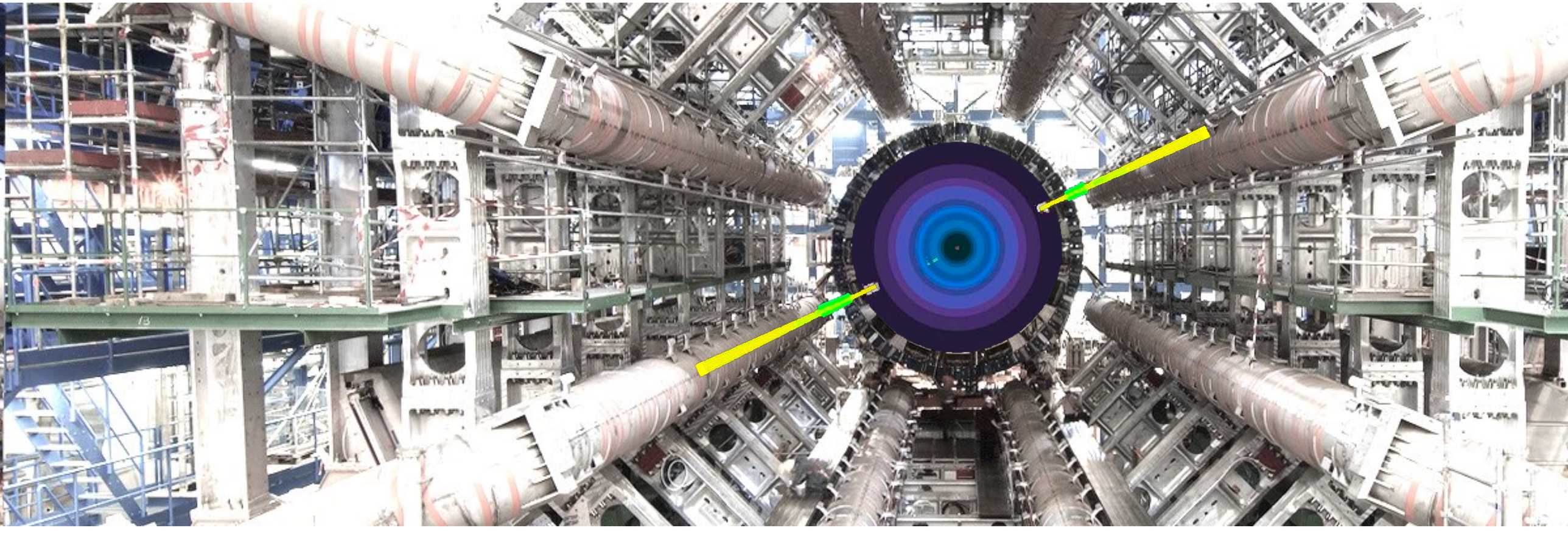


Observation of light-by-light scattering and measurements of photon-photon collisions at ATLAS

Iwona Grabowska-Bold (AGH UST, Kraków)
for the ATLAS Collaboration

Photon2019, INFN Frascati, June 3-7th

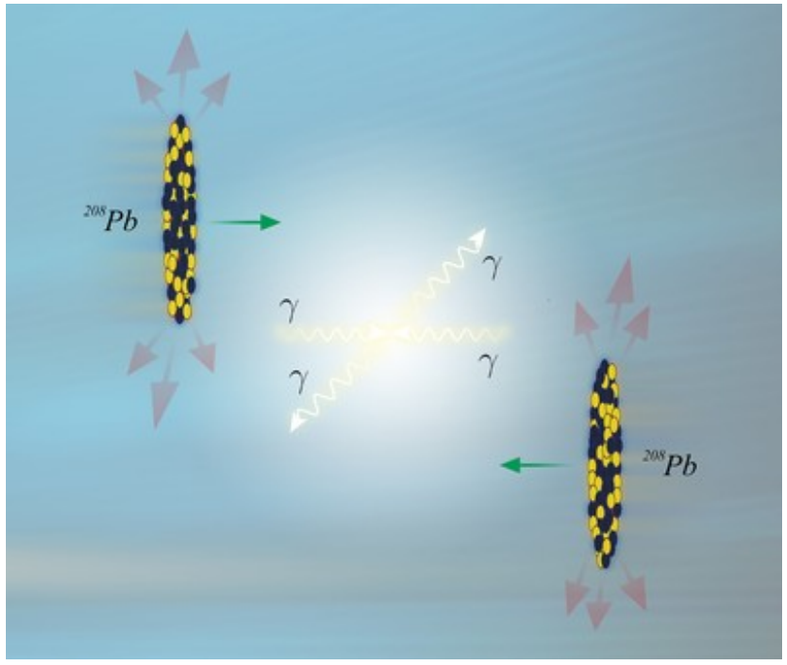
INTRODUCTION

- **Proton** or **lead-ion beams** at the LHC can act as a source of photons

- This talk focuses on $\gamma\gamma$ interactions
  - Precise test of **Quantum Electrodynamics** (QED)
    - $\gamma\gamma \to l^+l^-$ acts as a standard candle thanks to its sizeable cross section
  - Large int luminosity opens a window for **rare processes** (W^+W^-, Higgs, light-by-light)
    - Accessible in colliders for the first time
  - Also a tool to study **new physics**
    - Anomalous gauge couplings, new particles, axion searches, etc

- The following results are discussed from **ATLAS**:
  - Exclusive production of **di-muon pairs** in **pp collisions** **NEW**
    - PLB 777 (2018) 303
  - Exclusive production of **W^+W^- pairs** and search for exclusive **Higgs boson** in **pp collisions**
    - PRD 94 (2016) 3, 032011
  - Observation of **light-by-light scattering** in **Pb+Pb collisions** **NEW**
    - arXiv:1904.03536 submitted for PRL

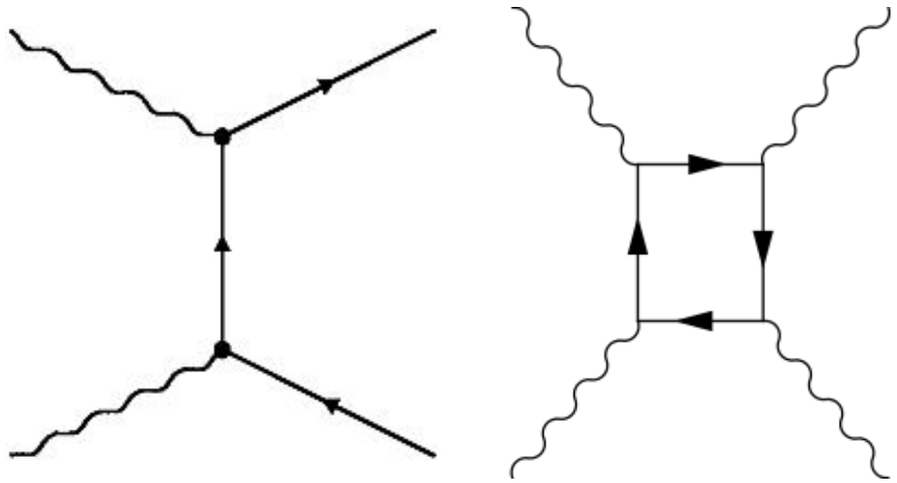
PHOTON–PHOTON PHYSICS AT COLLIDERS



- Basis for photon-photon physics by Fermi (1925), Weizsacker (1934) and Williams (1934)
- Formulation of **Equivalent Photon Approximation** (**EPA**)
  - EM fields associated with beams of charged particles can be treated as a beam of quasi-real photons with small virtualities
- Cross sections for processes **AA(γγ) → AA(X)**, where A stands for proton or lead beam, are calculated using:
  - Number of equivalent photons by integration of relevant **EM form factors**

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

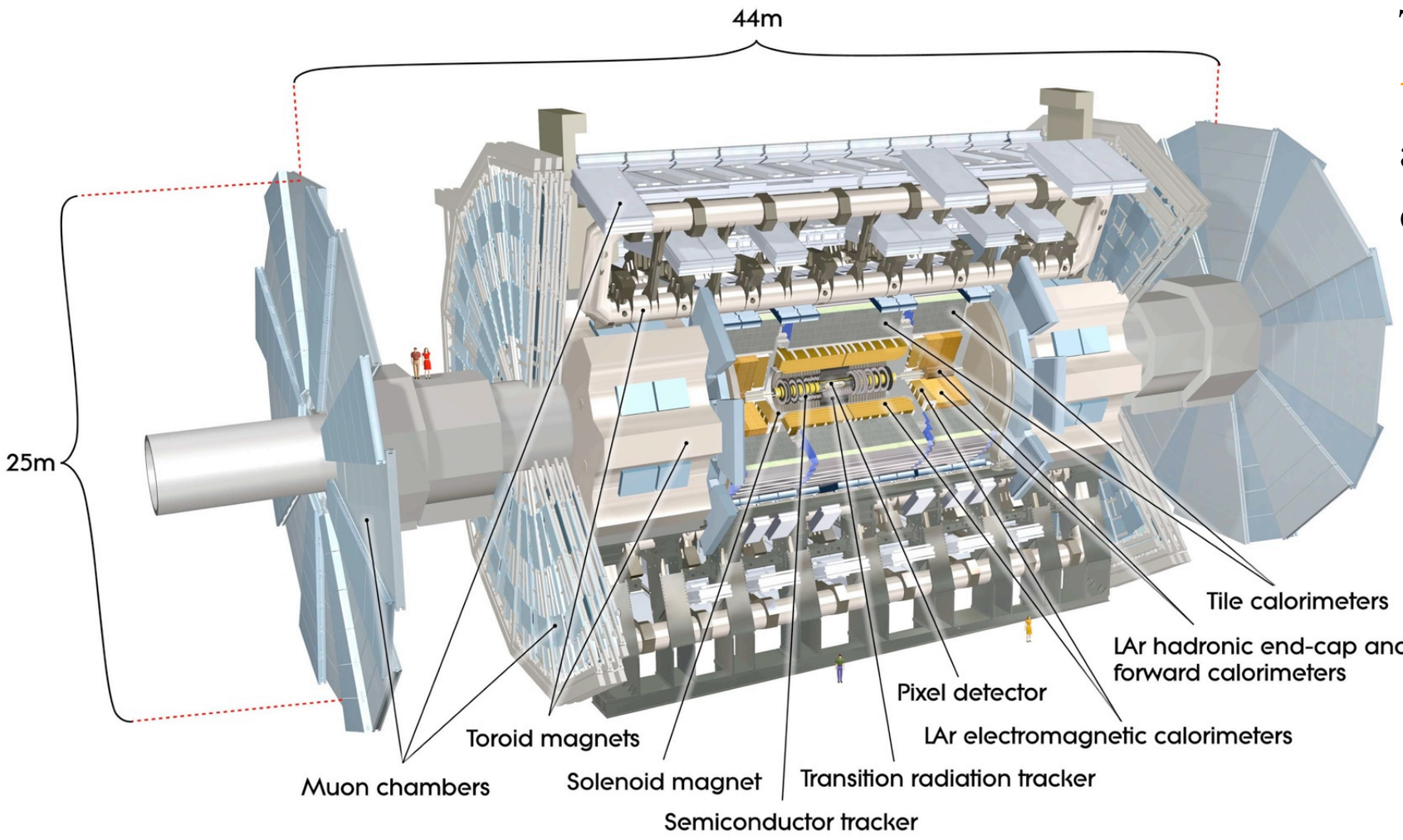
$$Q^2 < 1/R^2 \qquad \omega_{\max} \approx \gamma/R$$



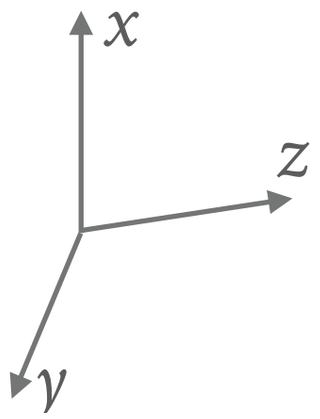
  - **Elementary cross section** of γγ → X in QED

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

ATLAS DETECTOR



Three main components: inner tracker, electromagnetic (EM) and hadronic (HAD) calorimeters, and muon system

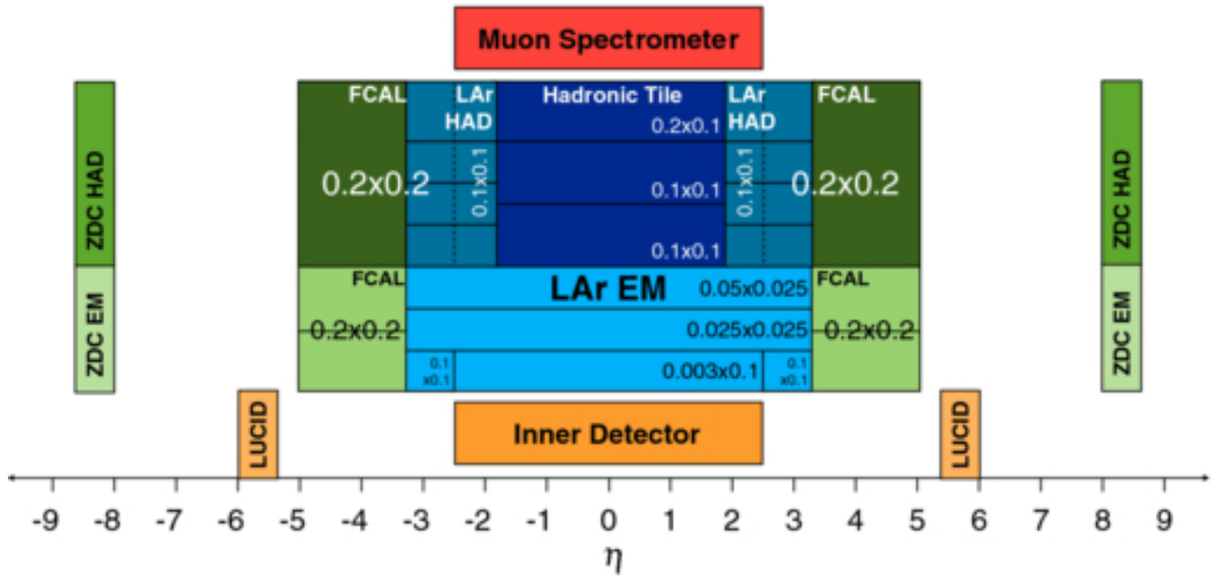


ϕ - full azimuthal acceptance

η - broad pseudorapidity coverage

p_T - transverse momentum for charged particles above **100 (400) MeV** in Pb+Pb (pp), and photons above **2.5 GeV**

Outgoing protons/ions are not tagged: prospects for proton-tagging in **M.Trzebinski**'s talk, **Wed 14:45**

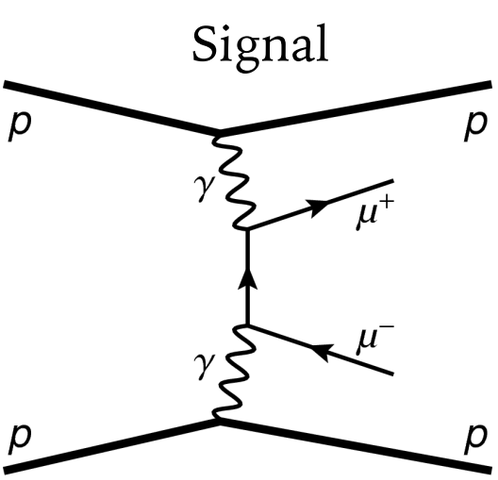


EXCLUSIVE DIMUON PRODUCTION

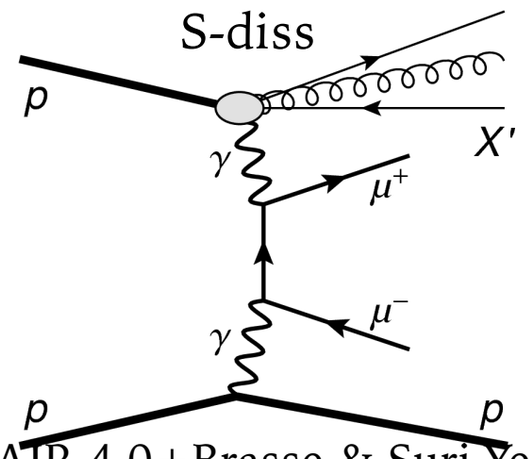
- Production of $\gamma\gamma \to \mu^+\mu^-$ in pp collisions at **13 TeV** with **3.2 fb^{-1}** [PLB 777 (2018) 303]
  - Kinematic requirements: $12 < m_{\mu^+\mu^-} < 70$ GeV $\quad |\eta^{\mu}| < 2.4$

$$p_{\mathrm{T}}^{\mu} > 6 \text{ GeV} \quad \text{for} \quad 12 < m_{\mu^+\mu^-} < 30 \text{ GeV}$$
$$p_{\mathrm{T}}^{\mu} > 10 \text{ GeV} \quad \text{for} \quad m_{\mu^+\mu^-} > 30 \text{ GeV}$$

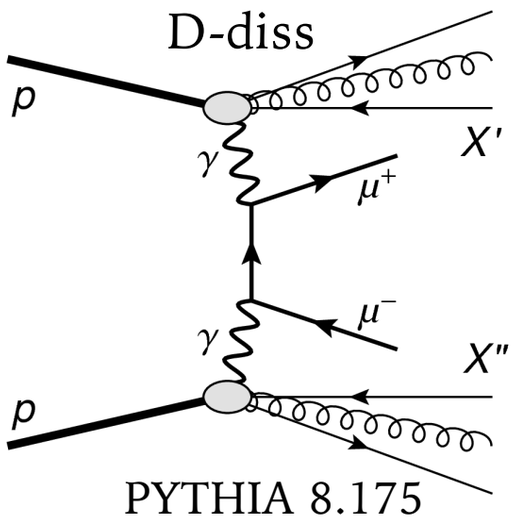
- Analysis methodology largely based on the earlier ATLAS publication for $\gamma\gamma \to l^+l^-$ at 7 TeV with $l^{\pm}=e^{\pm},\mu^{\pm}$ [PLB 749 (2015) 242-261]
- Main challenges: larger pileup, background evaluation, topological triggers



