Lepton Flavour Violation searches at FCC-ee

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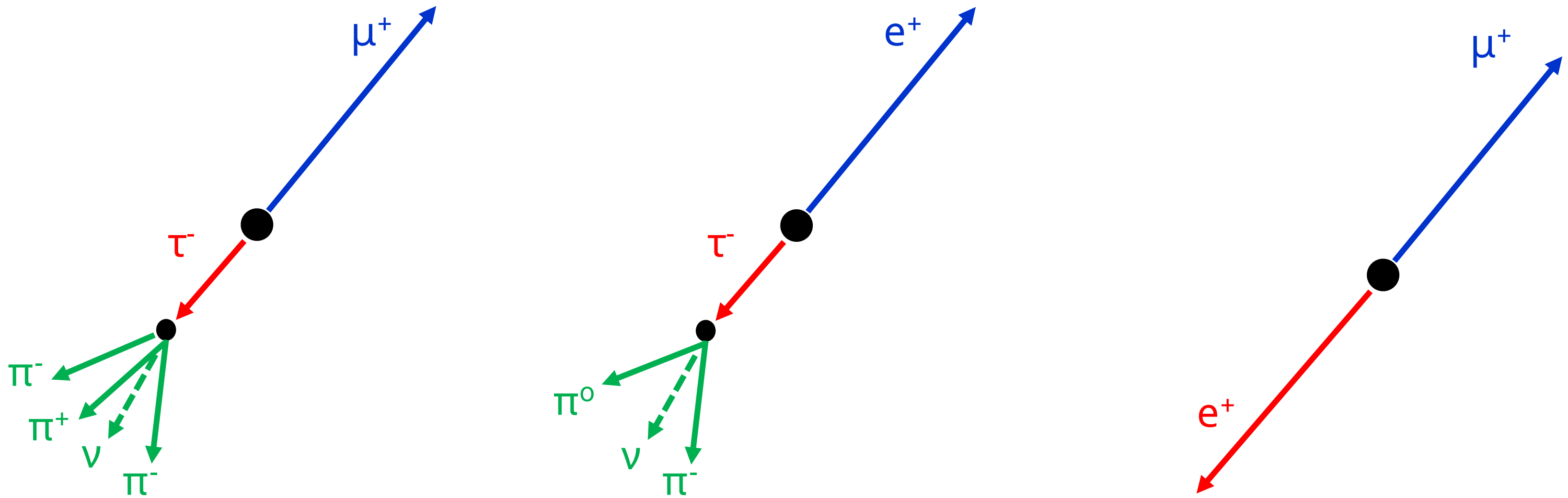
Updated to correct a few typos

Motivation and Outline

- FCC-ee will produce very large event samples. Interesting for rare decay searches, in particular those of **Lepton Flavour Violation**
  - **10^{12} Z decays** (possibly 10^{13})
  - Hence **6.7 x 10^{10} τ decays** (possibly 6.7 x 10^{11})
- Main motivation for this work
  - Identify **Detector Requirements** to make optimal use of FCC-ee sample for LFV

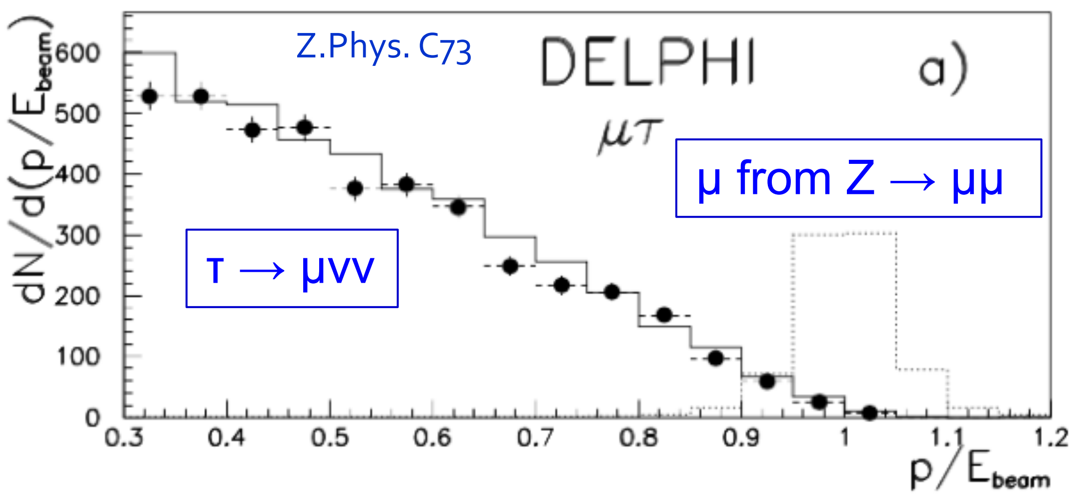
- Outline:
  - **Z decays**
    - A first study of Z → eτ, Z → μτ
    - Some thoughts of Z → eμ
  - **τ decays**
    - A first study of τ → eγ, τ → μγ
    - Some thoughts on $\tau^- \rightarrow l^- l^+ l^-$

LFV Z decays



$Z \to e\tau$ and $Z \to \mu\tau$

- Current limits:
  - **$Br(Z \to e\tau) < 9.8 \times 10^{-6}$** LEP/OPAL ($4 \times 10^6$ Z decays)
  - **$Br(Z \to \mu\tau) < 12. \times 10^{-6}$** LEP/DELPHI ($4 \times 10^6$ Z decays)
- Method:
  - Identify **clear tau decay** in one hemisphere
  - Look for **"beam-energy" lepton** (electron or muon) in other hemisphere
- Limitation: How to define "beam-energy" lepton
  - Unavoidable background from $\tau \to e\nu\nu$ / $\tau \to \mu\nu\nu$ with two (very) soft neutrinos
  - How much background depends on energy/momentum resolution
  - Example DELPHI

