# Exclusive soft reactions
# in high-energy proton-proton collisions

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# The pomeron in high energy scattering

- For soft high-energy reactions ( large c.m. energy of the collision $\sqrt{s}$ but small momentum transfers $\sqrt{|t|}$ ) first-principle calculations are not possible → we use Regge-type models.
  High-energy hadronic reactions are dominated by pomeron (IP) *t*-channel exchange.

  The pomeron was postulated in 1961 [Gribov] to explain the slowly rising hadronic cross section with increasing energy.

  Using the optical theorem $\sigma_{tot}(s) = \frac{1}{s}\mathrm{Im}A(s,t=0)$:

$$\sigma_{tot}(s) \sim C_{\mathbb{P}} \left(\frac{s}{s_0}\right)^{\alpha_{\mathbb{P}}(0)-1}$$

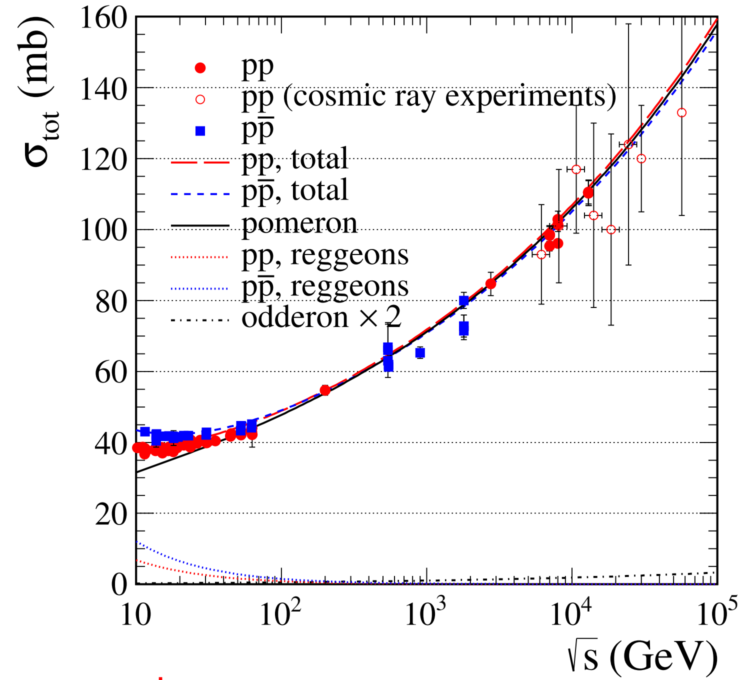
IP-hadron coupling

scale parameter $s_0 \simeq 1\ \mathrm{GeV}^2$

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

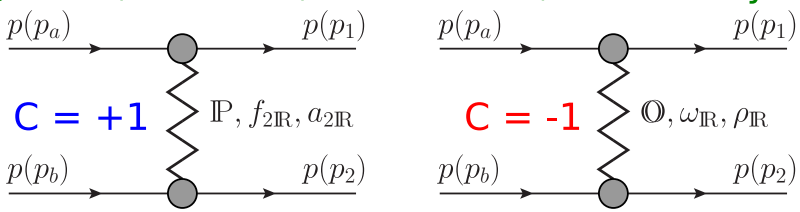
intercept: $\alpha_{\mathbb{P}}(0) \simeq 1.08 - 1.09$

(for reggeons is about 0.5)




- Pomeron has vacuum quantum numbers: charge, color, isospin, charge conjugation (C = +1), parity … But what about spin?
  → [Otto Nachtmann, Annals Phys. 209 (1991) 436]
  based on investigations of soft high-energy reactions in QCD using functional integral techniques the pomeron exchange can be understood as a coherent sum of elementary spin 2 + 4 + 6 +… exchanges.

- An effective model with such a tensor pomeron has been constructed with effective propagators and vertices derived from Lagrangians for the couplings.
  [Ewerz, Maniatis, Nachtmann, Annals Phys. 342 (2014) 31]

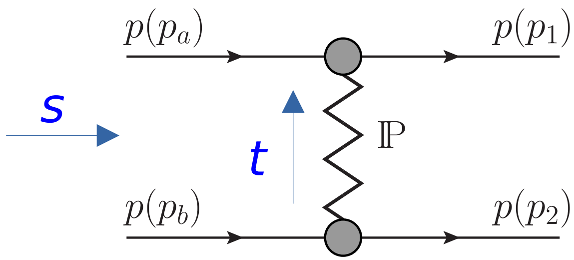


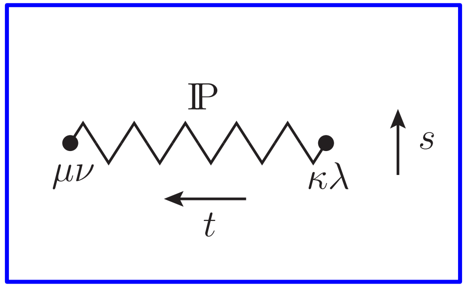

The pomeron (IP) and the C=+1 reggeons are treated as effective rank-2 symmetric tensor exchanges, in particular regarding their coupling to particles, the C= -1 exchanges (odderon and reggeons) are treated as vector exchanges.

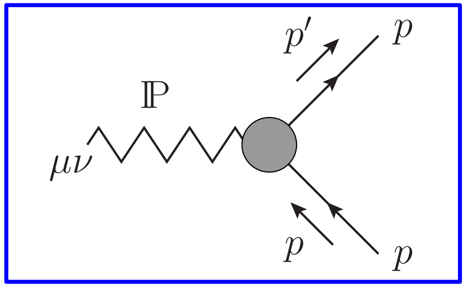
- A tensor character of the pomeron is also prefered in holographic QCD
  see e.g. Brower, Polchinski, Strassler, Tan, JHEP 12 (2007) 005; Domokos, Harvey, Mann, PRD 80 (2009) 126015; Iatrakis, Ramamurti, Shuryak, PRD 94 (2016) 045005

# Pomeron: tensor vs vector

- Tensor pomeron, C = +1 (effective symmetric tensor exchange)




Ewerz, Maniatis, Nachtmann,
Ann. Phys. 342 (2014) 31

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

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

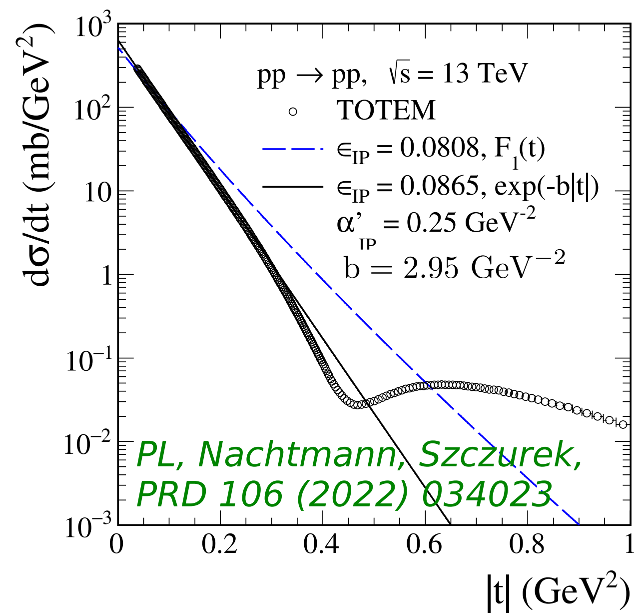
$\mathbb{P}$ trajectory : $\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}}\,t$ $\begin{cases} \alpha_{\mathbb{P}}(0) = 1 + \epsilon_{\mathbb{P}} \simeq 1.08 - 1.09 \\ \alpha'_{\mathbb{P}} = 0.25\ \text{GeV}^{-2} \end{cases}$

$F_1(t)$ : form factor

$\tilde{\alpha}'_{\mathbb{P}}$ : scale parameter, $\quad \tilde{\alpha}'_{\mathbb{P}} = 0.25\ \text{GeV}^{-2}$

$\beta_{\mathbb{P}pp}$ : coupling parameter, $\quad \beta_{\mathbb{P}pp} = 1.87\ \text{GeV}^{-1}$

"Pomeron Physics and QCD", Donnachie, Dosch, Landshoff, Nachtmann, CUP, 2002



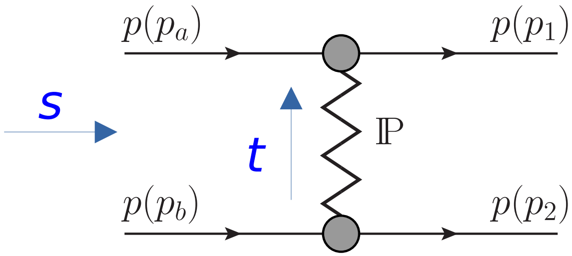

- Vector pomeron, C = -1 (Donnachie-Landshoff pomeron)

$$i\Delta^{(\mathbb{P}_V)}_{\mu\nu}(s,t) = \frac{1}{M_0^2}g_{\mu\nu}(-is\tilde{\alpha}'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1}$$

$$i\Gamma^{(\mathbb{P}_V pp)}_{\mu}(p',p) = -i3\beta_{\mathbb{P}pp}F_1(t)M_0\gamma_\mu\,, \qquad M_0 = 1\ \text{GeV}$$

# Pomeron: tensor vs vector

- **Helicity in proton-proton elastic scattering and the spin structure of the soft IP**




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

Each proton is labelled by its helicity λ = ± ½ which is the spin projection along its direction of motion. We choose the s-channel c.m. frame. There are 5 independent s-channel helicity amplitudes.

Studying the ratio $r_5$ of single-helicity-flip to non-flip amplitudes

$$r_5(s,t) = \frac{2m_p\,\phi_5(s,t)}{\sqrt{-t}\,\mathrm{Im}[\phi_1(s,t)+\phi_3(s,t)]}$$

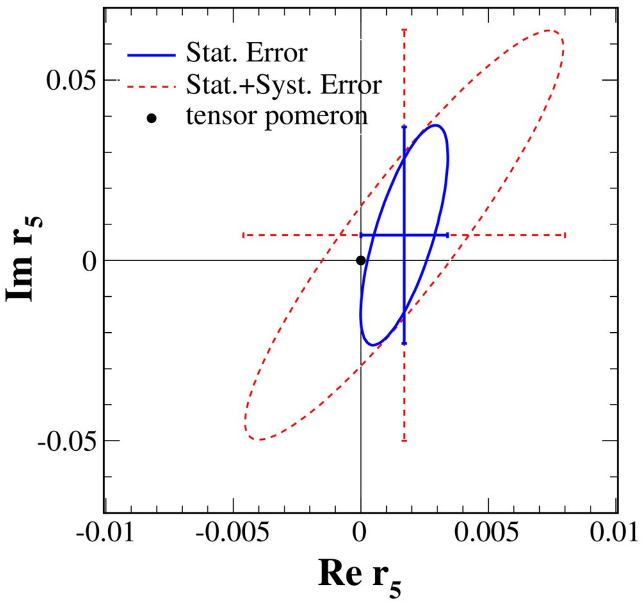
we found that STAR data *[L. Adamczyk et al. (STAR Collaboration) PLB 719 (2013) 62]* measured at

$$\sqrt{s} = 200\ \mathrm{GeV}, \quad 0.003 \leqslant |t| \leqslant 0.035\ \mathrm{GeV}^2$$

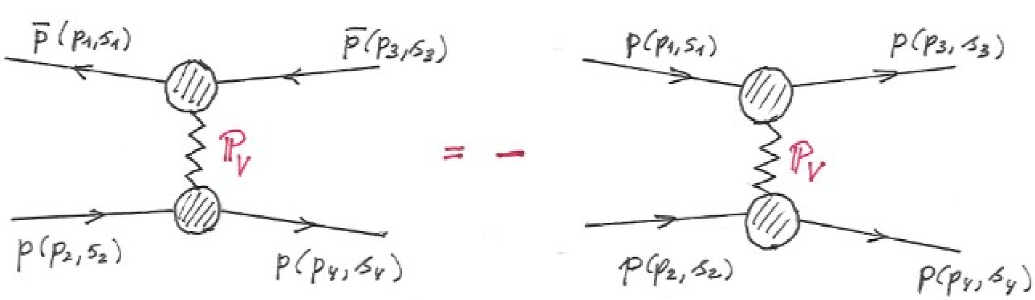
are compatible with the tensor pomeron ansatz while they exclude a scalar character of the pomeron:

$$r_5^{I\!P_T}(s,t) = -\frac{m_p^2}{s}\left[i + \tan\left(\frac{\pi}{2}(\alpha_{I\!P}(t)-1)\right)\right],\ r_5^{I\!P_T}(s,0) = (-0.28 - i2.20)\times 10^{-5}$$

$$r_5^{I\!P_S}(s,t) = -\frac{1}{2}\left[i + \tan\left(\frac{\pi}{2}(\alpha_{I\!P}(t)-1)\right)\right],\ r_5^{I\!P_S}(s,0) = -0.064 - i0.500$$




- **Problem with the vector pomeron (C = -1):**



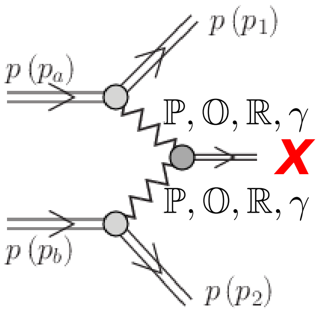

$$i\Gamma_\mu^{(\mathbb{P}_V pp)}(p',p) = -i\Gamma_\mu^{(\mathbb{P}_V \bar{p}\bar{p})}(p',p)$$

$$\sigma_{tot} = \frac{1}{2\sqrt{s(s-4m_p^2)}}\mathrm{Im}\left[\phi_1(s,0)+\phi_3(s,0)\right]$$

$$\sigma_{tot}(\bar{p}p)|_{\mathbb{P}_V} = -\sigma_{tot}(pp)|_{\mathbb{P}_V}$$

# Applications of the tensor-pomeron and vector-odderon approach

- **Helicity in proton-proton elastic scattering and the spin structure of the soft pomeron**
  *Ewerz, P.L., Nachtmann, Szczurek, PLB 763 (2016) 382*
- **Central Exclusive Production (CEP),** *p p → p p* ***X****, P.L., Nachtmann, Szczurek:*

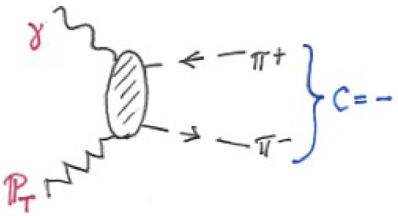



***X***: $\eta$, $\eta'$, $f_0$ — *Annals Phys. 344 (2014) 301*
$\rho^0$ and $\pi^+\pi^-$ continuum — *PRD91 (2015) 074023*
$\pi^+\pi^-$ continuum, $f_2(1270) \to \pi^+\pi^-$ — *PRD93 (2016) 054015; PRD101 (2020) 034008*
$\pi^+\pi^-\pi^+\pi^-$, $\rho^0\rho^0$ — *PRD94 (2016) 034017*
$\rho^0$ with proton diss. — *PRD95 (2017) 034036*
$p\bar{p}$ — *PRD97 (2018) 094027*
$K^+K^-$ — *PRD98 (2018) 014001*
$\phi \to K^+K^-$, $\mu^+\mu^-$ — *PRD101 (2020) 094012* } odderon exchange
$\phi\phi \to K^+K^-K^+K^-$, $f_2(2340)$ — *PRD99 (2019) 094034* } odderon exchange
$f_1(1285)$, $f_1(1420)$ — *PRD102 (2020) 114003* [with J. Leutgeb and A. Rebhan]
$K^{*0}\bar{K}^{*0}$ -continuum vs $f_2(1950)$ — *P.L., PRD103 (2021) 054039*

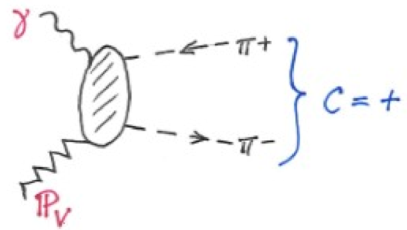
- **Bremsstrahlung and CEP of photon**, *P.L., Nachtmann, Szczurek*
  - $\pi\pi \to \pi\pi\,\gamma$ — *PRD 105 (2022) 014022*
  - $pp \to pp\,\gamma$ — *PRD 106 (2022) 034023; PRD107 (2023) 074014*
  - $pp \to pp\,\gamma\gamma$ — *PLB 843 (2023) 138053*

- **Photoproduction and low *x* DIS** *Britzger, Ewerz, Glazov, Nachtmann, Schmitt, PRD100 (2019) 114007*
  and **low x DVCS** *P.L., Nachtmann, Szczurek, PLB835 (2022) 137497*

- ***γ p → π⁺ π⁻ p*** *Bolz, Ewerz, Maniatis, Nachtmann, Sauter, Schöning, JHEP 01 (2015) 151*
  interference between $\gamma p \to (\rho^0 \to \pi^+\pi^-)p$ (pomeron exch.) and $\gamma p \to (f_2(1270) \to \pi^+\pi^-)p$ (odderon exch.) → $\pi^+\pi^-$ charge asymmetries




$\pi^+\pi^-$ in antisymmetric state

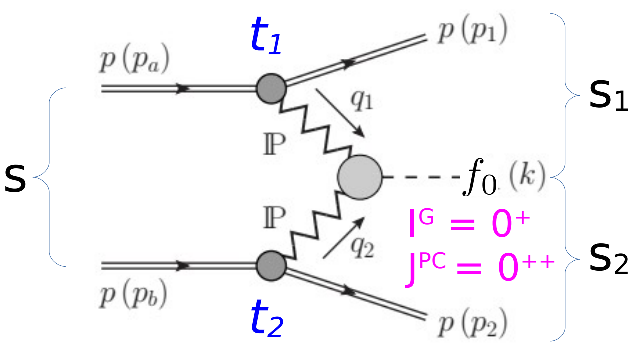



$\pi^+\pi^-$ in symmetric state

For a tensor (vector) pomeron the $\pi^+\pi^-$ pair is in antisymmetric (symmetric) state under the exchange $\pi^+ \longleftrightarrow \pi^-$. Since the pomeron has C = +1 the $\pi^+\pi^-$ pair must be in antisymmetric state. This gives a further clear evidence against a vector nature of the pomeron.

# Central Exclusive Production (CEP)

At high energies double pomeron exchange (DPE) is dominant production mechanism of resonances.



