Searches for γ-coupled ALPs & massive gravitons at FCC-hh

FCC-hh Studies for the next EU Strategy: kick-off meetg

CERN, 3rd Sept 2024

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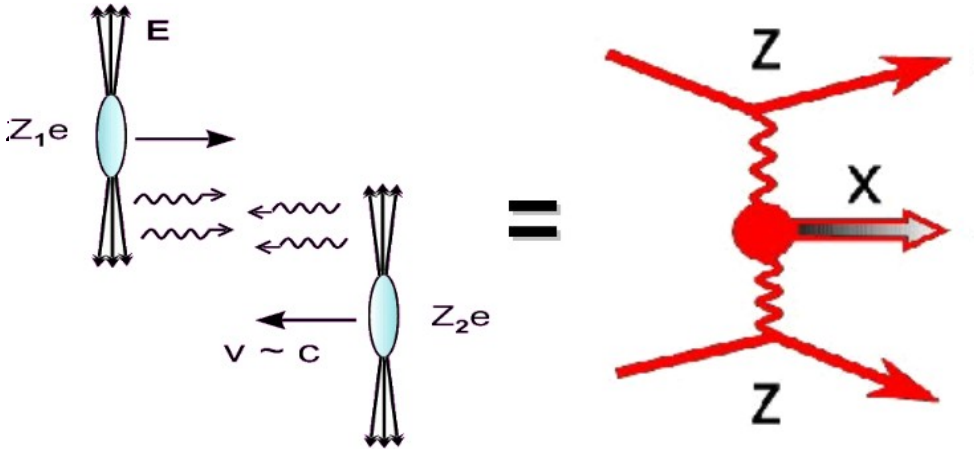
Prelude…. LHC has proven a unique γγ collider

- Electromagnetic ultra-peripheral colls. (UPCs): $b_{min} > R_A + R_B$, hadrons survive
- EM field = Weizsäcker-Williams (Equivalent Photon Approx.) photon flux:



- Huge photon fluxes:
  $\sigma(\gamma\gamma) \approx Z^4$ ($\approx 5 \cdot 10^7$ for PbPb) times larger than p,$e^{\pm}$
- Beam-energy dependence:
  Photon luminosities increase as $\propto \log^3(\sqrt{s})$

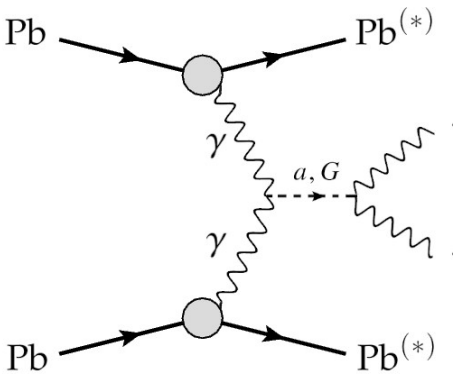
- Quasi-real γ (coherent emission): $Q \approx 1/R \approx 0.03$ GeV (Pb), 0.28 GeV (p)
- Max. (longitudinal) γ energies: $\omega < \omega_{max} \approx \frac{\gamma}{R} \approx 80$ GeV (Pb), 2.5 TeV (p)

System	$\sqrt{s_{NN}}$	$\mathcal{L}_{int}$	$E_{beam1} + E_{beam2}$	γ_L	R_A	E_γ^{max}	$\sqrt{s_{\gamma\gamma}^{max}}$
Pb-Pb	5.52 TeV	5 nb^{-1}	2.76 + 2.76 TeV	2960	7.1 fm	80 GeV	160 GeV
p-Pb	8.8 TeV	1 pb^{-1}	7.0 + 2.76 TeV	7450, 2960	0.7, 7.1 fm	2.45 TeV, 130 GeV	2.6 TeV
p-p	14 TeV	150 fb^{-1}	7.0 + 7.0 TeV	7450	0.7 fm	2.45 TeV	4.5 TeV

- Single *X* = C-even (spin 0,2) resonances only (Landau-Yang + C symmetry)

ALP searches via $\gamma\gamma \to a \to \gamma\gamma$ in PbPb(5 TeV)

- Search for $\gamma\gamma \to a \to \gamma\gamma$ excess over LbL ($\gamma\gamma \to \gamma\gamma$) continuum in PbPb(5.02 TeV):



- Analysis strategy:

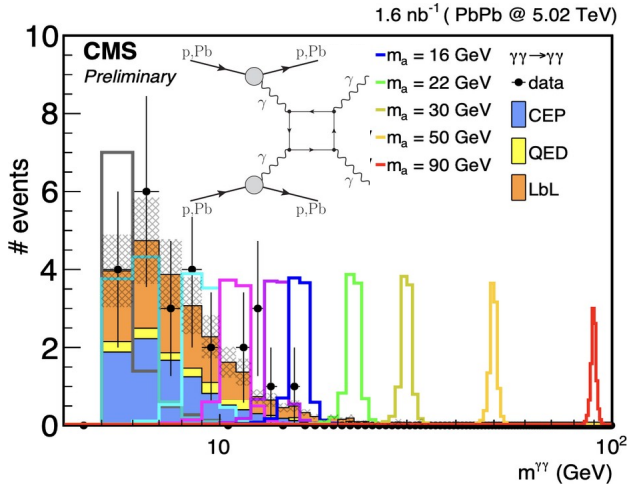
  Exclusive $\gamma\gamma$ (zero extra activity)