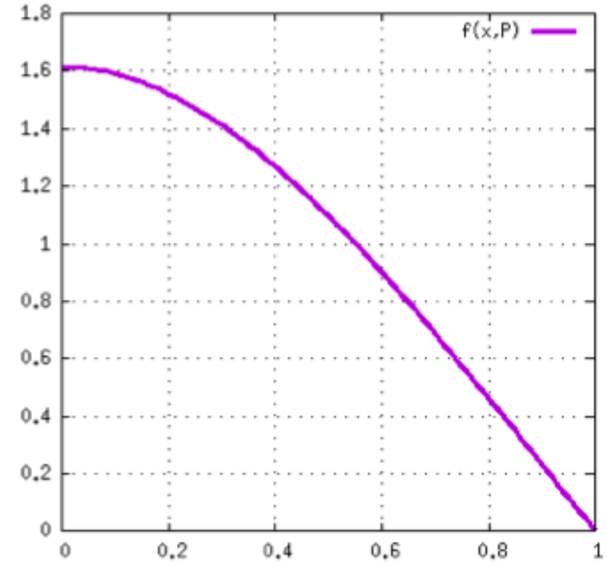


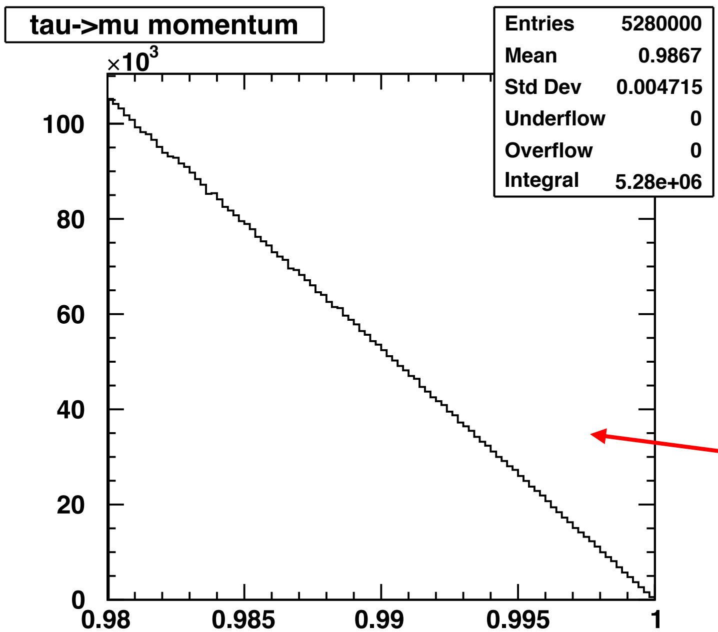
$\tau \longrightarrow \mu\nu\nu$ momentum spectrum

In terms of $x = p_\mu / p_{\mathrm{beam}}$

$$f(x) = \frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}x} = \frac{1}{3}\left[\left(5 - 9x^2 + 4x^3\right) + P\left(1 - 9x^2 + 8x^3\right)\right]$$

where *P* is tau polarisation.





Expand to first order in (*x*-1) around $x \simeq 1$

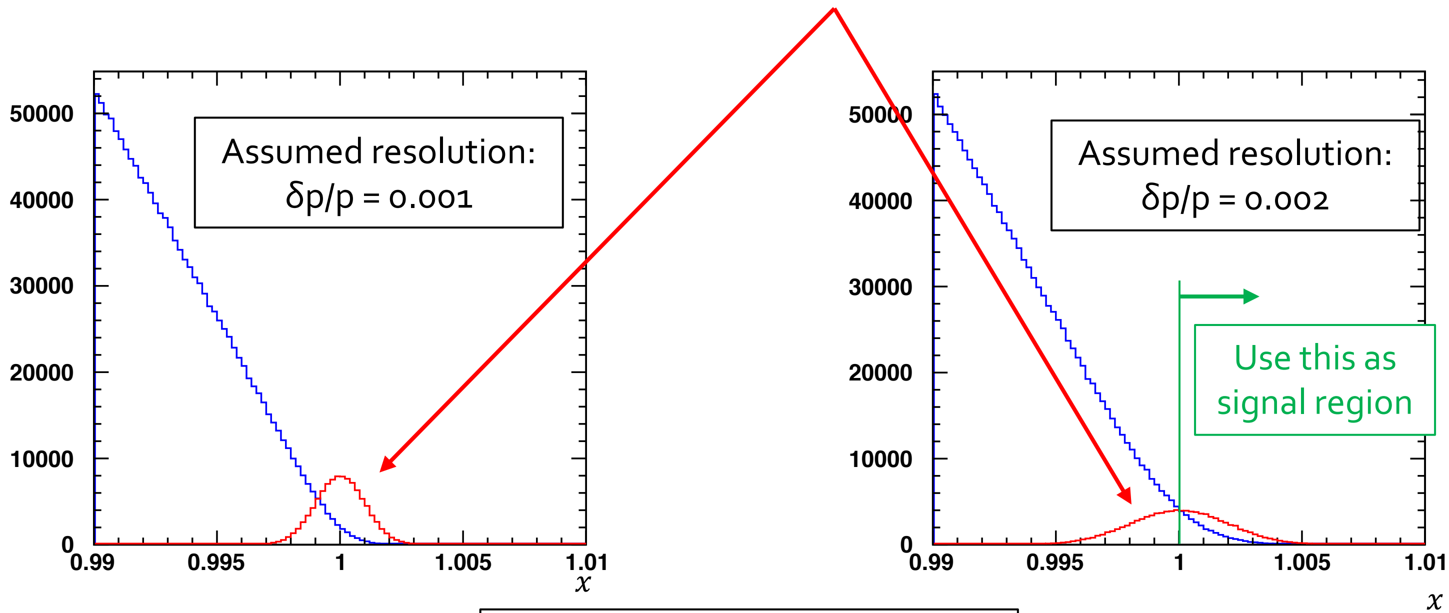
$$f(x) = 2[1 - P](1 - x) \simeq 2.3(1 - x)$$

