τ challenge at FCC-ee

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ILC IDT Physics group Meeting
16 October 2021

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**

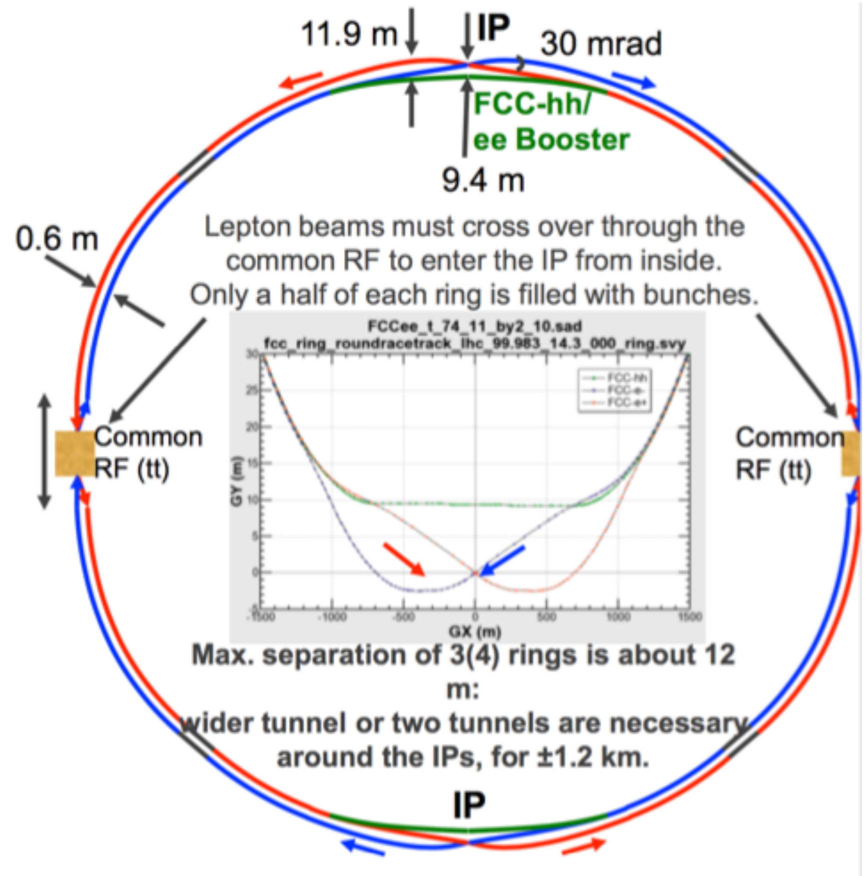
References:

- 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

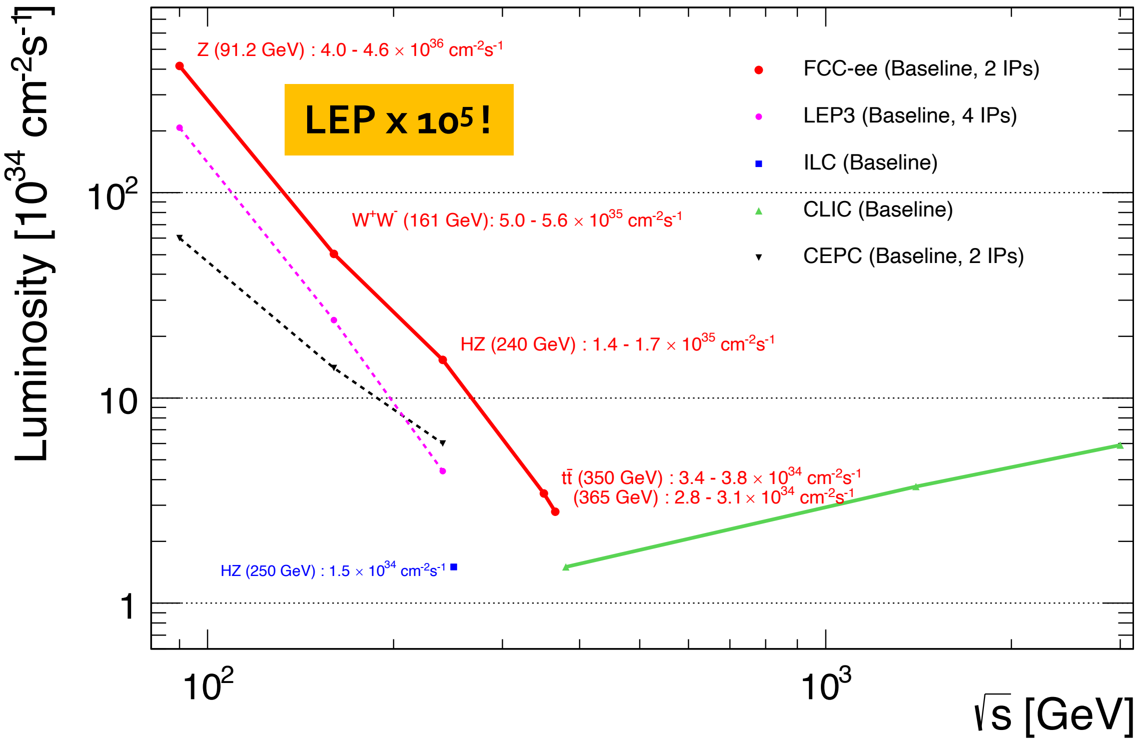
Future Circular Collider Feasibility Study initiated by CERN Council in June 2021

- *"…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.

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

A wealth of EW and Higgs Precision Measurements

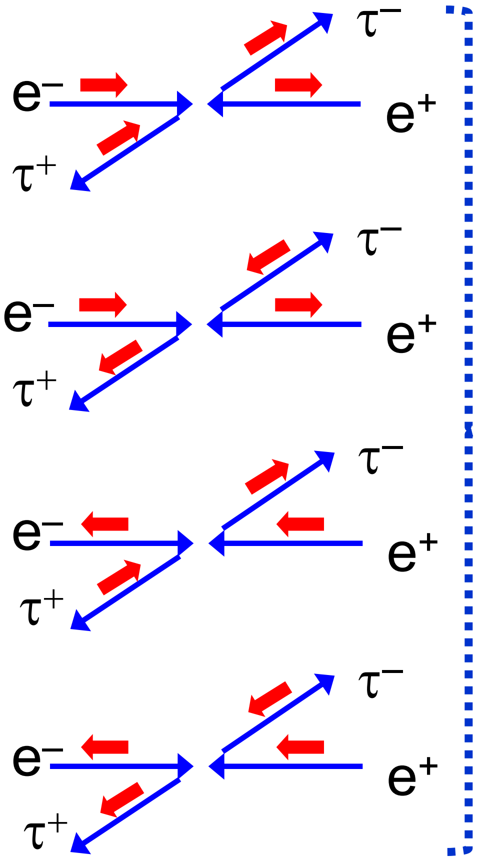
Observable	Measurement	Current precision	FCC-ee stat.	FCC-ee syst.	Challenge
m_Z (keV)	Z lineshape	91186700 ± 2200	5	100	E_{Beam} calib
Γ_Z (keV)	Z lineshape	2495200 ± 2300	8	100	E_{Beam} calib
R_l ($\times 10^3$)	Ratio had to lept	20767 ± 25	0.01	0.2–1	Lepton accept
$\alpha_s(m_Z)$ ($\times 10^4$)	From 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	$g \to bb$
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	$e^+e^- \to \gamma Z$, $Z \to \nu\nu$, $\ell\ell$	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

