Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

Mateusz Dyndal (DESY)

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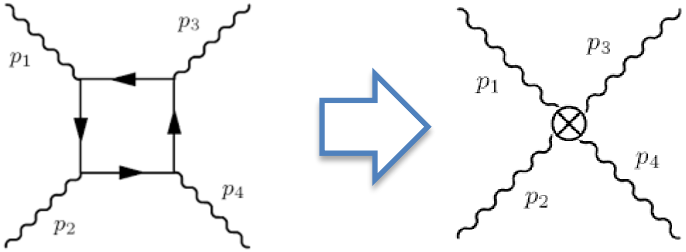
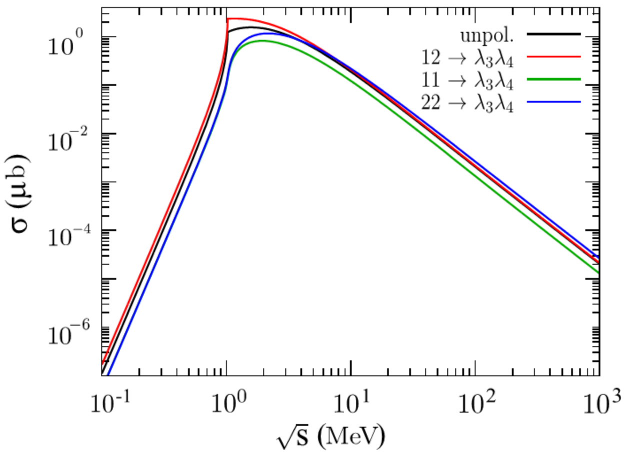
Motivation

- Euler-Heisenberg (effective) Lagrangian [Z. Phys. 98 (1936) 714]
- Original motivation: calculate the rate for light-by-light (LbyL) scattering
  - Applying it for LbyL corresponds to a tree-level calculations (valid only in low-energy limit i.e. $p \ll m_e$):

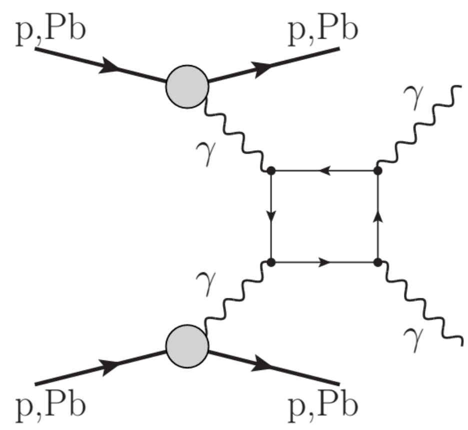


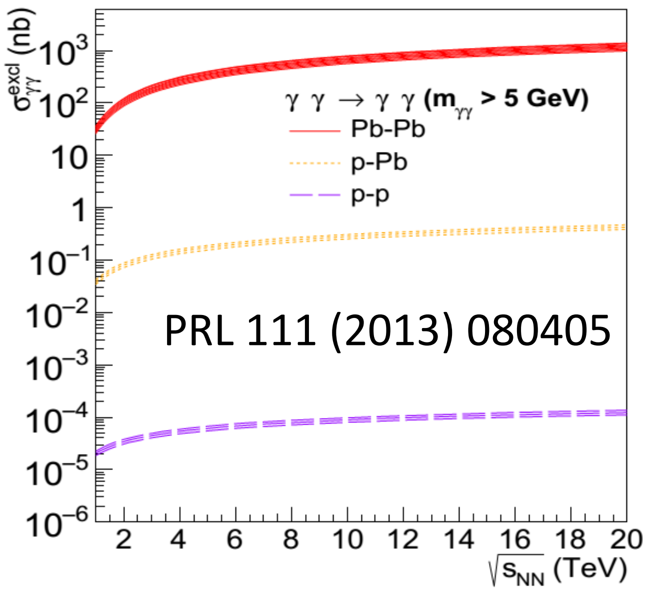
- Exact calculations: <u>loops</u>
  - Box diagrams involve charged fermions and W bosons



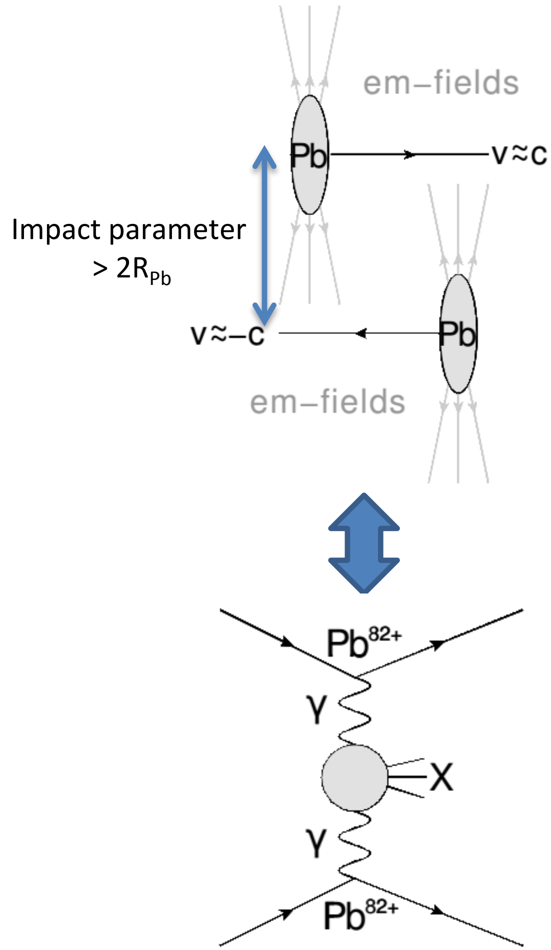
Motivation

- LbyL scattering can be tested in hadron-hadron collisions
- Recent phenomenological studies/preditions for SM rates in pp/Pb-Pb collisions:
  - [PRL 111 (2013) 080405]
  - [PRC 93 (2016) no.4, 044907]
- (Relatively) high $m_{\gamma\gamma}$ can be probed here -> proposed as a possible channel to study
  - Anomalous gauge couplings
  - Contributions from BSM particles (axions etc.)





Theory: ZZ ($\gamma\gamma$) $\rightarrow$ ZZ X scattering



[Fermi, Nuovo Cim. 2 (1925) 143]

[Weizsacker, Z. Phys. 88 (1934) 612]
[Williams, Phys. Rev. 45 (10 1934) 729]

The cross section for ZZ ($\gamma\gamma$) $\rightarrow$ ZZ X process is calculated using:

(1) Number of equivalent photons (EPA) by integration of relevant EM form factors:

