15th workshop on non-perturbative Quantum Chromodynamics

Central exclusive production at RHIC and LHC

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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
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.

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.

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:

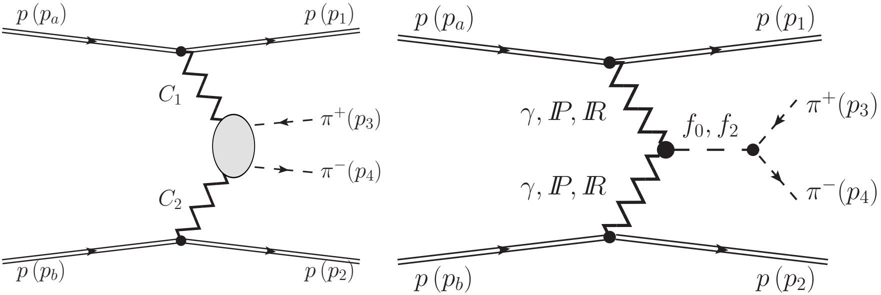
$$d\sigma = \frac{1}{2s} \overline{|\mathcal{M}_{pp \to ppM\bar{M}}|^2} \tag{3}$$

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

$$\frac{d^3 p_1}{(2\pi)^3 2E_1} \frac{d^3 p_2}{(2\pi)^3 2E_2} \frac{d^3 p_3}{(2\pi)^3 2E_3} \frac{d^3 p_4}{(2\pi)^3 2E_4} \tag{4}$$

- Any differential distribution can be calculated
- Include absorption effects

$pp \to pp\pi^+\pi^-$



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

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

$pp \to pp\pi^+\pi^-$

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

$$\mathcal{M}_{pp\to pp\pi^+\pi^-} = \mathcal{M}^{\pi\pi-\mathrm{continuum}}_{pp\to pp\pi^+\pi^-} + \mathcal{M}^{\pi\pi-\mathrm{resonances}}_{pp\to pp\pi^+\pi^-} \, . \tag{5}$$

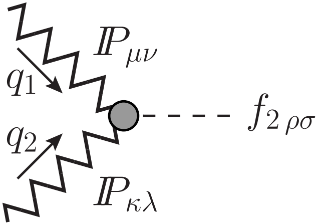
Absorption effects should be included in addition

Resonances

Scalar/pseudoscalar resonances:

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

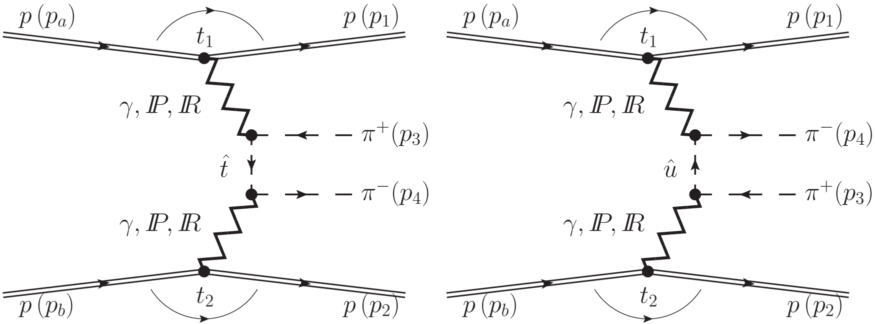
Tensor resonances:



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.

$pp \to pp\pi^+\pi^-$



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

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

$pp \to pp\pi^+\pi^-$

The $\mathbb{P}\mathbb{P}$-exchange amplitude can be written as

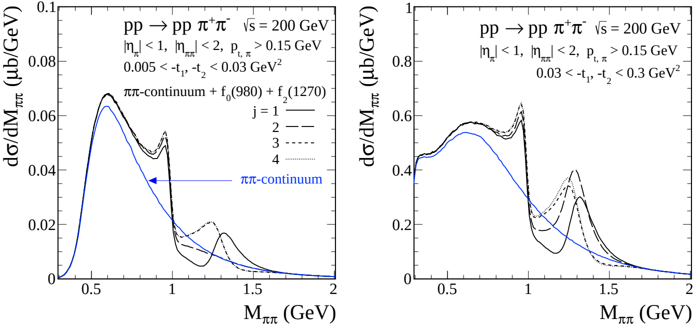
$$\mathcal{M}^{(\mathbf{PP}\to\pi^+\pi^-)} = \mathcal{M}^{(\hat{t})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^+\pi^-} + \mathcal{M}^{(\hat{u})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^+\pi^-}\,, \tag{6}$$

where

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

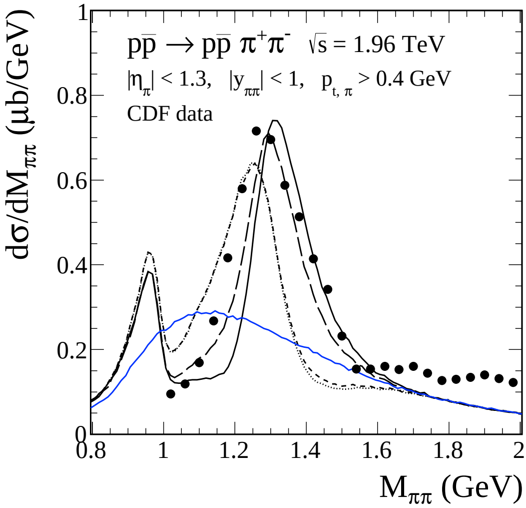
$$\begin{aligned}\mathcal{M}^{(\hat{u})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^+\pi^-} \simeq\ & 3\beta_{\mathbf{P}NN}\,2(p_1+p_a)_{\mu_1}(p_1+p_a)_{\nu_1}\,\delta_{\lambda_1\lambda_a}\,F_1(t_1)F_M(t_1)\\ &\times 2\beta_{\mathbf{P}\pi\pi}\,(p_4+p_u)^{\mu_1}(p_4+p_u)^{\nu_1}\,\frac{1}{4s_{14}}(-is_{14}\alpha'_{\mathbf{P}})^{\alpha_{\mathbf{P}}(t_1)-1}\,\fra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

$pp \to pp\pi^+\pi^-$



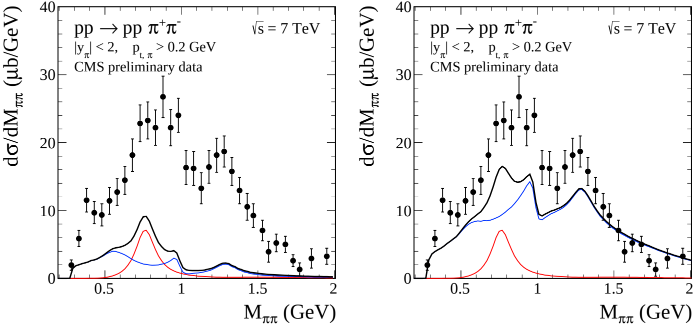
Interesting (negative) interference of $f_0(980)$
and two-pion continuum.