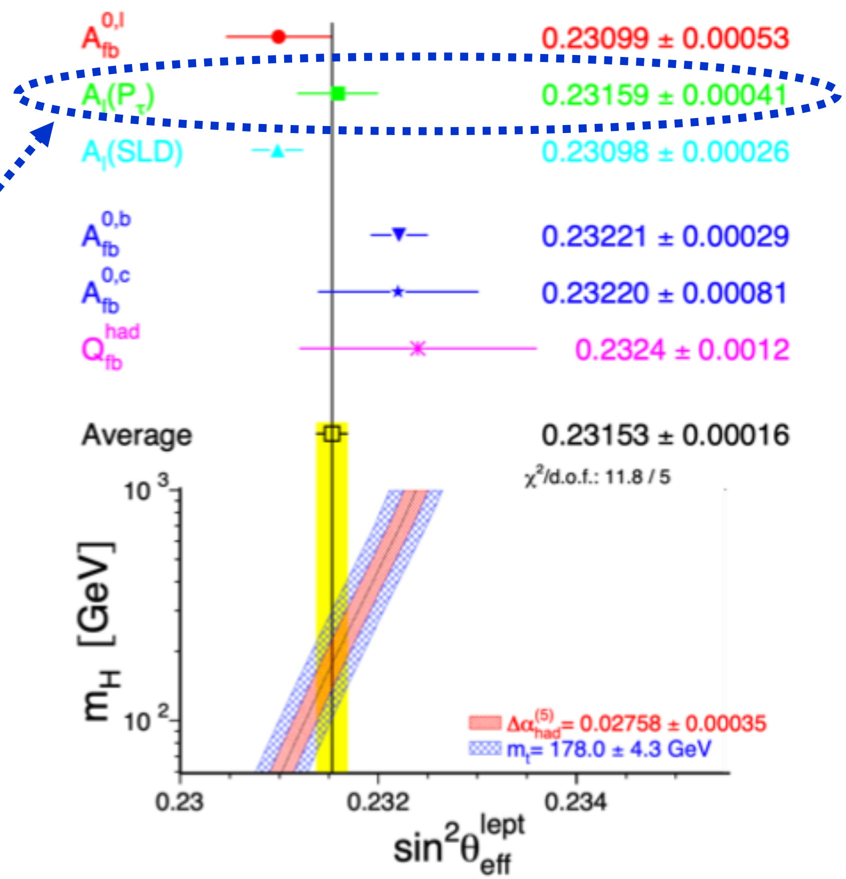
Higgs

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 …

τ Polarisation Measurement

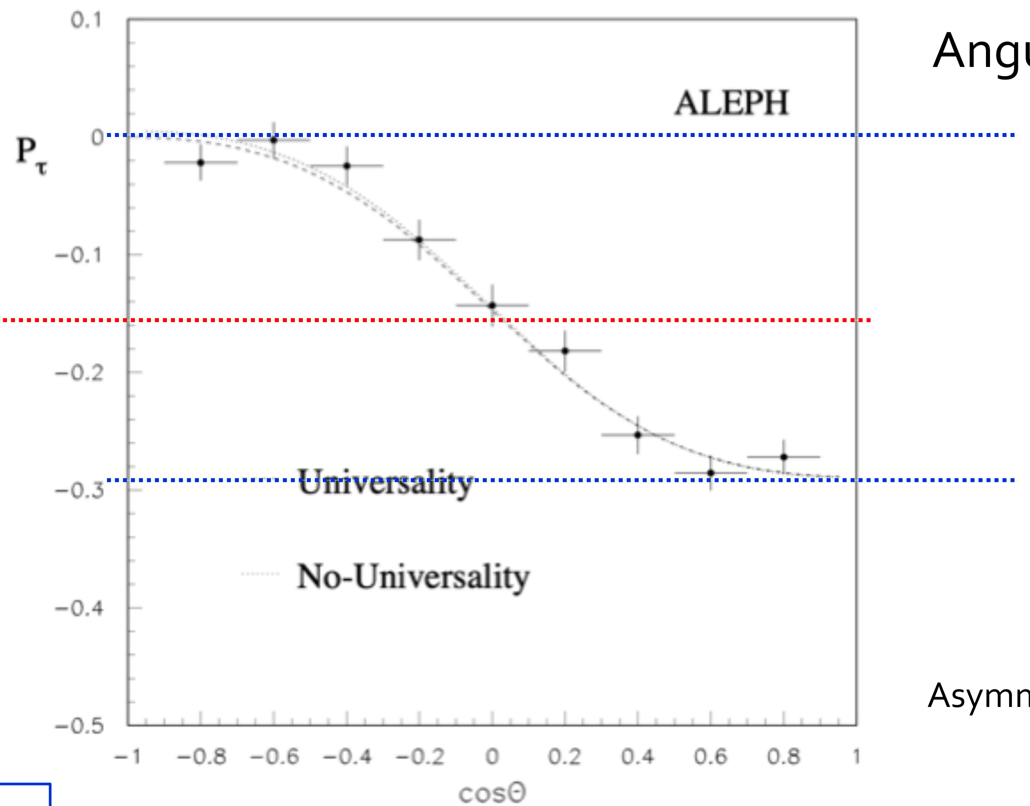




Example: LEP experiment aleph

Mean polarisation

$\mathcal{A}_\tau$



Angular dependence

$\mathcal{A}_e$

Asymmetri-like measurement:
Low systematics

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

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

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

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

Experimental aspects

Use τ decays as spin analysers (V-A)

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

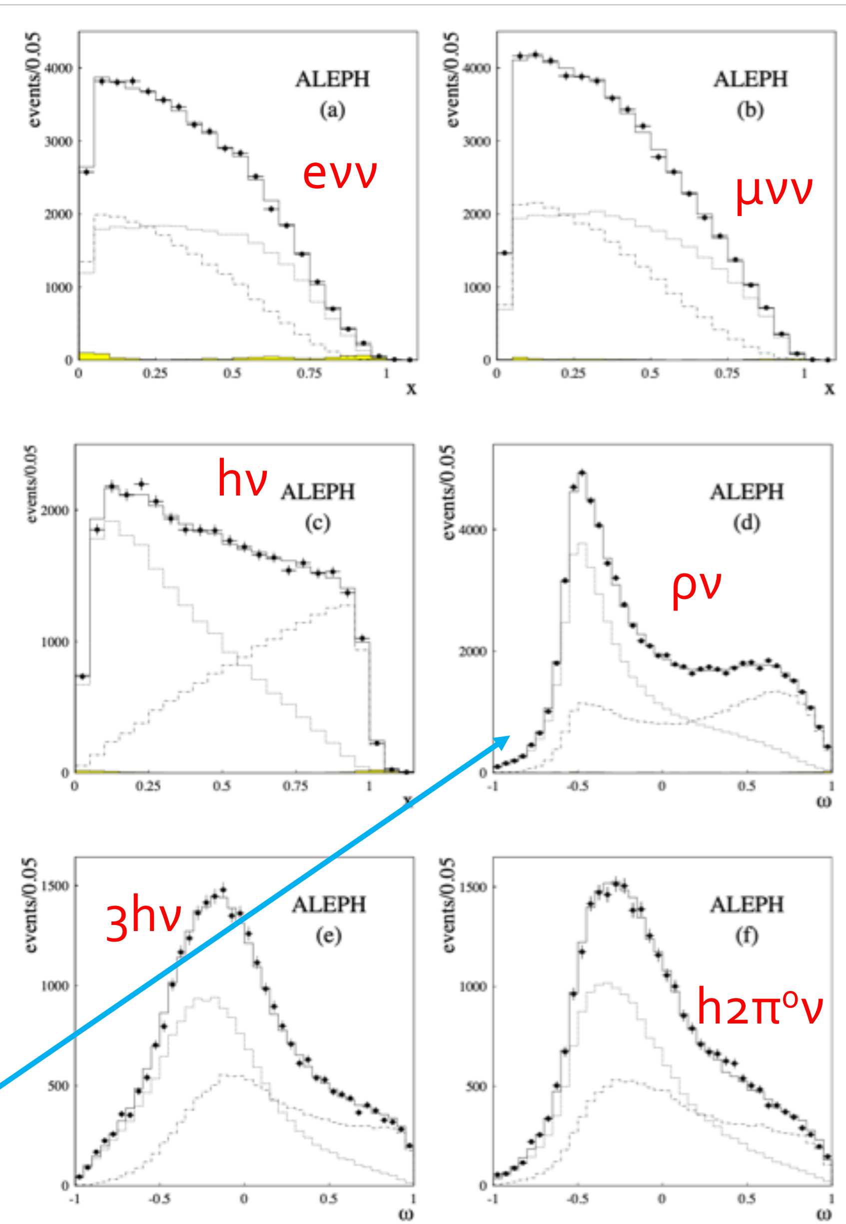
Example: $\tau^- \rightarrow \rho^-\nu \rightarrow \pi^-\pi^0\nu$