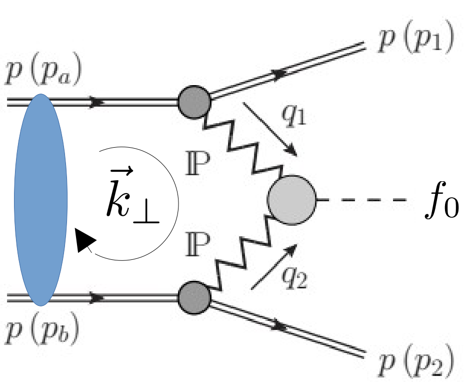

$p\ (p_a\ ,\ \lambda_a) + p\ (p_b\ ,\ \lambda_b) \to p\ (p_1\ ,\ \lambda_1) + f_0\,(k) + p\ (p_2\ ,\ \lambda_2),\quad \lambda_i = \pm 1/2$

The Born amplitude is written in terms of the the effective pomeron-proton vertex function, pomeron propagator, and the pomeron-pomeron-$f_0$ vertex:

$$\mathcal{M}^{\rm Born}_{\lambda_a\lambda_b\to\lambda_1\lambda_2 f_0} = (-i)\bar{u}(p_1,\lambda_1) i\Gamma^{(I\!\!Ppp)}_{\mu_1\nu_1}(p_1,p_a) u(p_a,\lambda_a) \times i\Delta^{(I\!\!P)\,\mu_1\nu_1,\alpha_1\beta_1}(s_1,t_1)\, i\Gamma^{(I\!\!PI\!\!Pf_0)}_{\alpha_1\beta_1,\alpha_2\beta_2}(q_1,q_2)\, i\Delta^{(I\!\!P)\,\alpha_2\beta_2,\mu_2\nu_2}(s_2,t_2) \times \bar{u}(p_2,\lambda_2) i\Gamma^{(I\!\!Ppp)}_{\mu_2\nu_2}(p_2,p_b) u(p_b,\lambda_b)$$

$$q_1 = p_a - p_1,\quad q_2 = p_b - p_2,\quad k = q_1 + q_2$$
$$t_1 = q_1^2,\quad t_2 = q_2^2,\quad m_{f_1}^2 = k^2$$
$$s = (p_a + p_b)^2 = (p_1 + p_2 + k)^2\,,\ \text{c.m. energy squared}$$
$$s_1 = (p_1 + k)^2,\quad s_2 = (p_2 + k)^2$$

- To give the full physical amplitude we should include absorptive corrections to the Born amplitude:




$$\mathcal{M}_{pp\to ppf_0} = \mathcal{M}^{\rm Born}_{pp\to ppf_0} + \mathcal{M}^{pp-{\rm rescattering}}_{pp\to ppf_0}$$

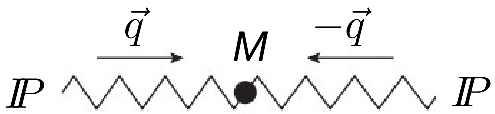
$$\mathcal{M}^{pp-{\rm rescattering}}_{pp\to ppf_0}(s,\vec{p}_{1\perp},\vec{p}_{2\perp}) = \frac{i}{8\pi^2 s}\int d^2\vec{k}_\perp \mathcal{M}^{\rm Born}_{pp\to ppf_0}(s,\vec{p}_{1\perp}-\vec{k}_\perp,\vec{p}_{2\perp}+\vec{k}_\perp) \times \mathcal{M}^{I\!\!P-{\rm exchange}}_{pp\to pp}(s,-\vec{k}_\perp^2)$$

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

# CEP, *IP-IP-M* couplings

$l$ – orbital angular momentum
$S$ – total $I\!P I\!P$ spin, we have $S \in \{0, 1, 2, 3, 4\}$
$J$ – total angular momentum (spin of produced meson)
$P$ – parity of meson
and Bose symmetry requires $l - S$ to be even

We consider the annihilation of two "pomeron particles" of spin 2 giving a meson *M*, in the rest system of *M*,




| $l$ | $S$ | $\|l - S\| \leqslant J \leqslant l + S$ | $P = (-1)^l$ |
|---|---|---|---|
| 0 | 0 | 0 | + |
| | 2 | 2 | |
| | 4 | 4 | |
| 1 | 1 | 0, 1, 2 | − |
| | 3 | 2, 3, 4 | |
| 2 | 0 | 2 | + |
| | 2 | 0,1,2,3,4 | |
| | 4 | 2,3,4,5,6 | |
| 3 | 1 | 2,3,4 | − |
| | 3 | 0,1,2,3,4,5,6 | |
| 4 | 0 | 4 | + |
| | 2 | 2,3,4,5,6 | |
| | 4 | 0,1,2,3,4,5,6,7,8 | |
| 5 | 1 | 4.5.6 | − |
| | 3 | 2,3,4,5,6,7,8 | |
| 6 | 0 | 6 | + |
| | 2 | 4,5,6,7,8 | |
| | 4 | 2,3,4,5,6,7,8,9,10 | |

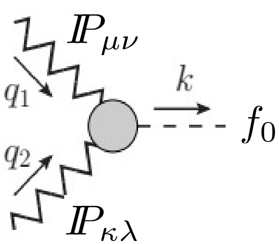
For each value of ($\ell$,$S$) we can construct a covariant Lagrangian density coupling the field operator for the meson $\chi$ to the pomeron fields $I\!P_{\mu\nu}$.

The lowest ($\ell$,$S$) term for a scalar meson $J^{PC} = 0^{++}$ is (0,0).

The Lagrangian for a scalar meson corresponding to ($\ell$,$S$) = (0,0) is

$$\mathcal{L}'_{I\!P I\!P M}(x) = M_0\, g'_{I\!P I\!P M}\, I\!P_{\mu\nu}(x) I\!P^{\mu\nu}(x)\chi(x)$$

with $M_0 \equiv 1$ GeV, and $g'_{I\!P I\!P M}$ the dimensionless coupling constant.




The 'bare' vertex obtained from $\mathcal{L}'_{I\!P I\!P M}$ reads

$$i\Gamma'^{(I\!P I\!P f_0)}_{\mu\nu,\kappa\lambda} = i\, g'_{I\!P I\!P f_0} M_0 \left( g_{\mu\kappa} g_{\nu\lambda} + g_{\mu\lambda} g_{\nu\kappa} - \frac{1}{2} g_{\mu\nu} g_{\kappa\lambda} \right)$$

The 'bare' vertex for ($\ell$,$S$) = (2,2) obtained from $\mathcal{L}''_{I\!P I\!P M}$ is

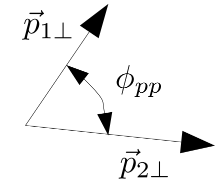
$$i\Gamma''^{(I\!P I\!P f_0)}_{\mu\nu,\kappa\lambda}(q_1, q_2) = i \frac{g''_{I\!P I\!P f_0}}{2M_0} \left[ q_{1\kappa} q_{2\mu} g_{\nu\lambda} + q_{1\kappa} q_{2\nu} g_{\mu\lambda} + q_{1\lambda} q_{2\mu} g_{\nu\kappa} + q_{1\lambda} q_{2\nu} g_{\mu\kappa} - 2(q_1 \cdot q_2)(g_{\mu\kappa} g_{\nu\lambda} + g_{\nu\kappa} g_{\mu\lambda}) \right]$$

**In CEP reaction** we must take into account that hadrons are extended objects → we introduce form factor

$$i\Gamma^{(I\!P I\!P f_0)}_{\mu\nu,\kappa\lambda}(q_1, q_2) = \left( i\Gamma'^{(I\!P I\!P f_0)}_{\mu\nu,\kappa\lambda} + i\Gamma''^{(I\!P I\!P f_0)}_{\mu\nu,\kappa\lambda}(q_1, q_2) + i\Gamma'''^{(I\!P I\!P f_0)}_{\mu\nu,\kappa\lambda}(q_1, q_2) \right) F_{I\!P I\!P f_0}(q_1^2, q_2^2, k^2)$$

The values of the coupling constants (*g'*, *g''*, *g'''*) are not known as they are of nonperturbative origin and have to be determined from experiment. In general more than one ($\ell$,S) coupling term is needed for the description of experimental results.

# CEP, *IP-IP-M* couplings



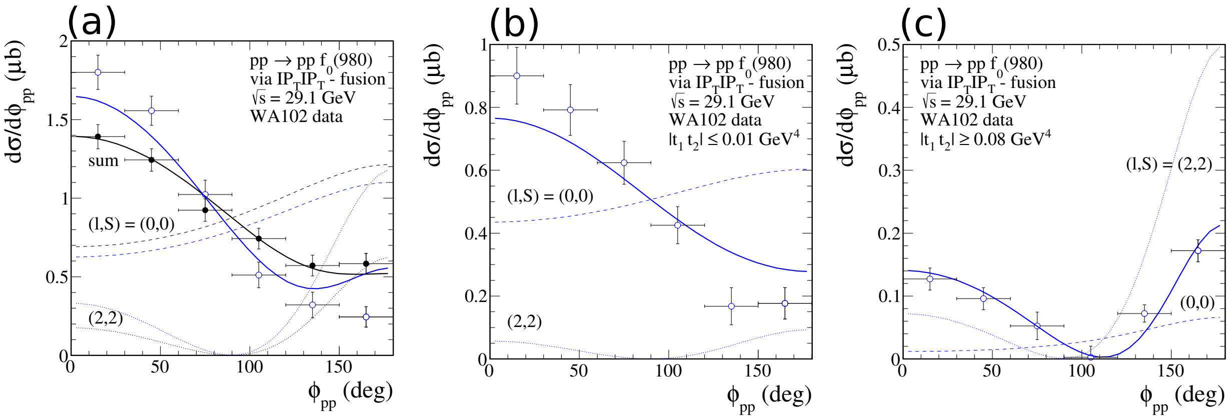

**WA102 Collaboration** observed that:

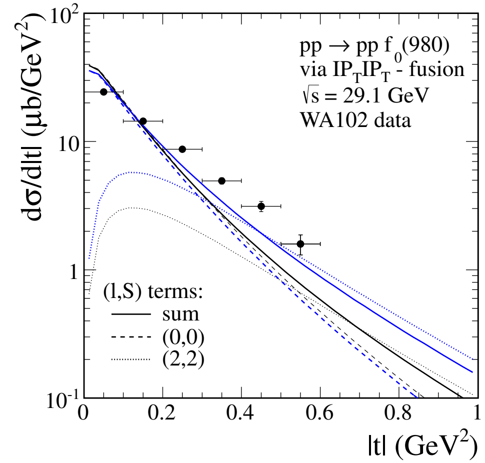
- there is an important qualitative difference in the $\phi_{pp}$ distribution:
  - → $f_0(1370)$, $f_2(1270)$ and $f'_2(1525)$ peak as $\phi_{pp} \to \pi$
  - → $f_0(980)$, $f_0(1500)$, $f_0(1710)$ peak at $\phi_{pp} \to 0$
- the "undisputed" $q\bar{q}$ states (i.e. $\eta$, $\eta'$, $f_1(1285)$, $f_2(1270)$, $f'_2(1525)$) are suppressed when $dP_t \to 0$, whereas the states which could have a non-$q\bar{q}$ or a large 'gluonic component' *e.g.* $f_0(1500)$, $f_0(1710)$, $f_2(1950)$, $f_2(2340)$ (potential glueballs) are prominent

"glueball filter variable" F. Close

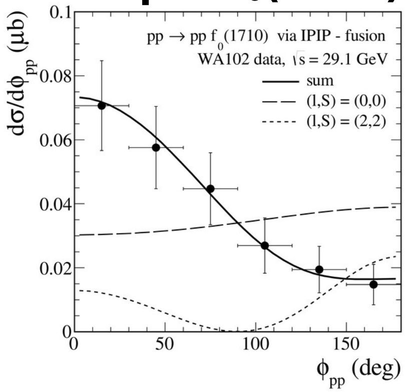
$$dP_t = |d\vec{P}_t| = |\vec{q}_{1\perp} - \vec{q}_{2\perp}| = |\vec{p}_{2\perp} - \vec{p}_{1\perp}|$$

**Example: $f_0(980)$** *[PL, Nachtmann, Szczurek, Annals Phys. 344 (2014) 301; PRD98 (2018) 014001]*




**Example: $f_0(1710)$**




- for $f_0(980)$ both $(\ell,S) = (0,0)$ and $(2,2)$ contributions are necessary and the same for $f_0(1500)$ and $f_0(1710)$, but for $f_0(1370)$ only $(\ell,S) = (0,0)$
- at $|t| \to 0$ the (2,2) component vanishes
- also theoretical predictions of $dP_t$ seem to be qualitatively consistent with data

- at low energies (WA102) the socondary exchanges (f2-reggeon) may also play an important role

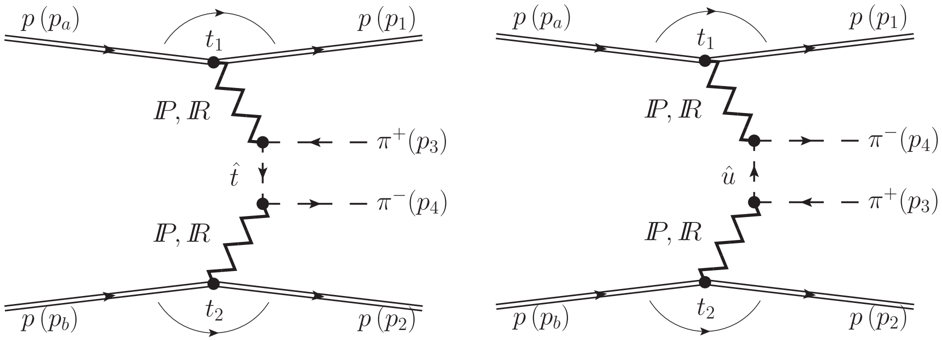
Our results and WA102 data (black points [1] and blue points [2]) have been normalised to the mean value of the total cross sections given in [3]. The WA102 data in panels (b) and (c) are obtained from [2] with the normalisation calculated in the model themselves for lack of experimental information.

[1] WA102 Collaboration, D. Barberis et al., PLB 462 (1999) 462; [2] PLB 467 (1999) 165; [3] A. Kirk, PLB 489 (2000) 29

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

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

$$\mathcal{M}^{\pi\pi-\mathrm{continuum}}_{pp\to pp\pi^+\pi^-} = \mathcal{M}^{(\mathbb{P}\mathbb{P}\to\pi^+\pi^-)} + \mathcal{M}^{(\mathbb{P}f_{2\mathbb{R}}\to\pi^+\pi^-)} + \mathcal{M}^{(f_{2\mathbb{R}}\mathbb{P}\to\pi^+\pi^-)} + \mathcal{M}^{(f_{2\mathbb{R}}f_{2\mathbb{R}}\to\pi^+\pi^-)}$$




$$\mathcal{M}^{(\mathbb{P}\mathbb{P}\to\pi^+\pi^-)} = \mathcal{M}^{(\hat{\mathrm{t}})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^+\pi^-} + \mathcal{M}^{(\hat{\mathrm{u}})}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^+\pi^-}$$

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

here $p_t = p_a - p_1 - p_3$
$s_{ij} = (p_i + p_j)^2$

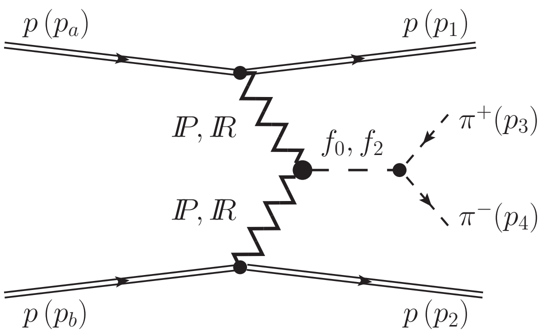
$$i\Gamma^{(\mathbb{P}\pi\pi)}_{\mu\nu}(k',k) = -i2\beta_{\mathbb{P}\pi\pi}\left[(k'+k)_\mu(k'+k)_\nu - \frac{1}{4}g_{\mu\nu}(k'+k)^2\right] F_M((k'-k)^2)\hat{F}_\pi(p_t^2)$$

where $\beta_{\mathbb{P}\pi\pi} = 1.76~\mathrm{GeV}^{-1}$, $\quad F_M(t) = \dfrac{1}{1-t/\Lambda_0^2}$, $\quad \Lambda_0^2 = 0.5 - 0.8~\mathrm{GeV}^2$

$$\hat{F}_\pi(p_t^2) = \exp\left(\frac{p_t^2 - m_\pi^2}{\Lambda^2_{\mathrm{off},E}}\right) \quad \text{or} \quad \hat{F}_\pi(p_t^2) = \frac{\Lambda^2_{\mathrm{off},M} - m_\pi^2}{\Lambda^2_{\mathrm{off},M} - p_t^2}\,,$$

where $\Lambda_{\mathrm{off},E}$ or $\Lambda_{\mathrm{off},M}$ could be adjusted to experimental data

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




$$\mathcal{M}^{\pi\pi-\text{resonances}}_{pp\to pp\pi^+\pi^-} = \mathcal{M}^{(\mathbb{P}\mathbb{P}\to f_0\to\pi^+\pi^-)}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^+\pi^-} + \mathcal{M}^{(\mathbb{P}\mathbb{P}\to f_2\to\pi^+\pi^-)}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\pi^+\pi^-}$$

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

$$i\Gamma^{(f_2\pi\pi)}_{\mu\nu}(p_3,p_4) = -i\,\frac{g_{f_2\pi\pi}}{2M_0}\left[(p_3-p_4)_\mu(p_3-p_4)_\nu - \frac{1}{4}g_{\mu\nu}(p_3-p_4)^2\right]F^{(f_2\pi\pi)}(p_{34}^2)$$

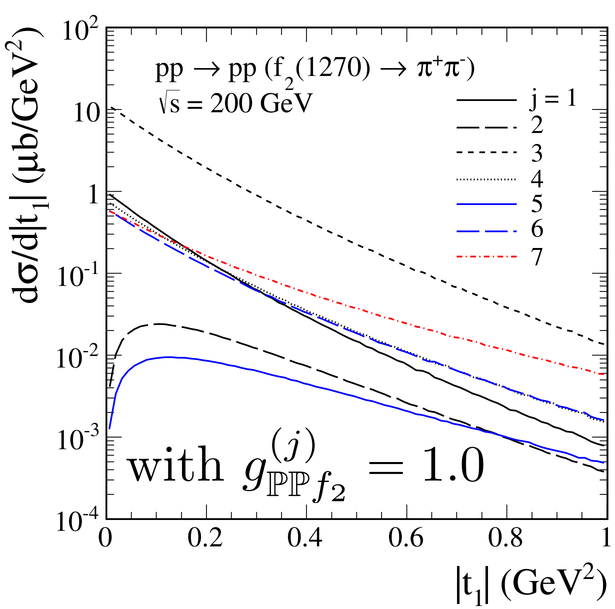
here $p_{34} = q_1 + q_2$

where $g_{f_2(1270)\pi\pi} = 9.26$ is obtained from the partial decay width

$M_0 = 1$ GeV

The general **IP IP f2 coupling is a combination of 7 basic couplings** (tensorial structures):

$$i\Gamma^{(\mathbb{P}\mathbb{P}f_2)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = \left(i\Gamma'^{(\mathbb{P}\mathbb{P}f_2)(1)}_{\mu\nu,\kappa\lambda,\rho\sigma} + \sum_{j=2}^{7} i\Gamma''^{(\mathbb{P}\mathbb{P}f_2)(j)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2)\right)F_{\mathbb{P}\mathbb{P}f_2}(q_1^2,q_2^2,p_{34}^2)$$




where $F_{\mathbb{P}\mathbb{P}f_2}$ is a form factor for which we make a factorised ansatz

$$F_{\mathbb{P}\mathbb{P}f_2}(t_1,t_2,p_{34}^2) = \exp\left(\frac{t_1+t_2}{\Lambda_E^2}\right)F^{(\mathbb{P}\mathbb{P}f_2)}(p_{34}^2)\,,\quad \Lambda_E = 0.7\text{ GeV}$$

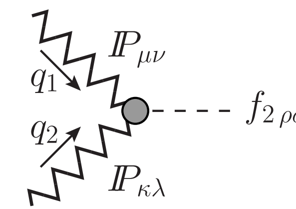
$$F^{(f_2\pi\pi)}(p_{34}^2) = F^{(\mathbb{P}\mathbb{P}f_2)}(p_{34}^2) = \exp\left(\frac{-(p_{34}^2-m_{f_2}^2)^2}{\Lambda_{f_2}^4}\right),\quad \Lambda_{f_2} = 1\text{ GeV}$$

The couplings j = 1, ..., 7 can be associate to the following orbital angular momentum and spin of the two "real pomerons" ($\ell$,$S$) values:
(0,2), (2,0)-(2,2), (2,0)+(2,2), (2,4), (4,2), (4,4), (6,4).

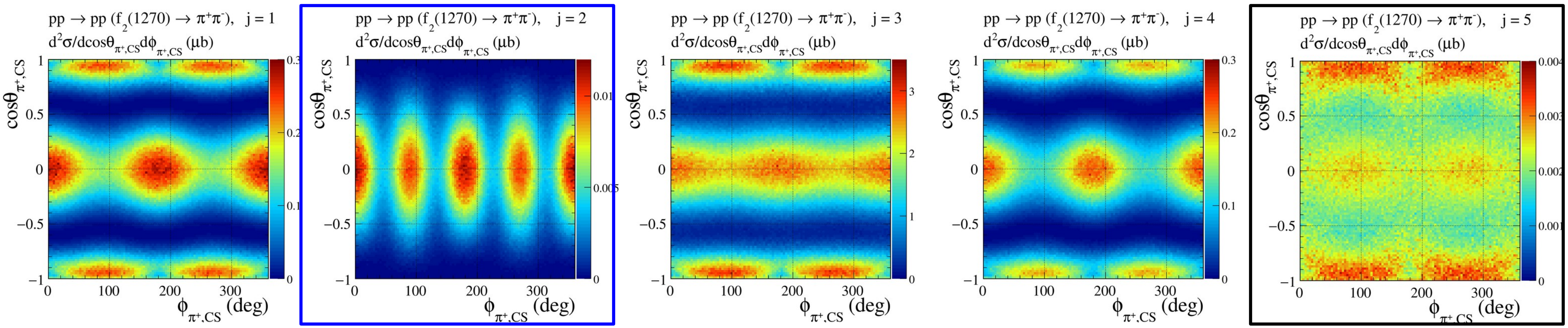
# $pp \to pp\, \pi^+\pi^-$

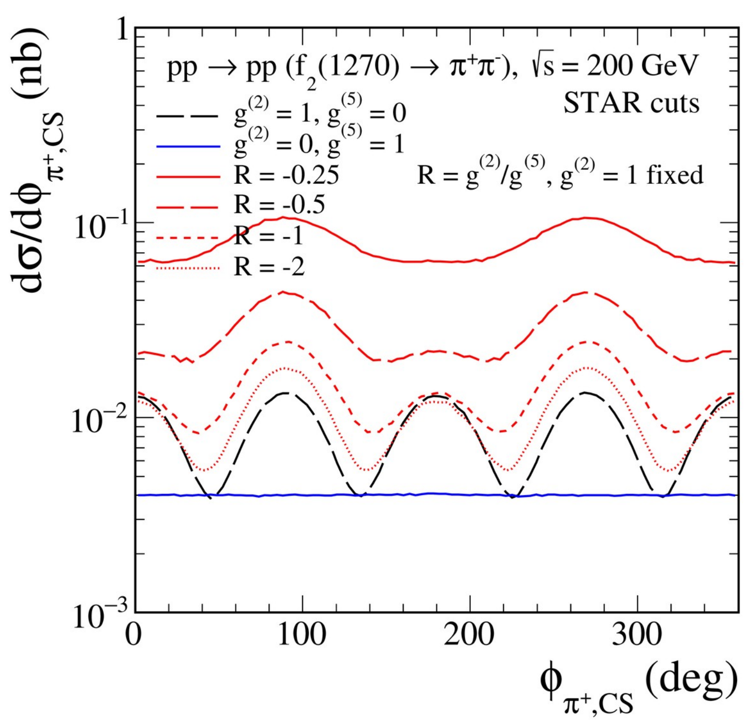
PL, O. Nachtmann, A. Szczurek, Phys.Rev. D101 (2020) 034008

We have considered the possibility to extract the Pomeron-Pomeron-$f_2(1270)$ coupling from the analysis of pion angular distributions in the π+π- rest system, using the Collins-Soper (CS) and Gottfried-Jackson (GJ) reference frames.




j = 1 j = 2 j = 3 j = 4 j = 5




Different tensorial couplings generate very different pattern !

