Tau physics at FCC-ee

Snowmass2021 - Letter of Interest

Tau lepton properties and lepton universality measurements at the FCC-ee

Thematic Areas:
■ EF04: EW Physics: EW Precision Physics and constraining new physics
■ EF03: EW Physics: Heavy flavor and top quark physics

Contact Information:
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Authors:
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LoI #252

Abstract:
The FCC-ee is a frontier Higgs, Top, Electroweak, and Flavour factory. It will be operated in a 100-km circular tunnel built in the CERN area, and will serve as the first step of the FCC integrated programme towards $\geq$ 100-TeV proton-proton collisions in the same infrastructure [1]. With its huge luminosity at Z-pole energies, unrivalled samples of 5×10^{12} Z decays will be produced at multiple interaction points. The five orders of magnitude larger statistics than at LEP opens the possibility of much improved measurements of τ-lepton properties—lifetime, (leptonic) branching fractions, and mass—in $\tau^+\tau^-$ final states. Such measurements provides interesting tests of lepton universality, in effect probing whether the Fermi coupling constant is the same in τ decays as in μ decays. The ultimate goal, that experimental errors match the statistical accuracy, leads to highly demanding requirements on detector design. This Letter of Interest describes some of the many challenges presented by this benchmark measurement.

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Tau exclusive branching fractions and tau polarisation observables at the FCC-ee

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■ EF04: EW Physics: EW Precision Physics and constraining new physics
■ EF05: QCD and strong interactions:Precision QCD

Contact Information:
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Authors:
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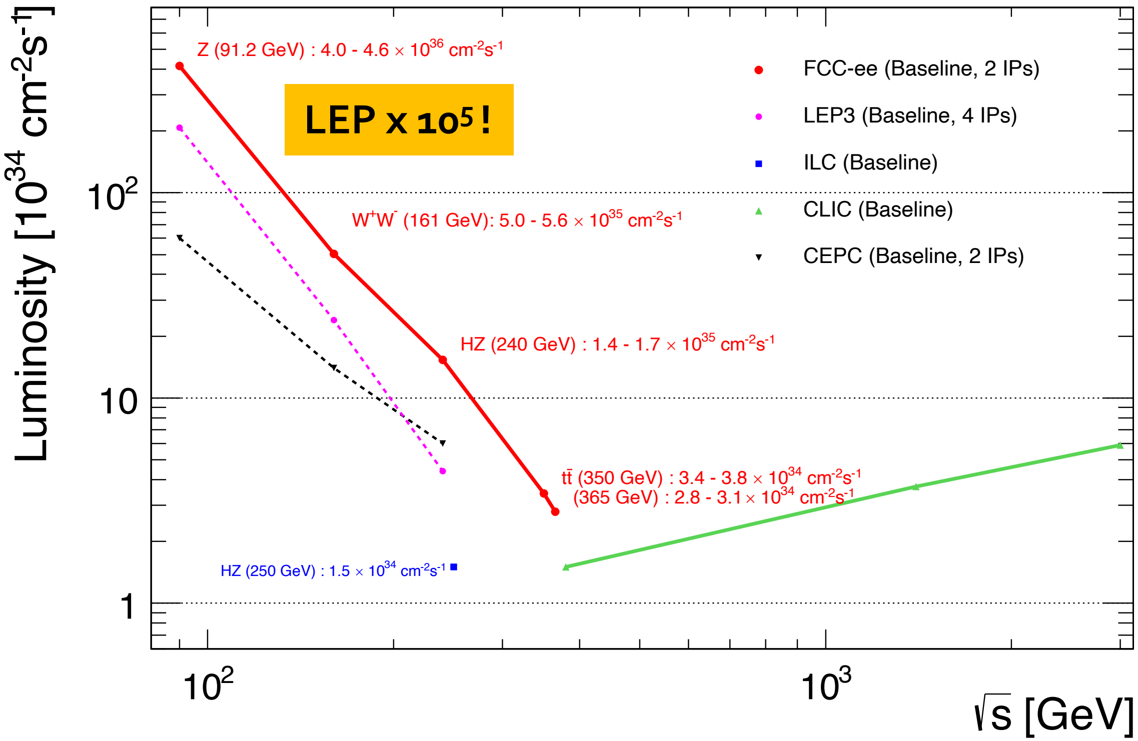
LoI #255

