Central exclusive diffractive production of axial-vector f_1 mesons in proton-proton collisions

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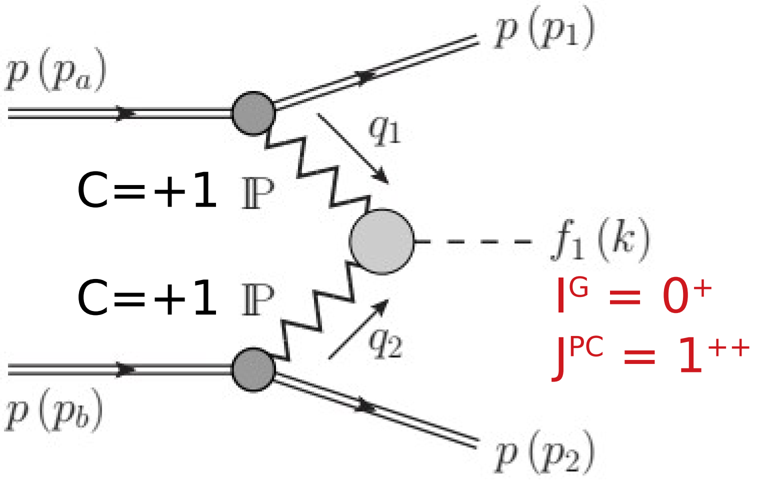
based on Phys. Rev. D102 (2020) 114003

DIS 2021
XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects
April 12-16, 2021, Stony Brook University [virtual event]

Introduction

In this talk we will be concerned with central exclusive production (CEP) of $f_1(1285)$ meson in proton-proton collisions

$$p\,(p_a) + p\,(p_b) \rightarrow p\,(p_1) + f_1\,(k) + p\,(p_2)$$



At high energies this should be mainly due to double pomeron (IP) exchange.

We treat our reaction in the tensor-pomeron approach
[Ewerz, Maniatis, Nachtmann, Ann. Phys. 342 (2014) 31]

- The (soft) pomeron and the charge conjugation C=+1 reggeons are described as effective rank 2 symmetric tensor exchanges
- The odderon and the C= -1 reggeons are described as effective vector exchanges

This approach has a good basis from nonperturbative QCD considerations.
The IP exch. can be understood as a coherent sum of exchanges of spin 2+4+6+ ...
[Nachtmann, Ann. Phys. 209 (1991) 436]

A tensor character of the pomeron is also preferred 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*

Applications of tensor-pomeron model to diffractive processes

$\gamma p \to \pi^+ \pi^- p$ *Bolz, Ewerz, Maniatis, Nachtmann, Sauter, Schöning, JHEP 01 (2015) 151*

There will be interference between $\gamma p \to (\rho^0 \to \pi^+ \pi^-)p$ (pomeron exchange) and $\gamma p \to (f_2(1270) \to \pi^+ \pi^-)p$ (odderon exchange) processes

Photoproduction and low *x* DIS

Britzger, Ewerz, Glazov, Nachtmann, Schmitt, PRD100 (2019) 114007

Helicity in proton-proton elastic scattering and the spin structure of the pomeron

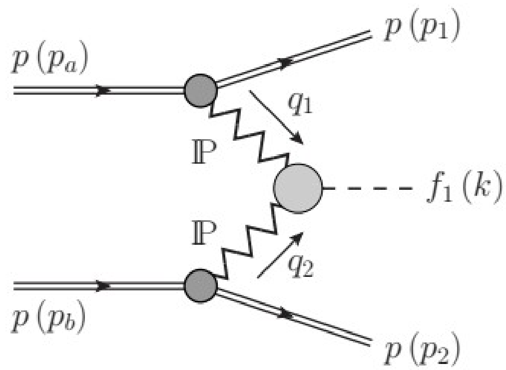
Ewerz, P.L., Nachtmann, Szczurek, PLB 763 (2016) 382

Studying the ratio r_5 of single-helicity-flip to non-flip amplitudes we found that the STAR data *[Adamczyk et al., PLB 719 (2013) 62]* are consistent with the tensor pomeron model while they clearly exclude a scalar pomeron. Vector pomeron is in contradiction to the rules of QFT.

CEP reactions, $p\,p \to p\,p\,\boldsymbol{X}$,

	$\boldsymbol{X}$: η, η', f_0	*P.L., Nachtmann, Szczurek: Ann. Phys. 344 (2014) 301*
	ρ^0	*PRD91 (2015) 074023*
	$\pi^+\pi^-$, f_0, f_2	*PRD93 (2016) 054015*
	$\pi^+\pi^-\pi^+\pi^-$, $\rho^0\rho^0$	*PRD94 (2016) 034017*
	ρ^0 with proton diss.	*PRD95 (2017) 034036*
odderon exchange:	$p\bar{p}$	*PRD97 (2018) 094027*
	K^+K^-	*PRD98 (2018) 014001*
odderon exchange:	$\phi\phi$, $K^+K^-K^+K^-$,	*PRD99 (2019) 094034*
	$f_2(1270) \to \pi^+\pi^-$	*PRD101 (2020) 034008*
odderon exchange:	$\phi \to K^+K^-$, $\mu^+\mu^-$	*PRD101 (2020) 094012*
	$f_1(1285)$, $f_1(1420)$	*PRD102 (2020) 114003*
	$K^{*0}\,\bar{K}^{*0}$, $f_2(1950)$	*PRD103 (2021) 054039*

