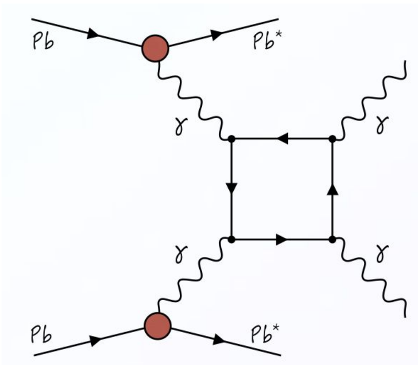
Measurements of light-by-light scattering, Breit-Wheeler e^+e^- production, and searches for axion-like particles in PbPb collisions at $\sqrt{S_{NN}} = 5.02$ TeV

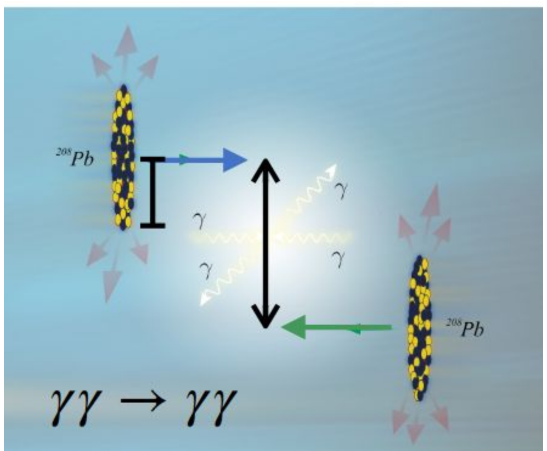
Ruchi Chudasama

On behalf of the CMS collaboration

4 May 2022

Light by light scattering

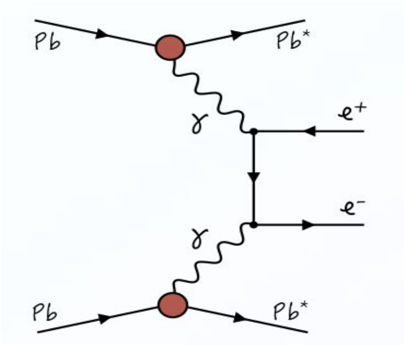




- Light-by-light ($\gamma\gamma \rightarrow \gamma\gamma$) scattering: a fundamental quantum-mechanical process in QED.
- The process proceeds through a loop of charged SM particles.
- It could also go through a loop containing new charged particles or through the s-channel with spin-even/odd resonances (axions, monopoles).
- Proposal: Use ultra-peripheral collisions (UPCs) : $b > 2X\ R_{Pb}$
  $\rightarrow$ PbPb collisions favorable, photon flux $\alpha\ Z^2$ per Pb
- Quasi-real photons, $Q \sim 1/R \approx 0.06$ GeV (Pb), 0.28 GeV (p)
- Maximum photon energy : $E_{max} \leq \gamma_L/R \approx 80$ GeV (Pb), 2.5 TeV (p)

Background contribution

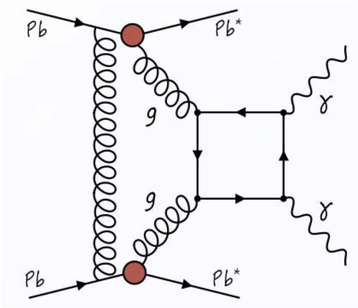
[Comp.Phys.Comm. 212 (2017) 258-268]



Exclusive QED $\gamma\gamma \rightarrow e^+e^-$ (Breit-Wheeler) process

- Large cross-section allows for precision QED measurement
  - Effective tool for studying the modeling of incoming photon fluxes,
  - Effects of nuclear breakup
- Electrons may be misidentified as photons if they undergo hard bremsstrahlung where neither of the track get reconstructed.
- Generated with STARLIGHT v2.76.

[Eur. Phys. J. C 76 (2016) 9]

