NIELS BOHR INSTITUTE
UNIVERSITY OF COPENHAGEN

Charged Lepton Flavour Violations at the FCC-ee

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Snowmass2021
Rare Processes and Precision Frontier Townhall Meeting
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Picture and slide layout, courtesy Jörg Wenninger

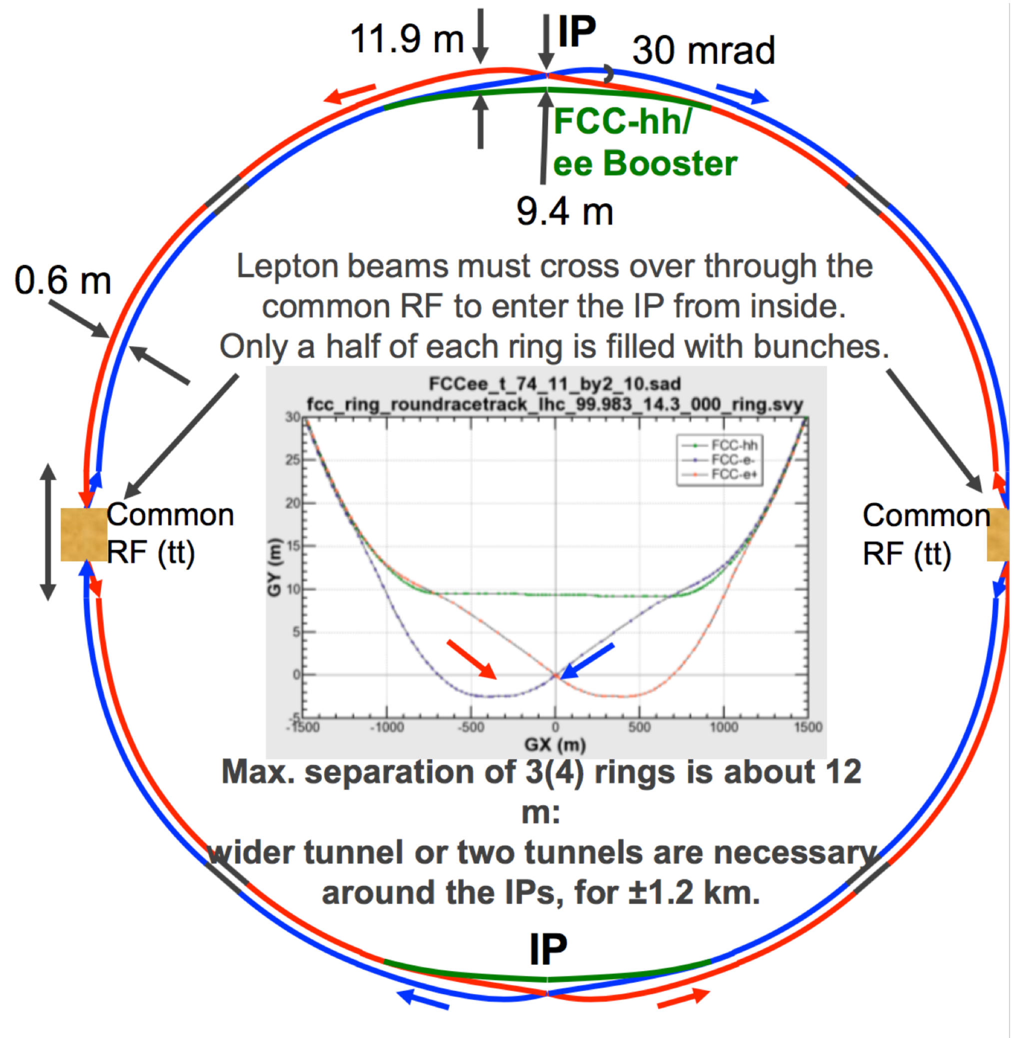
Outline

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

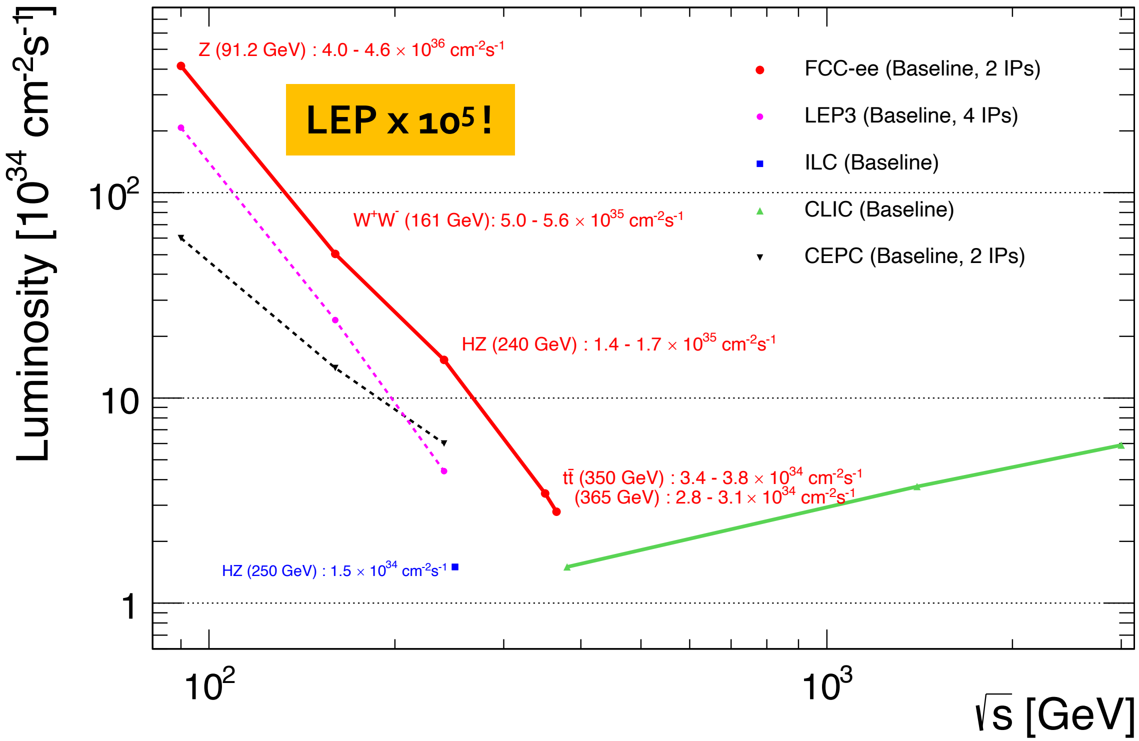
References:

- 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.
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)
Common
RF (tt)
Common
RF (tt)
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

Enormous statistics of Z bosons and of τ leptons

Z peak	E_{CM} : 91 GeV	5×10^{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

Z decays	5×10^{12}
$Z \rightarrow \tau^+\tau^-$	1.7×10^{11}
1 vs. 3 prongs	4.2×10^{10}
3 vs. 3 prong	3.6×10^9
1 vs. 5 prong	2.8×10^8
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
Γ_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_ℓ	1196 ± 30	0.1	0.4–1.6	ditto
R_b ($\times 10^6$)	Ratio bb to hadrons	216290 ± 660	0.3	< 60	$g \rightarrow bb$
N_ν ($\times 10^3$)	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)	τ pol charge assym	1498 ± 49	0.15	< 2	
m_W (MeV)	WW threshold scan	80385000 ± 15000	600	300	E_{Beam} calib
N_ν	$e^+e^- \rightarrow \gamma Z$, $Z \rightarrow \nu\nu$, $\ell\ell$	2.92 ± 0.05	0.001	< 0.001	?
$\alpha_s(m_W)$ ($\times 10^4$)	From R_ℓ^W	1170 ± 420	3	small	Lepton accept
m_{top} (MeV)	tt threshold scan	172740 ± 500	20	small	QCD corr
Γ_{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

