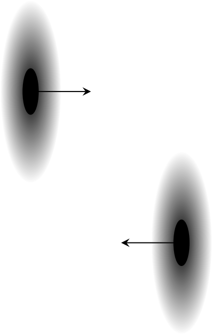
Ultraperipheral collisions at the Large Hadron Collider: survival factor

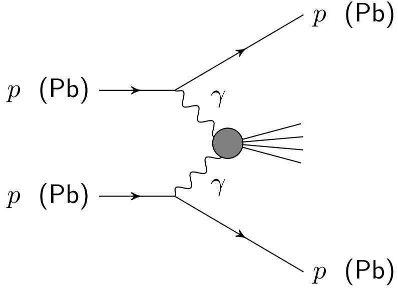
S. I. Godunov, V. A. Novikov, A. N. Rozanov, M. I. Vysotsky,
E. V. Zhemchugov

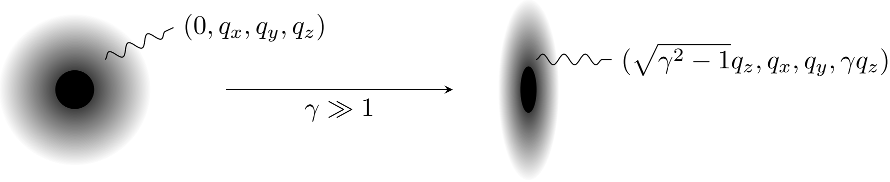
Lebedev Physical Institute
Moscow, Russia

LPI
June 11, 2021

Ultraperipheral collisions at the LHC

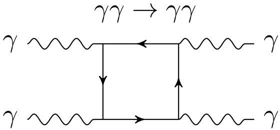




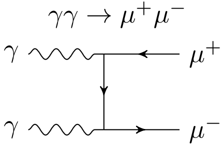


Photon virtuality: $Q^2 \equiv -q^2 = q_x^2 + q_y^2 + q_z^2 \ll (\gamma q_z)^2 \equiv \omega^2$ Studied processes:

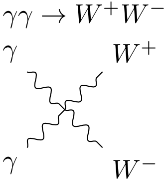
Photon-photon processes studied at LHC



Nature Physics 13, 852 (2017)
Phys.Lett. B797, 134826 (2019)

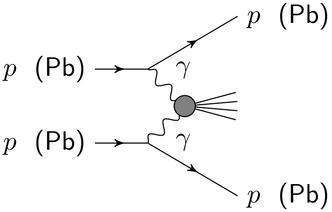


Phys.Lett. B777, 303 (2018)
JHEP 1201, 052 (2012)



Phys.Rev. D94, 032011 (2016)
JHEP 1608, 119 (2016)

p vs Pb

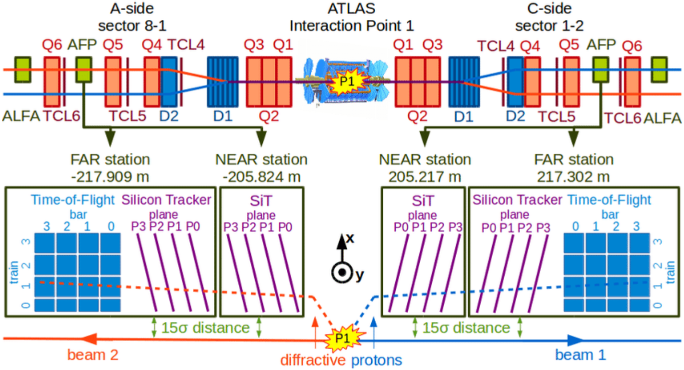


$$\sigma \sim Z^4$$

	pp	Pb Pb
Energy	13 TeV	5.02 TeV/(nucleon pair)
Z	1	82
Z^4	1	$4.5 \cdot 10^7$
Luminosity	159 fb^{-1}	2.4 nb^{-1}
	ratio:	$6.6 \cdot 10^7$
Duration	21 months (Run 2)	2 months (2015, 2018)
$\sqrt{s_{\gamma\gamma}}$	$\lesssim 2.6$ TeV	$\lesssim 160$ GeV

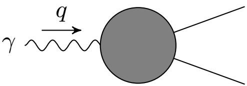
p vs Pb: forward detectors

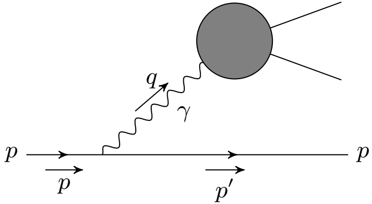
[1909.10827]



Distance from the IP, m	200	420
ξ range	0.015–0.15	0.002–0.02
6.5 TeV p energy loss, GeV	97.5–975	13–130
in the center-of-mass frame, MeV	14–141	1.9–19
0.5 PeV ^{208}Pb energy loss, TeV	7.8–78	1.0–10
in the center-of-mass frame, GeV	2.9–29	0.37–3.7

Equivalent photons approximation

Let $A_{\text{real}} =$ 

, $A_{\text{virtual}} =$ 

.

Then $A_{\text{virtual}} = A_{\text{real}} \frac{Ze}{-q^2} \frac{2E}{\omega} |\vec{q}_\perp|$.

$$\mathrm{d}\sigma_{\text{real}} = |A_{\text{real}}|^2 (2\pi)^4 \delta^{(4)}(P_f - P_i) \frac{1}{4m\omega} \mathrm{d}\rho$$

$$\mathrm{d}\sigma_{\text{virtual}} = |A_{\text{virtual}}|^2 (2\pi)^4 \delta^{(4)}(P_f - P_i) \frac{1}{4mE} \frac{\mathrm{d}^3 p'}{2E(2\pi)^3} \mathrm{d}\rho$$

EPA:

$$\mathrm{d}\sigma_{\text{virtual}} = \mathrm{d}\sigma_{\text{real}} \cdot n(\vec{q})\, \mathrm{d}^3 q$$

$$n(\vec{q}) = \frac{Z^2 \alpha}{\pi^2} \frac{\vec{q}_\perp^{\,2}}{\omega q^4}$$

[Berestetsky, Lifshitz, Pitaevsky, Theoretical Physics vol. 4, §99]

