Light by Light scattering

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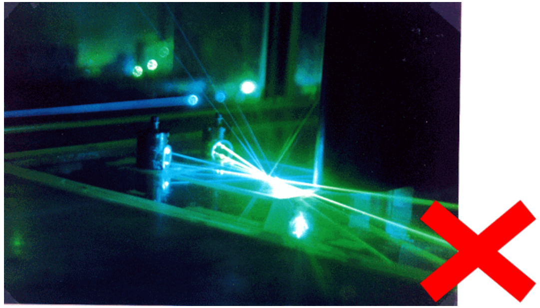
Outline

- Physical Motivation
    - What is LbyL and Why to probe it
- Measurement principle
    - Heavy Ion UPC
    - ATLAS detector
- Analysis
    - Trigger, Reconstruction, PID
    - Signal, Background, Selection
    - Results and Uncertainty
- Discussion

Physical Motivation

- What is LbyL (Light by Light scattering?)
- In Classical world



$$\frac{\partial}{\partial x_i} B_i = 0$$

$$\frac{\partial}{\partial x_i} E_j \epsilon_{ijk} + \frac{1}{c}\frac{\partial B_k}{\partial t} = 0$$

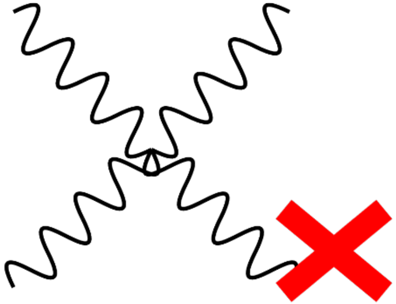
$$\frac{\partial}{\partial x_k} E_k = 4\pi\rho$$

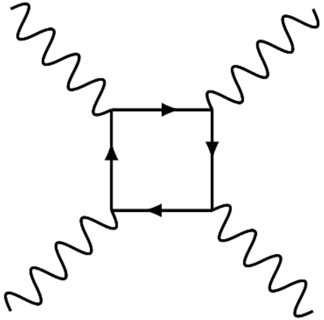
$$\frac{\partial}{\partial x_i} B_j \epsilon_{ijk} - \frac{1}{c}\frac{\partial E_k}{\partial t} = \frac{4\pi}{c} J_k$$

$$B_j = \frac{\partial}{\partial x_m} A_n \epsilon_{mnj}$$

$$E_k = -\frac{\partial}{\partial x_k}\phi - \frac{1}{c}\frac{\partial A_k}{\partial t}$$

- In Quantum world





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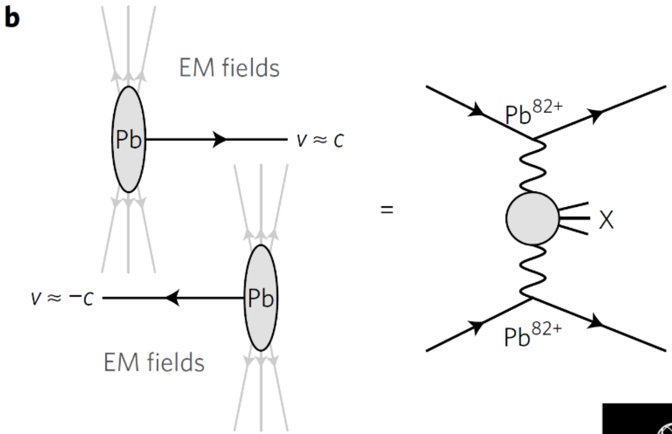
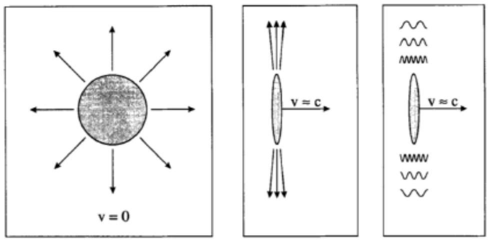
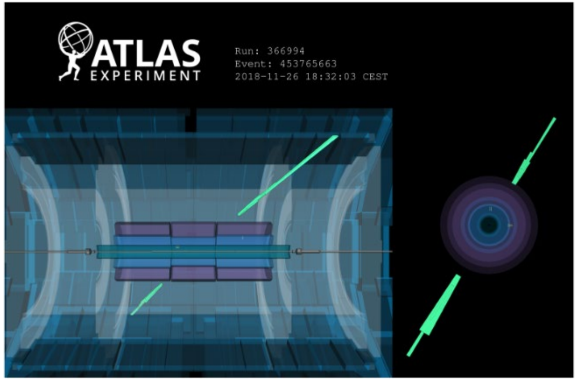
Physical Motivation

- What is the *photon* here?
- Incoming photon:
  - “Quasi-real" photons
  - Relativistic EM field
  - EPA theory [see backup]
- Outgoing photon:
  - Real back-to-back photons
  - Acoplanarity (1-ΔΦ/π, how it is “back-to-back”)
  - Energy and momentum
- Nothing more





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



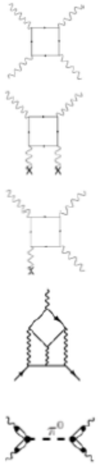
Physical Motivation

- Other related experiments:
  - Static nulcei incolved
- Why this experiment highlights?
  - "Real and direct " Light by Light scattering
  - High event rate and multi probing observables

Previous experiments

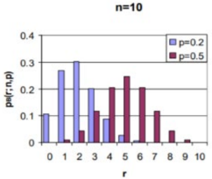
- Experimental status prior to the ATLAS result

