Measurement of light-by-light scattering in ATLAS

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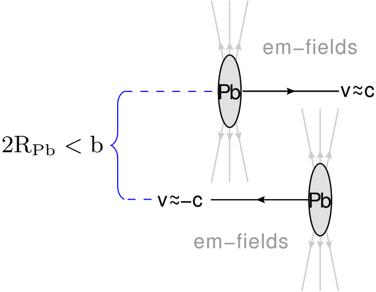
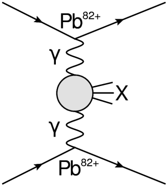
21 April 2017





[Fermi, Nuovo Cim. 2 (1925) 143]
[Weizsacker, Z. Phys. 88 (1934) 612]
[Williams, Phys. Rev. 45 (10 1934) 729]

Equivalent Photon Approximation (EPA)

$$\sigma^{\mathrm{EPA}}_{\mathrm{A_1A_2}(\gamma\gamma)\to \mathrm{A_1A_2X}} = \iint \mathrm{d}\omega_1 \mathrm{d}\omega_2\, \mathrm{n_1}(\omega_1)\, \mathrm{n_2}(\omega_2)\, \sigma_{\gamma\gamma\to \mathrm{X}}(\mathrm{W}_{\gamma\gamma})$$

with $$\mathrm{n}(\mathrm{b},\omega) = \frac{\mathrm{Z}^2\alpha_{\mathrm{em}}}{\pi\omega}\left|\int \mathrm{d}q_\perp q_\perp^2 \frac{\mathrm{F}(\mathrm{Q}^2)}{\mathrm{Q}^2} \mathrm{J_1}(\mathrm{b}q_\perp)\right|^2$$

$$\mathrm{Q}^2 < \frac{1}{\mathrm{R}^2} \quad \text{and} \quad \omega_{\max} \approx \frac{\gamma}{\mathrm{R}}$$

LHC as a photon-photon collider

pp collisions

Pros

- harder EPA γ spectrum ($\omega_{\max} \sim$ TeV)
- more data available $\left(\sim 35\,\text{fb}^{-1}\right)$

Cons

- large pile-up (multiple interactions per bunch crossing)
- problems with triggering on low p_T objects

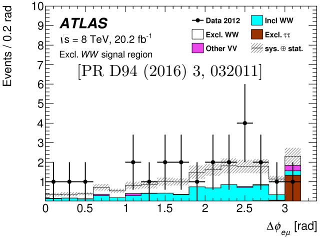
Pb+Pb collisions

Pros

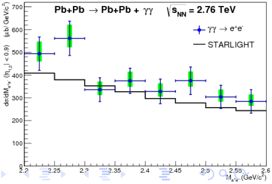
- AA $(\gamma\gamma)$ x-sec $\propto Z^4$
- gluonic x-sec $\propto A^2$ $\Rightarrow$ lower QCD bkg.
- low pile-up ($< 1\%$)

Cons

- softer EPA γ spectrum ($\omega_{\max} \sim 0.1$TeV)
- relatively small data sample

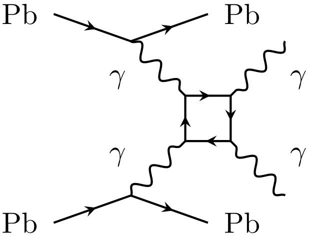


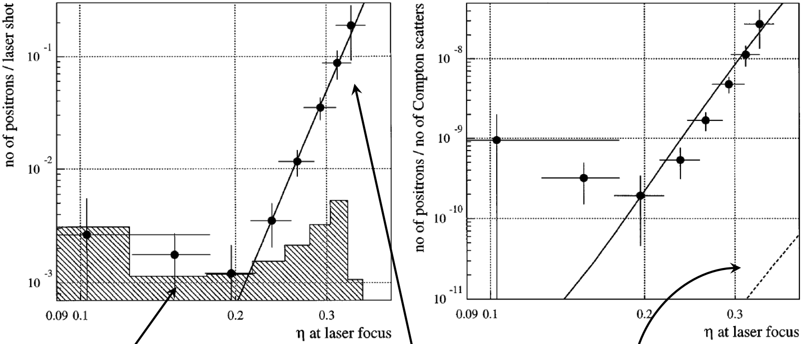
[ALICE Collaboration,EPJC 73 (2013) 2617]



Motivation

- first direct observation of $\gamma\gamma \to \gamma\gamma$ scattering
- previous indirect measurements used:
  a) multi-photon Breit-Wheeler reaction ($\omega + n\omega_0 \to e^+e^-$) [PRL 79 (1997) 1626]
  b) photon splitting
  c) Delbrück scattering





