Leptophilic Z′ bosons at the FCC-ee

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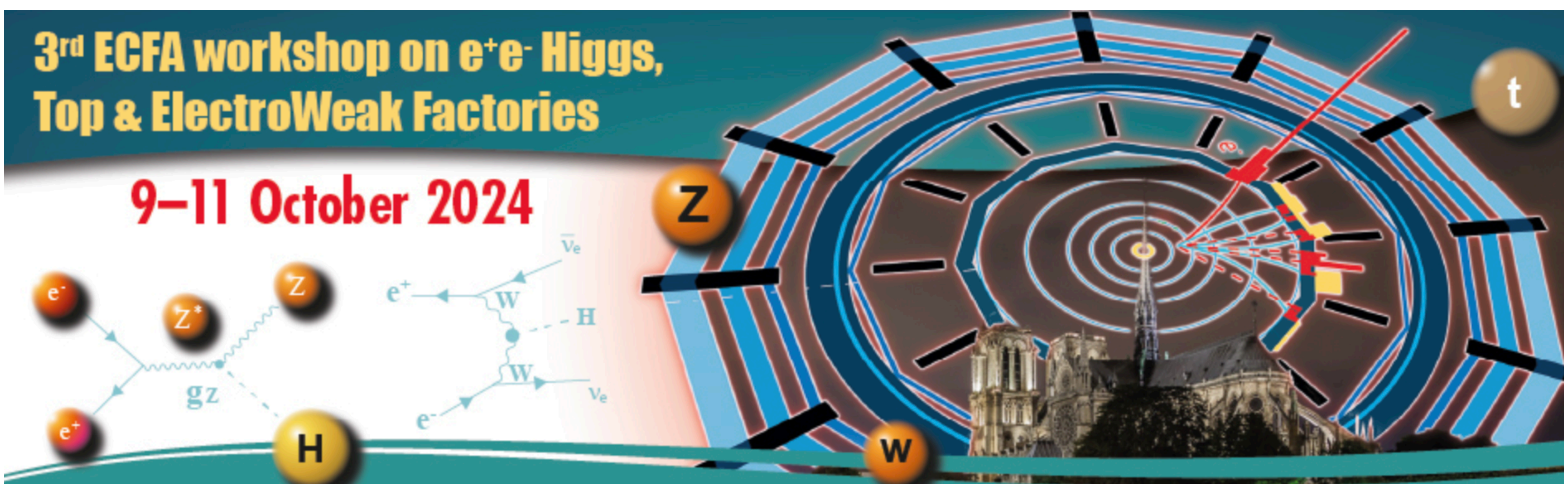
Based on: R. Gonzalez Suarez, B. Pattnaik, J. Zurita, arXiv 2410.vsoon



3rd ECFA workshop on e+ e- Higgs,Top and Electroweak Factories, 9-11 October 2024

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 $(g-2)_\mu$ and the R_K anomalies…]

Li-Lj models

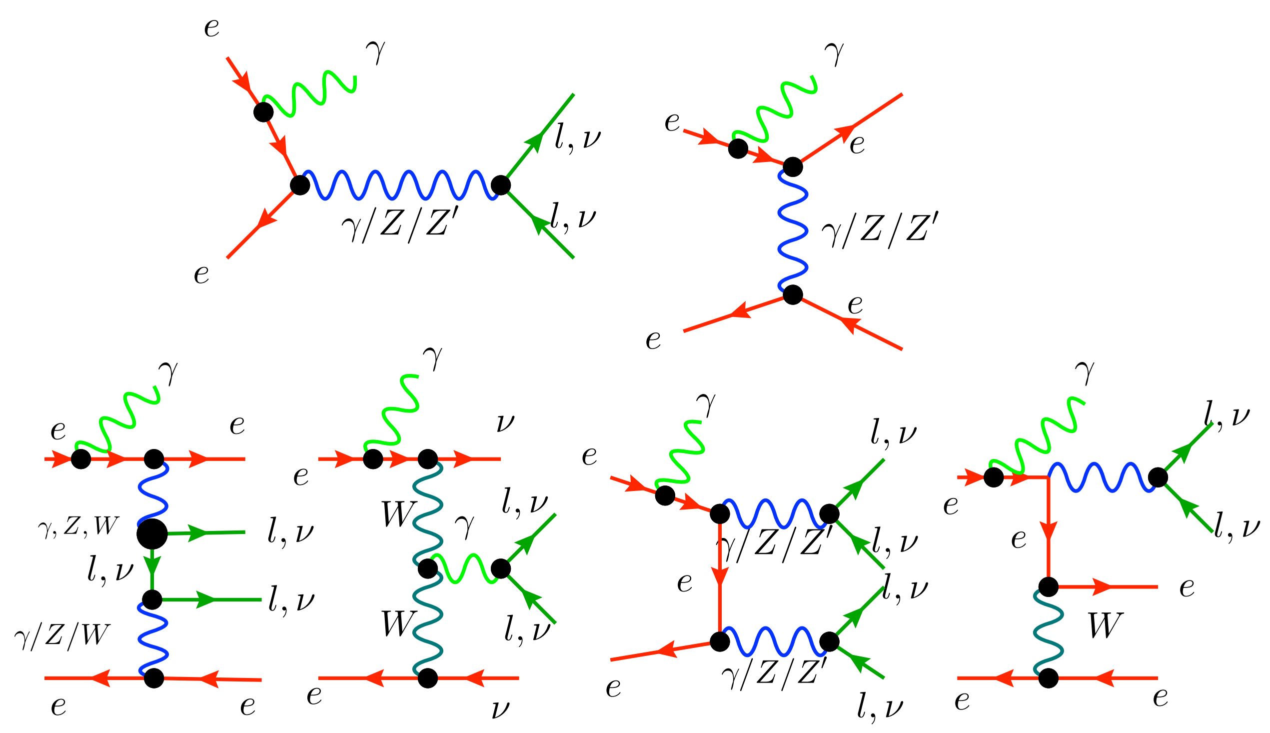
- We consider Le-Lτ and Le-Lμ models, to have tree level couplings eeZ′.

