Search for axion-like particles in PbPb collisions at the LHC

Dr. Ruchi Chudasama
DHEP, TIFR

Based on the results from
PRL 118, 171801 (2017)
Phys Lett B 797 (2019) 134826
JHEP 03 (2021) 243

tata institute of fundamental research

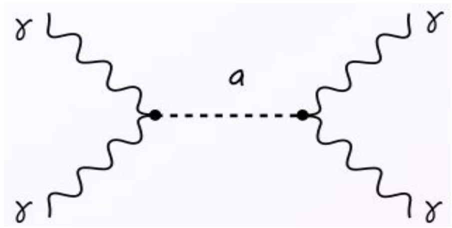
Free Meson seminar
18.11.2021

Axion-like particles

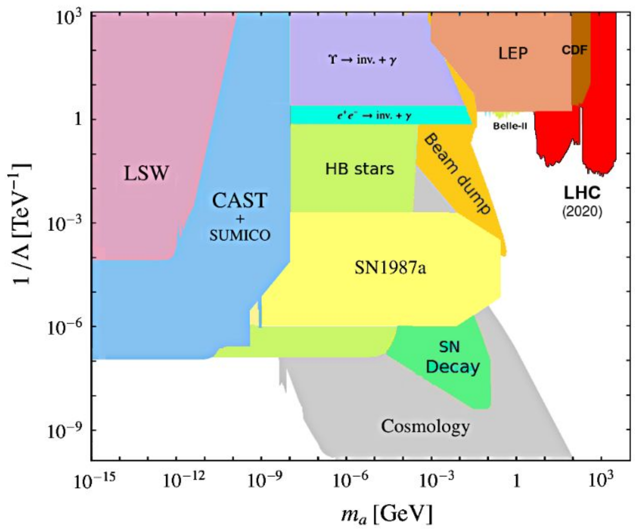
- Axions are scalar/pseudo-scalar complex fields, postulated to solve strong CP problem in QCD
- Axion-like particles (ALPs) : Pseudo-scalars can couple to SM particles, where mass coupling relation is not fixed.
- The coupling of the pseudoscalar ALP to photons is described by a Lagrangian

$$\mathcal{L} = \frac{1}{2}\partial^{\mu} a \partial_{\mu} a - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

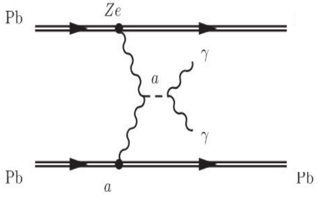
m_a : axion mass, $g_{a\gamma}$ coupling constant to photon



- $\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta}$ implies that ALPs can be produced by photon–photon fusion and can decay into a diphoton system.



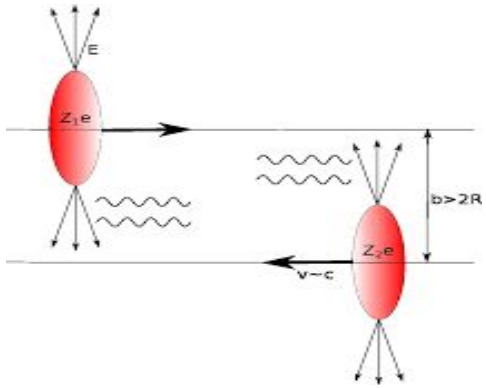
- Search for ALPs in ultra-peripheral collisions (UPC) heavy ion collisions.



Comparison of Heavy-ion UPC vs pp collisions

- Ultra-peripheral collisions (UPCs) : $b > 2 \cdot R_{Pb}$
- Passing heavy ions generate huge electromagnetic fields (10^{14} T)

- Electromagnetic field can be treated as quasi real photons.
  - Heavy nuclei ⟶ large photon flux ($\propto Z^2$)



	Pb-Pb collisions	p-p collisions
Center of mass energy	$\sqrt{SNN} = \sqrt{S_{pp}} * Z/A$ = 5.02 TeV	$\sqrt{S_{pp}}$ = 13 TeV
Luminosity	(390 + 1600) μb^{-1} (2015 + 2018)	~ 160 fb^{-1}
Enhancement	5 X 10^7 (Z^4 wrt pp)	1
Max γ energy ($\propto$1/R)	~ 170 GeV (R~ 7 fm for Pb)	~ 1 TeV (R~ 1 fm for p)
Background	Clean exclusive events	Large pile-up
Region of sensitivity	m_a ~ 10 GeV	m_a ~ 100 GeV

Today we discuss only public results by ATLAS and CMS collaborations.

ALP production in UPC

- For UPC, total cross section for ALP production in the narrow width approximation is

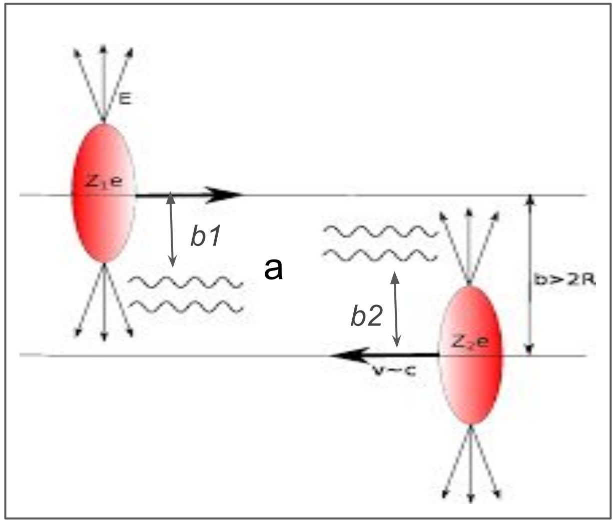
$$\sigma_a = \frac{8\pi^2}{m_a}\Gamma(a \to \gamma\gamma)\mathcal{L}_{\gamma\gamma}(m_a^2)$$

- Where $\Gamma(a \to \gamma\gamma) = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$ is the decay width of ALP into two photons.

- $\mathcal{L}_{\gamma\gamma}(m_a^2)$ is the photon-photon luminosity, evaluated at m_a

$$\mathcal{L}_{\gamma\gamma}(\hat{s}) = \frac{1}{\hat{s}}\int d^2\vec{b}_1 d^2\vec{b}_2 dE_1 dE_2 N(E_1, \vec{b}_1) N(E_2, \vec{b}_2) \times P(|\vec{b}_1 - \vec{b}_2|)\delta(\hat{s} - 4E_1E_2),$$

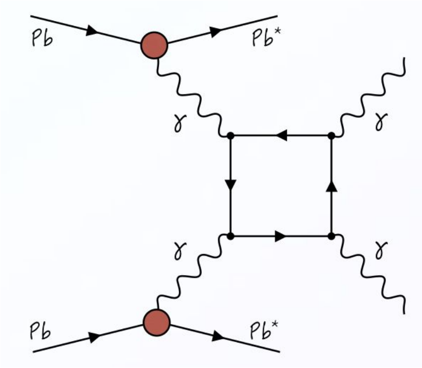
  - $b_{1,2}$ are impact parameters (ion centers to interaction point)
  - $E_{1,2}$: energies of incoming photon
  - $N(E_{1,2}, b_{1,2})$ photon flux function
  - P is the probability for the absence of hadronic interactions.



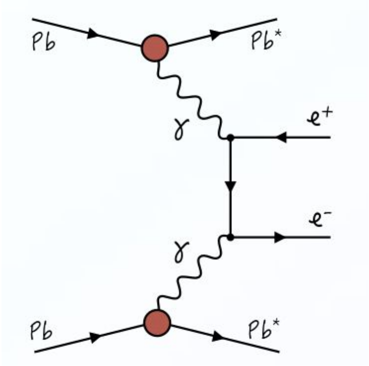
- In order to ensure the Ultra-peripheral collisions:
  - The integral is restricted to $|b_{1,2}| > R_A$
  - Virtuality of each photon $Q = \sqrt{(E^2 - \vec{p}^2)}$, needs to be smaller than $1/R_A$ in order to probe it as a whole electrically charged object.

Analysis strategy: main features

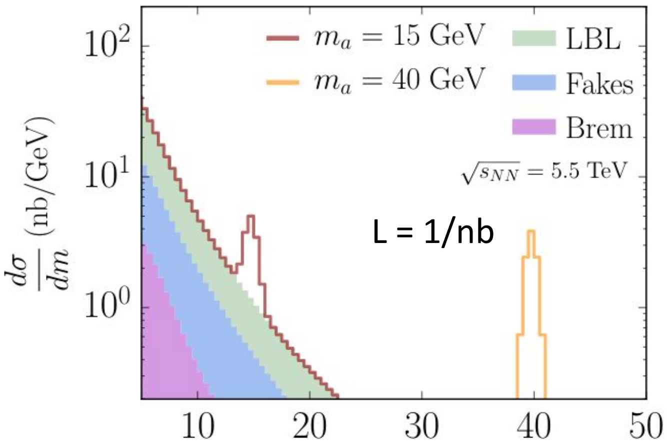
- The production of an axion-like particle as a resonance in the γγ → a → γγ is expected to modify the rates of the light-by-light (LbyL) scattering process.
- ALPs of 2 typical mass values: m_a ~ 15 GeV (Λ = 17 TeV) and m_a ~ 40 GeV(Λ=8 TeV) has been considered, taking into account energy resolution of 0.5 GeV, cross-section 5 nb.
- **Same final state as LbyL (γγ → γγ) process, recently observed by CMS and ATLAS in PbPb UPC.**
- **Fake: γγ → e^+e^- undergoes pair production, electron and positron are misidentified as photon.**
- Brem: hard bremsstrahlung from electron from **γγ → e^+e^-** process



LbyL (γγ → γγ) process

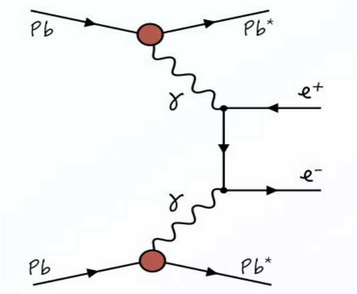


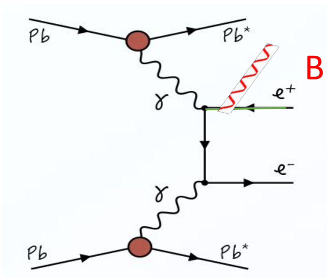
QED (γγ → γγ → e^+e^-) process

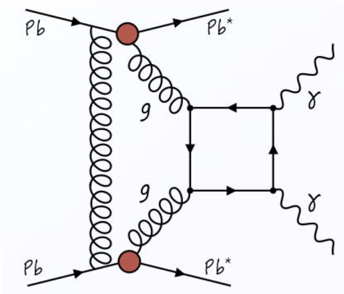


PRL 118, 171801 (2017)

Background contributions







Fake + Brem from Exclusive QED $\gamma\gamma \rightarrow e^+e^-$ process

- $\sigma_{\gamma\gamma \rightarrow e+e-}$: 20 mb without any fiducial cuts
- Fake: Both electron and positron are misidentified as photons.
- Brem: Electrons may be misidentified as photons if they undergo hard bremsstrahlung where neither of the track get reconstructed.
- Generated with STARLIGHT.
- Can be reduced with tight photon identification cuts.

