LVF processes involving τ leptons FCC-ee Perspectives

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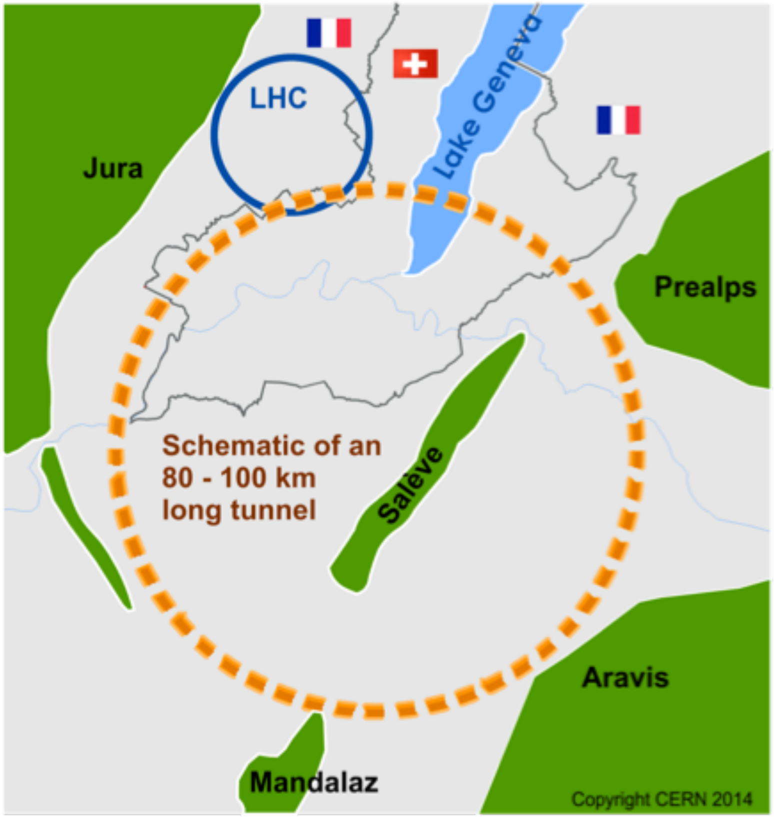
Picture and slide layout, courtesy Jörg Wenninger

The Future Circular Collider(s)

International collaboration to Study Colliders fitting in a new ~100 km infrastructure, in the Geneva region

- Ultimate goal:
  - **$\gtrsim$ 100 TeV pp-collider: FCC-hh**
    - Defining infrastructure requirements
- Possible first stage:
  - **e^+e^- collider: FCC-ee**
    - **High Lumi, E_{cm} = 90-400 GeV**



European Strategy:

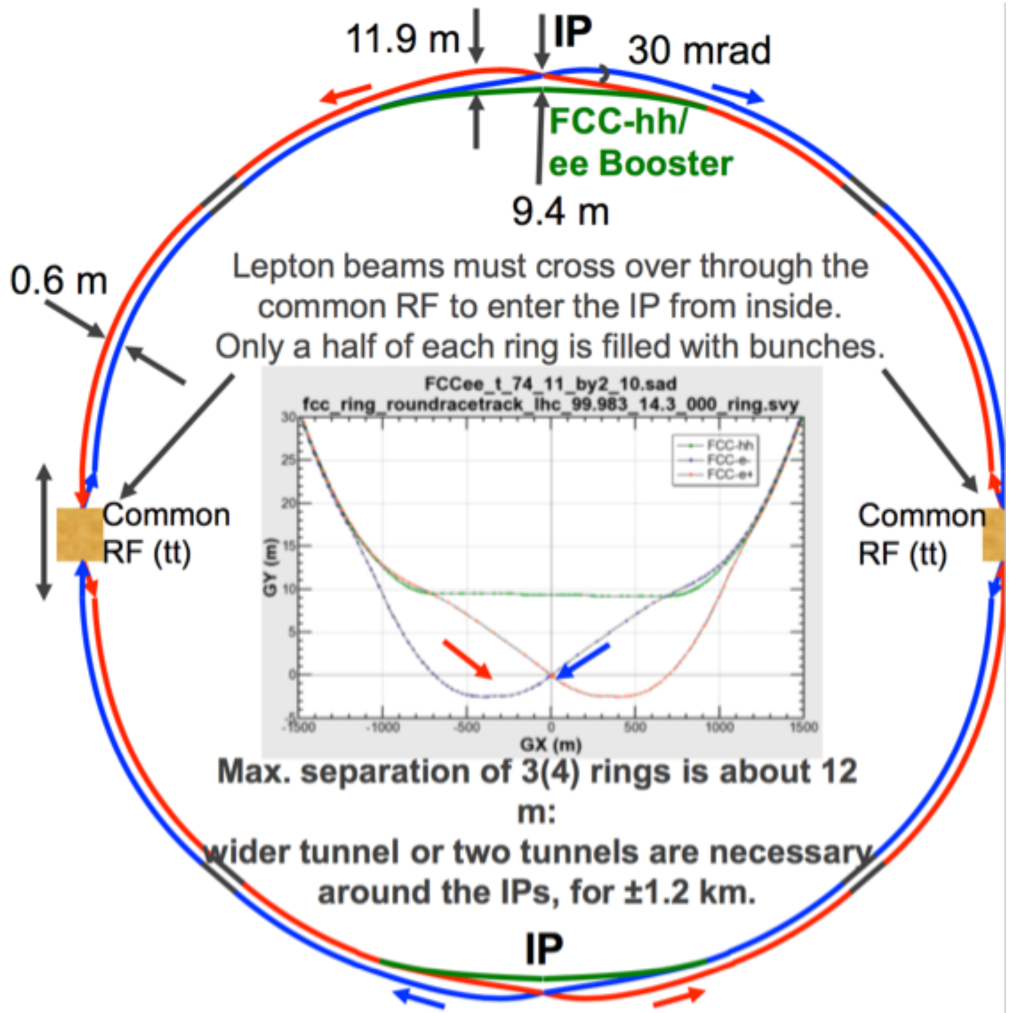
> • *Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.*

