UNIVERSITÀ DEGLI STUDI DI PADOVA

INFN PADOVA

Axion results from the LHC, including future prospects

DAVIDE ZULIANI, on behalf of the ATLAS, CMS and LHCb collaborations
UNIVERSITY AND INFN OF PADOVA

LHCP (BELGRADE) - MAY 22, 2023

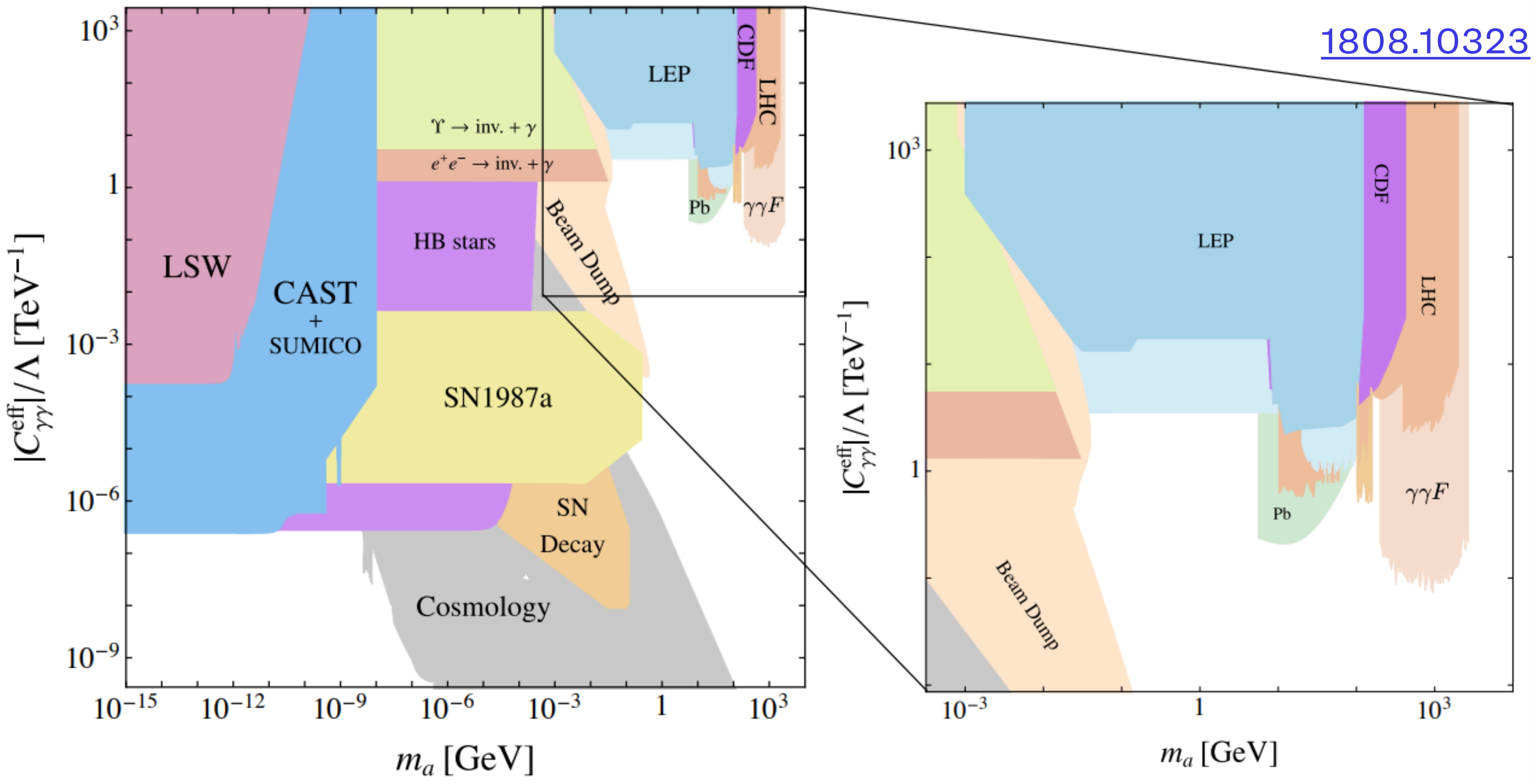
Introduction to Axion Like Particles (ALPs)

- Axions have been postulated in 1977 to solve the strong CP problem
- Very light (pseudo)scalars particles
  - If no dependence between mass and coupling → ALPs!
- ALPs are pseudo Nambu-Goldstone bosons associated to Spontaneous Symmetry Breaking

- Several motivations to search for ALPs:
  - Could be valid DM candidate, or DM mediator
  - Could explain g-2 discrepancies

- ALPs can couple to different sectors of the SM
  - Different kind of searches at colliders!

1808.10323



Overview of LHC results

ATLAS EXPERIMENT

- $pp \to pp\gamma\gamma$
- $pp \to a \to \gamma\gamma$
- $\mathrm{PbPb} \to a \to \gamma\gamma$

CMS

- $\mathrm{PbPb} \to a \to \gamma\gamma$
- $H \to aa \to \gamma\gamma\gamma\gamma$
- $pp \to pp\gamma\gamma$

LHCb

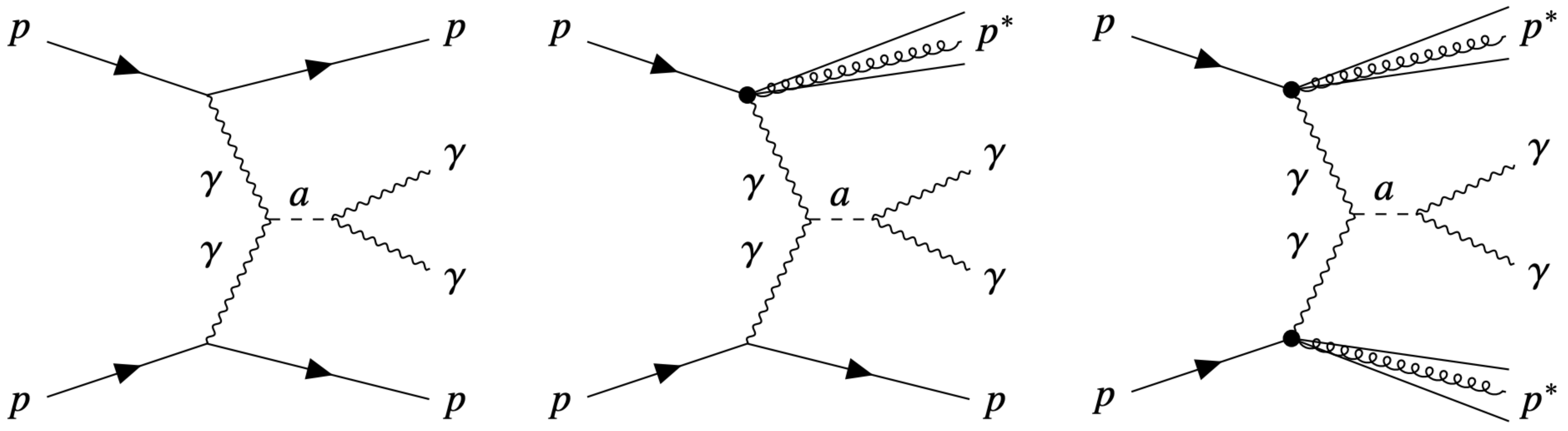
- $pp \to a \to \gamma\gamma$

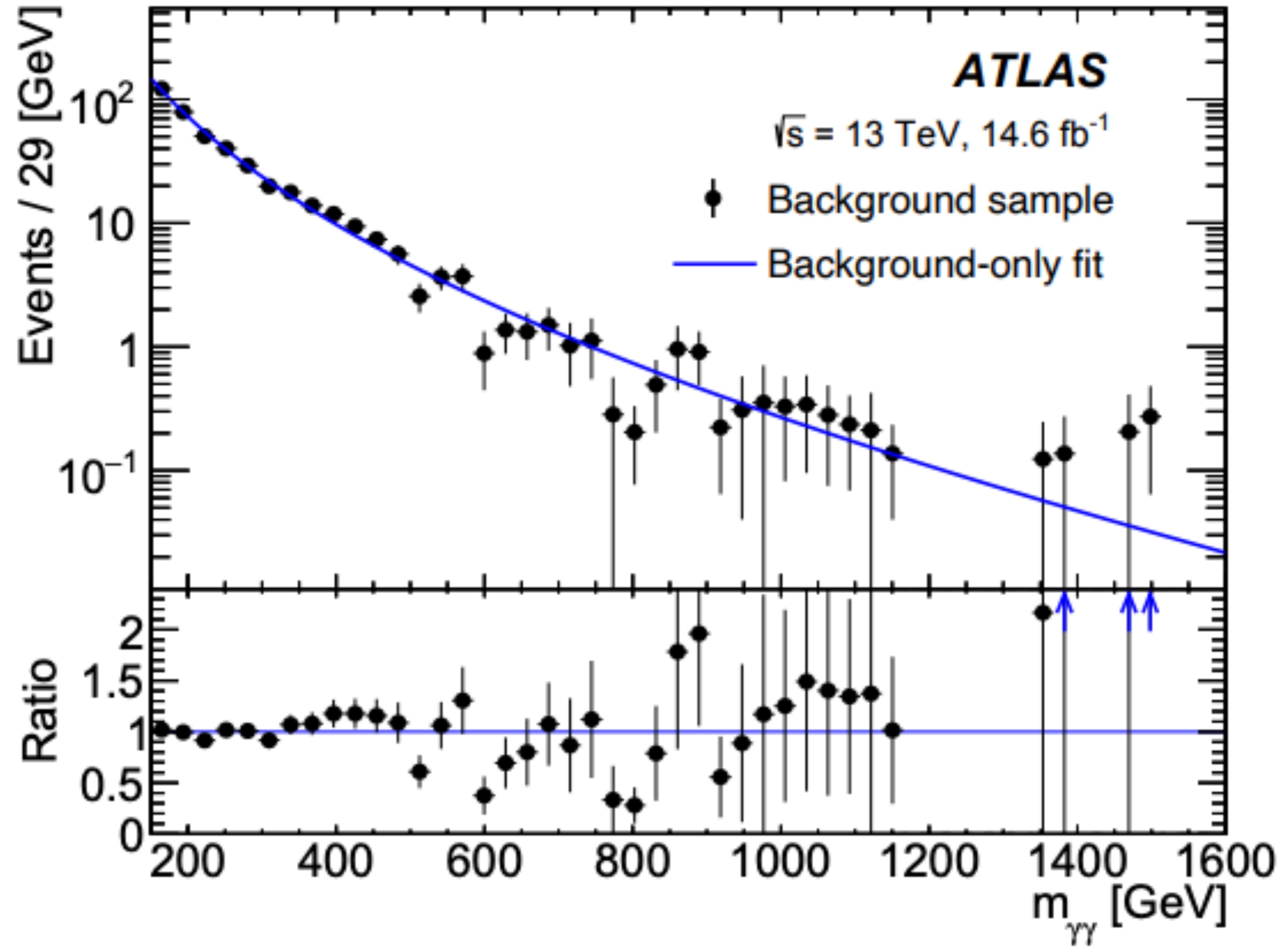
$pp \to pp\gamma\gamma$

ATLAS EXPERIMENT

2304.10953

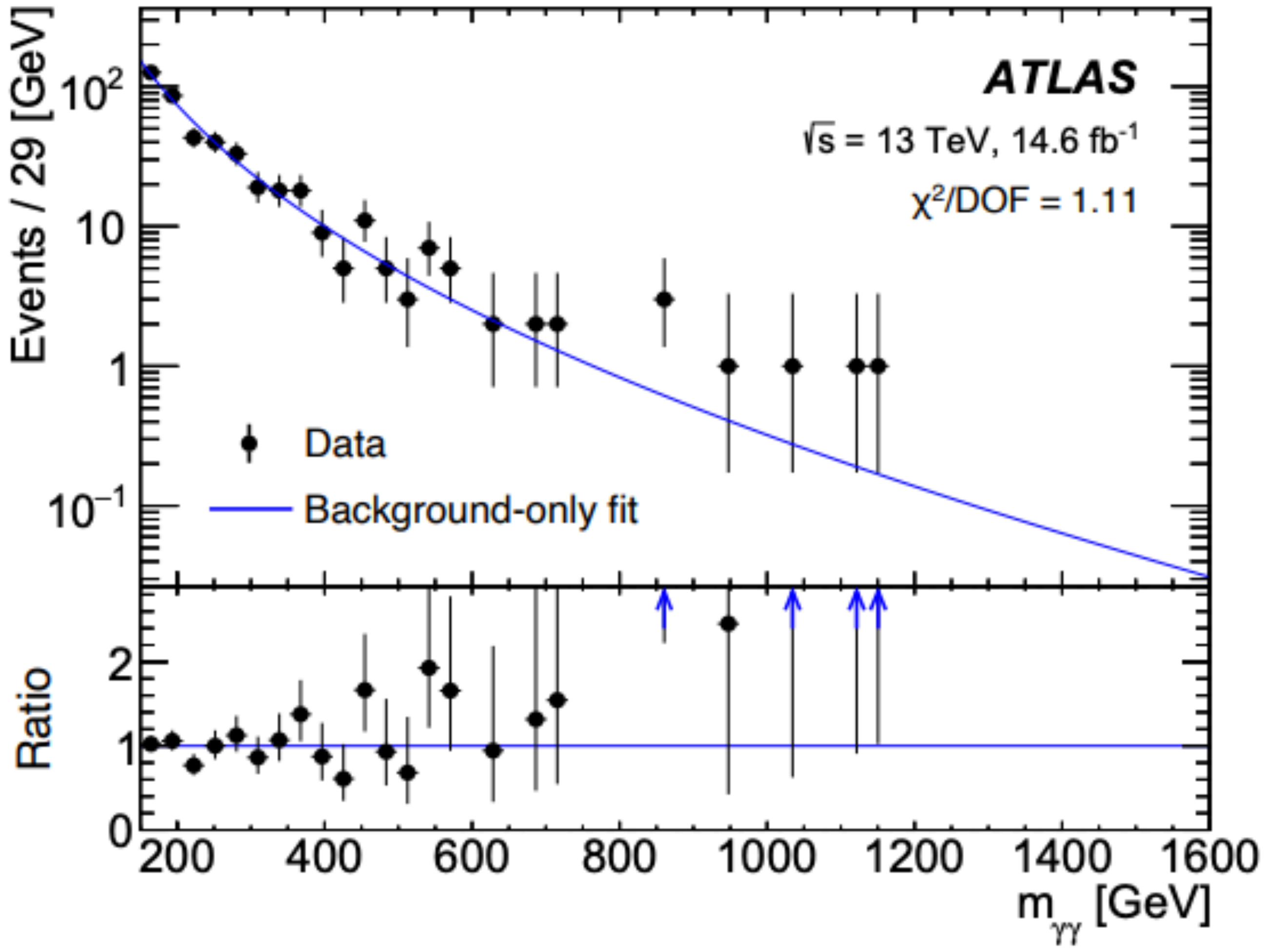
- Goal: search for forward proton scattering with light-by-light scattering
- Dataset: 2017 data, with $\mathscr{L} = 14.6\ \text{fb}^{-1}$ and $\sqrt{s} = 13\ \text{TeV}$
- Tag forward protons (with AFP) while detecting pair of photons in th central detector
- Target mass range: $150 < m_a < 1600\ \text{GeV}$
- Three possible interactions: exclusive, single (SD) and double dissociative (DD)
- Diphoton trigger: two EM clusters with $E_T > 25{,}35\ \text{GeV}$
- Tight selection requirements:
  - $E_T > 22\ \text{GeV},\ |\eta| < 2.37$
  - $p_T > 40\ \text{GeV}$
  - $|\Delta\xi| = |\xi_{AFP} - \xi\gamma\gamma| < 0.004 + 0.1\xi_{\gamma\gamma}$, where $\xi = 1 - E_{\text{scattered}}/E_{\text{beam}}$
- Signal modeling with DSCB fitting MadGraph simulations
- Main background: pair of photons (or misidentified jet) in the same bunch crossing