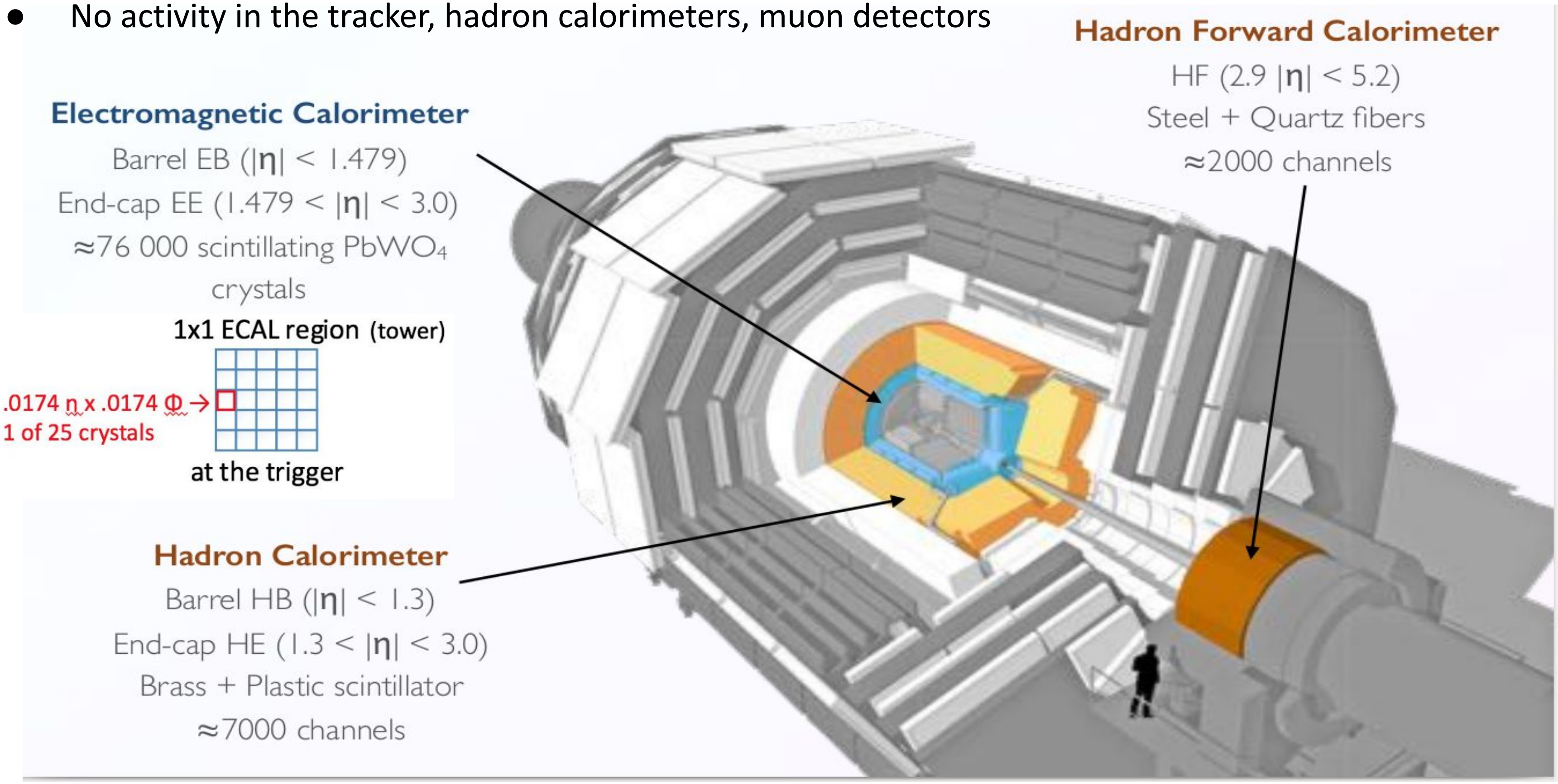
Central exclusive production (CEP) + residual background

- Generated with SUPERCHIC
  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.

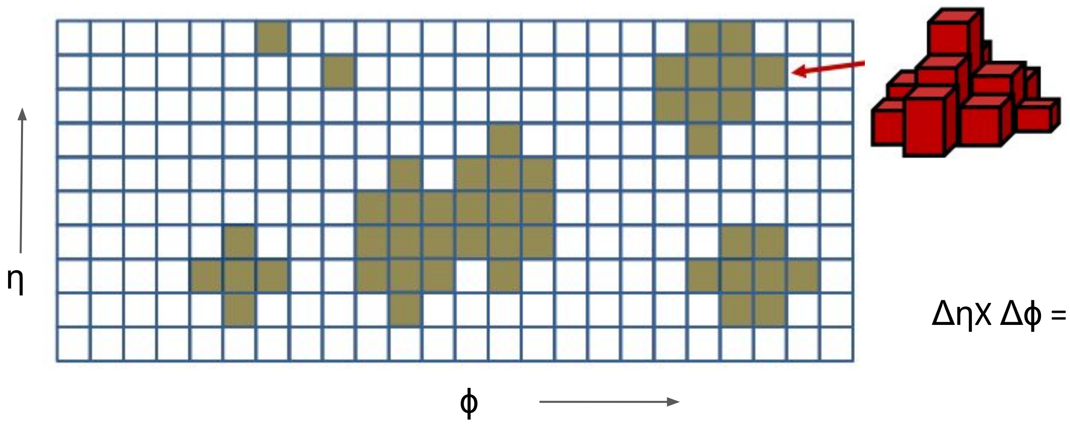
Experimental search at the LHC

The CMS detector

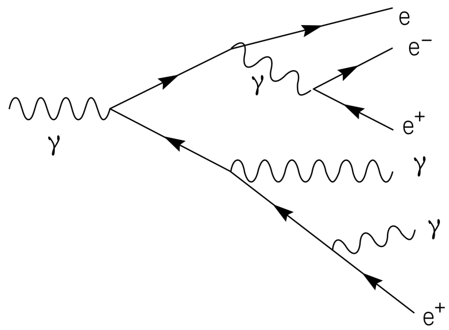
- Photons from light-by-light scattering measurable over |η|< 2.5, barrel and endacp calorimeters
- Exclusivity condition over |η|< 5.2, utilizing forward calorimeters as well
- Final state - just two tower in the ECAL
- No activity in the tracker, hadron calorimeters, muon detectors

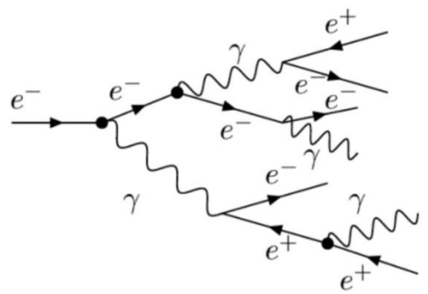


Reconstructing e & γ in the ECAL



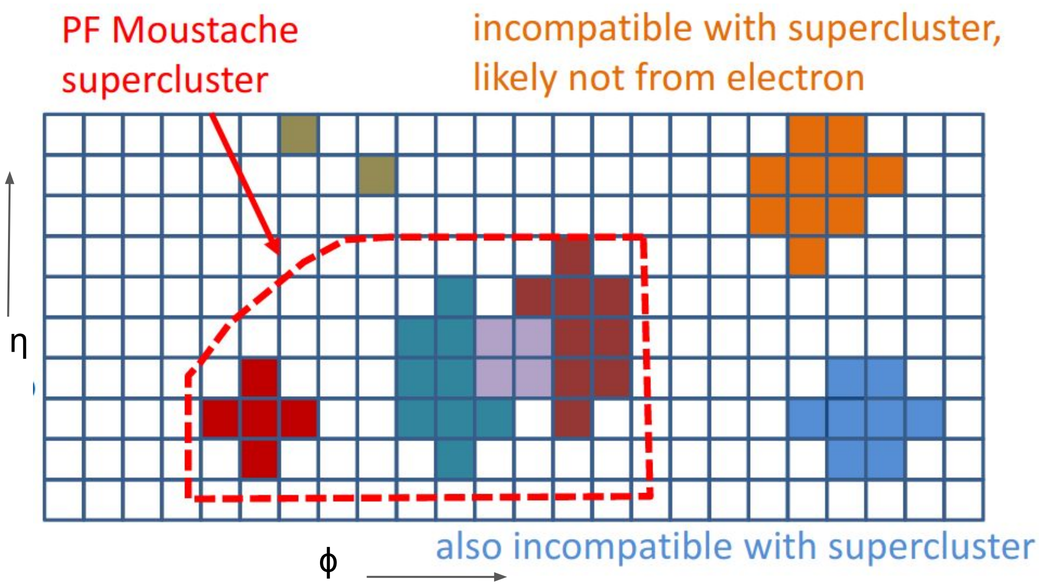
$\Delta\eta \times \Delta\phi = 0.0174 \times 0.0174$

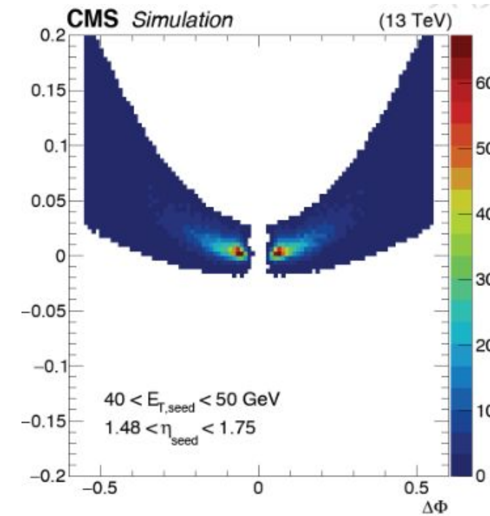




- Construction of individual particles from the reconstructed energy deposits in calorimeter crystals.
- Starts by grouping together the crystals with energy > ~ 80 MeV in EB and ~300 MeV in EE (2-3 times bigger than the electronic noise).
- **Seed cluster** : the one with maximum energy deposit in specific region with $E_T > 1$ GeV
- Find other clusters nearby the seed cluster to form a **supercluster** → **Mustache SC**

