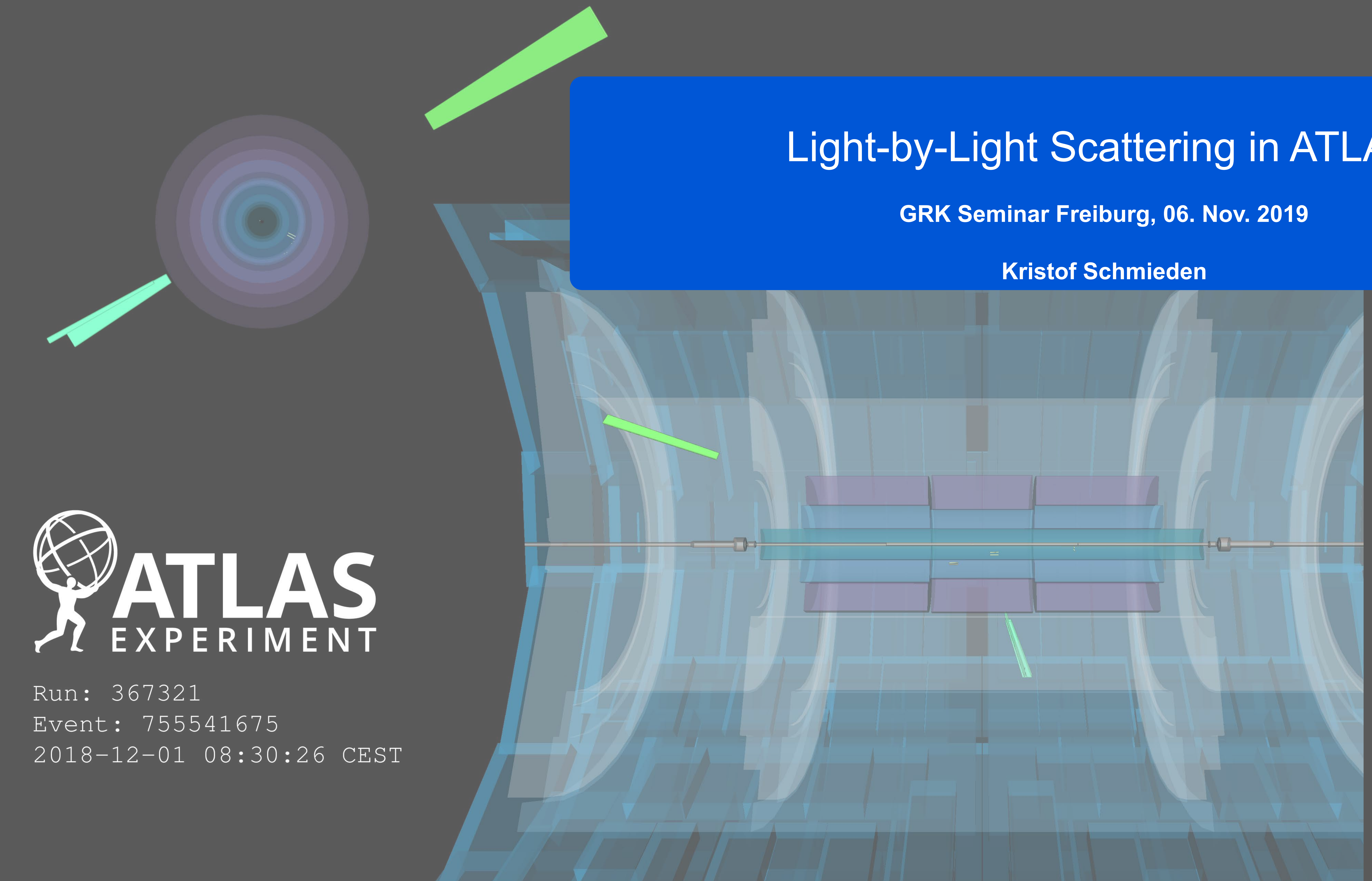
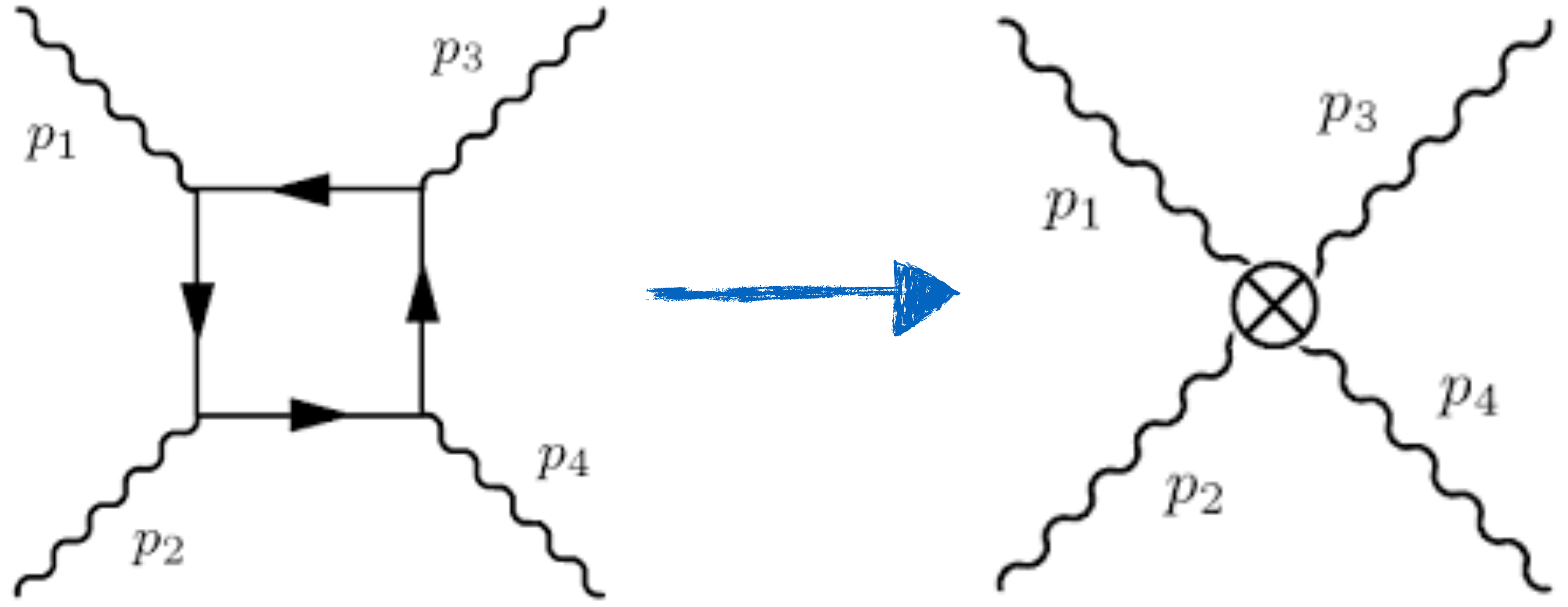
Light-by-Light Scattering in ATLAS

GRK Seminar Freiburg, 06. Nov. 2019

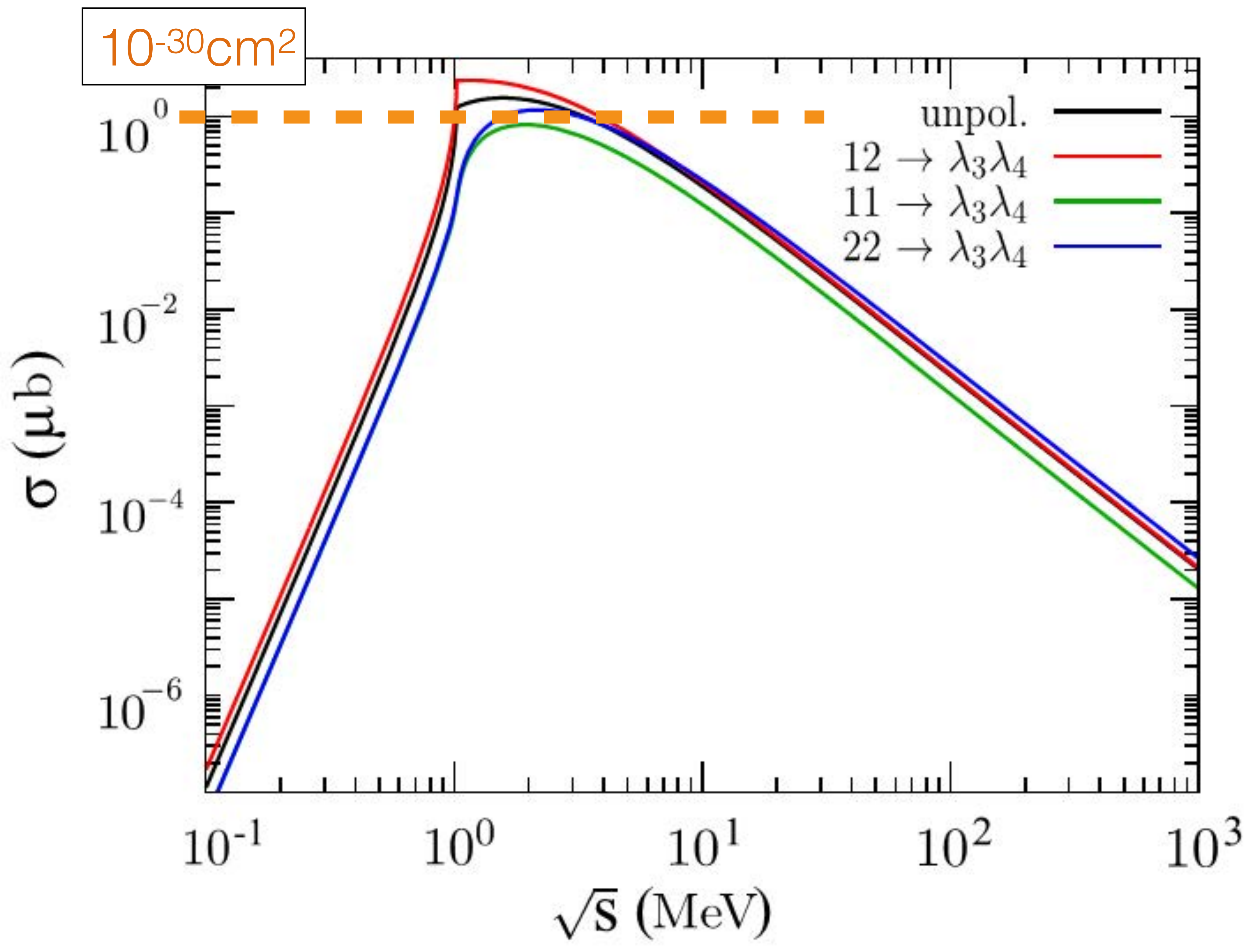
Kristof Schmieden





- The story starts in the **early 30ies**:
  - Dirac's theory developed and positrons discovered
    - Evident that light could scatter off light via pair-production
    (Halpern & Heisenberg)
  - Heisenberg, Euler, Kockel
    - Using effective Lagrangian to calculate cross section ($E_\gamma \ll m_e$)
      - ~ 10^{-70}cm^2 for visible light, 10^{-30}cm^2 for γ-radiation

    [Naturwissensch. 23, 246, 1935],[Z. Phys. 98 (1936) 714]
- Exact calculation: loop calculation needed
  - Box diagram involving charged fermions and W-Boson



- Early experimental approach:
  - Search for scattering of visible photons using focused sunlight

[Hughes and Jauncey, Phys. Rev. (36 1930), 773]

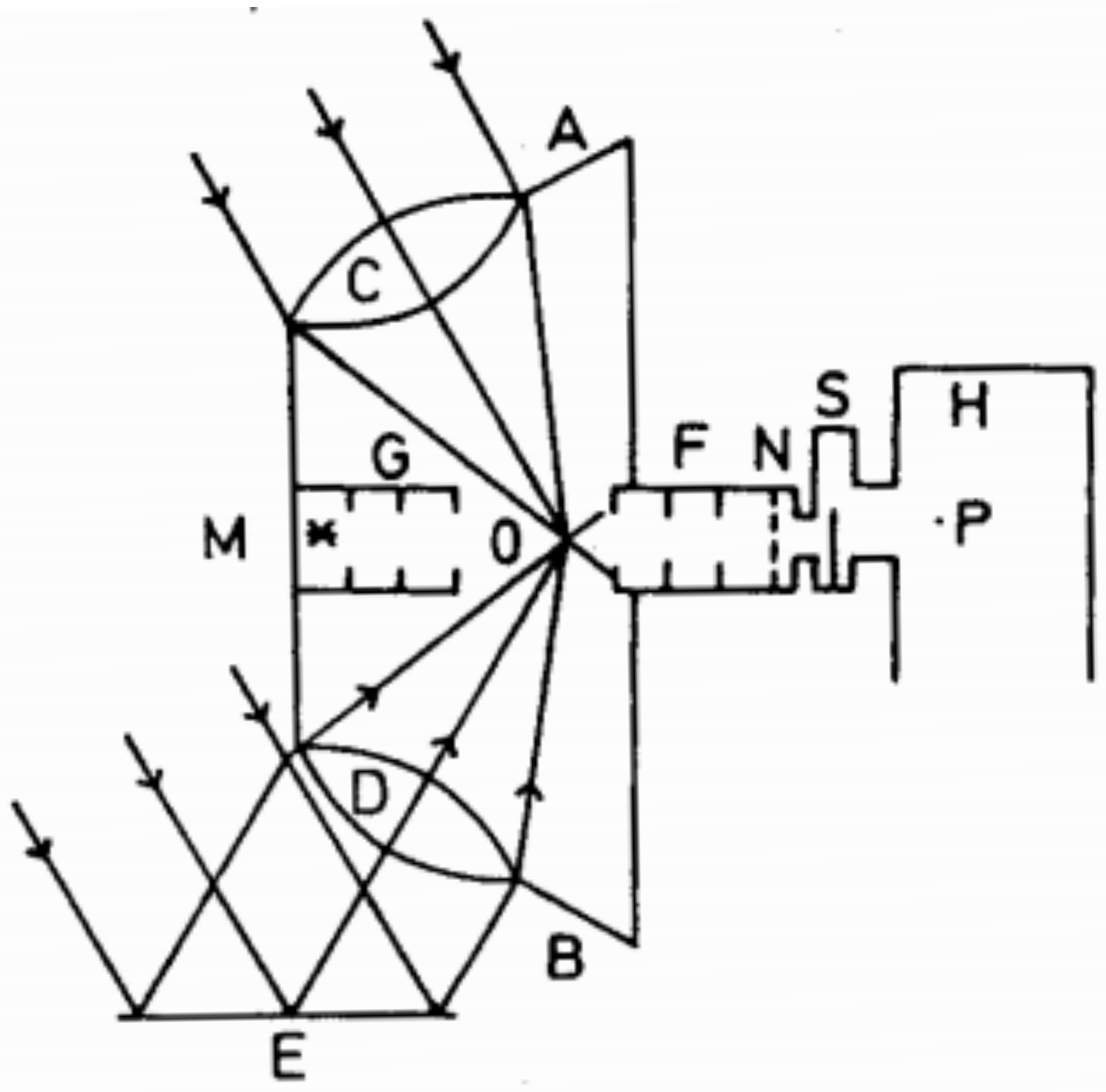


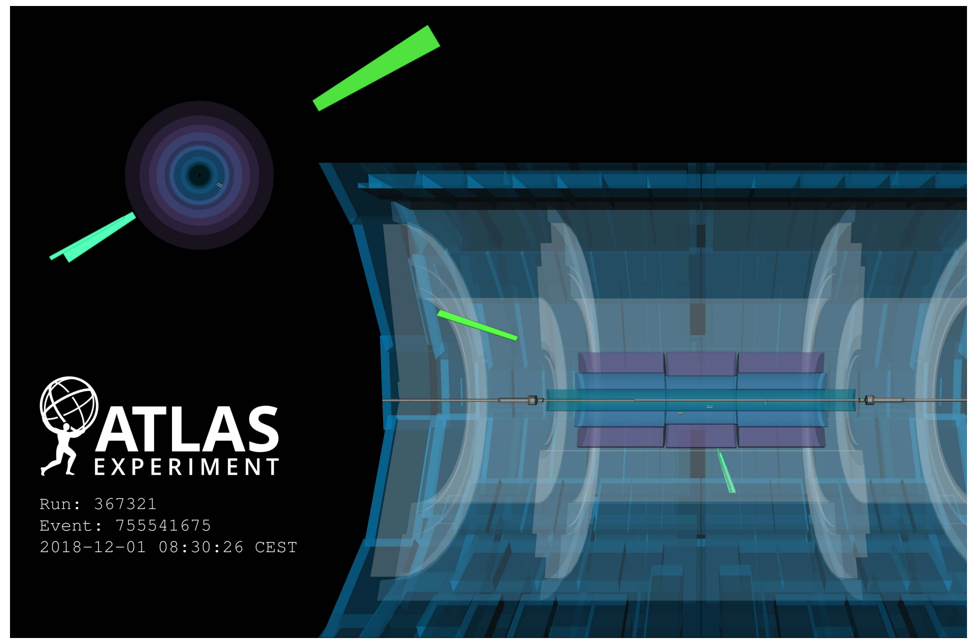
Figure 3 Apparatus for a light-light scattering experiment: The two lenses C and D focus sun light on the same spot O in a light-tight box AB. The dark-adapted eye of an observer at the point P serves as the detector for scattered light.

- No light was detected
  - "Calculations show that if the photon has a cross section, its area must be less than $3\text{x}10^{-20}$ cm^2."

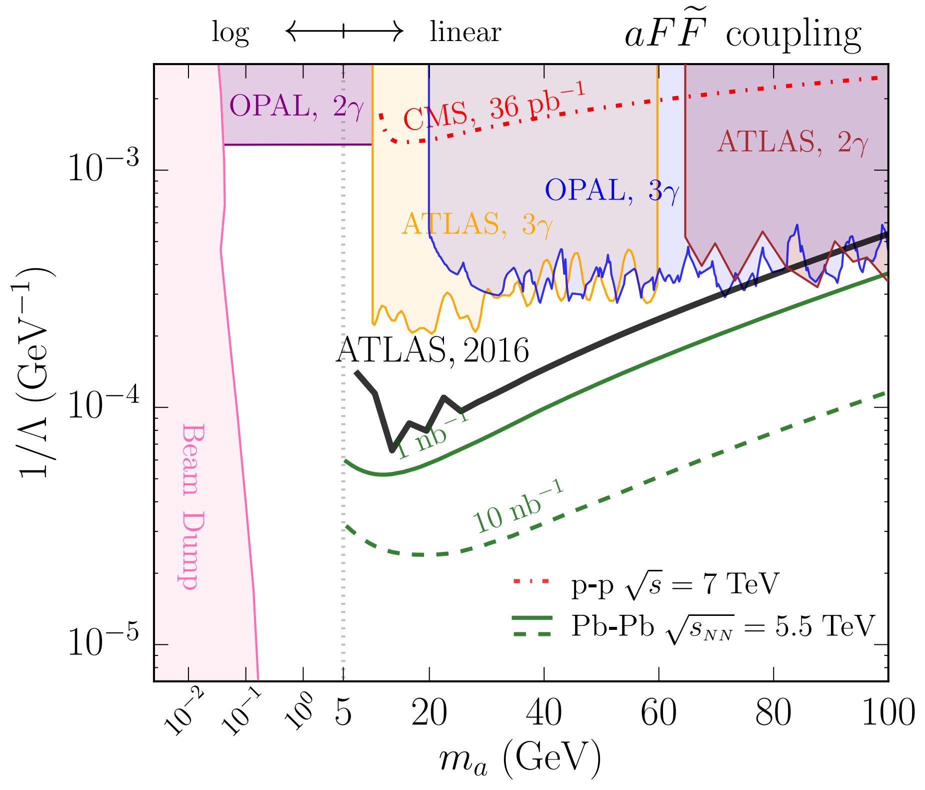
- Cross section for visible light actually is:
  - 10^{-60}cm^2!

Outline

- Observing Light-byLight scattering at the LHC
  - The ATLAS measurement



- What's next?
  - Sensitivity to axion-like particles & other BSM models
  - Ideas for measurement anomalous magnetic moment of the tau lepton

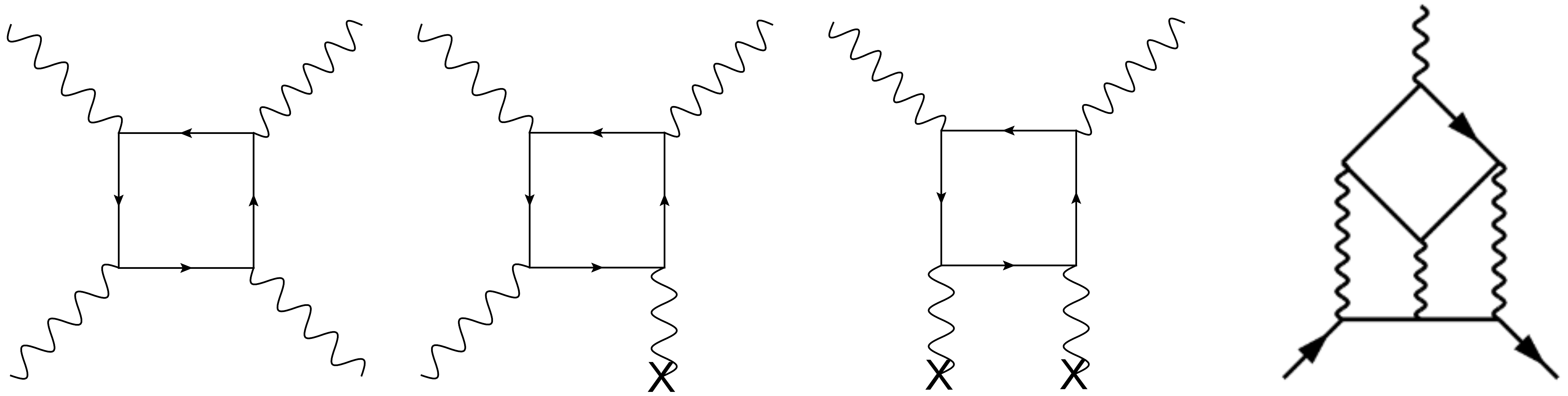


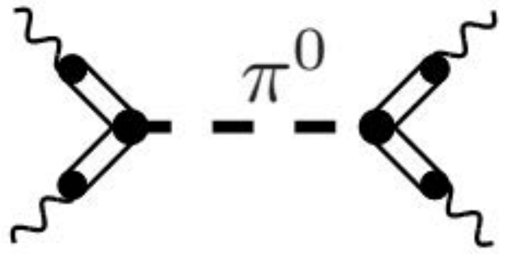
Overview of Light-by-Light scattering

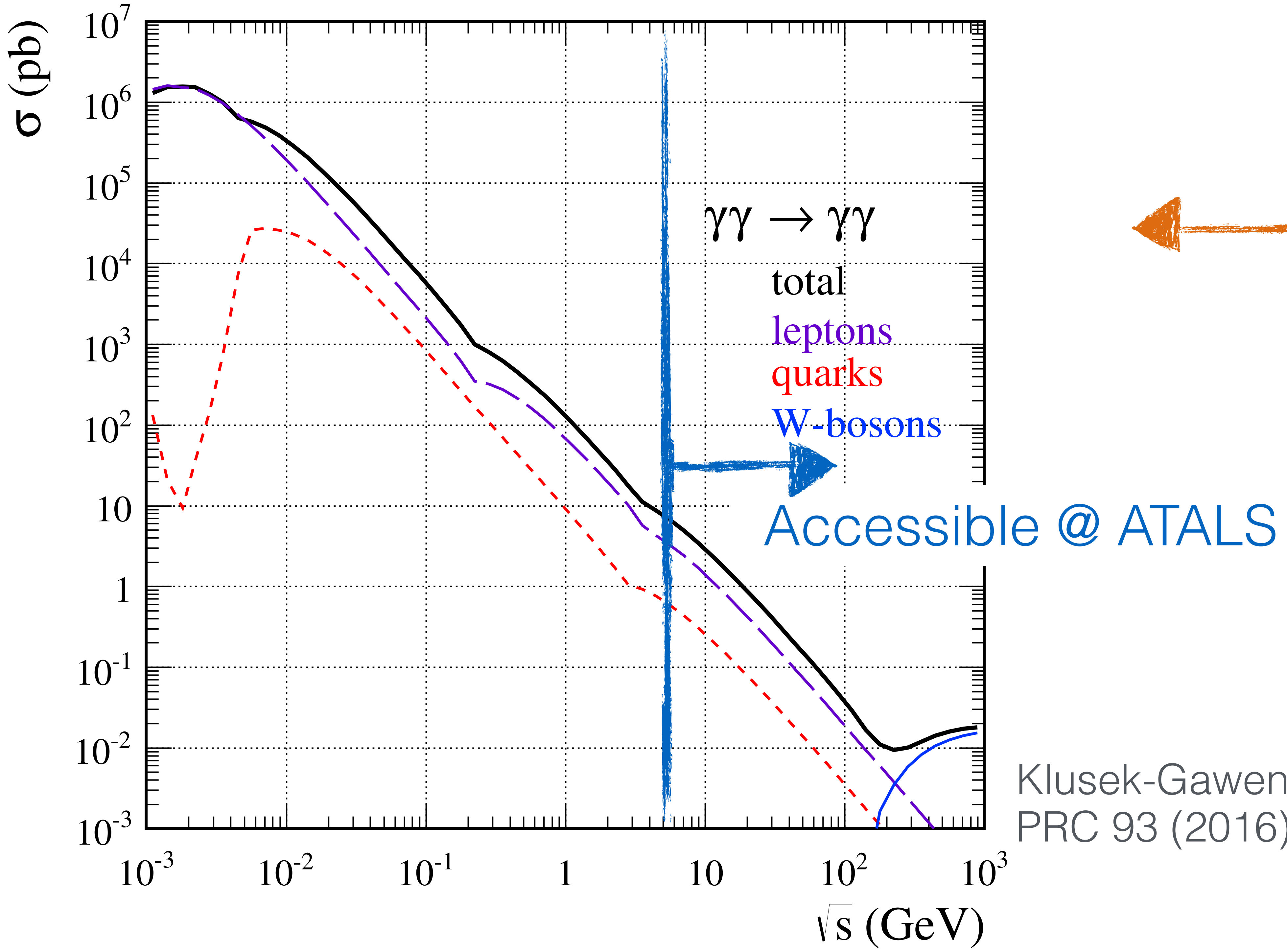
- Several names known for Light-by-Light scattering
  - Depending on number of virtual photons

  - Photon - Photon scattering: 4 real photons
    - Pseudo-scalar meson production in S-channel

  - Photons splitting : 1 virtual, 3 real photons
  - Delbrück scattering [1933]: 2 virtual, 2 real photons
  - Lepton g-2: 3 virtual, 1 real photon







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

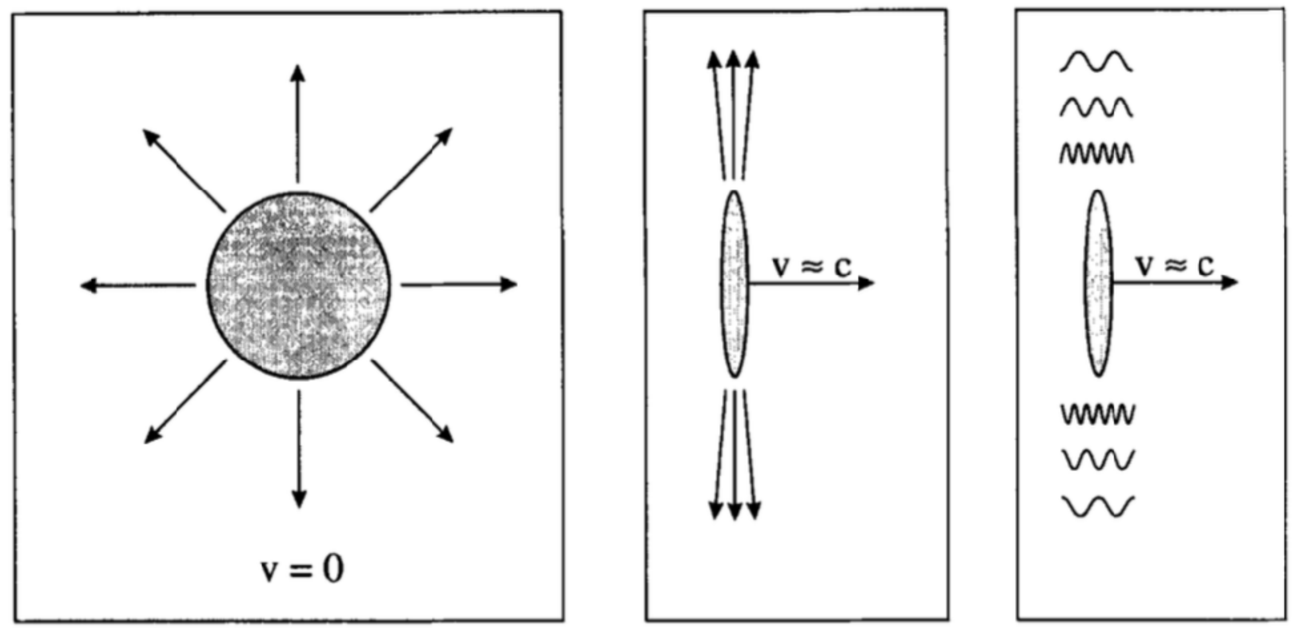
- Source of photons?