for *P* = -0.15.

For 10^{12} Z decays, 5.3 x 10^6 muons with x>0.98

Insert signal and smear track momenta

- In these plots, assume **Br(Z → τμ) = 10^{-7}**, i.e. 100,000 muons



Here, 100% signal efficiency

Sensitivity to signal:

- Since number of background events is high, use primitive estimator: **s/√b**
- **s** and **b** are number of signal and background events, respectively, in **signal region**
  - For now, chose signal region as **x>1**
    - Close to optimal cut value
    - Eventually one will do more sophisticated statistical analysis, but for now…
- 95% c.l. corresponds approximately to number of signal events equal: $\mathbf{s_{95} = 2\sqrt{b}}$

Sensitivity estimate for 10^{12} Z decays

Before presenting estimate, have to make some assumption about signal and background efficiency (assumed to be the same).

Here assume ε = 25%.

Momentum resolution [10^{-3}]	#background events b	#signal events for 2σ excess s_{95}	Limit Br(Z→τμ) [10^{-9}]
0.5	420	41	0.33
1	1640	81	0.65
2	6550	162	1.3
4	26200	324	2.6

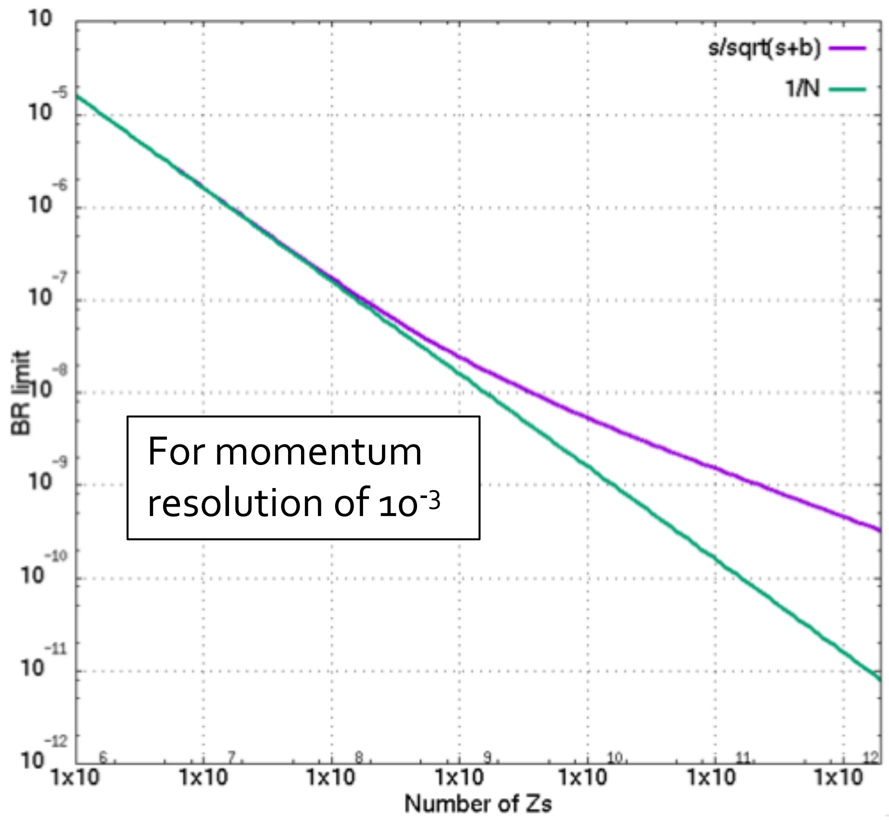
1×10^{-9}

- Observe, that limit scales linearly with momentum resolution:
  - With linearly falling momentum spectrum, b scales quadratic in resolution
  - Since limit depends on √b, limit is then linear in resolution

ILC detectors report $\sigma(p_T)/p_T = 2 \times 10^{-5}\, p_T \oplus 1 \times 10^{-3}$. Hence **$1.4 \times 10^{-3}$** at p = 45.6 GeV.
FCC-ee **beam energy spread** is about 0.5×10^{-3} at 45.6 GeV

Dependence on number of Zs

In general case, when number of background events can be small, use estimator of significance: **s/√(s+b)**