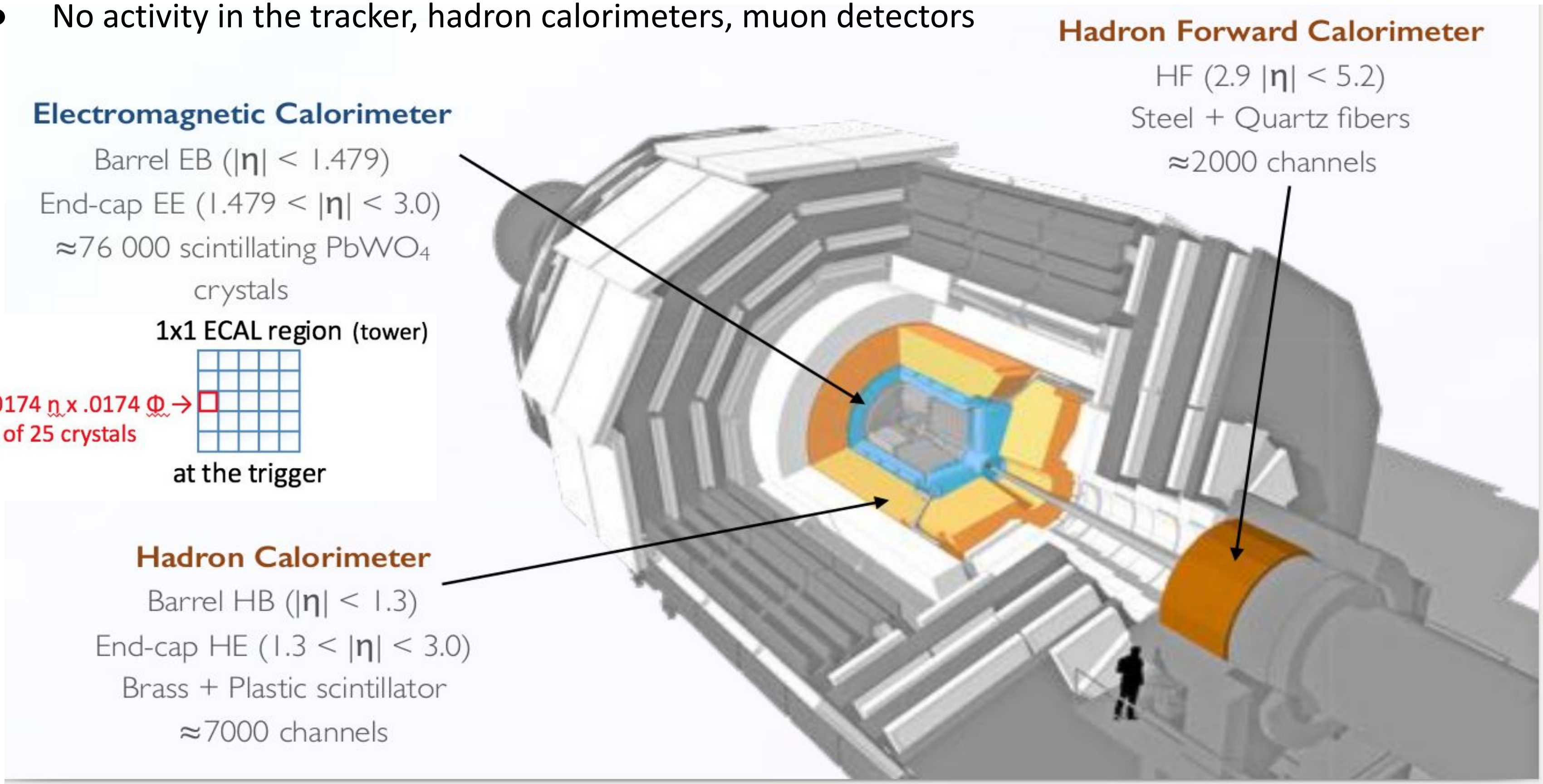


Central exclusive production (CEP) + residual background

- Generated with SUPERCHIC v2.0 used for analysis with 2015 PbPb data. pp process scaled for HI collision by $A^2 R_g^4$, S^2 =100% A=208, $R_g \approx 0.7$ (gluon shadowing correction), S^2 = probability to produce the diphoton system exclusively without any other hadronic activity.
- Large theoretical uncertainty due to modeling of rapidity gap survival probability (normalized from data in control-region)
- Larger p_T exchange than LbyL, photons are NOT exactly back-to-back suppressed by acoplanarity cuts.

The CMS detector

- Photons from light-by-light scattering measurable over |η|< 2.5, barrel and endacp calorimeters
- Exclusivity condition over |η|< 5.2, utilizing forward calorimeters as well
- Final state - just two tower in the ECAL
- No activity in the tracker, hadron calorimeters, muon detectors



Data sample @ CMS in LHC Run 2

Data

PbPb @ 5.02 TeV (2015, 2018)

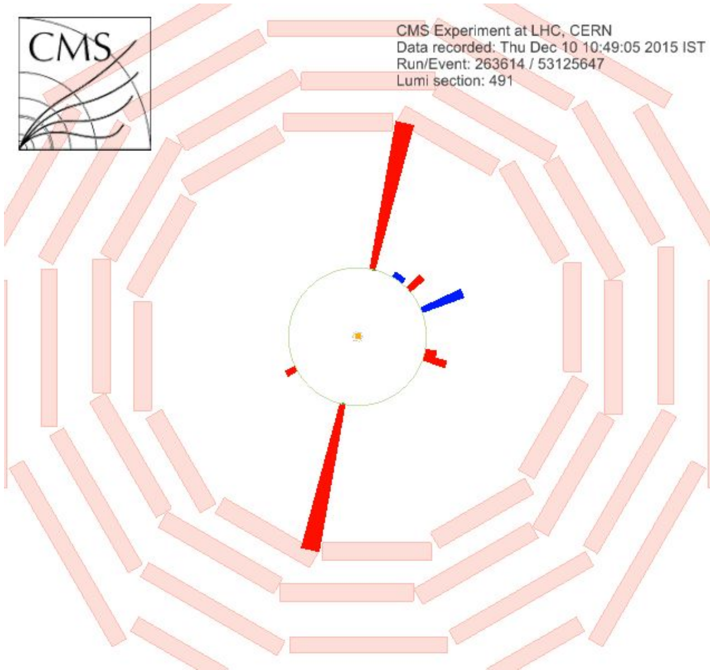
Total integrated luminosity L_{int} = 390 μb^{-1}, 1600 μb^{-1}

Trigger

- At least two photons/electrons in ECAL with E_T > 2 GeV each.
- At least one of the two Hadron Forward (HF) calorimeters empty (no signal).

Photon reconstruction

- Photons of interest in the low E_T (2-10 GeV) region,
- Standard CMS high-E_T e/γ reconstruction (E_T > 10 GeV) retuned for this analysis,
- Identification of photons:
  - removal of decay photons from neutral hadrons using cut on shower shape
  - cleaning of unusually high (spikes) energy deposits due to high energy particles from collision hitting directly the photodetector
    → require four neighboring hits to contain significant fraction (>5%) of the highest energy hit (shower formation).



Results based on CMS 2015 data are presented here.

Search for LbyL process in PbPb UPC

Charged exclusivity
Reject events with any tracks with $p_T > 0.1$ GeV

Neutral exclusivity
Reject events with any activity above noise threshold in electromagnetic, hadronic and forward calorimeters ($|\eta| < 5.2$) far from photon candidates:

Acoplanarity : $A_\phi = (1-\Delta\phi/\pi) < 0.01$
Required $A_\phi < 0.01$ **(back-to-back photons in azimuthal direction)**

Other selection:
$p_T(\gamma\gamma) < 1$ GeV reduced all non-exclusive backgrounds.
Invariant mass $m_{\gamma\gamma} > 5$ GeV

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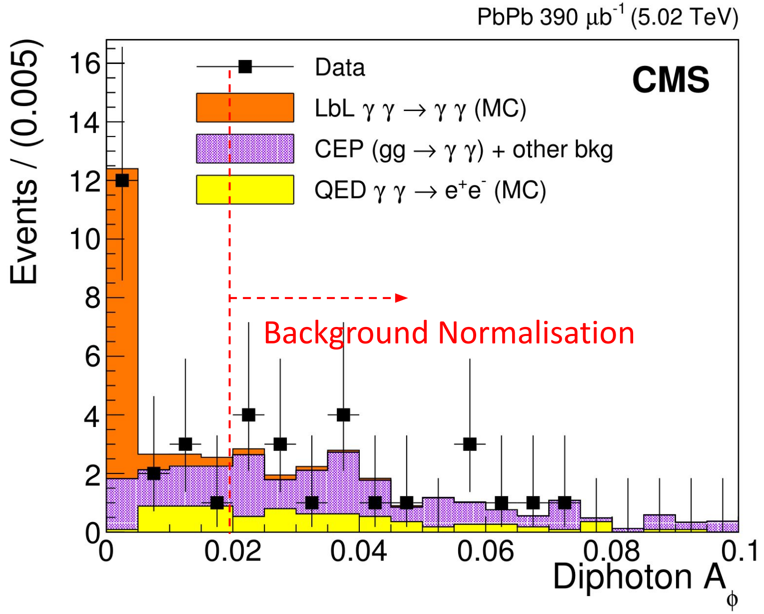
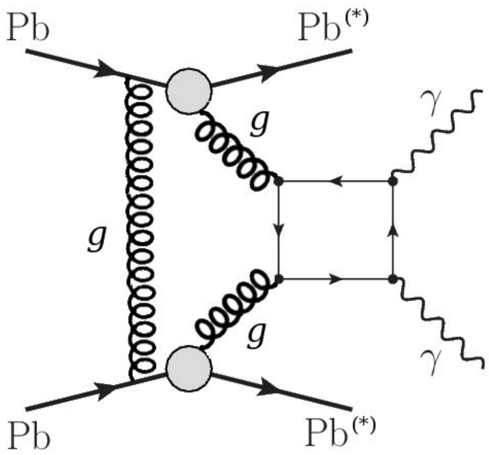
Selection criteria	Data	LbL MC	QED e^+e^- MC	CEP MC+other (normalised to data)
Charged exclusivity	648	11.1 ± 1.2 (theo)	10.3 ± 1.0 (stat)	24.3 ± 8.1 (stat)
Neutral exclusivity	108	10.8 ± 1.1 (theo)	10.1 ± 1.0 (stat)	23.6 ± 7.9 (stat)
Diphoton $p_T < 1$ GeV	39	10.2 ± 1.1 (theo)	7.7 ± 1.0 (stat)	19.5 ± 6.5 (stat)
Diphoton acoplanarity < 0.01	14	9.0 ± 0.9 (theo)	1.0 ± 0.3 (stat)	3.0 ± 1.1 (stat)