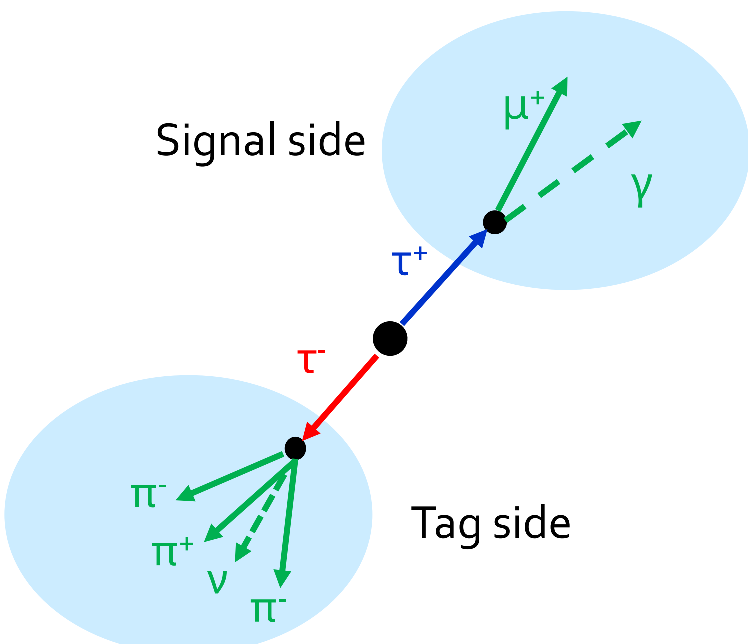
Higgs

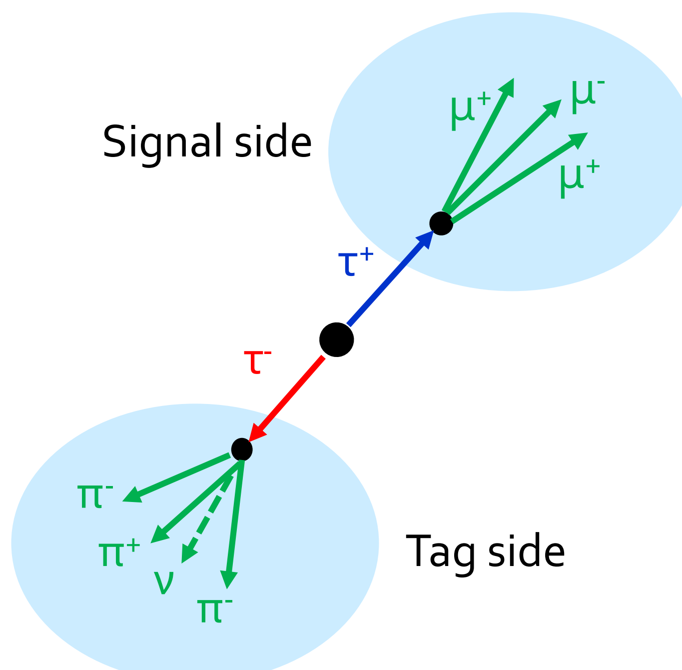
Coupling	HL-LHC	FCC-ee
g_{HWW}	1.4%	0.43%
g_{HZZ}	1.3%	0.17%
g_{Hbb}	2.9%	0.61%
g_{Hcc}	SM	1.21%
$g_{H\tau\tau}$	1.7%	0.74%
$g_{H\mu\mu}$	4.4%	9.0%
$g_{H\gamma\gamma}$	1.6%	3.9%
g_{Hgg}	1.8%	1.0%
BR_{EXOT}	SM	< 1.0%
Γ_H	SM	1.3%
g_{Htt}	2.5%	-
g_{HHH}	50%	34%

... 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 x 10^{-8}** BaBar, 10.6 GeV; 4.8 x 10^8 $e^+e^- \to \tau^+\tau^-$: 1.6 expected bckg
  - **Br($\tau^- \to \mu^-\gamma$) < 4.4 x 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 γ from ISR/FSR and μ from $\tau \to \mu\nu\bar{\nu}$
- **At FCC-ee, with 1.7 x 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

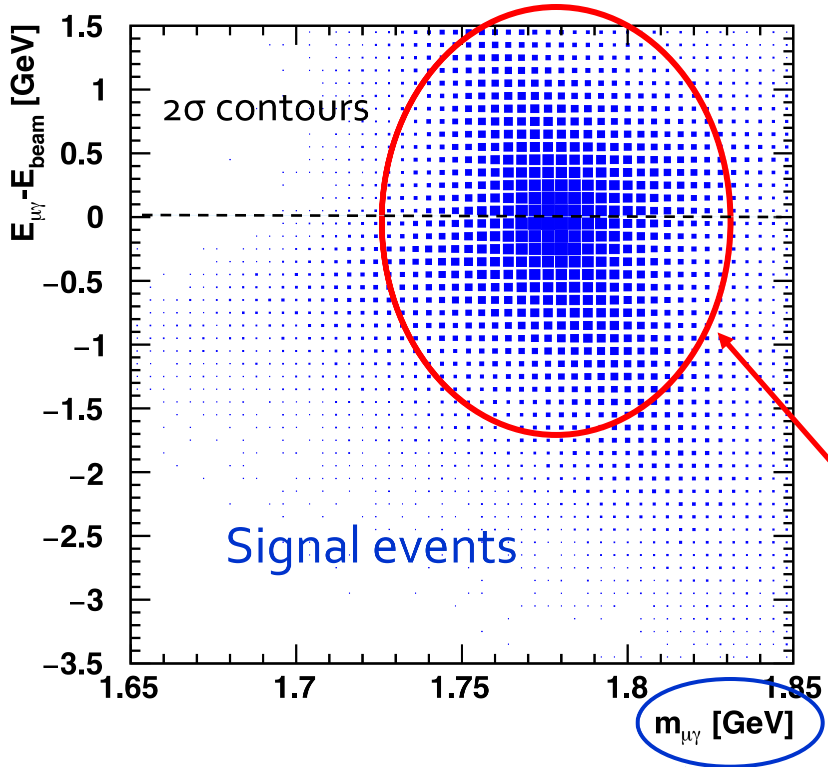
2 x 10^{-9}

  - 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: $\mathbf{e^+e^- \to Z \to \tau^+\tau^-(\gamma)}$, with $\mathbf{\tau^- \to \mu^-\gamma}$