$pp \to pp\pi^+\pi^-$



Not completely exclusive data (protons not measured).

$pp \to pp\pi^+\pi^-$

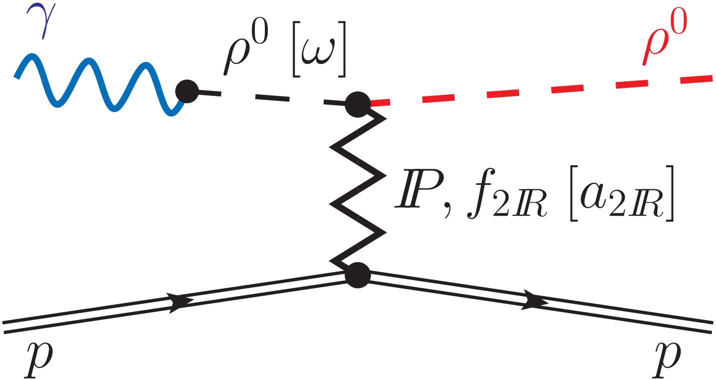


The parameters fixed to the CDF data.

Warning: Preliminary CMS data

Photoproduction at HERA

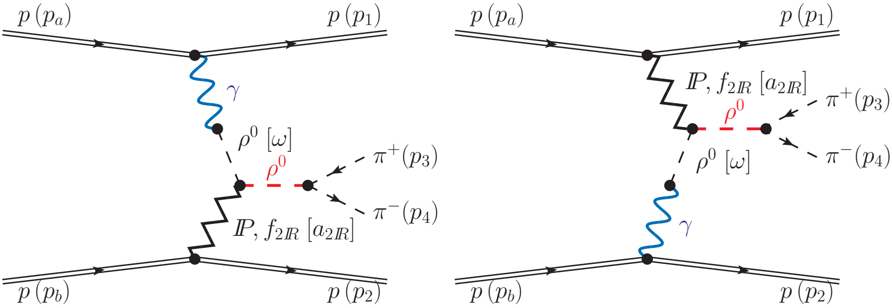
VDM (vector dominance model) mechanism:



Can be inserted to *pp* collisions.

$pp \to pp\pi^+\pi^-$

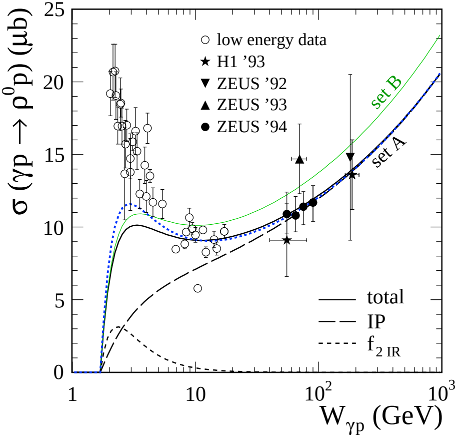
photon induced production of ρ^0 resonances



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

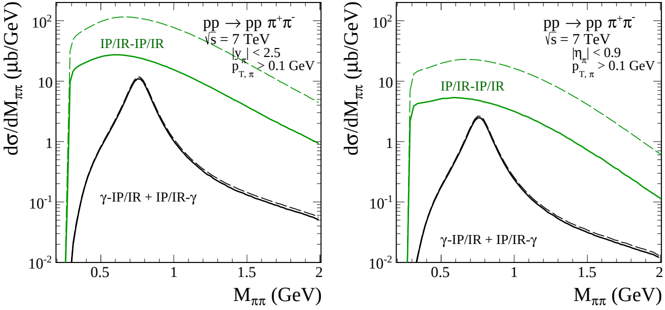
P.Lebiedowicz, O. Nachtmann and A. Szczurek, Phys. Rev. **D91** *(2015) 074023.*

HERA data



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

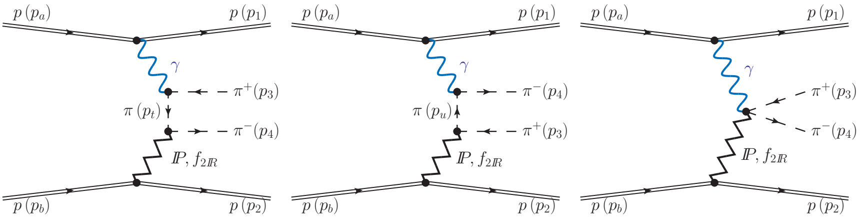
$pp \to pp\pi^+\pi^-$



with absorption effects included

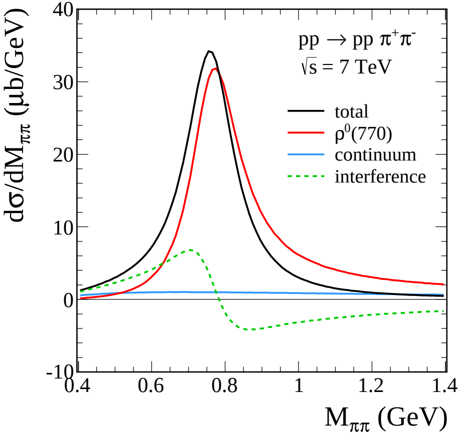
$pp \to pp\pi^+\pi^-$

photon induced diffractive continuum



So-called Söding mechanism.

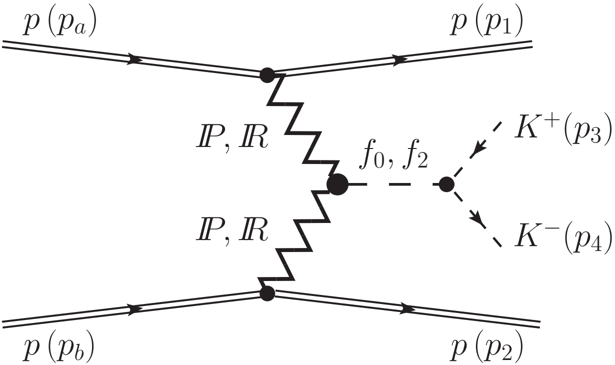
Interference effect



Modification of the spectral shape (skewdness).