← we examine the combination of two couplings j = 2 and 5 in order to get two maxima at $\phi_{\pi,CS} = \pi/2$ and $3/2\pi$ (observed in COMPASS experiment in GJ frame and confirmed in STAR and ATLAS-ALFA)

We compared the model results with the STAR@200GeV and preliminary ATLAS-ALFA@13TeV data assuming:

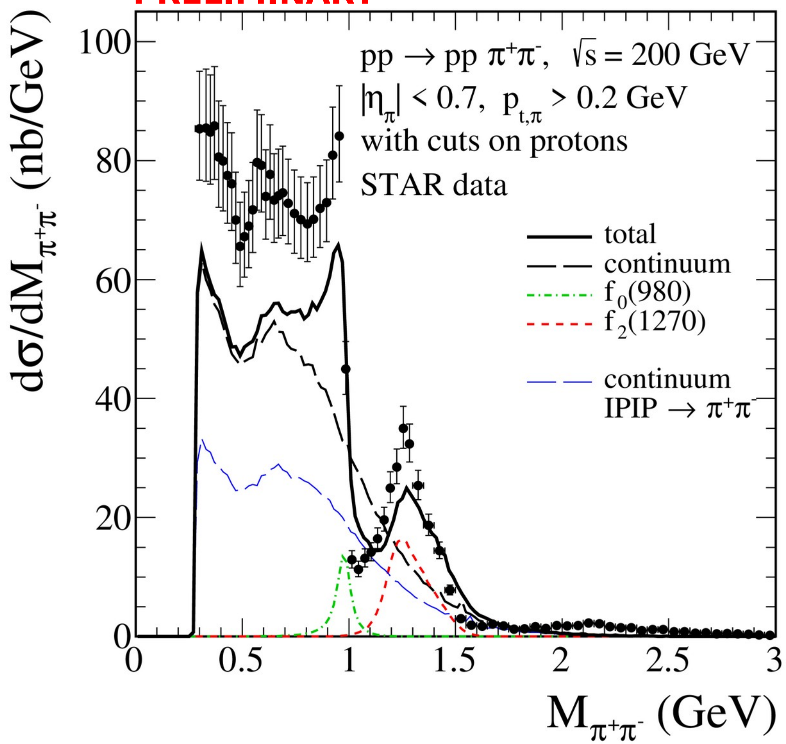
for $f_2(1270)$: $g^{(2)} / g^{(5)} = 5 / (-12)$ , R ≈ - 0.42
for $f_0(980)$: g' = 0.4, g'' = 3.0

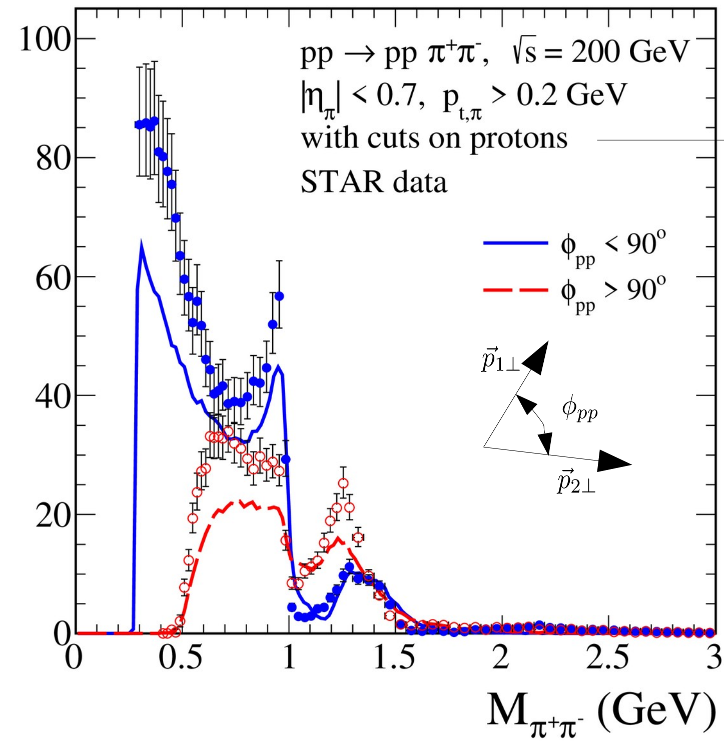
$$\Lambda_E = 0.7 \text{ GeV and } \Lambda_{f_2} = \Lambda_{f_0} = 1 \text{ GeV}$$

for dipion-continuum: $\Lambda_0^2 = 0.8\ \text{GeV}^2,\ \Lambda_{\text{off},E} = 1\ \text{GeV}$

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

**PRELIMINARY**




**STAR data**
JHEP 07 (2020) 178

Two forward-scattered proton tracks in Roman Pot detectors, one on each side of the interaction region, each of transverse momentum satisfying

$(p_x + 0.3\ \mathrm{GeV})^2 + p_y^2 < 0.25\ \mathrm{GeV}^2$

$0.2\ \mathrm{GeV} < |p_y| < 0.4\ \mathrm{GeV}$

$p_x > -0.2\ \mathrm{GeV}$

Detection of protons selects $-t > 0.04\ \mathrm{GeV}^2$ which suppresses γ-IP fusion processes, e.g. ρ(770) → π+π-.

**STAR results**

$\sigma_{\rm fid}(\phi_{pp} < 90^o) = 44.1 \pm 0.2({\rm stat})^{+4.6}_{-4.2}({\rm syst})\,{\rm nb}$

$\sigma_{\rm fid}(\phi_{pp} > 90^o) = 21.1 \pm 0.2({\rm stat})^{+2.1}_{-1.9}({\rm syst})\,{\rm nb}$

**Model results**

$\langle S^2\rangle = \sigma_{abs}/\sigma_{Born}$

$\sigma_{\rm total}(\phi_{pp} < 90^o) = 34.59\,{\rm nb}, \quad < S^2 >= 0.47$

$\sigma_{\rm total}(\phi_{pp} > 90^o) = 15.56\,{\rm nb}, \quad < S^2 >= 0.27$

$\sigma_{\rm total} = 50.15\,{\rm nb}, \quad < S^2 >= 0.38$

$\sigma_{\rm continuum} = 43.18\,{\rm nb}, \quad < S^2 >= 0.37$

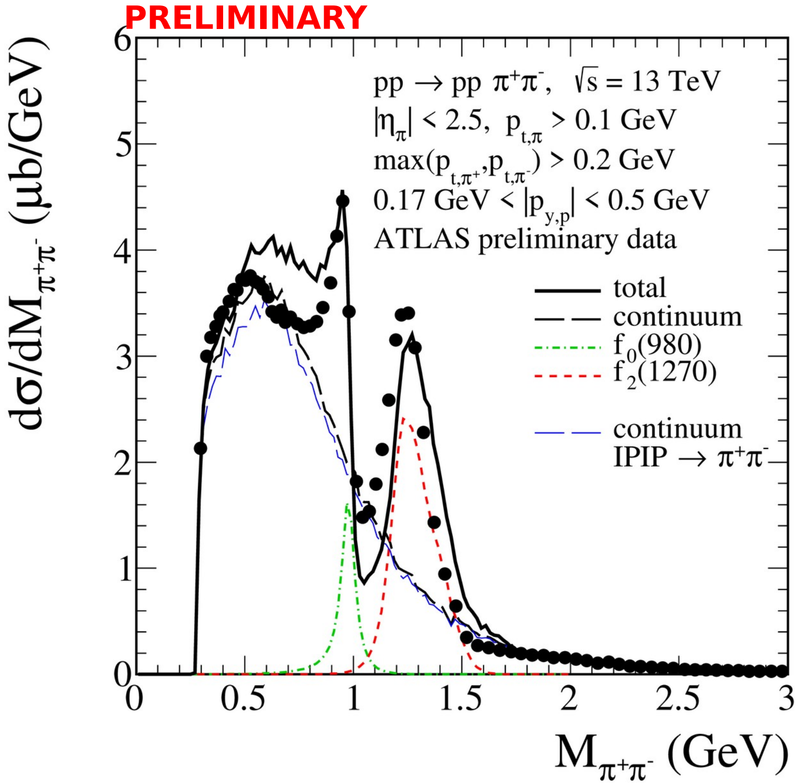
$\sigma_{f_0(980)} = 1.38\,{\rm nb}, \quad < S^2 >= 0.53$

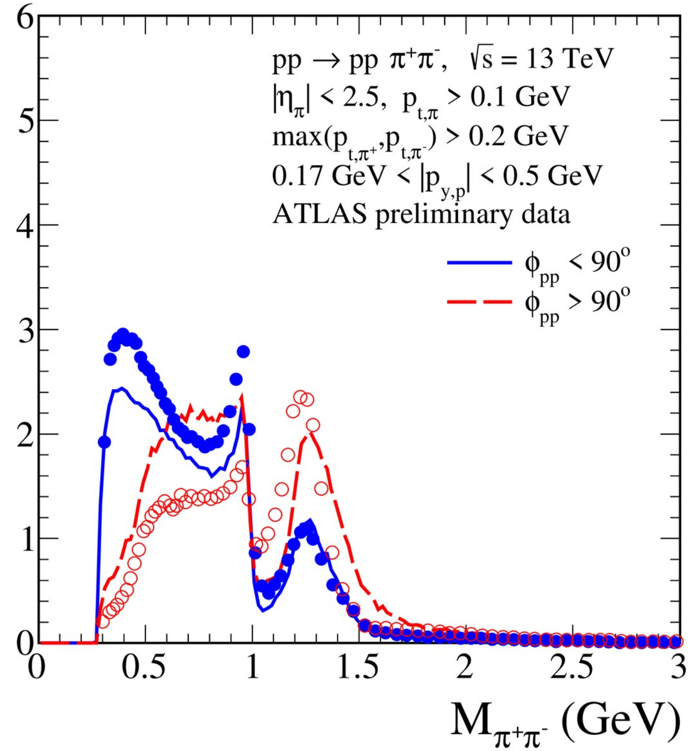
$\sigma_{f_2(1270)} = 3.92\,{\rm nb}, \quad < S^2 >= 0.6$

- The STAR detector acceptance naturally splits the fiducial region into two ranges of $\phi_{pp}$, which are differently sensitive to absorption effects. The structure in cross section below 0.6 GeV is caused by the fiducial cuts (acceptance) applied to the forward-scattered protons. Peak at 1 GeV followed by sharp drop of the cross section consistent with $f_0(980)$, peak between 1–1.5 GeV consistent with $f_2(1270)$.
- We take into account the non-resonant continuum (including both pomeron and reggeon exchanges) and two resonances, $f_0(980)$ and $f_2(1270)$, created by pomeron-pomeron fusion. The complete results indicates a large interference effect.
- Devaition of our minimal model from the data → this might result from the presence of the $f_0(500)$, $f_0(1370)$, $f_0(1500)$, and $f_0(1710)$ states, and rescattering corrections due to pion-proton and/or pion-pion interactions in the final state.

- Available are also preliminary STAR data at 510 GeV (PoS ICHEP2020 (2021) 530, PoS(EPS-HEP2021)339)

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




**ATLAS-ALFA preliminary data**
R. Sikora, doctoral thesis, CERN-THESIS-2020-235

Two forward protons were measured in ALFA on both sides of ATLAS.

**ATLAS-ALFA preliminary results**

$$\sigma_{\text{fid}}(\phi_{pp} < 90^o) = 2.089 \pm 0.003(\text{stat})^{+0.071}_{-0.067}(\text{syst})\,\mu\text{b}$$

$$\sigma_{\text{fid}}(\phi_{pp} > 90^o) = 1.565 \pm 0.005(\text{stat})^{+0.055}_{-0.051}(\text{syst})\,\mu\text{b}$$

**Model results** $\quad \langle S^2 \rangle = \sigma_{abs}/\sigma_{Born}$

$$\sigma_{\text{total}}(\phi_{pp} < 90^o) = 1.81\,\mu\text{b}, \quad <S^2>= 0.20$$

$$\sigma_{\text{total}}(\phi_{pp} > 90^o) = 2.05\,\mu\text{b}, \quad <S^2>= 0.29$$

$$\sigma_{\text{total}} = 3.87\,\mu\text{b}, \quad <S^2>= 0.24$$

$$\sigma_{\text{continuum}} = 2.94\,\mu\text{b}, \quad <S^2>= 0.22$$

$$\sigma_{f_0(980)} = 0.17\,\mu\text{b}, \quad <S^2>= 0.43$$

$$\sigma_{f_2(1270)} = 0.58\,\mu\text{b}, \quad <S^2>= 0.34$$

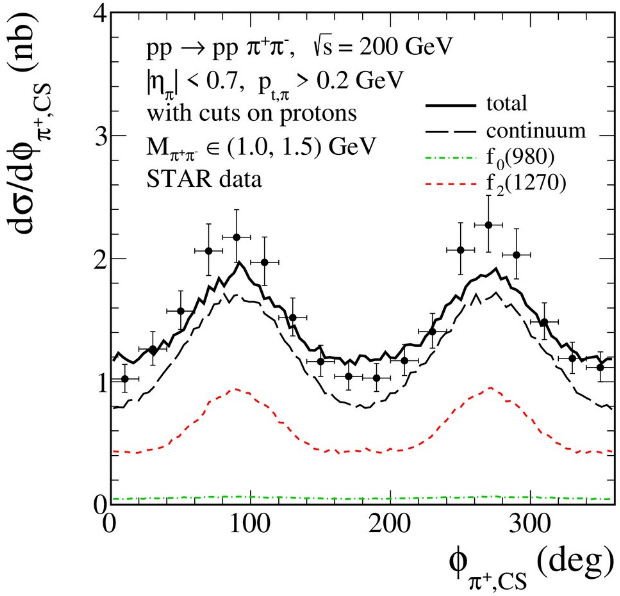
- In data: the $\phi_{pp} < 90^o$ range, the region of $f_2(1270)$ resonance is significantly suppresses, while the $f_0(980)$ state is enhanced compared to the $\phi_{pp} > 90^o$ range. This $\phi_{pp}$ dependence is consistent with the observation made by the WA102 Collaboration.

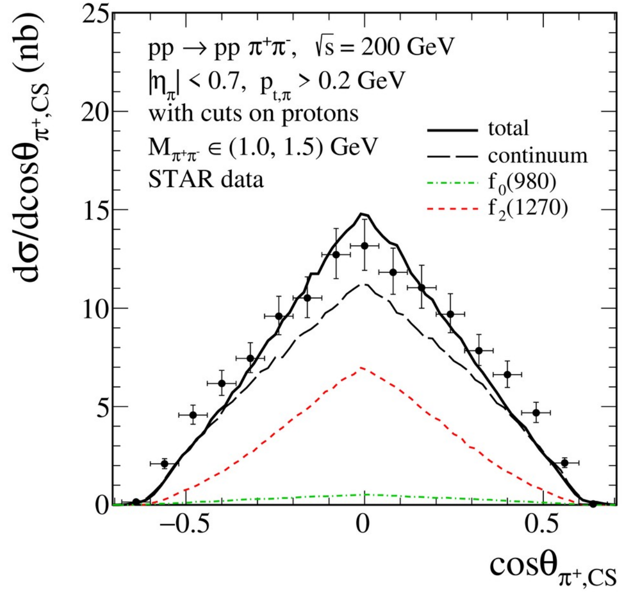
- The $f_2(1270)$ is enhanced and more distinct in the fiducial cross section measured at ATLAS than at STAR → CEP of $f_2(1270)$ grows with increasing four-momentum transfer

# *pp → pp π⁺π⁻*

**PRELIMINARY**

**STAR data** JHEP 07 (2020) 178



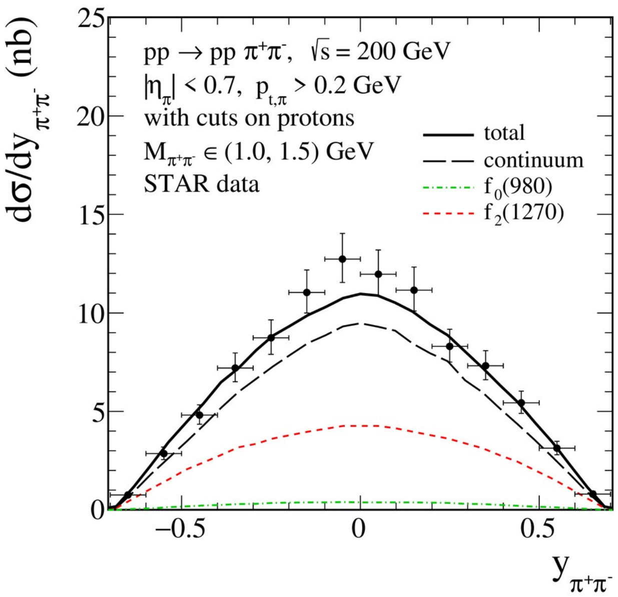



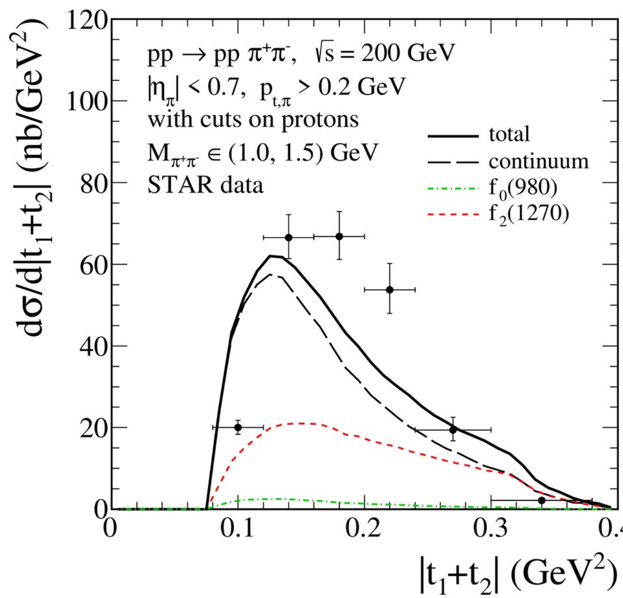

with cuts on protons

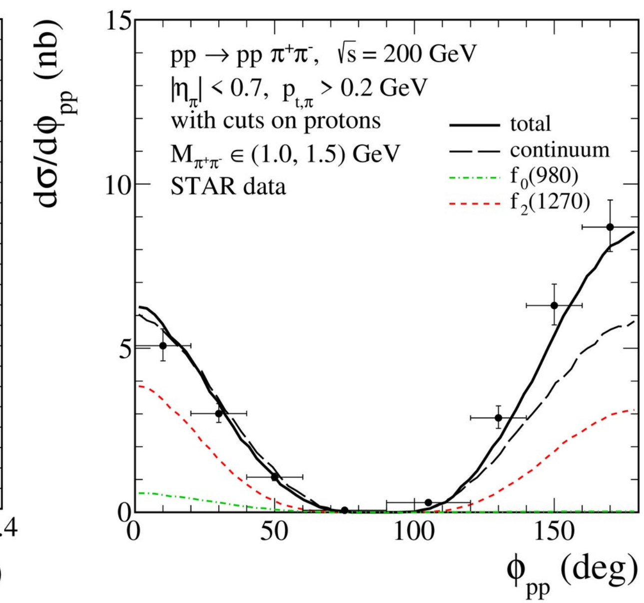
$(p_x + 0.3\ \mathrm{GeV})^2 + p_y^2 < 0.25\ \mathrm{GeV}^2$

