τ challenge at FCC-ee

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CEPC Workshop
24 May 2022

Picture and slide layout, courtesy Jörg Wenninger

Outline

a. **Brief on FCC-ee**
b. **τ Polarisation Measurement**
c. **τ-lepton Properties and Lepton Universality**
d. **Lepton Flavour Violating Z decays**
e. **Lepton Flavour Violating τ decays**

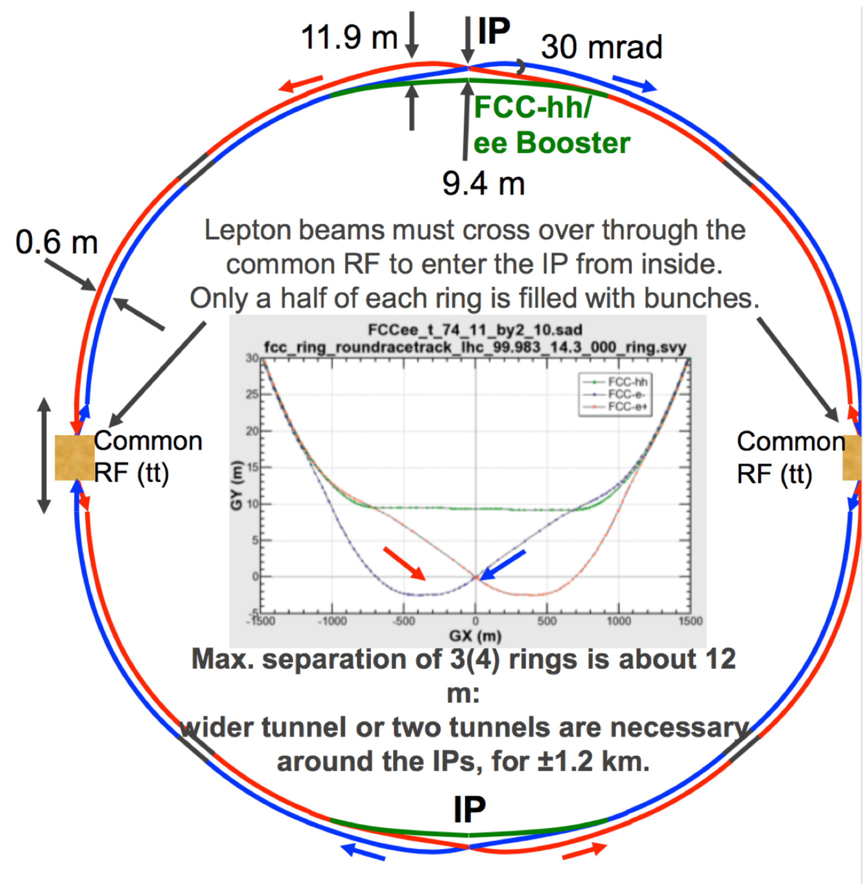
References:

- 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
- MD, *The τ challenges at FCC-ee*, arXiv:2107.12832

FCC-ee

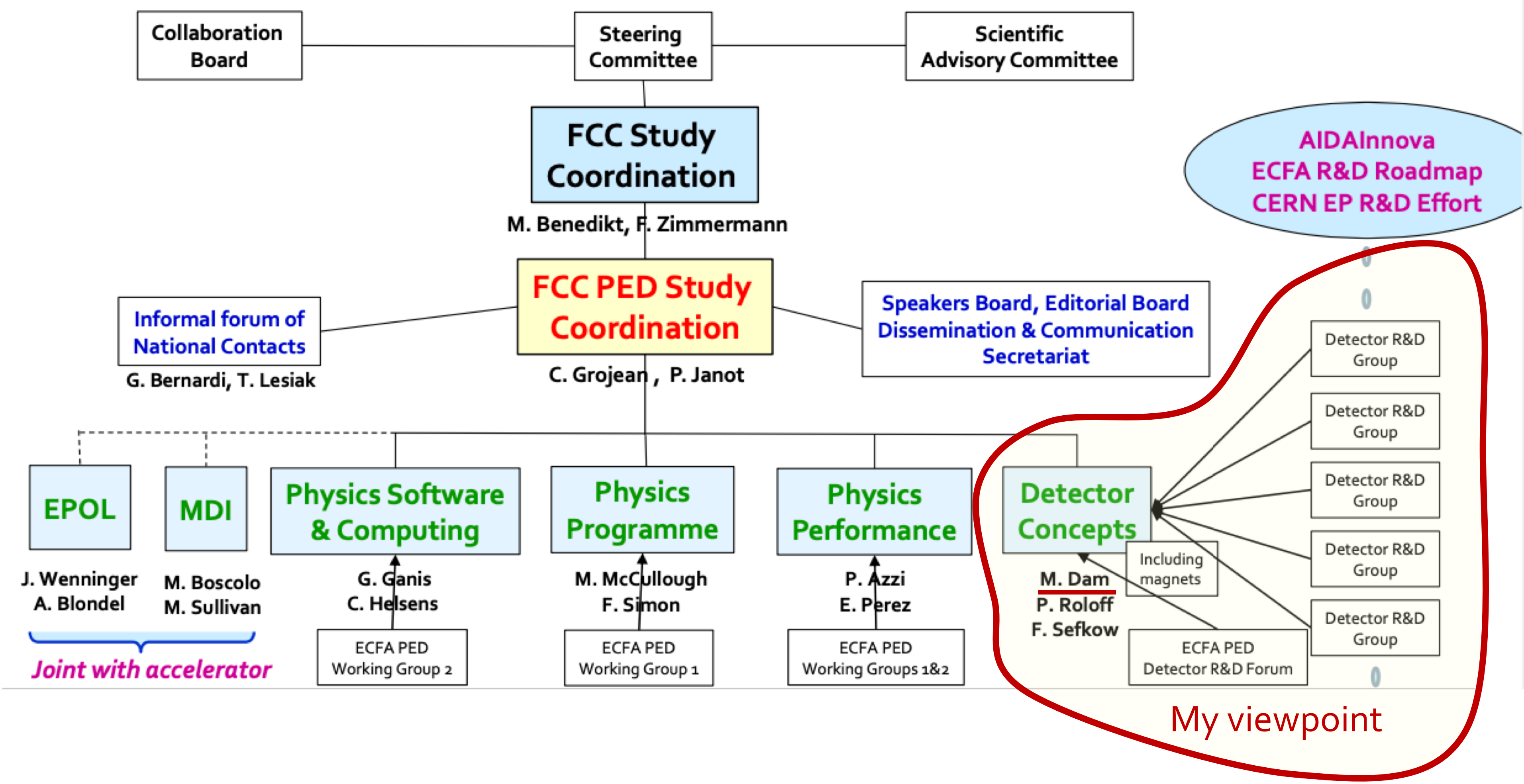
Future Circular Collider Feasibility Study initiated by CERN Council in June 2021

- *"…conclusion on the placement and feasibility by end 2025."*
- *"The focus will be on the tunnel and the **first stage collider (FCC-ee)**…"*

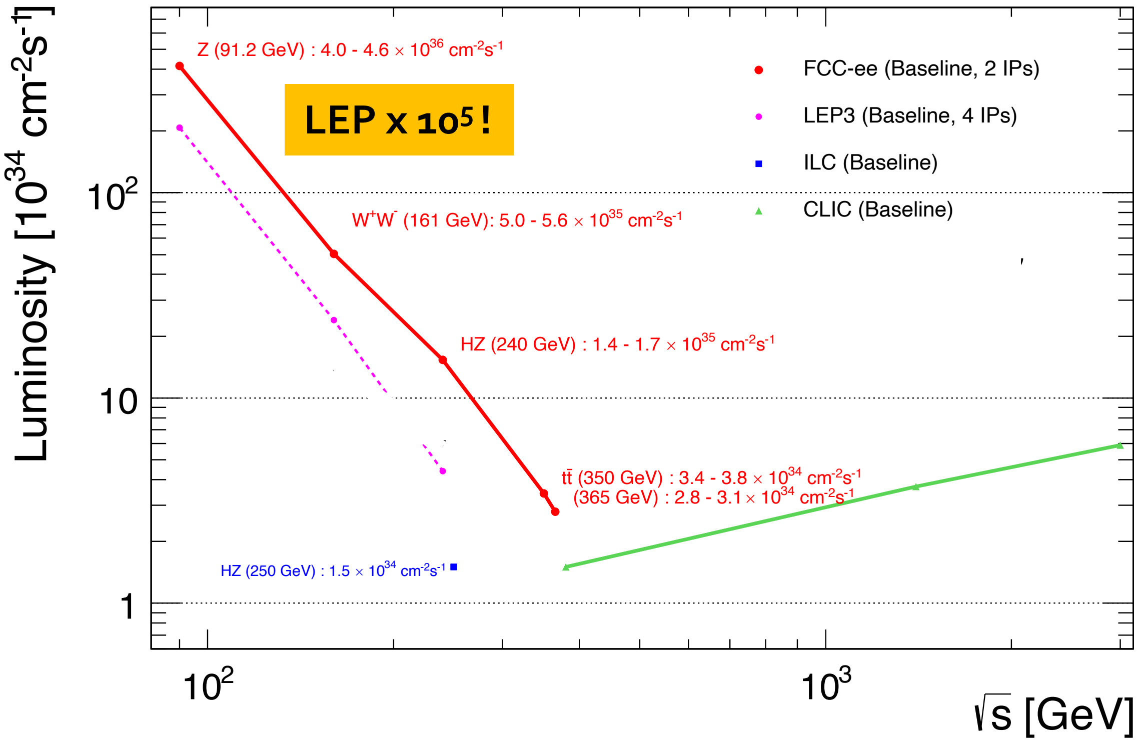


Layout now updated to (possibly) allow for four interaction points.

