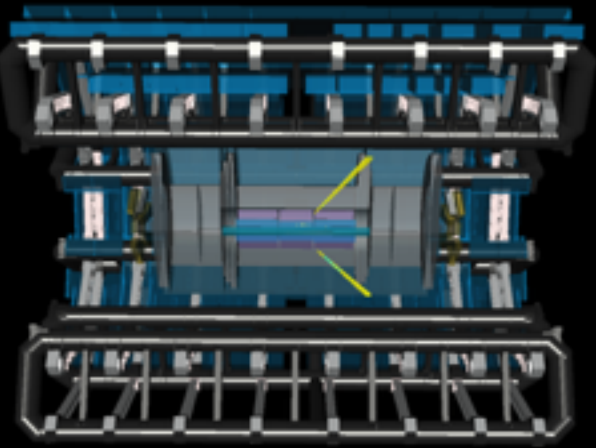
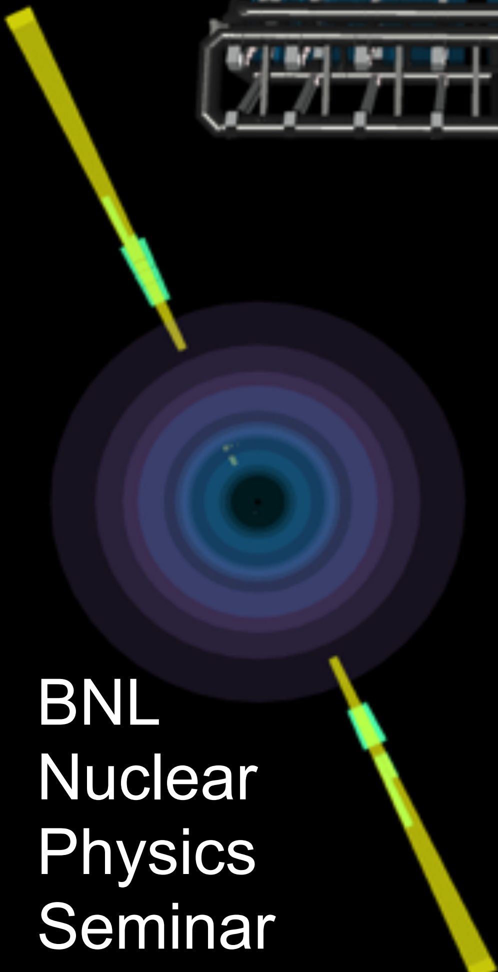
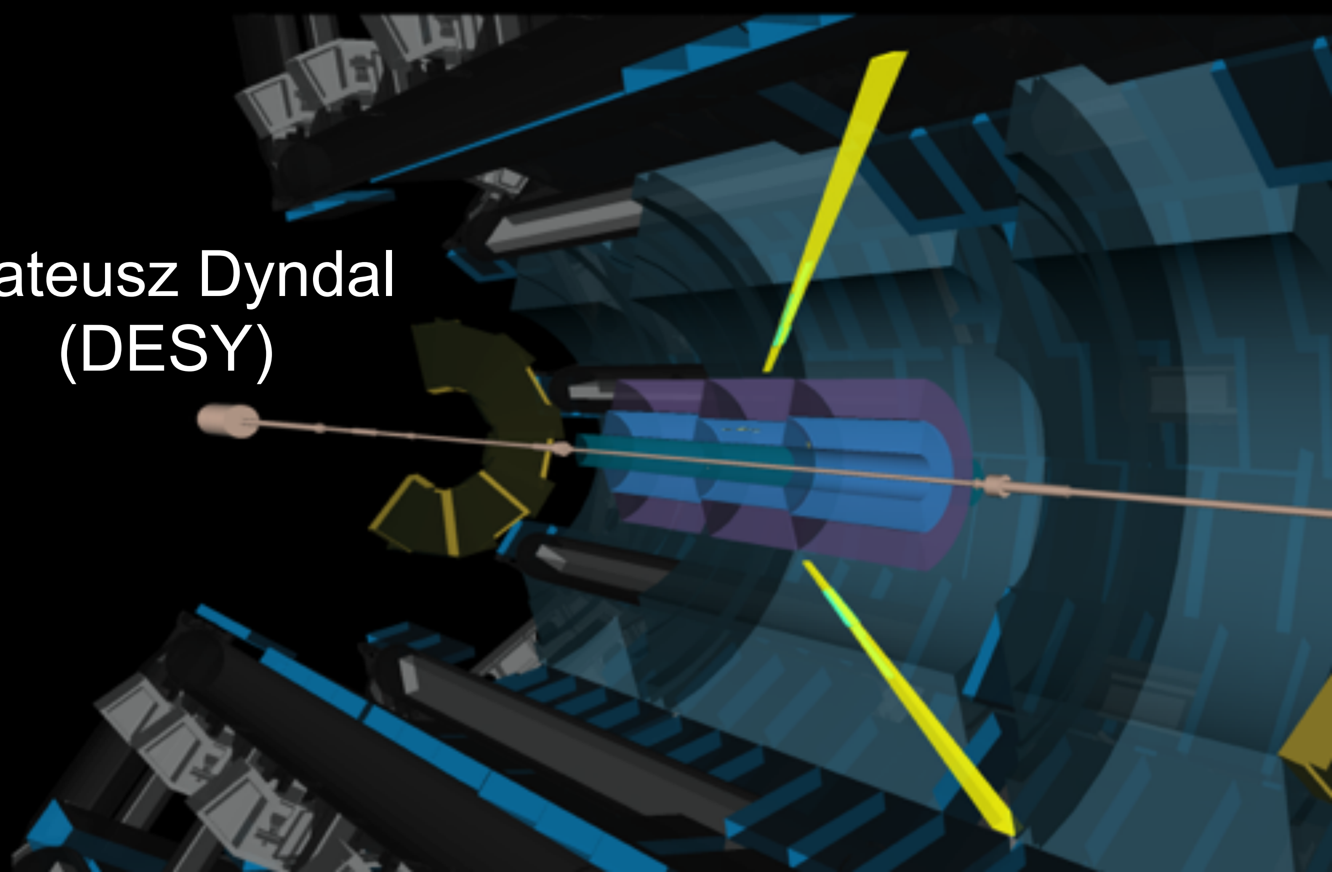


Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC





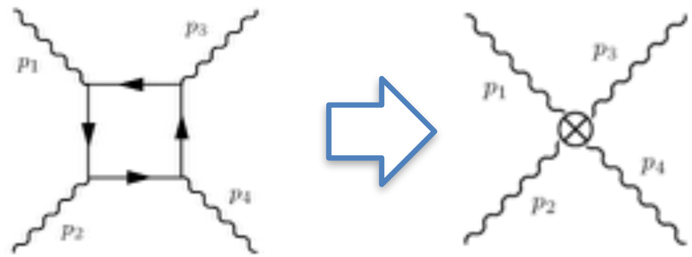
Mateusz Dyndal
(DESY)

BNL
Nuclear
Physics
Seminar

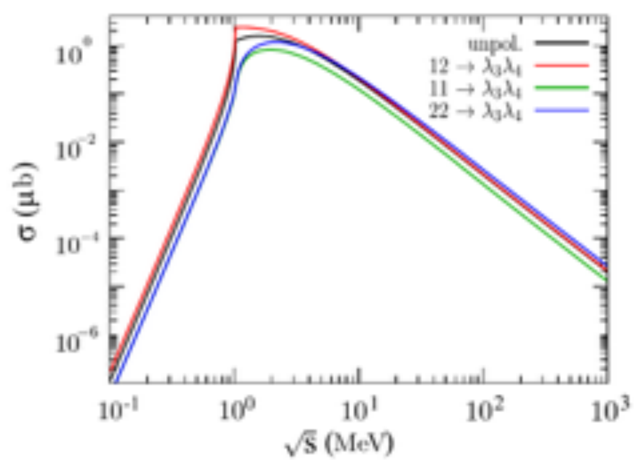
13 December 2016

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 << m_e):

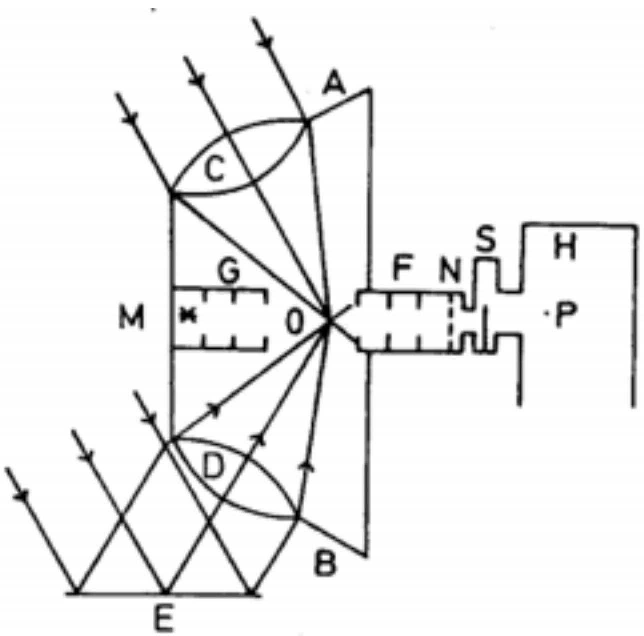


- Exact calculations: <u>loops</u>
    - Box diagrams involve charged fermions and W bosons



LbyL scattering: experimental approach

[Hughes and Jauncey, Phys. Rev. (36 1930), 773]



Light-light box experiment

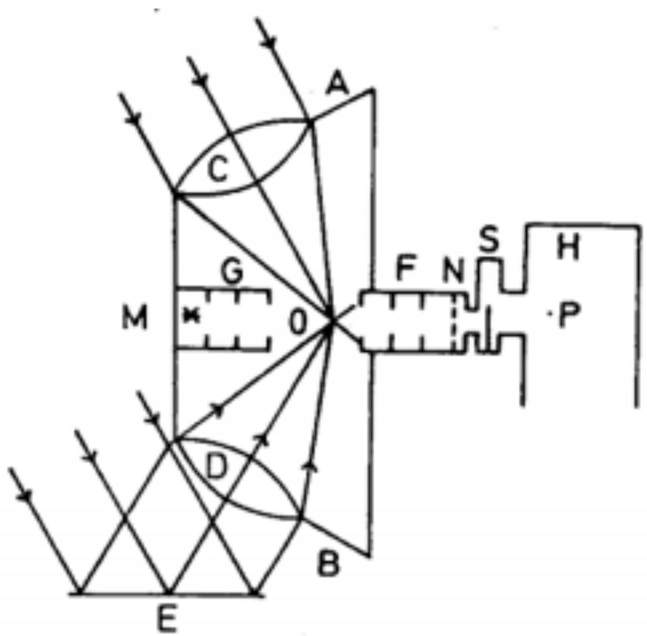
``No light was detected."

