DIS2019

Searching for odderon in exclusive reactions: $pp \to pp p\bar{p}$, $pp \to pp\phi\phi$ and $pp \to pp\phi$

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Our works on central production

Our recent works on central production:

1. Production of $\pi^+\pi^-$ pairs in
   $pp \to pp\pi^+\pi^-$ reaction.
2. Production of K^+K^- pairs in
   $pp \to ppK^+K^-$ reaction.
3. Production of two pairs of $\pi^+\pi^-$ in $pp \to pp\pi^+\pi^-\pi^+\pi^-$ reaction
   Three pomeron exchanges (!)
4. Production of $\phi\phi$ final state
   $pp \to ppK^+K^-K^+K^-$ reaction
   in quest for glueballs and odderon exchange.
5. Production of $p\bar{p}$ pairs in
   $pp \to pp(p\bar{p})$ reaction
   interesting spin effects for Regge-like reactions.
6. Exclusive production of J/ψ meson in $pp \to ppJ/\psi$ 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 $\sqrt{s} > 2$-3 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.
- $pp \to pp$, $p\bar{p} \to p\bar{p}$
  $\pi^+ p \to \pi^+ p$, $\pi^- p \to \pi^- p$
  $K^+ p \to K^+ p$, $K^- p \to K^- p$
- 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 $2 \to 3$, $2 \to 4$, 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:

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

and fulfils the following relations

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

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

Soft Odderon

- $C = -1$ partner of pomeron
  Lukaszuk, Nicolescu, Lett. Nuovo Cim. **8**, 405 (1973)
- Does it exist ?
- 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 at al.
- Here odderon in $pp \to ppM$ and $pp \to pph\bar{h}$.
- In our tensorial approach odderon is a vectorial exchange.
- Odderon propagator:

$$i\Delta^{(\mathbb{O})}_{\mu\nu}(s,t) = -ig_{\mu\nu}\frac{\eta_{\mathbb{O}}}{M_0^2}(-is\alpha'_{\mathbb{O}})^{\alpha_{\mathbb{O}}(t)-1}\,, \tag{3}$$

$$\alpha_{\mathbb{O}}(t) = \alpha_{\mathbb{O}}(0) + \alpha'_{\mathbb{O}}\,t\,, \tag{4}$$

Exclusive reactions

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

$$d\sigma = \frac{1}{2s}\overline{|\mathcal{M}_{pp\to ppM\bar{M}}|^2} \tag{5}$$

$$(2\pi)^4\delta^4\left(p_a + p_b - p_1 - p_2 - p_3 - p_4\right)$$

$$\frac{d^3p_1}{(2\pi)^3 2E_1}\frac{d^3p_2}{(2\pi)^3 2E_2}\frac{d^3p_3}{(2\pi)^3 2E_3}\frac{d^3p_4}{(2\pi)^3 2E_4} \tag{6}$$

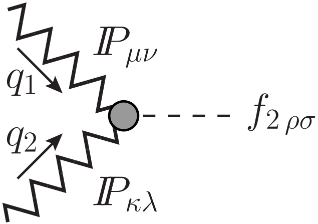
- In general 8-fold integration.
  We have special choice of integration variables adjusted to CEP.
- Any differential distribution can be calculated
- Include absorption effects

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.
Only one (!) fits to experimental characteristics.

Different $\mathbb{P}\mathbb{P} \to f_2$ couplings

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

$$\begin{aligned} i\Gamma^{(\mathbb{P}\mathbb{P}f_2)(2)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{2i}{M_0}\, g^{(2)}_{\mathbb{P}\mathbb{P}f_2} \Big((q_1\cdot q_2)\, R_{\mu\nu\rho_1\alpha}\, R_{\kappa\lambda\sigma_1}{}^{\alpha} - q_{1\rho_1}\, q_2^{\mu_1}\, R_{\mu\nu\mu_1\alpha}\, R_{\kappa\lambda\sigma_1}{}^{\alpha} \\ - q_1^{\mu_1}\, q_{2\sigma_1}\, R_{\mu\nu\rho_1\alpha}\, R_{\kappa\lambda\mu_1}{}^{\alpha} + q_{1\rho_1}\, q_{2\sigma_1}\, R_{\mu\nu\kappa\lambda} \Big) R_{\rho} \end{aligned} \tag{8}$$

$$\begin{aligned} i\Gamma^{(\mathbb{P}\mathbb{P}f_2)(3)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{2i}{M_0}\, g^{(3)}_{\mathbb{P}\mathbb{P}f_2} \Big((q_1\cdot q_2)\, R_{\mu\nu\rho_1\alpha}\, R_{\kappa\lambda\sigma_1}{}^{\alpha} + q_{1\rho_1}\, q_2^{\mu_1}\, R_{\mu\nu\mu_1\alpha}\, R_{\kappa\lambda\sigma_1}{}^{\alpha} \\ + q_1^{\mu_1}\, q_{2\sigma_1}\, R_{\mu\nu\rho_1\alpha}\, R_{\kappa\lambda\mu_1}{}^{\alpha} + q_{1\rho_1}\, q_{2\sigma_1}\, R_{\mu\nu\kappa\lambda} \Big) R_{\rho} \end{aligned} \tag{9}$$