Abstract:
The FCC-ee is a frontier Higgs, Top, Electroweak, and Flavour factory. It will be operated in a 100-km circular tunnel built in the CERN area, and will serve as the first step of the FCC integrated programme towards $\geq$ 100 TeV proton-proton collisions in the same infrastructure [1]. With its huge luminosity at Z-pole energies, unrivalled samples of 5×10^{12} Z-decays will be produced at multiple interaction points. This opens the possibility for very precise measurements of τ leptons including their exclusive branching fractions and their polarisation in Z decays, one of the most precise electroweak observables. This letter of interest concentrates on some of the main experimental challenges in τ-lepton measurements, namely the inter-channel separation and the precise measurement of the final state kinematics. This relies critically on the precise measurement of photons and π^0s (and other neutral particles) in the calorimeter system, on the precise tracking of high-multiplicity collimated topologies, and—at least for the exclusive branching fractions—on the ability to separate pions from kaons over the full momentum range.

Luminosity & Statistics



Z peak	E_{CM} : 91 GeV	5 x 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

Enormous statistics.
Also for τ-leptons

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

τ-lepton properties and Lepton Universality

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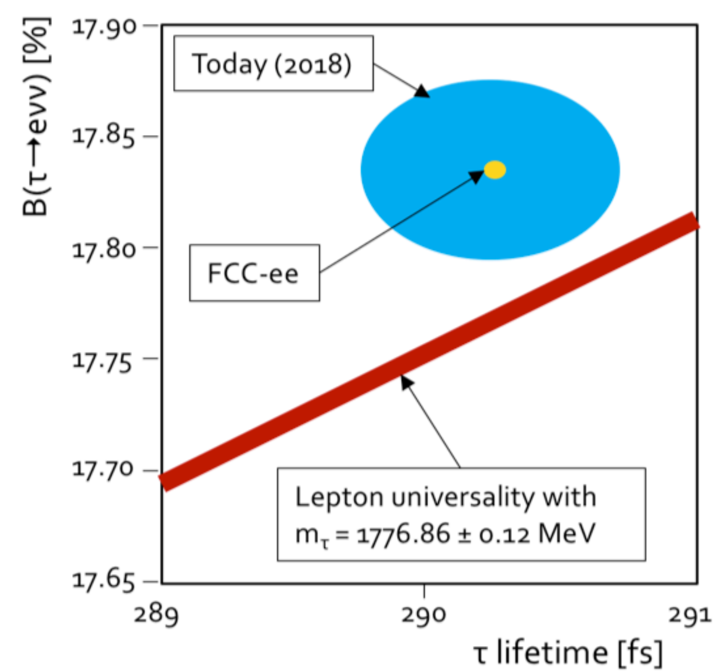
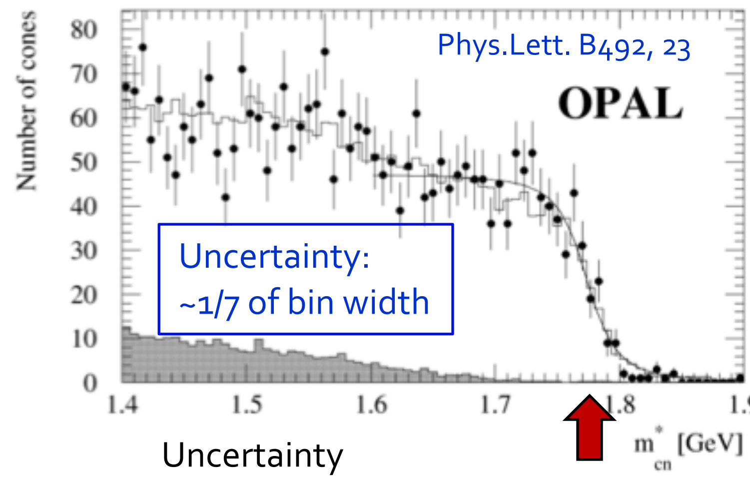
a) Mass
b) Lifetime
c) Leptonic branching fractions



Tau Mass (i)