- 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	$3h$	$h\,2\pi^0$	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

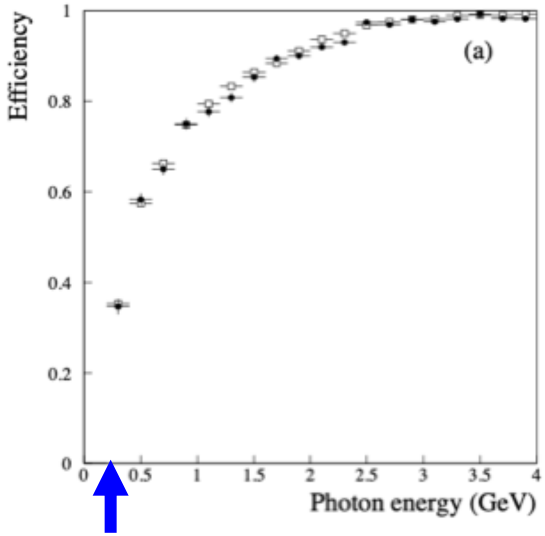
Source	h	ρ	$3h$	$h\,2\pi^0$	e	μ	Incl. h
			$\mathcal{A}_e$				
tracking	0.04	-	-	-	-	0.05	-
non-τ back.	0.11	0.09	0.04	0.22	0.91	0.24	0.17
modelling	-	-	0.40	0.40	-	-	-
TOTAL	0.12	0.09	0.40	0.47	0.91	0.25	0.17

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

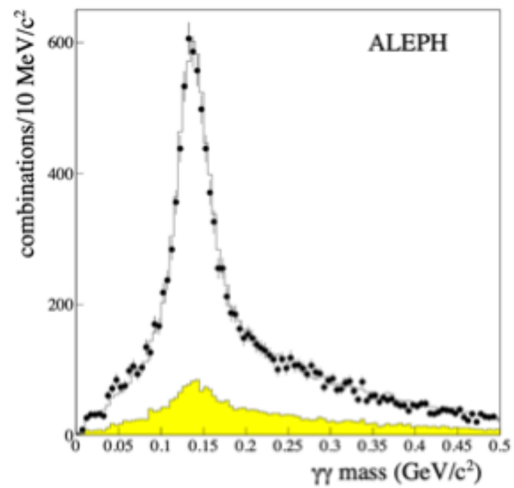
The single most important systematics (on the most precise channels) is due to photon and π^0 identification

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)

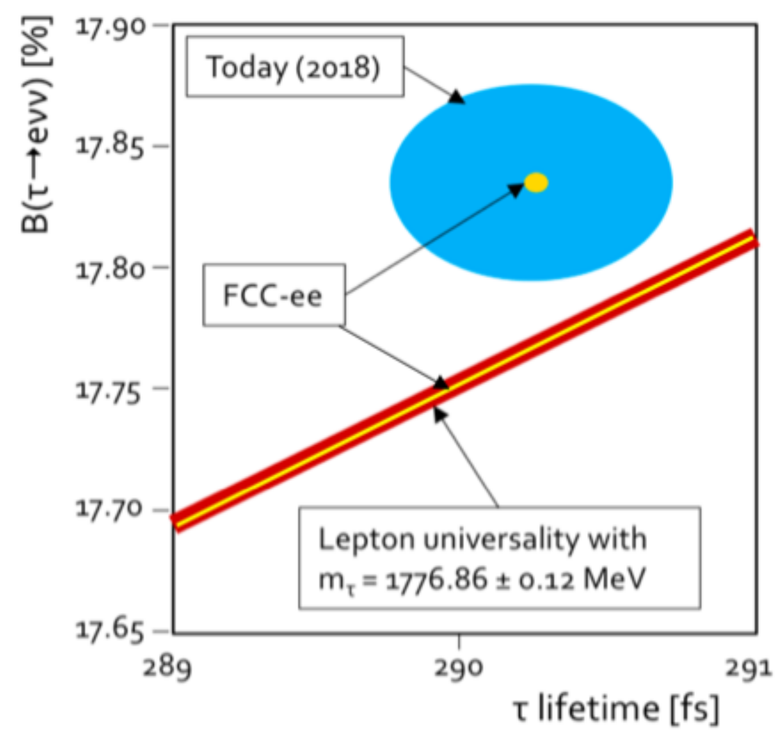
reconstructed \ true

	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

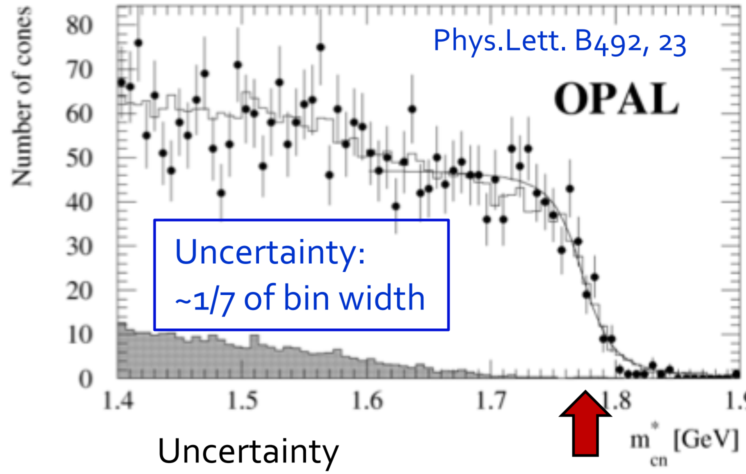
τ-lepton properties and Lepton Universality

a) Mass
b) Lifetime
c) Leptonic branching fractions



Tau Mass (i)

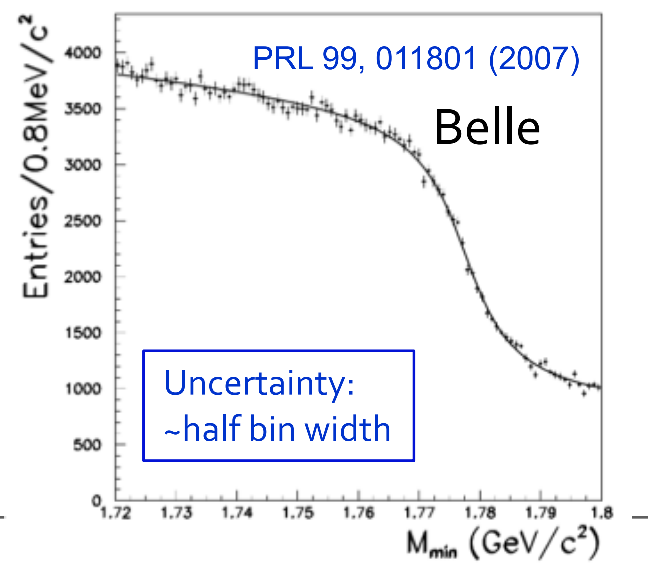
- **Current world average:** $m_\tau = 1776.86 \pm 0.12$ MeV
- Best in world: BES3 (threshold scan) $m_\tau = 1776.91 \pm 0.12\ (\text{stat.})\ ^{+0.10}_{-0.13}\ (\text{syst.})$ MeV
- Best at LEP: OPAL $m_\tau = 1775.1 \pm 1.6\ (\text{stat.}) \pm 1.0\ (\text{syst.})$ MeV
  - About factor 10 from world's best
  - Main result from endpoint of distribution of pseudo-mass in $\tau \to 3\pi^\pm(n\pi^0)\nu_\tau$
  - 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)

