Future studies of exclusive diffractive bremsstrahlung of one and two photons

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Introduction

- Inclusive differential production cross-section of forward photons in *pp* collisions was measured using RHICf detector and LHCf detector (Adriani et al.).

  In the ATLAS-LHCf combined analysis (ATLAS-CONF-2017-075) the forward-photon spectra were measured by the LHCf detector and the inner tracking system of the ATLAS detector, which is used to identify diffractive events. In this method, the energy spectrum of photons has been obtained in two regions of photon rapidity ($8.81 < y < 8.99$ and $y > 10.94$) for events with no charged particles having $p_t > 100$ MeV and $|\eta| < 2.5$.

- At high energies, the $pp \to pp\gamma$ reaction has not yet been measured. Feasibilty studies of exclusive diffractive bremsstrahlung cross sections were performed for LHC energies using ATLAS forward detectors (Chwastowski et al.). This was done within "old" Lebiedowicz-Szczurek approach.

- ATLAS-LHCf analysis, ATLAS PUB Note: *Physics potential of a combined data taking of the LHCf and ATLAS Roman Pot detectors, ATL-PHYS-PUB-2023-024*

- We consider a new possibility to measure <u>exclusive diffractive bremsstrahlung</u> with LHCf (photon) and ATLAS AFP (proton).

  We work within the tensor-pomeron model as proposed by Ewerz, Maniatis, Nachtmann [Ann. Phys. 342 (2014) 31] for soft hadronic high-energy reactions.

Introduction

- Here we discuss exclusive diffractive bremsstrahlung of one and two photons in *pp* collisions for the LHC energy (13 TeV) and at forward photon rapidities.

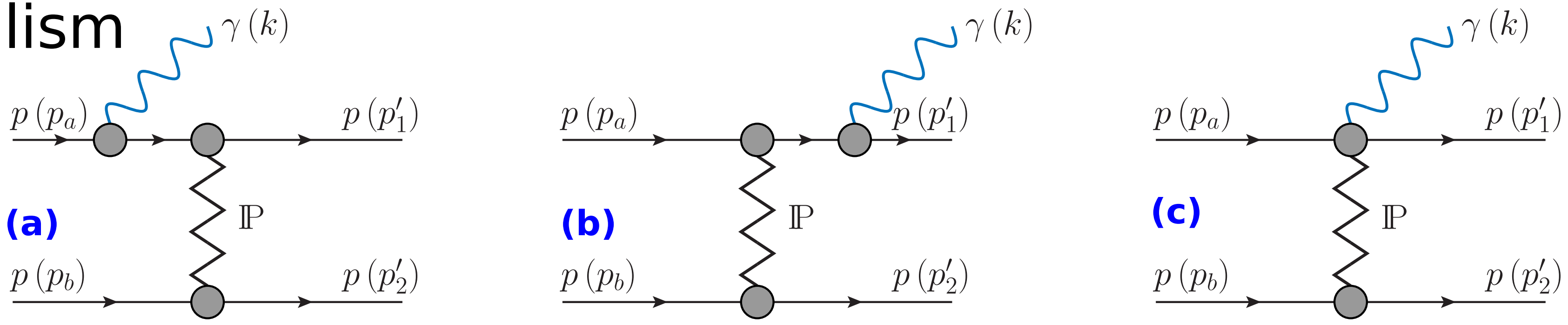
- Exclusive single photon bremsstrahlung was discussed by Lebiedowicz, Nachtmann, and Szczurek:
  - $\pi\pi \to \pi\pi\gamma$ PRD 105 (2022) 014022; Erratum PRD 109 (2024) 099901
  - $pp \to pp\gamma$ PRD 106 (2022) 034023, PRD 107 (2023) 074014, PLB 843 (2023) 138053
  - $\pi p \to \pi p\gamma$ PRD 109 (2024) 094042, arXiv:2307.12673 [hep-ph]

- Planned future upgrade of the ALICE experiment at the LHC (ALICE 3, arXiv:2211.02491 [physics.ins-det])

- Anomalous soft photons, see Bailhache et al., arXiv:2406.17959 [nucl-ex].

  A measurement of the soft-photon production at the LHC could shed light on a long-standing discrepancy between the theoretical predictions of the bremssthralung (based on the soft-photon theorem) and the measured soft-photon spectra in several hadronic reactions.

Formalism



+ 3 diagrams where the photon is emitted from the second proton line p_b-$p_{2'}$

- Diffractive photon-bremsstrahlung amplitude contains 6 diagrams. The amplitudes (a, b, d, e) corresponding to photon emission from the external protons are determined by the off-shell *pp* elastic scattering amplitude. The contact terms, (c) and (f), are needed in order to satisfy gauge-invariance constraints.

- The inclusive cross section for the real-photon yield

$$d\sigma(pp \to pp\gamma) = \frac{1}{2\sqrt{s(s-4m_p^2)}} \frac{d^3k}{(2\pi)^3\, 2k^0} \int \frac{d^3p_1'}{(2\pi)^3\, 2p_1'^0} \frac{d^3p_2'}{(2\pi)^3\, 2p_2'^0} (2\pi)^4 \delta^{(4)}(p_1' + p_2' + k - p_a - p_b)$$
$$\times \frac{1}{4} \sum_{p\,\mathrm{spins}} \mathcal{M}_\mu(p_1',p_2') \big(\mathcal{M}_\nu(p_1',p_2')\big)^* (-g^{\mu\nu})$$

where $\sum_{\lambda_\gamma} (\epsilon^\mu)^* \epsilon^\nu = -g^{\mu\nu}$

Formalism

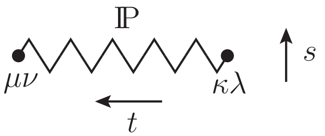
- Standard γpp vertex and proton propagator:

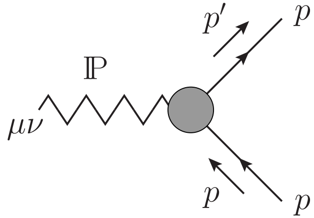
$$i\Gamma_{\mu}^{(\gamma pp)}(p',p) = -ie\left[F_1(0)\gamma_\mu + \frac{i}{2m_p}\sigma_{\mu\nu}q^\nu F_2(0)\right] \qquad iS_F(p) = \frac{i}{\not{p} - m_p + i\epsilon} = i\frac{\not{p} + m_p}{p^2 - m_p^2 + i\epsilon}$$

$$q = p' - p\,, \quad F_1(0) = 1\,, \quad F_2(0) = \kappa_p = 1.7928$$

- Ward-Takahashi identity: $(p'-p)^\mu \Gamma_{\mu}^{(\gamma pp)}(p',p) = -e\left[S_F^{-1}(p') - S_F^{-1}(p)\right]$

- Propagator for tensor-pomeron exchange and pomeron-proton vertex:



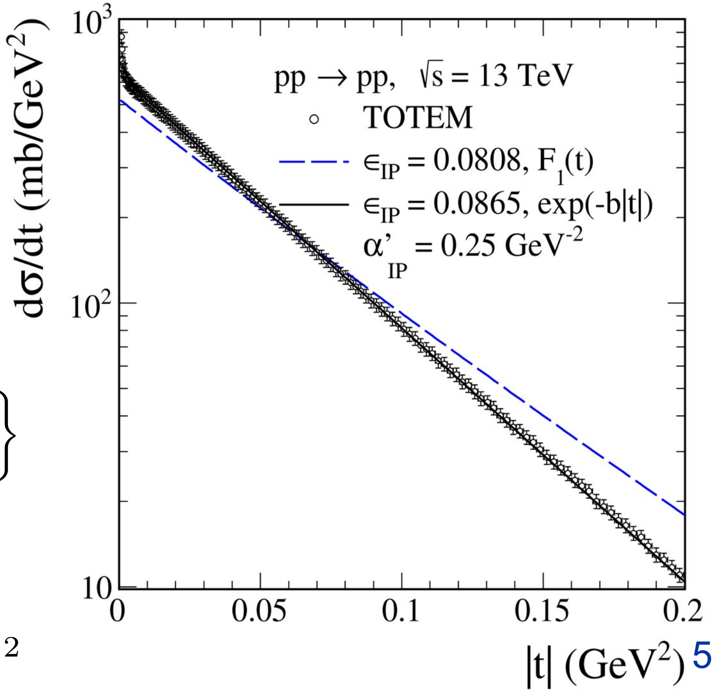


$$i\Delta^{(\mathbb{P})}_{\mu\nu,\kappa\lambda}(s,t) = \frac{1}{4s}\left(g_{\mu\kappa}g_{\nu\lambda} + g_{\mu\lambda}g_{\nu\kappa} - \frac{1}{2}g_{\mu\nu}g_{\kappa\lambda}\right)(-is\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1}$$

$$\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}}t\,, \quad \alpha_{\mathbb{P}}(0) = 1 + \epsilon_{\mathbb{P}} = 1.0808, \quad \alpha'_{\mathbb{P}} = 0.25\,\mathrm{GeV}^{-2}$$

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

$$\beta_{\mathbb{P}pp} = 1.87\ \mathrm{GeV}^{-1}$$



G. Antchev et al. (TOTEM Coll.),
Eur. Phys. J. C79 (2019) 785, Eur. Phys. J. C79 (2019) 861

We find from comparison to the TOTEM dσ/dt data:

$$\epsilon_{\mathbb{P}} = 0.0865 \qquad F_1(t) \to F(t) = \exp(-b\,|t|) \qquad \text{with } b = 2.95\ \mathrm{GeV}^{-2}$$

Formalism

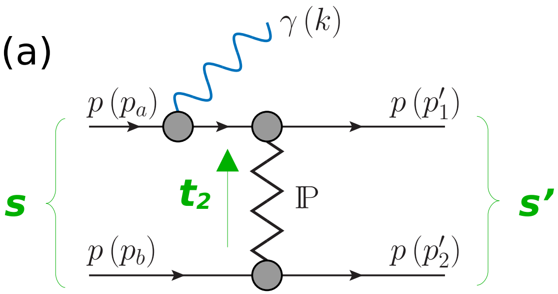
- The kinematic variables for the $pp \to pp\gamma$ reaction are:

$$s = (p_a + p_b)^2 = (p_1' + p_2' + k)^2$$
$$s' = (p_a + p_b - k)^2 = (p_1' + p_2')^2$$
$$t_1 = (p_a - p_1')^2 = (p_b - p_2' - k)^2$$
$$t_2 = (p_b - p_2')^2 = (p_a - p_1' - k)^2$$

$$\mathcal{F}_{\mathbb{P}}(s,t) = \left[3\beta_{\mathbb{P}pp}F(t)\right]^2 \frac{1}{4s}(-is\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1}$$

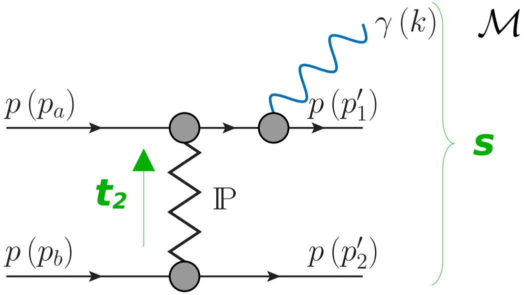
- We get with the off-shell scattering amplitudes (with only IP exchange) for diagrams (a) and (b):

(a)



$$\begin{aligned}
\mathcal{M}^{(a)}_{\mu} &= -\bar{u}_{1'} \otimes \bar{u}_{2'}\, \mathcal{M}^{(0)}(p_a - k, p_b, p_1', p_2') \left[S_F(p_a - k)\Gamma^{(\gamma pp)}_{\mu}(p_a - k, p_a)\, u_a\right] \otimes u_b \\
&= e\bar{u}_{1'} \otimes \bar{u}_{2'} \Big\{ i\mathcal{F}_{\mathbb{P}}(s', t_2) \Big[\gamma^{\alpha} \otimes \gamma_{\alpha}(p_a - k + p_1', p_b + p_2') + (\not{p}_b + \not{p}_2') \otimes (\not{p}_a - \not{k} + \not{p}_1') \\
&\quad - \frac{1}{2}(\not{p}_a - \not{k} + \not{p}_1') \otimes (\not{p}_b + \not{p}_2')\Big]\Big\} \\
&\quad \times \Big[\frac{\not{p}_a - \not{k} + m_p}{(p_a - k)^2 - m_p^2 + i\varepsilon}\Big(\gamma_{\mu} - \frac{i}{2m_p}\sigma_{\mu\nu}k^{\nu}F_2(0)\Big)u_a\Big] \otimes u_b
\end{aligned}$$

