# Charged Lepton Flavour Violations at the FCC-ee

Mogens Dam
Niels Bohr Institute
Copenhagen

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Rare Processes and Precision Frontier Townhall Meeting
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*Picture and slide layout, courtesy Jörg Wenninger*

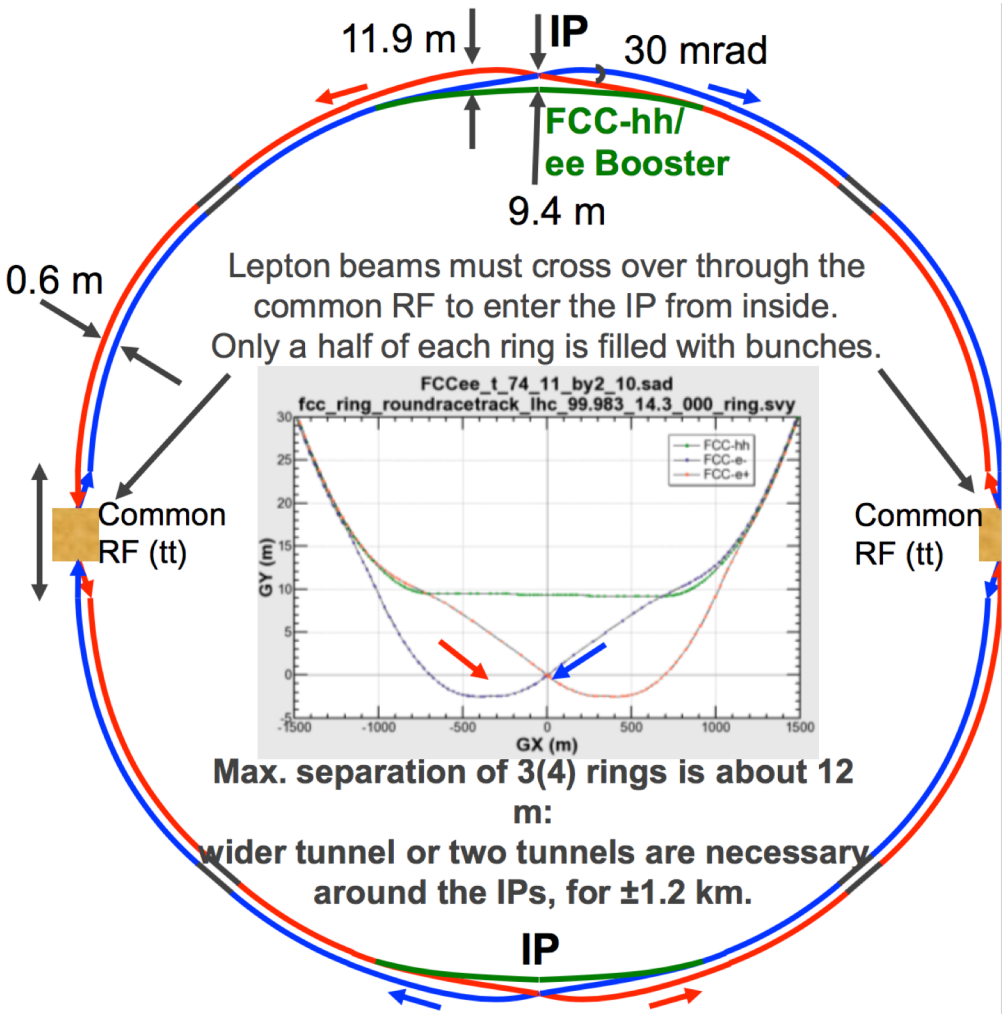
# Outline

a. **Extremely brief on FCC-ee**
b. **Charged Lepton Flavour Violating τ decays**
c. **Charged Lepton Flavour Violating Z decays**

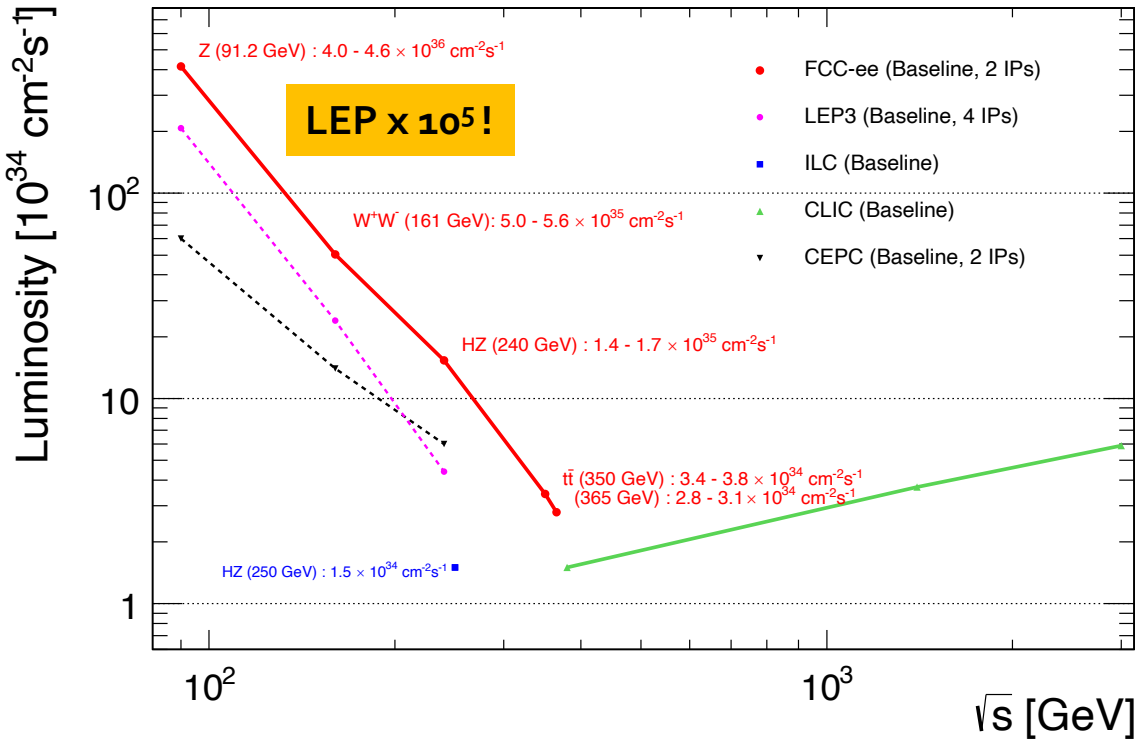

References:

- FCC CDR Volume 1
- MD, **Tau-lepton Physics at the FCC-ee circular $e^+e^-$ Collider**
  *SciPost Phys.Proc.* 1 (2019) 041,
  DOI: 10.21468/SciPostPhysProc.1.041

# FCC-ee


11.9 m
IP
30 mrad
FCC-hh/
ee Booster
9.4 m
0.6 m
Lepton beams must cross over through the common RF to enter the IP from inside.
Only a half of each ring is filled with bunches.
Common RF (tt)
Common RF (tt)
FCCee_t_74_11_by2_10.sad
fcc_ring_roundracetrack_lhc_99.983_14.3_000_ring.svy
FCC-hh
FCC-e-
FCC-e+
GY (m)
GX (m)
Max. separation of 3(4) rings is about 12 m:
wider tunnel or two tunnels are necessary around the IPs, for ±1.2 km.
IP

# Luminosity & Statistics




In this talk, concentrate on the Z-pole energy point

| | | | | |
|---|---|---|---|---|
| Z peak | $E_{CM}$ : 91 GeV | 5 x $10^{12}$ | $e^+e^- \rightarrow Z$ | 4 years |
| WW threshold | $E_{CM}$ : 161 GeV | $10^8$ | $e^+e^- \rightarrow WW$ | 1 year |
| ZH threshold | $E_{CM}$ : 240 GeV | $10^6$ | $e^+e^- \rightarrow ZH$ | 3 years |
| $t\bar{t}$ threshold | $E_{CM}$ : 350 GeV | $10^6$ | $e^+e^- \rightarrow t\bar{t}$ | 5 years |

Enormous statistics of Z bosons and of τ leptons

| | |
|---|---|
| Z decays | 5 x $10^{12}$ |
| $Z \rightarrow \tau^+\tau^-$ | 1.7 x $10^{11}$ |
| 1 vs. 3 prongs | 4.2 x $10^{10}$ |
| 3 vs. 3 prong | 3.6 x $10^9$ |
| 1 vs. 5 prong | 2.8 x $10^8$ |
| 1 vs. 7 prong | < 87,000 |
| 1 vs 9 prong | ? |

# A wealth of EW and Higgs Precision Measurements

| Observable | Measurement | Current precision | FCC-ee stat. | FCC-ee syst. | Challenge |
|---|---|---|---|---|---|
| $m_Z$ (keV) | Z lineshape | 91186700 ± 2200 | 5 | 100 | $E_{Beam}$ calib |
| $\Gamma_Z$ (keV) | Z lineshape | 2495200 ± 2300 | 8 | 100 | $E_{Beam}$ calib |
| $R_l$ ($\times 10^3$) | Ratio had to lept | 20767 ± 25 | 0.01 | 0.2–1 | Lepton accept |
| $\alpha_s(m_Z)$ ($\times 10^4$) | From $R_\ell$ | 1196 ± 30 | 0.1 | 0.4–1.6 | ditto |
| $R_b$ ($\times 10^6$) | Ratio bb to hadrons | 216290 ± 660 | 0.3 | < 60 | $g \to bb$ |
| $N_\nu$ ($\times 10^3$) | Peak cross section | 2991 ± 7 | 0.005 | < 1 | Lumi meast |
| $\sin^2\theta_W^{eff}$ ($\times 10^6$) | From $A_{FB}^{\mu\mu}$ at Z peak | 231480 ± 160 | 3 | 2–5 | $E_{Beam}$ calib |
| $1/\alpha_{QED}(m_Z)$ ($\times 10^3$) | From $A_{FB}^{\mu\mu}$ off-peak | 128952 ± 14 | 4 | small | QED corr. |
| $A_{FB}^{pol,\tau}$ ($10^4$) | $\tau$ pol charge assym | 1498 ± 49 | 0.15 | < 2 | |
| $m_w$ (MeV) | WW threshold scan | 80385000 ± 15000 | 600 | 300 | $E_{Beam}$ calib |
| $N_\nu$ | $e^+e^- \to \gamma Z$, $Z \to \nu\nu$, $\ell\ell$ | 2.92 ± 0.05 | 0.001 | < 0.001 | ? |
| $\alpha_s(m_W)$ ($\times 10^4$) | From $R_\ell^W$ | 1170 ± 420 | 3 | small | Lepton accept |
| $m_{top}$ (MeV) | tt threshold scan | 172740 ± 500 | 20 | small | QCD corr |
| $\Gamma_{top}$ (MeV) | tt threshold scan | 1410± 190 | 40 | small | QCD corr |
| $\lambda_{top} / \lambda_{top}^{SM}$ | tt threshold scan | 1.2 ± 0.3 | 0.08 | small | QCD corr |

