Central exclusive production of K^+K^- pairs in proton-proton collisions

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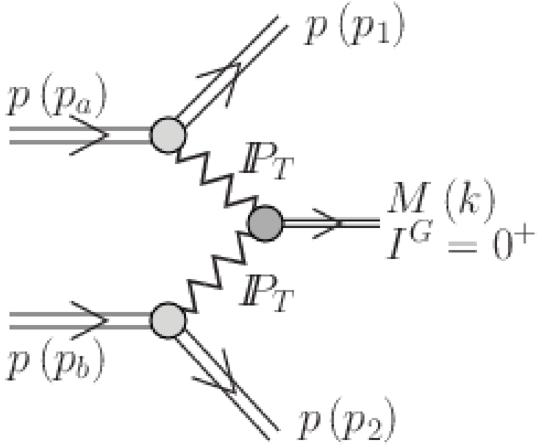
Overview

- Central Exclusive Production (CEP) in *pp* collisions
- Model for high-energy soft reactions – tensor pomeron approach
- Results for $p\,p \to p\,p\,K^+K^-$
  - diffractive mechanism – dikaon continuum, scalar and tensor resonances
  - photoproduction mechanism – $\phi(1020)$ and continuum
- *Preliminary results of* $p\,p \to p\,p\,K^+K^-K^+K^-$ via intermediate $\phi(1020)\phi(1020)$ states
- Conclusions

Central production of light mesons in *pp* collisions

- As predicted by Regge theory the diffractive cross section at high energy is dominated by double pomeron exchange (DPE)
- QCD image of pomeron implies that DPE is a gluon-rich process

  → therefore gluonic bound states (glueballs) could be preferentially produced



J^{PC}	mesons
0^{-+}	η , $\eta'(958)$
0^{++}	$f_0(500)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$
1^{++}	$f_1(1285)$, $f_1(1420)$
2^{++}	$f_2(1270)$, $f_2'(1525)$, $f_2(1950)$
4^{++}	$f_4(2050)$

glueballs

- Such processes were studied extensively at CERN starting from the ISR experiments (AFS and ABCDHW), later by the WA76 and WA102 collaborations, and more recently by the COMPASS collaboration.

  The measurement of two charged pions in $p\bar{p}$ collisions was performed by the CDF collaboration at Tevatron.

  New results are expected from current experiments at the LHC (ALICE, ATLAS+ALFA, CMS+TOTEM, LHCb), and at the RHIC (STAR).

Tensor pomeron approach

C. Ewerz, M. Maniatis, O. Nachtmann, Annals Phys. 342 (2014) 31

- A model for soft high-energy scattering was developed.
  Considered reactions: $NN \to NN$, $\pi N \to \pi N$, $\rho N \to \rho N$

- The model was formulated in terms of effective propagators and vertices for the exchange objects:
  $C = +1$ (pomeron, f_{2IR}, a_{2IR}) exchanges are represented as rank-two tensor
  $C = -1$ (odderon, ω_{IR}, ρ_{IR}) exchange are represented as vector

- All vertices respect the standard C parity and crossing rules of QFT.
  The propagators respect the crossing properties of amplitudes in QFT and the power-law ansätze from the Regge model

C. Ewerz, P. L., O. Nachtmann, A. Szczurek, Phys. Lett. B763 (2016) 382

The tensor-pomeron is consistent with the experimental data on the helicity structure of small-t *pp* elastic scattering from the STAR experiment (PLB 719 (2013))

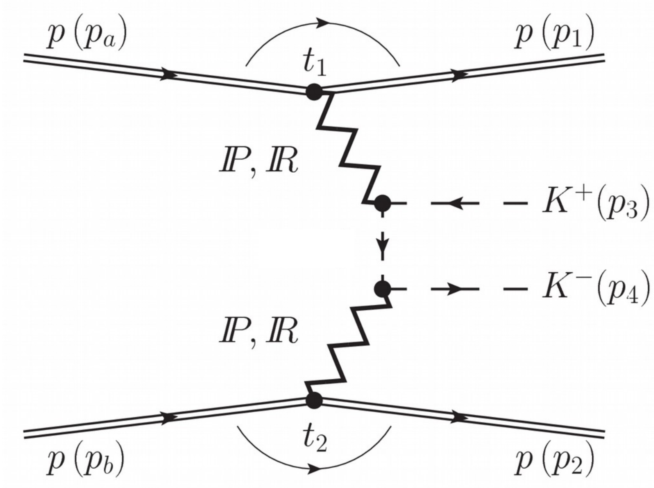
P. L., O. Nachtmann, A. Szczurek, Central exclusive production of mesons:

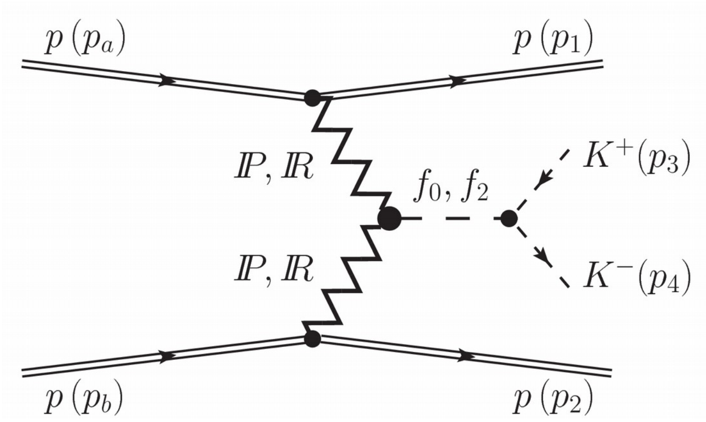
$pp \to pp\, M(0^{++})$, $pp \to pp\, M(0^{-+})$	Annals Phys. 344 (2014) 301
$pp \to pp\, \pi^+ \pi^-$	PRD 91 (2015) 074023, PRD 93 (2016) 054015
$pp \to pp\, \pi^+ \pi^- \pi^+ \pi^-$	PRD 94 (2016) 034017
$pp \to p\, \rho^0\, (\pi^0 p)$, $pp \to p\, \rho^0\, (\pi^+ n)$	PRD 95 (2017) 034036
$\boldsymbol{pp \to pp\, K^+ K^-}$	arXiv:1804.04706

We keep checking whether it works for different other processes.
So far yes! Further tests are needed.

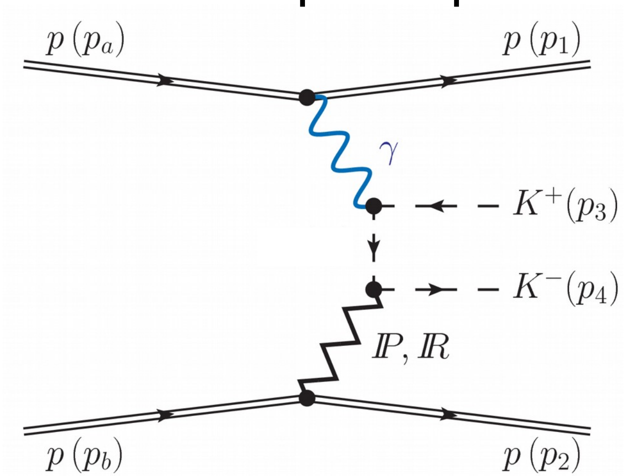
$pp \to pp\, K^+K^-$

- double-pomeron/reggeon dikaon continuum and resonance production

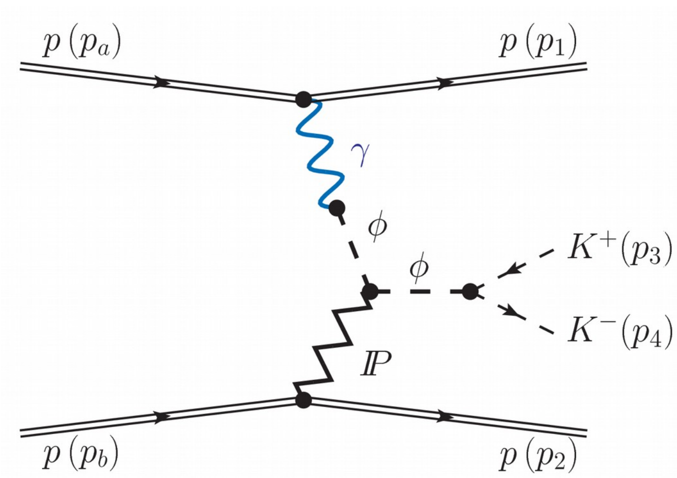




- diffractive photoproduction



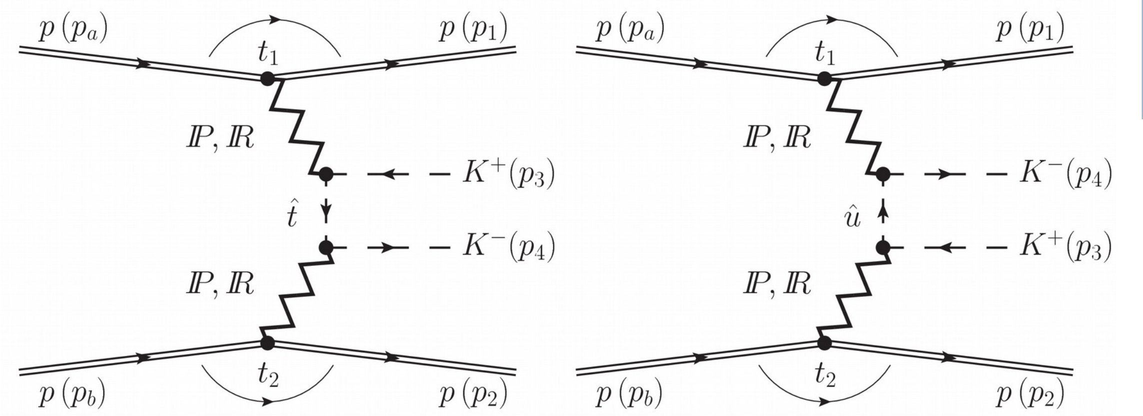
(Drell-Söding mechanism)



\+ *IPγ - fusion* diagrams

- $\mathcal{M}_{pp\to ppK^+K^-} = \mathcal{M}^{KK-\text{continuum}}_{pp\to ppK^+K^-} + \mathcal{M}^{KK-\text{resonances}}_{pp\to ppK^+K^-}$

Diffractive K^+K^- continuum production



$$\mathcal{M}^{KK-\text{continuum}}_{pp\to ppK^+K^-} = \mathcal{M}^{(I\!PI\!P\to K^+K^-)} + \mathcal{M}^{(I\!PI\!R\to K^+K^-)} + \mathcal{M}^{(I\!RI\!P\to K^+K^-)} + \mathcal{M}^{(I\!RI\!R\to K^+K^-)}$$

$$\mathcal{M}^{(I\!PI\!P\to K^+K^-)} = \mathcal{M}^{(\hat{t})} + \mathcal{M}^{(\hat{u})}$$

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

$$\mathcal{M}^{(\hat{t})} = (-i)\bar{u}(p_1,\lambda_1) i\Gamma^{(I\!Ppp)}_{\mu_1\nu_1}(p_1,p_a) u(p_a,\lambda_a)\, i\Delta^{(I\!P)\,\mu_1\nu_1,\alpha_1\beta_1}(s_{13},t_1)\, i\Gamma^{(I\!PKK)}_{\alpha_1\beta_1}(\hat{p}_t,-p_3)$$
$$\times\, i\Delta^{(K)}(\hat{p}_t)\, i\Gamma^{(I\!PKK)}_{\alpha_2\beta_2}(p_4,\hat{p}_t)\, i\Delta^{(I\!P)\,\alpha_2\beta_2,\mu_2\nu_2}(s_{24},t_2)\, \bar{u}(p_2,\lambda_2) i\Gamma^{(I\!Ppp)}_{\mu_2\nu_2}(p_2,p_b) u(p_b,\lambda_b)$$

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

$$\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P}t\,, \quad \alpha_{I\!P}(0) = 1.0808, \quad \alpha'_{I\!P} = 0.25\,\mathrm{GeV}^{-2}$$

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

$$i\Gamma^{(I\!PKK)}_{\mu\nu}(k',k) = -i2\beta_{I\!PKK}\left[(k'+k)_\mu(k'+k)_\nu - \frac{1}{4}g_{\mu\nu}(k'+k)^2\right] F_M((k'-k)^2)$$

off-shell effects of intermediate kaons $F_K(\hat{k}^2) = \dfrac{\Lambda^2_{off,M} - m_K^2}{\Lambda^2_{off,M} - \hat{k}^2}$ $\Lambda_{\text{off,M}} = 0.7$ GeV

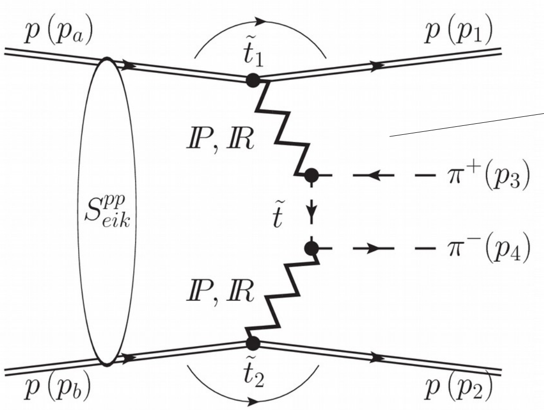
The IP/IR-proton and IP/IR-kaon coupling constants are obtained from fits to nucelon-nuclen and kaon-nucleon total cross section data, respectively.

