Leptophilic Z′ bosons at the FCC(-ee)

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Based on: R. Gonzalez Suarez, B. Pattnaik, J. Zurita, arXiv 2410.12903 [accepted by PRD]

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Leptophilic Z’

- What if New Physics does not couple to hadrons at tree level? Hard time to get robust LHC bounds, great target for lepton colliders (FCC-ee, MuC, CLIC, ILC, etc)

- But isn’t it a desperate measure because no new physics has been found at the LHC?

- Leptophilic models can arise naturally in BSM extensions. In particular, if we consider a new neutral vector boson Z’ (or call it dark photon if you like it) the groups B-L, L_i - L_j are anomaly free.

- But isn’t this minimality just an aesthetic artefact, without any solid theoretical foundation?

- Not really! a leptophilic Z’ can fit neutrino masses, serve as a portal to the dark sector, solve the Hubble tension, drive leptogenesis, etc. [it could also solve the gone (g-2)μ and the R_K anomalies…]

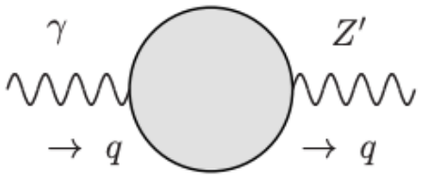
Li-Lj models

- We consider Le-Lτ and Le-Lμ models, to have tree level couplings eeZ′.

$$\mathscr{L} \supset -g'(\bar{L}_i\gamma^\mu L_i - \bar{L}_j\gamma^\mu L_j + \bar{l}_{i,R}\gamma^\mu l_{i,R} - \bar{l}_{j,R}\gamma^\mu l_{j,R})Z'_\mu + \frac{1}{2}(m_{Z'})^2 Z'^\mu Z'_\mu.$$

- Simple model, only two free parameters: $g', m_{Z'}$

- Kinetic mixing ignored here: loop induced and $(m_l/m_{Z'})^2$ suppressed.

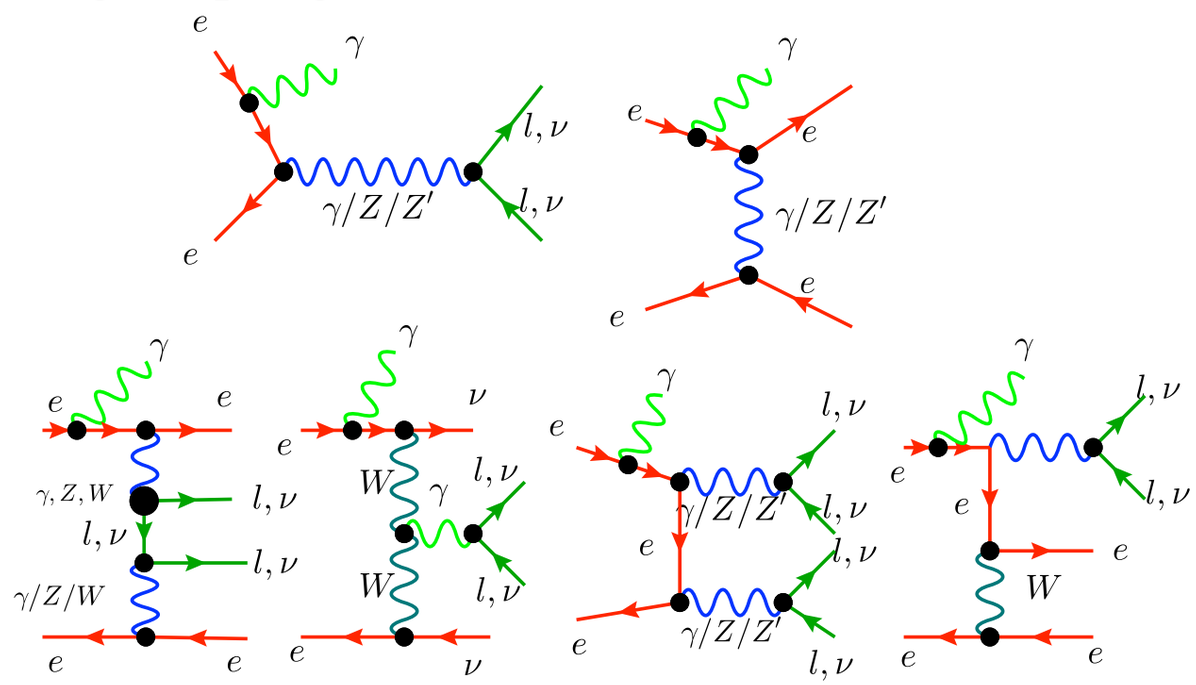


- Studied for:

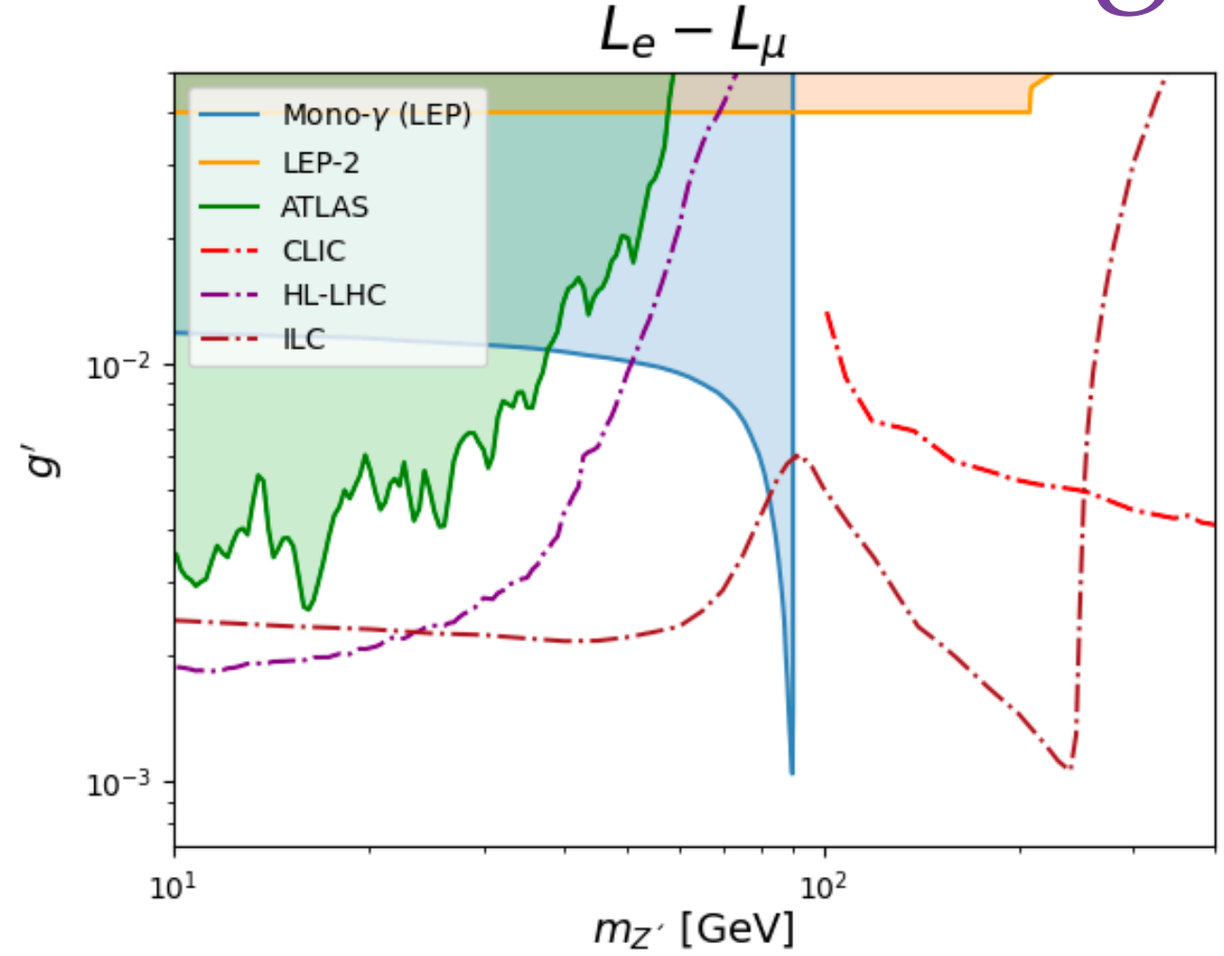
-ILC@250 GeV [Kalinowski et al, 2107.11194] [actually Z′ mediating to a dark sector]