$0.2\ \mathrm{GeV} < |p_y| < 0.4\ \mathrm{GeV}$

$p_x > -0.2\ \mathrm{GeV}$



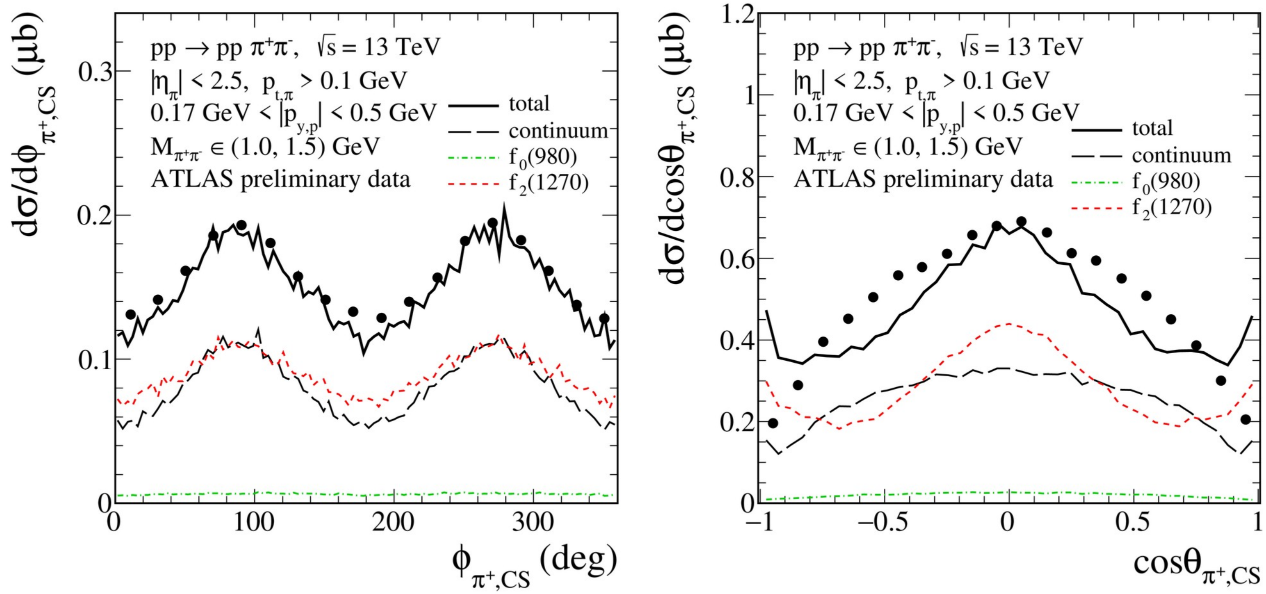



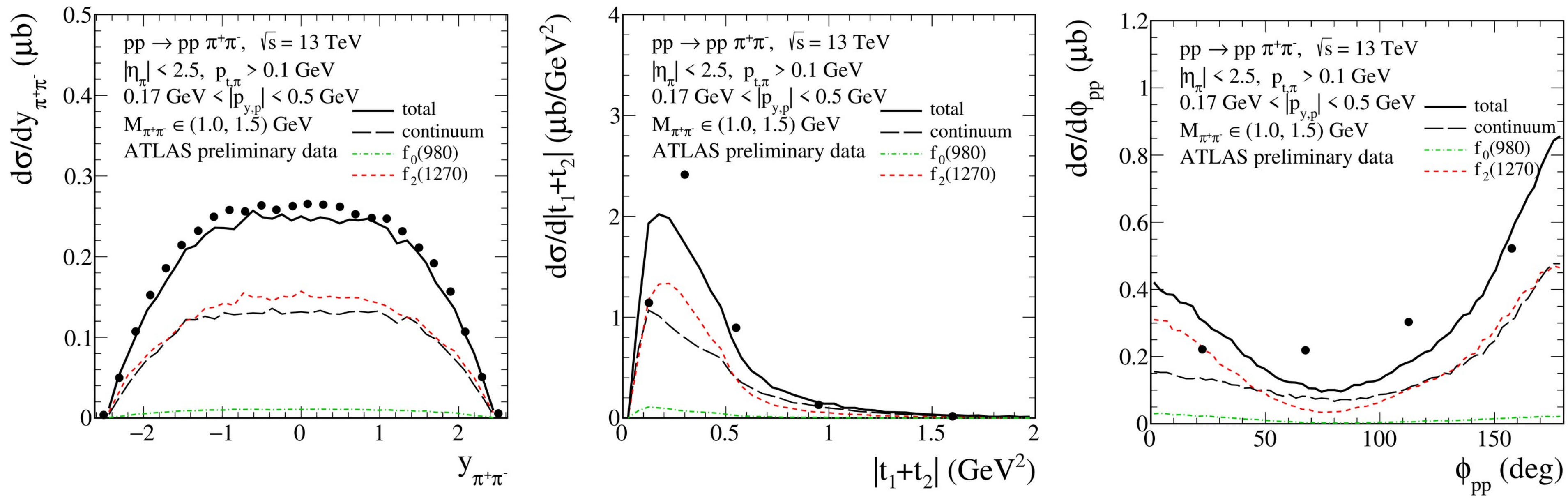



# $pp \to pp\, \pi^+\pi^-$

**PRELIMINARY**

**ATLAS-ALFA preliminary data**
R. Sikora, doctoral thesis,
CERN-THESIS-2020-235
with cuts on protons
0.17 GeV < $|p_{y,p}|$ < 0.5 GeV

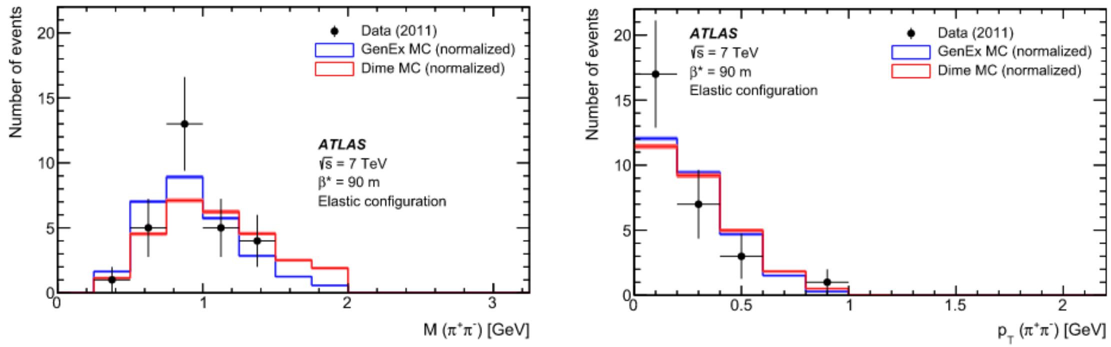


# *pp → pp $\pi^+\pi^-$*

**ATLAS Collaboration**

**First measurement of the purely exclusive pion-pair cross section at the LHC** **[Eur. Phys. J. C (2023) 83:627]**




| Exclusive $\pi^+\pi^-$ cross-section [μb] | |
|---|---|
| **Elastic configuration** | |
| Measurement | $4.8 \pm 1.0$ (stat) $^{+0.3}_{-0.2}$ (syst) $\pm$ 0.1 (lumi) $\pm$ 0.1 (model) |
| GENEX ×0.22 (absorptive correction) | 1.5 |
| DIME | 1.6 |
| **Anti-elastic configuration** | |
| Measurement | $9 \pm 6$ (stat) $^{+1}_{-1}$ (syst) $\pm$ 1 (lumi) $\pm$ 1 (model) |
| GENEX ×0.22 (absorptive correction) | 2 |
| DIME | 3 |

- The pion pairs were detected in the ATLAS central detector while outgoing protons were measured in the forward ATLAS ALFA detector system, using 80 μb-1 of low-luminosity data
- Two topological (non-overlapping) configurations are used in this analysis, “elastic” and “anti-elastic”, according to the sign of the product of the y-axis projection of proton momenta (elastic has a negative sign, while anti-elastic a positive one)
- Fiducial region:
  $|\eta_\pi| < 2.5,\ p_{t,\pi} > 0.1\ \mathrm{GeV},\ M_{\pi\pi} < 2\ \mathrm{GeV}$ and additional conditions on y-components of the proton momenta in both configurations
- Upper panels: Distributions for the data and MC simulations after applying all event selections, but without a background subtraction (~10%) applied to the data. Each of the MC samples (dipion continuum only) is normalized to the data
- Limited statistical precision: 28 events (elastic configuration) + 3 events (anti-elastic)

**Model results:**

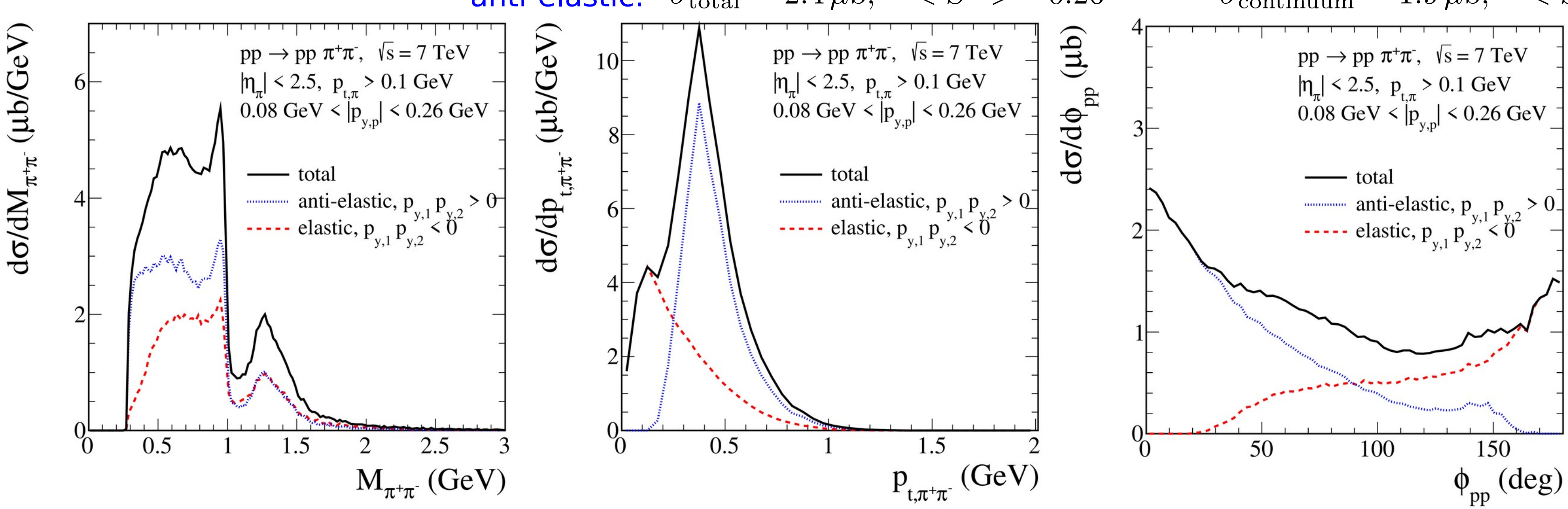
elastic: $\sigma_{\mathrm{total}} = 1.6\,\mu\mathrm{b}, \quad <S^2>= 0.19$

anti-elastic: $\sigma_{\mathrm{total}} = 2.4\,\mu\mathrm{b}, \quad <S^2>= 0.26$

vs

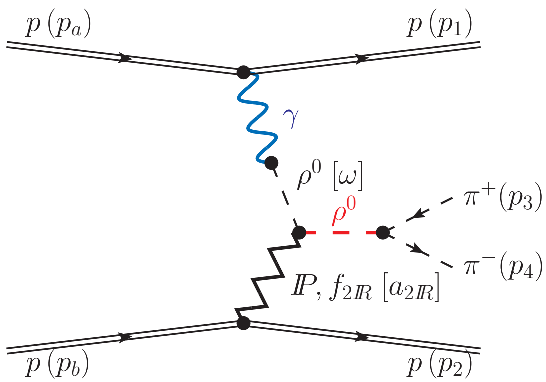
$\sigma_{\mathrm{continuum}} = 1.3\,\mu\mathrm{b}, \quad <S^2>= 0.18$

$\sigma_{\mathrm{continuum}} = 1.9\,\mu\mathrm{b}, \quad <S^2>= 0.24$

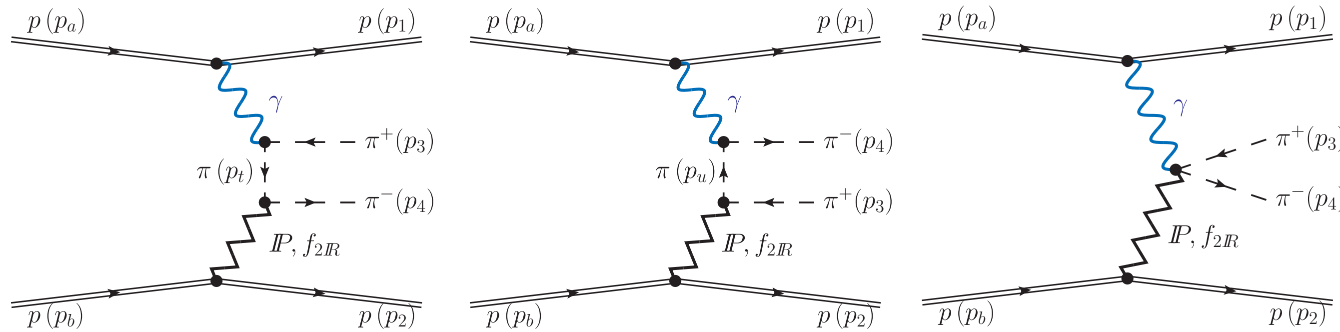



- Absorption effect is kinematics and model (choice of IPIPM couplings) dependent

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




photoproduction of $\rho^0(770)$



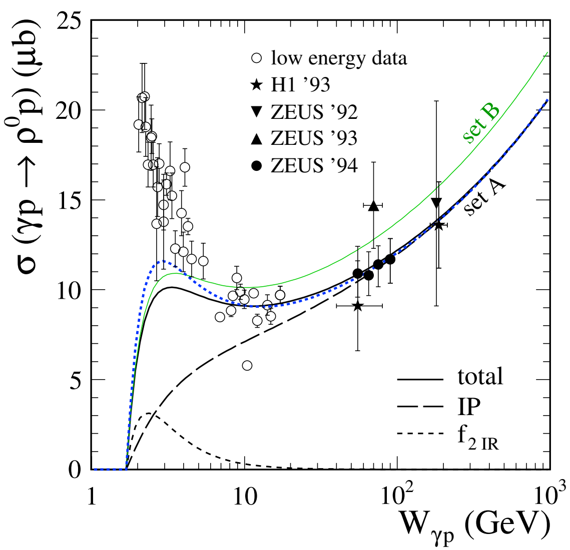

dipion continuum (Drell-Söding mechanism)

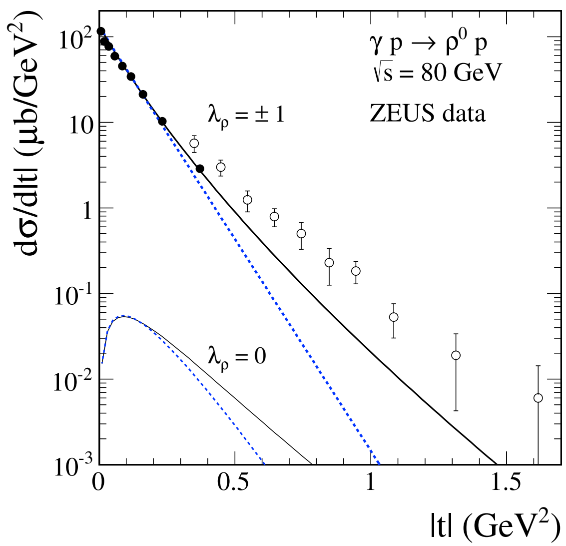
- The IPρρ and $f_{2R}\rho\rho$ vertices are taken with the same structure as for $f_2\gamma\gamma$ coupling (for 'on-shell' $f_2 \to \gamma\gamma$ reaction, a and b parametrise the so-called helicity-0 and helicity-2 amplitudes)

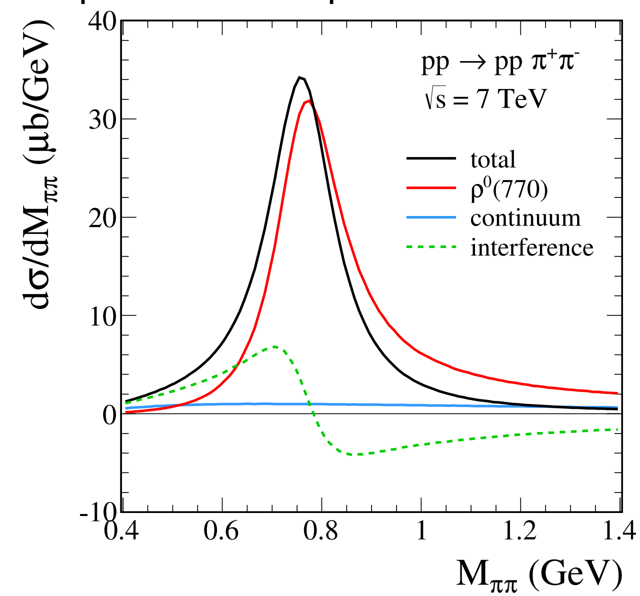
$$i\Gamma^{(I\!P\rho\rho)}_{\mu\nu\kappa\lambda}(k',k) = iF_M((k'-k)^2)\left[2a_{I\!P\rho\rho}\,\Gamma^{(0)}_{\mu\nu\kappa\lambda}(k',-k) - b_{I\!P\rho\rho}\,\Gamma^{(2)}_{\mu\nu\kappa\lambda}(k',-k)\right]$$

- Coupling parameters of tensor pomeron and $f_2$-reggeon exchanges are fixed based on the HERA experimental data for the $\gamma p \to \rho^0 p$ reaction.

- We formulated a gauge-invariant version of the Drell-Söding mechanism.
  The interference of dipion continuum with $\rho^0$ produces the skewing of the $\rho^0$ meson shape.

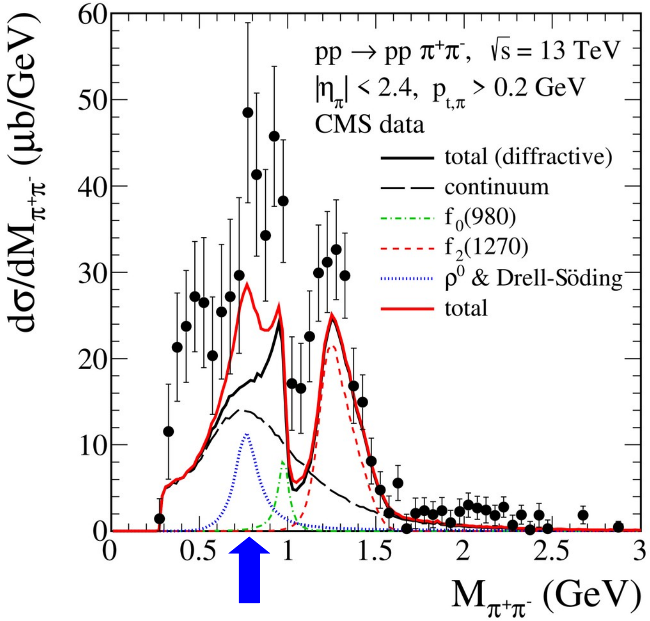


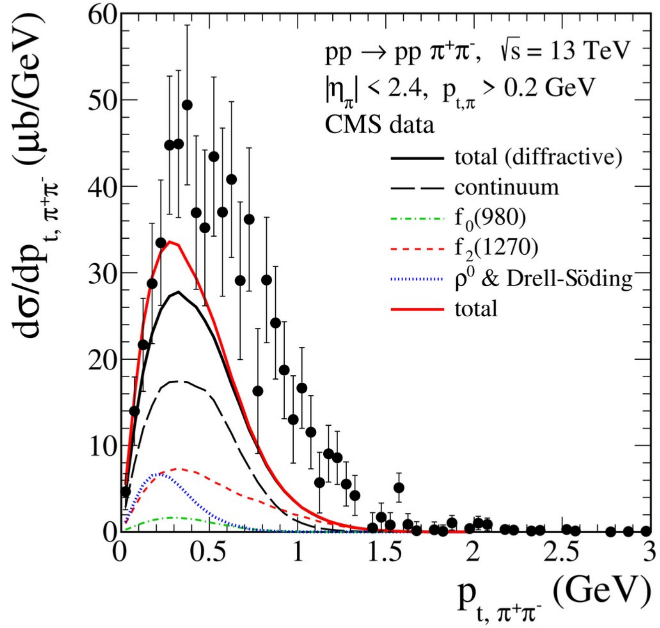



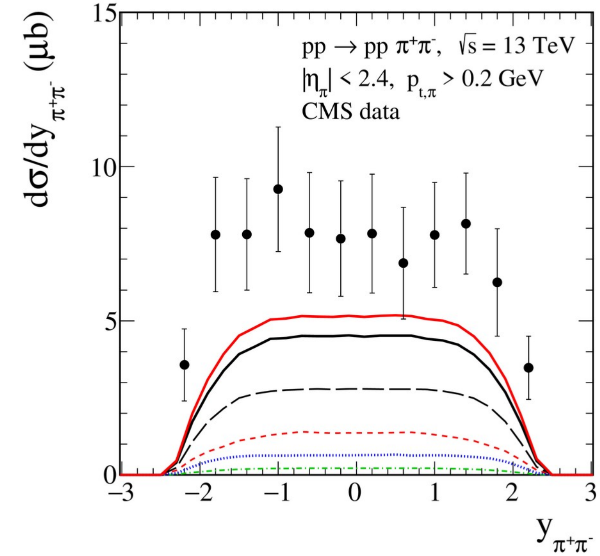



# $pp \to pp\,\pi^+\pi^-$

- **Comparison with CMS data, Eur. Phys. J. C 80 (2020) 718**
  → rapidity gap method (gaps between the $\pi^+\pi^-$ system and the outgoing protons) – no proton tagging
  This measurement is not fully exclusive and the data contains contributions associated with one and both protons undergoing dissociation.