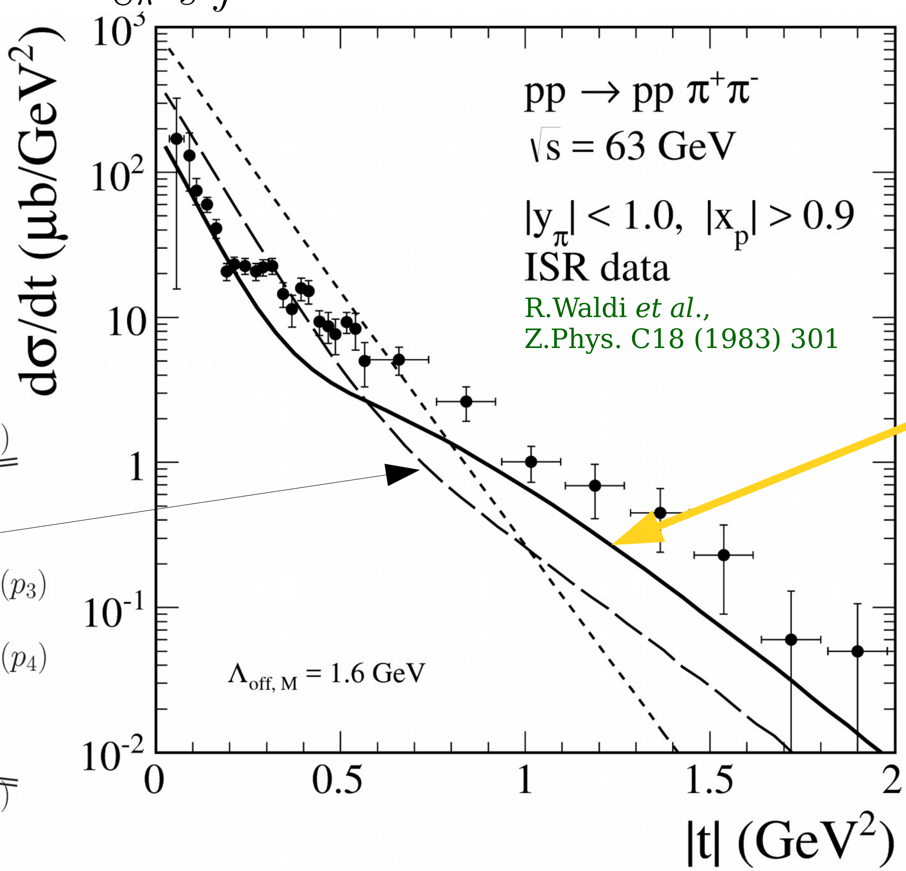
Absorption effects

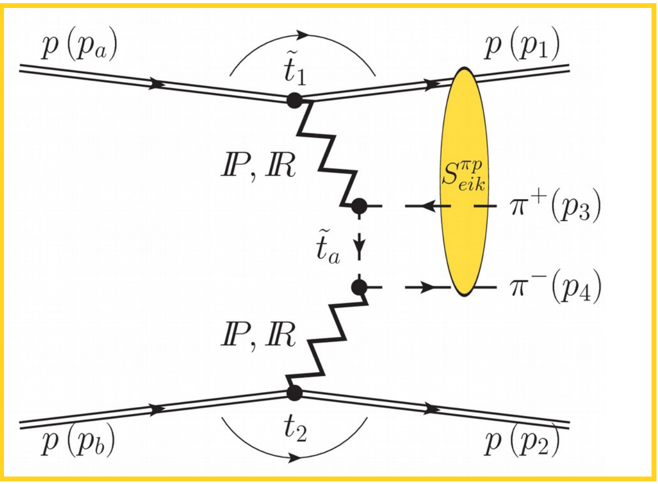
Absorption effects should be included in addition:

$$\mathcal{M}_{pp\to ppK^+K^-} = \mathcal{M}^{Born} + \mathcal{M}^{pp-rescatt.} + \mathcal{M}^{Kp-rescat.}$$

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







see P. L., A. Szczurek,
Phys. Rev. D92 (2015) 054001

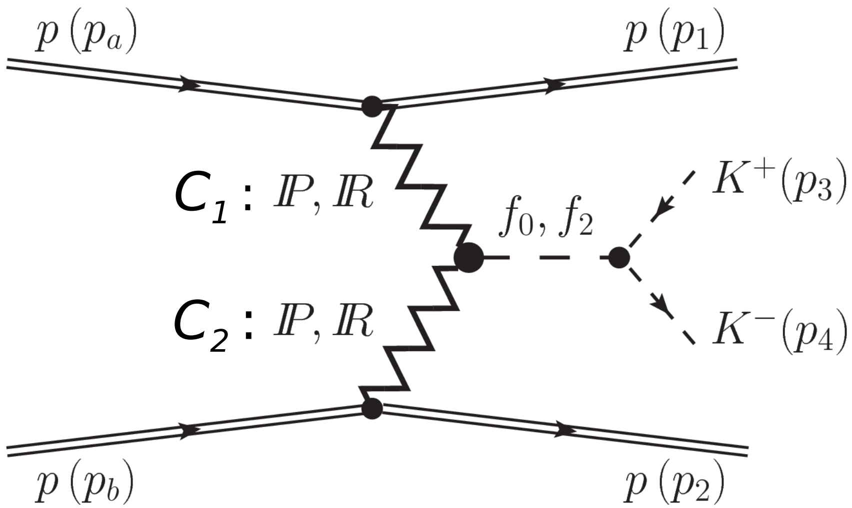
Such effect is quantified by gap survival probability factor < S²>
(ratio of absorbed-to-Born cross section)

$< S^2 > \simeq 0.1 - 0.2$ for diffractive processes at LHC

$< S^2 > \simeq 0.8 - 0.9$ for photoproduction at LHC

Absorption effects can be included effectively: $$\frac{d\sigma^{absorbed}}{dM_{KK}} = \frac{d\sigma^{Born}}{dM_{KK}} \times < S^2 >$$

Diffractive resonant production



Exchange object	C	G
$I\!P$	1	1
$f_{2I\!R}$	1	1
$a_{2I\!R}$	1	-1
$\mathbb{O}$	-1	-1
$\omega_{I\!R}$	-1	-1
$\rho_{I\!R}$	-1	1

(C_1, C_2) production modes:
$(I\!P + f_{2I\!R}, I\!P + f_{2I\!R}),\ (a_{2I\!R}, a_{2I\!R}),$
$(\mathbb{O} + \omega_{I\!R}, \mathbb{O} + \omega_{I\!R}),\ (\rho_{I\!R}, \rho_{I\!R})$

$$\mathcal{M}^{(I\!PI\!P \to f_2' \to K^+K^-)} = (-i)\, \bar{u}(p_1,\lambda_1) i\Gamma^{(I\!Ppp)}_{\mu_1\nu_1}(p_1,p_a) u(p_a,\lambda_a)\; i\Delta^{(I\!P)\,\mu_1\nu_1,\alpha_1\beta_1}(s_1,t_1)$$
$$\times\, i\Gamma^{(I\!PI\!Pf_2')}_{\alpha_1\beta_1,\alpha_2\beta_2,\rho\sigma}(q_1,q_2)\; i\Delta^{(f_2')\,\rho\sigma,\alpha\beta}(p_{34})\; i\Gamma^{(f_2'KK)}_{\alpha\beta}(p_3,p_4)$$
$$\times\, i\Delta^{(I\!P)\,\alpha_2\beta_2,\mu_2\nu_2}(s_2,t_2)\; \bar{u}(p_2,\lambda_2) i\Gamma^{(I\!Ppp)}_{\mu_2\nu_2}(p_2,p_b) u(p_b,\lambda_b)$$

$$i\Gamma^{(I\!PI\!Pf_2')}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = \left(i\Gamma^{(I\!PI\!Pf_2')(1)}_{\mu\nu,\kappa\lambda,\rho\sigma}\,|_{bare} + \sum_{j=2}^{7} i\Gamma^{(I\!PI\!Pf_2')(j)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2)\,|_{bare} \right) F_M(q_1^2) F_M(q_2^2) F^{(I\!PI\!Pf_2')}(p_{34}^2)$$

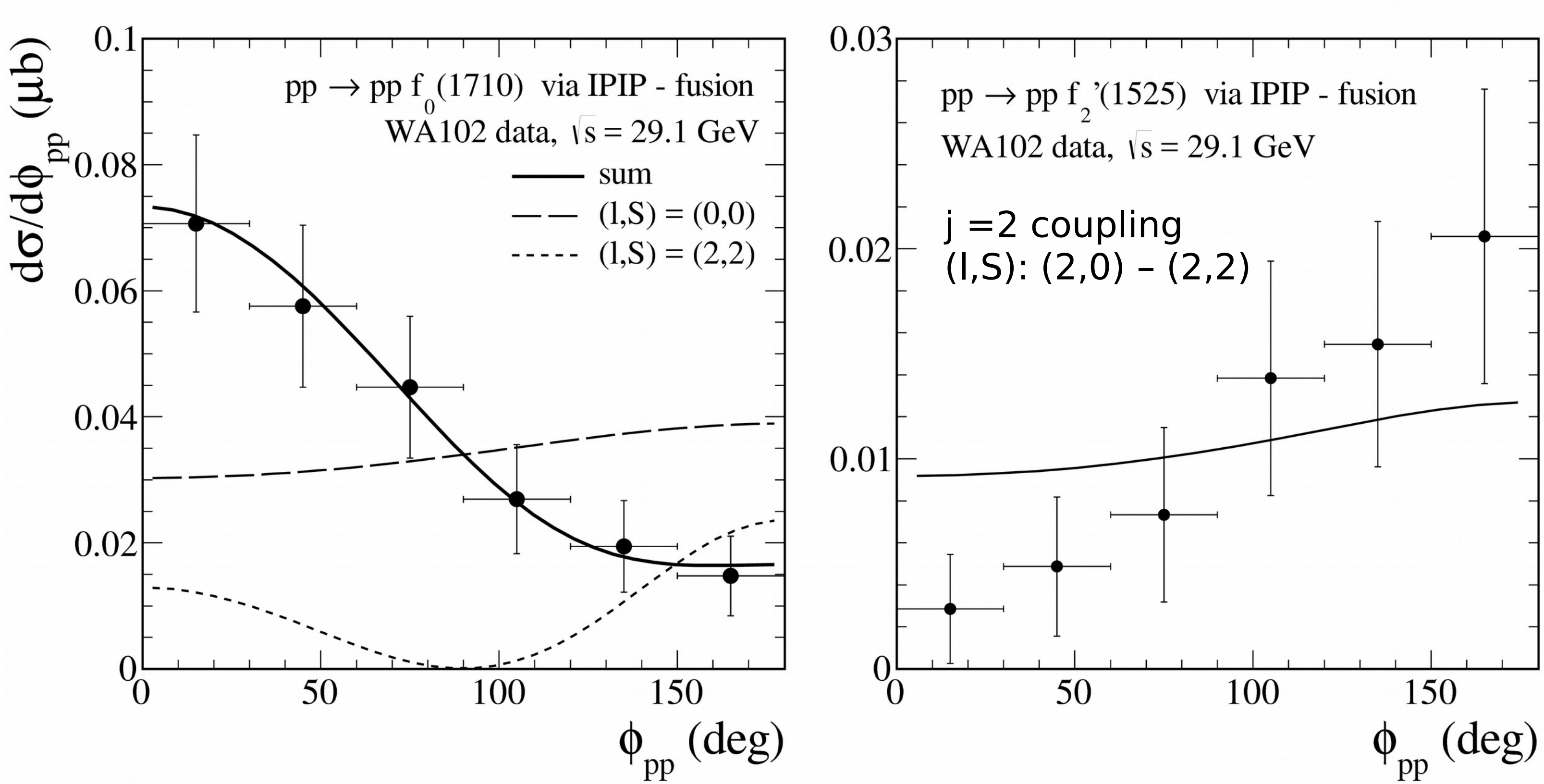
$$p_{34} = q_1 + q_2$$

The choice of IPIPM couplings must be determined from experimental data.

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

where $g_{f_2'K^+K^-} = 7.32$ was obtained from the corresponding partial decay width

We assume that $F^{(f_2'KK)}(p_{34}^2) = F^{(I\!PI\!Pf_2')}(p_{34}^2) = \exp\left(\frac{-(p_{34}^2 - m_{f_2'}^2)^2}{\Lambda_{f_2}^4} \right),\quad \Lambda_{f_2} = 1$ GeV.



Our results and WA102 data have been normalized to the mean value of the total cross section given by A. Kirk, Phys. Lett. B489 (2000) 29

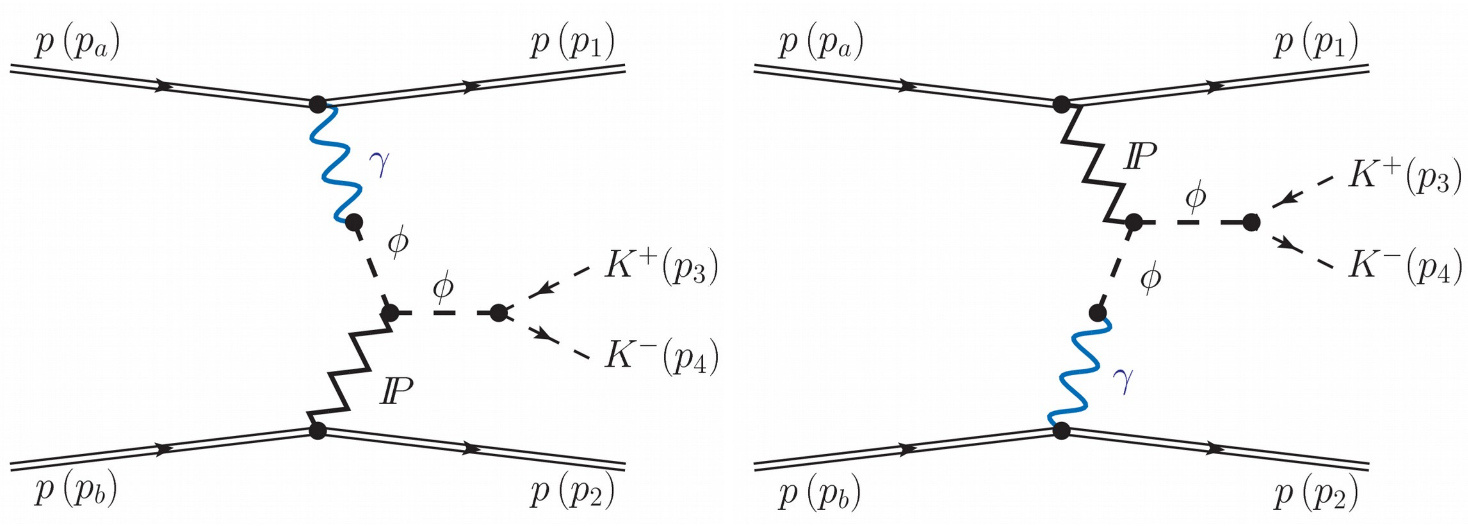
- There is an important qualitative difference in the ϕ_{pp} distribution:
  $f_0(1370)$, $f_2(1270)$ and $f'_2(1525)$ peak as $\phi_{pp} \to \pi$
  $f_0(980)$, $f_0(1500)$, $f_0(1710)$ peak at $\phi_{pp} \to 0$

