Tau Physics at FCC-ee

15th International Workshop on Tau Lepton Physics, 24-28 Sep. 2018
The Future Circular Colliders

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

- Ultimate goal:
  - 100 TeV pp-collider: FCC-hh
    - Defining infrastructure requirements

- Possible first step:
  - e⁺e⁻ collider: FCC-ee
    - High Lumi, $E_{\text{cm}} = 90-400$ GeV

CDR and cost review to appear Q4 2018 for European Strategy Update

Resources:
- First Look at the Physics Case of TLEP
- Physics at the FCC-hh, a 100 TeV pp collider
- 1st FCC Physics Workshop, Jan 2017
- 2nd FCC Physics Workshop, Jan 2018
Outline

a. FCC-ee
b. Lepton Flavour Violating Z decays
c. Lepton Universality
d. Lepton Flavour Violating $\tau$ decays
FCC-ee

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.

Max. separation of 3(4) rings is about 12 m:

wider tunnel or two tunnels are necessary around the IPs, for ±1.2 km.
Luminosity & Statistics

Enormous statistics. Also for τ-leptons

<table>
<thead>
<tr>
<th>Process</th>
<th>E$_{CM}$ (GeV)</th>
<th>Luminosity ($10^{34}$ cm$^{-2}$s$^{-1}$)</th>
<th>Year(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z peak</td>
<td>91</td>
<td>5 x 10$^{12}$</td>
<td>4</td>
</tr>
<tr>
<td>WW threshold</td>
<td>161</td>
<td>10$^8$</td>
<td>1</td>
</tr>
<tr>
<td>ZH threshold</td>
<td>240</td>
<td>10$^6$</td>
<td>3</td>
</tr>
<tr>
<td>tt threshold</td>
<td>350</td>
<td>10$^6$</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>E$_{CM}$ (GeV)</th>
<th>Luminosity ($10^{34}$ cm$^{-2}$s$^{-1}$)</th>
<th>Year(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z decays</td>
<td></td>
<td></td>
<td>5 x 10$^{12}$</td>
</tr>
<tr>
<td>Z → τ$^+τ^-$</td>
<td></td>
<td></td>
<td>1.7 x 10$^{11}$</td>
</tr>
<tr>
<td>1 vs. 3 prongs</td>
<td></td>
<td></td>
<td>4.2 x 10$^{10}$</td>
</tr>
<tr>
<td>3 vs. 3 prong</td>
<td></td>
<td></td>
<td>3.6 x 10$^9$</td>
</tr>
<tr>
<td>1 vs. 5 prong</td>
<td></td>
<td></td>
<td>2.8 x 10$^8$</td>
</tr>
<tr>
<td>1 vs. 7 prong</td>
<td></td>
<td></td>
<td>&lt; 87,000</td>
</tr>
<tr>
<td>1 vs. 9 prong</td>
<td></td>
<td></td>
<td>?</td>
</tr>
</tbody>
</table>
FCC-ee Detector Designs

- Baseline detector #1: CLD
  - The CLIC detector is being adapted for FCC-ee
  - Changeover mostly straightforward
    - Smaller beam pipe radius (15 mm)
      - Inner pixel layer closer to IP
    - Smaller B field
      - Larger tracker radius (1.5 $\rightarrow$ 2.2 m)
    - Lower collision energies
      - Thinner HCAL (4.2 $\rightarrow$ 3.7 m)
  - Continous operation (no power pulsing)
    - Increased cooling
    - Thicker pixel/tracker layers
    - Reduced calorimeter granularity

- Baseline detector #2: IDEA Concept
  - Main "peculiarities"
    - Extremely light drift chamber
    - Dual readout calorimeter
    - Coil inside calorimeters
A wealth of EW and Higgs Precision Measurements