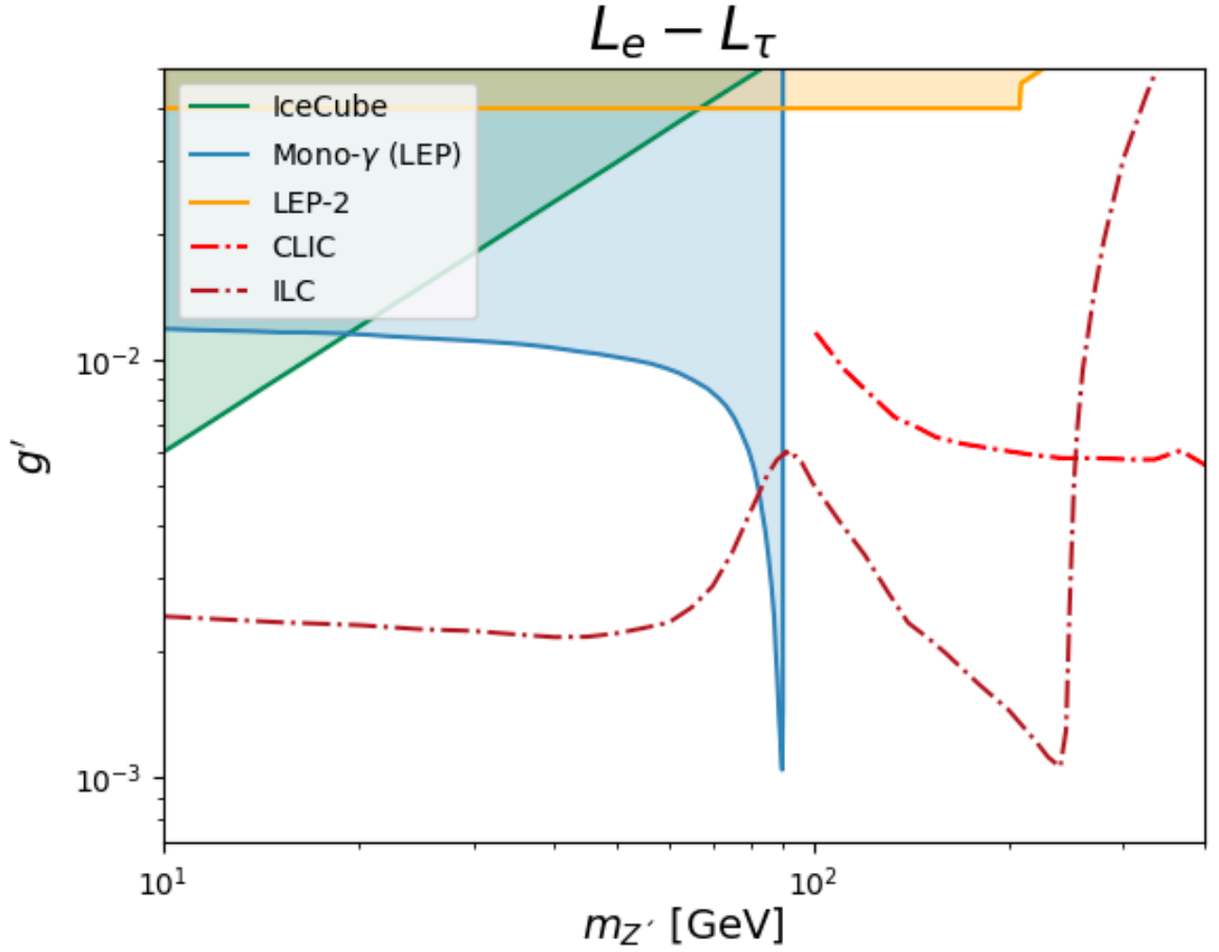
- e^+e^-, $\mu^+\mu^-$ @ 3 TeV [Dasgupta et al, 2308.12804].

-FCC-ee with flavor violating couplings [Goudelis et al, 2312.14103].



Existing constraints





- $m_{Z'} \lesssim 10$ GeV, $g' \lesssim 10^{-4}$ Babar, other low energy experiments [not shown].
- LEP searches (mono-γ, $e^+e^- \to e^+e^-$).
- LHC: ATLAS and CMS searches for $pp \to Z\mu^+\mu^- \to 4\mu$, only for μ-couplings. ATLAS includes W boson, 140 fb^{-1} (2402.15212), CMS only Z, 78 fb^{-1} (1808.03684).
- IceCube constraints non-standard ν interactions in matter (applies only to τ).

Fertile territory for FCC-ee to explore, in particular light masses that have not been studied at ILC, CLIC, MuC.

Pipeline

- MG5_aMC@NLO + Pythia 8 +Delphes, with IDEA card.
- Selection cuts (aligned with IDEA thresholds)
  - $e, \mu : p_T > 0.5$ GeV, $|\eta| \leq 2.5$, $\Delta R(l, X) > 0.5$.
  - $\gamma : E > 2$GeV, $p_T > 0.5$ GeV, $|\eta| \leq 3.0$, $\Delta R(\gamma, X) > 0.5$.
  - $\tau : p_T > 1$ GeV, $|\eta| \leq 3.0$, $\Delta R(\tau, X) > 0.5$,
- Object efficiencies (from IDEA card): $\epsilon_{e,\mu,\gamma} = 0.99, \epsilon_\tau = 0.6$
- Signal: $e^+e^- \to \gamma X$ with $X = l^+l^-, \nu\nu$
- Backgrounds:

  irreducible: $X = l^+l^-, \nu\nu$.
  reducible: $X = l^+l^-l^+l^-, l^+l^-\nu\nu, \nu\nu\nu\nu$.