Mustache Supercluster

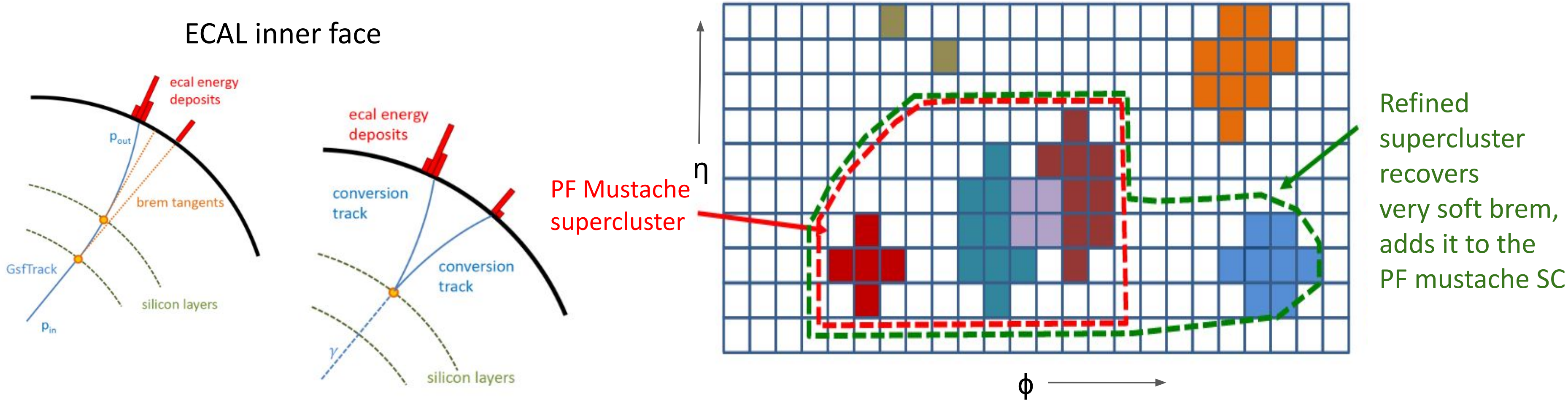




Mustache Supercluster

- **Mustache Supercluster :** collect cluster around seed cluster to make supercluster
  - Photon converts via pair production (losses recovered.)
  - Electrons bend in phi, Bremsstrahlung from electron is tangential to the electron trajectory is recovered

Photon reconstruction



- **Refined Supercluster:** Brem cluster which are much separated from electron and not collected by *Mustache SC* is recovered by *Refined SC.*
  - The points at which track intersects a layer, a tangent is drawn and extended to the ECAL surface
  - The cluster falling at tangent is included in the mustache SC to give the final refined SC
  - Gaussian sum filter (GSF) tracking for electrons.
  - In global event description all electrons and photons are made of these final refined SCs

Data sample @ CMS in LHC Run 2

Data

PbPb @ 5.02 TeV (2015, 2018)

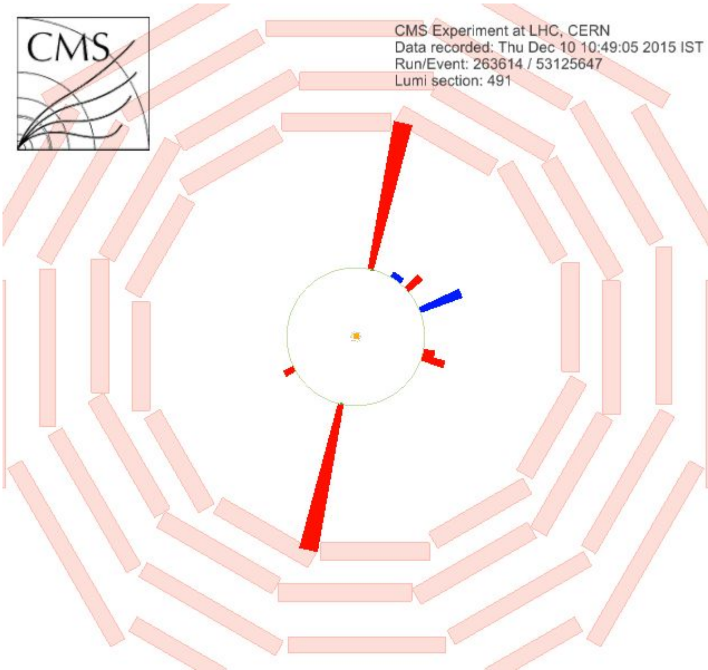
Total integrated luminosity L_{int} = 390 μb^{-1} , 1600 μb^{-1}

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

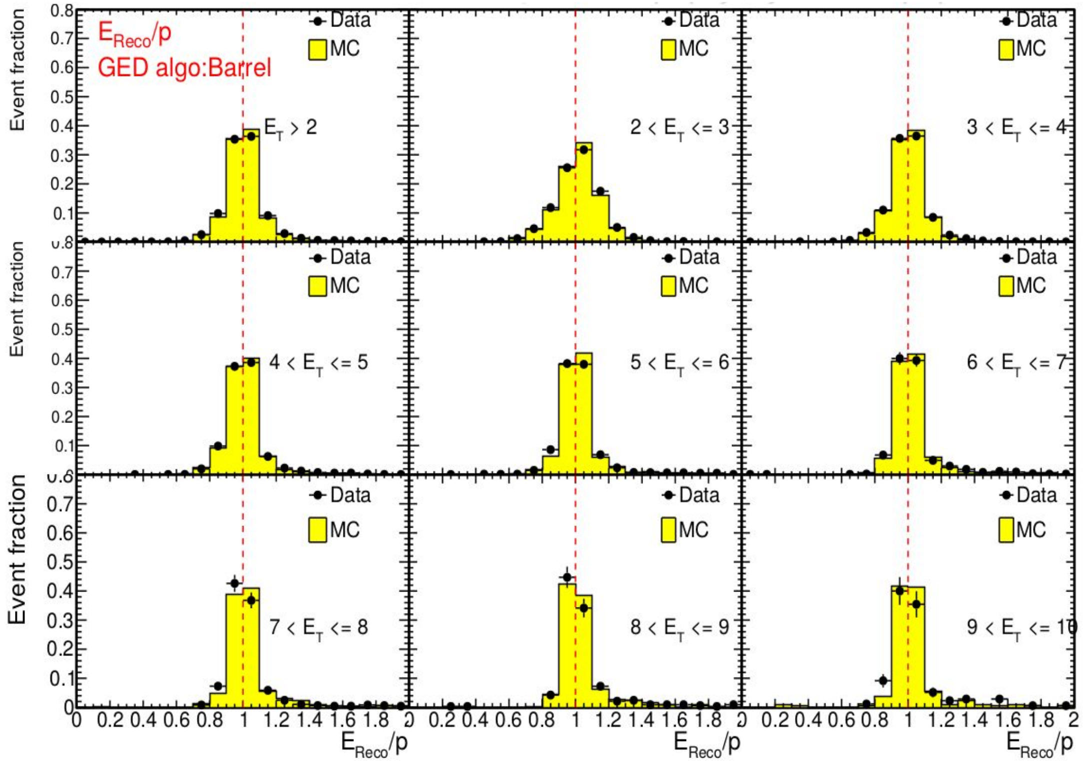
- Photons of interest in the low E_T (2-10 GeV) region,
- Standard CMS high-E_T e/γ reconstruction (E_T > 10 GeV) retuned for this analysis,
- Identification of photons:
  - removal of decay photons from neutral hadrons using cut on shower shape
  - cleaning of unusually high (spikes) energy deposits 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).

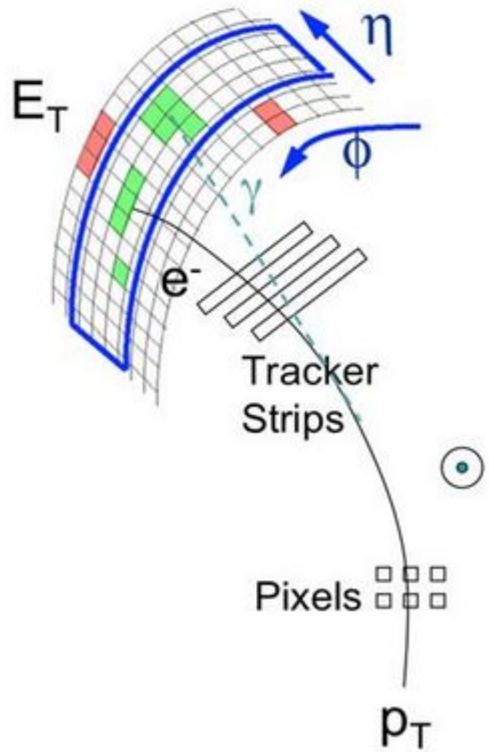


Results based on CMS 2018 data are not public as yet → not presented here.

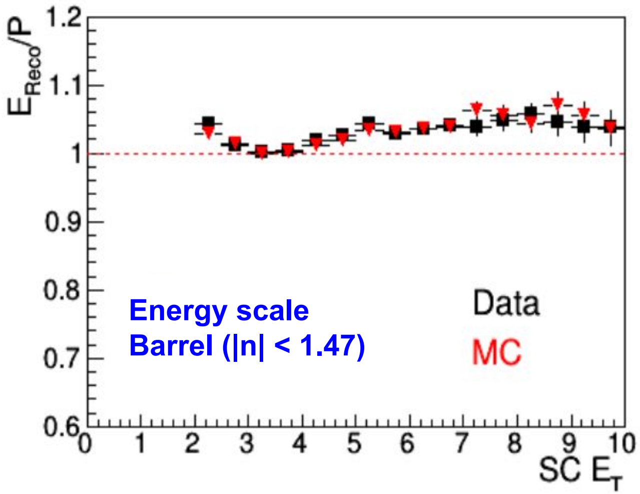
Photon energy scale and resolution

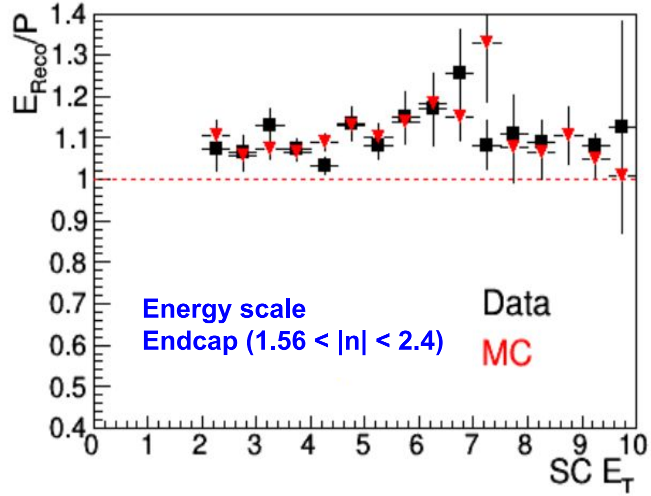
- Energy scale and resolution studied with QED $\gamma\gamma \rightarrow e^+e^-$ process with data-driven method, use E/p variable
  - E – energy of supercluster , p : momentum of track ,
  - E/p fitted with Gaussian function
  - E/p should be ~ 1 for electron, neglecting e mass.



