Exclusive diffractive photon bremsstrahlung at high energies

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Contents

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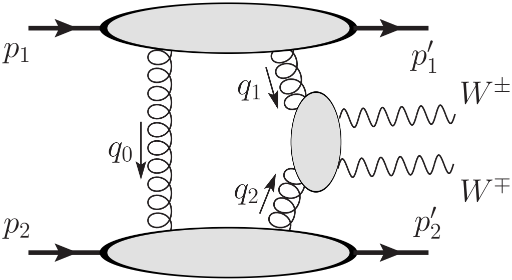
Introduction

- 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.

$pp \to pp\gamma\gamma$



Lebiedowicz, Pasechnik, Szczurek

Nucl. Phys. **B867** (2013) 61.

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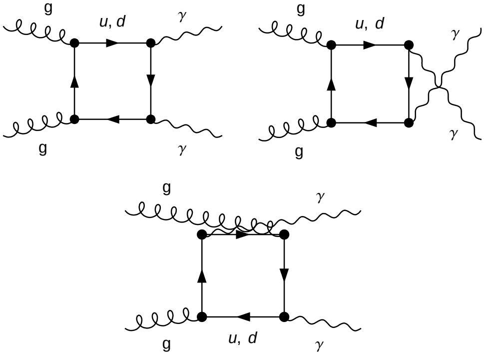

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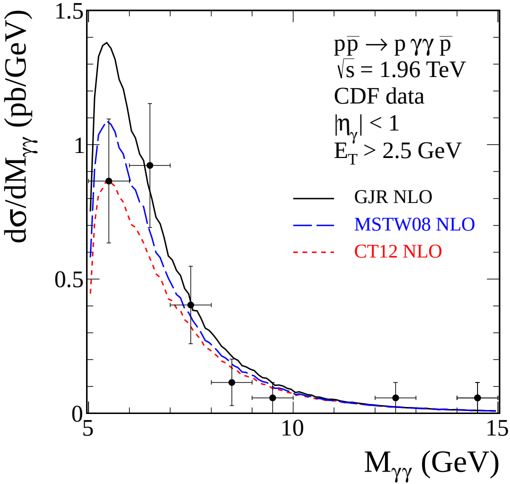
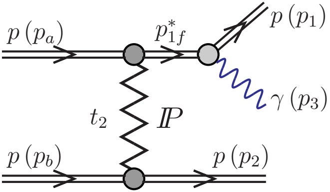
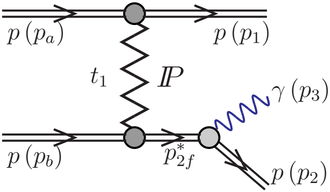
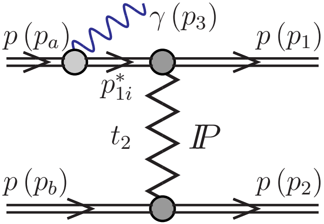
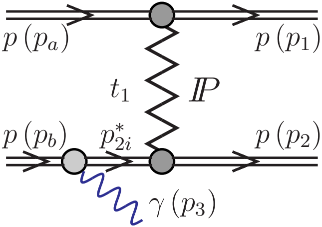