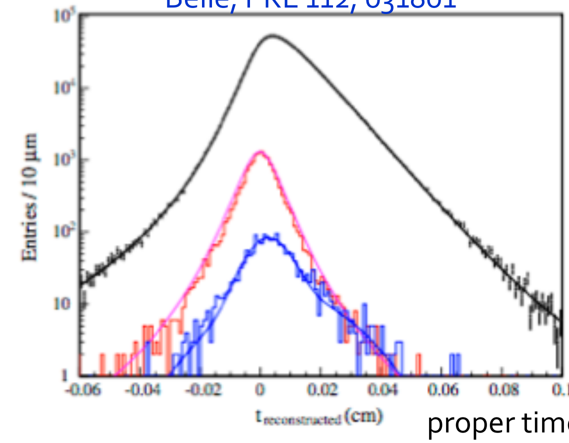
- Prospects for FCC-ee:
  - 3 prong, 5 prongs, (perhaps even 7 prongs?)
  - Statistics 10^5 times OPAL: **δ_{stat} = 0.004 MeV**
  - Systematics:
    - At FCC-ee, E_{BEAM} determined to better than 0.1 MeV (~ 1 ppm) from resonant spin depolarisation
      - Negligible effect on m_τ
    - Control of mass scale
      - Suggest to exploit 10^9 $J/\psi \rightarrow \mu\mu$ 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

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

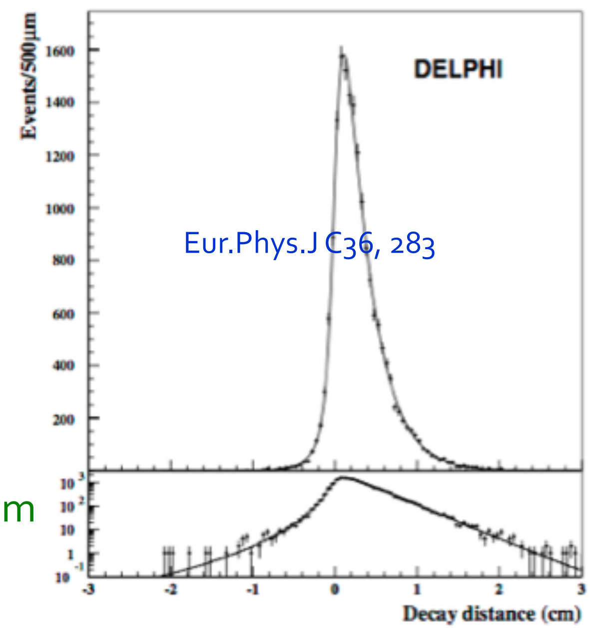
⇒ **Key:** precise control of momentum scale also in dense, multi-prong topologies

Tau Lifetime (i)

- **Current world average:** **τ_τ = 290.3 ± 0.5 fs**
- **Best in world** (Belle): **τ_τ = 290.17 ± 0.53 $_{stat}$ ± 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 (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



- **Best at LEP** (DELPHI): **τ_τ = 290.0 ± 1.4 $_{stat}$ ± 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 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



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
    possibly 10 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 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, will learn a lot. Suggest a factor 10 improvement wrt Aleph:

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

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

Summary of Precisions & Lepton Universality

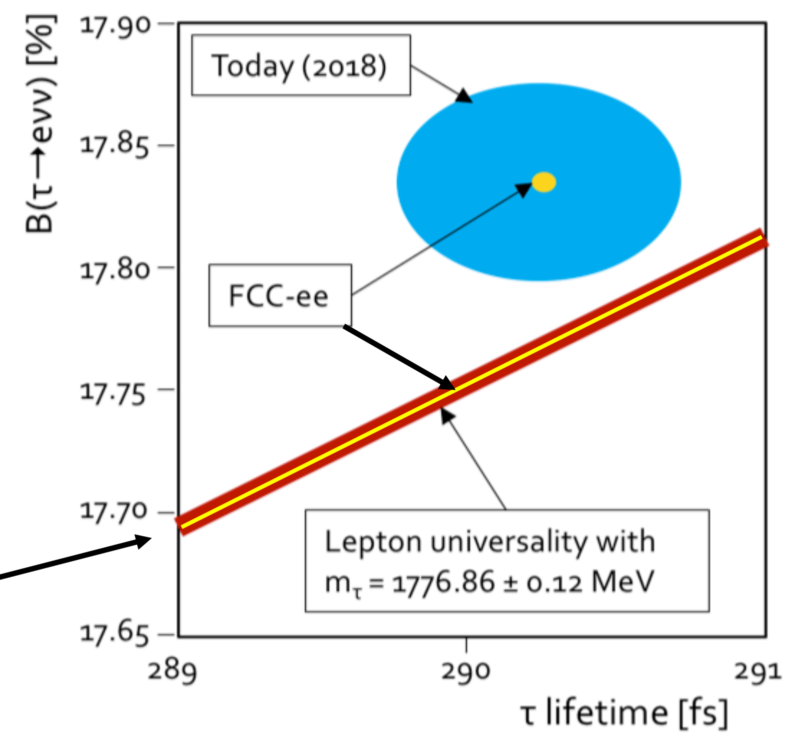
Observable	Measurement	Current precision	FCC-ee **stat.**	**Possible syst.**	Challenge
m_τ [MeV]	Threshold / inv. mass endpoint	1776.86 **± 0.12**	**0.004**	**0.04 (?)**	Mass scale
τ_τ [fs]	Flight distance	290.3 **± 0.5 fs**	**0.001**	**0.04**	Vertex detector alignment
B($\tau \to e\nu\nu$) [%]	Selection 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

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



Example of precision challenge: Universality of Fermi constant

The Fermi constant is measured in μ decays and defined by

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

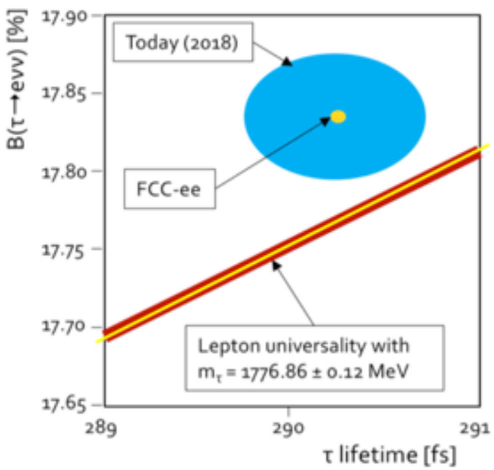
(known to 0.5 ppm)

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)

Universality supported by current data
- 1σ error ellipse (blue) consistent with mass (red)