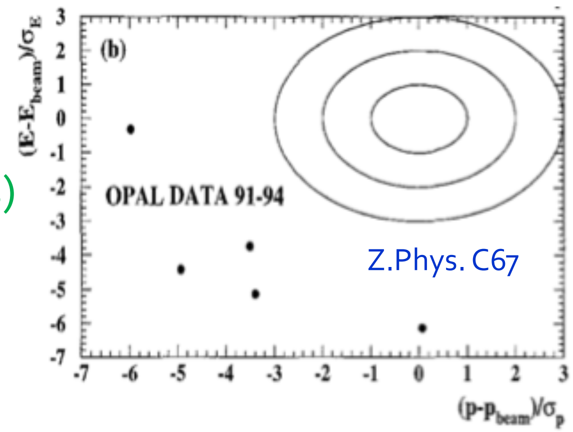


As for all searches, limit falls

- as 1/N as long as number of background events is negligible
- as 1/√N when number of background events is sizeable

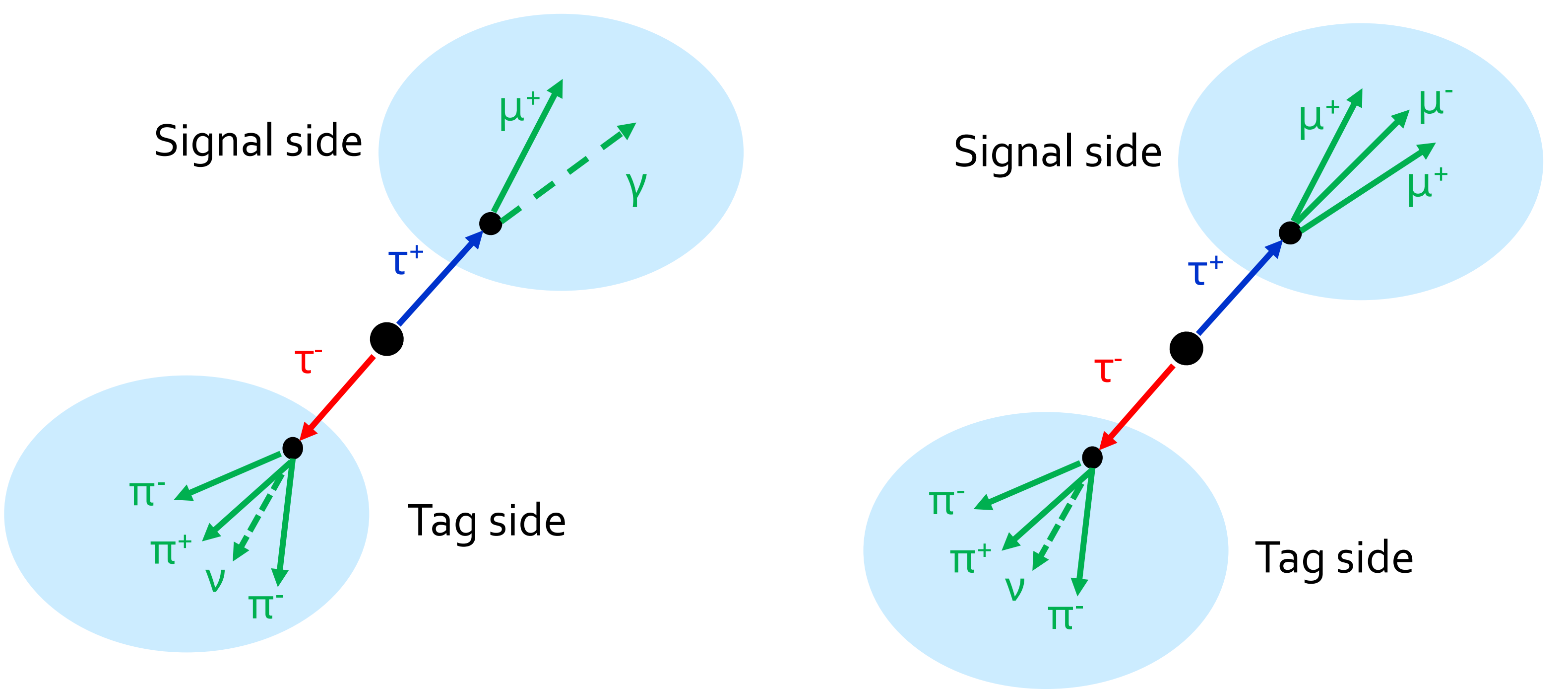
Z → eμ

- Current limit:
  - **7.5 x 10^{-7} LHC/ATLAS** (20 fb^{-1}; no candidates)
  - **1.7 x 10^{-6} LEP/OPAL** (4.0 x 10^{6} Z decays: no candidates)



- Clean experimental signature:
  - Beam energy electron vs. beam energy muon
- Main experimental challenge:
  - **Catastrophic bremsstrahlung energy loss** of muon in electromagnetic calorimeter
    - Muon would deposit (nearly) full energy in ECAL: Misidentification μ → e
    - NA62: Probability of muon to deposit more than 95% of energy in ECAL: **4 x 10^{-6}**
    - Possible to reduce by
      - ECAL longitudinal segmentation: Require energy > mip in first few radiation lengths
      - Aggressive veto on HCAL energy deposit and muon chamber hits
    - If dE/dx mesaurement available, some independent e/μ separation at 45.6 GeV
      - Could give handle to determine misidentification probability P(μ → e)
      - Notice: ATLAS uses transition radiation as part of electron ID.
- FCC-ee:
  - Misidentification from catastrophic energy loss corresponds to limit of about Br(Z →eμ) ≃ 10^{-7}
  - Possibly do O(10) better than that (?) **Br(Z →eμ) ~ 10^{-8}**