- The WA102 Collaboration observed that the undisputed $q\bar{q}$ states *(i.e.* η, η', $f_1(1285)$, $f_2(1270)$, $f'_2(1525)$) are suppressed when $dP_t \to 0$, whereas the glueball candidates ($f_0(1500)$, $f_0(1710)$) survive

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

"glueball filter variable" F. Close

Diffractive $\phi(1020)$ photoproduction mechanism



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

$$i\Gamma^{(I\!P\phi\phi)}_{\rho_2\rho_1\alpha\beta}(k',k) = iF_M\left((k'-k)^2\right)\left[2a_{I\!P\phi\phi}\,\Gamma^{(0)}_{\mu\nu\kappa\lambda}(k',-k) - b_{I\!P\phi\phi}\,\Gamma^{(2)}_{\mu\nu\kappa\lambda}(k',-k)\right]$$

tensorial functions: C.Ewerz, M.Maniatis and O.Nachtmann, Annals Phys. 342 (2014) 31

Photoproduction of $\phi(1020)$ meson

$$\mathcal{M}_{\gamma p \to \phi p}(s,t) \cong ie\frac{m_\phi^2}{\gamma_\phi}\,\Delta_T^{(\phi)}(0)\,(\epsilon^{(\phi)\,\mu})^*\epsilon^{(\gamma)\,\nu}\left[2a_{I\!P\phi\phi}\,\Gamma^{(0)}_{\mu\nu\kappa\lambda}(p_\phi,-q) - b_{I\!P\phi\phi}\,\Gamma^{(2)}_{\mu\nu\kappa\lambda}(p_\phi,-q)\right]$$
$$\times 3\beta_{I\!PNN}\,\frac{1}{2s}(-is\alpha'_{I\!P})^{\alpha_{I\!P}(t)-1}\,(p_2+p_b)^\kappa(p_2+p_b)^\lambda\,\delta_{\lambda_2\lambda_b}F_1(t)F_M(t)$$

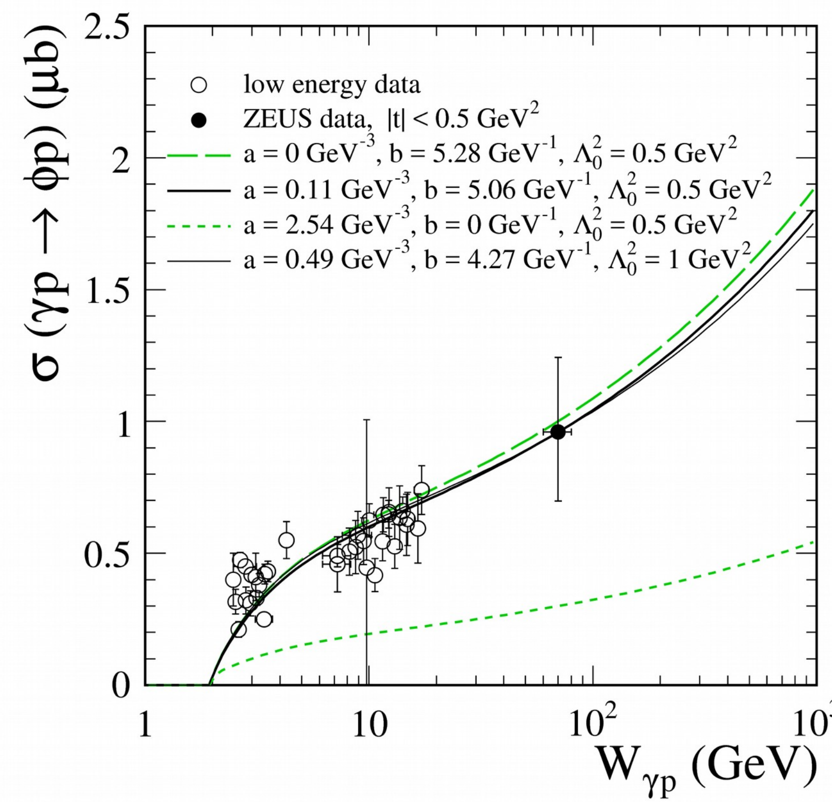
$$F_M(t) = \frac{1}{1-t/\Lambda_0^2}$$

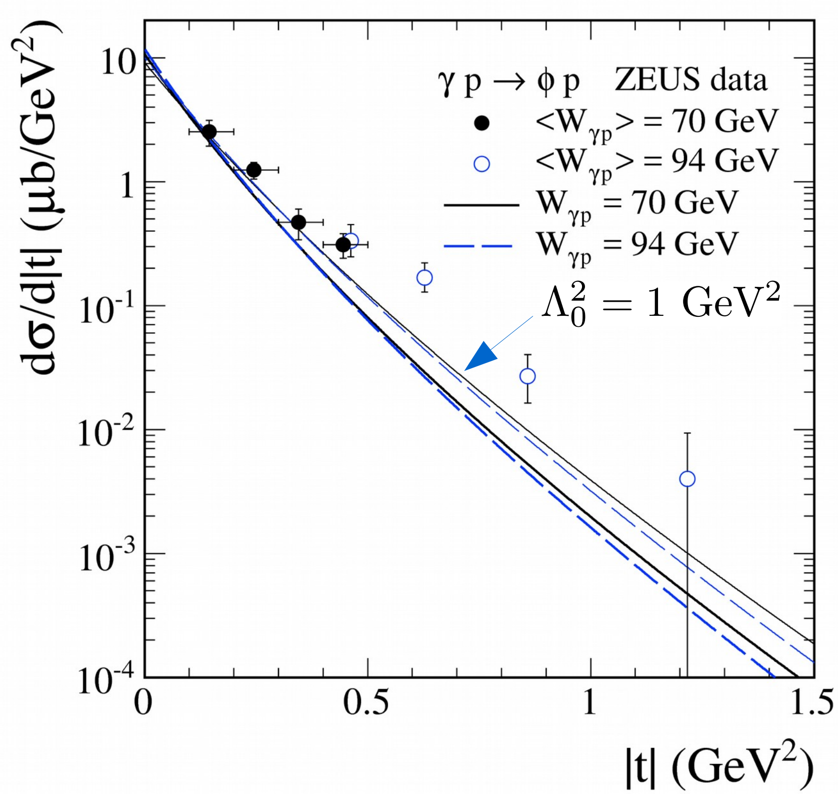
Assumption (based on the additive quark model)

$$\sigma_{tot}(\phi(\epsilon^{(m)}),p) = \sigma_{tot}(K^+,p) + \sigma_{tot}(K^-,p) - \sigma_{tot}(\pi^-,p)$$

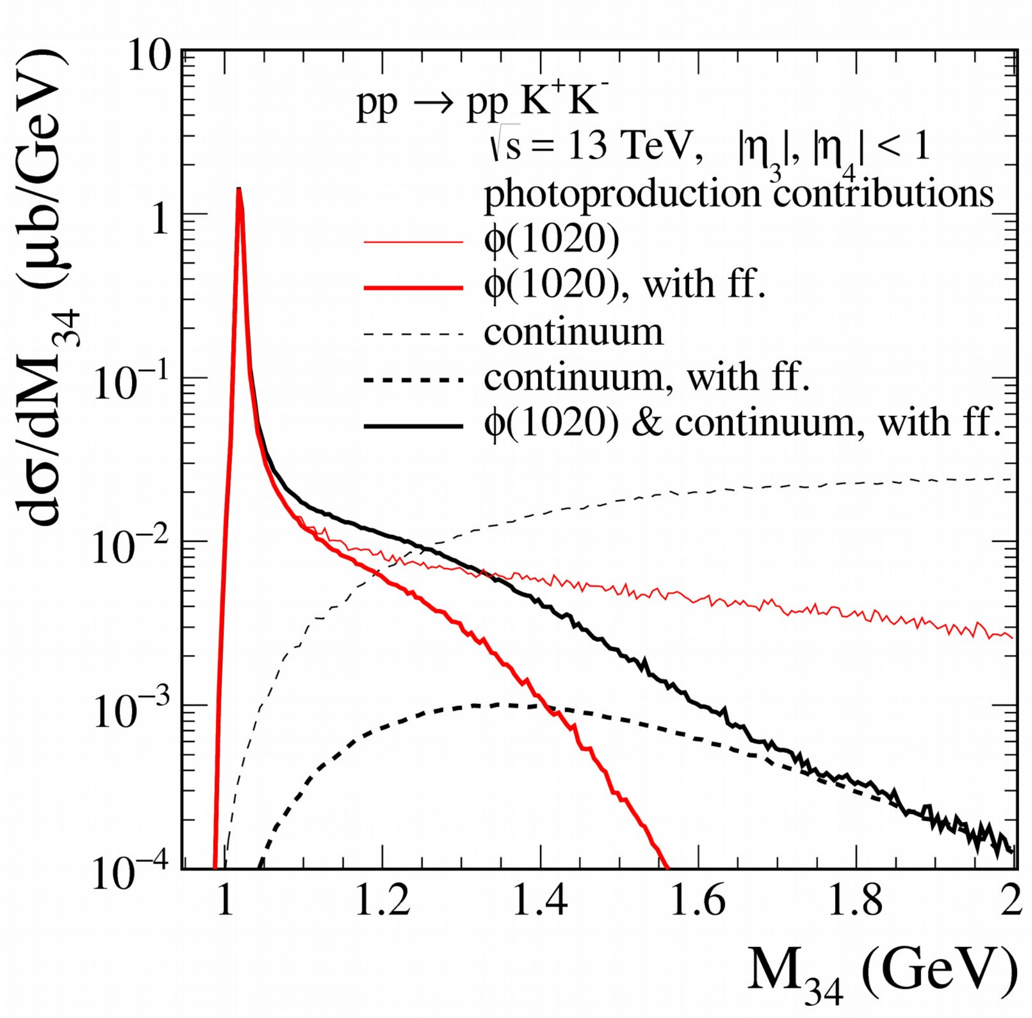
for transversely polarised ϕ mesons (m = ±1)

We get $2m_\phi^2\,a_{I\!P\phi\phi} + b_{I\!P\phi\phi} = 4(2\beta_{I\!PKK} - \beta_{I\!P\pi\pi}) = 5.28\,\mathrm{GeV}^{-1}$



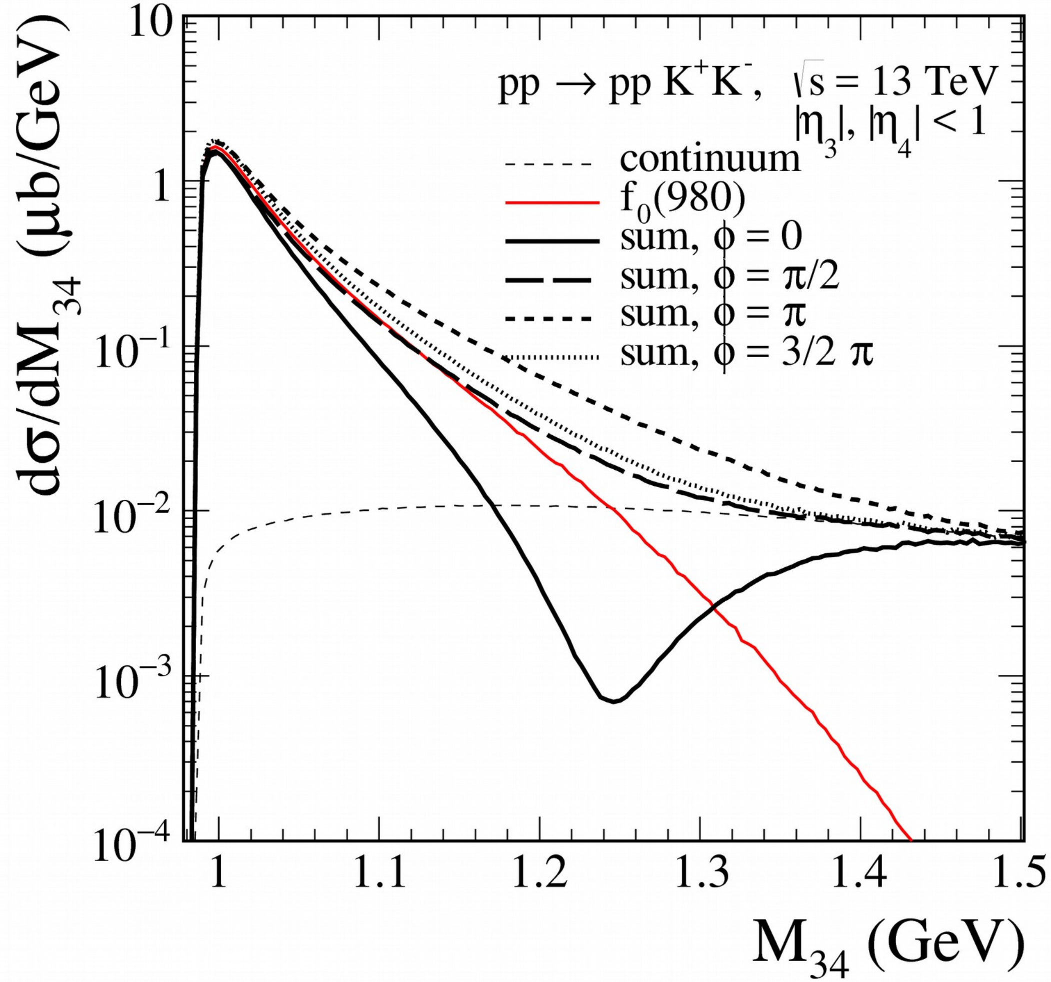


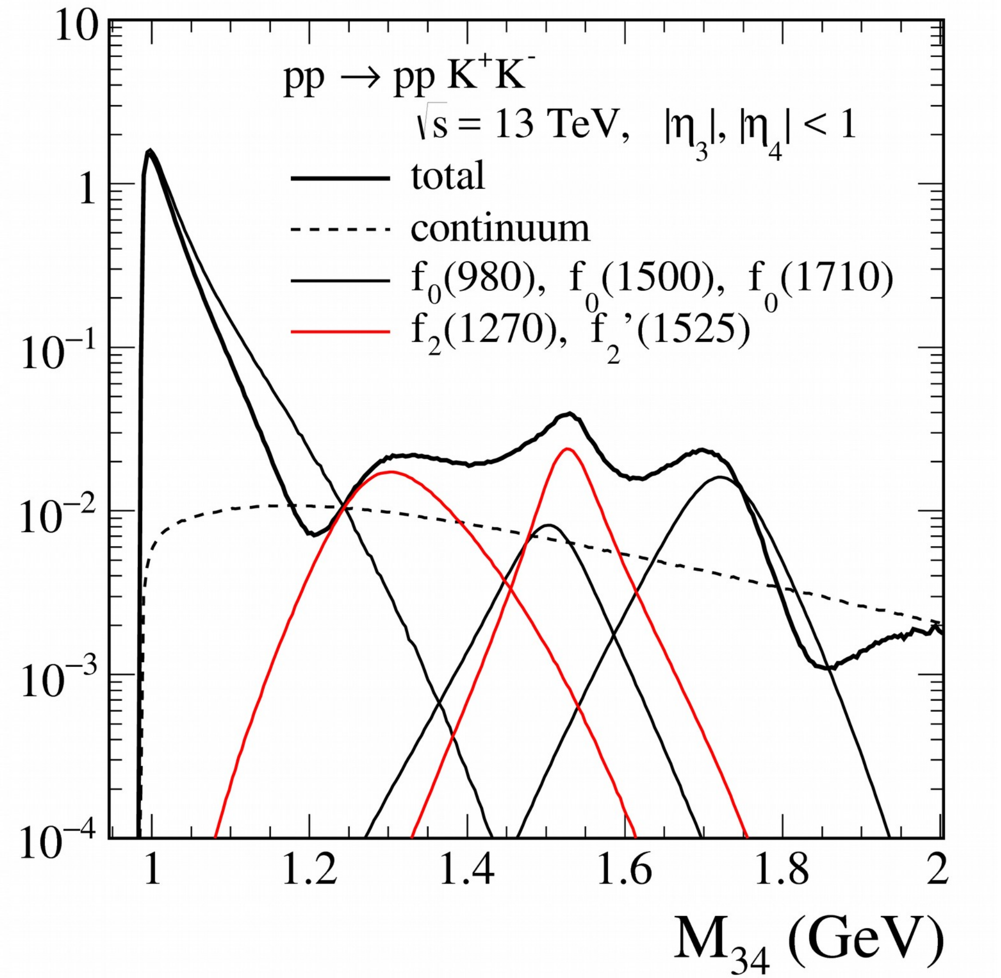
$pp \to pp\, K^+K^-$ (photoproduction mechanism)