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>m_Z (MeV)</td>
<td>Lineshape</td>
<td>91187.5 ± 2.1</td>
<td>0.005</td>
<td>&lt; 0.1</td>
<td>QED corr.</td>
</tr>
<tr>
<td>Γ_Z (MeV)</td>
<td>Lineshape</td>
<td>2495.2 ± 2.3</td>
<td>0.008</td>
<td>&lt; 0.1</td>
<td>QED corr.</td>
</tr>
<tr>
<td>R_l</td>
<td>Peak</td>
<td>20.767 ± 0.025</td>
<td>0.00001</td>
<td>&lt; 0.001</td>
<td>Statistics</td>
</tr>
<tr>
<td>R_b</td>
<td>Peak</td>
<td>0.21629 ± 0.00066</td>
<td>0.0000003</td>
<td>&lt; 0.000006</td>
<td>g → bb</td>
</tr>
<tr>
<td>N_ν</td>
<td>Peak</td>
<td>2.984 ± 0.008</td>
<td>0.00004</td>
<td>&lt; 0.004</td>
<td>Lumi meas</td>
</tr>
<tr>
<td>sin^2θ_W^{eff}</td>
<td>A_{FB}^{#mu} (peak)</td>
<td>0.23148 ± 0.00016</td>
<td>0.0000003</td>
<td>0.0000006</td>
<td>Beam energy</td>
</tr>
<tr>
<td>1/α_{QED}(m_Z)</td>
<td>A_{FB}^{#mu} (off-peak)</td>
<td>128.952 ± 0.014</td>
<td>0.004</td>
<td>&lt; 0.004</td>
<td>QED corr.</td>
</tr>
<tr>
<td>α_s(m_Z)</td>
<td>R_l</td>
<td>0.1190 ± 0.0025</td>
<td>0.000001</td>
<td>0.0001</td>
<td>New Physics</td>
</tr>
<tr>
<td>m_w (MeV)</td>
<td>Threshold scan</td>
<td>80385 ± 15</td>
<td>0.3</td>
<td>&lt; 0.5</td>
<td>EW Corr.</td>
</tr>
<tr>
<td>N_ν</td>
<td>e^+e^- → γ Z, Z → νν, ll</td>
<td>2.92 ± 0.05</td>
<td>0.001</td>
<td>&lt; 0.001</td>
<td>?</td>
</tr>
<tr>
<td>α_s(m_w)</td>
<td>B_{had} = (Γ_{had}/Γ_{tot})_W</td>
<td>67.41 ± 0.27</td>
<td>0.000018</td>
<td>&lt; 0.0001</td>
<td>CKM Matrix</td>
</tr>
<tr>
<td>m_top (MeV)</td>
<td>Threshold scan</td>
<td>173340 ± 760 ± 500</td>
<td>10</td>
<td>20</td>
<td>QCD corr.</td>
</tr>
<tr>
<td>Γ_top (MeV)</td>
<td>Threshold scan</td>
<td>?</td>
<td>25</td>
<td>?</td>
<td>α_s(m_Z)</td>
</tr>
<tr>
<td>λ_top</td>
<td>Threshold scan</td>
<td>μ = 1.2 ± 0.4</td>
<td>15%</td>
<td>?</td>
<td>α_s(m_Z)</td>
</tr>
</tbody>
</table>

And on top we can also do some tau physics

Coupling          | HL-LHC | FCC-ee |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>g_{HWW}</td>
<td>3.5%</td>
<td>0.47%</td>
</tr>
<tr>
<td>g_{HZZ}</td>
<td>3.5%</td>
<td>0.22%</td>
</tr>
<tr>
<td>g_{Hbb}</td>
<td>8.2%</td>
<td>0.68%</td>
</tr>
<tr>
<td>g_{Hcc}</td>
<td>SM</td>
<td>1.2%</td>
</tr>
<tr>
<td>g_{Htt}</td>
<td>6.5%</td>
<td>0.80%</td>
</tr>
<tr>
<td>g_{H#mu}</td>
<td>5.0%</td>
<td>8.6%</td>
</tr>
<tr>
<td>g_{H#gamma}</td>
<td>3.6%</td>
<td>3.8%</td>
</tr>
<tr>
<td>g_{Hgg}</td>
<td>3.9%</td>
<td>1.0%</td>
</tr>
<tr>
<td>g_{HZY}</td>
<td>~12%</td>
<td>?</td>
</tr>
<tr>
<td>BR_{EXOT}</td>
<td>SM</td>
<td>&lt; 1.1%</td>
</tr>
<tr>
<td>Γ_H</td>
<td>~50%</td>
<td>1.6%</td>
</tr>
<tr>
<td>g_{Htt}</td>
<td>4.2%</td>
<td>10% (*)</td>
</tr>
<tr>
<td>g_{HHHH}</td>
<td>30-50%</td>
<td>40%(*)</td>
</tr>
</tbody>
</table>
LFV Z decays

\[ \pi^- \rightarrow \mu^+ + \tau^- + \pi^- + \pi^0 + e^+ + \nu \]