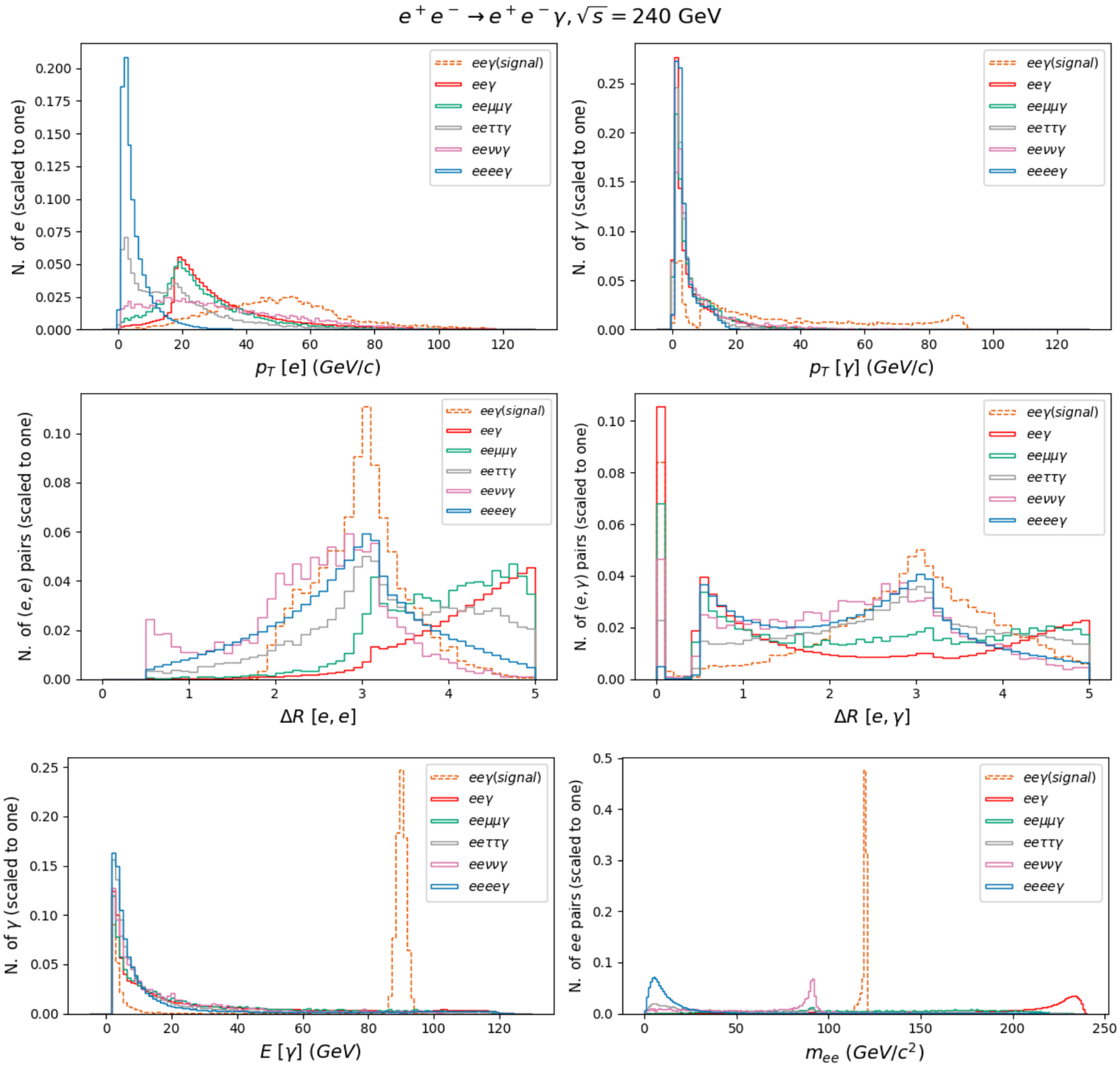
Run Name	E_{beam} [GeV]	$\int \mathcal{L}$ [ab^{-1}]
Z	45.6	205
WW	80	10
ZH	120	7.2
$t\bar{t}$	182.5	2.68

More on backgrounds…

- Simulated 2->3 $e^+e^- \to \gamma l^+l^-, \gamma\nu\nu$ and 2->5 ($e^+e^- \to \gamma l^+l^-l^+l^-, \gamma l^+l^-\nu\nu, \gamma\nu\nu\nu\nu$).
- Jets faking leptons are not included.
- Large sample sizes (in particular for Z-pole run).

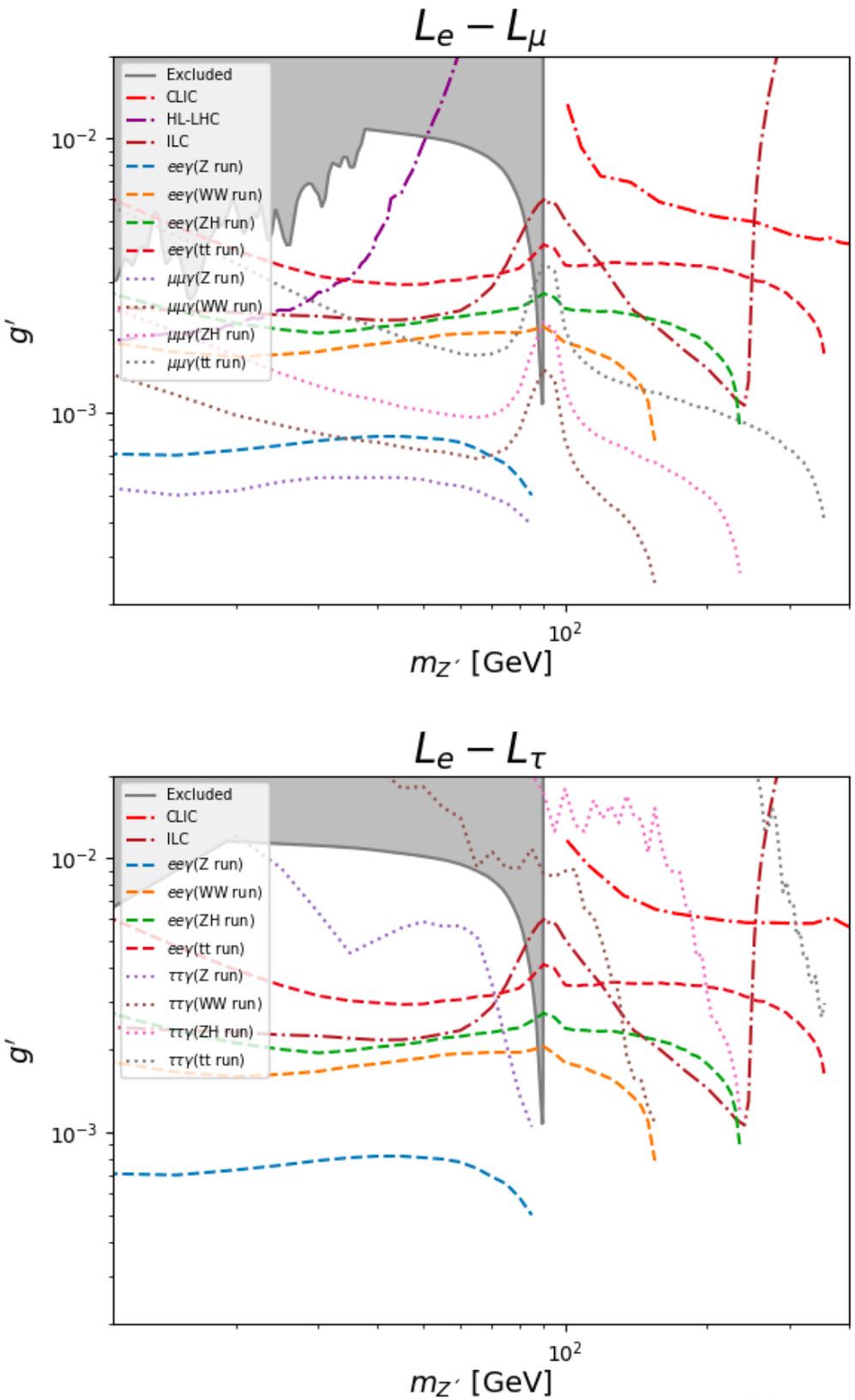
Process $e^+e^- \to \gamma + \ldots$	N_{ev}, Z run	N_{ev}, WW run	N_{ev}, ZH run	N_{ev}, $t\bar{t}$ run
$\mu\mu$	2.3×10^{10}	2.1×10^{7}	5.5×10^{6}	8.44×10^{5}
ee	8.63×10^{10}	1.26×10^{9}	4.5×10^{8}	7.9×10^{7}
$\tau\tau$	2.3×10^{10}	2.1×10^{7}	5.7×10^{6}	8.82×10^{5}
$\nu\nu$	2.2×10^{9}	5.9×10^{7}	3.3×10^{7}	1.35×10^{7}
$\mu\mu\mu\mu$	1.2×10^{5}	1.4×10^{4}	6.3×10^{3}	1.4×10^{3}
$\mu\mu ee$	8×10^{7}	5.03×10^{6}	4.16×10^{6}	1.73×10^{6}
$\mu\mu\tau\tau$	1.43×10^{9}	9.9×10^{6}	1.7×10^{8}	2.3×10^{6}
$\mu\mu\nu\nu$	8×10^{3}	1.8×10^{4}	1.56×10^{4}	6.7×10^{3}
$eeee$	7.6×10^{7}	4.86×10^{6}	4.04×10^{6}	1.78×10^{6}
$ee\tau\tau$	3×10^{7}	1.1×10^{6}	8.9×10^{5}	3.82×10^{5}
$ee\nu\nu$	1.28×10^{4}	2×10^{4}	2.5×10^{4}	1.16×10^{4}
$\tau\tau\tau\tau$	5×10^{5}	6.3×10^{3}	4.5×10^{3}	1×10^{3}
$\tau\tau\nu\nu$	4×10^{3}	2.3×10^{4}	1.6×10^{5}	4×10^{4}
$\nu\nu\nu\nu$	0.5	1.12×10^{4}	8.1×10^{3}	4.6×10^{3}