``Calculations show that if the photon has a cross section, its area must be less than $3x10^{-20}$ cm^2."

(First?) Apparatus for a light-light scattering experiment: The two lenses C and D focus sun light on the same spot O in a light-tight box AB. The dark-adapted eye of an observer at the point P serves as the detector for scattered light.

LbyL scattering: experimental approach

[Hughes and Jauncey, Phys. Rev. (36 1930), 773]



Light-light box experiment

``No light was detected."

``Calculations show that if the photon has a cross section, its area must be less than **3×10^{-20} cm^2**."

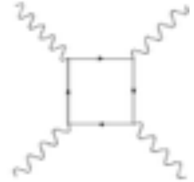
(First?) Apparatus for a light-light scattering experiment: The two lenses C and D focus sun light on the same spot 0 in a light-tight box AB. The dark-adapted eye of an observer at the point P serves as the detector for scattered light.

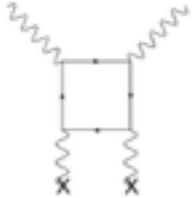
The cross section for scattering of visible light is of the order of **10^{-60} cm^2**

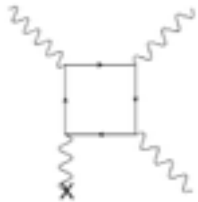
Previous experiments

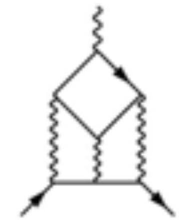
- Experimental status prior to the ATLAS result

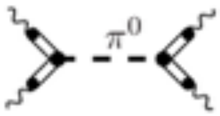
Elastic LbyL scattering	γγ -> γγ	Not observed
Delbruck scattering	γZ -> γZ	Observed ('53 - '98)
Photon splitting in Z field	γZ -> γγZ	Observed (2002)
Vacuum electric/magnetic birefringence	γF -> γF	Not observed
Photon splitting in electric/magnetic field	γF -> γγF	Not observed
Impact on muon (electron)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





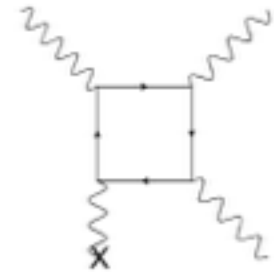


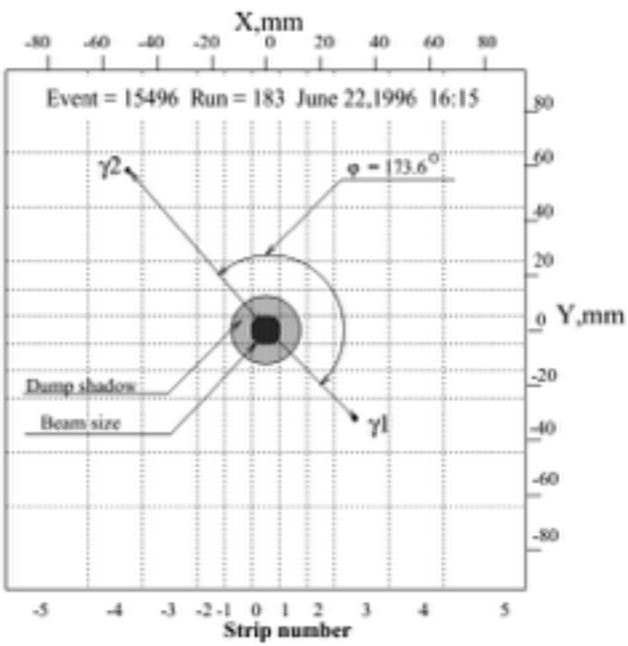


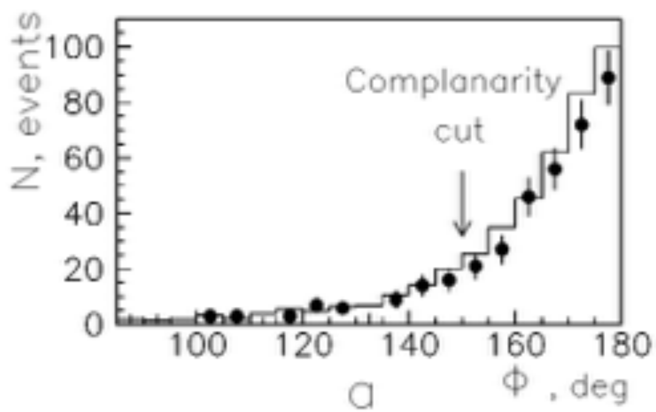


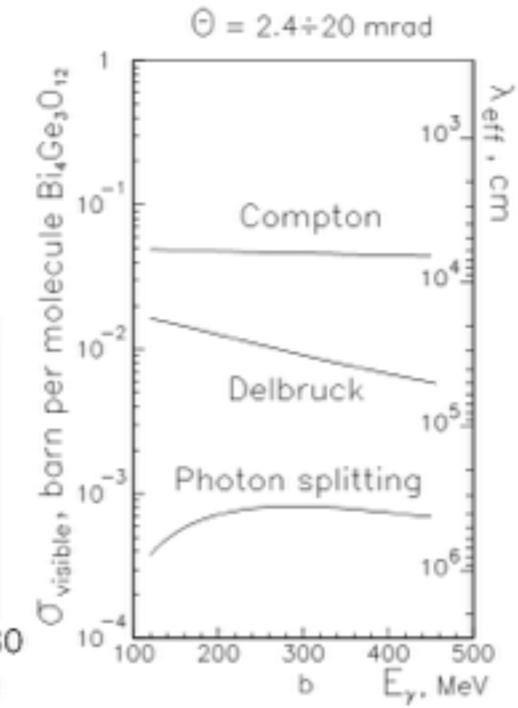
Photon splitting

- 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









Impact on muon g-2

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

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

$$a_\mu = (g_\mu - 2)/2$$

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

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

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

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

- Data/theory status:

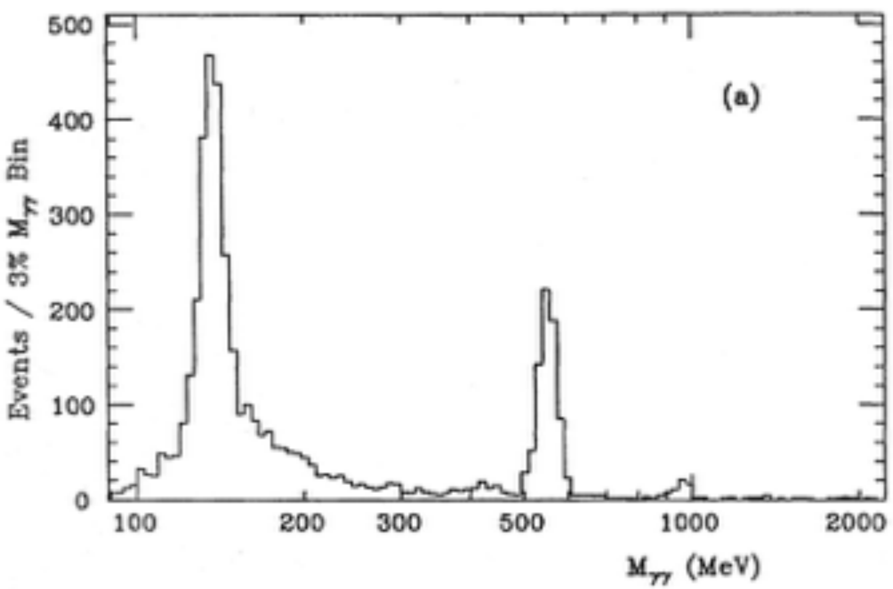
$$a_\mu^{\mathrm{exp}} = 1.16592080(63) \times 10^{-3}$$
$$a_\mu^{\mathrm{the}} = 1.16591790(65) \times 10^{-3}$$