Shown in yellow: first guestimates on FCC-ee precisions

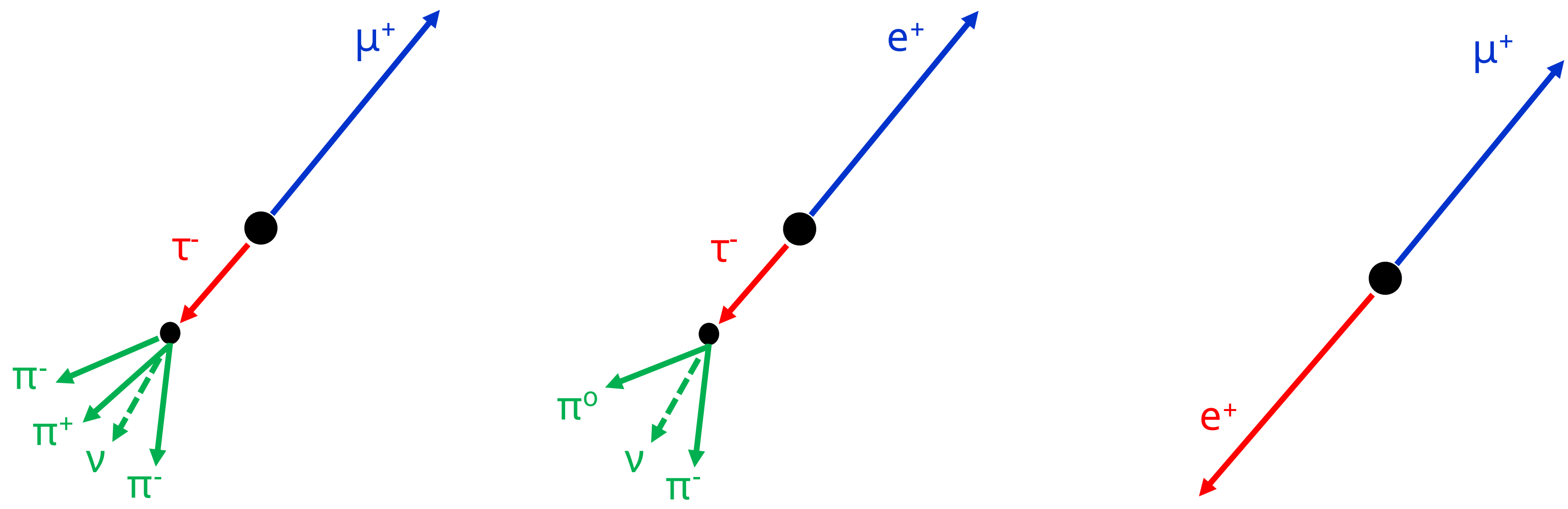
$$\frac{\delta G_F^\tau}{G_F^\tau} = \frac{5}{2}\frac{\delta m_\tau}{m_\tau} \oplus \frac{1}{2}\frac{\delta \tau_\tau}{\tau_\tau} \oplus \frac{1}{2}\frac{\delta \mathscr{B}}{\mathscr{B}}$$

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

FCC-ee: Will see 3x10[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

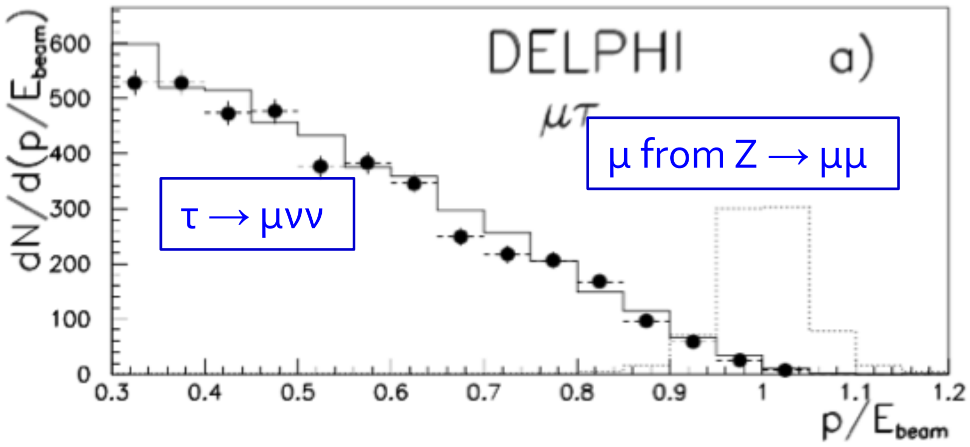
LFV Z decays



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

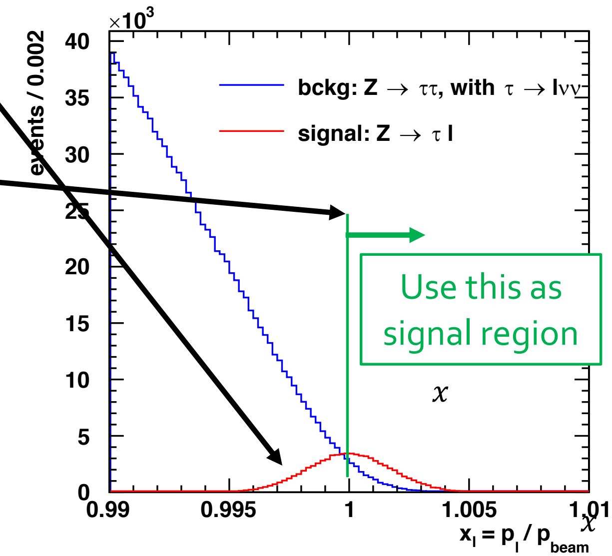
- Current limits
  - **Br($Z \to e\tau$) < 8.1 × 10^{-6}** LHC/ATLAS (139 fb^{-1} ⇒ 2.8 x 10^8 Z decays)
  - **Br($Z \to \mu\tau$) < 9.5 × 10^{-6}** [Nature Phys. 17 no. 7 (2021)]
- LEP limits – best for > 20 years untill ICHEP20
  - **Br($Z \to e\tau$) < 9.8 × 10^{-6}** LEP/OPAL (4 x 10^6 Z decays)
  - **Br($Z \to \mu\tau$) < 12. × 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



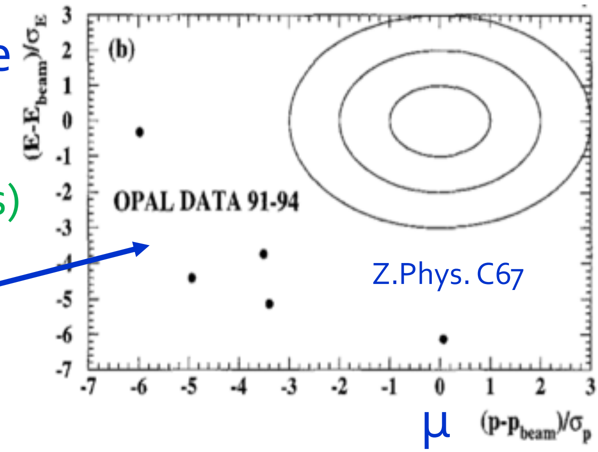
$Z \to \ell\tau$ - Study of Sensitivity

- 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 → τμ) = 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→ 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.



