

Exclusive bremsstrahlung of photons at high energies

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in collaboration with Piotr Lebiedowicz

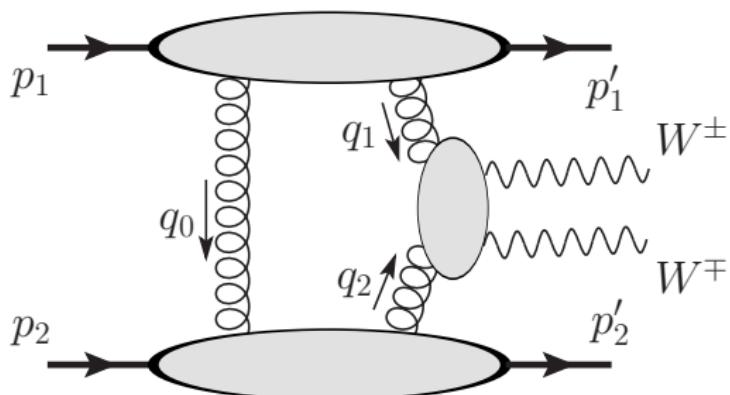


Introduction

- Inclusive photon production at high energies in several Monte Carlo
- Exclusive **single** photon bremsstrahlung at high energy was practically not studied.
- Only recently **classical bremsstrahlung**, approximate formulas, point-like particles.
- Monte Carlo generators do not include it.
- What are relevant mechanisms ?
- Vector mesons bremsstrahlung (**Cisek,Lebiedowicz,Schäfer, A.S.**)
- Differential distributions ?
- New **test of dynamics** of diffractive processes.
- Good test for and of **forward detectors**.