Equivalent photons approximation

$$\mathrm{d}\sigma_{\mathsf{virtual}} = \mathrm{d}\sigma_{\mathsf{real}} \cdot n(\vec{q})\mathrm{d}^3 p' = \mathrm{d}\sigma_{\mathsf{real}} \cdot n(\omega)\mathrm{d}\omega$$

$$n_0(\vec{q}) = \frac{Z^2\alpha}{\pi^2}\frac{\vec{q}_\perp^{\,2}}{\omega q^4} = \frac{Z^2\alpha}{\pi^2}\frac{\vec{q}_\perp^{\,2}}{\left(q_\perp^2 + (\omega/\gamma)^2\right)^2},$$

$$n_0(\omega) = \int n_0(\vec{q})\mathrm{d}^2 q_\perp$$

$$= 2\pi \int\limits_0^{\hat{q}} n_0(\vec{q}) q_\perp \mathrm{d}q_\perp$$

$$= \frac{Z^2\alpha}{\pi\omega}\left\{\ln\left[1 + \left(\frac{\hat{q}\gamma}{\omega}\right)^2\right] - \frac{1}{1 + \left(\frac{\omega}{\hat{q}\gamma}\right)^2}\right\}$$

$$\approx (\omega \ll \hat{q}\gamma) \approx \frac{2Z^2\alpha}{\pi\omega}\ln\frac{\hat{q}\gamma}{\omega}$$

$$\hat{q} = ?$$

EPA spectrum cutoff (p)

For the proton, $\hat{q} \approx \Lambda_{\mathsf{QCD}} = 0.2$–$0.3$ GeV.
Dirac form factor (dipole approximation):

$$\mathcal{J}_\mu = F(q^2)\bar{\psi}\gamma_\mu\psi,\ F_2(Q^2) \approx \frac{1}{\left(1 + \frac{Q^2}{\Lambda^2}\right)^2}\ \ (Q^2 \ll 4m_p^2),\ \Lambda^2 = 0.61\ \text{GeV}^2.$$

EPA spectrum with form factor:

$$n_2(\vec{q}) = \frac{Z^2\alpha}{\pi^2}\frac{\vec{q}_\perp^{\,2}}{\omega q^4}\frac{1}{\left(1 + \frac{Q^2}{\Lambda^2}\right)^2},$$

$$n_2(\omega) = \int n_2(\vec{q})\mathrm{d}^2 q = 2\pi\int\limits_0^\infty n_2(\vec{q})q_\perp\mathrm{d}q_\perp \approx \frac{2Z^2\alpha}{\pi\omega}\left(\ln\frac{\Lambda\gamma}{\omega} - \frac{17}{12}\right)\ (\omega \ll \Lambda\gamma)$$

In the leading logarithmic approximation

$$n_2(\omega) \approx n_0(\omega) = \frac{2Z^2\alpha}{\pi\omega}\ln\frac{\hat{q}\gamma}{\omega}$$

hence $\hat{q} = \Lambda\mathrm{e}^{-\frac{17}{12}} \approx 189$ MeV; $\hat{q}\gamma \approx 1.3$ TeV for collision energy 13 TeV.

EPA spectrum cutoff (Pb)

Form factor (monopole approximation):

$$F_1(Q^2) \approx \frac{1}{1+\frac{Q^2}{\Lambda^2}},\ \Lambda = 80 \text{ MeV}.$$

EPA spectrum:

$$n_1(\vec{q}) = \frac{Z^2\alpha}{\pi^2}\frac{\vec{q}_\perp^{\,2}}{\omega q^4}\frac{1}{1+\frac{Q^2}{\Lambda^2}},$$
$$n_1(\omega) = \frac{2Z^2\alpha}{\pi\omega}\left(\ln\frac{\Lambda\gamma}{\omega}-1\right)\ (\omega \ll \Lambda\gamma).$$

Hence $\hat{q} = \Lambda \mathrm{e}^{-1} \approx 29$ MeV; $\hat{q}\gamma \approx 79$ GeV for collision energy 5.03 TeV/(nucleon pair).

Proton form factor

$$F_p(Q^2) = \frac{G_E(Q^2) + \tau G_M(Q^2)}{1+\tau}$$

$$G_E(Q^2) = \frac{1}{\left(1 + \frac{Q^2}{\Lambda^2}\right)^2}$$

$$G_M(Q^2) = \frac{\mu_p}{\left(1 + \frac{Q^2}{\Lambda^2}\right)^2}$$

$$\tau = \frac{Q^2}{4m_p^2} \lesssim 0.01$$

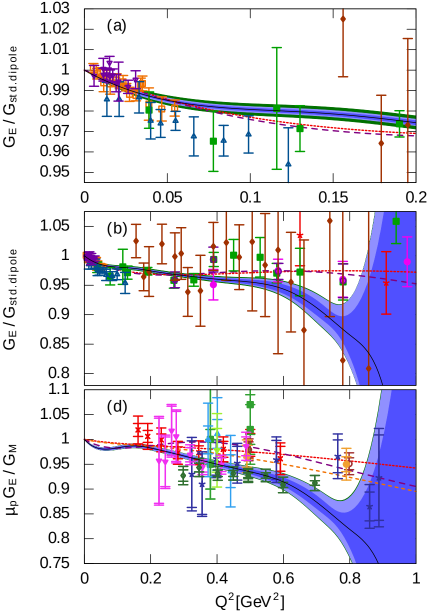
$$\mu_p = 2.79$$

$$\Lambda^2_{\text{std.}} = 0.71 \text{ GeV}^2$$

Proton radius

$r_p = 0.8751 \text{ fm} = 12/\Lambda^2$

$\Rightarrow \Lambda^2 = 0.61 \text{ GeV}^2$.



