Tau Physics at FCC-ee

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Slightly updated for 11th FCC-ee Workshop, CERN, January 2019

Picture and slide layout, courtesy Jörg Wenninger

The Future Circular Colliders

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

- Ultimate goal:

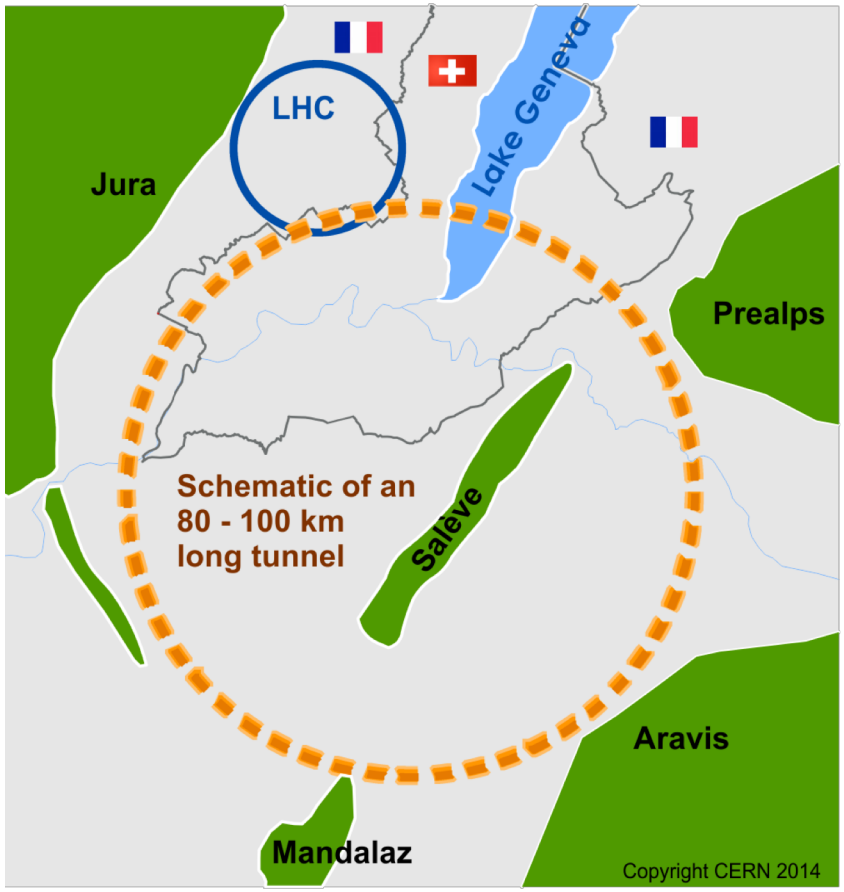
  100 TeV pp-collider: FCC-hh

  - Defining infrastructure requirements

- Possible first step:

  e^+e^- collider: FCC-ee

  - **High Lumi, E_{cm} = 90-400 GeV**



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

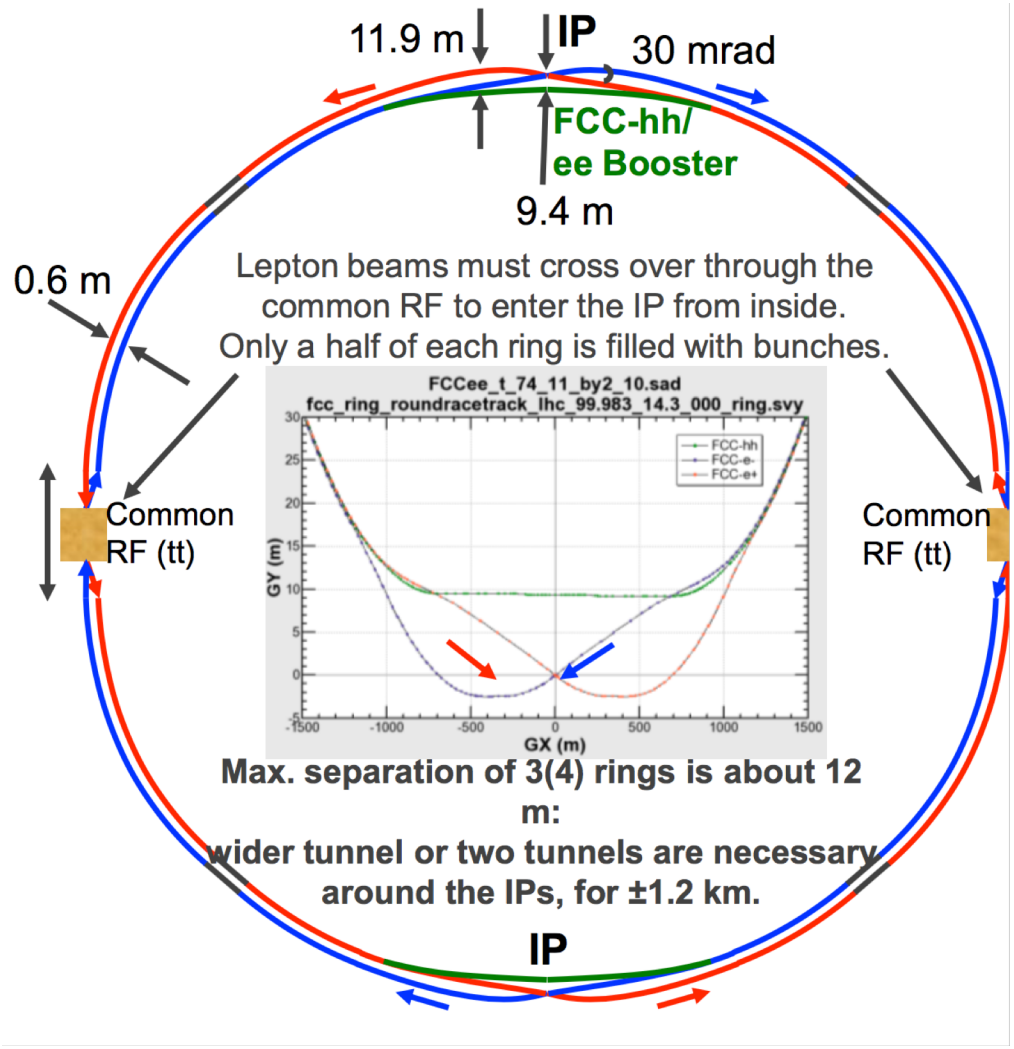
Resources:

- 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

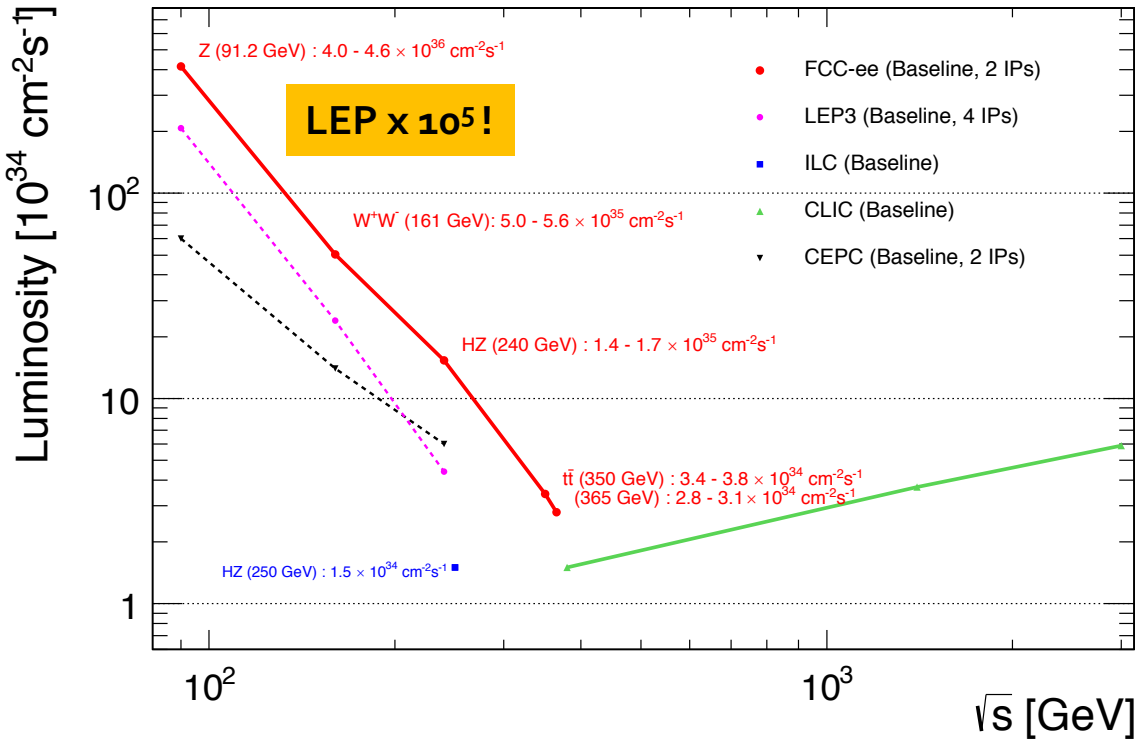
Outline

a. FCC-ee
b. τ-lepton Properties and Lepton Universality
c. Lepton Flavour Violating Z decays
d. Lepton Flavour Violating τ decays

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



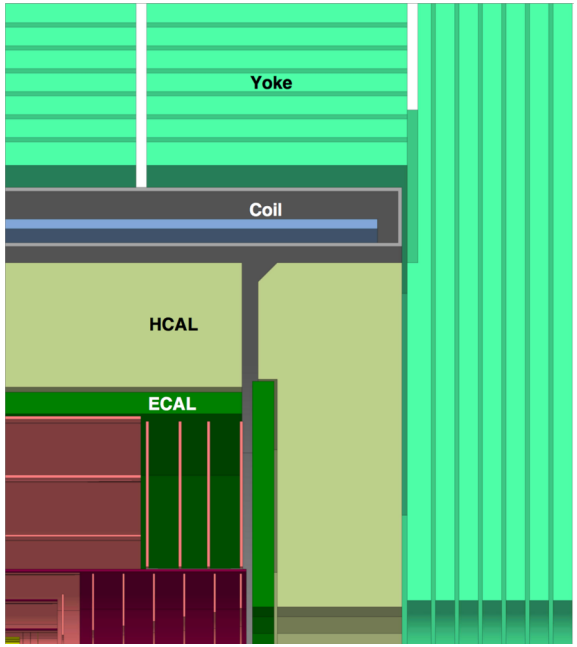
Z peak	E_{CM} : 91 GeV	5 x 10^{12}	$e^+e^- \rightarrow Z$	4 years
WW threshold	E_{CM} : 161 GeV	10^8	$e^+e^- \rightarrow WW$	1 year
ZH threshold	E_{CM} : 240 GeV	10^6	$e^+e^- \rightarrow ZH$	3 years
$t\bar{t}$ threshold	E_{CM} : 350 GeV	10^6	$e^+e^- \rightarrow t\bar{t}$	5 years

Enormous statistics.
Also for τ-leptons

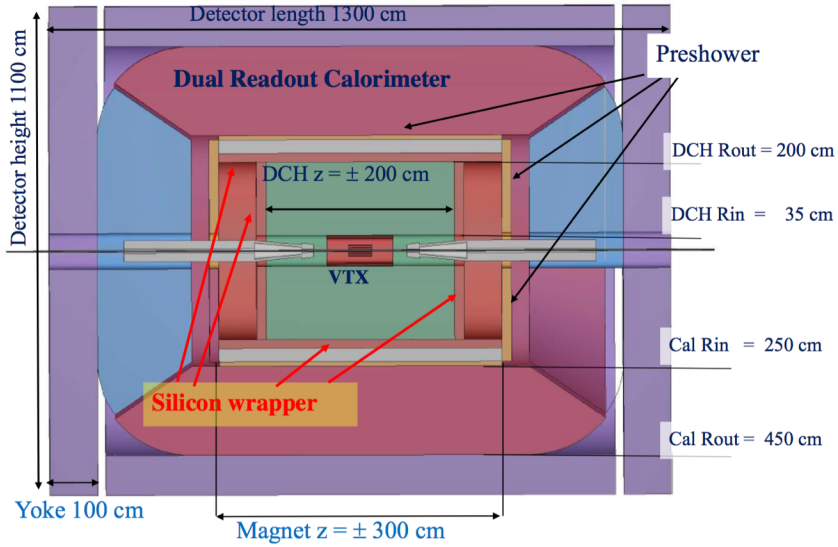
Z decays	5 x 10^{12}
$Z \rightarrow \tau^+\tau^-$	1.7 x 10^{11}
1 vs. 3 prongs	4.2 x 10^{10}
3 vs. 3 prong	3.6 x 10^9
1 vs. 5 prong	2.8 x 10^8
1 vs. 7 prong	< 87,000
1 vs 9 prong	?

FCC-ee Detector Designs

- Baseline detector #1: **CLD**
  - The CLIC detector is being adapted for FCC-ee
  - Changeover mostly straigtforward
    - Smaller beam pipe radius (15 mm)
      - Inner pixel layer closer to IP
    - Smaller B field
      - Larger tracker radius (1.5 → 2.2 m)
    - Lower collision energies
      - Thinner HCAL (4.2 → 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

Electroweak

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corr.
R_l	Peak	20.767 ± 0.025	0.0001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \to bb$
N_ν	Peak	2.984 ± 0.008	0.00004	< 0.004	Lumi meast
$\sin^2\theta_W^{eff}$	$A_{FB}^{\mu\mu}$ (peak)	0.23148 ± 0.00016	0.000003	0.000006	Beam energy
$1/\alpha_{QED}(m_Z)$	$A_{FB}^{\mu\mu}$ (off-peak)	128.952 ± 0.014	0.004	< 0.004	QED corr.
$\alpha_s(m_Z)$	R_l	0.1190 ± 0.0025	0.00001	0.0001	New Physics
m_w (MeV)	Threshold scan	80385 ± 15	0.3	< 0.5	EW Corr.
N_ν	$e^+e^- \to \gamma Z, Z \to \nu\nu, ll$	2.92 ± 0.05	0.001	< 0.001	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 ± 0.27	0.00018	< 0.0001	CKM Matrix
m_{top} (MeV)	Threshold scan	173340 ± 760 ± 500	10	20	QCD corr.
Γ_{top} (MeV)	Threshold scan	?	25	?	$\alpha_s(m_Z)$
λ_{top}	Threshold scan	μ = 1.2 ± 0.4	15%	?	$\alpha_s(m_Z)$