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



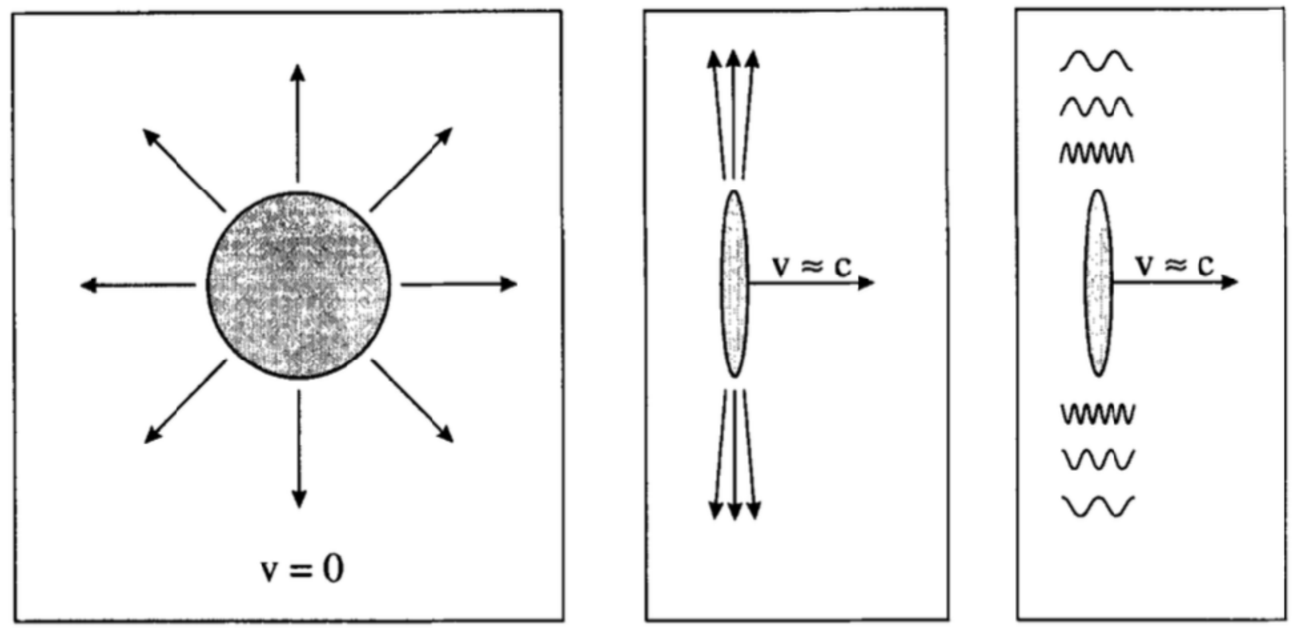
[Fermi, Nuovo Cim. 2 (1925) 143]

Ultra Peripheral Heavy Ion Collisions - LHC as photon collider

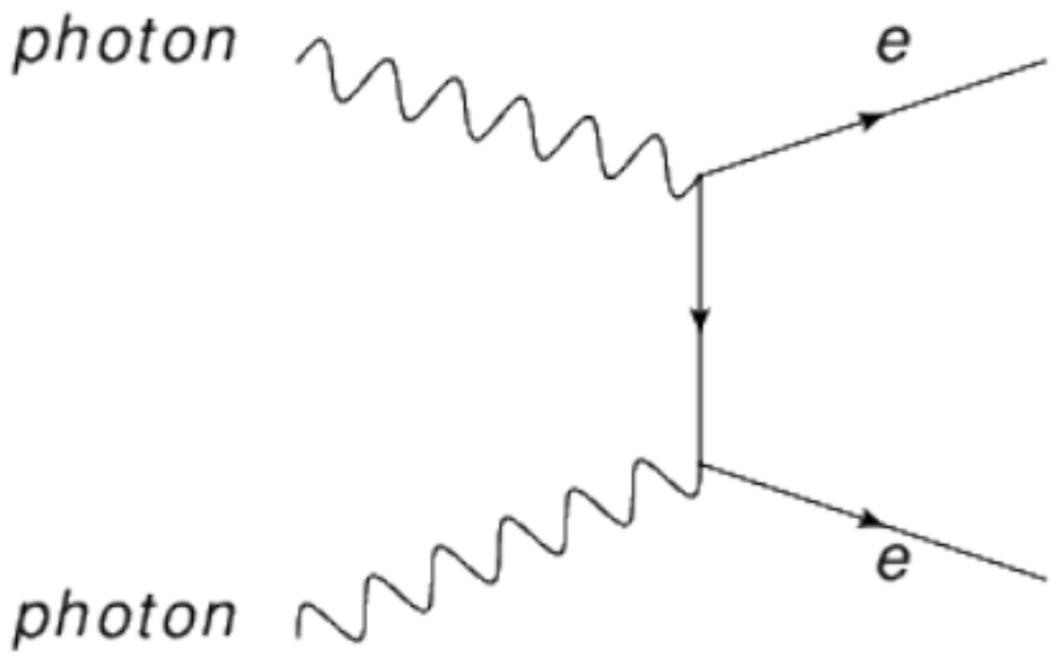
- Relativistic nuclei are intense source of (quasi-real) photons

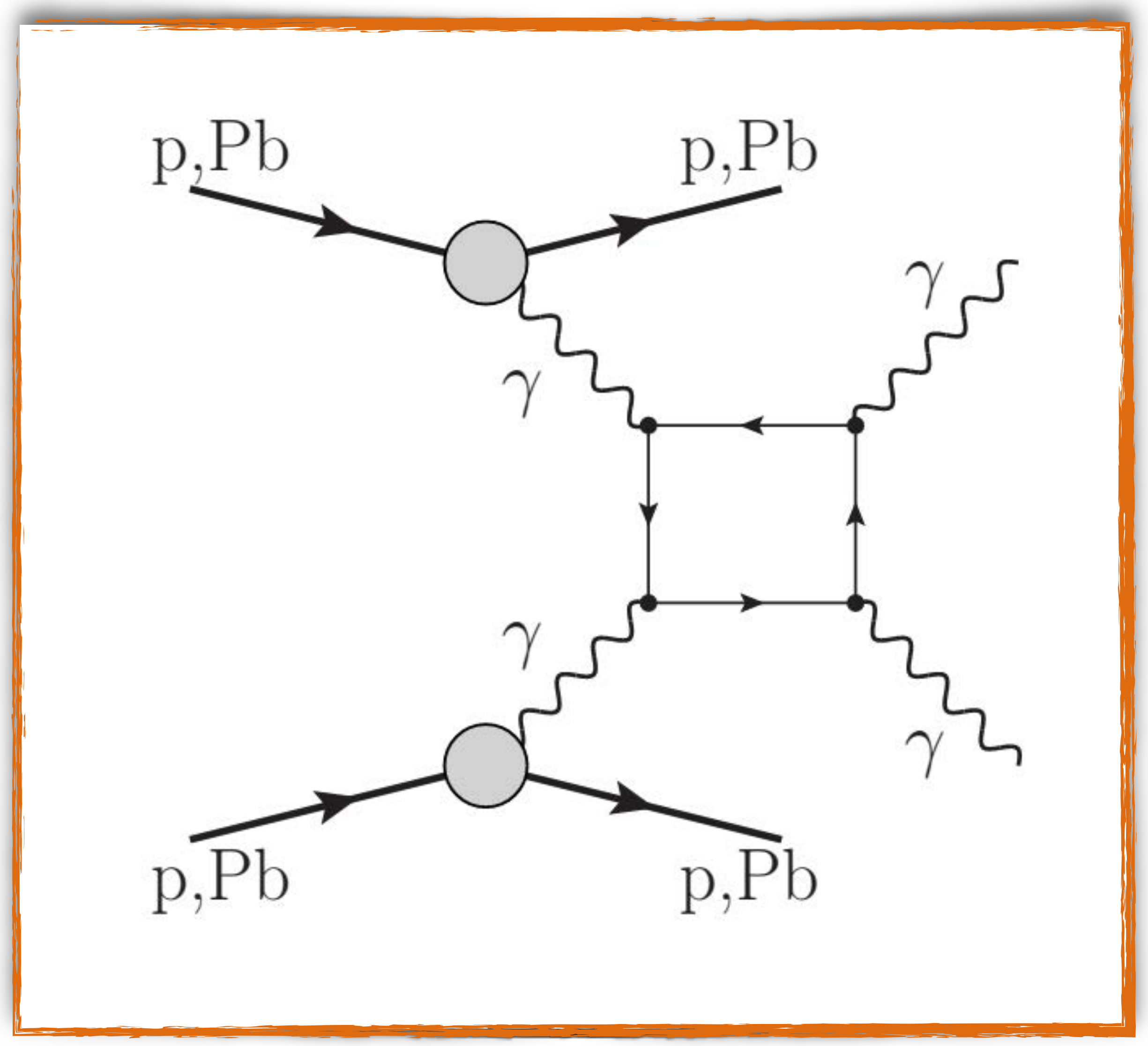
- Equivalent photon flux scales with Z^4
  - PbPb beams at LHC are a superb source of high energy photons!

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



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





- Various types of photon interactions possible

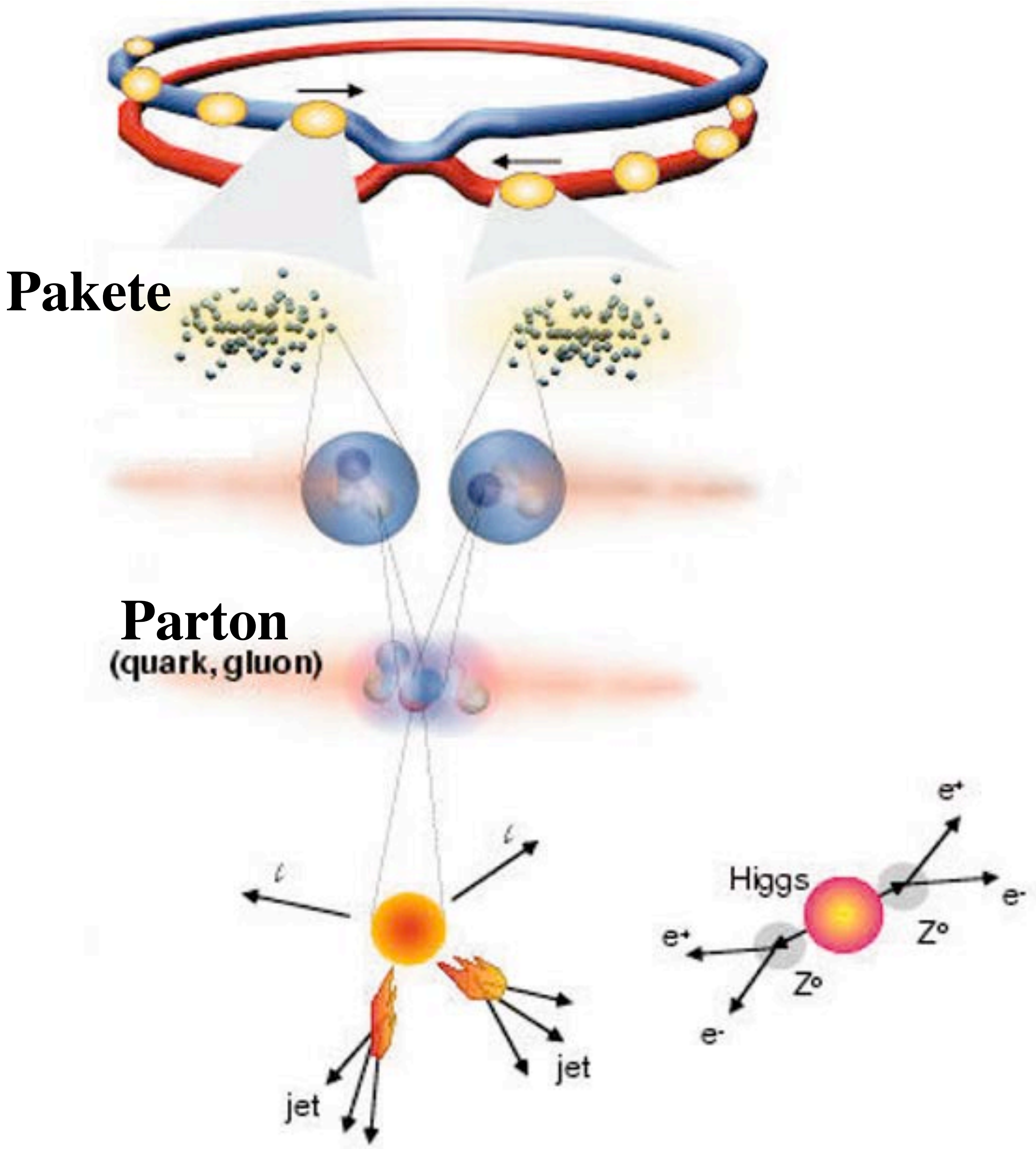
  - Photon-Pomeron: e.g. exclusive J/Psi production
  - Photons - Gluon: photo production of jets
  - Photon - Photon:
    - Producing fermion pairs (e.g. e^+e^-)
    - Light - by - Light scattering
      - QED interaction
      - Mediated via box-diagram
      - Beam particles stay intact

- 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

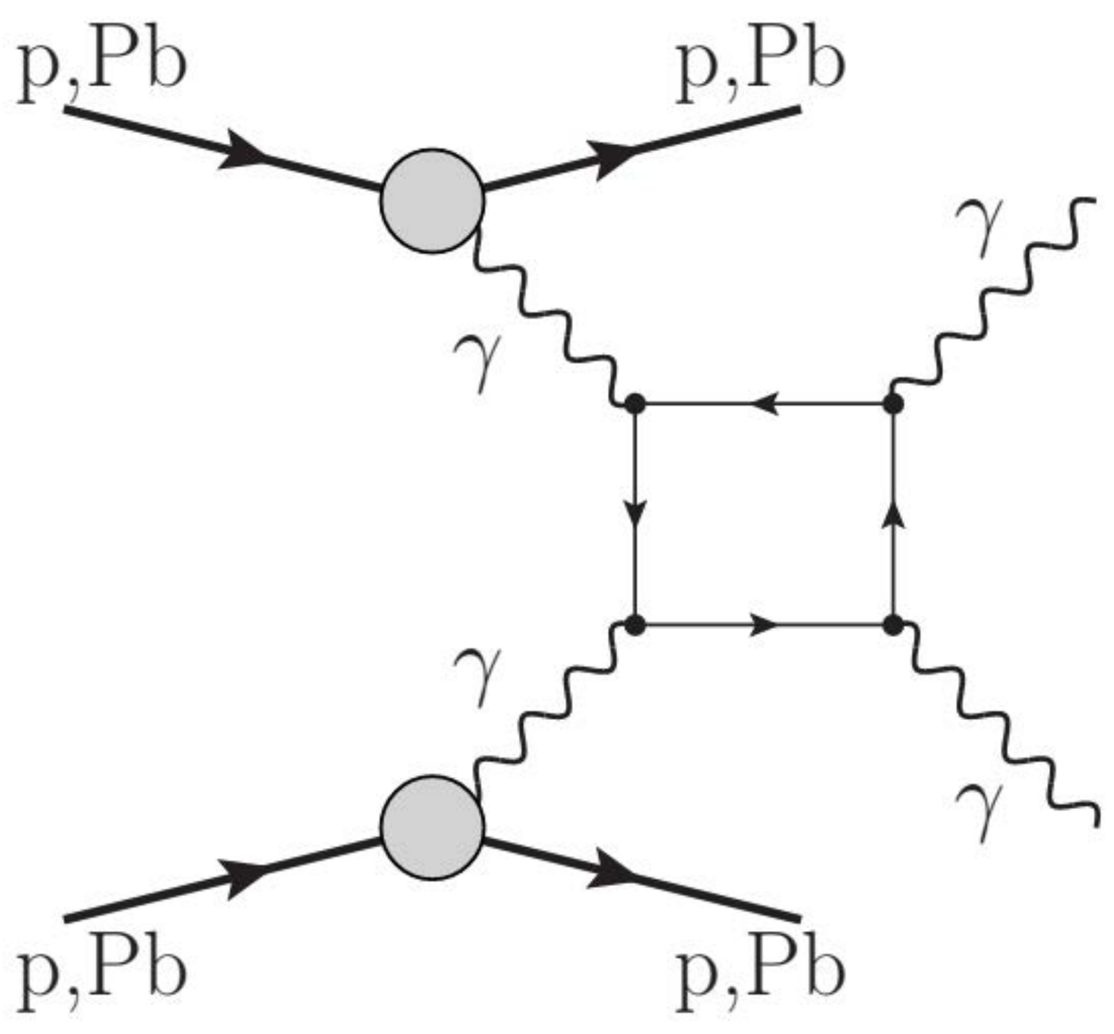


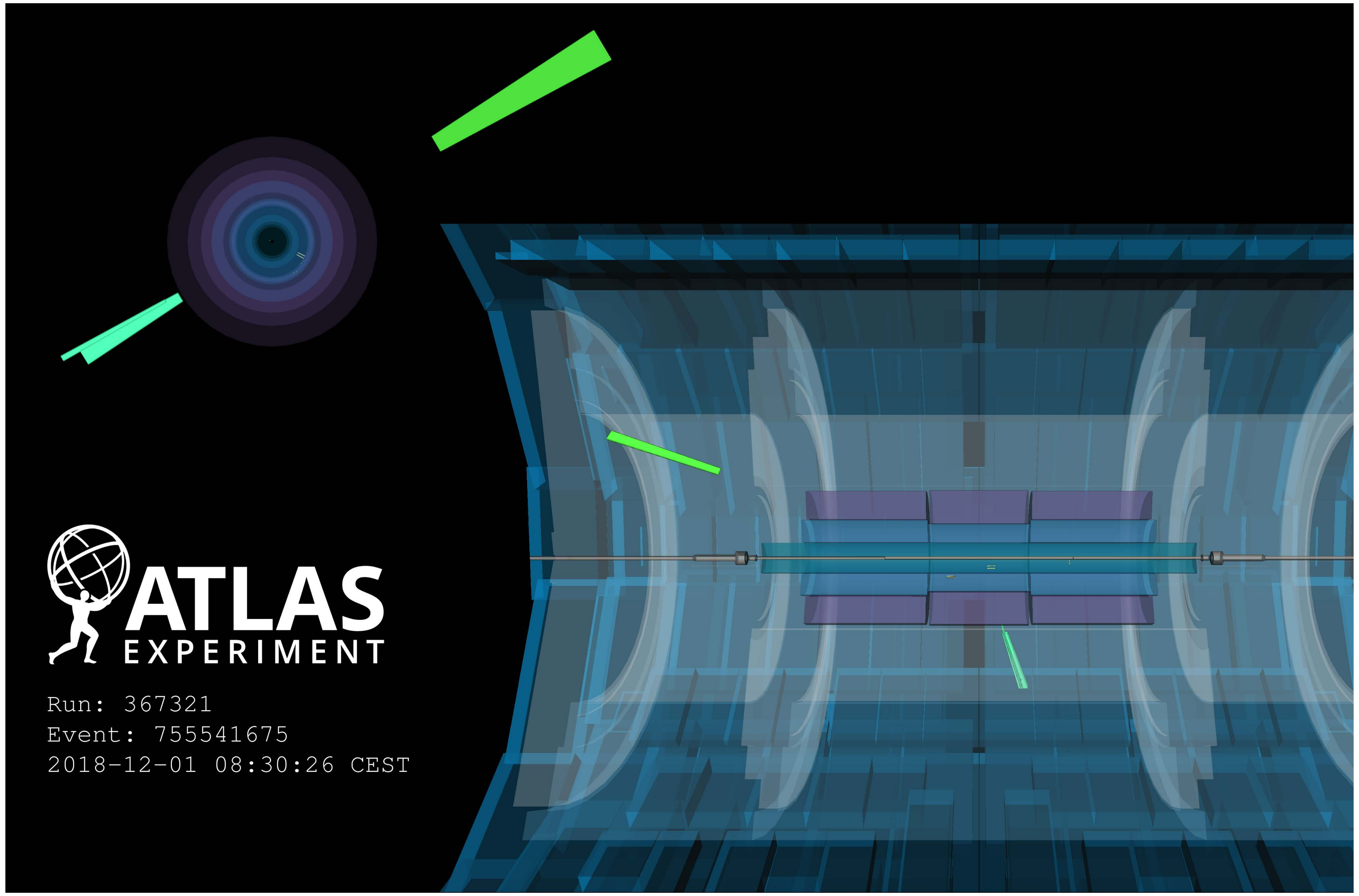
How to measure the $\gamma\gamma \to \gamma\gamma$ process

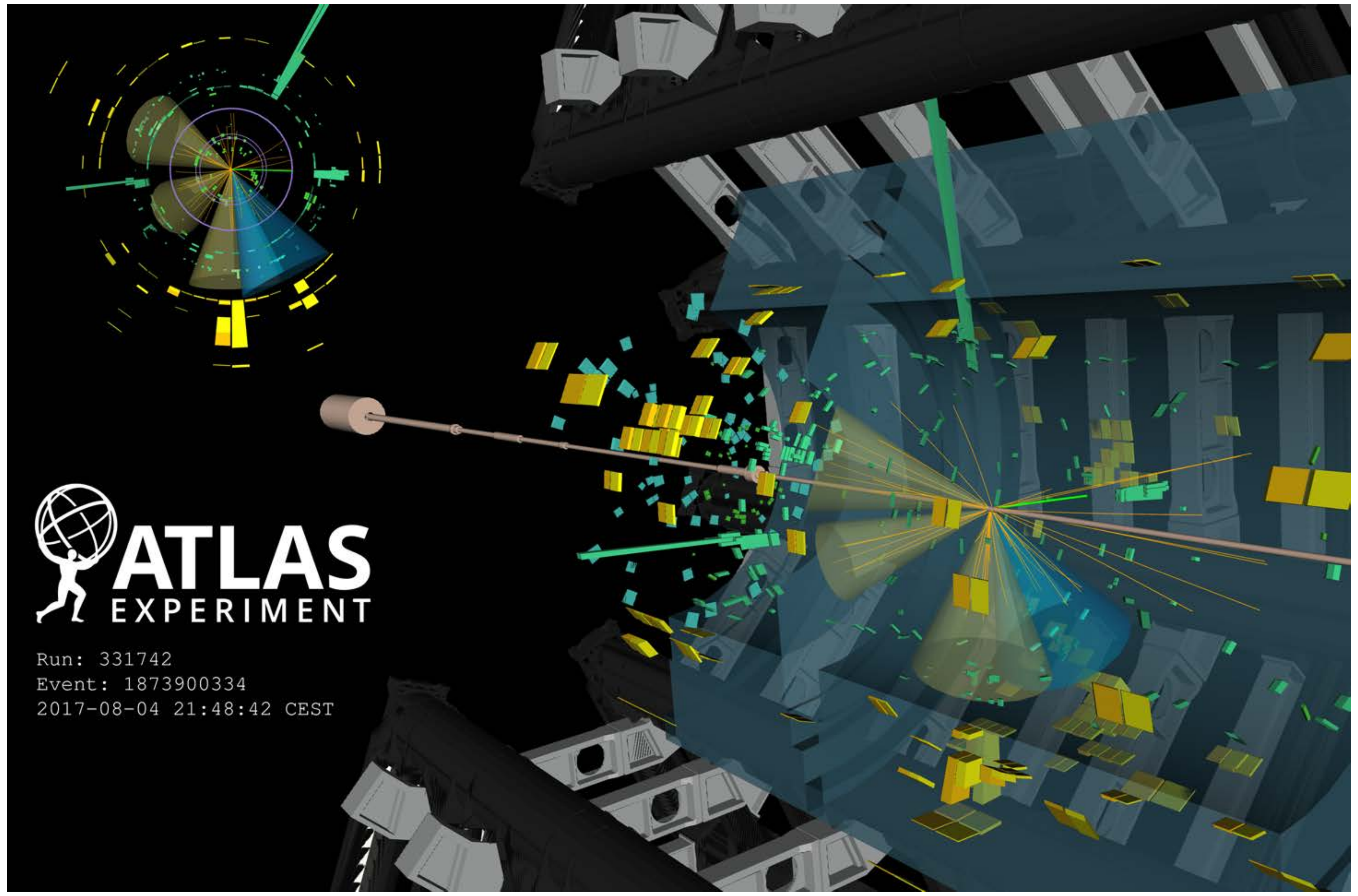
- Experimental signature:
  - 2 exclusive photons in the final state
  - Photons are back - to - back in ϕ
    - $A_\phi = 1 - |\Delta\phi| / \pi < 0.01$
- Cross section steeply falling with increasing energy
  - Looking for low energy photons: $E_T > 3$ GeV
- Very **unusual topology** and **energy range** for a high energy collider experiment
  - Interesting challenge :-)

2016: Nature Physics 13 (2017) 852

2019: Phys.Rev.Lett. 123 (2019)