Outline

a. **Brief on FCC-ee**
b. **Lepton Flavour Violating τ decays**
c. **Lepton Flavour Violating Z decays**

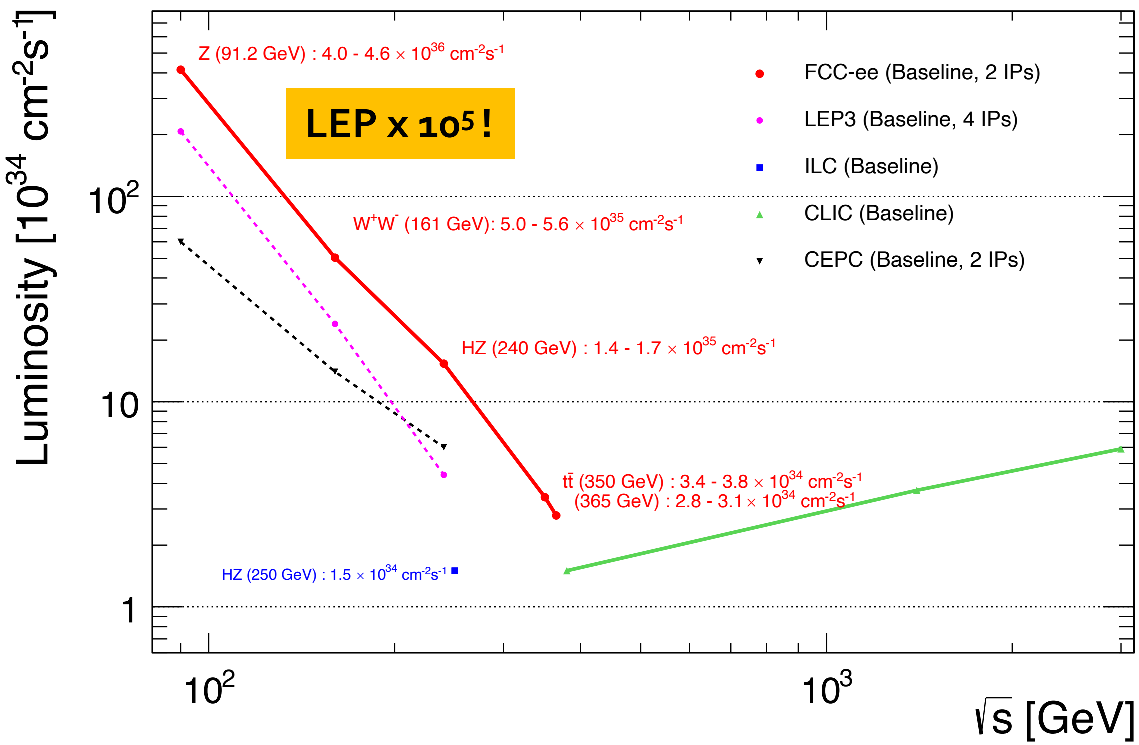
References:
- FCC CDR Volume 1
- Mogens Dam
  Tau-lepton Physics at the FCC-ee circular e^+e^- Collider
  SciPost Phys.Proc. 1 (2019) 041,
  DOI: 10.21468/SciPostPhysProc.1.041

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



Enormous statistics.
Also for τ-leptons

Z decays	5×10^{12}
$Z \to \tau^+\tau^-$	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	?

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

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 (×10³)	Ratio had to lept	20767 ± 25	0.01	0.2–1	Lepton accept
$\alpha\alpha_s(m_Z)$ (×10⁴)	From R_ℓ	1196 ± 30	0.1	0.4–1.6	ditto
R_b (×10⁶)	Ratio bb to hadrons	216290 ± 660	0.3	< 60	g → bb
N_ν (×10³)	Peak cross section	2991 ± 7	0.005	< 1	Lumi meast
$\sin^2\theta_W^{eff}$ (×10⁶)	From $A_{FB}^{\mu\mu}$ at Z peak	231480 ± 160	3	2–5	E_{Beam} calib
$1/\alpha_{QED}(m_Z)$ (×10³)	From $A_{FB}^{\mu\mu}$ off-peak	128952 ± 14	4	small	QED corr.
$A_{FB}^{pol,\tau}$ (10⁴)	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	?
$\alpha_s(m_W)$ (×10⁴)	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