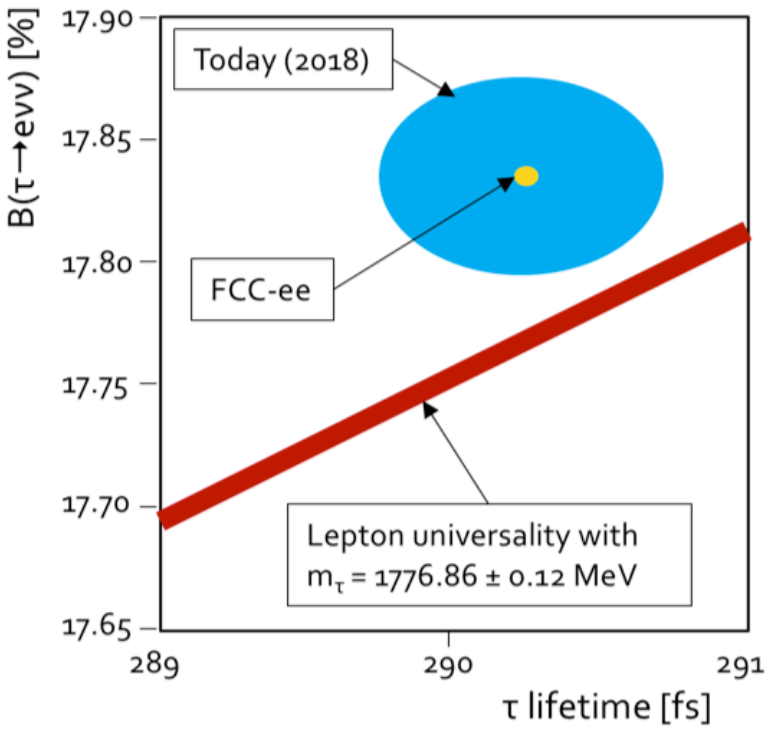
Higgs

Coupling	HL-LHC	FCC-ee
g_{HWW}	3.5%	0.47%
g_{HZZ}	3.5%	0.22%
g_{Hbb}	8.2%	0.68%
g_{Hcc}	SM	1.2%
$g_{H\tau\tau}$	6.5%	0.80%
$g_{H\mu\mu}$	5.0%	8.6%
$g_{H\gamma\gamma}$	3.6%	3.8%
g_{Hgg}	3.9%	1.0%
$g_{HZ\gamma}$	~12%	?
BR_{EXOT}	SM	< 1.1%
Γ_H	~50%	1.6%
g_{Htt}	4.2%	10% (*)
g_{HHH}	30-50% ?	40%(*)

And on top, we can also do some tau physics…

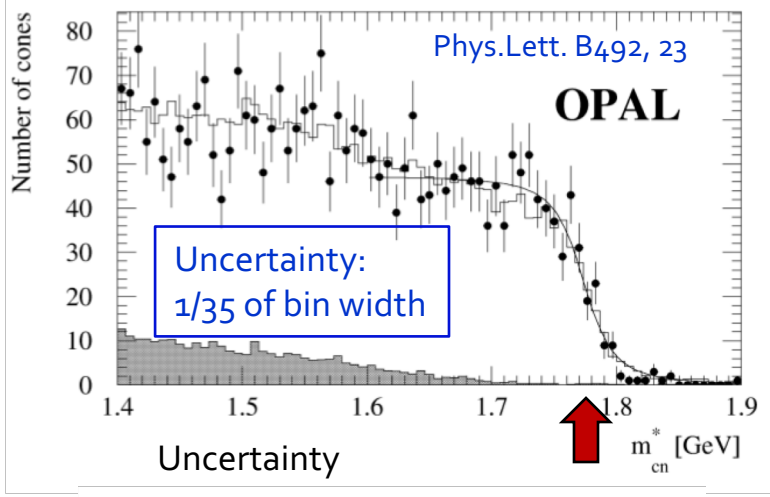
τ-lepton properties and Lepton Universality

a) Mass
b) Lifetime
c) Leptonic branching fractions



Tau Mass (i)

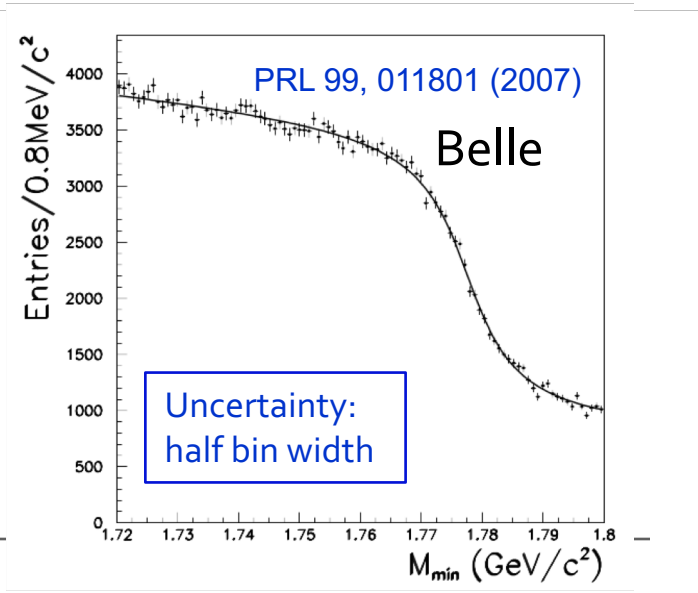
- **Current world average:** $m_\tau = 1776.86 \pm 0.12$ MeV
- Best in world: BES3 (threshold scan) $m_\tau = 1776.91 \pm 0.12\,(\text{stat.})\ ^{+0.10}_{-0.13}\,(\text{syst.})$ MeV
- Best at LEP: OPAL $m_\tau = 1775.1 \pm 1.6\,(\text{stat.}) \pm 1.0\,(\text{syst.})$ MeV
  - About factor 10 from world's best
  - Main result from endpoint of distribution of pseudo-mass in $\tau \to 3\pi^\pm(n\pi^0)\nu_\tau$
  - Dominant systematics:
    - Momentum scale: 0.9 MeV
    - Energy scale: 0.25 MeV (including also π^0 modes)
    - Dynamics of τ 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: $M_{min} = \sqrt{M_{3\pi}^2 + 2(E_{beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})}$

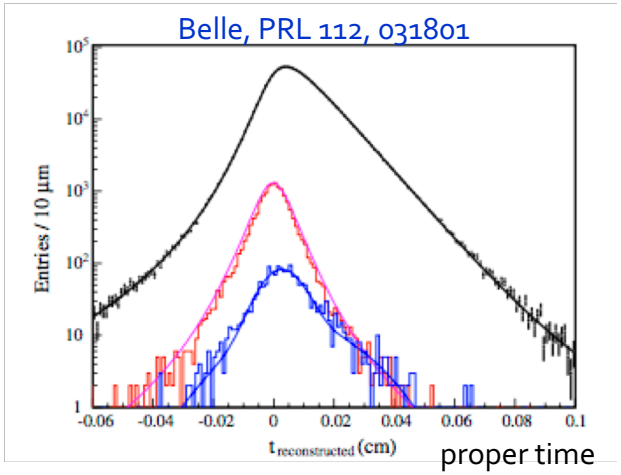


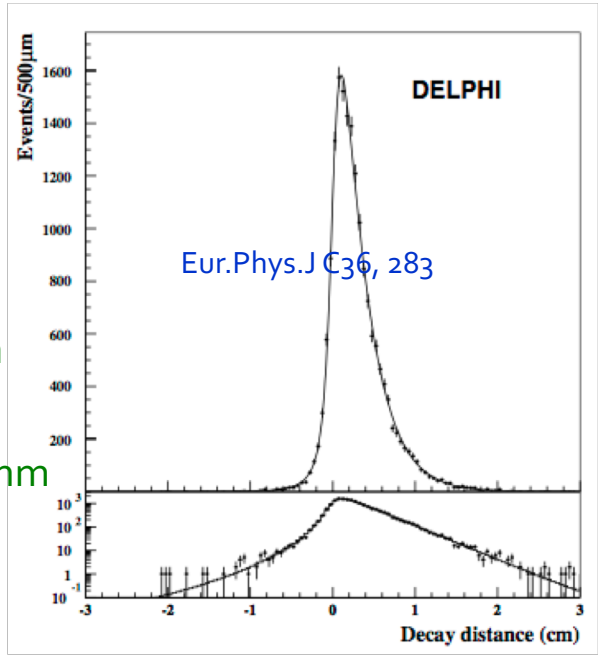
Tau Mass (ii)