95% CL on the residual background from showers of lost beam particles after subtracting the laser-off positron rate

power law fitted to the data

simulation of trident process
$\omega + n\omega_0 \to e'e^+e^-$

Abstract

A signal of 106 ± 14 positrons above background has been observed in collisions of a low-emittance 46.6 GeV electron beam with terawatt pulses from a Nd:glass laser at 527 nm wavelength in an experiment at the Final Focus Test Beam at SLAC. The positrons are interpreted as arising from a two-step process in which laser photons are backscattered to GeV energies by the electron beam followed by a collision between the high-energy photon and several laser photons to produce an electron-positron pair. These results are the first laboratory evidence for inelastic light-by-light scattering involving only real photons. [S0031-9007(97)04008-8]

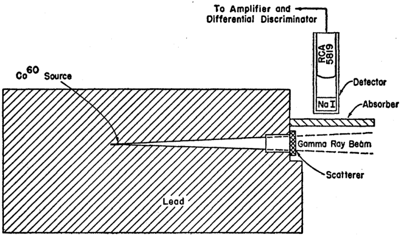


FIG. 1. Experimental arrangement.

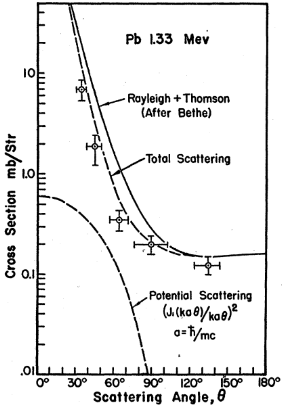
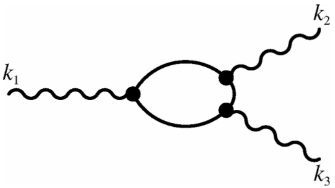
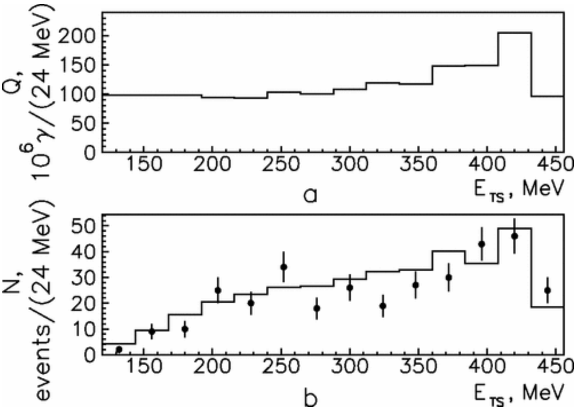


FIG. 2. The cross section in millibarns per steradian for the elastic scattering of 1.33-Mev gamma-rays by lead. The curve marked total scattering is a very rough estimate of Rayleigh, Thomson, and potential scattering combined.



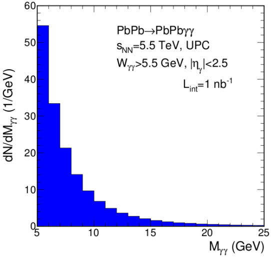


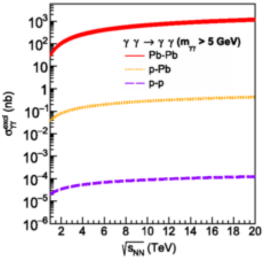
- source: Compton scattered laser light
- Compton scattered electron E measured
- both final γ detected

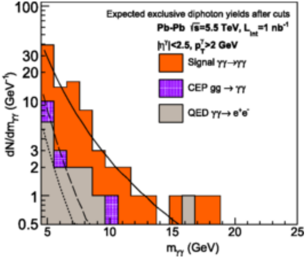
DATA	TARGET	Q, 10^9	$N_{\varphi>150^\circ}$	$N_{\varphi<150^\circ}$
Experiment	$Bi_4Ge_3O_{12}$	1.63	336±18	82±9
Experiment	no target	0.37	10±3	10±3
MC photon splitting	$Bi_4Ge_3O_{12}$	6.52	364±10	72±5
MC Delbrück scattering	$Bi_4Ge_3O_{12}$	1.63	2±1	16±4
MC other backgrounds	$Bi_4Ge_3O_{12}$	1.63	0	16±4

