NIELS BOHR INSTITUTE
UNIVERSITY OF
COPENHAGEN

Tau Experimental Challenges

Mogens Dam
Niels Bohr Institute

ECFA e+e- Collider Miniworkshop: Two-fermion physics

March 21, 2024

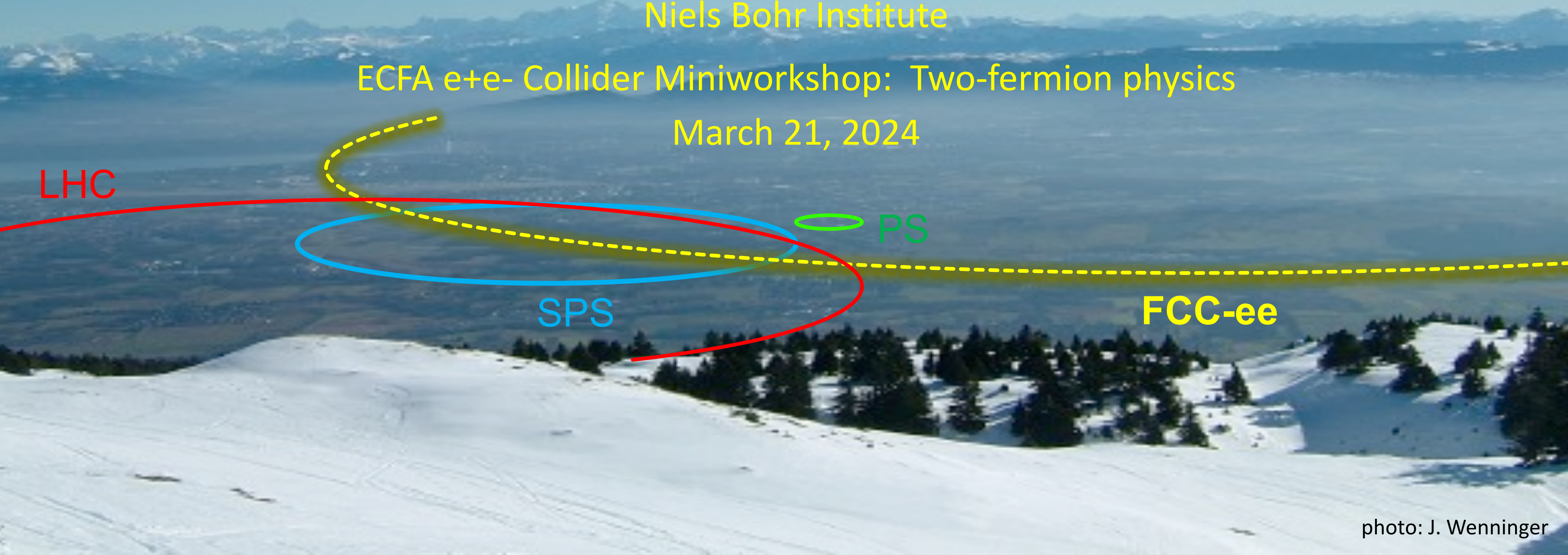
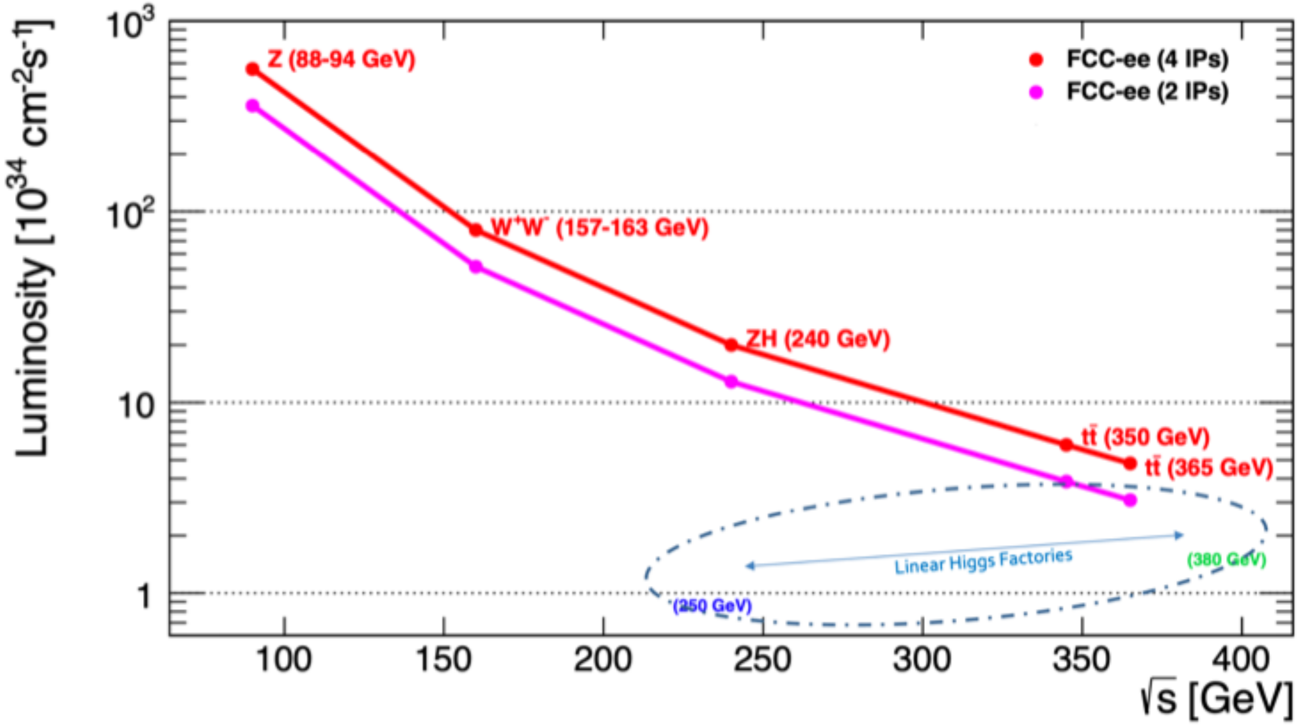