Elastic LbyL scattering	γγ -> γγ	Not observed
Delbruck scattering	γZ -> γZ	Observed ('53 - '98)
Photon splitting in Z field	γZ -> γγZ	Observed (2002)
Vacuum electric/magnetic birefringence	γF -> γF	Not observed
Photon splitting in electric/magnetic field	γF -> γγF	Not observed
Impact on muon (electron) g-2	Bl -> l	"Observed"
Hadronic LbyL (direct)	ZZ -> $\pi^0/\eta/\eta'$ -> γγ	Observed ('85 - '88)



Measurement Principle

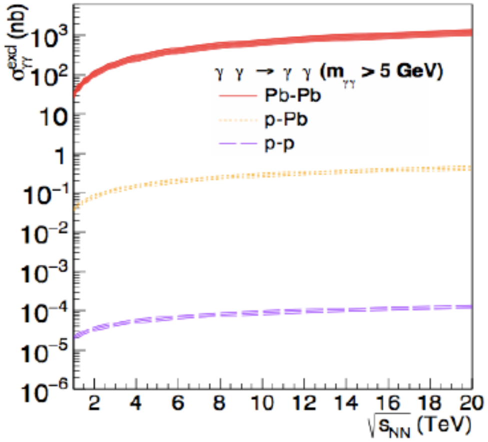
- Counting experiment



- LHC as heavy ion collider

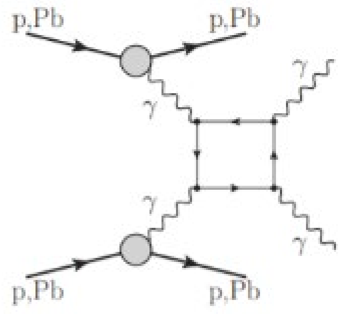
System	$\sqrt{s_{NN}}$ (TeV)	$\mathcal{L}_{AB} \cdot \Delta t$ (per year)	γ	R_A (fm)	ω_{max} (GeV)	$\sqrt{s^{max}_{\gamma\gamma}}$ (GeV)	$\sigma^{excl}_{\gamma\gamma\to\gamma\gamma}$ $[m_{\gamma\gamma} > 5$ GeV$]$	$N^{excl}_{\gamma\gamma}$ (per year) $[m_{\gamma\gamma} > 5$ GeV, after cuts$]$
p-p	14	1 fb^{-1}	7455	0.7	2450	4500	105 ± 10 fb	12
p-Pb	8.8	200 nb^{-1}	4690	7.1	130	260	260 ± 26 pb	6
Pb-Pb	5.5	1 nb^{-1}	2930	7.1	80	160	370 ± 70 nb	70

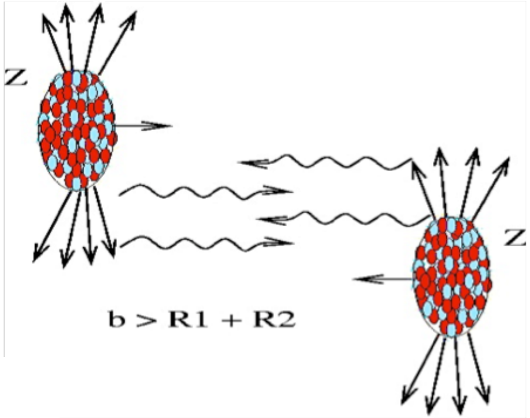
- Clean: almost no pileup
- QED scales with Z^4
- CEP reduced (w/ UPC)
- 0.49/nb @ 5.02TeV (2015) ~ 35 evts.
- 1.73/nb @ 5.02TeV (2018) ~ 121 evts.

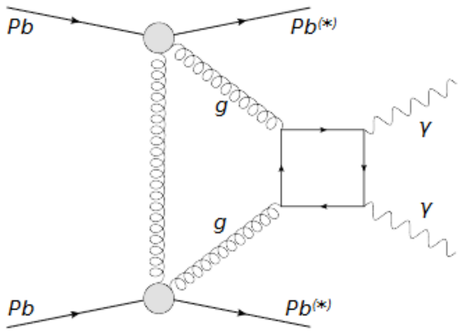


Measurement Principle

- Scale up the cross section
  - Heavy ion (big Z, intense EM, increased QED)
  - UPC (suppress Strong Int.)
- First LHC-based LbyL observation
  - High energy
  - High luminosity
  - ATLAS detector
- Theory modeling
  - Special **MC generator** for Heavy ion
  - **CEP** QCD BG (gg->yy)
  - Other BG

