Light-by-light scattering in lead-lead collisions in the ATLAS experiment - from evidence to observation

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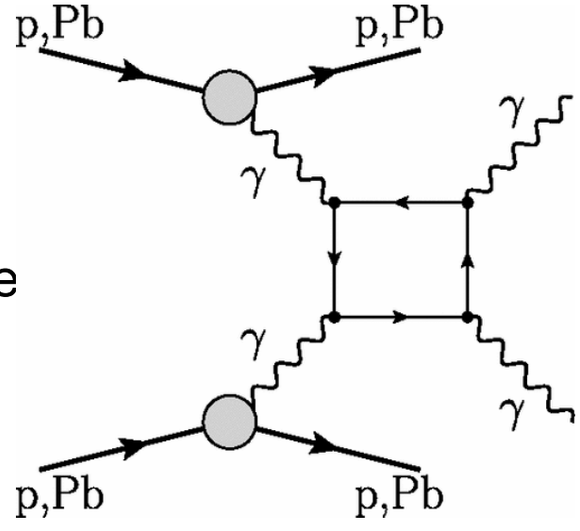
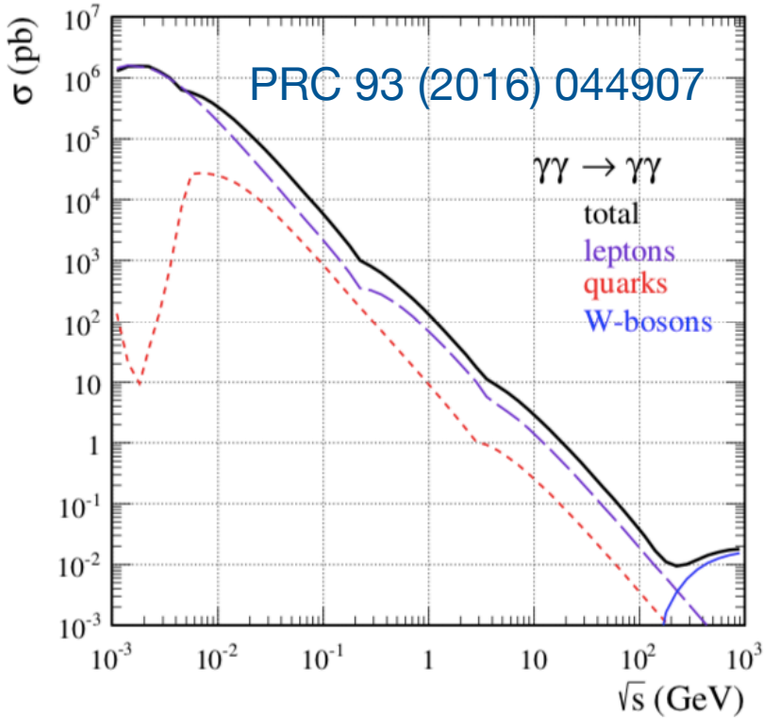
Introduction

- Light-by-light (LbyL) scattering is a rare QED process, which is forbidden in classical electrodynamics
  - It was postulated in 1930s, but it was **not measured directly until 2017** because of its small cross-section
- In QED, the γγ → γγ reaction proceeds at lowest order in the fine-structure constant (α_{em}) via virtual one-loop box diagrams involving fermions
- Measurement of LbyL is sensitive to new physics
- Photon-photon interactions can be observed in **heavy-ion collisions** due to large EM fields associated with relativistic ions (cross-sections scale with ~Z^4)
- EM field is treated as a beam of quasi-real photons with small virtuality (equivalent photon approximation)
- Two datasets from Pb+Pb collisions at 5.02 TeV were collected by ATLAS detector and resulted in LbyL measurements
  - **0.48 nb^{-1}** in 2015: Nature Physics 13 (2017) 852
  - **1.73 nb^{-1}** in 2018: ATLAS-CONF-2019-002 **NEW**
- Also CMS experiment reported evidence of LbyL based on 2015 Pb+Pb data: arXiv:1810.04602

