin degrees of freedom in the Regge calculus.

# Role of subleading reggeons



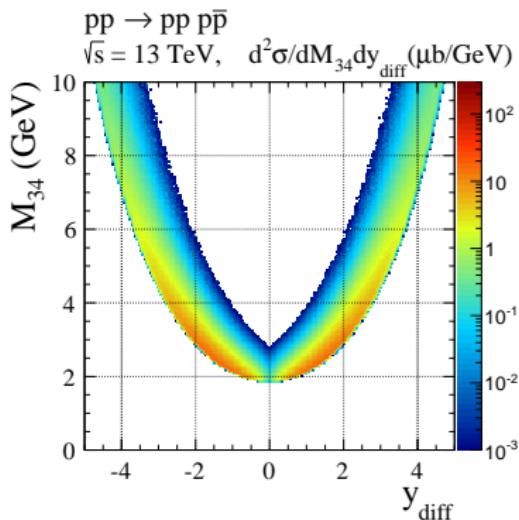
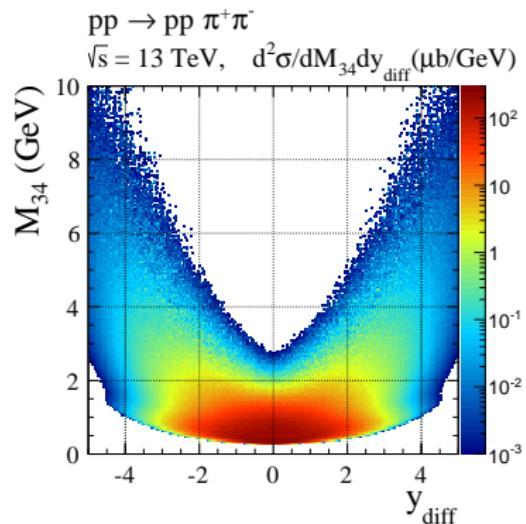
Even at  $\sqrt{s} = 13 \text{ TeV}$  a sizeable effect of subleading reggeons.

$M_{p\bar{p}} X y_{diff}$



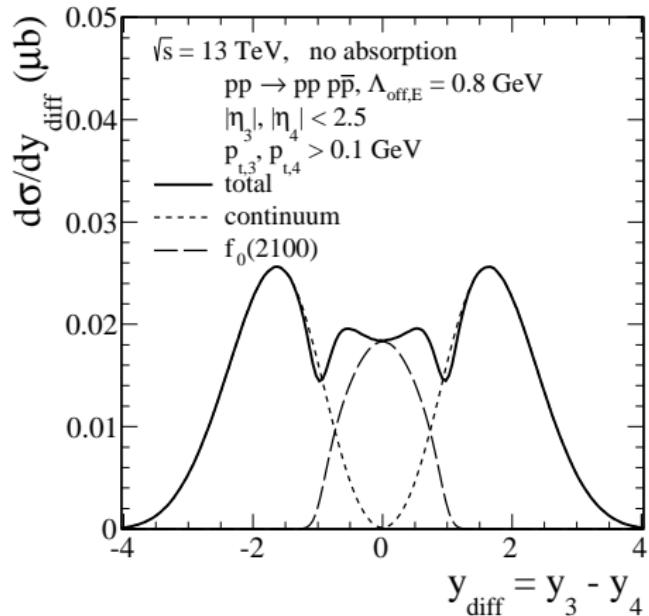
Region inside of the ridge seems promising  
in searches for resonances

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



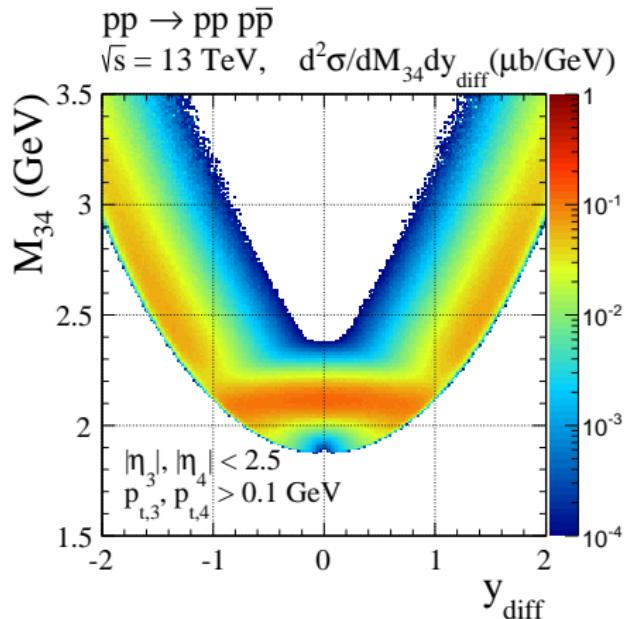
Different situation for  $\pi^+\pi^-$  and  $p\bar{p}$