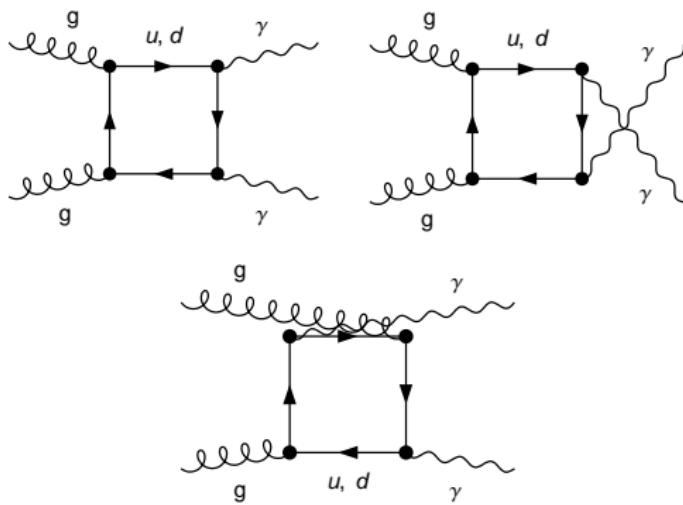
$pp \rightarrow pp\gamma\gamma$



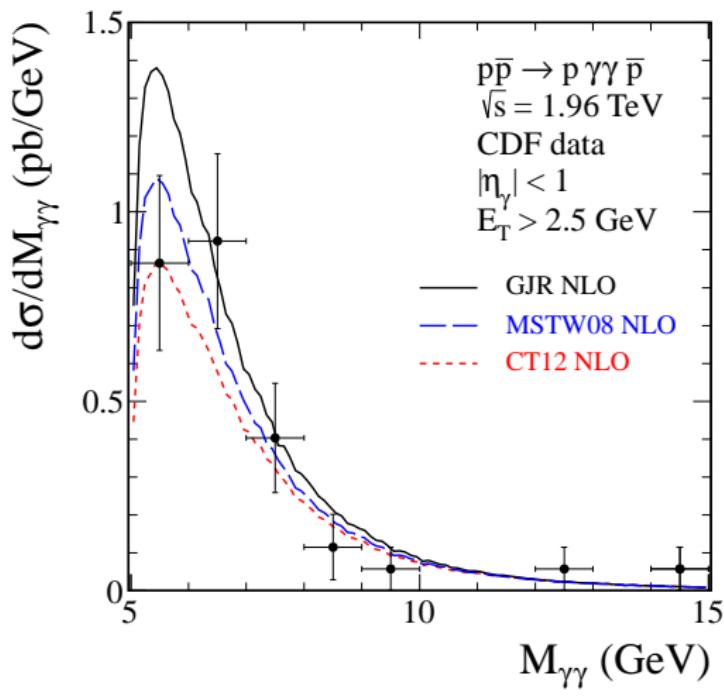
Lebiedowicz, Pasechnik, Szczurek

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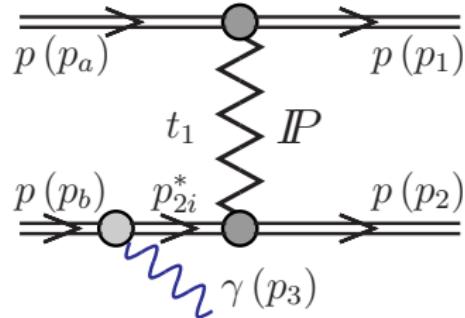
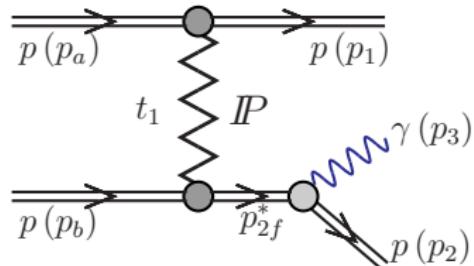
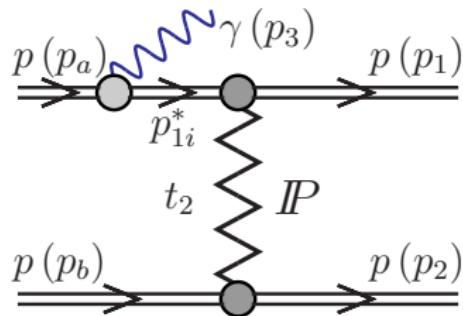
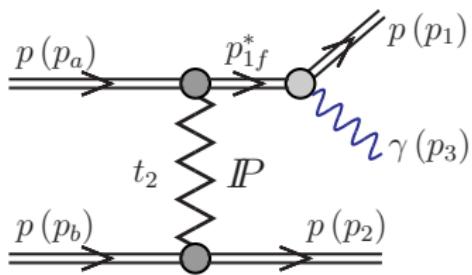
$pp \rightarrow pp\gamma\gamma$



$pp \rightarrow pp\gamma\gamma$



Classical bremsstrahlung



Classical bremsstrahlung

$$\begin{aligned}
 M_{\bar{n}_a \bar{n}_b \rightarrow \bar{n}_1 \bar{n}_2 \bar{n}_\gamma}^{(a)} &= e \bar{u}(\rho_1, \bar{n}_1) \gamma^\mu S_N(p_{1f}^{*2}) u(\rho_a, \bar{n}_a) \varepsilon_\mu^*(\rho_\gamma, \bar{n}_\gamma) F_{\gamma N^* N}(p_{1f}^{*2}) F_{PN^* N}(p_{1f}^{*2}) \\
 &\times i s_{ab} C_P^{NN} \left(\frac{s_{ab}}{s_0} \right)^{\alpha_P(t_2)-1} \exp \left(\frac{B_P^{NN} t_2}{2} \right) \delta_{\bar{n}_2 \bar{n}_b}, \tag{1}
 \end{aligned}$$

$$\begin{aligned}
 M_{\bar{n}_a \bar{n}_b \rightarrow \bar{n}_1 \bar{n}_2 \bar{n}_\gamma}^{(b)} &= e \bar{u}(\rho_2, \bar{n}_2) \gamma^\mu S_N(p_{2f}^{*2}) u(\rho_b, \bar{n}_b) \varepsilon_\mu^*(\rho_\gamma, \bar{n}_\gamma) F_{\gamma N^* N}(p_{2f}^{*2}) F_{PN^* N}(p_{2f}^{*2}) \\
 &\times i s_{ab} C_P^{NN} \left(\frac{s_{ab}}{s_0} \right)^{\alpha_P(t_1)-1} \exp \left(\frac{B_P^{NN} t_1}{2} \right) \delta_{\bar{n}_1 \bar{n}_a}, \tag{2}
 \end{aligned}$$

$$\begin{aligned}
 M_{\bar{n}_a \bar{n}_b \rightarrow \bar{n}_1 \bar{n}_2 \bar{n}_\gamma}^{(c)} &= e \bar{u}(\rho_1, \bar{n}_1) S_N(p_{1f}^{*2}) \gamma^\mu u(\rho_a, \bar{n}_a) \varepsilon_\mu^*(\rho_\gamma, \bar{n}_\gamma) F_{\gamma NN^*}(p_{1f}^{*2}) F_{PN^* N}(p_{1f}^{*2}) \\
 &\times i s_{12} C_P^{NN} \left(\frac{s_{12}}{s_0} \right)^{\alpha_P(t_2)-1} \exp \left(\frac{B_P^{NN} t_2}{2} \right) \delta_{\bar{n}_2 \bar{n}_b}, \tag{3}
 \end{aligned}$$

$$\begin{aligned}
 M_{\bar{n}_a \bar{n}_b \rightarrow \bar{n}_1 \bar{n}_2 \bar{n}_\gamma}^{(d)} &= e \bar{u}(\rho_2, \bar{n}_2) S_N(p_{2f}^{*2}) \gamma^\mu u(\rho_b, \bar{n}_b) \varepsilon_\mu^*(\rho_\gamma, \bar{n}_\gamma) F_{\gamma NN^*}(p_{2f}^{*2}) F_{PN^* N}(p_{2f}^{*2}) \\
 &\times i s_{12} C_P^{NN} \left(\frac{s_{12}}{s_0} \right)^{\alpha_P(t_1)-1} \exp \left(\frac{B_P^{NN} t_1}{2} \right) \delta_{\bar{n}_1 \bar{n}_a}. \tag{4}
 \end{aligned}$$



Classical bremsstrahlung

$$t_{1,2} = (p_{a,b} - p_{1,2})^2 = q_{1,2}^2,$$

$$p_{1i,2i}^{*2} = (p_{a,b} - p_\gamma)^2,$$

$$p_{1f,2f}^{*2} = (p_{1,2} + p_\gamma)^2$$

$$s_{ij} = (p_i + p_j)^2$$

$$a_p(t) = 1.0808 + 0.25 t.$$

$$B(s) = B_0 + 2a'_p \ln\left(\frac{s}{s_0}\right)$$

where we use the value $s_0 = 1 \text{ GeV}^2$ and $B_0 = 9 \text{ GeV}^{-2}$.