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

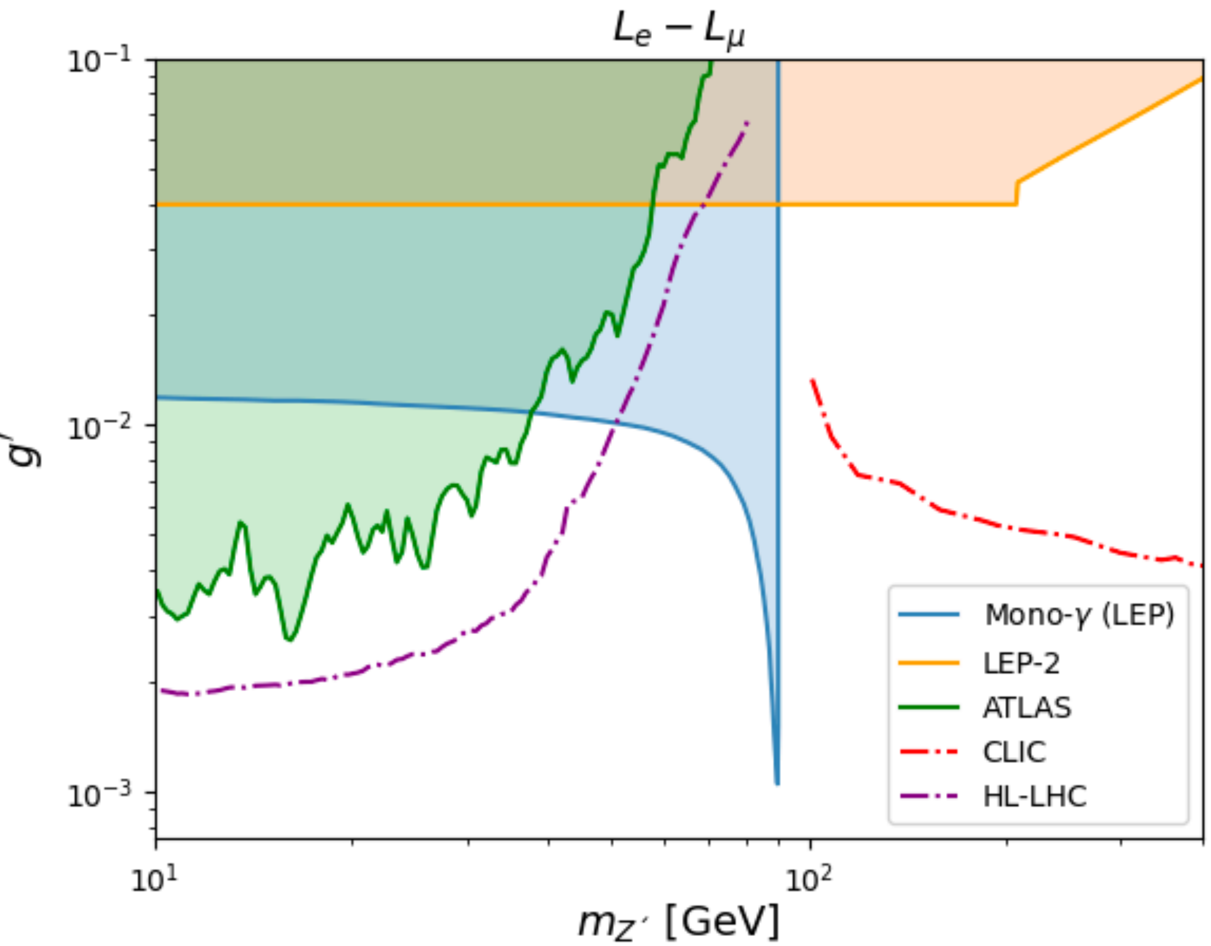
- Simple model, only two free parameters: $g', m_{Z'}$