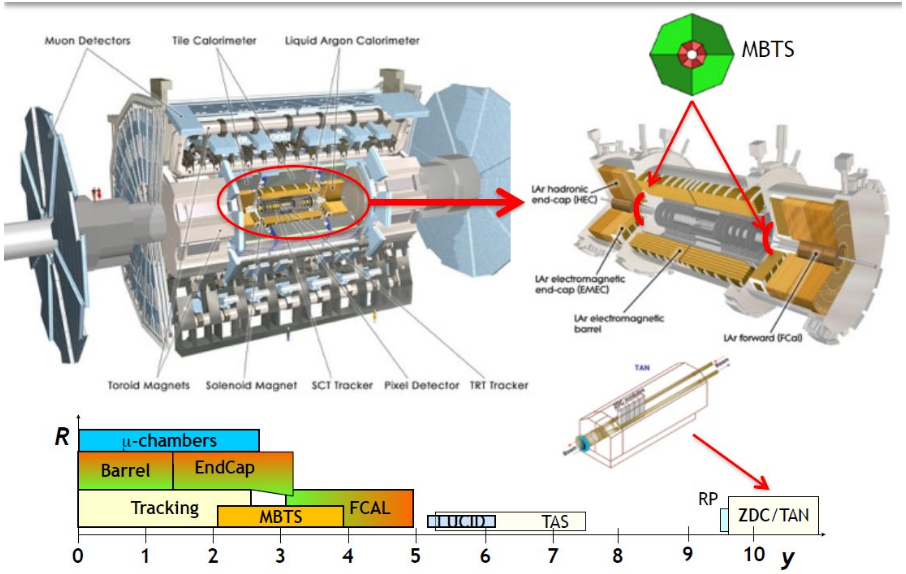






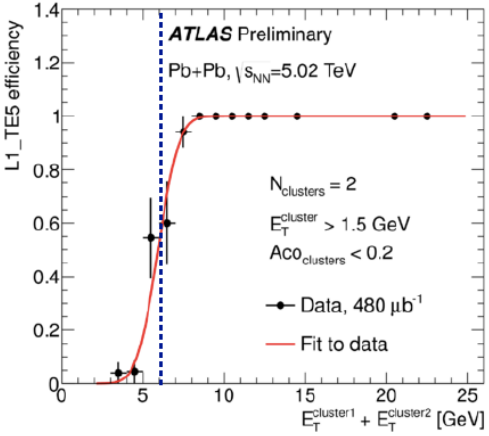
ATLAS Detector

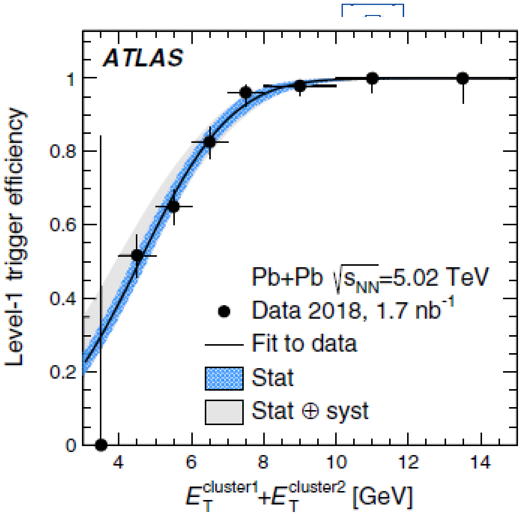
- Inner detector
  - -> charged-particle, |η| < 2.5
- EM and hadronic calorimeters
  - -> provide energy measurements up to |η|=4.9
- minimum-bias trigger scintillators (MBTSs)
  - -> outer 2.07 < |η| < 2.76
  - -> inner 2.76 < |η| < 2.86
- Forward calorimeters (FCAL)
  - -> cover the range of 3.2 < |η| < 4.9.
- The zero-degree calorimeters (ZDC)
  - ->detect neutral particles, including neutrons emitted from the nucleus.

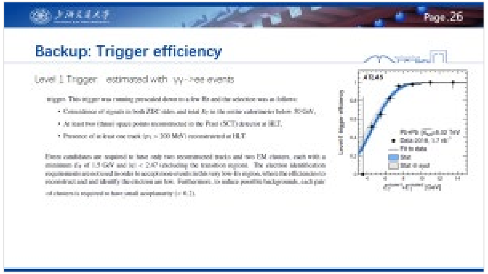


Trigger efficiency

- Dedicated trigger for LbyL was designed
- 2015 version
  - total E_T in 5-200GeV [70%-100%]
  - MBTS veto (>1 hit in inner ring) [98%]
  - Pixel detector veto (> 10hits) [100%]
- 2018 version
  - (At least one E_T >1GeV && total E_T in 4-200GeV) ||
    (At least two E_T >1GeV && total E_T <50GeV) [60%-100%]
  - FCAL veto (more than noise) [99%]
  - Pixel detector veto (> 15hits) [100%]
- Efficiency estimate
  - γγ->e+e- passing another independent trigger(ZDC-based)