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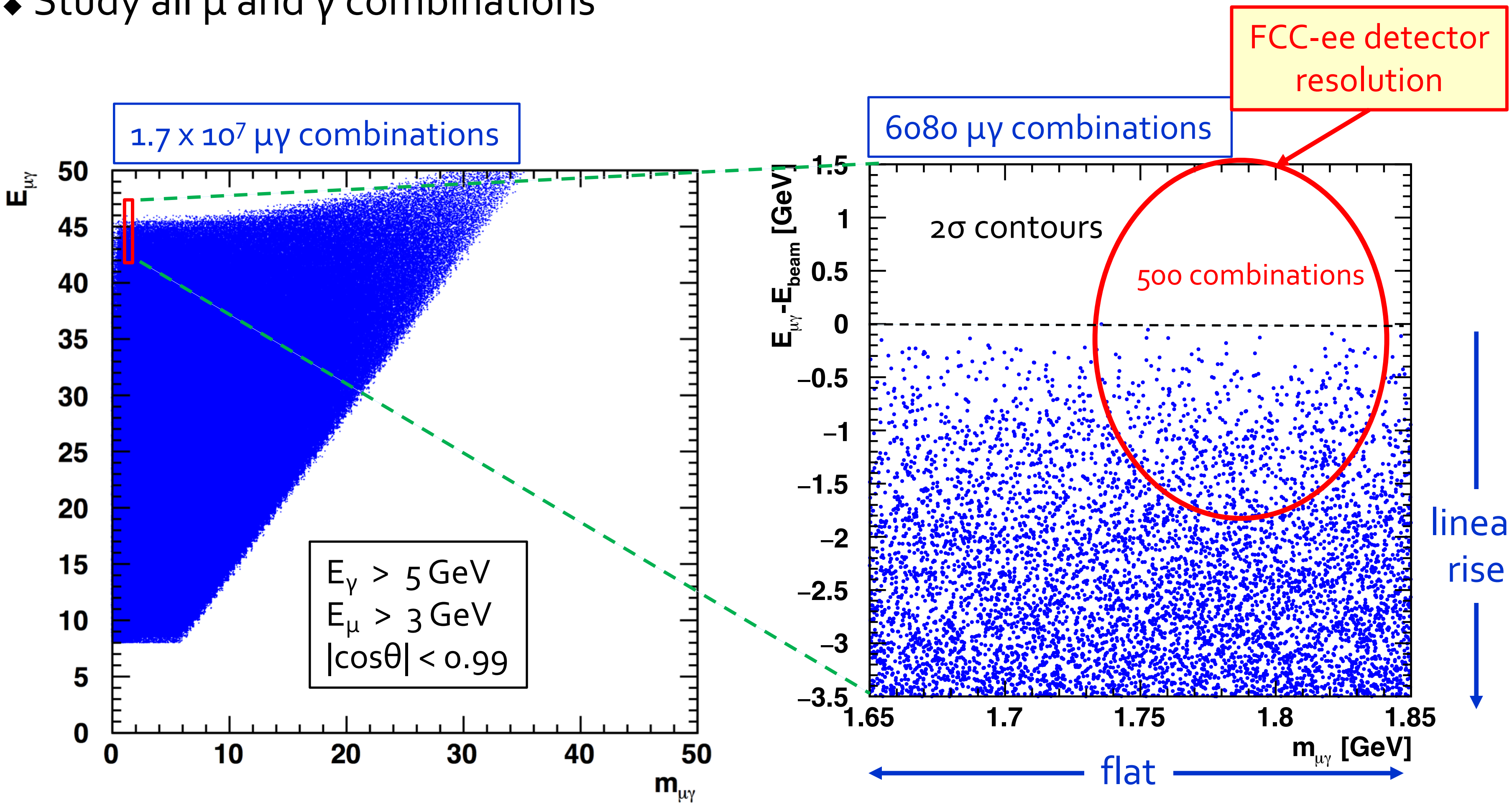
$\tau \to \mu\gamma$ Study – The background

- Background: Generate 5×10^8 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 (1.6% of full FCC-ee statistics)
- Study all μ and γ combinations