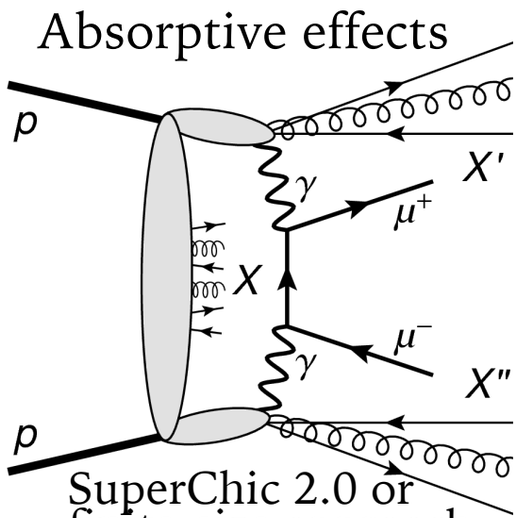
HERWIG 7.0



LPAIR 4.0+Brasse & Suri-Yennie structure function for proton diss

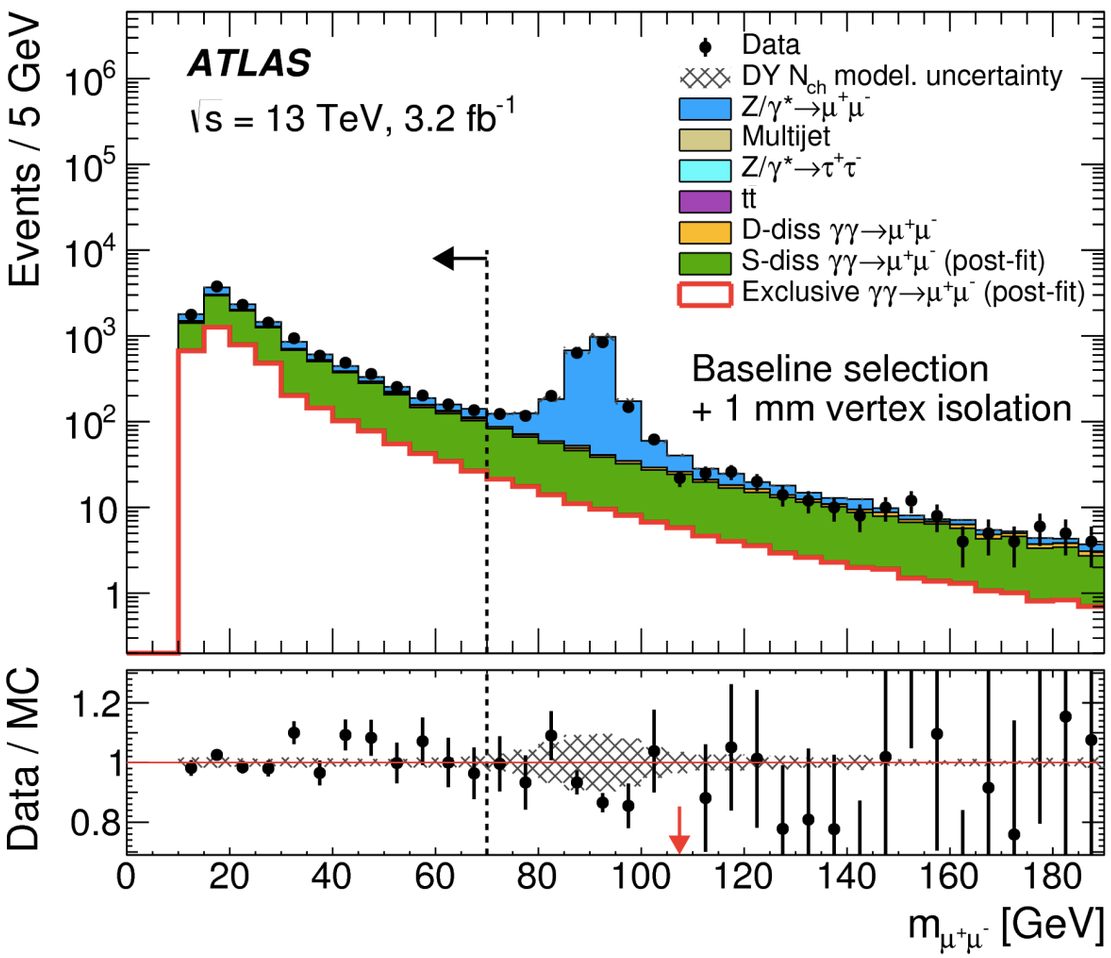


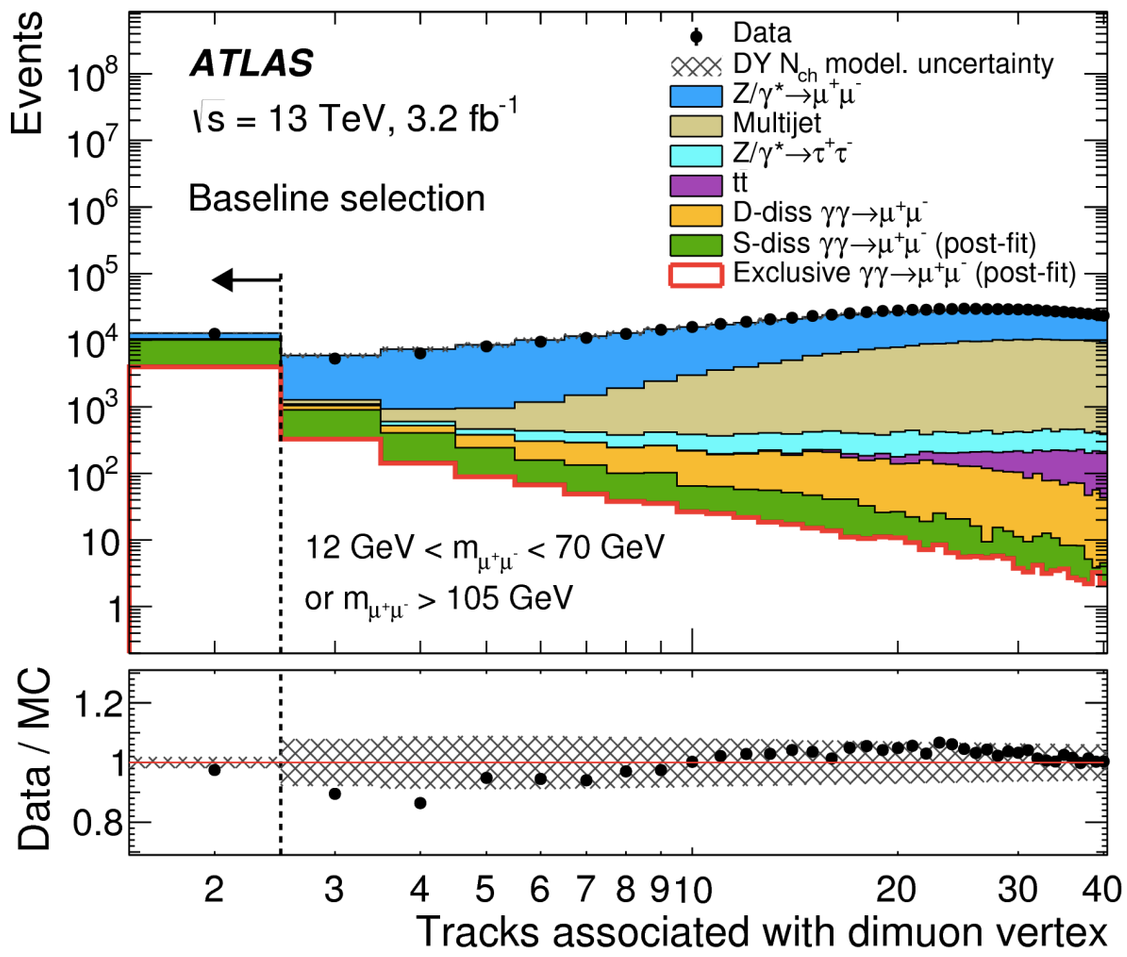
PYTHIA 8.175



SuperChic 2.0 or finite-size approach

DIMUON PRODUCTION: CONTROL PLOTS



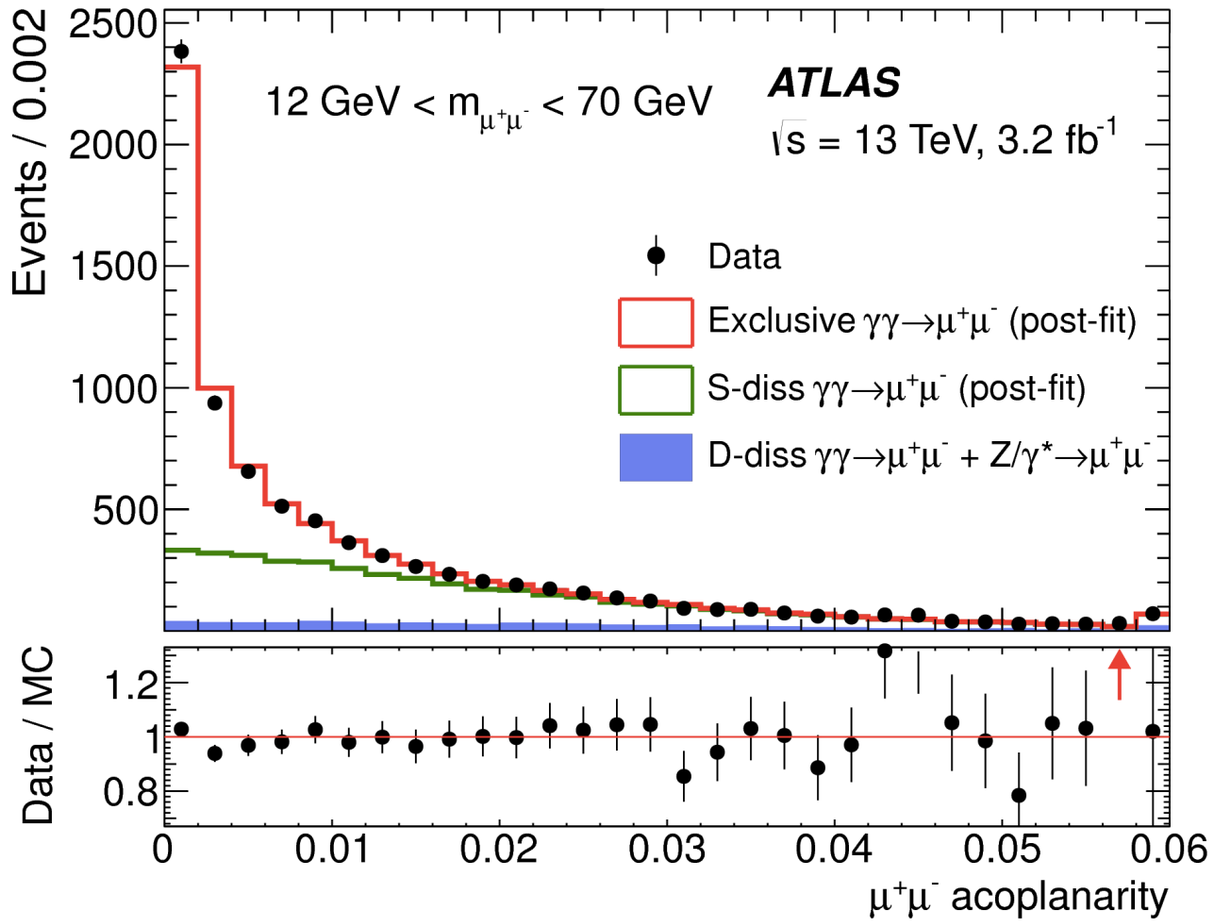


- Three requirements imposed to suppress backgrounds
  - **Invariant mass**: $12 < m_{\mu+\mu-} < 70$ GeV suppresses Drell-Yan
  - **Exclusivity selection**: events with **only two tracks** at the dimuon vertex
    - Veto additional tracks with $p_T > 400$ MeV in $|\eta| < 2.5$
  - **Transverse momentum**: $p_T^{\mu^+\mu^-} < 1.5$ GeV suppresses S-diss
- Remaining backgrounds: S-diss, Z/γ*→μμ, D-diss

DIMUON PRODUCTION: CROSS SECTION

- 7 952 events pass all selection requirements
  - Background (~50%) evaluated from a fit in the acoplanarity distribution

$$\text{Acoplanarity} = 1 - \frac{|\Delta\phi_{\mu^+\mu^-}|}{\pi}$$



- Measured fiducial cross section:

$$\sigma^{\text{fid}}_{\gamma\gamma\to\mu^+\mu^-} = 3.12 \pm 0.07\ (\text{stat.}) \pm 0.14\ (\text{syst.})\ \text{pb}$$

- Compared to theory predictions:

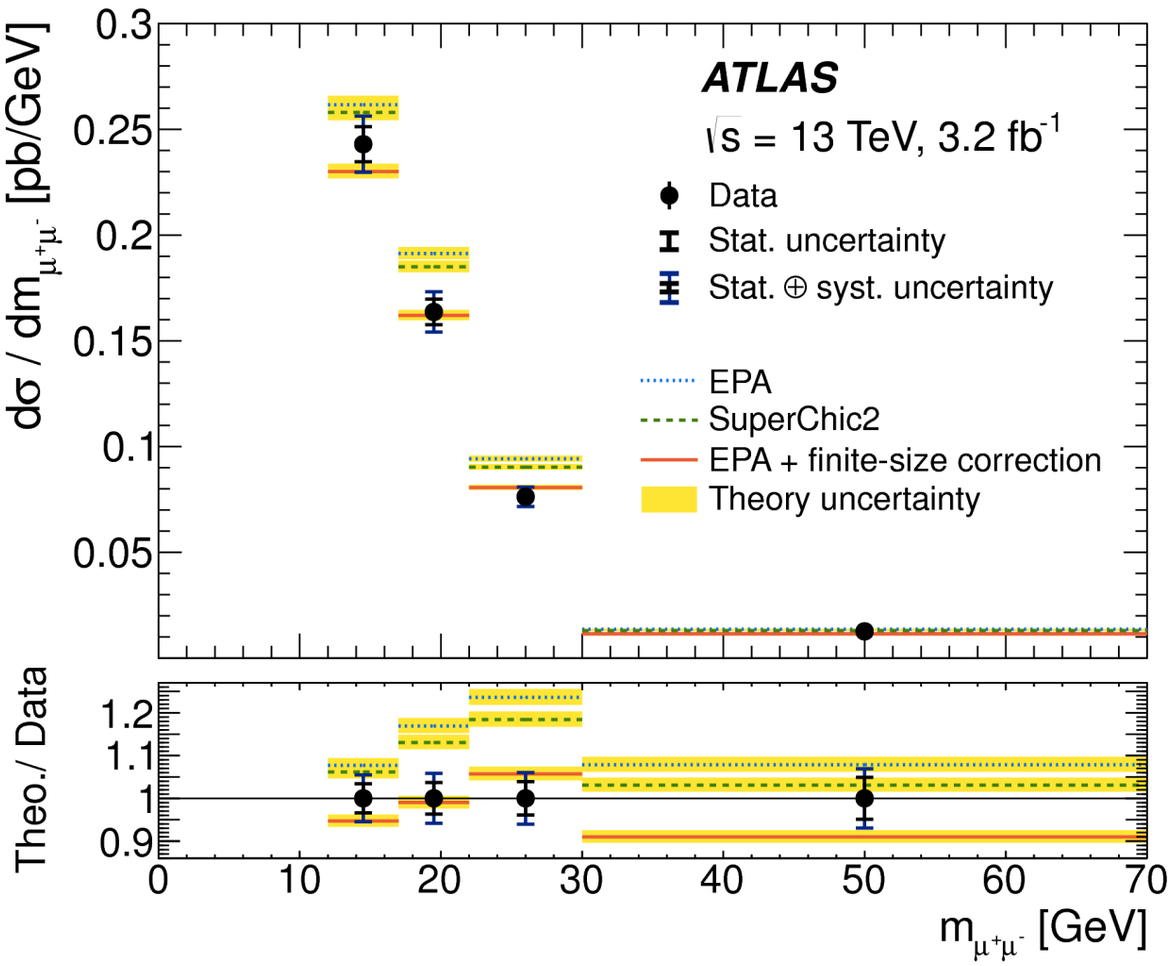
$$\sigma^{\text{EPA}}_{\gamma\gamma\to\mu^+\mu^-} = 3.56 \pm 0.05\ \text{pb}$$

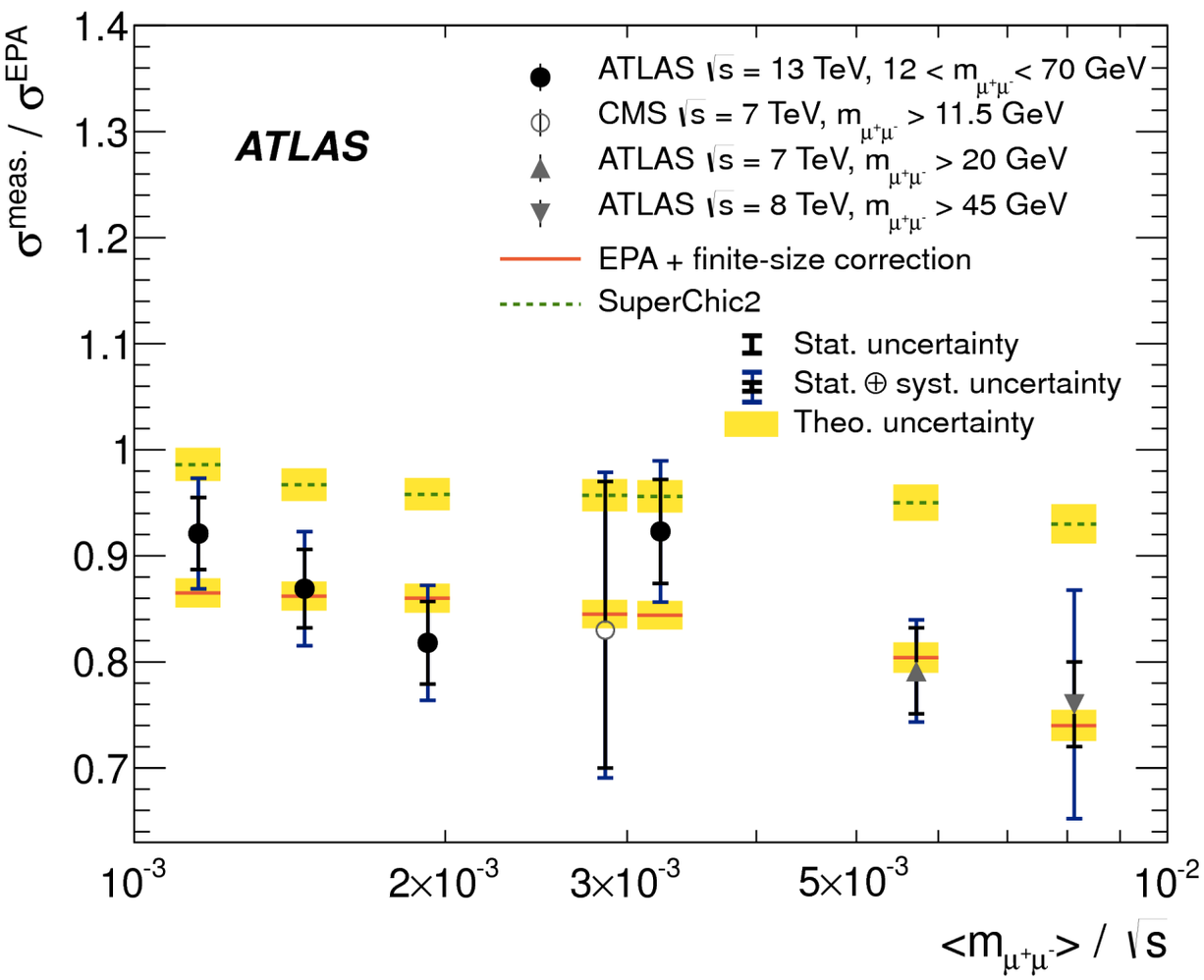
$$\sigma^{\text{EPA,FSC}}_{\gamma\gamma\to\mu^+\mu^-} = 3.06 \pm 0.05\ \text{pb}$$

$$\sigma^{\text{SuperChic2}}_{\gamma\gamma\to\mu^+\mu^-} = 3.45 \pm 0.05\ \text{pb}$$

- **Best agreement** with calculations including **absorptive effects**
- Total systematic uncertainty dominated by **shape modelling** (3.3%) in data, and knowledge of **proton form factor** (1.5%) in predictions

DIMUON PRODUCTION: DIFFERENTIAL CROSS SECTION



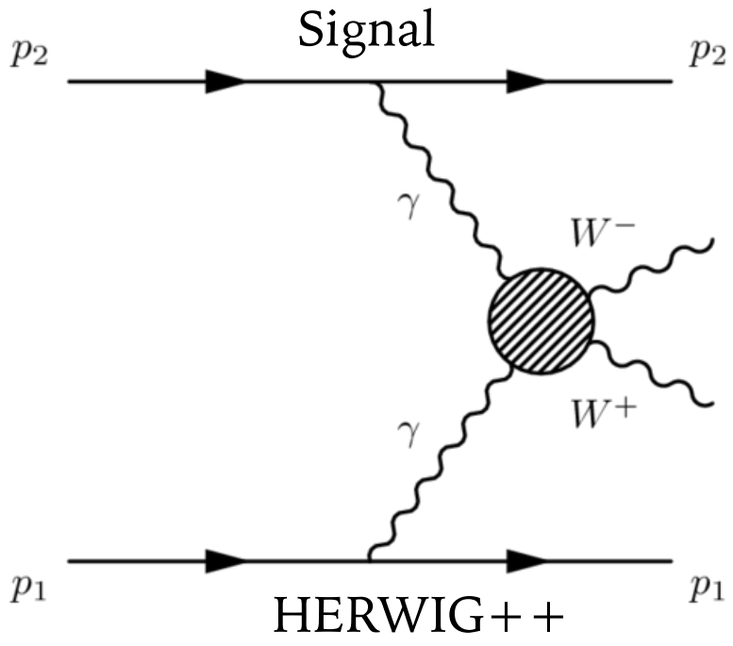


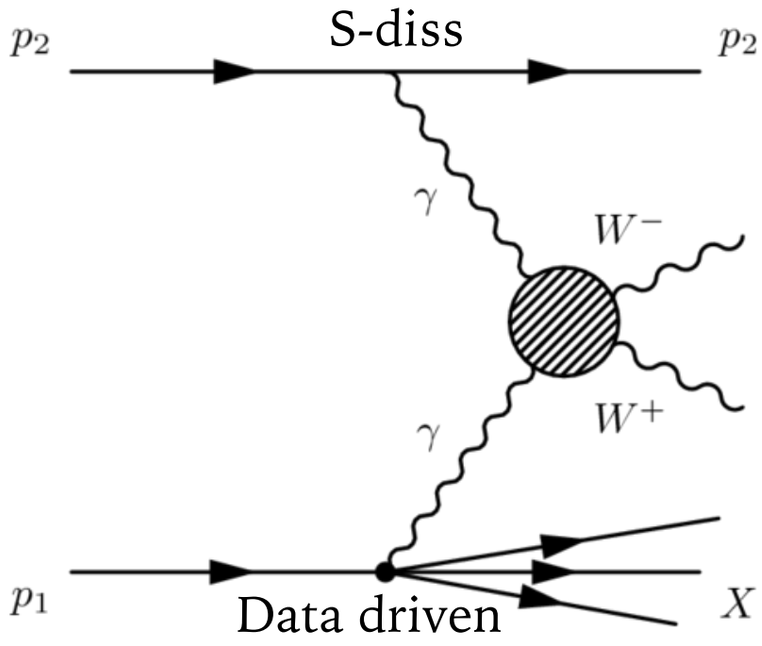
- Differential cross section extracted in four $m_{\mu+\mu-}$ bins
- **Predictions with absorptive effects** are in better agreement with the data
- Departure of $\sigma^{meas}/\sigma^{EPA}$ from unity indicates that the size of the **absorptive corrections** tends to **increase with the scale**