Results for photon induced continuum (Drell-Söding mechanism) and ϕ photoproduction without and with off-shell ϕ meson form factor included in the amplitudes

$pp \to pp\, K^+K^-$ (purely diffractive mechanism)





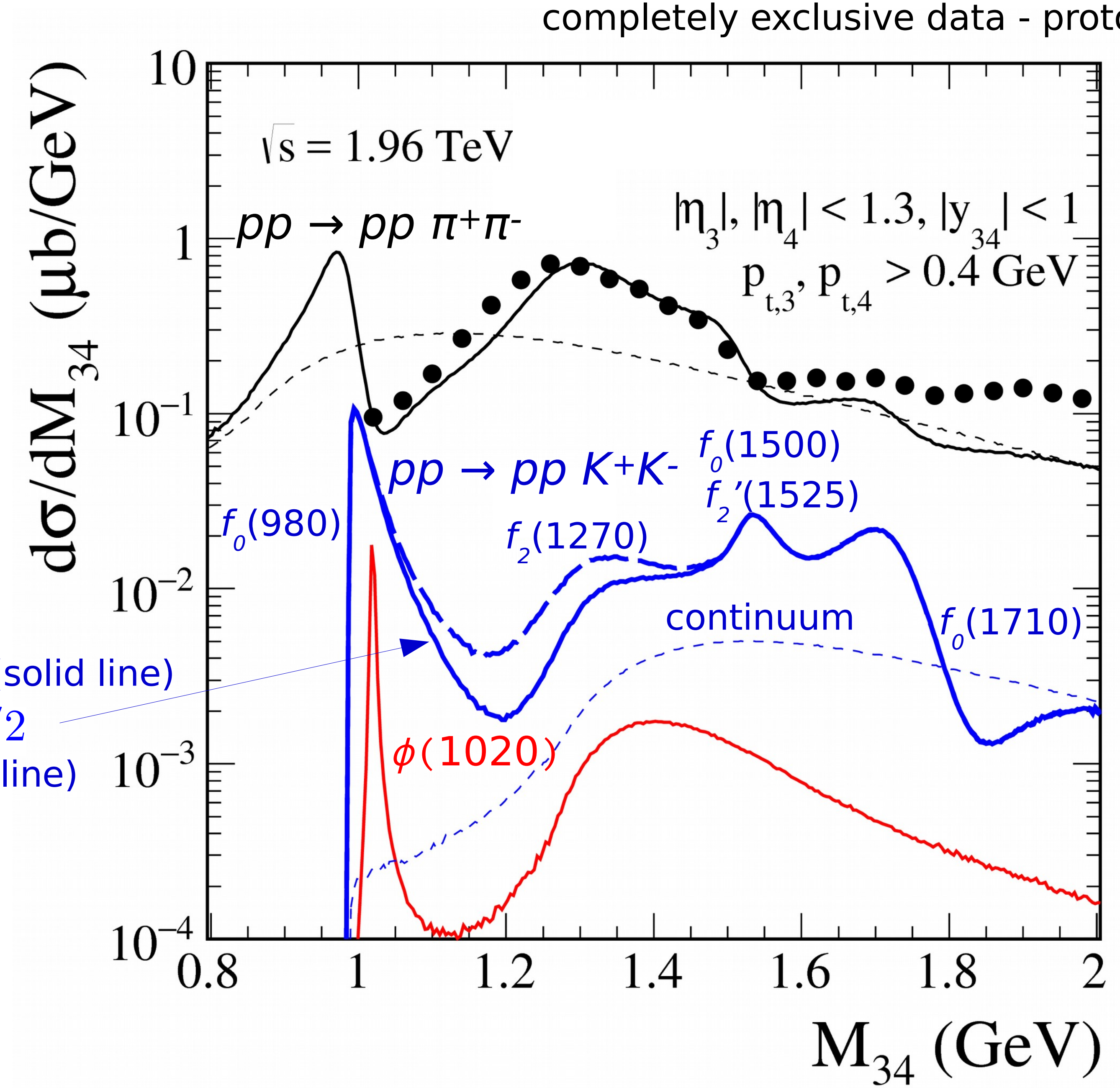
- Results for different values of the relative phase $\phi_{f0(980)}$ in the coupling constant

$$g_{f_0(980)K^+K^-} \to g_{f_0(980)K^+K^-}\, e^{i\phi_{f_0(980)}}$$

- Large interference effect of the continuum and the f_0(980) terms

- Many resonances may participate

CDF data from
T. A. Aaltonen et al., PRD 91 (2015) 091101 (not completely exclusive data - protons not measured)



Absorption effects included

$< S^2 >= 0.1$

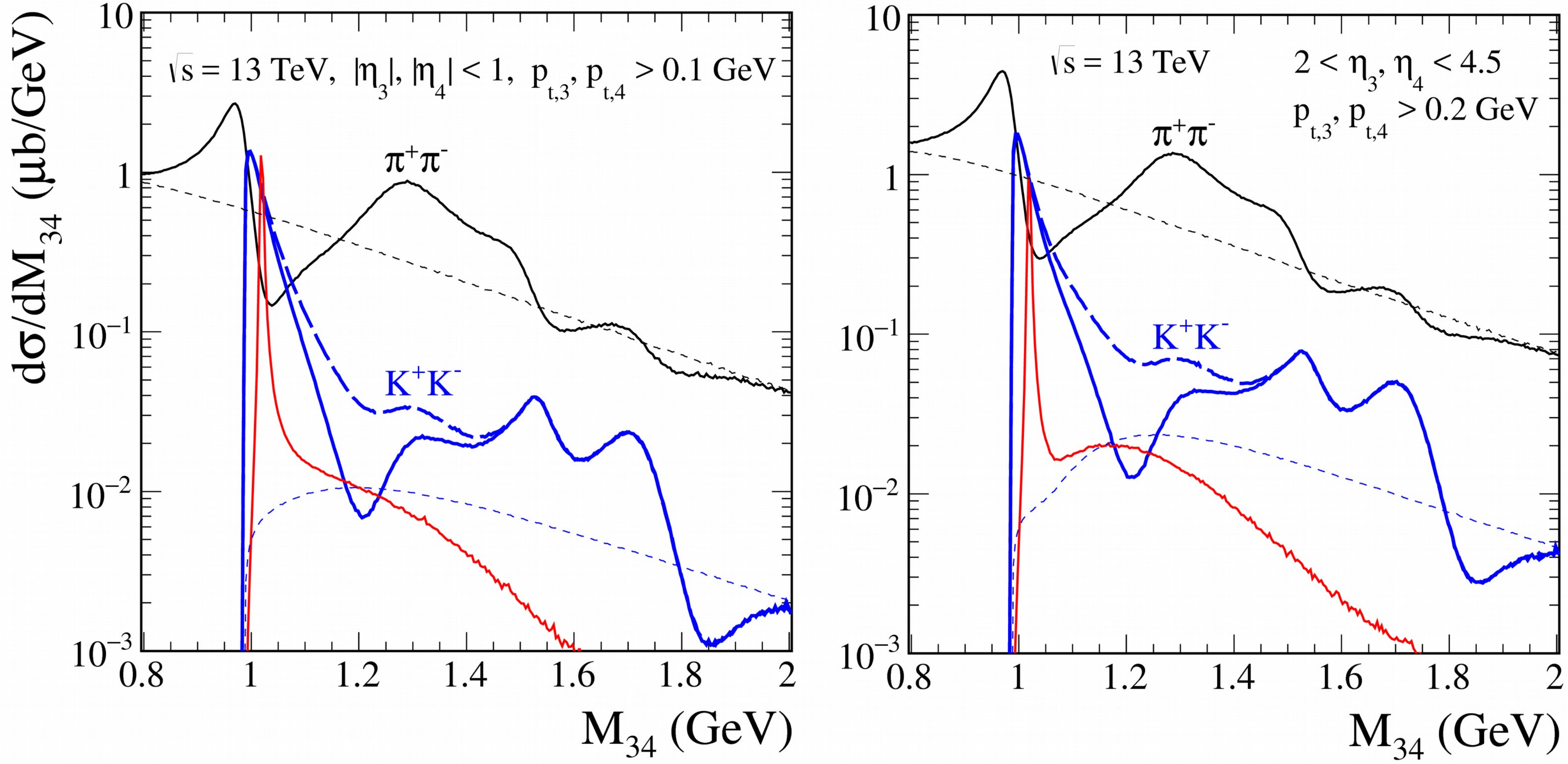
$< S^2 >= 0.1$

$< S^2 >= 0.9$

Results for
$\phi_{f_0(980)} = 0$ (solid line)
$\phi_{f_0(980)} = \pi/2$ (dashed line)

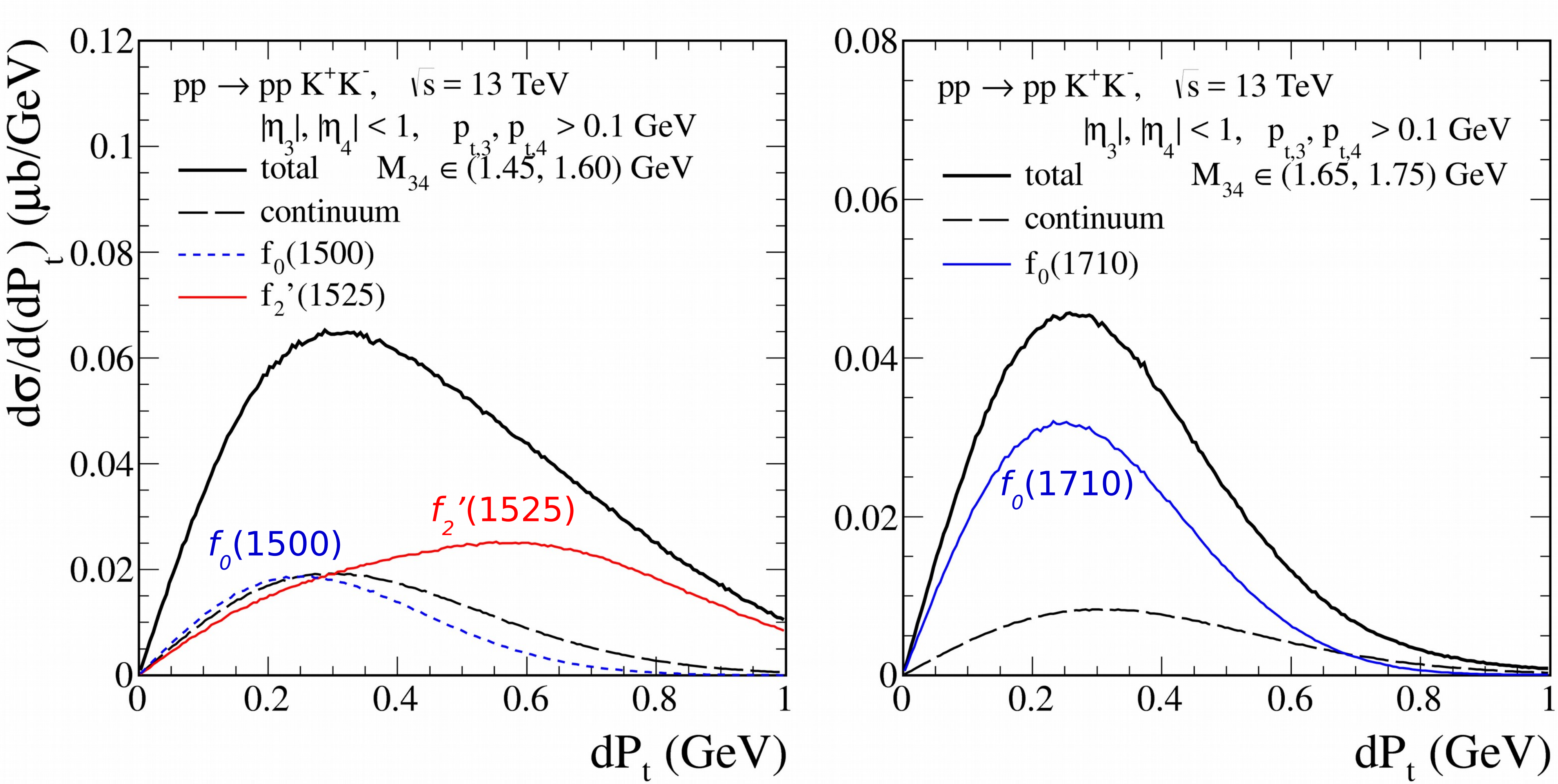
Limited CDF acceptance, in particular p_t > 0.4 GeV condition, causes a suppression of cross section in low-mass region.

