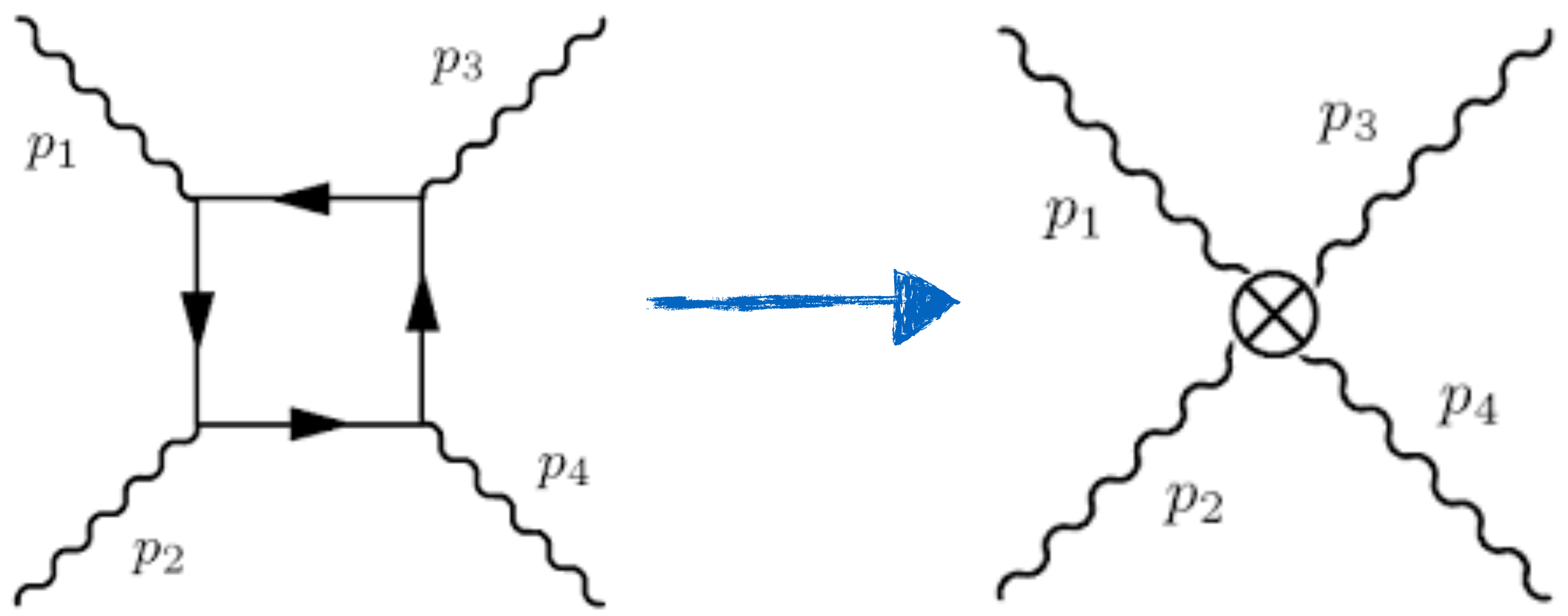
# Observation of Light-by-Light Scattering in ATLAS

**Vacuum fluctuations & Gravity, 30 April 2019**

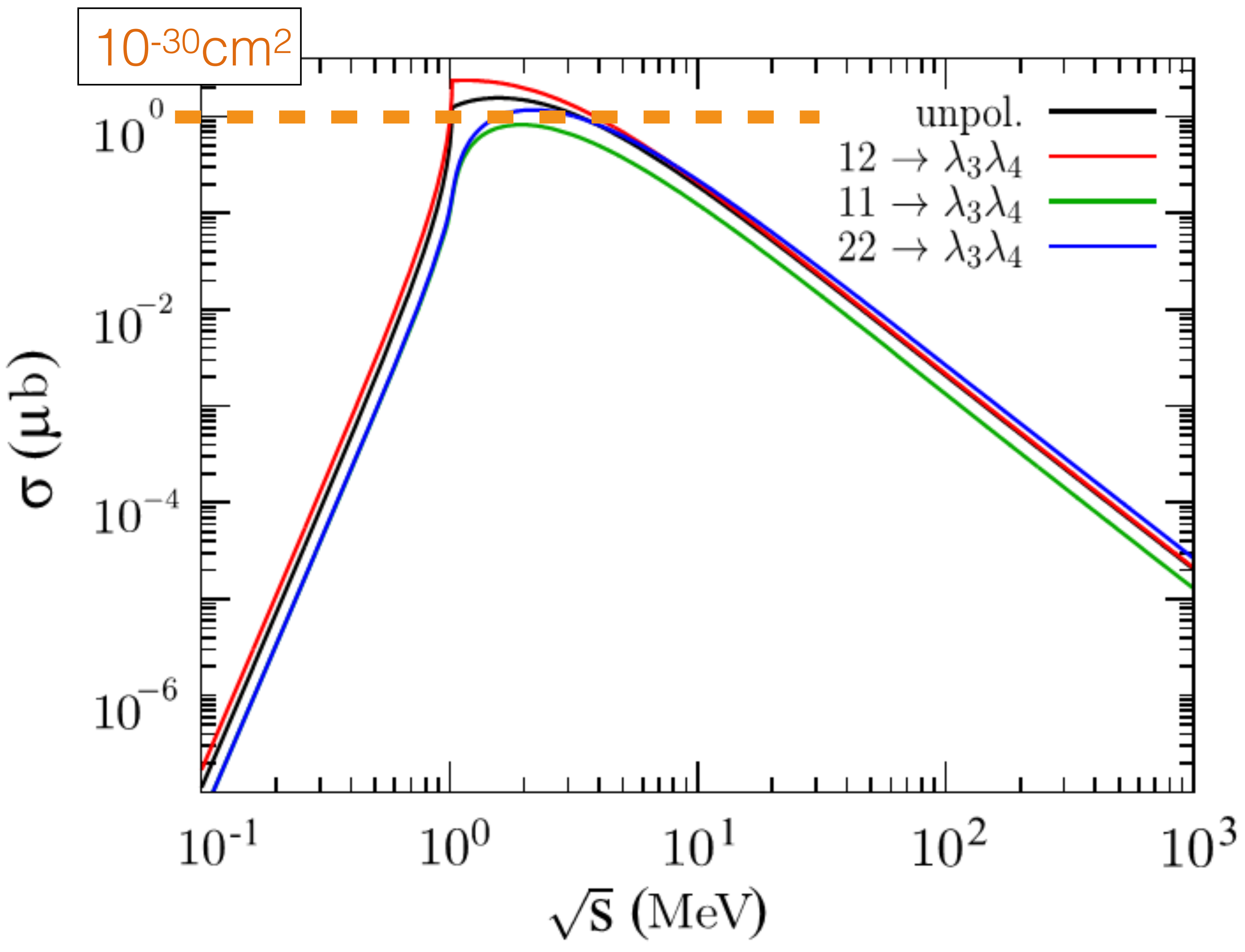
**Kristof Schmieden**, on behalf of the ATLAS collaboration


CERN




- The story starts with 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 $\gamma$-radiation

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



# Introduction - Historical context of Light-by-Light scattering

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

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

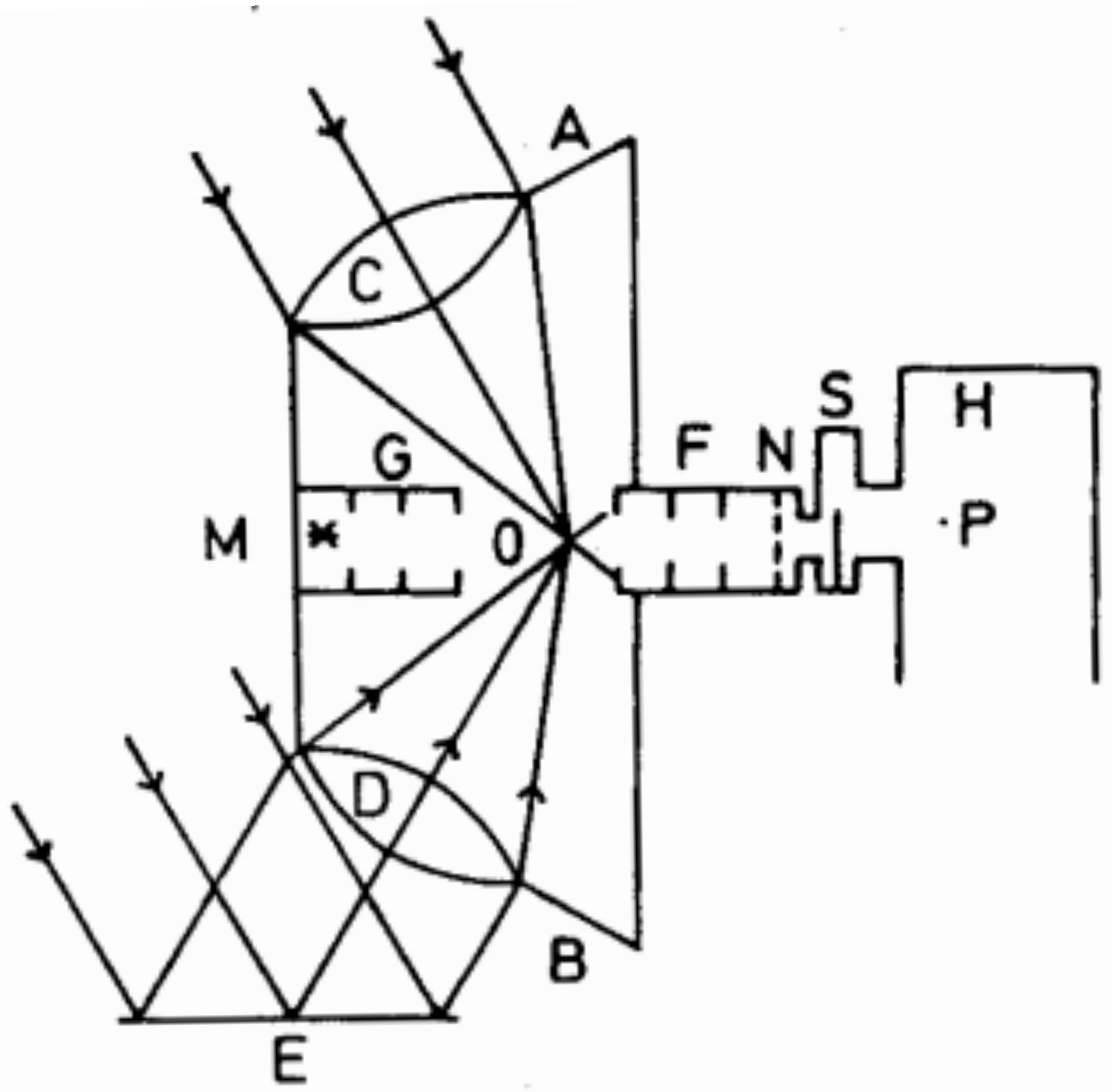


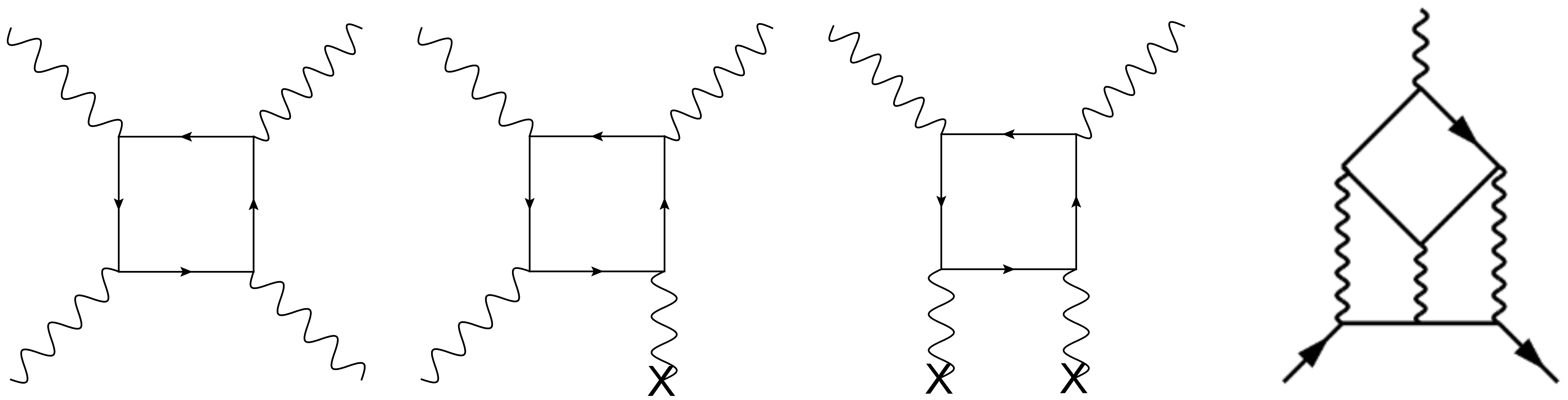

Figure 3 Apparatus for a light-light scattering experiment: The two lenses C and D focus sun light on the same spot O in a light-tight box AB. The dark-adapted eye of an observer at the point P serves as the detector for scattered light.

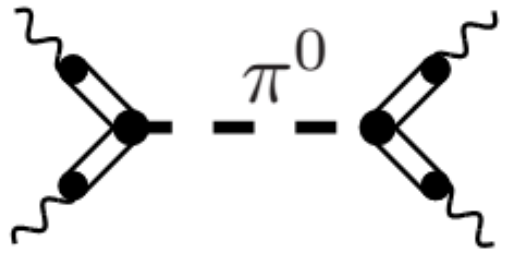
- No light was detected
  - "Calculations show that if the photon has a cross section, its area must be less than $3\text{x}10^{-20}$ cm$^2$."

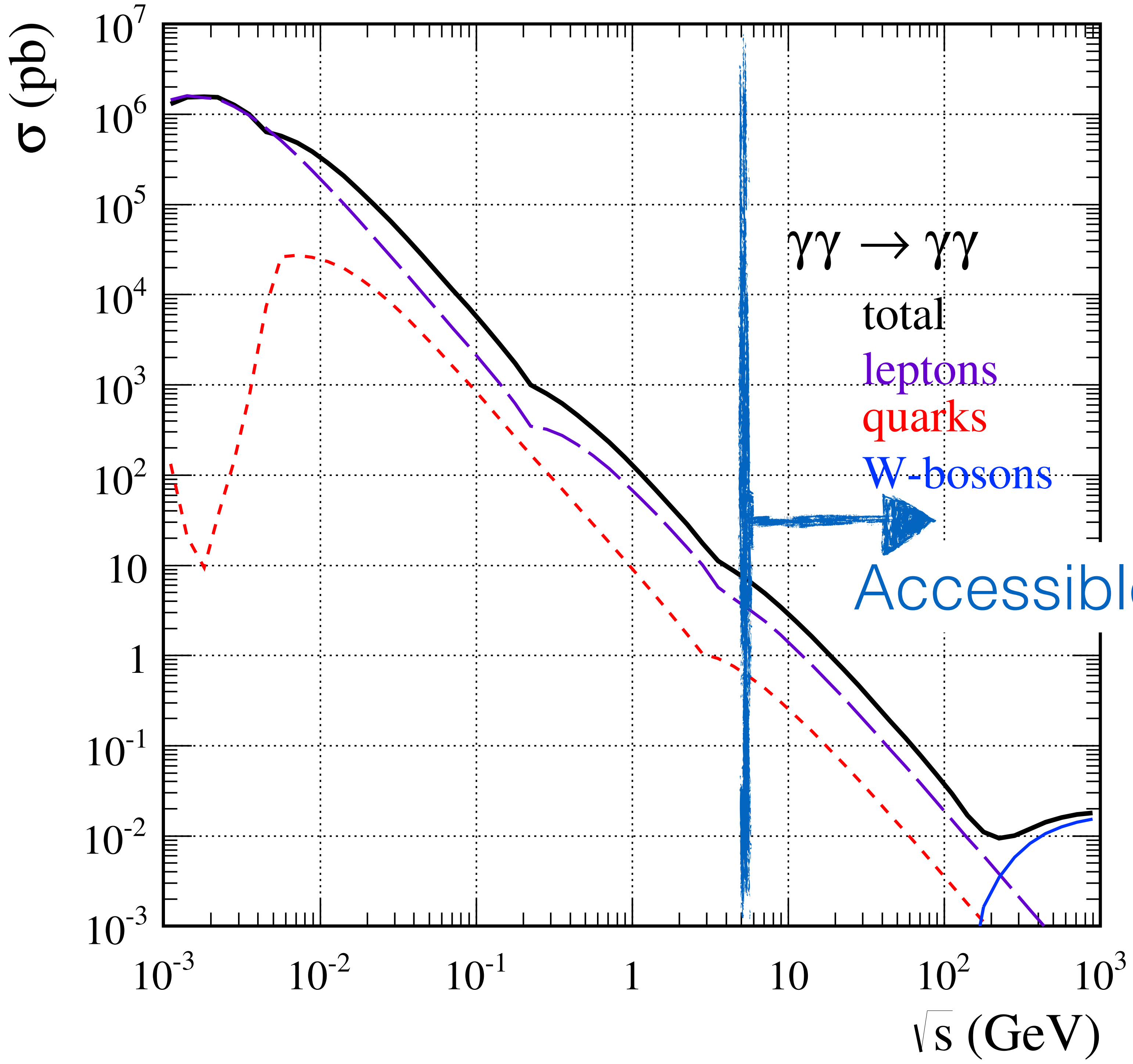
- Cross section for visible light actually is:
  - $10^{-60}$cm$^2$!

# 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
  - Electron / Muon g-2: 3 virtual, 1 real photon



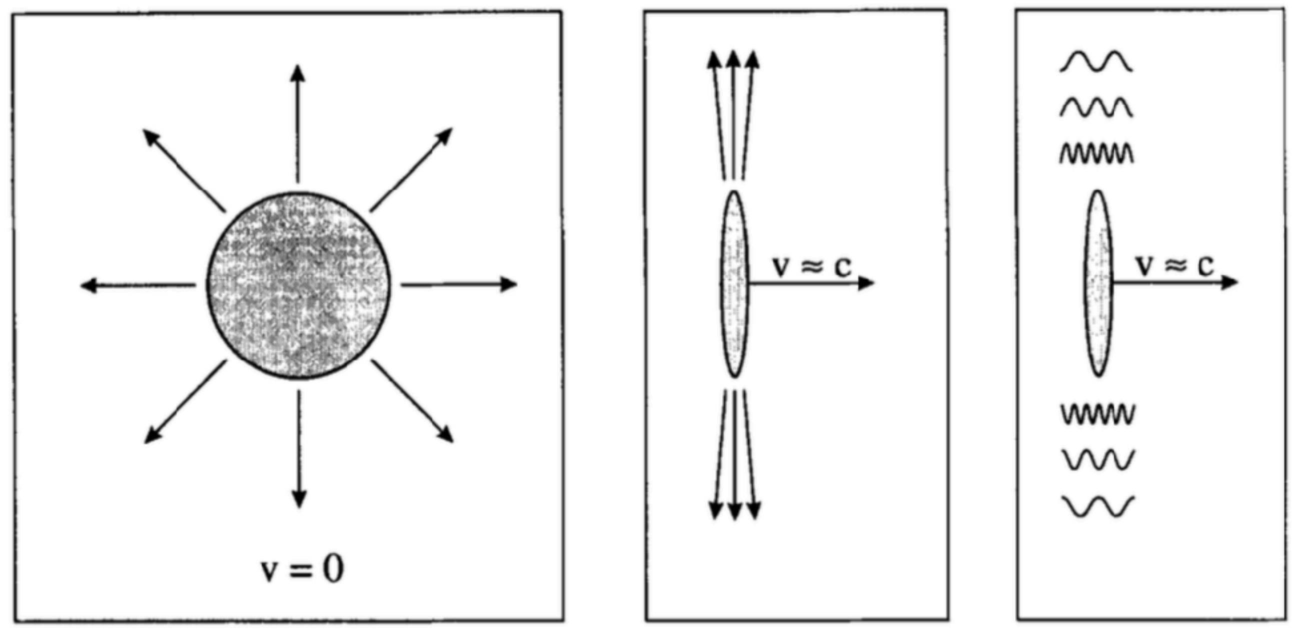

Accessible @ ATALS

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 collisions at LHC are a superb source of high energy photons!
- Maximum photons energy:
  - $E_{max} <= \gamma/R$ ~80 GeV
    - Lorentz factor $\gamma$ up to 2800 @ LHC