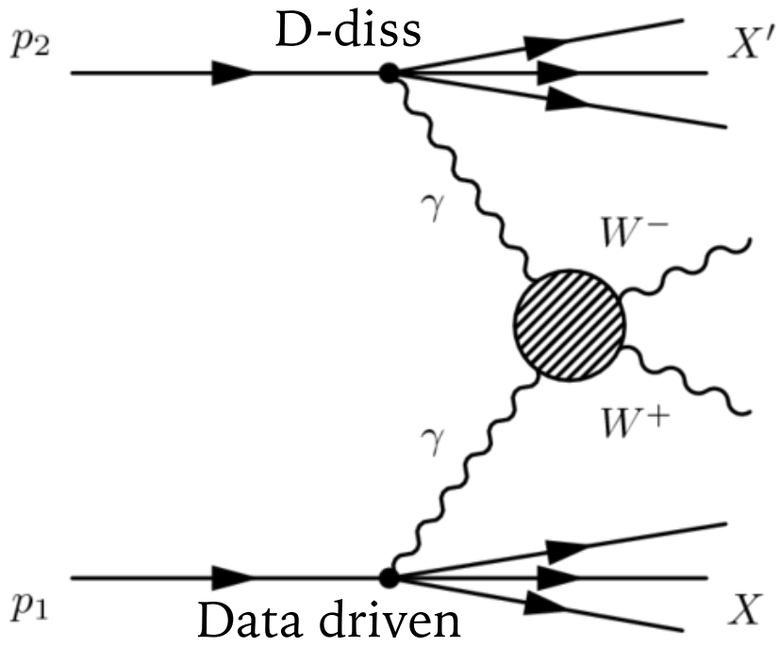
EXCLUSIVE W+W- PRODUCTION

- Measurement of $\gamma\gamma \rightarrow W^+W^-$ production using $e^{\pm}\mu^{\pm}$ decays [PRD 94 (2016) 3, 032011]
  - pp collisions at 8 TeV with 20.2 fb^{-1} of data from 2012
  - Kinematic requirements: $p_{\mathrm{T}}^{\ell 1} > 25$ GeV $\quad p_{\mathrm{T}}^{\ell 2} > 20$ GeV

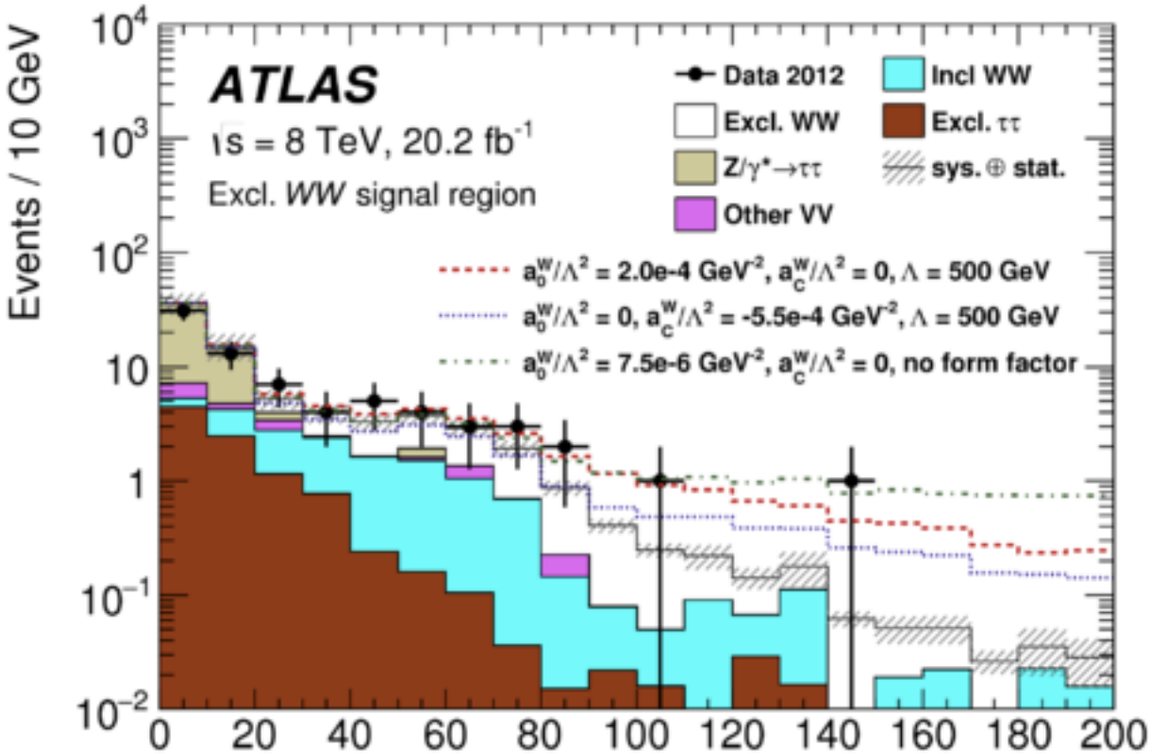
    $m_{e\mu} > 20$ GeV $\qquad p_{\mathrm{T}}^{e\mu} > 30$ GeV
  - Process sensitive to **anomalous quartic gauge couplings** (**aQGC**)
  - Also search for **exclusive Higgs production** in W^+W^- decay mode, then $e^{\pm}\mu^{\pm}$ (not discussed)
    - Six event candidates observed in the data, 3.0±0.8 events from bkg expected
    - **Upper limit** at 95% CL on the total cross section set up to **1.2 pb**
- Main challenges: pileup and exclusivity selection, inclusive W^+W^- background evaluation

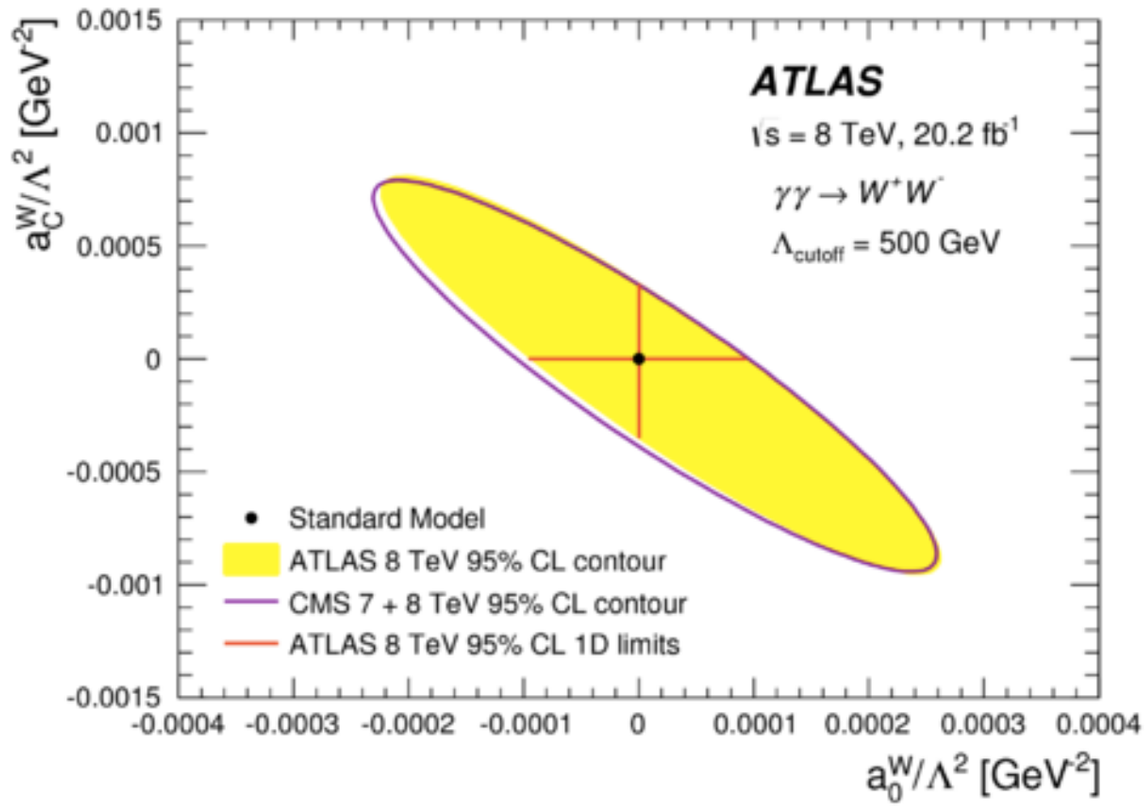






EXCLUSIVE W+W−: CROSS SECTIONS AND AQGC





- Measured cross section:

$$\sigma^{\text{meas}}_{\gamma\gamma\to W^+W^-\to e^\pm\mu^\pm X} = 6.9 \pm 2.2\ (\text{stat}) \pm 1.4\ (\text{syst})\ \text{fb}$$

  - Systematics dominated by bkg determination (18%) and exclusivity selection (10%)

- Predicted cross section:

$$\sigma^{\text{HERWIG++}}_{\gamma\gamma\to W^+W^-\to e^\pm\mu^\pm X} = 4.4 \pm 0.3\ \text{fb}$$

  - **In good agreement** with the data

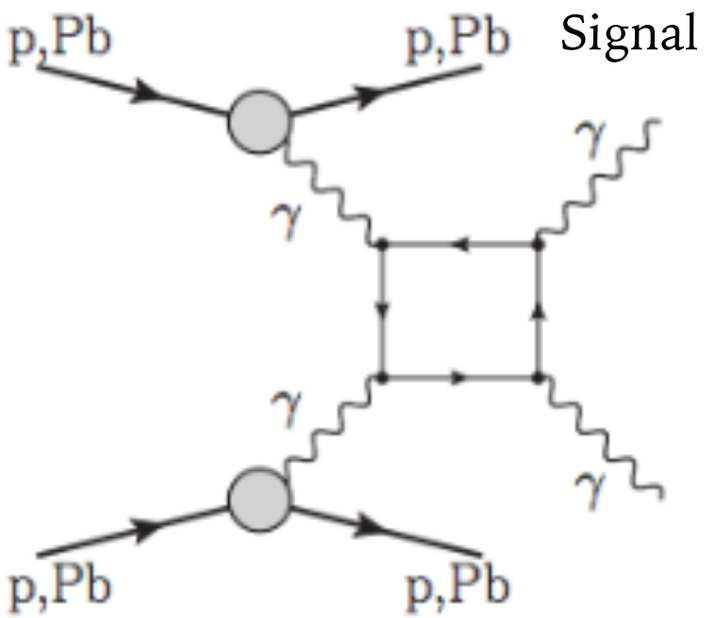
- **Signal significance** amounts to **3σ**

- aQGC limits extracted for $p_T^{e\mu} > 120$ GeV where backgrounds are suppressed
- One event candidate used in a likelihood test to establish limits
- **Limits are compatible** with the **CMS combined 7 TeV and 8 TeV results**

LIGHT-BY-LIGHT SCATTERING

- LbyL scattering measured in **2018 Pb+Pb** data with 1.7 nb^{-1} [arXiv: 1904.03536]
  - **Fundamental QED** process with a **tiny cross section**
    - Prior to LHC, tested indirectly in measurements of the anomalous magnetic moment of the electron and muon
  - Proposed as a neat channel to study
    - Anomalous gauge couplings
    - Possible contributions from new particles beyond SM
  - Analysis methodology based on the ATLAS evidence paper based on **2015 Pb+Pb** data with 0.49 nb^{-1} [Nat. Phys. 13 (2017) 852–858]

- Several improvements introduced:
  - Factor of **3.6 more statistics**
  - **Better trigger efficiency**
  - **Improved photon reconstruction** efficiency at low E_T
  - And **better photon identification** leading to larger background rejection
  - New developments in **generators** (**SuperChic3.0**)

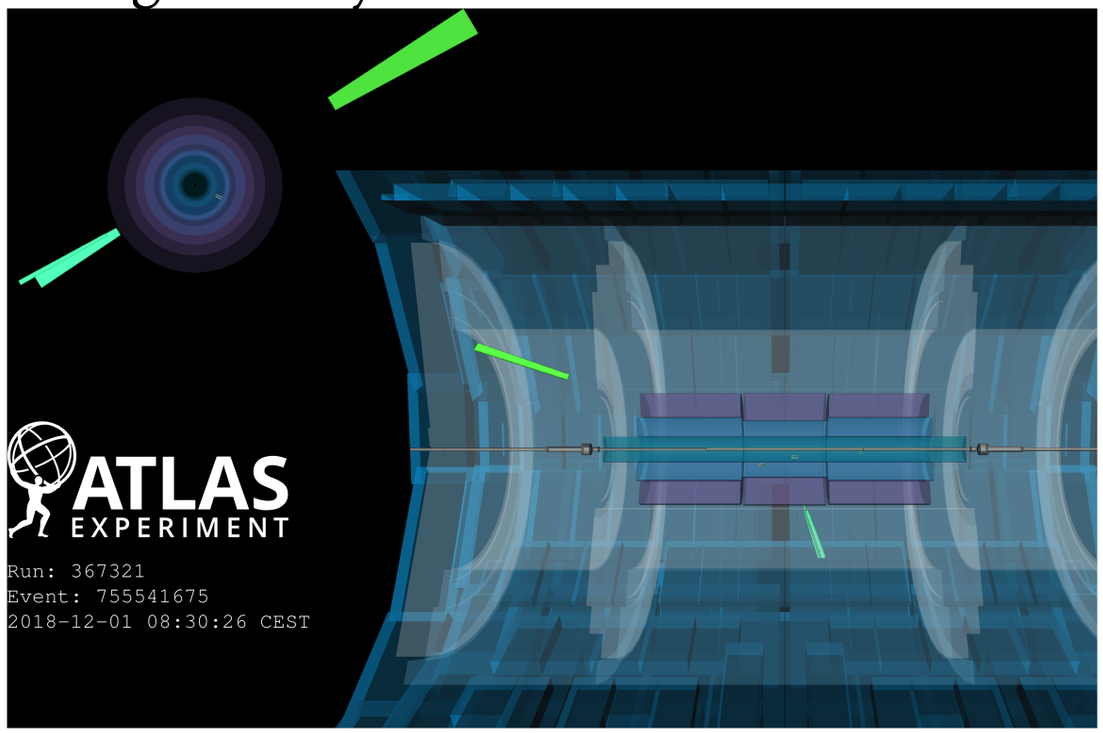


Signal

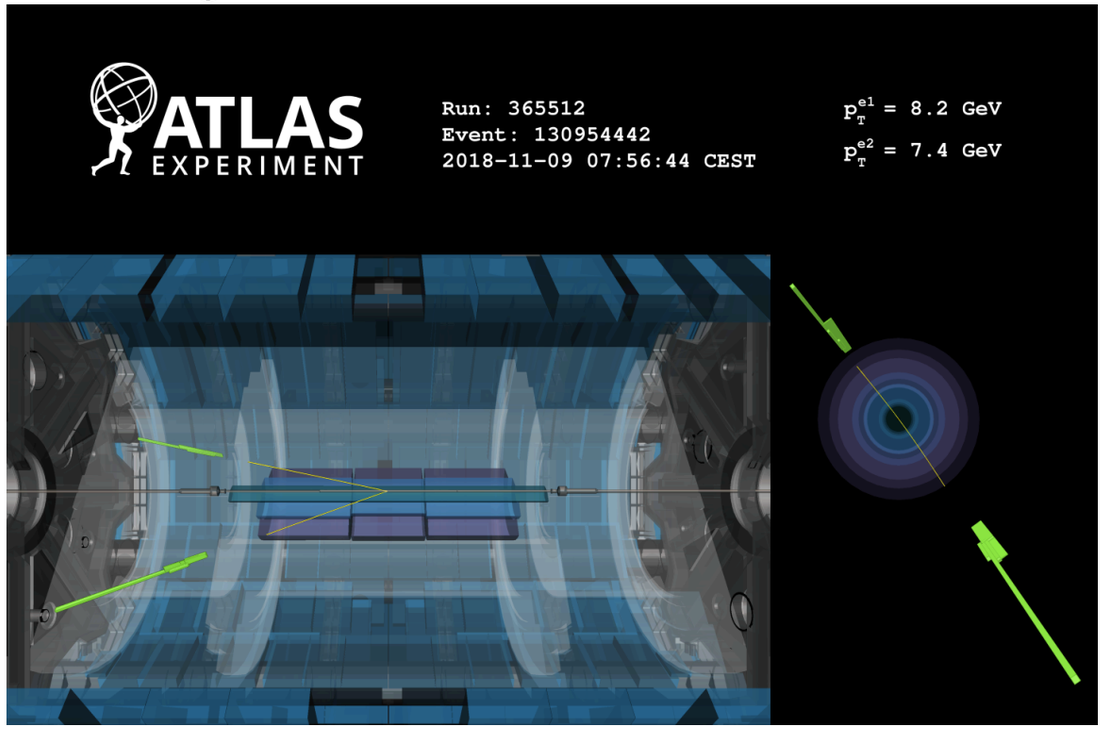
LBYL: ANALYSIS SELECTION

- Good-quality data in the detector
- Trigger
- Exactly two photons with $\mathbf{E_T > 3\ GeV}$ and $\mathbf{|\eta| < 2.37}$, excluding the crack region $1.37 < |\eta| < 1.52$
- Invariant diphoton mass $\mathbf{M_{inv} > 6\ GeV}$
- **Veto extra activity** in the ID in $|\eta| < 2.5$
  - No tracks with $p_T > 100$ MeV
  - No pixel tracks with $p_T > 50$ MeV and $|\Delta\eta(\gamma,\text{track})| < 0.5$
- **Back-to-back topology**
  - $p_T^{\gamma\gamma} < 1$ GeV
  - Acoplanarity $\text{Aco} = 1 - \frac{|\Delta\phi_{\gamma\gamma}|}{\pi} < 0.01$

