LHC as a photon-photon collider

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based on M. I. Vysotsky, E. V. Zhemchugov, arXiv:1806.07238

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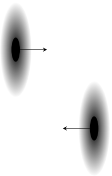
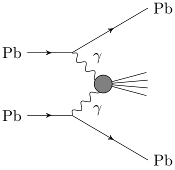
pp or Pb Pb?





$$\sigma \sim Z^4$$

- Integrated luminosity in pp collisions at 13 TeV, provided by the LHC to CMS in Run 2: 119 fb^{-1} current, 150 fb^{-1} expected.
- Integrated luminosity in Pb Pb collisions provided by the LHC to CMS in HI run (2015): 0.7 nb^{-1}.
- Luminosity ratio (expected): $2.1 \cdot 10^8$.
- For Pb, $Z = 82$; $Z^4 \approx 4.5 \cdot 10^7$.
- There could be about 5 times more events of New Physics in $\gamma\gamma$ collisions in pp than there were in Pb Pb data.
- HI run duration is ≈ 20 days, Run 2 duration is ≈ 500 days (not counting the 2015).

A question on whether the heavy ion luminosity should be increased might open to discussion.

Exclusive $\gamma\gamma \longrightarrow \mu^+\mu^-$ process

Goal: derive analytical formulas to describe experimental data.

Experimental data:

1. [1708.04053] (ATLAS): $pp \to pp\mu^+\mu^-$ at collision energy 13 TeV with integrated luminosity of 3.2 fb^{-1}.
   Fiducial cross section: 3.12 ± 0.07 (stat.) $\pm\, 0.10$ (syst.) pb.
   Cuts on the muon system parameters:

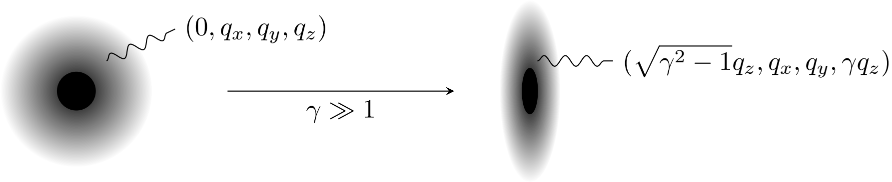
Invariant mass range	Transverse momentum	Pseudorapidity
12 GeV $< m_{\mu\mu} < 30$ GeV	> 6 GeV	< 2.4
30 GeV $< m_{\mu\mu} < 70$ GeV	> 10 GeV	< 2.4

2. ATLAS-CONF-2016-025: Pb Pb $\to$ Pb Pb $\mu^+\mu^-$ at collision energy per nucleon pair 5.02 TeV with integrated luminosity of 515 μb^{-1}.
   Fiducial cross section: 32.2 ± 0.3 (stat.)$^{+4.0}_{-3.4}$ (syst.) μb.
   Cuts on the muon system parameters:

Invariant mass range	Transverse momentum	Pseudorapidity
10 GeV $< m_{\mu\mu} < 100$ GeV	> 4 GeV	< 2.4

Equivalent photon approximation

E. Fermi, Z. Physik 29, 315 (1924),
C. F. V. Weizsäcker, Z. Physik 88, 612 (1934),
E. J. Williams, Kgl. Danske Vidensk. Selskab. Mat.-Fiz. Medd. 13, 4 (1935),
L. D. Landau, E. M. Lifshitz, Phys. Zs. Sowjet 6, 244 (1934).



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

So,(almost) real photons!

Equivalent photon approximation

Berestetsky, Lifshitz, Pitaevsky, Theoretical Physics vol. 4,
Budnev, Ginzburg, Meledin, Serbo, Phys. Rep. 15 (1975) 181-282.