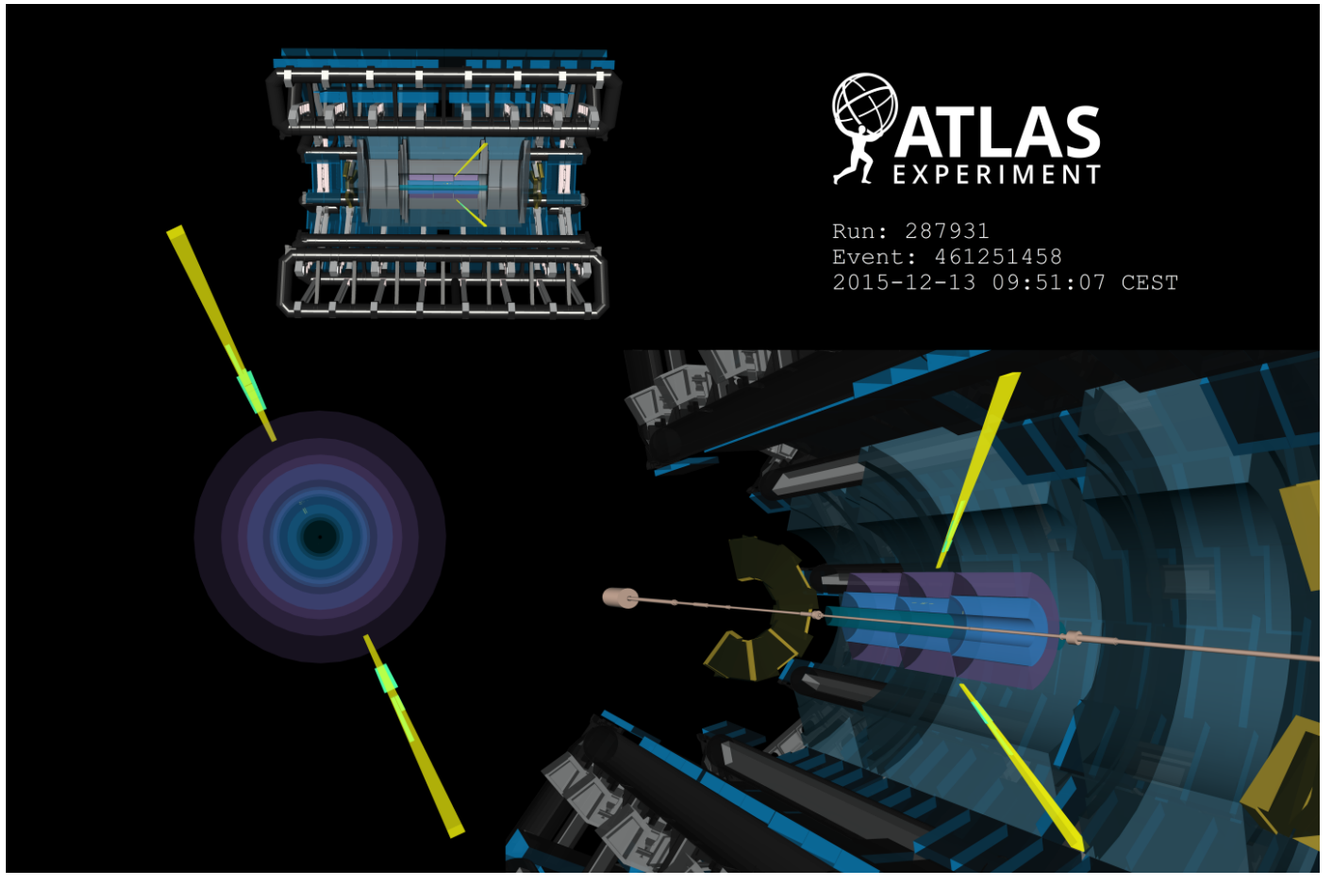




Analysis setup for 2015 data

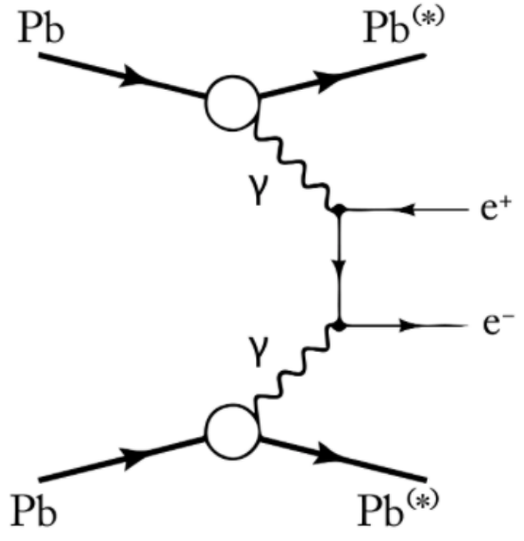
Nature Physics 13 (2017) 852

- LbyL scattering events have a very **simple signature**: two back-to-back low-E_T (of the order of a few GeV) photons and „nothing else” in the detector
- **Dedicated trigger** for low-E_T diphoton events: low activity in EM calorimeter (total E_T at Level-1 between 5 and 200 GeV), minimal activity in the tracker and no activity in forward direction
- Caveat: ATLAS detector is optimised for detection of high energy particles
  - Many ingredients inefficient for low-E_T region: trigger, photon reconstruction, photon identification
- **Photon identification** (ID) technique based on three shower shape variables developed to increase efficiency in low-E_T region
- The **signal selection** included:
  - Two photons with $E_T > 3$ GeV and $|\eta| < 2.4$
  - $m_{\gamma\gamma} > 6$ GeV
  - $p^{\gamma\gamma}_T < 2$ GeV
  - Diphoton reduced acoplanarity, $Aco = 1-|\Delta\phi|/\pi < 0.01$

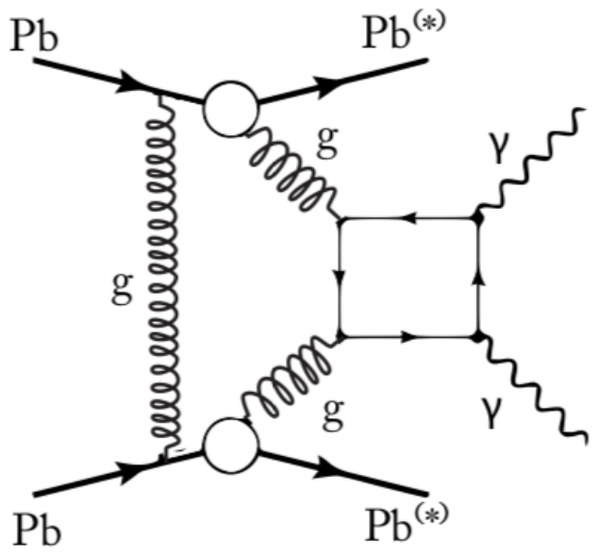


Backgrounds

- Various background sources considered:
  - Exclusive dielectron production **γγ → e+e-:**
    - Contribute to the signal region when tracks not reconstructed, or bremsstrahlung photons emitted



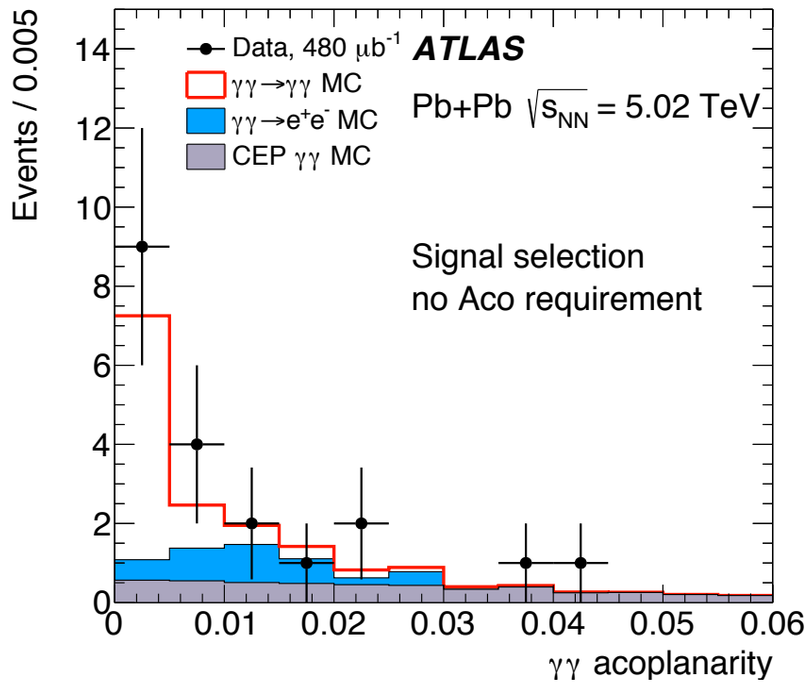
  - Central Exclusive Production (CEP) **gg → γγ:**
    - Event kinematics very similar to signal, but different shape of acoplanarity distribution
  - **Fakes** (calo noise, cosmics)
  - **Others**, found negligible (exclusive di-meson production (e.g. $\pi^0\pi^0$), γγ → ττ, γγ → qq, γγ → eeγγ, γγ → η_b → γγ, γPb → ϒ → 3γ, ion bremsstrahlung)



