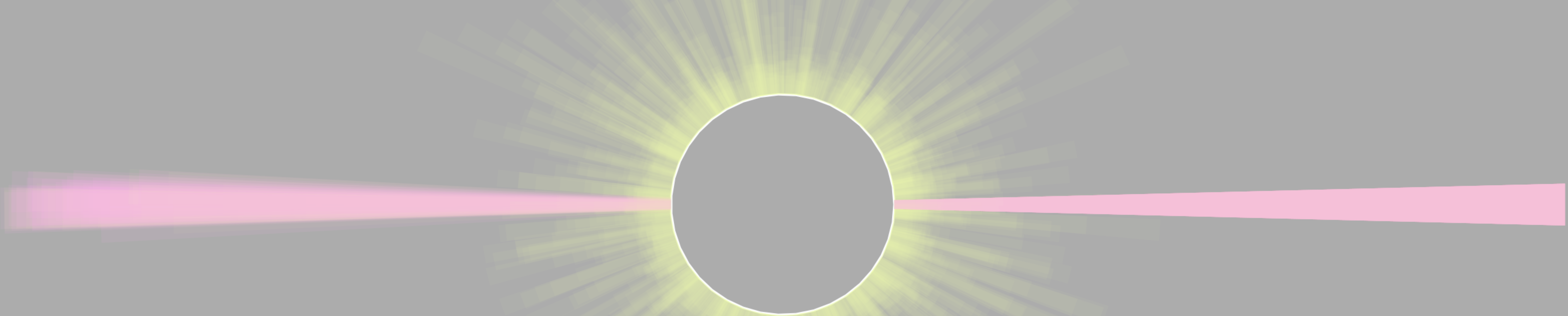
Measurement of Breit-Wheeler process, light-by-light scattering and searches for axion-like particles in UPC PbPb @ 5.02TeV at CMS



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for the CMS collaboration

CMS-PAS-HIN-21-015

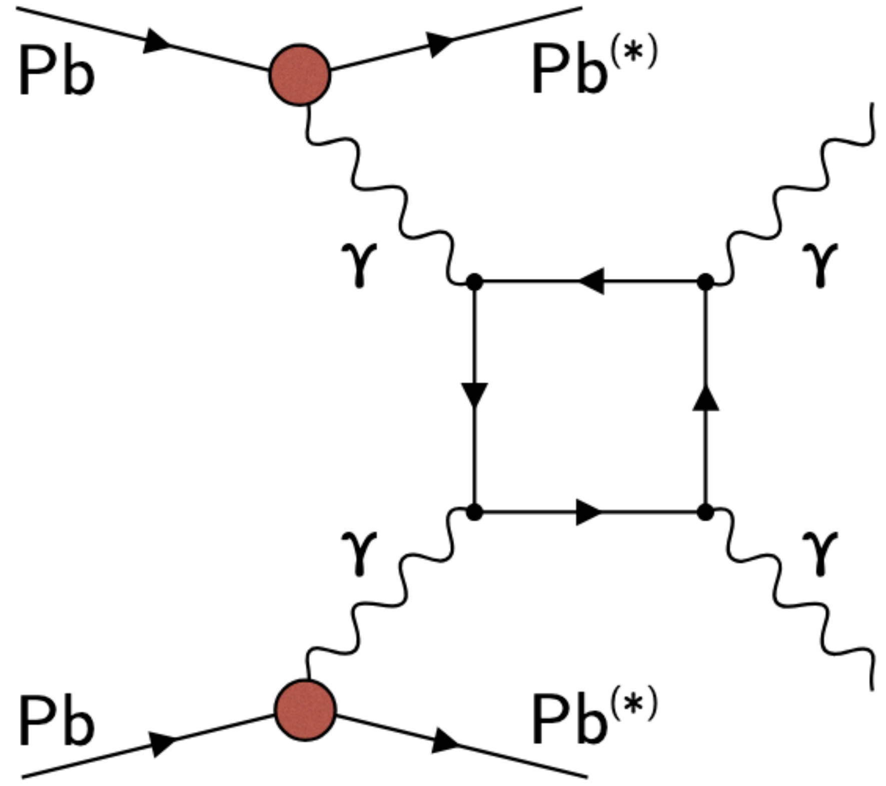
22-27th September, Hard Probes 2024, Nagasaki

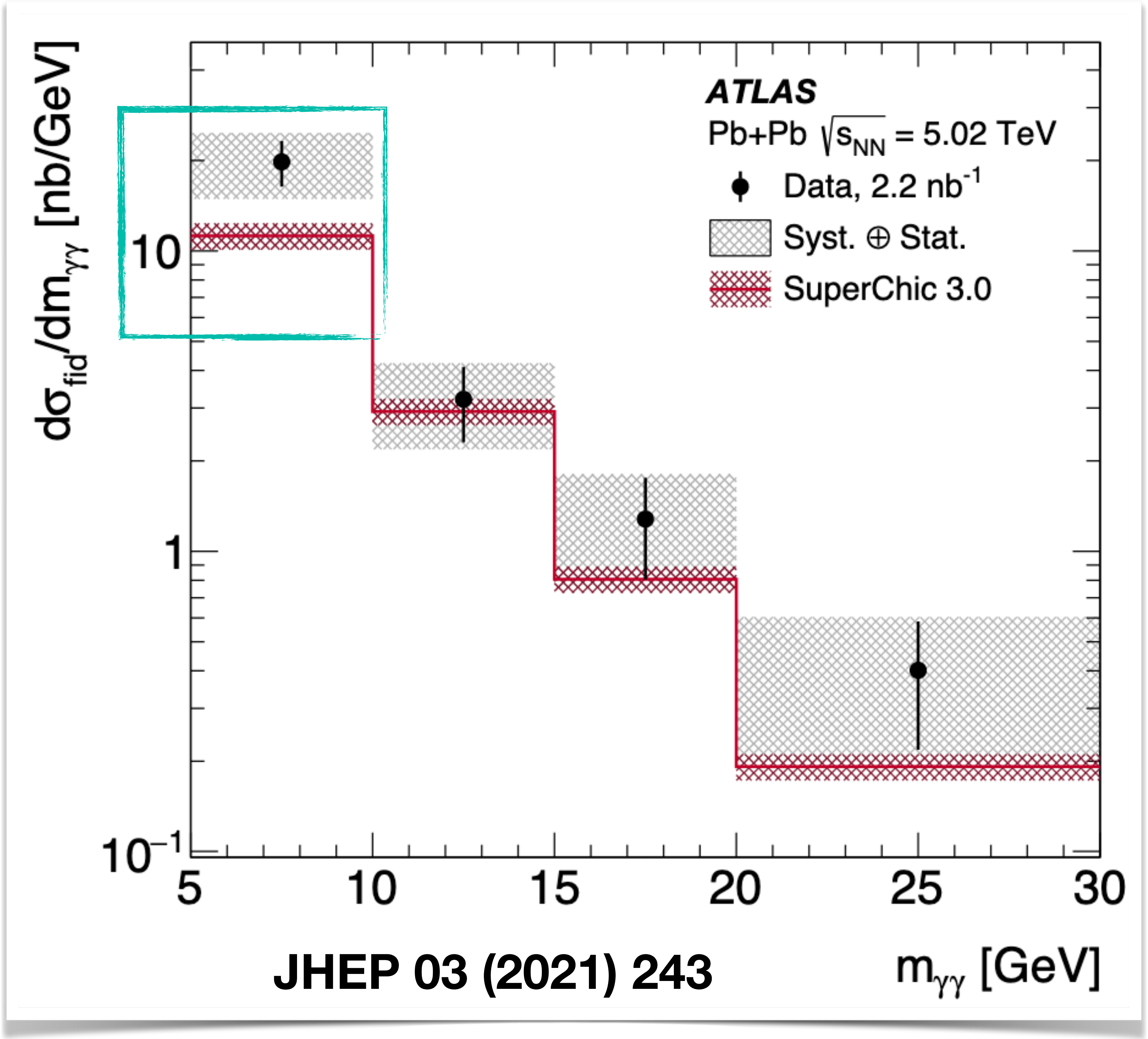
Outline

- Introduction
- Signal selection
- Results
  - Breit-Wheeler (B-W) process
  - Light-by-light (LbyL) scattering
  - Limits on axion-like particles (ALPs) production
- Summary

Light-by-light Scattering

- Fundamental quantum-mechanical process proceeds through virtual one-loop box diagrams.
- In ultra-peripheral collisions (UPC), cross-section enhanced by Z^4, Z = 82 for Pb

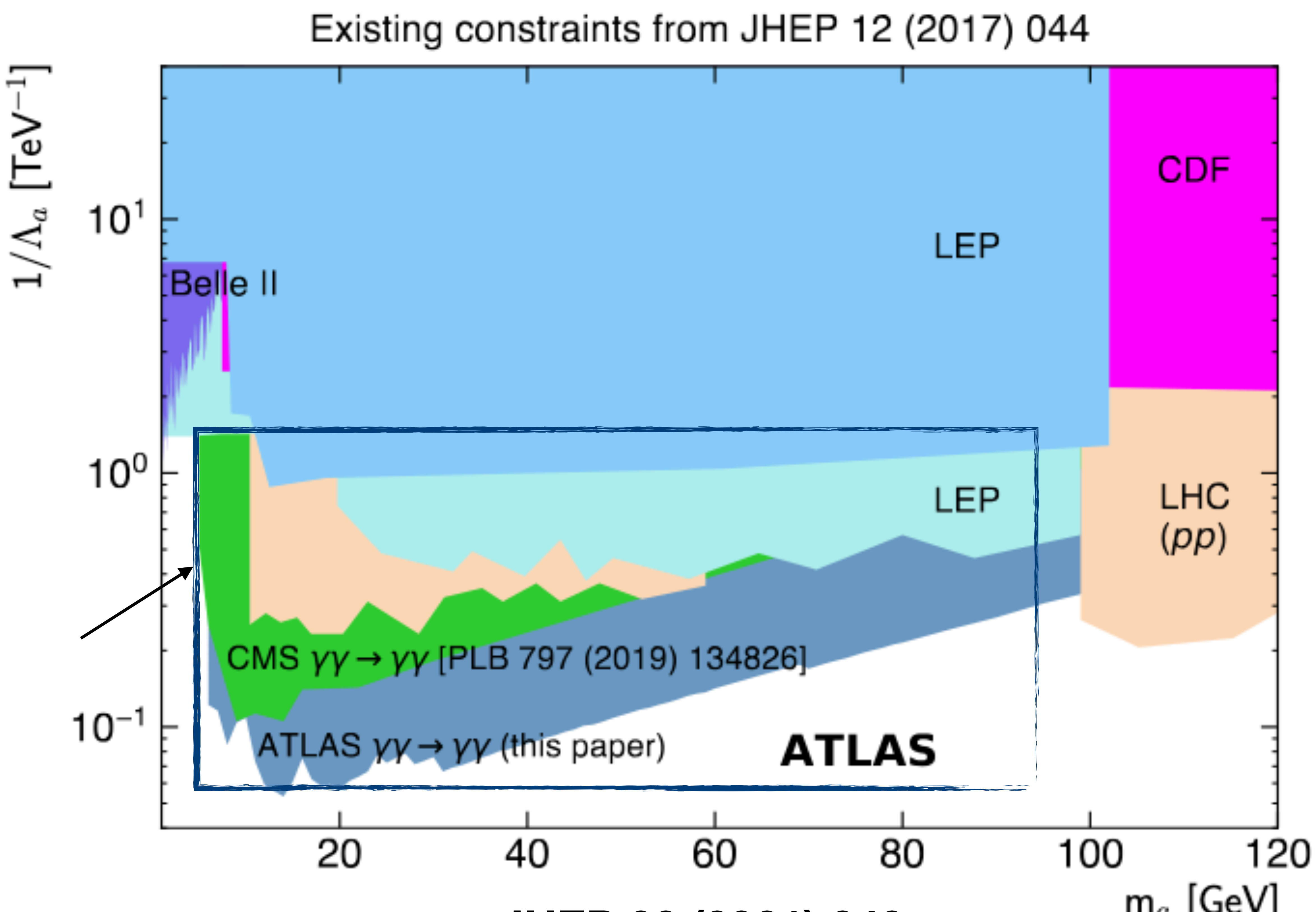




- Evidence by ATLAS (2017) and CMS (2019), observation by ATLAS (2019) in UPC PbPb collisions
- From ATLAS measurement, σ_{fid} $(\gamma\gamma \rightarrow \gamma\gamma)$ = 120±17(stat) ±13(syst)±4(lumi)nb is ≈ 1.5 time higher than predicted 80±8nb

Searches for Axion-Like Particles

- Exclusive $\gamma\gamma \to \gamma\gamma$ process also a clean channel to search for BSM particles such as spin-0 axion-like particles



