Evidence for Light-by-Light scattering and searches for Axion-Like-Particles from ultra-peripheral PbPb collisions at 5 TeV

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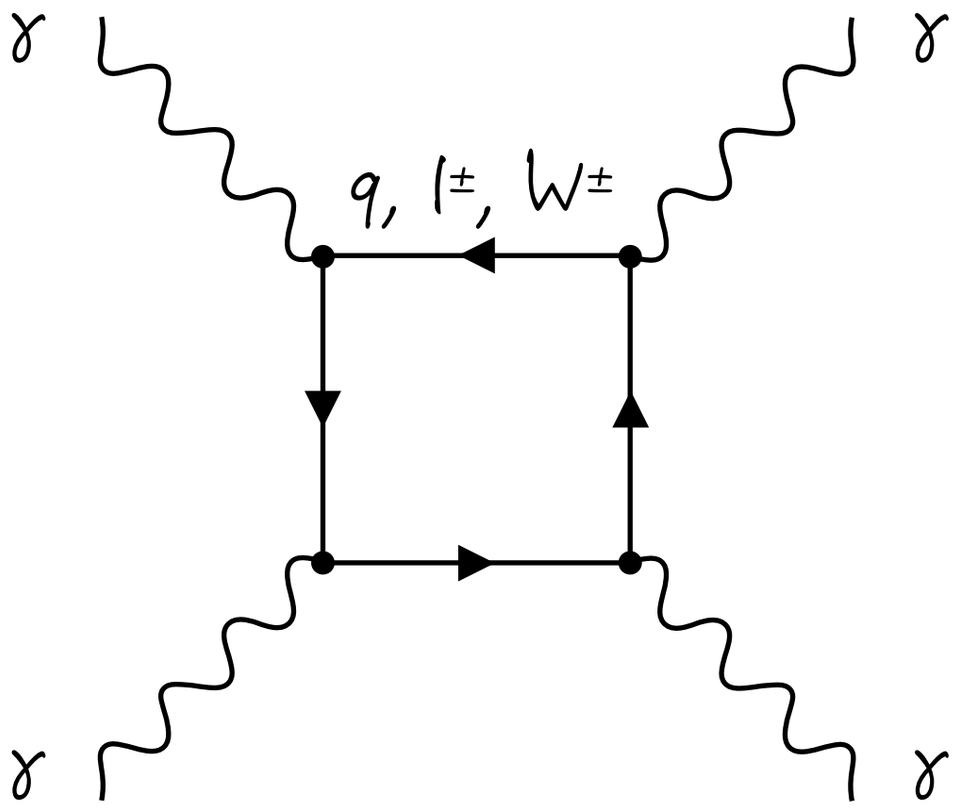
for the CMS Collaboration

PAS: cds.cern.ch/record/2319158

Introduction

- **Elastic photon-photon scattering** is a fundamental quantum-mechanical process.
  So far, it remains unobserved…
- the loop could also contain new charged particles (**SUSY**) or new spin-even resonances (**axions**, **monopoles**).



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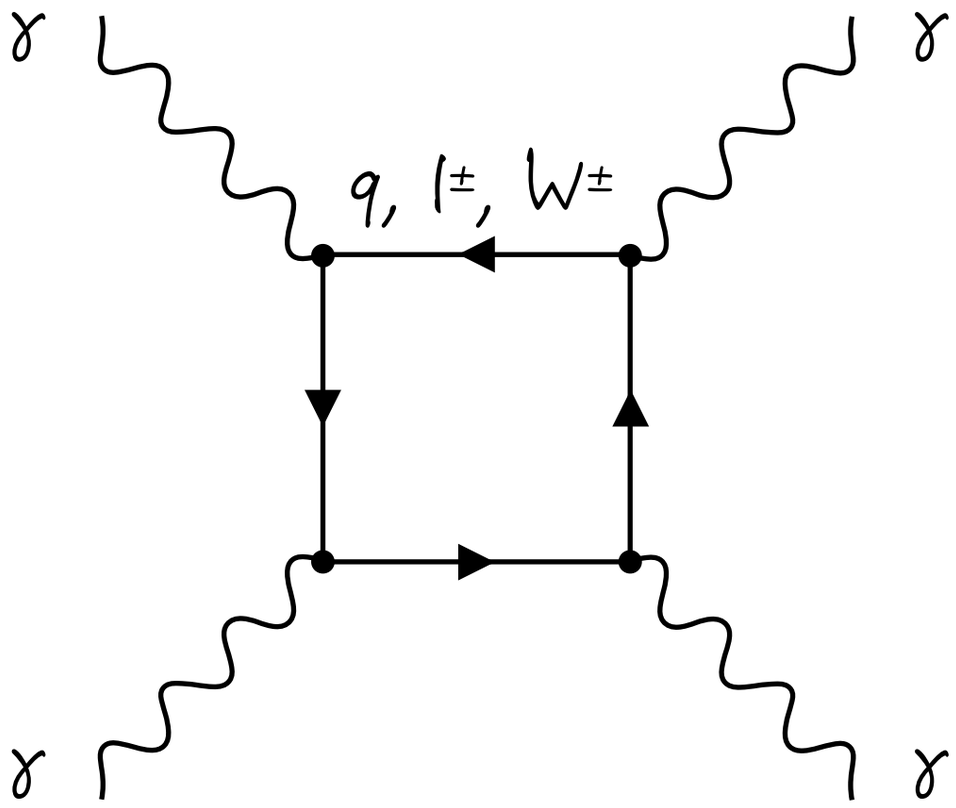

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  Delbrück scattering (γ deflection in the nucleus field),
- the difficulty to observe this process comes from a
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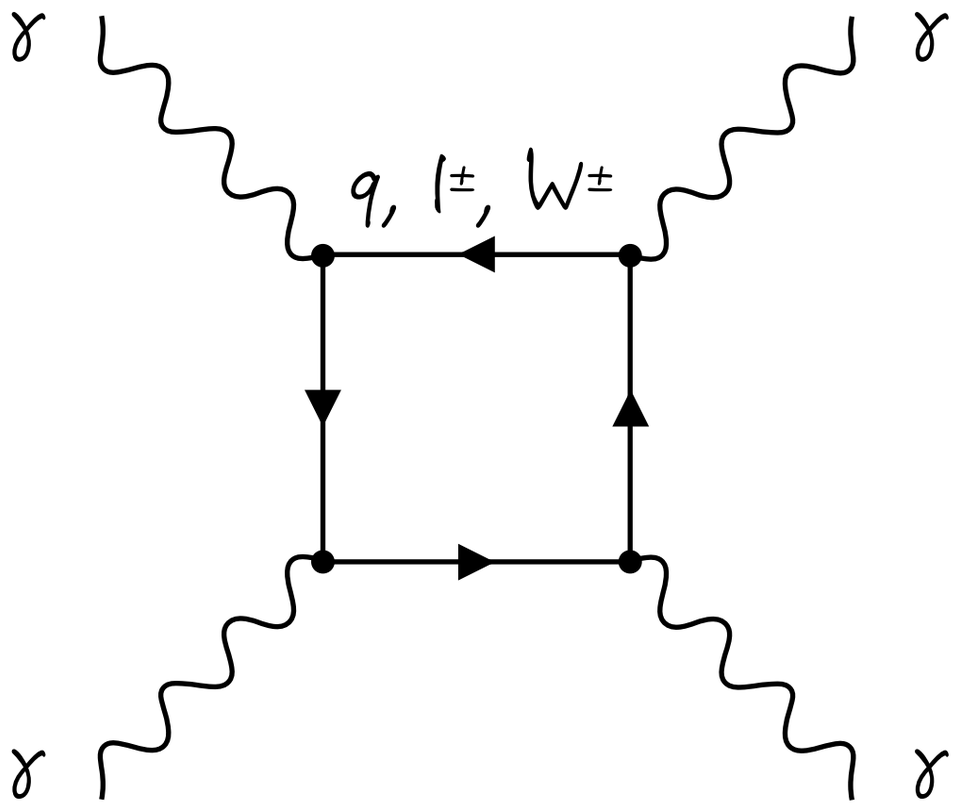

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  Delbrück scattering (γ deflection in the nucleus field),
- the difficulty to observe this process comes from a
  very low cross-section: ~O(α^4)≈10^{-9},

- several **experimental approaches** were proposed:
  - **Compton** backscattered photons **agains laser** photons,
  - photon-photon collisions from **microwave waveguides, cavities of high-power lasers**,
  - **photon colliders**: scattering laser-light off two $e^{\pm}$ beams,
  - ultra-peripheral (electromagnetic) interactions of proton/**lead beams at the LHC**.

Introduction

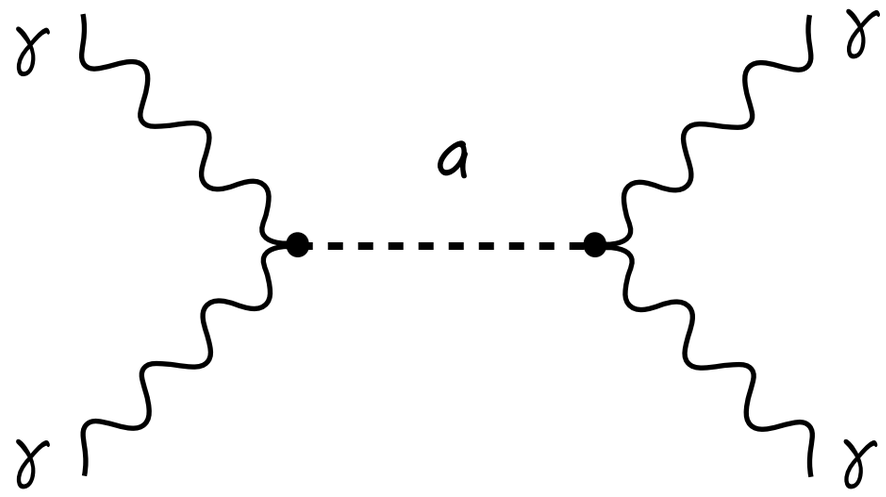
Exclusive $\gamma\gamma \rightarrow \gamma\gamma$ is also sensitive to physics signals beyond the SM such as axions.

Axions

- Axions arise from Peccei-Quinn mechanism which promotes QCD mixing θ_{QCD} to a field,
- they solve in an elegant way the strong CP problem,
- they are a natural dark-matter candidates,
- characteristic two-photon vertex → light shining through the wall experiments,
- original axions (small masses, symmetry breaking scale ≈ EW scale) ruled out.

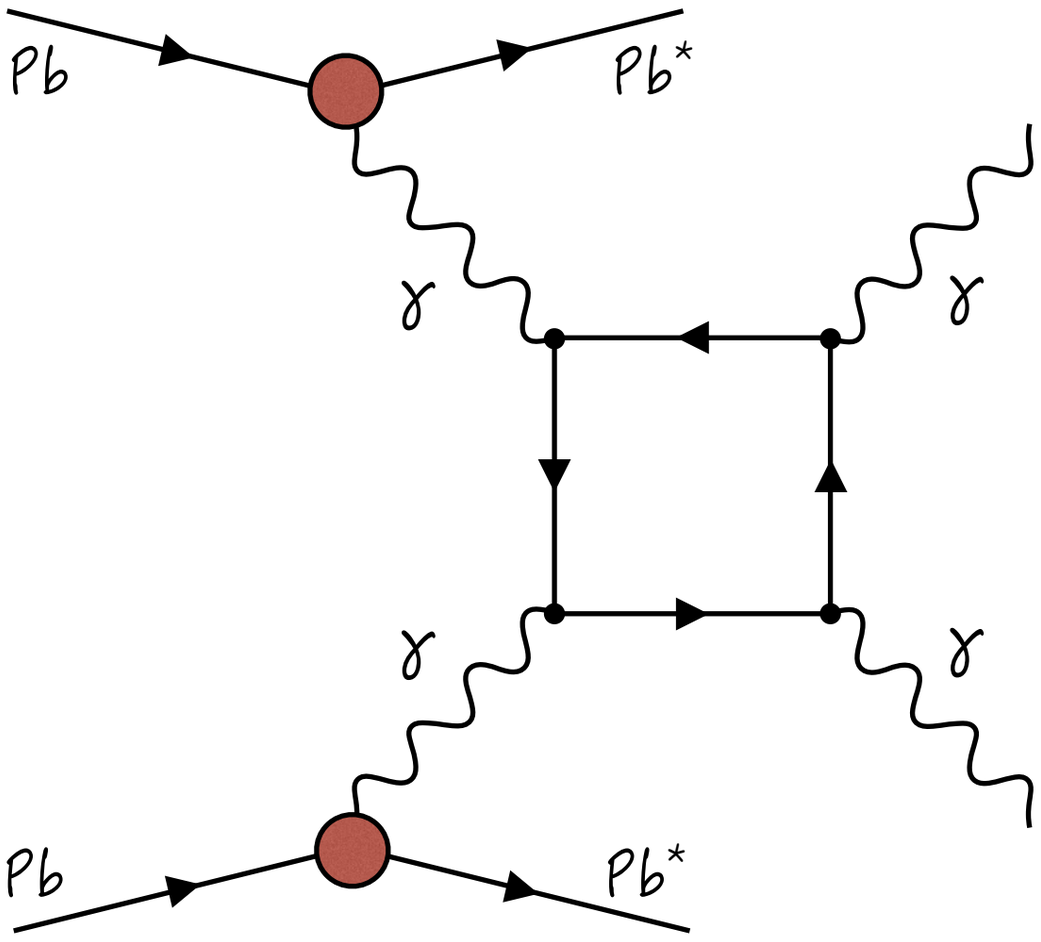
Axion Like Particles (ALPs)

- more general class of elementary pseudo-scalar particles, where mass-coupling relation is not fixed,
- axions or ALPs occur automatically in many extensions of SM.