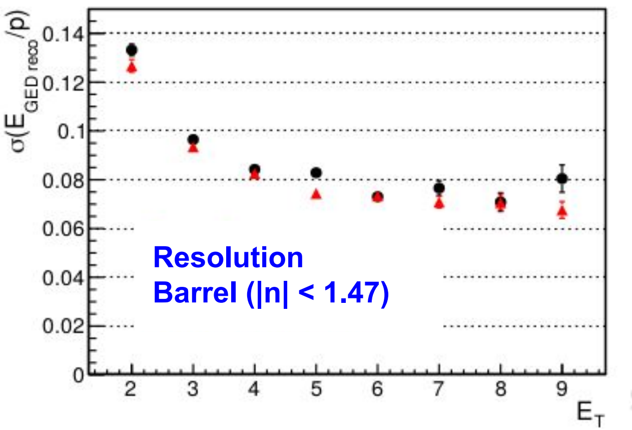


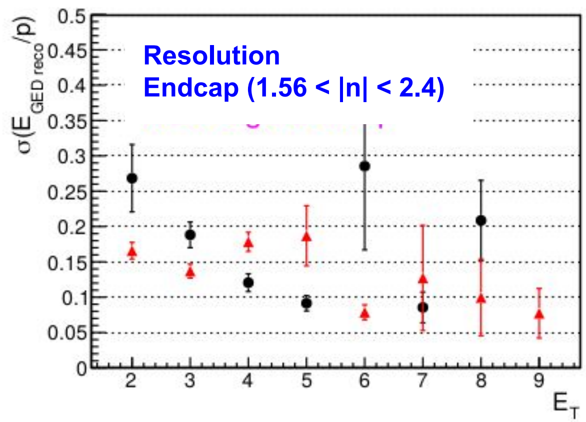
Photon energy scale and resolution





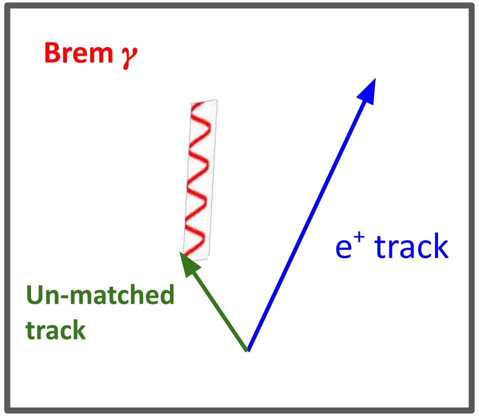
- The energy scale accounts for imperfect response of the detector.
- Derived energy scale is within 5% (15%) of the unity in barrel (endcap) region.



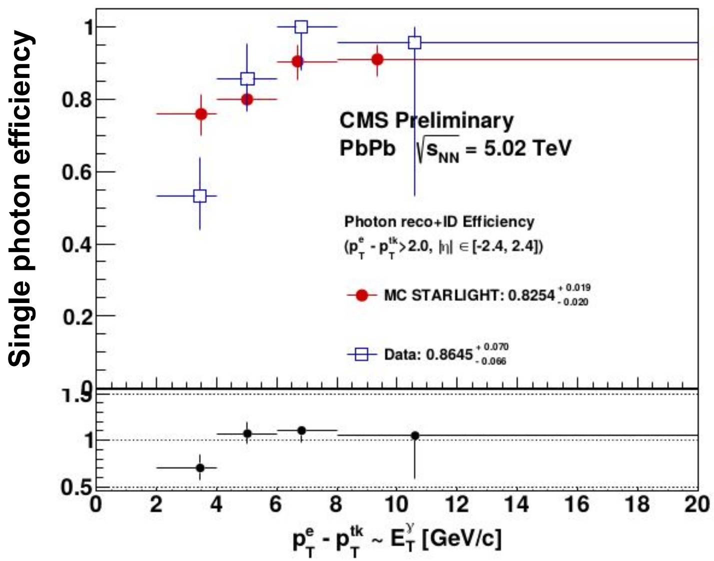


- Resolution ~ 14 (28) % in barrel (endcap) region at lower E_T.
- Eg., E_T = 2 GeV is measured with an uncertainty of ~0.3 (~0.5) GeV

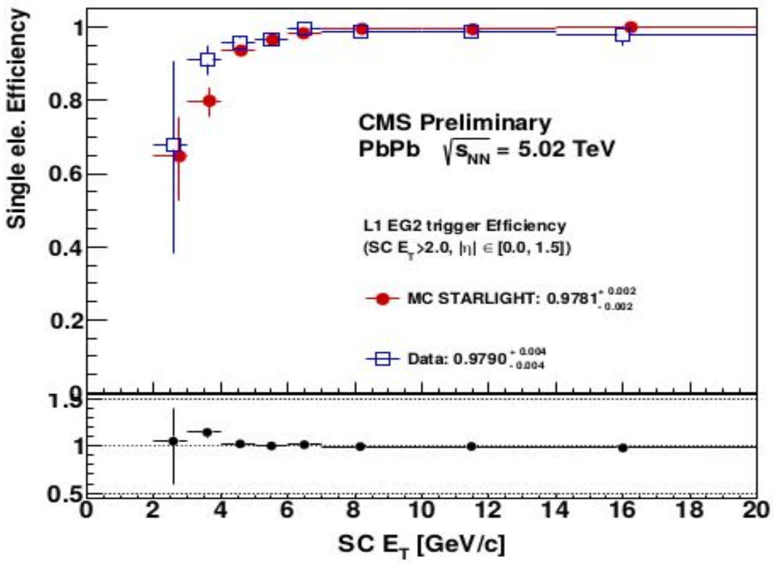
Photon reconstruction and identification efficiency

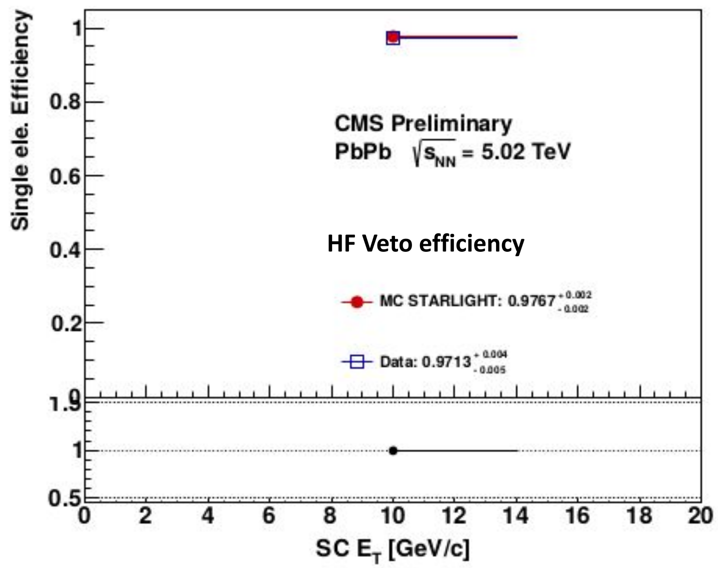


- QED $\gamma\gamma \to e^+e^-$ events: one of the electrons emits a hard brem γ
- Back-to-back electrons have almost equal energy
- Each event contains: 1 Brem γ + 1 e track + 1 track not matching SuperCluster in ECAL
- Tag: Electron ($p_T >$ 5 GeV) passing ID, matched to L1 EG5 seed in $\Delta r < 0.5$
- Probe: unmatched track with $p_T < 3$ GeV, Acop (tag, probe) < 0.5
- Passing probe: exactly one γ ($p_T >2$ GeV) within $\Delta r < 0.5$ of the unmatched track



Photon trigger efficiency





- Trigger consists of two parts:
  - 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).

- Broadly, efficiency for triggering photon is ~ 97% above 5 GeV
  efficiency for vetoing energy deposit in forward calorimeter is ~ 97% above 10 GeV

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 foward calorimeters ($|\eta| < 5.2$) far from photon candidates:

→ Remove if $|\Delta\eta| > 0.15$, $|\Delta\phi| > 0.7(0.4)$ in EB (EE).

- All towers in hadron calorimeters should be comparable with the expected noise (~ 3 GeV)

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

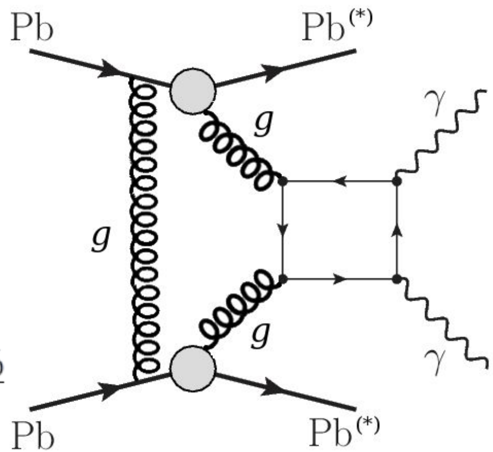
Other selection:
$p_T(\gamma\gamma) < 1$ GeV reduced all non-exclusive backgrounds.

