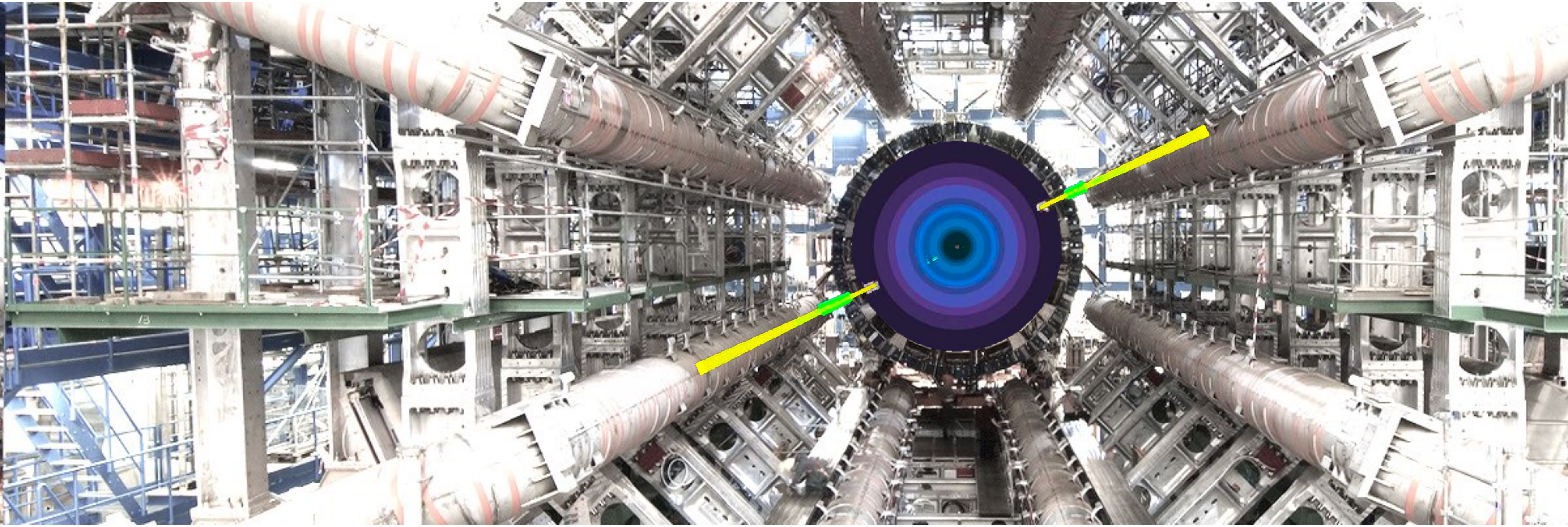

Pierwszy bezpośredni pomiar rozpraszania foton-foton

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Katedra Oddziaływań i Detekcji Cząstek

Seminarium WFiIS
Kraków, 17 listopada 2017

OUTLINE

- Introduction to light-by-light (LbyL) scattering
  - Earlier indirect measurement(s)
  - How to measure LbyL at the Large Hadron Collider (LHC)?
  - The LHC as a photon-photon collider
- Measurement of LbyL in the ATLAS experiment
  - Photon identification
  - Challenges with low-momentum photons
  - Trigger
  - Background processes
  - Results: first direct evidence of LbyL scattering
  - A few limits for beyond-Standard Model searches
- Summary and outlook

INTRODUCTION

INTRODUCTION

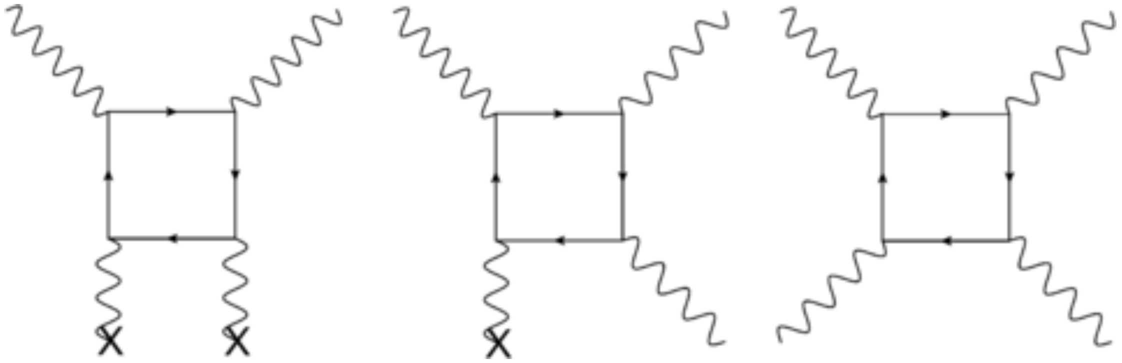
- In 1935 Hans Euler defends and publishes his PhD thesis *“On the scattering of light by light based on Dirac's theory”* under Werner Heisenberg's supervision
- They demonstrated for the first time that Paul Dirac's introduction of the positron opens the possibility that photons in electron-positron pair production scatter with each other and calculated the cross section for this process
- Introduction of Euler–Heisenberg Lagrangian laid the basis for the quantitative treatment of vacuum polarisation
- By treating the vacuum as a medium, it predicts rates of quantum electrodynamics (QED) light interaction processes
- Robert Karplus and Maurice Neuman calculated the full amplitude $O(\alpha^4_{em} \approx 3 \times 10^{-9})$ in 1951
  - Tiny cross section, not measured directly so far

H.Euler (1909-1941)

W.Heisenberg (1901-1976)

Their work predicted existence of several processes involving photons:

- Delbruck scattering (1953)
- Photon splitting (2002)
- Light-by-light scattering (2017)



EXAMPLE: INDIRECT LBYL MEASUREMENT

$$\mu = -\frac{g}{2}\mu_B \frac{\mathbf{S}}{\hbar/2}$$

$$\mu_B = e\hbar/(2m)$$

- Prior to 2017, only indirect measurements of LbyL existed
- Electron magnetic moment, μ
- Magnitude of μ scaled by the Bohr magneton, g/2
- g/2=1 for a point electron in the Dirac description
- QED predicts that vacuum fluctuations and polarisation slightly increase this value
- Physics beyond Standard Model could deviate it from unity even more
- Result of g/2 published in 2008 by the Harvard group (Phys. Rev. Lett. 100, 120801 (2008))

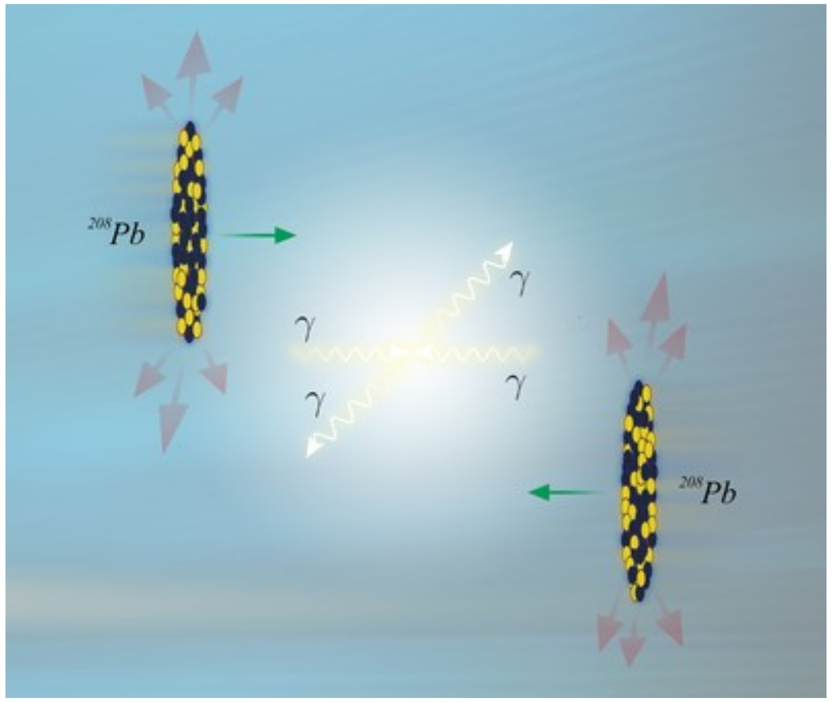
$$g/2 = 1.00115965218073(28)$$

  - An uncertainty is 2.7 smaller w.r.t. the previous measurement
  - This measurement and QED theory determine the fine structure constant with an uncertainty 20 times smaller than before (Phys. Rev. Lett. 99, 110406 (2007))

$$1/\alpha = 137.035999084(51)$$

  - Further improvements in precision are limited by the theory predictions

PHOTON-PHOTON PHYSICS AT COLLIDERS

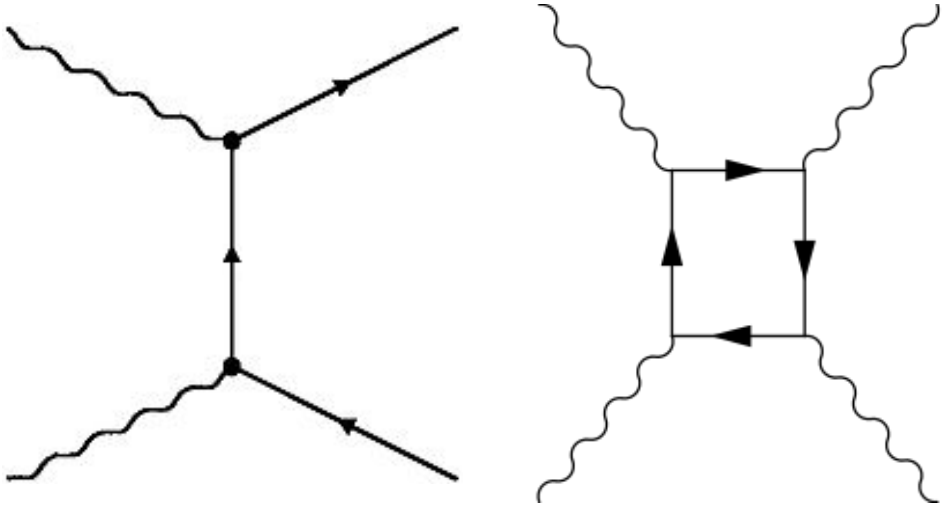


- Basis for photon-photon physics by
  - Fermi, Nuovo Cim. 2 (1925) 143
  - Weizsacker, Z. Phys. 88 (1934) 612
  - Williams, Phys. Rev. 45 (10 1934) 729
- Led to formulation of Weizsacker-Williams Approximation or Equivalent Photon Approximation (EPA)

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

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

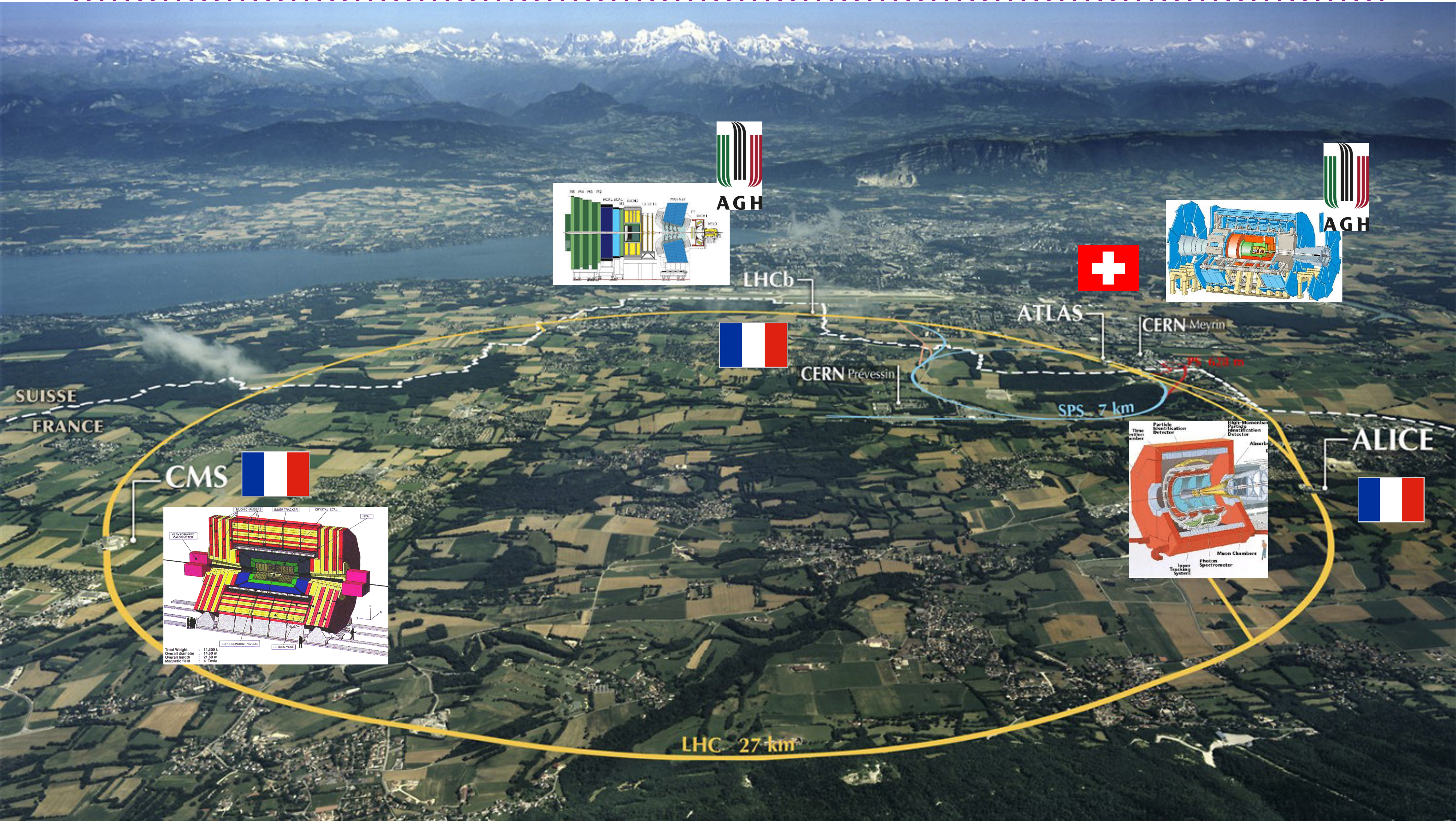
$$Q^2 < 1/R^2 \qquad \omega_{\max} \approx \gamma/R$$



  - Cross section of γγ → X (elementary):

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

LARGE HADRON COLLIDER



- Large Hadron Collider (LHC) is a 27 km long machine
- Most of the time collides protons-protons at 0.9, 7, 8 (2009-2013) and 13 TeV (2015-present)
- One month per year is dedicated to a heavy-ion (HI) program with lead-lead collisions at 2.76 TeV (2010, 2011) and 5.02 TeV (2015)

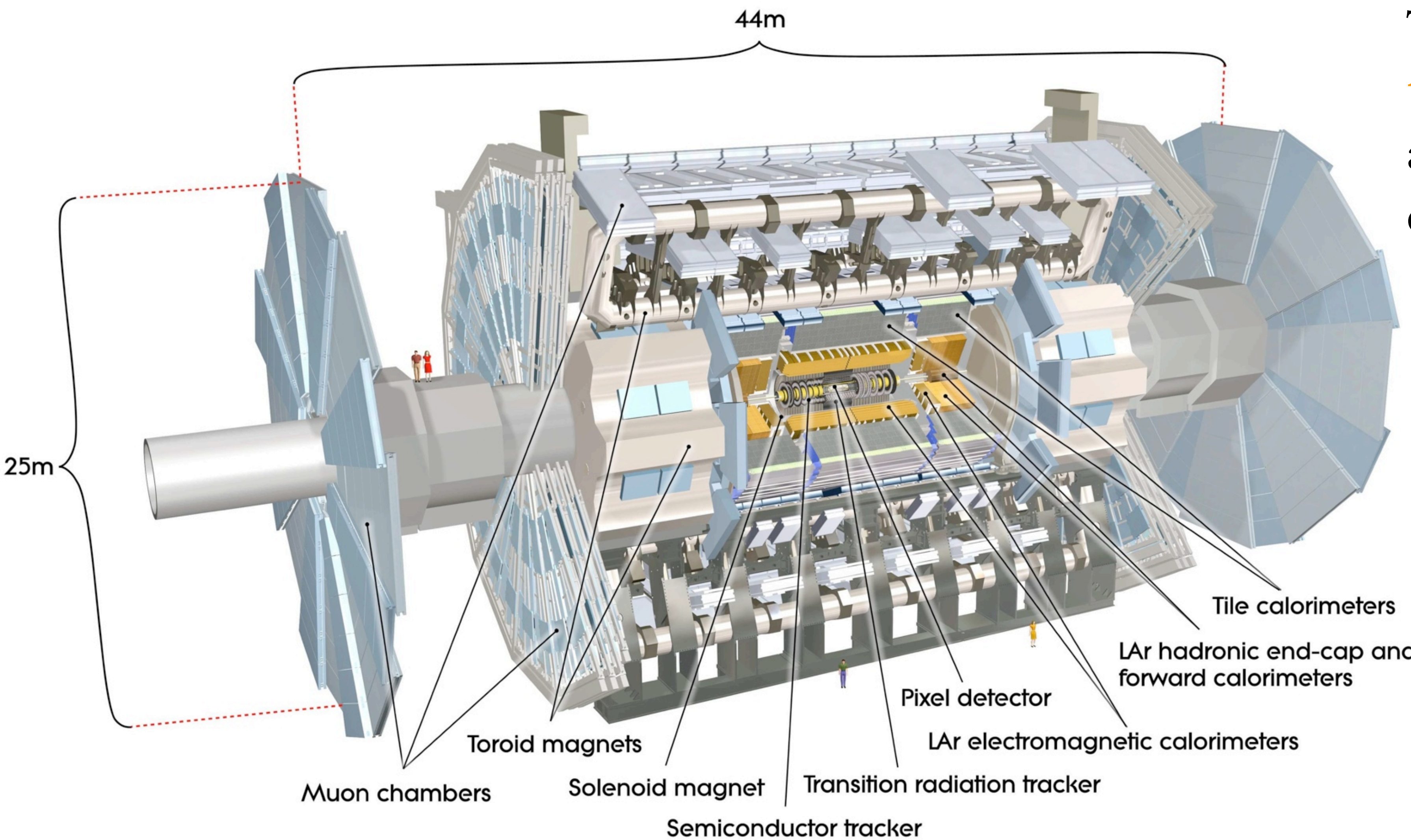
DATA SETS AT THE LHC

- Run 1 (2009-2013) provided collisions at lower energy
- In Run 2 (2015-present) the centre-of-mass energy has almost been doubled
  - Opportunity to study energy dependence
  - Advantage of all three colliding systems at 5.02 TeV