LIGHT-BY-LIGHT IN UPCS

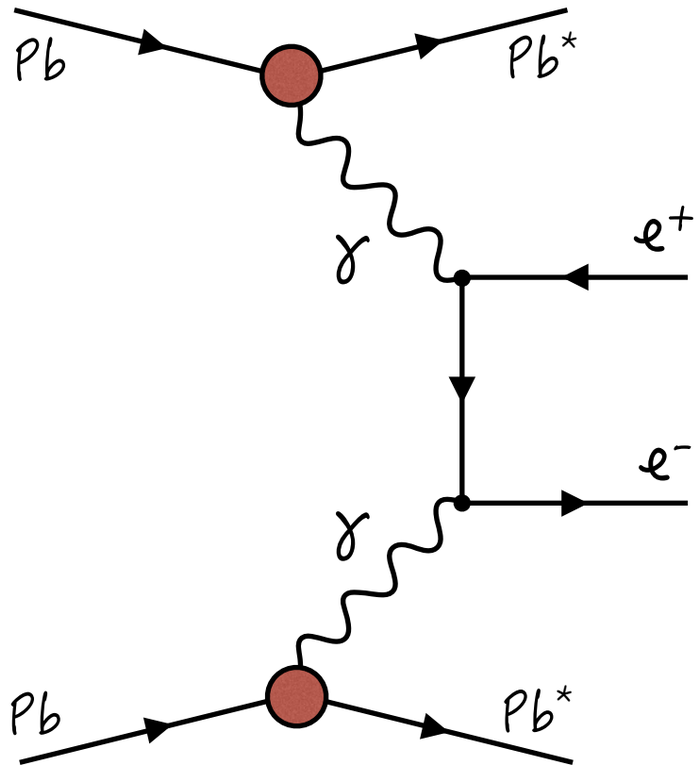
- Proposal: **use ultra-peripheral heavy-ion collisions** (UPC of HI): $b > 2 \cdot R_{Pb}$,
- passing heavy ions generate **huge EM fields** (10^{14} T),
- **cross-section is amplified** by Z^4, for PbPb ($Z=82$) $\sigma_{\gamma\gamma\to\gamma\gamma}$ is $5 \cdot 10^7$ higher than for p-p or e^+e^-,



- **quasi-real photons** (coherence): $Q \sim 1/R \approx 0.06$ GeV (Pb), 0.28 GeV (p),
- **maximum γ energies** at LHC $\omega_{max} \sim \gamma_L/R \approx 80$ GeV (Pb), 2.5 TeV (p).

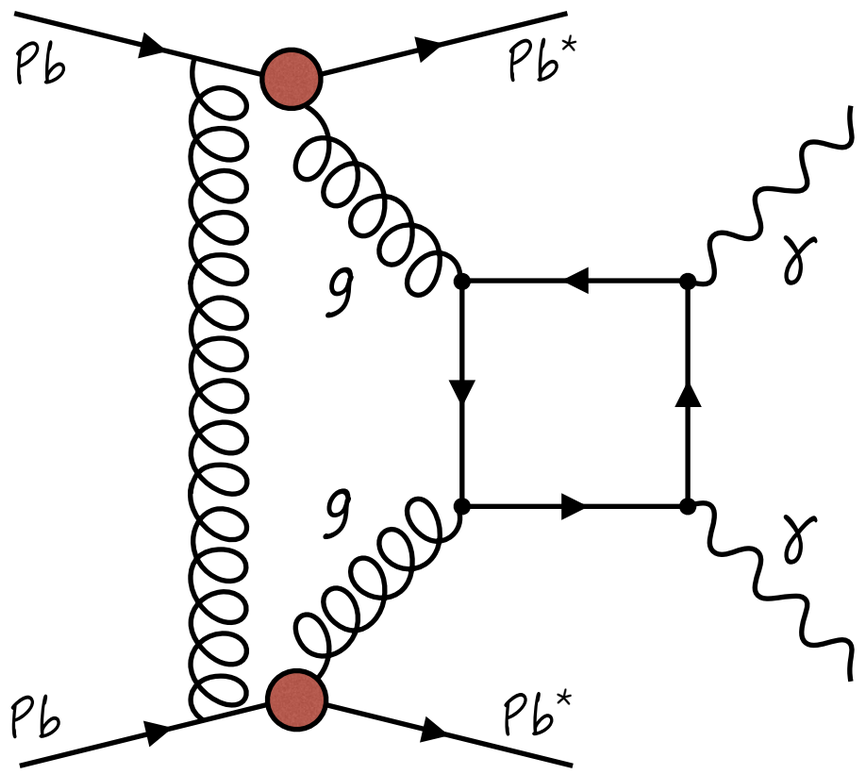
- **generated with MadGraph** v.5 MC generator,
- **W± contributions** only relevant for $m_{\gamma\gamma} > 2 \cdot m_W$, **hadronic loops** only for $m_{\gamma\gamma} \lesssim 2$ GeV,
- generated **cross-section**: $\sigma_{\gamma\gamma\to\gamma\gamma} = 1.85$ μb ($|\eta| < 5.0$, $m_{\gamma\gamma} > 2.5$ GeV).

Background processes



Exclusive QED e^+e^-

- electrons may be misidentified as photons if they undergo hard bremsstrahlung and they are not reconstructed,
- generated with STARLIGHT,
- $\sigma_{\gamma\gamma\to ee}$ = 20.6 mb (without cuts),
- can be reduced with tight γ identification cuts.



Central Exclusive Production (CEP)

- generated with SUPERCHIC 2.0,
- p-p cross section scaled by $A^2R_g^4$, A=208, $R_g \approx 0.7$ (gluon shadowing correction),
- large theoretical uncertainty due to modeling of rapidity gap survival probability (normalized from data in control-region),
- $\sigma_{gg\to\gamma\gamma}$ = 15 μb,
- larger p_T exchange than LbL, photons less back-to-back. Suppressed by acoplanarity cuts.

CMS DETECTOR

- **Photons from light-by-light** scattering measurable in **CMS** over |η|<2.5, exclusivity condition over |η|<5.2,
- **final state** - just two tower in the ECAL, no activity in the tracker, hadron calorimeters, muon detectors.

Electromagnetic Calorimeter

Barrel EB (|η| < 1.479)

End-cap EE (1.479 < |η| < 3.0)

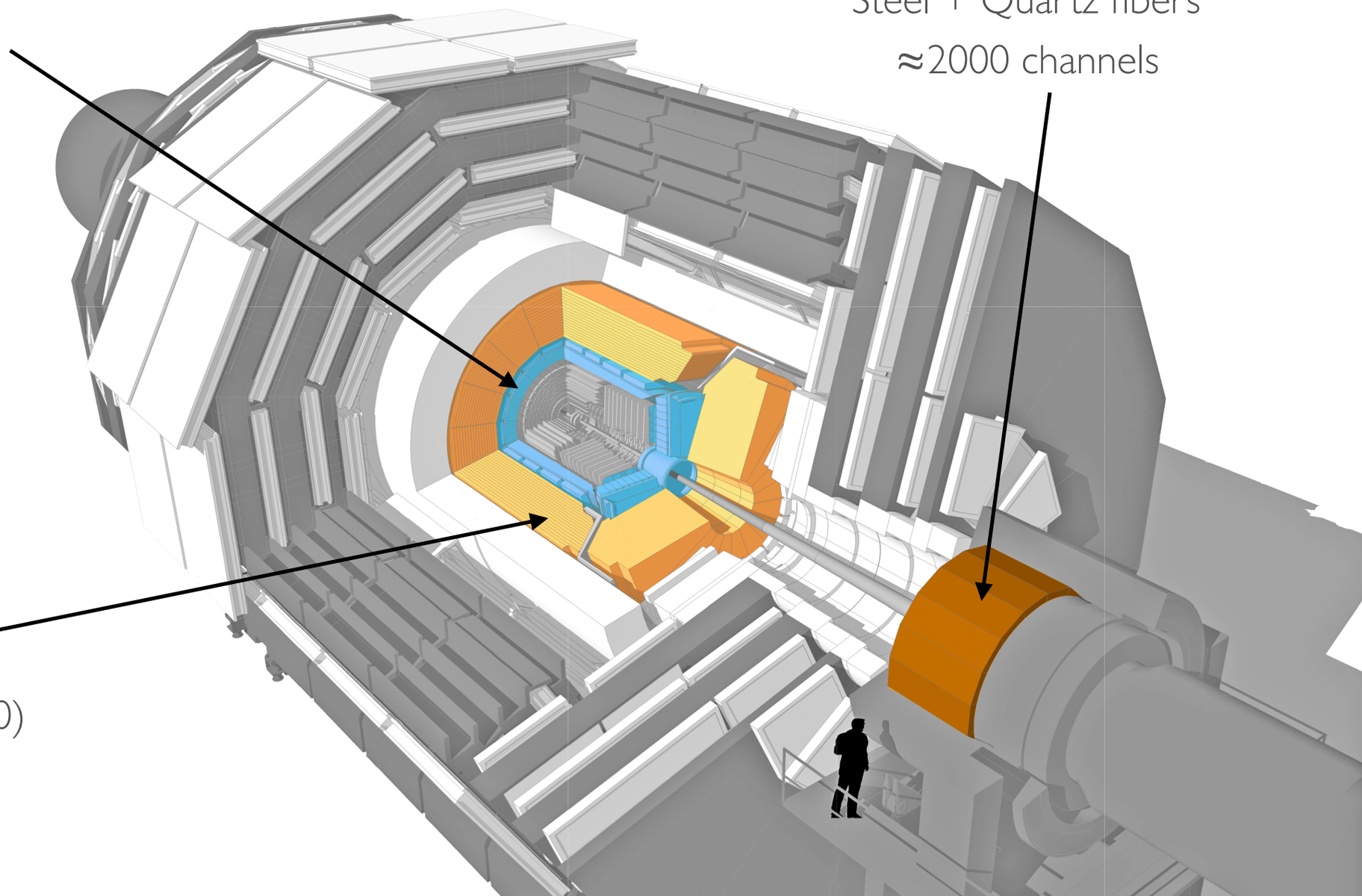
≈76 000 scintillating $PbWO_4$ crystals

Hadron Forward Calorimeter

HF (2.9 |η| < 5.2)

Steel + Quartz fibers

≈2000 channels



Hadron Calorimeter

Barrel HB (|η| < 1.3)

End-cap HE (1.3 < |η| < 3.0)

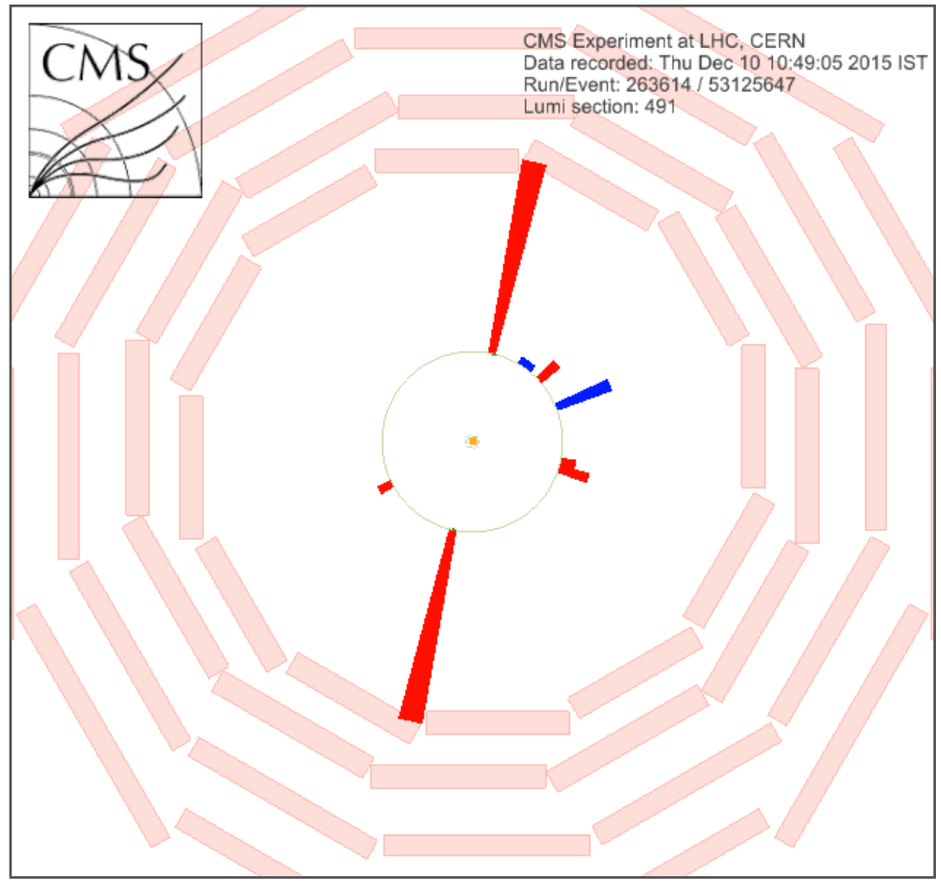
Brass + Plastic scintillator

≈7000 channels

Data sample

Data sample

- PbPb @ 5.02 TeV (2015),
- total integrated luminosity L_{int} = 390 μb^{-1}.