Feasibility Study: Physics, Experiment and Detector Pillar



Luminosity & Statistics



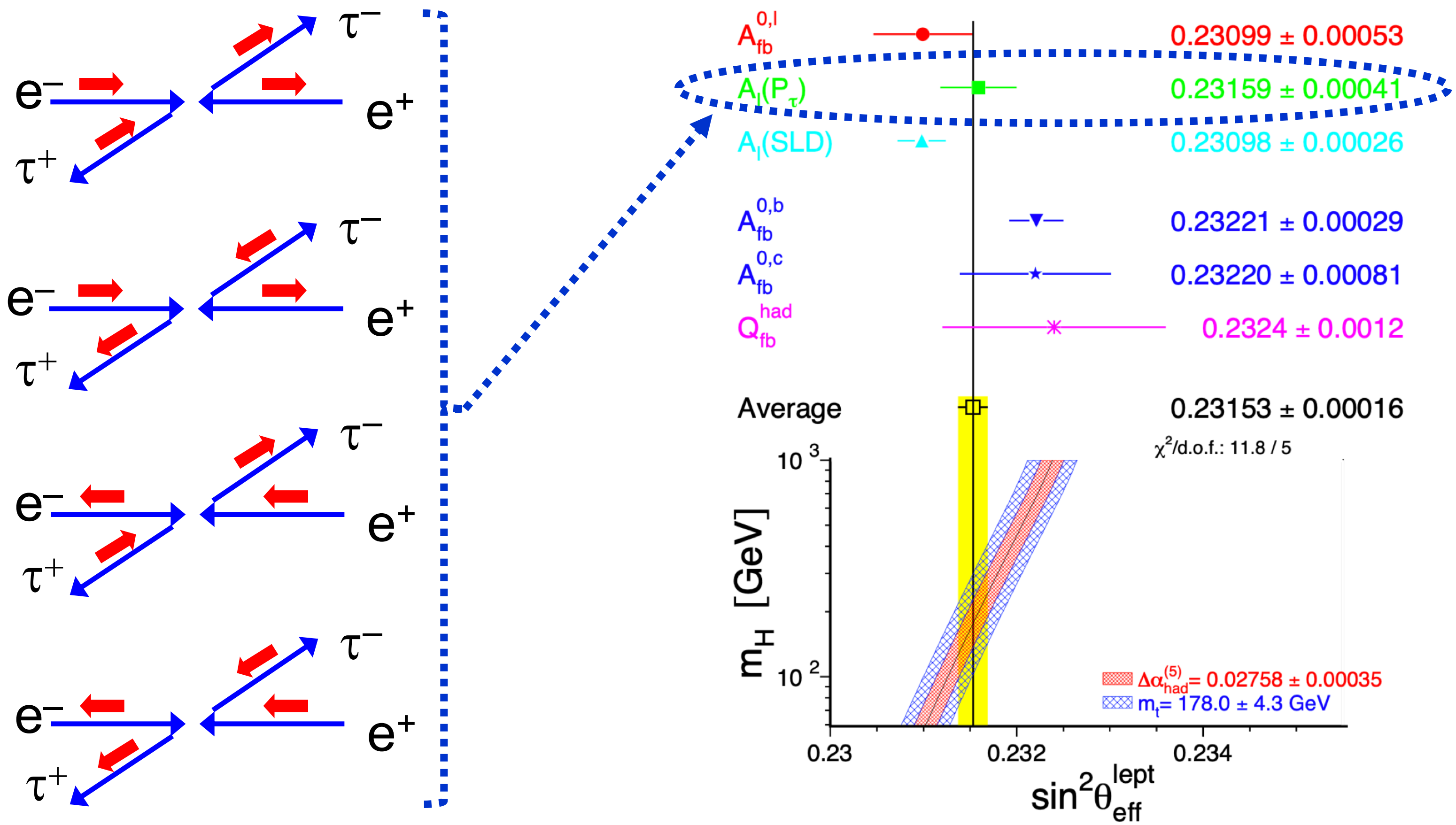
In this talk, concentrate on the Z-pole energy point

Enormous statistics of Z bosons and of 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

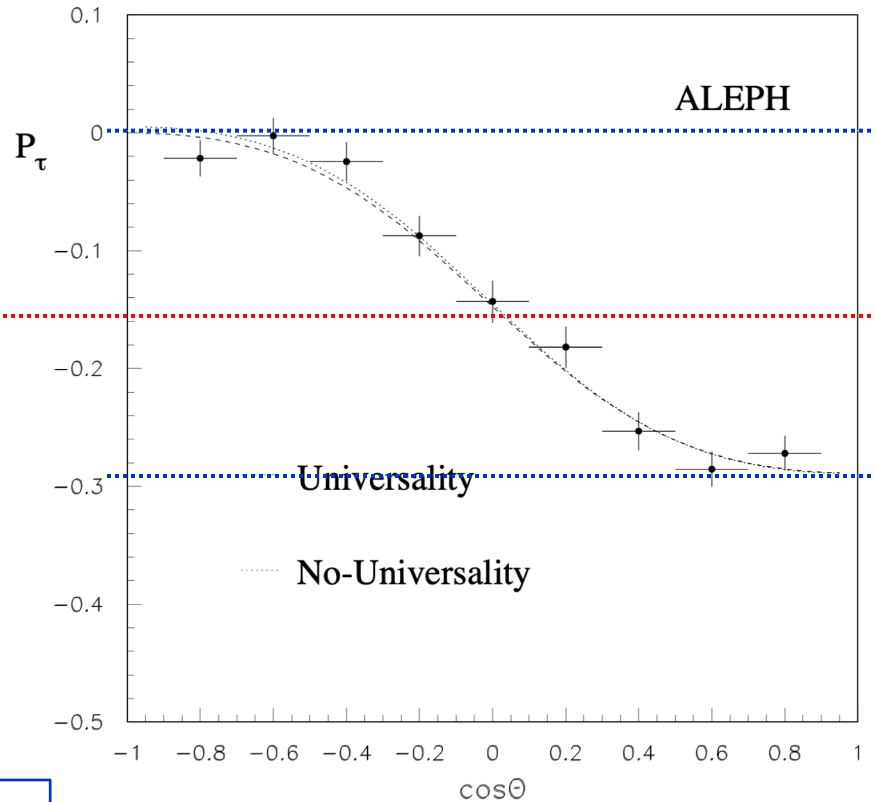
τ Polarisation Measurement



Example: LEP experiment aleph

Mean polarisation

Angular dependence



$\mathcal{A}_\tau$

$\mathcal{A}_e$

Asymmetri-like measurement:
Low systematics

Eur.Phys.J.C20:401-430,2001

$\mathcal{A}_\tau = 0.1451 \pm 0.0052 \pm 0.0029$

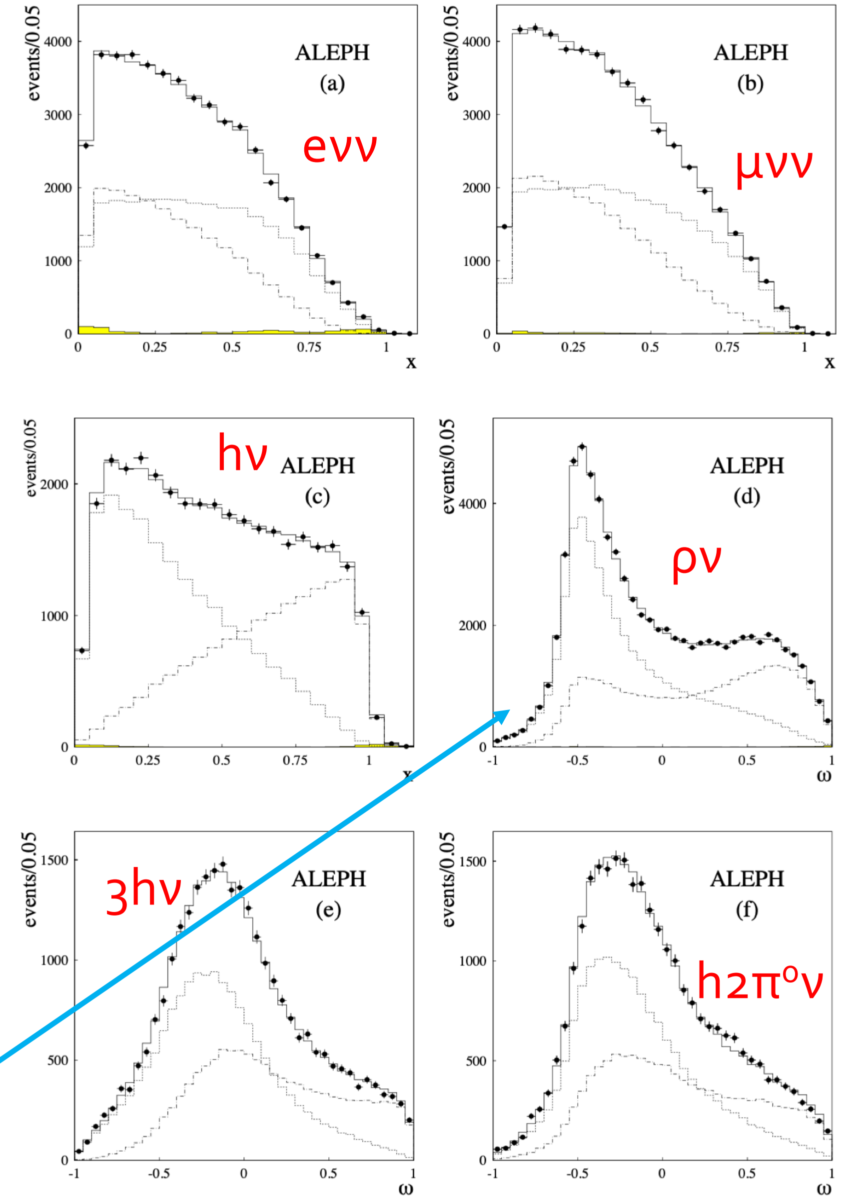
$\mathcal{A}_e = 0.1504 \pm 0.0068 \pm 0.0008$