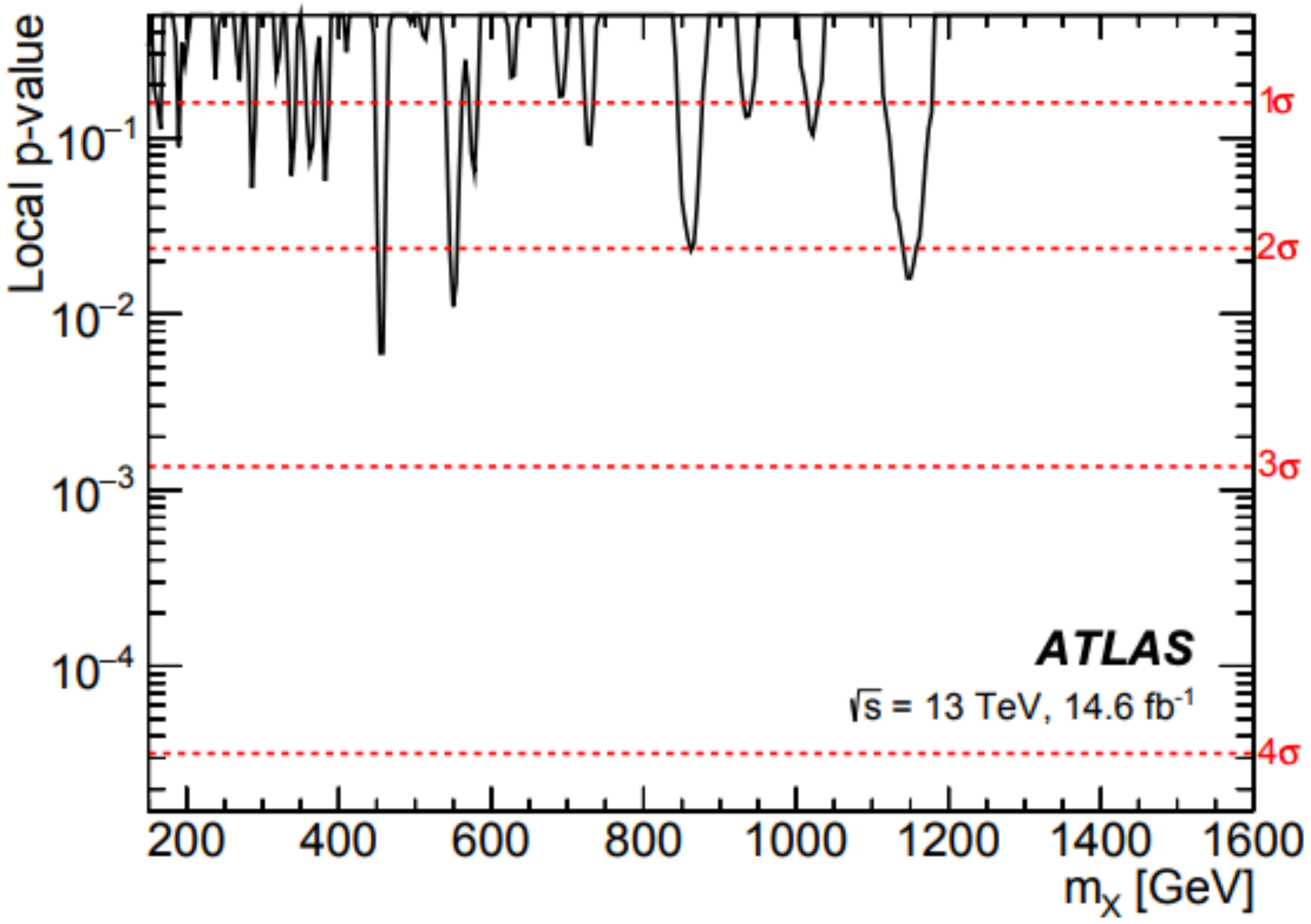


$pp \to pp\gamma\gamma$

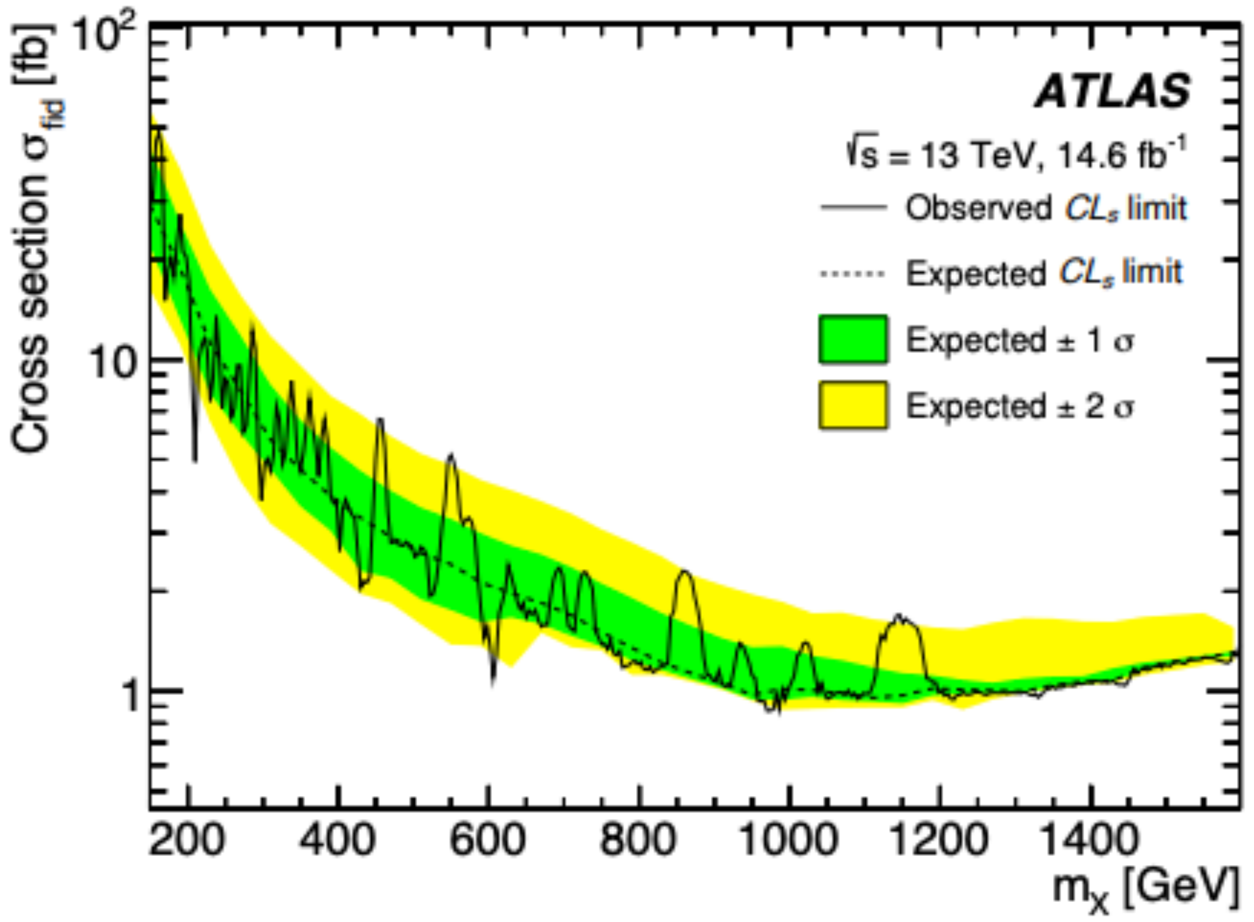
2304.10953

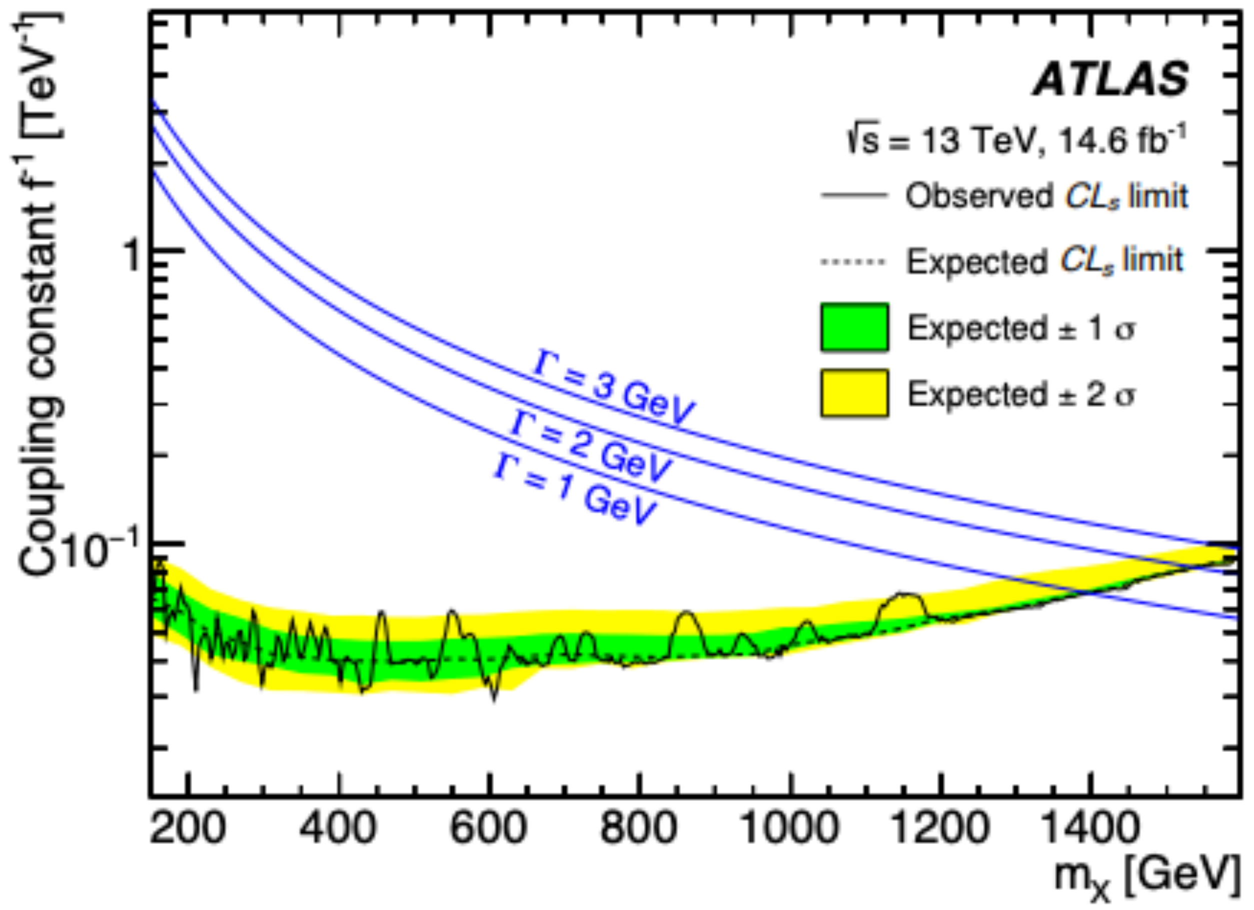


- Unbinned maximum-likelihood fit it to $m_{\gamma\gamma}$
  - Fit procedure dominated by statistical uncertainty
  - Systematic uncertainties are included as nuisance parameters
- 441 events are found in the $[150,1600]$ GeV range
- Local p-value evaluation shows an excess at $m_{\gamma\gamma} = 454$ GeV



- Upper limits computed at 95% CL assuming a 100% BR to photons
- No signal is observed and data are compatible with SM





