Electromagnetic processes in ultra peripheral lead-lead collisions with ATLAS

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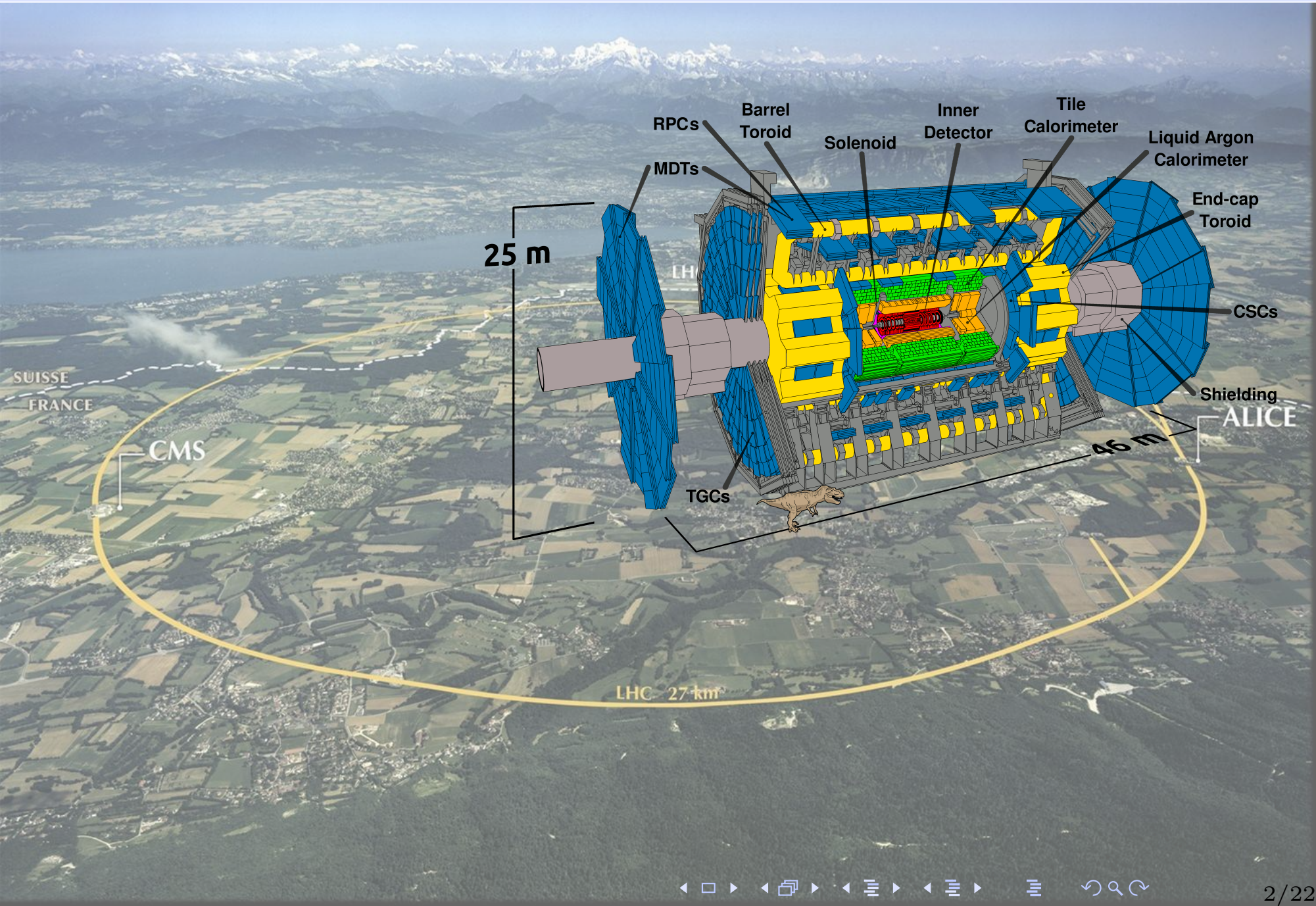
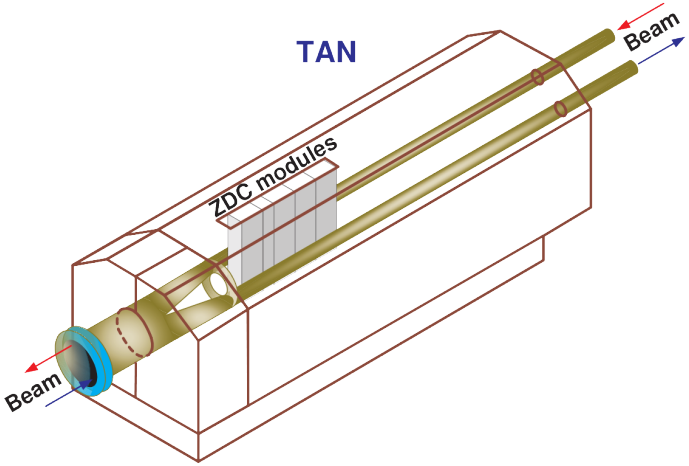
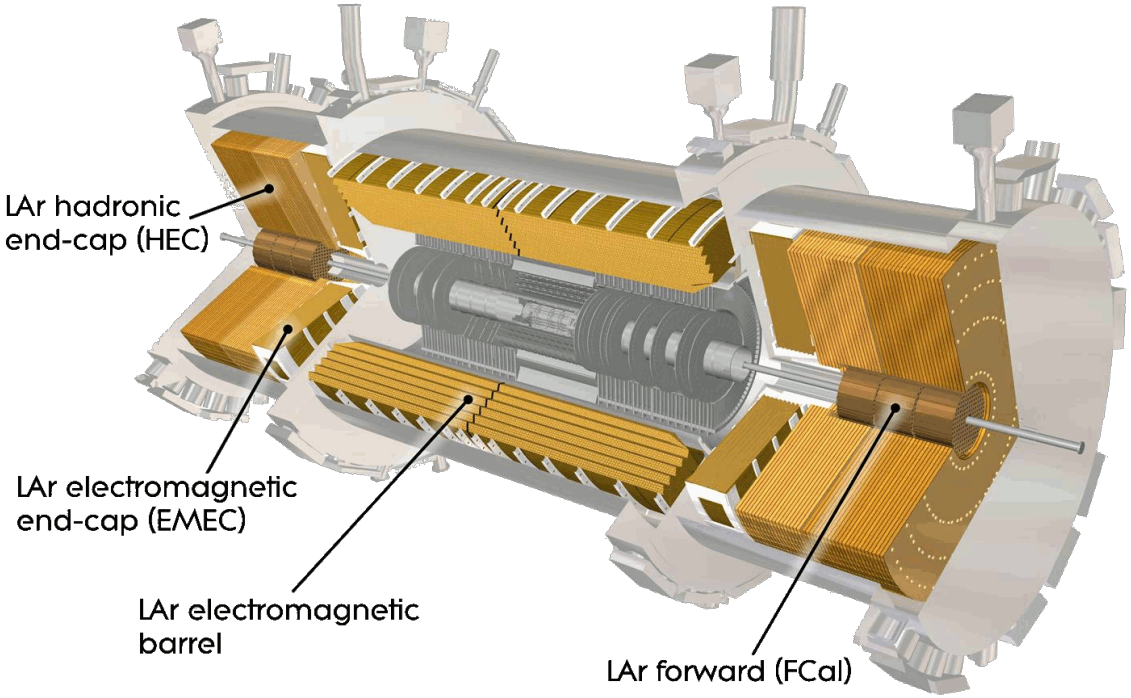
The LHC and the ATLAS detector