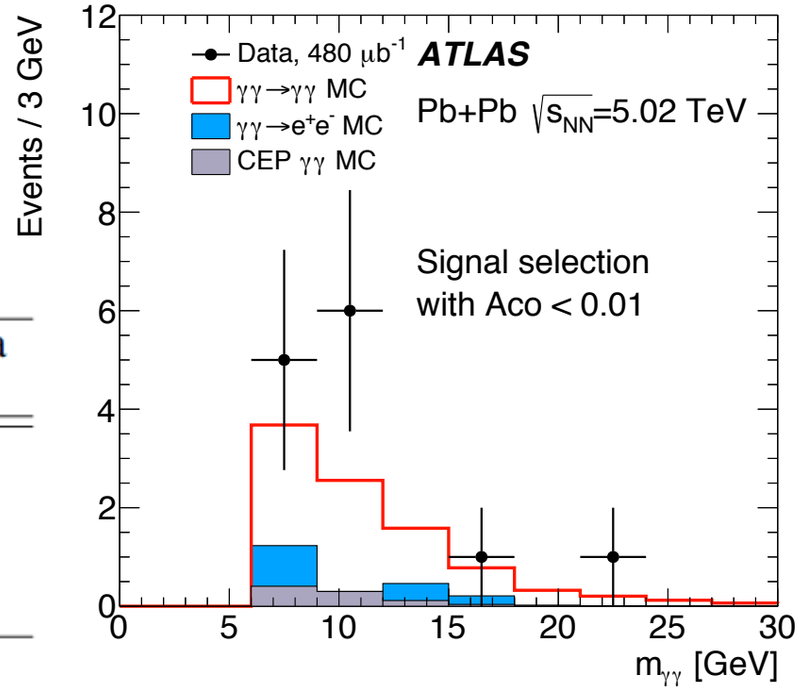
Results from 2015

- Background contributions from exclusive e+e- pairs, Central Exclusive Production of γγ, hadronic fakes were included
  - Other sources of background found negligible
- Main background from e+e-
- 13 events found in the signal region, 7.3 signal events and 2.6 background events are expected
- Excess corresponds to 4.4σ statistical significance over background only hypothesis

Nature Physics 13 (2017) 852



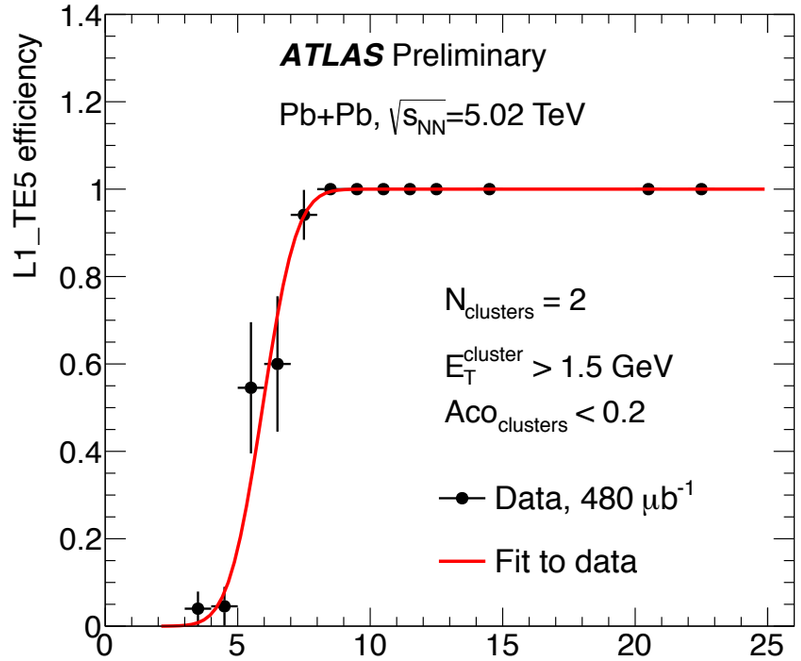
- The fiducial cross section after background subtraction and analysis corrections, is measured to be 70±24(stat)±17(syst) nb
  - In agreement with Standard Model predictions



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
$N_{\text{trk}} = 0$	4.0	4.5	6	19	33	8.7	39
$p_{\text{T}}^{\gamma\gamma} < 2$ 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	

Improvements in 2018 analysis - trigger

- In preparation to 2018 Pb+Pb data taking, a strong emphasis was put to improve the trigger strategy in 2018 heavy-ion data-taking (especially at the Level-1)
- Main improvements are:
  - Optimised calorimeter noise settings
  - Lower requirement on total E_T at Level-1:
    - Finally two approaches used: requirement of two EM clusters with $E_T > 1$ GeV OR one such EM cluster and total E_T at Level-1 above 4 GeV
- Optimisation performed on Xe+Xe sample from 2017
- Some modifications at High Level Trigger (redefinition of forward gap & relaxing the veto on activity in the tracker)
- Efficiency at Level-1 improved in 2018 wrt 2015



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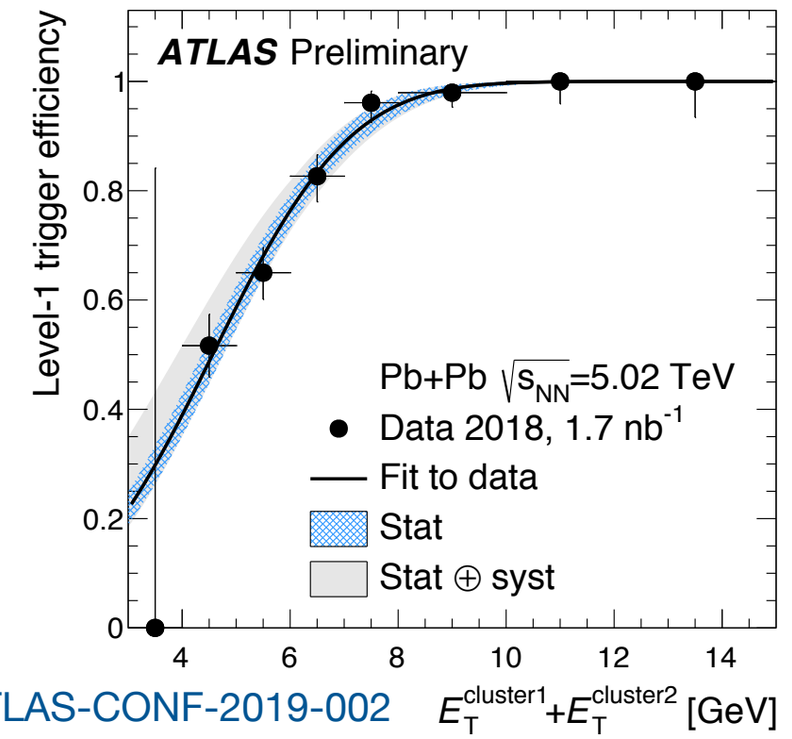

