Axion-like Particles via γ-fusion @FCC-e^+e^-

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28th International Workshop on Weak Interactions and Neutrinos

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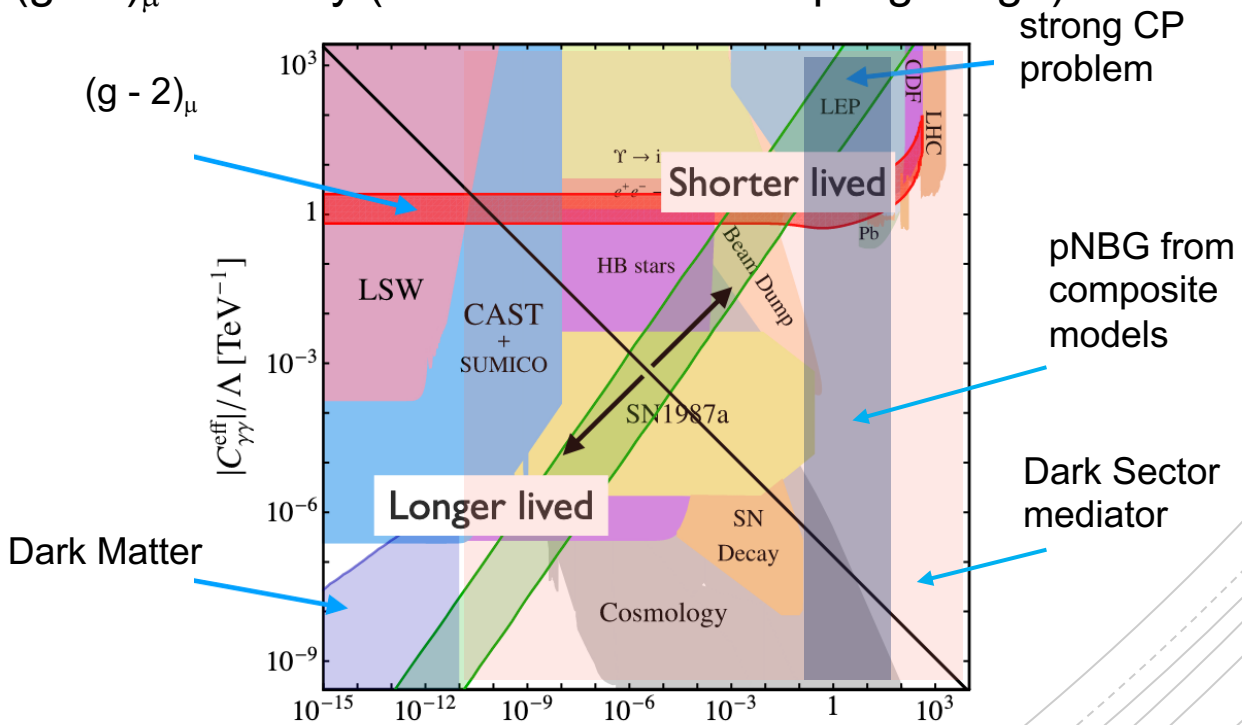
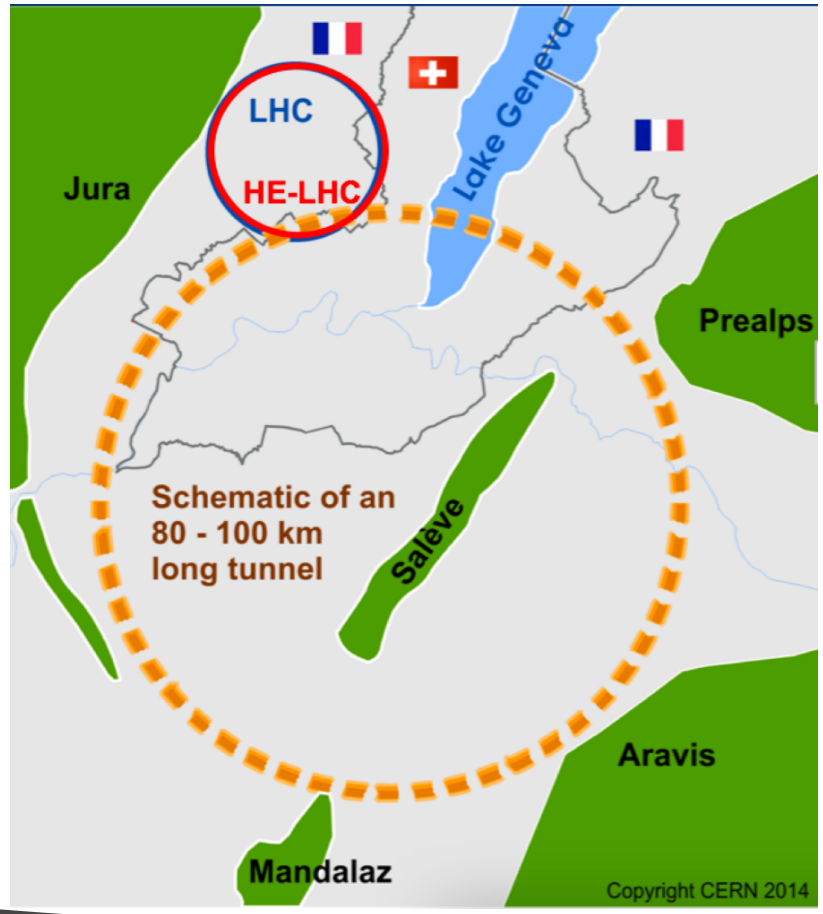
Axion-like particles (ALPs) are pseudoscalars suggested in many SM extensions:

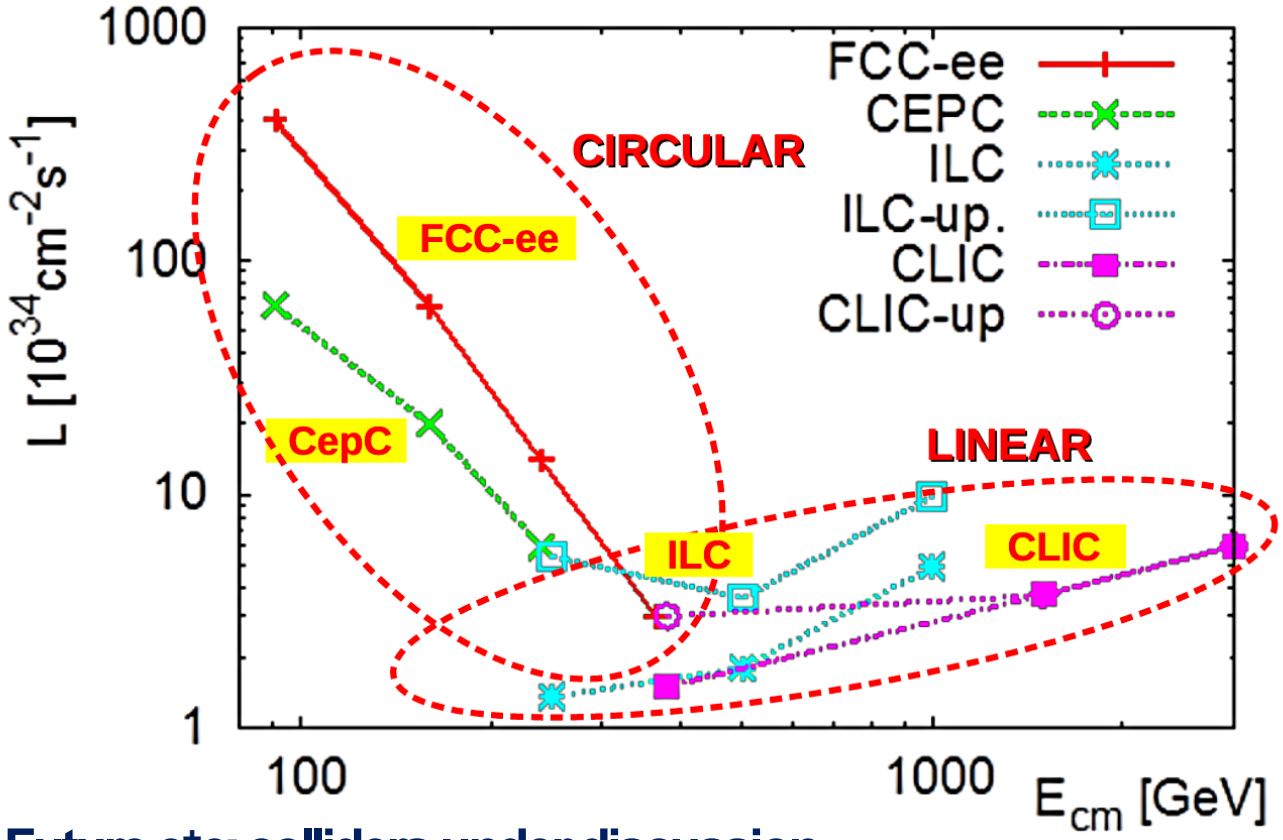
Motivations

1. Solve strong CP problem (with explicit m_a vs. SM-couplings proportionality).
2. Dark Matter candidate (for stable very light m_a), or dark sector mediator (higher mass values)
3. Pseudo Nambu-Goldstone boson of new spontaneously broken global symmetries (π^0-like) in high-energy SM extensions (for $m_a \sim$ GeV)
4. Solve $(g - 2)_\mu$ anomaly (over narrow SM coupling range)



[Figure adapted from Andrea Thamm link]