**Current limits:**

- $\text{Br}(Z \rightarrow e\tau) < 9.8 \times 10^{-6}$  
  LEP/OPAL  
  (4 $\times 10^6$ Z decays)

- $\text{Br}(Z \rightarrow \mu\tau) < 12. \times 10^{-6}$  
  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 $\tau \rightarrow e\nu\nu / \tau \rightarrow \mu\nu\nu$ with two (very) soft neutrinos
- How much background depends on energy/momentum resolution
- Example DELPHI

---

**Figure:**

- Diagram showing the distribution of $dN/d(p/E_{beam})$ for $Z \rightarrow e\tau$ and $Z \rightarrow \mu\tau$ processes in DELPHI experiment.

---

**Caption:**

- Z.Phys. C73
- $\tau \rightarrow \mu\nu\nu$
- $\mu$ from $Z \rightarrow \mu\mu$
Z → ℓτ - Study of Sensitivity

- Generate very upper part of μ momentum spectrum from τ → μνν decays
  - Luminosity equivalent to 5x10^{12} Z decays
- Inject LFV signal of adjustable strength
  - Here for illustration, Br(Z → τμ) = 10^{-7}, i.e. 500,000 e/μ
- Smear momentum by variable amounts, here 3x10^{-3}
- Define x > 1 as signal region
- Derive 95% confidence limit on excess in signal region
- Findings:
  - Sensitivity scales **linear** with momentum resolution
  - Detectors for FCC-ee (CLD and IDEA) have a momentum resolution at p=45.6 GeV of about 3x10^{-3}
    - Ten times better than for LEP detectors
  - Contribution from beam-energy spread (0.5 x 10^{-3}) is negligible
- Sensitivity for 5 x 10^{12} Z decays, δp/p = 3x10^{-3}, 25% signal and bkg efficiency (clear tau)
  - For Z→τμ, can probe BRs down to 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.
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)

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 \(dE/dx\) measurement available, some independent \(e/\mu\) separation at 45.6 GeV
    - Could give handle to determine misidentification probability \(P(\mu \rightarrow e)\)
    - Notice: ATLAS uses transition radiation as part of electron ID.

FCC-\(ee\):
- Misidentification from catastrophic energy loss corresponds to limit of about \(\text{Br}(Z \rightarrow e\mu) \approx 10^{-7}\)
- Possibly do \(O(10)\) better than that

\(\text{Br}(Z \rightarrow e\mu) \sim 10^{-8}\)
Lepton Universality

In $\tau$ decays
a) mass
b) lifetime
c) leptonic branching fractions

In $b$ decays

Lepton universality with $m_\tau = 1776.86 \pm 0.12$ MeV

Today (2018)

FCC-ee
**Tau Mass (i)**

- **Current world average:** $m_\tau = 1776.86 \pm 0.12 \text{ MeV}
- **Best in world:** BES3 (threshold scan) $m_\tau = 1776.91 \pm 0.12 \text{ (stat.) } +0.10_{-0.13} \text{ (syst.) MeV}
- **Best at LEP:** OPAL
  - About factor 10 from world’s best
  - Main result from endpoint of distribution of pseudo-mass in $\tau \rightarrow 3\pi^{\pm}(\pi^{0})\nu_\tau$
  - Dominant systematics:
    - Momentum scale: 0.9 MeV
    - Energy scale: 0.25 MeV
    - Dynamics of $\tau$ decay: 0.10 MeV
- **Same method from Belle**
  - Main systematics
    - Beam energy & tracking system calib.: 0.26 MeV
    - Parameterisation of the spectrum edge: 0.18 MeV

$$m_\tau = 1776.61 \pm 0.13 \text{ (stat.) } \pm 0.35 \text{ (syst.) MeV}$$

---

Pseudo-mass: $M_{\text{min}} = \sqrt{M_{3\pi}^2 + 2(E_{\text{beam}} - E_{3\pi})(E_{3\pi} - P_{3\pi})}$

---

Phys. Lett. B492, 23

OPAL

Uncertainty: one third bin size

Belle

PRL 99, 011801 (2007)

Uncertainty: half bin size
Prospects for FCC-ee:

- 3 prong, 5 prongs, (perhaps even 7 prongs?)
- Statistics $10^5$ times OPAL: $\delta_{\text{stat}} = 0.005 \text{ MeV}$
- Systematics:
  - At FCC-ee, $E_{\text{BEAM}}$ known to better than 0.1 MeV (~ 1 ppm) from resonant depolarisation
    - Negligible effect on $m_\tau$
  - Likely dominant experimental contribution comes from understanding of the mass scale
    - Use $D^0 \rightarrow K^- \pi^+ / K^- \pi^+ \pi^- \pi^-$ and $D^+ \rightarrow K^- \pi^+ \pi^+$ to fix mass scale ($m_D$ known to 50 keV)
    - Use high stats $e^+e^- \rightarrow \mu^+\mu^-$ sample to fix momentum scale. Extrapolate down to momenta typical for $\tau \rightarrow 3\pi$.
  - Hope to reduce uncertainty from parametrisation of spectrum edge by use of theoretical spectrum checked against high statistics data
  - Cross checks using 5-prongs
- Suggested overall systematics: $\delta_{\text{syst}} = 0.120 \text{ MeV}$
  - Could potentially touch current precision but probably no substantial improvement
Current world average: \( \tau_{\tau} = 290.3 \pm 0.5 \text{ fs} \)

Best in world (Belle): \( \tau_{\tau} = 290.17 \pm 0.53_{\text{stat}} \pm 0.22_{\text{syst}} \text{ fs} \)
- Large statistics: 711 fb\(^{-1}\) @ \( \Upsilon(4s) \): \( 6.3 \times 10^8 \tau^+\tau^- \) events
- Use 3 vs. 3 prong events; reconstruct 2 secondary vertices + primary vertex
- Measure flight distance \( \Rightarrow \) proper time
- Dominant systematics: Vertex detector alignment to \( \sim 0.25 \mu m \)
  - Vertex detector outside 15 mm beam pipe

Best at LEP (DELPHI): \( \tau_{\tau} = 290.0 \pm 1.4_{\text{stat}} \pm 1.0_{\text{syst}} \text{ fs} \)
- “Low” statistics: \( \sim 250,000 \tau^+\tau^- \) events
- Three methods:
  - Decay length (1v3 + 3v3), impact parameter difference (1v1), miss distance (1v1)
  - Lowest systematics from decay length (1v3)
    - Dominant systematics: Vertex detector alignment to 7.5 \( \mu m \)
      - Alignment with data (q\( \bar{q} \) events): statistics limited
    - Vertex detector: 7.5 \( \mu m \) point resolution at 63, 90, and 109 mm
Prospects at FCC-ee

- Small beam-pipe radius (15 mm): Vertex detector with 3 μm space points at 18, 38, 58 mm
  - [DELPHI: 63, 90, 109 mm]
- Impact parametre resolution ~5 times better than at LEP for relevant momenta
  - DELPHI: \( a = 20 \mu m, b = 65 \mu m \)
  - FCC-ee: \( a = 3 \mu m, b = 15 \mu m \)
  - Belle: \( a = 19 \mu m, b = 50 \mu m \)
- Assume same alignment uncertainty as Belle:
  - 0.25 μm, i.e. factor 30 improvement wrt DELPHI.
  - Possible systematics on flight distance method: 1.3/30 fs i.e.
    \[
    \delta_{syst} = 0.04 \text{ fs}
    \]

Further prospects: lifetime can be measured with different systematics in many modes

- 1v1: impact parameter difference, miss distance
- 1v3: flight distance
- 3v3 (4x10^9 events): flight distance sum
Tau Leptonic Branching Fractions

- **World average**
  - \( B(\tau \to e\nu\nu) = 17.82 \pm 0.05 \% \) ; \( B(\tau \to \mu\nu\nu) = 17.39 \pm 0.05 \% \)

- **Dominated by ALEPH**
  - \( B(\tau \to e\nu\nu) = 17.837 \pm 0.072_{\text{stat}} \pm 0.036_{\text{syst}} \% \) ; \( B(\tau \to \mu\nu\nu) = 17.319 \pm 0.070_{\text{stat}} \pm 0.032_{\text{syst}} \% \)

- **Three uncertainty contributions were dominant in the Aleph measurement**
  - Selection efficiency: \( 0.021 / 0.020 \% \)
  - Non-\( \tau^+\tau^- \) background: \( 0.029 / 0.020 \% \)
  - Particle ID: \( 0019 / 0.021 \% \)
  - All of these are limited by statistics: size of test samples, etc.