Matrix element



The relevant kinematic quantities:

$$s = (p_a + p_b)^2 \quad \text{c.m. energy squared}$$

$$q_1 = p_a - p_1\,, \quad q_2 = p_b - p_2\,, \quad k = q_1 + q_2$$

$$t_1 = q_1^2\,, \quad t_2 = q_2^2\,, \quad m_{f_1}^2 = k^2$$

$$s_1 = (p_a + q_2)^2\,, \quad s_2 = (p_b + q_1)^2$$

The Born-level amplitude:

$$\begin{aligned}\mathcal{M}^{\text{Born}}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\lambda_{f_1}} = \; & (-i)\,(\epsilon^{\mu}(\lambda_{f_1}))^*\,\bar{u}(p_1,\lambda_1)\,i\Gamma^{(I\!\!Ppp)}_{\mu_1\nu_1}(p_1,p_a)\,u(p_a,\lambda_a) \\ & \times i\Delta^{(I\!\!P)\,\mu_1\nu_1,\alpha_1\beta_1}(s_1,t_1)\; i\Gamma^{(I\!\!PI\!\!Pf_1)}_{\alpha_1\beta_1,\alpha_2\beta_2,\mu}(q_1,q_2)\; i\Delta^{(I\!\!P)\,\alpha_2\beta_2,\mu_2\nu_2}(s_2,t_2) \\ & \times \bar{u}(p_2,\lambda_2)\,i\Gamma^{(I\!\!Ppp)}_{\mu_2\nu_2}(p_2,p_b)\,u(p_b,\lambda_b)\end{aligned}$$

with the effective pomeron propagator and the pomeron-proton vertex

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

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

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

$$\beta_{I\!\!PNN} = 1.87\ \text{GeV}^{-1}, \quad F_1(t)\text{: Dirac form factor of the proton}$$

Absorption effects:

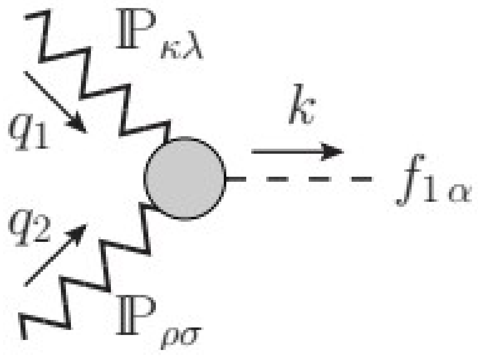
$$\mathcal{M}_{pp\to ppf_1} = \mathcal{M}^{\text{Born}}_{pp\to ppf_1} + \mathcal{M}^{pp-\text{rescattering}}_{pp\to ppf_1}$$

$$\mathcal{M}^{pp-\text{rescattering}}_{pp\to ppf_1}(s,\vec{p}_{1\perp},\vec{p}_{2\perp}) = \frac{i}{8\pi^2 s}\int d^2\vec{k}_\perp\,\mathcal{M}^{\text{Born}}_{pp\to ppf_1}(s,\vec{p}_{1\perp}-\vec{k}_\perp,\vec{p}_{2\perp}+\vec{k}_\perp)\,\mathcal{M}^{I\!\!P-\text{exchange}}_{pp\to pp}(s,-\vec{k}_\perp^2)$$

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

In practice we work with the amplitudes in the high-energy approximation.

The *IP IP f₁* coupling



coupling Lagrangian $\mathcal{L}^{(I\!\!P I\!\!P f_1)}$

↓

"bare" vertex function $i\Gamma^{(I\!\!P I\!\!P f_1)}_{\kappa\lambda,\rho\sigma,\alpha}(q_1, q_2)\,|_{\rm bare}$

↓ CEP reaction

vertex function supplemented by suitable form factor

$$i\Gamma^{(I\!\!P I\!\!P f_1)}_{\kappa\lambda,\rho\sigma,\alpha}(q_1, q_2) = i\Gamma^{(I\!\!P I\!\!P f_1)}_{\kappa\lambda,\rho\sigma,\alpha}(q_1, q_2)\,|_{\rm bare}\,\tilde{F}_{I\!\!P I\!\!P f_1}(q_1^2, q_2^2, k^2)$$

For the on-shell meson we have set $k^2 = m_{f_1}^2$.