Background estimation

Central exclusive production + residual background

- Normalized from acoplanarity measured in data in control region $A_\phi > 0.02$, where LbyL is negligible.
- Acoplanarity cut ($A_\phi < 0.01$) removes most of the CEP background.
- **Estimated CEP + residual background after cuts: 3.0 ± 1.1 (stat).**





[Phys.Lett.B 797 (2019) 134826](#)

Estimation of QED $\gamma\gamma \rightarrow e^+e^-$ (Breit-Wheeler) process

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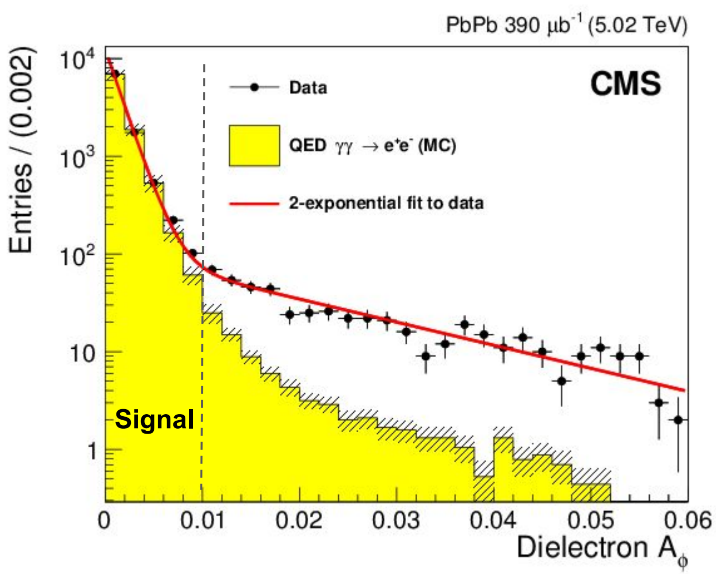
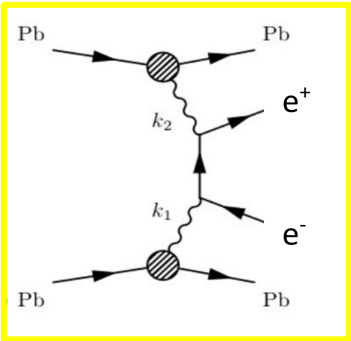
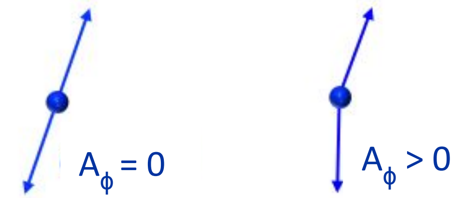
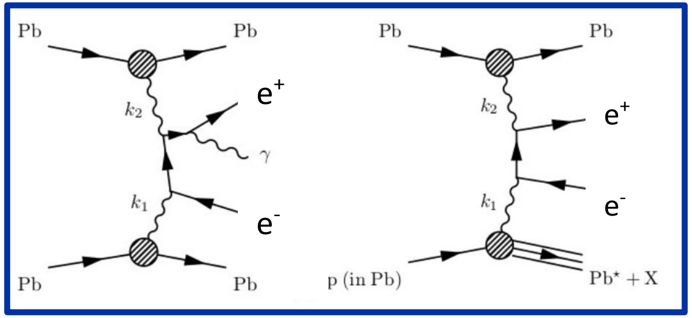