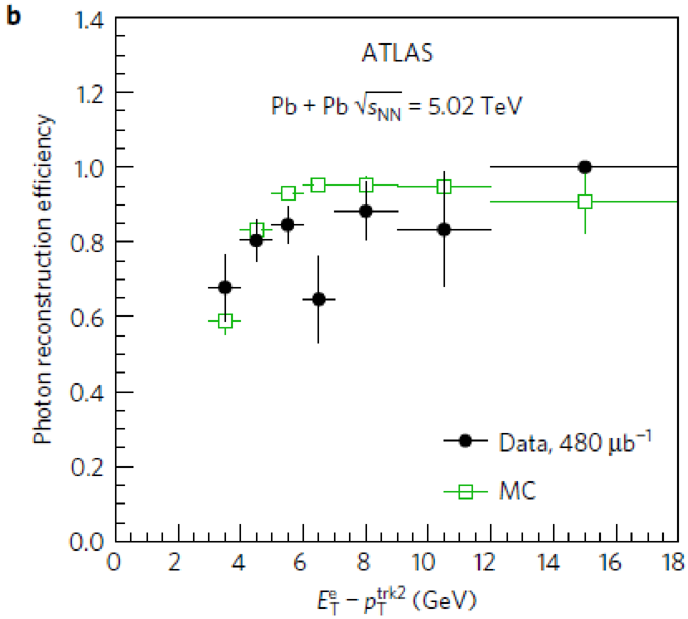






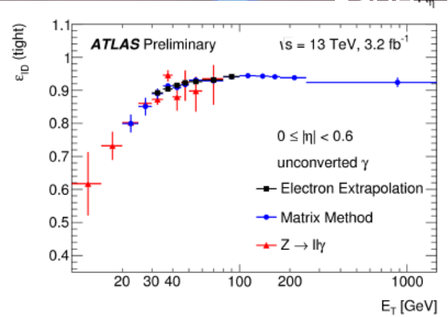
Reconstruction

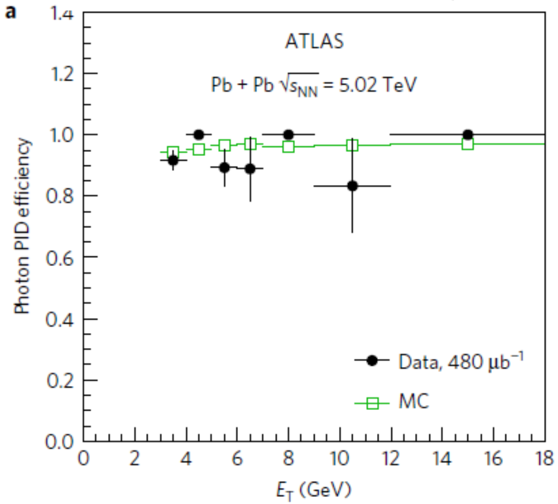
- EM cluster (EM calo)+ tracking information (ITD)
- Selection
  - ~~Poorly functioning calorimeter cells~~
  - ~~Out-of-time candidates.~~
- Efficiency study (5-10% uncert.)
  - γγ->e+e-γ hard-bremsstrahlung
  - tag: electron matched one track within $\Delta R < 1.0$
  - probe: $E_T^\gamma \approx (E_T^e - p_T^{trk2})$.
- Cluster energy resolution (8%)
  - γγ->e+e- events => p_T expects to be balanced
  - By measuring $E_T^{cl1} - E_T^{cl2}$
- EM cluster energy scale (5% uncert.)
  - By measuring E_T / p_T^{trk}
- One of the main uncertainty source
  - 5-10% relative uncertainty at low E_T (3-6GeV)



PID

- ALTAS detector is not designed for such low energy photon
  - Think about Higgs, myy~100GeV level
- Special optimized PID and detailed efficiency study
  - Use shower shape and MVA method
    - Based on 3 variables(lateral width, energy difference, and first layer reconstructed energy fraction)
    - MVA based (details missing from paper)
  - Finally reached 95% efficiency (but w/ uncer. 16% in σ measurement)
    - Measured using high-pT γγ->l+l- FSR samples
    - Data and MC agrees
    - Cross-checked with Z->μ+μ-γ, γγ->e+e-γ hard-bremsstrahlung process and all consistent.





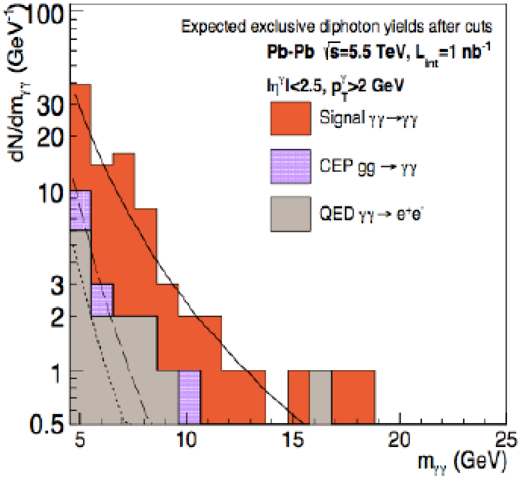
$$Eff = \frac{N_{ID\ recon}}{N_{recon}}$$

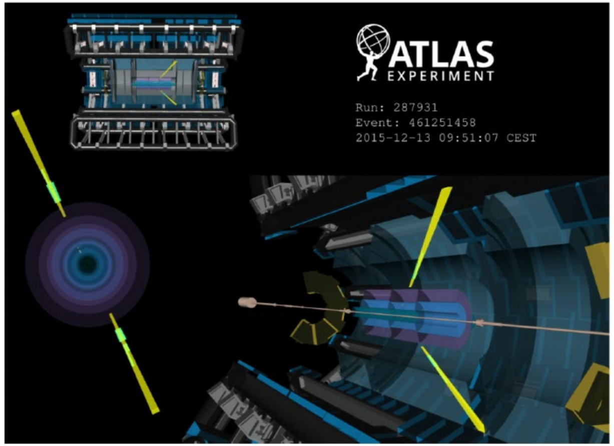
Signal topology and selection

➢Exclusive light-light scattering

- Exactly two photons (Two showers in EM calorimeter
- no Tracks in ID(suppress γγ->e^+e^-)
- E_T > 3 GeV, |η| < 2.37, $m_{\gamma\gamma}$ > 6 GeV (pre-selection)
- $p_T(\gamma\gamma)$ < 2 GeV (fake photon background reduction (dominated by cosmic-ray muons inducing EM clusters)
- back-to-back topology (Diphoton acoplanarity < 0.01)

$$A_\phi = (1 - |\Delta\phi_{\gamma\gamma}|/\pi) < 0.01 \Rightarrow |\Delta\phi_{\gamma\gamma}| \approx \pi$$

