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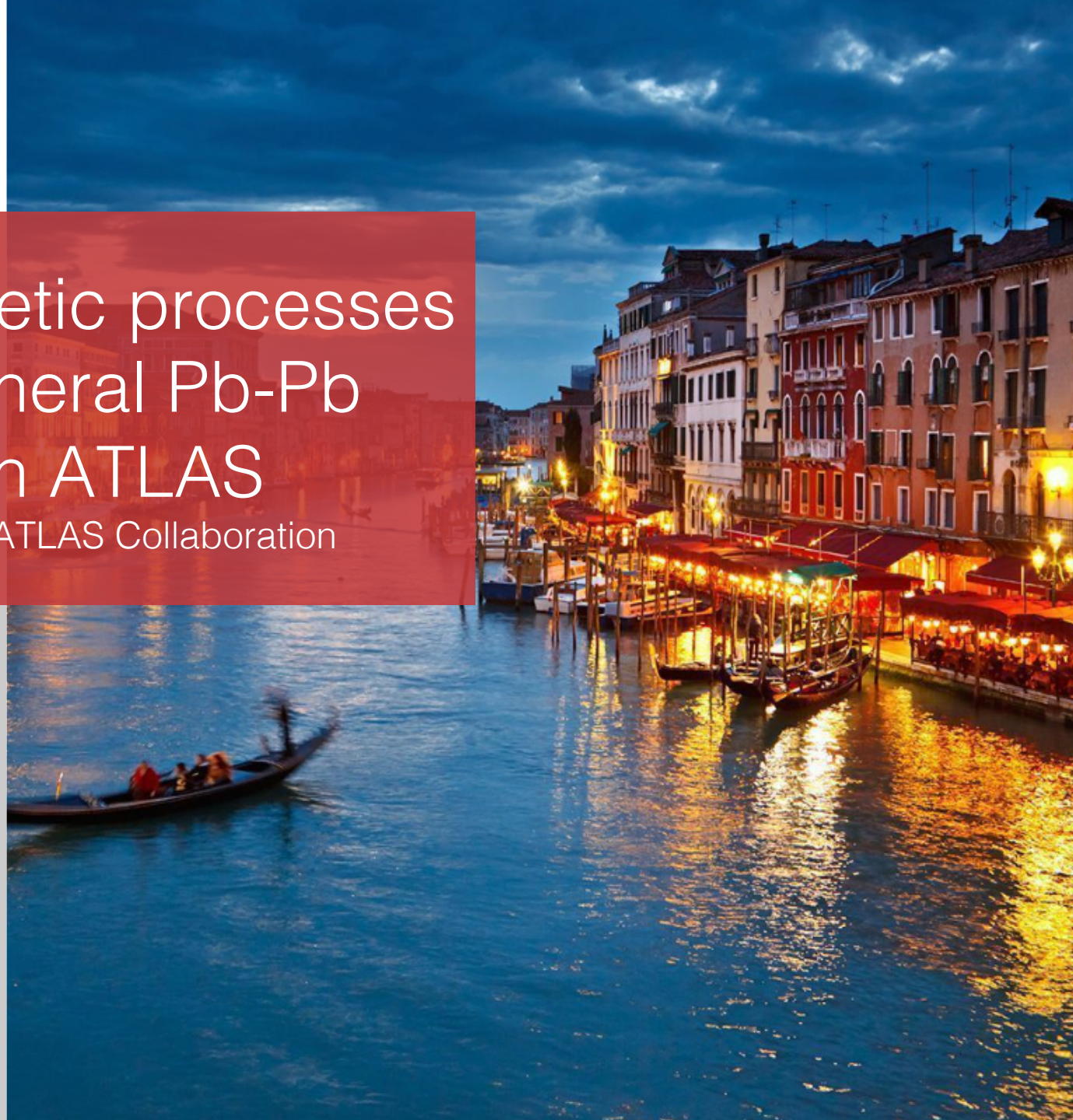
Electromagnetic processes in ultra peripheral Pb-Pb collisions with ATLAS

M. Schott on behalf the ATLAS Collaboration

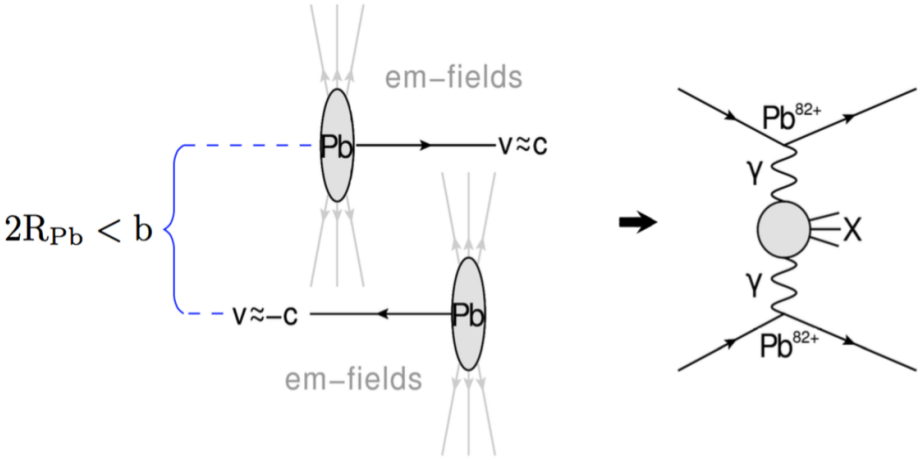


ATLAS EXPERIMENT

Prof. Dr. Matthias Schott

Electromagnetic interactions in Pb+Pb collisions

- Ion beams with relativistic energies used to produce hot and dense quark-gluon matter
- Their large EM-fields (up to ≈10^{14} T) allow photon-induced reactions
  - in "ultra-peripheral collisions": impact parameter is large
    - → suppress strong interactions
- The cross section for AA(γγ) → AA X process is calculated using
  - 1st step: Number of equivalent photons (EPA) by integration of relevant EM form factors
  - 2nd step: EW γγ → X (elementary) cross section