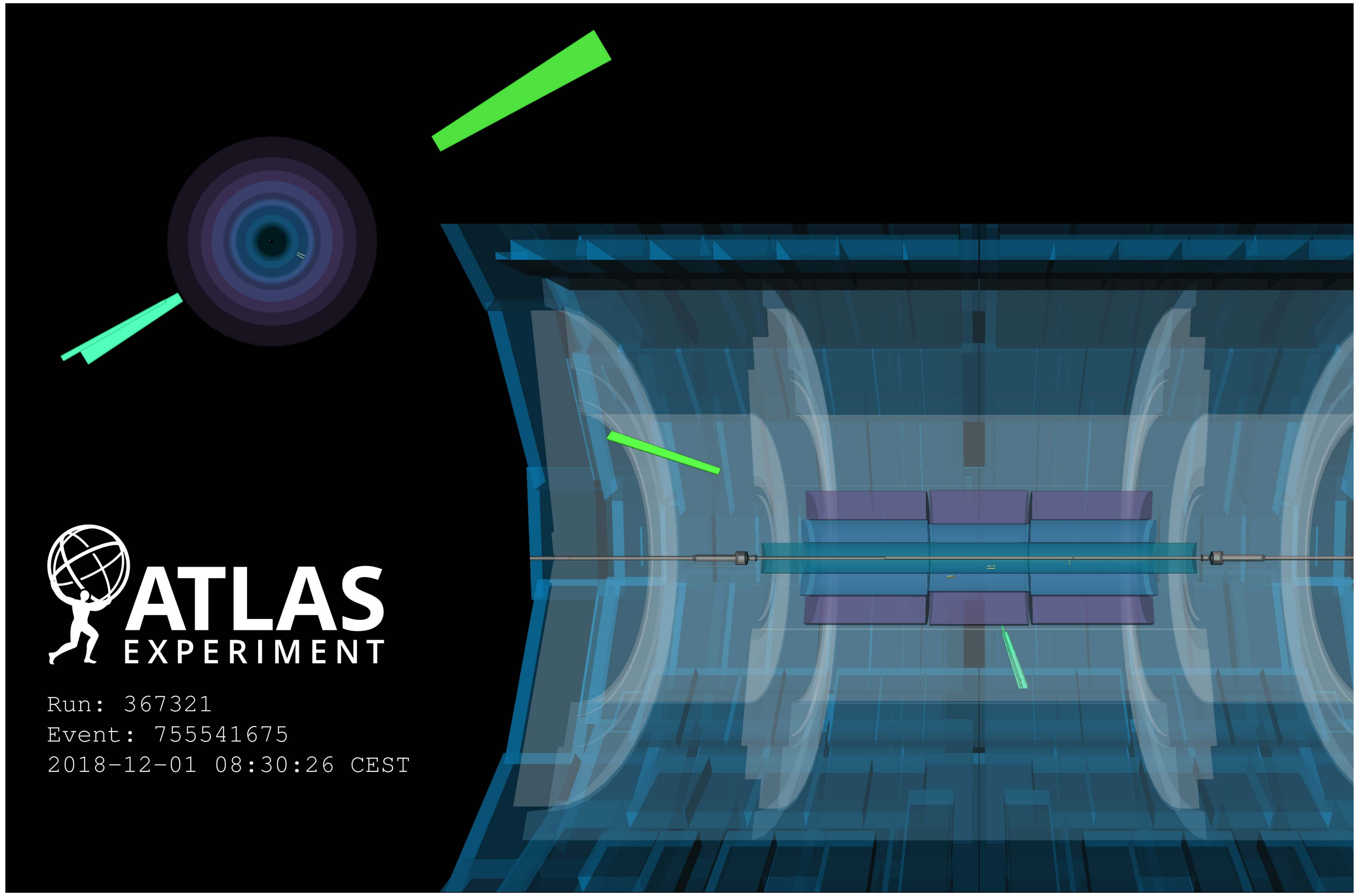


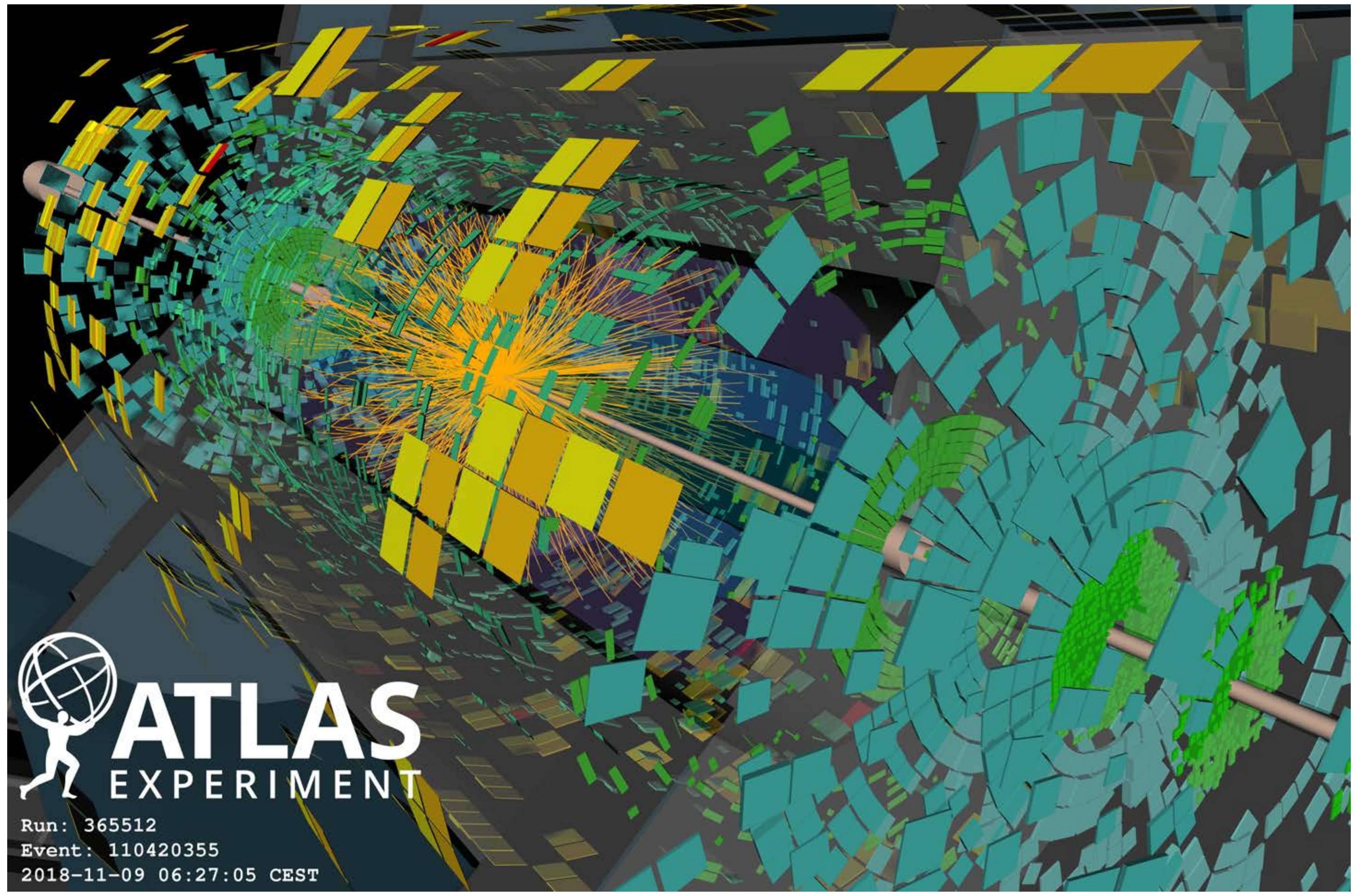




- pp collision

- Light-by-Light scattering candidate event





- PbPb collision

Triggering

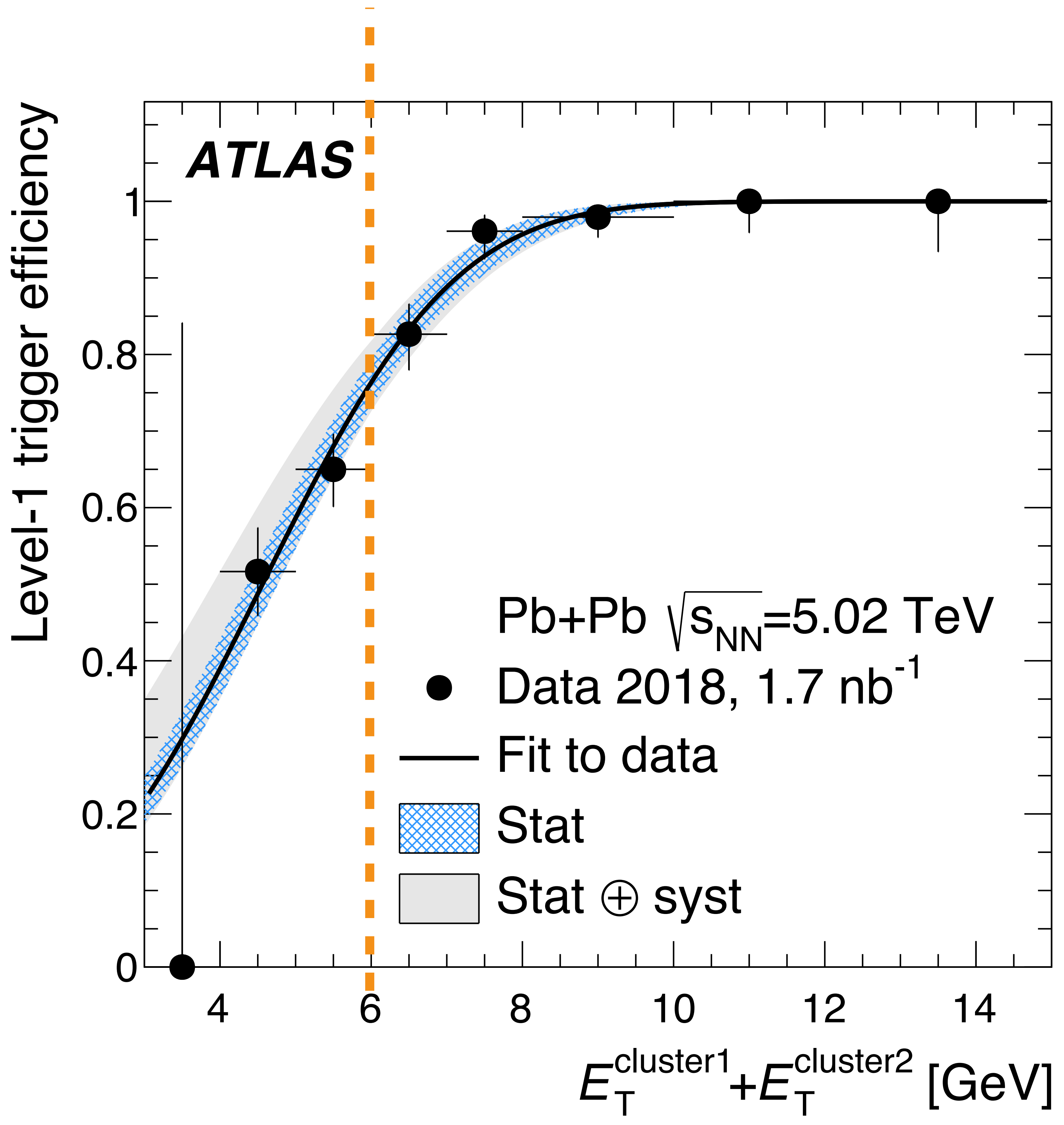
- L1 requirements (OR):
  - $\geq$ 1 EM cluster with $E_T(\gamma) > 1$ GeV && 4 GeV < total E_T < 200 GeV
  - $\geq$ 2 EM clusters with $E_T(\gamma) > 1$ GeV && total E_T < 50 GeV

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

- Support Triggers:
  - Sum E_T < 50 GeV & FCal Veto & < 15 tracks & > 2 tracks
  - HLT_mb_sptrk_exclusiveloose_vetosp1500_L1VTE20

Triggering

- L1 requirements (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



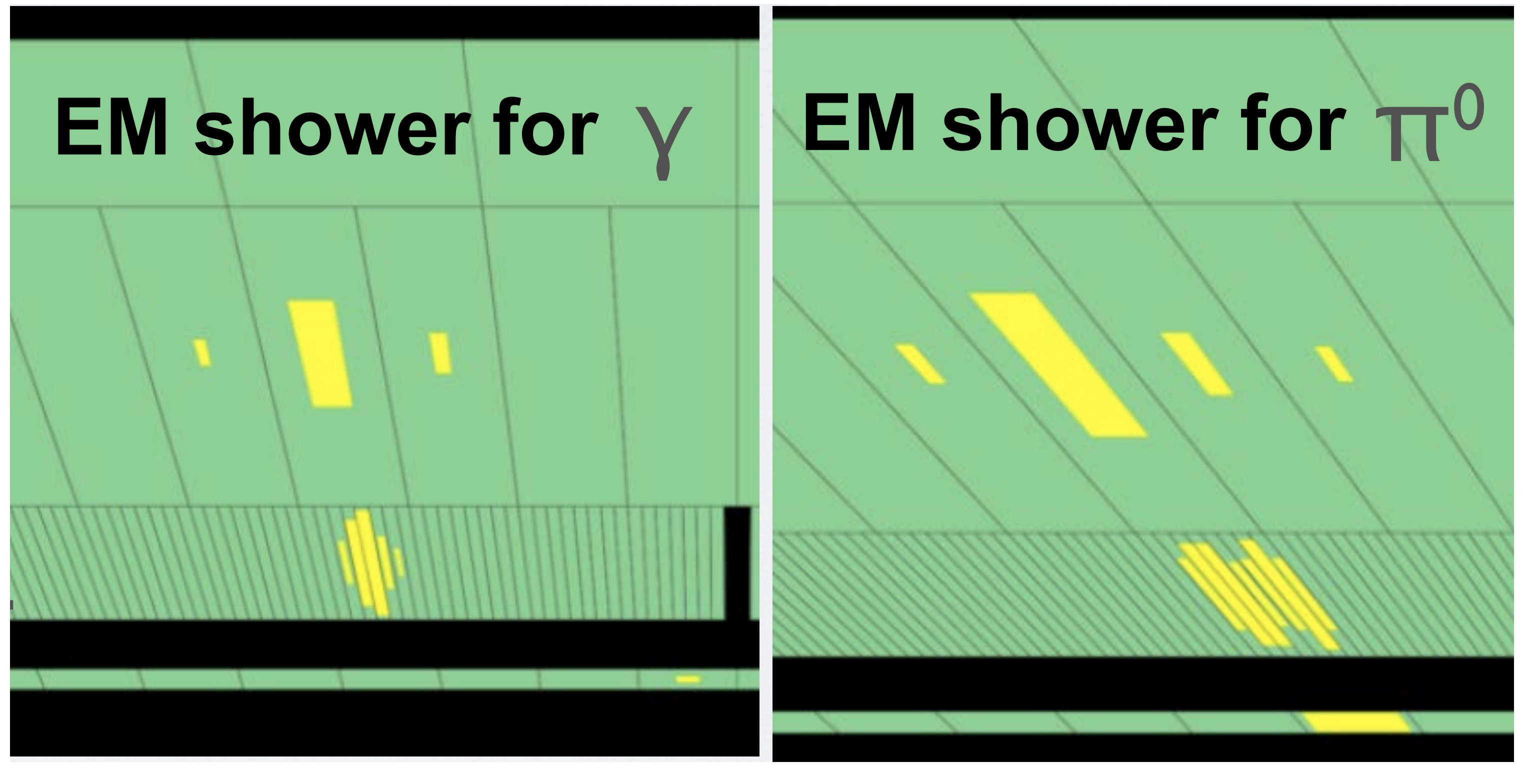
- HLT Requirements (AND):
  - ΣE_T (FCal) < 3 GeV on both sides
  - ≤ 15 hits in pixel detector
    - Tagging of exclusive photon final state

- Support Triggers:
  - Sum E_T < 50 GeV & FCal Veto & < 15 tracks & > 2 tracks
  - HLT_mb_sptrk_exclusiveloose_vetosp1500_L1VTE20

- Trigger efficiency determined using e^+e^- final states
  - Triggered by independent support triggers
- Applied to simulated events to correct yield

Photon reconstruction and identification

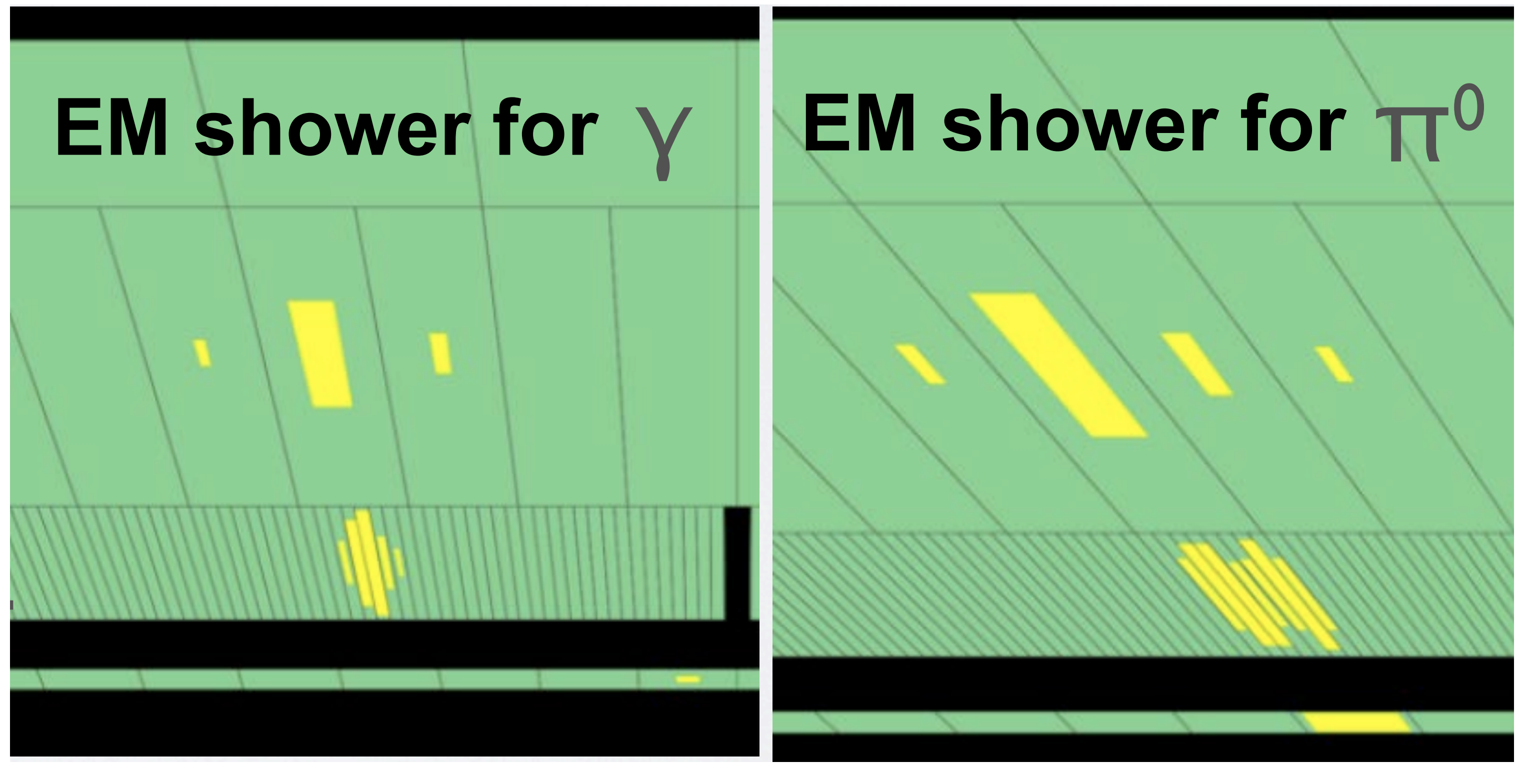
- Photon reconstruction:
  - Using default photon reconstruction algorithm
    - Entries in calorimeter cells are grouped to clusters
    - Track matching performed
      ➡ Electrons / Photons
      - Some overlap allowed



- 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

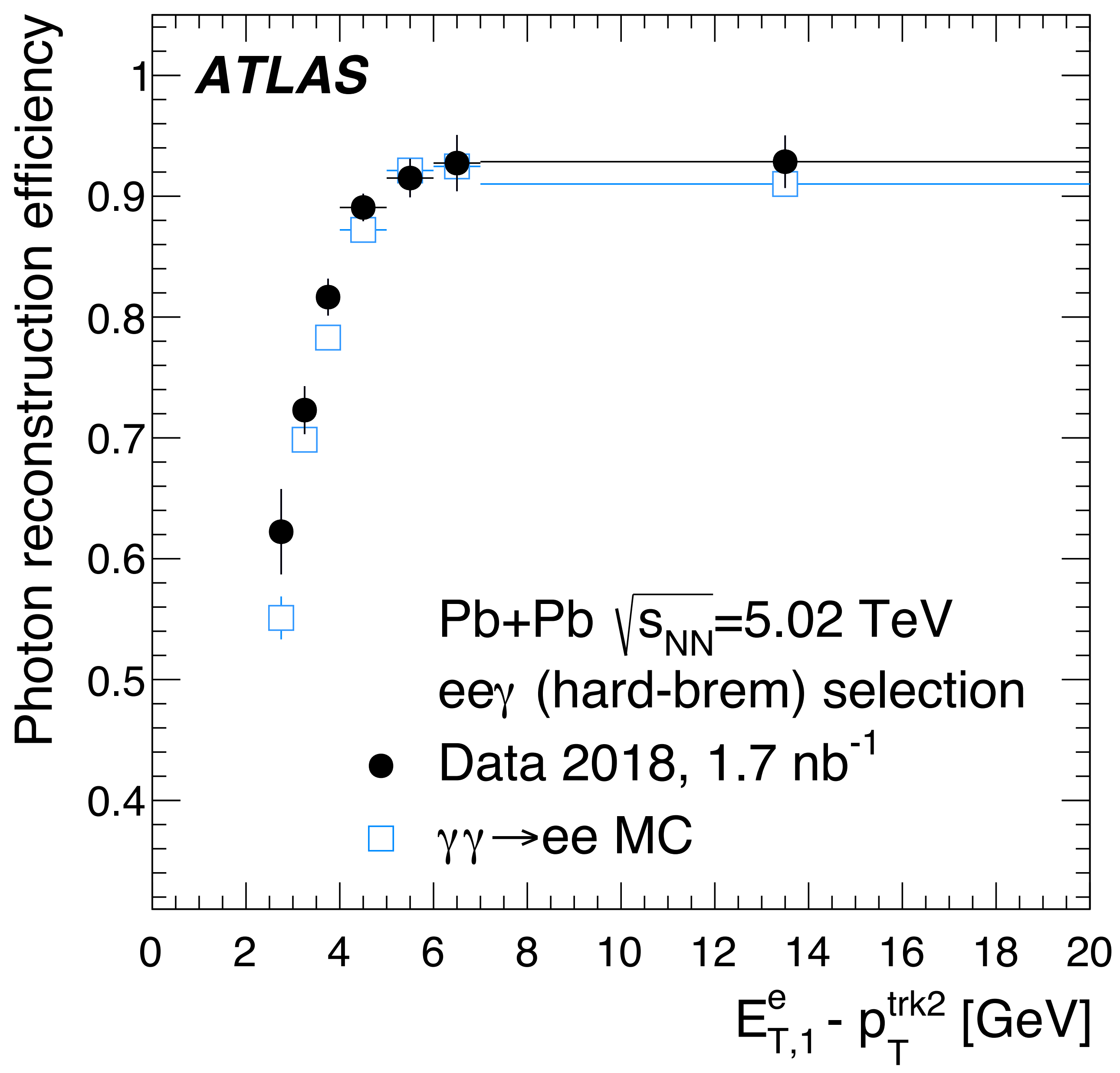
Photon reconstruction and identification

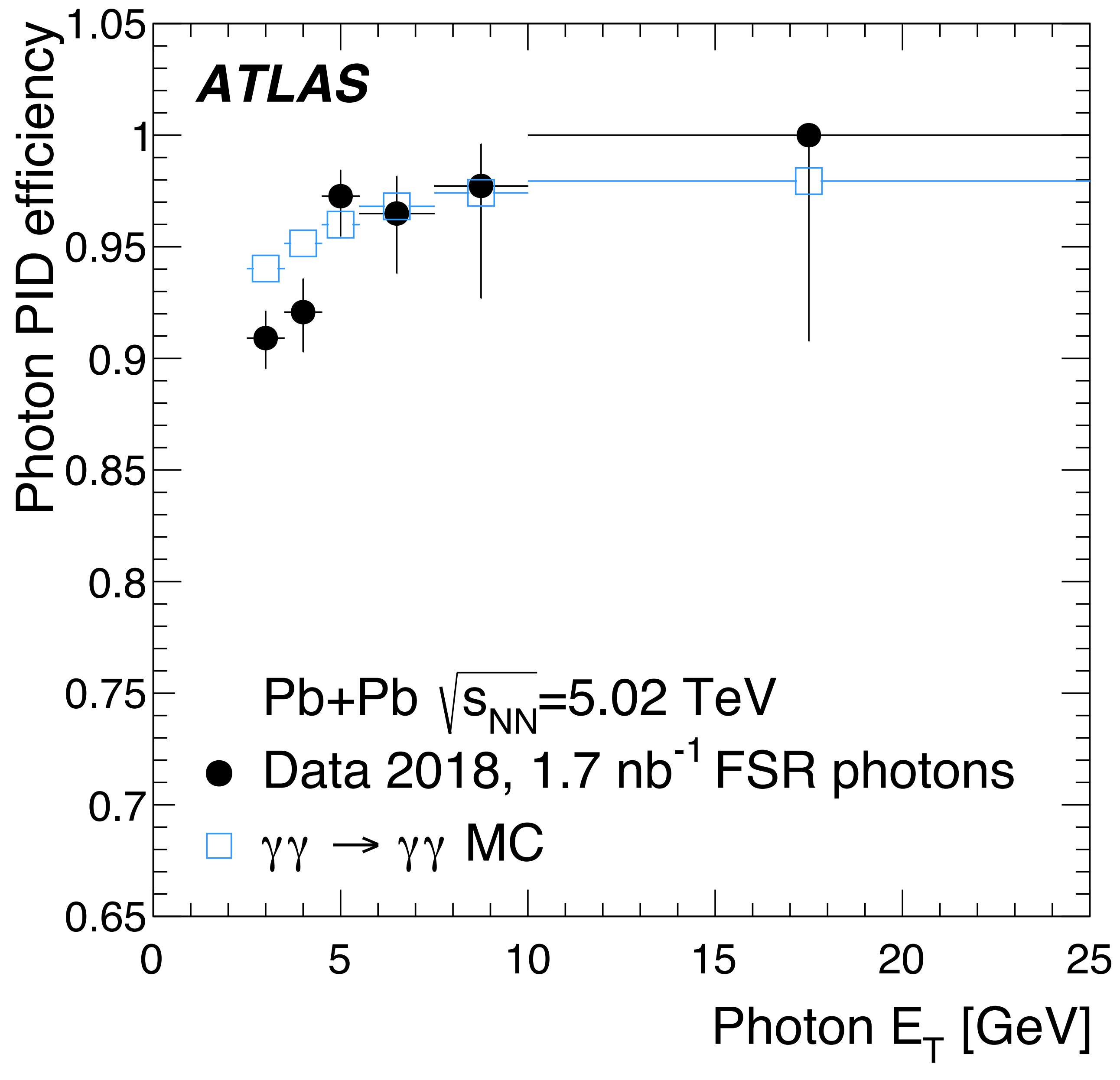
- Photon reconstruction:
  - Using default photon reconstruction algorithm
    - Entries in calorimeter cells are grouped to clusters
    - Track matching performed
      - ➡ Electrons / Photons
      - Some overlap allowed



- 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

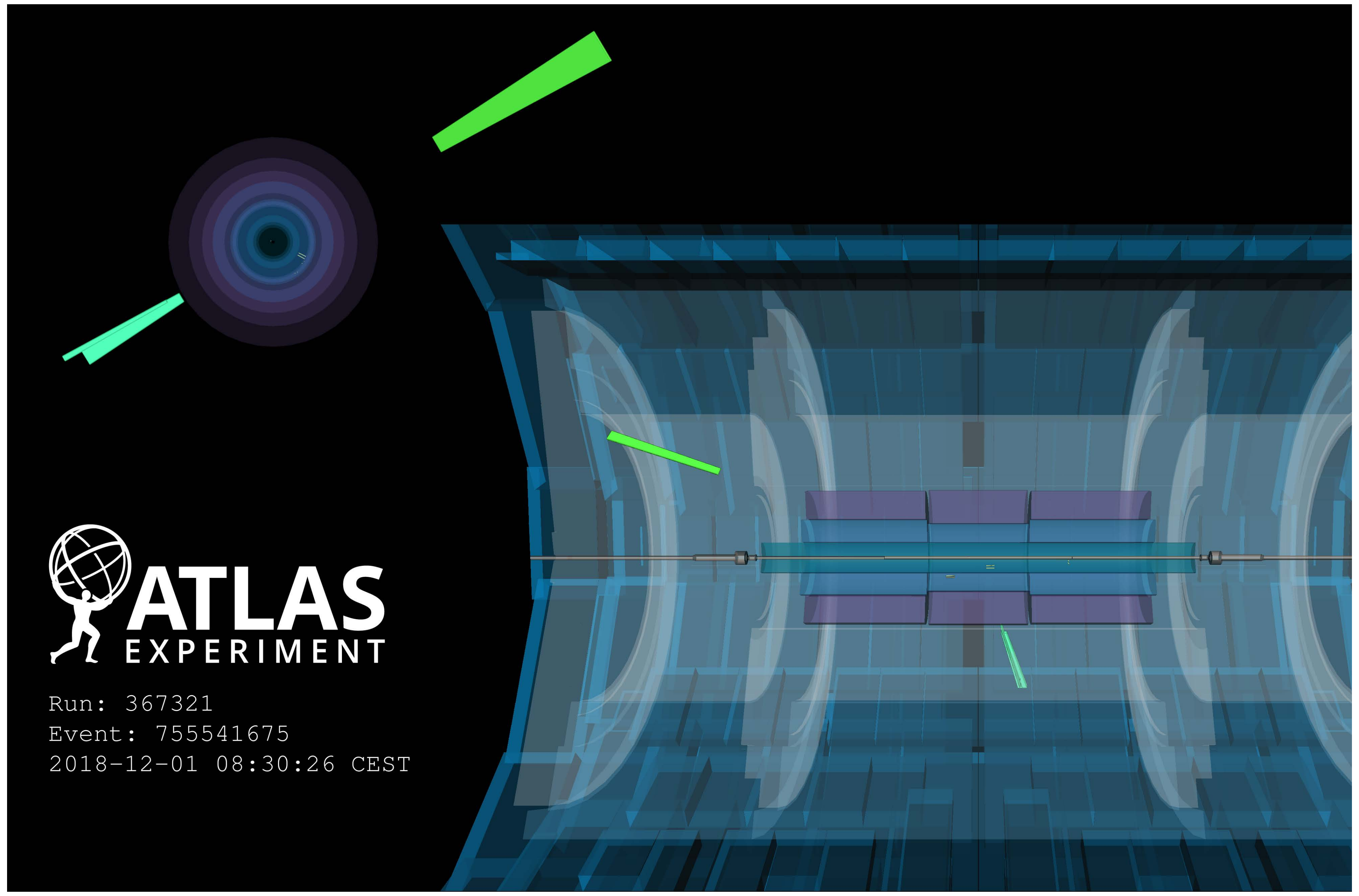
- Efficiency measurement:
  - Using e^+e^- events where a hard bremsstrahlung photon was radiated
  - $ee\gamma$ final state selection:
    - Exactly 1 electron $p_T > 4$ GeV && 1 additional track
    - Track $p_T < 1.5$ GeV
      - Photon with $E_T > 2.5$ GeV must be present in Event!