Cut applied	Data	LbyL MC	QED MC	CEP MC
Trigger	2.7067e+06	17.59	20058	43.3
Two photons within acceptance	141476	14.11	15776	31.6
Photon ID	121713	13.8	15486	30.6
Invmass > 5 GeV	77102	13.4	15286	28.3
Charged exclusivity	648	11.1	10.3	24.3
Neutral exclusivity	108	10.8	10.1	23.6
Diphoton pT < 1 GeV	39	10.2	7.7	19.5
Acoplanarity < 0.01	14	9.0	1.0	3.0

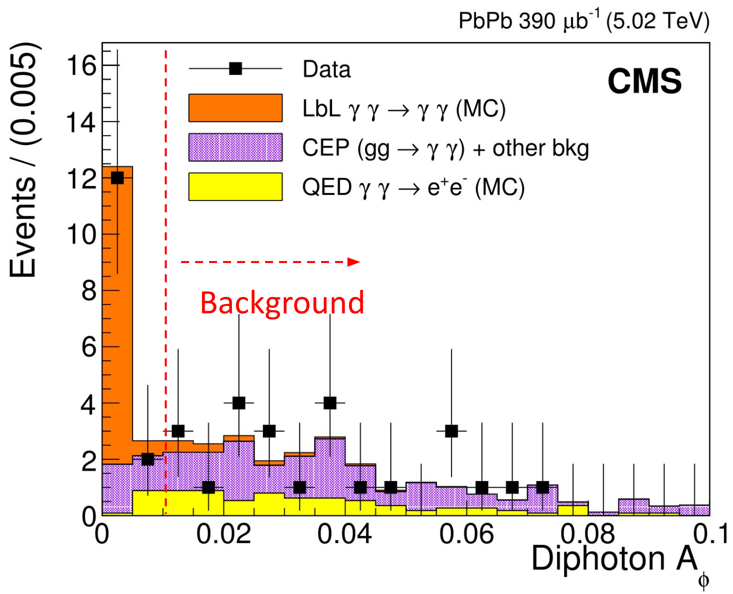
Background estimation

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).**

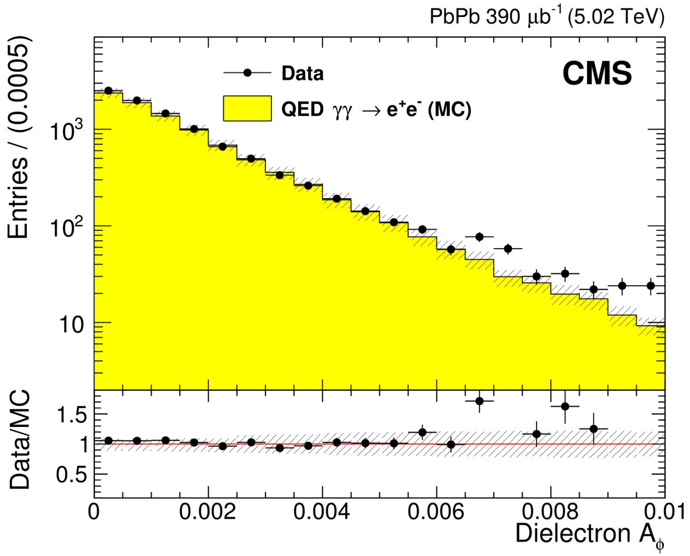


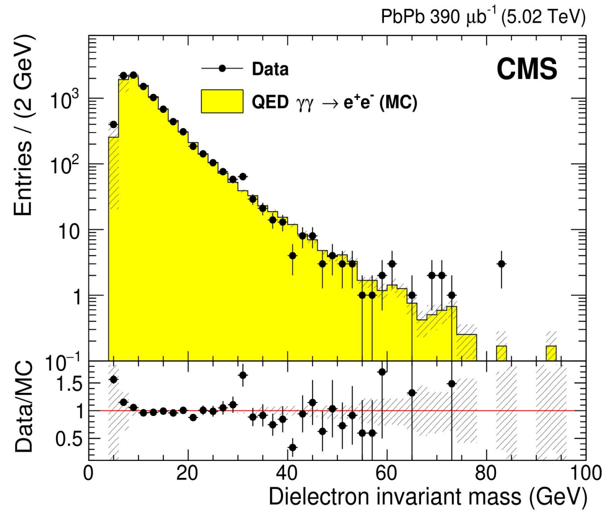
Phys.Lett. B797 (2019) 134826

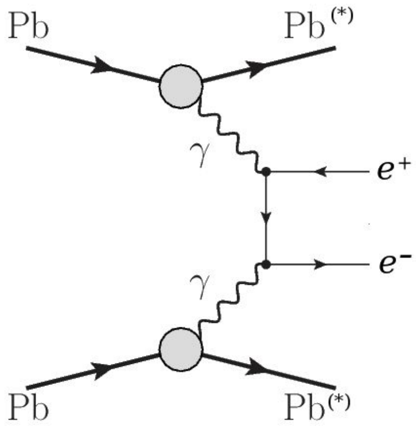


QED Background estimation

- 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.







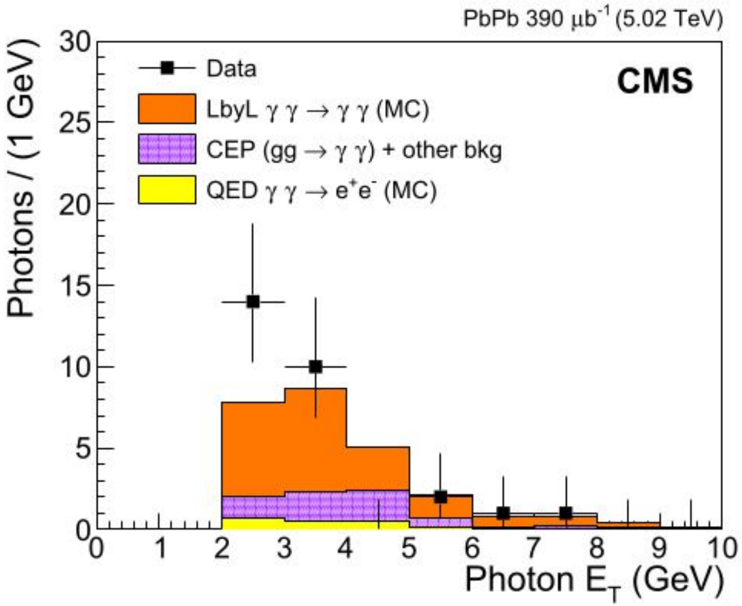
Confirms quality of e/γ reco. validity of exclusive event selection criteria, as well as of MC predictions for PbPb UPCs.

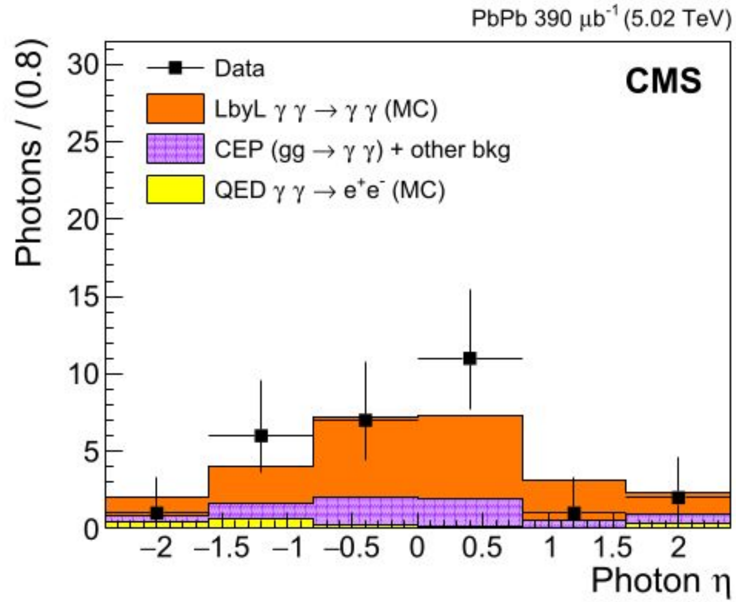
QED background in LbL signal region: 1.0 ± 0.3 (stat).

Phys.Lett. B797 (2019) 134826

kinematic distributions : photons

PLB 797 (2019) 134826

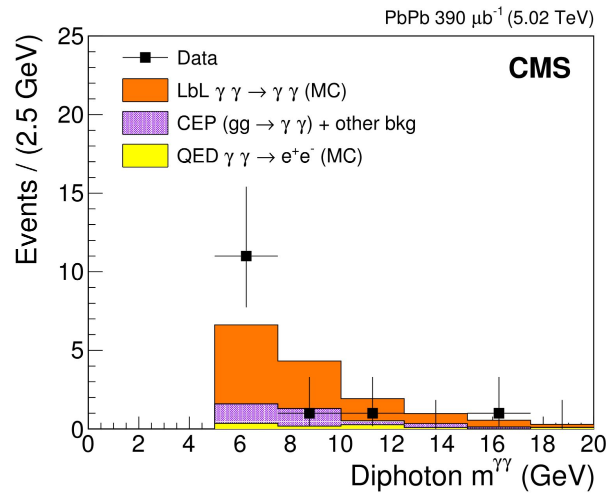


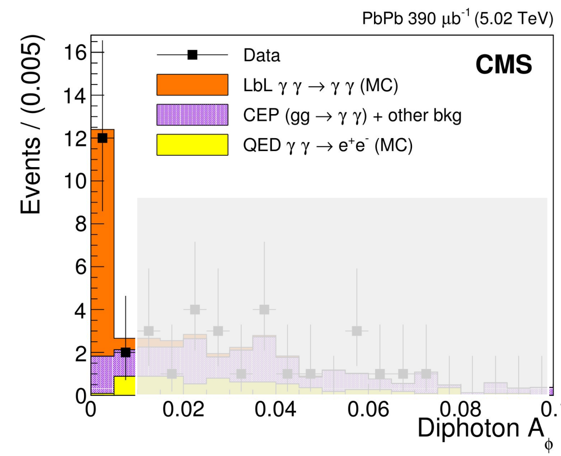


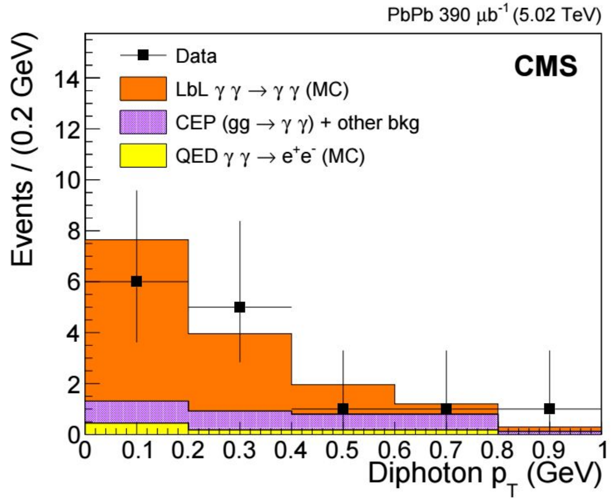
- Signal region: $|\eta| < 2.4$, $E_T > 2$ GeV, $m_{\gamma\gamma} > 5$ GeV, $A_\phi < 0.01$

kinematic distributions : diphotons

PLB 797 (2019) 134826







- Observed 14 candidate light-by-light events
- Expected signal=9.0 ± 0.9 and background 4.0 ± 1.2
- The measured yields and kinematic distributions are in good agreement with the MC.