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

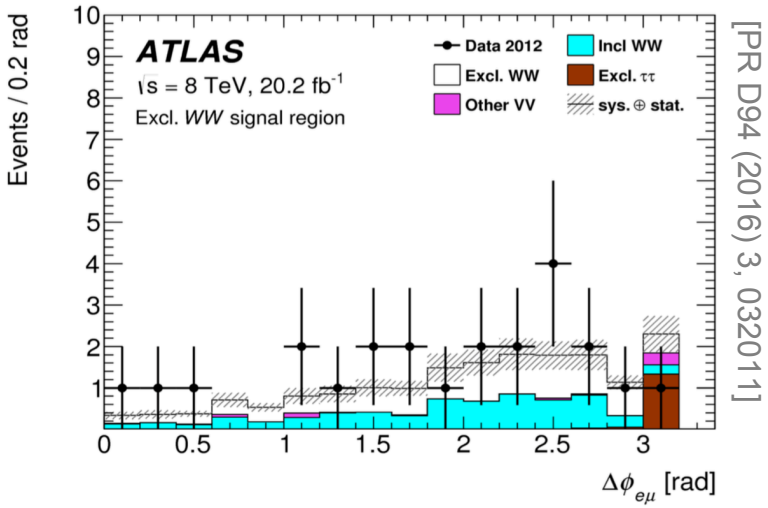
$$Q^2 < 1/R^2 \qquad \omega_{max} \approx \gamma/R$$

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

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

LHC as a Photon Collider

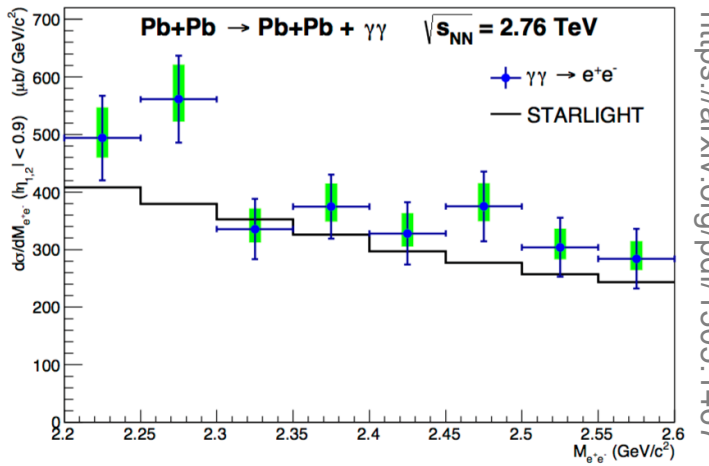
- Use quasi-real photons at the LHC to study many interesting physics processes!
- Proton-Proton Collisions



[PR D94 (2016) 3, 032011]

  - harder EPA spectrum (ω_{max}~TeV)
  - large pile-up (multiple interactions per bunch crossing)
  - large datasets available, O(10 fb^{-1})
  - hard to trigger on low-pT objects