Recent SM Predictions for the LHC

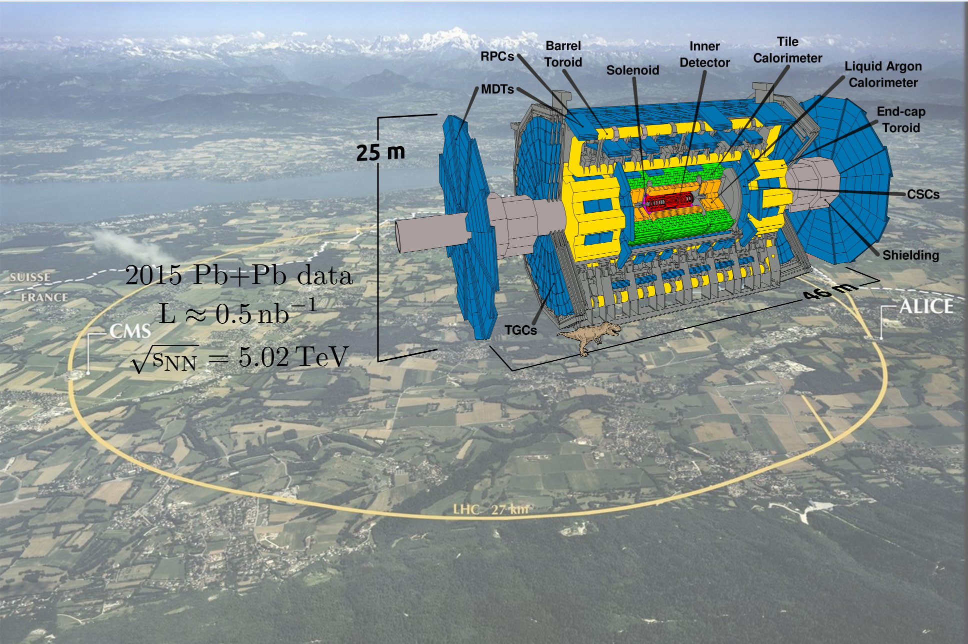
[A. Szczurek et al. PRC 93 (2016) 4, 044907], [D. d'Enterria et al. PRL 111 (2013) 080405]







The LHC and the ATLAS detector

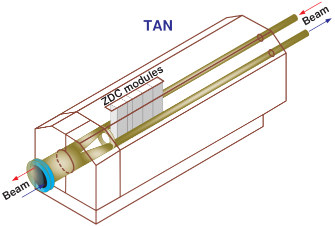


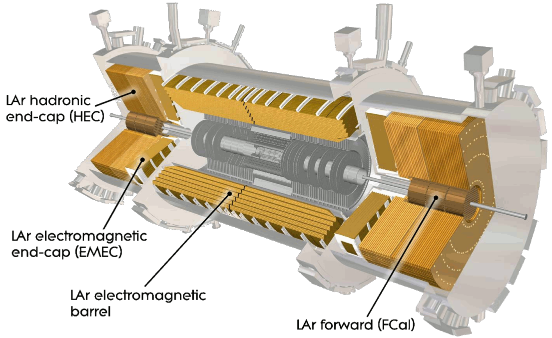
2015 Pb+Pb data

$L \approx 0.5\,\mathrm{nb}^{-1}$

$\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$

The ATLAS detector components





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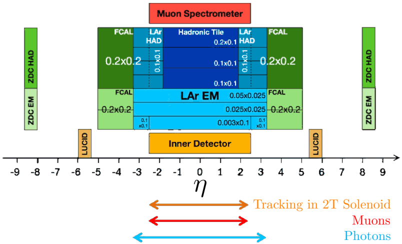
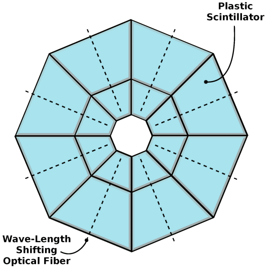
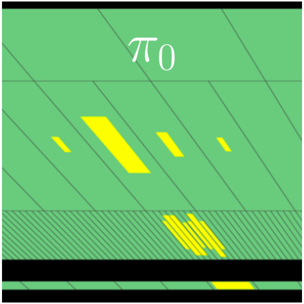


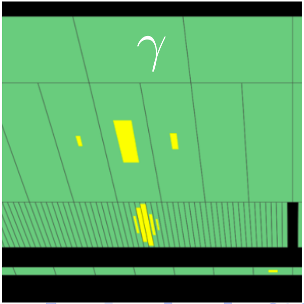


γ cuts: $E_T > 3\,\mathrm{GeV}$, $|\eta| < 2.37$

Shower shape variables used to γ PID

- E_{ratio} $\equiv$ ratio of the energy difference associated with the largest and second largest energy deposits to the sum of these deposits in the first layer of EM calo
- f_1 $\equiv$ fraction of energy reconstructed in the first layer with respect to the total energy of the cluster
- W_{eta2} $\equiv$ lateral width of the shower in the middle layer