Trigger

- at least two photons/electrons in ECAL with E_T > 2 GeV each,
- at least one of the two Hadron Forward (HF) calos empty.

Reconstruction

- photons of interest in the low E_T (2-10 GeV) region,
- standard CMS high-E_T e/γ reco (E_T > 10 GeV) retuned for this analysis,
- pre-selecting events with exactly two photons with E_T > 2 GeV,
- identification of photons:
  - removal of decay photons by shower shape: $\sigma_{i\eta i\eta}$ < 0.02 (0.06) in barrel (endcap),
  - cleaning spikes (direct ionization of the photodiode) - four neighboring hits must contain significant fraction (>5%) of the highest energy hit.

Data selection

Neutral exclusivity cuts

- reject events with towers above noice threshold in ECAL, HCAL or HF ($|\eta|<5.2$) far from photons candidates:
  - $|\Delta\eta|>0.15$, $|\Delta\Phi|>0.7$ (0.4) in EB (EE),
  - any tower in hadron calorimeters (HB, HE or HF).

Charged exclusivity cuts

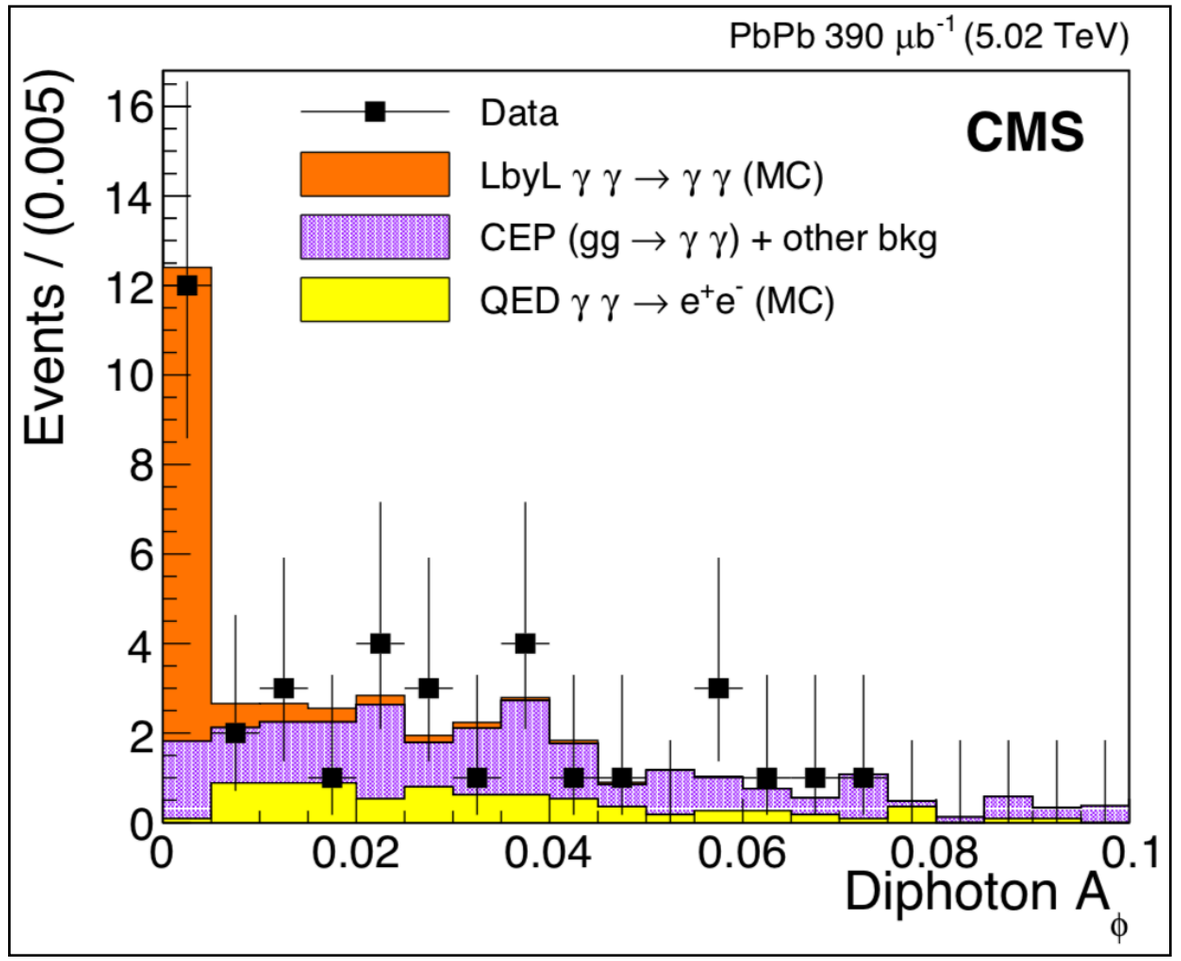
- reject events with any charged particle with $p_T > 0.1$ GeV.

Acoplanarity

- definition: $A_\Phi = 1-\Delta\Phi_{\gamma\gamma}/\pi$,
- signal has very low acoplanarity ($A_\Phi < 0.008$), CEP has flat A_Φ in range 0-0.2,
- cut applied: $A_\Phi < 0.01$.

Other cuts

- diphoton $p_{\gamma\gamma} < 1$ GeV to reduce all non-exclusive photon backgrounds.

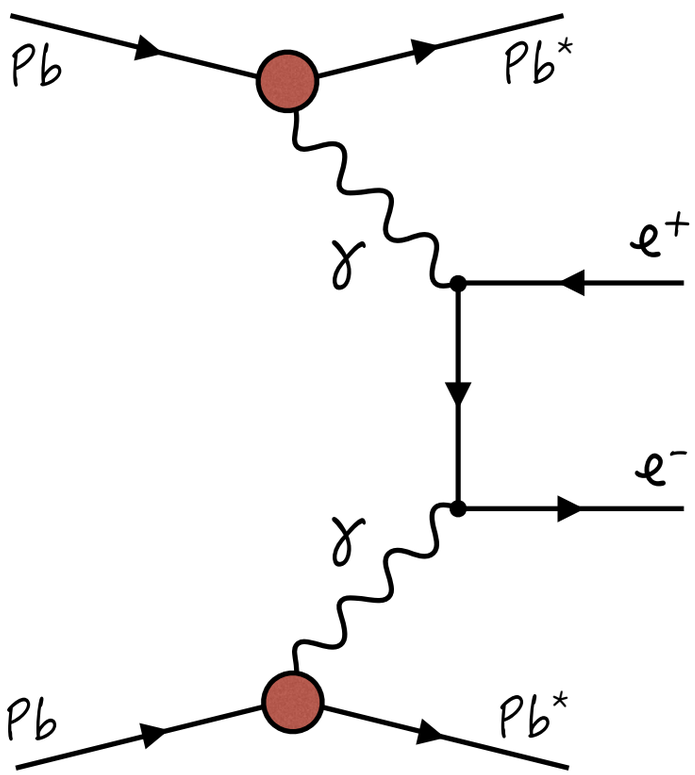


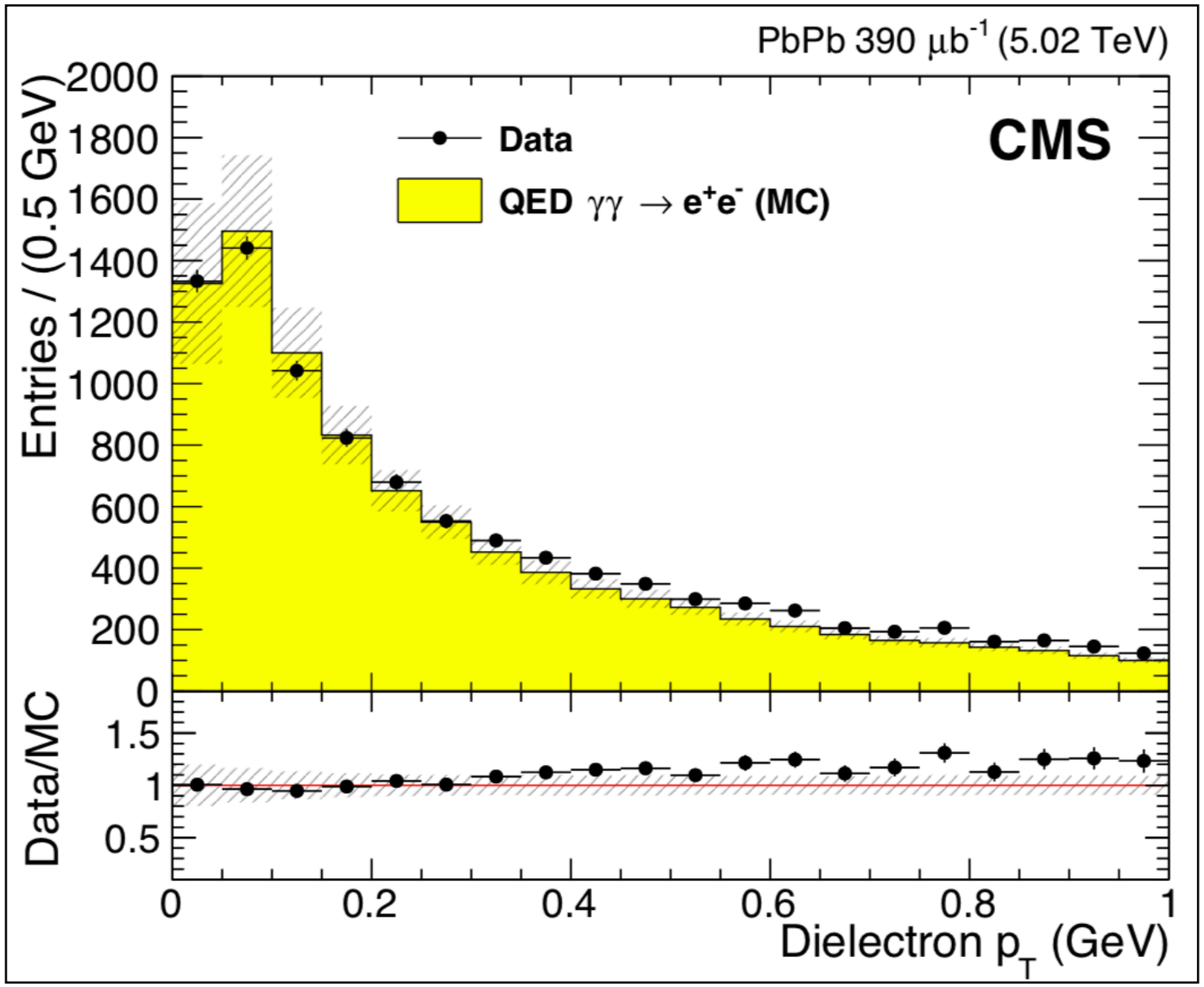
BACKGROUND ANALYSIS

QED e^+e^- background

- the same analysis repeated, now requiring exclusive **e^+e^- pair instead of $\gamma\gamma$**,
- **kinematic distributions** reproduced well by the Starlight MC generator (except increasing acoplanarity tail from $\gamma\gamma \rightarrow e^+e^-(\gamma)$),
- **confirms quality** of:
  - electron/photon reconstruction,
  - event selection criteria,
  - MC predictions for PbPb UPCs,
- estimated e^+e^- background after cuts:

1.0 ± 0.3 events.