Results

LbyL to QED cross-sections ratio

PLB 797 (2019) 134826

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

  → takes 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

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

- Estimated cross section ratio:

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

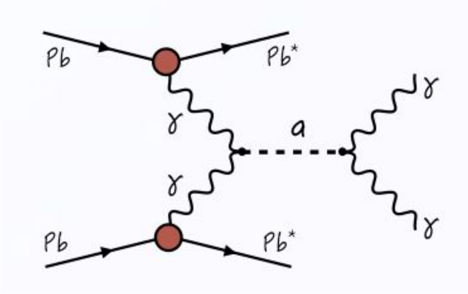
Fiducial LbyL cross section

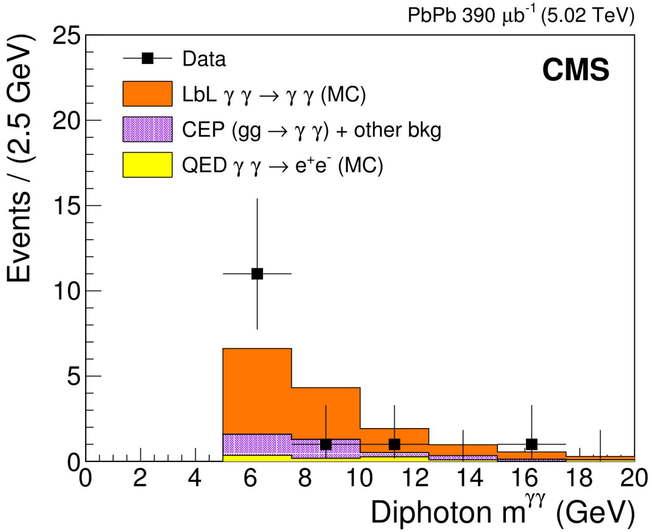
- Obtained by multiplying the cross section from STARLIGHT, simulation : $\sigma_{\gamma\gamma\rightarrow e+e-}$ = 4.82 ± 0.15 (th) mb
- **Measured: 120 ± 46 (stat) ± 28 (syst) ± 4 (th) nb** (Expected: 138 ± 14 nb from MADGRAPH)

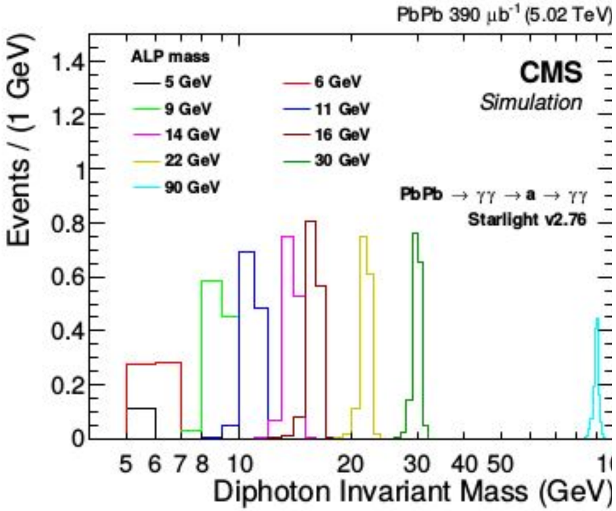
Photon reconstruction and identification ($SF^{\gamma, reco+ID}$)	(2×9)%
Electron reconstruction and identification ($SF^{e, reco+ID}$)	(2×2.5)%
Trigger	12%
Size of simulated background samples	6%
Total	23%

Axion like particle search at CMS

- Measured diphoton invariant mass distribution used to search for pseudoscalar axion-like particles $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$
- LbyL, QED, and CEP + other processes considered as background.
- Simulated ALP samples from starlight generator, m_a :5 to 90 GeV
- Estimated ALP acceptance, efficiency and expected reconstructed diphoton mass template from MC, efficiencies corrected same way as for LbL analysis.





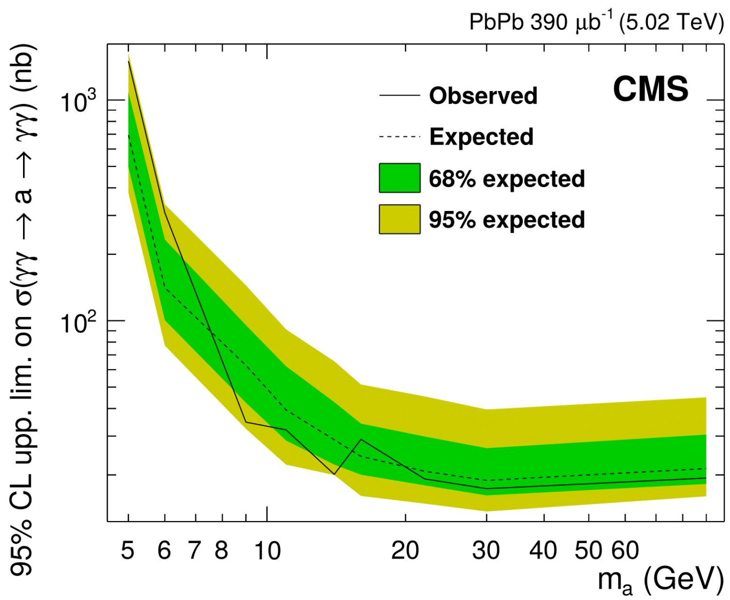


Axion like particle search at CMS

PLB 797 (2019) 134826

- A binned maximum likelihood fit of the signal and background contributions is performed on the data.
- Systematic uncertainties are included as nuisance parameters with a log-normal prior.

- **No significant ALP excess observed in data above LbL+ backgrounds**

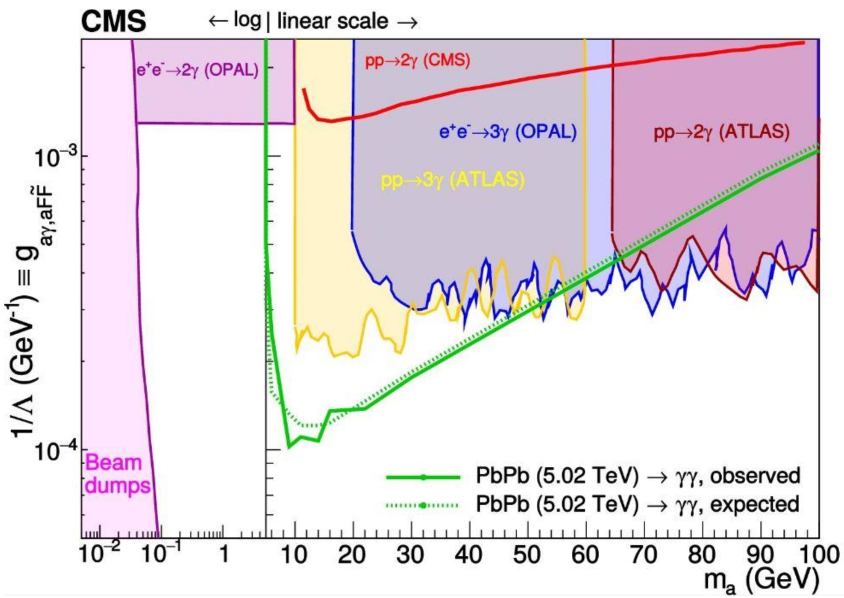


- Upper limits for σ (γγ→a→γγ) at 95% confidence level extracted assuming 100% a → γγ branching ratio.

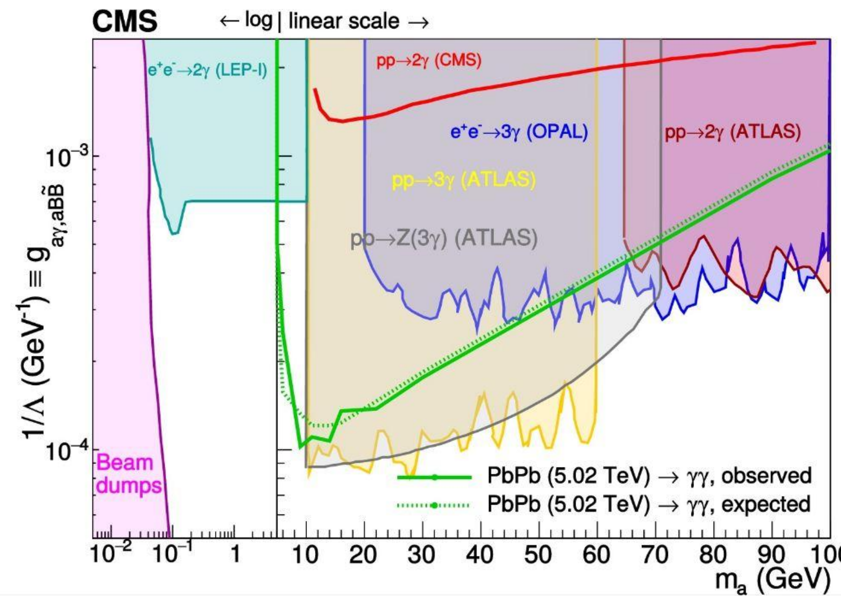
Axion like particle search at CMS

PLB 797 (2019) 134826

- Limits in cross-section ⟶ limits in $g_{a\gamma}$ vs. m_a plane ($g_{a\gamma} = 1/\Lambda$)
- **ALP couplings to electromagnetic current : new constraints in the m_a =5–50 GeV region**