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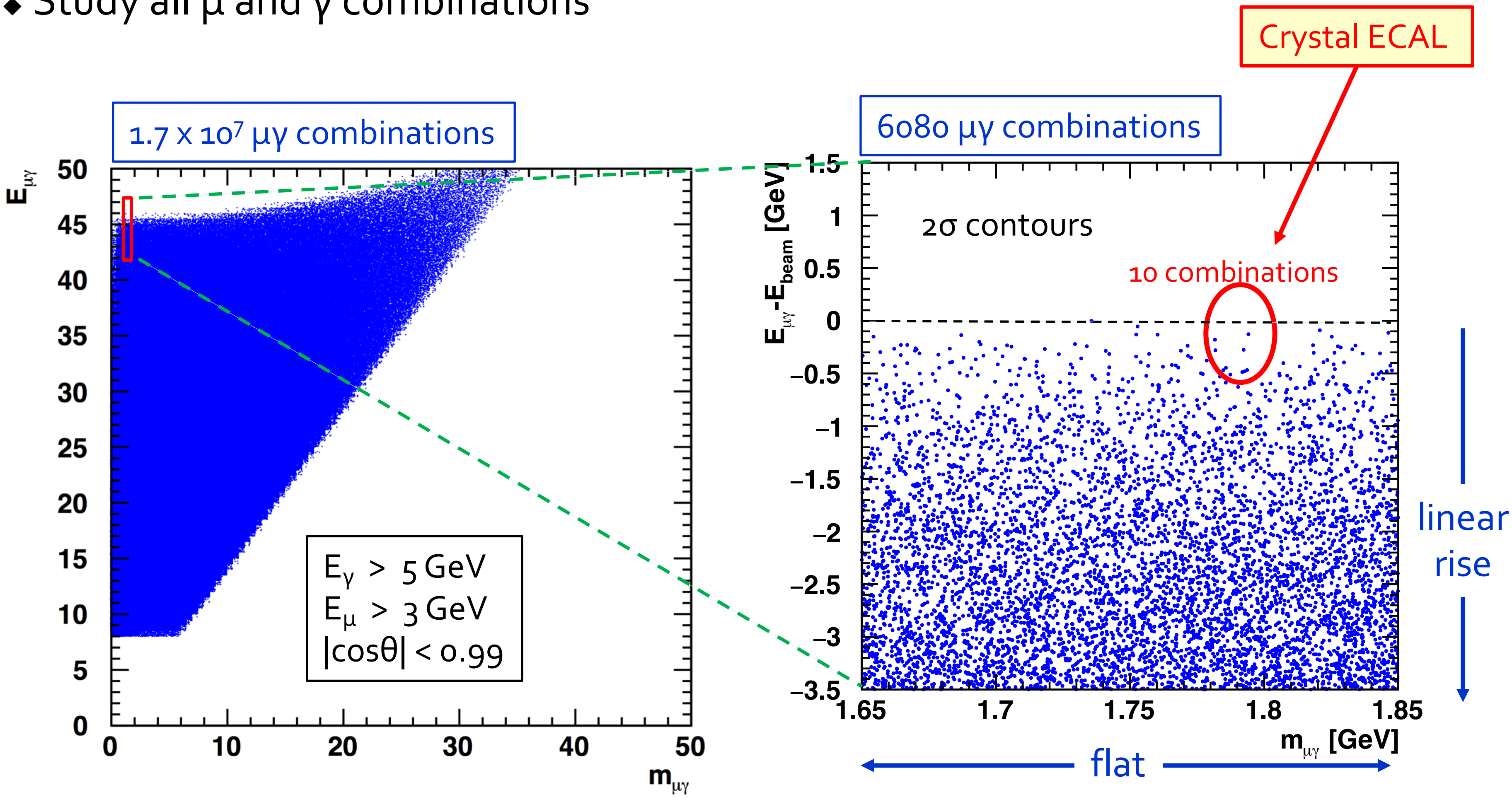
