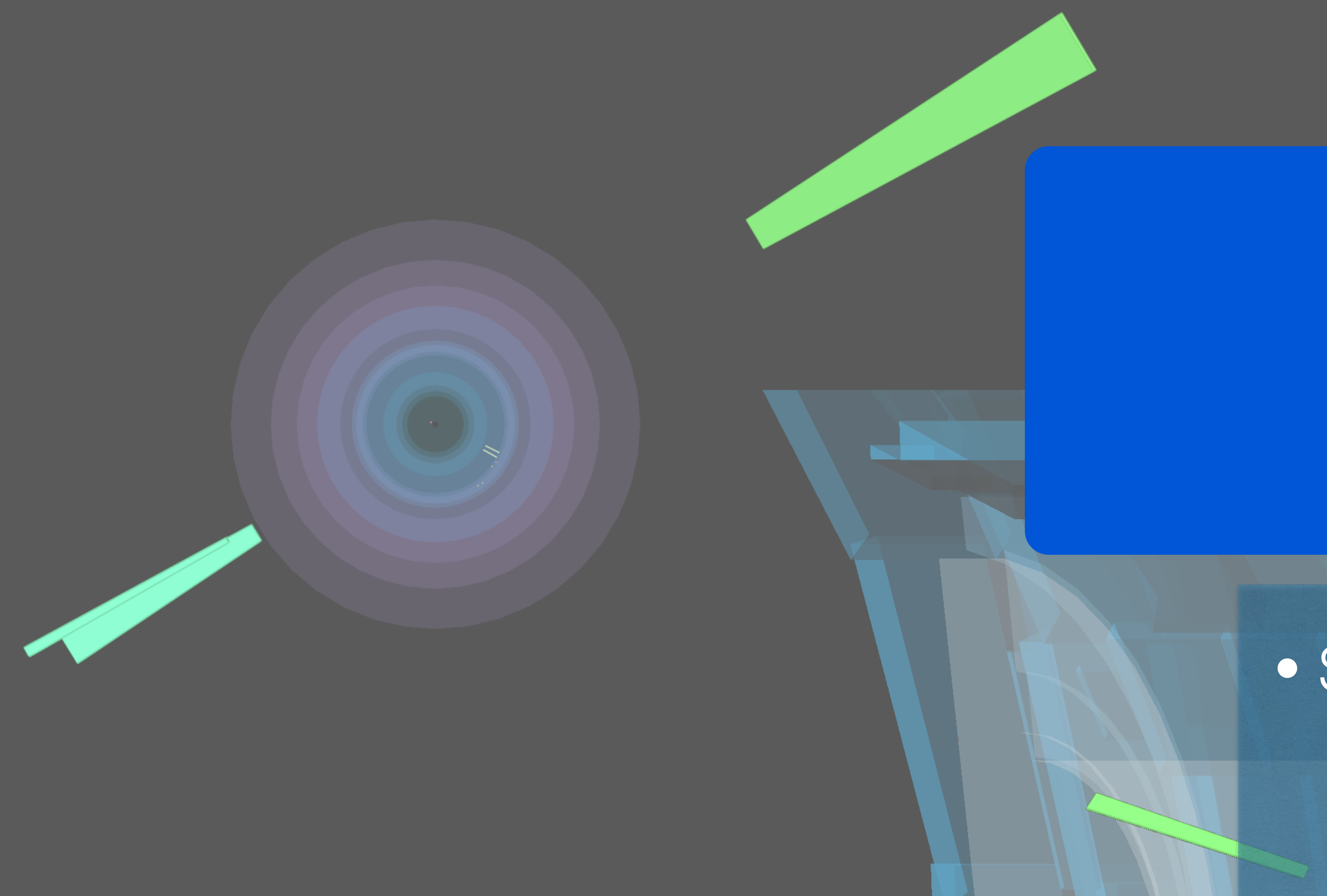
Photon-photon fusion and tau g-2 measurement

DISCRETE22 - 09/11/2022

Kristof Schmieden, on behalf of the ATLAS collaboration

- Setting the stage: **Heavy Ion collisions as Photon Collider**
- Light-by-Light scattering and ALPs
- Photon-Photon production of di-lepton pairs
- Measurement of $(g\text{-}2)_{tau}$



ATLAS EXPERIMENT

Run: 367321
Event: 755541675
2018-12-01 08:30:26 CEST

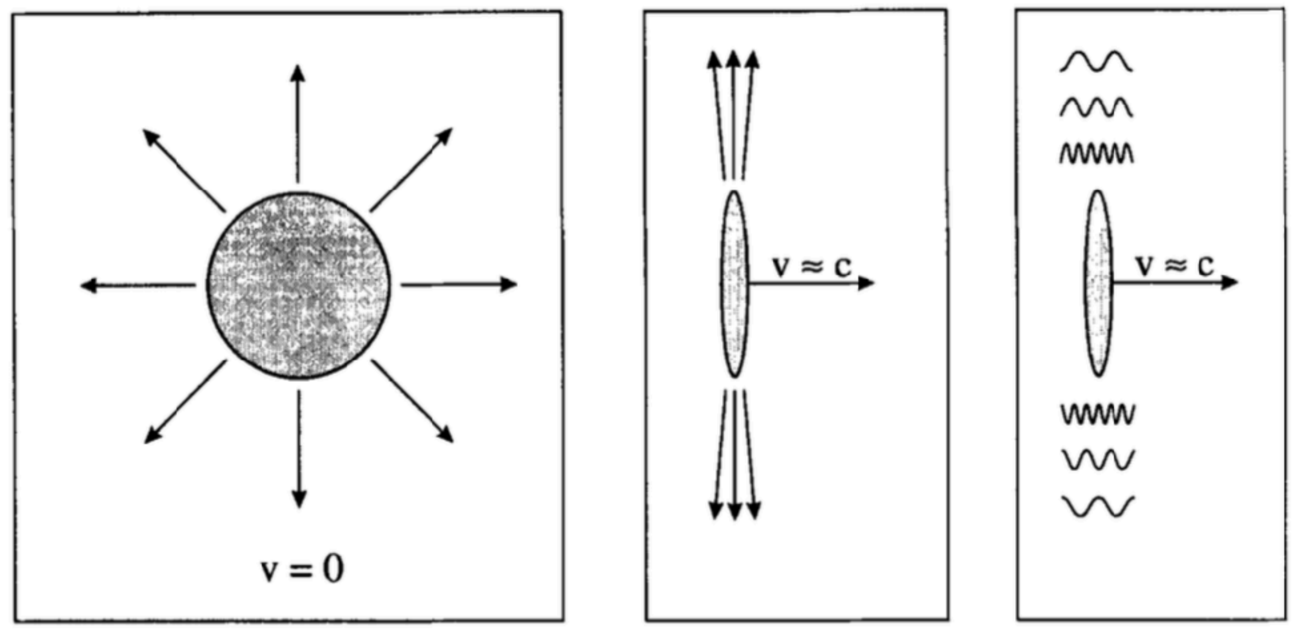
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Ultra Peripheral Heavy Ion Collisions - LHC as photon collider

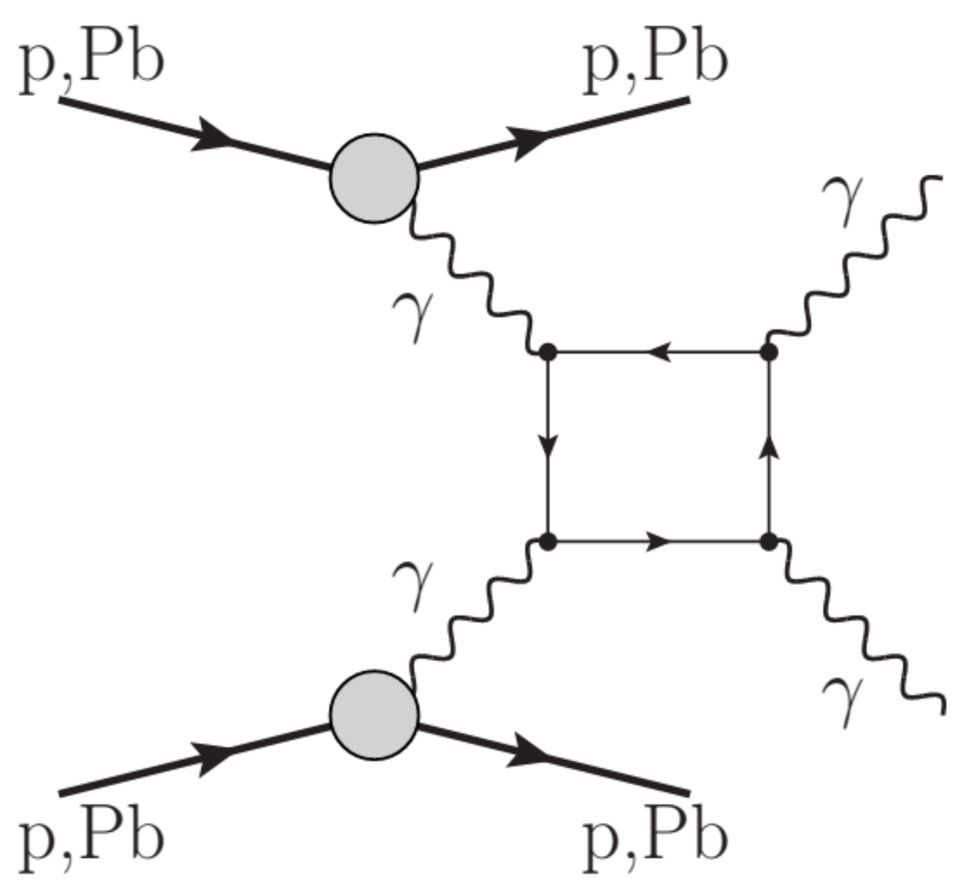
- Relativistic nuclei are intense source of (quasi-real) photons

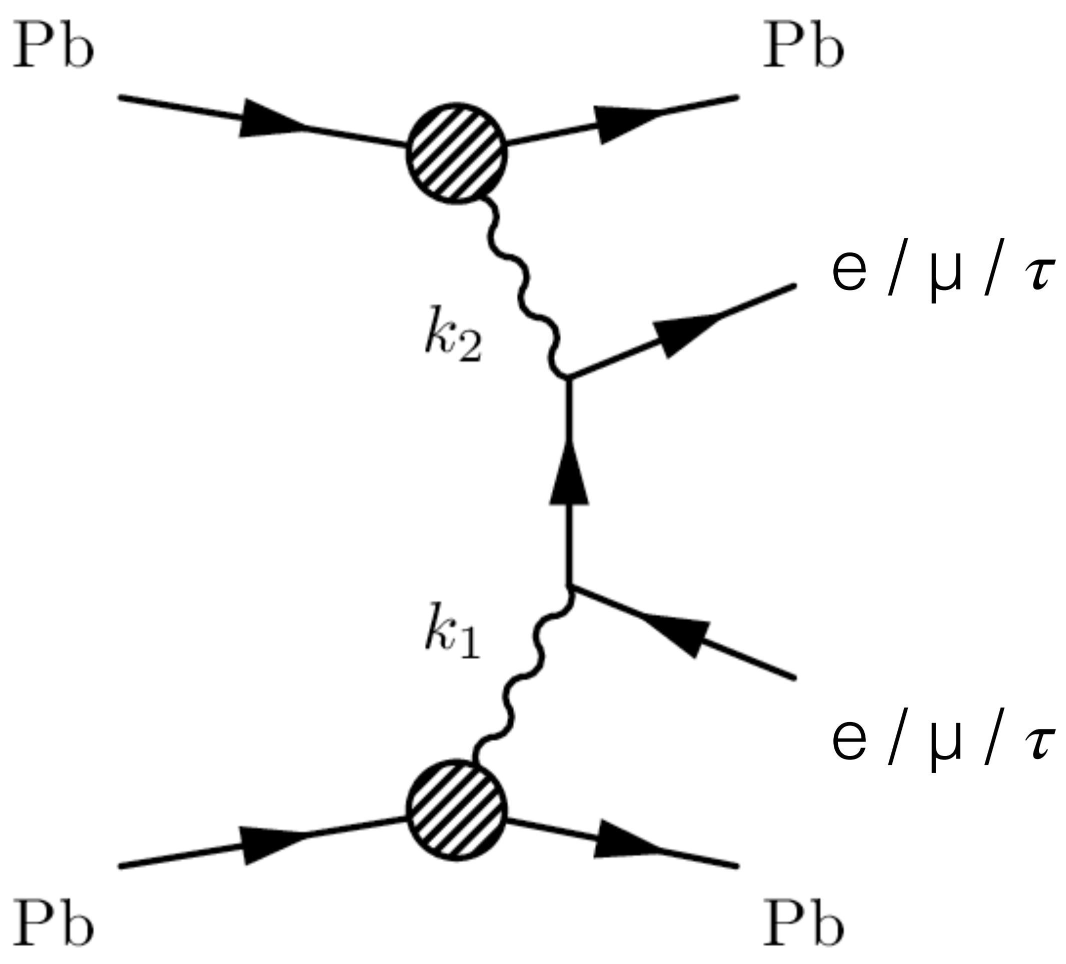
- Equivalent photon flux scales with Z^4
  - Pb beams at LHC are a superb source of high energy photons!

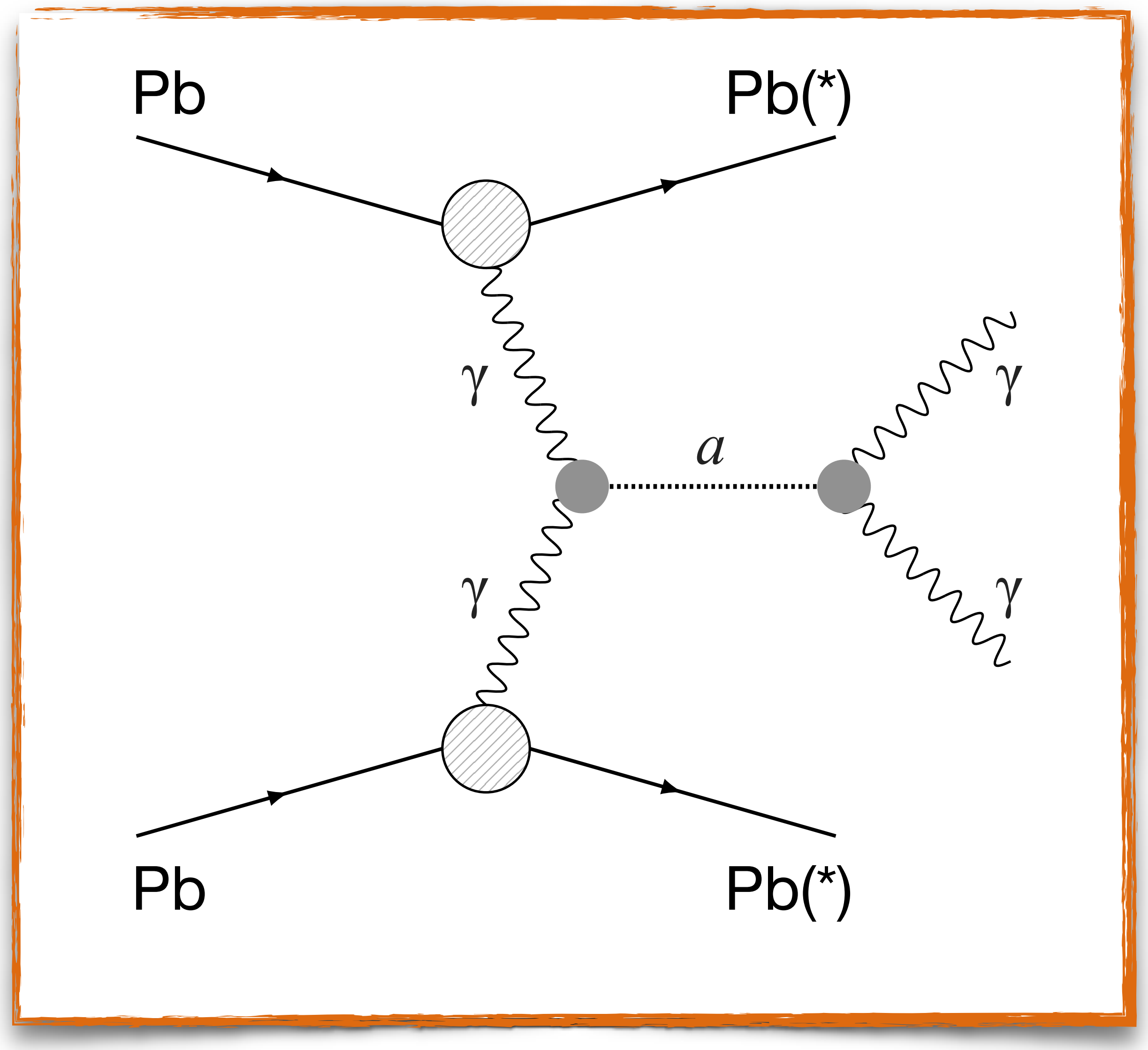
- Maximum photons energy:
  - $E_{max} <= \gamma/R$ ~80 GeV
    - Lorentz factor γ up to 2700 @ LHC



[Fermi, Nuovo Cim. 2 (1925) 143]







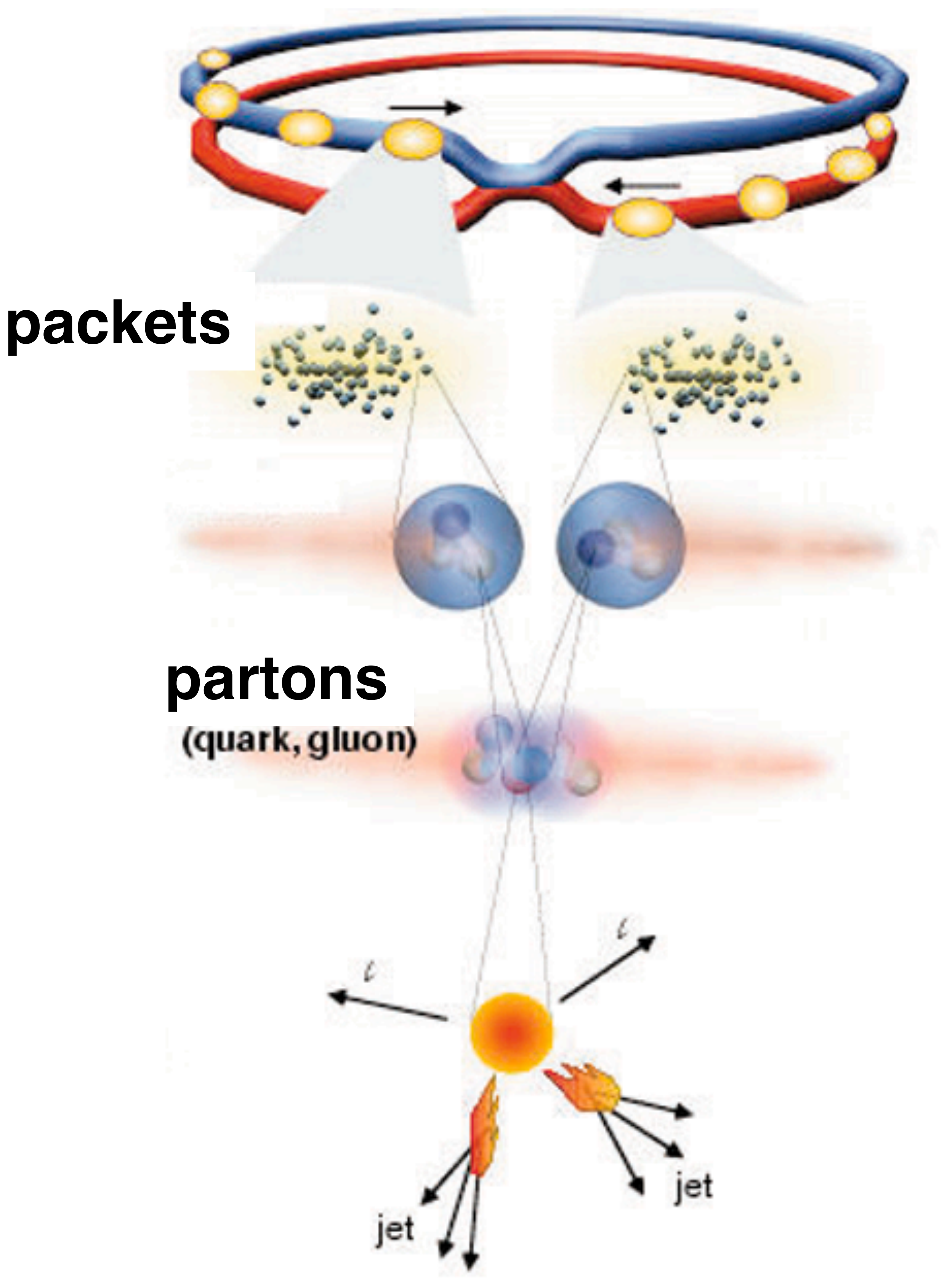
- First proposal to measure LbyL scattering at LHC in 2013:
  [D. d'Enterria, G. G. da Silveira Phys. Rev. Lett. 111, 080405]

Heavy Ion beams at the LHC

- Usually operates with **proton @** 6.5 TeV beam energy
- ~1 month / per year:
  - **Lead** ions instead of protons @ 2.76 TeV / nucleon

- Proton operation:
  - Bunch crossings every 25ns (40 MHz)
  - ~60 simultaneous pp collision per bunch crossing
    - 'Pileup'

- Heavy ion operation:
  - Bunch crossings every 75ns (13 MHz)
  - ~0.004 simultaneous PbPb collision per bunch crossing
    - **Essentially no pileup at all**
    - Only EM interaction in most bunch crossings! (UPC events)
      - Used for photon physics



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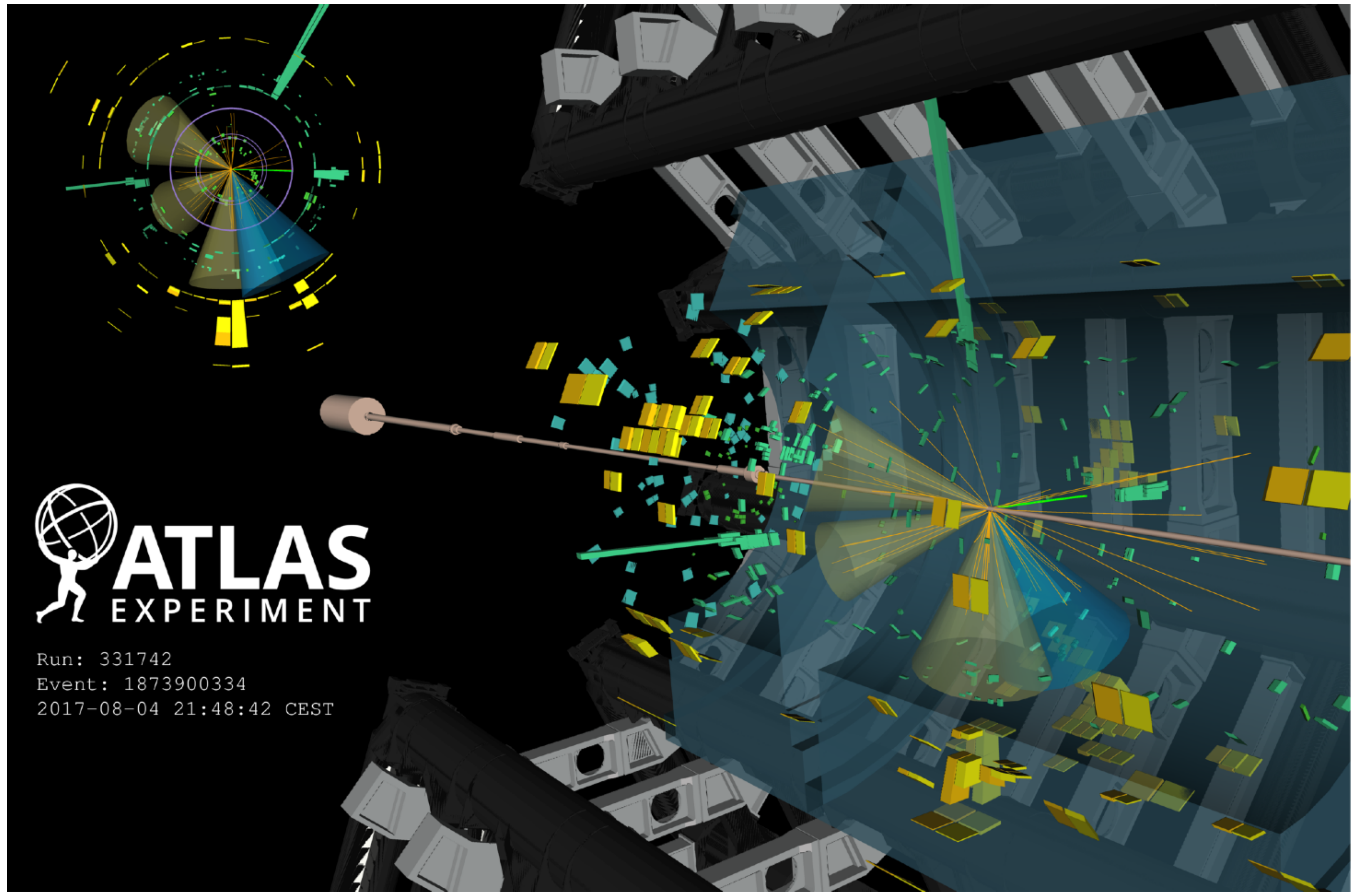
- $\gamma\gamma$ fusion studies in pp collision
  - Require tagging of scattered beam protons
  - Pileup, larger background
  - Invariant mass range of final state di-lepton system:
  - m > 20 GeV, up to several 100 GeV

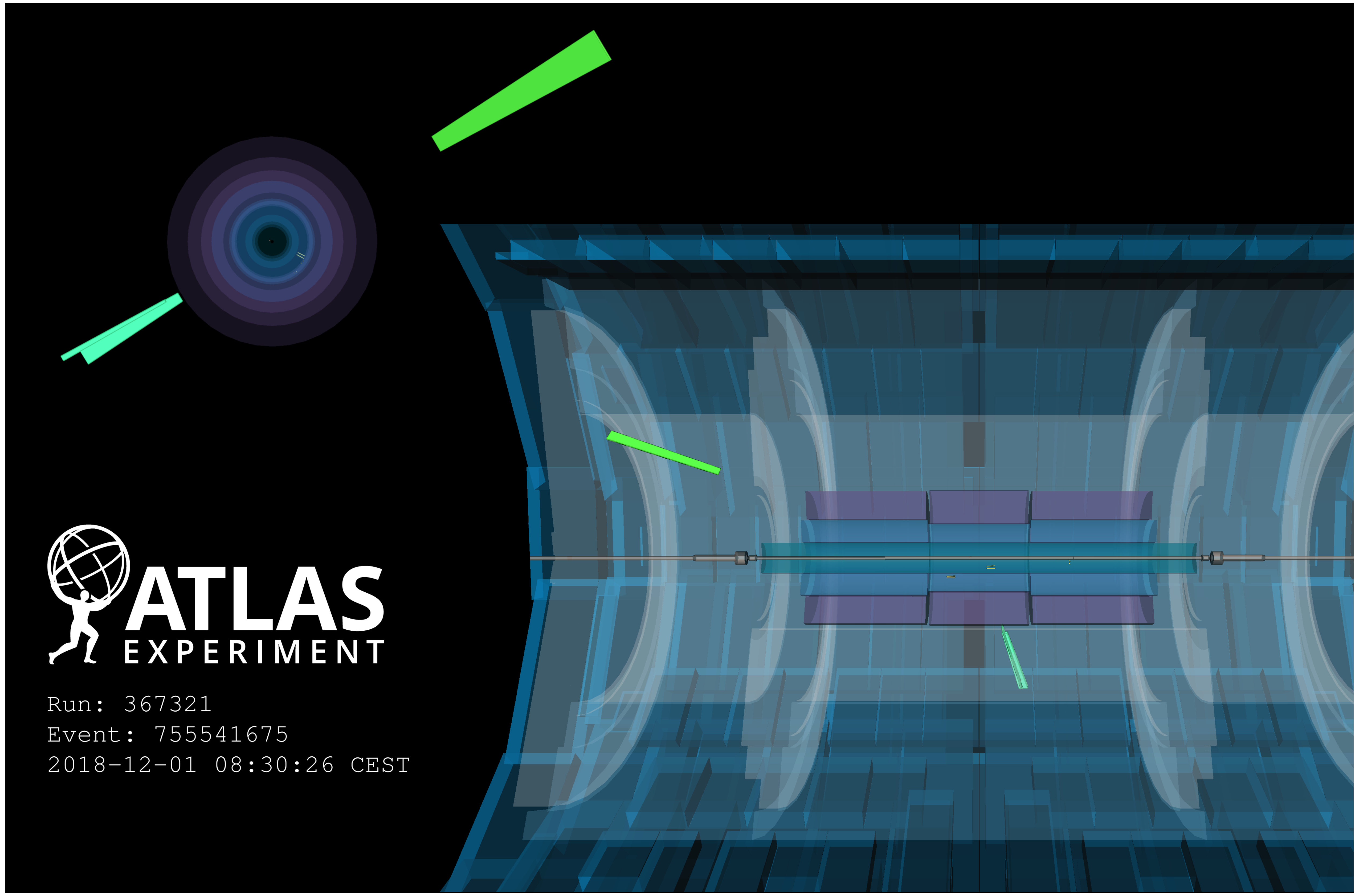
[Phys. Rev. Lett. 125 (2020) 261801]

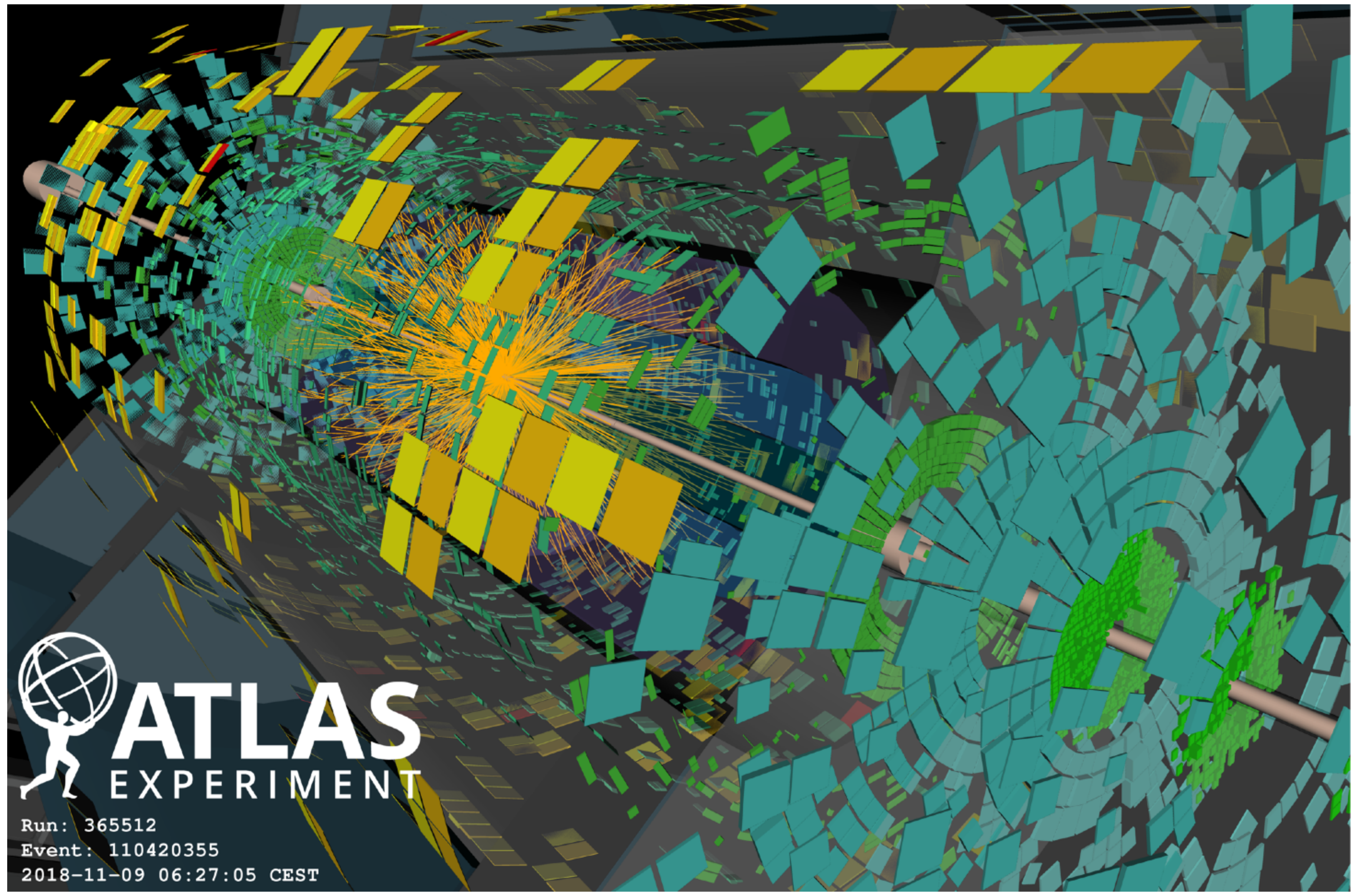
[Phys. Lett. B 816 (2021) 136190]



- pp collision

- Light-by-Light scattering candidate event



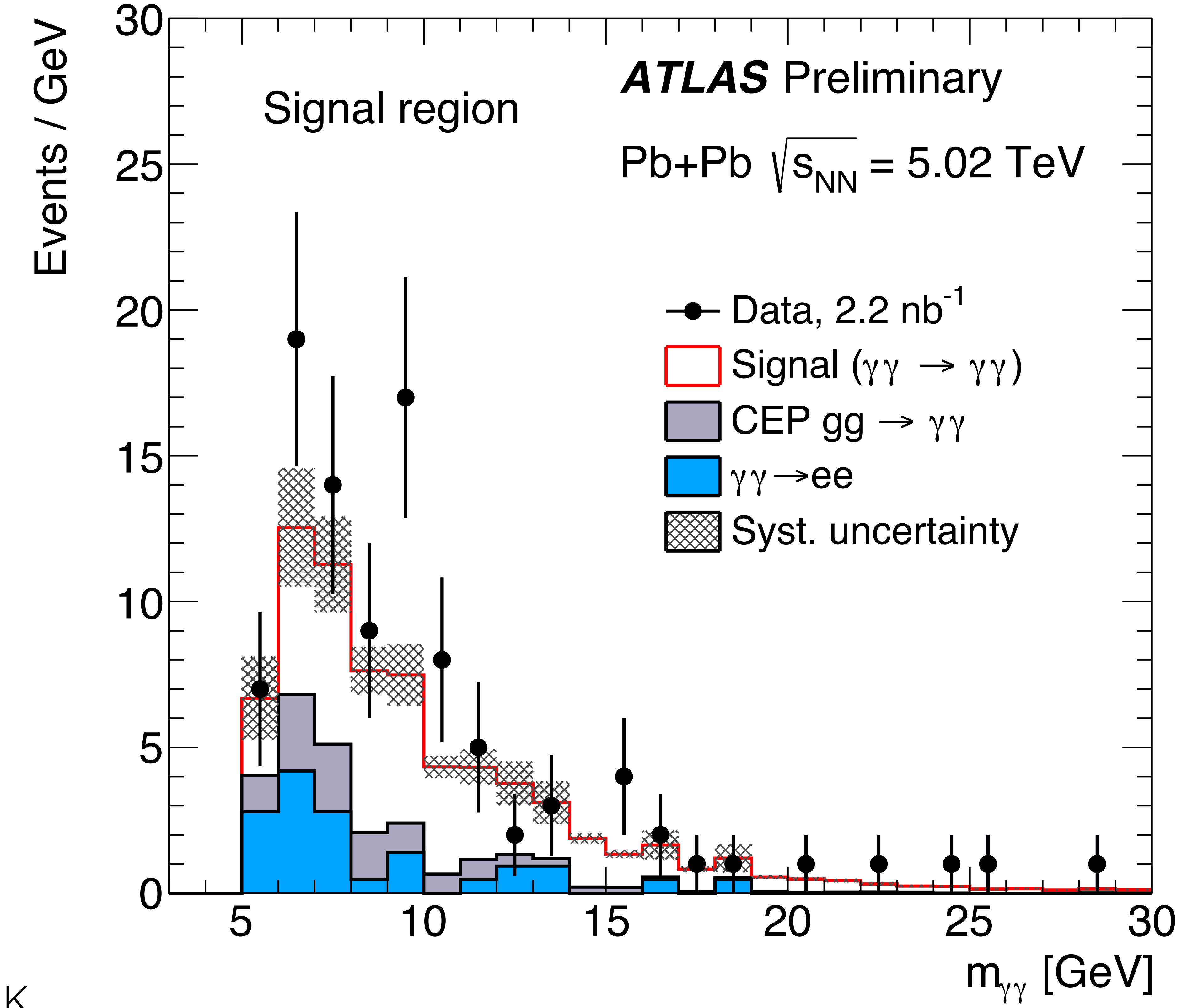


- PbPb collision

Current Limits on ALPs from HI (and also pp) collisions

ATLAS: JHEP 03 (2021) 243

- 97 candidate events,
  - Expected background: 27 ± 5
- Cross section:
  - Measured: 120 ± 17 (stat) ± 13 (sys) ± 4 (lumi) nb
  - SM expectations: 78 ± 8 nb (from SuperChic3.0)
- **Ratio data / MC: 1.5**