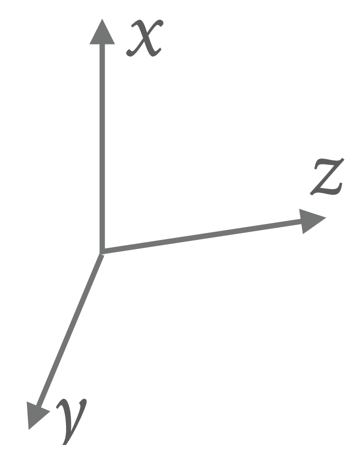
	System	Year	sqrt(s_{NN}) [TeV]	L_{int}
Run 1	**pp**	**2012**	**8**	**19.4 fb^{-1}**
	Pb+Pb	2011	2.76	0.14 nb^{-1}
	pp	2013	2.76	4 pb^{-1}
	p+Pb	2013	5.02	29 nb^{-1}
Run 2	**pp**	**2015-17**	**13**	**85 fb^{-1}**
	pp	2015	5.02	28 pb^{-1}
	Pb+Pb	**2015**	**5.02**	**0.49 nb^{-1}**
	p+Pb	2016	5.02	0.5 nb^{-1}
	p+Pb	2016	8.16	0.16 pb^{-1}
	Xe+Xe	2017	5.4	3 μb^{-1}
	pp	2017	5.02	~100-200 pb^{-1}

NOW

ATLAS DETECTOR



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



Variables:

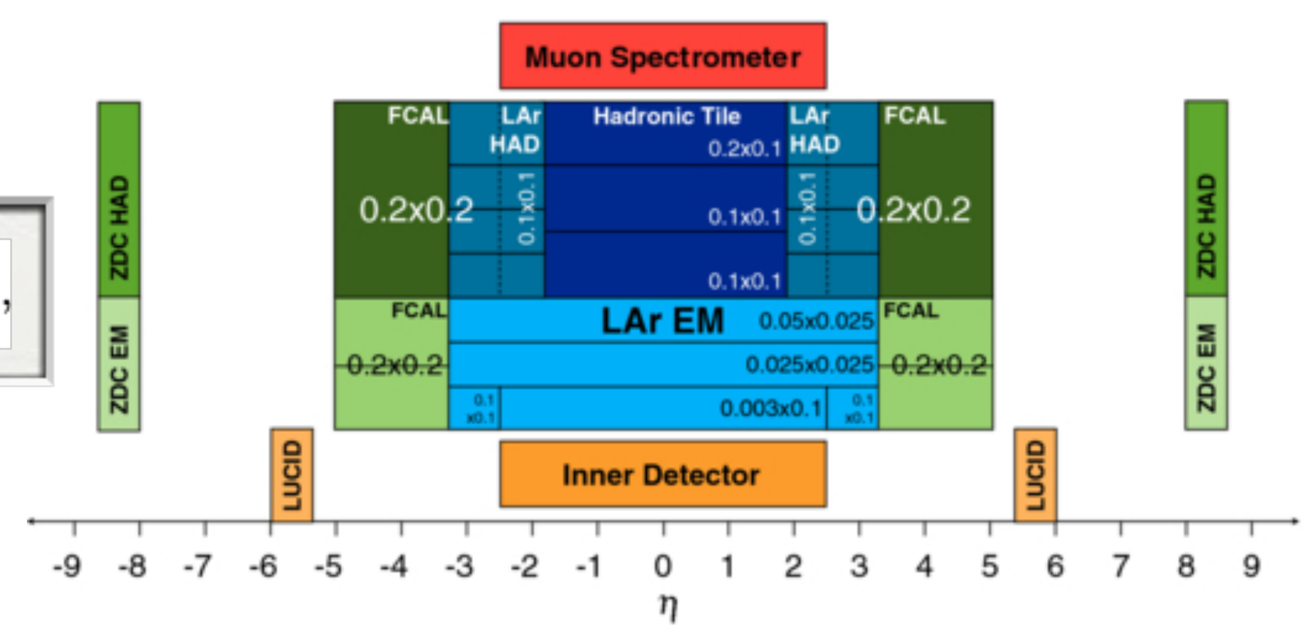
ϕ - full azimuthal acceptance

η- broad pseudorapidity coverage

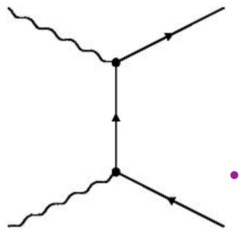
p_T - transverse momentum

$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$

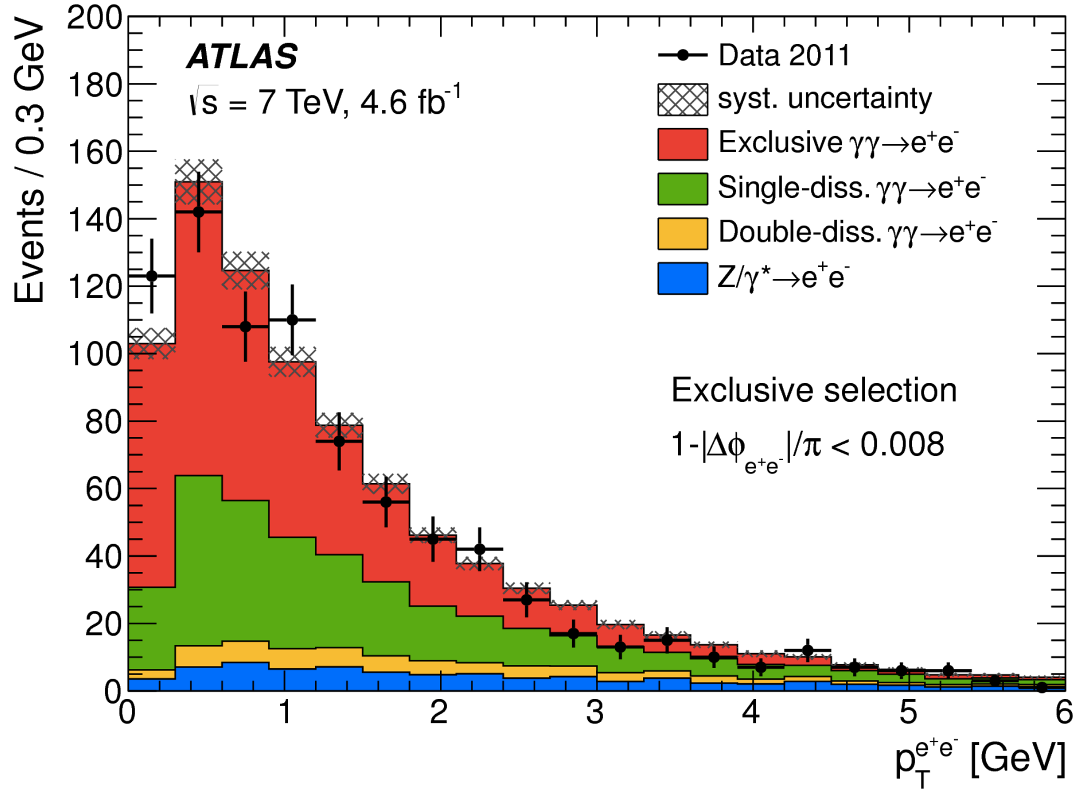
$$p_{\mathrm{T}} = \sqrt{p_{\mathrm{x}}^2 + p_{\mathrm{y}}^2}$$

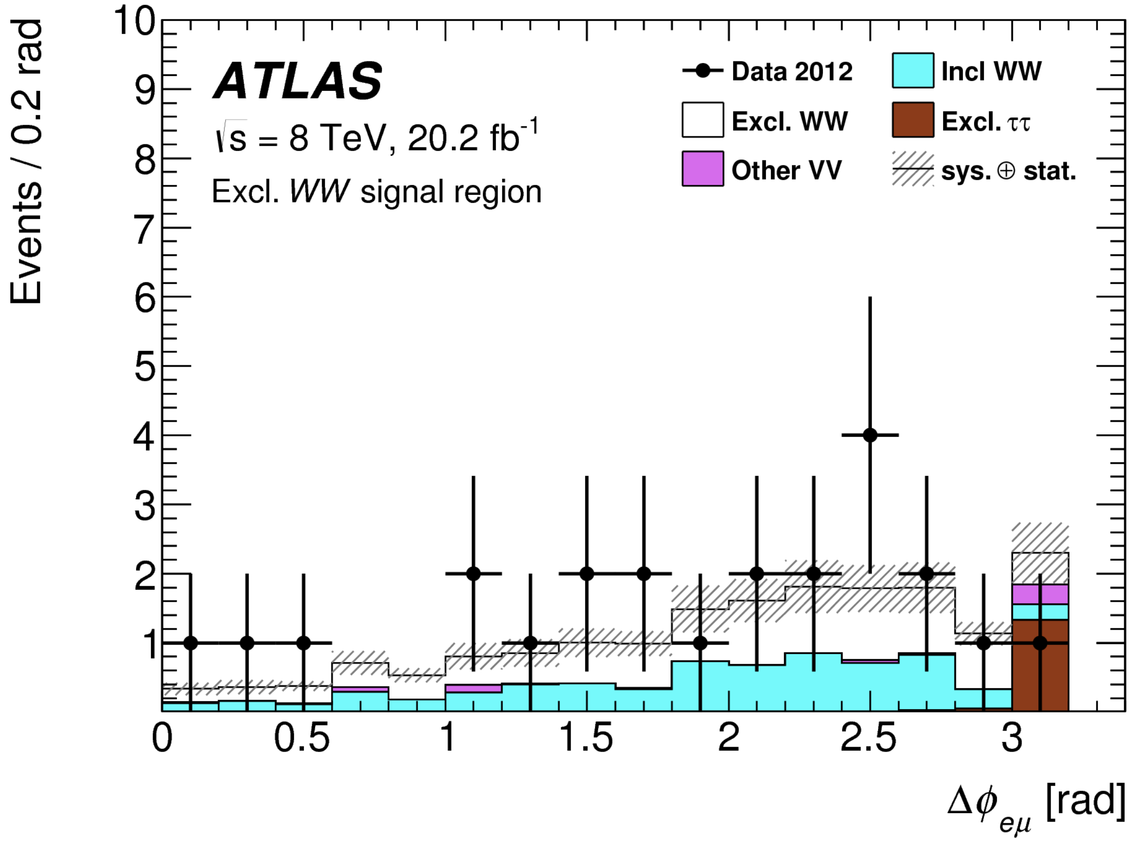


EXCLUSIVE MEASUREMENTS IN PP COLLISIONS

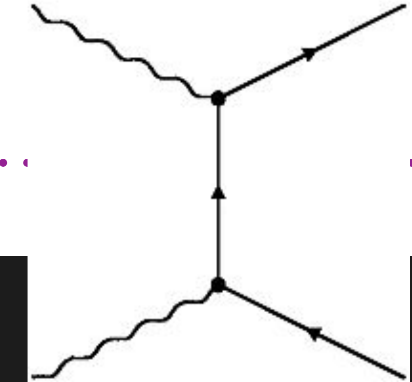


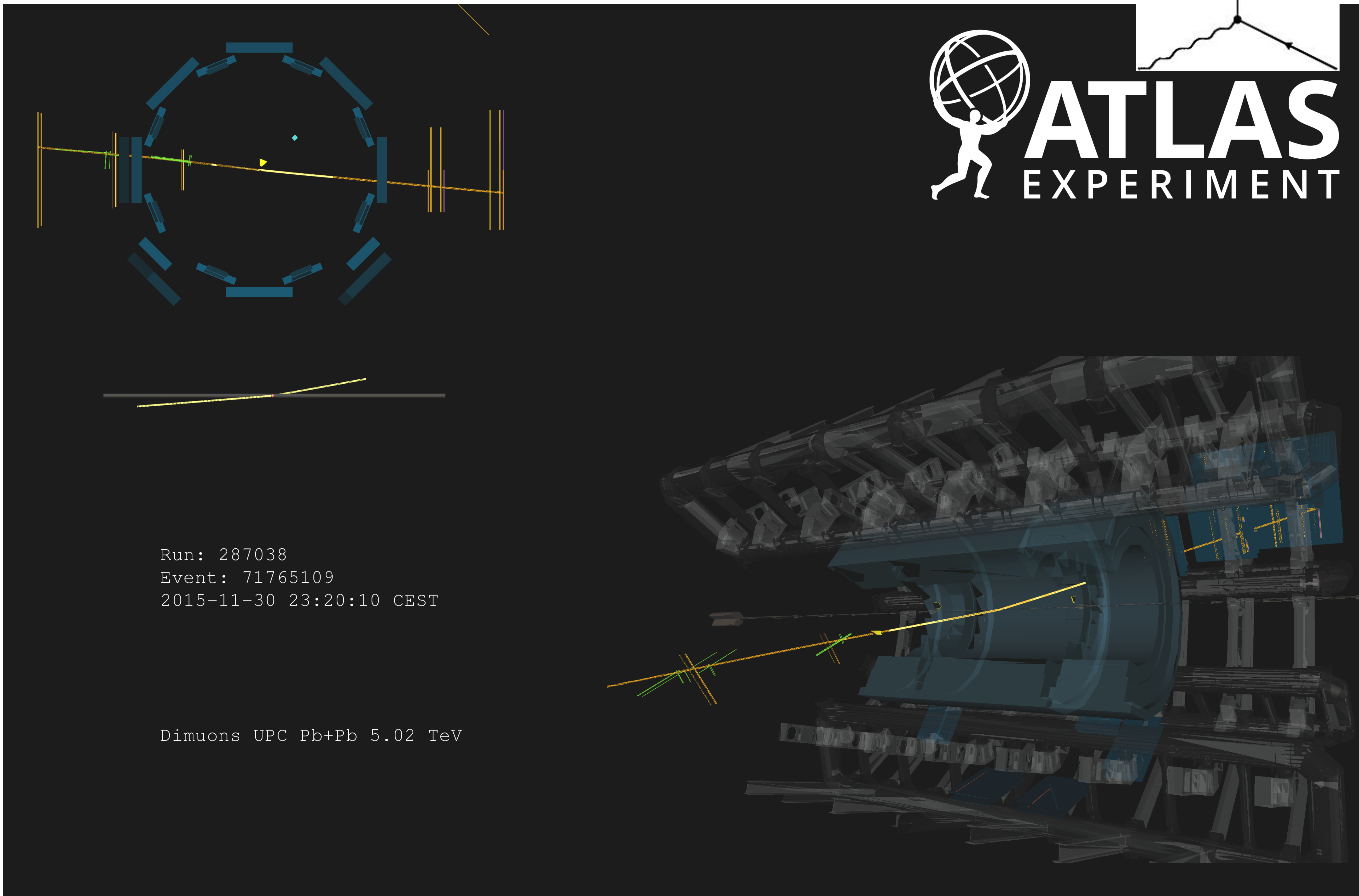
- $\gamma\gamma \rightarrow l^+l^-$ production PLB 749 (2015) 242-261
  - pp collisions at 7 TeV with 4.6 fb^{-1} of data
  - In agreement with Standard Model predictions
- $\gamma\gamma \rightarrow W^+W^-$ production PRD94 (2016) 3, 032011
  - pp collisions at 8 TeV with 20.2 fb^{-1} of data
  - Establish 3σ evidence for W^+W^- production which is consistent with theory
  - Search for $\gamma\gamma \rightarrow H^+H^-$, upper limit set to 1.2 pb