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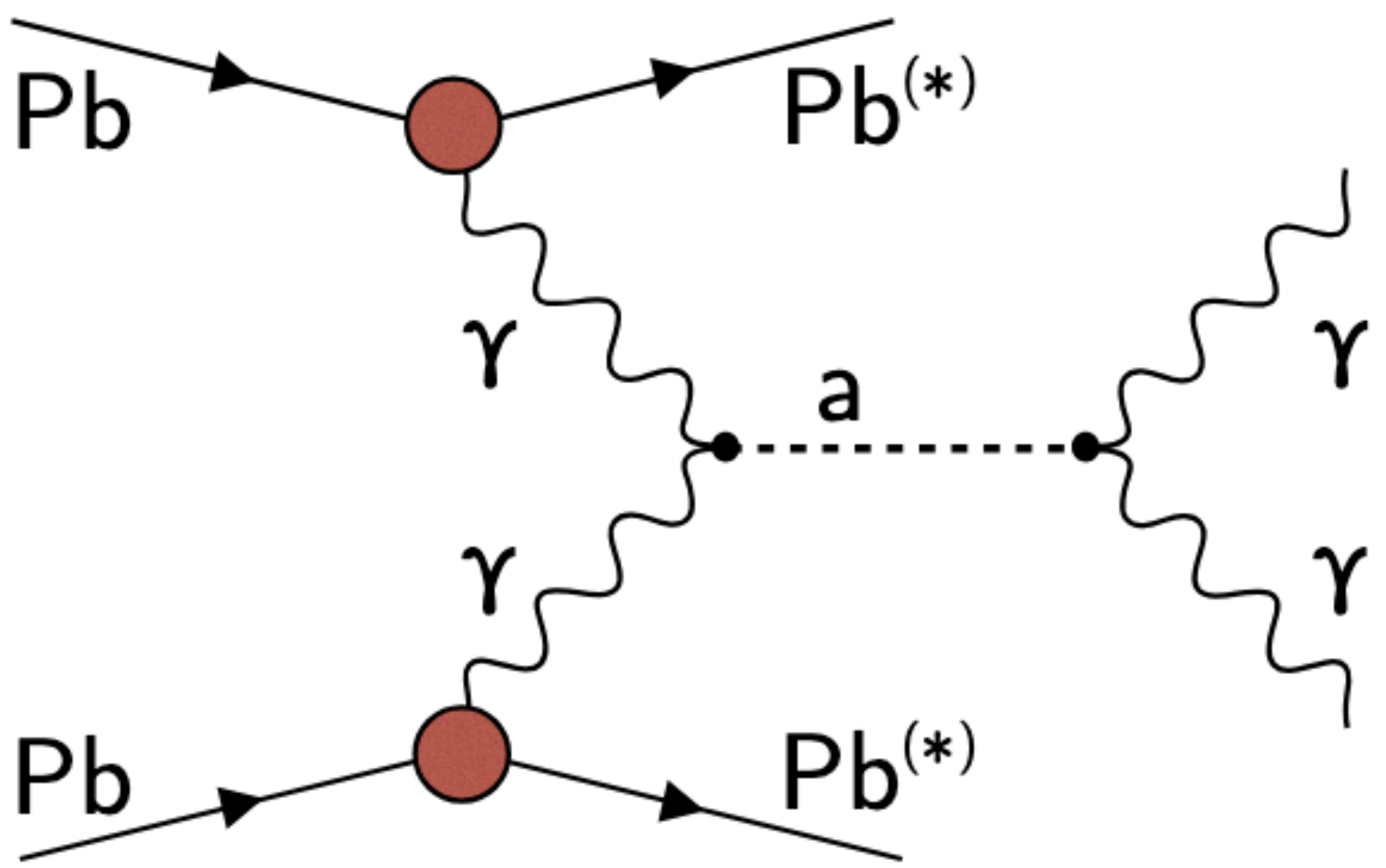
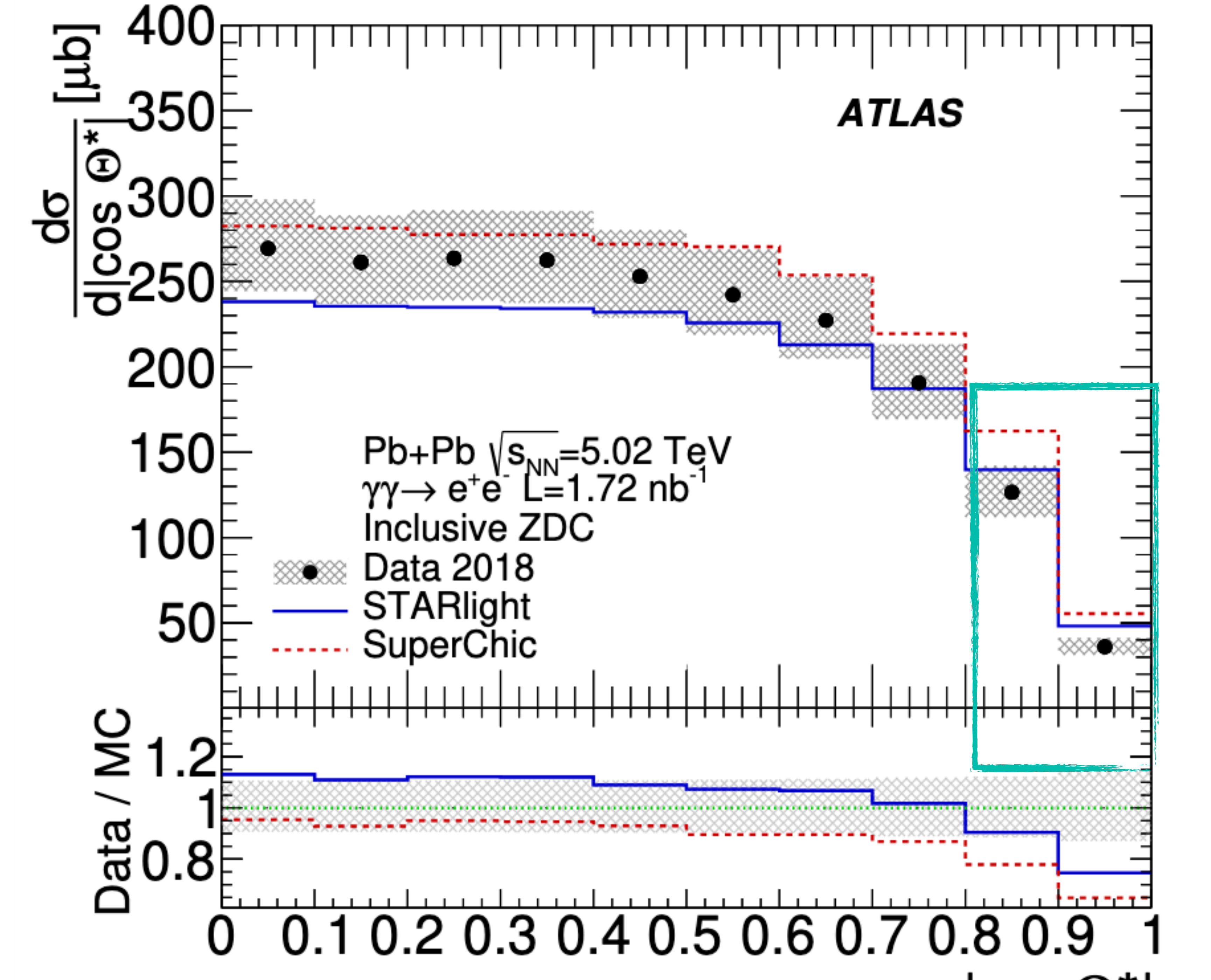


- CMS PbPb UPC (2019) set first competitive limits in ALPs production ($\gamma\gamma \to a \to \gamma\gamma$) in the 5-90 GeV mass range. ATLAS (2019) measurement now superseded except in the lowest mass

Other Exclusive Processes

Breit-Wheeler process (B-W)

- Both electron and positron misidentified as photons
- One of the background for light-by-light process
- Discrepancy between data and Superchic in higher $|y_{ee}|$ and at $|\cos\theta^*| \approx 1$ from ATLAS measurement



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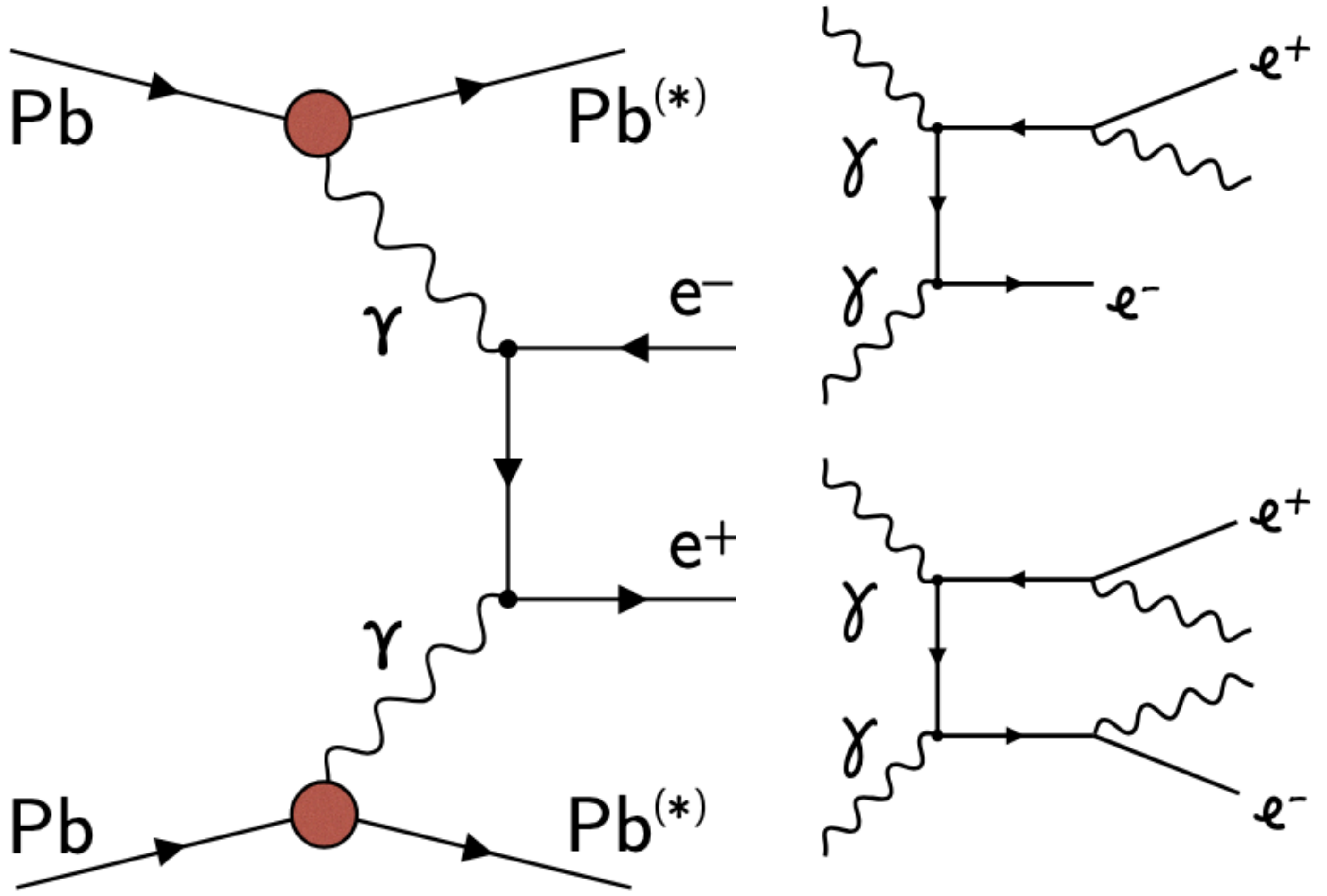
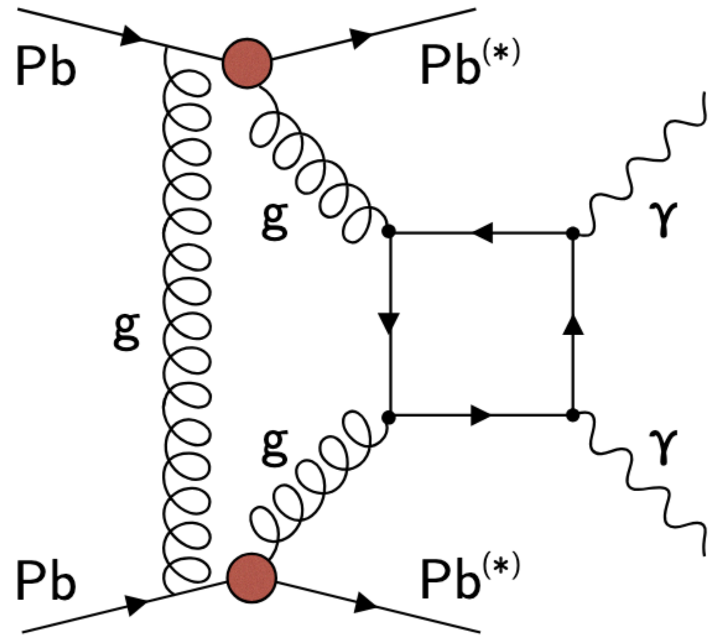


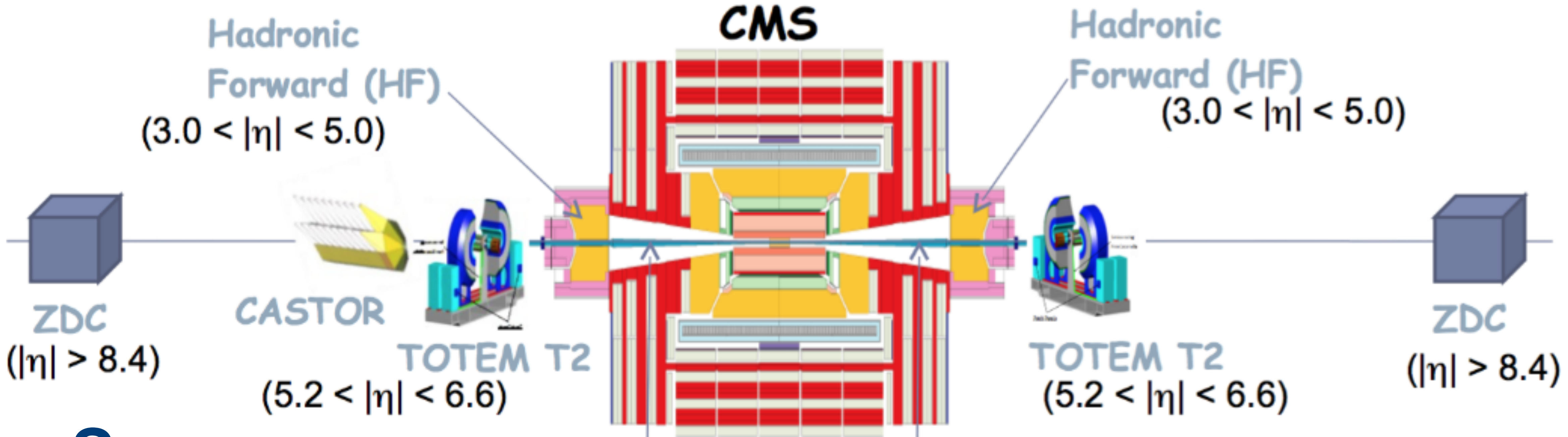
Central exclusive production (CEP)

- Gluon exchanges between the Pb ions.
- Photons are not exactly back to back, high acoplanarity