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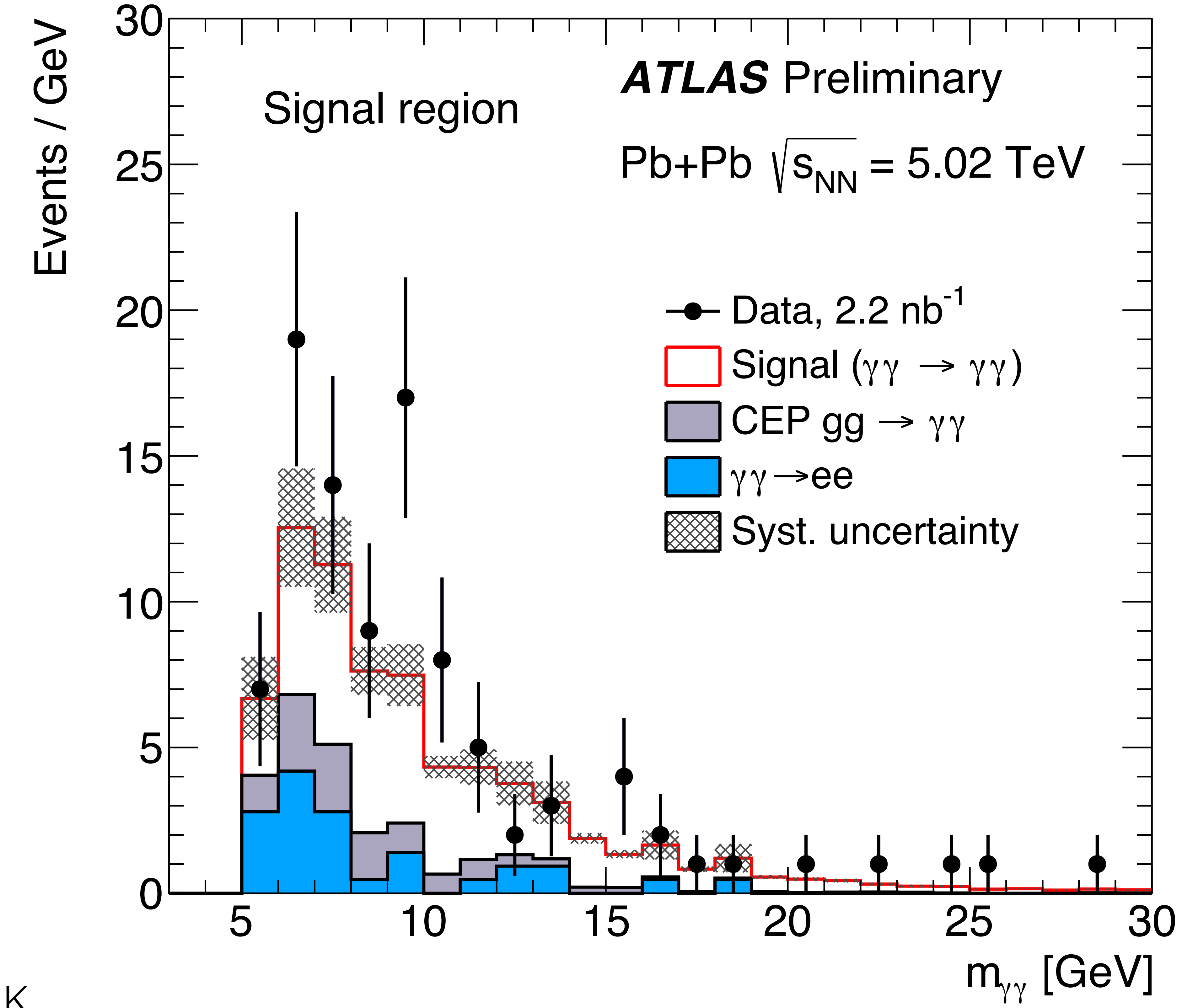
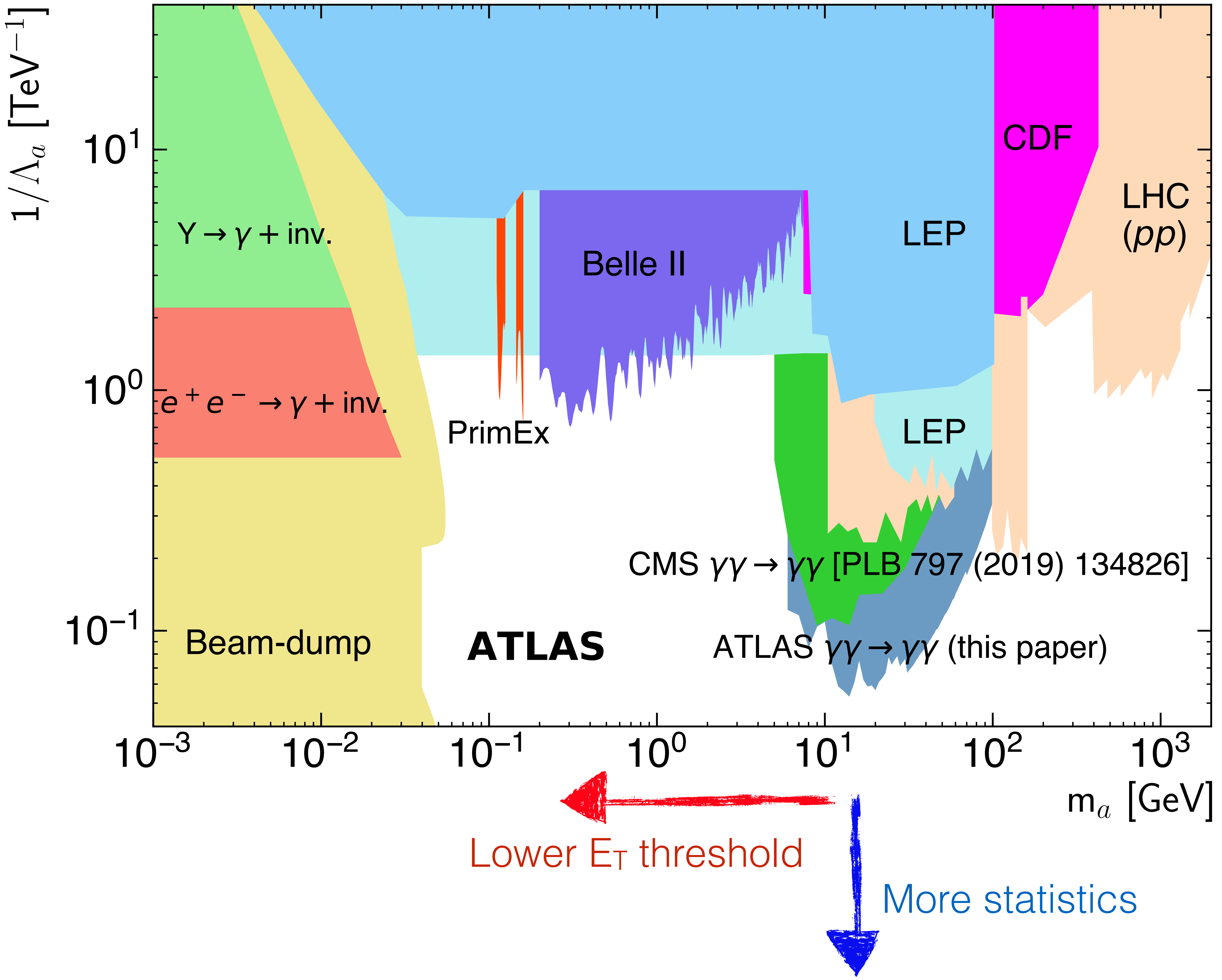
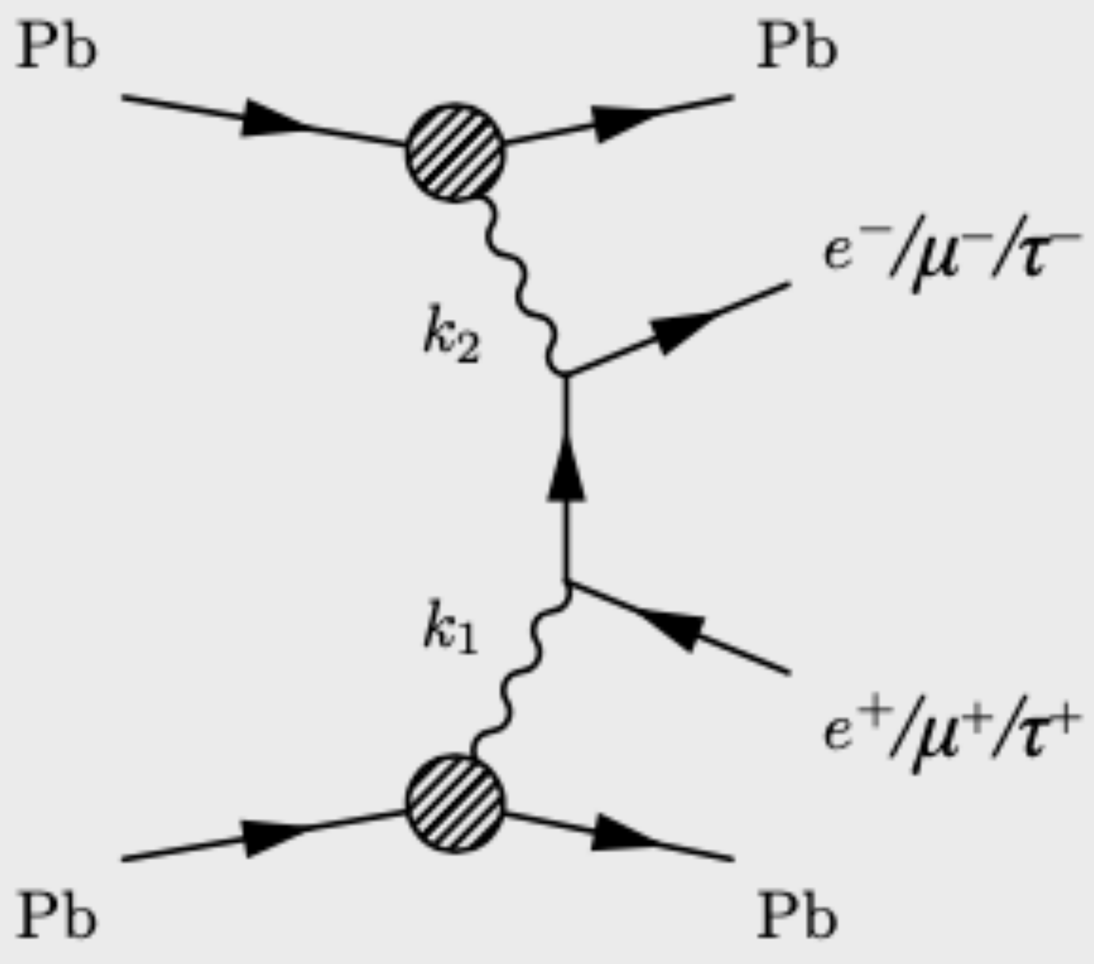
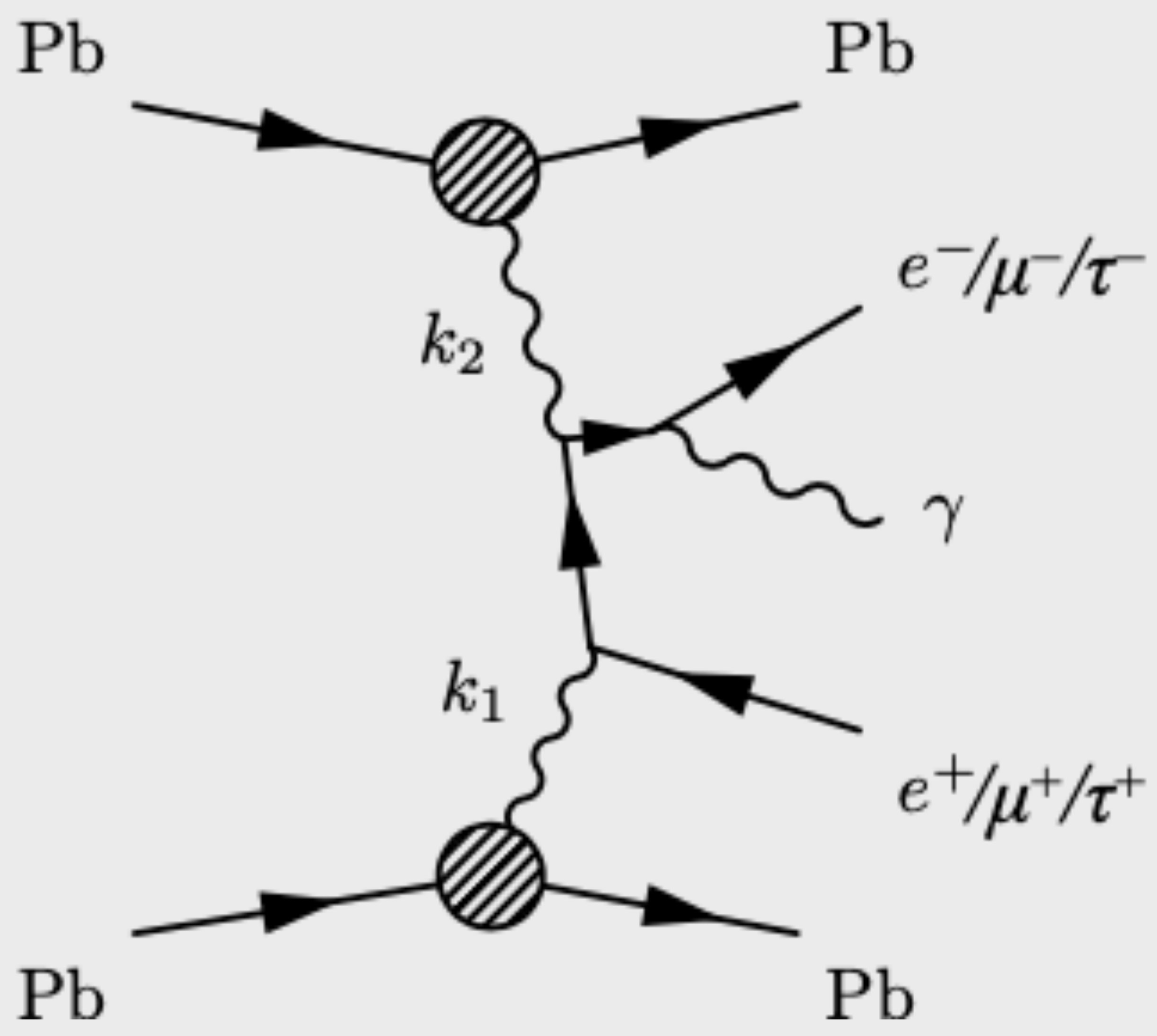


Existing constraints from JHEP 12 (2017) 044

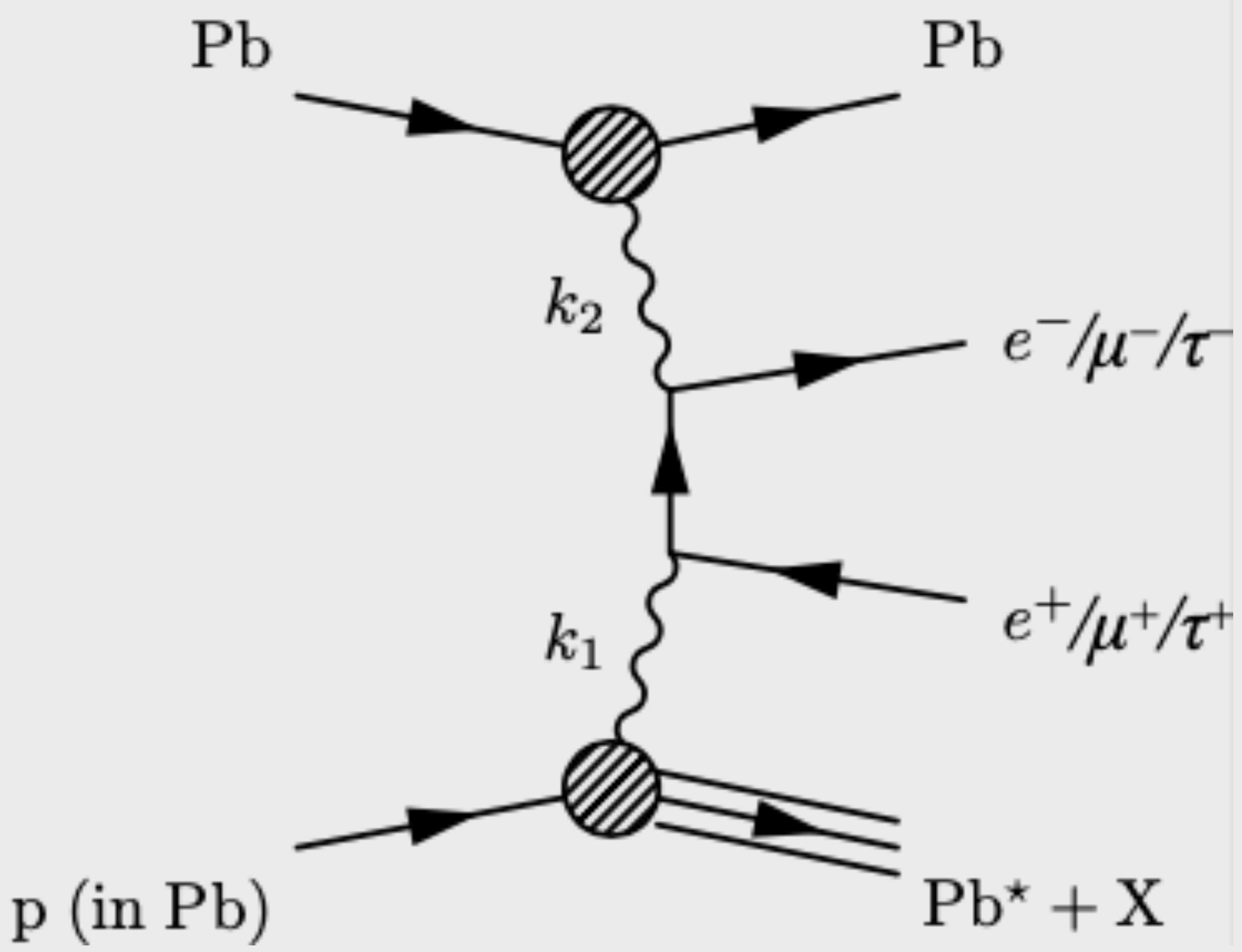




Signal (LO)



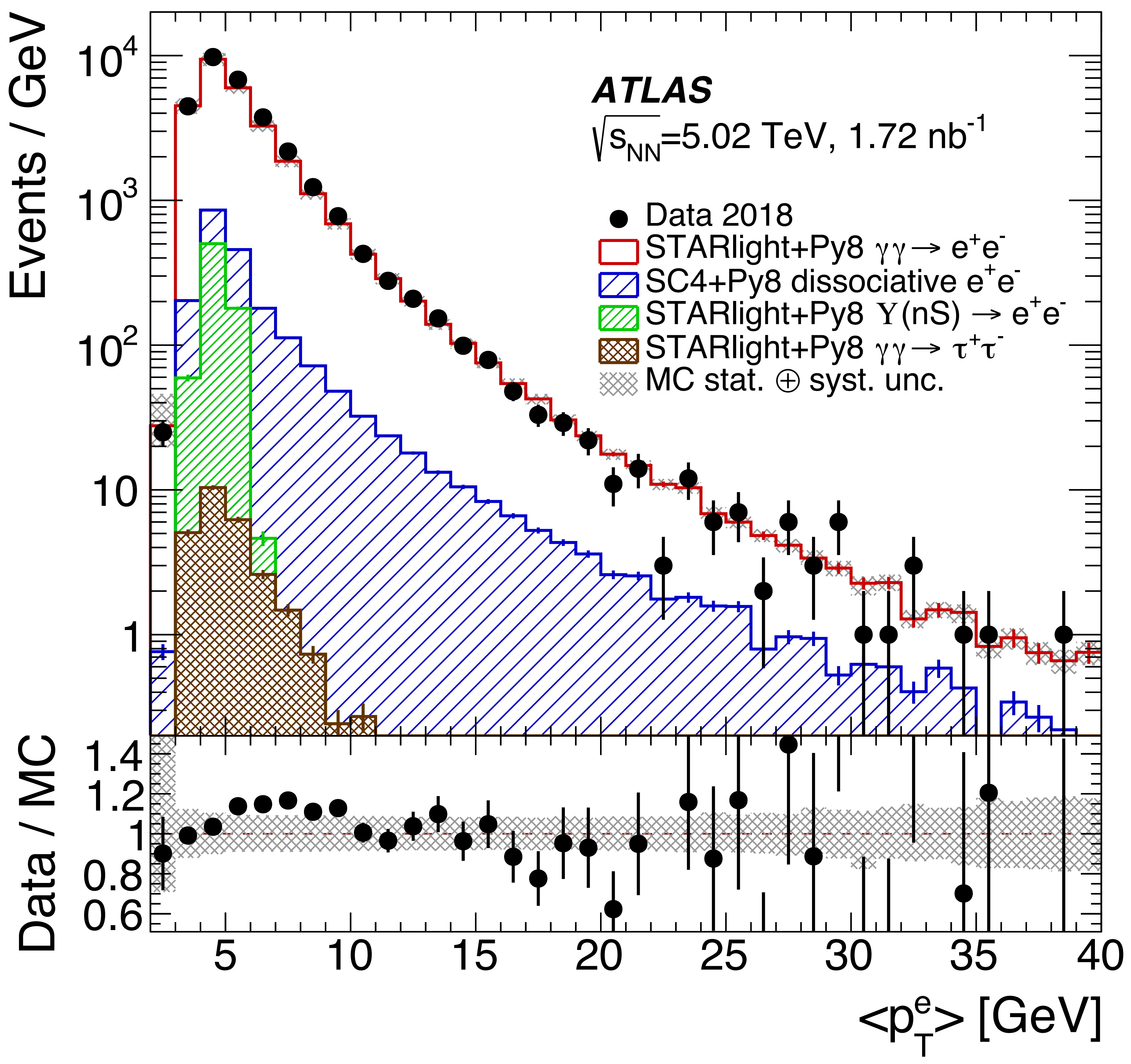
Signal (FSR)



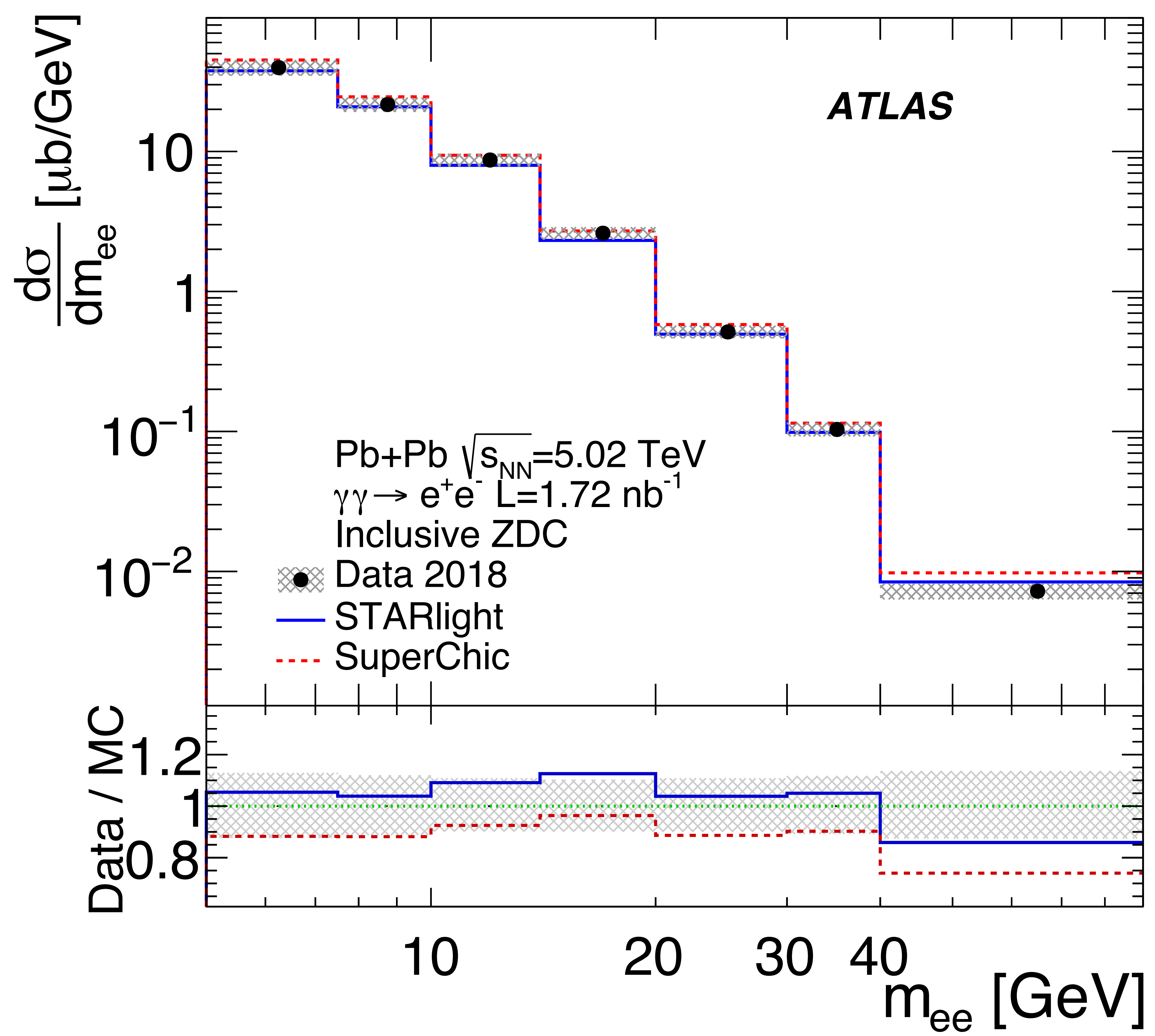
Dissociative background

arxiv: 2207.12781

- Transverse momentum distribution



- Invariant Di-Electron mass, compared to theory calculations



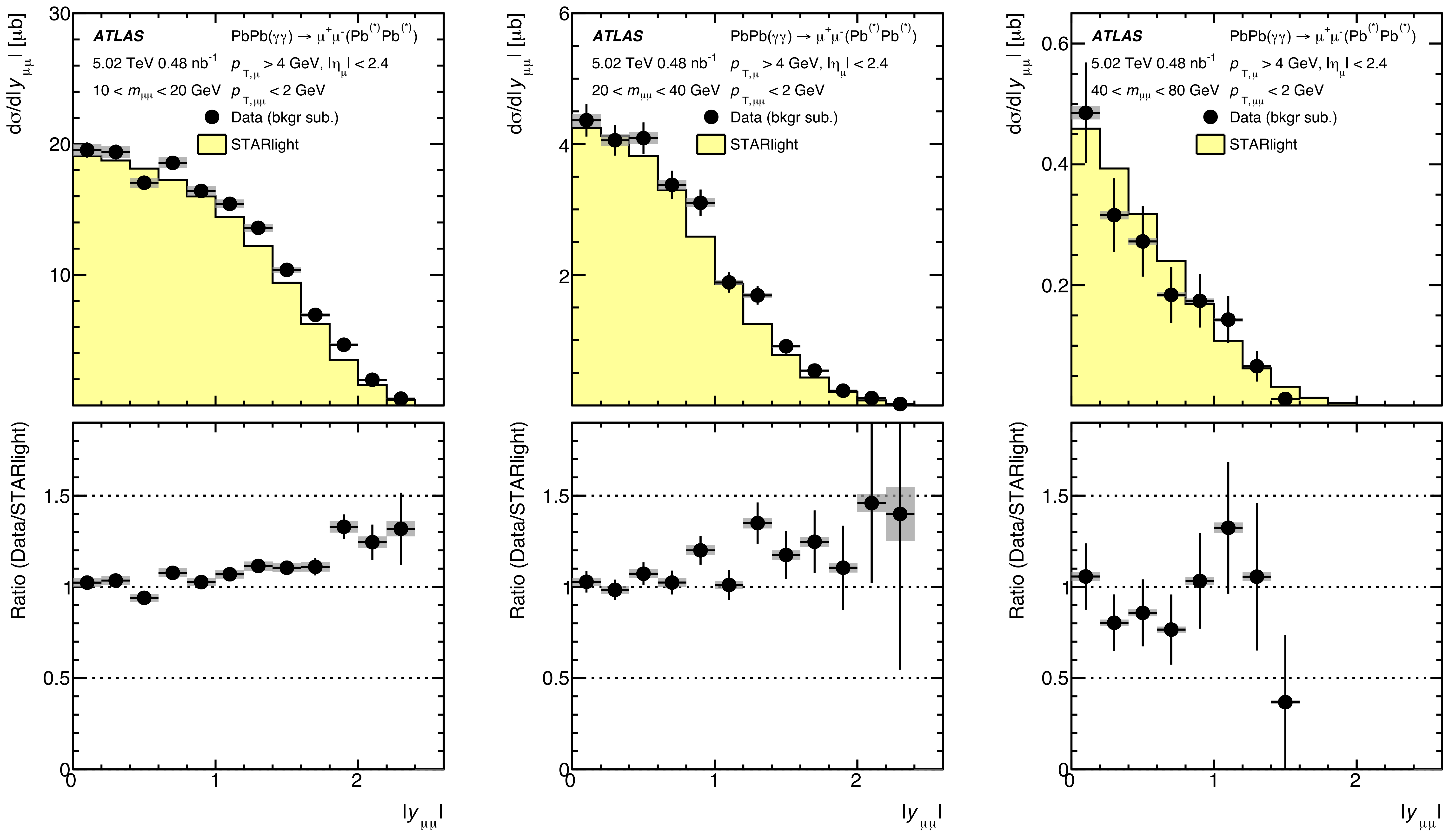
- Selection:
  - Photon initial state tag
  - Electrons: p_T > 2.5 GeV, |η| < 2.47
  - Exactly 2 electrons, exactly 2 tracks, no muon hits

- Selection:
  - pT_{ee} < 2 GeV
  - m_{ee} > 5 GeV

- Di-Muon Rapidity distribution in bins of invariant mass compared to theory calculation

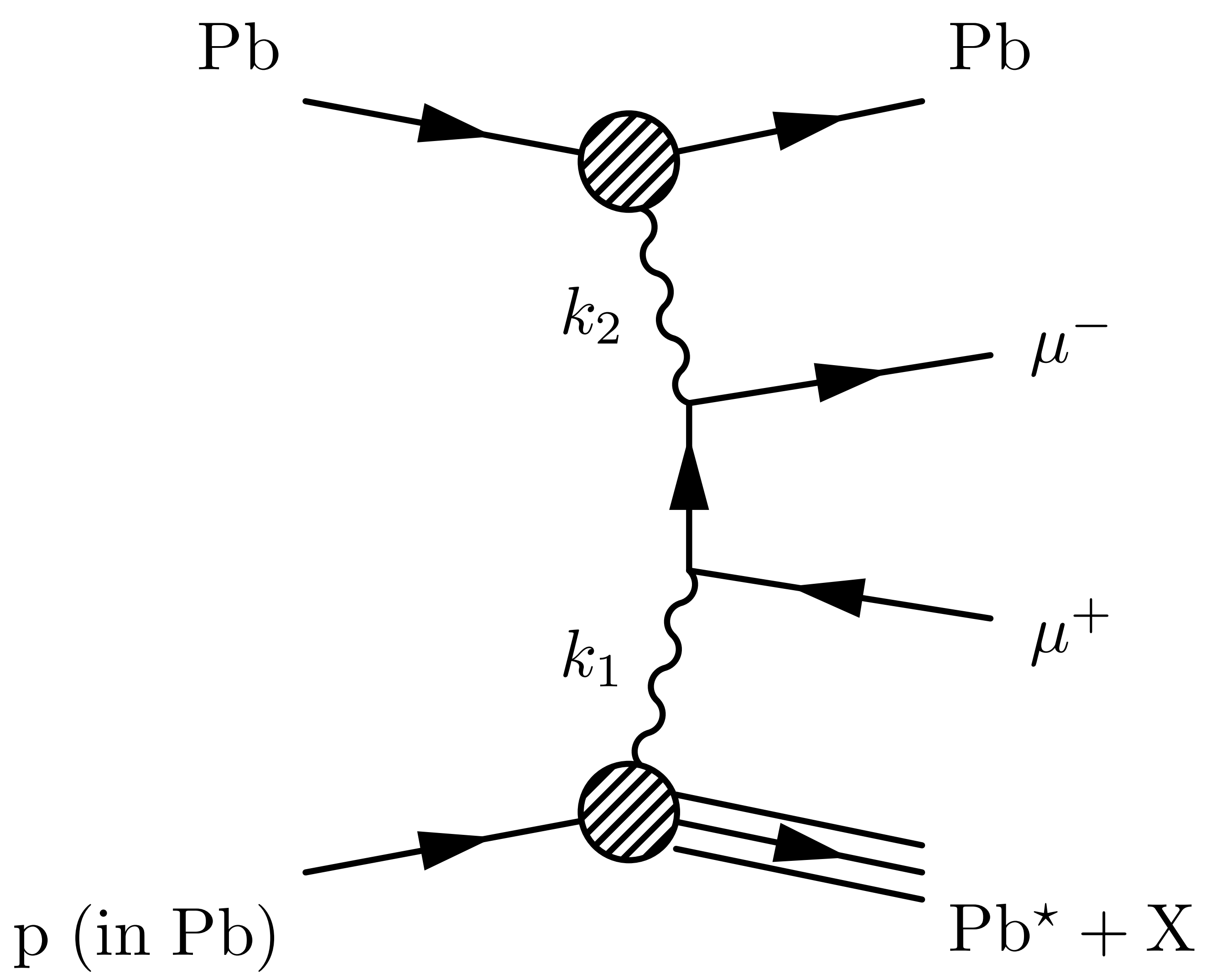
- Muon selection:
  - Photon initial state tag:
    - exclusively 2 muons
    - No additional tracks with $p_T > 0.1$ GeV
  - $p_T > 4$ GeV, $|\eta| < 2.4$
  - Exactly 2 muons, oppositely charged

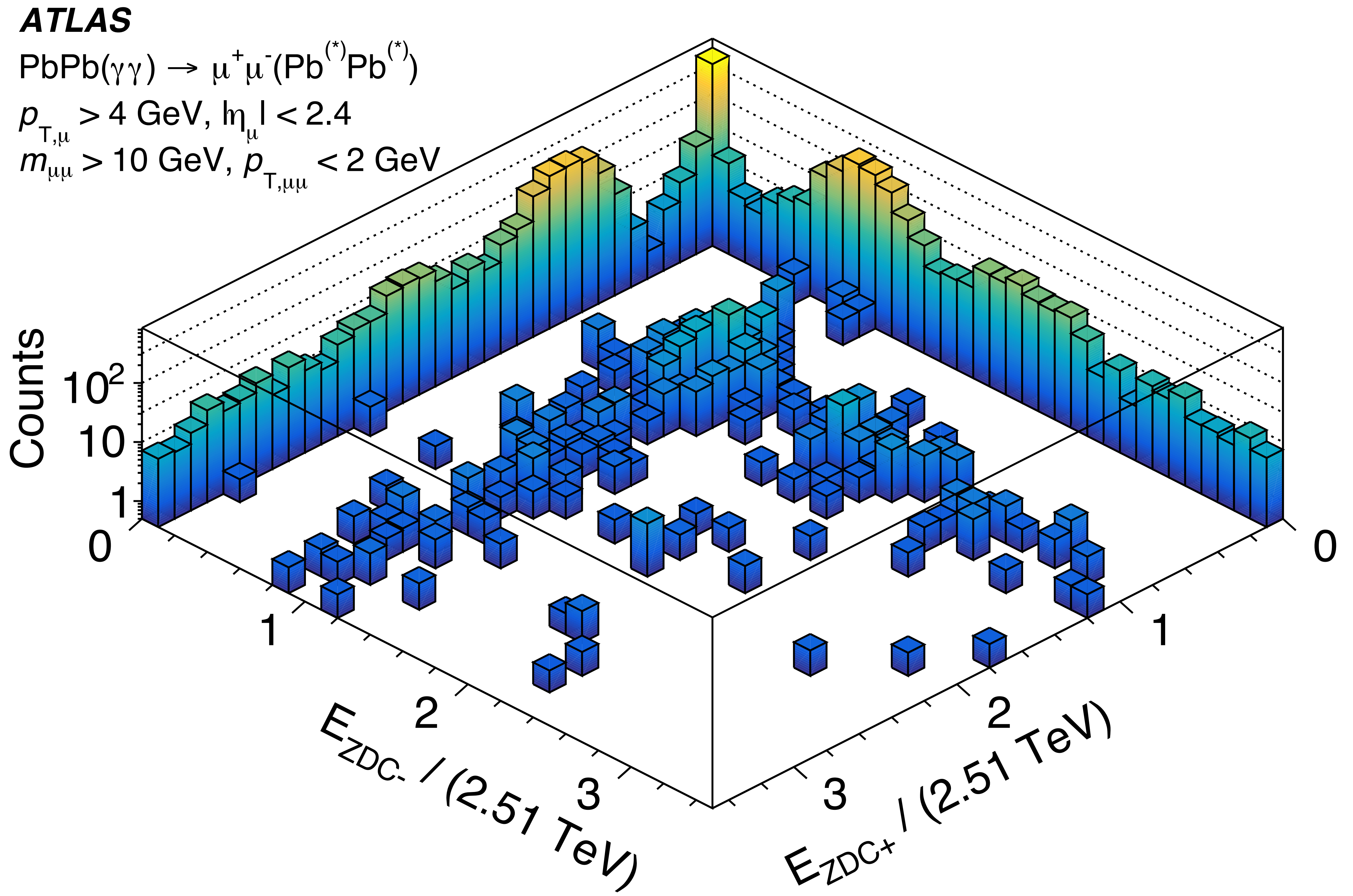
- Di-μ selection:
  - $pT_{\mu\mu} < 2$ GeV
  - $m_{\mu\mu} > 10$ GeV

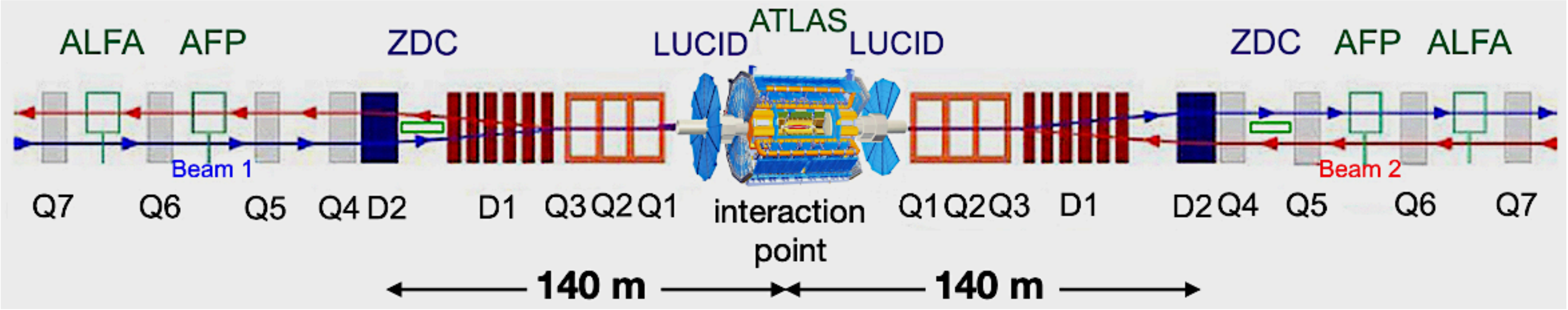


Suppression of dissociative background:

Phys. Rev. C 104 (2021) 024906

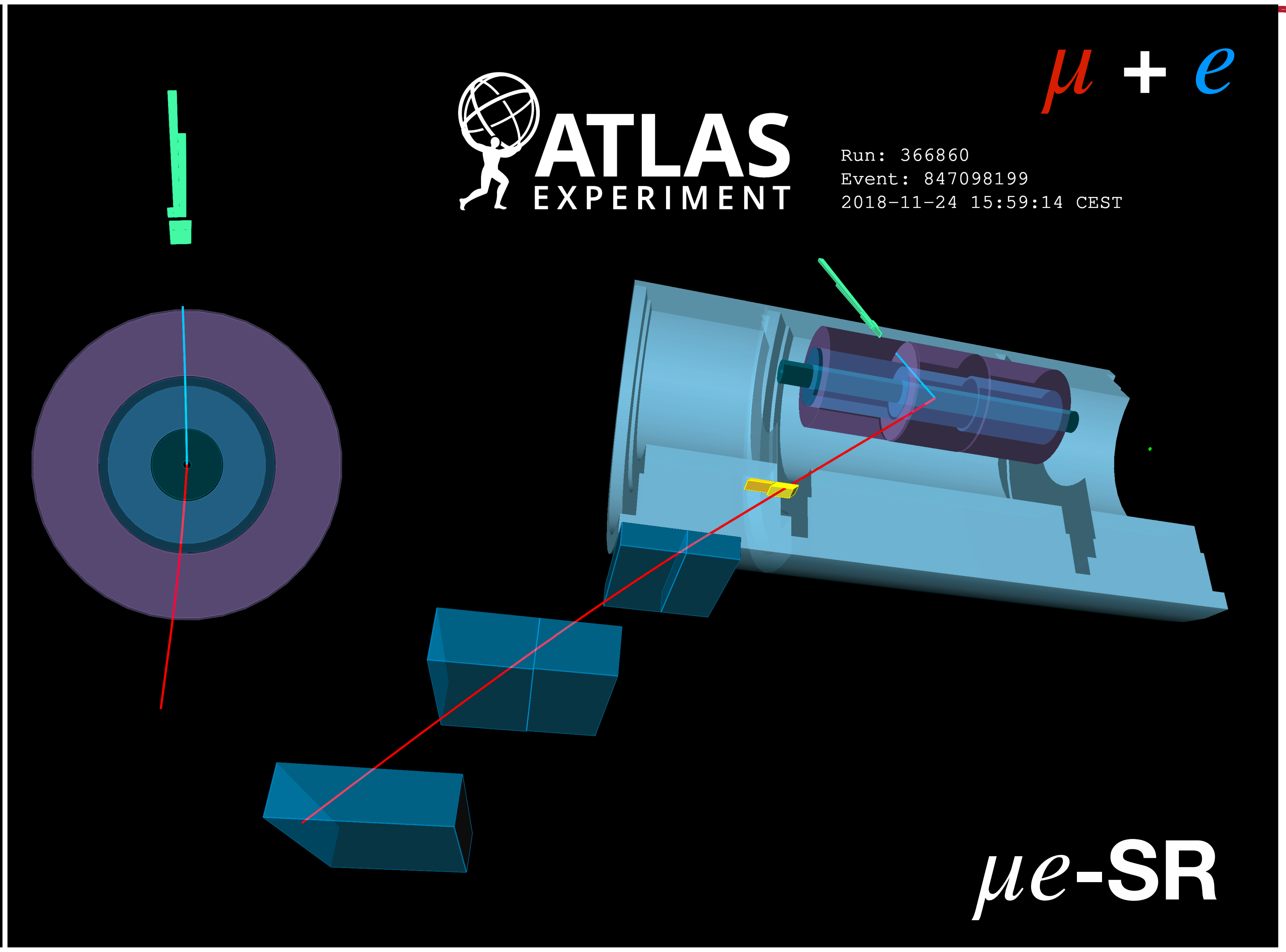


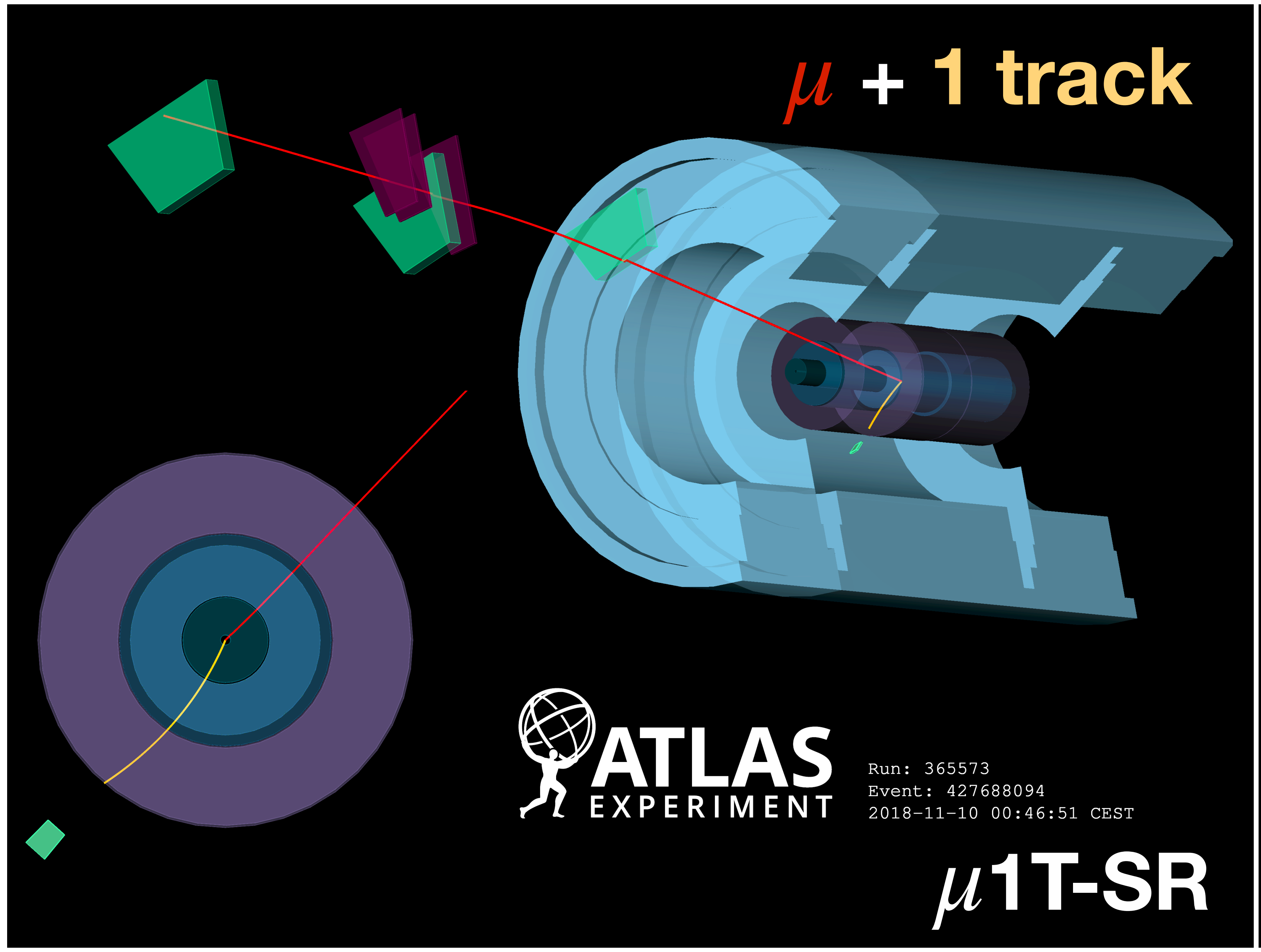


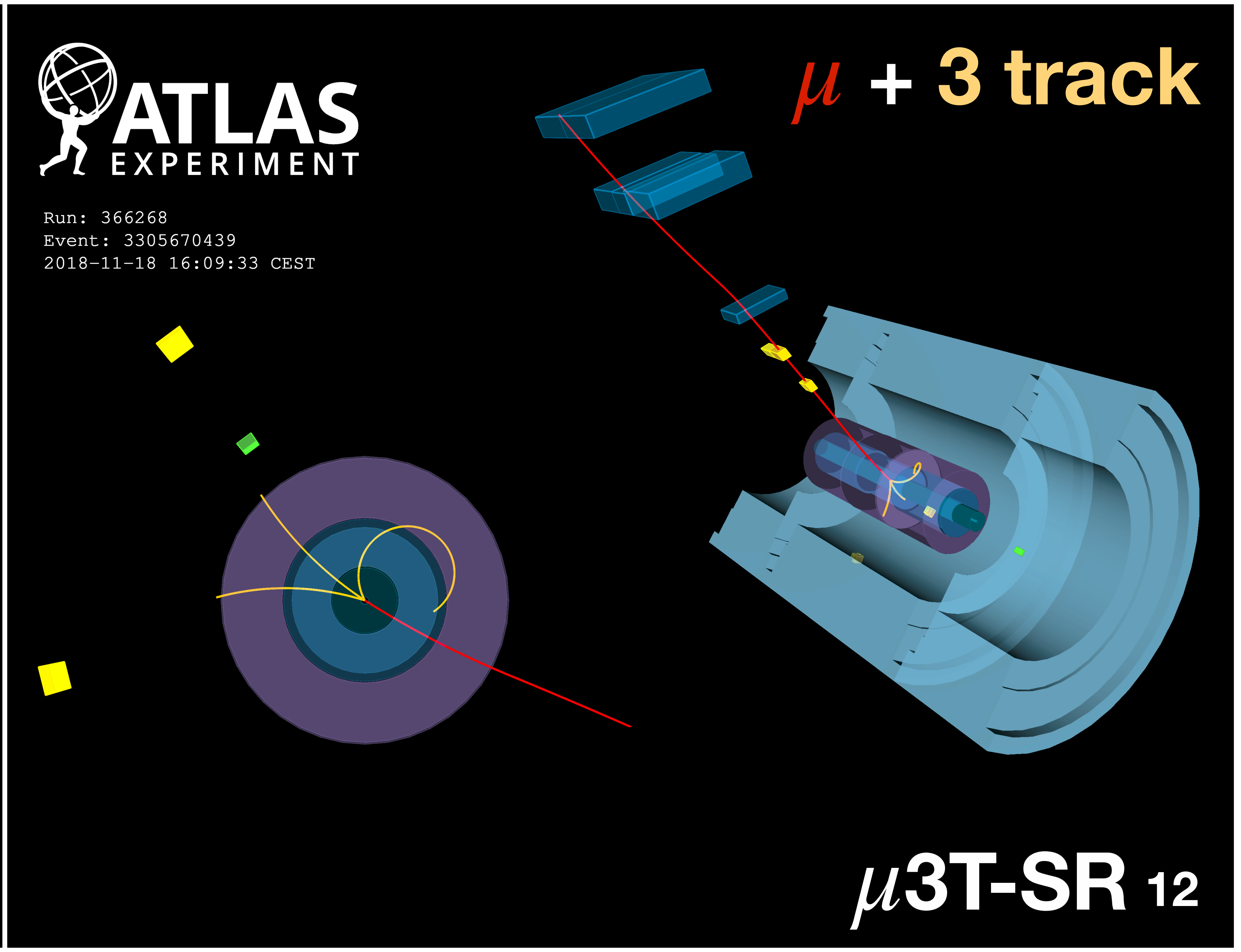


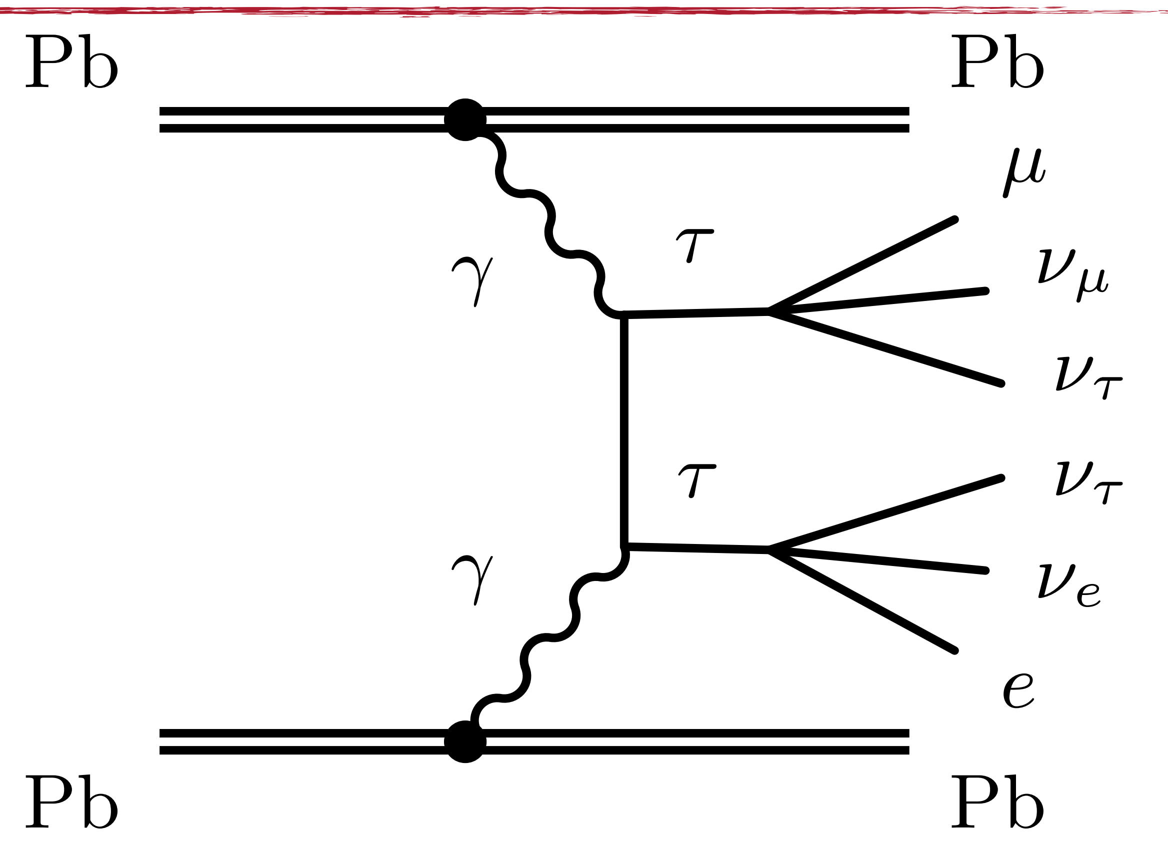
arxiv: 2204.13478, accepted for publication in Phys. Rev. Lett.

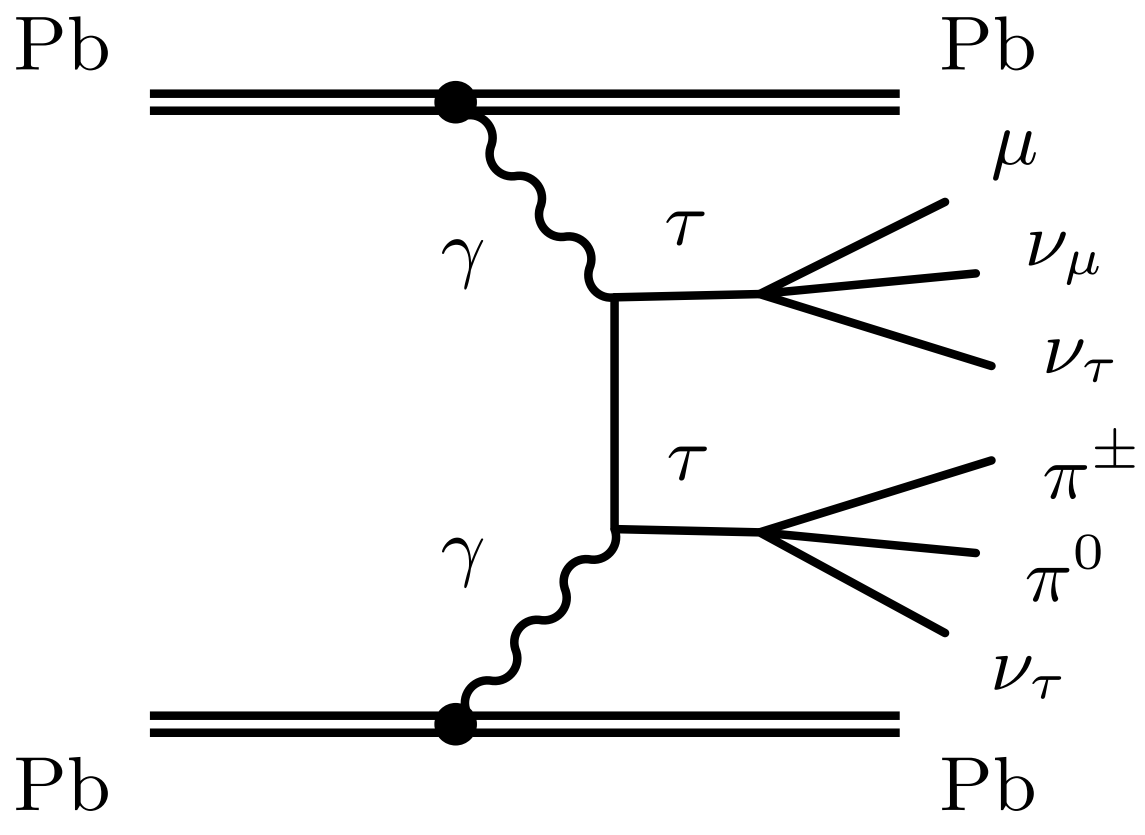
Signal Regions (SRs)

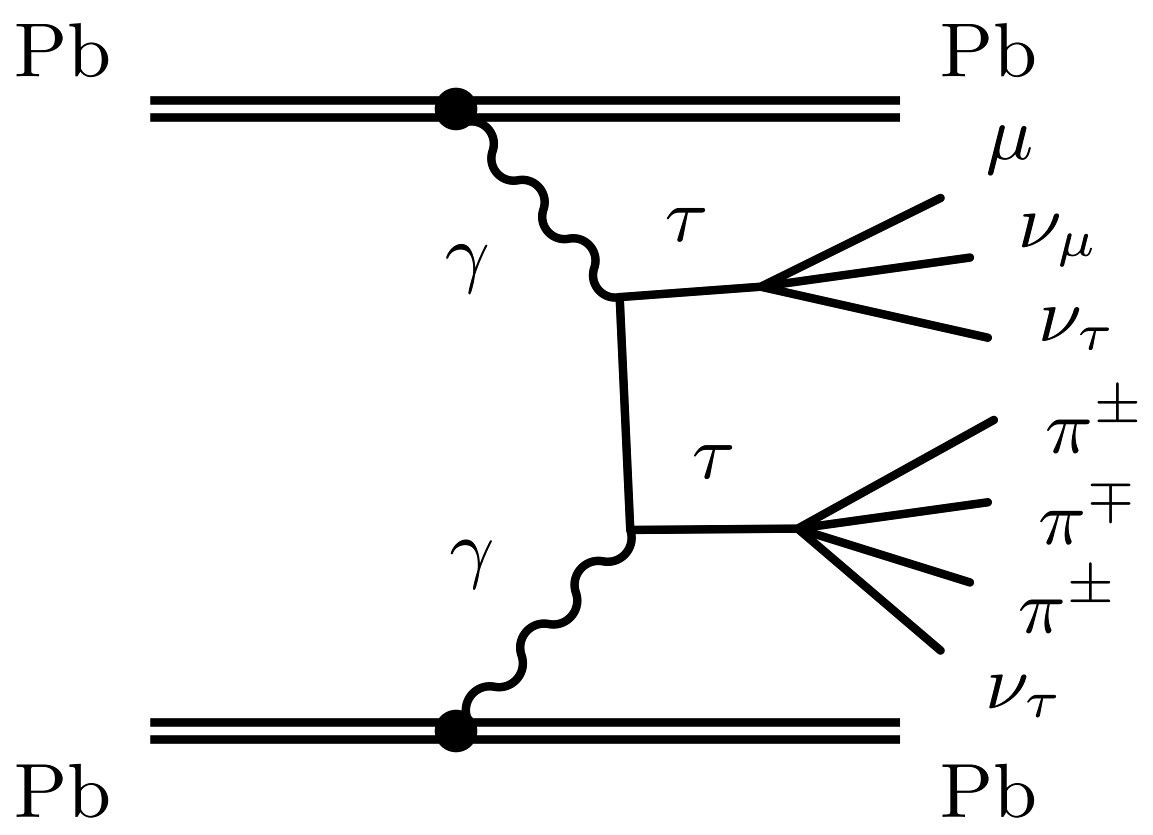








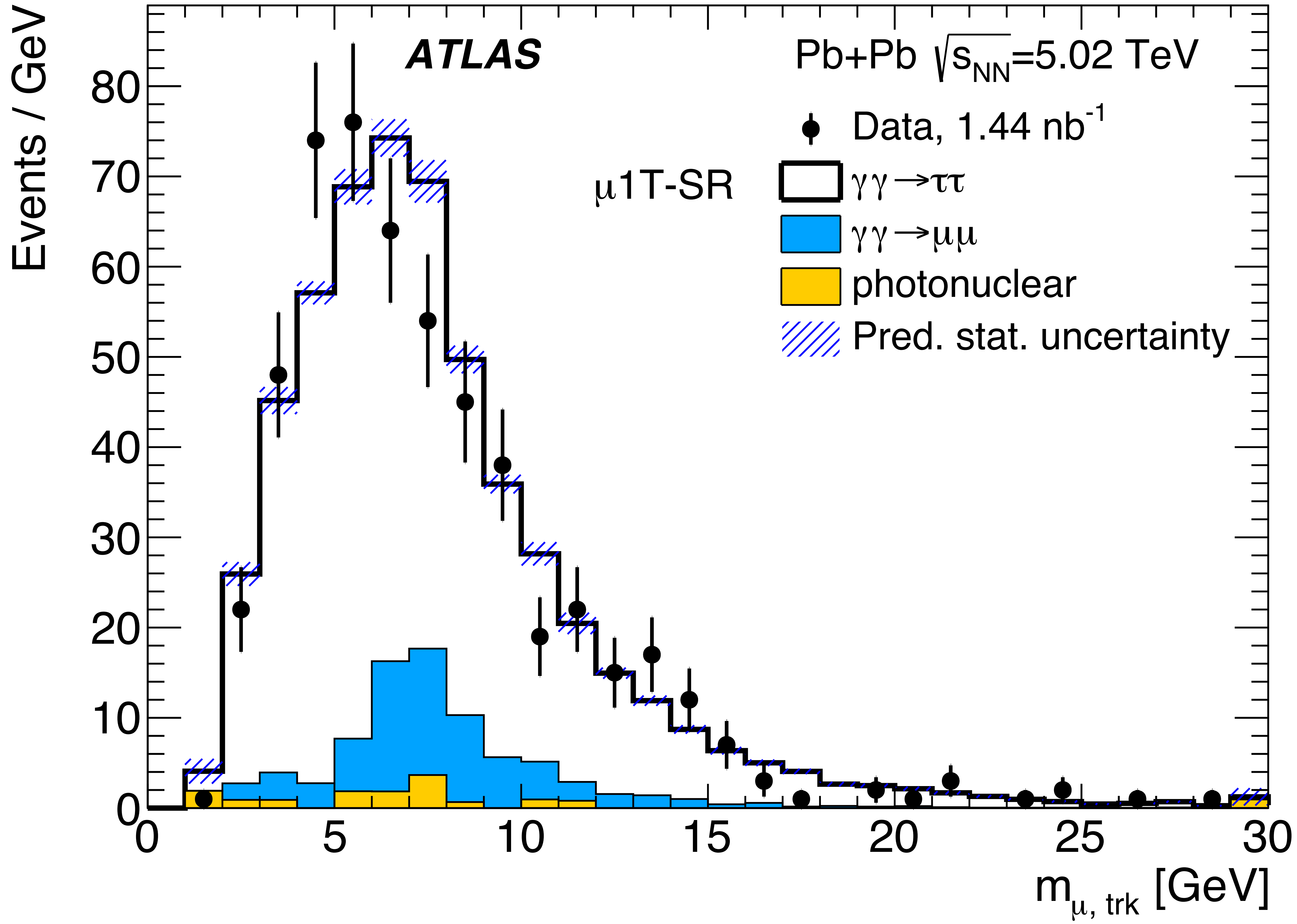




Anomalous magnetic moment of tau

arxiv: 2204.13478

- Clear observation of di-tau production



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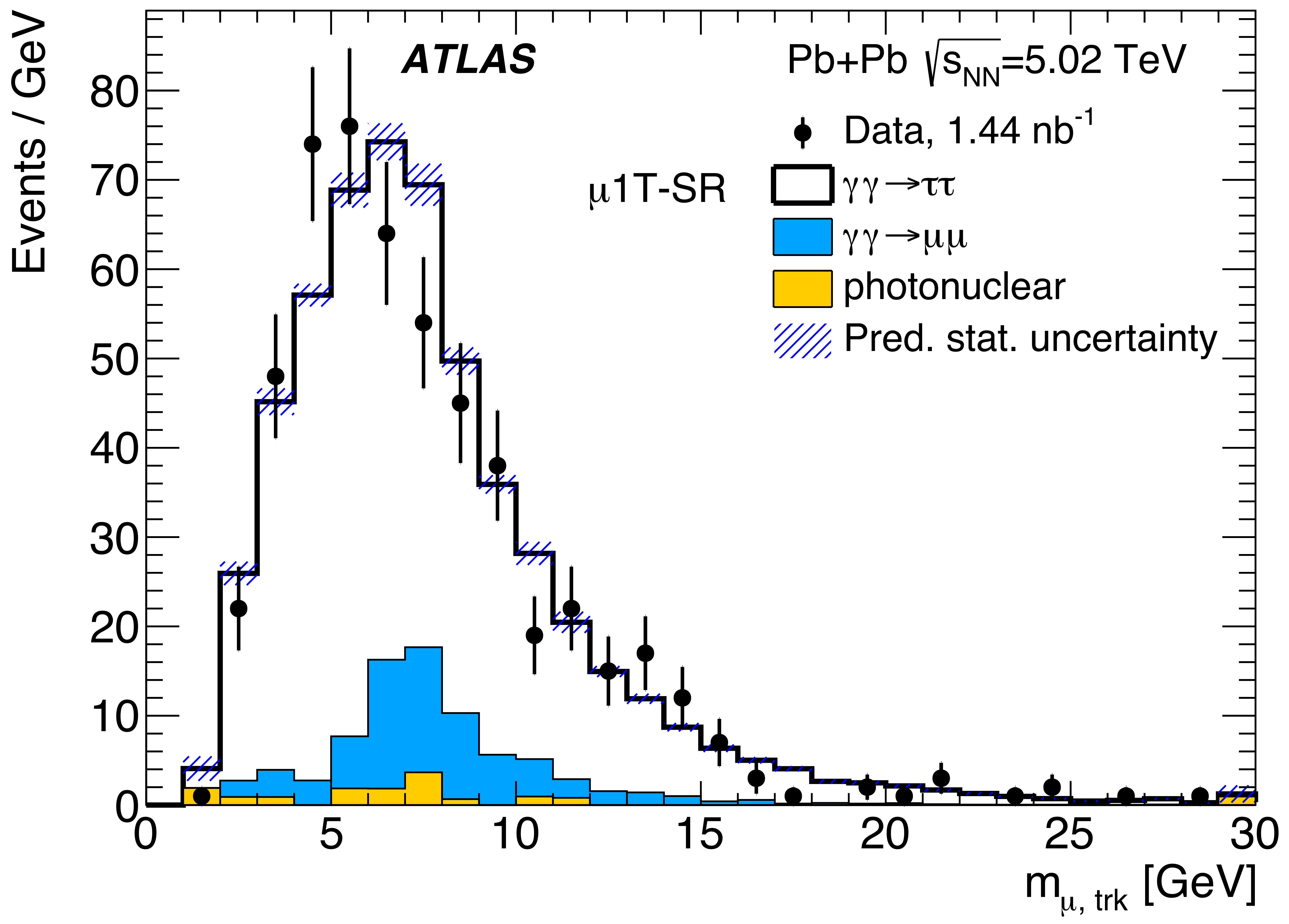
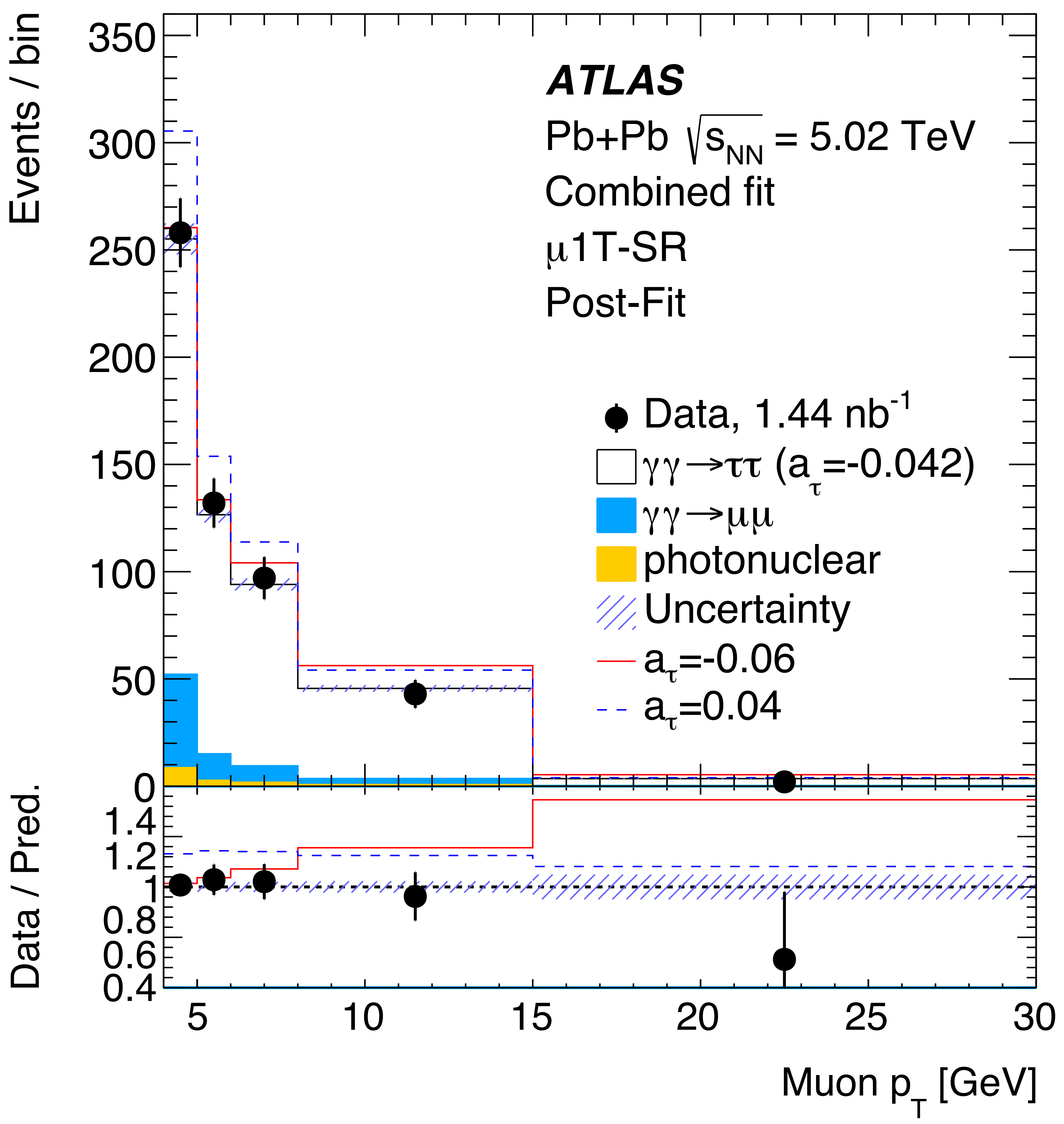
• Clear observation of di-tau production

• Muon pT Spectrum sensitive to a_τ distribution

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





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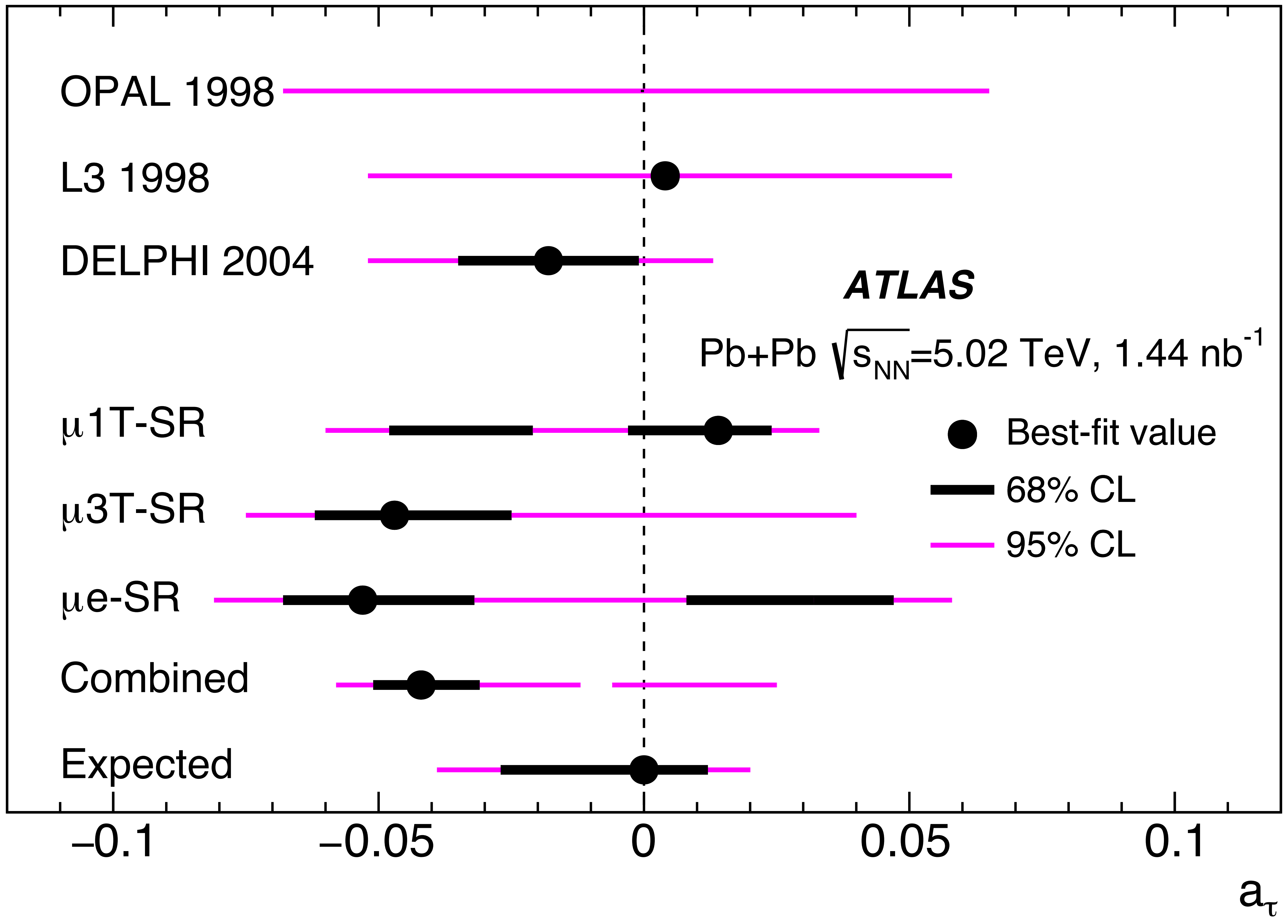
- First limits on a_τ since 2004
- First Measurement of a_τ in heavy ion collisions
- Competitive with DELPHI
  - 5% precision on a_τ
  - Statistical uncertainty dominates
- Similar analysis also from CMS



[DELPHI result: Eur. Phys. J. C 35 (2004) 159]