ATLAS-CONF-2019-002

Improvements in 2018 analysis - photon ID

- The nominal ATLAS photon ID working points optimised for high-E_T photons
- Already in 2015 a dedicated photon ID was used to increase the efficiency in low-E_T region
- The improvements introduced in 2018 analysis:
  - Switch from cut-based selection to neural network based
  - Use three additional shower shape variables
  - Use η dependent ID
  - Better background rejection
- ID efficiency on signal MC maintained 95%, in agreement with efficiency measured with FSR photons

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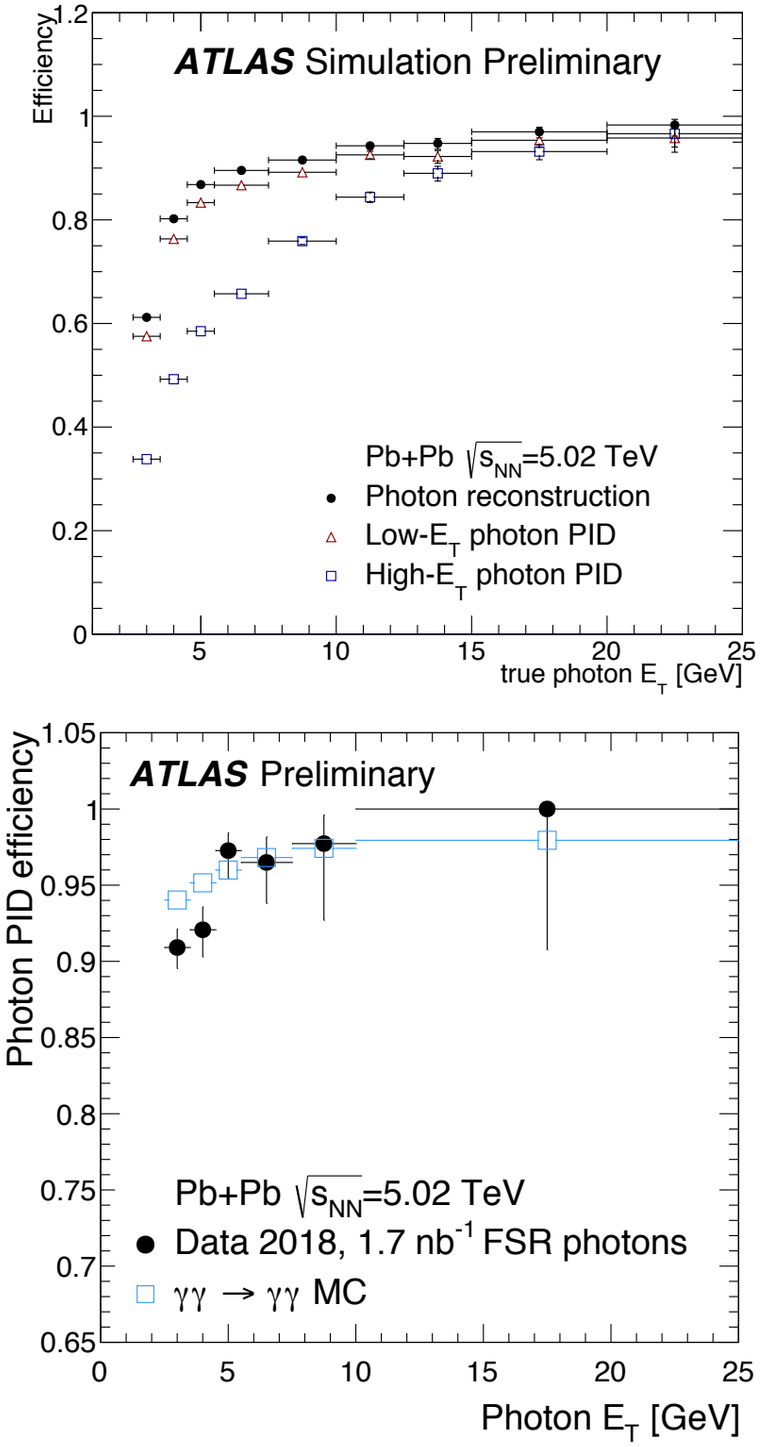
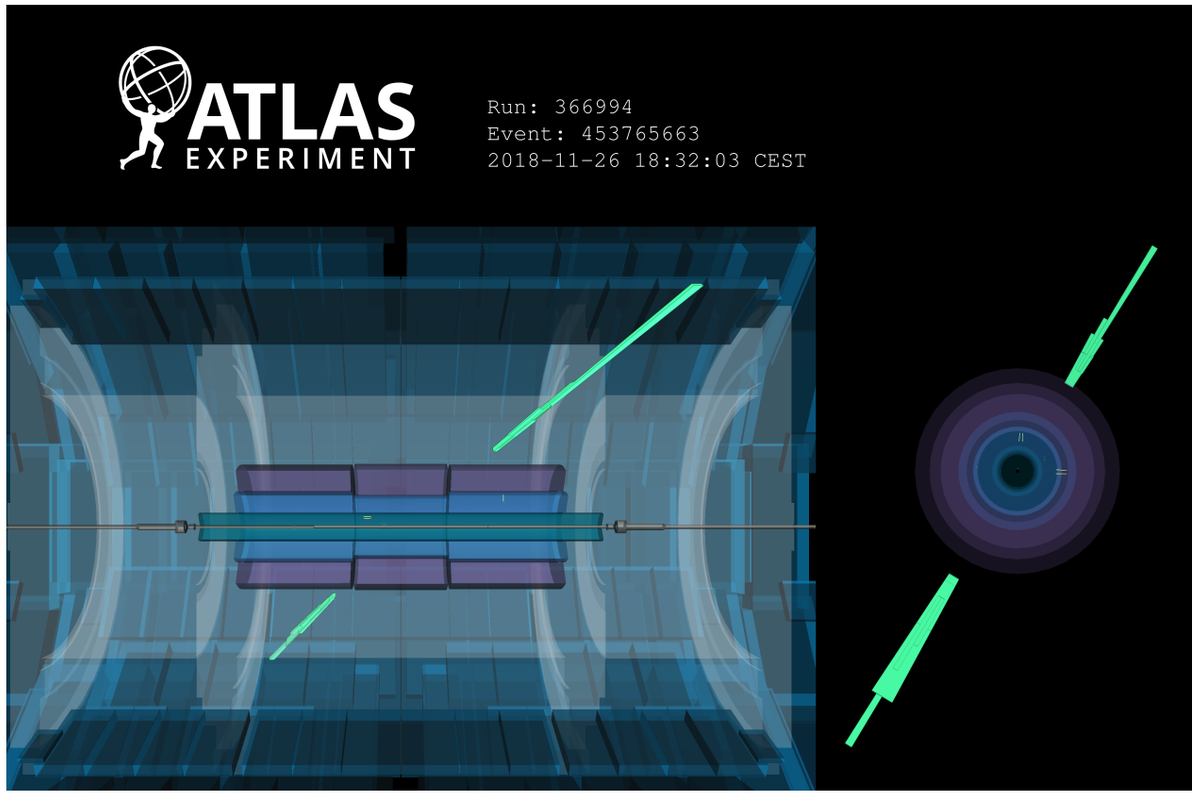