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

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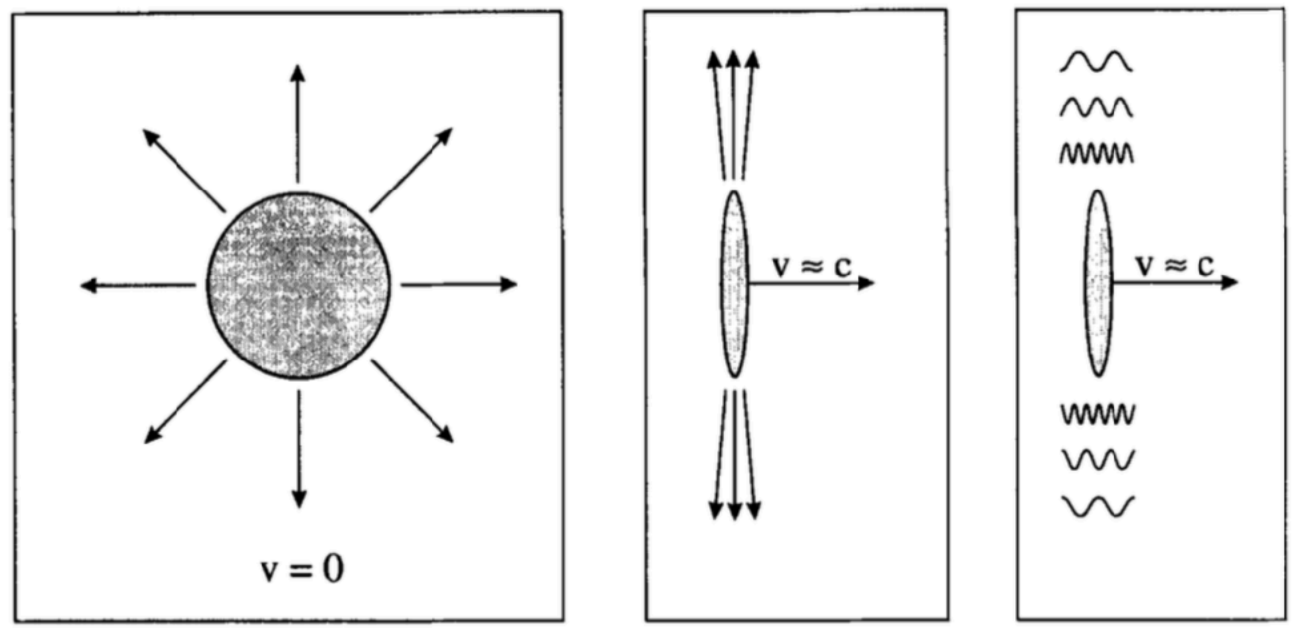
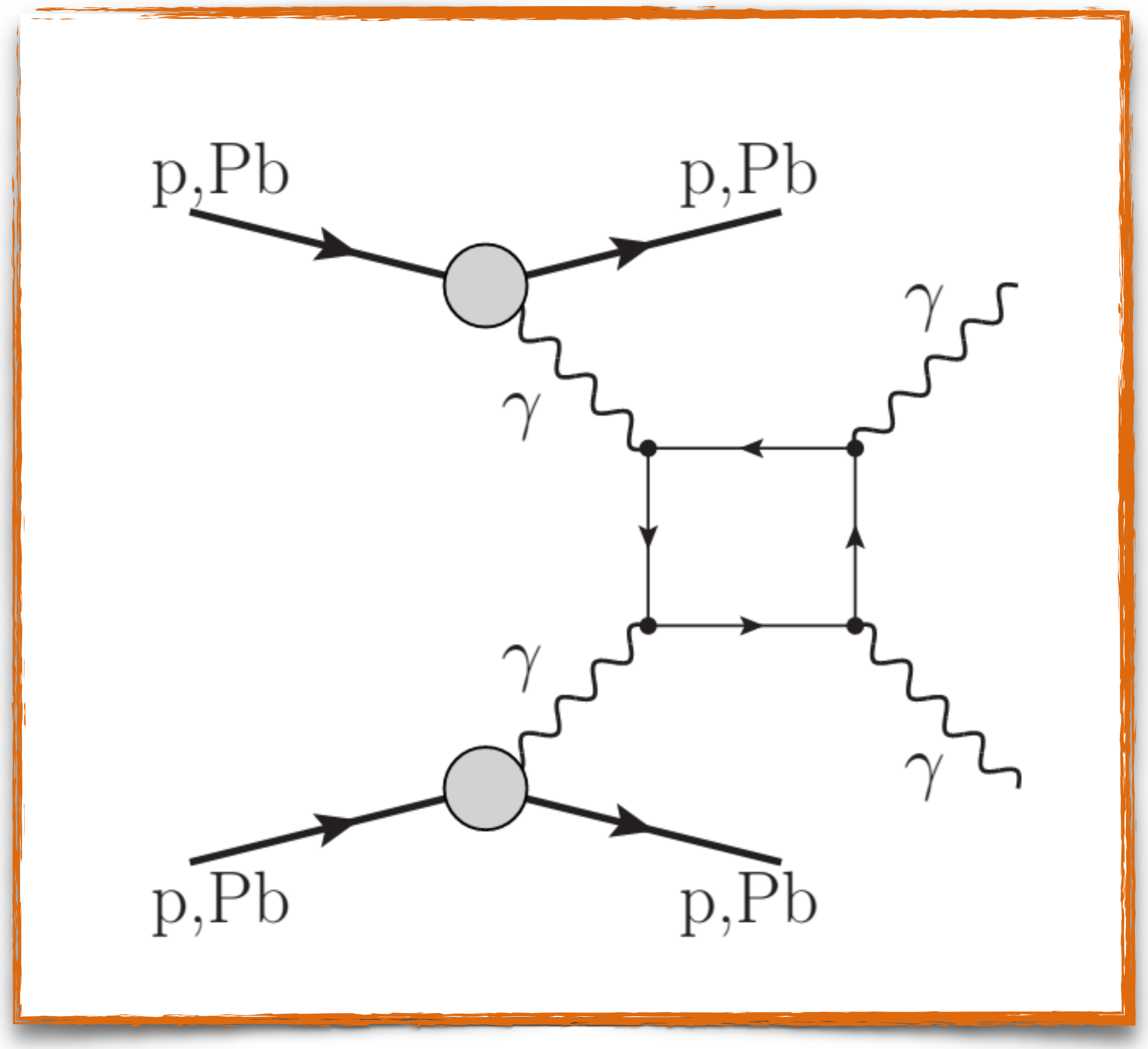


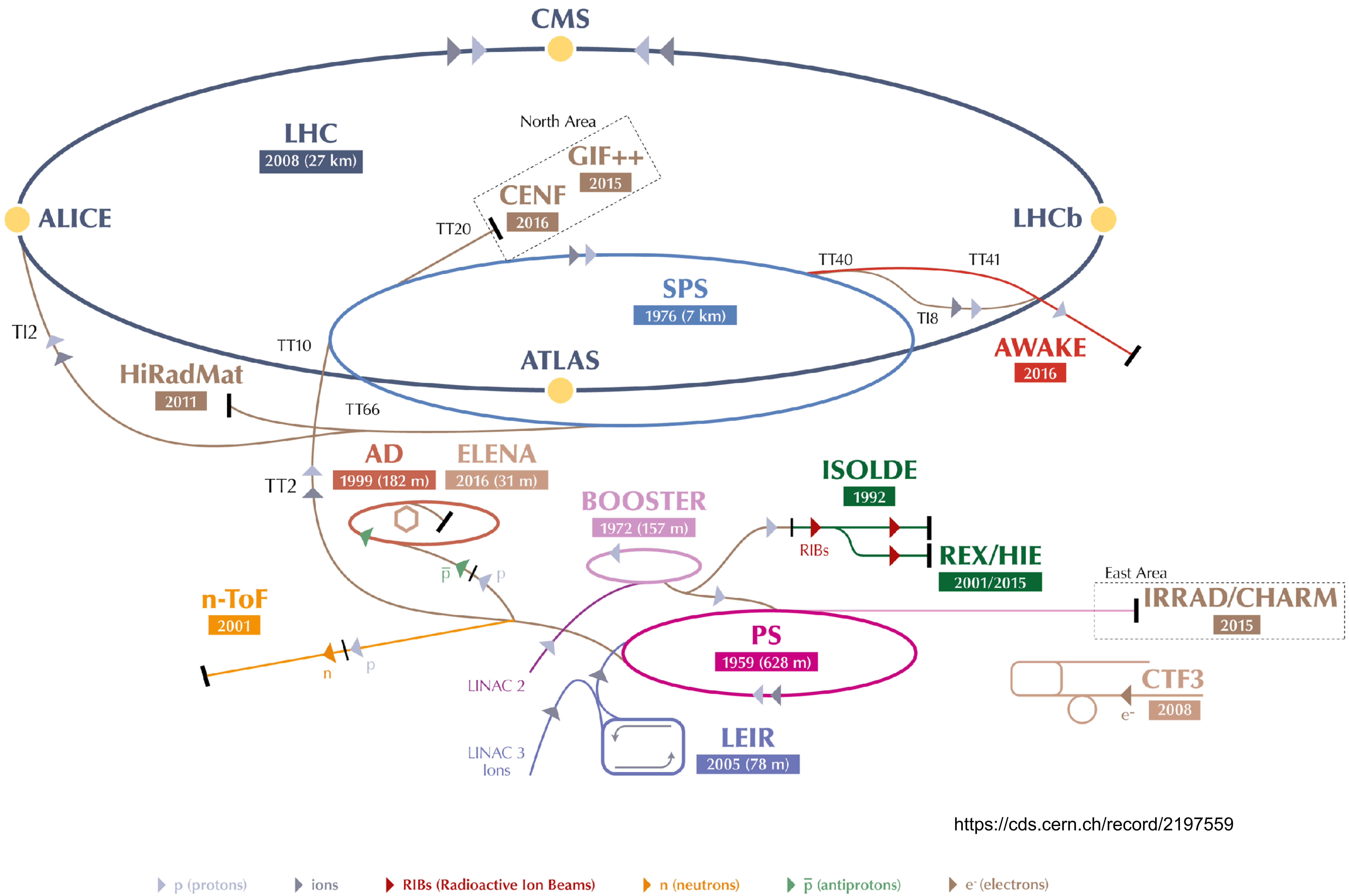

[Fermi, Nuovo Cim. 2 (1925) 143]




- Various types of photon interactions possible
  - Photon-Pomeron: e.g. exclusive J/Phi production
  - Photons - Gluon: photo production of jets
  - Photon - Photon: Light - by - Light scattering
    - QED interaction
    - Mediated via box-diagram
    - Beam particles stay intact

- **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

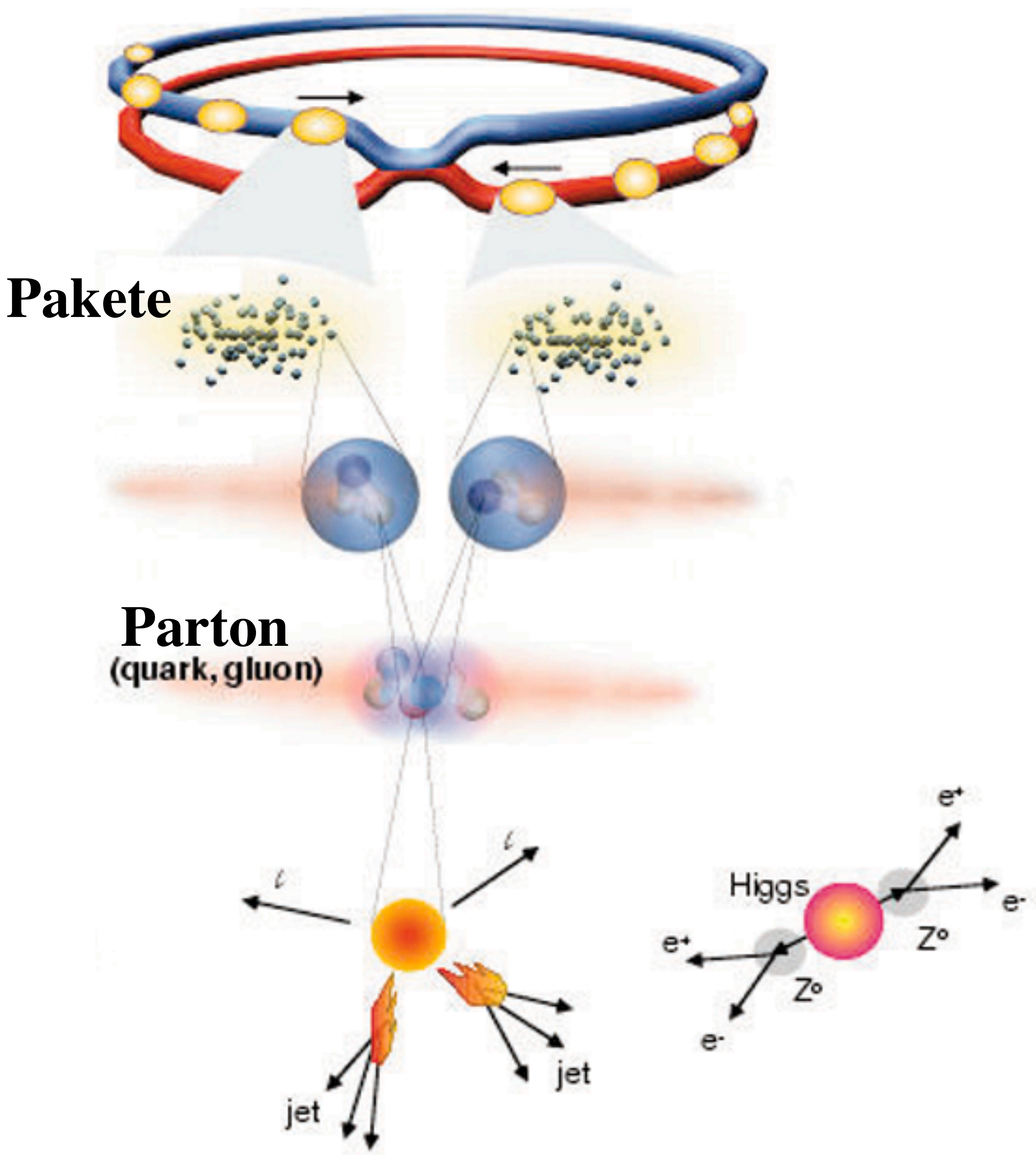
- **CERN's accelerator complex**

- LHC:
  - Usually operates with **proton @** 6.5 GeV beam energy

  - ~1 month / per year:
    - **Lead** ions instead of protons

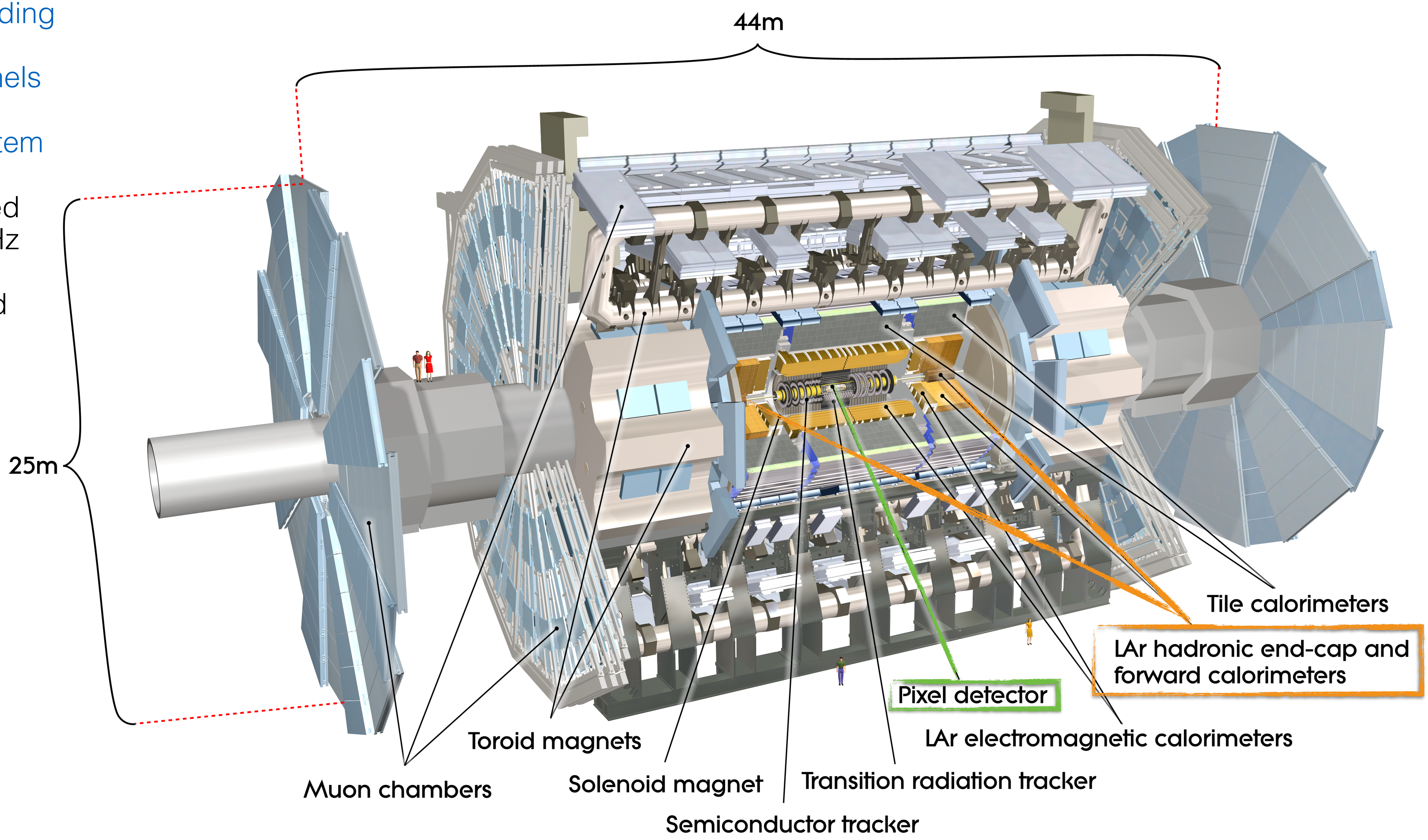
- Proton operation:
  - Bunch crossings every 25ns (40 MHz)
  - ~60 simultaneous pp collision per bunch crossing
    - 'Pileup'

- Heavy ion operation:
  - Bunch crossings every 75ns (13 MHz)
  - ~0.004 simultaneous PbPb collision per bunch crossing
    - Essentially no pileup at all



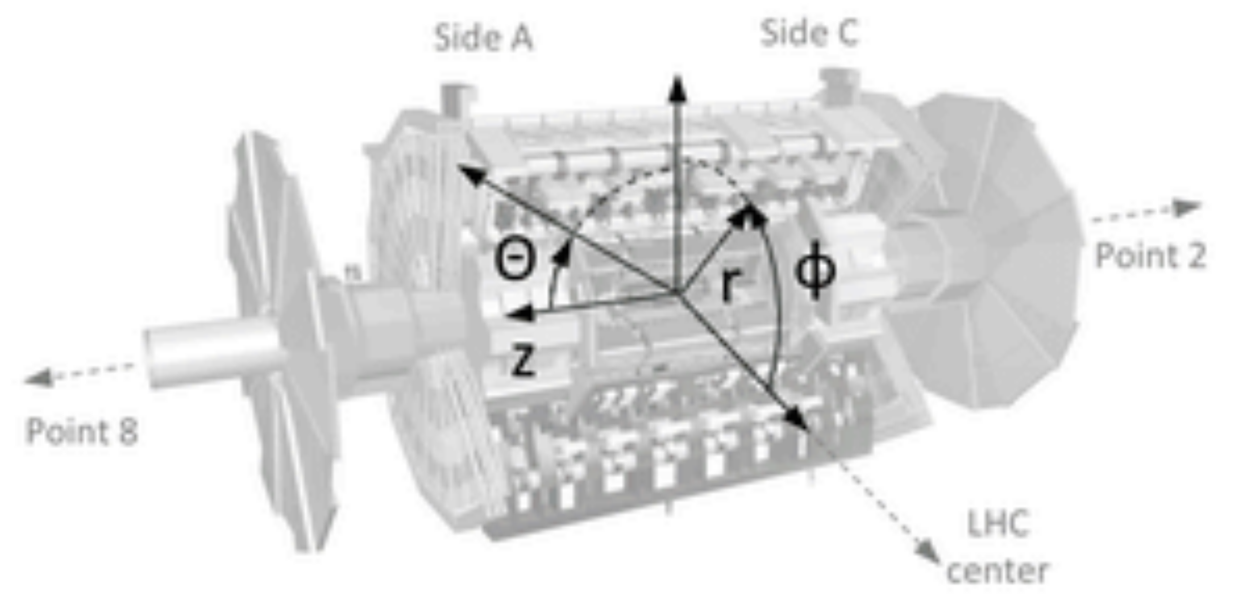
# The ATLAS Detector

- 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)

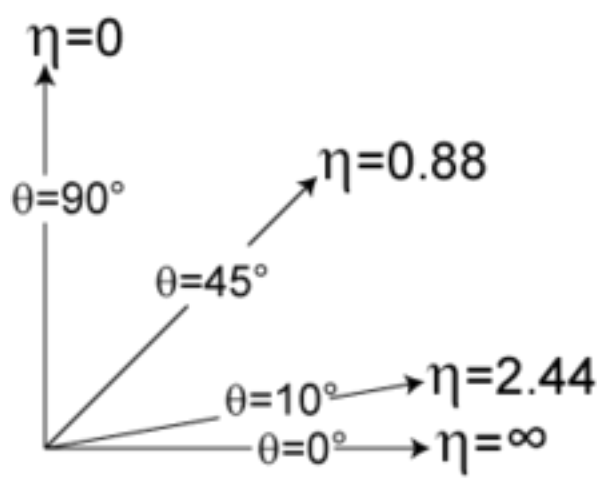


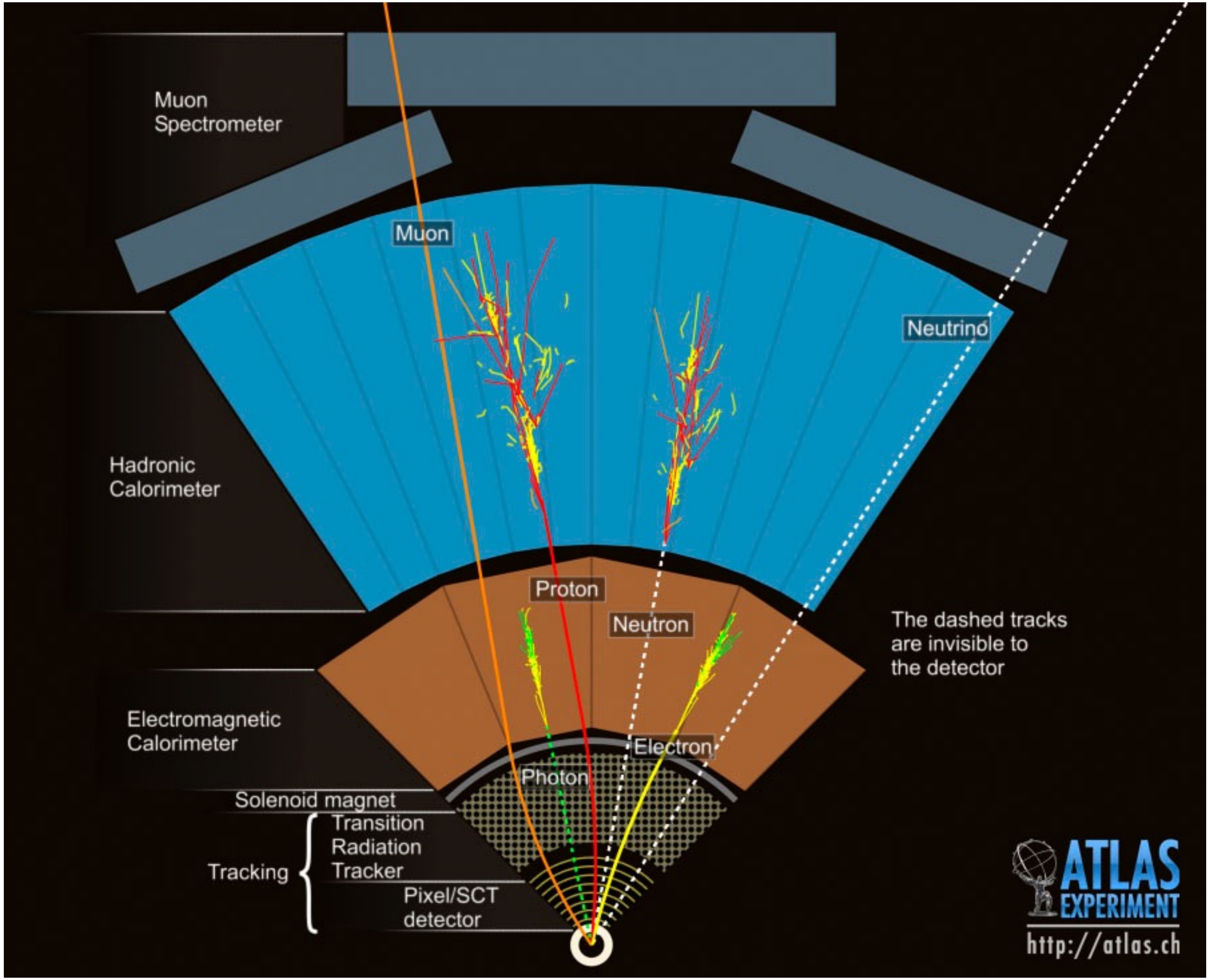
# The ATLAS Detector

- ~100M readout channels
- 100kHz readout (~1.5 MB/event)
  - 1 kHz to disk
- 'Textbook' like multi purpose detector
- ATLAS coordinate system:
  - $\eta$ = -ln tan($\theta$/2), $\phi$