$\Rightarrow$ assuming universality: $\sin^2\theta_W^{eff} = 0.23130 \pm 0.00048$

Experimental aspects

Use τ decays as spin analysers (V-A decay)

- Two helicity states result in different kinematic distributions that are fitted to observed distribution of appropriate variables
- Divide (typically) into six decay modes →



Important aspects

- Selection of $e^+e^- \to \tau^+\tau^-$ events
  - Backgrounds from qq, ee, μμ, γγ
- Interchannel separation
  - Mainly internally between different **h+nπ⁰** states => **Photon** and **π⁰** reconstruction
- Selection efficiency and backgrounds as function of kinematic variables
- Reconstruction of kinematic variables

Important example: $\tau^- \to \rho^-\nu \to \pi^-\pi^0\nu$

- Here polarisation is extracted from two angles

$$\cos\theta \propto \frac{E_{\pi^-}+E_{\pi^0}}{E_{\text{beam}}} \qquad \cos\psi \propto \frac{E_{\pi^-}-E_{\pi^0}}{E_{\pi^-}+E_{\pi^0}}$$

$\pi^-\pi^0$ energy sum difference

Combined into 1D "optimal observable"

Results and precisions – case aleph

Obtained results

Channel	$\mathcal{A}_\tau$ (%)	$\mathcal{A}_e$ (%)
hadron	$15.21 \pm 0.98 \pm 0.49$	$15.28 \pm 1.30 \pm 0.12$
rho	$13.79 \pm 0.84 \pm 0.38$	$14.66 \pm 1.12 \pm 0.09$
a1(3h)	$14.77 \pm 1.60 \pm 1.00$	$13.58 \pm 2.11 \pm 0.40$
a1(h2π^0)	$16.34 \pm 2.06 \pm 1.52$	$15.62 \pm 2.72 \pm 0.47$
electron	$13.64 \pm 2.33 \pm 0.96$	$14.09 \pm 3.17 \pm 0.91$
muon	$13.64 \pm 2.09 \pm 0.93$	$11.77 \pm 2.77 \pm 0.25$
pion inclusive	$14.93 \pm 0.83 \pm 0.87$	$14.91 \pm 1.11 \pm 0.17$
Combined	$14.44 \pm 0.55 \pm 0.27$	$14.58 \pm 0.73 \pm 0.10$

Most precise channels

Eur.Phys.J.C20:401-430,2001

systematics

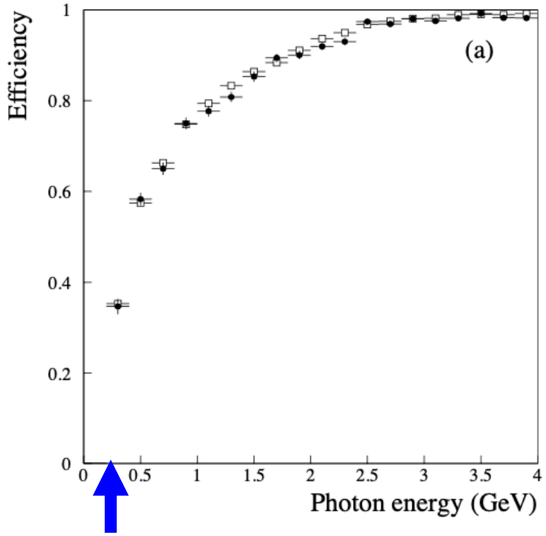
Source	h	ρ	$3\,h$	$h\,2\pi^0$	e	μ	Incl. h
			$\mathcal{A}_\tau$				
selection	-	0.01	-	-	0.14	0.02	0.08
tracking	0.06	-	0.22	-	-	0.10	-
ECAL scale	0.15	0.11	0.21	1.10	0.47	-	-
PID	0.15	0.06	0.04	0.01	0.07	0.07	0.18
misid.	0.05	-	-	-	0.08	0.03	0.05
photon	0.22	0.24	0.37	0.22	-	-	-
non-τ back.	0.19	0.08	0.05	0.18	0.54	0.67	0.15
τ BR	0.09	0.04	0.10	0.26	0.03	0.03	0.78
modelling	-	-	0.70	0.70	-	-	0.09
MC stat	0.30	0.26	0.49	0.63	0.61	0.63	0.26
TOTAL	0.49	0.38	1.00	1.52	0.96	0.93	0.87
			$\mathcal{A}_e$				
Source	h	ρ	$3\,h$	$h\,2\pi^0$	e	μ	Incl. h
tracking	0.04	-	-	-	-	0.05	-
non-τ back.	0.11	0.09	0.04	0.22	0.91	0.24	0.17
modelling	-	-	0.40	0.40	-	-	-
TOTAL	0.12	0.09	0.40	0.47	0.91	0.25	0.17

- LEP measurement statistics limited
- At FCC-ee, ~ $10^{5\text{-}6}$ larger statistics: Need much reduced systematics

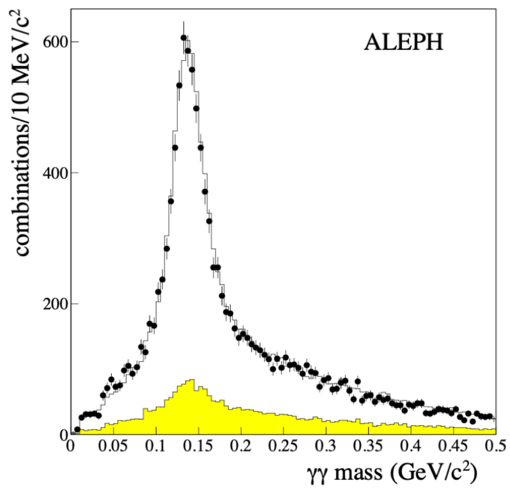
The single most important systematics (on the most precise channels) is due to photon and π^0 identification

γ and π⁰ reconstruction in τ decays – case aleph

Foton reconstruction efficiency. Starting at 250 MeV



γγ mass of additional photons in hemispheres where one π⁰ has been already identified



Migration matrix (part)

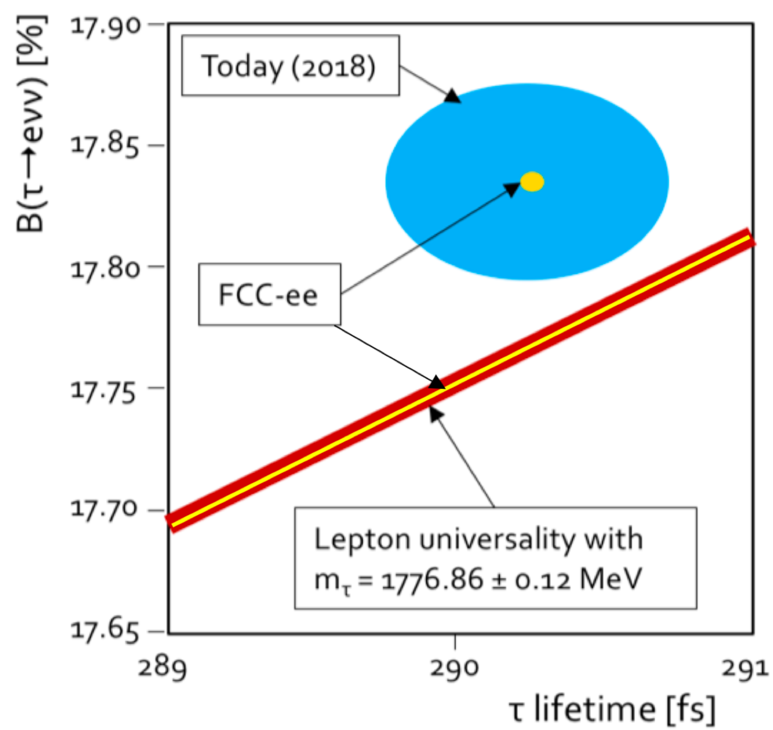
reconstructed / true

	e	μ	h	$h\pi^0$	$h2\pi^0$	$h3\pi^0$	$h4\pi^0$	$3h$
e	73.26	0.01	0.41	0.45	0.34	0.25	0.74	0.02
μ	0.01	74.49	0.63	0.22	0.07	0.21	0.33	0.01
h	0.25	0.75	65.03	3.56	0.34	0.06	0.00	1.44
$h\pi^0$	1.02	0.26	4.70	68.19	11.31	2.15	0.49	0.48
$h2\pi^0$	0.12	0.01	0.33	5.67	57.68	23.13	7.57	0.08
$h3\pi^0$	0.01	0.00	0.07	0.41	6.92	43.06	38.15	0.01
$h4\pi^0$	0.00	0.00	0.02	0.05	0.67	6.25	25.26	0.00
$3h$	0.01	0.02	0.25	0.07	0.03	0.00	0.00	67.98