Signal selection

ATLAS-CONF-2019-002

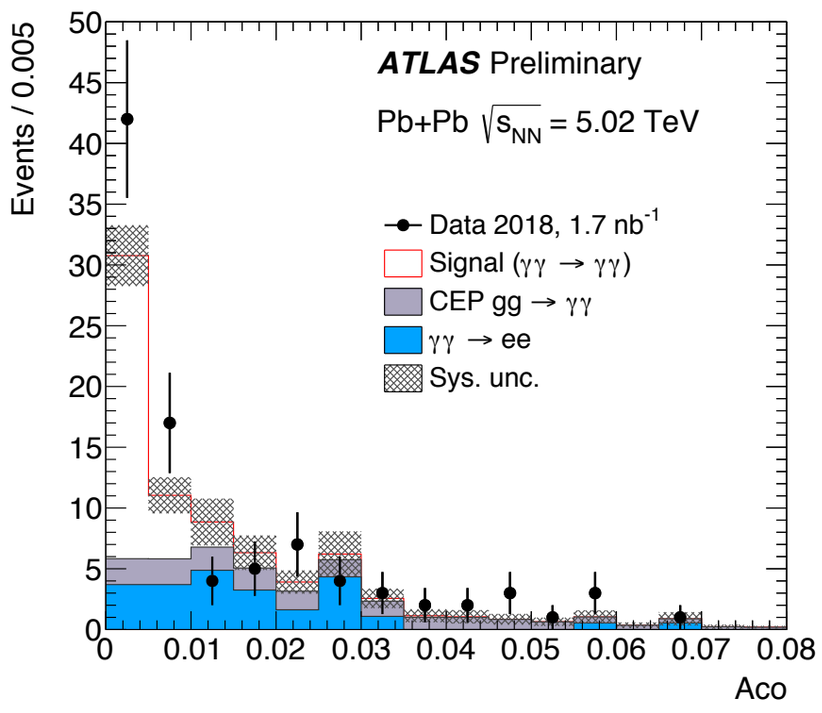
- Events are selected using following requirements:
  - Two photons
    - Identification: NN working point
    - $E_T > 3$ GeV, $|\eta| < 2.37$
  - LbyL scattering topology
    - $m_{\gamma\gamma} > 6$ GeV
    - Veto extra particle activity:
      to suppress e+e- background
      - Requiring no tracks ($p_T > 100$ MeV)
        and no pixel tracks ($p_T > 50$ MeV, $|\Delta\eta| < 0.5$ photon-pixelTrk matching)
    - Selecting back-to-back topology: to suppress fakes and CEP background
      - $p_T^{\gamma\gamma} < 1$ GeV (2 GeV for $m_{\gamma\gamma} > 12$ GeV)
      - Diphoton acoplanarity < 0.01