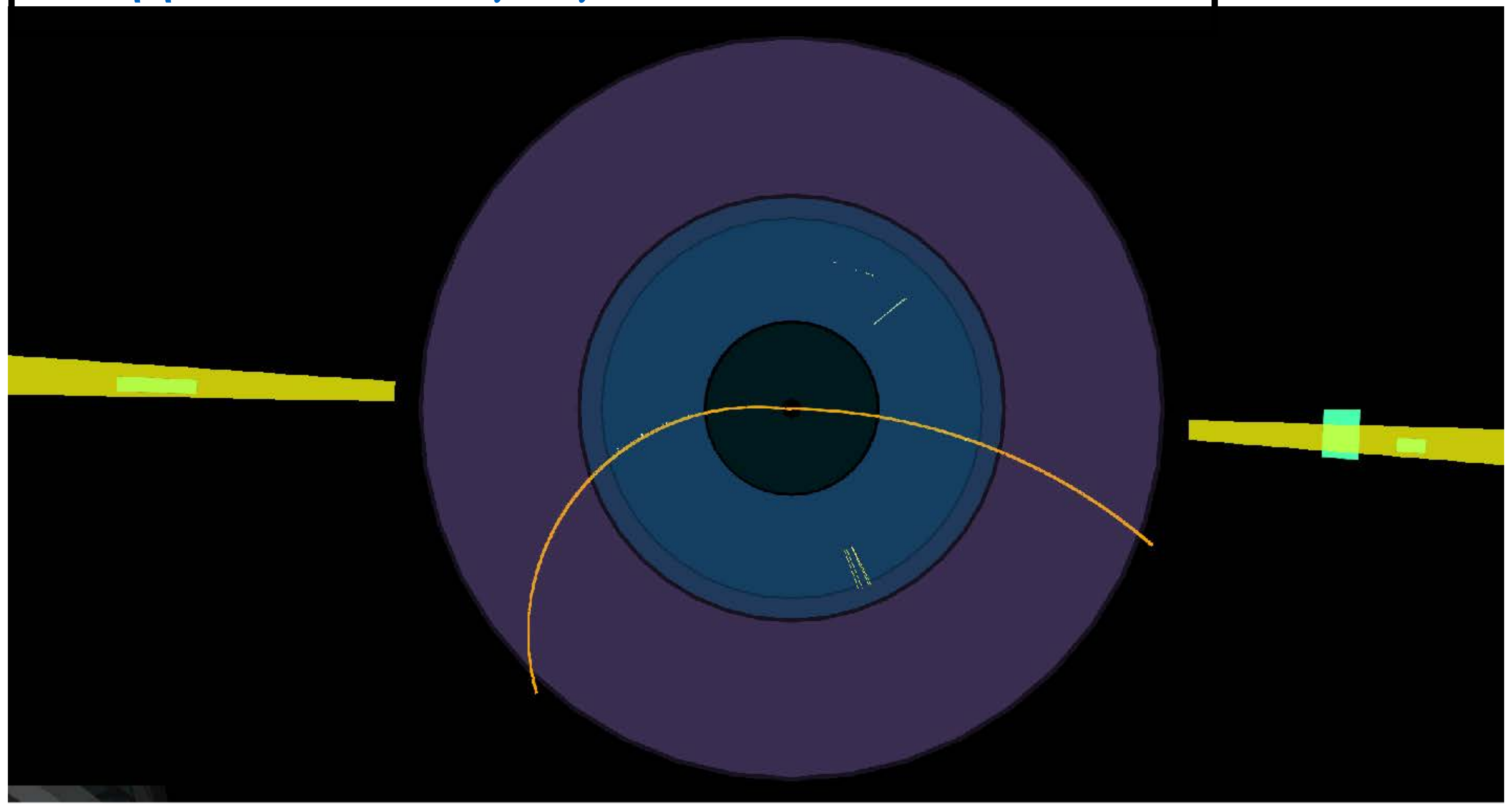


Event Selection

- Trigger
- Exactly 2 photons with E_T > 3 GeV && $|\eta|$ < 2.37
  Excluding 1.37 < $|\eta|$ < 1.52
- Invariant di-photon mass $M_{\gamma\gamma}$ > 6 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 processes

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

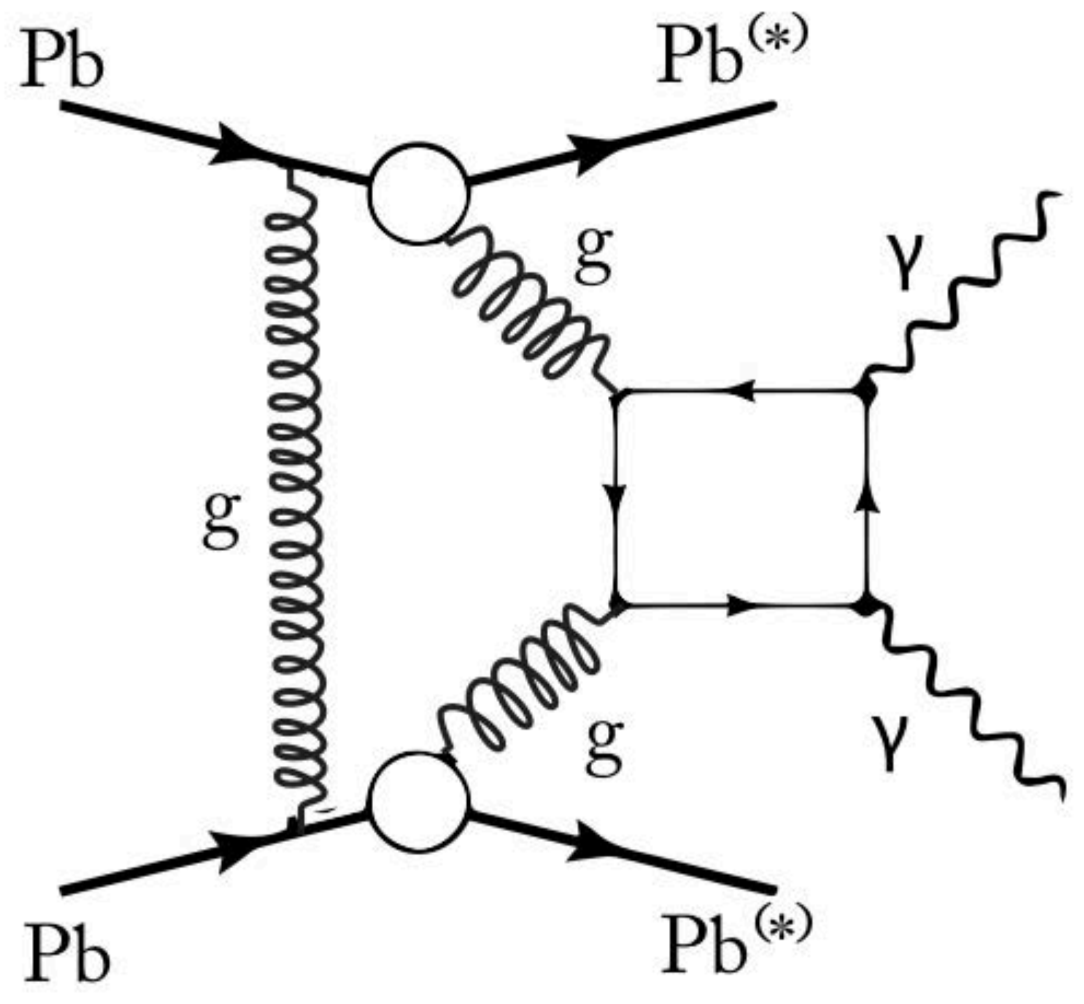
- Central Exclusive Production of 2 photons (**CEP**): $gg \rightarrow \gamma\gamma$
  - Coloured initial state: significant intrinsic transverse momentum!
    - Broader shape of A_ϕ distribution
    - Control region defined to study CEP: aco > 0.01

- 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: 20%

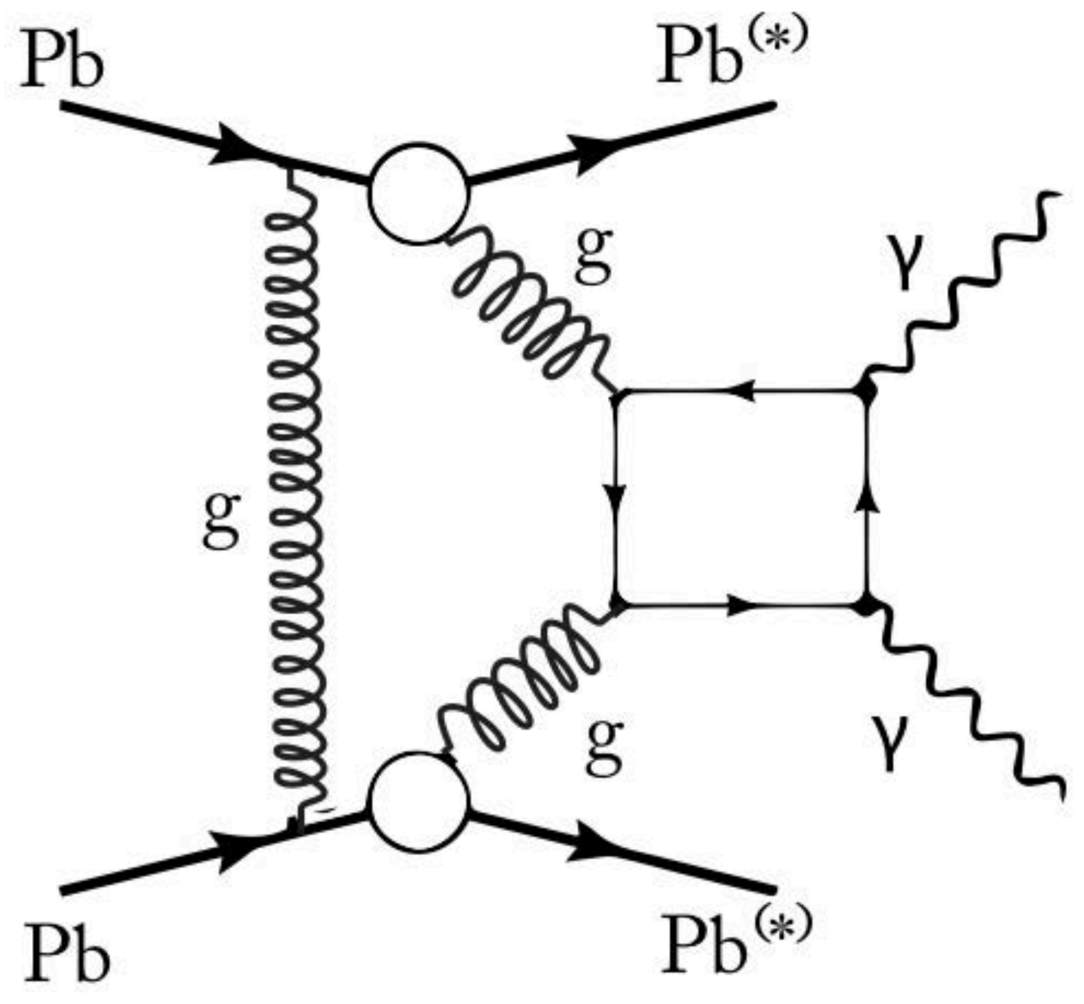
- Expected events in signal region: 5 ± 1

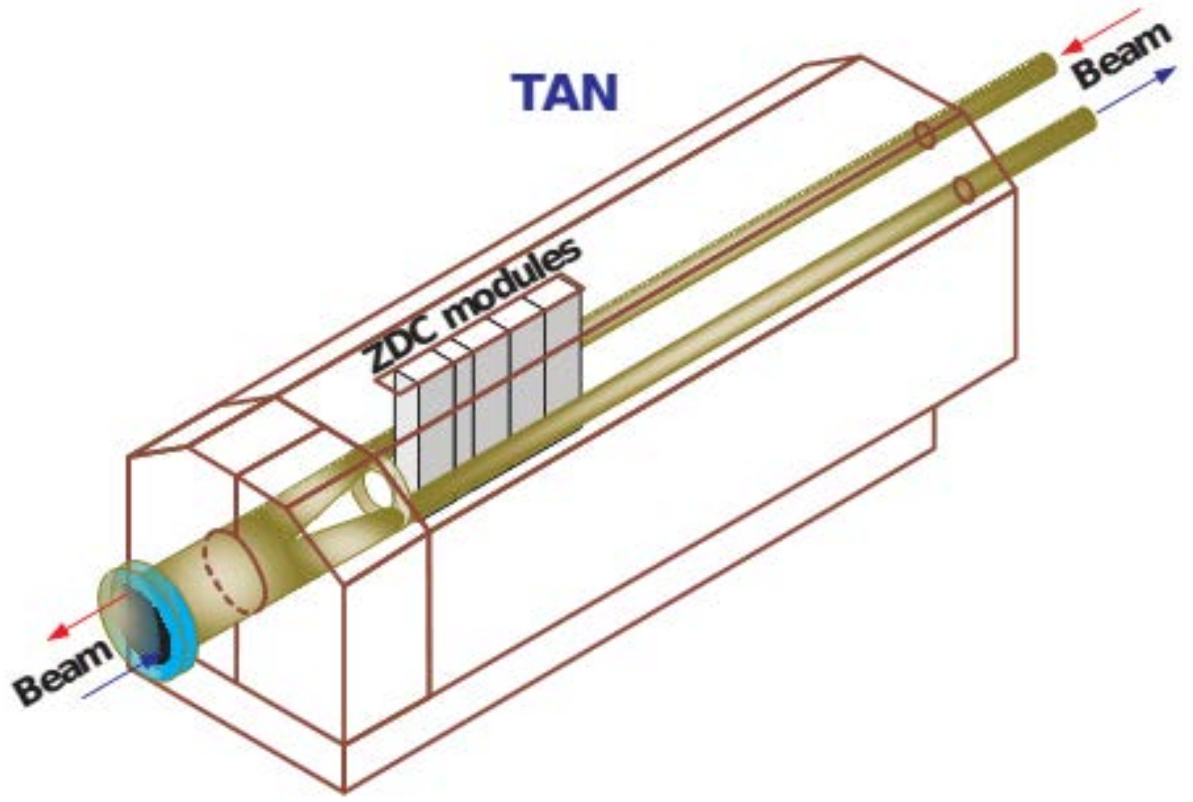


Background processes

- **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: 20%
- Expected events in signal region: 5 ± 1
- 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 :)

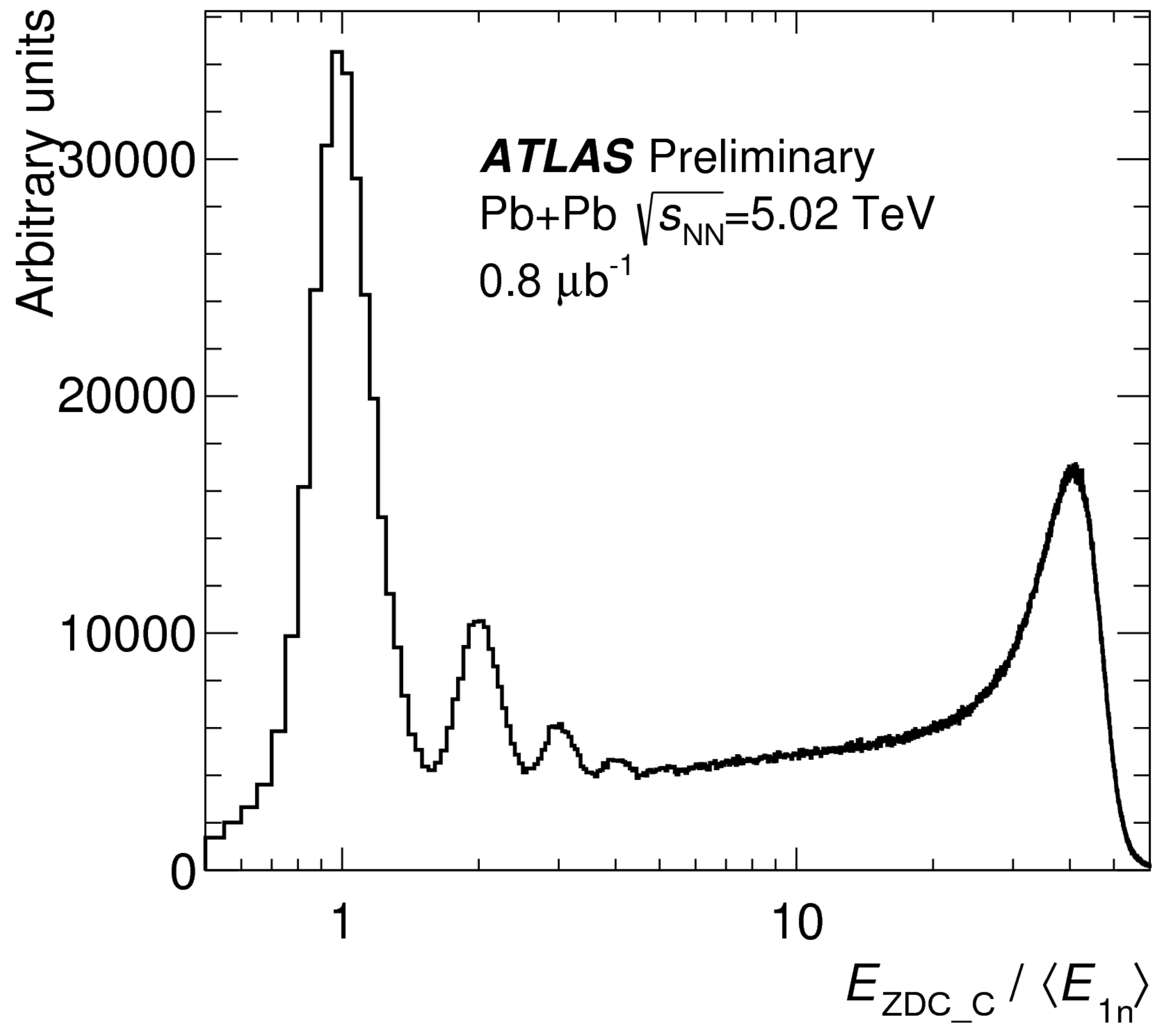




- ± 140m from ATLAS IP
- $8.3 < |\eta| < \inf$

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

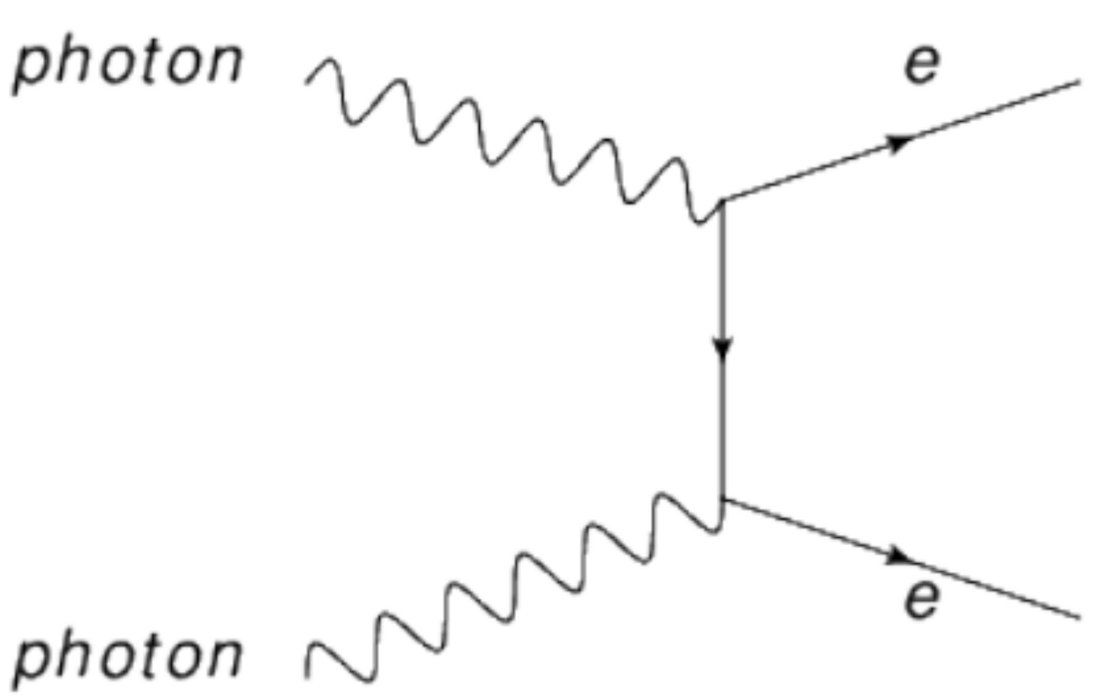
$$r^{\mathrm{pred}}_{\mathrm{ZDC/noZDC}} \approx \frac{\mathrm{CEP} + 0.2 * (\mathrm{signal} + ee)}{0.8 * (\mathrm{signal} + ee)}$$

- 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%

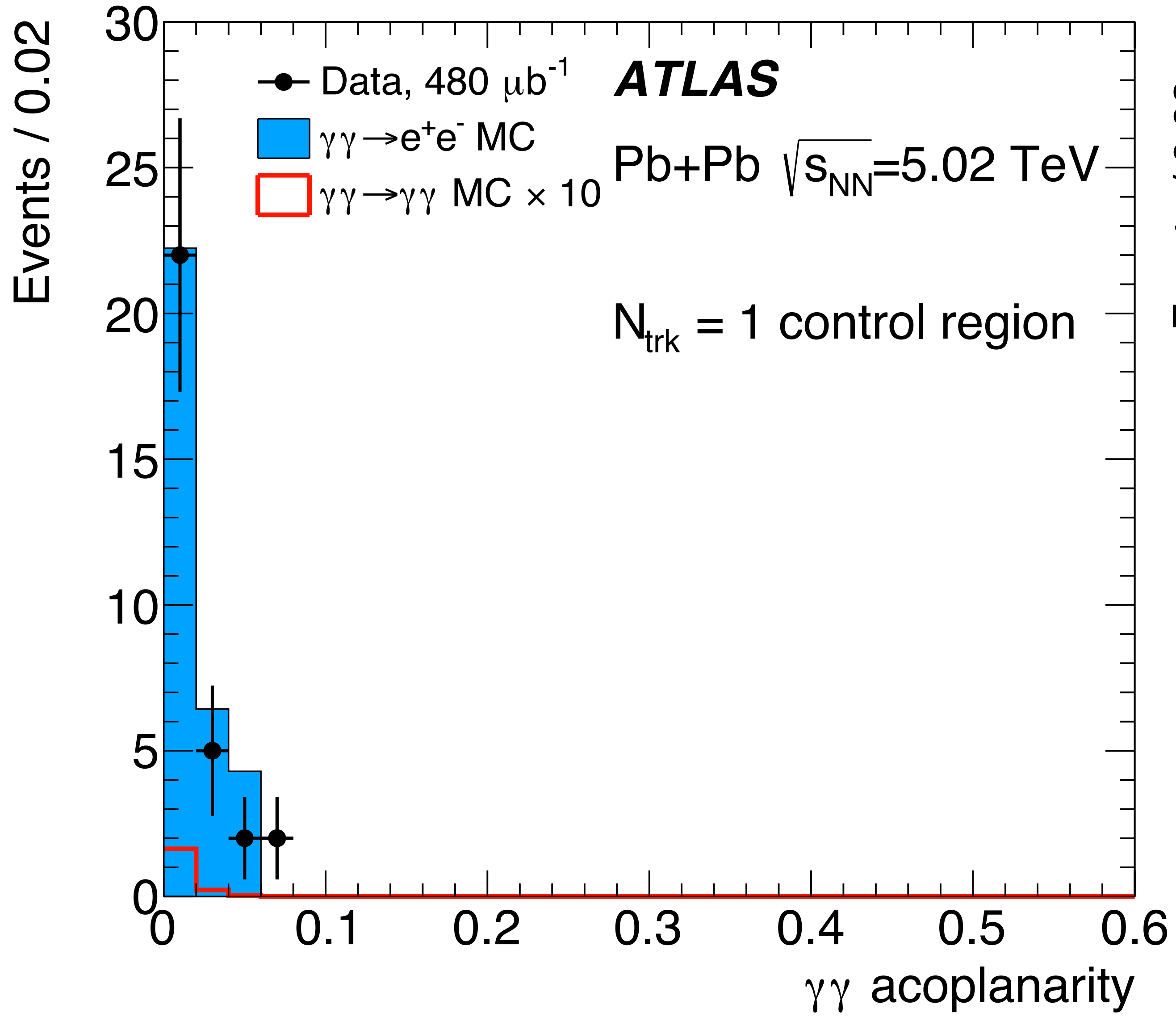
Background processes

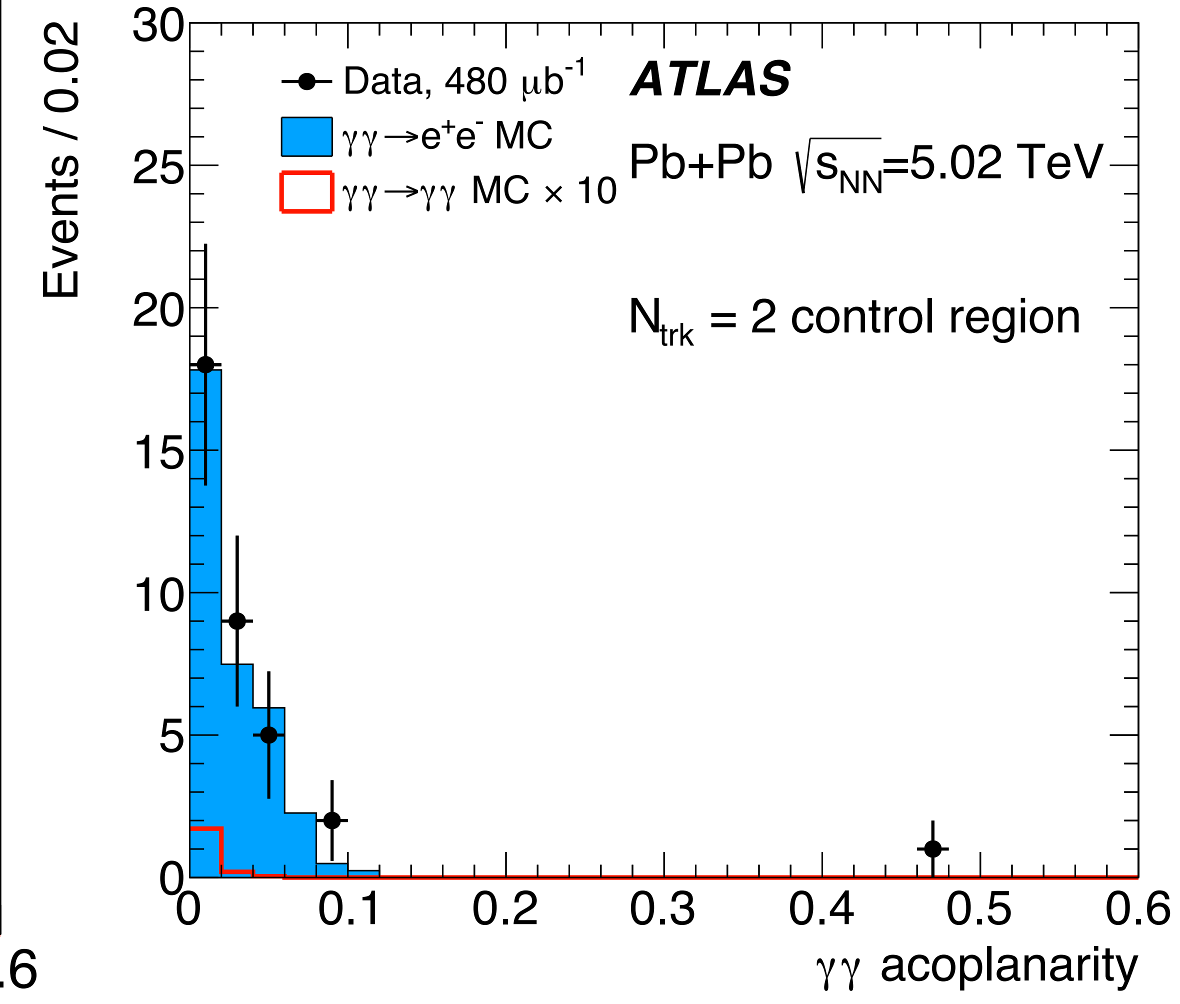
- **What else has a similar signature?**



- 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: 7 ± 3

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

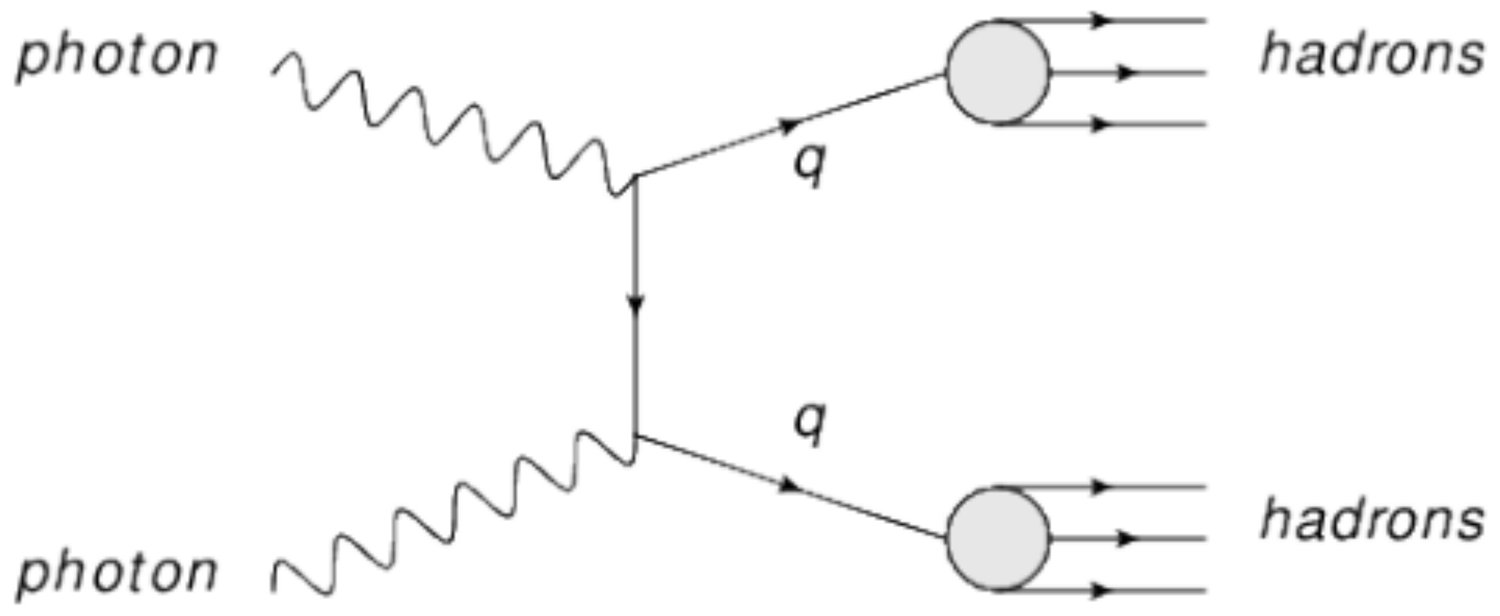




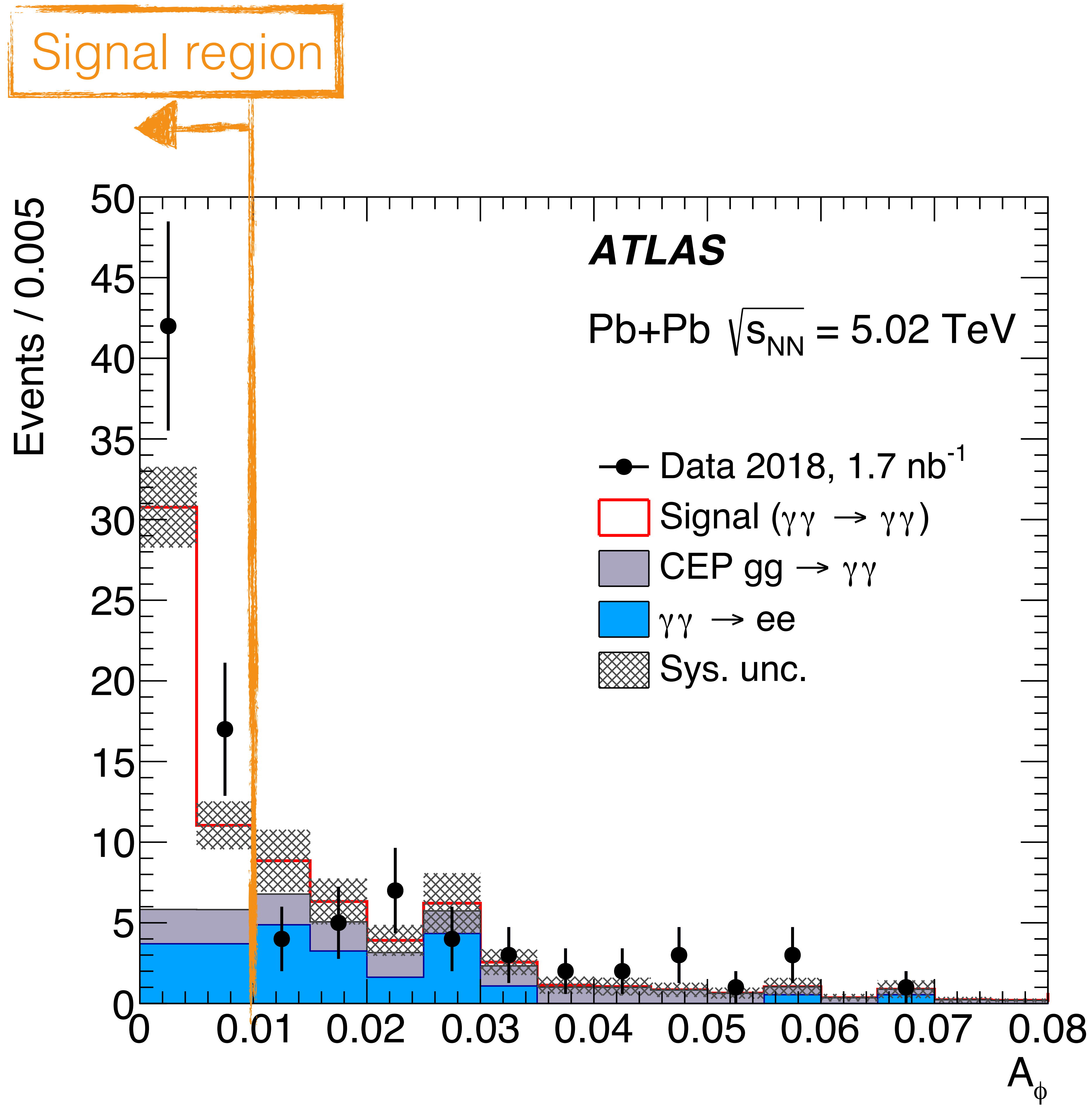
Background processes

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

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



- **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
    - 2% impact on MC yields, for both 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: 2%

