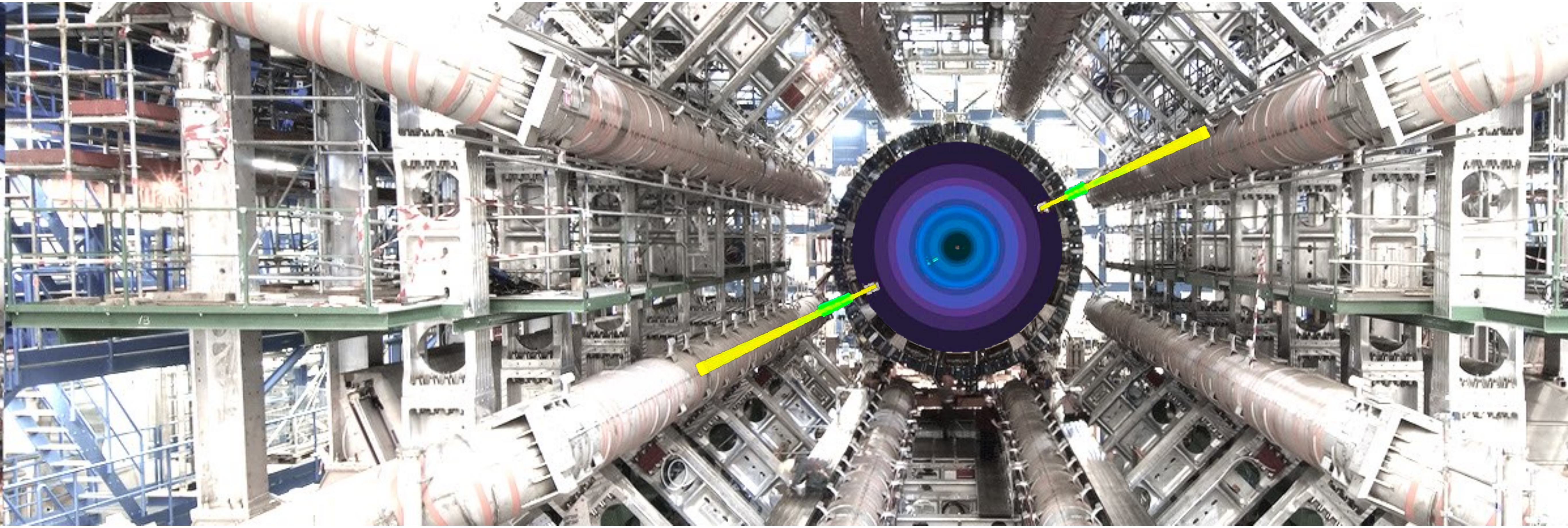


Rozpraszanie foton-foton narzędziem do poszukiwania cząstek spoza Modelu Standardowego

Iwona Grabowska-Bołd
Katedra Oddziaływań i Detekcji Cząstek
Seminarium WFiIS AGH
Kraków, 5 marca 2021

AGH

UCZELNIA BADAWCZA
INICJATYWA DOSKONAŁOŚCI

ATLAS EXPERIMENT

OUR PAPER

- New paper submitted and accepted for Journal of High Energy Physics
  - Measurement of LbyL based on **all data** collected by **ATLAS** (2015+2018 data)
  - Search for new hypothetical particles
  - Leading contributions from dr Prabhakar Palni, dr Klaudia Maj, dr Mateusz Dyndał (CERN), MSc Agnieszka Ogrodnik and IGB
- Earlier work:
  - 4.4σ evidence published in Nature Physics 13 (2017) 852 (2015 data set)
  - 8.2σ observation published in Phys. Rev. Lett. 123 (2019) 052001 (2018 data)

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

Submitted to: JHEP

CERN-EP-2020-135
13th August 2020

arXiv:2008.05355v1 [hep-ex] 12 Aug 2020

Measurement of light-by-light scattering and search for axion-like particles with 2.2 nb^{-1} of Pb+Pb data with the ATLAS detector

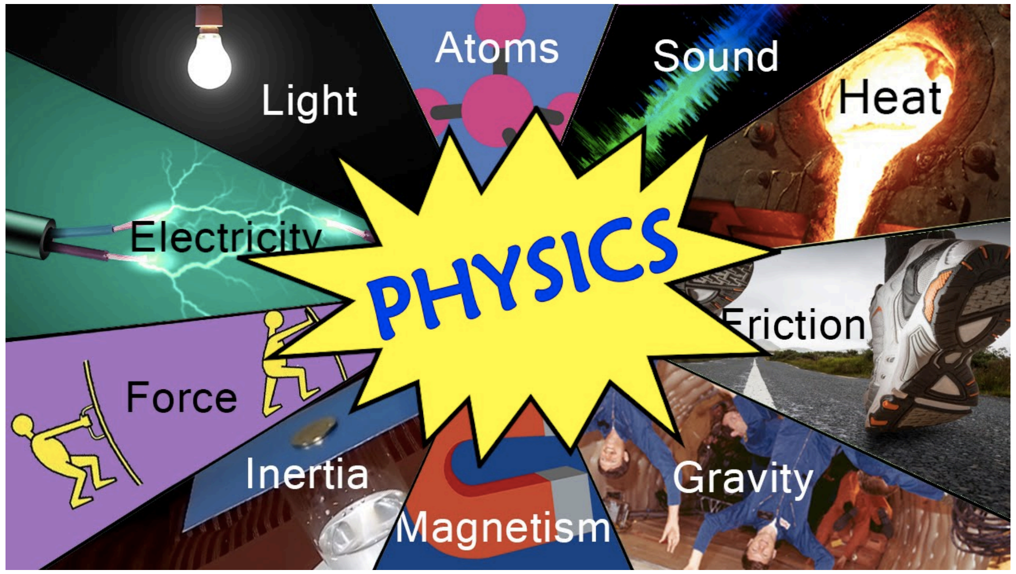
The ATLAS Collaboration

This paper describes a measurement of light-by-light scattering based on Pb+Pb collision data recorded by the ATLAS experiment during Run 2 of the LHC. The study uses 2.2 nb^{-1} of integrated luminosity collected in 2015 and 2018 at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV. Light-by-light scattering candidates are selected in events with two photons produced exclusively, each with transverse energy $E_{\mathrm{T}}^{\gamma} > 2.5$ GeV, pseudorapidity $|\eta_{\gamma}| < 2.37$, diphoton invariant mass $m_{\gamma\gamma} > 5$ GeV, and with small diphoton transverse momentum and diphoton acoplanarity. The integrated and differential fiducial cross sections are measured and compared with theoretical predictions. The diphoton invariant mass distribution is used to set limits on the production of axion-like particles. This result provides the most stringent limits to date on axion-like particle production for masses in the range 6–100 GeV. Cross sections above 2 to 70 nb are excluded at the 95% CL in that mass interval.

OUTLINE

- Introduction to light-by-light (LbyL) scattering
  - First attempts to measure it
  - How to measure LbyL at the Large Hadron Collider (LHC)
- Experimental challenges in measurements of LbyL in the ATLAS experiment
  - Photon identification
  - Trigger
  - Background processes
- New results
- Search for new particles beyond the Standard Model
- Summary and outlook

INTRODUCTION



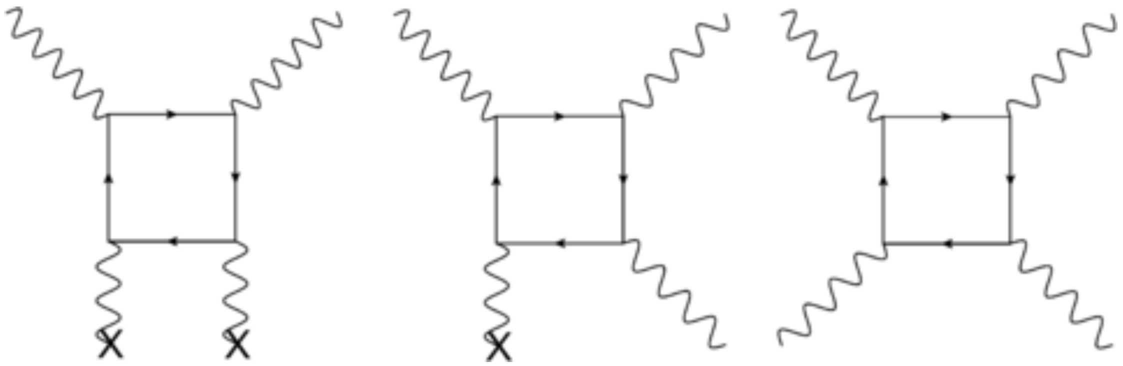
INTRODUCTION

- 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 for decades

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 (2019)



FIRST EXPERIMENTAL ATTEMPTS TO LBYL

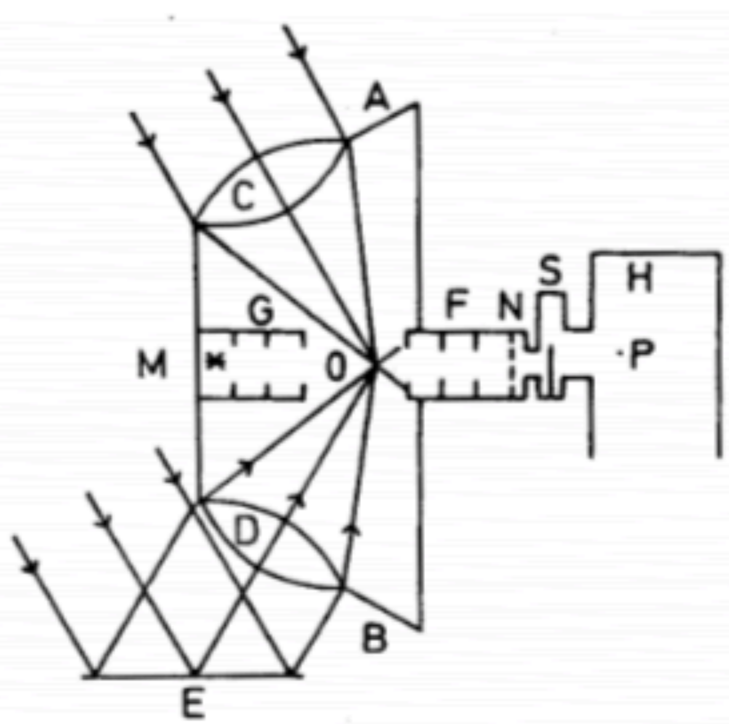
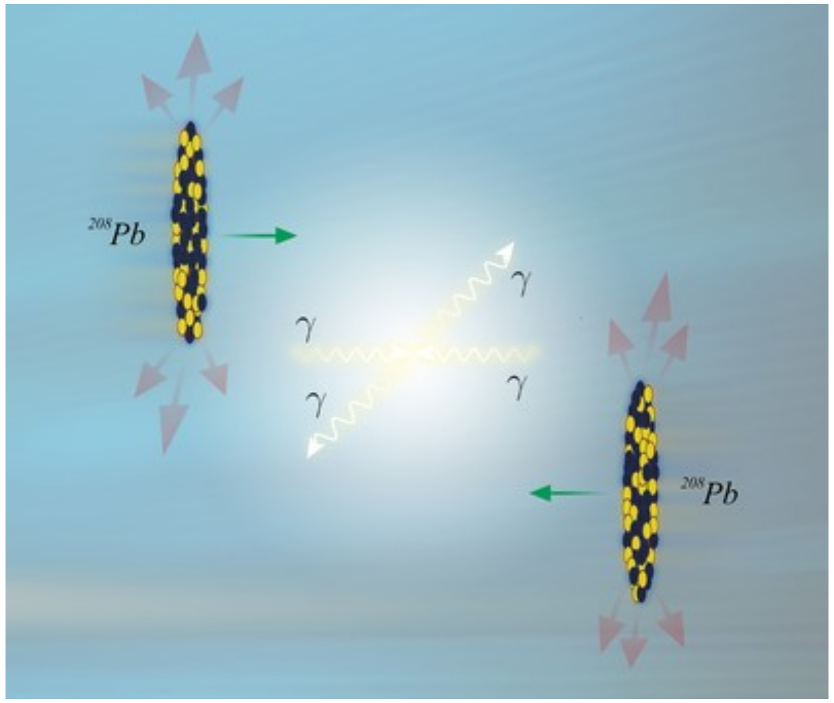


Figure 3 Apparatus for a light-light scattering experiment: The two lenses C and D focus sun light on the same spot O in a light-tight box AB. The dark-adapted eye of an observer at the point P serves as the detector for scattered light.

- Search for scattering of visible photons using focused sunlight by Hughes and Jauncey in [Phys. Rev. 36 (1930), 773]
- 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 ."
- Cross section for visible light actually is: 10^{-60} cm^2!

PHOTON-PHOTON PHYSICS AT COLLIDERS



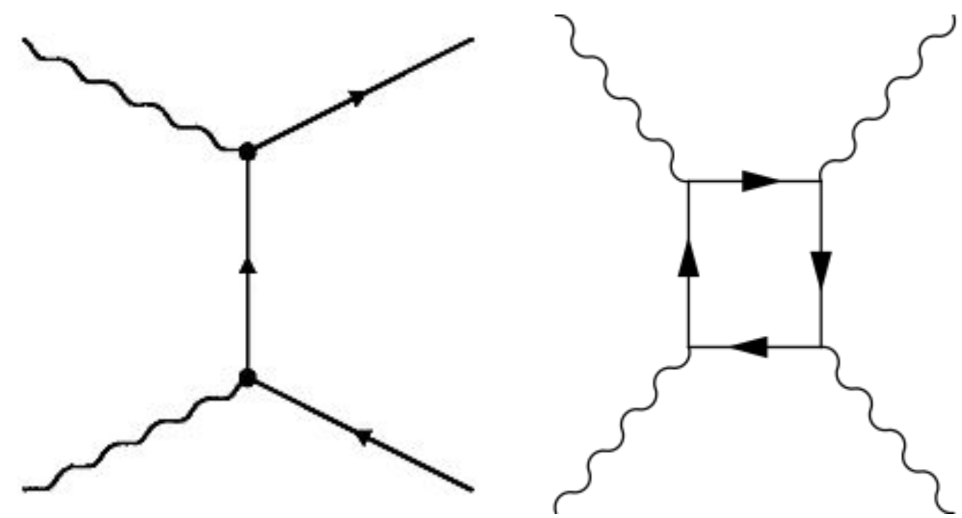
- Basis for photon-photon physics by
  - Fermi, Nuovo Cim. 2 (1925) 143
  - Weizsacker, Z. Phys. 88 (1934) 612
  - Williams, Phys. Rev. 45 (10 1934) 729
- Led to formulation of Weizsacker-Williams Approximation or **Equivalent Photon Approximation** (**EPA**)

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

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

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

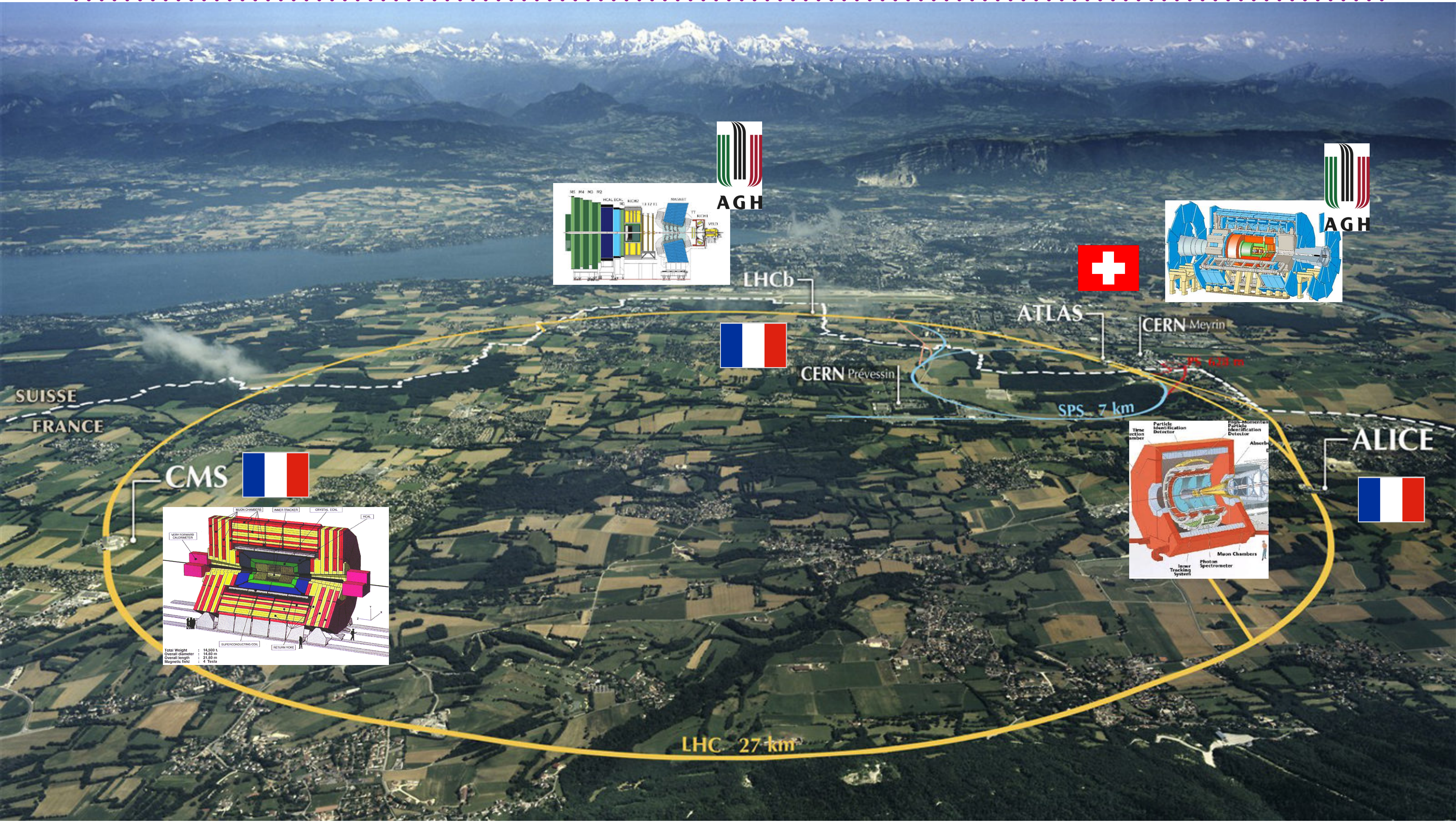
Z^4 **enhancement in Pb+Pb** over pp



  - Elementary cross section of ɣɣ → X:

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

LARGE HADRON COLLIDER



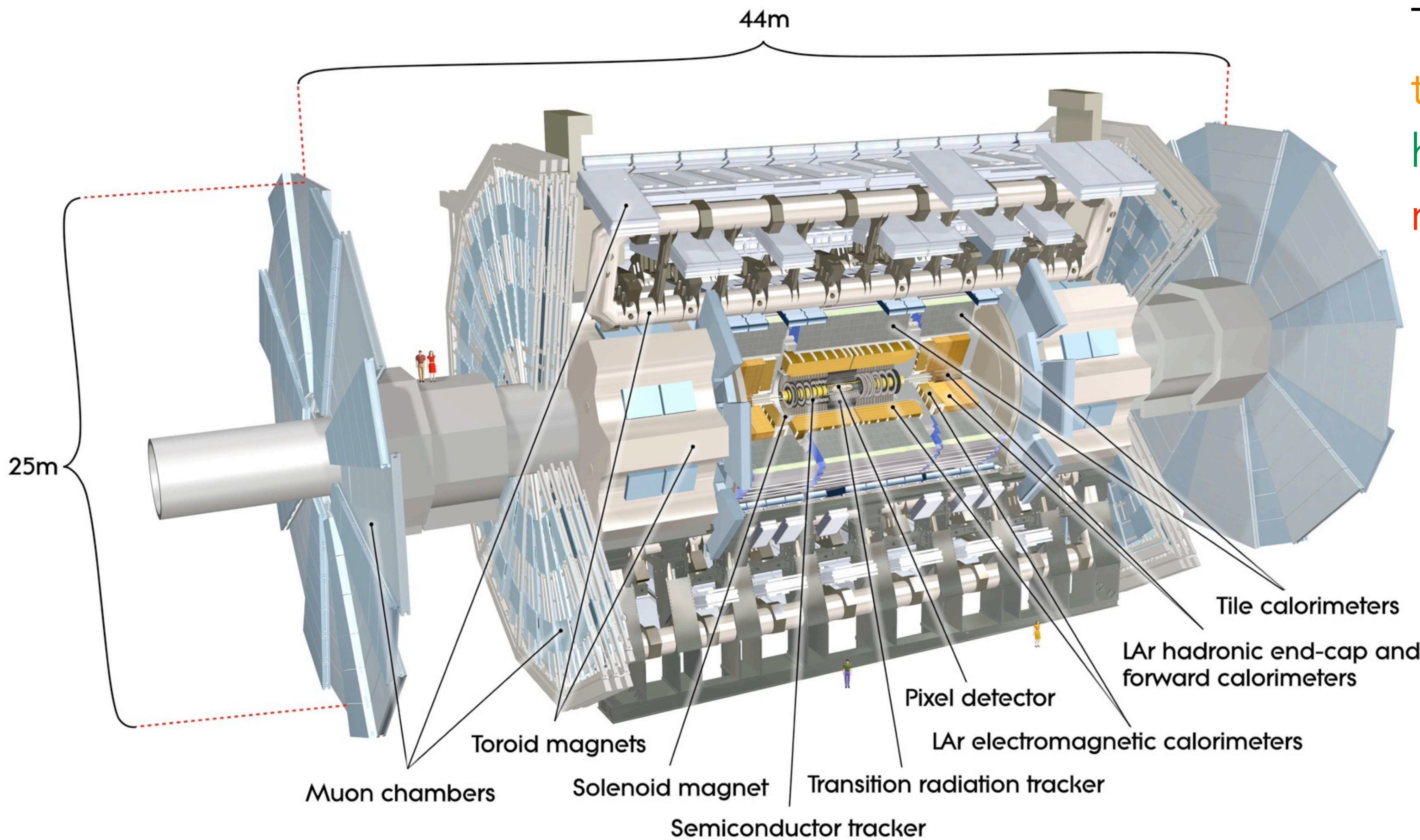
- Large Hadron Collider (LHC) is a 27 km long machine
- Most of the time collides protons-protons at 0.9, 7, 8 (2009-2013) and 13 TeV (2015-2018)
- One month per year is dedicated to a heavy-ion (HI) programme with lead-lead collisions at 2.76 TeV (2010, 2011) and 5.02 TeV (2015, 2018)