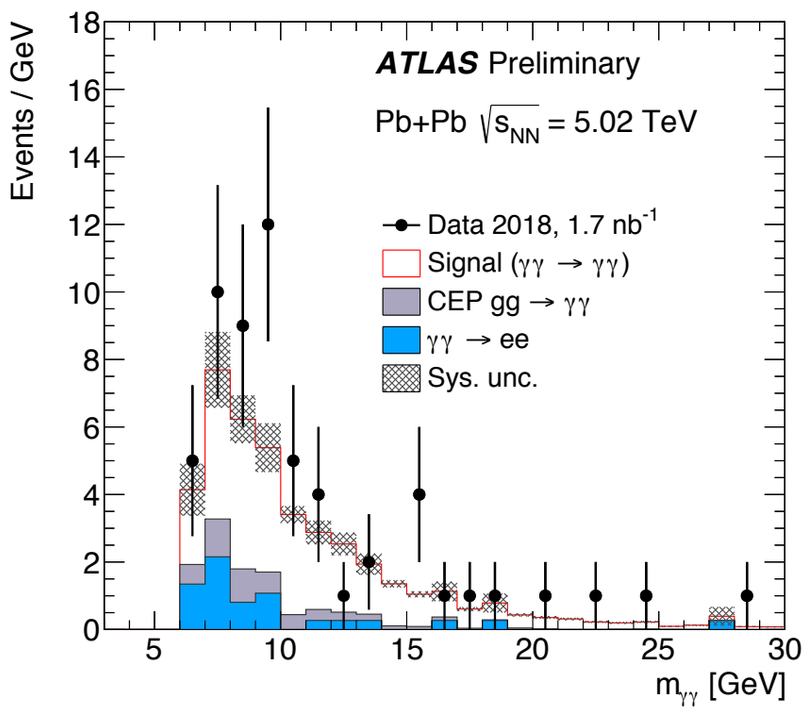


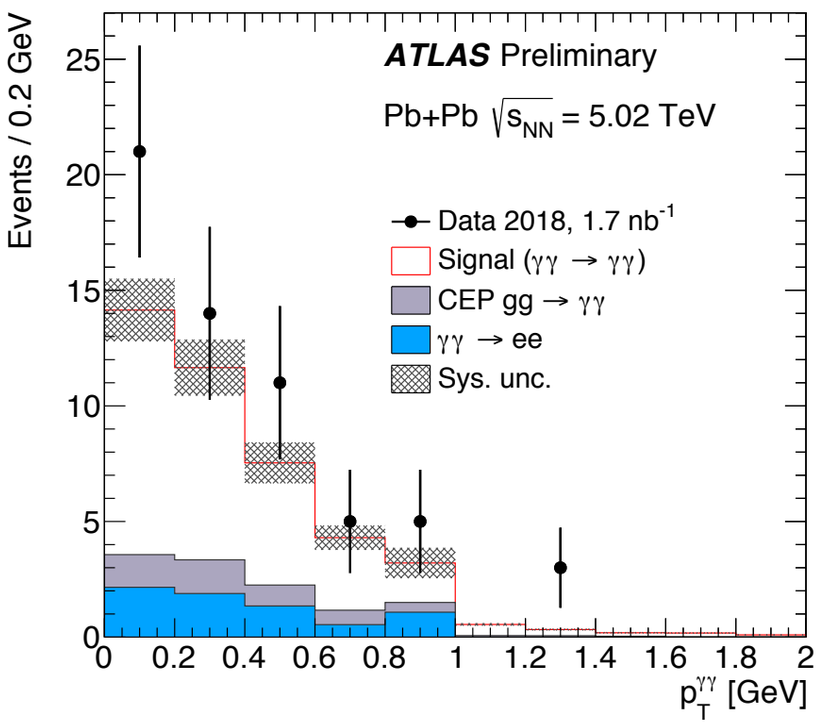
Results from 2018

ATLAS-CONF-2019-002

- In total **59 events** passing the signal selection are observed, with a background expectation of 12 ± 3 events
- Signal significance measured with events having Aco < 0.005, where 42 events pass signal selection and 6 ± 2 background events are expected
- Observed **signal significance** over the background only hypothesis is of **8.2σ** (expected 6.2σ)
- The corresponding fiducial cross section is **78 ± 13 (stat.) ± 8 (syst.) nb**
- SM predictions: **49 ± 5 nb** (Szczurek et al.) and **48 ± 5 nb** (SuperChic3)





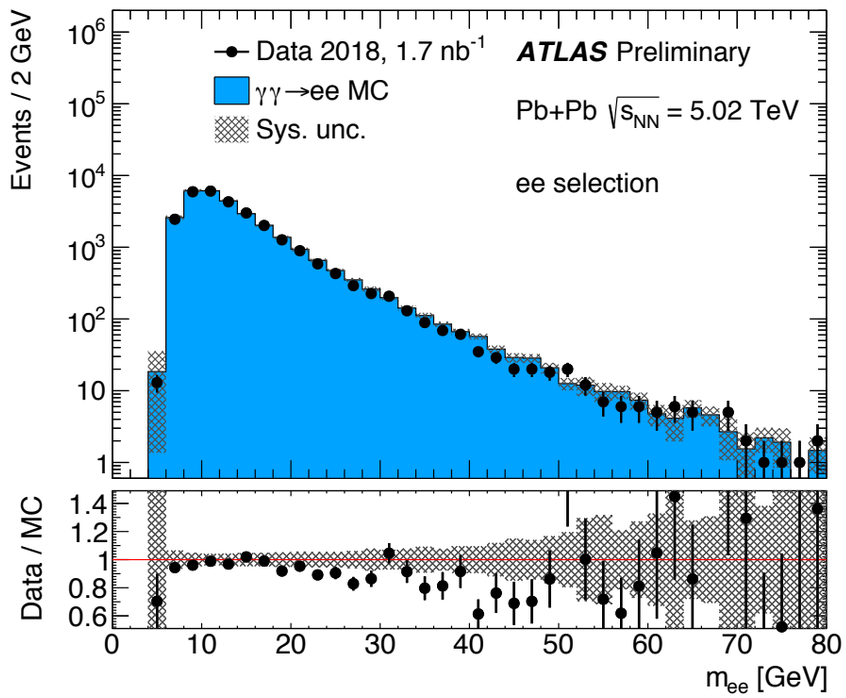


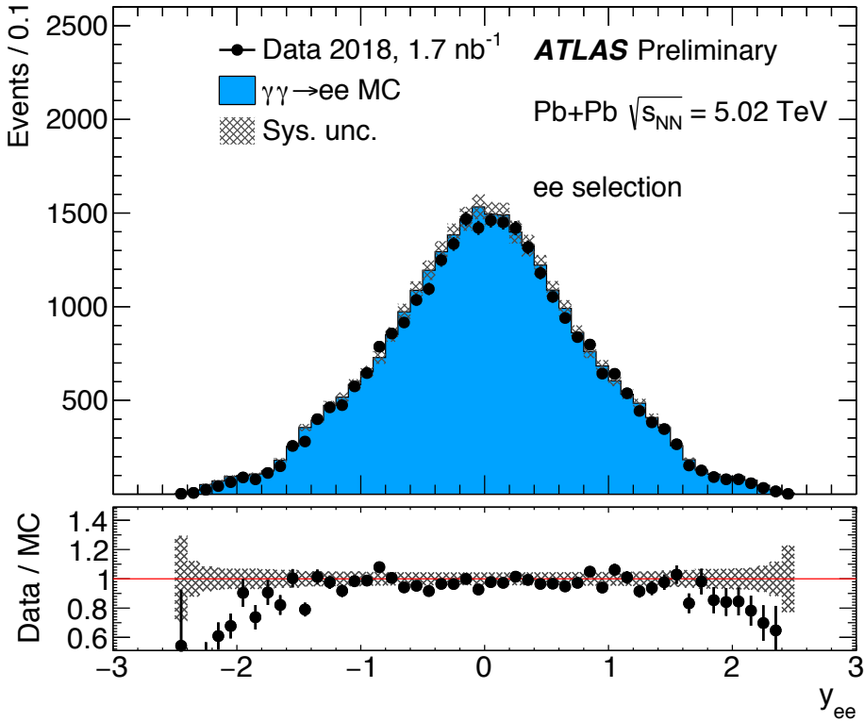
Summary

- **Light-by-light scattering** was measured with the ATLAS detector
- Two results were obtained, using data from **Pb+Pb collisions** at 5.02 TeV from 2015 and 2018
- New, preliminary result was presented for the first time on Moriond EW conference on March 17th, 2019
- Precision of the new measurement greatly improved thanks to the larger dataset and improved analysis techniques:
  - The observed **signal significance** gives evidence with 4.4σ in 2015, and observation with 8.2σ in 2018
  - Measured fiducial **cross-section**: 70 ± 24 (stat.) ±17 (syst.) nb in 2015 vs. 78 ± 13 (stat.) ± 7 (syst.) ± 3 (lumi.) nb in 2018
- Ratio of the measured **cross-section** to the SM predictions is 1.59 ± 0.33