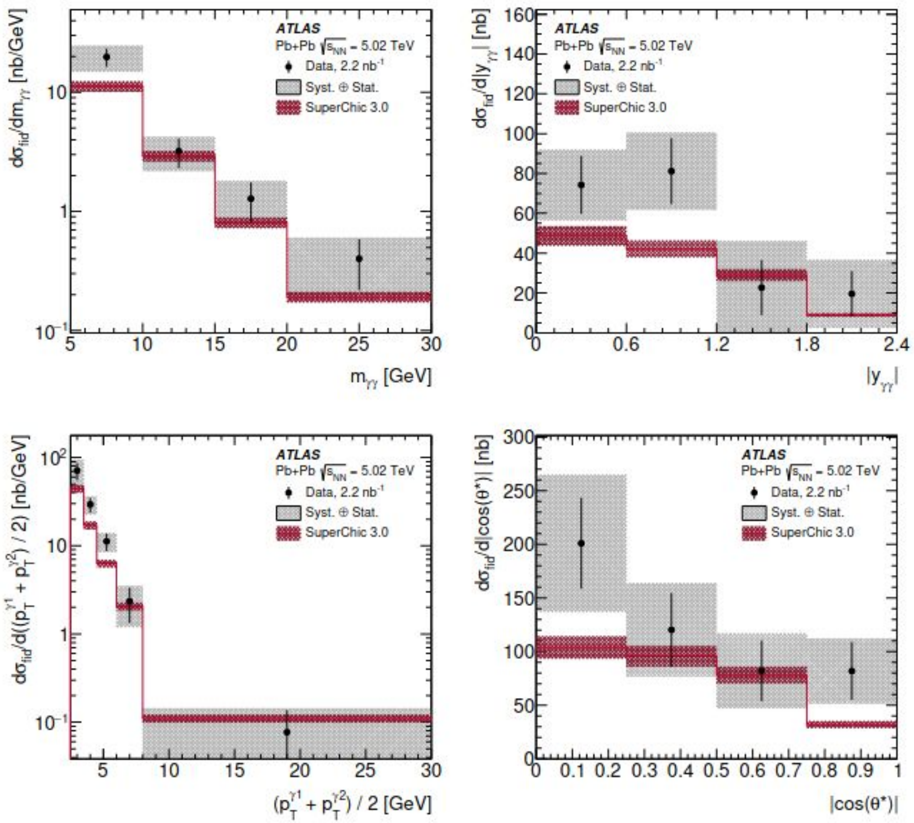
coupling only to photons (with operator $aF\tilde{F}/4\Lambda$)



coupling to hypercharge (with operator $aB\tilde{B}$ / $4\Lambda\cos^2\theta_W$)

Light-by-light scattering : ATLAS (2015 + 2018)

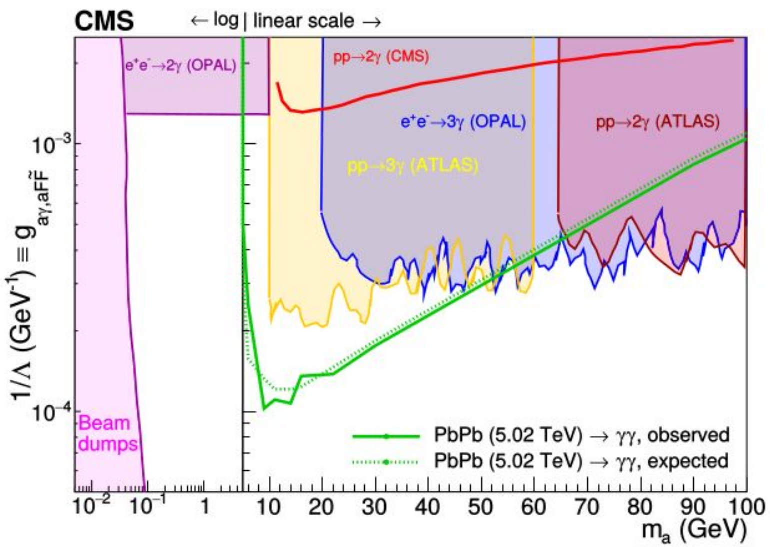
ATLAS JHEP 03 (2021) 243

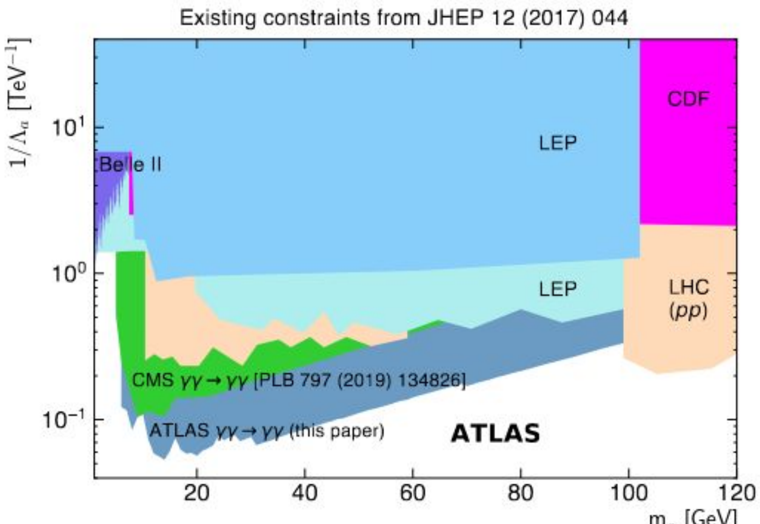


- ATLAS 2015+ 2018 PbPb data, luminosity 2.2 nb^{-1}
- Analysis strategy and event selection criteria similar to CMS
- **Measured fiducial cross-section**
  120 ± 17 (stat.) ± 13 (syst.) ± 4 (lumi.) nb
  Superchic MC expectation : 78 ± 8 nb
  Data to theory ratio: 1.5 ± 0.32

Light-by-light scattering : ATLAS (2015 + 2018)

- ALP samples for masses generated from STARLIGHT ATLAS : 6-100 GeV (CMS   : 5-90 GeV)
- **No significant ALP excess observed in data above LbL+ backgrounds**
- **Cross-sections above 2 to 70 nb are excluded at the 95% CL in 6-100 GeV mass interval by ATLAS**
  ⟶ Most stringent constraint at present in this mass region by PbPb UPC at LHC
- **CMS analysis ongoing with 2018 data, plan to combine 2015 + 2018 data ⟶ STAY TUNED!**

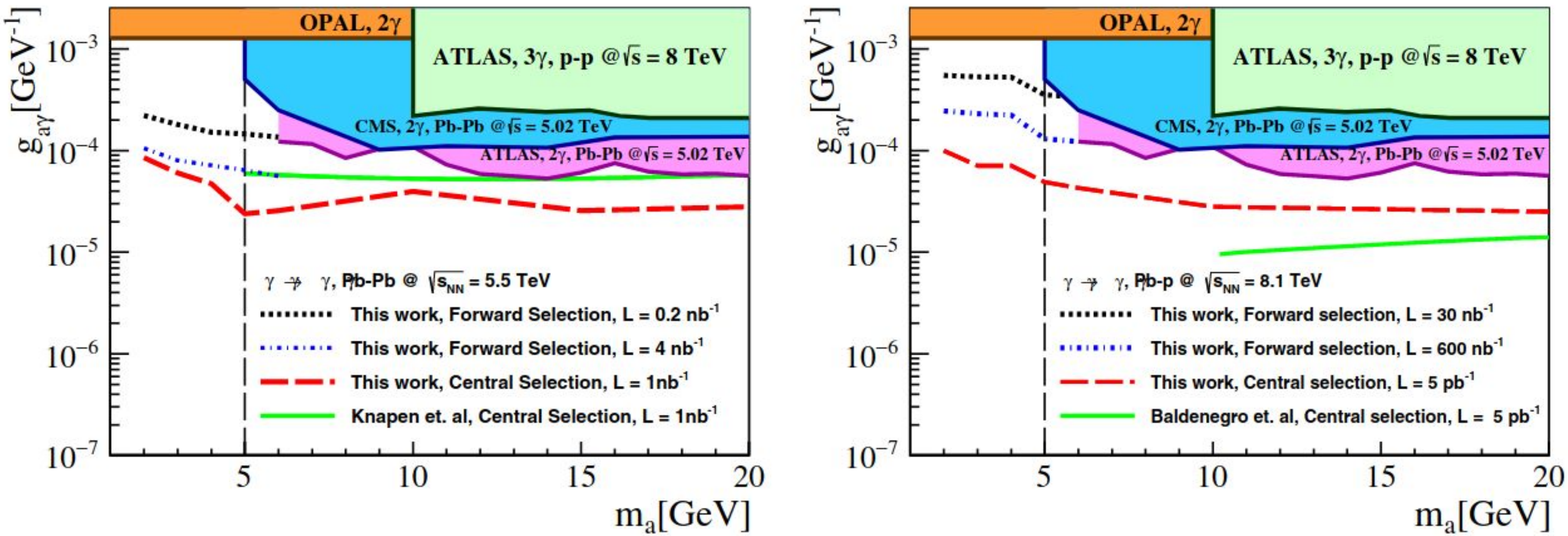




ATLAS JHEP 03 (2021) 243

Measurement can be improved in lower mass region by LHCb

LHCb eta coverage : 2.0 < |η| < 4.2, photon p_T > 0.2 GeV , $m_{\gamma\gamma}$ > 1 GeV



Eur. Phys. J. C (2021) 81 :522

Summary

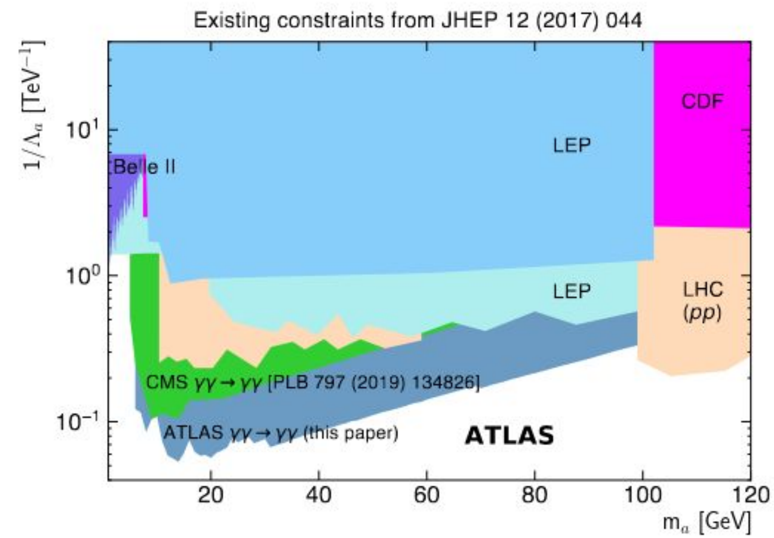
- Ultra-peripheral PbPb collisions at LHC used to search for axion-like particles.
- Light-by-light scattering, QED process of electron pair production and Central Exclusive Production identified as the main background

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

- **Observation for LbL scattering: 8.2 sigma significance provided by ATLAS using 2018 PbPb collisions.**

- No significant excess in $m_{\gamma\gamma}$ distribution.

- Most stringent limits on axion-like particles for masses 5-100 GeV.