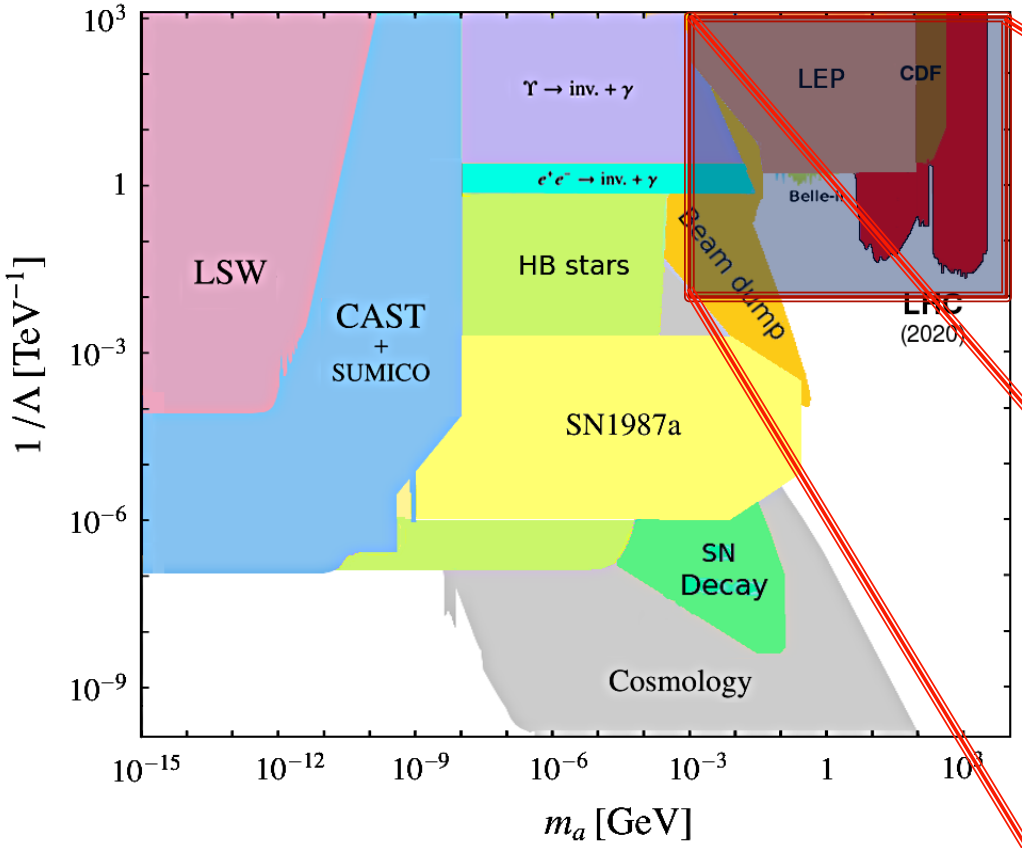


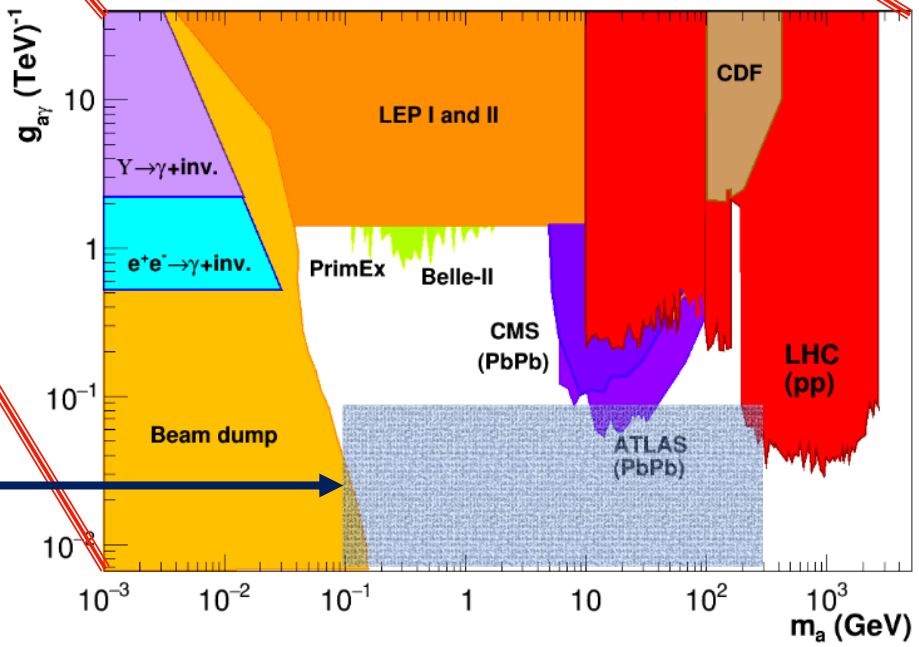


Future e^+e^- colliders under discussion

- International FCC Collaboration (CERN as host lab) to study hadron collider at 100Km tunnel.
- FCC-e^+e^- as first step.
- FCC-e^+e^- features lumis a few times larger than other machines over 90–240 GeV
- High-precision detectors and huge data samples expected at $\sqrt{s}$ = 91, 160, 240 GeV, 365 GeV, useable for ALP searches.

What can be achieved, via γγ-fusion at FCC-ee, in the heavy-ALP region ($m_a \gtrsim 0.1$ GeV)?





Benchmark coupling at $g_{a\gamma} \sim 0.1$ TeV^{-1} for the following working points:

$\sqrt{s}$=91 GeV: m_a = 0.1, 0.5, 1, 10, 50 GeV

$\sqrt{s}$=160 GeV: plus m_a = 100 GeV

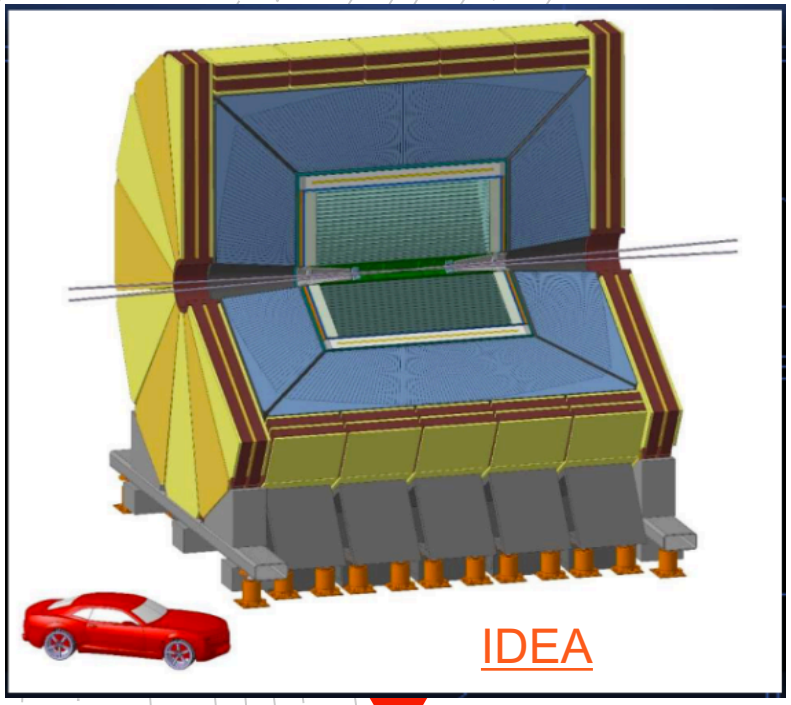
$\sqrt{s}$=240 GeV: plus m_a = 150, 200 GeV

$\sqrt{s}$=365 GeV: plus m_a = 250, 300 GeV

[Figure from David d'Enterria, arXiv:2102.08971]

Production of an Axion–like particle (ALP) via the two–body photon decay channel according to the Lagrangian:

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



See M. Dams talk

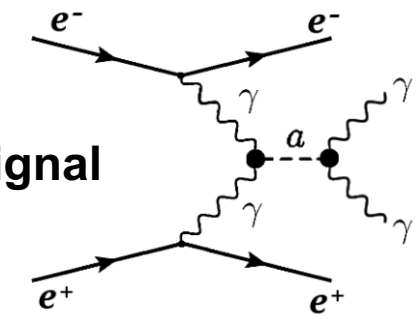
- New, innovative, cheaper, detector
- Ultra-light drift chamber
- Dual Readout calorimeter Solenoid inside calorimeter

*IDEA - International Detector for Ep Accelerators

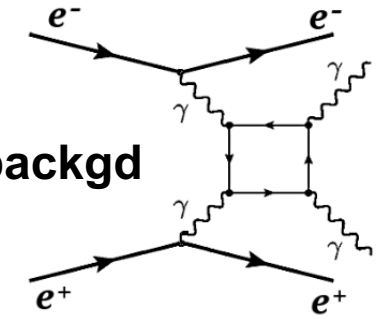
SuperChic v4.X MC to generate ALP signal & irreducible light-by-light background. Reference: https://arxiv.org/pdf/1512.03069.pdf

$$\Gamma = \frac{g_{a\gamma}^2 m_a^3}{64\pi}$$

ALP signal



LbyL backgd



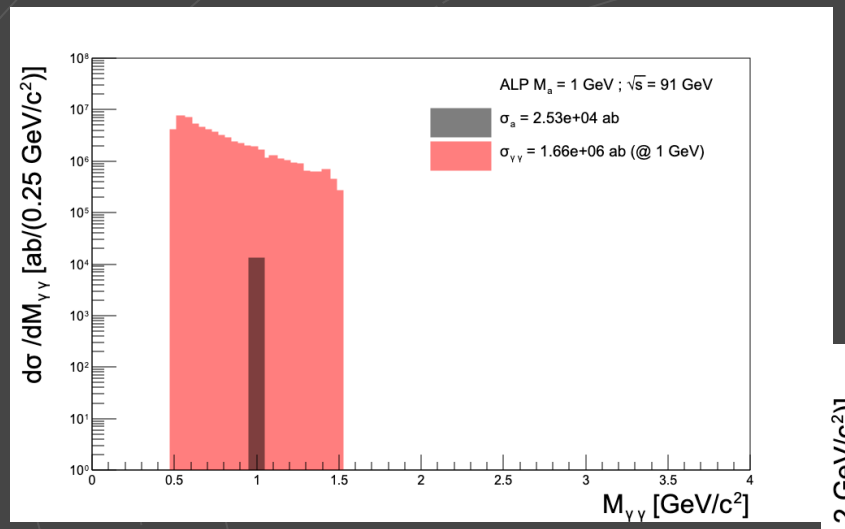
FCC-e^+e^- detector simulation with Delphes IDEA* card, after Pythia8 processing, under realistic FCC-e^+e^- environment conditions following the FCC-ee machine parameters in the Conceptual Design Report (CDR).