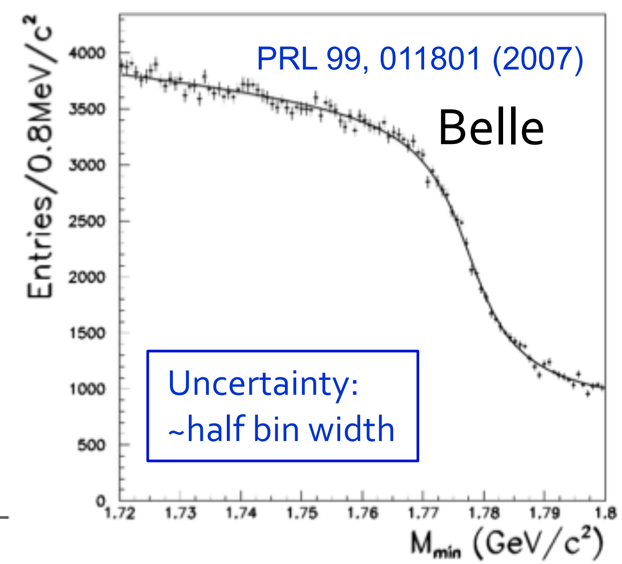
- **Current world average:** m_τ = 1776.86 ± 0.12 MeV
- Best in world: BES3 (threshold scan) $m_\tau = 1776.91 \pm 0.12\ (\text{stat.})\ ^{+0.10}_{-0.13}\ (\text{syst.})$ MeV
- Best at LEP: OPAL m_τ = 1775.1 ± 1.6 (stat.) ± 1.0 (syst.) MeV
  - About factor 10 from world's best
  - Main result from endpoint 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_τ = 1776.61 ± 0.13 (stat.) ± 0.35 (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

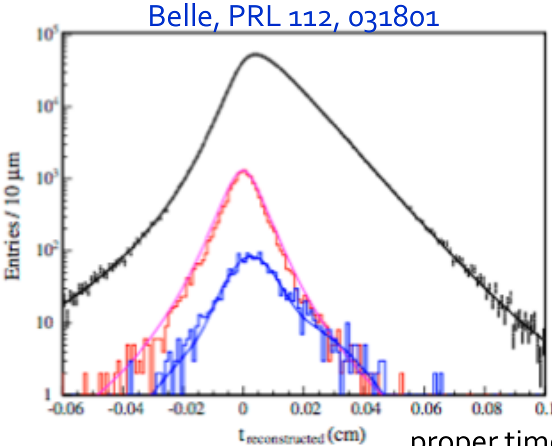
$$\delta_{syst} \lesssim 0.04 \text{ MeV}$$

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

Tau Lifetime (i)

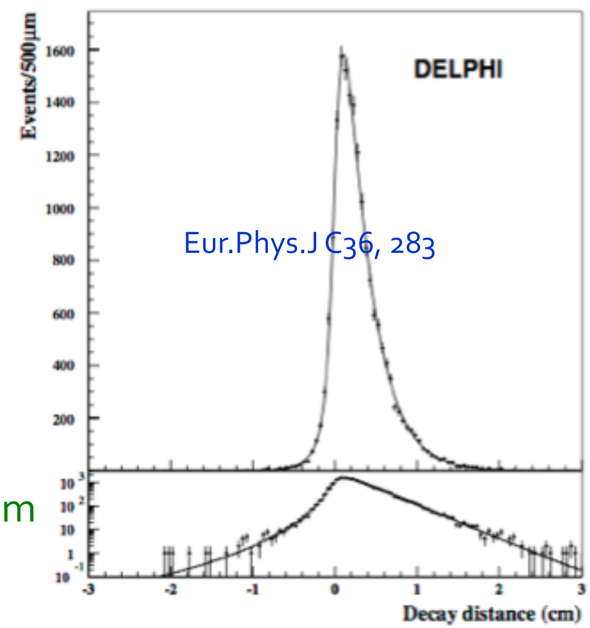
- **Current world average:** **τ_τ = 290.3 ± 0.5 fs**
- **Best in world** (Belle): **τ_τ = 290.17 ± 0.53 $_{stat}$ ± 0.22 $_{syst}$ fs**
  - Large statistics: 711 fb^{-1} @ Υ(4s): 6.3 x 10^8 $\tau^+\tau^-$ events
  - Use 3 vs. 3 prong events (1.1M events); reconstruct 2 secondary vertices + primary vertex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