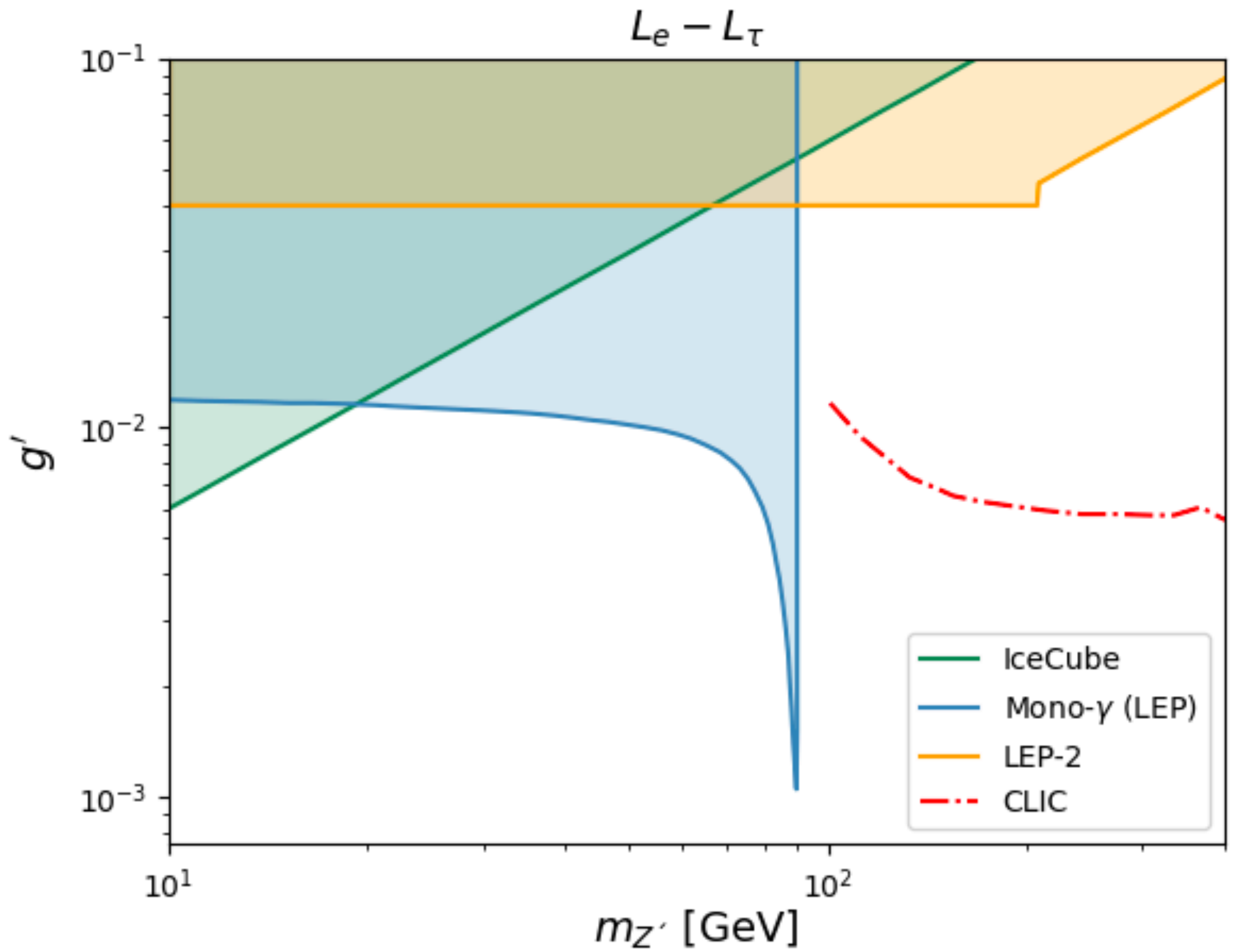
- Kinetic mixing ignored here: loop induced and $(m_l/m_{Z'})^2$ suppressed.

- Studied for 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, $e^+e^- \to e^+e^-$).
- LHCL 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 CLIC and/or MuC.

Pipeline

- MG5_aMC@NLO + Pythia 8 +Delphes, with IDEA card.
- Selection cuts (aligned with IDEA thresholds)
  - $e, \mu : p_T > 0.5$ GeV, $|\eta| \leq 2.5$, ΔR(l, X) > 0.5.
  - $\gamma : E > 2$GeV, $\mathrm{p_T} > 0.5$ GeV, $|\eta| \leq 3.0$, ΔR(γ, X) > 0.5.
  - $\tau : p_T > 1$ GeV, $|\eta| \leq 3.0$, ΔR(τ, 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: $X = l^+l^-l^+l^-, l^+l^-\nu\nu, \nu\nu\nu\nu$.