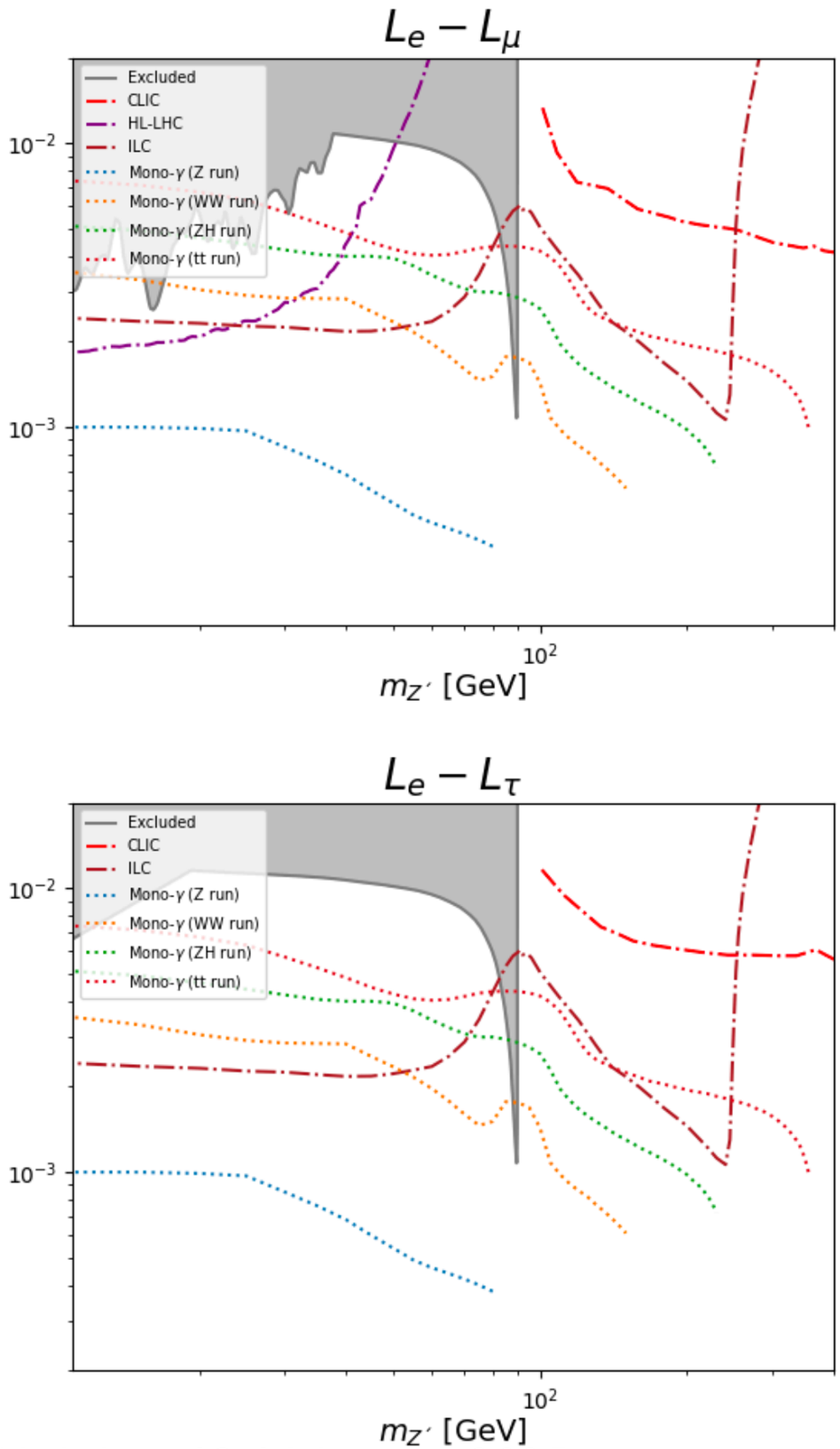
Strategy



m_{ll} :sharp peak over a flat background, Eγ:broader peak. Vary $|m_{ll}-m_{Z'}| < \Delta_{ll}$.