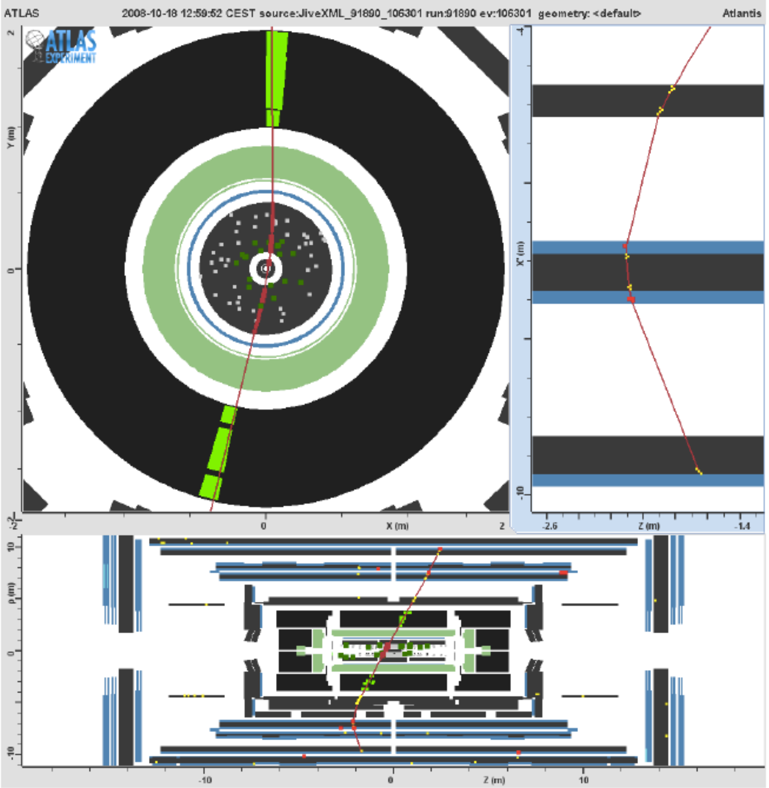




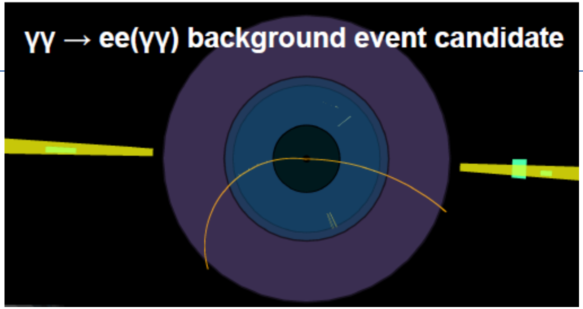
Background process

➤ Cosmic muons?

- One cosmic muon is seen as two deposits in the detector, very high rate: 700 Hz
- Very rarely it passes through an interaction point and does not deposit tracks in the ID
- Muons leave signals in the Muon Spectrometer
- Calorimetric clusters from muons have different shapes
- Cosmic background can be fully suppressed => $p_T(\gamma\gamma) < 2$ GeV and shower-shape requirement



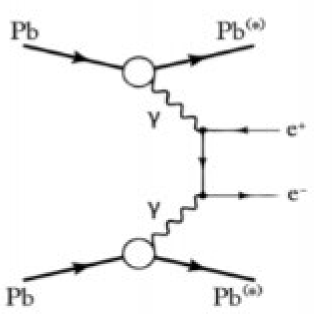
Background Process: $\gamma\gamma \to e^+e^-$



➢ Exclusive production of electron pairs: $\gamma\gamma \to e^+e^-$

- Occur when the electron track is not reconstructed or the electron emits a hard bremsstrahlung photon
- Very high cross section α^2_{em} times higher comparing to LbyL
- Electron and photons are distinct objects: electrons deposit tracks
- Production precisely known from QED, can be evaluated and subtracted
- What about if tracks are not measured in the ID?

=> Data-driven method(Define 2 control regions: exactly two photons passing the signal selection but also requiring one or two associated pixel tracks)



Background Process: $\gamma\gamma \to e^+e^-$

- What about if tracks are not measured in the ID?

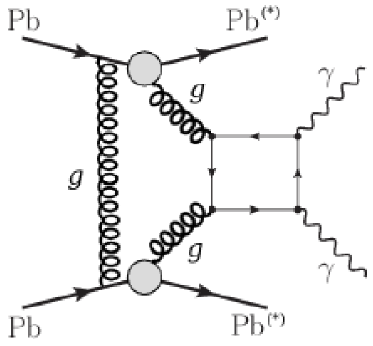
  => Data-driven method(2 control regions: exactly two photons passing the signal selection but also requiring one or two associated pixel tracks)

- The event yield observed in these two CRs is extrapolated to the signal region using the probability to miss the electron pixel track if the electron track is not reconstructed (p^e_{mistag}).

  In order to verify the stability of the p^e_{mistag} evaluation method, the A_ϕ requirement is dropped and the difference with the nominal selection is taken as a systematic uncertainty. This leads to p^e_{mistag} =47 ±9%.

- The number of $\gamma\gamma \to e^+e^-$ events in the signal region is estimated to be 7 ±1(stat) ±3(syst), where the uncertainty accounts for the CR statistical uncertainty, the pe mistag uncertainty, and the difference found between the two CRs.