off-shell nucleon

$$F(p^*) = \frac{\Lambda_N^4}{(p^{*,2} - m_N^2)^2 + \Lambda_N^4} \quad (5)$$

this form used at low-energy bremsstrahlung

Classical bremsstrahlung

When the off-shell effects of the participating protons are neglected, hence the γNN^* and $\gamma N^* N$ vertices are parametrized by the on-shell proton e.m. form factors in terms of the Dirac and Pauli form factors $F_1(p_\gamma^2)$ and $F_2(p_\gamma^2)$ given by

$$e\gamma^\mu F_{\gamma NN} F_{PNN} \rightarrow e \left[F_1(p_\gamma^2) \gamma^\mu - \frac{i}{2m_N} F_2(p_\gamma^2) \sigma^{\mu\nu} p_{\gamma\nu} \right] \quad (6)$$

$$\text{where } \sigma^{\mu\nu} = \frac{i}{2} [\gamma^\mu, \gamma^\nu] = \frac{i}{2} (\gamma^\mu \gamma^\nu - \gamma^\nu \gamma^\mu).$$

$$F_1(p_\gamma^2 = 0) = 1 \text{ and } F_2(p_\gamma^2 = 0) = \kappa_p = 1.79.$$

The propagators of the intermediate nucleons

$$S_N(p_{1f,2f}^{*2}) = \frac{i(p_{1f,2f_v}^* \gamma^v + m_N)}{p_{1f,2f}^{*2} - m_N^2}, \quad S_N(p_{1i,2i}^{*2}) = \frac{i(p_{1i,2i_v}^* \gamma^v + m_N)}{p_{1i,2i}^{*2} - m_N^2}. \quad (7)$$

Classical bremsstrahlung

The polarization vectors of real photon are defined in the proton-proton center-of-mass frame

$$\varepsilon(p_\gamma, \pm 1) = \frac{1}{\sqrt{2}}(0, i \sin \phi \mp \cos \vartheta \cos \phi, -i \cos \phi \mp \cos \vartheta \sin \phi, \pm \sin \vartheta), \quad (8)$$

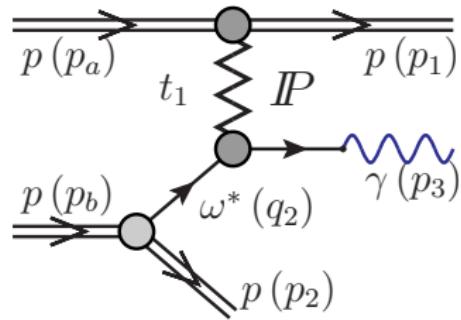
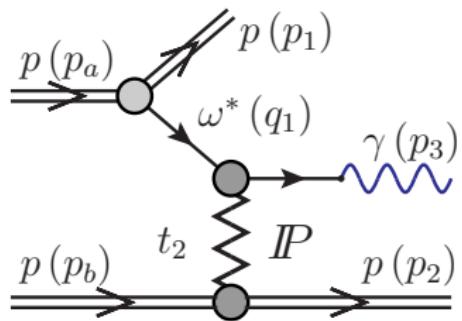
It is easy to check that:

$$\varepsilon^\mu(p, \hat{\lambda}) \varepsilon_\mu^*(p, \hat{\lambda}) = -1, \quad (9)$$

$$p^\mu \varepsilon_\mu(p, \hat{\lambda}) = 0. \quad (10)$$



Vector meson rescattering



Vector meson is off-mass shell.

Similar diagrams for ρ^0 meson.

The diagrams for ω and ρ^0 interfere.

Vector meson rescattering

$$\begin{aligned} M_{\bar{\rho}_a \bar{\rho}_b \rightarrow \bar{\rho}_1 \bar{\rho}_2 \bar{\rho}_\gamma}^{(e)} &= \bar{u}(\rho_1, \bar{\rho}_1) \gamma^\mu u(\rho_a, \bar{\rho}_a) S_{\mu\nu}(t_1) \varepsilon^{\nu*}(\rho_\gamma, \bar{\rho}_\gamma) g_{\omega NN} F_{\omega^* NN}(t_1) F_{P\omega^*\omega}(t_1) C_{\omega \rightarrow \gamma} \\ &\times i s_{23} C_p^{\omega N} \left(\frac{s_{23}}{s_0} \right)^{a_p(t_2)-1} \left(\frac{s_{13}}{s_{th}} \right)^{a_\omega(t_1)-1} \exp \left(\frac{B_p^{\omega N} t_2}{2} \right) \delta_{\bar{\rho}_2 \bar{\rho}_b}. \end{aligned} \quad (11)$$

$$\begin{aligned} M_{\bar{\rho}_a \bar{\rho}_b \rightarrow \bar{\rho}_1 \bar{\rho}_2 \bar{\rho}_\gamma}^{(f)} &= \bar{u}(\rho_2, \bar{\rho}_2) \gamma^\mu u(\rho_b, \bar{\rho}_b) S_{\mu\nu}(t_2) \varepsilon^{\nu*}(\rho_\gamma, \bar{\rho}_\gamma) g_{\omega NN} F_{\omega^* NN}(t_2) F_{P\omega^*\omega}(t_2) C_{\omega \rightarrow \gamma} \\ &\times i s_{13} C_p^{\omega N} \left(\frac{s_{13}}{s_0} \right)^{a_p(t_1)-1} \left(\frac{s_{23}}{s_{th}} \right)^{a_\omega(t_2)-1} \exp \left(\frac{B_p^{\omega N} t_1}{2} \right) \delta_{\bar{\rho}_1 \bar{\rho}_a}, \end{aligned} \quad (12)$$