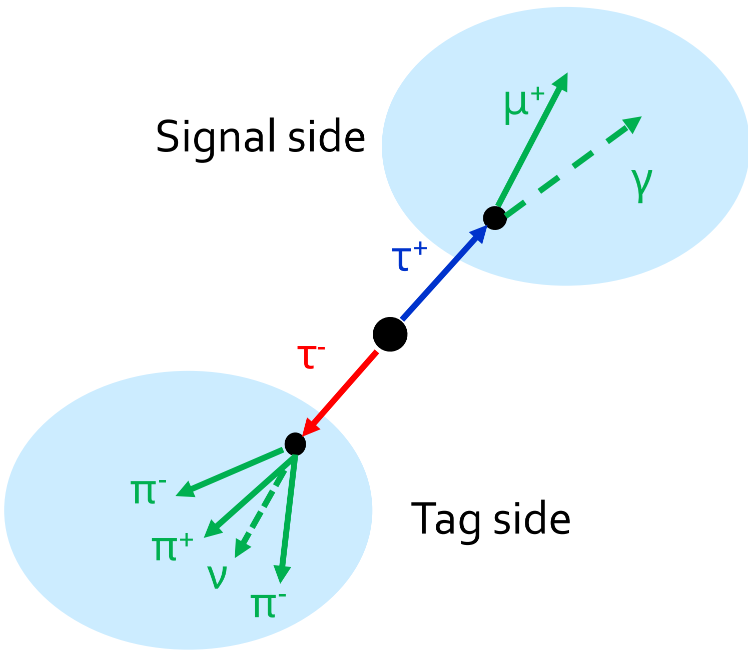
Higgs

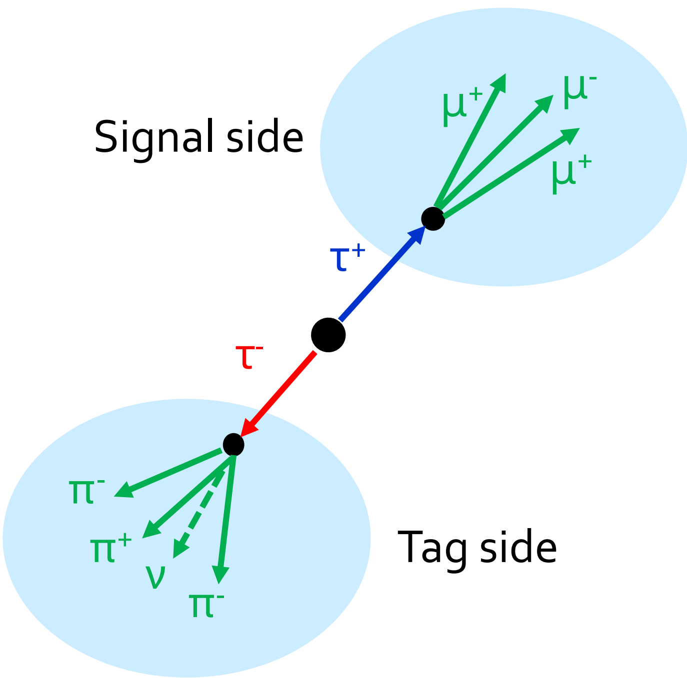
Coupling	HL-LHC	FCC-ee
g_{HWW}	1.4%	0.43%
g_{HZZ}	1.3%	0.17%
g_{Hbb}	2.9%	0.61%
g_{Hcc}	SM	1.21%
$g_{H\tau\tau}$	1.7%	0.74%
$g_{H\mu\mu}$	4.4%	9.0%
$g_{H\gamma\gamma}$	1.6%	3.9%
g_{Hgg}	1.8%	1.0%
BR_{EXOT}	SM	< 1.0%
Γ_H	SM	1.3%
g_{Htt}	2.5%	-
g_{HHH}	50%	34%

… and, on top of that, we can do quite a bit of heavy flavour physics including τ …

LFV τ decays

Two benchmark modes:





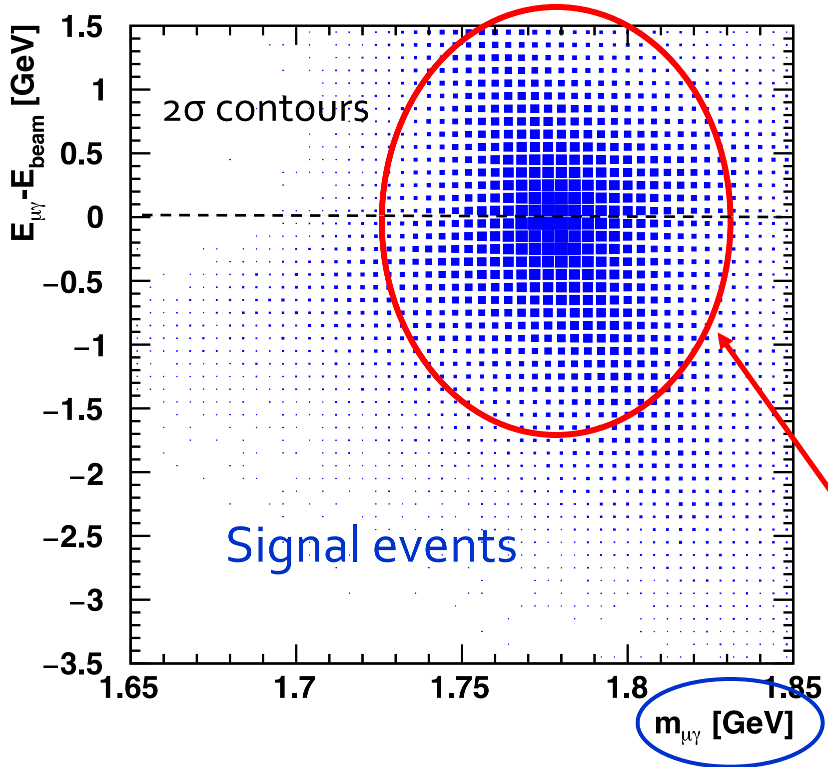
$\tau^- \to e^-\gamma$, $\tau^- \to \mu^-\gamma$

- **Current limits:**
  - **$Br(\tau^- \to e^-\gamma) < 3.3 \times 10^{-8}$** BaBar, 10.6 GeV; 4.8×10^8 $e^+e^- \to \tau^+\tau^-$: 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 γ from ISR/FSR and μ from $\tau \to \mu\nu\bar{\nu}$
- **At FCC-ee, with 1.7×10^{11} $\tau^+\tau^-$ events, what can be expected?**
  - Boost 8-9 times higher than at B-factories
  - Detector resolutions rather different, especially ECAL
  - Parametrised study of signal and the main background, $e^+e^- \to \tau^+\tau^-\gamma$, performed
    - See following 2 pages
  - From this study (assuming a 25% signal and background efficiency), projected BR sensitivity:

2×10^{-9}

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

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



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:

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

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

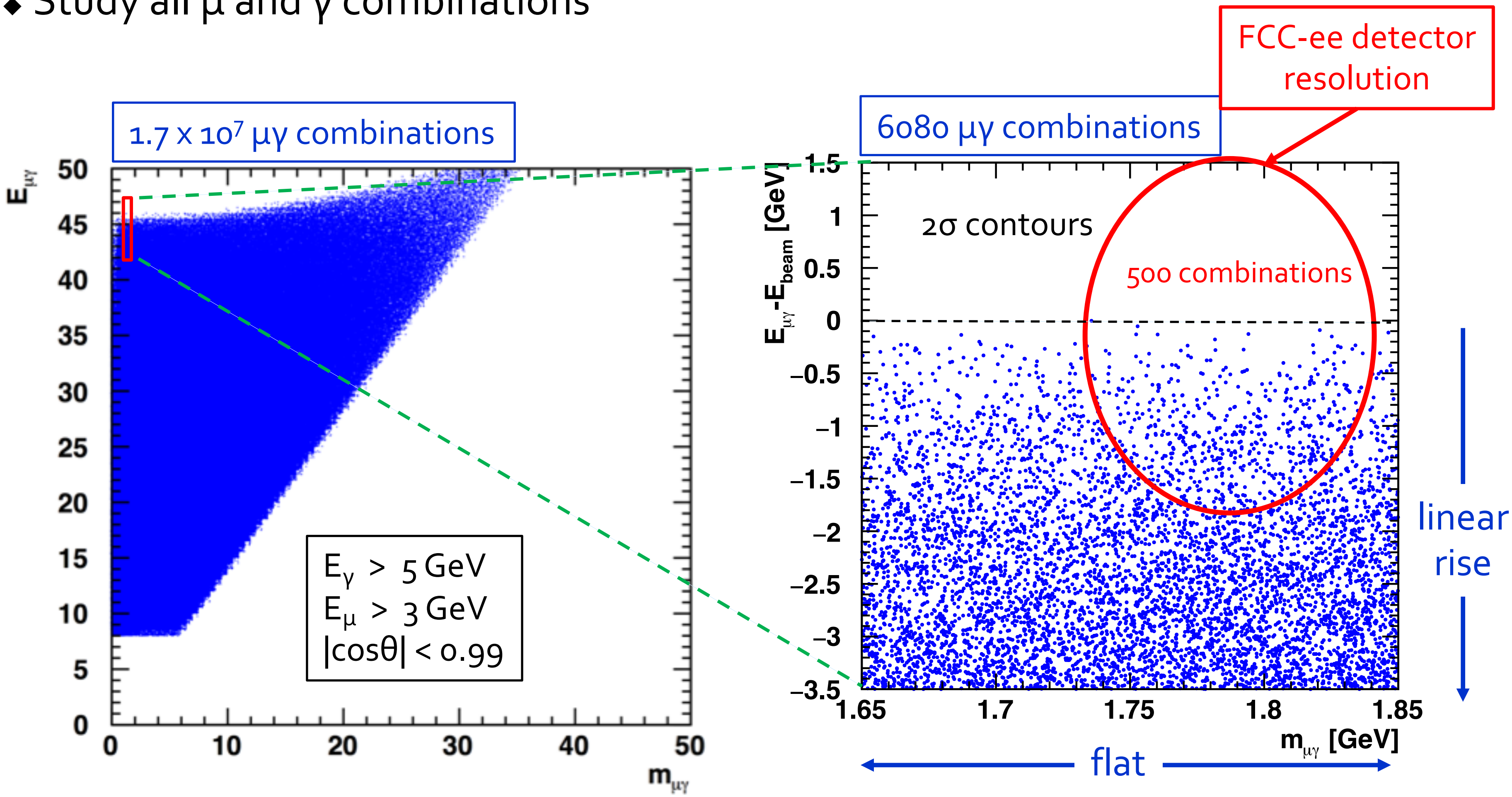
- Muon momentum [GeV]
  $\sigma(p_T)/p_T = 2\times10^{-5} \times p_T \oplus 1\times10^{-3}$
- Photon ECAL energy [GeV]
  $\sigma(E)/E = 0.165/\sqrt{E} \oplus 0.010/E \oplus 0.011$
- Photon ECAL spatial [mm]
  $\sigma(x) = \sigma(y) = (6/E \oplus 2)$ mm