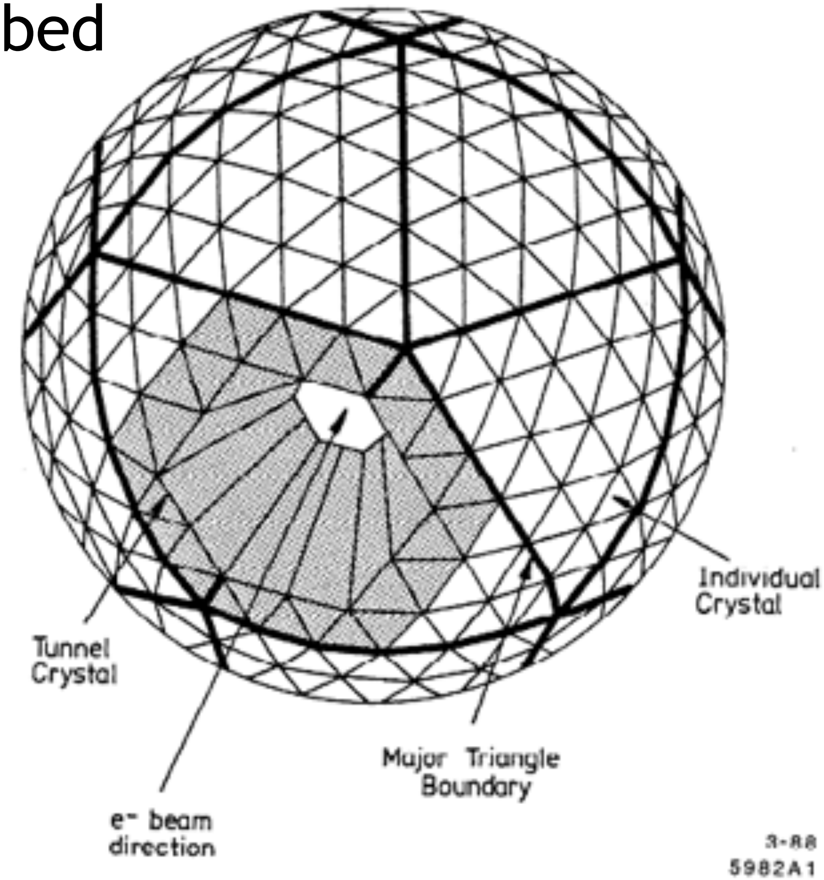
$$\delta a_\mu^{\mathrm{NP?}} = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{the}} = (290 \pm 90) \times 10^{-11}$$

~3σ discrepancy

Hadronic LbyL

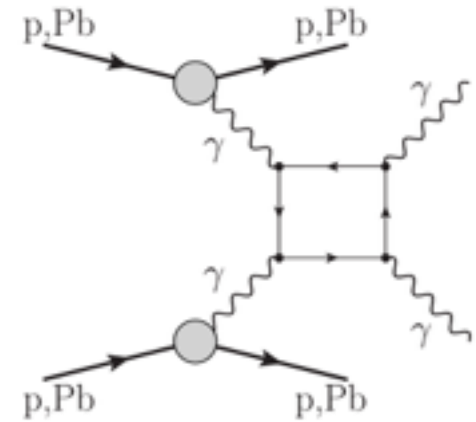
- Tested directly at e^+e^- colliders at SLAC/DESY (80's)
- The first and only observation of **$\gamma\gamma \to \pi^0 \to \gamma\gamma$** done with Crystal Ball detector at DORIS II [Phys. Rev. D38 (1988) 1365]
- 0.1 GeV < m < 3 GeV region is probed
- Measurement is used to derive partial widths, $\Gamma_{\pi 0/\eta/\eta' \to \gamma\gamma}$

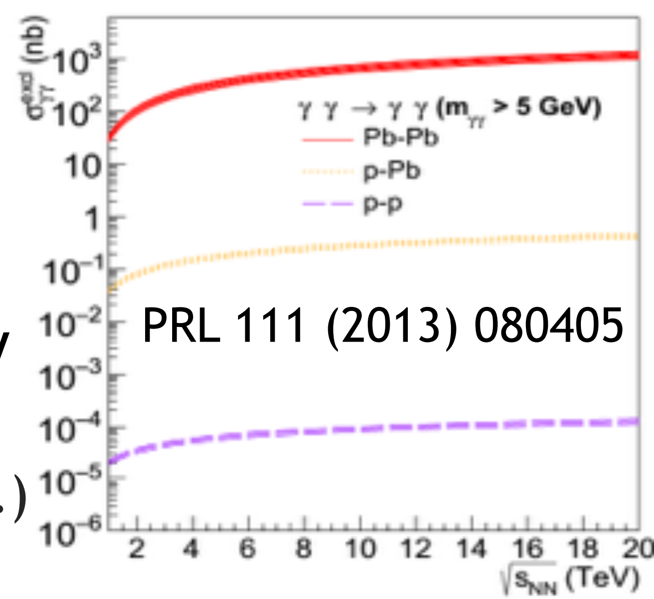




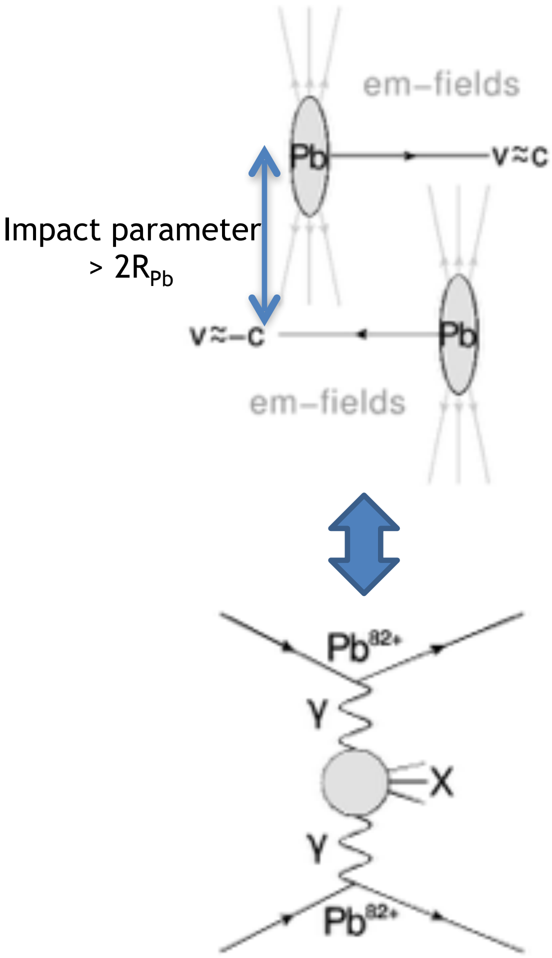
LbyL in hadron-hadron collisions

- LbyL scattering can be tested in h-h collisions
- Formally, **LbyL in h-h == ZZ -> γγ ZZ** process
  - However, the initial photons have very small virtualities, eg $Q^2 < 10^{-3}$ GeV^2 for LHC Pb-Pb -> Quasi-elastic LbyL scattering
- Recent phenomenological studies/preditions for SM rates in pp/Pb-Pb collisions at the LHC
  - [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 (γγ) → 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 (γγ) → ZZ X** process is calculated using:

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

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

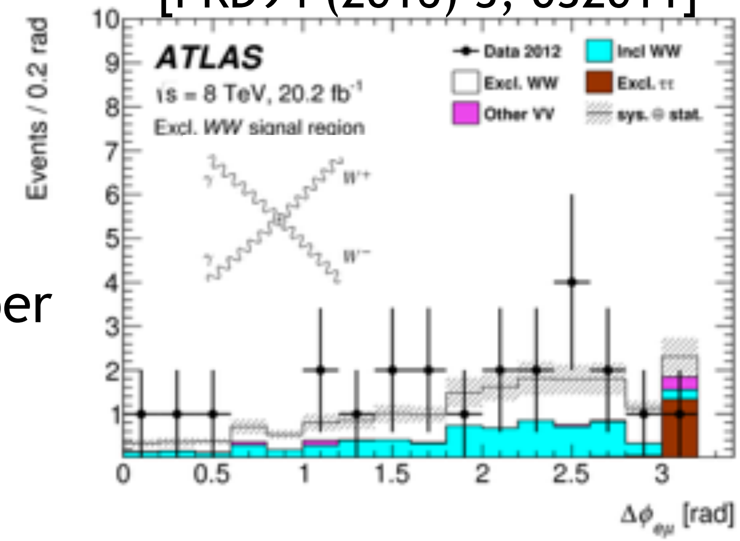
$$Q^2 < 1/R^2 \qquad \omega_{\max} \approx \gamma/R$$

(2) EW γγ → **X** (elementary) cross section

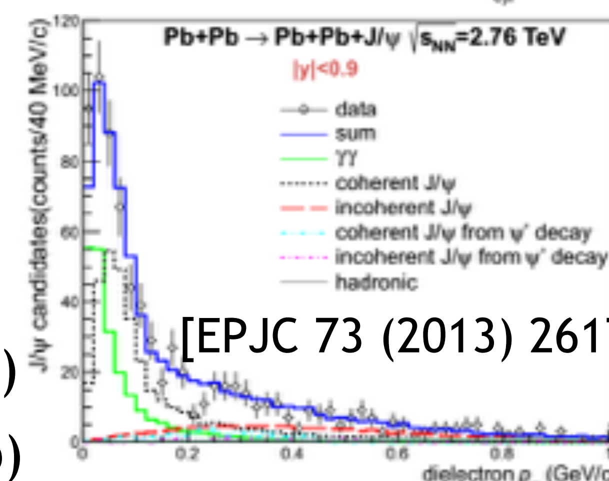
$$\sigma^{\mathrm{EPA}}_{A_1A_2(\gamma\gamma)\rightarrow A_1A_2X} = \iint d\omega_1\, d\omega_2\; n_1(\omega_1)\; n_2(\omega_2)\; \sigma_{\gamma\gamma\rightarrow X}(W_{\gamma\gamma})$$