[1307.6227]

Proton EPA spectrum

Proton form factor with magnetic contribution taken into account:

$$F_p(Q^2) = \frac{G_E(Q^2) + \tau G_M(Q^2)}{1+\tau},$$

$$G_E(Q^2) = \frac{1}{\left(1 + \frac{Q^2}{\Lambda^2}\right)^2}, \qquad G_M(Q^2) = \frac{\mu_p}{\left(1 + \frac{Q^2}{\Lambda^2}\right)^2}$$

$$\tau = \frac{Q^2}{4m_p^2} \lesssim 0.01,\ \Lambda^2 = 0.61\ \text{GeV}^2,\ \mu_p = 2.79.$$

EPA spectrum:

$$\begin{aligned} n_p(\omega) = \frac{\alpha}{\pi\omega} \Bigg\{ &\left(1 + 4u - 2(\mu_p - 1)\frac{u}{v}\right) \ln\left(1 + \frac{1}{u}\right) - \frac{24u^2 + 42u + 17}{6(u+1)^2} \\ &+ \frac{\mu_p - 1}{(v-1)^4} \left[\frac{\mu_p - 1}{v-1}(1 + 4u + 3v) - 2\left(1 + \frac{u}{v}\right)\right] \ln\frac{u+v}{u+1} \\ &+ (\mu_p - 1)\, \frac{6u^2(v^2 - 3v + 3) + 3u(3v^2 - 9v + 10) + 2v^2 - 7v + 11}{3(u+1)^2(v-1)^3} \\ &- (\mu_p - 1)^2\, \frac{24u^2 + 6u(v+7) - v^2 + 8v + 17}{6(u+1)^2(v-1)^4} \Bigg\}, \end{aligned}$$

$$u = (\omega/\Lambda\gamma)^2,\ v = (2m_p/\Lambda)^2.$$

^{208}Pb form factor

Charge distribution is provided in form of Bessel spherical functions:

$$\rho(r) = \sum_{k=1}^{N} a_k j_0(k\pi r/R)\Theta(R-r);\; j_0(x) = \sin(x)/x.$$

a_k, R are numerical parameters.
Form factor is the Fourier transform of charge:

$$F_{\mathsf{Pb}}(Q^2) = \frac{\int \rho(r) \mathrm{e}^{i\vec{q}\vec{r}} \mathrm{d}^3 r}{\int \rho(r) \mathrm{d}^3 r} = \frac{\sin QR}{QR} \frac{\sum\limits_{k=1}^{N} \frac{(-1)^k a_k}{(k\pi)^2 - (QR)^2}}{\sum\limits_{k=1}^{N} \frac{(-1)^k a_k}{(k\pi)^2}}.$$

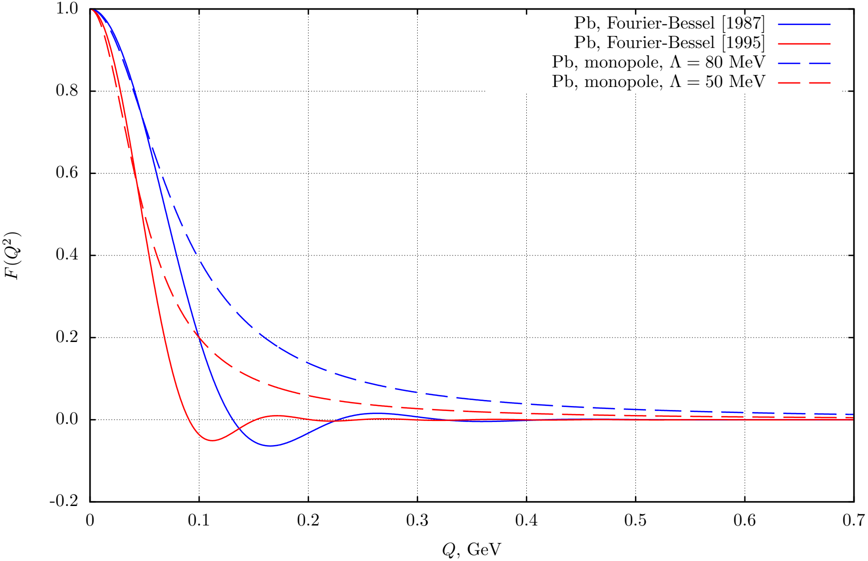
EPA spectrum:

$$n_{\mathsf{Pb}}(\omega) = \frac{2Z^2\alpha}{\pi\omega} \int\limits_0^\infty \left[\frac{F(q_\perp^2 + (\omega/\gamma)^2)}{q_\perp^2 + (\omega/\gamma)^2}\right]^2 q_\perp^3 \, \mathrm{d}q_\perp$$

Monopole approximation:

$$F_1(Q^2) = \frac{1}{1 + Q^2/\Lambda^2},\; n_1(\omega) = \frac{Z^2\alpha}{\pi\omega}\left[(1+2u)\ln\left(1 + \frac{1}{u}\right) - 2\right],\; u = \left(\frac{\omega}{\Lambda\gamma}\right)^2$$

^{208}Pb form factor



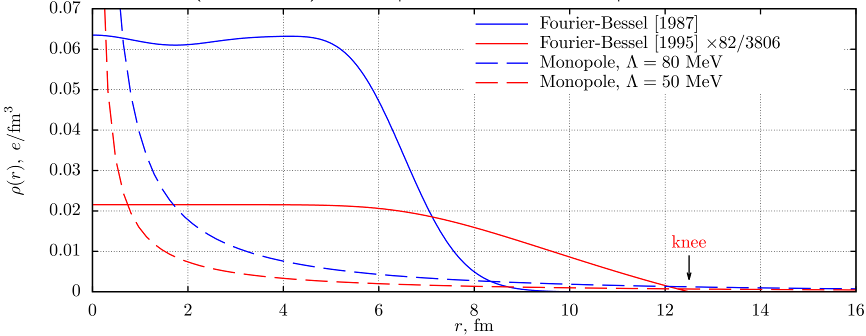
[1987]: At.Data and Nucl.Data Tabl. 36, 495 (1987)

[1995]: At.Data and Nucl.Data Tabl. 60, 177 (1995)

^{208}Pb charge density

$$\rho(r) = \sum_{k=1}^{N} a_k\, j_0(k\pi r/R)\,\Theta(R-r), \quad F(Q) = \frac{\int \rho(r) e^{i\vec{q}\vec{r}} d^3 r}{\int \rho(r) d^3 r}$$