(b)



$$\begin{aligned}
\mathcal{M}^{(b)}_{\mu} &= -\left[\bar{u}_{1'}\Gamma^{(\gamma pp)}_{\mu}(p_1', p_1' + k) S_F(p_1' + k)\right] \otimes \bar{u}_{2'}\, \mathcal{M}^{(0)}(p_a, p_b, p_1' + k, p_2')\, u_a \otimes u_b \\
&= e\Big[\bar{u}_{1'}\Big(\gamma_{\mu} - \frac{i}{2m_p}\sigma_{\mu\nu}k^{\nu}F_2(0)\Big)\frac{\not{p}_1' + \not{k} + m_p}{(p_1' + k)^2 - m_p^2 + i\varepsilon}\Big] \otimes \bar{u}_{2'} \\
&\quad \times \Big\{ i\mathcal{F}_{\mathbb{P}}(s, t_2)\Big[\gamma^{\alpha} \otimes \gamma_{\alpha}(p_a + p_1' + k, p_b + p_2') + (\not{p}_b + \not{p}_2') \otimes (\not{p}_a + \not{p}_1' + \not{k}) \\
&\quad - \frac{1}{2}(\not{p}_a + \not{p}_1' + \not{k}) \otimes (\not{p}_b + \not{p}_2')\Big]\Big\} u_a \otimes u_b
\end{aligned}$$

Formalism

Using the Ward-Takahashi identity we find

$$\begin{aligned} k^\mu \mathcal{M}_\mu^{(a)} &= -e\bar{u}_{1'} \otimes \bar{u}_{2'} \, \mathcal{M}^{(0)}(p_a - k, p_b, p_1', p_2') \, u_a \otimes u_b \,, \\ k^\mu \mathcal{M}_\mu^{(b)} &= e\bar{u}_{1'} \otimes \bar{u}_{2'} \, \mathcal{M}^{(0)}(p_a, p_b, p_1' + k, p_2') \, u_a \otimes u_b \,. \end{aligned}$$

Now we impose the gauge invariance condition which must hold also for the photon emission from the p_a-p_1' lines in (a – c) diagrams alone:

$$k^\mu \big(\mathcal{M}_\mu^{(a)} + \mathcal{M}_\mu^{(b)} + \mathcal{M}_\mu^{(c)} \big) = 0 \,.$$

We obtain then:

$$\begin{aligned} k^\mu \mathcal{M}_\mu^{(c)} &= -k^\mu \mathcal{M}_\mu^{(a)} - k^\mu \mathcal{M}_\mu^{(b)} \\ &= e\bar{u}_{1'} \otimes \bar{u}_{2'} \big[\mathcal{M}^{(0)}(p_a - k, p_b, p_1', p_2') - \mathcal{M}^{(0)}(p_a, p_b, p_1' + k, p_2') \big] u_a \otimes u_b \end{aligned}$$

The explicit expressions of these terms are given in
Lebiedowicz, Nachtmann, Szczurek, PRD 106 (2022) 034023.

We can write

$$\mathcal{M}_\mu^{(\text{standard})} = \mathcal{M}_\mu^{(a)} + \mathcal{M}_\mu^{(b)} + \mathcal{M}_\mu^{(c)} + \mathcal{M}_\mu^{(d)} + \mathcal{M}_\mu^{(e)} + \mathcal{M}_\mu^{(f)} = \sum_{j=1}^{7} \big(\mathcal{M}_\mu^{(a+b+c)\,j} + \mathcal{M}_\mu^{(d+e+f)\,j} \big)$$

all subamplitudes (a+b+c) and (d+e+f)
are separately gauge invariant

Formalism

For $j = 1, 2, 4$ we have

$$\mathcal{M}_\mu^{(a+b+c)\,1} = e\bar{u}_{1'} \otimes \bar{u}_{2'} \big\{ i\mathcal{F}_{\mathbb{P}}(s, t_2) \big[\gamma^\alpha \otimes \gamma_\alpha (p_a + p'_1, p_b + p'_2) + (\not{p}_b + \not{p}'_2) \otimes (\not{p}_a + \not{p}'_1) - 2m_p^2 1 \otimes 1 \big] \times \Big[\frac{2p_{a\mu} - k_\mu}{-2p_a \cdot k + k^2 + i\varepsilon} + \frac{2p'_{1\mu} + k_\mu}{2p'_1 \cdot k + k^2 + i\varepsilon} \Big] \big\} u_a \otimes u_b$$

← the subamplitude j = 1 contains the pole term ∝ 1/ω for ω → 0

$$\mathcal{M}_\mu^{(a+b+c)\,2} = e\bar{u}_{1'} \otimes \bar{u}_{2'} \big\{ i\mathcal{F}_{\mathbb{P}}(s', t_2) \frac{1}{-2p_a \cdot k + k^2 + i\varepsilon} \times \big[\gamma^\alpha \otimes \gamma_\alpha (p_a + p'_1 - k, p_b + p'_2) + (\not{p}_b + \not{p}'_2) \otimes (\not{p}_a + \not{p}'_1 - \not{k}) \big] \times \big[k_\mu - \not{k}\gamma_\mu + \frac{F_2(0)}{2m_p} \big(2p_{a\mu} \not{k} - 2(p_a \cdot k)\gamma_\mu + 2m_p(k_\mu - \not{k}\gamma_\mu) - (\not{k}k_\mu - k^2\gamma_\mu) \big) \big] \otimes 1 \big\} u_a \otimes u_b$$

$$\mathcal{M}_\mu^{(a+b+c)\,4} = e\bar{u}_{1'} \otimes \bar{u}_{2'} \big\{ i\mathcal{F}_{\mathbb{P}}(s, t_2) \frac{1}{2p'_1 \cdot k + k^2 + i\varepsilon} \times \big[-(k_\mu - \gamma_\mu \not{k}) + \frac{F_2(0)}{2m_p} \big(-2p'_{1\mu} \not{k} + 2(p'_1 \cdot k)\gamma_\mu - 2m_p(k_\mu - \gamma_\mu \not{k}) - (k_\mu \not{k} - k^2\gamma_\mu) \big) \big] \otimes 1 \times \big[\gamma^\alpha \otimes \gamma_\alpha (p_a + p'_1 + k, p_b + p'_2) + (\not{p}_b + \not{p}'_2) \otimes (\not{p}_a + \not{p}'_1 + \not{k}) \big] \big\} u_a \otimes u_b$$

Here $\mathcal{F}_{\mathbb{P}}(s,t) = \big[3\beta_{\mathbb{P}pp} F(t) \big]^2 \frac{1}{4s} (-is\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1}$

The terms j = 2 and 4 have no singularity for ω → 0.
The main term there comes from the anomalous magnetic moment $F_2(0)$.