The ATLAS detector components

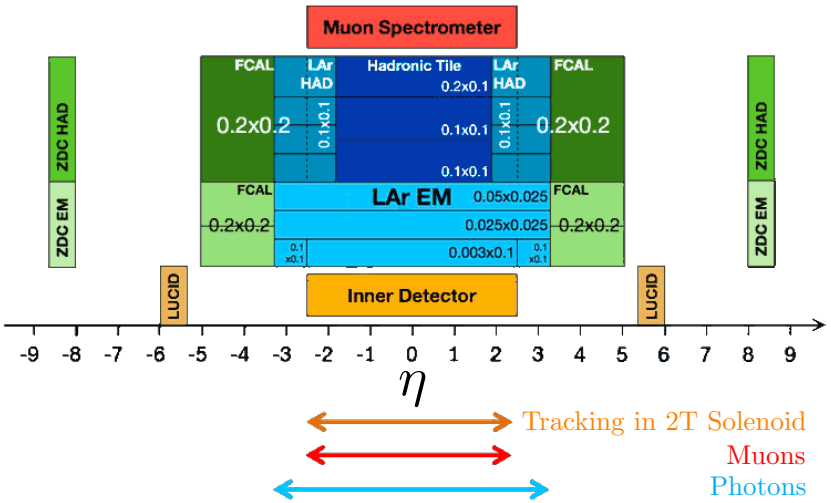


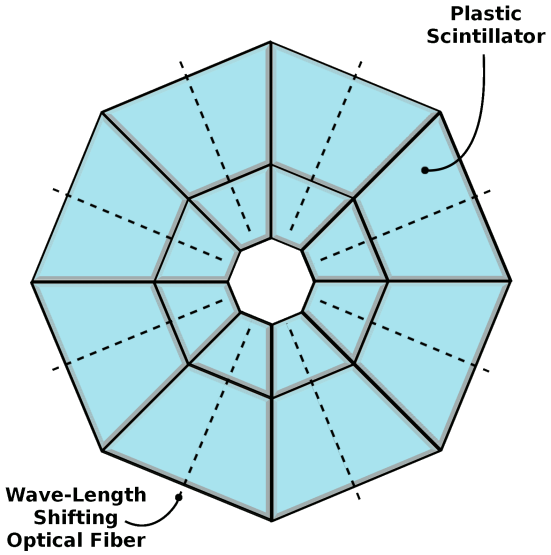


2015 Pb+Pb data

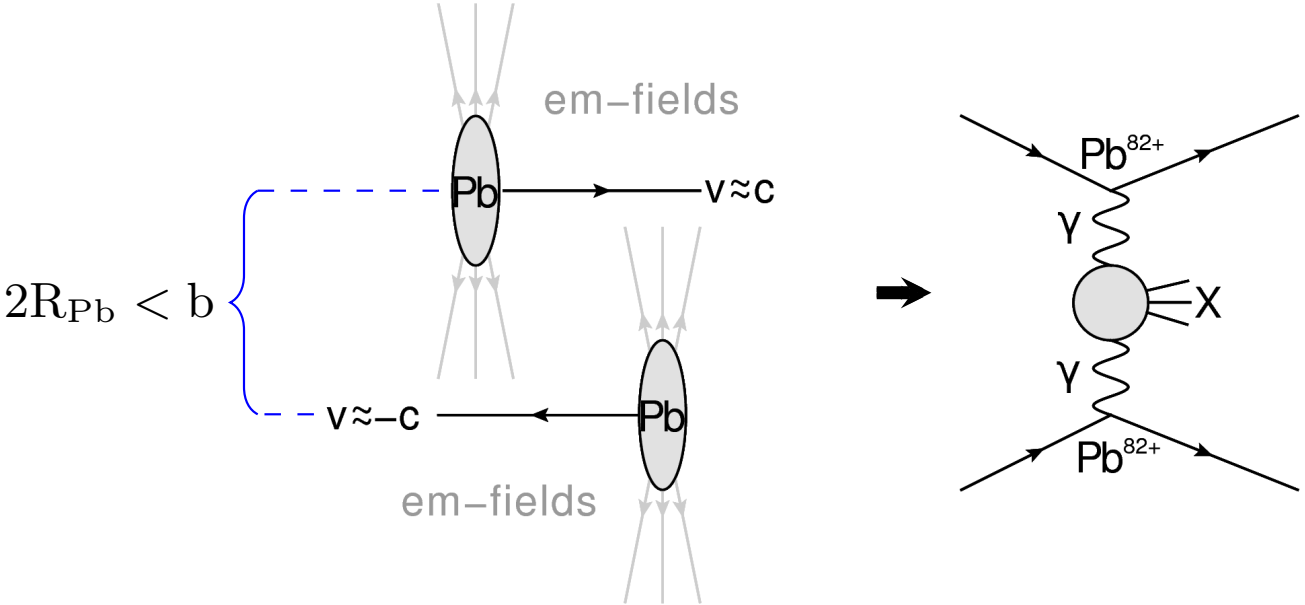
$$L \approx 0.5\,\mathrm{nb}^{-1}$$

$$\sqrt{s_{NN}} = 5.02\,\mathrm{TeV}$$





Electromagnetic interactions in Pb+Pb collisions



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

Equivalent Photon Approximation (EPA)

$$\sigma^{\mathrm{EPA}}_{\mathrm{A_1A_2}(\gamma\gamma)\to\mathrm{A_1A_2X}} = \iint \mathrm{d}\omega_1 \mathrm{d}\omega_2\, \mathrm{n}_1(\omega_1)\, \mathrm{n}_2(\omega_2)\, \sigma_{\gamma\gamma\to\mathrm{X}}(\mathrm{W}_{\gamma\gamma})$$

$$\text{with} \quad \mathrm{n}(\mathrm{b},\omega) = \frac{\mathrm{Z}^2\alpha_{\mathrm{em}}}{\pi\omega}\left|\int \mathrm{dq}_\perp \mathrm{q}_\perp^2 \frac{\mathrm{F}(\mathrm{Q}^2)}{\mathrm{Q}^2}\mathrm{J}_1(\mathrm{bq}_\perp)\right|^2$$

$$\mathrm{Q}^2 < \frac{1}{\mathrm{R}^2} \quad \text{and} \quad \omega_{\mathrm{max}} \approx \frac{\gamma}{\mathrm{R}}$$

LHC as a photon-photon collider

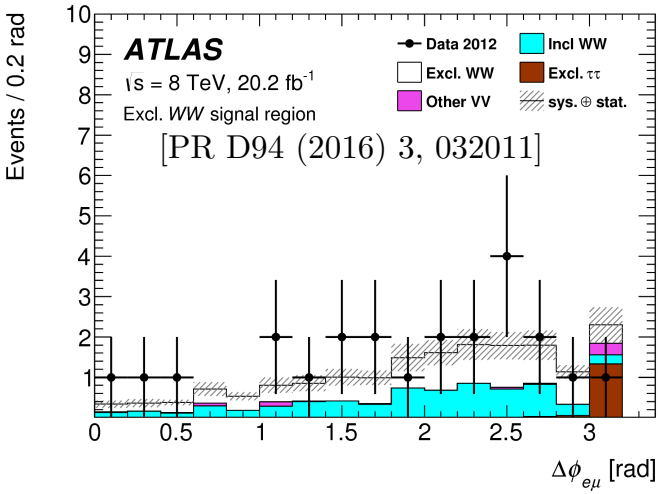
pp collisions

Pros

- harder EPA γ spectrum ($\omega_{\max} \sim$ TeV)
- more data available ($\sim 35\,\mathrm{fb}^{-1}$)

Cons

- large pile-up (multiple interactions per bunch crossing)
- problems with triggering on low p_T objects



[PR D94 (2016) 3, 032011]

Pb+Pb collisions

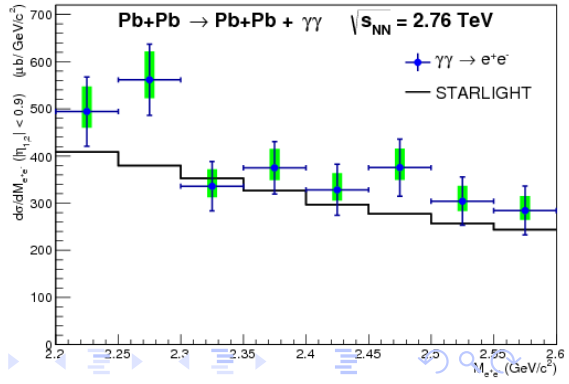
Pros

- AA ($\gamma\gamma$) x-sec $\propto Z^4$
- gluonic x-sec $\propto A^2$ $\Rightarrow$ lower QCD bkg.
- low pile-up ($< 1\%$)