- Prospects for FCC-ee:
  - 3 prong, 5 prongs, (perhaps even 7 prongs?)
  - Statistics 10^5 times OPAL: **δ_{stat} = 0.004 MeV**
  - Systematics:
    - At FCC-ee, E_{BEAM} known to better than 0.1 MeV (~ 1 ppm) from resonant depolarisation
      - Negligible effect on m_τ
    - Likely dominant experimental contribution comes from understanding of the mass scale
      - Use high stats $e^+e^- \rightarrow \mu^+\mu^-$ sample to fix momentum scale. Extrapolate down to momenta typical for $\tau \rightarrow 3\pi$.
      - 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)
    - 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: **δ_{syst} = 0.1 MeV**
    - Could potentially touch current precision but probably no substantial improvement ?

Tau Lifetime (i)

- **Current world average:** $\tau_\tau = 290.3 \pm 0.5$ fs
- **Best in world** (Belle): $\tau_\tau = 290.17 \pm 0.53_{stat} \pm 0.22_{syst}$ fs
  - Large statistics: 711 fb^{-1} @ Υ(4s): 6.3 x 10^8 $\tau^+\tau^-$ events
  - Use 3 vs. 3 prong events; reconstruct 2 secondary vertices + primary vertex
  - Measure flight distance => proper time
  - Dominant systematics: Vertex detector alignment to ~0.25 μm
    - Vertex detector outside 15 mm beam pipe
- **Best at LEP** (DELPHI): $\tau_\tau = 290.0 \pm 1.4_{stat} \pm 1.0_{syst}$ fs
  - "Low" statistics: ~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 μm
      - Alignment with data ($q\bar{q}$ events): statistics limited
    - Vertex detector: 7.5 μm point resolution at 63, 90, and 109 mm





Tau Lifetime (ii)

- Prospects at FCC-ee
  - Small beam-pipe radius (15 mm): Vertex detector with 3 μm space points at 18, 38, 58 mm

    [DELPHI: 7.5 μm @63, 90, 109 mm]
  - Impact parametre resolution ~5 times better than at LEP for relevant momenta
    - DELPHI: a = 20 μm, b = 65 μm
    - Belle: a = 19 μm, b = 50 μm
    - FCC-ee: a = 3 μm, b = 15 μm

$$\sigma(d_0) = \sqrt{a^2 + b^2 \cdot GeV^2/(p^2 \sin^3(\theta))}.$$

  - 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

$$\delta_{syst} = 0.04 \text{ fs} \quad ; \quad \delta_{stat} = 0.001 \text{ fs}$$

- Further prospects: lifetime can be measured with different systematics in many modes
  - 1v1: impact parameter difference, miss distance
  - 1v3: flight distance
  - 3v3 (4×10^9 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
  - **$B(\tau \to e\nu\nu) = 17.837 \pm 0.072_{stat} \pm 0.036_{syst}$ %** ; **$B(\tau \to \mu\nu\nu) = 17.319 \pm 0.070_{stat} \pm 0.032_{syst}$ %**
- Three uncertainty contributions dominant in the Aleph measurement
  - Selection efficiency: 0.021 / 0.020 %
  - Non-$\tau^+\tau^-$ background: 0.029 / 0.020 %
  - Particle ID: 0.019 / 0.021 %
  - All of these were limited by statistics: size of test samples, etc.
- Prospects at FCC-ee
  - Enormous statistics:

$$\delta_{stat} = 0.0001 \ \%$$

  - 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, δ_{syst} varied by factor ~3
        - Lesson: **Design your detector with care!**

With the large statistics we will learn a lot. Suggest a factor 10 improvement wrt ALEPH:

$$\delta_{syst} = 0.003 \ \%$$

Summary of Precisions & Lepton Universality

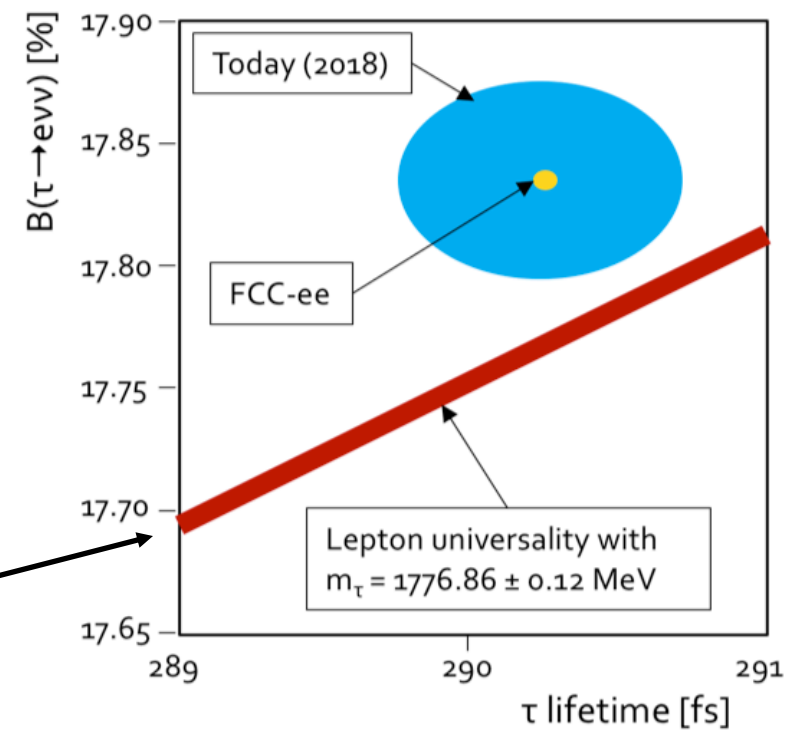
Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_τ [MeV]	Threshold / inv. mass endpoint	1776.86 ± 0.12	0.004	0.1	Mass scale
τ_τ [fs]	Flight distance	290.3 ± 0.5 fs	0.001	0.04	Vertex detector alignment
$B(\tau\to e\nu\nu)$ [%]	Selection of $\tau^+\tau^-$, identification of final state	17.82 ± 0.05	0.0001	0.003	Efficiency, bkg, Particle ID
$B(\tau\to \mu\nu\nu)$ [%]		17.39 ± 0.05			

Lepton Universality Tests:

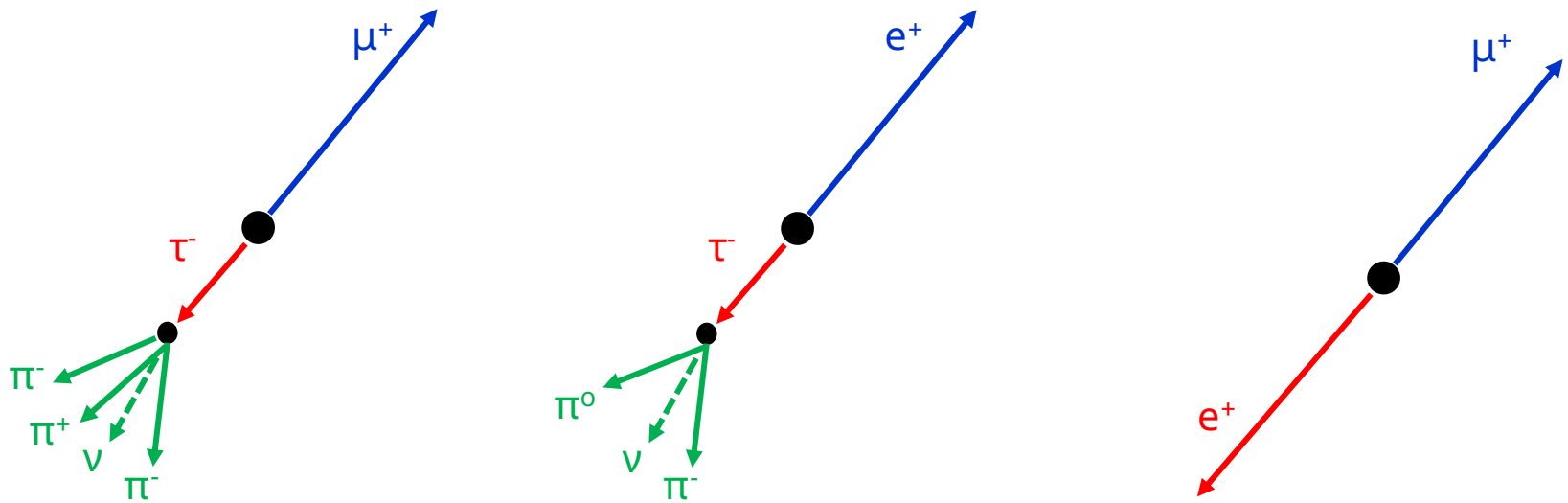
Quantity	Measurement	Current precision	FCC-ee precision
$\lvert g_\mu/g_e\rvert$	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$	1.0018 ± 0.0014	Improvement by a factor 10 or more
$\lvert g_\tau/g_\mu\rvert$	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$	1.0030 ± 0.0015	

With the precise FCC-ee measurements of lifetime and BRs, m_τ could become the limiting measurement in the universality test

$$\left(\frac{g_\tau}{g_\mu}\right)^2 \simeq \frac{\tau_\mu}{\tau_\tau} BF(\tau^- \to e^-\bar{\nu}_e\nu_\tau)\left(\frac{m_\mu}{m_\tau}\right)^5$$

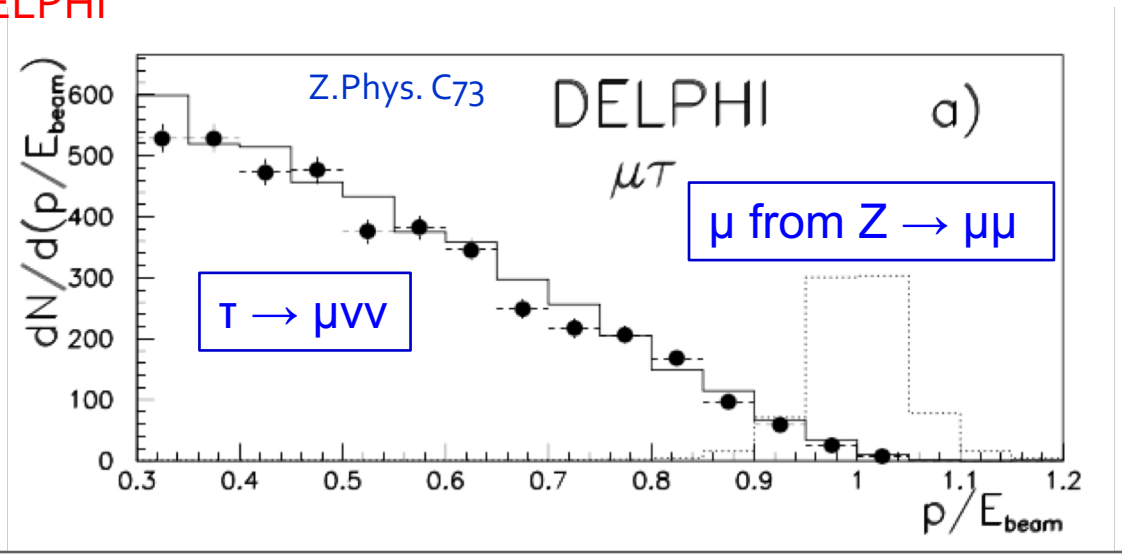


LFV Z decays



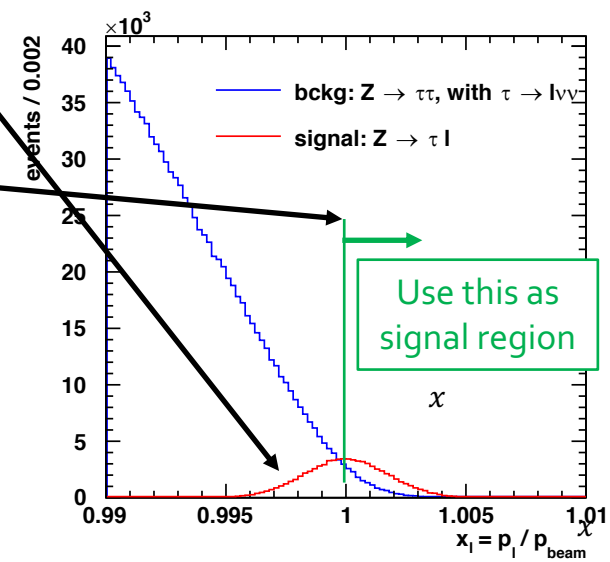
$Z \to e\tau$ and $Z \to \mu\tau$

- 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

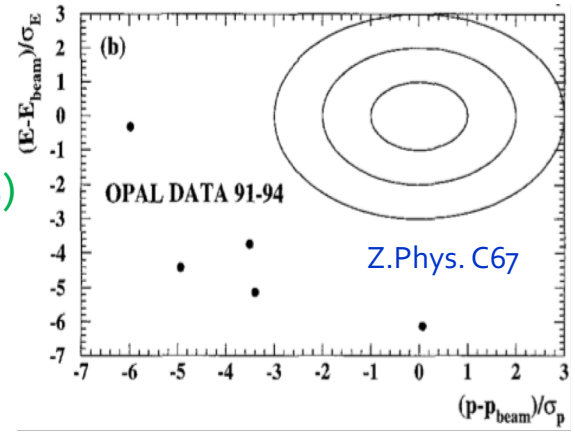
- Generate very upper part of μ momentum spectrum from $\tau \rightarrow \mu\nu\nu$ decays
  - Luminosity equivalent to 5×10^{12} Z decays
- Inject LFV signal of adjustable strength
  - Here for illustration, **$Br(Z \rightarrow \tau\mu) = 10^{-7}$**, i.e. 500,000 e/μ
- Smear momentum by variable amounts,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