⇒ **Key:** Overall detector design; good ECAL pattern recognition essential

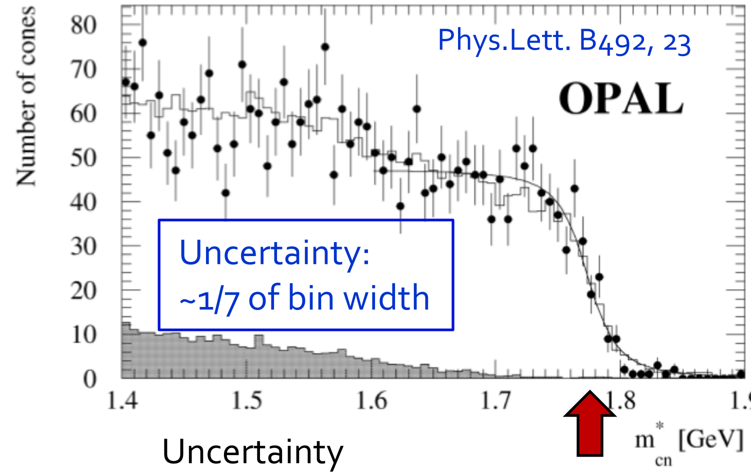
τ-lepton properties and Lepton Universality

a) Mass
b) Lifetime
c) Leptonic branching fractions



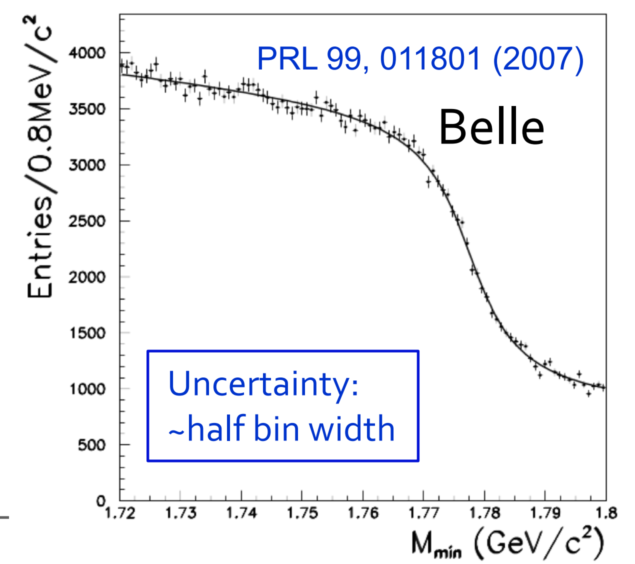
Tau Mass (i)

- **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 $\tau \rightarrow 3\pi^\pm(n\pi^0)\nu_\tau$
  - Dominant systematics
    - Momentum scale: 0.9 MeV
    - ECAL 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, …
  - Statistics 10^5 times OPAL: **δ_{stat} = 0.004 MeV**
  - Systematics:
    - At FCC-ee, E_{beam} determined to better than 0.1 MeV (~ 1 ppm) from resonant spin depolarisation
      - Negligible effect on m_τ
    - Control of mass scale
      - Suggest to exploit 10^9 $J/\psi \to \mu\mu$ from Z decays as reference, with $m(J/\psi)$ known to 0.006 MeV (2 ppm) from KEDR
    - Reduce uncertainty from parametrisation of spectrum edge by use of theoretical spectrum checked against high statistics data
    - Cross checks using 5-prongs
  - Overall systematics:
    - Study to be performed to shed more light on this. Improvement with respect to current measurements seems possible. Suggest

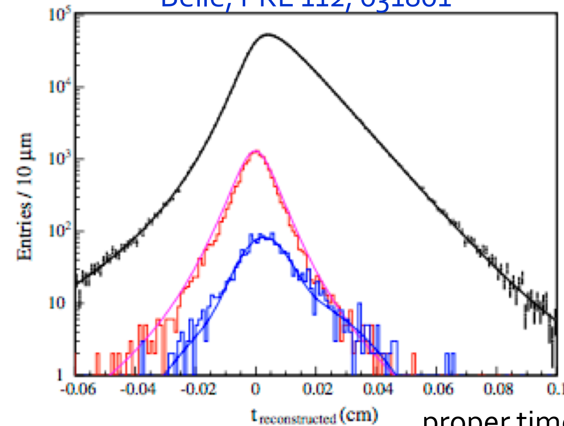
$$\delta_{syst} \lesssim 0.04 \text{ MeV}$$

⇒ **Key:** precise control of momentum scale also in dense, multi-prong topologies

Tau Lifetime (i)

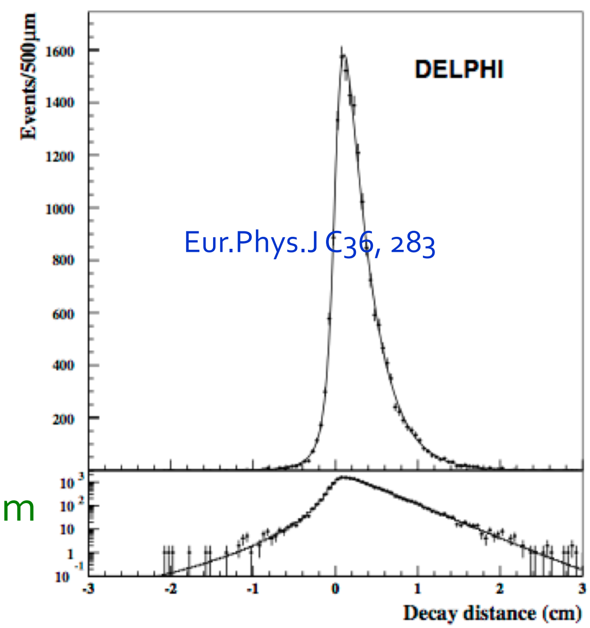
- **Current world average:** τ_τ **= 290.3 ± 0.5 fs**
- **Best in world** (Belle): τ_τ **= 290.17 ± 0.53** $_{\text{stat}}$ **± 0.22** $_{\text{syst}}$ **fs**
  - Large statistics: 711 fb^{-1} @ Y(4s): 6.3 x 10^{8} $\tau^+\tau^-$ events
  - Use 3 vs. 3 prong events (1.1M events); reconstruct 2 secondary vertices + primary vertex
  - Measure flight distance ⇒ proper time
  - Dominant systematics: Vertex detector alignment to ~0.25 μm
    - Vertex detector outside 15 mm beam pipe

Belle, PRL 112, 031801



proper time

- **Best at LEP** (DELPHI): τ_τ **= 290.0 ± 1.4** $_{\text{stat}}$ **± 1.0** $_{\text{syst}}$ **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 method (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



Eur.Phys.J C36, 283

Tau Lifetime (ii)

- Prospects at FCC-ee
  - Small beam-pipe radius (10 mm): Vertex detector with 3 μm space points at 13, 33, 53 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

δ_{syst} **= 0.04 fs** ; δ_{stat} **= 0.001 fs**

- Further prospects: lifetime can be measured with different systematics in many modes
  - 1v1: impact parameter difference, miss distance
  - 1v3: flight distance
  - 3v3 (4 x 10^9 events): flight distance sum

⇒ **Key:** Careful design and precise control of vertex detector

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 @ LEP
  - **$B(\tau\to e\nu\nu) = 17.837 \pm 0.072_{stat} \pm 0.036_{syst}$ %** ; **$B(\tau\to \mu\nu\nu) = 17.319 \pm 0.070_{stat} \pm 0.032_{syst}$ %**
- Three uncertainty contributions dominant in 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:

$$\delta_{stat} = 10^{-6}$$

  - 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, will learn a lot. Suggest a factor 10 improvement w.r.t. Aleph:

$$\delta_{syst} = 3 \times 10^{-5}$$

⇒ **Key:** Many ingredients; tracking, calorimetry, overall detector design

Summary of Precisions & Lepton Universality

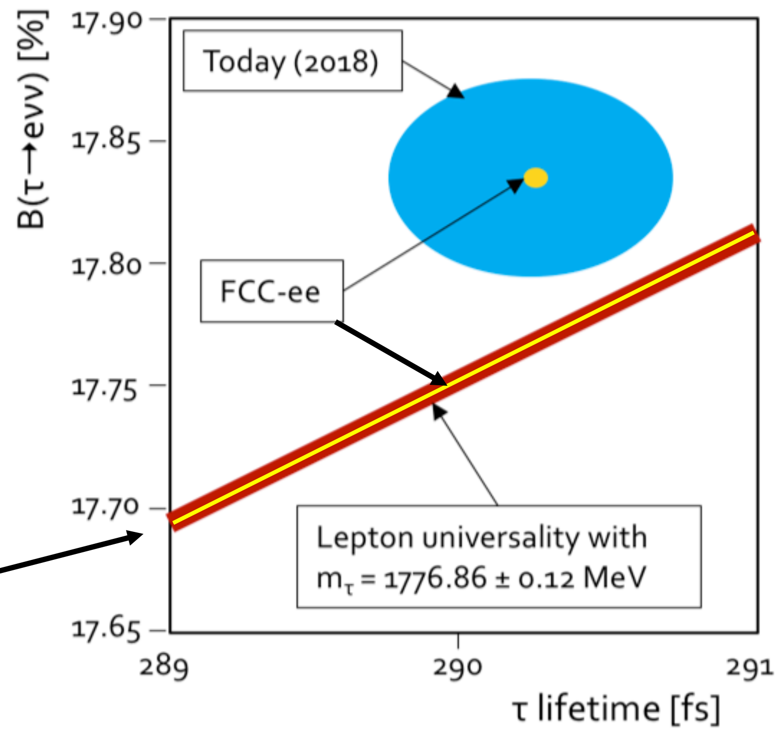
Observable	Measurement	Current precision	FCC-ee **stat.**	**Possible syst.**	Challenge
m_τ [MeV]	Threshold / inv. mass endpoint	1776.86 **± 0.12**	**0.004**	**0.04**	Mass scale
τ_τ [fs]	Flight distance	290.3 **± 0.5 fs**	**0.001**	**0.04**	Vertex detector alignment
B(τ→eνν) [%]	Selection of $\tau^+\tau^-$,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

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



Example of precision challenge: Universality of Fermi constant

Andreas Crivellin and John Ellis.