Trigger

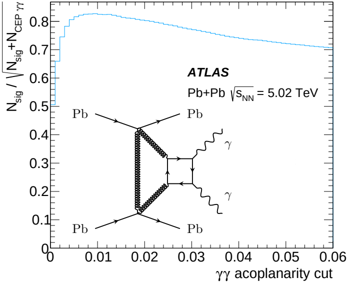
- total E_T in calorimeter between 5 and 200 GeV
- no more than one hit in inner MBTS
- less than 10 hits in the pixel detector

Event Selection

- two photons with $E_T > 3\,\text{GeV}$, $|\eta| < 2.37$
- no tracks from IP
- $m_{\gamma\gamma} > 6\,\text{GeV}$, $p_T^{\gamma\gamma} < 2\,\text{GeV}$
- $\text{Aco} = \left(1 - \frac{\Delta\phi}{\pi}\right) < 0.01$

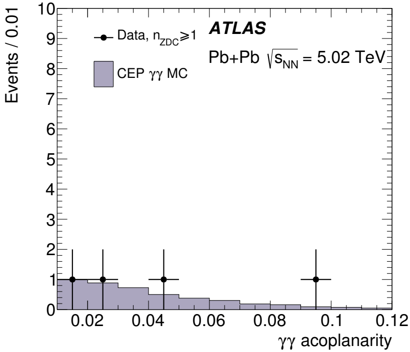
Main sources of bkg.

- Central Exclusive Production (CEP) $gg \to \gamma\gamma$
- misidentification of electrons from $\gamma\gamma \to ee$



More about background

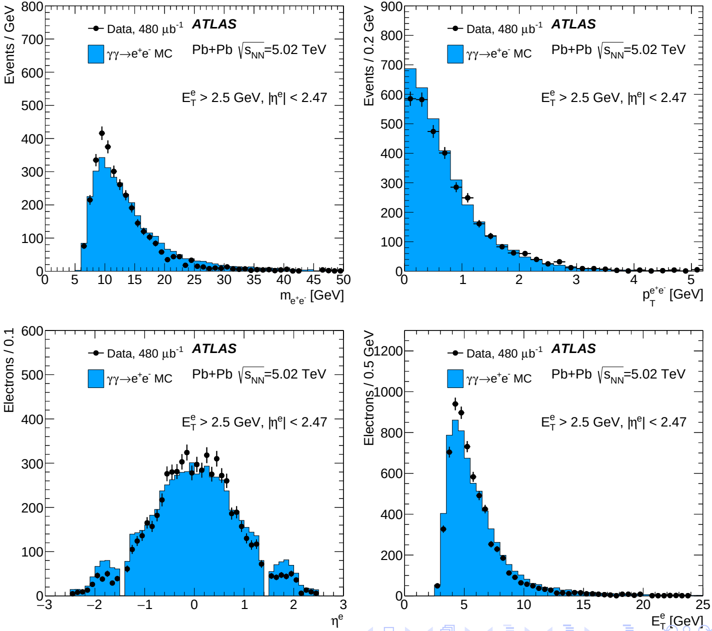
MCID	Process	Generator	Events	Mass range	Generator-level cuts	σ
420060	$\gamma\gamma \to \gamma\gamma$	HepMCAscii	95k	$m > 4$ GeV	$p_T^\gamma > 2$ GeV, $\lvert\eta^\gamma\rvert < 2.7$	147 ± 30 nb
420052	$\gamma\gamma \to e^+e^-$	Starlight	1M	$m > 4$ GeV	$p_T^e > 1$ GeV, $\lvert\eta^e\rvert < 2.7$	171 ± 34 μb
420061	$gg \to \gamma\gamma$	Superchic2	50k	$m > 4$ GeV	$p_T^\gamma > 2$ GeV, $\lvert\eta^\gamma\rvert < 2.7$	440 ± 220 nb
420062	$\gamma\gamma \to q\bar{q}$	Herwig++	100k	$m > 4$ GeV	$p_T^q > 2$ GeV, $\lvert\eta^q\rvert < 2.8$	180 ± 36 μb

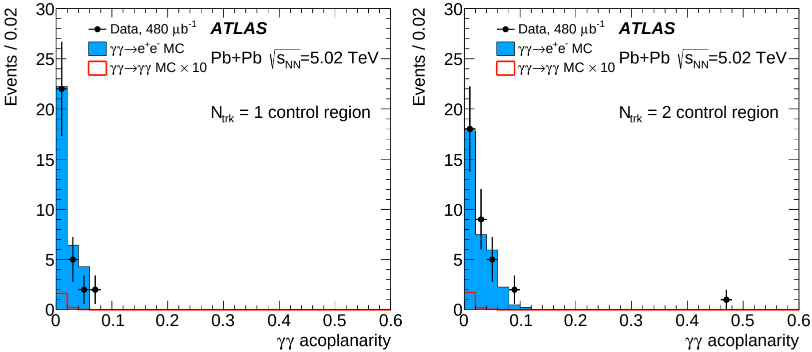


CEP of $\gamma\gamma$

- normalisation from fit to the data in region of Aco > 0.02
- ± 0.01 as a systematic
- ZDC based studies as a cross check