DATA AVAILABLE AT THE LHC

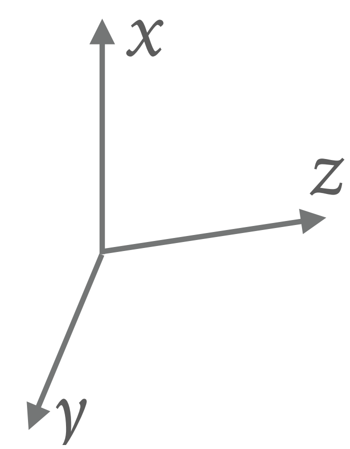
- Years 2009-2013 (Run 1) early collisions at lower energy
- Years 2015-2018 (Run 2) the centre-of-mass energy was doubled
  - Opportunity to study energy dependence
  - Large integrated luminosity
- Years 2019-2021 a long shutdown is ongoing

	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**	**2015-18**	**13**	**139 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}
	Pb+Pb	**2018**	**5.02**	**1.73 nb^{-1}**

ATLAS DETECTOR



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



Variables:

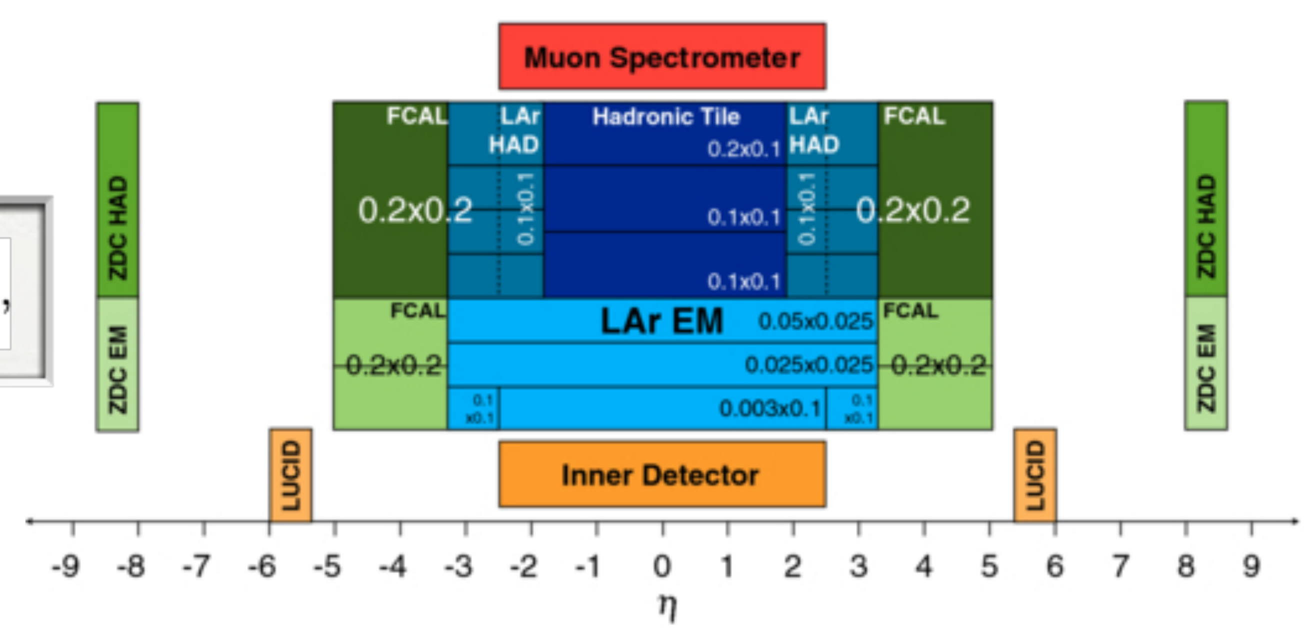
ϕ - full azimuthal acceptance

η- broad pseudorapidity coverage

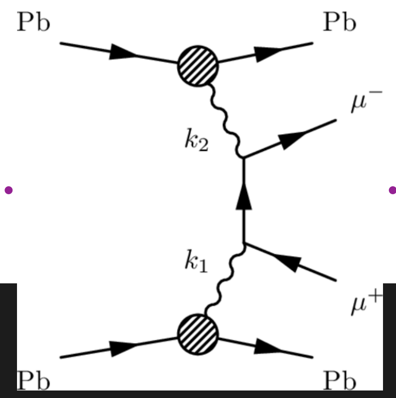
p_T - transverse momentum

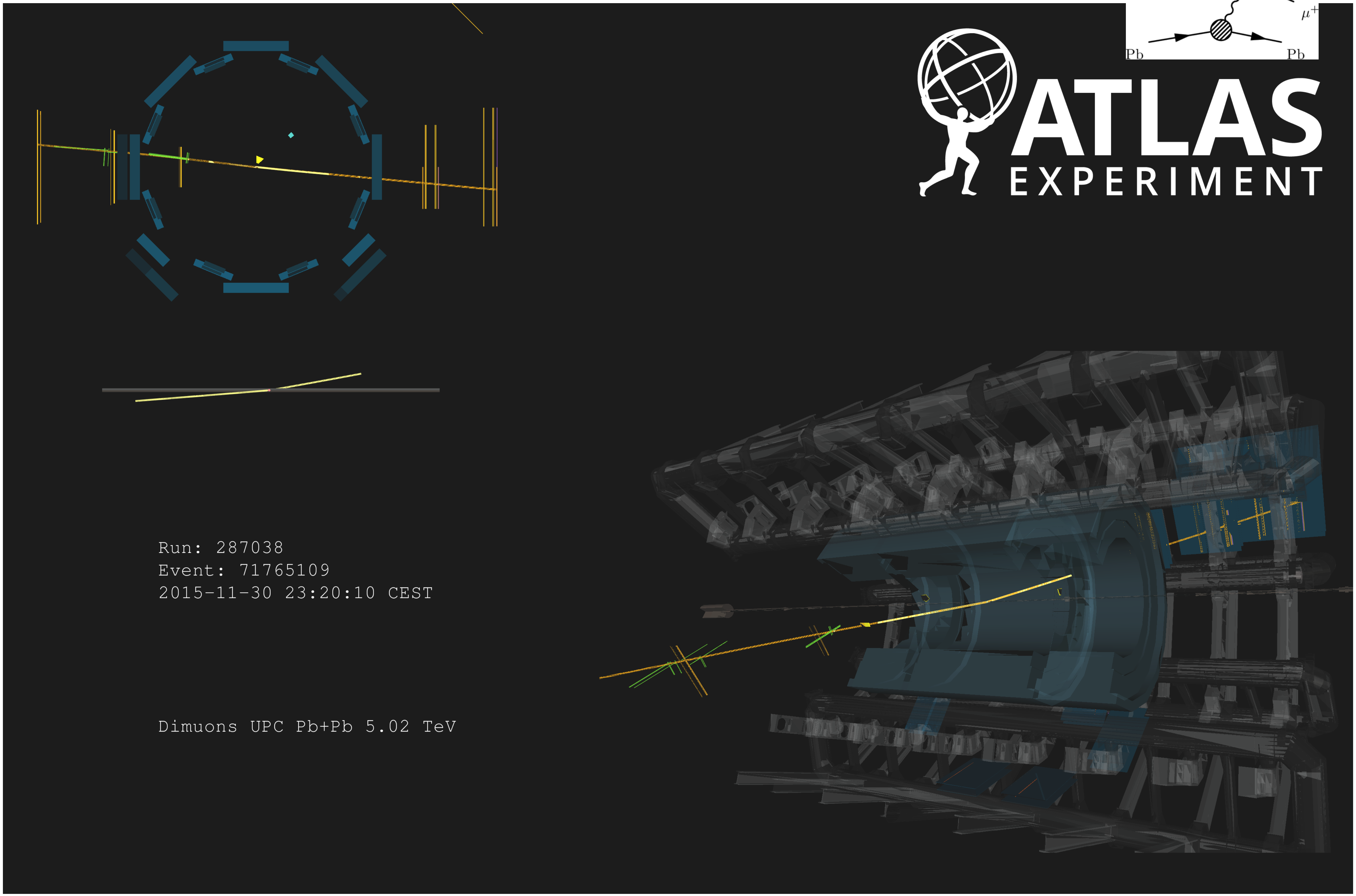
$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$

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



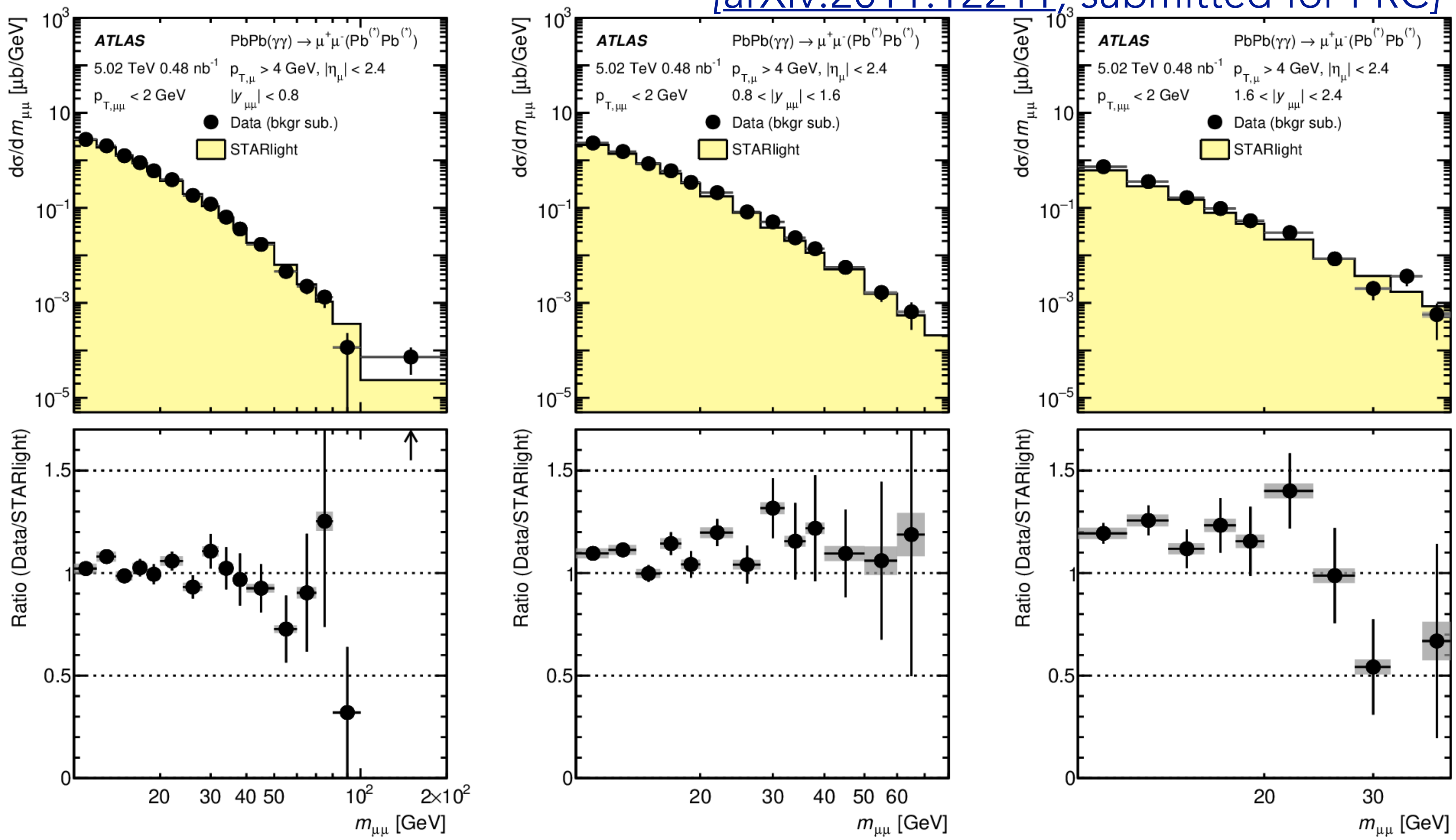
SINGLE EXCLUSIVE DIMUON EVENT IN PB+PB





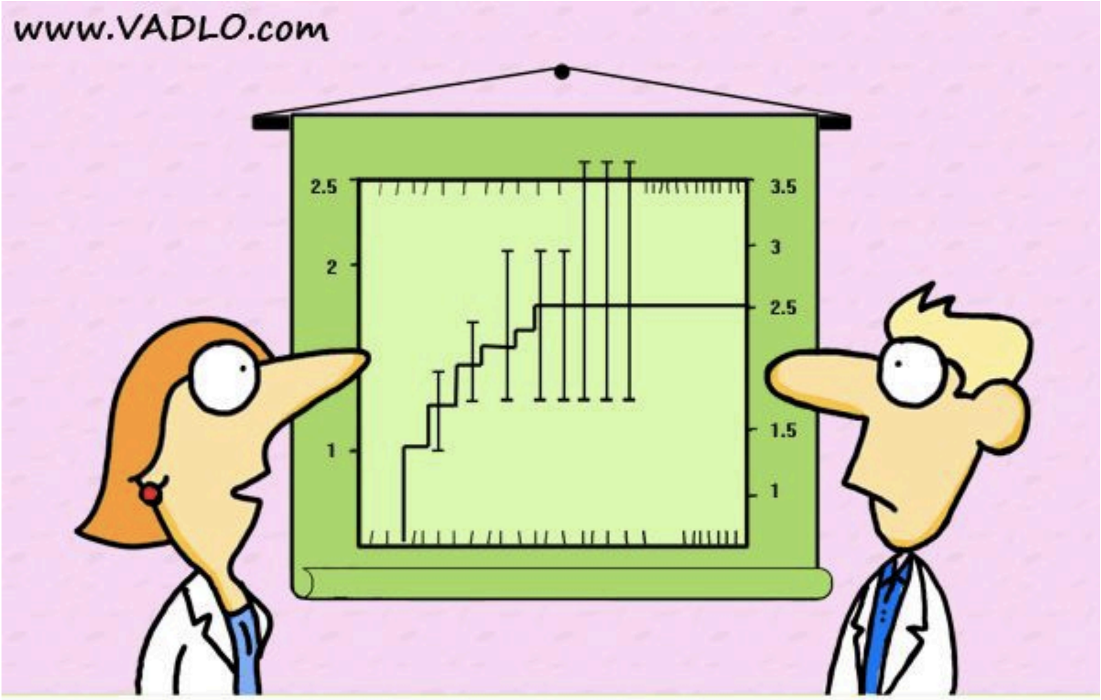
EXCLUSIVE DIMUON PRODUCTION IN PB+PB COLLISIONS

[arXiv:2011.12211, submitted for PRC]



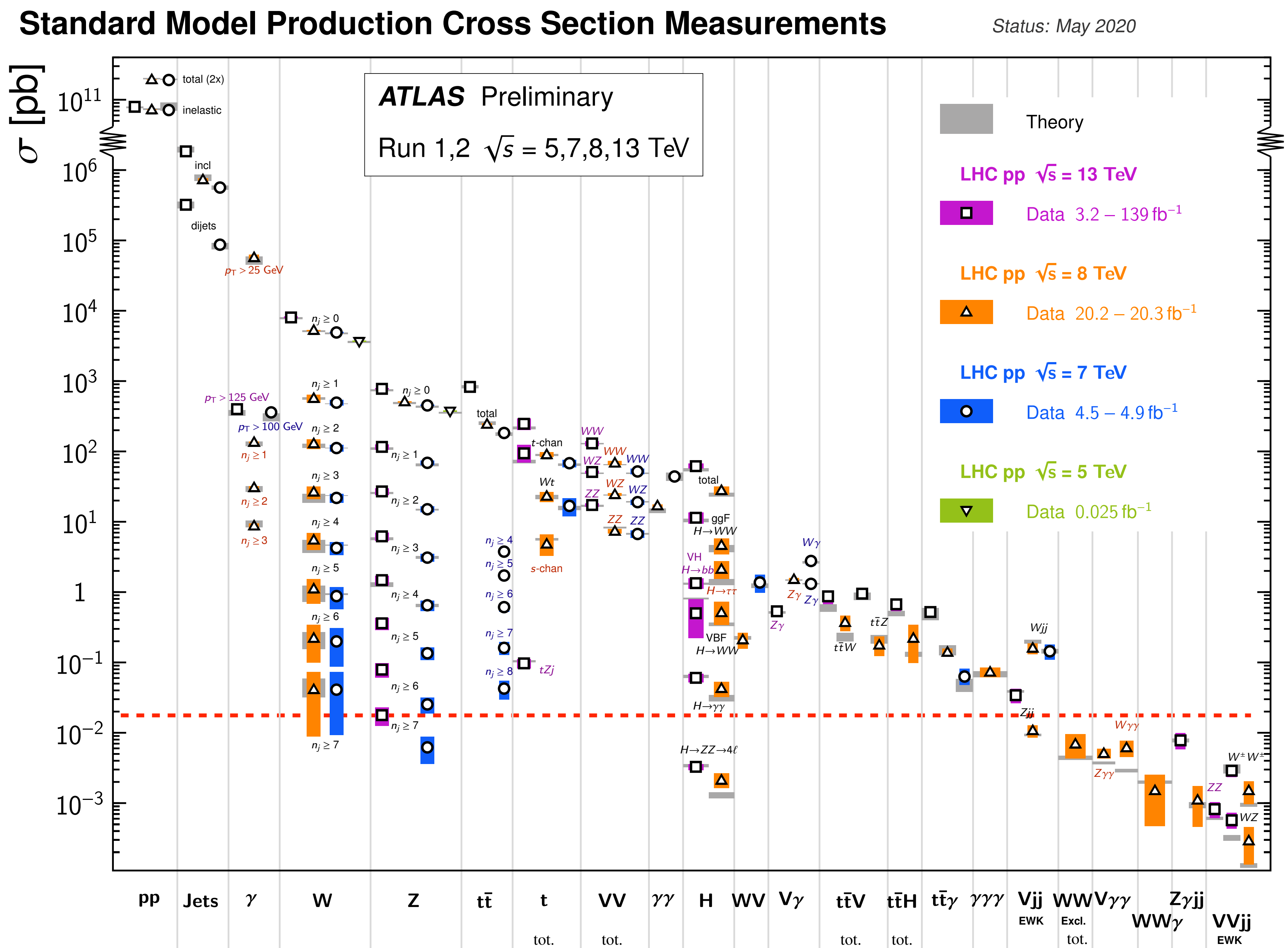
- ATLAS measured the ɣ ɣ → μ+μ- production in Pb+Pb collisions at 5.02 TeV
  - 12 132 event candidates selected
- Cross sections for exclusive dimuon production in $m_{\mu\mu}$ in three intervals of $y_{\mu\mu}$ are measured
  - **34.1±0.3(stat.) +0.7 (syst.) μb** and compared to predictions **32.1 μb**
- 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 dimuon masses at the LHC

EXPERIMENTAL CHALLENGES



"Did you really have to show the error bars?"

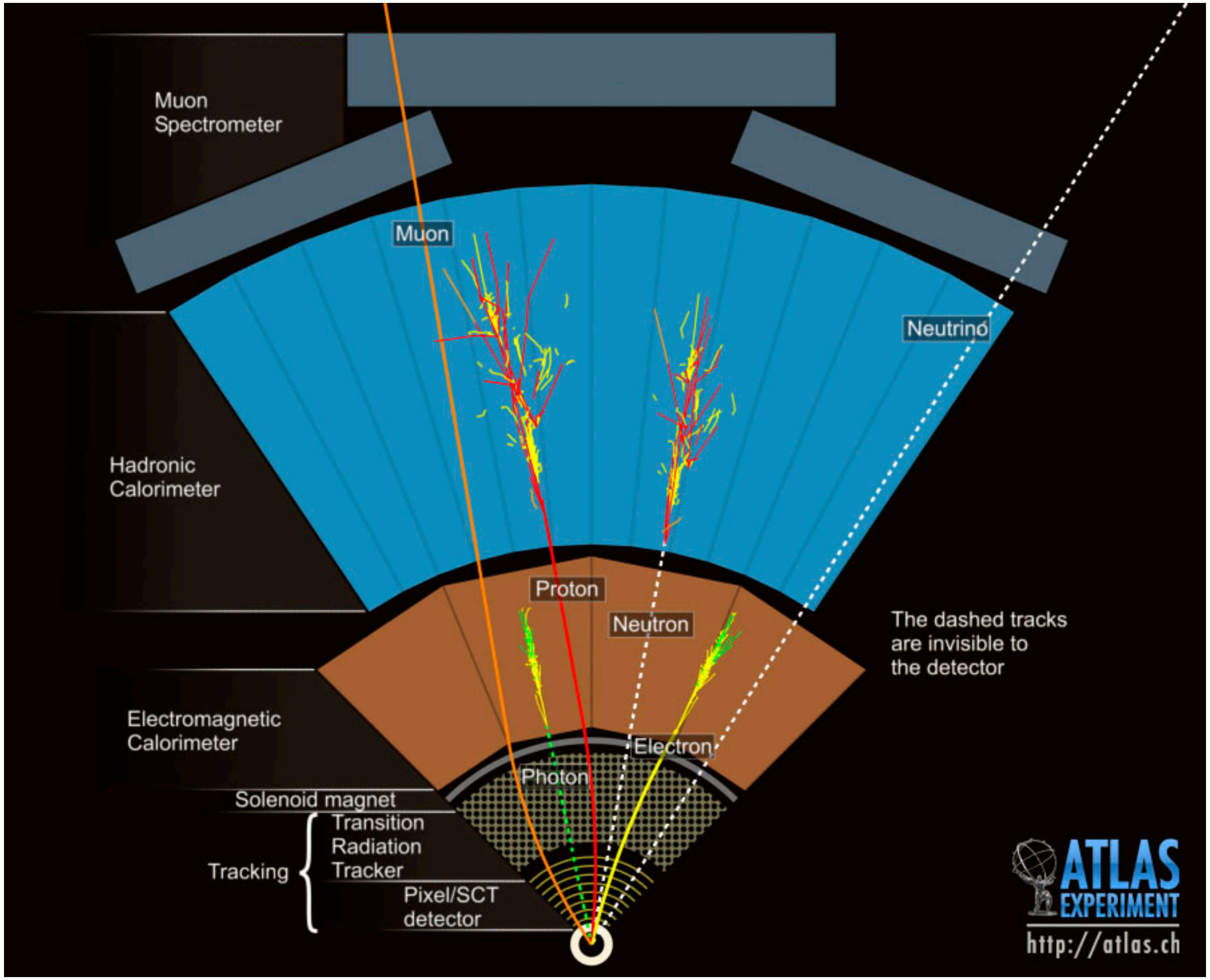
CROSS SECTIONS IN PERSPECTIVE



- ➤ ATLAS measures cross sections for a broad variety of Standard Model processes
  - ➤ In pp collisions at 5, 7, 8 and 13 TeV
- ➤ Measurements span 14 orders of magnitudes
- ➤ Excellent agreement with the Standard Model
- ➤ Red dashed line indicates a LbyL cross section in pp collisions at 14 TeV