FCC-ee limits





$$\mathcal{Z} = \frac{N_s}{\sqrt{N_s + N_b + \lambda^2 N_b^2}},$$

$\lambda = 0$ ref. value

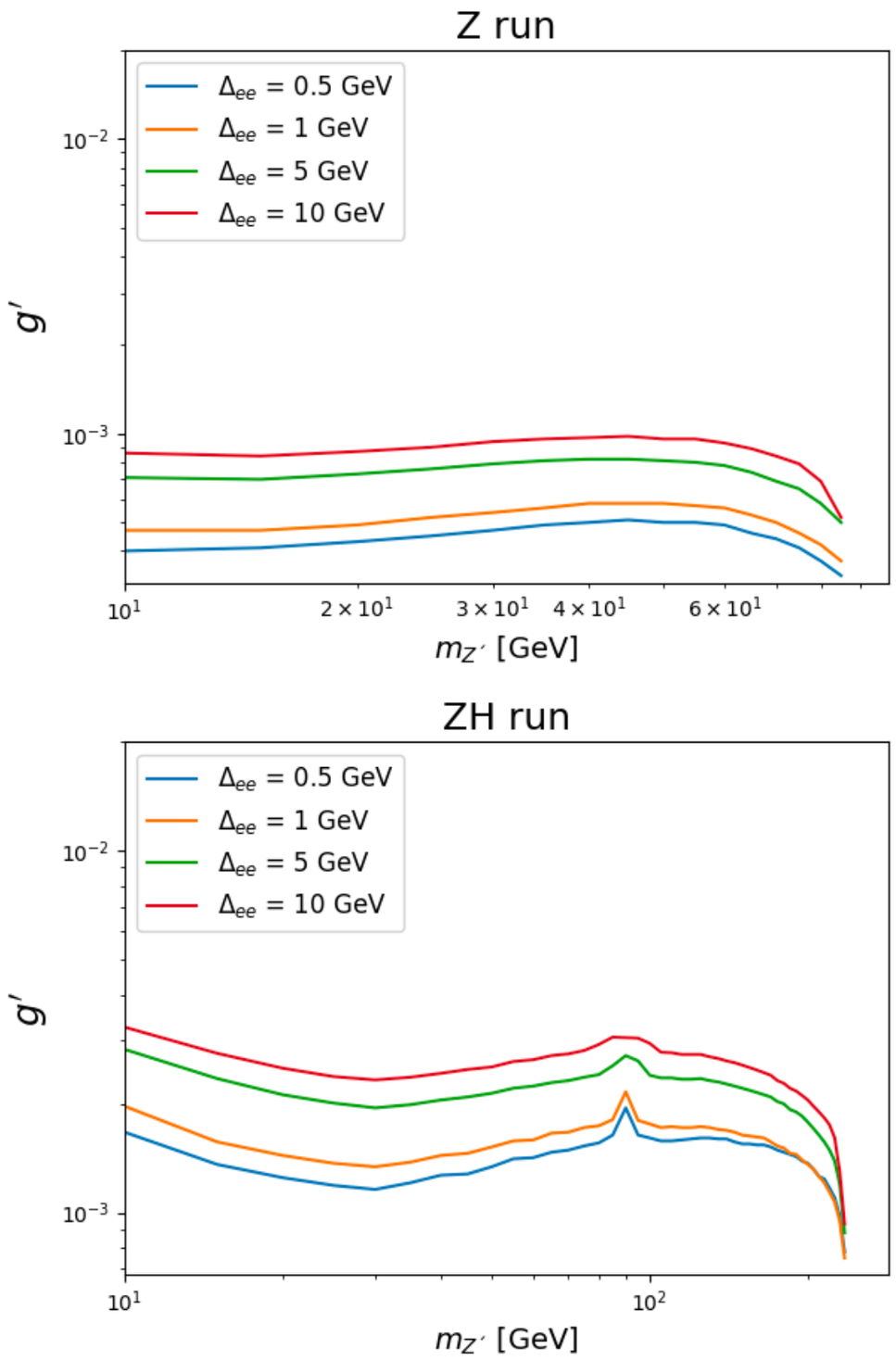
$\Delta_{ll} = 5$ GeV

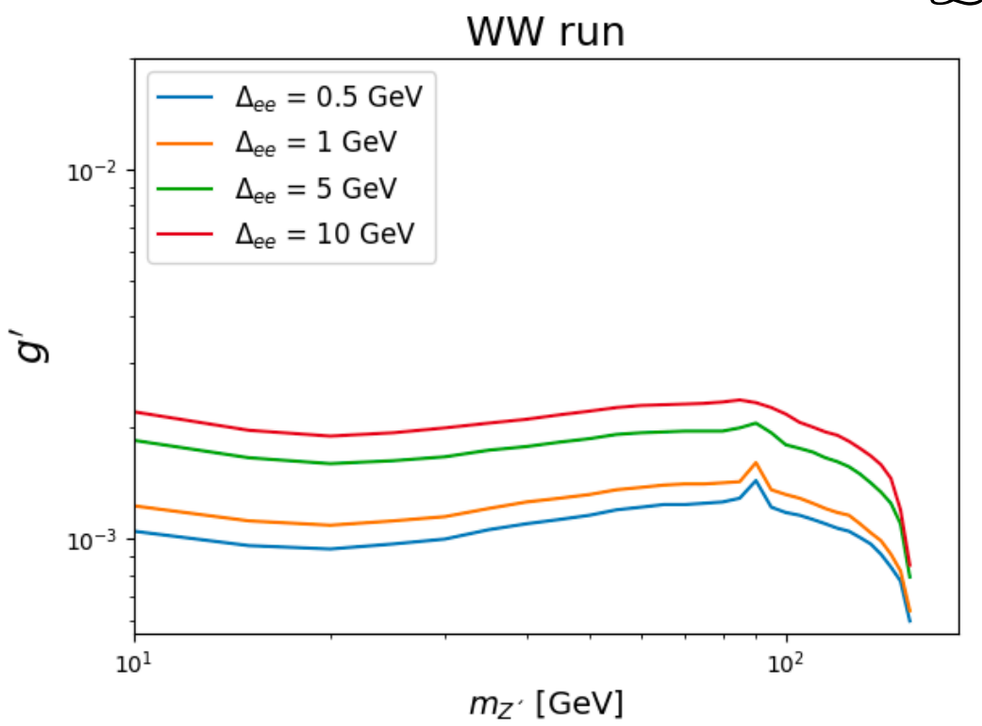
$\Delta_\gamma = 5$ GeV

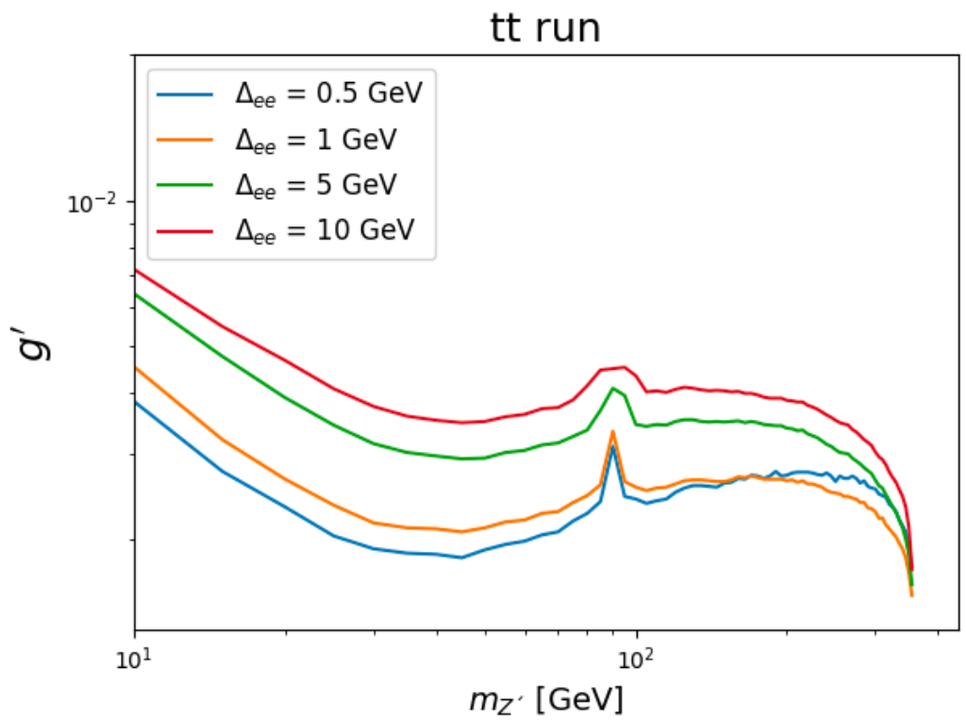
Variations on mass window

$$e^+e^- \to e^+e^-\gamma$$

$$\mathcal{Z} = 2$$



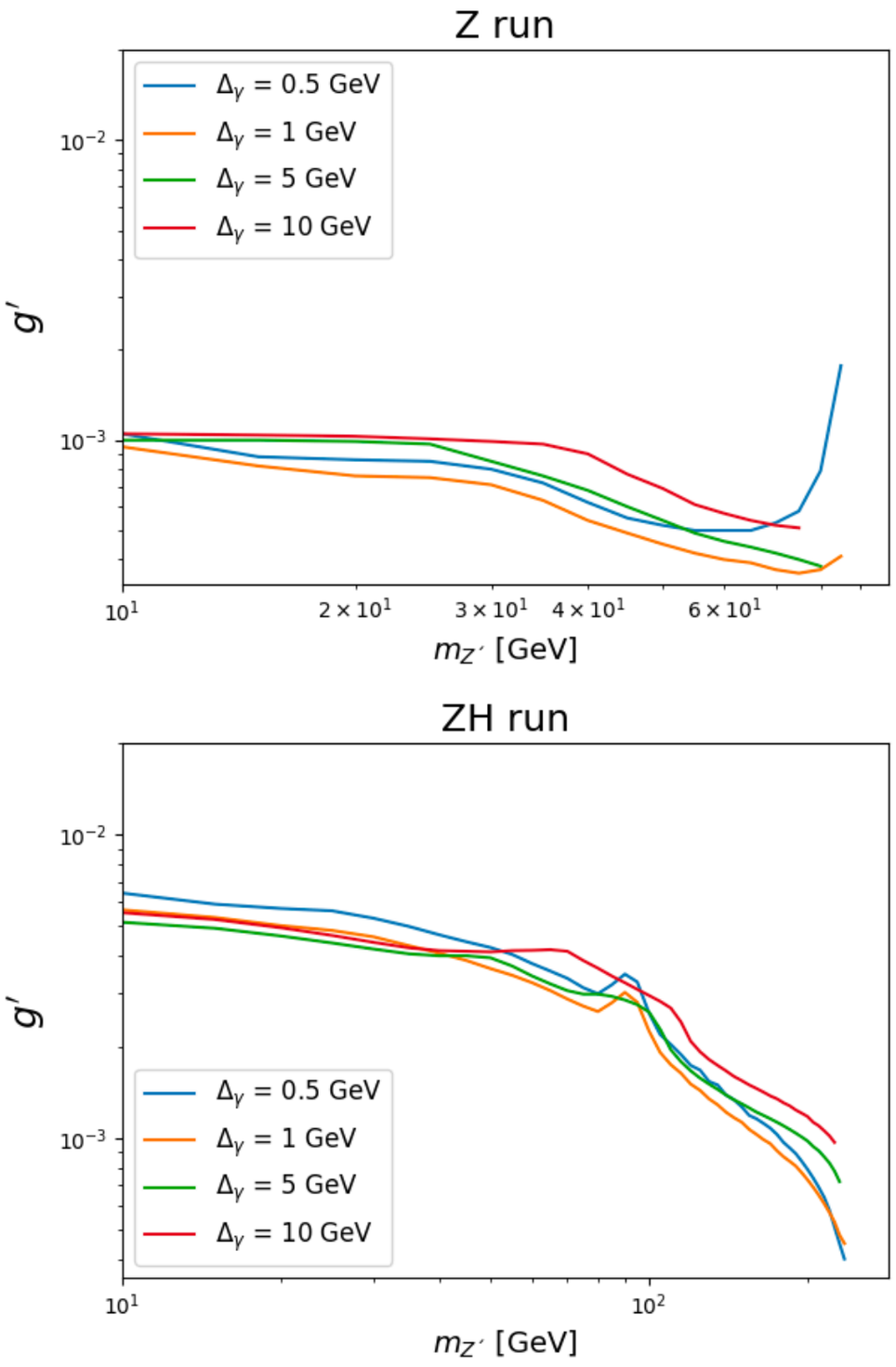


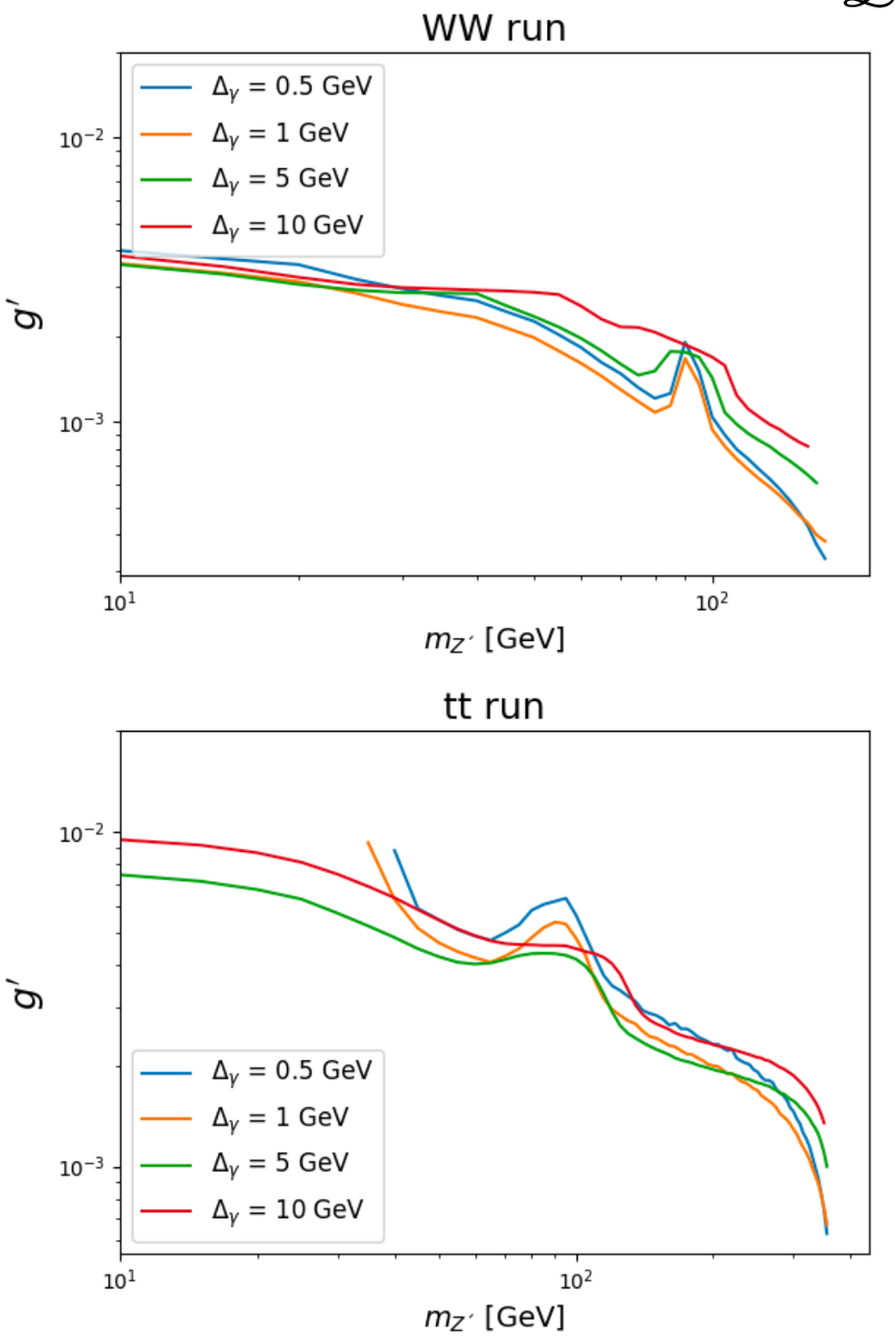