More about background $\gamma\gamma \to e^+e^-$



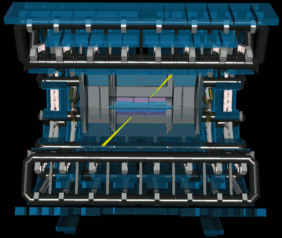


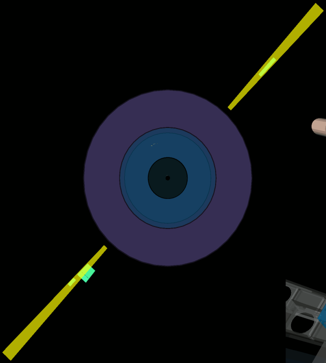
- precision limited by the data statistic
- conservative uncertainty of 25% assigned to MC

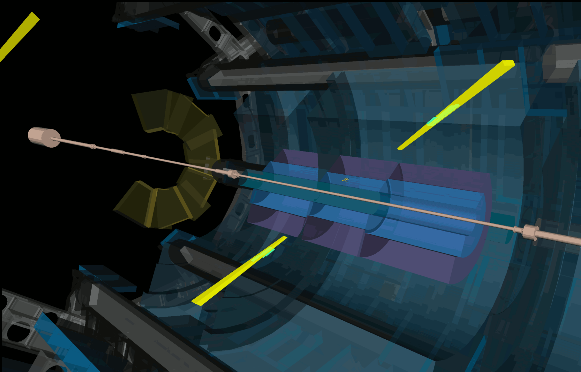
Search for light-by-light scattering
[arXiv:1702.01625]

ATLAS EXPERIMENT

Run: 287924
Event: 106830493
2015-12-12 19:41:56 CEST





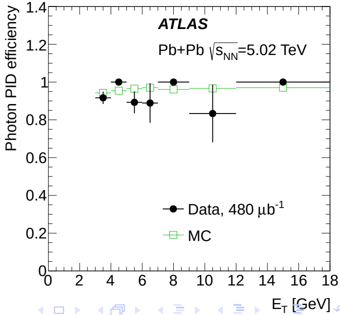


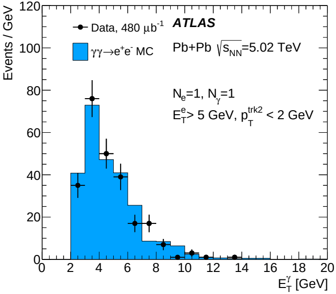
Trigger efficiency ($\gamma\gamma \to e^+e^-$)

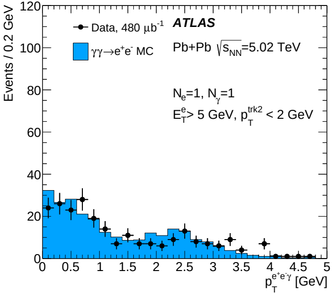
- independent trigger: coincidence of signals in both ZDC sides and a requirement on the total E_T in the calorimeter below 50 GeV.
- events with only two reconstructed tracks and two EM energy clusters (with cl Aco < 0.2)
- about 70% at $\left(E_T^{cl1} + E_T^{cl2}\right) = 6\,\text{GeV}$ to 100% above 9 GeV
- error function parametrisation used to reweight the MC
- MBTS veto studied using supporting trigger $(98 \pm 2)\,\%$

γ PID ($\gamma\gamma \to e^+e^-$)

- one photon and two tracks
- FSR selection: $p_T^{tt\gamma} < 1\,\text{GeV}$

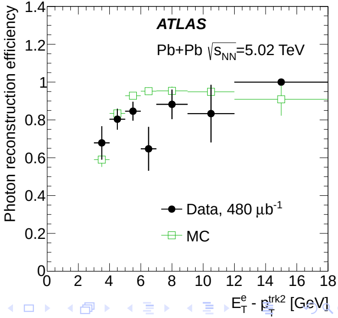






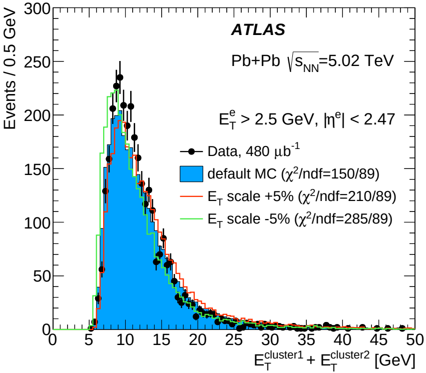
γ reco ($\gamma\gamma \to e^+e^-$) with hard bremsstrahlung