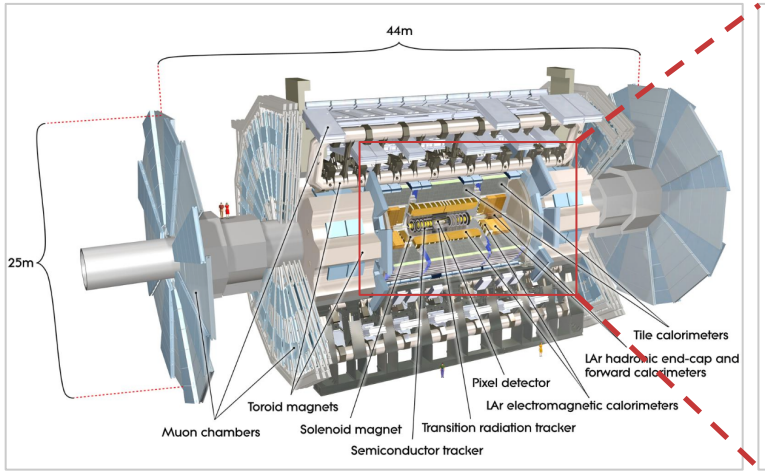
- Pb+Pb collisions

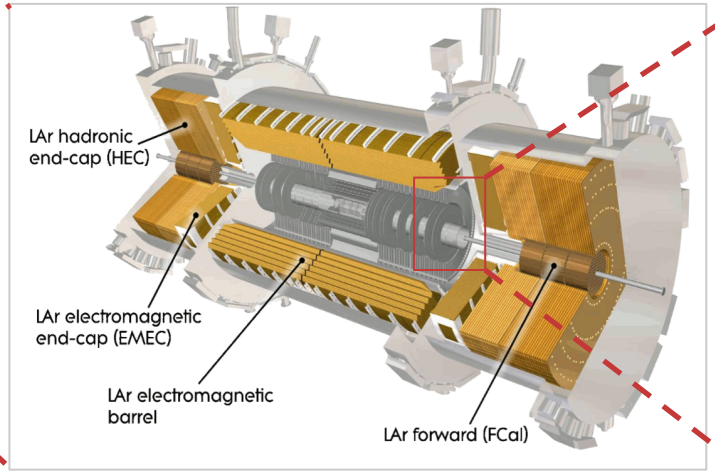


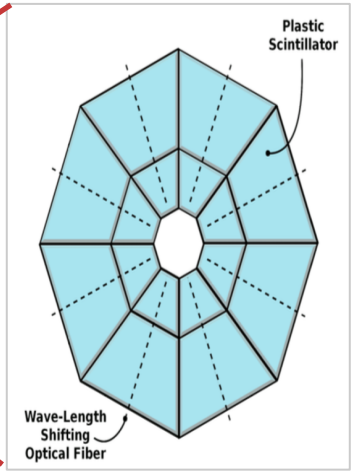
https://arxiv.org/pdf/1305.1467

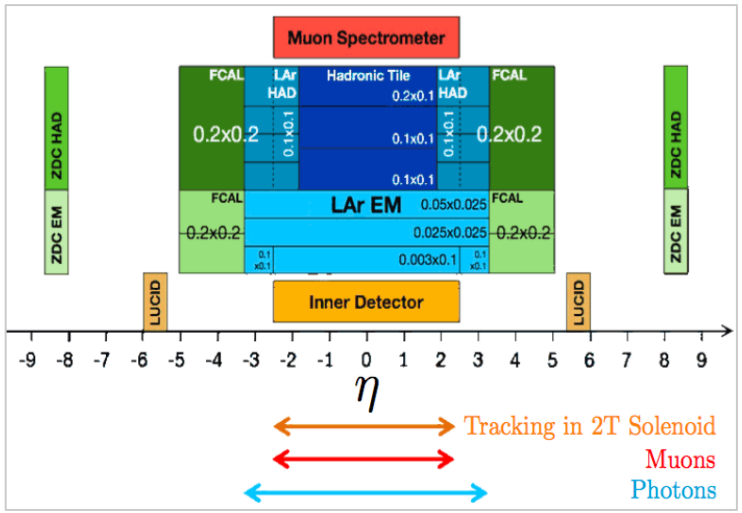
  - softer EPA spectrum (ω_{max}~100 GeV)
  - cross-sections scale as Z^4
  - Negligible pile-up (<<1%)
    - Exclusivity requirements on the final state veto's QCD processes
  - Smaller data-sets compared to p-p

How to Select UPC Events with the ATLAS Detector?





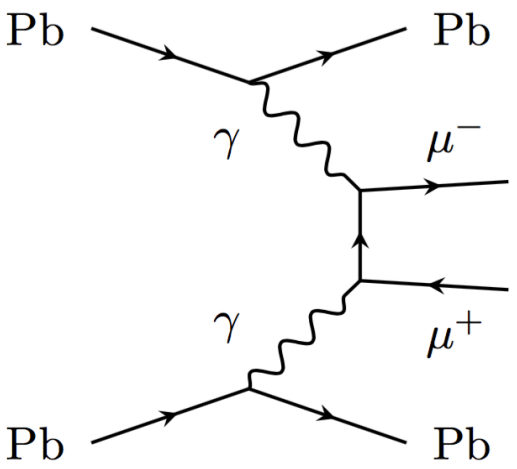


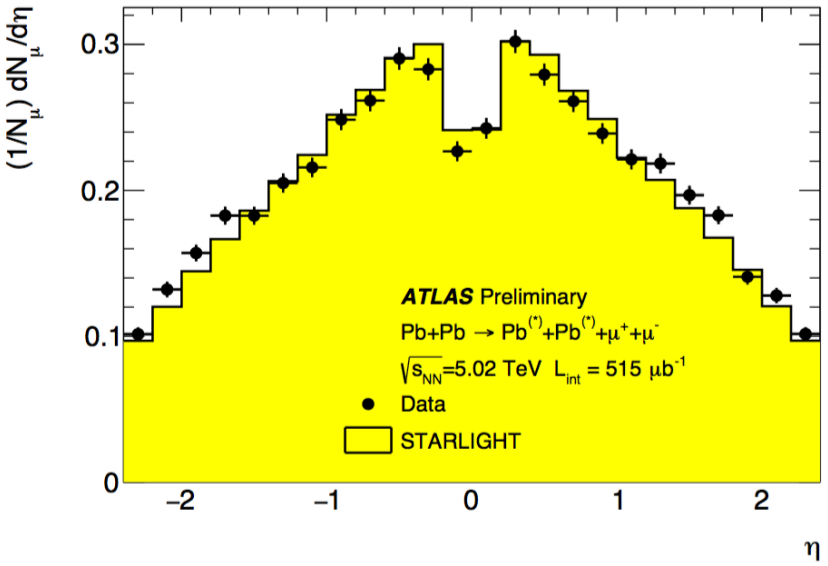


- Pb ions/protons escape into the beam pipe
- In addition to inner detector need
  - MBTS detectors: scintillator plates at $2.07 < |\eta| < 2.76$ and $2.76 < |\eta| < 3.86$
  - zero degree calorimeters (ZDCs) located 140m from IP covering $|\eta| > 8.3$

Measurement of high-mass dimuon pairs (1/3)

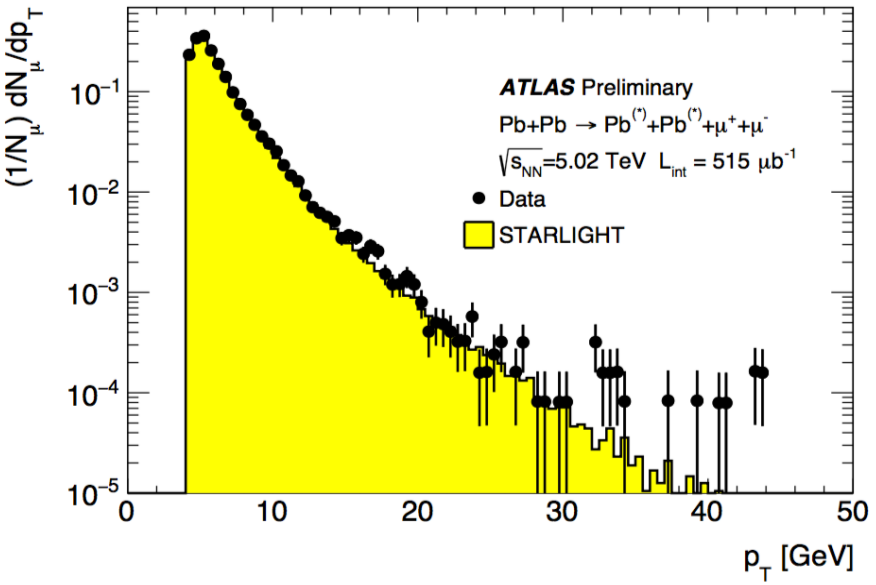
- Measurement of γγ→μμ in ultra-peripheral lead-lead collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
  - [ATLAS-CONF-2016-025]
  - Extension of ALICE's di-lepton mass measurement (m_{ll} up to 10 GeV)
- Trigger
  - At least 1 loose muon
  - Total E_T in the calorimeter < 50 GeV
  - At least one track with 200 MeV
  - No more than 1 hit in inner MBTS
- Event selection
  - 2 opposite-sign, good-quality muons
  - with p_T >4 GeV, |η|<2.4, $m_{\mu\mu}$>10 GeV
  - Reconstructed vertex with no additional tracks
  - 12069 di-muon pairs were selected

