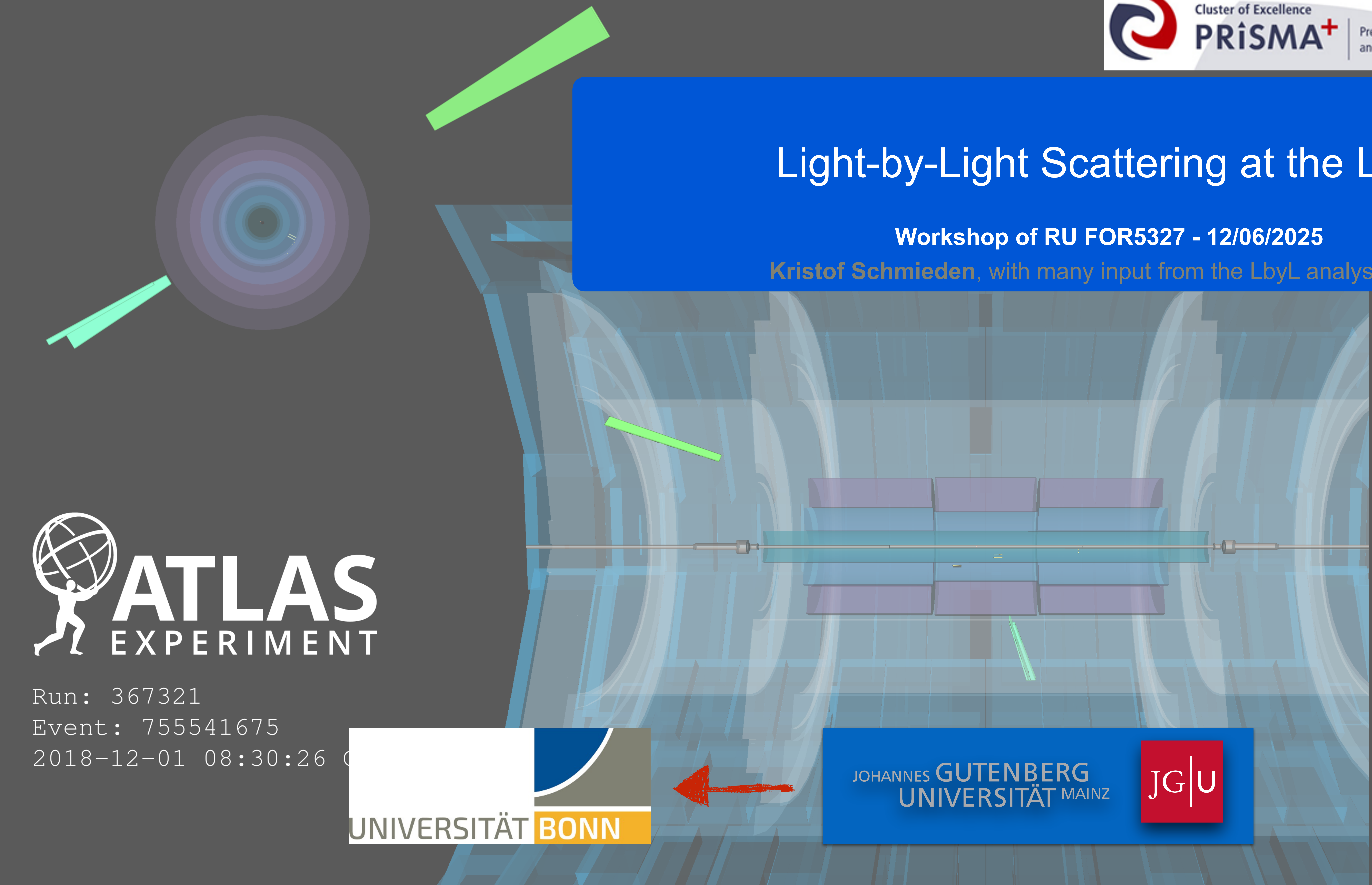
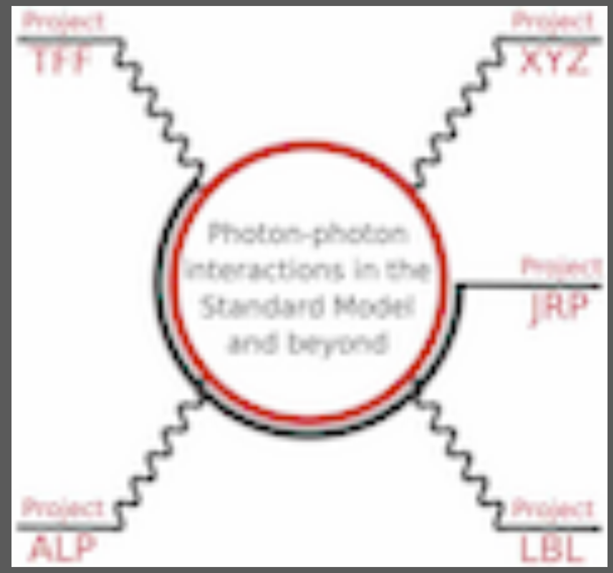
Light-by-Light Scattering at the LHC

Workshop of RU FOR5327 - 12/06/2025

Kristof Schmieden, with many input from the LbyL analysis team





Cluster of Excellence PRISMA+ Precision Physics, Fundamental Interactions and Structure of Matter
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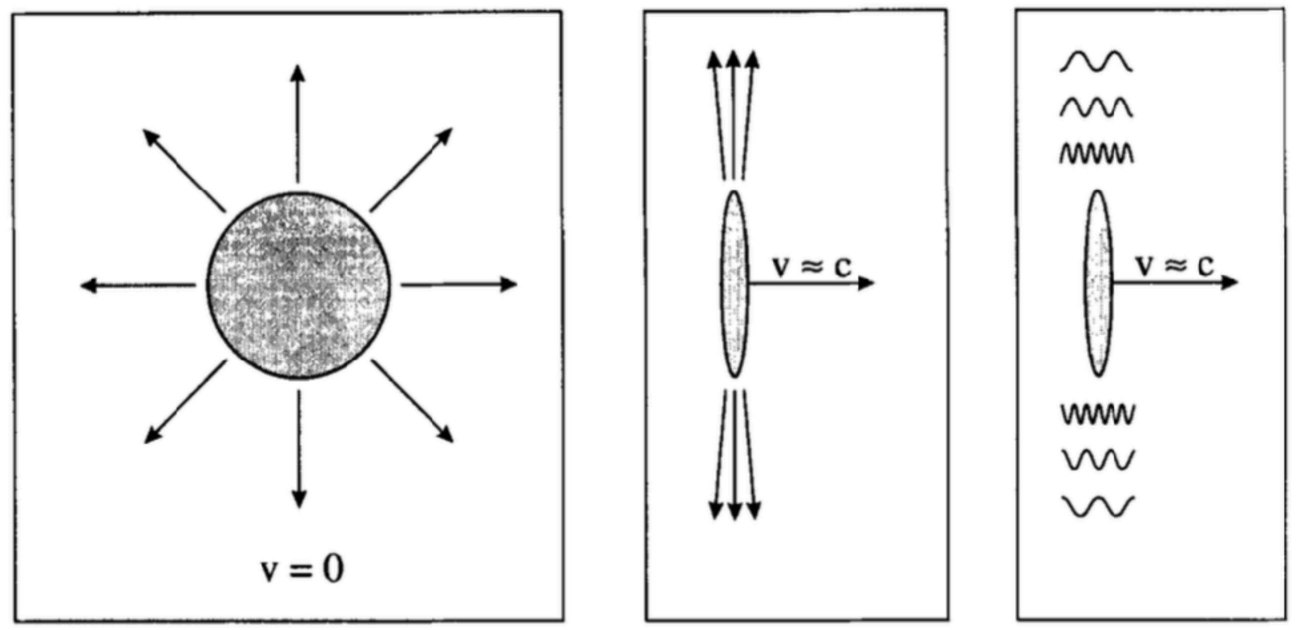
Ultra Peripheral Heavy Ion Collisions - LHC as photon collider

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

- Equivalent photon flux scales with Z^4
  - PbPb 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]

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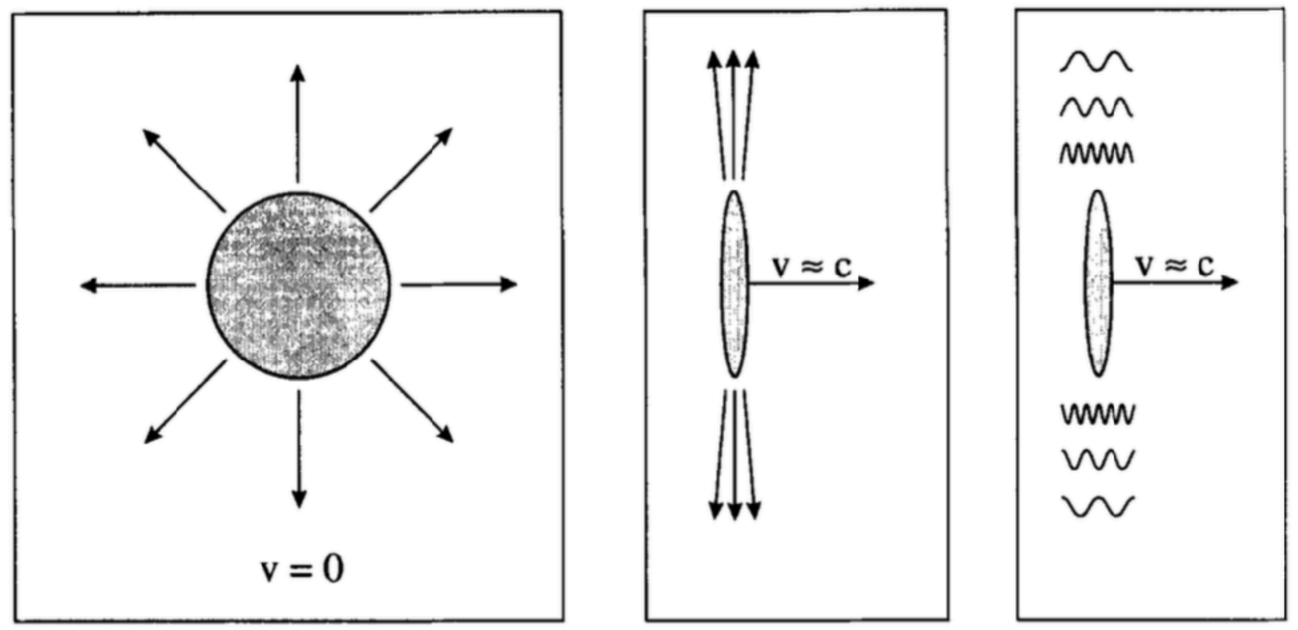
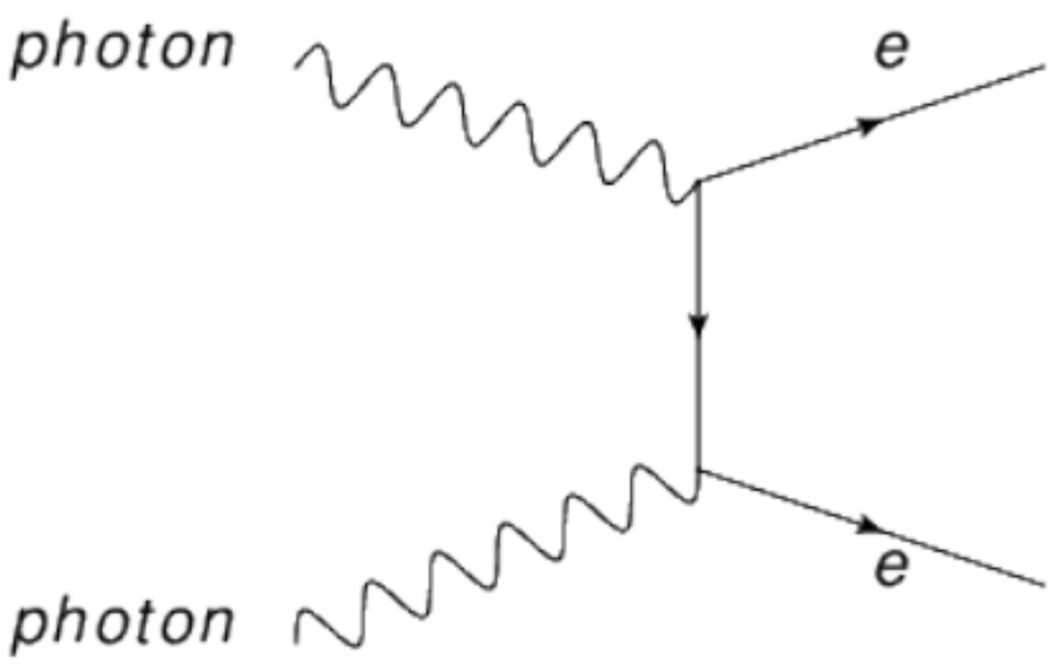
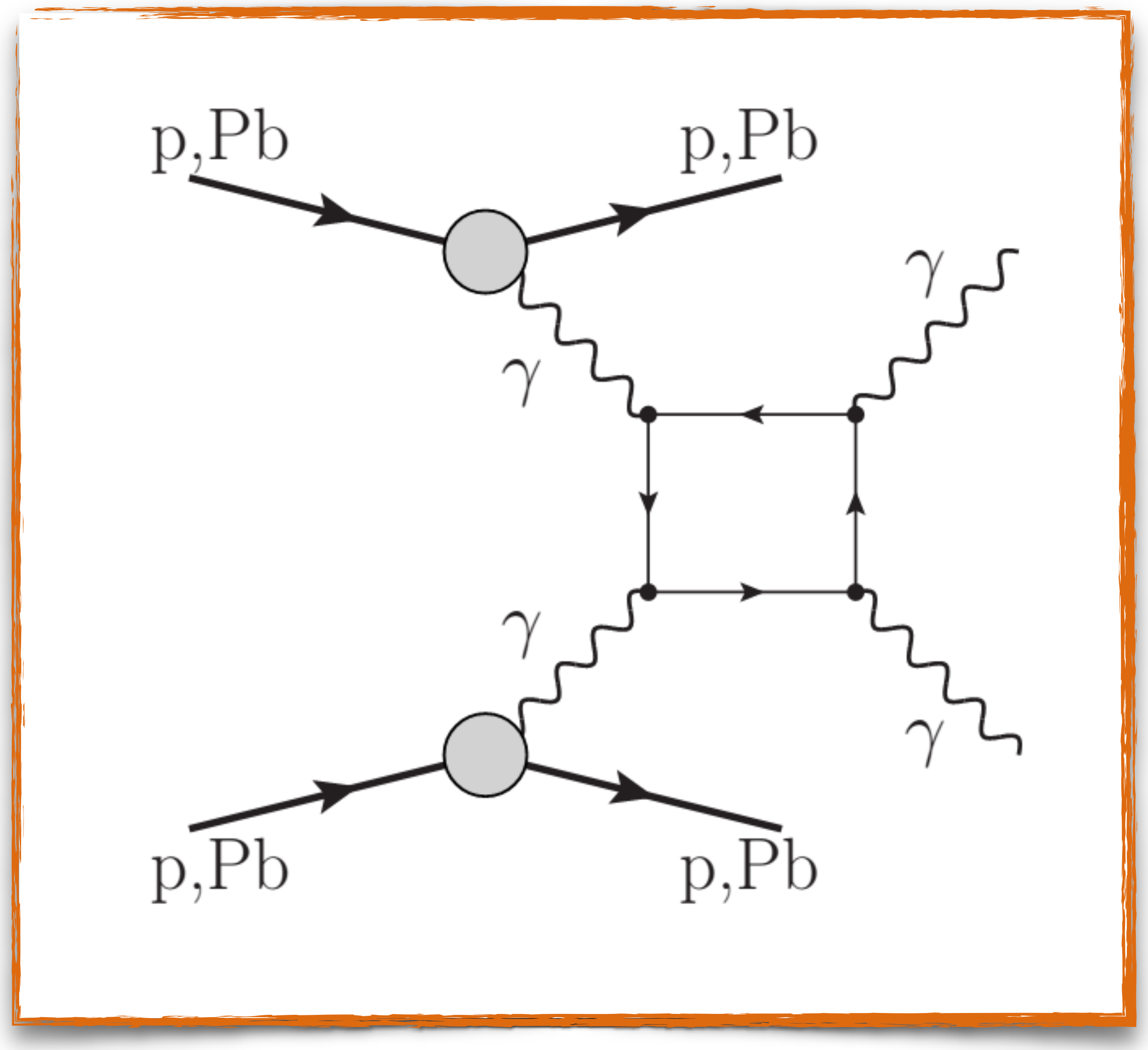


[Fermi, Nuovo Cim. 2 (1925) 143]

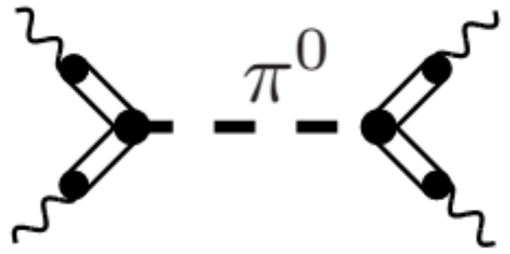
- Various types of photon interactions possible

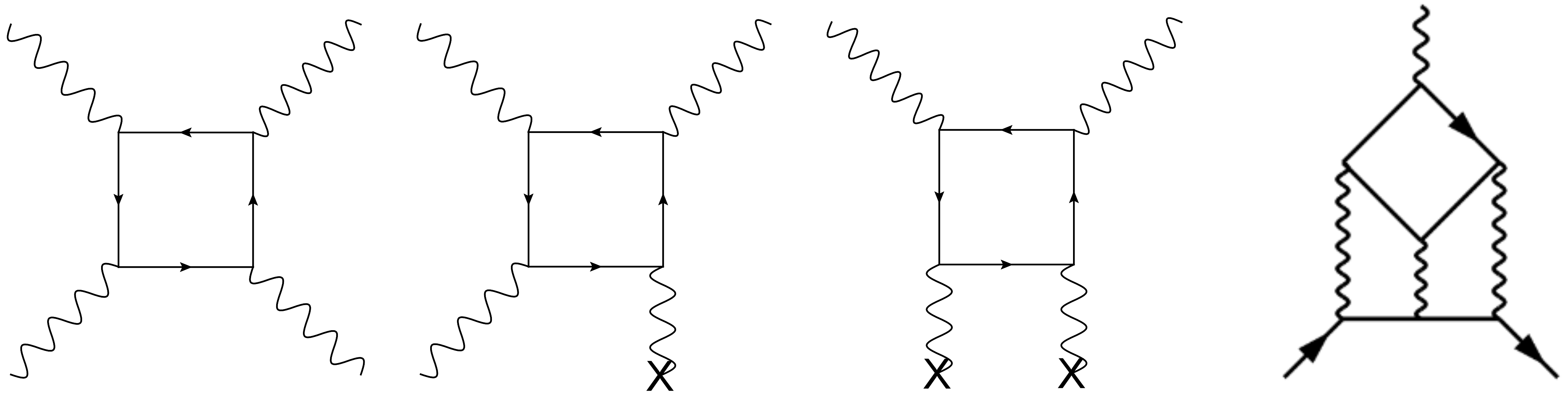


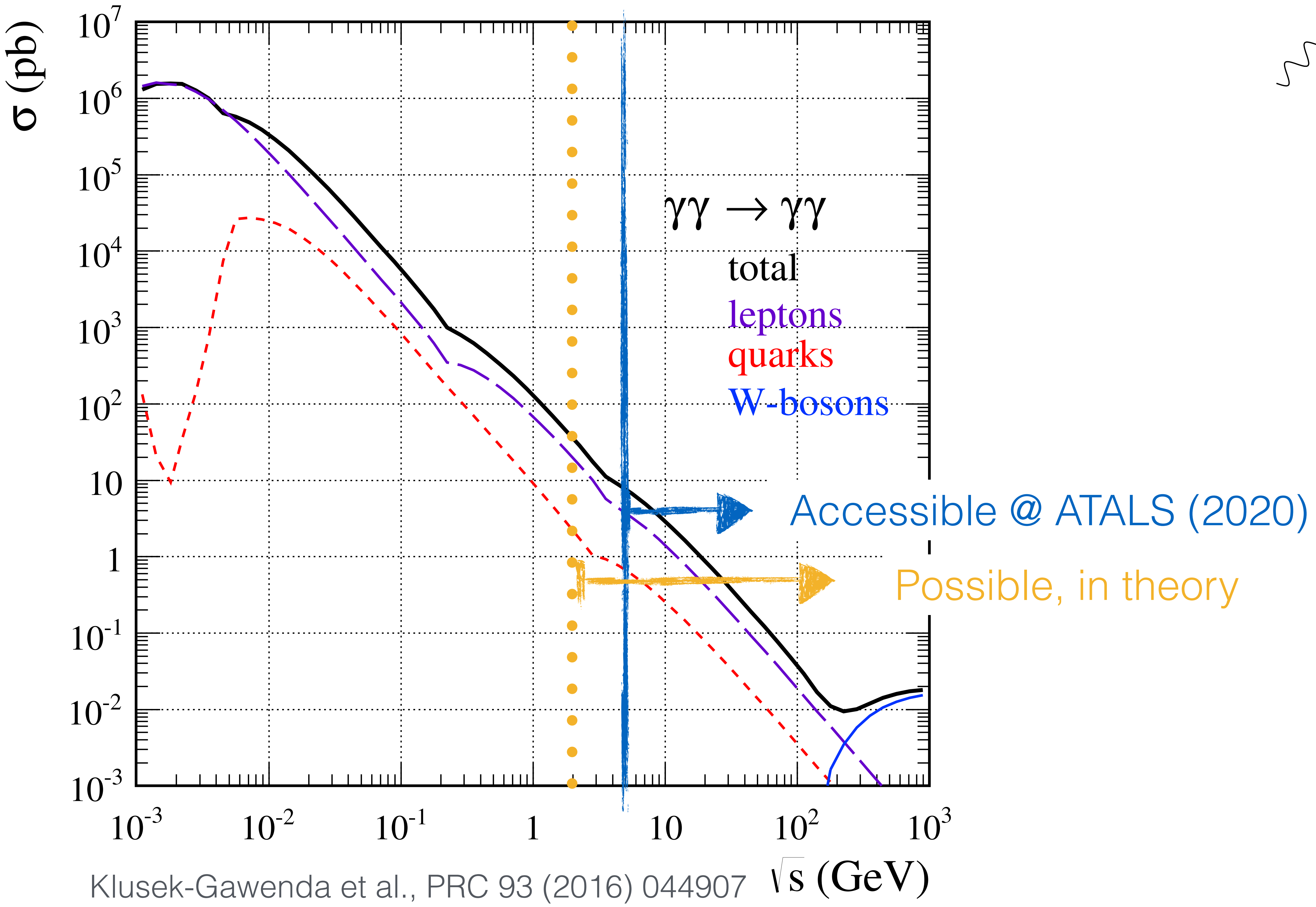


- Photon-Pomeron: e.g. exclusive J/Psi production
- Photons - Gluon: photo production of jets
- Photon - Photon:
  - Producing fermion pairs (e.g. e^+e^-)
  - Light - by - Light scattering
    - QED interaction
    - Mediated via box-diagram
    - Beam particles stay intact