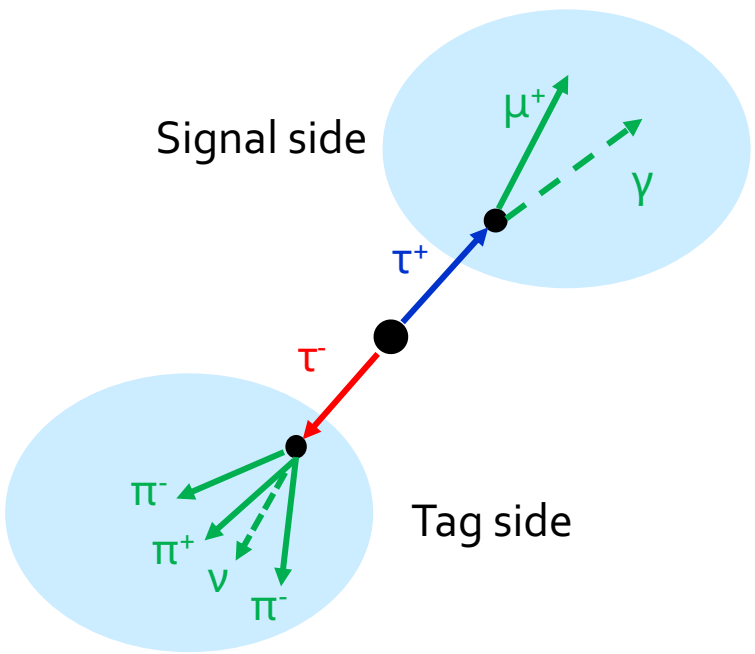
## Higgs

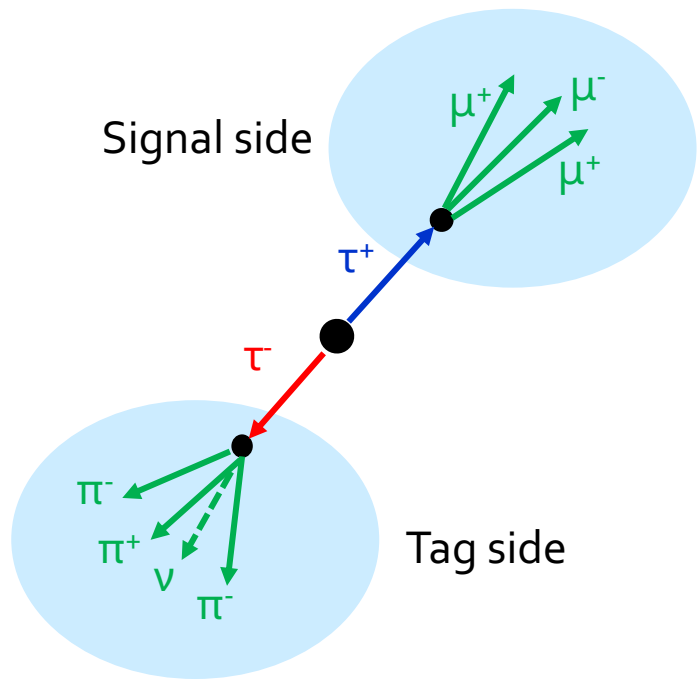
| Coupling | HL-LHC | FCC-ee |
|---|---|---|
| $g_{HWW}$ | 1.4% | 0.43% |
| $g_{HZZ}$ | 1.3% | 0.17% |
| $g_{Hbb}$ | 2.9% | 0.61% |
| $g_{Hcc}$ | SM | 1.21% |
| $g_{H\tau\tau}$ | 1.7% | 0.74% |
| $g_{H\mu\mu}$ | 4.4% | 9.0% |
| $g_{H\gamma\gamma}$ | 1.6% | 3.9% |
| $g_{Hgg}$ | 1.8% | 1.0% |
| $BR_{EXOT}$ | SM | < 1.0% |
| $\Gamma_H$ | SM | 1.3% |
| $g_{Htt}$ | 2.5% | - |
| $g_{HHH}$ | 50% | 34% |

… and, on top of that, the phenomenal statistics allows sensitivity to rare processes …

# CLFV τ decays

Two benchmark modes:



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

- **Current limits:**
  - **$Br(\tau^- \to e^-\gamma) < 3.3 \times 10^{-8}$** BaBar, 10.6 GeV; $4.8 \times 10^8$ $e^+e^- \to \tau^+\tau^-$ : 1.6 expected bckg
  - **$Br(\tau^- \to \mu^-\gamma) < 4.4 \times 10^{-8}$** 3.6 expected bckg
- **Main background:** Radiative events (IRS+FSR), $e^+e^- \to \tau^+\tau^-\gamma$
  - $\tau \to \mu\gamma$ decay faked by combination of $\gamma$ from ISR/FSR and $\mu$ from $\tau \to \mu\nu\bar{\nu}$
- **At FCC-ee, with $1.7 \times 10^{11}$ $\tau^+\tau^-$ events, what can be expected?**
  - Boost 8-9 times higher than at B-factories
  - Detector resolutions rather different, probably especially ECAL
  - Parametrised study of signal and the main background, $e^+e^- \to \tau^+\tau^-\gamma$, performed
    - Following 3 pages
  - From study (assuming 25% signal & background efficiency), projected BR sensitivity

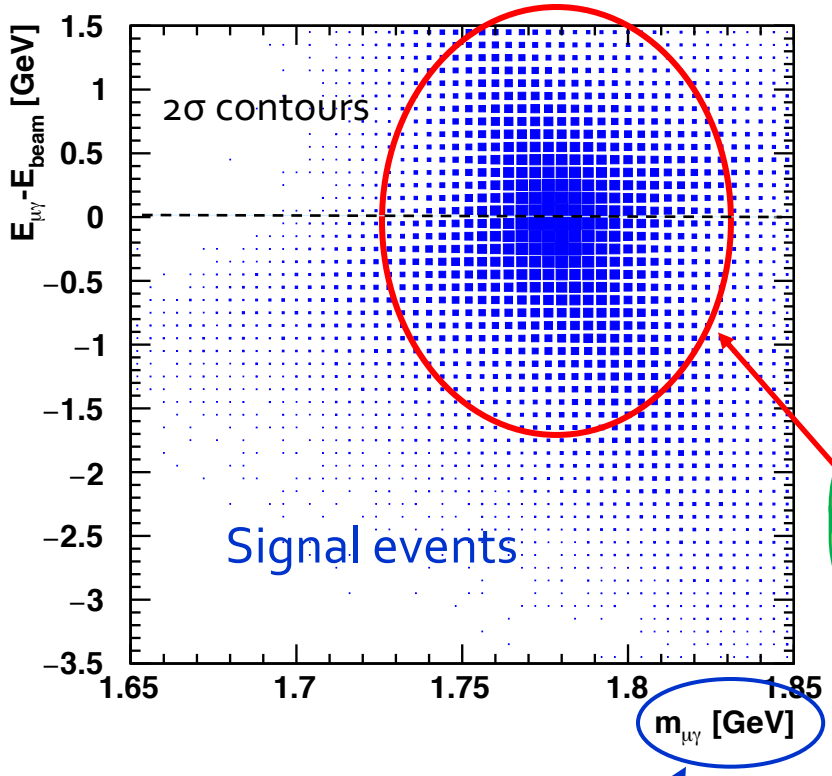
$$\boxed{2 \times 10^{-9}}$$

  - With the recently suggested crystal ECAL, possible a factor of about 6-10 better

2008.00338

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

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




Smear with assumed FCC-ee detector resolutions (ILC-like detector):

- 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 [mm]

  $\sigma(x) = \sigma(y) = (6/E \oplus 2)$ mm

**FCC-ee** effective resolution for $\tau \to \mu\gamma$

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

In order to de-correlate the E and m variables, this mass is in fact the measured mass scaled by measured energy over beam energy:

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

Recent suggestion: Crystal ECAL for FCC-ee

$\sigma(E)/E = 0.03/\sqrt{E} \oplus 0.011$

Resolution ellipse factor ~4 smaller in both directions

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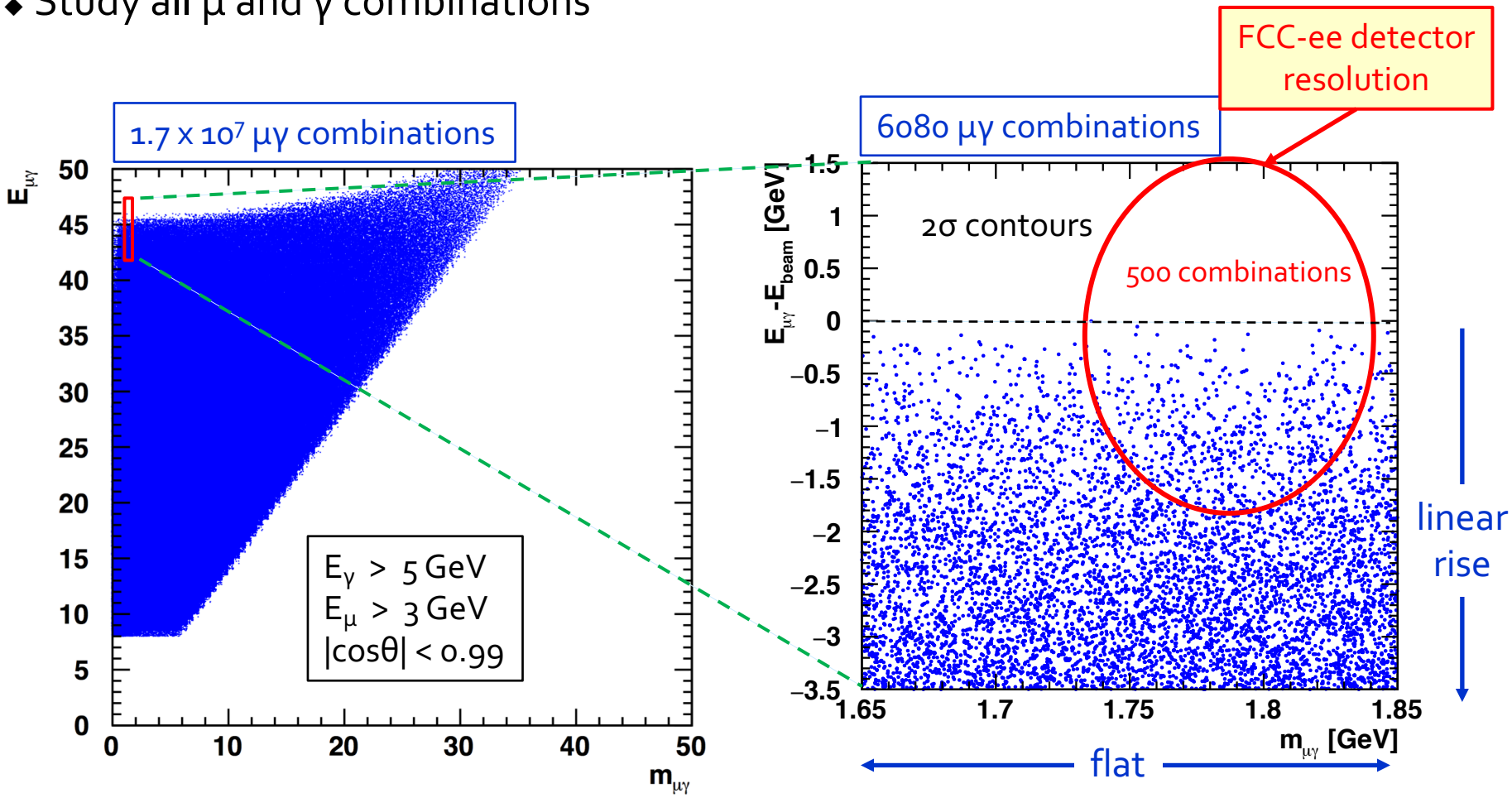
# $\tau \to \mu\gamma$ Study – The background

- Background: Generate $5 \times 10^8$ events $e^+e^- \to Z \to \tau^+\tau^-(\gamma) \to (\mu^+\nu\nu)(\mu^-\nu\nu)(\gamma)$
  - $1 \times 10^9$ $\tau \to \mu\nu\nu$ decays corresponding to
    - $5.7 \times 10^9$ $\tau$ decays from $8.4 \times 10^{10}$ Z decays (1.6% of full FCC-ee statistics)
- Study all $\mu$ and $\gamma$ combinations