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

$$Q^2 < 1/R^2 \qquad \omega_{\max} \approx \gamma/R$$

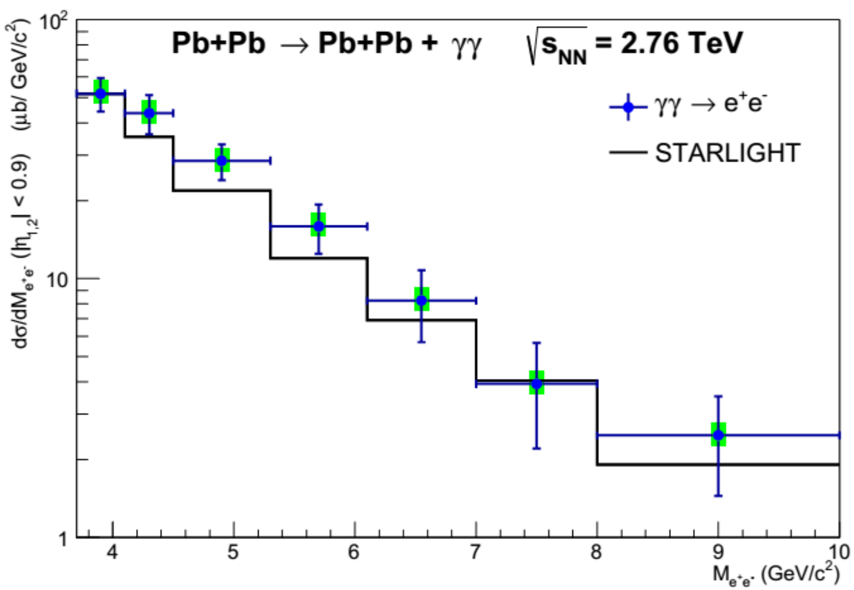
(2) EW $\gamma\gamma \rightarrow$ **X** (elementary) cross section

$$\boxed{\sigma^{\mathrm{EPA}}_{A_1A_2(\gamma\gamma)\rightarrow A_1A_2X} = \iint \mathrm{d}\omega_1\ \mathrm{d}\omega_2\ n_1(\omega_1)\ n_2(\omega_2)\ \sigma_{\gamma\gamma\rightarrow X}(W_{\gamma\gamma})}$$

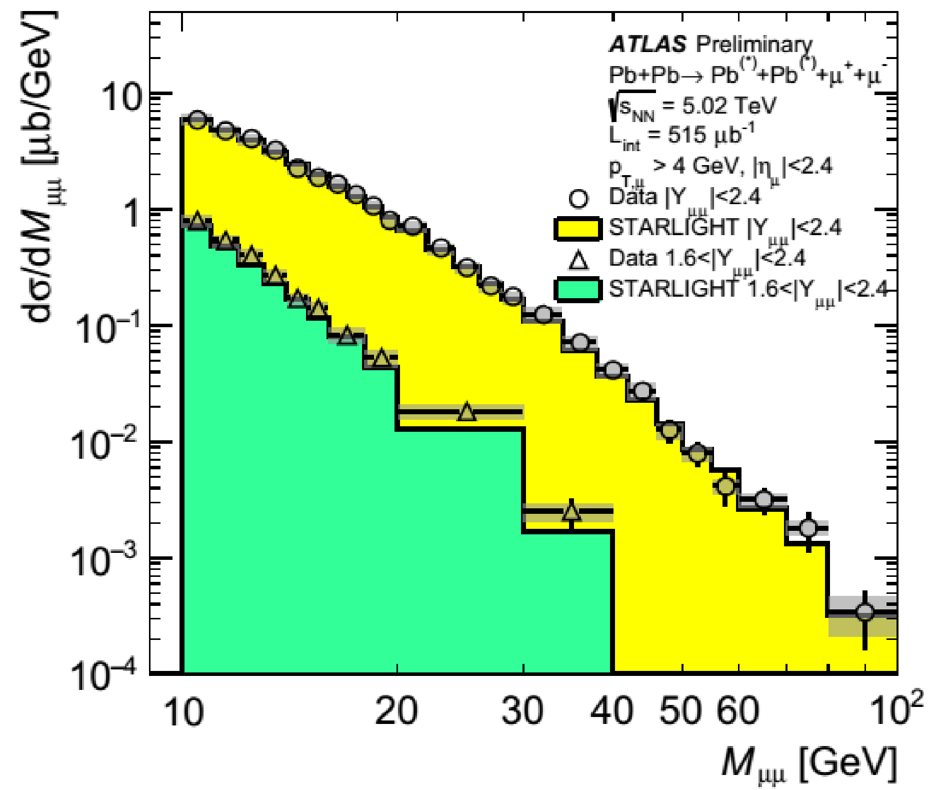
Testing EPA at the LHC

- Non-resonant $\gamma\gamma \rightarrow \ell^+\ell^-$ is a good benchmark process
- Studied by both ALICE and ATLAS
- Good agreement with Starlight (EPA + LO elementary cross section) is found

[EPJC 73 (2013) 2617]



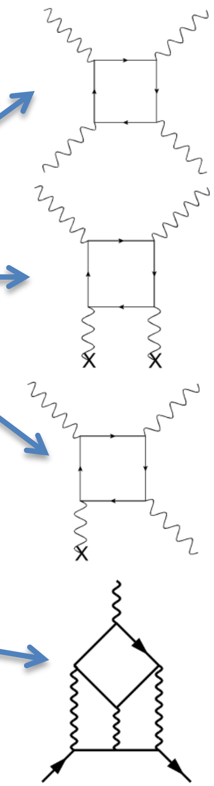
[ATLAS-CONF-2016-025]



Previous experiments

- Experimental status prior to the ATLAS result

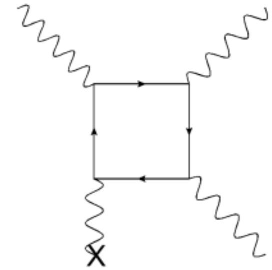
Elastic LbyL scattering	$\gamma\gamma \rightarrow \gamma\gamma$	Not observed
Delbruck scattering	$\gamma Z \rightarrow \gamma Z$	Observed ('53 - '98)
Photon splitting in Z field	$\gamma Z \rightarrow \gamma\gamma Z$	Observed (2002)
Vacuum electric/magnetic birefringence	$\gamma F \rightarrow \gamma F$	Not observed
Photon splitting in electric/magnetic field	$\gamma F \rightarrow \gamma\gamma F$	Not observed
Muon (electron) g-2	$B\ell \rightarrow \ell$	''Observed''

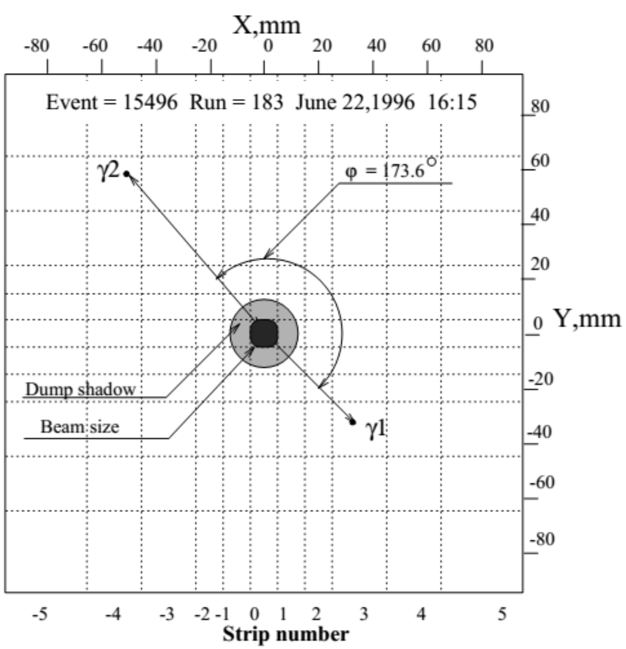


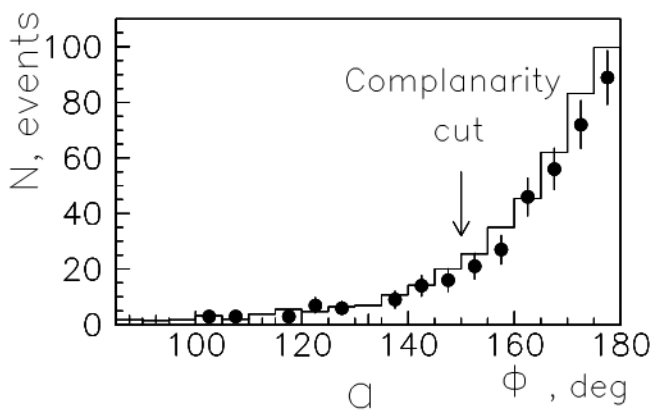
- Formally, LbyL scattering in heavy-ion collisions can be treated as **ZZ -> γγ ZZ** process
- However, the initial photons have very small virtualities, $Q^2 < 10^{-3}$ GeV^2 (they are quasi-real) -> Quasi-elastic LbyL scattering