Overview of Light-by-Light scattering





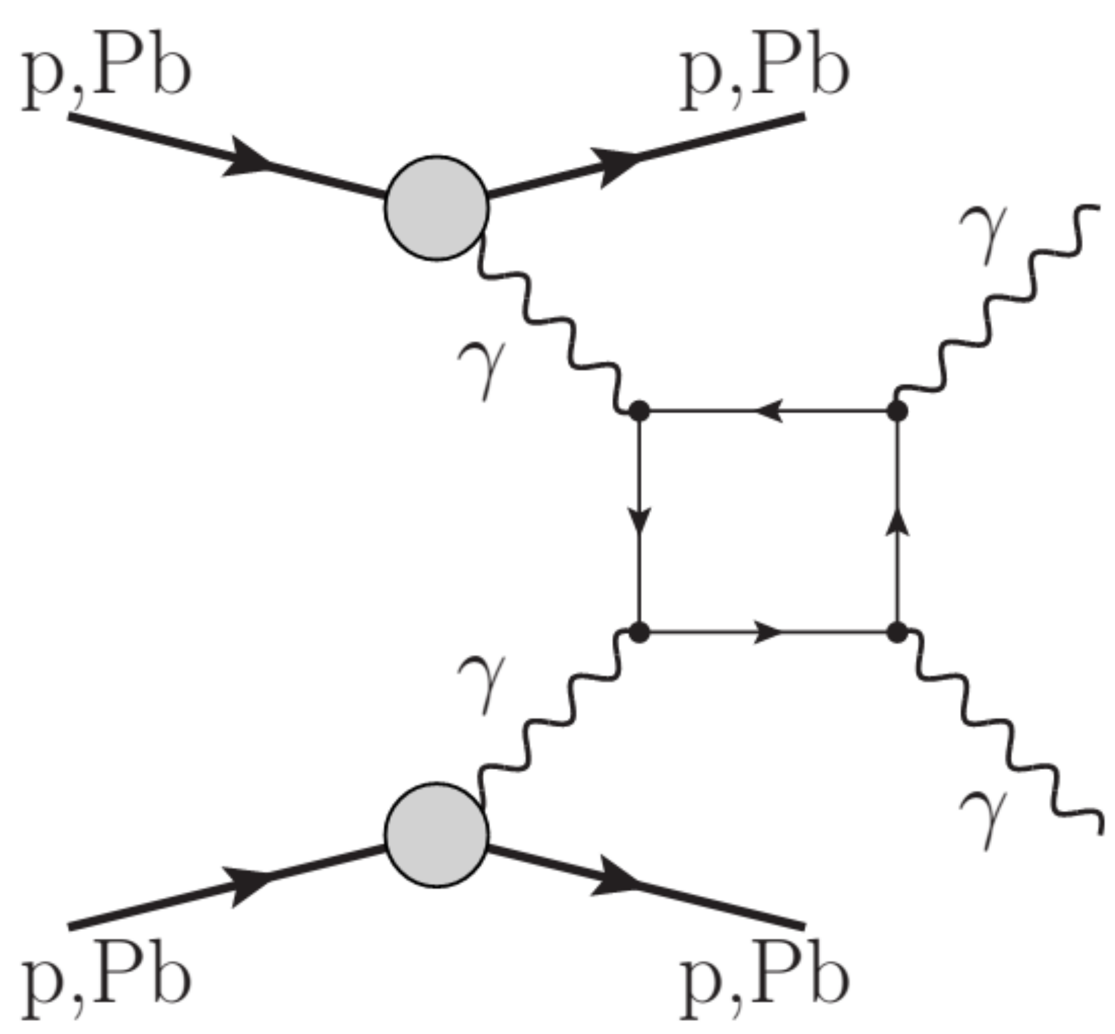


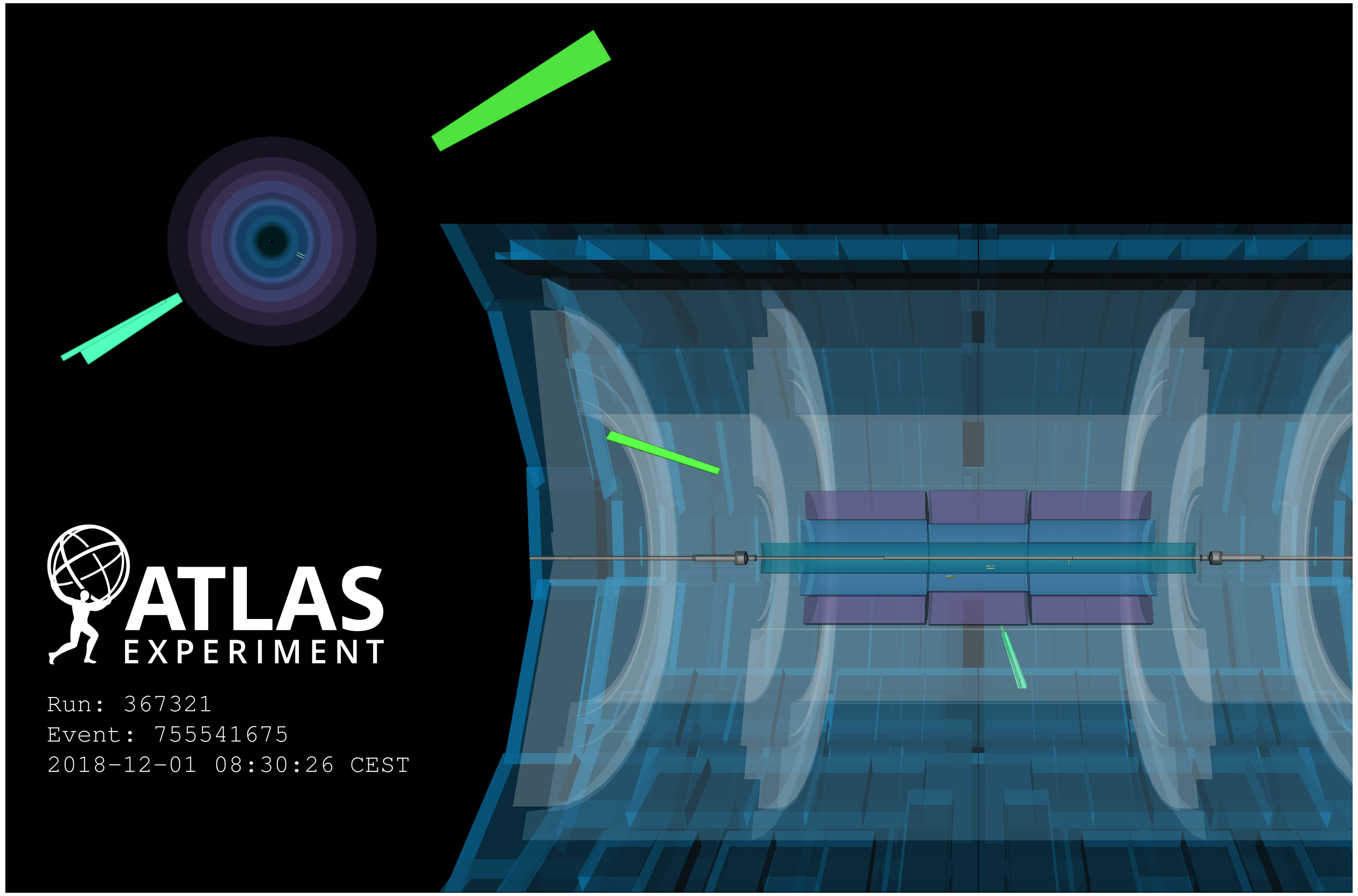
Klusek-Gawenda et al., PRC 93 (2016) 044907

- Cross section box-diagram
  - Broken down by particle type in loop
- Cross section of elementary process: ~10 pb

Brief history of $\gamma\gamma \to \gamma\gamma$ measurements @ LHC

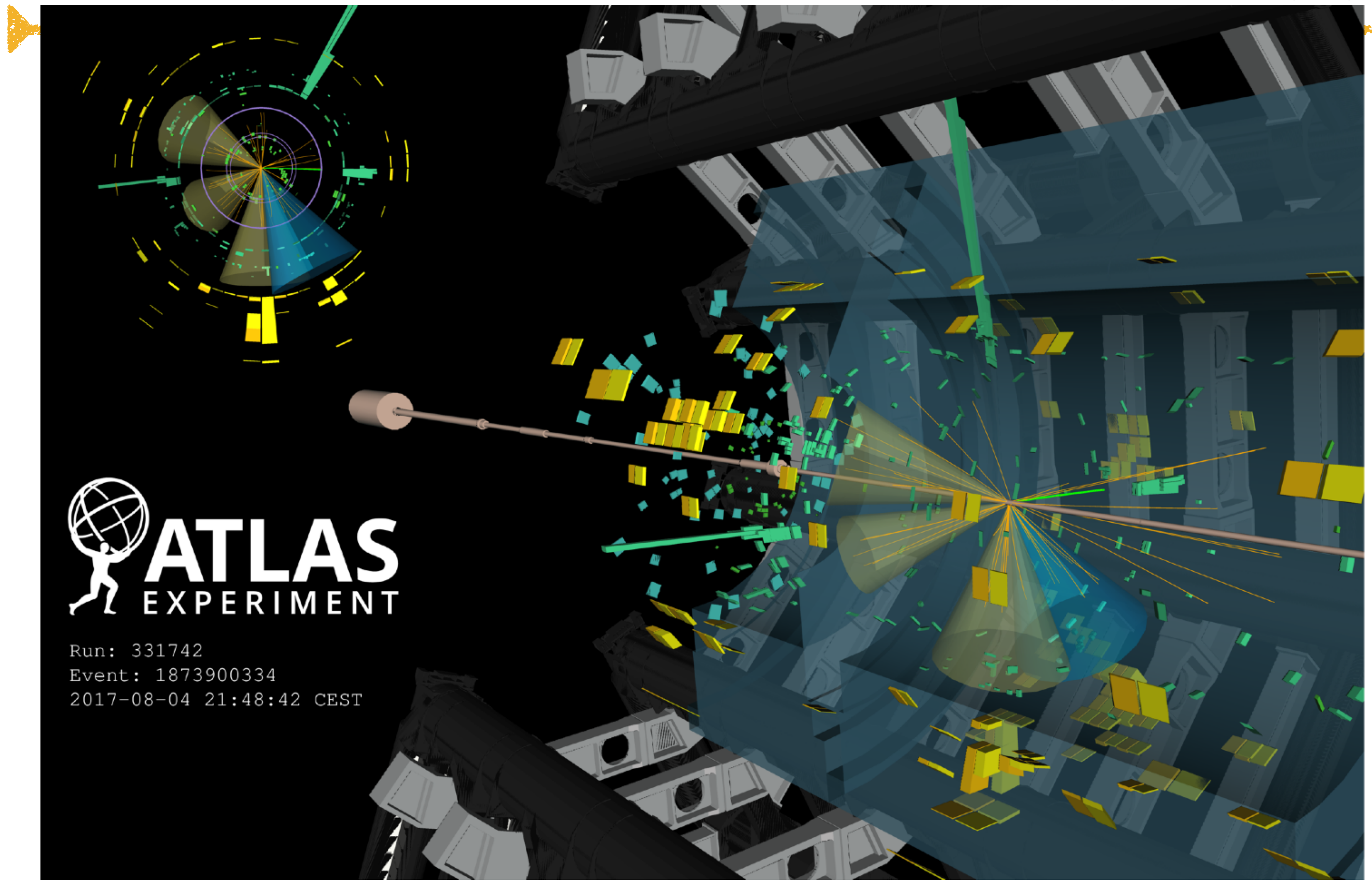
	Evidence	Obervation	Measurement
ATLAS:	2016: Nature Physics 13 (2017) 852	2019: Phys.Rev.Lett. 123 (2019)	2020: JHEP 03 (2021) 243
CMS:	2019: Phys. Lett. B 797 (2019) 134826		2024: Acc. in JHEP



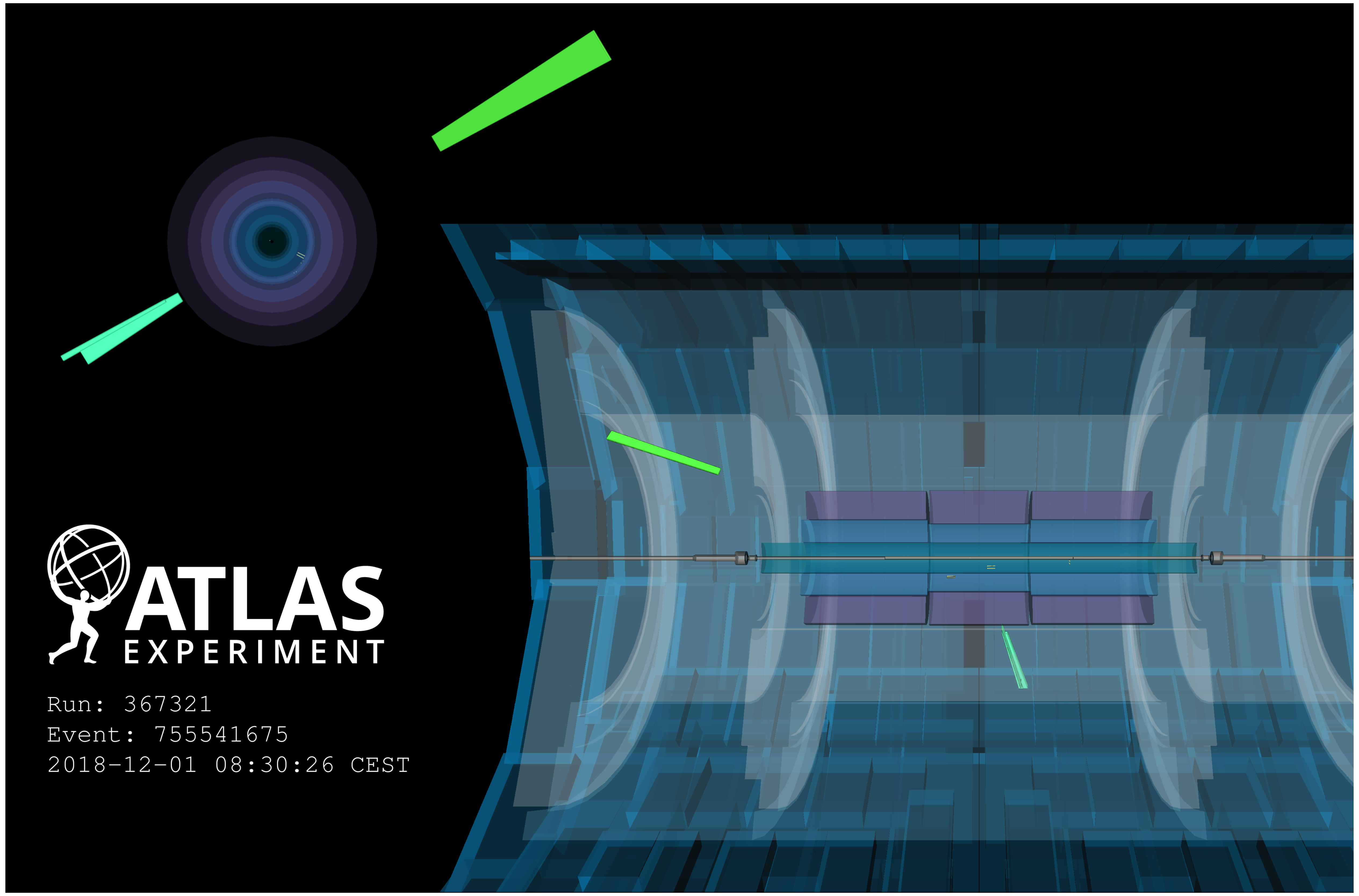


How to measure the $\gamma\gamma \to \gamma\gamma$ process

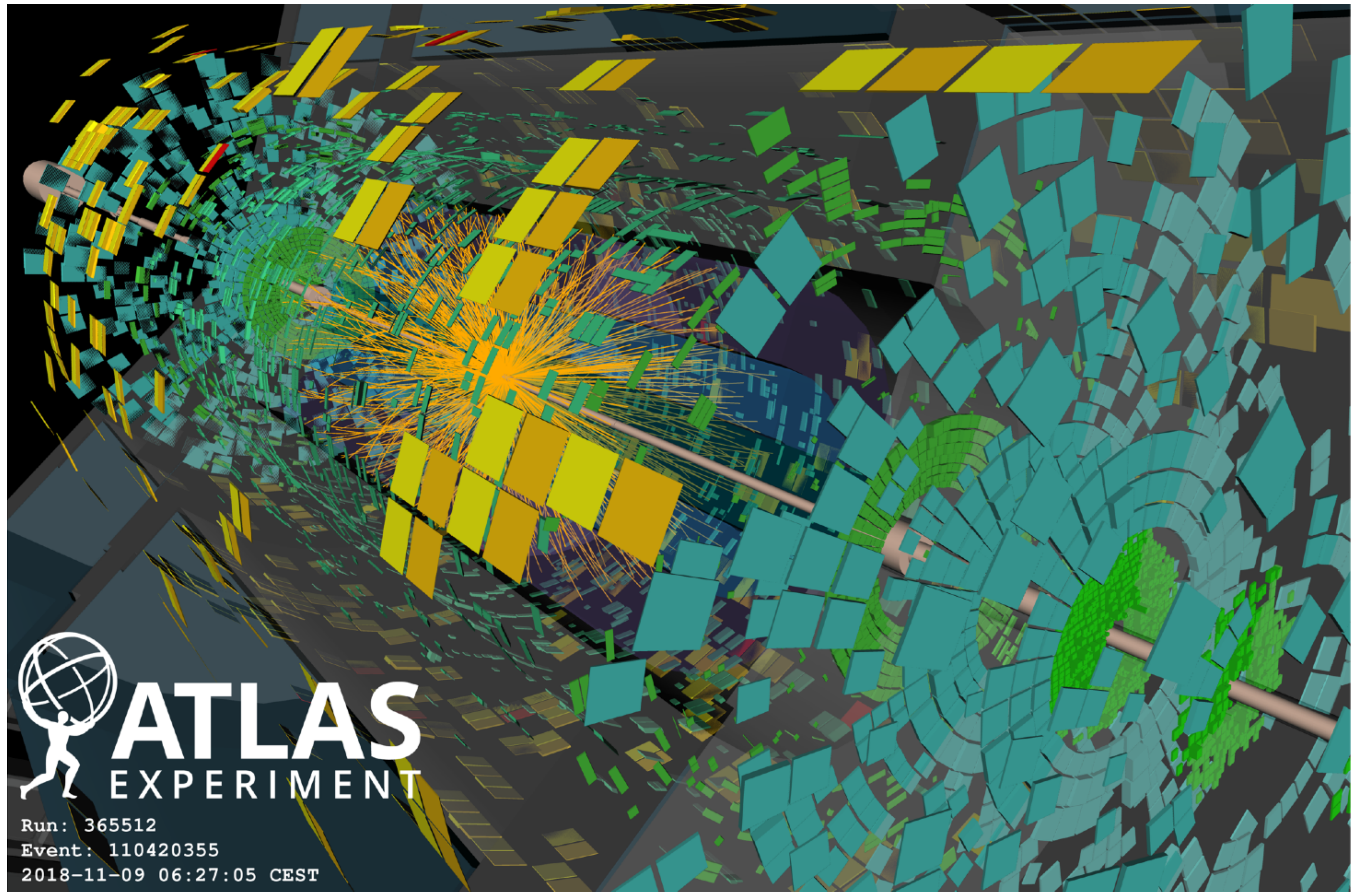
- pp collision



- Light-by-Light scattering candidate event

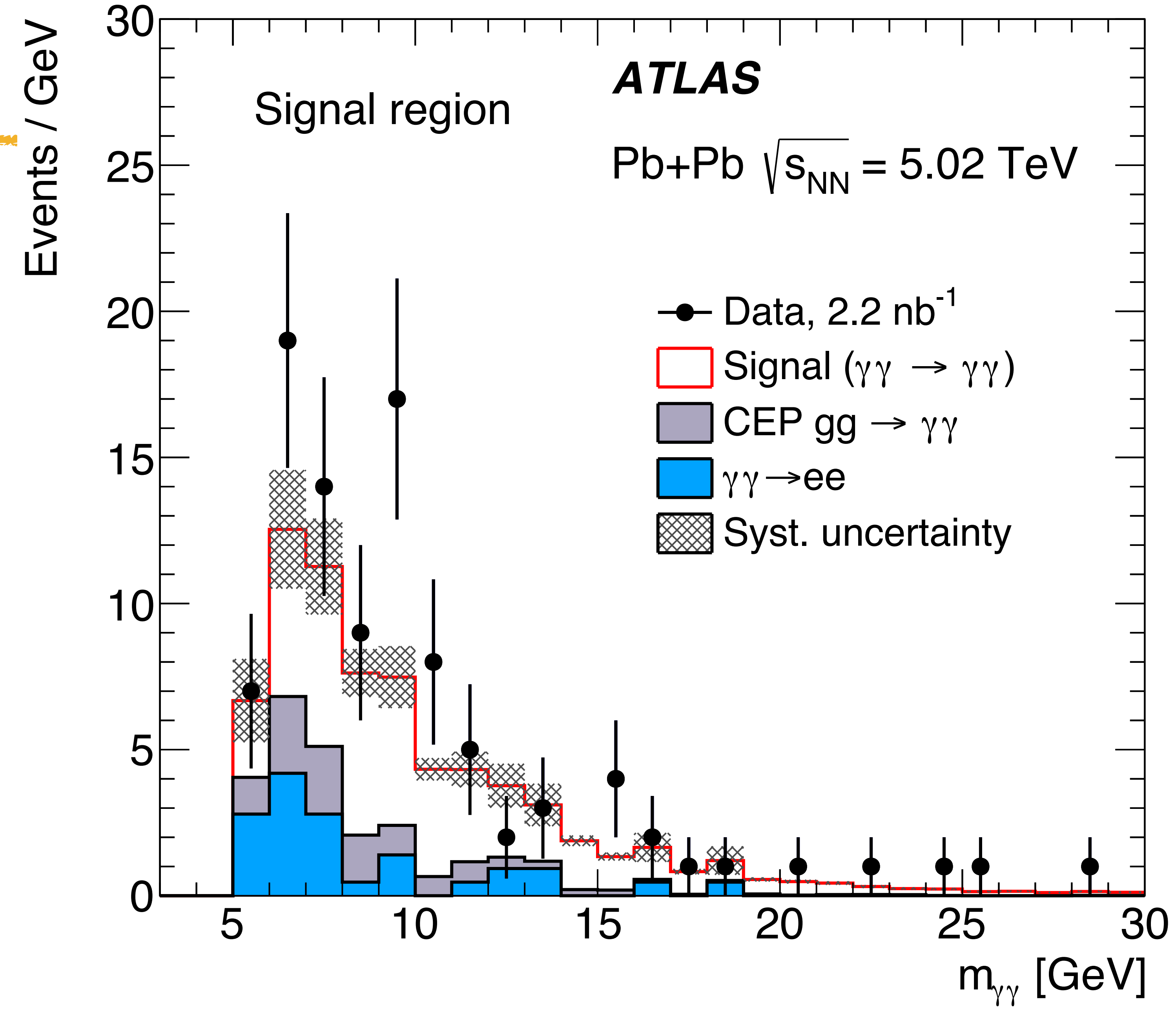


- PbPb collision



Most Recent Results

- **ATLAS**: 2018 + 2015 Data: **2.2 nb^{-1} of PbPb** data analysed
  - **97 Events observed**, Background: 27 ± 5



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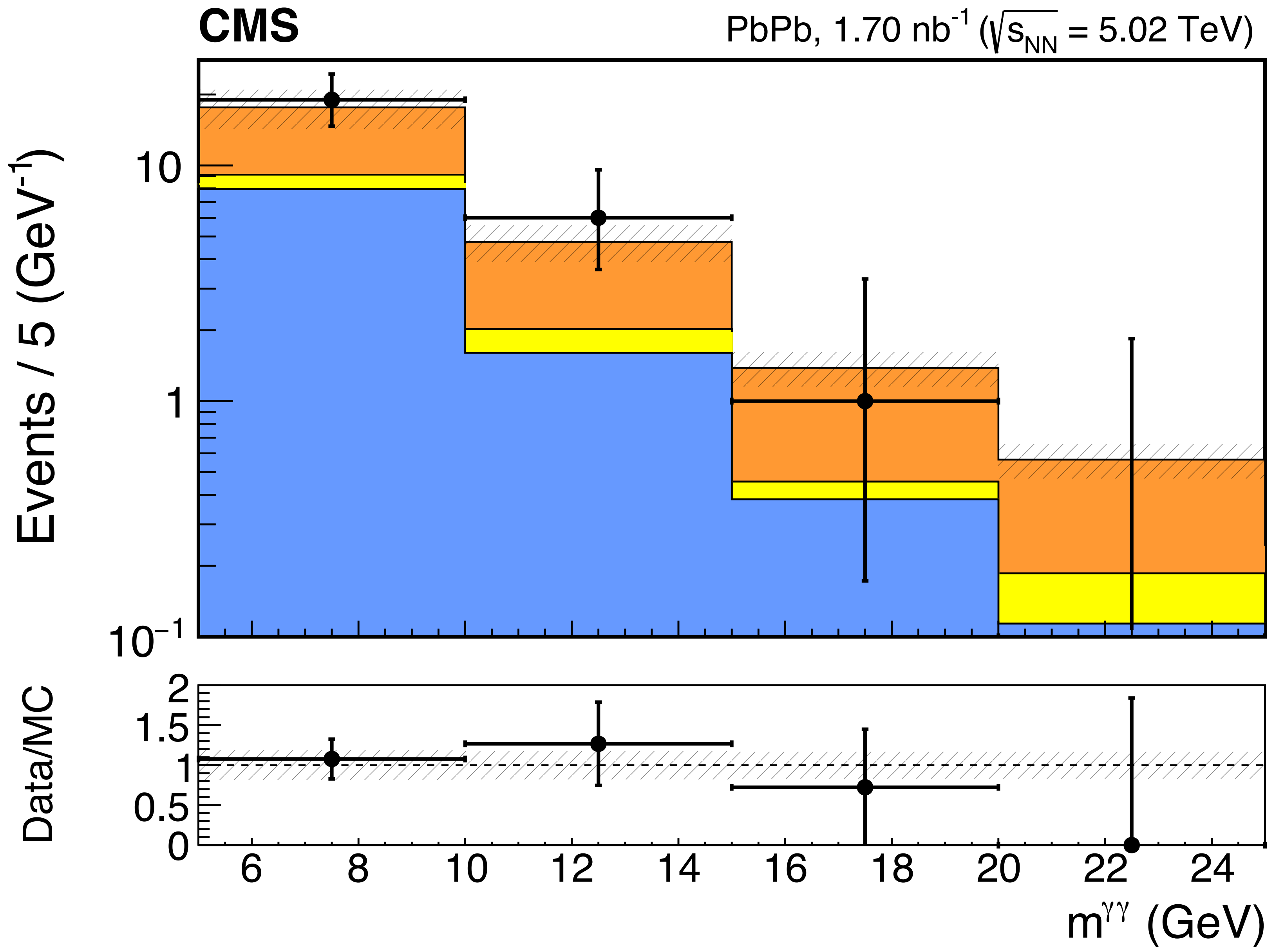