$pp \to pp\, K^+K^-$ vs $pp \to pp\, \pi^+\pi^-$



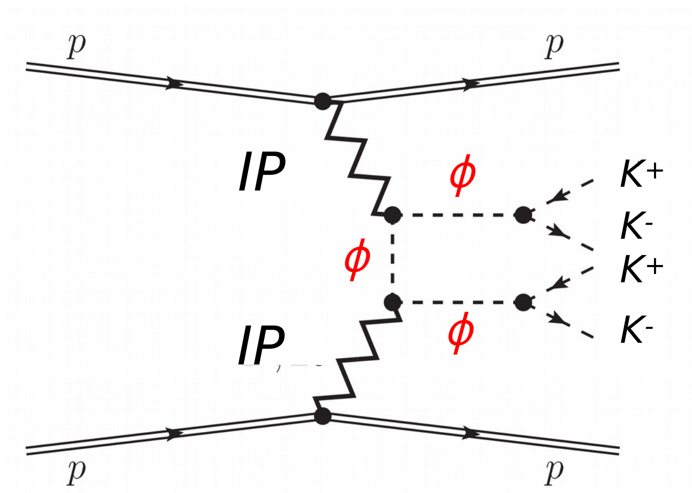
We expect that one could observe the $\phi(1020)$ resonance term, especially when no restrictions on the leading protons are included (ALICE, CMS, LHCb)

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



- dP_t "glueball filter variable" distributions in two K^+K^- invariant mass windows
- We see that the maximum for the $q\bar{q}$ state $f'_2(1525)$ is around of $dP_t = 0.6$ GeV while for the scalar glueball candidates $f_0(1500)$ & $f_0(1710)$ is about 0.25 GeV

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



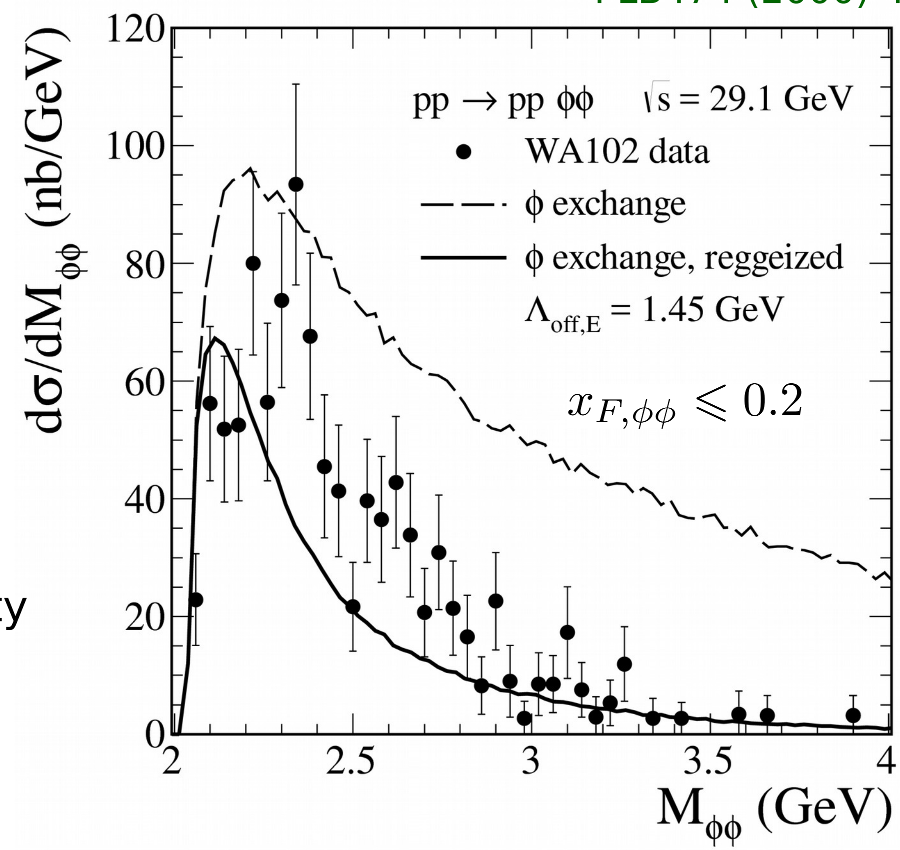
$\phi\phi$ system has $I^G = 0^+$ and C=+1

- reggeization effect

$$\Delta^{(\phi)}_{\mu\nu}(\hat{k}) \to \Delta^{(\phi)}_{\mu\nu}(\hat{k}) \left(\frac{s_{34}}{4m_\phi^2}\right)^{\alpha_{I\!R}(\hat{k}^2)-1}$$

becomes crucial when the separation in rapidity between two ϕ mesons increases $|Y_3 - Y_4| > 0$

WA102 data: D. Barberis *et al.*, PLB432 (1998) 436
PLB474 (2000) 423

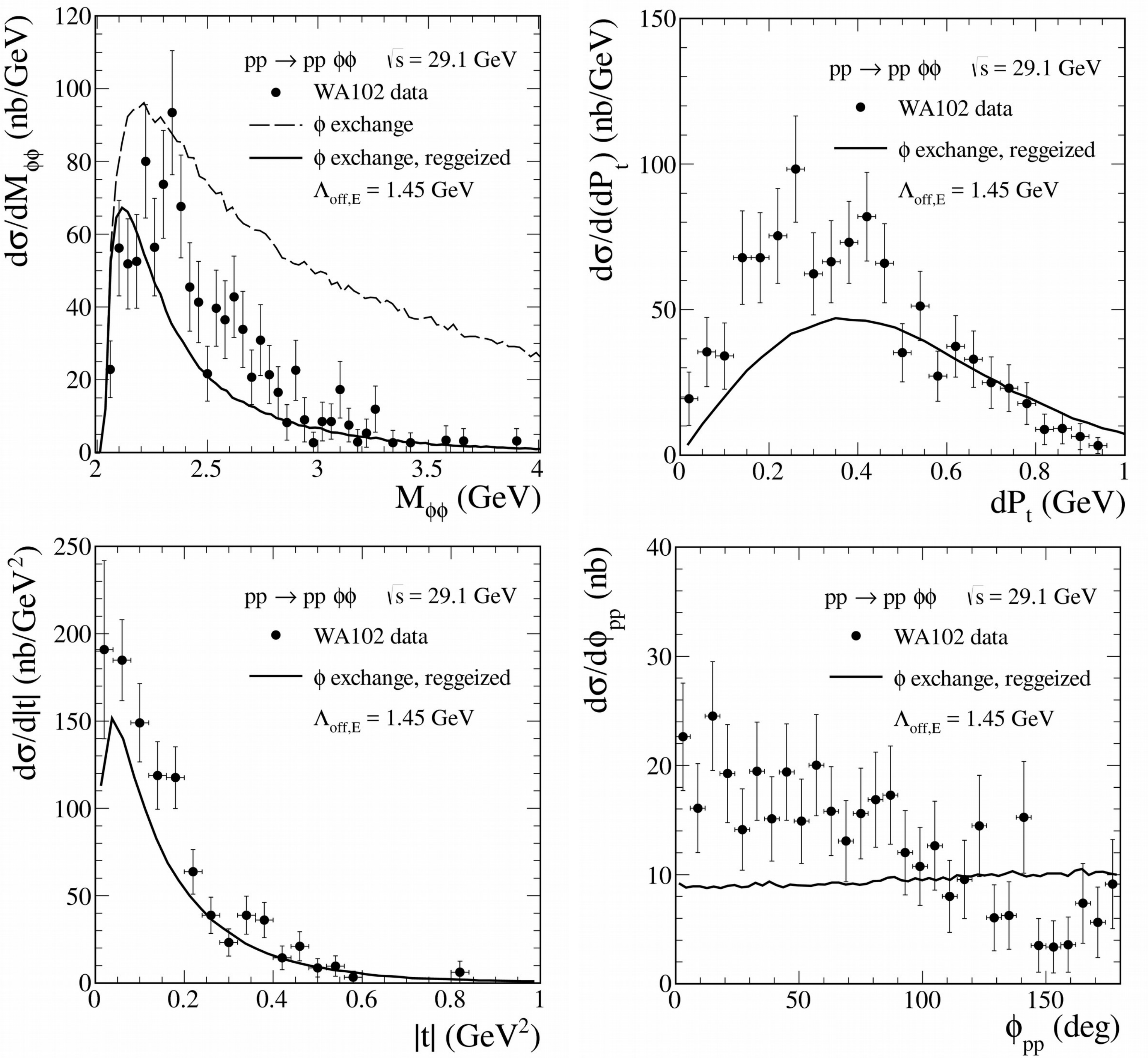


$$\sigma_{2\to6} = [BR(\phi \to K^+K^-)]^2 \int_{2m_K}^{\max\{m_{X_3}\}} \int_{2m_K}^{\max\{m_{X_4}\}} \sigma_{2\to4}(\ldots, m_{X_3}, m_{X_4})\, f_M(m_{X_3})\, f_M(m_{X_4})\, dm_{X_3}\, dm_{X_4}$$

with the spectral functions of meson $f_M(m_{X_i}) = A_N \left(1 - \frac{4m_K^2}{m_{X_i}^2}\right)^{3/2} \frac{\frac{2}{\pi} m_\phi^2 \Gamma_{\phi,tot}}{(m_{X_i}^2 - m_\phi^2)^2 + m_\phi^2 \Gamma_{\phi,tot}^2}$

The WA102 data points have been normalized to $\sigma_{exp} = 41$ nb from PLB432 (1998) 436

$x_{F,\phi\phi} \leqslant 0.2$

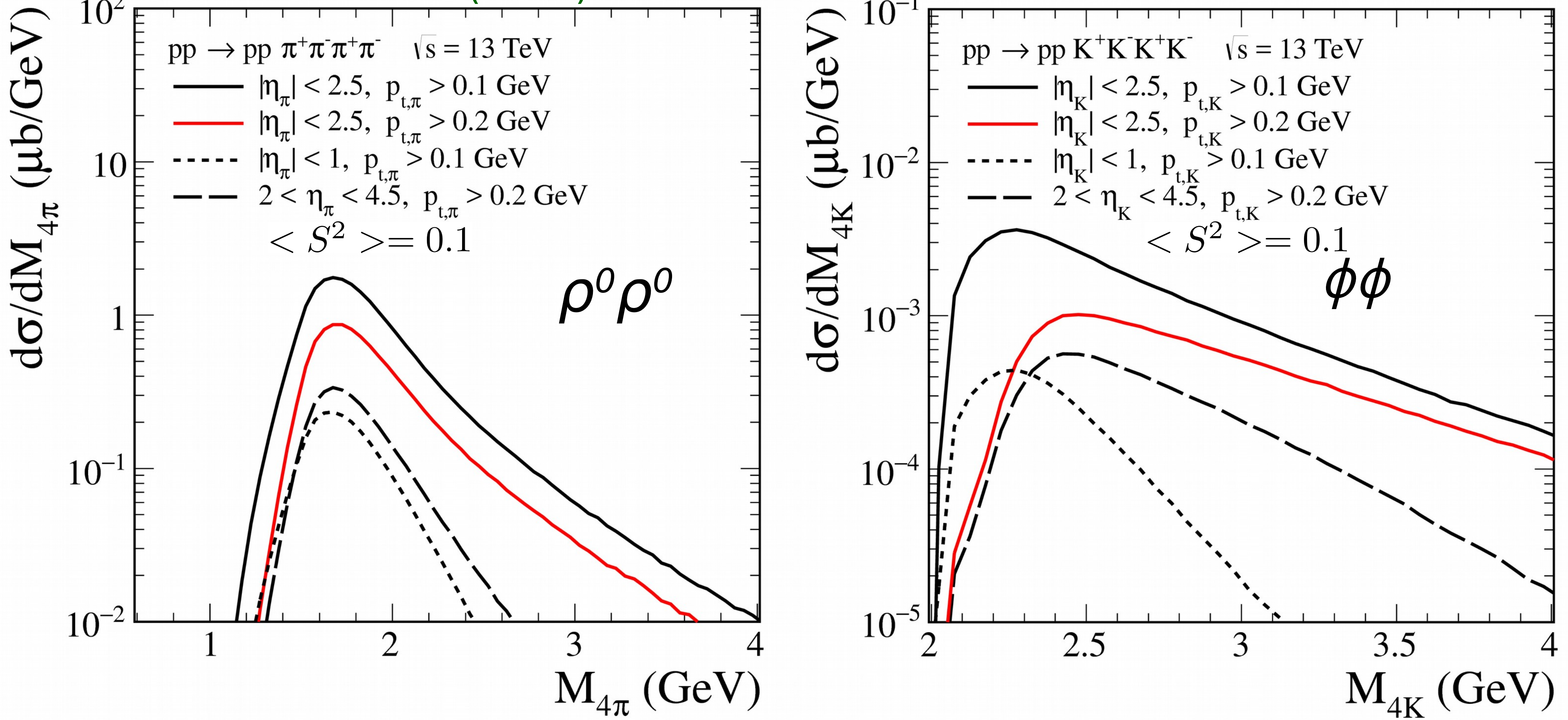


WA102 data: D. Barberis *et al.*, PLB432 (1998) 436

see also D. Barberis *et al.*, PLB474 (2000) 423

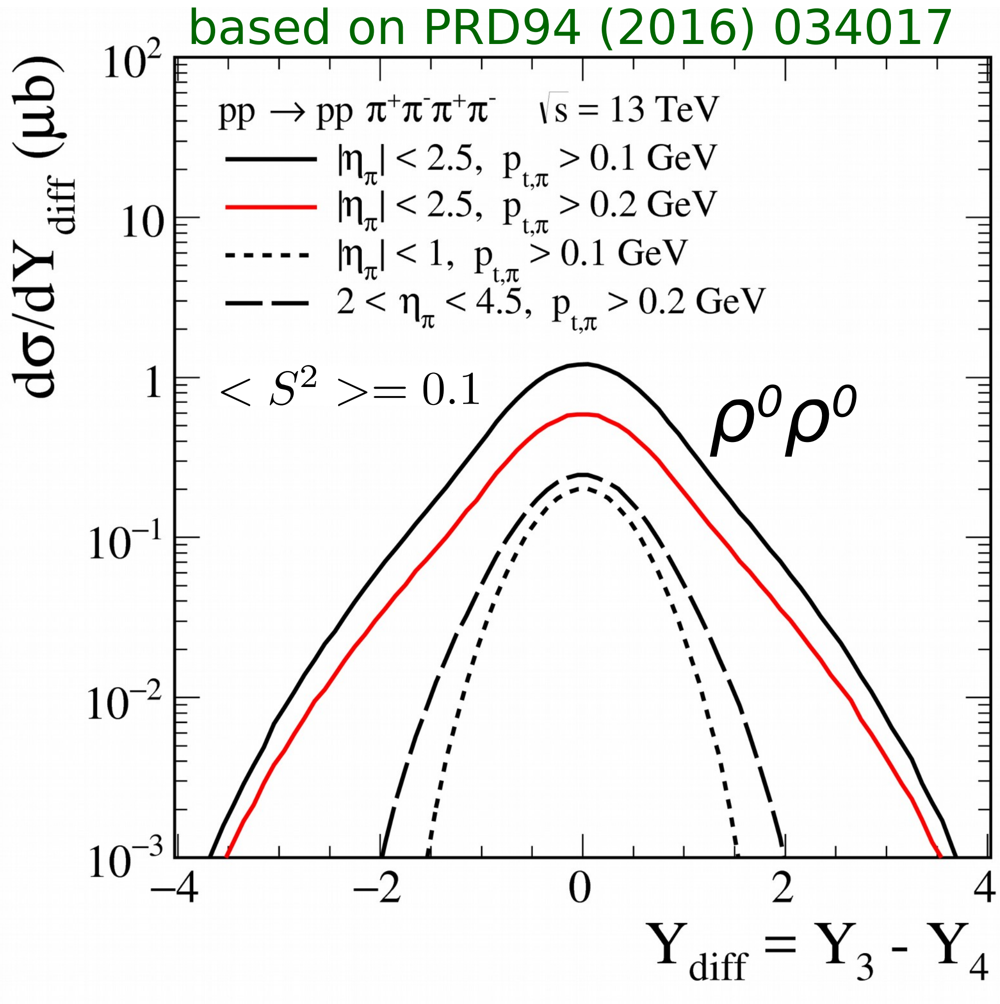
$\rho^0\rho^0$ contribution vs $\phi\phi$ contribution