From this, determine **FCC-ee** effective detector resolution for $\tau \rightarrow \mu\gamma$

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

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

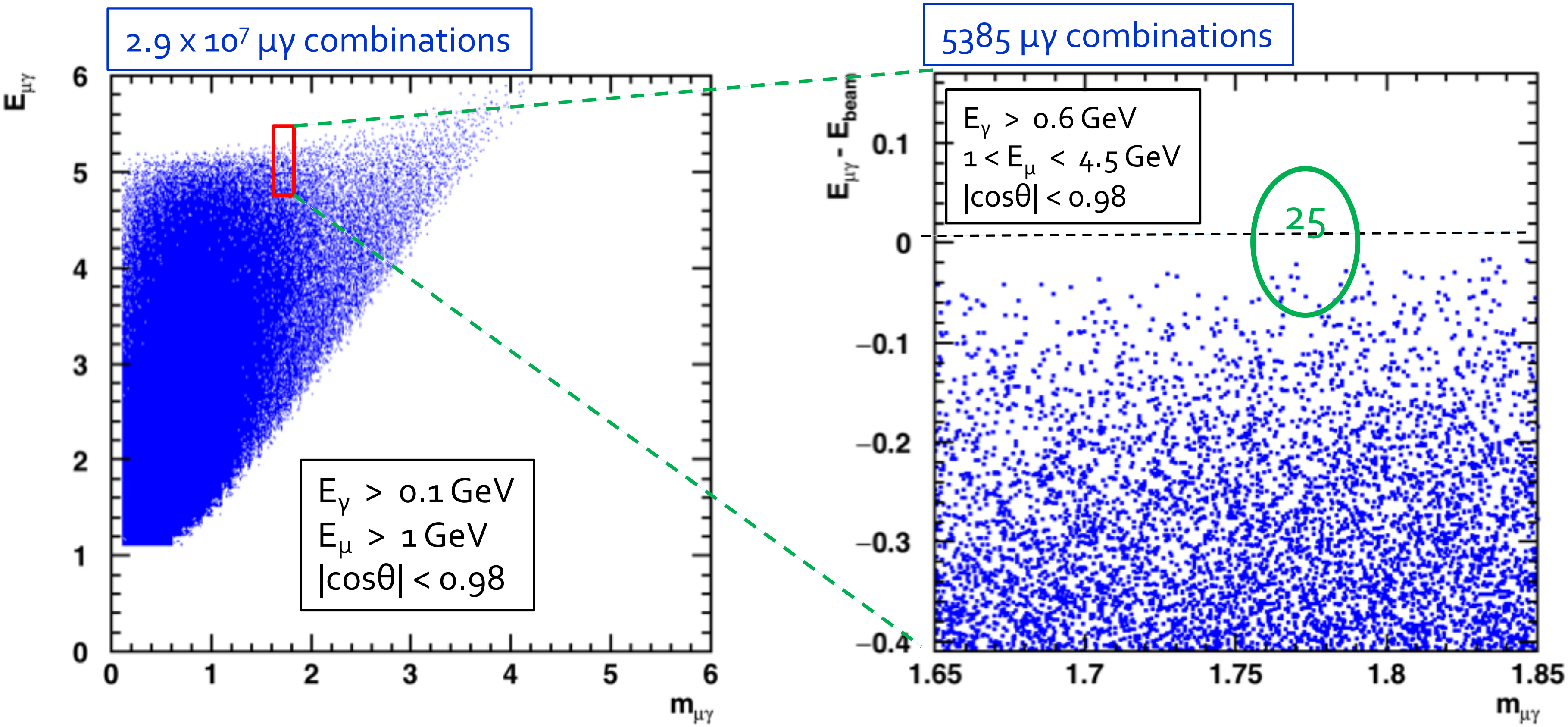
- Background: Generate 5 x 10^8 events $e^+e^- \to Z \to \tau^+\tau^-(\gamma) \to (\mu^+\nu\nu)(\mu^-\nu\nu)(\gamma)$
  - 1 x 10^9 $\tau \to \mu\nu\nu$ decays corresponding to
    - 5.7 x 10^9 τ decays from 8.4 x 10^{10} Z decays (1.6% of full FCC-ee statistics)
- Study all μ and γ combinations