Classical bremsstrahlung









Classical bremsstrahlung

$$
\begin{aligned}
\mathcal{M}^{(a)}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\lambda_3} &= e\,\bar{u}(p_1,\lambda_1)\not\epsilon^*(p_3,\lambda_3)S_N(p_{1f}^2)\gamma^\mu u(p_a,\lambda_a)\;F_{\gamma N^* N}(p_{1f}^2)\;F_{\mathbb{P}NN^*}(p_{1f}^2) \\
&\times\quad i s\,C_{\mathbb{P}}^{NN}\left(\frac{s}{s_0}\right)^{\alpha_{\mathbb{P}}(t_2)-1}\exp\left(\frac{B_{\mathbb{P}}^{NN}t_2}{2}\right)\frac{1}{2s}\;\bar{u}(p_2,\lambda_2)\gamma_\mu u(p_b,\lambda_b)\,, && (1)\\
\mathcal{M}^{(b)}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\lambda_3} &= e\,\bar{u}(p_2,\lambda_2)\not\epsilon^*(p_3,\lambda_3)S_N(p_{2f}^2)\gamma^\mu u(p_b,\lambda_b)\;F_{\gamma N^* N}(p_{2f}^2)\;F_{\mathbb{P}NN^*}(p_{2f}^2) \\
&\times\quad i s\,C_{\mathbb{P}}^{NN}\left(\frac{s}{s_0}\right)^{\alpha_{\mathbb{P}}(t_1)-1}\exp\left(\frac{B_{\mathbb{P}}^{NN}t_1}{2}\right)\frac{1}{2s}\;\bar{u}(p_1,\lambda_1)\gamma_\mu u(p_a,\lambda_a)\,, && (2)\\
\mathcal{M}^{(c)}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\lambda_3} &= e\,\bar{u}(p_1,\lambda_1)\gamma^\mu S_N(p_{1i}^2)\not\epsilon^*(p_3,\lambda_3)u(p_a,\lambda_a)\;F_{\gamma NN^*}(p_{1i}^2)\;F_{\mathbb{P}N^* N}(p_{1i}^2) \\
&\times\quad i s_{12}\,C_{\mathbb{P}}^{NN}\left(\frac{s_{12}}{s_0}\right)^{\alpha_{\mathbb{P}}(t_2)-1}\exp\left(\frac{B_{\mathbb{P}}^{NN}t_2}{2}\right)\frac{1}{2s_{12}}\;\bar{u}(p_2,\lambda_2)\gamma_\mu u(p_b,\lambda_b)\,, && (3)\\
\mathcal{M}^{(d)}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\lambda_3} &= e\,\bar{u}(p_2,\lambda_2)\gamma^\mu S_N(p_{2i}^2)\not\epsilon^*(p_3,\lambda_3)u(p_b,\lambda_b)\;F_{\gamma NN^*}(p_{2i}^2)\;F_{\mathbb{P}N^* N}(p_{2i}^2) \\
&\times\quad i s_{12}\,C_{\mathbb{P}}^{NN}\left(\frac{s_{12}}{s_0}\right)^{\alpha_{\mathbb{P}}(t_1)-1}\exp\left(\frac{B_{\mathbb{P}}^{NN}t_1}{2}\right)\frac{1}{2s_{12}}\;\bar{u}(p_1,\lambda_1)\gamma_\mu u(p_a,\lambda_a)\,, && (4)
\end{aligned}
$$

Classical bremsstrahlung

$t_{1,2} = (p_{a,b} - p_{1,2})^2 = q^2_{1,2},$
$p^{*2}_{1i,2i} = (p_{a,b} - p_\gamma)^2,$
$p^{*2}_{1f,2f} = (p_{1,2} + p_\gamma)^2$
$s_{ij} = (p_i + p_j)^2$
$\alpha_{I\!P}(t) = 1.0808 + 0.25\, t.$
$B(s) = B_0 + 2\alpha'_{I\!P} \ln\left(\frac{s}{s_0}\right)$

where we use the value s_0 = 1 GeV^2 and B_0 = 9 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

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

where $\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu] = \frac{i}{2}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)$.
$F_1(p_\gamma^2 = 0) = 1$ and $F_2(p_\gamma^2 = 0) = \kappa_p = 1.79$.
The propagators of the intermediate nucleons

$$S_N(p^{*2}_{1f,2f}) = \frac{i(p^*_{1f,2f_\nu}\gamma^\nu + m_N)}{p^{*2}_{1f,2f} - m_N^2}, \quad S_N(p^{*2}_{1i,2i}) = \frac{i(p^*_{1i,2i_\nu}\gamma^\nu + m_N)}{p^{*2}_{1i,2i} - m_N^2}. \qquad (7)$$