	[1987] Quoted	[1987] Actual	[1995] Quoted	[1995] Actual
$Z = \int \rho(r) d^3 r$	82	82.03	82	3806
$\langle r^2 \rangle^{1/2} = \left(\frac{\int \rho(r) r^2 d^3 r}{\int \rho(r) d^3 r} \right)^{\frac{1}{2}}$, fm	5.499(1)	5.501	5.4785	8.0850

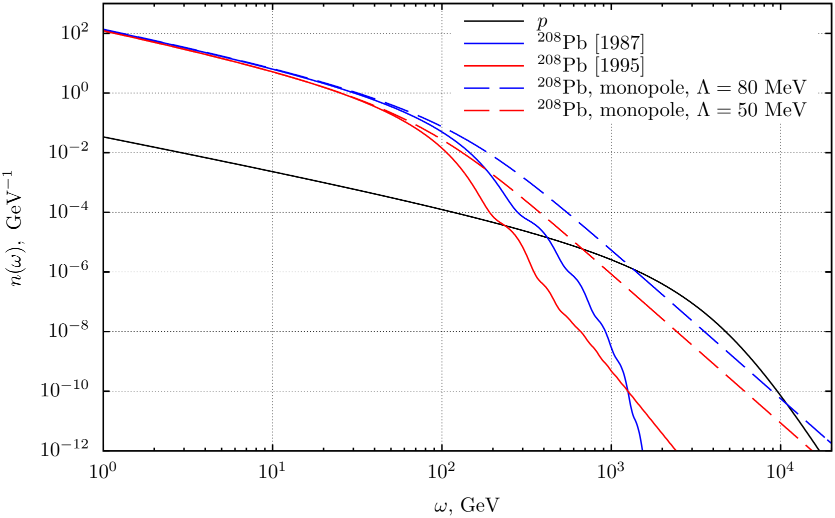


[1987]: At.Data and Nucl.Data Tabl. 36, 495 (1987)

[1995]: At.Data and Nucl.Data Tabl. 60, 177 (1995) ?

EPA spectra

$E_p = 6.5$ TeV, $E_{\text{Pb}} = 522$ TeV (2.5 TeV/nucleon)



$\hat{q}_p \gamma_p = 1.3$ TeV, $\hat{q}_{\text{Pb}} \gamma_{\text{Pb}} = 79$ GeV

Photon-photon luminosity

$$\sigma(AB \to ABX) = \int_0^\infty \mathrm{d}\omega_1 \int_0^\infty \mathrm{d}\omega_2 \sigma(\gamma\gamma \to X)\, n_A(\omega_1)\, n_B(\omega_2)$$

Let $s = 4\omega_1\omega_2$, $y = \frac{1}{2}\ln\frac{\omega_1}{\omega_2}$ ($\sqrt{s}$ — invariant mass of the system produced, y — its rapidity). Then

$$\sigma(AB \to ABX) = \int_0^\infty \mathrm{d}s\, \sigma(\gamma\gamma \to X)\frac{\mathrm{d}L_{AB}}{\mathrm{d}s},$$

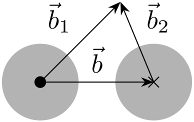
where

$$\frac{\mathrm{d}L_{AB}}{\mathrm{d}s} = \frac{1}{4}\int_{-\infty}^{\infty} \mathrm{d}y\, n_A\left(\tfrac{\sqrt{s}}{2}\mathrm{e}^{y}\right)\, n_B\left(\tfrac{\sqrt{s}}{2}\mathrm{e}^{-y}\right)$$

is the photon-photon luminosity.

EPA spectrum and cross section

With the sizes of the colliding particles neglected:



$$n(\omega) = \frac{2Z^2\alpha}{\pi\omega} \int\limits_0^\infty \left[\frac{F(\sqrt{q_\perp^2 + (\omega/\gamma)^2})}{q_\perp^2 + (\omega/\gamma)^2} \right]^2 q_\perp^3 \, \mathrm{d}q_\perp,$$

$$\sigma(AB \to ABX) = \int\limits_0^\infty \mathrm{d}\omega_1 \int\limits_0^\infty \mathrm{d}\omega_2 \, \sigma(\gamma\gamma \to X) \, n_A(\omega_1) \, n_B(\omega_2).$$

With the sizes of the colliding particles taken into account:

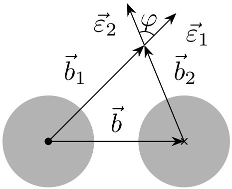
$$n(\omega) = \int n(b,\omega) \, \mathrm{d}^2 b, \quad n(b,\omega) = \frac{Z^2\alpha}{\pi^2\omega} \left[\int\limits_0^\infty \frac{F(\sqrt{q_\perp^2 + (\omega/\gamma)^2})}{q_\perp + (\omega/\gamma)^2} J_1(bq_\perp) \, q_\perp^2 \, \mathrm{d}q_\perp \right]^2,$$

$$\sigma(AB \to ABX)$$

$$= \int\limits_0^\infty \mathrm{d}\omega_1 \int\limits_0^\infty \mathrm{d}\omega_2 \int \mathrm{d}^2 b_1 \int \mathrm{d}^2 b_2 \, \sigma(\gamma\gamma \to X) \, n_A(b_1,\omega_1) \, n_B(b_2,\omega_2) \, P_{AB}(|\vec{b}_1 - \vec{b}_2|).$$

$P_{AB}(b)$ is the probability for the colliding particles to survive after the collision with the impact parameter b.