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

- Total: 7% on the detector correction factor C

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
    - 2% impact on MC yields, for both 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: 2%

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

- Total: 7% on the detector correction factor C

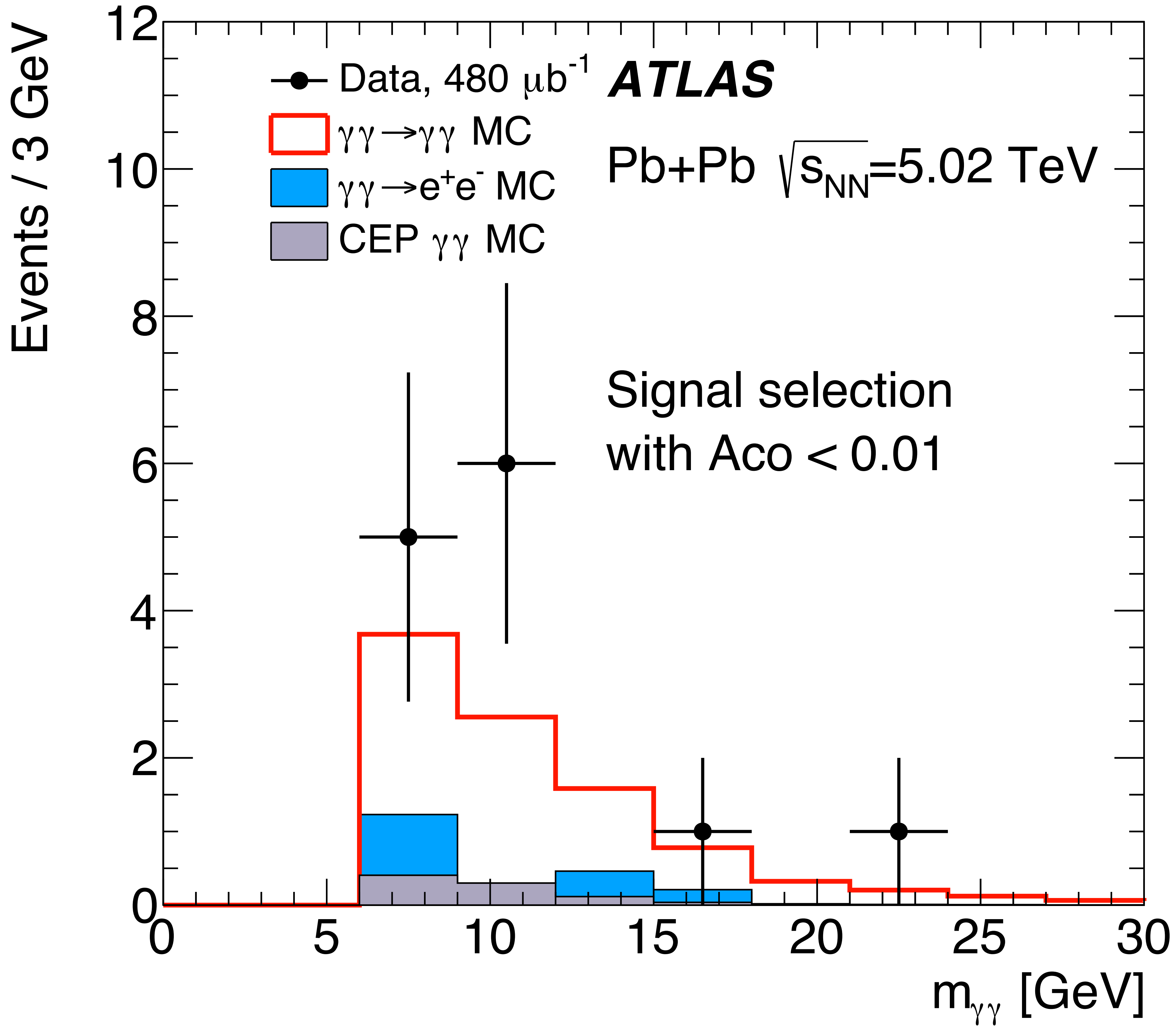
- Uncertainty on total background: 21%

Source of uncertainty	Variation
CEP Aco > 0.01 CR stat uncertainty	±0.06
CEP Superchic2 vs Superchic3 uncertainty	±0.09
ee CR stat uncertainty	±0.12
ee CR variation uncertainty	±0.11
ee p^{e}_{mistag} variation uncertainty	±0.07
EG scale uncertainty	±0.005
EG resolution uncertainty	±0.01
Photon angular resolution uncertainty	±0.01
Trigger uncertainty	±0.004
photon reco uncertainty	±0.002
photon PID uncertainty	±0.001
Total	±0.21

Results on 2015 data

2016: Nature Physics 13 (2017) 852

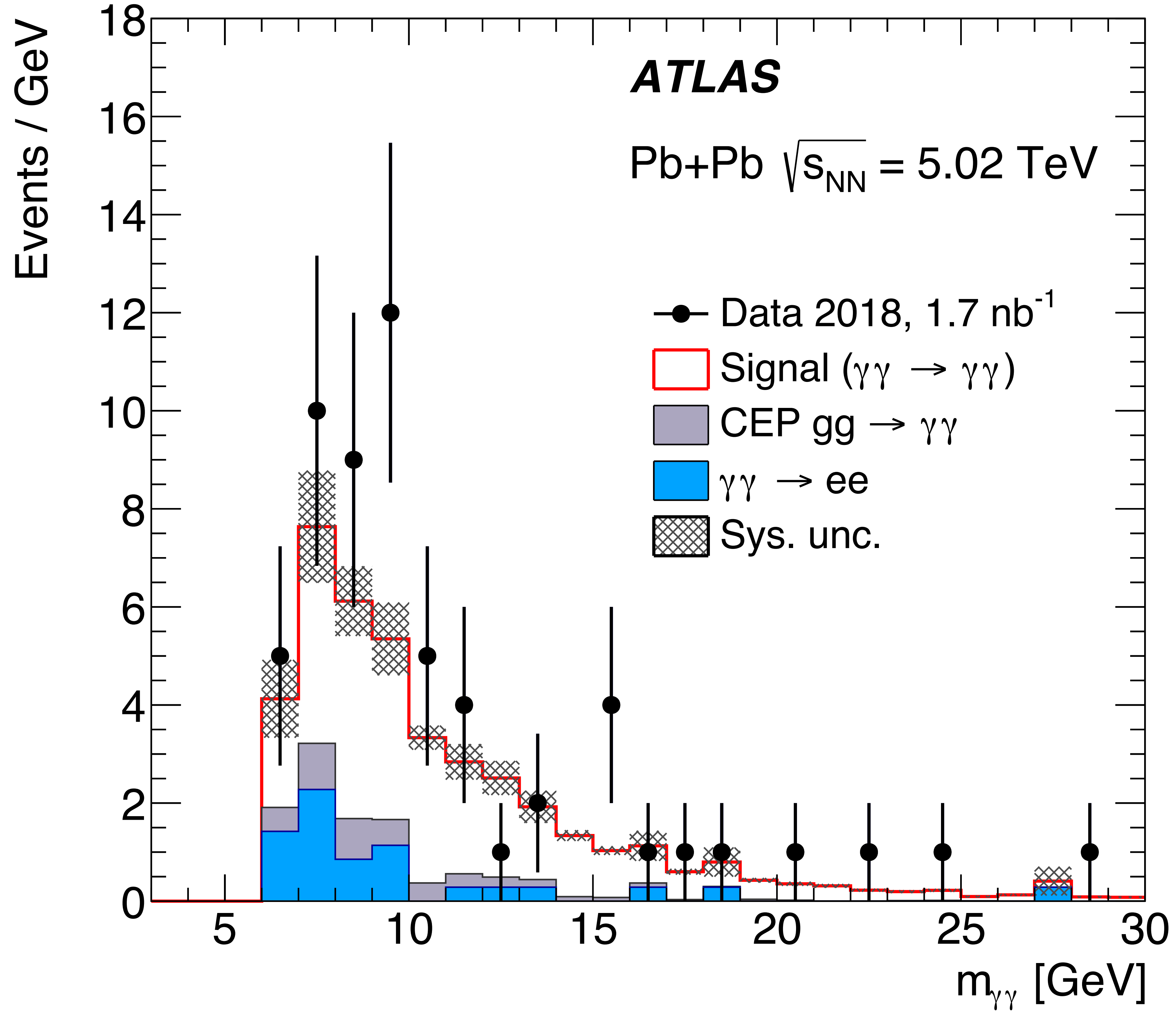
- Very similar analysis, some optimisations missing
  - 480µb^{-1} of PbPb data recorded in 2015
  - **First Evidence of Light-by-Light scattering** released in 2016 by ATLAS
    - Compatible result by CMS
- **13 Events observed**, Background: 2.6 ± 0.7
- Cross section:
  - Measured: 70 ± 20 (stat) ± 17 (sys) nb
  - SM expectations: 49 ± 5 nb
- Significance: **4.4σ** (3.8σ expected)



Results on 2018 data

2019: Phys.Rev.Lett. 123 (2019)

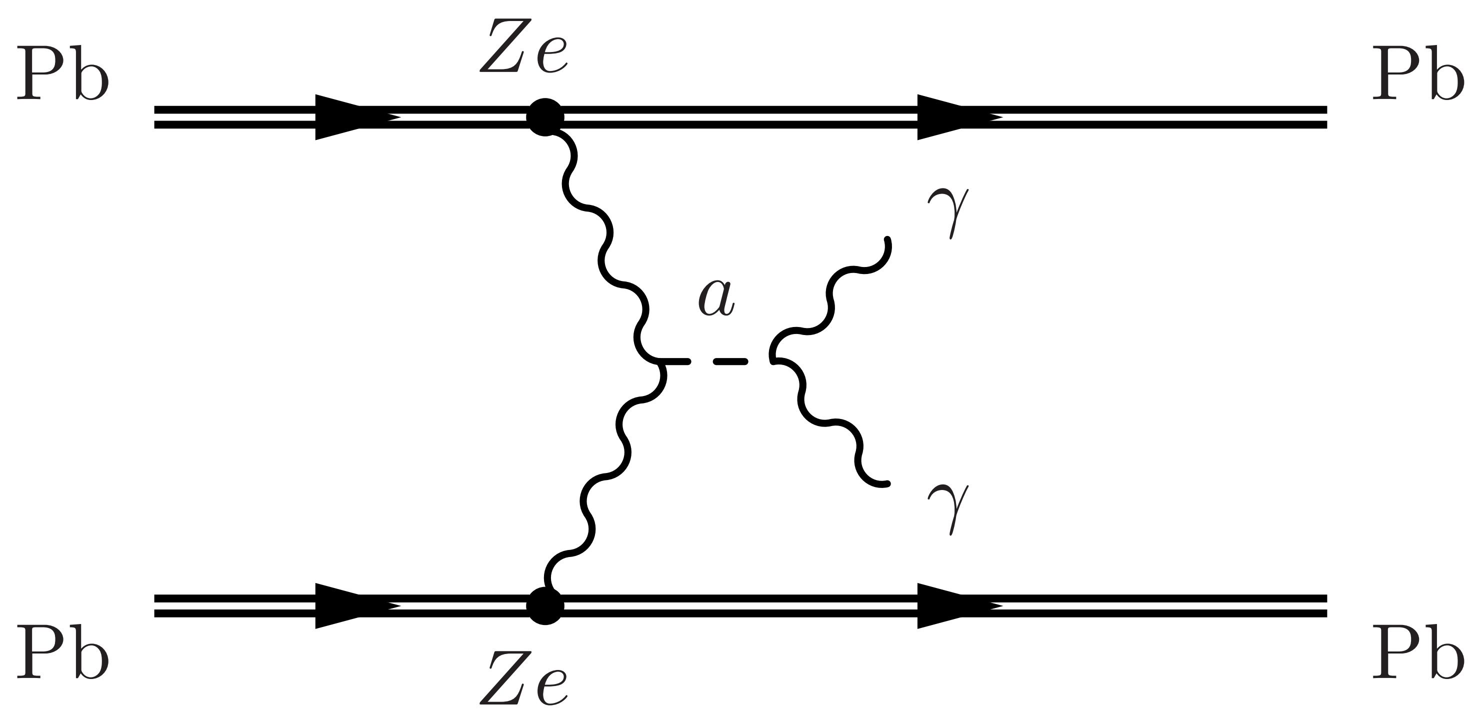
- 2018 Data: **1.7 nb^{-1} of PbPb** data analysed
  - **59 Events observed**, Background: 12 ± 3
  - Cross section:
    - Measured: 78 ± 13 (stat) ± 8 (sys) nb
    - SM expectations: 49 ± 5 nb
  - **Significance: 8.2σ** (6.2σ expected)



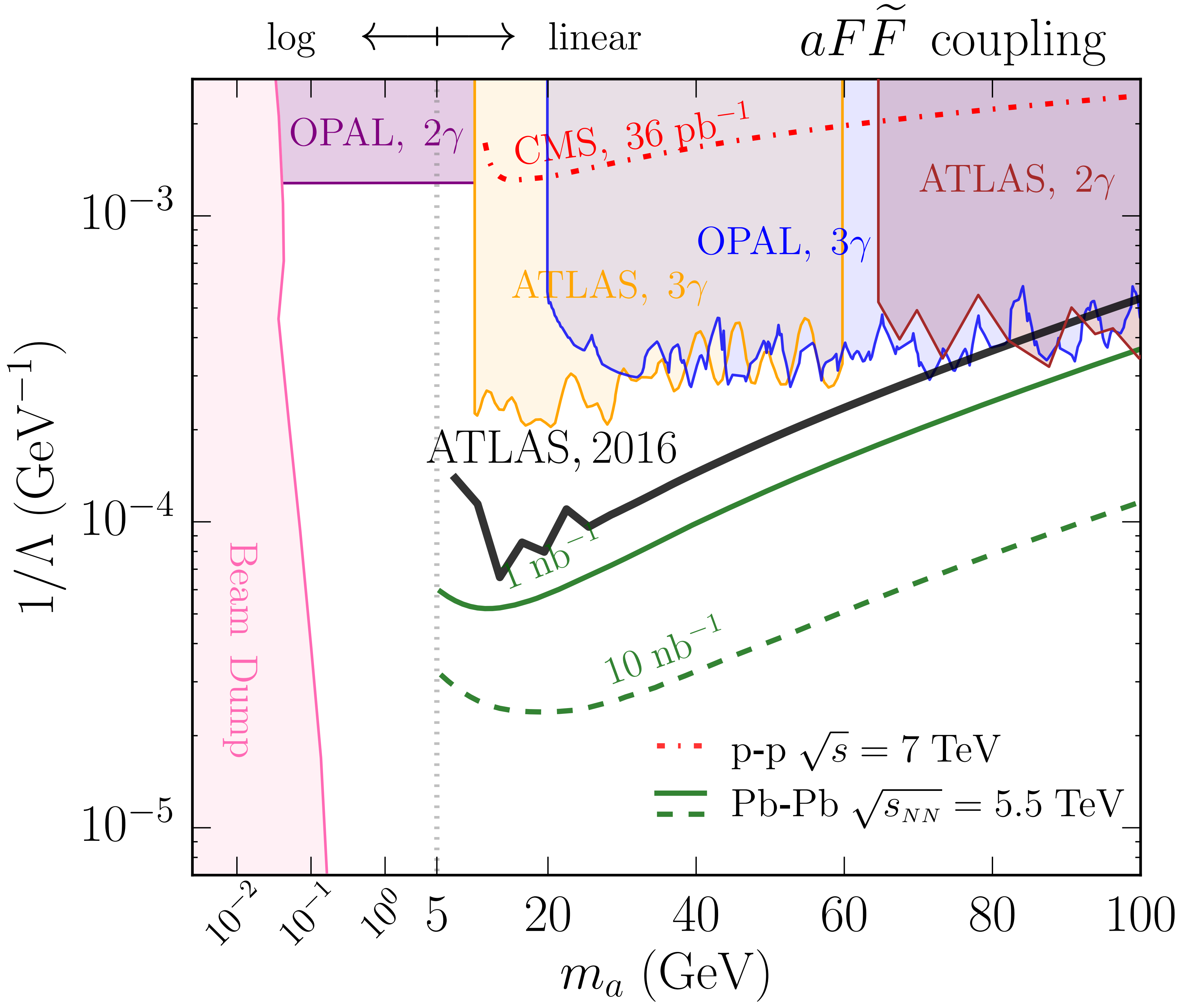
- Light-by-Light scattering of GeV photons observed
- Compatibility with SM prediction within 1.8 standard deviations

- Being interesting in it's own right, there's more to learn from this result:
  - Measurement can be transformed into limits on specific models beyond the standard model

- Axion like particles:
  - (pseudo-) scalar particles that are too heavy to solve strong CP problem
    - Will couple to photons, may couple to anything else
  - Identical signature as Light-by-Light scattering
    - Resonant behaviour



Reinterpretation of ATLAS 2016 result
Knapen et al.: arXiv:1709.07110v1



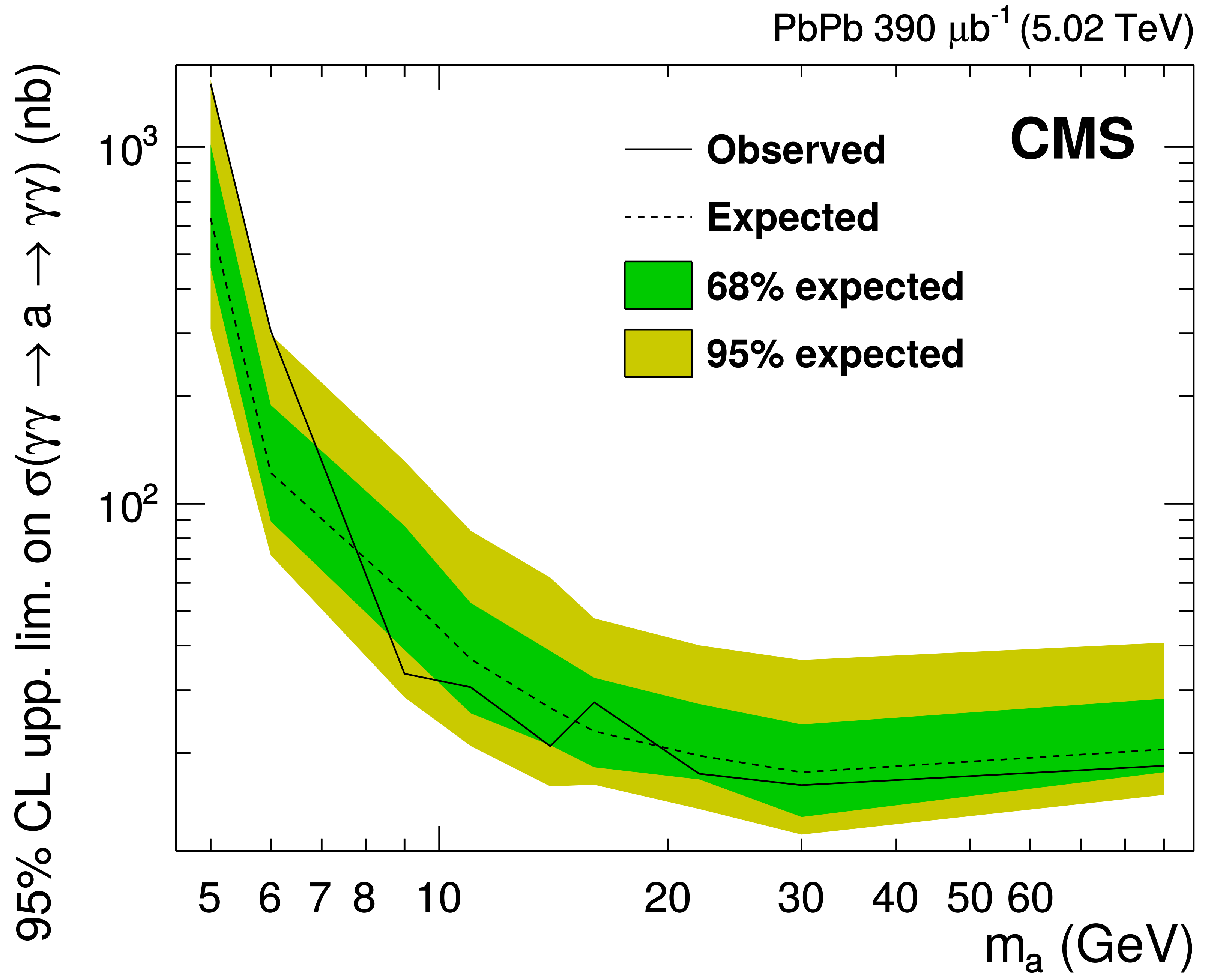
Active field:
- Phenomenological work: arxiv:1607.06083,
- Latest CMS result: Phys.Lett. B797 (2019)

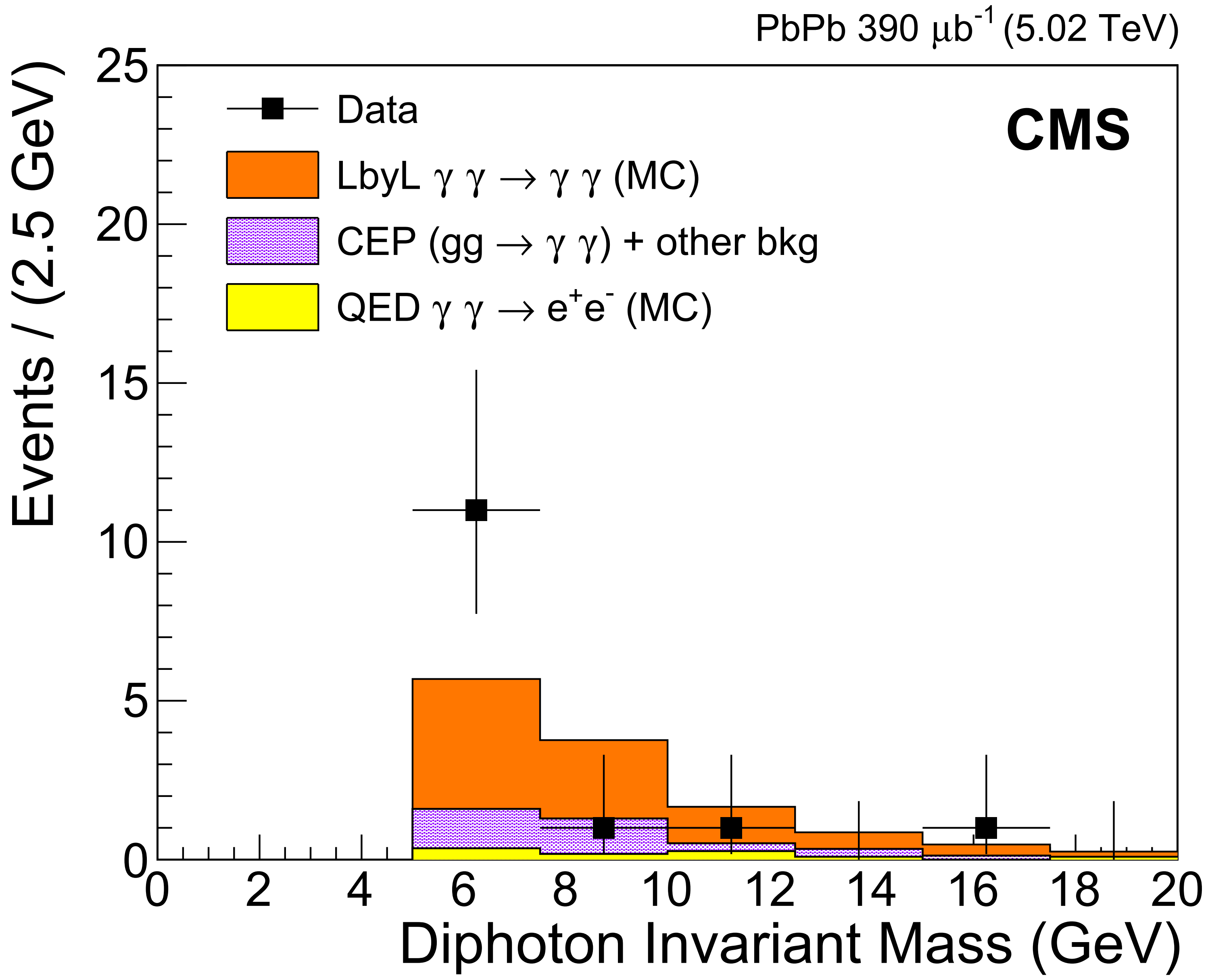
Interpretation - Search for new Axion Like Particles: CMS

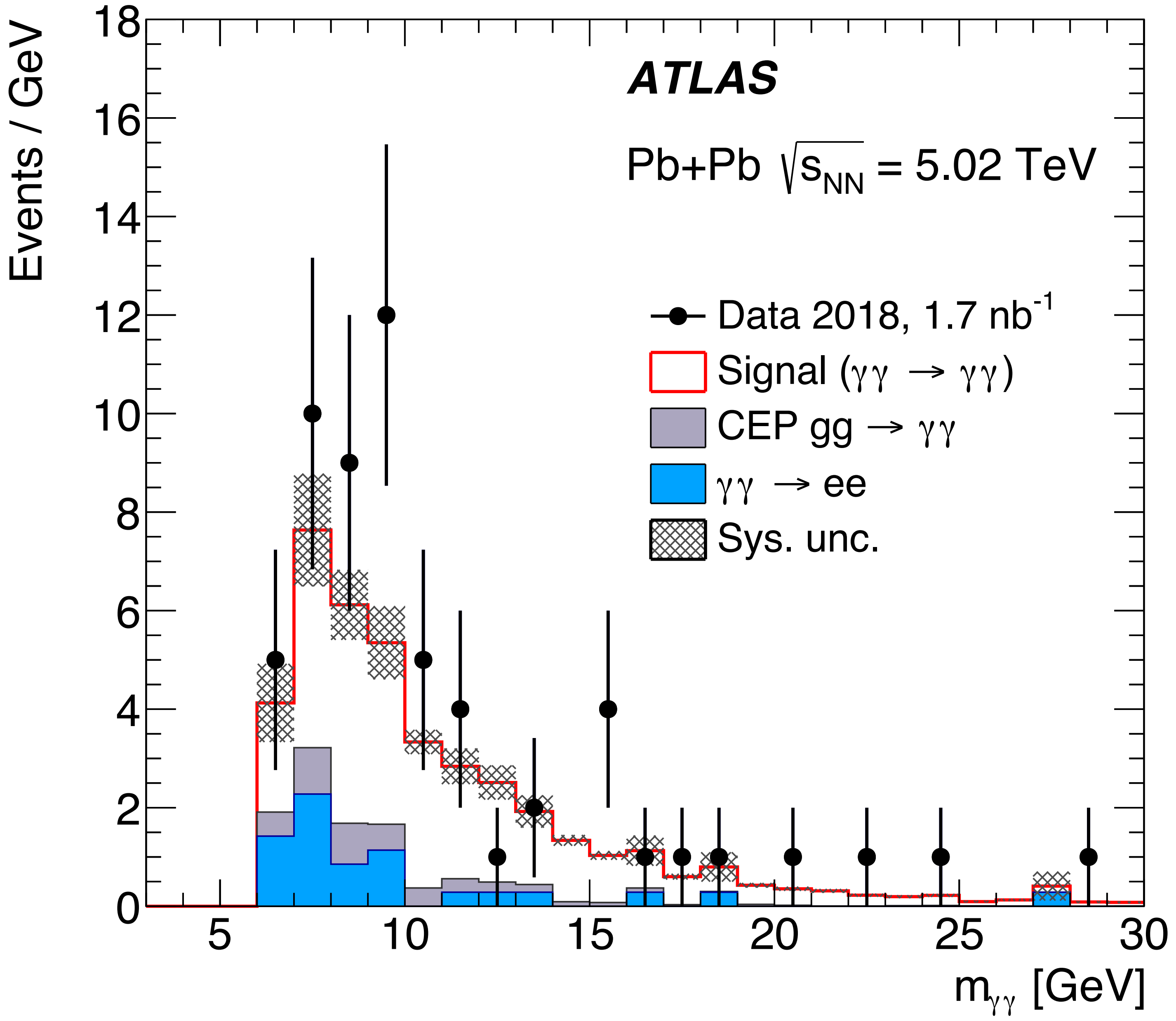
Phys.Lett. B797 (2019)