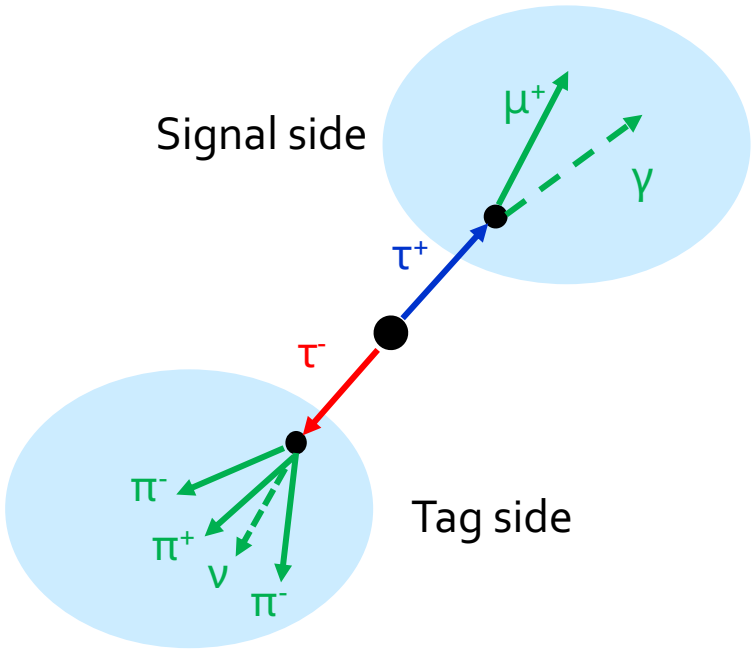
- Sensitivity for 5×10^{12} Z decays, $\delta p/p = 1.8 \times 10^{-3}$, 25% signal and bkg efficiency (clear tau)
  - For $Z \rightarrow \tau\mu$, sensitivity down to BRs of **10^{-9}**
  - For $Z \rightarrow \tau e$, similar sensitivity **10^{-9}**
    - Momentum resolution of electrons tend to be slightly worse than muons due to bremsstrahlung. However, downwards smearing is not a major concern.

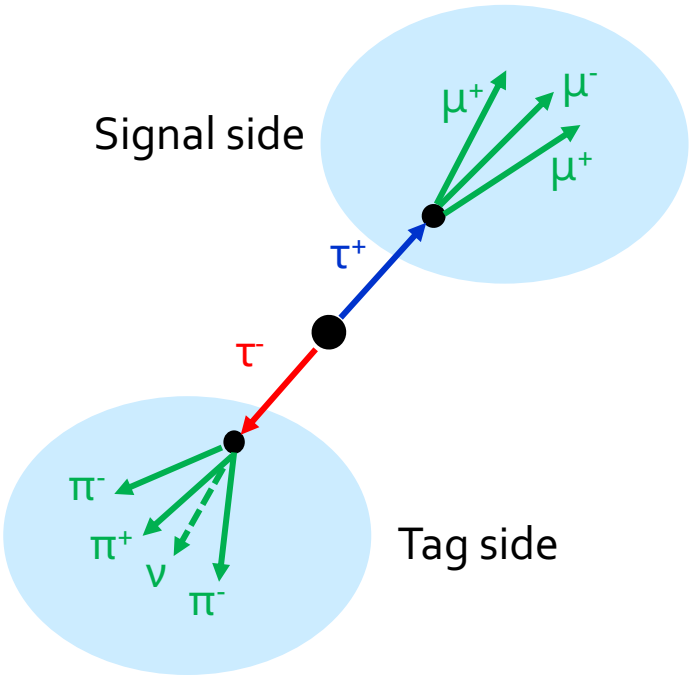
$Z \rightarrow e\mu$

- 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 $\mu \rightarrow e$
    - NA62: Probability of muon to deposit more than 95% of energy in ECAL: **4×10^{-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 $P(\mu \rightarrow e)$
      - Notice: ATLAS uses transition radiation as part of electron ID.
- FCC-ee:
  - Misidentification from catastrophic energy loss corresponds to limit of about $Br(Z \rightarrow e\mu) \simeq 10^{-8}$
  - Possibly do O(10) better than that **$Br(Z \rightarrow e\mu) \sim 10^{-9}$** (probably even 10^{-10} with IDEA dE/dx)



LFV τ decays


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

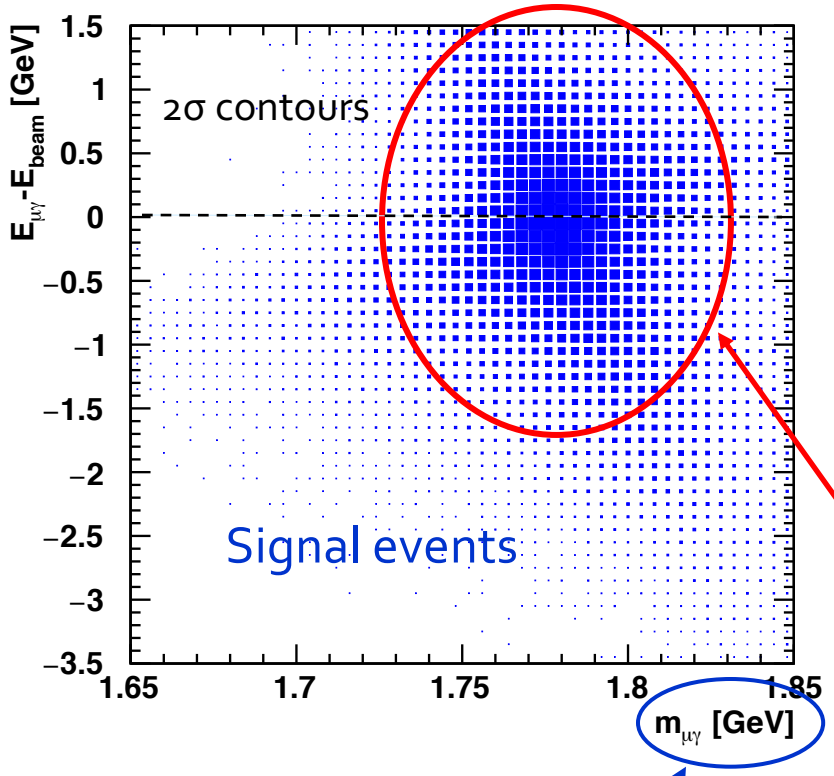

Signal side
μ+
μ-
μ+
τ+
τ-
π-
π+
ν
π-
Tag side

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

- 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 $\tau \to \mu\bar{\nu}\nu$
- At FCC-ee, with 1.7×10^{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, $e^+e^- \to \tau^+\tau^-\gamma$, performed
    - See two following 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 $\tau^- \rightarrow \mu^-\gamma$



Smear with assumed FCC-ee detector resolutions:

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

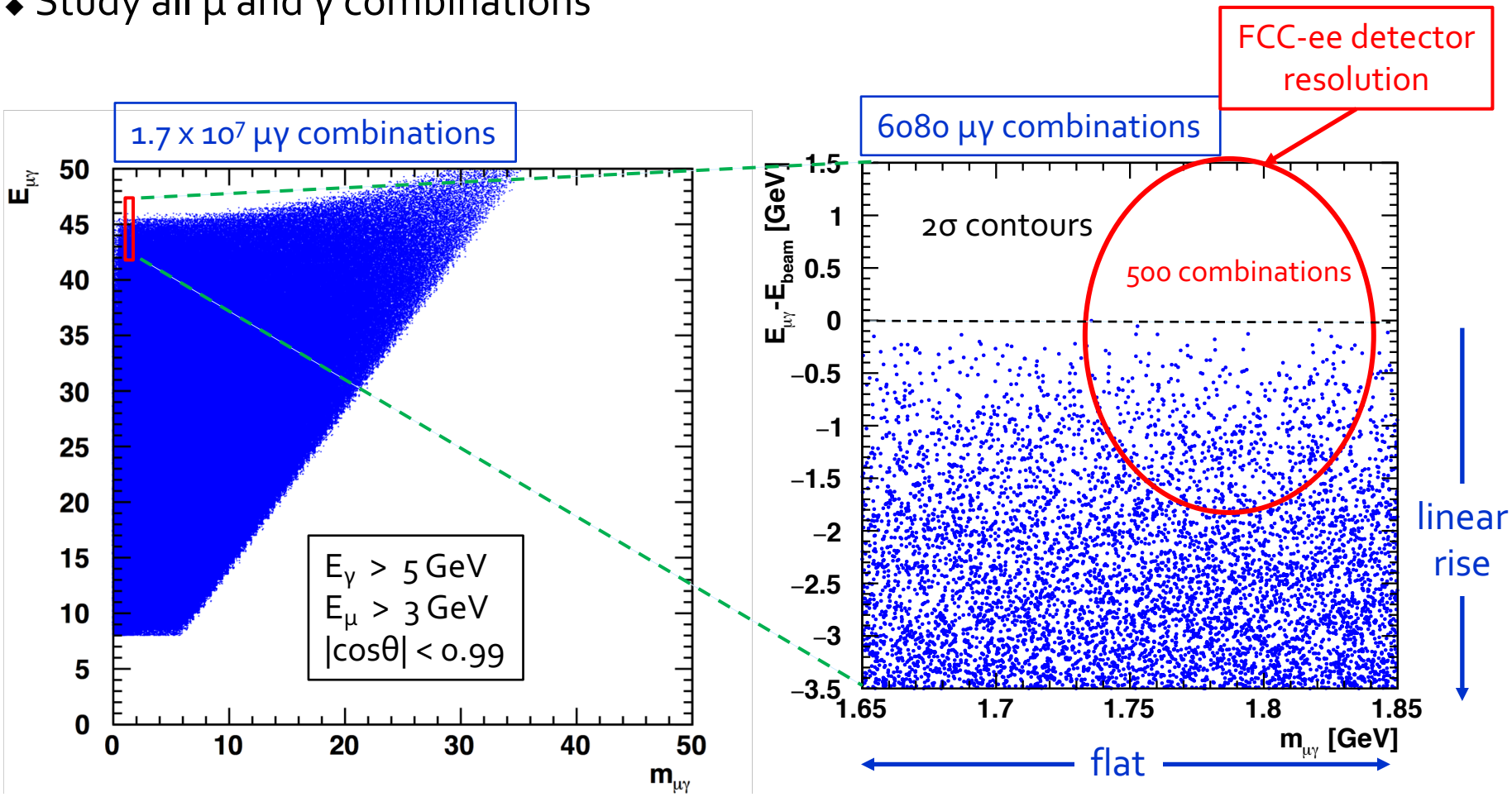
$\sigma(m_{\gamma\mu}) = 26$ MeV; $\sigma(E_{\gamma\mu}) = 850$ MeV

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

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

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

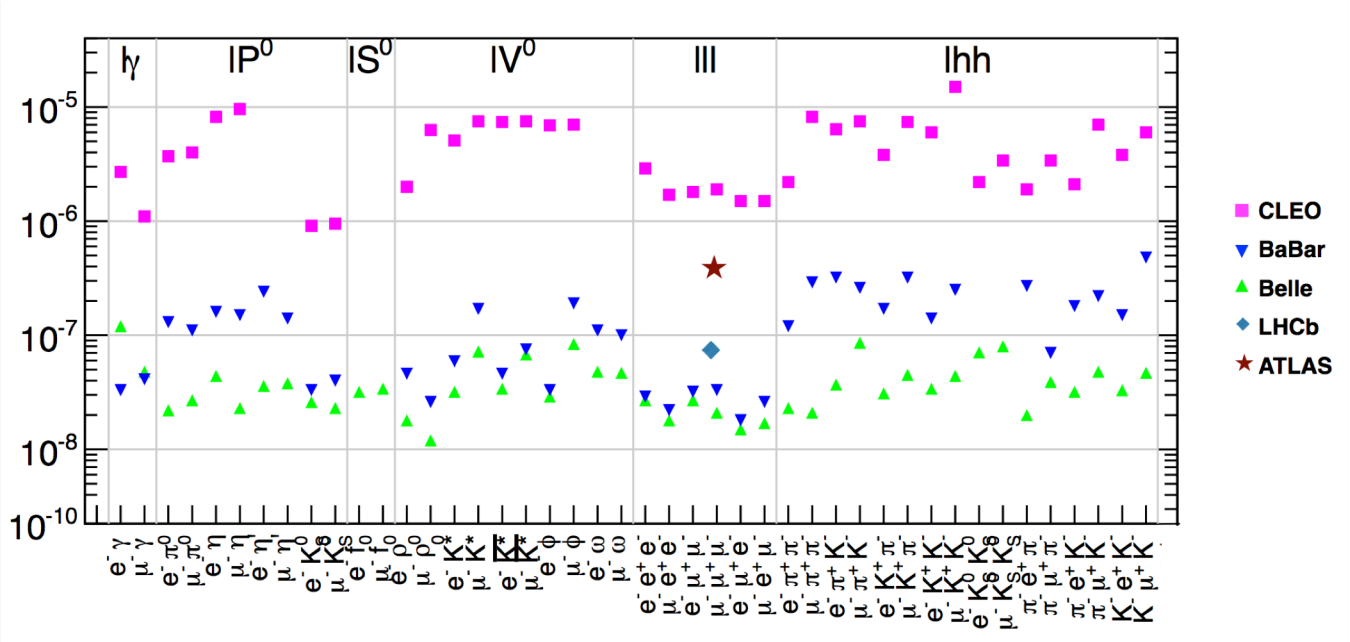
- Background: Generate 5×10^8 events $e^+e^- \rightarrow Z \rightarrow \tau^+\tau^-(\gamma) \rightarrow (\mu^+\nu\nu)(\mu^-\nu\nu)(\gamma)$
  - 1×10^9 $\tau \rightarrow \mu\nu\nu$ decays corresponding to
    - 5.7×10^9 τ decays from 8.4×10^{10} Z decays
- Study all μ and γ combinations



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

- 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 deccay modes to search when time comes…