PHOTON IDENTIFICATION IN ATLAS

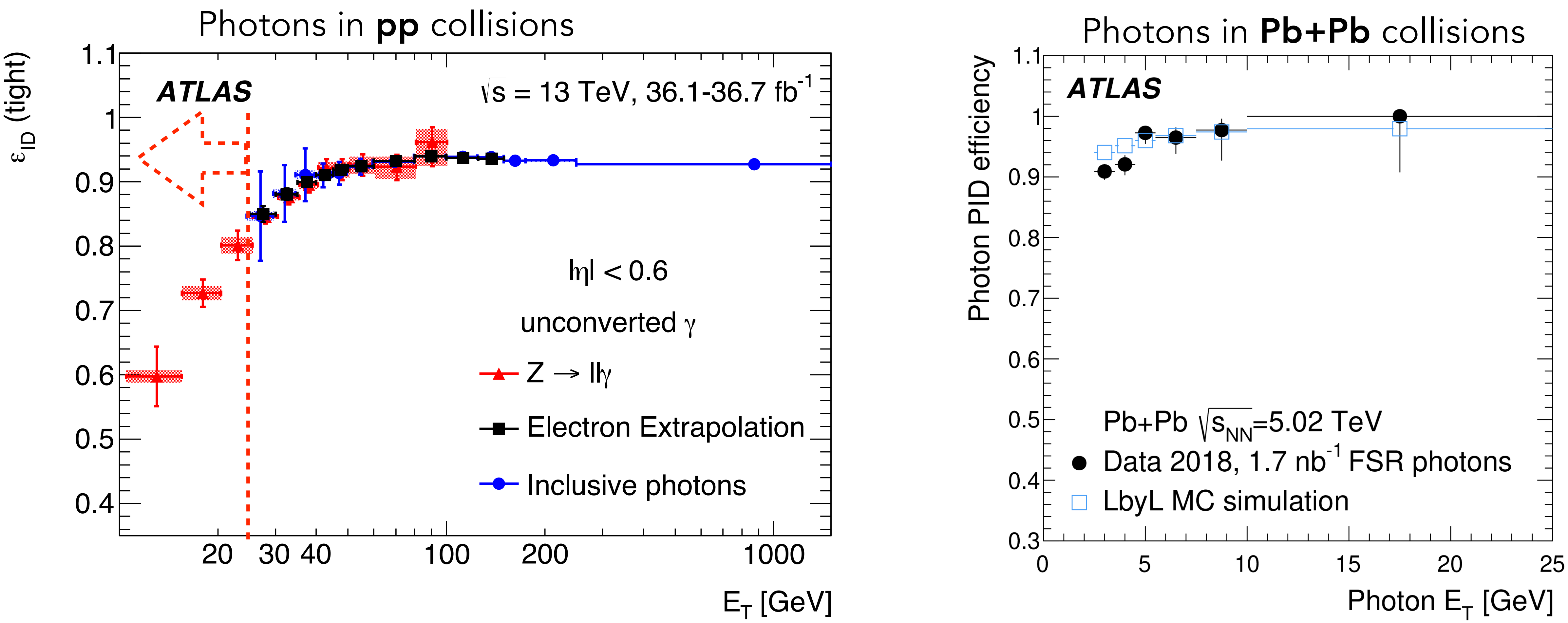
- Photons do not create tracks in the ID, they deposit most of their energy in the EM calorimeter
  - Potential small leakage to HAD calorimeter (isolation)
- Simple signature:
  - Photon = EM cluster
  - Unless they convert to a e+e- pair



Possible issues:

- An electron with a low-quality track might mimic a photon
- Track reconstruction efficiency is 80% in pp collisions in ATLAS
- A low-p_T electron may emit bremsstrahlung, and bend in a magnetic field w/o deep entering to the ID

PHOTON EFFICIENCY IN ATLAS

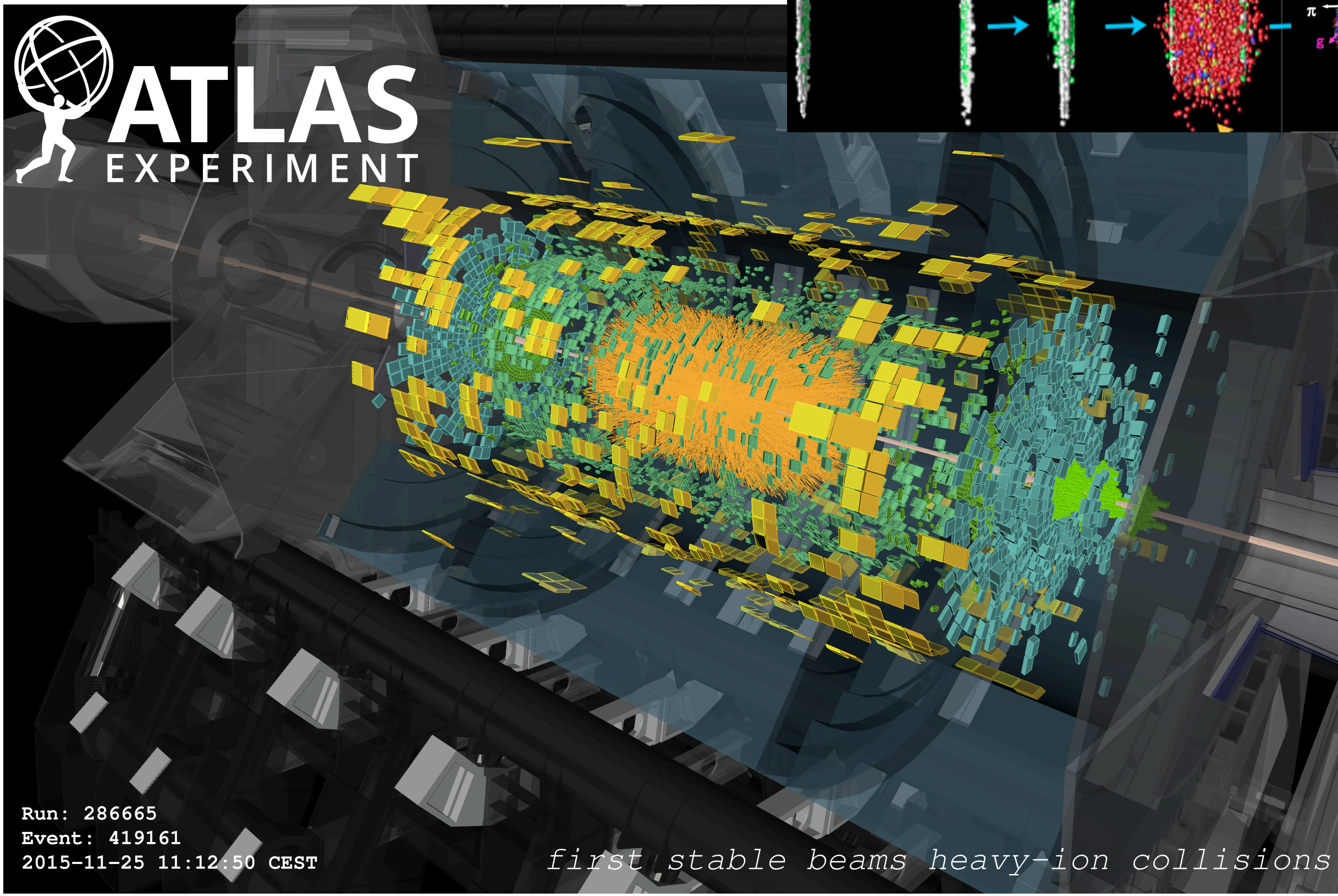


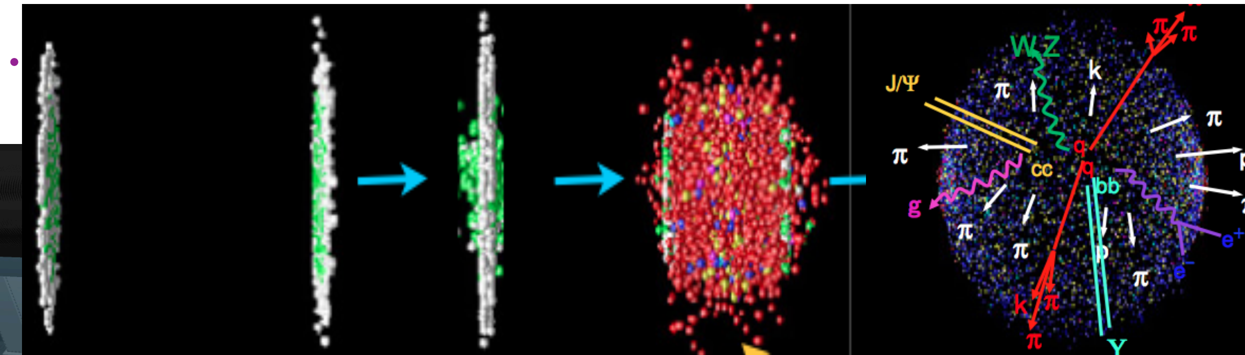
- Typical measurements with photons use p_T>40 GeV
- While LbyL photons have p_T in a region of 2.5-25 GeV
- Default ATLAS photon identification is not optimal for low-p_T photons from LbyL
  - Photon identification efficiency is below 60%, for two photons - below 36%
- Dedicated optimisation has been developed for low-p_T photons
  - Based on **artificial neural network**
  - Vey good performance: constant 95% photon identification efficiency

TRIGGER: EVENT FILTERING IN REAL TIME

- Interaction rate:
  - **40 MHz** in pp collisions
  - **300 kHz** in Pb+Pb collisions
- ATLAS can record and analyse about **1 kHz**
- 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 heavily involved in trigger preparations to 2015 and 2018 Pb+Pb runs

TYPICAL PB+PB EVENT IN ATLAS



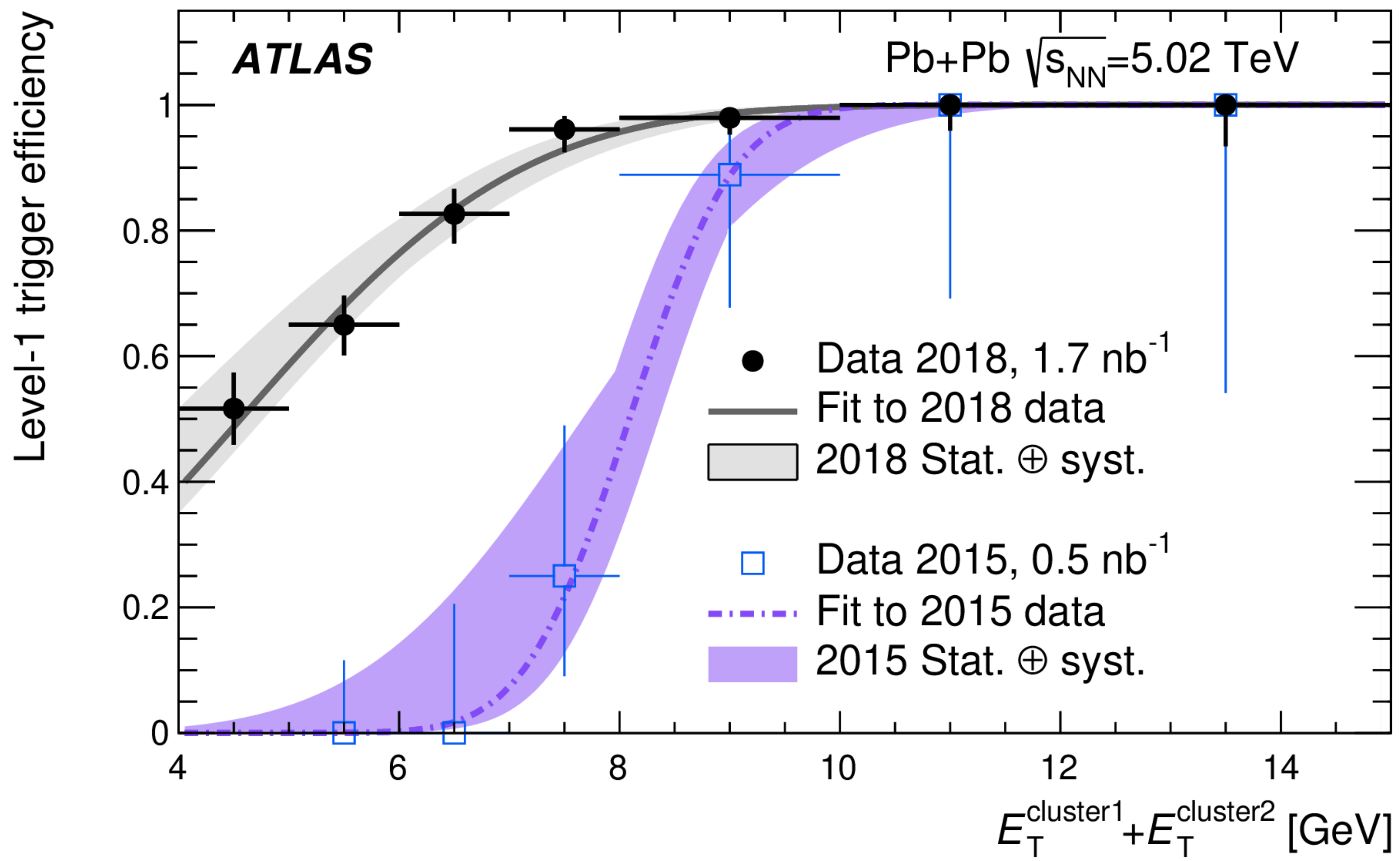


- A lot of activity in the entire detector
- It is a challenge to trigger and then reconstruct these events

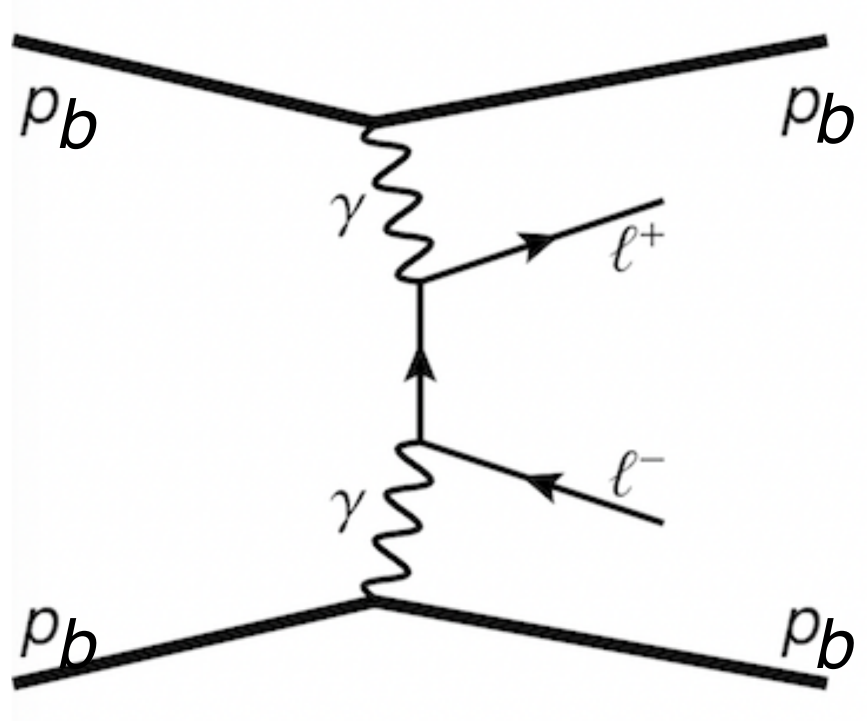
TRIGGER FOR LOW-PT PHOTONS

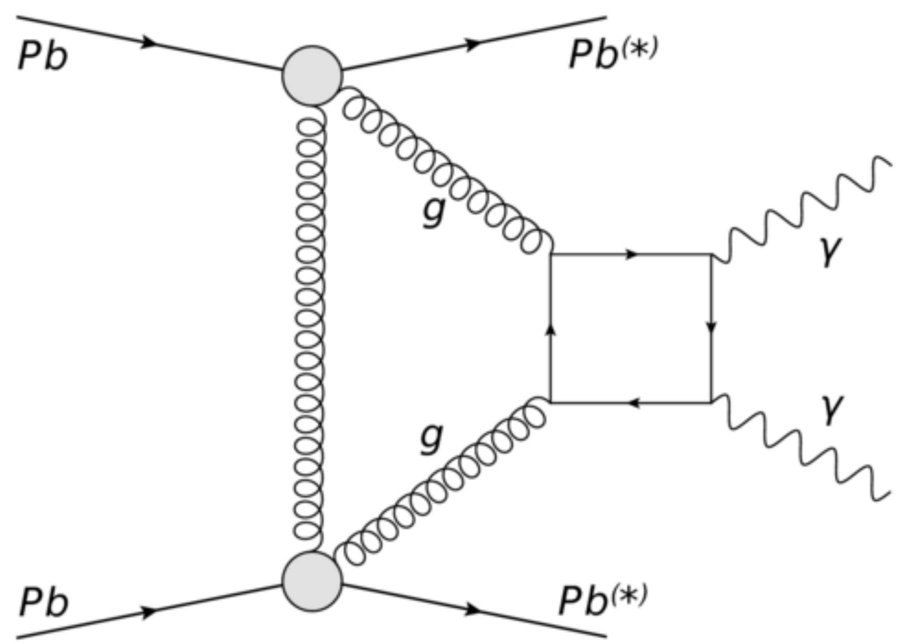
- Dedicated trigger for LbyL events has been designed:
  - Expected **O(10)** signal events out of **4 billion** interactions
  - Two-step approach: events accepted at Level-1 at O(1k Hz) rate and High Level Trigger at O(10 Hz) rate
  - Trigger efficiency studied with a novel method using $\gamma\gamma \rightarrow e^{+}e^{-}$ process in data
  - Great improvement between 2015 and 2018 Level-1 performance

- In 2018 Pb+Pb data set:
  - Efficiency grows from 60% at 5 GeV to 100% at 9 GeV
  - The analysis uses $E_{T}^{\mathrm{cluster1}} + E_{T}^{\mathrm{cluster2}} > 5$ GeV
- In 2015 Pb+Pb data set:
  - Significant inefficiency below 8 GeV in $E_{T}^{\mathrm{cluster1}} + E_{T}^{\mathrm{cluster2}}$
- Expect most of events from the 2018 data set



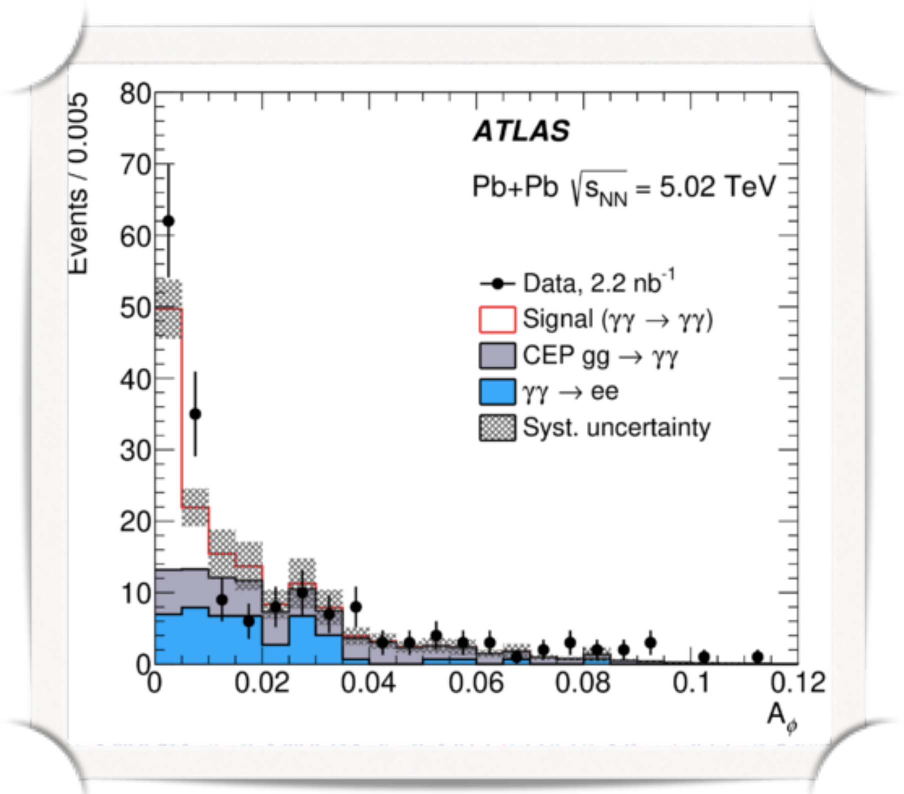
BACKGROUND PROCESSES WITH ELECTRONS AND PHOTONS





- Very detailed background studies:
  - What process can mimic two photons in Pb+Pb collisions at the LHC?
  - Exclusive production of electron pairs: $\gamma\gamma \rightarrow e^+e^-$
    - **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: $gg \rightarrow \gamma\gamma$
    - Signature is the same as for LbyL, rely on data-driven techniques to evaluate this contribution
  - Also other rare processes have ben considered