We use two types of form factor:

- $\tilde{F}^{(I\!\!P I\!\!P f_1)}(t_1, t_2, m_{f_1}^2) = F_M(t_1)F_M(t_2), \quad F_M(t) = \dfrac{1}{1 - t/\Lambda_0^2}, \quad \Lambda_0^2 = 0.5\ \mathrm{GeV}^2$
- $\tilde{F}^{(I\!\!P I\!\!P f_1)}(t_1, t_2, m_{f_1}^2) = \exp\left(\dfrac{t_1 + t_2}{\Lambda_E^2}\right)$

where the cutoff constant Λ_E should be adjusted to experimental data

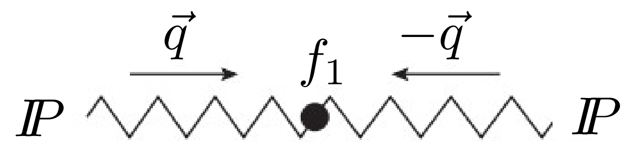
We follow two strategies for constructing coupling Lagrangian $\mathcal{L}^{(I\!P I\!P f_1)}$:

(1) Phenomenological approach. First we consider a fictitious process: the fusion of two “real spin 2 pomerons” (or tensor glueballs) of mass m giving an f_1 meson of $J^{PC} = 1^{++}$

$$I\!P(m,\epsilon_1) + I\!P(m,\epsilon_2) \to f_1(m_{f_1},\epsilon)$$

$\epsilon_{1,2}$: polarisation tensors, ϵ : polarisation vector

We work in the rest system of the f_1 meson:



The spin 2 of these “real pomerons” can be combined to a total spin S ($0 \leq S \leq 4$) and this must be combined with the orbital angular momentum ℓ to give $J^{PC} = 1^{++}$. There are exactly two possibilities: $(\ell,S) = (2,2)$ and $(4,4)$.

Corresponding couplings are:

$$\mathcal{L}^{(2,2)}_{I\!P I\!P f_1} = \frac{g'_{I\!P I\!P f_1}}{32\,M_0^2}\Big(I\!P_{\kappa\lambda} \overleftrightarrow{\partial}_{\mu} \overleftrightarrow{\partial}_{\nu} I\!P_{\rho\sigma}\Big)\Big(\partial_\alpha U_\beta - \partial_\beta U_\alpha\Big)\,\Gamma^{(8)\,\kappa\lambda,\rho\sigma,\mu\nu,\alpha\beta}$$

$$\mathcal{L}^{(4,4)}_{I\!P I\!P f_1} = \frac{g''_{I\!P I\!P f_1}}{24 \times 32\,M_0^4}\Big(I\!P_{\kappa\lambda} \overleftrightarrow{\partial}_{\mu_1} \overleftrightarrow{\partial}_{\mu_2} \overleftrightarrow{\partial}_{\mu_3} \overleftrightarrow{\partial}_{\mu_4} I\!P_{\rho\sigma}\Big)\Big(\partial_\alpha U_\beta - \partial_\beta U_\alpha\Big)\,\Gamma^{(10)\,\kappa\lambda,\rho\sigma,\mu_1\mu_2\mu_3\mu_4,\alpha\beta}$$

Here $M_0 \equiv 1$ GeV, $g'_{I\!P I\!P f_1}, g''_{I\!P I\!P f_1}$: dimensionless coupling parameters,

$I\!P_{\kappa\lambda}$ effective pomeron field, U_α f_1 field, $\overleftrightarrow{\partial}_\mu = \overrightarrow{\partial}_\mu - \overleftarrow{\partial}_\mu$ asymmetric derivative, and $\Gamma^{(8)}, \Gamma^{(10)}$ are known tensor functions.

(2) Holographic QCD approach using the Sakai-Sugimoto model.
There, the *IP IP f_1* coupling can be derived from the bulk Chern-Simons (CS) term requiring consistency of supergravity and the gravitational anomaly.

$$\mathcal{L}^{\rm CS} = \varkappa' \, U_\alpha \, \varepsilon^{\alpha\beta\gamma\delta} \, I\!P^{\mu}{}_{\beta} \, \partial_\delta I\!P_{\gamma\mu} + \varkappa'' \, U_\alpha \varepsilon^{\alpha\beta\gamma\delta} \left(\partial_\nu P^{\mu}{}_{\beta}\right)\left(\partial_\delta\partial_\mu I\!P^{\nu}{}_{\gamma} - \partial_\delta\partial^\nu I\!P_{\gamma\mu}\right)$$

$$\varkappa' : \text{dimensionless}, \quad \varkappa'' : \text{dimension GeV}^{-2}$$

Sakai, Sugimoto, Prog. Theor. Phys. 113 (2005) 843; 114 (2005) 1083,
Leutgeb, Rebhan, PRD 101 (2020) 114015

For our fictitious reaction with real pomerons there is strict equivalence

$$\mathcal{L}^{\rm CS} \,\widehat{=}\, \mathcal{L}^{(2,2)} + \mathcal{L}^{(4,4)}$$

if the couplings satisfy:

$$g'_{I\!P I\!P f_1} = -\varkappa' \frac{M_0^2}{k^2} - \varkappa'' \frac{M_0^2(k^2-2m^2)}{2k^2}$$

$$g''_{I\!P I\!P f_1} = \varkappa'' \frac{2M_0^4}{k^2}$$

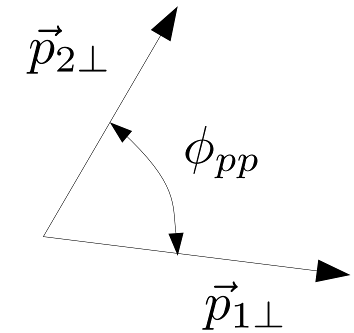
where k^2 is invariant mass squared of the resonance f_1.