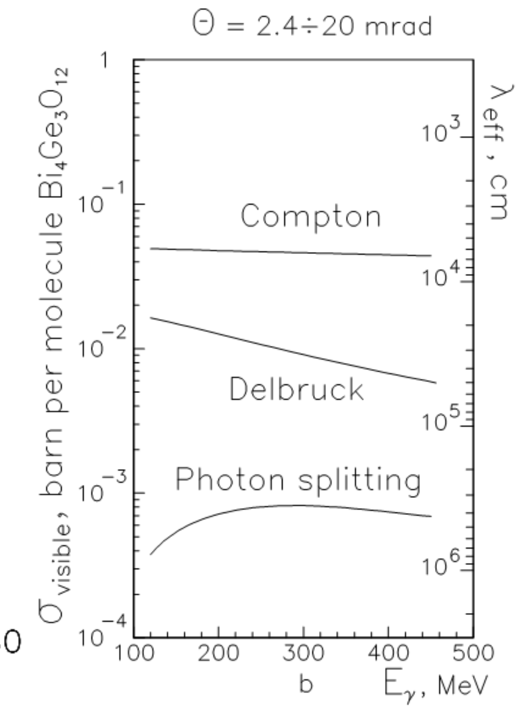
Photon splitting

- First observation [PRL 89 (2002) 061802]
  - ROKK-1M facility at the VEPP-4M collider
  - Tagged photon beam experiment (BGO target)
  - Photon energy region: 120-450 MeV
  - ~400 candidate events are observed, in agreement with QED expectations



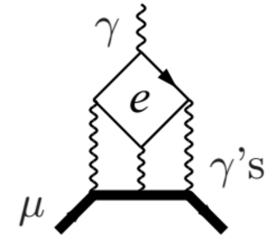






Muon g-2

- Significant contribution of LbyL graphs with electron loop
  - Dominate sixth-order QED contributions
  - ”Surprisingly large” factor $a_\mu^{(6)}(\mathrm{lbl}, e) \; = \; \frac{2}{3}\pi^2 \ln \frac{m_\mu}{m_e} + \cdots$



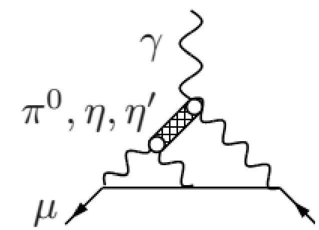
$$a_\mu^{(6)}(\mathrm{lbl}, e) \simeq 20.947\,924\,89(16) \left(\frac{\alpha}{\pi}\right)^3 = 2.625\,351\,02(2) \times 10^{-7}$$

$$\boxed{a_\mu = (g_\mu - 2)/2}$$

$$a_\mu^{(6)\ \mathrm{QED}} = 24.050\,509\,64\,(46) \left(\frac{\alpha}{\pi}\right)^3$$

[Phys.Rept. 477 (2009) 1-110]

- ”Hadronic” LbyL contribution is relatively small
  - Dominated by pseudoscalar exchange diagrams



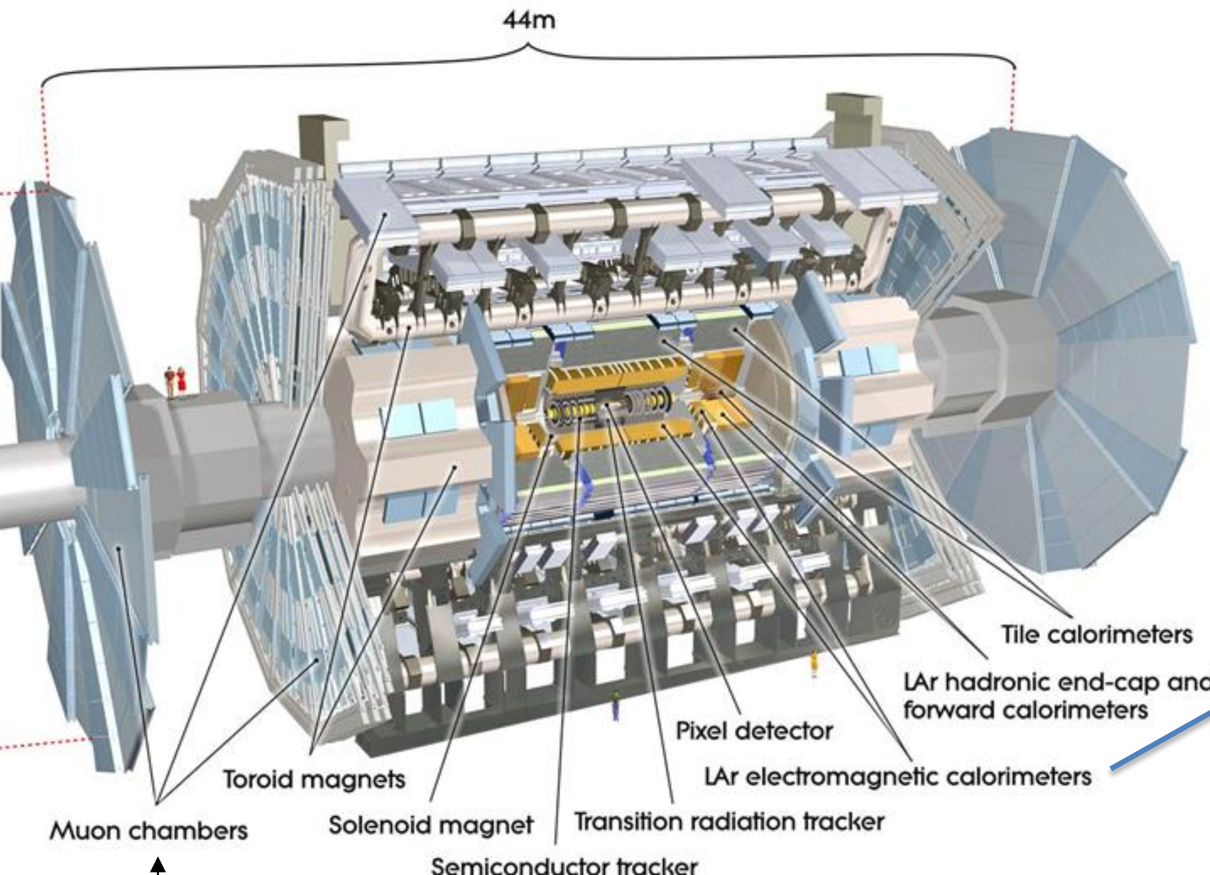
$$a_\mu^{\mathrm{LbL;PS}} = (99 \pm 16) \times 10^{-11} \longrightarrow a_\mu^{\mathrm{LbL;had}} = (116 \pm 39) \times 10^{-11}$$