RESULTS

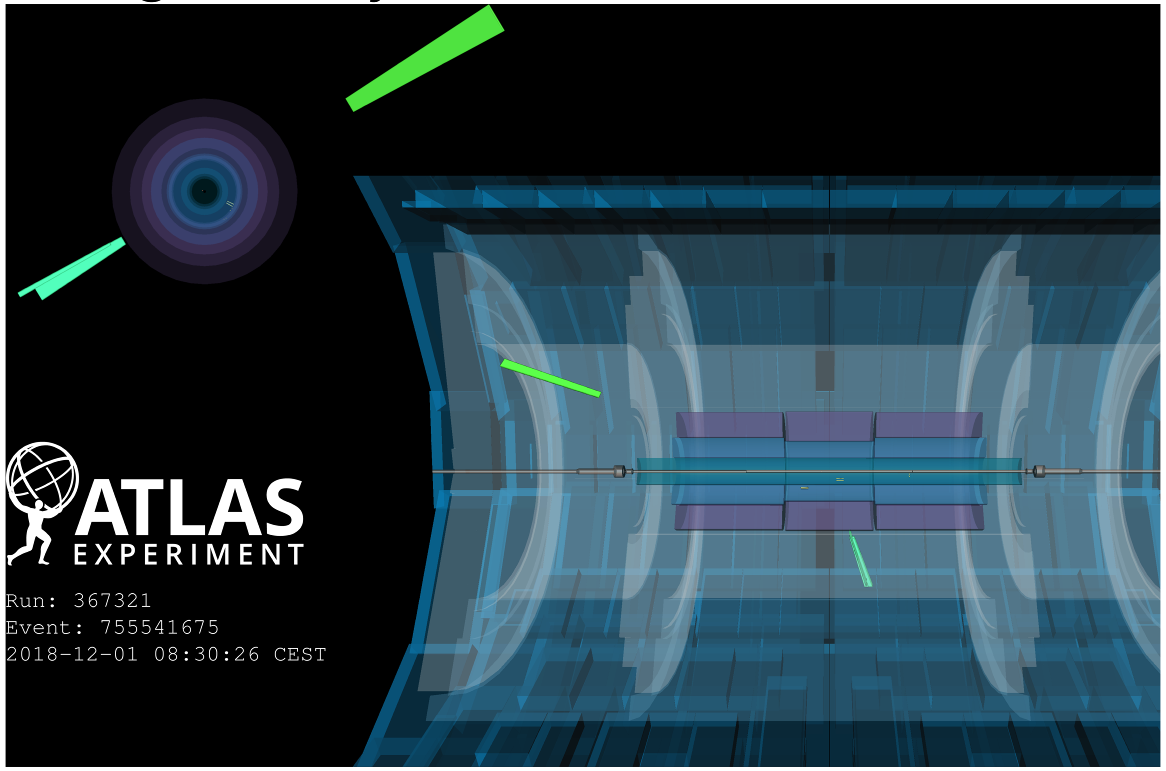


ATLAS
Pb+Pb $\sqrt{s_{NN}}$ = 5.02 TeV
Data, 2.2 nb^{-1}
Signal ($\gamma\gamma \rightarrow \gamma\gamma$)
CEP gg $\rightarrow \gamma\gamma$
$\gamma\gamma \rightarrow$ ee
Syst. uncertainty
Events / 0.005
A_ϕ
0
10
20
30
40
50
60
70
80
0.02
0.04
0.06
0.08
0.1
0.12

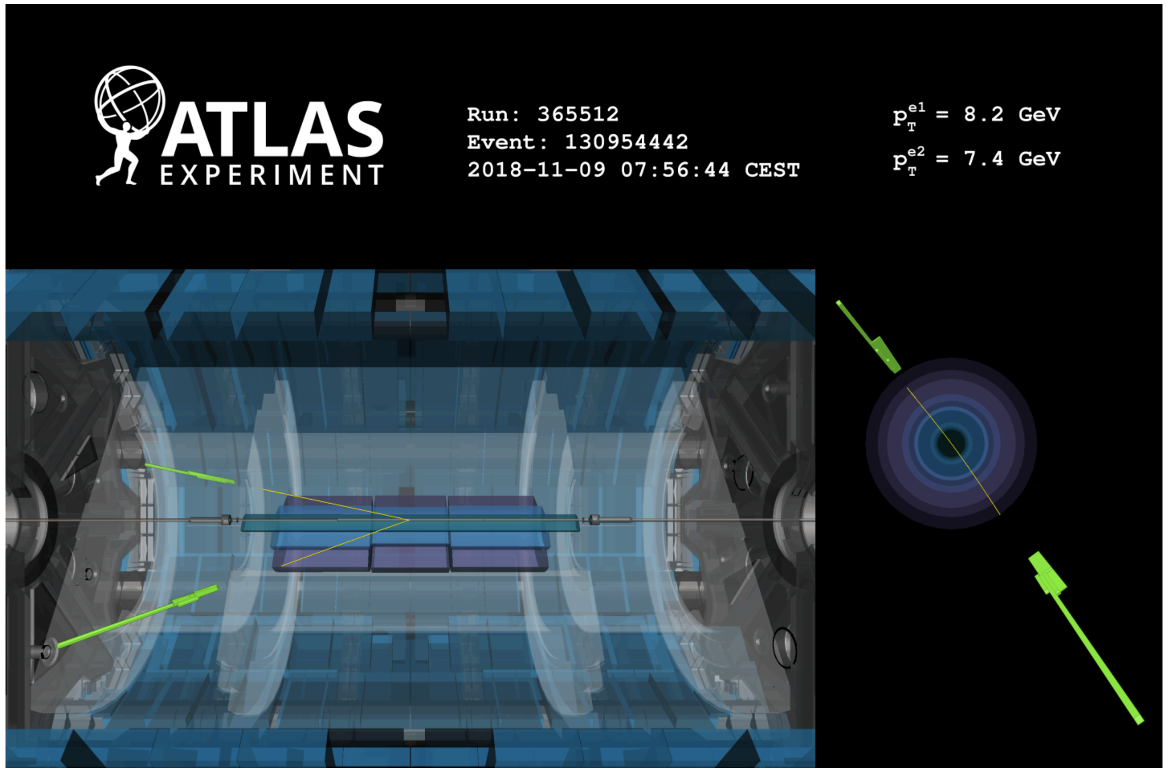
LBYL EVENT SELECTION

- Good-quality data in the detector
- Trigger
- Exactly two photons with $\mathbf{p_T > 2.5}$ **GeV** and **|η|<2.37**, excluding the crack region 1.37<|η|<1.52
- Invariant diphoton mass $\mathbf{M_{inv} > 5}$ **GeV**
- **Veto extra activity** in the ID in |η|<2.5
  - No reconstructed tracks with $p_T > 100$ MeV
  - No reconstructed 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 $\mathrm{Aco} = 1 - \dfrac{|\Delta\phi_{\gamma\gamma}|}{\pi} < 0.01$

Signal: LbyL event candidate



Background: e⁺e⁻ event candidate



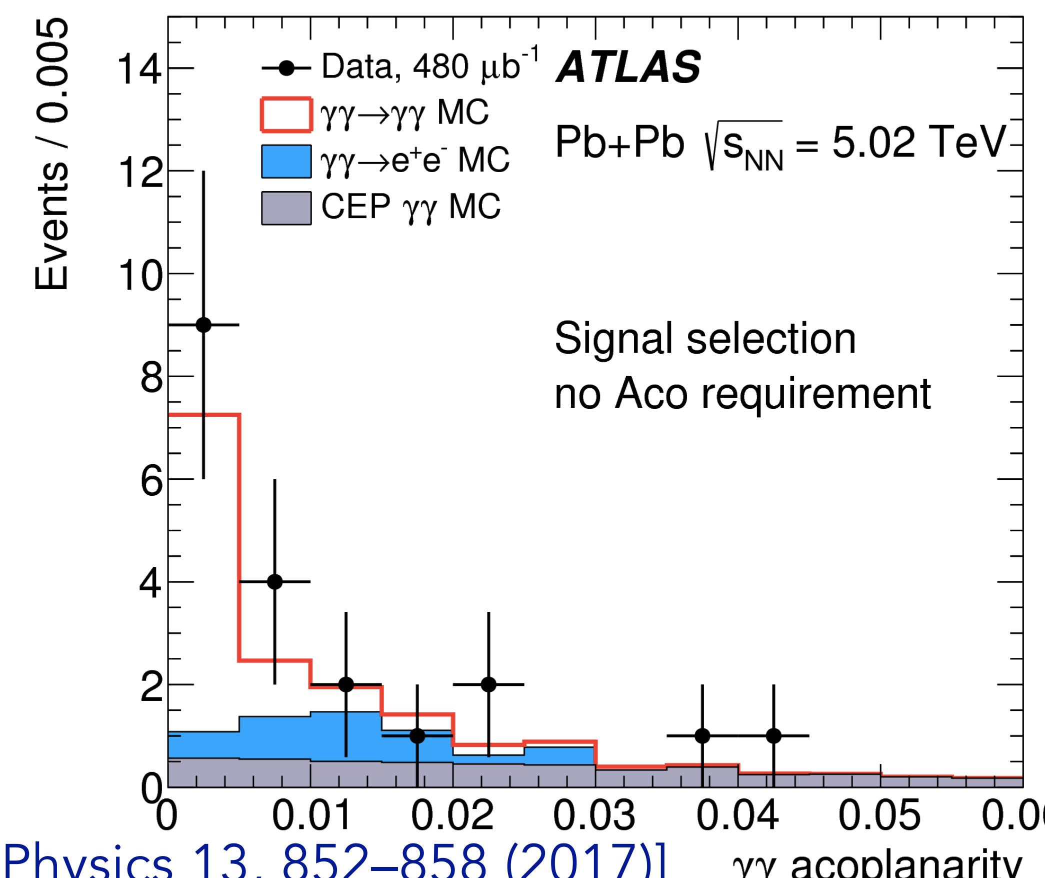
FIRST LBYL SCATTERING MEASUREMENTS

- First **strong evidence** measurements published by **ATLAS** (2017) and **CMS** (2019)
  - ATLAS: p_T>3 GeV and $M_{\gamma\gamma}$>6 GeV
  - CMS: p_T>2 GeV and $M_{\gamma\gamma}$>5 GeV
- Excess consistent with the LbyL signal from Standard Model
  - ATLAS: **4.4σ significance** with **13 event candidates**, with 2.6±0.7 events from background
  - CMS: **4.1σ significance** with **14 event candidates**, about 3 events from background

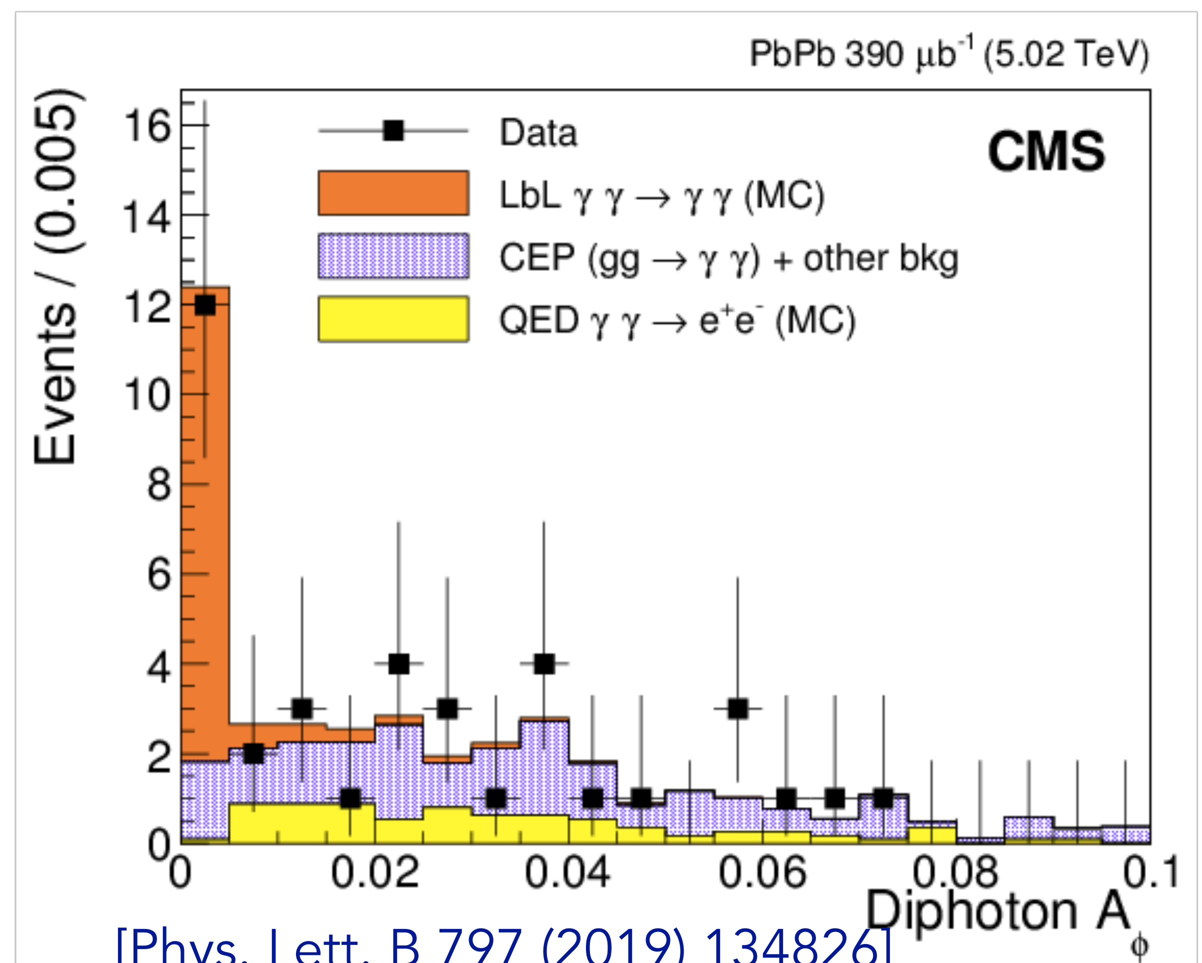
Measured cross sections:

ATLAS - σ_{fid}=70±20 (stat) ± 17 (syst) nb, **CMS** - σ_{fid}=120±46 (stat) ± 28 (syst) ± 4 (th) nb

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



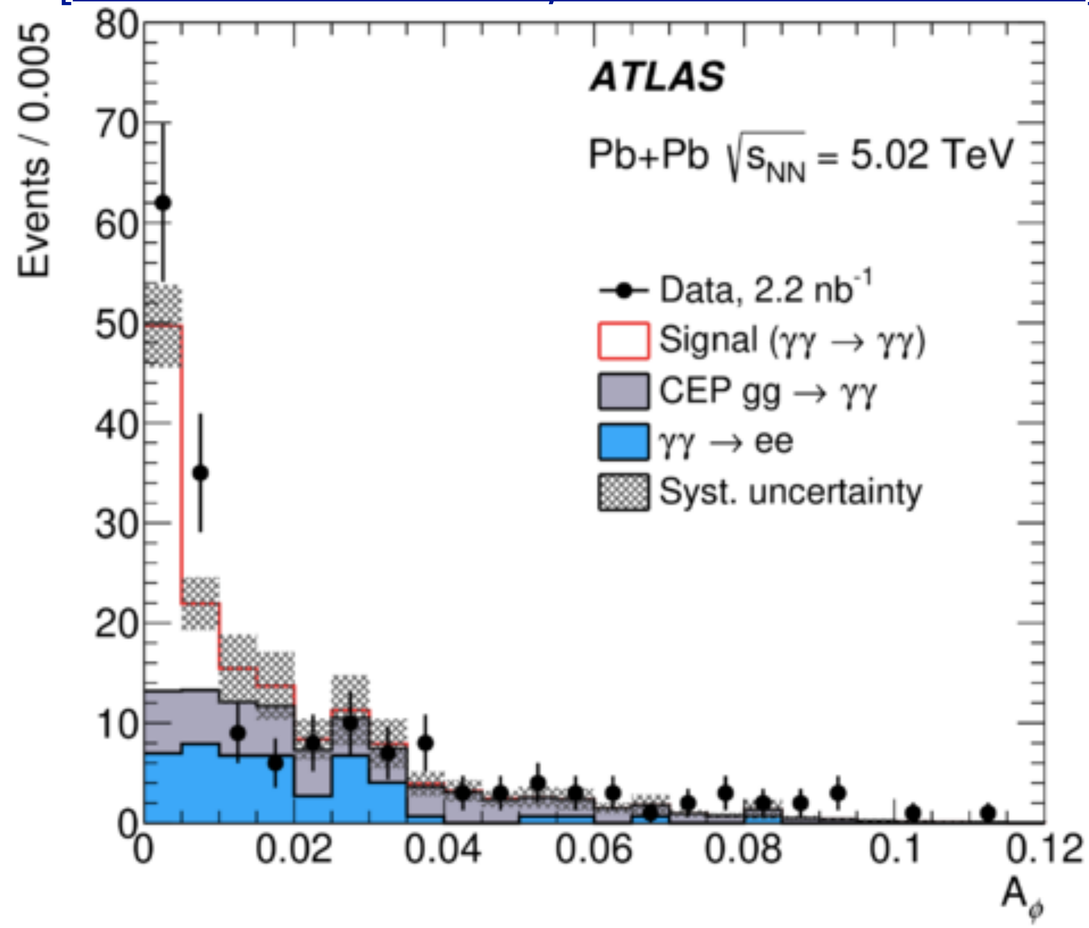
[Nature Physics 13, 852–858 (2017)]



[Phys. Lett. B 797 (2019) 134826]

NEW LBYL RESULTS FROM ATLAS

[arXiv: 2008.05355, submitted for JHEP]



- New measurement based on **2015+2018 data sets** with 2.2 nb^{-1}
- In total **97 events** observed, with 27 events from backgrounds are expected
  - Background contributions from $\gamma\gamma \rightarrow e^+e^-$ (15±7) and $gg \rightarrow \gamma\gamma$ (12±3)
- Cross section in the fiducial region $p_T^\gamma > 2.5$ GeV, $m_{\gamma\gamma} > 5$ GeV, $|\eta^\gamma| < 2.4$, $p_T^{\gamma\gamma} < 1$ GeV

$$\sigma_{\text{fid}}^{\text{meas}} = 120 \pm 17\ (\text{stat.}) \pm 13\ (\text{syst.}) \pm 4\ (\text{lumi.})\ \text{nb}$$

- Comparison to theory predictions

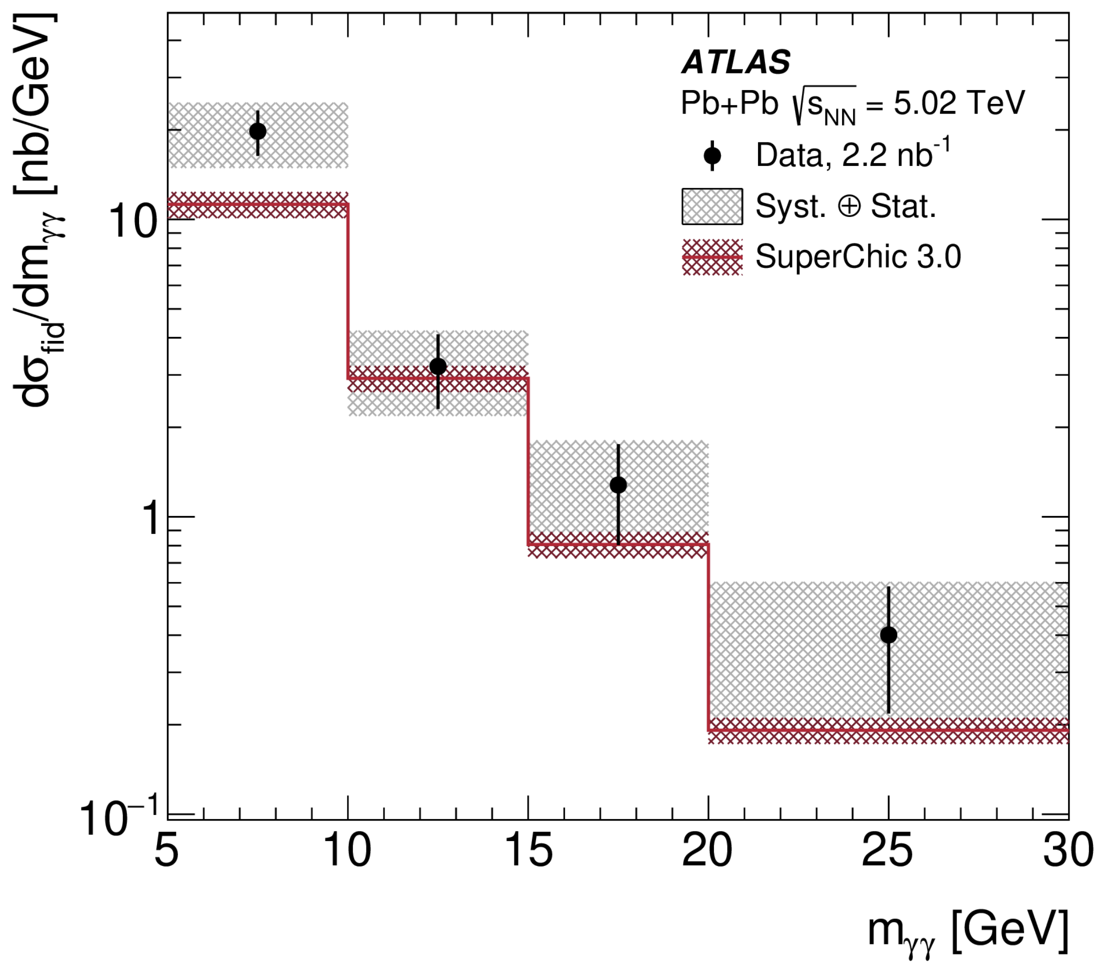
$\sigma_{\text{fid}}^{\text{theory1}} = 80 \pm 8$ nb by M.Klusek-Gawenda et al. [Phys. Rev. C 93 (2016) 044907]