Most Recent Results

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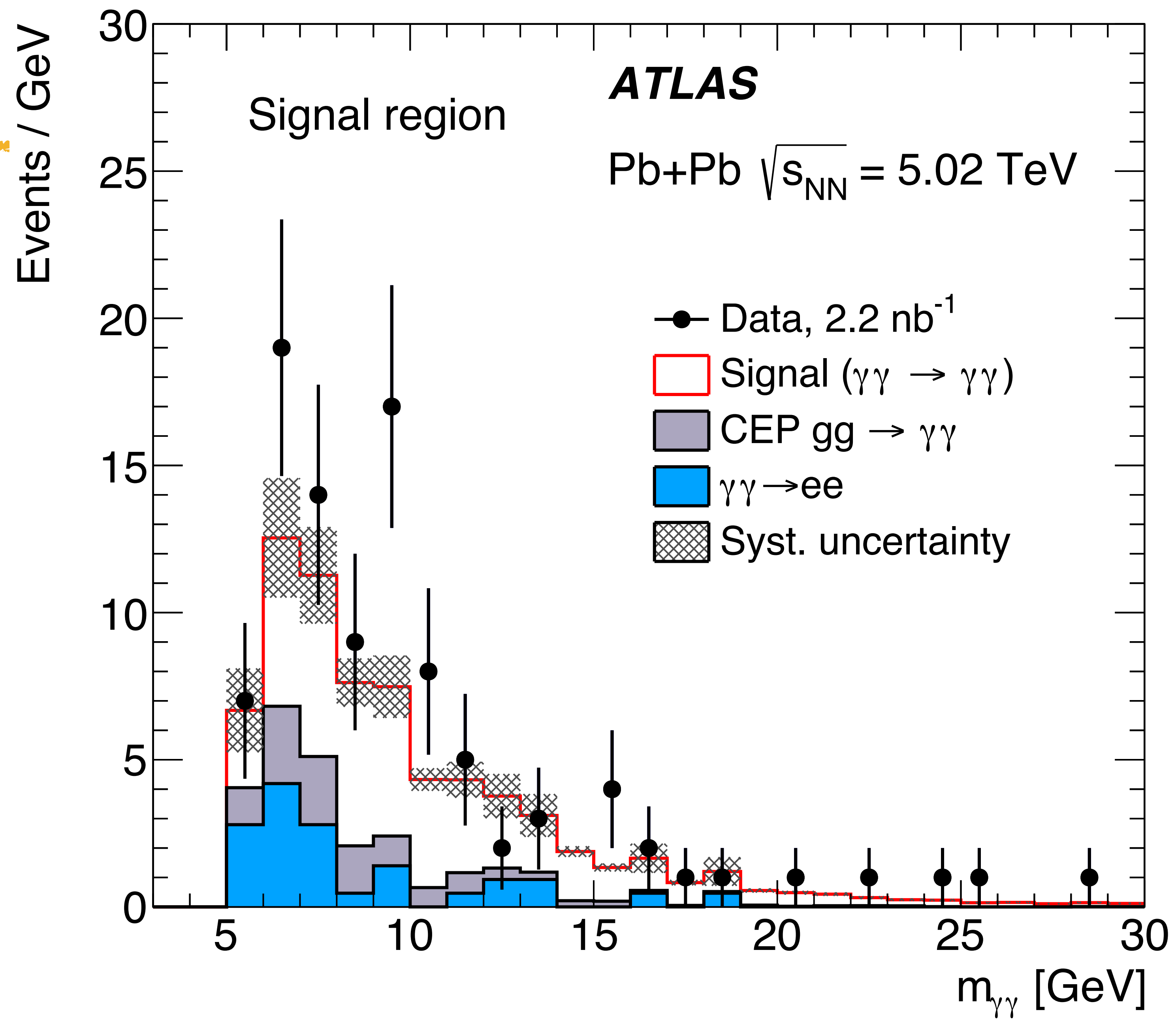
  - Cross section:
    - Measured: 120 ± 17 (stat) ± 13 (sys) ± 4 (lumi) nb
    - SuperChic3.0: 78 ± 8 nb
  - Ratio data / MC: 1.5



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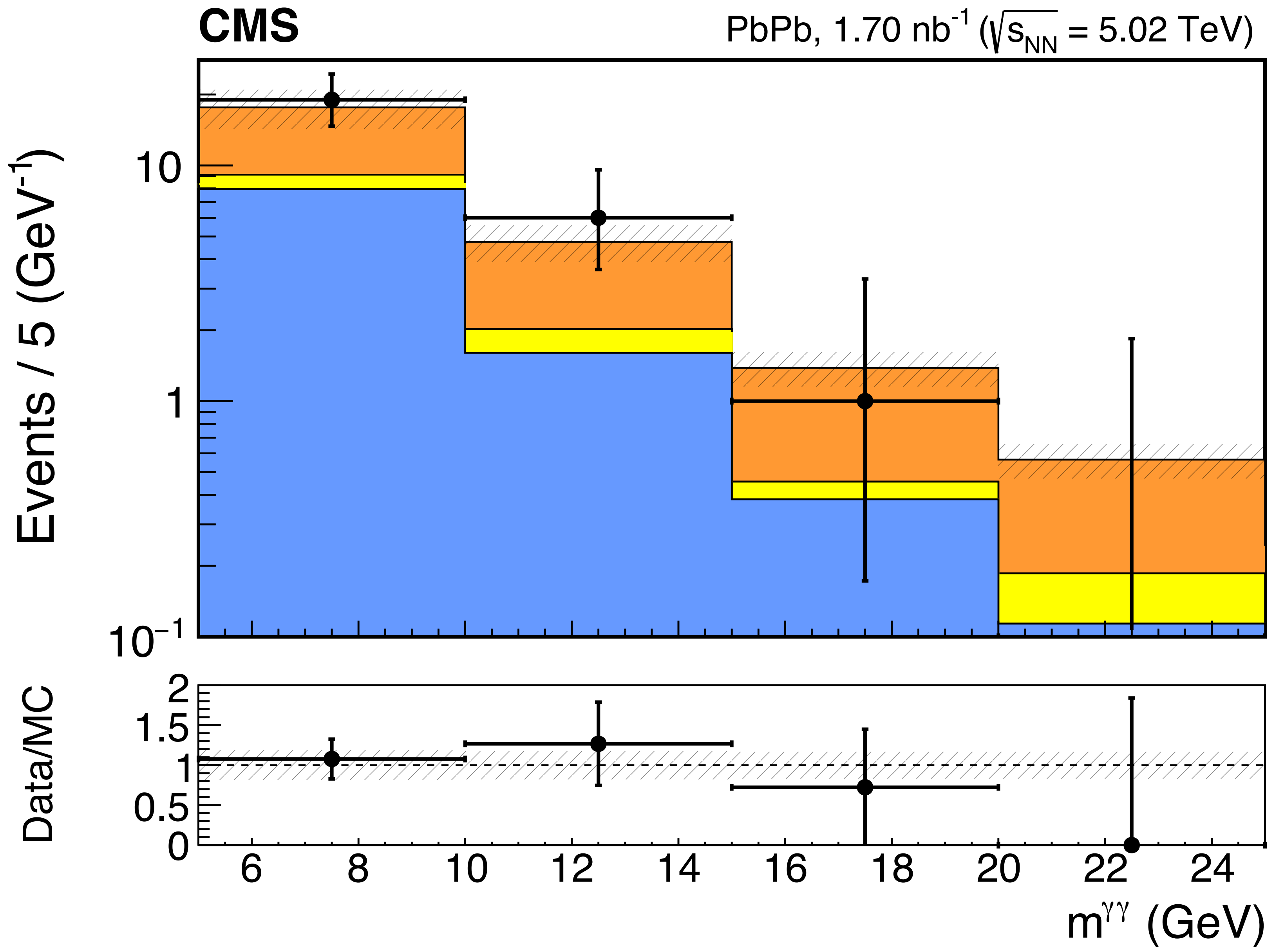

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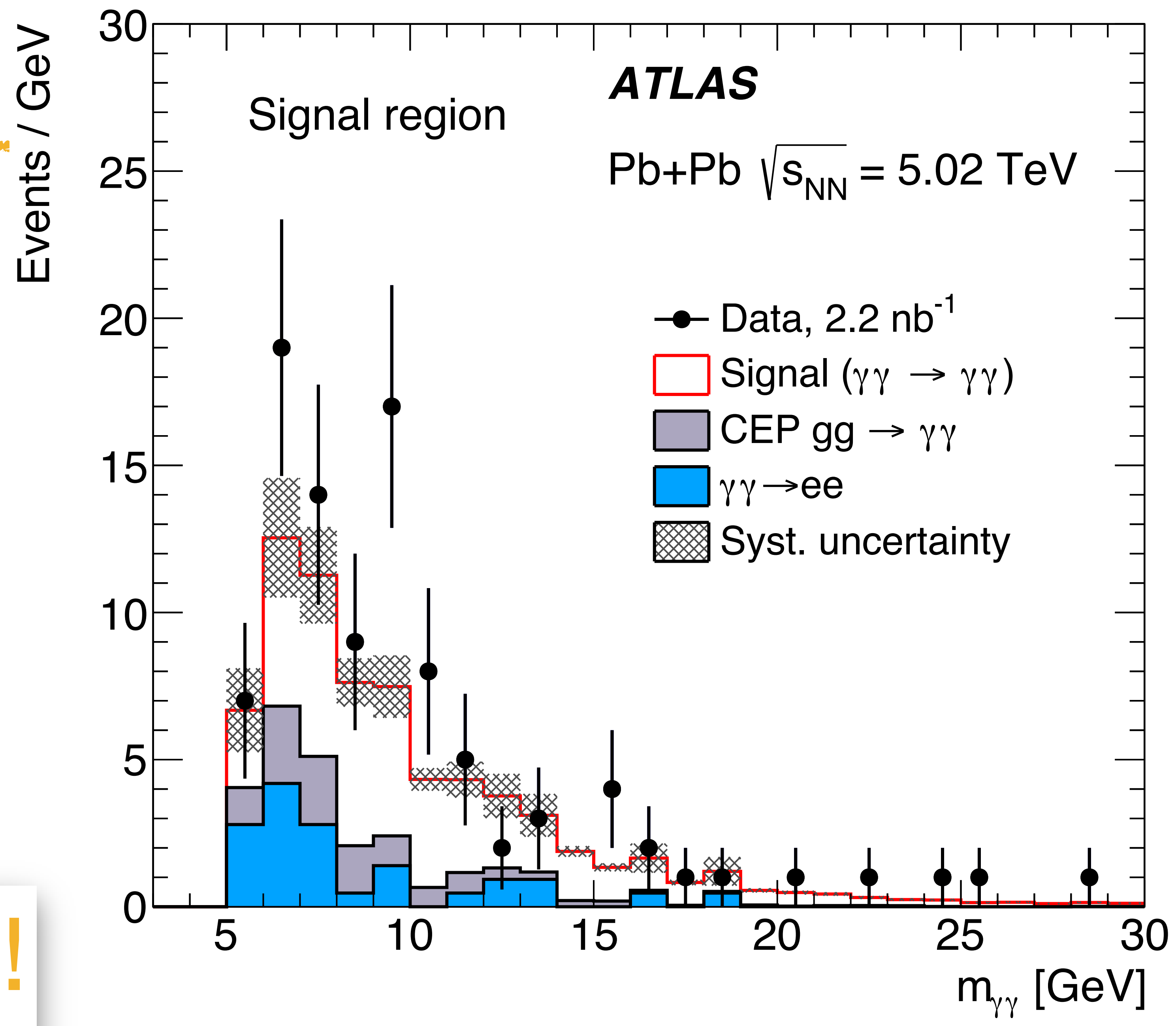

Significantly different Acceptances!

=> Photon reconstruction, Trigger

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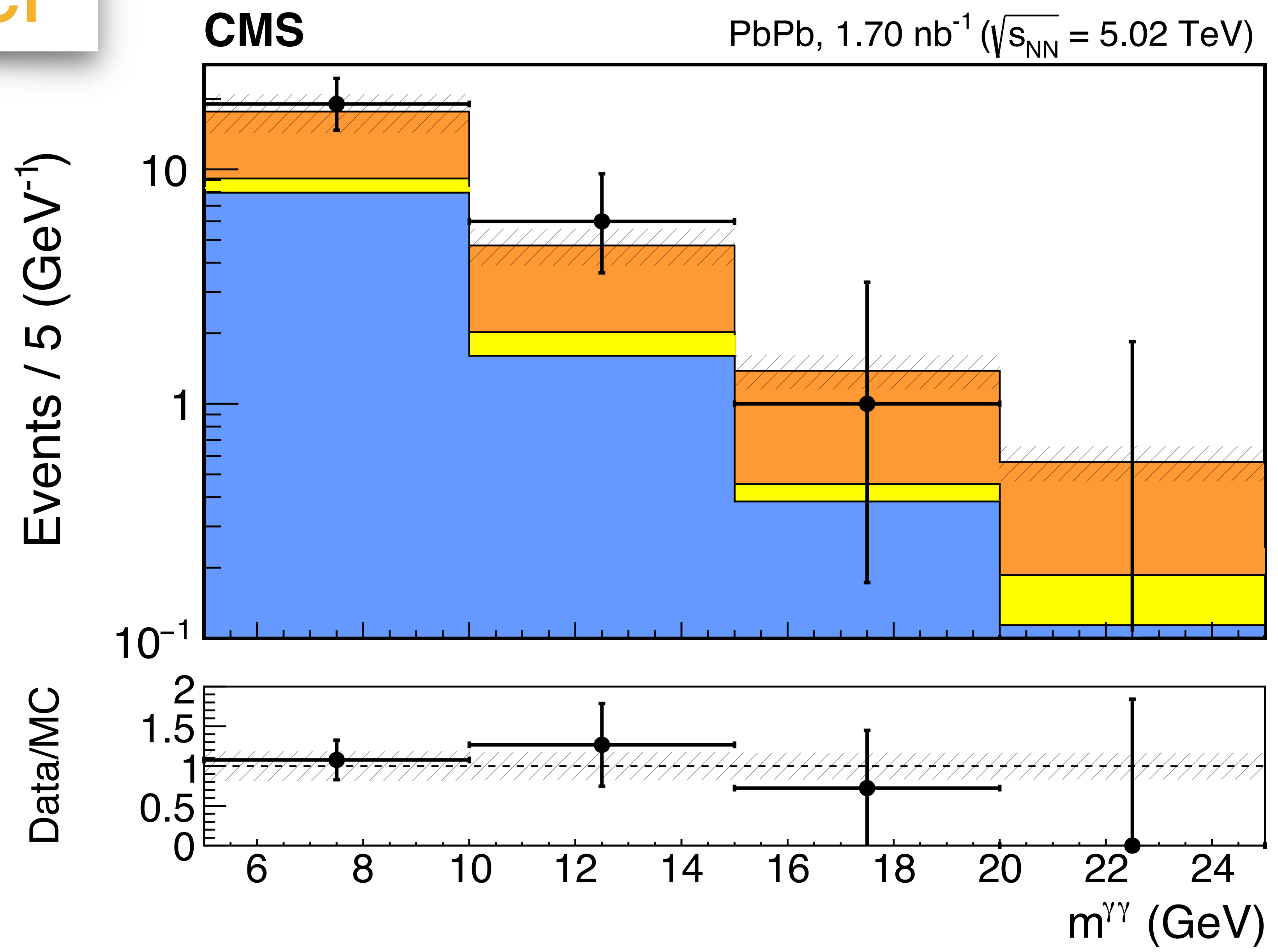
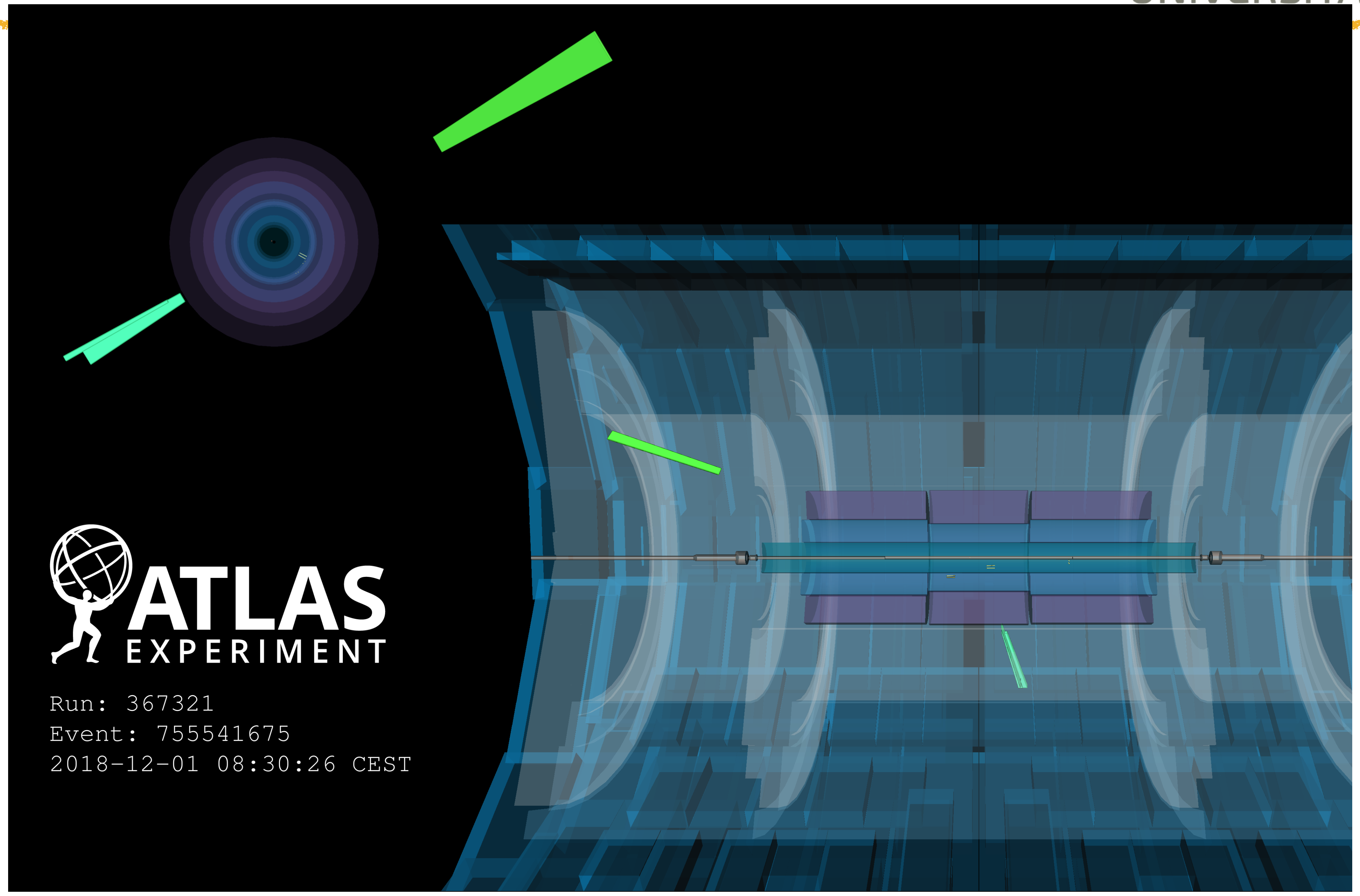


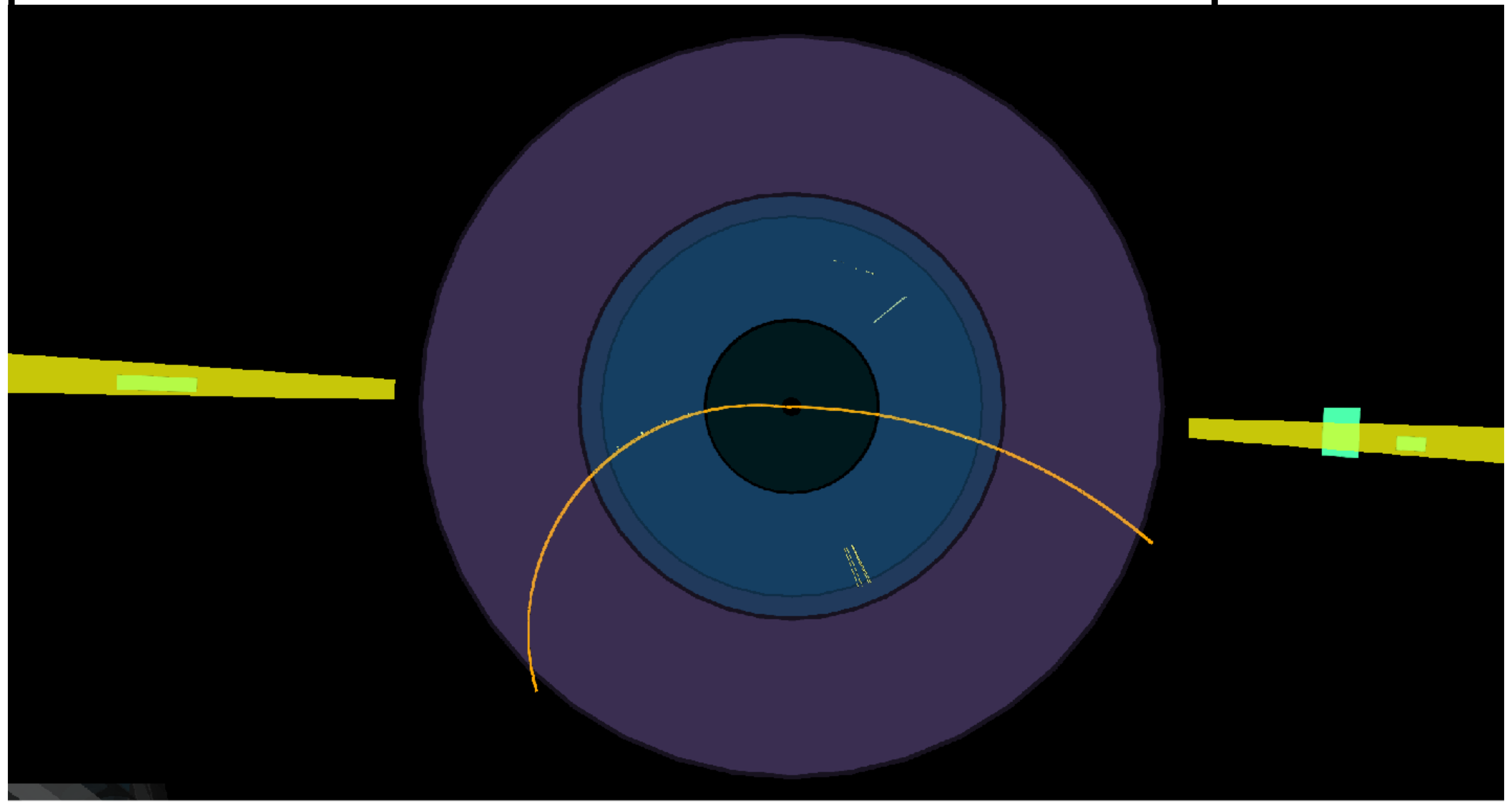
How to measure the $\gamma\gamma \to \gamma\gamma$ process

Event Selection

- Trigger
- Exactly 2 photons with
  ATLAS: $E_T > 2.5$ GeV && $|\eta| < 2.37$, Excluding $1.37 < |\eta| < 1.5$
  CMS: $E_T > 2$ GeV && $|\eta| < 2.2$
- Invariant di-photon mass $M_{\gamma\gamma} > 5$ GeV
- Exclusivity requirements
  - No reconstructed tracks ($p_T > 100$ MeV)
  - Similar for CMS
- Back-to-Back topology
  - $p_T(\gamma\gamma) < 1$ GeV (rejects cosmic muons)
  - Reduced acoplanarity < 0.01 ($A_\phi = 1 - |\Delta\phi| / \pi$)



$\gamma\gamma \to e^+e^- \to e\gamma\ e\gamma$ candidate event:

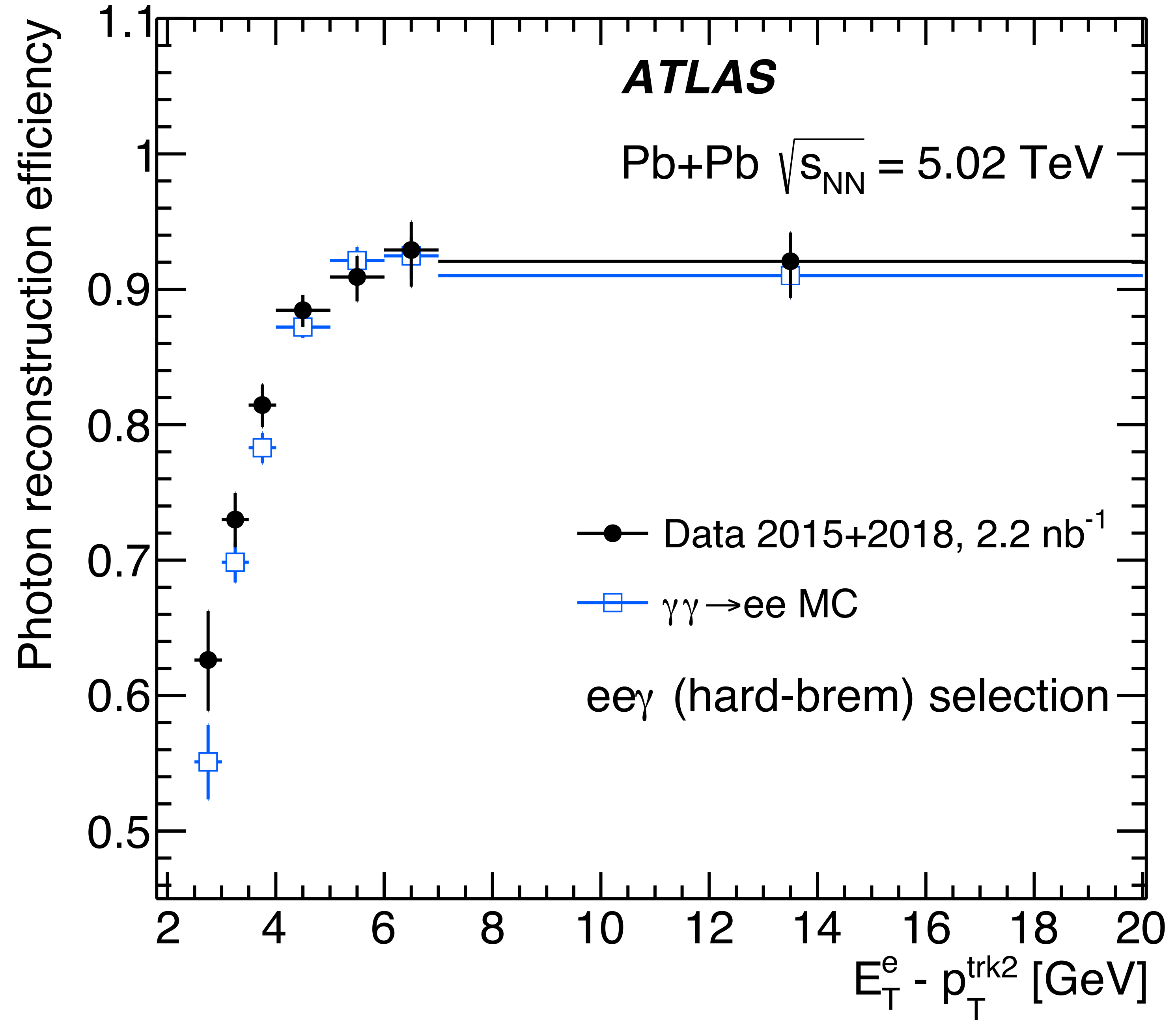


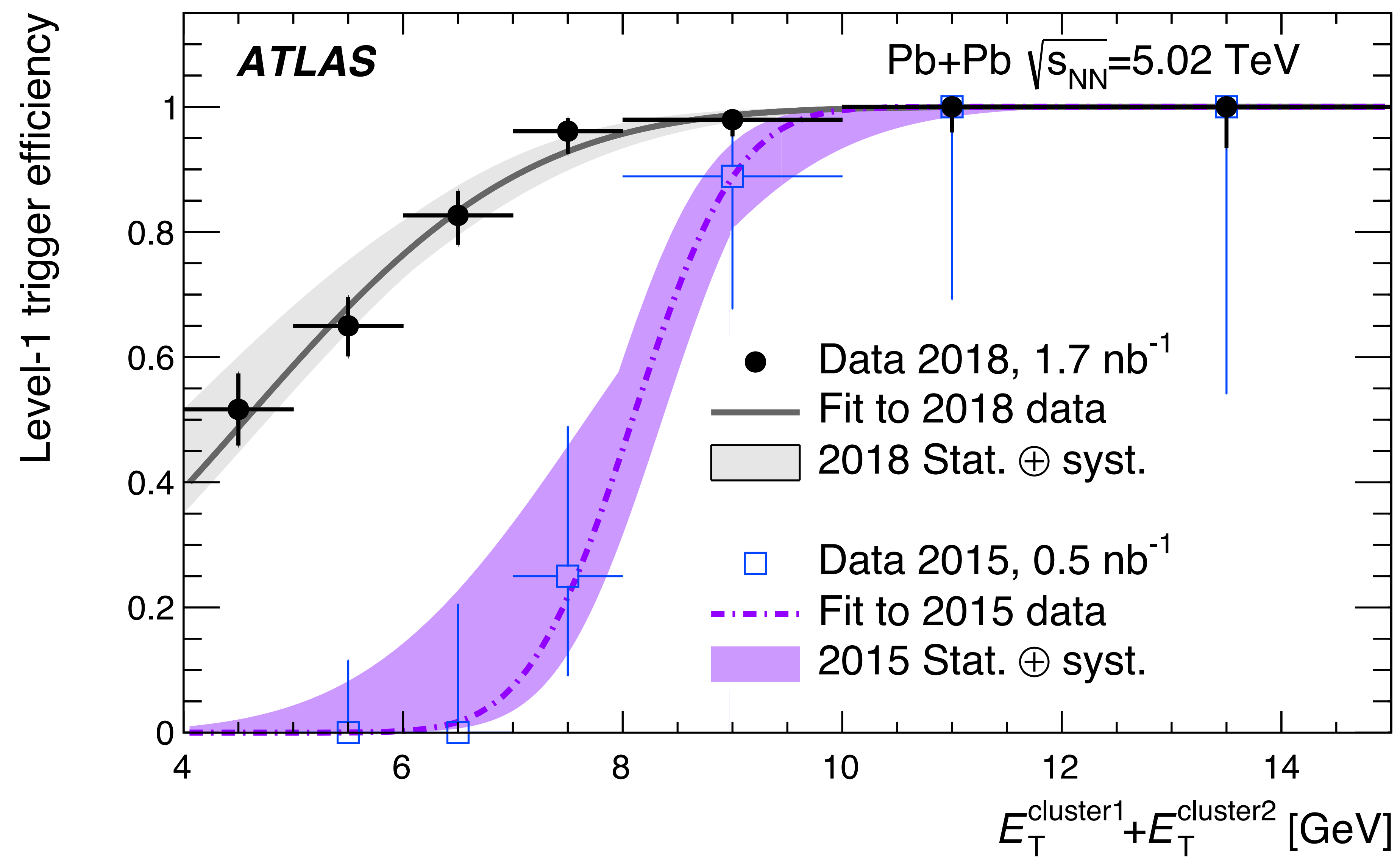
How to measure the $\gamma\gamma \rightarrow \gamma\gamma$ process

Efficiencies

- **CMS**: corrected di-photon Efficiency: 8.0 (1.1) %
  - Photon reconstruction: 76.7 %
  - **Photon ID: 50.0%**
  - Di-Photon Trigger: 80%

- **ATLAS**:
  - Photon reconstruction: 63% - 92%
  - **Photon ID: 95%**
  - Di-Photon Trigger: 50% - 100%





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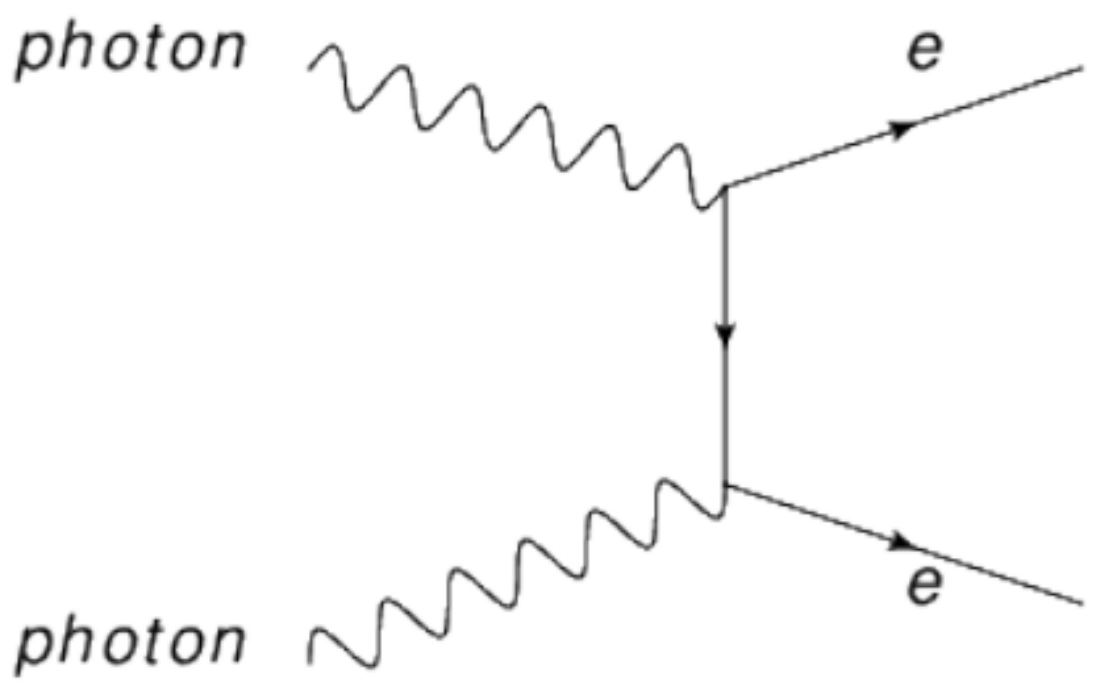
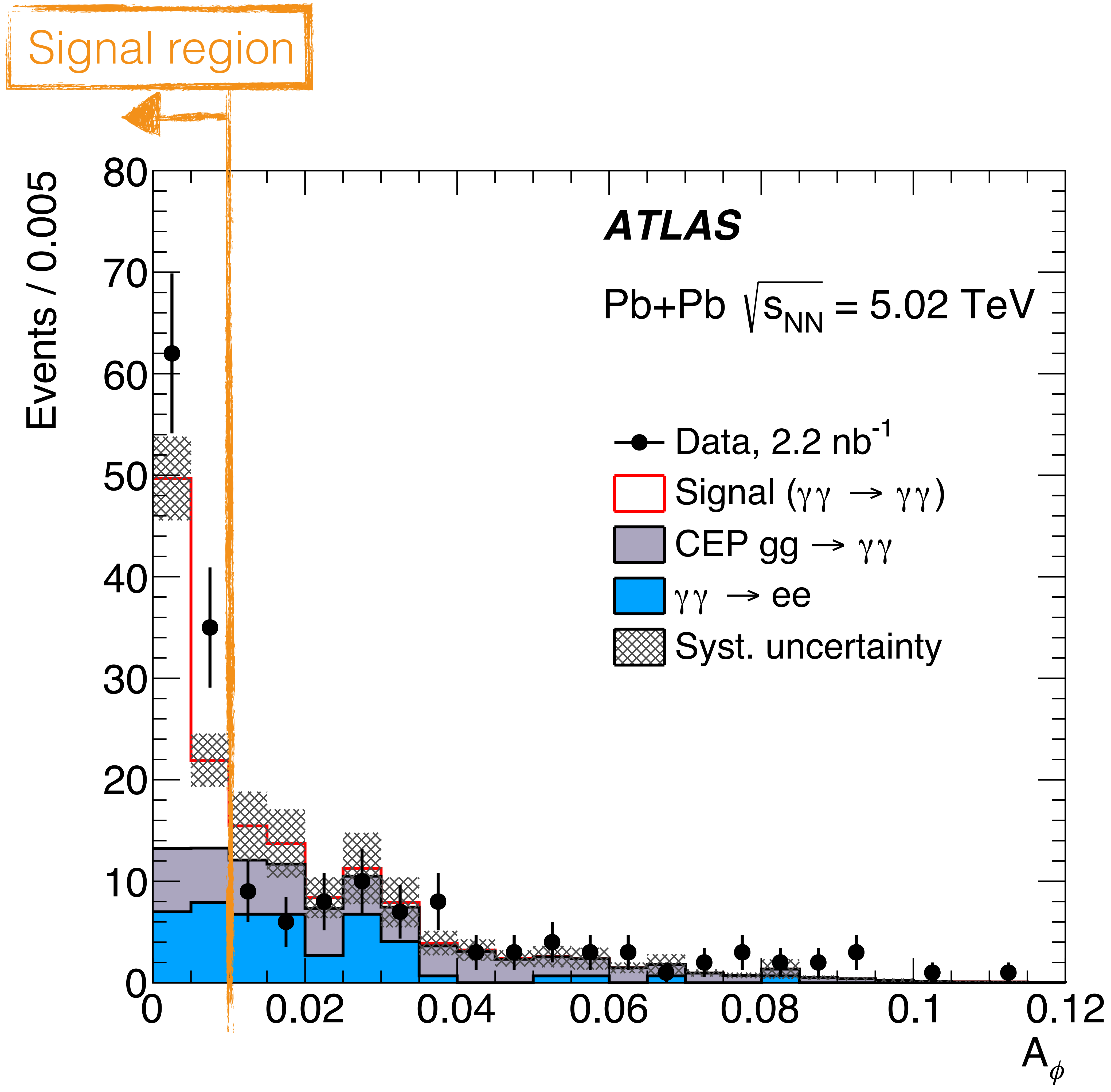
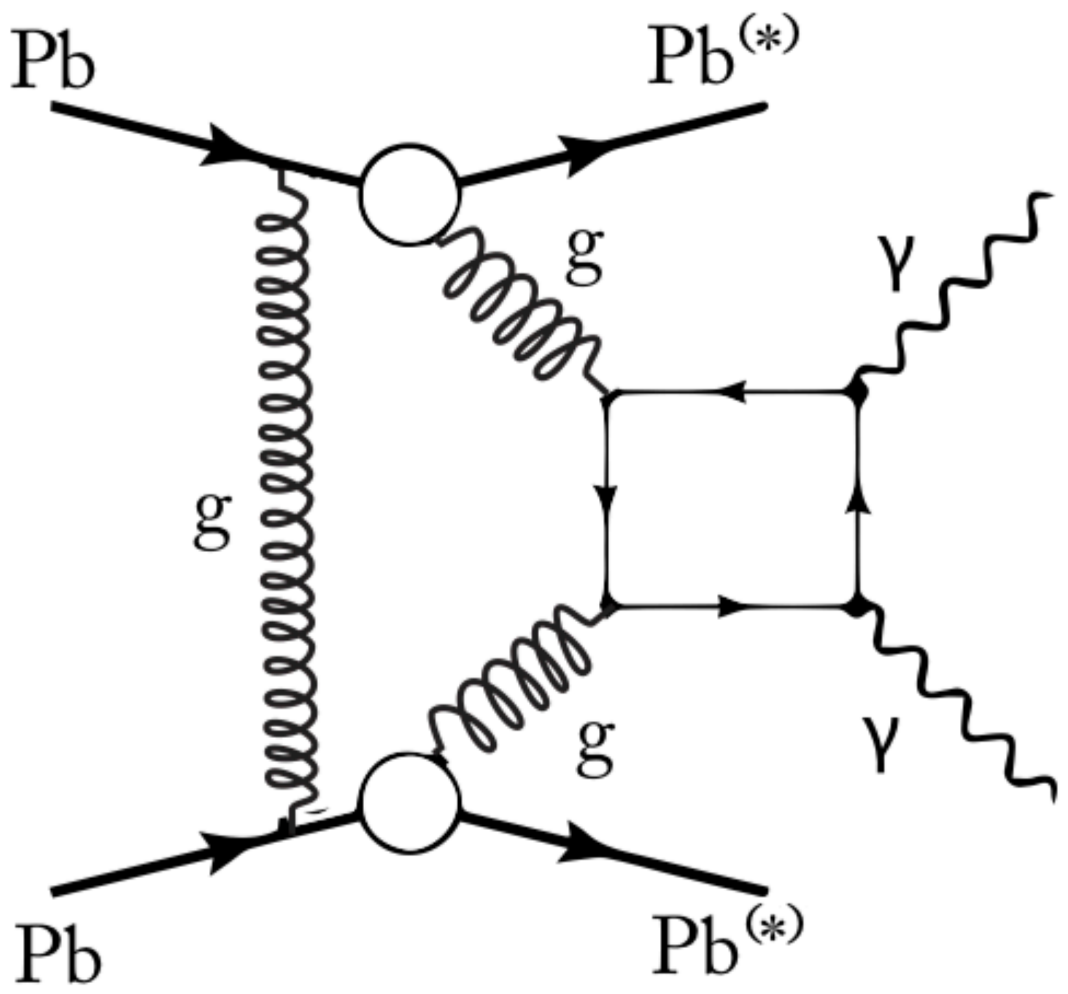
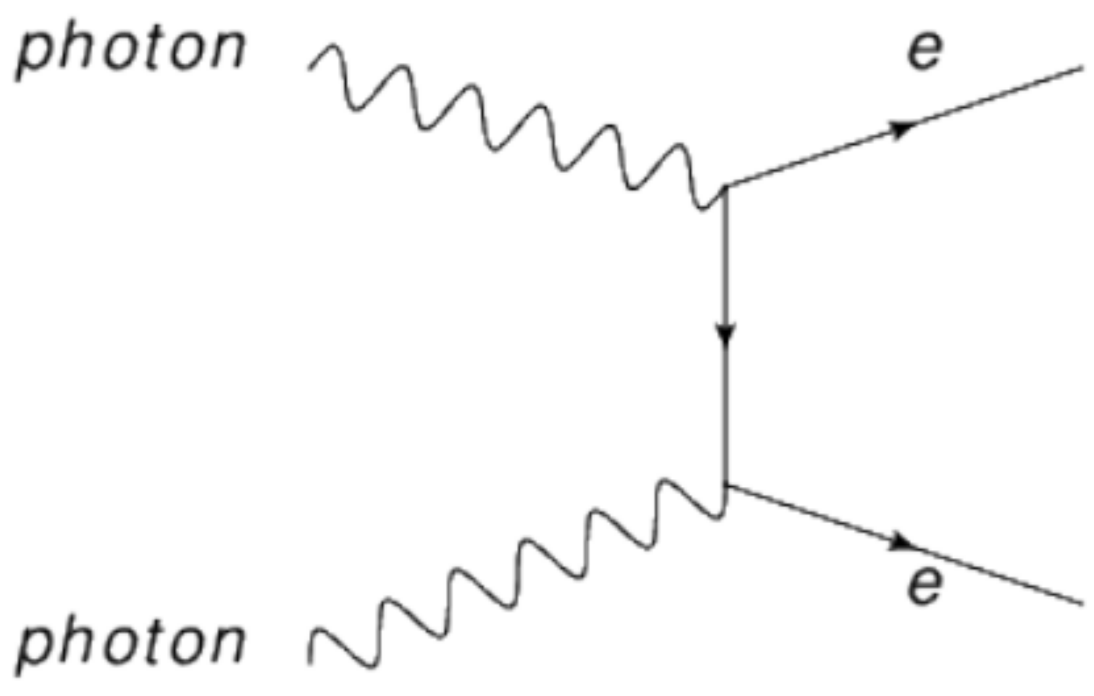


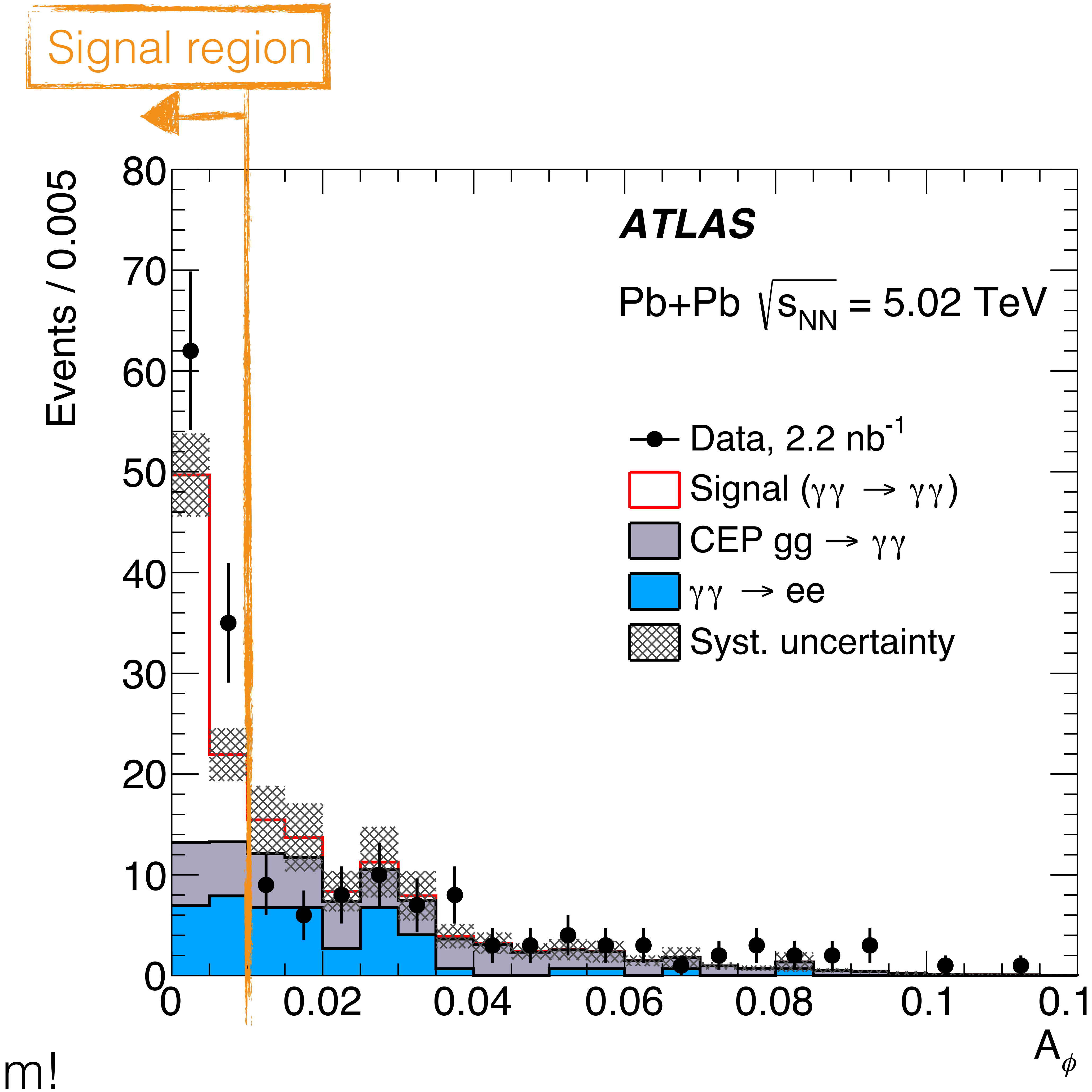


- Two main background contributions:
  - Exclusive production of **e^+e^- electron pairs**
    - Both electrons misidentified as photons
    - Broader A_ϕ distribution compared to signal
      - Electrons bent in magnetic field

Background processes







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    - Both electrons misidentified as photons
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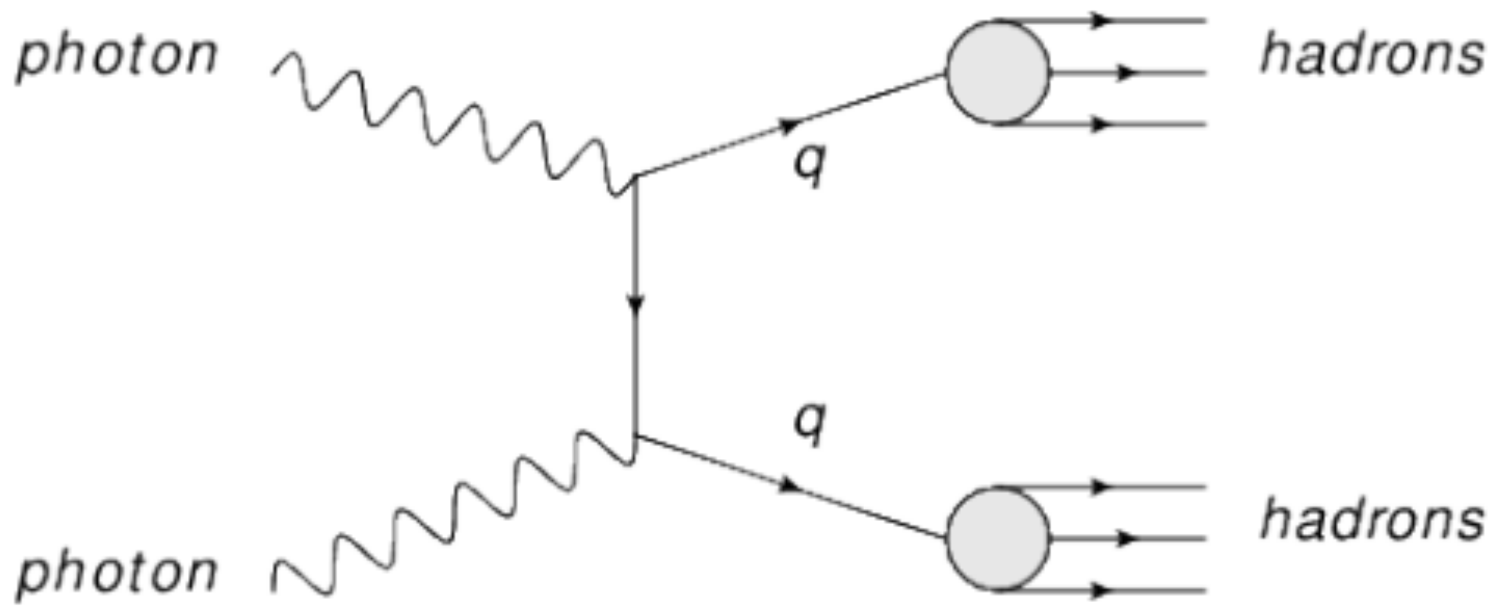
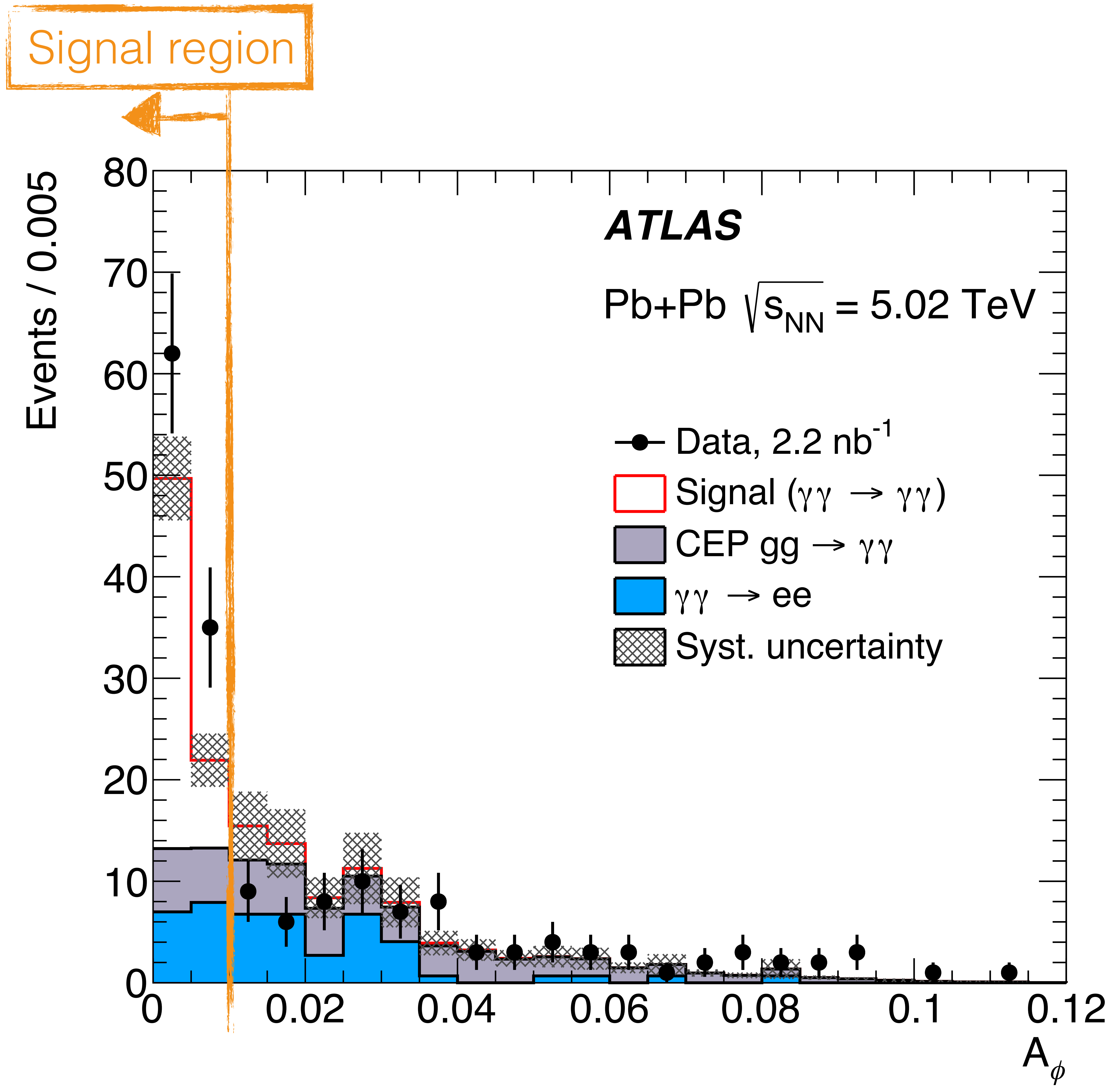
- Central Exclusive Production of 2 photons (**CEP**): **gg → $\gamma\gamma$**
  - Coloured initial state: significant intrinsic transverse momentum!
  - Broader shape of $A\phi$ distribution