Different $\mathbb{P}\mathbb{P} \to f_2$ couplings

$$i\Gamma^{(\mathbb{P}\mathbb{P}f_2)(4)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{i}{M_0}\, g^{(4)}_{\mathbb{P}\mathbb{P}f_2} \Big(q_1^{\alpha_1}\, q_2^{\mu_1}\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1} + q_2^{\alpha_1}\, q_1^{\mu_1}\, R_{\mu\nu\alpha_1\lambda_1}\, R_{\kappa\lambda\mu_1\nu} \tag{10}$$

$$i\Gamma^{(\mathbb{P}\mathbb{P}f_2)(5)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{2i}{M_0^3}\, g^{(5)}_{\mathbb{P}\mathbb{P}f_2} \Big(q_1^{\mu_1}\, q_2^{\nu_1}\, R_{\mu\nu\nu_1\alpha}\, R_{\kappa\lambda\mu_1}{}^{\alpha} + q_1^{\nu_1}\, q_2^{\mu_1}\, R_{\mu\nu\mu_1\alpha}\, R_{\kappa\lambda\nu_1}{}^{\alpha}$$

$$-2\, (q_1 \cdot q_2)\, R_{\mu\nu\kappa\lambda} \Big) q_{1\alpha_1}\, q_{2\lambda_1}\, R^{\alpha_1\lambda_1}{}_{\rho\sigma}\,, \tag{11}$$

$$i\Gamma^{(\mathbb{P}\mathbb{P}f_2)(6)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = \frac{i}{M_0^3}\, g^{(6)}_{\mathbb{P}\mathbb{P}f_2} \Big(q_1^{\alpha_1}\, q_1^{\lambda_1}\, q_2^{\mu_1}\, q_{2\rho_1}\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1}$$

$$+\, q_2^{\alpha_1}\, q_2^{\lambda_1}\, q_1^{\mu_1}\, q_{1\rho_1}\, R_{\mu\nu\alpha_1\lambda_1}\, R_{\kappa\lambda\mu_1\nu_1} \Big) R^{\nu_1\rho_1}{}_{\rho\sigma}\,, \tag{12}$$

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

$pp \to pp\phi\phi$

- Observed by WA102, no theoretical interpretation
- Several mechanisms possible a priori
  - continuum ("ϕ" 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 $J/\psi \to \gamma\phi\phi$.
    Are they produced in CEP ?
  - Odderon exchange ?

Our recent analysis:
Lebiedowicz, Nachtmann, Szczurek, arXiv.1901.11490.

$pp \to pp\phi\phi$

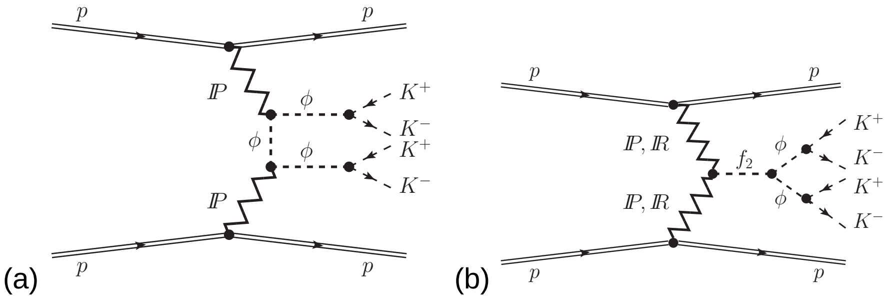


Figure: The "Born level" diagrams for double-pomeron/reggeon central exclusive $\phi\phi$ production and their subsequent decays into $K^+K^-K^+K^-$ in proton-proton collisions. In (a) we have the continuum $\phi\phi$ production, in (b) $\phi\phi$ production via an f_2 resonance. Other resonances, e.g.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

Some details of the calculation

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

$$\boldsymbol{dP_t} = \boldsymbol{q_{t,1}} - \boldsymbol{q_{t,2}} = \boldsymbol{p_{t,2}} - \boldsymbol{p_{t,1}}\,, \quad dP_t = |\boldsymbol{dP_t}|\,, \tag{14}$$

$f_2 \to \phi\phi$ decay

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

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

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.

ϕ-exchange reggeization

$$\Delta^{(\phi)}_{\rho_1\rho_2}(\hat{p}) \to \Delta^{(\phi)}_{\rho_1\rho_2}(\hat{p}) \left(\exp(i\phi(s_{34})) \, \frac{s_{34}}{s_0} \right)^{\alpha_\phi(\hat{p}^2)-1}, \tag{16}$$

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 $\alpha'_\phi = 0.9$ GeV^{-2}.
In order to have a correct phase behaviour we introduced the function $\exp(i\phi(s_{34}))$ with

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

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_{diff} = 0 reproduce meson physics, suggested by (Harland-Lang, Khoze, Ryskin).
We propose a formula for the ϕ propagator which interpolates between the regions of low $\mathrm{Y_{diff}}$, where we use the standard ϕ meson propagator, and of high $\mathrm{Y_{diff}}$ where we use the reggeized form:

$$\Delta^{(\phi)}_{\rho_1\rho_2}(\hat{p}) \to \Delta^{(\phi)}_{\rho_1\rho_2}(\hat{p})\, F(\mathrm{Y_{diff}}) + \Delta^{(\phi)}_{\rho_1\rho_2}(\hat{p})\, [1 - F(\mathrm{Y_{diff}})] \left(\exp(i\phi(s_{34}))\, \frac{s_{34}}{s_0} \right)^{\alpha_\phi(\hat{p}^2)-1} . \tag{18}$$

We use a simple function:

$$F(\mathrm{Y_{diff}}) = \exp\left(-\mathrm{c_y}|\mathrm{Y_{diff}}|\right) . \tag{19}$$

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

$pp \to pp\phi\phi$, WA102 data, spin dependence

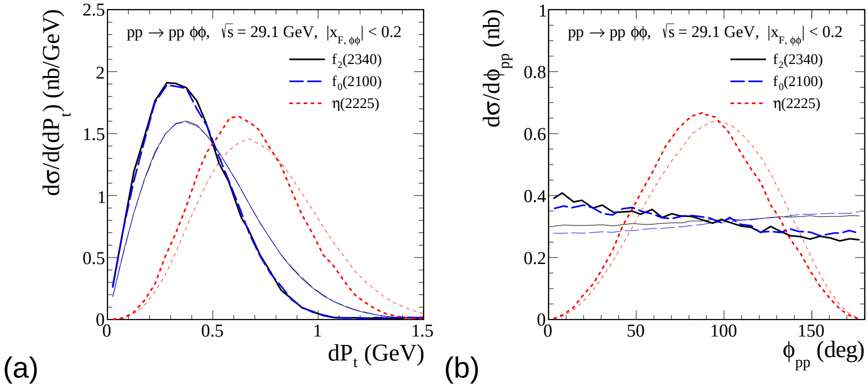


Figure: The distribution in $\mathrm{dP_t}$ (14) and in ϕ_{pp} for the central exclusive $\phi\phi$ production at $\sqrt{s} = 29.1$ GeV and $|x_{F,\phi\phi}| \leqslant 0.2$. The results for scalar, pseudoscalar and tensor resonances without (the thin lines) and with (the thick lines) absorptive corrections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