Acoplanarity
$A_\phi = 1 - (\phi^+ - \phi^-) / \pi$

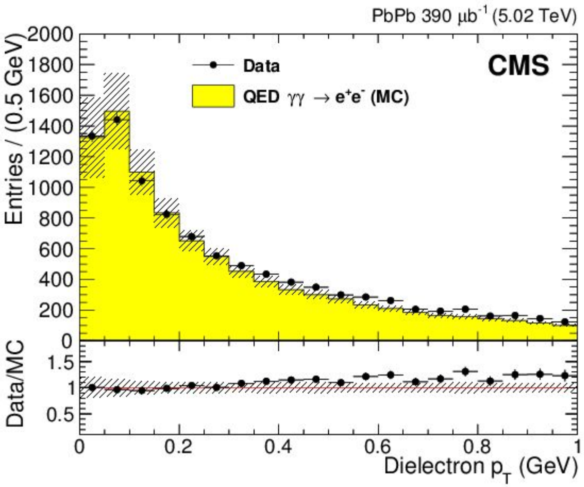


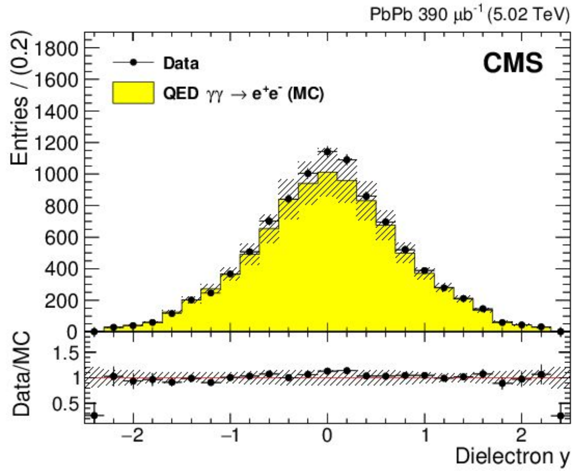


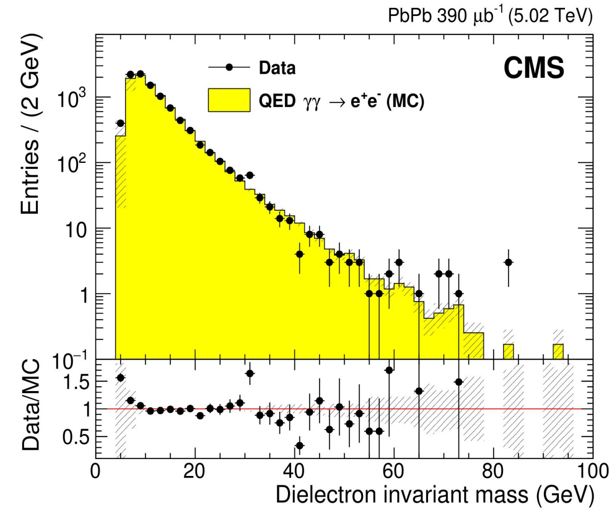
FSR **Dissociated Pb**

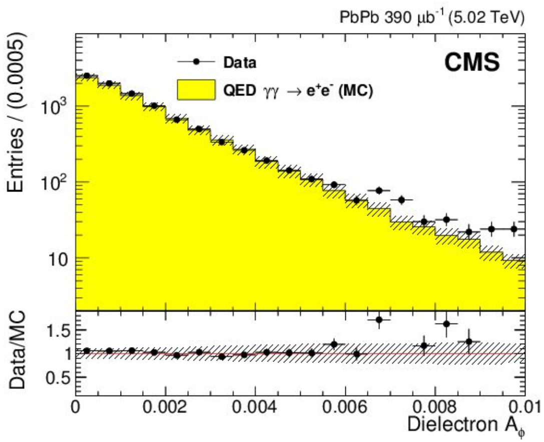
- Two exponentials fitted for signal and background
  - Background from FSR and Pb dissociation (excitation of one or both ions via photon absorption into giant Dipole Resonance (GDR) or higher excited state, emits neutron while decaying to ground state).
  - None of the available MC for PbPb models these backgrounds
- Purity estimated from the amplitude of two exponentials: 0.960 +/- 0.002 (stat), for A_ϕ <0.01

Data-MC comparison for QED γγ → e⁺e⁻ (Breit-Wheeler) process









- Control region: same analysis re-done with LbyL cuts, except requiring 2 opposite-sign electrons instead of γγ.
- Very good data-MC agreement over m_{e+e-} ~ 5-90 GeV.
- Confirms the quality of the electromagnetic particle reconstruction, exclusive event selection criteria and the MC predictions.

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kinematic distributions : photons

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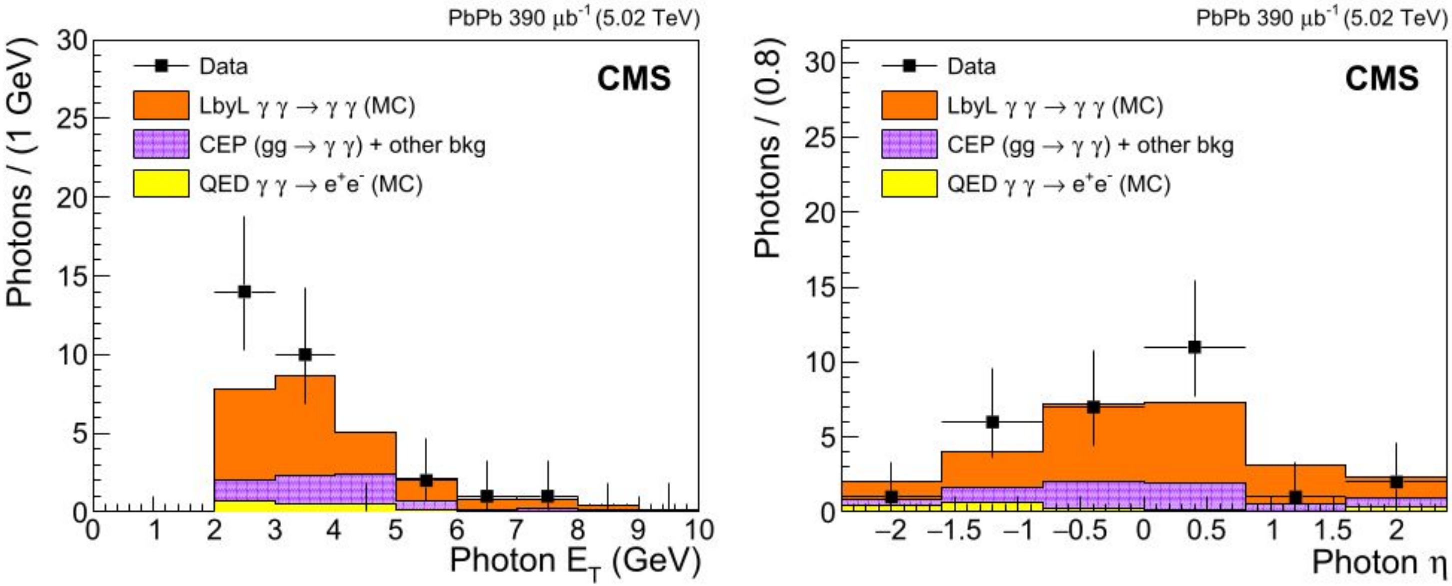
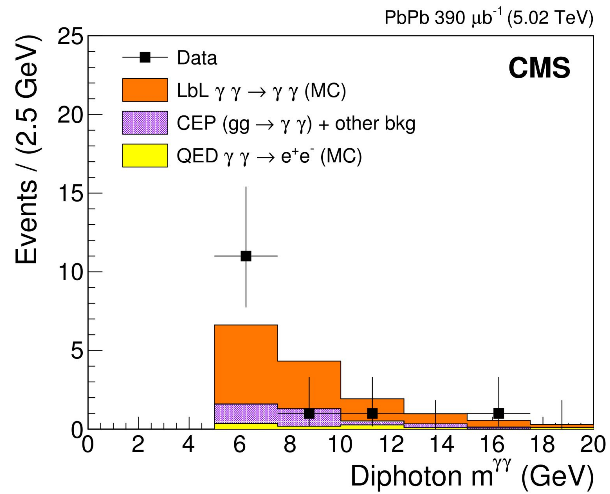
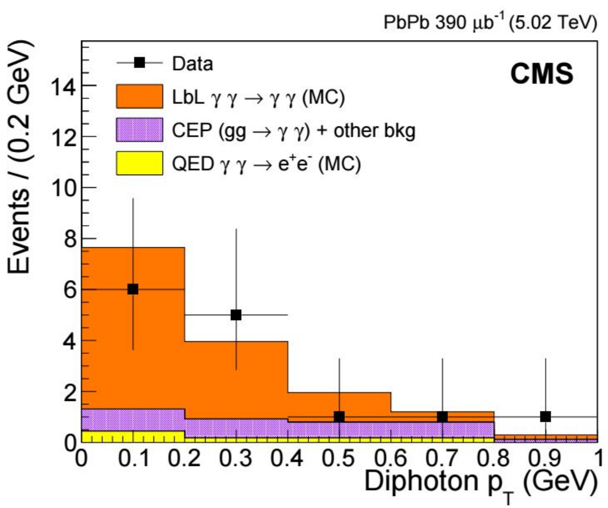
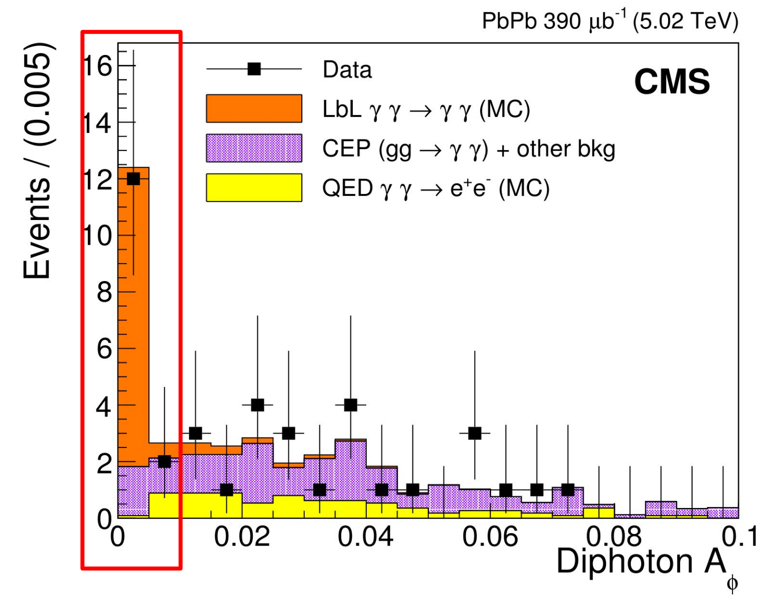