Signal: LbyL event candidate



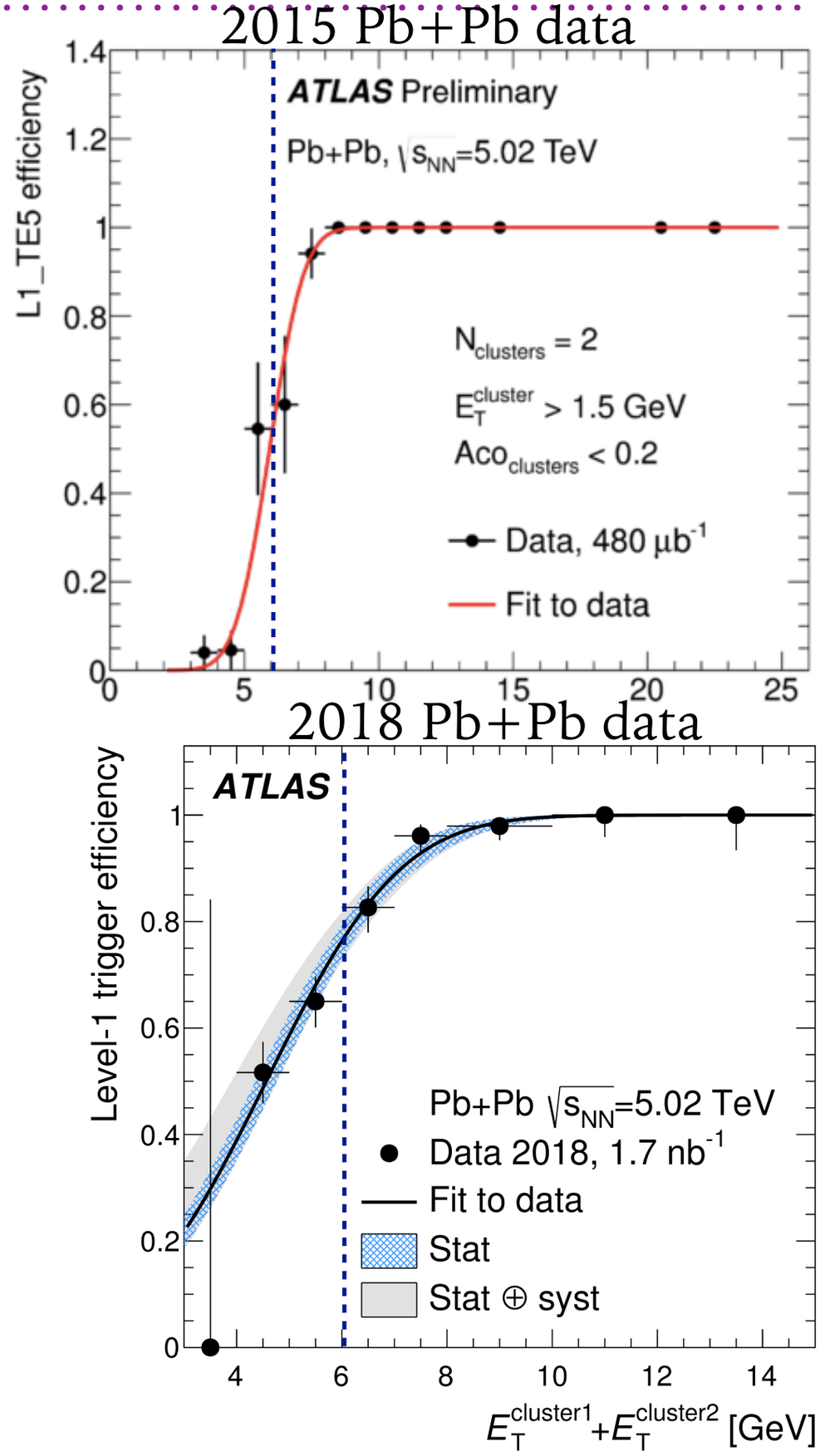
Background: e^+e^- event candidate



LBYL: TRIGGER PERFORMANCE

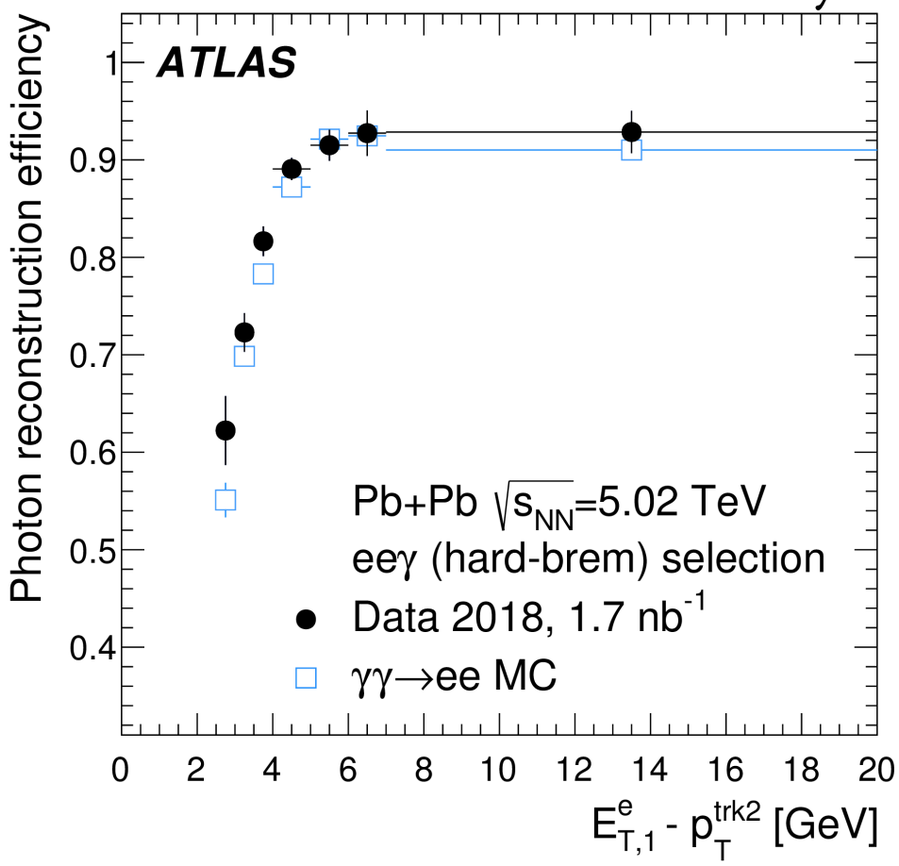
- Trigger strategy in 2018 Pb+Pb run
  - At Level-1: lower **total E_T** threshold of **4 GeV** in coincidence with **1 GeV EM** threshold
  - At HLT: at most 15 Pixel hits, a **new veto requirement** (use FCal instead of MBTS)

- Trigger efficiency studied using $\gamma\gamma \to e^+e^-$ process in data
  - At Level-1: **great improvement of trigger efficiency** at low photon E_T comparing to 2015
  - **Potential** to go **lower in photon E_T > 2.5 GeV** exists
  - At HLT: efficiency is above 99%

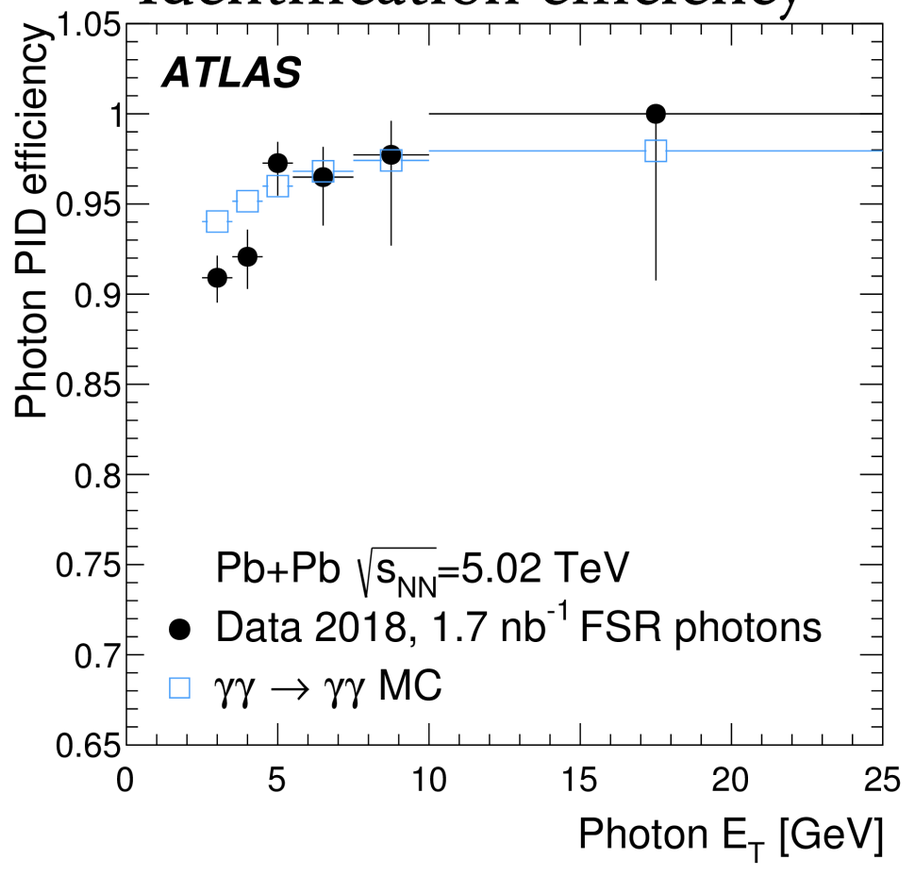


LBYL: LOW-ET PHOTON PERFORMANCE

Reconstruction efficiency

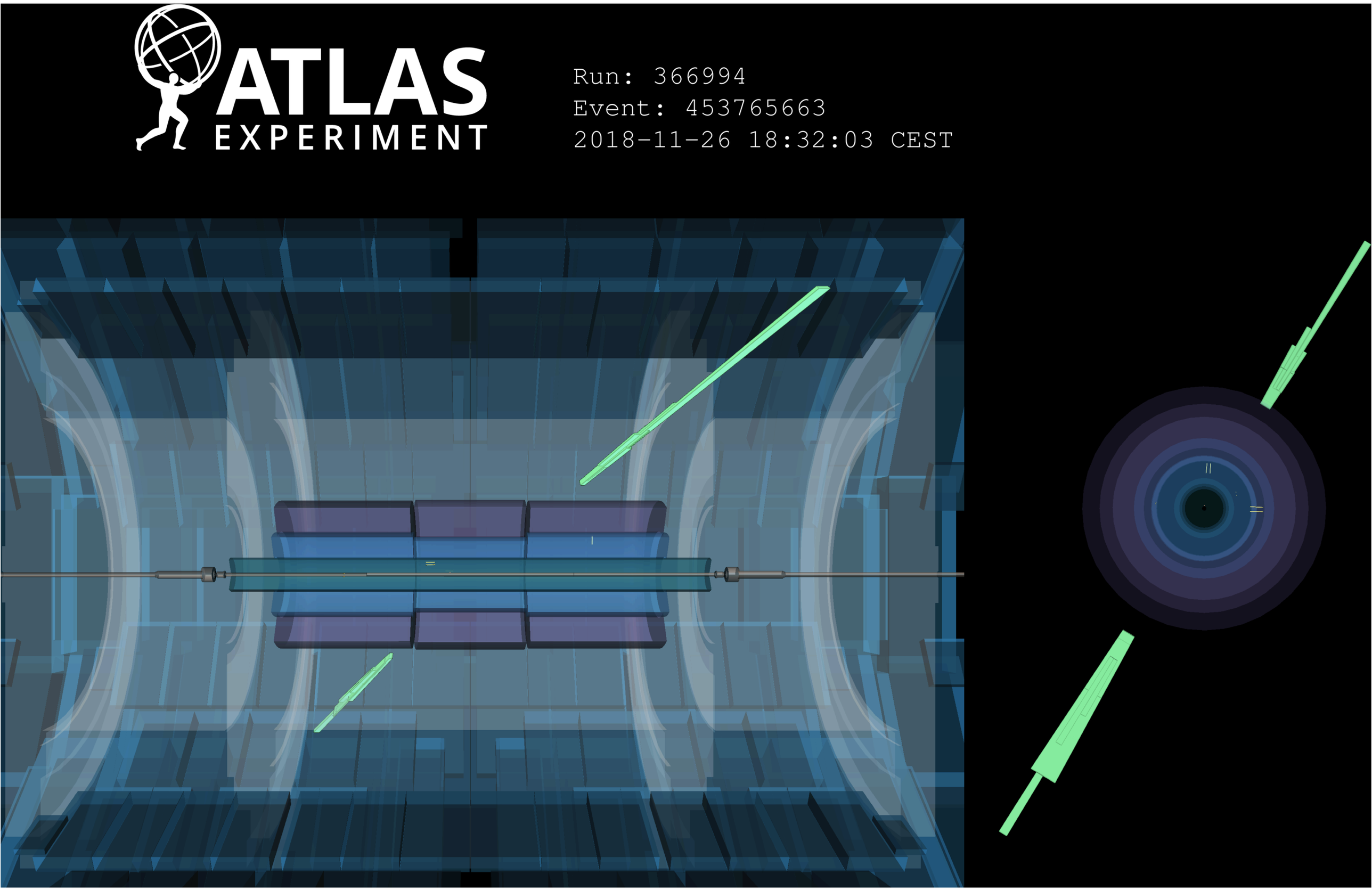


Identification efficiency

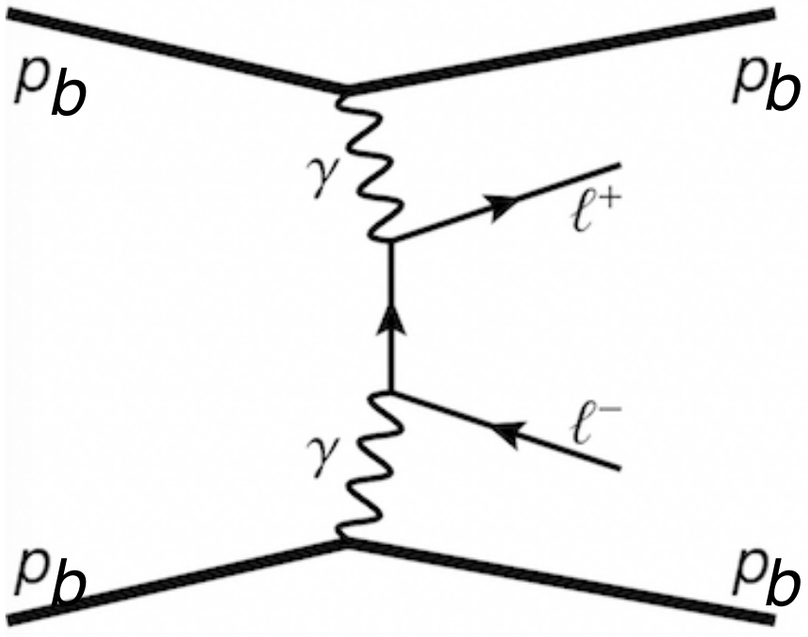


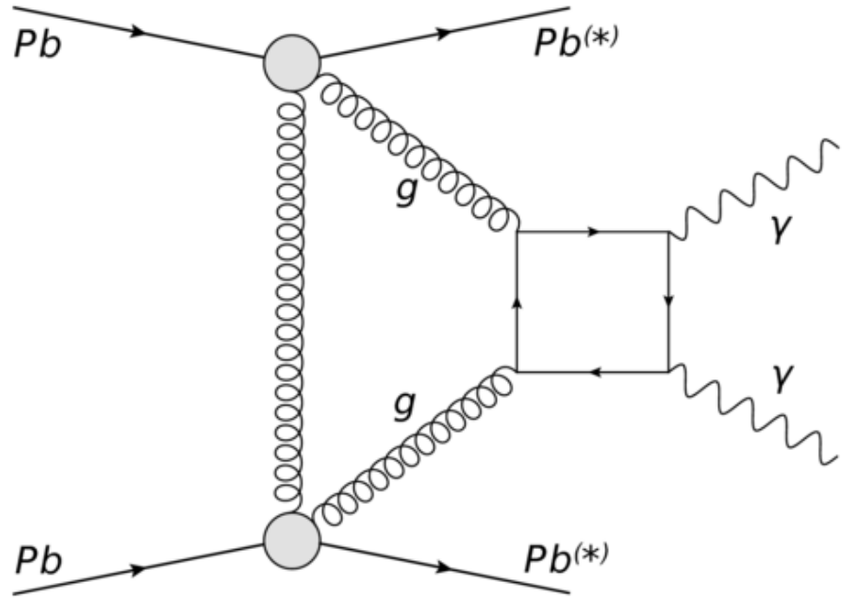
- **Significant improvement** in reconstruction efficiency for photons in $2.5<E_T<4$ GeV
  - Use hard bremsstrahlung photons to extract efficiency in data and MC simulation
  - Efficiency is **60%** for $\mathbf{E_T=2.5}$ **GeV**
- **Identification efficiency optimised** for low-E_T photons
  - Efficiency **exceeds 90%**
- Good modelling in MC simulation
  - Differences between data and MC simulation included in dedicated corrections

LBYL: EVENT CANDIDATE



LBYL: BACKGROUND PROCESSES

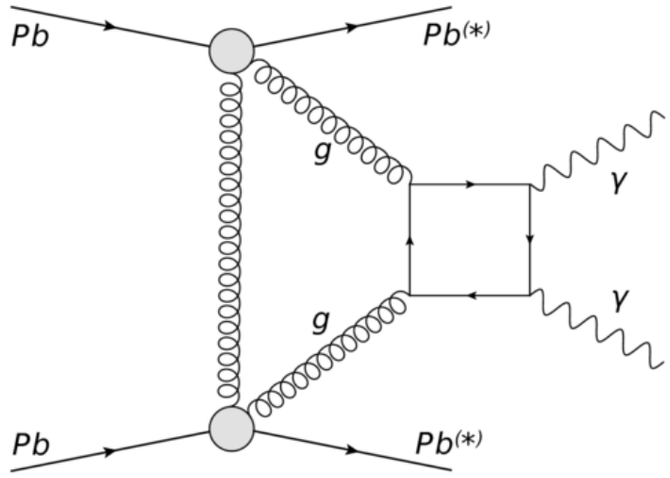


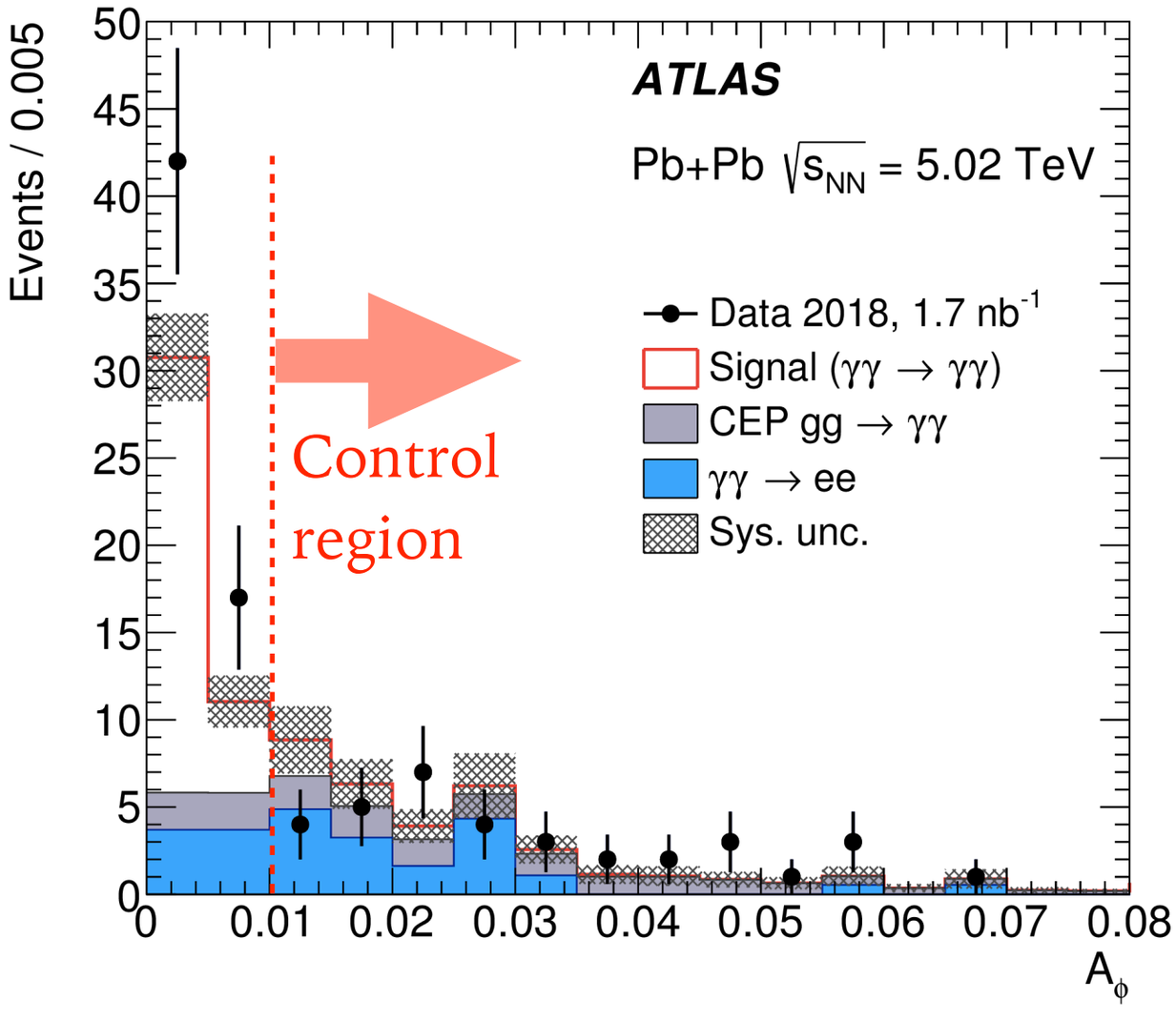


- Several background sources considered:
  - Exclusive production of electron pairs: **γγ → e^+e^-**
    - Very high cross section α^2_{em} times higher comparing to LbyL
    - Suppressed with track and pixel-track vetos
    - Remaining contribution evaluated using a data-driven method
  - Central Exclusive Production of the diphoton system: **gg → γγ**
    - Identical signature to LbyL photons
  - Also other rare processes e.g. γγ → qq–bar, $\pi^0\pi^0$, $\pi^+\pi^-$,γγ → e^+e^-γγ, etc, and found to be **negligible**