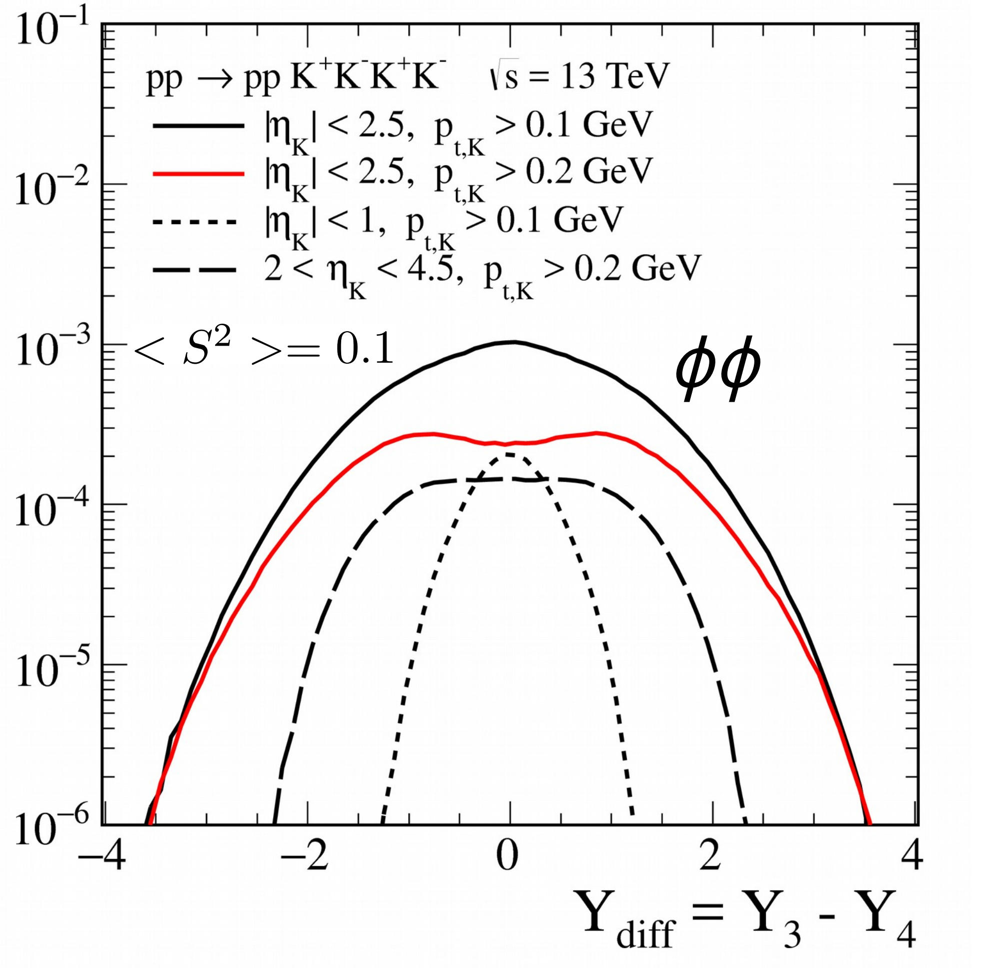
based on PRD94 (2016) 034017



- $\phi\phi$ offers a favourable channel in which to search for the decay of glueballs (lattice calculations predict for the tensor glueball a mass of about 2.3 GeV)
- Any experimentally observed distortions from our predictions may therefore signal a presence of resonances

$\rho^0\rho^0$ contribution vs $\phi\phi$ contribution





Y_3 means $Y_{K^+K^-}$ where the kaons are produced from a ϕ meson decay

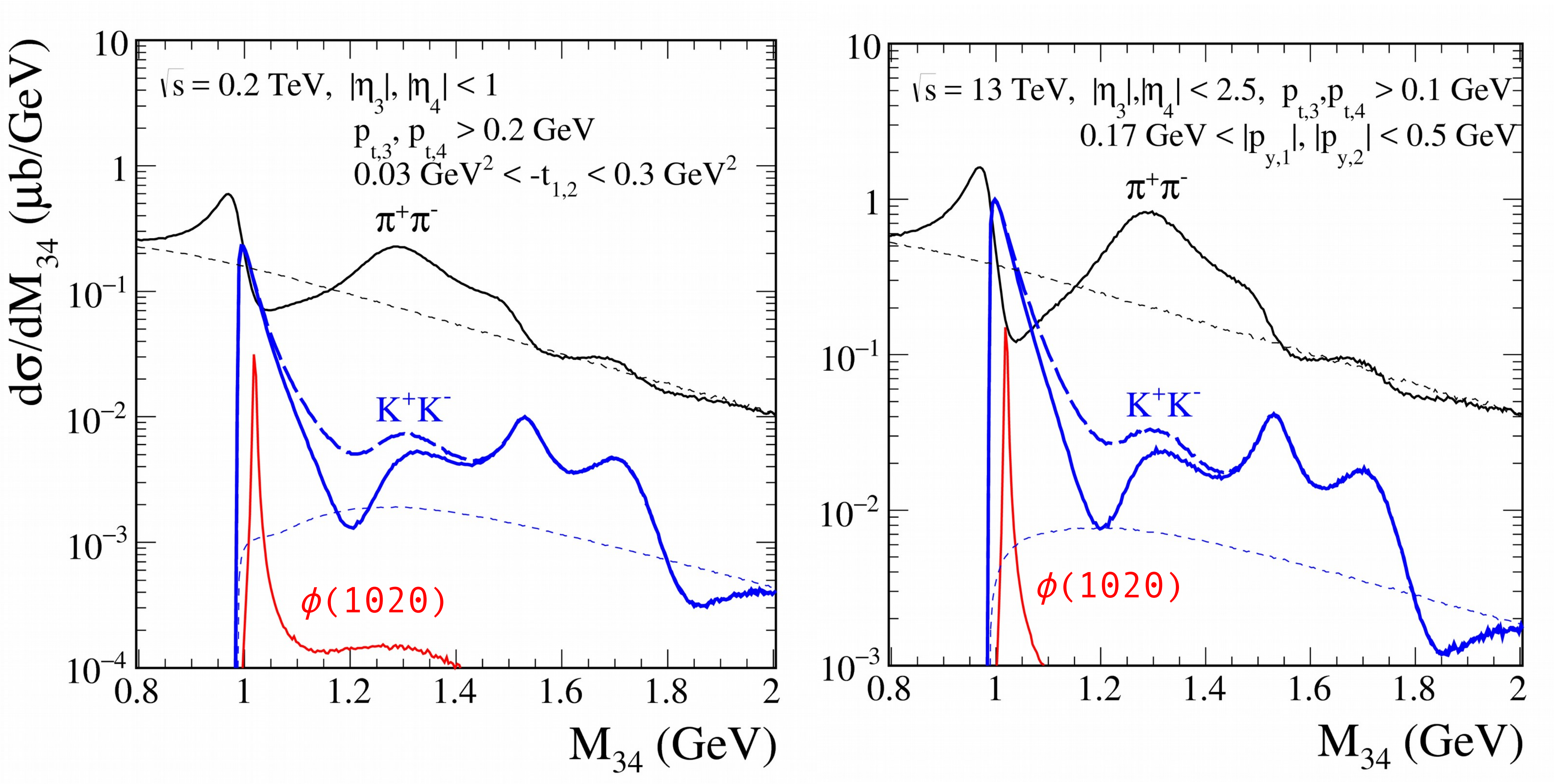
Conclusions

- We have given a consistence treatment of central exclusive K^+K^- continuum and resonance production in *pp* collisions within tensor-pomeron approach
- All amplitudes are formulated in terms of effective vertices and propagators respecting the standard crossing and charge conjugation relations of QFT
- The K^+K^- invariant mass has a rich structure which strongly depends on kinematical cuts (continuum, resonances, interference)
- First results for the $pp \to pp\, K^+K^-K^+K^-$ reaction via $\phi\phi$ intermediate states $\to$ favourable channel in which to search for the decay of glueballs
- Exclusive data expected from LHCb, ALICE, CMS+TOTEM, ATLAS+ALFA, and STAR experiments should provide further information

Thank you for your attention!

Backup

$pp \to pp\, K^+K^-$ vs $pp \to pp\, \pi^+\pi^-$



IP IP M couplings

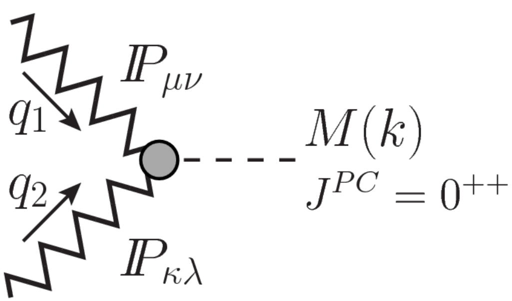
P. L., O. Nachtmann, A. Szczurek,
Annals Phys. 344 (2014) 301;
Phys. Rev. D93 (2016) 054015

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

l	S	$\lvert l-S\rvert \leqslant J \leqslant l+S$	$P=(-1)^l$
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	

In table we list the values of *J* and *P* of mesons which can be produced in annihilation of two “real tensor pomerons”. For each value of *l, S, J*, and *P* we can construct a covariant Lagrangian density coupling *L*' the field operator for the meson *M* to the pomeron fields and then we can obtain the “bare” vertices corresponding to the *l* and *S.*

The lowest (*l*,*S*) term for a scalar meson $J^{PC} = 0^{++}$ is (0,0) while for a tensor meson $J^{PC} = 2^{++}$ is (0,2).



For a scalar mesons the “bare” tensorial *IP-IP-M* vertices corresponding to (*l*,*S*) = (0,0) and (2,2) terms are

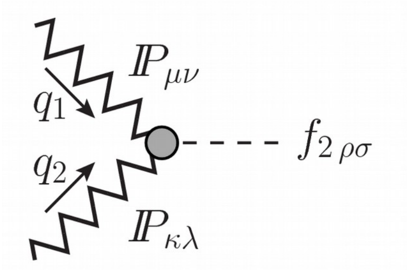
$$i\Gamma'^{(\mathbb{P}\mathbb{P}\to M)}_{\mu\nu,\kappa\lambda} = i\, g'_{\mathbb{P}\mathbb{P}M}\, M_0 \left(g_{\mu\kappa} g_{\nu\lambda} + g_{\mu\lambda} g_{\nu\kappa} - \frac{1}{2} g_{\mu\nu} g_{\kappa\lambda} \right)$$

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

The choice of IPIPM couplings must be determined from experimental data.