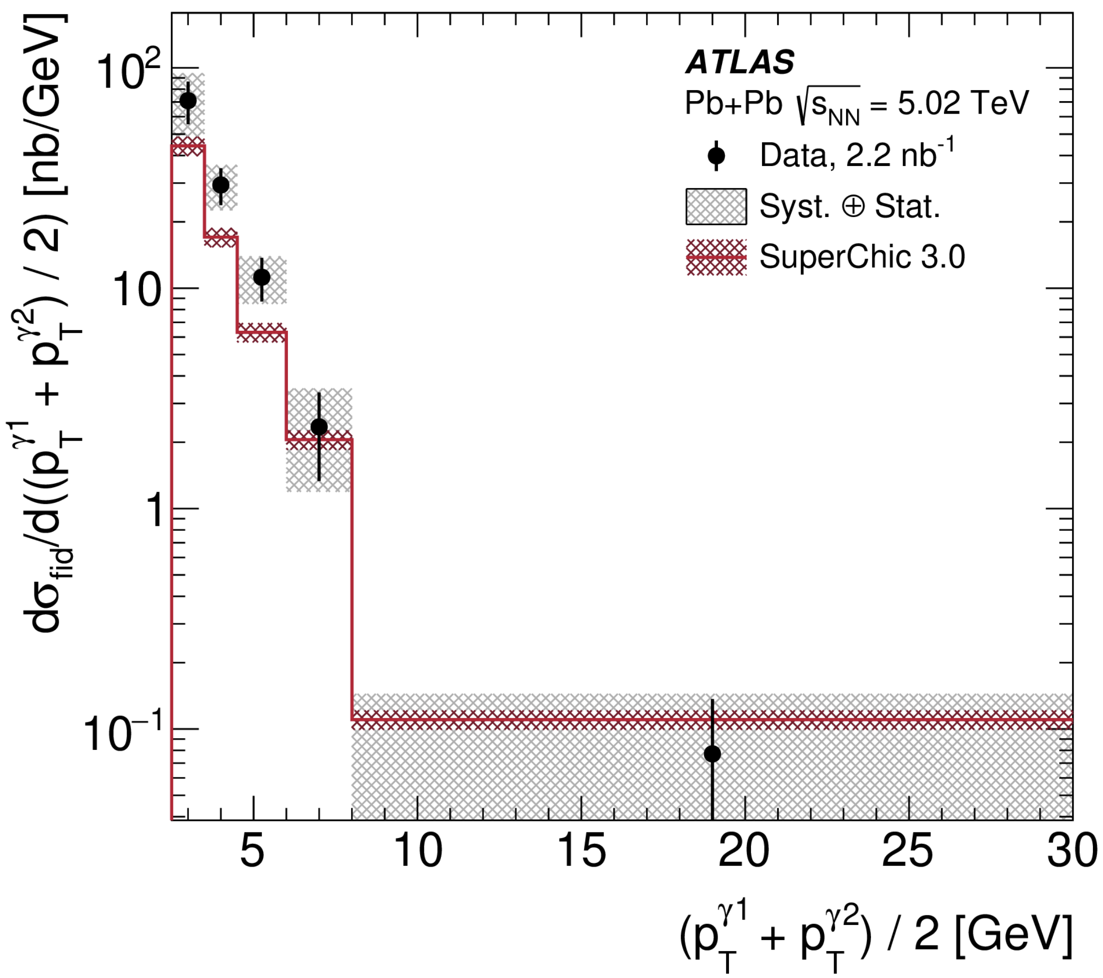
$\sigma_{\text{fid}}^{\text{theory2}} = 78 \pm 8$ nb from SuperChic 3.0 [Eur. Phys. J. C 79 (2019) 39]

  - Reasonable agreement

NEW LBYL RESULTS FROM ATLAS

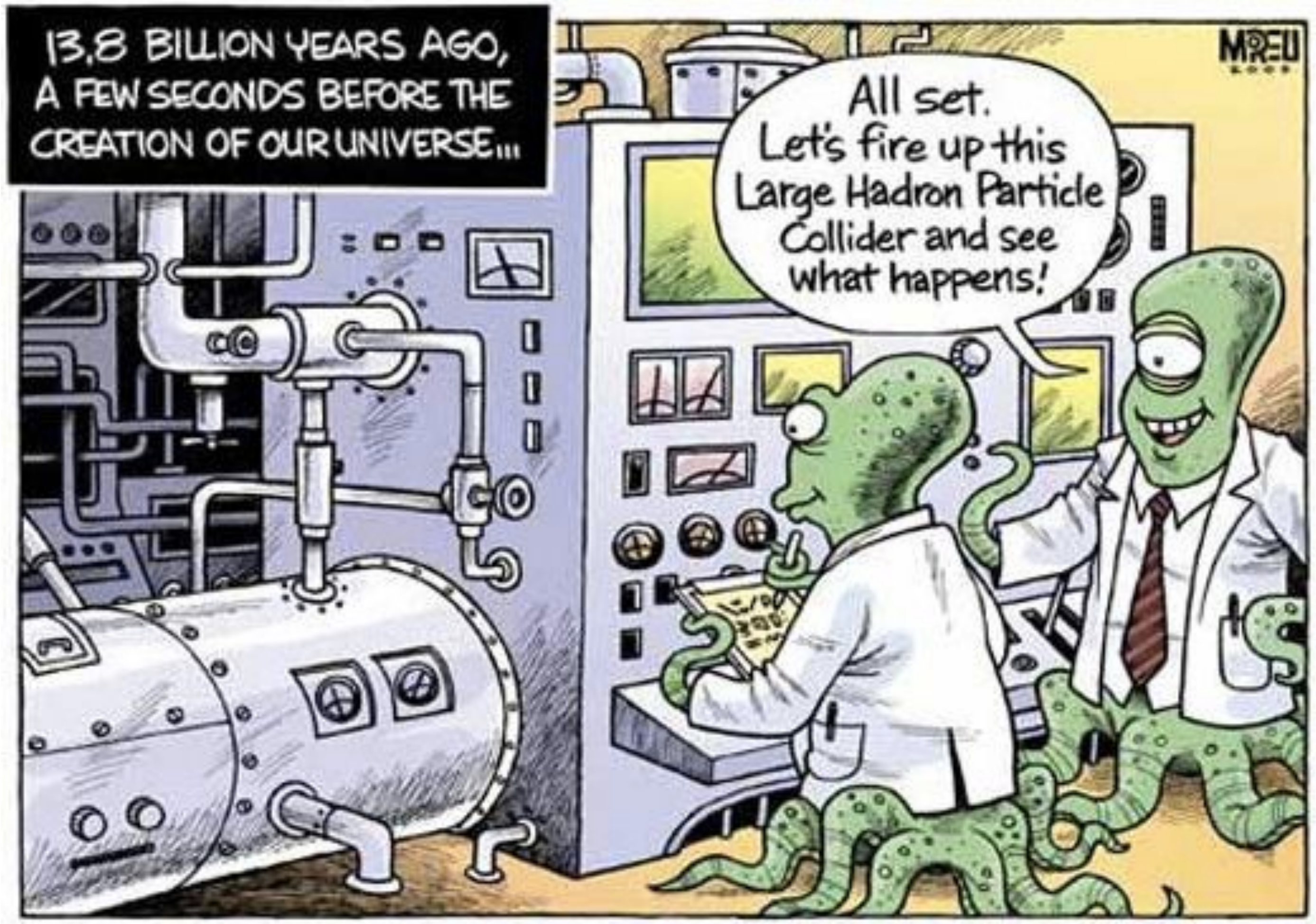
[arXiv: 2008.05355, submitted for JHEP]



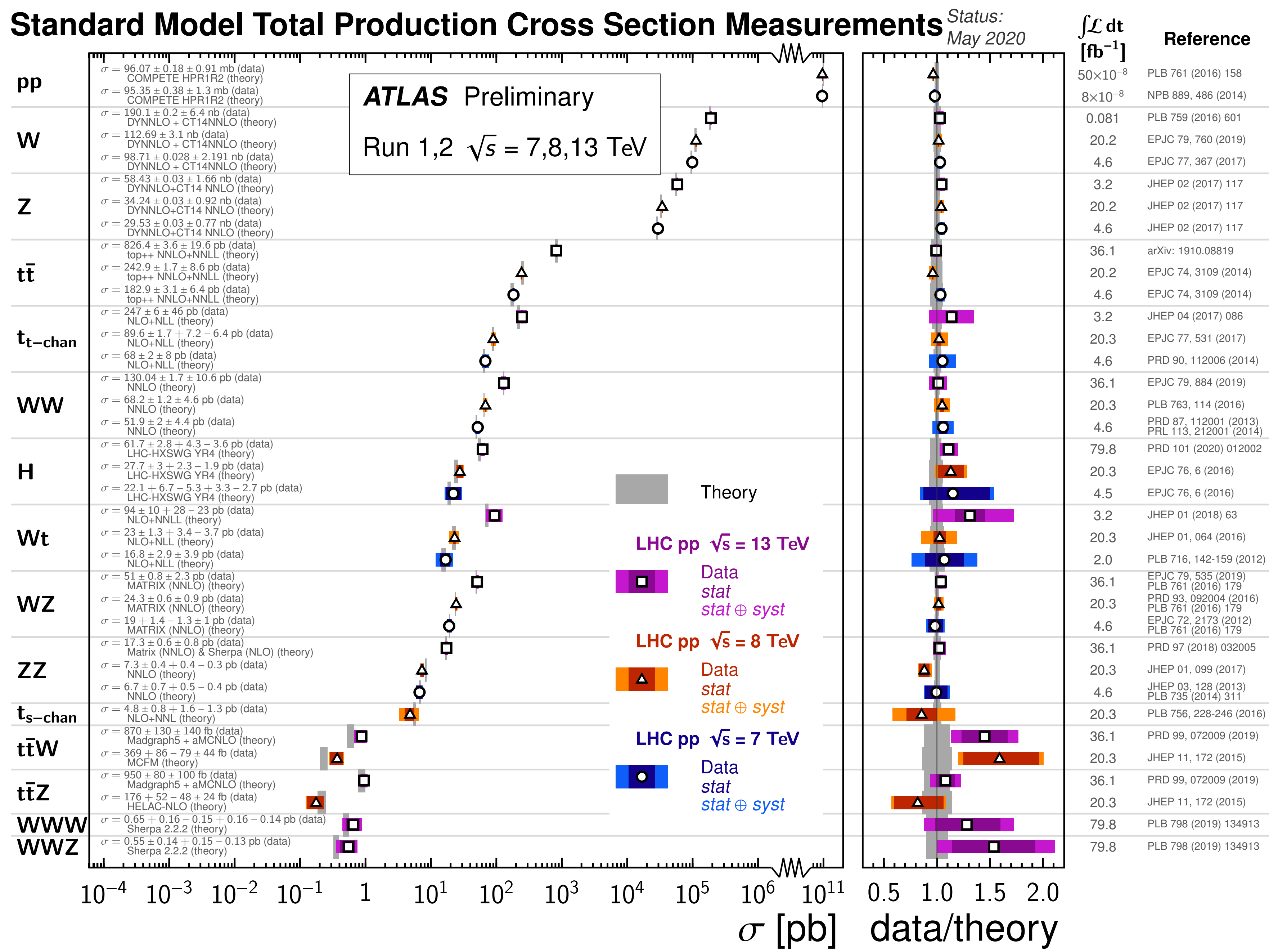


- New measurement based on **2015+2018 data sets** with 2.2 nb^{-1}
- Fiducial region defined by $p_T^\gamma > 2.5$ GeV, $m_{\gamma\gamma} > 5$ GeV, $|\eta^\gamma| < 2.4$, $p_T^{\gamma\gamma} < 1$ GeV
- **Differential cross sections** have been measured in four variables for the first time
  - After background subtraction
  - **Good agreement in shape**, some differences in the normalisation

SEARCH FOR UNKNOWN



STANDARD MODEL

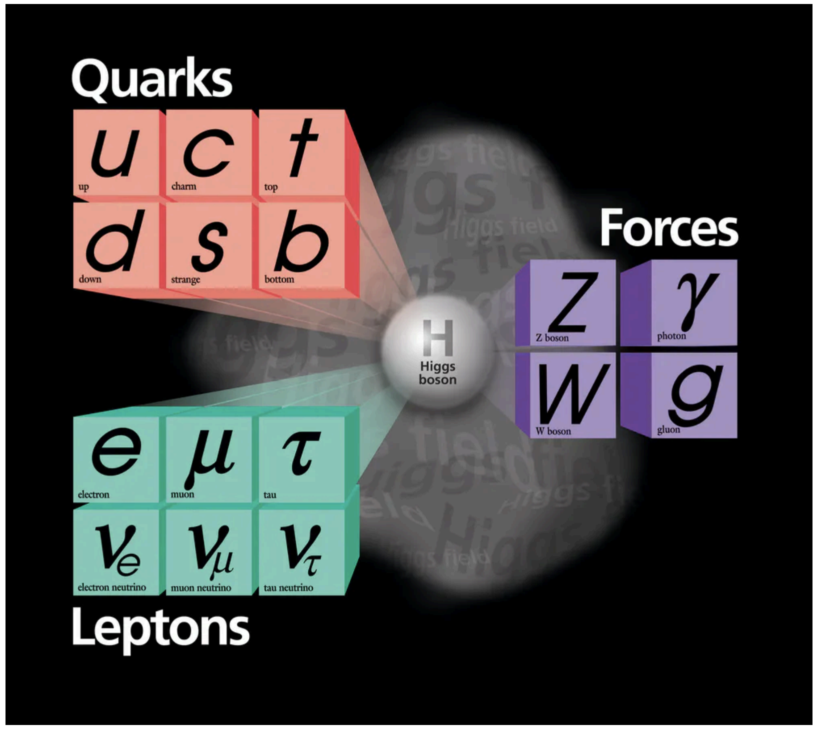


➤ Standard Model does a very good job in the description of pp data collected at the LHC

- ➤ Over 12 orders of magnitude!
- ➤ Including a discovery of **Higgs boson** in 2012
- ➤ But …

SHORTCOMINGS OF STANDARD MODEL

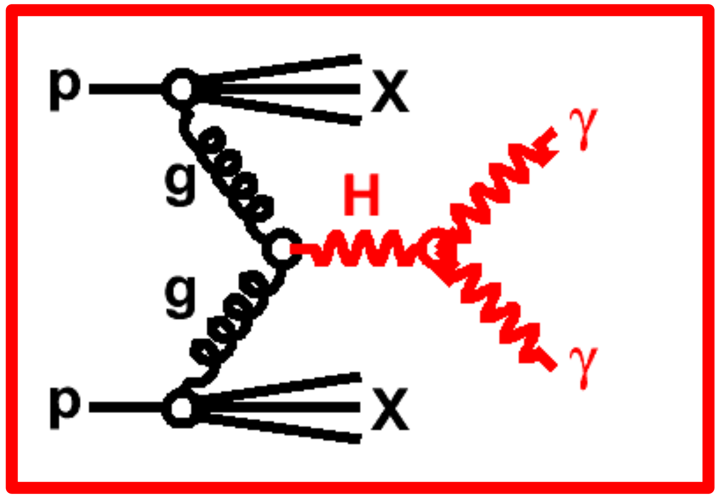
- Standard Model does not provide answers to all fundamental questions of physics
- List of some open issues:
  - Matter-antimatter asymmetry in the Universe
  - Dark matter and dark energy
  - Gravity
  - Strong CP violation
  - Neutrino mass
  - Grand unification
  - ….



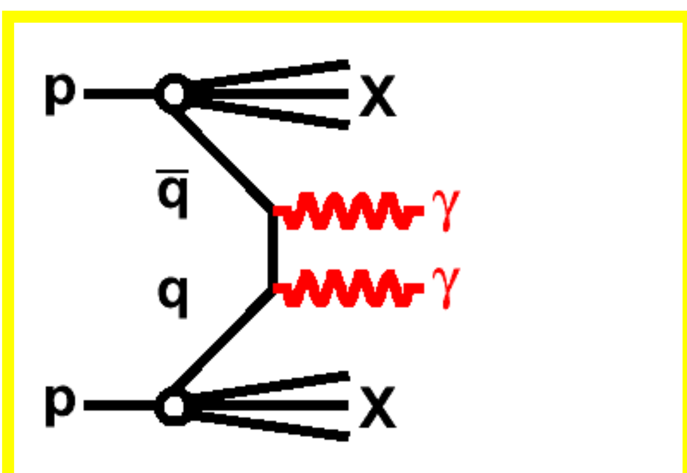
- Therefore, Standard Model cannot be the final theory
- This motivates searches for new phenomena, and new particles

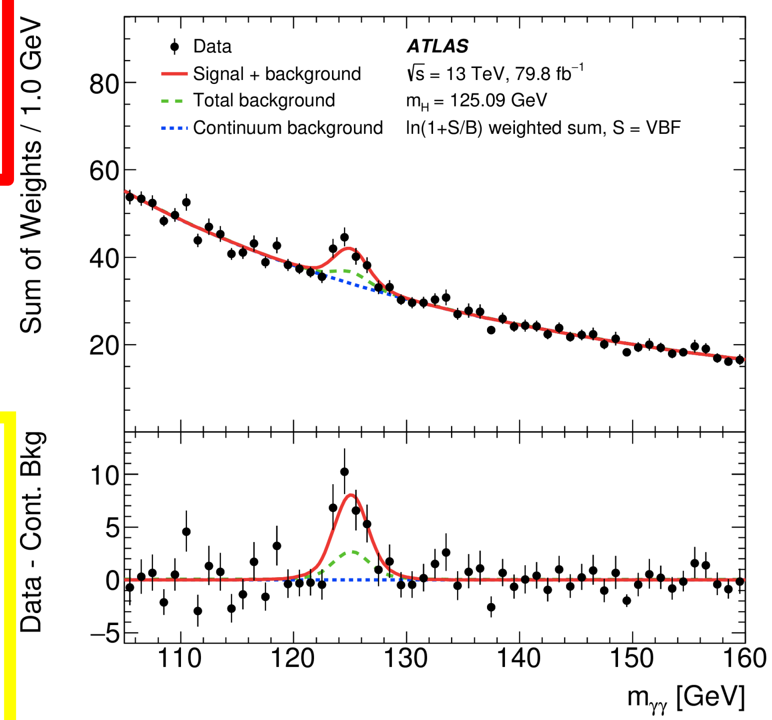
METHOD OF SEARCHING FOR NEW PARTICLES

Signal Higgs boson→γγ



Background event



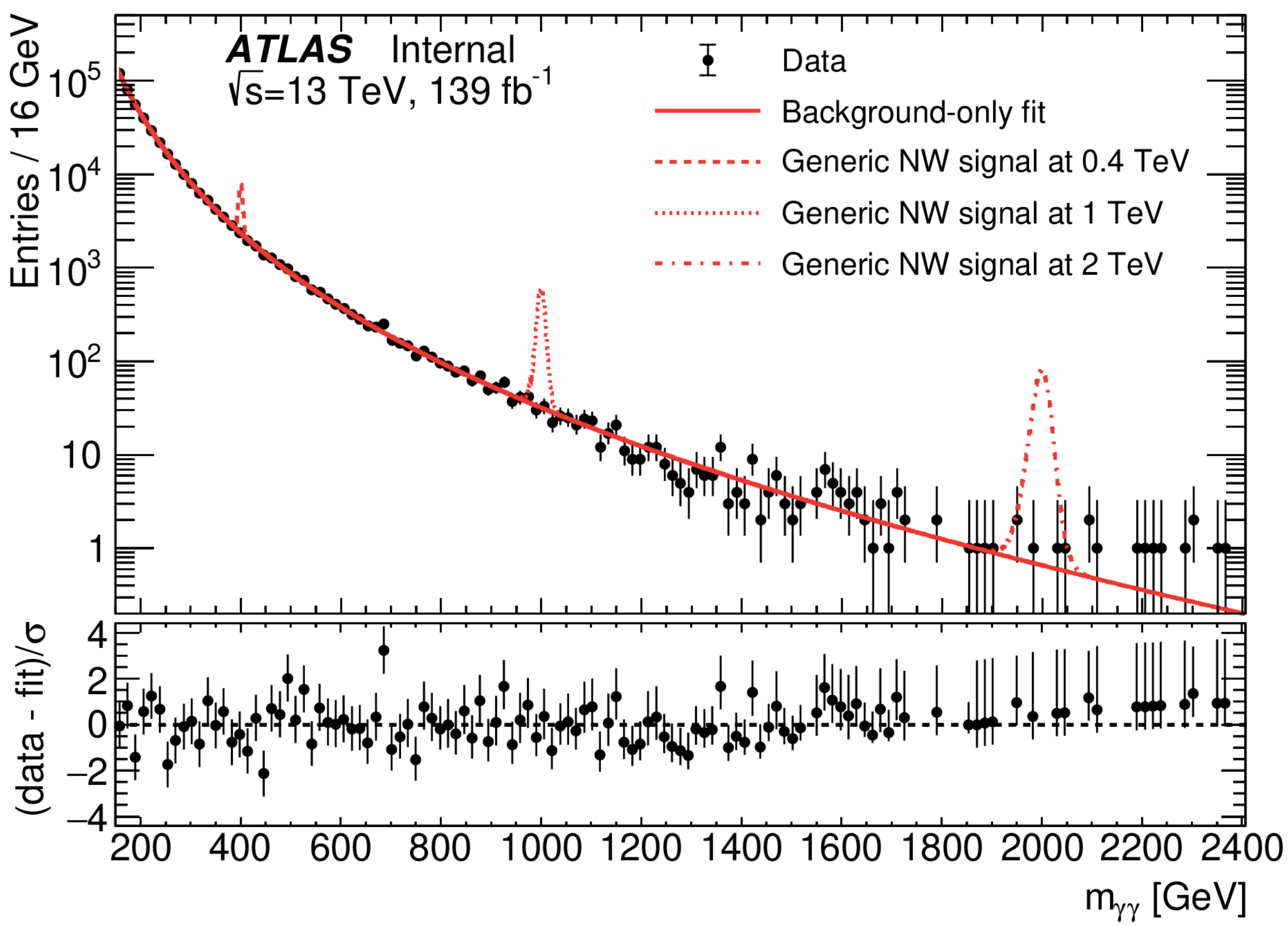


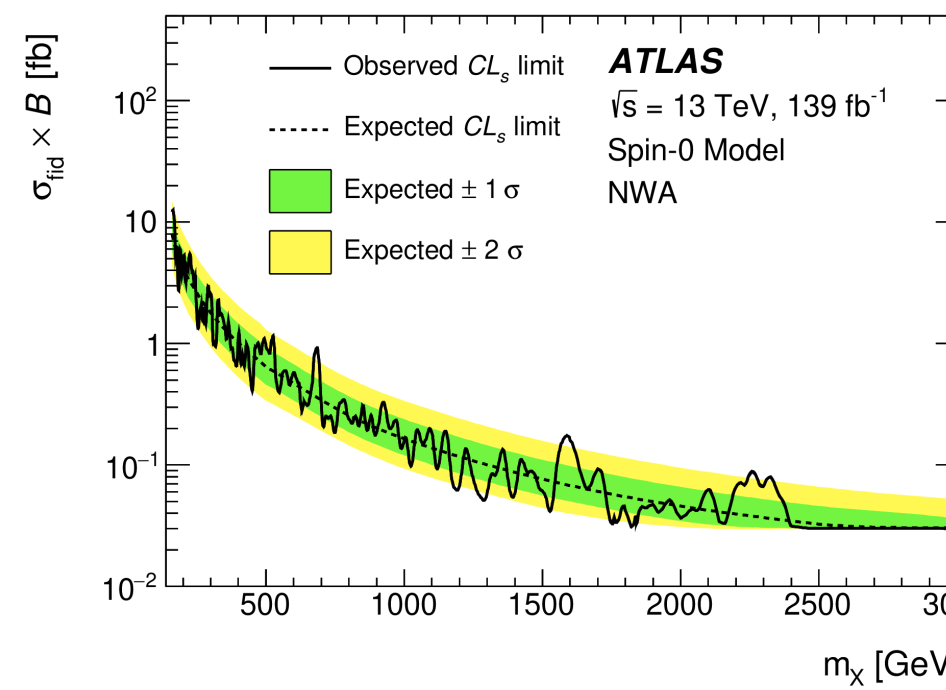
- Higgs boson decays into two high-energy photons
  - Energy and angles at which the photons move carry information about the mother particle from which they were created
- But there are background processes that also have two final photons
  - On the $m_{\gamma\gamma}$ distribution they do not give a peak
- This technique was used to establish the **Higgs boson** discovery in **2012**

$$m_X = m_H = \sqrt{E^2 - p^2} = m_{\gamma\gamma} = 2E_1E_2(1 - \cos\alpha)$$

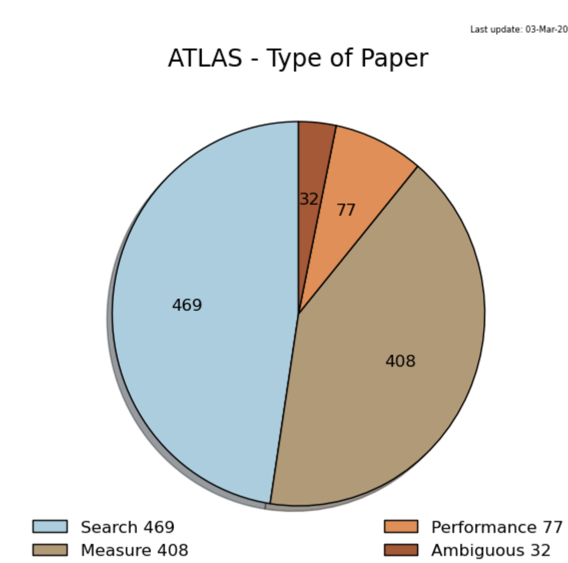
MANY SEARCHES ONGOING AT THE LHC

[arXiv: 2102.13405]