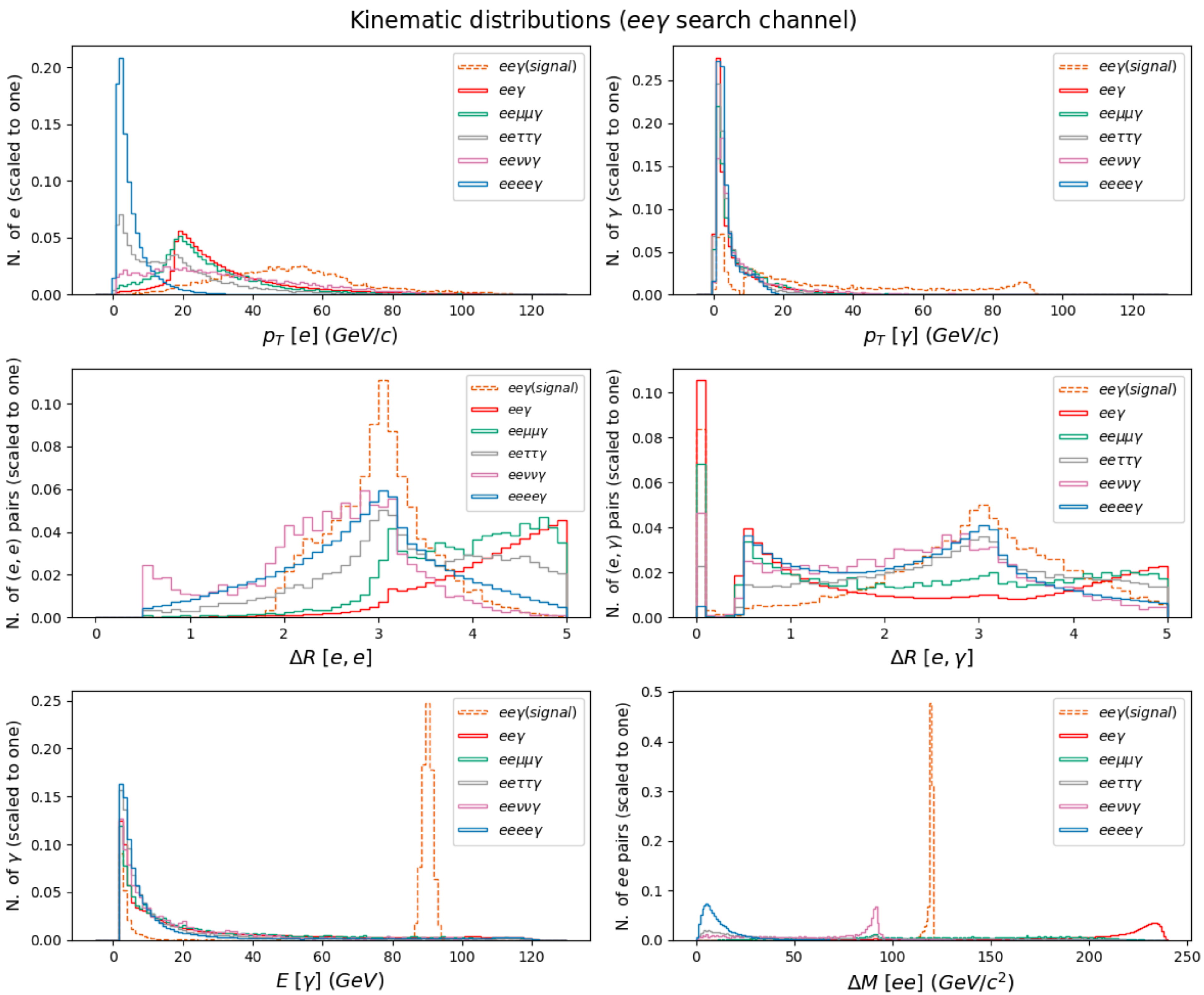
Run Name	E_{beam} [GeV]	$\int \mathcal{L}$ [ab^{-1}]
Z	45.6	205
WW	80	10
ZH	120	7.2
$t\bar{t}$	182.5	2.68

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).