Formalism

- We compare our standard (exact) results to two soft-photon approximations, SPA1 and SPA2, where we keep in the radiative amplitudes only the pole terms proportional to 1/ω:
  - SPA1

$$\mathcal{M}_{\mu,\,\mathrm{SPA1}} = e\mathcal{M}^{(\mathrm{on\ shell})\,pp}(s,t)\Big[-\frac{p_{a\mu}}{(p_a\cdot k)}+\frac{p_{1\mu}}{(p_1\cdot k)}-\frac{p_{b\mu}}{(p_b\cdot k)}+\frac{p_{2\mu}}{(p_2\cdot k)}\Big]$$

$$d\sigma(pp\to pp\gamma)_{\mathrm{SPA1}} = \frac{d^3k}{(2\pi)^3\,2k^0}\int d^3p_1\,d^3p_2\,e^2\,\frac{d\sigma(pp\to pp)}{d^3p_1 d^3p_2} \times\Big[-\frac{p_{a\mu}}{(p_a\cdot k)}+\frac{p_{1\mu}}{(p_1\cdot k)}-\frac{p_{b\mu}}{(p_b\cdot k)}+\frac{p_{2\mu}}{(p_2\cdot k)}\Big]\Big[-\frac{p_{a\nu}}{(p_a\cdot k)}+\frac{p_{1\nu}}{(p_1\cdot k)}-\frac{p_{b\nu}}{(p_b\cdot k)}+\frac{p_{2\nu}}{(p_2\cdot k)}\Big](-g^{\mu\nu})$$

$$\frac{d\sigma(pp\to pp)}{d^3p_1 d^3p_2} = \frac{1}{2\sqrt{s(s-4m_p^2)}}\,\frac{1}{(2\pi)^3\,2p_1^0\,(2\pi)^3\,2p_2^0}(2\pi)^4\delta^{(4)}(p_1+p_2-p_a-p_b)\,\frac{1}{4}\sum_{p\,\mathrm{spins}}|\mathcal{M}^{(\mathrm{on\ shell})\,pp}(s,t)|^2$$

in high-energy small-angle limit

$$\mathcal{M}(s,t) \approx i8s^2\mathcal{F}_{\mathbb{P}pp}(s,t)\delta_{\lambda_1\lambda_a}\delta_{\lambda_2\lambda_b}$$
$$\approx i2s\big[3\beta_{\mathbb{P}pp}F(t)\big]^2(-is\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1}\delta_{\lambda_1\lambda_a}\delta_{\lambda_2\lambda_b}$$

  - SPA2

$$\mathcal{M}_{\mu,\,\mathrm{SPA2}} = \mathcal{M}_\mu^{(a+b+c)\,1}(s,t_2)+\mathcal{M}_\mu^{(d+e+f)\,1}(s,t_1)$$

Results, $pp \to pp\gamma$

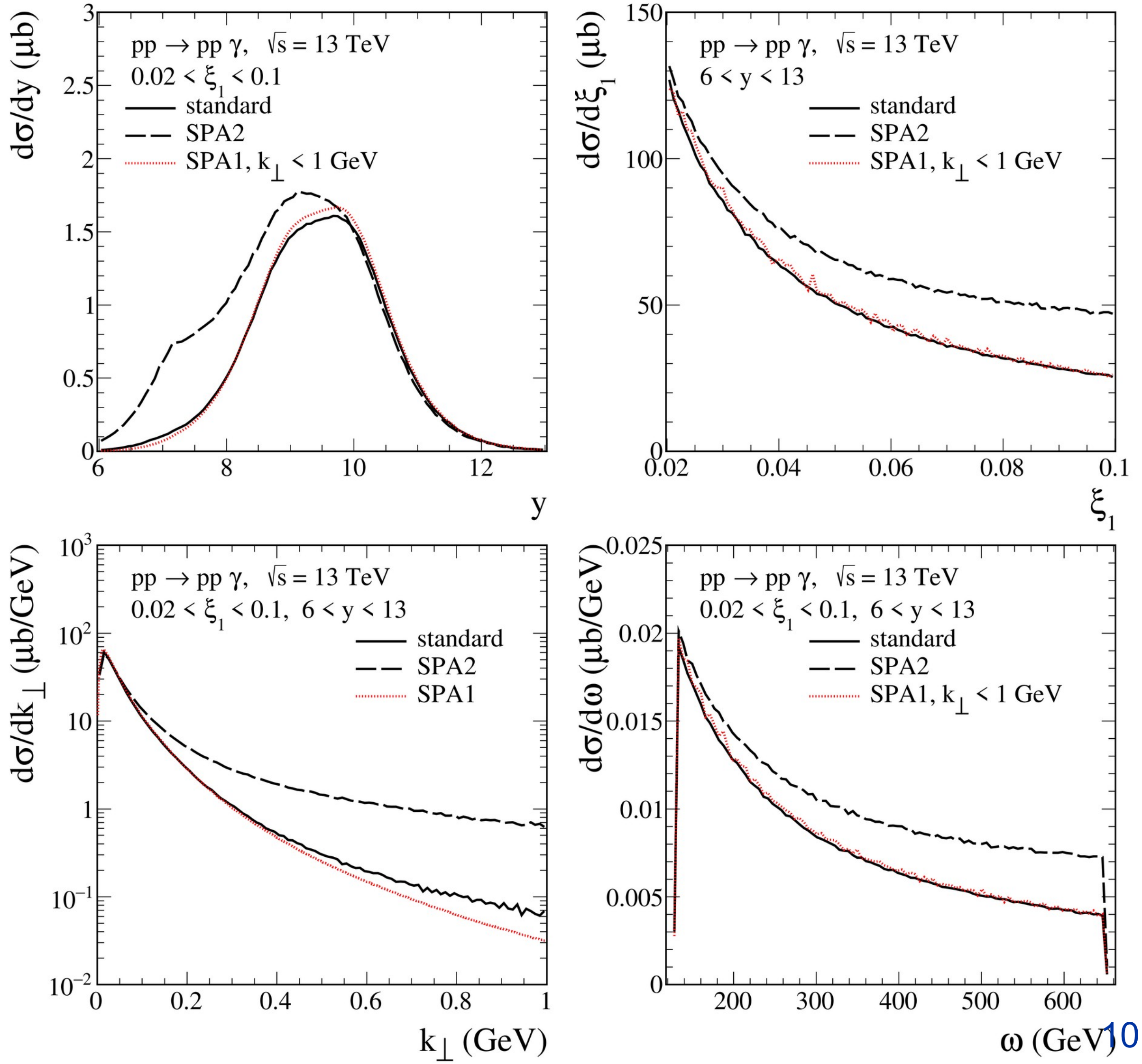
In the forward-rapidity region (LHCf) and for **proton relative energy loss 0.02 < ξ_1 <0.1** (AFP)
our standard (exact) results and SPA1 results are very close to each other.