$pp \to pp\phi\phi$, WA102 data

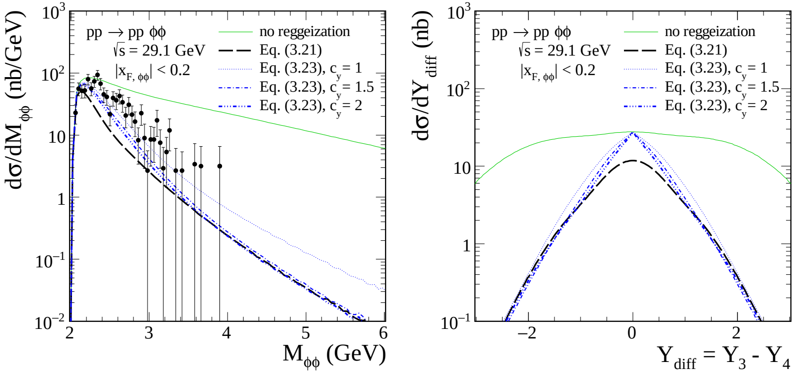


Figure: The distributions in $\phi\phi$ invariant mass (the left panel) and in $\mathrm{Y}_{\mathrm{diff}}$, the rapidity distance between the two ϕ mesons, (the right panel) for the ϕ-exchange continuum contribution. The calculations were done for $\sqrt{s} = 29.1$ GeV and $|x_{F,\phi\phi}| \leqslant 0.2$. In the left panel we show the WA102 experimental data normalised to $\sigma_{\mathrm{exp}}^{(\phi\phi)} = 41$ 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

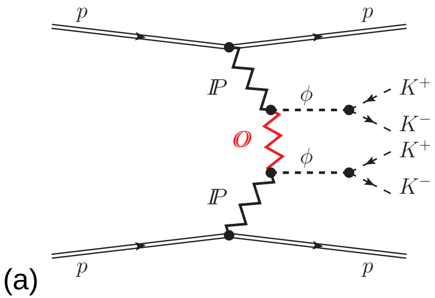


Figure: The Born level diagrams for diffractive production of a ϕ-meson pair with one and two odderon exchanges.

No coupling to protons in diagram (a).

Odderon exchange

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

$$i\Delta^{(\mathbb{O})}_{\mu\nu}(s,t) = -ig_{\mu\nu}\frac{\eta_{\mathbb{O}}}{M_0^2}(s\alpha'_{\mathbb{O}})^{\alpha_{\mathbb{O}}(t)-1}\,, \tag{20}$$

$$\alpha_{\mathbb{O}}(t) = \alpha_{\mathbb{O}}(0) + \alpha'_{\mathbb{O}}\,t\,, \tag{21}$$

where in (20) we have $M_0^{-2} = 1\ (\mathrm{GeV})^{-2}$ for dimensional reasons. Further more, we shall assume representative values for the odderon parameters

$$\eta_{\mathbb{O}} = -1\,, \qquad \alpha_{\mathbb{O}}(0) = 1.05\,, \qquad \alpha'_{\mathbb{O}} = 0.25\ \mathrm{GeV}^{-2}\,. \tag{22}$$

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 $\mathbb{O}$ and the ϕ outwards, the following formula:

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

Odderon exchange

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

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

where we adopt the monopole form

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

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 Λ^2 in the form factor can be adjusted to experimental data.

Continuum with photon exchange

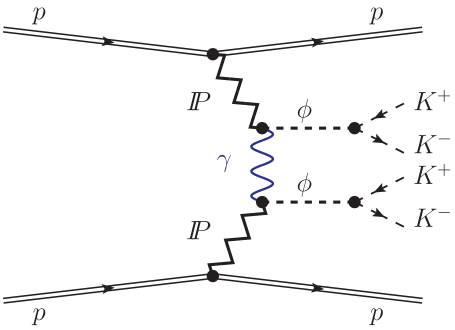


Figure: The “Born level” diagram for diffractive production of a ϕ-meson pair with an intermediate photon exchange.

This turned out to be small

Invariant mass distribution, ϕ exchange+$f_2(2340)$

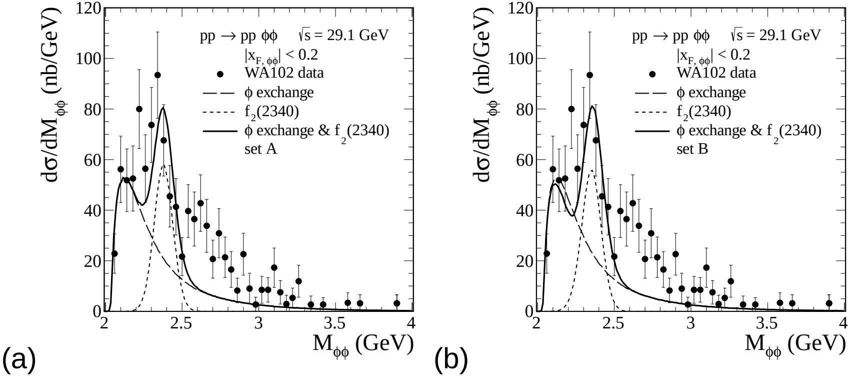


Figure: Invariant mass distributions for the central $\phi\phi$ system compared to the WA102 data at $\sqrt{s} = 29.1$ GeV and $|x_{F,\phi\phi}| \leqslant 0.2$. The data points have been normalized to the total cross section $\sigma_{exp}^{(\phi\phi)} = 41$ nb. We show results for two different $f_2 \to \phi\phi$ couplings set A, (panel (a)) or set B (panel (b))) The long-dashed line corresponds to the reggeized ϕ-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_{diff}, ϕ exchange+$f_2(2340)$