r-ϕ-z cylindrical coordinates and Θ - visualization



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

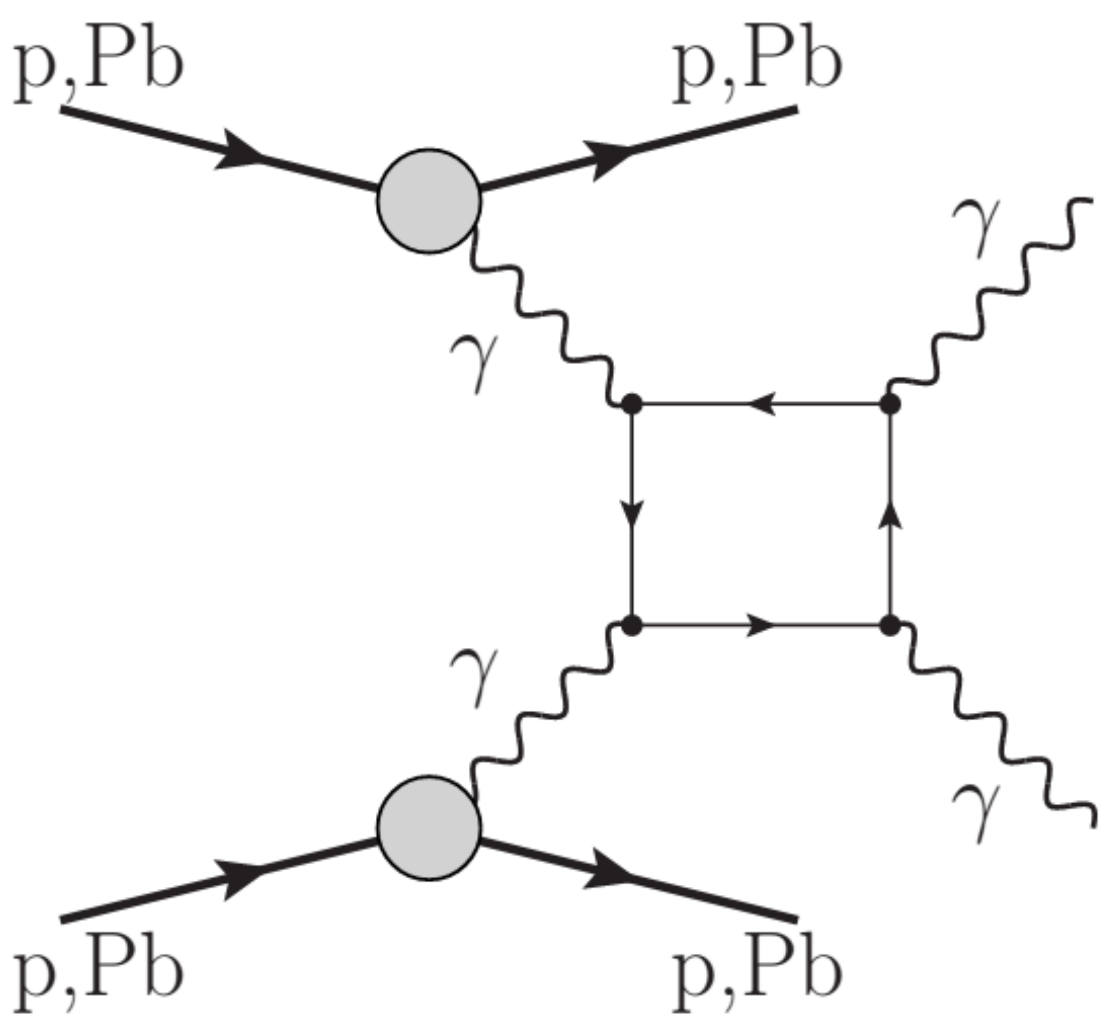
- Experimental signature:
  - 2 exclusive photons in the final state
  - Photons are back - to - back in $\phi$
    - $A_\phi = 1 - |\Delta\phi| / \pi < 0.01$

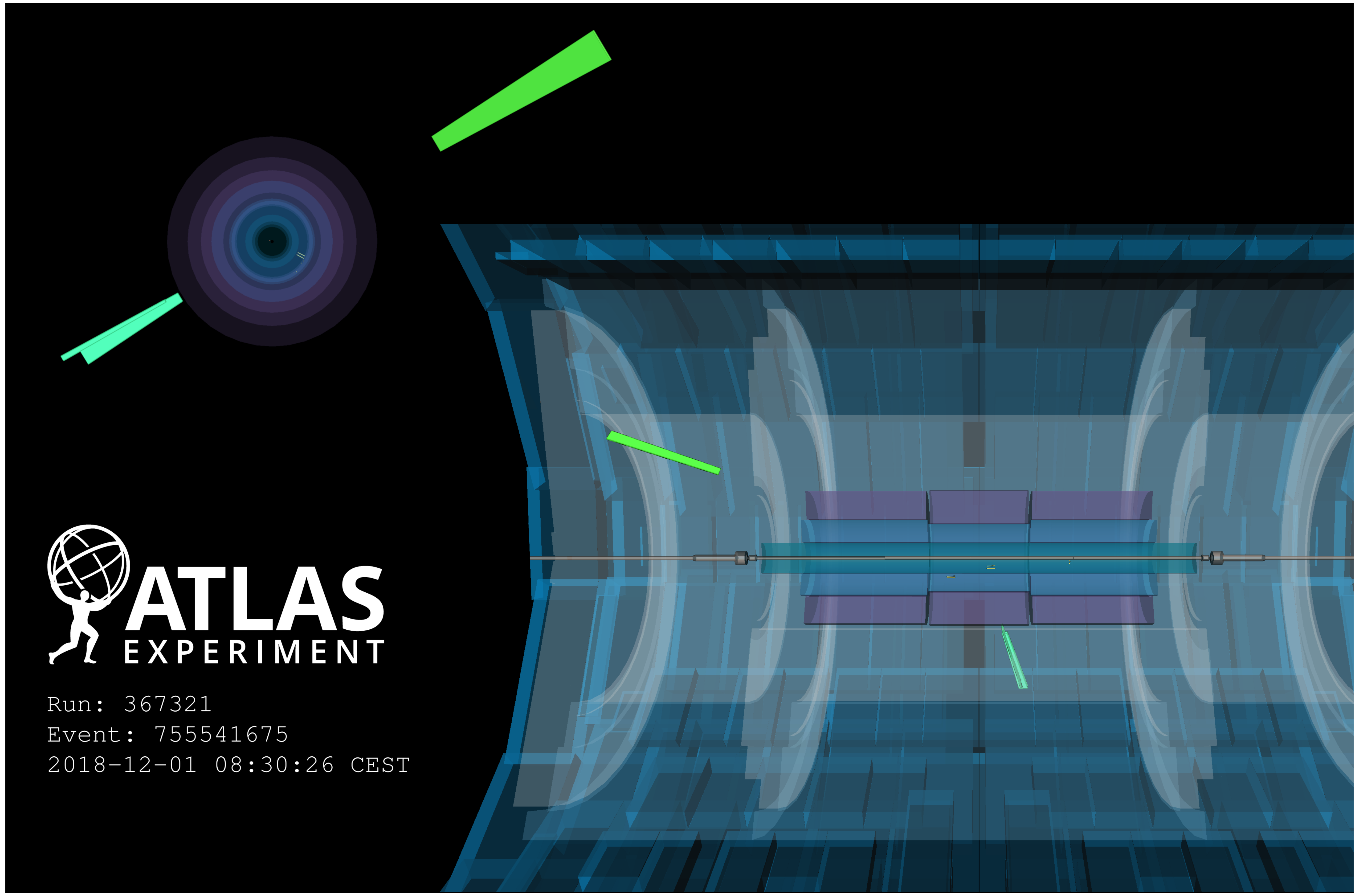
2016: Nature Physics 13 (2017) 852

2018: arXiv:1904.03536

- Cross section steeply falling with increasing energy
  - Looking for low energy photons: E > 3 GeV
    - Challenging!

- Very **unusual topology** and **energy range** for a high energy collider experiment
  - Interesting challenge :-)



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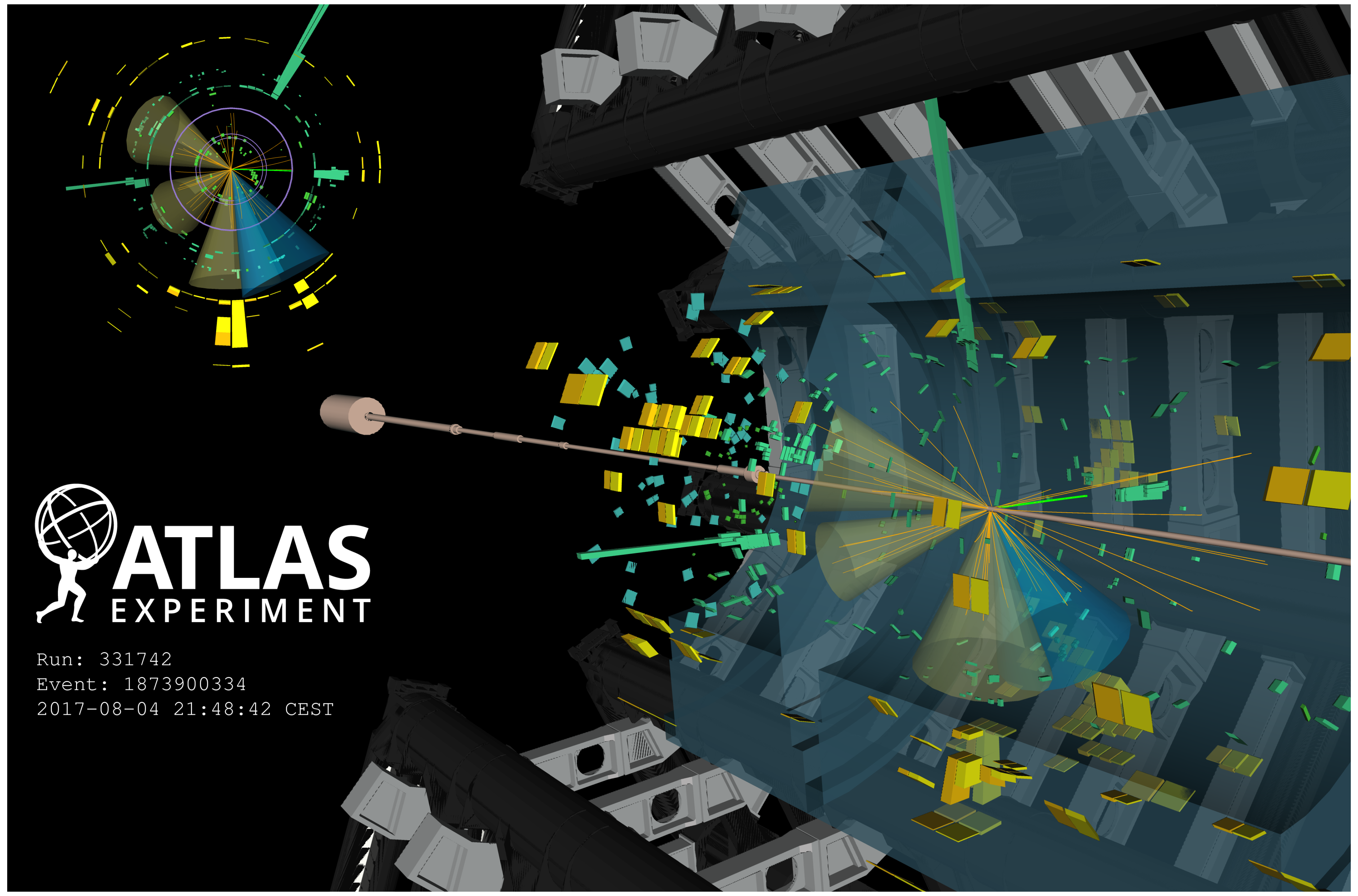
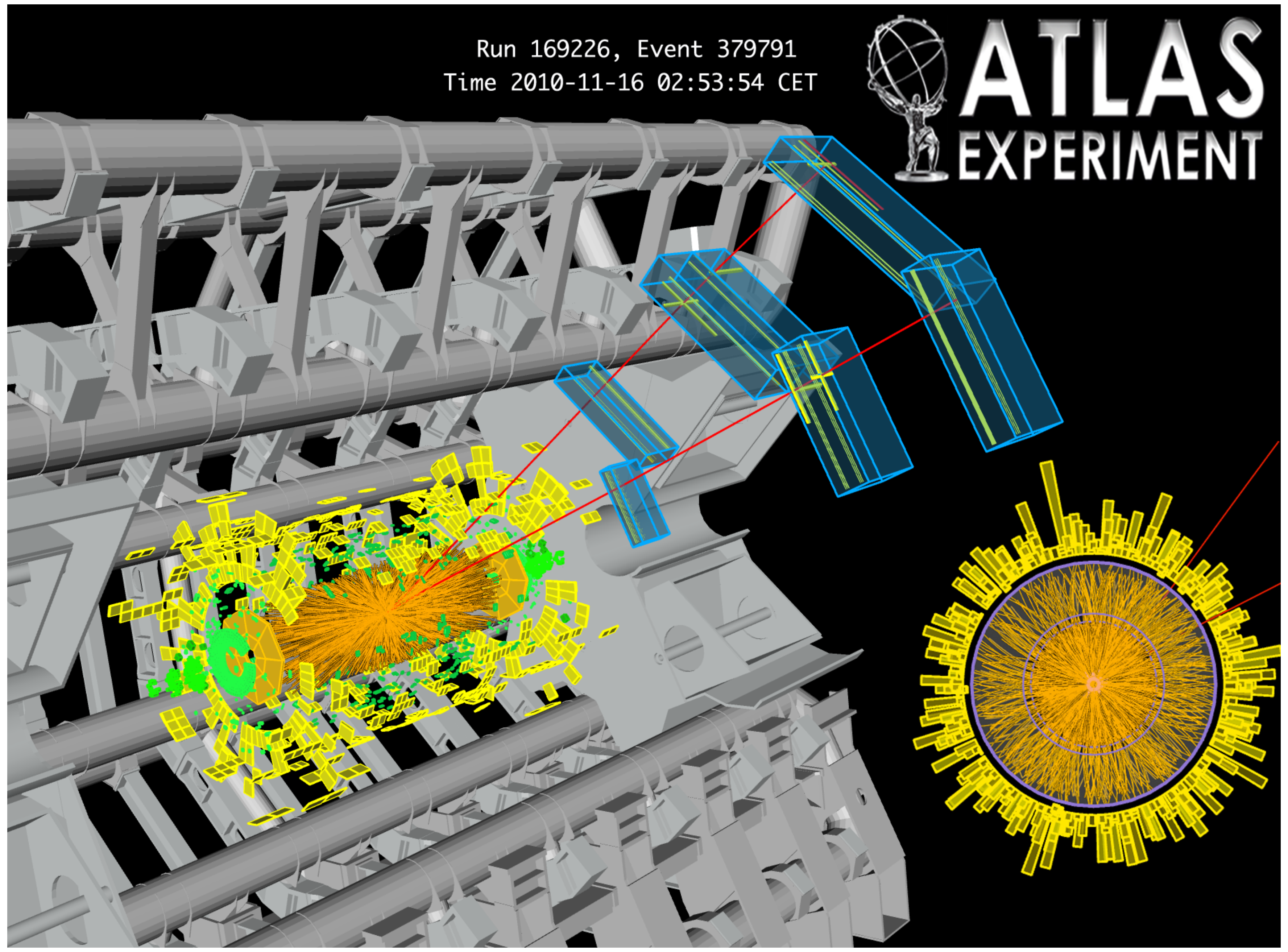
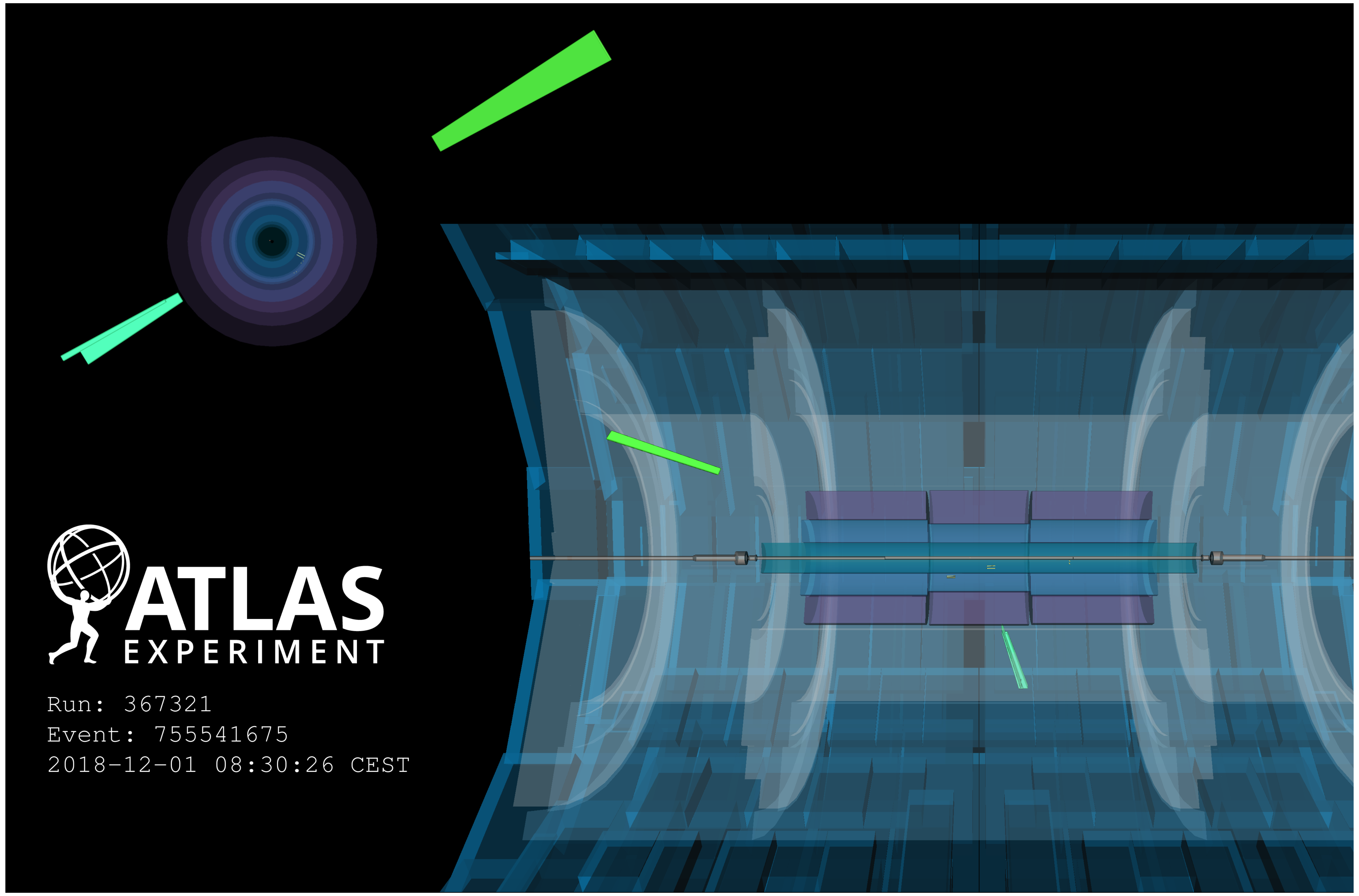