EXOTIC FLAVOURS AT THE FCC

CERNCOURIER Volume 62 Number 1 January/February 2022

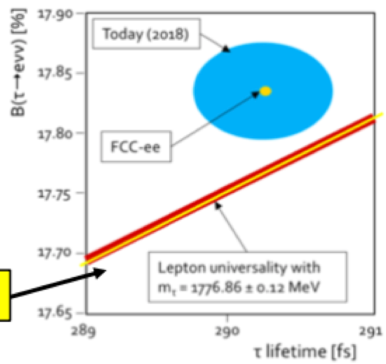
Here, a new-physics effect at a relative sub-per-mille level compared to the SM would suffice to explain the anomaly. This could be achieved by a heavy new lepton or a massive gauge boson affecting the determination of the Fermi constant that parametrises the strength of the weak interactions. As the Fermi constant can also be determined from the global electroweak fit, for which Z decays are crucial inputs, FCC-ee would again be the perfect machine to investigate this anomaly, as it could improve the precision by a large factor (see "High precision" figure). Indeed, the Fermi constant may be determined directly to one part in 10^5 from the enormous sample ($>10^{11}$) of Z decays to tau leptons.

10 ppm !!

M. Dam, SciPostPhys.Proc.1,041(2019)

Property	Current WA	FCC-ee stat	FCC-ee syst
Mass [MeV]	1776.86 +/- 0.12	0.004	0.1
Electron BF [%]	17.82 +/- 0.05	0.0001	0.003
Muon BF	17.39 +/- 0.05	0.0001	0.003
Lifetime [fs]	290.3 +/- 0.5	0.005	0.04

Shown in yellow: first *guestimates* on FCC-ee precisions



The Fermi constant is measured in μ decays and defined by

$$\left(G_F^\mu\right)^2 = 192\pi^3 \frac{\tau_\mu}{m_\mu^5}$$ (known to 0.5 ppm)

Similarly can define Fermi constant measured in τ decays by

$$\left(G_F^\tau\right)^2 = 192\pi^3 \frac{\tau_\tau}{m_\tau^5} \cdot \frac{1}{\mathscr{B}(\tau \to e\nu\nu)}$$ (known to 1700 ppm)

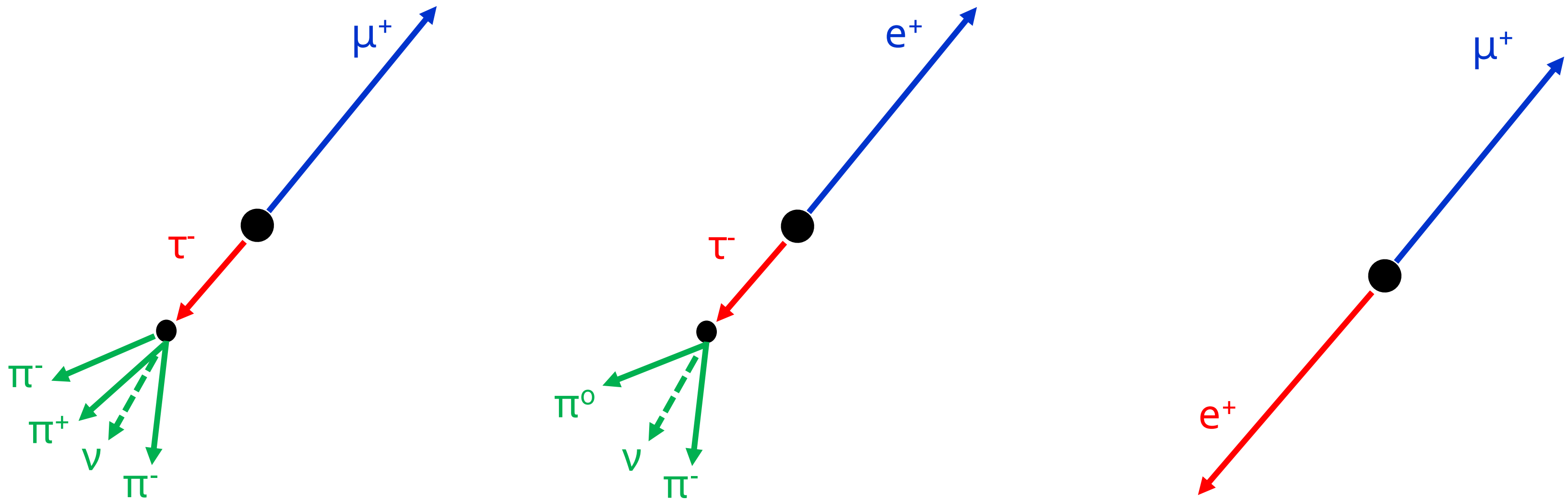
$$\frac{\delta G_F^\tau}{G_F^\tau} = \frac{5}{2}\frac{\delta m_\tau}{m_\tau} \oplus \frac{1}{2}\frac{\delta \tau_\tau}{\tau_\tau} \oplus \frac{1}{2}\frac{\delta \mathscr{B}}{\mathscr{B}}$$

Today: 67 ppm BES | 1700 ppm Belle | 1700 ppm LEP

FCC-ee: Will see 3×10^{11} τ decays
Statistical uncertainties at the 10 ppm level
How well can we control systematics?

m_τ	Use J/ψ mass as reference (known to 2 ppm)	tracking
τ_τ	Laboratory flight distance of 2.2 mm ⇒ 10 ppm corresponds to 22 nm (!!)	vertex detector
$\mathscr{B}$	No improvement since LEP (statistics limited) Depends primarily e^-/π^- (& e^-/ρ^-) separation	ECAL dE/dx

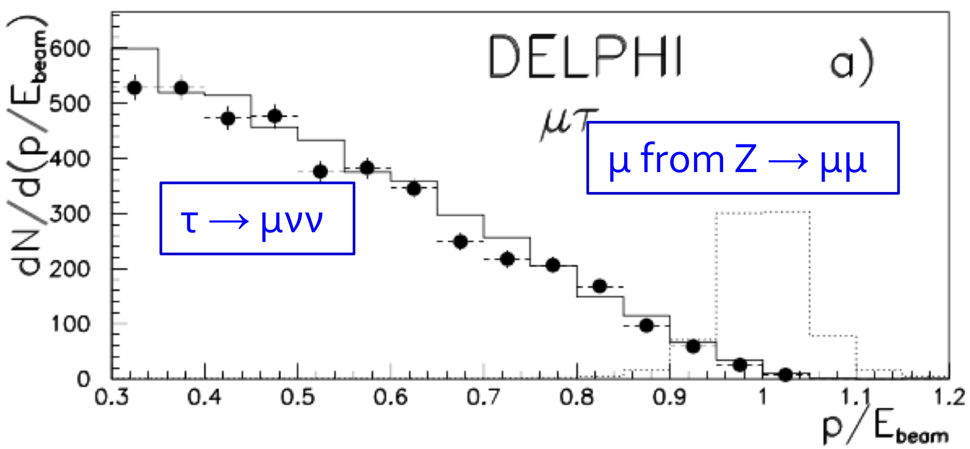
LFV Z decays



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

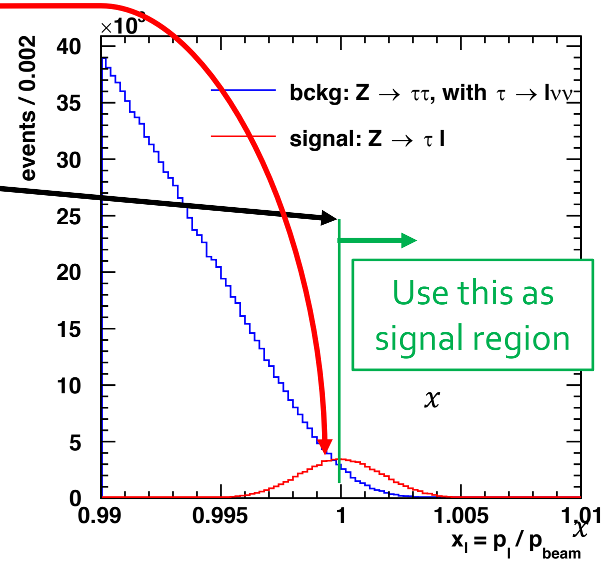
- Current limits
  - **$Br(Z \to e\tau) < 5.0 \times 10^{-6}$** LHC/ATLAS (139 fb^{-1} ⇒ 8 x 10^9 Z decays)
  - **$Br(Z \to \mu\tau) < 6.5 \times 10^{-6}$** [Nature Phys. 17 no. 7 (2021)]
- LEP limits – best for > 20 years untill ICHEP20
  - **$Br(Z \to e\tau) < 9.8 \times 10^{-6}$** LEP/OPAL (4 x 10^6 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