LBYL: CEP BACKGROUND

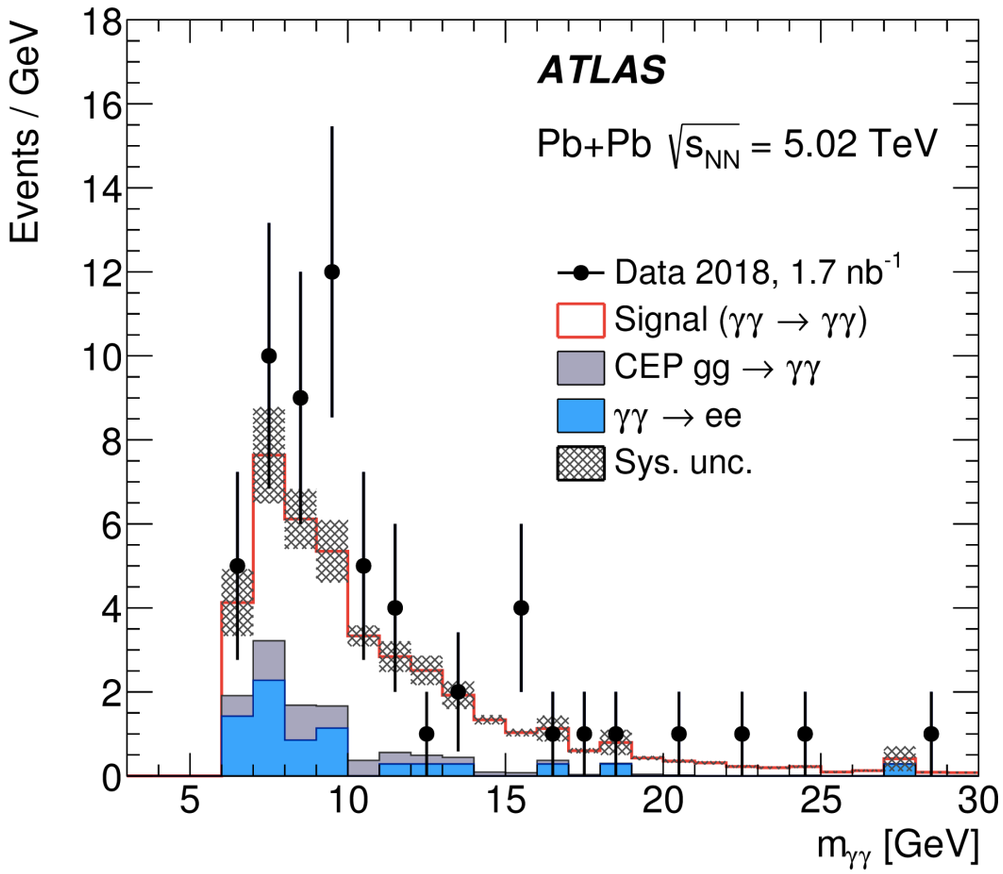
- Coloured initial state: larger **initial transverse momentum** and **broader shape of Aco** distribution
- Evaluated from a **control region** in data (Aco>0.01)
  - Shape taken from **SuperChic3.0** MC simulation
  - Normalised to data
  - Uncertainty dominated by limited statistics (**17%**)
- Then extrapolated to the signal region
  - Amounts to **4±1 events**
  - Numbers in agreement with ZDC signal

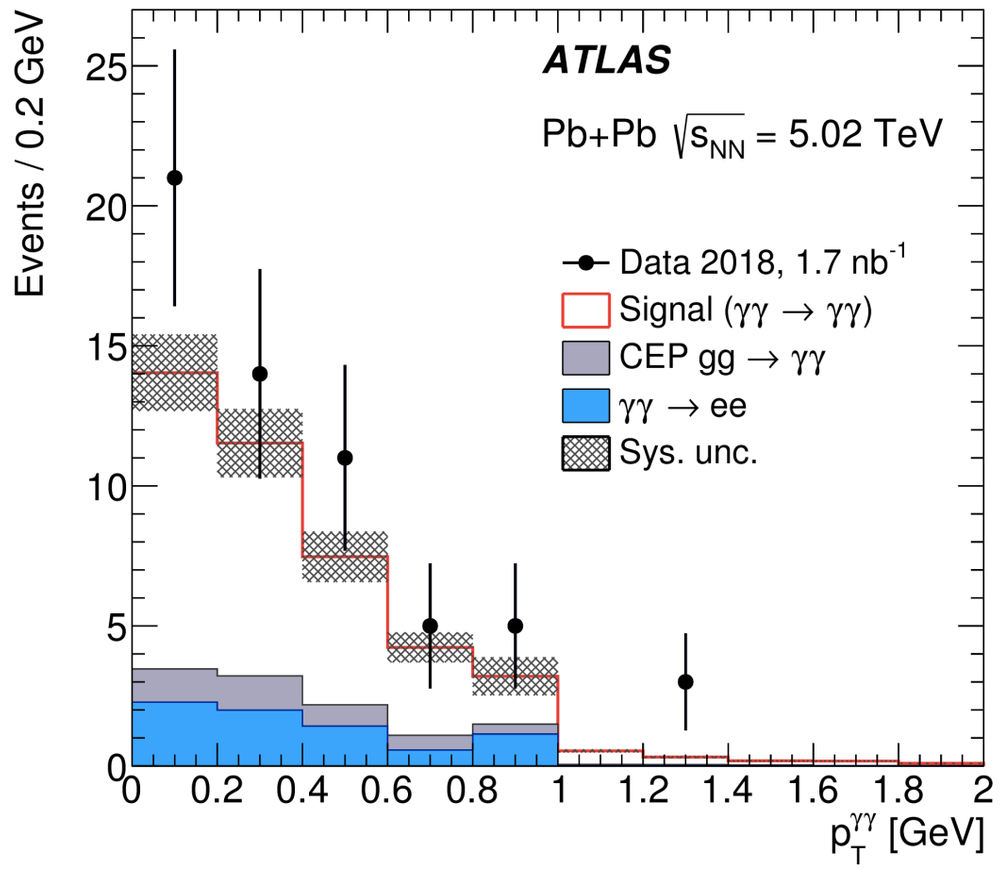




LBYL: CROSS SECTIONS

arXiv:1904.03536





- Analysis of **2018 Pb+Pb** data with **1.73 nb^{-1}**
  - Many analysis improvements led to a **better precision**
  - **59 events observed**, estimated background: 12 ± 3
  - Cross section:

$$\sigma_{\text{fid}}^{\text{meas}} = 78 \pm 13\ (\text{stat}) \pm 7\ (\text{syst}) \pm 3\ (\text{lumi})\ \text{nb}$$

$$\sigma_{\text{fid}}^{\text{pred,[1]}} = 45 \pm 5\ \text{nb}$$

$$\sigma_{\text{fid}}^{\text{pred,[2]}} = 50 \pm 5\ \text{nb}$$

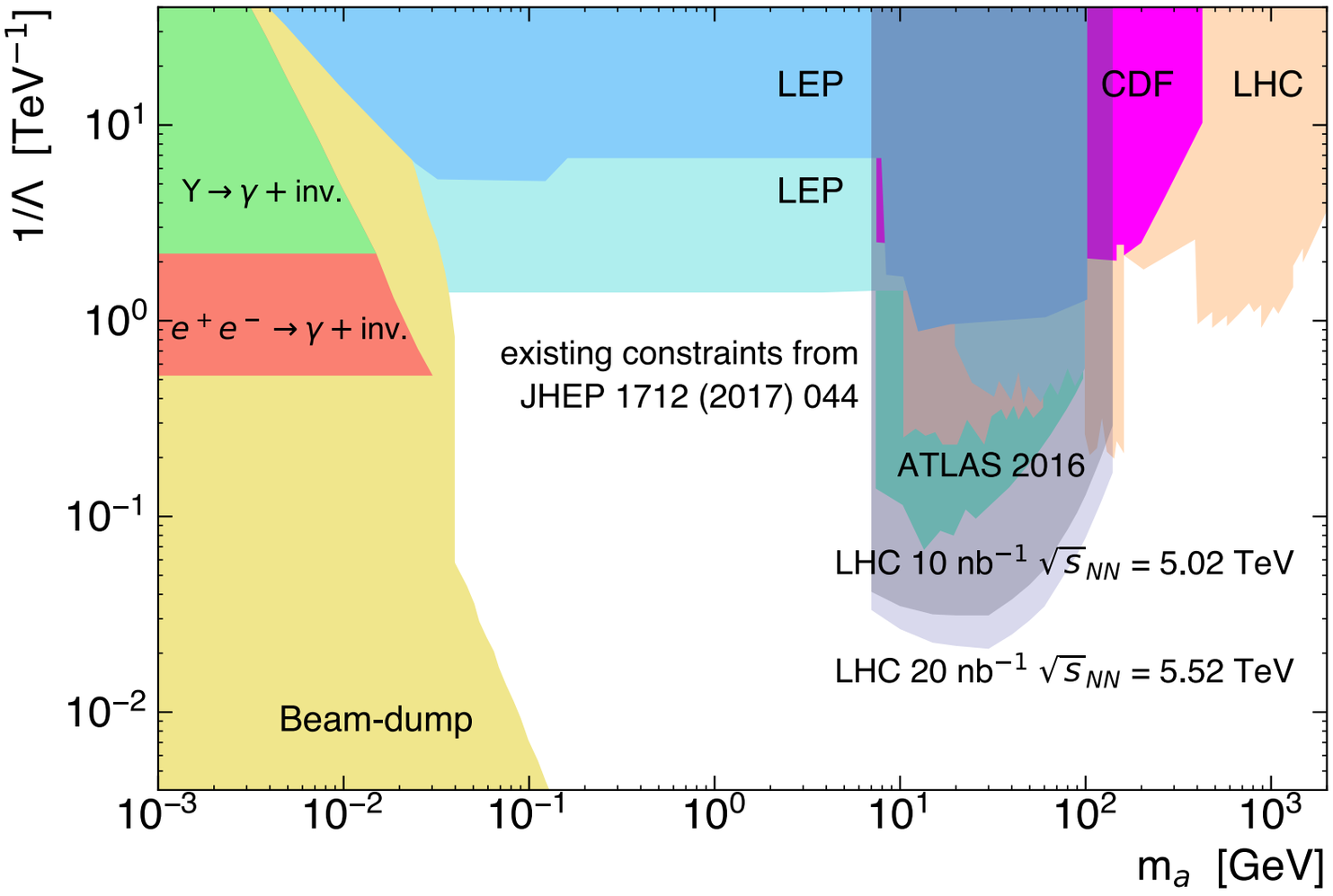
$$\sigma_{\text{fid}}^{\text{pred,[3]}} = 51 \pm 5\ \text{nb}$$

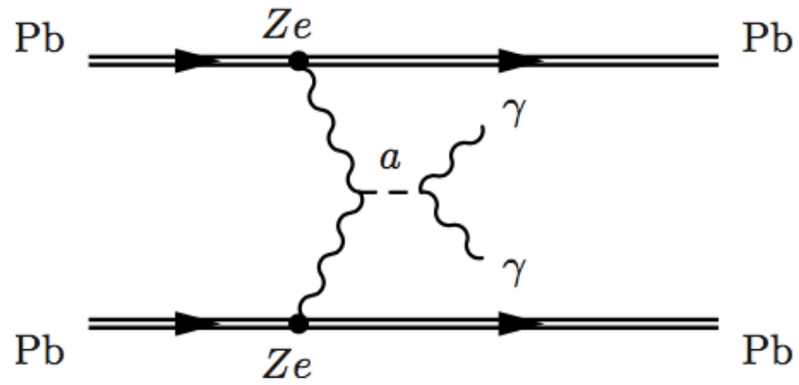
  - **Significance of 8.2σ** (6.2σ expected) establishes the **observation**
  - Compatibility with SM predictions within 1.8 standard deviations

[1] D. d'Enterria et al, [2] SuperChic3.0, [3] M. Klusek-Gawenda et al

LBYL: AXION SEARCHES

arXiv:1812.06772 (CERN Yellow Report)
ATL-PHYS-PUB-2018-018





arXiv:1709.07110

- Search for **axion-like particles** (ALP) using 2015 Pb+Pb UPC data
- **Most stringent limits** on ALP at **$6 < m_a < 100$ GeV** have been derived
- Limits agree with results from the CMS paper [arXiv:1810.04602]
- Other interpretations: magnetic monopoles [PRL 118 (2017) 261802]

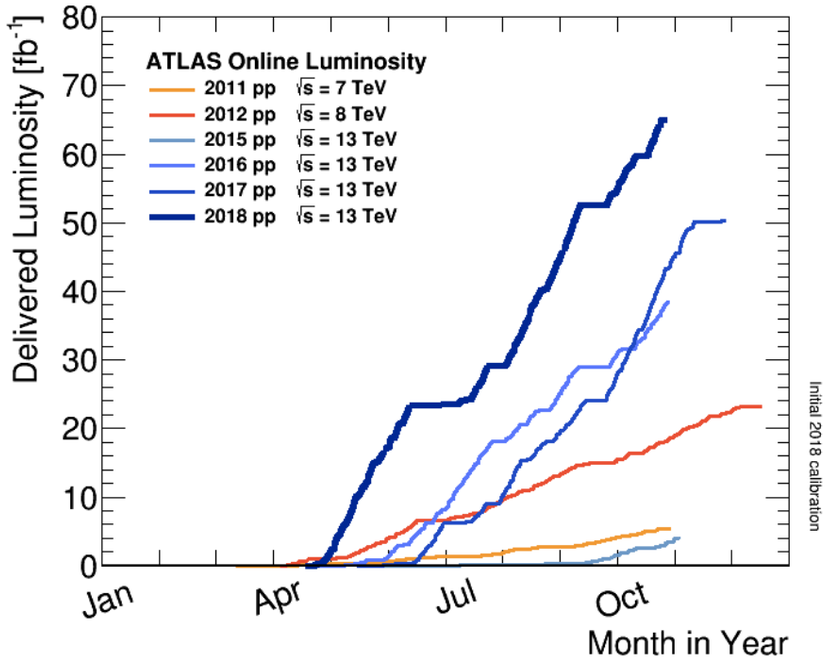
SUMMARY

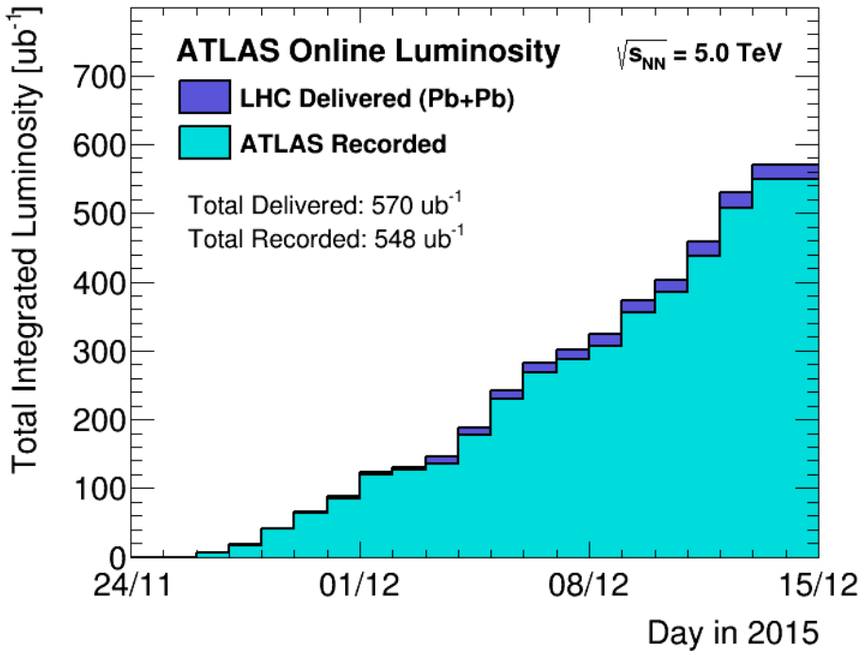
- Cross sections for **photon-induced processes** have been measured in ATLAS
  - $\gamma\gamma \to \mu^+\mu^-$ production in **pp collisions** at 13 TeV (2015 run)
  - $\gamma\gamma \to W^+W^-$ production in **pp collisions** at 8 TeV (2012 run)
  - **Light-by-light scattering** in **Pb+Pb collisions** at 5.02 TeV (2018 run)
- Large integrated luminosities of pp collisions make $\gamma\gamma \to \mu^+\mu^-$ production a precision measurement
  - EPA framework holds for LHC energies
  - **Absorptive effects** play an important role in the data description
- Access to rare processes
  - $\gamma\gamma \to W^+W^-$ production used to extract limits on anomalous quartic gauge couplings
  - First **8.2σ observation** of **light-by-light scattering** established at the LHC
    - Compatibility with SM predictions within 1.8 standard deviations

BACK-UP SLIDES

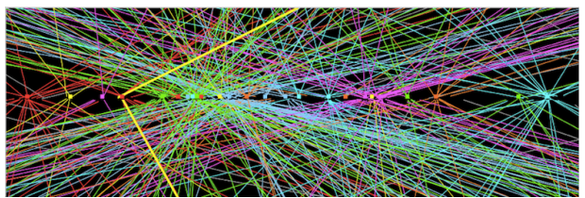
LBYL IN PP OR PB+PB COLLISIONS?

System	$\sqrt{s_{\mathrm{NN}}}$ (TeV)	$\mathcal{L}_{\mathrm{AB}} \cdot \Delta t$ (per year)	γ	R_{A} (fm)	$\omega_{\max}$ (GeV)	$\sqrt{s_{\gamma\gamma}^{\max}}$ (GeV)	$\sigma_{\gamma\gamma\to\gamma\gamma}^{\mathrm{excl}}$ $[\mathrm{m}_{\gamma\gamma} > 5$ GeV]	$N_{\gamma\gamma}^{\mathrm{excl}}$ (per year) $[\mathrm{m}_{\gamma\gamma} > 5$ 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





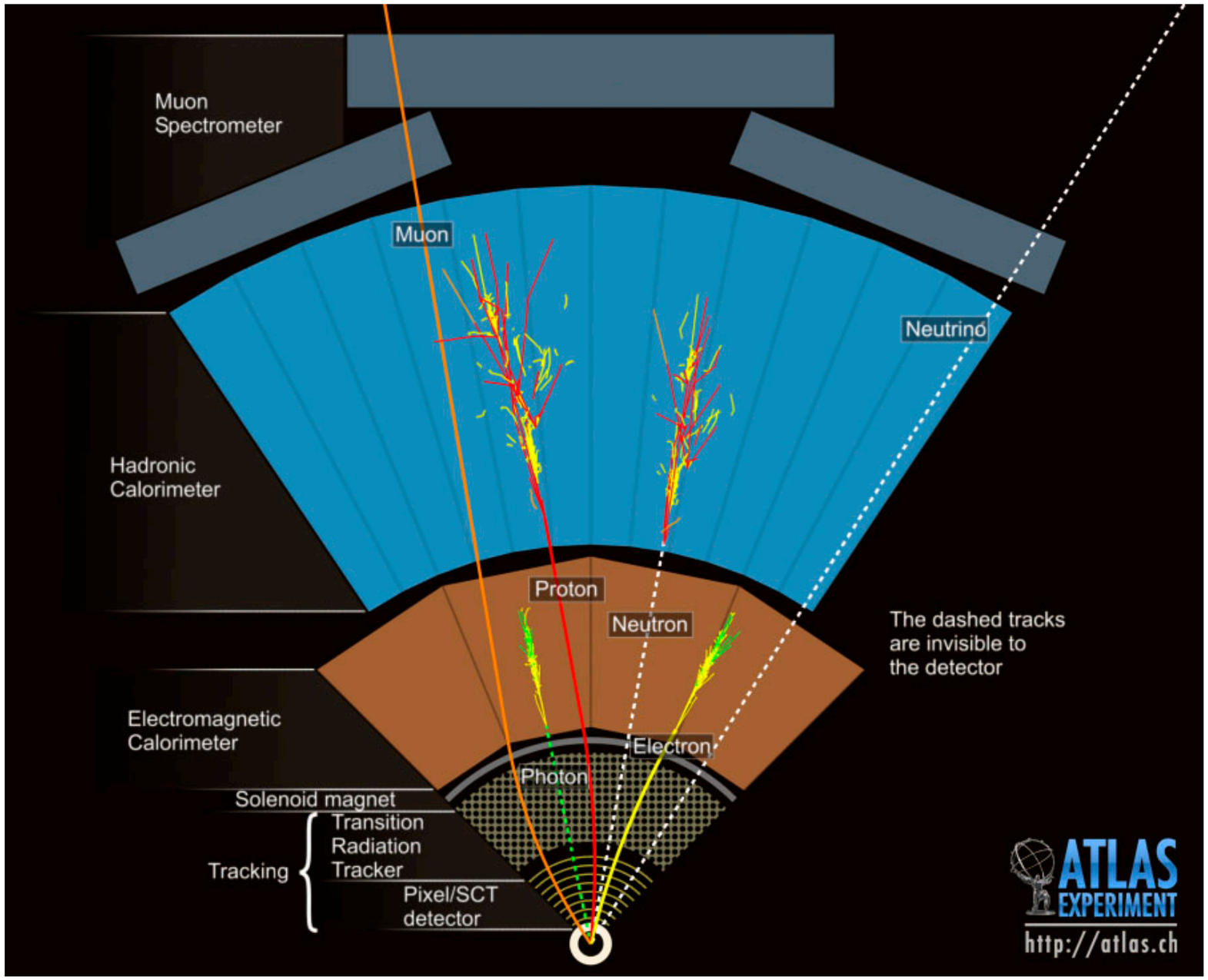
- LbyL in **proton-proton system**:
  - In total 140 fb^{-1} at 13 TeV → **~1 600 events**
  - Harder photon spectrum
  - Larger backgrounds from Central Exclusive Production (CEP)
  - **Larger pileup** - up to 80 simultaneous interactions