IP-IP-f₂ couplings

In order to write the corresponding formulae of vertices in a compact and convenient form we find it useful to define the tensor $R_{\mu\nu\kappa\lambda} = \frac{1}{2} g_{\mu\kappa} g_{\nu\lambda} + \frac{1}{2} g_{\mu\lambda} g_{\nu\kappa} - \frac{1}{4} g_{\mu\nu} g_{\kappa\lambda}$



$$i\Gamma^{(I\!PI\!Pf_2)(1)}_{\mu\nu,\kappa\lambda,\rho\sigma} = 2i\, g^{(1)}_{I\!PI\!Pf_2} M_0\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1}\, R_{\rho\sigma\rho_1\sigma_1}\, g^{\nu_1\alpha_1}\, g^{\lambda_1\rho_1}\, g^{\sigma_1\mu_1}$$

$$i\Gamma^{(I\!PI\!Pf_2)(2)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{2i}{M_0}\, g^{(2)}_{I\!PI\!Pf_2} \Big((q_1\cdot q_2)\, R_{\mu\nu\rho_1\alpha}\, R_{\kappa\lambda\sigma_1}{}^{\alpha} - q_{1\rho_1}\, q_2^{\mu_1}\, R_{\mu\nu\mu_1\alpha}\, R_{\kappa\lambda\sigma_1}{}^{\alpha} - q_1^{\mu_1}\, q_{2\sigma_1}\, R_{\mu\nu\rho_1\alpha}\, R_{\kappa\lambda\mu_1}{}^{\alpha} + q_{1\rho_1}\, q_{2\sigma_1}\, R_{\mu\nu\kappa\lambda} \Big) R_{\rho\sigma}{}^{\rho_1\sigma_1}$$

$$i\Gamma^{(I\!PI\!Pf_2)(3)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{2i}{M_0}\, g^{(3)}_{I\!PI\!Pf_2} \Big((q_1\cdot q_2)\, R_{\mu\nu\rho_1\alpha}\, R_{\kappa\lambda\sigma_1}{}^{\alpha} + q_{1\rho_1}\, q_2^{\mu_1}\, R_{\mu\nu\mu_1\alpha}\, R_{\kappa\lambda\sigma_1}{}^{\alpha} + q_1^{\mu_1}\, q_{2\sigma_1}\, R_{\mu\nu\rho_1\alpha}\, R_{\kappa\lambda\mu_1}{}^{\alpha} + q_{1\rho_1}\, q_{2\sigma_1}\, R_{\mu\nu\kappa\lambda} \Big) R_{\rho\sigma}{}^{\rho_1\sigma_1}$$

$$i\Gamma^{(I\!PI\!Pf_2)(4)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{i}{M_0}\, g^{(4)}_{I\!PI\!Pf_2} \Big(q_1^{\alpha_1}\, q_2^{\mu_1}\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1} + q_2^{\alpha_1}\, q_1^{\mu_1}\, R_{\mu\nu\alpha_1\lambda_1}\, R_{\kappa\lambda\mu_1\nu_1} \Big) R^{\nu_1\lambda_1}{}_{\rho\sigma}$$

$$i\Gamma^{(I\!PI\!Pf_2)(5)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{2i}{M_0^3}\, g^{(5)}_{I\!PI\!Pf_2} \Big(q_1^{\mu_1}\, q_2^{\nu_1}\, R_{\mu\nu\nu_1\alpha}\, R_{\kappa\lambda\mu_1}{}^{\alpha} + q_1^{\nu_1}\, q_2^{\mu_1}\, R_{\mu\nu\mu_1\alpha}\, R_{\kappa\lambda\nu_1}{}^{\alpha} - 2(q_1\cdot q_2)\, R_{\mu\nu\kappa\lambda} \Big) q_{1\alpha_1}\, q_{2\lambda_1}\, R^{\alpha_1\lambda_1}{}_{\rho\sigma}$$

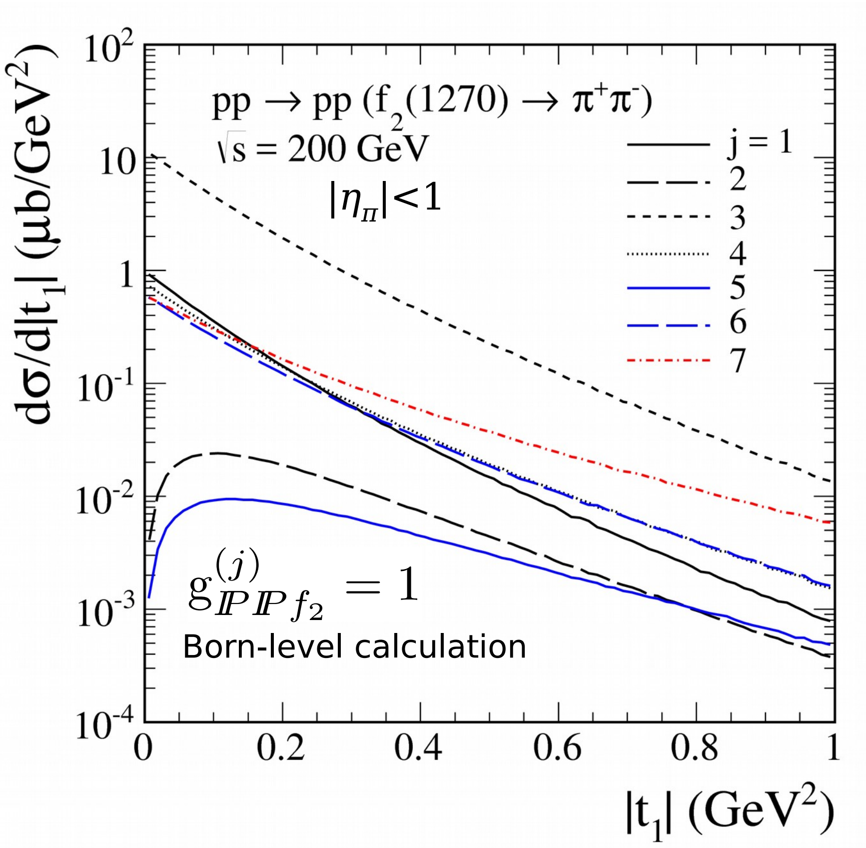
$$i\Gamma^{(I\!PI\!Pf_2)(6)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = \frac{i}{M_0^3}\, g^{(6)}_{I\!PI\!Pf_2} \Big(q_1^{\alpha_1}\, q_1^{\lambda_1}\, q_2^{\mu_1}\, q_{2\rho_1}\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1} + q_2^{\alpha_1}\, q_2^{\lambda_1}\, q_1^{\mu_1}\, q_{1\rho_1}\, R_{\mu\nu\alpha_1\lambda_1}\, R_{\kappa\lambda\mu_1\nu_1} \Big) R^{\nu_1\rho_1}{}_{\rho\sigma}$$

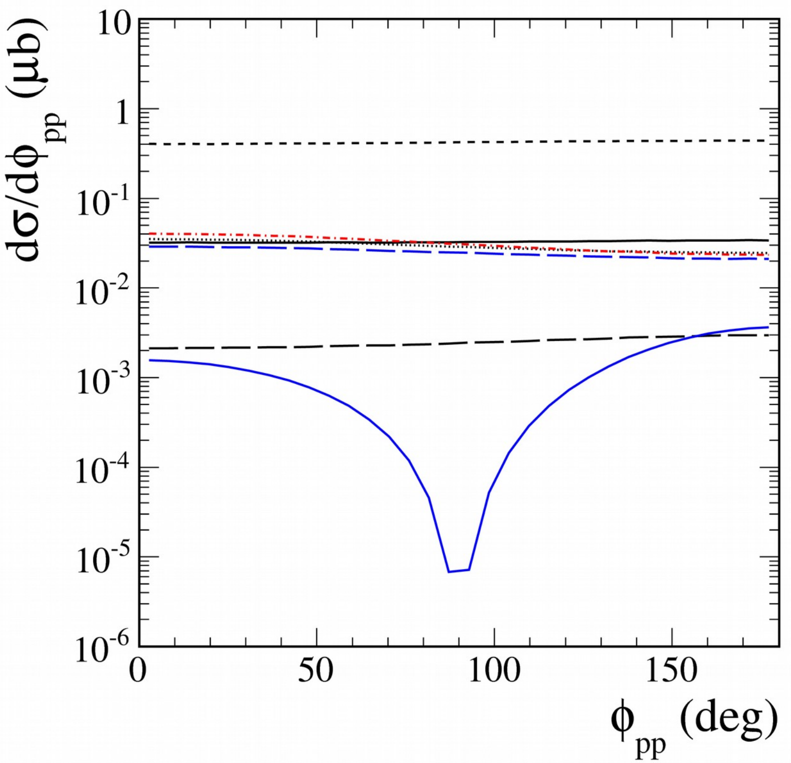
$$i\Gamma^{(I\!PI\!Pf_2)(7)}_{\mu\nu,\kappa\lambda,\rho\sigma}(q_1,q_2) = -\frac{2i}{M_0^5}\, g^{(7)}_{I\!PI\!Pf_2}\, q_1^{\rho_1}\, q_1^{\alpha_1}\, q_1^{\lambda_1}\, q_2^{\sigma_1}\, q_2^{\mu_1}\, q_2^{\nu_1}\, R_{\mu\nu\mu_1\nu_1}\, R_{\kappa\lambda\alpha_1\lambda_1}\, R_{\rho\sigma\rho_1\sigma_1}$$

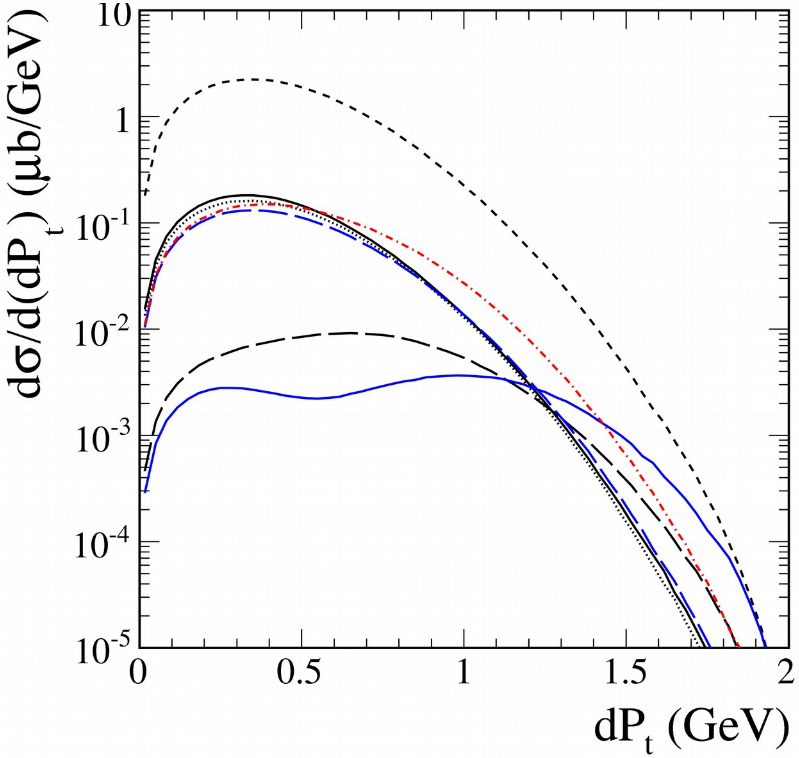
We can associate the couplings j = 1, ..., 7 with (*l*,*S*) values:
(0,2), (2,0) – (2,2), (2,0) + (2,2), (2,4), (4,2), (4,4), (6,4), respectively.

see P. L., O. Nachtmann, A. Szczurek, Phys. Rev. D93 (2016) 054015

f_2(1270) resonance





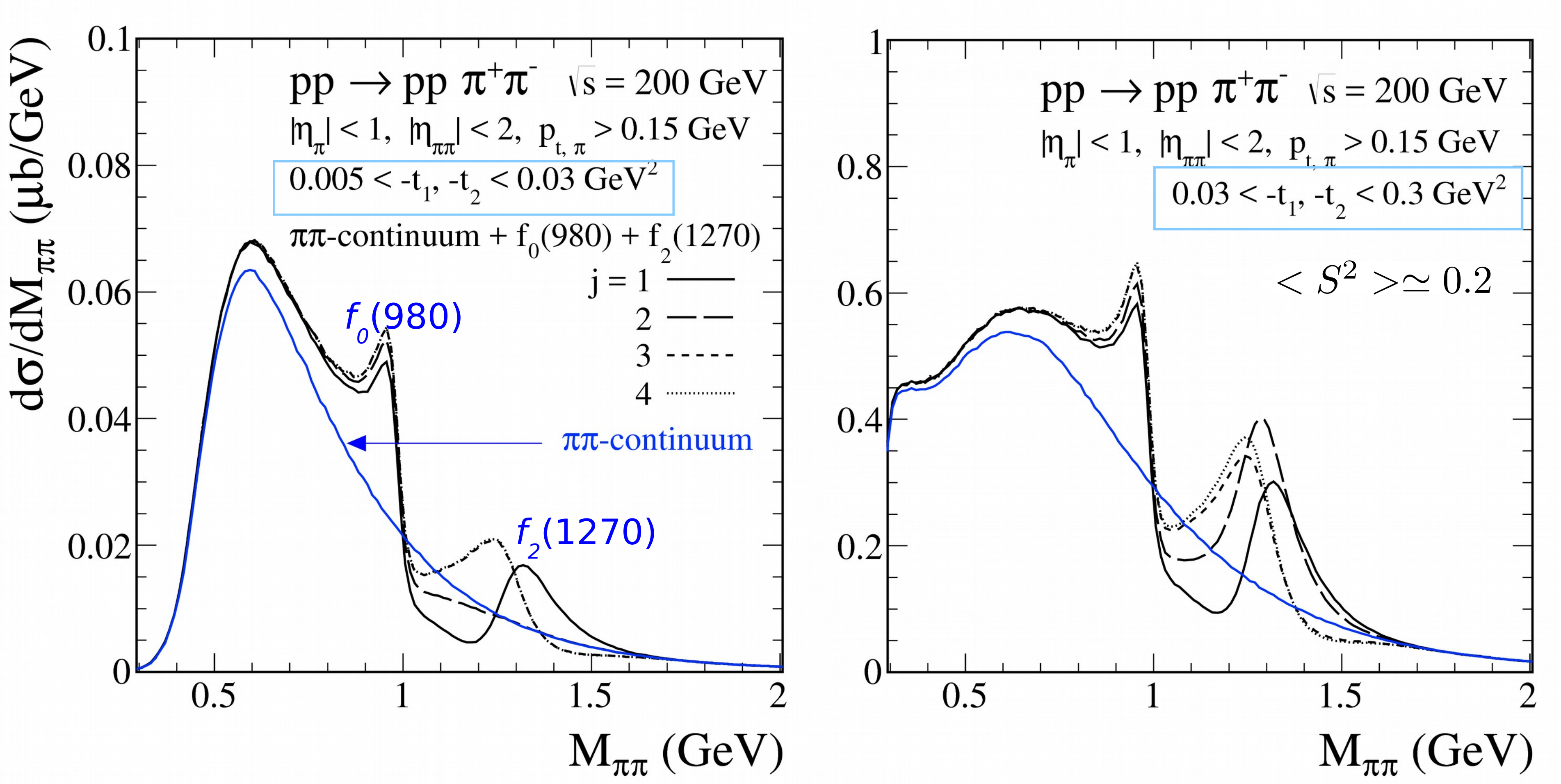


j = 2 coupling is in agreement with experimental observations (WA102, COMPASS, ISR)

→ f_2(1270) peaks at ϕ_{pp}~180° and is most prominently observed at large |t|

→ suppressed as $dP_t \rightarrow 0$ (undisputed $q\bar{q}$ state)