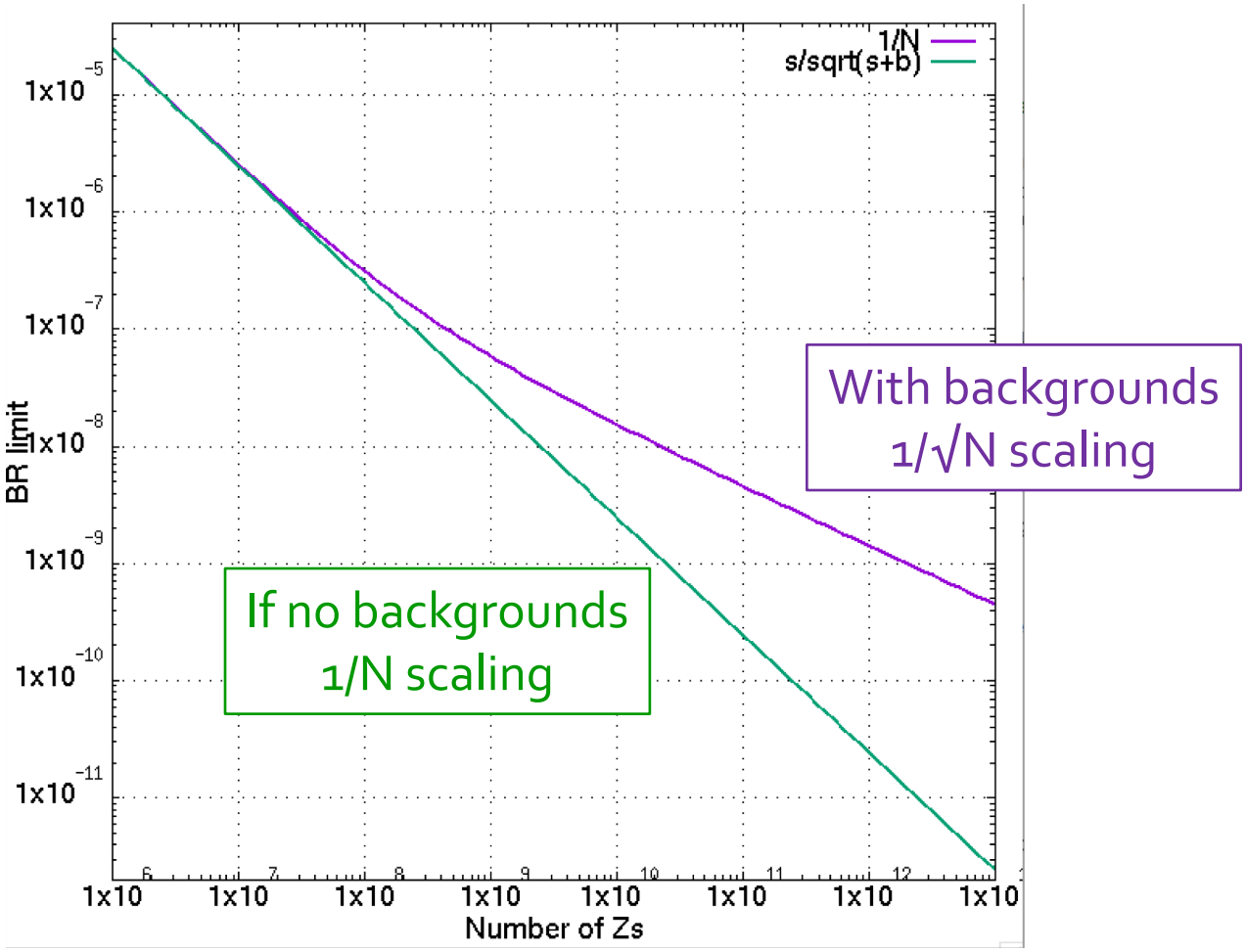
Summary

- With an unrivalled luminosity, the four stage FCC-ee programme foresees the production of 5×10^{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 1.7×10^{11} $\tau^+\tau^-$ pairs:
  - **Improved lepton universality test by O(10) or more. Down to 10^{-4} level on coupling ratios**
    - Substantial improvement in τ lifetime measurement: O(300) statistical, O(10) systematic
    - Substantial improvement in τ branching fractions: O(300) statistical, O(~10) systematic
    - Possibly competitive measurement of τ mass
  - **Searches for lepton flavour violating Z decays more sensitive than today by factor $O(10^4)$**
    - **Sensitivities down to 10^{-9}**
  - Searches for lepton flavour violating τ decays with sensitivites comparable with recent Belle2 projections (arxiv:1808.10567)
    - $\lesssim$ **10^{-10}** (for channels with no background) to **few x 10^{-9}**

- Plus, of course
  - Tau polarisation measurement for $\sin^2\theta_W$, α_S, τ neutrino mass, etc., etc.

Extra Slides

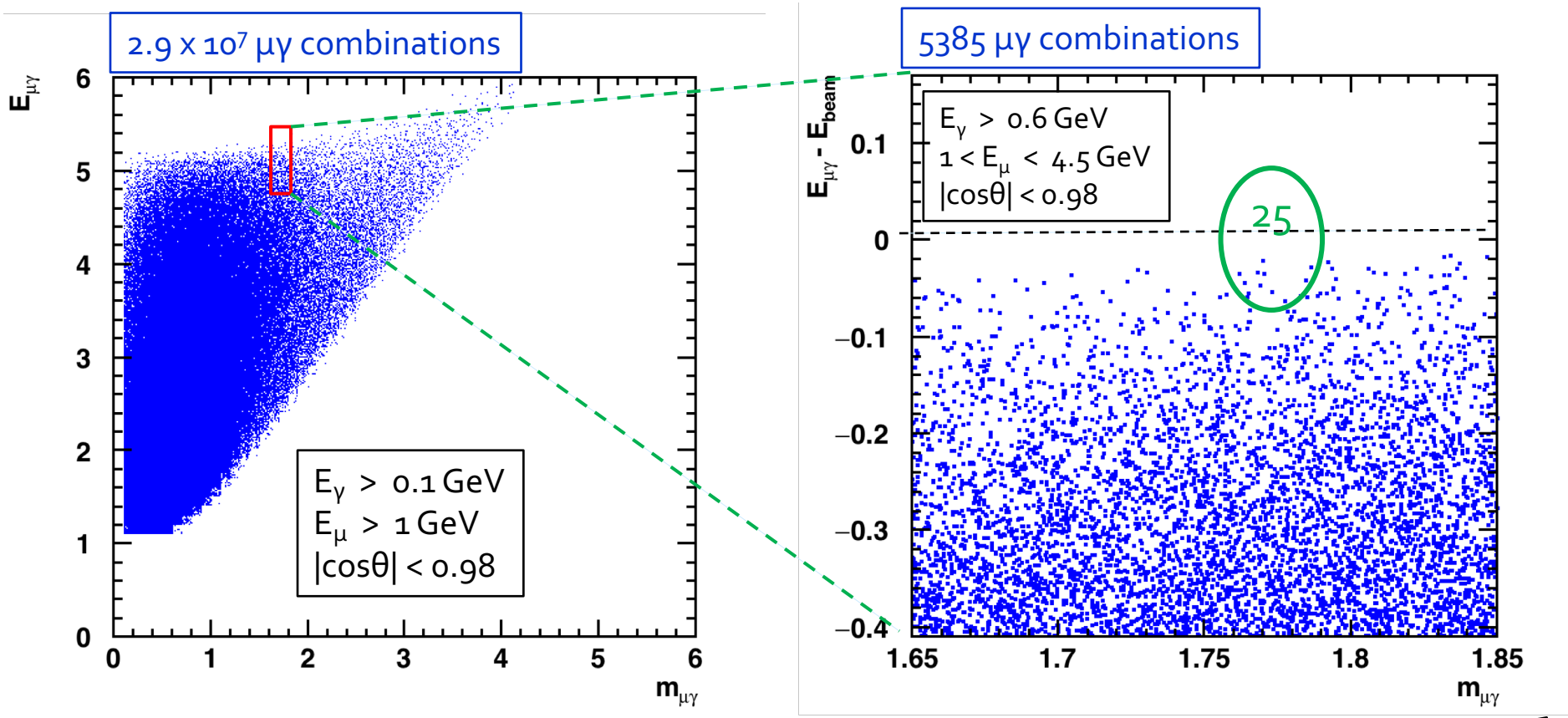
Scaling of Z → ℓτ sensitivity with #events



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

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

- Again 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}**

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

Agrees within a factor 2
Not too bad