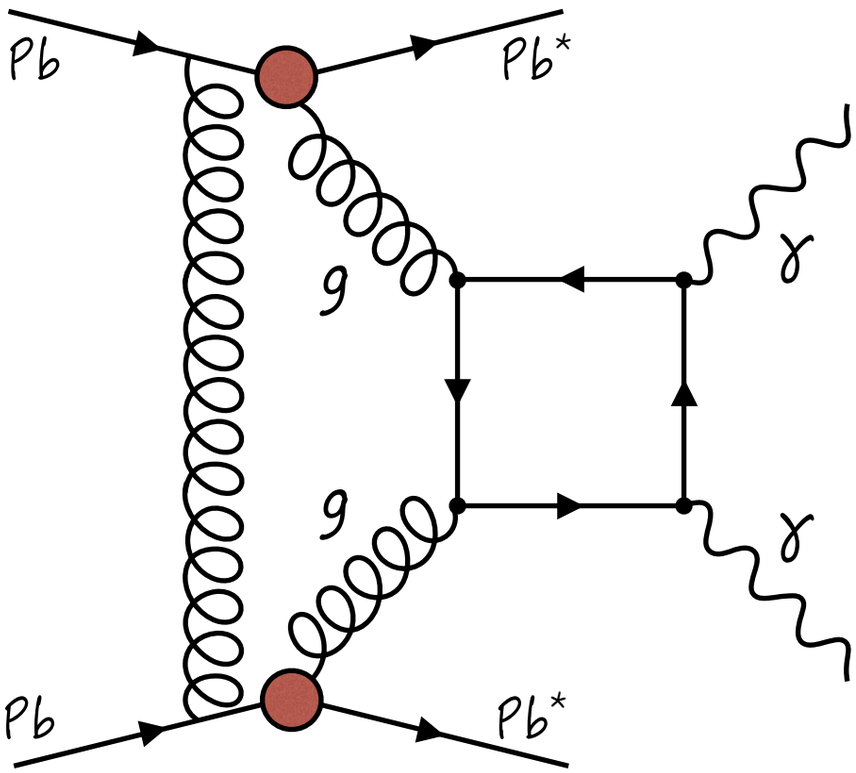


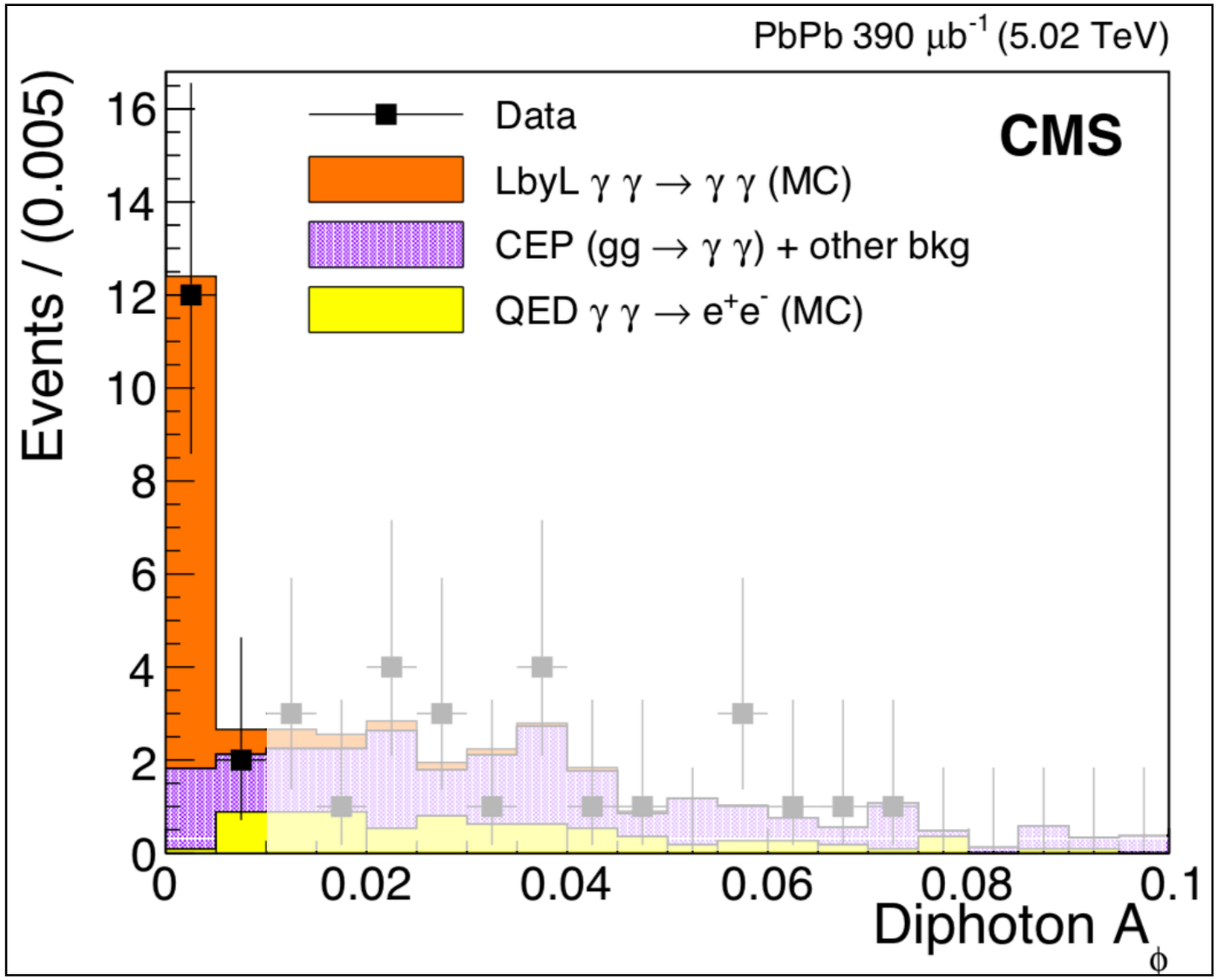
BACKGROUND ANALYSIS

CEP + other residual backgrounds

- normalized from acoplanarity measured in data for $A_\Phi > 0.02$, where LbyL is negligible,
- acoplanarity cut ($A_\Phi < 0.01$) removes most of the CEP background,
- estimated CEP background after cuts:

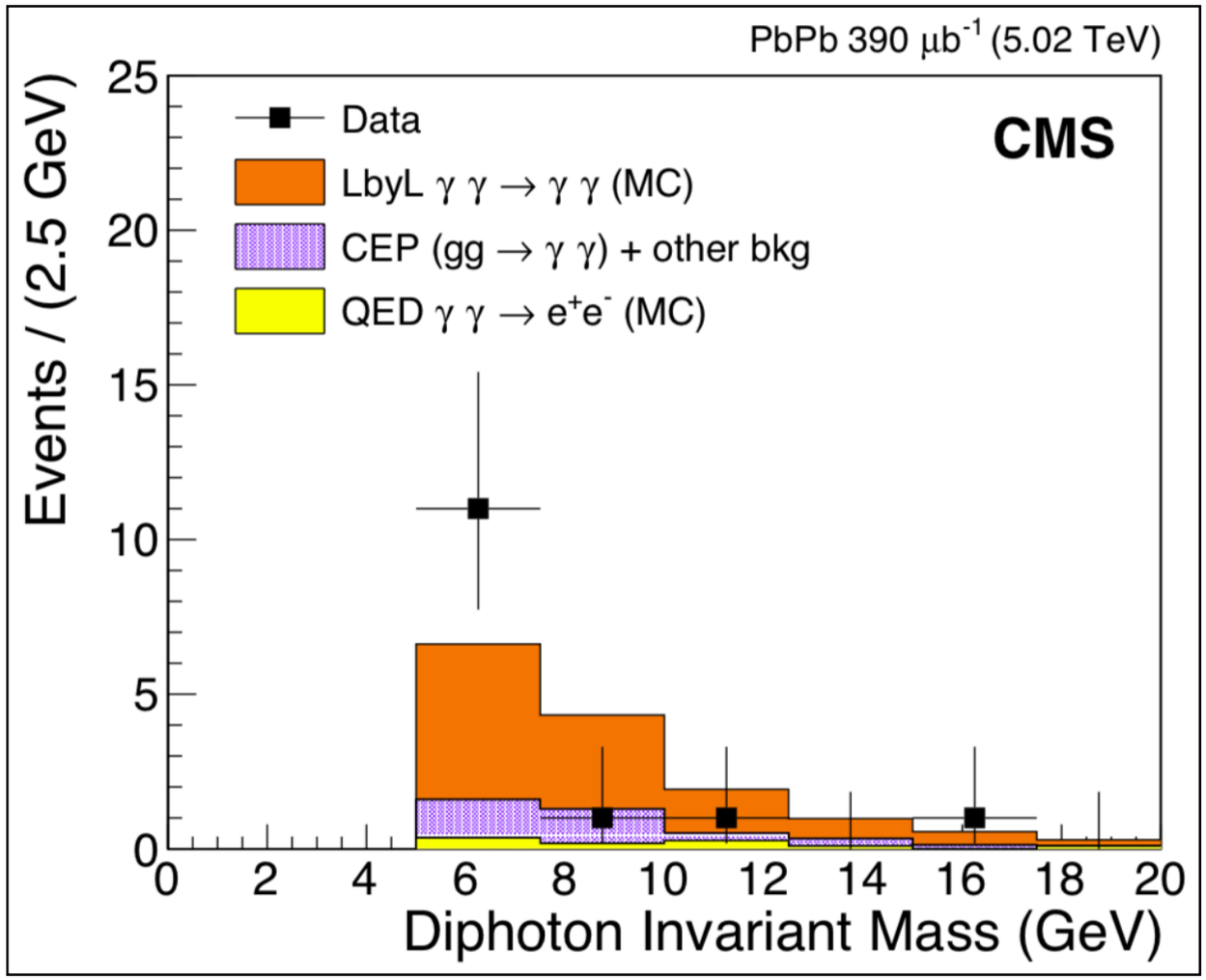
  3.0 ± 1.1 events.

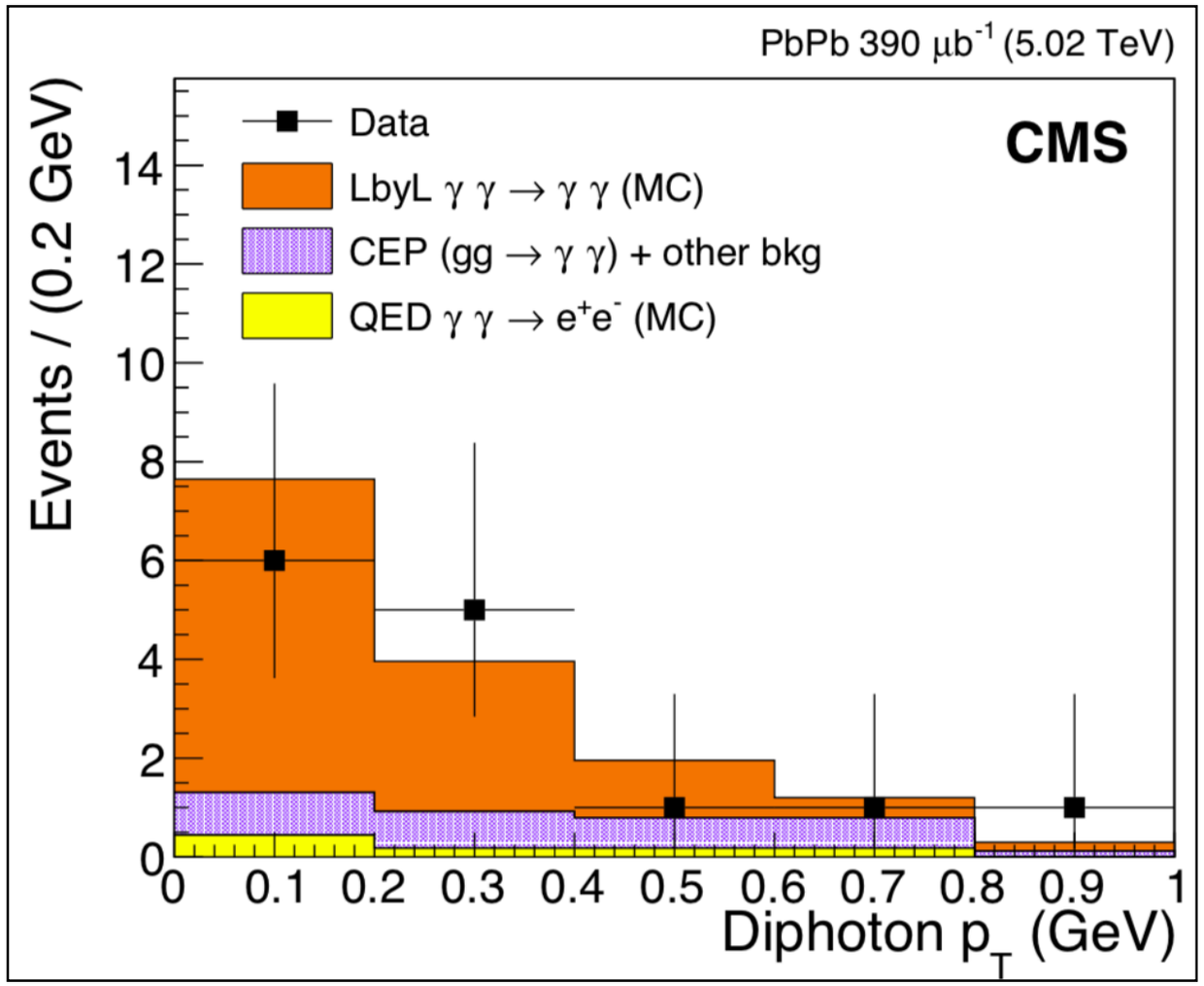




KINEMATIC DISTRIBUTIONS

Measured distributions reproduced well by the sum of LbL signal and QED + CEP backgrounds:

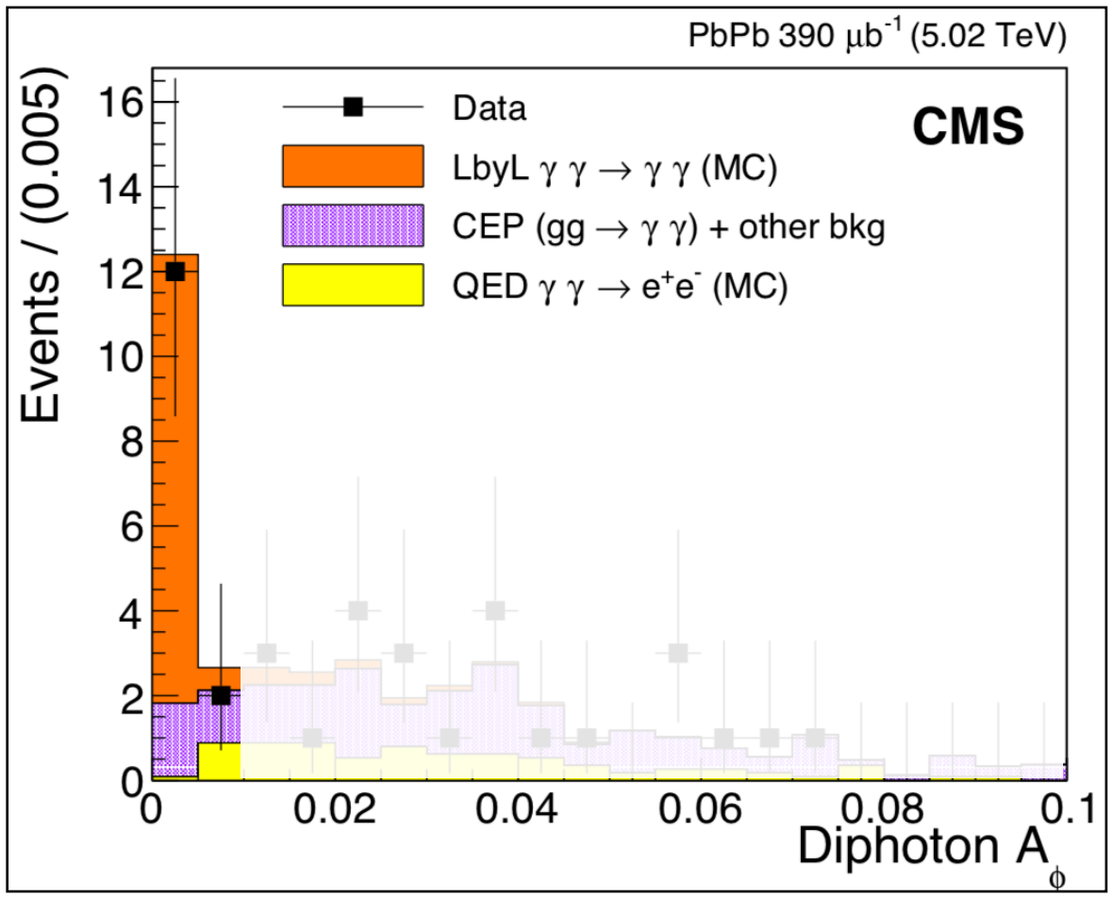




RESULTS

Number of events

- signal region: $|\eta| < 2.4$, $E_T > 2$ GeV, $m_{\gamma\gamma} > 5$ GeV,
- observed: **14 light-by-light events**,
- expected: **11.1 ± 1.1 (th) signal** and **4.0 ± 1.2 (stat) background** events,
- significance (from acoplanarity distribution) → observed: **4.1σ** (expected: 4.4σ)



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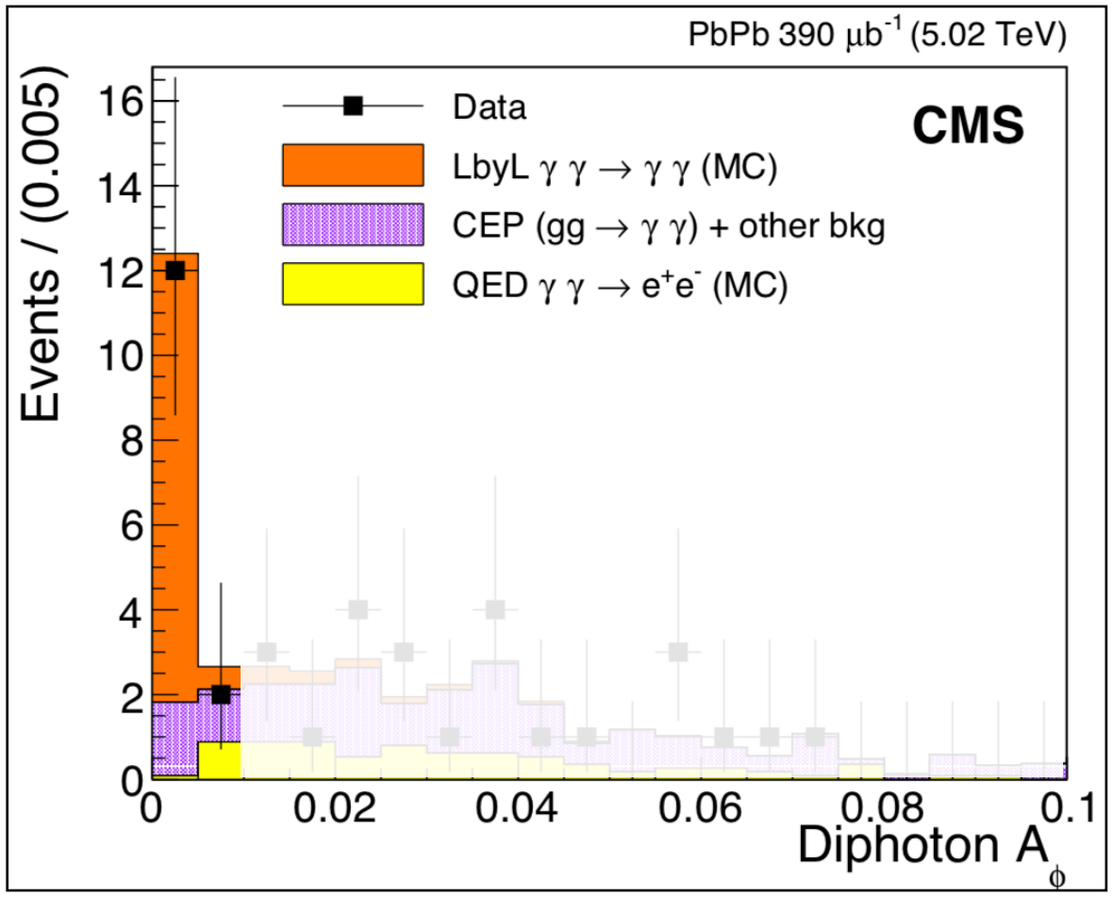

LbyL to QED cross-sections ratio

- $\sigma_{\gamma\gamma\to\gamma\gamma}/\sigma_{\gamma\gamma\to e^+e^-}$ extracted, taking into account:
  - efficiency of the trigger,
  - γ/electron reconstruction and identification efficiency,
  - stat. uncertainty on MC background estimation,
- exclusivity (neutral and charged) uncertainties cancel out,
- measured:

$\sigma_{\gamma\gamma\to\gamma\gamma}/\sigma_{\gamma\gamma\to e^+e^-} = [25.0 \pm 9.6\ (\text{stat}) \pm 5.8\ (\text{syst})] \times 10^{-6}$

Photon reconstruction and identification	(2 × 9)%
Electron reconstruction and identification	(2 × 2.5)%
Trigger	12%
MC backgrounds (stat.)	8%
Total	24%

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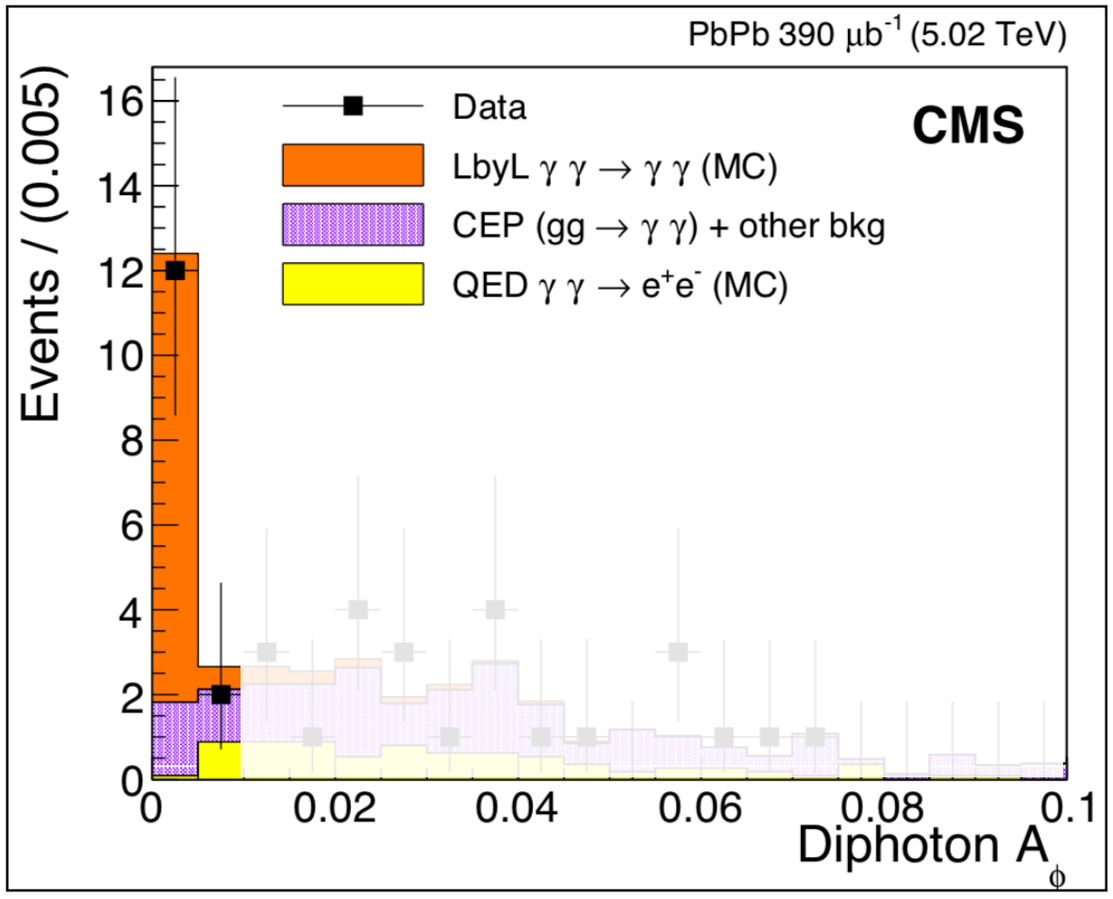

Fiducial LbyL cross section

- from STARLIGHT, $\sigma_{\gamma\gamma\to e^+e^-} = 4.82 \pm 0.15$ (th) mb,
- expected: **138 ± 14 nb**,
- measured: **120 ± 46 (stat) ± 28 (syst) ± 4 (th) nb**.