This is also the region where soft-photon theorem should be applicable.

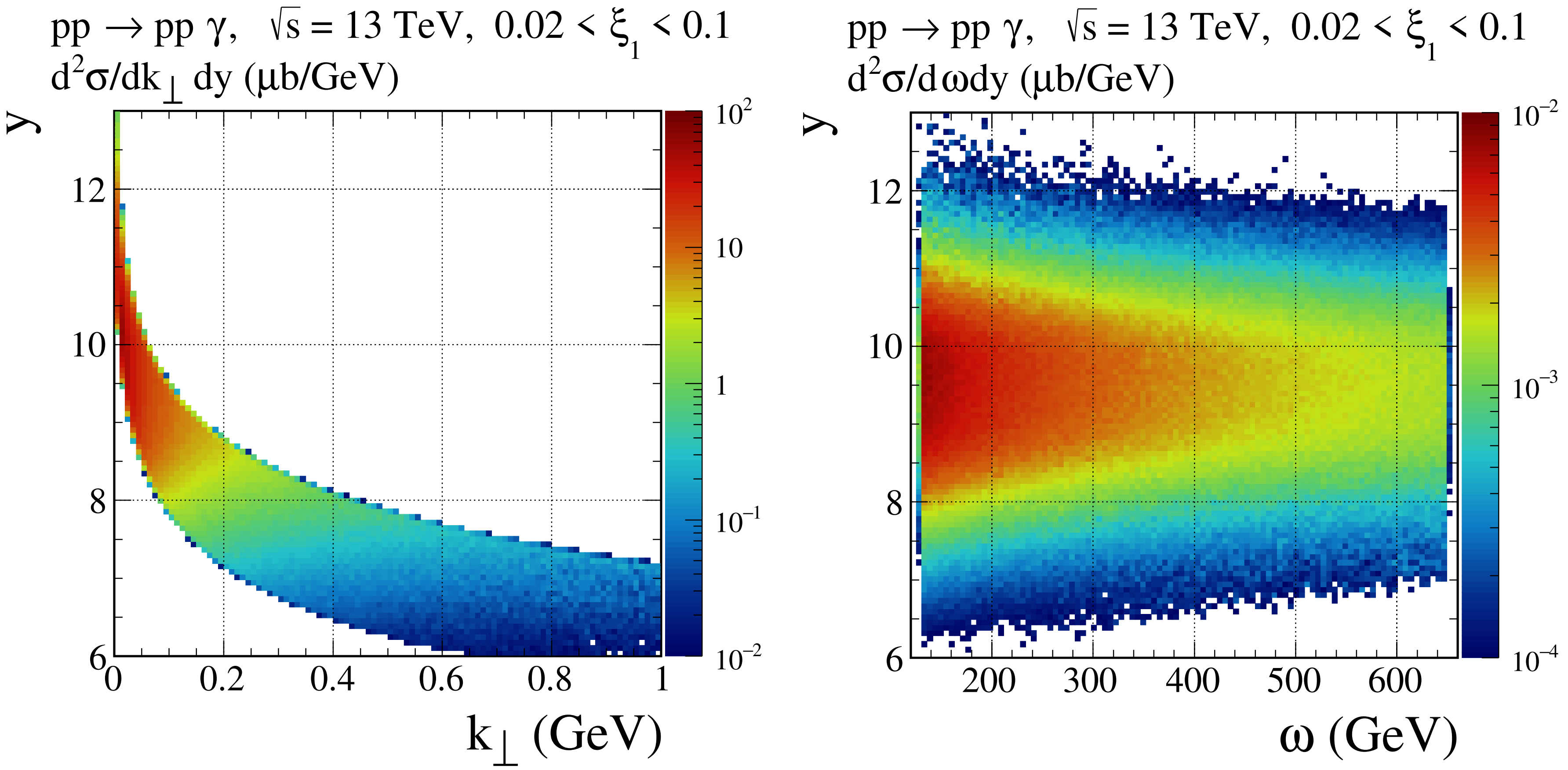
$$p_a \cdot k \approx p_1' \cdot k < 1\ \mathrm{GeV}^2$$