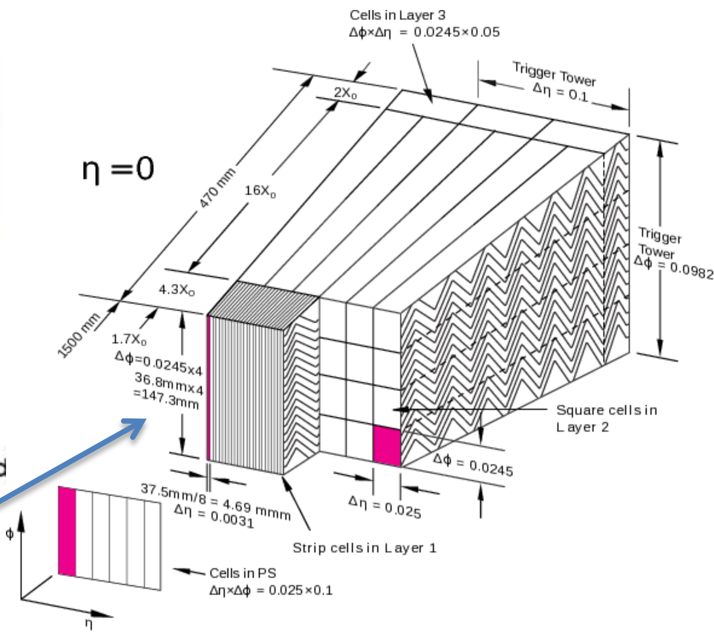
- Current experimental status:

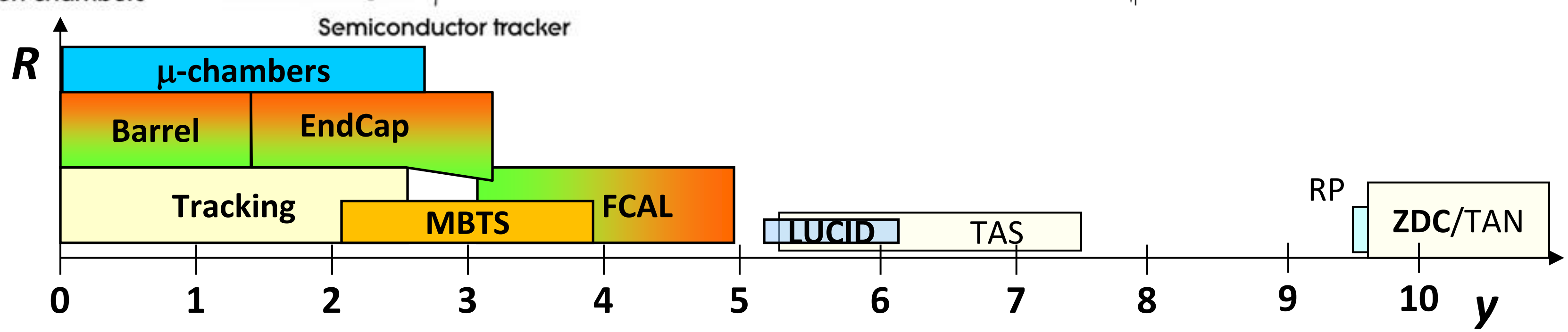
$$\left.\begin{aligned} a_\mu^{\mathrm{exp}} &= 1.16592080(63) \times 10^{-3} \\ a_\mu^{\mathrm{the}} &= 1.16591790(65) \times 10^{-3} \end{aligned}\right\} \quad \delta a_\mu^{\mathrm{NP?}} = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{the}} = (290 \pm 90) \times 10^{-11}$$

~3σ discrepancy

The ATLAS detector





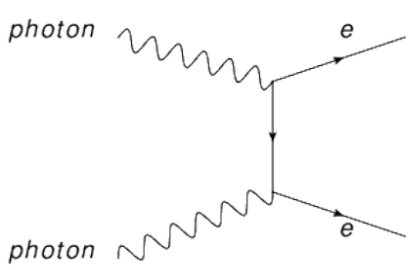


Data and MC samples

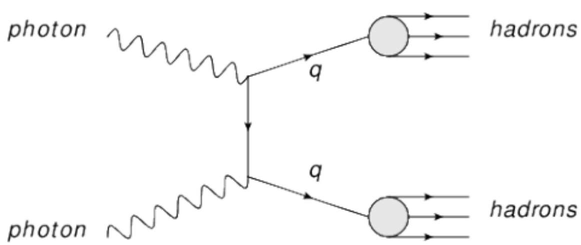
- Data: 34 runs from 2015 Pb+Pb campaign are used
- Total integrated luminosity: 0.48 nb^{-1}
  - 6% relative uncertainty

- MC simulated events
  - Signal MC sample to study event characteristics and correction factor
  - Several background MC samples are used for processes:

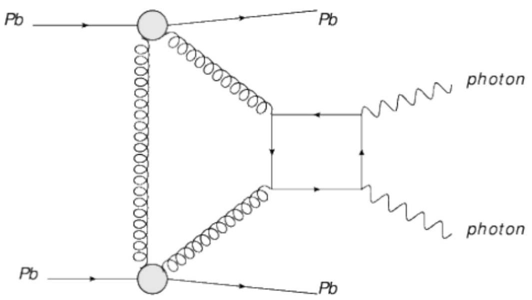
γγ -> ee



γγ -> qq



CEP gg -> γγ



Object definition

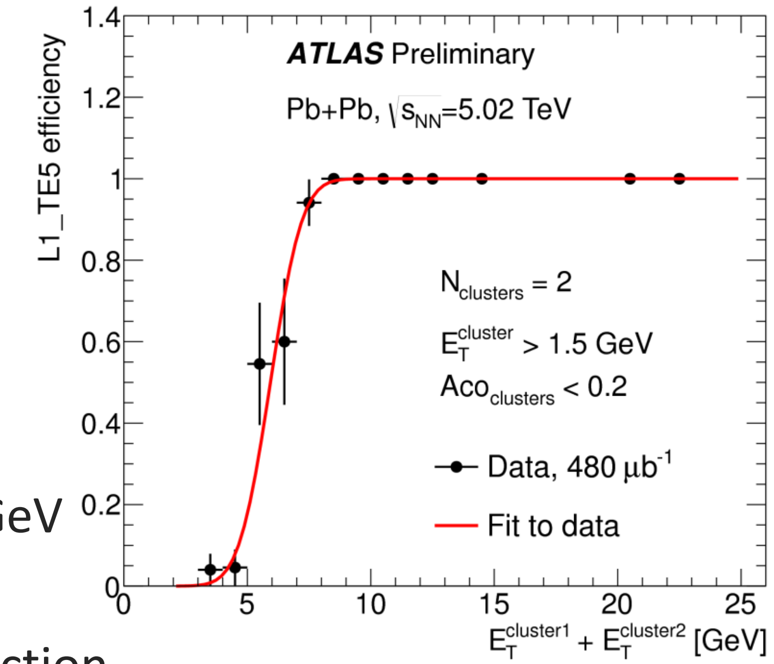
- $\gamma\gamma \to \gamma\gamma$ cross section decreases very fast with $m_{\gamma\gamma}$ and/or E_T
  - **Low-E_T photons need to be used**
- Photons
  - $E_T > 3$ GeV, $|\eta| < 2.37$ (crack region excluded), OQ requirements, photon PID based on three shower-shape variables is used:

E_{ratio}	Ratio of the energy difference associated with the largest and second largest energy deposits to the sum of these energies in the first EM calo layer
f_1	Fraction of energy reconstructed in the first layer with respect to the total energy of the cluster
w_{eta2}	Lateral width of the shower in the middle layer

- Charged-particle tracks (help to reduce $\gamma\gamma \to ee$ part)
  - $p_T > 100$ MeV, $|eta| < 2.5$, $N_{pix} \geq 1$
- Electrons (to study e.g. photon reconstruction efficiency in hard-bremsstrahlung process)
  - (EM)Loose PID, $E_T > 2.5$ GeV, $|eta| < 2.47$ (crack region excluded), OQ requirements