LHC as a photon-photon collider

- Many intersting measurements can be done with pp/Pb-Pb beams of quasi-real photons at the LHC [PRD94 (2016) 3, 032011]



- **pp collisions:**
  - \+ harder EPA spectrum (ω_{max} ~ TeV)
  - \+ large datasets available, O(10 fb^{-1})
  - \- large pile-up (multiple interactions per bunch crossing)
  - \- hard to trigger on low-p_T objects
- **Pb-Pb collisions:**
  - \+ ZZ ($\gamma\gamma$) cross-sections scale as Z^4
  - \+ gluonic cross-sections scale as ~A^2 (lower QCD background expected wrt pp)
  - \+ low pile-up (<1%)
  - \- Relatively soft EPA spectrum (ω_{max}~100 GeV)
  - \- Short LHC PbPb campaigns (compared to pp)

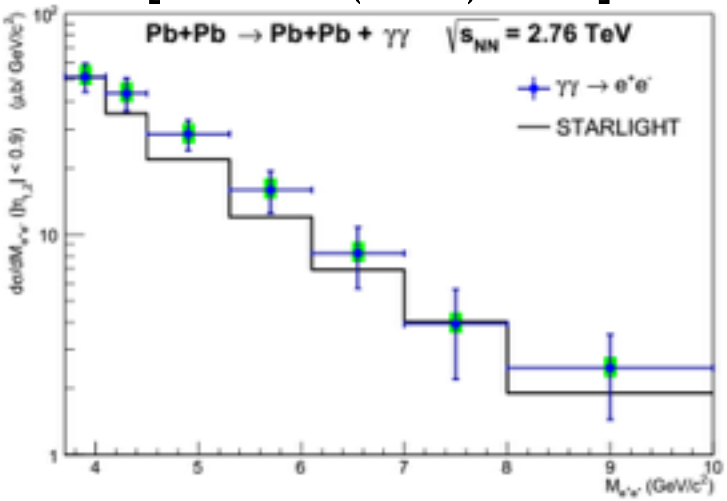


[EPJC 73 (2013) 2617]

Testing Pb-Pb EPA at the LHC

- Non-resonant γγ -> **l^+l^-** is a good benchmark process
- Studied by both ALICE and ATLAS
- Good agreement with Starlight (EPA + LO xs)

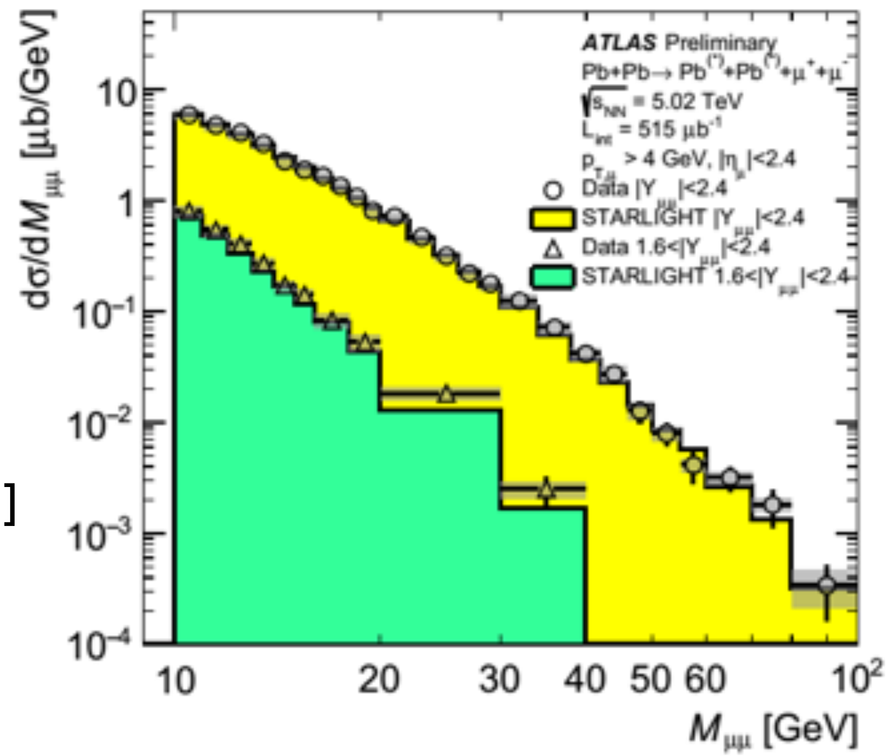
[EPJC 73 (2013) 2617]



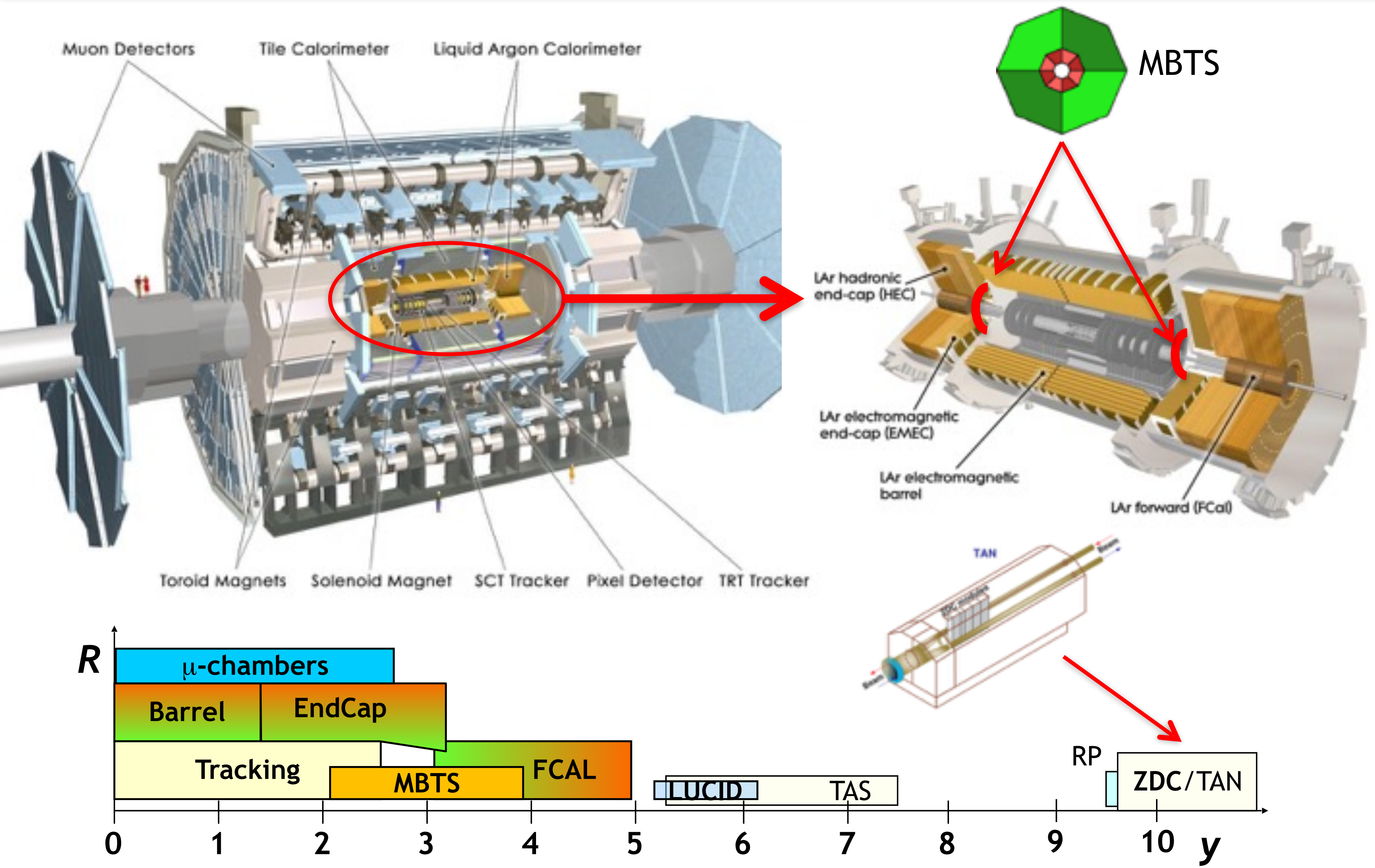
cf PHENIX measurement [PLB679 (2009) 321-329]

$m_{e^+e^-}$ [GeV/c^2]	$d^2\sigma/dm_{e^+e^-}dy\vert_{y=0}$ [μb/(GeV/c^2)] data	STARLIGHT
e^+e^- continuum [2.0,2.8]	86 ± 23 (stat) ± 16 (syst)	90
e^+e^- continuum [2.0,2.3]	129 ± 47 (stat) ± 28 (syst)	138
e^+e^- continuum [2.3,2.8]	60 ± 24 (stat) ± 14 (syst)	61

[ATLAS-CONF-2016-025]