- LbyL in peripheral **lead-lead collisions**:
  - 0.48 (2015) + 1.73 (2018) nb^{-1} at 5.02 TeV → **~150 events**
  - Softer photon spectrum
  - Background from CEP reduced
  - Almost **no pileup** - very clean environment for photon studies

PHOTON RECONSTRUCTION IN ATLAS

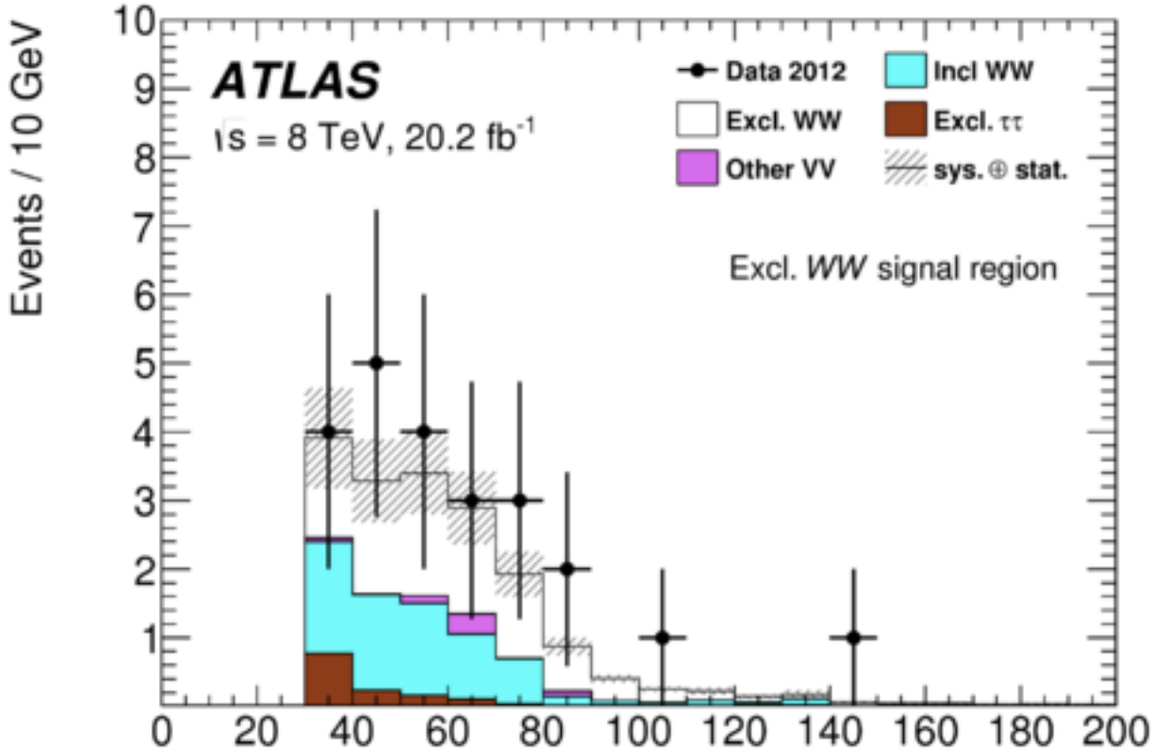
- Photons do not create tracks in the ID, they deposit most of their energy in the EM calorimeter
  - Potential small leakage to HAD calorimeter (isolation)
- Simple signature:
  - Photon = EM cluster
- Unless they convert to an e^+e^- pair

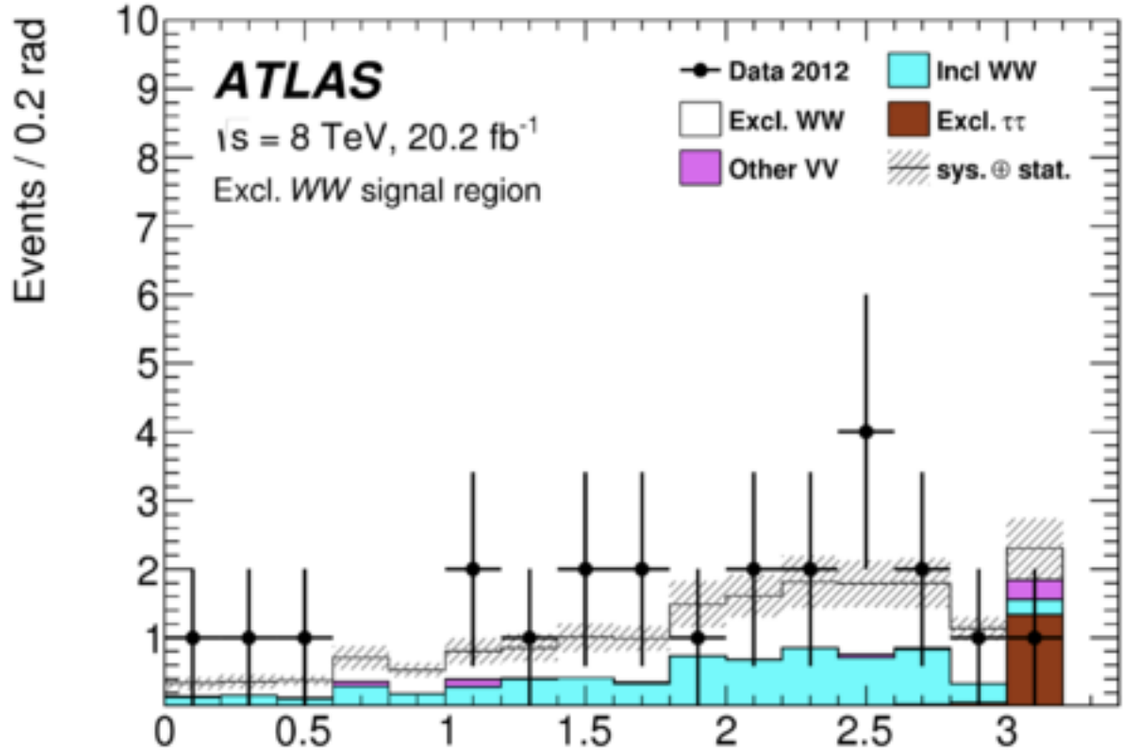


Possible issues:

- Track reconstruction efficiency is ~80% in pp collisions in ATLAS
- An electron with a low-quality track might mimic a photon

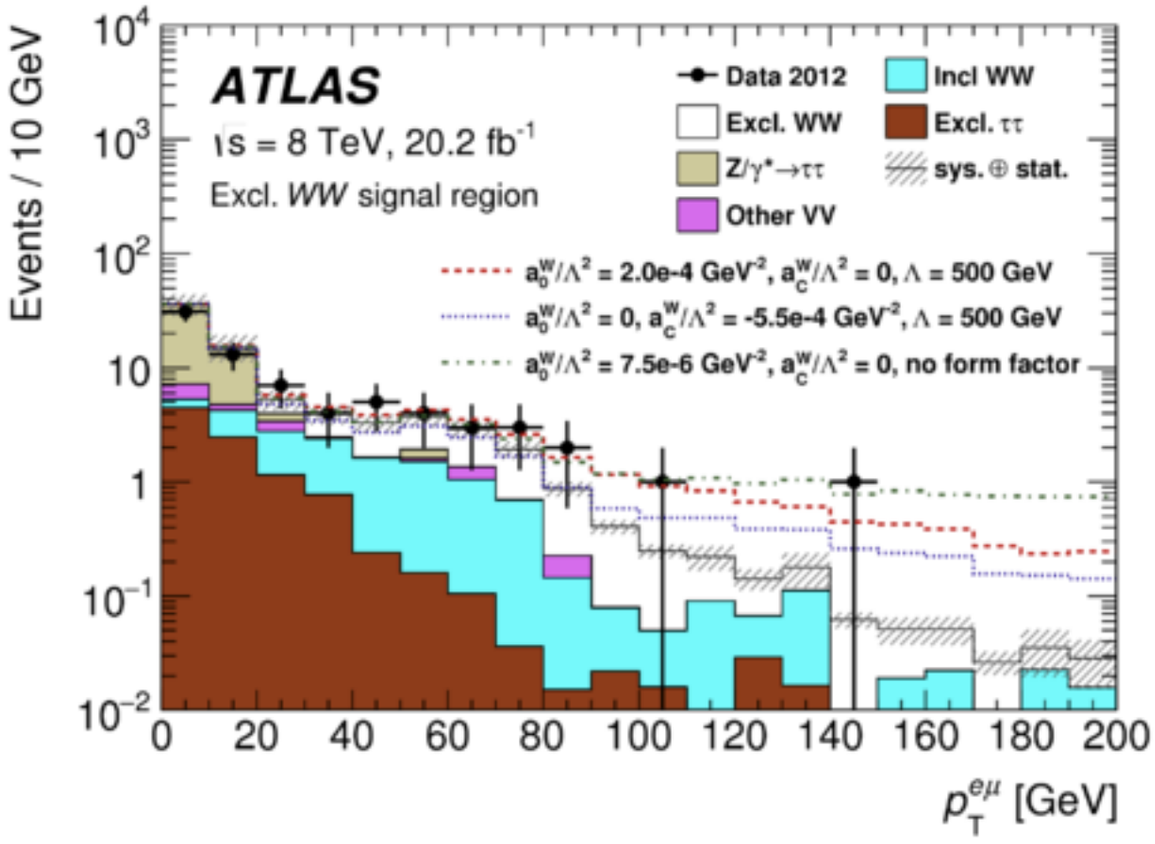
EXCLUSIVE W+W−: CROSS SECTIONS

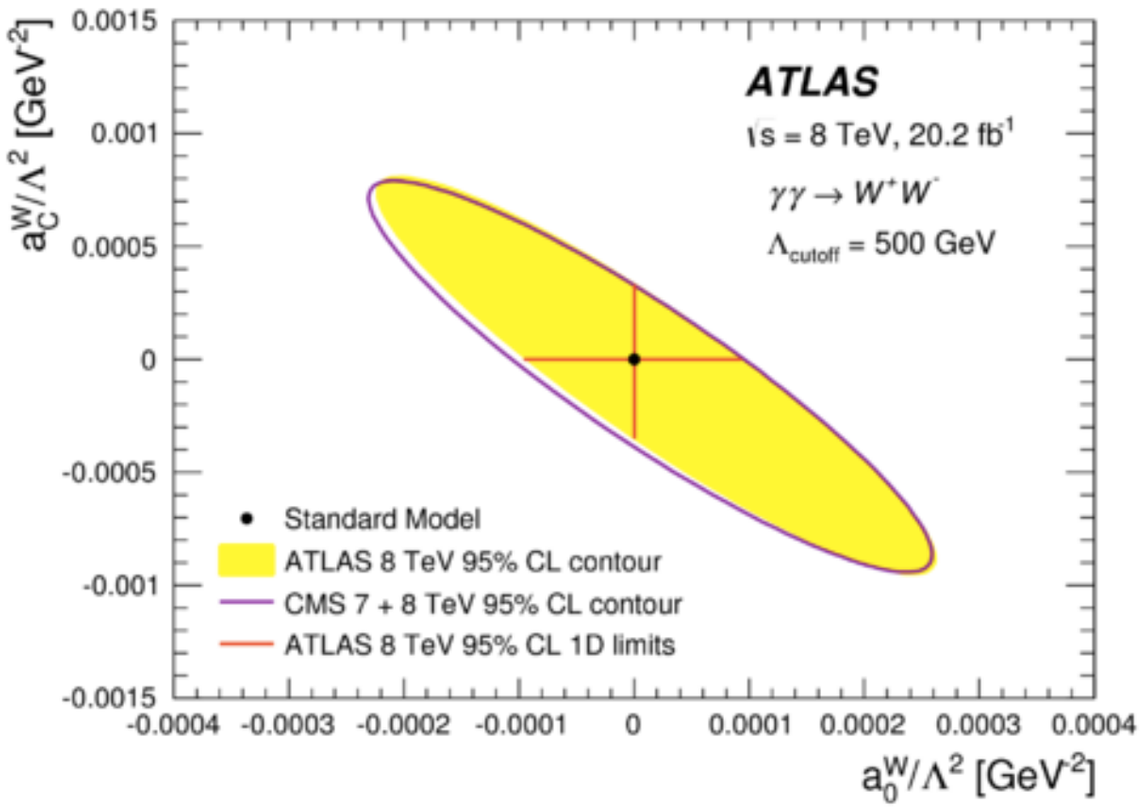




- 23 events in the data while 9.3±1.2 signal events expected
  - Total background: 8.3±2.6 events dominated by inclusive W^+W^- production
- Measured cross section: $\sigma^{\text{meas}}_{\gamma\gamma\to W^+W^-\to e^\pm\mu^\pm X} = 6.9 \pm 2.2\ (\text{stat}) \pm 1.4\ (\text{syst})\ \text{fb}$
  - Systematic uncertainty dominated by bkg determination (18%) and exclusivity selection (10%)
- Predicted cross section: $\sigma^{\text{HERWIG++}}_{\gamma\gamma\to W^+W^-\to e^\pm\mu^\pm X} = 4.4 \pm 0.3\ \text{fb}$
  - **In good agreement** with the data
- **Signal significance** amounts to **3σ**

EXCLUSIVE W+W−: LIMITS ON AQGC





- aQGC limits extracted for $p_T^{e\mu} > 120$ GeV where backgrounds are suppressed
- 95% CL limits measured with a likelihood test using one event as a constraint
- **Limits are compatible** with the **CMS combined 7 TeV and 8 TeV results**

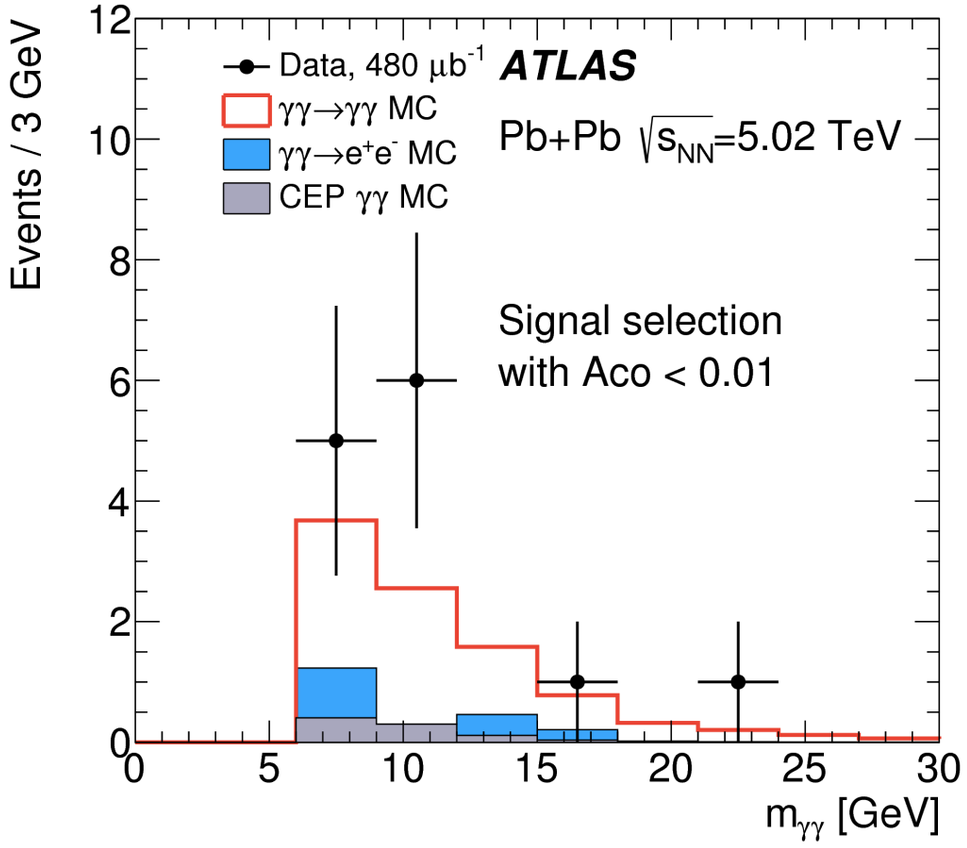
SYSTEMATIC UNCERTAINTIES FOR 2015 LBYL

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 dominant systematic uncertainty is due to photon PID efficiency in the 2015 LbyL measurement

LBYL: RESULTS FROM 2015

- Search for signal LbyL candidates:
  - 2015 Pb+Pb data with 0.48 nb^{-1}
  - Backgrounds subtracted from exclusive dielectron production and diphotons from CEP
- Excess in the data consistent with the LbyL signal from Standard Model
  - **13 events observed** in total, while **2.6 expected from background**
  - First direct evidence of the light-by-light signal at high energies
  - Result consistent with the CMS LbyL measurement from 2018 [arXiv:1810.04602]



Signal significance: 4.4σ, expected significance: 3.8σ

Measured cross section:

$$\sigma_{\text{fid}}^{\text{meas}} = 70 \pm 20\ (stat) \pm 17\ (syst)\ \text{nb}$$

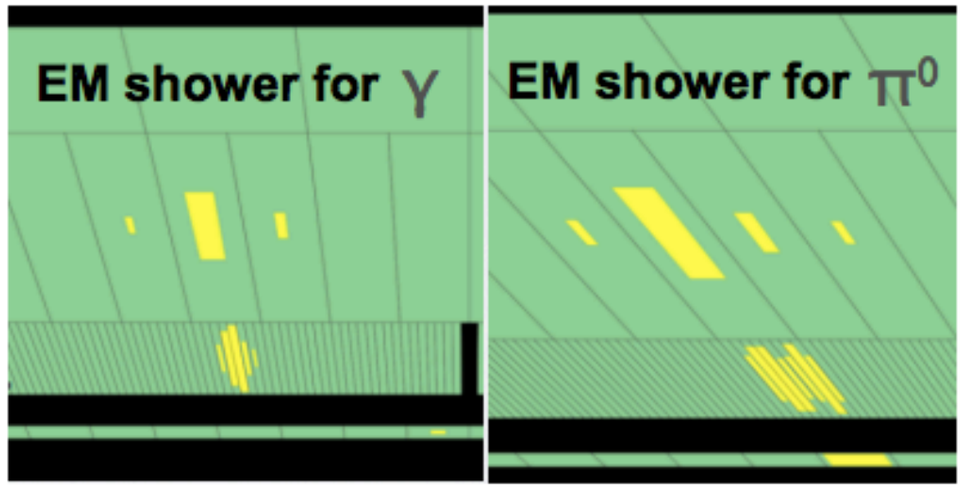
$$\sigma_{\text{fid}}^{\text{pred}} = 49 \pm 5\ \text{nb}$$

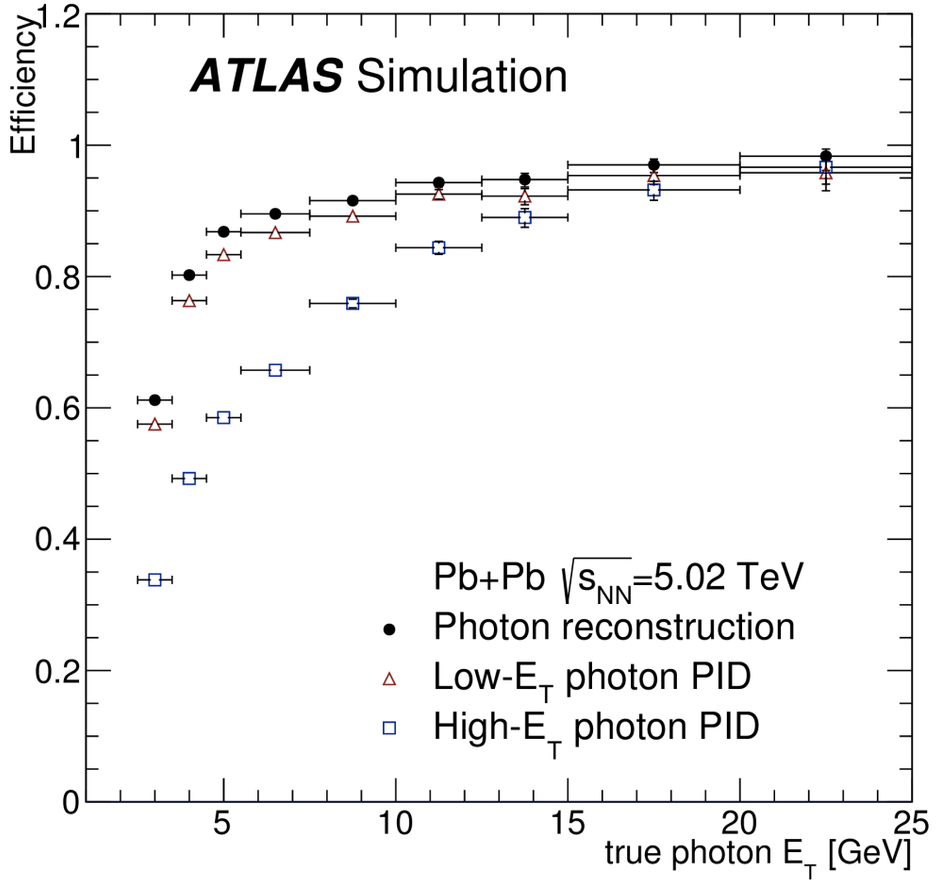
In agreement with Standard Model [arXiv: 1601.07001, 1305.7142]