  $m_{\gamma\gamma} > 5$ GeV (softest γ possible)

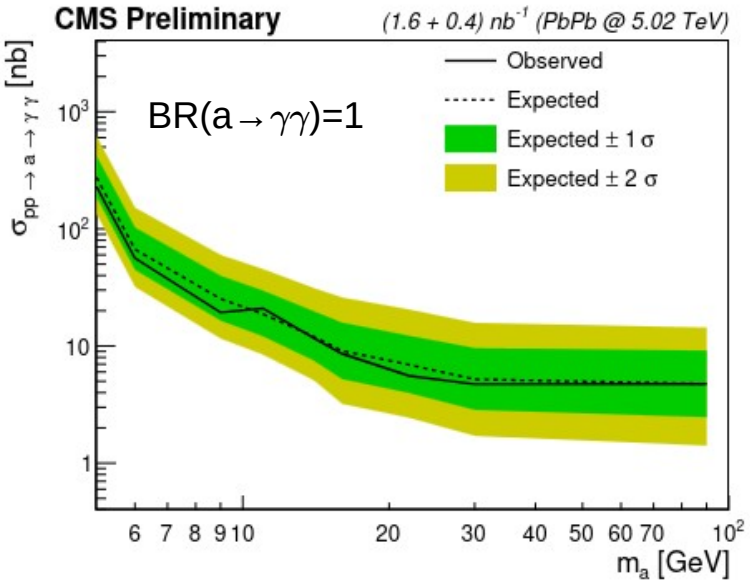
  $Aco_{\gamma\gamma} < 1\%$ ($\gamma\gamma$ back-to-back)

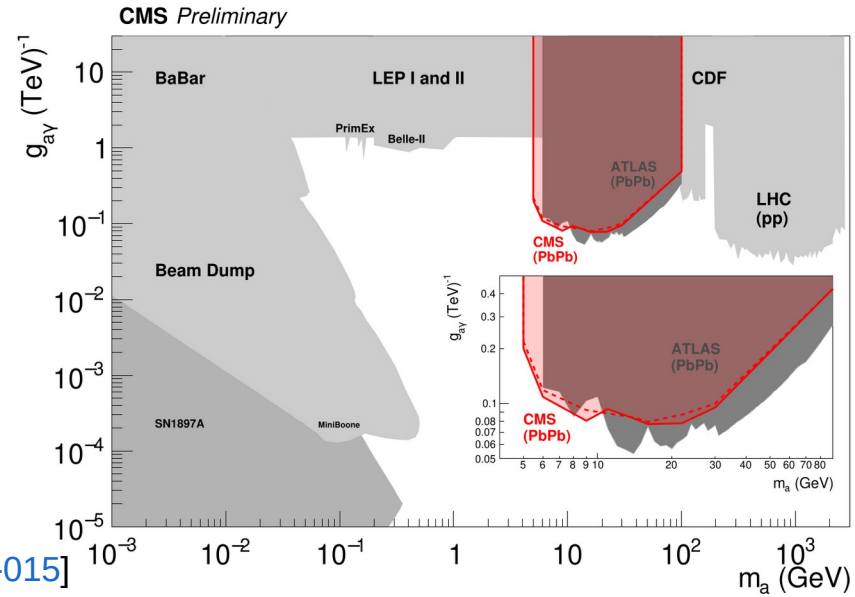
- Injected ALPs signals:

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



- No excess: Most stringent ALPs limits of $g_{a\gamma} > 0.05$ TeV^{-1} over m_a = 5–10 GeV

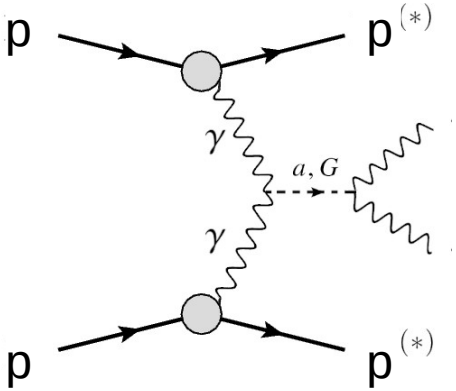




[CMS-HIN-21-015]

ALP searches via $\gamma\gamma \to a \to \gamma\gamma$ in pp(13 TeV)

- Search for $\gamma\gamma \to a \to \gamma\gamma$ excess over LbL ($\gamma\gamma \to \gamma\gamma$) continuum in p-p (13 TeV):