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

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

$$= 2\pi\int_0^{\hat{q}} n(\vec{q}) q_\perp \mathrm{d}q_\perp$$

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

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

$\hat{q} = ?$

EPA: $q_\perp$ cutoff

For the proton, $\hat{q} \approx \Lambda_{\text{QCD}} = 0.2$–$0.3$ GeV.
Dirac form factor:

$$\mathcal{J}_\mu = F(q^2)\bar{\psi}\gamma_\mu\psi,\ \ F(q^2) \approx \frac{1}{\left(1 - \frac{q^2}{\Lambda^2}\right)^2} \ \ (-q^2 \ll 4m_p^2),\ \ \Lambda^2 = 0.71 \text{ GeV}^2.$$

EPA spectrum with form factor:

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

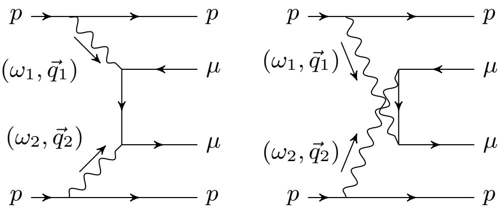
$$n'(\omega) = \int n'(\vec{q})\mathrm{d}^2q = 2\pi\int\limits_0^\infty n'(\vec{q})q_\perp \mathrm{d}q_\perp \approx \frac{2Z^2\alpha}{\pi\omega}\left(\ln\frac{\Lambda\gamma}{\omega} - \frac{17}{12}\right)\ \ (\omega \ll \Lambda\gamma)$$

In the leading logarithmic approximation

$$n'(\omega) \approx n(\omega)$$

hence $\hat{q} = \Lambda \mathrm{e}^{-\frac{17}{12}} \approx 204$ MeV.
For Pb, $\Lambda \approx 80$ MeV [hep-ph/0606069] and $\hat{q} \approx 20$ MeV.
An integral over $q_\perp$ should be cut at $\min(\hat{q}, m_{\mu\mu}) = \hat{q}$;
think about electron-positron pair production.

Total cross section



$$\mathrm{d}\sigma(pp(\gamma\gamma) \to \mu^+\mu^- pp) = \sigma(\gamma\gamma \to \mu^+\mu^-) \cdot n(\omega) n(\omega') \mathrm{d}\omega \mathrm{d}\omega',$$

$$\sigma(\gamma\gamma \to \mu^+\mu^-) = \frac{4\pi\alpha^2}{s} \left[\left(1 + \frac{4m_\mu^2}{s} - \frac{8m_\mu^4}{s^2}\right) \ln \frac{1+\sqrt{1-\frac{4m_\mu^2}{s}}}{1-\sqrt{1-\frac{4m_\mu^2}{s}}} - \left(1 + \frac{4m_\mu^2}{s}\right) \sqrt{1 - \frac{4m_\mu^2}{s}} \right]$$

Integration constraints: $s \equiv (q + q')^2 > 4m_\mu^2$, $\omega < \hat{q}\gamma$, $\omega' < \hat{q}\gamma$.

Change of variables: $s = 4\omega\omega'$, $x = \frac{\omega}{\omega'}$; $\omega = \sqrt{\frac{sx}{4}}$, $\omega' = \sqrt{\frac{s}{4x}}$

$(2m_\mu)^2 < s < (2\hat{q}\gamma)^2$, $\frac{(2\hat{q}\gamma)^2}{s} > x > \frac{s}{(2\hat{q}\gamma)^2}$.

$$\sigma(pp(\gamma\gamma) \to pp\mu^+\mu^-) \approx 8 \cdot \frac{28}{27} \frac{\alpha^4}{\pi m_\mu^2} \ln^3 \frac{\hat{q}\gamma}{m_\mu} \approx 2.2 \cdot 10^5 \text{ pb}$$

Cut on invariant mass

70 GeV $> \sqrt{s} > 12$ GeV $\gg m_\mu = 0.106$ GeV.

$$\sigma(\gamma\gamma \to \mu^+\mu^-) \approx \frac{4\pi\alpha^2}{s}\left(\ln\frac{s}{m_\mu^2} - 1\right)$$

$$\sigma_{\text{fid.}}^{(\hat{s})}(pp(\gamma\gamma) \to pp\mu^+\mu^-) = \int\limits_{\hat{s}_{\text{min}}}^{\hat{s}_{\text{max}}} \mathrm{d}s\, \sigma(\gamma\gamma \to \mu^+\mu^-) \int\limits_{s/(2\hat{q}\gamma)^2}^{(2\hat{q}\gamma)^2/s} \frac{\mathrm{d}x}{8x} n\left(\sqrt{\frac{sx}{4}}\right) n\left(\sqrt{\frac{s}{4x}}\right)$$

$$= \frac{64\alpha^4}{3\pi} \int\limits_{\hat{s}_{\text{min}}}^{\hat{s}_{\text{max}}} \frac{\mathrm{d}s}{s^2}\left(\ln\frac{s}{m_\mu^2} - 1\right) \ln^3\frac{2\hat{q}\gamma}{\sqrt{s}}$$

$$\approx 54.1 \text{ pb} + 5.66 \text{ pb} = 59.7 \text{ pb}.$$

EPA accuracy

Two remarks:

1. Caution: Brodsky, Kinoshita, Terazawa; Terazawa:

$28/27$ (Landau, Lifshitz 1934) $\longrightarrow 14/9$

2. EPA accuracy, Budnev, Ginzburg, Meledin, Serbo:

$$\eta \sim ((\hat{q})^2/(\sqrt{s}m_\mu))^2 \frac{1}{\ln(E/\sqrt{s})} < 0.01$$

(Much worse for the electron-positron pair production).

Cut on transverse momentum

for 12 GeV $< \sqrt{s} < 30$ GeV: $\quad p_T > 6$ GeV,
for 30 GeV $< \sqrt{s} < 70$ GeV: $\quad p_T > 10$ GeV.

$$d\sigma(\gamma\gamma \to \mu^+\mu^-) = \frac{8\pi\alpha^2}{sp_T} \frac{1 - \frac{2p_T^2}{s}}{\sqrt{1 - \frac{4p_T^2}{s}}} dp_T \quad (4m_\mu^2 \ll s)$$

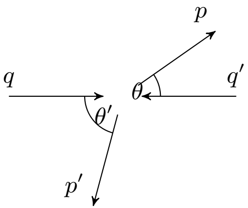
$$\sigma_{\text{fid.}}^{(\hat{s},\hat{p}_T)}(pp(\gamma\gamma) \to pp\mu^+\mu^-) = \int\limits_{\hat{s}_{\text{min}}}^{\hat{s}_{\text{max}}} ds \int\limits_{\hat{p}_T}^{\sqrt{s}/2} dp_T \int\limits_{s/(2\hat{q}\gamma)^2}^{(2\hat{q}\gamma)^2/s} \frac{dx}{8x} \frac{d\sigma(\gamma\gamma \to \mu^+\mu^-)}{dp_T} n\left(\sqrt{\frac{sx}{4}}\right) n\left(\sqrt{\frac{s}{4x}}\right)$$

$$= \frac{8\alpha^4}{3\pi} \int\limits_{\hat{s}_{\text{min}}}^{\hat{s}_{\text{max}}} ds \frac{1}{s^2} \ln^3 \frac{(2\hat{q}\gamma)^2}{s} \left(\ln \frac{1 + \sqrt{1 - \frac{4\hat{p}_T^2}{s}}}{1 - \sqrt{1 - \frac{4\hat{p}_T^2}{s}}} - \sqrt{1 - \frac{4\hat{p}_T^2}{s}} \right)$$

$$\approx 5.37 \text{ pb} + 0.91 \text{ pb} = 6.28 \text{ pb}.$$

Cut on pseudorapidity

Cut: $|\eta| < \hat{\eta} = 2.4$.
$\eta = -\ln\tan(\theta/2)$, so $10^\circ \lesssim \theta \lesssim 170^\circ$.



$$\frac{e^{-\hat{\eta}}}{1-\sqrt{1-\frac{4p_T^2}{s}}} < \frac{\omega}{p_T} < \frac{e^{\hat{\eta}}}{1+\sqrt{1-\frac{4p_T^2}{s}}}$$

ratio of photon energies x shouldn't be too small or too large:

$$\sigma_{\text{fid.}}^{(\hat{s},\hat{p}_T,\hat{\eta})}(pp(\gamma\gamma)\to pp\mu^+\mu^-) = \int\limits_{\hat{s}_{\text{min}}}^{\hat{s}_{\text{max}}} \mathrm{d}s \int\limits_{\hat{p}_T}^{\sqrt{s}/2} \mathrm{d}p_T \int\limits_{e^{-2\hat{\eta}}\cdot\frac{1+\sqrt{1-\frac{4p_T^2}{s}}}{1-\sqrt{1-\frac{4p_T^2}{s}}}}^{e^{2\hat{\eta}}\cdot\frac{1-\sqrt{1-\frac{4p_T^2}{s}}}{1+\sqrt{1-\frac{4p_T^2}{s}}}} \frac{\mathrm{d}x}{8x}\frac{\mathrm{d}\sigma(\gamma\gamma\to\mu^+\mu^-)}{\mathrm{d}p_T} n\left(\sqrt{\frac{sx}{4}}\right) n\left(\sqrt{\frac{s}{4x}}\right)$$

$$= \frac{4\alpha^4}{\pi}\int\limits_{\hat{s}_{\text{min}}}^{\hat{s}_{\text{max}}} \frac{\mathrm{d}s}{s^2} \int\limits_{\hat{p}_T}^{\sqrt{s}/2} \frac{\mathrm{d}p_T}{p_T}\frac{1-\frac{2p_T^2}{s}}{\sqrt{1-\frac{4p_T^2}{s}}} \int\limits_{e^{-2\hat{\eta}}\cdot\frac{1+\sqrt{1-\frac{4p_T^2}{s}}}{1-\sqrt{1-\frac{4p_T^2}{s}}}}^{e^{2\hat{\eta}}\cdot\frac{1-\sqrt{1-\frac{4p_T^2}{s}}}{1+\sqrt{1-\frac{4p_T^2}{s}}}} \frac{\mathrm{d}x}{x}\ln\frac{(2\hat{q}\gamma)^2}{sx}\ln\left(\frac{(2\hat{q}\gamma)^2}{s}\cdot x\right)$$

$$\approx 2.85\ \text{pb} + 0.50\ \text{pb} = 3.35\ \text{pb}$$

Theor. results used in experimental papers

Theoretical predictions obtained with the help of Monte Carlo method:

the `SuperCHIC` program (L. A. Harland-Lang, V. A. Khoze, M. G. Ryskin) gives

$$\sigma_{\text{fid.}}(pp\ (\gamma\gamma) \to pp\ \mu^+\mu^-) = 3.45 \pm 0.05 \text{ pb}; \tag{1}$$

EPA prediction corrected for absorptive effects (M. Dyndal, L. Schoeffel) gives

$$\sigma_{\text{fid.}}(pp\ (\gamma\gamma) \to pp\ \mu^+\mu^-) = 3.06 \pm 0.05 \text{ pb}. \tag{2}$$

calculations with the help of the STARLIGHT program (S. R. Klein, J. Nystrand, J. Seger, Yu. Gorbunov, J. Butterworth):

$$\sigma_{\text{fid.}}(\text{Pb Pb}\ (\gamma\gamma) \to \text{Pb Pb}\ \mu^+\mu^-) = 31.64 \pm 0.04\ \mu\text{b}. \tag{3}$$

Cuts summary

$pp(\gamma\gamma) \to \mu^+\mu^- pp$

No cuts		$2.2 \cdot 10^5$ pb
12 GeV $< \sqrt{s} <$ 30 GeV	54.0 pb	59.6 pb
30 GeV $< \sqrt{s} <$ 70 GeV	5.65 pb	
12 GeV $< \sqrt{s} <$ 30 GeV, $p_T >$ 6 GeV	5.37 pb	6.28 pb
30 GeV $< \sqrt{s} <$ 70 GeV, $p_T >$ 10 GeV	0.91 pb	
12 GeV $< \sqrt{s} <$ 30 GeV, $p_T >$ 6 GeV, $\lvert\eta\rvert < 2.4$	2.85 pb	3.35 pb
30 GeV $< \sqrt{s} <$ 70 GeV, $p_T >$ 10 GeV, $\lvert\eta\rvert < 2.4$	0.50 pb	

Pb Pb $(\gamma\gamma) \to \mu^+\mu^-$Pb Pb

No cuts	$2.80 \cdot 10^6$ μb
10 GeV $< \sqrt{s} <$ 100 GeV	119 μb
also $p_T >$ 4 GeV	34.2 μb
also $\lvert\eta\rvert < 2.4$	30.9 μb