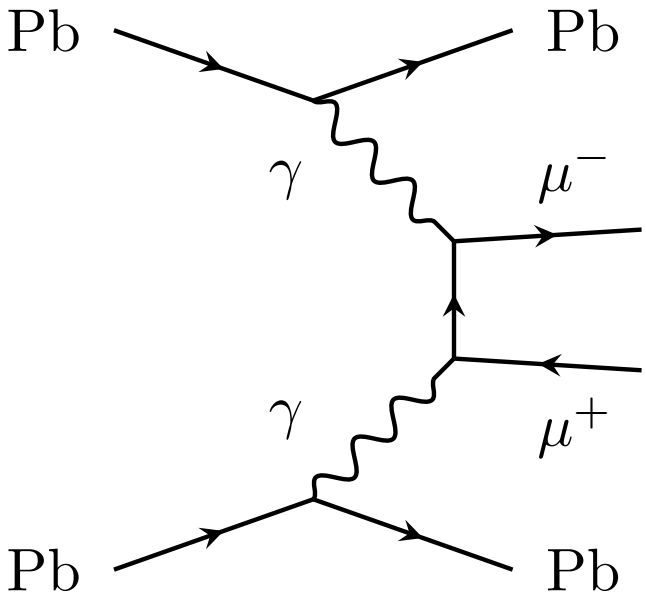
Cons

- softer EPA γ spectrum ($\omega_{\max} \sim 0.1$TeV)
- relatively small data sample

[ALICE Collaboration,EPJC 73 (2013) 2617]

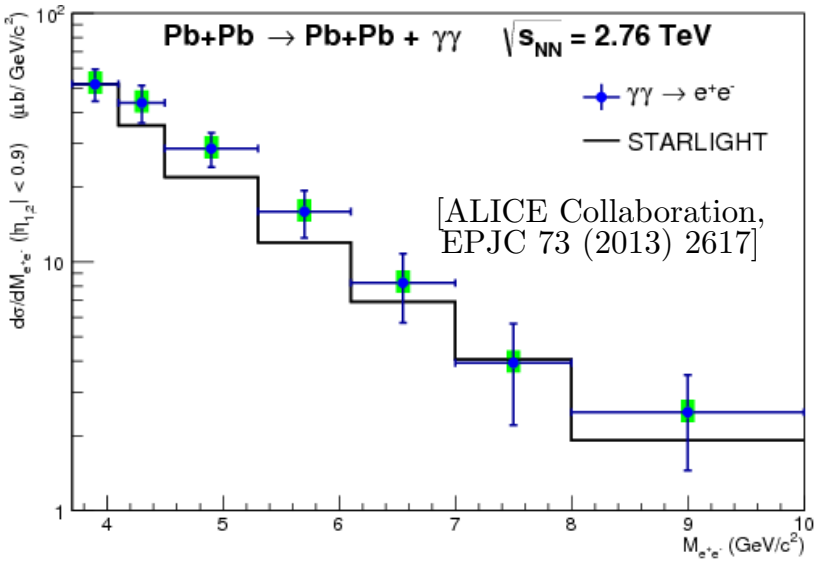


Measurement of high-mass di-muon pairs
[ATLAS-CONF-2016-025]



Motivation

Extension of ALICE's di-lepton mass measurement (m_{ll} up to 10 GeV)



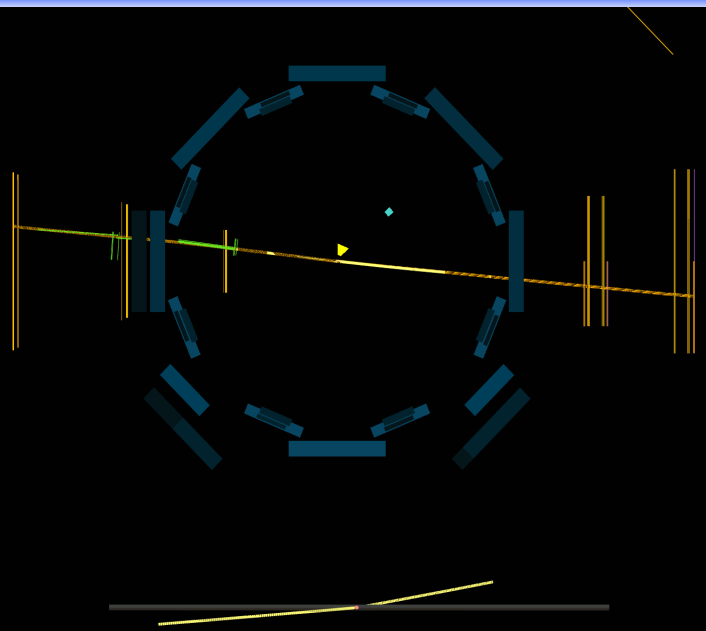
Trigger

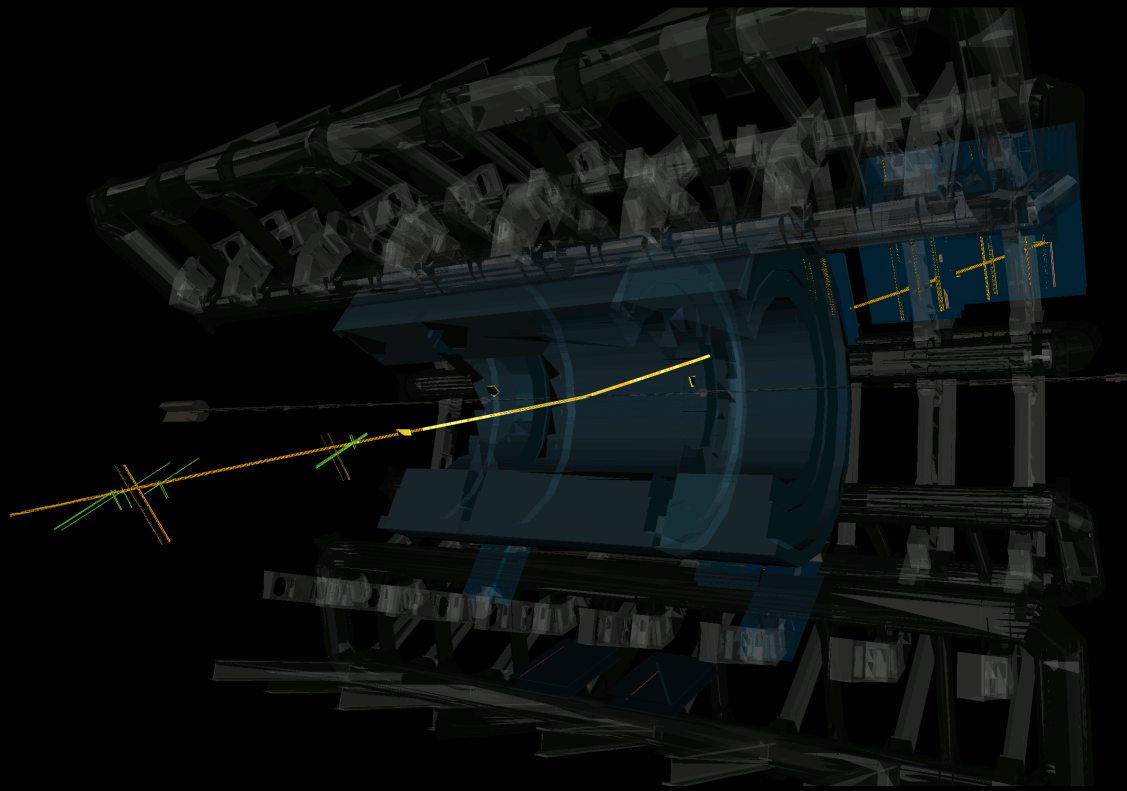
- at least 1 loose muon
- total E_T in the calorimeter < 50 GeV
- at least one 200 MeV track
- no more than 1 hit in inner MBTS arrays

Event selection

- 2 opposite-sign and good-quality muons with $p_T > 4$ GeV, $|\eta| < 2.4$, $m_{\mu\mu} > 10$ GeV
- reconstructed vertex with no additional tracks

Measurement of high-mass di-muon pairs
[ATLAS-CONF-2016-025]





Measurement of high-mass di-muon pairs
[ATLAS-CONF-2016-025]