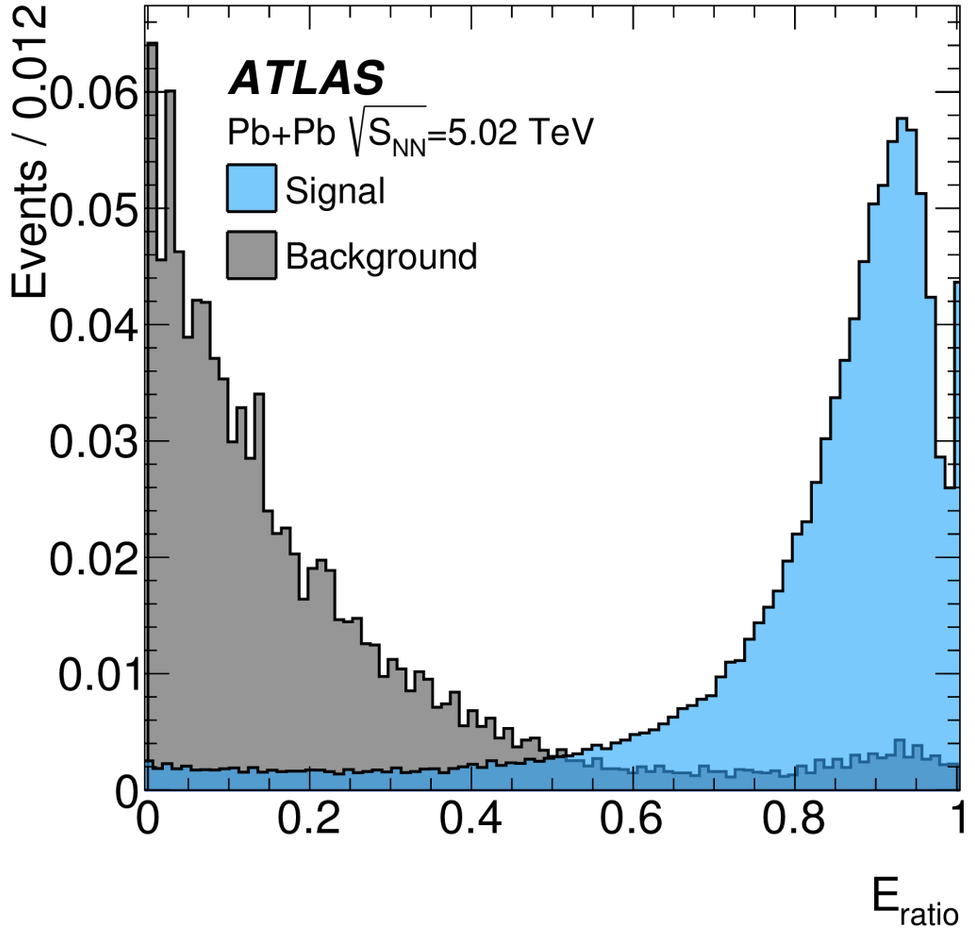
Nature Physics 13, 852–858 (2017)

PHOTON IDENTIFICATION IN ATLAS

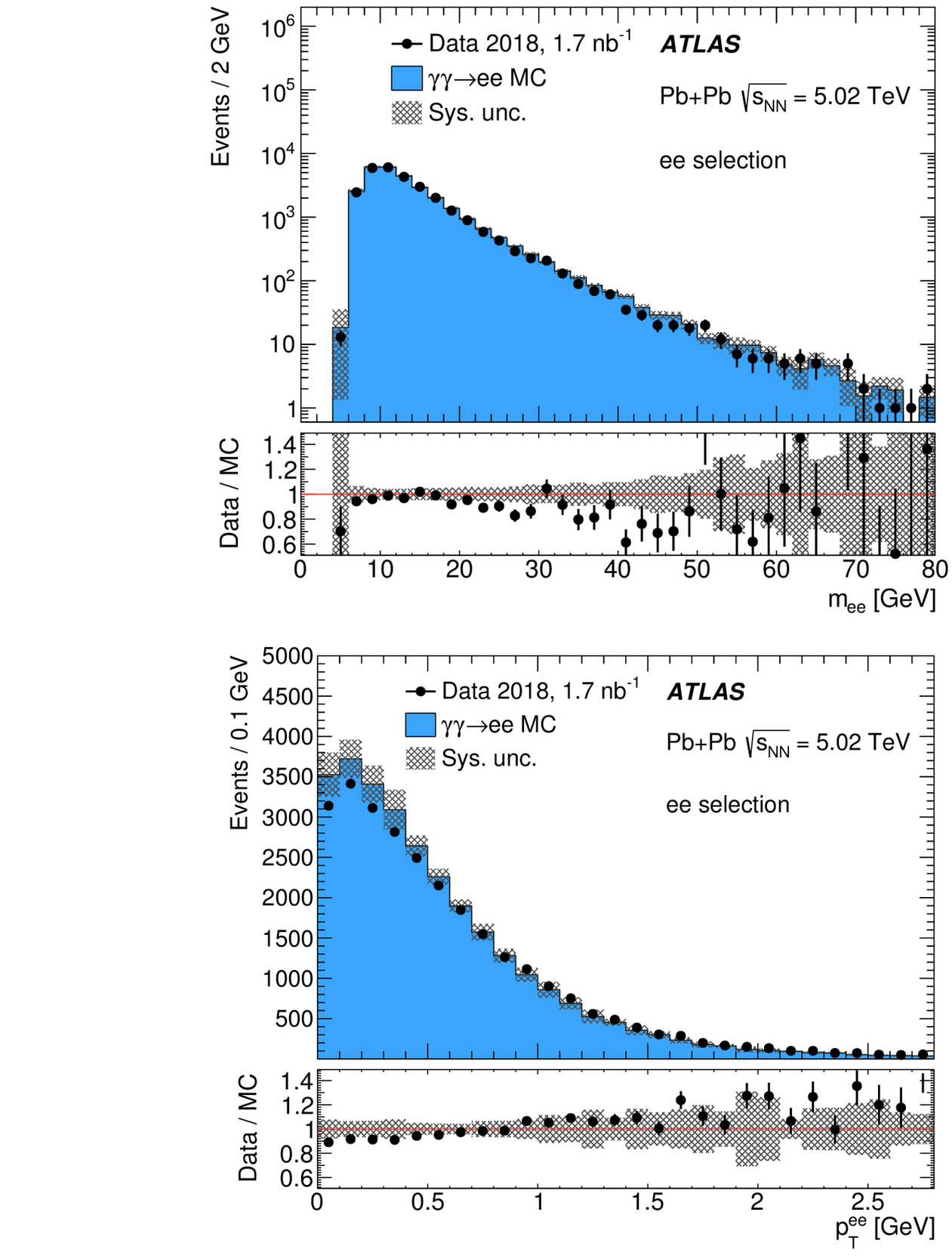
- Among reconstructed photon candidates, there is a lot of photons originating from background processes ($\pi^0 \rightarrow \gamma\gamma$, cosmics)
- Reject those using information (longitudinal and transverse) on shower shapes
  - Example: $\mathbf{E_{ratio}}$= fraction of energy reconstructed in the first layer of the EM calorimeter relative to the total energy of the cluster
  - Powerful tool to distinguish between LbyL photons and photons from other sources

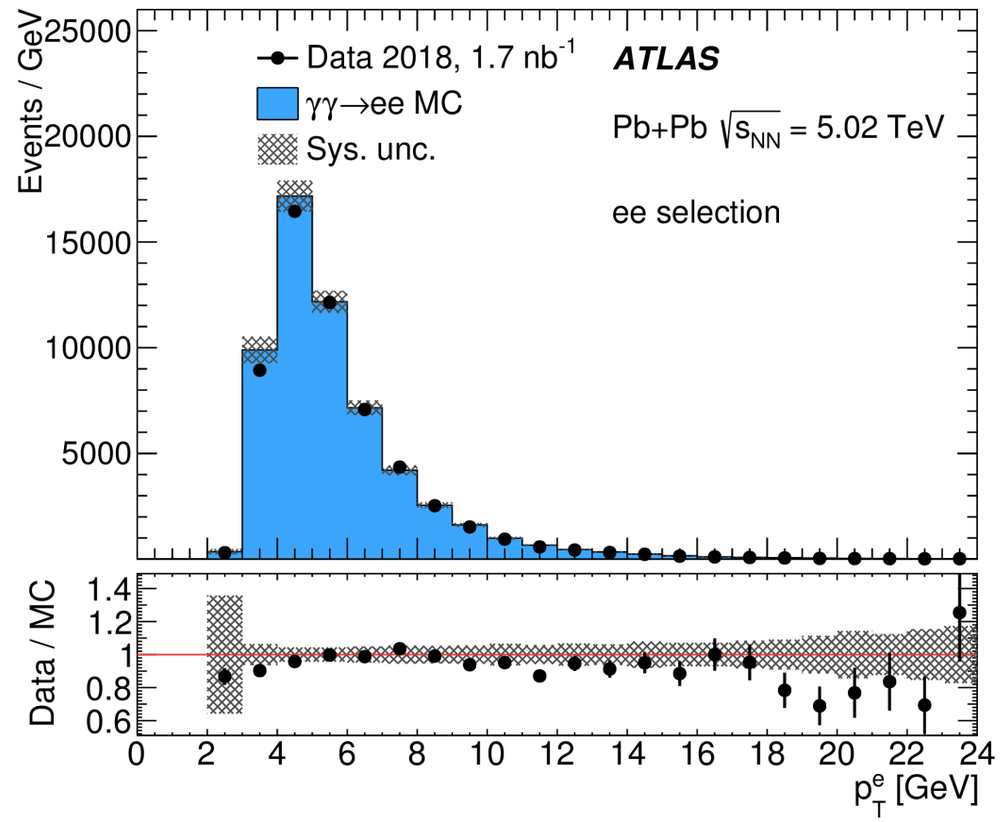




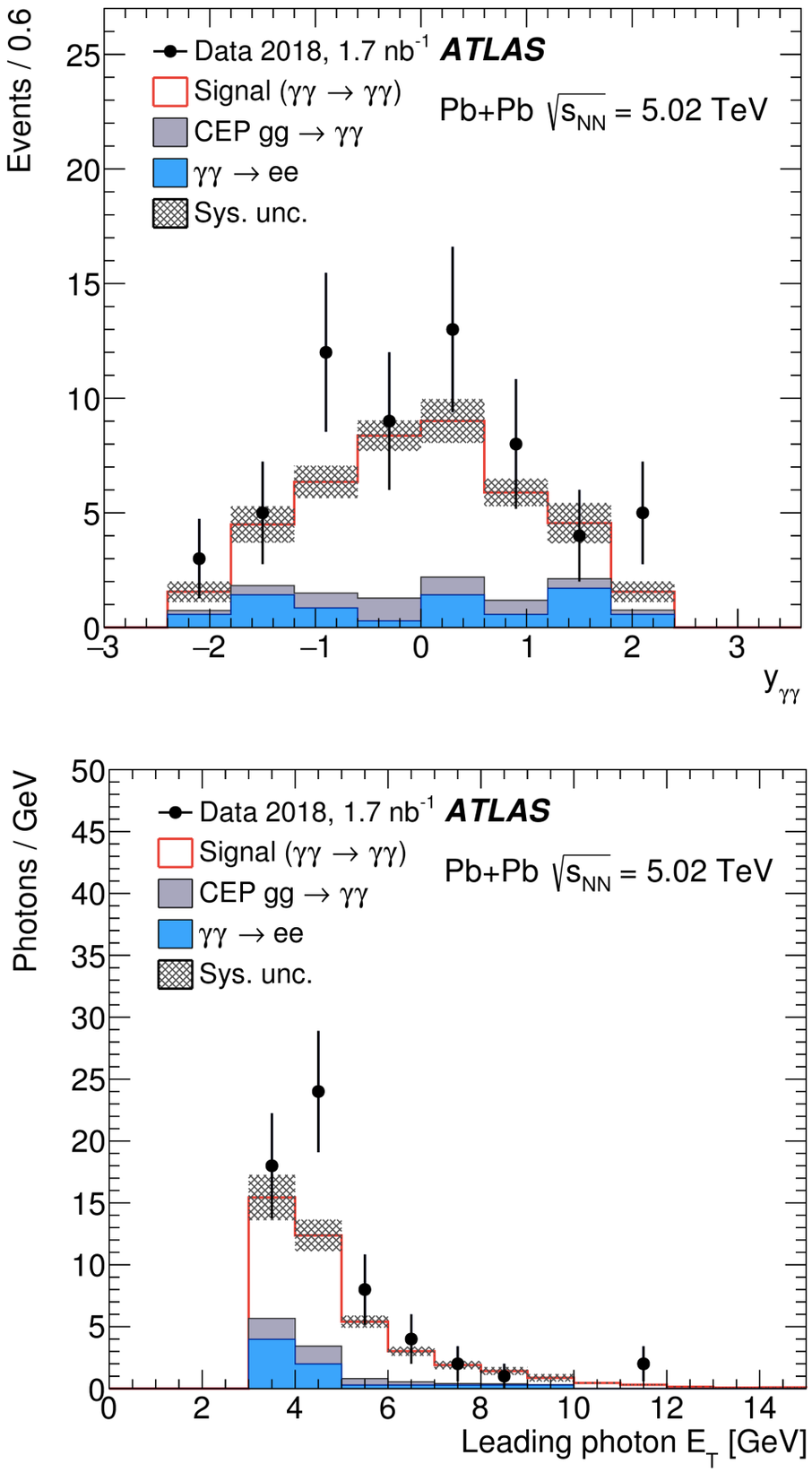


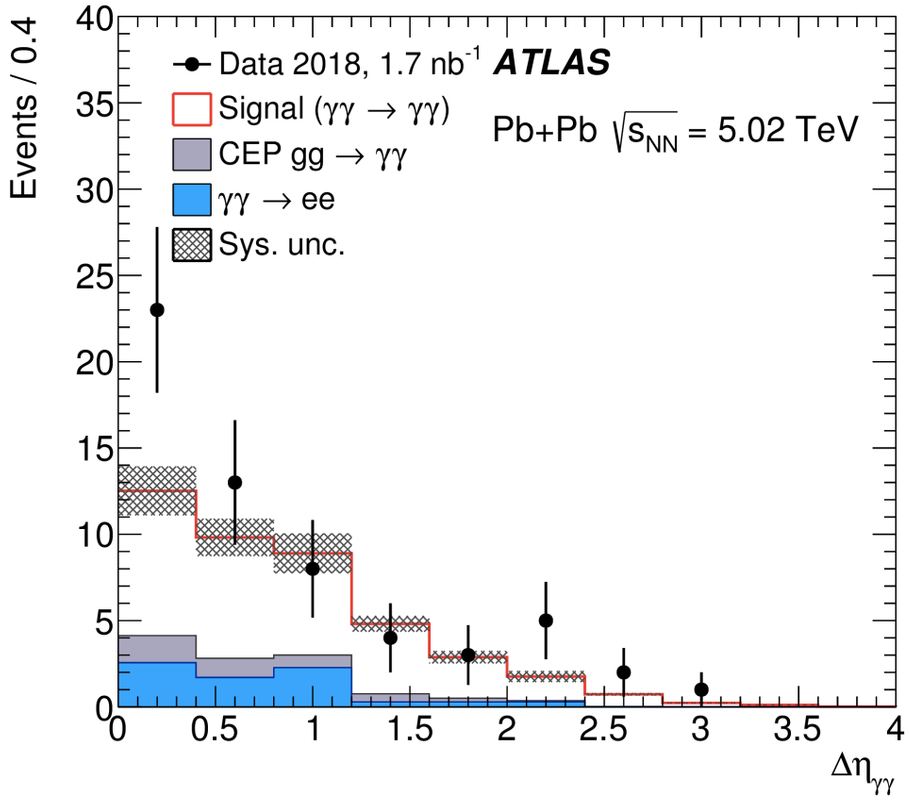
EXCLUSIVE DIELECTRON PRODUCTION

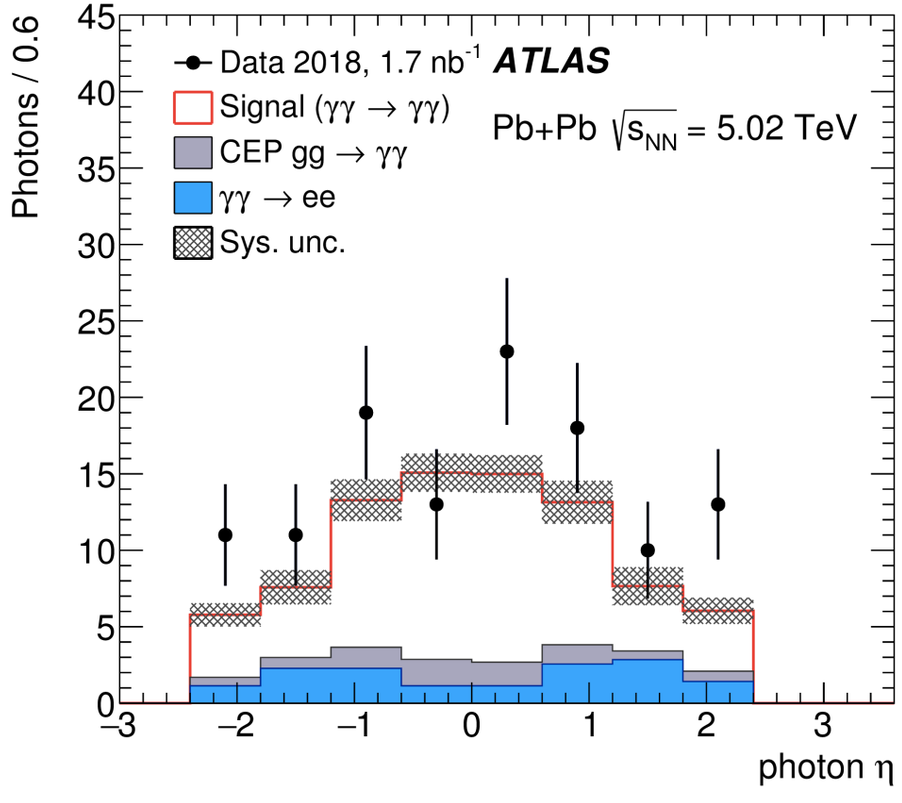




MORE LBYL DISTRIBUTIONS







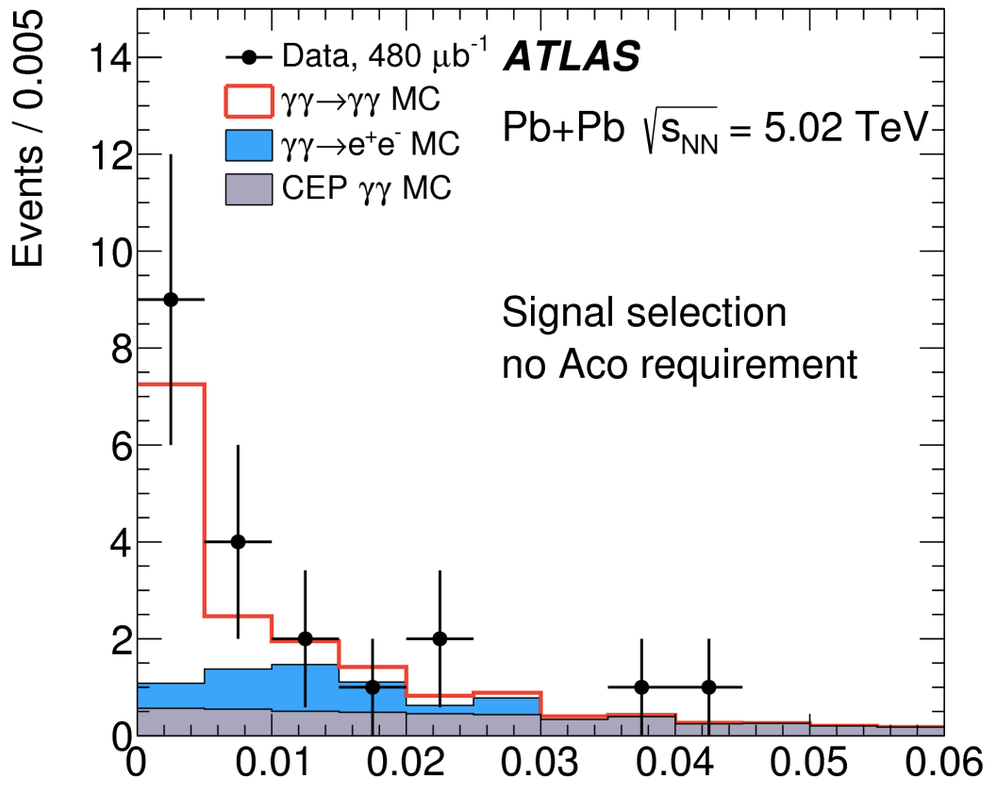
LIGHT-BY-LIGHT SCATTERING: 2015 RESULTS FROM CMS