$pp \to ppK^+K^-$

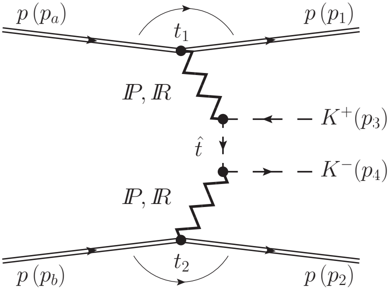
Purely diffractive resonance mechanisms:



P. Lebiedowicz, O. Nachtmann and A. Szczurek, arXiv:1804.04706, in print in Phys. Rev. **D**

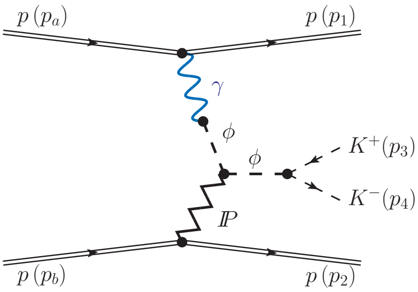
$pp \to ppK^+K^-$

Purely diffractive continuum mechanism:



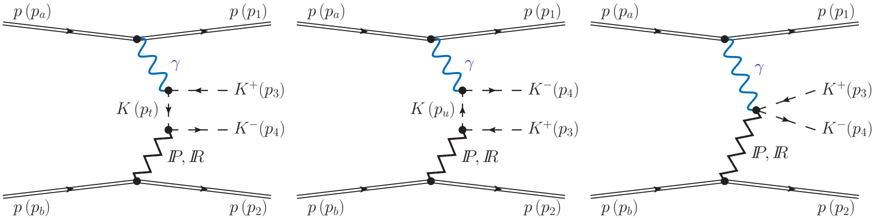
$pp \to ppK^+K^-$

Diffractive photoproduction resonance mechanism:

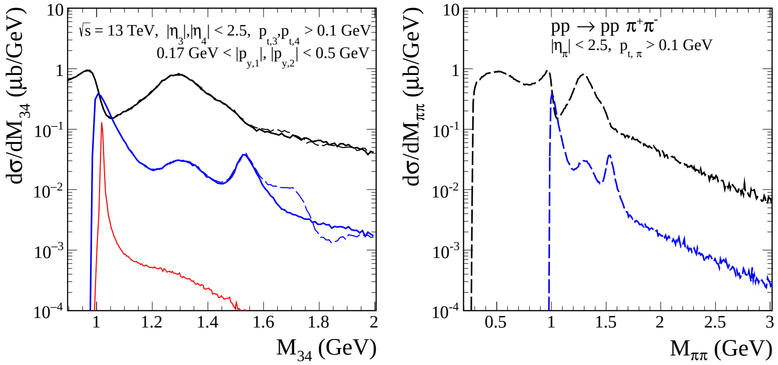


$pp \to ppK^+K^-$

Diffractive photoproduction continuum mechanism:

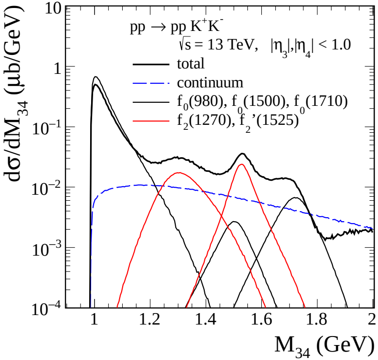


Results for CMS



CMS rapidity acceptance

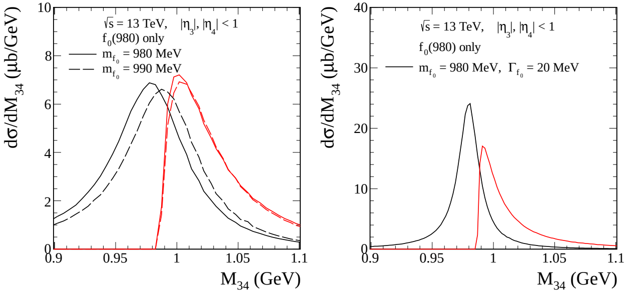
Resonance decomposition



Really many resonances may participate.

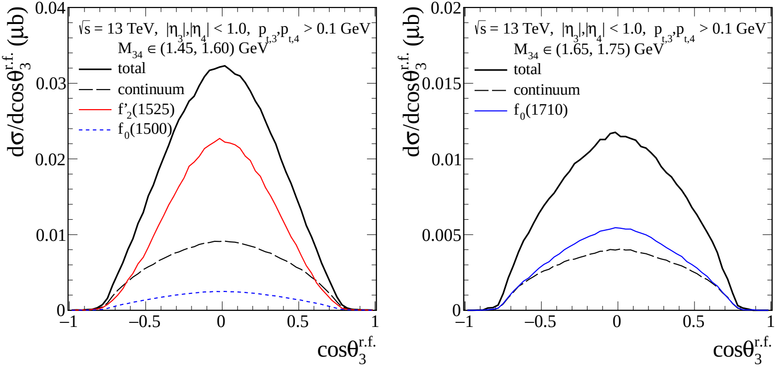
Parameters fixed by detailed knowledge of different reactions.

$f_0(980)$ line shape



left: Γ_{tot} = 70 MeV
right: Γ_{tot} = 20 MeV (Achasov-Shestakov)
Different position of the peak in $\pi^+\pi^-$ and K^+K^- channels.
$pp \to pp\phi$ gives contribution at the same $M_{K^+K^-}$ as $pp \to ppf_0(980)$
(the first reaction can be smoking-gun for observing effects of gluon saturation)

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

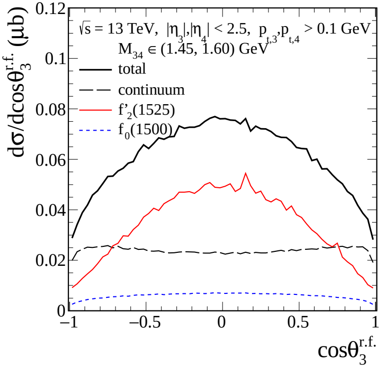


Not too instructive!

Too small range of rapidity?

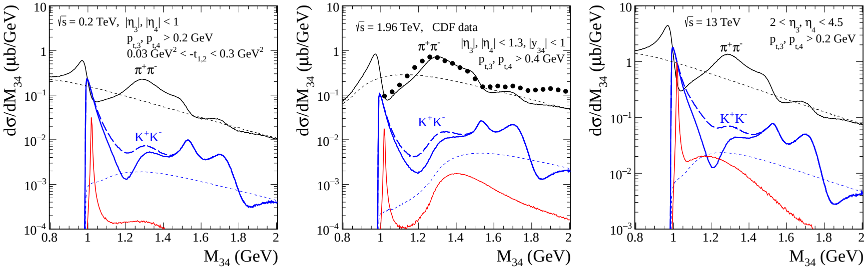
Can CMS measured such distributions?