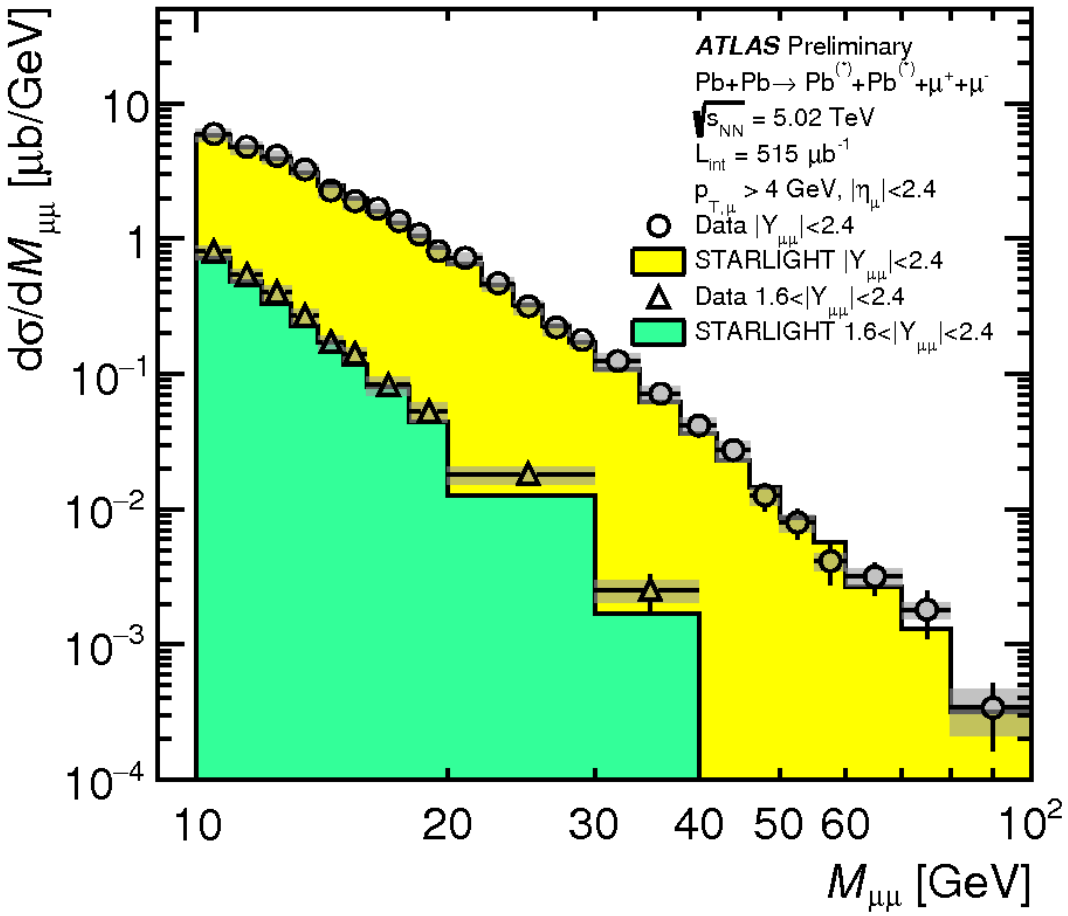
SINGLE EXCLUSIVE DI-MUON EVENT IN PB+PB

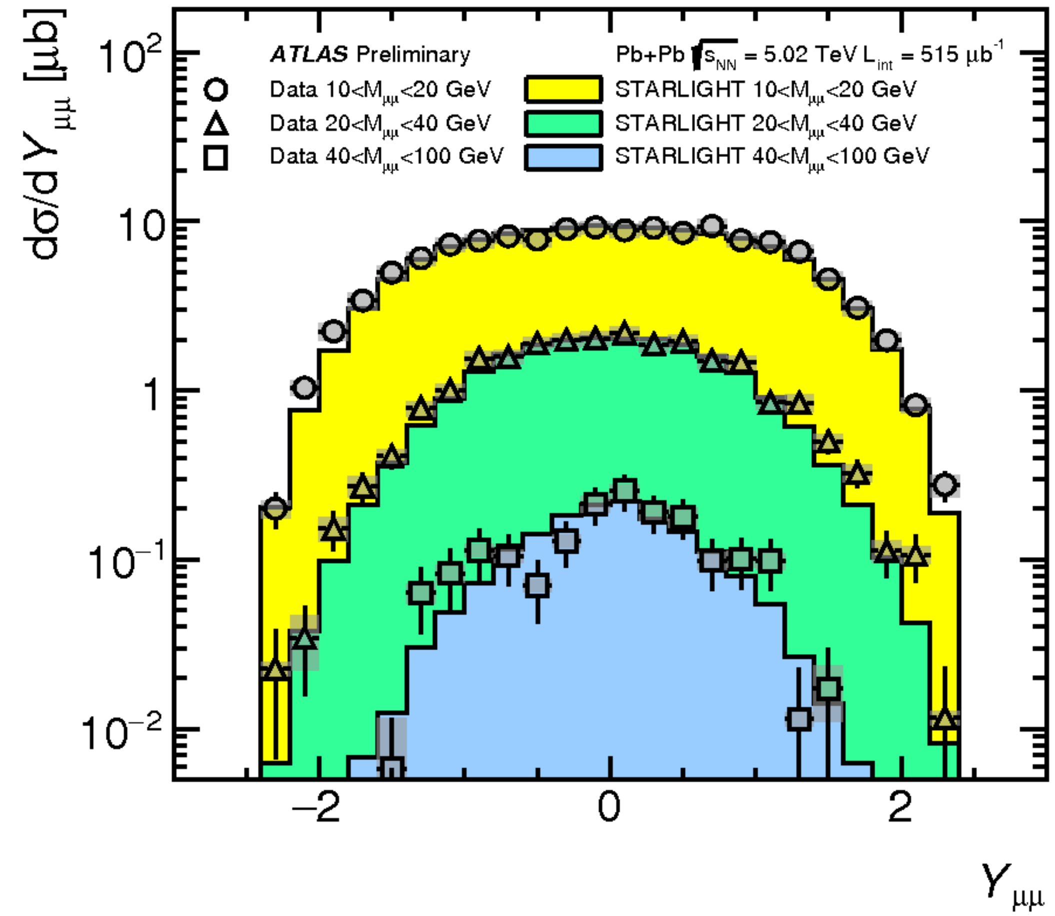




EXCLUSIVE DI-MUON PAIRS IN PB+PB COLLISIONS

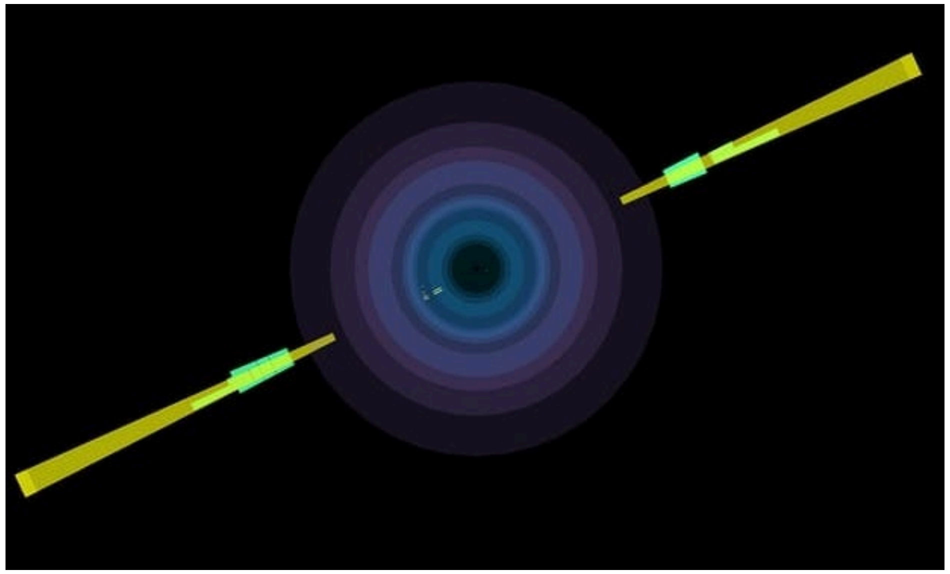
ATLAS-CONF-2016-025





- ATLAS measured the ɣ ɣ → 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 $Y_{\mu\mu}$ in Pb+Pb collisions at 5.02 TeV are extracted
  - 32.2±0.3(stat.) +4.0 −3.4 (syst.) μb and compared to predictions 31.64 ± 0.04(stat.) μb
- Data is compared to the theory predictions assuming signal comes from gamma-gamma interactions
  - Very good agreement found with Standard Model
- This is the most precise result for high di-muon masses at the LHC

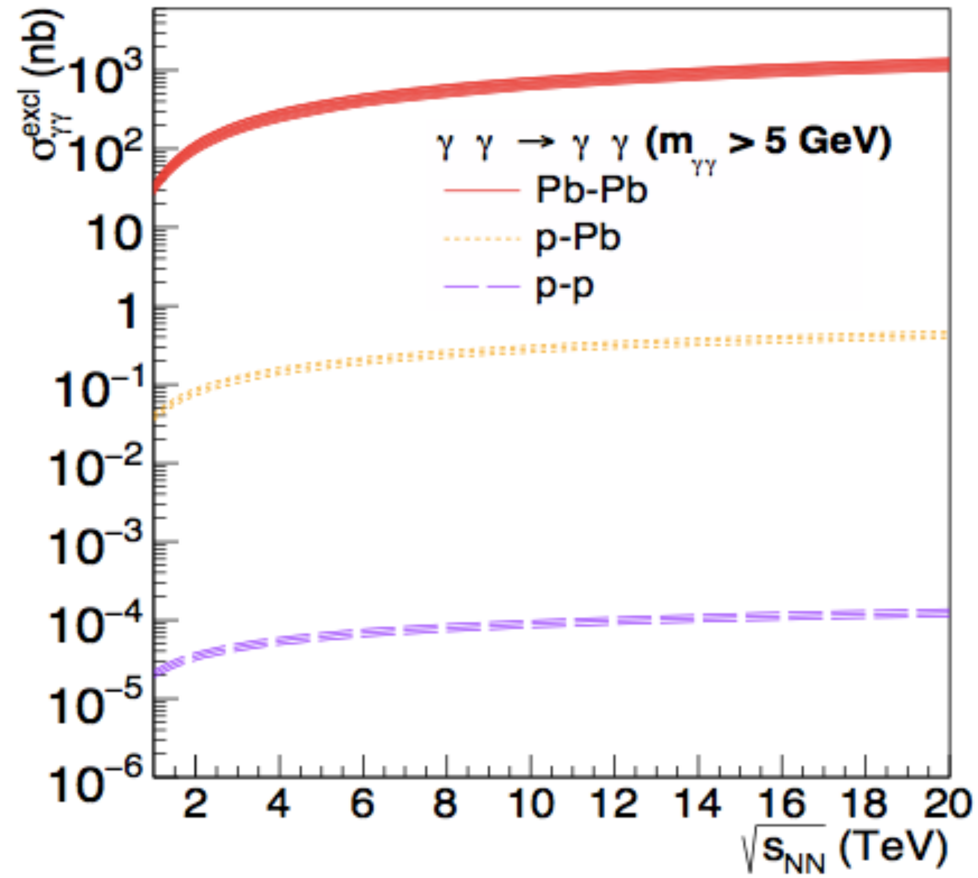
MEASUREMENT OF LIGHT-BY-LIGHT SCATTERING

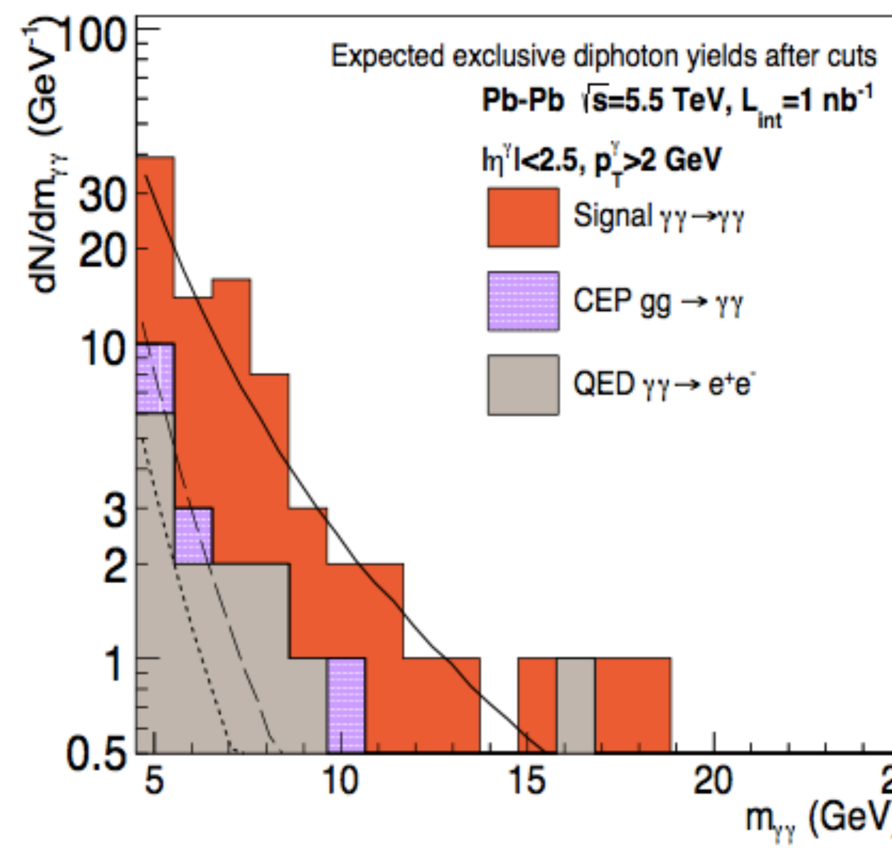


PREDICTIONS FOR LBYL AT THE LHC

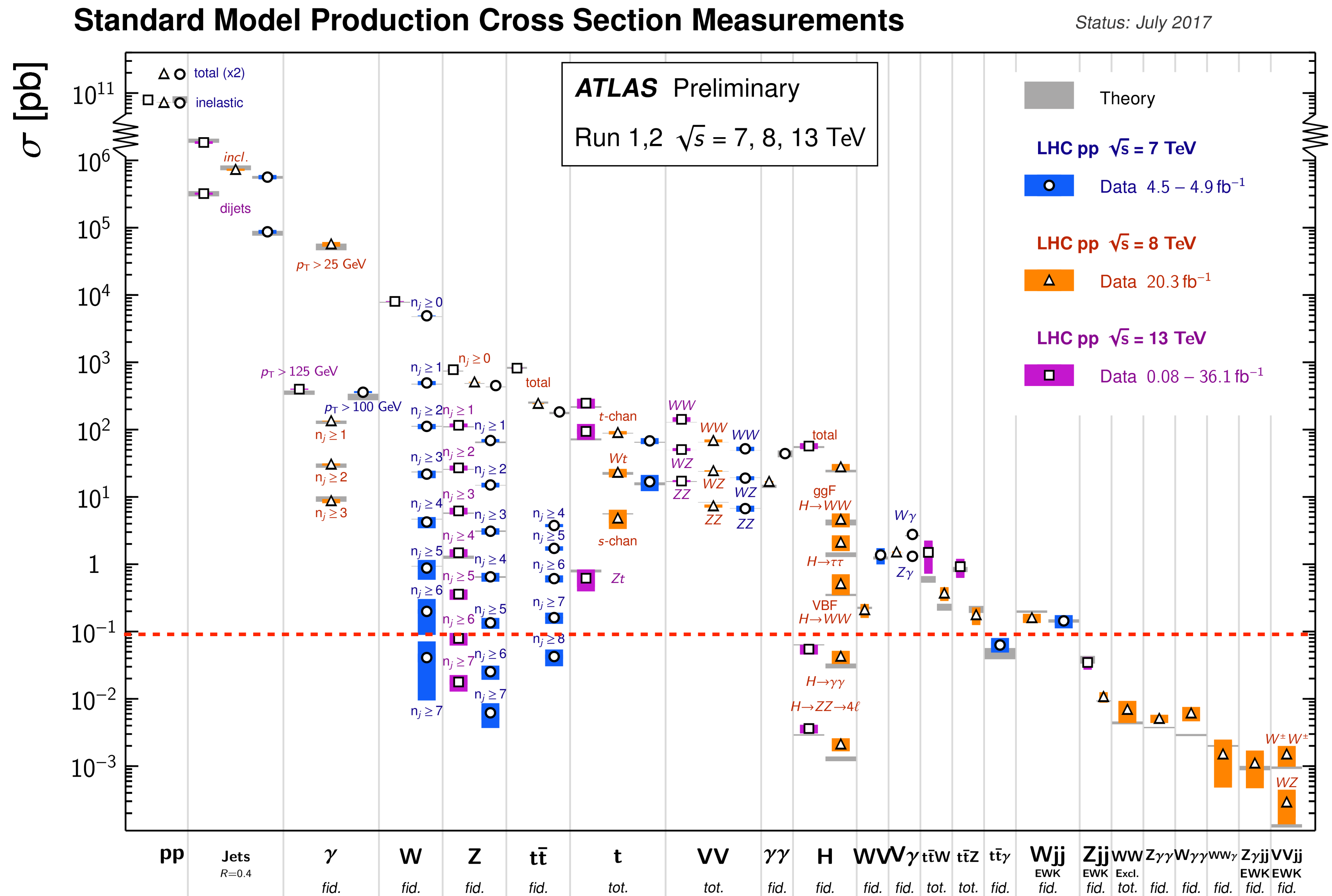
- The ATLAS LbyL measurement was inspired by two theory papers
  - From 2013: *Observation of LbyL scattering at the LHC* ([1] arxiv: 1305.7142) by D'Enterria (CERN) et al
  - From 2016: *LbyL scatterings in UPC at the LHC* ([2] arxiv: 1601.07001) by Szczurek (IFJ PAN) et al
- EPA theory applied to the LHC conditions
  - γγ luminosities are extremely enhanced for ion beams ($Z^4=5\times10^7$ for Pb beams)
  - First estimates prior to data taking were 18 events in 1 nb^{-1} predicted by [1] for $M_{\gamma\gamma}>5$ GeV, while [2] predicts ~8 times more
    - **Potentially could be seen at the LHC for the first time**
    - Erratum came later in Feb 2016 and made them consistent
  - Considered background processes
    - Relatively clean process for $M_{\gamma\gamma}>5$ GeV
    - Expected contributions from CEP gg → γγ and QED γγ → e^+e^-

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	*(3)* 12
p-Pb	8.8	200 nb^{-1}	4690	7.1	130	260	260 ± 26 pb	*(2)* 6
Pb-Pb	5.5	1 nb^{-1}	2930	7.1	80	160	370 ± 70 nb	*(18)* 70





CROSS SECTIONS IN PERSPECTIVE



- ➤ ATLAS measures cross sections for many Standard Model processes at 7, 8 and 13 TeV
- ➤ They span many orders of magnitudes
- ➤ In almost all cases excellent agreement with the Standard Model
- ➤ Red dashed line indicates a LbyL cross section in pp collisions at 14 TeV [1]

LBYL IN PROTON-PROTON OR LEAD-LEAD COLLISIONS?