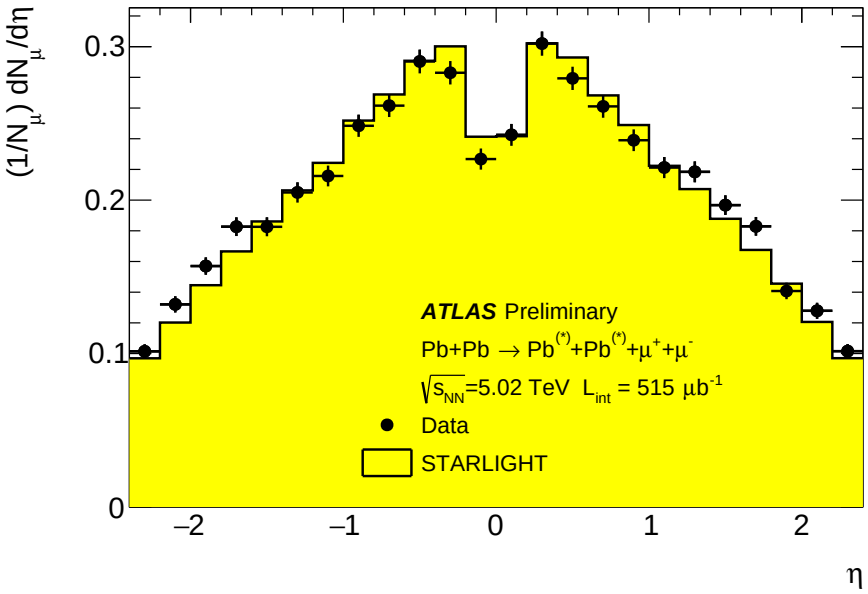
Signal modelling

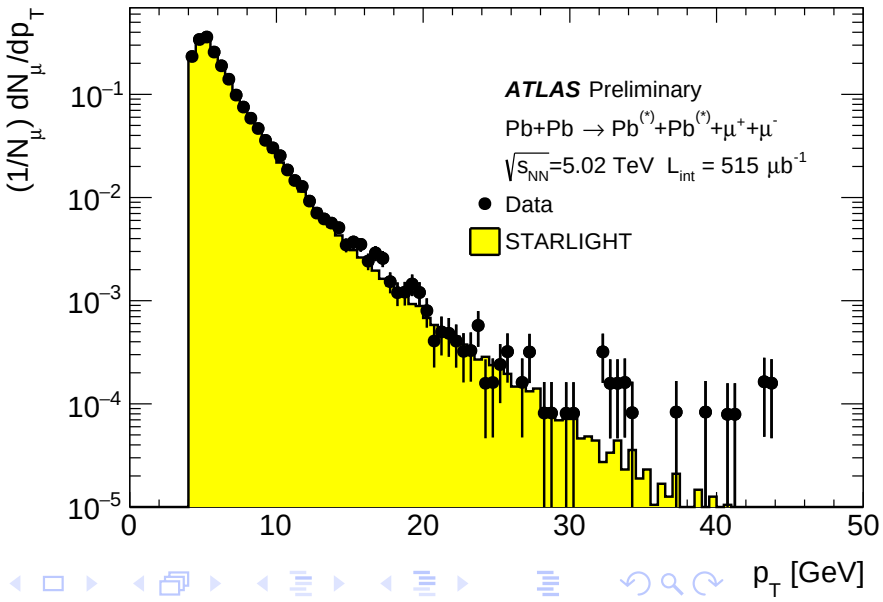
Starlight 1.1 (EPA + LO QED)

Total of 12069 di-muon pairs were selected in data

Corrections

- Trigger efficiency (data-driven) $\sim 80\%$
- Muon reco & identification efficiency (MC+scale factors) $\sim 90\%$
- Vertex efficiency (MC-driven) $\sim 95\%$

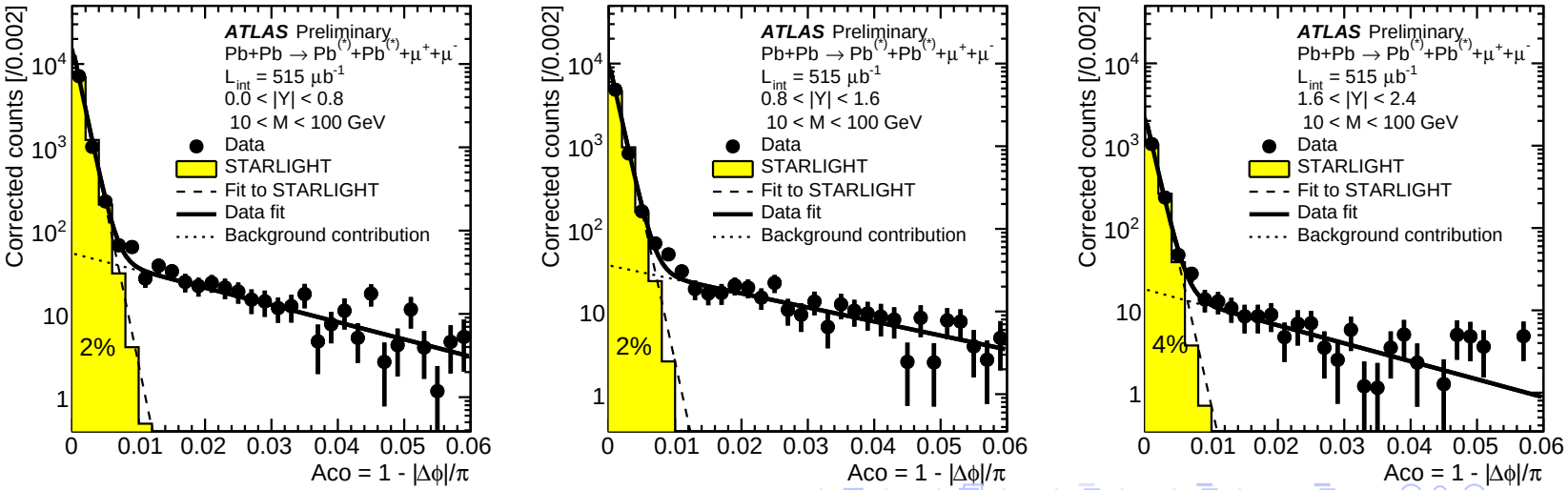




Measurement of high-mass di-muon pairs
[ATLAS-CONF-2016-025]

Acoplanarity distributions

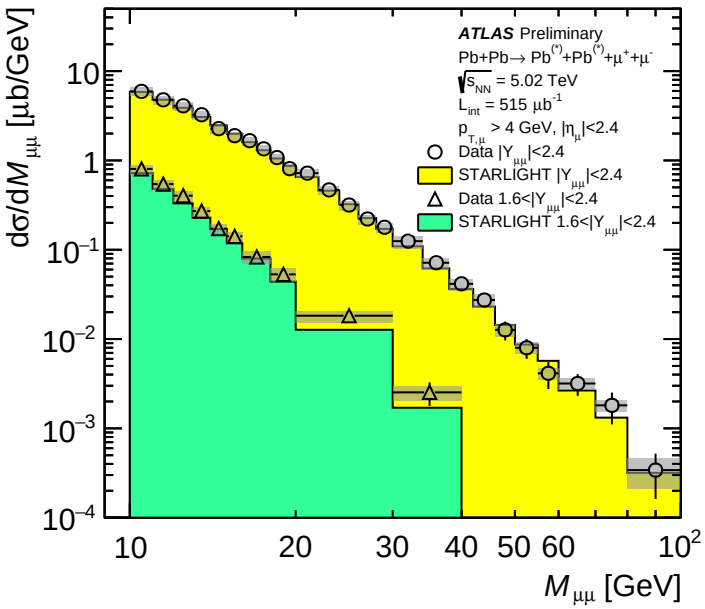
- di-muon pairs expected to be produced back-to-back
- presence of small tail in acoplanarity
- two assumptions tested:
  a) tail due to background
  b) tail due to higher order QED effects (not included in Starlight)
- average of a) and b) taken as a central value and a difference as a systematic uncertainty