Angular distribution in the KK rest frame



CMS range of rapidities

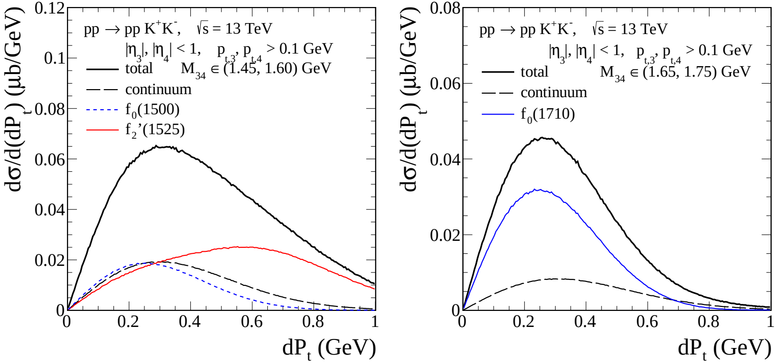
Predictions for different experiments



Can one observe ϕ meson ?

Glueball filter variable distribution

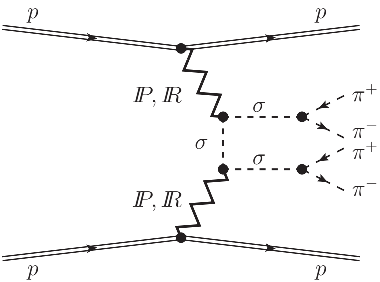
$$\boldsymbol{dP_t} = \boldsymbol{q_{t,1}} - \boldsymbol{q_{t,2}} = \boldsymbol{p_{t,2}} - \boldsymbol{p_{t,1}}\,, \quad dP_t = |\boldsymbol{dP_t}|\,. \tag{9}$$

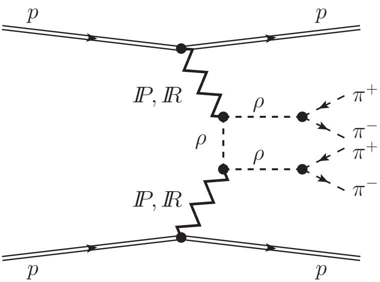


Some difference between continuum and resonances

$pp \to pp\pi^+\pi^-\pi^+\pi^-$

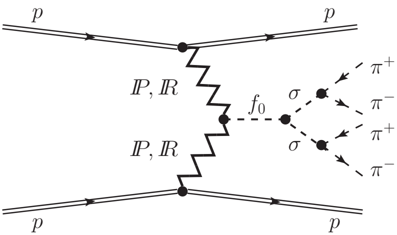
Double resonance production:

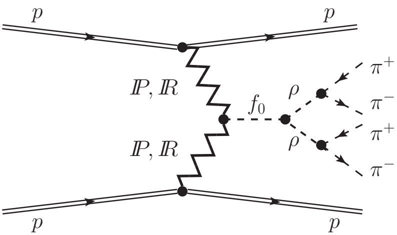




$pp \to pp\pi^+\pi^-\pi^+\pi^-$

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.

$pp \to pp\sigma\sigma$

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

$$\mathcal{M}^{(\sigma-\text{exchange})}_{pp\to pp\sigma\sigma} = \mathcal{M}^{(\mathbb{P}\mathbb{P}\to\sigma\sigma)} + \mathcal{M}^{(\mathbb{P}f_{2\mathbb{R}}\to\sigma\sigma)} + \mathcal{M}^{(f_{2\mathbb{R}}\mathbb{P}\to\sigma\sigma)} + \mathcal{M}^{(f_{2\mathbb{R}}f_{2\mathbb{R}}\to\sigma\sigma)} \tag{10}$$

For instance, the $\mathbb{P}\mathbb{P}$-exchange amplitude can be written as

$$\mathcal{M}^{(\mathbb{P}\mathbb{P}\to\sigma\sigma)} = \mathcal{M}^{(\hat{t})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\sigma\sigma} + \mathcal{M}^{(\hat{u})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\sigma\sigma} \tag{11}$$

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

$$\begin{aligned}\mathcal{M}^{(\hat{t})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\sigma\sigma} =& \\ &(-i)\bar{u}(p_1,\lambda_1)i\Gamma^{(\mathbb{P}pp)}_{\mu_1\nu_1}(p_1,p_a)u(p_a,\lambda_a)\, i\Delta^{(\mathbb{P})\,\mu_1\nu_1,\alpha_1\beta_1}(s_{13},t_1)\, i\Gamma^{(\mathbb{P}\sigma\sigma)}_{\alpha_1\beta_1}(p_t,-p_3)\, i\Delta^{(\sigma)}(p_t) \\ &\times i\Gamma^{(\mathbb{P}\sigma\sigma)}_{\alpha_2\beta_2}(p_4,p_t)\, i\Delta^{(\mathbb{P})\,\alpha_2\beta_2,\mu_2\nu_2}(s_{24},t_2)\,\bar{u}(p_2,\lambda_2)i\Gamma^{(\mathbb{P}pp)}_{\mu_2\nu_2}(p_2,p_b)u(p_b,\lambda_b)\,,\end{aligned} \tag{12}$$

$$\begin{aligned}\mathcal{M}^{(\hat{u})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\sigma\sigma} =& \\ &(-i)\,\bar{u}(p_1,\lambda_1)i\Gamma^{(\mathbb{P}pp)}_{\mu_1\nu_1}(p_1,p_a)u(p_a,\lambda_a)\, i\Delta^{(\mathbb{P})\,\mu_1\nu_1,\alpha_1\beta_1}(s_{14},t_1)\, i\Gamma^{(\mathbb{P}\sigma\sigma)}_{\alpha_1\beta_1}(p_4,p_u)\, i\Delta^{(\sigma)}(p_u) \\ &\times i\Gamma^{(\mathbb{P}\sigma\sigma)}_{\alpha_2\beta_2}(p_u,-p_3)\, i\Delta^{(\mathbb{P})\,\alpha_2\beta_2,\mu_2\nu_2}(s_{23},t_2)\,\bar{u}(p_2,\lambda_2)i\Gamma^{(\mathbb{P}pp)}_{\mu_2\nu_2}(p_2,p_b)u(p_b,\lambda_b)\,.\end{aligned} \tag{13}$$

$pp \to pp\rho^0\rho^0$

We write the amplitude as

$$\mathcal{M}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\rho\rho} = \left(\epsilon^{(\rho)}_{\rho_3}(\lambda_3)\right)^* \left(\epsilon^{(\rho)}_{\rho_4}(\lambda_4)\right)^* \mathcal{M}^{\rho_3\rho_4}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\rho\rho}\,, \tag{14}$$