System	$\sqrt{s_{NN}}$ (TeV)	$\mathcal{L}_{AB} \cdot \Delta t$ (per year)	γ	R_A (fm)	ω_{max} (GeV)	$\sqrt{s_{\gamma\gamma}^{max}}$ (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]
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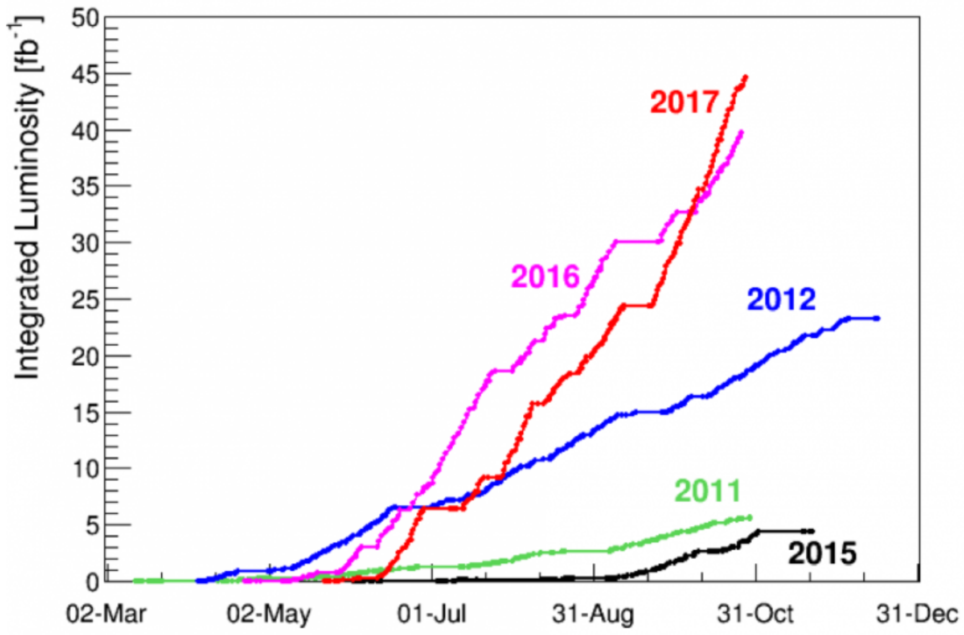
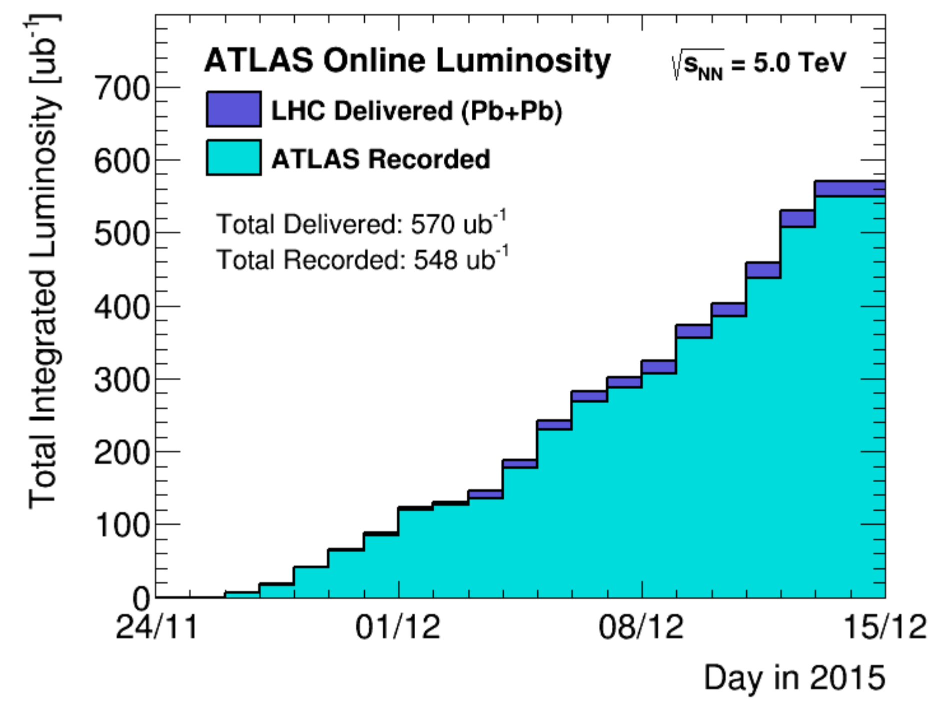
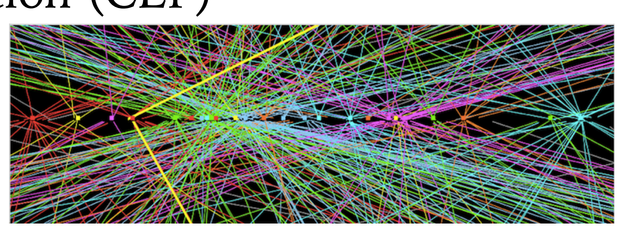
p-Pb	8.8	200 nb^{-1}	4690	7.1	130	260	260 ± 26 pb	6
Pb-Pb	5.5	1 nb^{-1}	2930	7.1	80	160	370 ± 70 nb	70





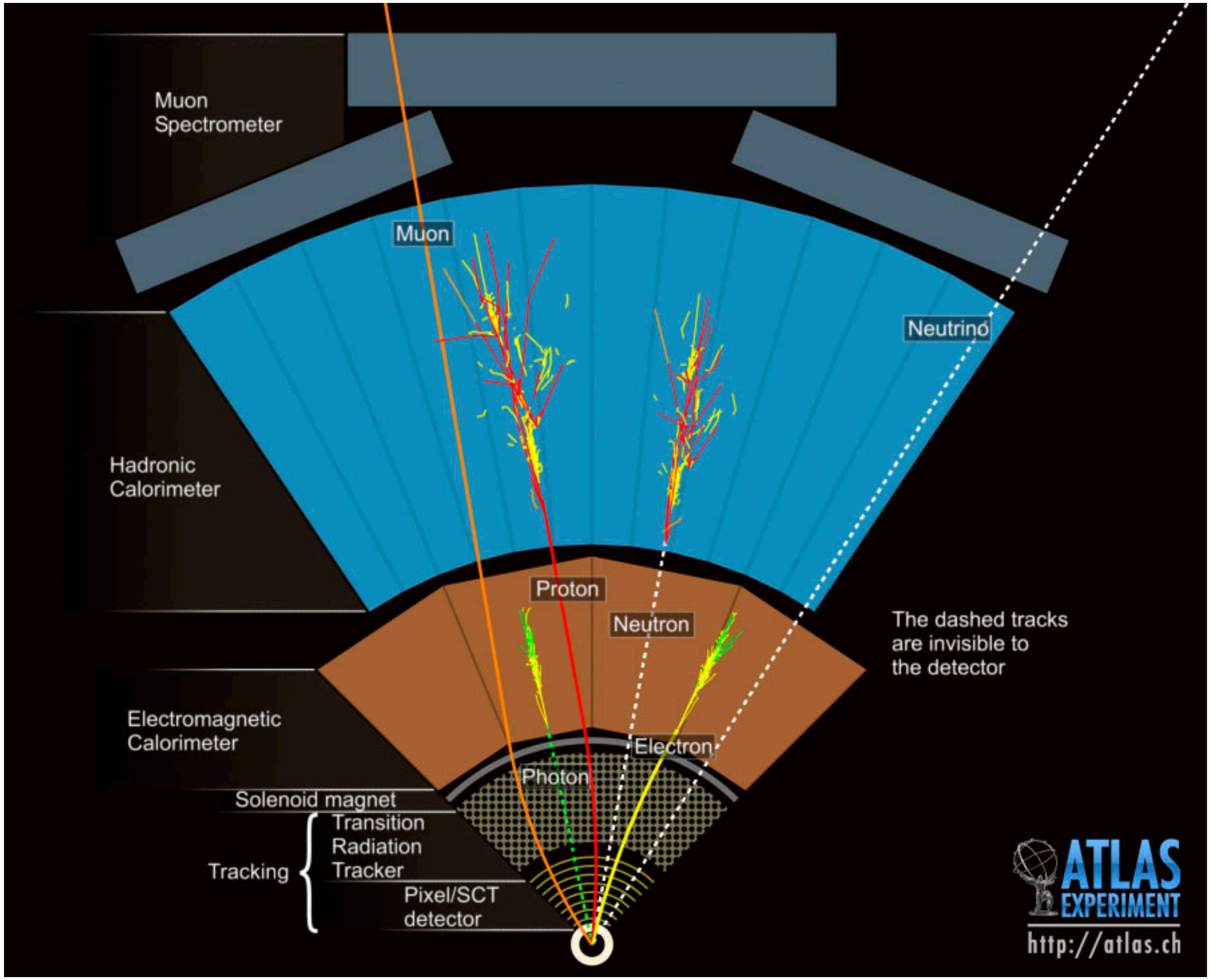
- LbyL in **proton-proton system**:
  - In total 100 fb^{-1} at 8 and 13 TeV —> ~1200 events
  - Harder photon spectrum
  - Larger pileup - in 2017 up to 60 simultaneous interactions
  - Larger backgrounds from Central Exclusive Production (CEP)



- LbyL in peripheral **lead-lead collisions**:
  - 0.5 nb^{-1} at 5.02 TeV —> ~35 events
  - Softer photon spectrum
  - Almost no pileup - very clean environment for photon studies
  - Background from CEP reduced

PHOTON IDENTIFICATION 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 a e+e- pair (next slide)

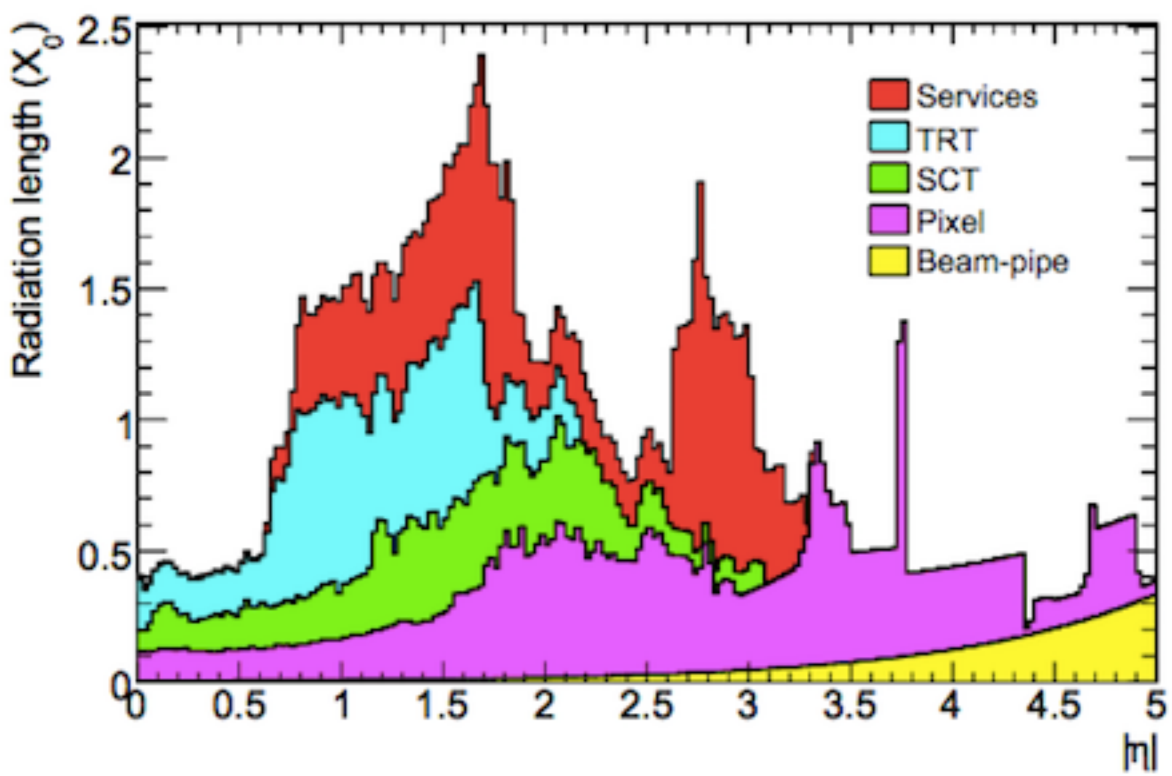


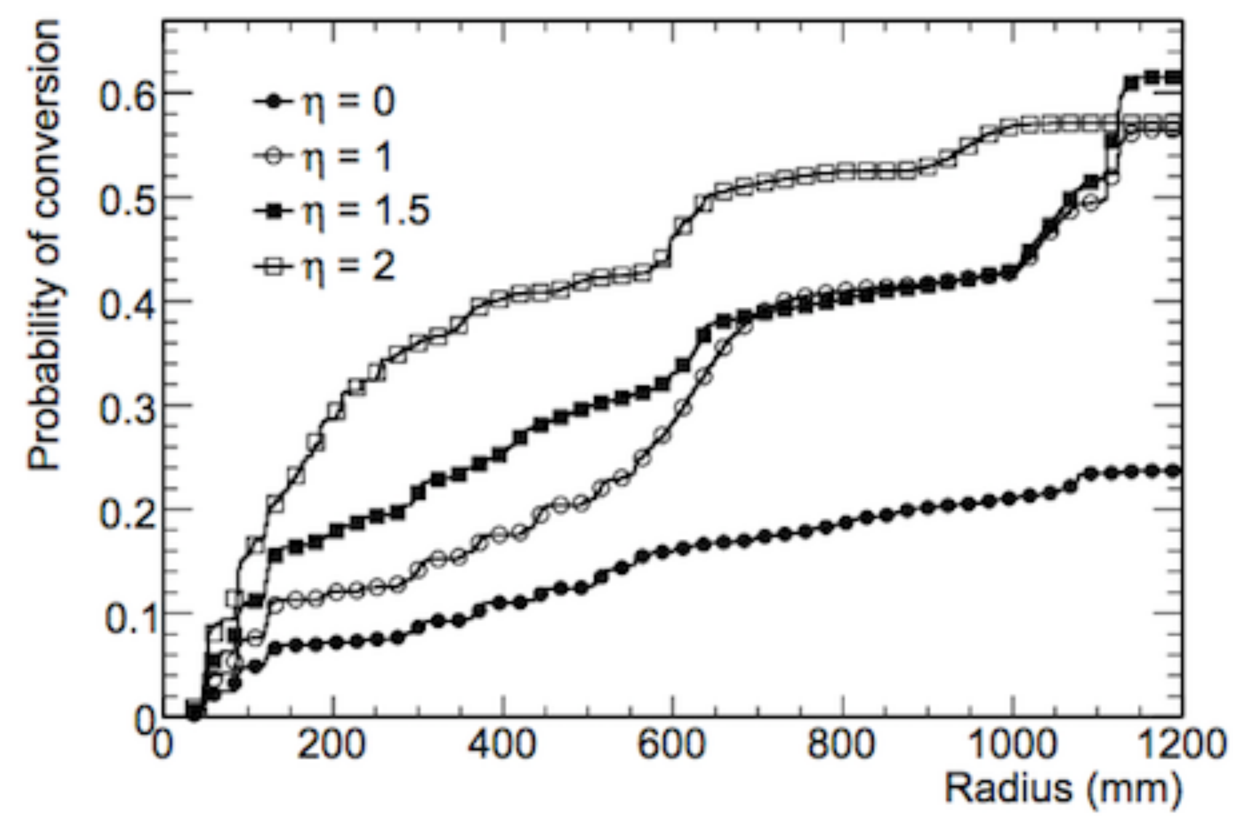
Possible issues:

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

PHOTON CONVERSIONS IN ATLAS

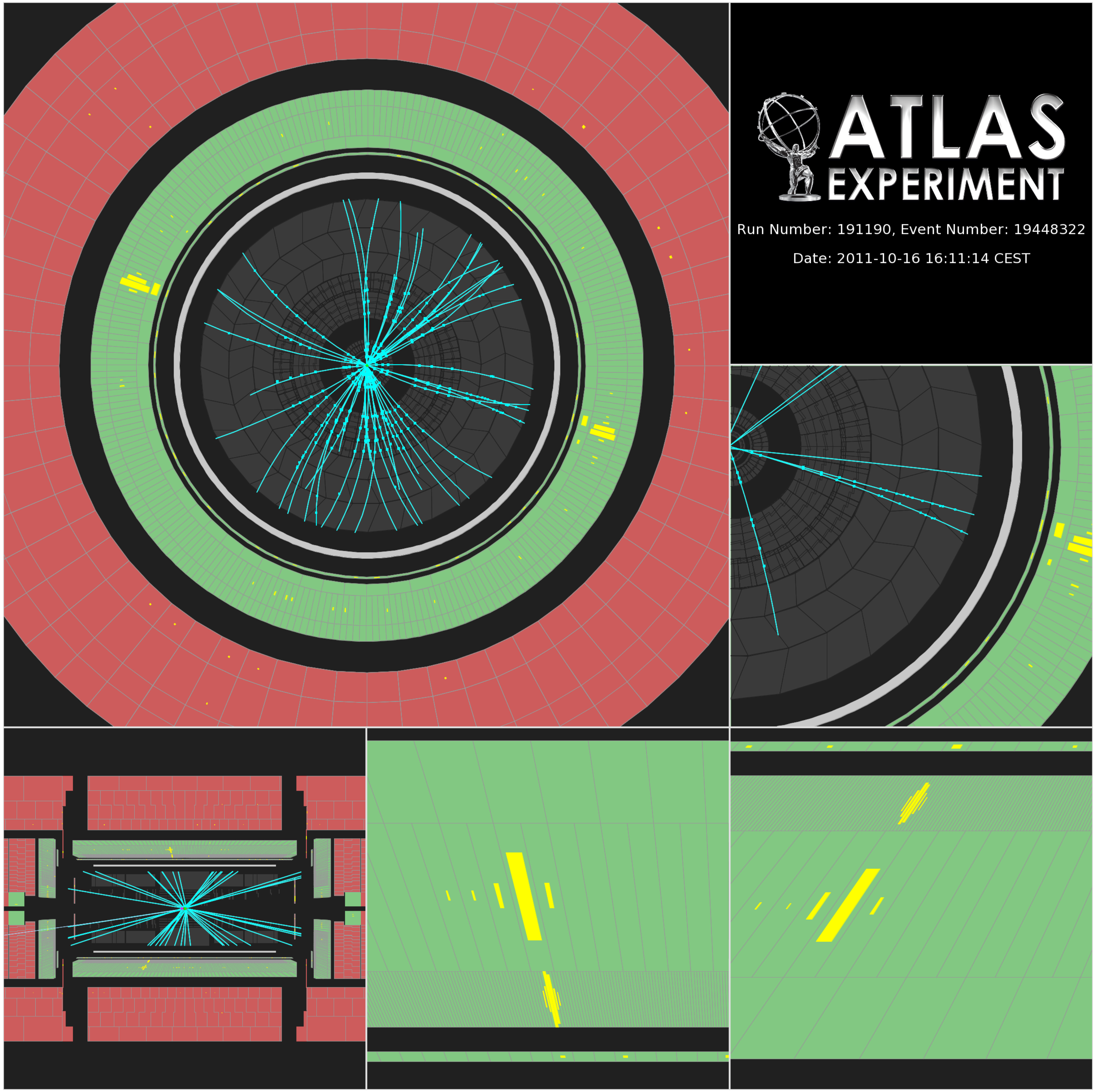
- There is a lot of inactive material in the ID which make a probability of photon conversion quite high
  - Weight: 4.5 tons
  - Active sensors and mechanics account each only for ~ 10% of material budget
- Momentum of the photon is not simply shared equally between the electron and the positron
  - Some fraction of the photon conversions will be highly asymmetric, and either the electron or the positron may be produced with very low energy
  - If energy falls below the threshold required to produce a reconstructable track in the ID, then the converted photon will be seen to have only one track, and will be difficult to distinguish from a single electron or positron

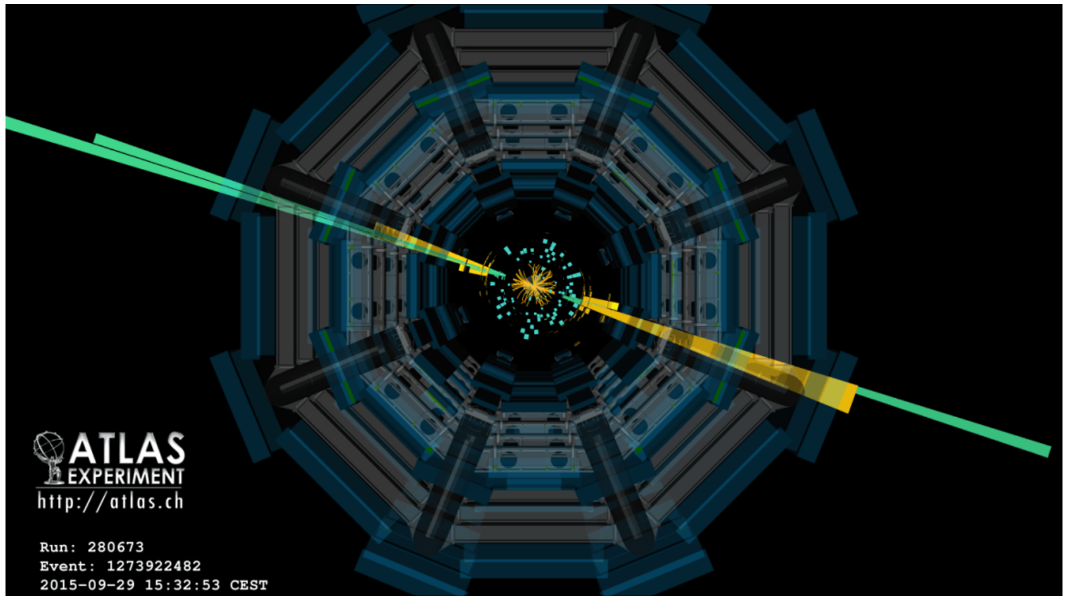




DI-PHOTON EVENT IN ATLAS

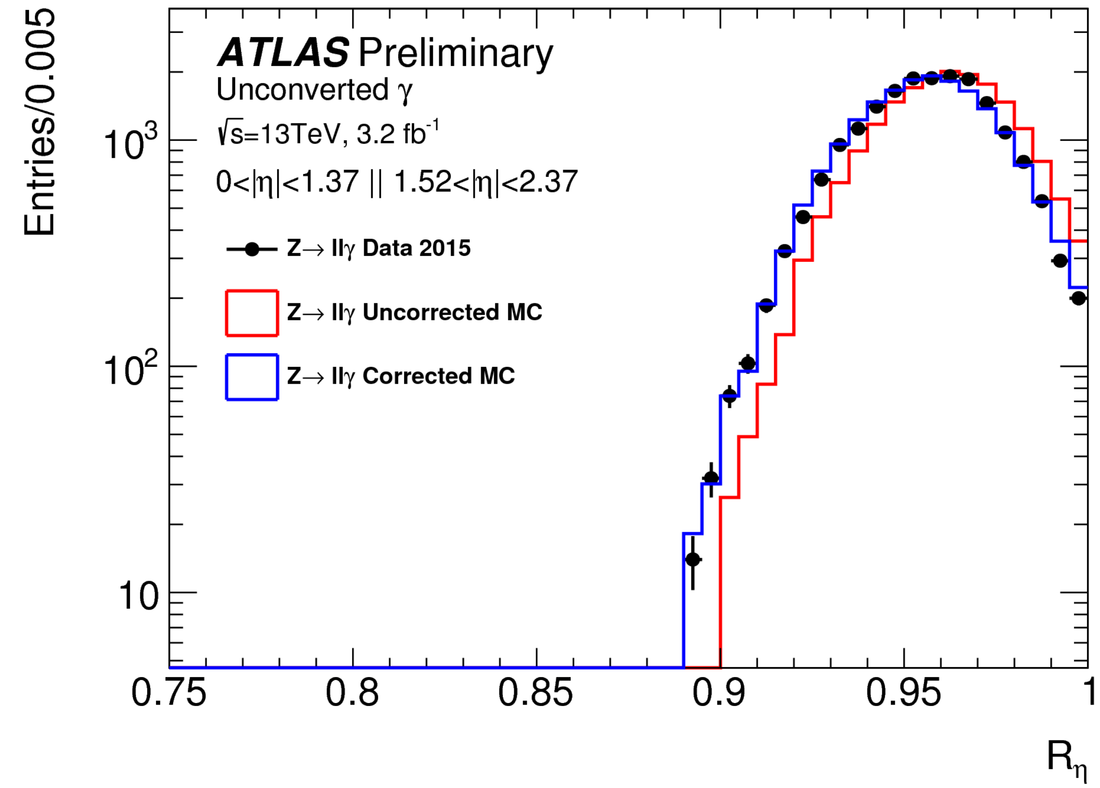
- ATLAS detector was designed to discover a Higgs boson which in the Standard Model decays to two photons
  - Large mass of di-photon system of 125 GeV, **single photon with p_T>30 GeV**
- Calorimeter has large granularity which helps in distinguishing between prompt photons and photons from pion decays