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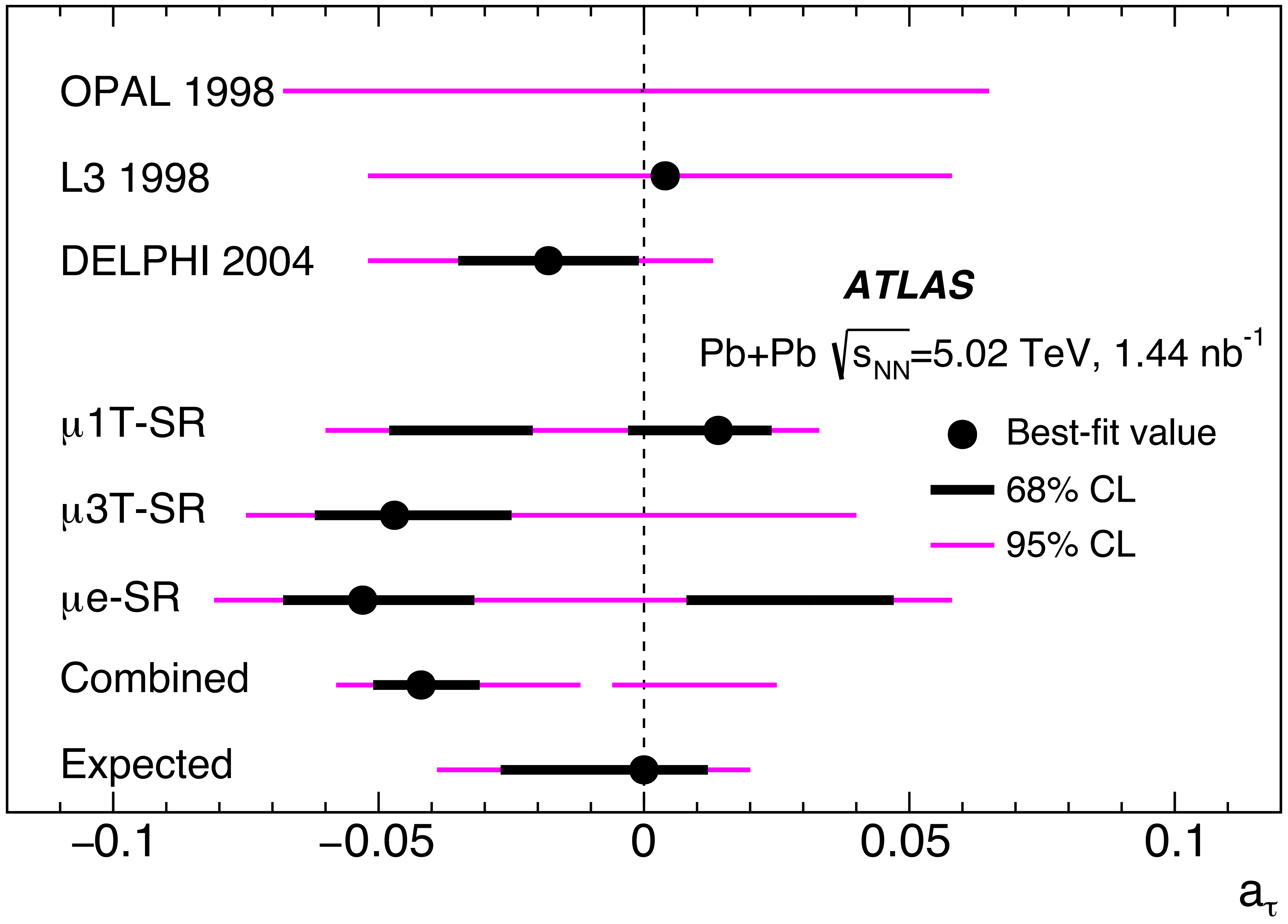
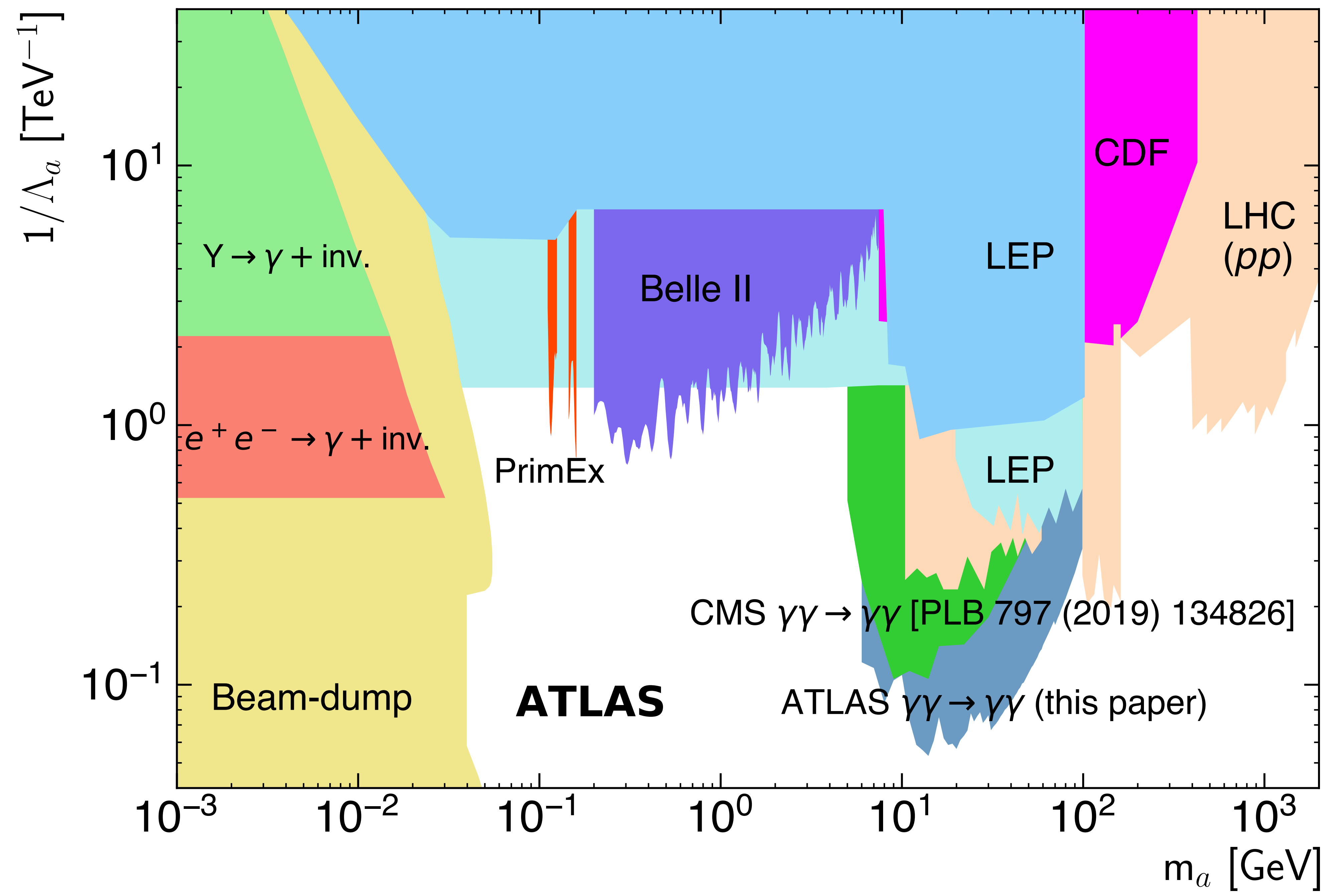
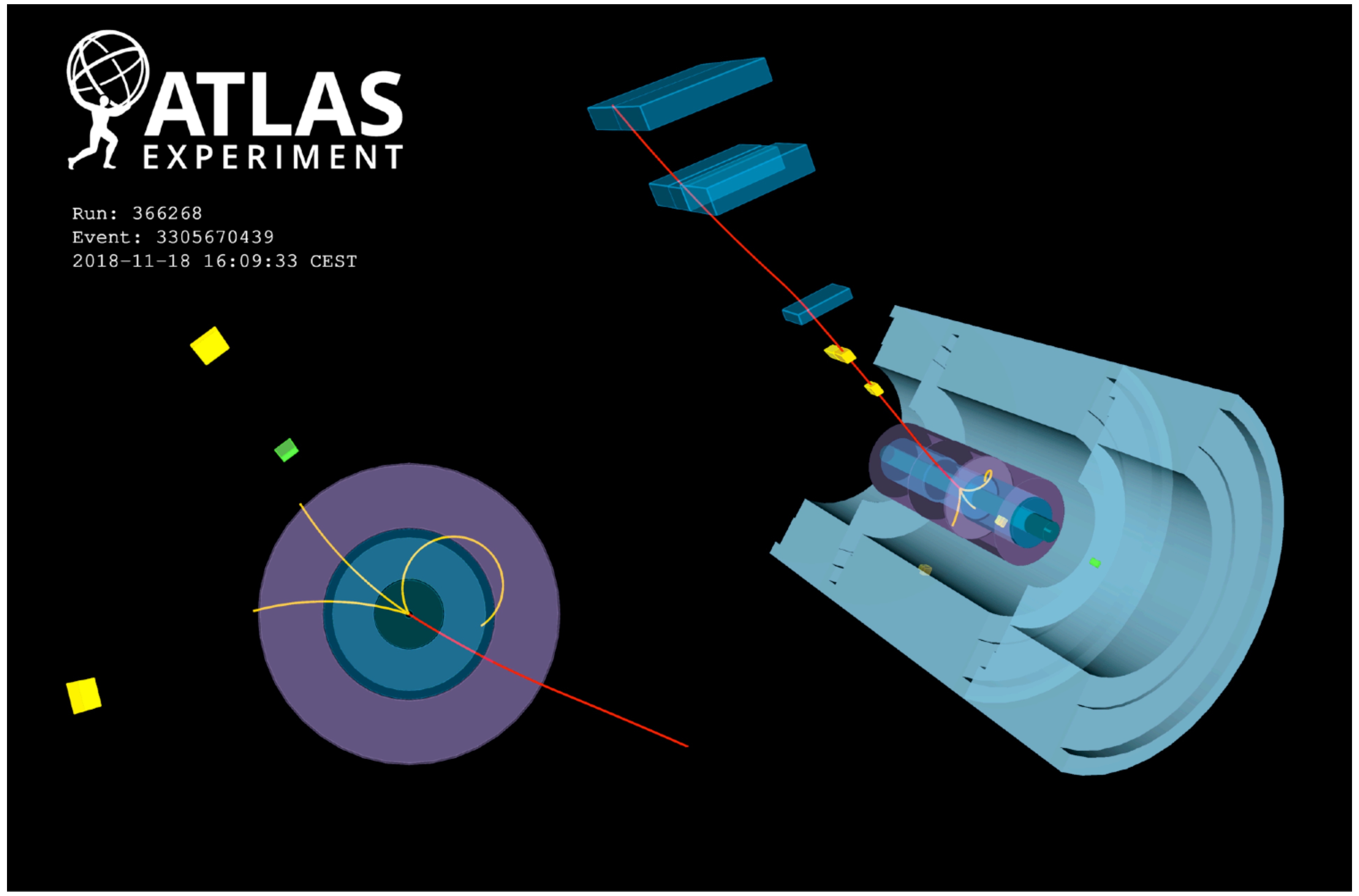


[DELPHI result: Eur. Phys. J. C 35 (2004) 159]

- a_τ probes 1-loop quantum fluctuations
- Indirectly sensitivity to BSM physics
  - SUSY predicts quadratic scaling with lepton mass
- Schwinger prediction: $\alpha/2\pi \simeq 0.001$

- LHC is a superb **photon collider** considering HI UPC events
  - Well suited environment to **photon / lepton production**
  - Sensitive to standard model precision parameters like g-2
  - Sensitive to physics beyond the standard model: e.g: ALPs





What's left to do?

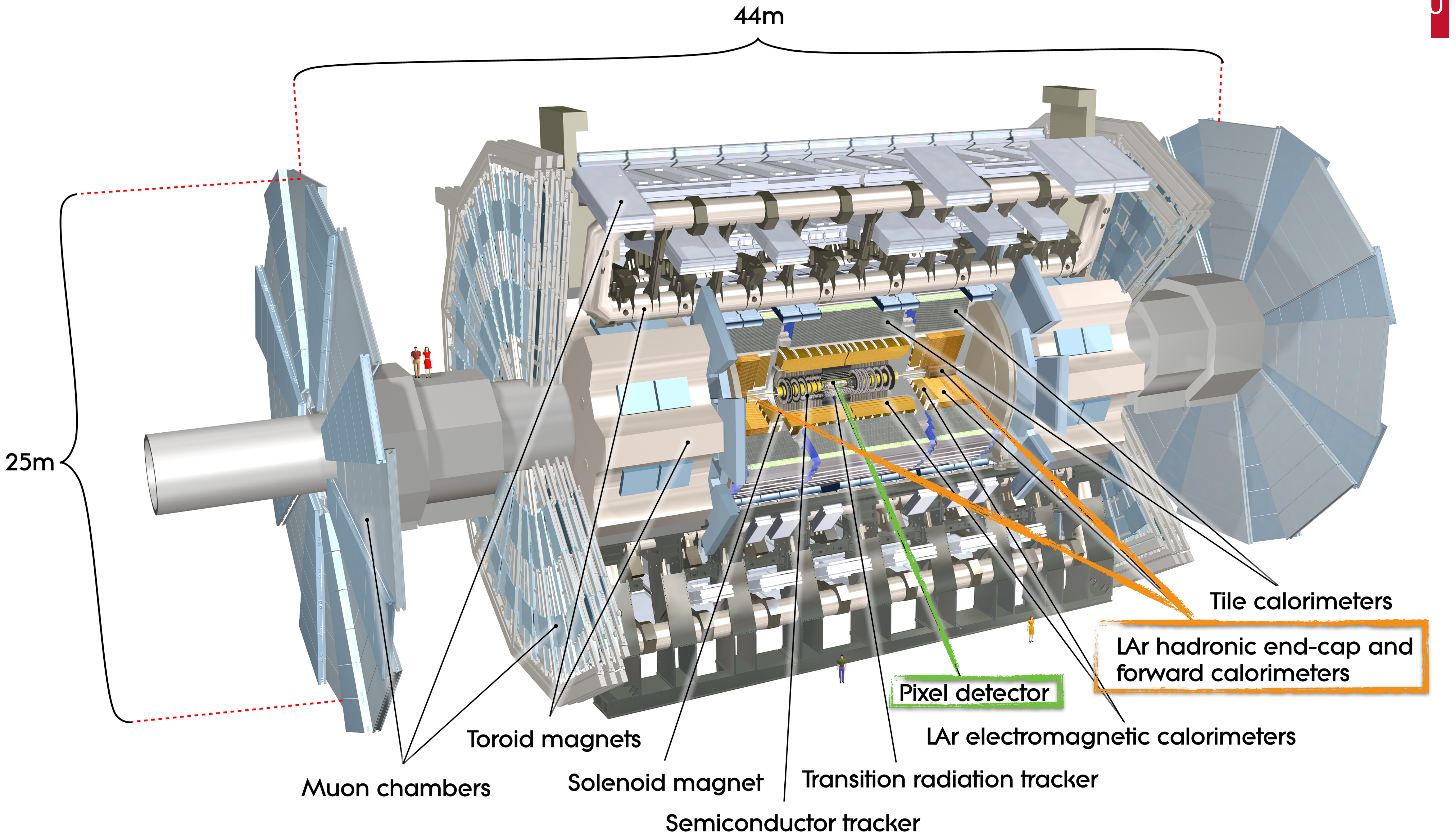
- **Refined analyses** & **more Data:**
  - Lower pT thresholds
  - Improved triggers
  - Refined object ID (tau's)

BACKUP

The ATLAS Detector

- Size of a 6 story building
- 100M readout channels
- 100 kHz readout
- 1 kHz to disk (~1.5 MB/event)

- Zero-Degree-Calorimeters (ZDC):
  - capture neutral particles in forward direction



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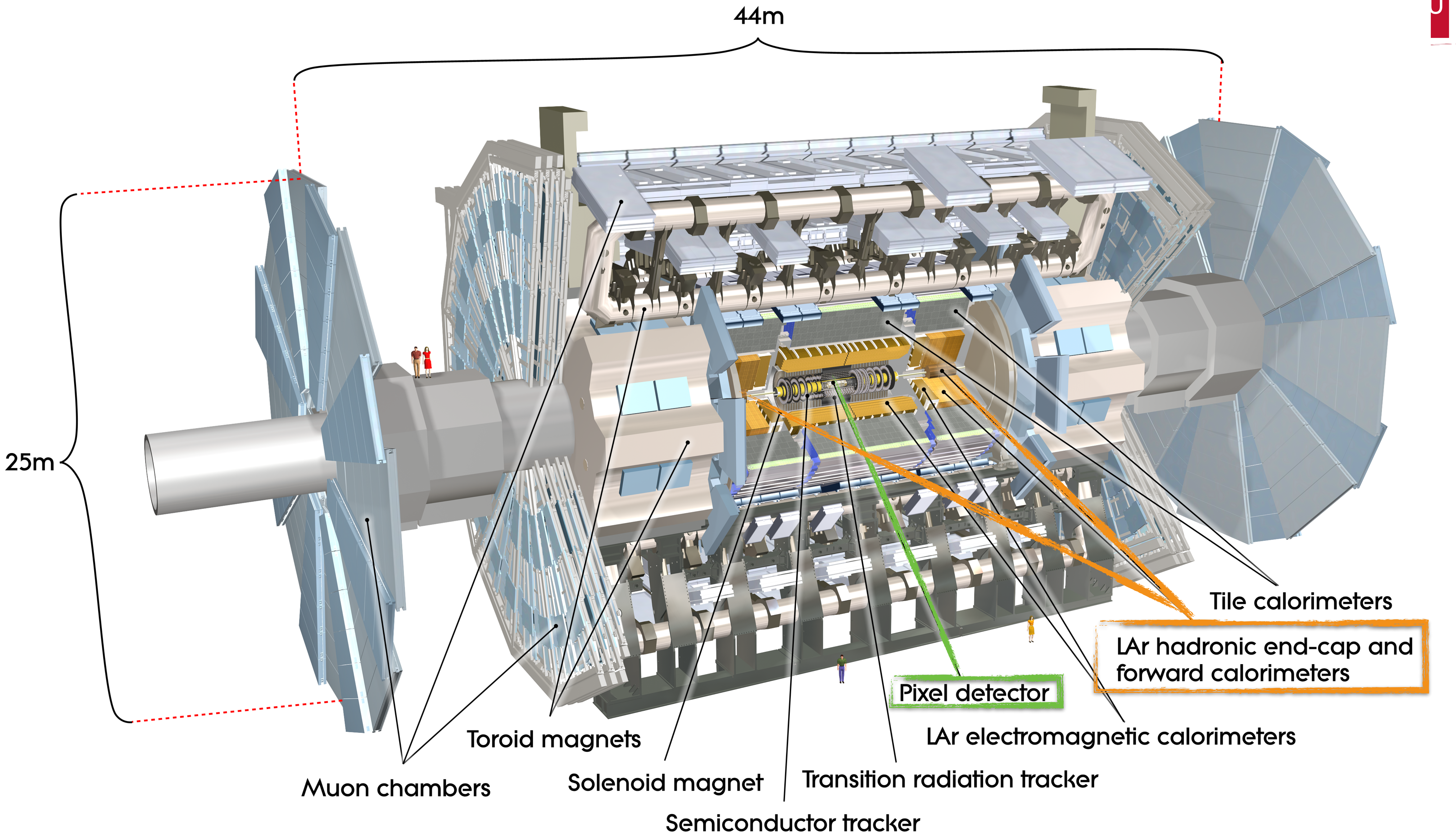
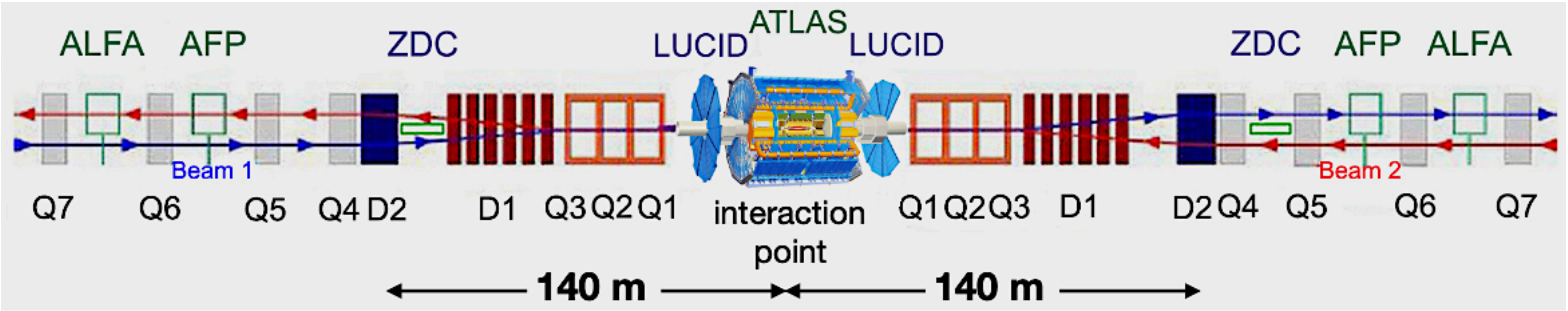
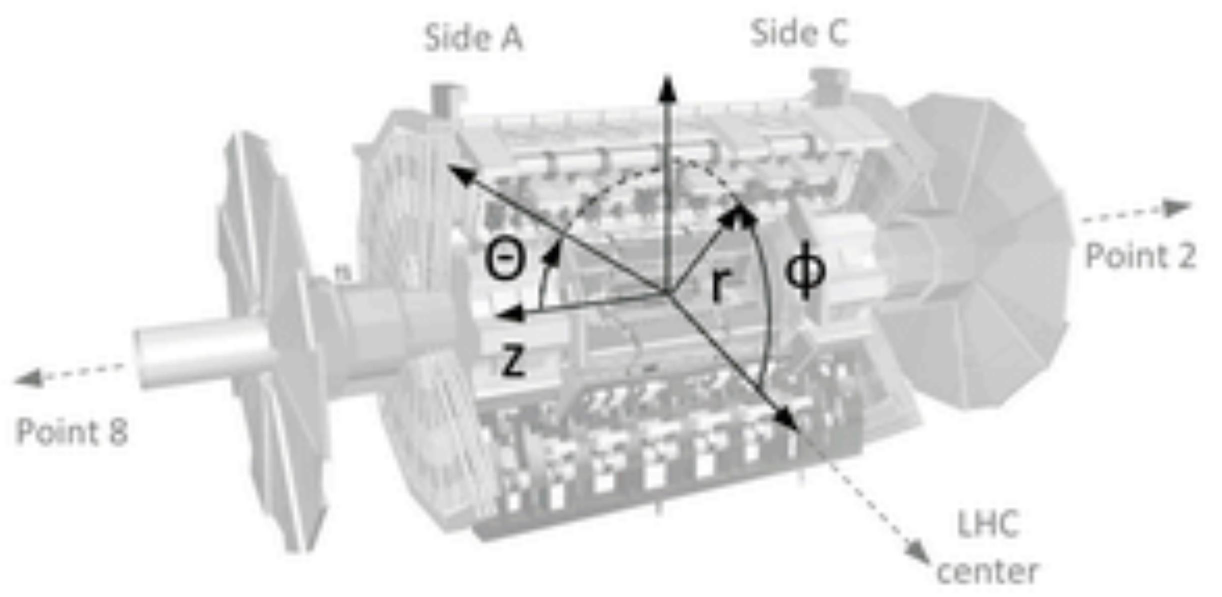
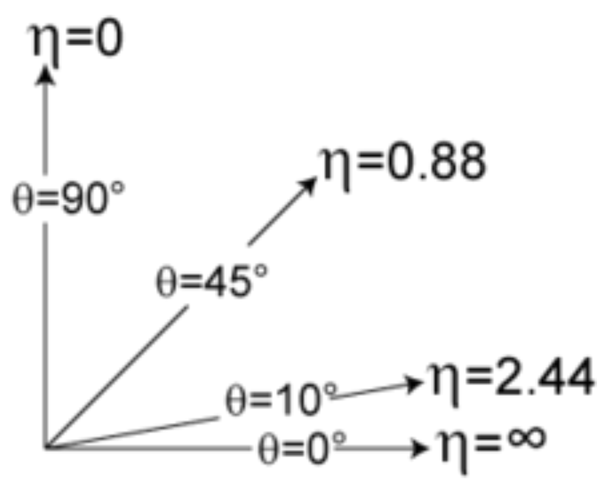


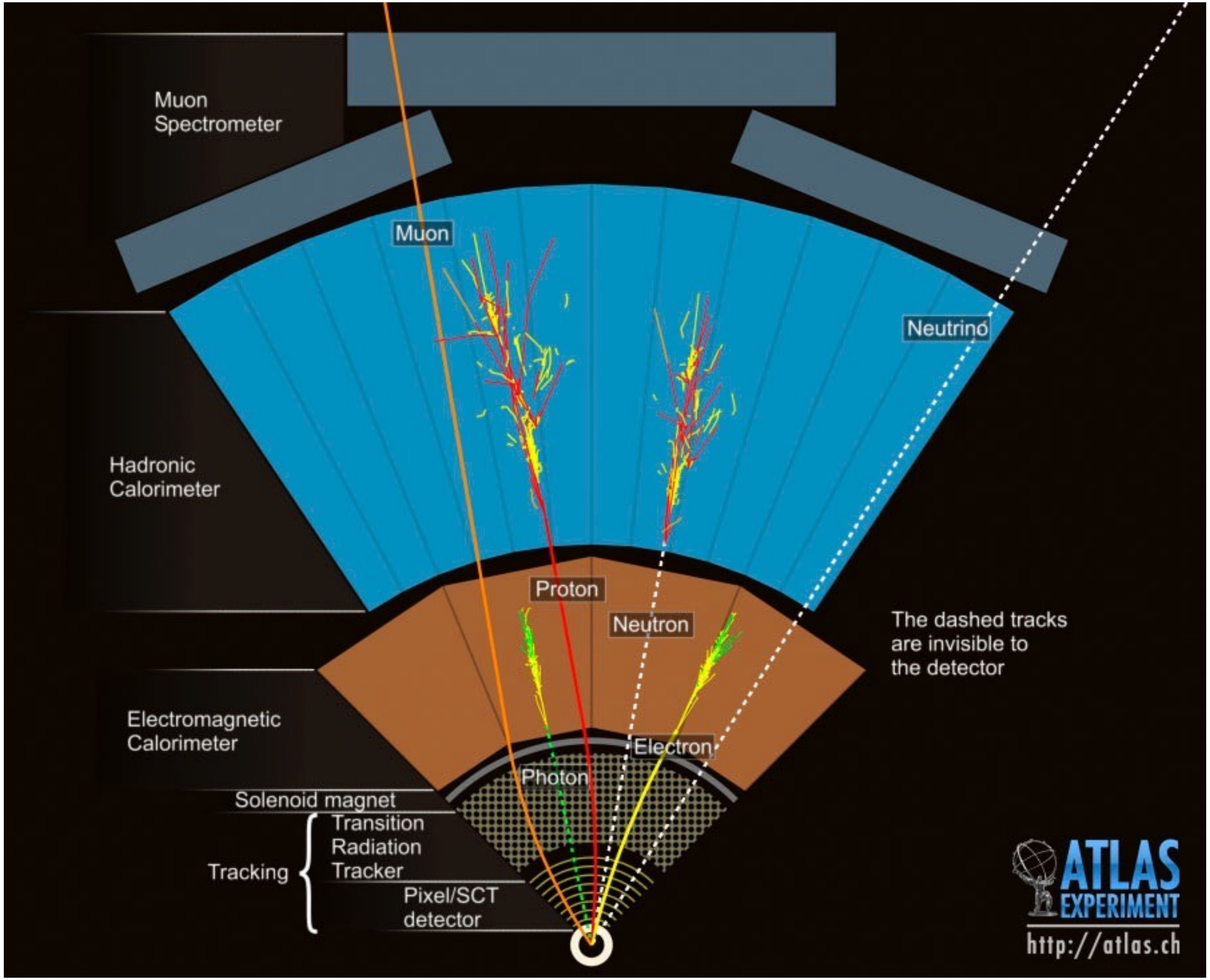


- ~100M readout channels
- 100kHz readout (~1.5 MB/event)
  - 1 kHz to disk
- 'Textbook' like multi purpose detector
- ATLAS coordinate system:
  - η = -ln tan(θ/2), ϕ



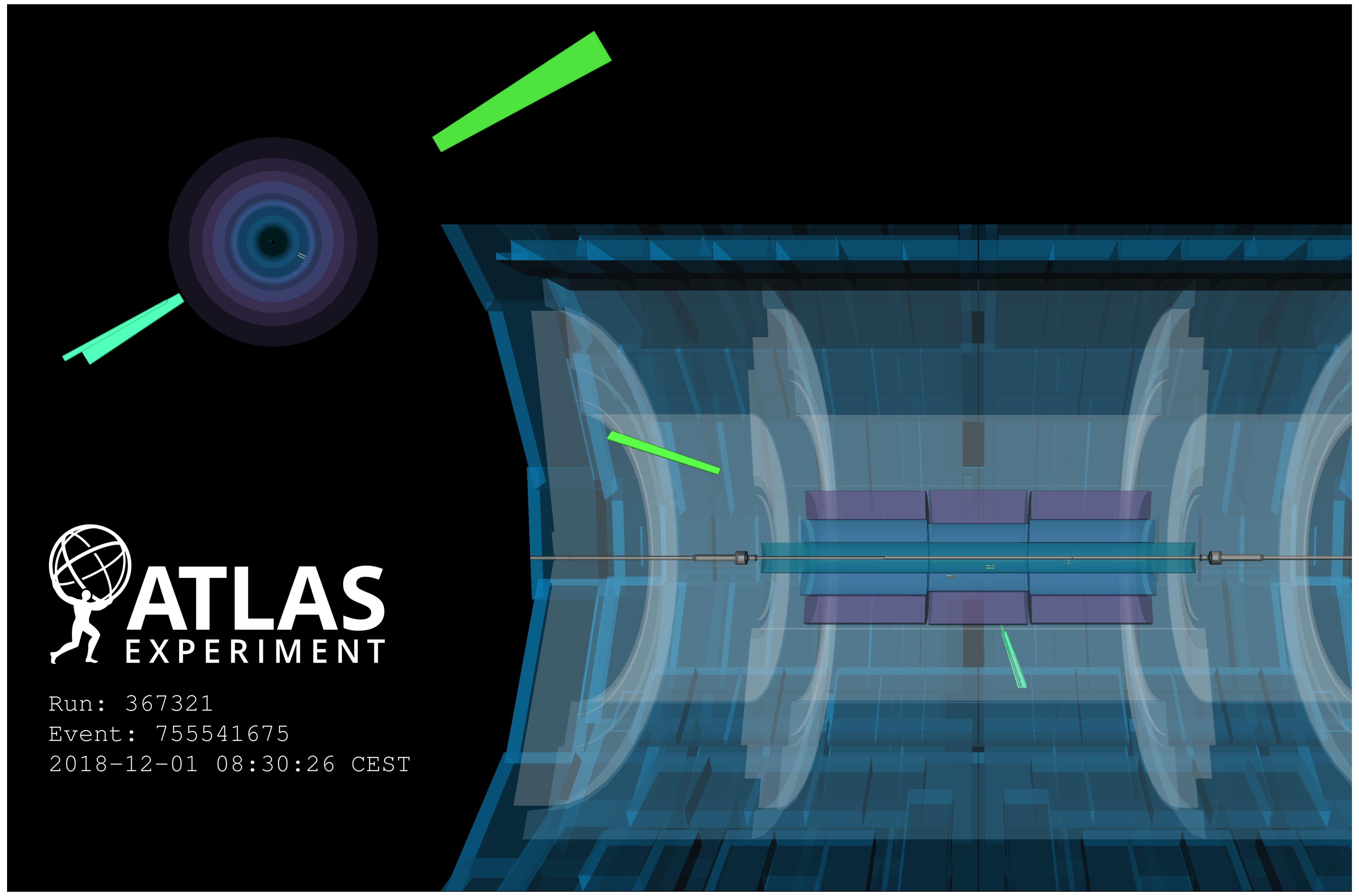
r-ϕ-z cylindrical coordinates and Θ - visualization



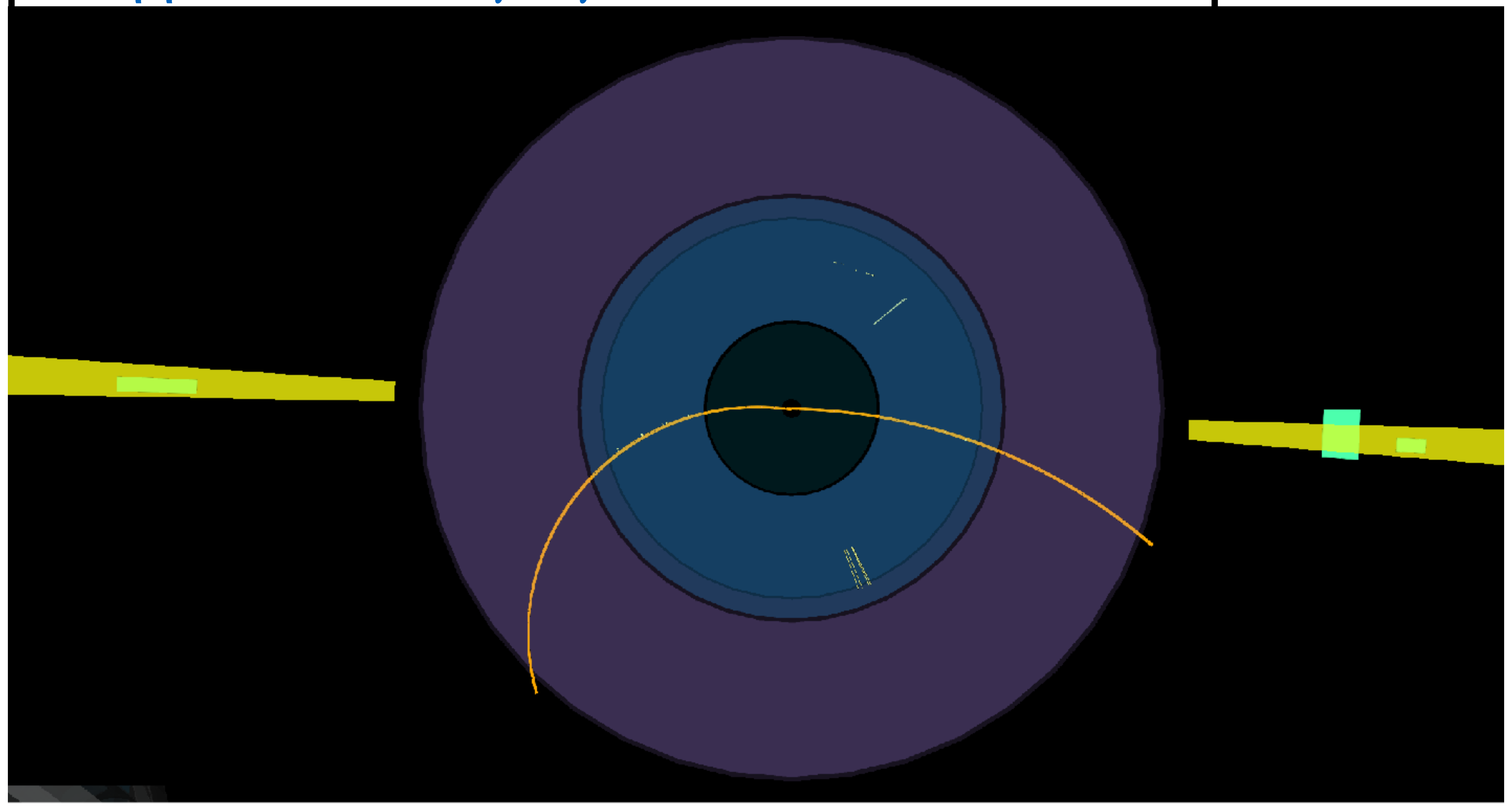


Event Selection

- Trigger
- Exactly 2 photons with $E_T > 2.5$ GeV && $|\eta| < 2.37$
  Excluding $1.37 < |\eta| < 1.52$
- Invariant di-photon mass $M_{\gamma\gamma} > 5$ GeV
- Veto any extra particle activity within $|\eta| < 2.5$
  - No reconstructed tracks ($p_T > 100$ MeV)
  - No reconstructed pixel tracks ($p_T > 50$ MeV, $|\Delta\eta\ (\gamma,\text{track})| < 0.5$)
- Back-to-Back topology
  - $p_T(\gamma\gamma) < 2$ GeV (rejects cosmic muons)
  - Reduced acoplanarity < 0.01 ($A_\phi = 1 - |\Delta\phi| / \pi$)



$\eta\eta \rightarrow e^+e^- \rightarrow e\gamma\ e\gamma$ candidate event:

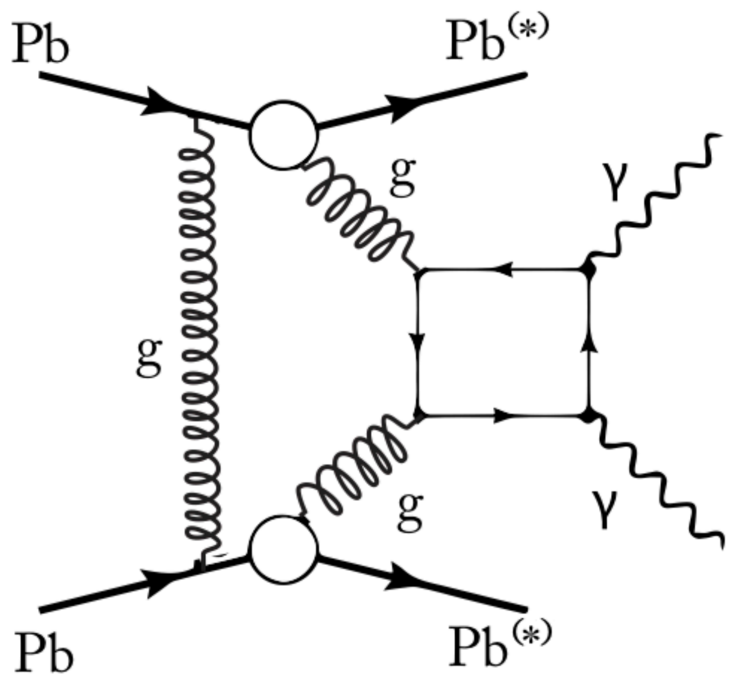


Background estimation & systematics on LbyL

Background to photon photon scattering

- **What else has a similar signature?**

- Central Exclusive Production of 2 photons (**CEP**): gg → $\gamma\gamma$
  - Coloured initial state: significant intrinsic transverse momentum!
    - Broader shape of **A_ϕ distribution**
    - Control region defined to study CEP: aco > 0.01



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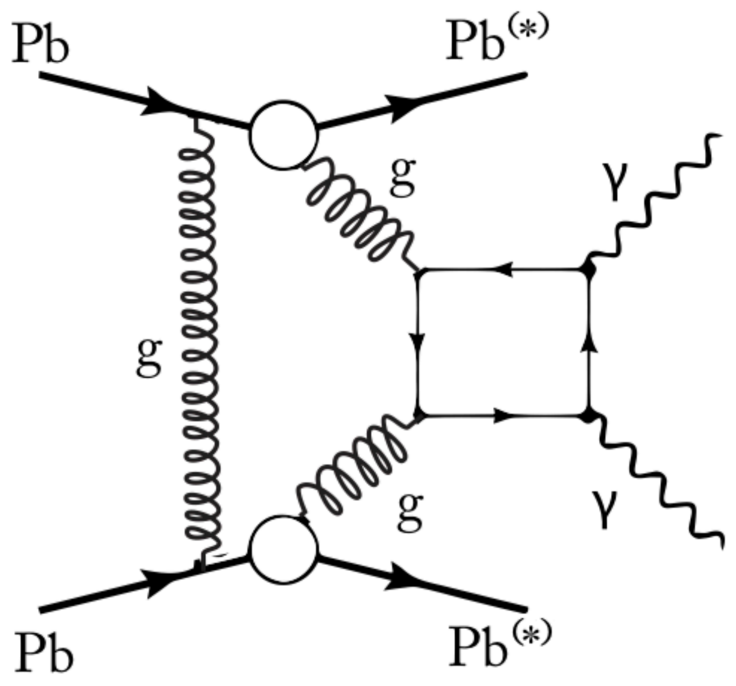