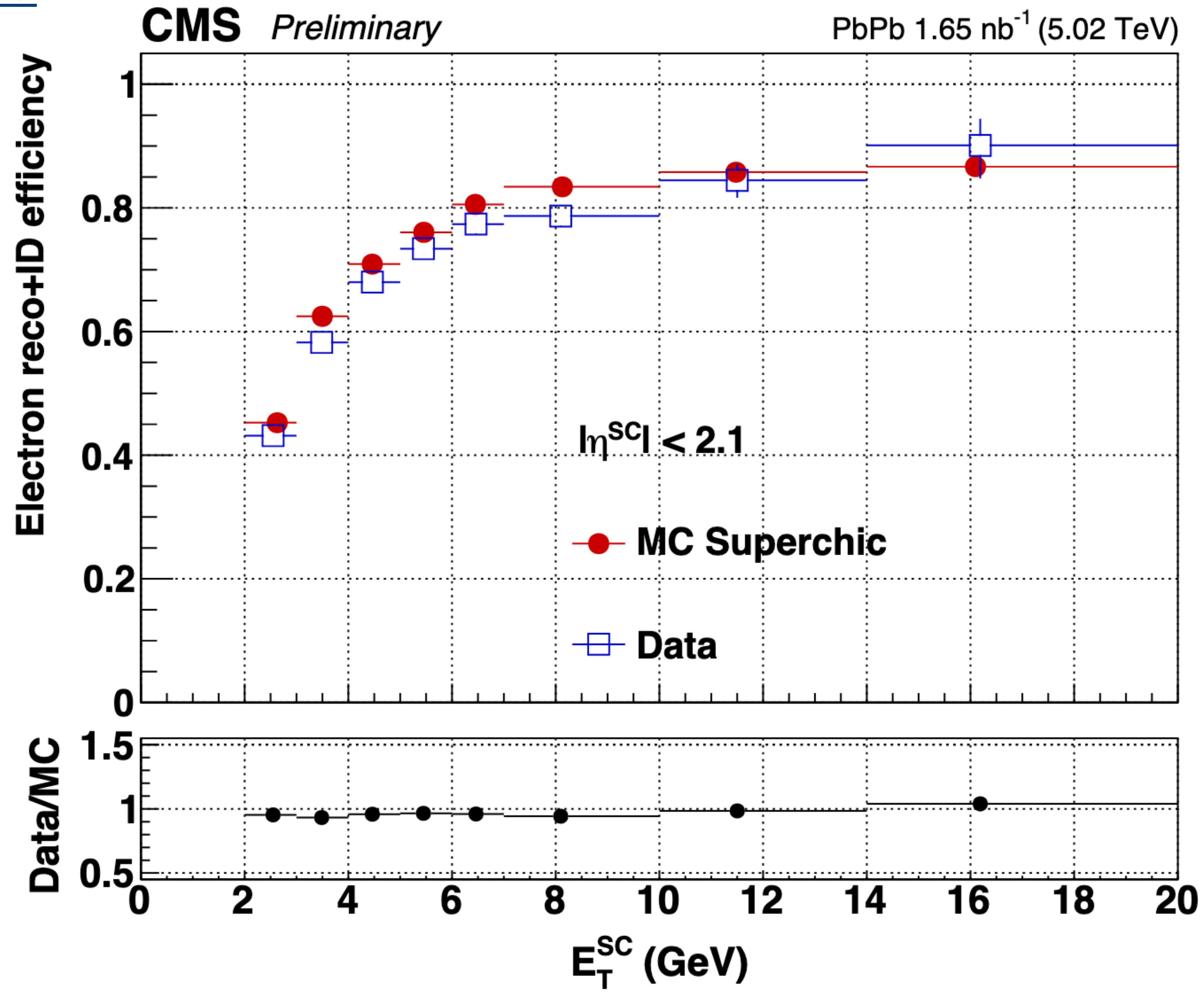


Signal Selection

- Modified low E_T γ/e reconstruction to go down to $E_T > 2$ GeV
- Two well reconstructed electrons/photons: $E_T > 2$ GeV , $|\eta| < 2.2$, invariant mass $m^{ee,\gamma\gamma} > 5$ GeV, $p_T^{ee,\gamma\gamma} < 1$ GeV, acoplanarity ($A_\phi = 1 - \Delta\phi^{ee,\gamma\gamma}/\pi$) < 0.01
- Excluding any other neutral particles and charged particles
- Less than 3 neutron emissions in both side Zero degree calorimeters



Source



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Breit-Wheeler Process

- 19689 dielectron events passing all selections
- Total systematic uncertainty 6.8% mainly dominated by trigger scale factor

$$\sigma_{\mathrm{fid}}(\gamma\gamma \to \mathrm{e}^+\mathrm{e}^-) = \frac{N^{\mathrm{ee,data}}}{C^{\mathrm{ee}}\mathcal{L}_{\mathrm{int}}} = 271.5 \pm 1.9\,(\mathrm{stat}) \pm 18.3\,(\mathrm{syst})\ \mu\mathrm{b}$$

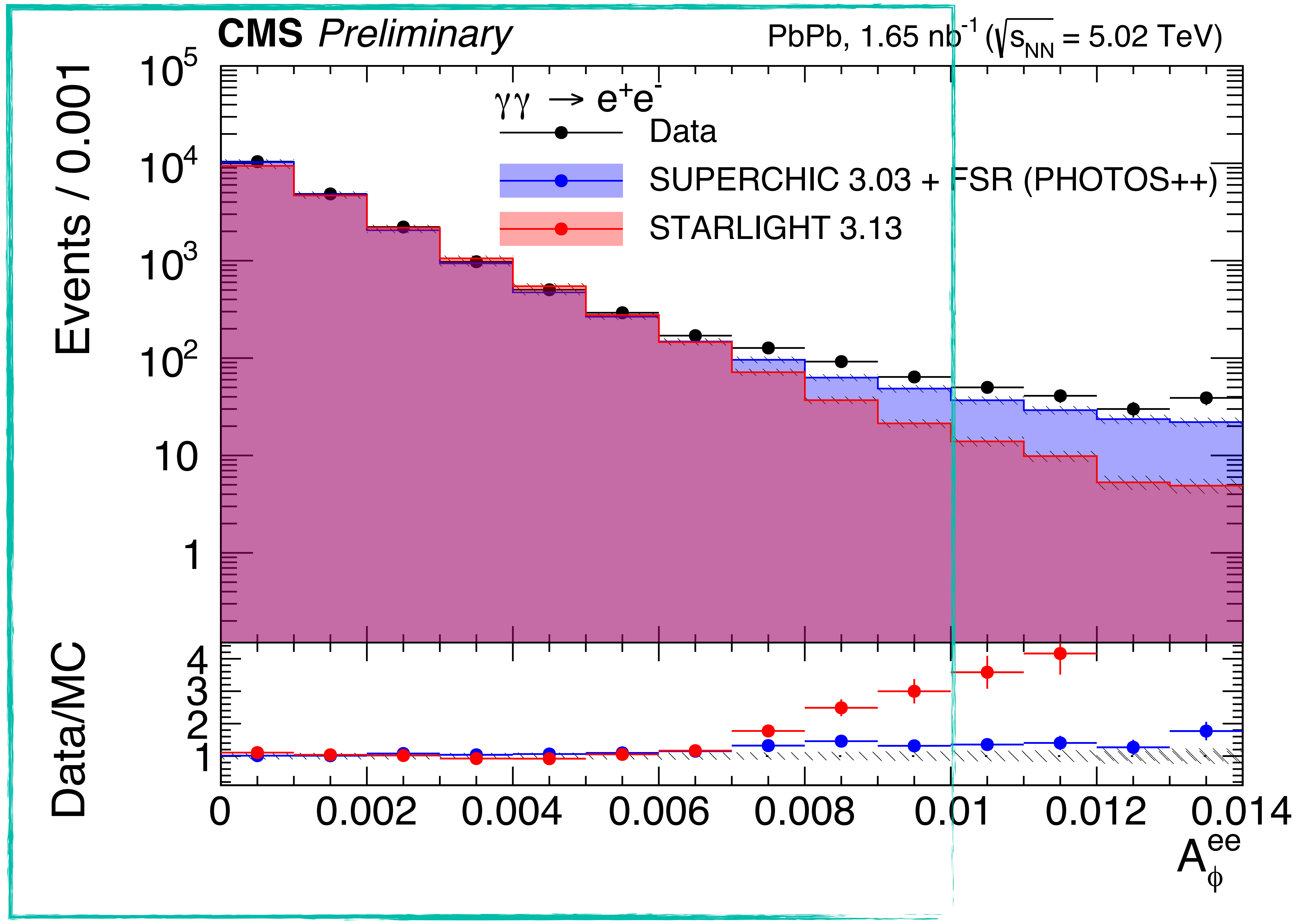
Theoretical predictions:

STARLIGHT 3.13: 251μb

SUPERCHIC 3.03 + FSR (PHOTOS++) : 261μb

gamma-UPC/MG5 + FSR (PY8) : 265 μb

Acoplanarity distribution A_ϕ^{ee}



- Superchic + FSR describes well the acoplanarity tail
- Negligible background

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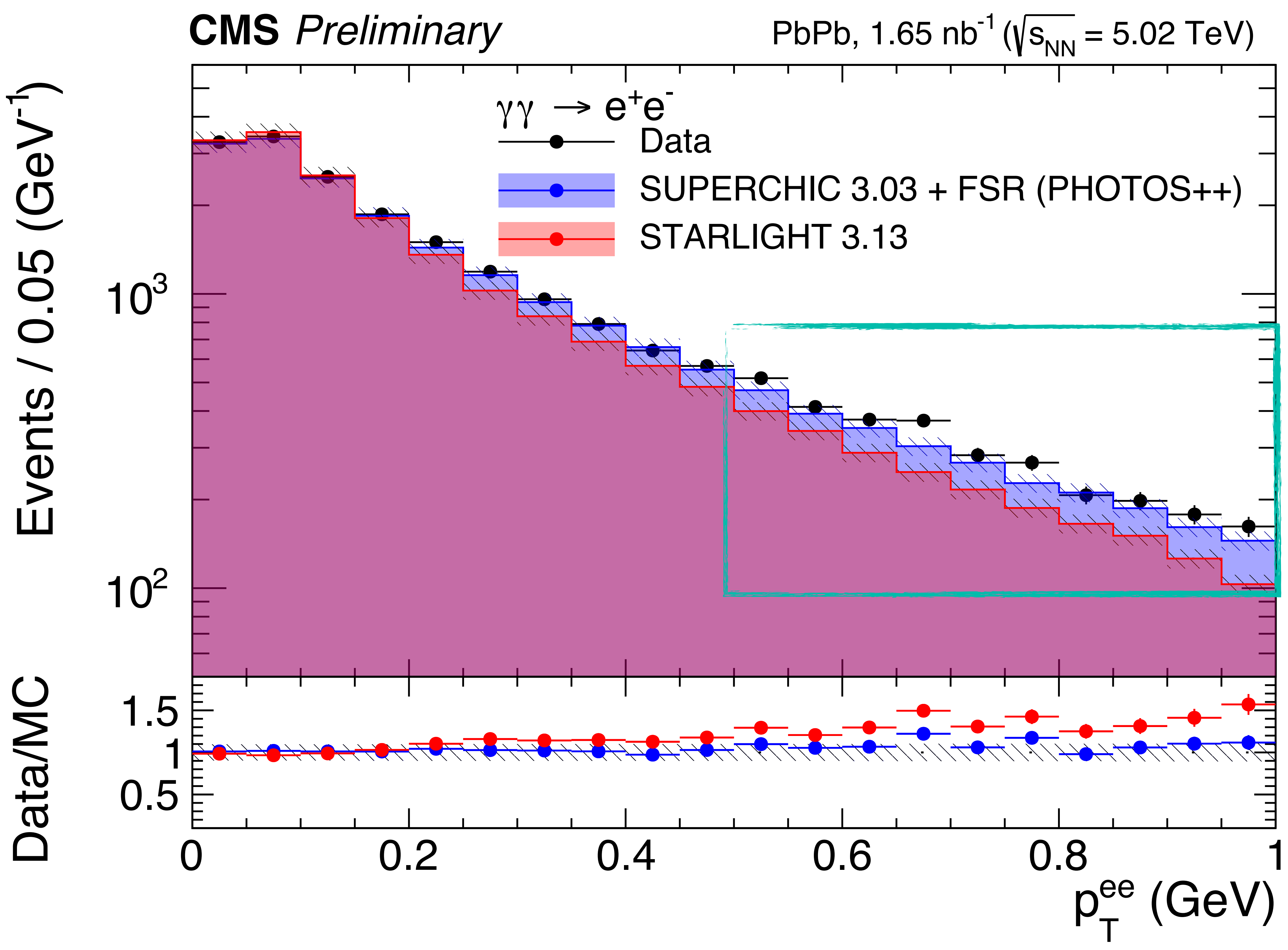
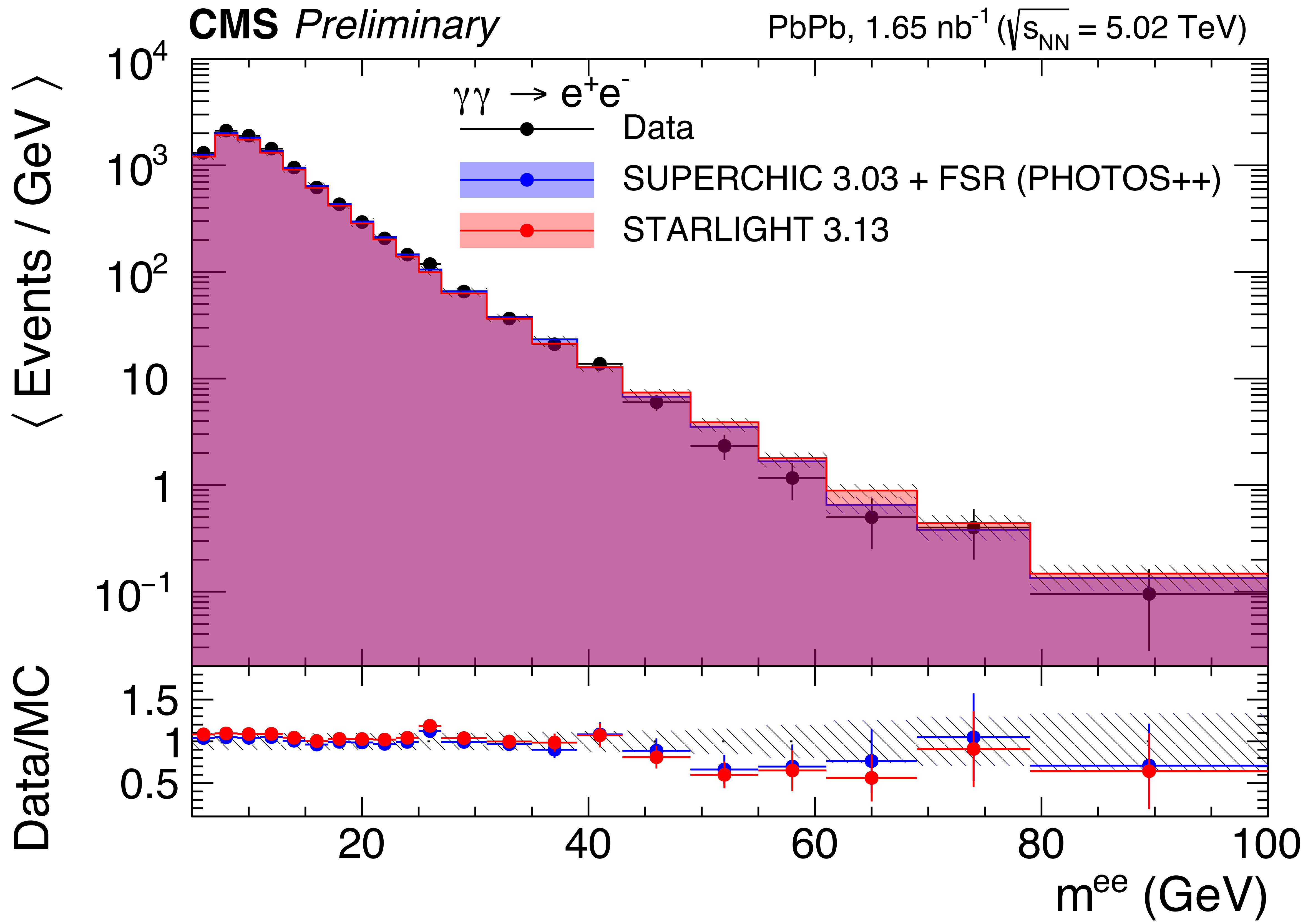
B-W Process : Detector Level Distribution