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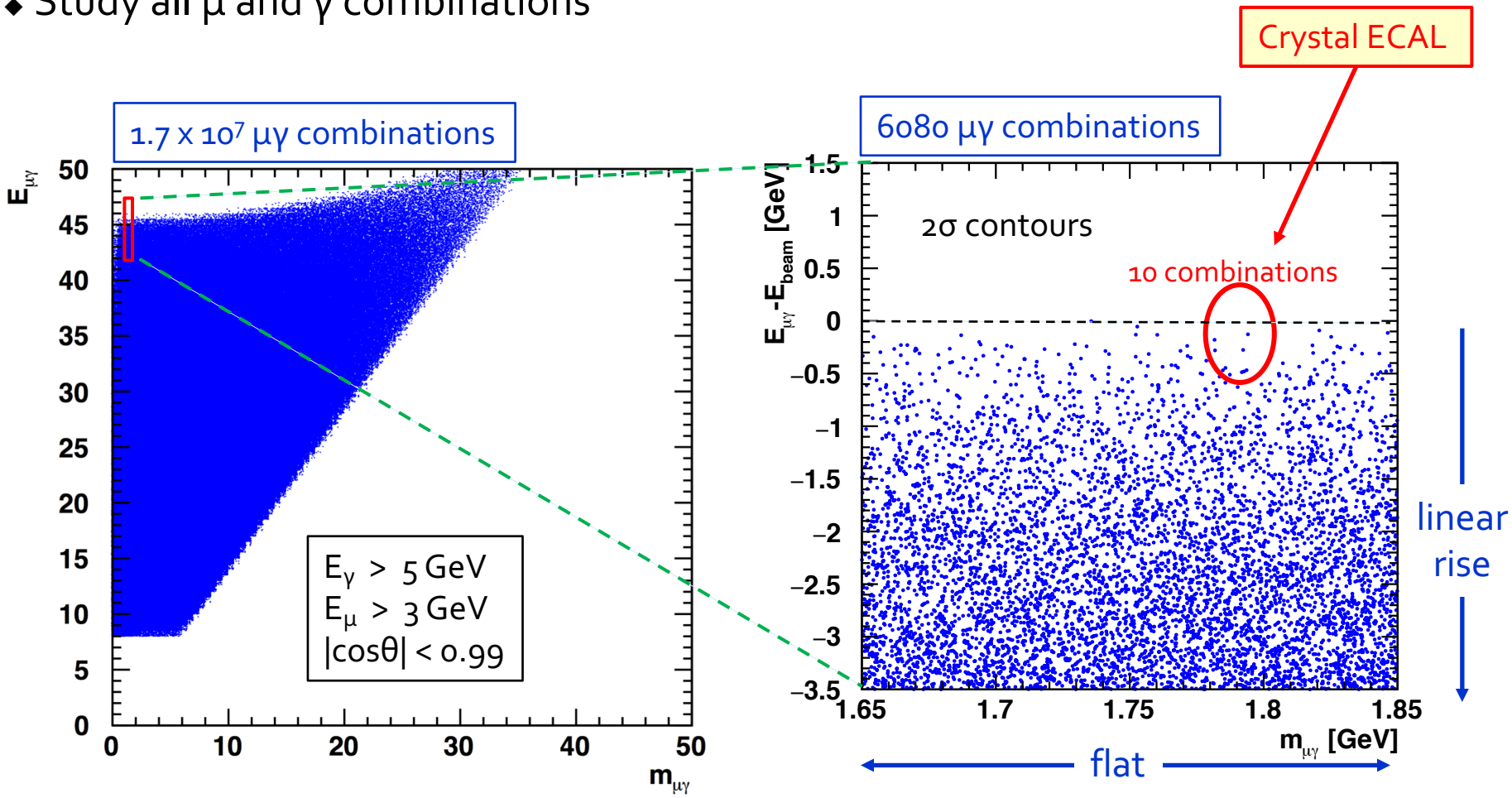
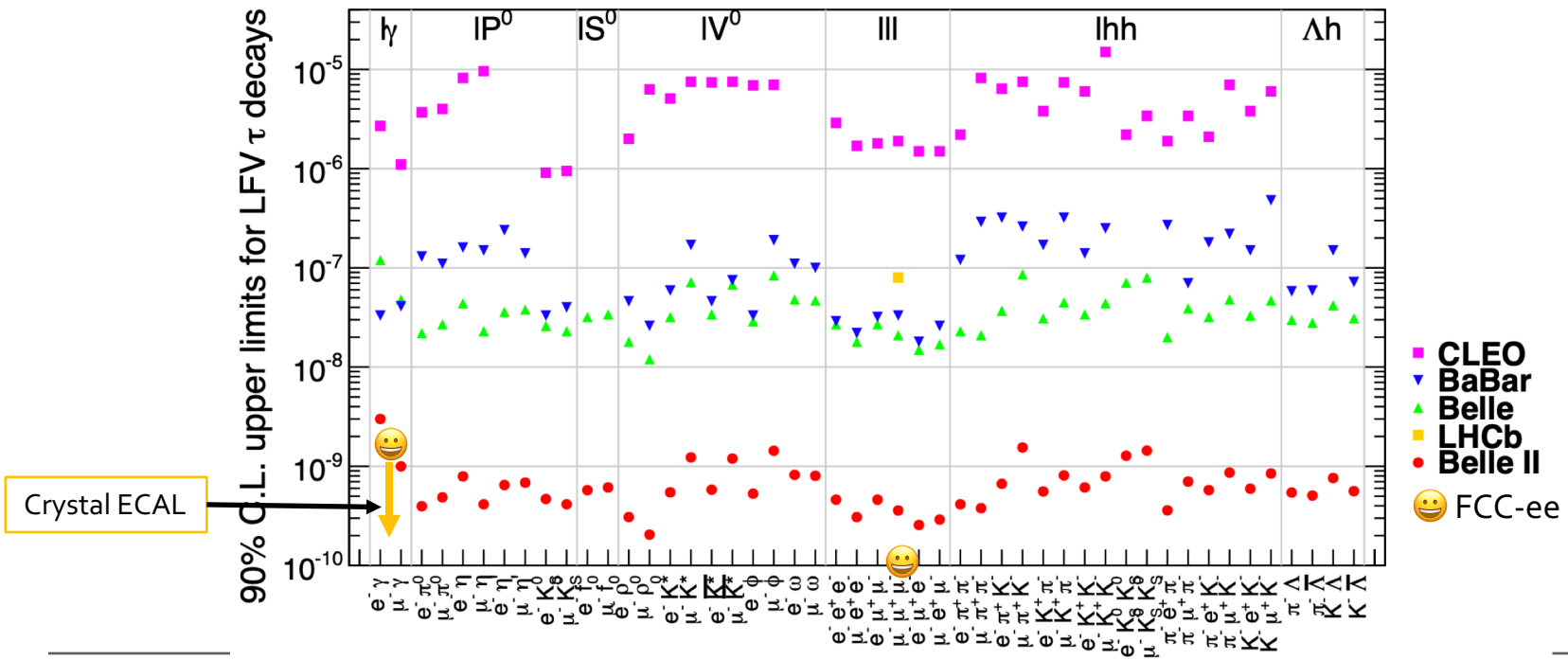
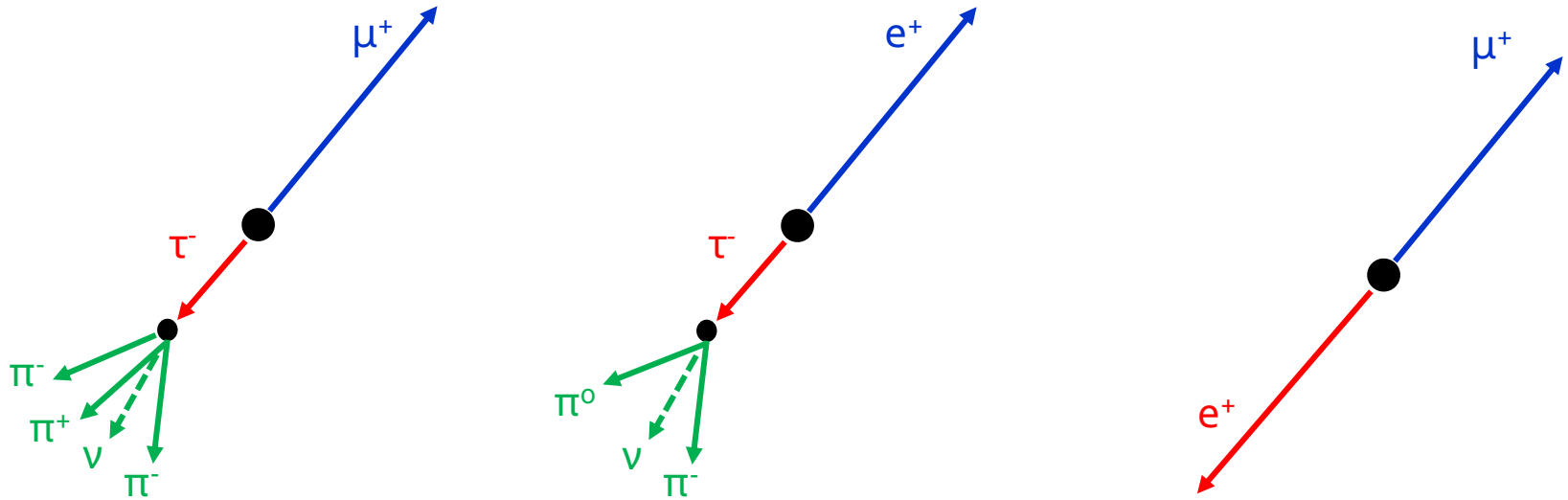