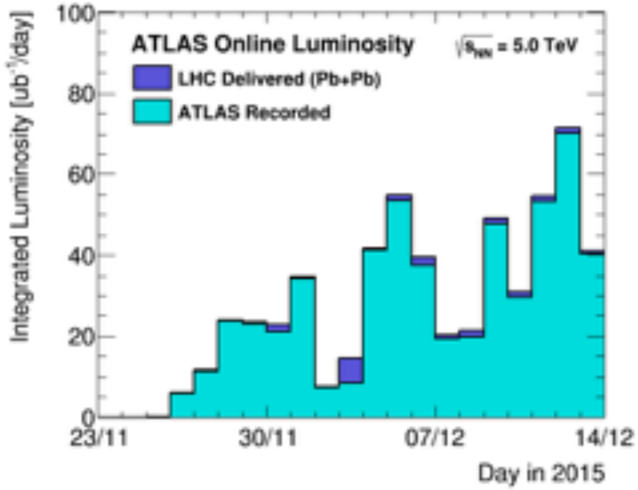


The ATLAS detector



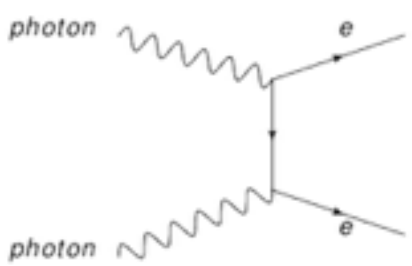
Data and MC samples

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

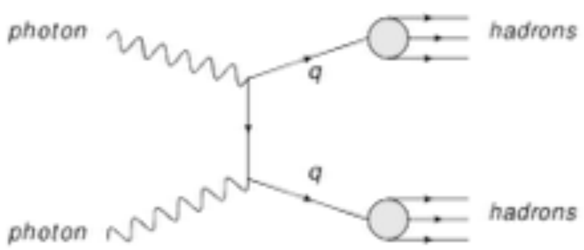


- MC simulated events
  - Signal MC sample to study event characteristics and correction factor
  - Several background MC samples are used for processes:

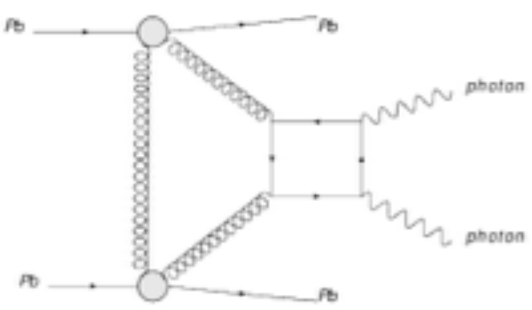
γγ -> ee



γγ -> qq



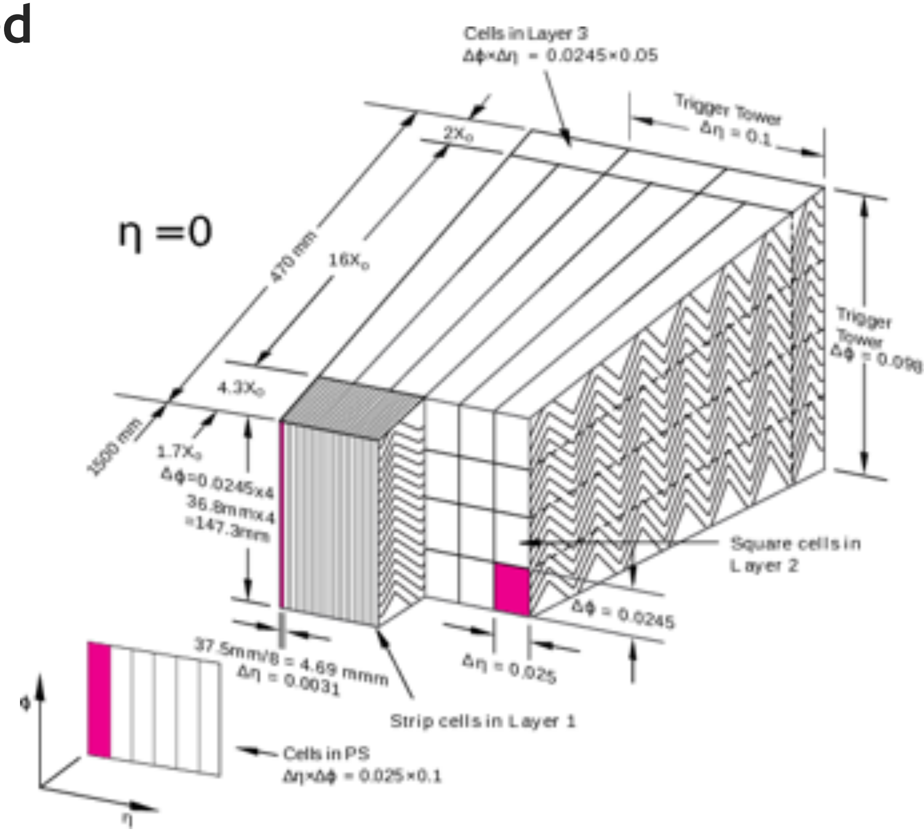
CEP gg -> γγ



Object definition

- $\gamma\gamma \to \gamma\gamma$ cross section decreases rapidly with $m_{\gamma\gamma}$ and/or E_T
  - **Low-E_T photons need to be used**
- Photons
  - **E_T > 3 GeV, |η| < 2.37**, photon PID based on three shower-shape variables is used:

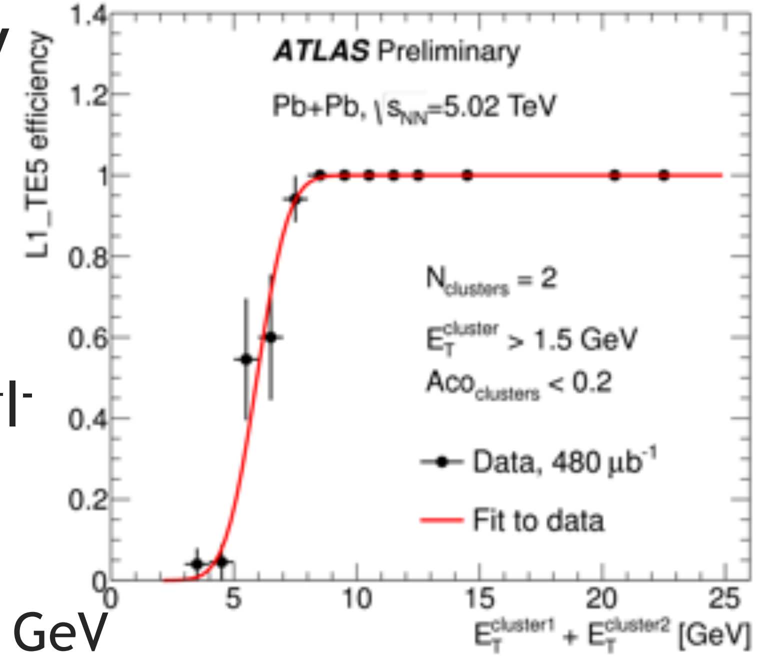
E_{ratio}	Ratio of the energy difference associated with the largest and second largest energy deposits to the sum of these energies in the **first layer** of EM calo
f_1	Fraction of energy reconstructed in the **first layer** with respect to the total energy of the cluster
w_{eta2}	Lateral width of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



- Charged-particle tracks (veto helps to reduce background)
  - p_T > 100 MeV, |η| < 2.5

Trigger

- **Dedicated trigger** is used to select γγ -> γγ event candidates
  - Unprescaled in full 2015 data-taking period
  - Total E_T in calo at L1: **5 GeV-200 GeV**
  - Veto on signals in inner MBTS
  - Between 0-10 hits in the pixel detector

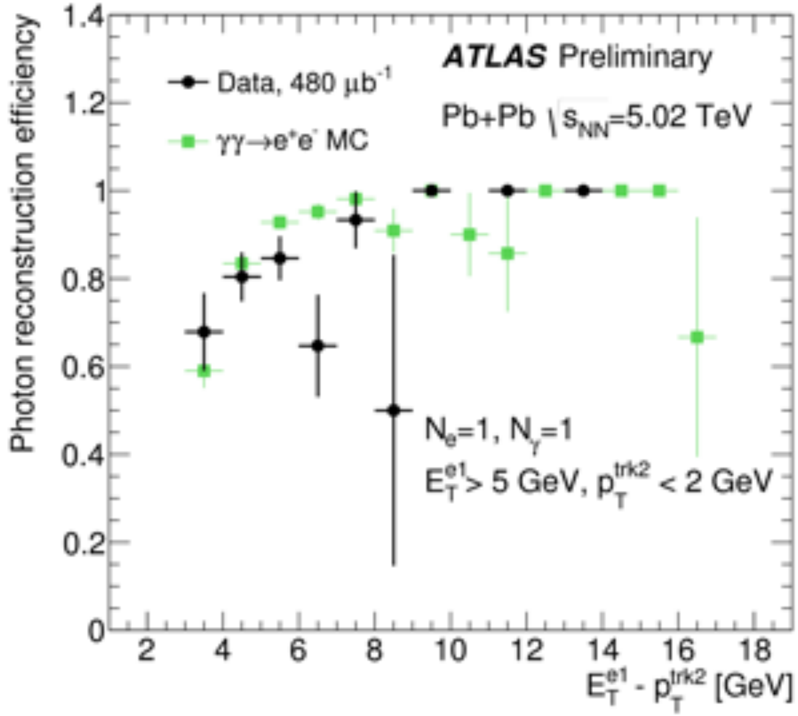


- Efficiency is estimated with γγ -> l^+l^- events passing supporting trigger (ZDC-based)
  - L1_TE5 reaches 100% at (E_{Tcl1}+E_{Tcl2})=8 GeV
  - MBTS veto is estimated to be (98 ± 2)%
  - Pixel detector activity requirement is ~100% efficient with negligible uncertainty (low noise, very high hit reconstruction efficiency and low conversion probability of signal photons in the pixel detector)