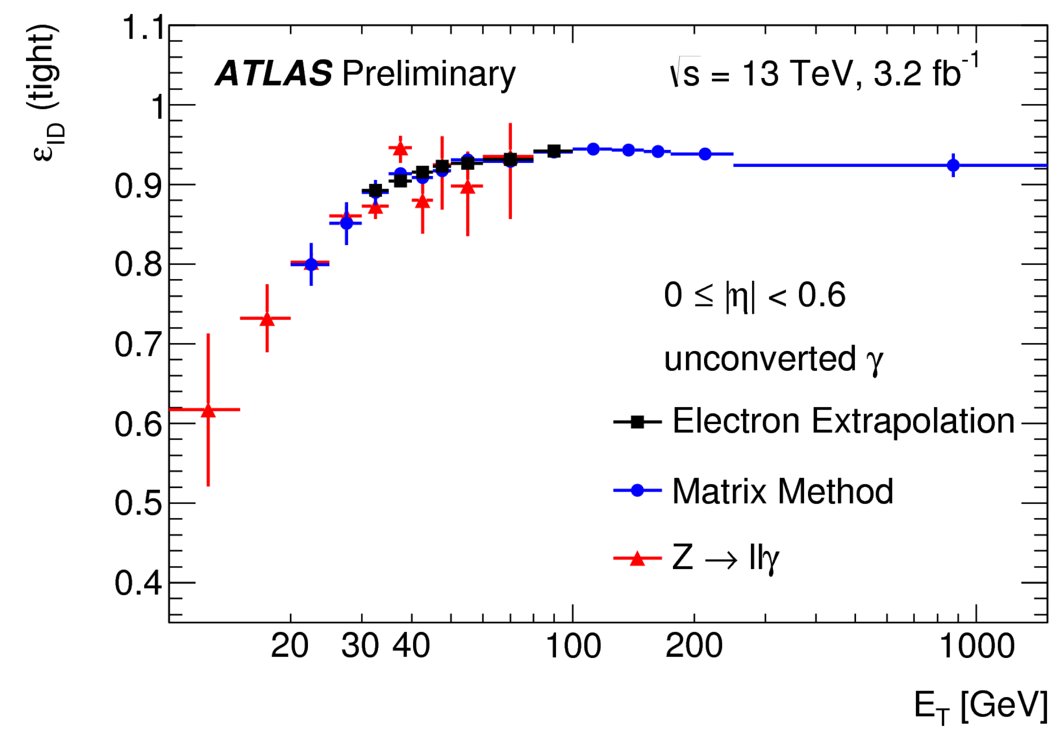




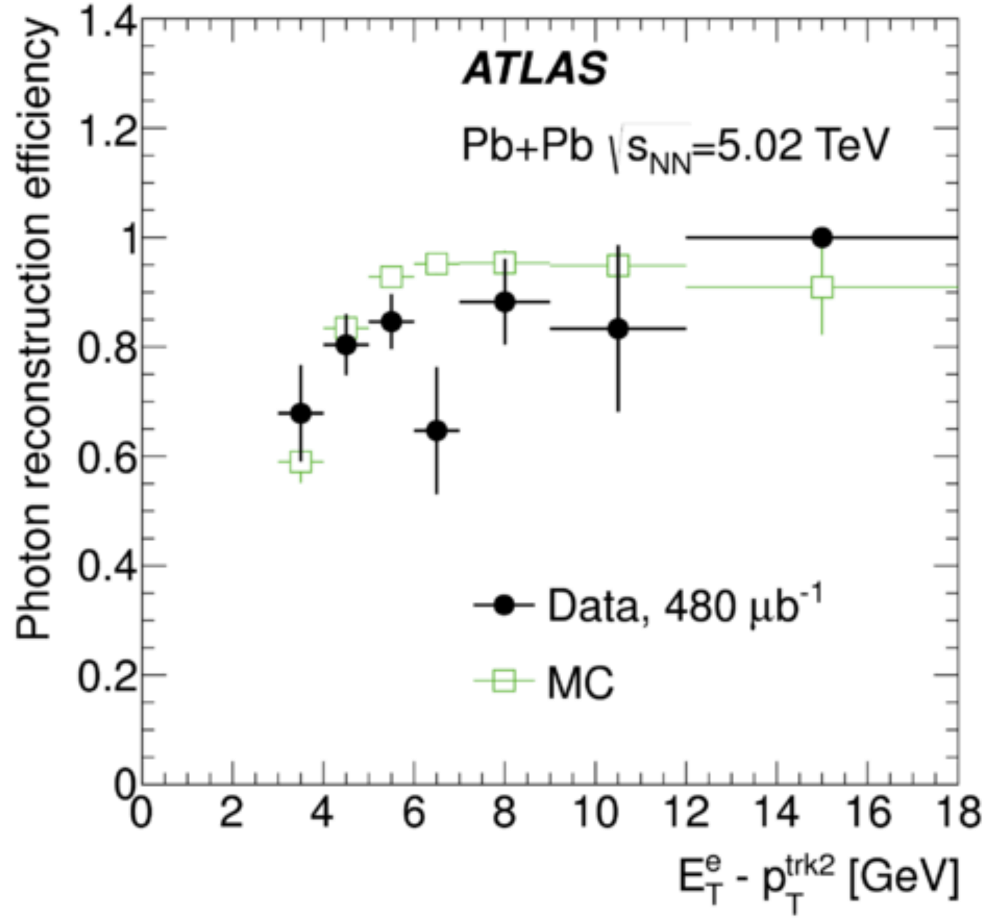
PHOTON IDENTIFICATION PERFORMANCE

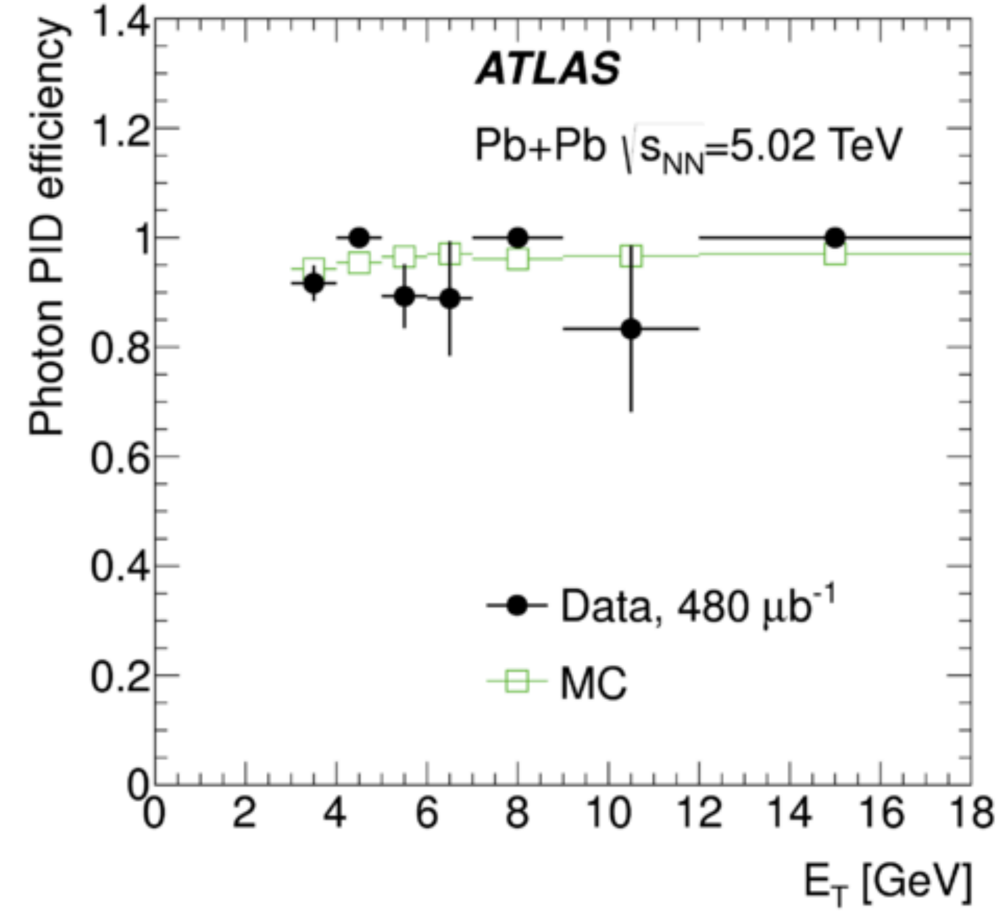
- ATLAS detector was designed to discover a Higgs boson which in the Standard Model decays to two photons
  - But Higgs has large mass 125 GeV, single photon with p_T>30 GeV
  - While LbyL photons are in the range 6-30 GeV, single photon with p_T>3 GeV
  - This posed a challenge for the analysis
- Very good description of photon shower shapes by Monte Carlo (MC) simulations
  - Important as some corrections are derived from MC
- Relatively low photon efficiency in the interesting region with photon 6<p_T<30 GeV
  - Without dedicated optimisation work, the signal could not be seen





LOW-PT PHOTON PERFORMANCE



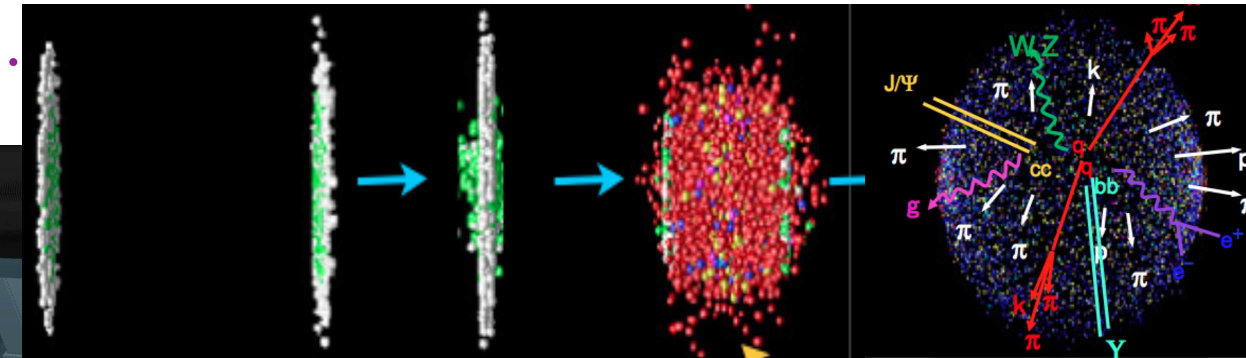


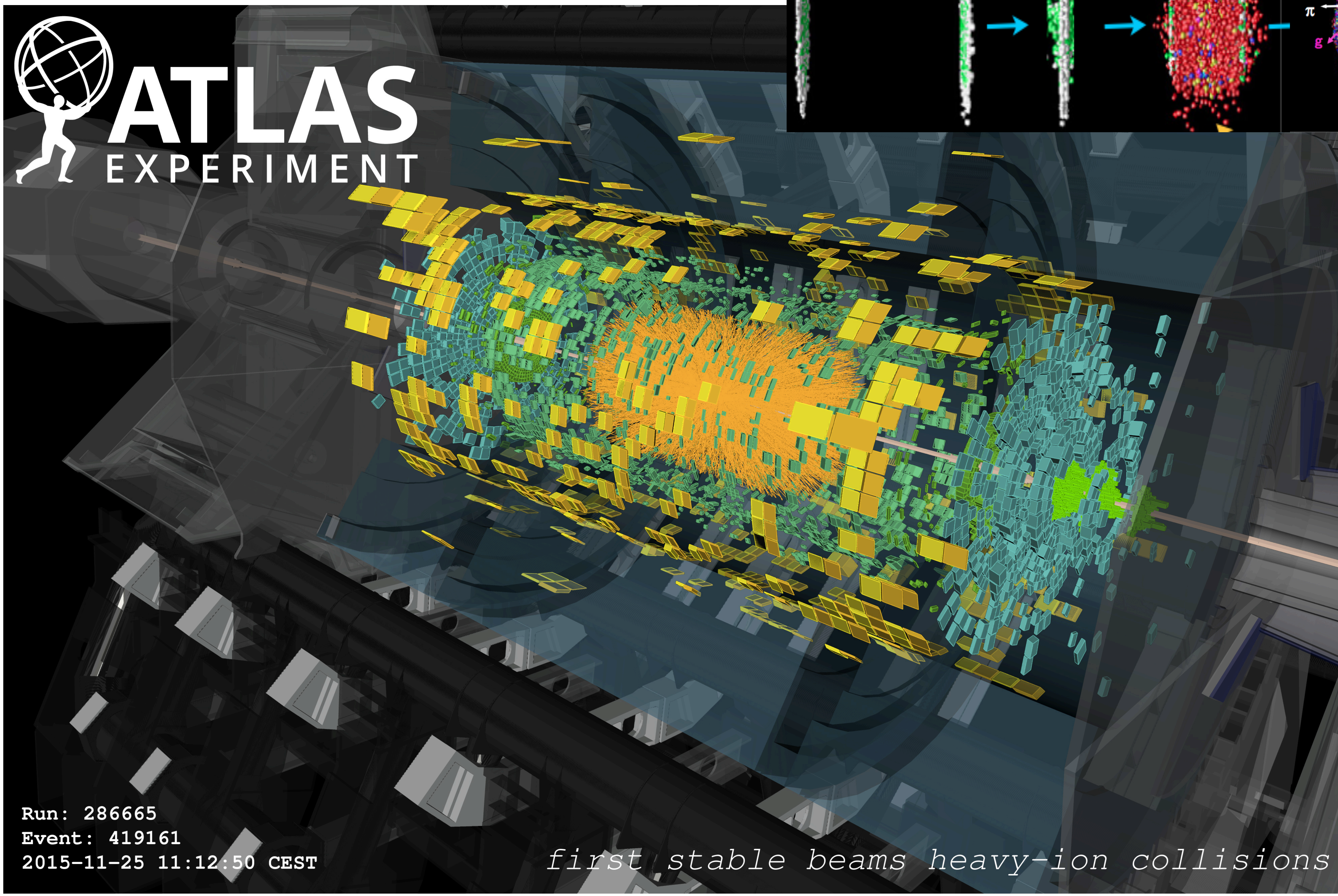
- Default ATLAS photon identification is not optimal for low-p_T photons from LbyL
  - Photon identification efficiency is below 50%, for two photons - below 25%
- Dedicated optimisation for photons resulted in very good performance
  - 95% photon identification efficiency

TRIGGER: HEART OF ATLAS

- Interaction rate:
  - 40 MHz in pp collisions
  - 200 kHz in Pb+Pb collisions
- ATLAS can record and analyse about 1 kHz
  - In 2015 it was even 700 Hz for Pb+Pb
- Trigger: online filtering system
  - Rejects 99.998% events in pp, and 99.5% events in Pb+Pb
  - Has to be inclusive not to miss potential signal
  - If one wants to measure a given process one has to have a dedicated trigger to select event candidates online
  - AGH UST was in charge of coordination of trigger preparations to the 2015 Pb+Pb run

TYPICAL PB+PB EVENT IN ATLAS



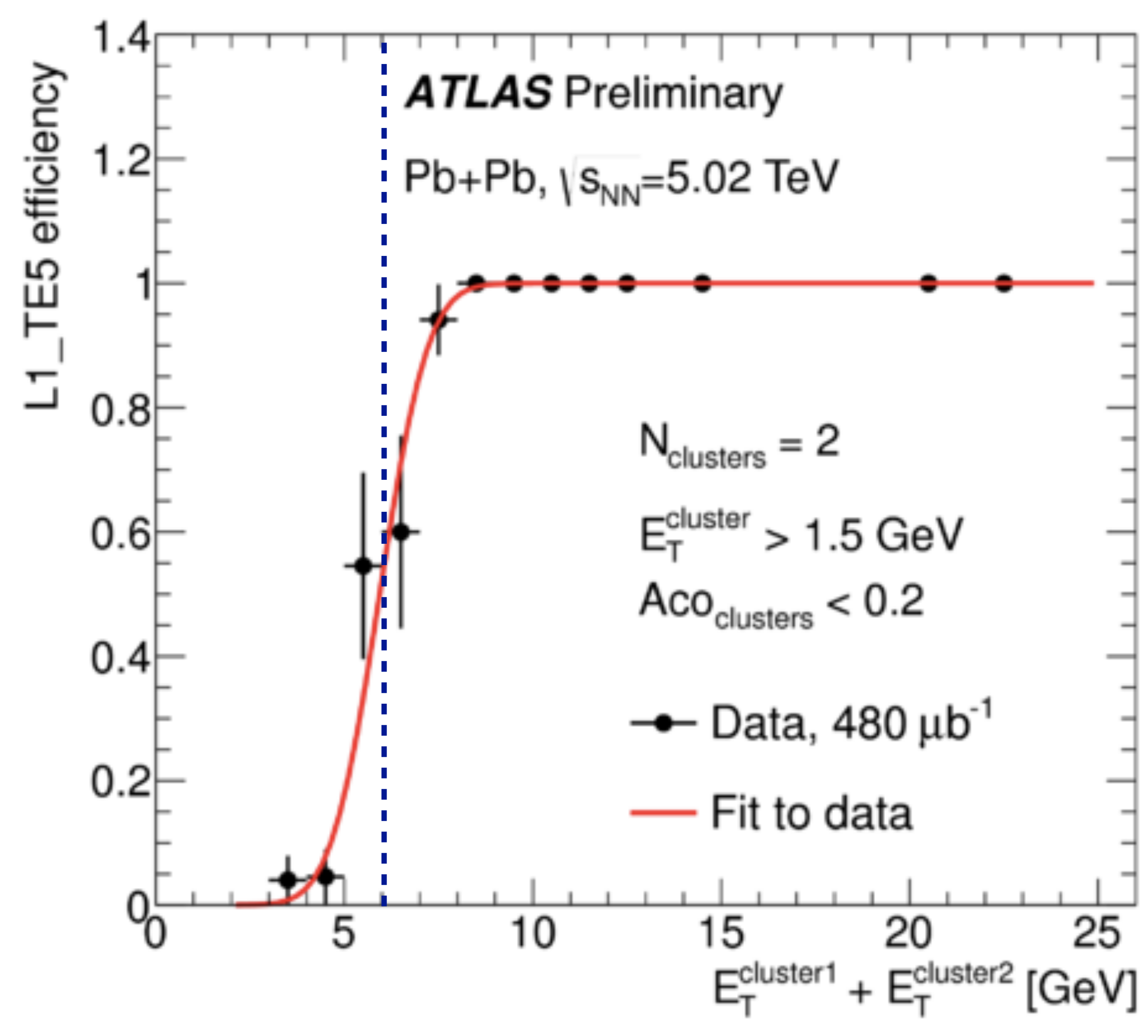


- A lot of activity in the entire detector
- It is a challenge to trigger and then reconstruct these events

TRIGGER FOR LOW-PT PHOTONS

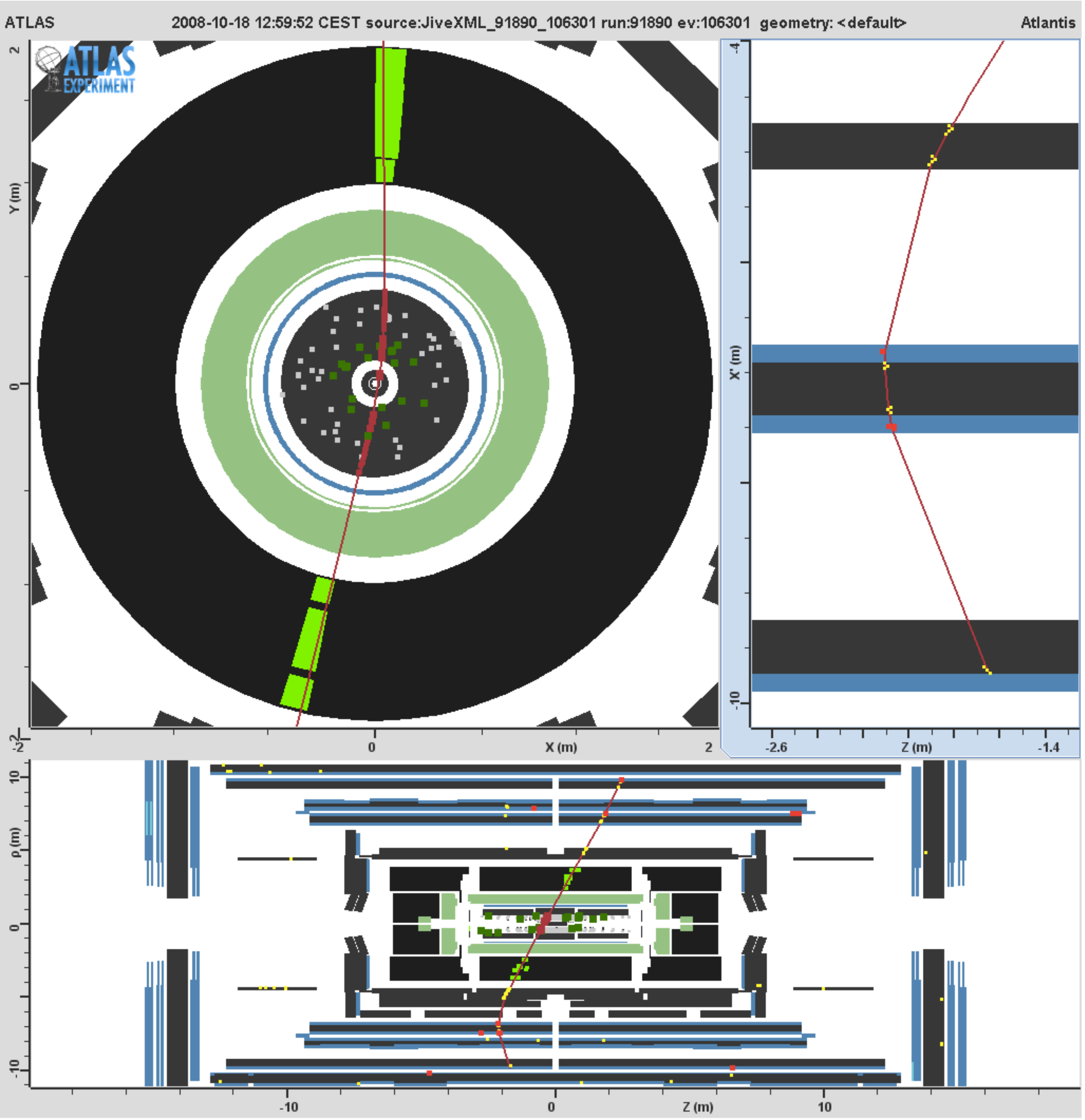
- Dedicated trigger for LbyL was implemented shortly before data taking in 2015:
  - Expected O(10) signal events out of 4 billion interactions
  - Total energy in the calorimeter > 5 GeV
  - Reject events with higher energy > 200 GeV
  - No activity in the forward detector (MBTS)
  - Maximum number of hits in the ID detector allowing for max four tracks from photon conversions

- Efficiency grows from 70% at 6 GeV to 100% at 9 GeV, not very well controlled below 6 GeV
- The analysis limited to **$M_{\gamma\gamma}$>6 GeV** which leads to the reduction in the cross section by a factor of TWO