For the CEP reaction the pomerons have invariant mass squared t_1, $t_2 < 0$ instead of m^2 and, in general, $t_1 \neq t_2$. Replacing above $2m^2 \to t_1 + t_2$ we expect for small $|t_1|$ and $|t_2|$ still approximate equivalence to hold.
This is confirmed by explicit numerical studies.

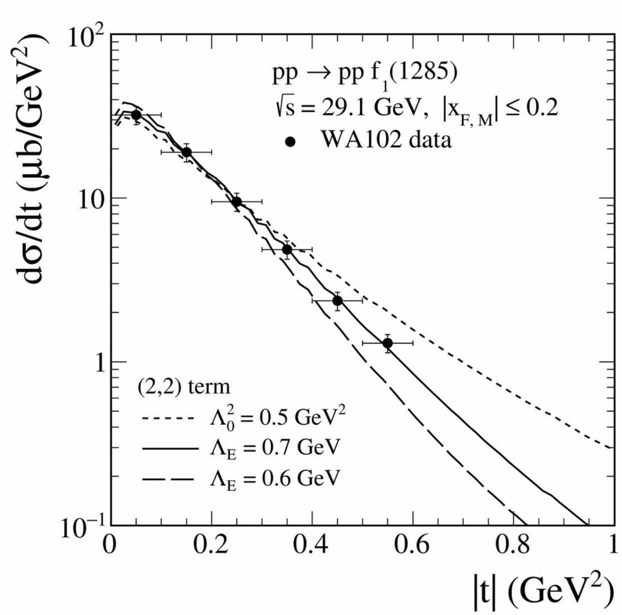
Comparison with experimental results from WA102@CERN

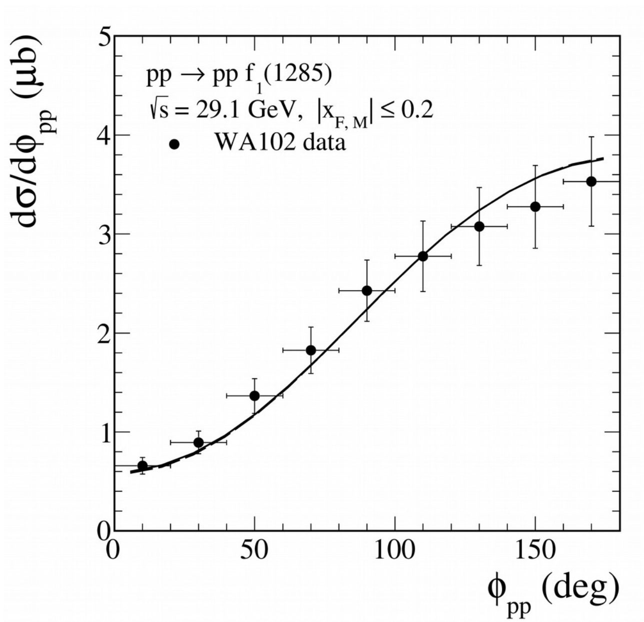
D. Barberis et al. (WA102 Collaboration), PLB 440 (1998) 225

	$\sqrt{s} = 29.1$ GeV, $\lvert x_{F,M} \rvert \leqslant 0.2$
$f_1(1285)$	$\sigma_{\rm exp} = (6919 \pm 886)$ nb