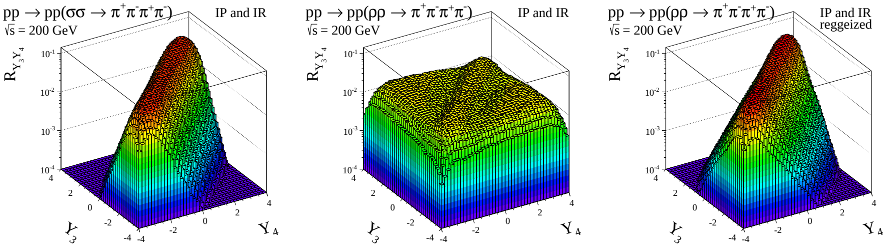
where $\epsilon^{(\rho)}_{\rho}(\lambda)$ are the polarisation vectors of the ρ meson.

$$\begin{aligned}
\mathcal{M}^{(\rho-\text{exchange})\,\rho_3\rho_4}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\rho\rho} \simeq\ & 2(p_1+p_a)_{\mu_1}(p_1+p_a)_{\nu_1}\,\delta_{\lambda_1\lambda_a}\,F_1(t_1)\,F_M(t_1) \\
\times \Big\{ & V^{\rho_3\rho_1\mu_1\nu_1}(s_{13},t_1,p_t,p_3)\,\Delta^{(\rho)}_{\rho_1\rho_2}(p_t)\,V^{\rho_4\rho_2\mu_2\nu_2}(s_{24},t_2,-p_t,p_4)\,\left[\hat{F}_\rho(p_t^2)\right]^2 \\
& + V^{\rho_4\rho_1\mu_1\nu_1}(s_{14},t_1,-p_u,p_4)\,\Delta^{(\rho)}_{\rho_1\rho_2}(p_u)\,V^{\rho_3\rho_2\mu_2\nu_2}(s_{23},t_2,p_u,p_3)\,\left[\hat{F}_\rho(p_u^2)\right]^2 \Big\} \\
\times\ & 2(p_2+p_b)_{\mu_2}(p_2+p_b)_{\nu_2}\,\delta_{\lambda_2\lambda_b}\,F_1(t_2)\,F_M(t_2)\,,
\end{aligned} \tag{15}$$

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

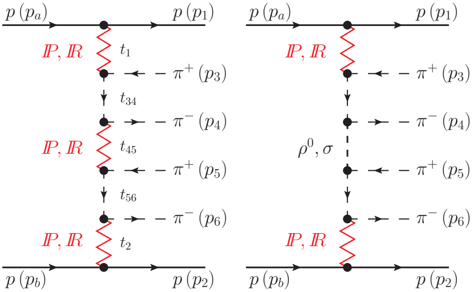
$$\begin{aligned}
V_{\mu\nu\kappa\lambda}(s,t,k_2,k_1) =\ & 2\Gamma^{(0)}_{\mu\nu\kappa\lambda}(k_1,k_2)\,\frac{1}{4s}\Big[3\beta_{\mathbf{P}NN}\,a_{\mathbf{P}\rho\rho}(-is\alpha'_{\mathbf{P}})^{\alpha_{\mathbf{P}}(t)-1} \\
& + \frac{1}{M_0}g_{f_{2\mathbf{R}}pp}\,a_{f_{2\mathbf{R}}\rho\rho}(-is\alpha'_{f_{2\mathbf{R}}})^{\alpha_{f_{2\mathbf{R}}}(t)-1}\Big] \\
& - \Gamma^{(2)}_{\mu\nu\kappa\lambda}(k_1,k_2)\,\frac{1}{4s}\Big[3\beta_{\mathbf{P}NN}\,b_{\mathbf{P}\rho\rho}(-is\alpha'_{\mathbf{P}})^{\alpha_{\mathbf{P}}(t)-1} \\
& + \frac{1}{M_0}g_{f_{2\mathbf{R}}pp}\,b_{f_{2\mathbf{R}}\rho\rho}(-is\alpha'_{f_{2\mathbf{R}}})^{\alpha_{f_{2\mathbf{R}}}(t)-1}\Big]\,.
\end{aligned} \tag{16}$$

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



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

$pp \to pp\pi^+\pi^-\pi^+\pi^-$



Only the first type of diagrams was included

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

$pp \to pp\pi^+\pi^-\pi^+\pi^-$

$$
\begin{aligned}
\mathcal{M} = {} & \frac{1}{2}\left(\mathcal{M}_{\{3456\}} + \mathcal{M}_{\{5436\}} + \mathcal{M}_{\{3654\}} + \mathcal{M}_{\{5634\}}\right) \\
& + \frac{1}{2}\left(\mathcal{M}_{\{4356\}} + \mathcal{M}_{\{4536\}} + \mathcal{M}_{\{6354\}} + \mathcal{M}_{\{6534\}}\right) \\
& + \frac{1}{2}\left(\mathcal{M}_{\{3465\}} + \mathcal{M}_{\{5463\}} + \mathcal{M}_{\{3645\}} + \mathcal{M}_{\{5643\}}\right) \\
& + \frac{1}{2}\left(\mathcal{M}_{\{4365\}} + \mathcal{M}_{\{4563\}} + \mathcal{M}_{\{6345\}} + \mathcal{M}_{\{6543\}}\right) ,
\end{aligned} \tag{17}
$$

$pp \to pp\pi^+\pi^-\pi^+\pi^-$

$$\mathcal{M}_{\{3456\}} = A_{\pi p}(s_{13}, t_1)\, \frac{F_\pi(t_{34})}{t_{34} - m_\pi^2}\, A_{\pi\pi}(s_{45}, t_{45})\, \frac{F_\pi(t_{56})}{t_{56} - m_\pi^2}\, A_{\pi p}(s_{26}, t_2)\,, \tag{18}$$

$$\mathcal{M}_{\{4356\}} = A_{\pi p}(s_{14}, t_1)\, \frac{F_\pi(t_{43})}{t_{43} - m_\pi^2}\, A_{\pi\pi}(s_{35}, t_{35})\, \frac{F_\pi(t_{56})}{t_{56} - m_\pi^2}\, A_{\pi p}(s_{26}, t_2)\,, \tag{19}$$

$$\mathcal{M}_{\{3465\}} = A_{\pi p}(s_{13}, t_1)\, \frac{F_\pi(t_{34})}{t_{34} - m_\pi^2}\, A_{\pi\pi}(s_{46}, t_{46})\, \frac{F_\pi(t_{65})}{t_{65} - m_\pi^2}\, A_{\pi p}(s_{25}, t_2)\,, \tag{20}$$

$$\mathcal{M}_{\{4365\}} = A_{\pi p}(s_{14}, t_1)\, \frac{F_\pi(t_{43})}{t_{43} - m_\pi^2}\, A_{\pi\pi}(s_{36}, t_{36})\, \frac{F_\pi(t_{65})}{t_{65} - m_\pi^2}\, A_{\pi p}(s_{25}, t_2)\,. \tag{21}$$