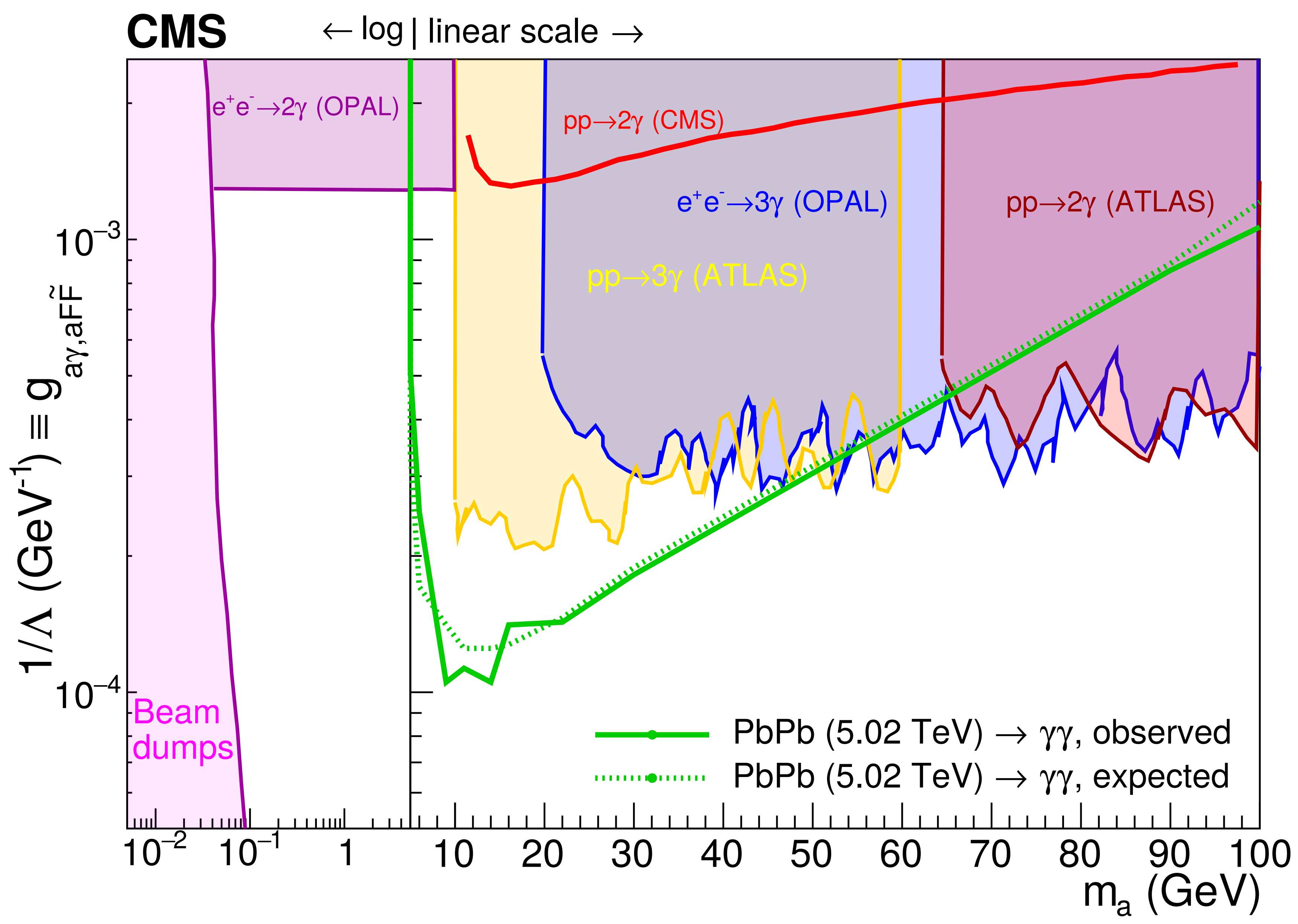
- $0.39\ nb^{-1}$, $E_T > 2$ GeV, m > 5 GeV
  - p_T (yy) < 1 GeV, |eta| < 2.4 => similar to ATLAS selection
  - 14 events observed, 4 background events expected

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









Interpretation - Other Models

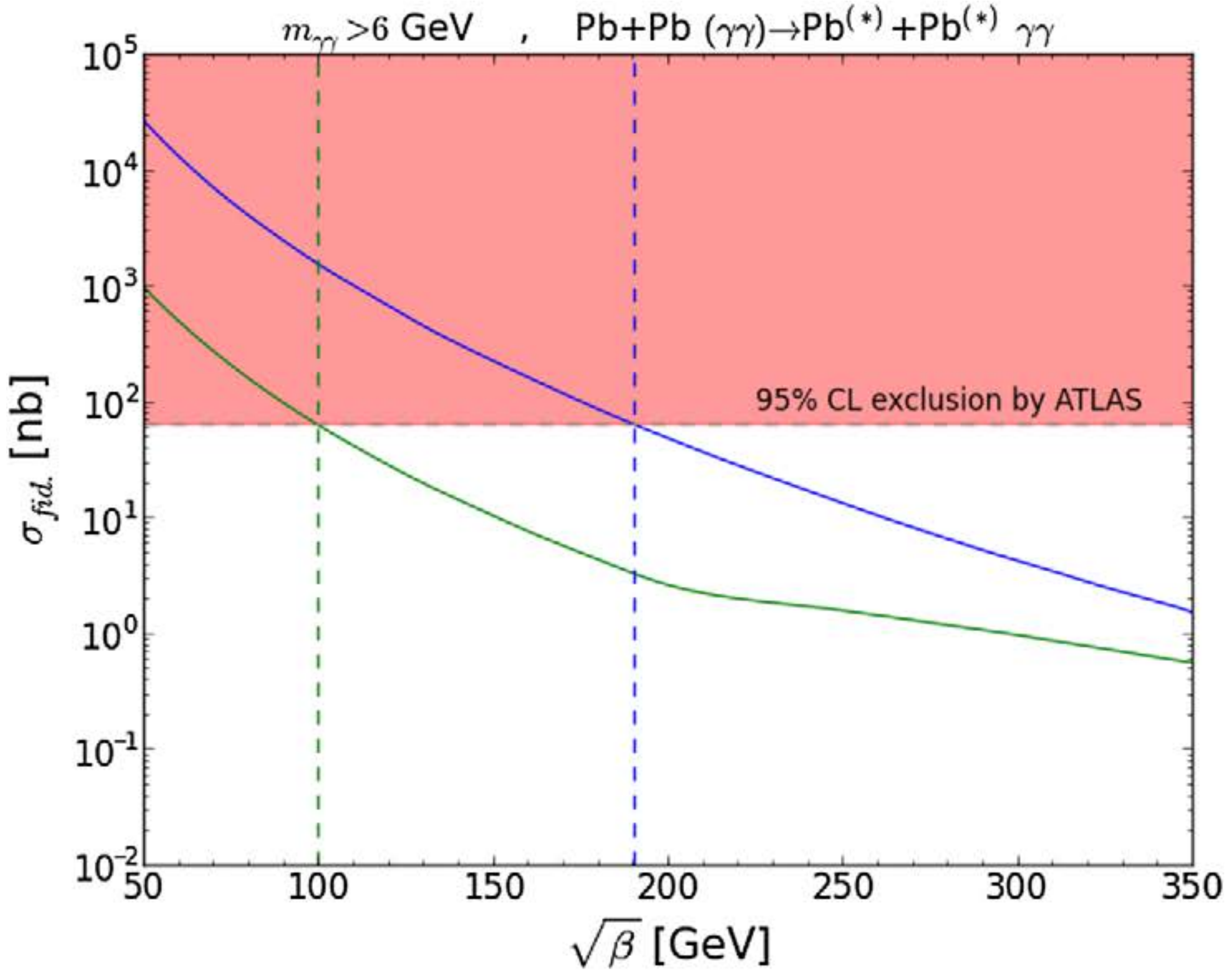
PRL 118, 261802 (2017)

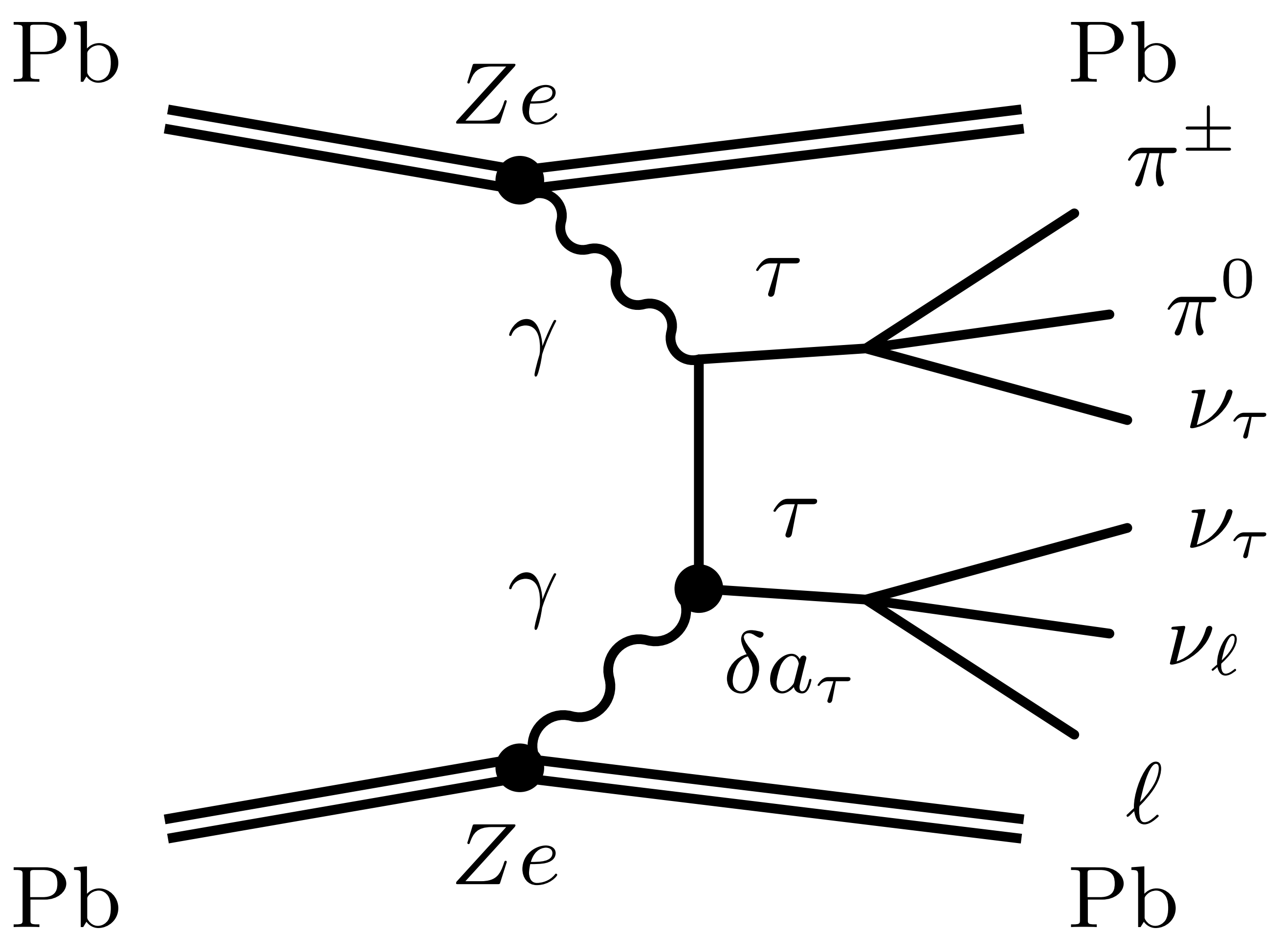
- Measurement can be transformed into limit on specific models beyond the standard model

- 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

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





- Electromagnetic interaction - $\gamma\tau$

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

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

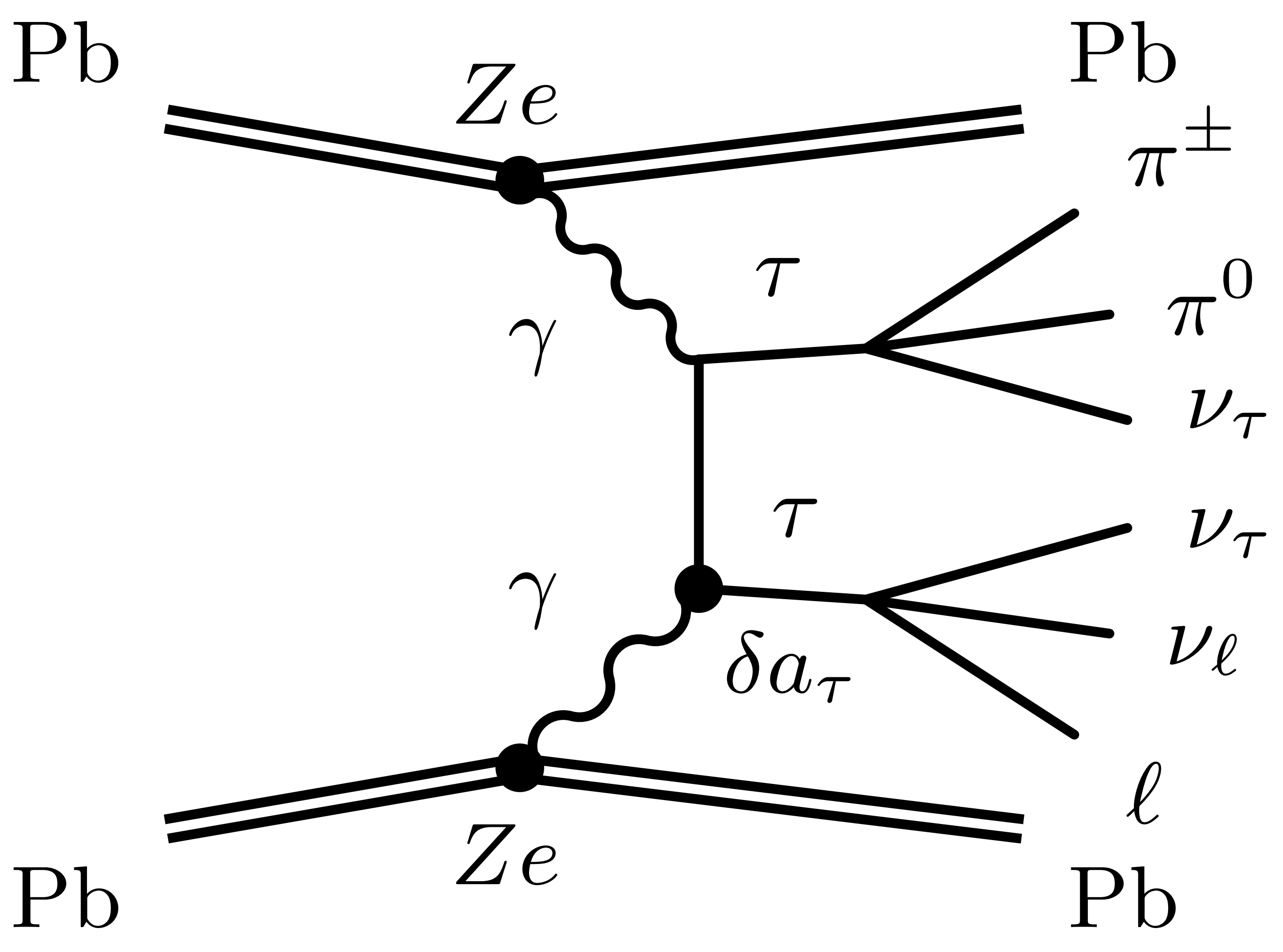
- $\gamma\gamma \rightarrow \tau\tau$ sensitive to electric & magnetic moments of tau!
  - a_τ : anomalous magnetic moment
  - d_τ: electric diplome moment
- Usage of UPC PbPb collisions suggest in 1991

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 : $\gamma\gamma \to \tau\tau$



- Electromagnetic interaction - $\gamma\tau$

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

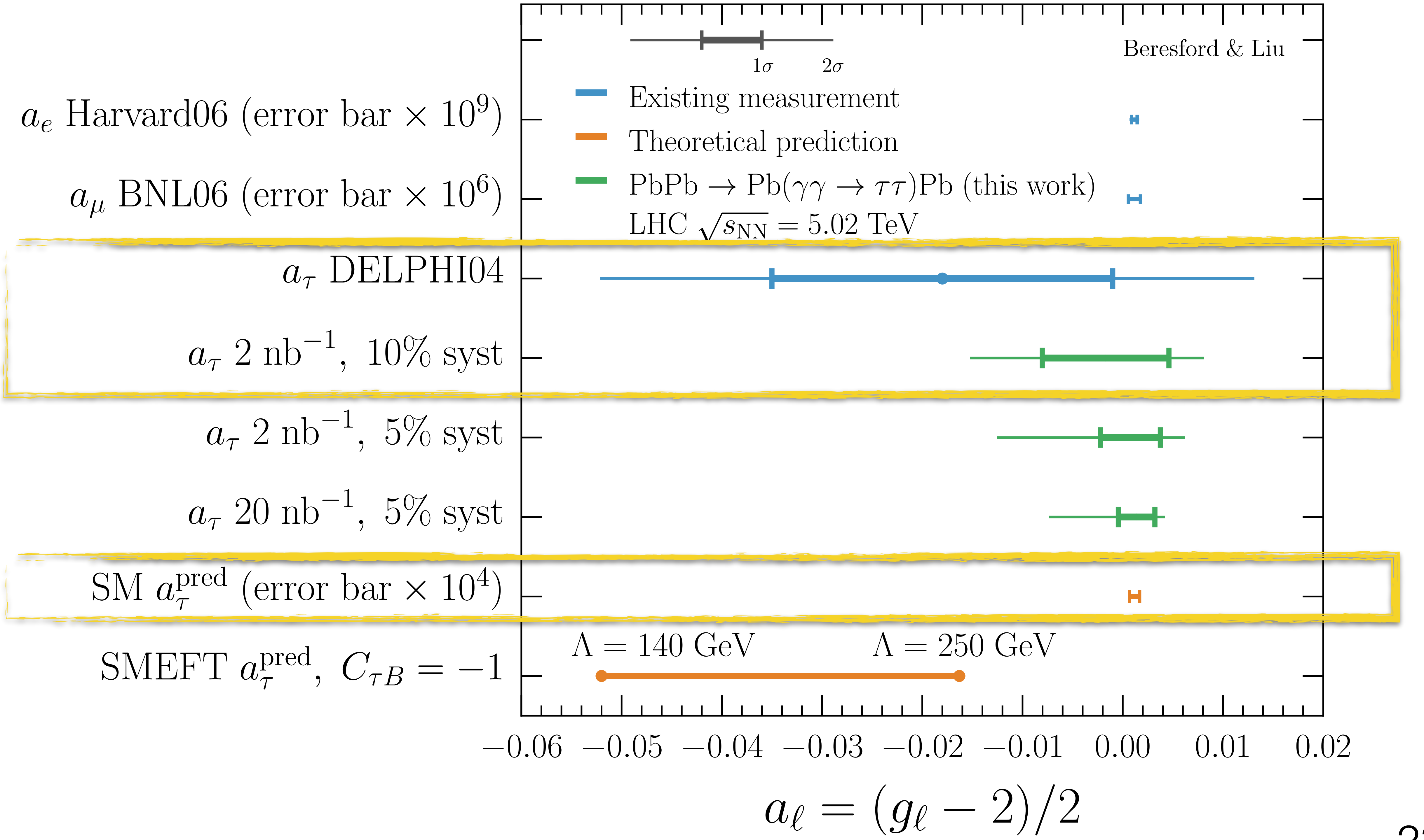
$$a_\tau^{\mathrm{exp}} = -0.018\,(17)$$
$$a_{\tau,\,\mathrm{SM}}^{\mathrm{pred}} = 0.001\,177\,21\,(5)$$

- $\gamma\gamma \to \tau\tau$ 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

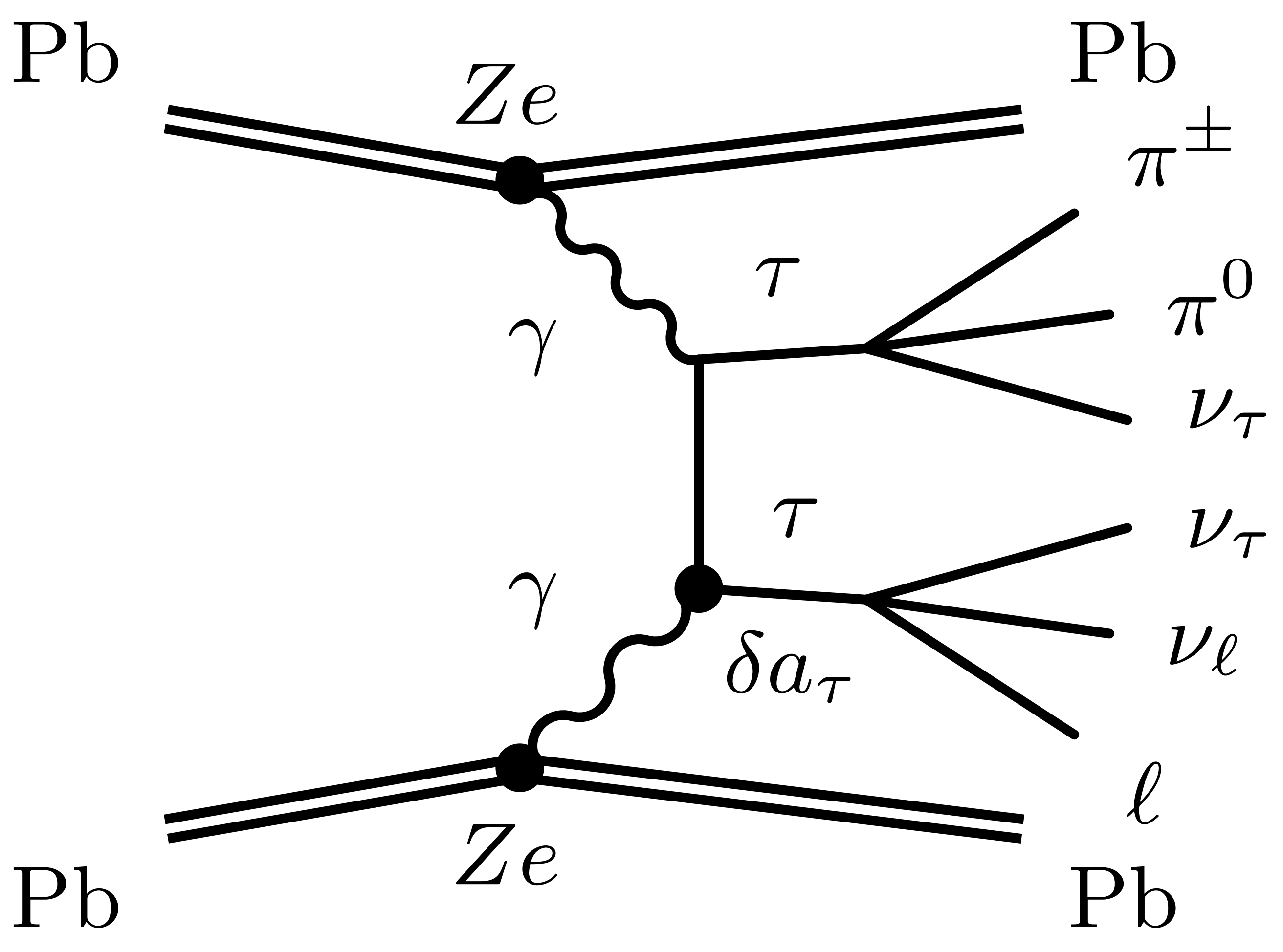
Phys.Lett. B271 (1991) 256-260

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

arXiv:1908.05180



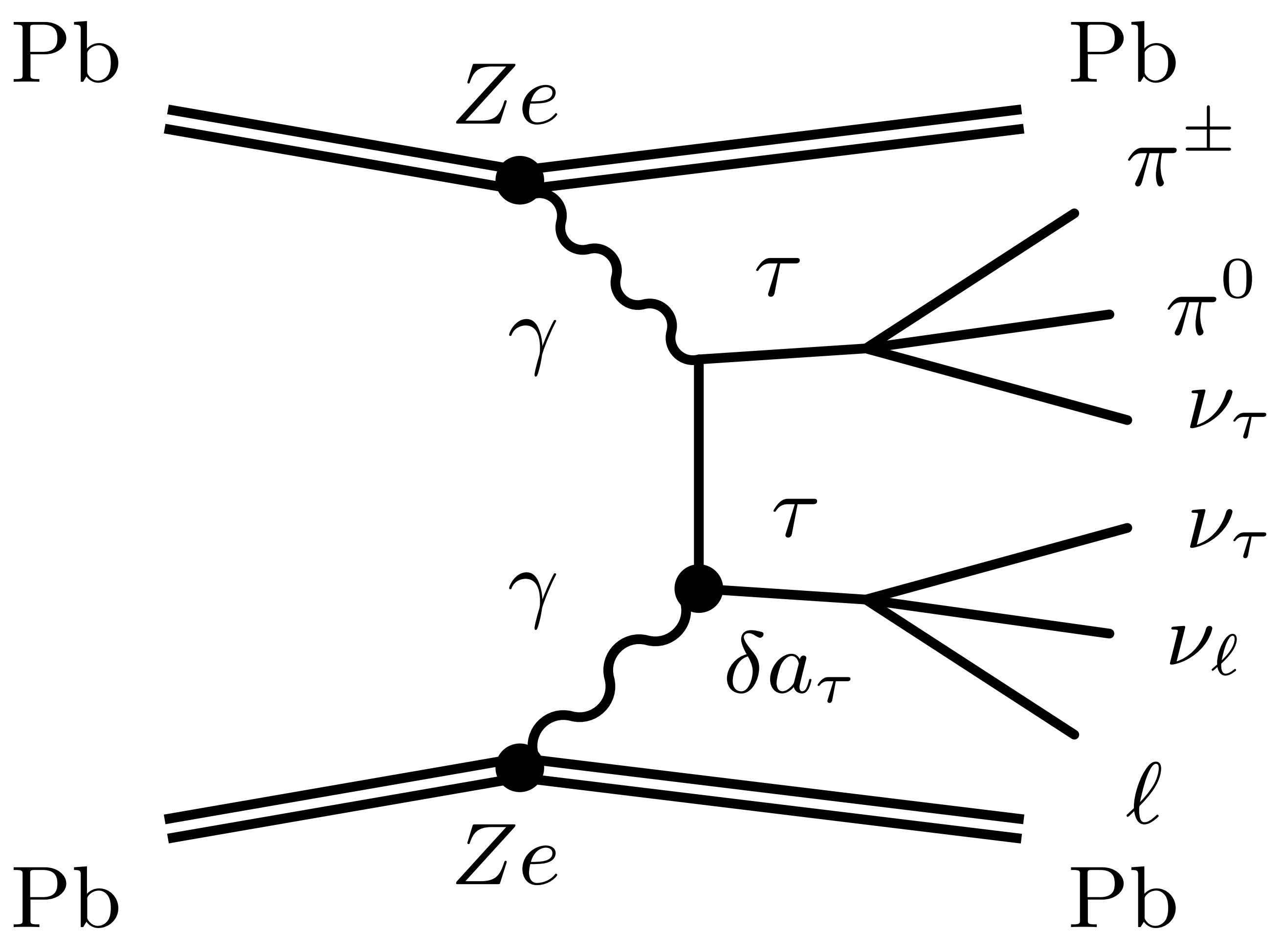
Tau anomalous magnetic moment : $\gamma\gamma \rightarrow \tau\tau$



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

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

- 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
  - 2 leptons with different flavour (very clean)
  - 1 lepton + 1 or 3 tracks
  - Difficult to tag photon initial state without requirement on $\Delta\phi$

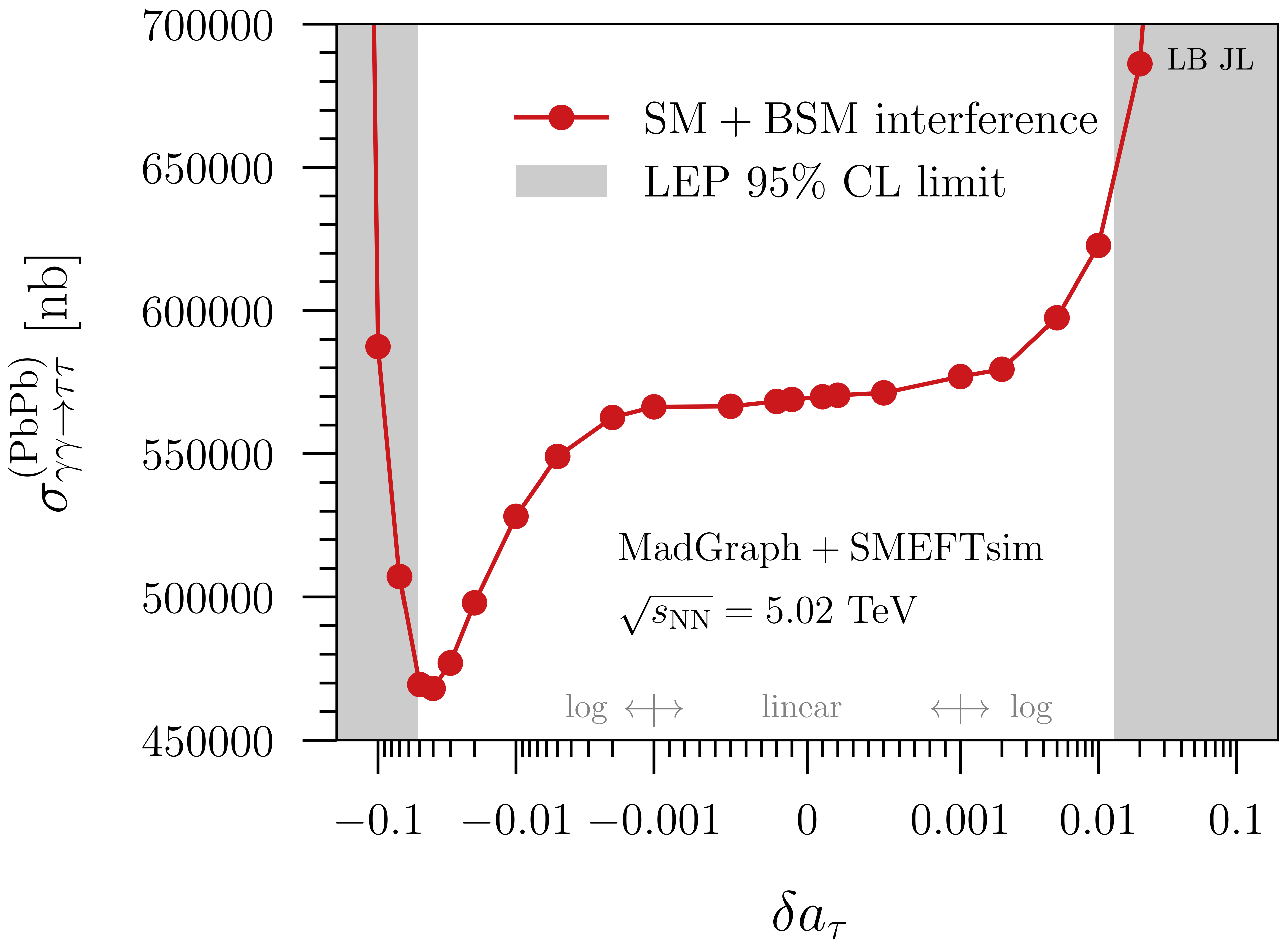


$$\mathcal{B}(\tau^\pm \to \pi^\pm \nu_\tau + \text{neutral pions}) = 45.6\%$$

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

- 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



- 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
  - 2 leptons with different flavour (very clean)
  - 1 lepton + 1 or 3 tracks
  - Difficult to tag photon initial state without requirement on $\Delta\phi$

Ongoing analysis in ATLAS

- Combine 2015 + 2018 data => 2.2 nb^{-1}
- Lower E_T threshold to 2.5 GeV
  - Expect ~90 events
- Unfold measured distributions
- ALP limits
- Limits on EFT operators

Ongoing analysis in ATLAS

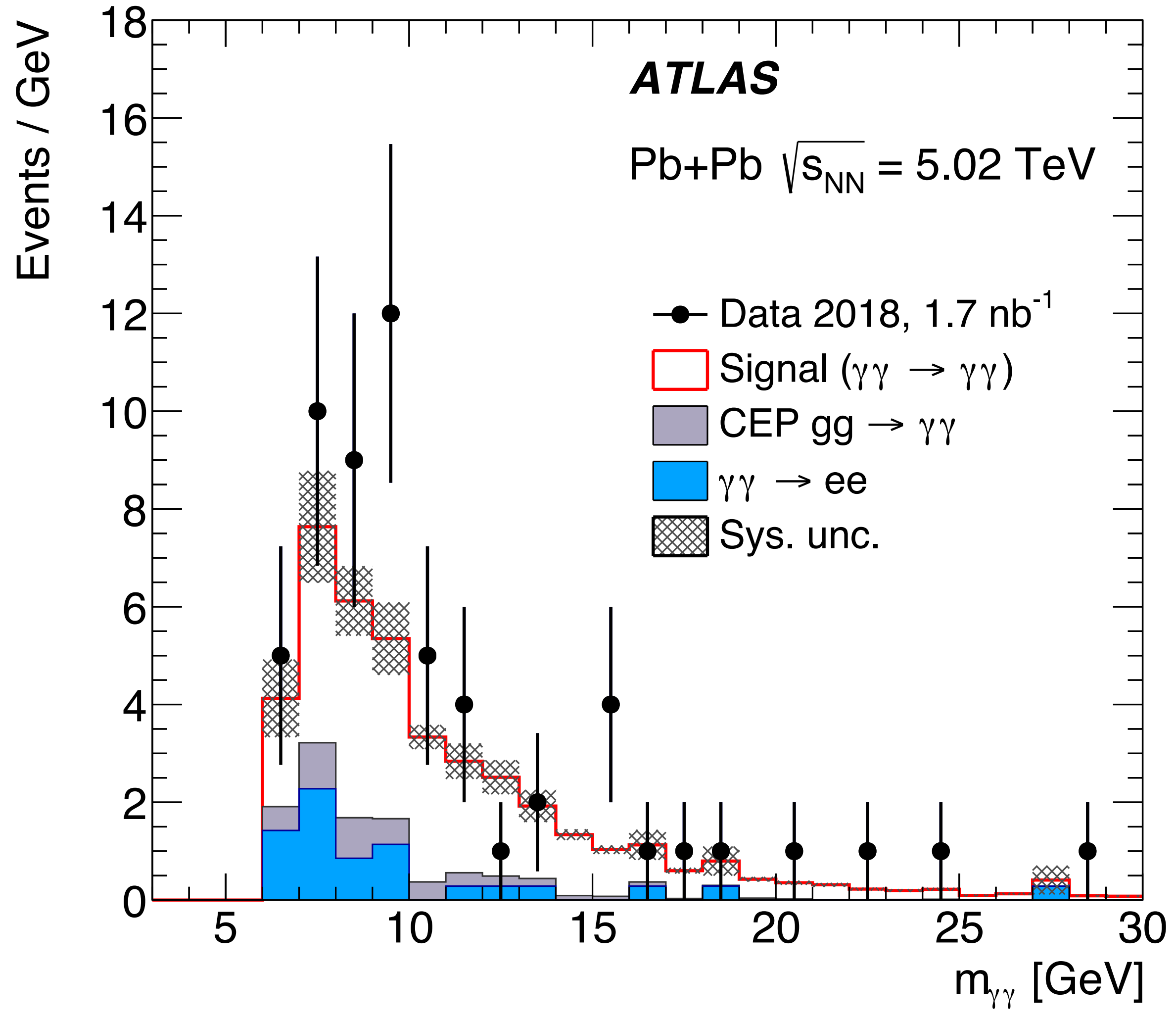
- Combine 2015 + 2018 data => 2.2 nb^{-1}
- Lower E_T threshold to 2.5 GeV
  - Expect ~90 events
- Unfold measured distributions
- ALP limits
- Limits on EFT operators

Where could we potentially go?