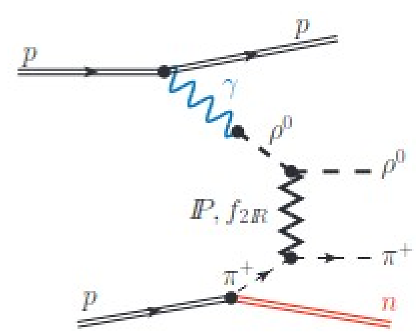



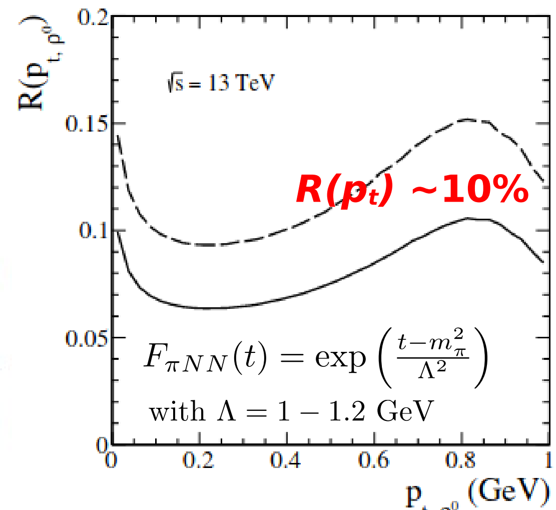

photoproduction contribution

- PL, Nachtmann, Szczurek, PRD95 (2017) 034036
  we considered the Drell-Hiida-Deck type mechanism with centrally produced $\rho^0$ associated with a very forward/backward $\pi N$ system.

$$\text{Plotted is } R(p_{t,\rho^0}) = \frac{d\sigma_{pp\to pN\rho^0\pi}/dp_{t,\rho^0}}{d\sigma_{pp\to pp\rho^0}/dp_{t,\rho^0}}$$

where $pN\rho^0\pi$ stands for $pn\rho^0\pi^+$ and $pp\rho^0\pi^0$

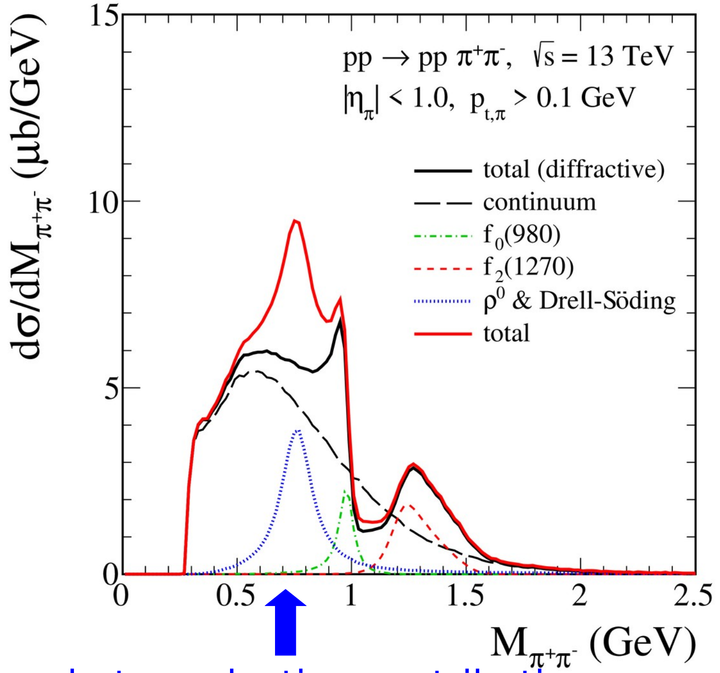


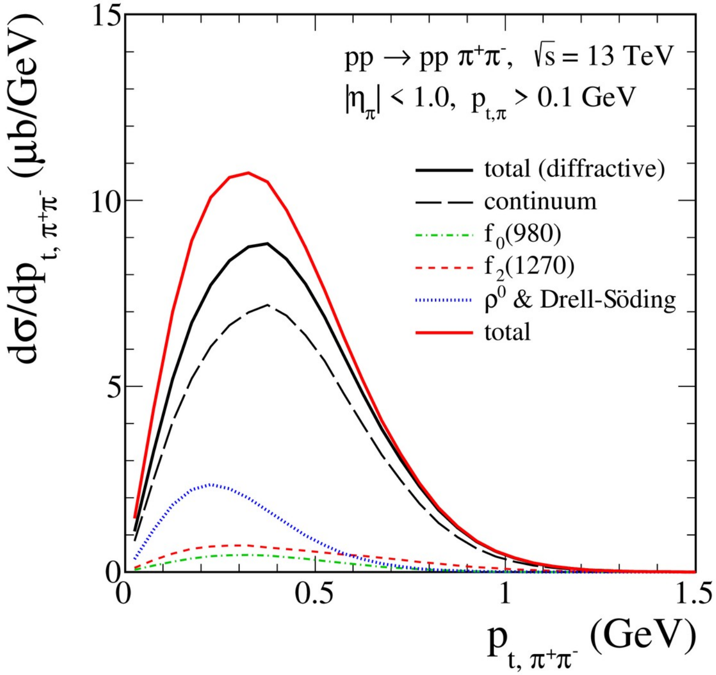

- CMS-TOTEM data, CMS PAS SMP-21-004
  CEP of charged hadron pairs in pp collisions at c.m. energy of 13 TeV is examined, based on data collected in a special high-$\beta^*$ run of the LHC. Events are selected by requiring both scattered protons detected in the TOTEM Roman Pots, exactly two oppositely charged identified particles in the CMS silicon tracker, and the enegy-momentum balance of these four particles. Acceptance region: $0.2$ GeV $< p_{1T}, p_{2T} < 0.8$ GeV, and for hadron rapidities $|y| < 2$.

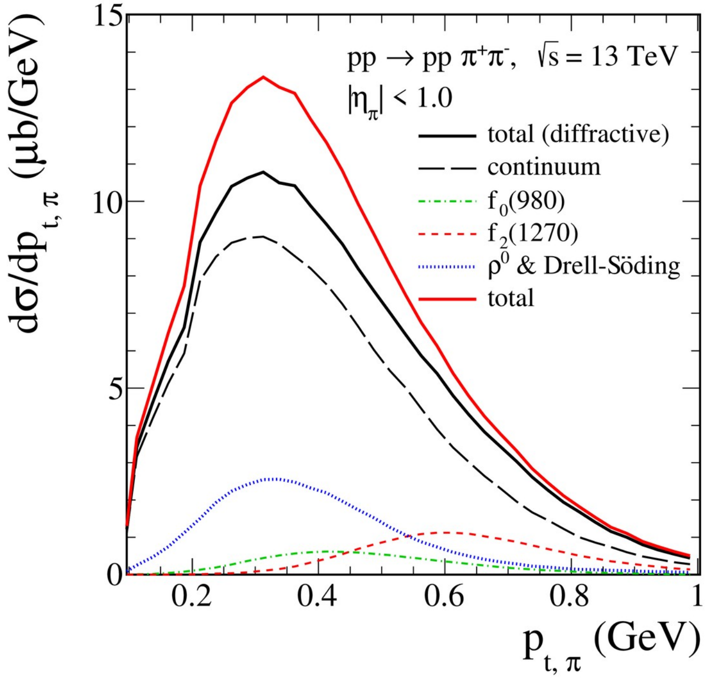
# $pp \to pp\ \pi^+\pi^-$

PRELIMINARY



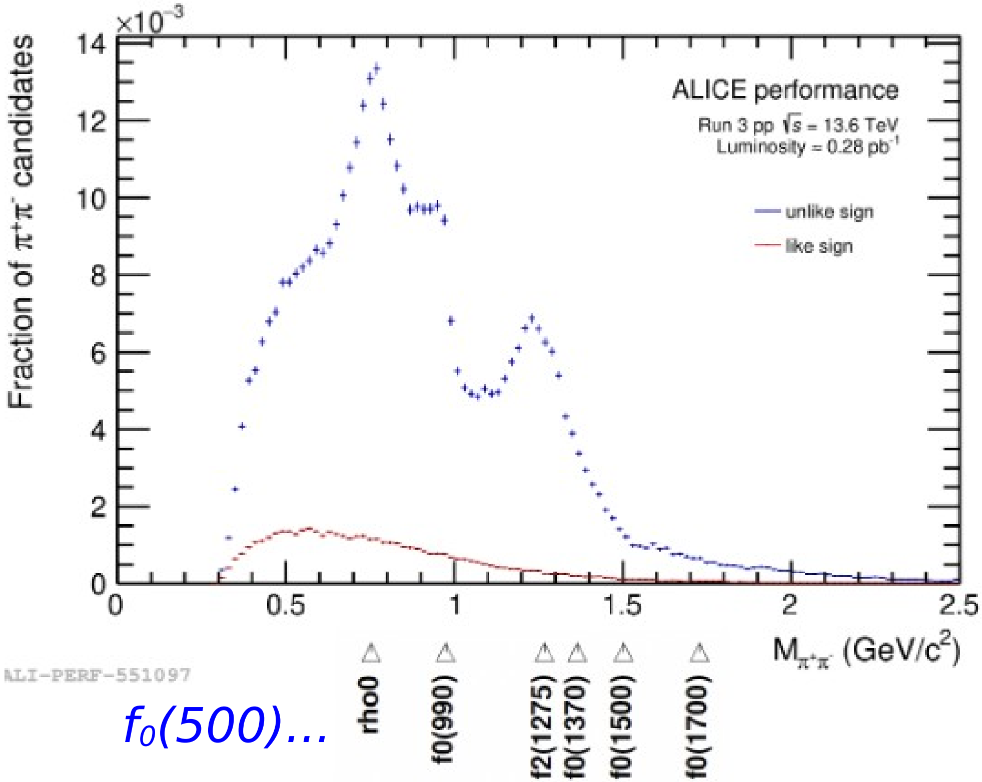

photoproduction contribution



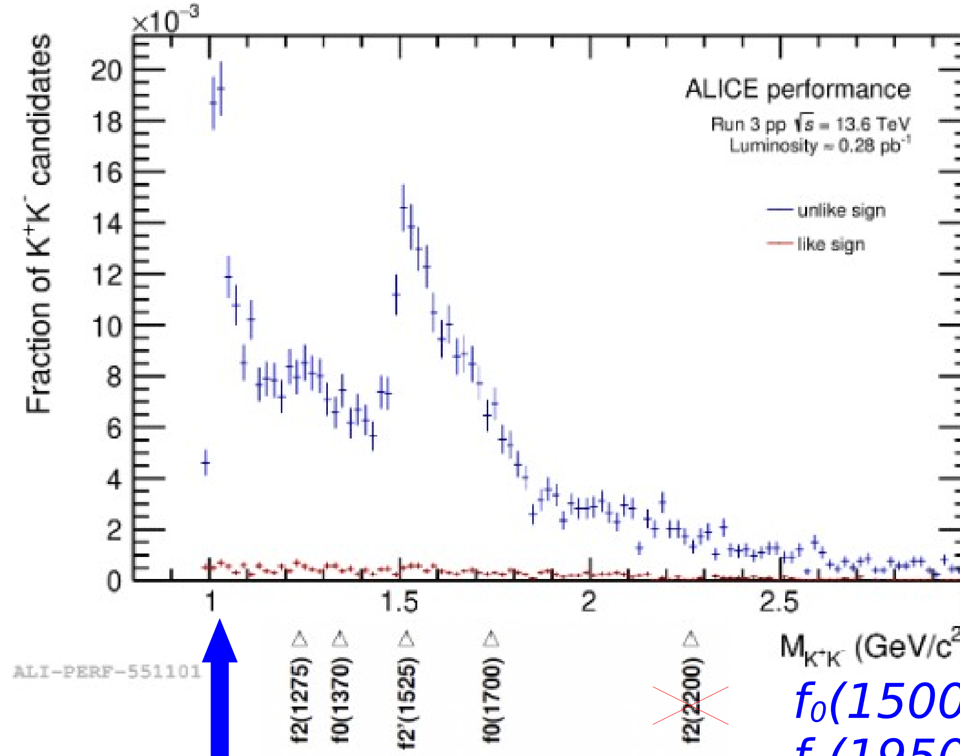



# $pp \to pp\, \pi^+\pi^-$ and $pp \to pp\, K^+K^-$

**ALICE Run 3 data,** presented by Minjung Kim at Quark Matter 2023
https://indico.cern.ch/event/1139644/contributions/5456343/attachments/2707489/4700646/QM2023_DGevent_mjkim_v4.pdf




$f_0(500)$...




$f_0(980)$ and $\phi(1020)$ (?)

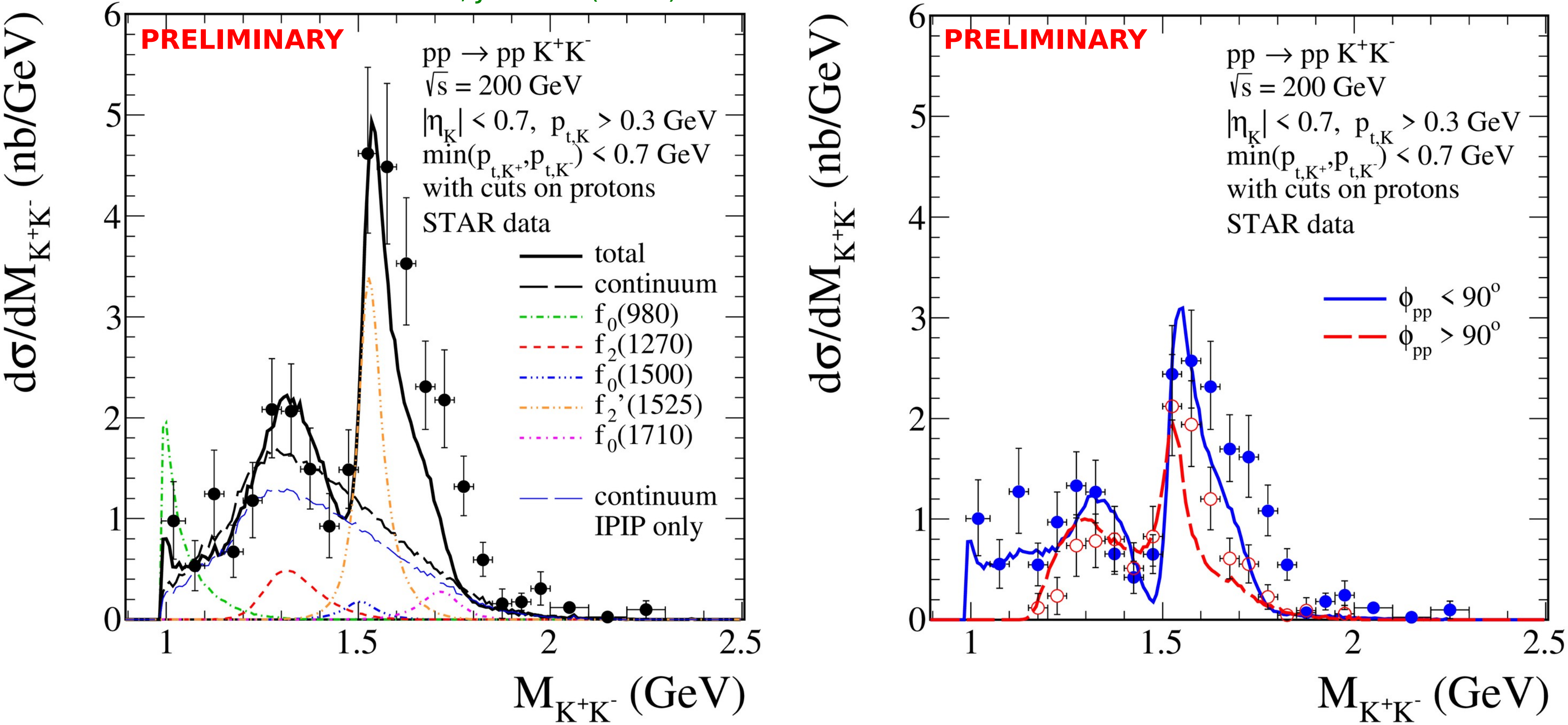
$f_0(1500)$
$f_2(1950)$
$f_2(2010)$
$f_0(2200)$...