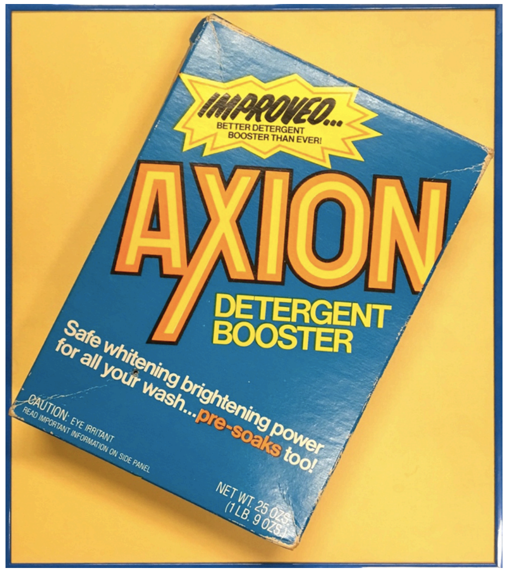


- Search for a new particle decaying to two photons from ATLAS
  - Measurement uses pp collisions at 13 TeV with 139 fb^{-1}
  - No excess over background has been found
  - Exclusion limits are derived (Brazilian plot)

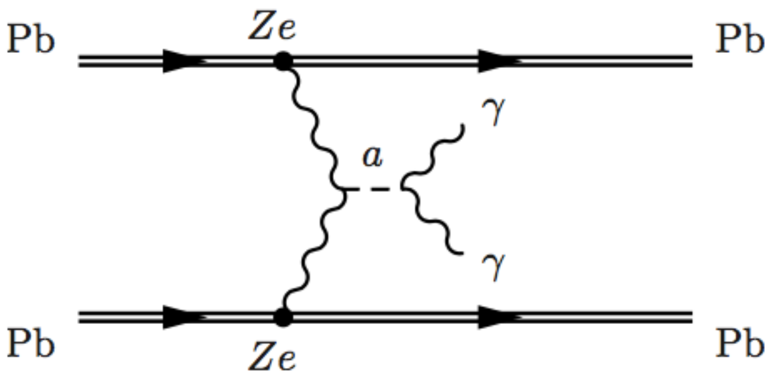


AXIONS OR AXION-LIKE PARTICLES

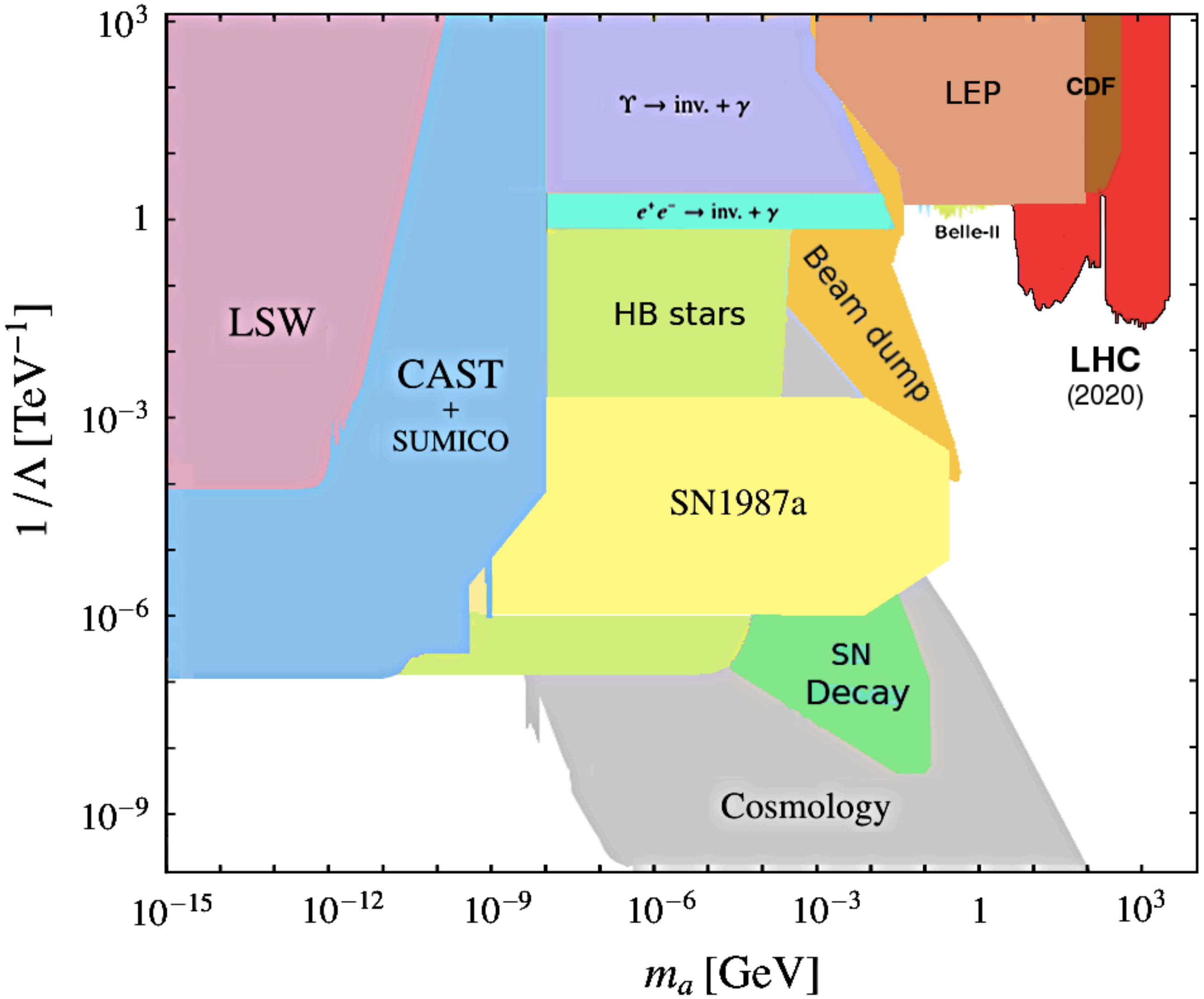
- In **1977**, a hypothetical particle proposed to solve one of **SM problems**
  - Named **axion** by Frank Wilczek, Steven Weinberg proposed - **Higglet**
  - Interacts: gravity, electromagnetic
  - Its non-zero mass m_a is not predicted by theory
  - It might be a possible component of **dark matter**
  - It may decay to **two photons**



- **Axion** and **axion-like particles** (ALP) have intensively been searched for in a broad range of masses
  - Using **cosmology**, **astrophysics** and **particle physics** data
  - Almost 1 preprint on arXiv per day

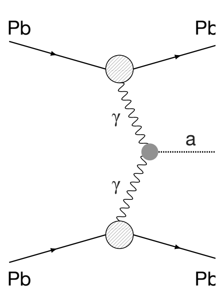


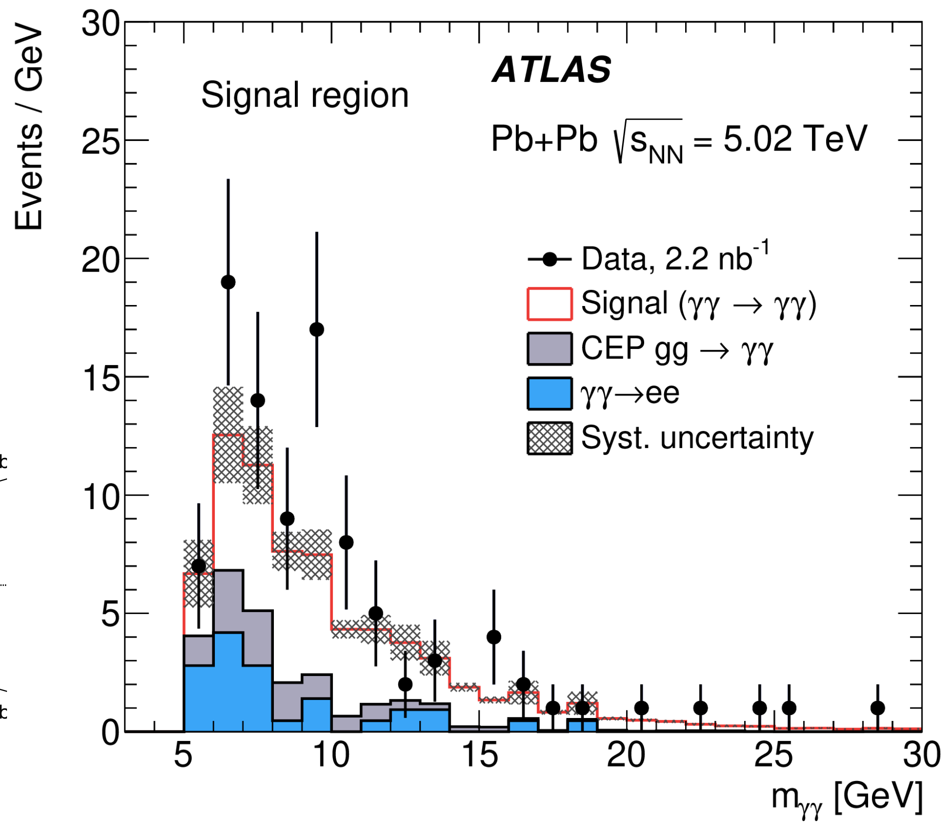
[arXiv:2102.08971]

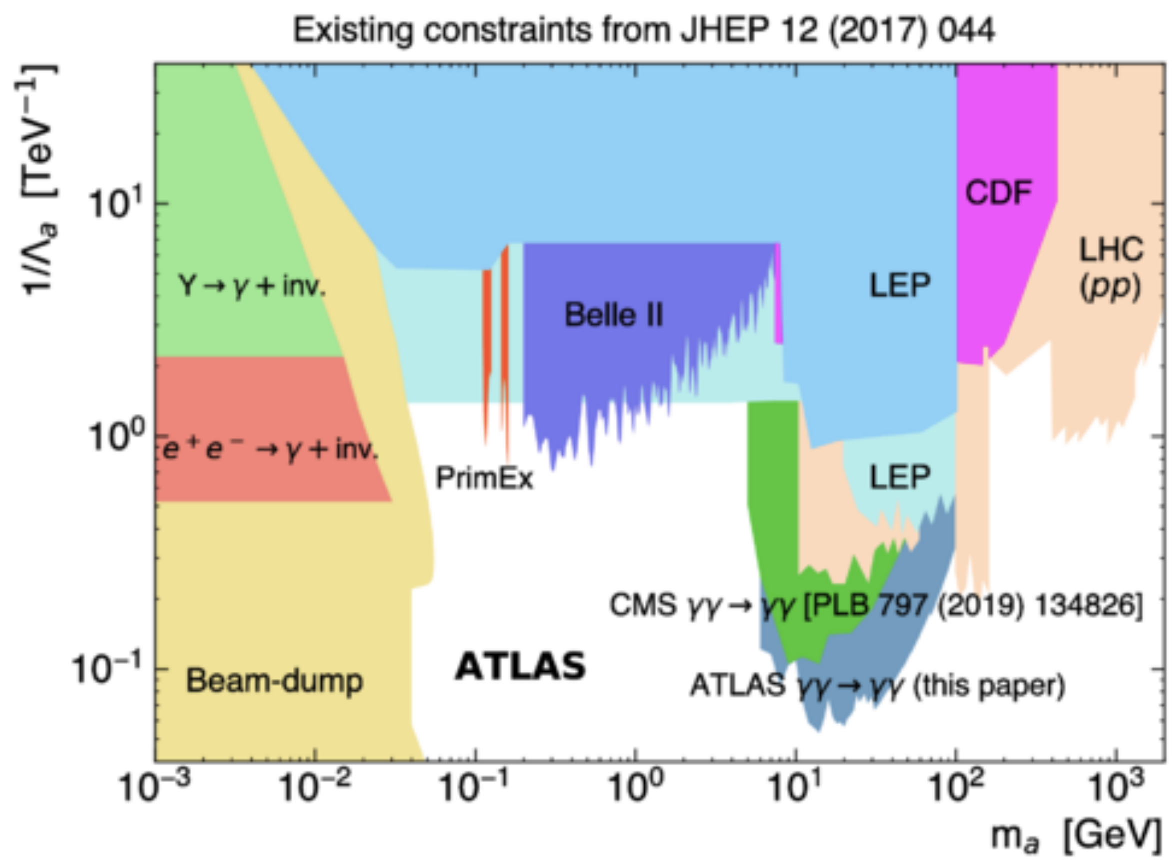


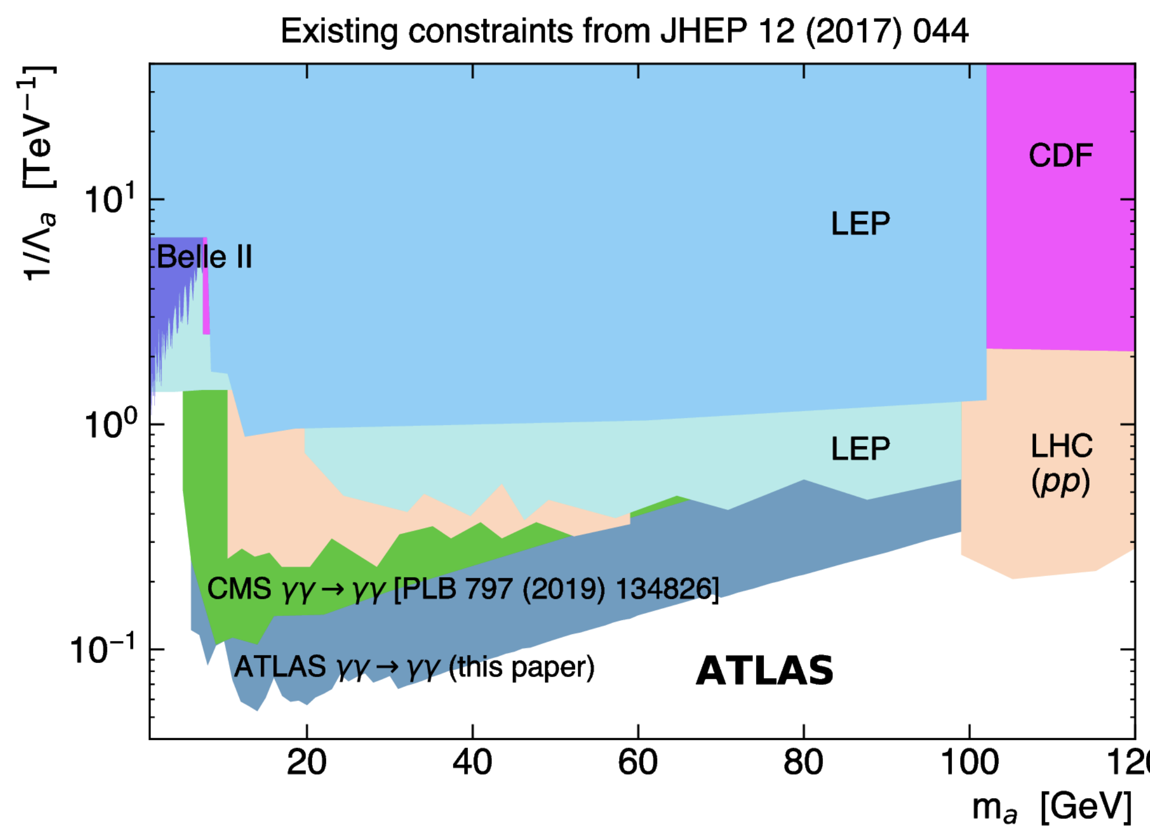
SEARCH FOR ALP

[arXiv: 2008.05355, submitted for JHEP]







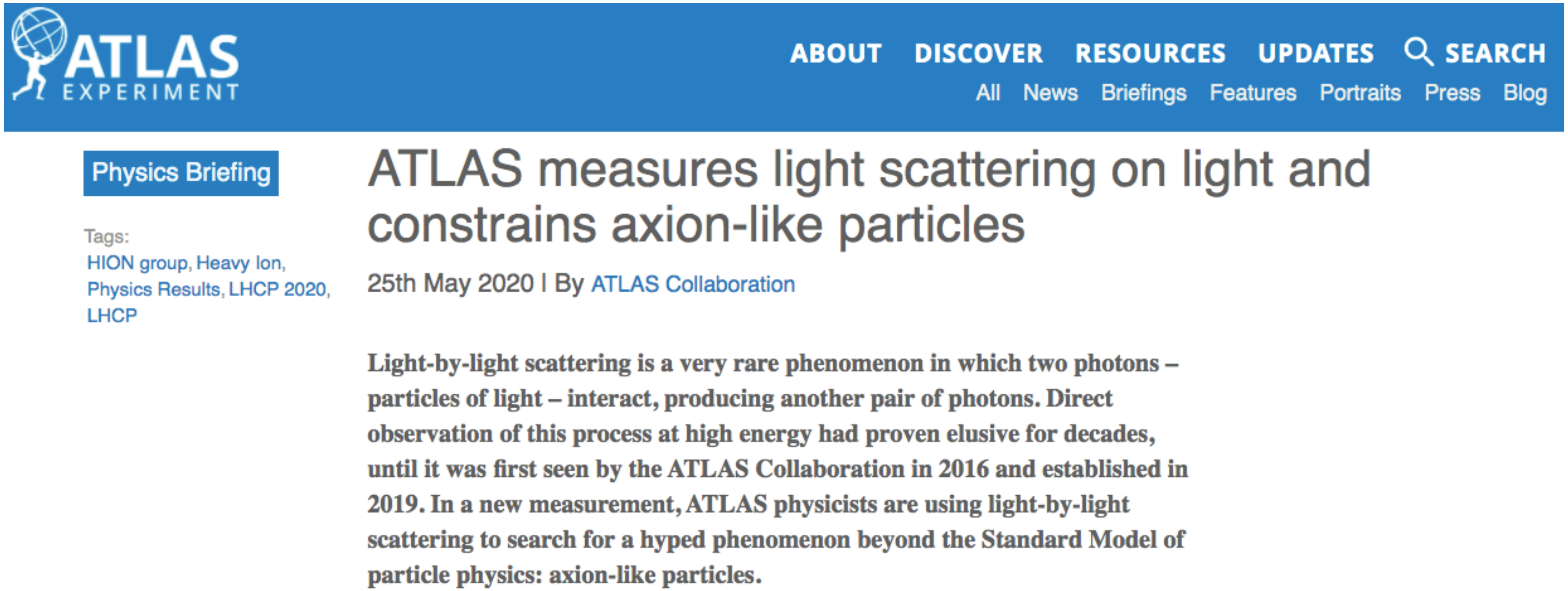


- Distribution of $m_{\gamma\gamma}$ used to **search for ALP** in $6 < m_{\gamma\gamma} < 100$ GeV range
  - Signal: $\gamma\gamma \to a \to \gamma\gamma$, BR($a \to \gamma\gamma$)=100%
  - Background: LbyL, $\gamma\gamma \to e^+e^-$, central exclusive production of $gg \to \gamma\gamma$
- 95% CL limits on cross section and coupling $1/\Lambda_a$
  - Largest deviation of 2.1σ at $m_{\gamma\gamma} \sim 10$ GeV
  - **The most stringent limit** established for ALP masses between 6-100 GeV

SUMMARY AND OUTLOOK

- Light-by-light scattering - a fundamental QED process - **has been measured directly** by the **ATLAS experiment** at the LHC
  - ATLAS is a leading experiment in this field of research
  - Members of the AGH UST have leading contributions to the LbyL measurement
  - In the **combined 2015+2018** data set, **97 events** were observed with a contribution of 27 background events
  - Results are consistent with Standard Model
  - Differential cross sections have been measured for the first time
  - Preprint submitted for publication in **Journal of High Energy Physics** [arXiv: 2008.05355]
- LbyL is sensitive to beyond-Standard Model physics
  - The diphoton mass distribution was used to search for axion-like particles
  - No significant excess has been found
  - The most stringent limits on ALP production derived for masses between 6-100 GeV
- Looking into the future
  - Expected 10 nb^{-1} in Run 3-4 with the upgraded ATLAS detector
  - In the meantime, other LHC experiments also have potential to contribute to LbyL measurements

MORE ON LBYL


ATLAS EXPERIMENT

ABOUT DISCOVER RESOURCES UPDATES SEARCH

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Physics Briefing

Tags:
HION group, Heavy Ion, Physics Results, LHCP 2020, LHCP

ATLAS measures light scattering on light and constrains axion-like particles

25th May 2020 | By ATLAS Collaboration

Light-by-light scattering is a very rare phenomenon in which two photons – particles of light – interact, producing another pair of photons. Direct observation of this process at high energy had proven elusive for decades, until it was first seen by the ATLAS Collaboration in 2016 and established in 2019. In a new measurement, ATLAS physicists are using light-by-light scattering to search for a hyped phenomenon beyond the Standard Model of particle physics: axion-like particles.