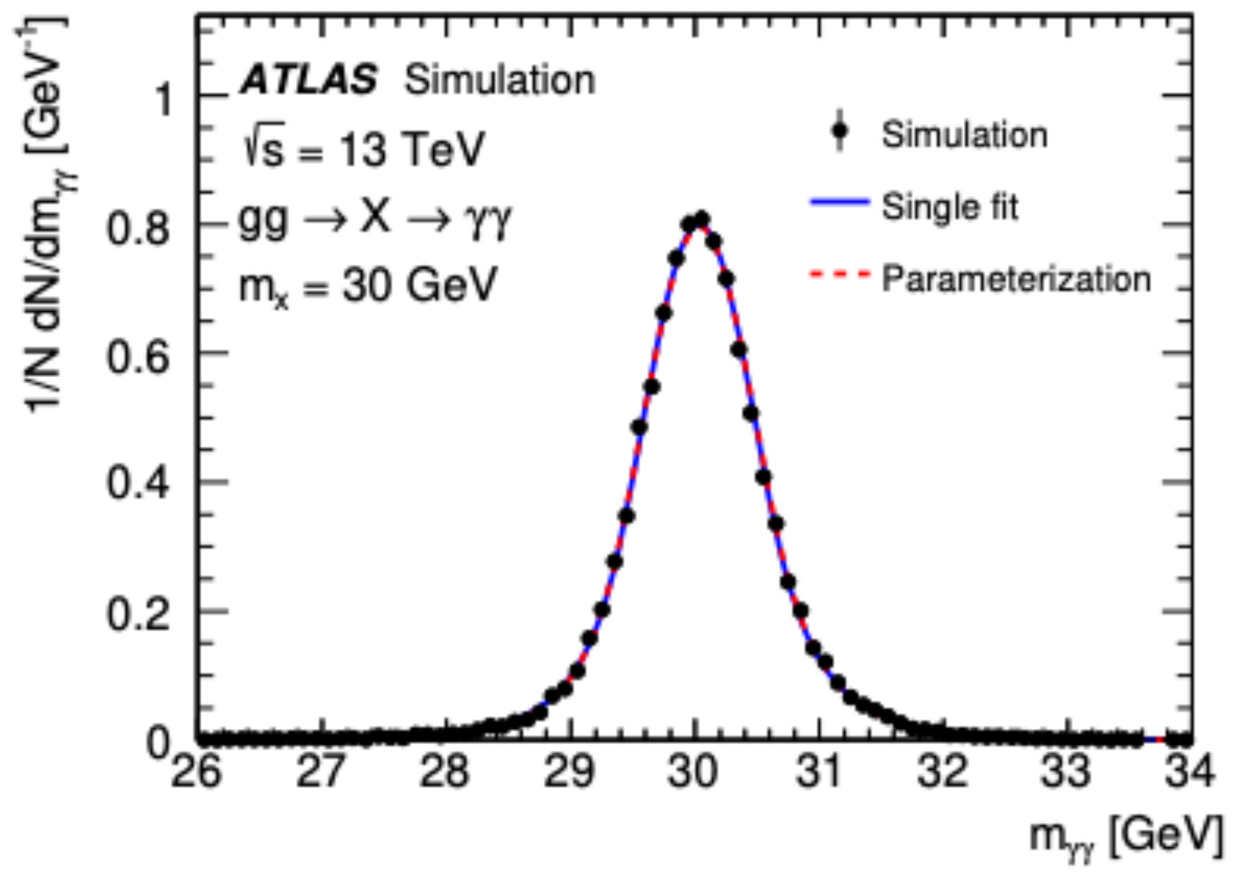
$pp \to a \to \gamma\gamma$

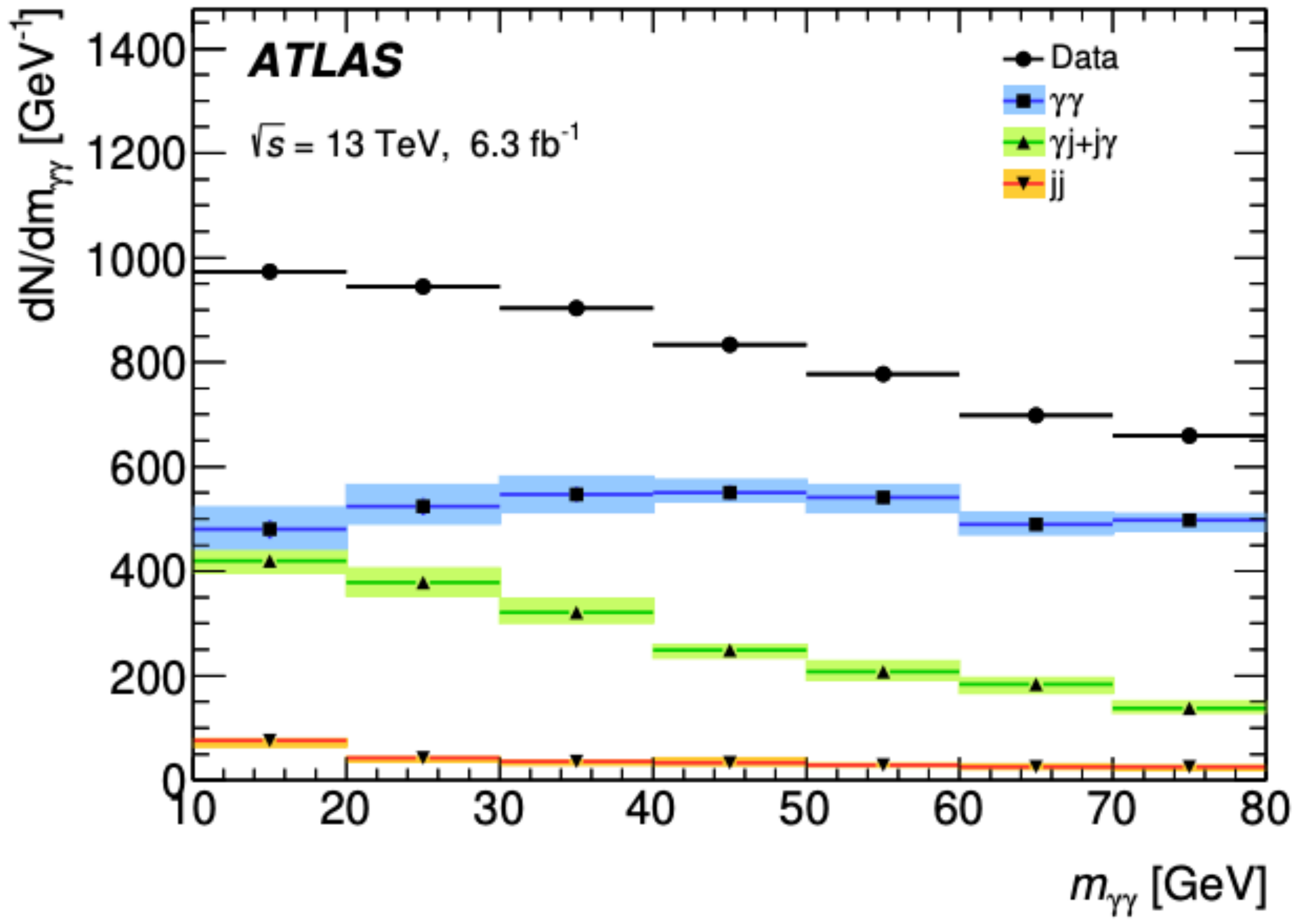
2211.04172

- Goal: search for boosted diphoton resonances, with $10 < m_{\gamma\gamma} < 70$ GeV
- Dataset: Run 2 data, with $\mathscr{L} = 138\ \text{fb}^{-1}$ and $\sqrt{s} = 13$ TeV
- Boosted topology → allows for search to lower masses

- Tight selection requirements for photons:
  - $E_T > 22$ GeV, $|\eta| < 2.37$
  - Shape of EM showers and leakage in HCAL
  - Photons are isolated
  - $p_T^{\gamma\gamma} > 50$ GeV

- Signal modeling with DSCB fitting MadGraph simulations
- Background components: $\gamma\gamma$, $\gamma + j$ and jj
- Data-driven technique to model backgrounds with analytic functions
  - Main uncertainty: limited size of simulated samples

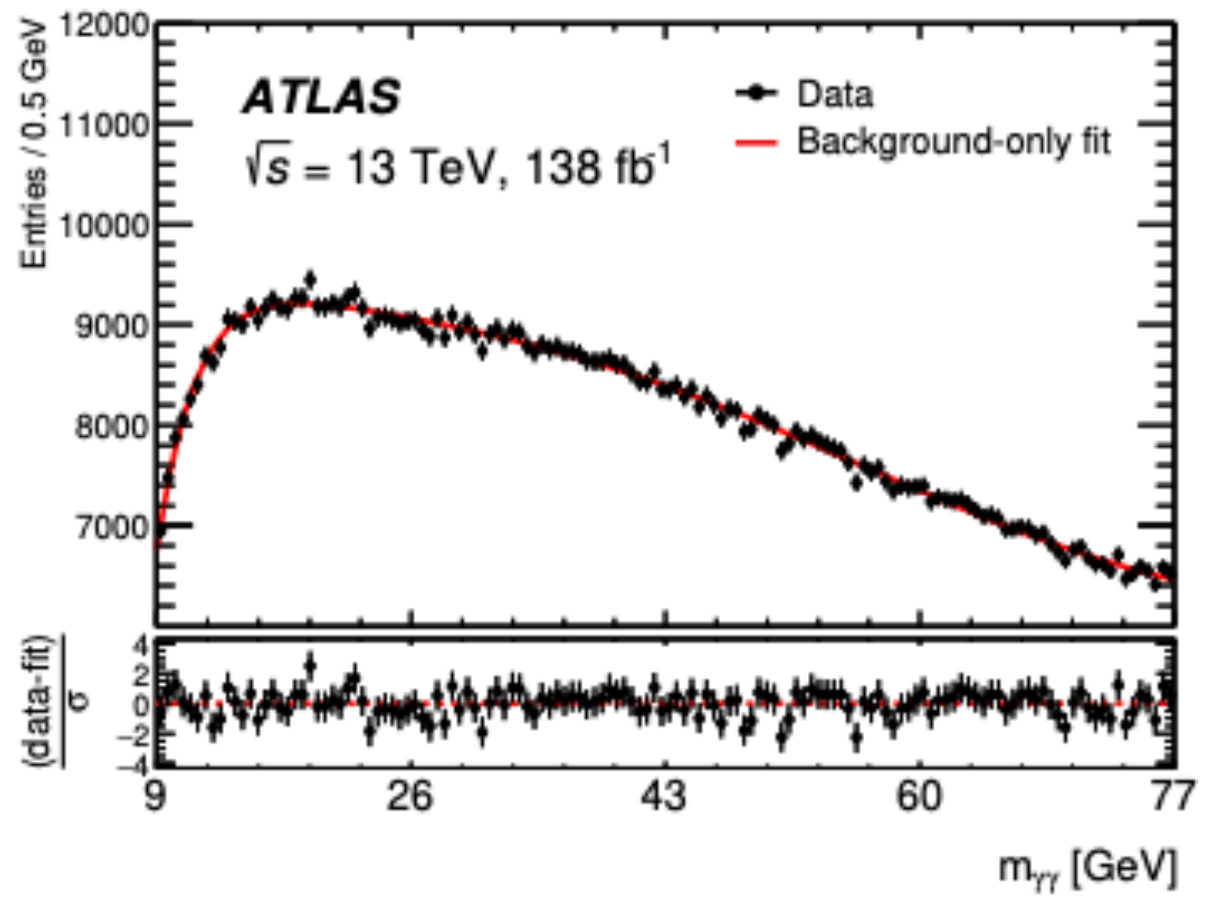


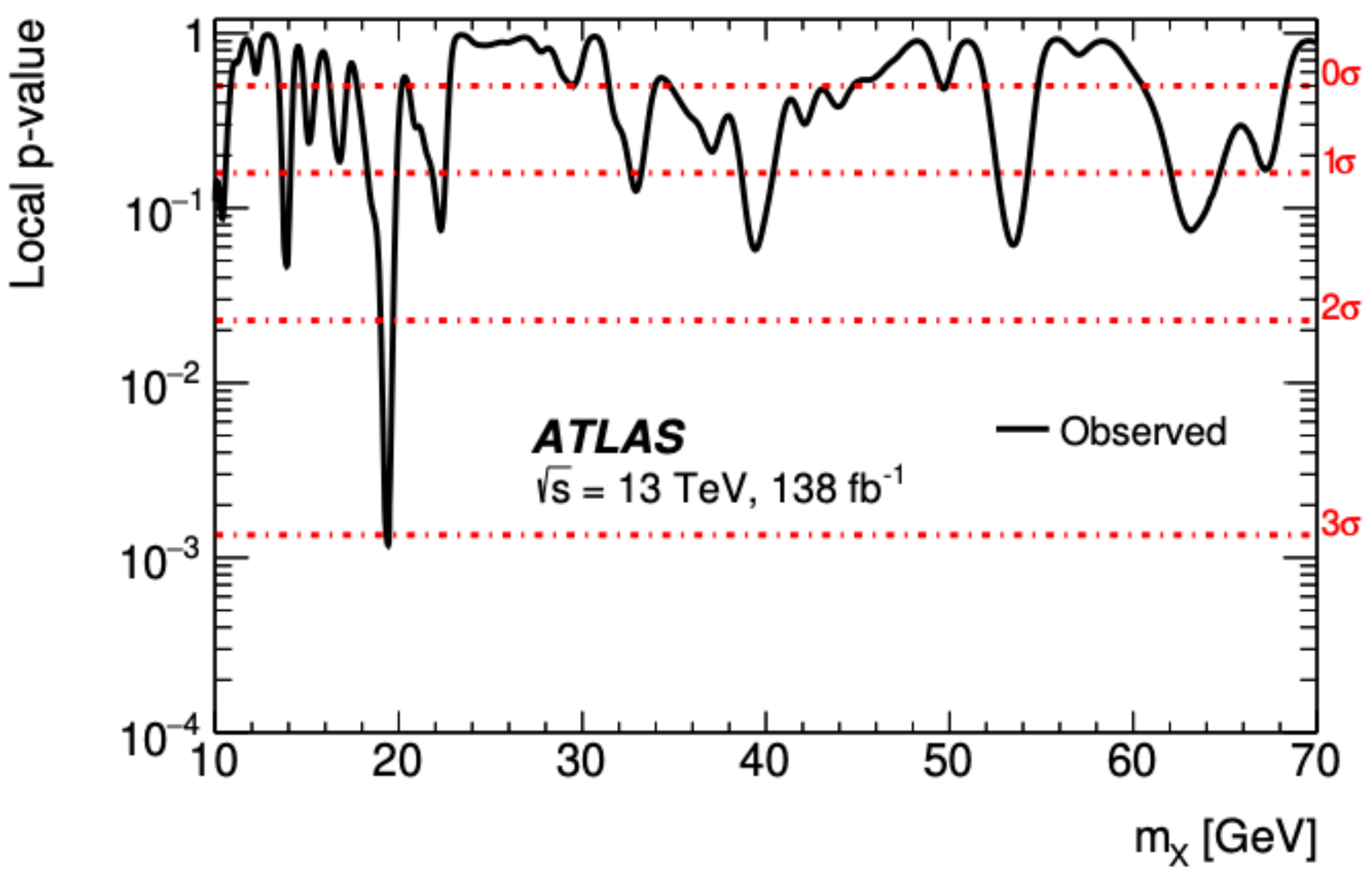


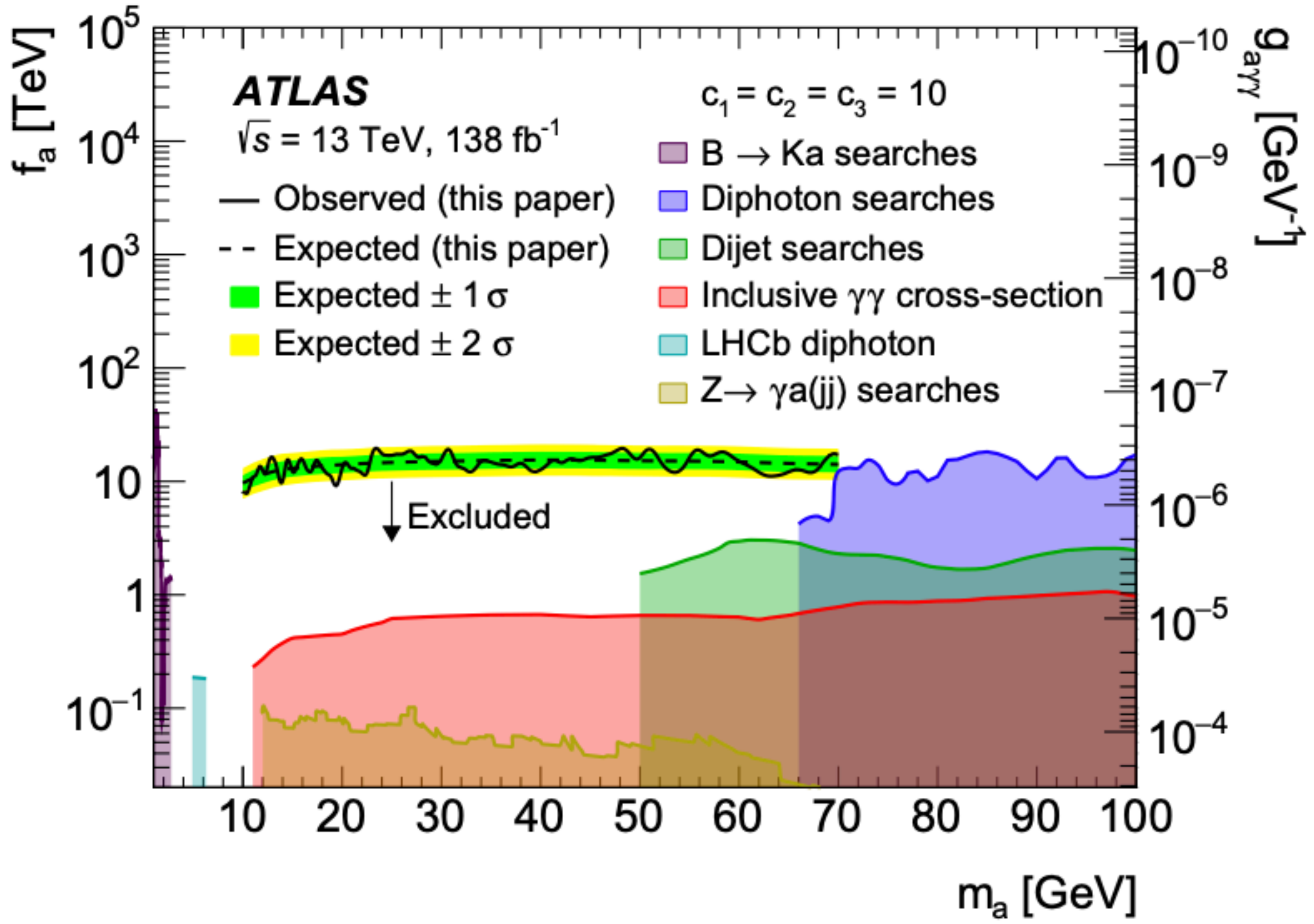
$pp \to a \to \gamma\gamma$

2211.04172

- Evaluation of $\sigma \cdot \mathscr{B}(a \to \gamma\gamma)$ in fiducial region $\to \sigma_{\text{fid}} \cdot \mathscr{B}(a \to \gamma\gamma) = \dfrac{N}{C \cdot \mathscr{L}}$
- N extracted with a binned maximum-likelihood fit to $m_{\gamma\gamma}$
- Systematic uncertainties are included as nuisance parameters
  - Highest uncertainty comes from background modelling
- No significant deviations from SM predictions are found







- Limits on $\sigma_{\text{fid}} \cdot \mathscr{B}(a \to \gamma\gamma)$ are recast in the parameter space of ALP
- Upper limit on $\sigma_{\text{fid}} \cdot \mathscr{B}(a \to \gamma\gamma)$ results in a lower limit on f_a
- Large portion of ALP parameter space is covered