Background process: gg->γγ

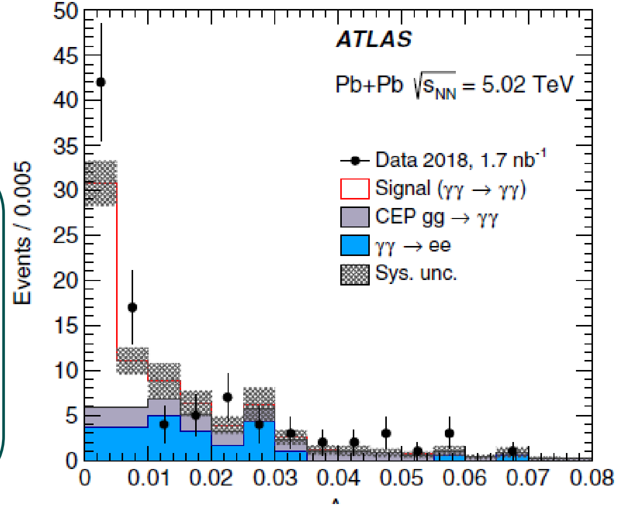


➢Central exclusive γγ production (CEP)

- Similar exclusive topology
- Relatively flat γγ acoplanarity distribution(wrt signal)

  <- transverse momentum transferred by the photon exchange

  is much smaller than that due to the colour-singlet state gluons



CEP process: gluons recoil against the Pb nucleus which then dissociates

γγ->e^+e^-: the curvature of the trajectory of the electrons in the detector magnetic field before they emit hard photons in their interactions with the ID material.

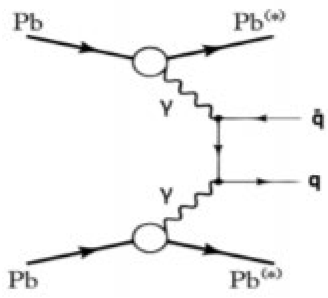
Background process: gg->γγ

- The $A_{\phi} < 0.01$ requirement significantly reduces the CEP $gg \to \gamma\gamma$ background.

  =>Define control region : $A_{\phi} > 0.01$, the statistical uncertainty of the number of events in control region (17%)

- All experimental uncertainties have negligible impact on the normalization of the CEP $gg \to \gamma\gamma$ background. The impact of the MC modeling of the A_{ϕ} shape is estimated using an alternative SUPERCHIC MC sample with no absorptive effects
- After applying the datadriven normalization procedure, this leads to a 25% change in the CEP background yield in the signal region, which is taken as a systematic uncertainty. The background due to the CEP process in the signal region is estimated to be 4±1 events.

Other negligible background process:



➢ $\gamma\gamma \rightarrow q\bar{q}$ production

- estimated using MC simulation based on HERWIG++ and found to be negligible

➢ Exclusive two-meson production

- Mesons can fake photons either by their intermediate decay into photons (neutral mesons: π0, η, η0) or by misreconstructed charged-particle tracks (charged mesons: for example π+, π− states).
- Strongly suppressed for $m_{\gamma\gamma}$>6GeV

➢ Bottomonia production $\gamma\gamma \rightarrow \eta_b \rightarrow \gamma\gamma$ or $\gamma\mathrm{Pb} \rightarrow \Upsilon \rightarrow \gamma\eta_b \rightarrow 3\gamma$

➢ The contribution from UPC events where both nuclei emit a bremsstrahlung photon

➢ $\gamma\gamma \rightarrow e^+e^-\gamma\gamma$ =>below 1% of the expected signal