Backup

- Performance of exclusive e+e- pairs - they are used for many cross-checks in the analysis





- MC simulation is normalized to integrated luminosity

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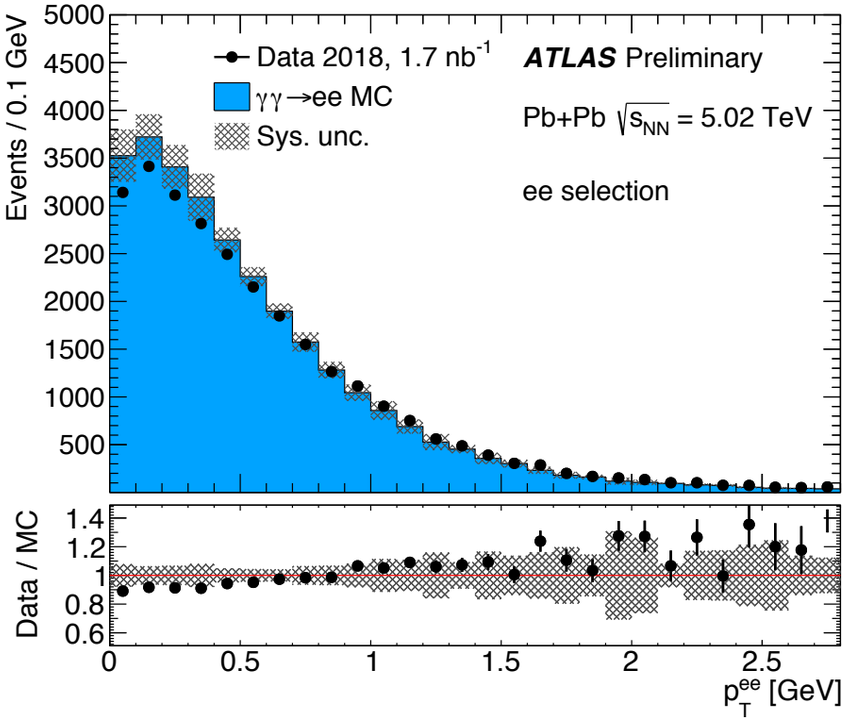
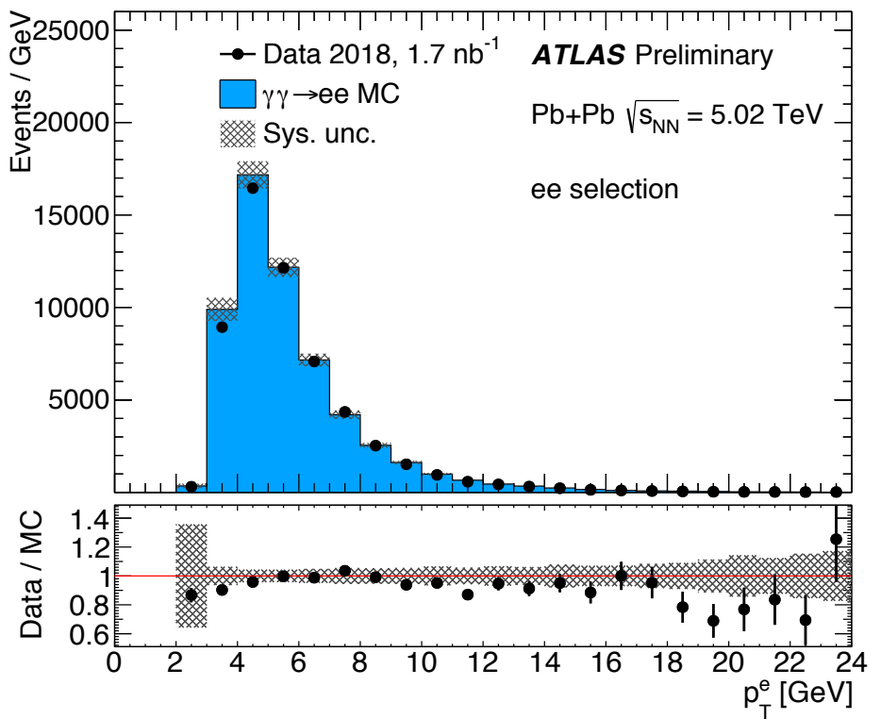
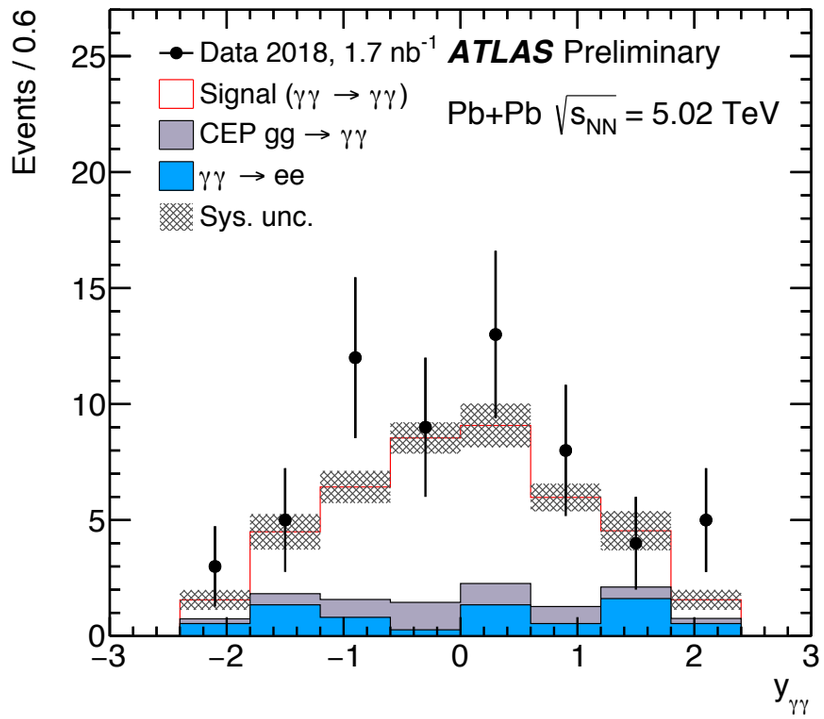
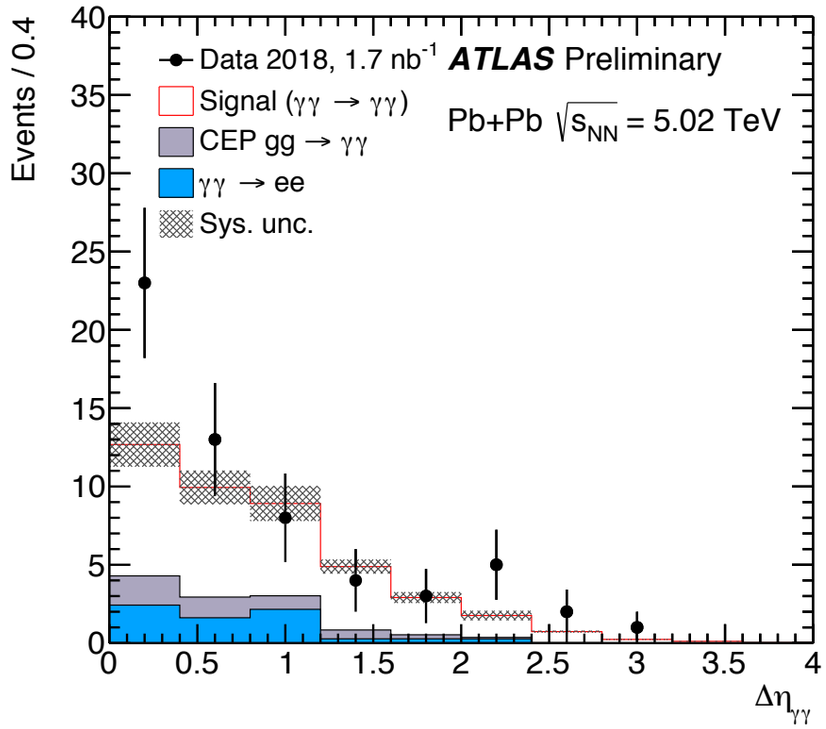