$pp \to pp\pi^+\pi^-\pi^+\pi^-$

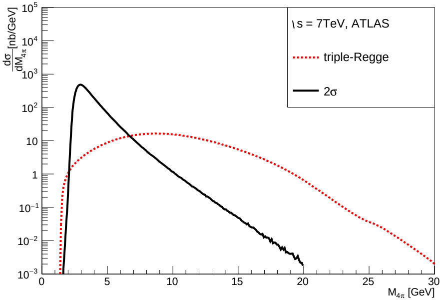
The subprocess amplitudes with the Regge exchanges are given as

$$A_{\pi p}(s,t) = \sum_{j=\mathbf{P},f_{2\mathbf{R}}} \eta_j \, s \, C^j_{\pi p} \left(\frac{s}{s_0}\right)^{\alpha_j(t)-1} F^j_{\pi p}(t)\,, \qquad (22)$$

$$A_{\pi\pi}(s,t) = \sum_{j=\mathbf{P},f_{2\mathbf{R}}} \eta_j \, s \, C^j_{\pi\pi} \left(\frac{s}{s_0}\right)^{\alpha_j(t)-1} F^j_{\pi\pi}(t)\,, \qquad (23)$$

where the signature factors are $\eta_{\mathbf{P}} = i$ and $\eta_{f_{2\mathbf{R}}} = i - 0.86$.

$pp \to pp\pi^+\pi^-\pi^+\pi^-$



Large 4π invariant masses

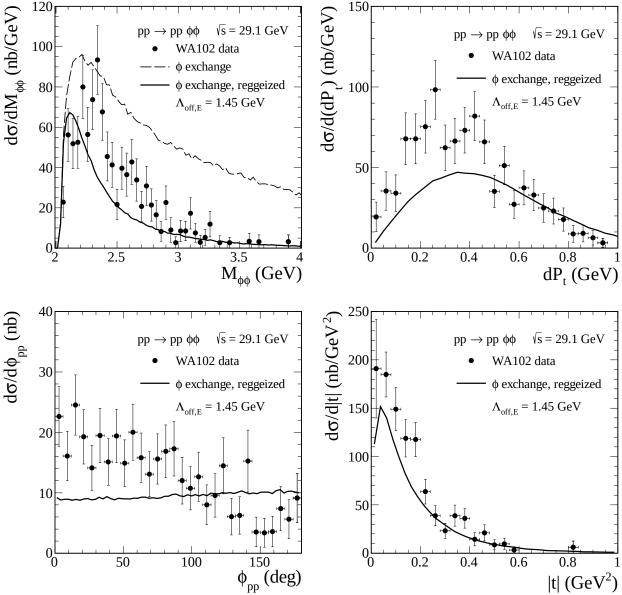
Good measurement for CMS (!)

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

$pp \to pp\phi\phi$

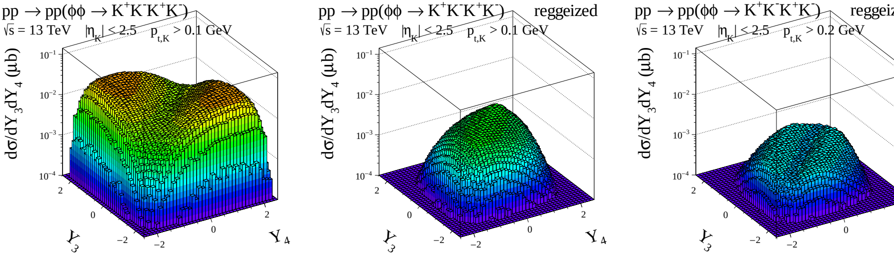
- Observed by WA102, no theoretical interpretation
- Two mechanisms possible a priori
  - continuum ("ϕ" exchange, reggeization (?))
  - $f_2(1950)$ (not yet, TTT structure)
  - glueball candidate(s), below ($f_0(1710)$) and above threshold
- Let us start exploration, preliminary results below

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

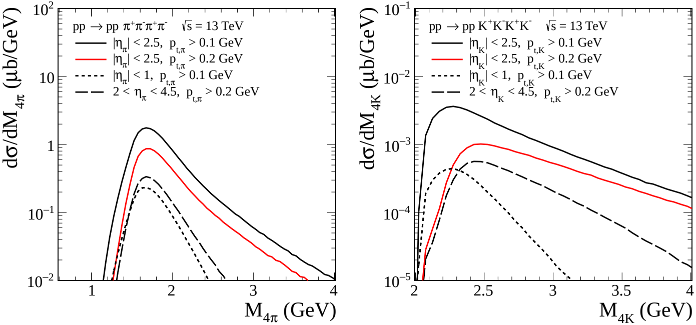


Not yet perfect

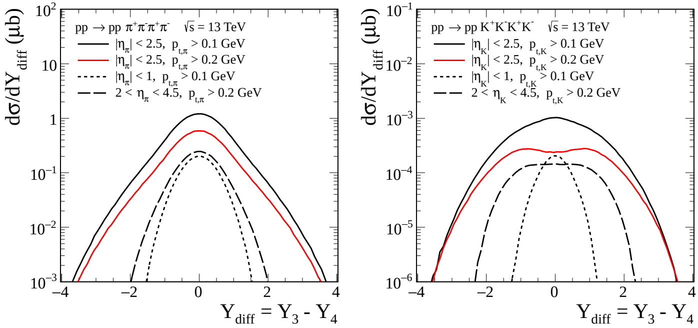
$pp \to pp\phi\phi$, predictions for the LHC



$pp \to pp p\bar{p}$, predictions for the LHC



$pp \to pp p\bar{p}$, predictions for the LHC

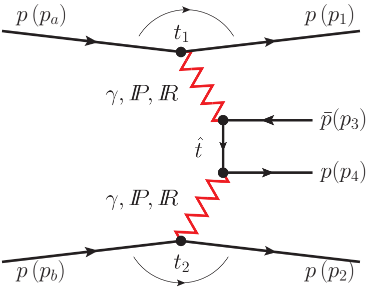


One should return to the topic once the data at the LHC are available

CMS and LHCb data analysis in progress

$pp \to ppp\bar{p}$

The continuum (nonresonance) contribution



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

$pp \to ppp\bar{p}$

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

$$\mathcal{M}_{pp\to pp\bar{p}p} = \mathcal{M}^{p\bar{p}-\mathrm{continuum}}_{pp\to pp\bar{p}p} + \mathcal{M}^{p\bar{p}-\mathrm{resonances}}_{pp\to pp\bar{p}p} \,. \tag{24}$$

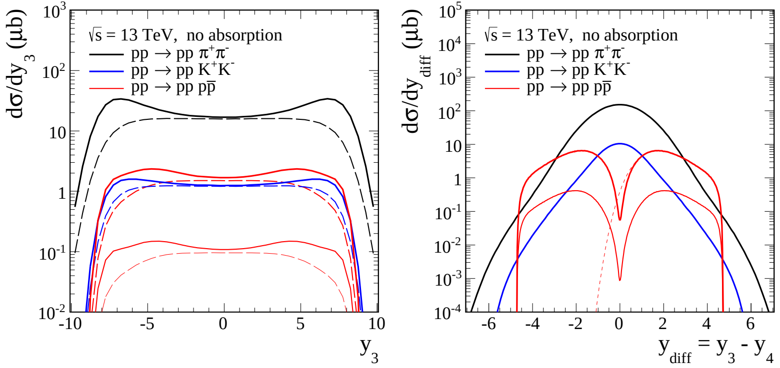
No $p\bar{p}$ resonances are known (to us) except of η_c and $\chi_c(0)$ mesons (see PDG).