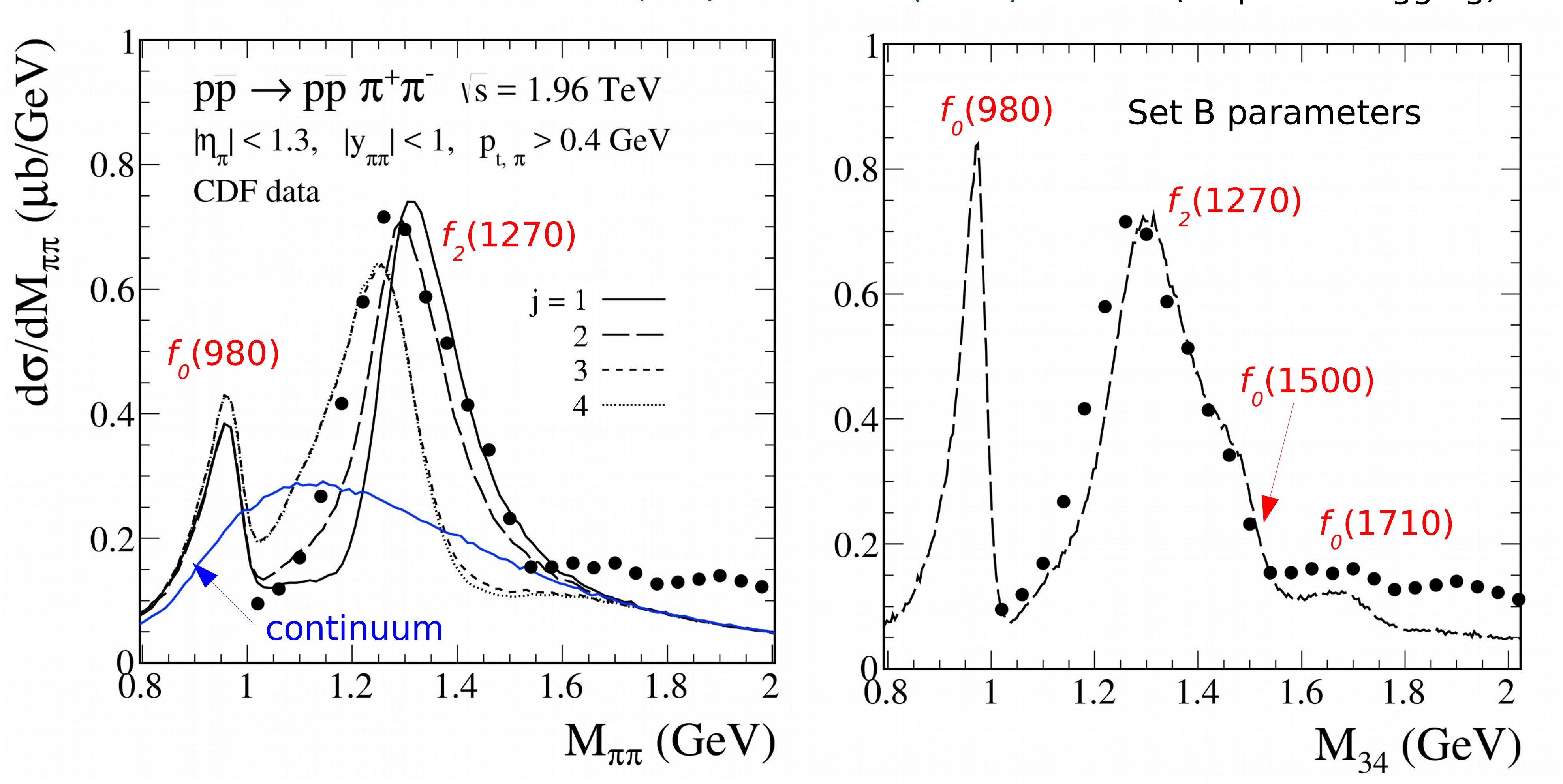
Diffractive mechanism: tensor resonance



- Interesting interference of f_0 (980) and two-pion continuum
- Different *IP IP* f_2 - couplings generate different interference pattern
- The relative contribution of the resonant f_2 (1270) and continuum strongly depends on the cut on $|t|$ → this may explain some observation made by the ISR collaborations

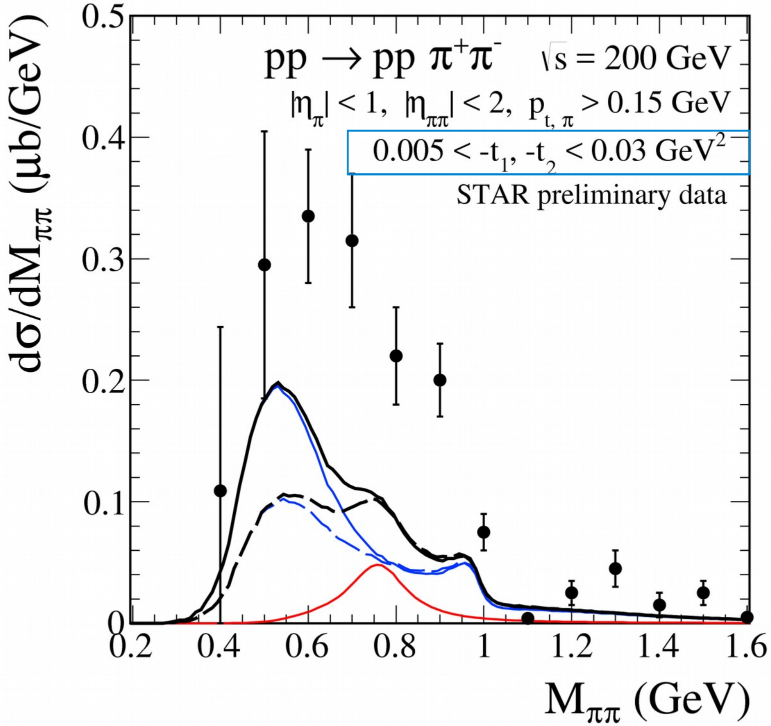
Comparison with CDF data

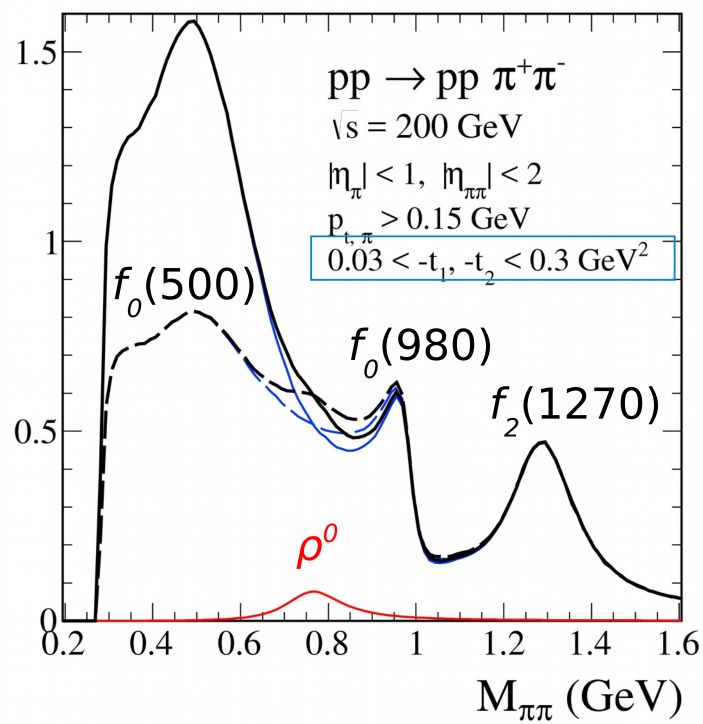
CDF data: T. A. Aaltonen et al., Phys.Rev. D91 (2015) 091101 (no proton tagging)

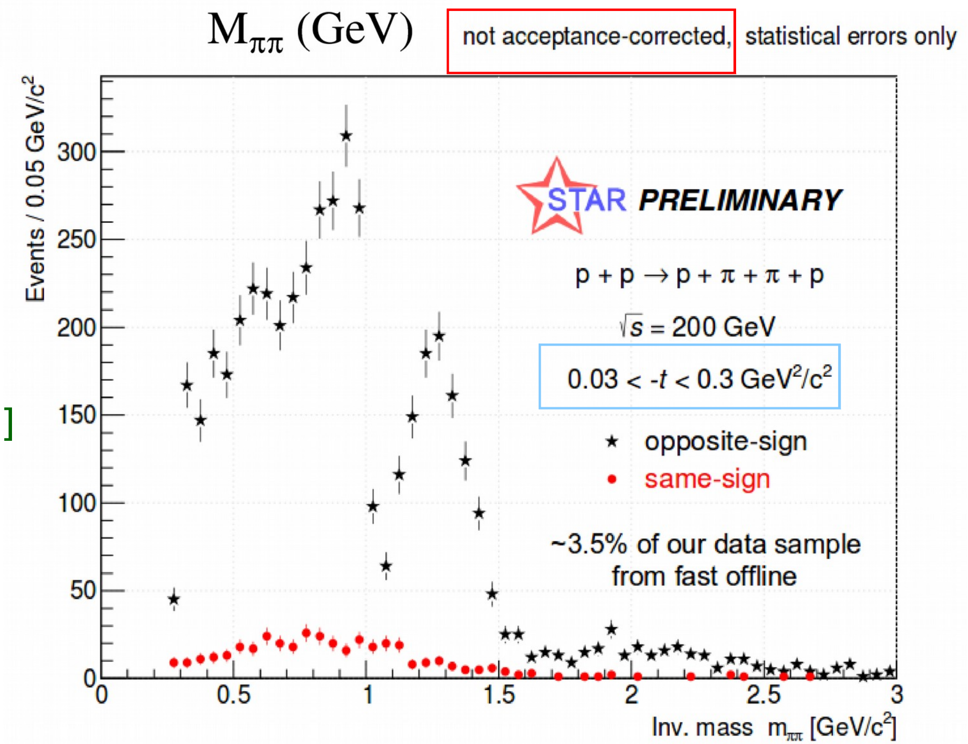


- The visible structure attributed to f_0 and $f_2(1270)$ mesons which interfere with the continuum
- We take the monopole form for off-shell pion form factors with $\Lambda_{off,M}$ = 0.7 GeV.
- Absorption effects were included: $\frac{d\sigma}{dM_{\pi\pi}} = \frac{d\sigma^{Born}}{dM_{\pi\pi}} \times < S^2 >, \qquad < S^2 >= 0.1$

Comparison with STAR preliminary data



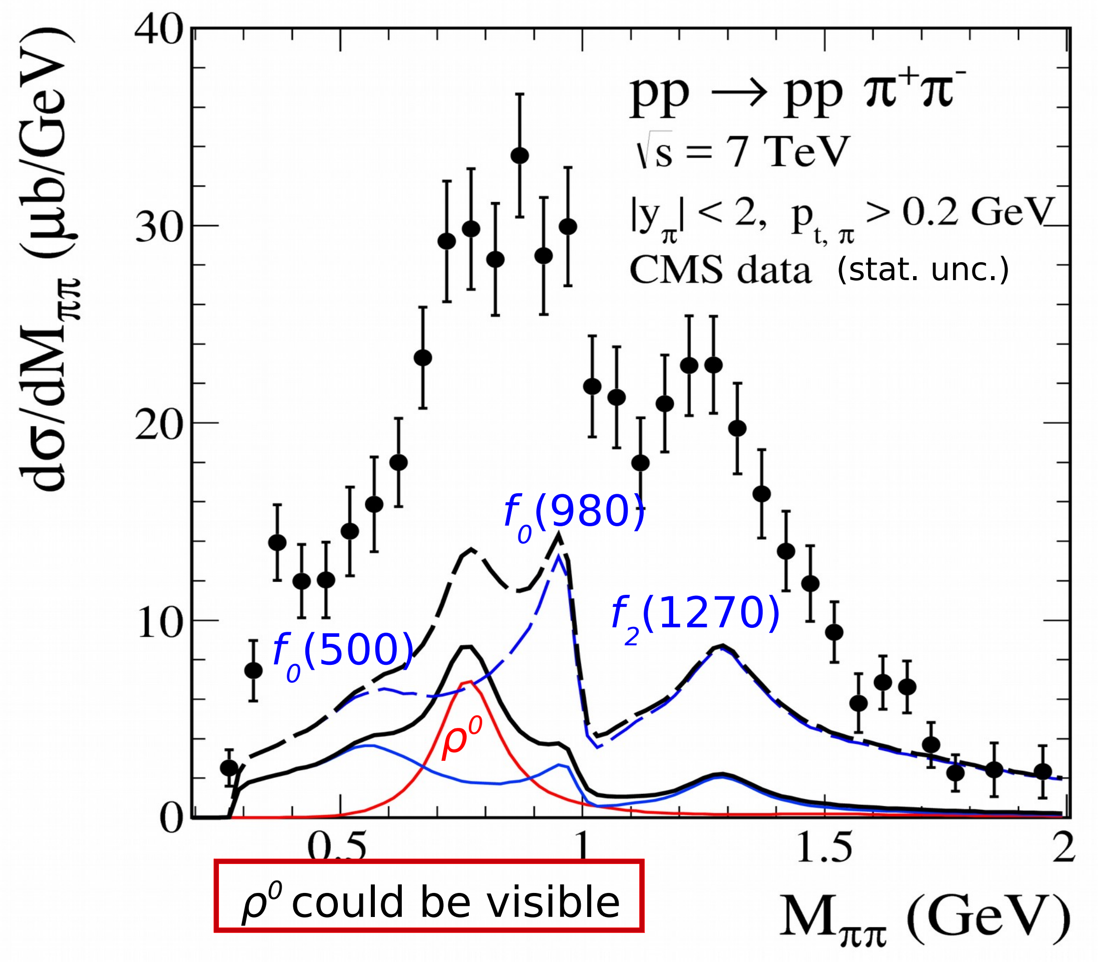




- Blue lines (diffractive term)
  red line (ρ^0 term)
  black lines (complete result)
- For f_2 term only (j=2) *IP-IP-*f_2 coupling was taken
- At $M_{\pi\pi}$ < 1 GeV also other processes may be important
  → $\pi\pi$ FSI effect (f_0(500) meson) [Au, Morgan, Pennington]

STAR preliminary data
for small |t| region: L.Adamczyk, W.Guryn, J.Turnau, Int.J.Mod.Phys. A29 (2014) 1446010
for larger |t|: W.Guryn, Acta Phys. Polon. B47 (2016) 53

Comparison with CMS ‘preliminary’ data



- Our model results (the same couplings as for CDF predictions, $< S^2 > = 0.1$) are much below the CMS data (CMS-FSQ-12-004) which could be due to contamination of non-exclusive processes (**one or both protons undergoing dissociation**).

- Purely exclusive data expected from STAR, CMS+TOTEM and ATLAS+ALFA should provide interesting information on the lightest glueballs and other mesons.

Acknowlegments

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