Variations on energy window

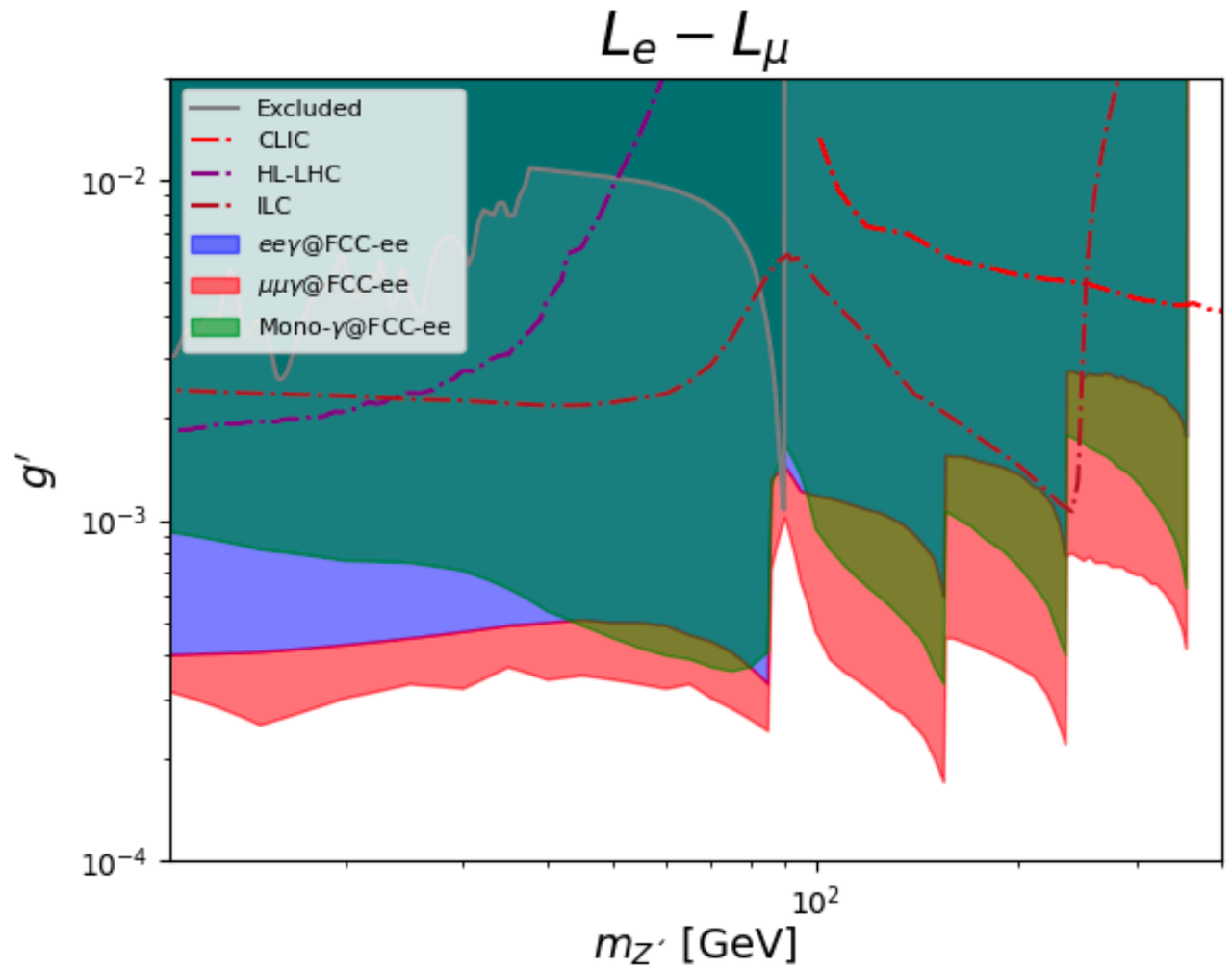
$$e^+e^- \to \nu\nu\gamma$$

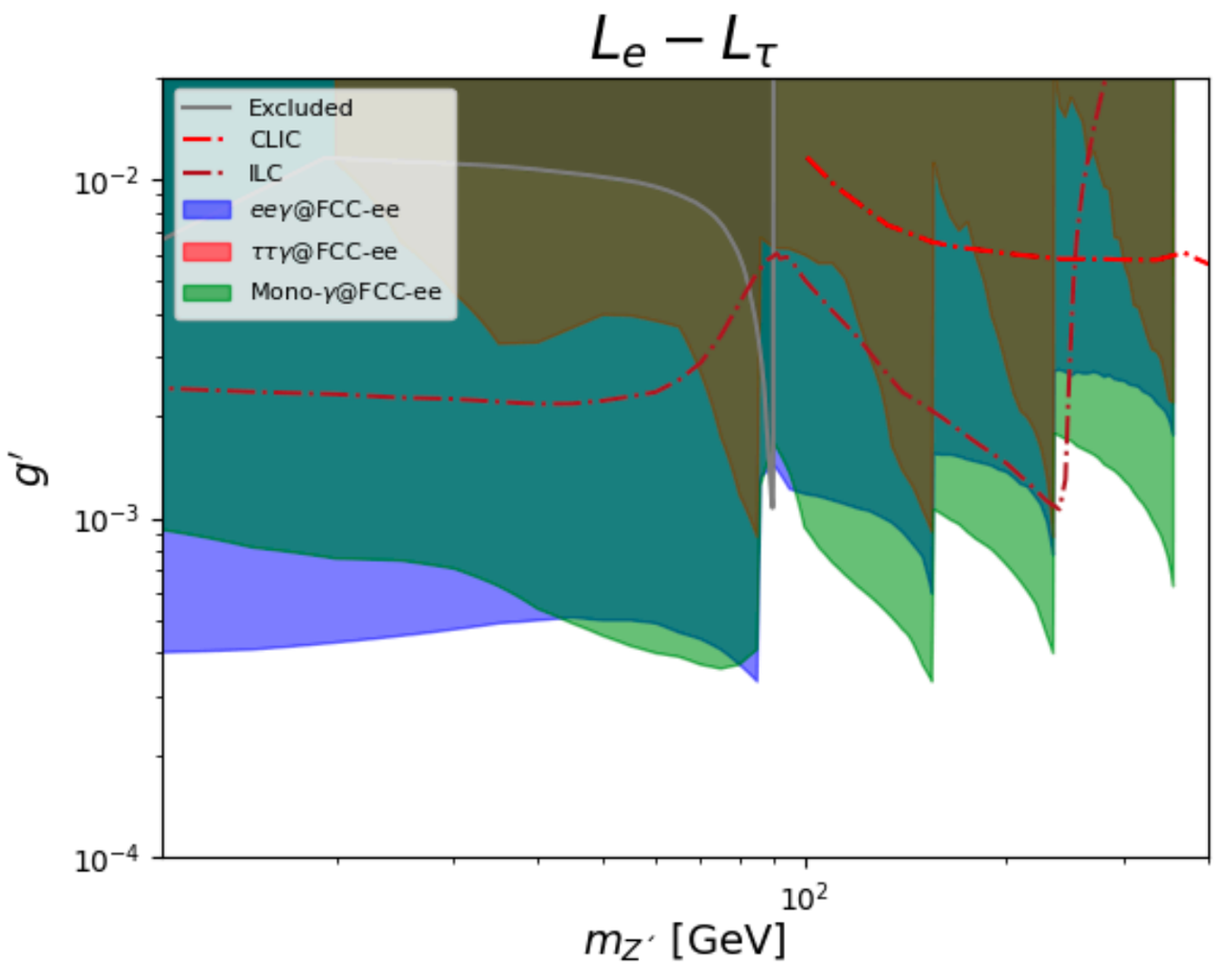
$$\mathcal{Z} = 2$$





Limits



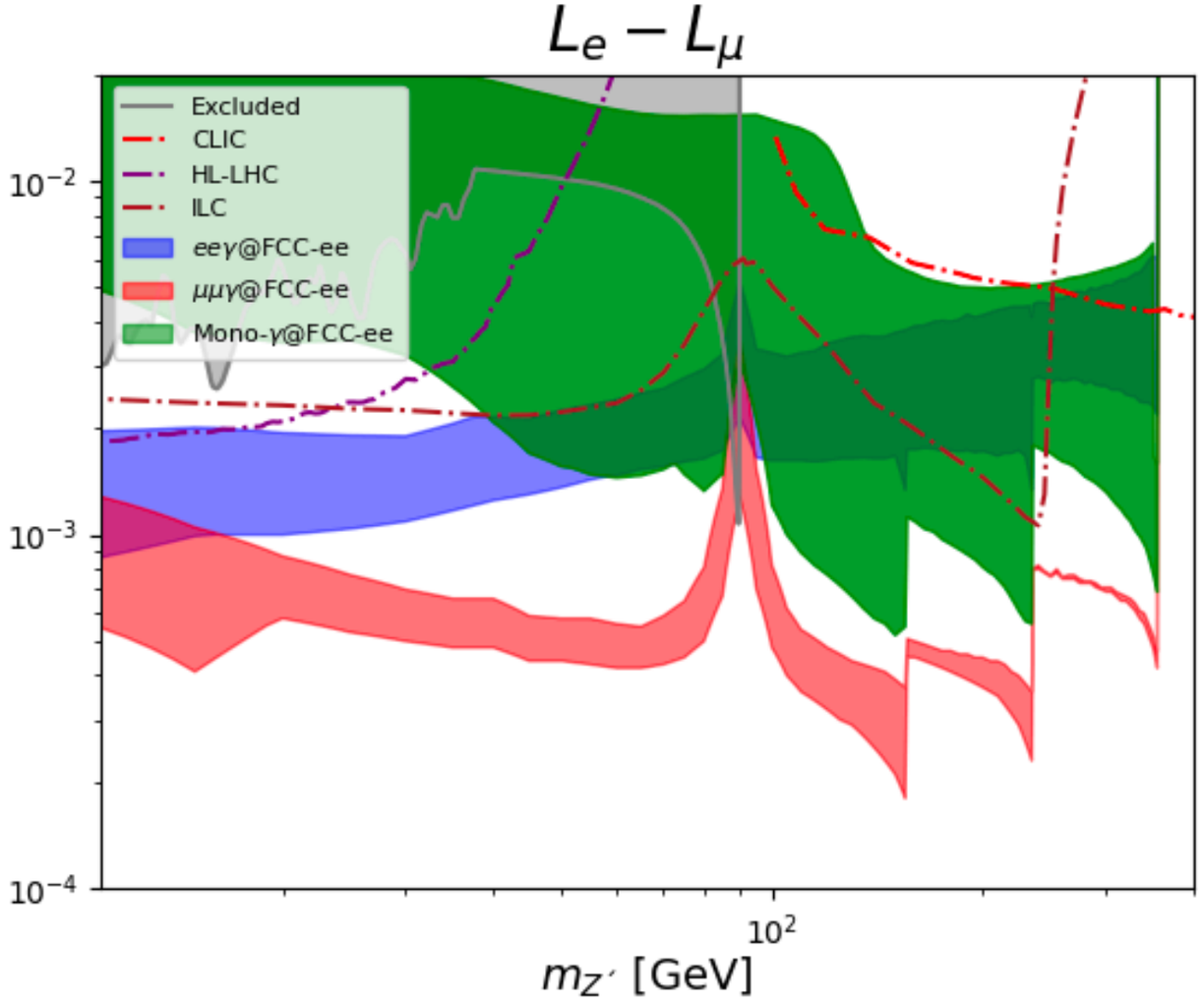


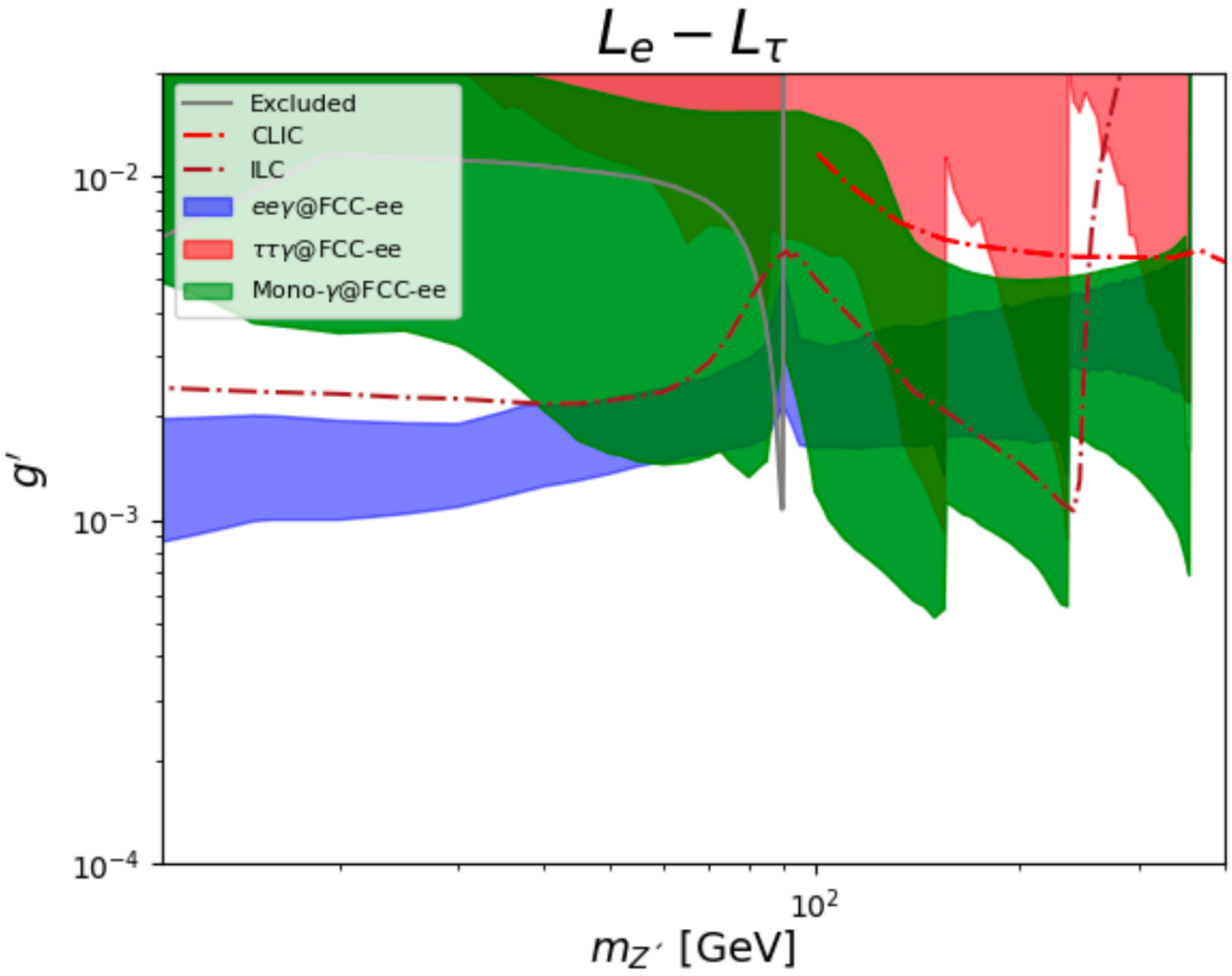
-Large impact of Δ_{ll} variation (4x improvement in g' exclusion with slimmer window).

-No large impact of E_γ resolution.

-Limits on g' of few x 10^{-4} achieved (for Z-pole run), up to tt-run limits better than those expected from ILC, CLIC. No systematics included [optimistic].

Systematics





$\mathcal{Z} = 2$, $\lambda \in [0.1 - 1]\,\%$. Using cuts optimised for λ=0.

g’ <= few x 10^{-3} (for Z-pole run), yet sensitivity often better than a factor of two with respect to other competitors in most of Z’ mass range.

Outlook

- FCC-ee has the upper hand when looking for leptophilic Z' models in the 10-365 GeV range (not only over LHC, but also over more energetic lepton colliders!).
- Our study informs how the reconstruction capabilities (notably di-lepton invariant masses, photon energy thresholds) impact on the expected limits.
- All in all, extend limits on new coupling from $O(10^{-2})$ to $O(10^{-4})$ exclusion!
- Z'-leptophilic could be a portal to dark matter -> future plans!
- This is a nice example of a wider class of models, a similar study can apply to e.g. light leptophilic scalars.