# $\tau^- \to \ell^-\ell^+\ell^-$

- Current limits:
  - All 6 combs. of $e^\pm$, $\mu^\pm$ : Br $\lesssim 2 \times 10^{-8}$ Belle@10.6 GeV; $7.2 \times 10^8$ $e^+e^- \to \tau^+\tau^-$ : no cand.
  - $\mu^-\mu^+\mu^-$ : Br $< 4.6 \times 10^{-8}$ LHCb 2.0 $fb^{-1}$ : background candidates
- FCC-ee prospects
  - Expect this search to have *very low* background, even with FCC-ee like statistics
  - Should be able to have sensitivity down to BRs of $\lesssim 10^{-10}$
- Many more decay modes to search for when time comes…



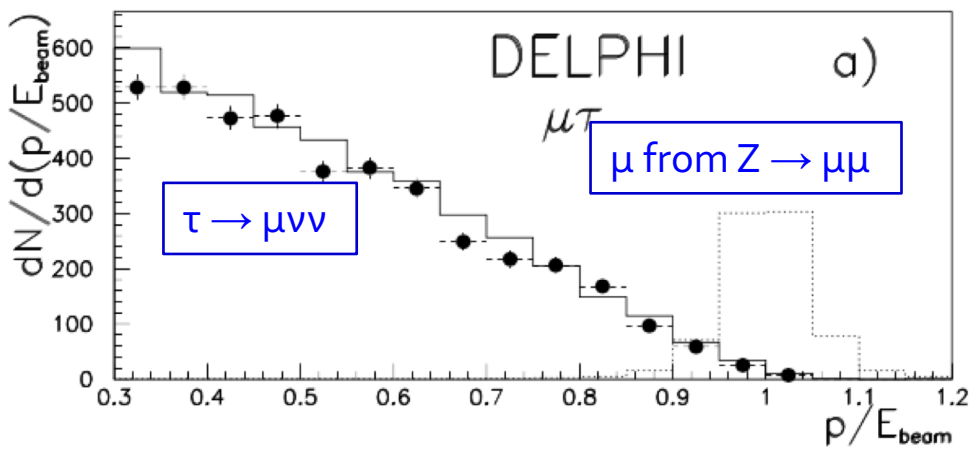
# LFV Z decays



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

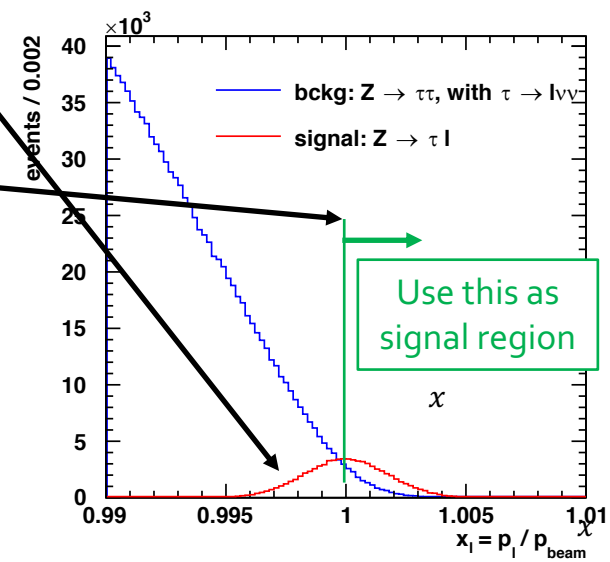
- Current limits
  - **$Br(Z \to e\tau) < 8.1 \times 10^{-6}$** LHC/ATLAS (139 $fb^{-1}$ ⇒ $2.8 \times 10^8$ Z decays)
  - **$Br(Z \to \mu\tau) < 9.5 \times 10^{-6}$** [ATLAS-CONF-2020-35]
- LEP limits – best for > 20 years untill ICHEP20
  - **$Br(Z \to e\tau) < 9.8 \times 10^{-6}$** LEP/OPAL ($4 \times 10^6$ Z decays)
  - **$Br(Z \to \mu\tau) < 12. \times 10^{-6}$** LEP/DELPHI ($4 \times 10^6$ Z decays)
- LEP 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:
Z.Phys. C73