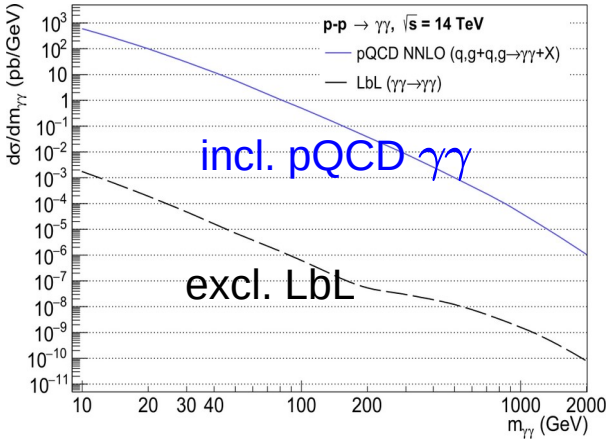


- Analysis strategy:

  $m_{\gamma\gamma}$ > 350 GeV (p's in PPS accept.)

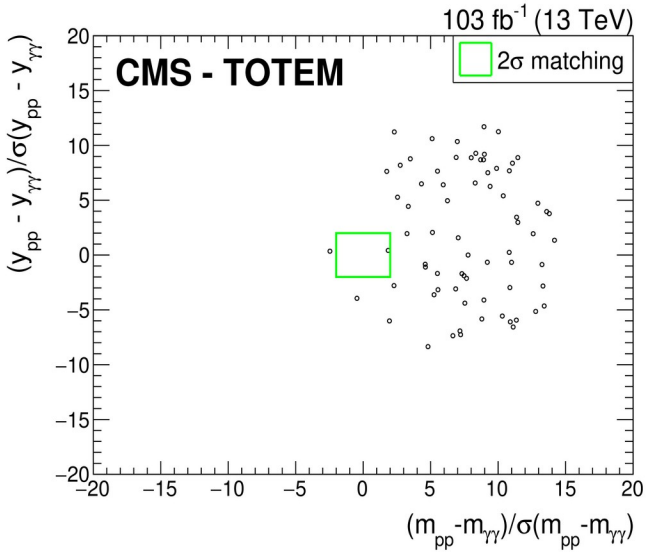
  $Aco_{\gamma\gamma}$ <1% ($\gamma\gamma$ back-to-back)

  Matching $m_{\gamma\gamma}$ & $y_{\gamma\gamma}$ in PPS & ECAL



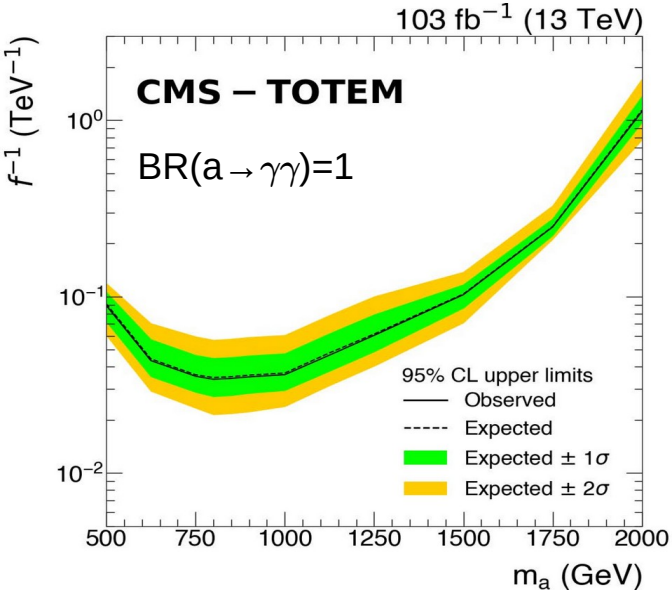
- No excess over random pileup pp tags + pQCD $\gamma\gamma$ production: 0 (1) evt expected (observed)

[CMS-EXO-21-007, arXiv:2311.02725]



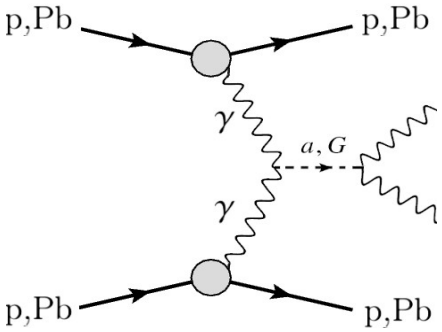
- Most stringent limits on ALPs ($g_{a\gamma}$ > 0.1–1 TeV^{-1}) over m_a = 0.5–2 TeV:

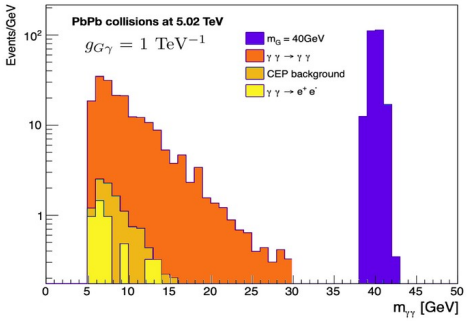
$$\mathcal{L} \supset \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{m_a^2}{2}a^2 - \frac{g_{a\gamma}}{4} a F^{\mu\nu}\tilde{F}_{\mu\nu}$$



Massive grav. searches via $\gamma\gamma \to G \to \gamma\gamma$ at the LHC

- Search for excess over LbL $\gamma\gamma \to \gamma\gamma$ from spin-2 graviton-like particles:



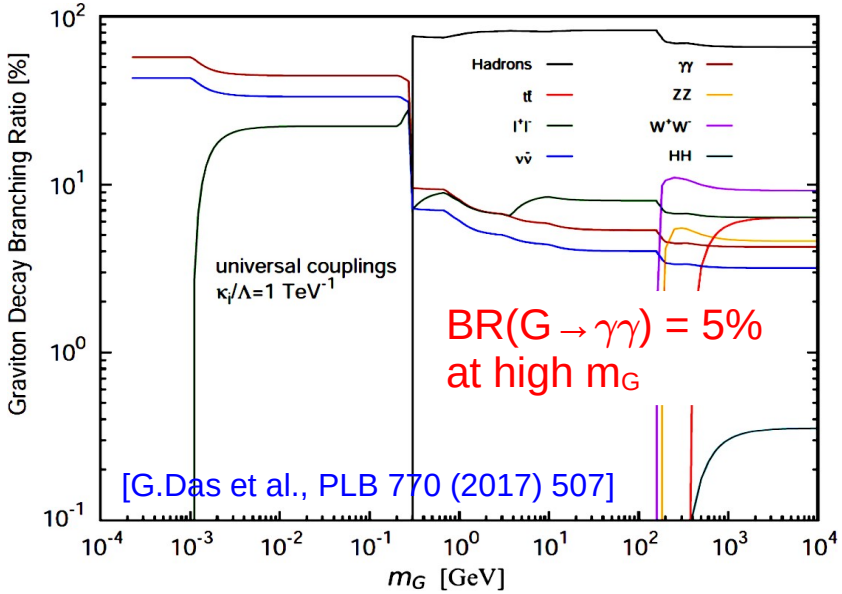


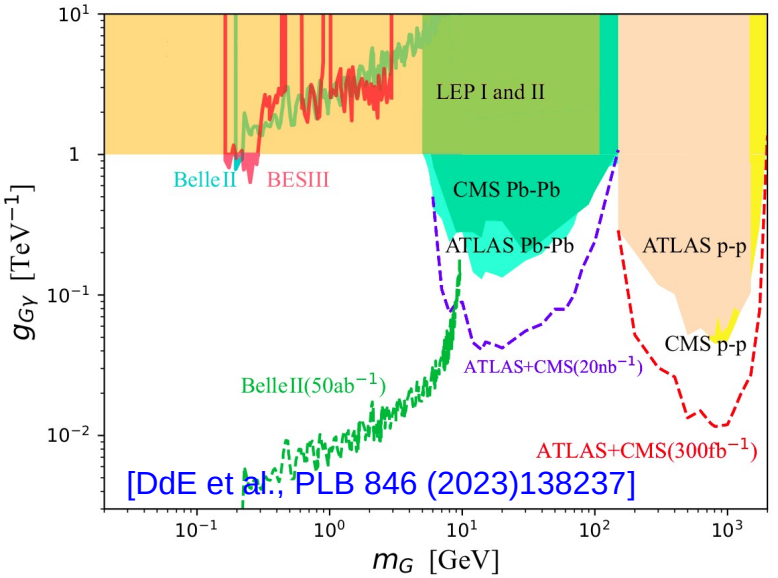
$$\sigma(a\,b \to a\,b + X) = 4\pi^2(2J+1)\frac{\Gamma_{\gamma\gamma}(X)}{m_X^2}\left.\frac{\mathrm{d}\mathcal{L}_{\gamma\gamma}^{(a\,b)}}{\mathrm{d}W_{\gamma\gamma}}\right|_{W_{\gamma\gamma}=m_X}$$

Naively, σ(G)=5×σ(ALP), but G should have universal couplings to SM particles

- Signal x-sections from Fierz-Pauli Lagrangian:

$$\mathscr{L}_{\mathrm{FP}} = -\frac{1}{2}(\partial_\rho G_{\mu\nu})^2 + \partial_\mu G_{\nu\rho}\partial^\nu G^{\mu\rho} - \partial_\mu G^{\mu\nu}\partial_\nu G + \frac{1}{2}(\partial_\rho G)^2 - \frac{1}{2}m_G^2\left((G_{\mu\nu})^2 - G^2\right),$$