- Common pp collision



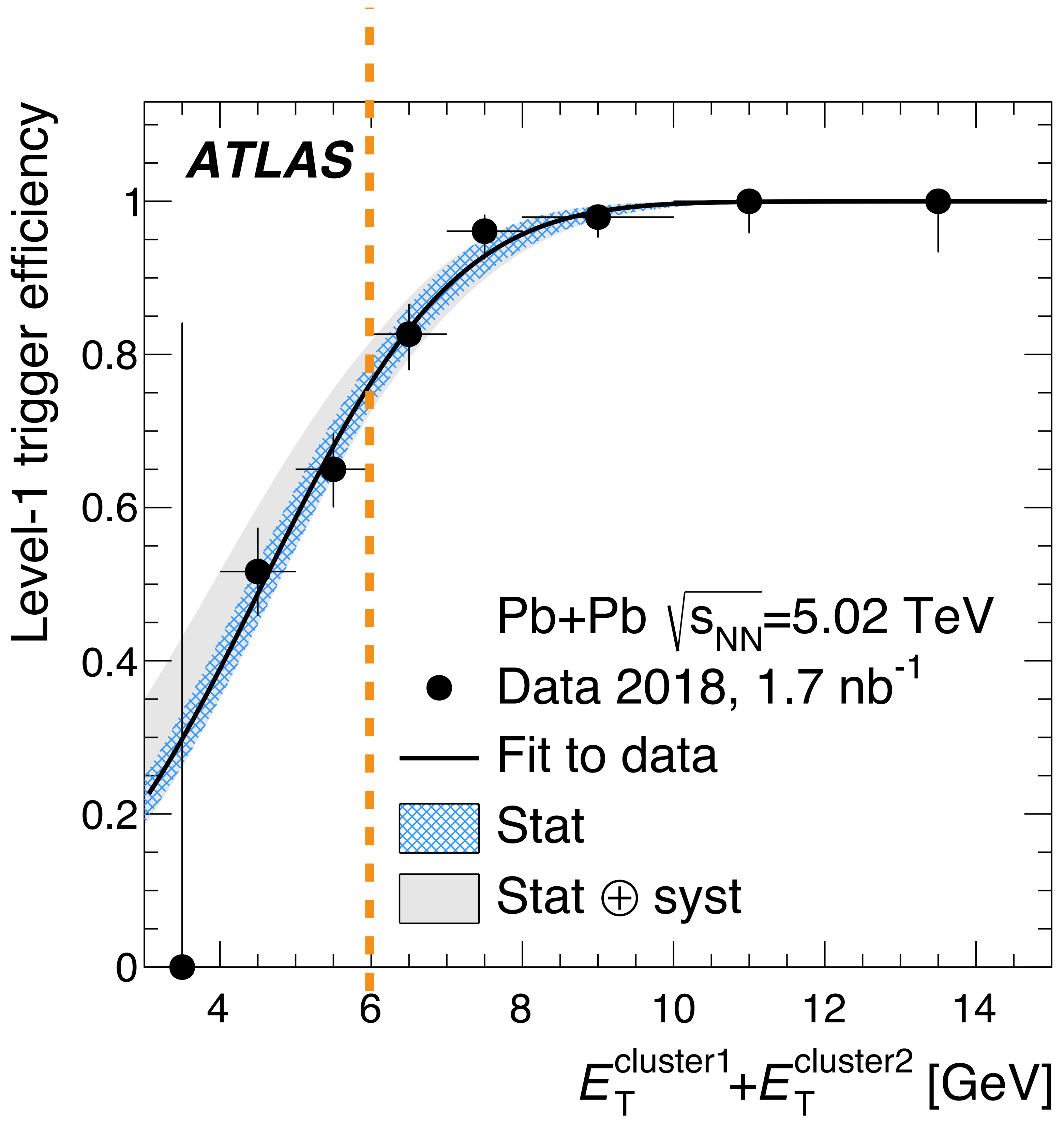

- Common PbPb collision

- Light-by-Light scattering candidate event



# Triggering

- ATLAS uses a 2-staged trigger system
  - 1st Stage: Hardware Based, 40MHz input, 100kHz output
    - Requirements (OR):
      - >= 1 EM cluster with $E_T$ > 1 GeV && 4 GeV < total $E_T$ < 200 GeV
      - >= 2 EM clusters with $E_T$ > 1 GeV && total $E_T$ < 50 GeV
  - 2nd Stage: PC-farm, 100kHz input, 1kHz output
    - Requirements (AND):
      - $\Sigma E_T$ (forward calorimeter) < 3 GeV on both sides
      - <= 15 hits in pixel detector
        - Tagging of exclusive photon final state

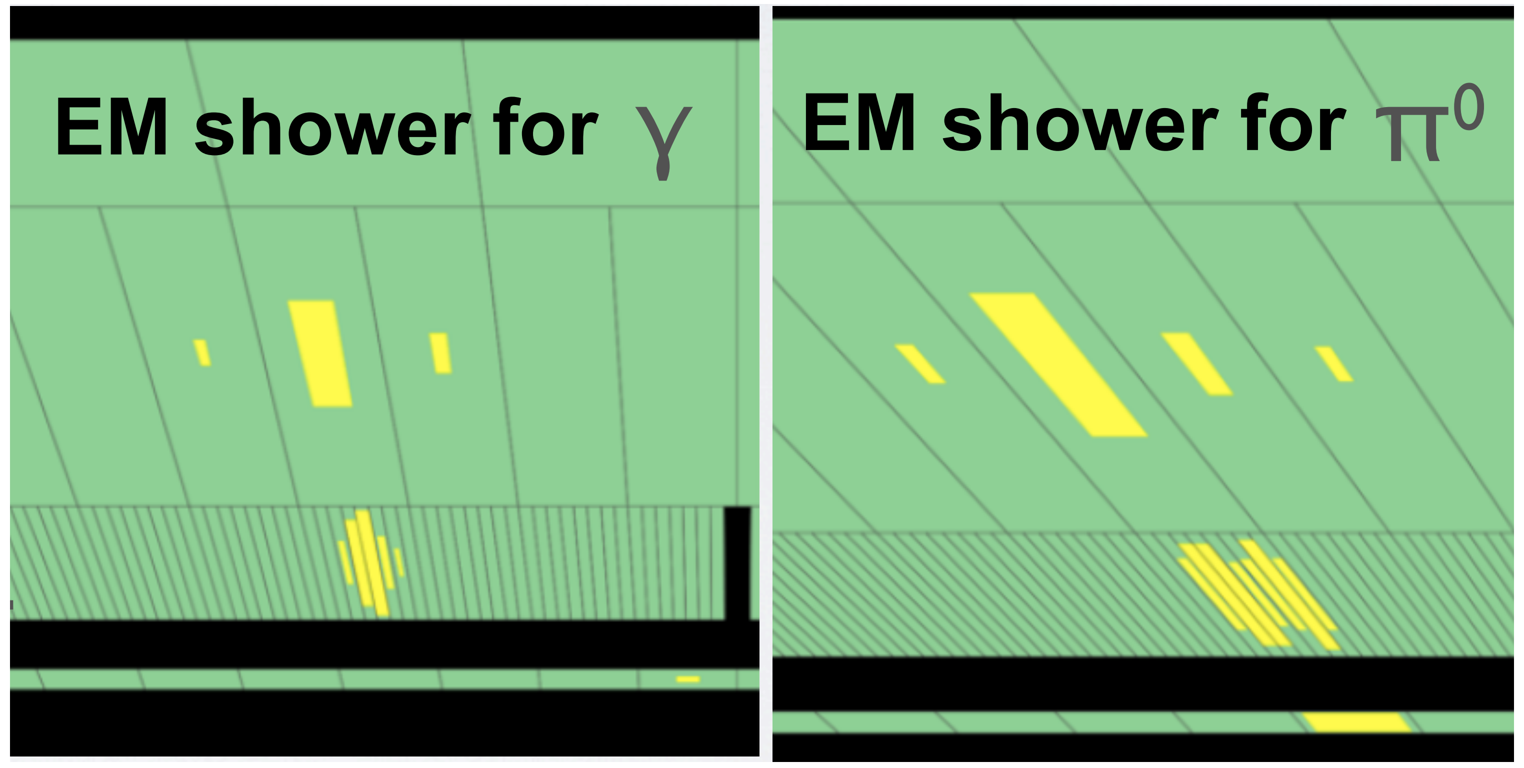



- Trigger efficiency determined using $e^+e^-$ final states
  - Triggered by independent support triggers
- Applied to simulated events to correct yield

2018: arXiv:1904.03536

# 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, optimised for low ET photons
  - Combination of EM calorimeter shower shape variables
    - Discrimination between photons, pions, electrons, noise

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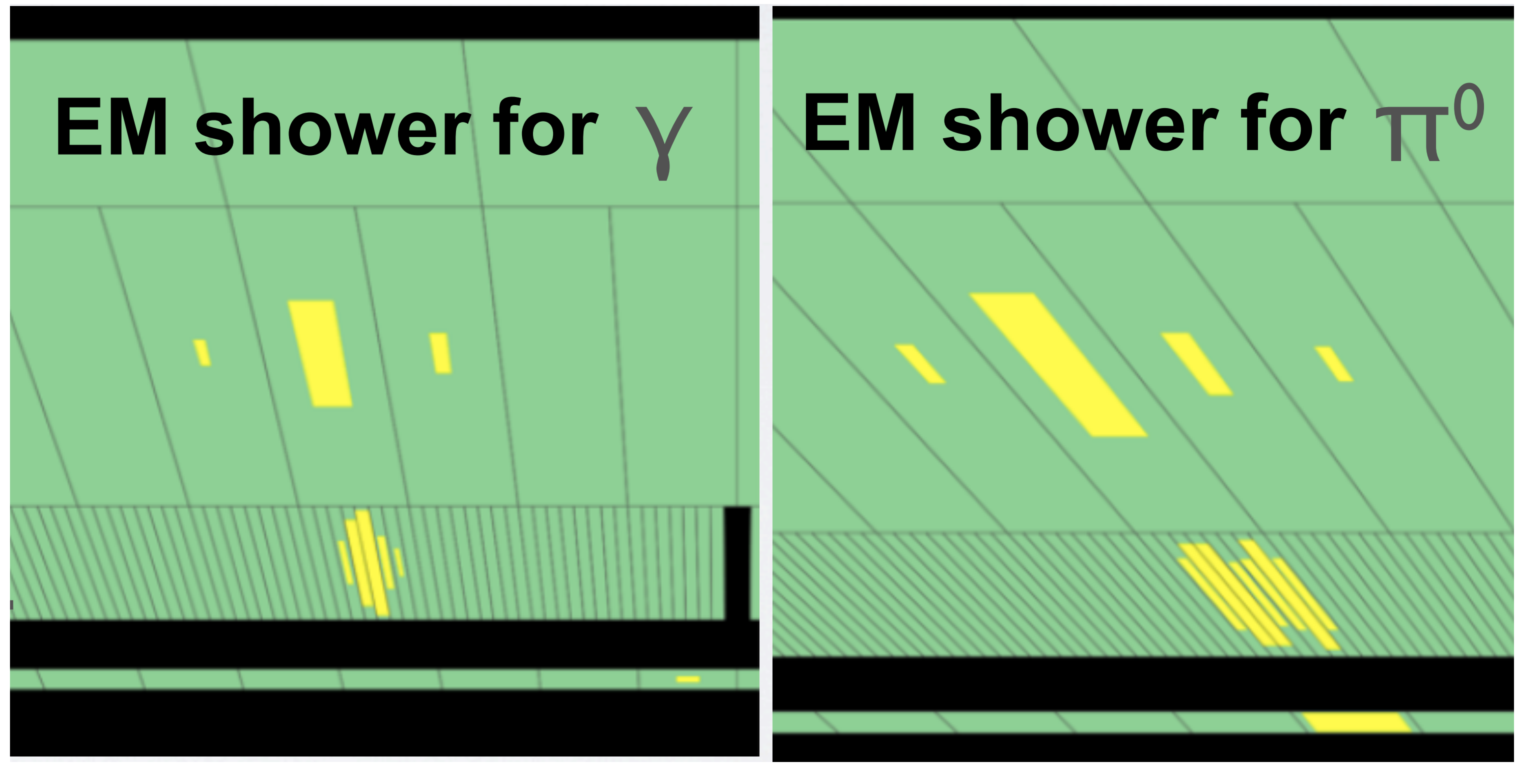


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  - Uses neural net, optimised for low ET photons
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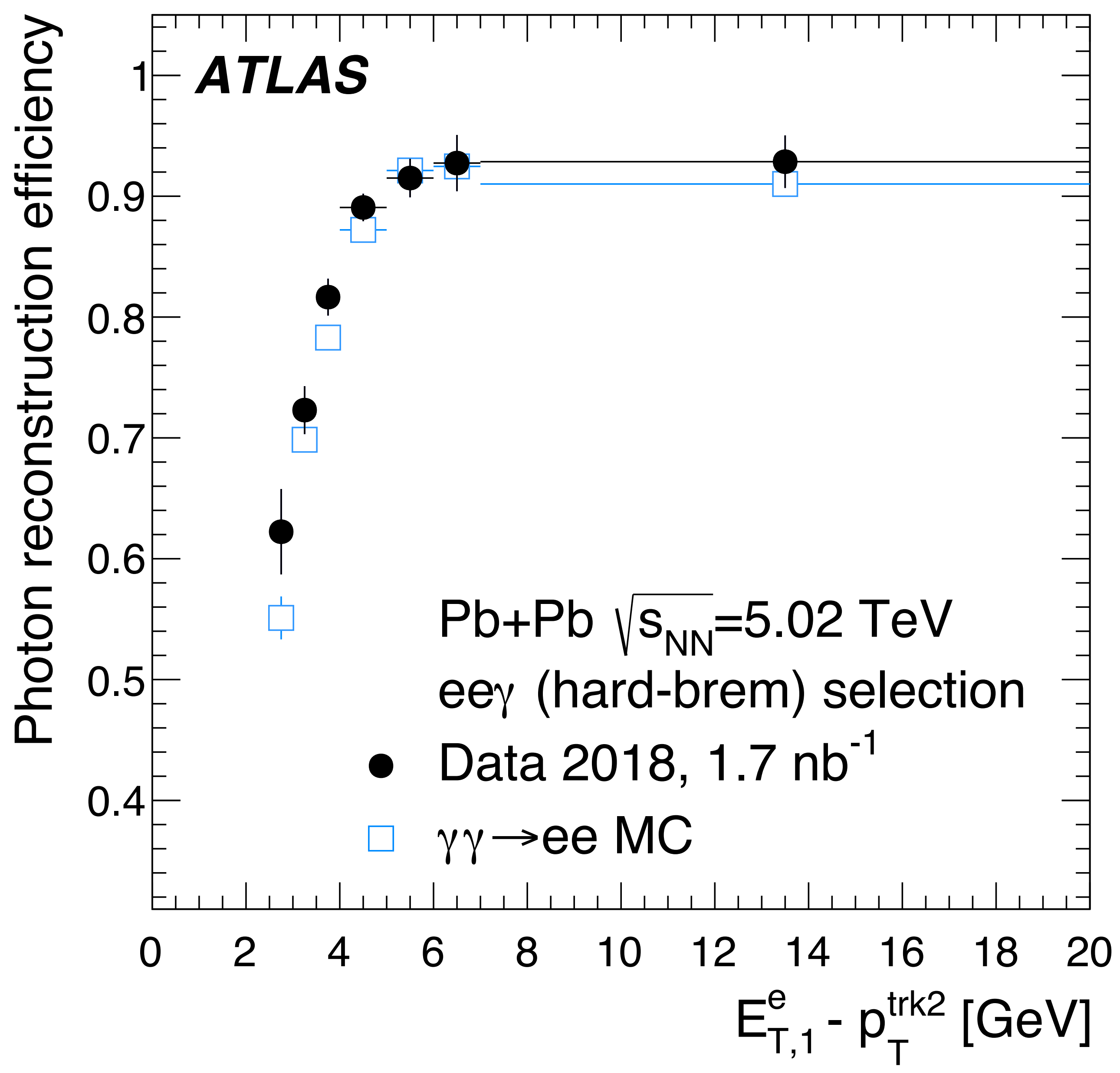
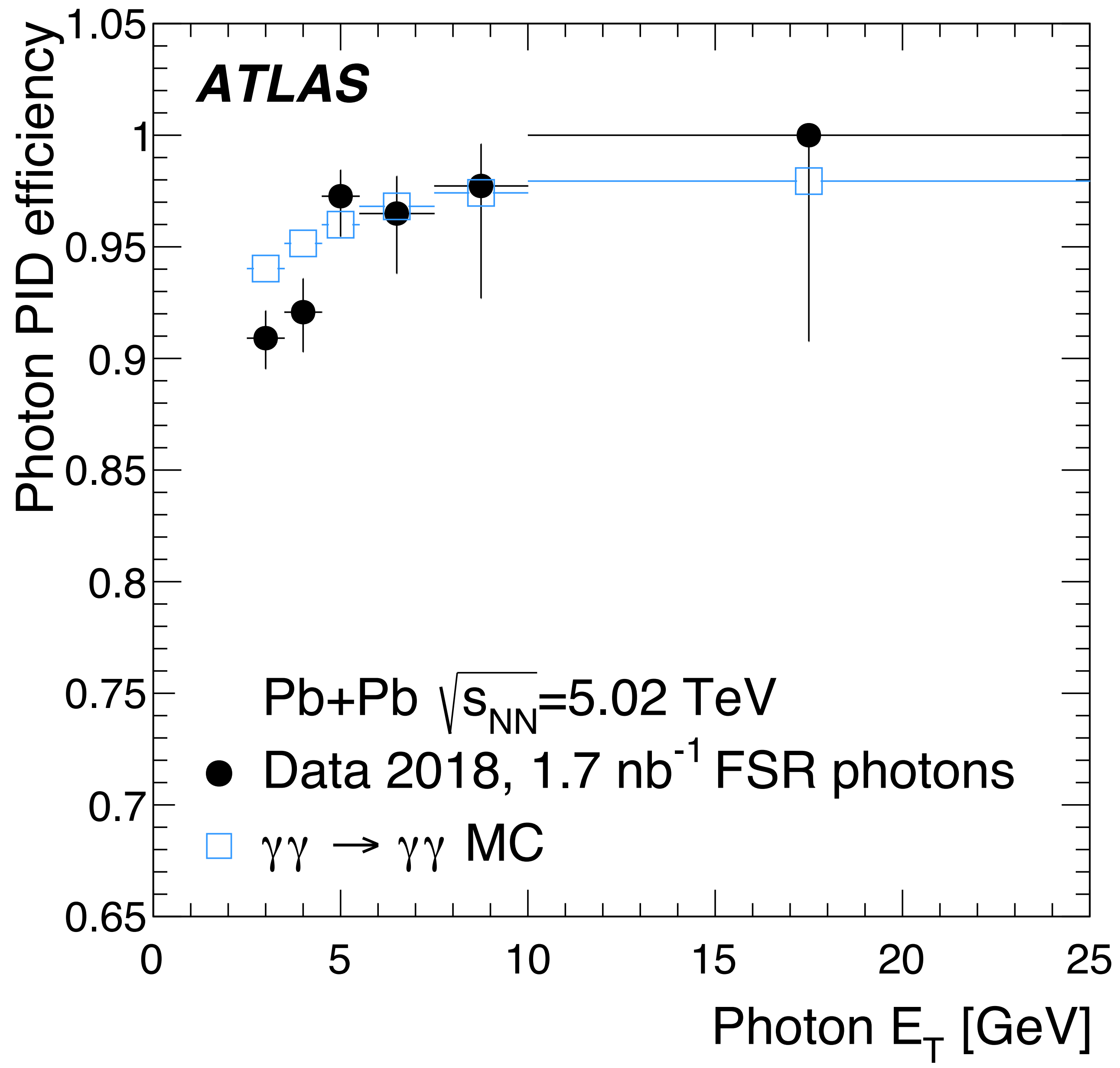
- Efficiency measurement:
  - Using $e^+e^-$ events where a hard bremsstrahlung photon was radiated
  - $ee\gamma$ final state selection:
    - Exactly 1 electron $p_T$ > 4 GeV && 1 additional track
    - Track $p_T$ < 1.5 GeV
      - Photon with $E_T$ > 2.5 GeV must be present in Event!

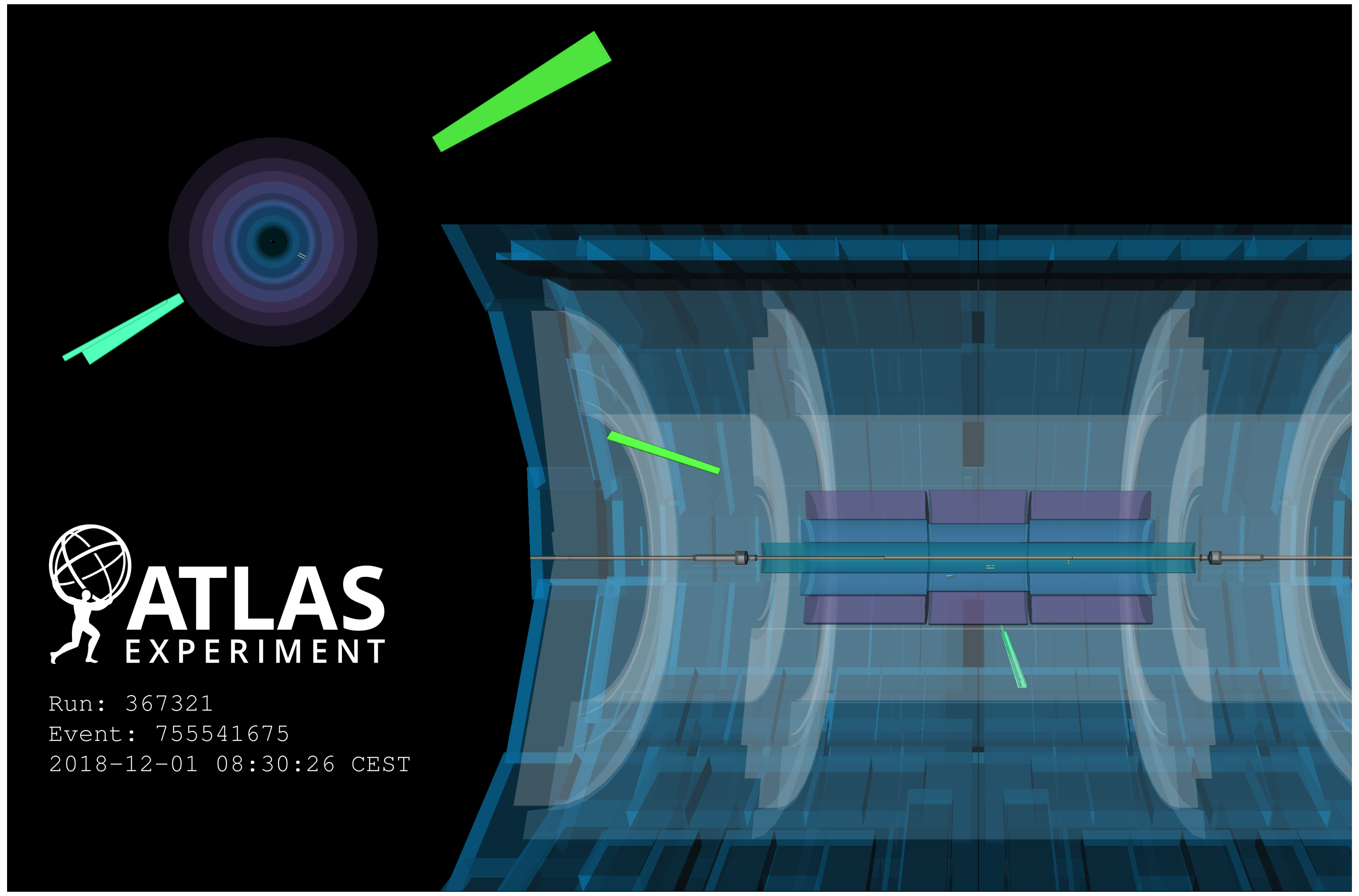


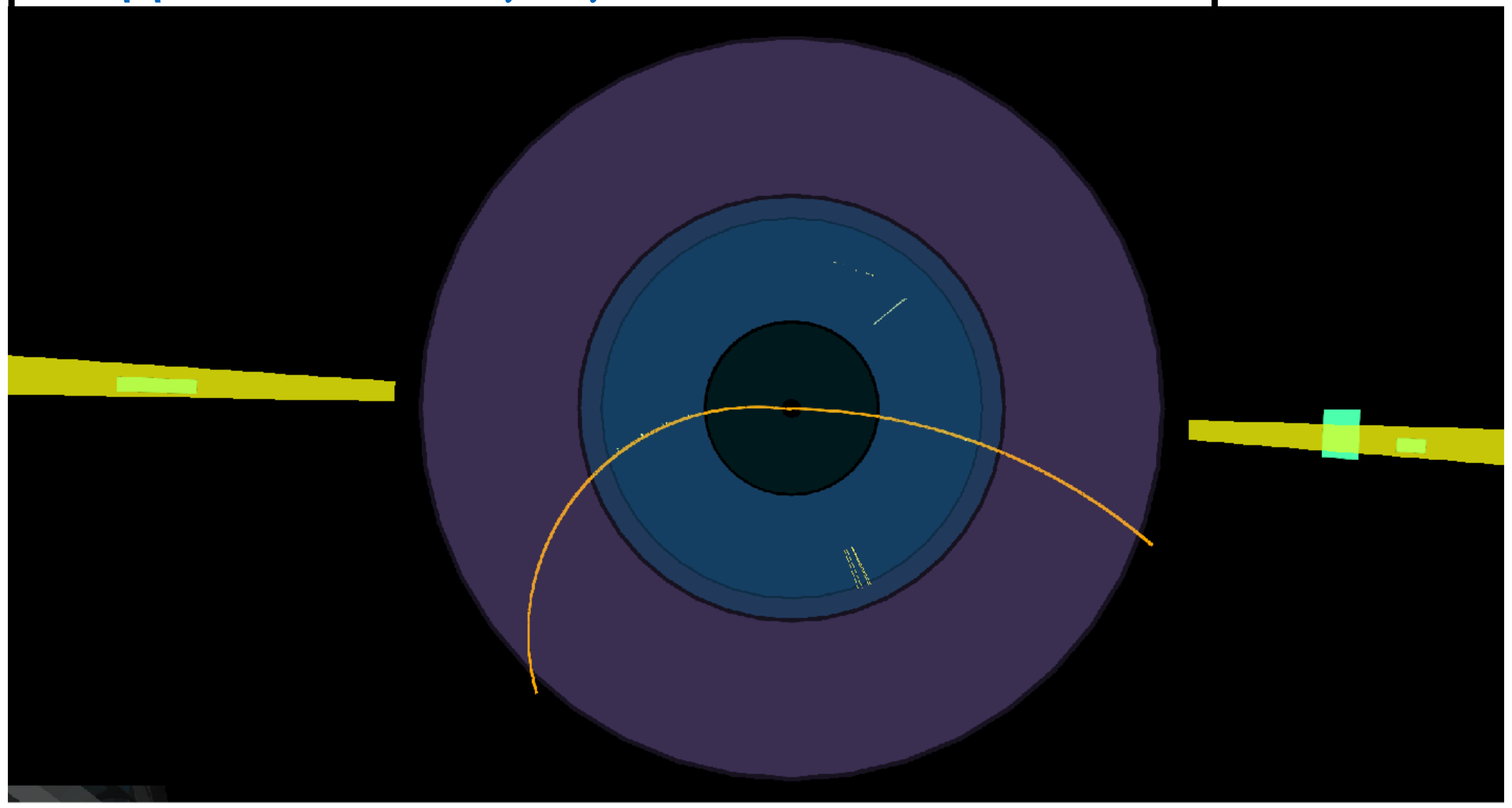

2018: arXiv:1904.03536

# Event Selection

- Detector must be in physics conditions
- 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?**