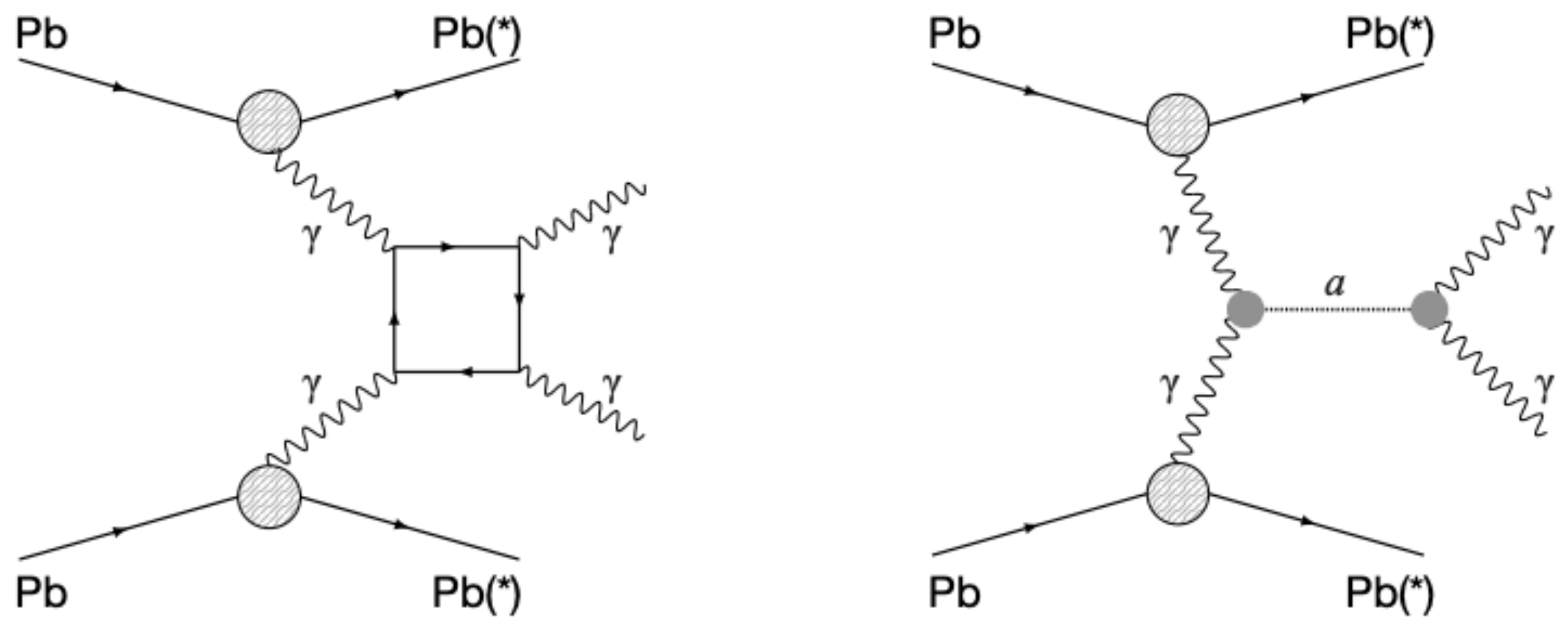
$\mathrm{PbPb} \to a \to \gamma\gamma$

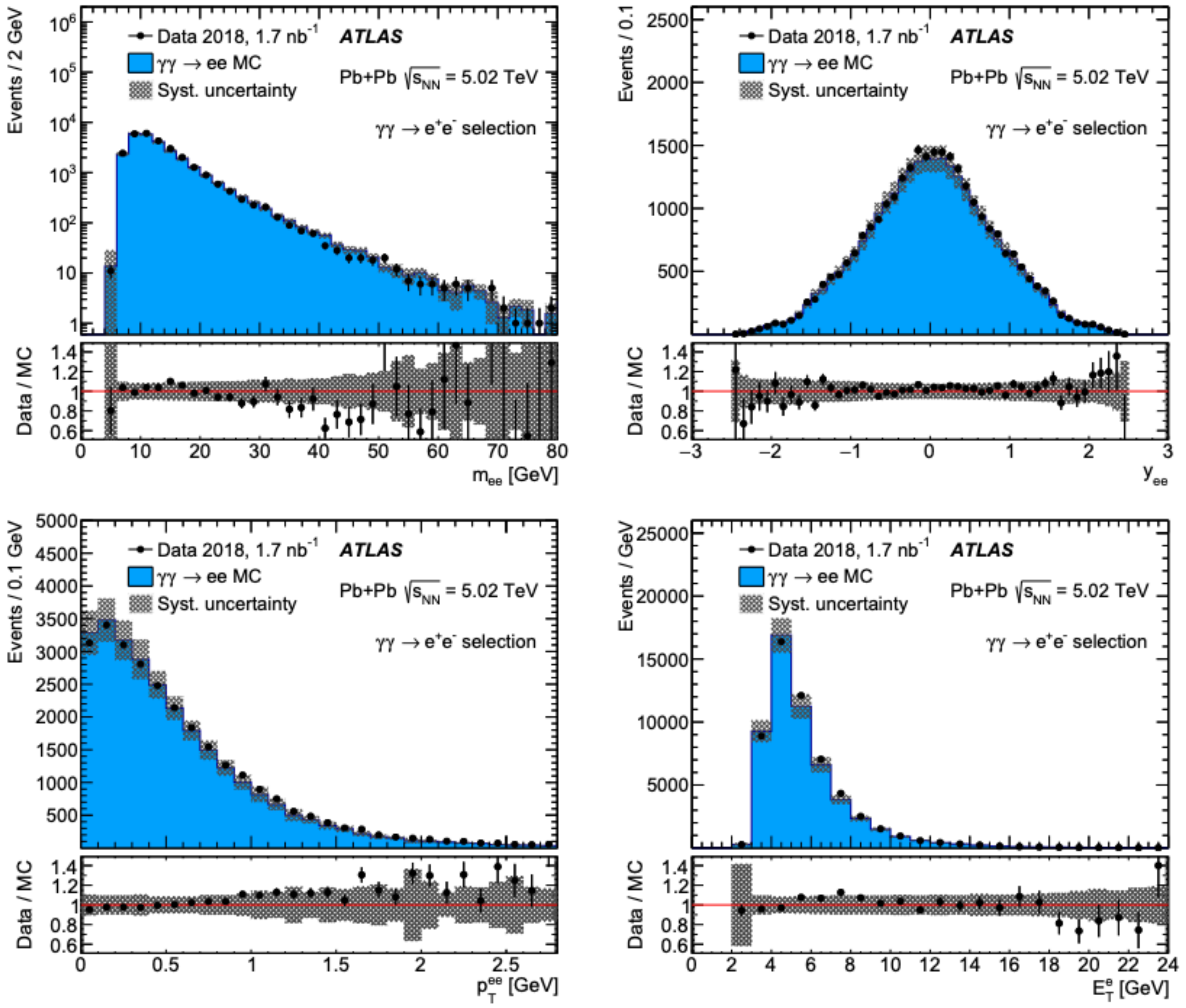
ATLAS EXPERIMENT
JHEP 03 (2021) 243

- Equivalent photon flux scales with Z^4
  - Pb beams optimal source of high energy photons
- Goal: measure light-by-light scattering based on PbPb collisions
- Dataset: Run 2 data, with $\mathscr{L} = 2.2\ \mathrm{nb}^{-1}$ and $\sqrt{s_{\mathrm{NN}}} = 5.02\ \mathrm{TeV}$
- Target mass range: $6 < m_a < 100\ \mathrm{GeV}$

- Requiring exactly two photons with:
  - $E_{\mathrm{T}} > 2\ \mathrm{GeV},\ |\eta| < 2.37$
  - $m_{\gamma\gamma} > 5\ \mathrm{GeV},\ p_{\mathrm{T}}^{\gamma\gamma} < 1\ \mathrm{GeV}$
  - Veto on charged-particle tracks

- Main backgrounds: $\gamma\gamma \to ee$ and CEP $\gamma\gamma$
  - Data-driven estimation with control regions

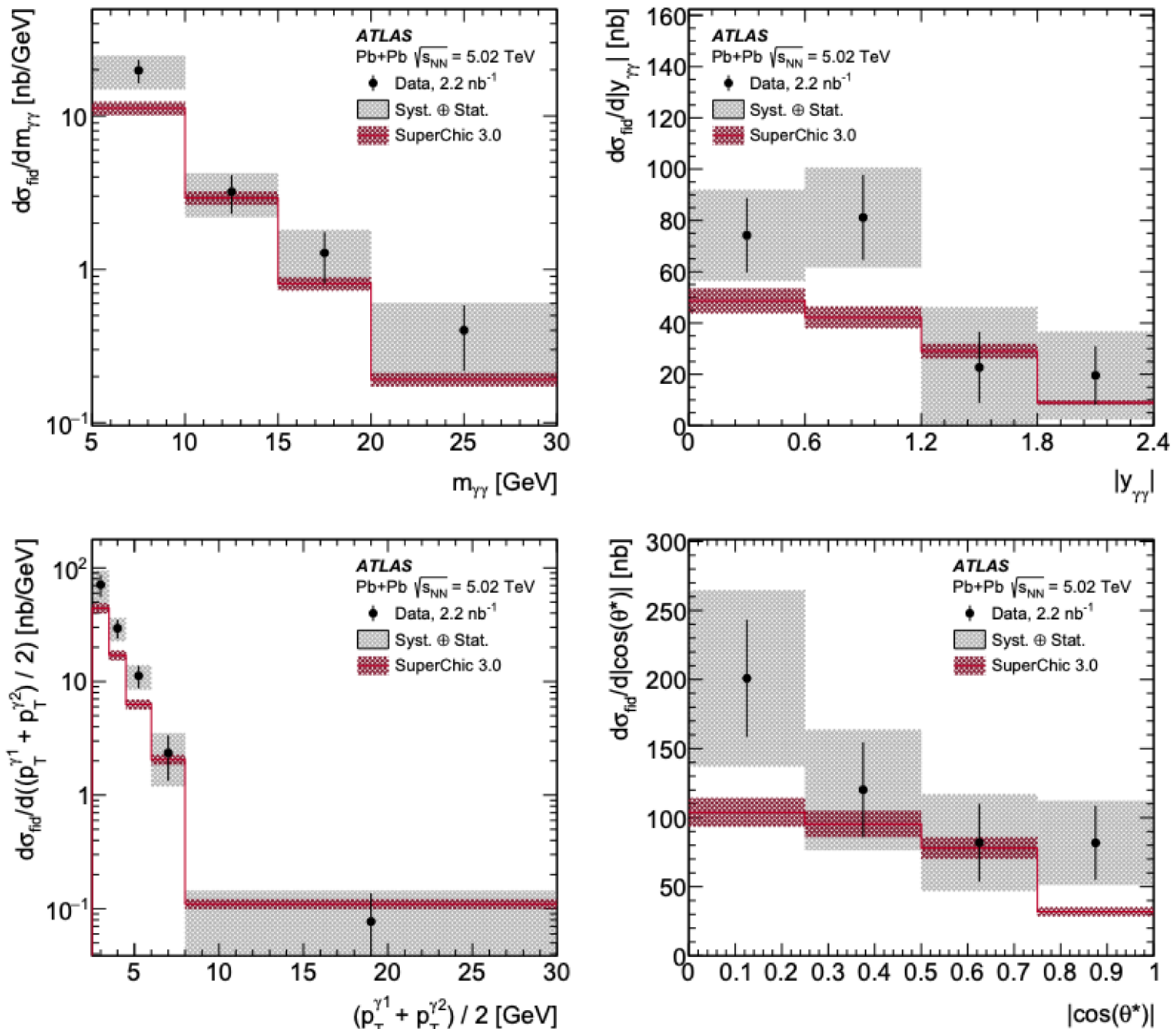




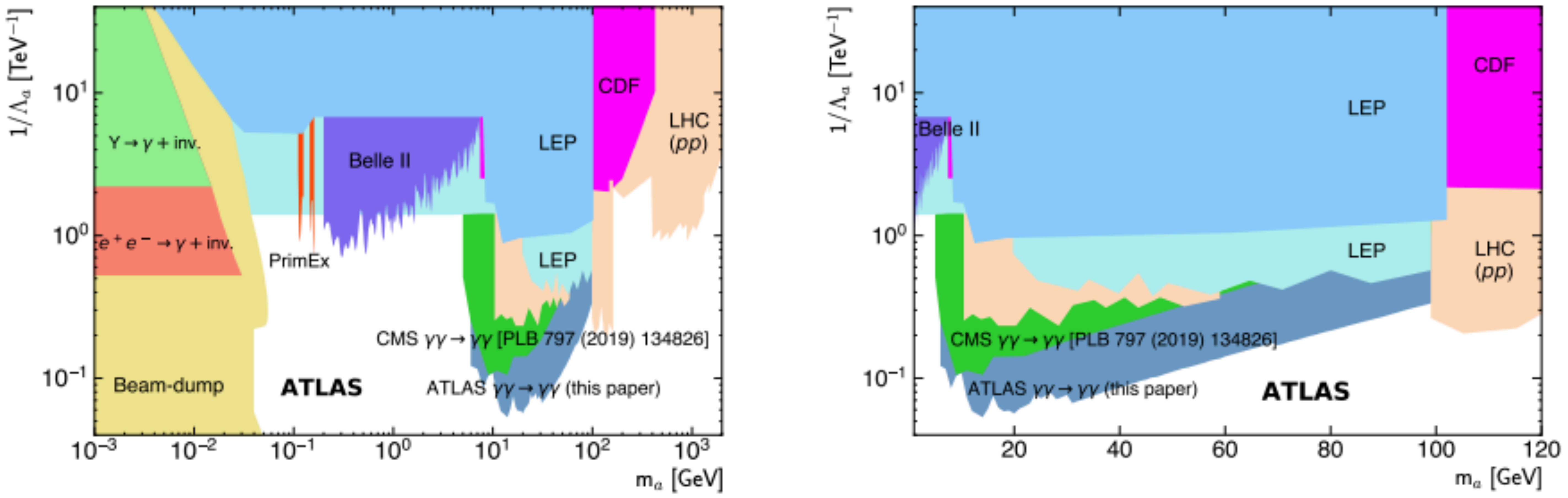
PbPb $\rightarrow a \rightarrow \gamma\gamma$

JHEP 03 (2021) 243

- Differential cross section as a function of $m_{\gamma\gamma}$, $|y_{\gamma\gamma}|$, $(p_T^{\gamma 1} + p_T^{\gamma 2})/2$ and $|\cos(\theta^*)|$
- Cross-section extracted as $\sigma_{\text{fid}} = (N_{\text{data}} - N_{\text{bckg}})/(C \cdot \mathscr{L})$