Background processes

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

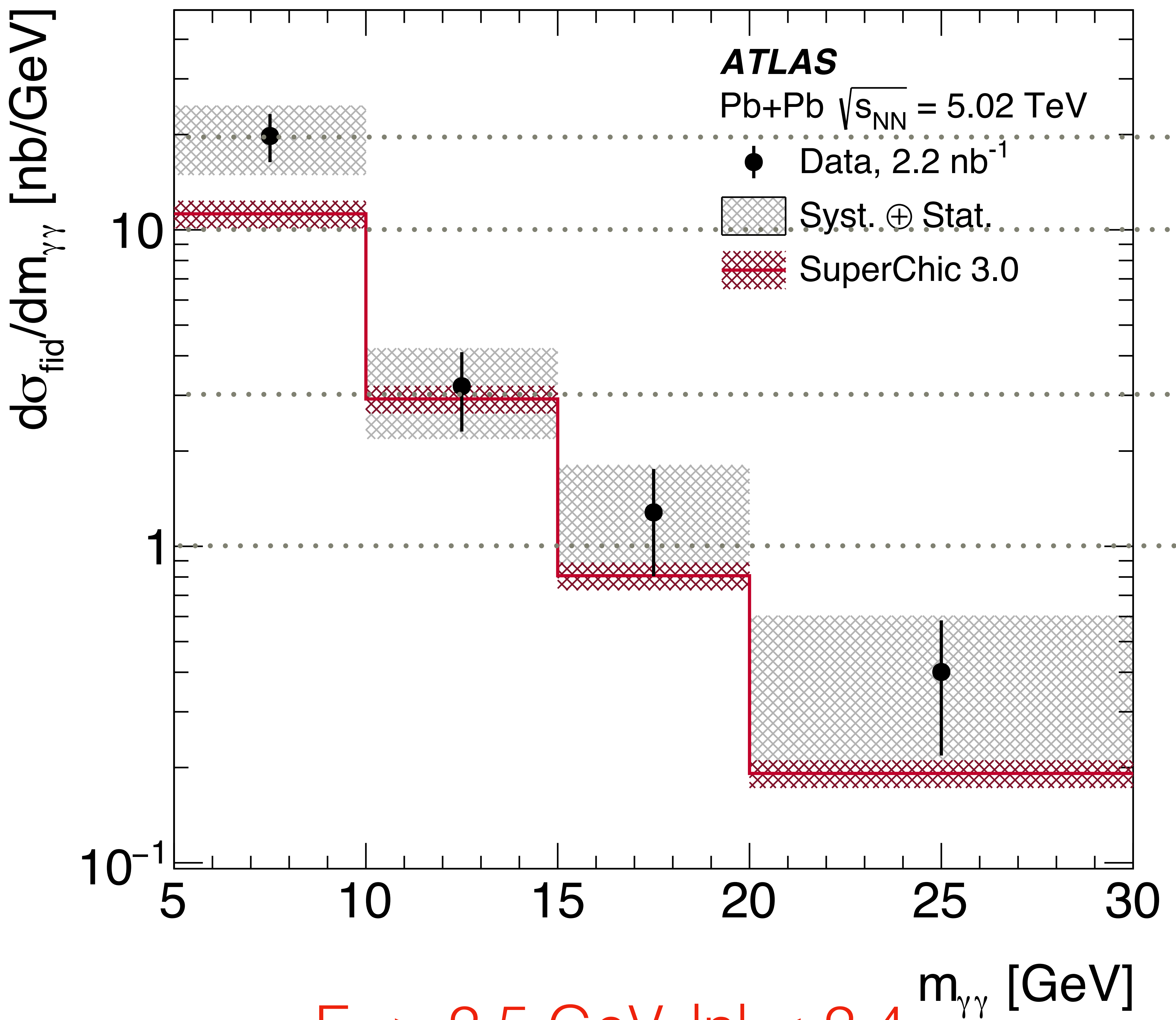




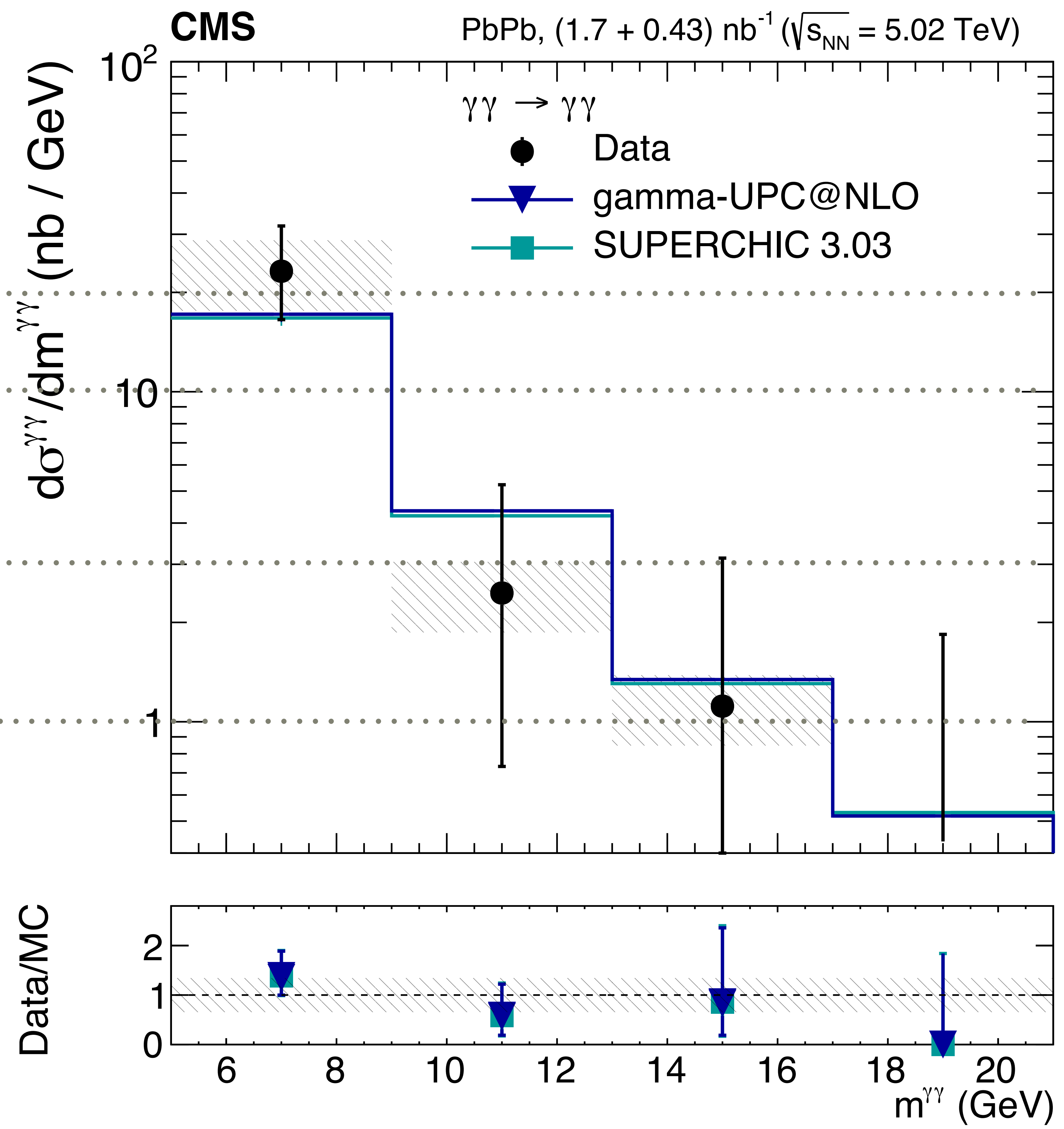
Unfolded fiducial cross section

- Measured data unfolded to remove detector effects
- Within fiducial volume
  - Slightly different for CMS and ATLAS!

2020: JHEP 03 (2021) 243



2024: Acc. in JHEP



Fiducial phase space:

ATLAS: $E_T > 2.5$ GeV, $|\eta| < 2.4$, $m_{\gamma\gamma} > 5$ GeV, $p^{\gamma\gamma}_T < 1$ GeV, $A_{\gamma\gamma} < 0.01$

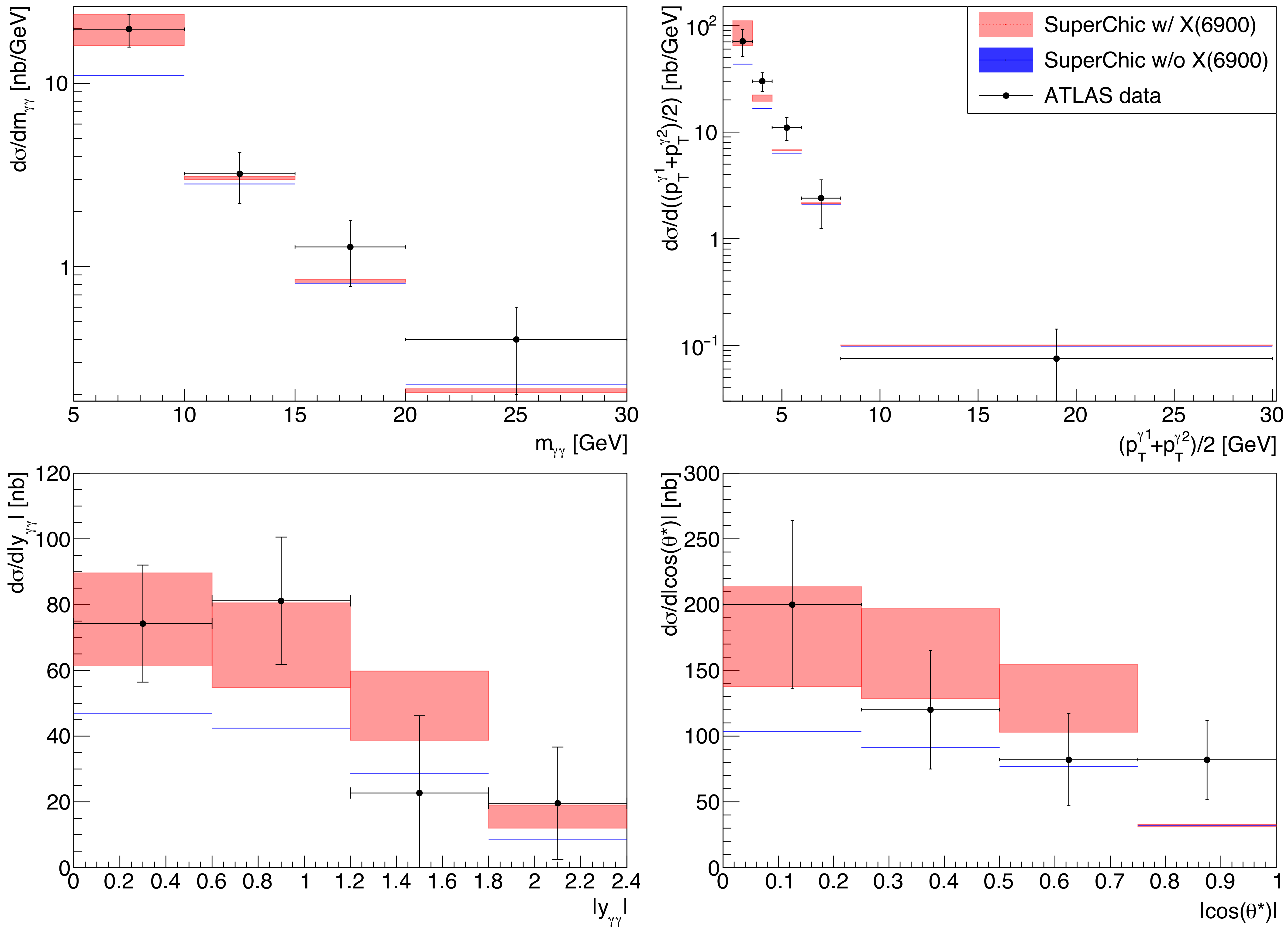
CMS: $E_T > 2$ GeV, $|\eta| < 2.2$, $m_{\gamma\gamma} > 5$ GeV, $p^{\gamma\gamma}_T < 1$ GeV, $A_{\gamma\gamma} < 0.01$

Any new particles hiding there?

What can one find in there? - New Particles

- New state in di-J/ψ mass distribution reported by LHCb => X(6900)
- Possibly lightest fully charmed tetraquark state
- State should couple to photons -> contribute to LyL scattering
- Included in SuperChic simulation and $\Gamma_{X\to\gamma\gamma}$ fitted to LbyL measurement data

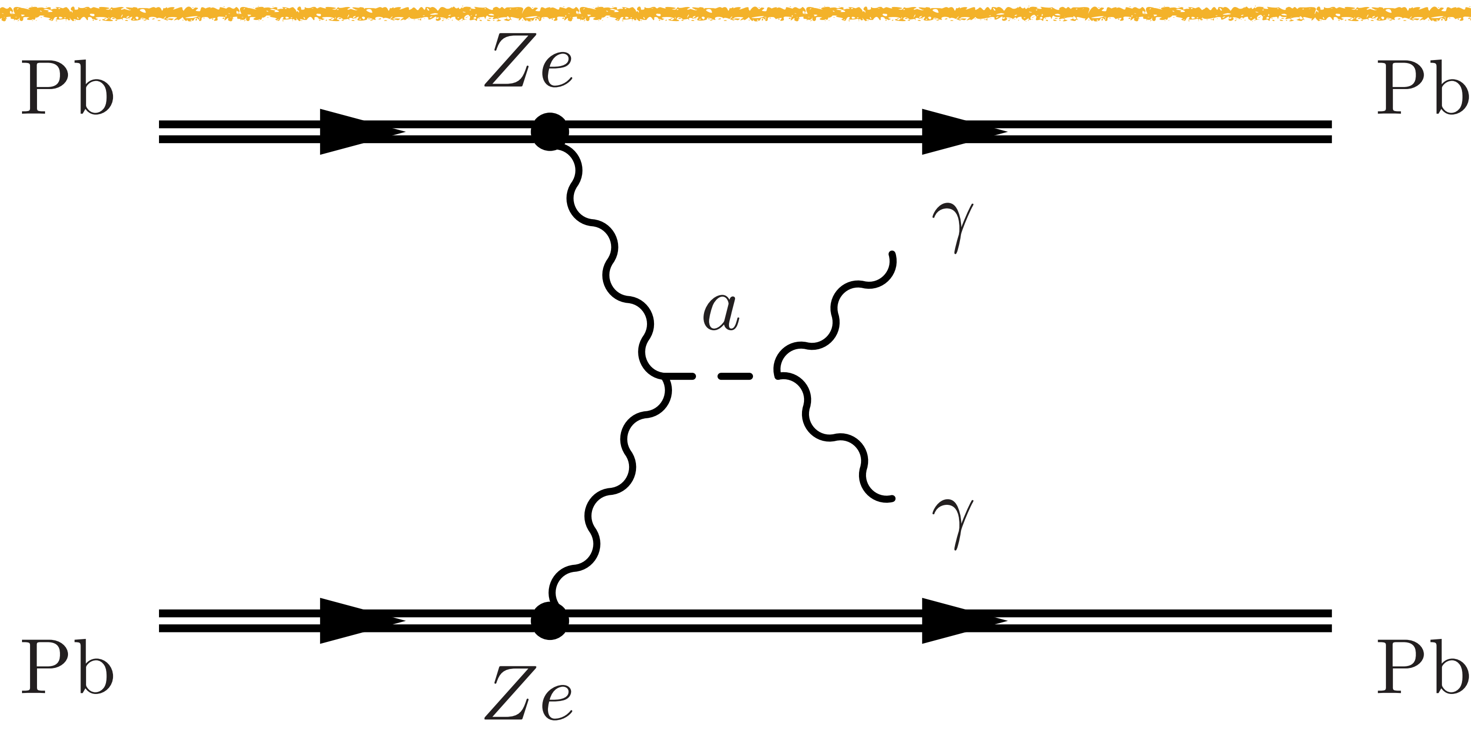
Parameter	Interference	No-interference
m_X [MeV]	$6886 \pm 11 \pm 11$	$6905 \pm 11 \pm 7$
$\Gamma_{X\to J/\psi J/\psi}$ [MeV]	$168 \pm 33 \pm 69$	$80 \pm 19 \pm 33$
$\Gamma_{X\to\gamma\gamma}$ [keV]	67^{+15}_{-19}	45^{+11}_{-14}

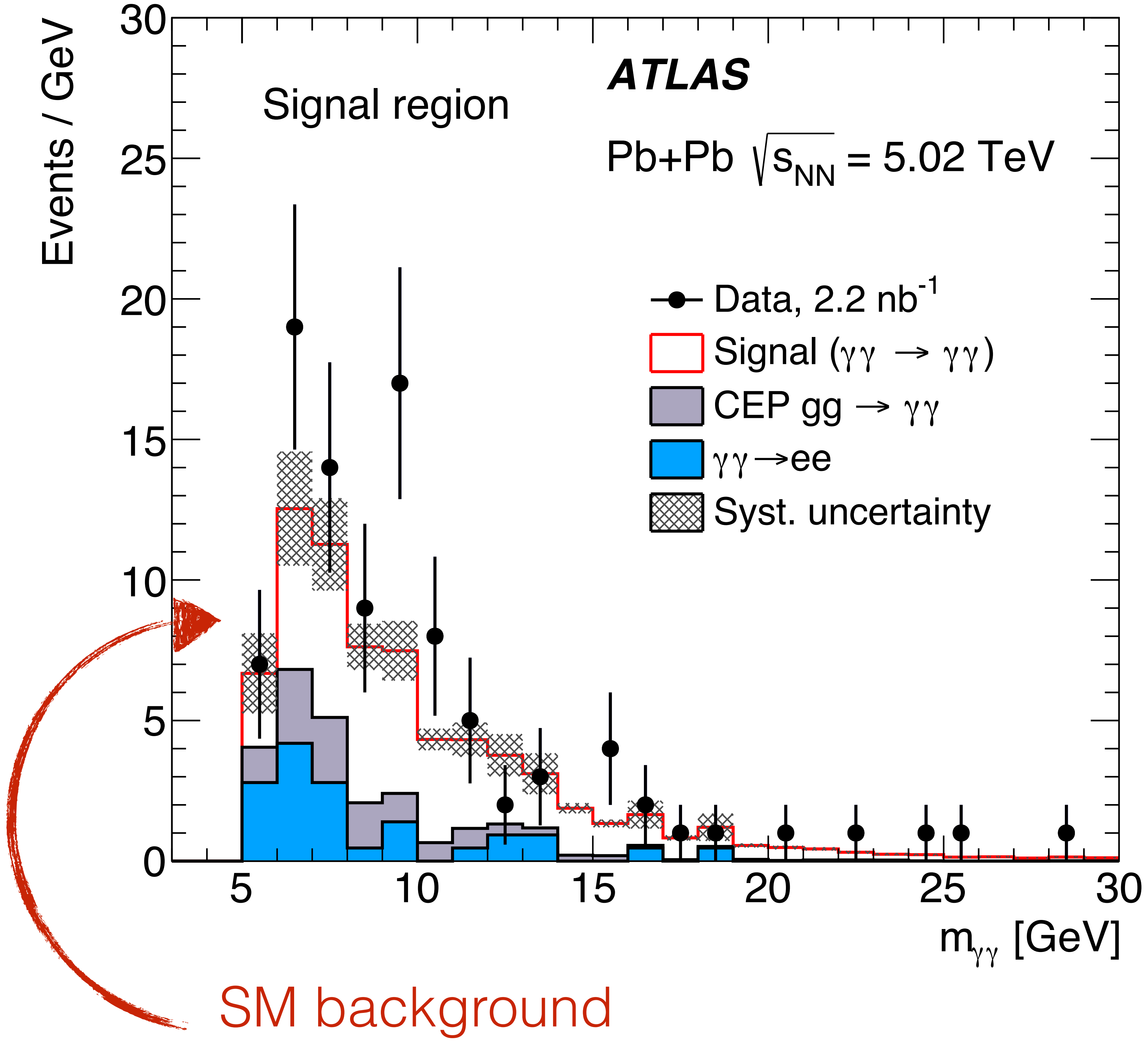


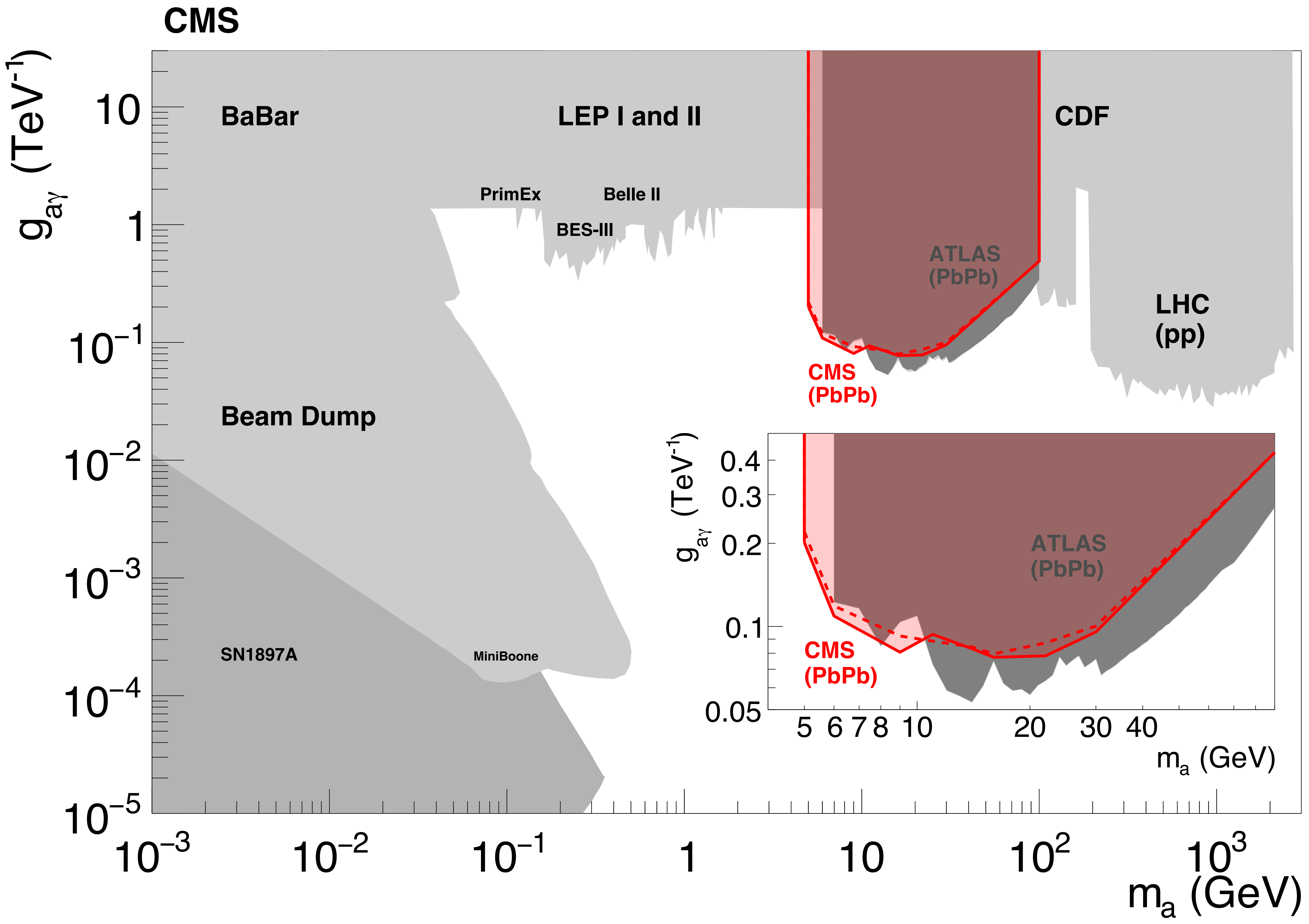
Biloshytskyi, Pascalutsa, et. Al
[Phys.Rev.D 106 (2022) 11, L111902, arXiv: 2207.13623]