- Dipion and dikaon Invariant mass distributions are composed of multiple physics sources, and not yet corrected for detector acceptance and efficiencies

- First look: visible resonance structures from photoproduction and double-pomeron exchange (double-gap events)

# $pp \to pp\, K^+K^-$

data: STAR Collaboration, JHEP 07 (2020) 178




- For $f_0(980)$ we have the ratio *[BaBar Collaboration, Aubert et al., PRD 74 (2006) 032003]* found from the $B$ meson decays $$\frac{\Gamma(f_0(980) \to K^+K^-)}{\Gamma(f_0(980) \to \pi^+\pi^-)} = 0.69 \pm 0.32$$

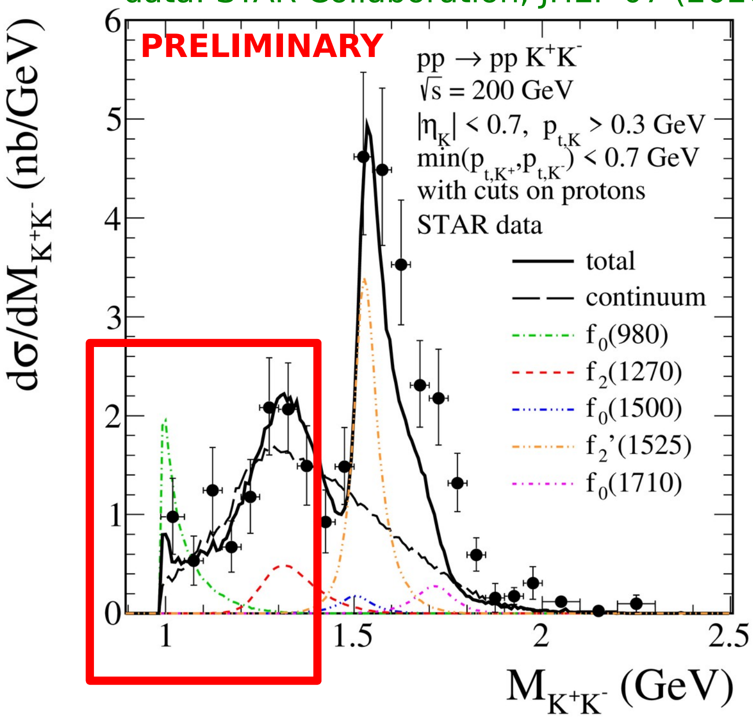
To obtain $f_0(980)K^+K^-$ coupling constant we assume the approximate relation

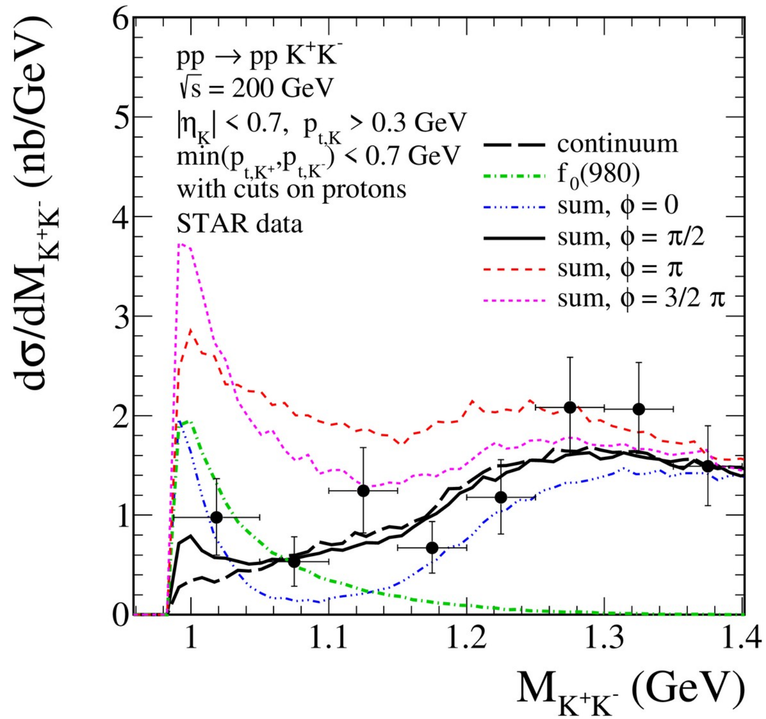
$$\frac{\sigma(f_0(980) \to K^+K^-)}{\sigma(f_0(980) \to \pi^+\pi^-)} = 0.69 \pm 0.32$$

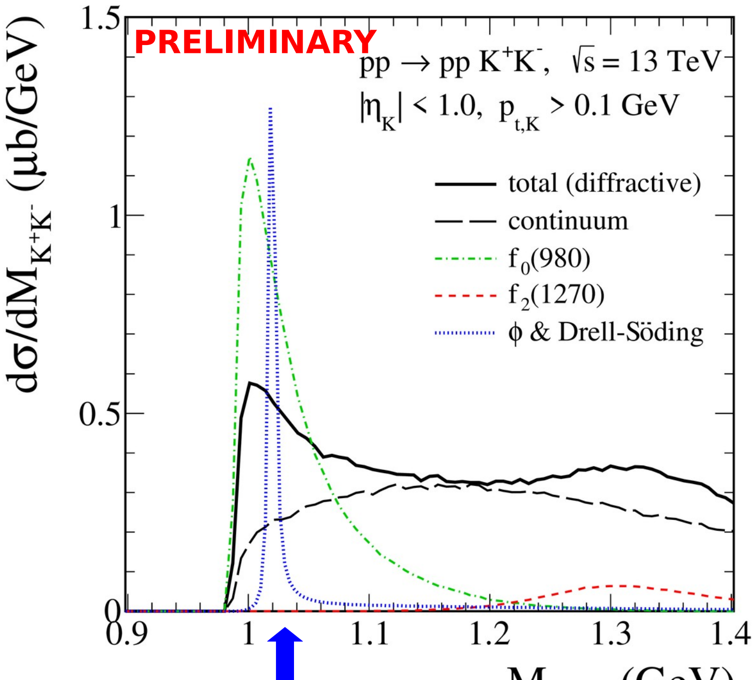
and we get $g_{f_0(980)K^+K^-} = 2.88^{+0.60}_{-0.77}$ with $m_{f_0(980)} = 980$ MeV and $\Gamma_{f_0(980)} = 50$ MeV.

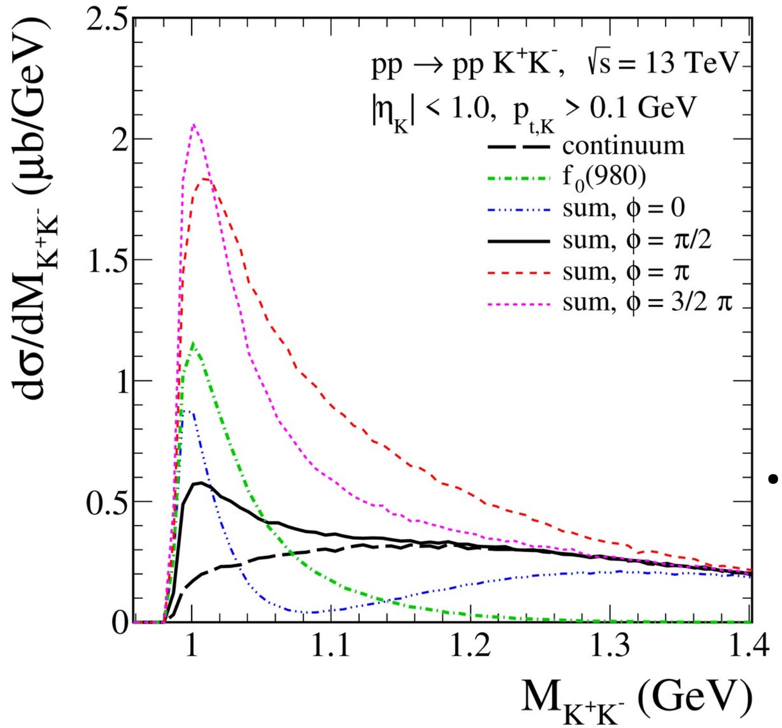
# $pp \rightarrow pp\, K^+K^-$

data: STAR Collaboration, JHEP 07 (2020) 178



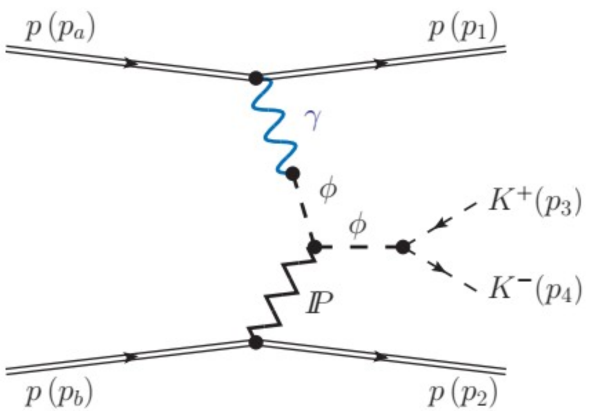



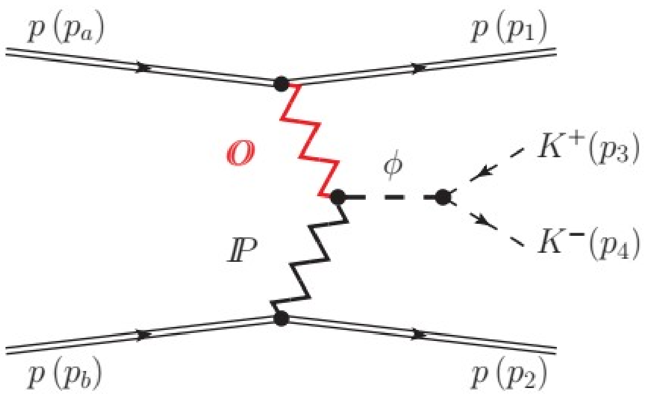




- We show results for different values of the relative phase $\phi_{f0(980)}$ in the coupling constant: $g_{f_0(980)K^+K^-} \times e^{i\phi_{f_0(980)}}$
- Complete result indicates a large interference effect of the continuum and the *f₀(980)* terms.
- The result for $\phi_{f0(980)}=0$ corresponds to the calculations with the phase used for π+π-. The phase for K+K- does not need to be the same as the production of π+π- and K+K- systems may be a complicated coupled-channel effect.
- In left bottom panel: The photoproduction term should be added coherently in amplitude

# $pp \to pp\ (\phi \to K^+K^-)$

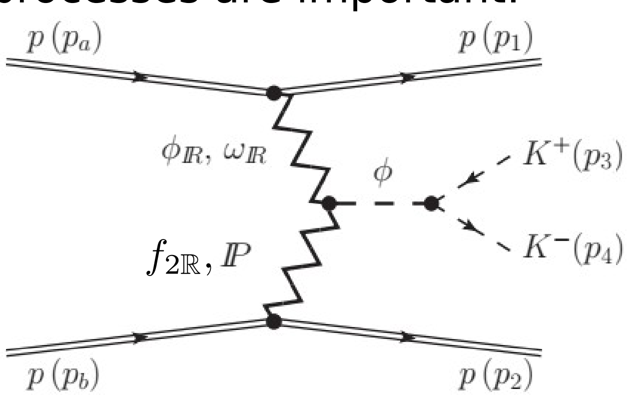
- The reaction $pp \to pp\phi$ was first suggested for an odderon search in *A. Schäfer, L. Mankiewicz, O. Nachtmann, Phys. Lett. B272 (1991) 419*. We have studied it within the tensor-pomeron model in *PL, O. Nachtmann, A. Szczurek, PRD101 (2020) 094012*. The $\phi$ can be identified e.g. by its $K^+K^-$ or $\mu^+\mu^-$ decays.
- At high energies (LHC) the main diagrams contributing are:




Because of the Okubo-Zweig-Iizuka (OZI) rule
exclusive $\phi$ production is dominated by IP exchange alone.

- At lower energies (WA102) the subleading processes are important:




Exchange objects:

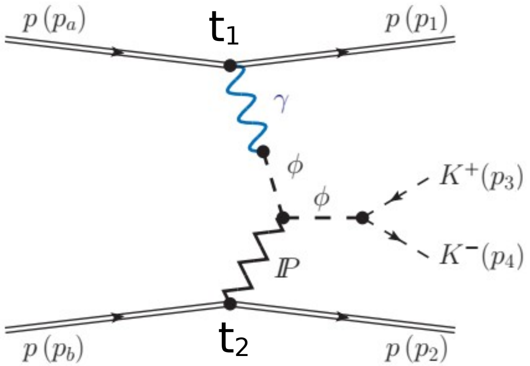
$\mathbb{P}$ (C = +1) pomeron

$\mathbb{O}$ (C= -1) odderon

$\mathbb{R}$ : $f_{2\mathbb{R}}$ (C = +1)
$\omega_{\mathbb{R}}, \phi_{\mathbb{R}}$ (C = -1) } reggeons

$\gamma$ (C = -1) photon

# $pp \to pp\ (\phi \to K^+K^-)$




**Photon-Pomeron fusion**

The Born amplitude (formulated in terms of effective propagators and vertices)

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

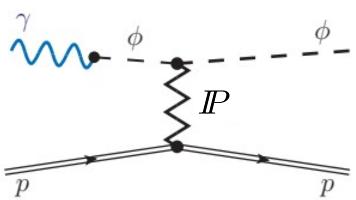
where $p_{34} = p_3 + p_4\,, q_1 = p_a - p_1\,, q_2 = p_b - p_2\,, t_i = q_i^2\,, s_i = (p_i + p_{34})^2$

Here we use the vector-meson dominance (VMD) model, in which the electromagnetic interaction is mediated by vector meson $\phi$.

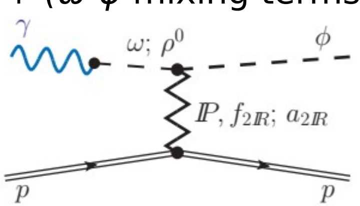
For the $I\!P\phi\phi$ vertex we take (in analogy to $f_2\gamma\gamma$ vertex):

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

The coupling parameters $a_{\mathbb{P}\phi\phi}$, $b_{\mathbb{P}\phi\phi}$ and the cut-off parameter $\Lambda_{0,\,\mathbb{P}\phi\phi}$ in form factor $F_M(t) = \frac{1}{1-t/\Lambda^2_{0,\mathbb{P}\phi\phi}}$ are fixed from the process $\gamma p \to \phi p$.

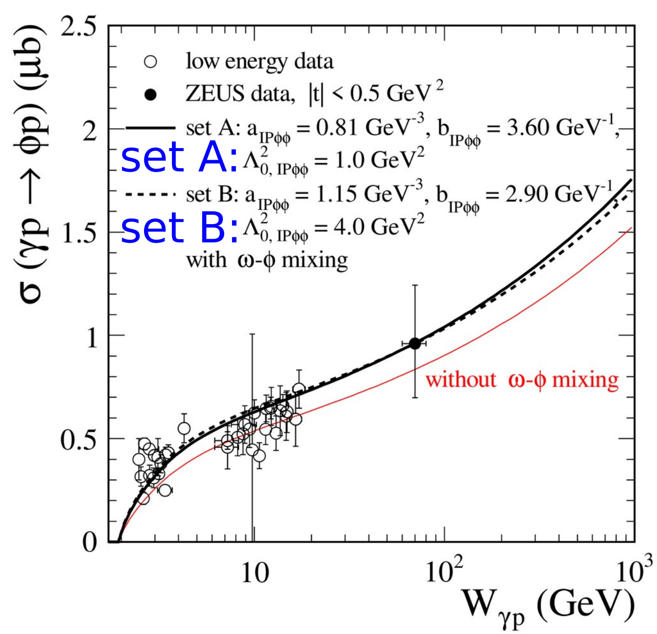


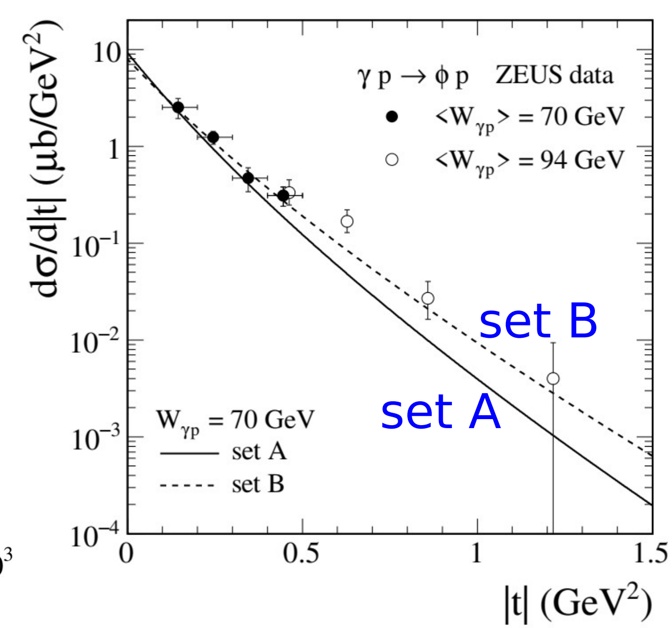

+ ($\omega$-$\phi$ mixing terms)




$$b_{\mathbb{P}\omega\phi} = -b_{\mathbb{P}\omega\omega}\,\tan(\Delta\theta_V) = -0.46\ \text{GeV}^{-1}$$

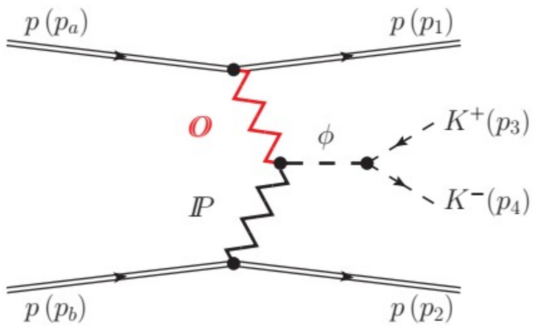
$$b_{\mathbb{P}\omega\omega} = 7.04\ \text{GeV}^{-1},\ \Delta\theta_V = 3.7^o$$



# $pp \to pp\ (\phi \to K^+K^-)$

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




**Odderon-Pomeron fusion**

Effective propagator of C = -1 odderon and odderon-proton vertex

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

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

In our calculations we shall choose as default values:

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

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

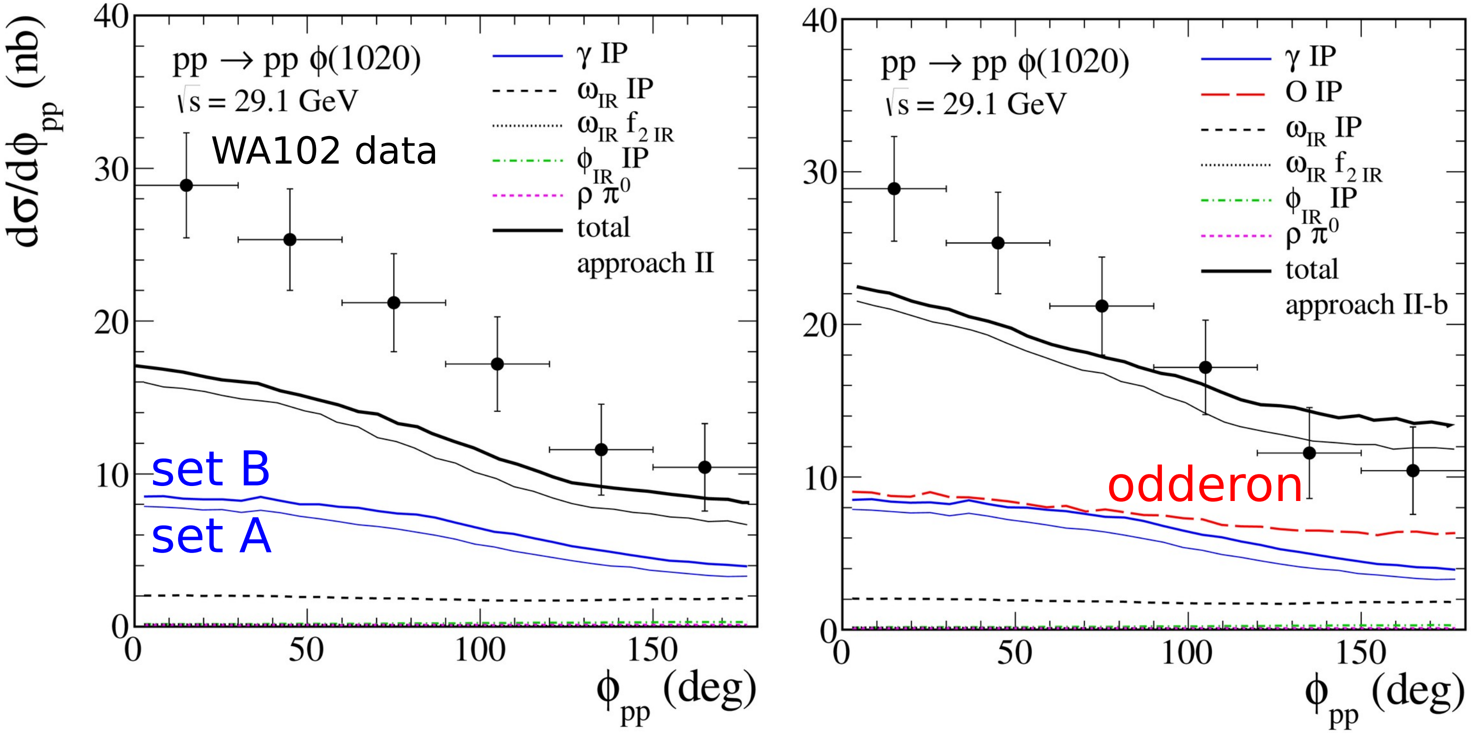
For the $\mathbb{P}\mathbb{O}\phi$ vertex we use an ansatz analogous to the $\mathbb{P}\phi\phi$ vertex:

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

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

- Absorption effects included: $\mathcal{M} = \mathcal{M}^{Born} + \mathcal{M}^{pp-rescattering}$

# $pp \to pp\,\phi$




- Distributions in $\phi_{pp}$ the azimuthal angle between the outgoing protons. Different fusion processes are considered → large interference effects.