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



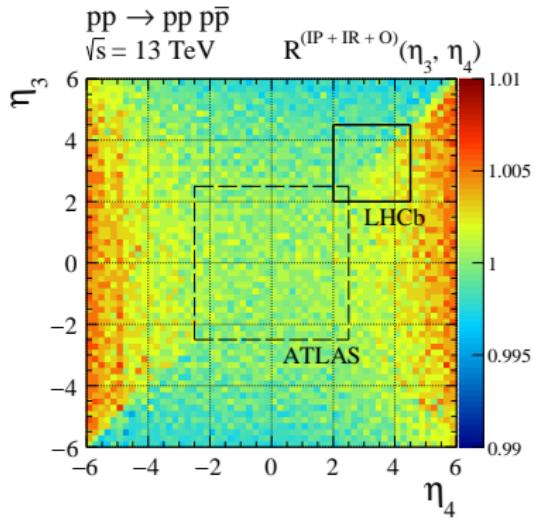
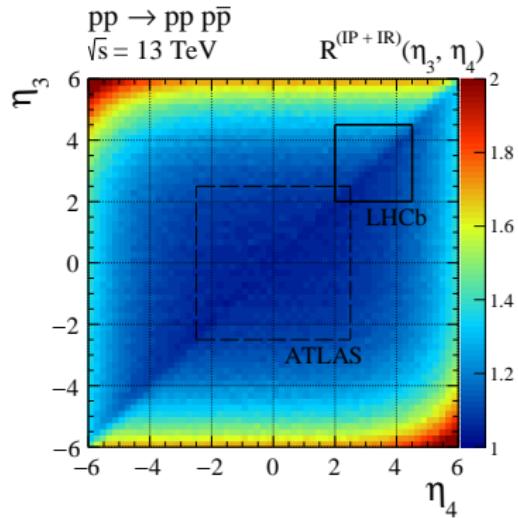
resonances may destroy the dip

# 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**

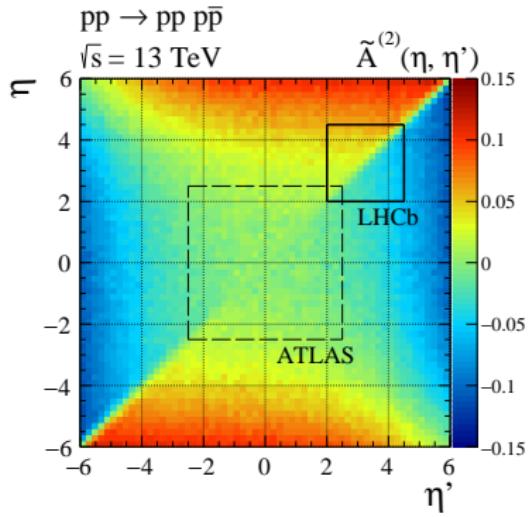
## Asymmetry between central $p$ and $\bar{p}$

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

$$\tilde{A}^{(2)}(\eta, \eta') = \frac{\frac{d^2\sigma}{d\eta_3 d\eta_4}(\eta, \eta') - \frac{d^2\sigma}{d\eta_3 d\eta_4}(\eta', \eta)}{\frac{d^2\sigma}{d\eta_3 d\eta_4}(\eta, \eta') + \frac{d^2\sigma}{d\eta_3 d\eta_4}(\eta', \eta)}. \quad (48)$$

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

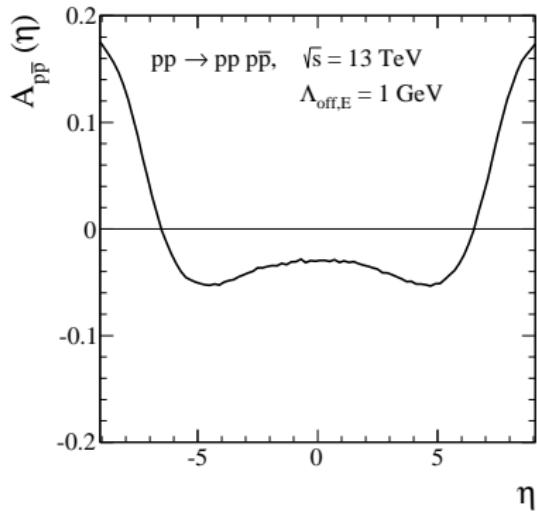
$$A = \frac{\sigma(p) - \sigma(\bar{p})}{\sigma(p) + \sigma(\bar{p})} \quad (49)$$