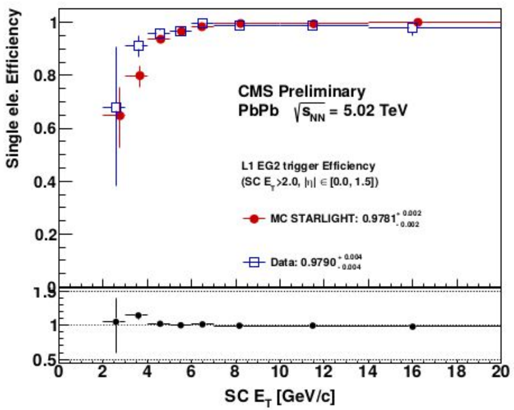
Backup

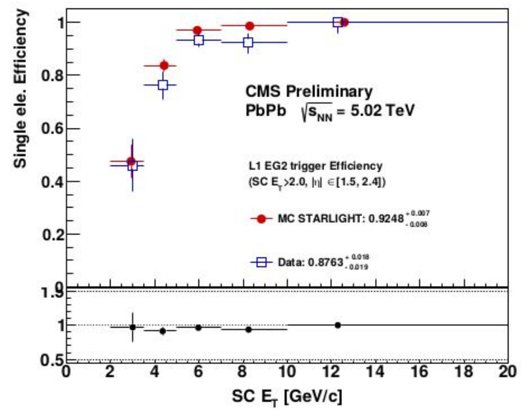
What are axions?

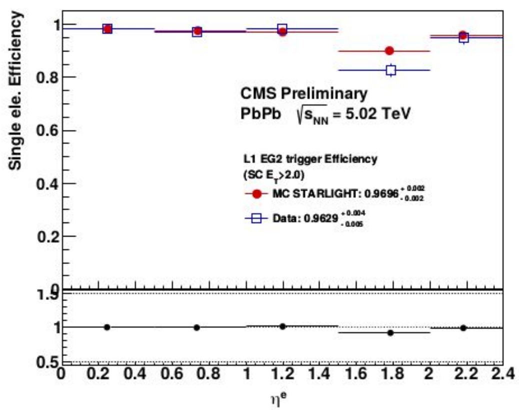
- QCD preserves CP symmetry although there could be a CP violating term in the Lagrangian density.
  Add QCD lagrangian with theta term.
- The strong CP problem is supported by the absence of a neutron electric dipole moment.
  Add the value of neutron electric dipole moment and understand why and how. Add reference.
- Axions: Scalar or pseudo-scalar complex fields, postulated by Peccei-Quinn to solve strong CP problem in QCD.
- Speculated that cold axions could have been produced in abundance during the QCD phase transition in the early universe and that they may constitute one element of the cold dark matter.
- Axion-like particles (ALPs)
  - Pseudo-scalars can couple to SM particles, where mass coupling relation is not fixed.
  - Appear in theories with spontaneously broken global symmetries as pseudo Nambu-Goldstone Boson.
- Focus of this presentation, ALPs coupling to photons.

Peccei, Quinn, PRL 38, 1440 (1977)
Weinberg, PRL 40, 223, (1978)
Wilczek, PRL 46, 279 (1978)

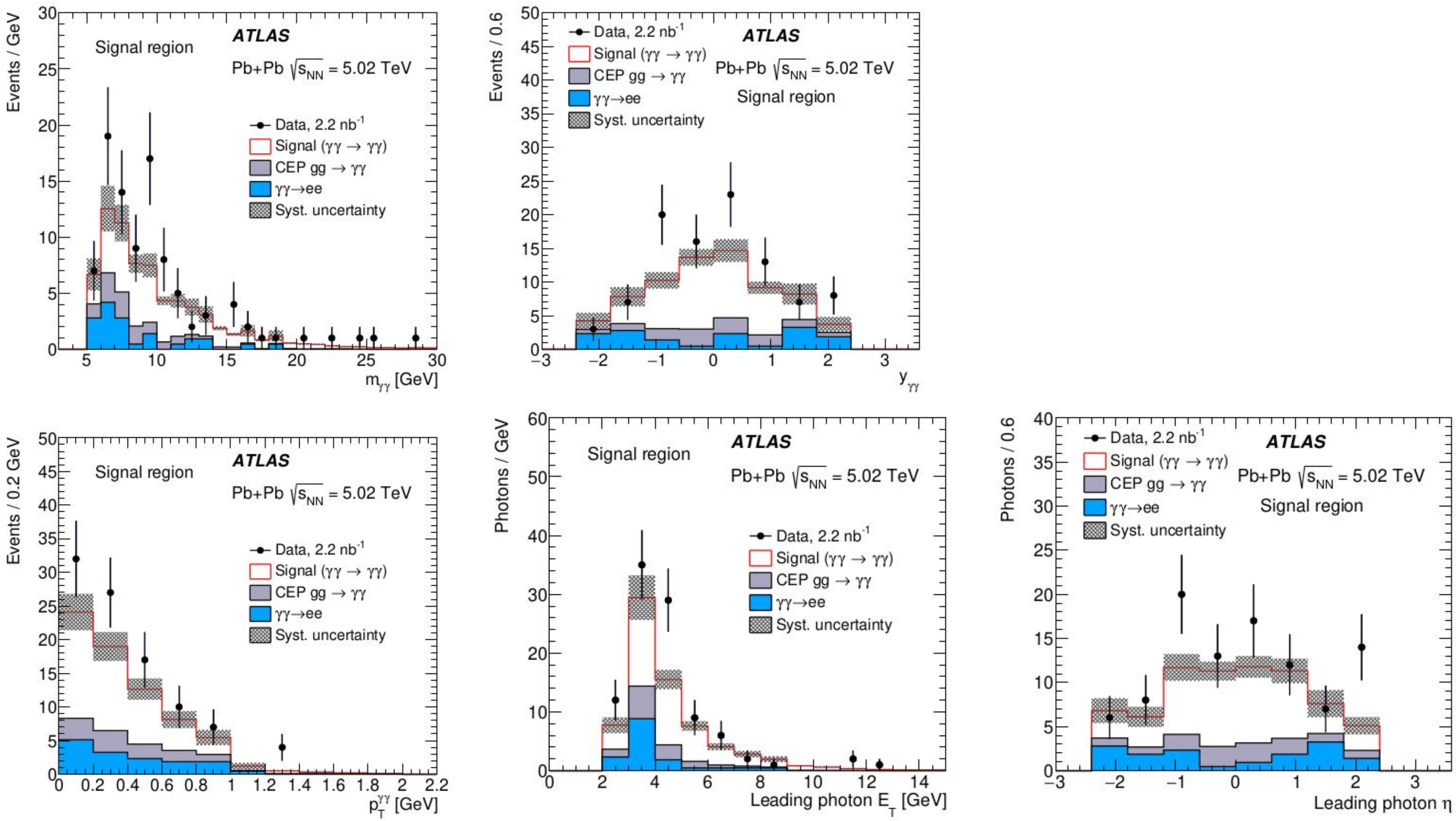
Photon trigger efficiency



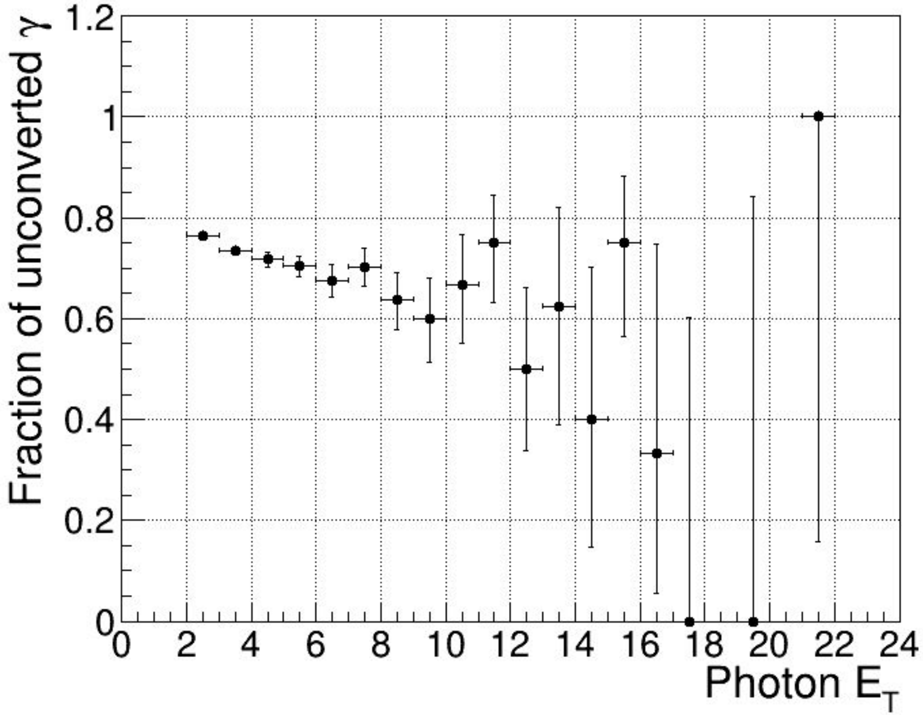


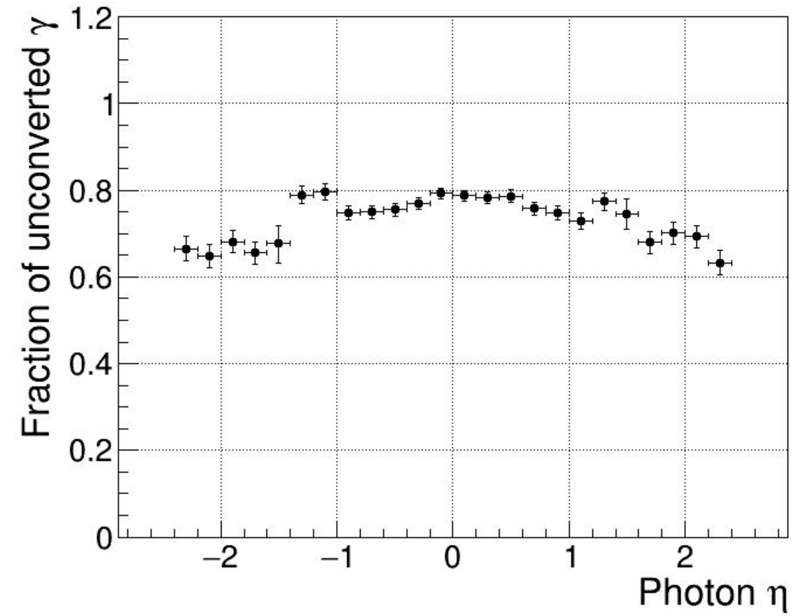


ATLAS (2015 + 2018)



CMS


Fraction of unconverted γ
Photon E_T


Fraction of unconverted γ
Photon η