Classical bremsstrahlung

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

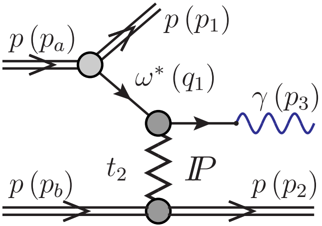
$$\varepsilon(p_\gamma, \pm 1) = \frac{1}{\sqrt{2}}\left(0, i\sin\varphi \mp \cos\vartheta\cos\varphi, -i\cos\varphi \mp \cos\vartheta\sin\varphi, \pm\sin\vartheta\right) , \quad (8)$$

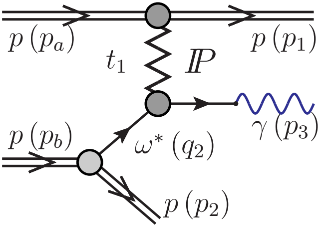
It is easy to check that:

$$\varepsilon^\mu(p,\lambda)\varepsilon^*_\mu(p,\lambda) = -1 \; , \quad (9)$$

$$p^\mu\varepsilon_\mu(p,\lambda) = 0 \; . \quad (10)$$

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

$$\mathcal{M}^{(e)}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\lambda_\gamma} = \bar{u}(p_1,\lambda_1)\gamma^{\mu}u(p_a,\lambda_a)S_{\mu\nu}(t_1)\varepsilon^{\nu*}(p_\gamma,\lambda_\gamma)\, g_{\omega NN}\, F_{\omega^* NN}(t_1)F_{\mathbb{P}\omega^*\omega}(t_1)\, C_{\omega\to\gamma}$$
$$\times\ i s_{23} C_{\mathbb{P}}^{\omega N}\left(\frac{s_{23}}{s_0}\right)^{\alpha_{\mathbb{P}}(t_2)-1}\left(\frac{s_{13}}{s_{th}}\right)^{\alpha_\omega(t_1)-1}\exp\left(\frac{B_{\mathbb{P}}^{\omega N} t_2}{2}\right)\delta_{\lambda_2\lambda_b}, \tag{11}$$

$$\mathcal{M}^{(f)}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\lambda_\gamma} = \bar{u}(p_2,\lambda_2)\gamma^{\mu}u(p_b,\lambda_b)S_{\mu\nu}(t_2)\varepsilon^{\nu*}(p_\gamma,\lambda_\gamma)\, g_{\omega NN}\, F_{\omega^* NN}(t_2)F_{\mathbb{P}\omega^*\omega}(t_2)\, C_{\omega\to\gamma}$$
$$\times\ i s_{13} C_{\mathbb{P}}^{\omega N}\left(\frac{s_{13}}{s_0}\right)^{\alpha_{\mathbb{P}}(t_1)-1}\left(\frac{s_{23}}{s_{th}}\right)^{\alpha_\omega(t_2)-1}\exp\left(\frac{B_{\mathbb{P}}^{\omega N} t_1}{2}\right)\delta_{\lambda_1\lambda_a}, \tag{12}$$

Vector meson rescattering

$C_{I\!P}^{\omega N} = C_{I\!P}^{\pi N} = 13.63$ mb (Donnachie-Landshoff)
$B_{I\!P}^{\omega N} = B_{I\!P}^{\pi N} = 5.5\ \mathrm{GeV}^{-2}$.

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

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

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

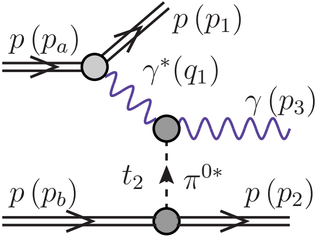
$C_{\omega\to\gamma} = \sqrt{a_{em}/20.5}$

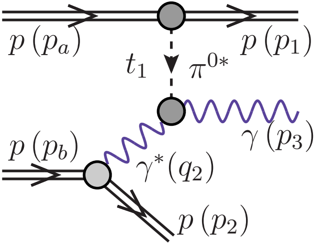
within vector dominance model with finite width corrections (Uleshchenko-Szczurek)