$0 \leqslant \phi_{pp} \leqslant \pi$

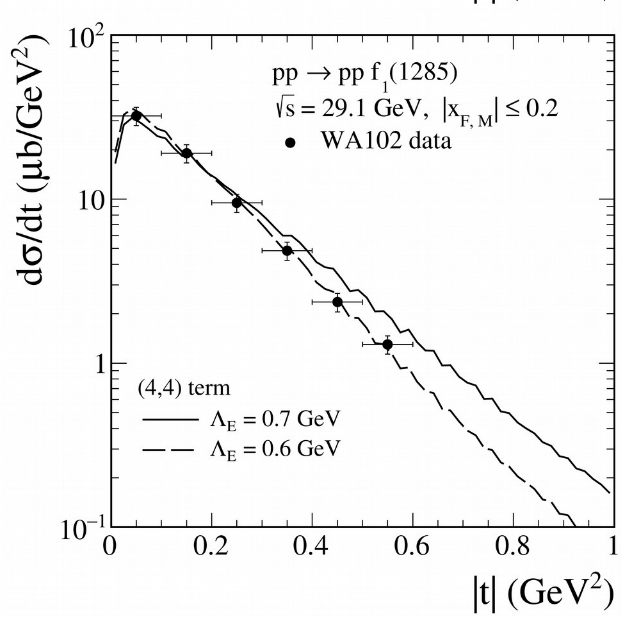


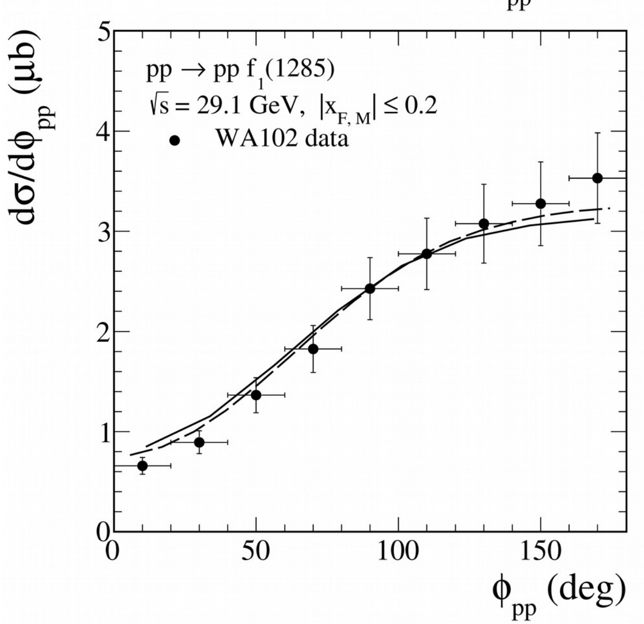


(ℓ,S) = (2,2) term only

$|g'_{I\!PI\!Pf_1}| = 4.89$

We get a reasonable description of WA102 data with $\Lambda_E = 0.7$ GeV





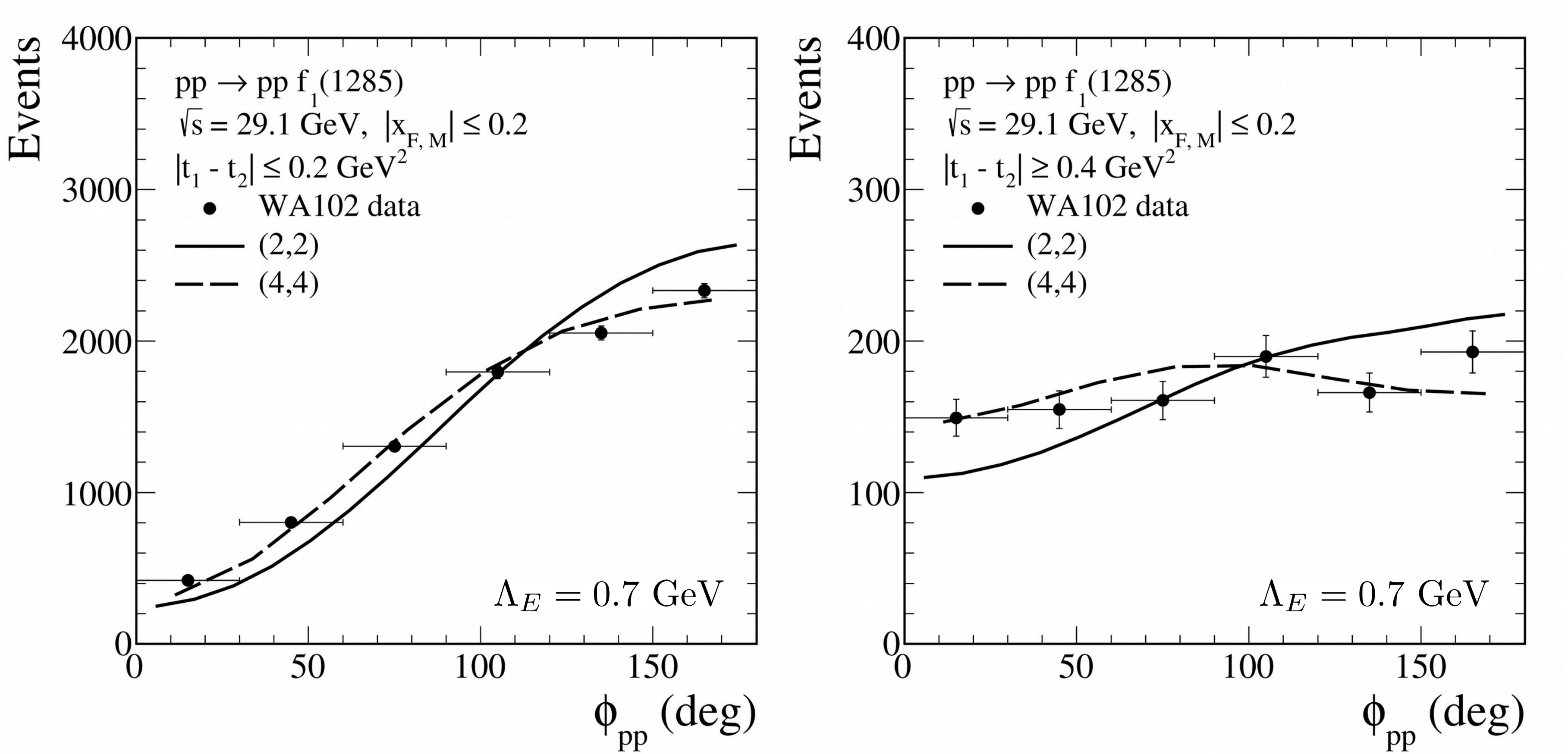
(ℓ,S) = (4,4) term only

$|g''_{I\!PI\!Pf_1}| = 10.31$

Absorption effects included,
$\langle S^2 \rangle = \sigma_{abs}/\sigma_{Born} \approx 0.5\text{-}0.7$