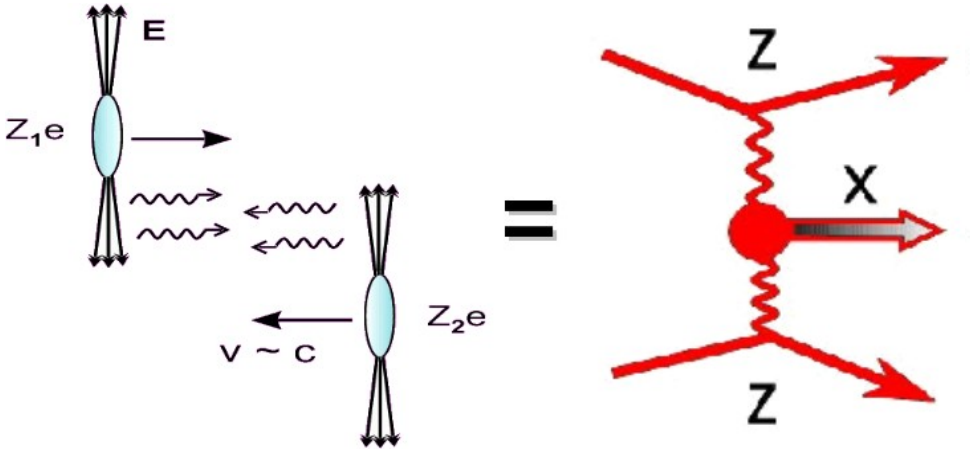




- Recast ALPs-GRAVs limits over $m_G \approx 5$ GeV–2 TeV w/ coupling $g_{G\gamma} \approx 0.05$–1 TeV^{-1}

FCC = unique photon-photon collider

- Electromagnetic ultra-peripheral colls. (UPCs): $b_{min} > R_A + R_B$, hadrons survive
- EM field = Weizsäcker-Williams (Equivalent Photon Approx.) photon flux:



- Huge photon fluxes:
  $\sigma(\gamma\gamma) \approx Z^4$ ($\approx 5 \cdot 10^7$ for PbPb) times larger than p,$e^{\pm}$
- Beam-energy dependence:
  Photon luminosities increase as $\propto \log^3(\sqrt{s})$

- Quasi-real γ (coherent emission): $Q \approx 1/R \approx 0.03$ GeV (Pb), 0.28 GeV (p)
- Max. (longitudinal) γ energies: $\omega < \omega_{max} \approx \frac{\gamma}{R} \approx 0.6$ TeV (Pb), 15 TeV (p)

System	$\sqrt{s_{NN}}$	$\mathcal{L}_{int}$	$E_{beam1} + E_{beam2}$	γ_L	R_A	E_γ^{max}	$\sqrt{s_{\gamma\gamma}^{max}}$
Pb-Pb	39.4 TeV	110 nb^{-1}	19.7 + 19.7 TeV	21 100	7.1 fm	600 GeV	1.2 TeV
p-Pb	62.8 TeV	29 pb^{-1}	50. + 19.7 TeV	53 300, 21 100	0.7,7.1 fm	15.2 TeV, 600 GeV	15.8 TeV
p-p	100 TeV	30 ab^{-1}	50. + 50. TeV	53 300	0.7 fm	15.2 TeV	30.5 TeV

▶ Repeat LHC ALPs/GRAVs analyses with ×10 higher $\sqrt{s}$ & $\mathcal{L}_{int}$ than LHC

MC generation & FCC-hh reconstruction

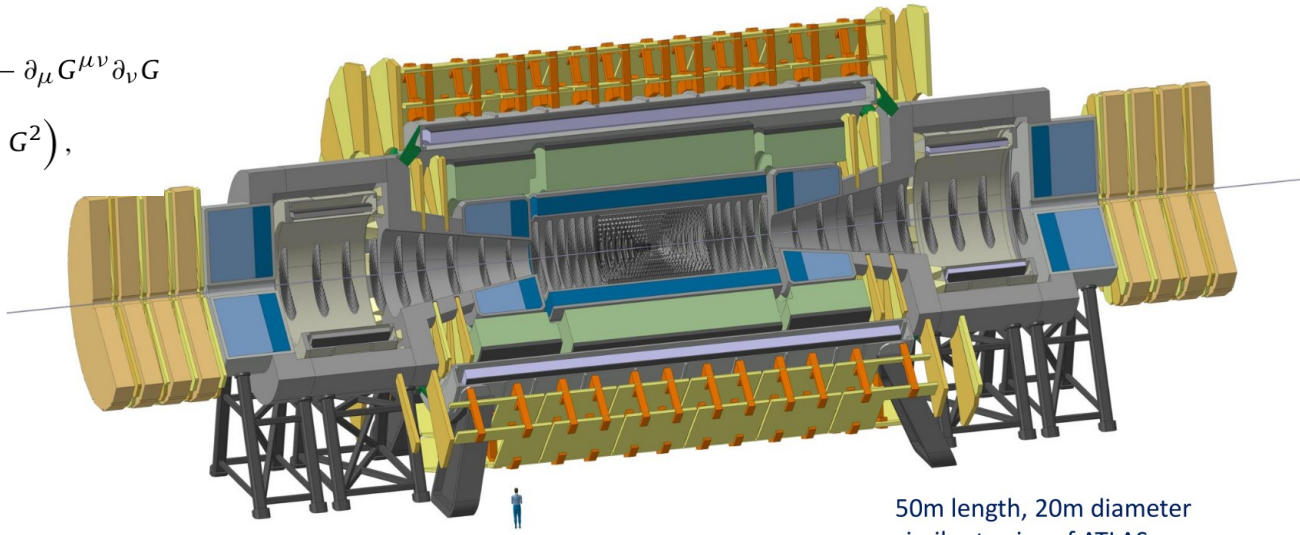
- gamma-UPC+MG5@NLO to generate ALPs,Gs,LbL LHE samples for pp(100TeV), pPb(63TeV), PbPb(39TeV) UPCs over $m_{a,G}$ = 5 GeV–30 TeV, $g_{a,G}$ = 0.1 TeV^{-1}