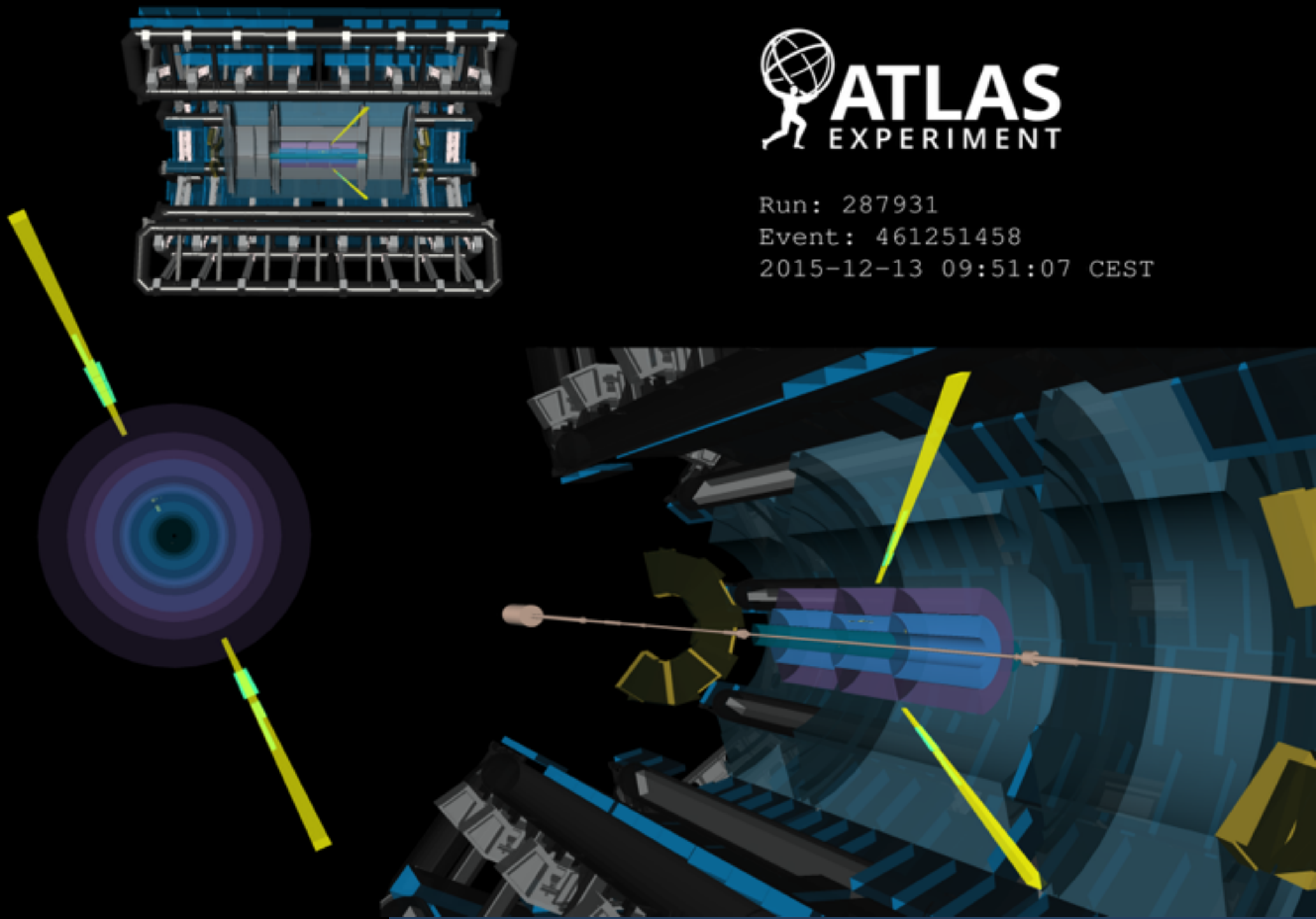
Photon performance cross-checks

- $\gamma\gamma \rightarrow l^+l^-$ (γ) events used to cross-check low-E_T photon performance
  - This includes: PID/reco efficiency, energy scale/resolution

- **Example:** yy -> 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 hard-brem photon is reconstructed
  - $E_T(y) \approx (E_T(e)$ - second track $p_T)$
- Photon reco efficiency extracted from data in agreement with MC



γγ -> γγ event characteristics

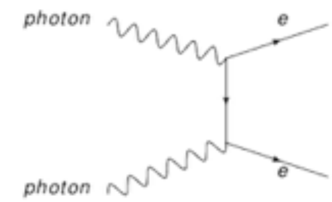


Event selection

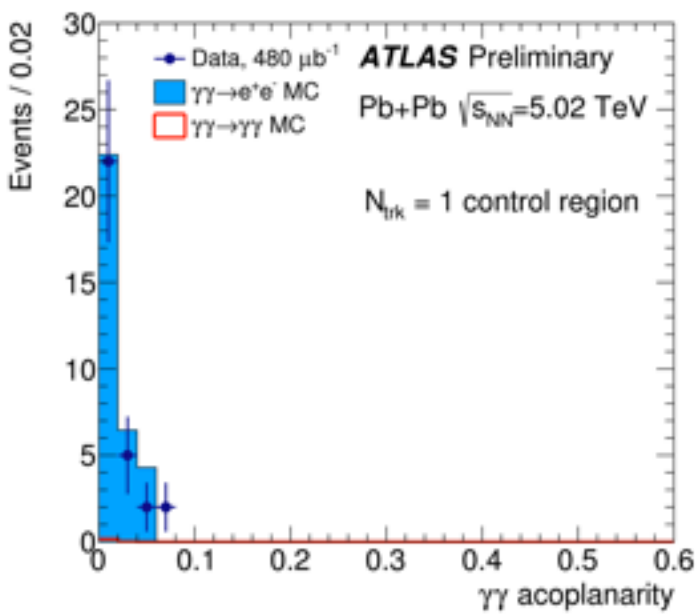
- Signal event characteristics -> set of cuts for background reduction
  - **== 2 photons** with photon E_T > 3 GeV, $|\eta|$ < 2.37 and $m_{\gamma\gamma}$ > 6 GeV -> event preselection
  - **N_{trk} = 0** -> almost no impact on signal MC events, significant reduction of γγ -> ee misID events
  - **$p_T(\gamma\gamma)$ < 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

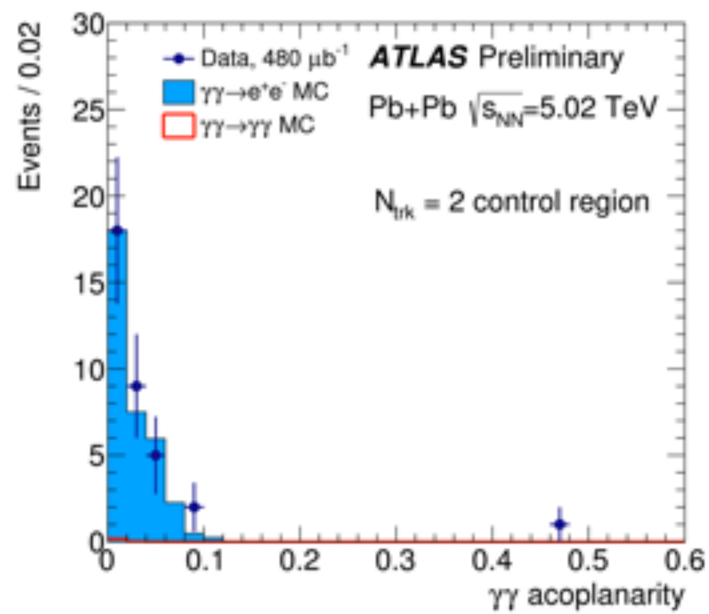
Background

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



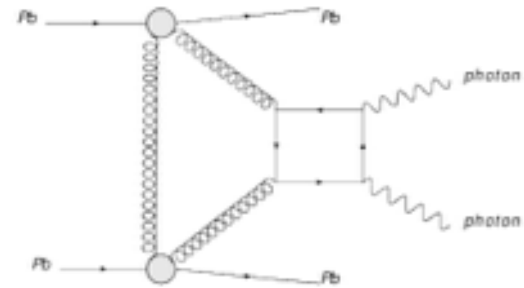
- N_{trk} = 0 cut is used to suppress γγ -> ee misID events
- ==2 photons with N_{trk} = 1(2) is a good control region for γγ -> ee misID background



