

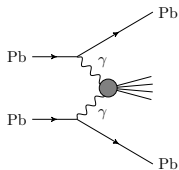
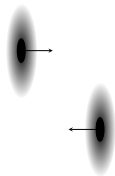
# LHC as a photon-photon collider

M. I. Vysotsky, MIPT, ITEP

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

Rencontres du Vietnam, Windows on the Universe  
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Quy Nhon

## $pp$ or Pb Pb?



$$\sigma \sim Z^4$$

- ▶ Integrated luminosity in  $pp$  collisions at 13 TeV, provided by the LHC to CMS in Run 2:  $119 \text{ fb}^{-1}$  current,  $150 \text{ fb}^{-1}$  expected.
- ▶ Integrated luminosity in Pb Pb collisions provided by the LHC to CMS in HI run (2015):  $0.7 \text{ nb}^{-1}$ .
- ▶ 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  $\approx 20$  days, Run 2 duration is  $\approx 500$  days (not counting the 2015).

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

# Exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ process

Goal: derive analytical formulas to describe experimental data.

Experimental data:

1. [1708.04053] (ATLAS):  $pp \rightarrow pp\mu^+\mu^-$  at collision energy 13 TeV with integrated luminosity of  $3.2 \text{ fb}^{-1}$ .

Fiducial cross section:  $3.12 \pm 0.07$  (stat.)  $\pm 0.10$  (syst.) pb.

Cuts on the muon system parameters:

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

2. ATLAS-CONF-2016-025: Pb Pb  $\rightarrow$  Pb Pb  $\mu^+\mu^-$  at collision energy per nucleon pair 5.02 TeV with integrated luminosity of  $515 \mu\text{b}^{-1}$ .

Fiducial cross section:  $32.2 \pm 0.3$  (stat.) $^{+4.0}_{-3.4}$  (syst.)  $\mu\text{b}$ .

Cuts on the muon system parameters:

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

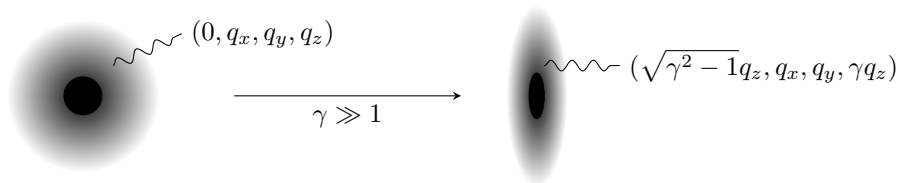
# Equivalent photon approximation

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.

$$\begin{aligned}n(\vec{q}) &= \frac{Z^2\alpha}{\pi^2} \frac{\vec{q}_\perp^2}{\omega q^4} = \frac{Z^2\alpha}{\pi^2} \frac{\vec{q}_\perp^2}{\omega (q_\perp^2 + (\omega/\gamma)^2)^2}, \\n(\omega) &= \int n(\vec{q}) d^2q_\perp \\&= 2\pi \int_0^{\hat{q}} n(\vec{q}) q_\perp dq_\perp \\&= \frac{Z^2\alpha}{\pi\omega} \left\{ \ln \left[ 1 + \left( \frac{\hat{q}\gamma}{\omega} \right)^2 \right] - \frac{1}{1 + (\omega/(\hat{q}\gamma))^2} \right\} \\&\approx (\omega \ll \hat{q}\gamma) \approx \frac{2Z^2\alpha}{\pi\omega} \ln \frac{\hat{q}\gamma}{\omega}\end{aligned}$$

$\hat{q} = ?$

## EPA: $q_{\perp}$ cutoff

For the proton,  $\hat{q} \approx \Lambda_{\text{QCD}} = 0.2\text{--}0.3$  GeV.