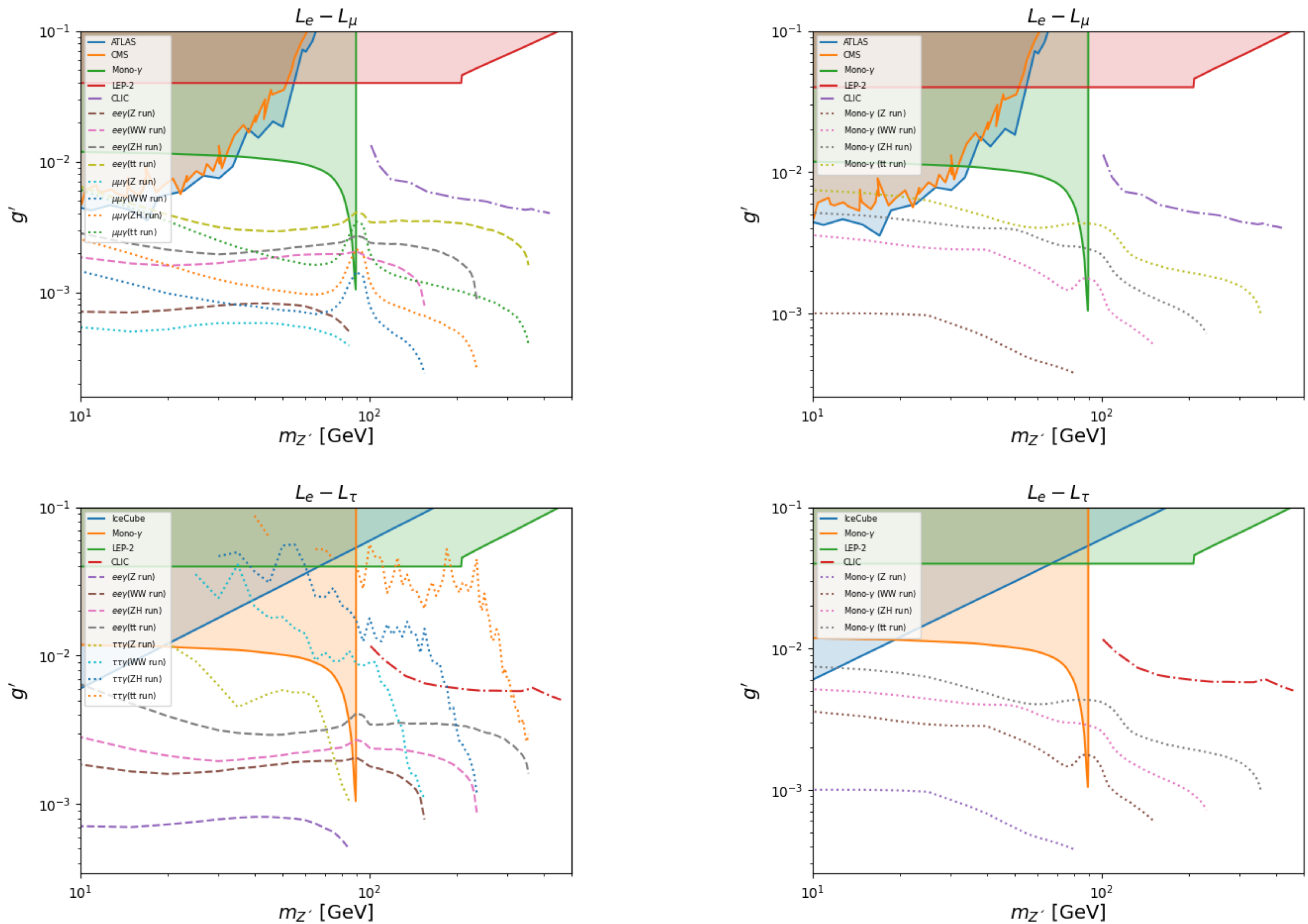
Process $e^+e^- \to \gamma + \ldots$	N_{ev}, Z run	N_{ev}, WW run	N_{ev}, ZH run	N_{ev}, $t\bar{t}$ run
$\mu\mu$	2.3×10^{10}	2.1×10^7	5.5×10^6	8.44×10^5
ee	8.63×10^{10}	1.26×10^9	4.5×10^8	7.9×10^7
$\tau\tau$	2.3×10^{10}	2.1×10^7	5.7×10^6	8.82×10^5
$\nu\nu$	2.2×10^9	5.9×10^7	3.3×10^7	1.35×10^7
$\mu\mu\mu\mu$	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