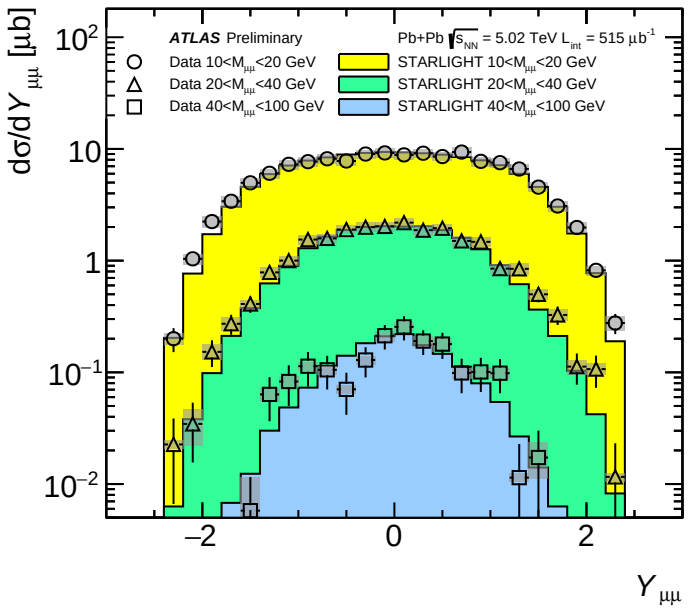


Measurement of high-mass di-muon pairs
[ATLAS-CONF-2016-025]

Results:

- main contribution to systematics from the luminosity uncertainty; total $\sim 10\%$
- total x-sec: $\sigma = 32.2 \pm 0.3(\text{stat.}) \pm 4.0(\text{syst.})\,\mu\text{b}$
- good agreement with Starlight in differential (with respect to $m_{\mu\mu}$, $y_{\mu\mu}$) and total x-sec's ($\sigma_{\text{Starlight}} = 31.6\,\mu\text{b}$)

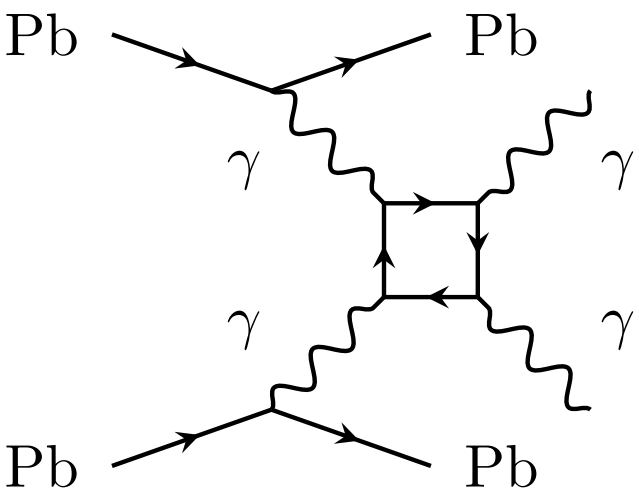




Search for light-by-light scattering
[arXiv:1702.01625]

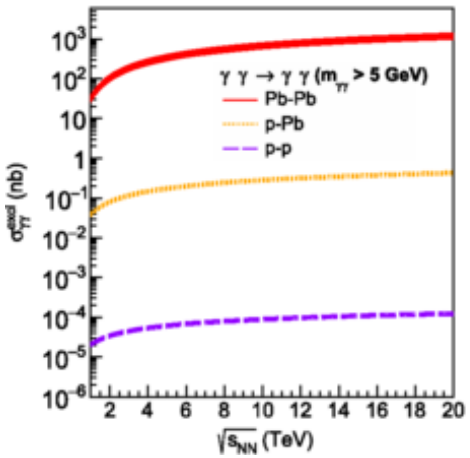
Motivation

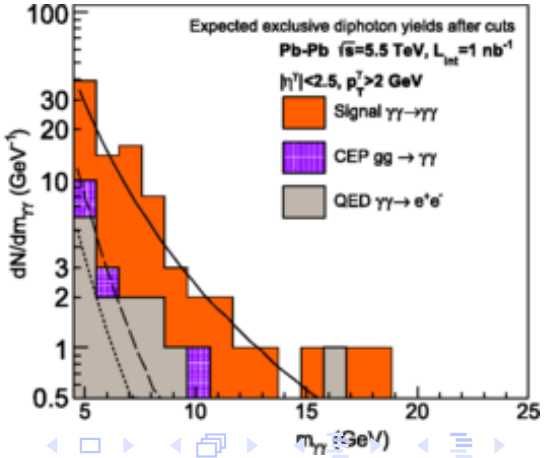
- first direct observation of $\gamma\gamma \to \gamma\gamma$ scattering
- previous indirect measurements used:
  a) multi-photon Breit-Wheeler reaction ($\omega + n\omega_0 \to e^+e^-$) [PRL 79 (1997) 1626]
  b) photon splitting
  c) Delbrück scattering



Recent SM Predictions for ATLAS

[A. Szczurek et al. PRC 93 (2016) 4, 044907], [D. d'Enterria et al. PRL 111 (2013) 080405]





Search for light-by-light scattering
[arXiv:1702.01625]

Trigger

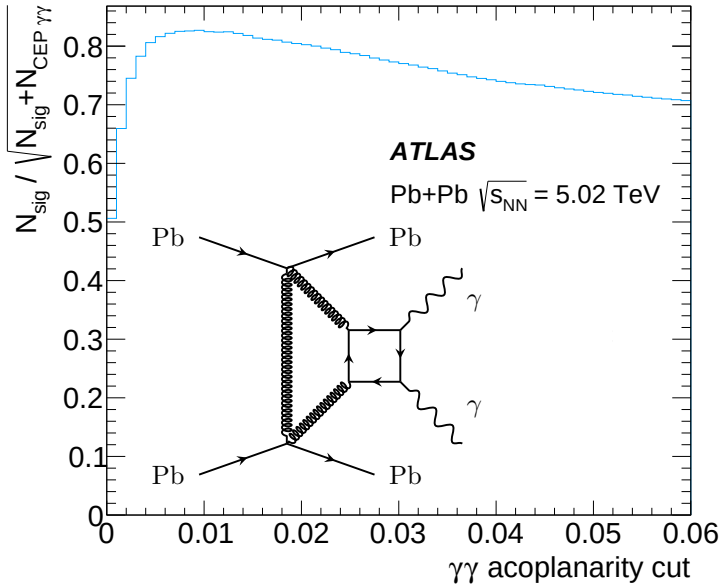
- total E_T in calorimeter between 5 and 200 GeV
- no more than one hit in inner MBTS
- less than 10 hits in the pixel detector

Event Selection

- two photons with $E_T > 3\,\text{GeV}$, $|\eta| < 2.37$
- no tracks from IP
- $m_{\gamma\gamma} > 6\,\text{GeV}$, $p_T^{\gamma\gamma} < 2\,\text{GeV}$
- $\text{Aco} = \left(1 - \frac{\Delta\phi}{\pi}\right) < 0.01$

Main sources of bkg.

- Central Exclusive Production (CEP) $gg \to \gamma\gamma$
- misidentification of electrons from $\gamma\gamma \to ee$