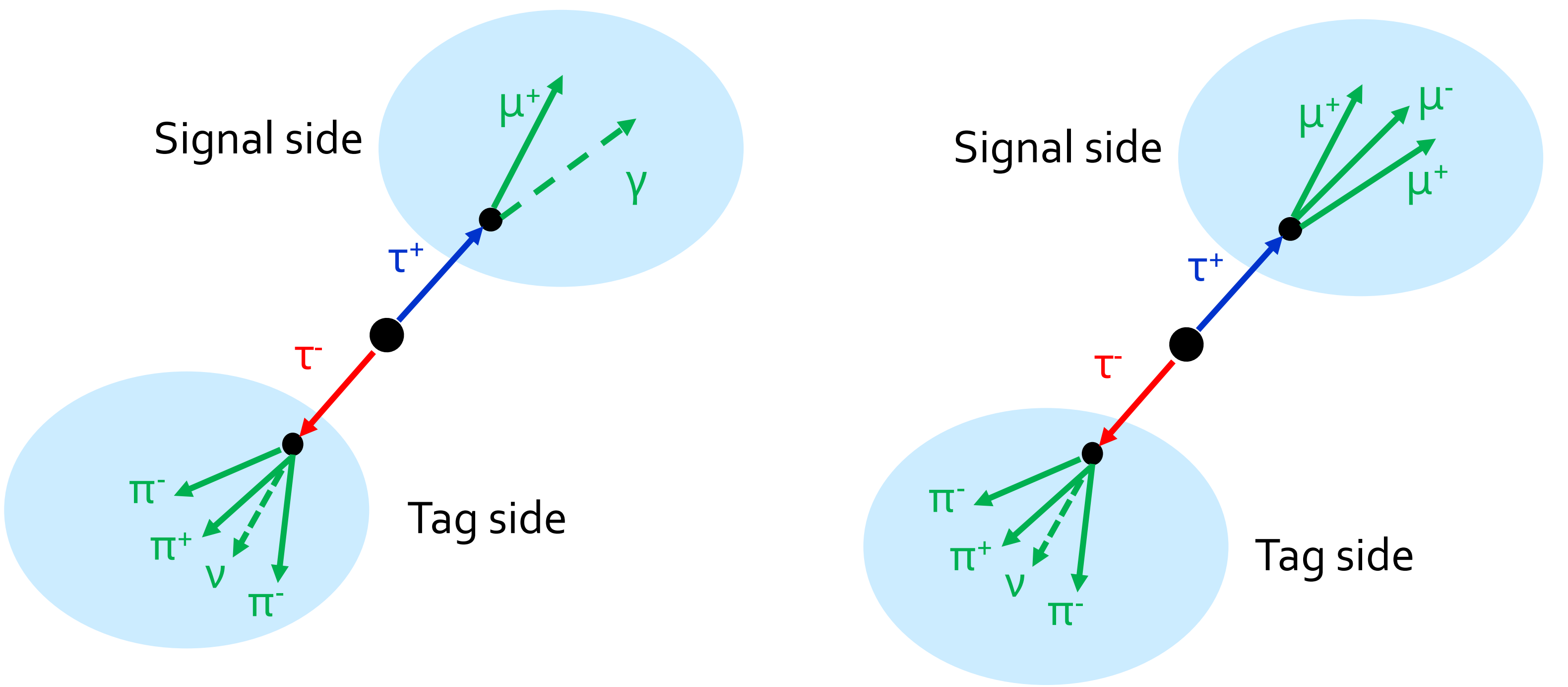
$Z \rightarrow e\mu$

- 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)
- 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: **4×10^{-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)

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

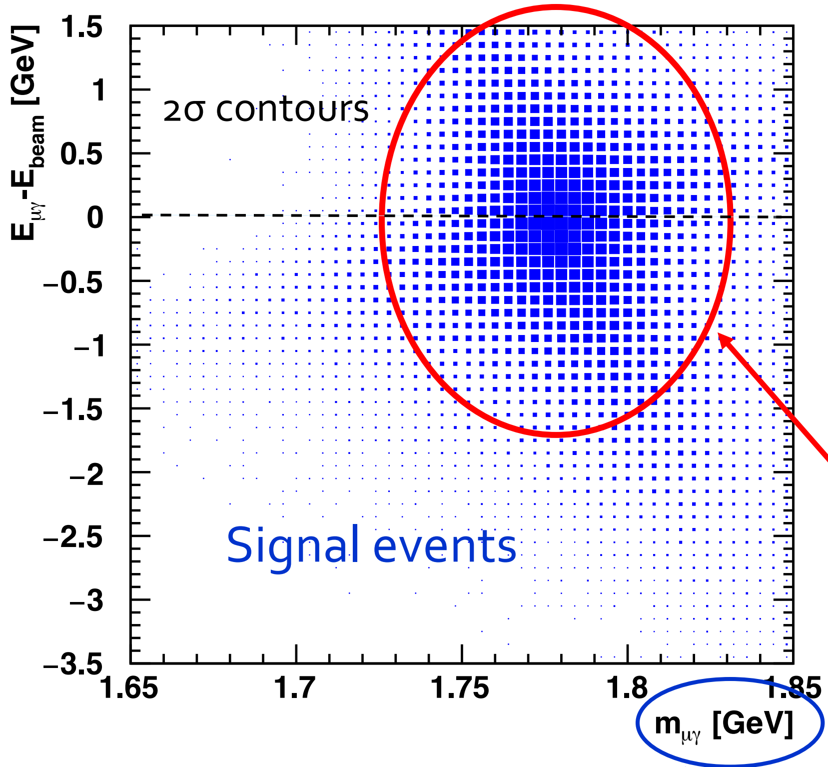
2×10^{-9}

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



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

- Muon momentum [GeV]
  $\sigma(p_T)/p_T = 2\text{x}10^{-5} \text{ x } p_T \oplus 1\text{x}10^{-3}$
- 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:

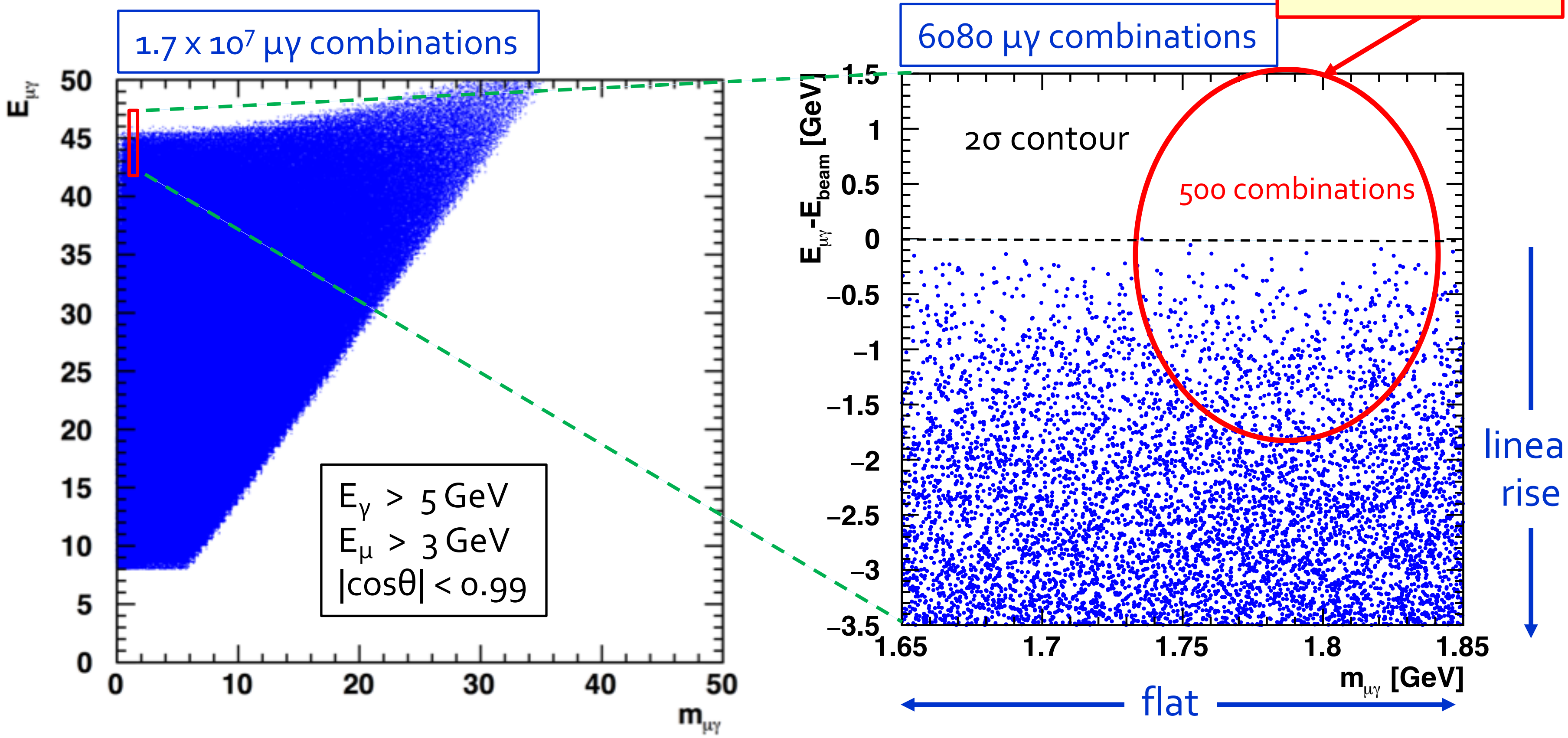
$$m_{\gamma\mu} = m_{raw} \text{ x } (E_{\gamma\mu}/E_{beam})$$