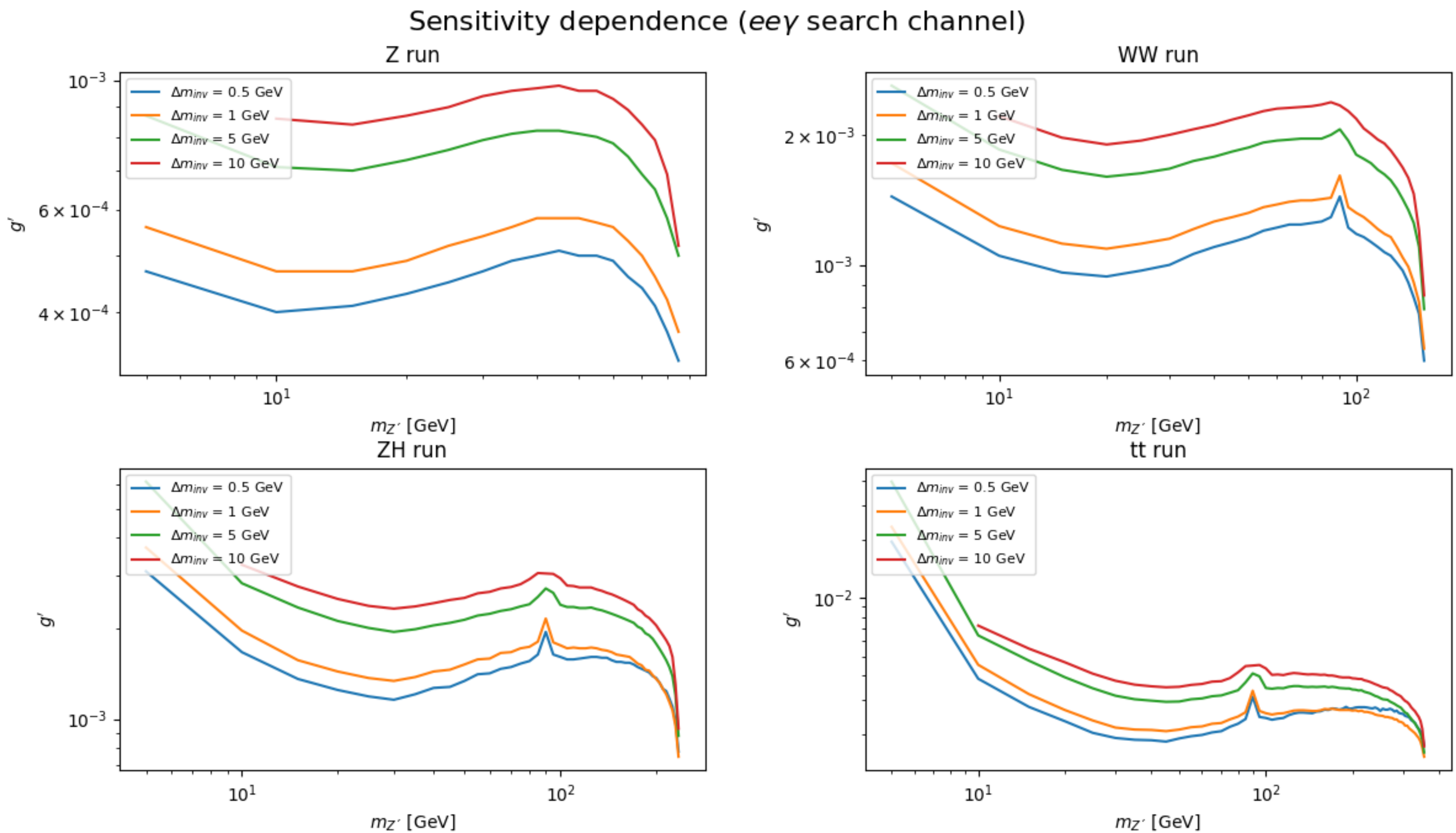


m_{ll} :sharp peak over a flat background, Eγ:broader peak. Vary | mll-mZ' | <Δ_{ll} .