Belle, PRL 112, 031801



proper time

- **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



Eur.Phys.J C36, 283

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

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

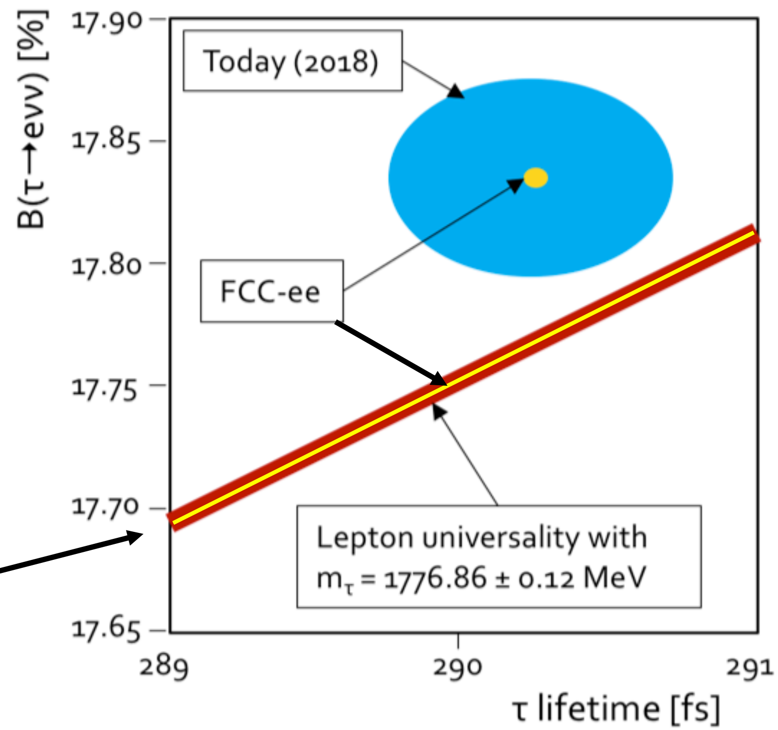
Observable	Measurement	Current precision	FCC-ee **stat.**	**Possible syst.**	Challenge
m_τ [MeV]	Threshold / inv. mass endpoint	1776.86 **± 0.12**	**0.004**	**0.04 (?)**	Mass scale
τ_τ [fs]	Flight distance	290.3 **± 0.5 fs**	**0.001**	**0.04**	Vertex detector alignment
$B(\tau \to e\nu\nu)$ [%]	Selection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