Polarization



$$\sigma(AB \to ABX) = \int\limits_0^\infty \mathrm{d}s \left[\sigma_\parallel(\gamma\gamma \to X) \frac{\mathrm{d}L^\parallel_{AB}}{\mathrm{d}s} + \sigma_\perp(\gamma\gamma \to X) \frac{\mathrm{d}L^\perp_{AB}}{\mathrm{d}s} \right],$$

where

$$\frac{\mathrm{d}L^\parallel_{AB}}{\mathrm{d}s} = \frac{1}{4} \int\limits_{-\infty}^{\infty} \mathrm{d}y \int \mathrm{d}^2 b_1 \int \mathrm{d}^2 b_2 \, n_A\left(b_1, \tfrac{\sqrt{s}}{2}\,\mathrm{e}^{y}\right) n_B\left(b_2, \tfrac{\sqrt{s}}{2}\,\mathrm{e}^{-y}\right) P_{AB}(b) \cos^2\varphi,$$

$$\frac{\mathrm{d}L^\perp_{AB}}{\mathrm{d}s} = \frac{1}{4} \int\limits_{-\infty}^{\infty} \mathrm{d}y \int \mathrm{d}^2 b_1 \int \mathrm{d}^2 b_2 \, n_A\left(b_1, \tfrac{\sqrt{s}}{2}\,\mathrm{e}^{y}\right) n_B\left(b_2, \tfrac{\sqrt{s}}{2}\,\mathrm{e}^{-y}\right) P_{AB}(b) \sin^2\varphi$$

are photon-photon luminosities.

Survival factor

$$\sigma(AB \to ABX)$$
$$= \int_0^\infty \mathrm{d}\omega_1 \int_0^\infty \mathrm{d}\omega_2 \int \mathrm{d}^2 b_1 \int \mathrm{d}^2 b_2 \, \sigma(\gamma\gamma \to X) \, n_A(b_1, \omega_1) \, n_B(b_2, \omega_2) \, P_{AB}(|\vec{b}_1 - \vec{b}_2|)$$

vs

$$\sigma(AB \to ABX) = \int_0^\infty \mathrm{d}\omega_1 \int_0^\infty \mathrm{d}\omega_2 \, \sigma(\gamma\gamma \to X) \, n_A(\omega_1) \, n_B(\omega_2)$$

$$S_{AB}^{\gamma\gamma}(\omega_1, \omega_2) = \frac{\mathrm{d}L_{AB}/\mathrm{d}\omega_1 \, \mathrm{d}\omega_2}{\mathrm{d}L_{AB}/\mathrm{d}\omega_1 \, \mathrm{d}\omega_2|_{P=1}}$$
$$S_{AB}^{\gamma\gamma}(s, y) = \frac{\mathrm{d}L_{AB}/\mathrm{d}s \, \mathrm{d}y}{\mathrm{d}L_{AB}/\mathrm{d}s \, \mathrm{d}y|_{P=1}}$$
$$S_{AB}(s) = \frac{\mathrm{d}L_{AB}/\mathrm{d}s}{\mathrm{d}L_{AB}/\mathrm{d}s|_{P=1}}$$

Here L_{AB} is the luminosity neglecting photons polarizations: $L_{AB} = L_{AB}^{\parallel} + L_{AB}^{\perp}$.

Proton EPA spectrum

$$F_p(Q^2) = \frac{G_E(Q^2) + \tau G_M(Q^2)}{1+\tau},$$

$$G_E(Q^2) = \frac{1}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}, \quad G_M(Q^2) = \frac{\mu_p}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}, \quad \tau = -\frac{Q^2}{4m_p^2},$$

$$n_p(b,\omega) = \frac{\alpha}{\pi^2\omega}\left[\frac{\omega}{\gamma}K_1\left(\frac{b\omega}{\gamma}\right) - \left(1 + \frac{(\mu_p - 1)\frac{\Lambda^4}{16m_p^4}}{\left(1-\frac{\Lambda^2}{4m_p^2}\right)^2}\right)\sqrt{\Lambda^2 + \frac{\omega^2}{\gamma^2}}\,K_1\left(b\sqrt{\Lambda^2+\frac{\omega^2}{\gamma^2}}\right)\right.$$
$$+ \frac{(\mu_p - 1)\frac{\Lambda^4}{16m_p^4}}{\left(1-\frac{\Lambda^2}{4m_p^2}\right)^2}\sqrt{4m_p^2 + \frac{\omega^2}{\gamma^2}}\,K_1\left(b\sqrt{4m_p^2+\frac{\omega^2}{\gamma^2}}\right)$$
$$\left. - \frac{1-\frac{\mu_p\Lambda^2}{4m_p^2}}{1-\frac{\Lambda^2}{4m_p^2}}\cdot\frac{b\Lambda^2}{2}K_0\left(b\sqrt{\Lambda^2+\frac{\omega^2}{\gamma^2}}\right)\right]^2,$$

$\gamma\gamma$ luminosities in pp collisions

In the case of pp collisions [hep-ph/0608271],

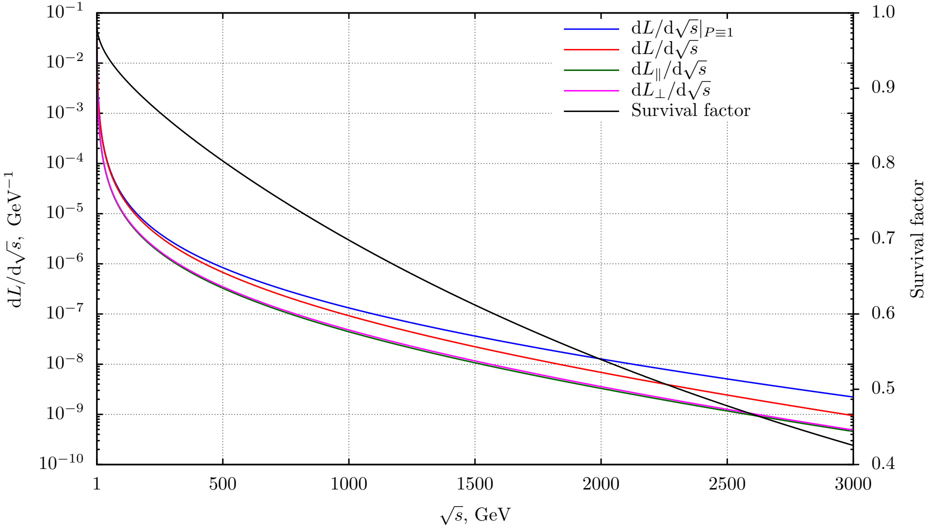
$$P_{pp}(b) = \left(1 - \mathrm{e}^{-\frac{b^2}{2B}}\right)^2, \; B = 21 \text{ GeV}^2$$