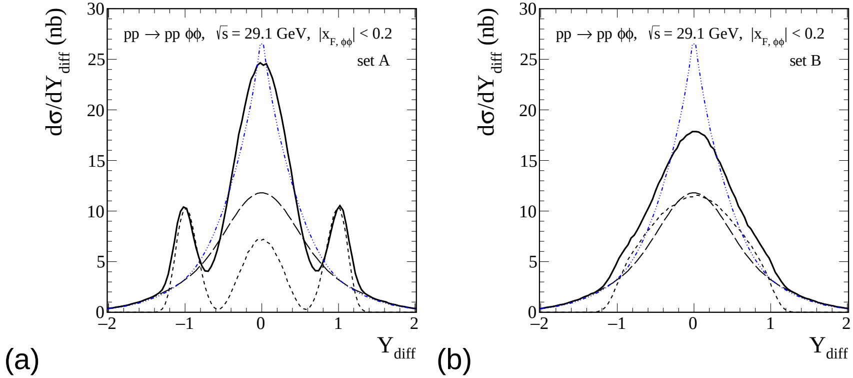
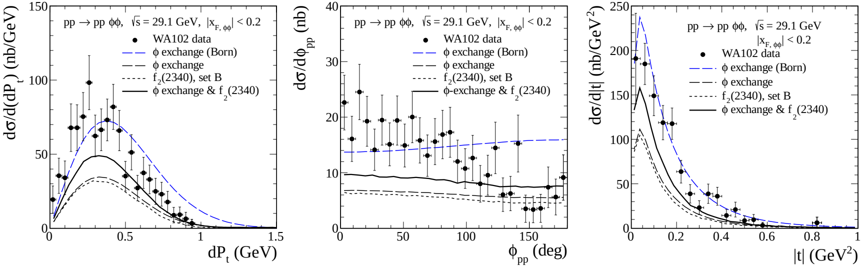


Figure: The distribution in rapidity distance between two centrally produced $\phi(1020)$ mesons $\mathrm{Y_{diff}} = \mathrm{Y_3} - \mathrm{Y_4}$ at $\sqrt{s} = 29.1$ GeV and for $|x_{F,\phi\phi}| \leqslant 0.2$. for two different $f_2 \to \phi\phi$ couplings. The absorption effects were included here.

WA102, some other distributions

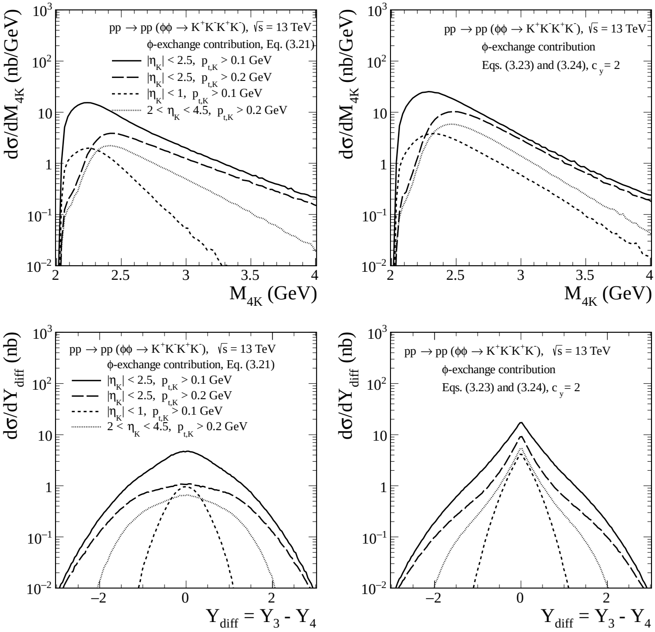


f_2(2340) and ϕ exchange

second choice of the $f_2 \to \phi\phi$ coupling

Something is still missing ?

Predictions for LHC, ϕ exchange only



Predictions for LHC, ϕ exchange only

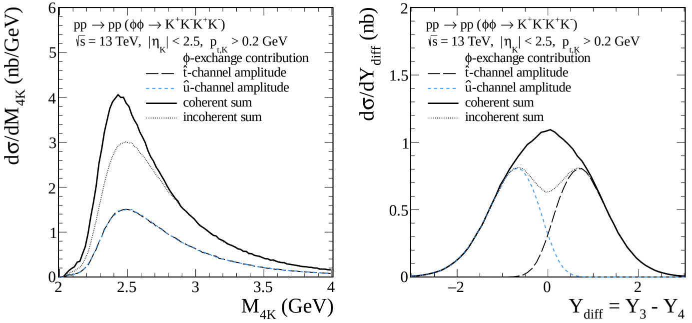


Figure: The $pp \to pp(\phi\phi \to K^+K^-K^+K^-)$ reaction calculated for $\sqrt{s} = 13$ TeV and $|\eta_K| < 2.5$, $p_{t,K} > 0.2$ GeV. The results for the ϕ(1020)-exchange contribution are presented. The black solid line correspond to the coherent sum of the $\hat{t}$- and $\hat{u}$-channel amplitudes. 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, ϕ-exchange