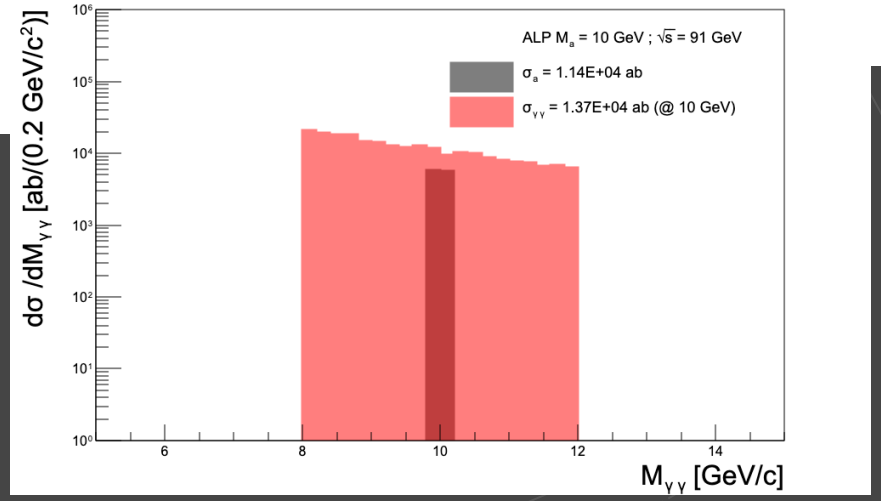
95%CL upper limits on the cross-section σ ($\gamma\ \gamma \rightarrow a \rightarrow \gamma\ \gamma$) and on the ALP-photon coupling $g_{a\gamma}$ (assuming BR($a \rightarrow \gamma\ \gamma$)=100%) over the mass range m_a = 0.1 -- 300 GeV (working points of previous slide)**.

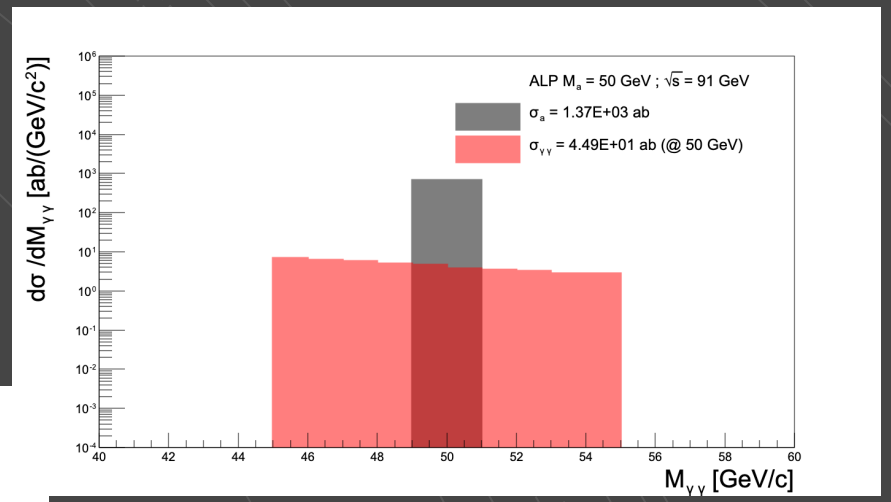
** **Results from DELPHES parametrized detector effects being worked out. Showing now here parton-level results.**

$\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ @FCC$-e^+e^-$ ($\sqrt{s} = 91$ GeV, $L_{int} = 48$ ab^{-1})

Parton Level distributions

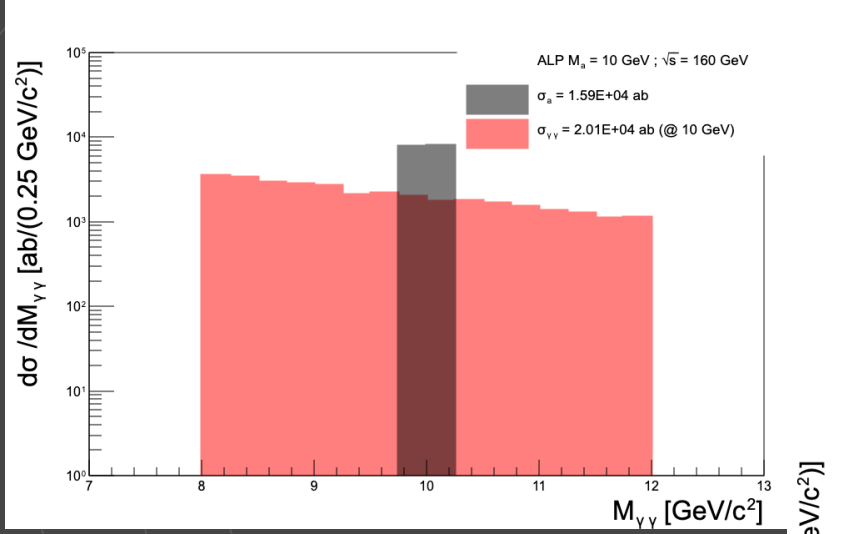


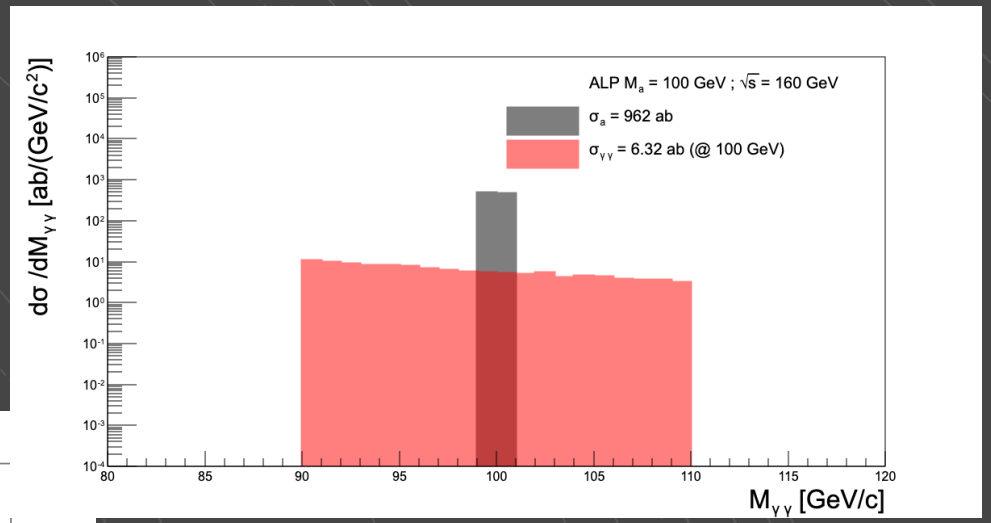


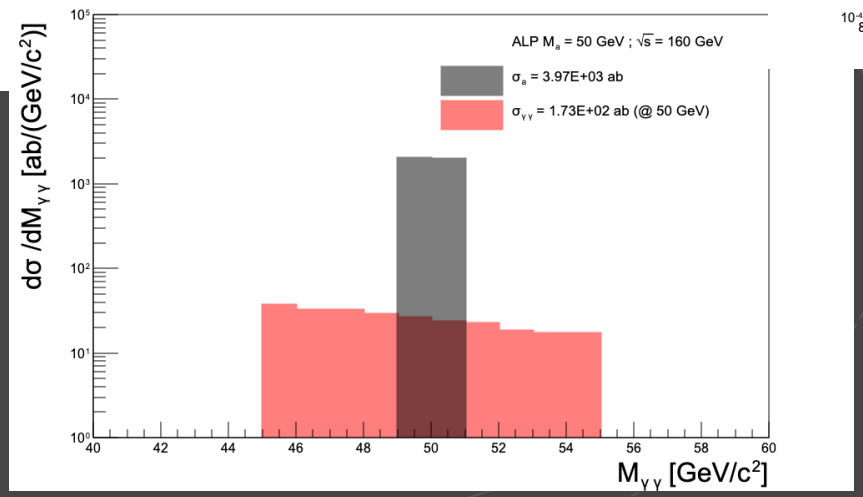


$\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ @FCC – e^+e^- ($\sqrt{s}$ = 160 GeV, L_{int} = 6 ab^{-1})