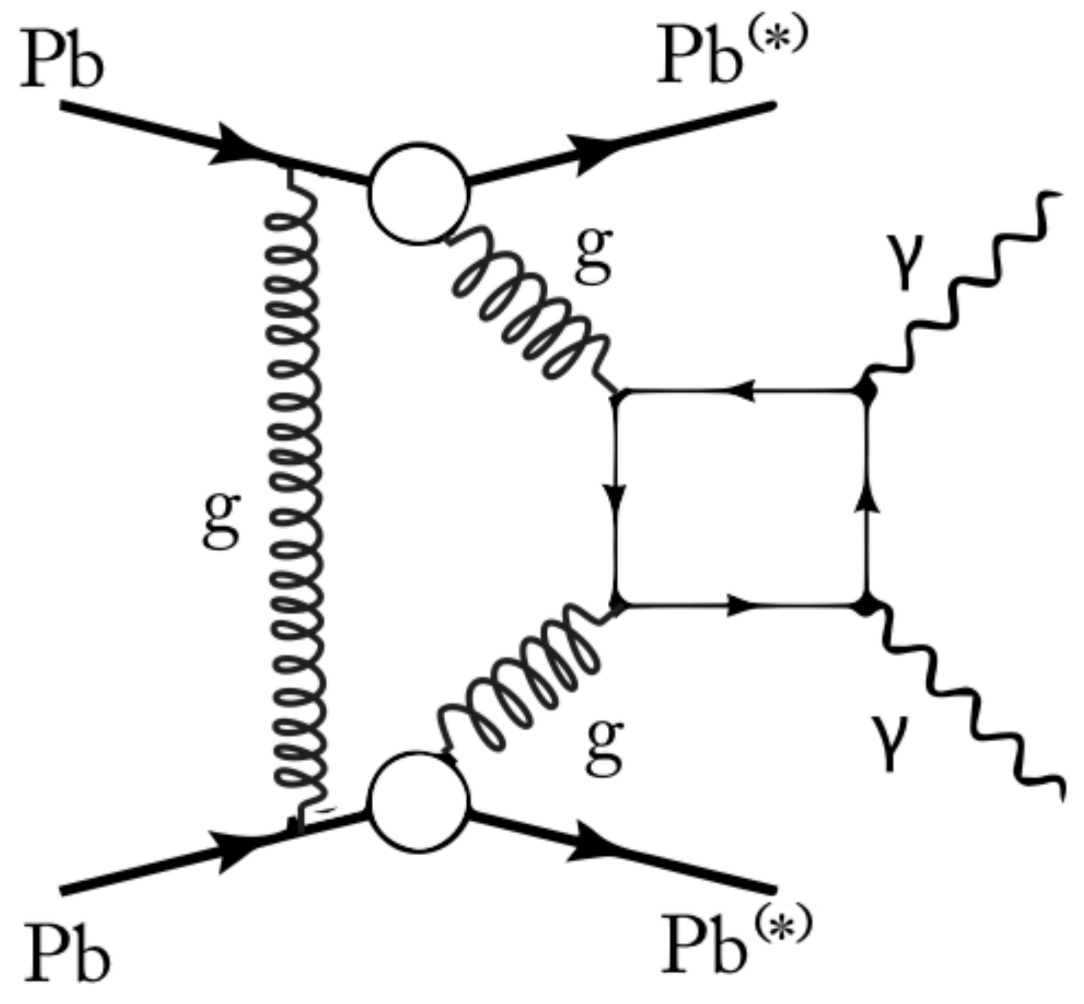
- Central Exclusive Production of 2 photons (**CEP**): gg → $\gamma\gamma$
  - Coloured initial state: significant intrinsic transverse momentum!
    - Broader shape of $A_\phi$ distribution
    - Control region defined to study CEP: aco > 0.01

- Shape of $A_\phi$ 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: 4 ± 1



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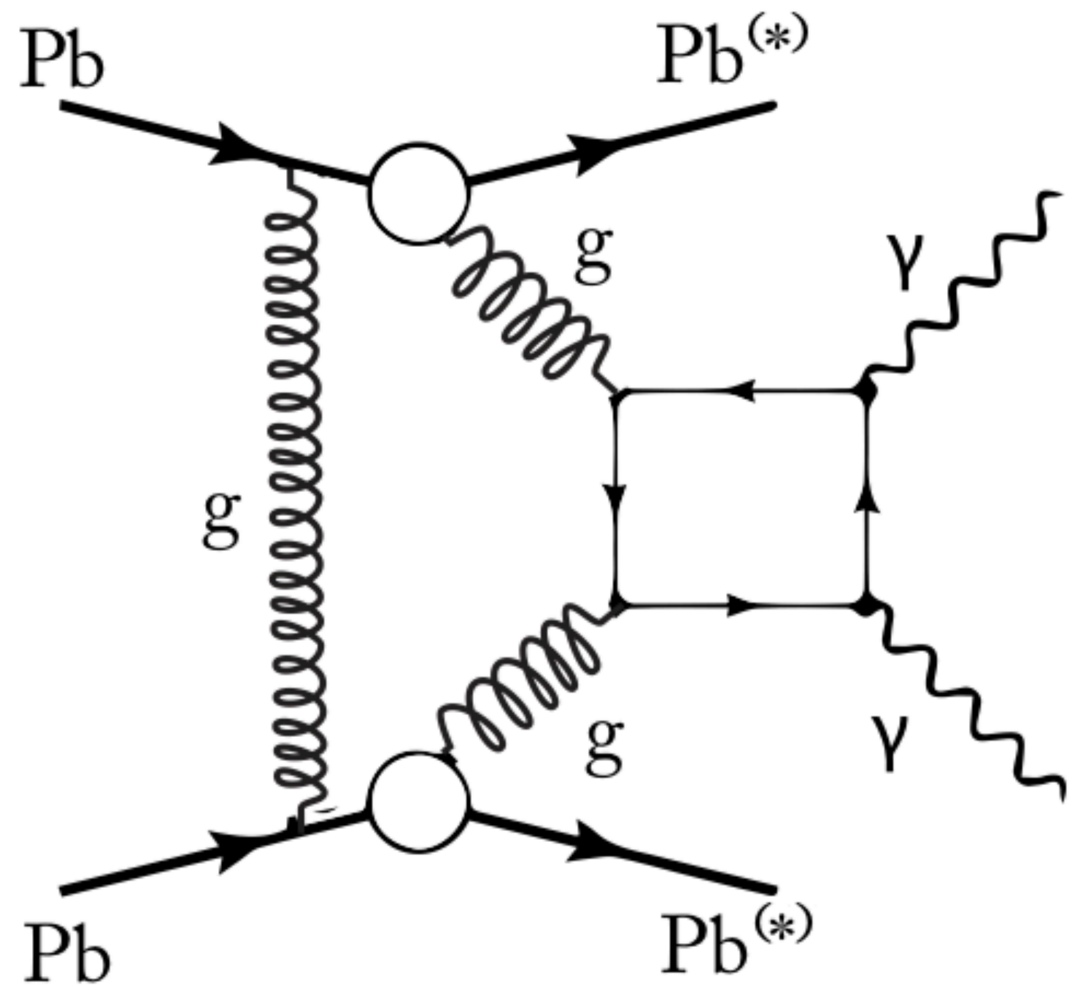
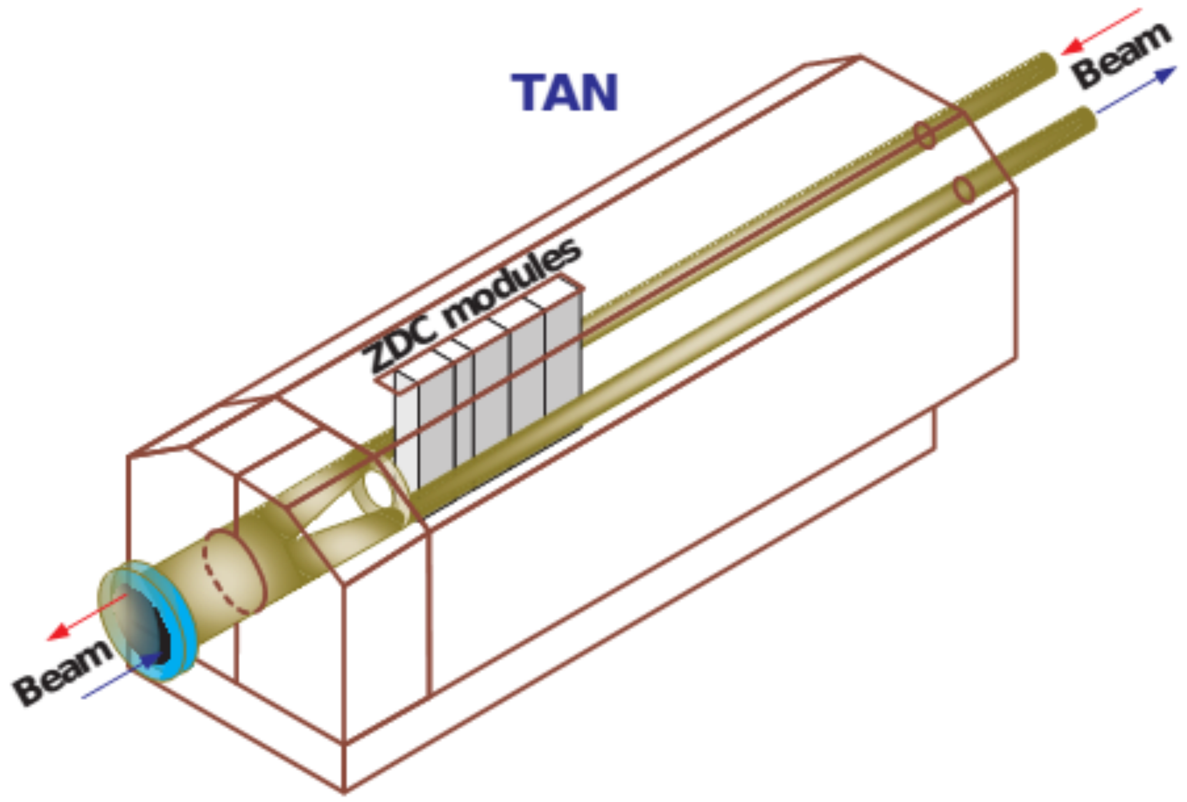



- Pb* dissociates, releasing neutrons detectable in the Zero Degree Calorimeter
  - Cross check of ZDC information for events in CEP control region:
    - Good agreement with expectations :)




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

# Background processes

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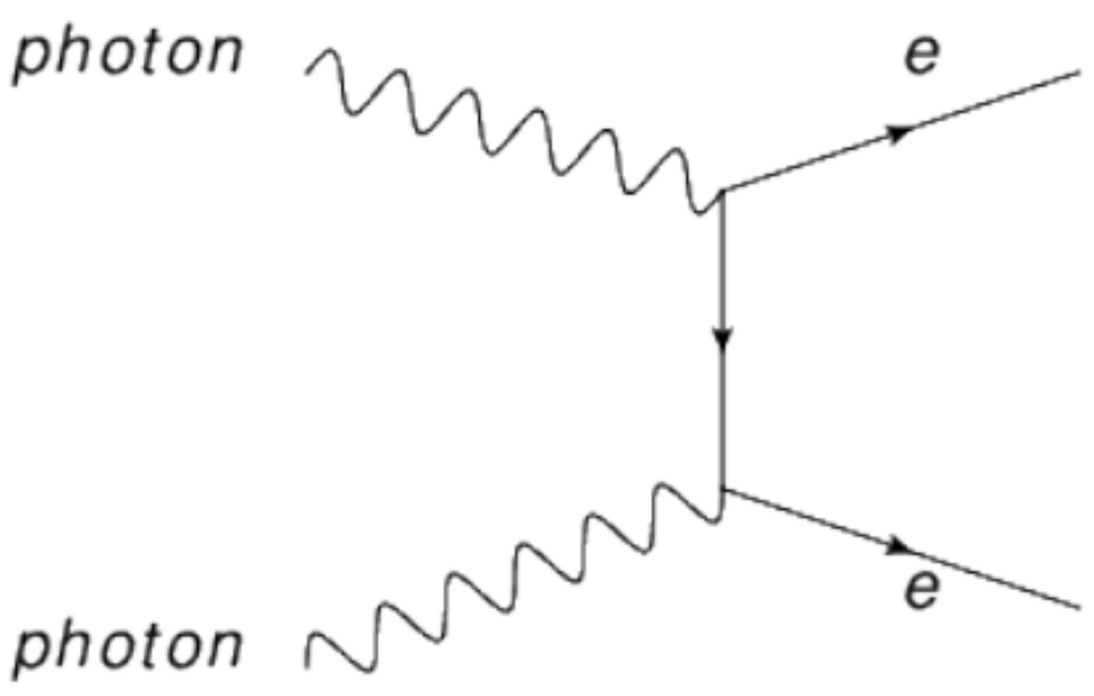
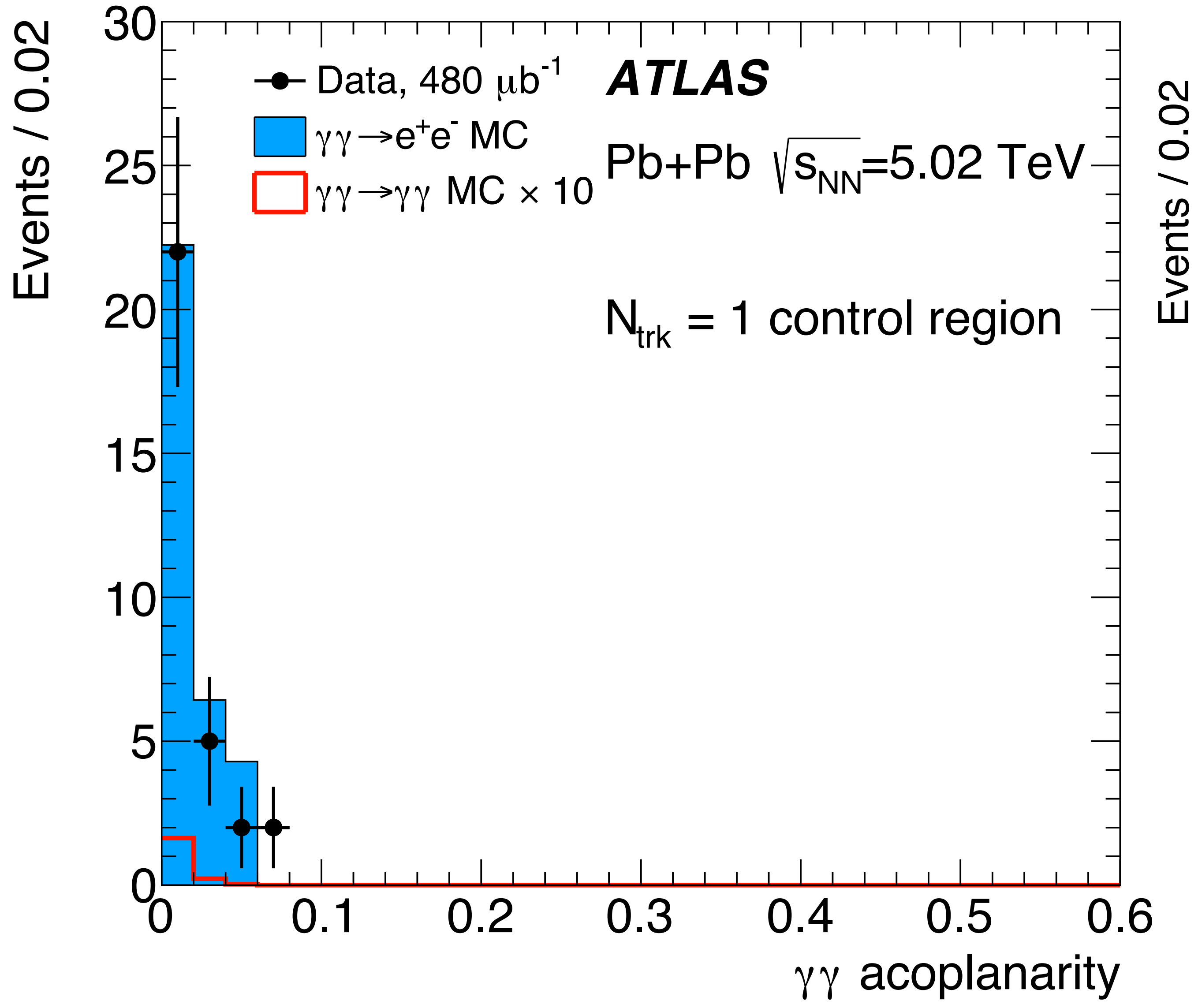
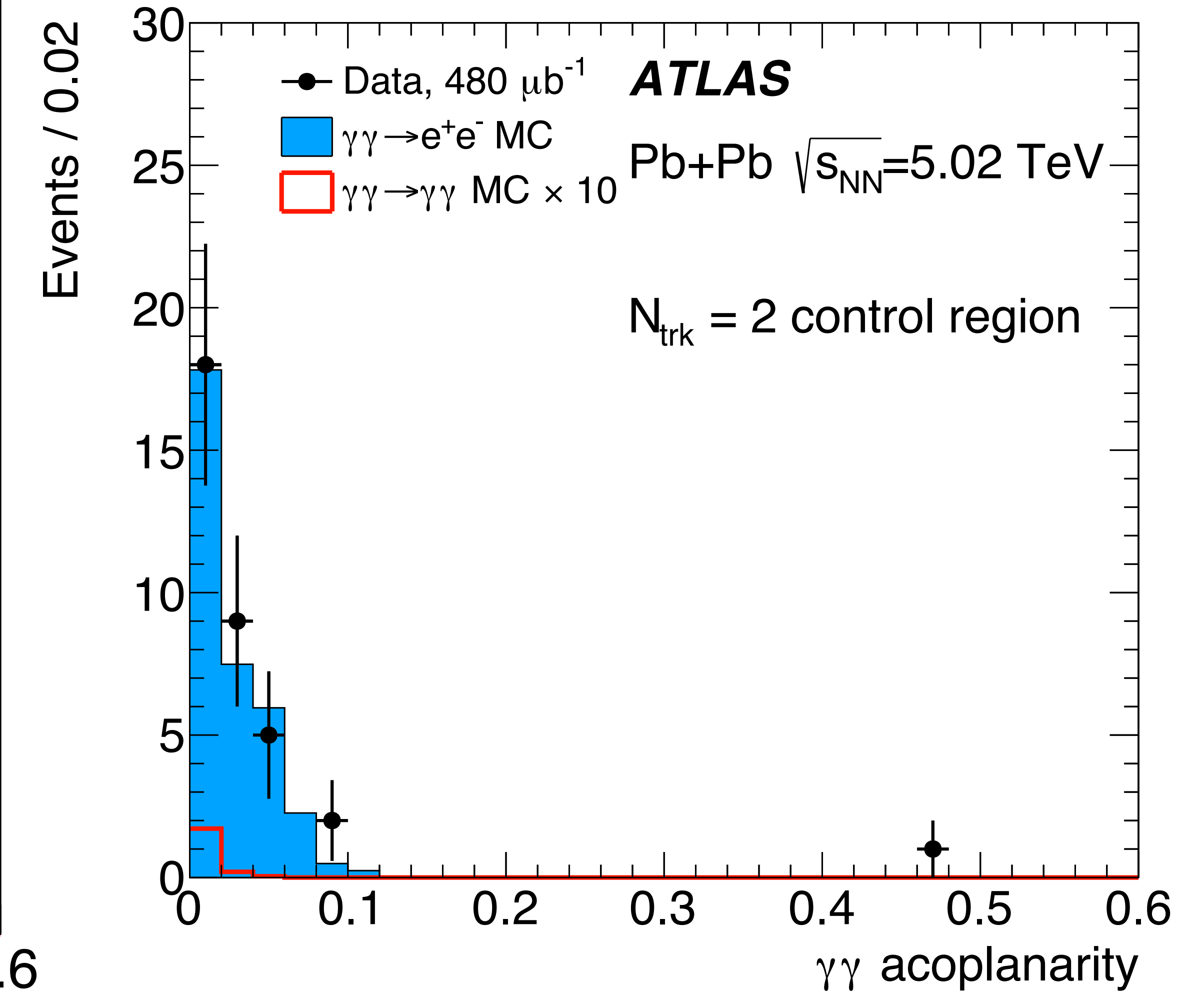