- Overall good agreement in the detector level distributions, Superchic + FSR (Photos++) describes the p_T^{ee} tail better than Starlight due to the adding of FSR





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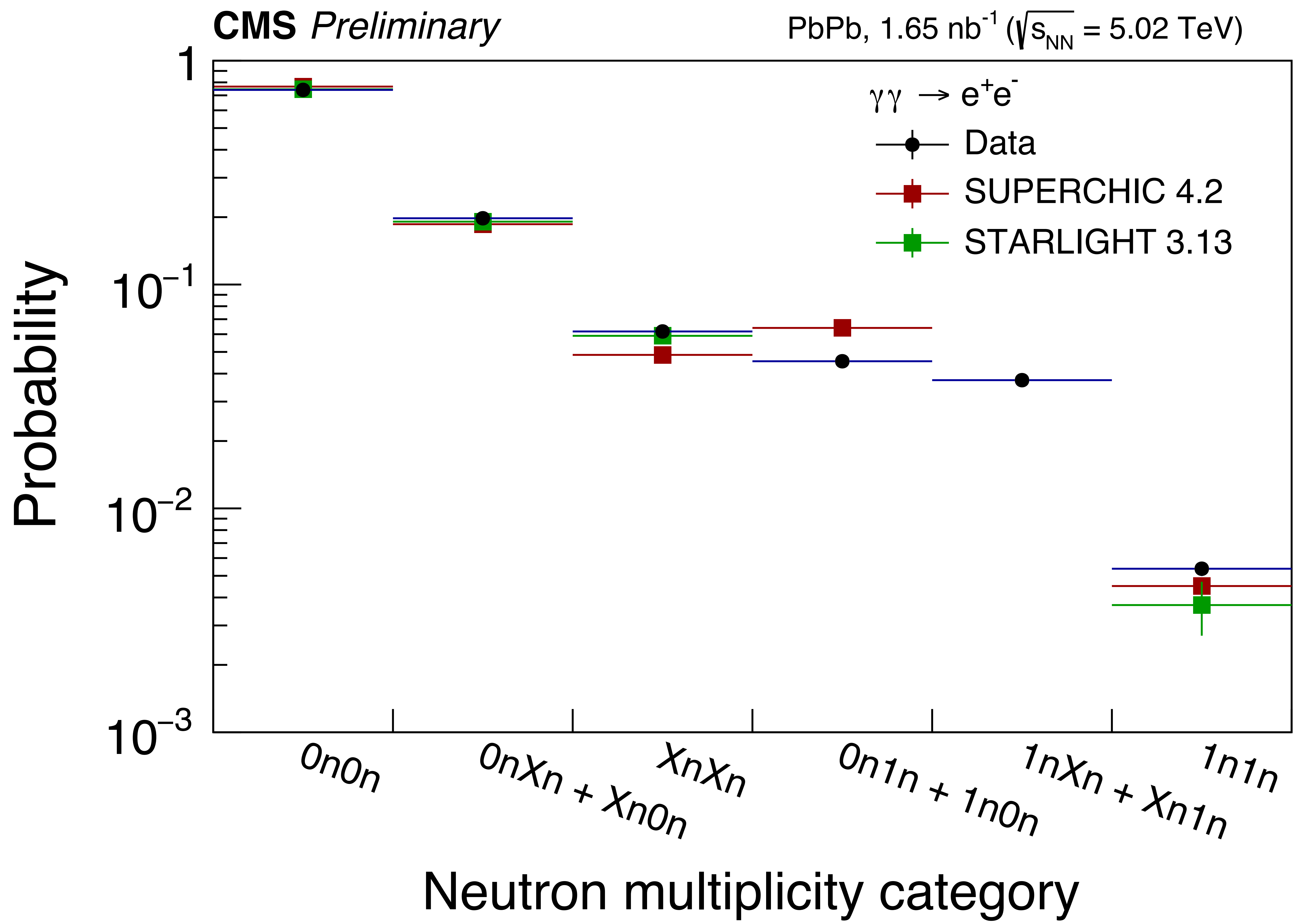
B-W Process : Neutron Emission Probability

- Events are categorized based on the neutron multiplicity and compared with predictions
- Probability ratios of different neutron multiplicities to the inclusive are in good agreement with Superchic 4.2 and Starlight 3.13
- Statistical uncertainty ± 2% uncertainty for neutron pileup correction



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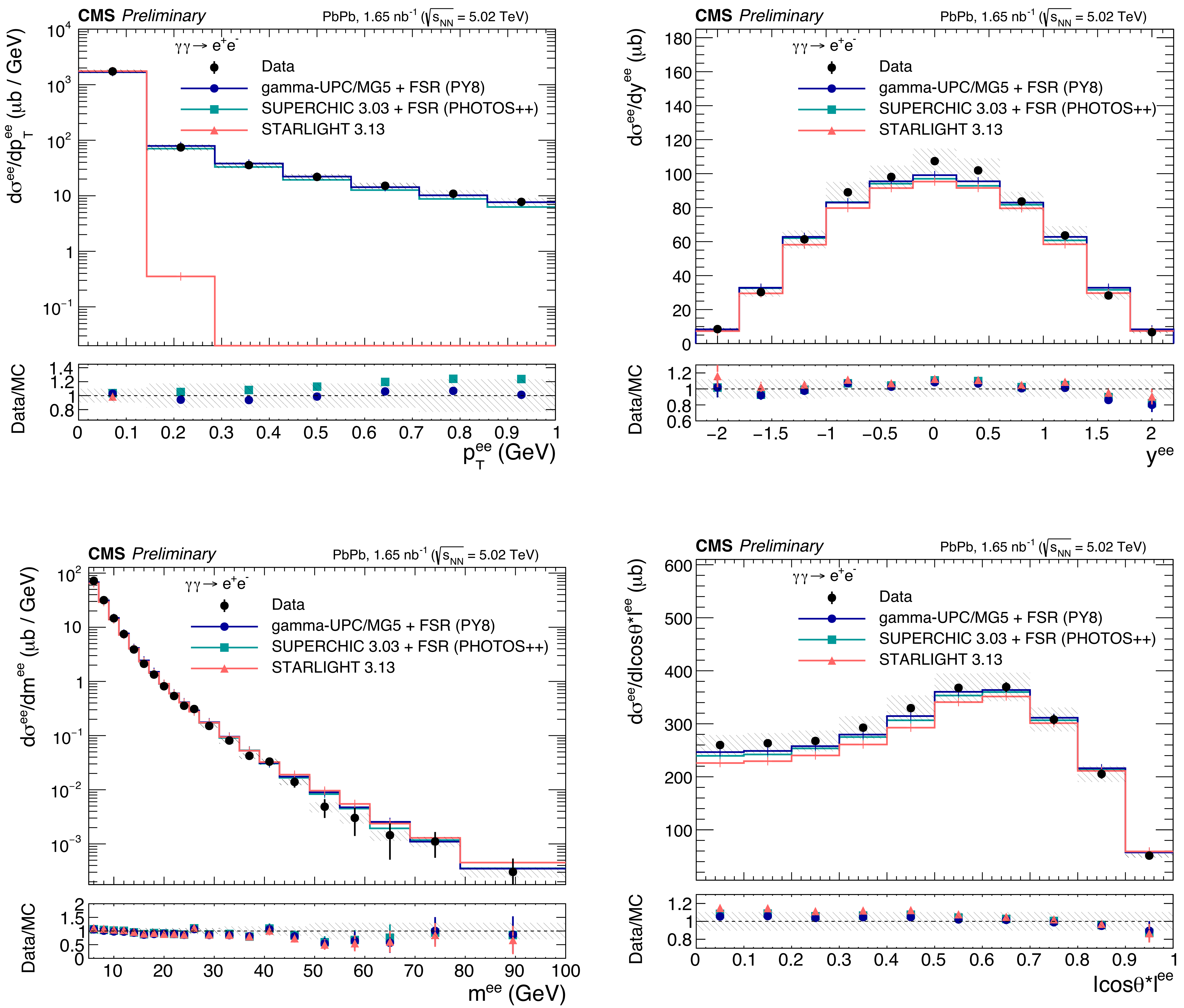
B-W Process: Unfolded Distribution

- Unfolded kinematic distributions compared with Superchic 3.03+FSR, gamma-UPC/MG5+FSR and Starlight 3.13, default unfolding performed with Superchic 3.03+FSR

- Average ±5% and in the tail ±15% uncertainty due to the unfolding added with the rest of systematics

- Within uncertainties very good agreement between data and predictions except the Starlight in p_T^{ee}



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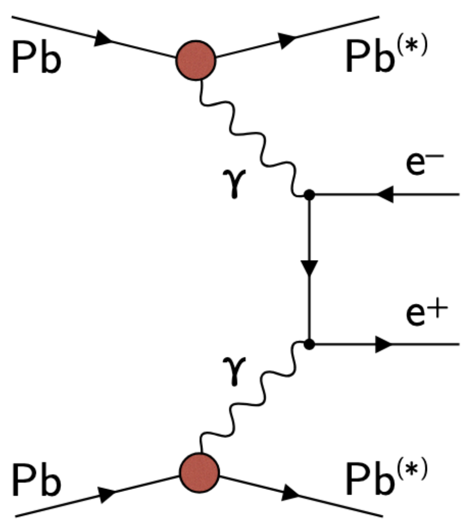
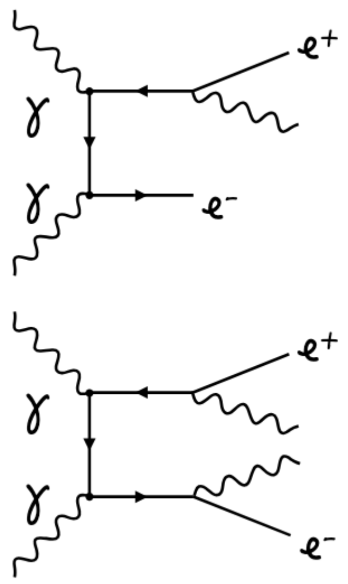
Light-by-light Process : Background Estimation

- In light-by-light process, two photons are expected to be exactly back to back, acoplanarity (A_ϕ) ≈ 0

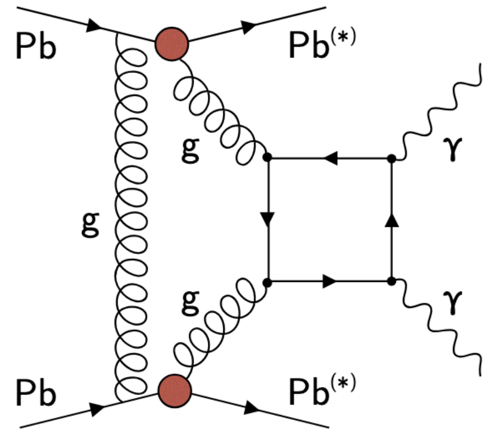
Background estimation:

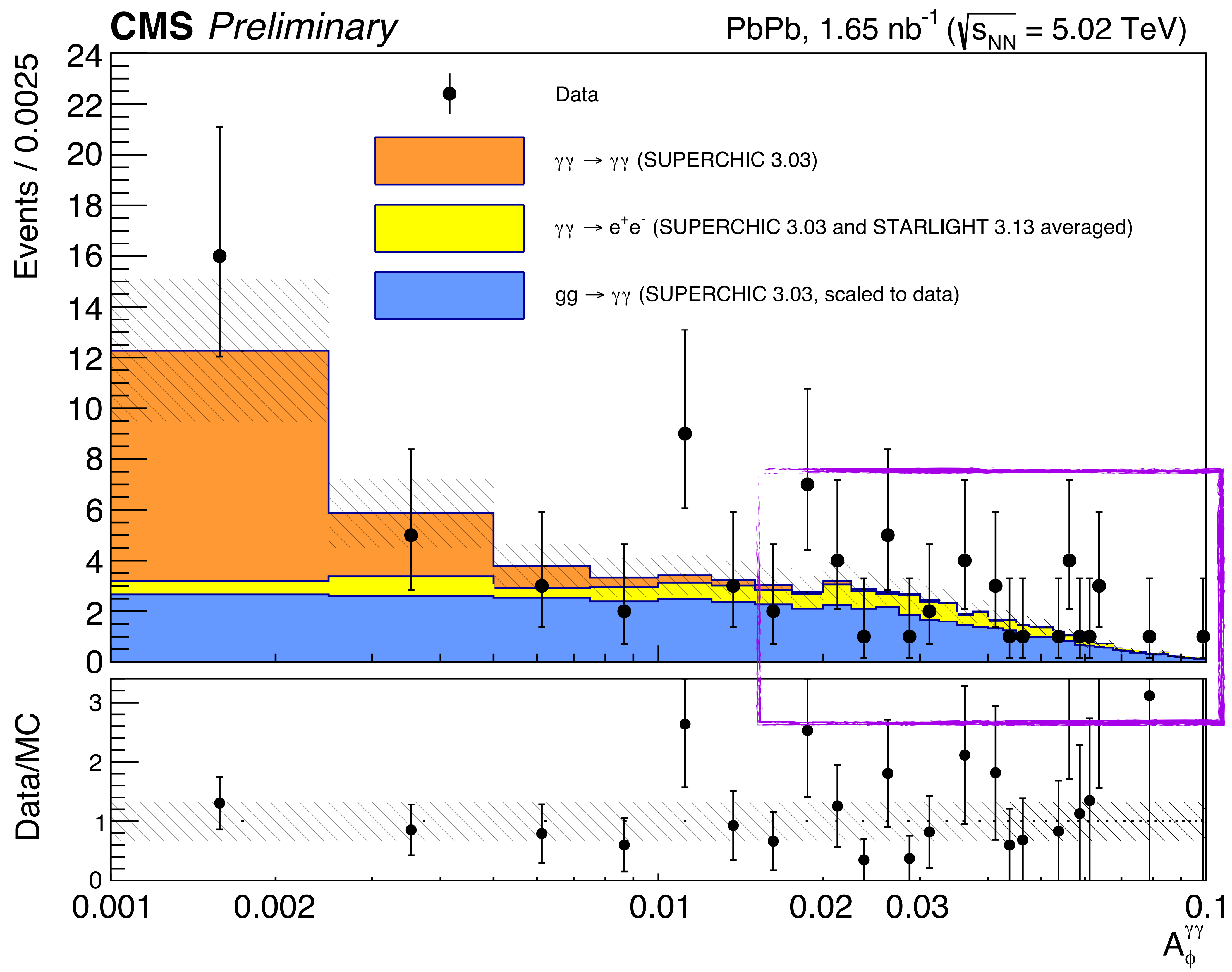
- Breit-Wheeler :
  - Averaging Superchic and Starlight MC to increase statistics





- CEP :
  - Large theoretical uncertainties on cross section
  - Normalized to data in the acoplanarity tail ($A_\phi > 0.015$)





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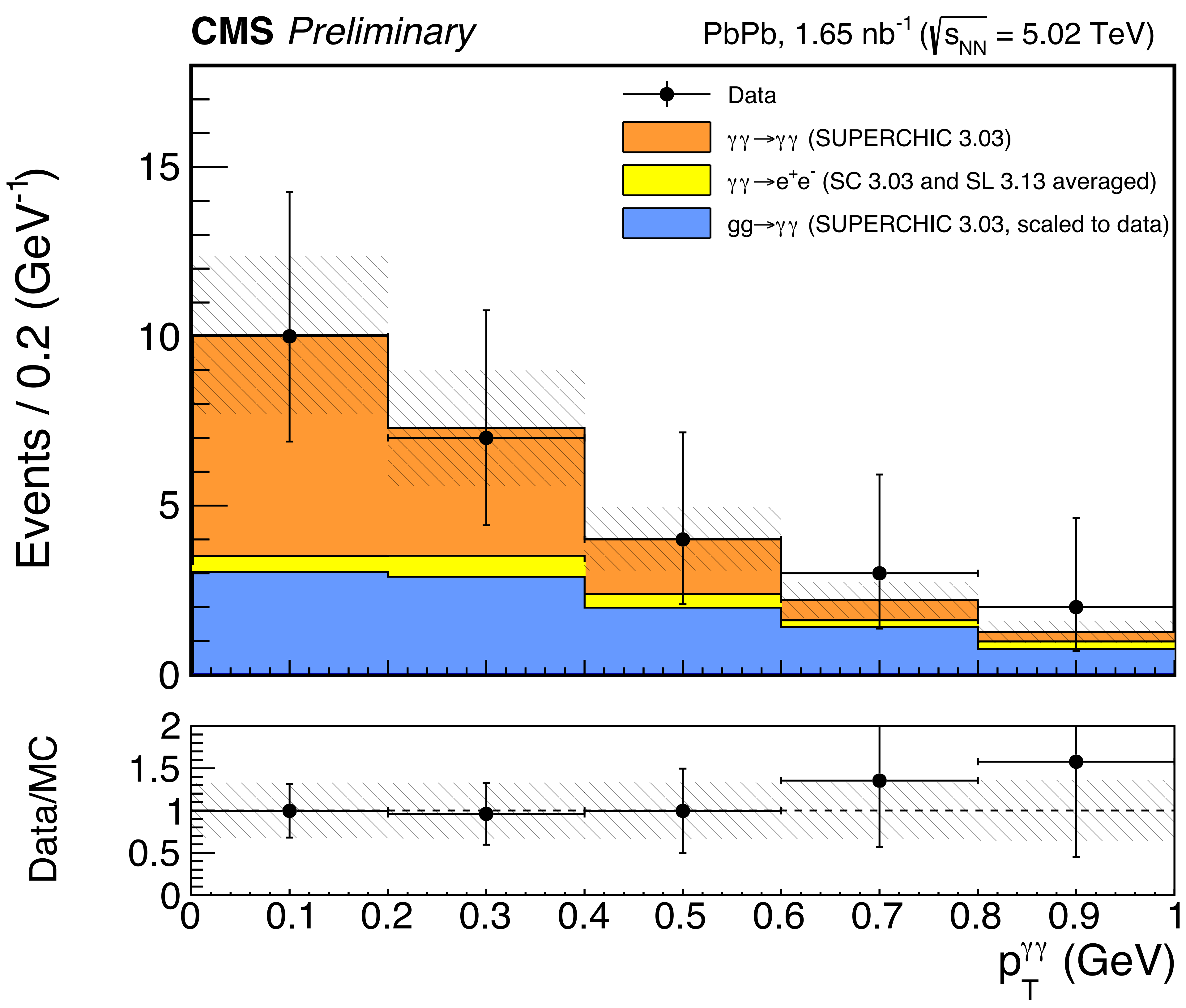
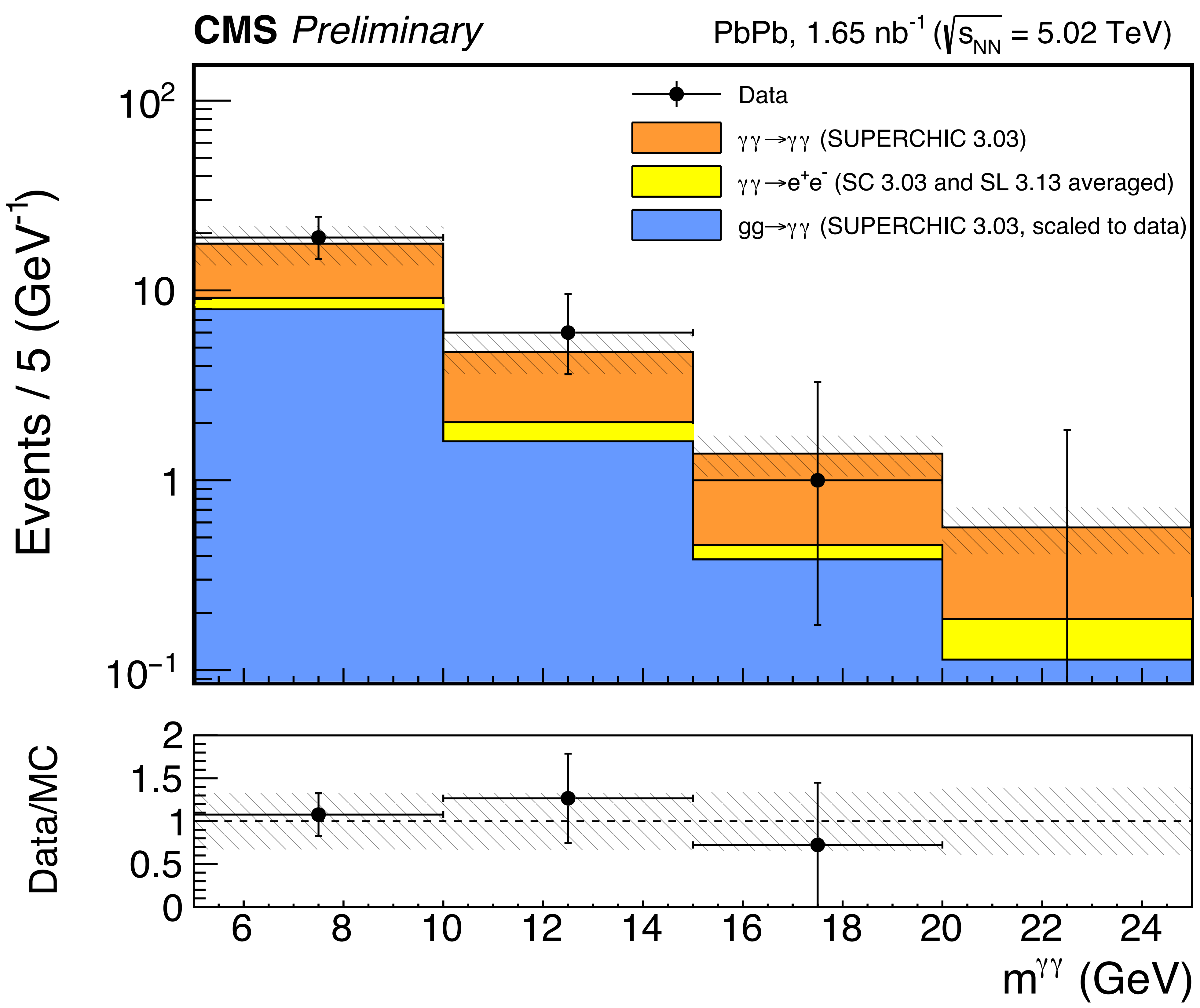
LbyL Process : Detector Level Distribution

- Good agreement in the detector level distributions between data, signal and background MCs





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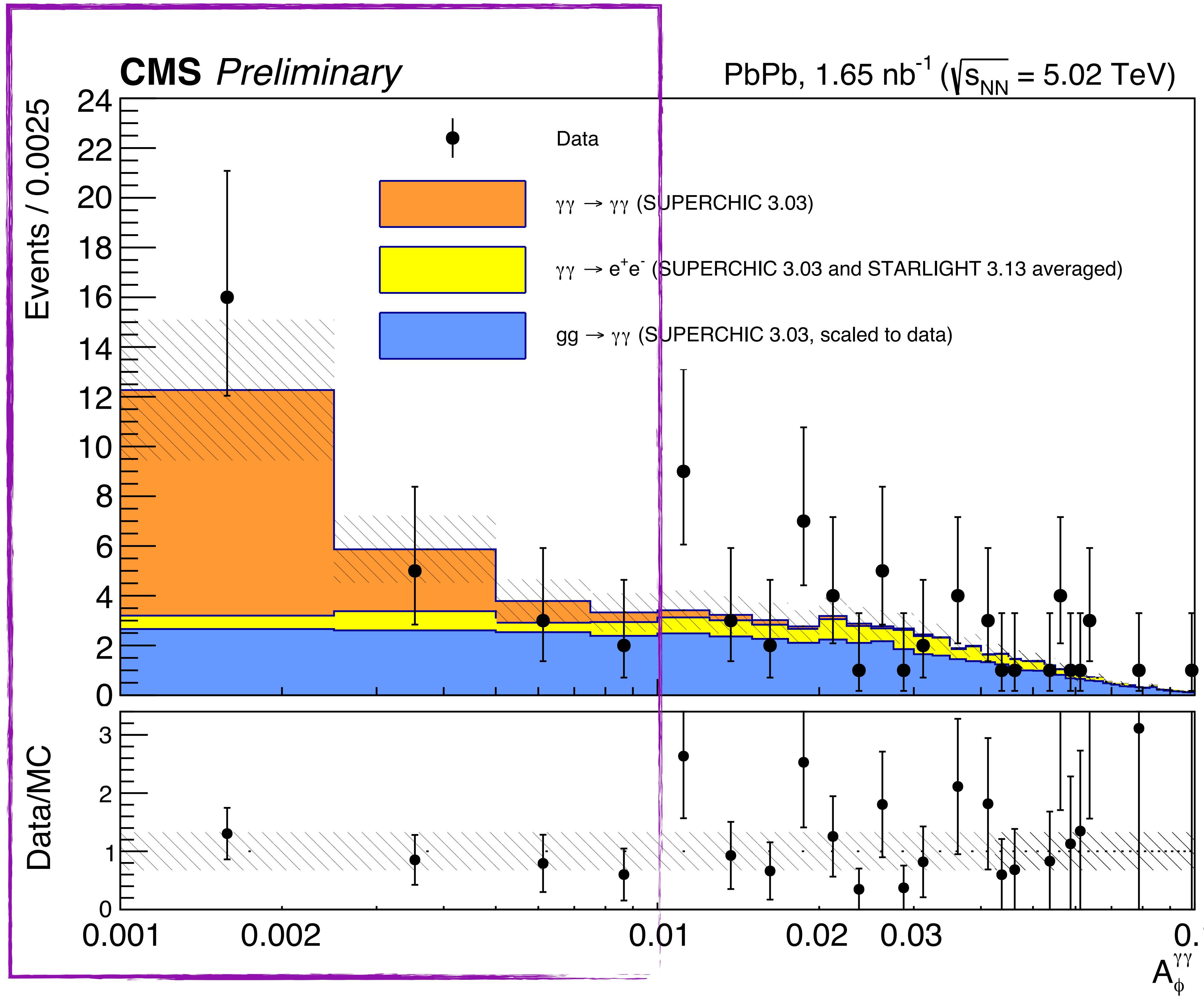
LbyL Process

- In the $A_\phi < 0.01$ region, total 26 data, 12.8 signal MC, 10.1 CEP MC, 1.9 QED e^+e^- events