Parton Level distributions

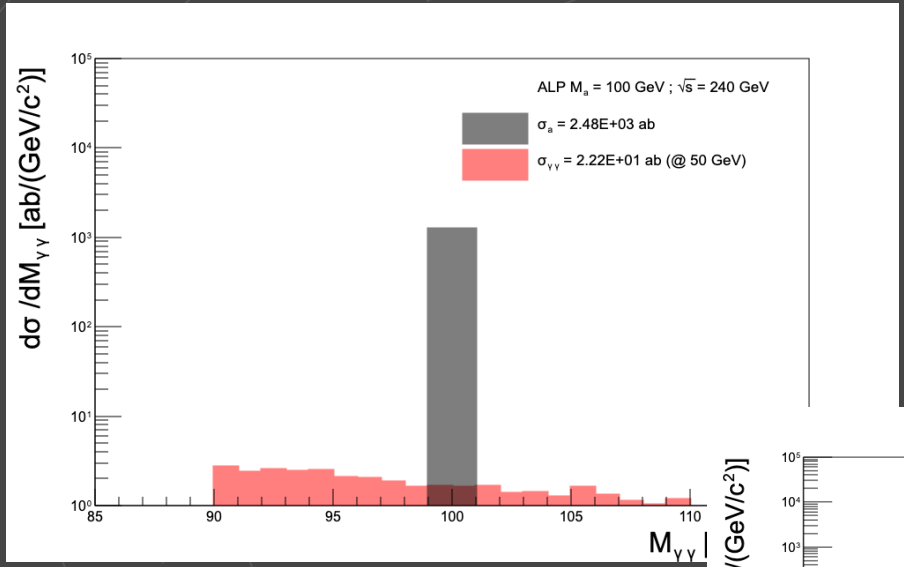


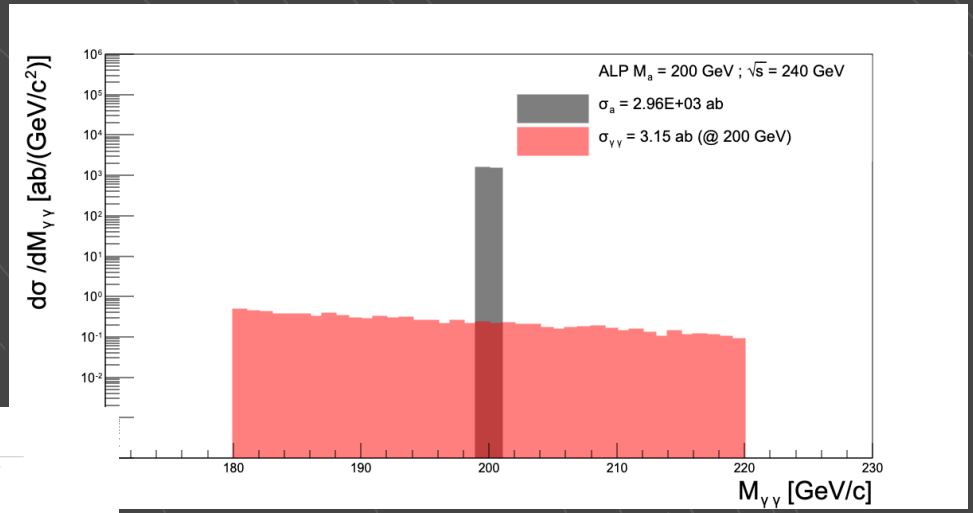


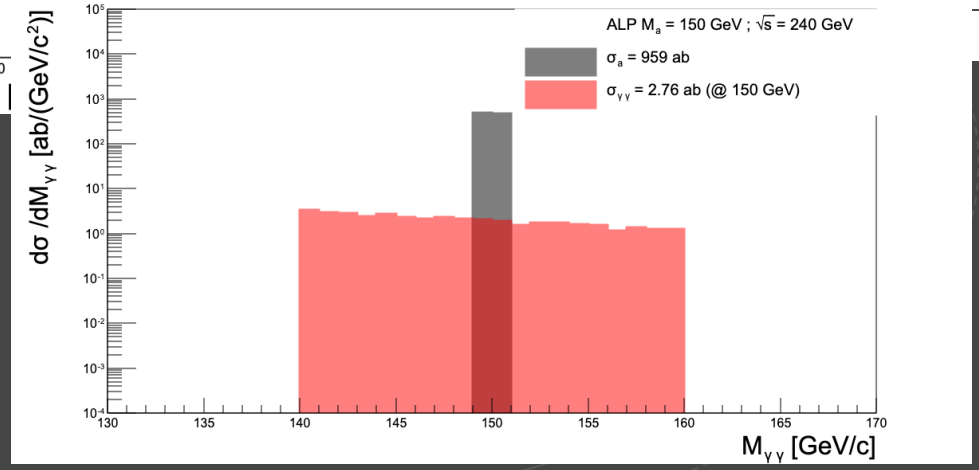


$\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ @FCC – e^+e^- ($\sqrt{s}$ = 240 GeV, L_{int} = 1.7 ab^{-1})

Parton Level distributions

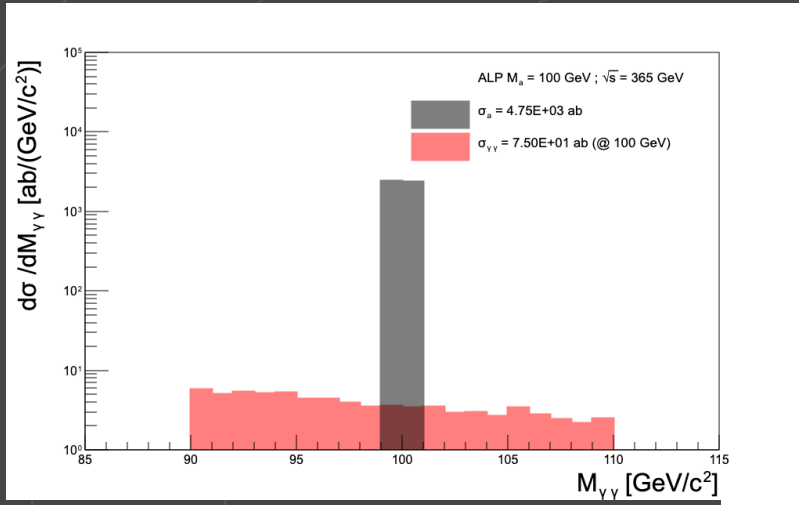


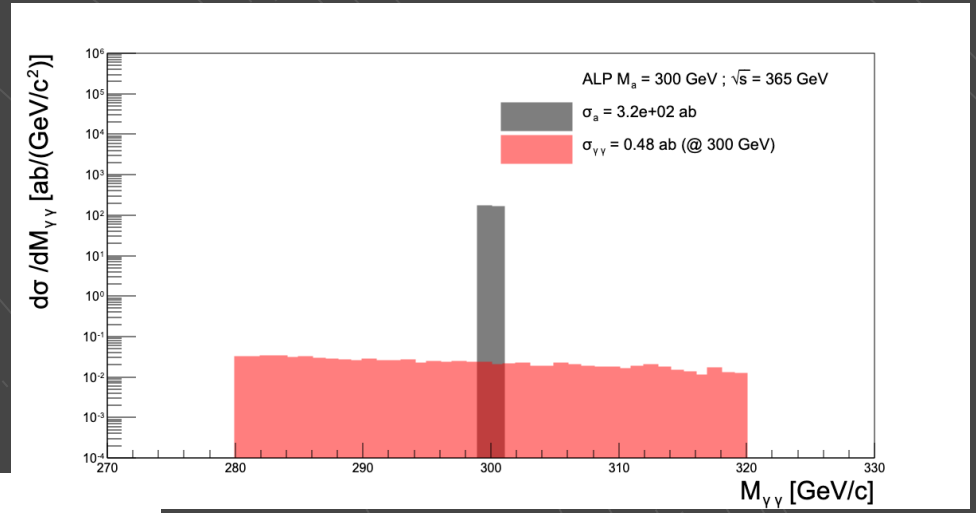


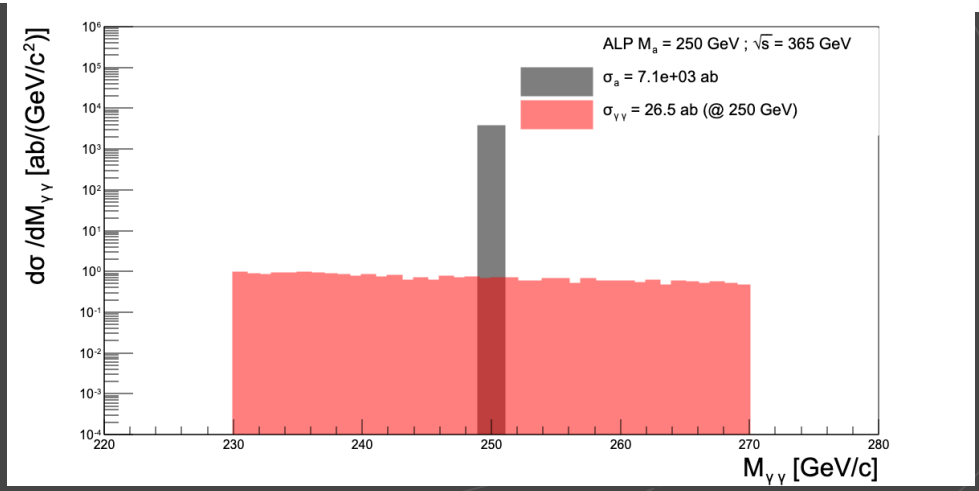


$\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ @FCC – e^+e^- ($\sqrt{s}$ = 365 GeV, L_{int} = 0.34 ab^{-1})