- LbyL measurement also done in Oct 2018 by CMS
  - Two photons with $E_T > 2$ GeV and $M_{\gamma\gamma} > 5$ GeV
  - Main background from exclusive dielectron production and diphotons from CEP
- Excess consistent with the LbyL signal from Standard Model
  - **Direct evidence (4.1σ) of the LbyL signal with 14 event candidates, about 3 events from background**

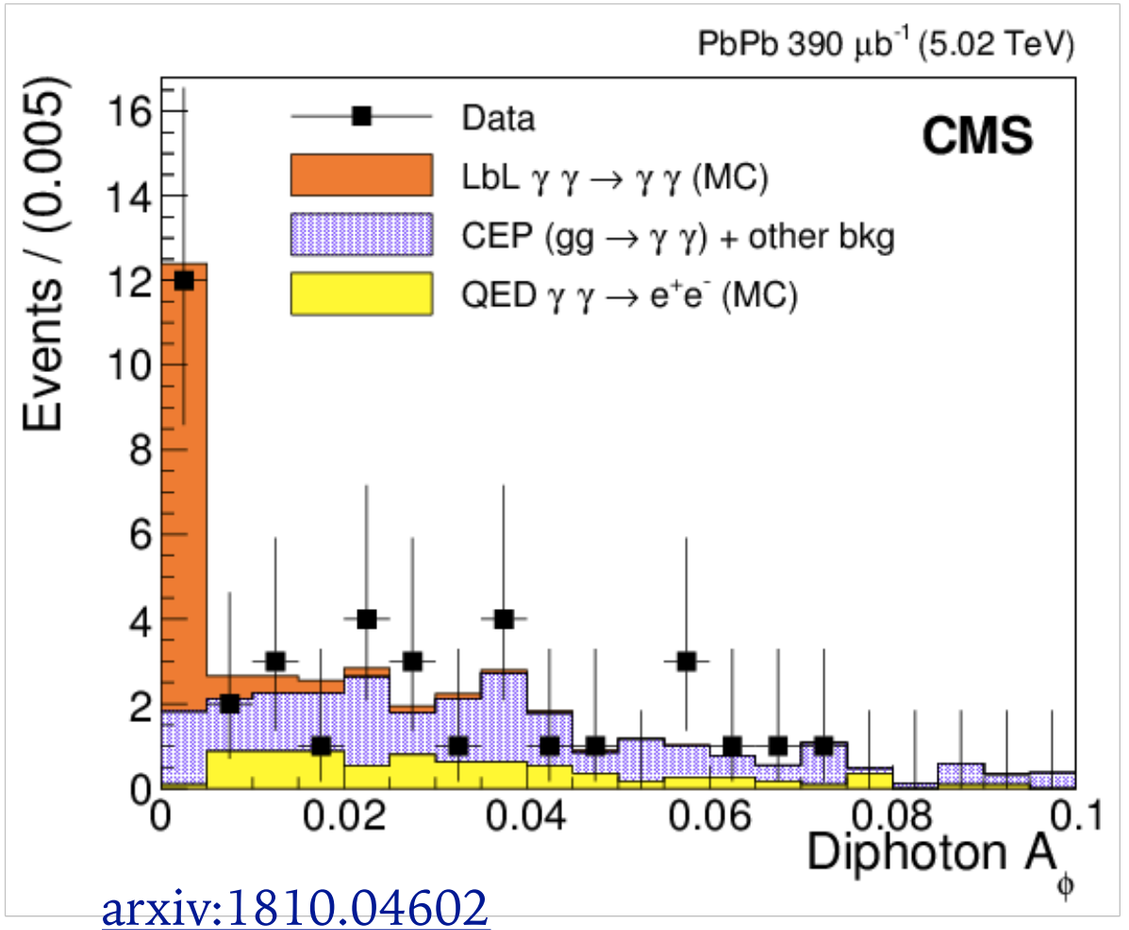
Measured cross sections:

ATLAS - $\sigma_{fid} = 70 \pm 20$ (stat) $\pm$ 17 (syst) nb, CMS - $\sigma_{fid} = 120 \pm 46$ (stat) $\pm$ 28 (syst) $\pm$ 4 (th) nb

In agreement with Standard Model (SM) [arXiv:1601.07001, 1305.7142]



Nature Physics 13, 852–858 (2017)

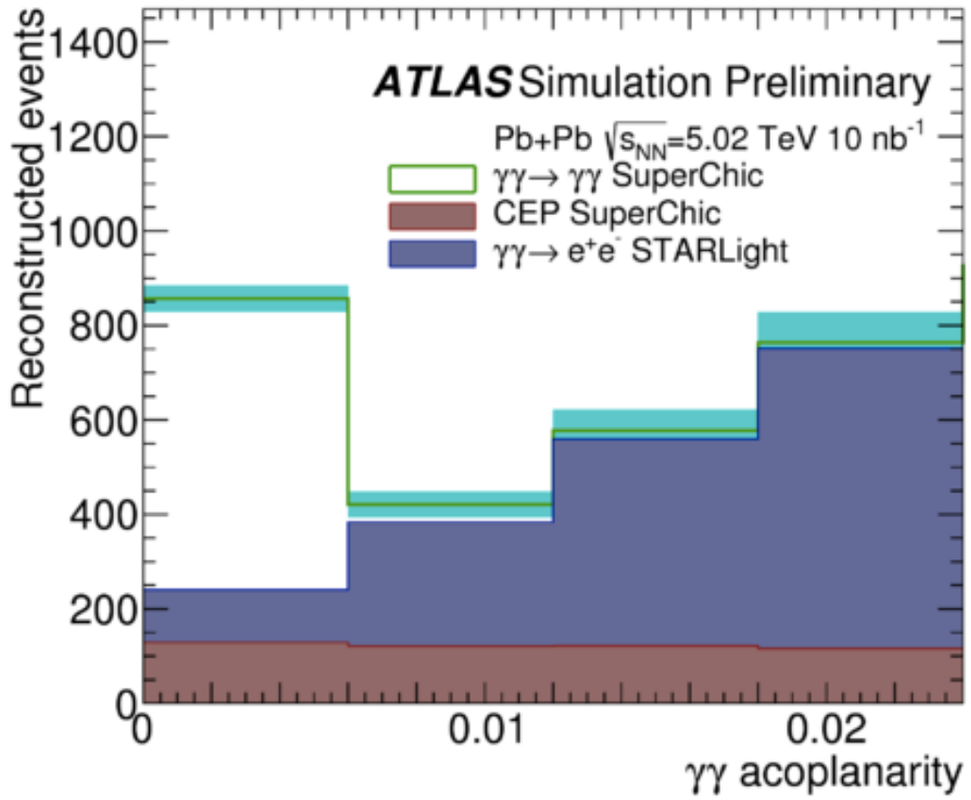


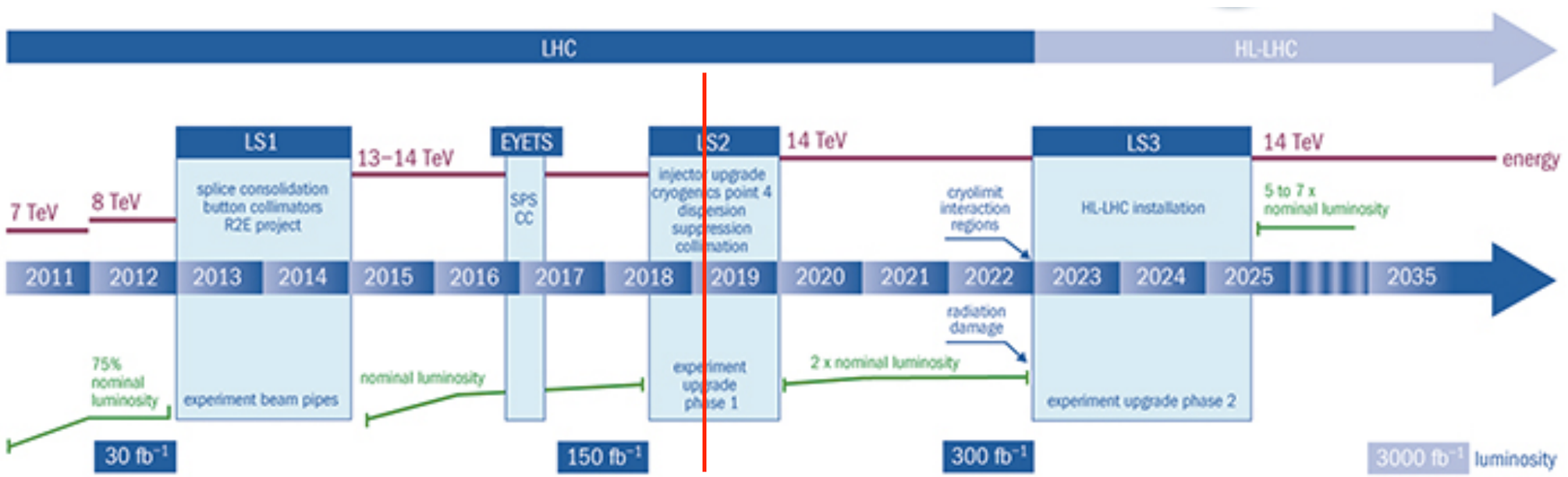
arxiv:1810.04602

PROSPECTS FOR LHC RUN 3–4

arXiv:1812.06772 (CERN Yellow Report)
ATL-PHYS-PUB-2018-018

- **Factor of 20** increase in integrated luminosity of Pb+Pb till the end of LHC operations
- **Extended acceptance** in pseudorapidity from $|\eta|<2.37$ to $|\eta|<4$ in both ATLAS and CMS
  - Leads to less than 10% increase in the LbyL cross section
- Reco-level studies:
  - Acoplanarity extracted using the 2015 analysis selection and photon PID with photon $E_T>2.5$ GeV and $M_{\gamma\gamma} > 5$ GeV
  - About **640 signal events expected** which are well separated from bkg processes





We are here, LS2 is in progress

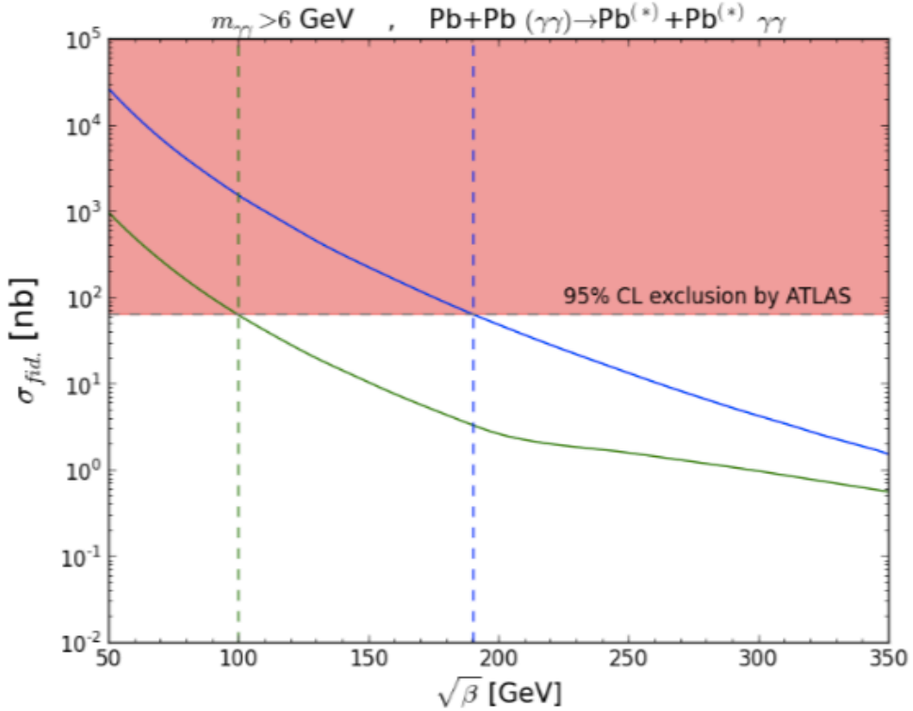
BSM SEARCHES: MAGNETIC MONOPOLES

- In 1934 Born and Infeld a conceptually distinct **nonlinear modification** of the Lagrangian of QED

$$\mathcal{L}_{\mathrm{BI}} = \beta^2\left(1-\sqrt{1+\frac{1}{2\beta^2}F_{\mu\nu}F^{\mu\nu}-\frac{1}{16\beta^4}(F_{\mu\nu}\tilde{F}^{\mu\nu})^2}\right)$$

  - where β is an a priori unknown parameter with the dimension of [Mass]², β ≡ M²

- In 1985 Fradkin and Tseytlin found a connection of BI theory with the string theory, extra dimensions
  - M might have any value between a few hundred GeV and the Planck scale ~ 10^{19} GeV
  - Recently it has been pointed out that a a finite-energy **electroweak monopole** is a solution
- John Ellis et al interpreted the LbyL measurement by ATLAS in the BI theory which allowed to put a lower limit on M (Phys. Rev. Lett. 118, 261802)



Limits:

$$M = \sqrt{\beta} \geq 100\ \mathrm{GeV}$$

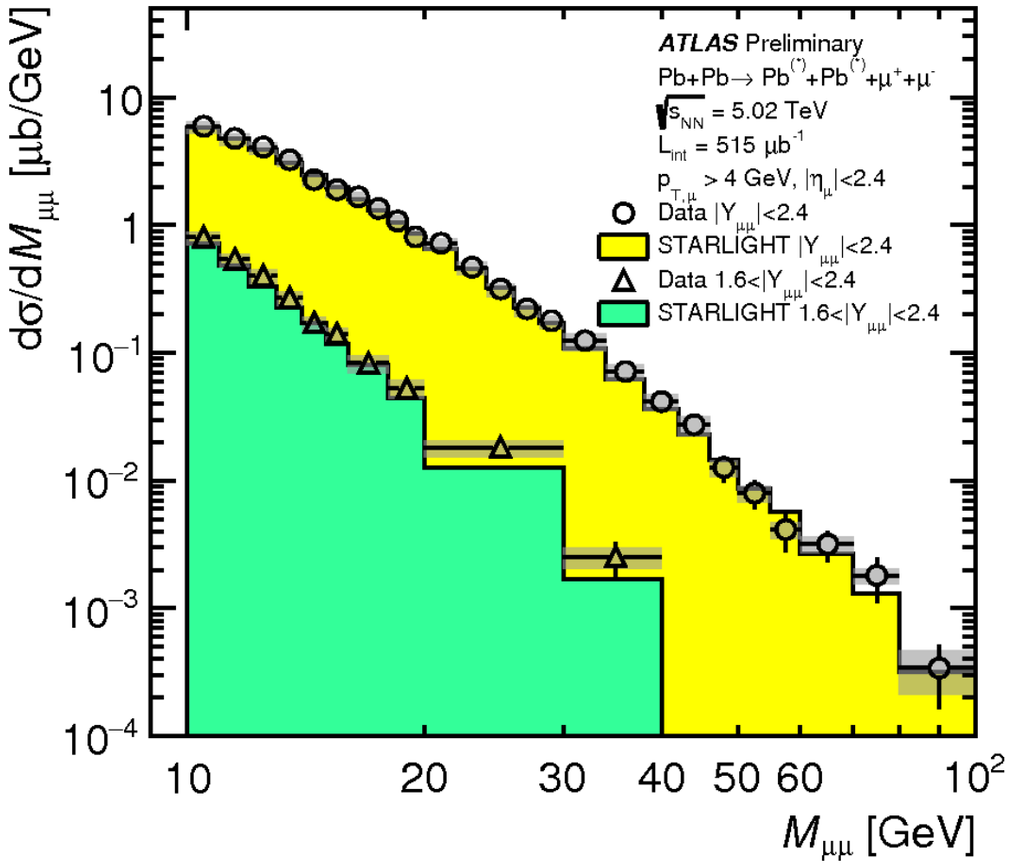
$$M_{\mathrm{monopole}} \geq 11\ \mathrm{TeV}$$

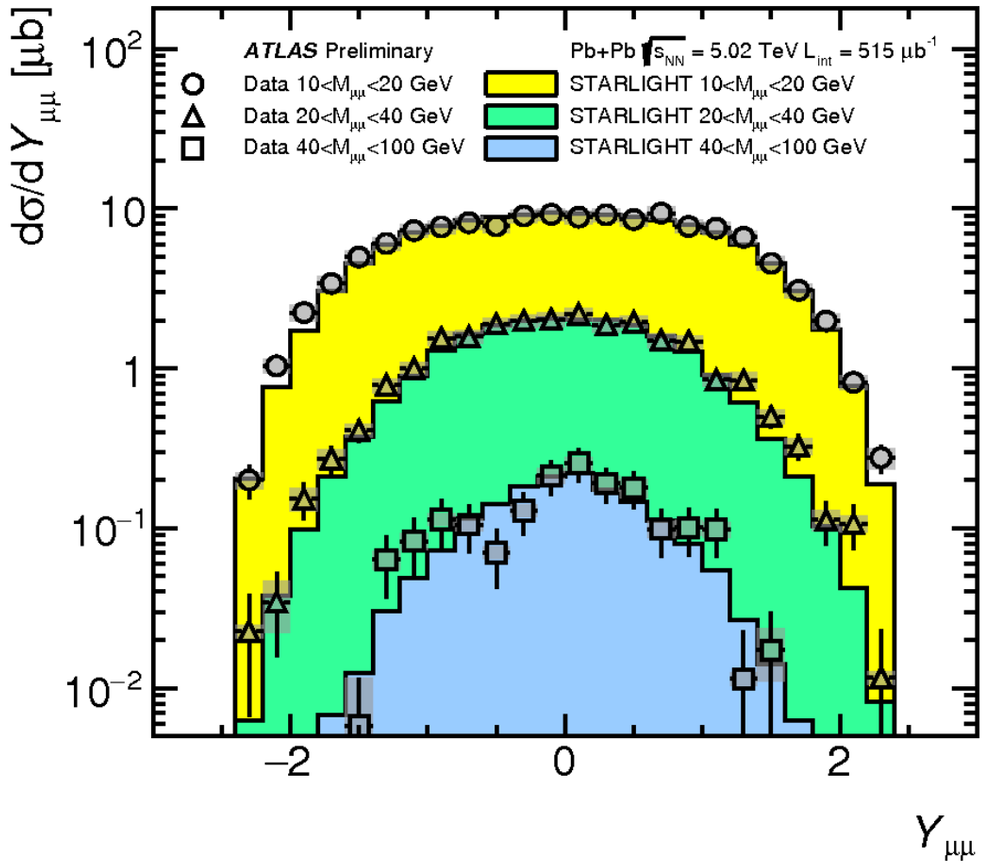
THREE orders of magnitude stronger limits than the previous one!

Unfortunately, this search is beyond the reach of MoEDAL or any other experiment at the LHC, but could lie within reach of a similar experiment at any future 100-TeV pp collider or of a cosmic ray experiment

EXCLUSIVE DIMUON PAIRS IN PB+PB COLLISIONS

ATLAS-CONF-2016-025





- ATLAS measured **γγ → μ⁺μ⁻** production in Pb+Pb collisions at 5.02 TeV
  - 12 069 event candidates selected
- Cross sections for exclusive di-muon production in $M_{\mu\mu}$ and $Y_{\mu\mu}$ are extracted

$$\sigma^{\text{meas}} = 32.2 \pm 0.3\ (stat.)^{+4.0}_{-3.4}\ (syst.)\ \mu b \qquad \sigma^{\text{STARLight}} = 31.64 \pm 0.04\ (stat.)\ \mu b$$

  - In good agreement with Standard Model
- This is **the most precise result** for high dimuon masses at the LHC