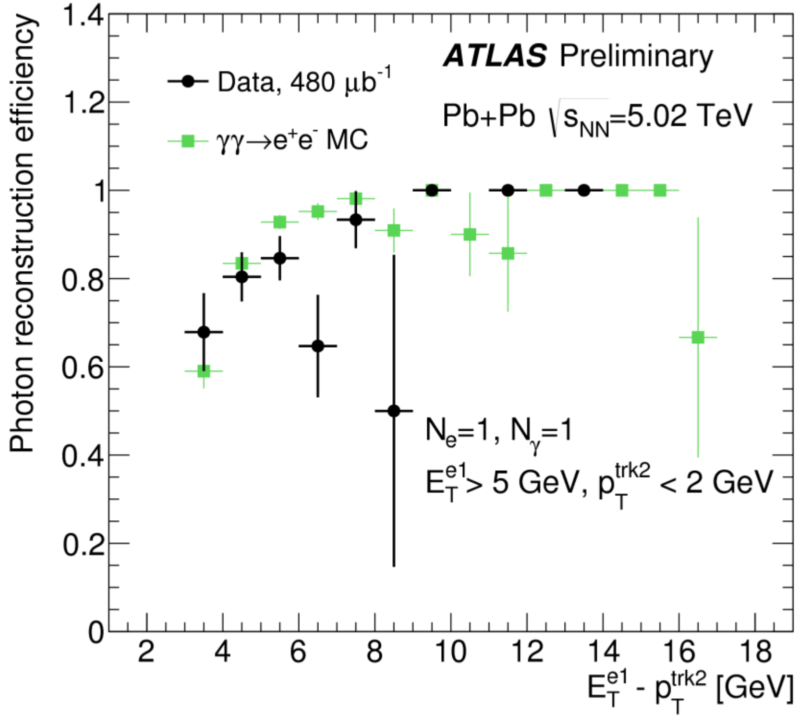
Trigger

- **Dedicated trigger** is used to select γγ -> γγ event candidates
  - Unprescaled in full 2015 data-taking period
  - L1_TE5_VTE200 at L1
  - Veto on signals in inner MBTS
  - Between 0-10 hits in the pixel detector
- Efficiency is estimated with γγ -> $\ell^+\ell^-$ events passing supporting trigger (ZDC-based)
  - L1_TE5 reaches 100% at (E_{Tcl1}+E_{Tcl2}) = 9 GeV
  - MBTS veto is estimated to be (98 ± 2)%
  - Due to low noise, very high hit reconstruction efficiency and low conversion probability of signal photons in the pixel detector, the requirement for its minimal activity is ~100% efficient with negligible uncertainty

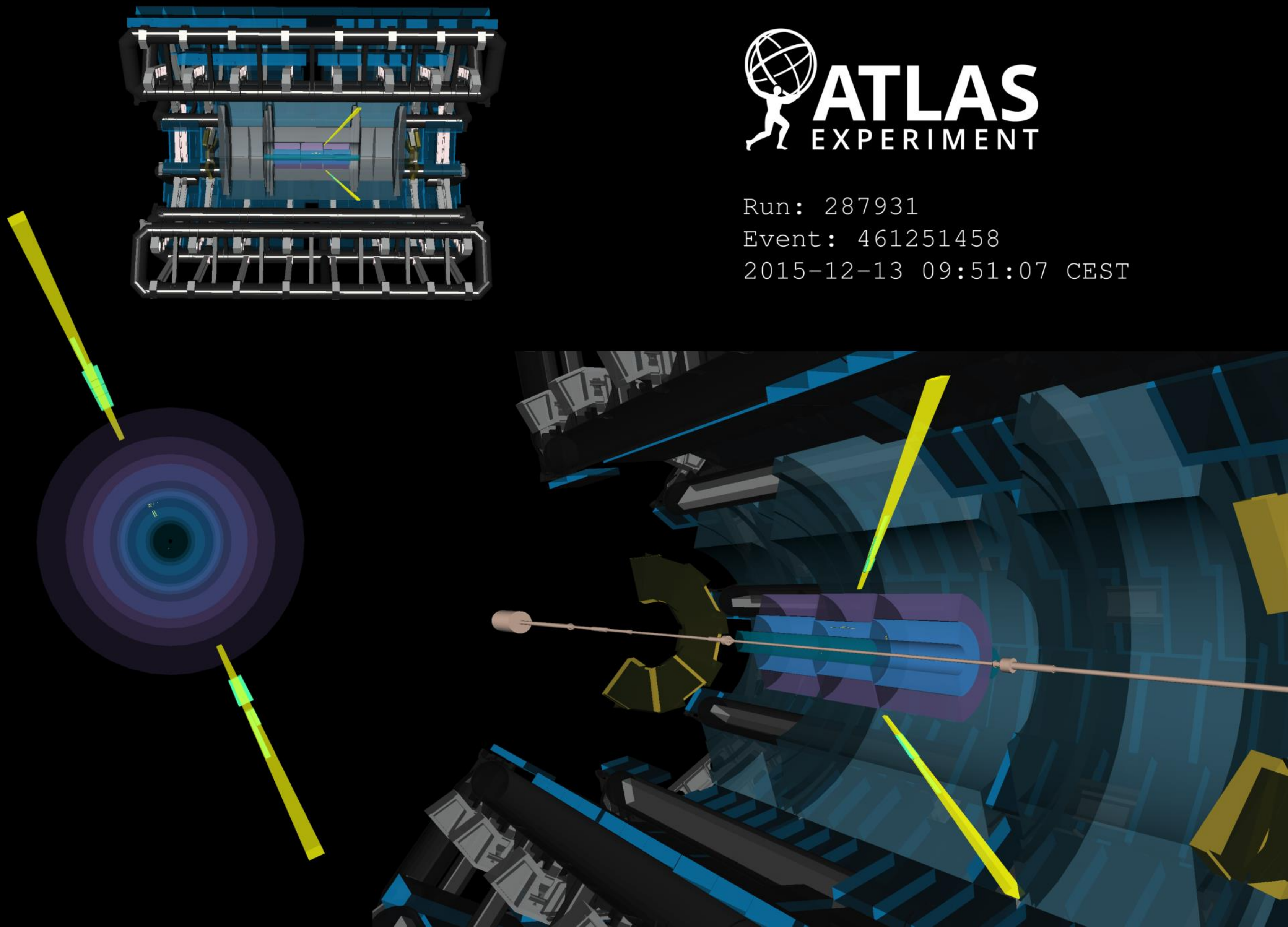


Photon performance cross-checks

- $\gamma\gamma \rightarrow \ell^+\ell^-(\gamma)$ events used to cross-check low-E_T photon performance
  - This includes: PID/reco efficiency, energy scale/resolution
- **Example:** γγ -> ee events with hard-bremstrahlung photon are used to extract photon reconstruction efficiency (Tag-and-Probe)
- Tag selection:
  - ==1 identified electron with $E_T > 5$ GeV
  - ==2 tracks, where p_T of track unmatched with electron < 2 GeV
- Probe selection:
  - Check how many times we reconstruct hard-bremsstrahlung photon
  - $E_T(\gamma) \approx (E_T(e)$ - second track $p_T)$
- Photon reco efficiency extracted from data in agreement with MC