Parton Level distributions

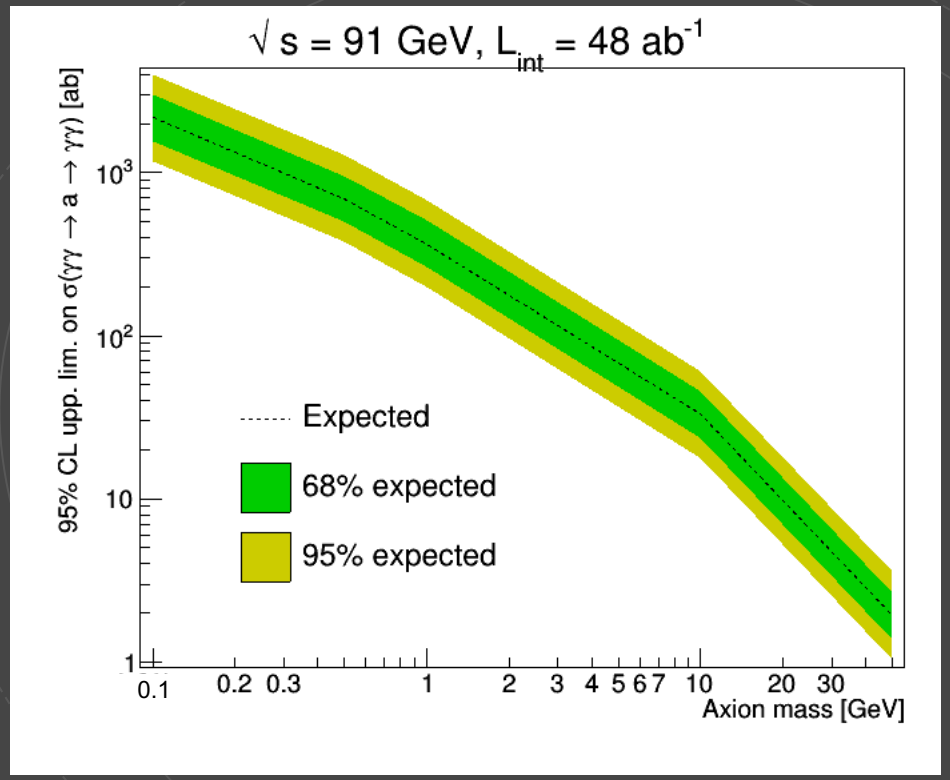


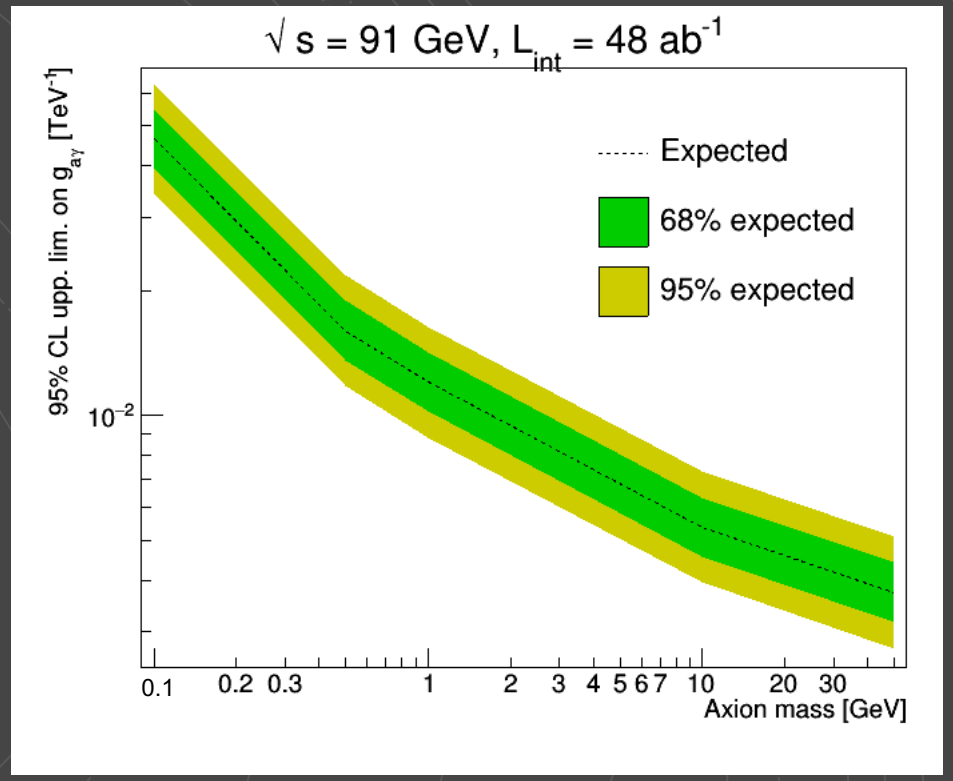




$\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ @FCC – e^+e^- ($\sqrt{s} = 91$ GeV, $L_{int} = 48$ ab^{-1})

95% CL upper limits





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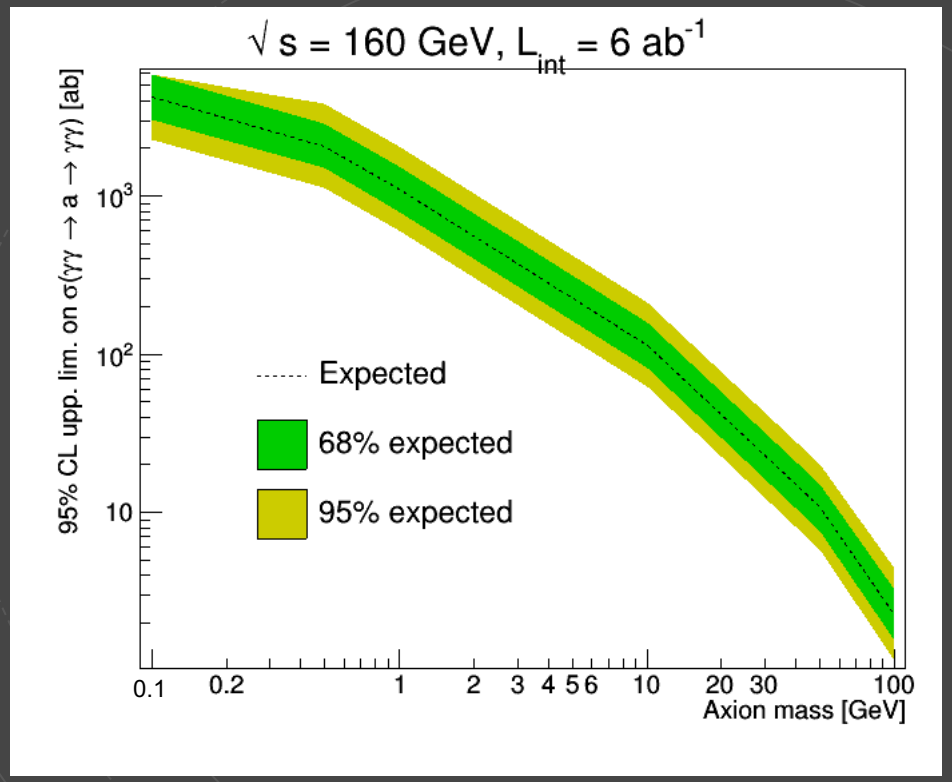
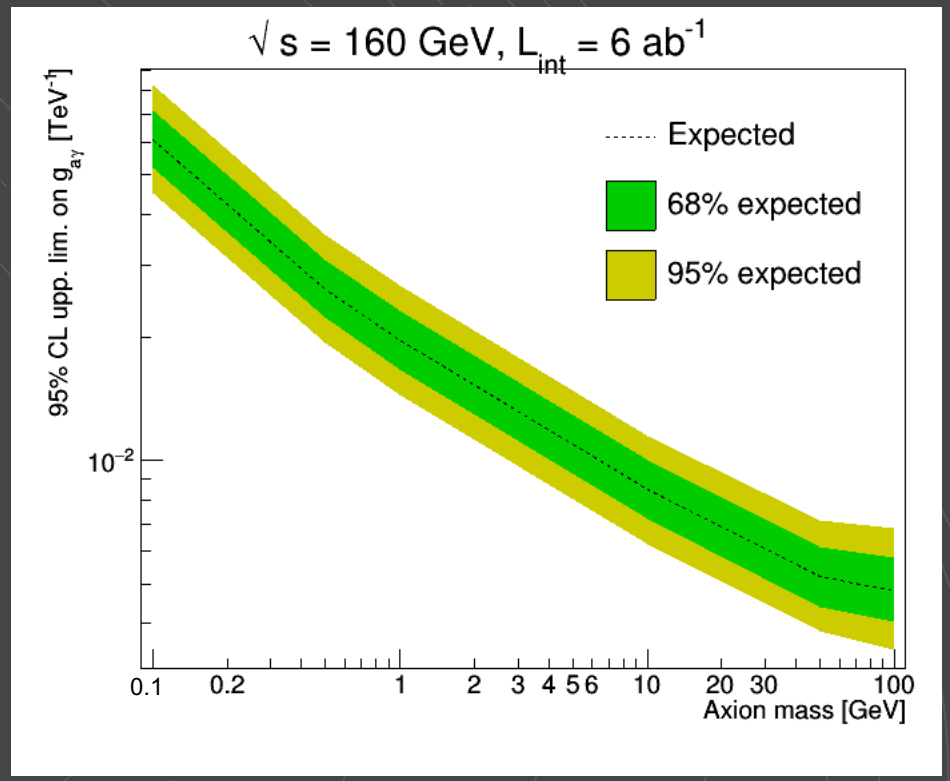
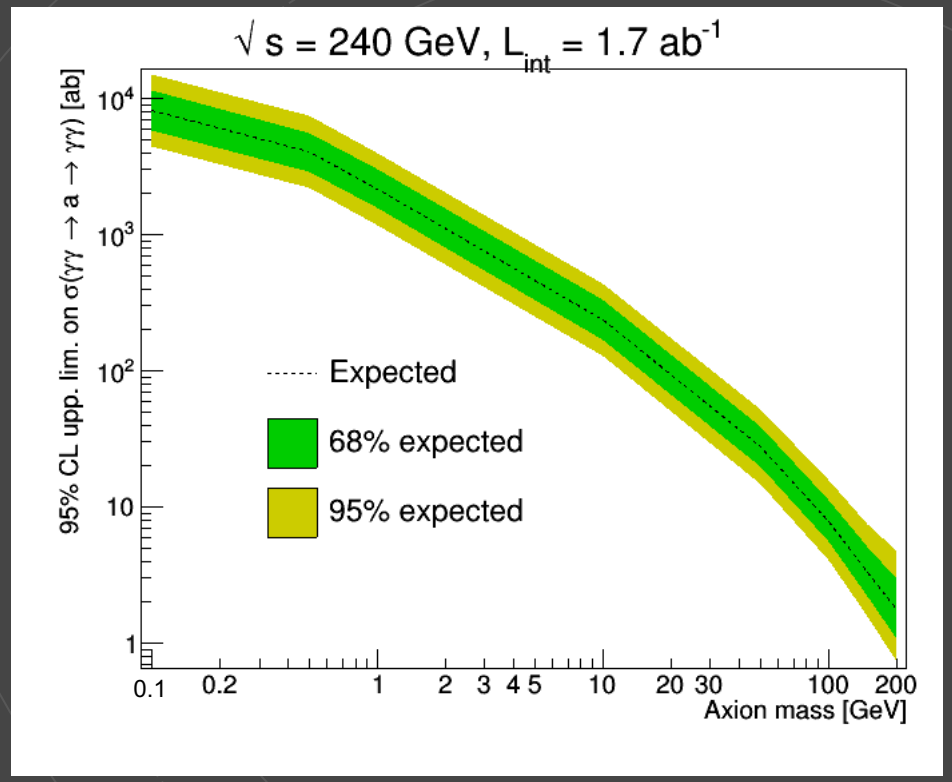
95% CL upper limits