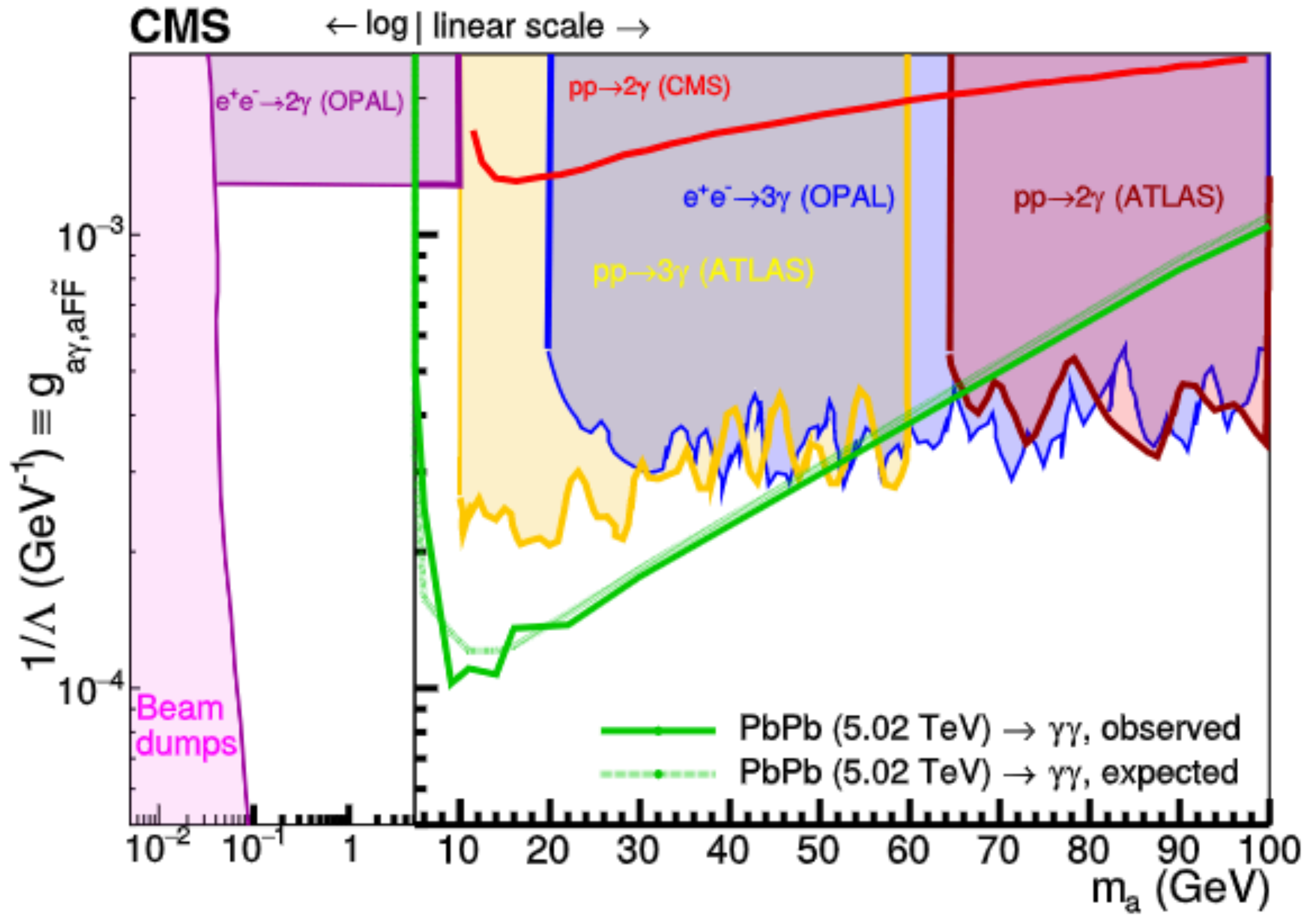
- Measurement limited by statistical uncertainty in all kinematic regions
- No signal events are observed
- Cross-section limits are interpreted as limits on the ALP couplings, assuming a 100% BR decay into photons

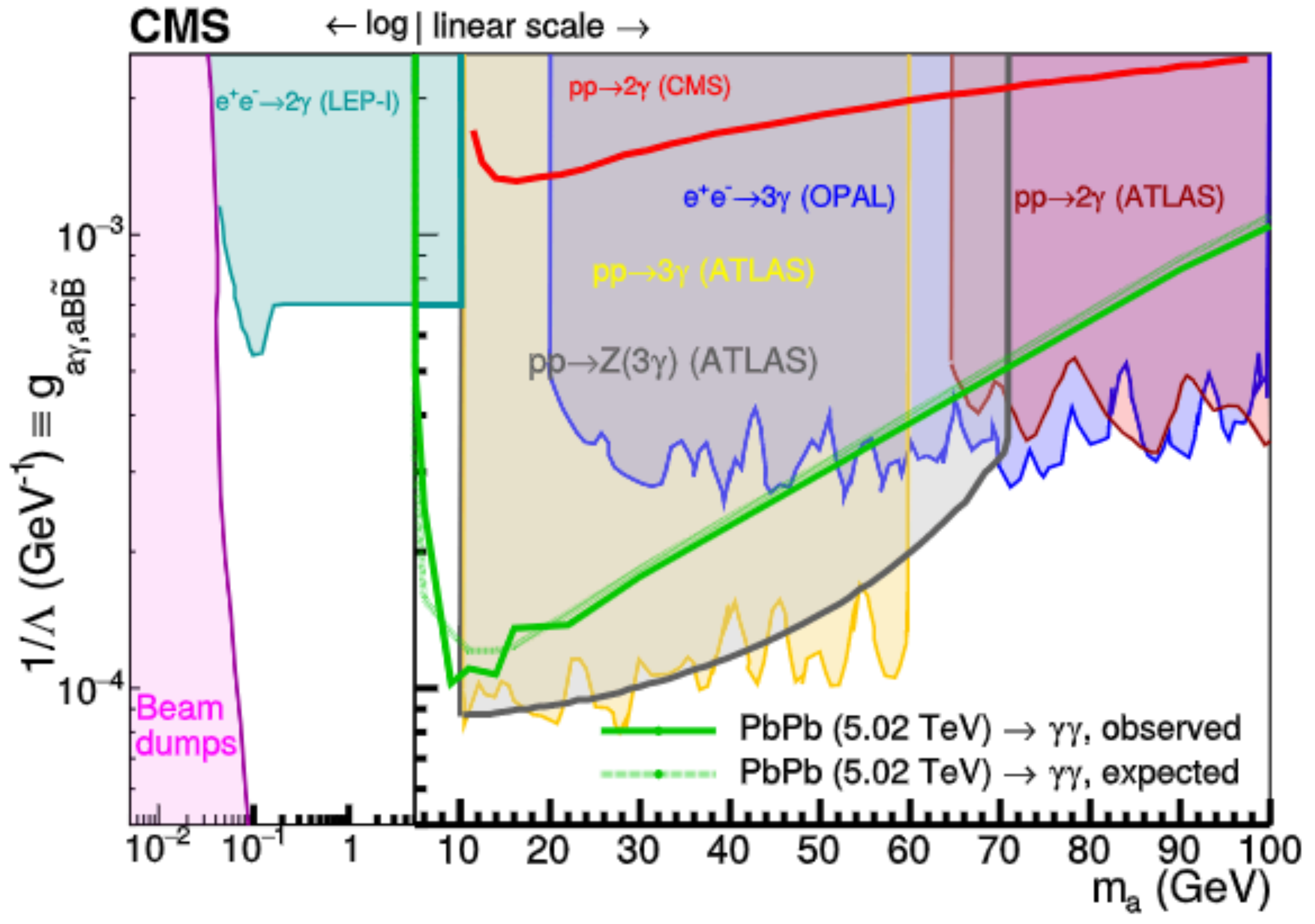


$\mathrm{PbPb} \to a \to \gamma\gamma$

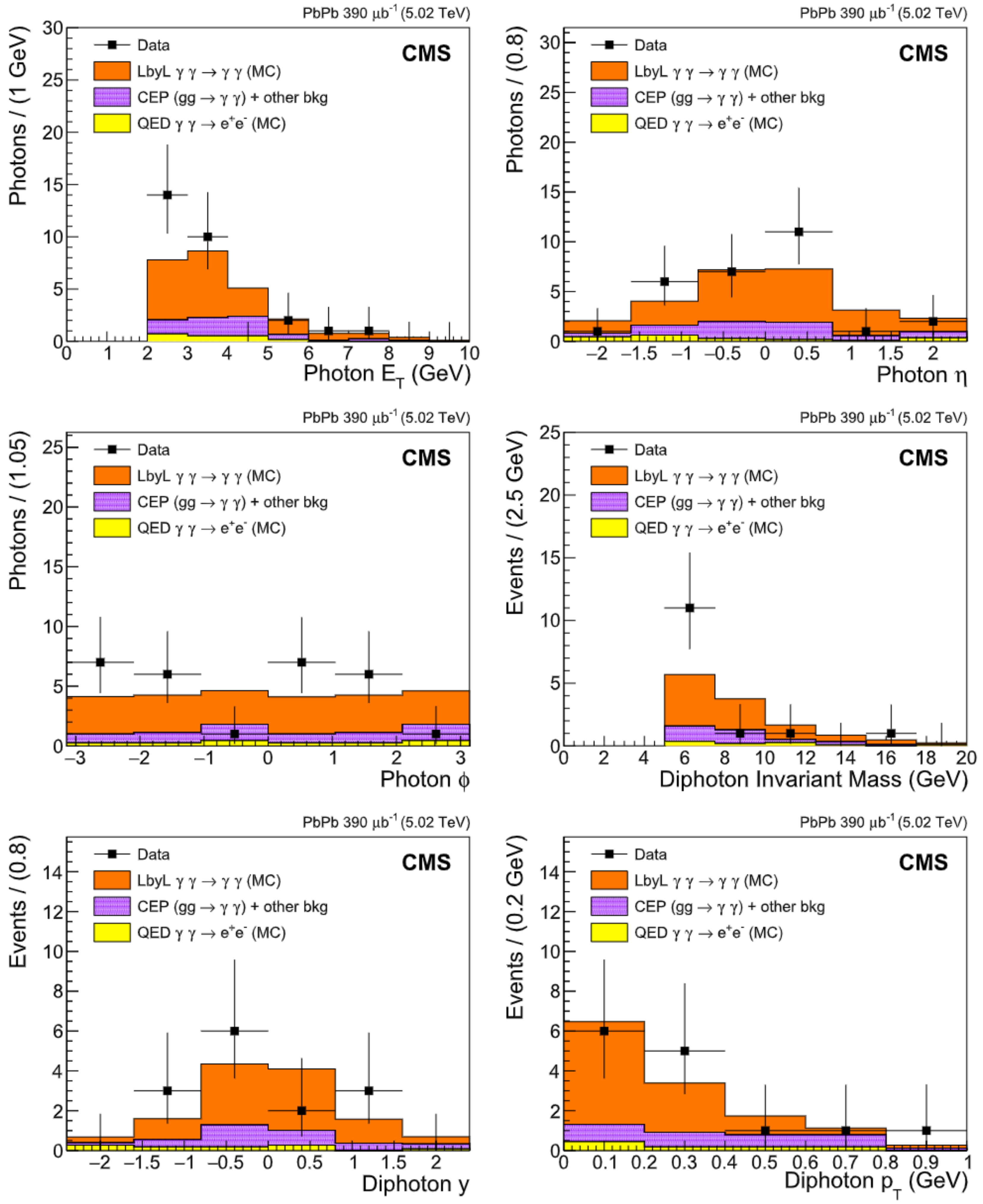
[Phys. Lett. B 797 (2019)]

- Similar study similar to the one performed by ATLAS
- Goal: measure light-by-light scattering based on PbPb collisions
- Dataset: Run 2 data, with $\mathscr{L} = 2.2\ \mathrm{nb}^{-1}$ and $\sqrt{s_{\mathrm{NN}}} = 5.02\ \mathrm{TeV}$
- Same selection requirements and analysis procedure as ATLAS

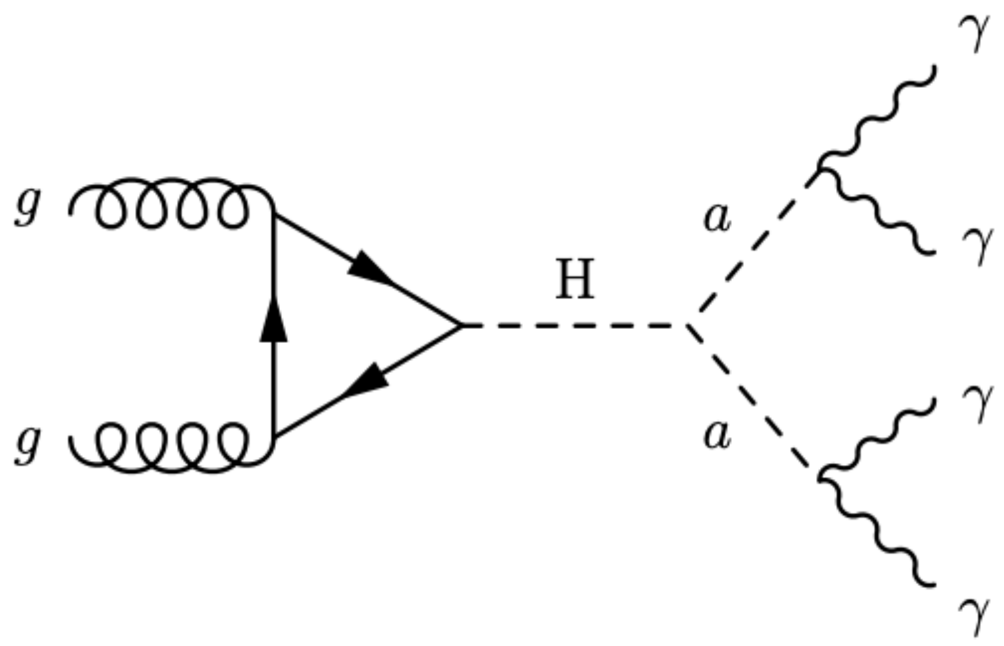




- Cross-section limits interpreted as limits on ALPs couplings:
  - ALPs coupling only to photons
  - ALPs coupling also to Z



$H \to aa \to \gamma\gamma\gamma\gamma$

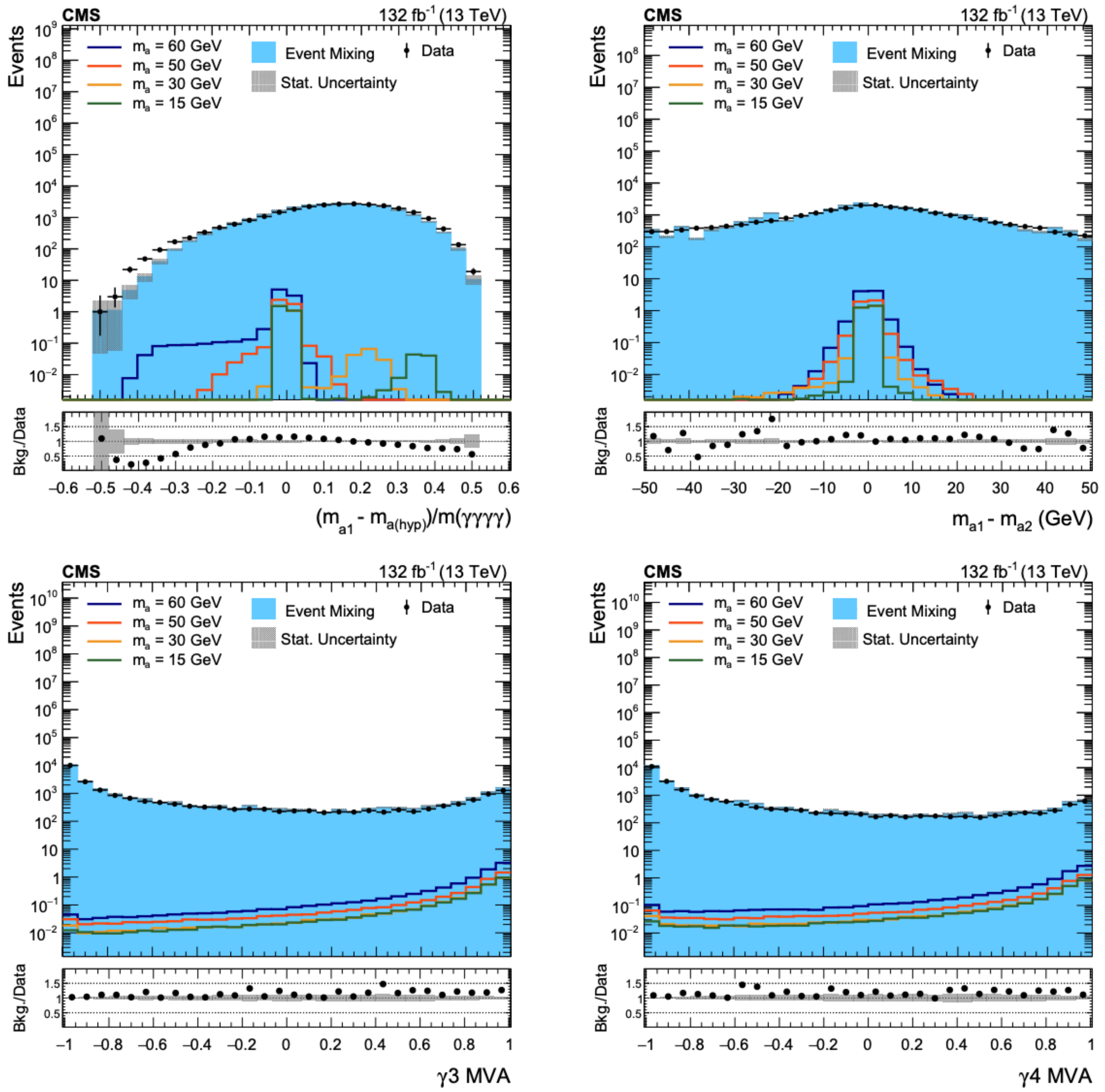


2208.01469

- Goal: search for exotic Higgs decay to a pair of light pseudoscalars
- Dataset: Run 2 data, with $\mathscr{L} = 132\ \text{fb}^{-1}$ and $\sqrt{s} = 13\ \text{TeV}$
- Identify 4 high-energetic and well-isolated photons