Vector meson rescattering

$$C_P^{\omega N} = C_P^{\pi N} = 13.63 \text{ mb} \text{ (Donnachie-Landshoff)}$$

$$B_P^{\omega N} = B_P^{\pi N} = 5.5 \text{ GeV}^{-2}.$$

The amplitudes are corrected to reproduce the high-energy Regge dependence.

$$a_\omega(t) = 0.5 + 0.9t \text{ and } s_{th} = (m_N + m_\omega)^2.$$

$$g_{\omega NN}^2/4\pi = 10 \text{ (different values have been used in the literature)}$$

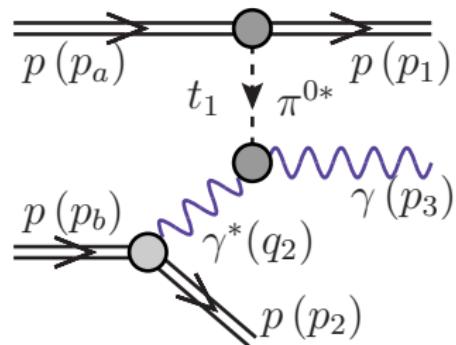
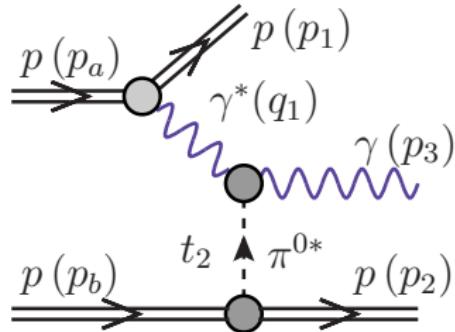
$$C_{\omega \rightarrow \gamma} = \sqrt{a_{em}/20.5}$$

within vector dominance model with finite width corrections
(Uleshchenko-Szczerba)

$$S_{\mu\nu}(t) = \frac{-g_{\mu\nu} + \frac{q_\mu q_\nu}{m_\omega^2}}{t - m_\omega^2}. \quad (13)$$

$$F_{\omega^* NN}(t_{1,2}) = \exp\left(\frac{t_{1,2} - m_\omega^2}{\Lambda_{\omega NN}^2}\right), F_{P\omega^*\omega}(t_{1,2}) = \exp\left(\frac{t_{1,2} - m_\omega^2}{\Lambda_{P\omega\omega}^2}\right). \quad (14)$$

Pion cloud contribution



Anomalous coupling, but off-shell pion

Pion cloud contribution

$$\begin{aligned}
 M_{\bar{\rho}_a \bar{\rho}_b \rightarrow \bar{\rho}_1 \bar{\rho}_2 \bar{\rho}_\gamma}^{\pi^0 - \text{exch.}} &= \bar{u}(\rho_1, \bar{r}_1) \Gamma_{\gamma^* NN}^a(q_1^2) u(\rho_a, \bar{r}_a) \\
 &\times \frac{-g_{a\beta}}{t_1} F_{\gamma\pi \rightarrow \gamma}(t_1, t_2) \ \color{red}\epsilon^{\beta\mu\nu\bar{\rho}}\color{black} q_{1\mu} p_{3v} \varepsilon_{\bar{\rho}}^*(\rho_\gamma, \bar{r}_\gamma) \\
 &\times \color{blue}g_{\pi^0 NN}\color{black} F_{\pi NN}(t_2) \frac{1}{t_2 - m_\pi^2} \bar{u}(\rho_2, \bar{r}_2) i\gamma_5 u(\rho_b, \bar{r}_b). \tag{15}
 \end{aligned}$$

$$\begin{aligned}
 M_{\bar{\rho}_a \bar{\rho}_b \rightarrow \bar{\rho}_1 \bar{\rho}_2 \bar{\rho}_\gamma}^{\pi^0 \gamma - \text{exch.}} &= \color{blue}g_{\pi^0 NN}\color{black} F_{\pi NN}(t_1) \frac{1}{t_1 - m_\pi^2} \bar{u}(\rho_1, \bar{r}_1) i\gamma_5 u(\rho_a, \bar{r}_a) \\
 &\times \frac{-g_{a\beta}}{t_2} F_{\gamma\pi \rightarrow \gamma}(t_2, t_1) \ \color{red}\epsilon^{\beta\mu\nu\bar{\rho}}\color{black} q_{2\mu} p_{3v} \varepsilon_{\bar{\rho}}^*(\rho_\gamma, \bar{r}_\gamma) \\
 &\times \bar{u}(\rho_2, \bar{r}_2) \Gamma_{\gamma^* NN}^a(q_2^2) u(\rho_b, \bar{r}_b). \tag{16}
 \end{aligned}$$