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



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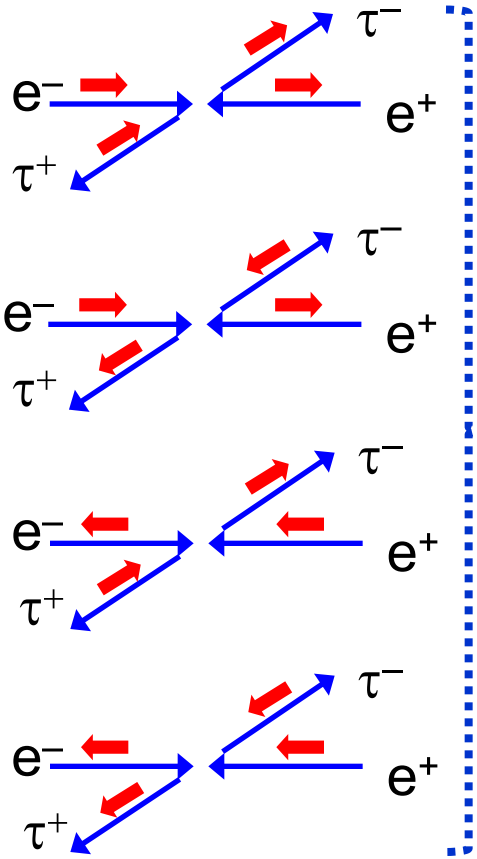
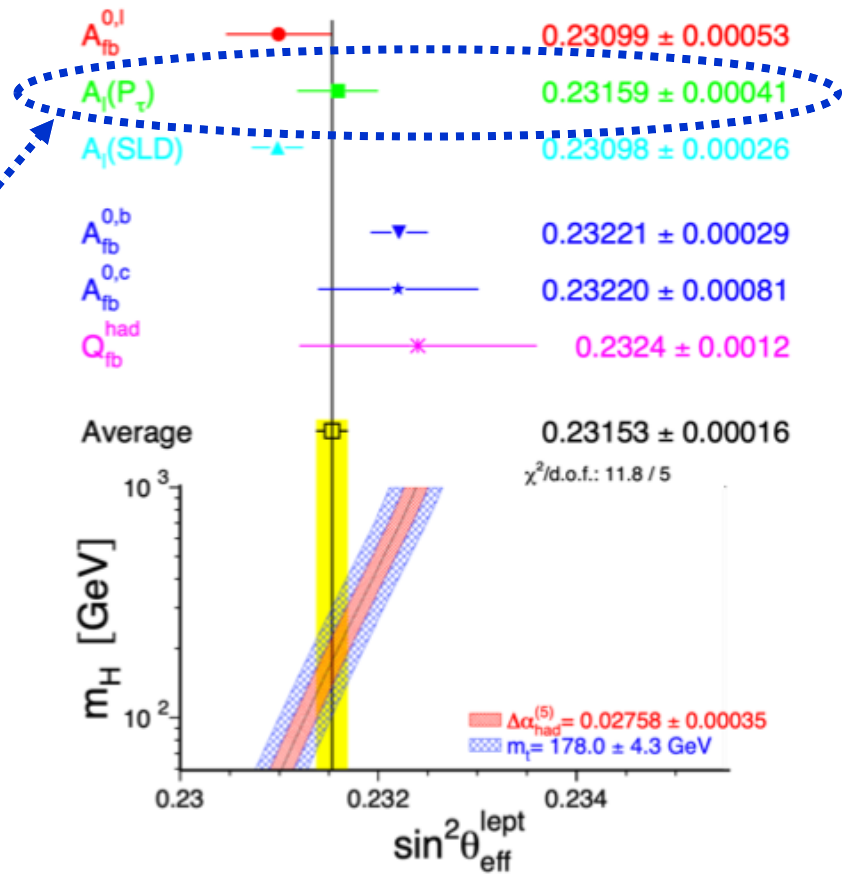
τ Polarisation Measurement