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

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

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



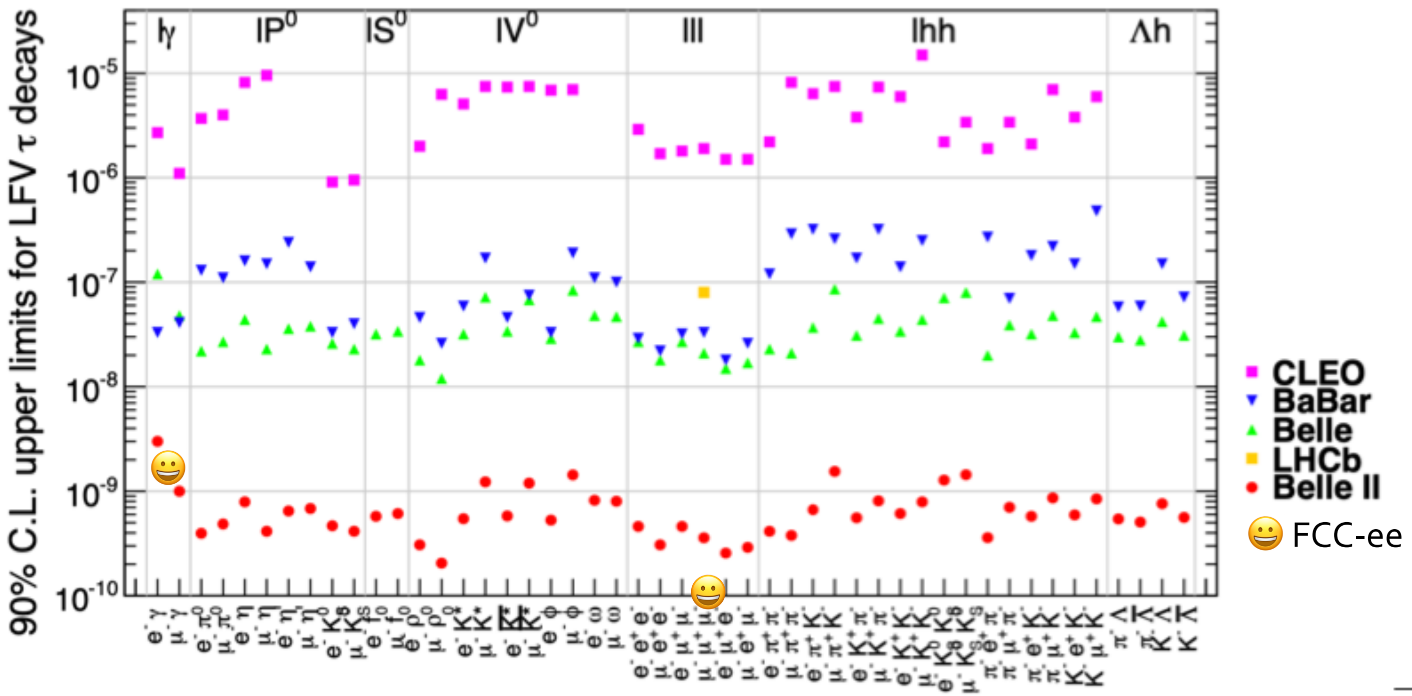
From this study, estimated limit: **1.9 x 10^{-9}**

Compare to my extrapolation of current BaBar limit to Belle2 statistics: ~3-4 x 10^{-9}