Photon-photon luminosities:

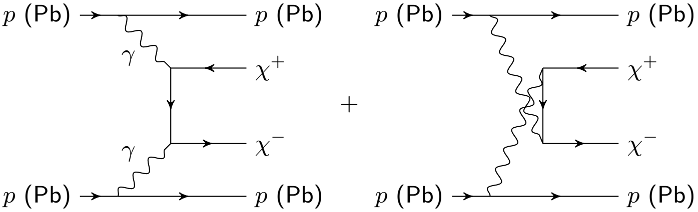
$$\frac{\mathrm{d}L_{pp}^{\parallel}}{\mathrm{d}s} = \frac{\pi^2}{2} \int\limits_{\hat{r}}^{\infty} b_1 \, \mathrm{d}b_1 \int\limits_{\hat{r}}^{\infty} b_2 \, \mathrm{d}b_2 \int\limits_{-\infty}^{\infty} \mathrm{d}y \, n_p\left(b_1, \tfrac{\sqrt{s}}{2}\,\mathrm{e}^{y}\right) n_p\left(b_2, \tfrac{\sqrt{s}}{2}\,\mathrm{e}^{-y}\right)$$
$$\times \left\{1 - 2\mathrm{e}^{-\frac{b_1^2+b_2^2}{2B}} \left[I_0\left(\frac{b_1 b_2}{B}\right) + I_2\left(\frac{b_1 b_2}{B}\right)\right] + \mathrm{e}^{-\frac{b_1^2+b_2^2}{B}} \left[I_0\left(\frac{2b_1 b_2}{B}\right) + I_2\left(\frac{2b_1 b_2}{B}\right)\right]\right\},$$

$$\frac{\mathrm{d}L_{pp}^{\perp}}{\mathrm{d}s} = \frac{\pi^2}{2} \int\limits_{\hat{r}}^{\infty} b_1 \, \mathrm{d}b_1 \int\limits_{\hat{r}}^{\infty} b_2 \, \mathrm{d}b_2 \int\limits_{-\infty}^{\infty} \mathrm{d}y \, n_p\left(b_1, \tfrac{\sqrt{s}}{2}\,\mathrm{e}^{y}\right) n_p\left(b_2, \tfrac{\sqrt{s}}{2}\,\mathrm{e}^{-y}\right)$$
$$\times \left\{1 - 2\mathrm{e}^{-\frac{b_1^2+b_2^2}{2B}} \left[I_0\left(\frac{b_1 b_2}{B}\right) - I_2\left(\frac{b_1 b_2}{B}\right)\right] + \mathrm{e}^{-\frac{b_1^2+b_2^2}{B}} \left[I_0\left(\frac{2b_1 b_2}{B}\right) - I_2\left(\frac{2b_1 b_2}{B}\right)\right]\right\}.$$

Survival factor in pp collisions



$pp \to pp\chi^+\chi^-$

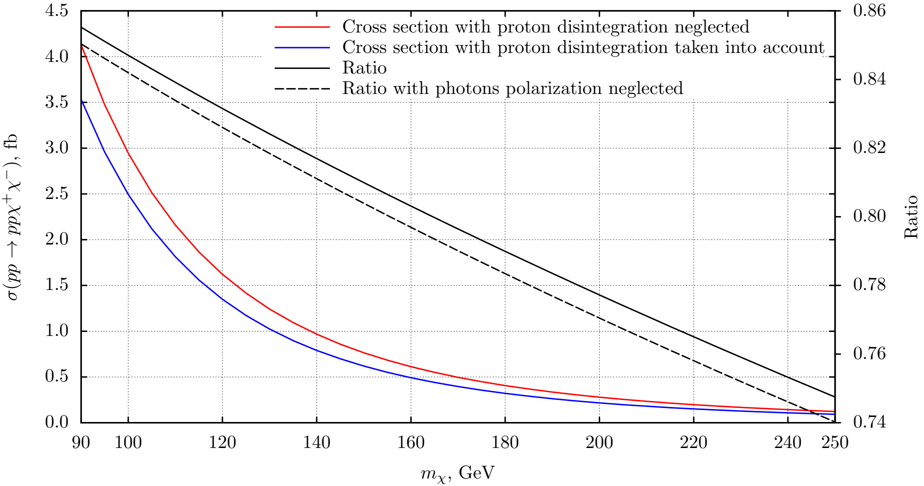


Breit-Wheeler cross sections [Phys.Rev. 46, 1087 (1934)]:

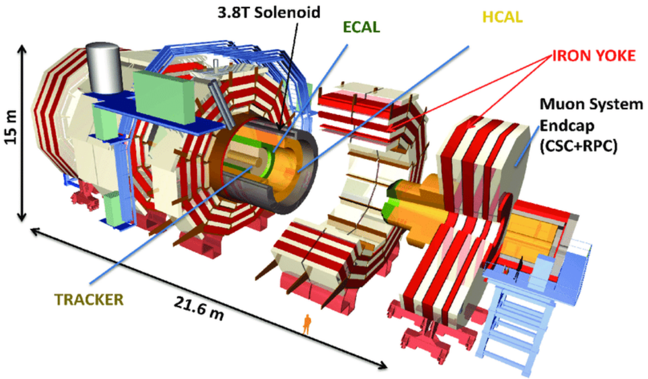
$$\sigma_{\parallel}(\gamma\gamma \to \chi^+\chi^-) = \frac{4\pi\alpha^2}{s}\left[\left(1 + \frac{4m_\chi^2}{s} - \frac{12m_\chi^4}{s^2}\right)\ln\frac{1+\sqrt{1-4m_\chi^2/s}}{1-\sqrt{1-4m_\chi^2/s}} - \left(1 + \frac{6m_\chi^2}{s}\right)\sqrt{1-\frac{4m_\chi^2}{s}}\right]$$

$$\sigma_{\perp}(\gamma\gamma \to \chi^+\chi^-) = \frac{4\pi\alpha^2}{s}\left[\left(1 + \frac{4m_\chi^2}{s} - \frac{4m_\chi^4}{s^2}\right)\ln\frac{1+\sqrt{1-4m_\chi^2/s}}{1-\sqrt{1-4m_\chi^2/s}} - \left(1 + \frac{2m_\chi^2}{s}\right)\sqrt{1-\frac{4m_\chi^2}{s}}\right]$$

$pp \to pp\chi^+\chi^-$



CMS detector

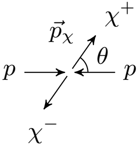


Typical experimental requirements: $|\eta| < \hat{\eta}$, $p_T > \hat{p}_T$.