- **Prospects at FCC-ee**
  - Enormous statistics:
    \[ \delta_{\text{stat}} = 0.0001 \% \]
  - Systematic uncertainty is hard to (gu)estimate at this point.
    - Depends intimately on the detailed performance of the detector(s)
      - At the end of the day, between LEP experiments, \( \delta_{\text{syst}} \) varied by up to a factor 3
        - Lesson: Design your detector with care!
    Let me put here as a placeholder a suggested factor 10 improvement wrt ALEPH:
    \[ \delta_{\text{syst}} = 0.003 \% \]
# Summary of Precisions & Lepton Universality

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_\tau$ [MeV]</td>
<td>Threshold / inv. mass endpoint</td>
<td>$1776.86 \pm 0.12$</td>
<td>$0.005$</td>
<td>$0.12$</td>
<td>Mass scale</td>
</tr>
<tr>
<td>$\tau_\tau$ [fs]</td>
<td>Flight distance</td>
<td>$290.3 \pm 0.5$ fs</td>
<td>$0.005$</td>
<td>$&lt; 0.040$</td>
<td>Vertex detector alignment</td>
</tr>
<tr>
<td>$B(\tau \to e\nu\nu)$ [%]</td>
<td>Selection of $\tau^+\tau^-$, identification of final state</td>
<td>$17.82 \pm 0.05$</td>
<td>$0.0001$</td>
<td>No estimate; possibly $0.003$</td>
<td>Efficiency, bkg, Particle ID</td>
</tr>
<tr>
<td>$B(\tau \to \mu\nu\nu)$ [%]</td>
<td></td>
<td>$17.39 \pm 0.05$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Lepton Universality Tests:

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Measurement</th>
<th>Current precision</th>
<th>FCC-ee precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>g_\mu/g_e</td>
<td>$</td>
<td>$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$</td>
</tr>
<tr>
<td>$</td>
<td>g_\tau/g_\mu</td>
<td>$</td>
<td>$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$</td>
</tr>
</tbody>
</table>

With the precise FCC-ee measurements of lifetime and BRs, $m_\tau$ could become the limiting measurement in the universality test.

$$\left(\frac{g_\tau}{g_\mu}\right)^2 \approx \frac{\tau_\mu}{\tau_\tau} \cdot \frac{\text{BF}(\tau^- \to e^-\nu_e\nu_\tau)}{\text{BF}(\tau^- \to \mu^-\nu_\mu\nu_\tau)} \left(\frac{m_\mu}{m_\tau}\right)^5$$

With $m_\tau = 1776.86 \pm 0.12$ MeV
Lepton flavour violations in $b$ decays

- Current tensions (several 2-3 $\sigma$ deviations) of Belle & LHCb data with SM predictions
  - In particular, lepton flavour universality is challenged in $b \rightarrow s\ell^+\ell^-$ transitions
    - For example, the rates of $B^0(B^+) \rightarrow K^{*0}(K^+)\ell^+\ell^-$ are different for $\ell = e$ and $\ell = \mu$
    - Differences are also observed in the lepton angular distributions
  - This effect, if real, could be enhanced for $\ell = \tau$, in $B \rightarrow K^{(*)}\tau^+\tau^-$
    - Extremely challenging in hadron colliders
    - With $10^{12} Z \rightarrow bb$, FCC-ee is beyond any foreseeable competition
      - Decay can be fully reconstructed
      - Full angular analysis possible
  - Also sensitive to new physics in $B_s \rightarrow \mu^+\mu^-$
    - None found so far at the LHC ($\sim 50$ events)

\[
BR(B_S^0 \rightarrow \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \sim SM
\]

- Expect a few 1000’s of events by the end of LHC
- $B_S \rightarrow \tau^+\tau^-$ is 250 times more abundant
  - But very difficult at the LHC
- Again, FCC-ee is beyond any foreseeable competition
  - Several 100,000 events expected – reconstruction efficiency under study
LFV $\tau$ decays

![Diagram of LFV $\tau$ decays](image-url)
Current limits:

- $\text{Br}(\tau^- \rightarrow e^- \gamma) < 3.3 \times 10^{-8}$, BaBar, 10.6 GeV; $4.8 \times 10^8 e^+ e^- \rightarrow \tau^+ \tau^- : 1.6$ expected bckg
- $\text{Br}(\tau^- \rightarrow \mu^- \gamma) < 4.4 \times 10^{-8}$