Pion cloud

Pion-to-nucleon form factor

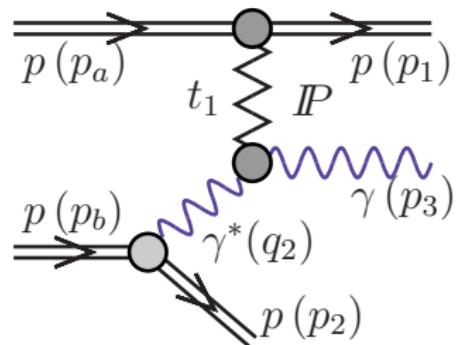
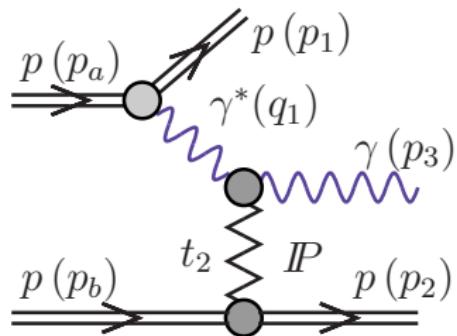
$$F_{\pi NN}(t_{1,2}) = \exp\left(\frac{t_{1,2} - m_\pi^2}{\Lambda_{\pi NN}^2}\right). \quad (17)$$

On-shell normalization

$$F_{\gamma\pi\rightarrow\gamma}(t_1, t_2) = \frac{N_c}{12\pi^2 f_\pi} \frac{m_\rho^2}{m_\rho^2 - t_1} \exp\left(\frac{t_2 - m_\pi^2}{\Lambda_{\gamma\pi\rightarrow\gamma}^2}\right) \quad (18)$$



Photon rescattering



photon-proton quasi-elastic scattering

Photon rescattering

Equivalent Photon Approximation

$$\begin{aligned}\frac{d\sigma}{dydp_{\perp}^2} &= z_1 f(z_1) \frac{d\sigma_{\gamma p \rightarrow \gamma p}}{dt_2} (W_{23}, t_2 \approx -p_{\perp}^2) \\ &+ z_2 f(z_2) \frac{d\sigma_{\gamma p \rightarrow \gamma p}}{dt_1} (W_{13}, t_1 \approx -p_{\perp}^2).\end{aligned}\quad (19)$$

$$E = p_{\perp} \cosh y \quad , \quad p_z = \pm \sqrt{E^2 - p_{\perp}^2} . \quad (20)$$

$$z_1 s = s_{13} \quad , \quad z_2 s = s_{23} \quad (21)$$

$$\begin{aligned}\frac{d\sigma_{\gamma p \rightarrow \gamma p}}{dt_1} (W_{13}, t_1) &= \frac{[\sigma_{tot}^{\gamma p}(W_{13})]^2}{16\pi} \exp(B_{\gamma p}(W_{13})t_1) \\ \frac{d\sigma_{\gamma p \rightarrow \gamma p}}{dt_2} (W_{23}, t_2) &= \frac{[\sigma_{tot}^{\gamma p}(W_{23})]^2}{16\pi} \exp(B_{\gamma p}(W_{23})t_2) .\end{aligned}\quad (22)$$



From the amplitude to cross section

Four-dimensional integration in:

$p_{1t}, p_{2t}, \gamma, \phi_{12}$

This is rather difficult !

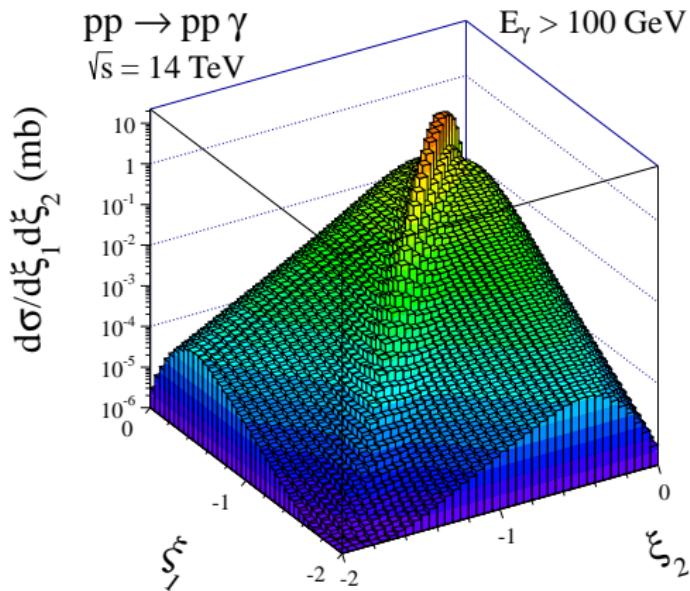
Better:

$$p_{1t} \rightarrow \xi_1 = \log_{10}(p_{1t}),$$

$$p_{2t} \rightarrow \xi_2 = \log_{10}(p_{2t})$$



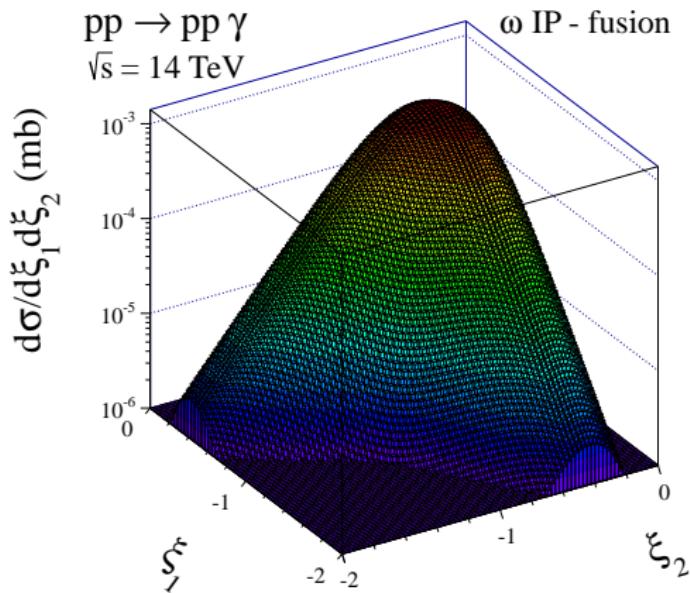
Two-dimensional integration, bremsstrahlung