- Quite standard selections for at least 4 photons:
  - $|\eta| < 2.37$ for all photons
  - $p_T > 30\ \text{GeV}$ ($p_T > 18\ \text{GeV}$) for (sub)leading photon, $p_T > 15\ \text{GeV}$ for remaining photons
  - Electron veto
  - $110 < m_{\gamma\gamma\gamma\gamma} < 180\ \text{GeV}$
  - 4-photon classifier (BDT) to distinguish signal versus background

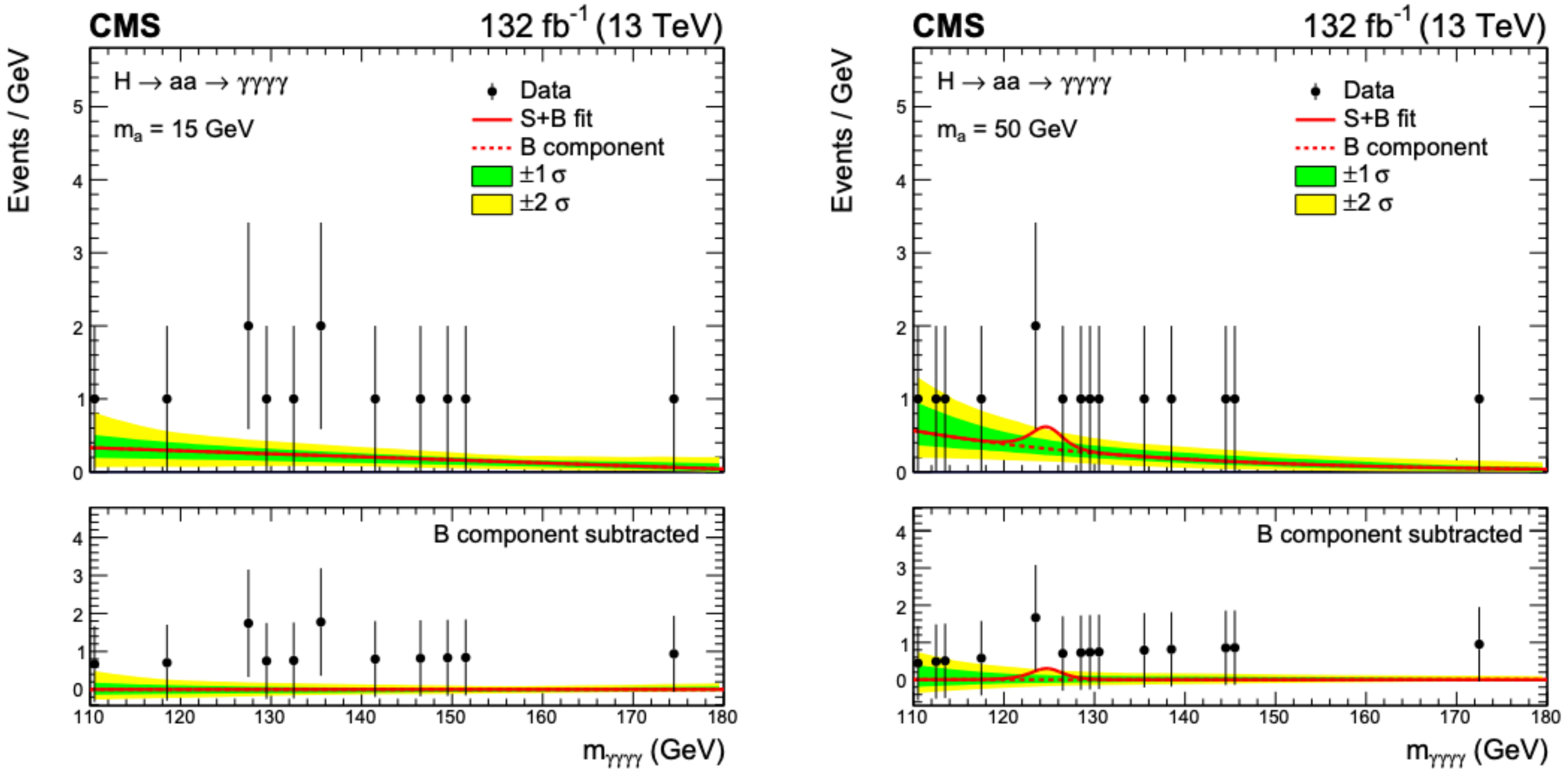
- Background estimation using data-driven method through "event mixing"



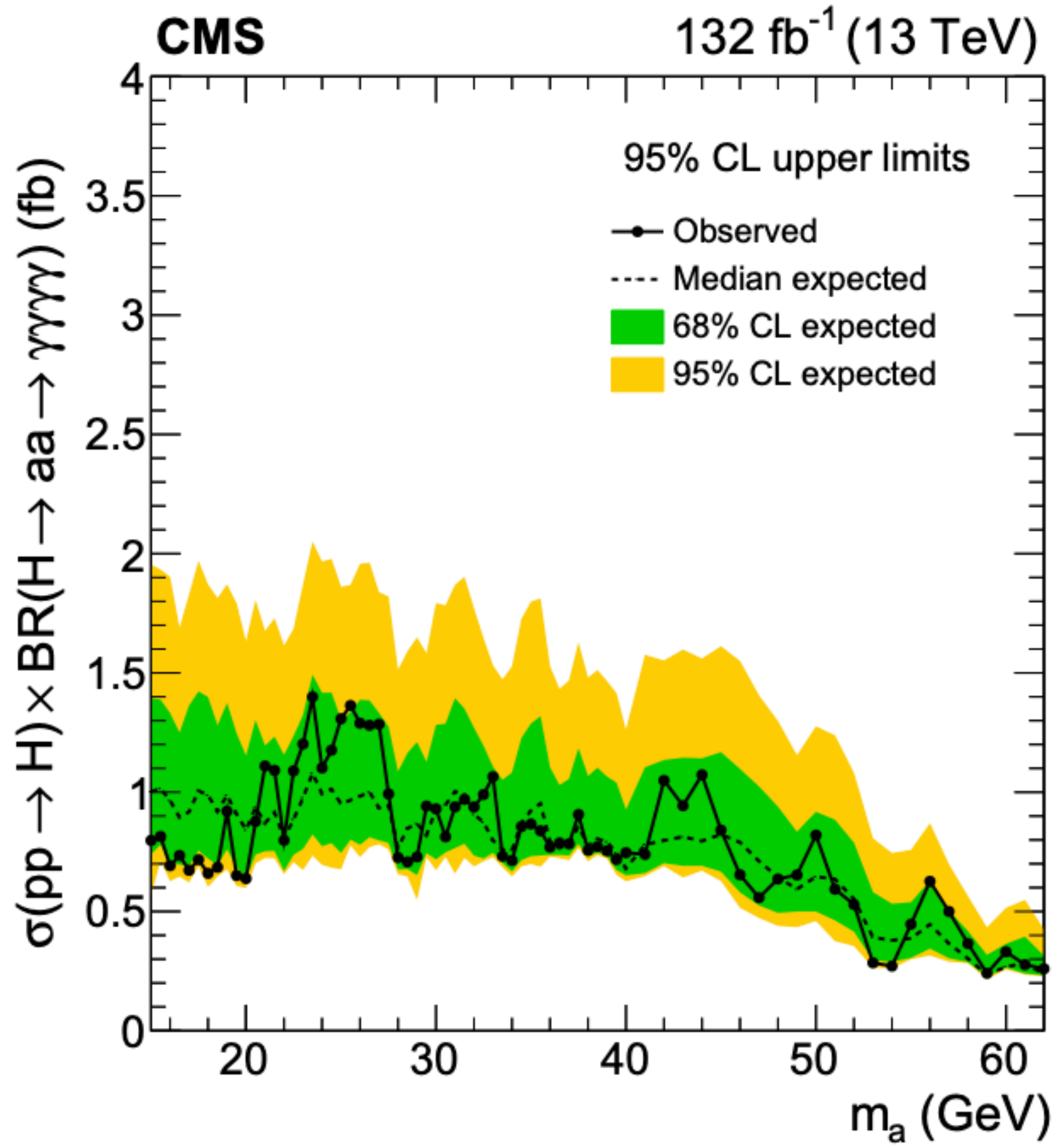
$H \to aa \to \gamma\gamma\gamma\gamma$

2208.01469

- Simultaneous unbinned maximum-likelihood fit of $m_{\gamma\gamma}$ in all analysis categories
- No deviation from SM expectation is found



- Upper limits at 95% CL
- Pseudoscalar bosons ranging in mass in $[15{,}62]$ GeV range



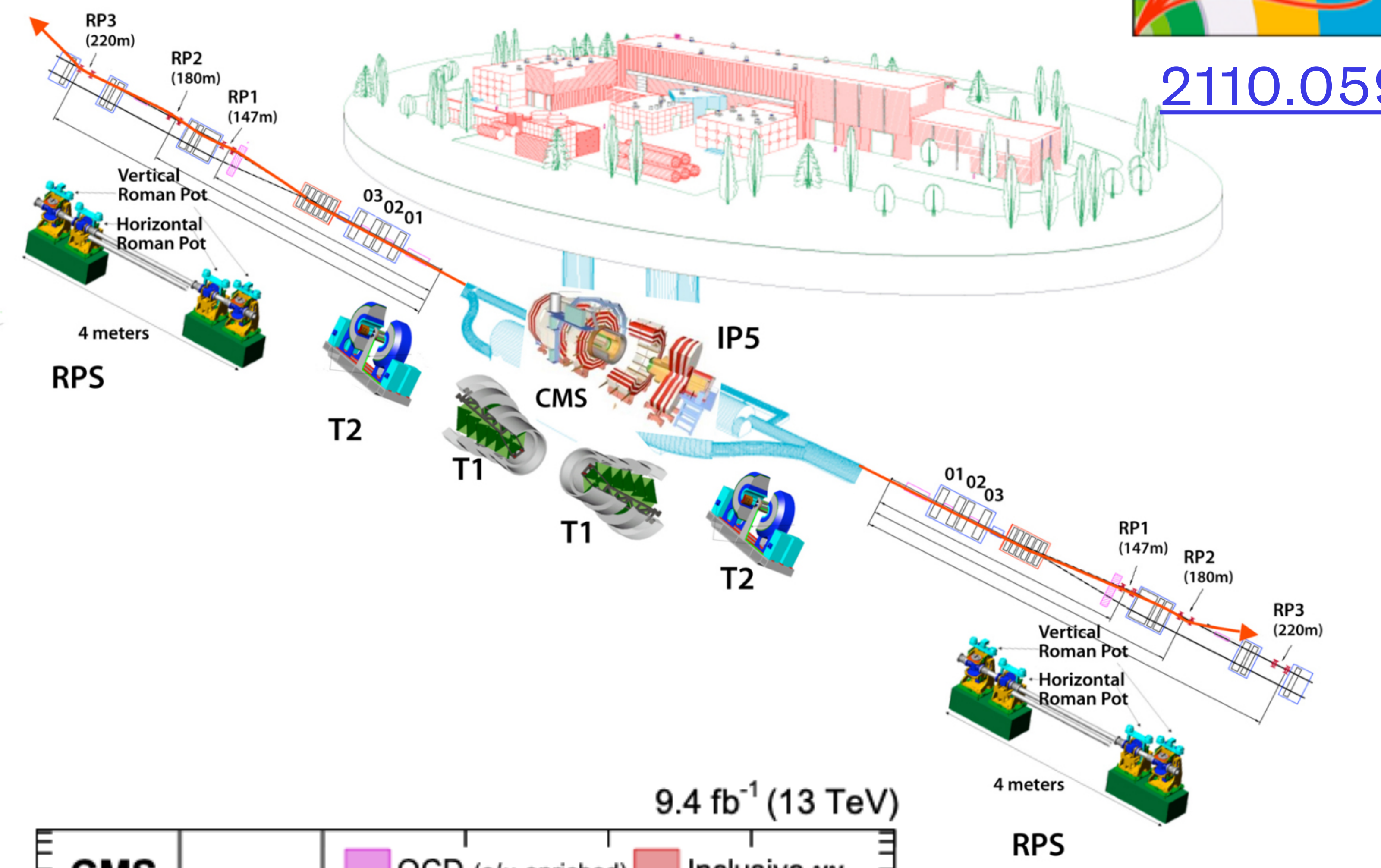
$pp \to pp\gamma\gamma$

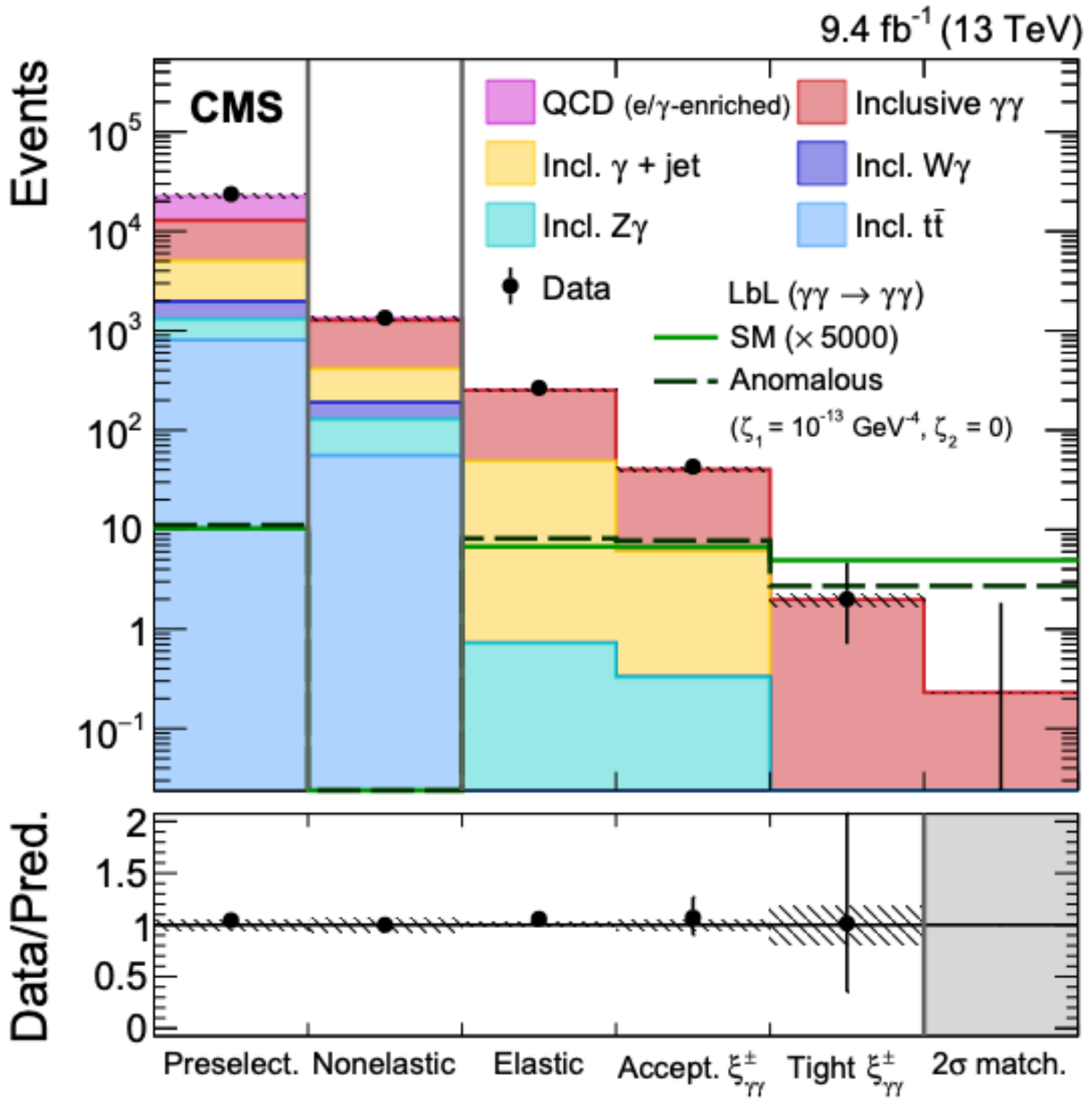
2110.05916

- Goal: search for forward proton scattering with light-by-light scattering
- Dataset: 2016 data, with $\mathscr{L} = 9.4\ \mathrm{fb}^{-1}$ and $\sqrt{s} = 13$ TeV, CMS+TOTEM
- Target mass range: $m_{\gamma\gamma} > 350$ GeV