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

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

Pion cloud contribution





Anomalous coupling, but off-shell pion

Pion cloud contribution

$$
\begin{aligned}
\mathcal{M}^{\gamma\pi^0-exch.}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\lambda_\gamma} &= \bar{u}(p_1,\lambda_1)\Gamma^{a}_{\gamma^* NN}(q_1^2)u(p_a,\lambda_a) \\
&\times \frac{-g_{a\beta}}{t_1} F_{\gamma\pi\to\gamma}(t_1,t_2)\, \varepsilon^{\beta\mu\nu\lambda}\, q_{1\mu}\, p_{3\nu}\varepsilon^*_{\lambda}(p_\gamma,\lambda_\gamma) \\
&\times g_{\pi^0 NN}F_{\pi NN}(t_2)\, \frac{1}{t_2-m_\pi^2}\, \bar{u}(p_2,\lambda_2)i\gamma_5 u(p_b,\lambda_b)\,,
\end{aligned} \tag{15}
$$

$$
\begin{aligned}
\mathcal{M}^{\pi^0\gamma-exch.}_{\lambda_a\lambda_b\to\lambda_1\lambda_2\lambda_\gamma} &= g_{\pi^0 NN}F_{\pi NN}(t_1)\, \frac{1}{t_1-m_\pi^2}\, \bar{u}(p_1,\lambda_1)i\gamma_5 u(p_a,\lambda_a) \\
&\times \frac{-g_{a\beta}}{t_2} F_{\gamma\pi\to\gamma}(t_2,t_1)\, \varepsilon^{\beta\mu\nu\lambda}\, q_{2\mu}\, p_{3\nu}\varepsilon^*_{\lambda}(p_\gamma,\lambda_\gamma) \\
&\times \bar{u}(p_2,\lambda_2)\Gamma^{a}_{\gamma^* NN}(q_2^2)u(p_b,\lambda_b)\,,
\end{aligned} \tag{16}
$$

Pion cloud

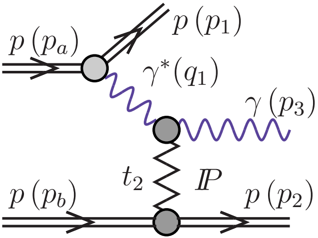
Pion-to-nucleon form factor

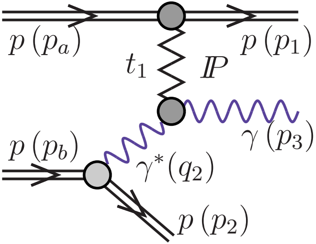
$$F_{\pi NN}(t_{1,2}) = \exp\left(\frac{t_{1,2} - m_\pi^2}{\Lambda_{\pi NN}^2}\right) . \quad (17)$$

On-shell normalization

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

Photon rescattering





photon-proton quasi-elastic scattering

Photon rescattering

Equivalent Photon Approximation

$$\frac{d\sigma}{dy dp_\perp^2} = z_1 f(z_1) \frac{d\sigma_{\gamma p \to \gamma p}}{dt_2}\left(W_{23}, t_2 \approx -p_\perp^2\right)$$
$$+ z_2 f(z_2) \frac{d\sigma_{\gamma p \to \gamma p}}{dt_1}\left(W_{13}, t_1 \approx -p_\perp^2\right) . \qquad (19)$$

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

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

$$\frac{d\sigma_{\gamma p \to \gamma p}}{dt_1}(W_{13}, t_1) = \frac{\left[\sigma_{tot}^{\gamma p}(W_{13})\right]^2}{16\pi} \exp\left(B_{\gamma p}(W_{13}) t_1\right)$$
$$\frac{d\sigma_{\gamma p \to \gamma p}}{dt_2}(W_{23}, t_2) = \frac{\left[\sigma_{tot}^{\gamma p}(W_{23})\right]^2}{16\pi} \exp\left(B_{\gamma p}(W_{23}) t_2\right) . \qquad (22)$$

From the amplitude to cross section

Four-dimensional integration in:

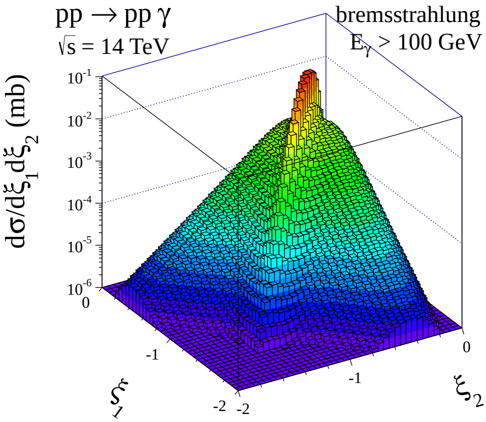
$p_{1t}, p_{2t}, y, \phi_{12}$

This is rather difficult !

Better:

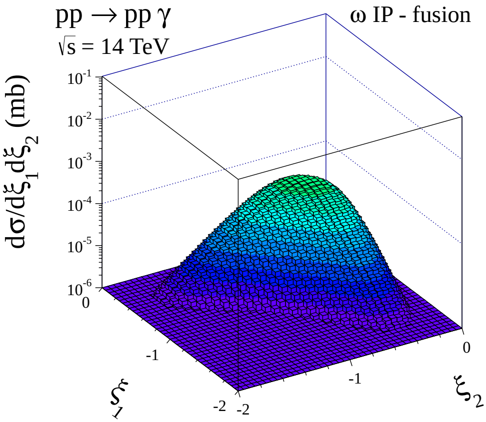
$p_{1t} \to \xi_1 = \log_{10}(p_{1t})$,
$p_{2t} \to \xi_2 = \log_{10}(p_{2t})$

Two-dimensional integration, bremsstrahlung



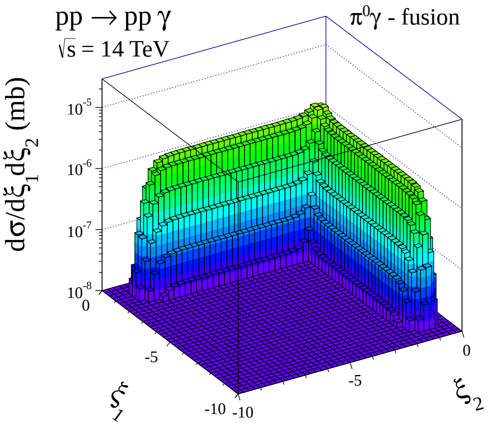
Enhancement on the diagonal(elastic scattering)

Two-dimensional integration, omega rescattering



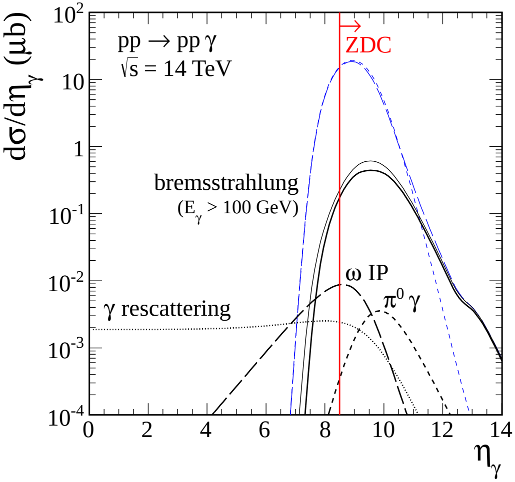
NN absorption should be included.