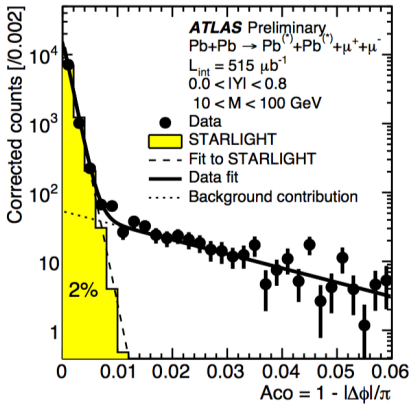


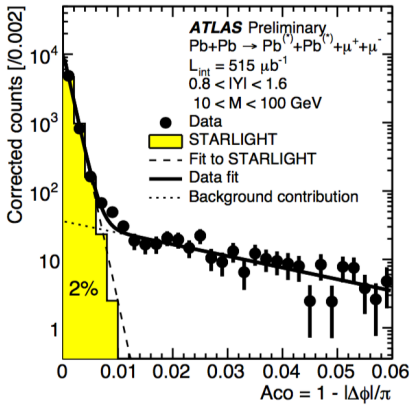


Measurement of high-mass dimuon pairs (2/3)

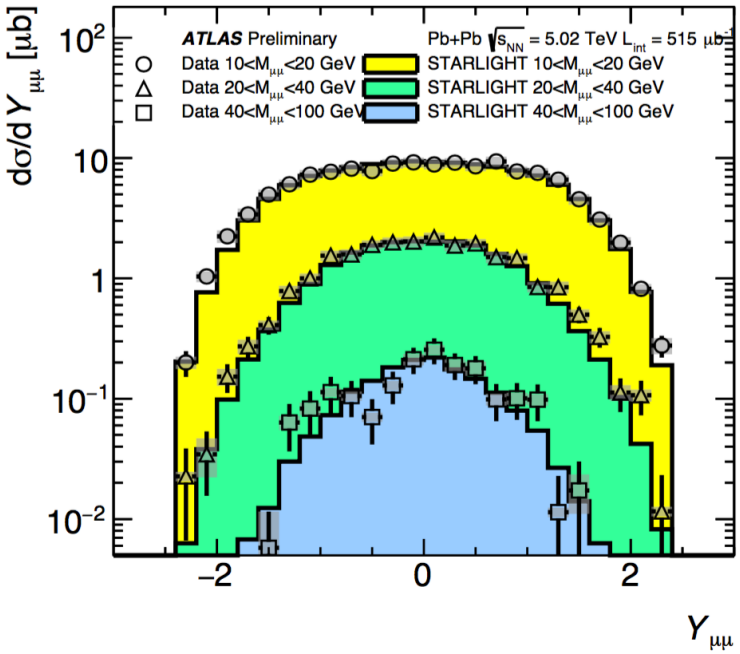
- Signal modeling
  - Starlight 1.1 (EPA + LO QED)
- Correct for differences in Data and MC
  - Trigger efficiency (data-driven): 80%
  - Muon efficiency (MC+SFs): 90%
  - Vertex efficiency (MC): 95%
- Kinematic distributions (Acoplanarity)
  - Most of μμ-pairs are back-to-back
  - Background visible at tails
- Two assumptions
  - tail is due to background
  - tail is due to missing HO QED
  - **Preliminary approach**: Average of both assumptions as central value
    - full difference as uncertainty

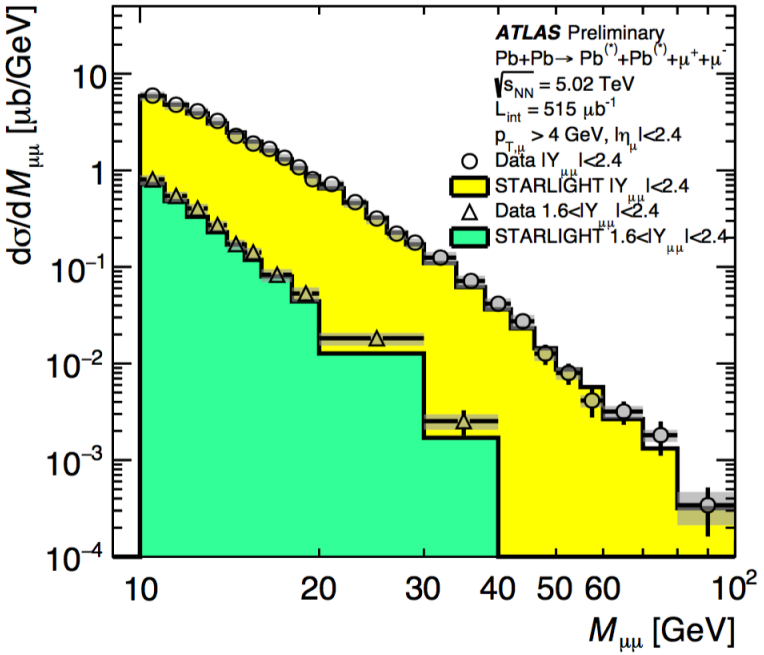






Measurement of high-mass dimuon pairs (3/3)