LFV τ decays



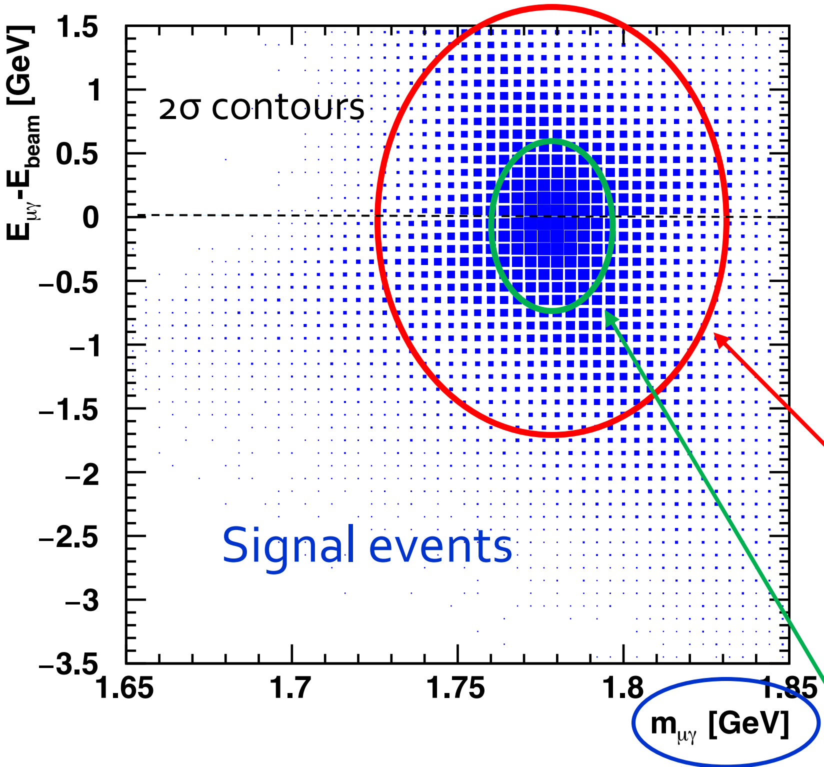
Signal side
μ+
γ
τ+
τ-
π-
π+
ν
π-
Tag side
Signal side
μ+
μ-
μ+
τ+
τ-
π-
π+
ν
π-
Tag side

$\tau^- \to e^-\gamma$, $\tau^- \to \mu^-\gamma$

- Current limits:
  - **$Br(\tau^- \to e^-\gamma) < 3.3 \times 10^{-8}$** BaBar, 10.6 GeV; 4.8×10^8 $e^+e^- \to \tau^+\tau^-$: 1.6 expected bckg
  - **$Br(\tau^- \to \mu^-\gamma) < 4.4 \times 10^{-8}$** 3.6 expected bckg
- Main background: Radiative events (IRS+FSR), $e^+e^- \to \tau^+\tau^-\gamma$
  - $\tau \to \mu\gamma$ faked by combination of γ from ISR/FSR and μ from $\tau \to \mu\nu$
- Prospects
  - Belle2 with similar resolution as BaBar will collect x100 statistics at SuperKEKb
  - Limits could reduce by factor 1/10, i.e.
    - $Br(\tau^- \to e^-\gamma) \simeq Br(\tau^- \to \mu^-\gamma) < 3 - 4 \times 10^{-9}$
- FCC-ee
  - With similar statistics as Belle2 (~ 5×10^{10} $\tau^+\tau^-$), what can be expected?
    - Perform simple study of signal and the main background, $e^+e^- \to \tau^+\tau^-\gamma$

$\tau \to \mu\gamma$ Study – The signal

- Generate **signal events** with pythia8: $e^+e^- \to Z \to \tau^+\tau^-(\gamma)$, with $\tau^- \to \mu^-\gamma$



Detector resolution **a la ILD** assumed:

- Muon momentum [GeV]
  $\sigma(p_T)/p_T = 2\times10^{-5} \times p_T \oplus 1\times10^{-3}$
- Photon ECAL energy [GeV]
  $\sigma(E)/E = 0.165/\sqrt{E} \oplus 0.010/E \oplus 0.011$
- Photon ECAL spatial
  $\sigma(x) = \sigma(y) = (6/E \oplus 2)$ mm