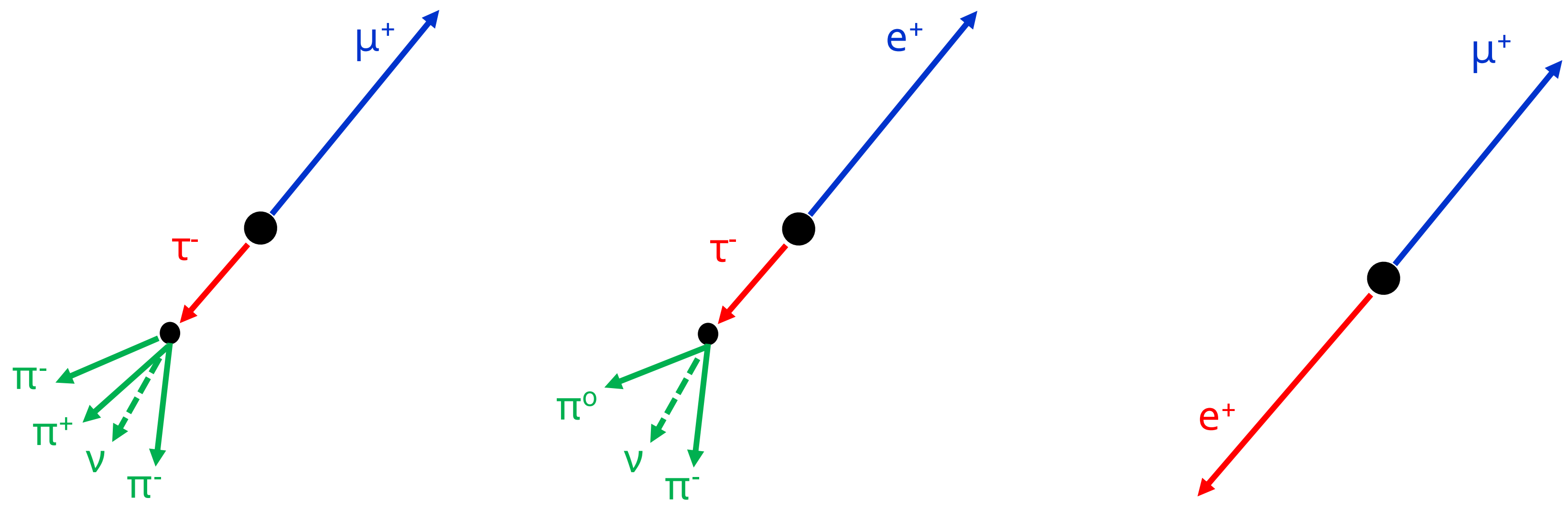
Agrees within a factor 2
Not too bad

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

- Current limits:
  - All 6 combs. of $e^\pm$, $\mu^\pm$: Br $\lesssim 2 \times 10^{-8}$ Belle@10.6 GeV; 7.2×10^8 $e^+e^- \to \tau^+\tau^-$: 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…

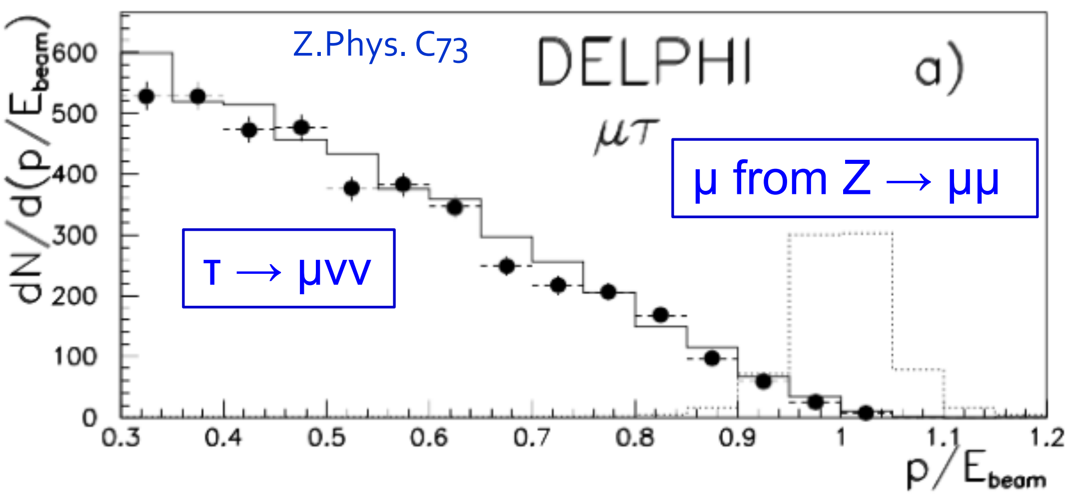


LFV Z decays



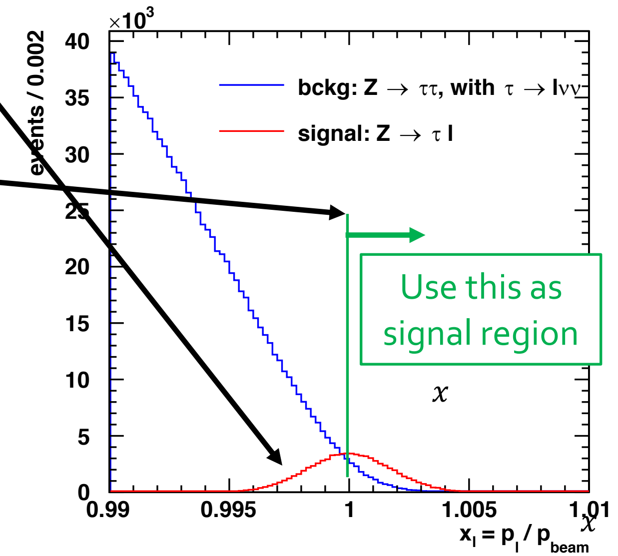
$Z \to e\tau$ and $Z \to \mu\tau$

- Current limits:
  - **$Br(Z \to e\tau) < 9.8 \times 10^{-6}$** 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