- Exclusive production of $e^+e^-$ electron pairs
  - Both electrons misidentified as photons
- Electrons bent in magnetic field
  - Broader $A_\phi$ distribution compared to signal
- Background rate estimated from data
  - 2 control regions:
    - Signal region + requiring 1 or 2 associated pixel tracks
    - Event yield from control regions extrapolated to signal region
      - using probability to miss pixel track if full track 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



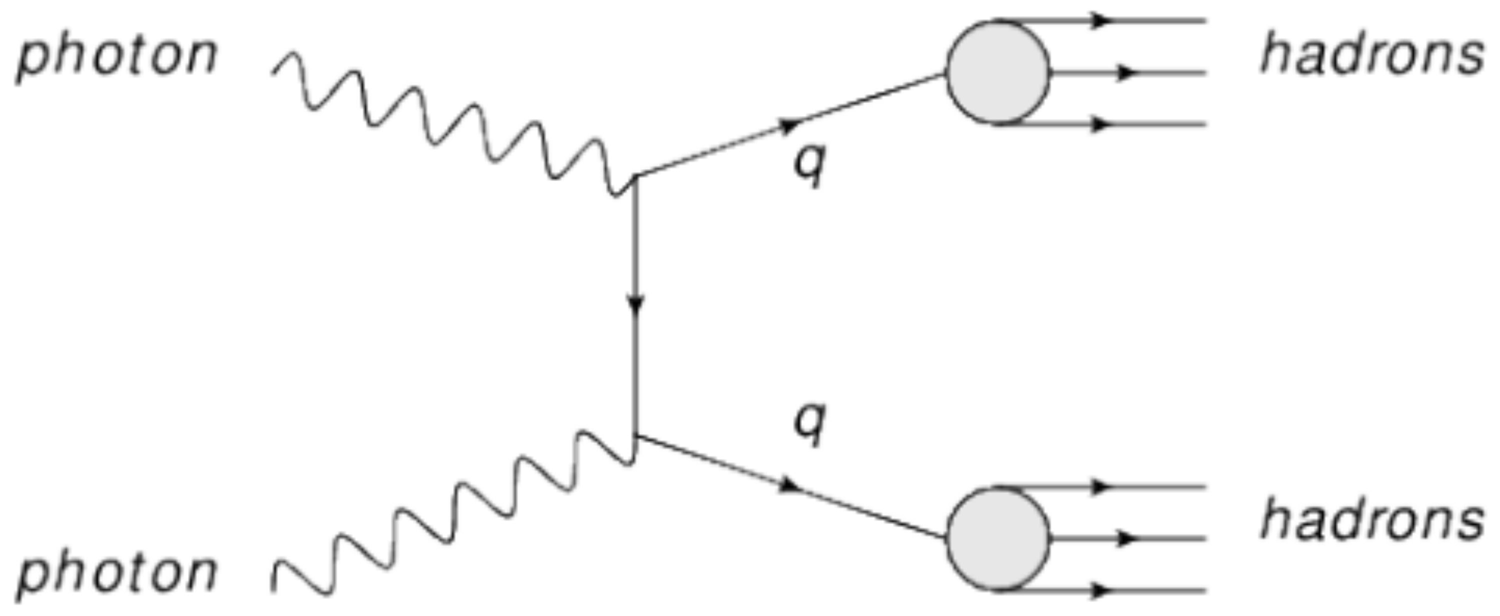



## Background processes

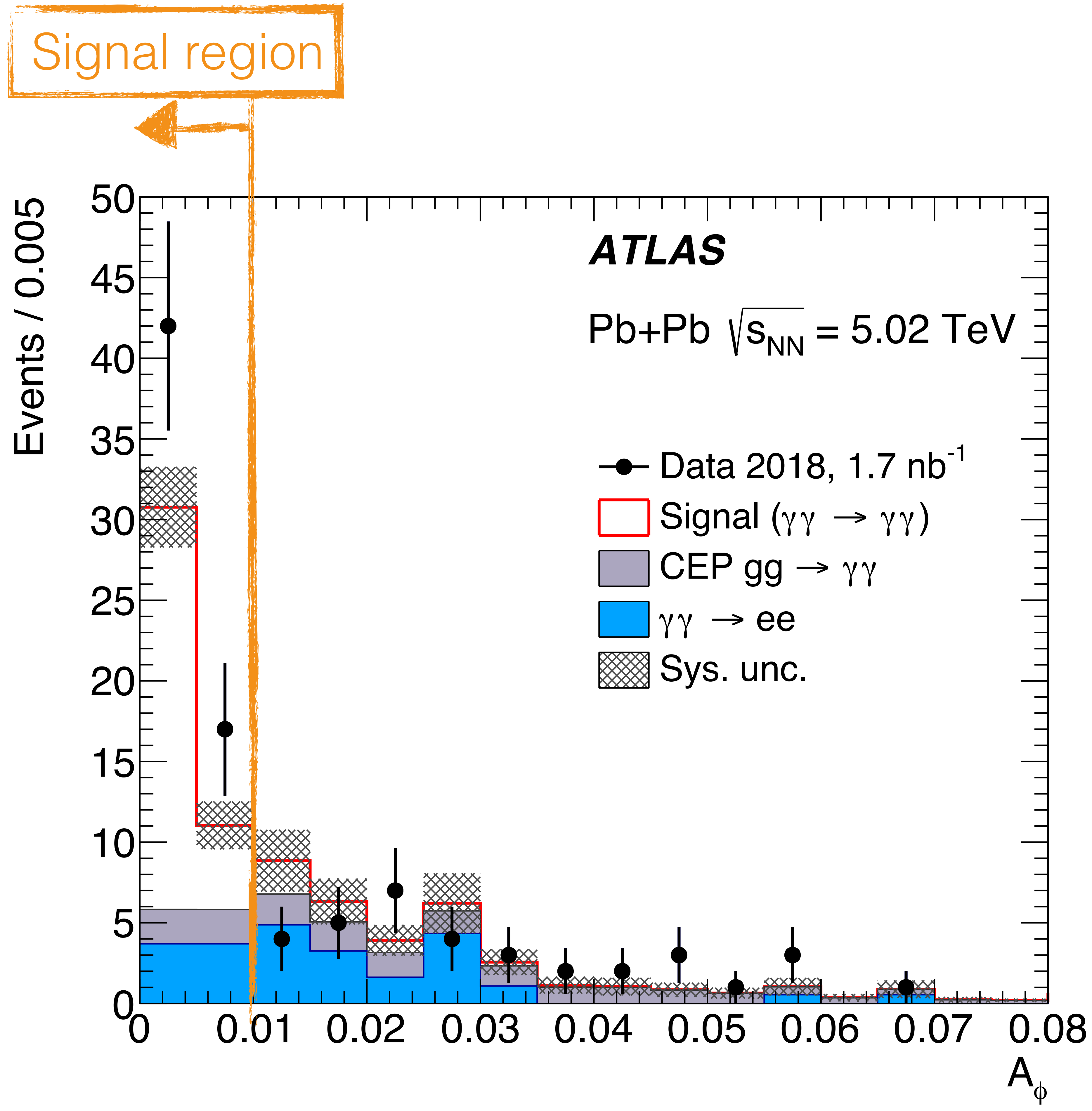
2018: arXiv:1904.03536

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

- 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 ~1pb)
  - Fake photons: Cosmic rays, calorimeter noise



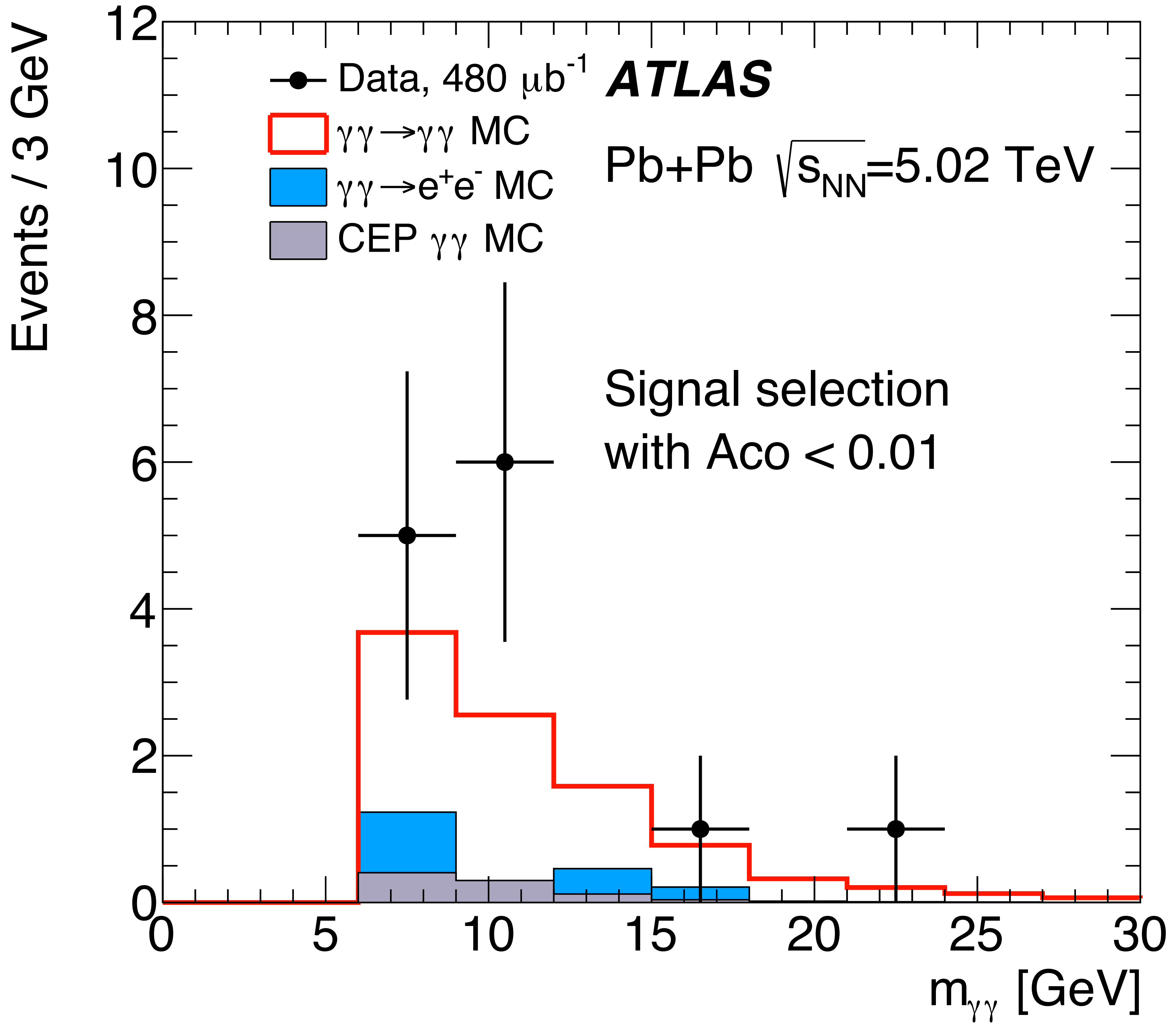

- **Total background + signal:**



- Very similar analysis, some optimisations missing
  - 480µb of PbPb data recorded in 2015
  - **First Evidence of Light-by-Light scattering** released in 2016 by ATLAS
    - Compatible result by CMS

2016: Nature Physics 13 (2017) 852

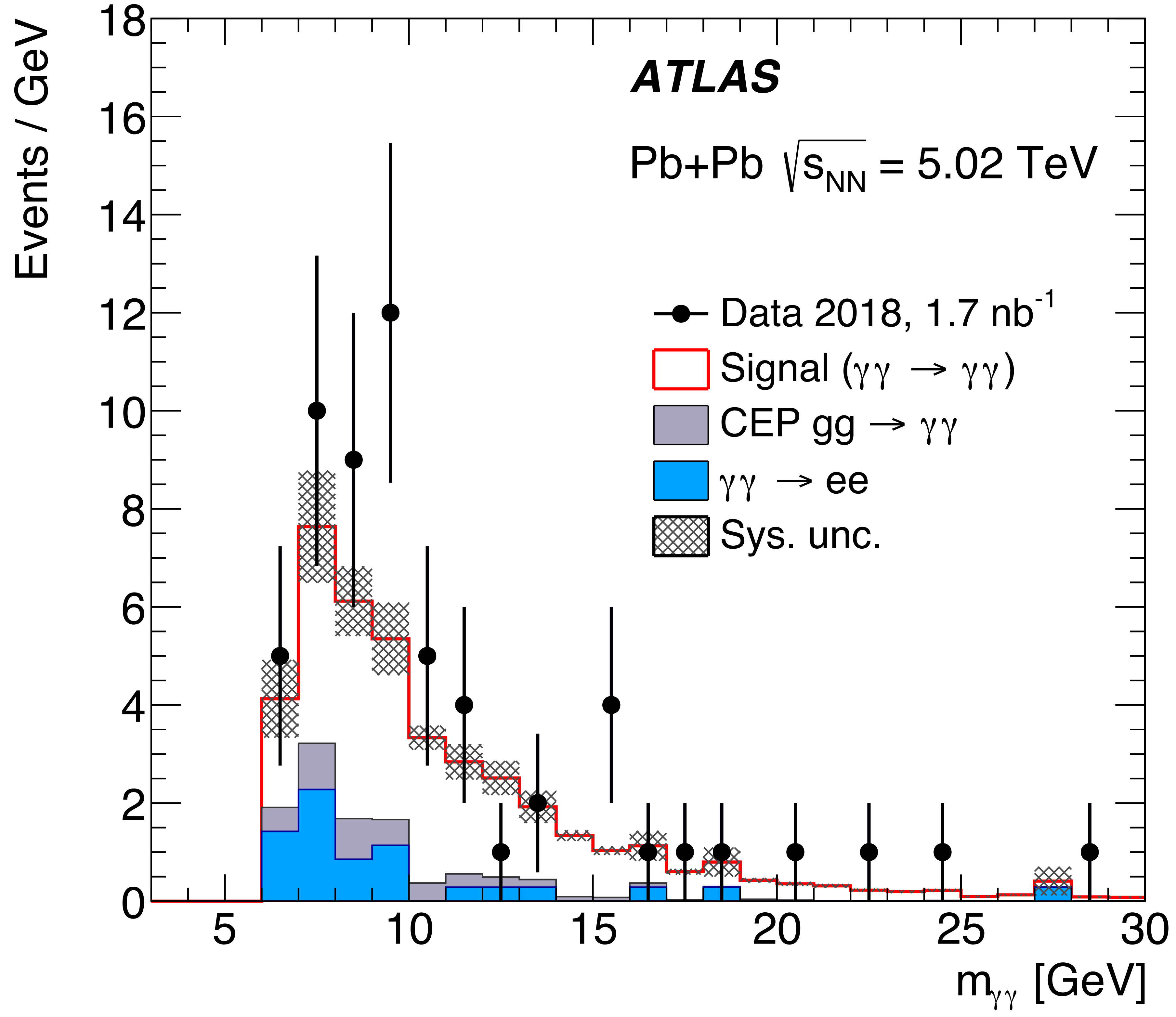
- **13 Events observed**, Background: 2.6 ± 0.7
- Cross section:
  - Measured: 70 ± 20 (stat) ± 17 (sys) nb
  - SM expectations: 49 ± 5 nb
- Significance: **4.4$\sigma$** (3.8$\sigma$ expected)



# Results on 2018 data

2018: arXiv:1904.03536

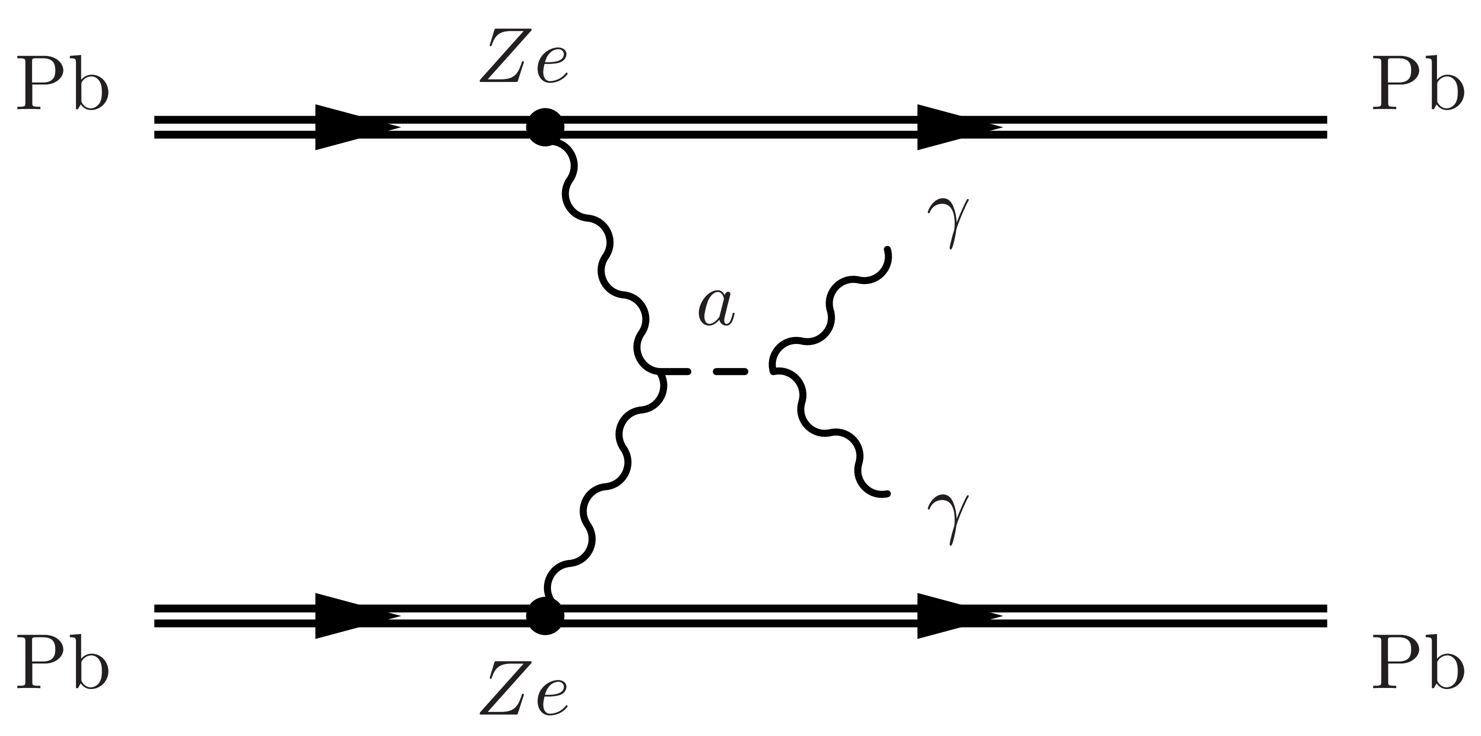
- 2018 Data: **1.7 nb$^{-1}$ of PbPb** data analysed
  - **59 Events observed**, Background: 12 ± 3
  - Cross section:
    - Measured: 78 ± 13 (stat) ± 8 (sys) nb
    - SM expectations: 49 ± 5 nb
  - **Significance: 8.2$\sigma$** (6.2$\sigma$ expected)



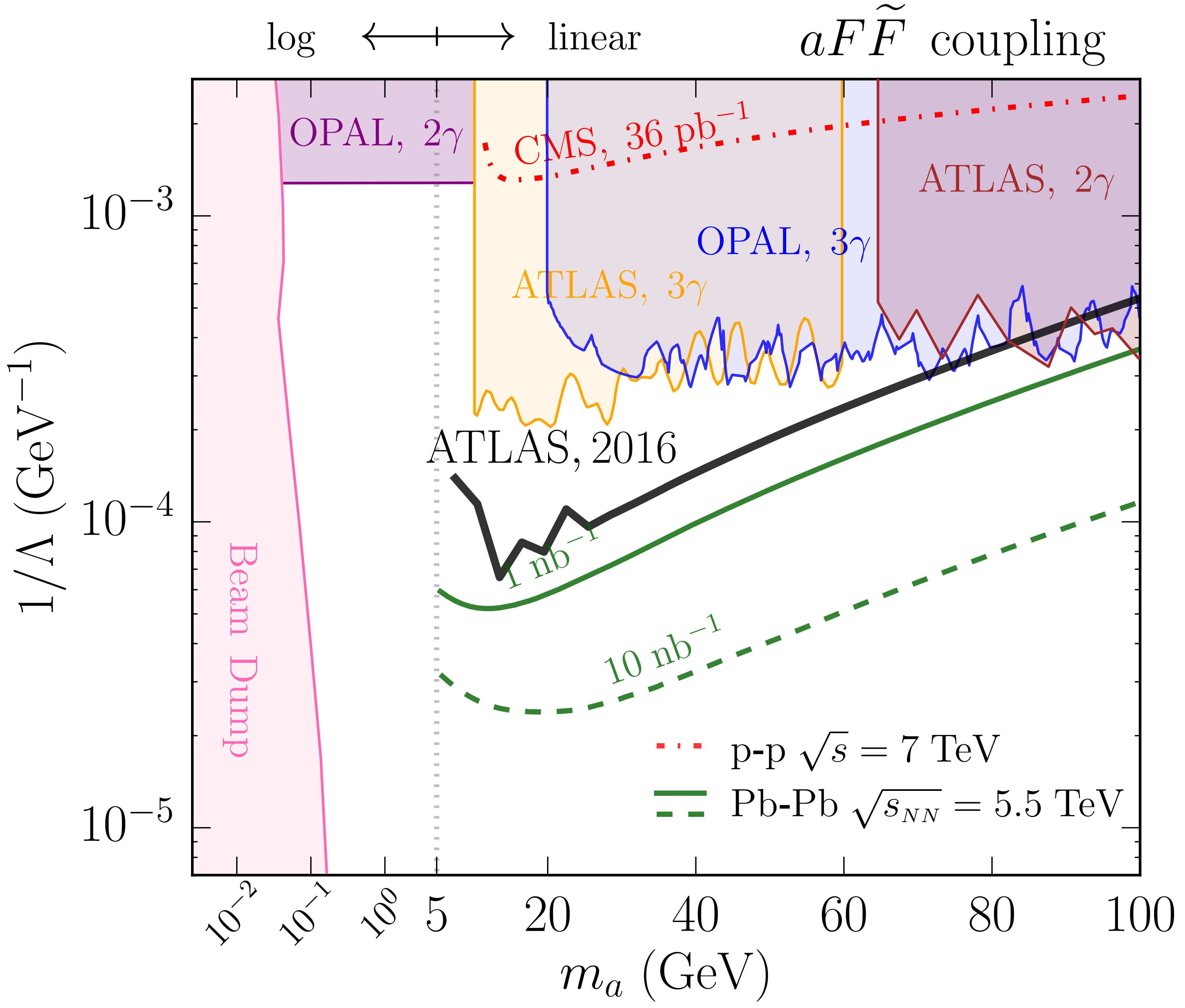

- Light-by-Light scattering of GeV photons observed
- Compatibility with prediction within 1.8 standard deviations