Systematic Uncertainties

Background normalisation	15%
Background shape	14%
Exclusive diphoton efficiencies	12.5%
Luminosity	1.5%
Total (statistical/nonstatistical)	24% (15%/19%)

$$\sigma_{\text{fid}}(\gamma\gamma \to \gamma\gamma) = \frac{N^{\gamma\gamma,\text{data}} - N^{\gamma\gamma,\text{bkg}}}{C^{\gamma\gamma}\mathcal{L}_{\text{int}}} = 107 \pm 33\,(\text{stat}) \pm 20\,(\text{syst})\,\text{nb}$$



Theoretical predictions:

LO (Superchic): 93 nb

NLO (gamma-UPC): 95.4 ± 2 nb

- σ_{fid} ($\gamma\gamma\to\gamma\gamma$) from data is well in agreement with NLO prediction

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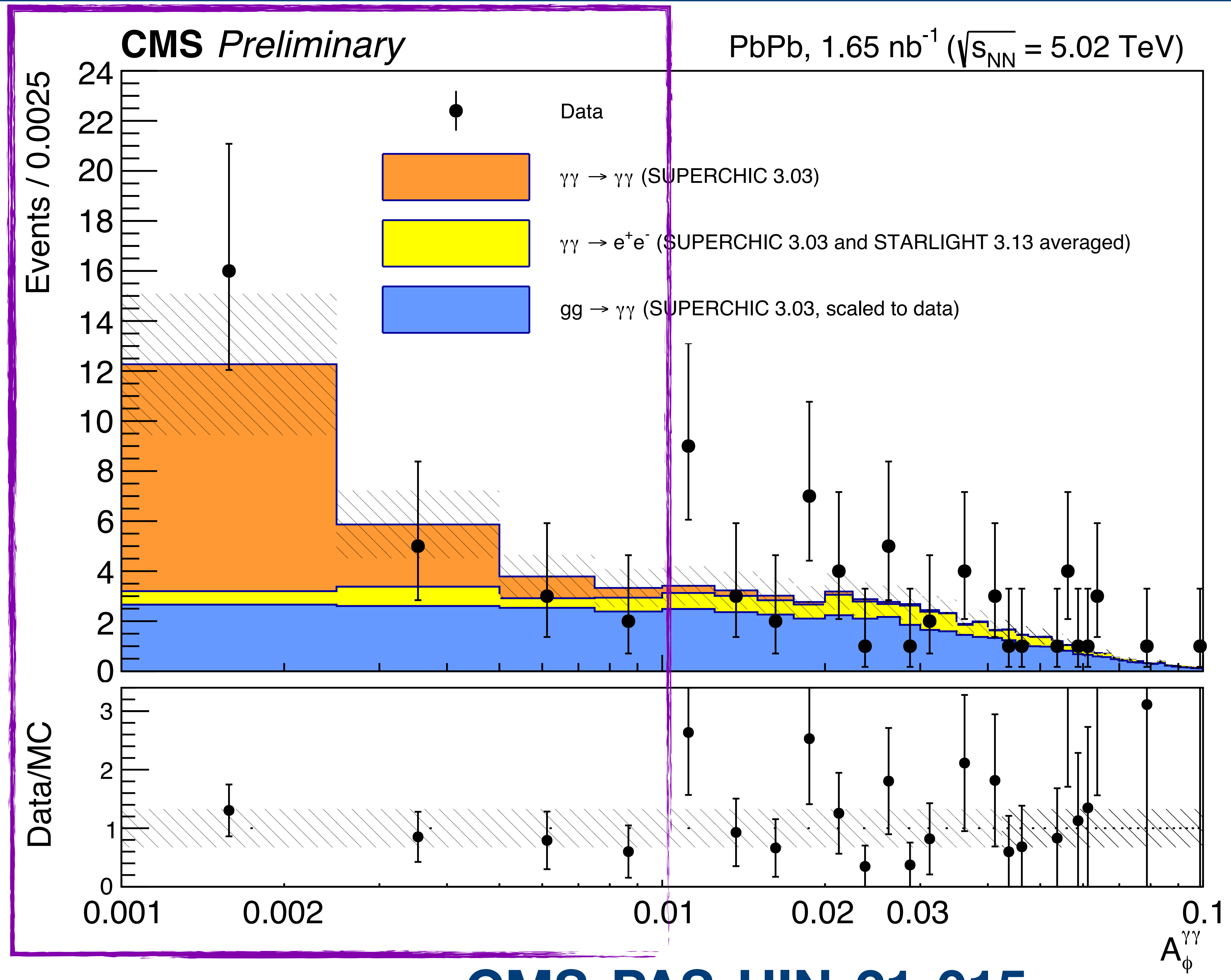
LbyL Process: Significance Estimation

- 2015 data also included in the significance calculation
- In 2015 data rapidity range was $|\eta| < 2.4$ and re-scaled for the rapidity $|\eta| < 2.2$
- Using acoplanarity shape, significance observed for 2018 + 2015 data is 5.8σ and expected is 4.4σ



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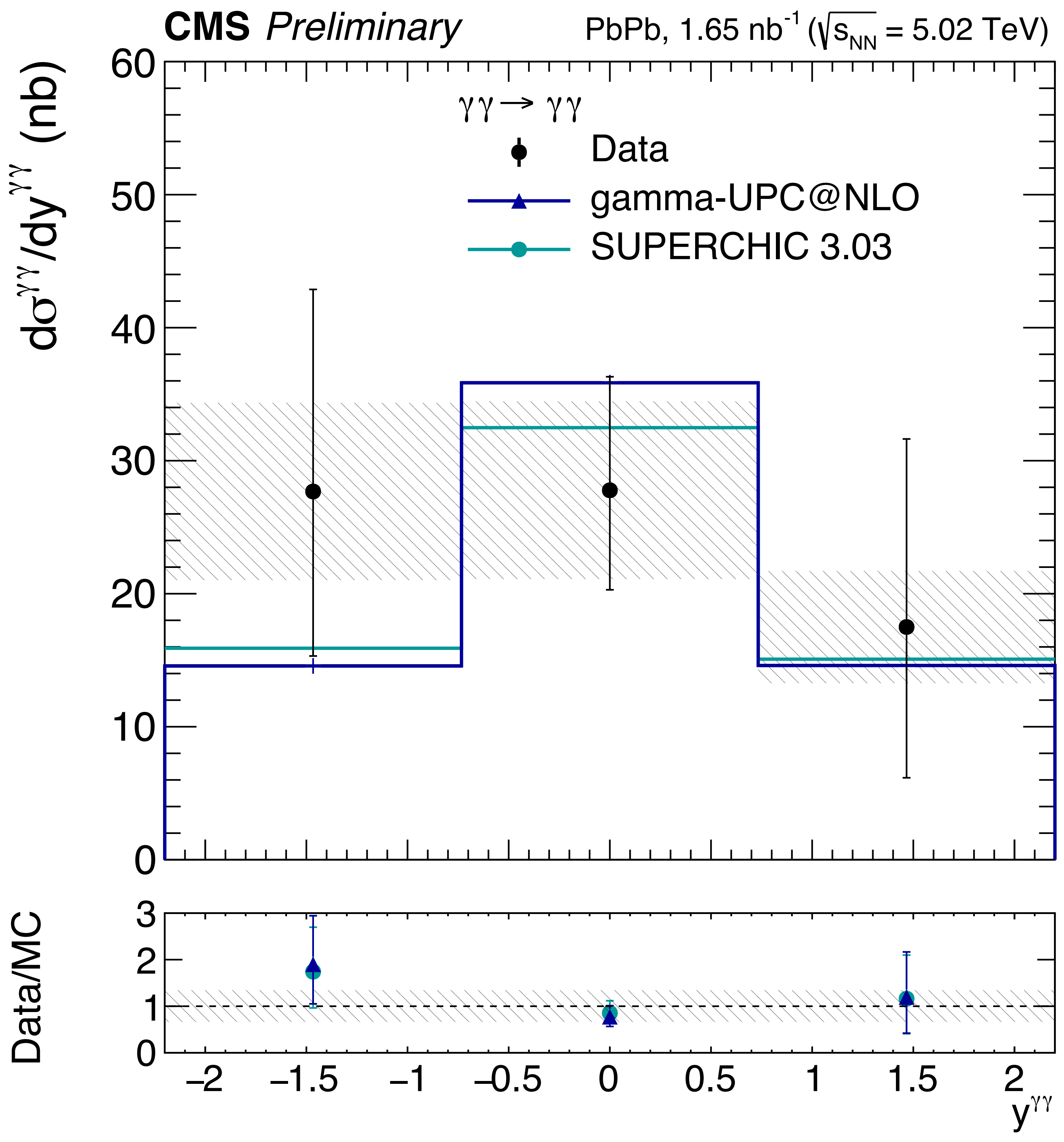
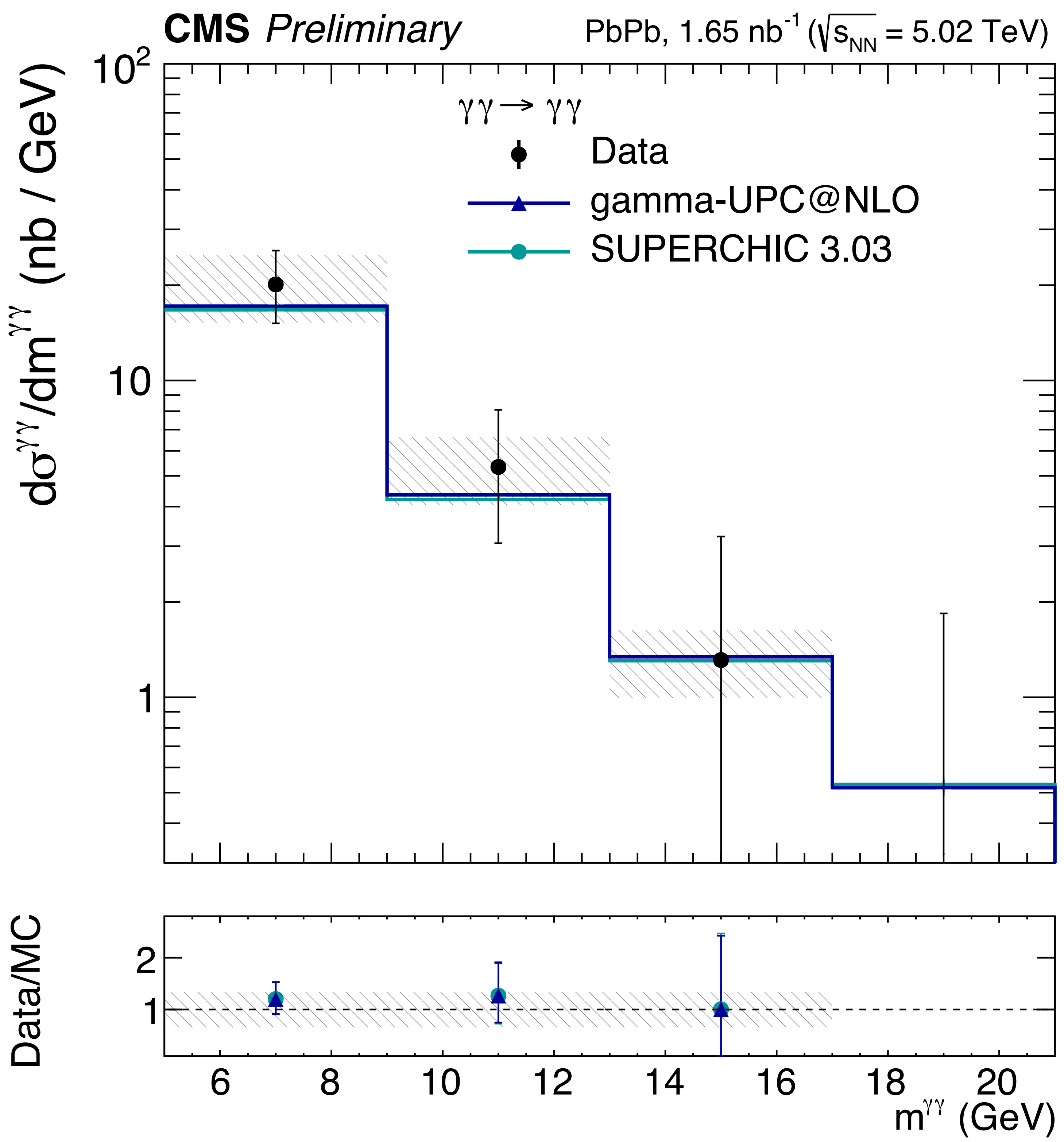
	Number of events after all cuts			Significance
	Data	LbL MC signal	QED+FSR + CEP MC backgds	obs. (exp.)
2015	14	9.0 ± 0.9	4.0 ± 1.2(stat)	3.7σ (3.8σ)
2018 (this analysis)	26	12.8 ± 3.1	12.0 ± 2.9(stat)	5.2σ (3.8σ)
2018 + 2015 ($\lvert\eta^\gamma\rvert$ corrected)	40	21.0 ± 3.2	15.6 ± 3.1(stat)	5.8σ (4.4σ)

LbyL Process: Unfolded Distribution

- Unfolded differential cross-sections compared with gamma-UPC@NLO, Superchic 3.03
- Default unfolding done using Superchic 3.03
- Within uncertainty agreement is good