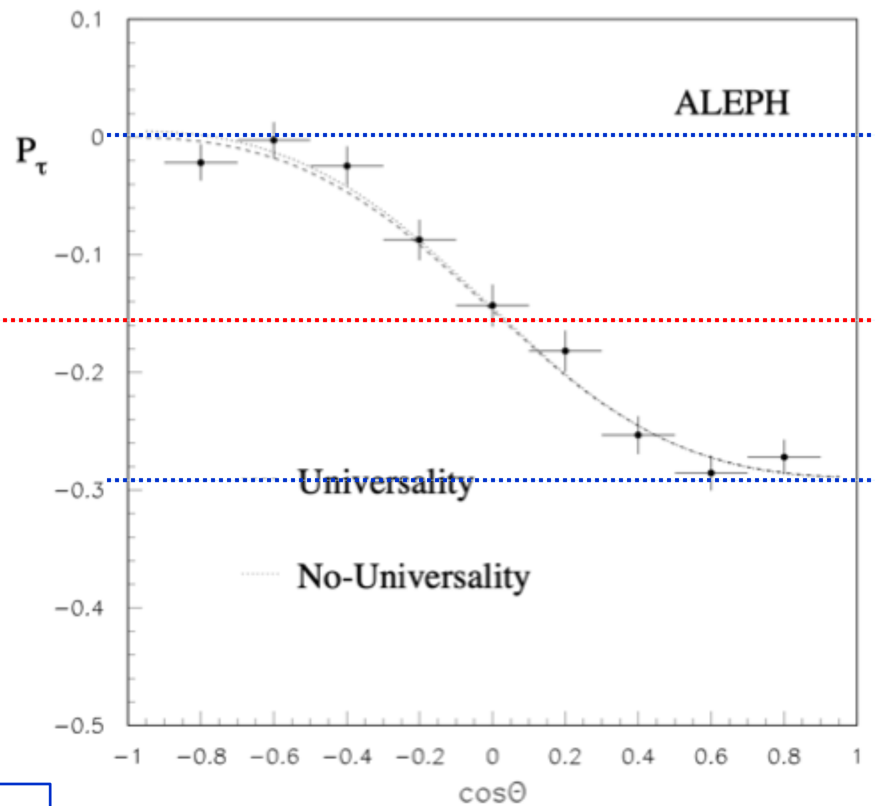




Example: LEP experiment aleph

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

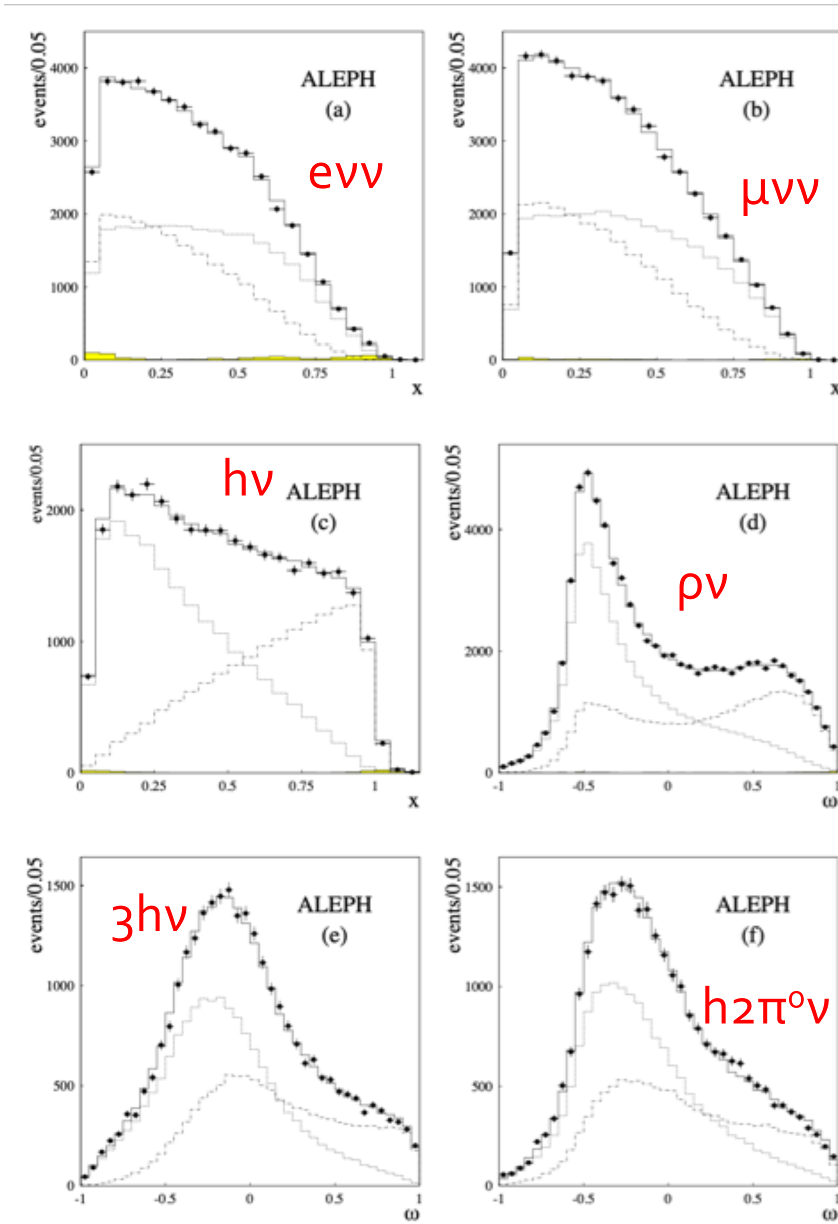
Experimental aspects

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 τ decays
  - Backgrounds from qq, ee, μμ, γγ
- Interchannel separation
  - Mainly between h+nπ^0 states
    => Photon and π^0 reconstruction
- Selection efficiency and backgrounds as function of kinematic variables
- Reconstruction of kinematic variables



Obtained results and precisions – case aleph

Obtained results

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

Channel	A_τ (%)	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($h2\pi^0$)	$16.34 \pm 2.06 \pm 1.52$	$15.62 \pm 2.72 \pm 0.47$
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

systematics

			A_τ				
Source	h	ρ	$3h$	$h2\pi^0$	e	μ	Incl. h
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