- one electron with $E_T > 5\,\mathrm{GeV}$ and two good quality tracks
- unmatched track: $p_T^{trk2} < 2\,\mathrm{GeV}$



Photon Performance Studies
(done with $\gamma\gamma \to l^+l^-$ events)

- trigger efficiency studies
- γ reconstruction with hard bremsstrahlung
- γ PID with FSR radiation
- γ energy scale and resolution



Systematic Uncertainty

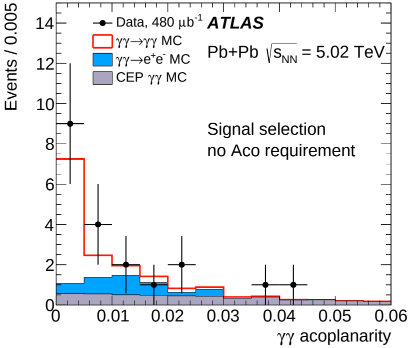
dominated by:

- γ reco
- γ PID

Source of uncertainty	Relative uncertainty
Trigger	5%
Photon reco efficiency	12%
Photon PID efficiency	16%
Photon energy scale	7%
Photon energy resolution	11%
Total	24%

Results: data - 13 event, expected - 7.3 signal and 2.6 bkg. events

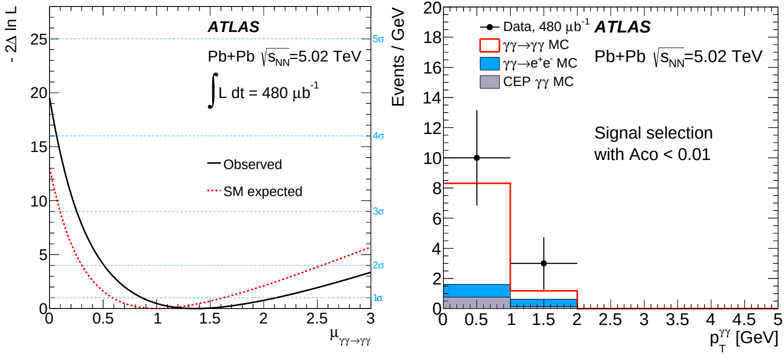
Selection	$\gamma\gamma \to e^+e^-$	CEP $gg \to \gamma\gamma$	Hadronic fakes	Other fakes	Total background	Signal	Data
Preselection	74	4.7	6	19	104	9.1	105
$N_{\mathrm{trk}} = 0$	4.0	4.5	6	19	33	8.7	39
$p_T^{\gamma\gamma} < 2$ GeV	3.5	4.4	3	1.3	12.2	8.5	21
Aco < 0.01	1.3	0.9	0.3	0.1	2.6	7.3	13
Uncertainty	0.3	0.5	0.3	0.1	0.7	1.5	



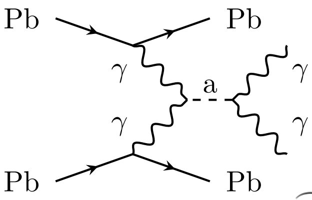
Results:

- significance of 4.4σ estimated using profile likelihood method (expected significance of 3.8σ)
- x-sec measured in fiducial region of $p_T^{\gamma} > 3\,\mathrm{GeV}$, $|\eta^{\gamma}| < 2.4$, $m_{\gamma\gamma} > 6\,\mathrm{GeV}$, $p_T^{\gamma\gamma} < 2\,\mathrm{GeV}$, $\mathrm{Aco} < 0.01$
  $\sigma = 70 \pm 20\,(\mathrm{stat.}) \pm 17\,(\mathrm{syst.})\,\mathrm{nb}$