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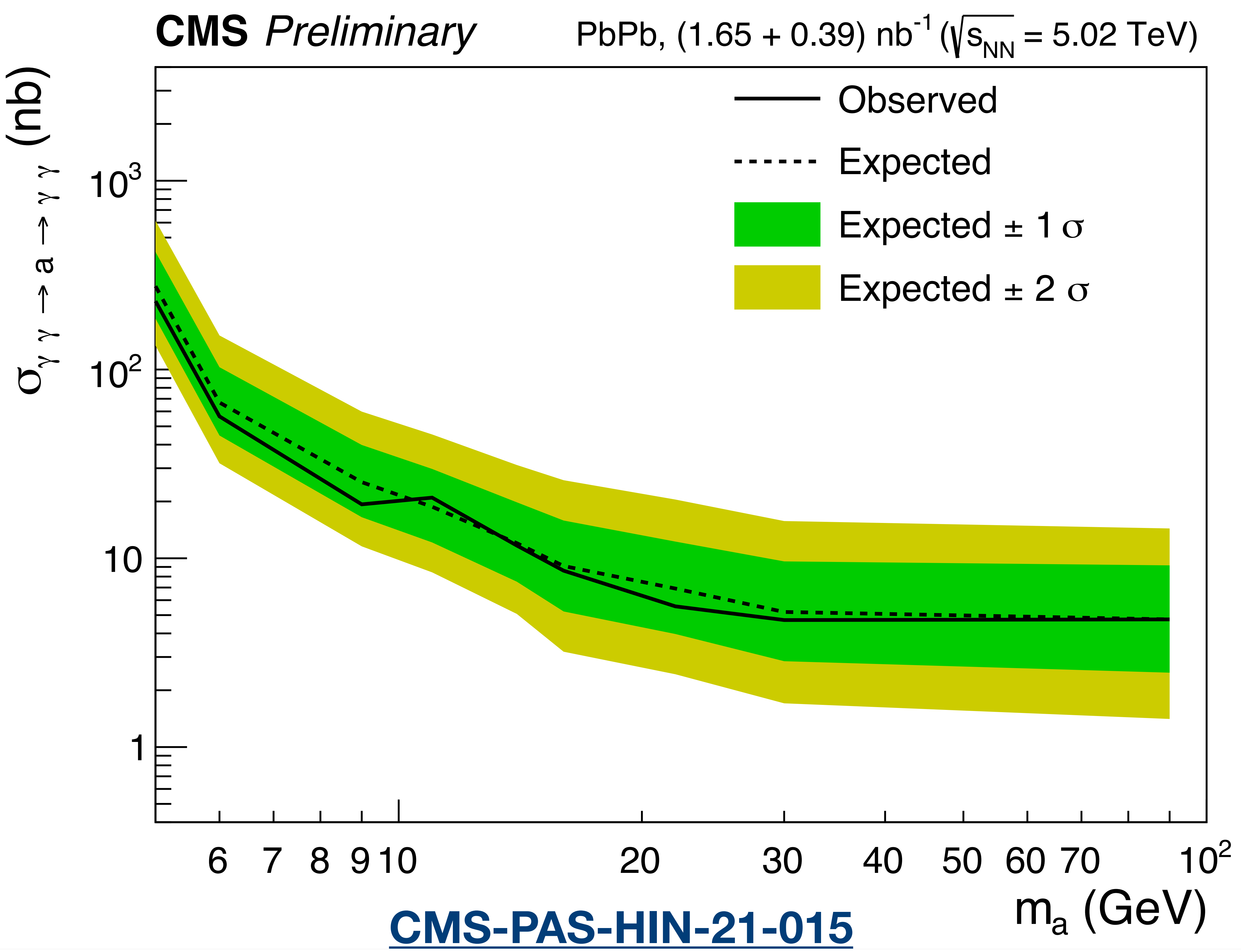
Limits on Axion-Like Particles

- Measured diphoton invariant mass distribution used to search for narrow resonances (ALPs) on top of the light-by-light continuum
- The limit on cross section **σ** ($\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$) for ALPs with masses range 5-90 GeV set in the 5-200 nb range



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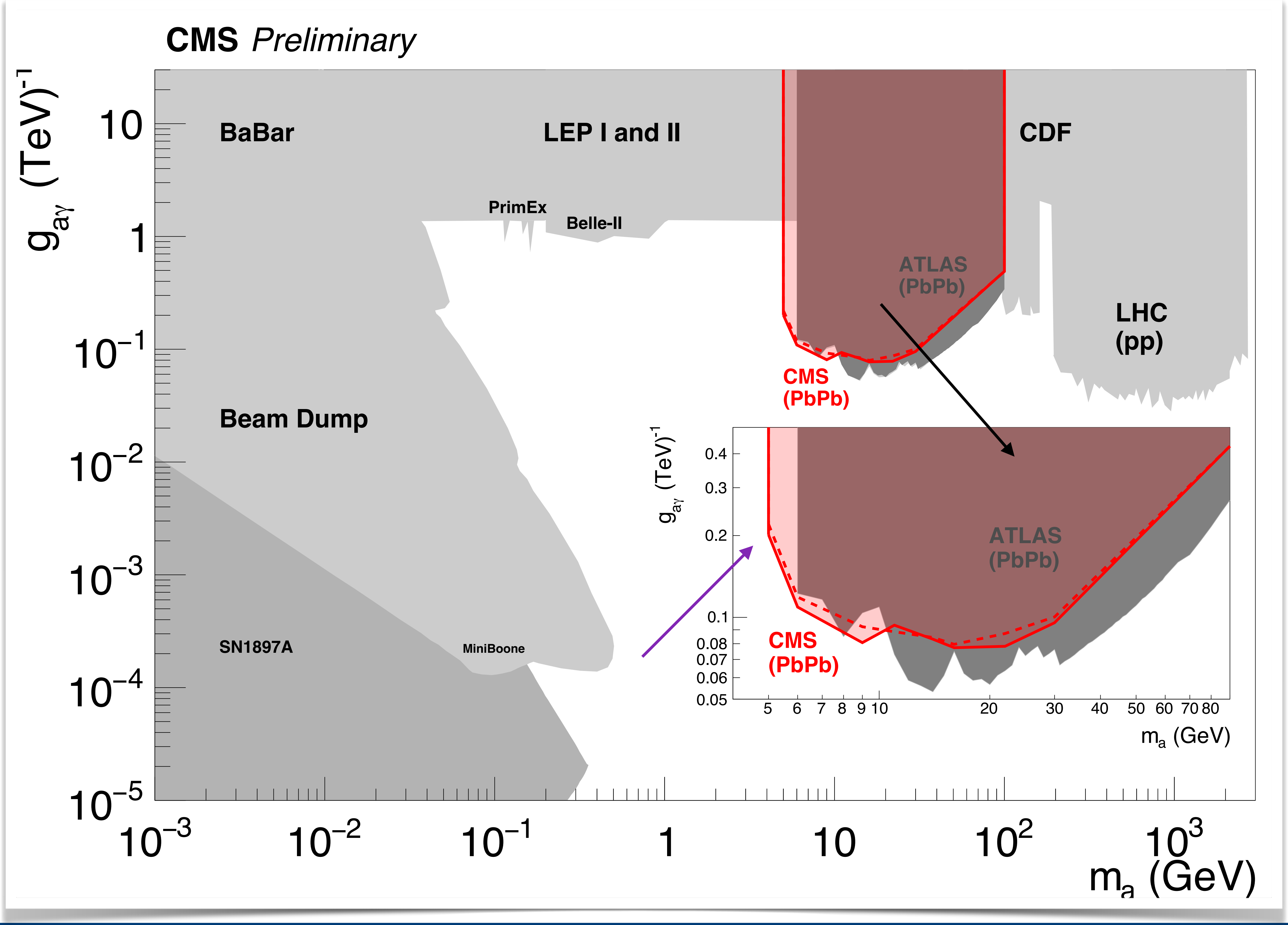
Limits on ALPs: Stringent Limit for 5-10 GeV Mass

- This limit on cross section σ ($\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$) for ALPs with mass range 5-90 GeV used to determine exclusion region in the $g_{a\gamma}$ vs. m_a plane
- Achieved the most stringent limit from 5-10 GeV



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Summary

Breit-Wheeler process:

- σ_{fid} ($\gamma\gamma \rightarrow e+e-$) = 271.5 ± 1.9 (stat) ± 18.3 (syst) μb well in agreement with Superchic 3.03 + FSR = 261 μb, Starlight 3.13 = 251 μb, gammaUPC/MG5 + FSR = 265 μb
- Neutron emission probability (first time measurement) is consistent with Superchic 4.2, Starlight 3.13
- Unfolded distribution is consistent with Superchic 3.03 + FSR , gammaUPC/MG5 + FSR, Starlight 3.13 except in p_T^{ee}

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Light-by-light process:

- σ_{fid} ($\gamma\gamma \to \gamma\gamma$) = 107 ± 33 (stat) ± 20 (syst) nb well in agreement with gammaUPC@NLO = 95.4 ± 2.0 nb
- Unfolded distribution is consistent with Superchic 3.03 , gammaUPC@NLO

Searches for ALPs:

- Set limits on the production of ALPs coupling to photons for ALP masses 5-90 GeV and currently the best for 5-10 GeV

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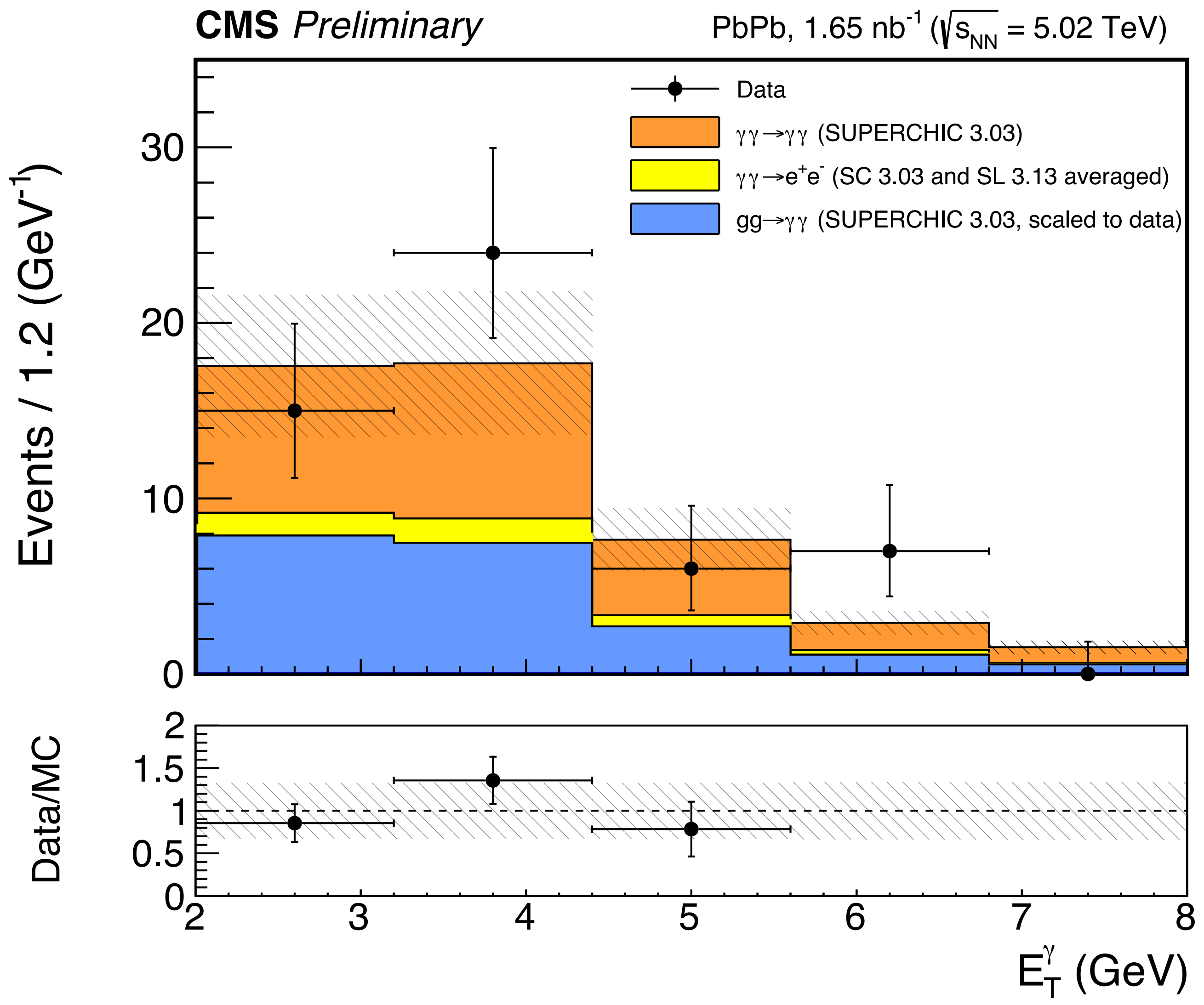
Visualization: Jeremi Niedziela (DESY)

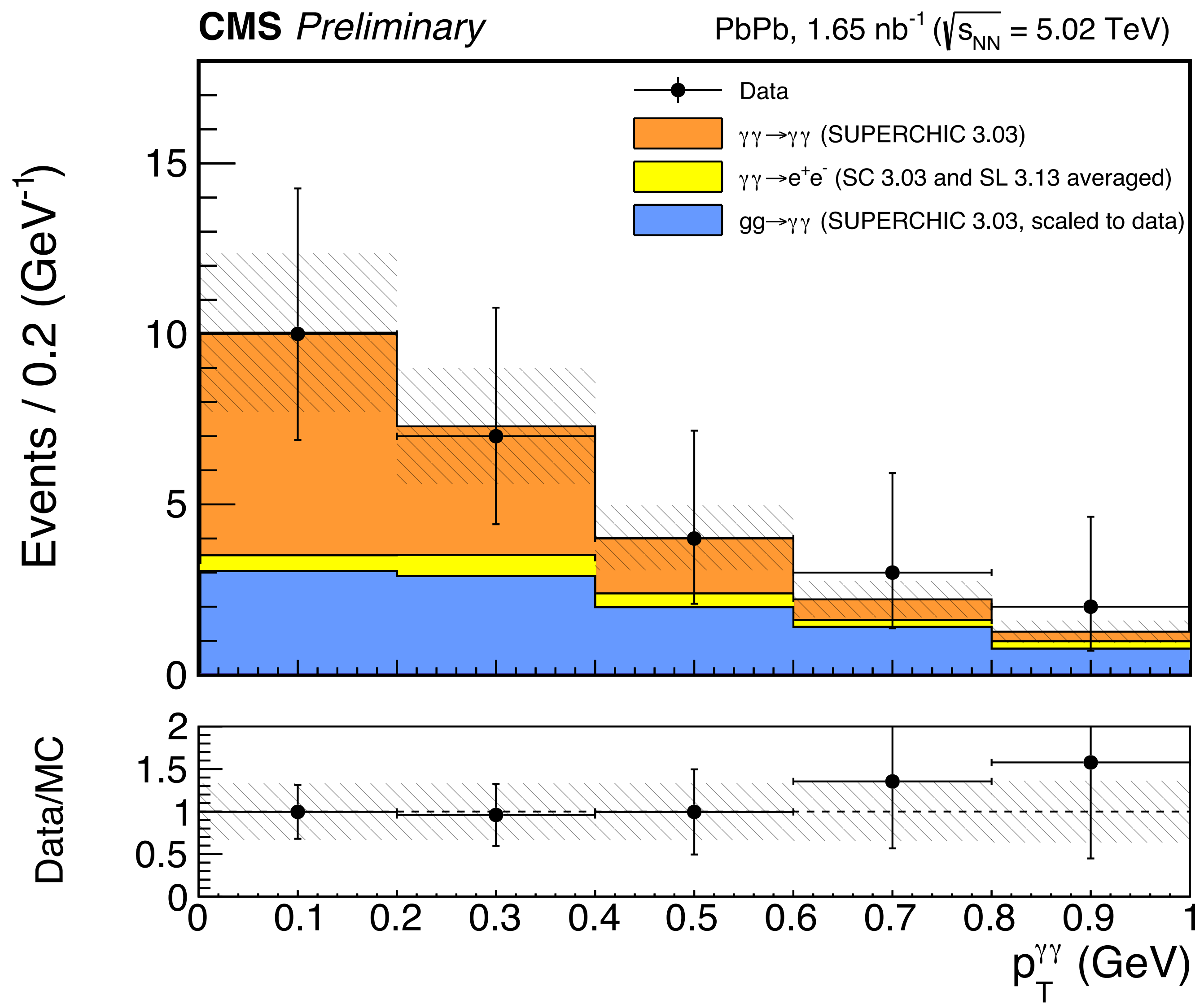
Thank you all for your attention and time!