depending on the kinematics

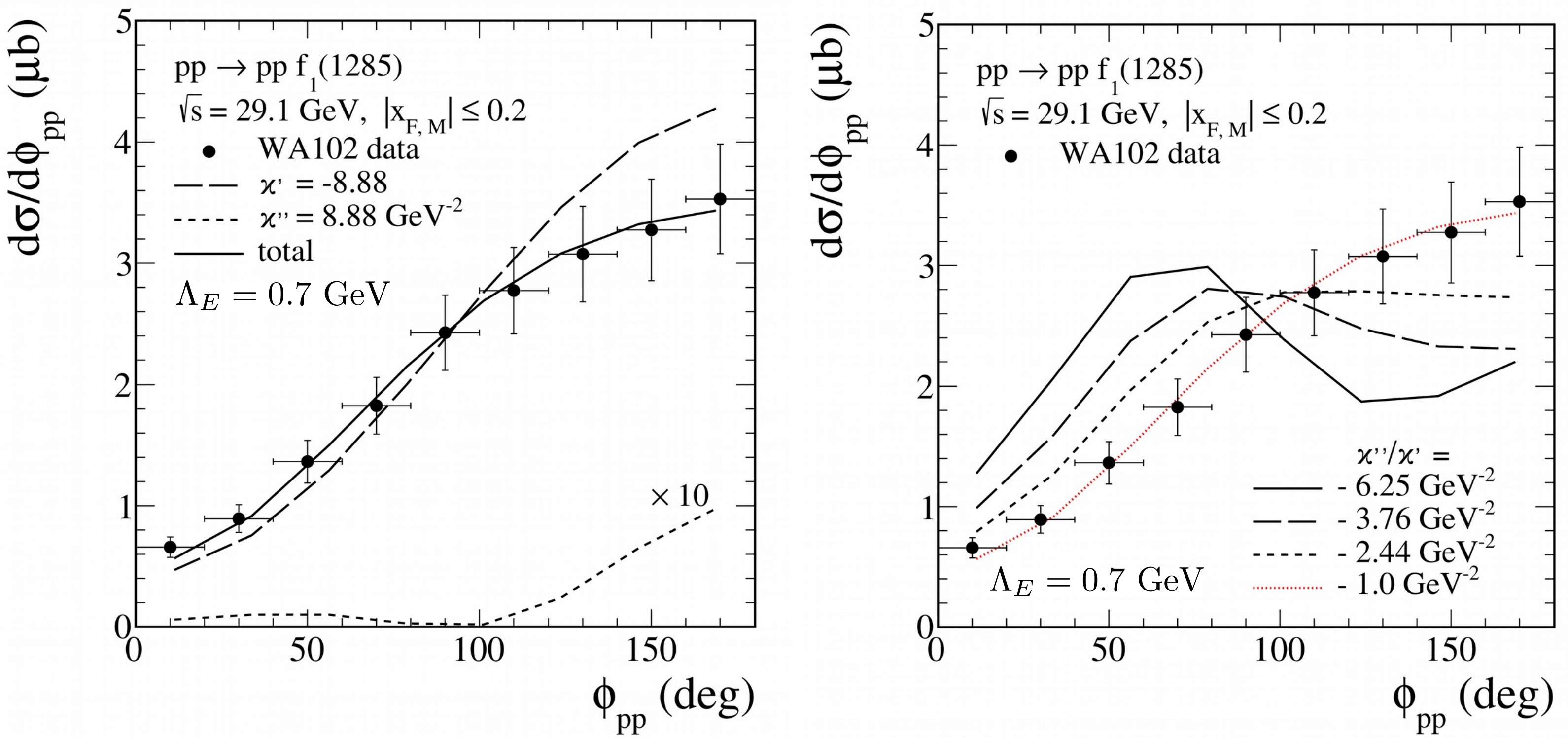
Comparison with data from: A. Kirk (WA102 Collaboration), Nucl. Phys. A 663 (2000) 608

The theoretical results have been normalized to the mean value of the number of events



- An almost ‘flat’ distribution at large values of $|t_1 - t_2|$ can be observed
  → absorption effects play a significant role there,
  large damping of contribution in the region $\phi_{pp} \sim \pi$