γγ -> γγ event characteristics

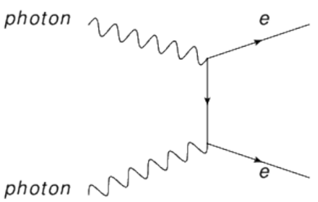


Event selection

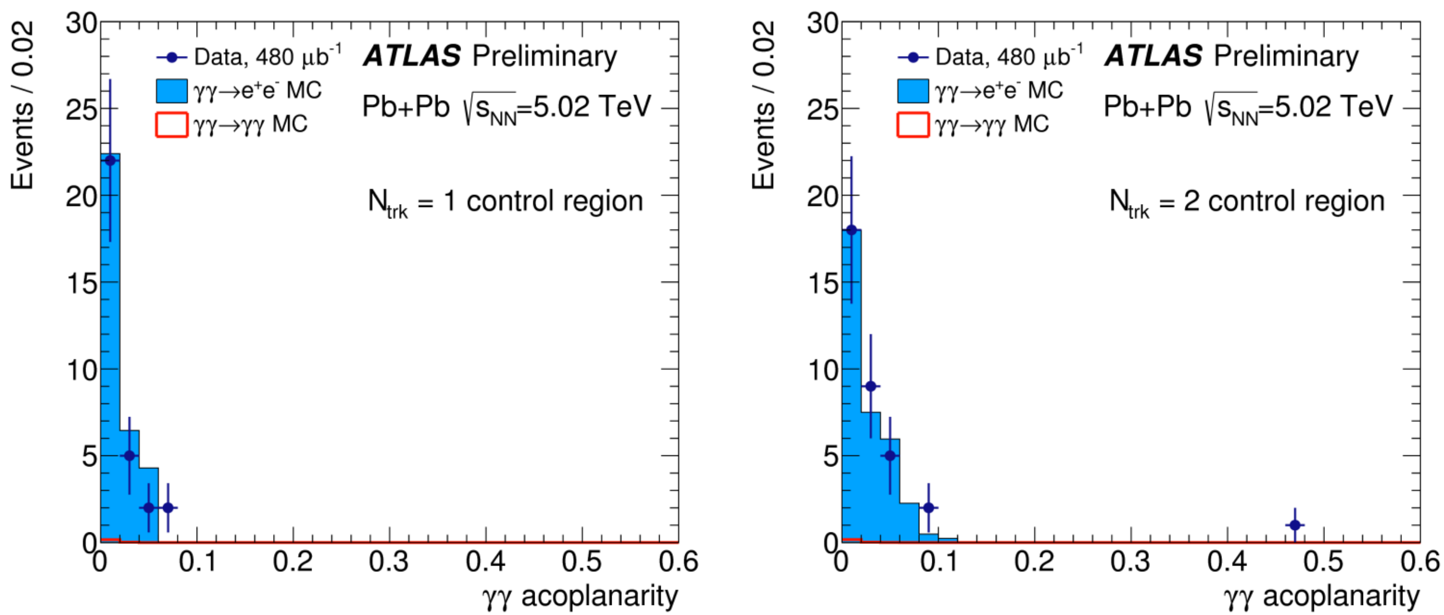
- Using signal events characteristics, defining a set of cuts for background reduction
  - == 2 photons with photon $E_T > 3$ GeV, $m_{\gamma\gamma} > 6$ GeV -> event preselection
  - $N_{trk} = 0$ -> almost no impact on signal MC events, significant reduction of $\gamma\gamma$ -> ee misID events
  - $p_T(\gamma\gamma) < 2$ GeV -> fake photon background reduction (dominated by cosmic-ray muons inducing EM clusters), no impact on signal events
  - Diphoton acoplanarity < 0.01 -> to reduce/control CEP gg->yy background

Backgrounds

- $\gamma\gamma$ -> ee misID events
  - Occur when the electron track is not reconstructed or the electron emits a hard bremsstrahlung photon

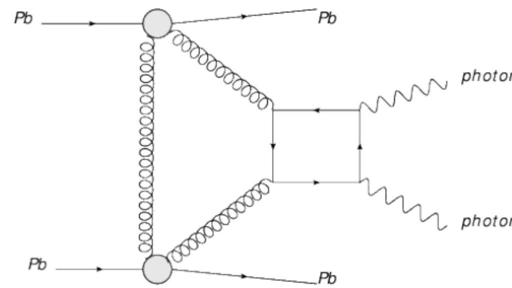


- N_{trk} = 0 cut is used to suppress $\gamma\gamma$ -> ee misID events
- ==2 photons with N_{trk} = 1(2) is a good control region for $\gamma\gamma$ -> ee misID background

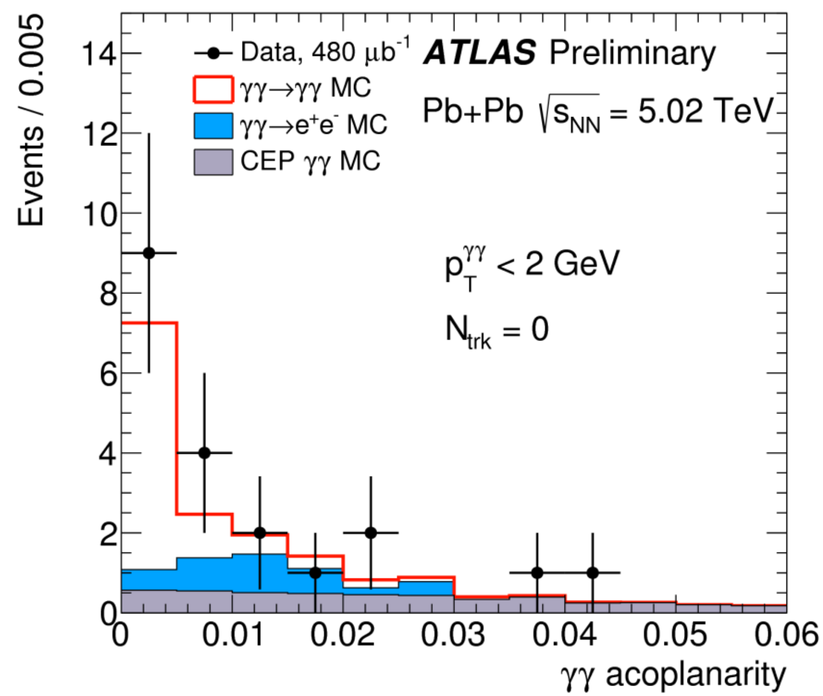


Backgrounds

- Central exclusive yy production
  - Similar exclusive topology
  - Relatively flat yy acoplanarity distribution (wrt signal), since the transverse momentum transferred by the photon exchange is much smaller than that due to the colour-singlet state gluons

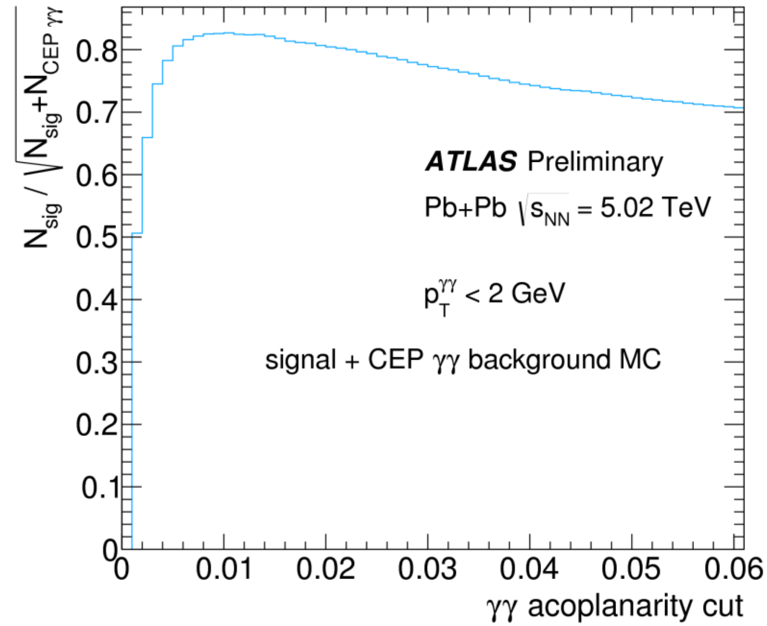


- CEP gg -> yy is reducibe with yy acoplanarity cut
- Idea: define Aco < Aco_cut as a signal region and use events with Aco > Aco_cut for CEP gg->yy background normalization (due to large theory uncertainties)