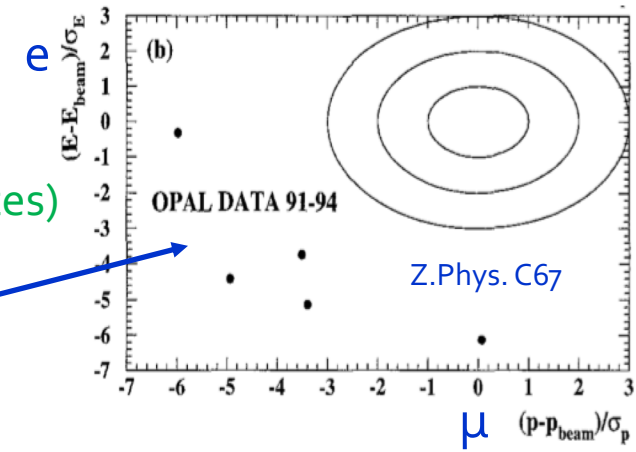
# $Z \to \ell\tau$ - Study of Sensitivity

- Generate (very) upper part of μ momentum spectrum for $\tau \to \mu\nu\nu$ decays
  - Luminosity equivalent to $5 \times 10^{12}$ Z decays
- Inject LFV signal of adjustable strength
  - Here for illustration, **$Br(Z \to \tau\mu) = 10^{-7}$**, i.e. 500,000 μ
- Smear momentum by variable amounts, here **$1.8 \times 10^{-3}$**
- Define $x > 1$ as signal region
- Derive 95% confidence limit on excess in signal region
- Findings:
  - Sensitivity scales **linear** with momentum resolution
  - FCC-ee detectors will (tentatively) have a momentum resolutiuon at p=45.6 GeV of **$1.5 \times 10^{-3}$**
    - Ten times better than for LEP detectors
  - Add contribution from FCC-ee beam-energy spread ($0.9 \times 10^{-3}$). Total: **$1.8 \times 10^{-3}$**
- Sensitivity for $5 \times 10^{12}$ Z decays, 25% signal and bkg efficiency (clear tau)
  - For $Z \to \tau\mu$, sensitivity down to BRs of **$\sim 10^{-9}$**
  - For $Z \to \tau e$, similar sensitivity **$\sim 10^{-9}$**
    - Momentum resolution of electrons tend to be slightly worse than muons due to bremsstrahlung. However, downwards smearing is not a major concern.



# $Z \rightarrow e\mu$

- Current limit:
  - **$7.5 \times 10^{-7}$ LHC/ATLAS** (20 $fb^{-1}$; no candidates)
  - **$1.7 \times 10^{-6}$ LEP/OPAL** ($4.0 \times 10^{6}$ Z decays: no candidates)
- In $e^+e^-$, 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 $\mu \rightarrow e$
    - NA62: Probability of muon to deposit more than 95% of energy in ECAL: **$4 \times 10^{-6}$**
    - 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 $P(\mu \rightarrow e)$
- FCC-ee:
  - Misidentification from catastrophic energy loss corresponds to limit of about $Br(Z \rightarrow e\mu) \simeq 10^{-8}$
  - Possibly do $\mathcal{O}(10)$ better than that **$Br(Z \rightarrow e\mu) \sim 10^{-9}$** (probably even $10^{-10}$ with IDEA dE/dx)

# Summary

- From $5 \times 10^{12}$ Z decays, FCC-ee will produce **$1.7 \times 10^{11}$ $\tau^+\tau^-$ pairs**
- Statistics comparable to (factor ~3 higher) Belle2 projection; higher boost ($\gamma$=25)
  - Boost is advantageous for many studies
- Searches for **lepton flavour violating τ decays**; sensitivites comparable to Belle2
  - For two benchmark studies, range from **$\lesssim 10^{-10}$** to **few x $10^{-9}$**
  - Many more studied to be pursued
- Improved sensitivity to **lepton flavour violating Z decays** by factors up to **$\mathcal{O}(10^4)$**
  - Sensitivities down to **$10^{-9}$** in all modes including τ modes

**Plus (not covered in this talk; other LoIs):**

- Potential for very precise $\sin^2\theta_W$ determination via **τ polarisation** measurement
- Hadronic branching ratios and spectral functions, $\alpha_s$, $\nu_\tau$ mass, …
- Improve **Lepton universality test** by 1 – 2 orders of magnitude down to $\mathcal{O}(10^{-5} - 10^{-4})$ level
  - Substantial improvement in **τ lifetime**
  - Substantial improvement in **τ (leptonic) branching fractions** (virtually no progress since LEP)
  - Possibly substantial improvement) of **τ mass** (mass scale from $10^9$ $Z \rightarrow J/\psi X \rightarrow \mu\mu X$)

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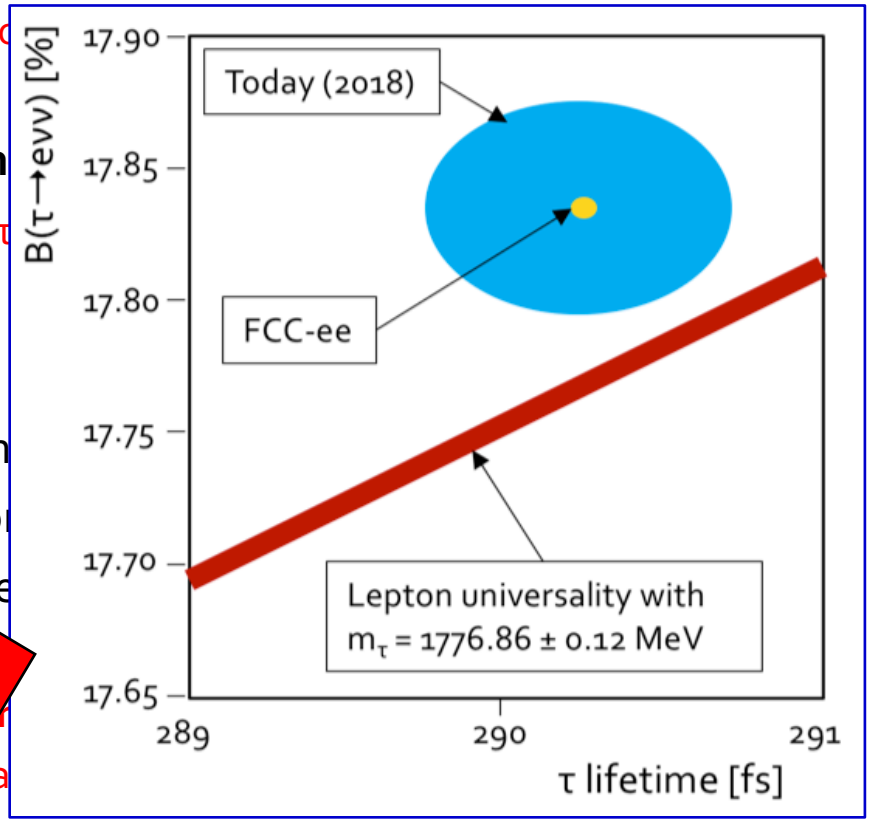