- It seems that the (ℓ,S) = (4,4) term best reproduces the shape of the WA102 data



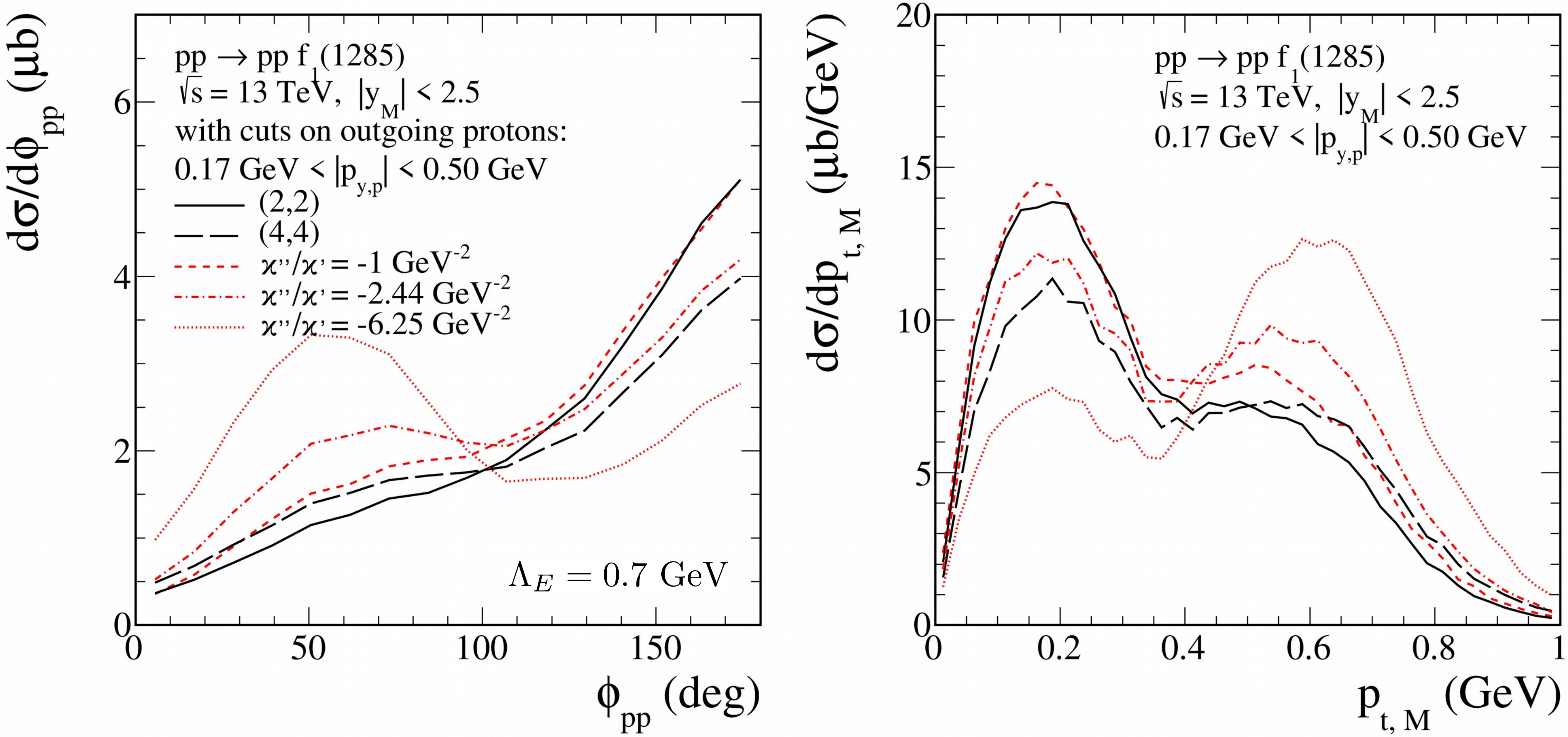
- (left panel) Fit to WA102 data using the Chern-Simons coupling.
  The relation between the (ℓ,S) and CS forms of the couplings:
  with $\varkappa' = -8.88, \quad \varkappa''/\varkappa' = -1.0\ \mathrm{GeV}^{-2}$ and setting $t_1 = t_2 = -0.1\ \mathrm{GeV}^2$
  we get: $g'_{I\!PI\!P f_1} = 0.42, \quad g''_{I\!PI\!P f_1} = 10.81$.
  This CS coupling corresponds practically to a pure (ℓ,S) = (4,4) coupling.

- (right panel) The prediction for $\varkappa''/\varkappa'$ obtained in the Sakai-Sugimoto model is

$$\varkappa''/\varkappa' = -5.631/M_{KK}^2 = -(6.25, 3.76, 2.44)\ \mathrm{GeV}^{-2} \text{ for } M_{KK} = (949, 1224, 1519)\ \mathrm{MeV}$$

  Usually M_{KK} (Kaluza-Klein mass scale) is fixed by matching the mass of the lowest vector meson to that of the physical ρ meson, leading to $M_{KK} = 949$ MeV.
  However, this choice leads to a tensor glueball mass which is too low, $M_T \approx 1.5$ GeV.
  The standard pomeron trajectory corresponds to $M_T \approx 1.9$ GeV,
  whereas lattice gauge theory indicates $M_T \approx 2.4$ GeV.