From here, determine **ILD-like** detector resolution for $\tau \to \mu\gamma$

$\sigma(m_{\gamma\mu}) = 26$ MeV; $\sigma(E_{\gamma\mu}) = 850$ MeV

For comparison, **BaBar** resolutions for this analysis are quoted to be

$\sigma(m_{\gamma\mu}) = 8.3$ MeV; $\sigma(E_{\gamma\mu}) = 42$ MeV

which when scaled to 45.6 GeV gives

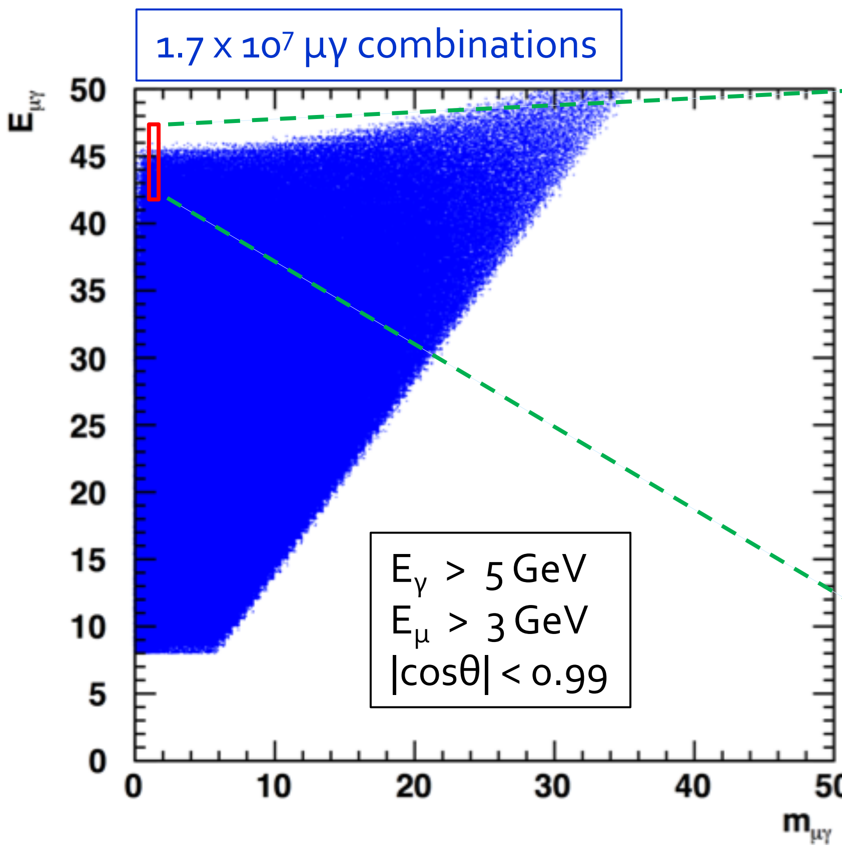
$\sigma(m_{\gamma\mu}) = 8.3$ MeV; $\sigma(E_{\gamma\mu}) = 360$ MeV

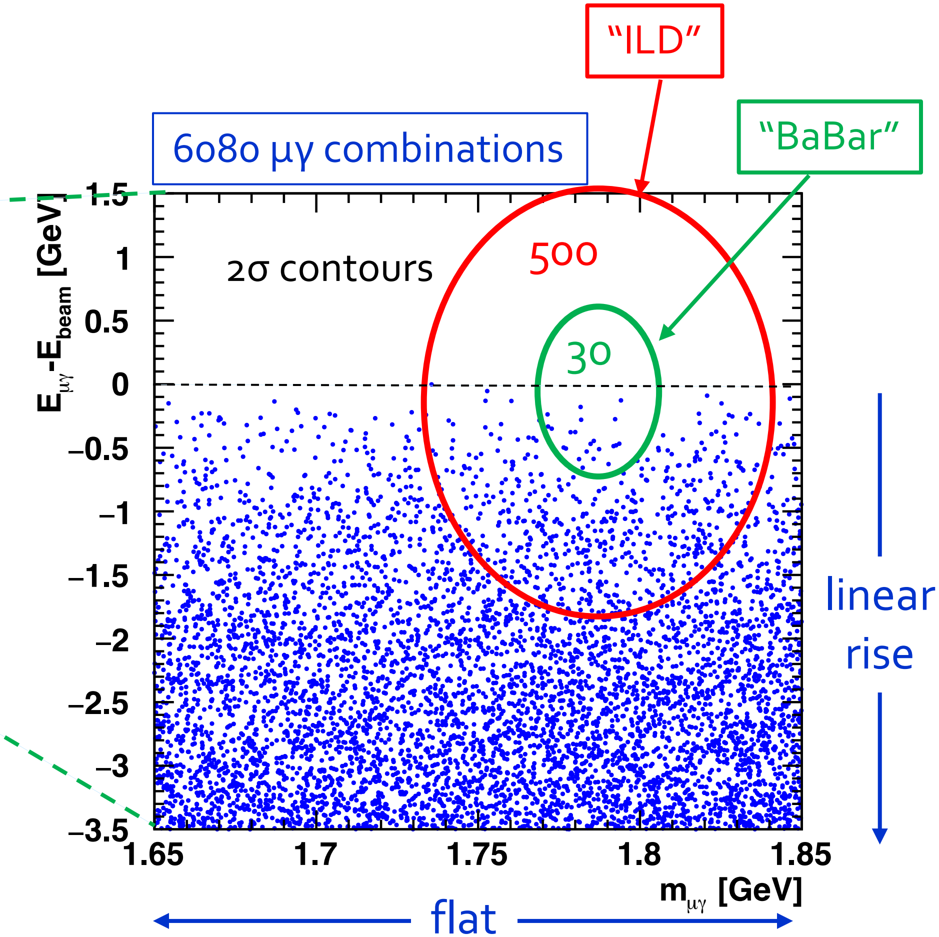
In order to de-correlate the E and m variables, this mass, $m_{\gamma\mu}$, is in fact the measured mass scaled by measured energy over beam energy:

$$m_{\gamma\mu} = m_{raw} \times (E_{\gamma\mu}/E_{beam})$$

$\tau \to \mu\gamma$ Study – The background

- Background: Generate 5×10^8 events $e^+e^- \to Z \to \tau^+\tau^-(\gamma) \to (\mu^+\nu\nu)(\mu^-\nu\nu)(\gamma)$
  - 1×10^9 $\tau \to \mu\nu\nu$ decays corresponding to
    - 5.7×10^9 τ decays from 8.4×10^{10} Z decays
- Study all μ and γ combinations