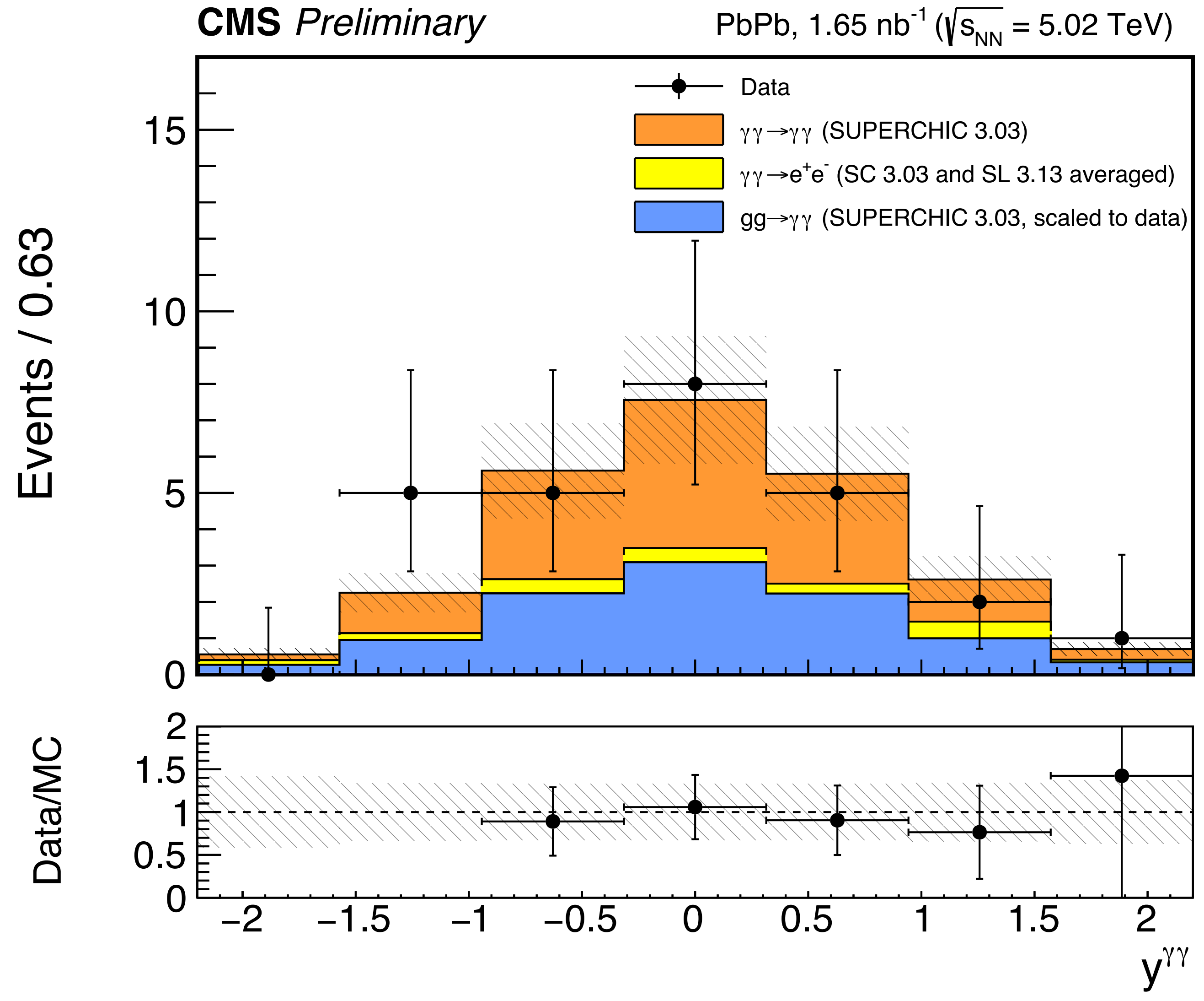
Extra

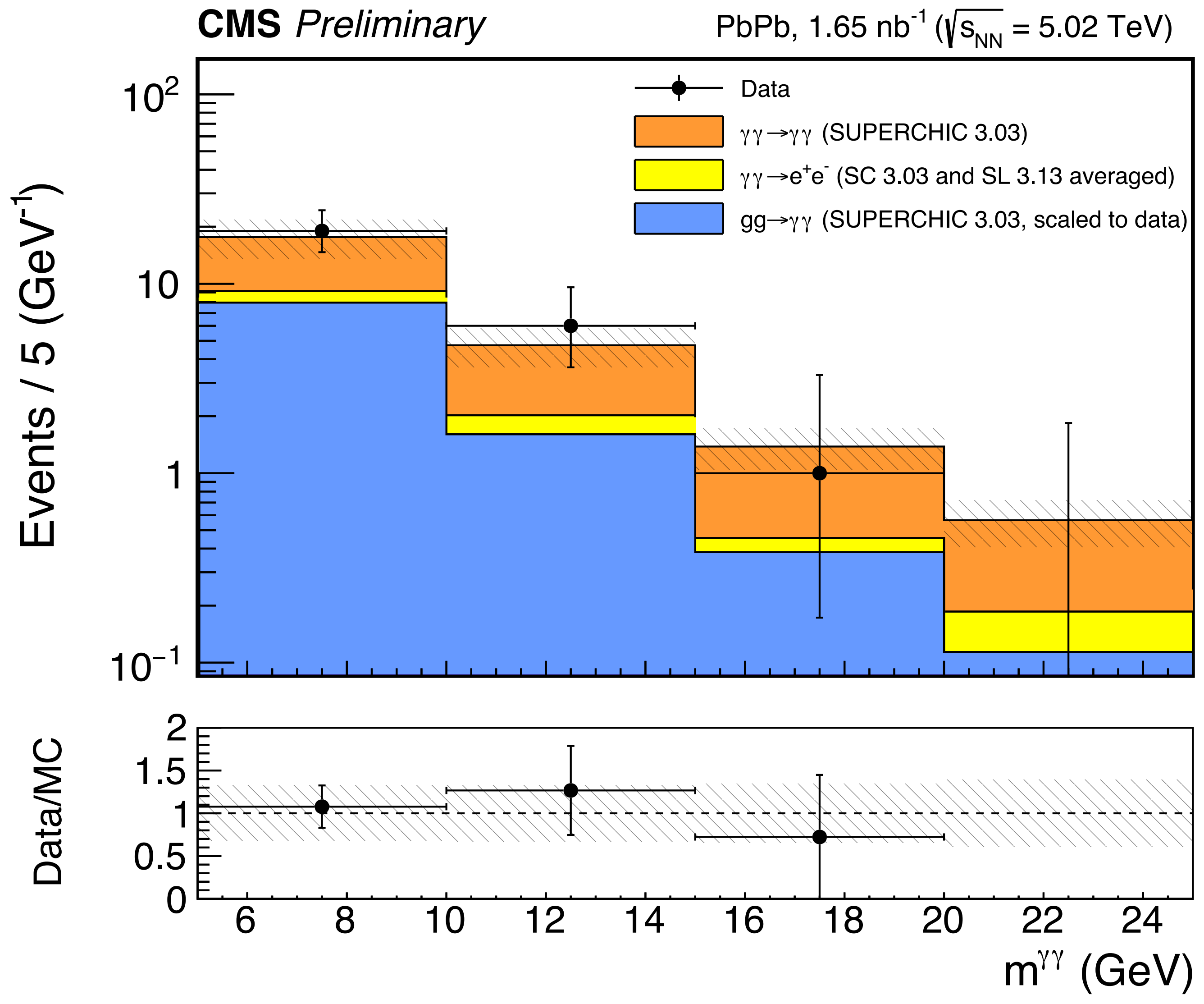
LbyL Process : Detector Level Distribution

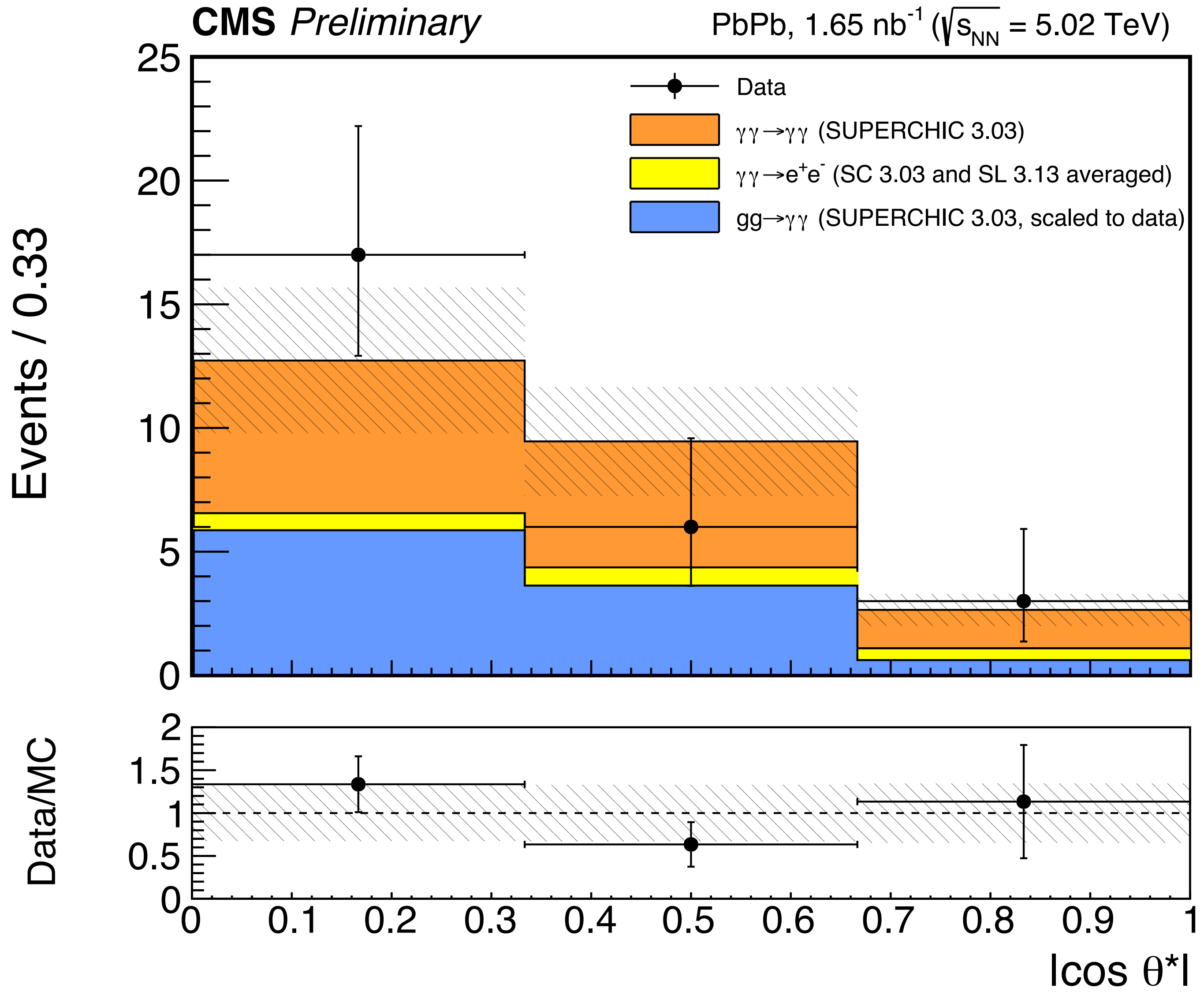
- Good agreement in the detector level distributions between data, signal and background MCs











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Scale Factors and Uncertainties

$$C^{\gamma\gamma,ee} = \varepsilon^{\gamma\gamma,ee} \times (SF^{\gamma,e,reco})^2 \times (SF^{\gamma,e,ID})^2 \times SF^{trig} \times SF^{ch.excl} \times SF^{neut.excl},$$

Diphoton efficiency from simulation	$\varepsilon^{\gamma\gamma}$	=	$(13.5 \pm 0.3)\%$
γ reco. and ID data-to-simulation scale factor	$SF^{\gamma,\text{reco+ID}}$	=	0.92 ± 0.06
Dielectron efficiency from simulation	ε^{ee}	=	$(7.2 \pm 0.1)\%$
$e^{\pm}$ reco. and ID data-to-simulation scale factor	$SF^{e,\text{ reco+ID}}$	=	0.94 ± 0.01
Trigger selection data-to-simulation scale factor	$SF^{\gamma\gamma,\text{trig}}$	=	0.88 ± 0.05
Charged exclusivity data-to-simulation scale factor	$SF^{\text{ch.excl}}$	=	0.93 ± 0.01
Neutral exclusivity data-to-simulation scale factor	$SF^{\text{neut.excl}}$	=	0.85 ± 0.01
Diphoton global efficiency, Eq. (1)	$C^{\gamma\gamma}$	=	$(8.0 \pm 1.1)\%$
Dielectron global efficiency, Eq. (1)	C^{ee}	=	$(4.4 \pm 0.3)\%$

Trigger SF	6.2%
MC-based e^+e^- efficiency	2%
Electron reconstruction and identification SF	$(2 \times 0.5)\%$
Charged exclusivity SF	1%
Neutral exclusivity SF	1%
Luminosity	1.5%
Total	6.8%