$pp \to ppp\bar{p}$

$$
\begin{aligned}
\mathcal{M}^{(\mathbf{PP}\to\bar{p}p)}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\lambda_3\lambda_4} = {} & (-i)\bar{u}(p_1,\lambda_1) i\Gamma^{(\mathbf{P}pp)}_{\mu_1\nu_1}(p_1,p_a)u(p_a,\lambda_a)\, i\Delta^{(\mathbf{P})\,\mu_1\nu_1,\alpha_1\beta_1}(s_{13},t_1) \\
& \times \bar{u}(p_4,\lambda_4)[i\Gamma^{(\mathbf{P}pp)}_{\alpha_2\beta_2}(p_4,p_t)\, i\Delta^{(p)}(p_t) i\Gamma^{(\mathbf{P}pp)}_{\alpha_1\beta_1}(p_t,-p_3) \\
& \quad + i\Gamma^{(\mathbf{P}pp)}_{\alpha_1\beta_1}(p_4,p_u)\, i\Delta^{(p)}(p_u) i\Gamma^{(\mathbf{P}pp)}_{\alpha_2\beta_2}(p_u,-p_3)\,]v(p_3,\lambda_3) \\
& \times i\Delta^{(\mathbf{P})\,\alpha_2\beta_2,\mu_2\nu_2}(s_{24},t_2)\,\bar{u}(p_2,\lambda_2) i\Gamma^{(\mathbf{P}pp)}_{\mu_2\nu_2}(p_2,p_b)u(p_b,\lambda_b)\,.
\end{aligned}
\tag{25}
$$

No absorption effects.

$pp \to ppp\bar{p}$

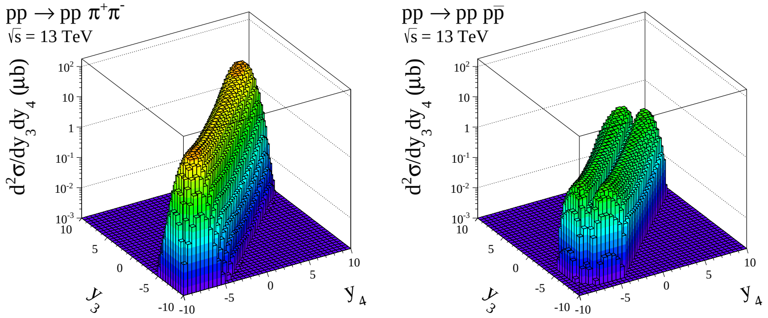


Surprising effect of the dip at $y_{diff} = 0$.

New effect for spin-1/2 particles

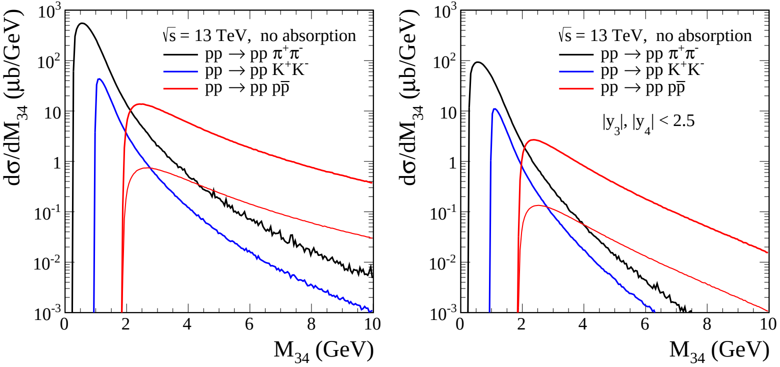
Good separation of t and u contributions.

$y_3 x y_4$ space



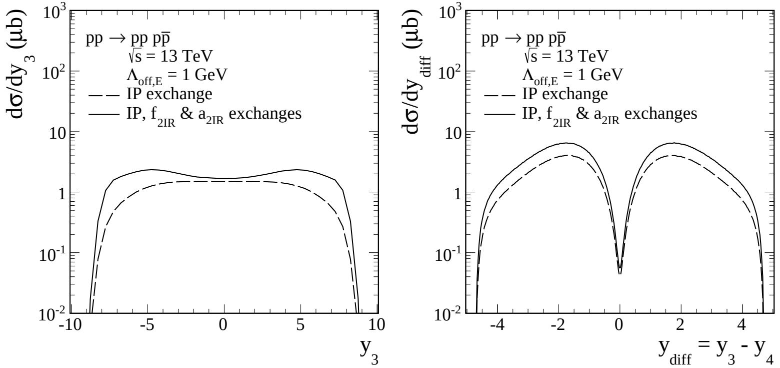
Completely different character.
The dip is everywhere on the diagonal
(ATLAS can do it, ALICE not really).

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



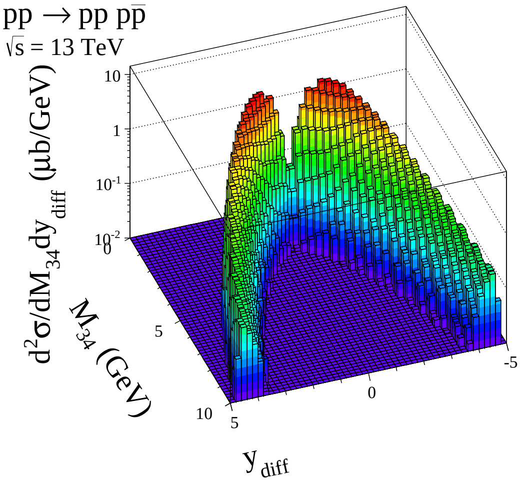
Different slope for pairs of pseudoscalar and for spin-1/2 hadrons.
We explicitly include spin degrees of freedom in the Regge calculus.