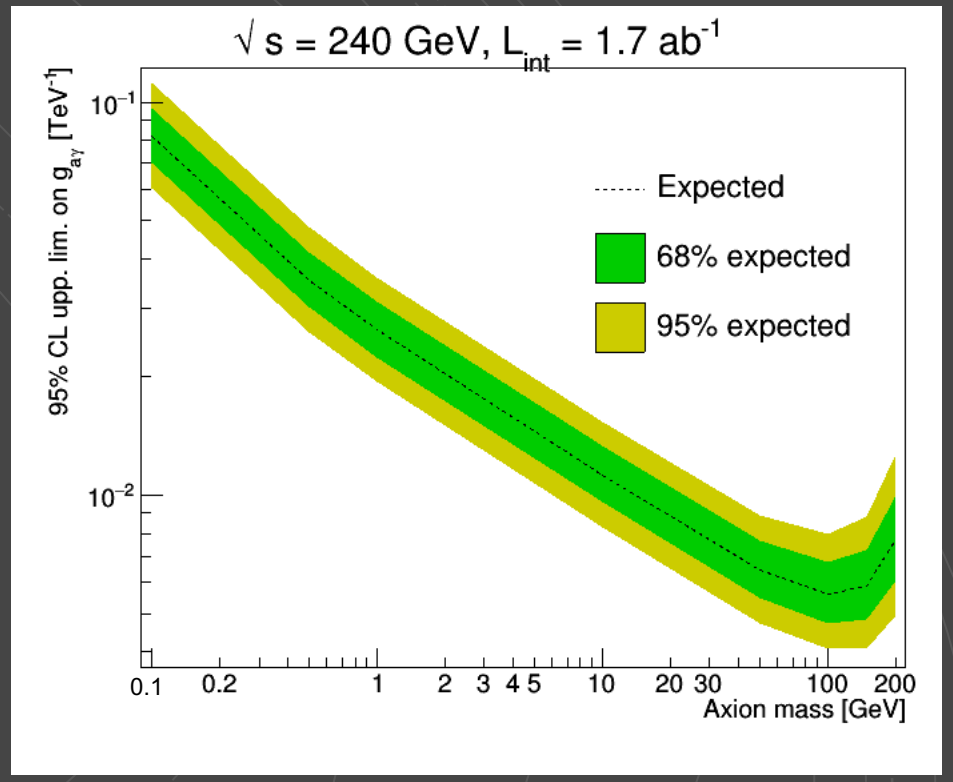




$\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ @FCC – e^+e^- ($\sqrt{s}$ = 240 GeV, L_{int} = 1.7 ab^{-1})