Kinematic distributions for γγ->γγ event candidate

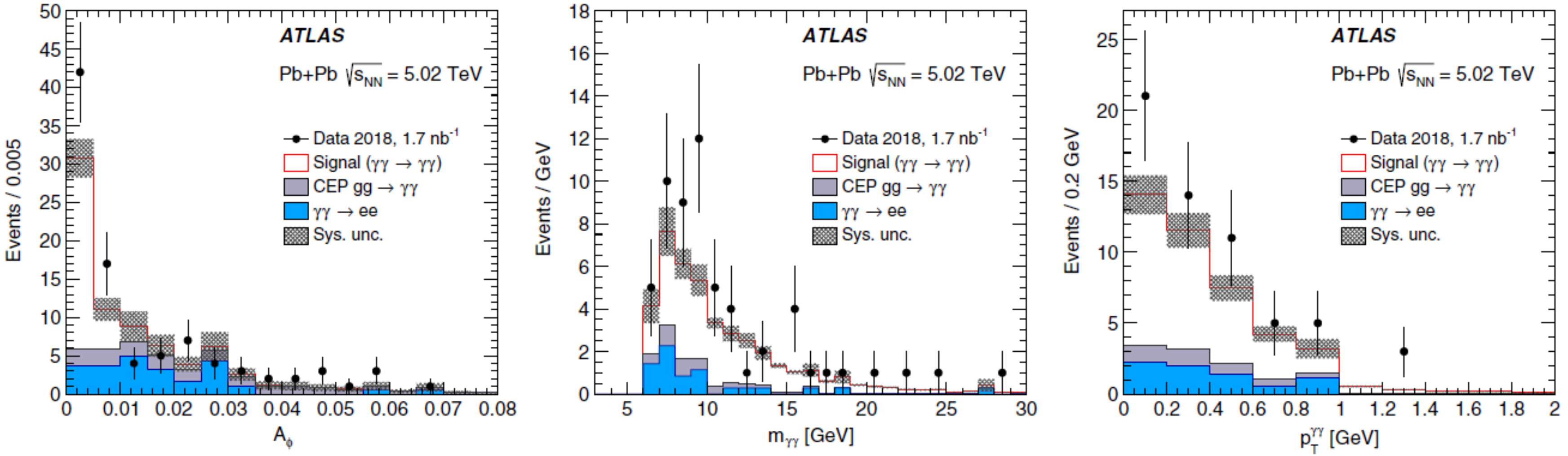


FIG. 2. (a) The diphoton A_ϕ distribution for events satisfying the signal selection, but before the $A_\phi < 0.01$ requirement. (b) Diphoton invariant mass and (c) diphoton transverse momentum for events satisfying the signal selection. Data (points) are compared with the sum of signal and background expectations (histograms). Systematic uncertainties of the signal and background processes, excluding that of the luminosity, are shown as shaded bands.

Results

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

Table 2 | Summary of systematic uncertainties.

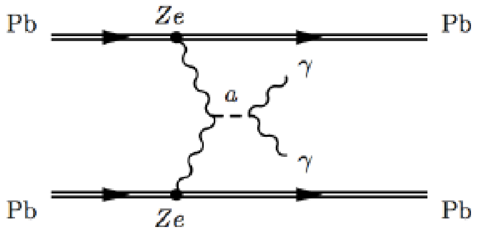
Source of uncertainty	Relative uncertainty
Trigger	5%
Photon reco. efficiency	12%
Photon PID efficiency	16%
Photon energy scale	7%
Photon energy resolution	11%
Total	24%

The table shows the relative systematic uncertainty on detector correction factor C broken into its individual contributions. The total is obtained by adding them in quadrature.

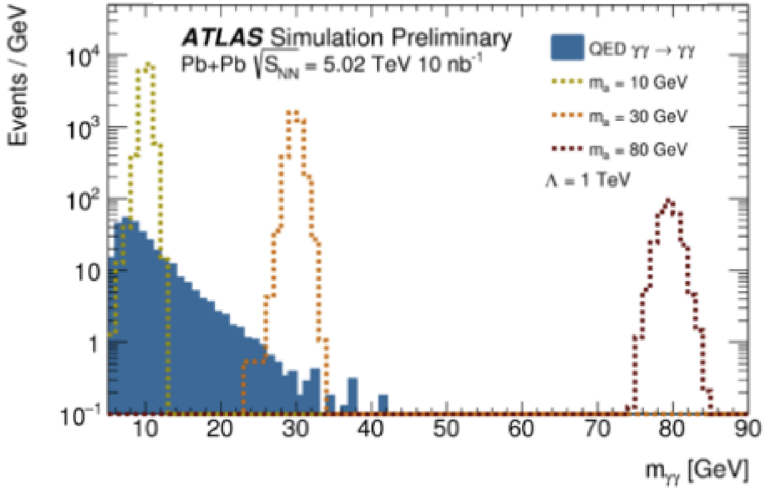
- 2015 480 μb-1
- A total of 13 candidate events were observed with an expected background of 2.6 ±0.7 events
- The measured fiducial cross-section is σ_{fid} =70±24 (stat.) ±17(syst.) nb, corresponding to a significance of 4.4.

- 2018 1.73 ±0.07nb−1
- 59 candidate events are observed for a background expectation of 12±3 events. The observed excess of events over the expected background has a significance of 8.2 standard deviations. The measured fiducial cross section is 78±13(stat)±7(syst)±3(lumi) nb. (SM predictions: 45 ±5 nb, 51±5nb, 50±5nb)

BSM search: Axions

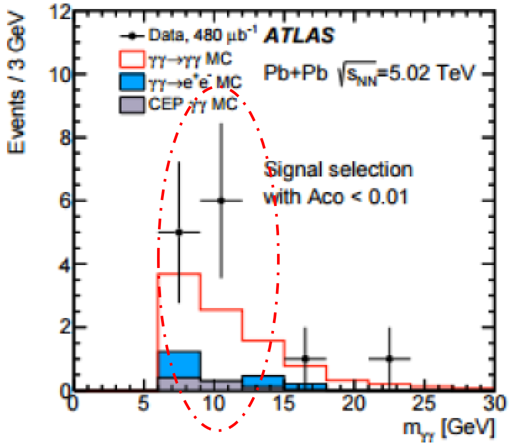


- Explore potential of UPC data in searches of axionlike particles (ALP) at relatively low m_a
  - Axion: hypothetical particle proposed in 1977
  - Interaction: gravity, electromagnetic
  - If it exists: it is a possible component of cold dark matter
- Using the ATLAS LbyL measurement with ~0.5 nb-1, the most stringent limits on axions at 6<ma<100 GeV have been derived
  - Studies use full MC simulation of the upgraded ATLAS tracker
  - Realistic $m_{\gamma\gamma}$ and background distributions
- Limits agree with results from S. Knappen at al[arXiv:1709.07110]



Discussion

- Really light by light scattering?
  - Someone## doubts that, even though it is “quasi-real”, it is not a real(on-shell) photon QED LbyL, since the CoM energy is too large than electron => which makes the QED LbyL hardly happens
  - Since the 6GeV and above “quasi-photon” is energetic enough to make QCD involved, the exchanged charged particle might be interpreted as quarks
  - However, how about hadronic resonance? like bottomonium $b\bar{b}$, at mass 9.86GeV or 9.91GeV (different spin-let) then di-photon decay.
  - The paper says, this possibility is excluded by some theory papers# => but how about the other theory papers## which doubts this?
  - More or less, the result(or at lease the interptation) is model dependent to some extent.