$Z \rightarrow \ell\tau$ - Study of Sensitivity

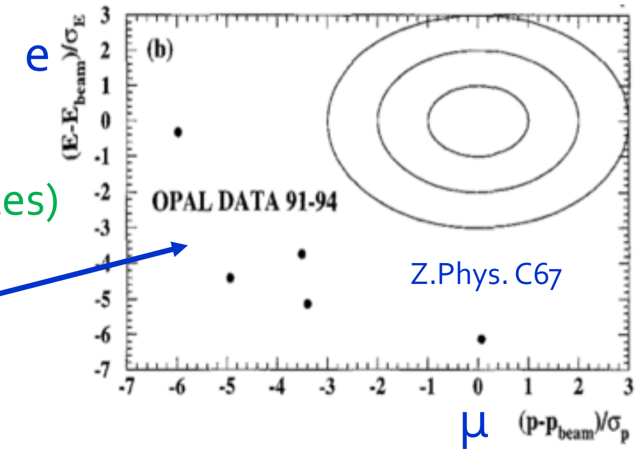
- Generate very upper part of μ momentum spectrum from τ → μνν decays
  - Luminosity equivalent to 5×10^{12} Z decays
- Inject LFV signal of adjustable strength
  - Here for illustration, **Br(Z → τμ) = $\mathbf{10^{-7}}$**, i.e. 500,000 e/μ
- Smear momentum by variable amounts, here **1.8×10^{-3}**
- 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 have a momentum resolutiuon at p=45.6 GeV of about **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, $\delta p/p = 1.8 \times 10^{-3}$, 25% signal and bkg efficiency (clear tau)
  - For Z→ τμ, sensitivity down to BRs of **10^{-9}**
  - For Z→τe, similar sensitivity **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 → eμ

- Current limit:
  - 7.5×10^{-7} **LHC/ATLAS** ($20\ fb^{-1}$; no candidates)
  - 1.7×10^{-6} **LEP/OPAL** (4.0×10^{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: $\mathbf{4 \times 10^{-6}}$
    - 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(μ → e)
      - Notice: ATLAS uses transition radiation signal as part of their electron ID.
- 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 **≲ 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):

- 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)
  - Competitive measurement (possibly substantial improvement) of **τ mass**

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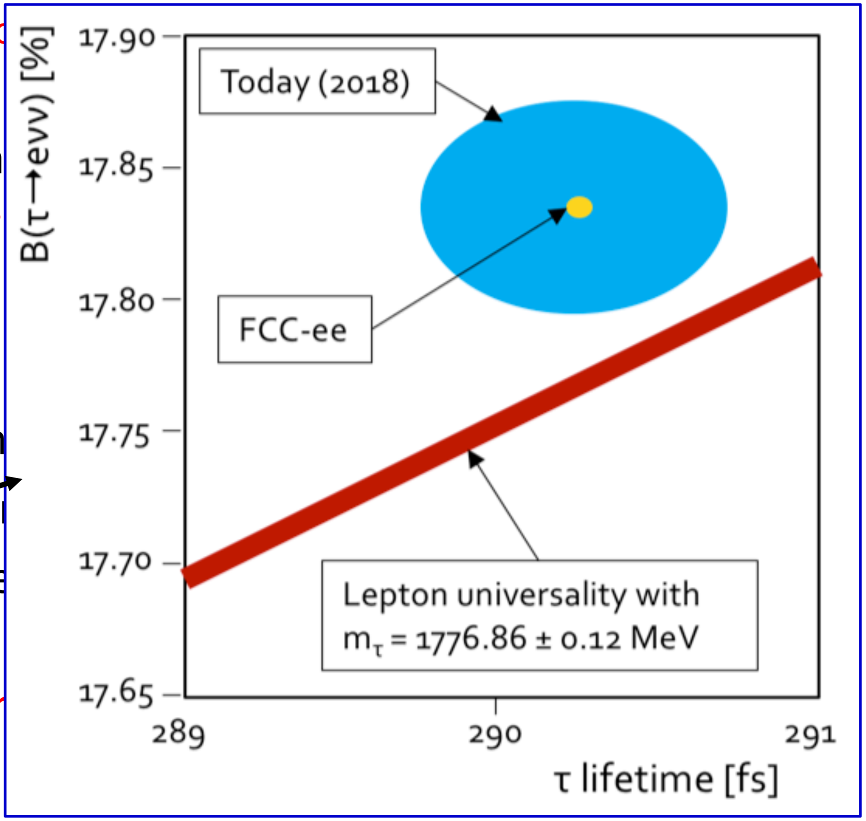

Detector requirements

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
    - Aleph @LEP did pretty well with 3x3 cm ECAL cells divided into three longitudinal samplings. Need study of "modern" calorimeter concepts
- **PID**
  - Necessary if one desires to separate π/K modes (0 – 45 GeV momentum range)
  - **Redundancy**: Provides valuable handle to create test samples for study of calorimetry
    - For drift chamber of IDEA detector concept, even for e/μ separation for all momenta

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- With its TeraZ programme, FCC-ee will be a phenomenal factory for the production of heavy flavour including τ-leptons
- Possibility of unprecedented precision on τ properties and rare decays
- Not obvious that an "off-the-shelf" e+e- Higgs-factory detector design would suffice to beat down the systematics
- Now, is the time to develop the precise detector requirements and to work on the optimisation of the detector design
- International participation very welcome

Extra Slides