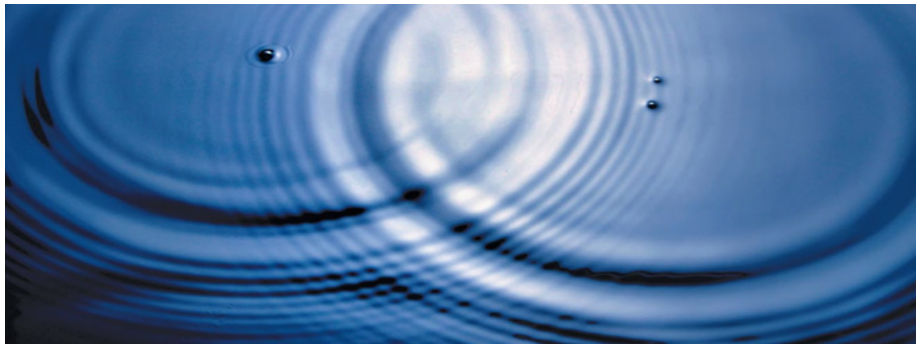




- Dominant systematic uncertainty due to luminosity: total syst. unc. ~=10%
- Differential distribution of $d\sigma/dm_{\mu\mu}$ and $d\sigma/dy_{\mu\mu}$ in good agreement with Starlight
- Result on total fiducial cross section
  - σ_{fid}=32.2 ±0.3 (stat.)±4.0(sys.) μb
- Theory prediction (Starlight)
  - $\sigma_{starlight}$ = 31.6 μb

Loop Corrections from 1935

- Defining feature of Maxwell's Equation: Super-position principle

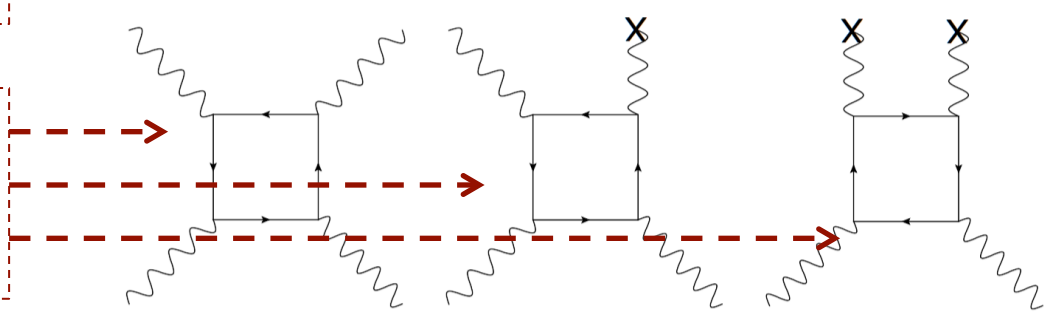


- Euler and Heisenberg calculated already in 1935 QED corrections to Maxwell's Equations, predicting

$$L_{eff}^{EHW} = L_0 + L_{eff}^{1} = \frac{1}{2}(E^2 - B^2) +$$

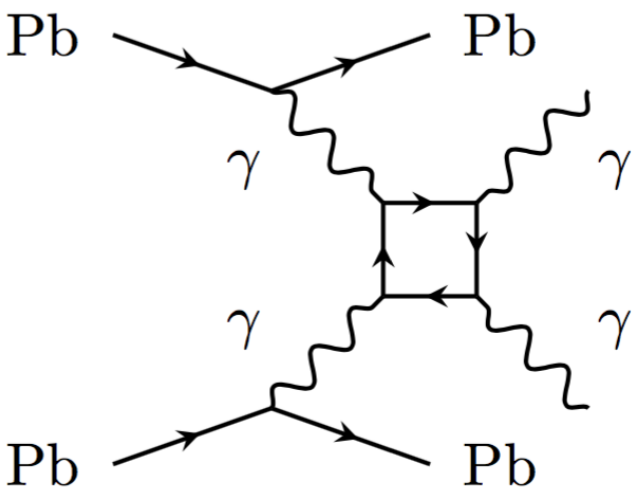
$$+\frac{2\alpha^2}{45m_e^4}\left[(E^2 - B^2)^2 + 7(\vec{E}\cdot\vec{B})^2\right]$$

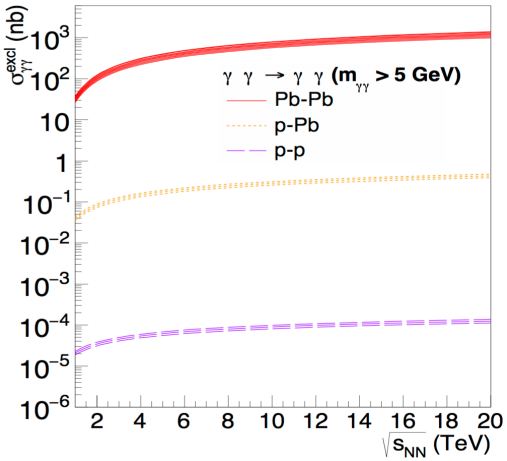
- Light-by-Light Scattering
- Photon-Splitting
- Vacuum Magnetic Birefringence