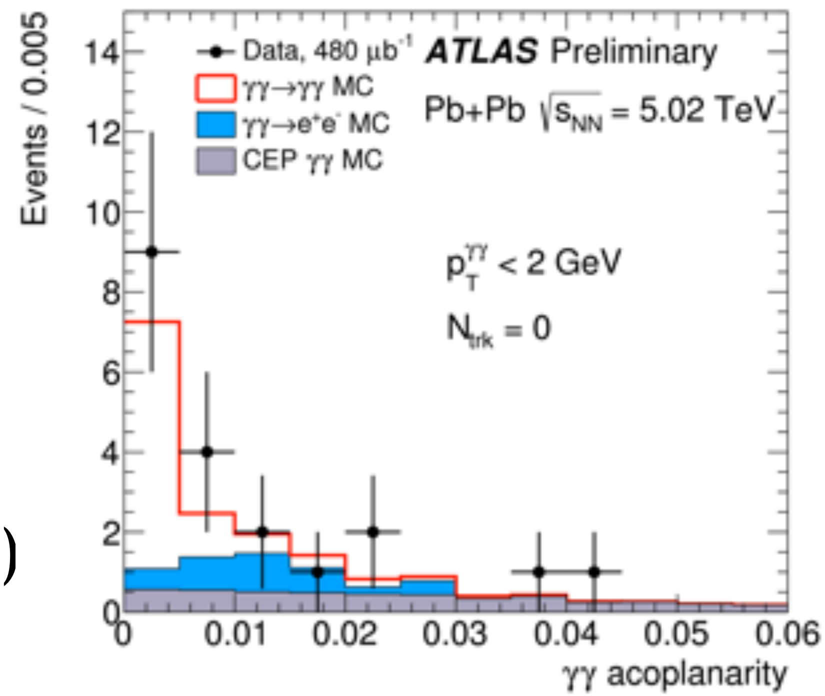


Background

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



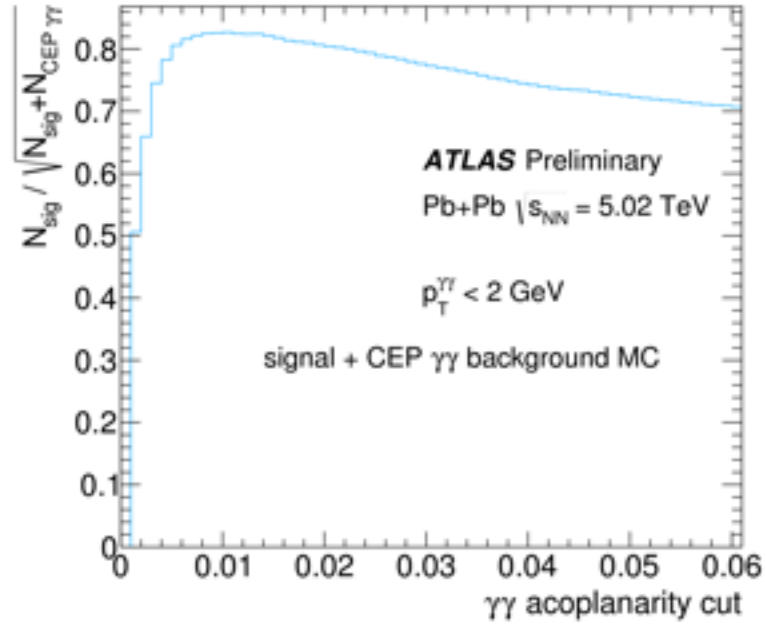
- CEP gg -> yy is reducibe with yy acoplanarity cut
- Idea: define Aco < Aco_cut as a signal region and use events with Aco > Aco_cut for CEP gg->yy background normalization (due to large theory uncertainties)



Background

- Central exclusive yy production

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



- CEP gg -> yy normalization:

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

(b = 0.02 used for the central value; b = 0.01 and b = 0.03 for systematic checks)

- Final estimation: $f^{\mathrm{norm},b=0.02}_{gg\to\gamma\gamma} = 0.5 \pm 0.3$

Other background

- Other background being considered (negligible)
  - **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
  - **CEP dimeson production** (e.g. gg -> π0 π0 -> 4y, gg -> ηη -> 4y etc.)
    -> estimated with MC models to be below 10% of CEP gg -> yy in the same kinematic region
  - **Other fake photons** (mostly induced by cosmic-ray muons)
    -> estimated 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 γγ -> l^+l^- 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:

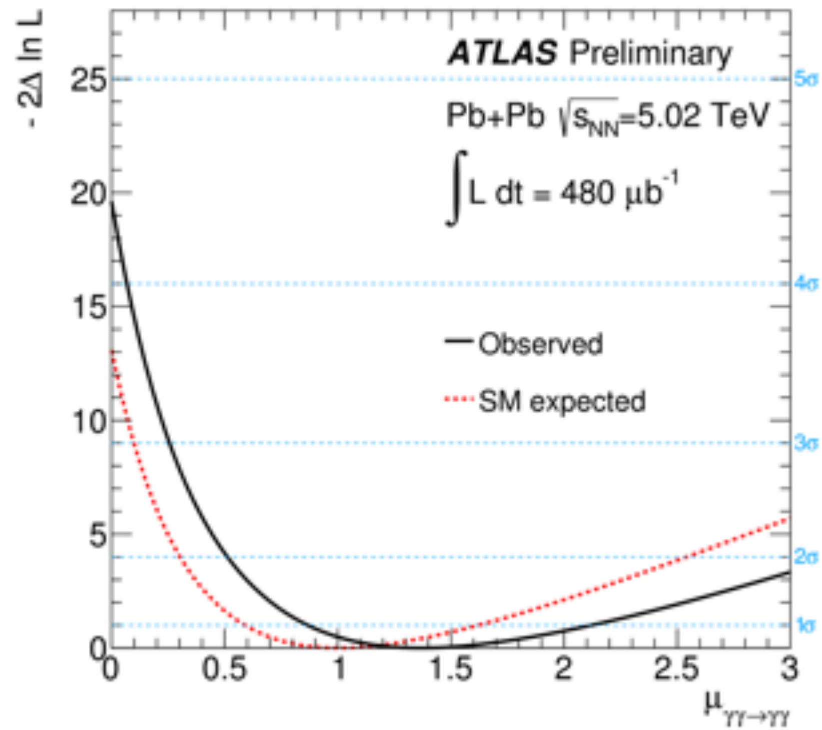
Source of uncertainty	Detector correction (C)
	0.31
Trigger	5%
Photon reco efficiency	12%
Photon PID efficiency	16%
Photon energy scale	7%
Photon energy resolution	11%
Total	24%

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
$N_{trk} = 0$	39	8.7	4.0	4.5	6	19	42
$p_T^{\gamma\gamma} < 2$ 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)

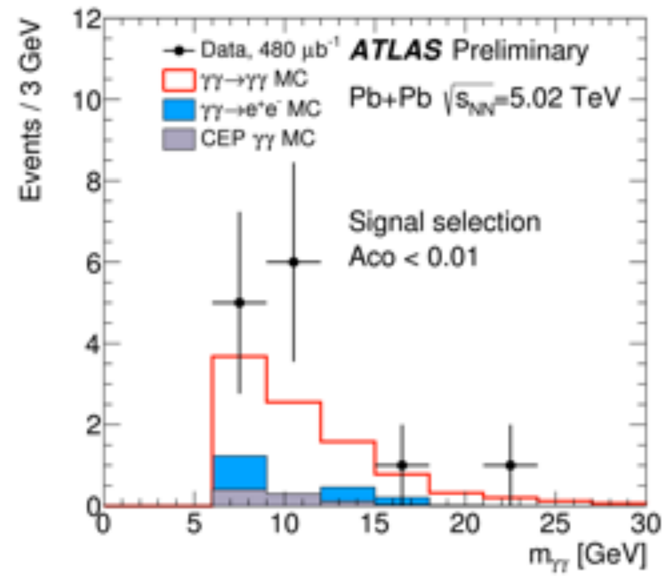


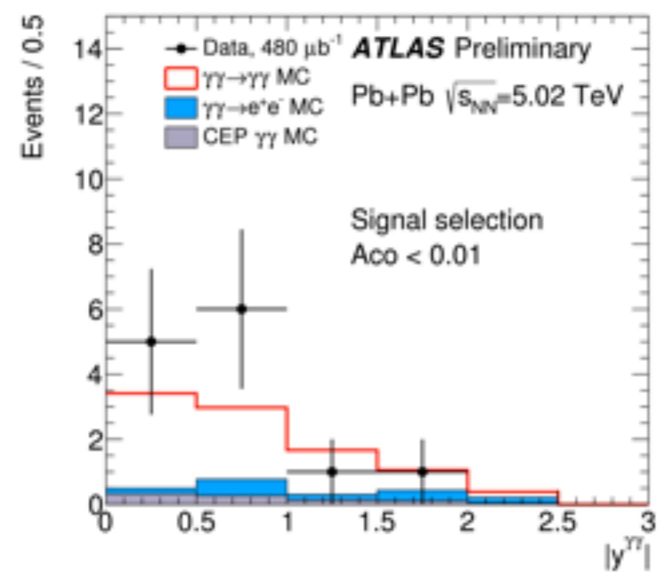
Results

- Fiducial cross section is estimated in the region:
  - $p_T(y) > 3$ GeV, $|\eta(y)| < 2.4$
  - $m_{yy} > 6$ GeV, $p_T(yy) < 2$ 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]