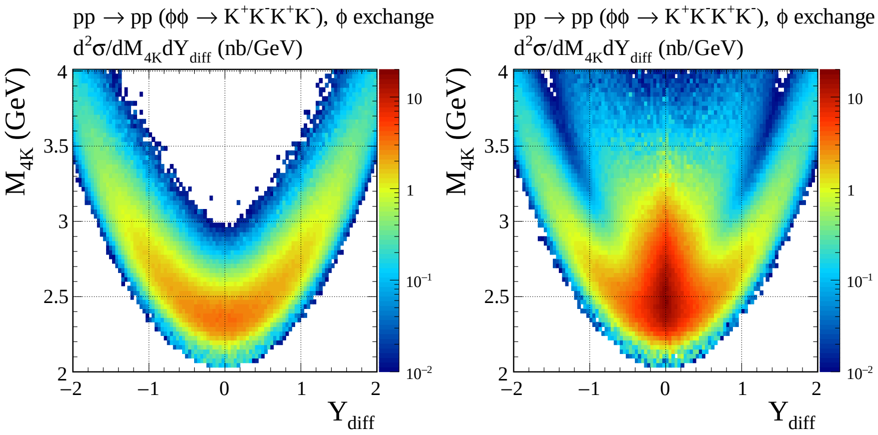
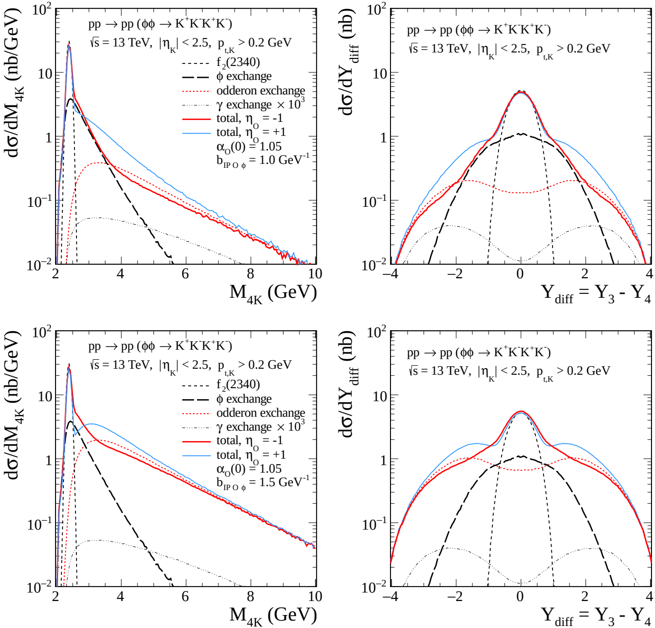
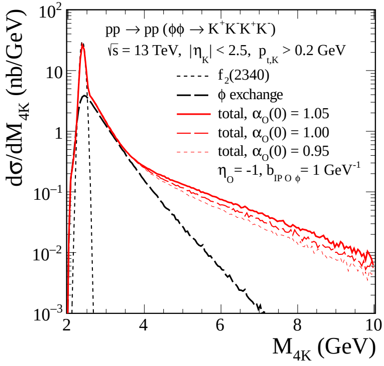


Figure: The two-dimensional distribution in (Y_{diff}, M_{4K}) for the diffractive continuum four-kaon production for $\sqrt{s} = 13$ TeV and $|\eta_K| < 2.5$, $p_{t,K} > 0.2$ GeV. Two different reggeization methods. The absorption effects are included here.

Odderon exchange at the LHC



Odderon at the LHC



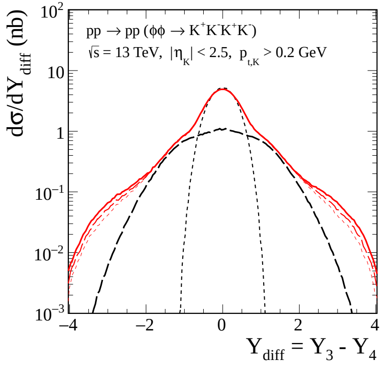
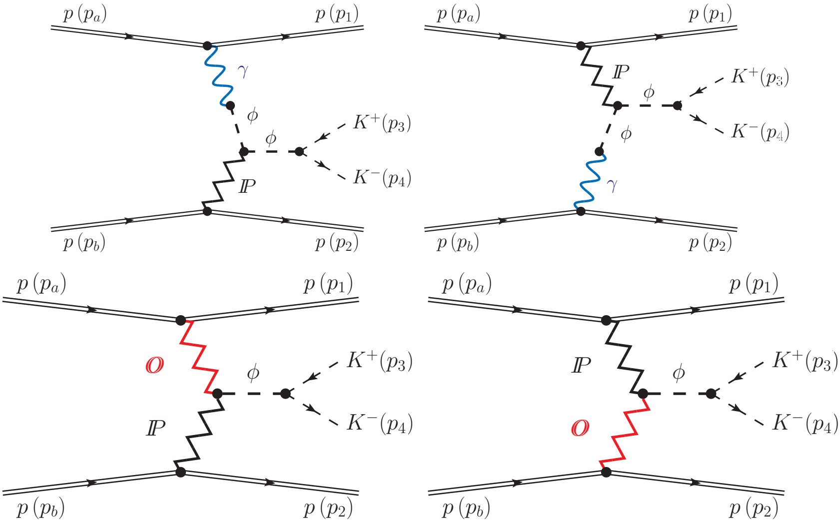


Figure: The complete results for $\sqrt{s} = 13$ TeV and $|\eta_K| < 2.5$, $p_{t,K} > 0.2$ GeV are shown. Here we show results for $\eta_{\mathbb{O}} = -1$ and for various values of the odderon intercept $\alpha_{\mathbb{O}}(0)$. Here we take $a_{\mathbb{P}\mathbb{O}\phi} = 0$ and $b_{\mathbb{P}\mathbb{O}\phi}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

Return to $pp \to pp\phi$



Odderon exchange contribution modifies the the photon-exchange contribution

Photoproduction process

$$\mathcal{M}^{(\gamma\mathbb{P})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2K^+K^-} = (-i)\bar{u}(p_1,\lambda_1) i\Gamma^{(\gamma pp)}_{\mu}(p_1,p_a)u(p_a,\lambda_a)$$
$$\times i\Delta^{(\gamma)\,\mu\sigma}(q_1)\, i\Gamma^{(\gamma\to\phi)}_{\sigma\nu}(q_1)\, i\Delta^{(\phi)\,\nu\rho_1}(q_1)\, i\Gamma^{(\mathbb{P}\phi\phi)}_{\rho_2\rho_1\alpha\beta}(p_{34},q_1)\, i\Delta^{(\phi)\,\rho_2\kappa}(p_{34})\, i\Gamma^{(\phi KK)}_{\kappa}(p_3,p_4)$$
$$\times i\Delta^{(\mathbb{P})\,\alpha\beta,\delta\eta}(s_2,t_2)\,\bar{u}(p_2,\lambda_2) i\Gamma^{(\mathbb{P}pp)}_{\delta\eta}(p_2,p_b)u(p_b,\lambda_b)\,. \tag{26}$$