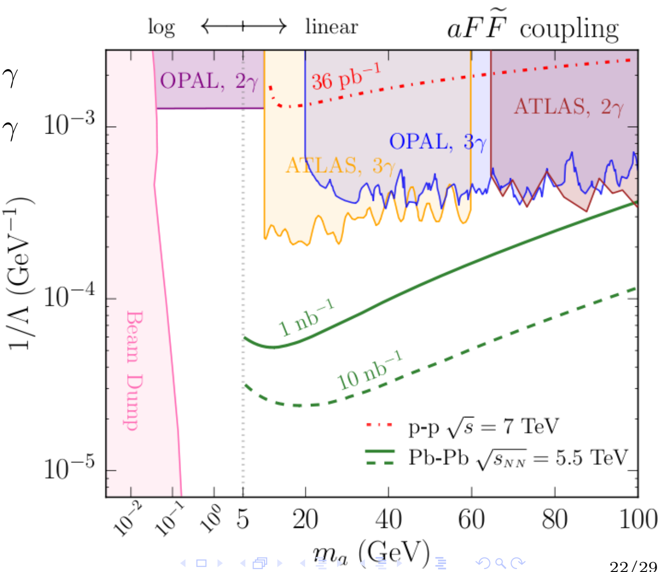
SM predictions: $45 \pm 9\,\mathrm{nb}$ ([PRL 111 (2013) 080405]), $49 \pm 10\,\mathrm{nb}$ ([PRC 93 (2016) no.4, 044907])



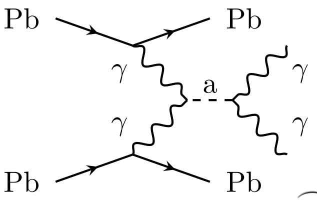
$$L_a = \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}\frac{a}{\Lambda}F\tilde{F}$$



expected axion searches sensitivity



$$L_a = \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4\cos^2\theta_W}\frac{a}{\Lambda}B\tilde{B}$$



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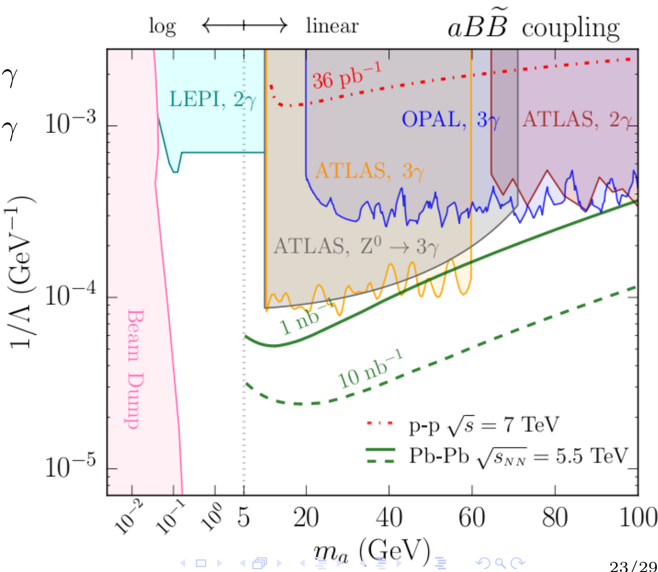
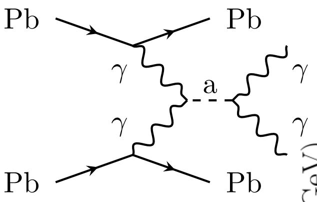
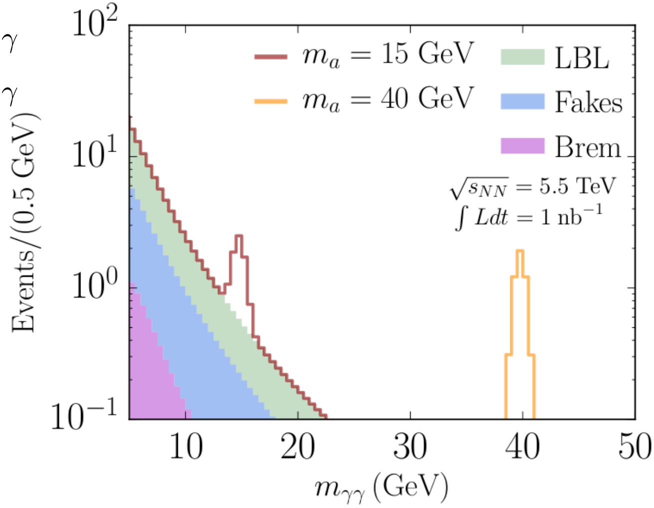
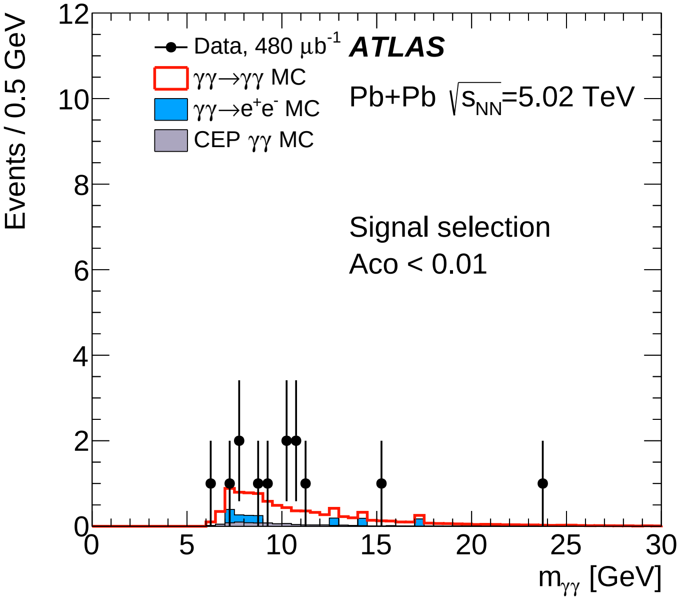