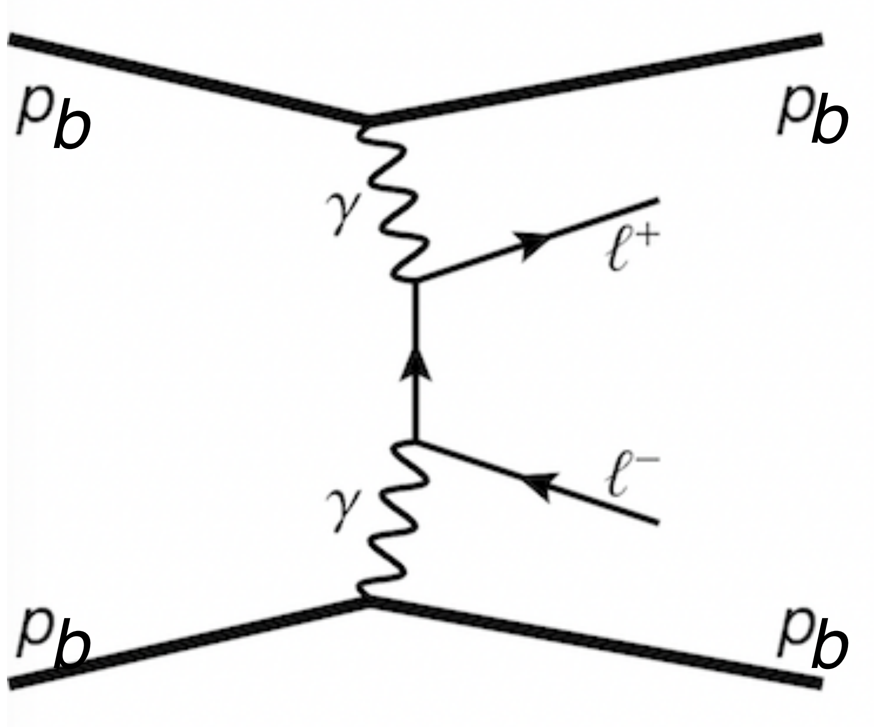


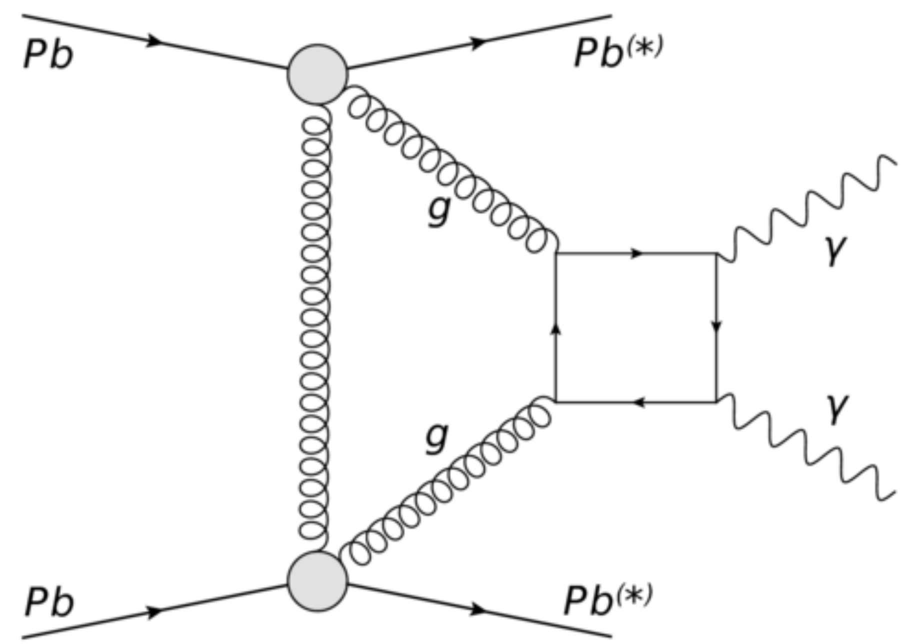
BACKGROUND PROCESSES: COSMIC MUONS

- Very detailed background studies:
- What process can mimic two photons in Pb+Pb collisions at the LHC?
- **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



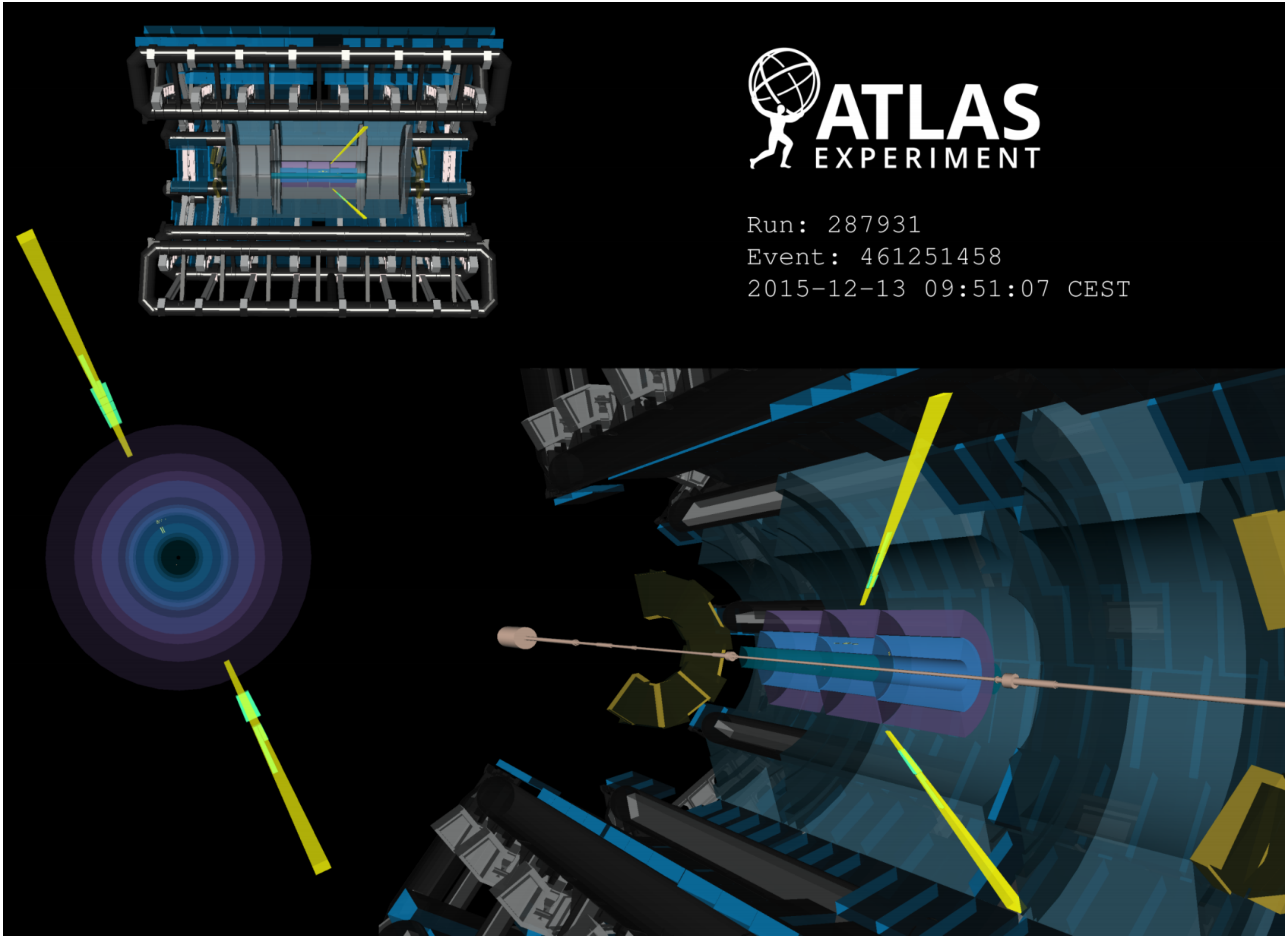
BACKGROUND PROCESSES WITH ELECTRONS AND PHOTONS





- Very detailed background studies:
  - What process can mimic two photons in Pb+Pb collisions at the LHC?
  - Exclusive production of electron pairs: ɣ ɣ → e+e-
    - Very high cross section α^2_{em} higher comparing to LbyL
    - Electron and photons are distinct objects: electrons deposit tracks
    - What about if tracks are not measured in the ID?
    - Production precisely known from QED, this background can be evaluated and subtracted
  - Central Exclusive Production: gg → ɣ ɣ
    - Signature is the same as for LbyL, authors of [1] demonstrated that its contribution is very low in Pb+Pb collisions
  - Also other rare processes considered

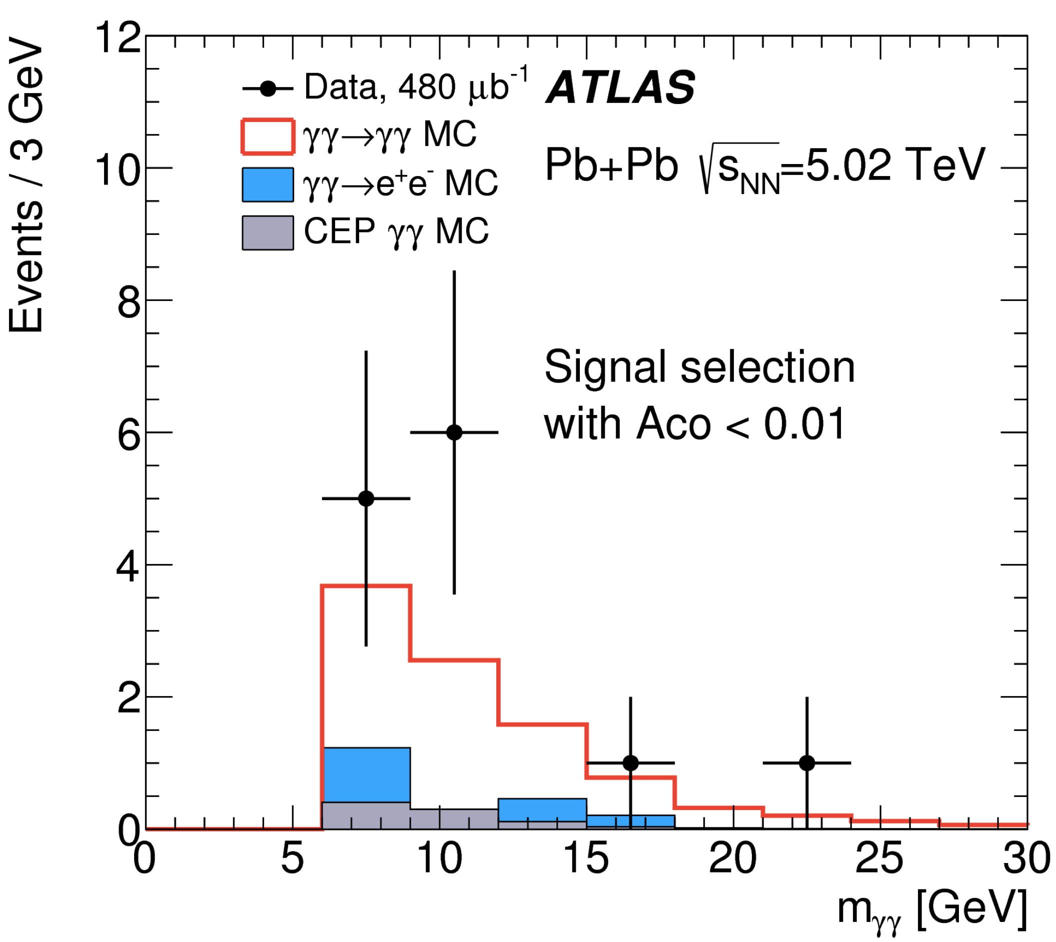
SINGLE LIGHT-BY-LIGHT EVENT



LIGHT-BY-LIGHT SCATTERING: RESULTS

[Nature Physics 13, 852–858 (2017)]

- Search for signal diphoton candidates:
  - Two photons with E_T>3 GeV and $M_{\gamma\gamma}$>6 GeV
  - Backgrounds subtracted from exclusive di-electron production and centra-exclusive production (CEP)
- Excess in the data consistent with the LbyL signal from Standard Model
  - **First direct evidence of the light-by-light signal**



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	

Signal significance: **4.4σ**, expected significance: 3.8σ

Measured cross section:

σ_{fid}=70±20 (stat) ± 17 (syst) nb

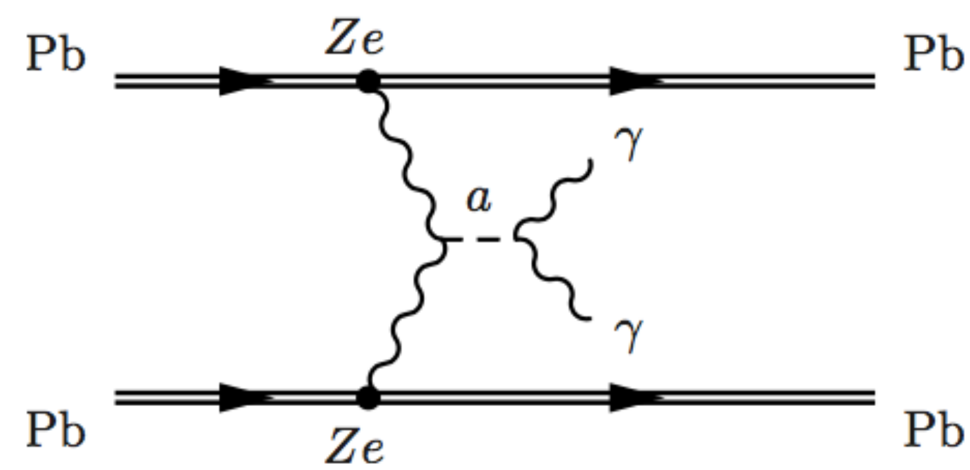
In agreement with Standard Model [arXiv: 1601.07001, 1305.7142]

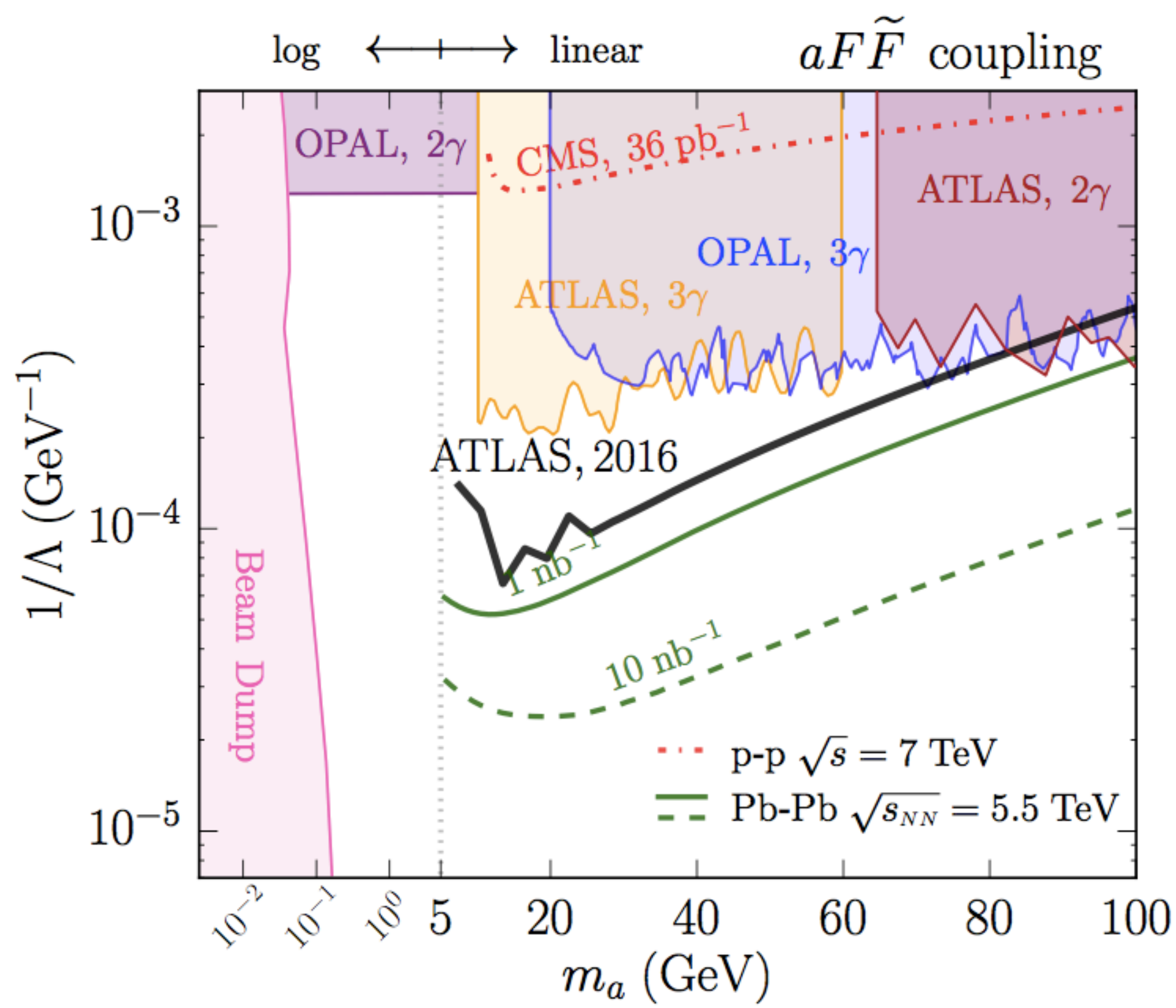
Looking forward to more events in 2018 Pb+Pb run

ARTICLES
PUBLISHED ONLINE: 14 AUGUST 2017 | DOI: 10.1038/NPHYS4208
nature physics

BSM SEARCHES: AXIONS

- ATLAS LbyL measurement allowed to constrain axion production
- Search for axion at the LHC
- Axion: hypothetical particle proposed in 1977
  - Interaction: gravity, electromagnetic
- If it exists: it is a possible component of cold dark matter
- Paper by Simon Knapen et al arXiv:: 1709.07110





1 Introduction

The LHC has completed its highest luminosity heavy-ion collision run (Pb-Pb), with ATLAS, CMS and ALICE all recording data at a centre-of-mass energy per nucleon of $\sqrt{s_{NN}} = 5.02$ TeV. In previous work [1] we showed that the large charge of the lead ions ($Z = 82$) results in a huge Z^4 coherent enhancement in the exclusive production of axion-like particles (ALPs) that couple to electromagnetism, which can lead to competitive limits for ALPs. This proceeding is an update to our previous work; we recast the analysis of the ATLAS 480 μb^{-1} data set [2] to provide limits on ALPs in the mass region 10 GeV $< m_a <$ 100 GeV. In line with the projections in [1], we find that the LHC heavy-ion data provides the strongest limits to date in this parameter range. While the physics potential of exclusive heavy ion collisions has been known for decades [3–5], to our knowledge this represents the first time LHC heavy-ion data sets the most stringent limit on a specific beyond the Standard Model physics scenario.