- Signal region: $|\eta| < 2.4$, $E_T > 2$ GeV, $m_{\gamma\gamma} > 5$ GeV, $A_\phi < 0.01$

kinematic distributions : diphotons







- Observed 14 candidate light-by-light events in signal region Diphoton $A_\phi < 0.01$
- Expected signal=9.0 ± 0.9 (stat.) and background 4.0 ± 1.2 (stat.)
- The measured yields and kinematic distributions are in good agreement with the MC.

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Results

LbyL to QED cross-sections ratio

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- $\sigma_{\gamma\gamma\to\gamma\gamma} / \sigma_{\gamma\gamma\to e+e-}$ extracted

  → helps cancel correlated theoretical uncertainties for the prediction
  → exclusivity (neutral and charged) uncertainties cancel out
  takes into account:
  -- efficiency of the trigger, γ/e reconstruction & identification efficiency
  -- stat. uncertainty on MC background estimation

LbyL significance from acoplanarity distribution : 3.7σ observed (3.5σ expected).

- Estimated cross section ratio:

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

Fiducial LbyL cross section

- Obtained by multiplying the cross section from STARLIGHT, simulation :$\sigma_{\gamma\gamma\to e+e-}$ = 4.82 ± 0.15 (th) mb
- **Measured: 120 ± 46 (stat) ± 28 (syst) ± 4 (th) nb** (Expected: 138 ± 14 nb from MADGRAPH)

Photon reconstruction and identification ($SF^{\gamma,\text{reco+ID}}$)	(2×9)%
Electron reconstruction and identification ($SF^{e,\text{reco+ID}}$)	(2×2.5)%
Trigger	12%
Size of simulated background samples	6%
Total	23%

Summary of light-by-light cross-sections

G. K. Krintiras, I. Grabowska-Bold, M. Kłusek-Gawenda,
É. Chapon, R. Chudasama, and R.Granier de Cassagnac
arXiv:2204.02845

- First time ever ATLAS and CMS results were combined for heavy ion collisions.
- σ^{fid}_{raw} measured cross-section by ATLAS and CMS
  - Differs in single photon E_T : ATLAS > 2.5 GeV, CMS > 2.0 GeV
- σ^{fid}_{cor} : Measured cross-sections scaled by an extrapolation factor to have similar fiducial region.
- E_T > 2.5 GeV, $|\eta| < 2.4$, $m_{\gamma\gamma} > 5$ GeV , $p_T(\gamma\gamma) < 1$ GeV, $A_\phi < 0.01$
- ATLAS: 120 ± 22 and CMS 91 ± 42 used in the average.

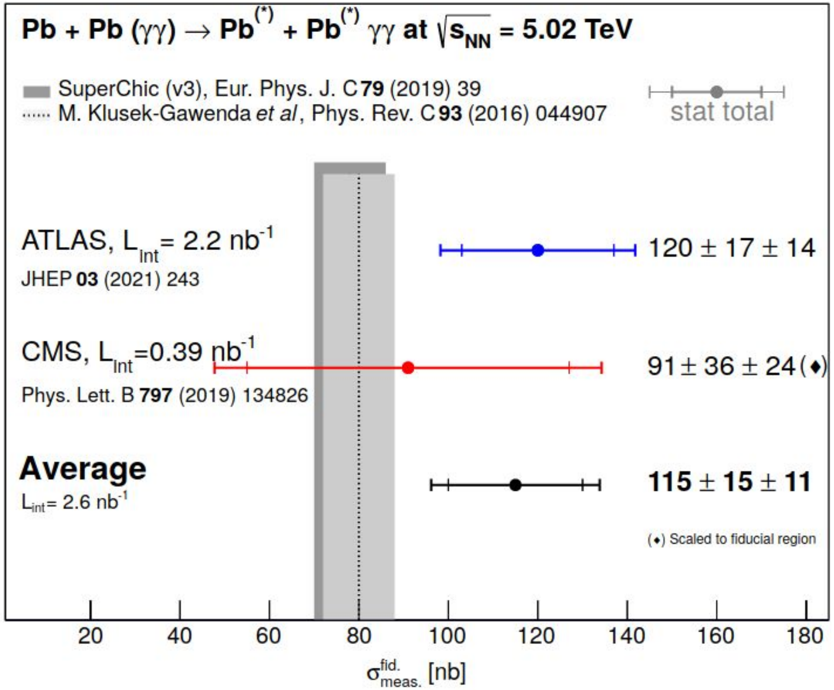
		ATLAS		CMS	
$\sqrt{s_{NN}}$	Year (Lumi. [nb^{-1}])	$\sigma^{fid.}_{raw}$ [nb]	$\sigma^{fid.}_{cor.}$ [nb]	$\sigma^{fid.}_{raw}$ [nb]	$\sigma^{fid.}_{cor.}$ [nb]
5.02 TeV	2015 (0.39–0.48)	70 ± 29 [11]	108 ± 45	120 ± 55 [12]	$\boxed{91 \pm 42^{\dagger}}$
	2018 (1.73)	78 ± 15 [15]	120 ± 23	—	—
	2015+2018 (2.2)	120 ± 22 [10]	$\boxed{120 \pm 22^{\dagger}}$	—	—

ATLAS + CMS averaged cross-section measurement

- Used Best Linear Unbiased Estimator (BLUE v2.4.0) to average the cross-sections.