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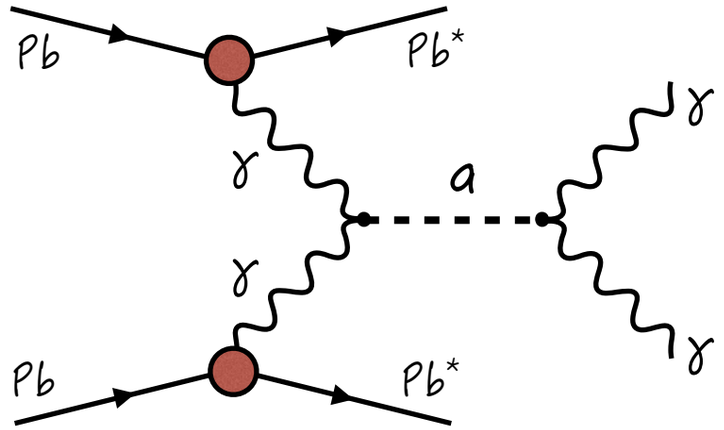
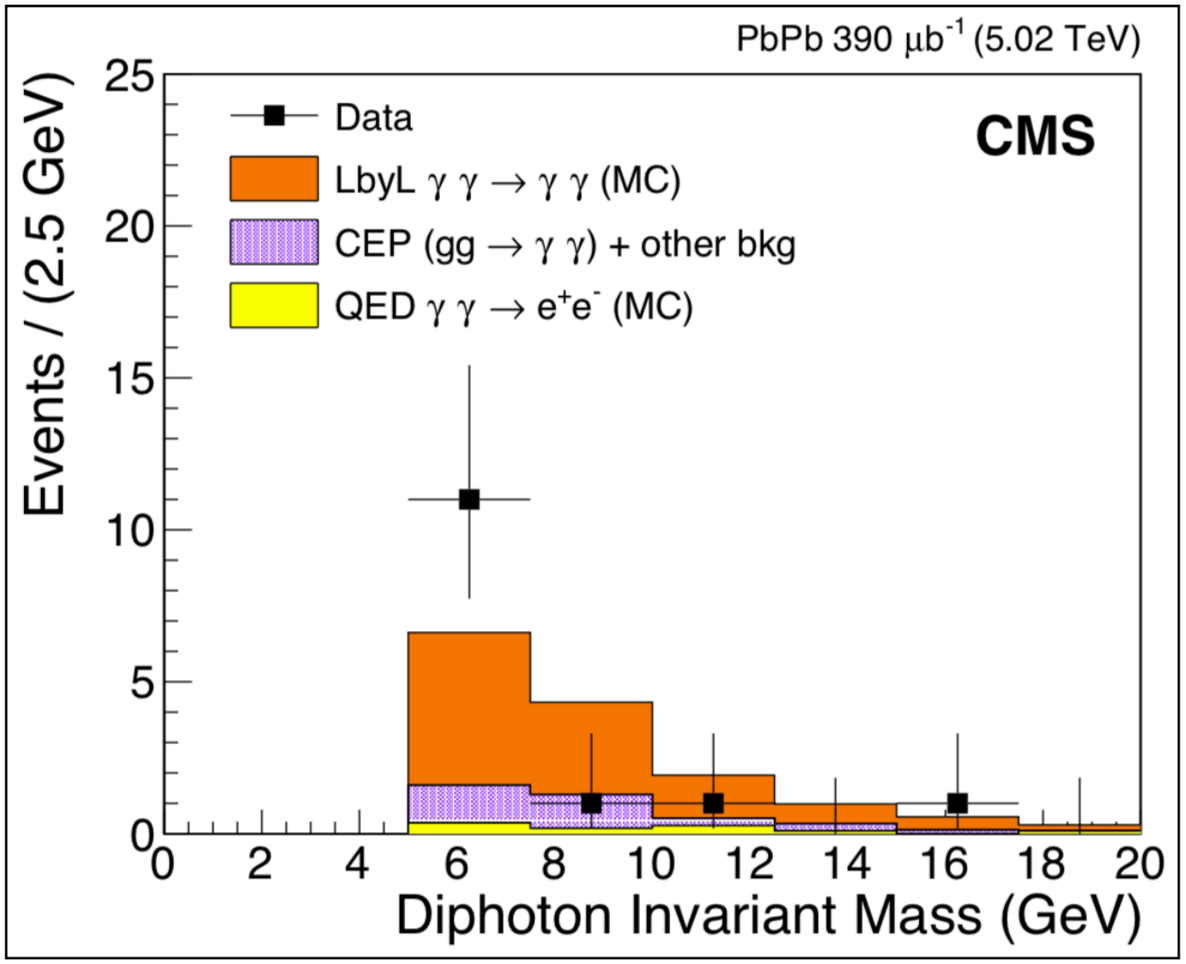
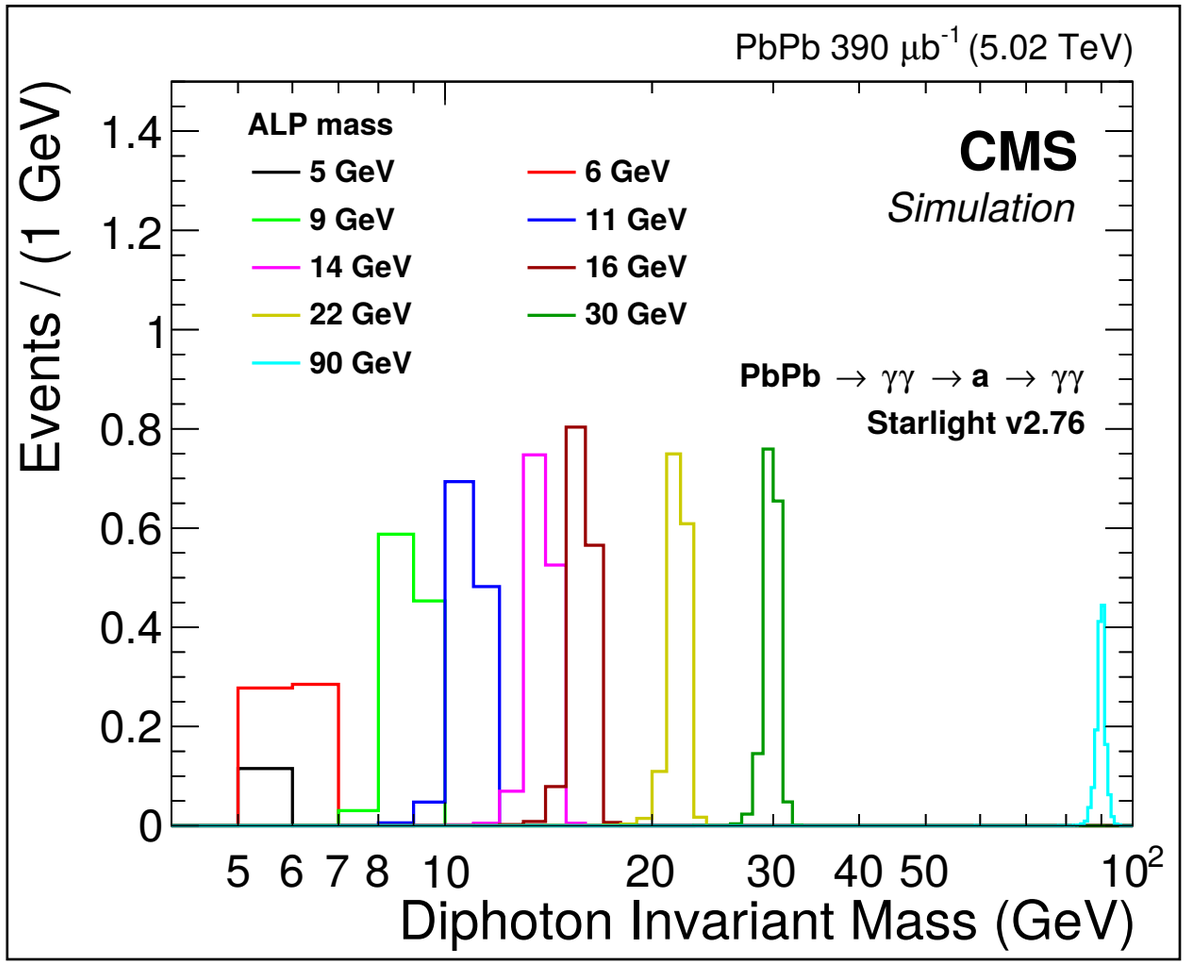
AXION-LIKE PARTICLE SEARCHES

- Exclusive diphoton final-state from resonant CP-odd **axion-like particles** (ALPs) production and decay,
- LbyL, QED and CEP considered as background in this analysis,
- **ALP samples**
  - generated with STARLIGHT (m_a = 5-90 GeV),
  - injected signals at various m_a analyzed after full detector simulation,
  - the same reconstruction procedure as in LbyL analysis.