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

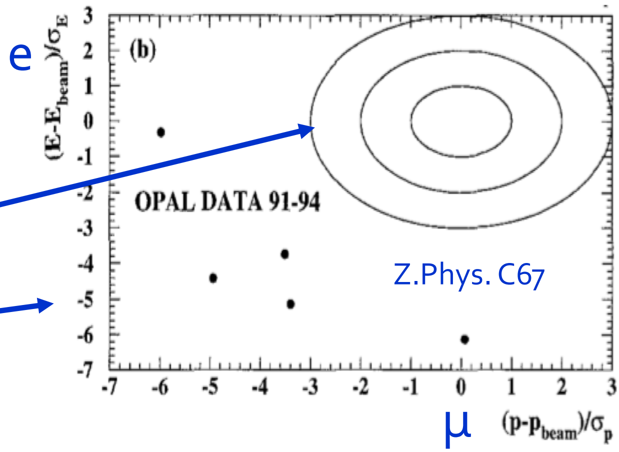
- Generate (very) upper part of μ momentum spectrum for $\tau \rightarrow \mu\nu\nu$ decays
  - Luminosity equivalent to 5×10^{12} Z decays
- Inject LFV signal of adjustable strength
  - Here for illustration, **$Br(Z \rightarrow \tau\mu) = 10^{-7}$**, i.e. 500,000 μs
- Smear momentum by adjustable amounts, here **1.8×10^{-3}**
- Define $x > 1$ as signal region
- Derive 95% confidence limit on excess in signal region
- Findings:
  - Sensitivity scales **linearly** 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 $Z \rightarrow \tau\mu$, sensitivity down to BFs of **$\sim 10^{-9}$**
  - For $Z \rightarrow \tau e$, 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.

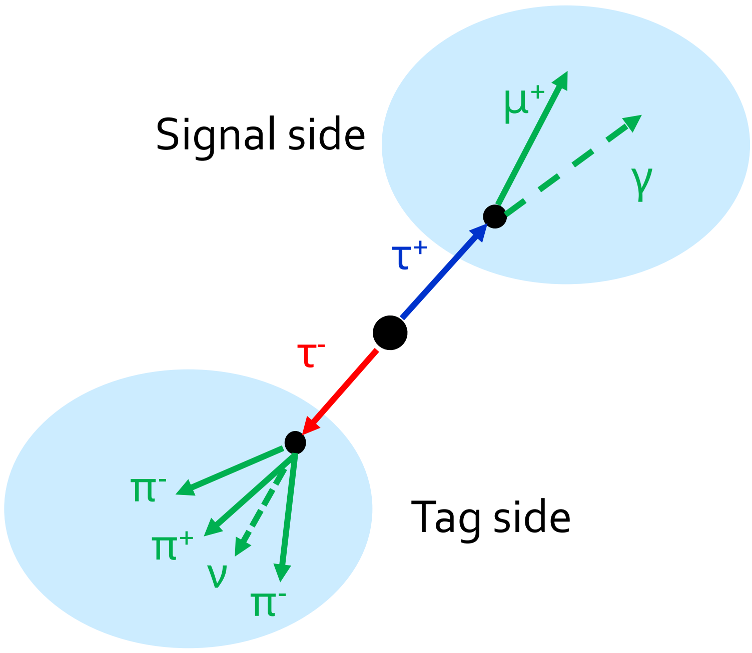
$Z \to e\mu$

- Current limits:
  - Best: **2.6×10^{-7}** **LHC/ATLAS** (8×10^{9} Zs ; 139 fb^{-1})
  - LEP: **1.7×10^{-6}** **LEP/OPAL** (4×10^{6} Zs: no candidates)
- In e^+e^-, clean experimental signature:
  - Beam energy electron vs. beam energy muon

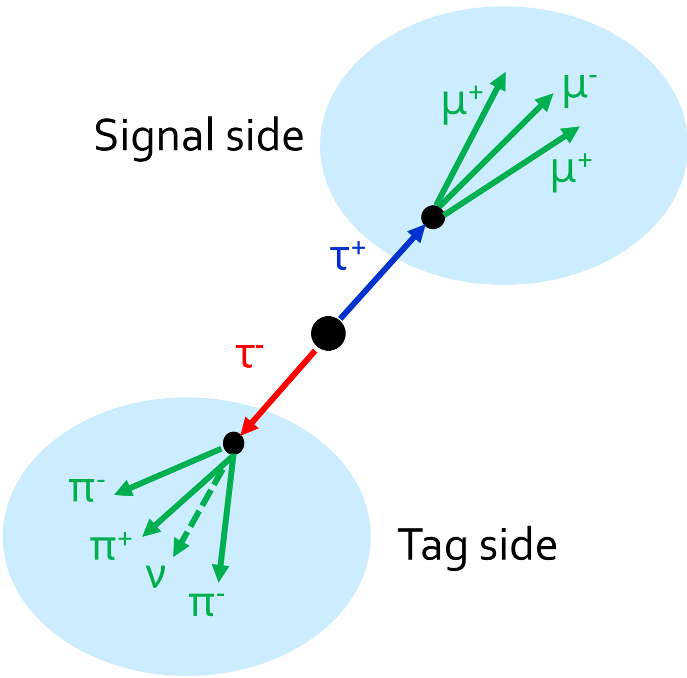


- Main experimental challenge:
  - **Catastrophic bremsstrahlung energy loss** of muon in electromagnetic calorimeter
    - Muon would deposit (nearly) full energy in ECAL: Misidentification $\mu \to e$
    - NA62: Probability of muon to deposit more than 95% of energy in ECAL: **4×10^{-6}**
    - Possible 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 $P(\mu \to e)$
- FCC-ee:
  - Misidentification from catastrophic energy loss corresponds to limit of about $Br(Z \to e\mu) \simeq 10^{-8}$
  - Possibly do $\mathcal{O}(10)$ better than that **$Br(Z \to e\mu) \sim 10^{-9}$** (probably even **$10^{-10}$** with IDEA like 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 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 (Xstal @ BaBar)
  - 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

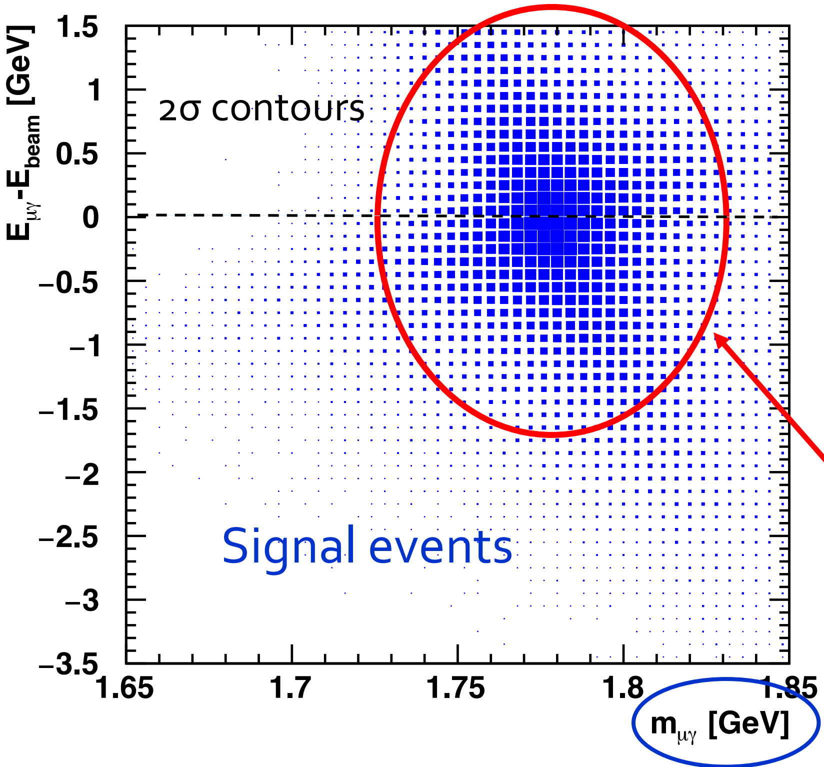
2 x 10^{-9}

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



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:

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

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 $\tau \to \mu\gamma$

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

Recent suggestion: Crystal ECAL for FCC-ee

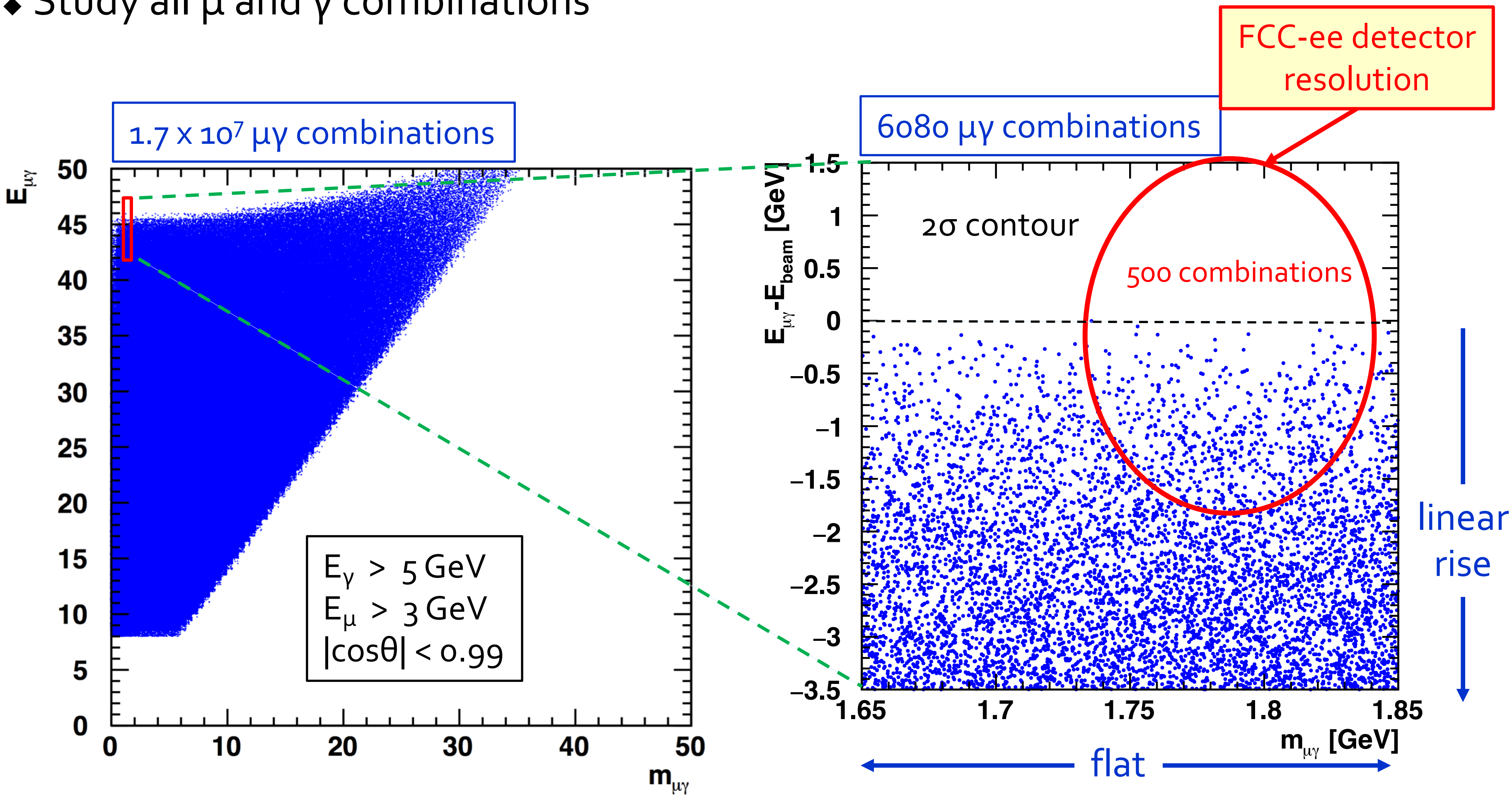
$\sigma(E)/E = 0.03/\sqrt{E} \oplus 0.011$

Resolution ellipse factor ~4 smaller in both directions

2008.00338

$\tau \to \mu\gamma$ 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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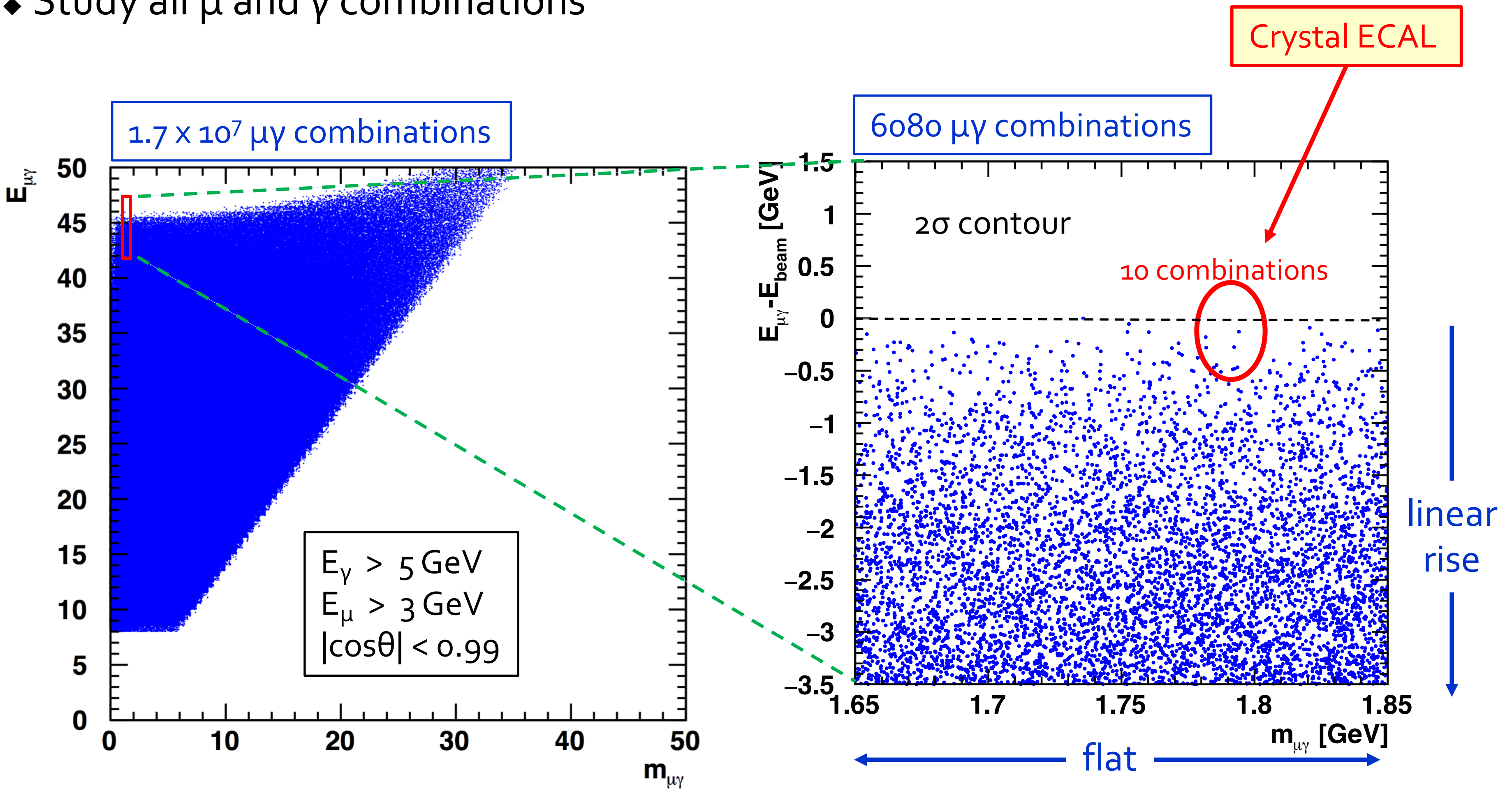
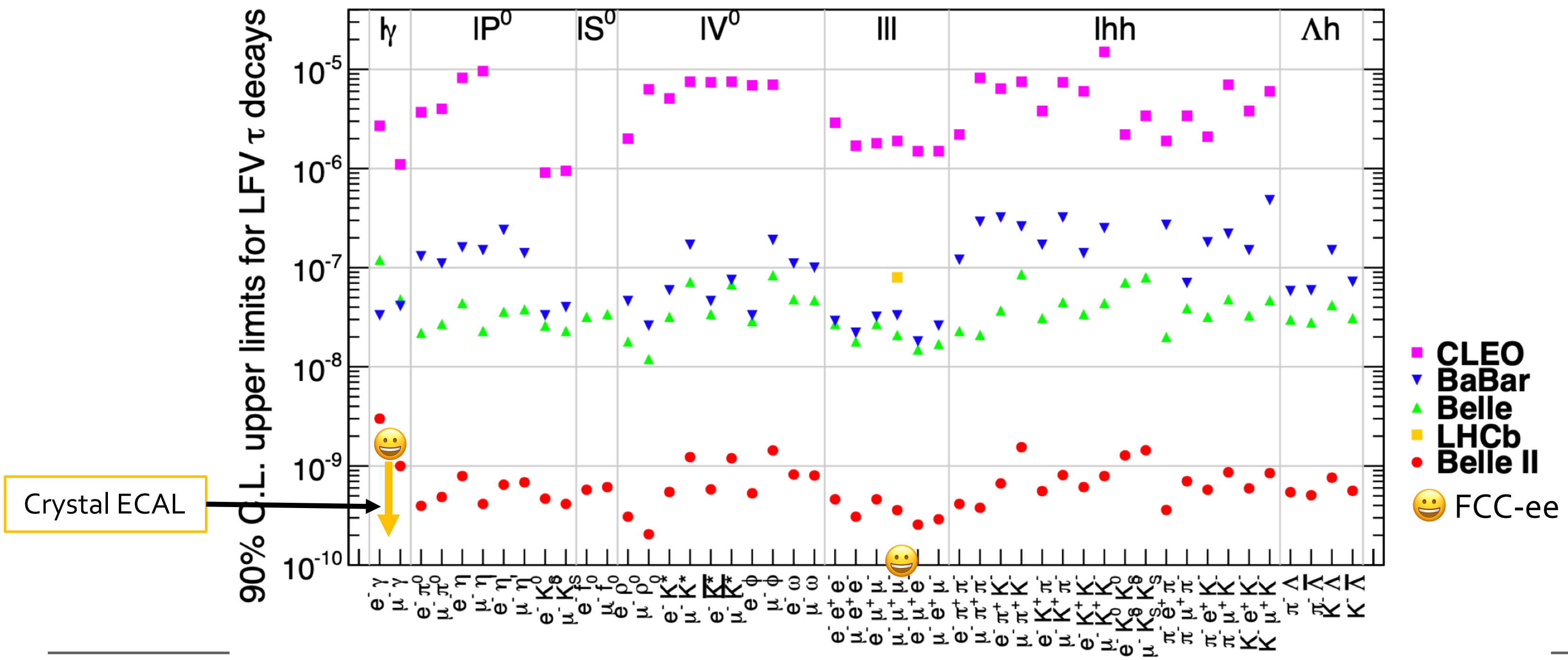