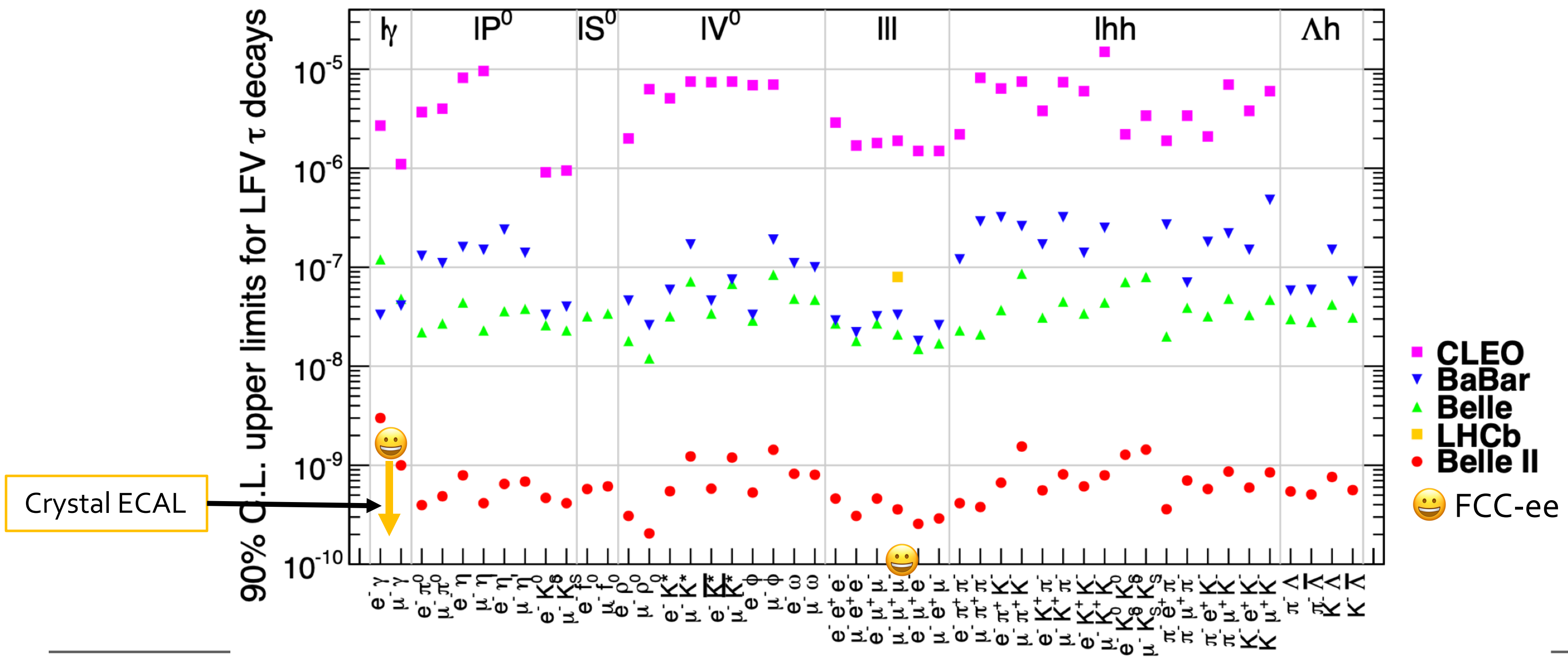
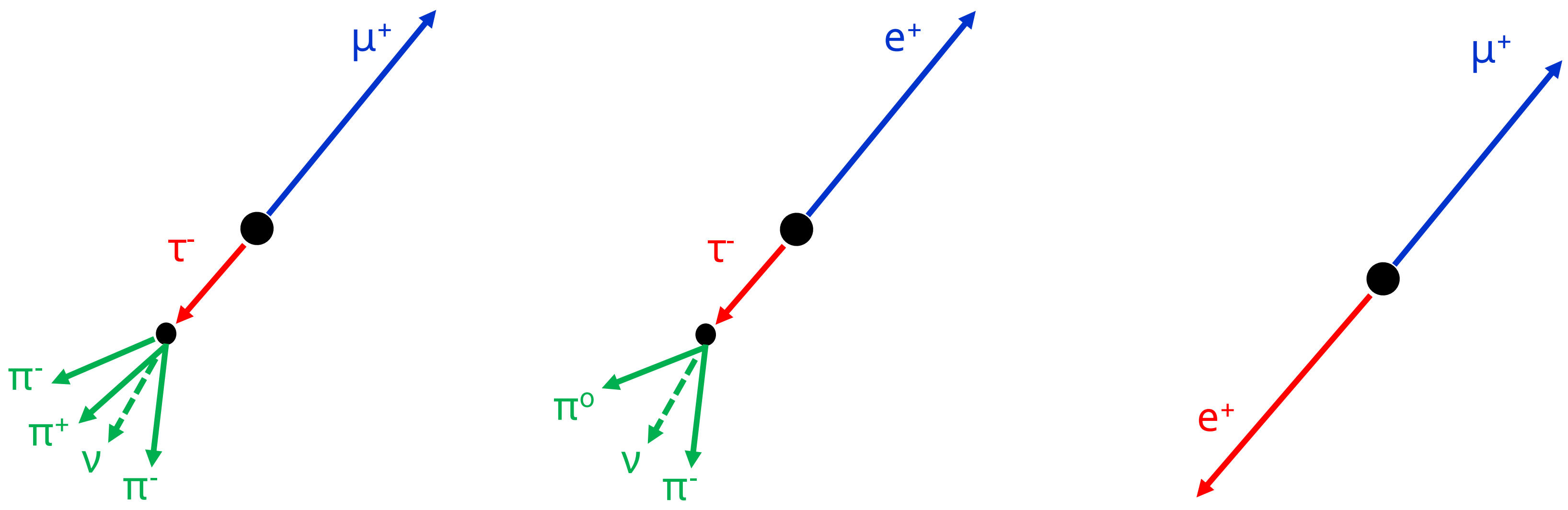