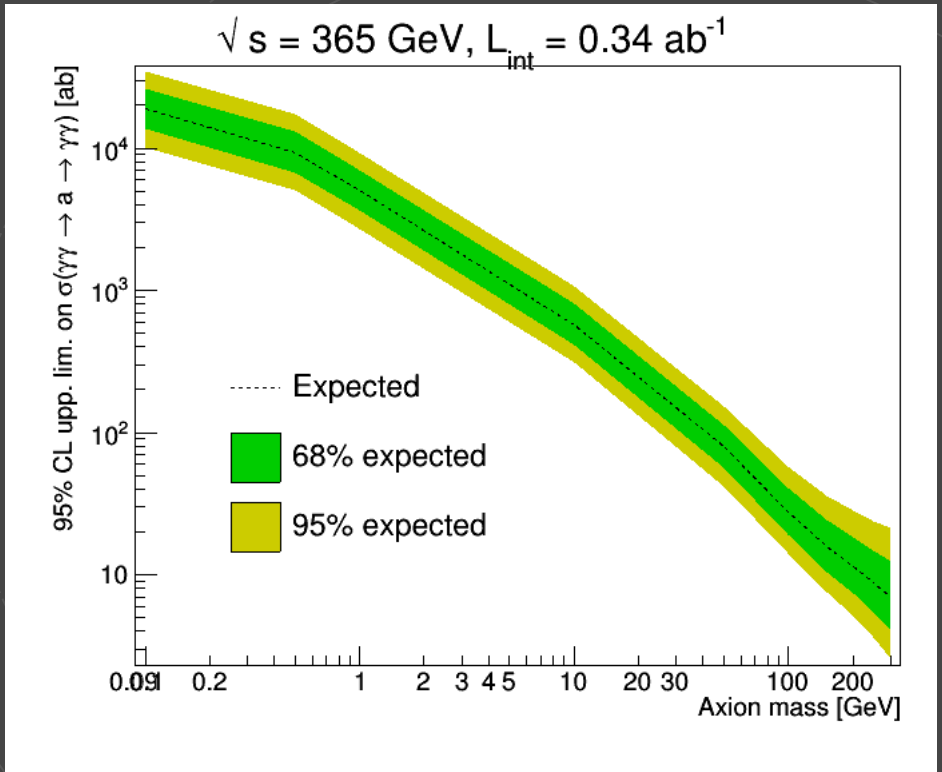
95% CL upper limits

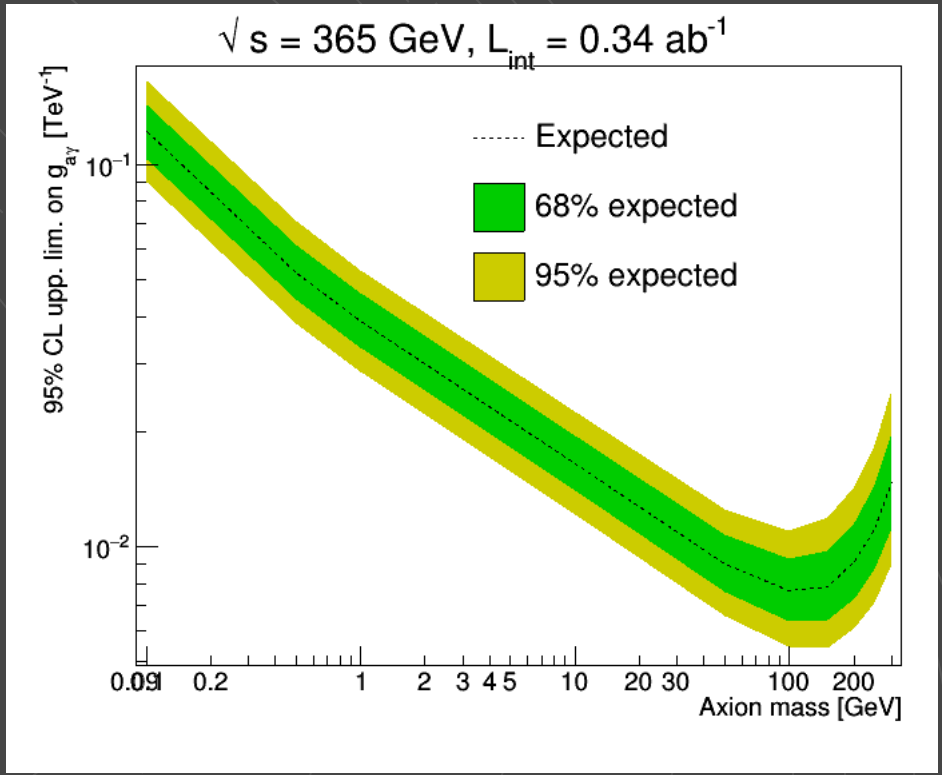


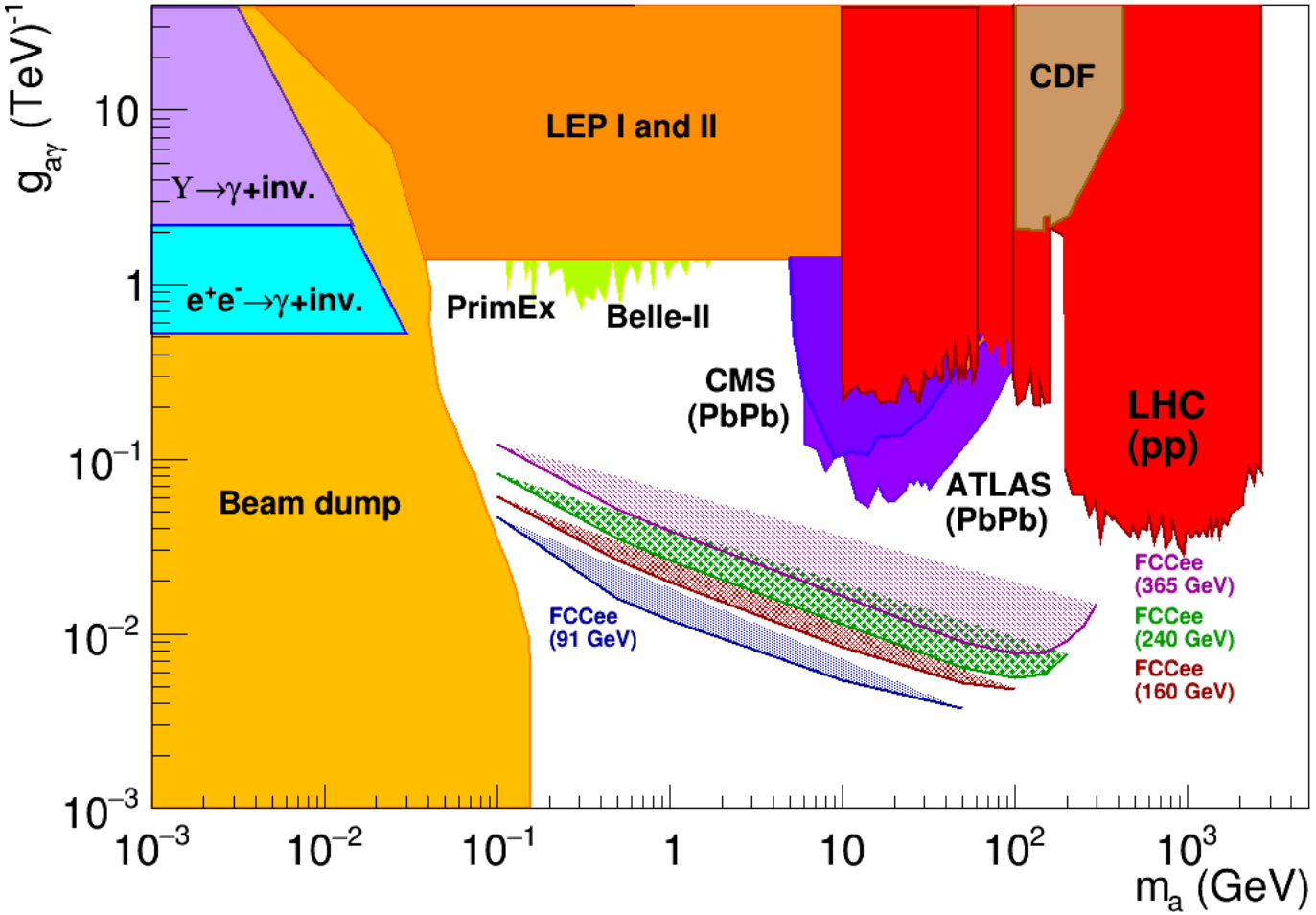


$\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ @FCC – e^+e^- ($\sqrt{s}$ = 365 GeV, L_{int} = 0.34 ab^{-1})

95% CL upper limits







- Very prominent upper limits @95% CL for ALPs searches in the mass range 0.1 GeV $\leq m_a \leq$ 300 GeV, with couplings to photons $g_{a\gamma}$ in the order of $\mathcal{O}(10^{-2} - 10^{-3})$ TeV $^{-1}$.
- FCC-ee coverage is 10 - 50 better than any other current experiment.

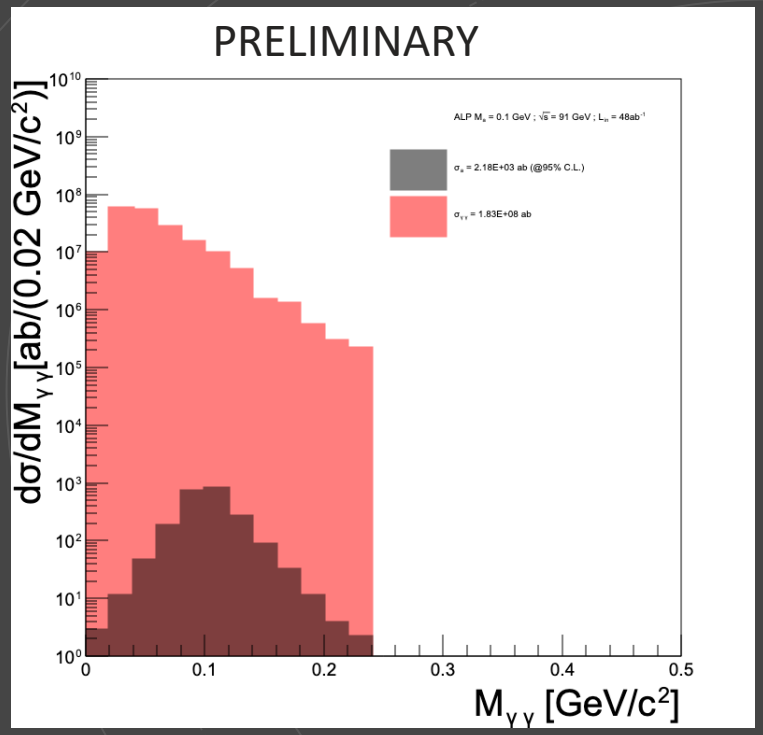
Conclusions

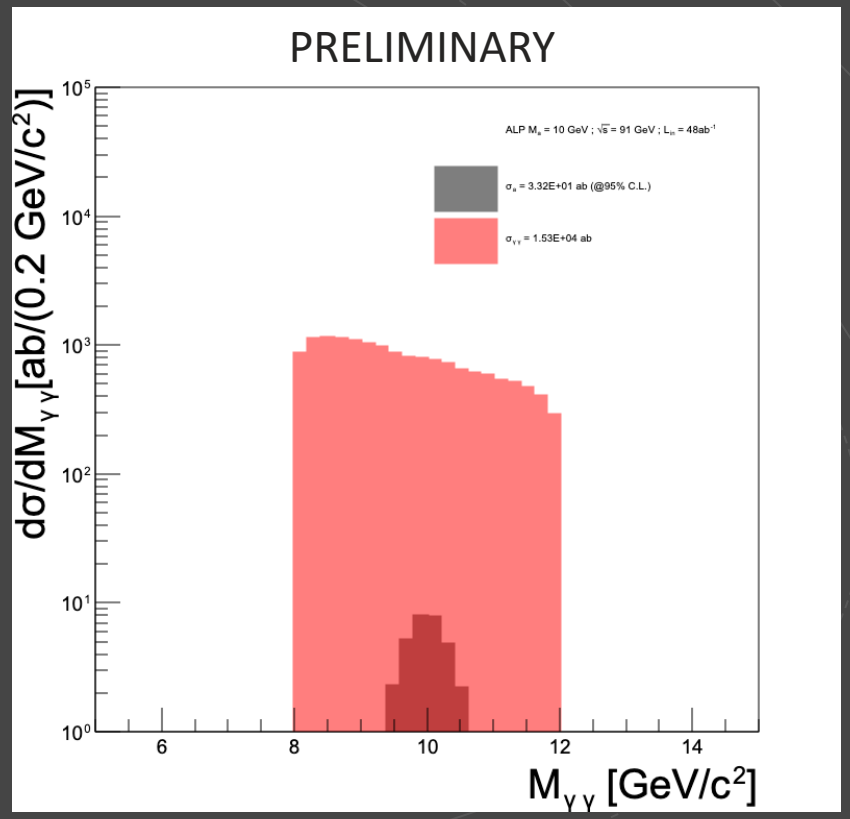
- Axion-like particles (ALP) are well-supported candidates for many extensions of the SM, motivating many experimental searches over a very broad range of masses, covered by collider, astrophysics, cosmology, low-energy precision,... measurements
- The Future Circular Collider (FCC), in all beam configuration, is an outstanding gg-collider strongly enabling the search for new physics. Here, in particular, we presented 95%CL upper limits for the FCC lepton beam scenario.
  - With $g_{a\gamma}$ couplings down to O(10^{-2} − 10^{-3}) TeV^{-1}, 10 -- 50 times better than current limits at particle colliders.
- Detector simulation, available from Pythia8 and Delphes tools, being worked out. Preliminary distributions in the backup slides.