- Selection requirements:
  - $p_{\mathrm{T}}^{\gamma} > 75$ GeV, $|\eta_\gamma| < 2.5$
  - Cut on cluster shape to ensure isolation (R_9 variable)
  - Cuts on $\xi_{\gamma\gamma}$, ξ

- Background contributions:
  - Inclusive $\gamma\gamma$
  - γ+jet, $\gamma + Z$, $\gamma + W$
- Tighter requirements keep only inclusive $\gamma\gamma$



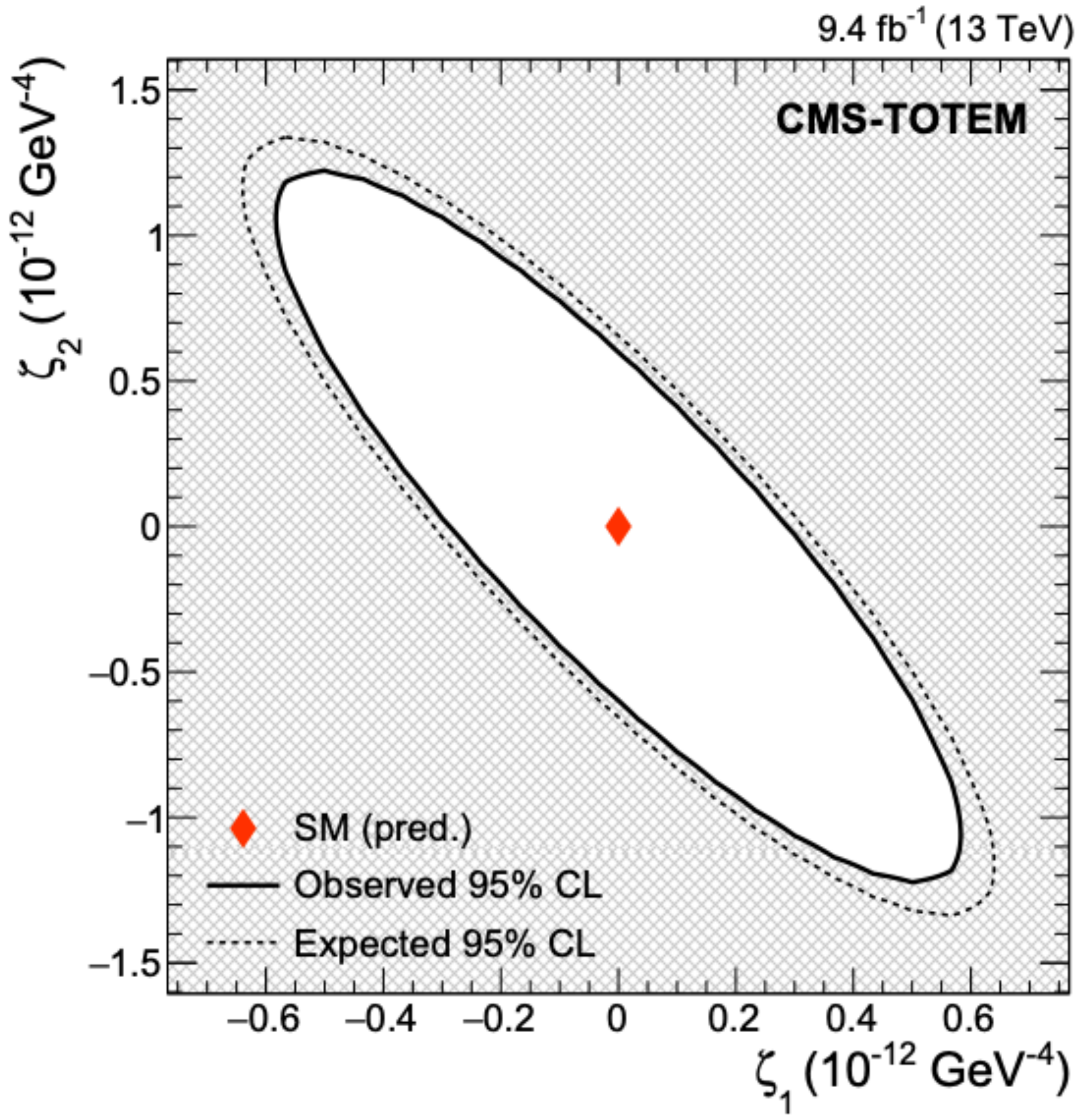


$pp \to pp\gamma\gamma$

2110.05916

- Limits on cross-section are used to probe 4-photon anomalous quartic gauge couplings

$$L_8^{\gamma\gamma\gamma\gamma} = \zeta_1 F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2 F_{\mu\nu} F^{\mu\rho} F_{\rho\sigma} F^{\sigma\nu}$$



- This analysis provided the first limit for the SM for light-by-light production cross-section at high energies

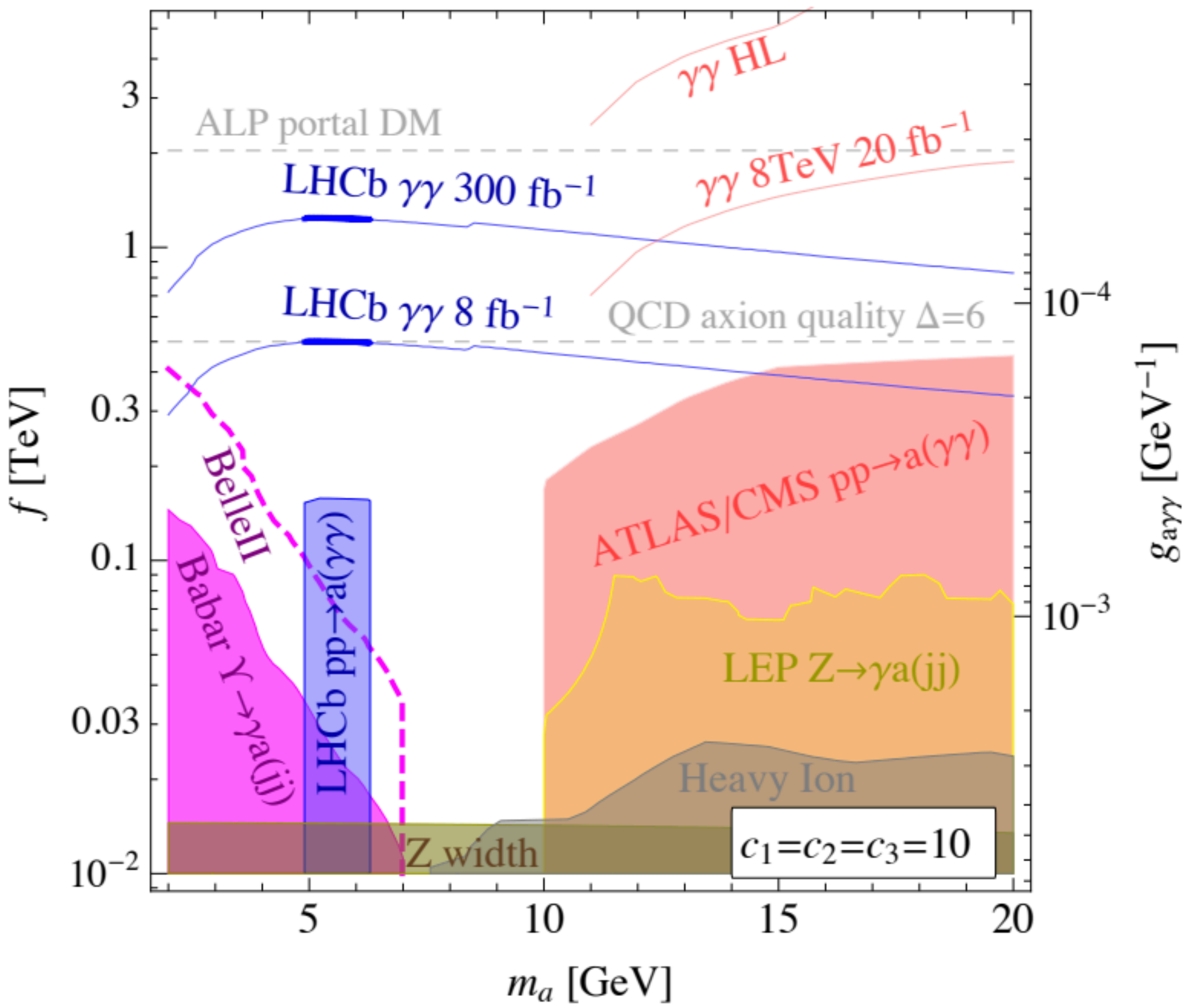
$pp \to a \to \gamma\gamma$

1810.09452

- Currently, light ALPs are not reachable by ATLAS and CMS → LHCb can go to lower masses!
- Dedicated trigger lines ($B_s \to \gamma\gamma$) to select low-energy photons
- Limits extraction using $80\ \text{pb}^{-1}$ of LHCb public data

LHCb-PUB-2018-006

Variable	*0CV*	*1CV LL*	*1CV DD*	*2CV*
Calo γ CL	> 0.3	> 0.3	> 0.3	–
Calo γ p [GeV/c]	> 6	> 6	> 6	–
Calo γ E_{T} [GeV]	> 3	> 3	> 3	–
Converted γ p_{T} [GeV/c]	–	> 2.0	> 2.0	> 2.0
Converted γ M [MeV/c^2]	–	< 60	< 60	< 60
Converted γ χ^2_{IP}	–	> 4	> 0	> 1
$\sum p_{\mathrm{T},\gamma}$ [GeV]	> 6.5	> 5.5	> 5.5	> 5
B^0_s p_{T} [GeV/c]	> 3.0	> 3.0	> 3.0	> 3.0
B^0_s χ^2_{vtx}	–	–	–	< 20
$M_{B^0_s}$ [GeV/c^2]	$[4.3, 6.3]$	$[4.3, 6.3]$	$[4.3, 6.3]$	$[4.5, 6.1]$
Fraction of signal	83.4%	4.3%	11.7%	0.6%

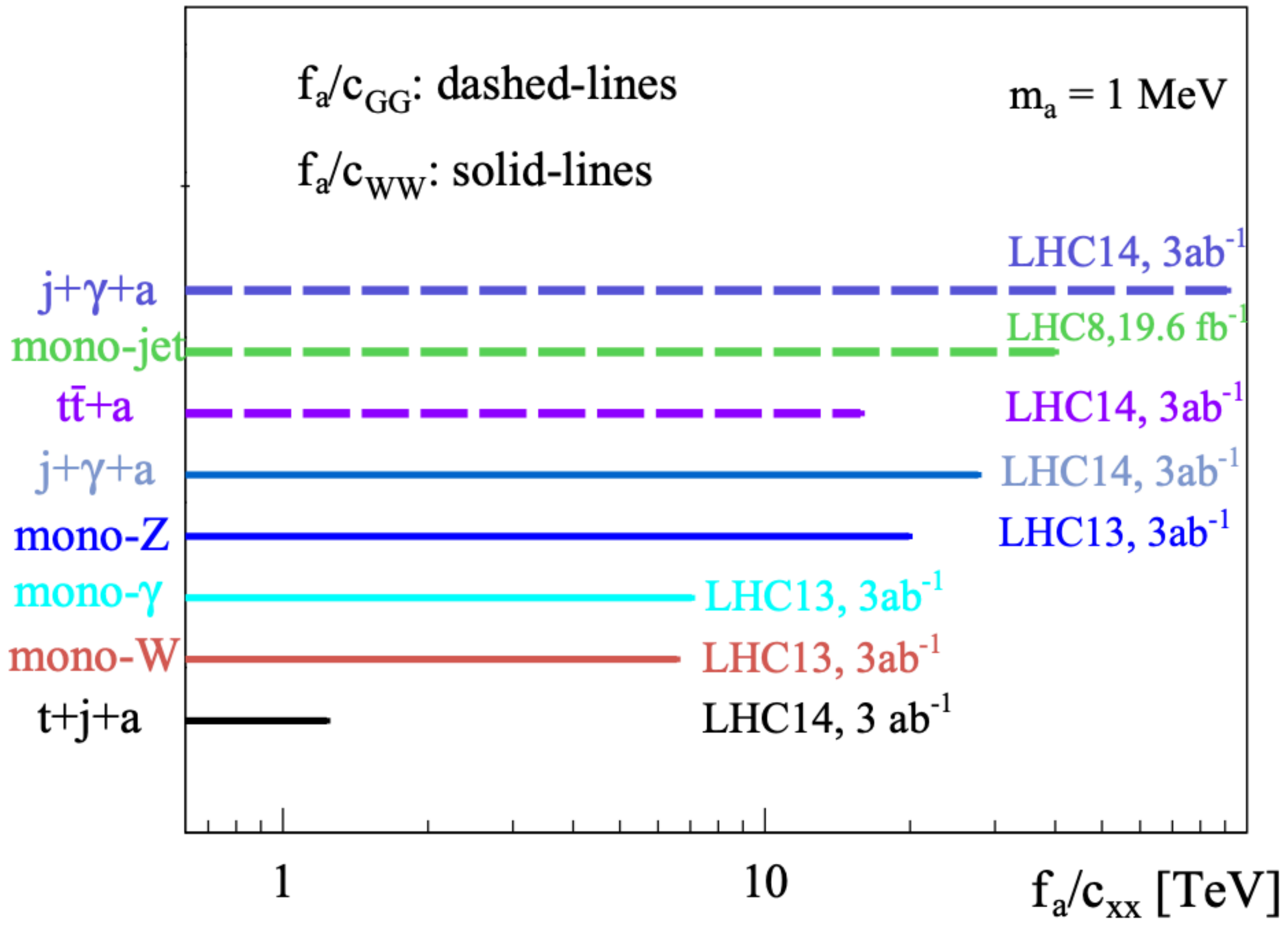


- Experimental analysis currently ongoing
  - Analysing data from 2018, using $\mathscr{L} = 2.07\ \text{fb}^{-1}$
  - Currently relying only on unconverted photons