$$\omega \approx \xi_1\, p_a^0 = \xi_1\, \frac{\sqrt{s}}{2}$$

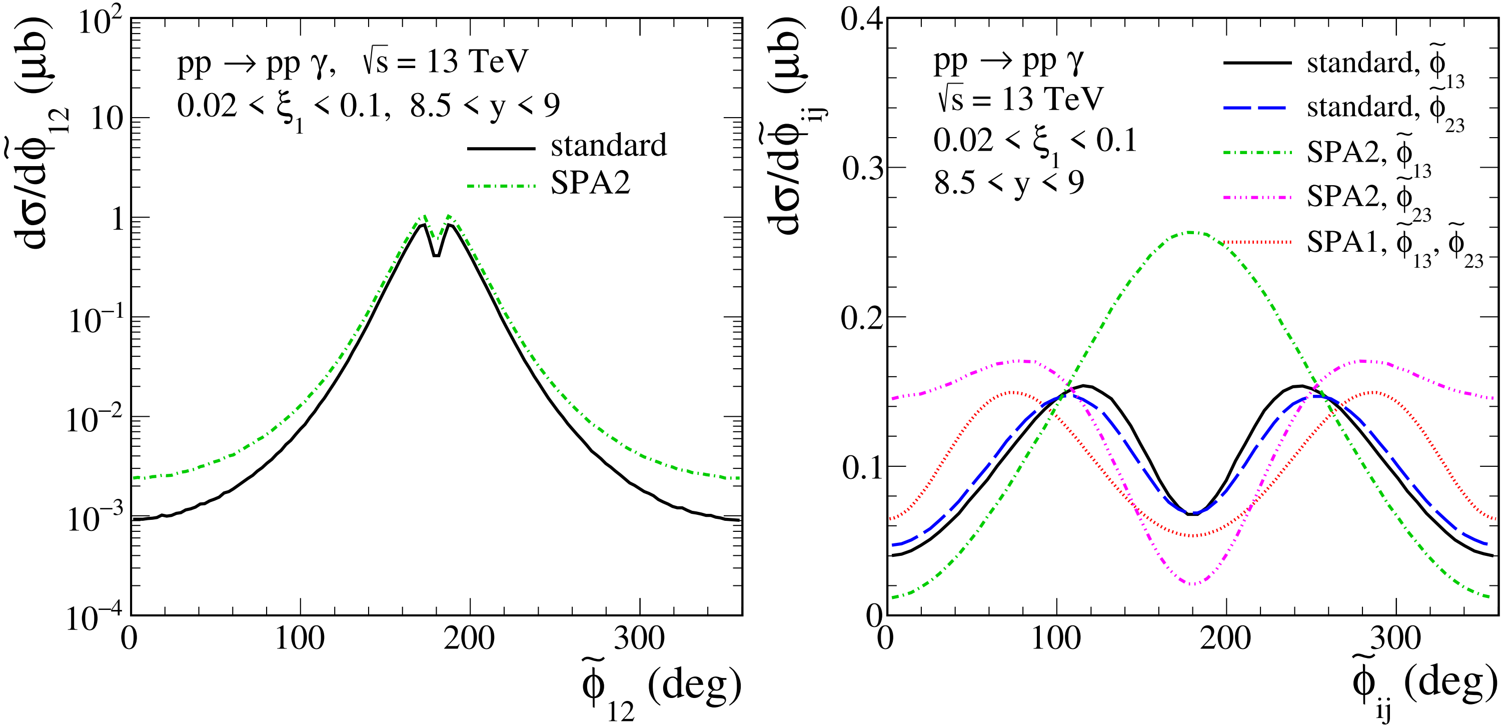
$$\xi_1 = \frac{p_b \cdot q_1}{p_b \cdot p_a} \approx \frac{p_a^0 - p_1'^0}{p_a^0} \approx \frac{k_\perp}{\sqrt{s}} \exp(\mathrm{y})$$