Search for light-by-light scattering
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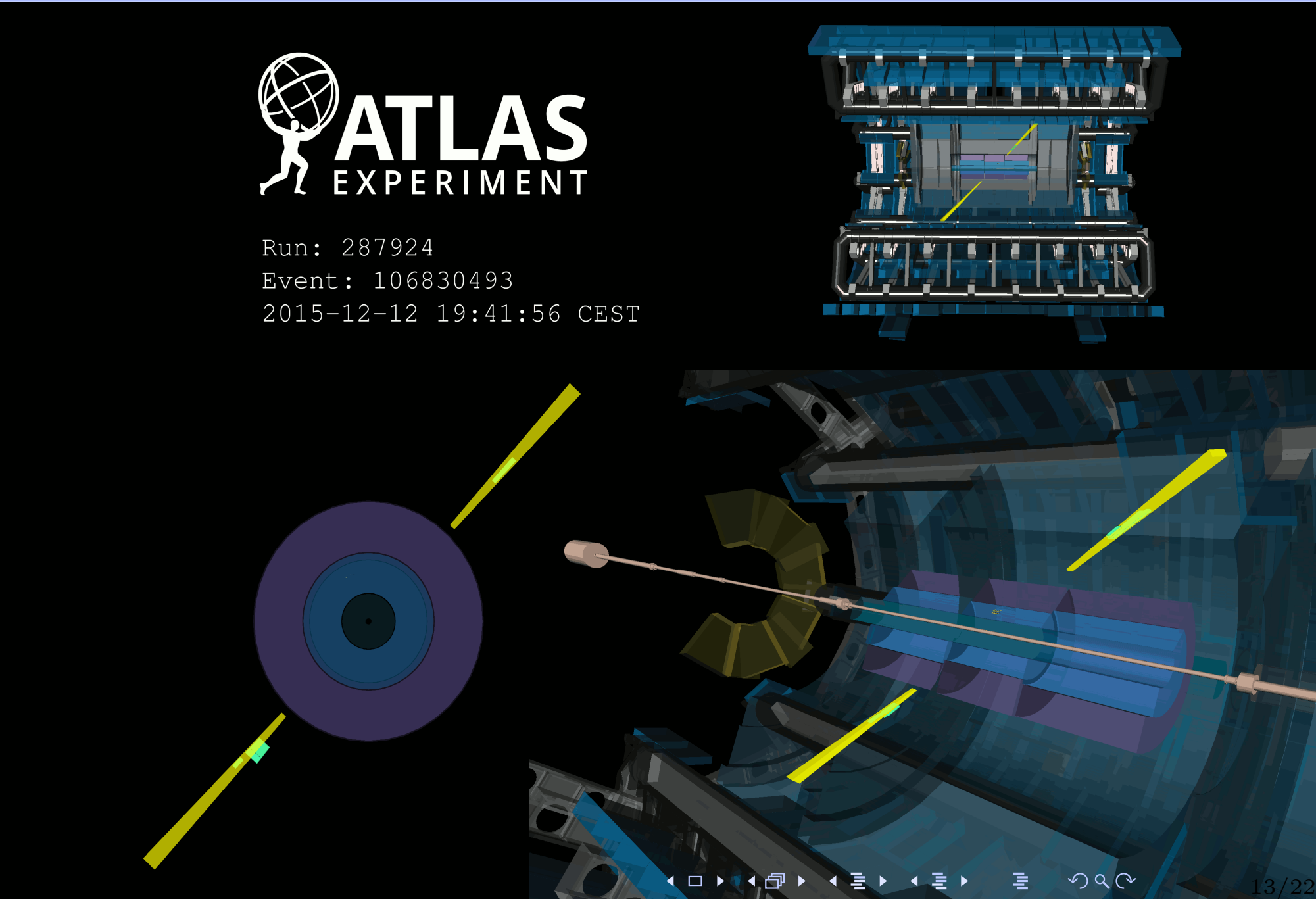
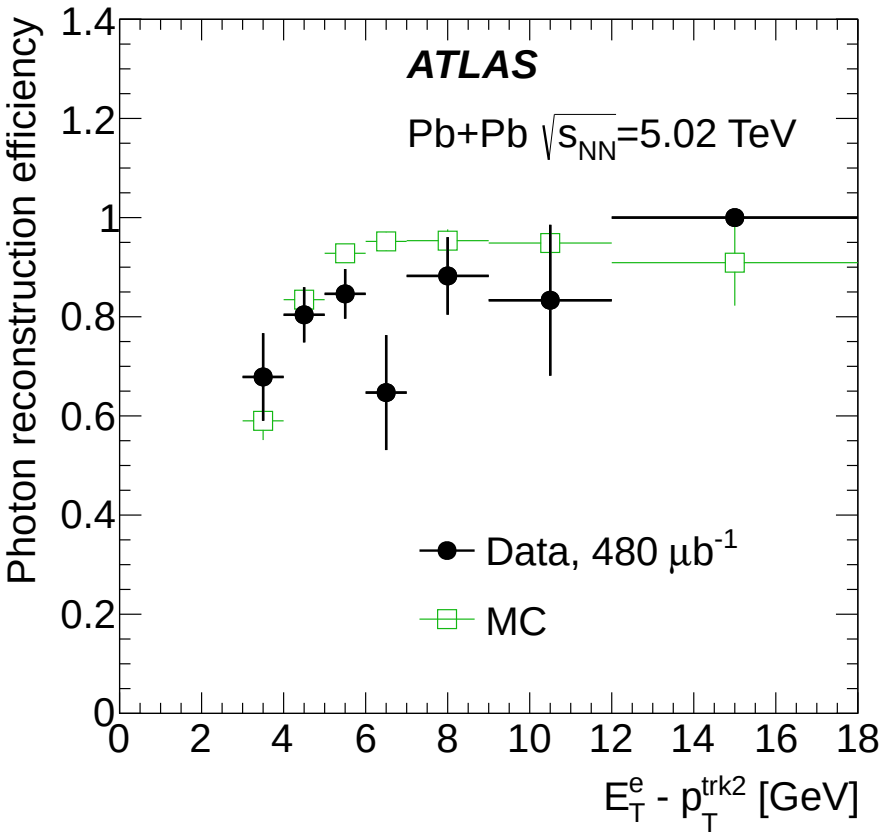


Search for light-by-light scattering
[arXiv:1702.01625]

Photon Performance Studies
(done with $\gamma\gamma \to l^+l^-$ events)

- trigger efficiency studies
- γ reconstruction with hard bremsstrahlung
- γ PID with FSR radiation
- γ energy scale and resolution



Systematic Uncertainty

dominated by:

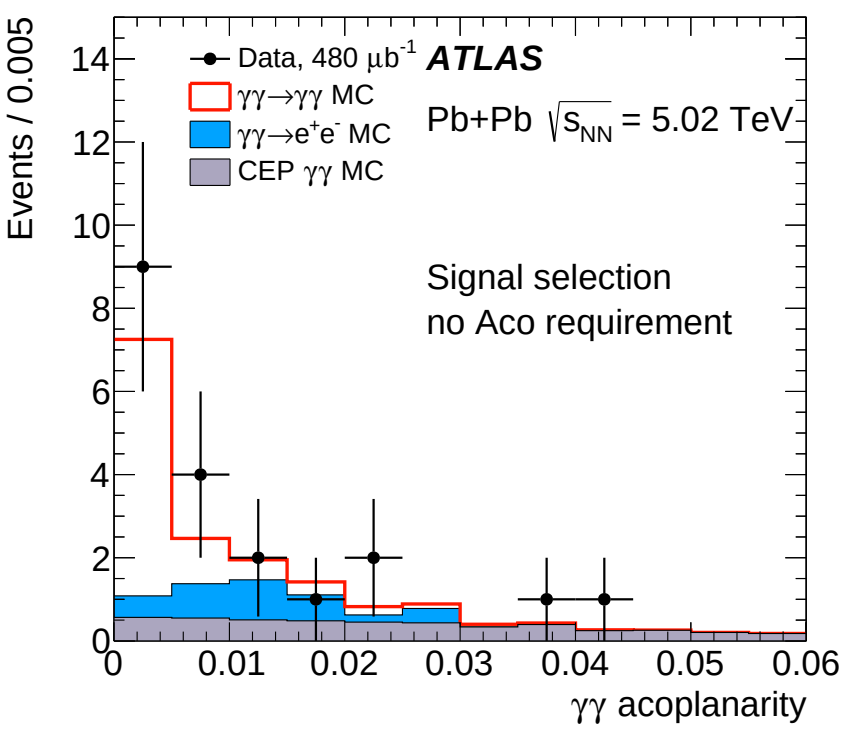
- γ reco
- γ PID

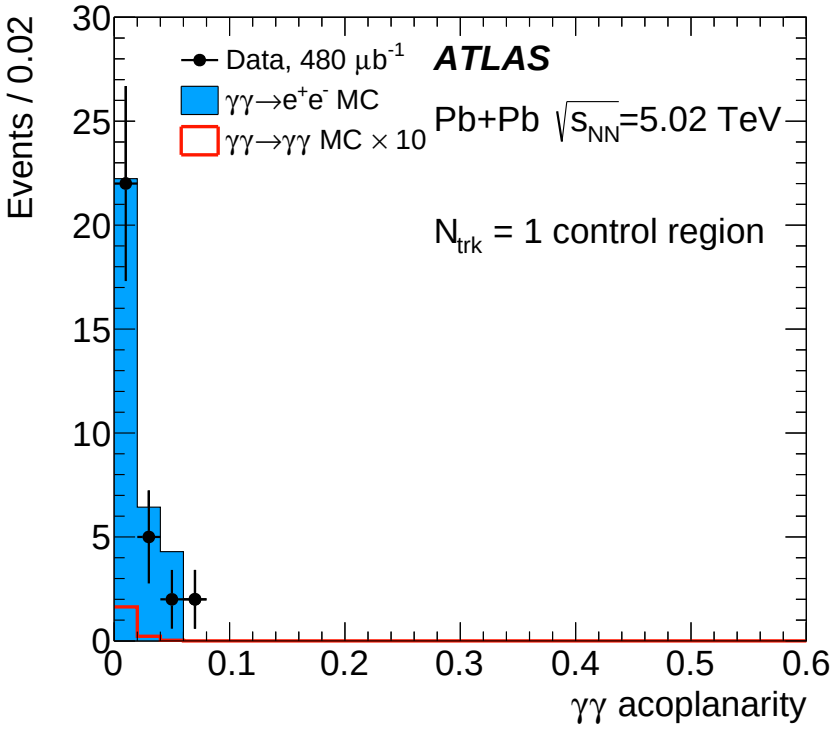
Source of uncertainty	Relative uncertainty
Trigger	5%
Photon reco efficiency	12%
Photon PID efficiency	16%
Photon energy scale	7%
Photon energy resolution	11%
Total	24%

Search for light-by-light scattering
[arXiv:1702.01625]

Results: data - 13 event, expected - 7.3 signal and 2.6 bkg. events

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	



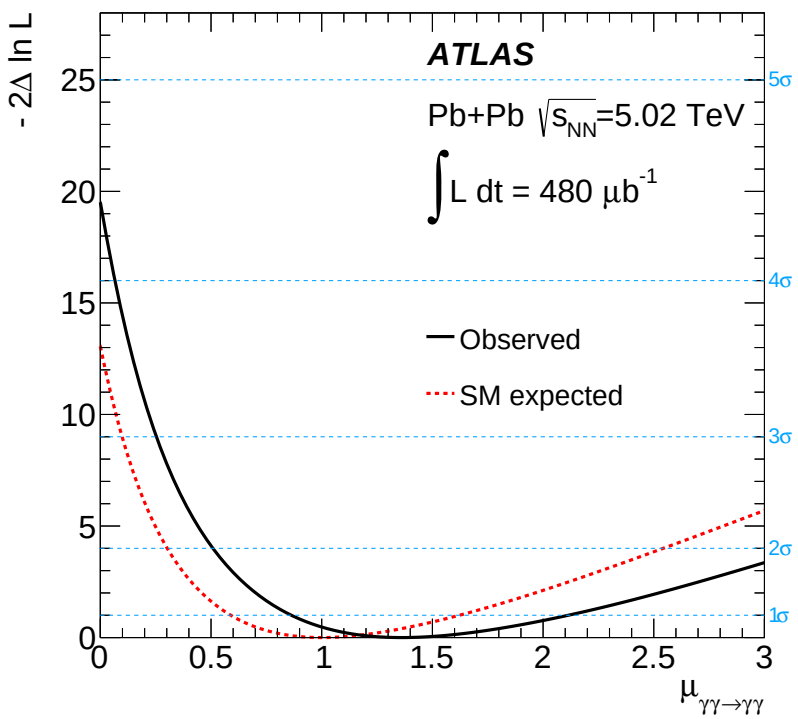


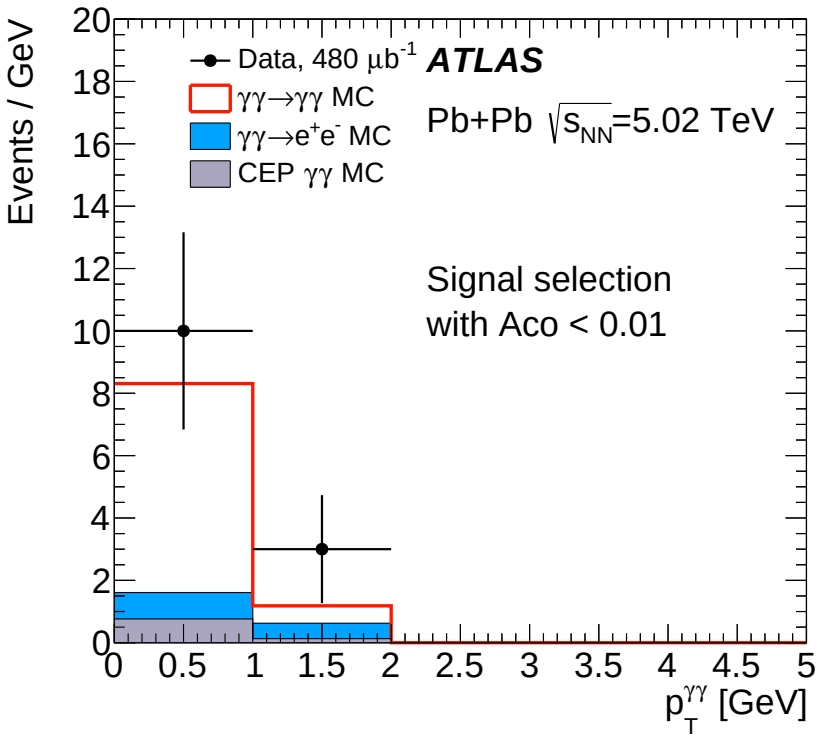
Search for light-by-light scattering
[arXiv:1702.01625]

Results:

- significance of 4.4σ estimated using profile likelihood method (expected significance of 3.8σ)
- x-sec measured in fiducial region of $p_T^{\gamma} > 3\,\mathrm{GeV}$, $|\eta^{\gamma}| < 2.4$, $m_{\gamma\gamma} > 6\,\mathrm{GeV}$, $p_T^{\gamma\gamma} < 2\,\mathrm{GeV}$, Aco < 0.01
  $\sigma = 70 \pm 20\,(\mathrm{stat.}) \pm 17\,(\mathrm{syst.})\,\mathrm{nb}$

SM predictions: $45 \pm 9\,\mathrm{nb}$ ([PRL 111 (2013) 080405]), $49 \pm 10\,\mathrm{nb}$ ([PRC 93 (2016) no.4, 044907])





Summary

- Cross-section for the exclusive production $\gamma\gamma \to \mu^+\mu^-$ was measured with ATLAS Pb+Pb data at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$
  - good agreement with LO QED predictions of Starlight.
- The first direct evidence for $\gamma\gamma \to \gamma\gamma$ scattering with significance of 4.4σ has been reported.
  - improvements in the precision expected with more Pb+Pb data to be collected in 2018

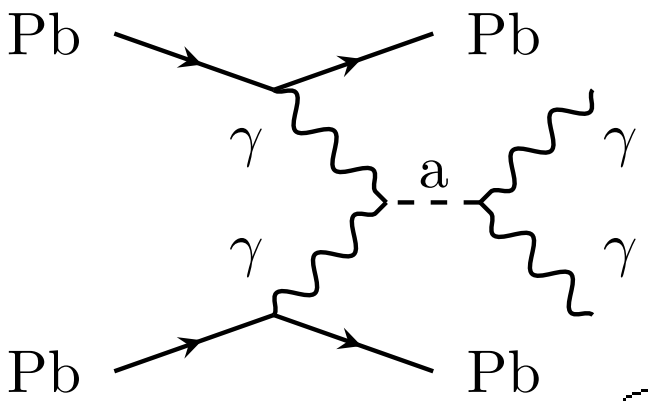
Thank You for Your Attention!