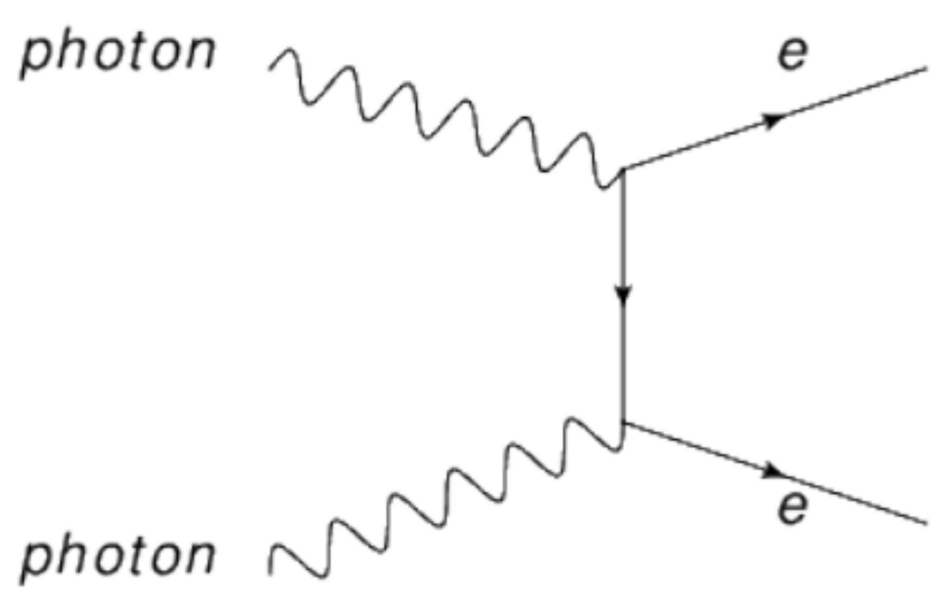

- Exclusive production of e^+e^- electron pairs
  - Both electrons misidentified as photons
  - Electrons bent in magnetic field
    - Broader $\mathbf{A_\phi}$ **distribution** compared to signal

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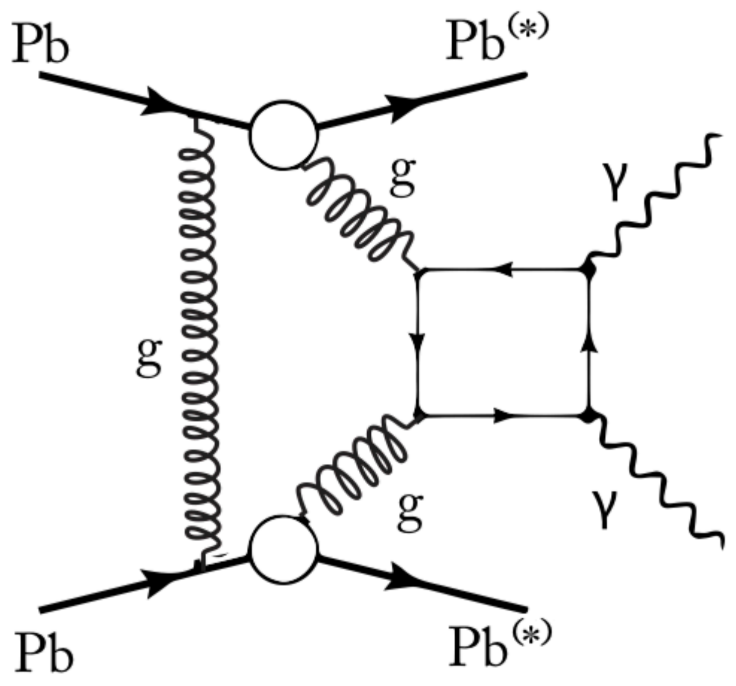
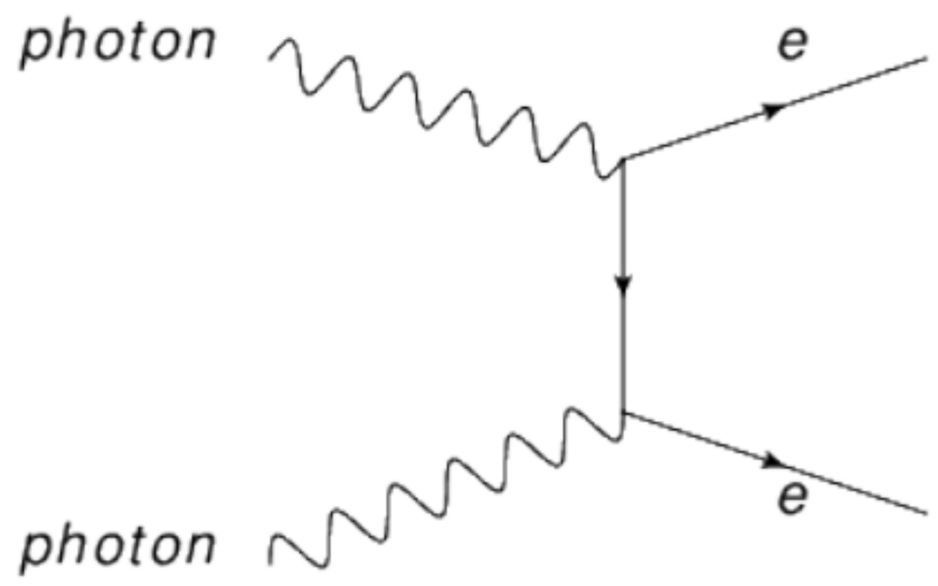
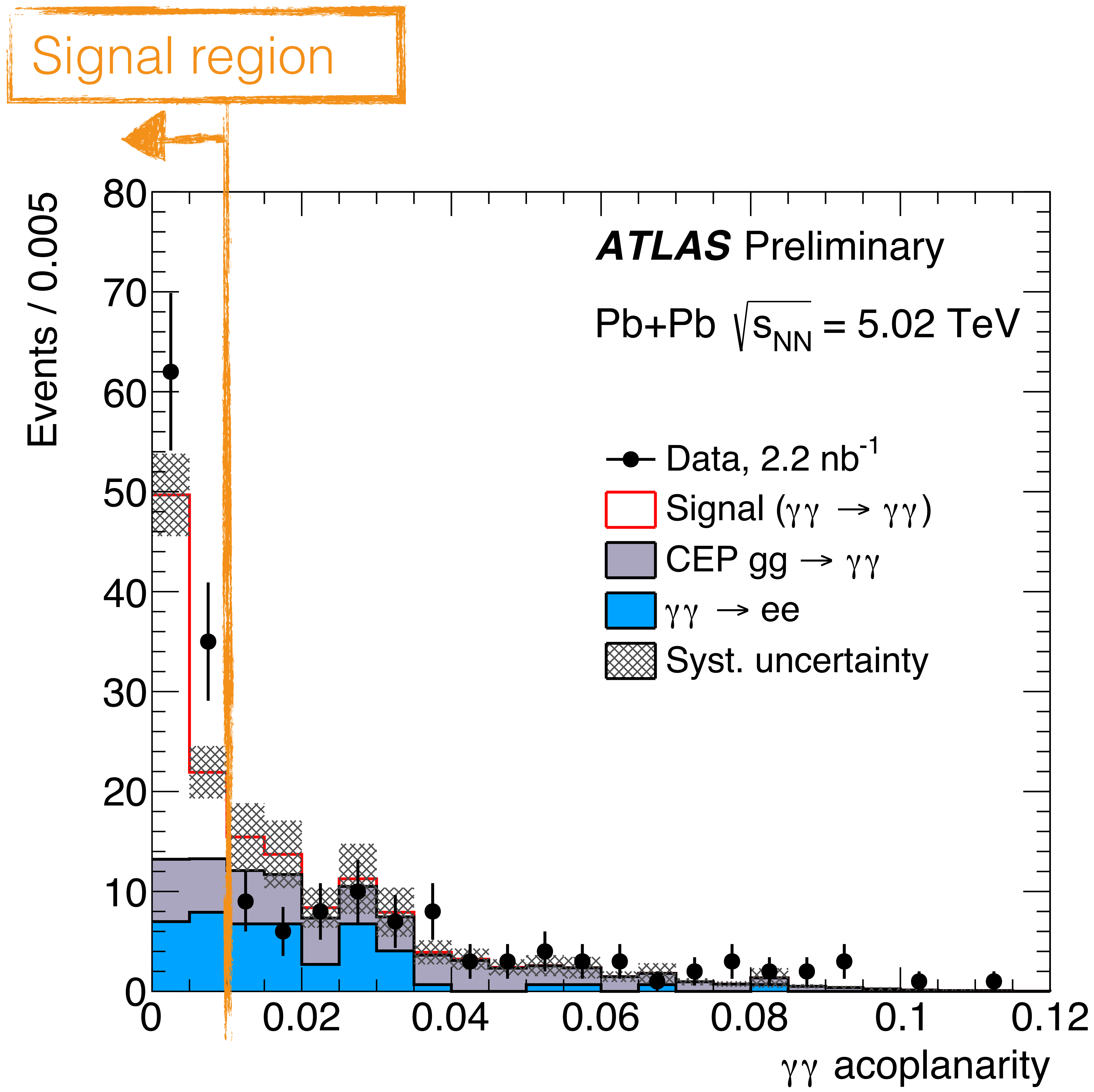
- Other potential backgrounds found to be negligible:
  - $\gamma\gamma \to$ qq
  - Exclusive di-meson production (pi0, eta, eta')
    - Also charged mesons considered
  - Bottomonia: $\gamma\gamma \to \eta_b \to \gamma\gamma$ (σ ~1 pb)
  - Fake photons: Cosmic rays, calorimeter noise







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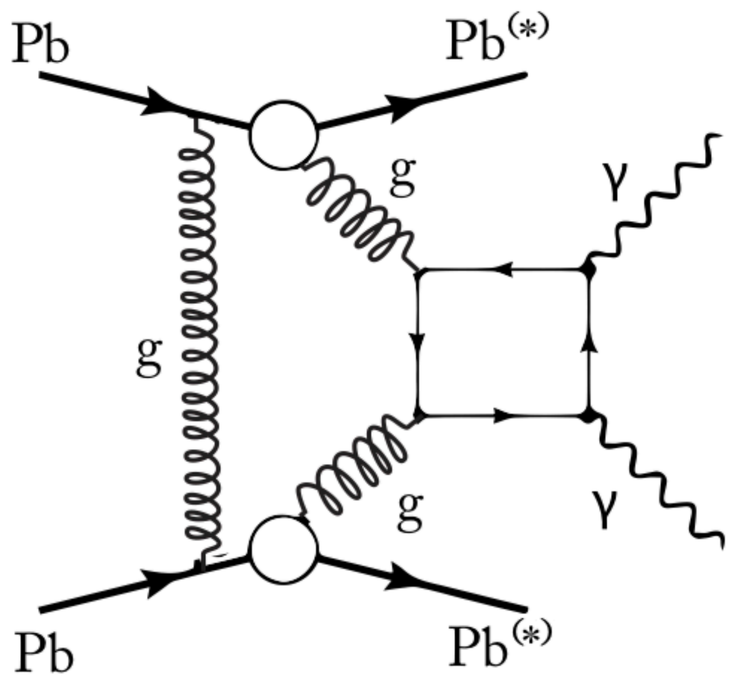

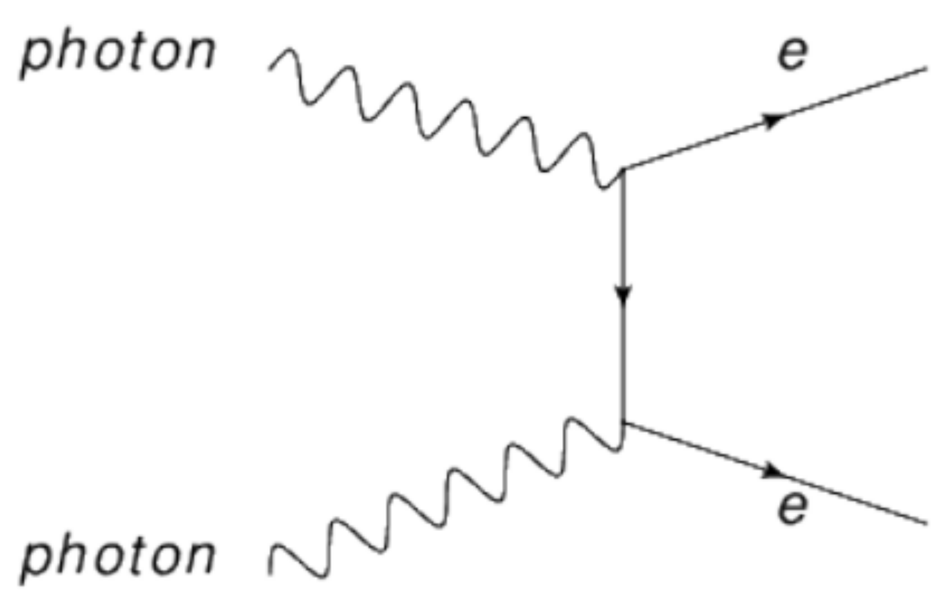

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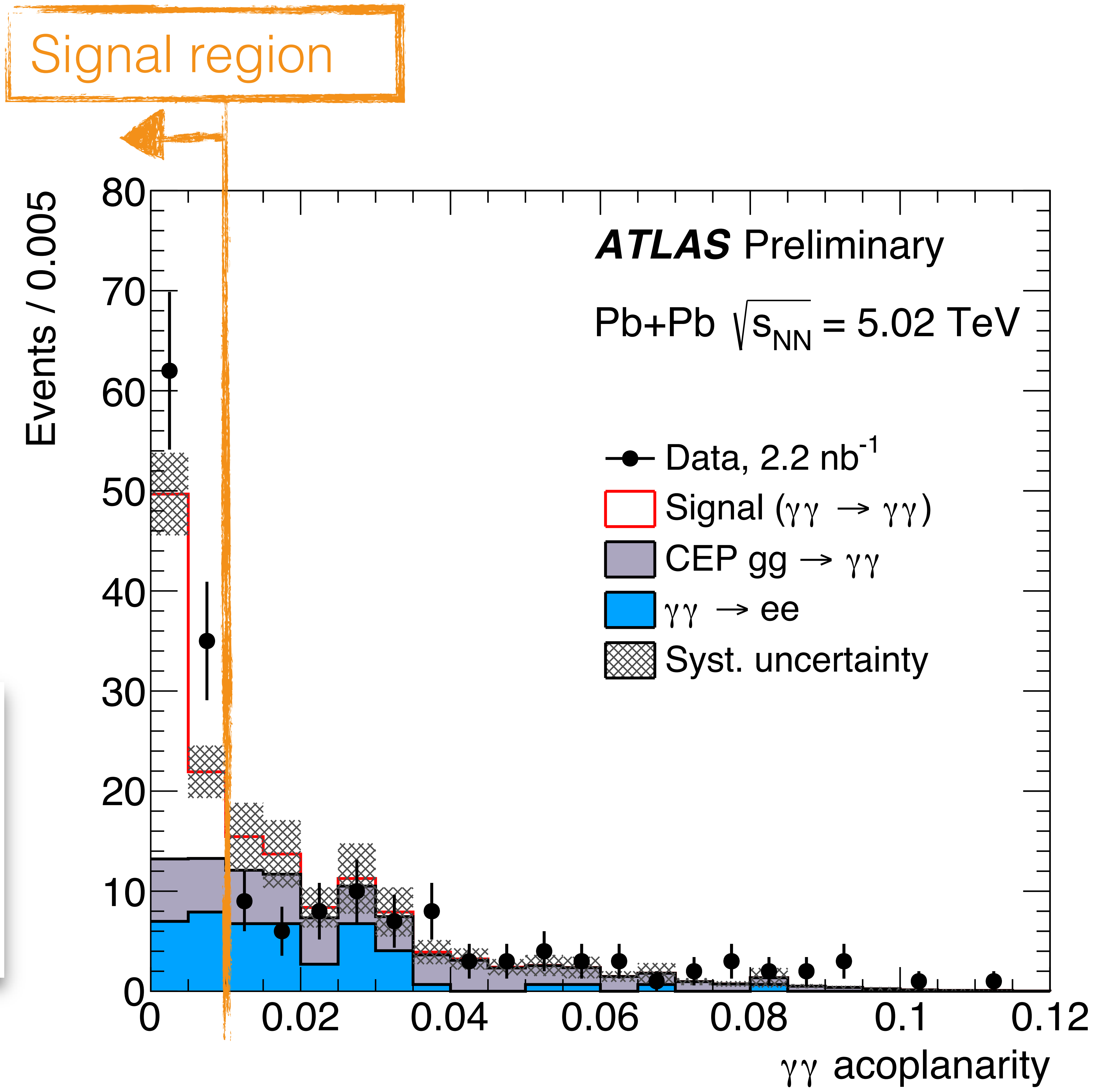

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  - Fake photons: Cosmic rays, calorimeter noise

No background produces peak in mass distribution!

Triggering

- L1 requirements
  - Dedicated trigger for 2018 run (OR):
    - ≥ 1 EM cluster with $E_T(\gamma) > 1$ GeV && 4 GeV < total E_T < 200 GeV
    - ≥ 2 EM clusters with $E_T(\gamma) > 1$ GeV && total E_T < 50 GeV

  (Note: **Cluster Noise** just below 1 GeV)

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  - **no forward activity:** ΣE_T (FCal) < 3 GeV on both sides
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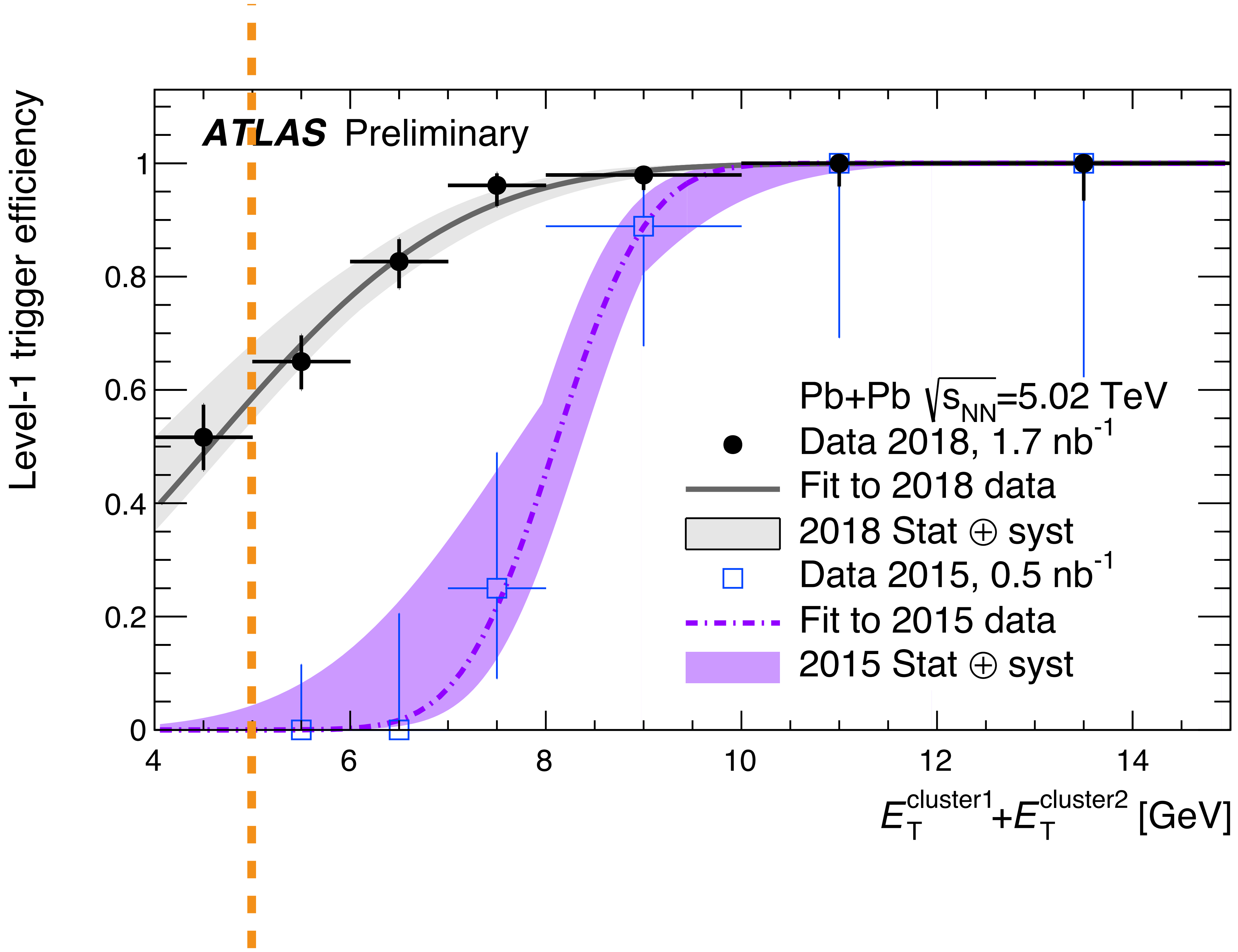

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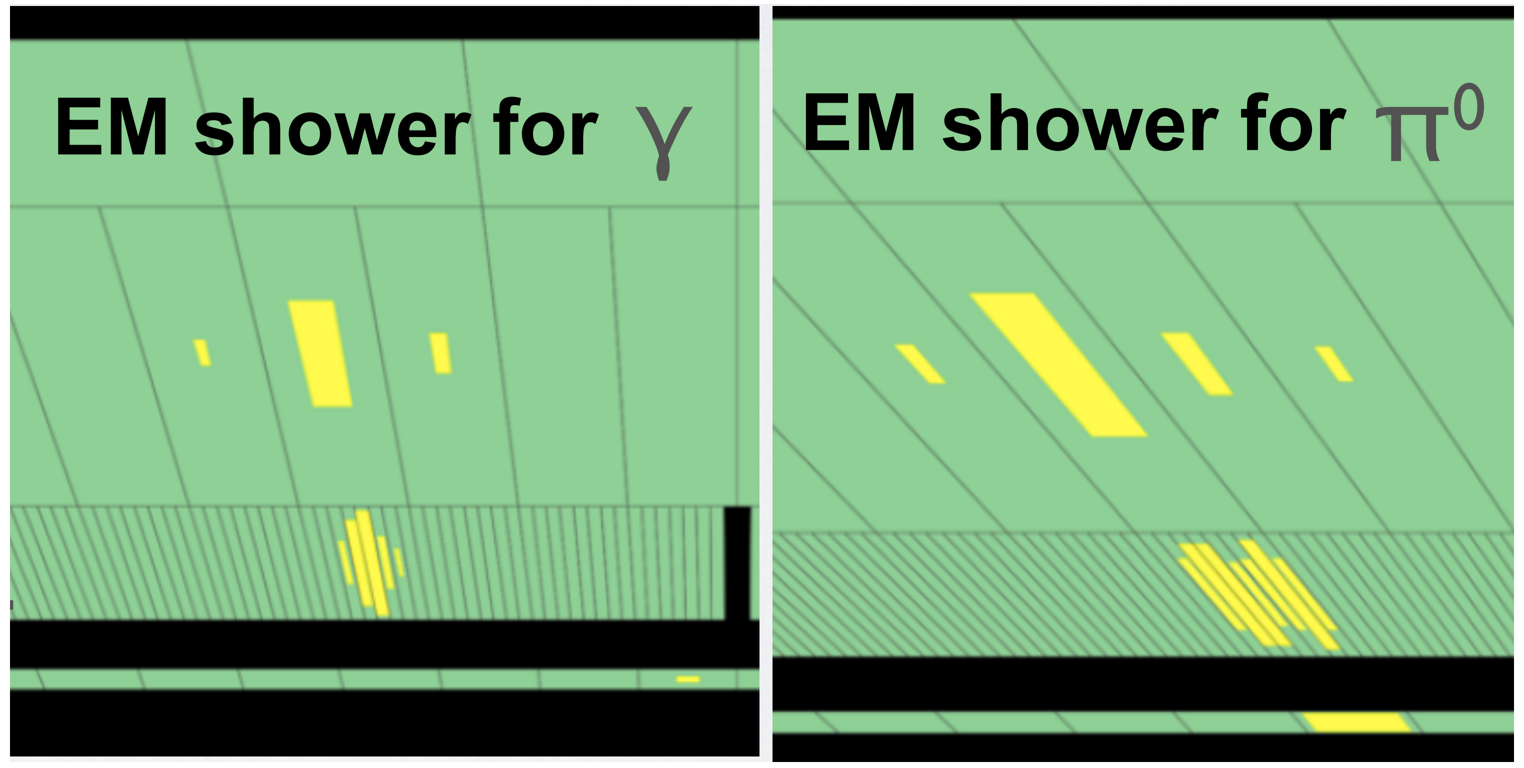
  - Tagging of exclusive photon final state

- Trigger efficiency determined using e^+e^- final states
  - Triggered by independent support triggers

Photon reconstruction and identification

- Photon reconstruction:
  - Using default photon reconstruction algorithm
    - Entries in calorimeter cells are grouped to clusters
    - Track matching performed
      - ➡ Electrons / Photons
      - Some overlap allowed



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  - Uses neural net (Keras), trained for low E_T photons
  - Combination of EM calorimeter shower shape variables
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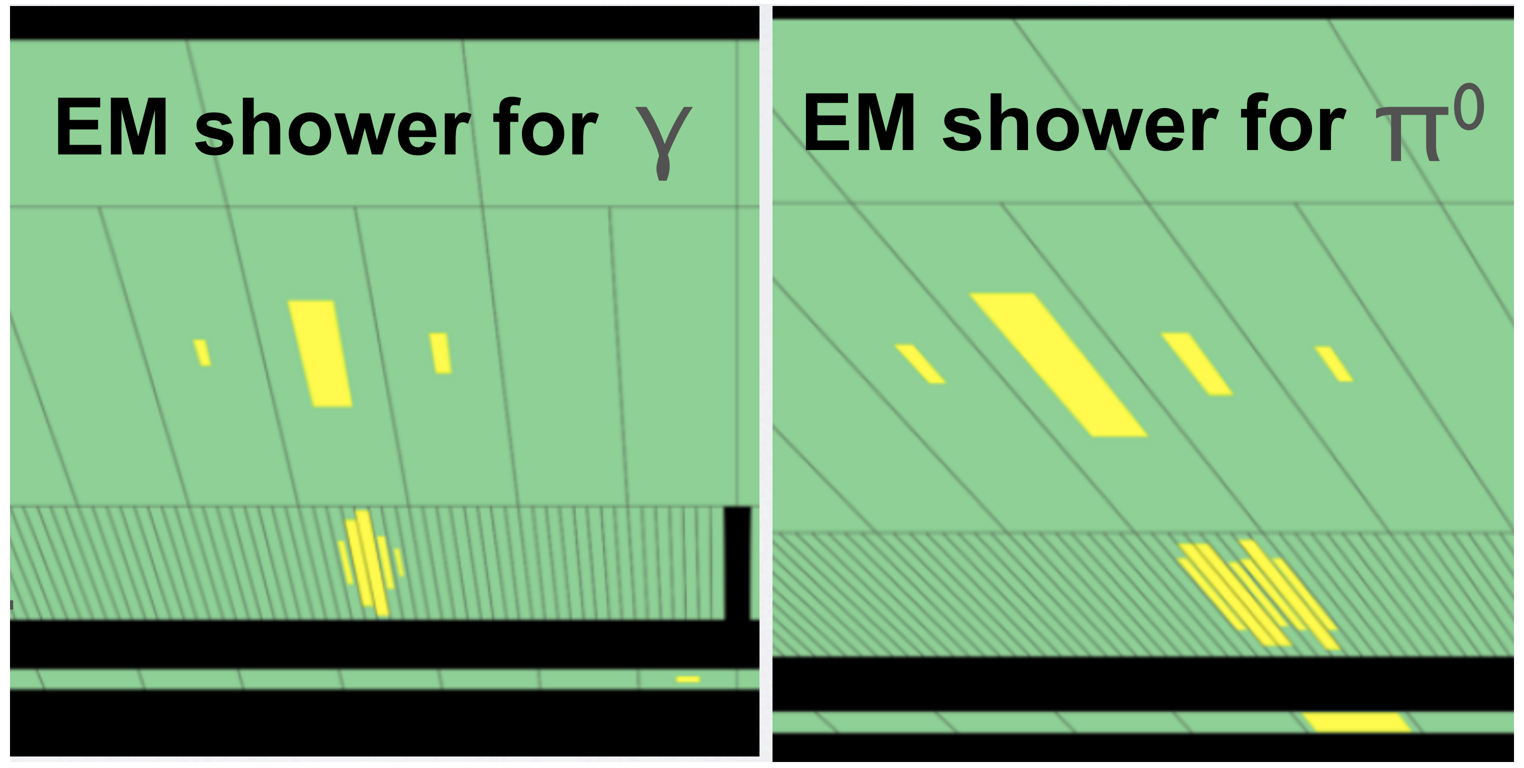

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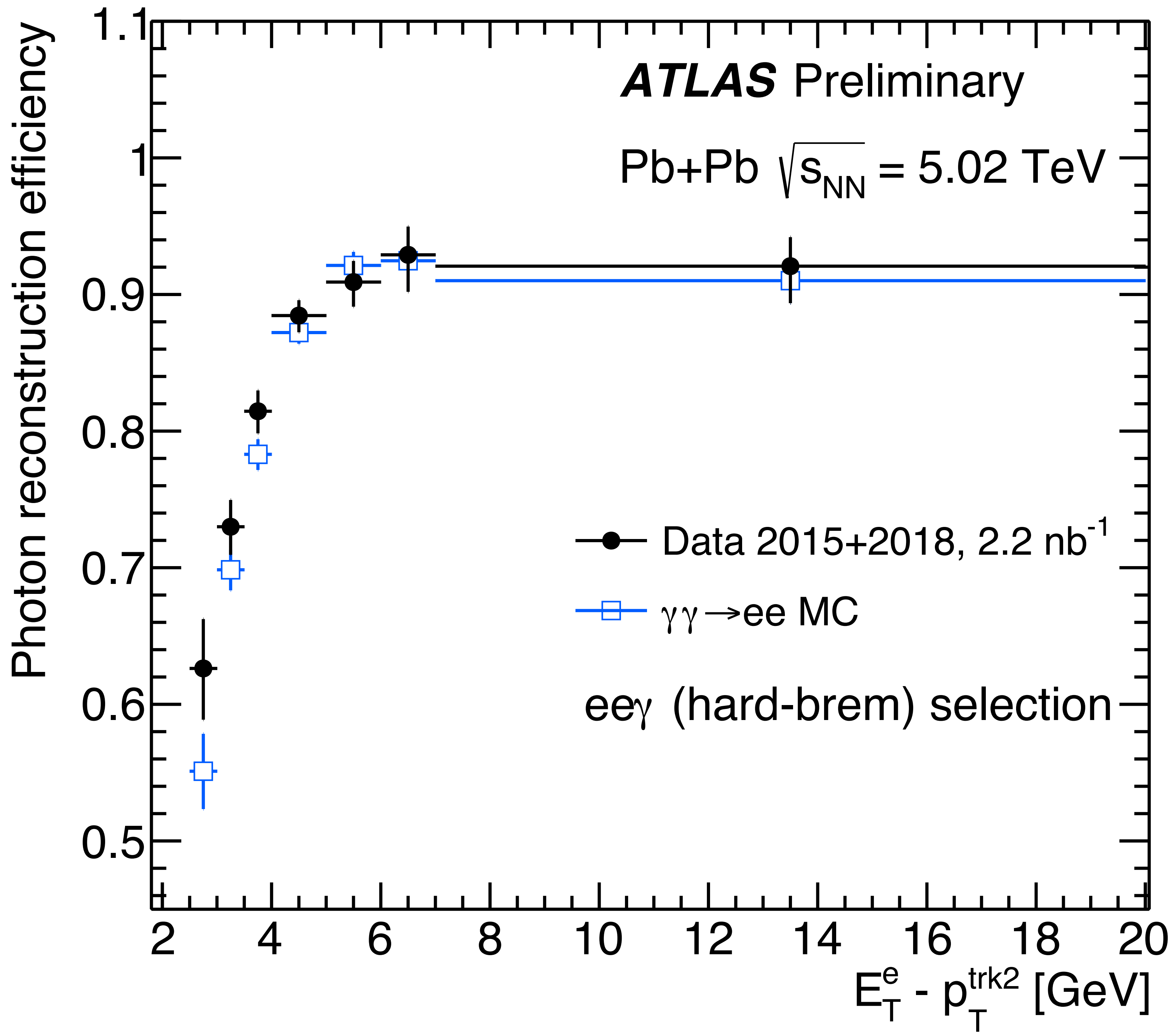
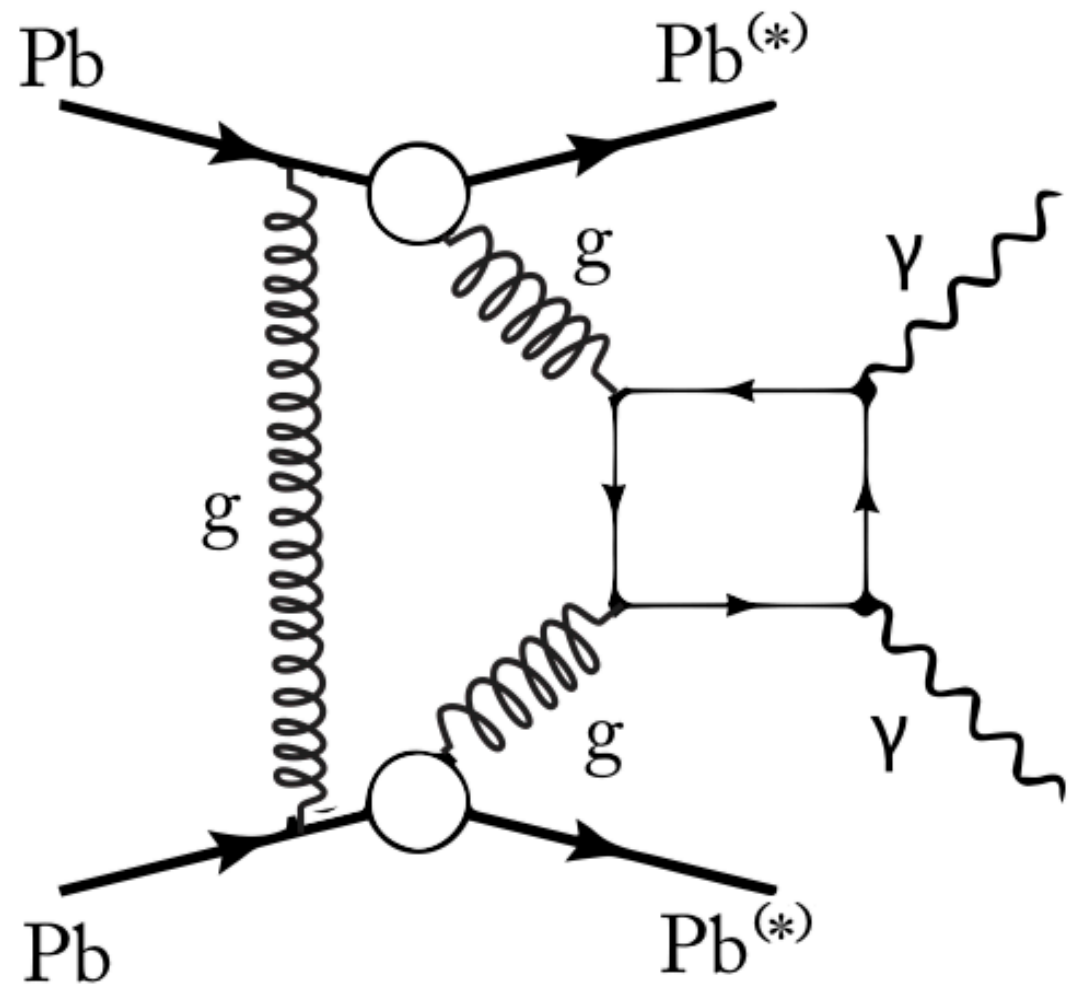


- Efficiency measurement:
  - Using e^+e^- events where a hard bremsstrahlung photon was radiated
  - $ee\gamma$ final state selection:
    - Exactly 1 electron p_T > 4 GeV && 1 additional track
    - Track p_T < 1.5 GeV
      - Photon with E_T > 2.5 GeV must be present in Event!