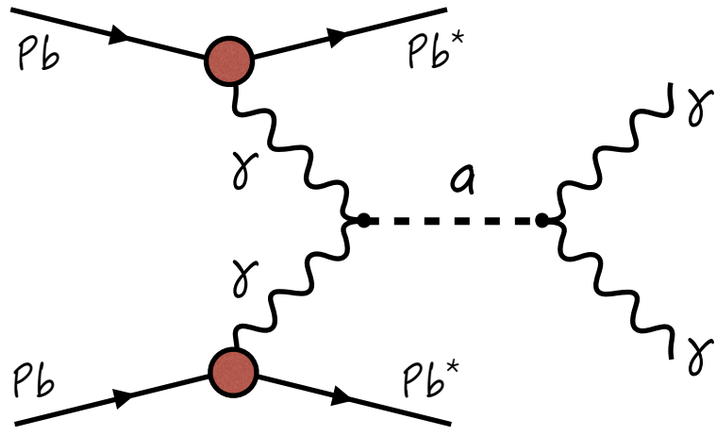


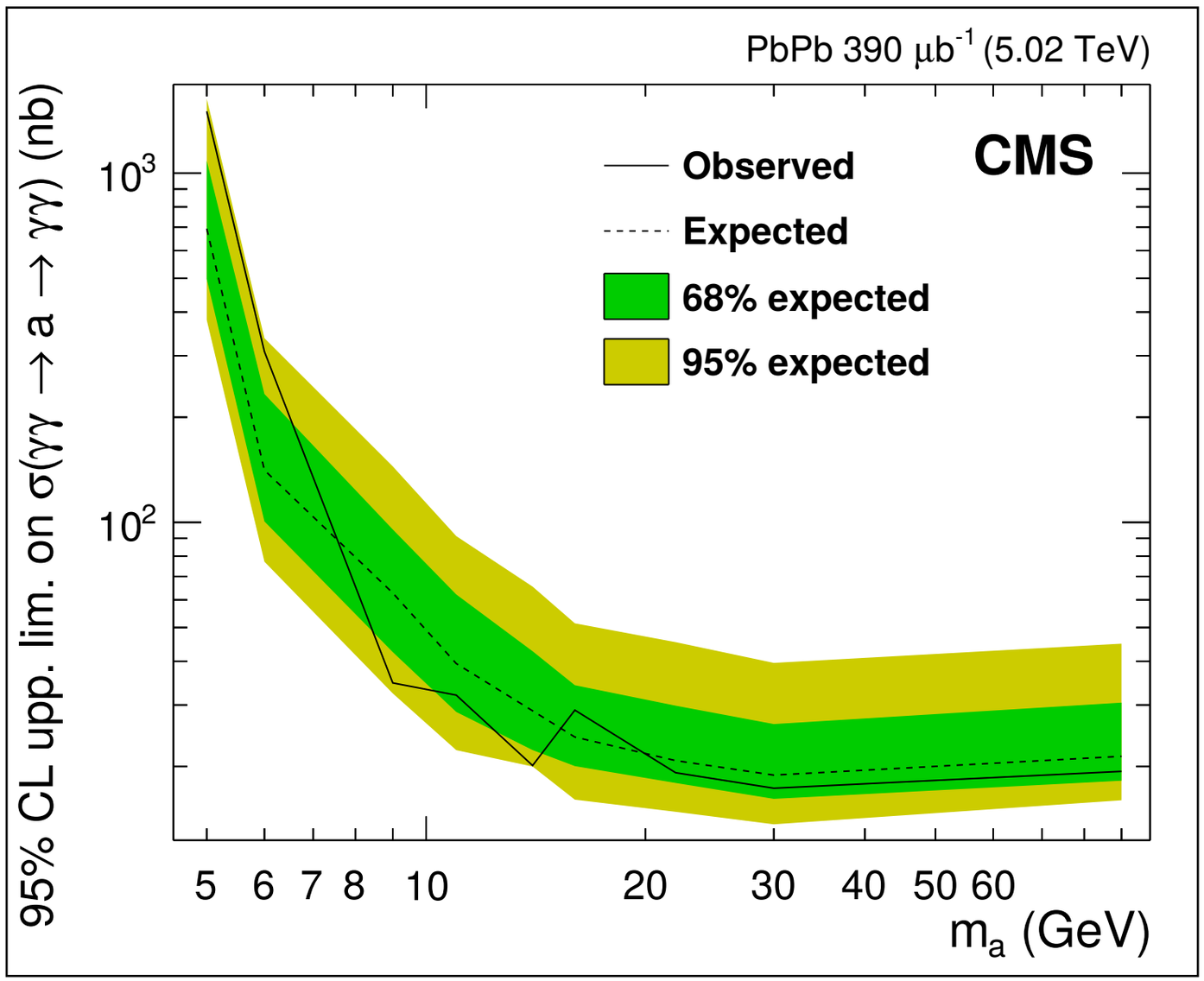




AXION-LIKE PARTICLE SEARCHES

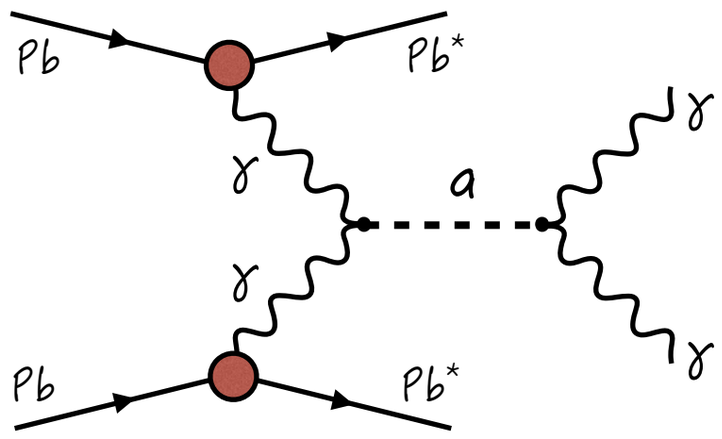
- **no significant ALP excess** observed in data above LbL+ backgrounds continuum,
- **limits in $\sigma_{\gamma\gamma\to a\to\gamma\gamma}$** at 95% confidence, 100% $\gamma\gamma$ branching ratio
  (CLs criterion with a profile likelihood as a test statistics).

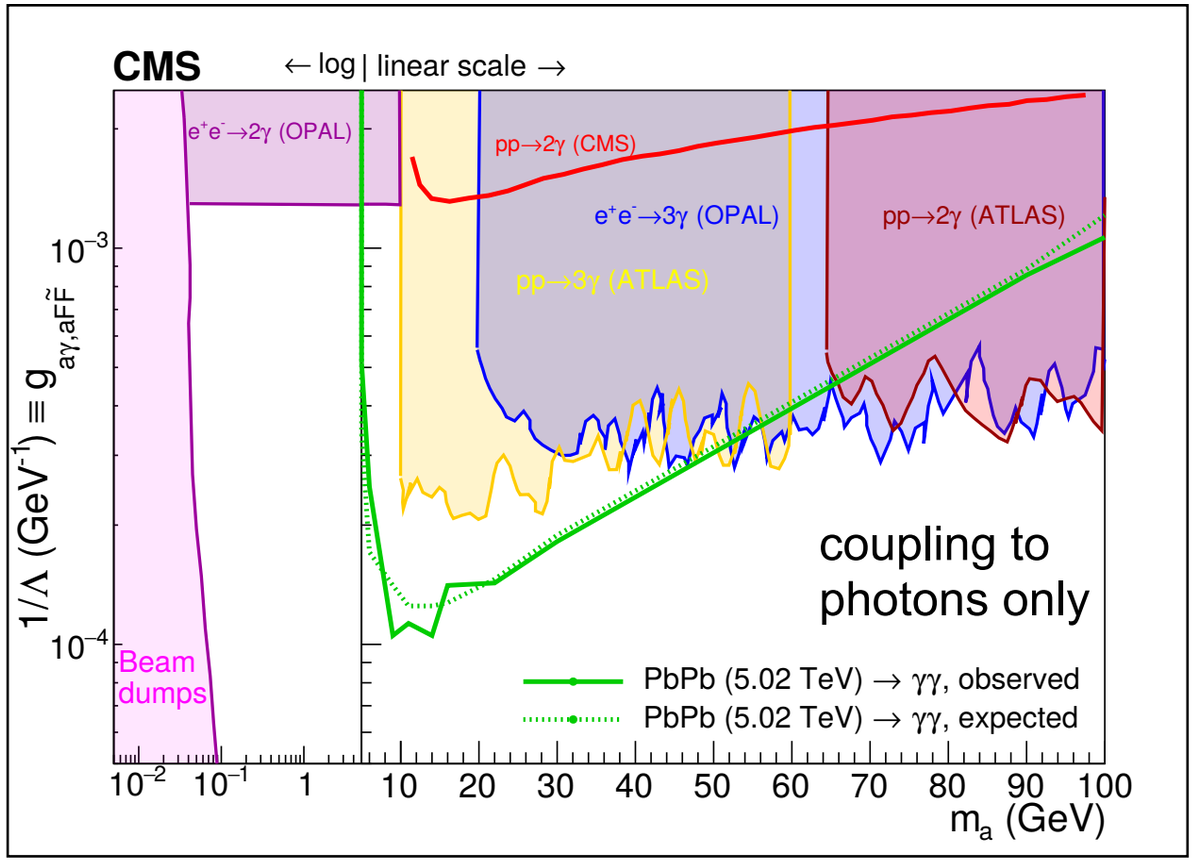


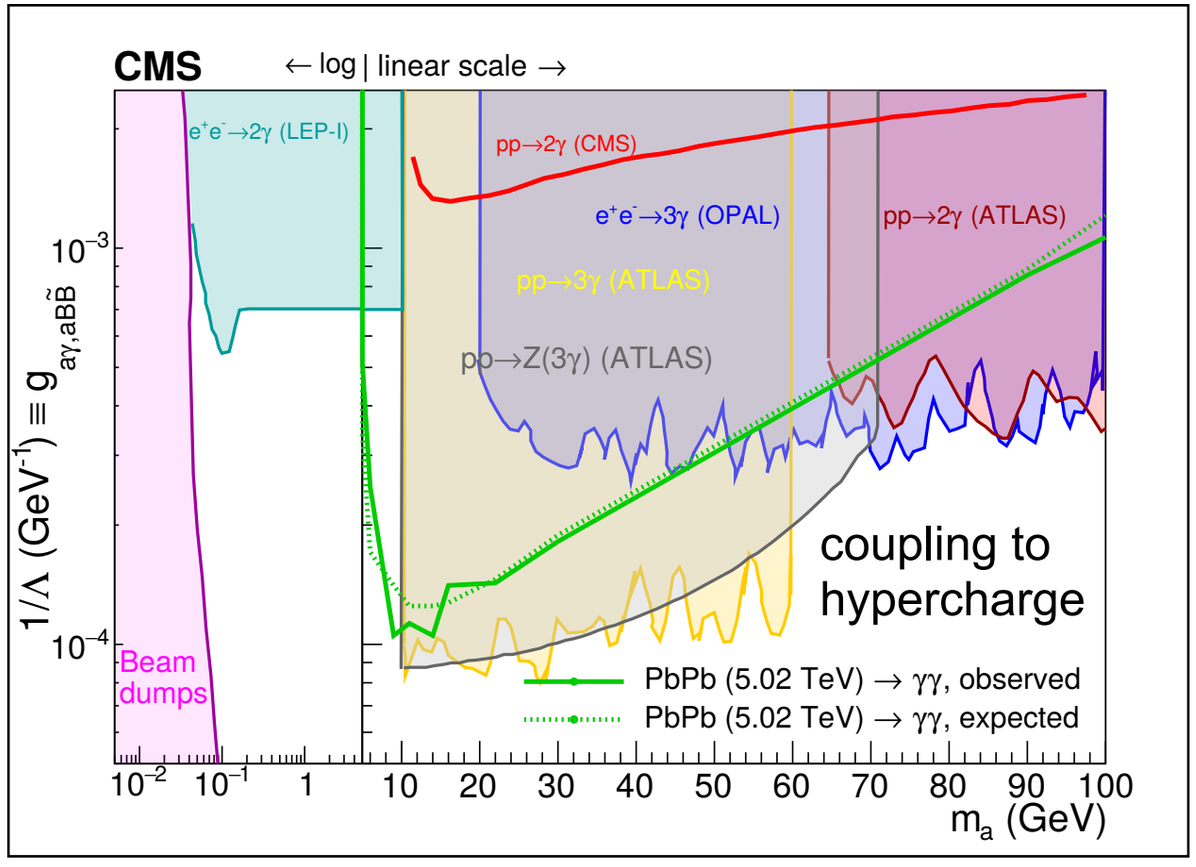


AXION-LIKE PARTICLE SEARCHES

- Limits in cross-section → **limits in $g_{a\gamma}$ vs. m_a plane** ($g_{a\gamma} = 1/\Lambda$)
- left plot: coupling only to photons (with operator $\frac{1}{4\Lambda} aF\tilde{F}$),
- right plot: coupling to hypercharge (with operator $\frac{1}{4\Lambda cos^2\theta_W} aB\tilde{B}$),
- **new limits** on axion-like particles over m_a = 5-50 GeV.







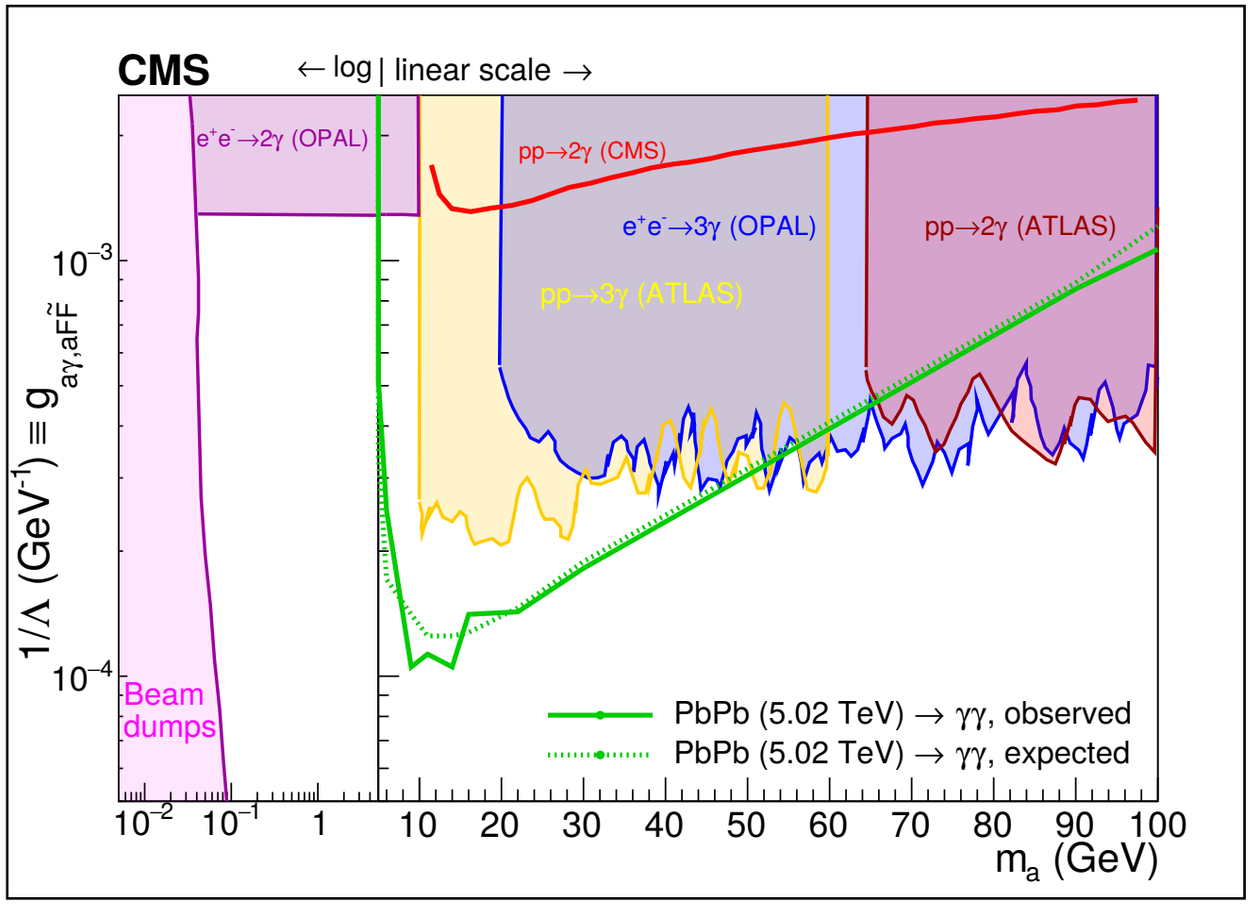
Conclusion

1. **Ultra-peripheral PbPb collisions** at LHC used to study **Light-by-Light** scattering,
2. QED and CEP identified as the main backgrounds,
3. Measurement of two-photon events with no other significant activity performed on 390 μb^{-1} PbPb @ 5.02 TeV,
4. **Evidence of LbL scattering**: 4.1 (4.4) sigma significance observed (expected)
5. **14 Light-by-Light events observed** - consistent with the SM predictions,
6. **Measured fiducial cross section**