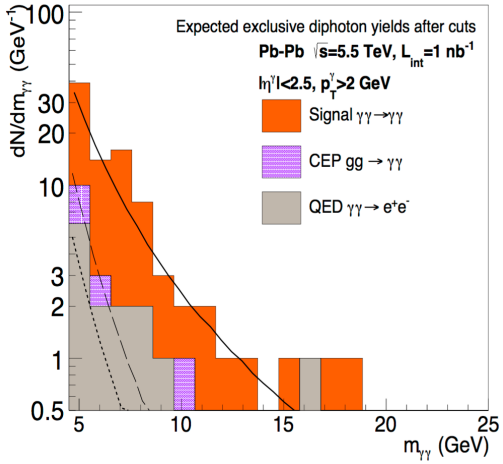


Search for Light-by-Light Scattering

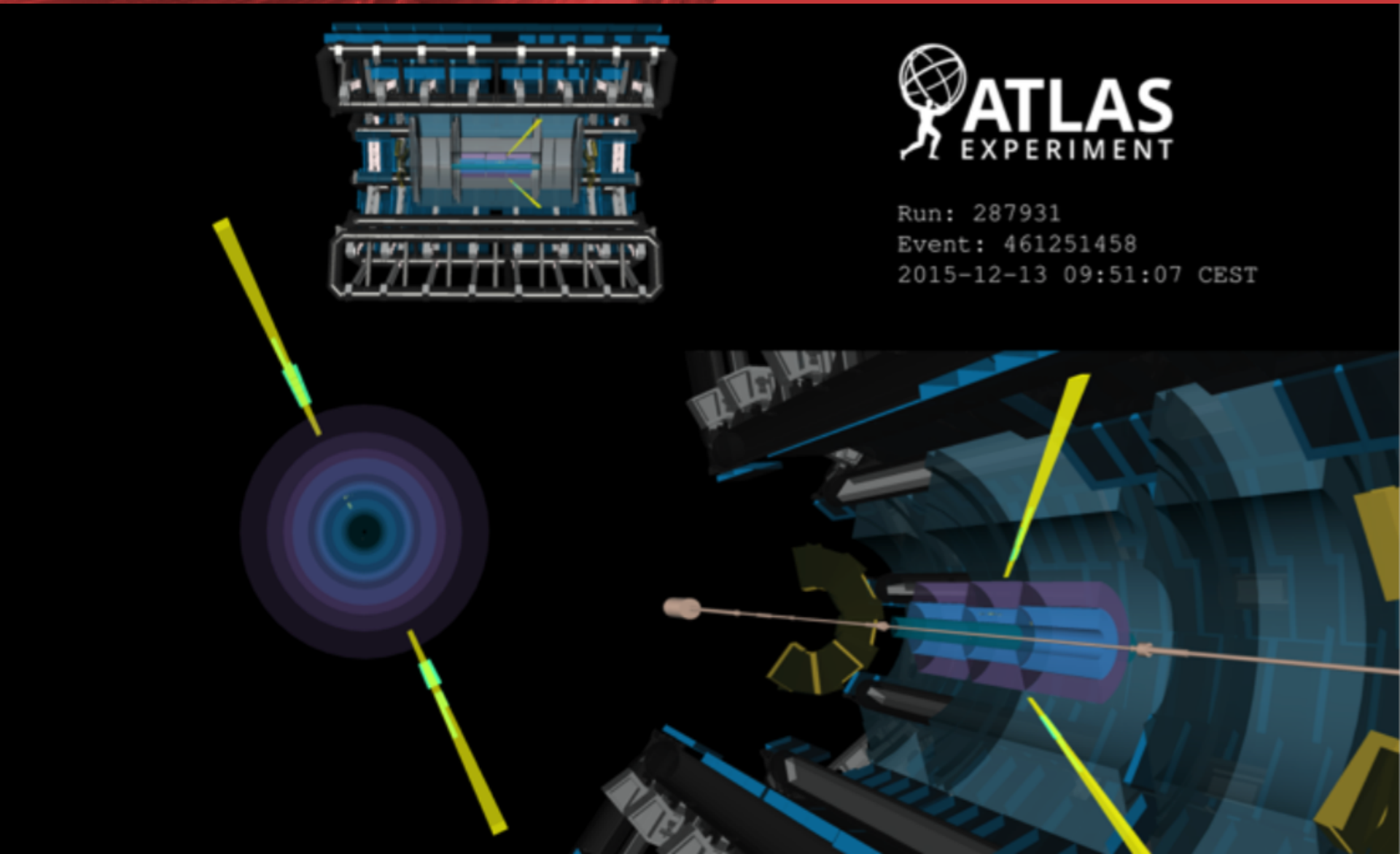
- Light-by-light scattering in ultra-peripheral Pb+Pb collisions
  - arxiv:1702.01625
- Idea based of this measurement based on [D. d'Enterria et al. PRL 111 (2013) 080405]
  - Follow up in [A. Szczurek et al. PRC 93 (2016) 4, 044907]
- Previous indirect measurements of Light-by-light ($\gamma\gamma \rightarrow \gamma\gamma$) scattering
  - multi-photon Breit-Wheeler reaction
  - photon splitting
  - Delbrück scattering