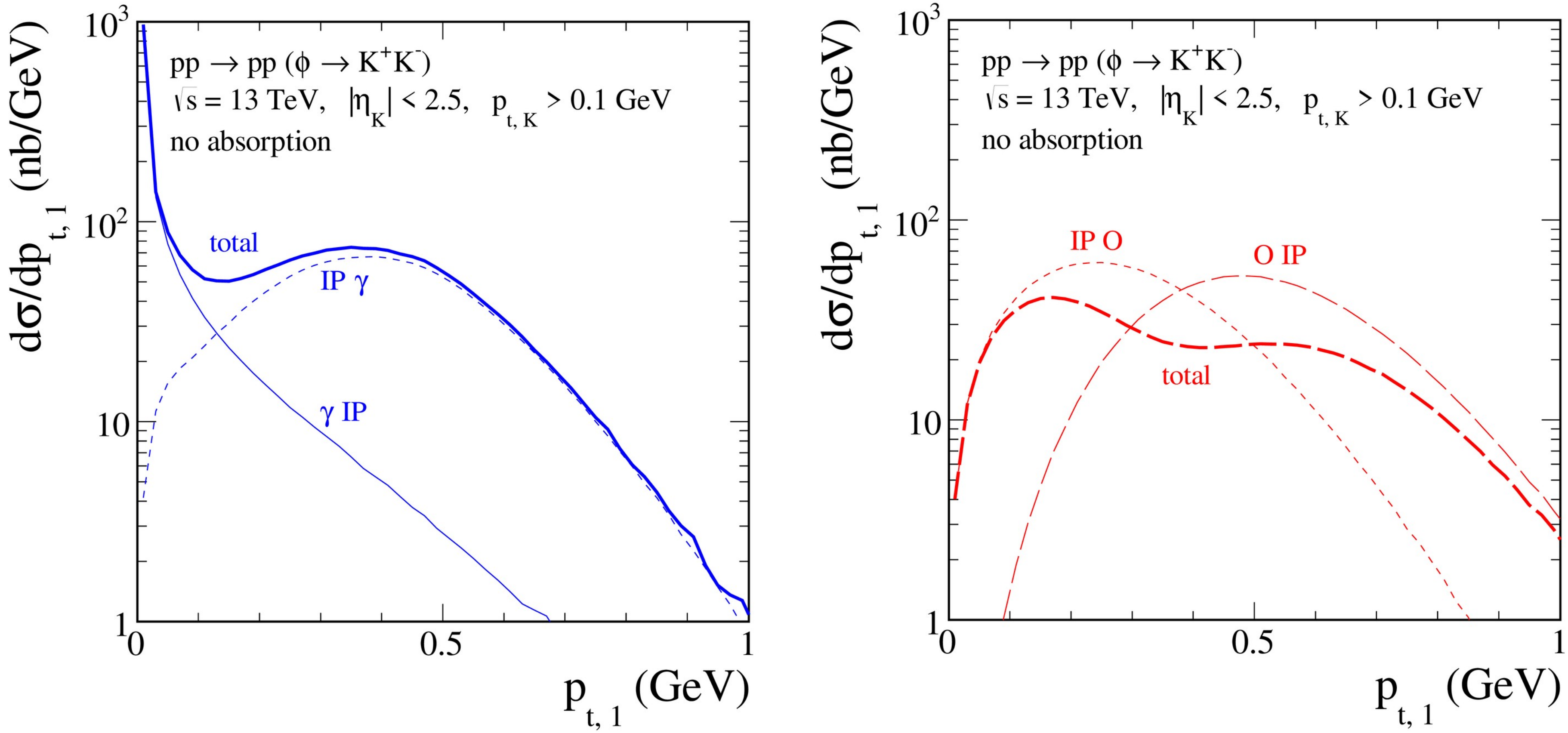
- Comparison of the model with the WA102 data [A. Kirk, PLB489 (2000) 29] gives an indication for odderon-exchange term and allow us to determine the model parameters for odderon contribution $a_{\mathbb{P}\mathbb{O}\phi} = -0.8\ \mathrm{GeV}^{-3}, \quad b_{\mathbb{P}\mathbb{O}\phi} = 1.6\ \mathrm{GeV}^{-1}, \quad \Lambda^2_{0,\,\mathbb{P}\mathbb{O}\phi} = 0.5\,\mathrm{GeV}^2$

- The total cross section is $\sigma_{\mathrm{exp}}(pp \to pp\phi) = (60 \pm 21)$ nb at $\sqrt{s} = 29.1$ GeV

- The ratio $R = \dfrac{d\sigma/d(\mathrm{dP_t} \leqslant 0.2\ \mathrm{GeV})}{d\sigma/d(\mathrm{dP_t} \geqslant 0.5\ \mathrm{GeV})}$ was also measured: $R_{\mathrm{exp}} = 0.18 \pm 0.07$

$\mathrm{dP_t} = |\vec{q}_{1\perp} - \vec{q}_{2\perp}| = |\vec{p}_{2\perp} - \vec{p}_{1\perp}|,$ $R_{\mathrm{th}} = 0.71$ (no odderon), $R_{\mathrm{th}} = 0.27$ (with odderon)

# $pp \to pp\ (\phi \to K^+K^-)$



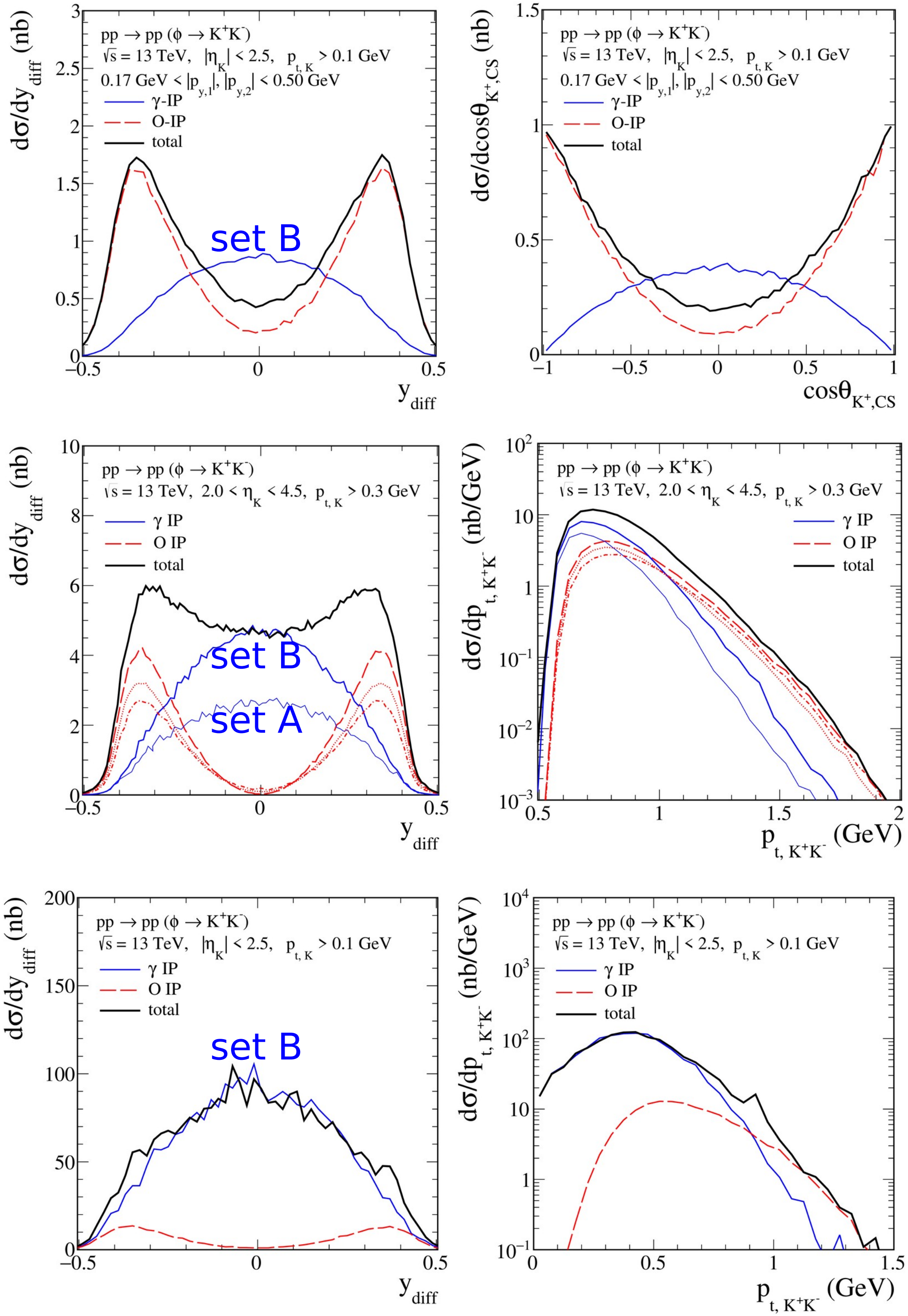

Can we distinguish γ and odderon (O) exchange?

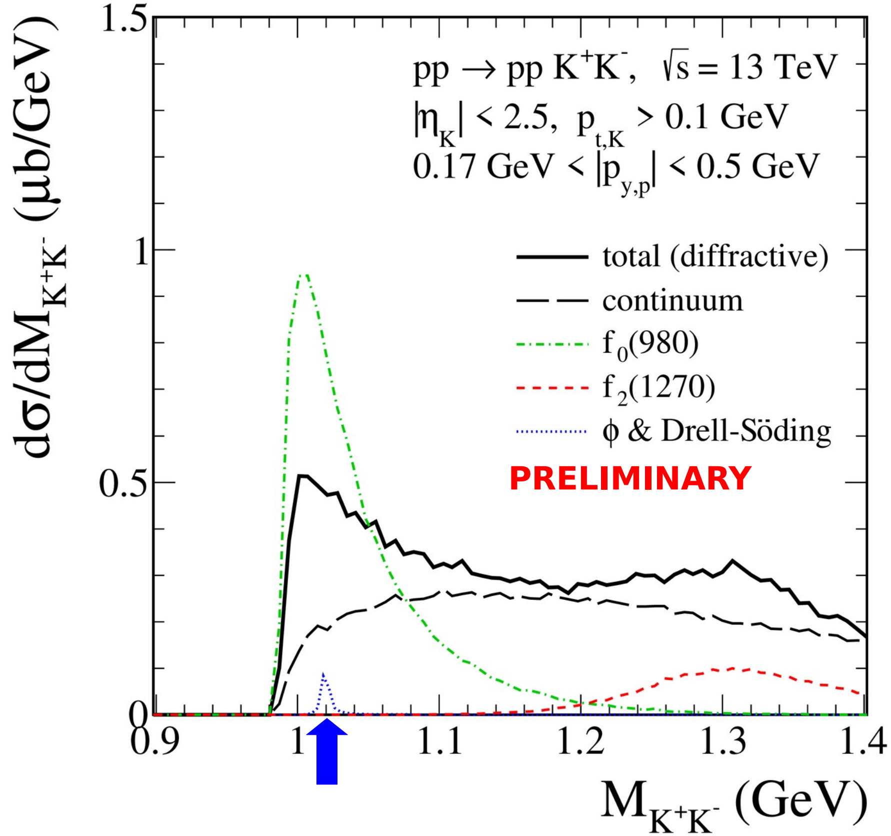
Shown are the Born results for two diagrams separately and for their coherent sum (total). Interference effects between the two amplitudes is visible, especially for OP-fusion mechanism.

Due to the γ exchange the protons are scattered only at small angles and the γP distribution has a singularity for $|t_1| \to 0$ ( $|t_1| = 0$ cannot be reached here from kinematics). In contrast, the OP distribution shows a dip for $|t_1| \to 0$.

For the ATLAS-ALFA kinematics, the absorption effects lead to a large damping of the cross section both for the purely diffractive and photoproduction contributions.

# $pp \to pp\ (\phi \to K^+K^-)$



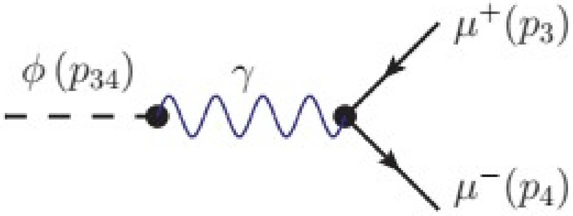

→ Odderon exchange gives ϕ mesons with larger $p_t$ than γ exchange

→ Interesting distribution in $y_{diff} = y_{K+} - y_{K-}$ (rapidity distance between the $K^+$ and $K^-$). From $\cos\theta_{K+,CS}$ distributions we can conclude that from γ-IP fusion the ϕ meson gets preferentially a transverse polarisation giving a distribution $\propto \sin^2\theta_{K+,CS}$. For the O-IP fusion the ϕ meson gets preferentially a longitudinal polarisation with distribution $\propto \cos^2\theta_{K+,CS}$.

# $pp \to pp\,\mu^+\mu^-$

The amplitudes for the $pp \to pp\mu^+\mu^-$ reaction through $\phi$ resonance production can be obtained from the $pp \to ppK^+K^-$ amplitudes with the replacement: $i\Gamma_\kappa^{(\phi KK)}(p_3, p_4) \to \bar{u}(p_4, \lambda_4) i\Gamma_\kappa^{(\phi\mu\mu)}(p_3, p_4) v(p_3, \lambda_3)$.

Here we describe the transition $\phi \to \gamma \to \mu^+\mu^-$ by an effective vertex:




$$i\Gamma_\kappa^{(\phi\mu\mu)}(p_3, p_4) = i g_{\phi\mu^+\mu^-}\,\gamma_\kappa$$

The decay rate $\phi \to \mu^+\mu^-$ is calculated from the diagram

$$\Gamma(\phi \to \mu^+\mu^-) = \frac{1}{12\pi}\,|g_{\phi\mu^+\mu^-}|^2\, m_\phi \left(1 + \frac{2m_\mu^2}{m_\phi^2}\right)\left(1 - \frac{4m_\mu^2}{m_\phi^2}\right)^{1/2}$$

From the experimental values (PDG)

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

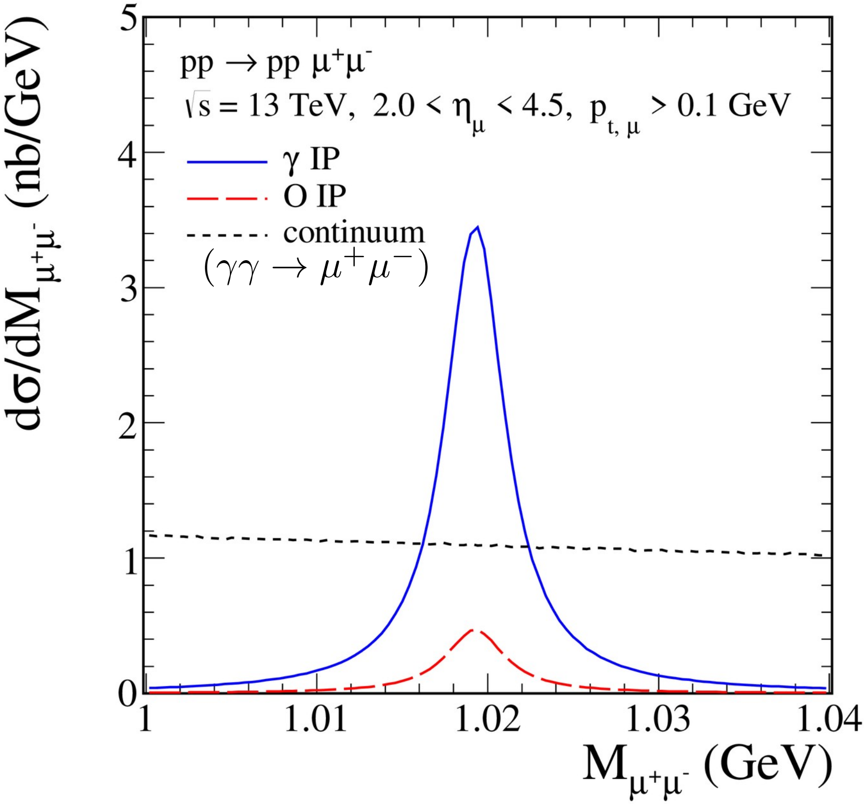
we get $g_{\phi\mu^+\mu^-} = (6.71 \pm 0.22) \times 10^{-3}$

Using VMD model we get:

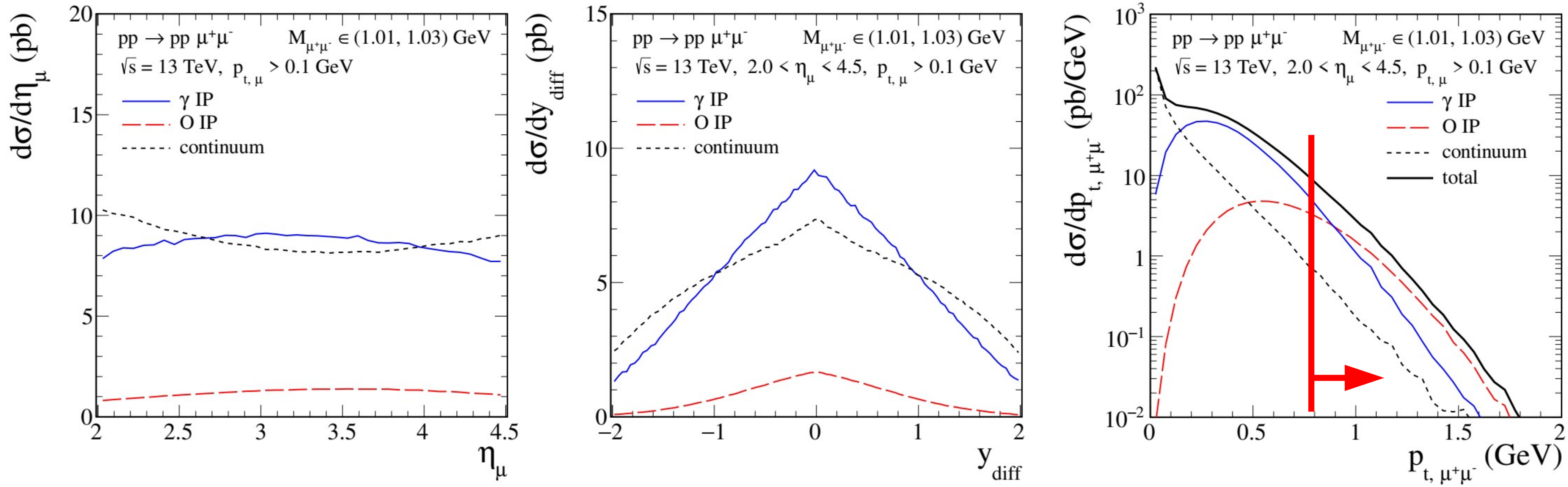
$$g_{\phi\mu^+\mu^-} = -e^2 \frac{1}{\gamma_\phi}\,, \quad \gamma_\phi < 0\,,$$

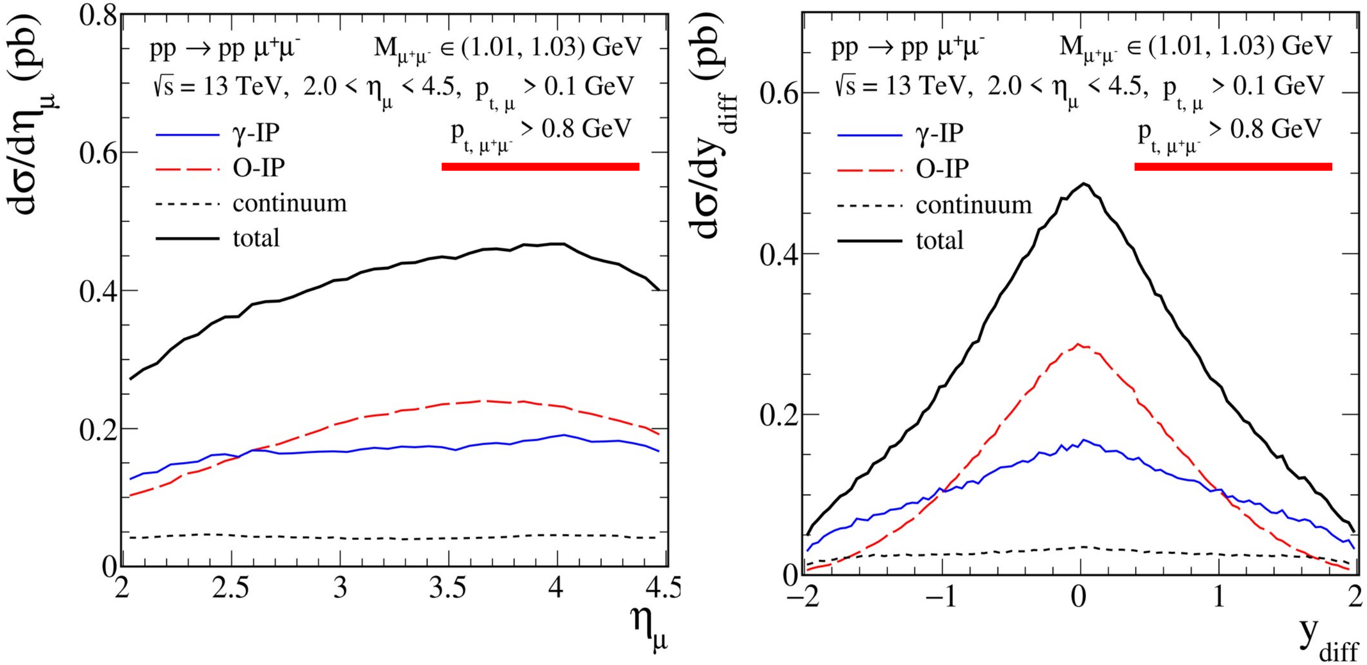
$$4\pi/\gamma_\phi^2 = 0.0716 \pm 0.0017$$

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



# $pp \to pp\ \mu^+\mu^-$




- $p_{t,\mu+\mu-}$ > 0.8 GeV → helpful to reduce the $\gamma\gamma \to \mu^+\mu^-$ continuum and $\gamma$ IP-fusion contributions
- In this reaction the absolute normalization of the cross section or detailed studies of shape of distributions should provide a hint whether one observes the odderon effects
- The new study of ϕ mesons CEP in their decay to muons is currently in progress at LHCb (with HeRSCheL allowing for a reduction of the background from proton dissociation)

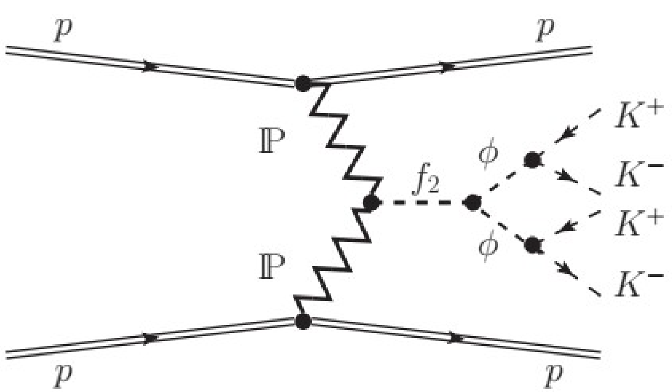
# Cross sections in nb for CEP of single $\phi$ in $pp$ collisions

Table 1: Cross sections in nb calculated for $\sqrt{s} = 13$ TeV in the dikaon/dimuon invariant mass region $M_{34} \in (1.01, 1.03)$ GeV and for some typical experimental cuts. The ratios of full and Born cross sections $\langle S^2 \rangle$ are shown.