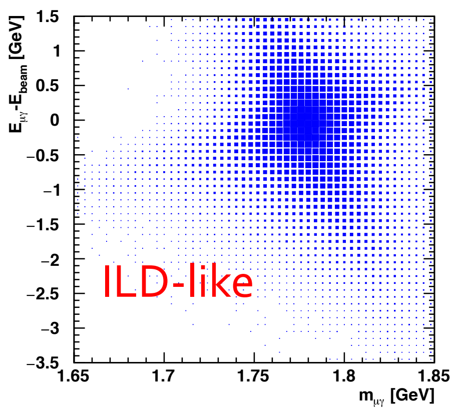


$\tau \to \mu\gamma$ Study (iii)

- Neglecting other background sources and assuming an overall selection efficiency of 8% these are the *lower bounds* on the Br limit which can be set
  - ILD-like resolution: 7.9×10^{-9}
  - BaBar-like resolution: 1.9×10^{-9}

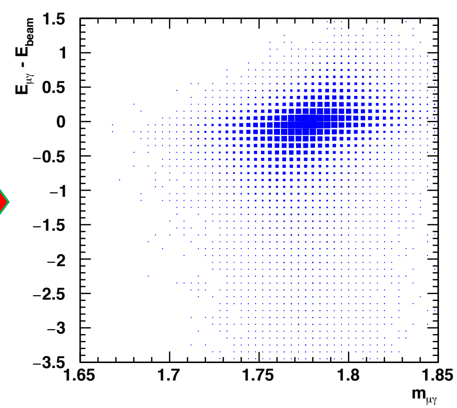
- Note
  - Background distribution is **flat in mass**
    - Background rises **linearly** with $\sigma_m \Rightarrow$ Limit decreases as $\sqrt{\sigma_m}$
  - Background distribution **rises linearly in energy** away from the signal at E_{beam}
    - Background rises **quadratically** with $\sigma_E \Rightarrow$ Limit decreases as σ_E
- Highest gain from improvement of energy measurement

Play a game



Same ECAL **anglar** resolution

BaBar-like flat 1.5% ECAL **energy** resolution



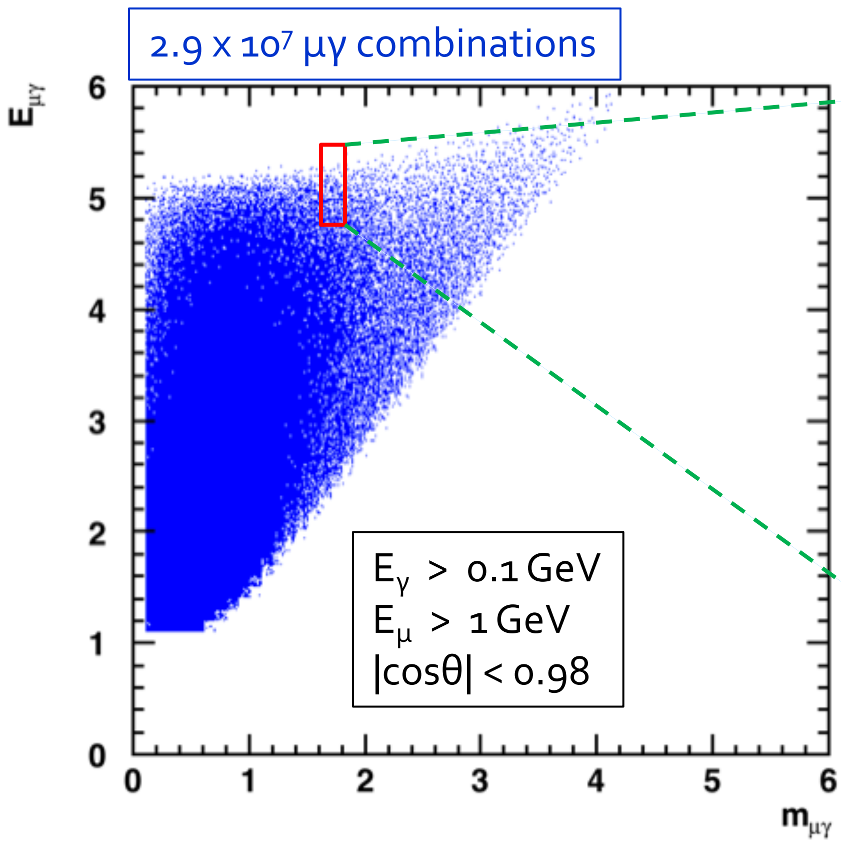
σ_m : 27 $\to$ 22 MeV
σ_E : 850 $\to$ 270 MeV