   $\sigma_{\gamma\gamma\to\gamma\gamma}$ = 120 ± 46 (stat) ± 4 (th) nb

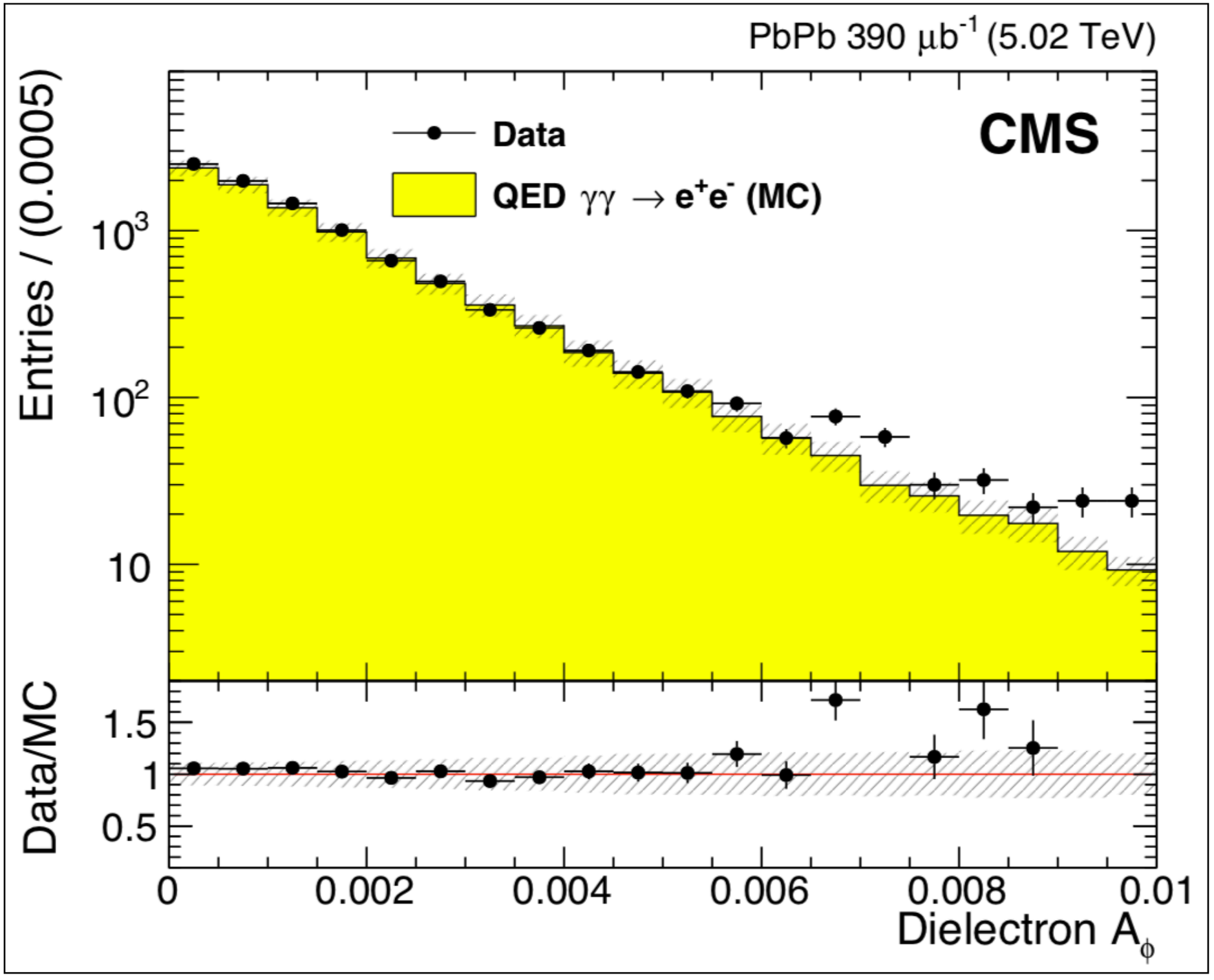
   - consistent with the SM predictions,
7. No significant excess in $m_{\gamma\gamma}$ distribution

   → competitive **limits on axion-like particles**.



Backup slides

BACKUP SLIDES



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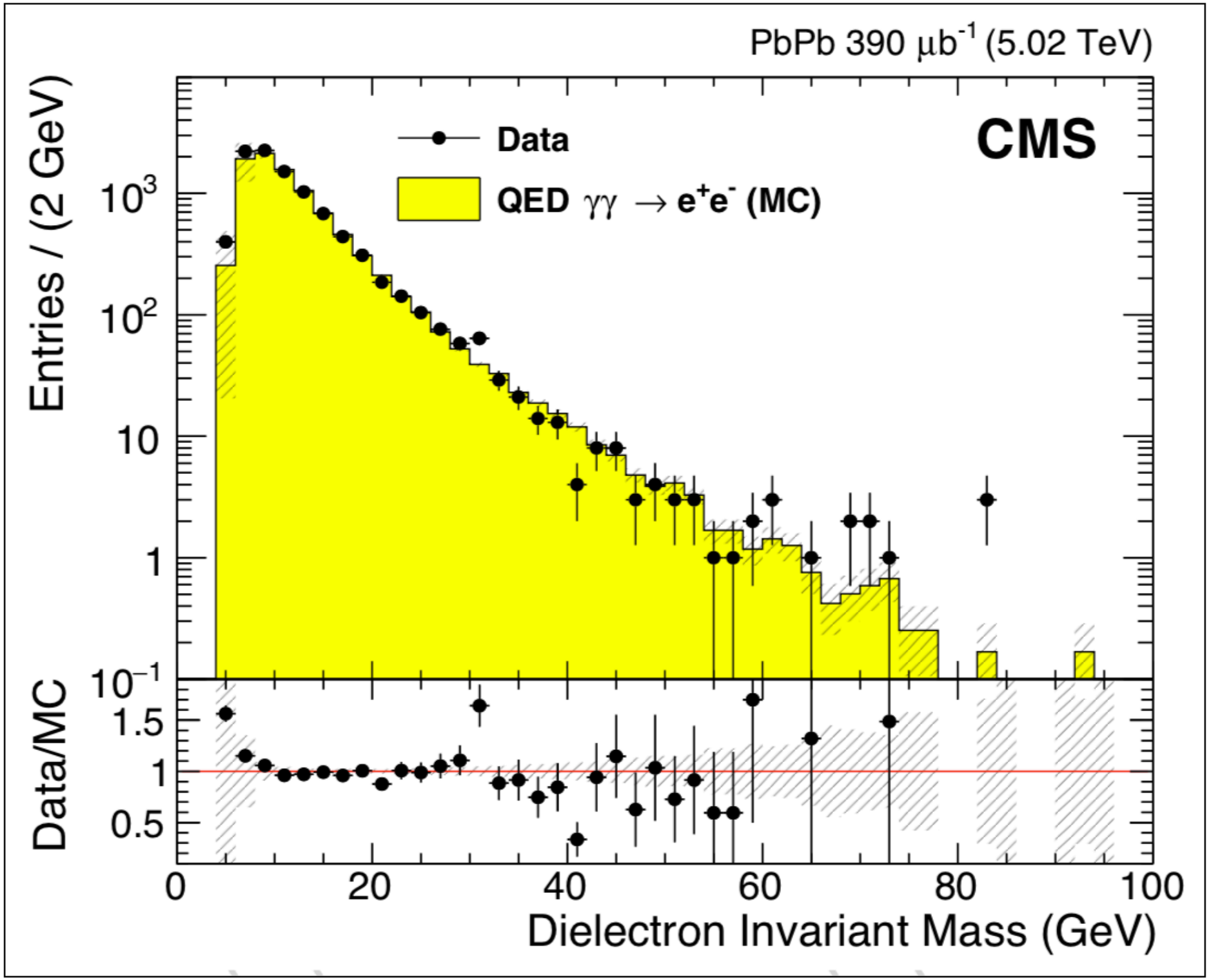

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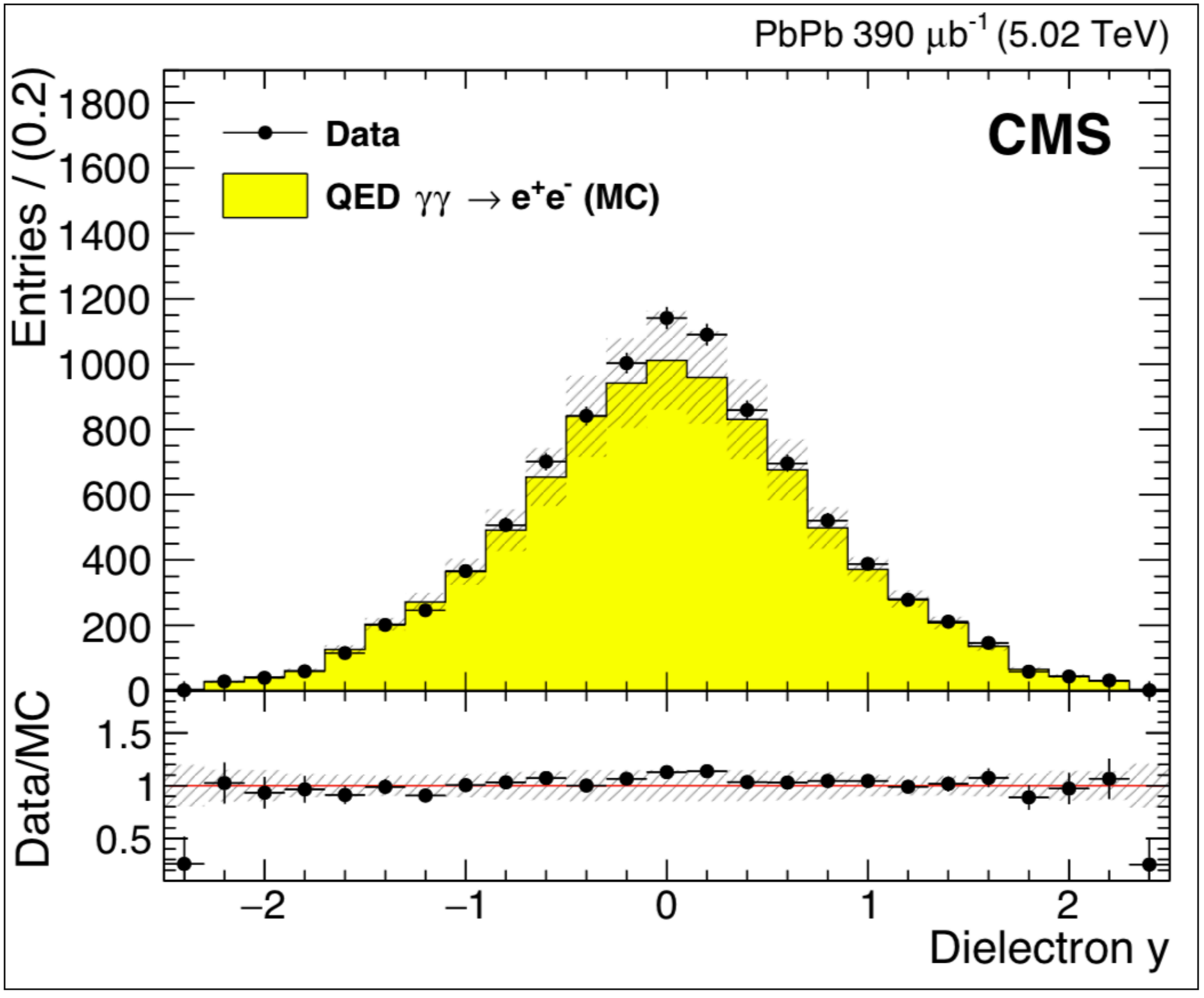

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