1708.04053 (ATLAS)

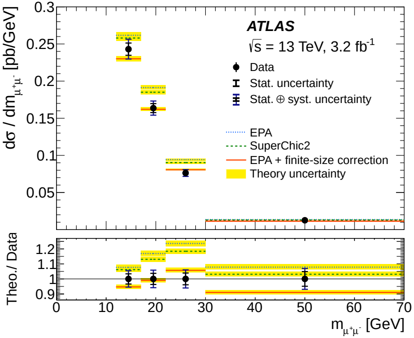
$pp \to pp\, \mu^+\mu^-$ with $\sqrt{s} = 13$ TeV and integrated luminosity of 3.2 fb^{-1}.

Cuts:

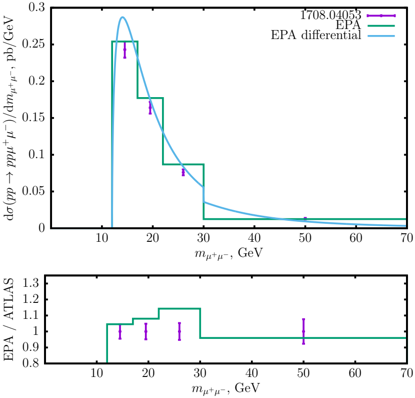
for 12 GeV $< m_{\mu\mu} < 30$ GeV: $p_T(\mu) > 6$ GeV, $|\eta(\mu)| < 2.4$.

for 30 GeV $< m_{\mu\mu} < 70$ GeV: $p_T(\mu) > 10$ GeV, $|\eta(\mu)| < 2.4$.

Experiment



EPA



Fiducial cross section:

3.12 ± 0.07 (stat.) $\pm\, 0.10$ (syst.) pb

3.35 pb

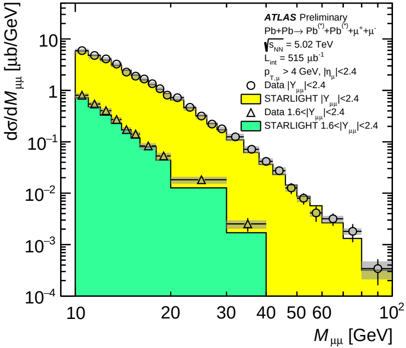
ATLAS-CONF-2016-025

Pb Pb $\to$ Pb Pb $\mu^+\mu^-$ with $\sqrt{s_{\rm NN}} = 5.02$ TeV and integrated luminosity of $515\ \mu$b^{-1}.
Cuts:

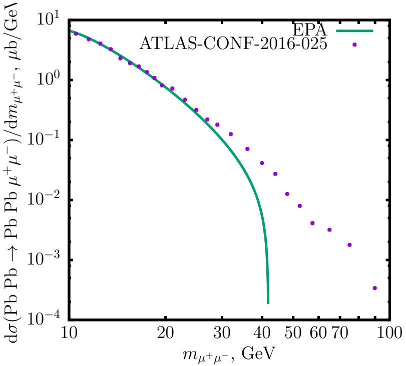
- 10 GeV $< m_{\mu\mu} < 100$ GeV.
- $p_T(\mu) > 4$ GeV.
- $|\eta(\mu)| < 2.4$.

$\hat{q}\gamma \approx 50$ GeV.

Experiment



EPA



Fiducial cross section:

32.2 ± 0.3 (stat.)$^{+4.0}_{-3.4}$ (syst.) μb

$30.9\ \mu$b

Conclusion

- The LHC can be used to search for New Physics in photon-photon collisions.
- Photon invariant mass can reach $2\hat{q}\gamma \approx 2.8$ TeV in pp collisions with $\sqrt{s_{pp}} = 13$ TeV and 100 GeV in Pb Pb collisions with $\sqrt{s_{NN}} = 5.03$ TeV.
- We have derived analytical formulas for the fiducial cross section of lepton pair production in peripheral collisions of charged particles. Experimental data were found to be in agreement with fiducial cross sections calculated for the reactions $pp(\gamma\gamma) \to pp\mu^+\mu^-$ and Pb Pb $(\gamma\gamma) \to$ Pb Pb $\mu^+\mu^-$.