Results, $pp \to pp\gamma$



Results,
pp → ppγ

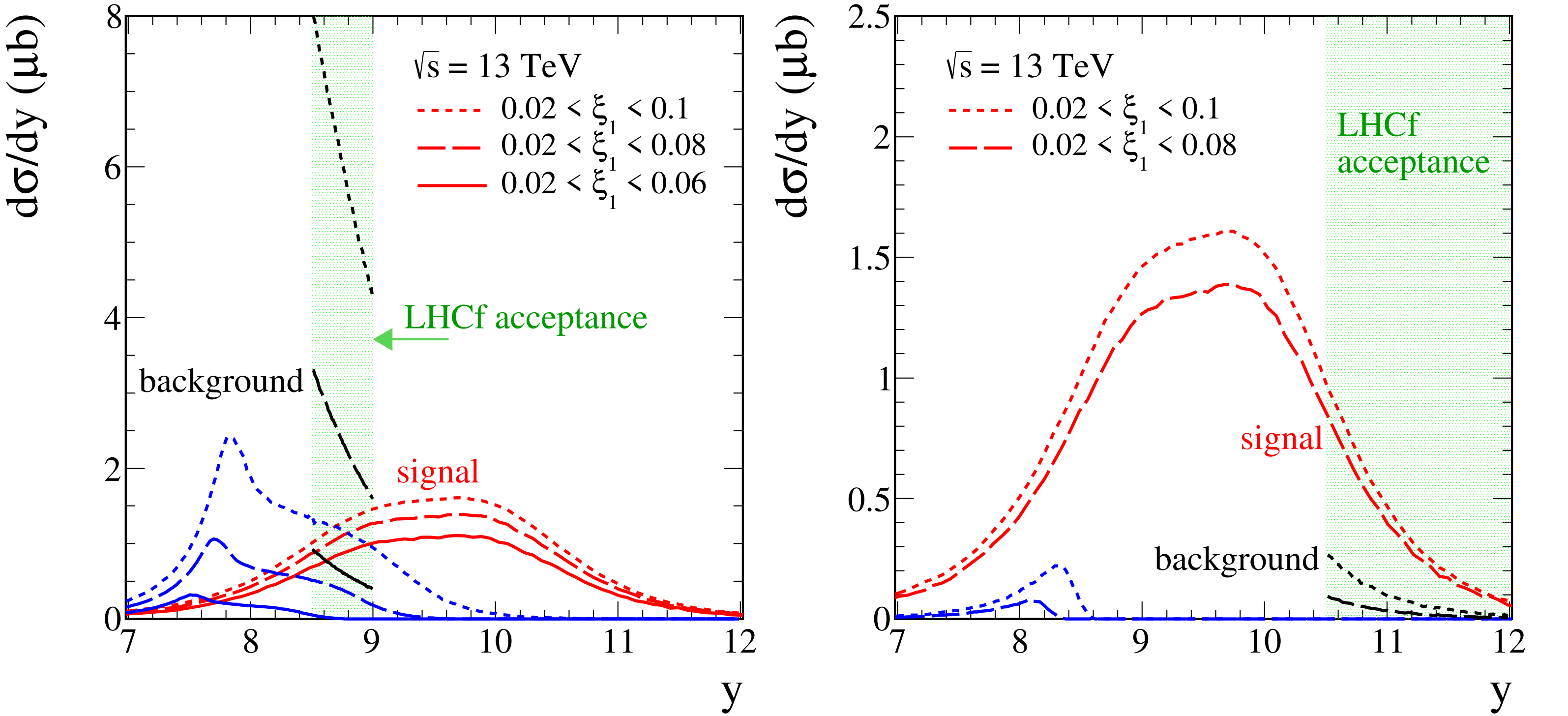


- The azimuthal angle correlations between outgoing particles

$$\tilde{\phi}_{ij} = \phi_i - \phi_j \mod(2\pi), \qquad 0 \leqslant \tilde{\phi}_{ij} < 2\pi$$

  are different for standard (exact) approach and for the SPA1 and SPA2 approaches.
- For SPA1 the outgoing protons are back-to-back $\tilde{\phi}_{12} = \pi$ (not shown here).
- The SPA2 results for the azimuthal angles between proton and photon (right panel) deviate very significantly from our standard results.

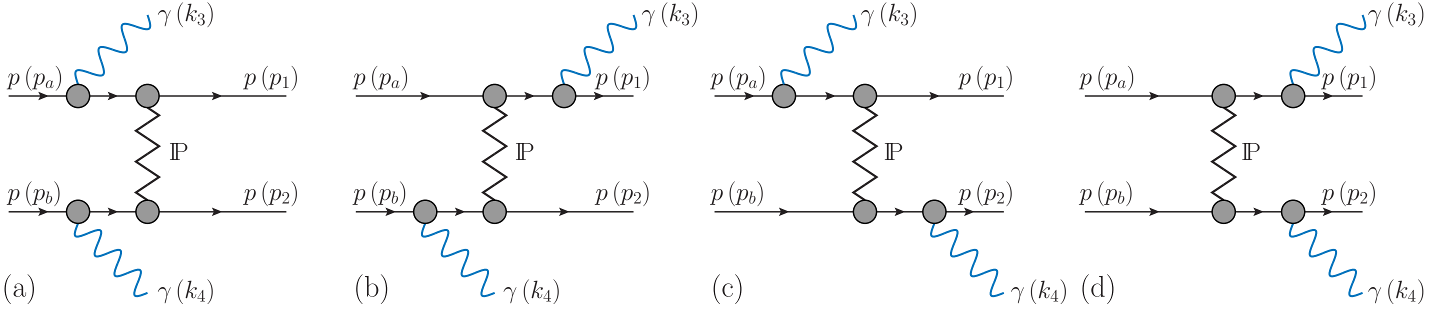
Results, $pp \to pp\gamma$



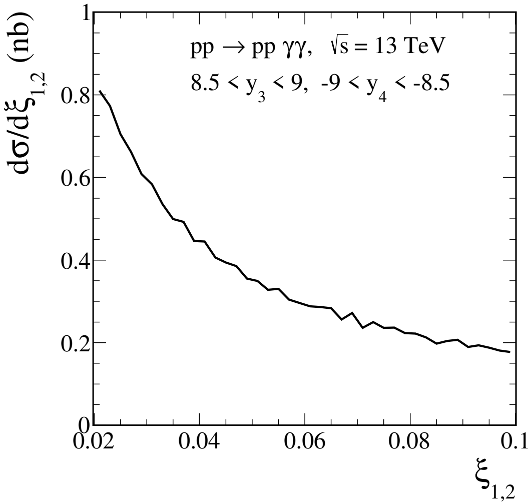
- Signal and background contributions in two LHCf acceptance regions. For the background contribution we show the distributions of both photons from the decay of π^0.
  Background: $pp \to pp\pi^0$ (DHD-type model based on Lebiedowicz, Szczurek PRD87 (2013) 074037).

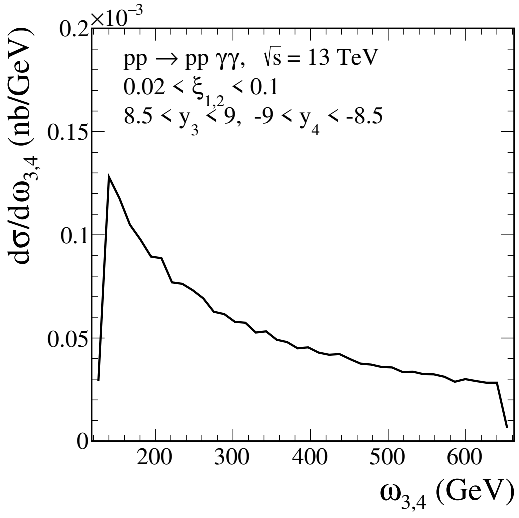
- One can increase the signal-to-background ratio to about 1 for the first LHCf acceptance region. For the second acceptance region the ratio > 3.5.
- In order to isolate our signal reaction it would be very helpful if the transverse momenta of the outgoing protons and photon could be measured.

Results, $pp \to pp\gamma\gamma$



$$\mathcal{M}_{\mu\nu,\,\mathrm{SPA1}} = e^2 \mathcal{M}^{(\text{on shell})\,pp}(s,t) \times \left[-\frac{p_{a\mu}}{(p_a \cdot k_3)} + \frac{p_{1\mu}}{(p_1 \cdot k_3)} \right] \times \left[-\frac{p_{b\nu}}{(p_b \cdot k_4)} + \frac{p_{2\nu}}{(p_2 \cdot k_4)} \right]$$





$\sigma \simeq 0.03$ nb for $\sqrt{s} = 13$ TeV
and $8.5 < y_3 < 9$, $-9 < y_4 < -8.5$ (LHCf),
$0.02 < \xi_{1,2} < 0.1$ (AFP)

$$\xi_{1,2} = \frac{k_{\perp 3}}{\sqrt{s}} \exp(\pm y_3) + \frac{k_{\perp 4}}{\sqrt{s}} \exp(\pm y_4)$$