Enhancement on the diagonal (elastic scattering)



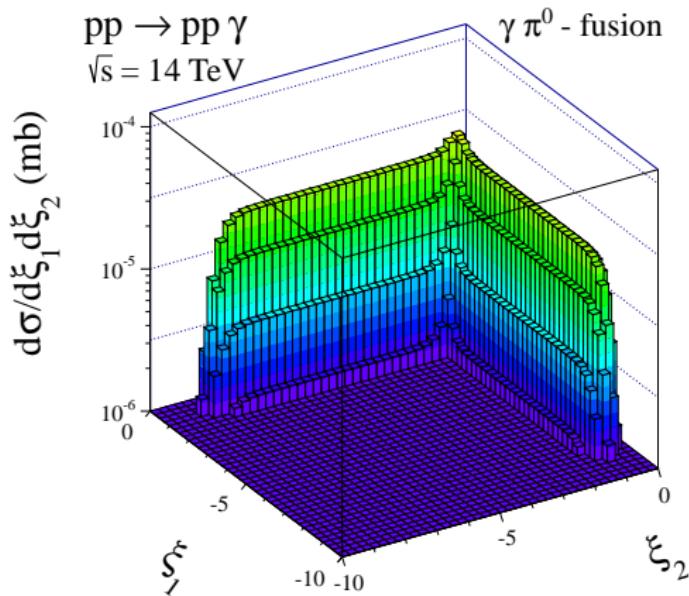
Two-dimensional integration, omega rescattering



NN absorption should be included.



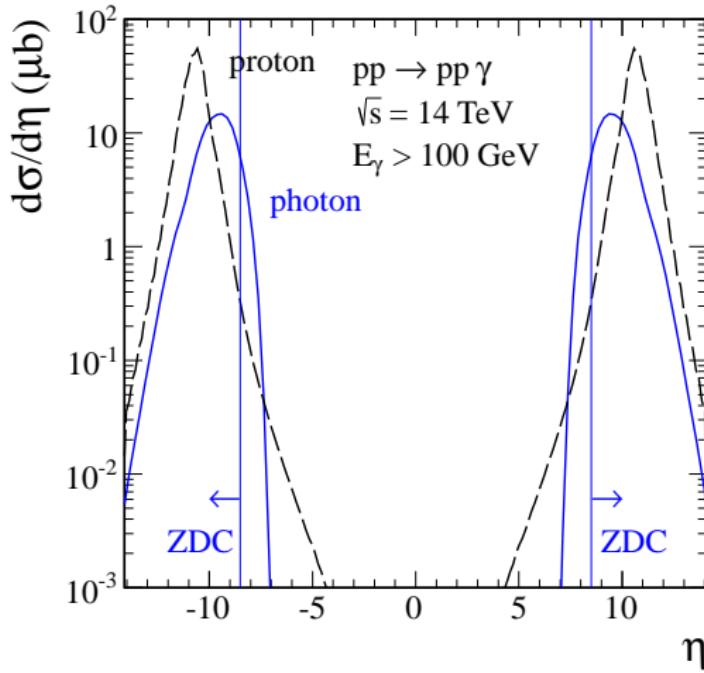
Two-dimensional integration, pion cloud



Absorption probably small



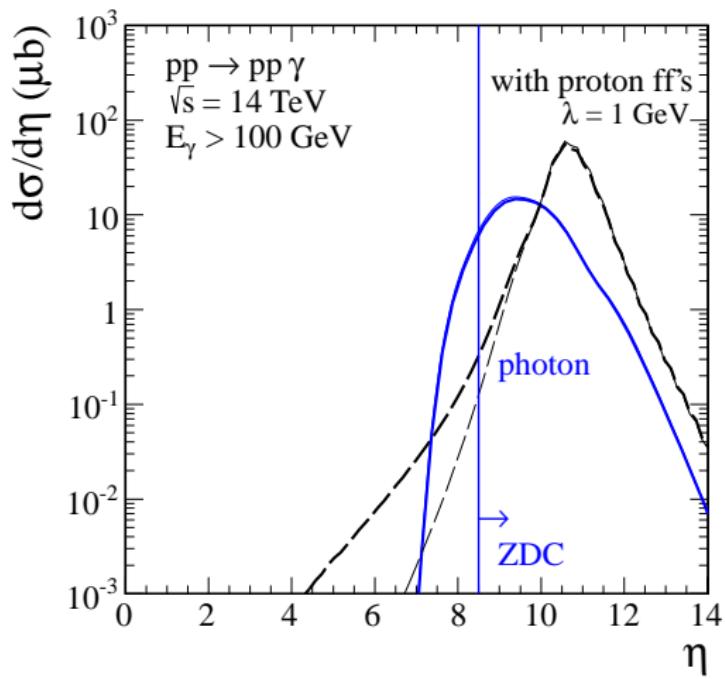
Pseudorapidity distribution of photons and protons