What can one find in there? ALPs

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







Challenges (& Plans) for LHC run - 3

More statistics

=> LHC run-3 and beyond

=> higher efficiency

LHC run-3

Analysis of 1.7 nb^{-1} data from 2023 **ongoing**

Lower E_T threshold:

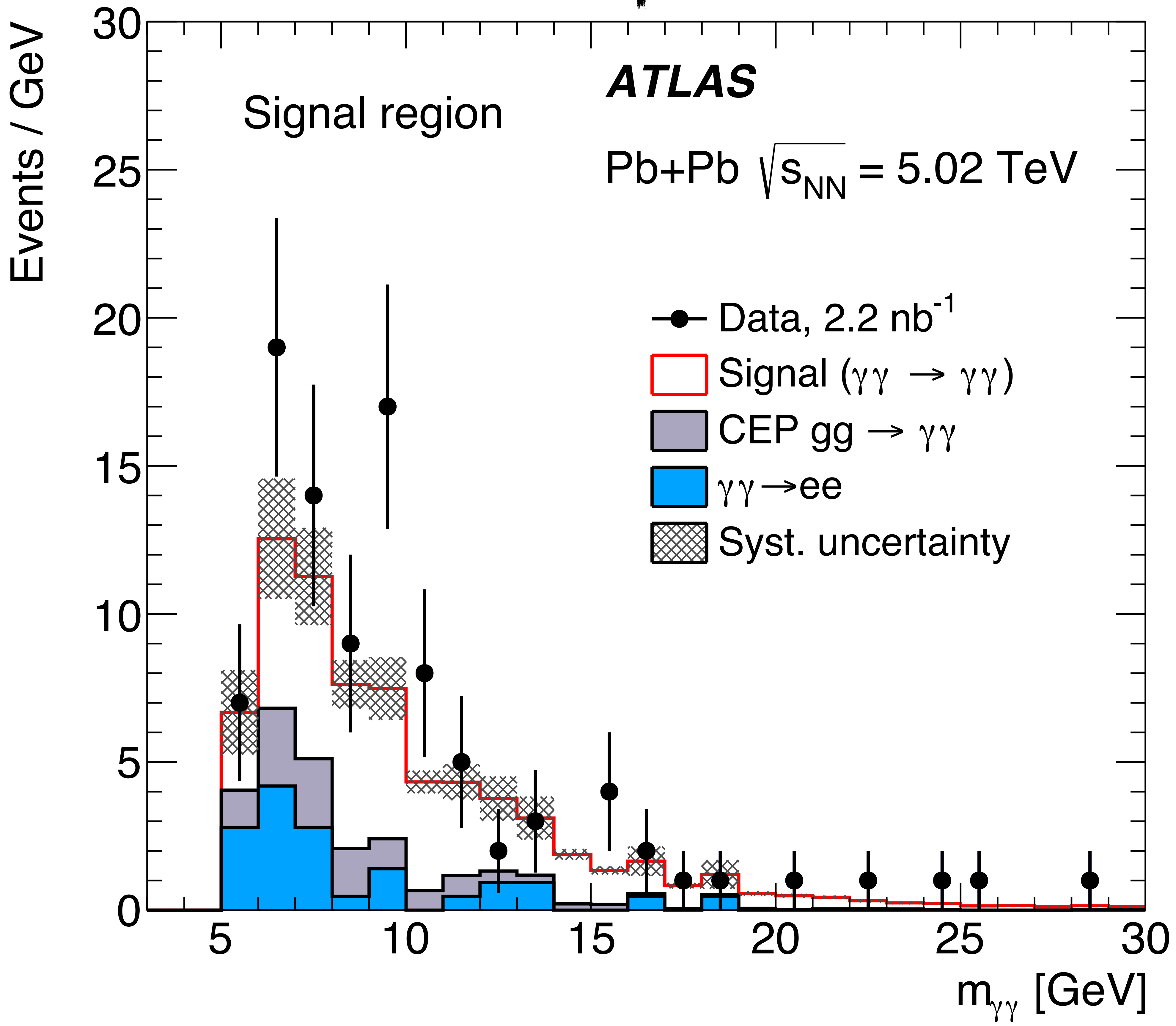
=> Trigger

Very difficult to lower threshold: Noise blows up rate

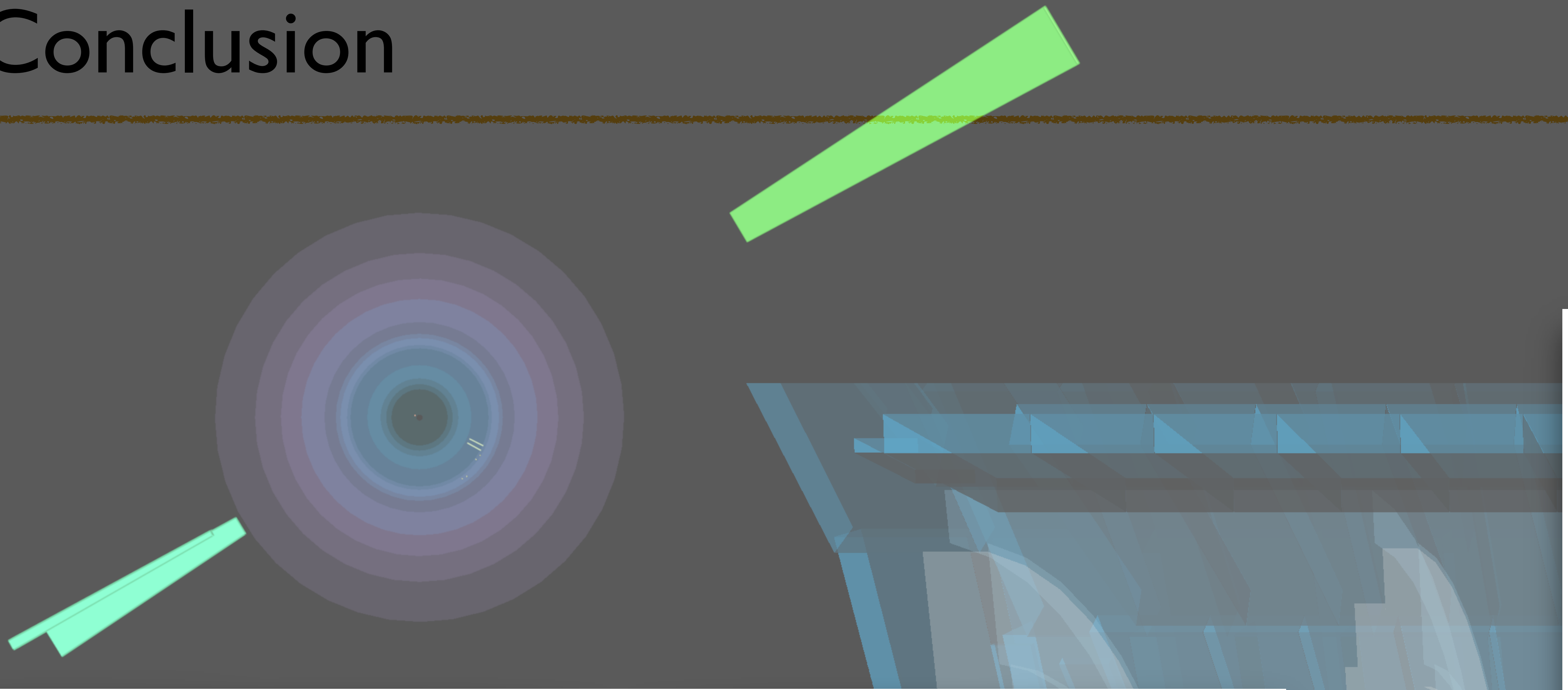
Higher calorimeter noise level in run-3 decreases low-ET photon efficiency by factor 3 for E_T < 3.5 GeV

=> Reconstruction

Completely new reconstruction algorithm of low ET photon candidates is possible, anyone interested?



Conclusion



- **PbPb collisions**: spectacular laboratory to study light-by-light scattering
- Significant progress at the LHC
- **Challenging** channel for HEP detectors: very **low E_T objects**
- Test a **variety of models** against results

What to expect in the near future:

- First LHC run-3 results with ~1.7 nb^{-1}
- **Tripple stats during run-3:**
  - Target integrated luminosity7 nb^{-1}
  - Next PbPb running scheduled for Nov. 25 and June 2026
- **Improved trigger algorithms**

Backup Slides

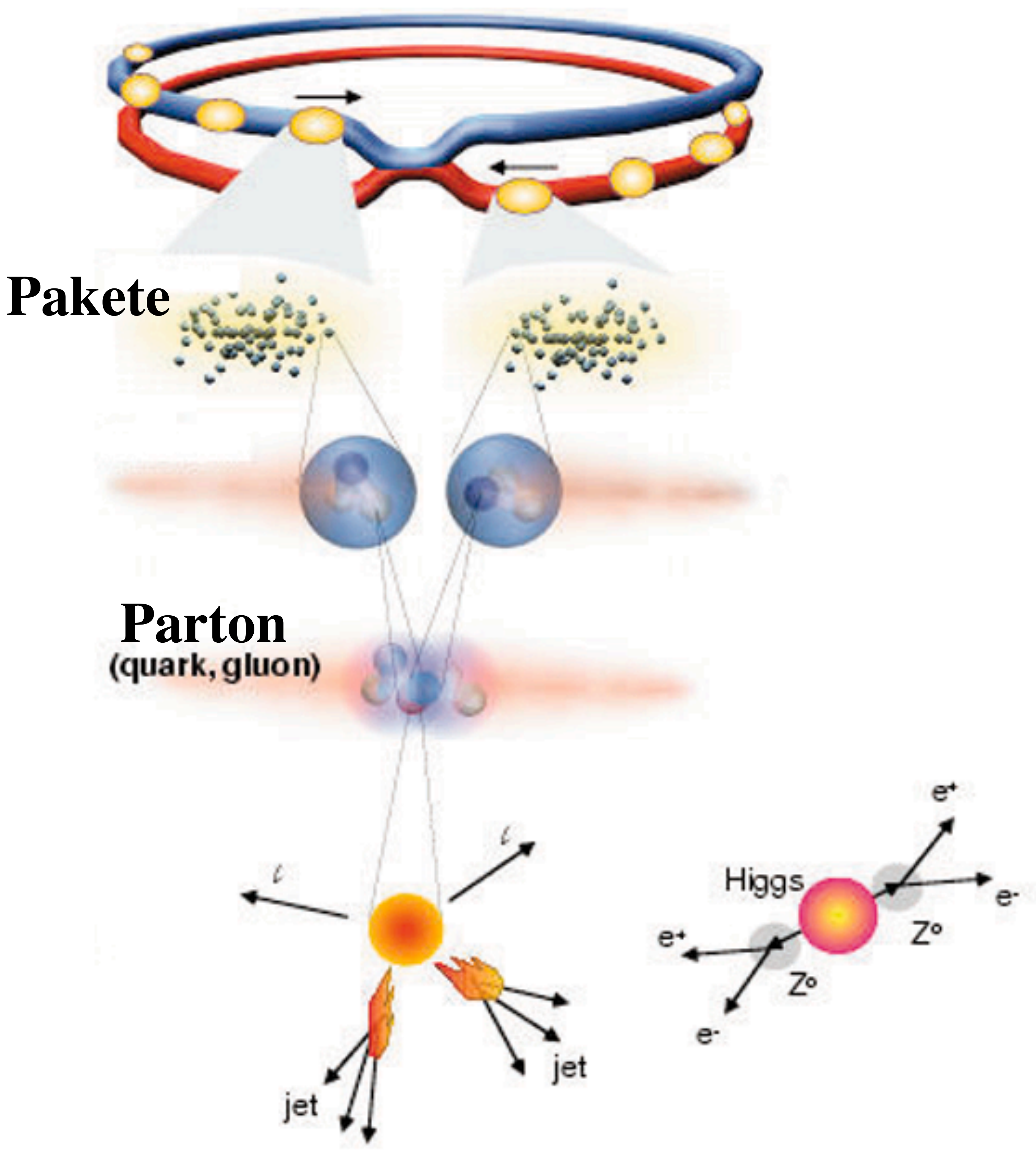
The LHC

- Usually operates with **proton @** 6.5 TeV beam energy

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

- ~1 month / per year:
  - **Lead** ions instead of protons @ 2.76 TeV / nucleon

- 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



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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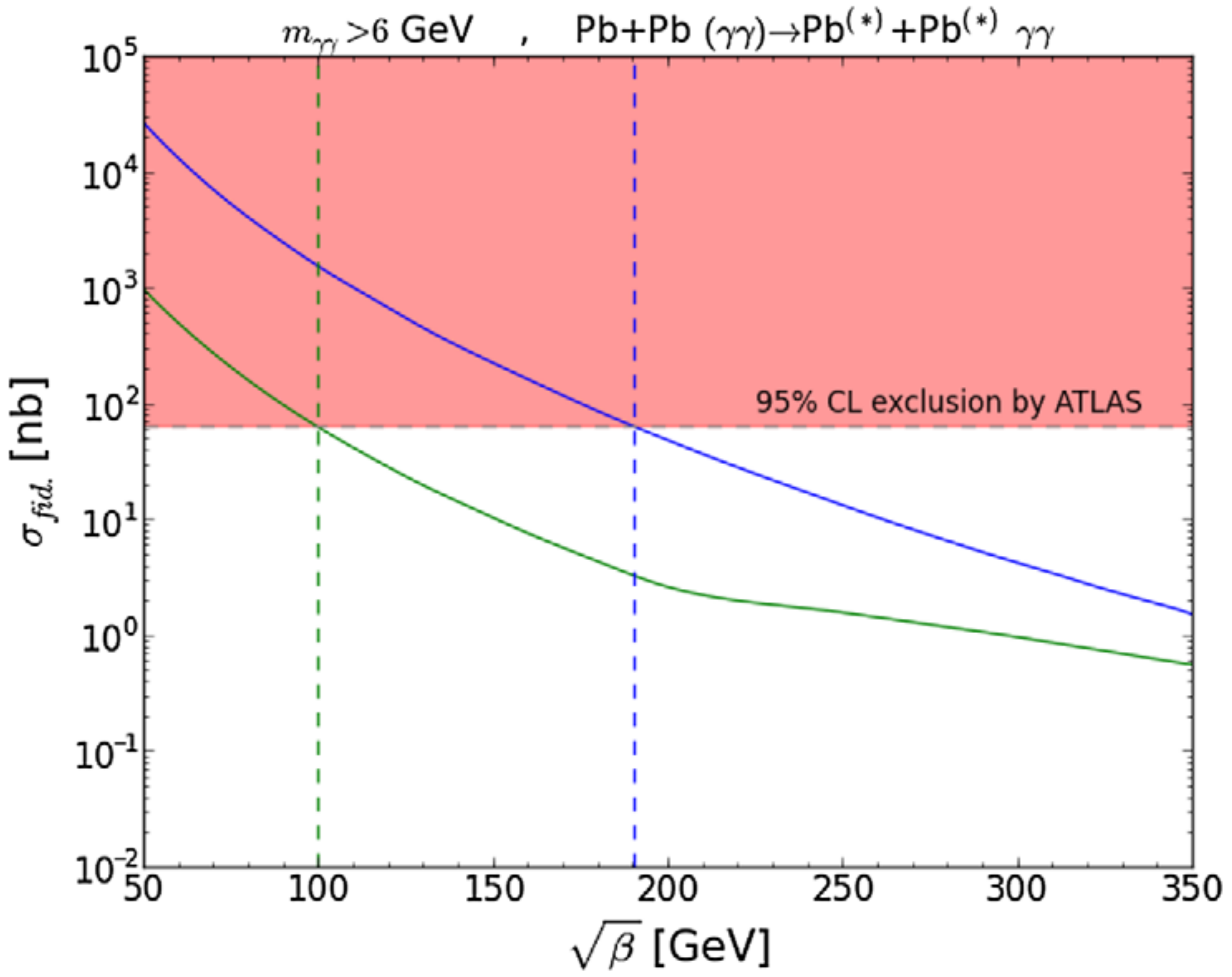
PRL 118, 261802 (2017)

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

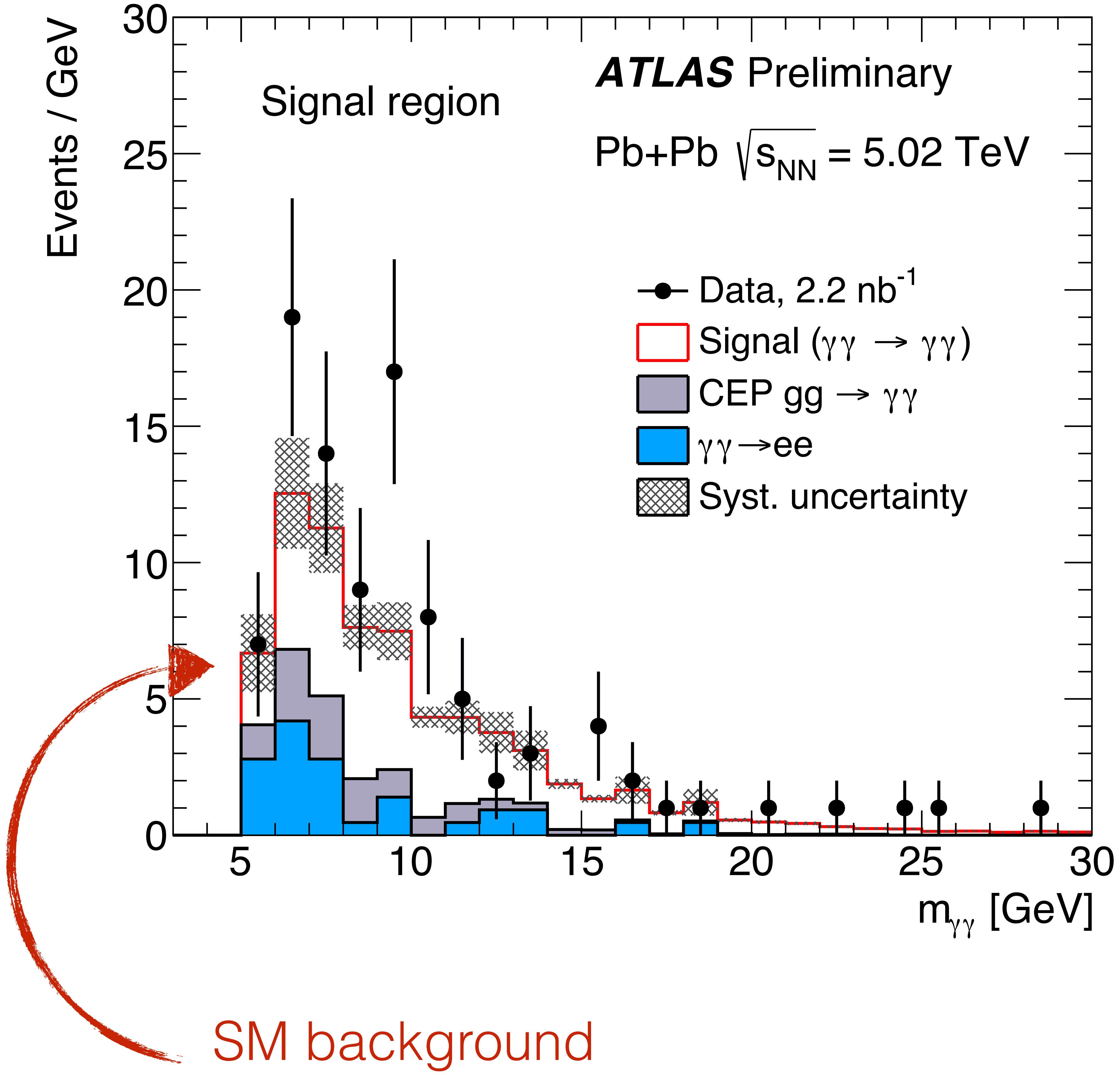
- Born - Infeld theory
  - Nonlinear extension to QED
    - Imposing an upper limit of the EM field strength [Born and Infeld, Proc. R. Soc. A 144, 425 (1934)]
    - More recently: connection to string theory [Fradkin and Tseytlin, Infeld, Phys. Lett. 163B, 123 (1985)]



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

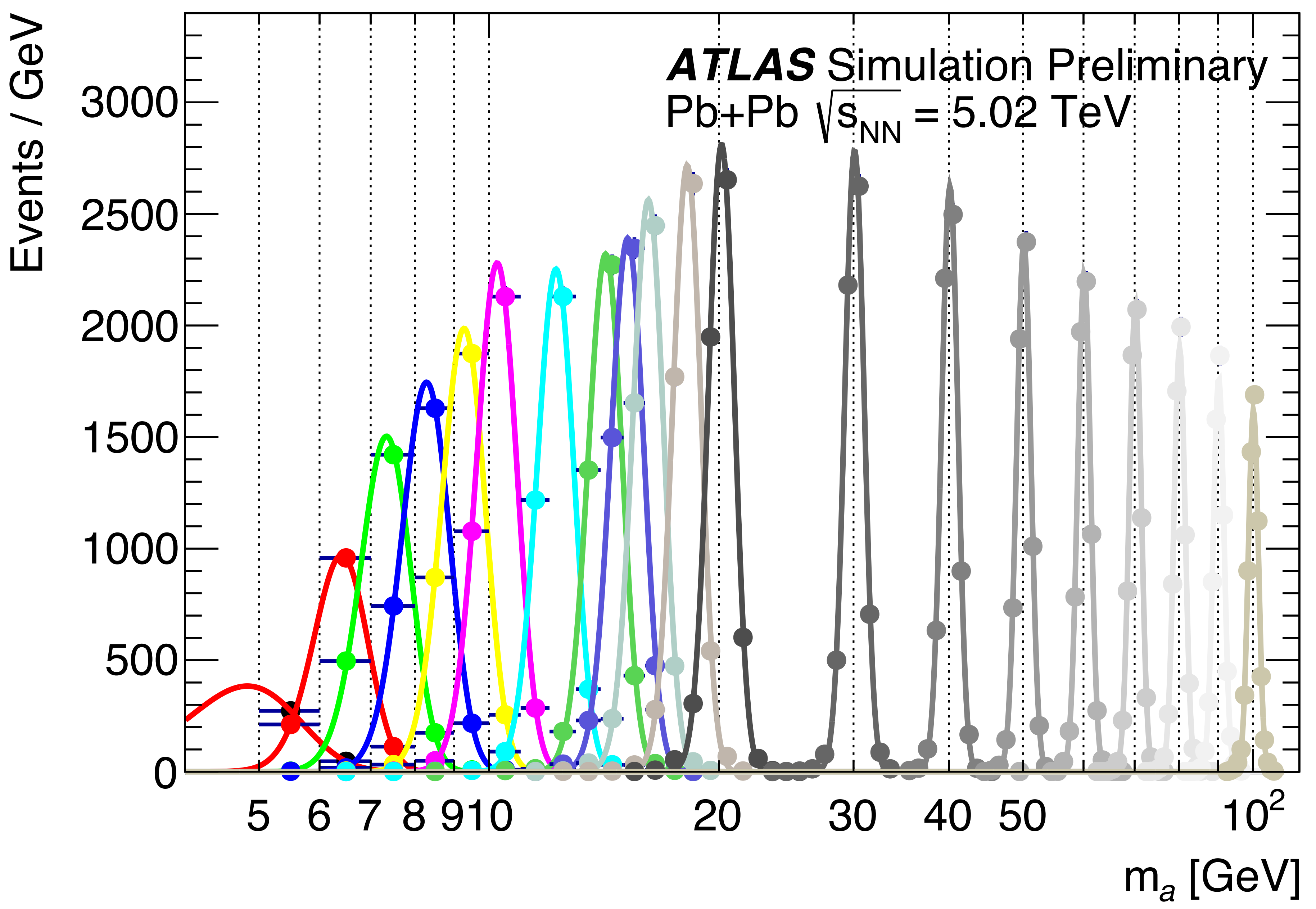
Interpretation - Search for new Axion Like Particles:

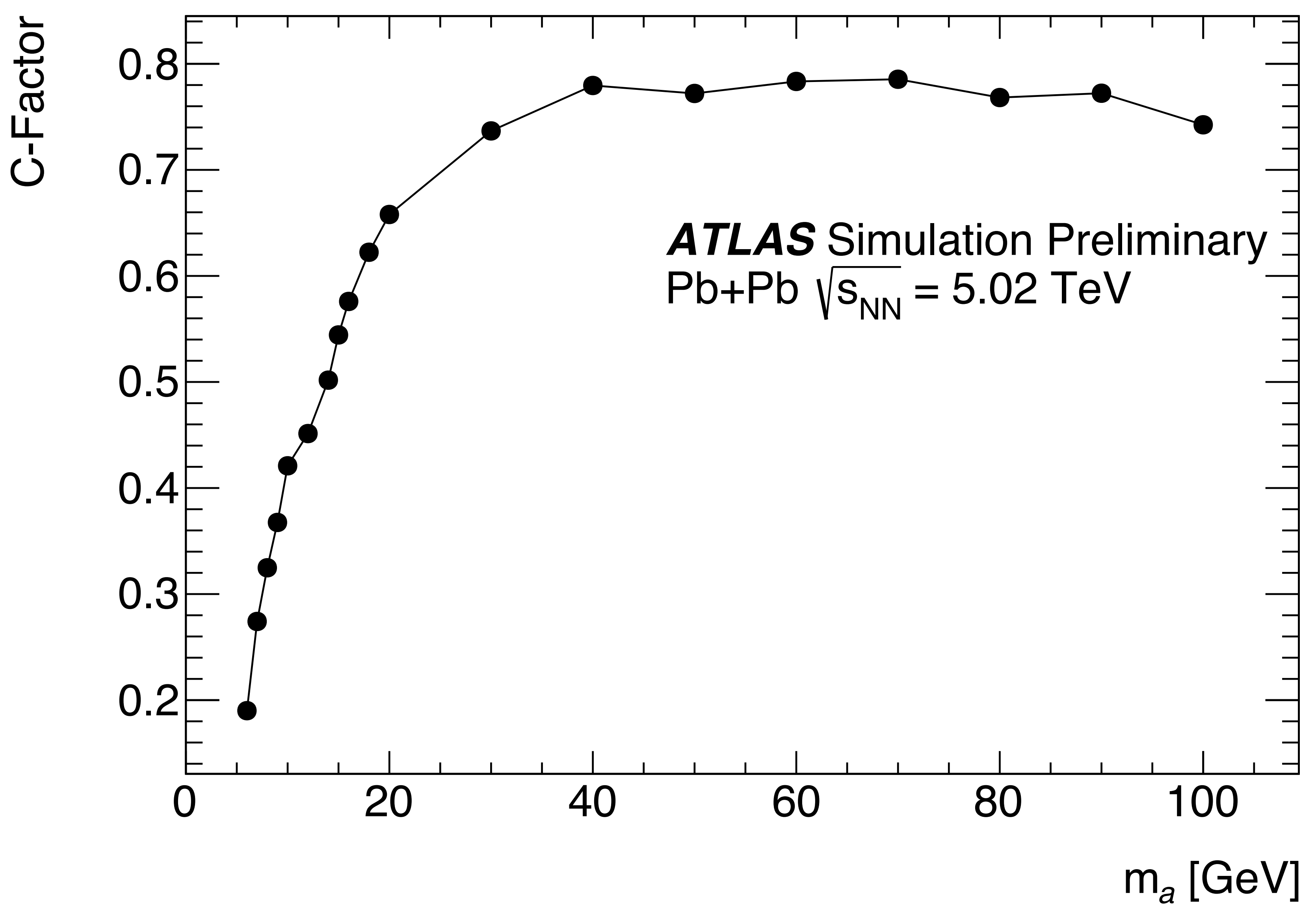
- ALP signal simulated using Starlight MC
- SM background: LbyL + CEP + ee
  - Extracting limit on the coupling to ALPs $1/\Lambda_a$



SM background

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

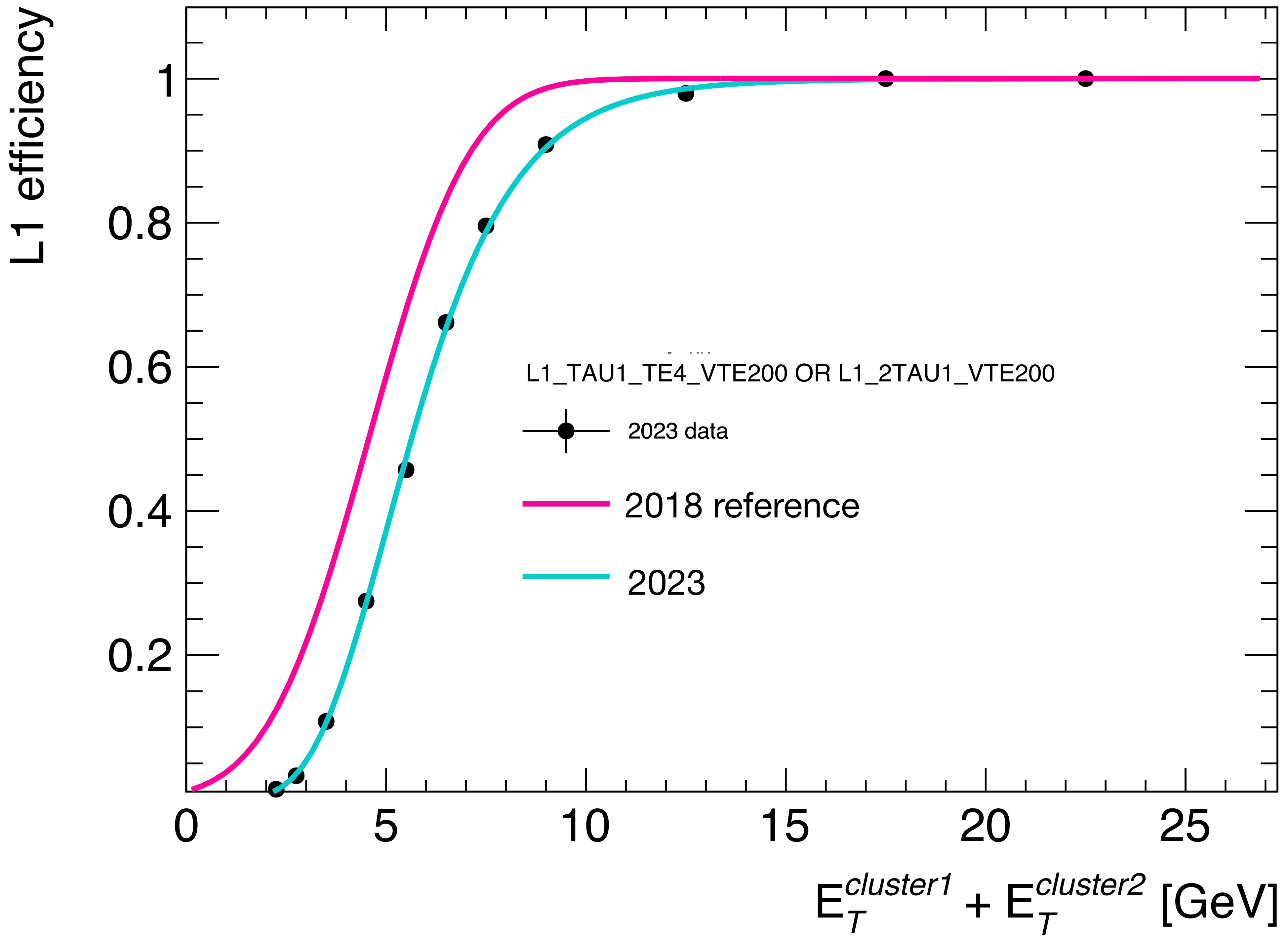




How to measure the $\gamma\gamma \rightarrow \gamma\gamma$ process

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

- HLT Requirements (AND):
  - ΣE_T (FCal) < 3 GeV on both sides
  - $\leq$ 15 hits in pixel detector
    - Tagging of exclusive photon final state



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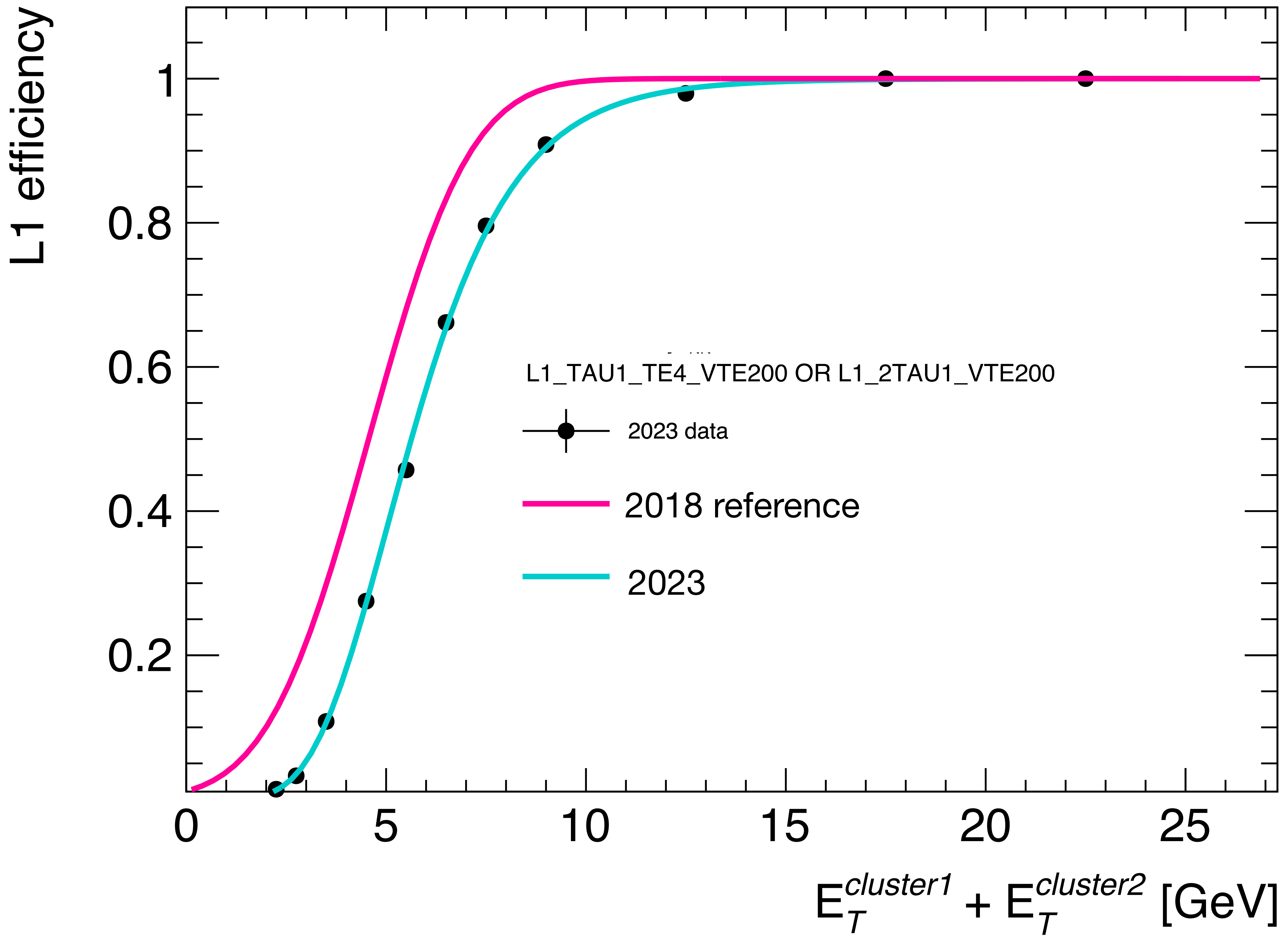
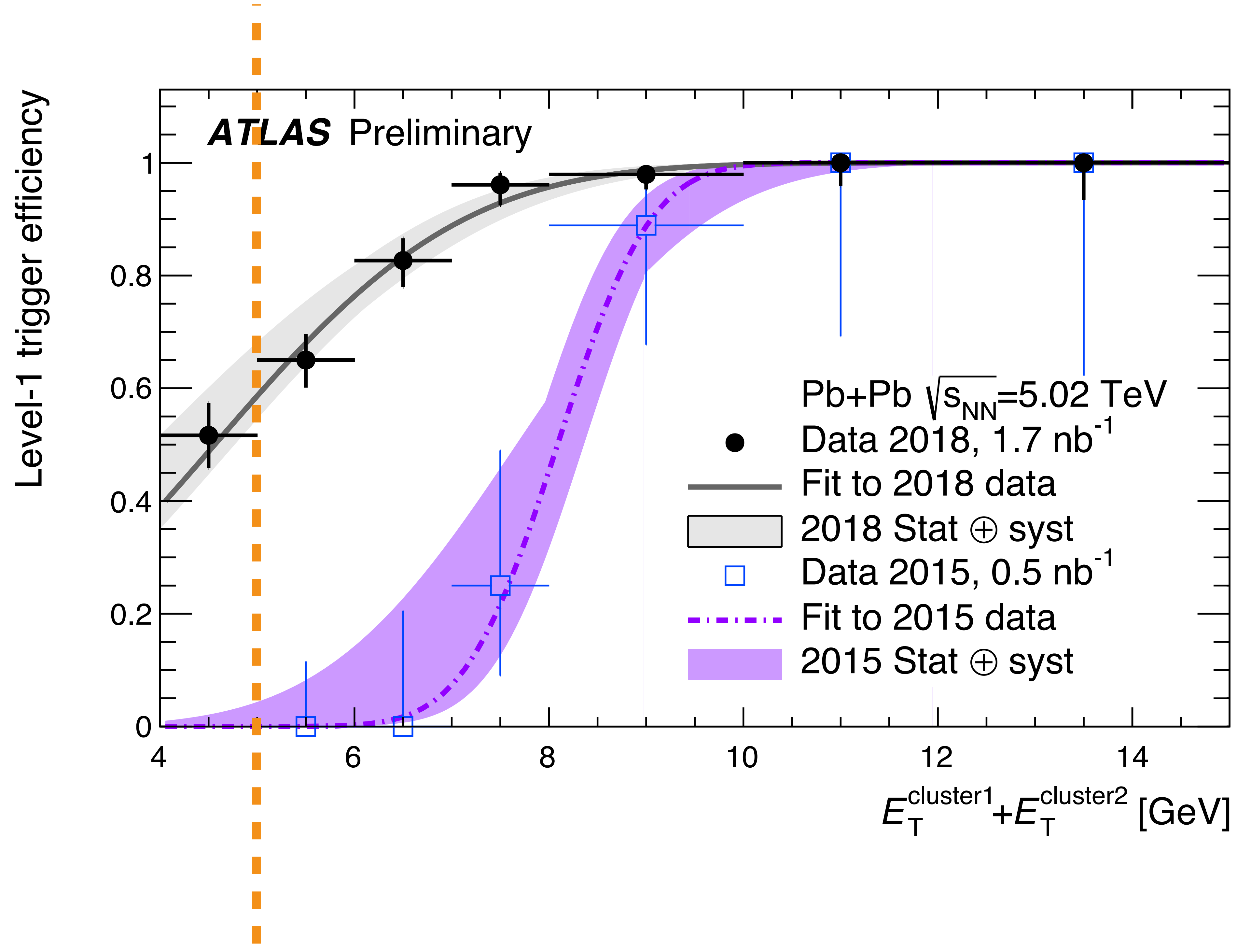
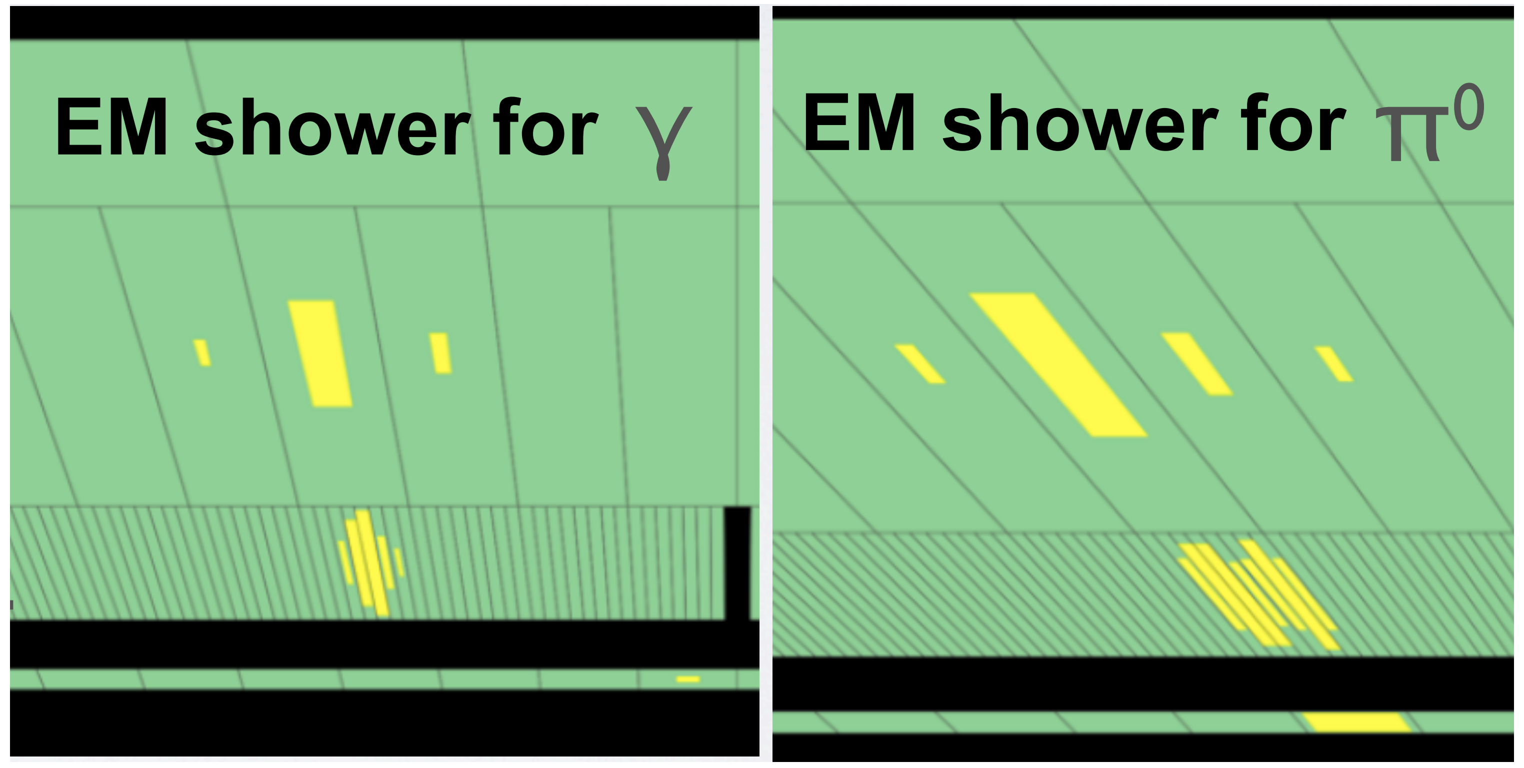
  - $\leq$ 15 hits in pixel detector
    - Tagging of exclusive photon final state





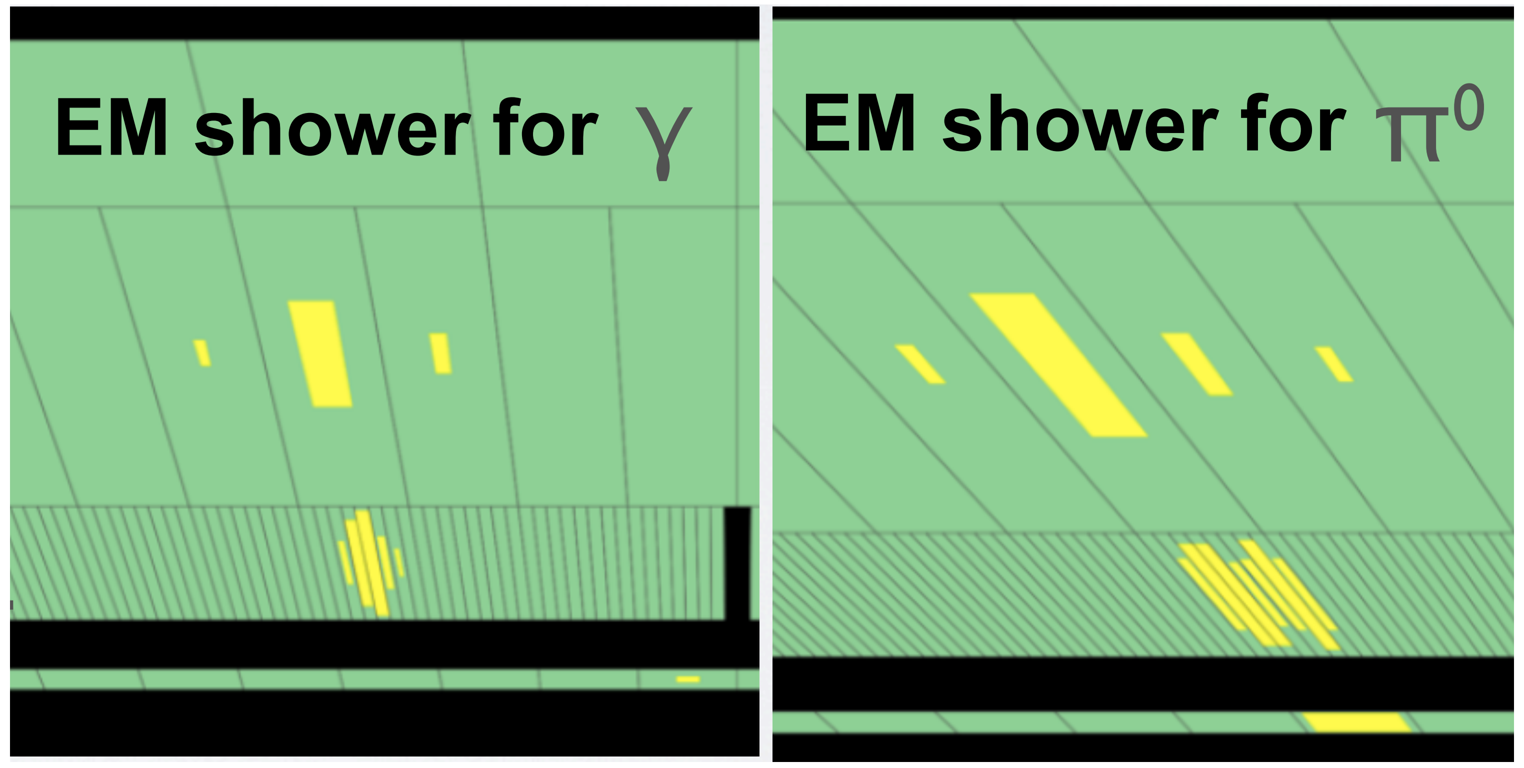
How to measure the $\gamma\gamma \to \gamma\gamma$ process