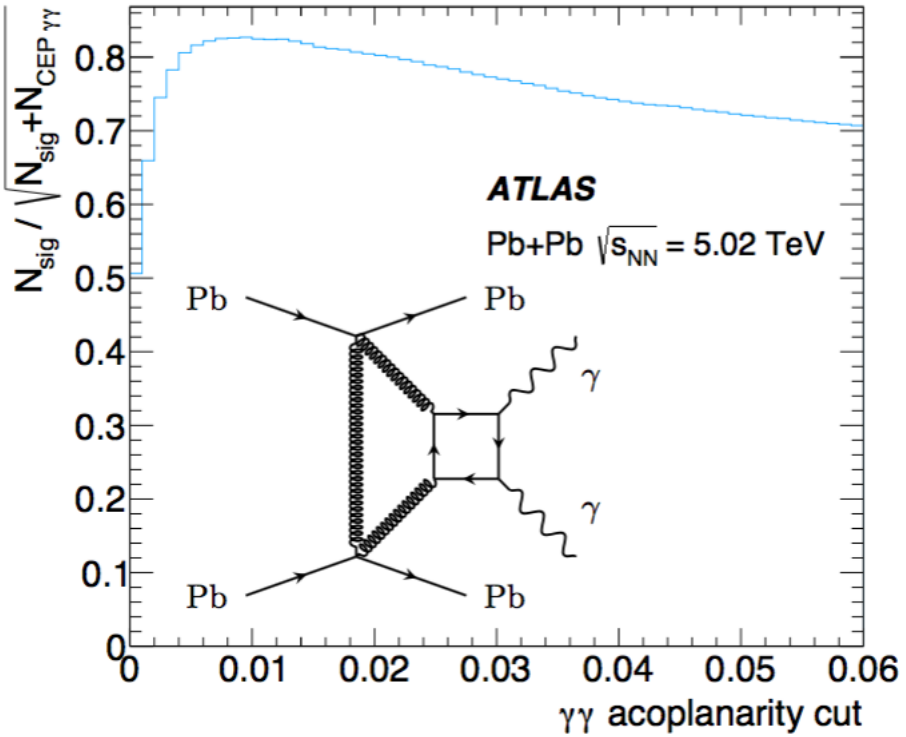


Light-by-Light Scattering Candidate



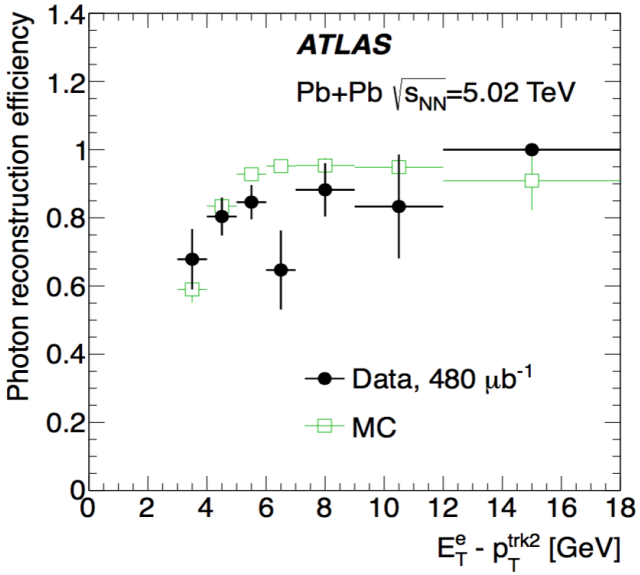
Search for Light-by-Light Scattering: Signal Selection

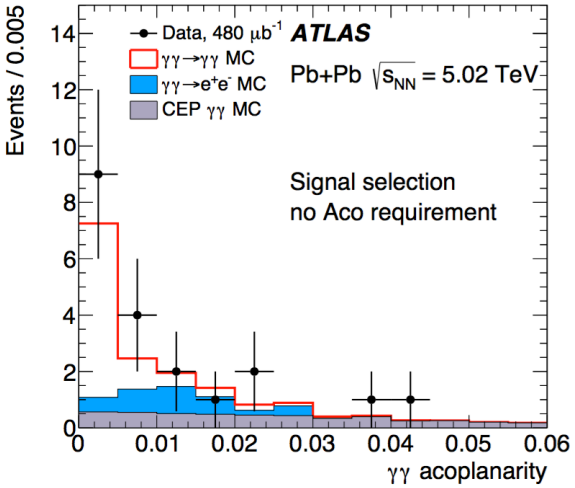
- Trigger
  - total E_T in calorimeter between 5 and 200 GeV
  - no more than one hit in inner MBTS
  - Less than 10 hits in the pixel detector
- Signal Selection
  - 2 photons with E_T>3 GeV, $|\eta| < 2.37$
  - no tracks from IP
  - $m_{\gamma\gamma} > 6$ GeV, $p_{\gamma\gamma} < 2$GeV
  - Aco= $1-\Delta\phi/\pi$ <0.01
- Main sources of bkg.
  - Central Exclusive Production (CEP) $gg \rightarrow \gamma\gamma$
  - Misidentified electrons from $\gamma\gamma \rightarrow ee$
  - Hadronic Fakes

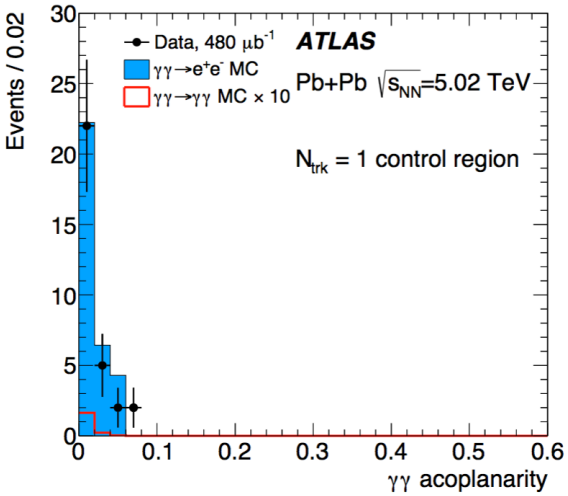


Search for Light-by-Light Scattering: Photon Performance

- Photon identification had to be optimized for low energies; performance studied in $\gamma\gamma \rightarrow l^+l^-$ events
  - energy scale and resolution
  - γ PID with FSR radiation
  - trigger efficiency studies
  - γ reconstruction with hard bremsstrahlung
- Systematic uncertainties dominated by photon PID and reconstruction efficiencies
- CEP background can be suppressed with Aco-cut
  - Data-driven estimation of normalisation
- Electron fake background can be also tested in data