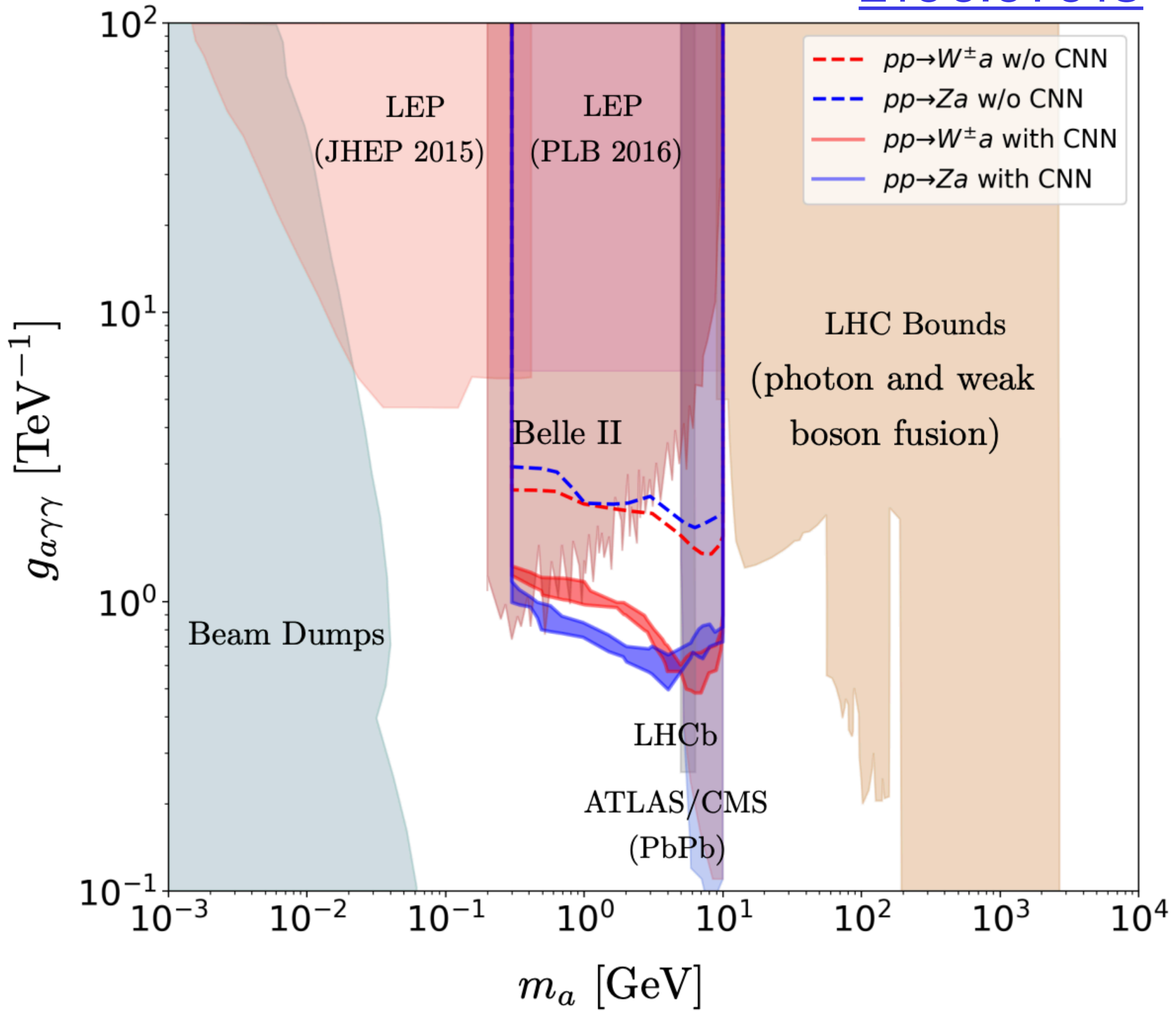
Future prospects

- ALPs searches are generally limited by statistics
  - Therefore, simply acquiring more data will help
- Also, different channels where different experiments can pose more stringent limits
- Last but not least, improving performance of analysis using advanced Machine Learning algorithms

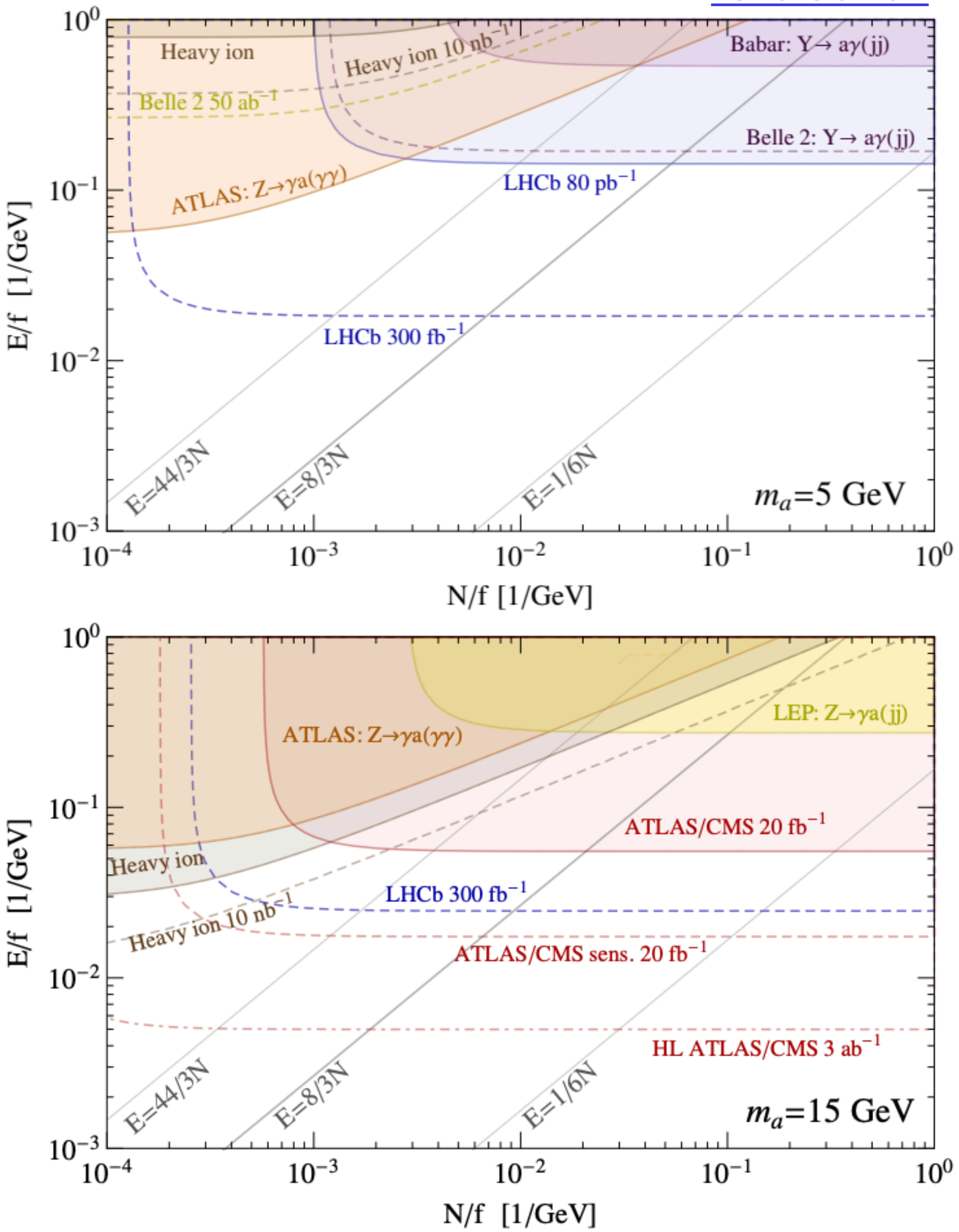
1901.03061



2106.07018



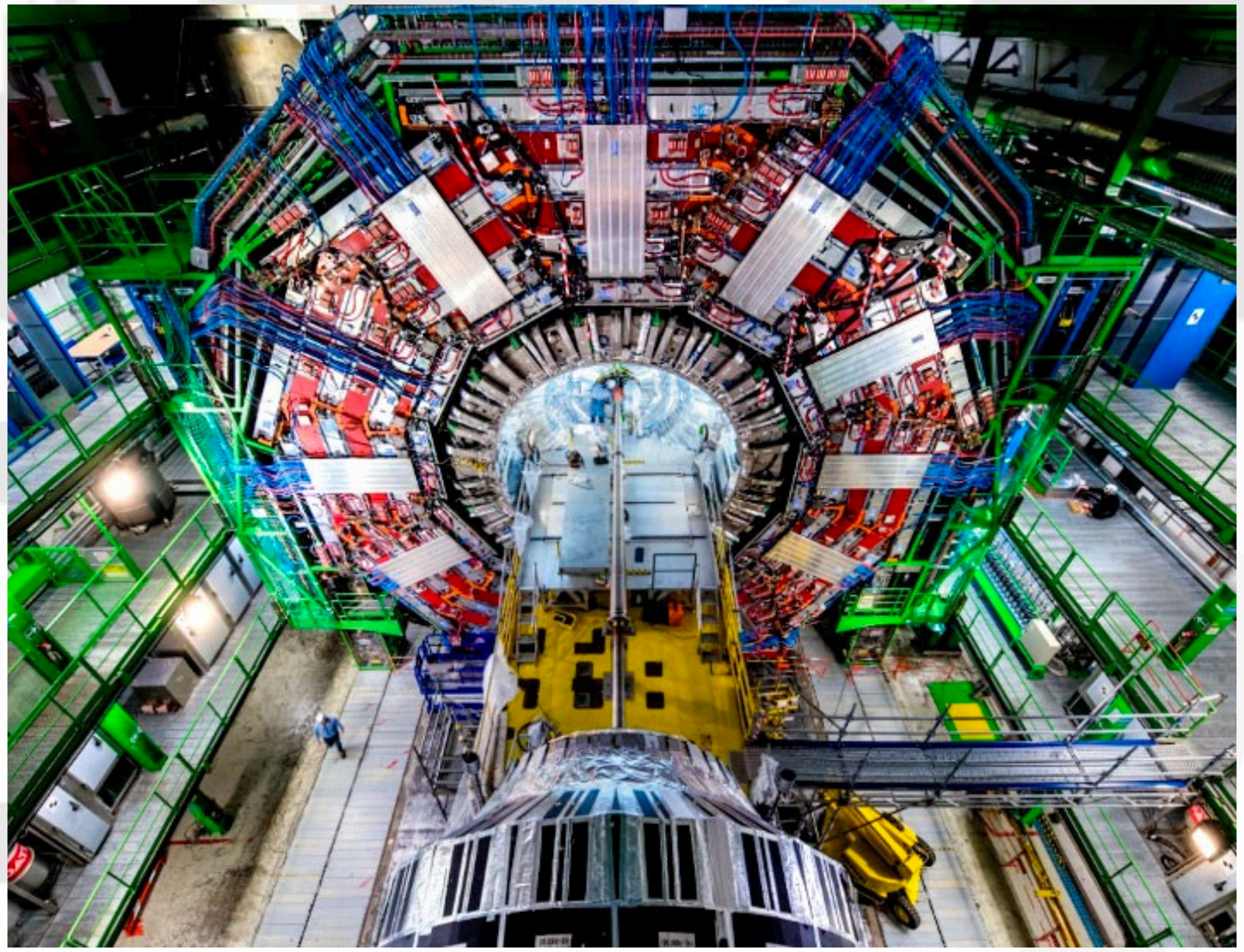
1810.09452

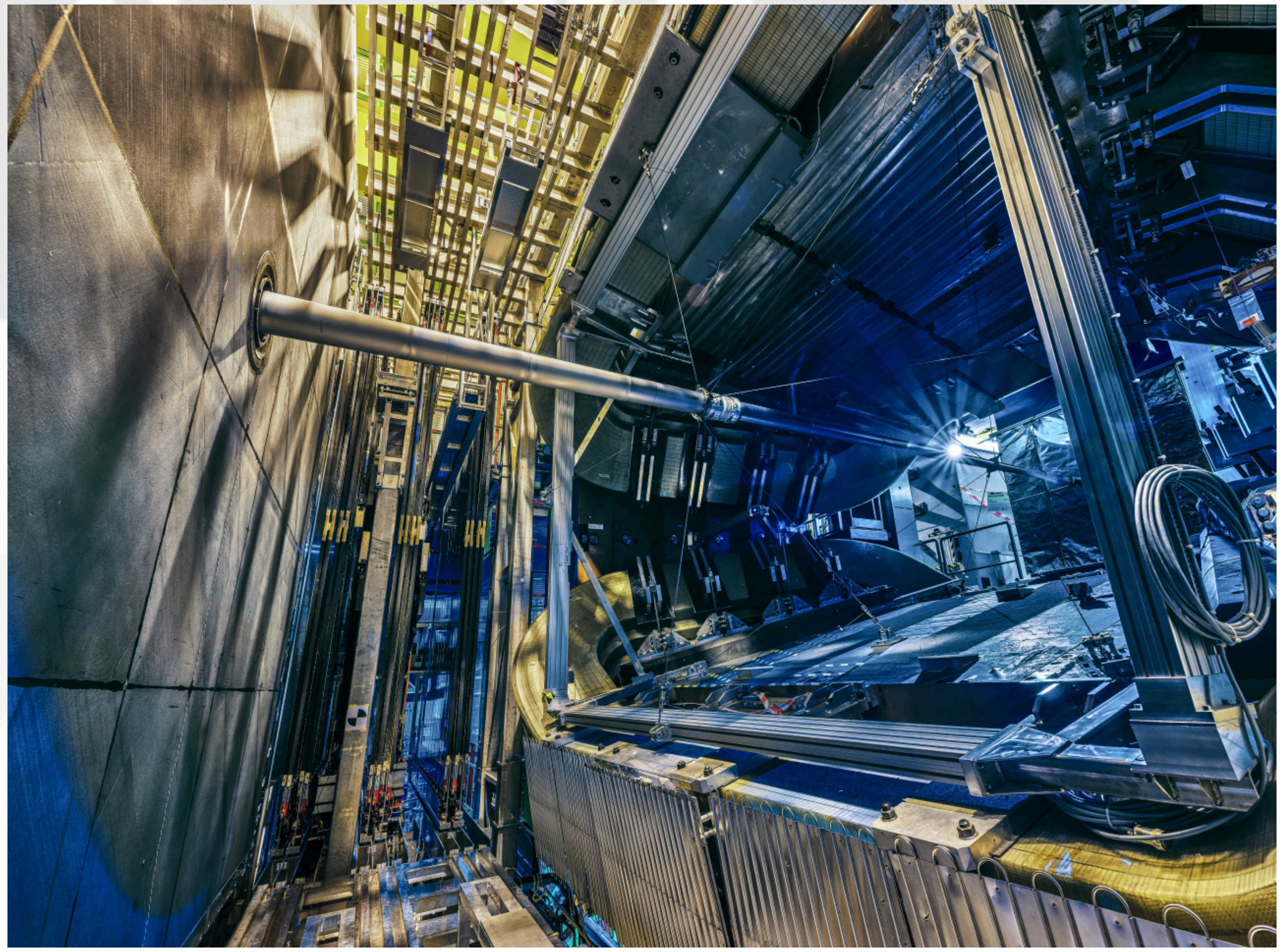


Conclusions

- In recent years, ALPs have been studied quite precisely and extensively
  - Different mass scales
  - Different signatures probing different couplings to SM (gluons, Higgs, photons,…)
- Results so far do not show signatures of ALPs

- **In the next years, we definitely expect more and more interesting results to come**





Thank you for your attention

LHCPhysics

Belgrade, 22 - 26 May 2023