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

$$\mathscr{L}_{\mathrm{FP}} = -\frac{1}{2}(\partial_\rho G_{\mu\nu})^2 + \partial_\mu G_{\nu\rho}\partial^\nu G^{\mu\rho} - \partial_\mu G^{\mu\nu}\partial_\nu G + \frac{1}{2}(\partial_\rho G)^2 - \frac{1}{2}m_{\mathrm{G}}^2\left((G_{\mu\nu})^2 - G^2\right),$$

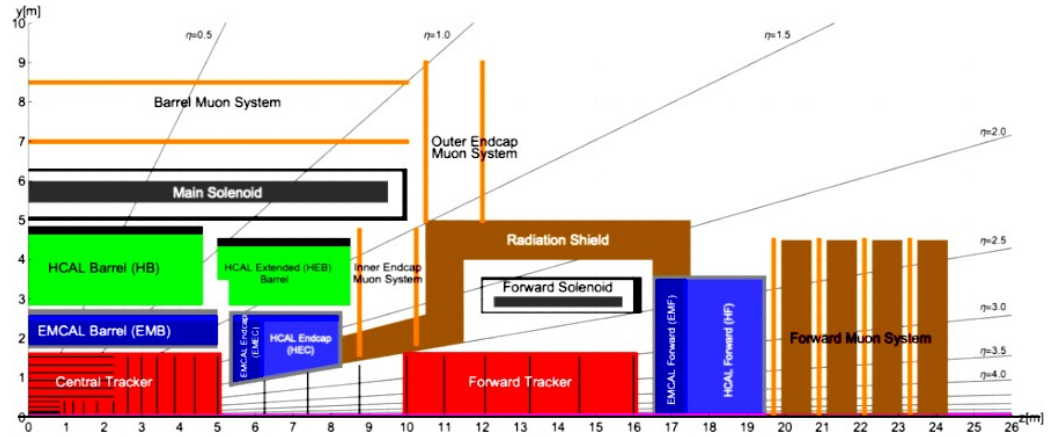
[H.-S. Shao, DdE arXiv:2207.03012]

- DELPHES card for FCC-hh Scenario II (nominal revisited) detector:



50m length, 20m diameter
similar to size of ATLAS

ECAL crystals from 2008.00338



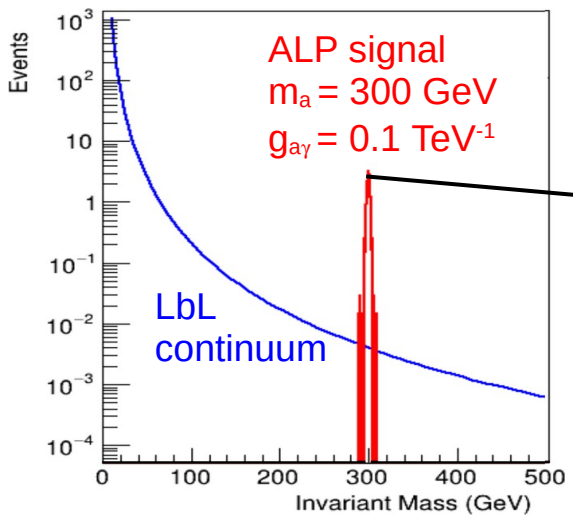
- Photons well reconstructed for p_T>2 GeV over |η|<6:

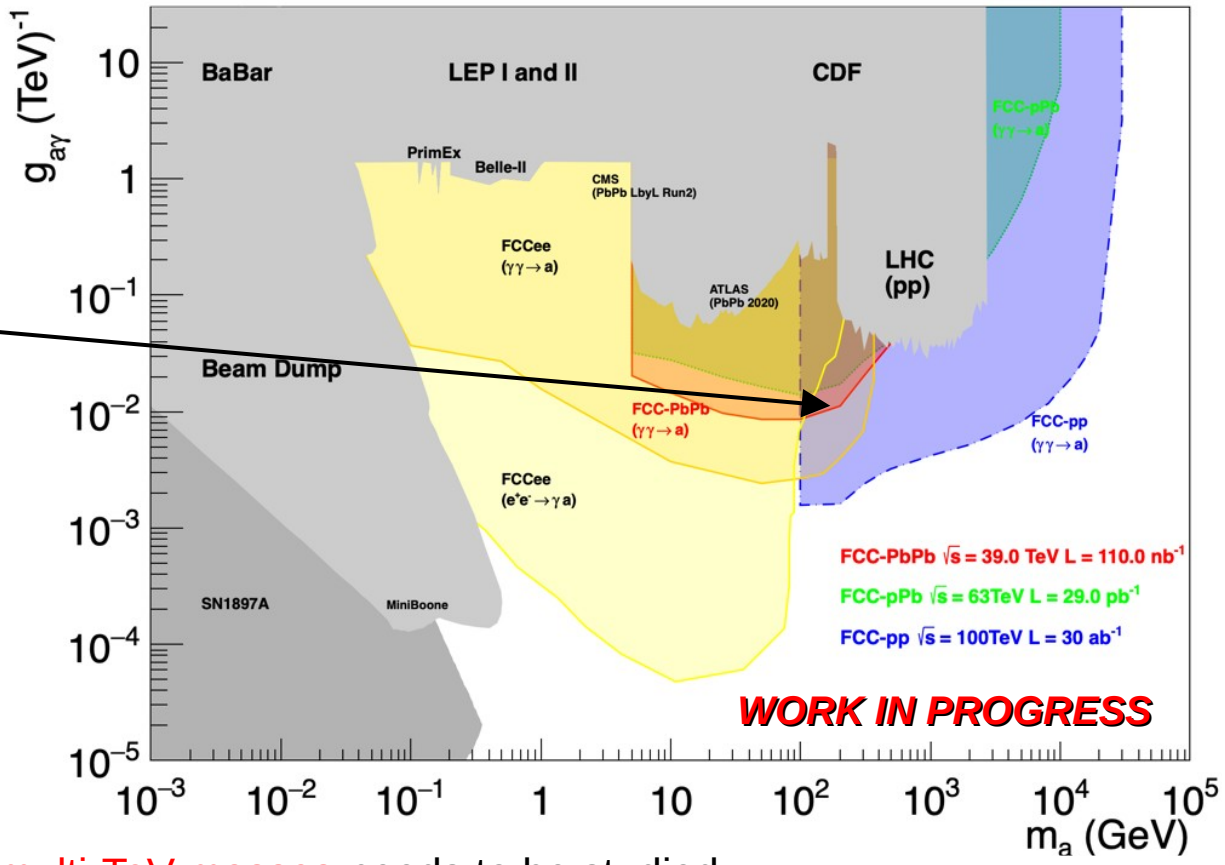
Expected ALPs limits at FCC-hh (preliminary)

- pp(100TeV): LHC limits at m_a = 0.1–1 TeV improved by 1–2 orders-of-magnitude, covers unexplored m_a = 2–30 TeV for ALPs with coupling down to $g_{a\gamma} = 5 \cdot 10^{-3}$ TeV^{-1}
- PbPb(39TeV) & pPb(63TeV): Bounds ~10 times beyond LHC, but not competitive wrt. FCC-ee(91 GeV): Z→a(γγ)γ, and pp(100 TeV) excl. γγ searches

Example:

PbPb(39 TeV, 110 nb^{-1})





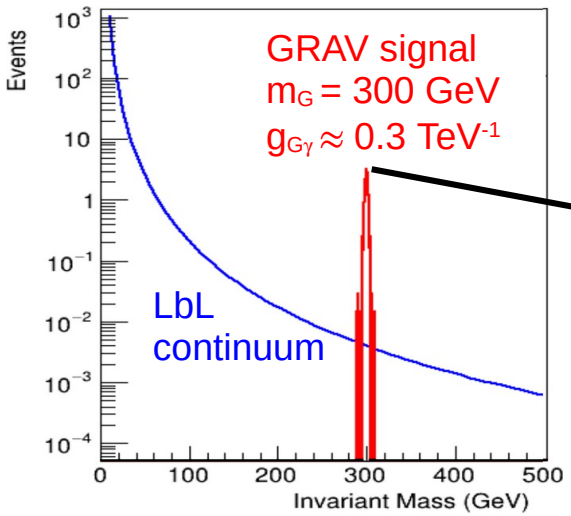
Note: Proton tagging up to multi-TeV masses needs to be studied