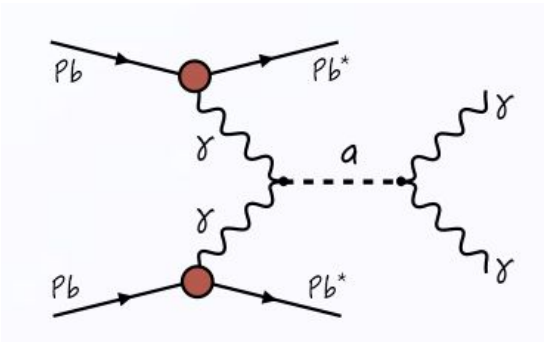
$$\sigma^{\text{fid.}}_{\text{meas.}} = 115 \pm 15\,(\text{stat.}) \pm 11\,(\text{syst.}) \pm 3\,(\text{lumi.}) \pm 3\,(\text{theo.})\ \text{nb}$$
$$= 115 \pm 19\ \text{nb},$$

- The averaged cross-section is consistent within ~2σ with standard model predictions.
- It is currently limited by the statistical uncertainty.



arXiv:2204.02845

Searches for axion-like particles in ultra-peripheral collisions



- Exclusive γγ → γγ is sensitive to physics signals beyond the SM such as resonant axion-like particles (ALPs).
- Pseudo-scalar particles (with mass vs. SM-coupling relation not fixed, different from QCD-axions).
- ALPs occur in many extensions of SM.
- Huge photon fluxes from PbPb UPC: used to search for ALPS with dominant coupling to photons.

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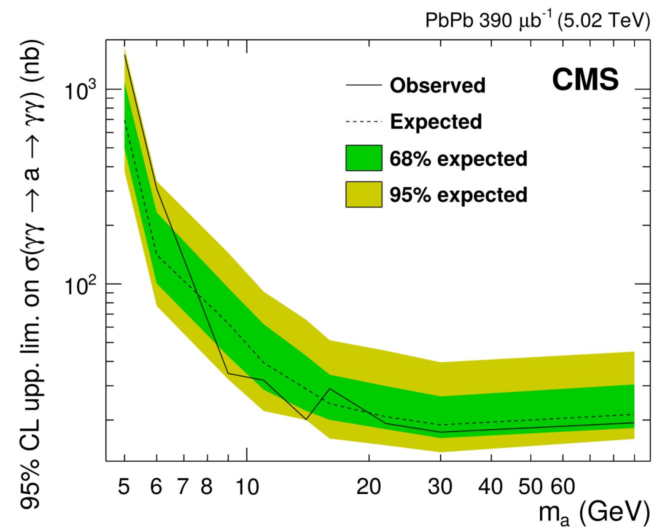
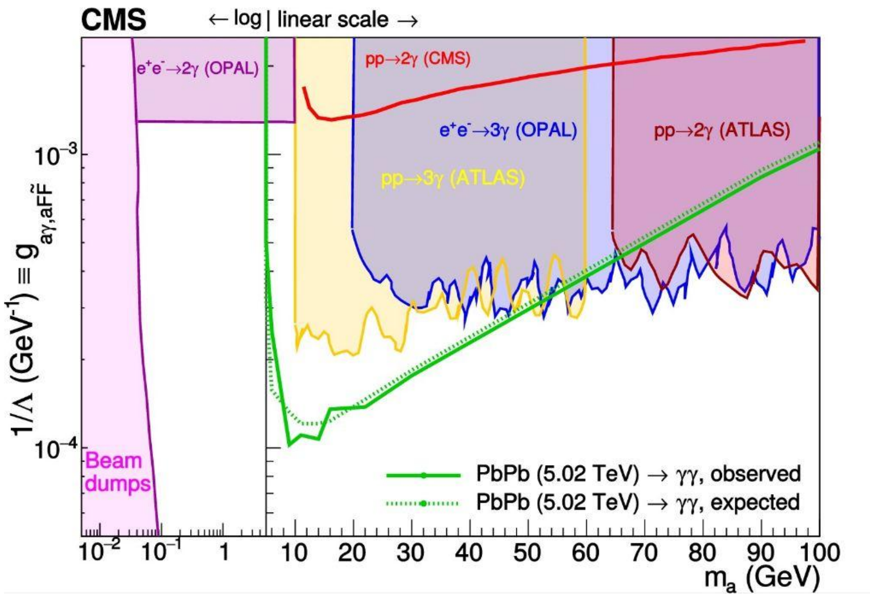
- Measured diphoton invariant mass distribution used for the search, LbyL, QED, and CEP processes considered as background.
- ALPS for mass: 5-90 GeV generated with STARLIGHT
- Upper limits for σ (γγ→a→γγ) at 95% confidence level extracted assuming 100% a → γγ branching ratio.

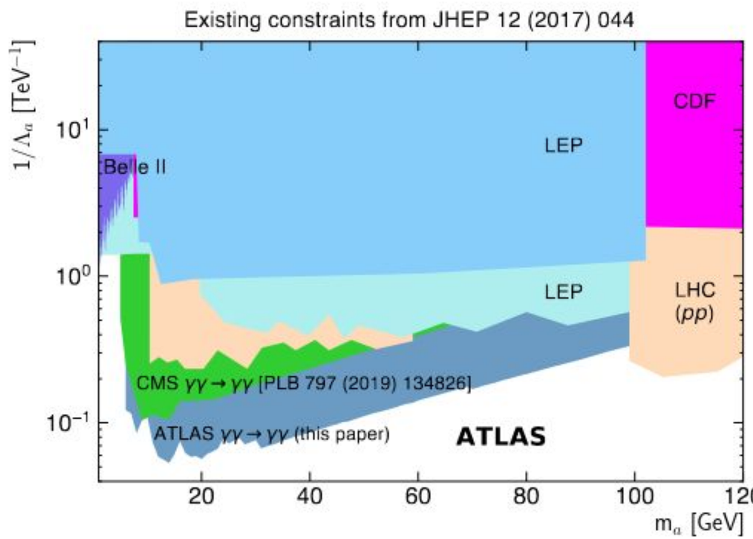


No significant ALP excess observed in data above LbL+ backgrounds

Axion like particle search at LHC

- CMS (PbPb UPC 2015) set first most competitive ALPs limits in $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ for masses 5-90 GeV (superseded now by ATLAS)
- Cross-sections above 2 to 70 nb are excluded at the 95% CL in 5-100 GeV mass interval by LHC.
- CMS analysis ongoing with 2018 data → stay tuned!