Background processes

- **What else has a similar signature?**

- Central Exclusive Production of 2 photons (**CEP**): gg → $\gamma\gamma$
  - Coloured initial state: significant intrinsic transverse momentum!
    - Broader shape of A_ϕ distribution
    - Control region defined to study CEP: aco > 0.01
- Shape of A_ϕ distribution taken from simulation (SuperChic v3.0)
    - Uncertainty estimated using simulation without secondary particle emission (absorptive effects)
- Normalisation measured in control region
    - Dominating uncertainty form limited statistics (17%)
- Overall uncertainty of CEP background in signal region: 25%
- Expected events in signal region: 12 ± 3



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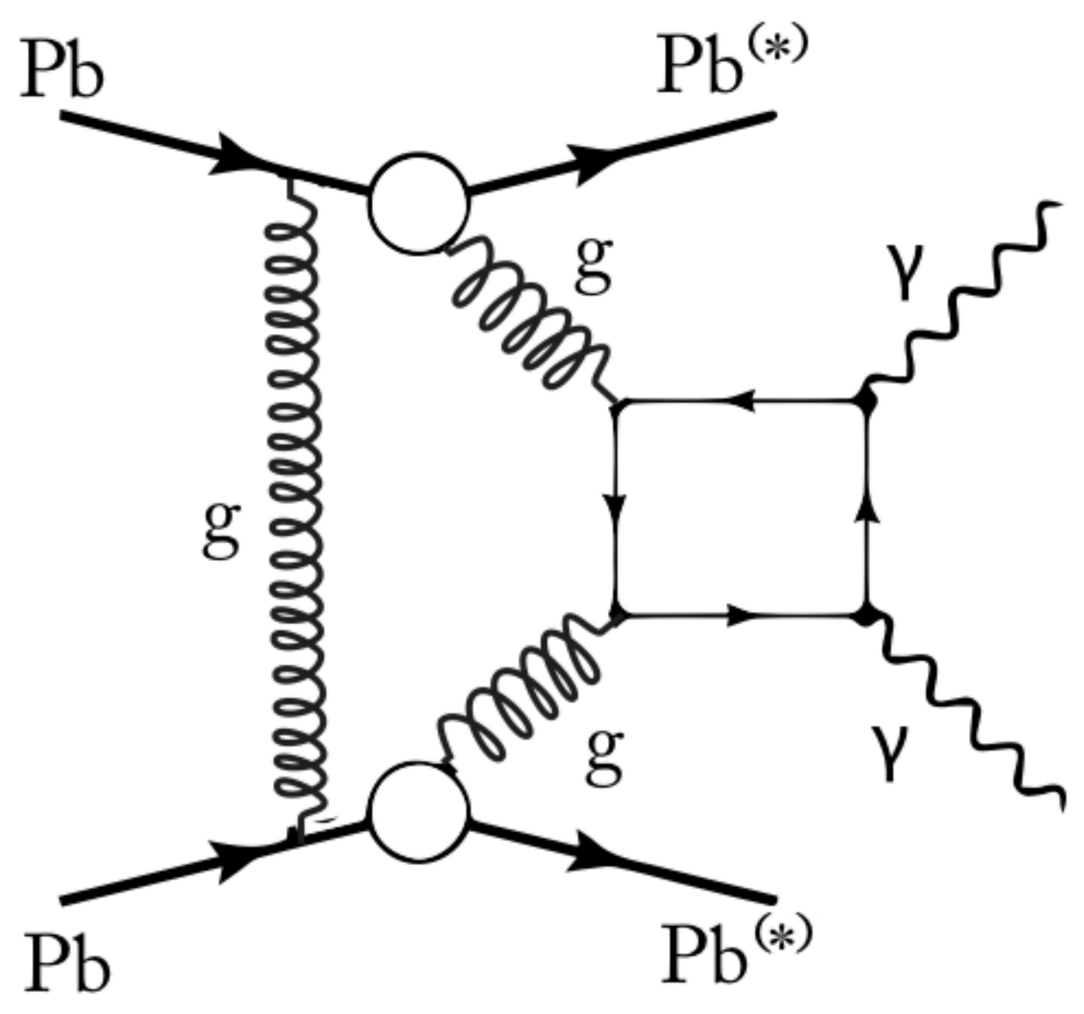

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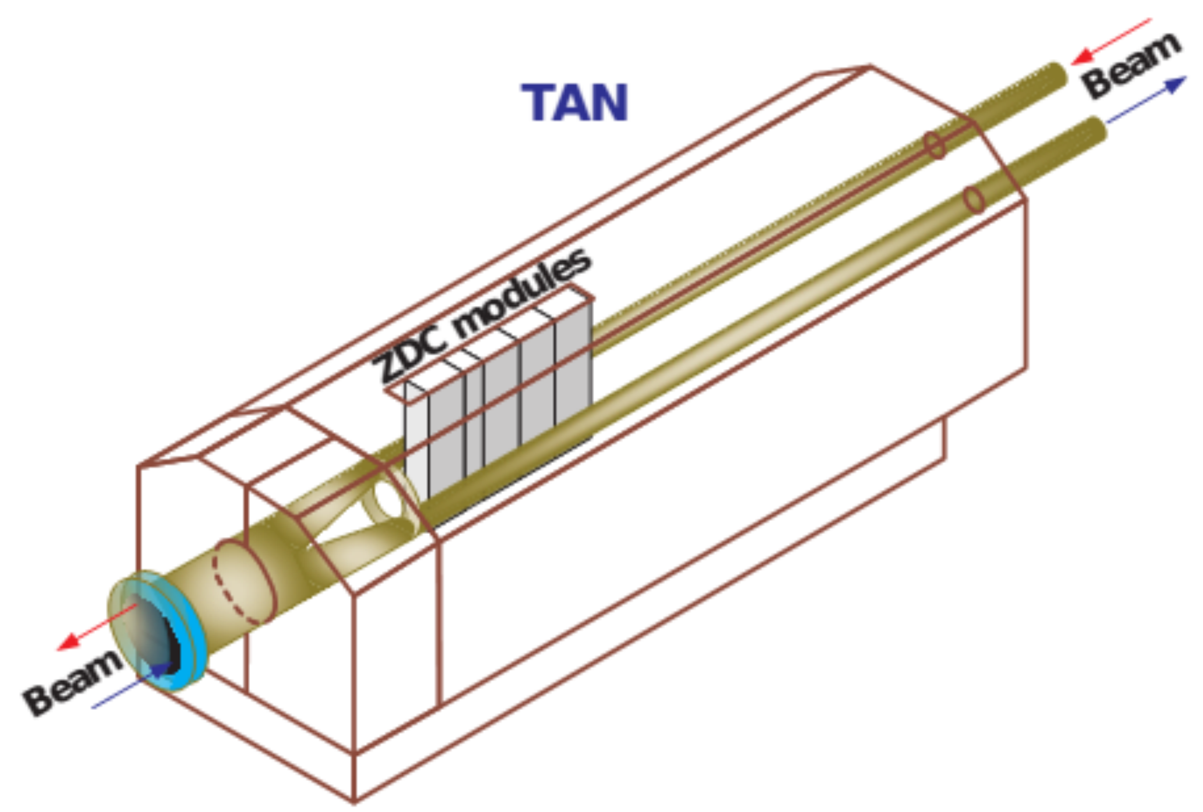
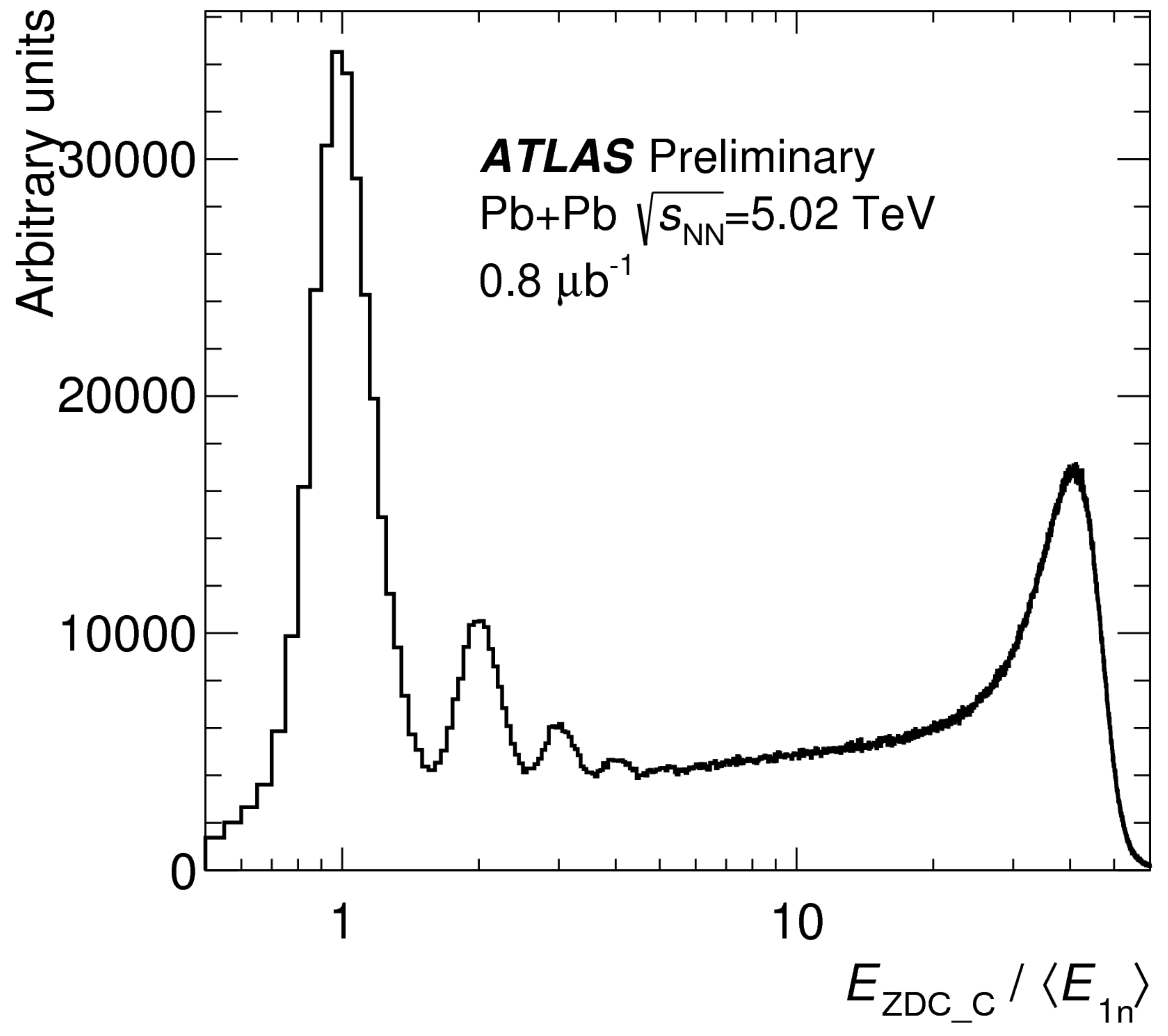
- Pb* dissociates, releasing neutrons detectable in the Zero Degree Calorimeter
  - Cross check of ZDC information for events in CEP control region:
    - Good agreement with expectations :)



- ± 140m from ATLAS IP
- $8.3 < |\eta| < \inf$

ZDC cross check on CEP background

- ZDC energy deposits
  - Single neutron peaks clearly visible



- More quantitatively
  - Expected that all CEP events have a signal in ZDC
  - 20% of yy and ee final states
  - Can calculated expected ratio of events with / without ZDC activity

$$r^{\text{pred}}_{\text{ZDC/noZDC}} \approx \frac{\text{CEP} + 0.2 * (\text{signal} + ee)}{0.8 * (\text{signal} + ee)}$$

- For E_T > 3 GeV:
  - r(pred.) = 1.5(0.5), r(meas) = 0.8

- To compensate difference:
  - Raise in the ee background yield of 20% needed
  - Well covered by uncertainty of 40%

Background processes

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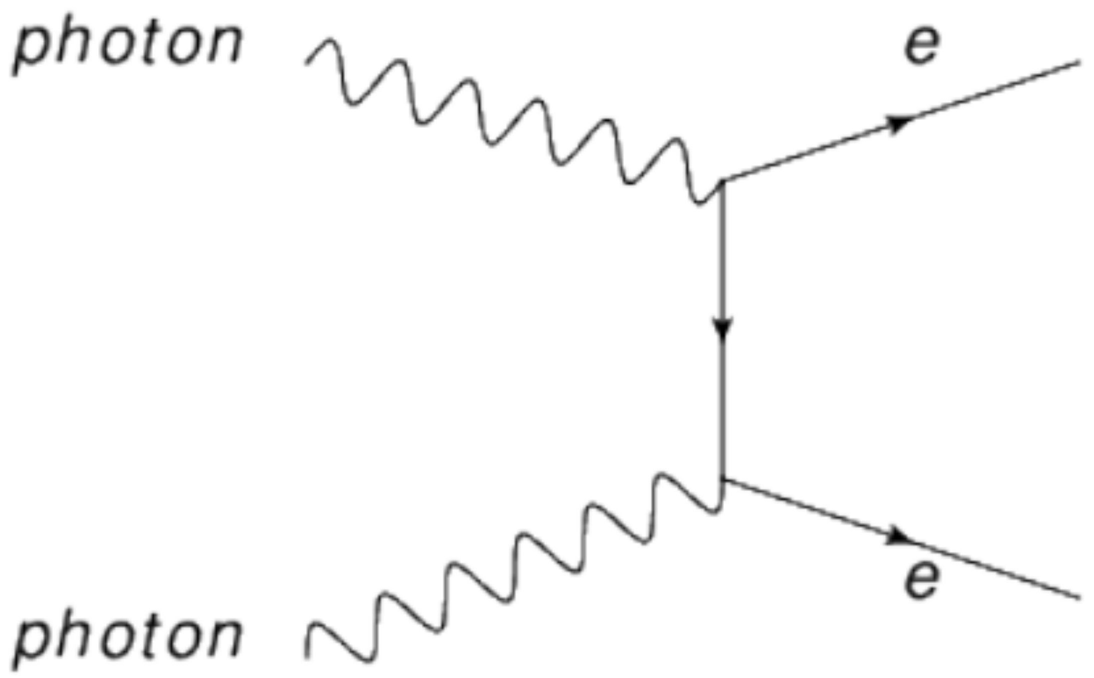
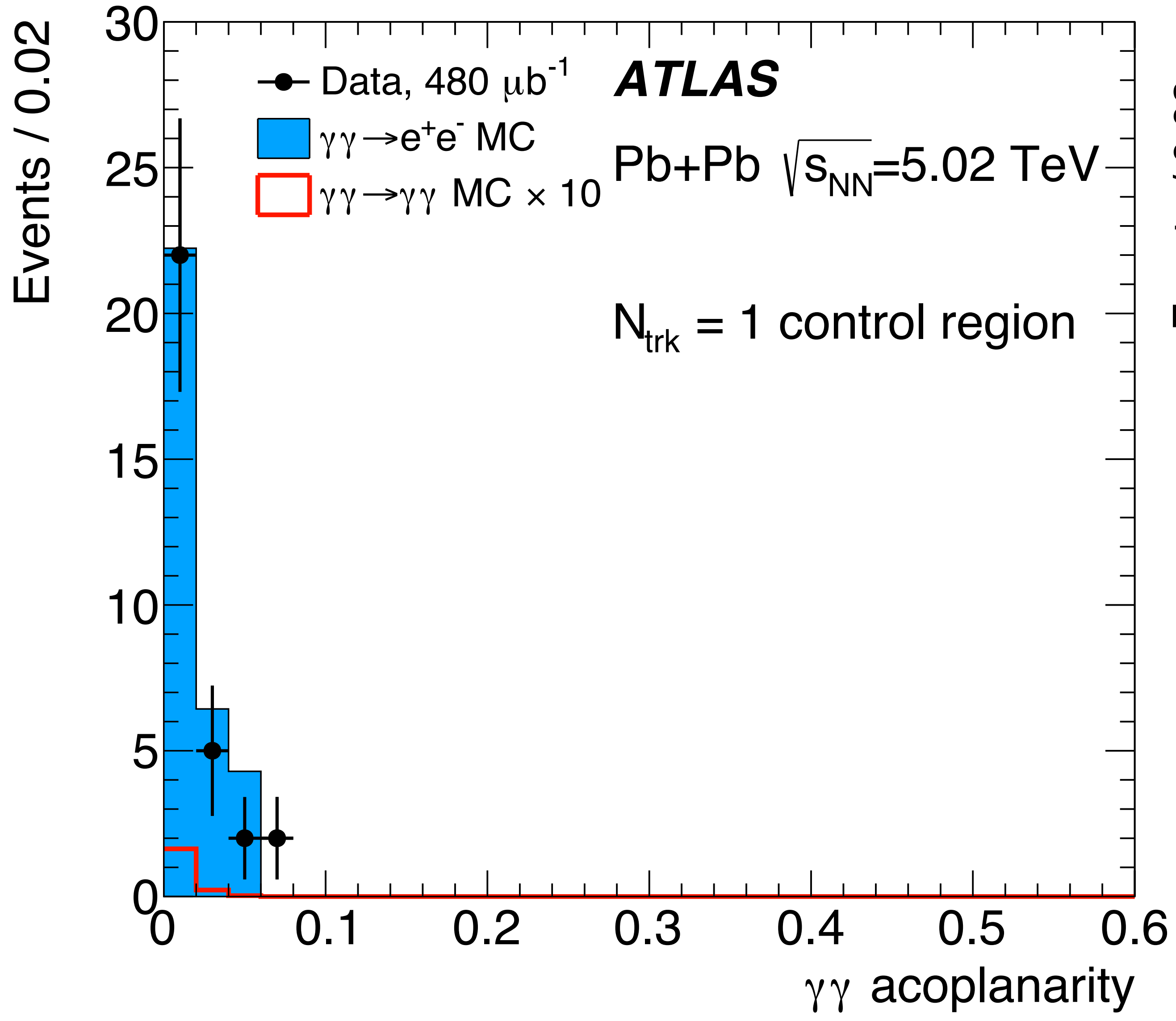
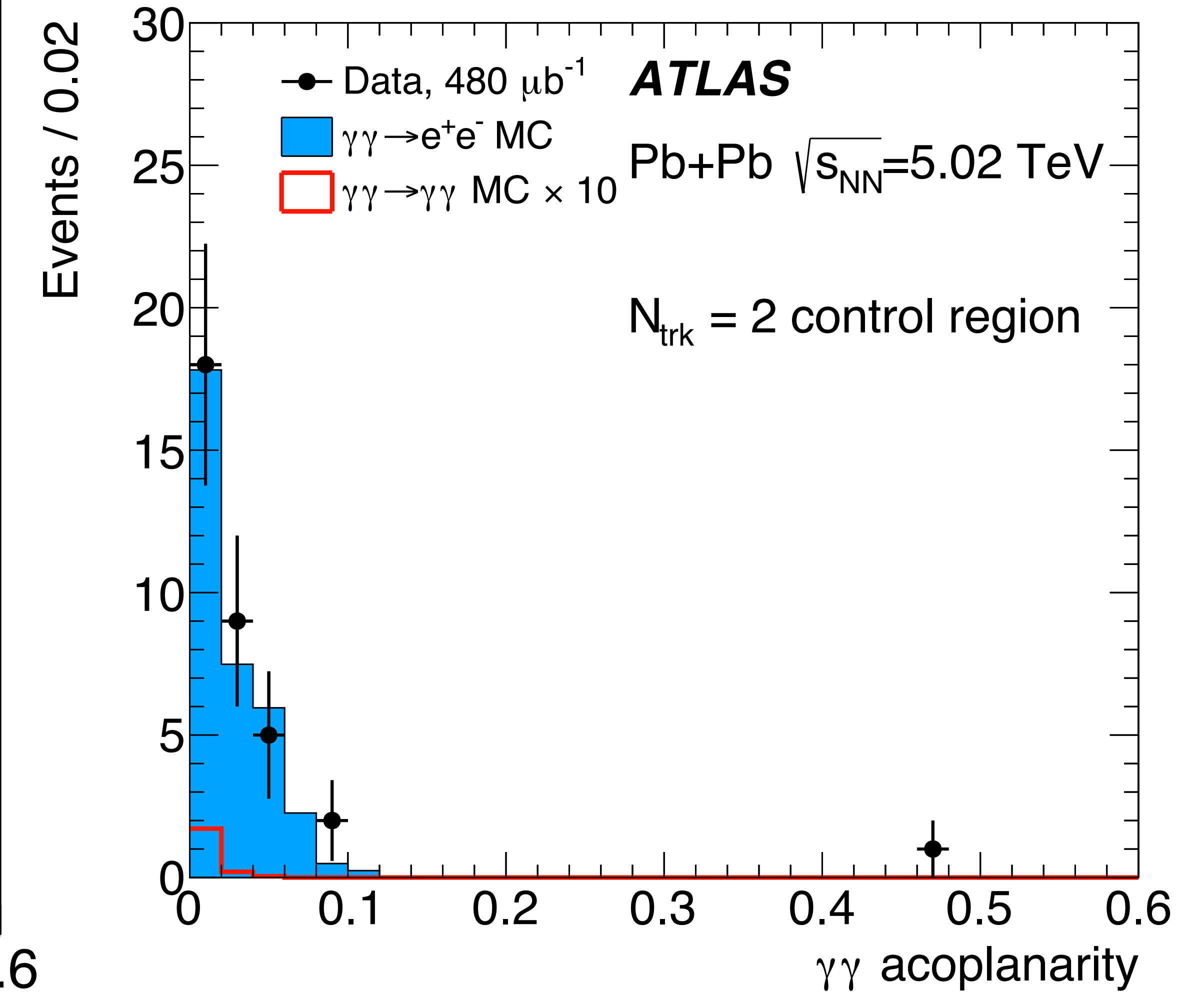


- Exclusive production of e^+e^- electron pairs
  - Both electrons misidentified as photons
- Electrons bent in magnetic field
  - Broader A_ϕ distribution compared to signal
- Background rate estimated from data
  - 2 control regions:
    - Signal region + requiring 1 or 2 associated pixel tracks
    - Event yield from control regions extrapolated to signal region
      - Needed: probability to miss pixel track if full track is not reconstructed p^e_{mistag}
    - p^e_{mistag} measured requiring 1 full track and exactly 2 signal photons: (47 ± 9)%
- Events in signal region: 15 ± 7

statistics, p^e_{mistag}, difference in CRs





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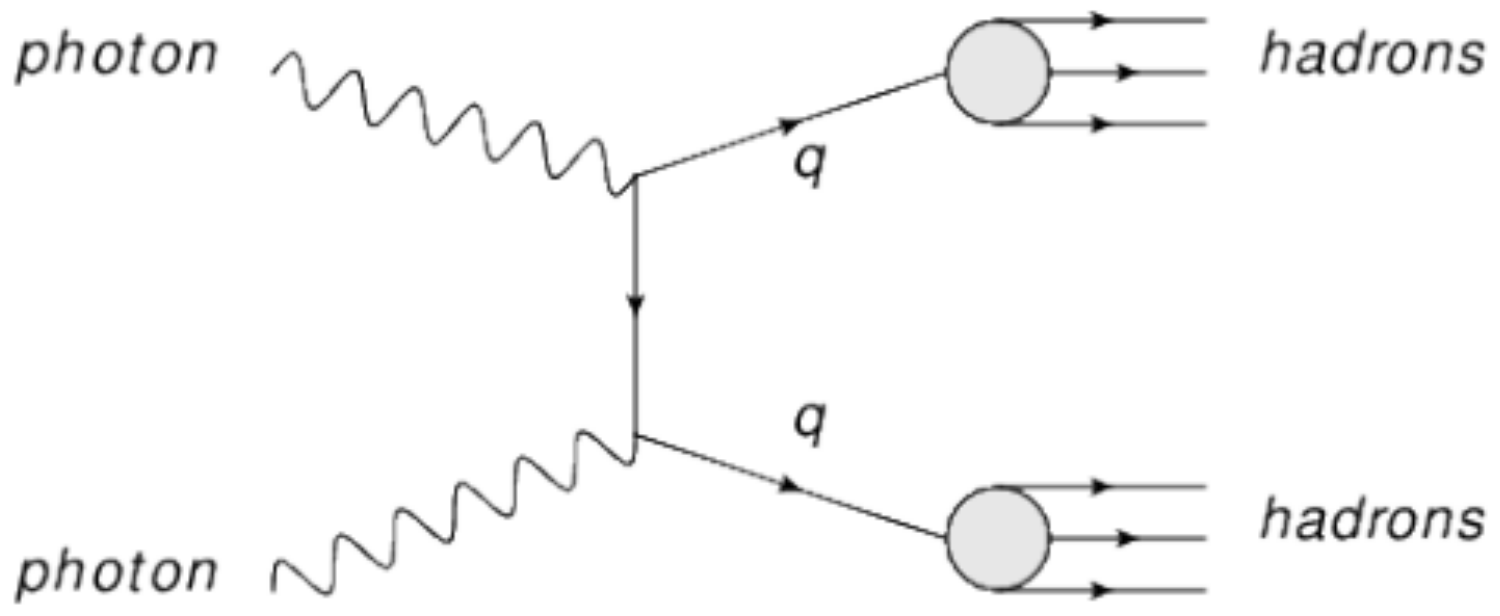
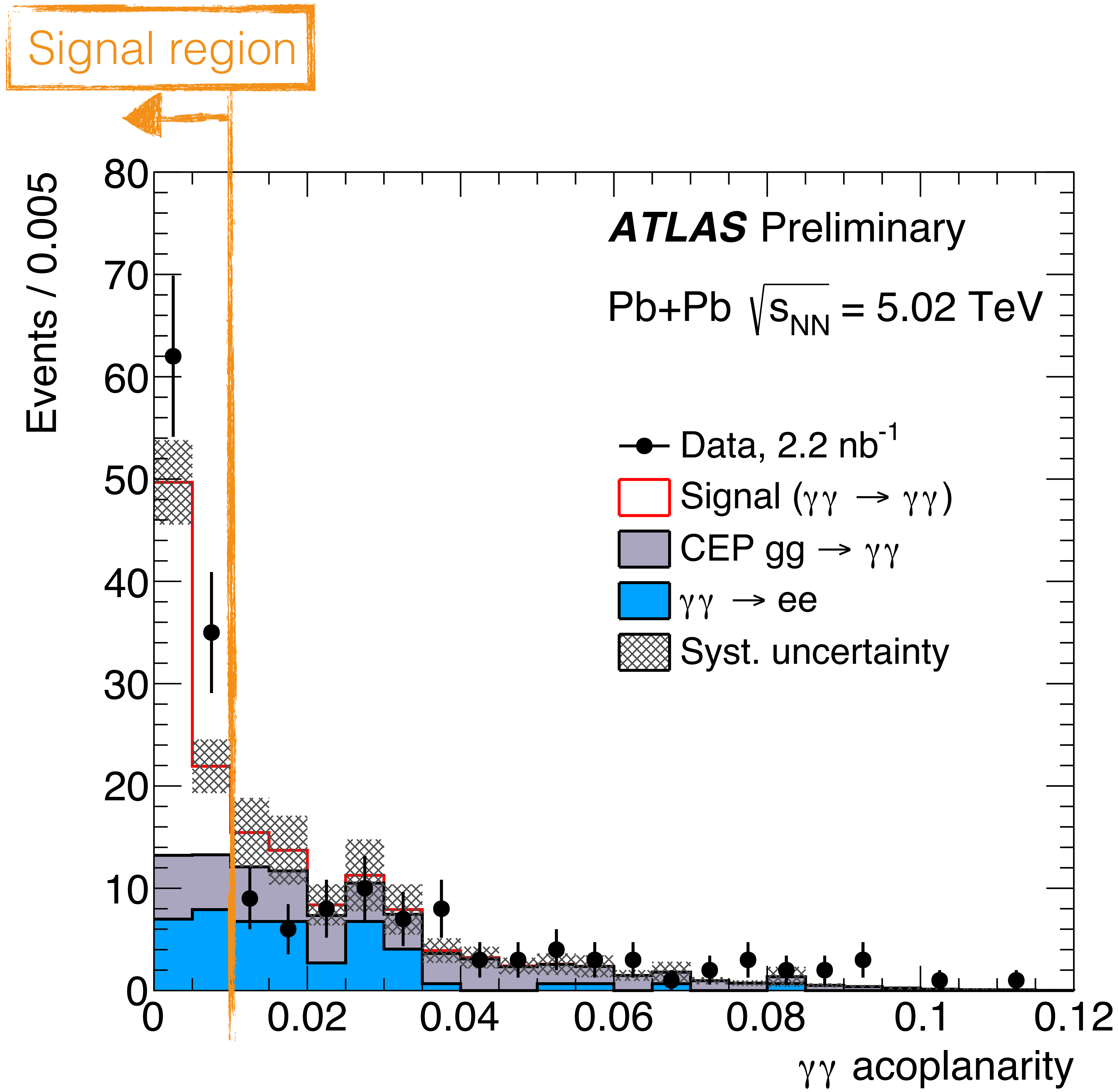


- **Total background + signal:**



Systematic Uncertainties

- Reco & PID SFs:
  - SFs derived in dependence of eta instead of p_T
    - Impact on measured C-factor taken as systematic unc.
    - **4% (Reco) 2% (PID)**
- Photon energy scale & resolution
  - Taken from EGamma-group recommendations
    - **1% and 2 %** impact on MC yields, for scale & resolution
- Angular resolution (in phi)
  - Comparing electron tracks to cluster in yy->ee events
  - Additional single cluster smearing in MC: $\sigma_\phi \approx 0.006$
    - Impact on CEP background: **1%**
    - Impact on SFs: **2%** (taken as systematic)

$$\sigma_{\phi^{\text{cluster}}} \approx \frac{(|\phi^{\text{cluster1}} - \phi^{\text{trk1}}| - |\phi^{\text{cluster2}} - \phi^{\text{trk2}}|)}{\sqrt{2}}$$

- Trigger
  - Three ee event selection criteria defined: loose, nominal, tight
    - Difference between those taken as systematic unc.
      - Max. Uncertainty: +10% -4% @ E_T(cluster sum) 5 GeV
      - **Overall: 5%**

- Alternative LbyL signal sample
  - Starlight instead of SuperChic
    - **1% impact on C**
  - Signal MC stats:
    - **1%**

- Uncertainty on total background: 28%

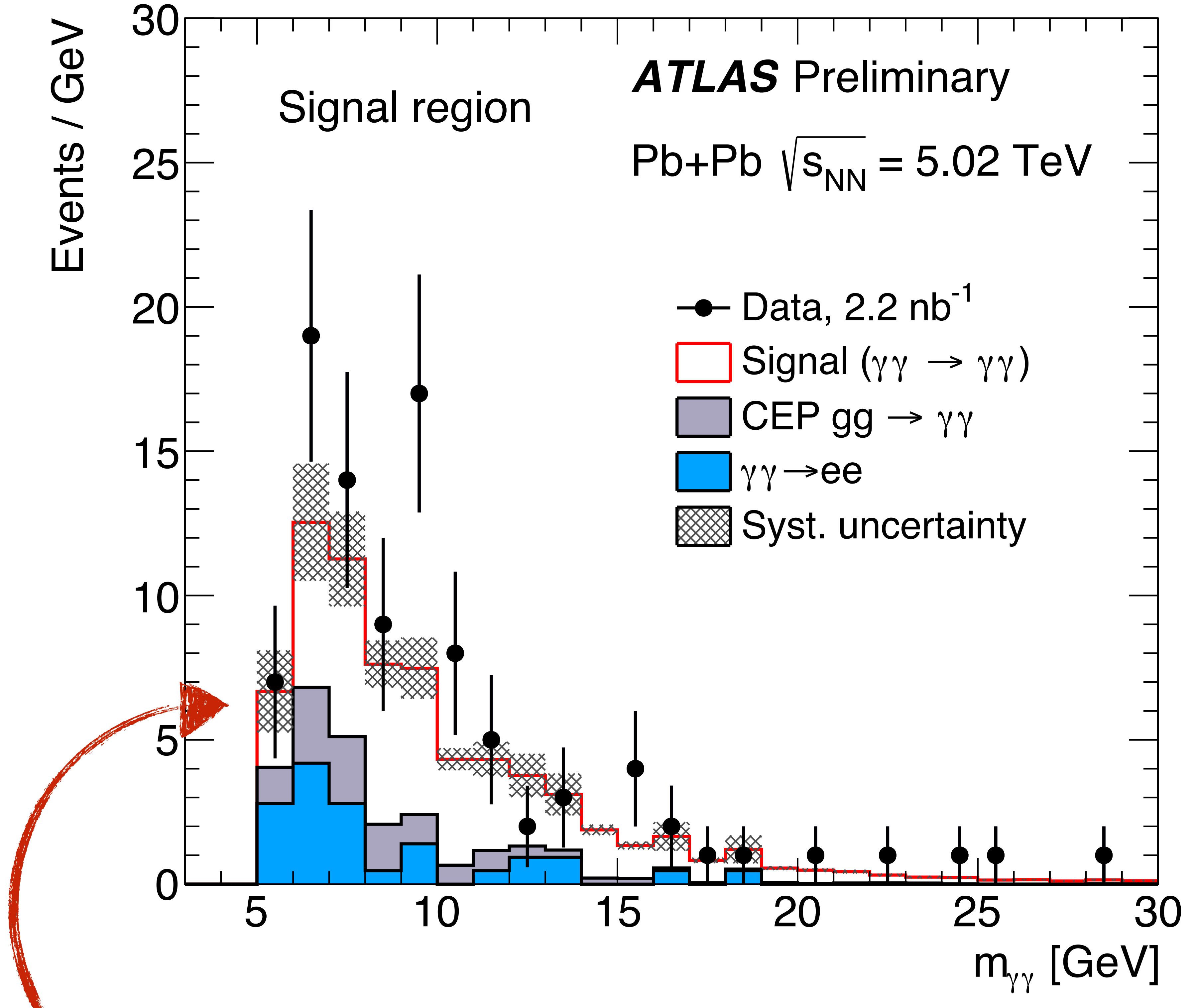
- Uncertainty on detector correction factor C: 8%

Source of uncertainty	Detector correction (C)
	0.263 ± 0.021
Trigger efficiency	5%
Photon reco. efficiency	4%
Photon PID efficiency	2%
Photon energy scale	1%
Photon energy resolution	2%
Photon angular resolution	2%
Alternative signal MC	1%
Signal MC statistics	1%
Total	8%

Interpretations

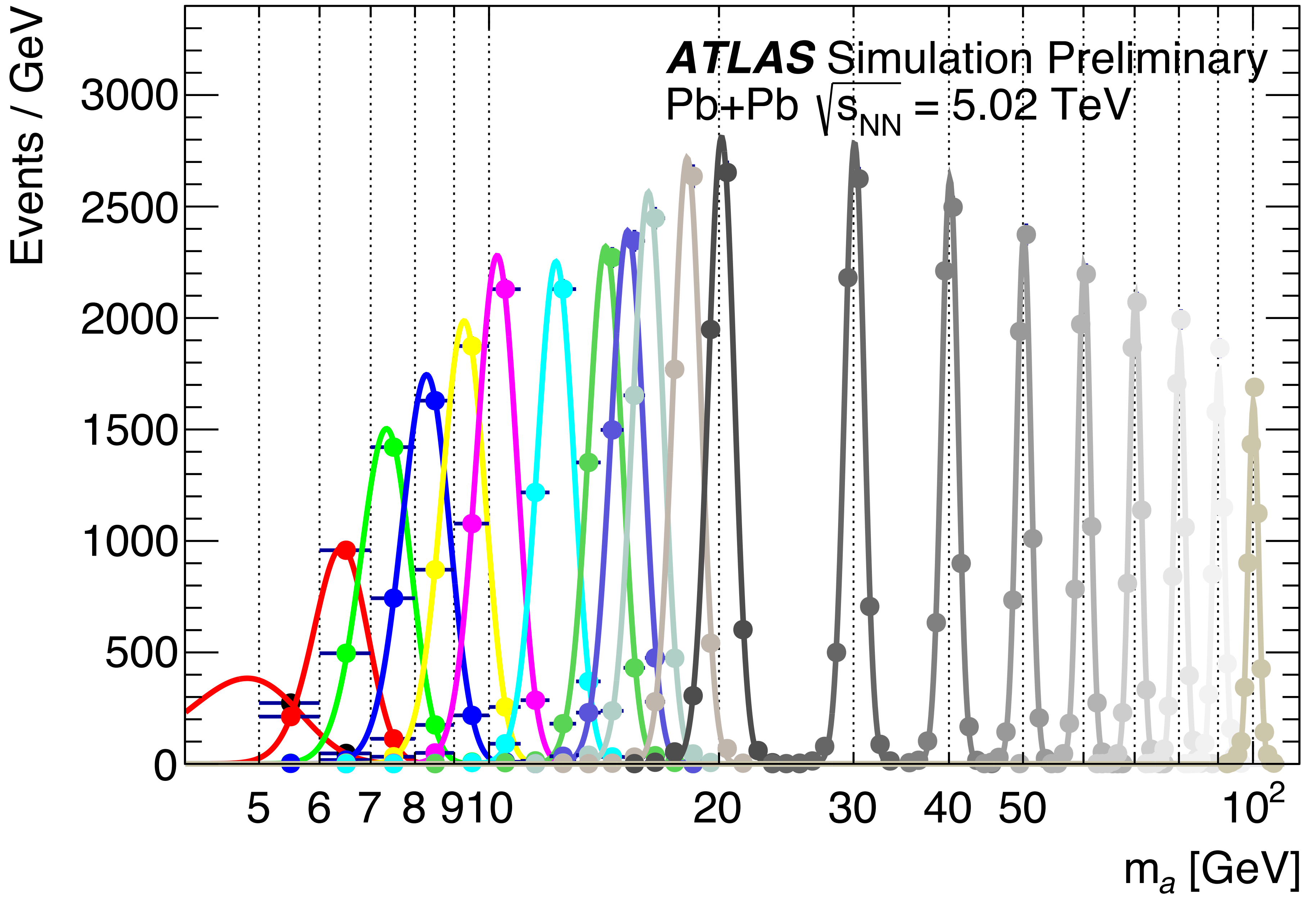
Interpretation - Search for Axion Like Particles:

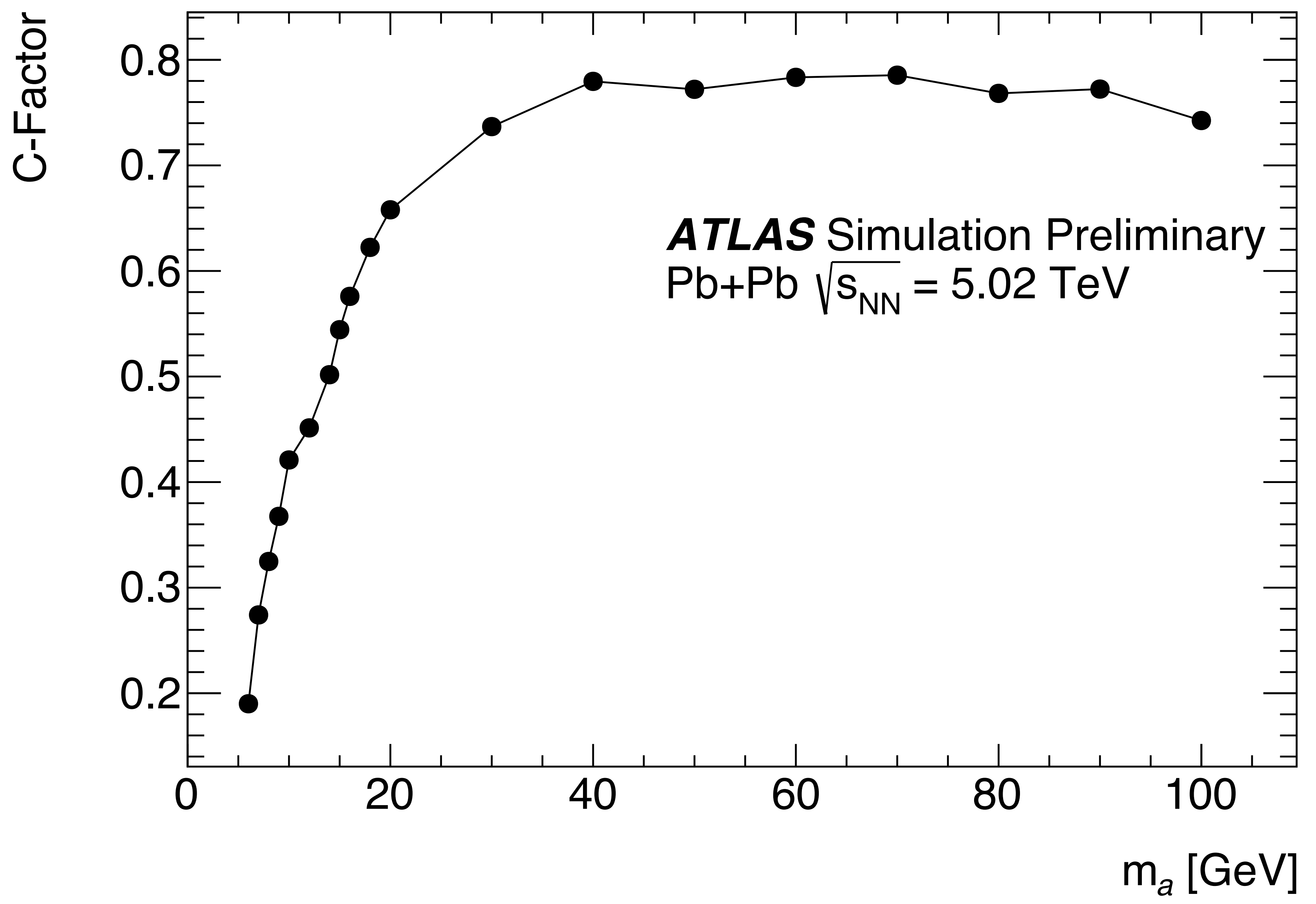
- ALP signal simulated using Starlight MC
- SM background: LbyL + CEP + ee
  - Extracting limit on the coupling to ALPs $1/\Lambda_a$



SM background

Expected ALP signal, $1/\Lambda_a$ = 1 TeV^{-1}





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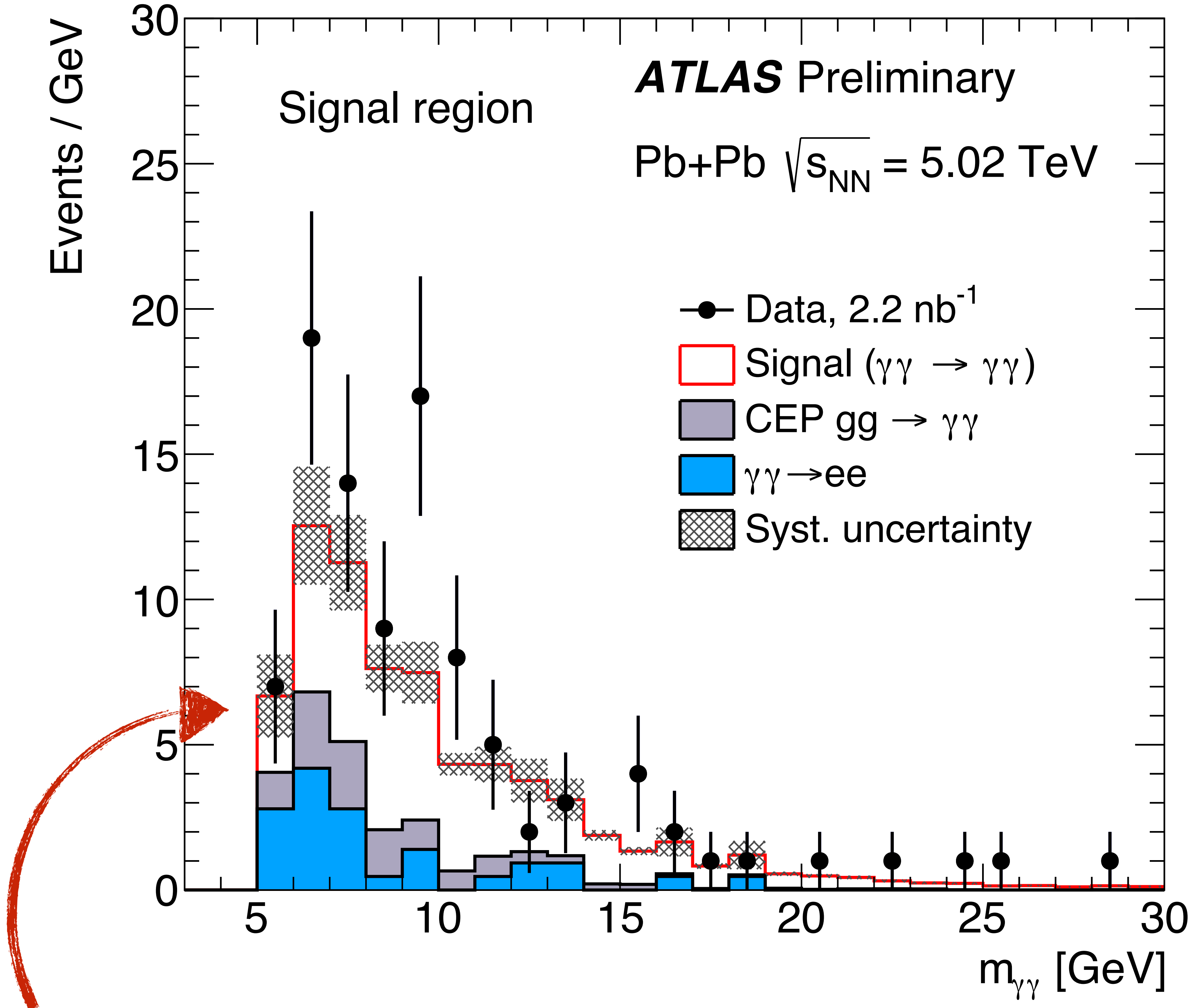

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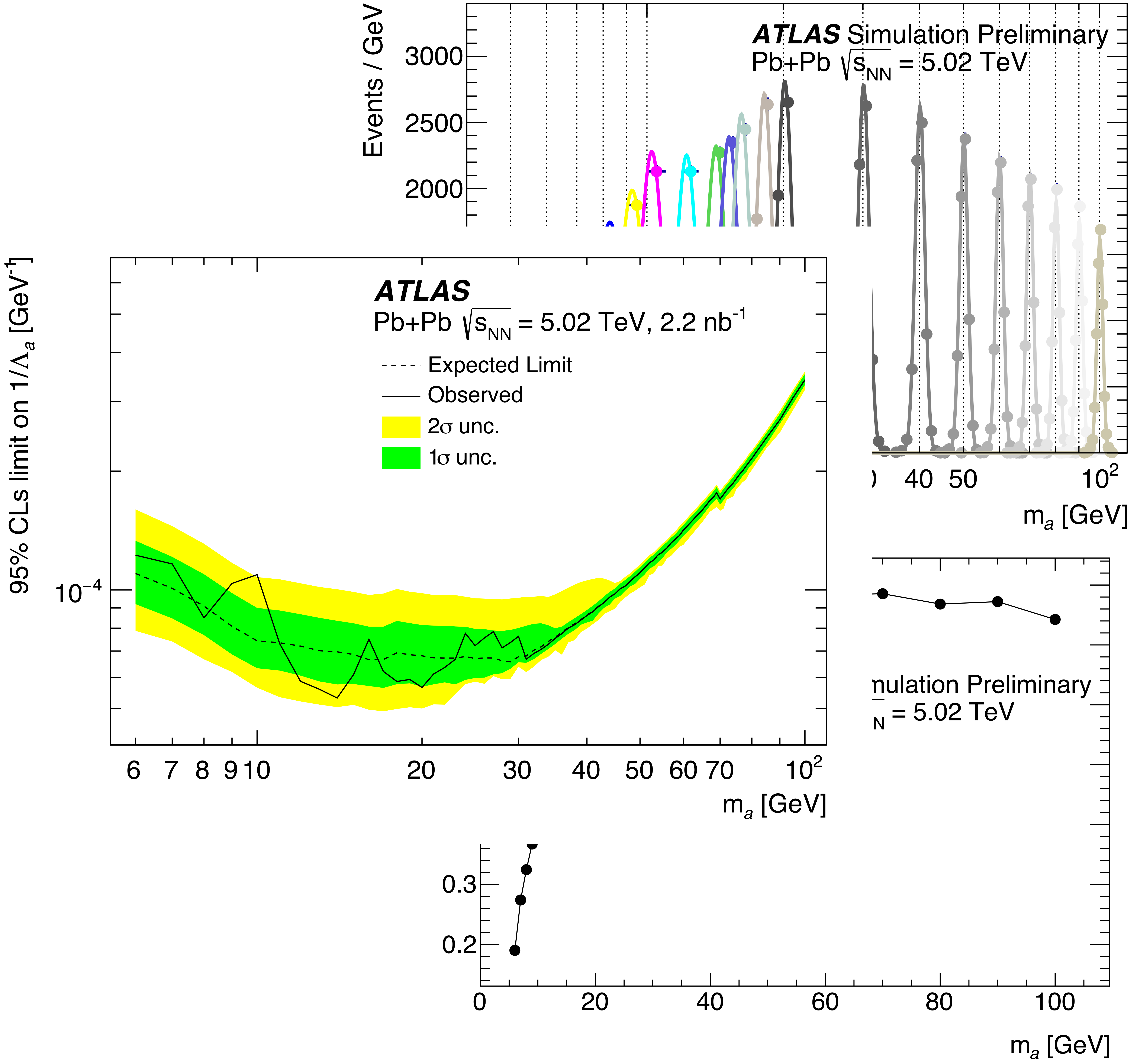

Interpretation - Search for New Physics

- Being interesting in it’s own right, there’s more to learn from this result:
  - Model independent interpretation using the effective field theory formalism (to be done)
  - Transformed into limits on specific models beyond the standard model
    - Two examples:

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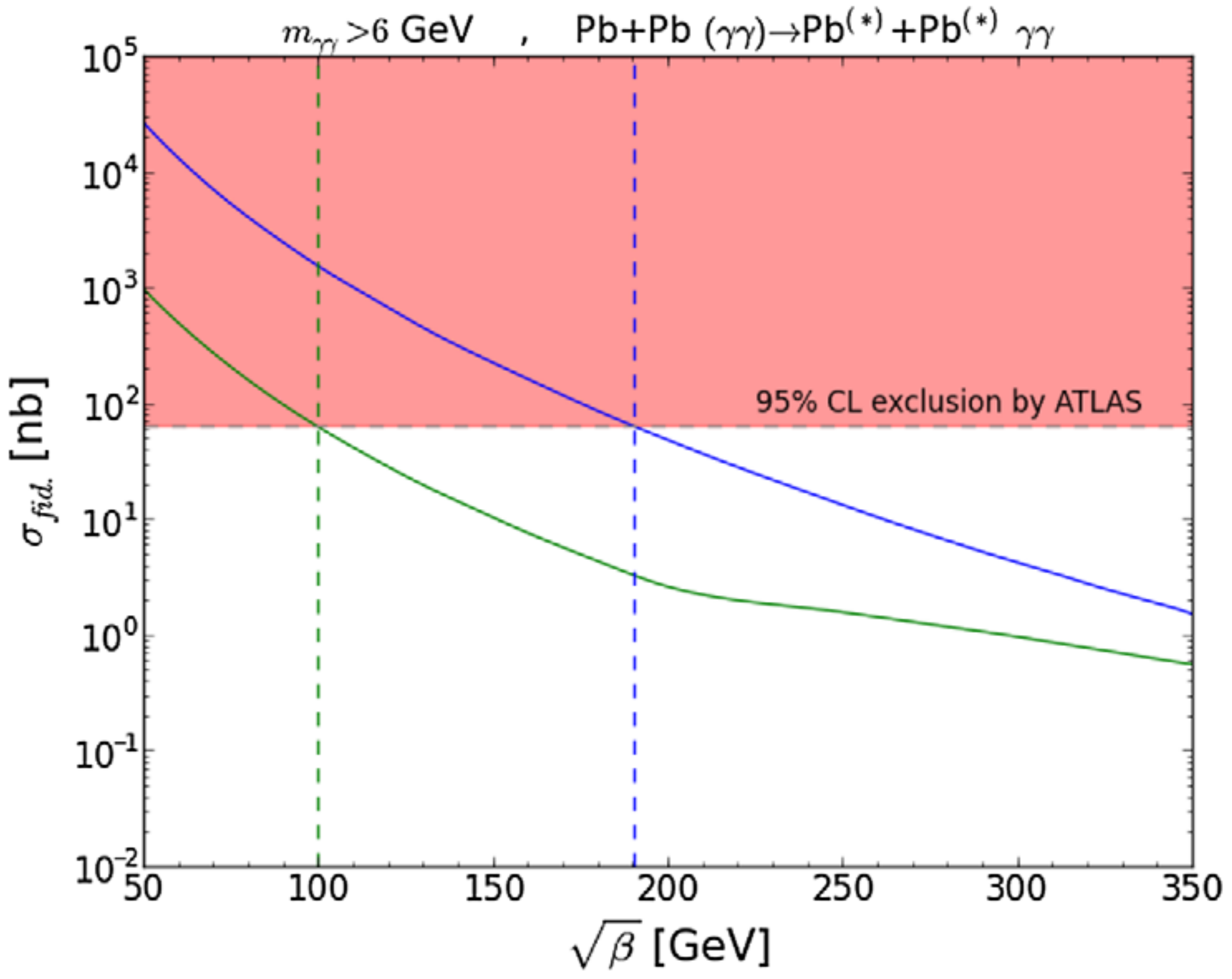
    - Two examples:

PRL 118, 261802 (2017)

Reinterpretation of ATLAS 2016 result:
Ellis et al, PRL 118, 261802 (2017)

- Born - Infeld theory
  - Nonlinear extension to QED
    - Imposing an upper limit of the EM field strength [Born and Infeld, Proc. R. Soc. A 144, 425 (1934)]
    - More recently: connection to string theory [Fradkin and Tseytlin, Infeld, Phys. Lett. 163B, 123 (1985)]

- Differential Light-by-Light scattering cross section can be turned into limit on mass scale appearing in B-I theory



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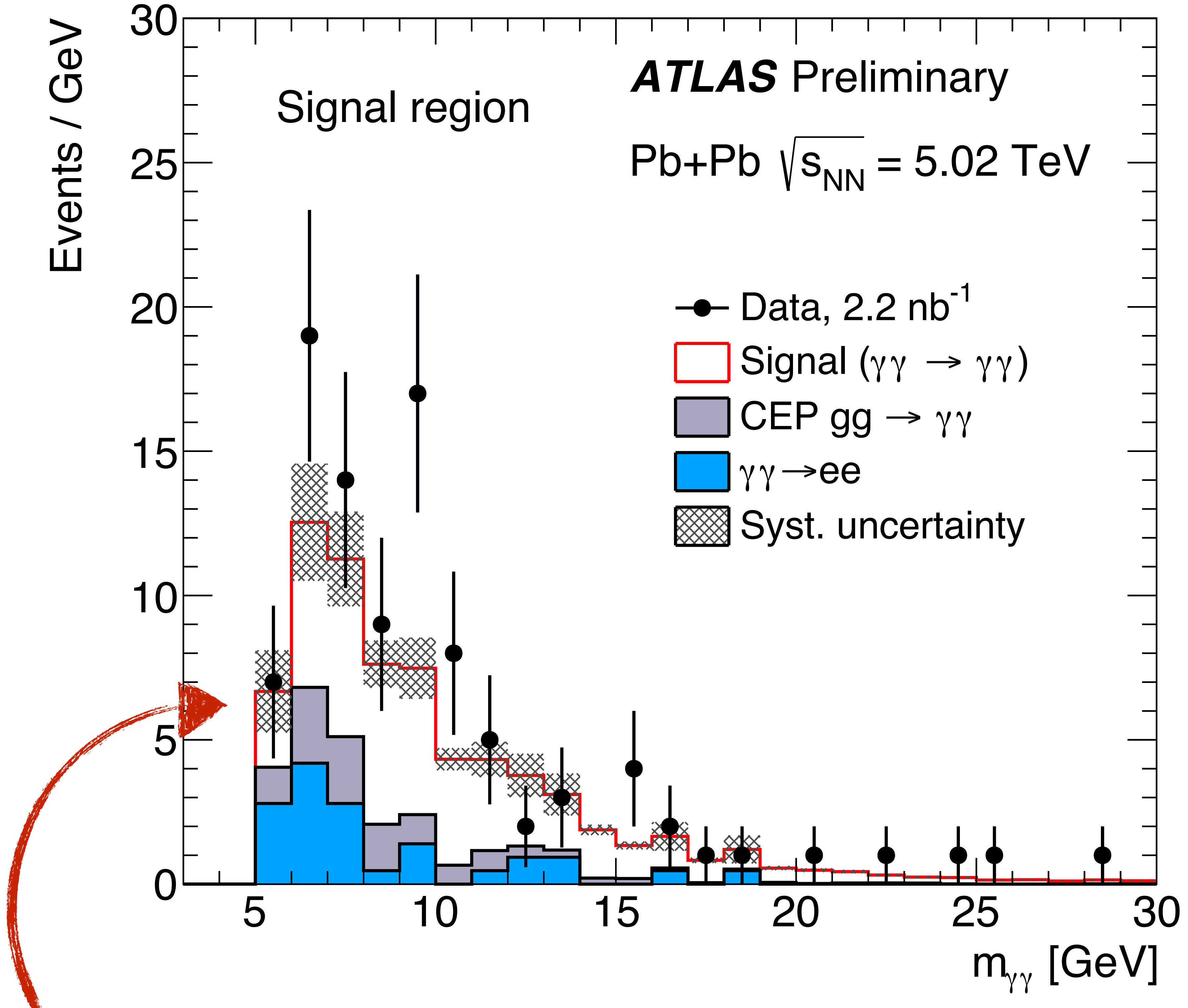

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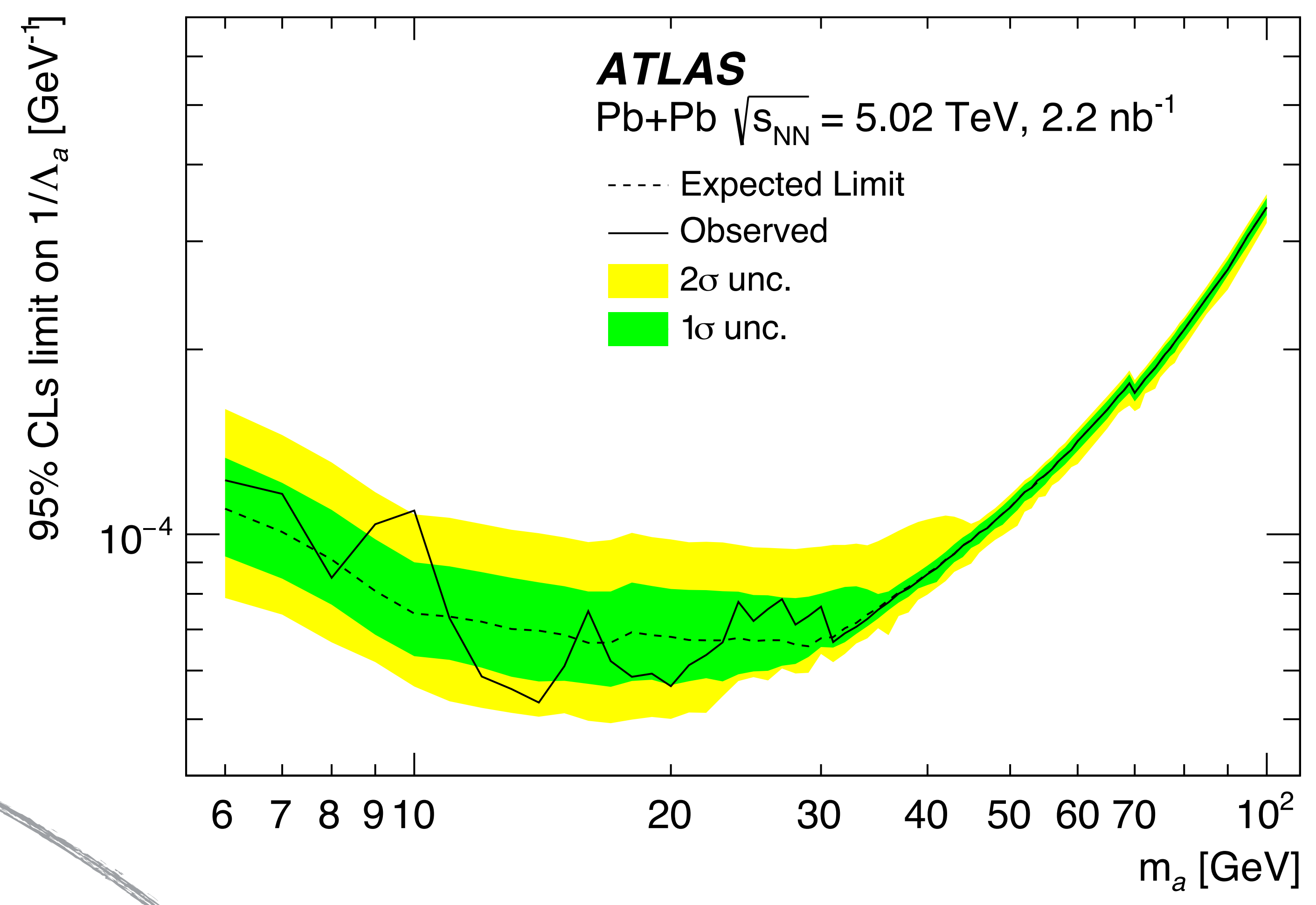
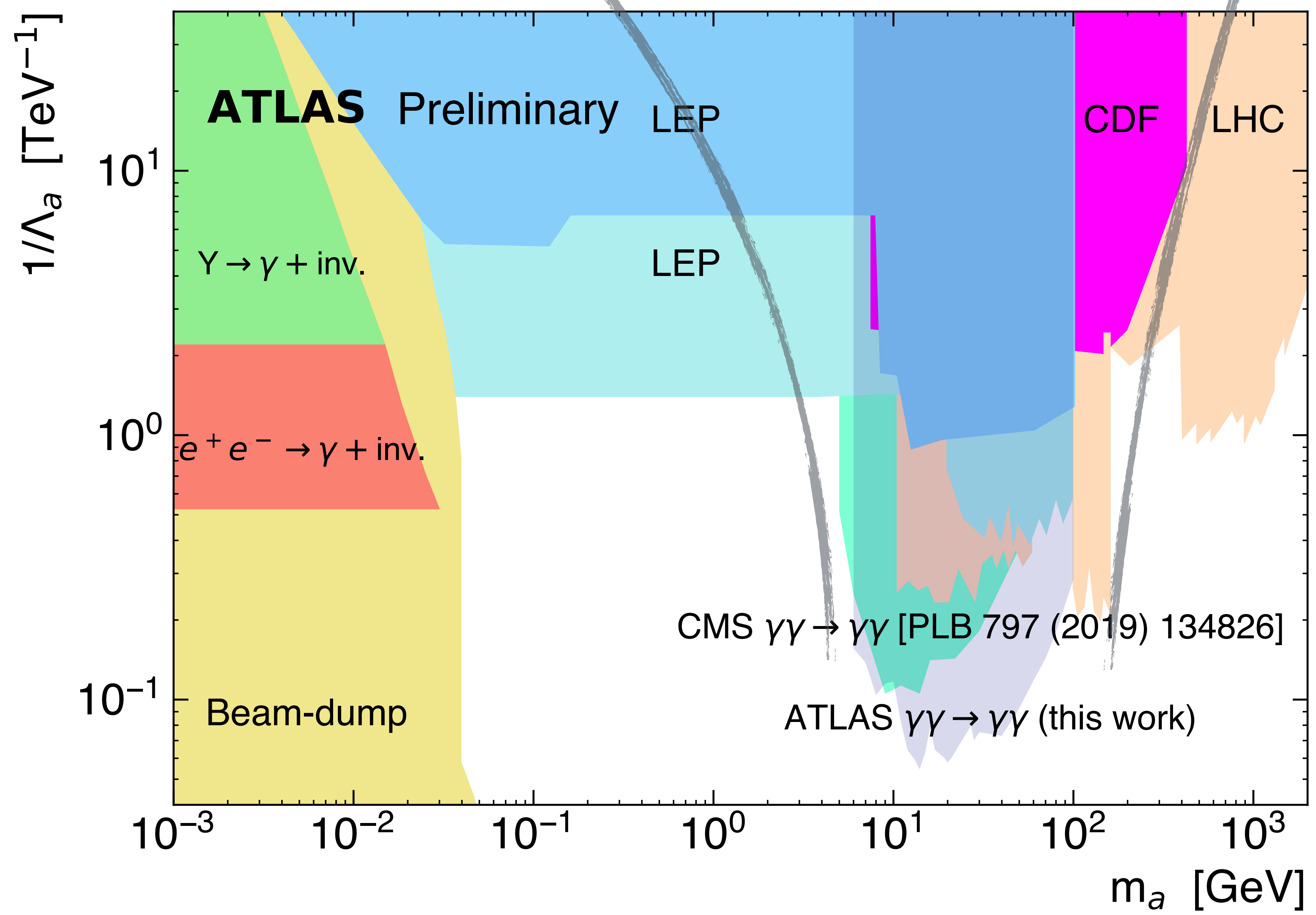


Extracted Limit

Existing constraints from JHEP 1712 (2017) 044



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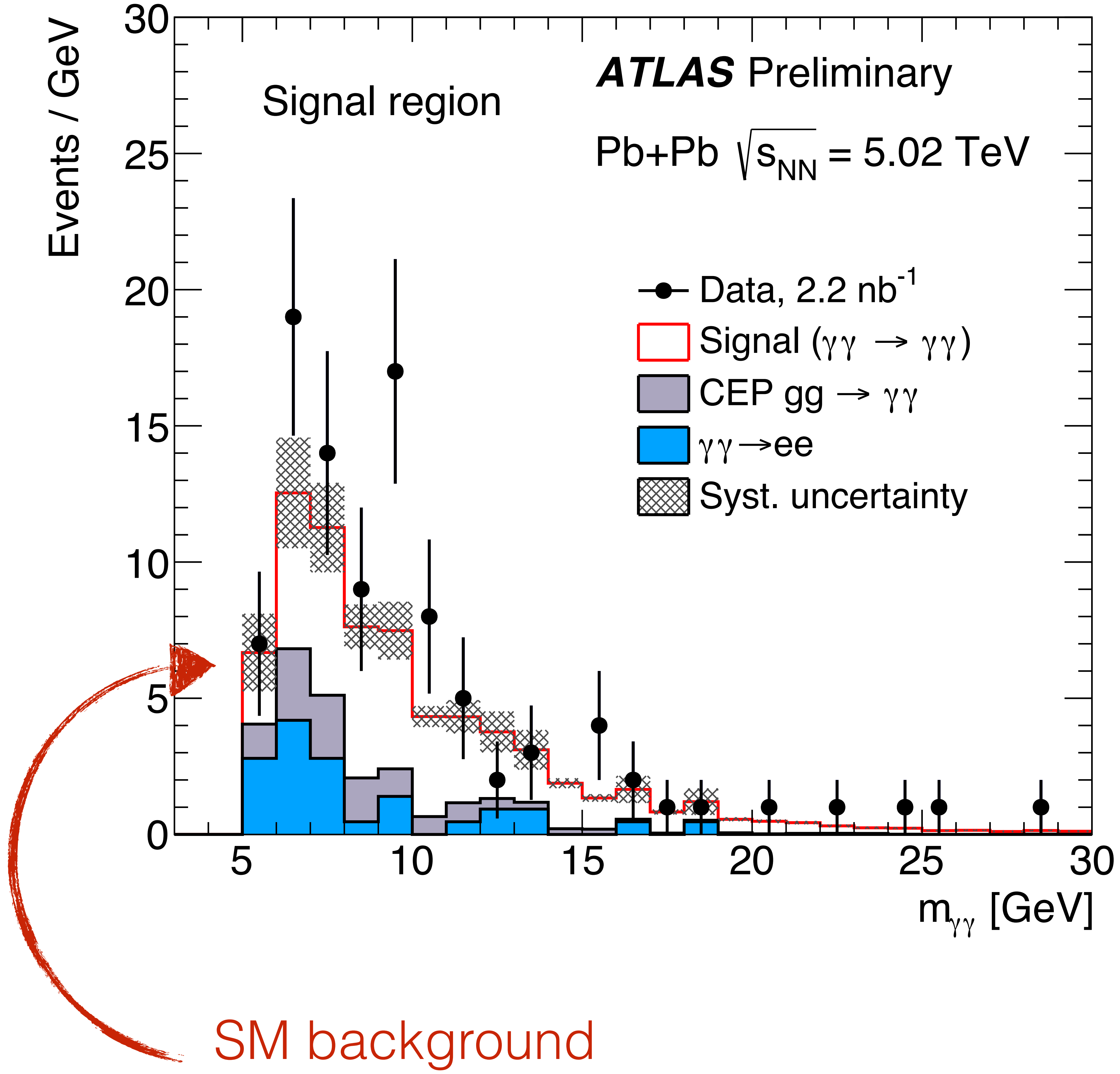
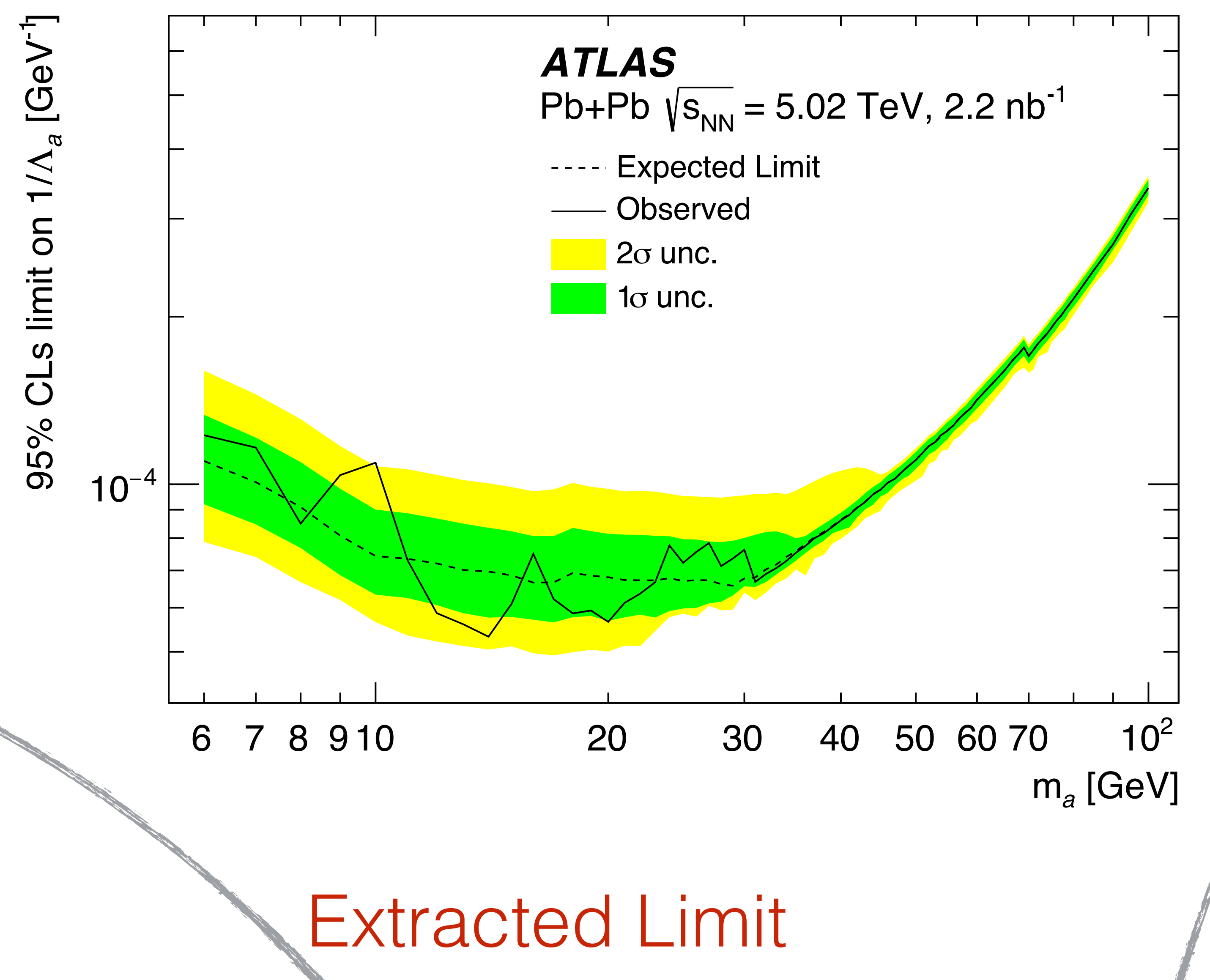
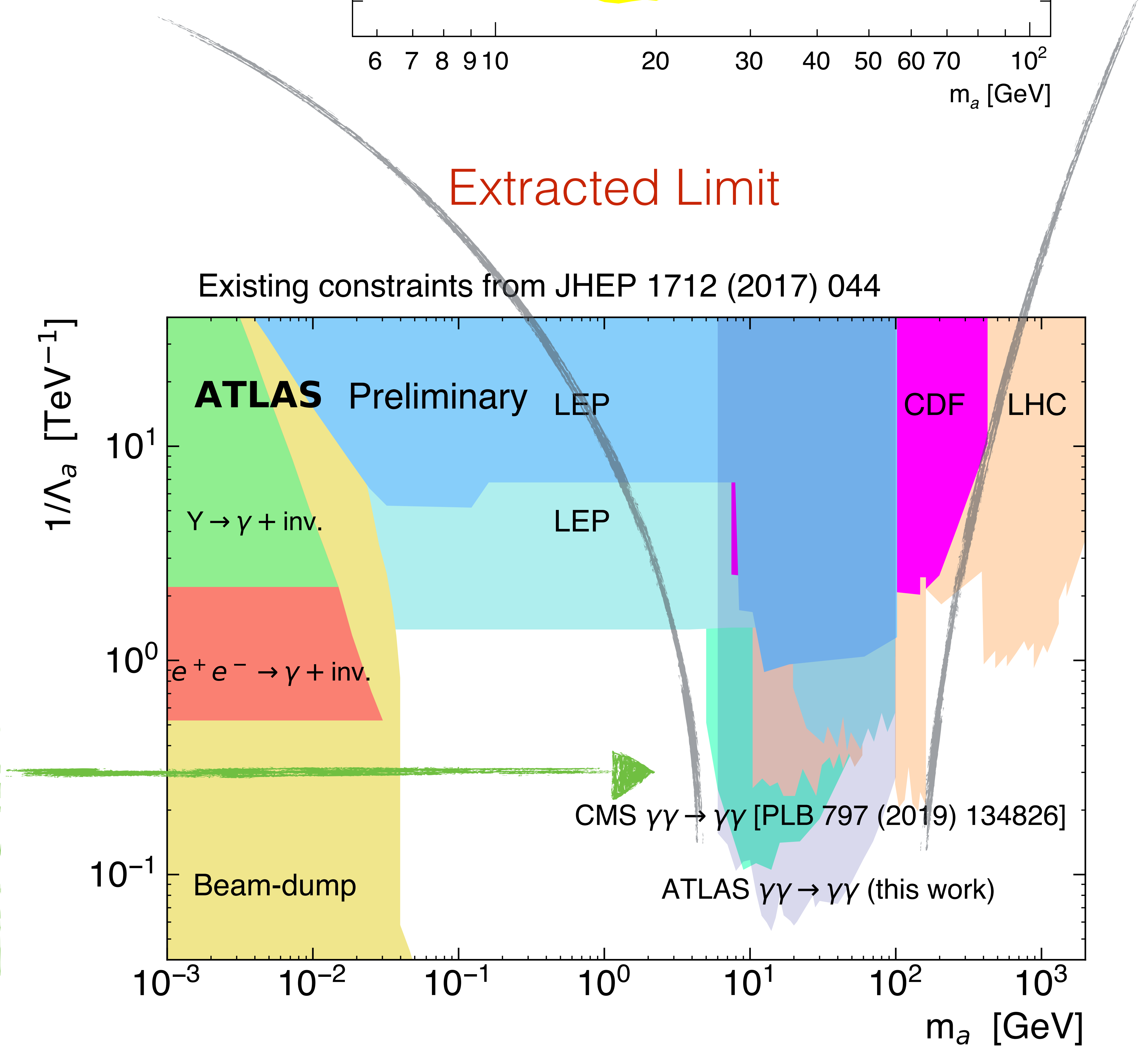