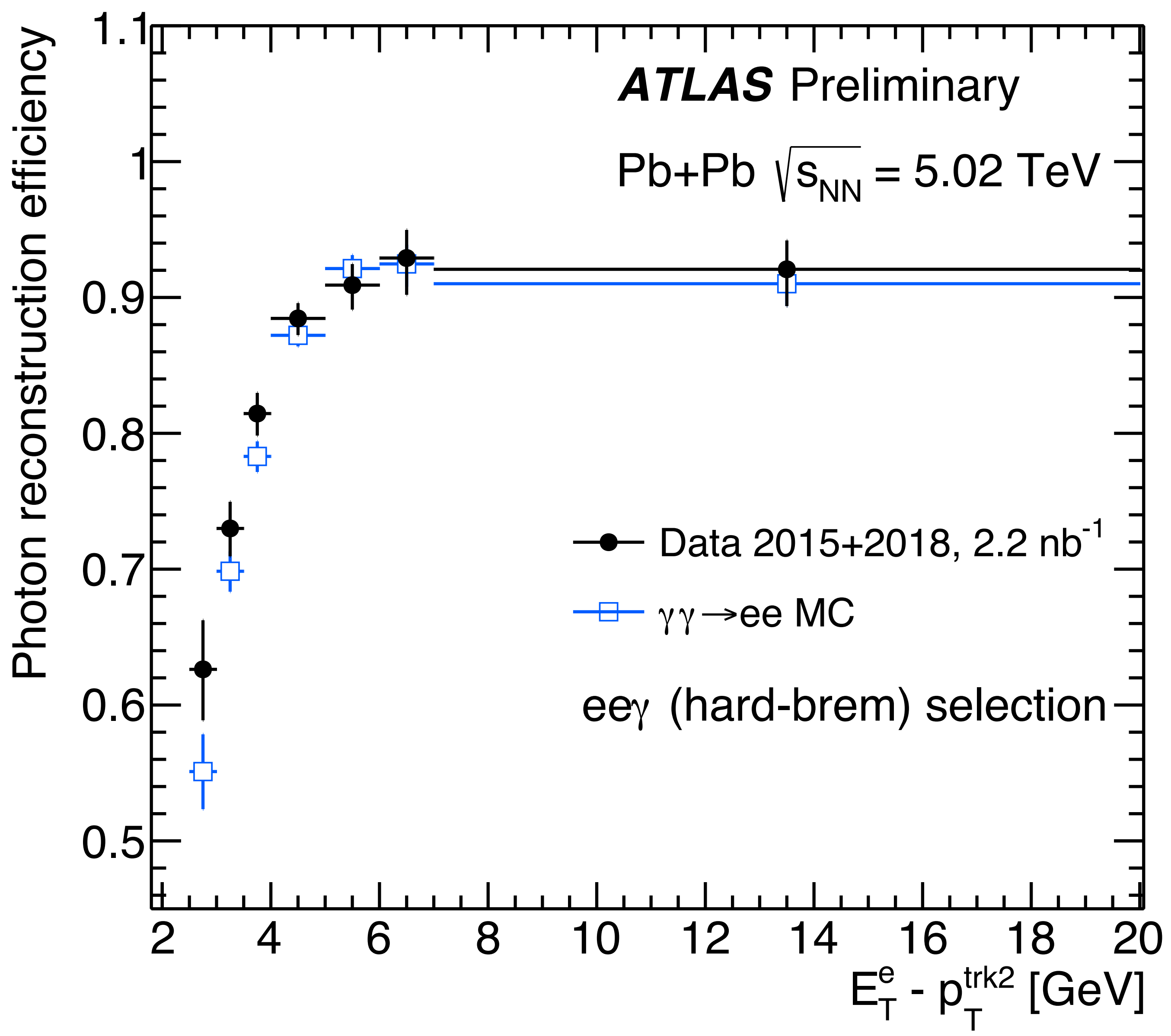


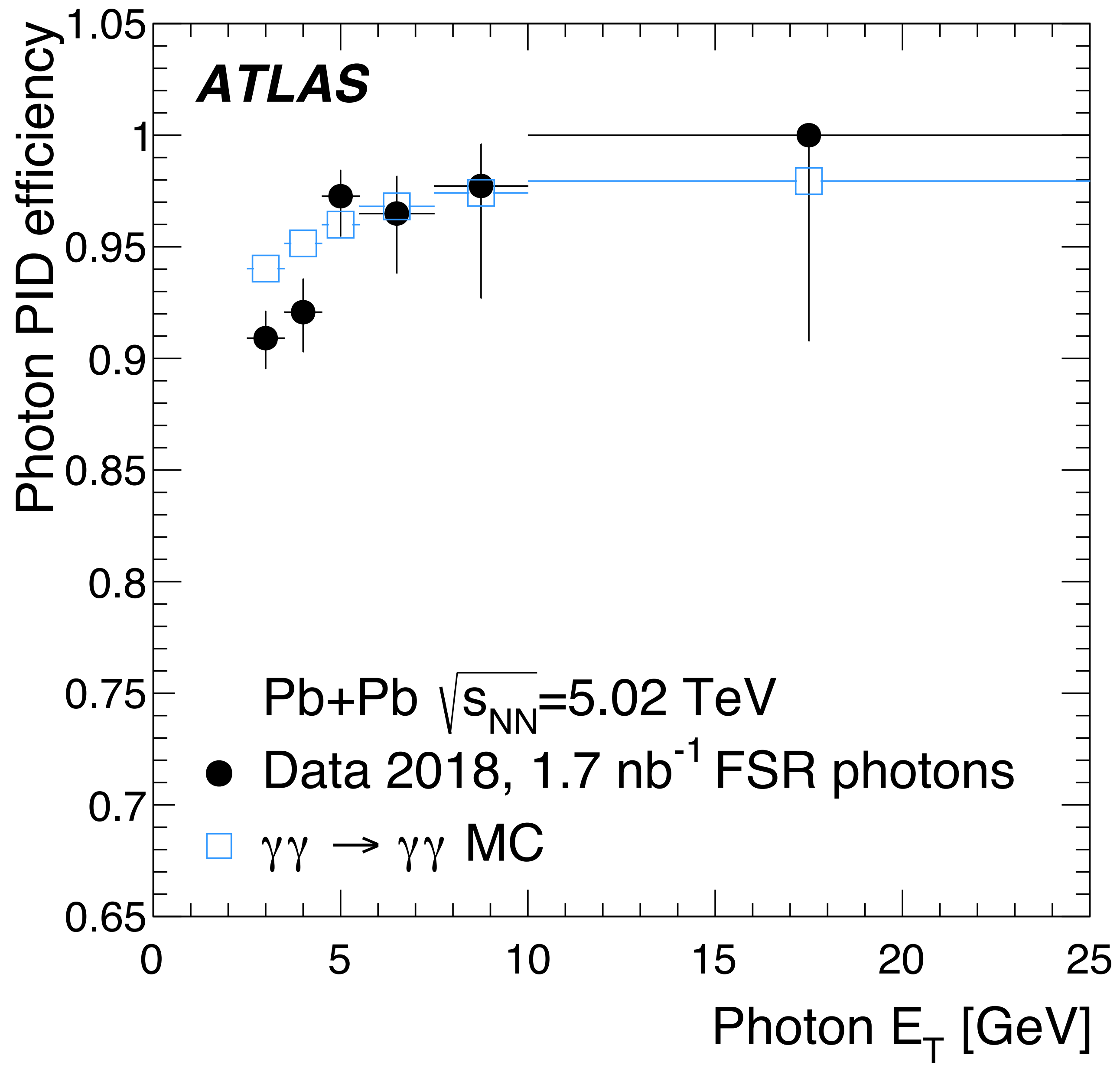
- Photon identification:
  - Uses neural net (Keras), trained for low E_T photons
  - Combination of EM calorimeter shower shape variables
    - Discrimination between photons, pions, electrons, noise

Photon reconstruction and identification

- 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!







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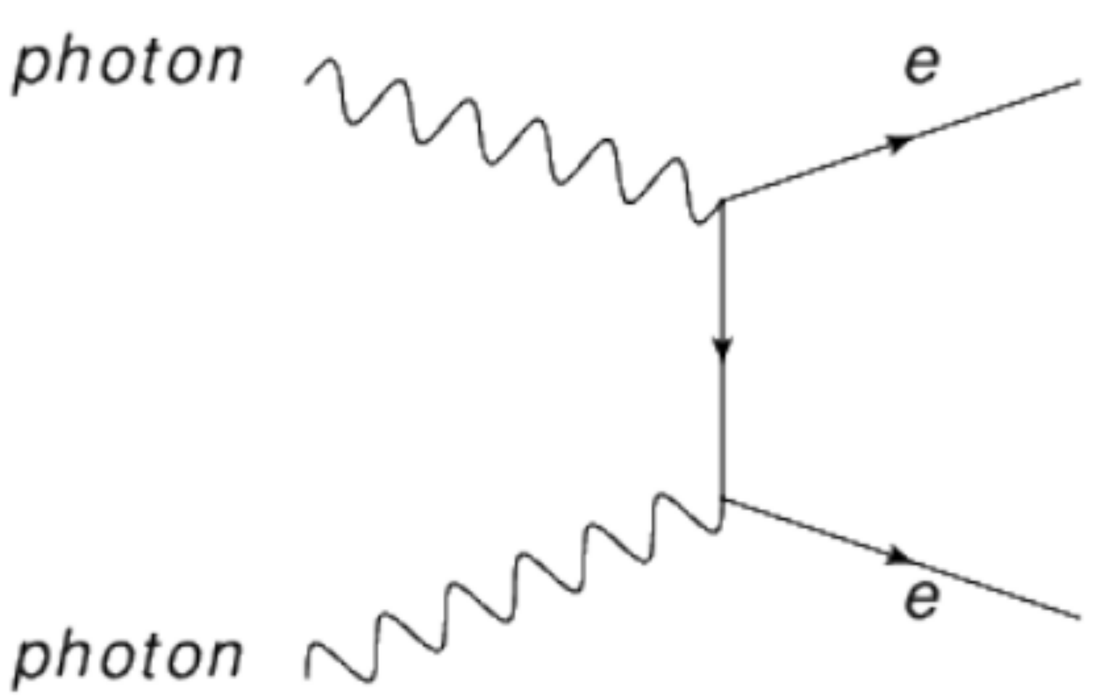
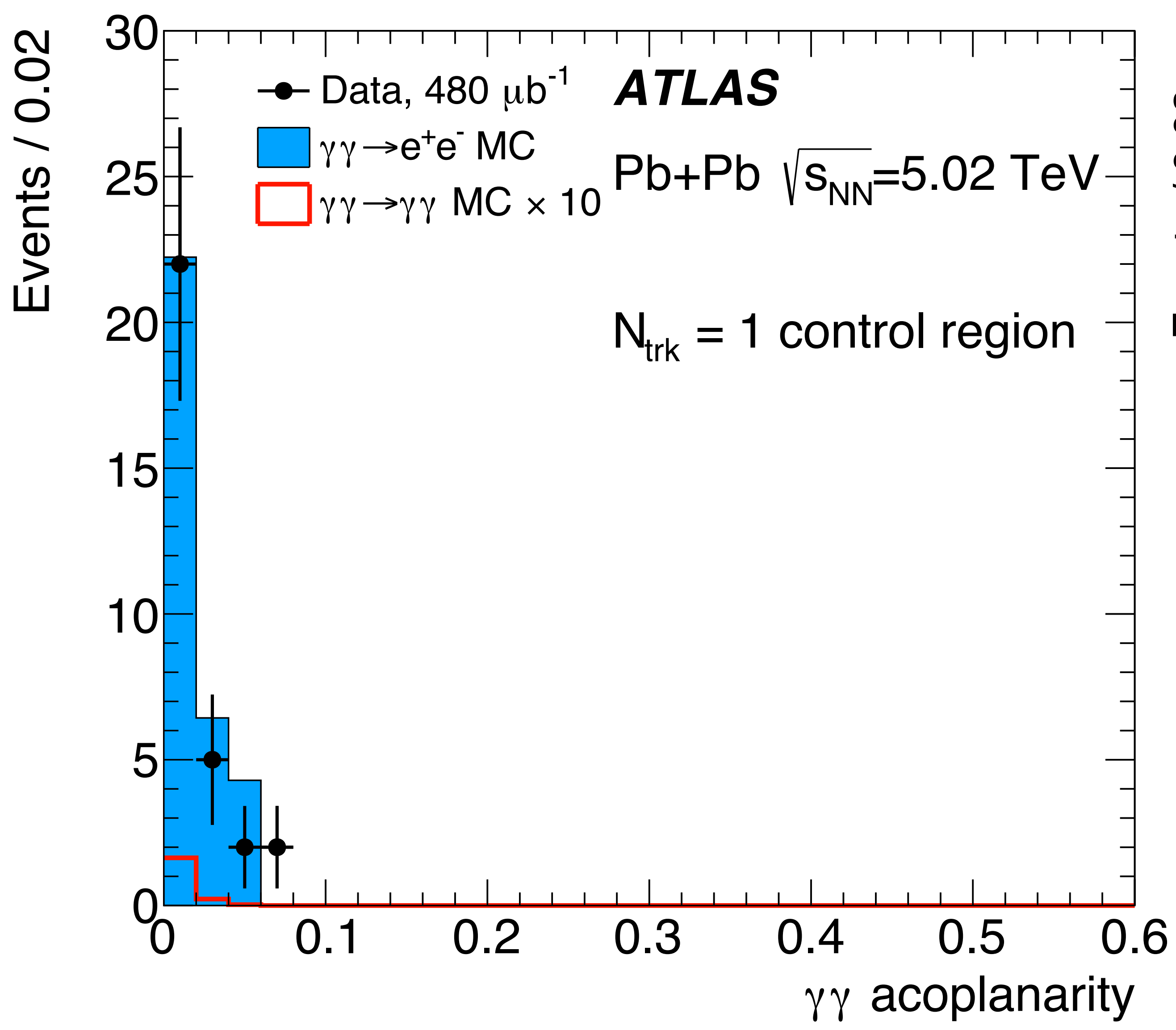
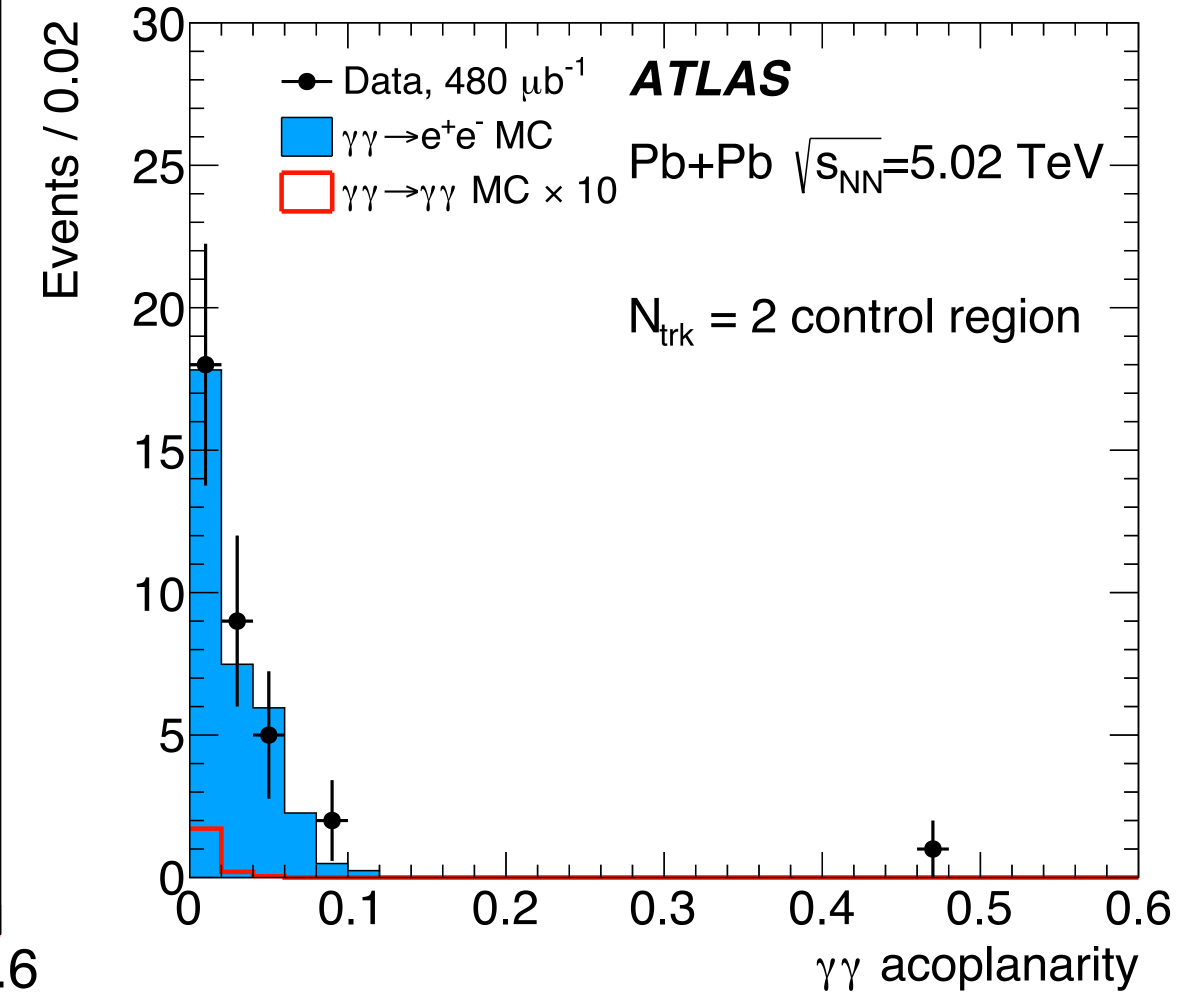
Background processes



- 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

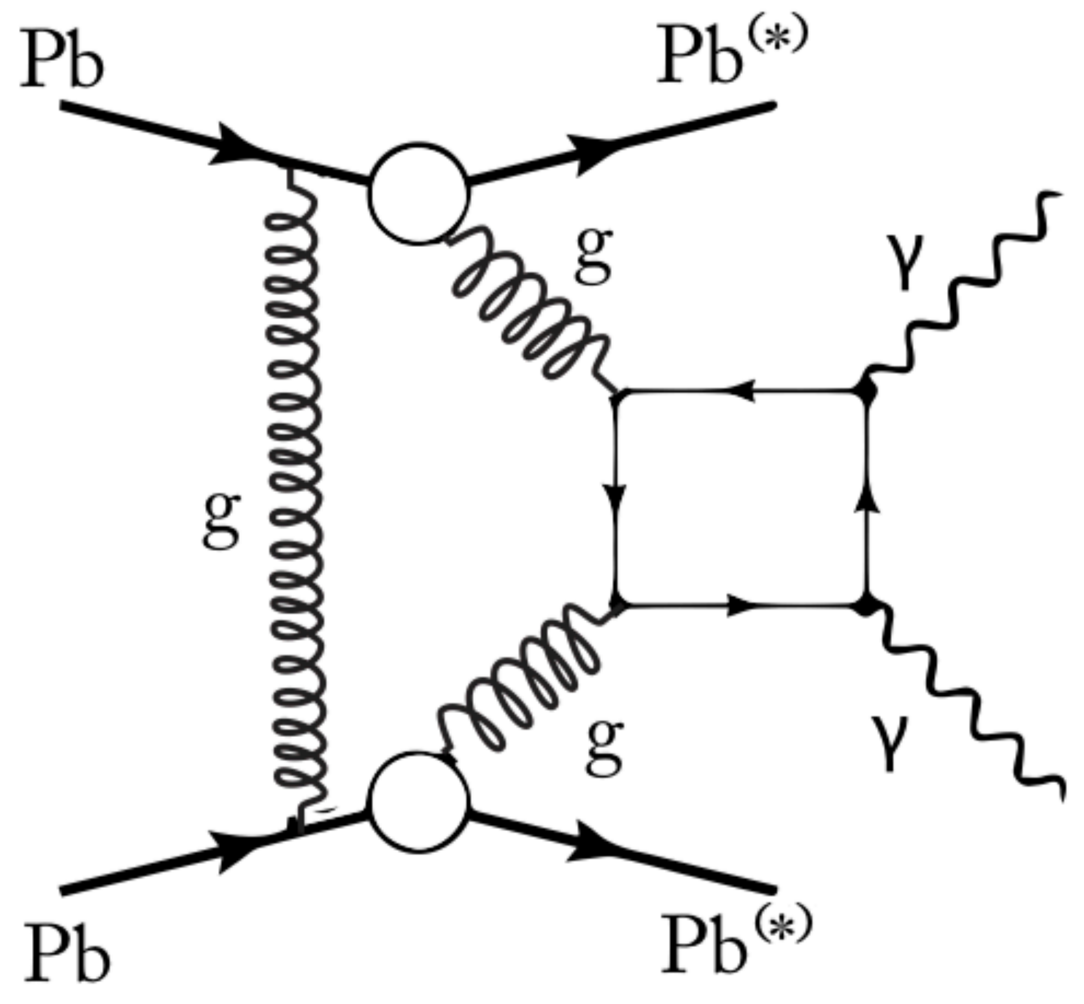
statistics, p^e_{mistag}, difference in CRs





Background processes

- Central Exclusive Production of 2 photons (**CEP**): $gg \to \gamma\gamma$
  - 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



Background processes

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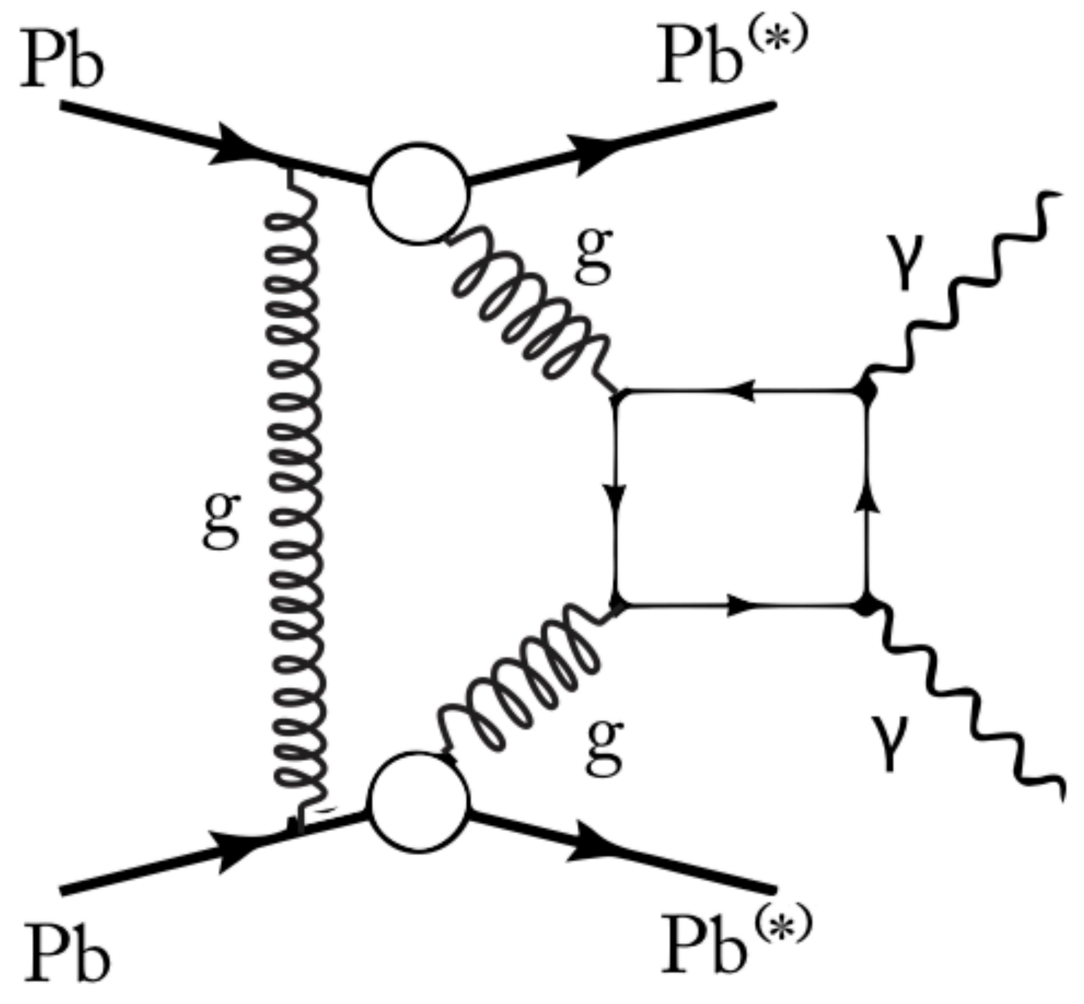
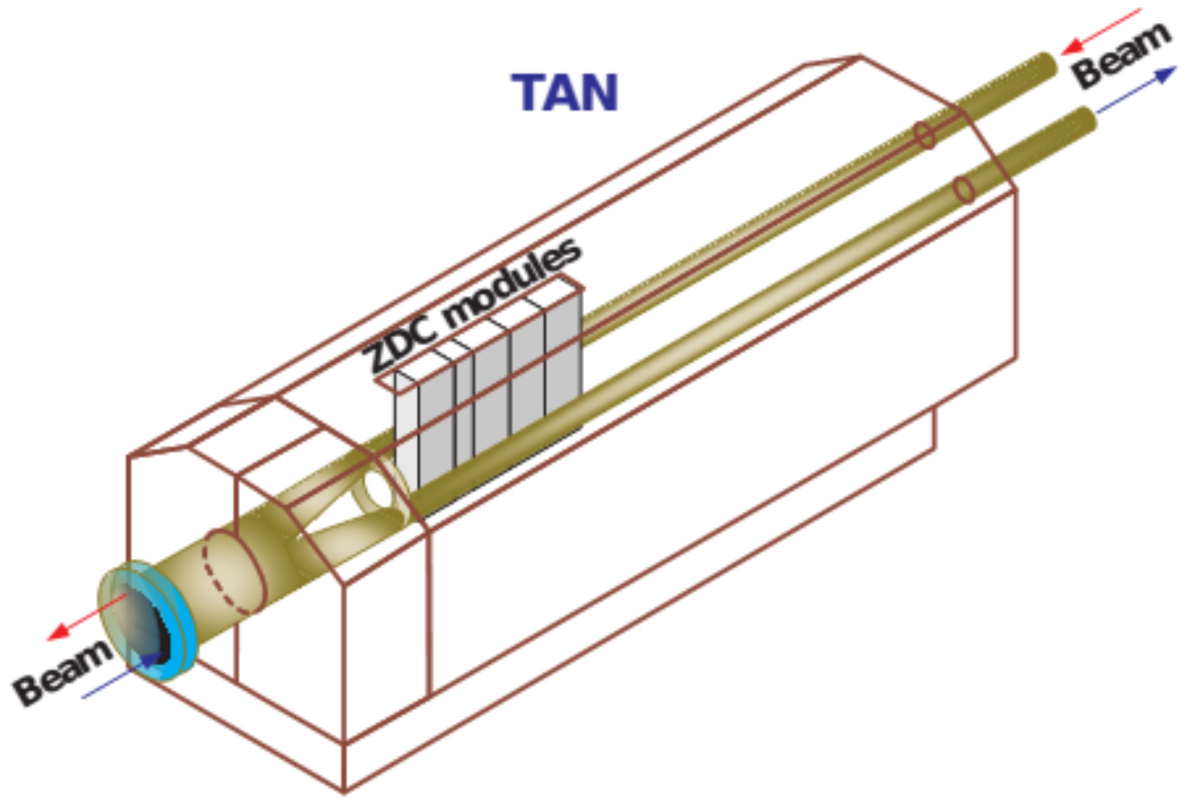


- Pb* dissociates, releasing neutrons detectable in the Zero Degree Calorimeter
  - Cross check of ZDC information for events in CEP control region:
    - Good agreement with expectations :)



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

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%

Differential distributions

- Measured distributions unfolded to particle level within fiducial region
    - $|\eta(\gamma)| < 2.4$ & $E_T(\gamma) > 2.5$ GeV
- Baysian unfolding with 1 iteration used
    - Corrects for migration from particle-level to detector level
    - Detector resolution
    - Reconstruction efficiencies
- Results compared to Prediction from Superchic 3.0
- Large statistical uncertainties
    - Everything compatible with SM