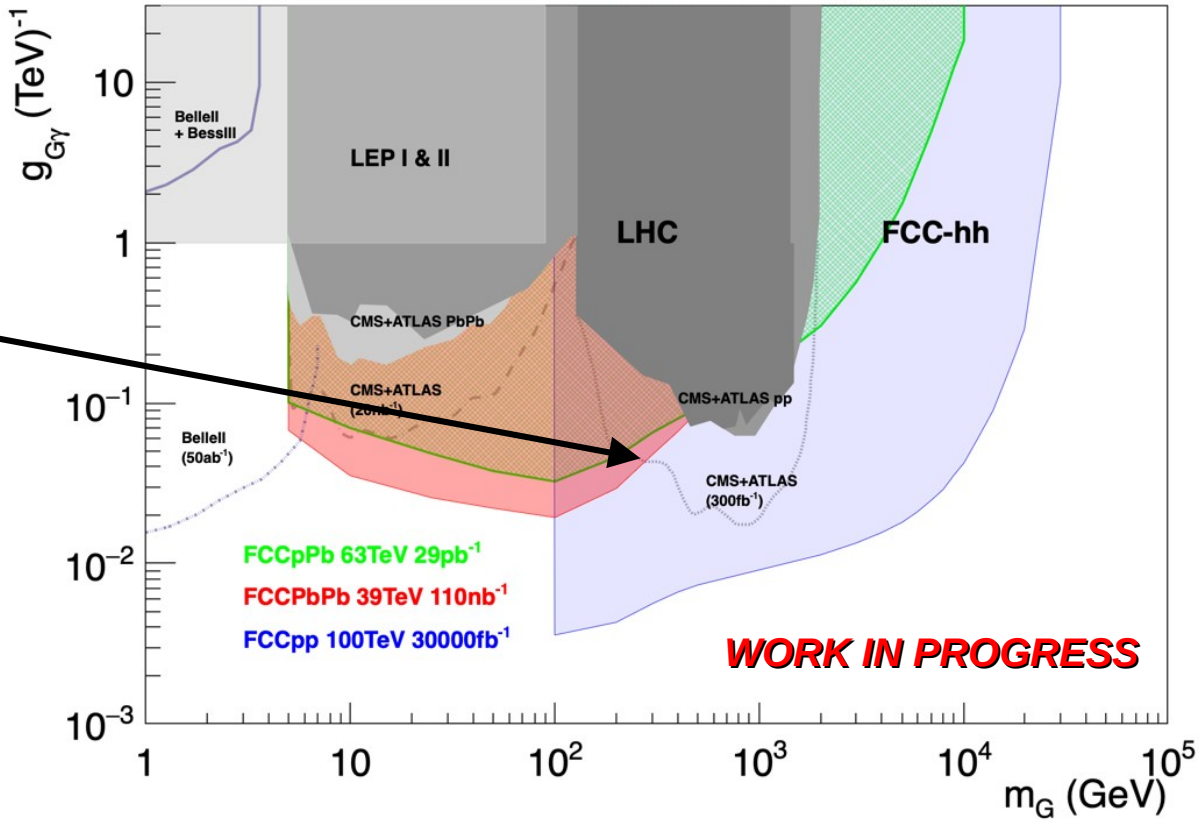
Expected GRAVs limits at FCC-hh (preliminary)

- pp(100TeV): Improves LHC limits at m_G = 0.1–1 TeV by 1–2 orders-of-magnitude, covers unexplored m_G = 2–30 TeV for massive gravs with coupling $g_{aG} > 10^{-2}$ TeV^{-1}
- PbPb(39TeV) & pPb(63TeV): Bounds beyond LHC for m_G = 5–100 GeV down to couplings $g_{aG} = 5 \cdot 10^{-2}$ TeV^{-1} *(but FCC-ee, to be studied, more competitive there...)*

Example:

PbPb(39 TeV, 110 nb^{-1})





Note: Proton tagging up to multi-TeV masses needs to be studied

Back-up slides

Heavy-ion collisions at the FCC-hh

- CM energy $\sqrt{s}$ = 100 TeV for pp means: $\sqrt{s_{NN}} = \sqrt{s}\sqrt{Z_1 Z_2 / A_1 A_2}$ for A-A colls.

  PbPb: $\sqrt{s_{NN}}$ = 39 TeV, L_{int} = 110 nb^{-1}/month

  pPb: $\sqrt{s_{NN}}$ = 63 TeV, L_{int} = 29 pb^{-1}/month

$\sqrt{s_{NN}}$: ×7 larger than LHC

L_{int}: ×10–30 larger than LHC

- Huge increase in cross sections (yields)

Table 1: Beam and machine parameters.

	Unit	Baseline		Ultimate	
Operation mode	-	Pb–Pb	p–Pb	Pb–Pb	p–Pb
Number of Pb bunches	-	2760		5400	
Bunch spacing	[ns]	100		50	
Peak luminosity (1 experiment)	$[10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	80	13300	320	55500
Integrated luminosity (1 experiment, 30 days)	$[\mathrm{nb}^{-1}]$	35	8000	110	29000