BSM SEARCHES: MAGNETIC MONOPOLES

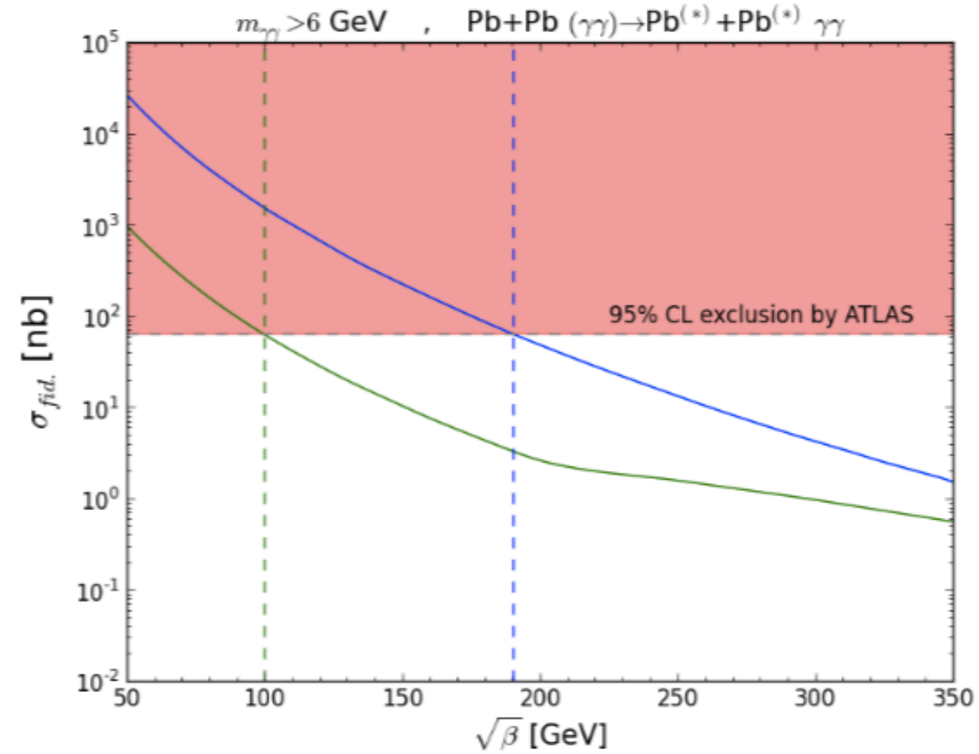
- In 1934 Born and Infeld a conceptually distinct nonlinear modification of the Lagrangian of QED

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

  - where β is an a priori unknown parameter with the dimension of [Mass]², $\beta \equiv M^2$

- 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 was pointed out that a a finite-energy electroweak monopole is a solution which is a consequence of the BI theory

- 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:

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

$$M_{\rm monopole} \geq 11 \text{ TeV}$$

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.

SUMMARY AND OUTLOOK

- Light-by-light scattering - a fundamental QED process - was measured directly by the ATLAS experiment at the LHC for the first time
  - AGH UST was a leading institute in the analysis team
  - 13 events were observed with a contribution of 2.6 background events —> 4.4 sigma evidence
  - Measurement is consistent with Standard Model
  - Published in Nature Physics in August 2017 *Nature Physics 13, 852–858 (2017)*
- LbyL is sensitive to beyond-Standard Model physics
  - Various theory groups used the ATLAS result to set up limits on their BSM predictions
    - Axions, monopoles, etc.
- Looking into the future:
  - Ongoing preparations to the 2018 Pb+Pb run: expected 0.5 nb^{-1} of data
  - Expected 10 nb^{-1} in Run 4 with the upgraded ATLAS detector

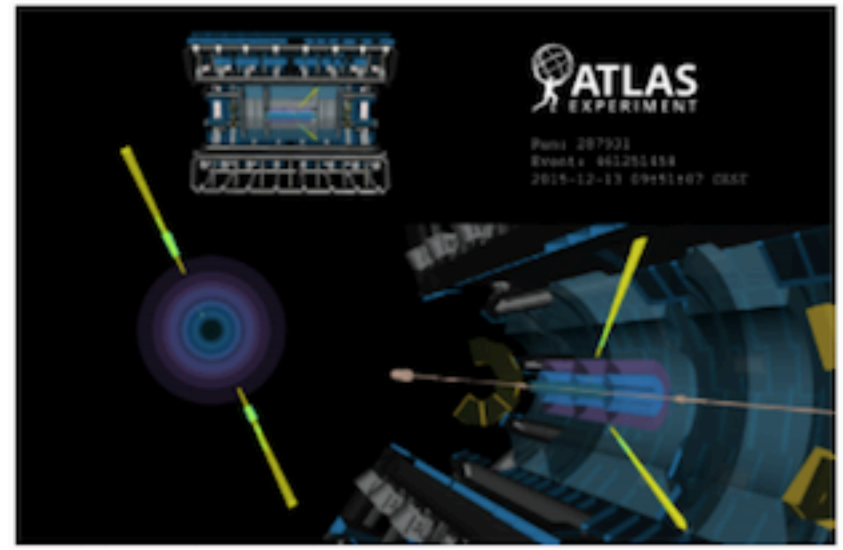
MORE ON LBYL

Press Statements

Press Statement

ATLAS sees first direct evidence of light-by-light scattering at high energy

14th August 2017 – Geneva, 14 August 2017. Physicists from the ATLAS experiment at CERN have found the first direct evidence of high energy light-by-light scattering, a very rare process in which two photons – particles of light – interact and change direction. The result, published today in Nature Physics, confirms one of the oldest predictions of quantum electrodynamics (QED).



Read more →

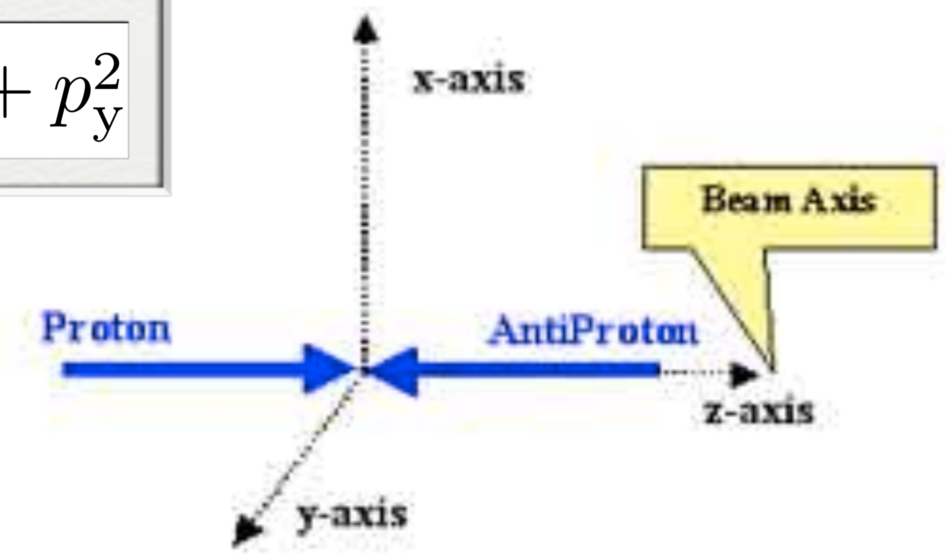
- ATLAS press statement: http://atlas.cern/updates/press-statement
- CERN press statement: https://home.cern/about/updates/2017/08/atlas-observes-direct-evidence-light-light-scattering
- CERN Courier: http://cerncourier.com/cws/article/cern/66878
- Recent review of work on light-by-light scattering: https://arxiv.org/abs/1711.05194
- And many more in English
- And Polish

BACK-UP SLIDES

DEFINITIONS

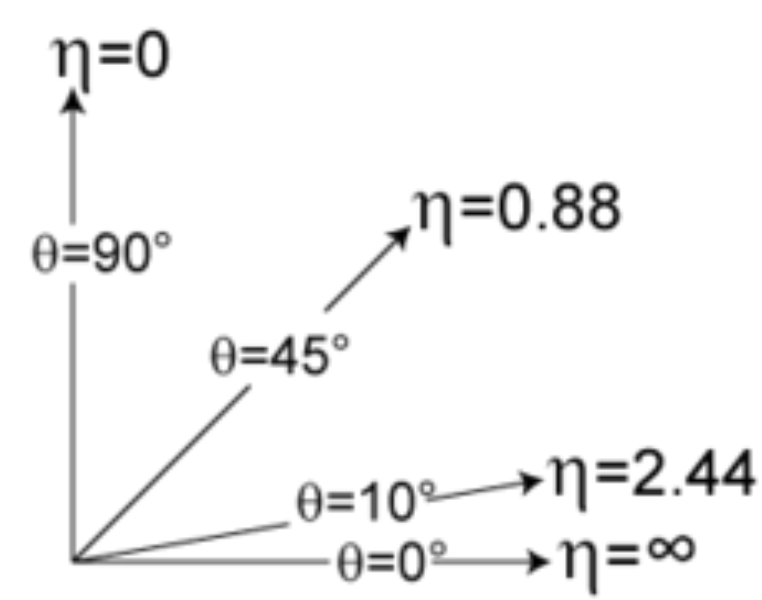
- Transverse momentum, p_T

$$p_{\rm T} = \sqrt{p_{\rm x}^2 + p_{\rm y}^2}$$



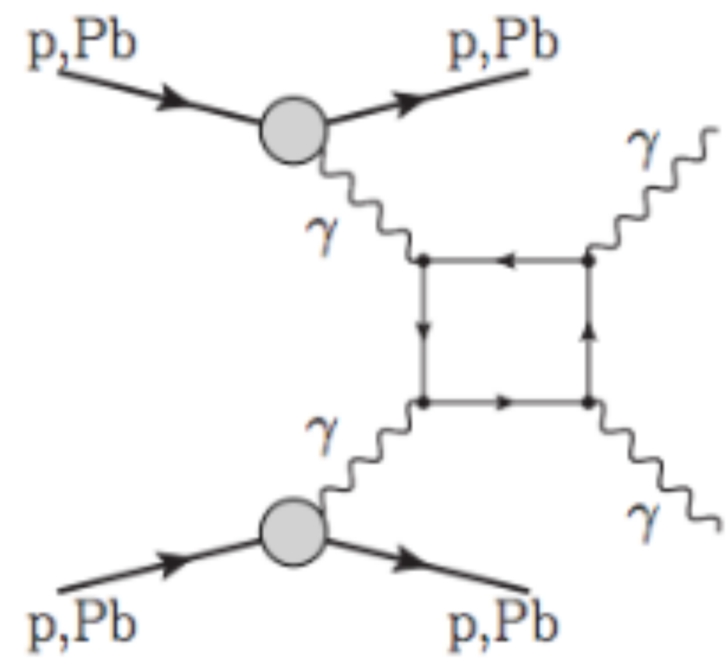
- Azimuthal angle, ϕ
- Polar angle, θ
- Pseudorapidity, η

$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$



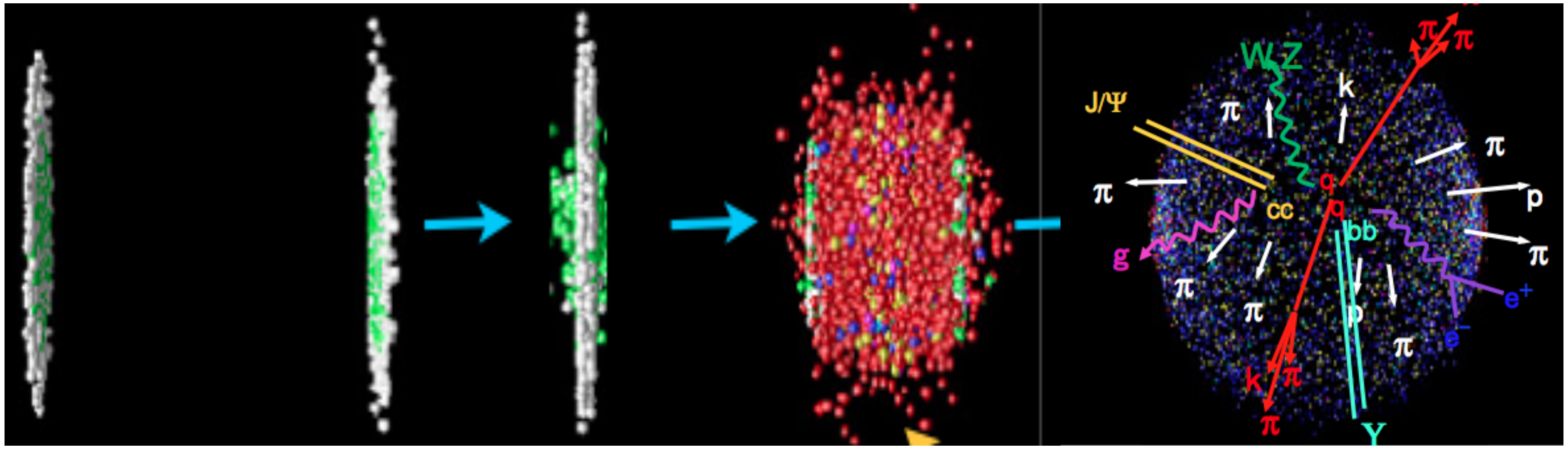
LBYL AT THE LHC

- Light-by-light scattering: elastic scattering of two photons
  - Tested indirectly in measurements of the anomalous magnetic moment of the electron and muon
  - Despite its fundamental simplicity, no direct observation so far due to tiny cross sections
- Proposed as a neat channel to study
  - anomalous gauge-couplings
  - possible contributions from charged SUSY partners of SM particles
- This measurement was inspired by two theory papers
  - Observation of LbyL scattering at the LHC ([1] arxiv:1305.7142)
  - LbyL scatterings in UPC at the LHC ([2]arxiv:1601.07001)
  - And Matthias Schott's presentation in the HITMF meeting before the HI 2015 run
    - Followed by development of the L-by-L trigger



- p,Pb is a source of EM fields
- $Q^2 < 4 \times 10^{-3}$ GeV^{-2} for Pb-Pb
- Box diagram involves charged fermions (leptons or quarks) and bosons ($W^{\pm}$)
- Di-photons produced at rest i.e. $p_T^{\gamma\gamma}$ small

HEAVY-ION PHYSICS PROGRAM IN ATLAS



One of the main goals of heavy-ion (HI) physics is to study the QGP

- Use variety of final states to provide insight into properties of the QGP
  - **Hard probes**
    - Color objects e.g. **jets**, hadrons – insight into partonic energy loss in the QGP
    - Colorless objects e.g. **electroweak bosons** – standard candles in the medium, look for nuclear effects on PDFs
  - **Bulk particle production**
    - Sensitivity to initial geometry, initial conditions, collective behaviour, etc
    - Understand the origin of ridge in small systems
  - **Ultra peripheral collisions**
    - Use gamma-gamma or gamma-nucleus interactions to study initial state, explore QED, also a potential window for BSM physics