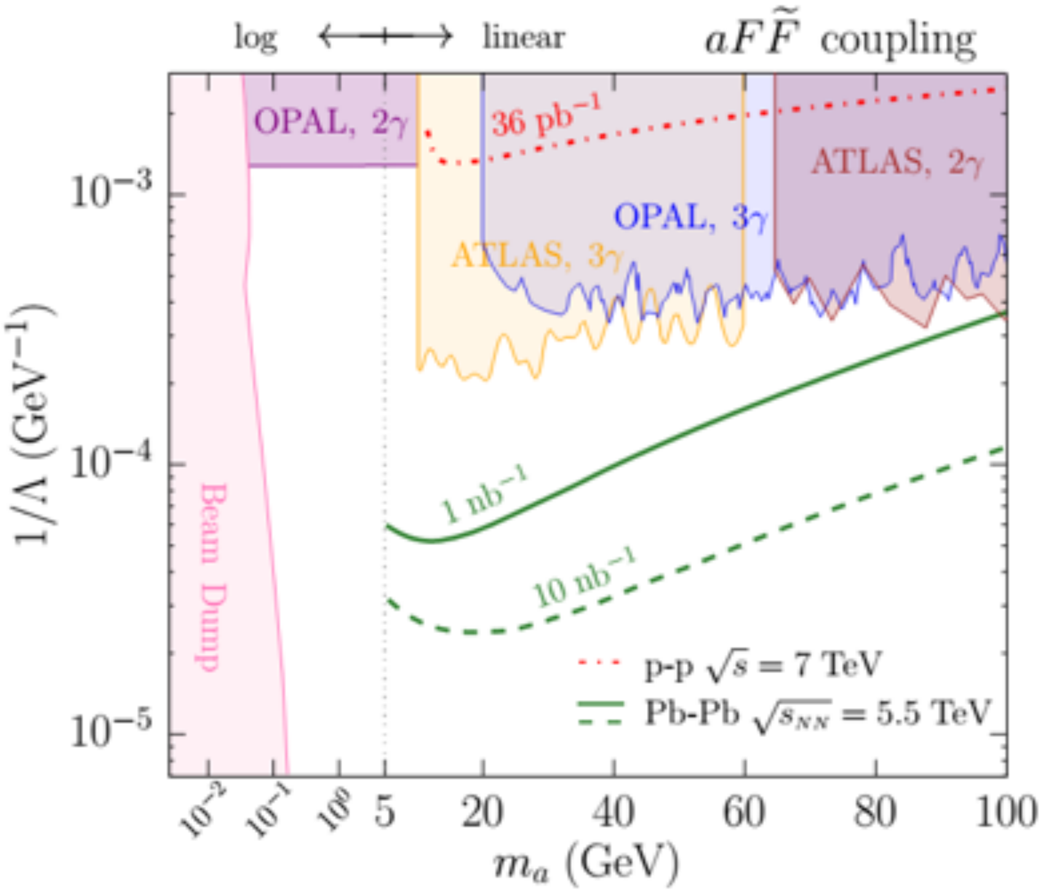




A look forward

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

[arXiv:1607.06083]



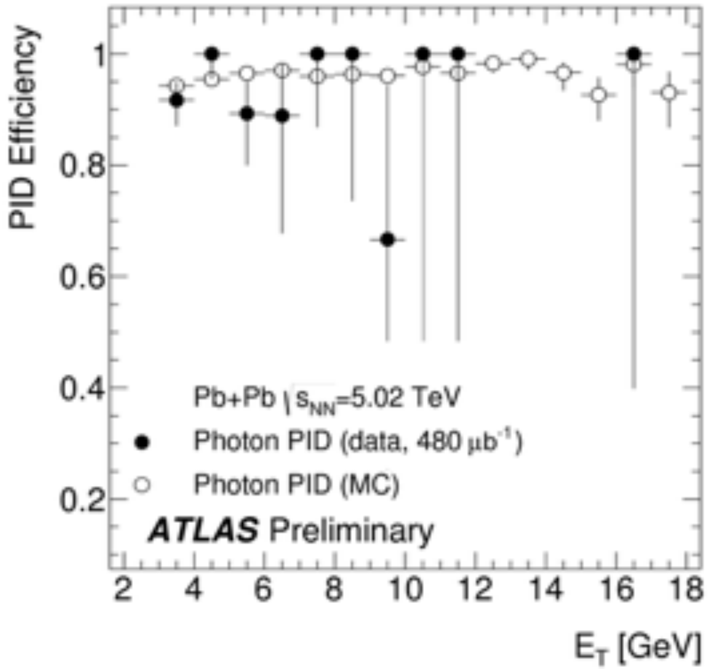
Summary

- 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)
- Measured fiducial cross section: **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

- $\gamma\gamma \rightarrow l^+l^- \gamma$ (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

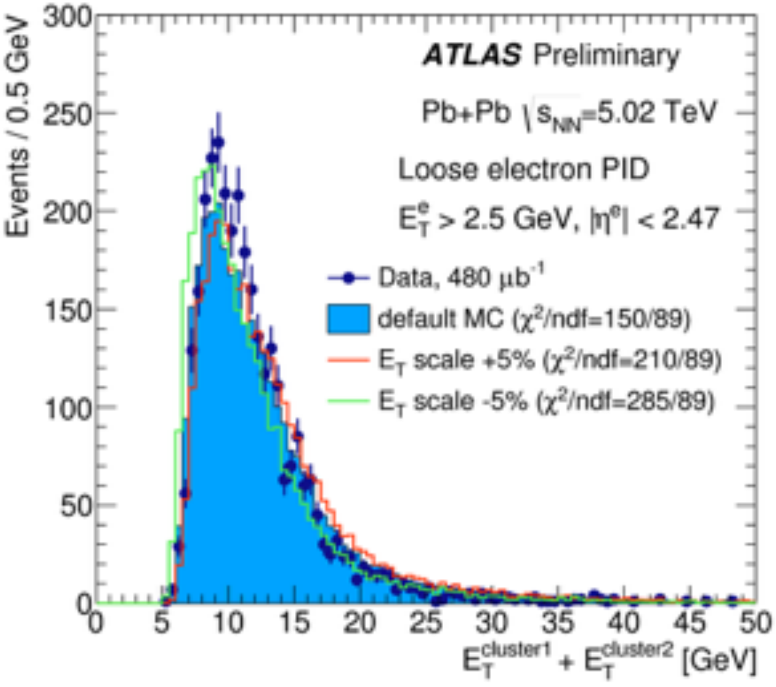


Photon performance cross-checks

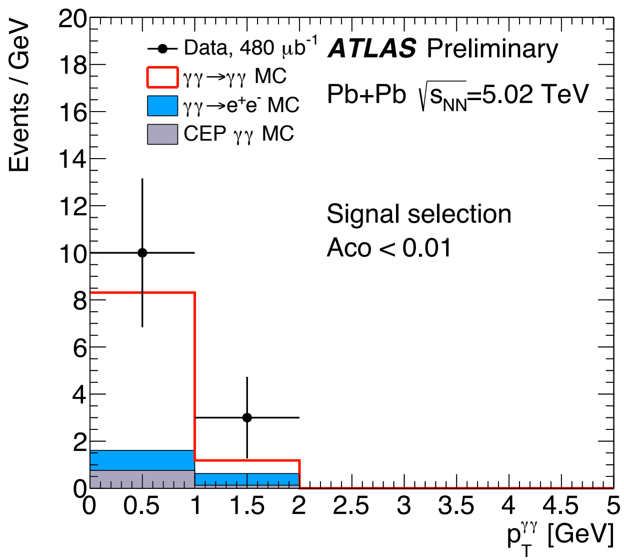
- Photon energy scale/resolution is cross-checked using **yy -> ee** event properties
- Idea: measure E_T(cl1) ± E_T(cl2) distributions in yy -> ee process

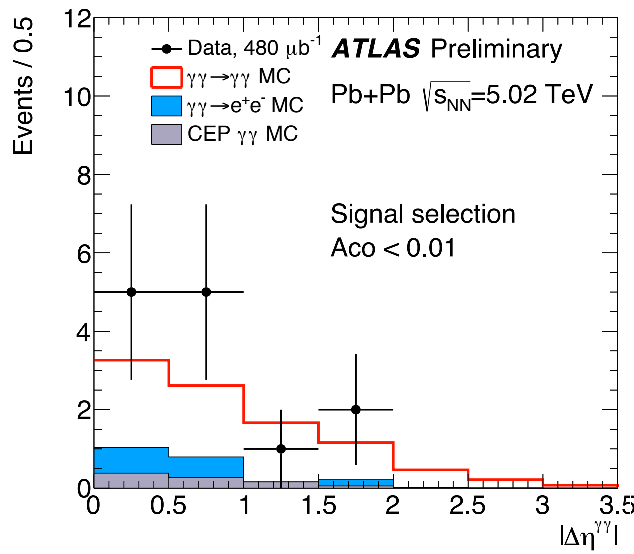
- Initial „theory" smearing very small ($\sigma_{pT(e1)\ -\ pT(e2)}$ below 0.03 GeV for E_T(cluster) > 3 GeV):
  - $\sigma_{Et(cluster)} \approx (\sigma_{Et(cluster1)\ -\ Et(cluster2)})/\text{sqrt}(2)$
  - $\sigma_{Et}/E_T \approx 8\%$ at low-E_T (< 10 GeV)
  - Data agrees with yy -> yy MC within 15%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

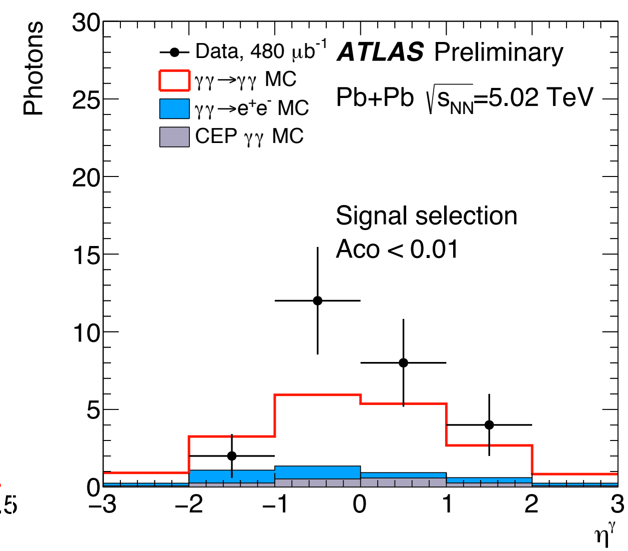
- E_T(cluster1) + E_T(cluster2) distributio sensitive to photon energy scale
  - Et scale is conservatively varied by ±5% in MC
  - Simple chi2 test can be used to check the data/MC improvement
  - Data nicely covered by ±5% bands in MC



yy -> yy control distributions







yy -> ee control distributions