Clear asymmetry

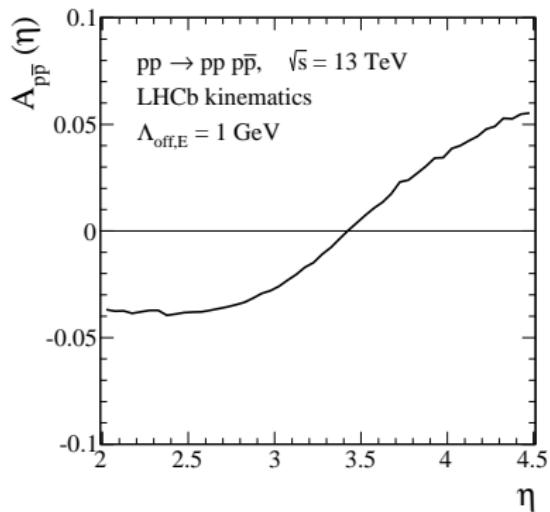
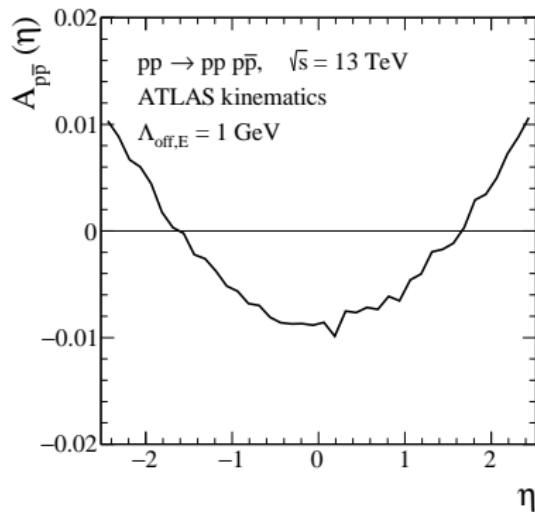
# Asymmetry between central $p$ and $\bar{p}$

Projection on one-dimension  
(full phase space)



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

Projection on one-dimension  
(experimental cuts)



## Conclusions, $pp \rightarrow pph^+ h^-$

- ▶ The Regge phenomenology was extended in practice 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.
- ▶ The dipion invariant mass has a rich structure which strongly depends on kinematical cuts (continuum, resonances, interference).
- ▶ Disagreement for  $pp \rightarrow \pi\pi pp$  with CMS data due to large dissociation contribution.  
ATLAS and STAR data expected.
- ▶ Angular distributions in the rest frame of  $M\bar{M}$  seems promising to fix  $\textbf{P}\textbf{P} \rightarrow R$  couplings. We have discussed  $\textbf{P}\textbf{P} \rightarrow f_2(1270) \rightarrow \pi^+\pi^-$ .
- ▶ Purely exclusive data expected from STAR, CMS+TOTEM and ATLAS+ALFA.

## Conclusions, $pp \rightarrow pph^+ h^-$

- ▶  $K^+ K^-$  has also rich invariant mass structure (resonances). Predictions have been done. Some ambiguities in predictions.
- ▶ Search for glueballs requires partial wave analyses and observations in different final states.
- ▶ Four-pion production is also interesting.
  - Double resonances, three-pomeron continuum.
  - Search for single resonances ( $f_0(1710)$ ).
- ▶  $\phi\phi$  ( $K^+ K^- K^+ K^-$ ) final state at  $\sqrt{s} = 29.1$  GeV has been approximately described including continuum contribution and a  $f_2$  resonance.
  - Predictions for LHC were shown.
  - Resonances (glueballs) can be present.
  - Searches for odderon exchange at large  $M_{\phi\phi}$  at the LHC.
  - Limit on pomeron-oddron- $\phi$  coupling.
- ▶  $p\bar{p}$  production has quite different characteristics ( $d\sigma/dM$  and  $d\sigma/dy_{diff}$  (dip)).
  - These are predictions of our approach. However resonances can destroy the dip.