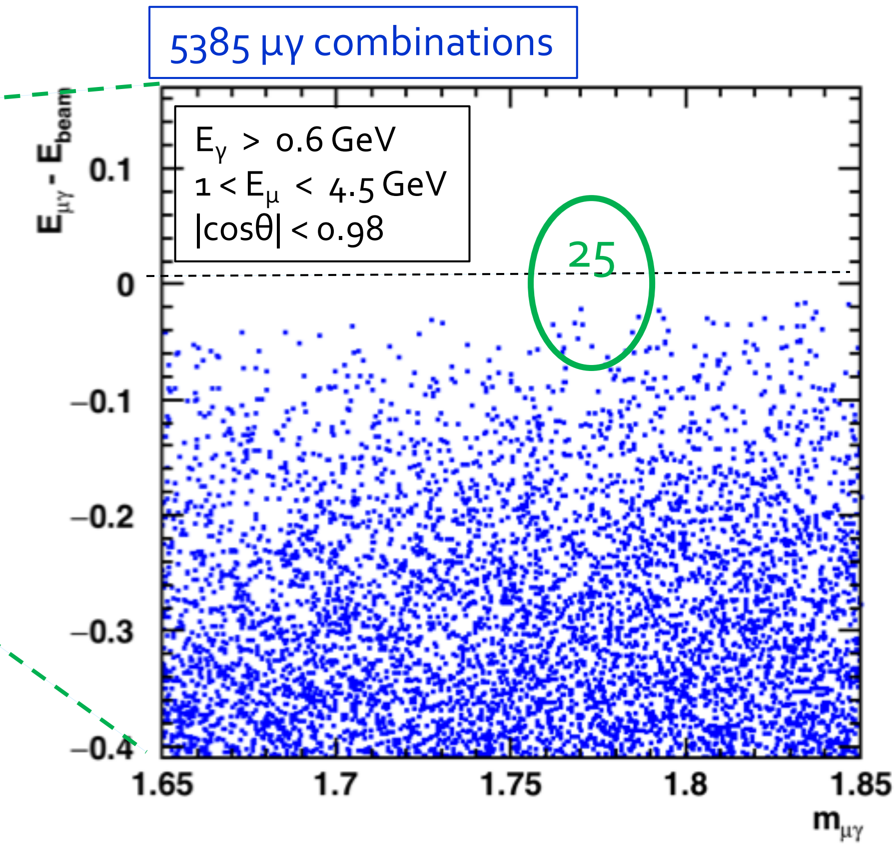
BR limit: 2.2×10^{-9}

$\tau \rightarrow \mu\gamma$ Study – Check of method

Cross check: Perform similar study at B-factory, $\sqrt{s}$ = 10.6 GeV

- Again 5 x 10^8 events $e^+e^- \rightarrow Z \rightarrow \tau^+\tau^-(\gamma) \rightarrow (\mu^+\nu\nu)(\mu^-\nu\nu)(\gamma)$





From this study, estimated limit: **1.9×10^{-9}**

Compare to my extrapolation of current BaBar limit: ~3-4 x 10^{-9}

Agrees within a factor 2
Not too bad

$\tau \rightarrow \mu\gamma$ Study – Rounding off

- Rounding off
  - Both facilities, FCC-ee and SuperKEKb, will produce ~ 5×10^{10} τ decays
  - Despite factor ~10 difference in collision energies, this study indicates that the two facilities could provide comparable limits on $\tau \rightarrow \mu\gamma$
    - Limits are of the order few x 10^{-9}, i.e. a factor 10 below current
  - The potential to set limits depend critically on detector resolution, in particular the ECAL resolution for photons
    - Energy resolution
      - Showed factor 4 improvement on limit going from 16.5%/√E to 1.5% flat
    - Spatial resolution
      - Typical **opening angle** between μ and γ in $\tau \rightarrow \mu\gamma$ is **70 mrad**; i.e. **140 mm** at ECAL surface. Need resolution at few mm level for mass resolution.

$\tau^- \rightarrow l^- l^+ l^-$

- Current limits:
  - All 6 combs. of $e^\pm$, $\mu^\pm$: $Br \lesssim 2 \times 10^{-8}$ Belle@10.6 GeV; 7.2×10^8 $e^+e^- \rightarrow \tau^+\tau^-$: no cand.
  - $\mu^-\mu^+\mu^-$: $Br < 4.6 \times 10^{-8}$ LHCb 2.0 fb^{-1} : background candidates
- Prospects
  - LHCb @ HL-LHC
    - Expect up to 1000 times higher integrated luminosity
    - Current search has backgrounds: Limit scales as $1/\sqrt{L}$
      - Possibly reach limit of order 2×10^{-9}
  - Belle2 @ SuperKEKB
    - Collect 50 ab^{-1} $\Rightarrow$ 4.6×10^{10} $\tau^+\tau^-$ pairs (x 64 wrt Belle1)
    - With current selection, will have 0.5-10 background events depending on channel
      - Limits will not continue to scale linear in 1/luminosity.
      - Possibly reach limits of order $Br \lesssim 1 \times 10^{-9}$
  - 10^{12} Zs @ FCC-ee
    - Similar statistics as Belle2: 3.4×10^{10} $\tau^+\tau^-$ pairs
    - No obvious reasons for major differences in efficiencies & backgrounds wrt Belle
      - Reach limits similar to Belle2.

Conclusions

Strong tests of Lepton Flavour Violation can be made from the large FCC-ee data sample

Caveat: First look

- 10^{12} Z decays:
  - For decays **Z → eτ and Z → μτ**, BRs down to **10^{-9}** can be probed
    - The reach is limited by the irreducible background from Z → ττ, with one tau decaying to τ → eνν (τ → μνν): end-point of momentum spectrum
    - Limit scales proportional to the μ (e) **momentum resolution** at p=45.6 GeV.
  - For decays **Z → eμ**, BRs down to **10^{-8}** may be possibly probed
    - The reach is probably limited by catastropic energy loss of muons in ECAL
    - Some control via **longitudinal segmentation in ECAL** and **dE/dx particle ID**
- From 6.7 x 10^{10} τ decays FCC-ee will be able to set limits similar to Belle2 from its comparable data sample:
  - For the decays **τ → eγ** and **τ → μγ**, BRs down to **few x 10^{-9}** may be probed
    - Here "few" varies by up to a factor 4 depending on the assumed ECAL energy resolution
  - For the decays **τ^-** → $l^- l^+ l^-$ a limit **below 10^{-9}** will be within reach