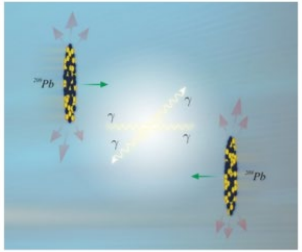
##: https://inspirehep.net/literature/1695543

Thanks

Backup: slide

PHOTON-PHOTON PHYSICS AT COLLIDERS

12

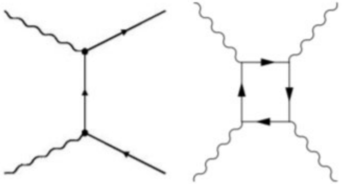


- Basis for photon-photon physics by
  - Fermi, Nuovo Cim. 2 (1925) 143
  - Weizsacker, Z. Phys. 88 (1934) 612
  - Williams, Phys. Rev. 45 (10 1934) 729
- Led to formulation of Weizsacker-Williams Approximation or Equivalent Photon Approximation (EPA)

- Cross section for processes AA(γγ) → AA(X) are calculated using:
  - Number of equivalent photons (EPA) by integration of relevant EM form factors

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

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



  - Cross section of γγ → X (elementary):

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

Pb+Pb(γγ)→ $Pb^{(*)}+Pb^{(*)}e^+e^-$

- validate the EM calorimeter energy scale and resolution
- To select γγ → e+e− candidates, events are required to pass the same trigger as for the diphoton selection. Each electron is reconstructed from an EM energy cluster in the calorimeter matched to a track in the ID. The γγ → e+e− events are selected by requiring exactly two oppositely charged electrons, no further charged-particle tracks coming from the interaction region, and dielectron reduced acoplanarity, $A\phi < 0.01$. The observed γγ → e+e− event yield in data is compatible with that expected from simulation.

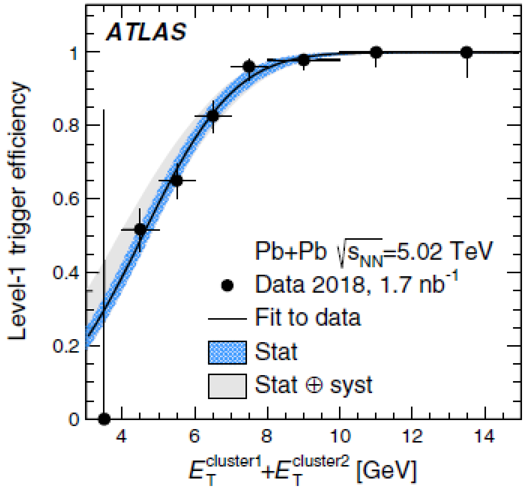
Backup: Trigger efficiency

Level 1 Trigger: estimated with γγ->ee events

trigger. This trigger was running prescaled down to a few Hz and the selection was as follows:

- Coincidence of signals in both ZDC sides and total E_T in the entire calorimeter below 50 GeV,
- At least two (three) space points reconstructed in the Pixel (SCT) detector at HLT,
- Presence of at least one track ($p_T > 200$ MeV) reconstructed at HLT.

Event candidates are required to have only two reconstructed tracks and two EM clusters, each with a minimum E_T of 1.5 GeV and $|\eta| < 2.47$ (excluding the transition region). The electron identification requirements are not used in order to accept more events in this very low-E_T region, where the efficiencies to reconstruct and and identify the electron are low. Furthermore, to reduce possible backgrounds, each pair of clusters is required to have small acoplanarity (< 0.2).



Backup: Theory

- Euler–Heisenberg Lagrangian
  - https://en.wikipedia.org/wiki/Euler%E2%80%93Heisenberg_Lagrangian

$$\mathcal{L} = -\mathcal{F} - \frac{1}{8\pi^2}\int_0^\infty \exp(-m^2 s)\left[(es)^2 \frac{\operatorname{Re}\cosh\left(es\sqrt{2(\mathcal{F}+i\mathcal{G})}\right)}{\operatorname{Im}\cosh\left(es\sqrt{2(\mathcal{F}+i\mathcal{G})}\right)}\mathcal{G} - \frac{2}{3}(es)^2\mathcal{F} - 1\right]\frac{ds}{s^3}$$

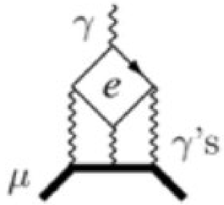
Here m is the electron mass, e the electron charge, $\mathcal{F} = \frac{1}{2}\left(\mathbf{B}^2 - \mathbf{E}^2\right)$, and $\mathcal{G} = \mathbf{E}\cdot\mathbf{B}$.

In the weak field limit, this becomes: $\mathcal{L} = \frac{1}{2}\left(\mathbf{E}^2 - \mathbf{B}^2\right) + \frac{2\alpha^2}{45m^4}\left[\left(\mathbf{E}^2 - \mathbf{B}^2\right)^2 + 7(\mathbf{E}\cdot\mathbf{B})^2\right]$

- g-2 contribution $a_\mu = (g_\mu - 2)/2$
  - Phys.Rept. 477 (2009) 1-110]

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

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



Backup: Theory

- EPA theory (Equivalent Photon Approximation)

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

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

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

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

- Q^2