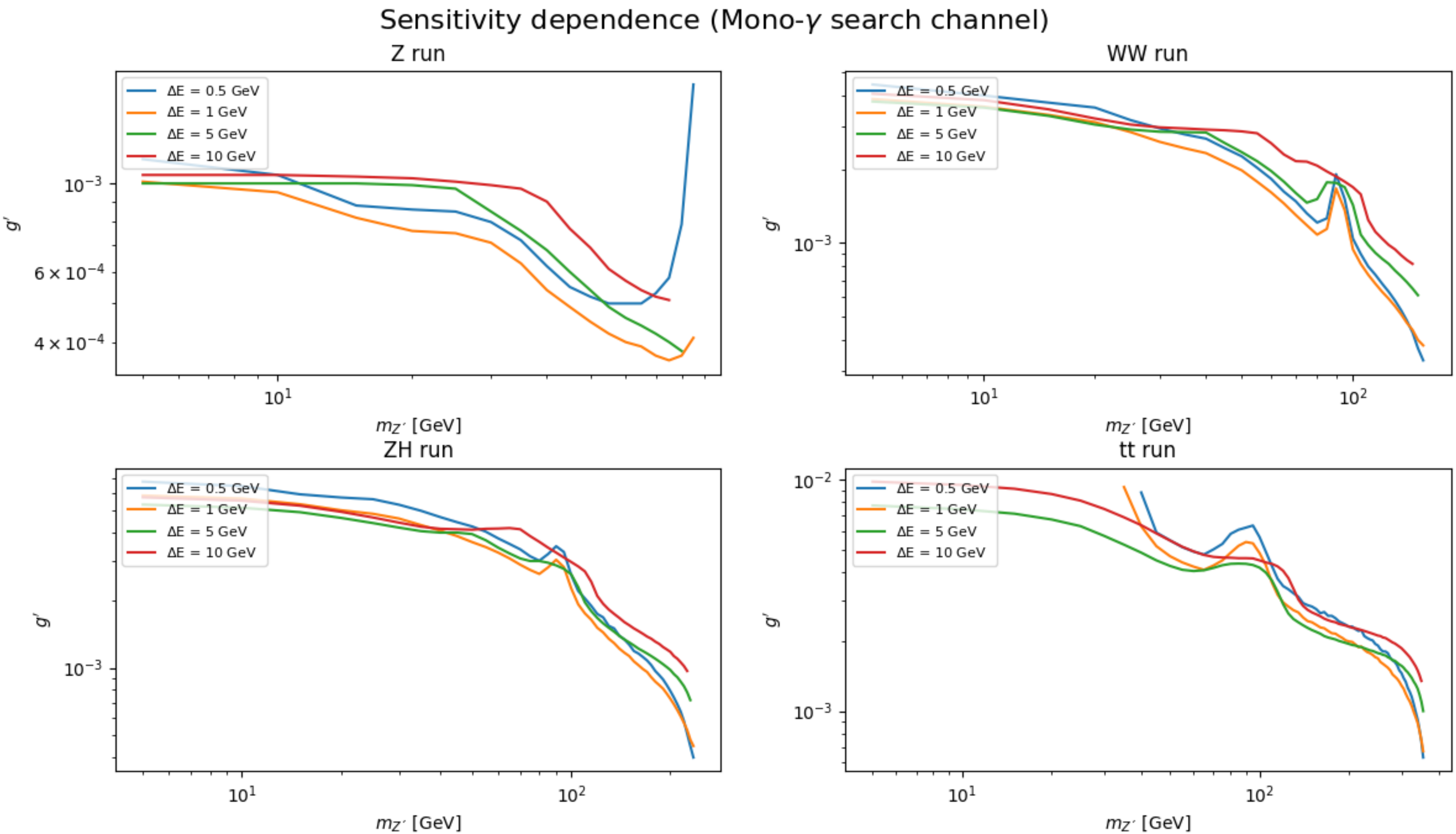
FCC-ee limits



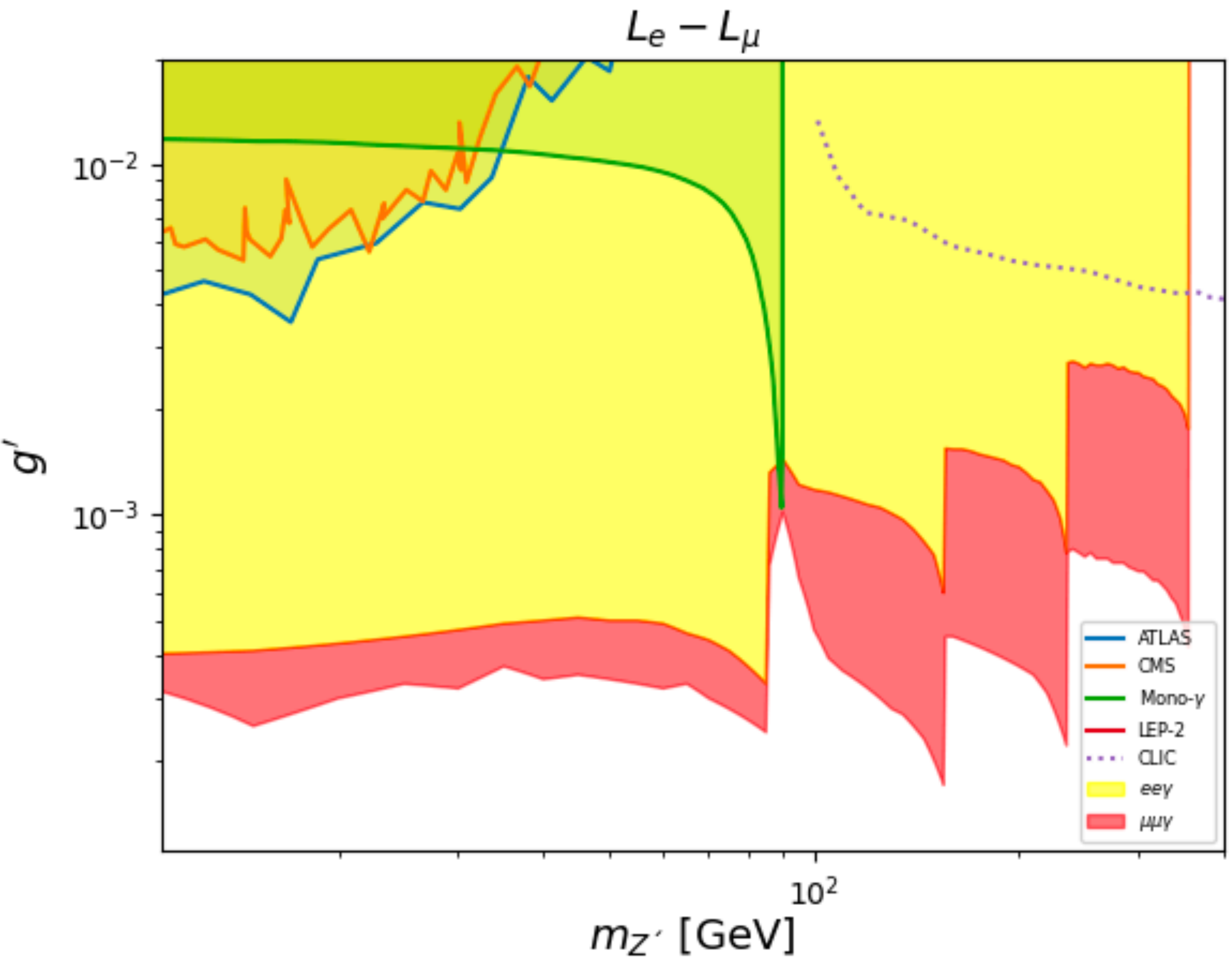
Variations on mass window

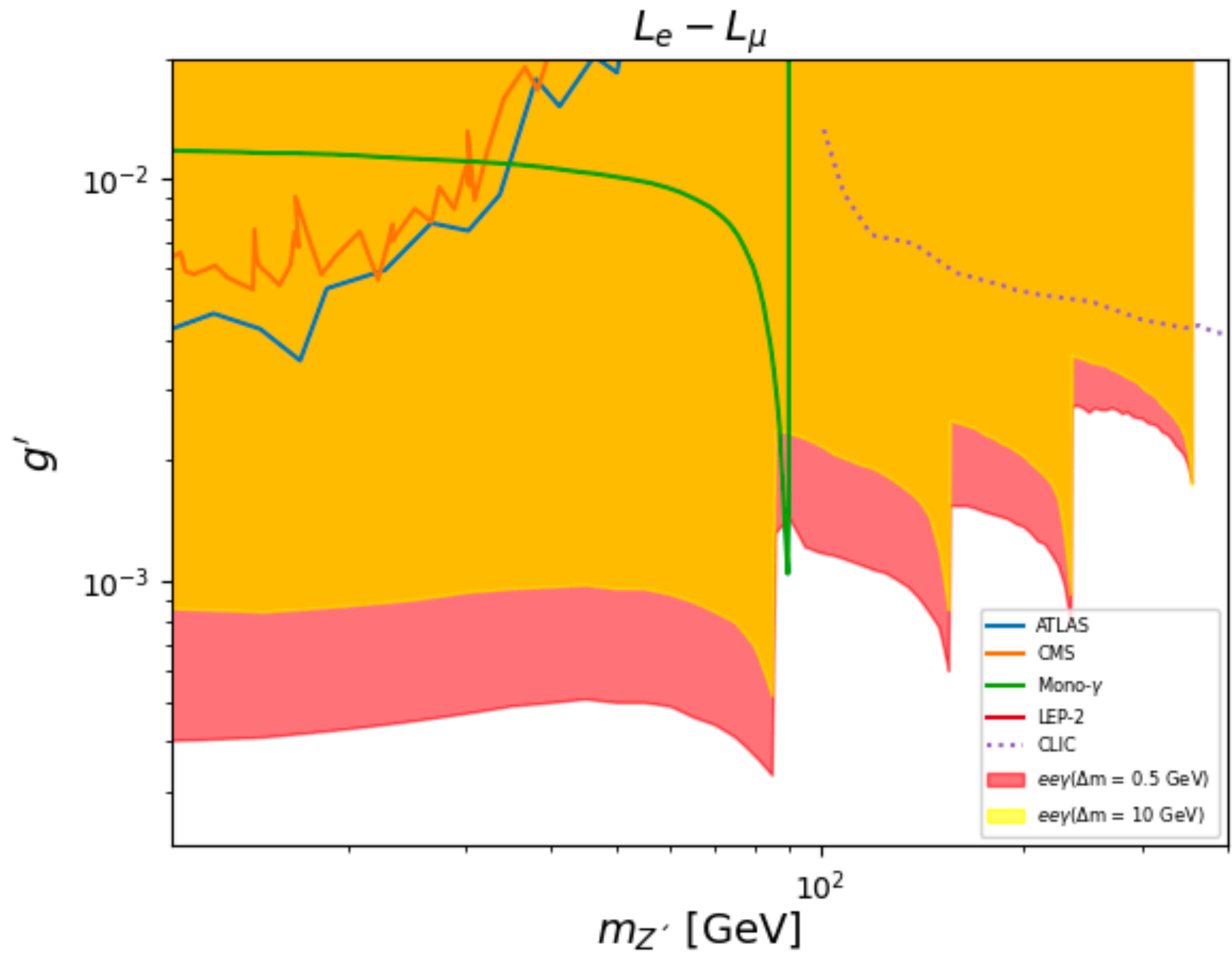


Variations on energy window



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 CLIC, MuC-3 [Dasgupta et al, 2308.12804]

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 CME 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 [see Cari Cessarotti's talk today]