Predictions for the LHC experiments



- The contribution with $\varkappa''/\varkappa' = -6.25\ \mathrm{GeV}^{-2}$ gives a significantly different shape
- The absorption effects are included, $\langle S^2 \rangle \approx 0.35$. They decrease the distributions mostly at higher values of ϕ_{pp} and at smaller values of $p_{t,M}$ (and also |t|).

  This could be tested in experiments at the LHC (ATLAS-ALFA, CMS-TOTEM) when both protons are measured.

- The GenEx MC event generator could be used in this context:

  [Kycia, Chwastowski, Staszewski, Turnau, Commun.Comput.Phys. 24 (2018) 860]

Cross sections in μb for $pp \to pp f_1(1285)$ for $\sqrt{s} = 13$ TeV

Contribution	Parameters $\Lambda_E = 0.7$ GeV,	$\lvert y_{f_1}\rvert < 1.0$	$\lvert y_{f_1}\rvert < 2.5$	$\lvert y_{f_1}\rvert < 2.5$, $0.17 < \lvert p_{y,p}\rvert < 0.50$ GeV	$2.0 < y_{f_1} < 4.5$
$(l,S) = (2,2)$	$g'_{I\!PI\!Pf_1} = 4.89$	14.8	37.5	6.46	18.9
$(l,S) = (4,4)$	$g''_{I\!PI\!Pf_1} = 10.31$	13.8	34.0	6.06	18.1
$(\varkappa', \varkappa'')$	$\varkappa''/\varkappa' = -6.25$ GeV^{-2}	18.6	45.8	7.14	23.1
$(\varkappa', \varkappa'')$	$\varkappa''/\varkappa' = -2.44$ GeV^{-2}	17.5	43.4	7.10	22.1
$(\varkappa', \varkappa'')$	$\varkappa''/\varkappa' = -1.0$ GeV^{-2}	16.6	41.0	7.09	20.5

- One of the most prominent decay modes of the $f_1(1285)$ is $f_1(1285) \to \pi^+\pi^-\pi^+\pi^-$
- There $f_1(1285)$ and $f_2(1270)$ are close in mass.
  We obtain for $\sqrt{s} = 13$ TeV and $\lvert y_M\rvert < 2.5$:

$$\sigma_{pp\to ppf_1(1285)} \times \mathcal{BR}(f_1(1285) \to 2\pi^+2\pi^-) = 34.0\ \mu\text{b} \times 0.112 = 3.8\ \mu\text{b}$$
$$\sigma_{pp\to ppf_2(1270)} \times \mathcal{BR}(f_2(1270) \to 2\pi^+2\pi^-) = 11.3\ \mu\text{b} \times 0.028 = 0.3\ \mu\text{b}$$

[CEP of $f_2(1270)$: PRD93 (2016) 054015, PRD101 (2020) 034008]

  As the $f_1(1285)$ has a much narrower width than the $f_2(1270)$ it would be seen in the M(4π) distribution as a sharp peak on top of $f_2(1270)$ and of the continuum

- $f_1(1285)$ is seen in the preliminary ATLAS-ALFA results for *pp* → *pp* $2\pi^+2\pi^-$ at $\sqrt{s} = 13$ TeV and for $\lvert\eta_\pi\rvert < 2.5, p_{t,\pi} > 0.1\,\text{GeV}, \max(p_{t,\pi}) > 0.2\,\text{GeV}$, $0.17\,\text{GeV} < \lvert p_{y,p}\rvert < 0.5\,\text{GeV}$ *[R. Sikora, CERN-THESIS-2020-235]*

- Theoretical studies of the reaction *pp* → *pp 4π* including both the resonances and continuum contributions in the tensor-pomeron approach → in progress
  [PRD94 (2016) 034017; PRD95 (2017) 094020]

Conclusions

- We have discussed in detail CEP of $f_1(1285)$ meson in *pp* collisions in the tensor-pomeron approach
- Different forms of the *IP IP* f_1 coupling are possible
- We obtain a good description of the WA102 data for the $pp \to pp\, f_1(1285)$ reaction assuming that the reaction is dominated by *IP* exchange already at $\sqrt{s} = 29.1$ GeV
- We have given predictions for experiments at the LHC $\sqrt{s} = 13$ TeV
  - ✔ total cross sections of σ = 6 – 41 μb (depending on the assumed cuts) and differential distributions
  - ✔ in all cases we have included - very important - absorptive corrections
- Detailed tests of the Sakai-Sugimoto model are possible
- Experimental studies of single meson CEP reactions will give many *IP IP M* coupling parameters. Their theoretical calculation is a challenging problem of nonperturbative QCD

Thank you for your attention