$$L_a = \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}\frac{a}{\Lambda}F\tilde{F}$$



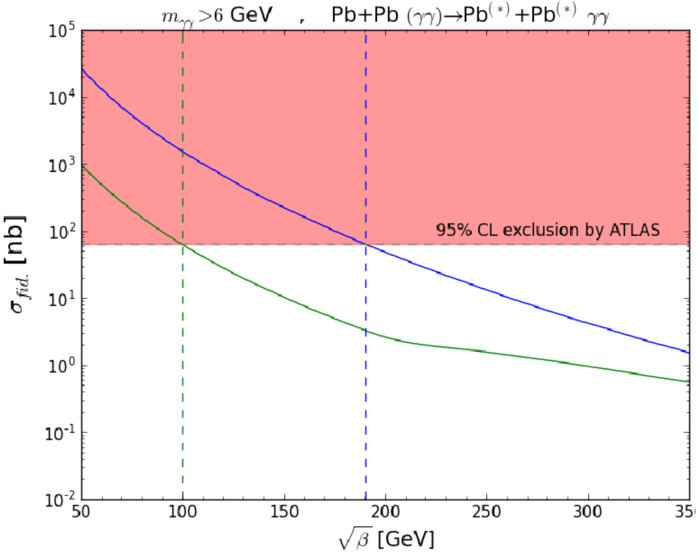
$\sigma_{ALP} = 5\,\text{nb}$, $m_a = 15\,\text{GeV}$ and $40\,\text{GeV}$
assumed E resolution of $0.5\,\text{GeV}$




Data, 480 μb-1
γγ→γγ MC
γγ→e+e- MC
CEP γγ MC
ATLAS
Pb+Pb √sNN=5.02 TeV
Signal selection
Aco < 0.01
Events / 0.5 GeV
mγγ [GeV]
0
2
4
6
8
10
12
0
5
10
15
20
25
30

LbyL Scattering Constraint on Born-Infeld Theory
[arXiv:1703.08450]

$$\mathrm{L_{QED}} = -\frac{1}{4}\mathrm{F}_{\mu\nu}\mathrm{F}^{\mu\nu} \to \mathrm{L_{BI}} = \beta^2\left(1 - \sqrt{1 + \frac{1}{2\beta^2}\mathrm{F}_{\mu\nu}\mathrm{F}^{\mu\nu} - \frac{1}{6\beta^4}\left(\mathrm{F}_{\mu\nu}\tilde{\mathrm{F}}^{\mu\nu}\right)^2}\right)$$



LbyL Scattering Constraint on Born-Infeld Theory
[arXiv:1703.08450]

- limit on Born-Infeld scale $\mathrm{M} = \sqrt{\beta} \gtrsim 100\,\mathrm{GeV}$ 5 orders of magnitude grater than the previous one from PVLAS
- in case of Born-Infeld SM extention with $\mathrm{U}(1)_{\mathrm{Y}}$ realized nonlineary $\mathrm{M_Y} = \cos\theta_{\mathrm{W}}\mathrm{M} \gtrsim 90\,\mathrm{GeV}$
  - such theory has finite-energy electroweak monopole solution less constrained by higgs than in other extensions of SM which because of $\mathrm{M_Y} \rightarrow \mathrm{M_{monopole}} \gtrsim 11\,\mathrm{TeV}$ is out of reach at the LHC

- The first direct evidence for $\gamma\gamma \to \gamma\gamma$ scattering with significance of 4.4σ has been reported.
  - improvements in the precision expected with more Pb+Pb data to be collected in 2018
- This result has already been used by J. Ellis et al. [arXiv:1703.08450] to derive the limits on Born-Infeld theory
- According to S. Knapen et al. [arXiv:1607.06083] UPC data can be used in BSM searches eg. for ALP

Thank You for Your Attention!