$\eta = -\ln\tan\frac{\theta}{2}$,

$y = \frac{1}{2}\ln\frac{E_\chi + p_\chi\cos\theta}{E_\chi - p_\chi\cos\theta} \overset{m_\chi \ll E_\chi}{=} \eta$

$p_T = p_\chi \sin\theta$



Fiducial cross section

$$\frac{\mathrm{d}\sigma_{\text{fid.}}(pp \to pp\chi^+\chi^-)}{\mathrm{d}s} = \int\limits_{\max\left(\hat{p}_T,\, \frac{\sqrt{s}}{2\cosh\hat{\eta}}\sqrt{1-\frac{4m_\chi^2}{s}}\right)}^{\frac{\sqrt{s}}{2}\sqrt{1-\frac{4m_\chi^2}{s}}} \mathrm{d}p_T \left[\frac{\mathrm{d}\sigma_\parallel(\gamma\gamma\to\chi^+\chi^-)}{\mathrm{d}p_T}\frac{\mathrm{d}\hat{L}^\parallel}{\mathrm{d}s} + \frac{\mathrm{d}\sigma_\perp(\gamma\gamma\to\chi^+\chi^-)}{\mathrm{d}p_T}\frac{\mathrm{d}\hat{L}^\perp}{\mathrm{d}s}\right]$$

Differential photon-photon cross sections:

$$\frac{\mathrm{d}\sigma_\parallel(\gamma\gamma\to\chi^+\chi^-)}{\mathrm{d}p_T} = \frac{8\pi\alpha^2 p_T}{s(p_T^2+m_\chi^2)} \cdot \frac{1-\dfrac{2(p_T^4 + 2m_\chi^4)}{s(p_T^2+m_\chi^2)}}{\sqrt{1-\dfrac{4(p_T^2+m_\chi^2)}{s}}}$$

$$\frac{\mathrm{d}\sigma_\perp(\gamma\gamma\to\chi^+\chi^-)}{\mathrm{d}p_T} = \frac{8\pi\alpha^2 p_T}{s(p_T^2+m_\chi^2)} \cdot \frac{1-\dfrac{2p_T^4}{s(p_T^2+m_\chi^2)}}{\sqrt{1-\dfrac{4(p_T^2+m_\chi^2)}{s}}}$$

Fiducial cross section

Fiducial luminosity:

$$\frac{\mathrm{d}\hat{L}^{\parallel}}{\mathrm{d}s} = \frac{1}{4} \iint \mathrm{d}^2 b_1 \, \mathrm{d}^2 b_2 \, P(b) \int\limits_{-\hat{y}}^{\hat{y}} \mathrm{d}y \, n\left(b_1, \tfrac{\sqrt{s}}{2}\, \mathrm{e}^{y}\right) \, n\left(b_2, \tfrac{\sqrt{s}}{2}\, \mathrm{e}^{-y}\right) \, \cos^2\varphi$$

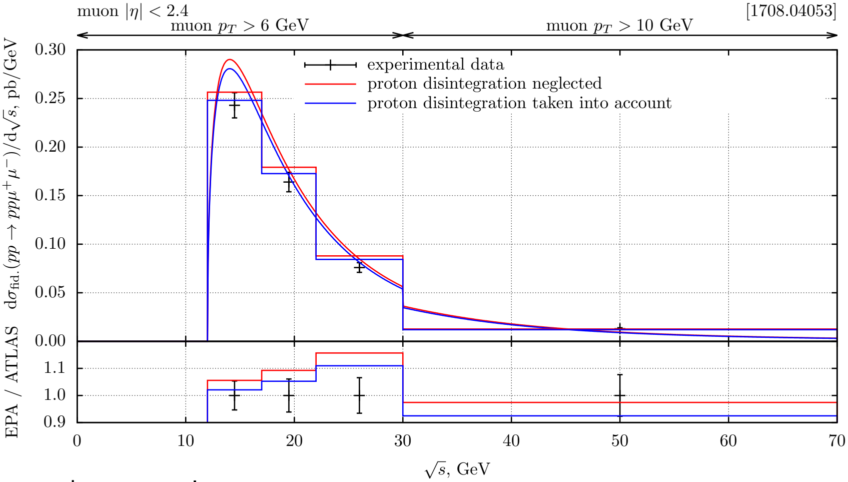
$$\frac{\mathrm{d}\hat{L}^{\perp}}{\mathrm{d}s} = \frac{1}{4} \iint \mathrm{d}^2 b_1 \, \mathrm{d}^2 b_2 \, P(b) \int\limits_{-\hat{y}}^{\hat{y}} \mathrm{d}y \, n\left(b_1, \tfrac{\sqrt{s}}{2}\, \mathrm{e}^{y}\right) \, n\left(b_2, \tfrac{\sqrt{s}}{2}\, \mathrm{e}^{-y}\right) \, \sin^2\varphi$$

Rapidity cut:

$$\hat{y} = \ln\left(\hat{Y} + \sqrt{\hat{Y}^2 + 1}\right),$$

$$\hat{Y} = \frac{\sqrt{s}\, p_T}{2(p_T^2 + m_\chi^2)} \left(\sinh\hat{\eta} - \sqrt{\cosh^2\hat{\eta} + \frac{m_\chi^2}{p_T^2}} \cdot \sqrt{1 - \frac{4(p_T^2 + m_\chi^2)}{s}}\right)$$

ATLAS experiment: $pp \to pp\mu^+\mu^-$



Integrated cross section:

- Experiment: 3.12 ± 0.07 (stat.) $\pm\, 0.10$ (syst.) pb.
- With proton disintegration neglected: 3.39 pb.
- With proton disintegration taken into account: 3.26 pb.