Backgrounds

- Central exclusive yy production



- The Aco_cut value is optimized to retain high signal significance
  - Aco_cut = 0.01 is used

- For CEP gg -> yy normalization, the following formula is used:

$$f_{gg\to\gamma\gamma}^{\mathrm{norm},b} = (N_{\mathrm{data}}(\mathrm{Aco} > b) - N_{\mathrm{sig}}(\mathrm{Aco} > b) - N_{\gamma\gamma\to e^+e^-}(\mathrm{Aco} > b))/N_{gg\to\gamma\gamma}(\mathrm{Aco} > b)$$

where b = 0.02 is used for the central value and b = 0.01 and b = 0.03 for systematic checks

- It is found that $f_{gg\to\gamma\gamma}^{\mathrm{norm},b=0.02} = 0.5 \pm 0.3$

Other backgrounds

- Other (negligible) backgrounds being studied:
  - **Fake photons from hadronic processes**: highly suppressed due to MBTS veto and N_{trk} = 0 requirements
    -> studied using Minimum Bias events in data extrapolated to signal region
  - **yy->qq (exclusive hadrons)** -> MC estimation -> considered negligible
  - **CEP dimeson production** (e.g. gg->pi0pi0->4y, gg->ηη->4y etc.)
    -> estimated with MC models to be below 10% of CEP gg->yy in the same kinematic region -> considered negligible
  - **Other fake photons** (mostly induced by cosmic-ray muons) -> estimated to be negligible (0.1 ± 0.1 evts in the signal region) using ABCD method
    - A - events passing f_1 cuts on photons, p_T (yy) < 2 GeV
    - B - events failing f_1 cuts on photons, p_T (yy) < 2 GeV
    - C - events passing f_1 cuts on photons, p_T (yy) > 2 GeV
    - D - events failing f_1 cuts on photons, p_T (yy) > 2 GeV
    - Results are cross-checked wrt other shower-shape variables and additional muon activity in MS

Systematic uncertainties

- Trigger efficiency uncertainty: dominated by yy-> $\ell^+\ell^-$ event statistics passing supporting trigger
- Photon reco/PID efficiency uncertainty: large impact from limited statistics of FSR/hard-bremsstrahlung photon samples
- Photon energy scale: ±5%
- Photon energy resolution: ±15%

- Impact on the C-factor:

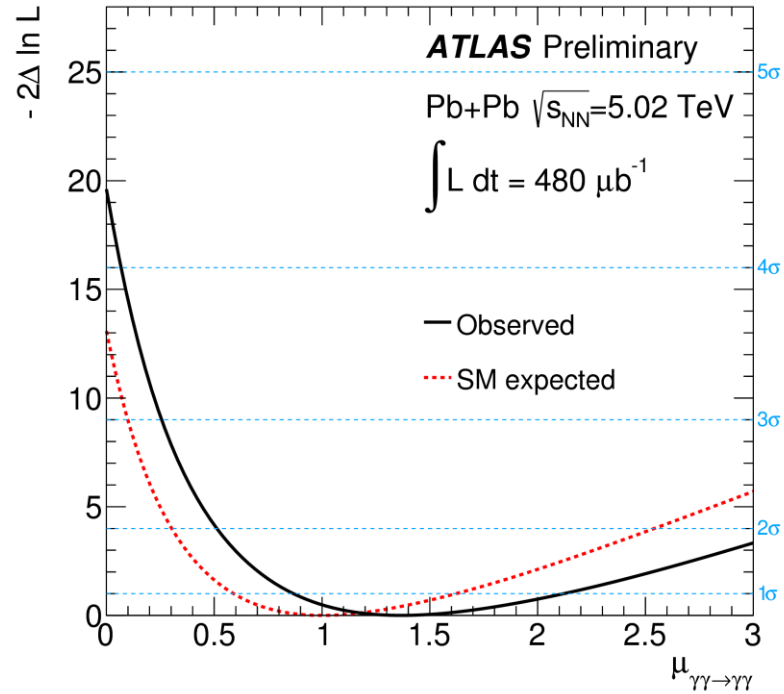
Source of uncertainty	Detector correction (C)
	0.31
Trigger	5%
Photon reco efficiency	12%
Photon PID efficiency	16%
Photon energy scale	7%
Photon energy resolution	11%
Total	24%

Results

- 13 events observed in data
- 7.3 signal events and 2.6 ± 0.7 background events are expected

Selection	Data	Signal	$\gamma\gamma \to e^+e^-$	CEP $gg \to \gamma\gamma$	Hadronic fakes	Other fakes	Total expected
Preselection	105	9.1	74	4.7	6	19	113
$N_{\mathrm{trk}} = 0$	39	8.7	4.0	4.5	6	19	42
$p_{\mathrm{T}}^{\gamma\gamma} < 2$ GeV	21	8.5	3.5	4.4	3	1.3	21
Aco < 0.01	13	7.3	1.3	0.9	0.3	0.1	9.9
Uncertainty		1.5	0.3	0.5	0.3	0.1	

- Significance is estimated using profile likelihood method (asymptothic formulae)
- Observed significance: **4.4σ** (3.8σ expected)

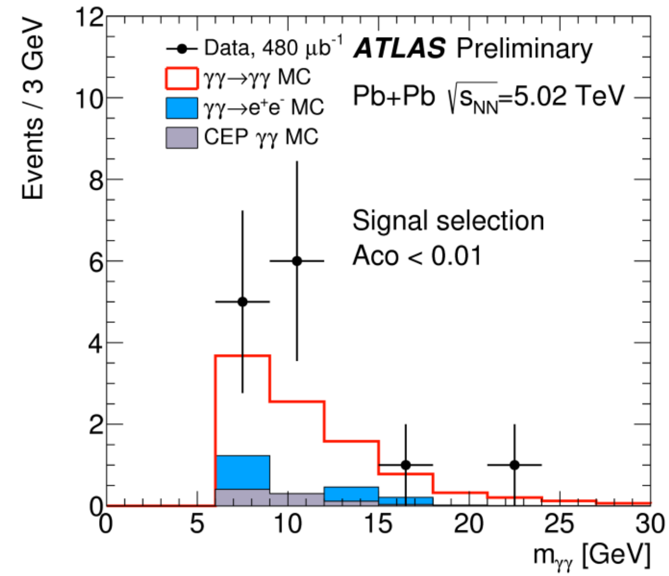


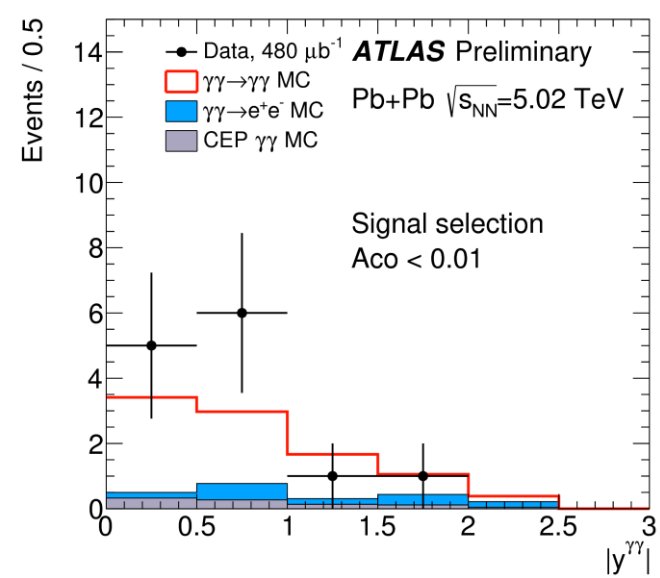
Results

- Fiducial cross section is estimated in the region:
  - $p_T(\gamma) > 3$ GeV, $|\eta(\gamma)| < 2.4$
  - $m_{\gamma\gamma} > 6$ GeV, $p_T(\gamma\gamma) < 2$ GeV,
  - Aco < 0.01
- **σ_{fid} = 70 ± 20 (stat.) ± 17(syst.) nb**

$$\sigma_{\text{fid}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{C \times \int L dt}$$