- Lowering E_T threshold:
  - Calorimeter cluster noise: 1 GeV
  - Exploit longitudinal boost
    - Cut on E (not E_T), $|\eta| < 2.5$
      - M_{inv} ~ 1 GeV
  - Trigger?
    - Difficult, even including topological requirements
- pp collisions (~fb of data):
  - Challenge: tagging of photon initial state
    - Dedicated low pileup runs
    - Proton tagging
- Proton tagging
  - Forward detectors in ATLAS: AFP
  - Different kinematic region:
    - M_{inv} > 350 GeV

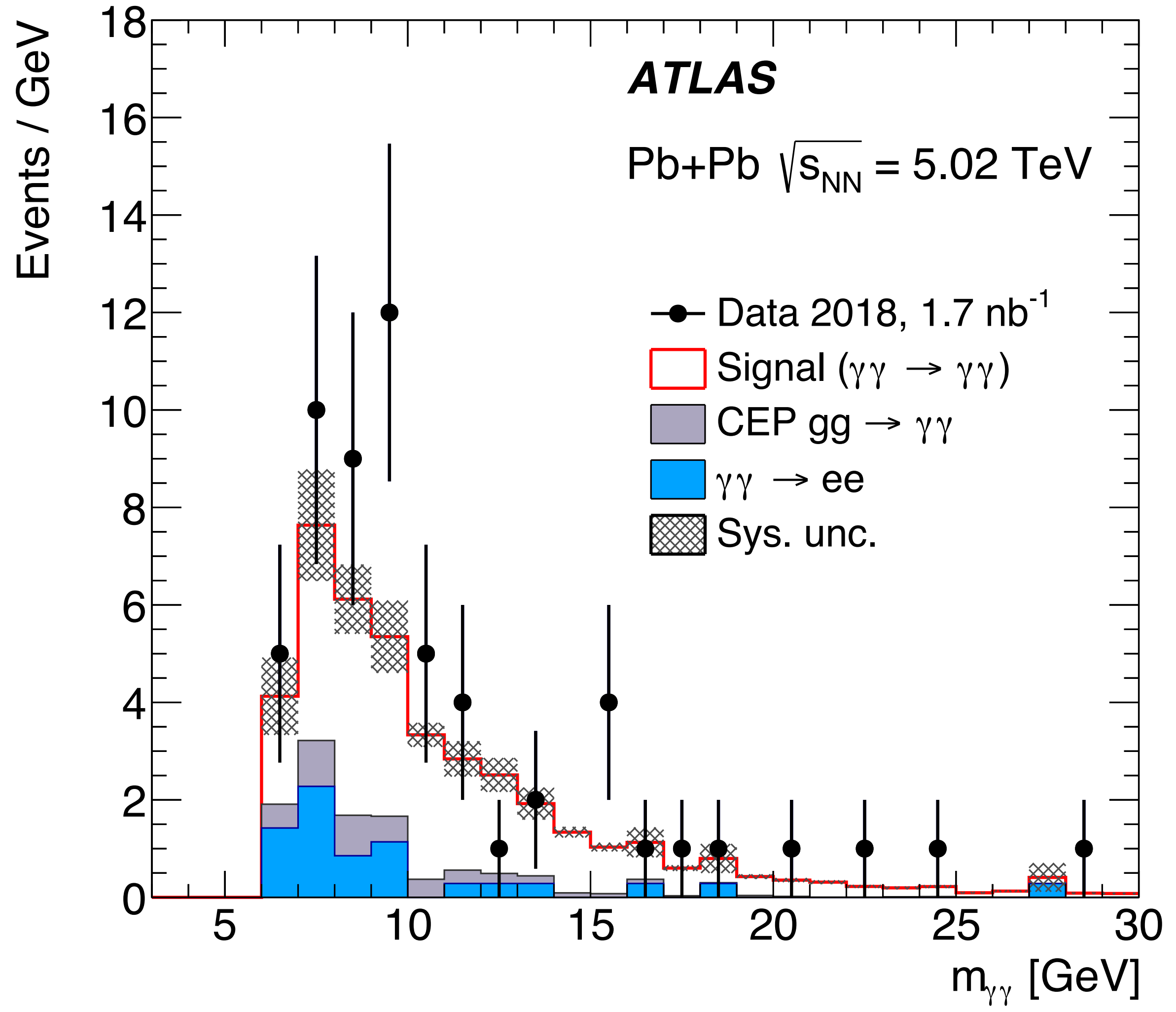
Summary

- First direct **observation of Light-by-Light scattering** at the **ATLAS** experiment
  - Hi collisions from the LHC used as photon collider
- **Challenging measurement**, very different from usual high energy analyses:
  - Low energy objects
  - Very little activity in detector
    - Difficult to trigger



- **59 Events observed** (12 background events expected)
- Measured fid. cross section for $m_{\gamma\gamma} > 6$ GeV: σ **= 78 ± 15 nb**
  - **Compatible with SM prediction**

- Useful to constrain several models beyond the standard model, e.g.
  - Axion like particles
  - Born-Infeld theory
- Lepton final states sensitive to:
  - G-2 (tau) measurement



- First direct **observation of Light-by-Light scattering** at the **ATLAS** experiment
  - Hi collisions from the LHC used as photon collider
- **Challenging measurement**, very different from usual high energy analyses:
  - Low energy objects
  - Very little activity in detector
    - Difficult to trigger

- **59 Events observed** (12 background events expected)
- Measured fid. cross section for $m_{\gamma\gamma} > 6$ GeV: σ **= 78 ± 15 nb**
  - **Compatible with SM prediction**

- Useful to constrain several models beyond the standard model, e.g.
  - Axion like particles
  - Born-Infeld theory
- Lepton final states sensitive to:
  - G-2 (tau) measurement

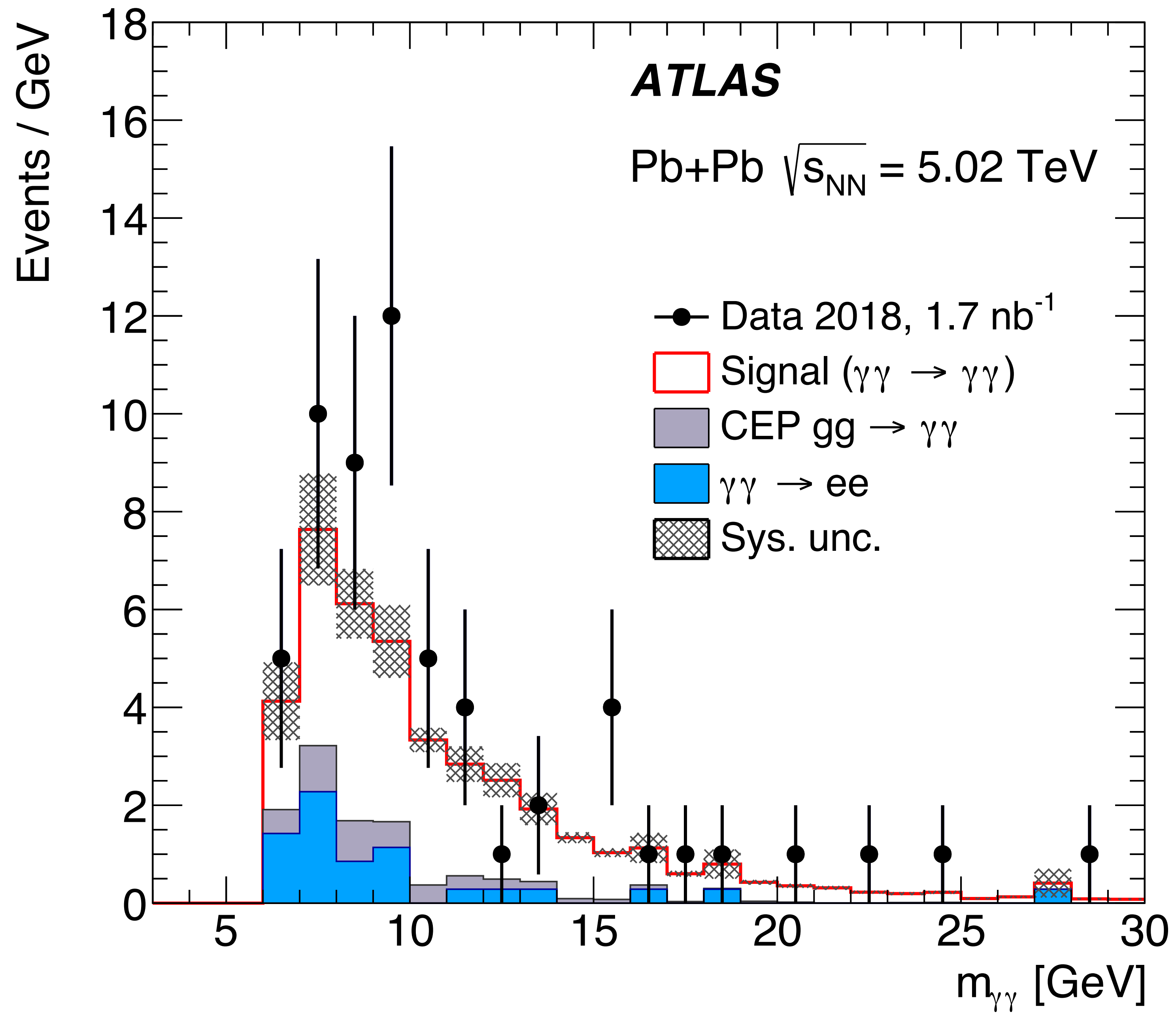
What's left to do?

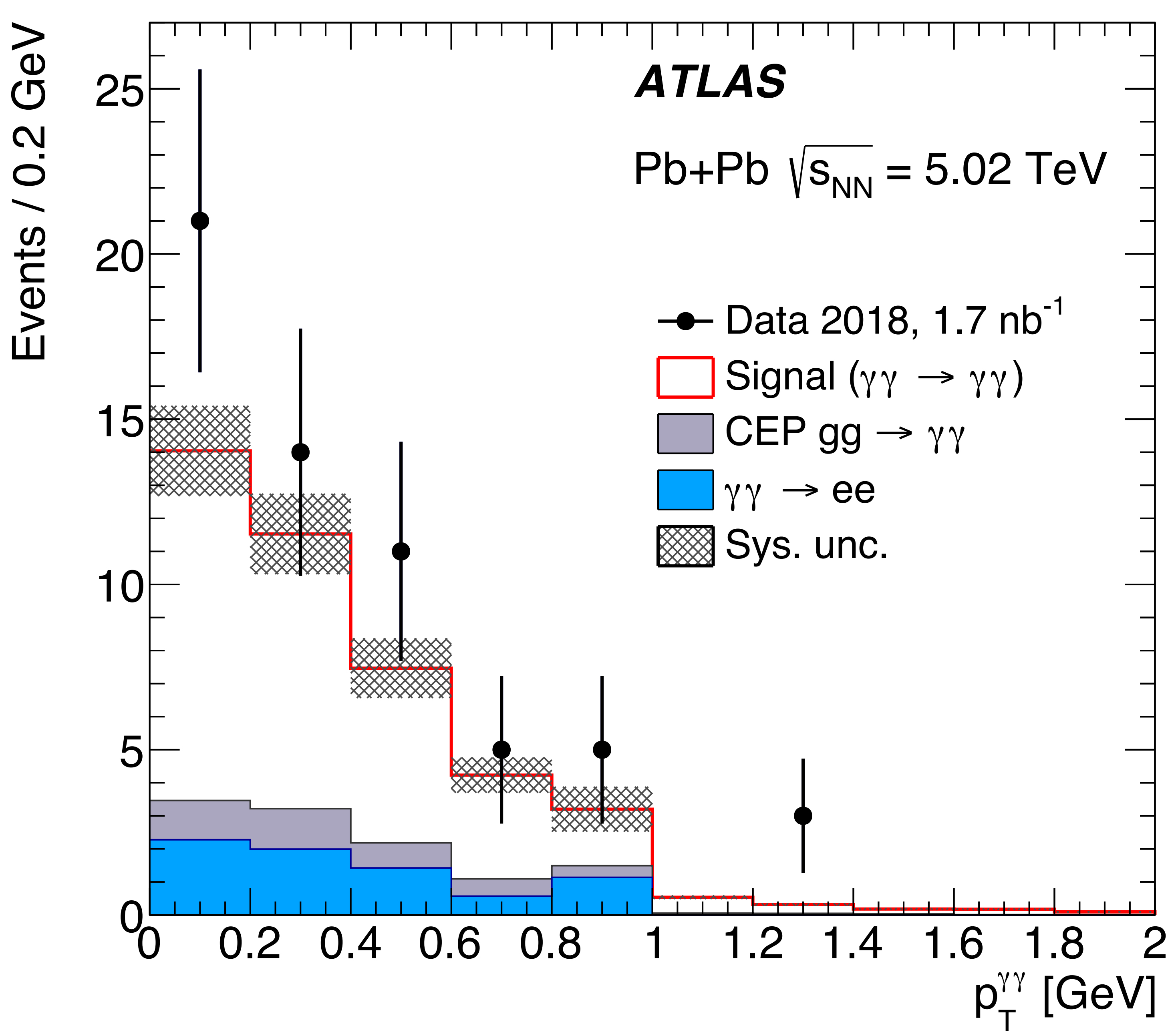
- Refined measurement of differential distributions
  - Combination of 2015 & 2018 data => 2.1nb^{-1}
- Derivation of improved limits on some BSM models
- Interpretations in the framework of effective couplings

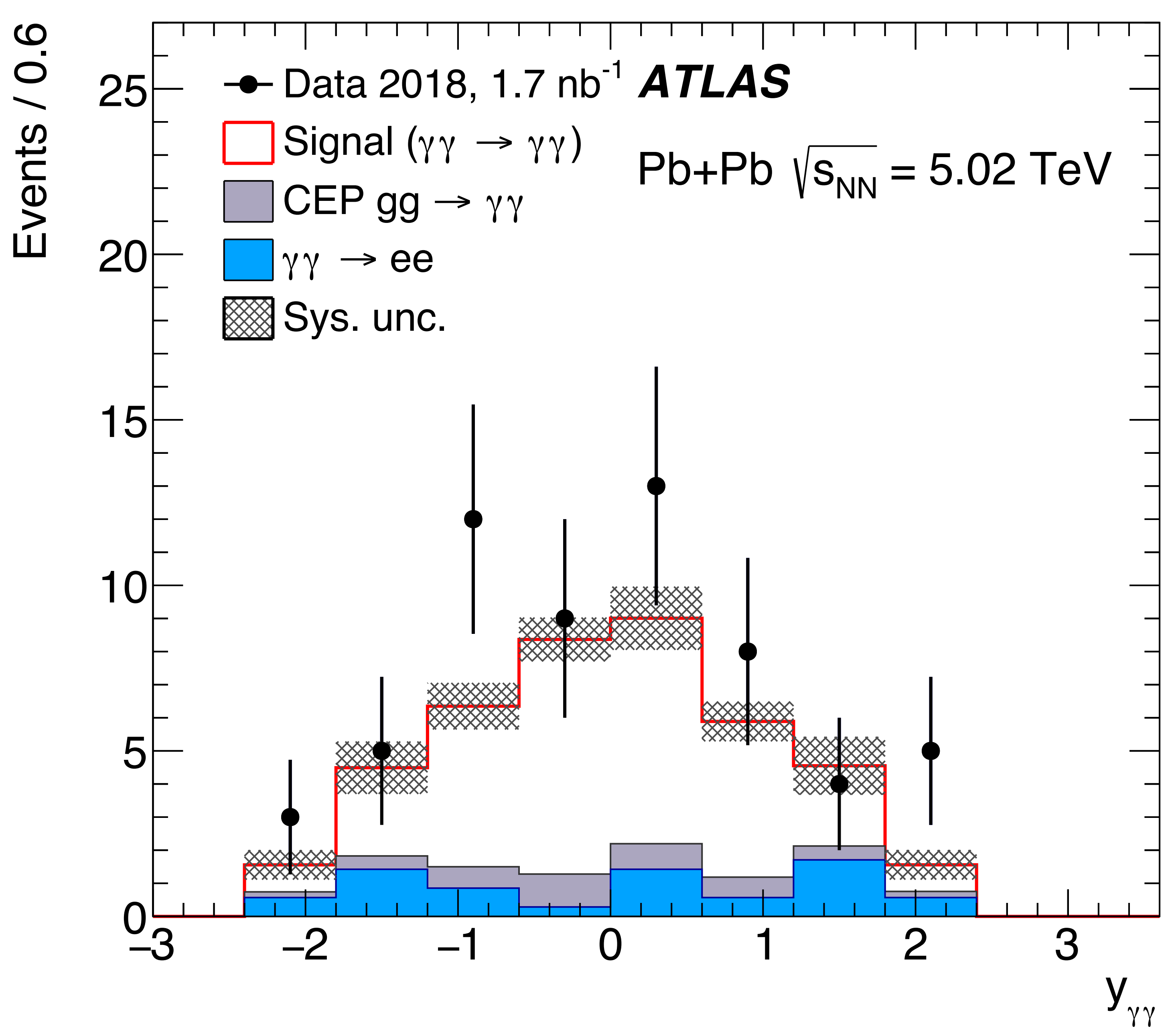
BACKUP

Additional Kinematic Distributions

2018: arXiv:1904.03536

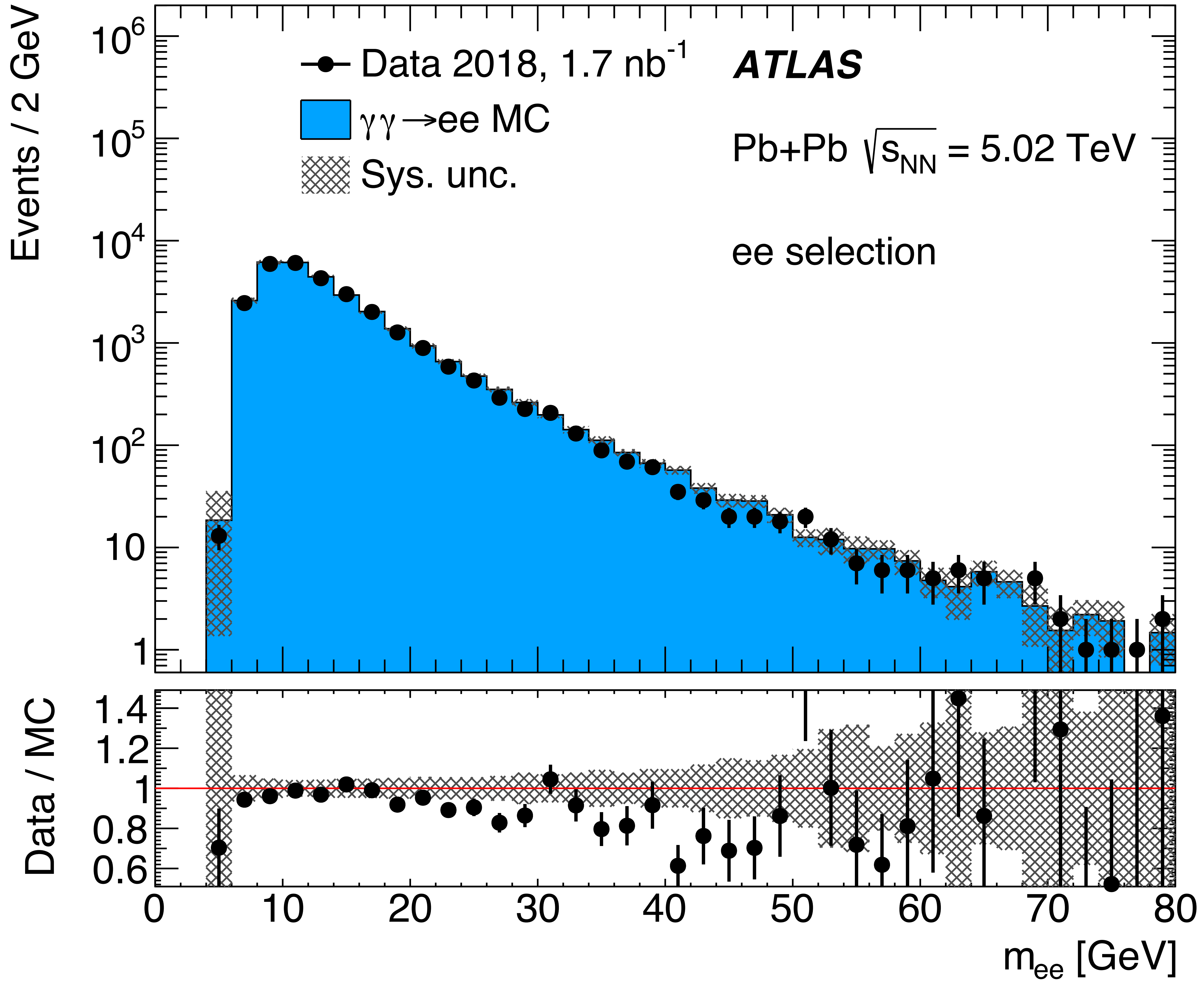






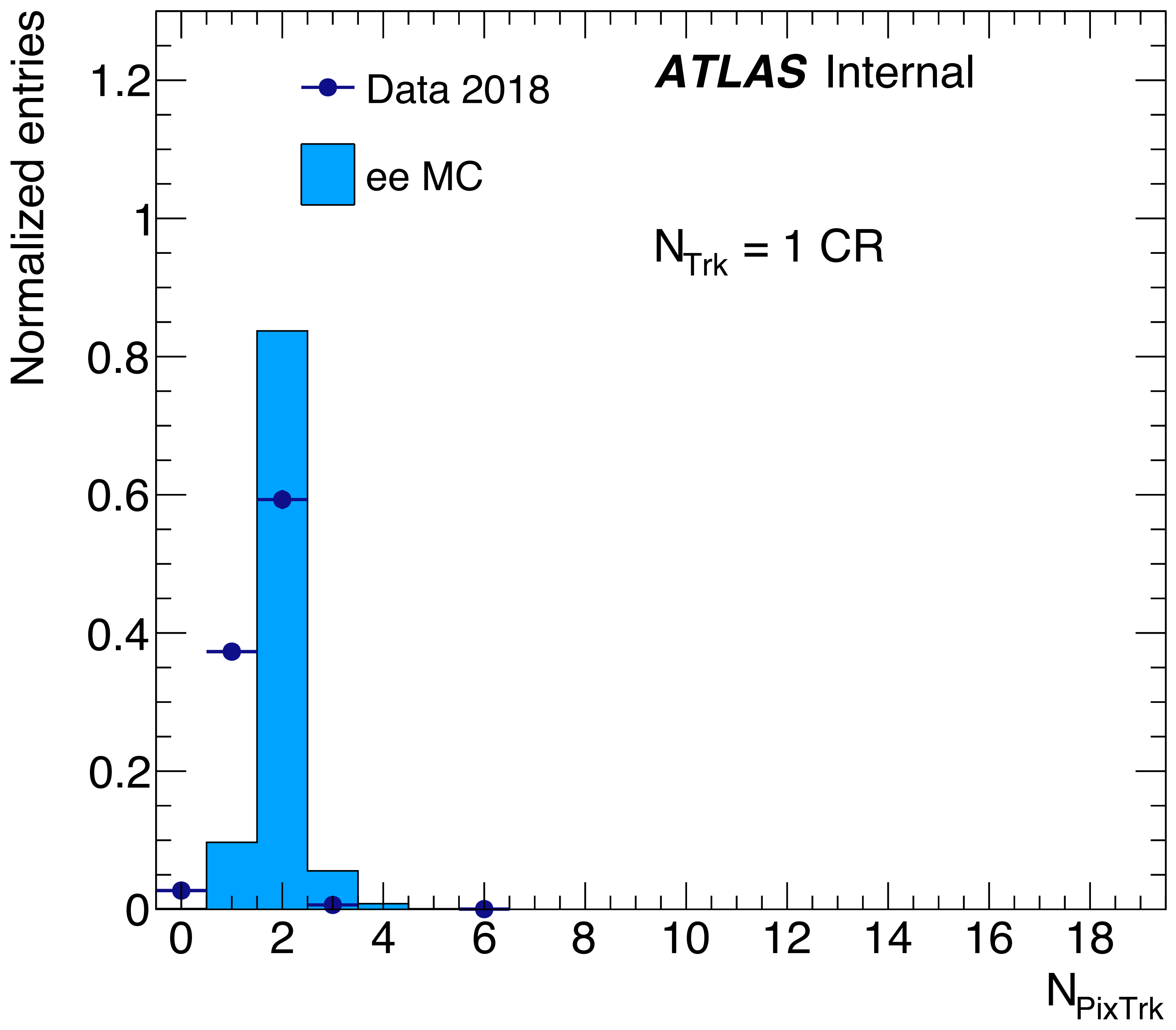
Electron studies

2018: arXiv:1904.03536



Details on peMistag

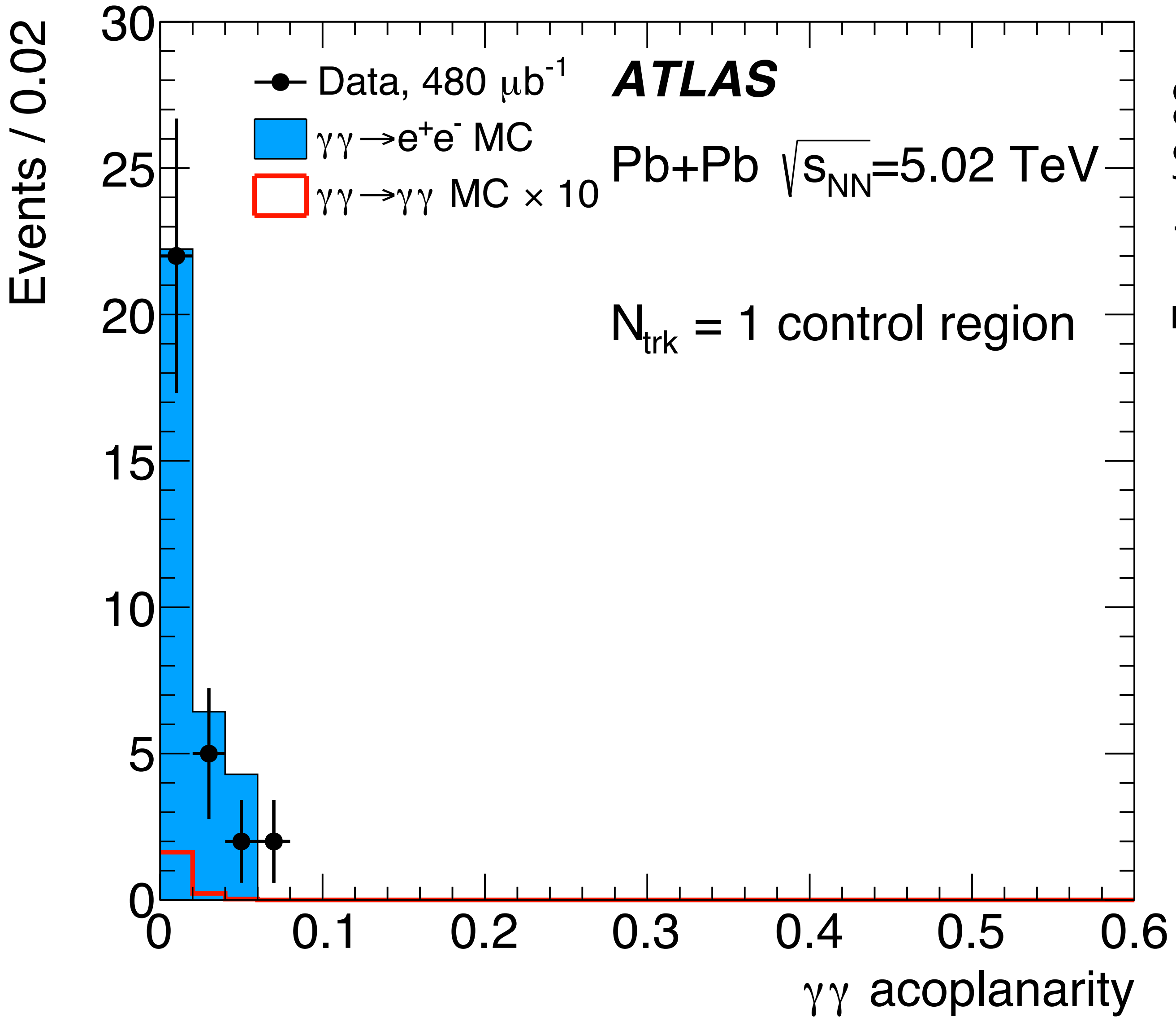
- Pixel tracks badly modelled in MC
  - Chance to miss a pixel track if the track is not reconstructed:
    - Data: 47%, MC: 10%