Pb Pb UPC

Form factor in monopole approximation:

$$F_1(Q^2) = \frac{1}{1 + \frac{Q^2}{\Lambda^2}}$$

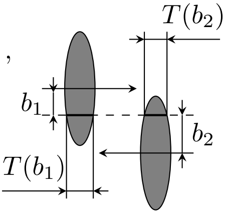
EPA spectrum:

$$n_1(b, \omega) = \frac{Z^2 \alpha}{\pi^2 \omega} \left[\frac{\omega}{\gamma} K_1\left(\frac{b\omega}{\gamma}\right) - \sqrt{\Lambda^2 + \frac{\omega}{\gamma}^2} K_1\left(b\sqrt{\Lambda^2 + \frac{\omega}{\gamma}^2}\right)\right]^2$$

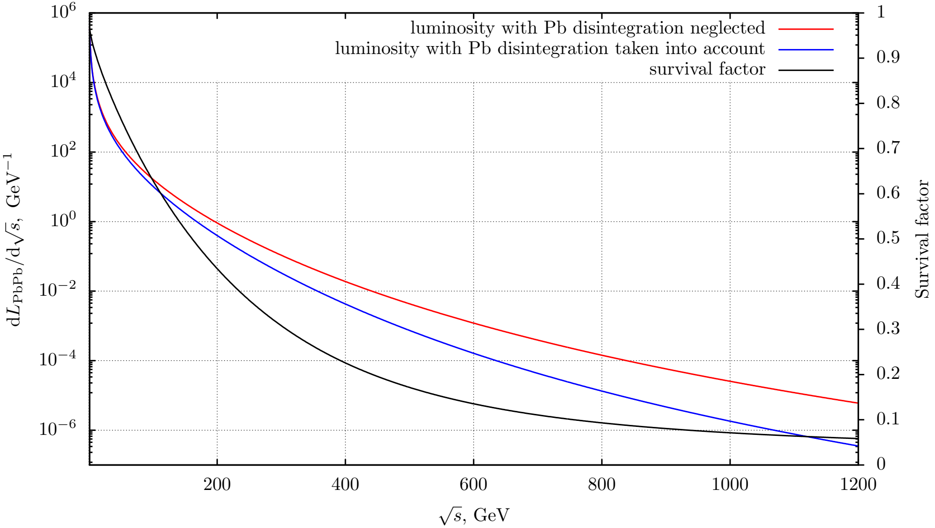
Pb survival probability [nucl-ex/0302016, 1607.03838]

$$P_{\mathsf{Pb}}(b) = \exp\left[-\sigma_{NN} \iint T(b_1)T(b_2)\delta^{(2)}(\vec{b} - \vec{b}_1 + \vec{b}_2)\mathrm{d}^2 b_1 \mathrm{d}^2 b_2\right],$$

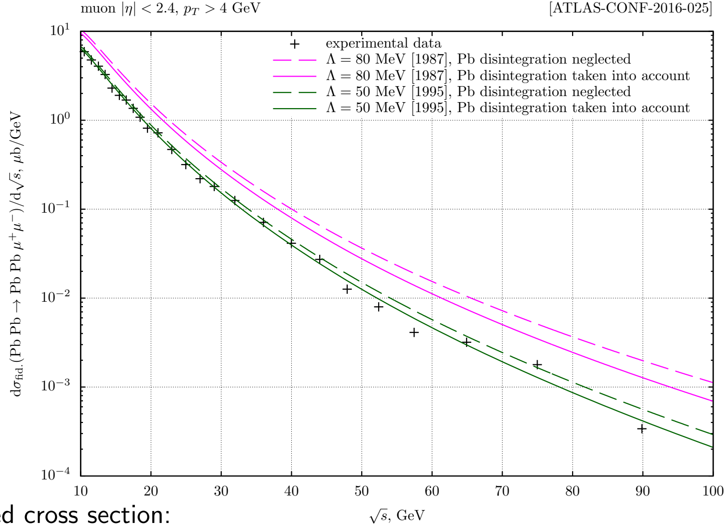
$$T(b) = \int_{-\infty}^{\infty} \rho_N(\sqrt{b^2 + z^2})\mathrm{d}z$$



Survival factor in PbPb collisions (preliminary)



ATLAS experiment: Pb Pb $\to$ Pb Pb $\mu^+\mu^-$ (preliminary)



Integrated cross section:

- Experiment: 32.3 ± 0.3 (stat.)$^{+4.0}_{-3.4}$ (syst.) μb.
- With Pb disintegration neglected ($\Lambda = 50$ MeV): 34.4 μb.
- With Pb disintegration taken into account ($\Lambda = 50$ MeV): 32.3 μb.

Literature

- E. Fermi. Z.Physik 29, 315 (1924).
- L. D. Landau, E. M. Lifshitz. Phys.Zs.Sowjet 6, 244 (1934).
- C. F. V. Weizsäcker. Z.Physik 88, 612 (1934).
- E. J. Williams. Kgl.Danske Vidensk.Selskab.Mat.-Fiz.Medd. 13, 4 (1935).
- V. M. Budnev, I. F. Ginzburg, G. V. Meledin, V. G. Serbo. Phys.Rep. 15, 181 (1975).
- R. Cahn, J. D. Jackson. Phys.Rev. D42, 3690 (1990).
- V. A. Khoze, A. D. Martin, R. Orava, M. G. Ryskin. Eur.Phys.J. C19, 313 (2001).
- L. A. Harland-Lang, M. Tasevsky, V. A. Khoze, M. G. Ryskin. Eur.Phys.J C80, 925 (2020).

Conclusions

- Ultraperipheral collisions is a way to study photon-photon collisions at the LHC.
- Reachable energies in photon-photon collisions are ~ 2.6 TeV in pp collisions and ~ 160 GeV in Pb Pb collisions at the current LHC energies.
- With EPA, many calculations can be performed analytically. Numerical integration is required, Monte Carlo simulation is not.
- Survival factor and photon-photon luminosities in pp collisions were calculated for invariant mass up to 3 TeV.