$\tau^- \rightarrow \ell^-\ell^+\ell^-$

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



Summary

- From 5 x 10^{12} Z decays, FCC-ee will produce **1.7 x 10^{11} $\tau^+\tau^-$ pairs**
- Factor ~3 higher statistics than Belle2 projection; plus higher boost (γ = 25)
  - Boost is advantageous for many studies
- Potential for very precise $\sin^2\theta_W$ determination via **τ polarisation** measurement
- Improve **Lepton universality test** by at least a factor 10 down to $\mathcal{O}(10^{-4})$ level
  - Substantial improvement in **τ lifetime**
  - Substantial improvement in **τ branching fractions**
    - Virtually no progress since LEP
  - Competitive measurement of **τ mass**
- Improved sensitivity to **lepton flavour violating Z decays** by factor **$\mathcal{O}(10^3)$**
  - Sensitivities down to **10^{-9}**
- Searches for **lepton flavour violating τ decays**; sensitivites comparable to Belle2
  - Range from $\lesssim$ **10^{-10}** to **few x 10^{-9}**

- Plus hadronic branching ratios and spectral functions, α_s, ν_τ mass, ...

Summary - Detector requirements

- Precision τ physics sets very strong detector requirements; 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
      - 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 secondary tracks from hadronic interaction in material
  - **Calorimetry**
    - Clean γ and π^0 reconstruction from ~0.2 to 45 GeV is key to precison τ physics
    - Collimated topologies: Important to be able to separate γs from closelying hadronic showers
  - **PID**
    - Necessary if one desires to separate π/K modes (0 – 45 GeV momentum range)
    - e/π separation at low momenta (where calorimetric separation is most difficult)
    - **Redundancy**: Provides valuable handle to create test samples for study of calorimetry
      - For IDEA drift chamber, even for e/μ separation

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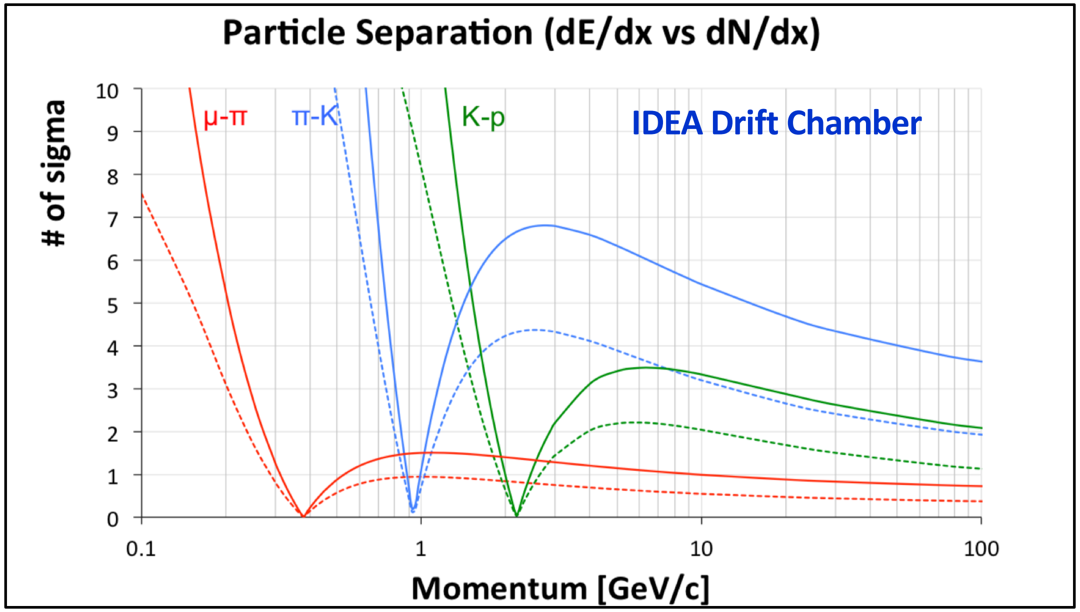
Important to optimise detector design **now** for this important and exciting physics



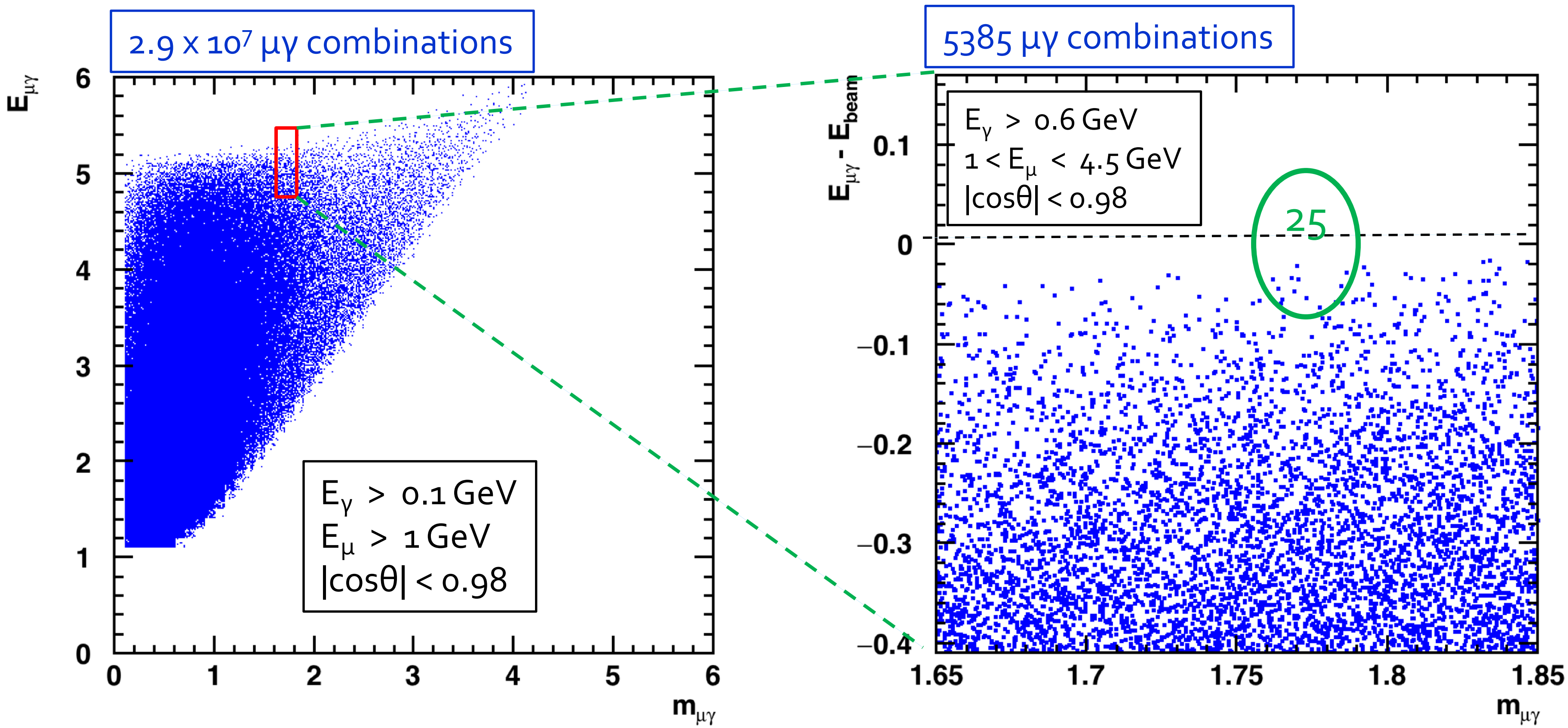
- To beat down uncertainties on ”calorimetric” identifications (e/π, e/μ, π/μ) it is essential to have available a perpendicular, independent, nondestructive identification tool
  - This is exactly what a powerful dE/dx measurement provides you!

Extra Slides

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

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

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



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

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

Agrees within a factor 2
Not too bad