- SM predictions:
  - 45 ± 9 nb [PRL 111 (2013) 080405]
  - 49 ± 10 nb [PRC 93 (2016) no.4, 044907]

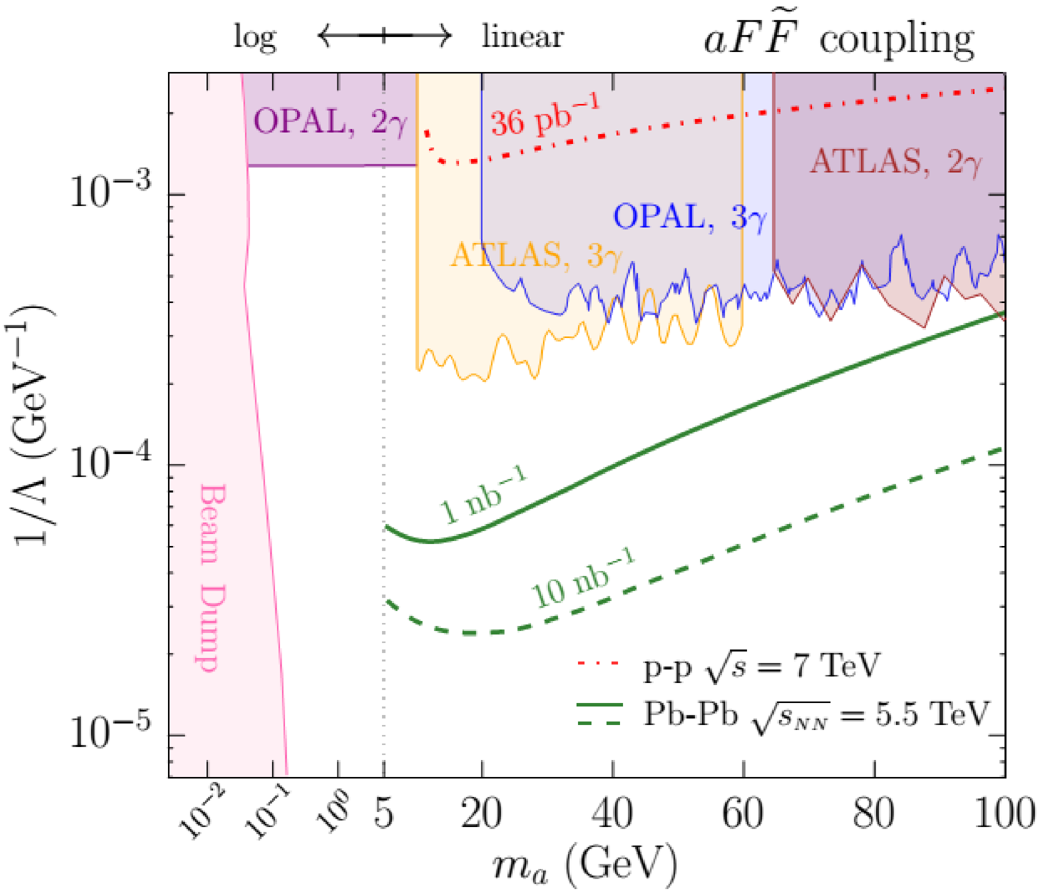




A look forward

- **Example: expected sensitivity for ALP searches**

[arXiv:1607.06083]



Summary

- A search for very rare QED process, light-by-light scattering, is performed in Pb+Pb collisions using 0.48 nb^{-1} of 2015 data

- 13 events observed in data, where 7.3 signal events and 2.6 ± 0.7 background events are expected
    - Observed significance over background-only hypothesis: 4.4σ (3.8σ expected)

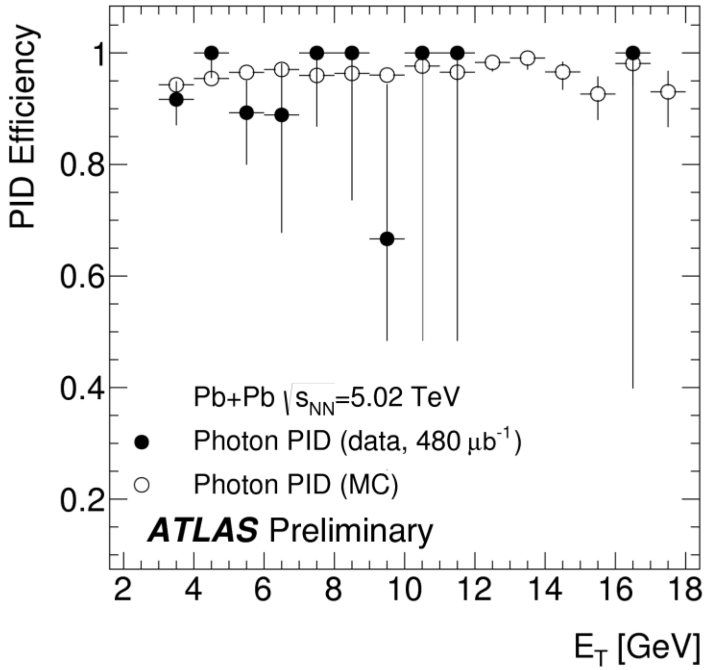
- Fiducial cross section is measured to be: 70 ± 20 (stat.) ± 17(syst.) nb
    - SM predictions: 45 ± 9 nb [PRL 111 (2013) 080405], 49 ± 10 nb [PRC 93 (2016) no.4, 044907]

- More details available at: ATLAS-CONF-2016-111

Backup

Photon performance cross-checks

- $\gamma\gamma \to \ell^+\ell^-\gamma$ (FSR) events are used for data-driven photon PID efficiency estimation
- Event selection:
  - Trigger: signal or supporting triggers are used
  - 2 OS tracks in back-to-back configuration, each with p_T > 1 GeV
  - $\Delta R(t\gamma) > 0.2$ to suppress e-bremsstrahlung photons
  - $p_T(tt\gamma) < 1$ GeV
- Photon PID efficiency is estimated as a function of photon E_T and compared with MC



Photon performance cross-checks

- Photon energy scale/resolution is cross-checked using **yy -> ee** event properties
- Idea: measure E_T(cl1) ± E_T(cl2) distributions in yy -> ee process

- Initial „theory" smearing very small ($\sigma_{pT(e1)\text{ - }pT(e2)}$ below 0.03 GeV for E_T(cluster) > 3 GeV):
  - $\sigma_{Et(cluster)} \approx (\sigma_{Et(cluster1)\text{ - }Et(cluster2)})/\mathrm{sqrt}(2)$
  - $\sigma_{Et}/E_T \approx 8\%$ at low-E_T (< 10 GeV)
  - Data agrees with yy -> yy MC within 15% at low-E_T

- E_T(cluster1) + E_T(cluster2) distribution sensitive to photon energy scale
  - Et scale is conservatively varied by ±5% in MC
  - Simple chi2 test can be used to check the data/MC improvement
  - Data nicely covered by ±5% bands in MC