- CMS result:
  - Similar analysis
  - Uses only 0.37nb^{-1}

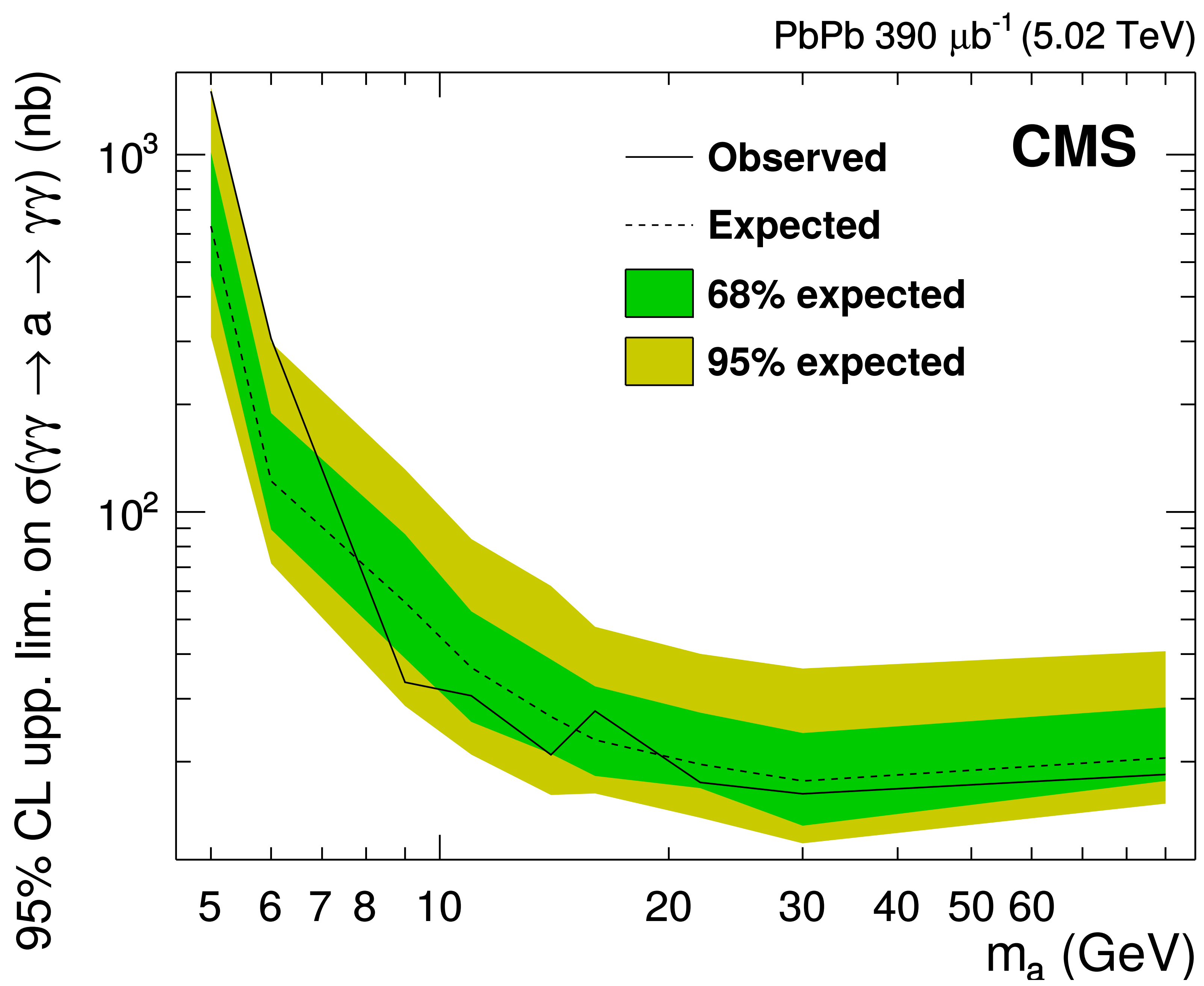


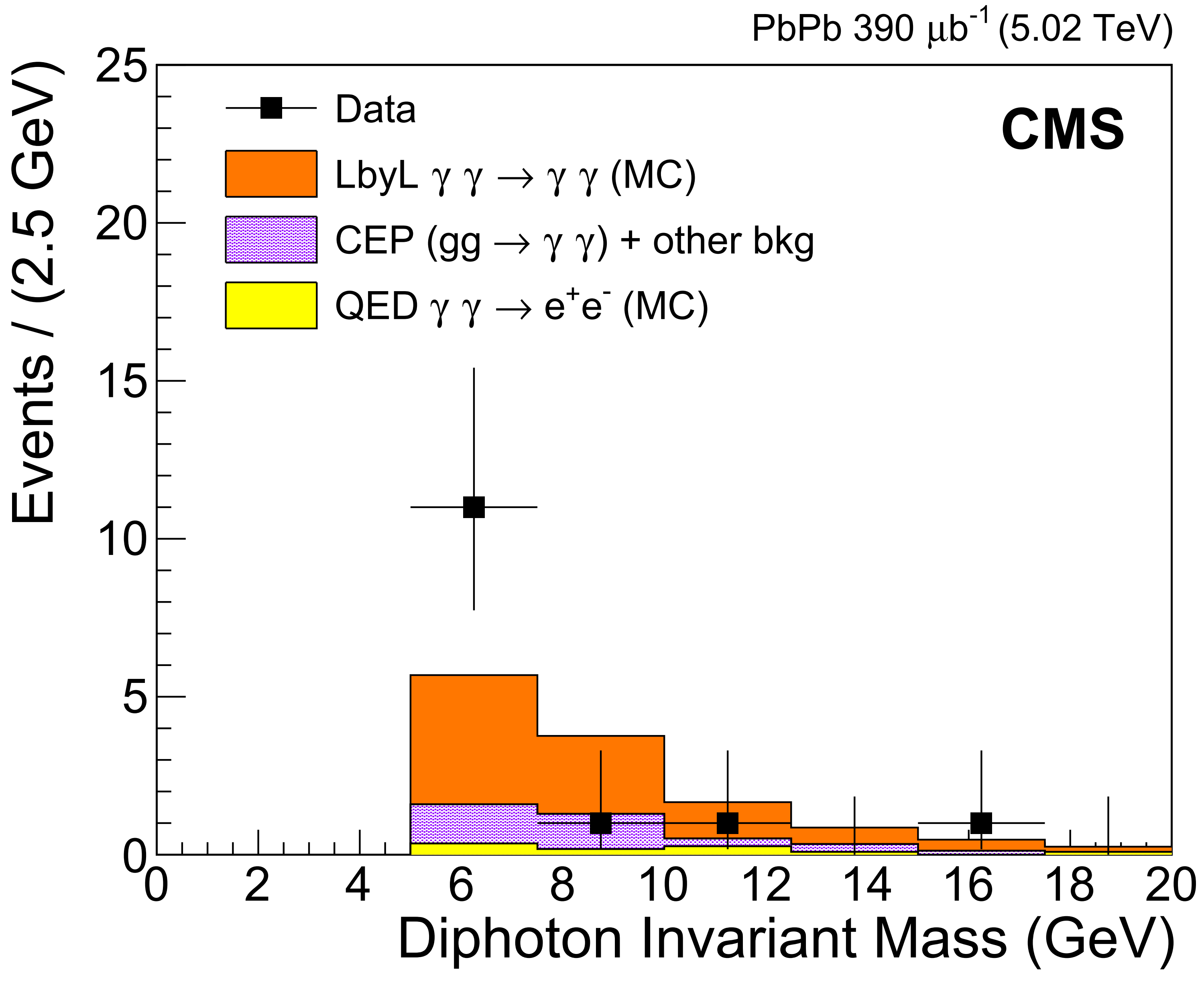
Interpretation - Search for new Axion Like Particles: CMS

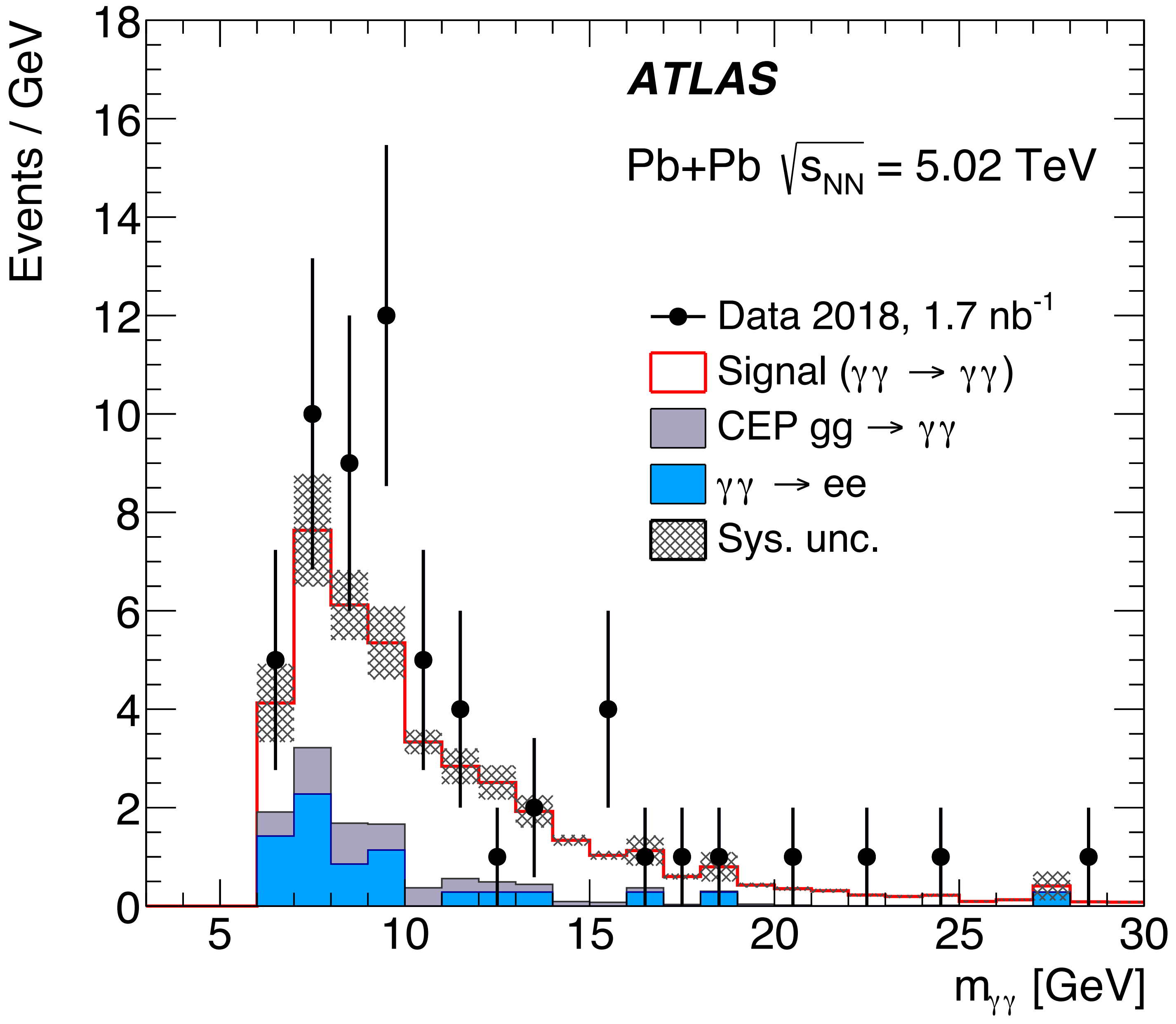
Phys.Lett. B797 (2019)

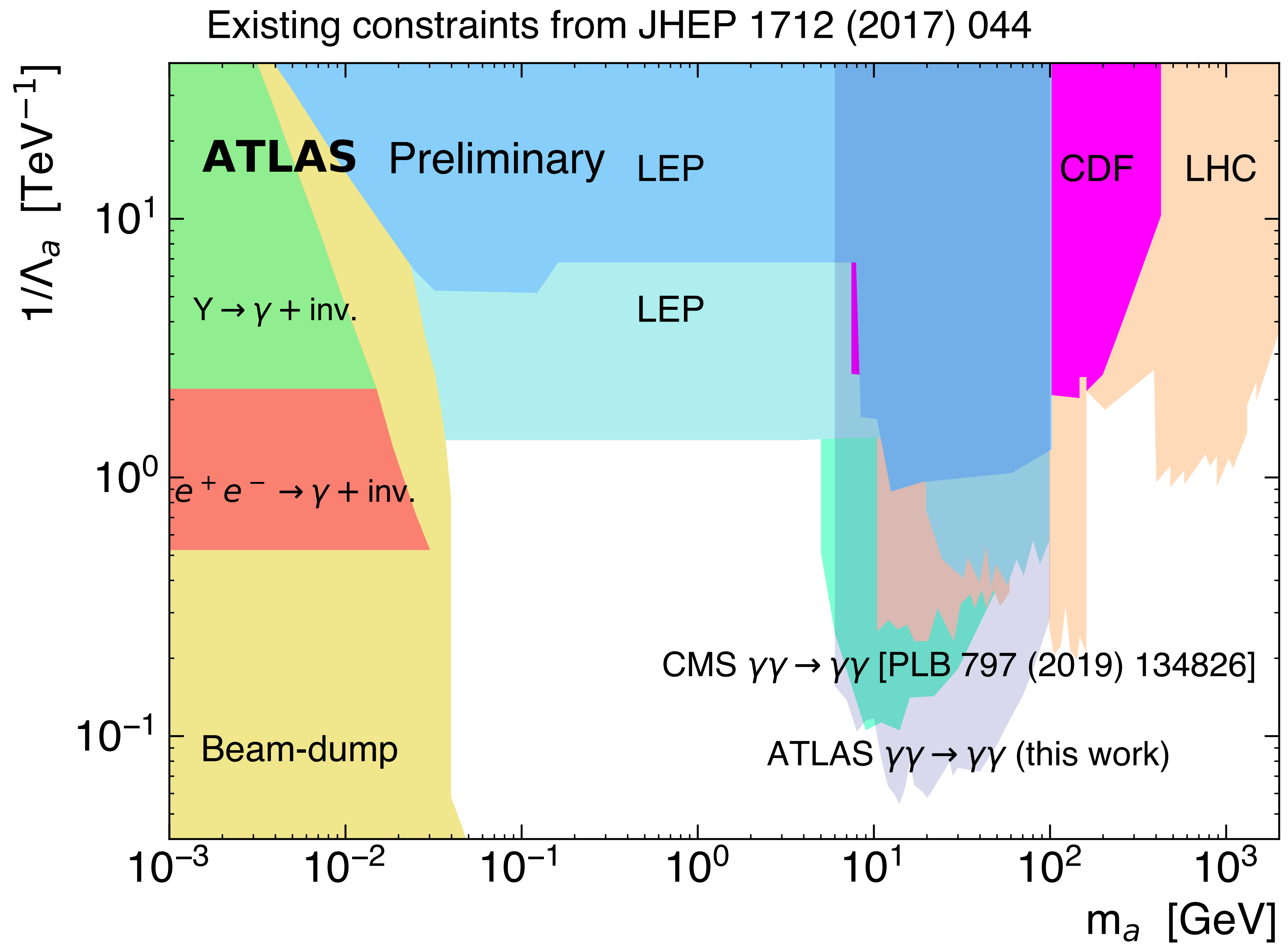
- 0.39 nb^{-1}, E_T > 2 GeV, m > 5 GeV
  - p_T (yy) < 1 GeV, |eta| < 2.4 => similar to ATLAS selection
  - 14 events observed, 4 background events expected

- ALP limits statistically limited
  - Factor 4 difference in statistics
  - Expect ~2 times lower limits from ATLAS soon

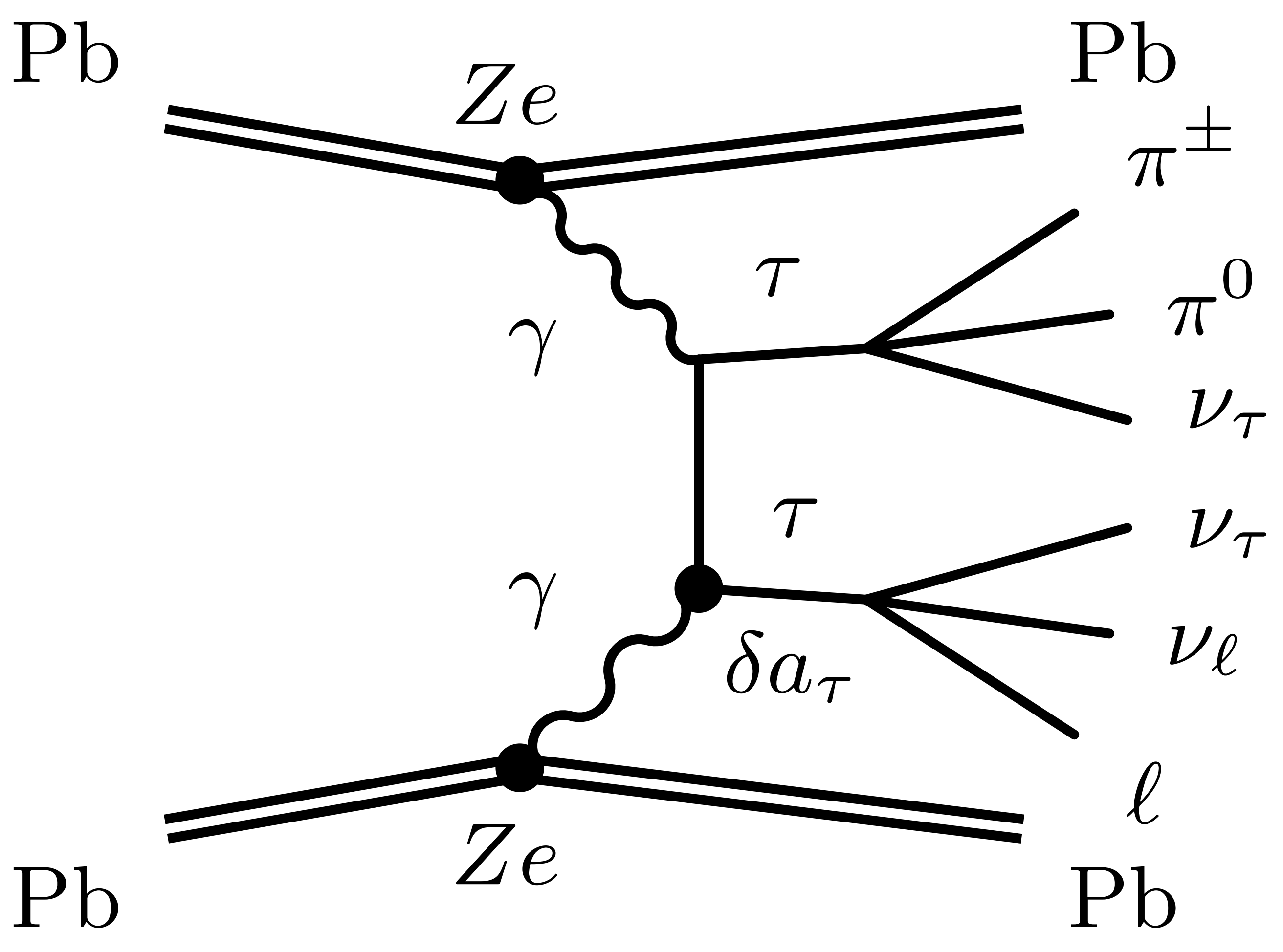








More on Taus



- Electromagnetic interaction - $\gamma\tau$

$$\mathcal{L} = \frac{1}{2}\bar{\tau}_{\mathrm{L}}\sigma^{\mu\nu}\left(a_\tau \frac{e}{2m_\tau} - \mathrm{i}d_\tau\gamma_5\right)\tau_{\mathrm{R}}F_{\mu\nu}$$

$$a_\tau^{\exp} = -0.018\,(17)$$
$$a_{\tau,\,\mathrm{SM}}^{\mathrm{pred}} = 0.001\,177\,21\,(5)$$

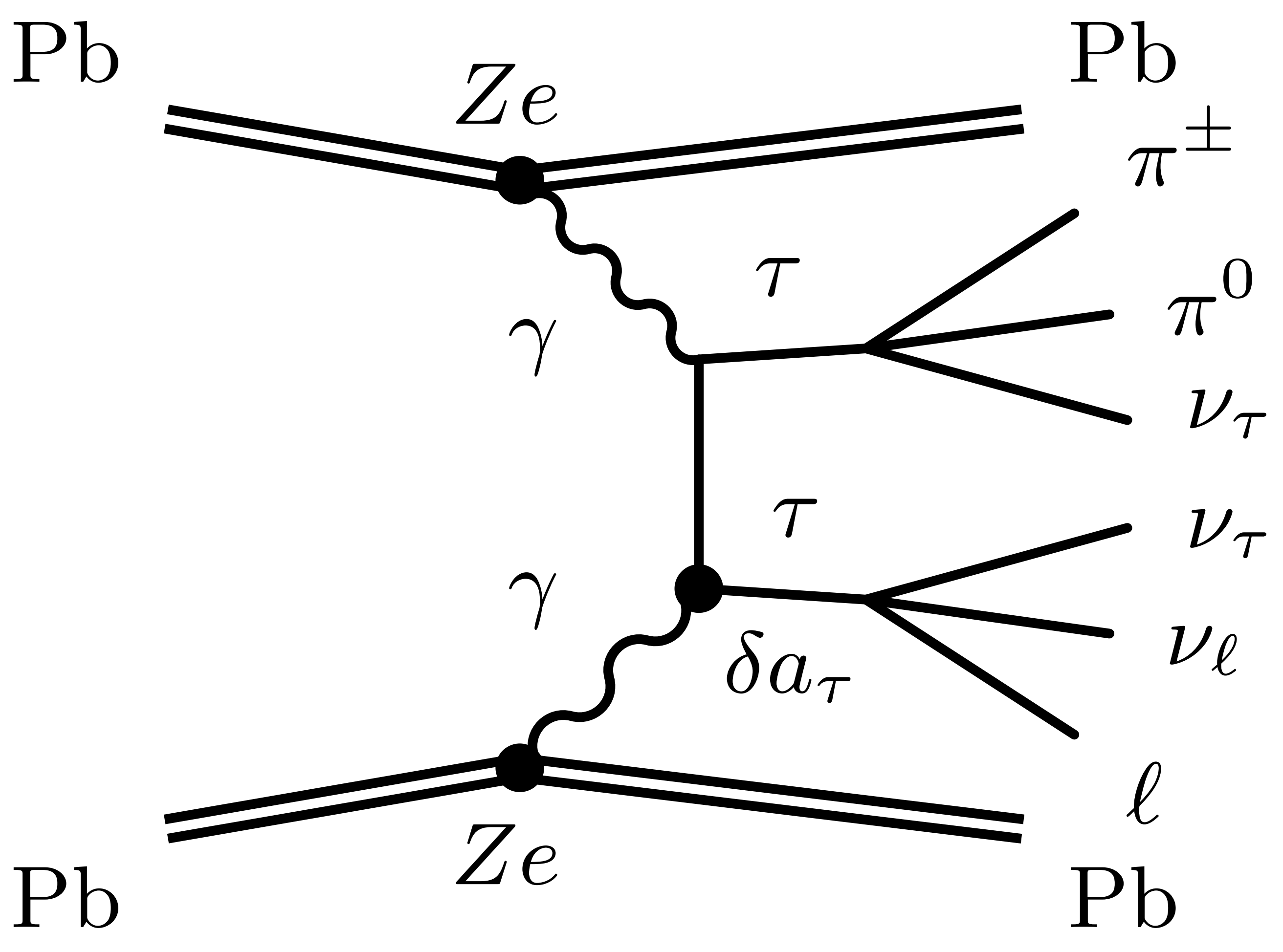
- $\gamma\gamma \rightarrow \tau\tau$ sensitive to electric & magnetic moments of tau!
  - a_τ : anomalous magnetic moment
  - d_τ: electric diplome moment
- Usage of UPC PbPb collisions suggest in 1991

Phys.Lett. B271 (1991) 256-260

- Sensitivity estimation at LHC brand new (Beresford & Liu)
  - 3x smaller uncertainties compared to LEP measurement

arXiv:1908.05180

Tau anomalous magnetic moment : $\gamma\gamma \to \tau\tau$



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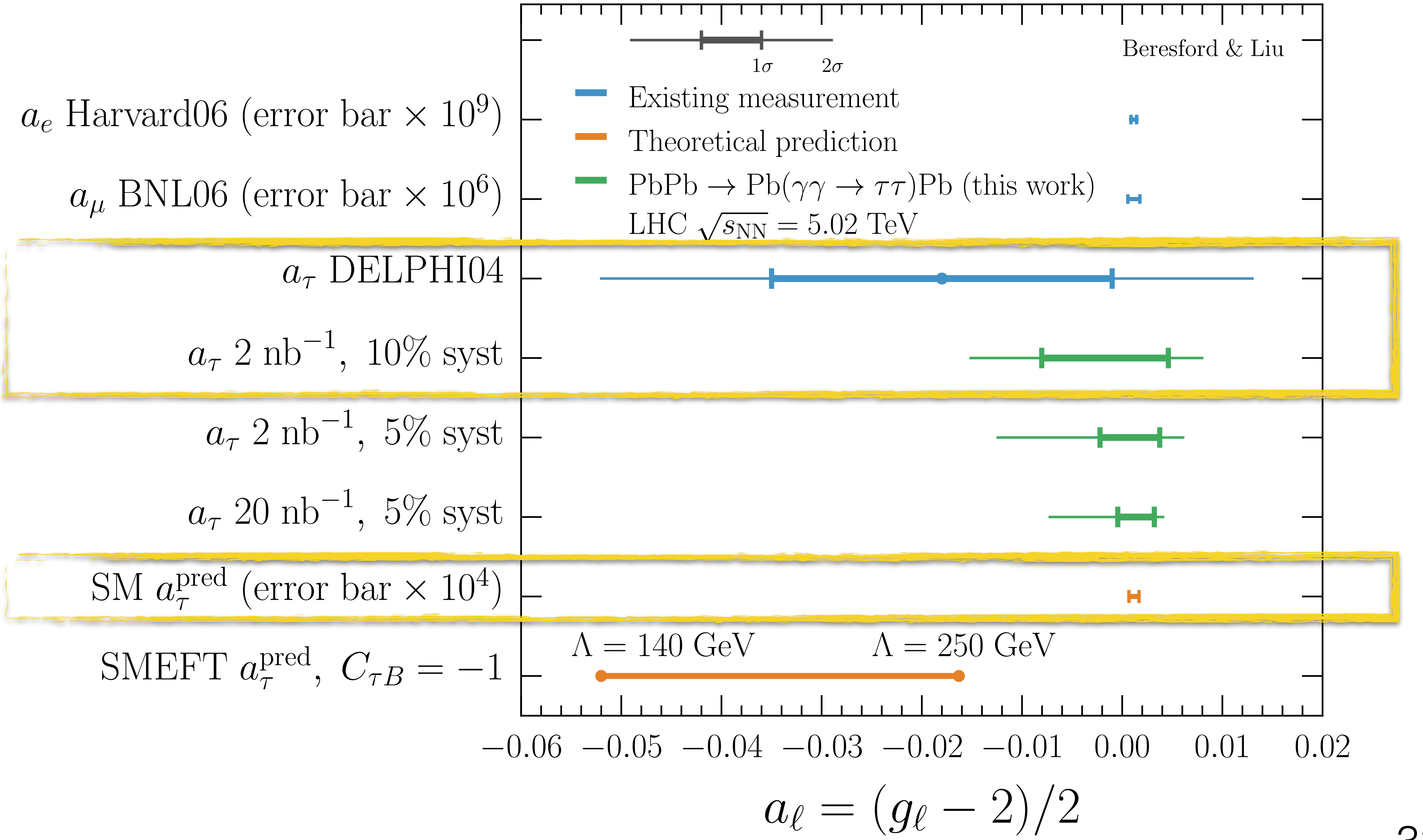

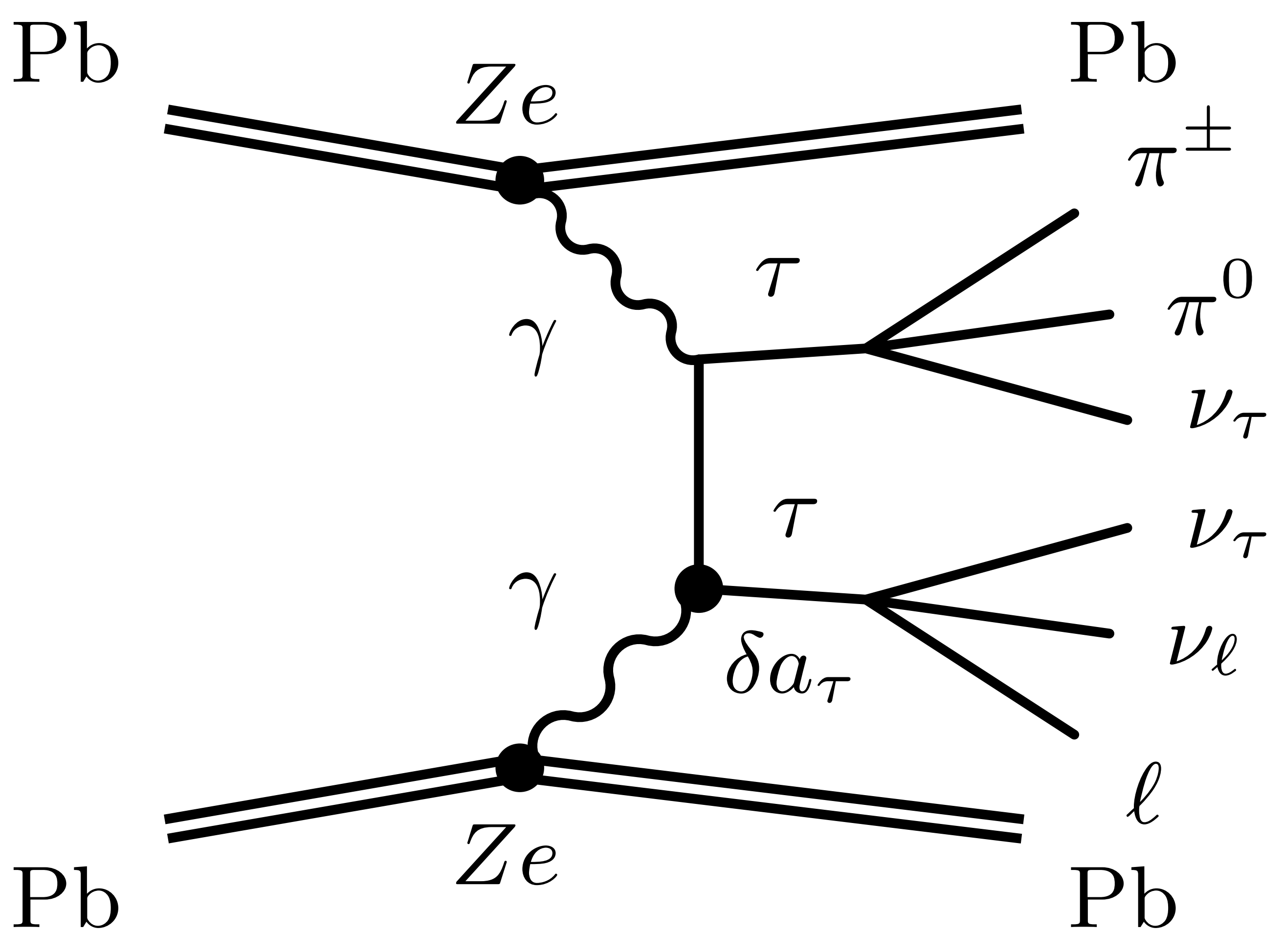

$$\mathcal{B}(\tau^\pm \to \pi^\pm \nu_\tau + \text{neutral pions}) = 45.6\%$$

$$\mathcal{B}(\tau^\pm \to \ell^\pm \nu_\ell \nu_\tau) = 35\%$$

- Challenges:
  - Trigger:
    - Similar triggers as used in Light-by-Light scattering analysis
  - Reconstruction:
    - Rely on lepton and tracks reconstruction
    - Track reach down to 0.5 GeV is standard
- Selection
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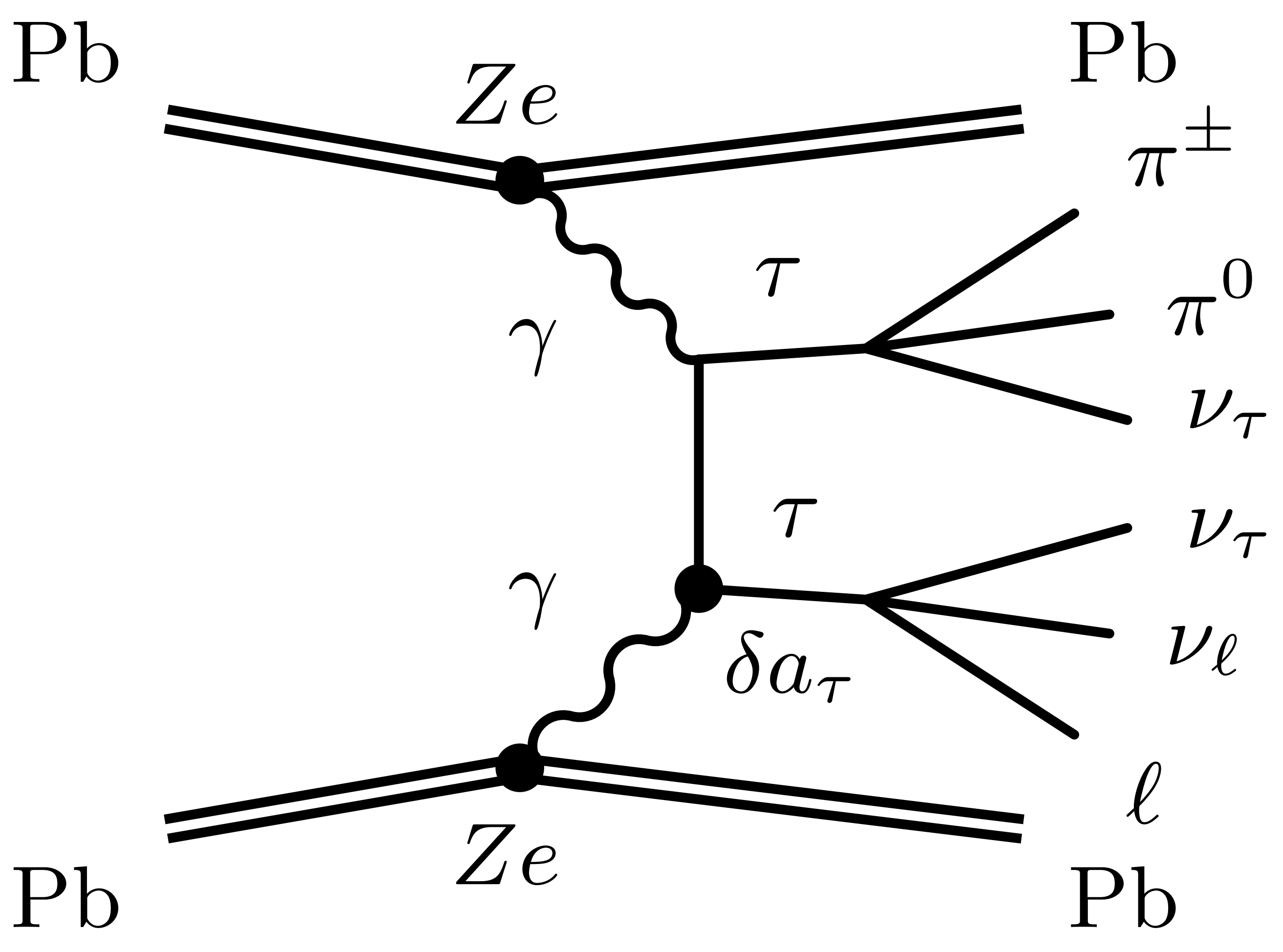

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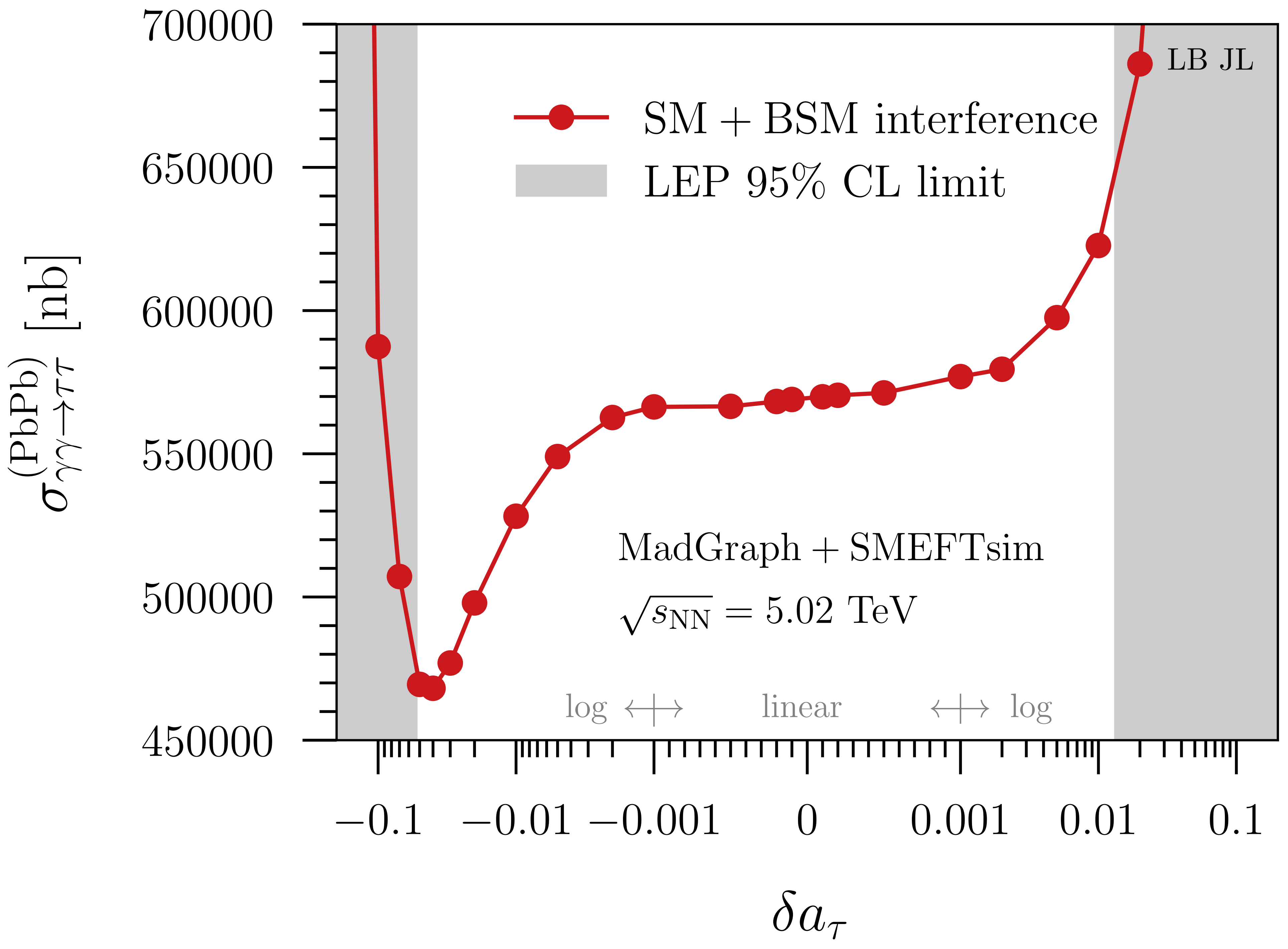
- Why are the tau-EM moments interesting?
  - a_τ poorly measured
  - Sensitive to BSM physics:
    - Tests lepton compositeness
    - SUSY at scale M_S => $\delta a_l \sim m_l^2 / M_S^2$
      - τ way more sensitive than μ
- Impact of BSM effects modelled in EFT vial 2 dim-6 operators:

arXiv:1908.05180



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