Dirac form factor:

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

EPA spectrum with form factor:

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

$$n'(\omega) = \int n'(\vec{q}) d^2q = 2\pi \int_0^{\infty} n'(\vec{q}) q_{\perp} dq_{\perp} \approx \frac{2Z^2 \alpha}{\pi \omega} \left( \ln \frac{\Lambda \gamma}{\omega} - \frac{17}{12} \right) \quad (\omega \ll \Lambda \gamma)$$

In the leading logarithmic approximation

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

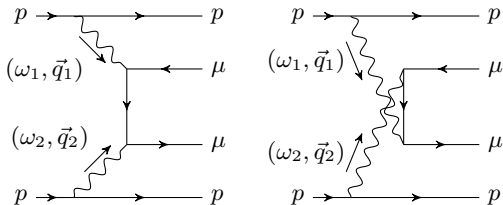
hence  $\hat{q} = \Lambda e^{-\frac{17}{12}} \approx 204$  MeV.

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



$$d\sigma(pp(\gamma\gamma) \rightarrow \mu^+ \mu^- pp) = \sigma(\gamma\gamma \rightarrow \mu^+ \mu^-) \cdot n(\omega)n(\omega')d\omega d\omega',$$

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

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

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

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

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

## Cut on invariant mass

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

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

$$\begin{aligned} \sigma_{\text{fid.}}^{(\hat{s})}(pp(\gamma\gamma) \rightarrow pp\mu^+\mu^-) &= \int_{\hat{s}_{\text{min}}}^{\hat{s}_{\text{max}}} ds \sigma(\gamma\gamma \rightarrow \mu^+\mu^-) \int_{s/(2\hat{q}\gamma)^2}^{(2\hat{q}\gamma)^2/s} \frac{dx}{8x} n\left(\sqrt{\frac{sx}{4}}\right) n\left(\sqrt{\frac{s}{4x}}\right) \\ &= \frac{64\alpha^4}{3\pi} \int_{\hat{s}_{\text{min}}}^{\hat{s}_{\text{max}}} \frac{ds}{s^2} \left( \ln \frac{s}{m_\mu^2} - 1 \right) \ln^3 \frac{2\hat{q}\gamma}{\sqrt{s}} \\ &\approx 54.1 \text{ pb} + 5.66 \text{ pb} = 59.7 \text{ pb}. \end{aligned}$$



# EPA accuracy

Two remarks:

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

28/27 (Landau, Lifshitz 1934)  $\rightarrow$  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  $12 \text{ GeV} < \sqrt{s} < 30 \text{ GeV}$ :  $p_T > 6 \text{ GeV}$ ,  
for  $30 \text{ GeV} < \sqrt{s} < 70 \text{ GeV}$ :  $p_T > 10 \text{ GeV}$ .

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

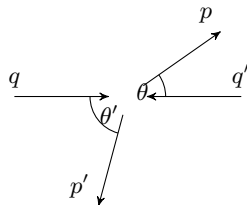
$$\begin{aligned} \sigma_{\text{fid.}}^{(\hat{s}, \hat{p}_T)}(pp(\gamma\gamma) \rightarrow pp\mu^+\mu^-) &= \int_{\hat{s}_{\text{min}}}^{\hat{s}_{\text{max}}} ds \int_{\hat{p}_T}^{\sqrt{s}/2} dp_T \int_{s/(2\hat{q}\gamma)^2}^{(2\hat{q}\gamma)^2/s} \frac{dx}{8x} \frac{d\sigma(\gamma\gamma \rightarrow \mu^+\mu^-)}{dp_T} n\left(\sqrt{\frac{sx}{4}}\right) n\left(\sqrt{\frac{s}{4x}}\right) \\ &= \frac{8\alpha^4}{3\pi} \int_{\hat{s}_{\text{min}}}^{\hat{s}_{\text{max}}} ds \frac{1}{s^2} \ln^3 \frac{(2\hat{q}\gamma)^2}{s} \left( \ln \frac{1 + \sqrt{1 - \frac{4\hat{p}_T^2}{s}}}{1 - \sqrt{1 - \frac{4\hat{p}_T^2}{s}}} - \sqrt{1 - \frac{4\hat{p}_T^2}{s}} \right) \\ &\approx 5.37 \text{ pb} + 0.91 \text{ pb} = 6.28 \text{ pb}. \end{aligned}$$