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

2008.00338

$\tau \to \mu\gamma$ 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



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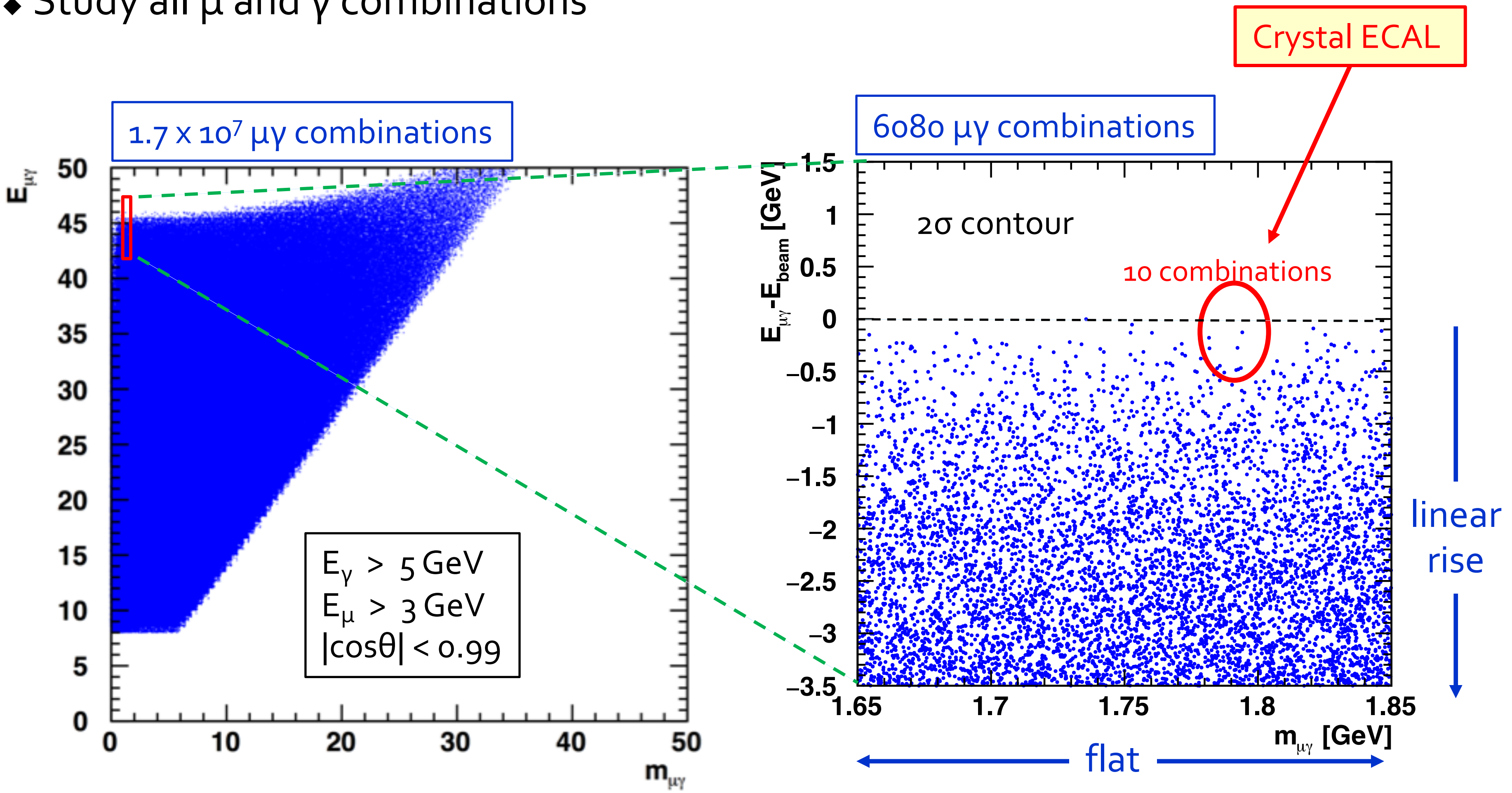
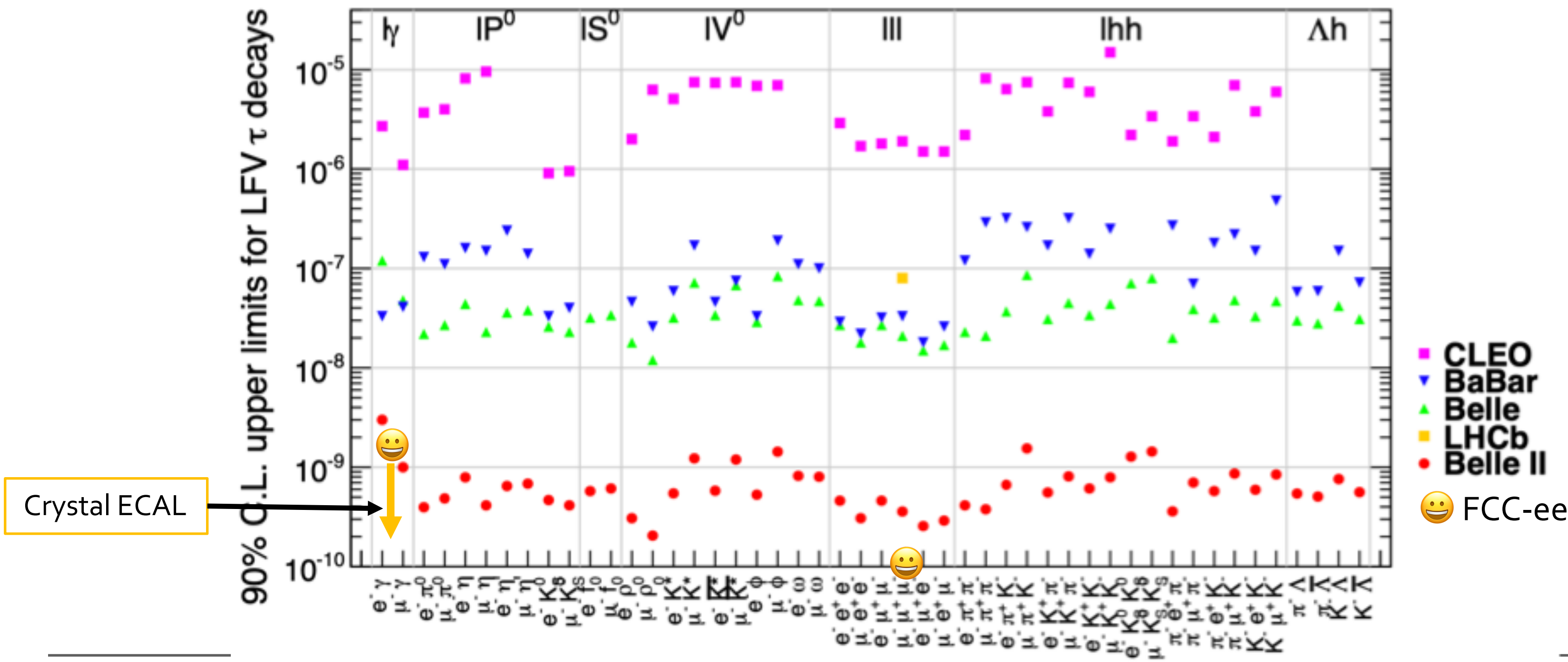