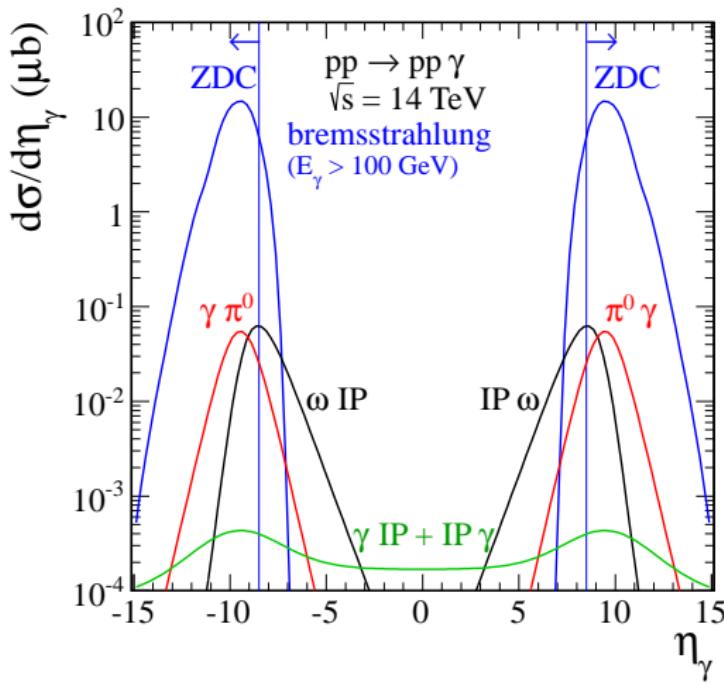
photon and proton strongly correlated



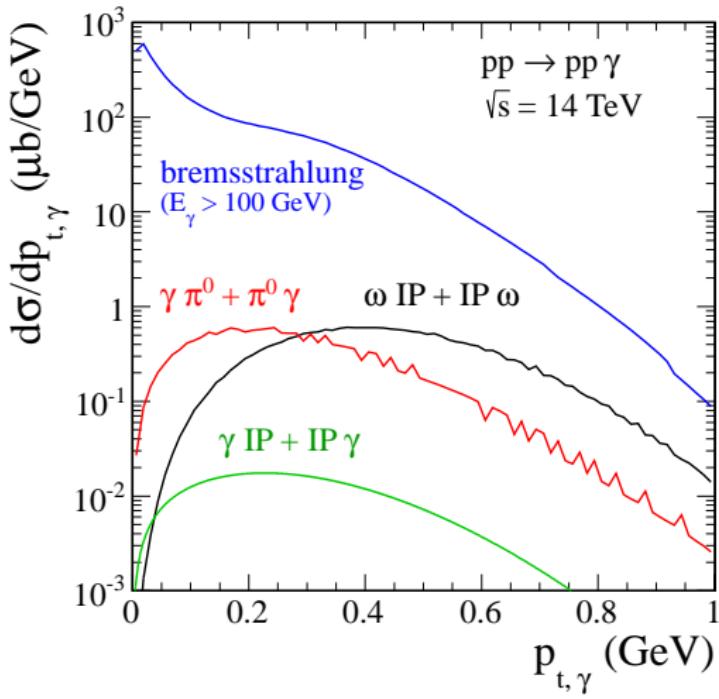
scalar vs spin-1/2 nucleons



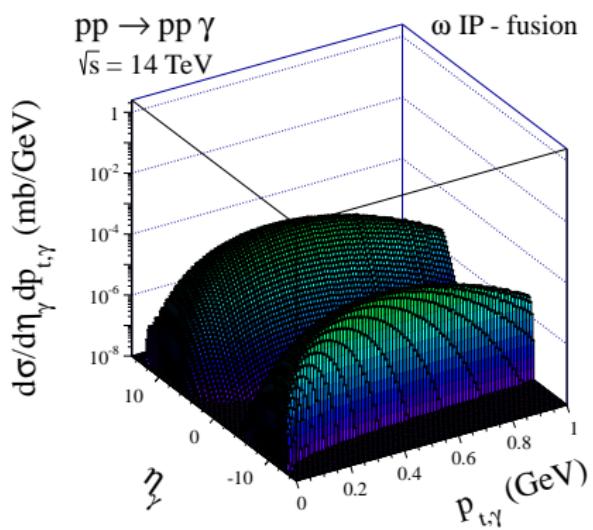
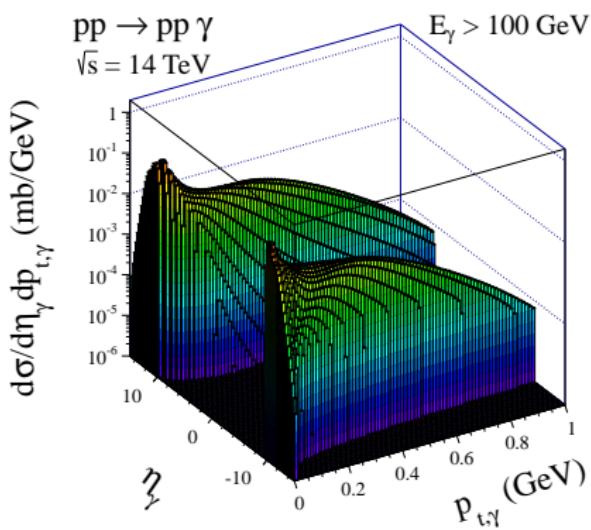
Pseudorapidity distribution of photons