Conclusions

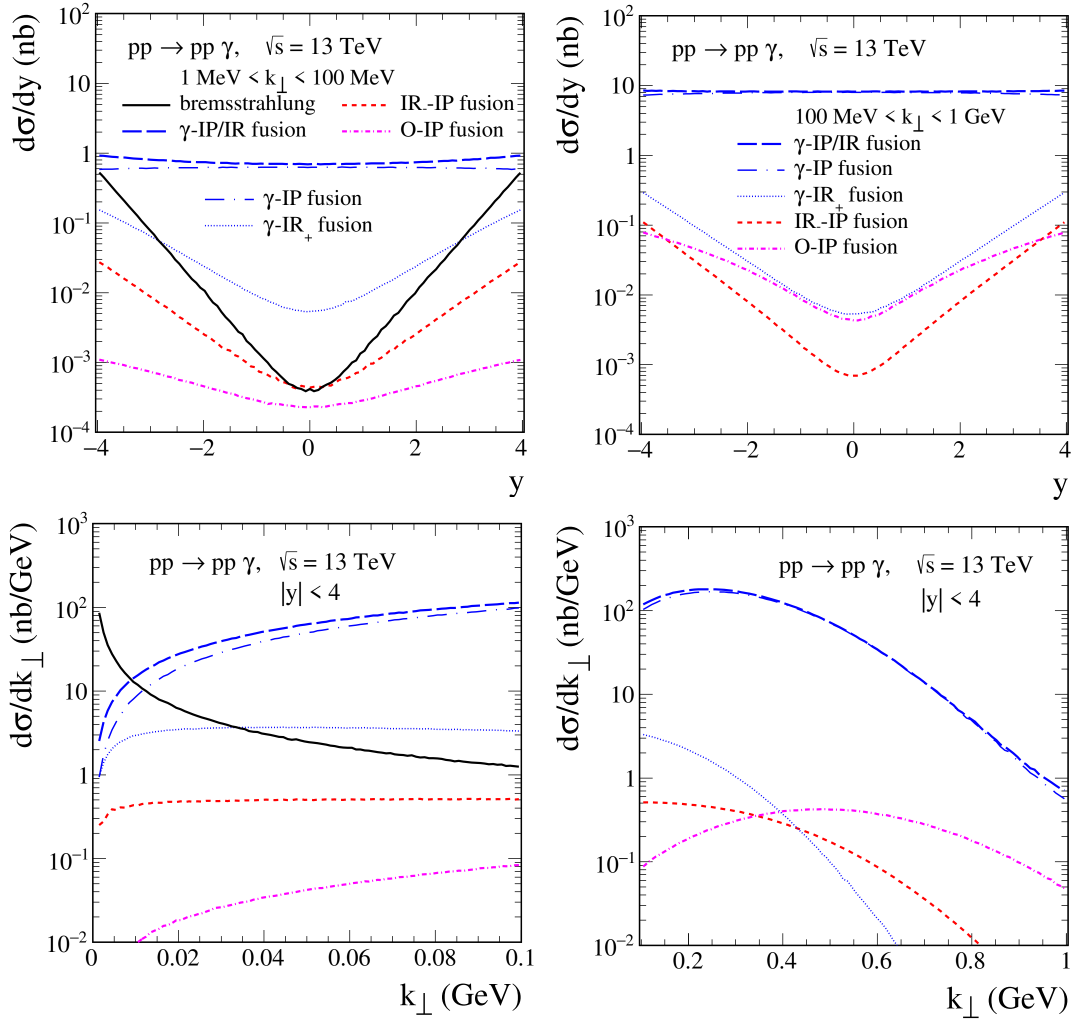
- We have studied single- and double-photon bremsstrahlung at very-forward photon rapidities in proton-proton collisions at the LHC.

- To claculate the radiative amplitudes the framework of the tensor-pomeron model was used. We have compared our standard (complete) bremsstrahlung results and the results using the approximations SPA1 and SPA2.

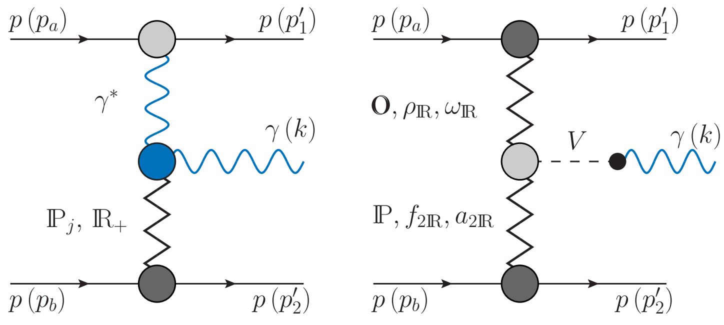
- The single photon bremsstrahlung mechanism should be identifiable by the measurement of proton (AFP) and photon (LHCf) on one side and by checking the exclusivity condition (no particles in the ATLAS detector) without explicit measurement of the opposite side proton. Whether this is sufficient requires further studies, since such a measurement will probably include one-side diffractive dissociation, which can be of the order of 25%.

- We have estimated the coincidence cross section (within SPA1) for $pp \to pp\gamma\gamma$ where photons are emitted in opposite sides of the ATLAS interaction point and can be measured by two different arms of LHCf. The cross section is rather small but should be measurable. A study of the background contributions should be done in future.

Results, *pp → ppγ*



Central exclusive production (CEP)



[Lebiedowicz et al., PRD 107 (2023) 074014]

At midrapidities, the photoproduction (left diagram) gives a much larger cross section than bremsstrahlung.
CEP via γ* - IP fusion is intimately related to DVCS (Phys.Lett.B 835 (2022) 137497).

The soft-photon bremsstrahlung is important in the forward rapidity range, |y| > 4, and at very small $k_\perp$.

Results

- Predictions for the proposed measurement of soft photon ($pp \to pp\gamma$) with the planned ALICE3 detector at the LHC.
- The width of the distribution in $\tilde{\phi}_{12}$ depends on the ω cut.
- For detailed comparisons of our predictions with experiment and in order to distinguish our standard and the approximate approaches (SPAs) measurement of the outgoing protons would be welcome.