$\tau^- \to \ell^-\ell^+\ell^-$

- 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. 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**
- Searches for **lepton flavour violating τ decays**; sensitivites comparable to Belle2
  - Range from **$\lesssim 10^{-10}$** to **few x 10^{-9}**
- Improved sensitivity to **lepton flavour violating Z decays** by factor **$\mathcal{O}(10^{3\text{-}4})$**
  - Sensitivities down to **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. $Z \rightarrow \mu\tau$, 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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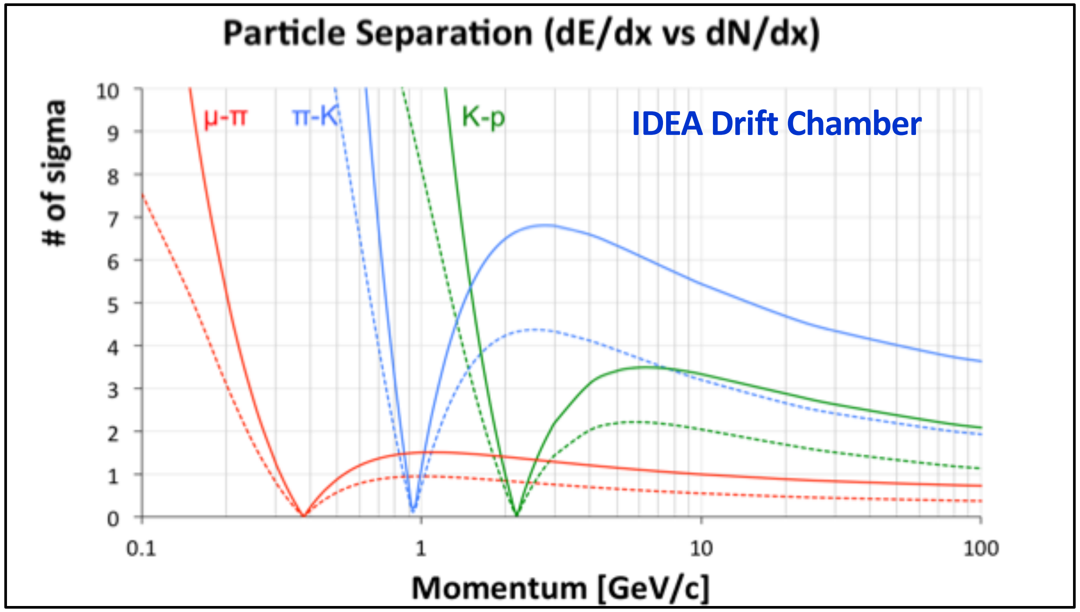
Important to optimise detector design **now** for this important and exciting physics

Epilogue - The Importance of Redundancy



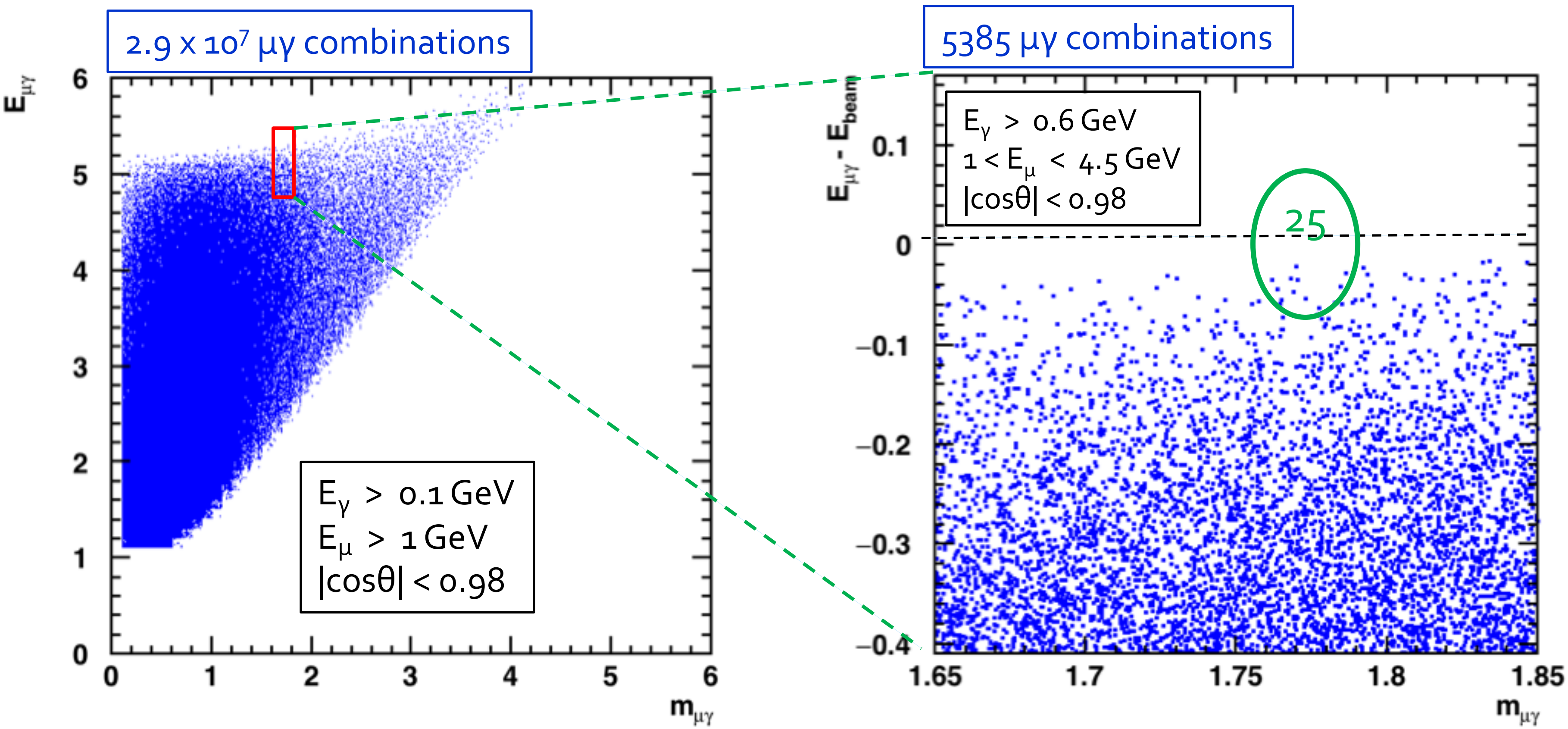
- To beat down uncertainties on "calorimetric" identifications (e/π, e/μ, π/μ) it is <u>essential</u> to have available a perpendicular, independent, nondestructive identification tool
  - This is exactly what a powerful dE/dx measurement provides you!

Extra Slides

$\tau \to \mu\gamma$ 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: **1.9×10^{-9}**

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

Agrees within a factor 2
Not too bad