$$\mathcal{M}^{(\gamma\mathbb{P})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2K^+K^-} = -i\,e^2\,\bar{u}(p_1,\lambda_1)\left[\gamma^{\alpha}F_1(t_1) + \frac{i}{2m_p}\sigma^{\alpha\alpha'}(p_1-p_a)_{\alpha'}F_2(t_1)\right]u(p_a,\lambda_a)$$
$$\times \frac{1}{t_1}\,\frac{(-m_\phi^2)}{t_1-m_\phi^2}\,\frac{1}{\gamma_\phi}\Delta_T^{(\phi)}(p_{34}^2)\,\frac{g_{\phi K^+K^-}}{2}\,(p_3-p_4)^{\beta}\,F^{(\phi KK)}(p_{34}^2)$$
$$\times\left[2a_{\mathbb{P}\phi\phi}\,\Gamma^{(0)}_{\alpha\beta\kappa\lambda}(p_{34},-q_1) - b_{\mathbb{P}\phi\phi}\,\Gamma^{(2)}_{\alpha\beta\kappa\lambda}(p_{34},-q_1)\right]\tilde{F}^{(\phi)}(t_1)\,\tilde{F}^{(\phi)}(p_{34}^2)\,F_M(t_2)$$
$$\times\frac{1}{2s_2}\left(-is_2\alpha'_{\mathbb{P}}\right)^{\alpha_{\mathbb{P}}(t_2)-1}\,3\beta_{\mathbb{P}NN}\,F_1(t_2)\,\bar{u}(p_2,\lambda_2)\left[\gamma^{\kappa}(p_2+p_b)^{\lambda}\right]u(p_b,\lambda_b)\,. \tag{27}$$

Pomeron-odderon fusion

$$
\begin{aligned}
\mathcal{M}^{(\mathbb{O}\mathbb{P})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2K^+K^-} = {} & (-i)\bar{u}(p_1,\lambda_1)i\Gamma^{(\mathbb{O}pp)}_{\mu}(p_1,p_a)u(p_a,\lambda_a) \\
& \times i\Delta^{(\mathbb{O})\,\mu\rho_1}(q_1)\,i\Gamma^{(\mathbb{P}\mathbb{O}\phi)}_{\rho_2\rho_1\alpha\beta}(p_{34},q_1)\,i\Delta^{(\phi)\,\rho_2\kappa}(p_{34})\,i\Gamma^{(\phi KK)}_{\kappa}(p_3,p_4) \\
& \times i\Delta^{(\mathbb{P})\,\alpha\beta,\delta\eta}(s_2,t_2)\,\bar{u}(p_2,\lambda_2)i\Gamma^{(\mathbb{P}pp)}_{\delta\eta}(p_2,p_b)u(p_b,\lambda_b)\,. \qquad (28)
\end{aligned}
$$

Other mechanisms for low/intermediate energies

- $\pi^0\rho^0 \to \phi$ and $\rho^0\pi^0 \to \phi$ fusion
  reggeization of ρ^0 very important,
  spin-flip dominance of ρ^0 echange
  $\phi \to \rho^0\pi^0$ is known.
- $\phi\mathbb{P} \to \phi$ and $\mathbb{P}\phi \to \phi$ fusion
  reggeization of ϕ was already discussed, $g_{\phi pp}$ is known (not very precisely) from low energies.
- $\eta\omega$ and $\omega\eta$ reggeization of ω

$pp \to pp\phi$, WA102 data

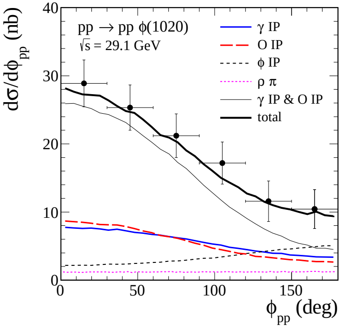


Figure: Azimuthal angle correlations between protons.

$g_{\mathbb{O}pp} = \frac{1}{10} g_{\mathbb{P}pp}$ (educated guess, TOTEM)
strong interference of $\gamma\mathbb{P}$ and $\mathbb{O}\mathbb{P}$

Other distributions for WA102

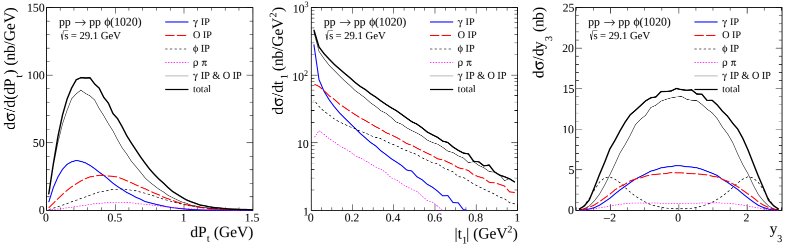


Figure: These distributions were not measured.

$pp \to pp\phi$, WA102 data

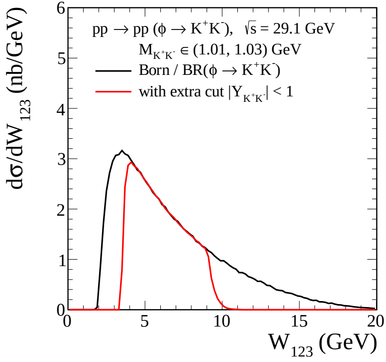


Figure: Photoproduction mechanism.

$W_{\gamma p}$ are relatively small

But we rather control the photoproduction cross section

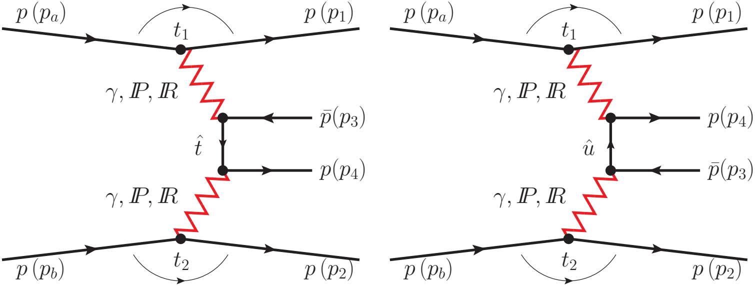
LHCb will measure the data for $pp \to pp\phi$.