# 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:

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

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

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

## 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

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

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

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

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

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

## Cuts summary

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

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, $ \eta  < 2.4$	2.85 pb	3.35 pb
30 GeV < $\sqrt{s}$ < 70 GeV, $p_T > 10$ GeV, $ \eta  < 2.4$	0.50 pb	

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

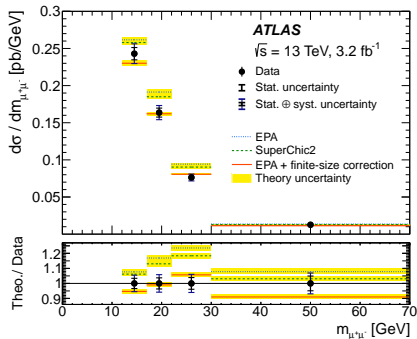
No cuts	$2.80 \cdot 10^6$ $\mu$ b
10 GeV < $\sqrt{s}$ < 100 GeV	119 $\mu$ b
also $p_T > 4$ GeV	34.2 $\mu$ b
also $ \eta  < 2.4$	30.9 $\mu$ b

# 1708.04053 (ATLAS)

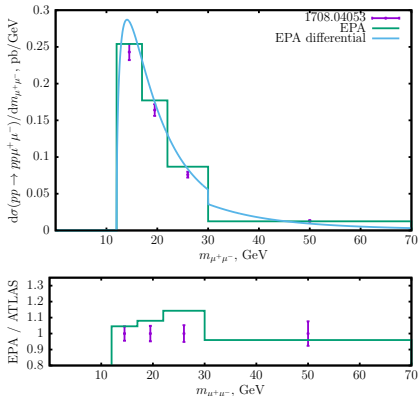
$pp \rightarrow pp \mu^+ \mu^-$  with  $\sqrt{s} = 13$  TeV and integrated luminosity of  $3.2 \text{ fb}^{-1}$ .

Cuts:  
 for  $12 \text{ GeV} < m_{\mu\mu} < 30 \text{ GeV}$ :  $p_T(\mu) > 6 \text{ GeV}$ ,  $|\eta(\mu)| < 2.4$ .  
 for  $30 \text{ GeV} < m_{\mu\mu} < 70 \text{ GeV}$ :  $p_T(\mu) > 10 \text{ GeV}$ ,  $|\eta(\mu)| < 2.4$ .

Experiment



EPA



Fiducial cross section:

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

3.35 pb

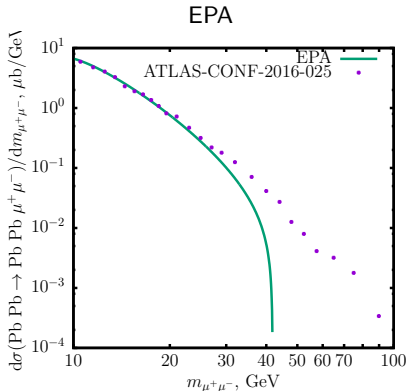
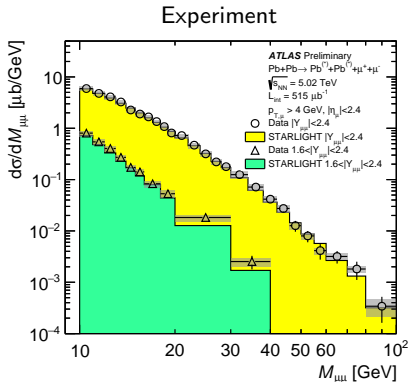
# ATLAS-CONF-2016-025

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

Cuts:

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

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



Fiducial cross section:

$$32.2 \pm 0.3 \text{ (stat.)}_{-3.4}^{+4.0} \text{ (syst.) } \mu\text{b}$$

$$30.9 \mu\text{b}$$

# 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  $pp(\gamma\gamma) \rightarrow pp\mu^+\mu^-$  and Pb Pb  $(\gamma\gamma) \rightarrow$  Pb Pb  $\mu^+\mu^-$ .