- ATLAS briefing (2020): https://atlas.cern/updates/briefing/light-scattering-light-constrains-axion-particles
- ATLAS briefing (2019): https://atlas.cern/updates/briefing/atlas-observes-light-scattering-light
- CERN press statement (2017): https://home.cern/about/updates/2017/08/atlas-observes-direct-evidence-light-light-scattering
- CERN Courier (2017): http://cerncourier.com/cws/article/cern/66878

BACK-UP SLIDES

EXAMPLE: INDIRECT LBYL MEASUREMENT (TBR)

$$\mu = -\frac{g}{2}\mu_{\rm B}\frac{\mathbf{S}}{\hbar/2}$$

$$\mu_{\rm B} = e\hbar/(2m)$$

- 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))

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

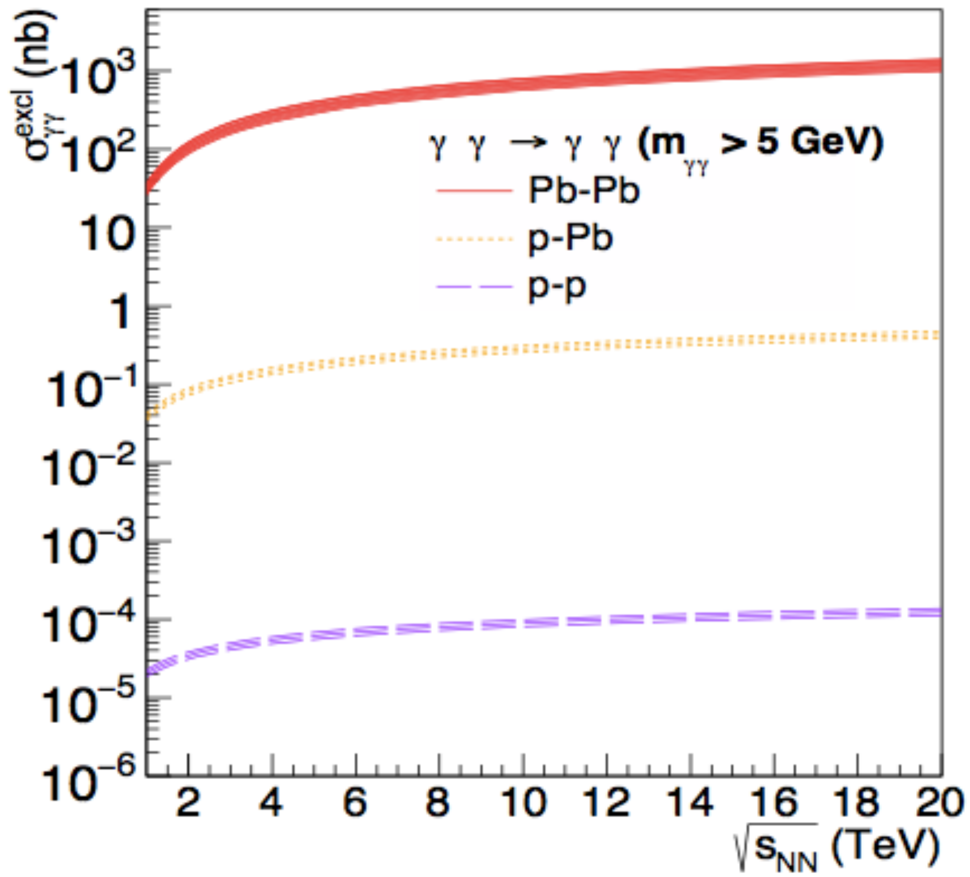
  - An uncertainty is 2.7 smaller w.r.t. the previous measurement
  - This measurement and QED theory determine the fine structure constant with an uncertainty 20 times smaller than before (Phys. Rev. Lett. 99, 110406 (2007))

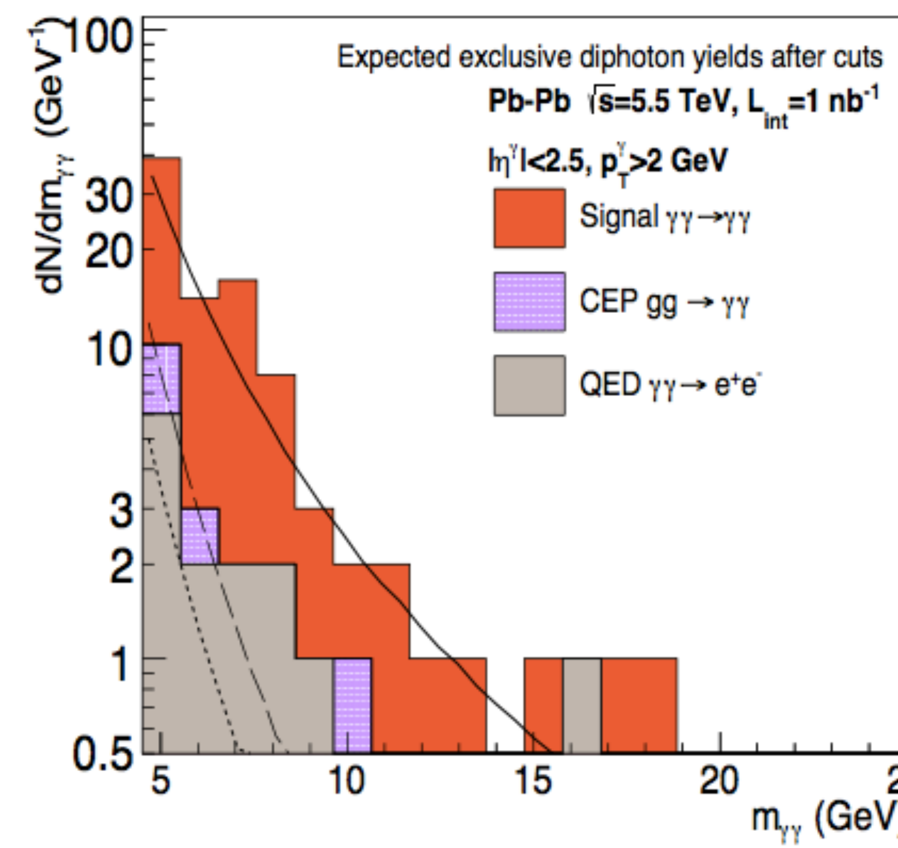
$$1/\alpha = 137.035999084(51)$$

  - Further improvements in precision are limited by the theory predictions

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=5x10^7 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

ATLAS SUSY Searches* - 95% CL Lower Limits

July 2020

ATLAS Preliminary

$\sqrt{s}$ = 13 TeV

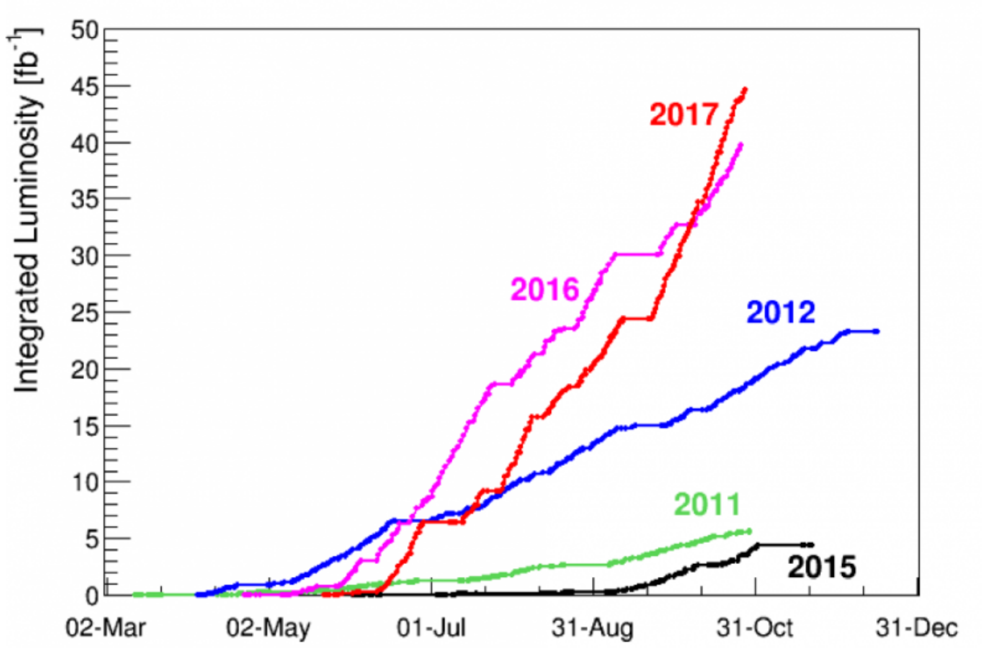
	Model	e, μ, τ, γ	Jets	$E_T^{\rm miss}$	$\int \mathcal{L}\, dt$ [fb^{-1}]	Mass limit		Conditions	Reference
Inclusive Searches	$\tilde q\tilde q$, $\tilde q \to q\tilde\chi^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde q$ [10× Degen.]	1.9	$m(\tilde\chi^0_1)$<400 GeV	ATLAS-CONF-2019-040
		mono-jet	1-3 jets	$E_T^{\rm miss}$	36.1	$\tilde q$ [1×, 8× Degen.]	0.43 0.71	$m(\tilde q)$-$m(\tilde\chi^0_1)$=5 GeV	1711.03301
	$\tilde g\tilde g$, $\tilde g \to q\bar q\tilde\chi^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde g$	2.35	$m(\tilde\chi^0_1)$=0 GeV	ATLAS-CONF-2019-040
						$\tilde g$ Forbidden	1.15-1.95	$m(\tilde\chi^0_1)$=1000 GeV	ATLAS-CONF-2019-040
	$\tilde g\tilde g$, $\tilde g \to q\bar q W\tilde\chi^0_1$	1 e,μ	2-6 jets		139	$\tilde g$	2.2	$m(\tilde\chi^0_1)$<600 GeV	ATLAS-CONF-2020-047
	$\tilde g\tilde g$, $\tilde g \to q\bar q(\ell\ell)\tilde\chi^0_1$	$ee,\mu\mu$	2 jets	$E_T^{\rm miss}$	36.1	$\tilde g$	1.2	$m(\tilde g)$-$m(\tilde\chi^0_1)$=50 GeV	1805.11381
	$\tilde g\tilde g$, $\tilde g \to qqWZ\tilde\chi^0_1$	0 e,μ	7-11 jets	$E_T^{\rm miss}$	139	$\tilde g$	1.97	$m(\tilde\chi^0_1)$ <600 GeV	ATLAS-CONF-2020-002
		SS e,μ	6 jets		139	$\tilde g$	1.15	$m(\tilde g)$-$m(\tilde\chi^0_1)$=200 GeV	1909.08457
	$\tilde g\tilde g$, $\tilde g \to t\bar t\tilde\chi^0_1$	0-1 e,μ	3 b	$E_T^{\rm miss}$	79.8	$\tilde g$	2.25	$m(\tilde\chi^0_1)$<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde g$	1.25	$m(\tilde g)$-$m(\tilde\chi^0_1)$=300 GeV	1909.08457
3^{rd} gen. squarks direct production	$\tilde b_1\tilde b_1$, $\tilde b_1 \to b\tilde\chi^0_1/t\tilde\chi^\pm_1$		Multiple		36.1	$\tilde b_1$ Forbidden	0.9	$m(\tilde\chi^0_1)$=300 GeV, BR($b\tilde\chi^0_1$)=1	1708.09266, 1711.03301
			Multiple		139	$\tilde b_1$ Forbidden	0.74	$m(\tilde\chi^0_1)$=200 GeV, $m(\tilde\chi^\pm_1)$=300 GeV, BR($t\tilde\chi^\pm_1$)=1	1909.08457
	$\tilde b_1\tilde b_1$, $\tilde b_1 \to b\tilde\chi^0_2 \to bh\tilde\chi^0_1$	0 e,μ	6 b	$E_T^{\rm miss}$	139	$\tilde b_1$ Forbidden	0.23-1.35	$\Delta m(\tilde\chi^0_2,\tilde\chi^0_1)$=130 GeV, $m(\tilde\chi^0_1)$=100 GeV	1908.03122
		2 τ	2 b	$E_T^{\rm miss}$	139	$\tilde b_1$	0.13-0.85	$\Delta m(\tilde\chi^0_2,\tilde\chi^0_1)$=130 GeV, $m(\tilde\chi^0_1)$=0 GeV	ATLAS-CONF-2020-031
	$\tilde t_1\tilde t_1$, $\tilde t_1 \to t\tilde\chi^0_1$	0-1 e,μ	≥ 1 jet	$E_T^{\rm miss}$	139	$\tilde t_1$	1.25	$m(\tilde\chi^0_1)$=1 GeV	ATLAS-CONF-2020-003, 2004.14060
	$\tilde t_1\tilde t_1$, $\tilde t_1 \to Wb\tilde\chi^0_1$	1 e,μ	3 jets/1 b	$E_T^{\rm miss}$	139	$\tilde t_1$	0.44-0.59	$m(\tilde\chi^0_1)$=400 GeV	ATLAS-CONF-2019-017
	$\tilde t_1\tilde t_1$, $\tilde t_1 \to \tilde\tau_1 b\nu$, $\tilde\tau_1 \to \tau\tilde G$	1 τ + 1 e,μ,τ	2 jets/1 b	$E_T^{\rm miss}$	36.1	$\tilde t_1$	1.16	$m(\tilde\tau_1)$=800 GeV	1803.10178
	$\tilde t_1\tilde t_1$, $\tilde t_1 \to c\tilde\chi^0_1$ / $\tilde c\tilde c$, $\tilde c \to c\tilde\chi^0_1$	0 e,μ	2 c	$E_T^{\rm miss}$	36.1	$\tilde c$	0.85	$m(\tilde\chi^0_1)$=0 GeV	1805.01649
						$\tilde t_1$	0.46	$m(\tilde t_1,\tilde c)$-$m(\tilde\chi^0_1)$=50 GeV	1805.01649
		0 e,μ	mono-jet	$E_T^{\rm miss}$	36.1	$\tilde t_1$	0.43	$m(\tilde t_1,\tilde c)$-$m(\tilde\chi^0_1)$=5 GeV	1711.03301
	$\tilde t_1\tilde t_1$, $\tilde t_1 \to t\tilde\chi^0_2$, $\tilde\chi^0_2 \to Z/h\tilde\chi^0_1$	1-2 e,μ	1-4 b	$E_T^{\rm miss}$	139	$\tilde t_1$	0.067-1.18	$m(\tilde\chi^0_2)$=500 GeV	SUSY-2018-09
	$\tilde t_2\tilde t_2$, $\tilde t_2 \to \tilde t_1 + Z$	3 e,μ	1 b	$E_T^{\rm miss}$	139	$\tilde t_2$ Forbidden	0.86	$m(\tilde\chi^0_1)$=360 GeV, $m(\tilde t_1)$-$m(\tilde\chi^0_1)$= 40 GeV	SUSY-2018-09
EW direct	$\tilde\chi^\pm_1\tilde\chi^0_2$ via WZ	3 e,μ		$E_T^{\rm miss}$	139	$\tilde\chi^\pm_1/\tilde\chi^0_2$	0.64	$m(\tilde\chi^0_1)$=0	ATLAS-CONF-2020-015
		$ee,\mu\mu$	≥ 1 jet	$E_T^{\rm miss}$	139	$\tilde\chi^\pm_1/\tilde\chi^0_2$	0.205	$m(\tilde\chi^\pm_1)$-$m(\tilde\chi^0_1)$=5 GeV	1911.12606
	$\tilde\chi^\pm_1\tilde\chi^\mp_1$ via WW	2 e,μ		$E_T^{\rm miss}$	139	$\tilde\chi^\pm_1$	0.42	$m(\tilde\chi^0_1)$=0	1908.08215
	$\tilde\chi^\pm_1\tilde\chi^0_2$ via Wh	0-1 e,μ	2 b/2 γ	$E_T^{\rm miss}$	139	$\tilde\chi^\pm_1/\tilde\chi^0_2$ Forbidden	0.74	$m(\tilde\chi^0_1)$=70 GeV	2004.10894, 1909.09226
	$\tilde\chi^\pm_1\tilde\chi^\mp_1$ via $\tilde\ell_L/\tilde\nu$	2 e,μ		$E_T^{\rm miss}$	139	$\tilde\chi^\pm_1$	1.0	$m(\tilde\ell,\tilde\nu)$=0.5($m(\tilde\chi^\pm_1)$+$m(\tilde\chi^0_1)$)	1908.08215
	$\tilde\tau\tilde\tau$, $\tilde\tau \to \tau\tilde\chi^0_1$	2 τ		$E_T^{\rm miss}$	139	$\tilde\tau$ [$\tilde\tau_L$, $\tilde\tau_{R,L}$]	0.16-0.3 0.12-0.39	$m(\tilde\chi^0_1)$=0	1911.06660
	$\tilde\ell_{L,R}\tilde\ell_{L,R}$, $\tilde\ell \to \ell\tilde\chi^0_1$	2 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde\ell$	0.7	$m(\tilde\chi^0_1)$=0	1908.08215
		$ee,\mu\mu$	≥ 1 jet	$E_T^{\rm miss}$	139	$\tilde\ell$	0.256	$m(\tilde\ell)$-$m(\tilde\chi^0_1)$=10 GeV	1911.12606
	$\tilde H\tilde H$, $\tilde H \to h\tilde G/Z\tilde G$	0 e,μ	≥ 3 b	$E_T^{\rm miss}$	36.1	$\tilde H$	0.13-0.23 0.29-0.88	BR($\tilde\chi^0_1 \to h\tilde G$)=1	1806.04030
		4 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde H$	0.55	BR($\tilde\chi^0_1 \to Z\tilde G$)=1	ATLAS-CONF-2020-040
Long-lived particles	Direct $\tilde\chi^+_1\tilde\chi^-_1$ prod., long-lived $\tilde\chi^\pm_1$	Disapp. trk	1 jet	$E_T^{\rm miss}$	36.1	$\tilde\chi^\pm_1$	0.46	Pure Wino	1712.02118
						$\tilde\chi^\pm_1$	0.15	Pure higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde g$ R-hadron		Multiple		36.1	$\tilde g$	2.0		1902.01636,1808.04095
	Metastable $\tilde g$ R-hadron, $\tilde g \to qq\tilde\chi^0_1$		Multiple		36.1	$\tilde g$ [$\tau(\tilde g)$ =10 ns, 0.2 ns]	2.05 2.4	$m(\tilde\chi^0_1)$=100 GeV	1710.04901,1808.04095
RPV	$\tilde\chi^\pm_1\tilde\chi^\mp_1/\tilde\chi^0_1$, $\tilde\chi^\pm_1 \to Z\ell \to \ell\ell\ell$	3 e,μ			139	$\tilde\chi^\pm_1/\tilde\chi^0_1$ [BR($Z\tau$)=1, BR(Ze)=1]	0.625 1.05	Pure Wino	ATLAS-CONF-2020-009
	LFV $pp \to \tilde\nu_\tau + X$, $\tilde\nu_\tau \to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$			3.2	$\tilde\nu_\tau$	1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde\chi^\pm_1\tilde\chi^\mp_1/\tilde\chi^0_2 \to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	$E_T^{\rm miss}$	36.1	$\tilde\chi^\pm_1/\tilde\chi^0_2$ [$\lambda_{i33} \neq 0$, $\lambda_{12k} \neq 0$]	0.82 1.33	$m(\tilde\chi^0_1)$=100 GeV	1804.03602
	$\tilde g\tilde g$, $\tilde g \to qq\tilde\chi^0_1$, $\tilde\chi^0_1 \to qqq$		4-5 large-R jets		36.1	$\tilde g$ [$m(\tilde\chi^0_1)$=200 GeV, 1100 GeV]	1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde g$ [λ''_{112}=2e-4, 2e-5]	1.05 2.0	$m(\tilde\chi^0_1)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde t\tilde t$, $\tilde t \to t\tilde\chi^0_1$, $\tilde\chi^0_1 \to tbs$		Multiple		36.1	$\tilde t$ [λ''_{323}=2e-4, 1e-2]	0.55 1.05	$m(\tilde\chi^0_1)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde t\tilde t$, $\tilde t \to b\tilde\chi^\pm_1$, $\tilde\chi^\pm_1 \to bbs$		≥ 4b		139	$\tilde t$ Forbidden	0.95	$m(\tilde\chi^\pm_1)$=500 GeV	ATLAS-CONF-2020-016
	$\tilde t_1\tilde t_1$, $\tilde t_1 \to bs$		2 jets + 2 b		36.7	$\tilde t_1$ [qq, bs]	0.42 0.61		1710.07171
	$\tilde t_1\tilde t_1$, $\tilde t_1 \to q\ell$	2 e,μ	2 b		36.1	$\tilde t_1$	0.4-1.45	BR($\tilde t_1 \to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde t_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9]	1.0 1.6	BR($\tilde t_1 \to q\mu$)=100%, $\cos\theta_t$=1	2003.11956

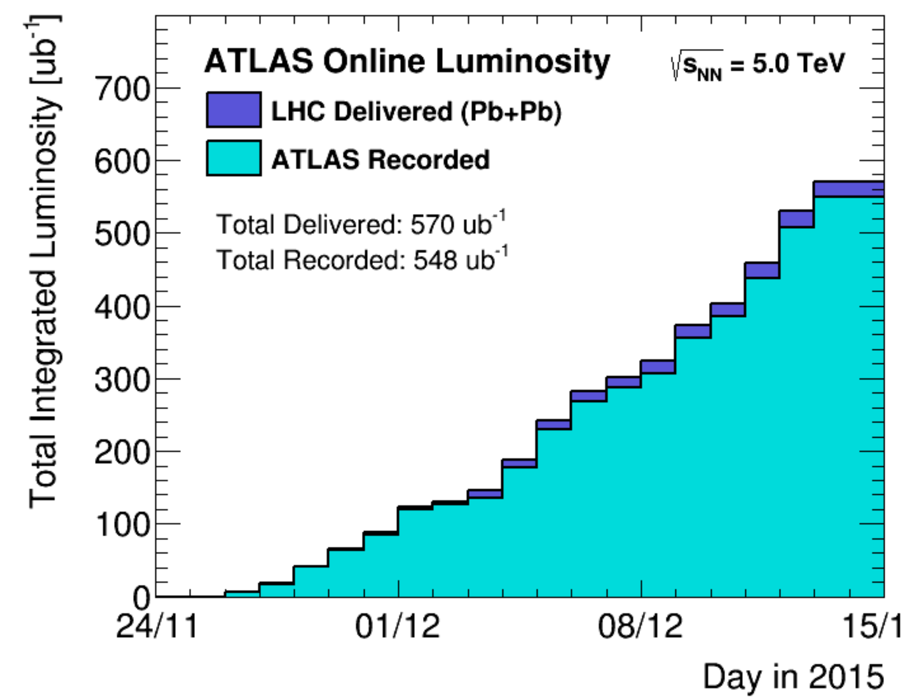
10^{-1} 1 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

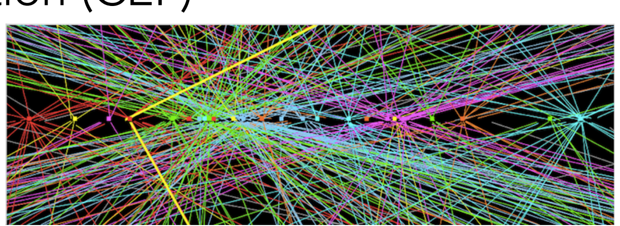
LBYL IN PROTON-PROTON OR LEAD-LEAD COLLISIONS?