Identify deviations from photoproduction.

Do we know photoproduction (saturation effects)?

$pp \to ppp\bar{p}$

The continuum (nonresonance) contribution



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

Possible exchanges

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

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

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

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

$pp \to ppp\bar{p}$

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

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

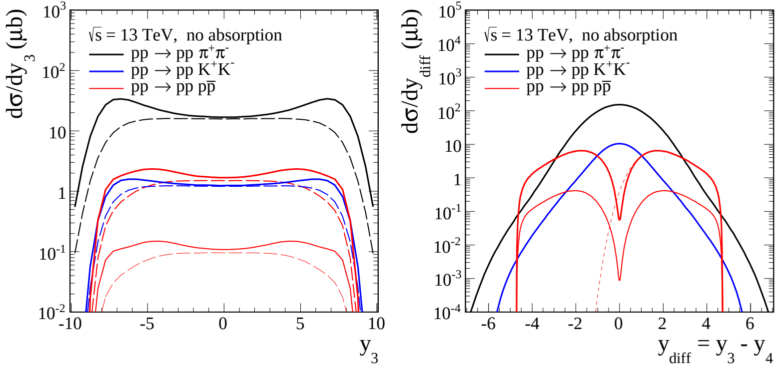
No $p\bar{p}$ resonances are known (to us) except of η_c and $\chi_c(0)$ mesons (see PDG).

$pp \to ppp\bar{p}$

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

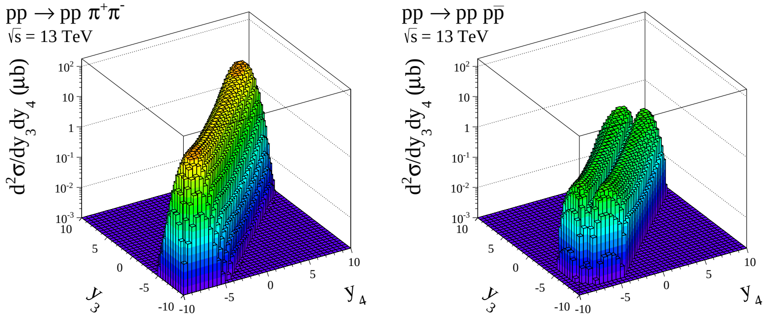
No absorption effects.

$pp \to ppp\bar{p}$



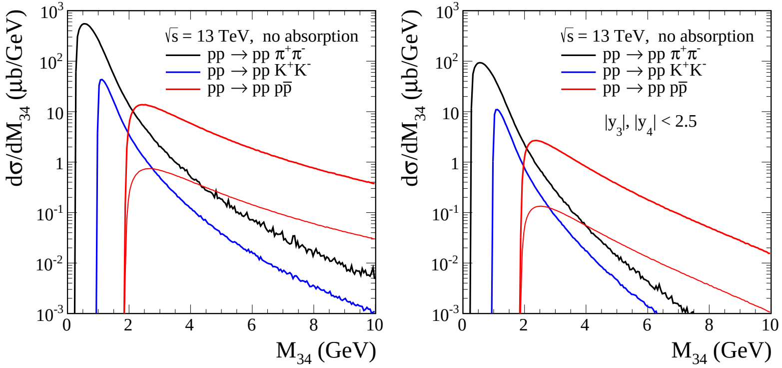
Surprising effect of the dip at $y_{diff} = 0$.
New effect for spin-1/2 particles
Good separation of t and u contributions.

$y_3 x y_4$ space



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

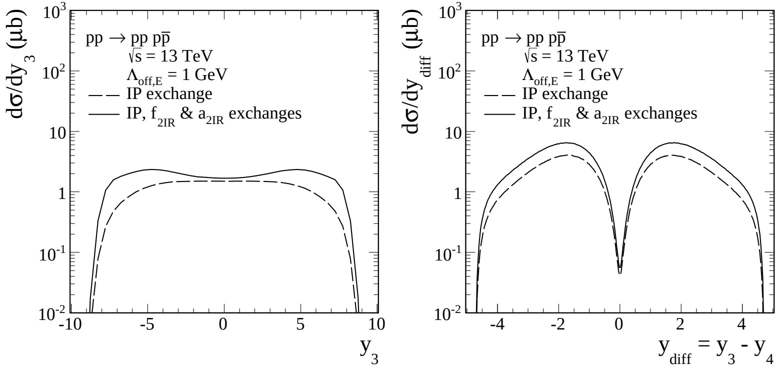
$M_{p\bar{p}}$-distribution



Different slope for pairs of pseudoscalar and for spin-1/2 hadrons.

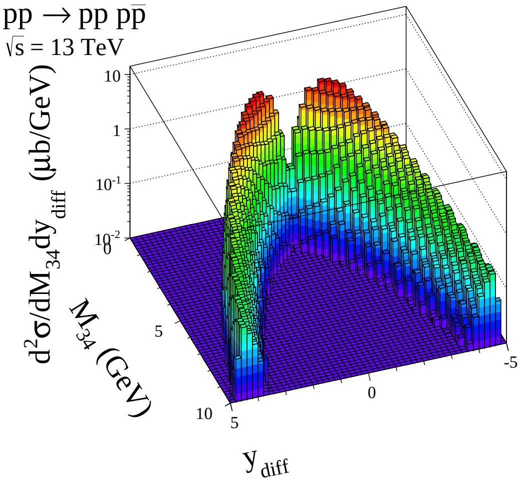
We explicitly include spin degrees of freedom in the Regge calculus.