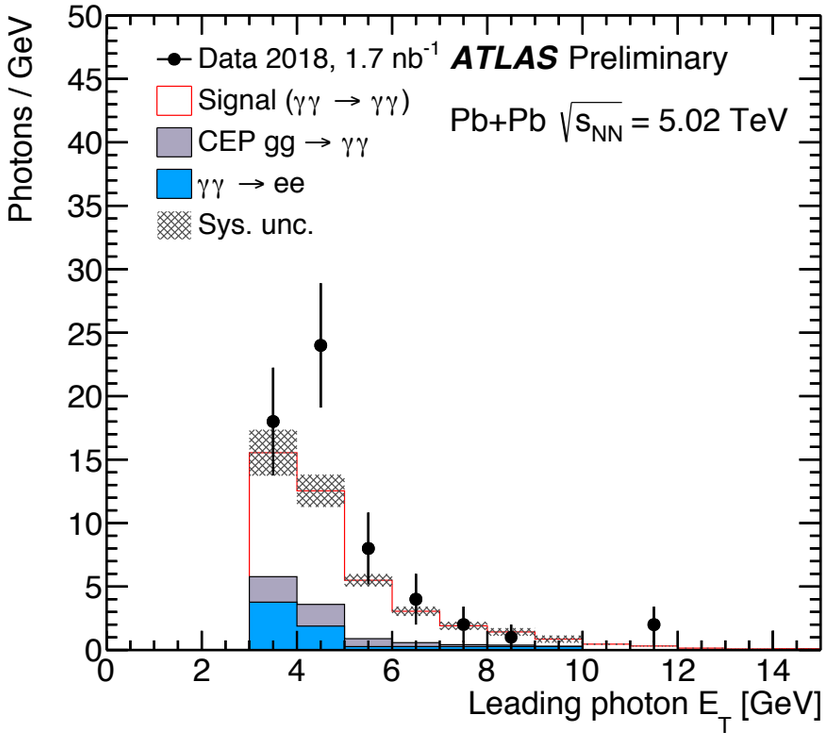


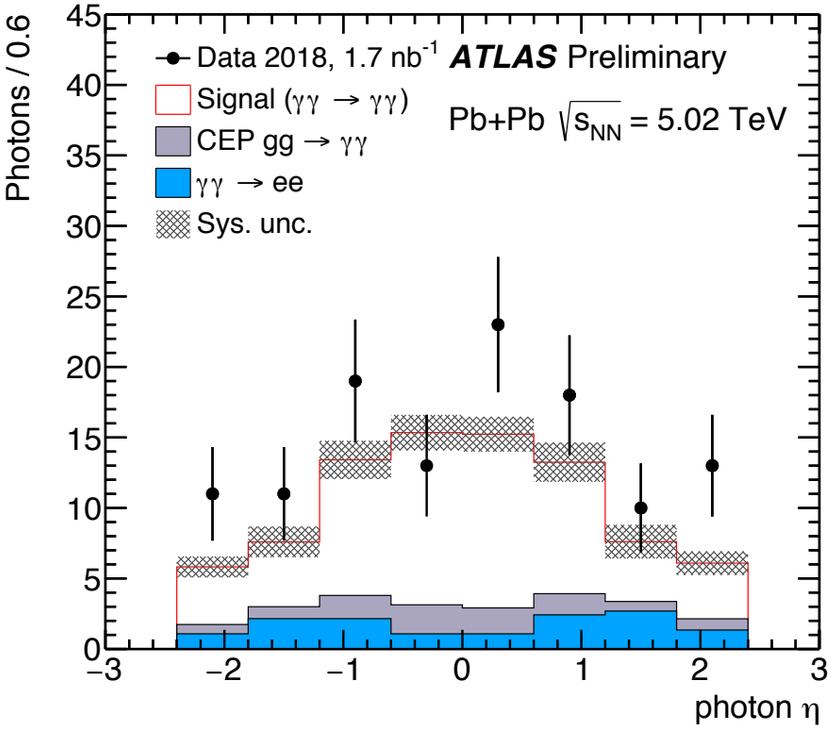
Backup

- Additional kinematic distributions for the signal region









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