Main background: Radiative events (IRS+FSR), $e^+ e^- \rightarrow \tau^+ \tau^- \gamma$
- $\tau \rightarrow \mu \gamma$ faked by combination of $\gamma$ from ISR/FSR and $\mu$ from $\tau \rightarrow \mu \nu \nu$

At FCC-ee, with $1.7 \times 10^{11} \tau^+ \tau^-$ events, what can be expected?
- Boost 4 - 5 times higher than at superKEKB
- Detector resolutions rather different, especially ECAL
- Parametrised study of signal and the main background, $e^+ e^- \rightarrow \tau^+ \tau^- \gamma$, performed
  - See two following pages
- From this study (assuming a 25% signal and background efficiency), projected BR limit: $2 \times 10^{-9}$
**τ → μγ Study – The signal**

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

**Smear with assumed FCC-ee detector resolutions:**
- Muon momentum [GeV]
  \[ \sigma(p_T)/p_T = 2 \times 10^{-5} \times p_T \oplus 1 \times 10^{-3} \]
- Photon ECAL energy [GeV]
  \[ \sigma(E)/E = 0.165/\sqrt{E} \oplus 0.010/E \oplus 0.011 \]
- Photon ECAL spatial
  \[ \sigma(x) = \sigma(y) = (6/E \oplus 2) \text{ mm} \]

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

\[ \sigma(m_{\gamma\mu}) = 26 \text{ MeV}; \quad \sigma(E_{\gamma\mu}) = 850 \text{ MeV} \]

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:

\[ m_{\gamma\mu} = m_{\text{raw}} \times (E_{\gamma\mu}/E_{\text{beam}}) \]
Background: Generate $5 \times 10^8$ events $e^+e^- \rightarrow Z \rightarrow \tau^+\tau^-(\gamma) \rightarrow (\mu^+\nu\nu)(\mu^-\nu\nu)(\gamma)$

- $1 \times 10^9 \tau \rightarrow \mu\nu\nu$ decays corresponding to
- $5.7 \times 10^9 \tau$ decays from $8.4 \times 10^{10} Z$ decays

Study all $\mu$ and $\gamma$ combinations
\( \tau^- \rightarrow \ell^- \ell^+ \ell^- \)

- Current limits:
  - All 6 combs. of e\(^\pm\), µ\(^\pm\): \( \text{Br} \lesssim 2 \times 10^{-8} \)  
    Belle@10.6 GeV; 7.2 \( \times 10^8 \) \( e^+e^- \rightarrow \tau^+\tau^- \): no cand.
  - \( \mu^-\mu^+\mu^- \): \( \text{Br} < 4.6 \times 10^{-8} \)  
    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 when time comes...
Summary

- With an unrivalled luminosity, the four stage FCC-ee programme foresees the production of $5 \times 10^{12}$ $Z$ decays in its first stage
- A treasure trove for precision measurements and discoveries
- Of most direct relevance to this conference is the production of $1.7 \times 10^{11}$ $\tau^+\tau^-$ pairs:
  - Searches for lepton flavour violating $Z$ decays more sensitive than today by factor $O(10^4)$
    - Sensitivities down to $10^{-9}$
  - Improved lepton universality test by $O(10)$ or more. Down to $10^{-4}$ level on coupling ratios
    - Substantial improvement in $\tau$ lifetime measurement: $O(300)$ statistical, $O(10)$ systematic
    - Substantial improvement in $\tau$ branching fractions: $O(300)$ statistical, $O(\sim10)$ systematic(?)
    - Possibly competitive measurement of $\tau$ mass
  - Searches for lepton flavour violating $\tau$ decays with sensitivities comparable with recent Belle2 projections (arxiv:1808.10567)
    - $\lesssim 10^{-10}$ (for channels with no background) to few $\times 10^{-9}$
- Plus, of course,
  - Tau polarisation measurement for $\sin^2\theta_W$, $\alpha_s$, $\tau$ neutrino mass, etc., etc.
Extra Slides
Scaling of $Z \rightarrow \ell\tau$ sensitivity with #events

- **If no backgrounds**: $1/N$ scaling
- **With backgrounds**: $1/\sqrt{N}$ scaling
Cross check: Perform similar study at B-factory, $\sqrt{s} = 10.6$ GeV

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

From this study, estimated limit: $1.9 \times 10^{-9}$

Compare to my extrapolation of current BaBar limit: $\sim 3-4 \times 10^{-9}$

Agrees within a factor 2

Not too bad