# Interpretation - Search for new Axion Like Particles

- Being interesting in it's own right, there's more to learn from this result:
  - Measurement can transformed into limit 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:

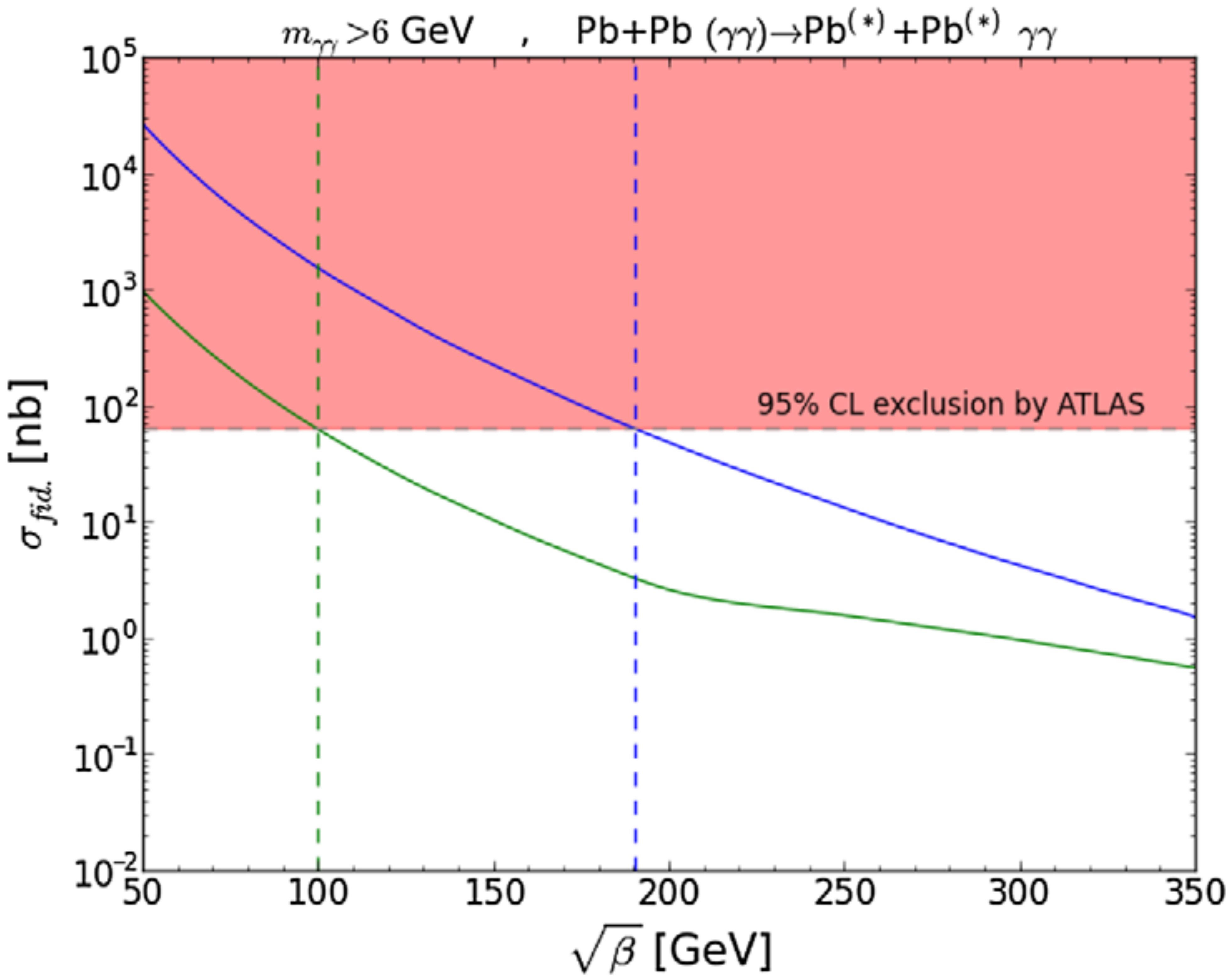
- Phenomenological work: arxiv:1607.06083,
- Latest CMS result: arXiv:1810.04602

- Being interesting in it’s own right, there’s more to learn from this result:
  - Measurement can 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)

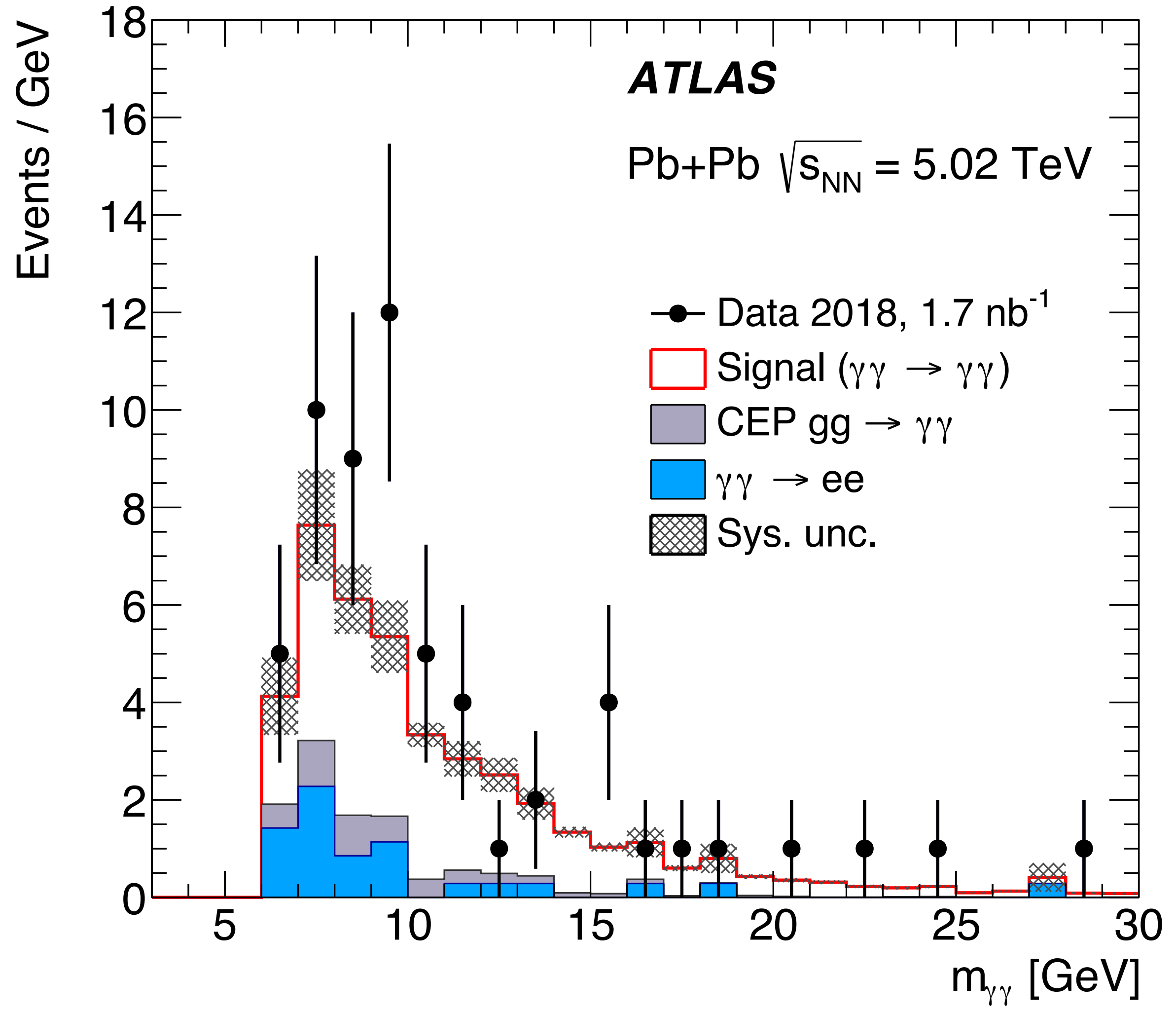


# Conclusions

2018: arXiv:1904.03536

- 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: $\sigma$ **= 78 ± 15 nb**
  - **Compatible with SM prediction**

- Useful to constrain several models beyond the standard model, e.g.
  - Axion like particles
  - Born-Infeld theory

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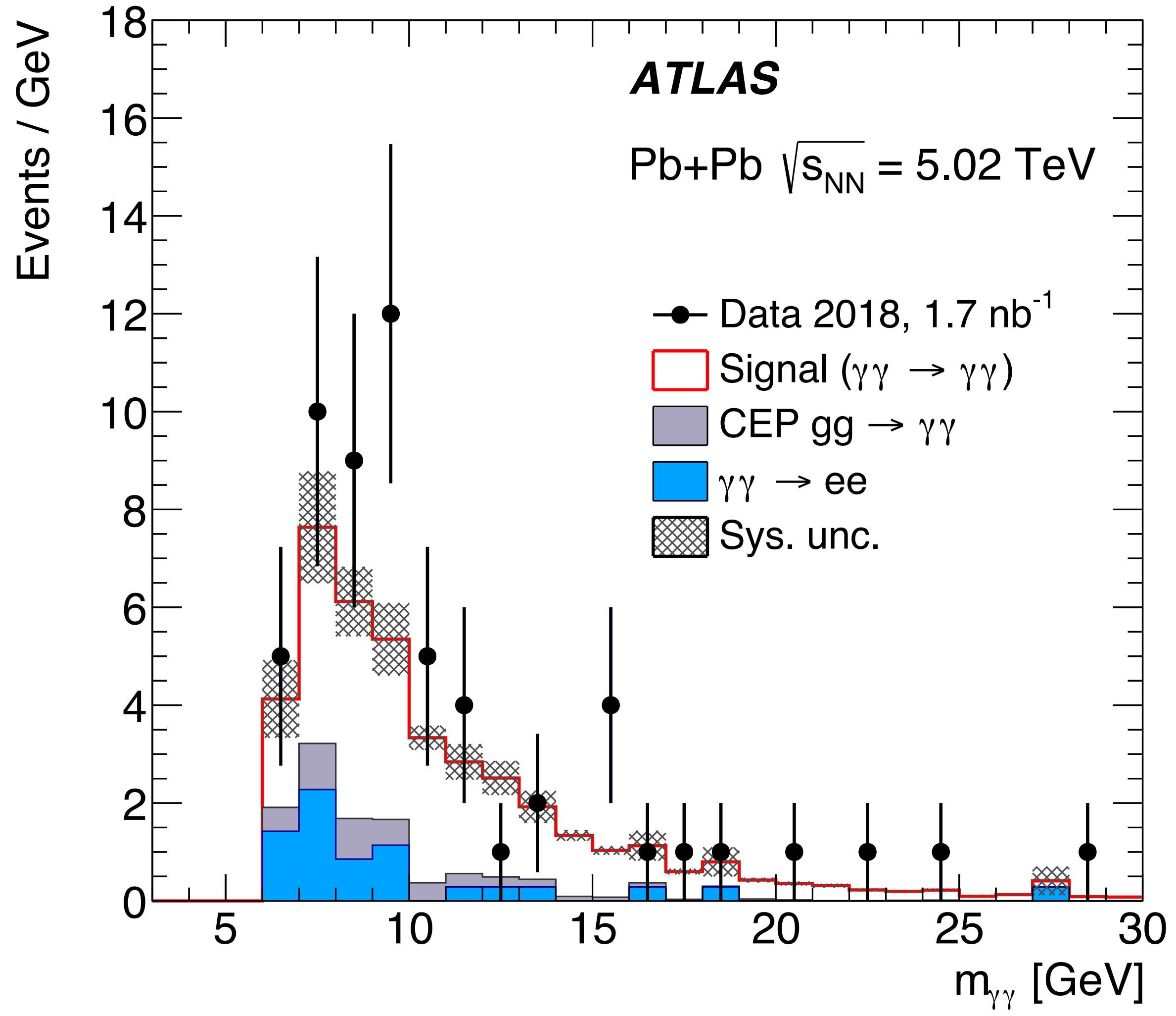
- First direct **observation of Light-by-Light scattering** at the **ATLAS** experiment
  - Hi collisions from the LHC used as photon collider
- **Challenging measurement**, very different from usual high energy analyses:
  - Low energy objects
  - Very little activity in detector
    - Difficult to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




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

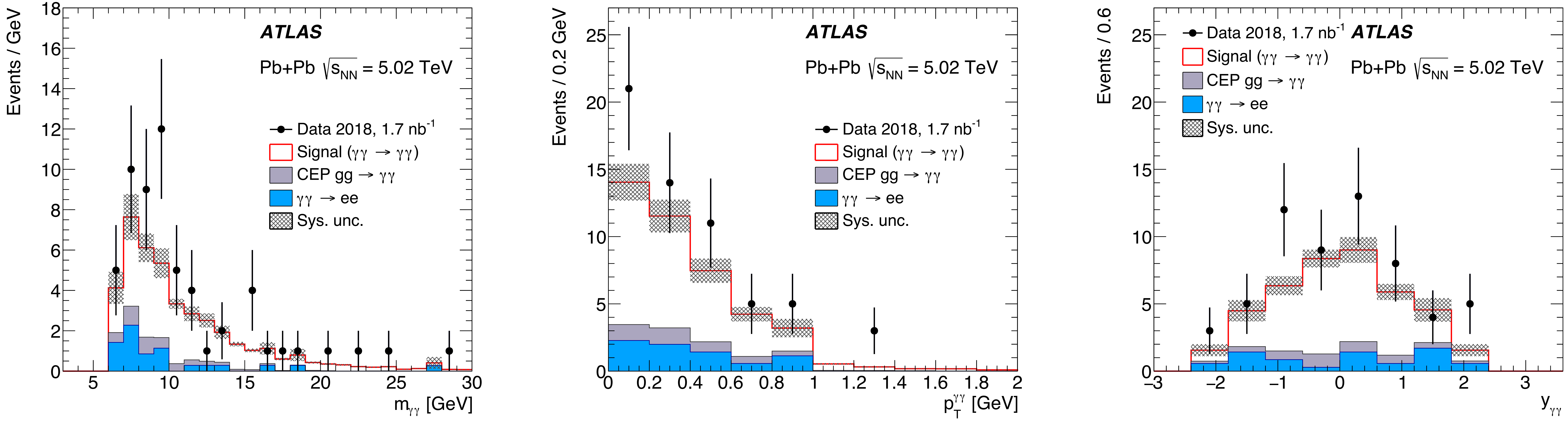
- Useful to constrain several models beyond the standard model, e.g.
  - Axion like particles
  - Born-Infeld theory

## What's left to do?

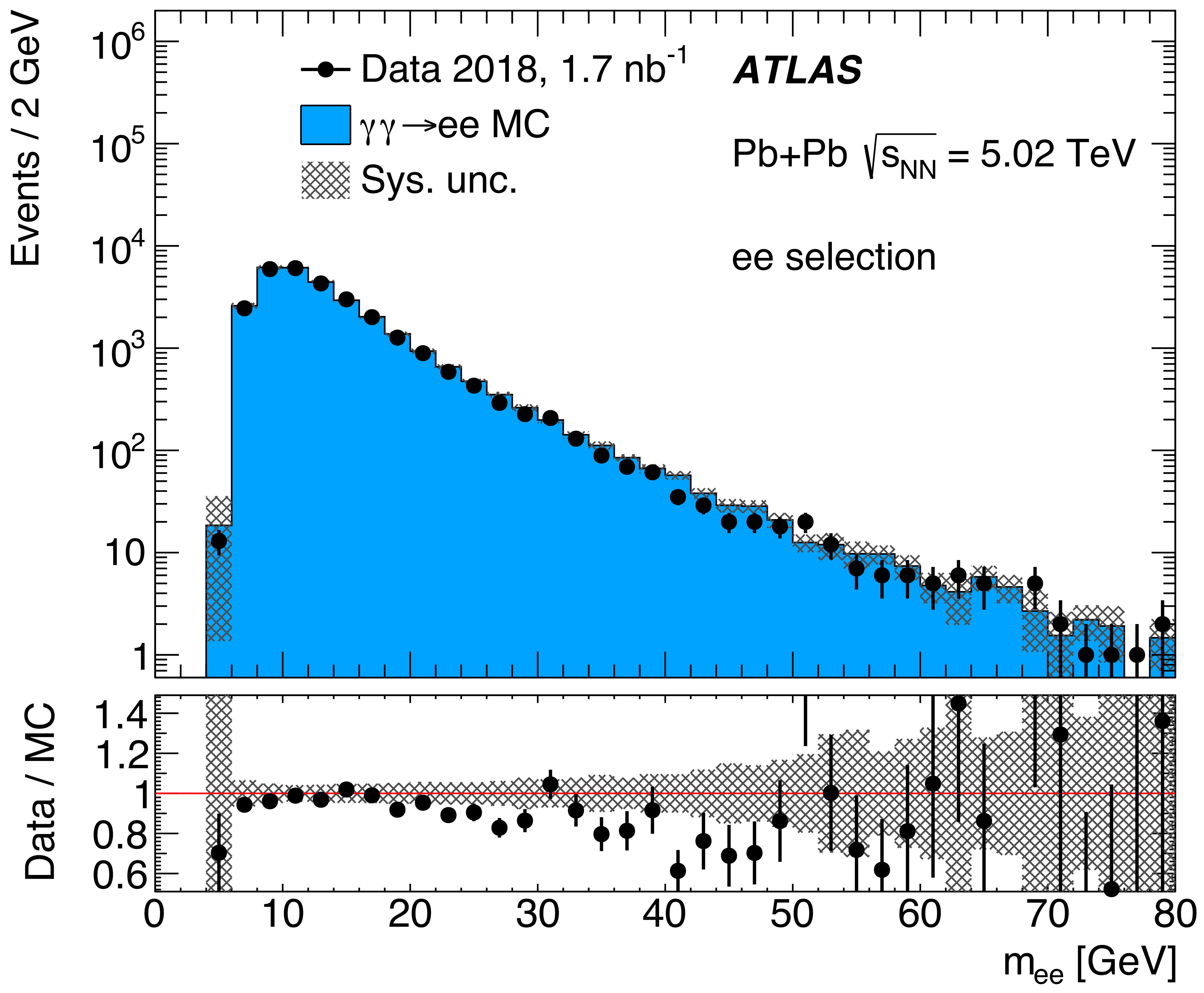
- Refined measurement of differential distributions
- Derivation of improved limits on some BSM models
- Interpretations in the framework of effective couplings