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]
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





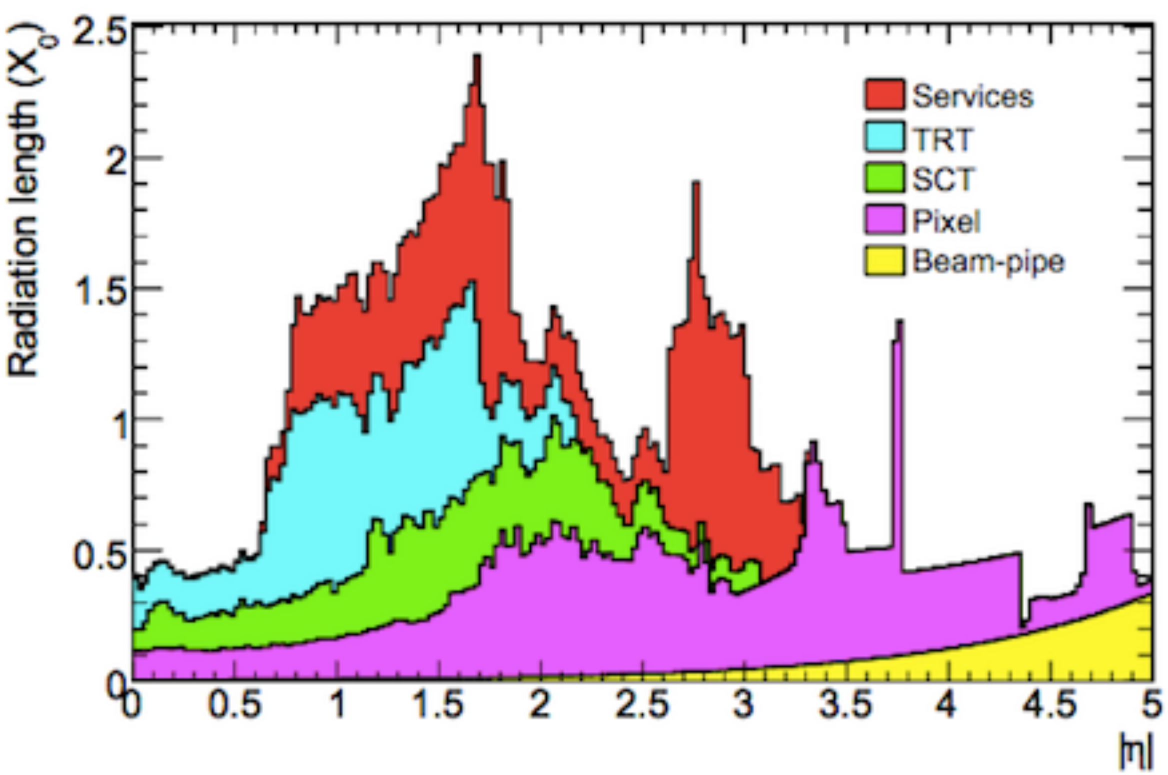
- LbyL in **proton-proton system**:
  - In total 100 fb^{-1} at 8 and 13 TeV —> ~1200 events
  - Harder photon spectrum
  - Larger pileup - in 2017 up to 60 simultaneous interactions
  - Larger backgrounds from Central Exclusive Production (CEP)

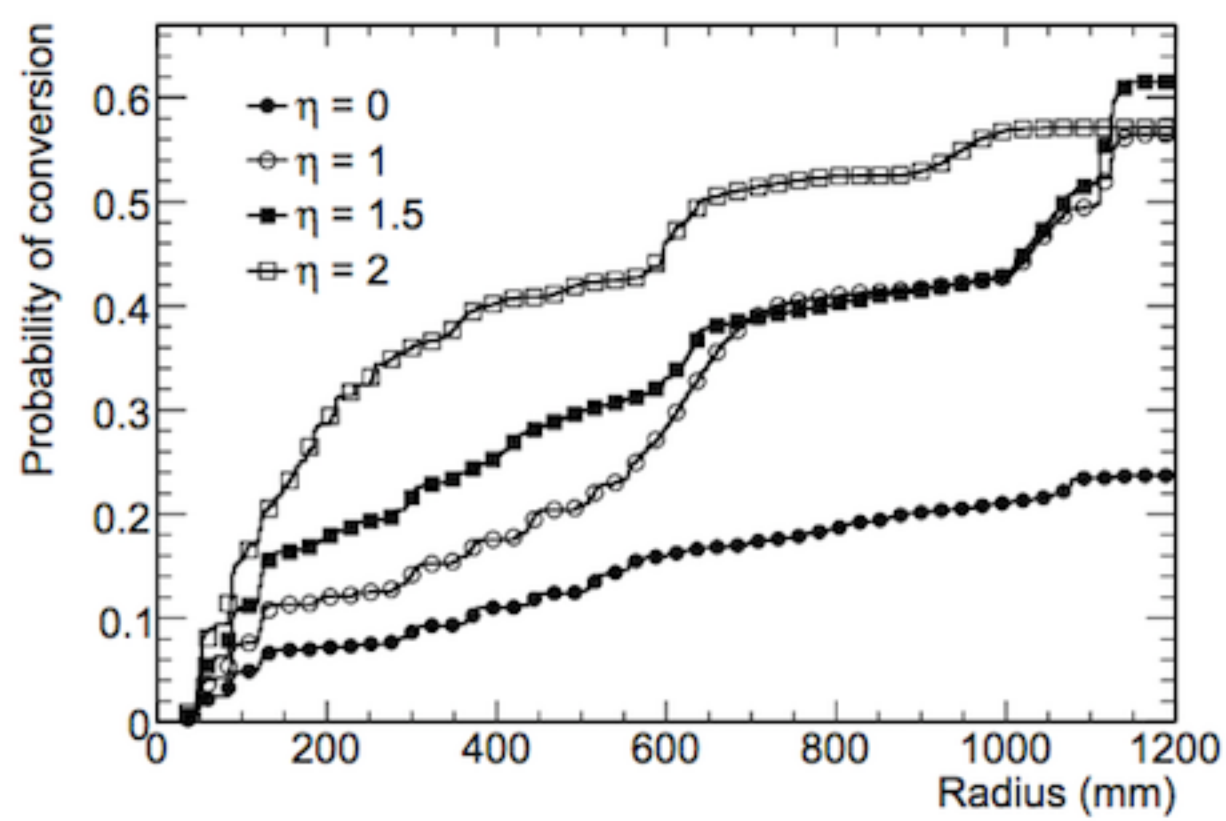


- LbyL in peripheral **lead-lead collisions**:
  - 0.5 nb^{-1} at 5.02 TeV —> ~35 events
  - Softer photon spectrum
  - Almost no pileup - very clean environment for photon studies
  - Background from CEP reduced

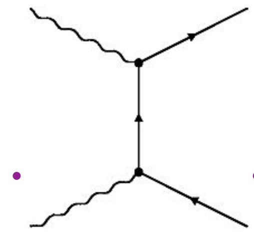
PHOTON CONVERSIONS IN ATLAS

- 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

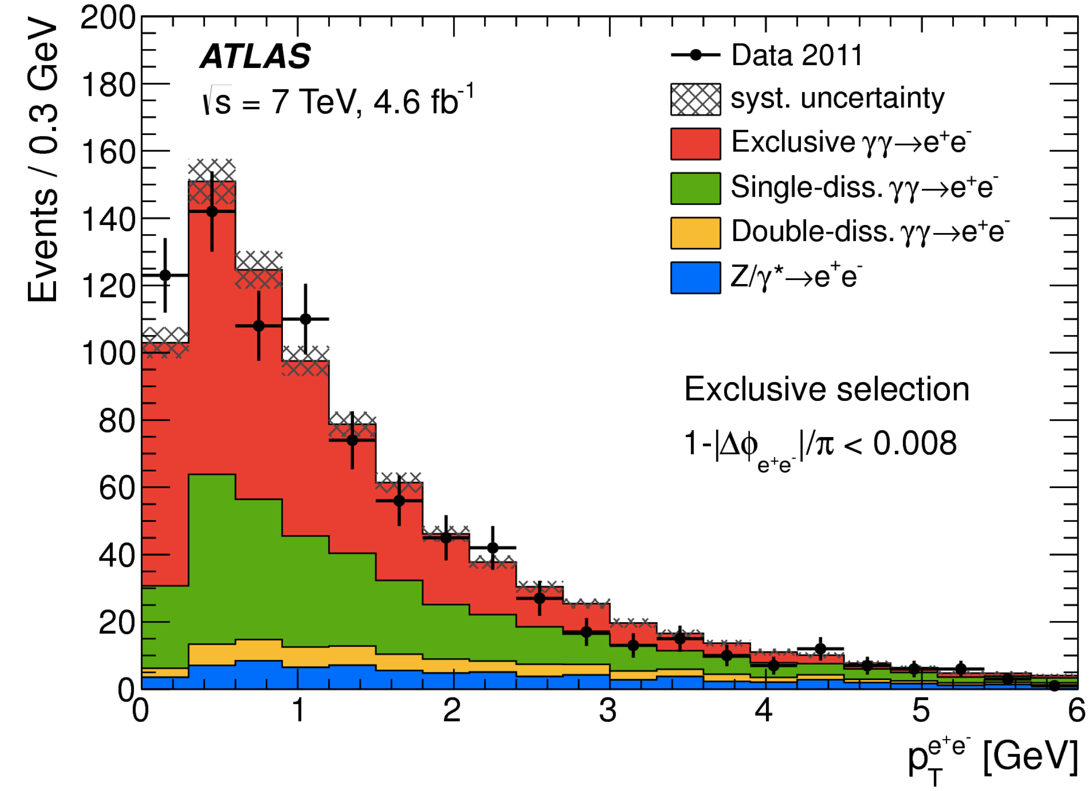


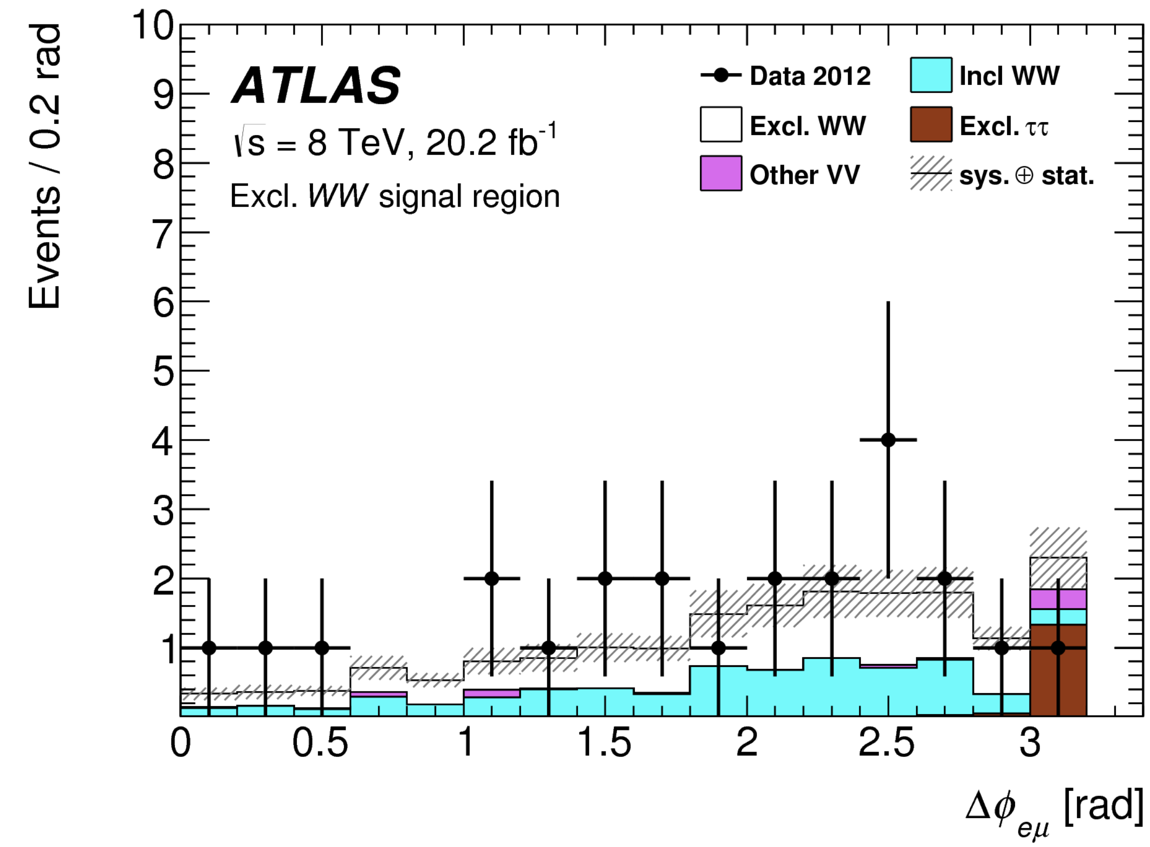


EXCLUSIVE MEASUREMENTS IN PP COLLISIONS



- ➤ $\gamma\gamma \rightarrow l+l-$ 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



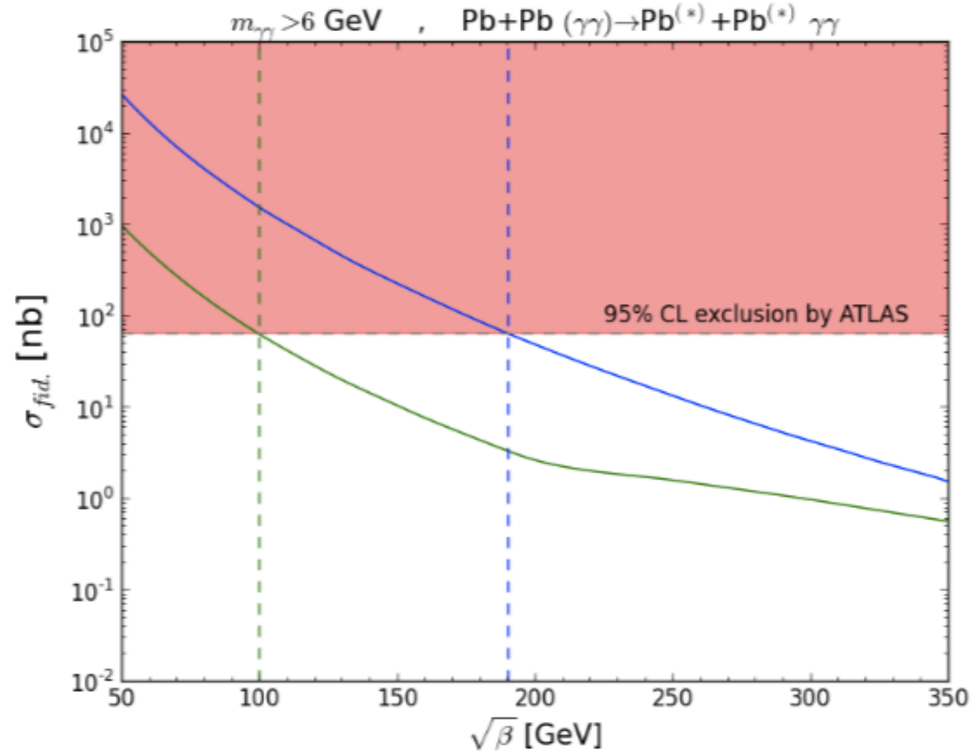


BSM SEARCHES: MAGNETIC MONOPOLES

- 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 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:

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

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

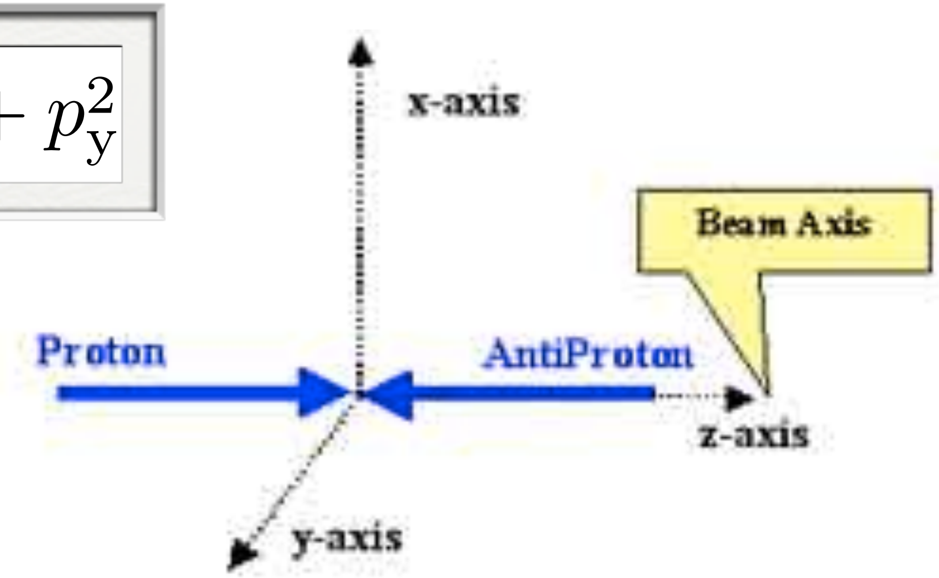
THREE orders of magnitude stronger limits than the previous one!

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.

DEFINITIONS

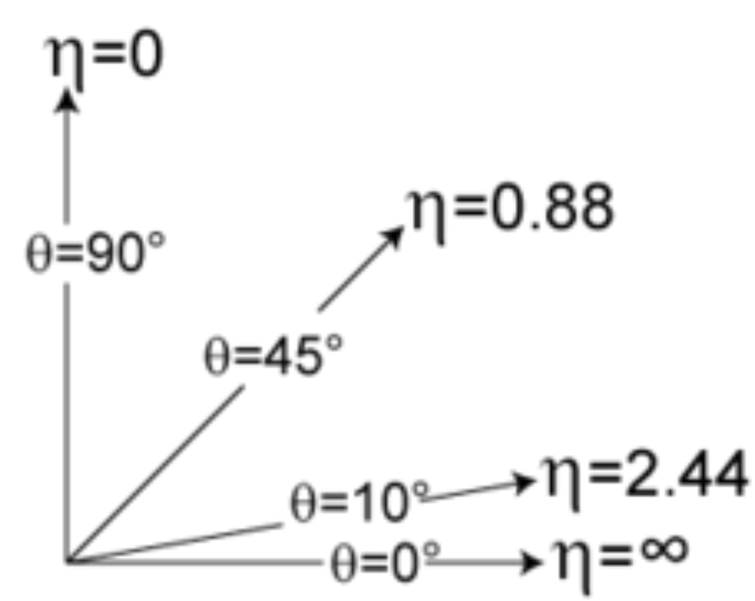
- Transverse momentum, p_T

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

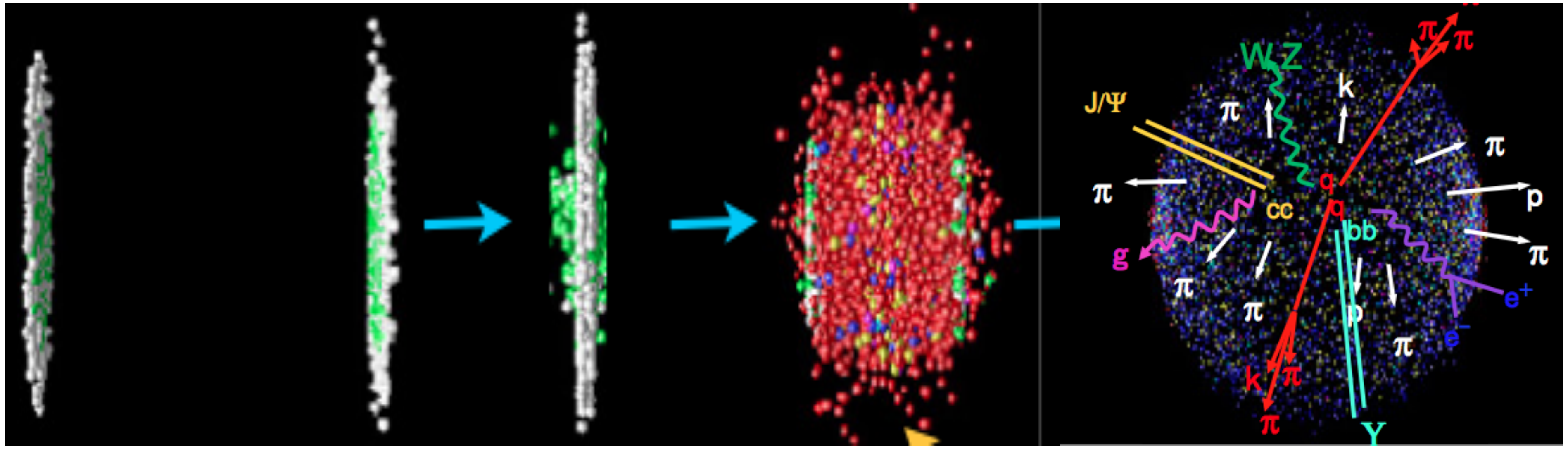


- Azimuthal angle, ϕ
- Polar angle, θ
- Pseudorapidity, η

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



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