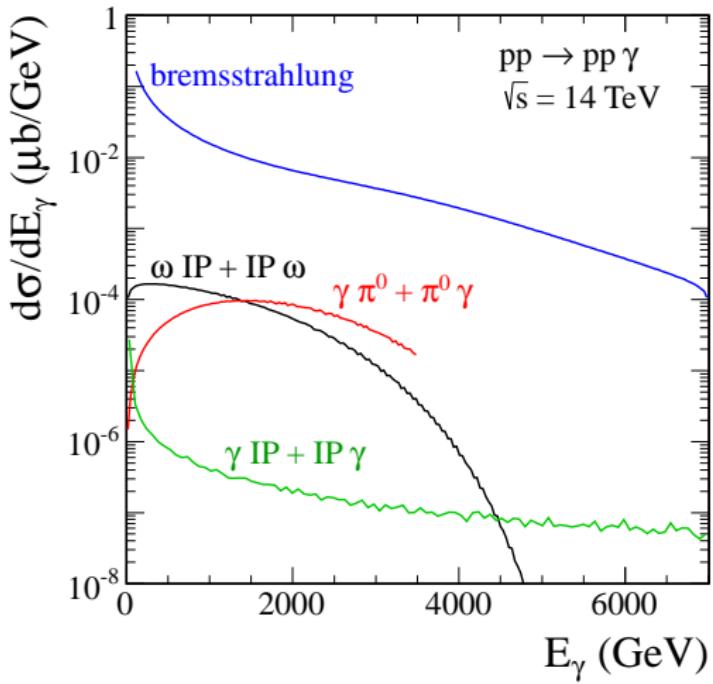
Transverse momentum of photons



Pseudorapidity-transverse momentum distributions



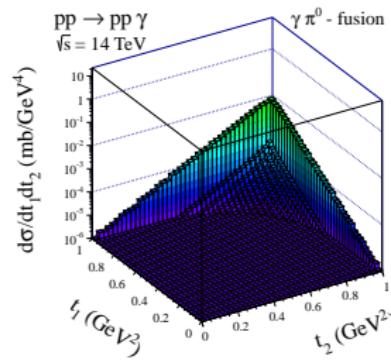
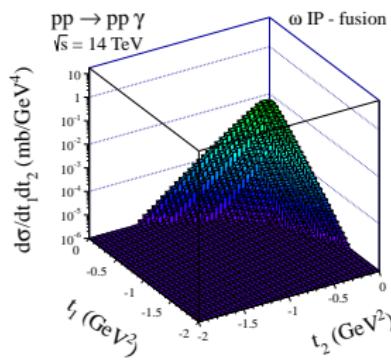
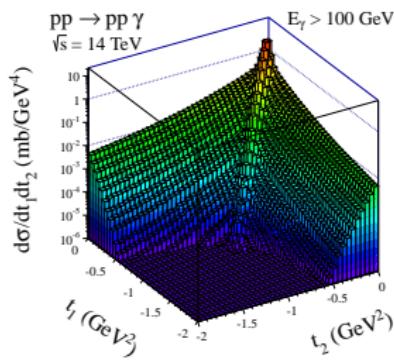
Energy of photons



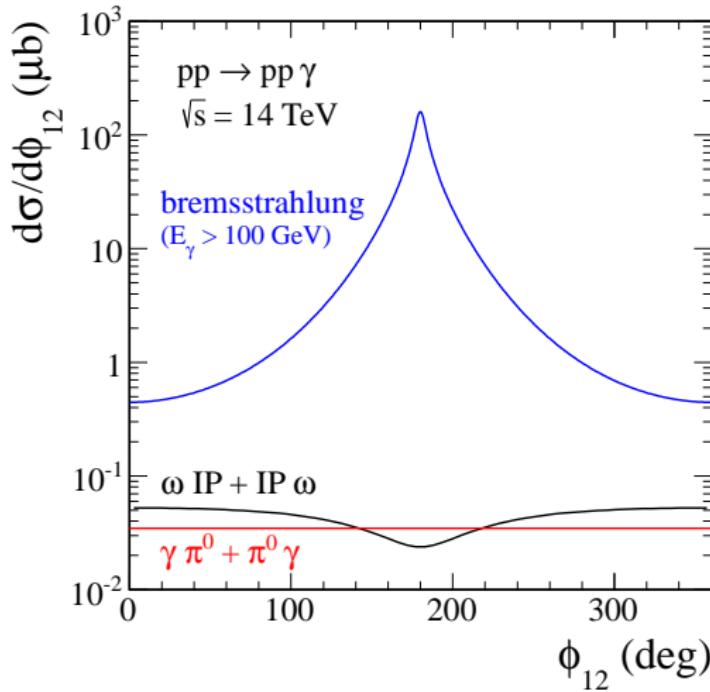
large photon energies



Proton-proton correlations



Proton-proton azimuthal correlations



reminiscence of elastic scattering



Comment on absorption effects

- classical bremsstrahlung

Includes effective nucleon-nucleon interaction.

Including absorption would be (to large extend) a double-counting.

- omega rescattering

effective ωN interaction -- effectively includes higher orders in ωN rescattering.

missing NN interaction

- pion cloud

probably small

never both t_1 and t_2 are large.

- photon rescattering

probably small

Either $p_{1t}(t_1)$ or $p_{2t}(t_2)$ are small.



Conclusions

- Exclusive photon production
- New mechanisms calculated for the first time.
- Classical bremsstrahlung gives the largest contribution.
- Photons are emitted very forward.
Could be measured by ZDC detectors.
- Protons are emitted at small angles.
Could be measured by ALPHA or TOTEM.
- Combination of both devices simultaneously would allow real measurement.
- Very small contribution at midrapidity.
- Next step → include absorption.