- Current limits:
  - All 6 combs. of $e^\pm$, $\mu^\pm$: Br $\lesssim 2 \times 10^{-8}$ Belle@10.6 GeV; 7.2×10^8 $e^+e^- \rightarrow \tau^+\tau^-$: no cand.
  - $\mu^-\mu^+\mu^-$: Br $< 4.6 \times 10^{-8}$ LHCb 2.0 fb^{-1} : background candidates
- FCC-ee prospects
  - Expect this search to have *very 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…



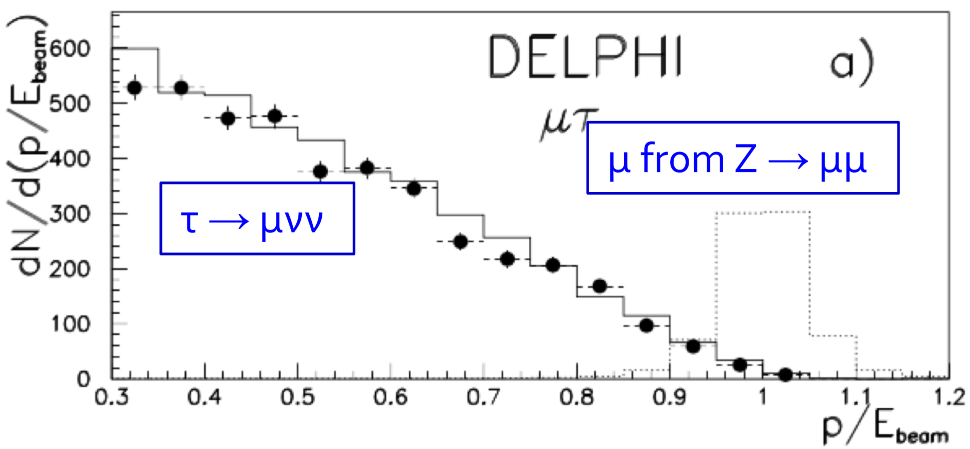
LFV Z decays



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

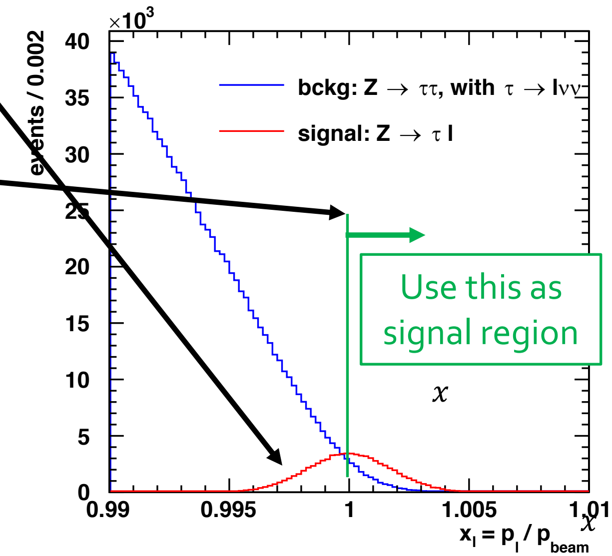
- Current limits
  - **Br($Z \to e\tau$) < 8.1×10^{-6}** LHC/ATLAS (139 fb^{-1} ⇒ 2.8 x 10^8 Z decays)
  - **Br($Z \to \mu\tau$) < 9.5×10^{-6}** [ATLAS-CONF-2020-35]
- LEP limits – best for > 20 years untill ICHEP20
  - **Br($Z \to e\tau$) < 9.8×10^{-6}** LEP/OPAL (4 x 10^6 Z decays)
  - **Br($Z \to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

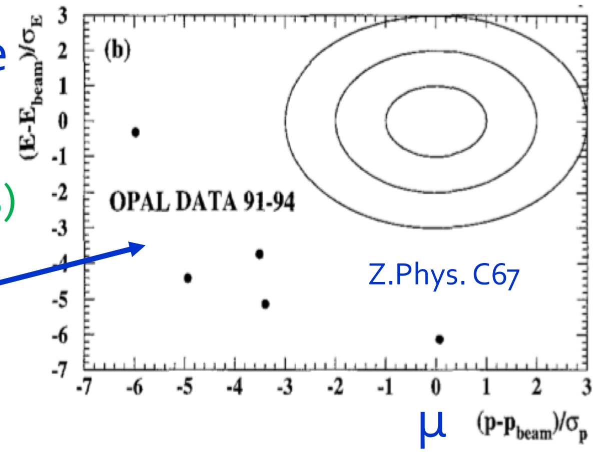
- Generate (very) upper part of μ momentum spectrum for $\tau \to \mu\nu\nu$ decays
  - Luminosity equivalent to 5×10^{12} Z decays
- Inject LFV signal of adjustable strength
  - Here for illustration, **Br($Z \to \tau\mu$) = 10^{-7}**, i.e. 500,000 μ
- Smear momentum by variable amounts, here **1.8×10^{-3}**
- 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 **1.5×10^{-3}**
    - Ten times better than for LEP detectors
  - Add contribution from FCC-ee beam-energy spread (0.9×10^{-3}). Total: **1.8×10^{-3}**



- Sensitivity for 5×10^{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 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)
- 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 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 $P(\mu \rightarrow e)$
- 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 x 10^{12} Z decays, FCC-ee will produce **1.7 x 10^{11} $\tau^+\tau^-$ pairs**
- Statistics comparable to (factor ~3 higher) Belle2 projection; higher boost (γ=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 **$\mathcal{O}(10^3)$**
  - 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, α_s, ν_τ 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 → J/ψX → μμX)

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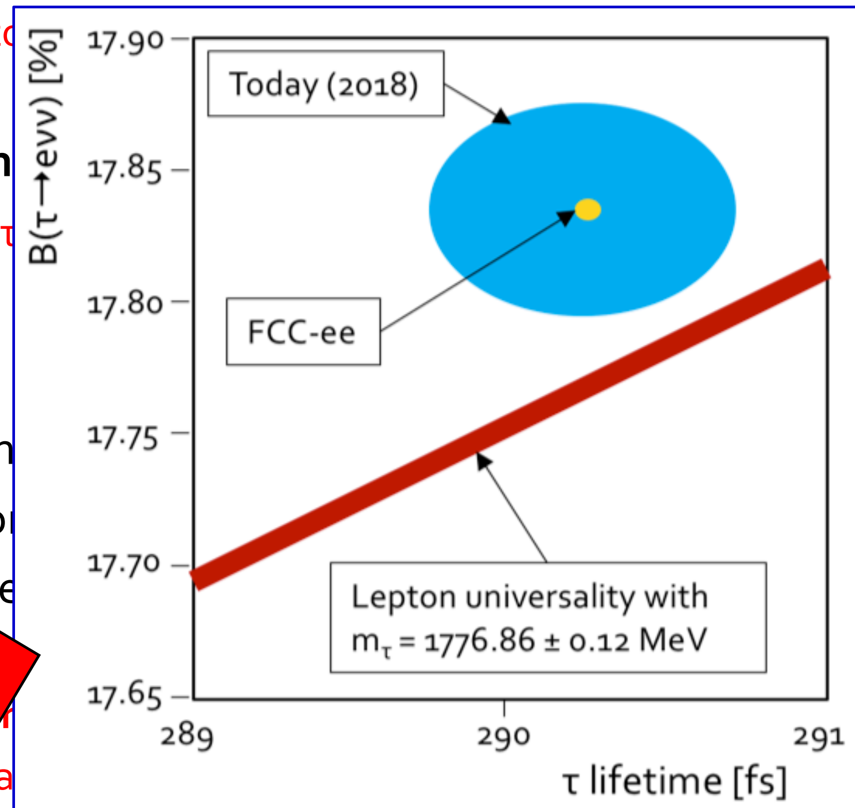