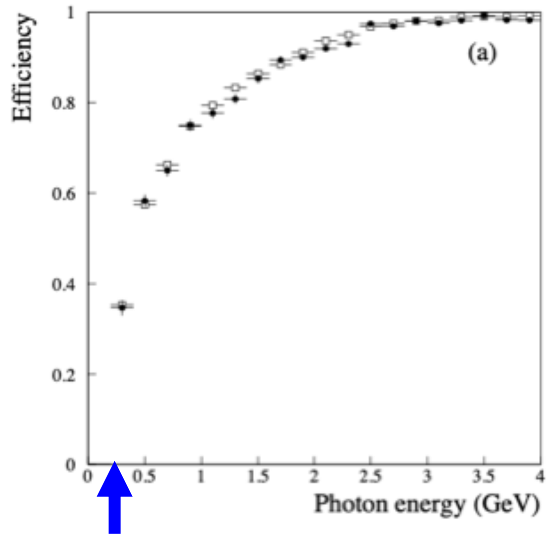
			A_e				
Source	h	ρ	$3h$	$h2\pi^0$	e	μ	Incl. h
tracking	0.04	-	-	-	-	0.05	-
non-τ back.	0.11	0.09	0.04	0.22	0.91	0.24	0.17
modelling	-	-	0.40	0.40	-	-	-
TOTAL	0.12	0.09	0.40	0.47	0.91	0.25	0.17

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

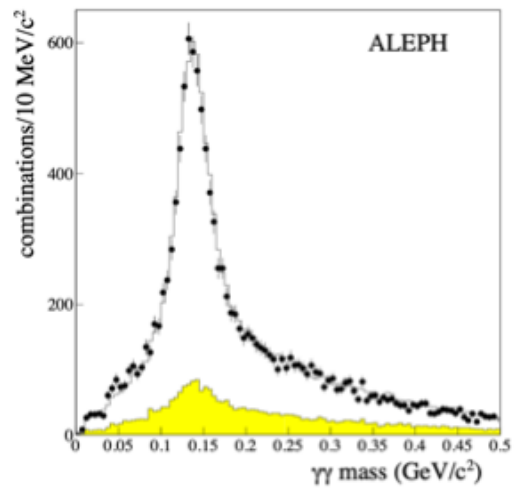
The single most important systematics (on the most precise channels) is due to photon and π^0 identification

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

Summary

- From 5×10^{12} Z decays, FCC-ee will produce **1.7×10^{11} $\tau^+\tau^-$ pairs**
- Factor ~3 higher statistics than Belle2 projection; plus higher boost ($\gamma = 25$)
  - Boost is advantageous for most studies
- Improve **Lepton universality test** by at least a factor 10 down to $\mathcal{O}(10^{-4})$ level
  - Improvement of **τ mass**
  - Substantial improvement in **τ lifetime**
  - Substantial improvement in **τ (leptonic) branching fractions**
- Potential for very precise $\sin^2\theta_W$ determination via **τ polarisation** measurement
- Improvements in hadronic branching fractions and spectral functions, α_s, ν_τ mass, ...

- Plus (not covered here)
  - Searches for **lepton flavour violating τ decays**; sensitivites comparable to Belle2
    - Range from **$\lesssim 10^{-10}$** to **few $\times 10^{-9}$**
  - Improved sensitivity to **lepton flavour violating Z decays** by factor **$\mathcal{O}(10^3)$**
    - Sensitivities down to **10^{-9}**

Summary - Detector requirements

- Precision τ physics sets very strong detector requirements; constitutes a good benchmark
  - **Vertexing**
    - Lifetime measurement to 10^{-4} corresponds to 0.22 μm flight distance
  - **Tracking**
    - Two (or rather multi) track separation: measure 3-, 5-, 7-, and perhaps even 9-prong decays
    - Extremely good control of momentum and mass scale
      - τ mass measurement
      - 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 al lowest momenta
    - **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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    - Extremely good control of momentum …
      - τ mass measurement
      - Sensitivity of … in momentum…
    - Low material … onic interaction in material
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Important to optimise detector design **now** for this important and exciting physics