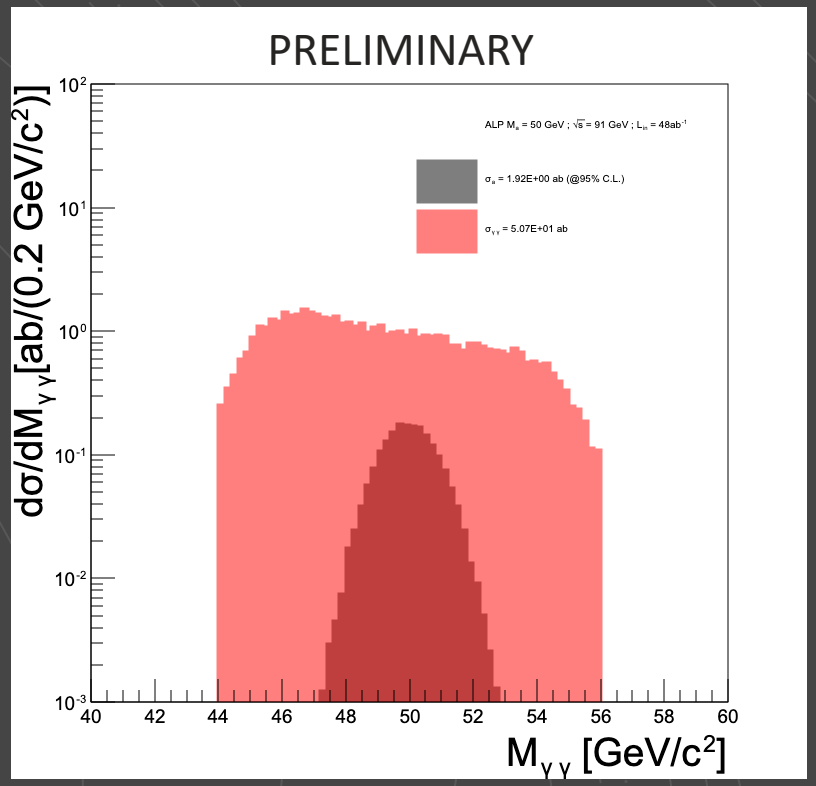
Backup slides

$\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ @FCC$-e^+e^-$ ($\sqrt{s} = 91$ GeV, $L_{int} = 48$ ab^{-1})

Delphes IDEA distributions ALP@95C.L.







FCC-ee Detector Requirements

Momentum resolution

$$\sigma_{pT}/p_T^2 \simeq 3 - 4 \times 10^{-5}$$

matching beam energy spread of $\delta E/E \simeq 1\text{-}2 \times 10^{-3}$

⇒ Mass reconstruction from lepton pairs

Reconstructed mass of lepton pair in HZ with $Z \to \ell^+\ell^-$

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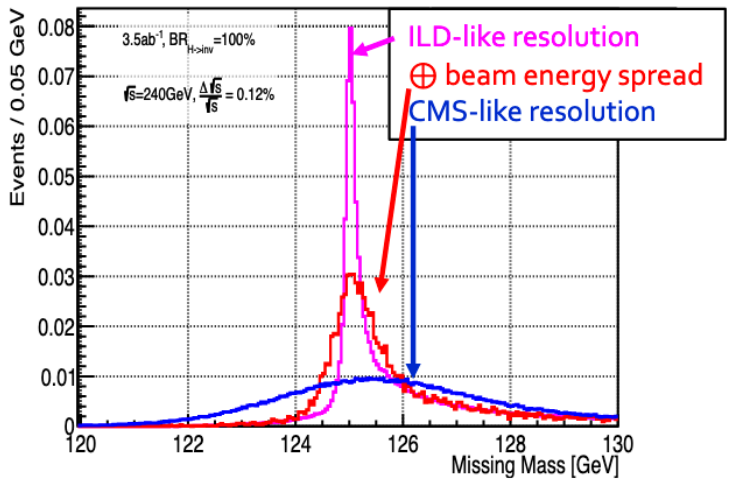


⇒ Endpoint of $Z \to \ell^+\ell^-$ momentum spectrum

- Probe to 10^{-9} level lepton flavour violation in $Z \to \tau e$, $Z \to \tau\mu$

⇒ …

Jet energy

$$\delta E/E \simeq 30\% / \sqrt{E}\ [\text{GeV}]$$

⇒ Mass reconstruction from jet pairs

Resolution important for control of (combinatorial) backgrounds in multi-jet final states

- $HZ \to$ 4 jets, tt^{bar} events, etc.
- At $\delta E/E \simeq 30\% / \sqrt{E}$ [GeV], detector resolution is *comparable* to natural widths of W and Z bosons

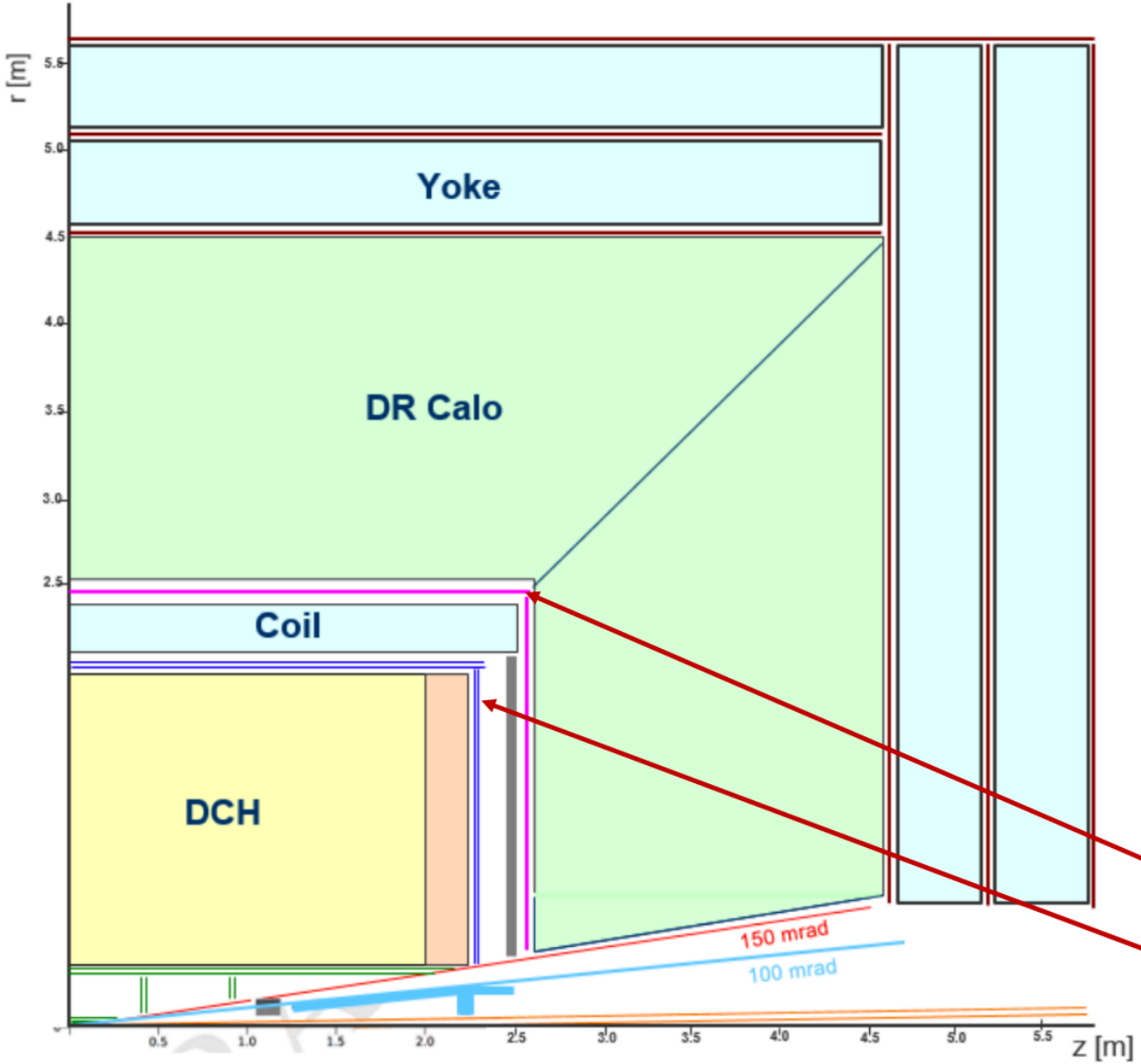
e/γ energy

$$\delta E/E \lesssim 15\% / \sqrt{E}\ [\text{GeV}]$$

⇒ Invariant masses

- $H \to \gamma\gamma$
- π^0 identification and measurement for τ polarisation measurement, etc.
- But also for searches of the kind $\tau \to \mu\gamma$

IDEA Detector Concept Layout



LEGENDA

- drift chamber
- drift chamber service area
- magnet and iron return yoke
- calorimeter
- Si pixels — 20μm × 20μm (inner barrel layers) r=17, 23, 31 mm; 50μm × 1mm (outer barrel layers) r=330-340 mm; 50μm × 50μm (forward disks) z=400-900 mm
- Si strips double stereo layer 50μm × 10cm
- μRwell double layer 0.4mm × 50cm
- μRwell double layer 1.5mm × 50cm
- absorber (lead)
- luminometer
- steel simulating compensating and shielding solenoids
- vacuum tube

pre-shower: 1-2 X_0

”silicon wrapper”

```
# inner radius of the solenoid, in m
set Radius 2.25

# half-length: z of the solenoid, in m
set HalfLength 2.5

# magnetic field, in T
set Bz 2.0
set ECalEnergyMin 0.5

set ECalResolutionFormula {
    (abs(eta) <= 0.88 )                    * sqrt(energy^2*0.01^2 + energy*0.11^2)+
    (abs(eta) > 0.88 && abs(eta) <= 3.0)    * sqrt(energy^2*0.01^2 + energy*0.11^2)
    }

set EfficiencyFormula {
        (energy < 2.0)                                  * (0.000)+
        (energy >= 2.0) * (abs(eta) <= 0.88)                  * (0.99) +
        (energy >= 2.0) * (abs(eta) >0.88 && abs(eta) <= 3.0) * (0.99) +
        (abs(eta) > 3.0)                                * (0.000)
  }

module Isolation PhotonIsolation {
set DeltaRMax 0.5
set PTMin 0.5
set PTRatioMax 999. }
```