Two-dimensional integration, pion cloud

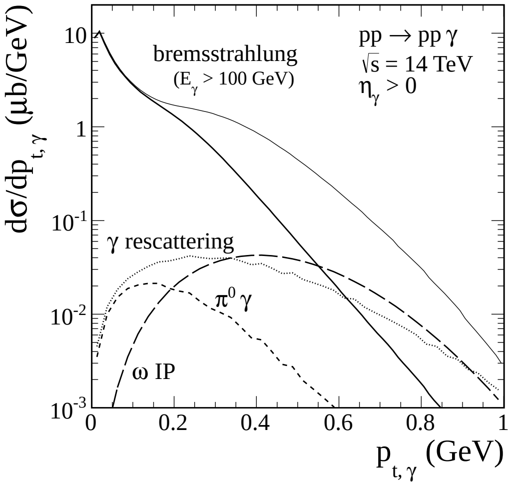


Absorption probably small

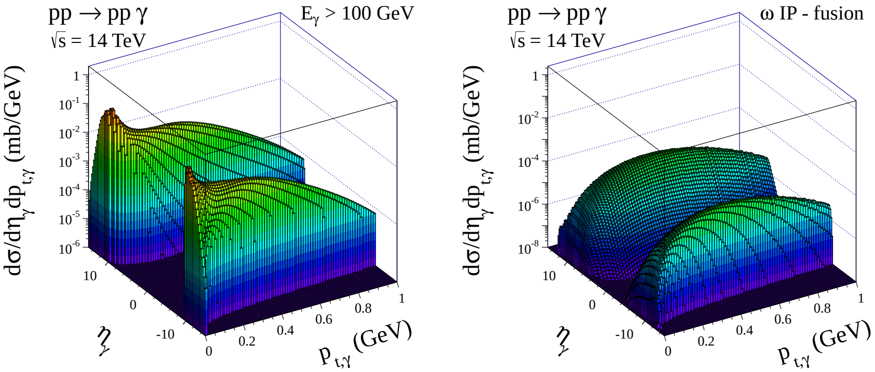
Pseudorapidity distribution of photons



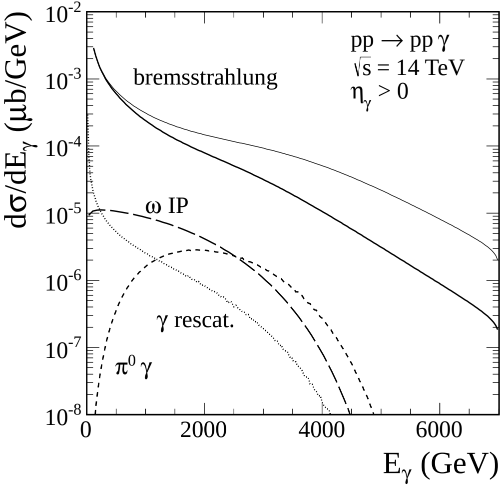
Transverse momentum of photons



Pseudorapidity-transverse momentum distributions

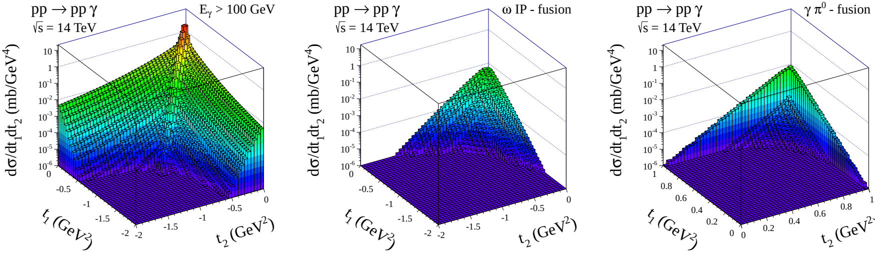


Energy of photons

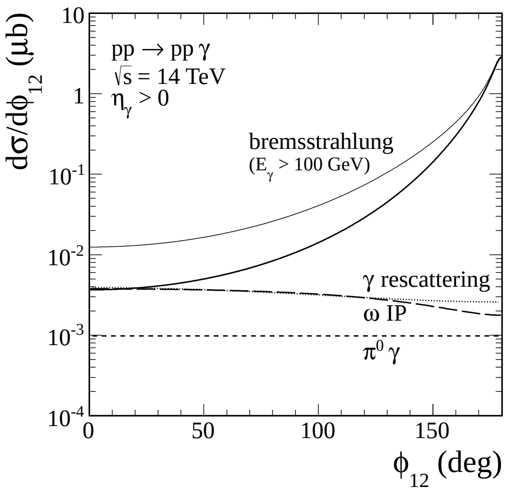


large photon energies

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 midrapidities.
- Next step → include absorption.