# Detector requirements

Precision τ physics sets very strong detector requirements; constitutes a good benchmark

- **Vertexing**
  - Lifetime measurement to $10^{-4}$ corresponds to 0.22 μm flight distance
- **Tracking**
  - Two (or rather multi) track separation: measure 3-, 5-, 7-, and perhaps even 9-prong decays
  - Extremely good control of momentum and mass scale
    - τ mass measurement (scale from ~$10^9$ J/psi from Z decays? $\delta m/m \simeq 2$ ppm)
    - Sensitivity of search for flavour violating Z decays, e.g. $Z \rightarrow \mu\tau$, scales linearly in momentum resolution at 45.6 GeV
  - Low material budget: Minimize confusion from hadronic interaction in material
- **Calorimetry**
  - Clean γ and $\pi^0$ reconstruction from 0.2 to 45 GeV is key to precison τ physics from Z decays
  - Collimated topologies: Important to be able to separate γs from closelying hadronic showers
- **PID**
  - Necessary if one desires to separate π/K τ-decay modes (0 – 45 GeV momentum range)
  - **Redundancy**: Provides valuable handle to create test samples for study of calorimetry

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  - ❑ **Redundancy**: Provides valuable handle to create test samples for study of calorimetry

- With its TeraZ programme, FCC-ee will be a phenomenal factory for the production of Z bosons and heavy flavour including τ leptons
- Unprecedented sensitivity to CLVF and to τ lepton properties
- Not obvious that an "off-the-shelf" e+e- Higgs-factory detector design would be optimal to beat minimize systematics
- Now, is the time to develop the precise detector requirements and to work on the optimisation of the detector design
- International participation welcome !

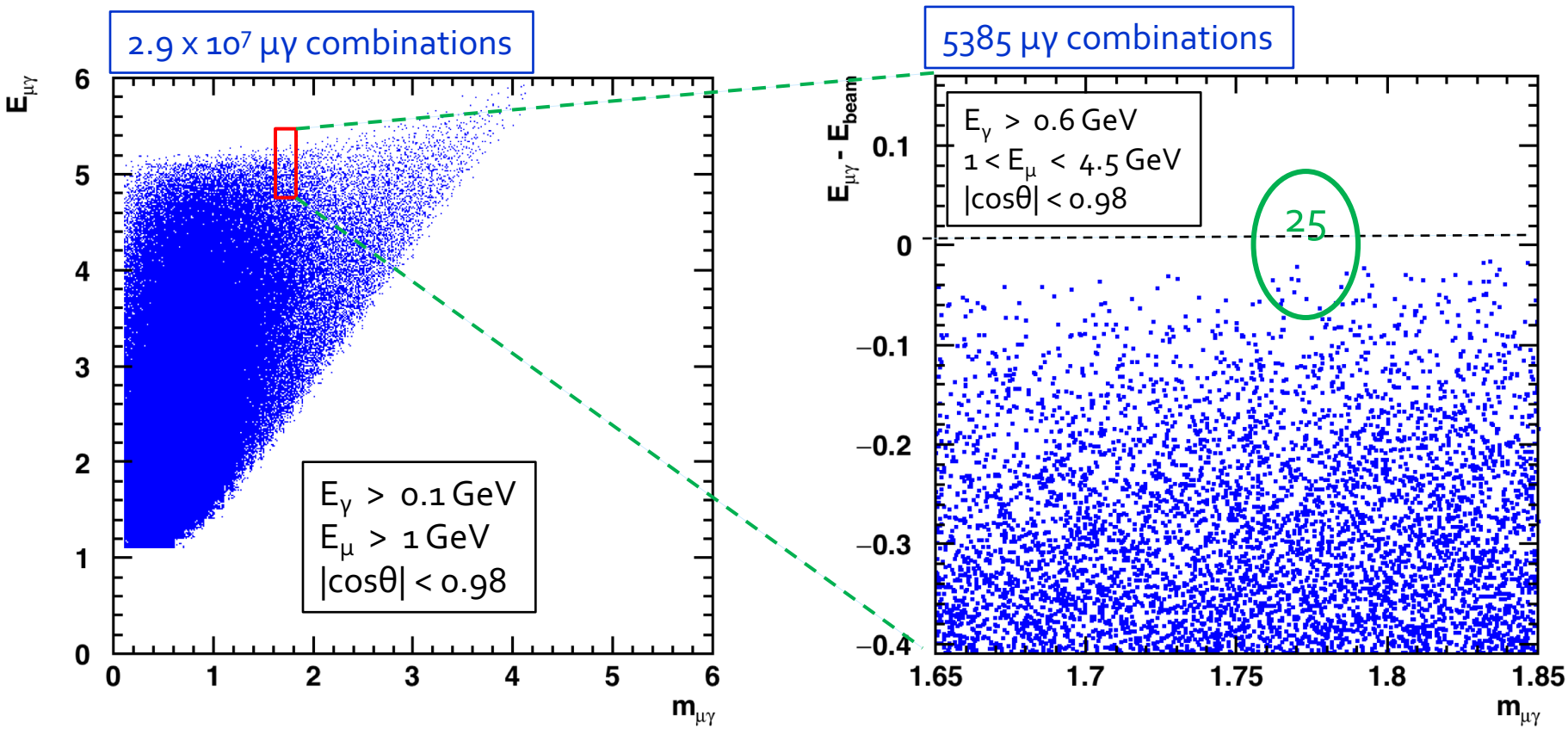
- Repository of all FCC Snowmass LoIs
- Next event: 4th FCC Physics and Experiments Workshop, Nov 9-13

# Extra Slides

# $\tau \to \mu\gamma$ Study – Check of method

**Cross check:** Perform similar study at B-factory, $\sqrt{s}$ = 10.6 GeV, 50 $ab^{-1}$

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




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

Compares well to projection from "Belle II Physics Book": 1-3 x $10^{-9}$