# BACKUP

2018: arXiv:1904.03536

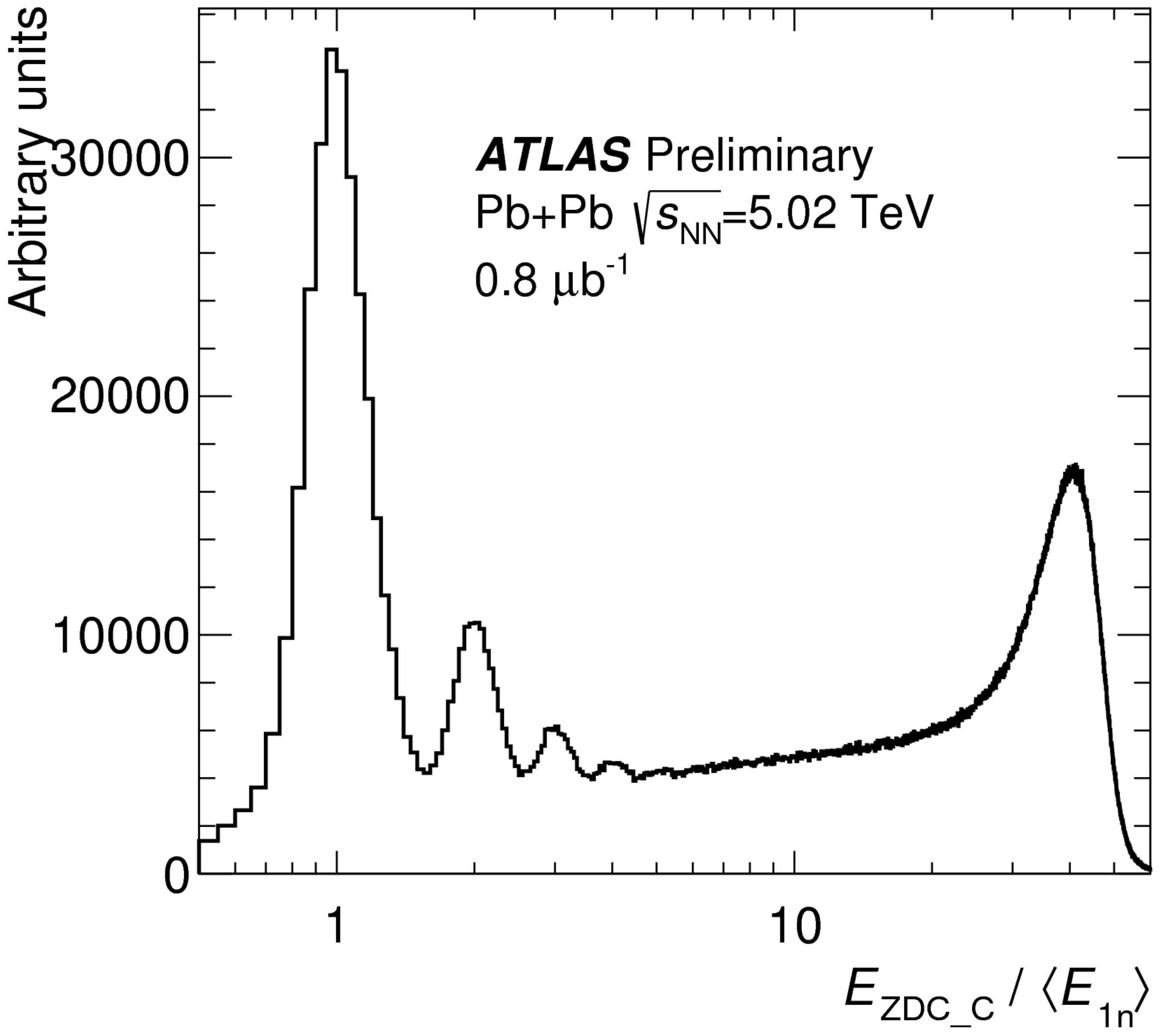


# Electron studies

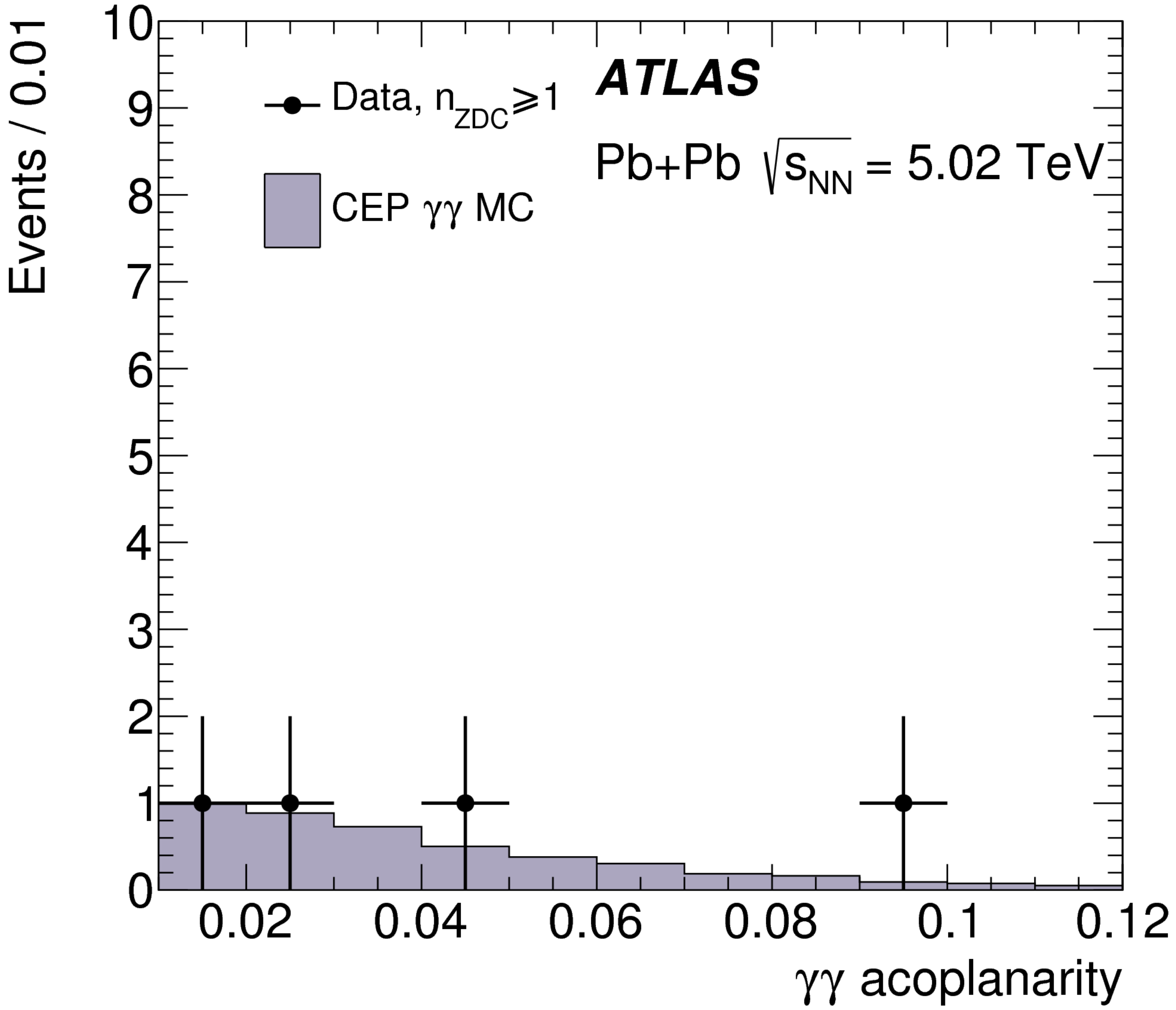


# ZDC cross check on CEP background

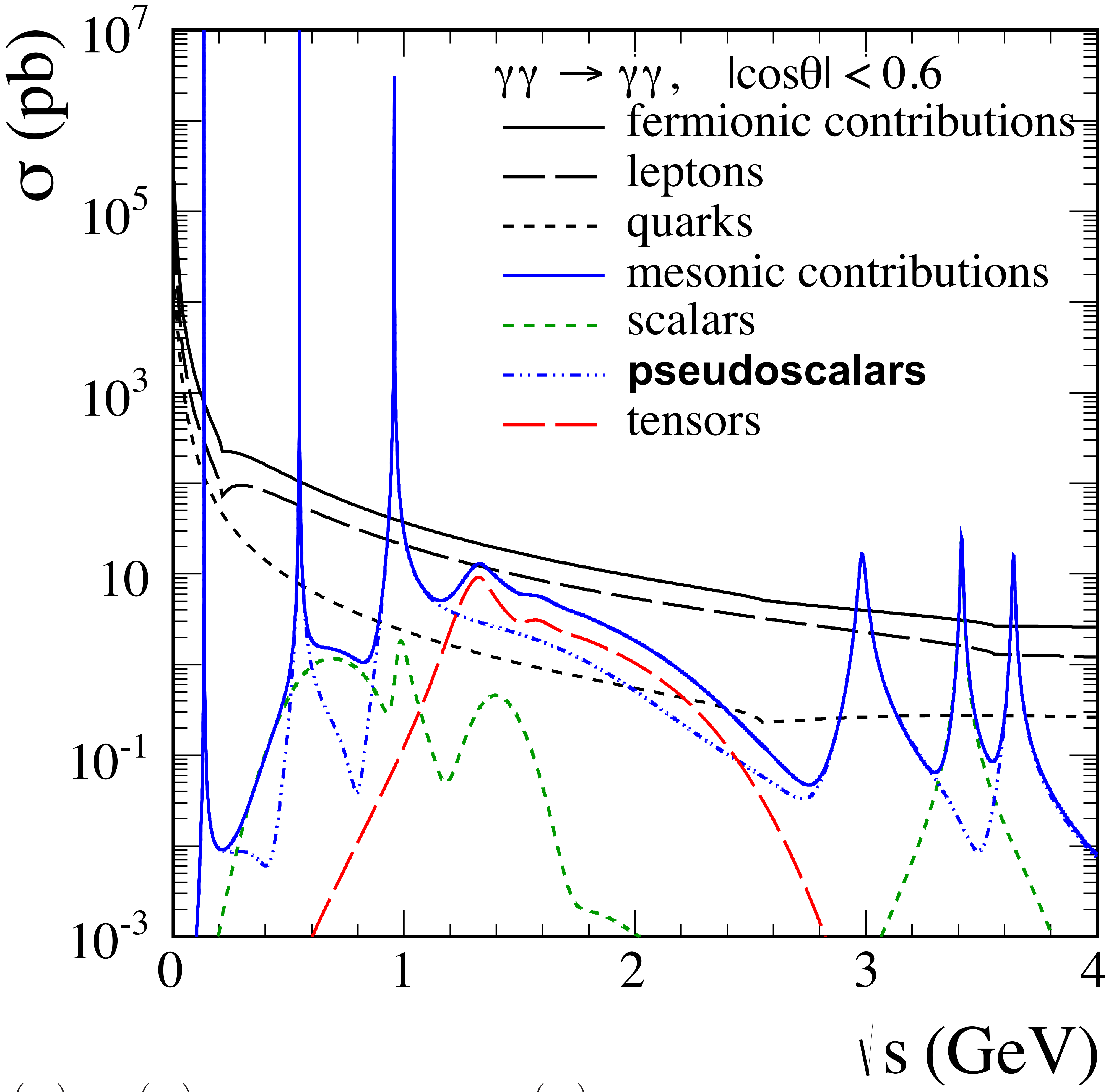
- CEP control region: $A_\phi > 0.01$
  - Additionally require energy deposit in ZDC corresponding to at least 1 neutron
- Simulation normalised from control region compatible with data
  - But very limited statistics
- ZDC energy deposits
  - Single neutron peaks clearly visible

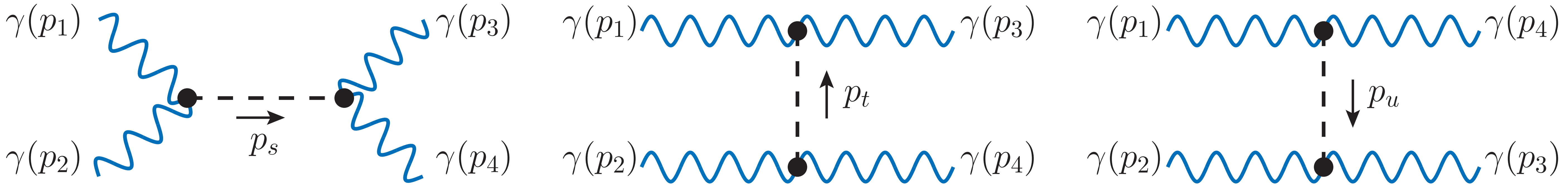



- 2015 data set



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



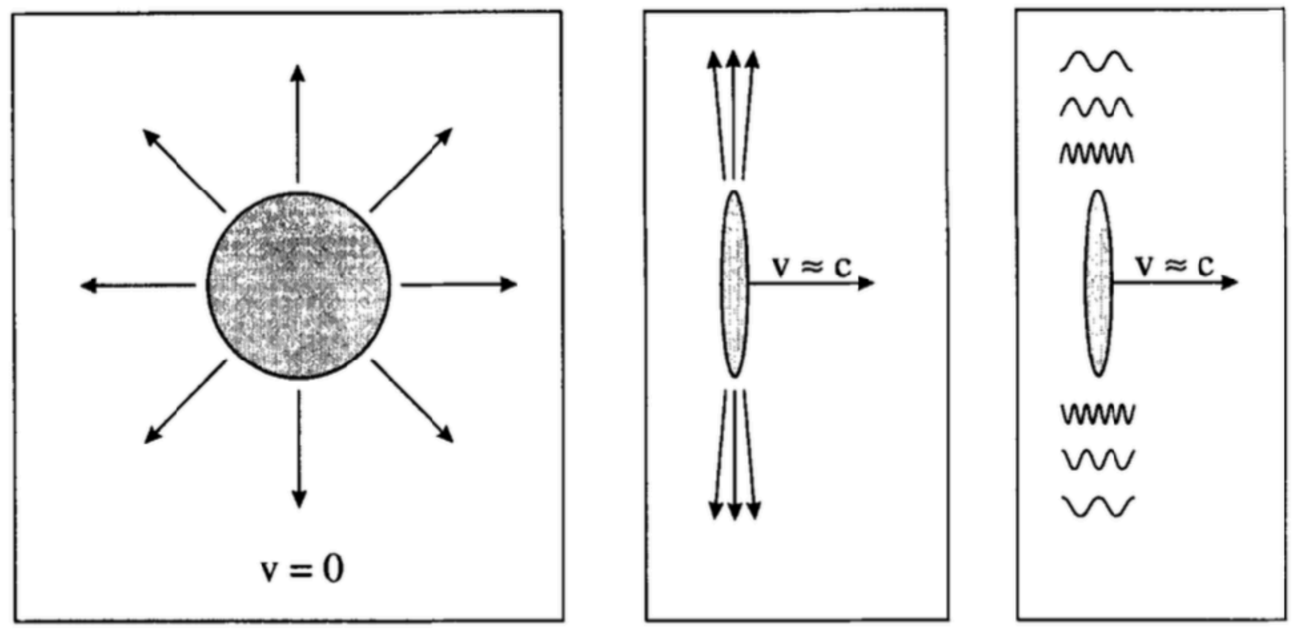



# Ultra Peripheral Heavy Ion Collisions - LHC as photon collider

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

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

- Maximum photons energy:
  - $E_{max} <= \gamma/R \sim 80$ GeV
    - Lorentz factor $\gamma$ up to 2800 @ LHC




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

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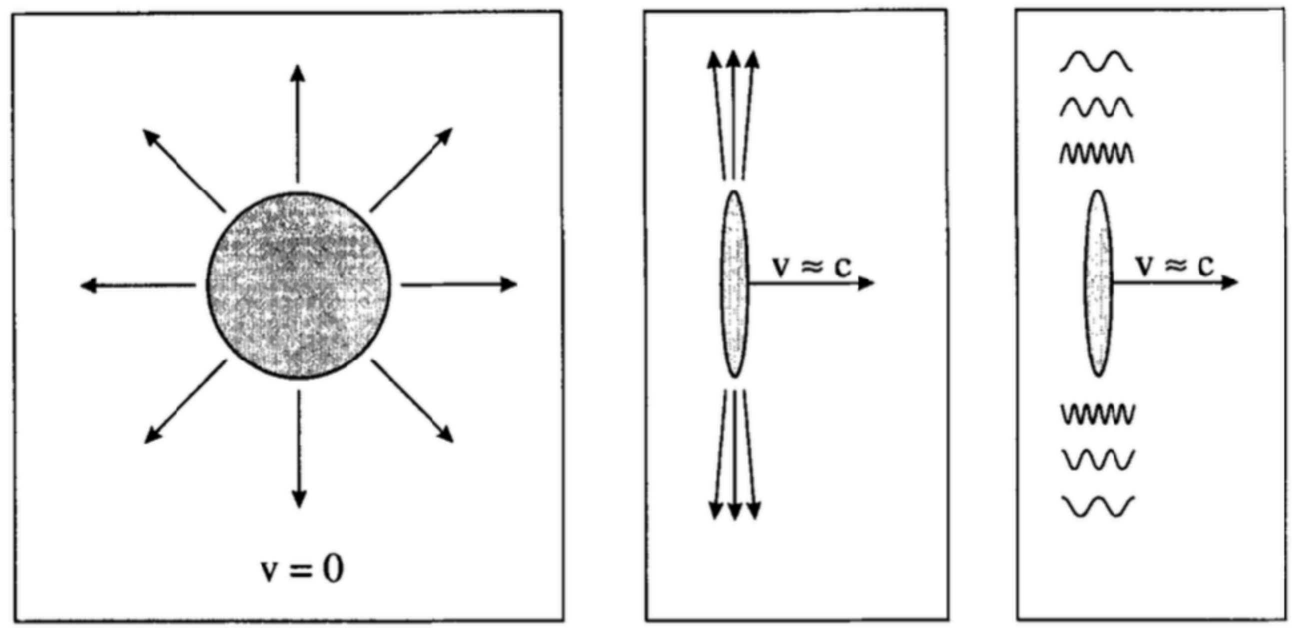
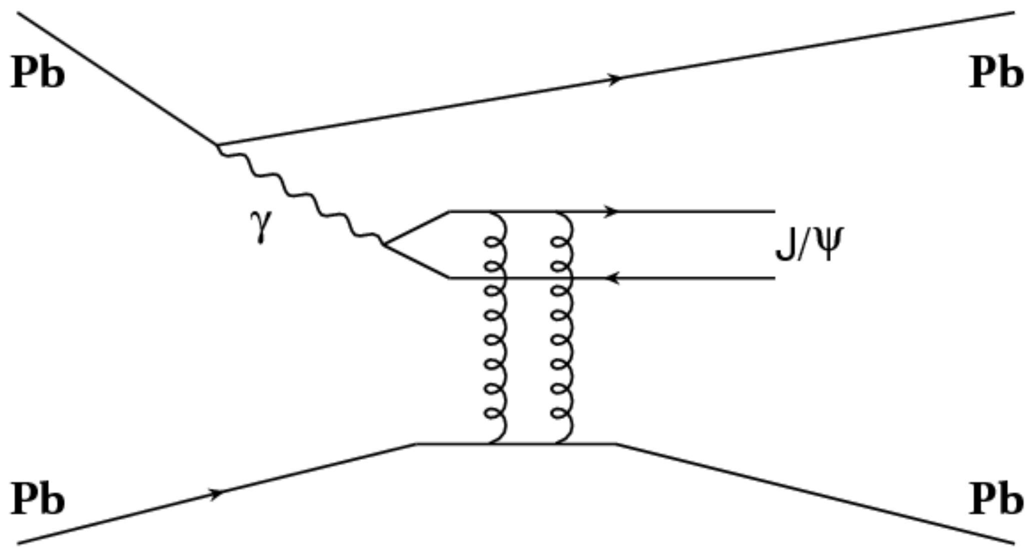
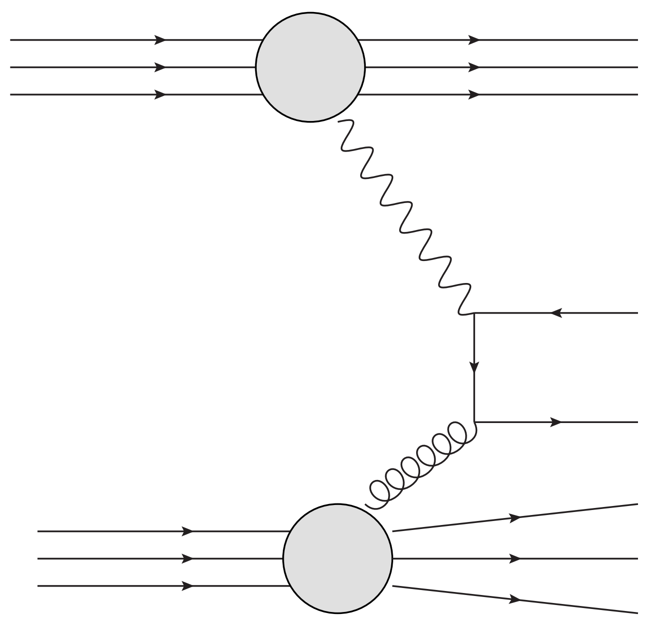
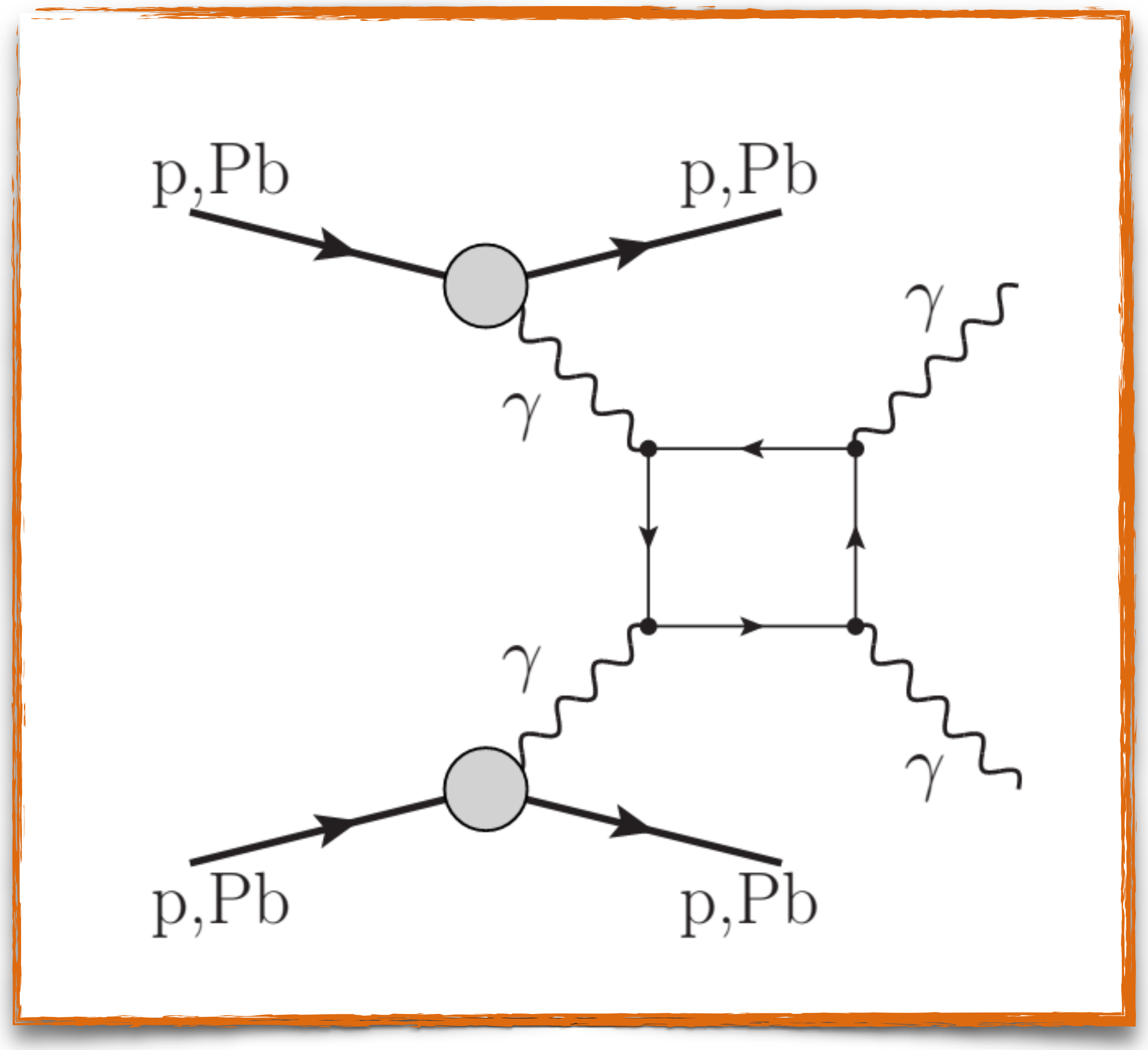



[Fermi, Nuovo Cim. 2 (1925) 143]






- Various types of photon interactions possible
  - Photon-Pomeron: e.g. exclusive J/Phi production
  - Photons - Gluon: photo production of jets
  - Photon - Photon: Light - by - Light scattering