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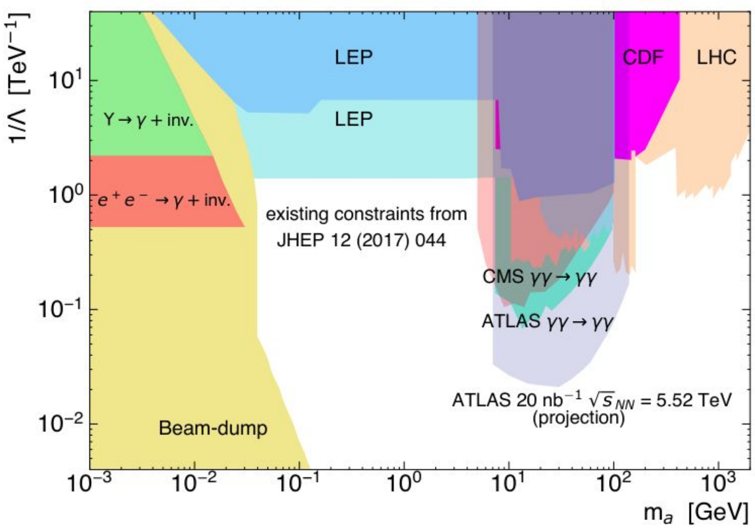
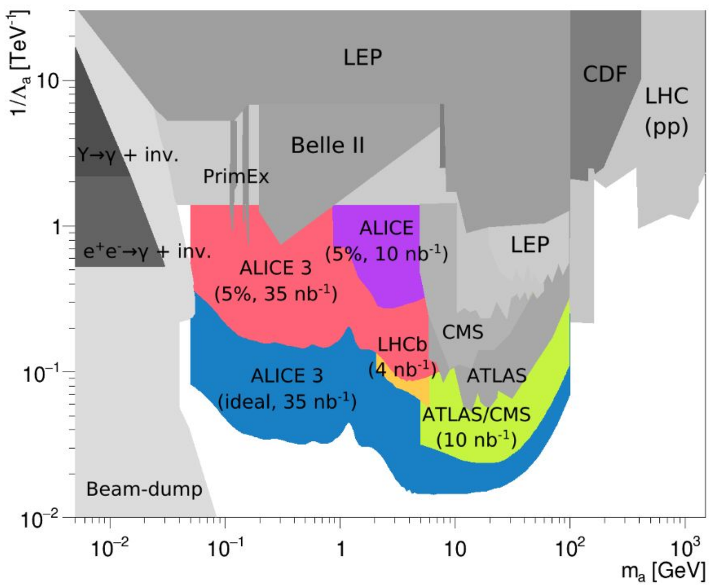
Future prospects

- The measurement of light-by-light scattering would greatly benefit from the increased luminosity and triggering capabilities in upcoming runs.
- ALICE and LHCb experiments can improve these limits for masses below 5 GeV in the future.



[ATLAS + CMS Snowmass white paper]

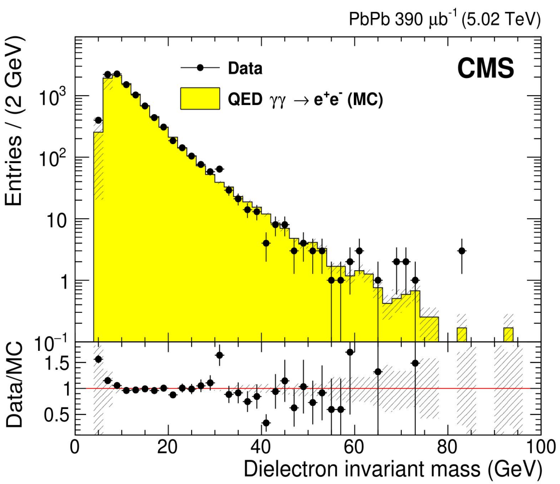


[arXiv: 2203.05939]

Summary

QED Breit-Wheeler process analysis:

- Very good data-MC agreement over m_{e+e-} ~ 5-90 GeV for Breit wheeler process.



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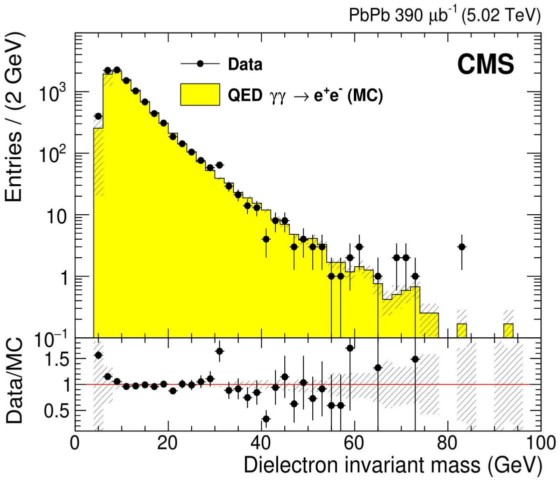
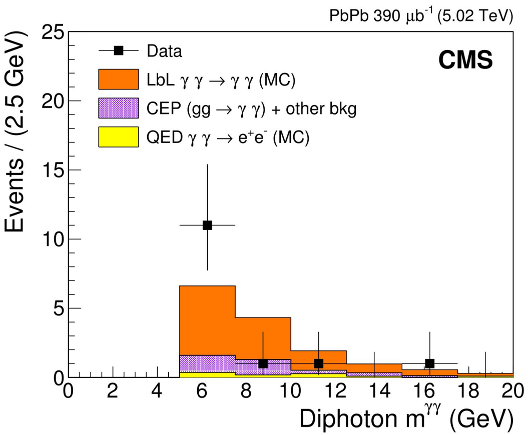
Light-by-Light analysis:

- Evidence of LbL scattering: 3.7 sigma significance observed at CMS using 2015 PbPb collisions.





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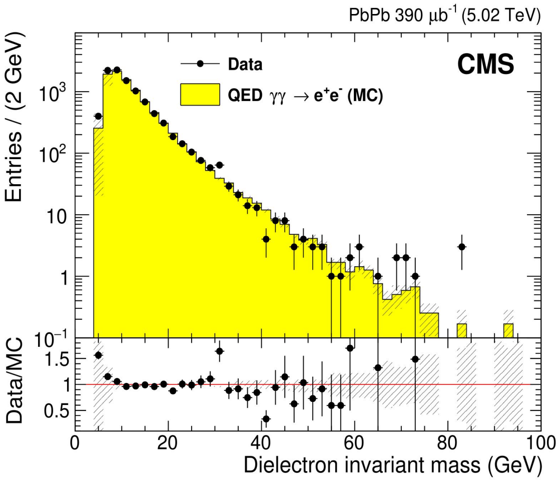
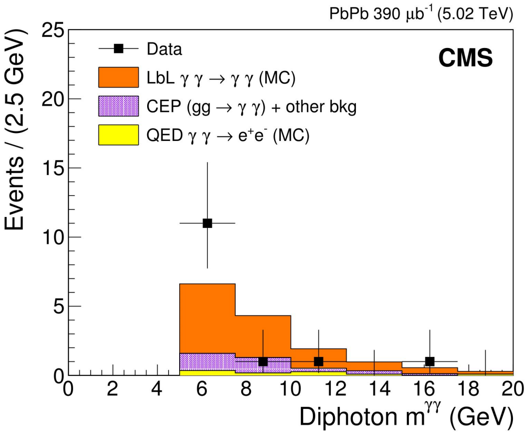
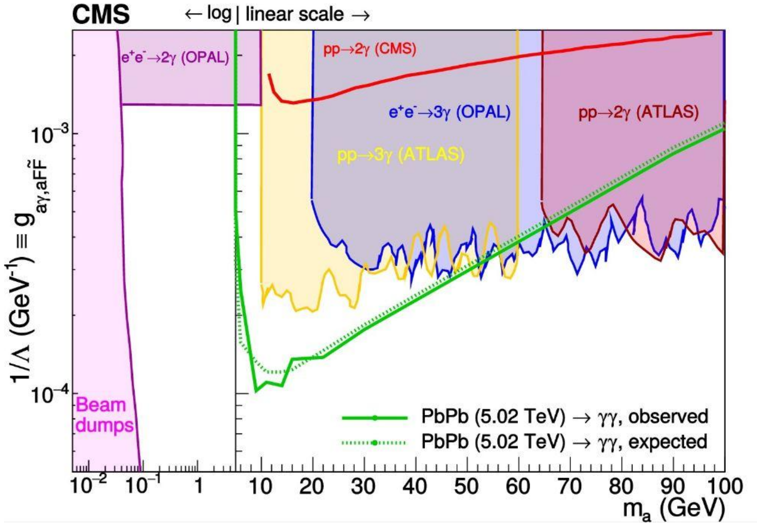
Searches for ALPs:

- No significant excess in $m_{\gamma\gamma}$ distribution.
- Limits on axion-like particles for masses 5-100 GeV.

Data analysis with 2018 data ongoing, stay tuned!



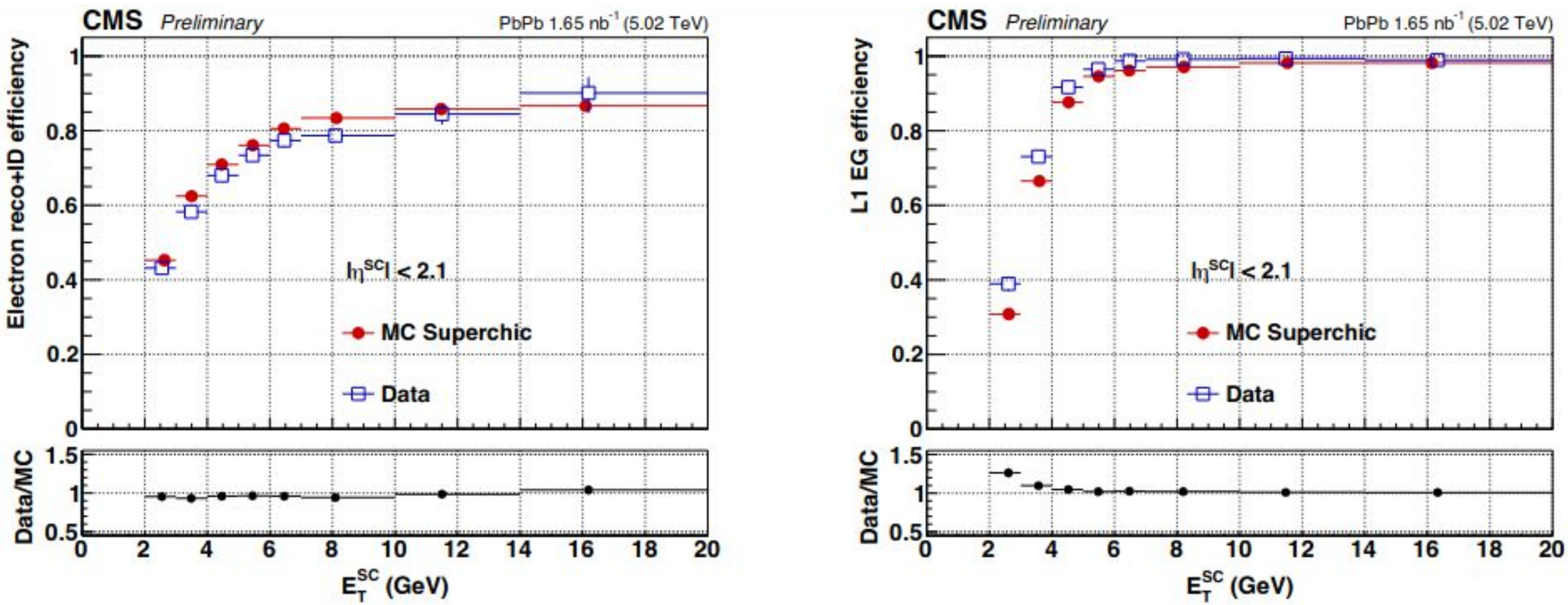




Backup

Electron and L1 EM cluster efficiency for 2018 PbPb

CMS DP -2022/006



Comparison of electron reconstruction+identification (left) and Level-1 electromagnetic cluster (right) efficiencies for data (blue) and Superchic [3] simulation (red) as a function of supercluster E_T for $|\eta| < 2.1$ derived in 2018 PbPb ultraperipheral collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The efficiencies are estimated using the tag and probe technique.

Superchic v3

European Physical Journal C 79 (2019) 39

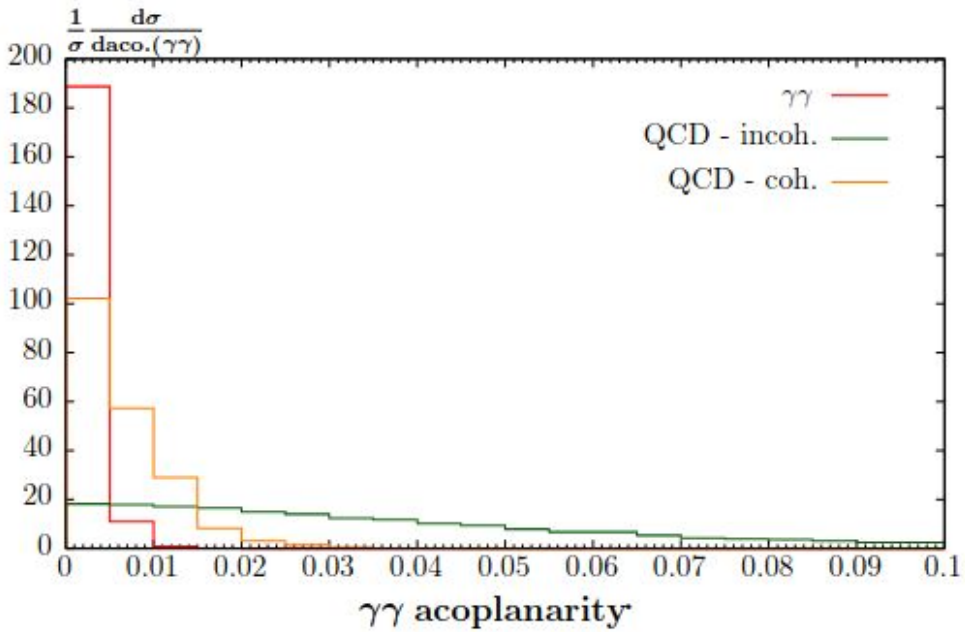


Fig. 9 Normalized differential cross sections for exclusive and semi-exclusive diphoton production with respect to the diphoton acoplanarity. The QED-initiated and QCD-initiated (both coherent and incoherent) processes are shown