Role of subleading reggeons



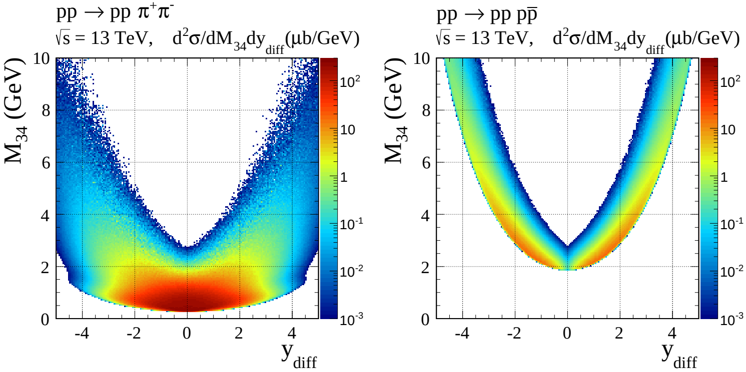
Even at $\sqrt{s}$ = 13 TeV a sizeable effect of subleading reggeons.

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



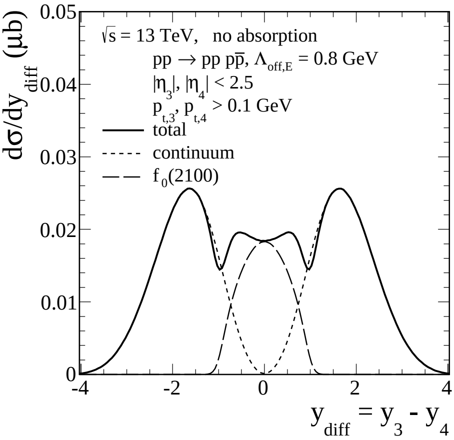
Region inside of the ridge seems promising
in searches for resonances

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



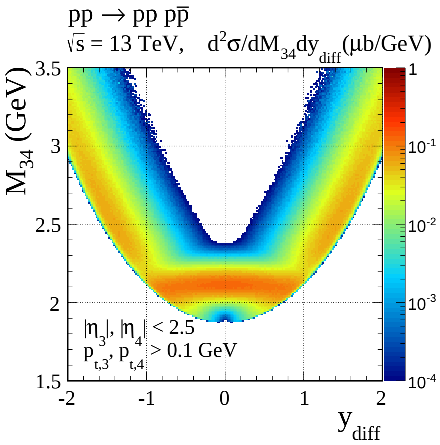
Different situation for $\pi^+\pi^-$ and $p\bar{p}$

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



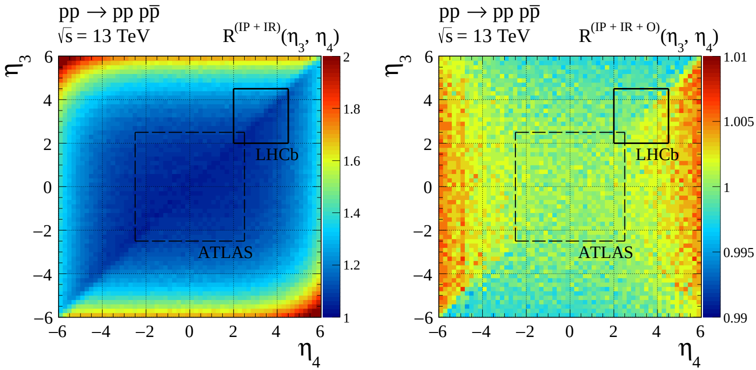
resonances may distroy the dip

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

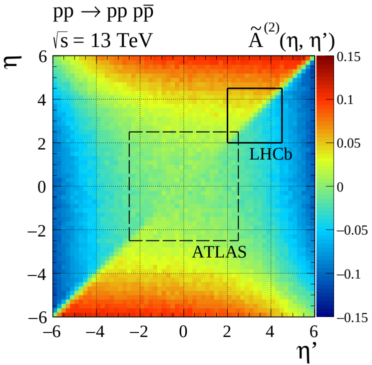
Asymmetry between central p and $\bar{p}$

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

$$\widetilde{A}^{(2)}(\eta,\eta') = \frac{\frac{d^2\sigma}{d\eta_3 d\eta_4}(\eta,\eta') - \frac{d^2\sigma}{d\eta_3 d\eta_4}(\eta',\eta)}{\frac{d^2\sigma}{d\eta_3 d\eta_4}(\eta,\eta') + \frac{d^2\sigma}{d\eta_3 d\eta_4}(\eta',\eta)} \,. \tag{26}$$

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

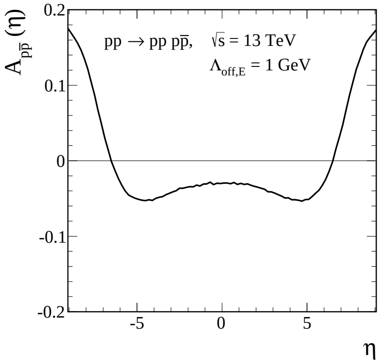
$$A = \frac{\sigma(p) - \sigma(\bar{p})}{\sigma(p) + \sigma(\bar{p})} \tag{27}$$



Clear asymmetry

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

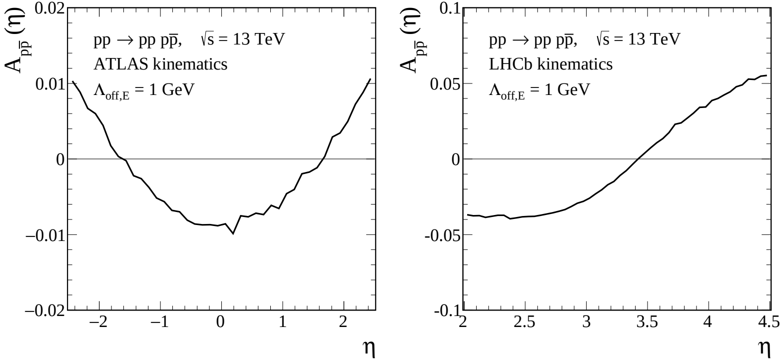
Projection on one-dimension
(full phase space)



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

Projection on one-dimension

(experimental cuts)



Conclusions, $pp \to pph^+h^-$

- The Regge phenomenology was extended in practice 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.
- The dipion invariant mass has a rich structure which strongly depends on kinematical cuts (continuum, resonances, interference).
- Disagreement with CMS data due to large dissociation contribution.
- Purely exclusive data expected from STAR, CMS+TOTEM and ATLAS+ALFA.

Conclusions, $pp \to pph^+h^-$

- 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.
  Predictions for LHC were shown.
  Resonances (glueballs) should be added.
- $p\bar{p}$ production has quite different characteristics ($d\sigma/dM$ and $d\sigma/dy_{diff}$ (dip)).
  These are predictions of our approach.