Role of subleading reggeons



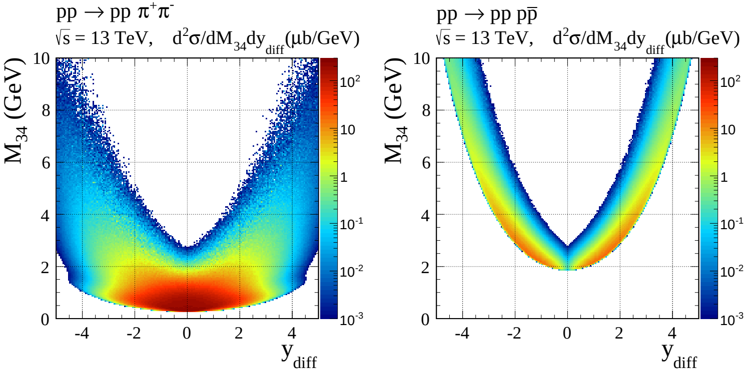
Even at $\sqrt{s}$ = 13 TeV a sizeable effect of subleading reggeons.

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



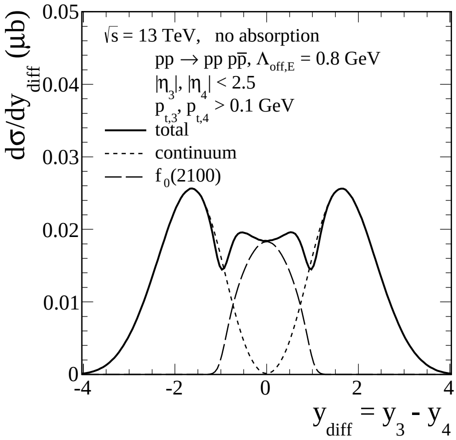
Region inside of the ridge seems promising
in searches for resonances

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



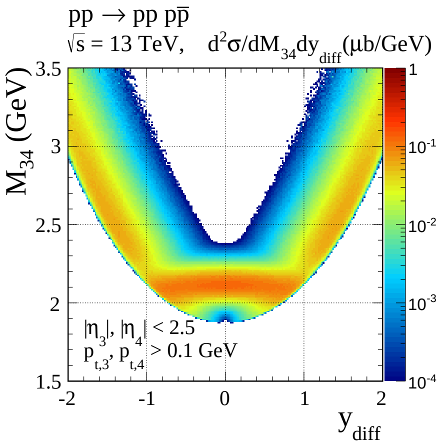
Different situation for $\pi^+\pi^-$ and $p\bar{p}$

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



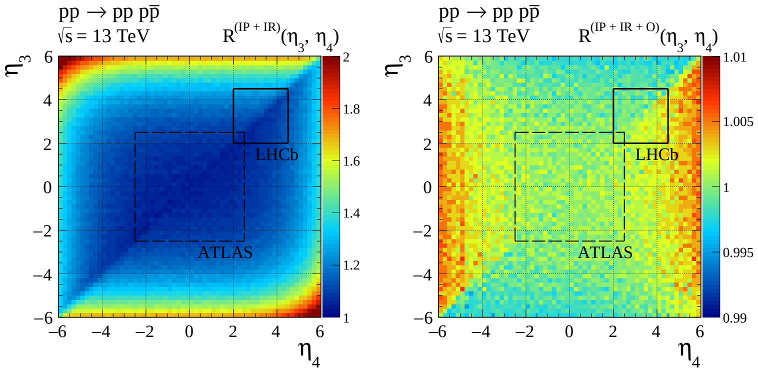
resonances may distroy the dip

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



resonances may distroy (close) the gorge

Role of ingredients, ratios



first: role of subleading reggeons
second: role of odderon

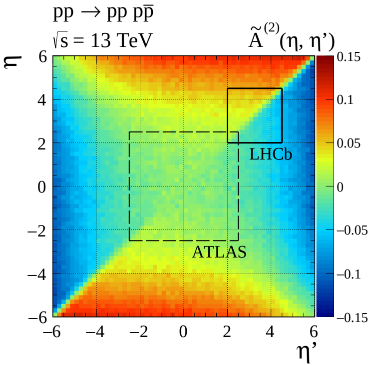
Asymmetry between central p and $\bar{p}$

In two dimensions (e.g. η_1, η_2) we can define the asymmetry:

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

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

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

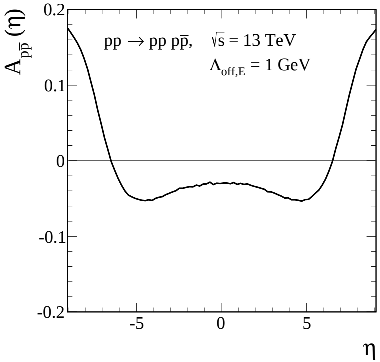


Clear asymmetry

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

Projection on one-dimension

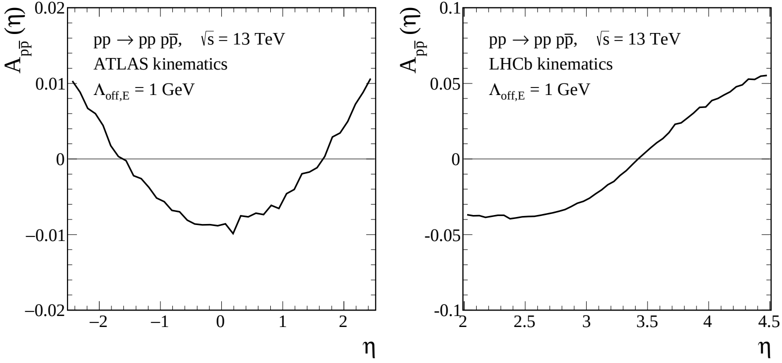
(full phase space)



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

Projection on one-dimension

(experimental cuts)



Conclusions

- The Regge phenomenology was extended to $2 \to 3$, $2 \to 4$ and $2 \to 6$ exclusive processes.
- The tensor pomeron/reggeon model was applied to many reactions.
- At lower energies tensor/vector reggeons.
- Three reactions ($pp \to pp\phi\phi$, $pp \to pp\phi$ and $pp \to ppp\bar{p}$ have been studied in the context of identifying odderon exchange.
- $pp \to pp\phi\phi$ seems promissing as here the odderon does not couple to protons. An upper limit for the odderon exchange has been etablished based on the WA102 data.
- This upper limit for the $\mathbb{P}\mathbb{O} \to \phi$ coupling was used for the $pp \to pp\phi$ 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 exchangs is probably larger than that for the odderon exchange.