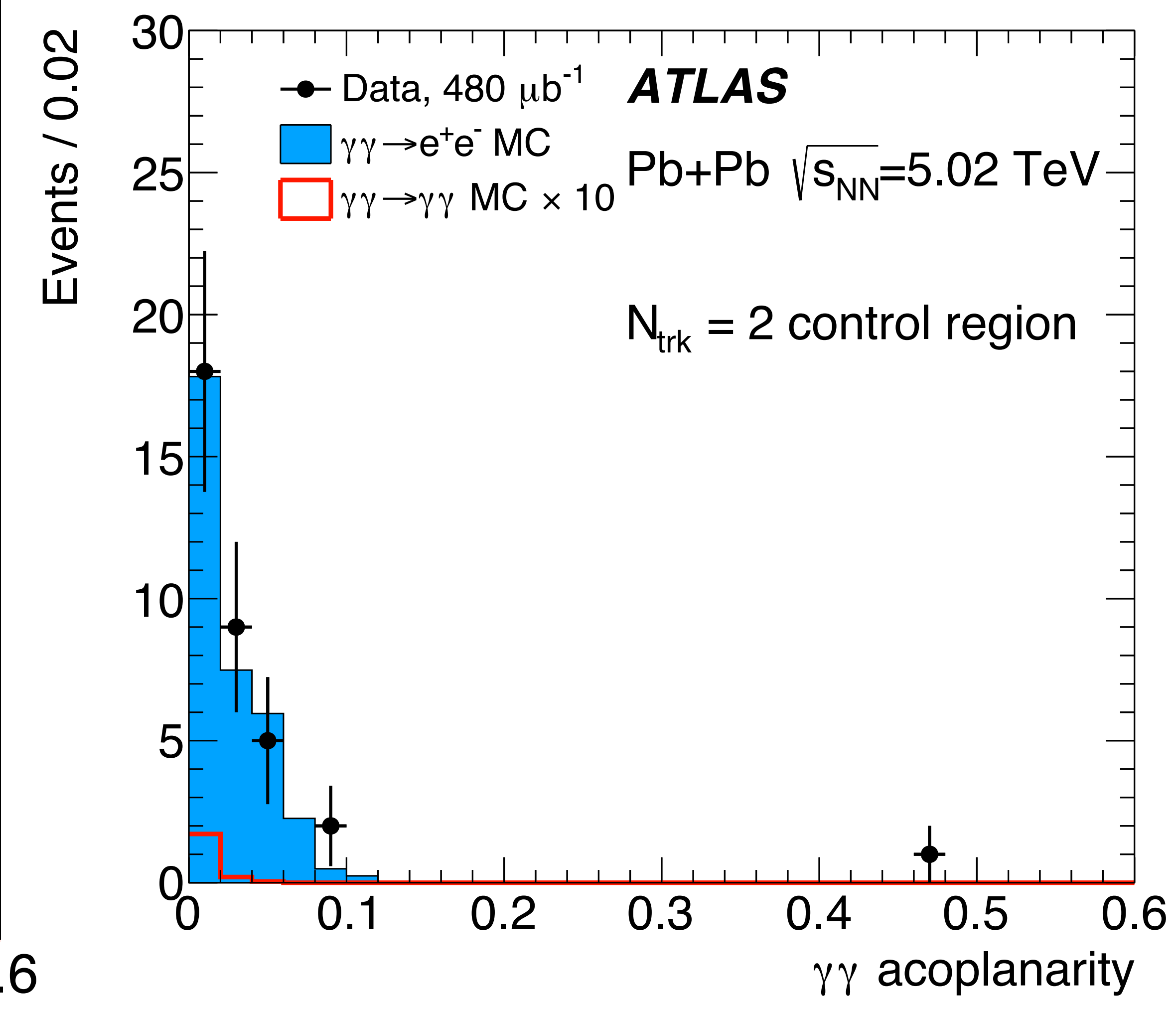


- Nominal selection + 1 reconstructed track matched to a photon cluster:
  - Selects ee events
- Check how often one or two PIX tracks are reconstructed => p^e_{mistag}

$$p^{\text{event}}_{N_{\text{Pix}}=0} = \left(p^{\text{e}}_{\text{mistag}}\right)^2$$

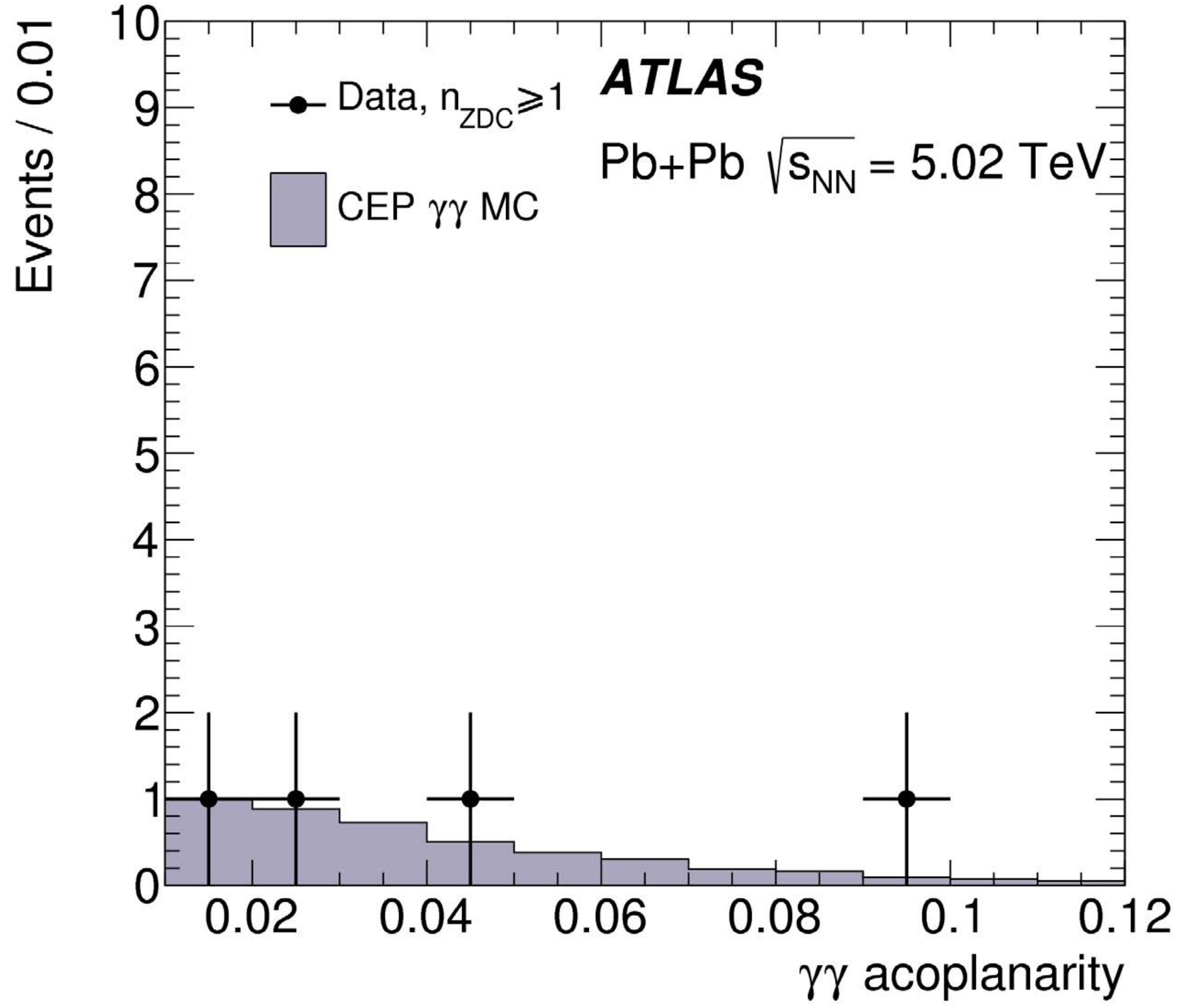
$$SR_{\text{expected}} = \left(N^{\text{events}}_{\text{CR}(N_{\text{PixTrk}}=1)} + N^{\text{events}}_{\text{CR}(N_{\text{PixTrk}}=2)}\right) \cdot \frac{p^{\text{event}}_{N_{\text{Pix}}=0}}{1 - p^{\text{event}}_{N_{\text{Pix}}=0}}$$



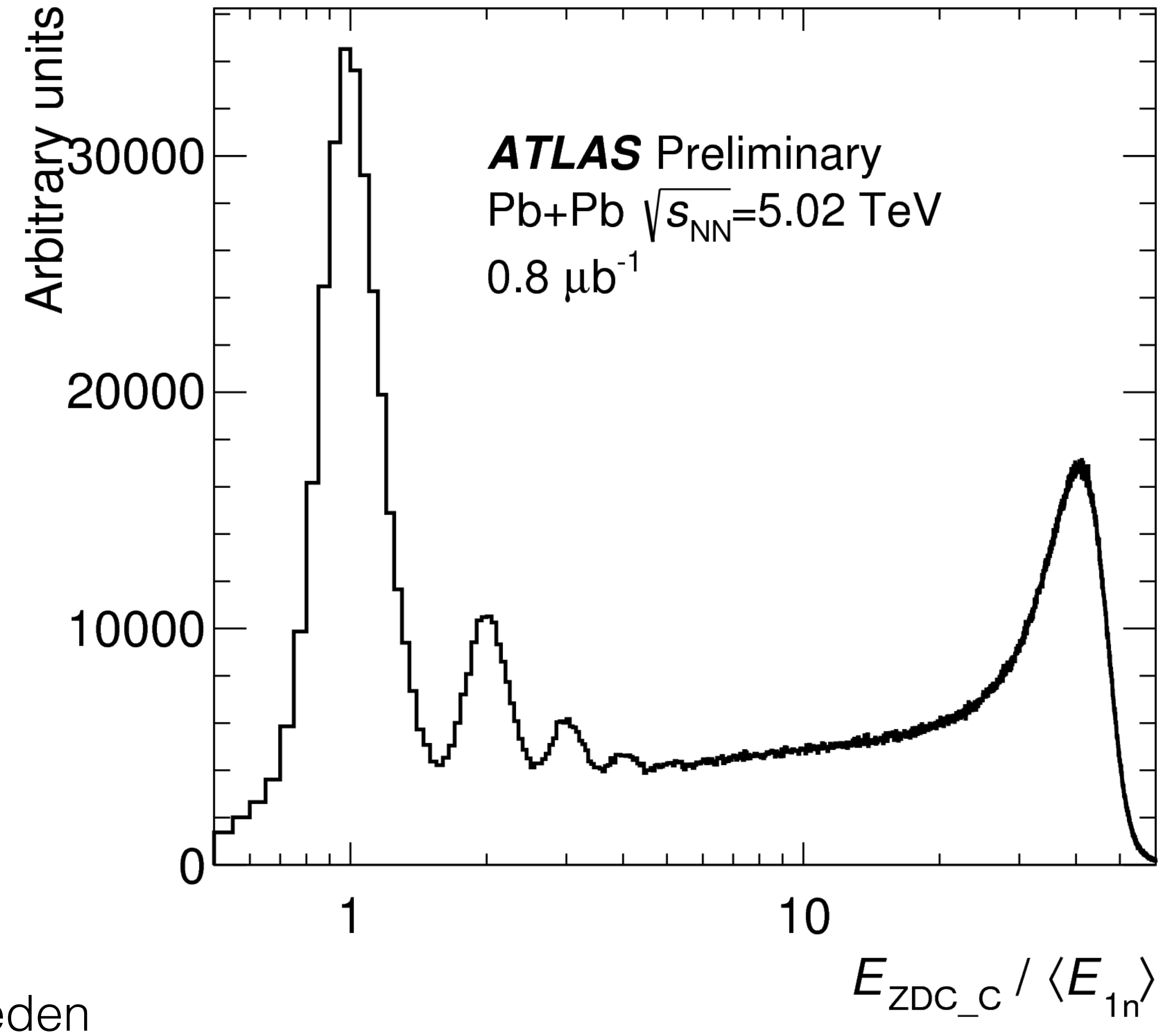


ZDC cross check on CEP background

- CEP control region: $A_\phi > 0.01$
  - Additionally require energy deposit in ZDC corresponding to at least 1 neutron
- Simulation normalised from control region compatible with data
  - But very limited statistics
- 2015 data set

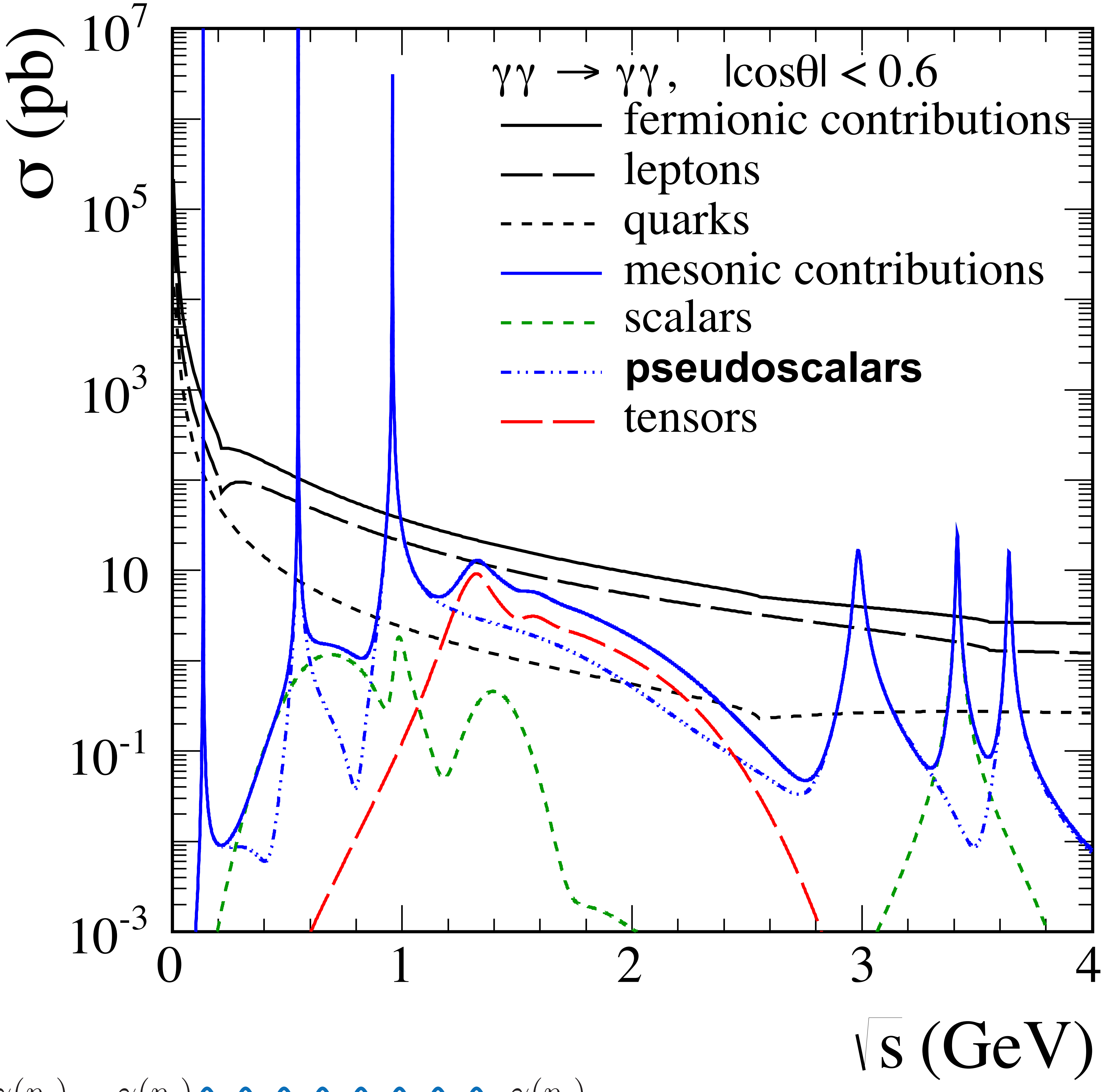


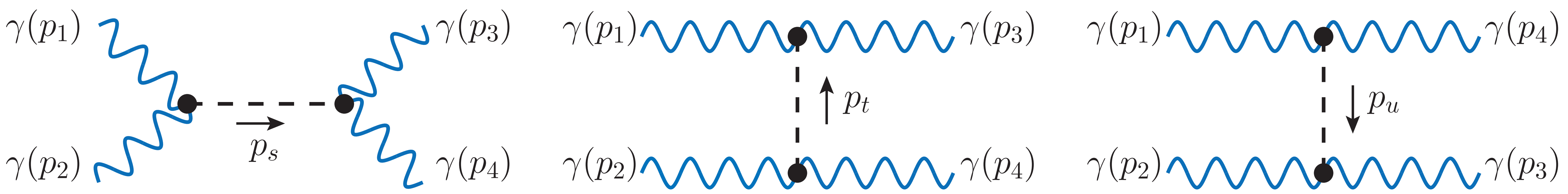
- ZDC energy deposits
  - Single neutron peaks clearly visible



Di-Photon spectrum at low energies => Mesons exchange

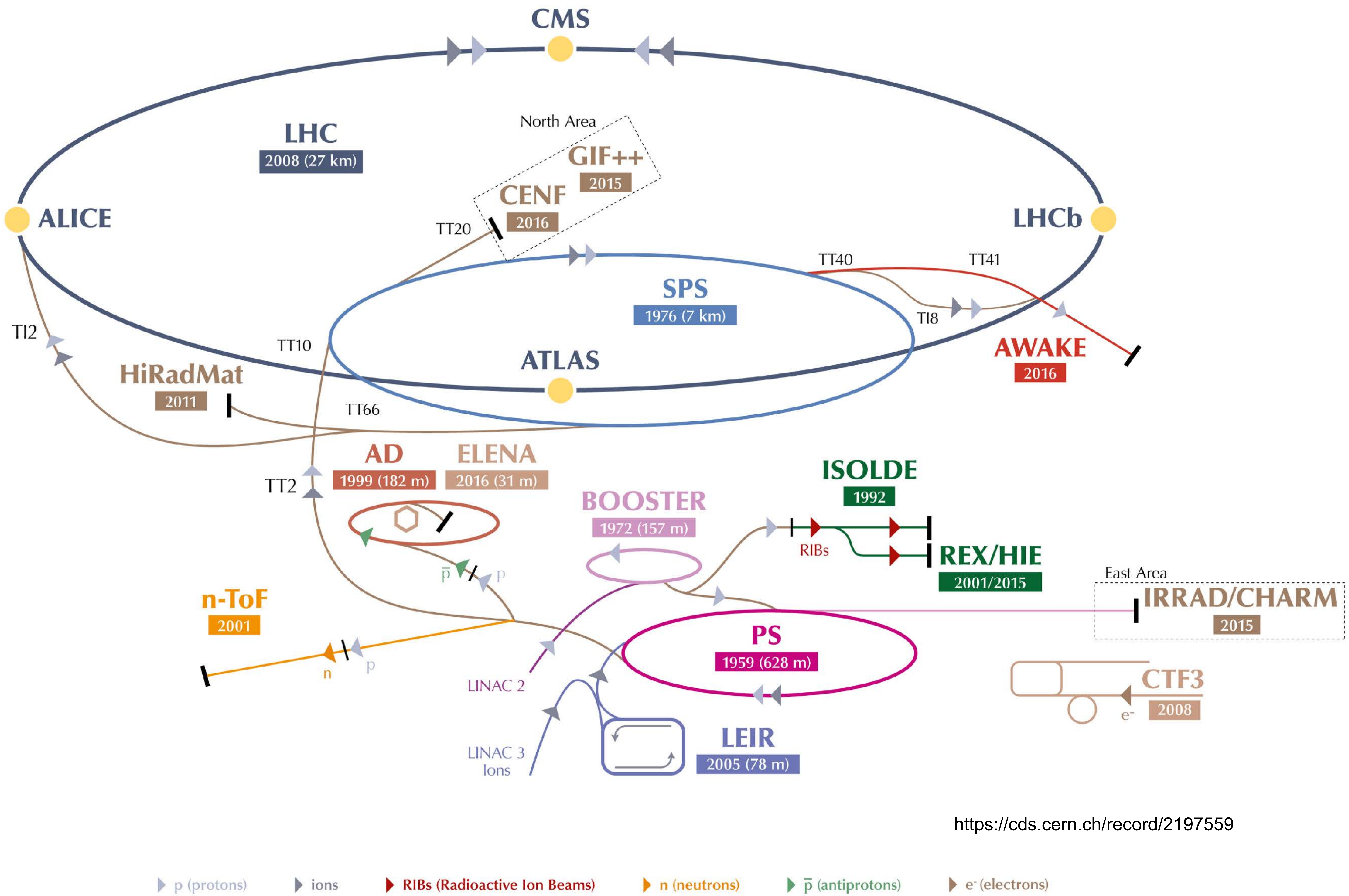
Lebiedowicz et al.
Phys. Lett. B 772 (2017) 330-335





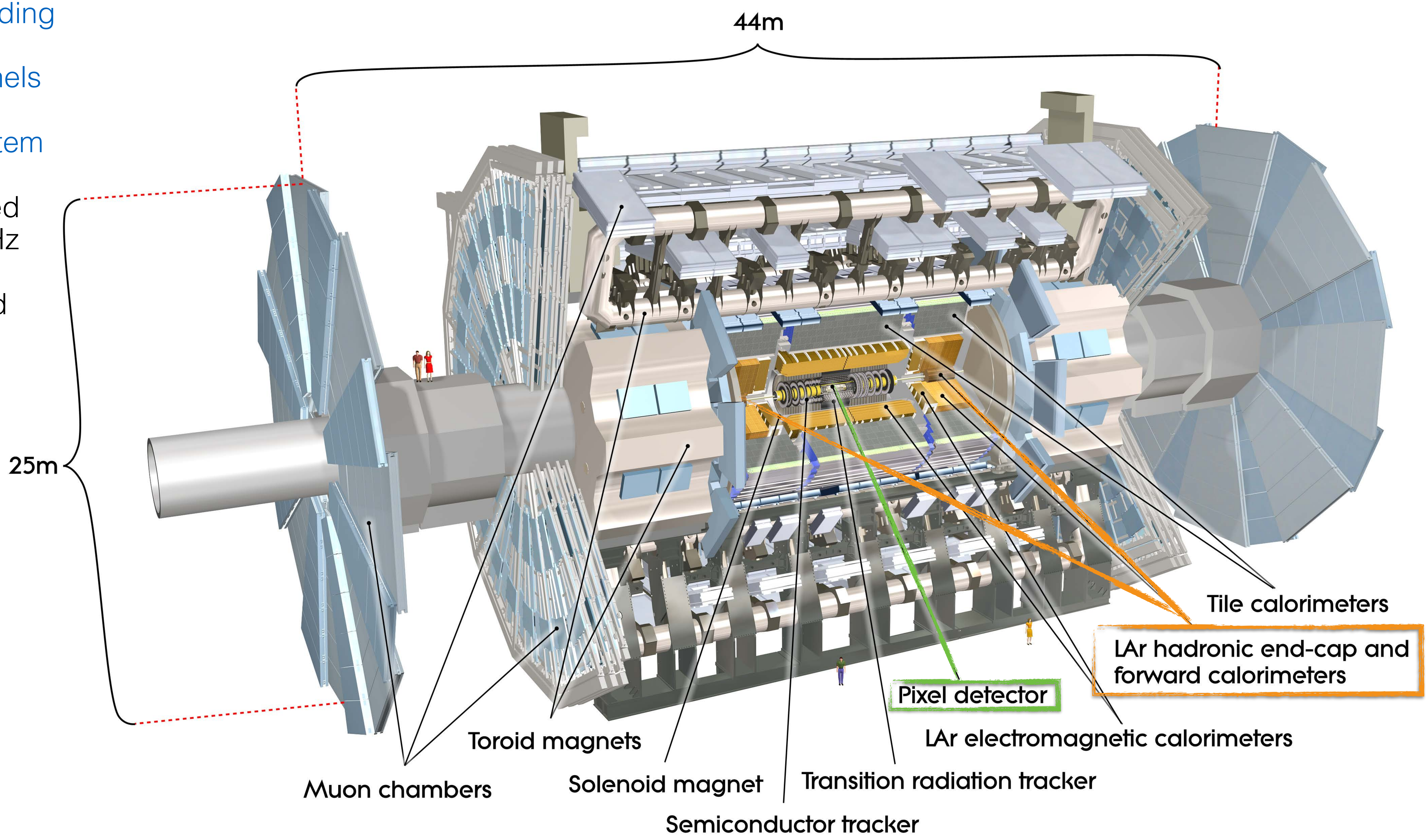
- **CERN's accelerator complex**

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



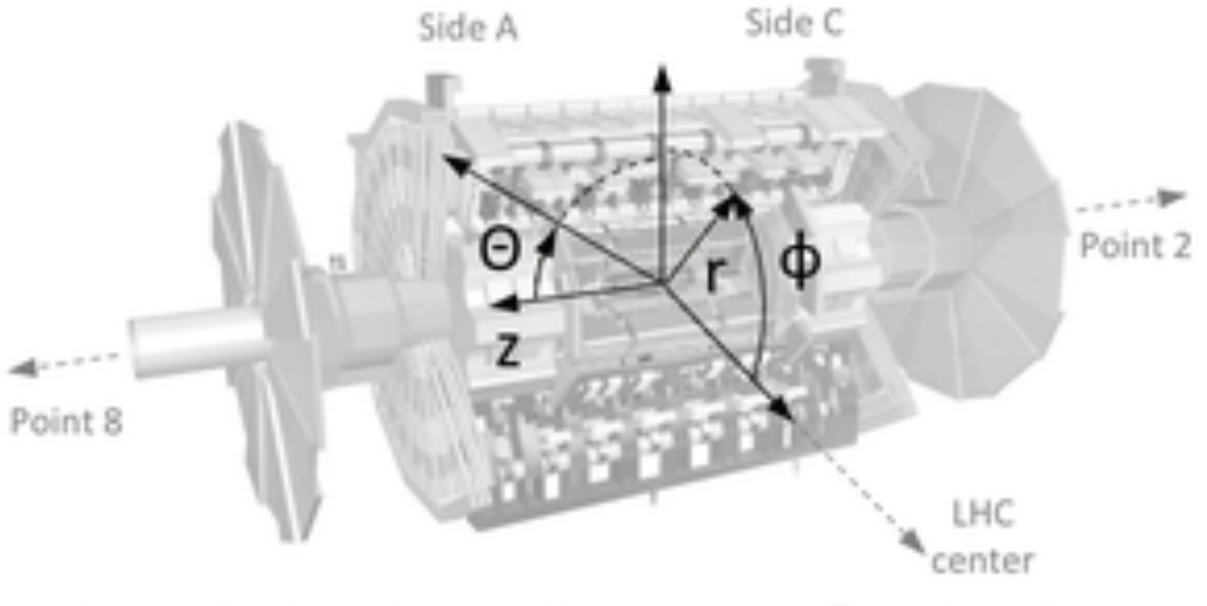
https://cds.cern.ch/record/2197559

- Size of a 6 story building
- 100M readout channels
- 2 staged trigger system
  - L1: hardware based
    - 40MHz -> 100kHz
  - L2: software based
    - 100kHz -> 1kHz
- 100 kHz readout
- 1 kHz to disk (~1.5 MB/event)



The ATLAS Detector

- ~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