Backup

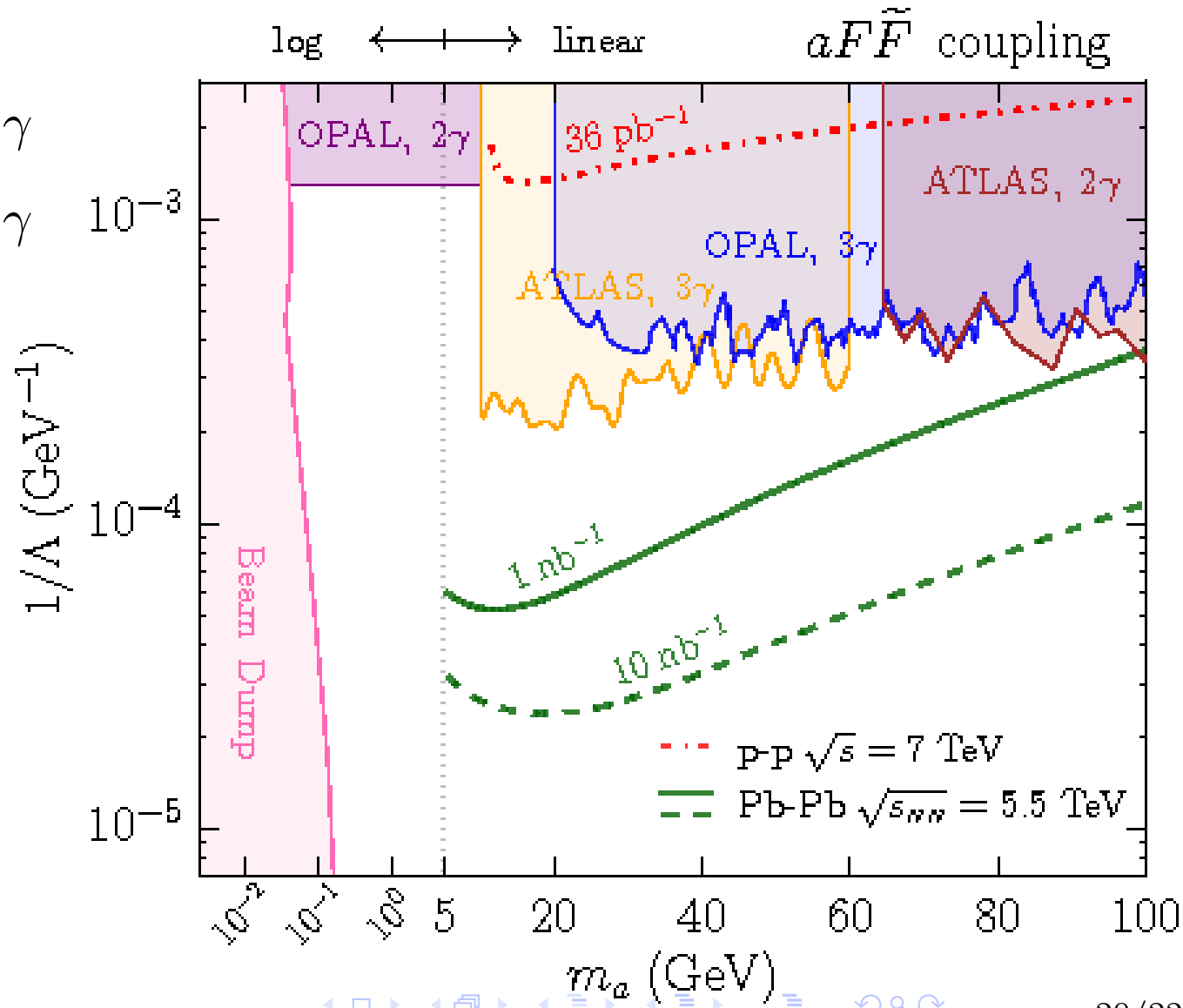
BSM Physics in HI - Axion Search With UPC

[arXiv:1607.06083]

$$L_a = \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}\frac{a}{\Lambda}F\tilde{F}$$



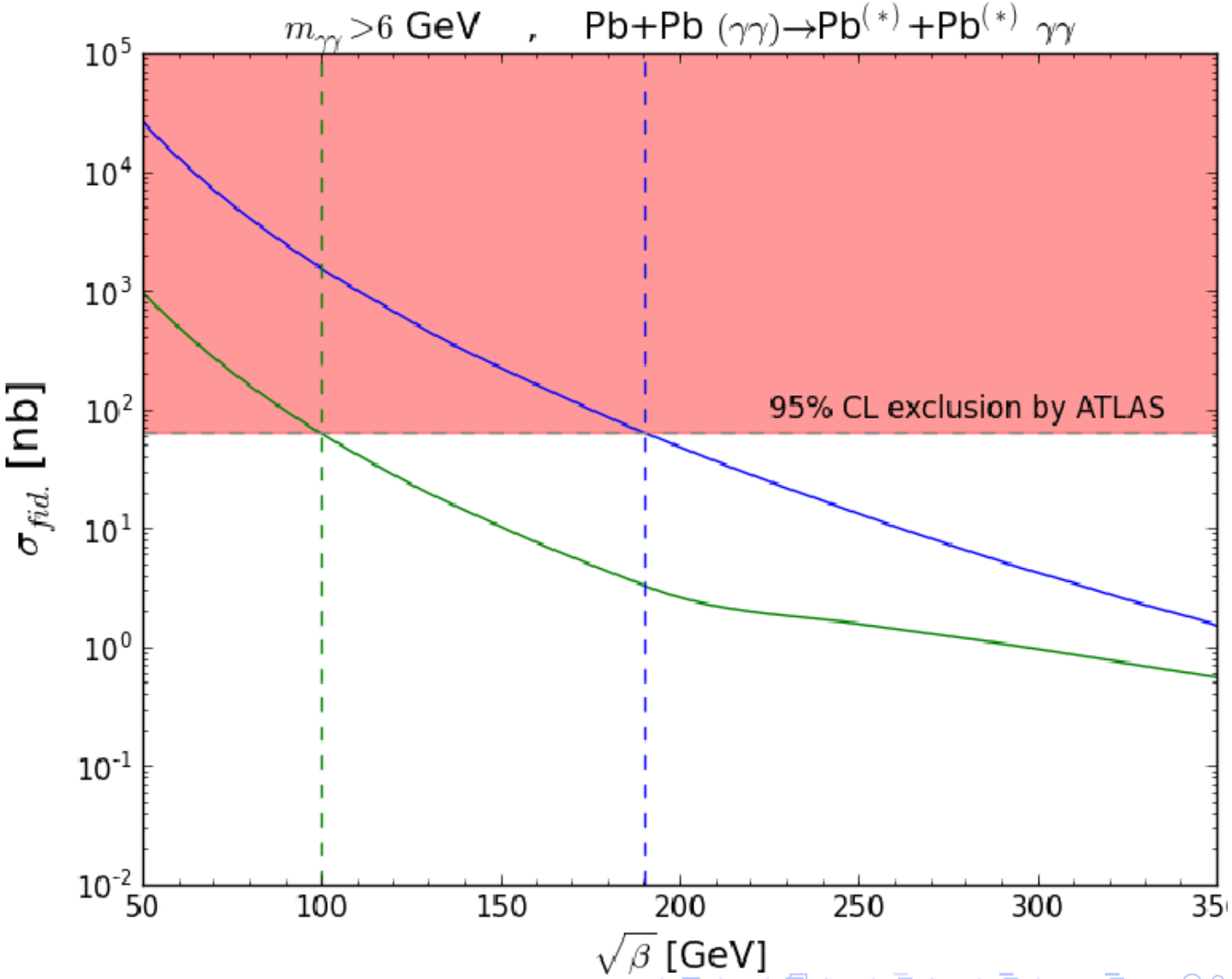
expected axion searches sensitivity



LbyL Scattering Constraint on Born-Infeld Theory

[arXiv:1703.08450]

$$L_{QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \rightarrow L_{BI} = \beta^2\left(1-\sqrt{1+\frac{1}{2\beta^2}F_{\mu\nu}F^{\mu\nu}-\frac{1}{6\beta^4}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)^2}\right)$$



LbyL - Photon Identification

γ cuts: $E_T > 3\,\mathrm{GeV}$, $|\eta| < 2.37$

Shower shape variables used to γ PID

- E_{ratio} $\equiv$ ratio of the energy difference associated with the largest and second largest energy deposits to the sum of these deposits in the first layer of EM calo
- f_1 $\equiv$ fraction of energy reconstructed in the first layer with respect to the total energy of the cluster
- W_{eta2} $\equiv$ lateral width of the shower in the middle layer