Detector requirements

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. $Z \to \mu\tau$, scales linearly in momentum resolution at 45.6 GeV
  - Low material budget: Minimize confusion from hadronic interaction in material
- **Calorimetry**
  - Clean γ and π^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

Detector requirements

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

- 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 !

- **Calorimetry**
  - Clean γ and π^0 reconstruction from 0.2 to 45 GeV is key to precison τ physics from Z decays

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

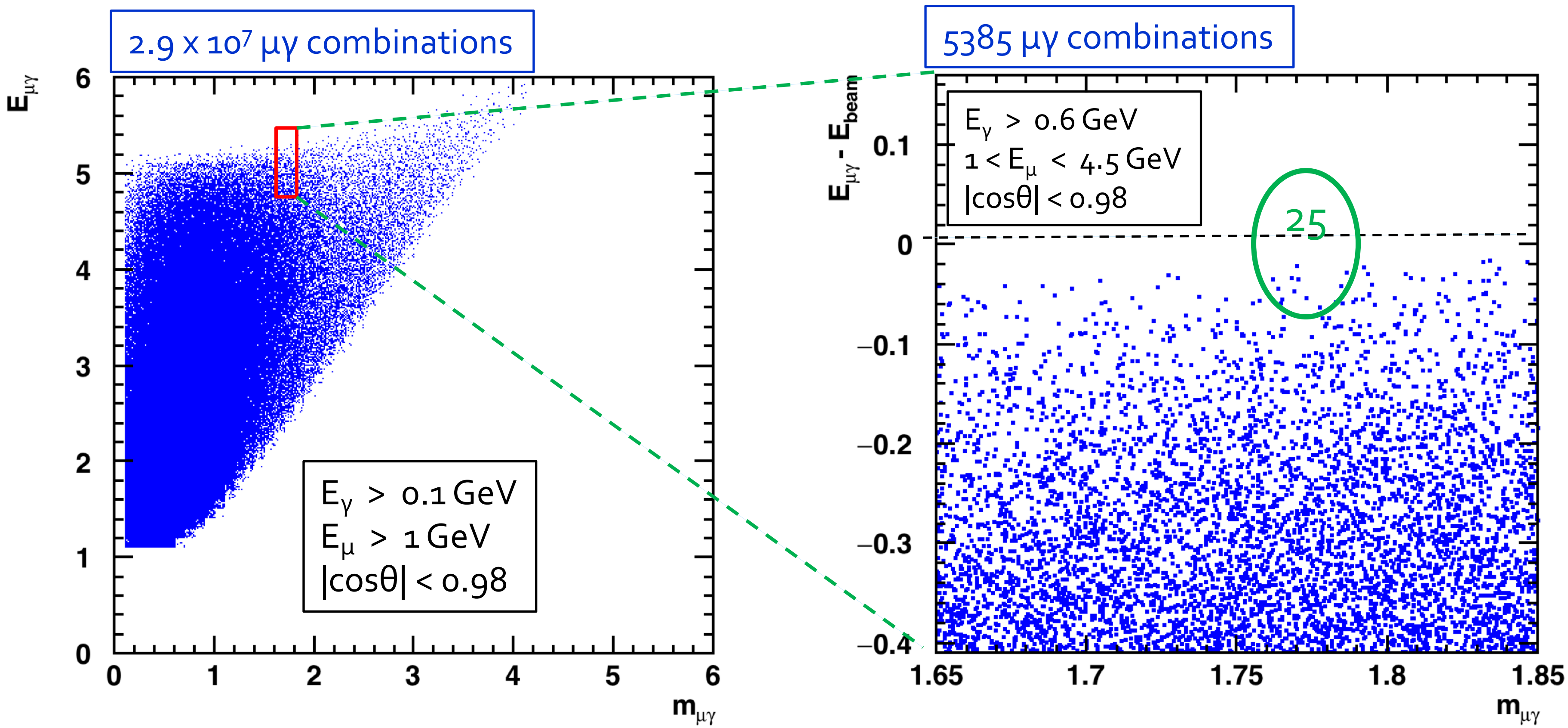
  - **Redundancy**: Provides valuable handle to create test samples for study of calorimetry

Extra Slides

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

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

- Again use 5×10^8 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}**

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