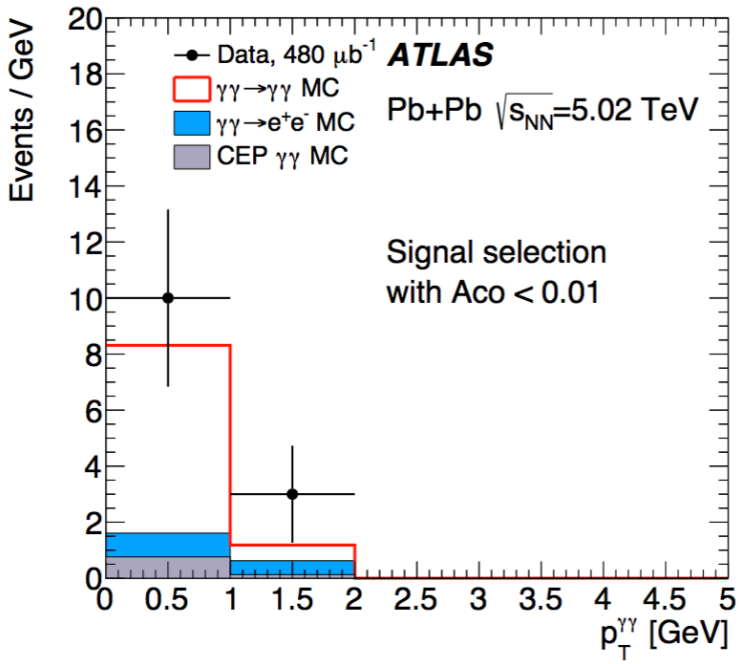




Evidence of Light-by-Light Scattering

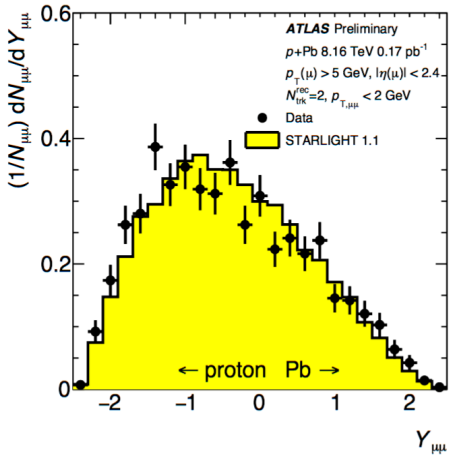
Selection	$\gamma\gamma \to e^+e^-$	CEP $gg \to \gamma\gamma$	Hadronic fakes	Other fakes	Total background	Signal	Data
Preselection	74	4.7	6	19	104	9.1	105
$N_{\mathrm{trk}} = 0$	4.0	4.5	6	19	33	8.7	39
$p_{\mathrm{T}}^{\gamma\gamma} < 2$ GeV	3.5	4.4	3	1.3	12.2	8.5	21
Aco < 0.01	1.3	0.9	0.3	0.1	2.6	7.3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

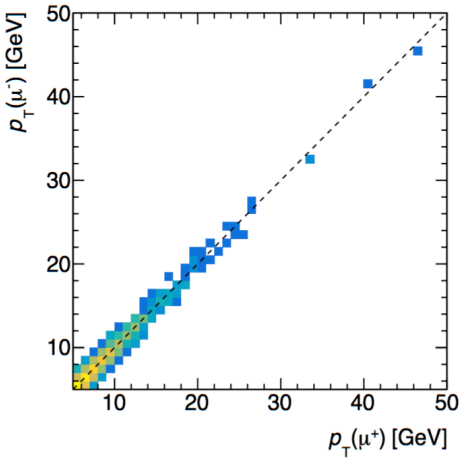
- 13 selected candidate events with a signal expectation of 7.3 and a background expectation of 2.6 events
- Significance of 4.4σ estimated using profile likelihood method (exp. significance of 3.8σ)
- x-sec measured in fiducial region
  - σ_{fid} = 70 ± 20 (stat.) ± 17 (syst.) nb
  - σ_{SM} = 49 ± 10 nb

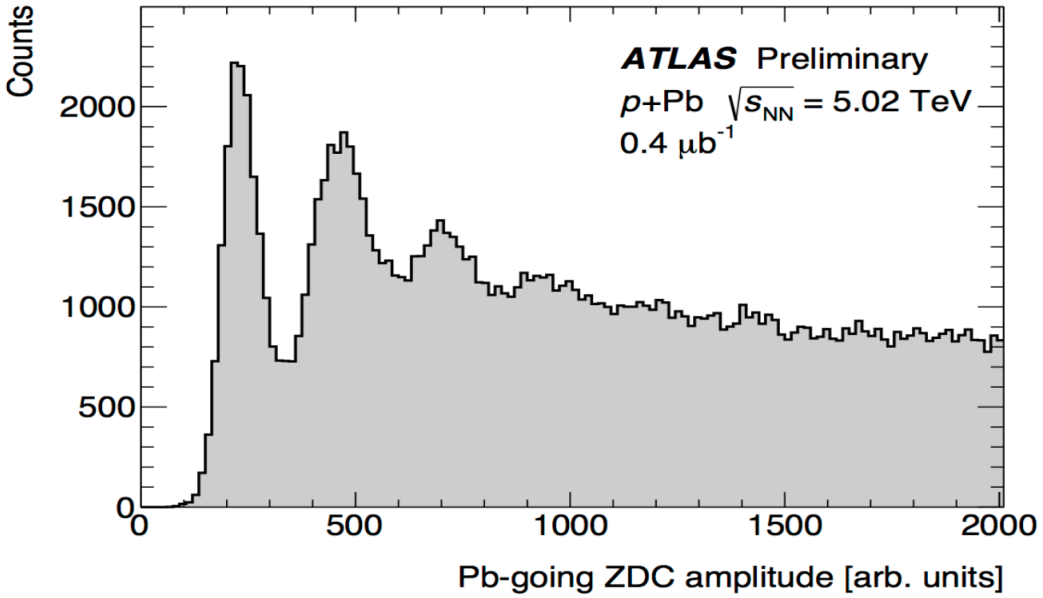


Prospects of electromagnetic Interactions at the LHC

- Upcoming Pb-Pb runs at the LHC allow to reach the 5σ level for Light-by-Light scattering
  - Search for contributions from BSM particles (axions etc.)
    - arXiv:1607.06083
- First results from 2016 p-Pb run
  - first look at dileptons distributions
  - beautiful neutron peaks of Pb going through the ZDC
  - …
- One Step further: photo-nuclear jet production in UPC events
- Many analyses ongoing!







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Summary

- Exclusive (QED) processes have been studied in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
- Cross sections of the exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ production have been measured
  - Consistent with the LO QED calculations from Starlight
- Evidence for SM $\gamma\gamma \rightarrow \gamma\gamma$ production (significance of 4.4σ)
  - Cross section in agreement with QED predictions
  - Looking forward to results from ALICE/CMS