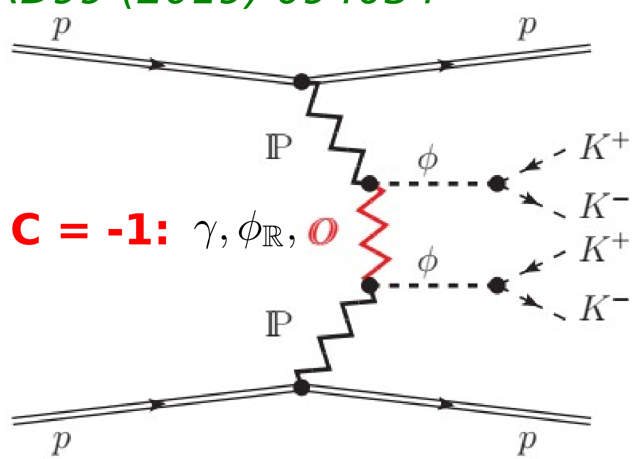
| | Cuts | Contributions | $\sigma^{(\mathrm{Born})}$ (nb) | $\sigma^{(\mathrm{full})}$ (nb) | $\langle S^2 \rangle$ |
|---|---|---|---|---|---|
| $pp \to pp\, K^+K^-$ | $\lvert\eta_K\rvert < 2.5$, $p_{t,K} > 0.1$ GeV | $\gamma\mathbb{P}$ fusion | 60.07 | 55.09 | 0.9 |
| | | $\mathbb{OP}$ fusion | 21.40 | 6.44 | 0.3 |
| | | $\gamma\mathbb{P}$ and $\mathbb{OP}$ | | 58.58 | |
| | $\lvert\eta_K\rvert < 2.5$, $p_{t,K} > 0.2$ GeV, 0.17 GeV $< \lvert p_{y,1}\rvert, \lvert p_{y,2}\rvert < 0.5$ GeV | $\gamma\mathbb{P}$ fusion | 1.07 | 0.24 | 0.2 |
| | | $\mathbb{OP}$ fusion | 2.10 | 0.61 | 0.3 |
| | | $\gamma\mathbb{P}$ and $\mathbb{OP}$ | | 0.70 | |
| | $2.0 < \eta_K < 4.5$, $p_{t,K} > 0.1$ GeV | $\gamma\mathbb{P}$ fusion | 43.18 | 40.07 | 0.9 |
| | | $\mathbb{OP}$ fusion | 16.73 | 4.70 | 0.3 |
| | | $\gamma\mathbb{P}$ and $\mathbb{OP}$ | | 43.28 | |
| | $2.0 < \eta_K < 4.5$, $p_{t,K} > 0.3$ GeV | $\gamma\mathbb{P}$ fusion | 3.09 | 2.57 | 0.8 |
| | | $\mathbb{OP}$ fusion | 6.57 | 1.64 | 0.3 |
| | | $\gamma\mathbb{P}$ and $\mathbb{OP}$ | | 4.24 | |
| | $2.0 < \eta_K < 4.5$, $p_{t,K} > 0.5$ GeV | $\gamma\mathbb{P}$ fusion | $0.93 \times 10^{-1}$ | $0.66 \times 10^{-1}$ | 0.7 |
| | | $\mathbb{OP}$ fusion | 0.88 | 0.16 | 0.2 |
| | | $\gamma\mathbb{P}$ and $\mathbb{OP}$ | | 0.24 | |
| $pp \to pp\, \mu^+\mu^-$ | $2.0 < \eta_\mu < 4.5$, $p_{t,\mu} > 0.1$ GeV | $\gamma\mathbb{P}$ fusion | $23.93 \times 10^{-3}$ | $20.96 \times 10^{-3}$ | 0.9 |
| | | $\mathbb{OP}$ fusion | $10.06 \times 10^{-3}$ | $3.02 \times 10^{-3}$ | 0.3 |
| | | $\gamma\mathbb{P}$ and $\mathbb{OP}$ | | $21.64 \times 10^{-3}$ | |
| | $2.0 < \eta_\mu < 4.5$, $p_{t,\mu} > 0.5$ GeV | $\gamma\mathbb{P}$ fusion | $1.21 \times 10^{-3}$ | $0.85 \times 10^{-3}$ | 0.7 |
| | | $\mathbb{OP}$ fusion | $1.49 \times 10^{-3}$ | $0.45 \times 10^{-3}$ | 0.2 |
| | | $\gamma\mathbb{P}$ and $\mathbb{OP}$ | | $1.07 \times 10^{-3}$ | |
| | $2.0 < \eta_\mu < 4.5$, $p_{t,\mu} > 0.1$ GeV, $p_{t,\mu^+\mu^-} > 0.8$ GeV | $\gamma\mathbb{P}$ fusion | $0.70 \times 10^{-3}$ | $0.41 \times 10^{-3}$ | 0.6 |
| | | $\mathbb{OP}$ fusion | $2.46 \times 10^{-3}$ | $0.51 \times 10^{-3}$ | 0.2 |
| | | $\gamma\mathbb{P}$ and $\mathbb{OP}$ | | $0.91 \times 10^{-3}$ | |

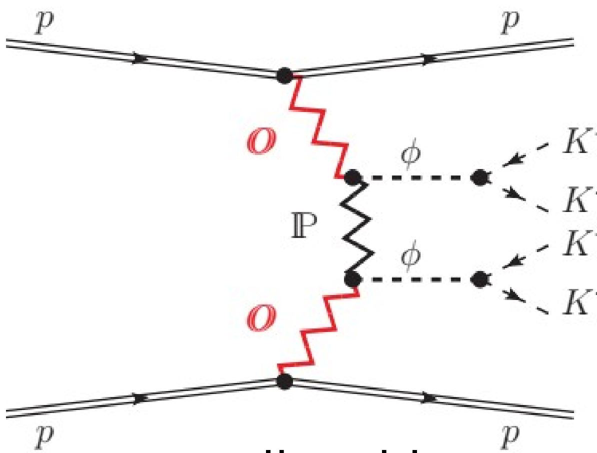
# $pp \to pp\ (\phi\phi \to K^+K^-K^+K^-)$

*P.L., O. Nachtmann, A. Szczurek, PRD99 (2019) 094034*




$f_2(2340)$ resonance
(tensor glueball production)




negligeable

$\beta_{\mathbb{O}pp} \ll \beta_{\mathbb{P}NN}$
coupling constants

- Some modifications are needed to simulate 2 → 6 reaction from 2 → 4 (smearing of $\phi$ masses due to their resonance distribution)

$$\sigma_{2\to 6} = [\mathcal{BR}(\phi \to K^+K^-)]^2 \int_{2m_K} \int_{2m_K} \sigma_{2\to 4}(\ldots, m_{X_3}, m_{X_4})\, f_\phi(m_{X_3})\, f_\phi(m_{X_4})\, dm_{X_3}\, dm_{X_4}$$

- At high energies we expect this reaction to be dominated by IPIP fusion processes.

Contributions with **C = -1** exchanges:

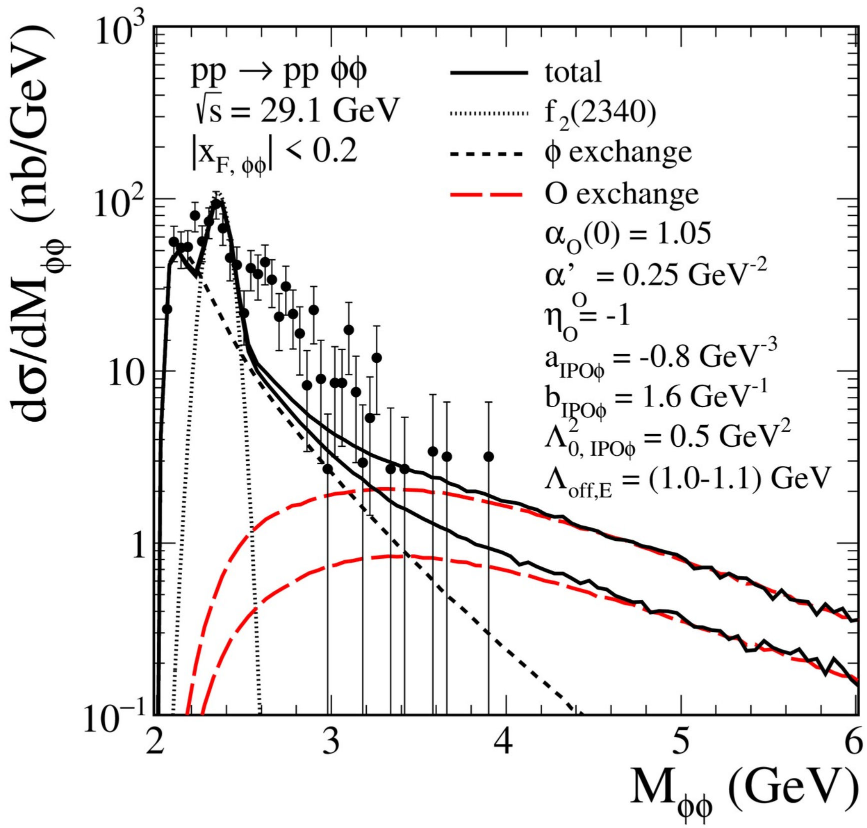
$$\gamma : \quad \text{negligeable}$$

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

$$\text{odderon } \mathbb{O} : \quad \propto \left(M_{\phi\phi}^2\right)^{\alpha_{\mathbb{O}}(\hat{t})-1}, \ \alpha_{\mathbb{O}}(0) \approx 1.0 \quad \text{will win for large } M_{\phi\phi}$$

We have the exchange of a $\phi$ or $\phi_R$ reggeon depending on kinematics.
The $\omega$ or $\omega_R$ contributions are expected to be very small since the $\phi$ meson is nearly $s\bar{s}$ state, the $\omega$ nearly a pure ( $u\bar{u} + d\bar{d}$ ) state.

# $pp \to pp\ (\phi\phi \to K^+K^-\ K^+K^-)$




WA102 data [PLB432 (1998) 436, PLB489 (2000) 29]

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

The $f_2(2300)$ and $f_2(2340)$ are good candidates for tensor glueball (or states with large 'gluonic component'). According to lattice-QCD simulations, the lightest tensor glueball has a mass between 2.2 – 2.4 GeV.

- We assumed that the $f_2(2340)$ resonance dominates low-$M_{\phi\phi}$ cross section with j = 1 IPIP$f_2$ coupling. For the $f_2\phi\phi$ vertex we take the ansatz in analogy to $f_2\gamma\gamma$ vertex.

- For $\phi$-exchange term the reggeization of the intermediate $\phi$ meson is necessary, in both the t- and u-channel amplitudes:

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

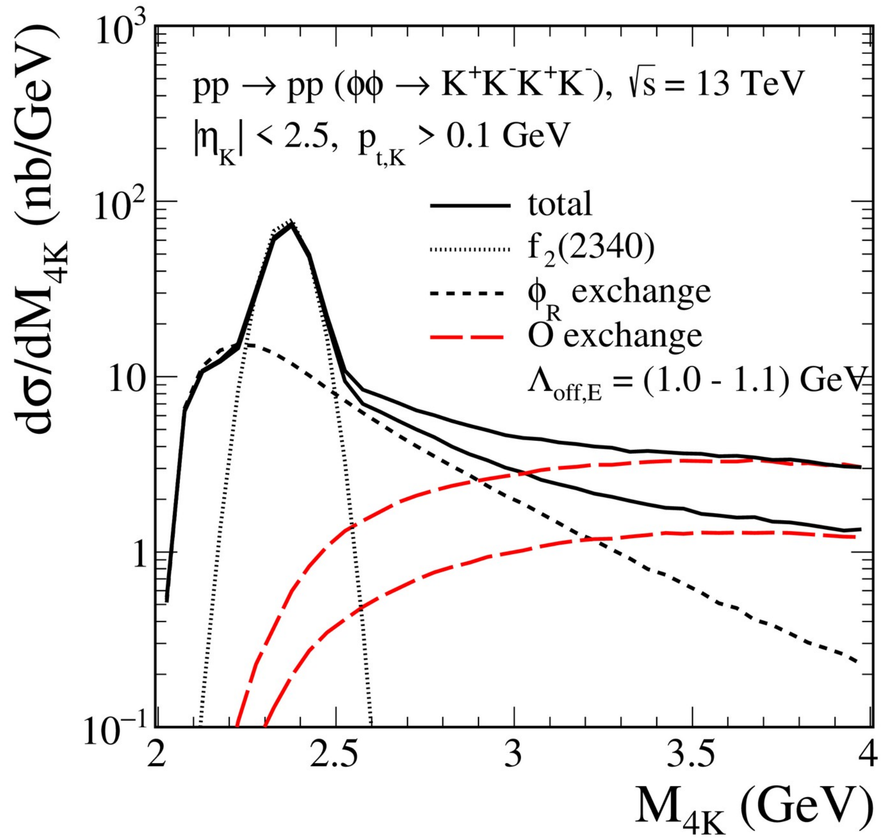
$$s_{34} = (p_3+p_4)^2 = \mathrm{M}^2_{\phi\phi}, \quad s_{\rm thr} = 4m^2_\phi$$

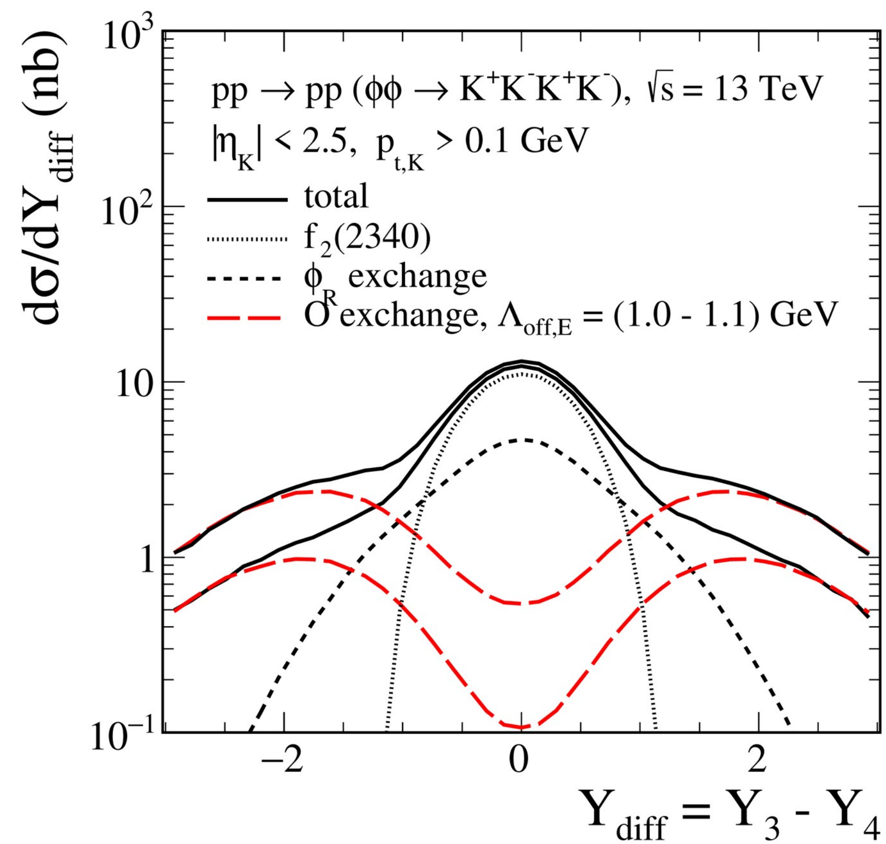
- At low energies $s_{34}$ the Regge type of interaction is not realistic and should be switched off. We multiply the odderon-exchange amplitude by phenomenological factor

$$F_{\rm thr}(s_{34}) = 1 - \exp\left(\frac{s_{\rm thr} - s_{34}}{s_{\rm thr}}\right)$$

- The form factors in the PO$\phi$ vertex guarantee that in our calculation the odderon only contributes in the Regge regime $|\hat{t}|, |\hat{u}| \ll s_{34}$ .

# $pp \to pp\ (\phi\phi \to K^+K^-\ K^+K^-)$




- The $f_2(2340)$ resonance should be visible on top of the $\phi_R$-exchange continuum contribution.

- The small intercept of the $\phi_R$-exchange, $\alpha_\phi(0) = 0.1$ makes this contribution steeply falling with increasing $M_{4K}$ and $|Y_{diff}|$. Therefore, an odderon with an intercept $\alpha_O(0) \sim 1.0$ should be distinguishable from other contributions and visible for $M_{4K} > 3$ GeV and $|Y_{diff}| > 2$.

Total cross section:
$\sigma = 20.6 – 27.1$ nb with $a_{PO\phi} = -0.8\ \text{GeV}^{-3}$, $b_{PO\phi} = 1.6\ \text{GeV}^{-1}$, and for $\Lambda_{off,E} = 1.0 – 1.1$ GeV (cutoff parameter in the $PO\phi$ form factor for off-shell odderon)

# Conclusions

- The tensor-pomeron and vector-odderon approach was applied to a variety exclusive soft reactions.

  All amplitudes are expressed in terms of effective vertices and propagators for the exchanged objects respecting the standard relations of QFT and the power-law ansätze from the Regge model.
  It is effective model where some parameters have to be determined from experiment.

- CEP offers many opportunities to study the production of hadronic resonances.

  The measurement of the transverse momenta of the outgoing protons allow to determine the azimuthal angle between them and ''glueball-filter variable''. Comparison of the model results with exclusive experimental data (STAR, ATLAS-ALFA, CMS-TOTEM) should allow a good determination of the IP-IP-Meson couplings.

- We have given examples of processes which can be studied at ALICE 3.

  For $pp \to pp\pi^+\pi^-$, we get a good description of the STAR (200 GeV) and preliminary ATLAS-ALFA (13 TeV) data taking into account diffractive continuum, $f_0(980)$, and $f_2(1270)$ resonances.
  Photoproduction of $\rho(770)$ is visible in CMS data (13 TeV) and ALICE Run 3 data (13.6 TeV),
  but there other processes with one and both protons undergoing dissociation may be important.

  The reaction $pp \to ppK^+K^-$ ($f_0(980)$ and $\phi(1020)$ resonances) has been studied.

  $pp \to pp(\phi\phi \to K^+K^-K^+K^-)$ is a good reaction to search for effects of tensor glueball [e.g. $f_2(2340)$] and odderon.

  CEP of $\phi \to \mu^+\mu^-$ and $\phi\phi \to 4K$ offers the possibility to determine the IPO$\phi$ coupling, at least, to derive an upper limit on the odderon contribution.

Thank you for your attention !