photo: J. Wenninger

FCC-ee Conditions and Statistics



Z peak	E_{CM} : 91 GeV	6×10^{12}	$e^+e^- \to Z$	4 years
WW threshold	E_{CM} : 161 GeV	2.4×10^8	$e^+e^- \to WW$	2 year
ZH threshold	E_{CM} : 240 GeV	1.4×10^6	$e^+e^- \to ZH$	3 years
$t\bar{t}$ threshold	E_{CM} : 350 GeV	1.9×10^6	$e^+e^- \to t\bar{t}$	5 years

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	?

Outline

a. τ Polarisation Measurement

b. τ-lepton Properties and Lepton Universality

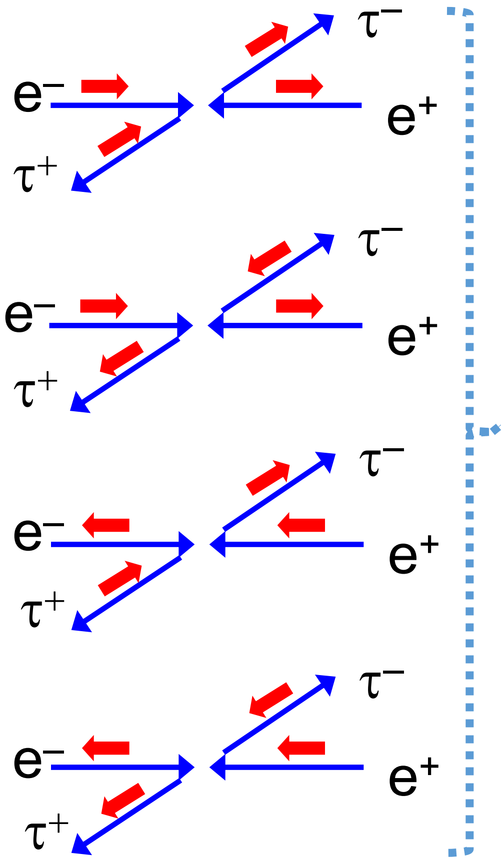
References:

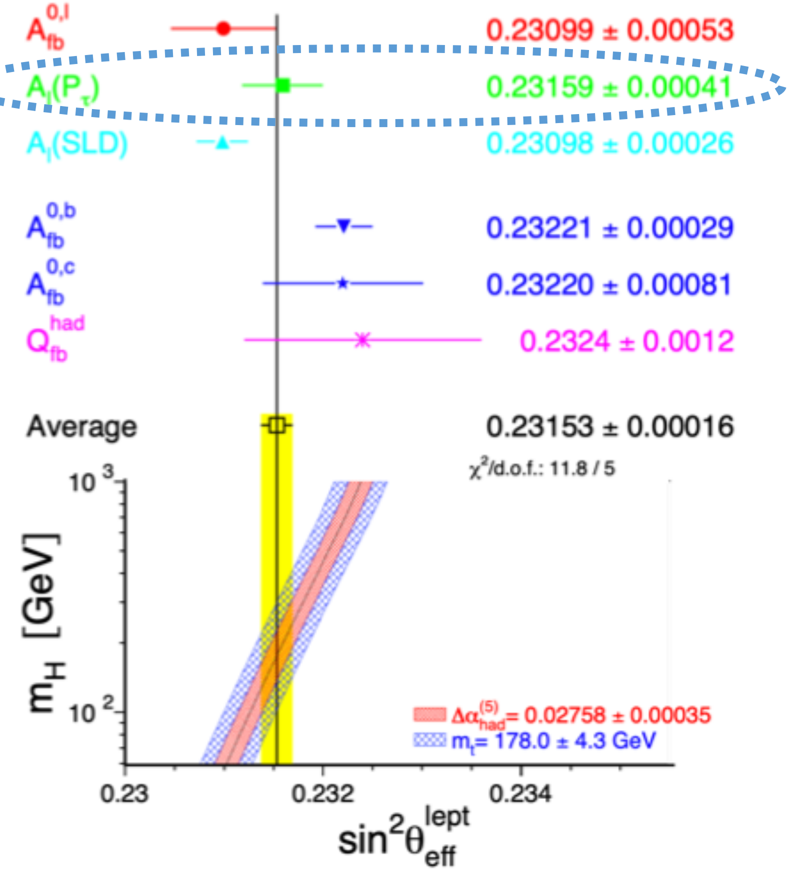
- FCC CDR Volume 1
- MD, *Tau-lepton Physics at the FCC-ee circular e^+e^- Collider,*
  SciPost Phys.Proc. 1 (2019) 041,
  DOI: 10.21468/SciPostPhysProc.1.041
- MD, *The τ challenges at FCC-ee,*
  Eur. Phys. J. Plus **136,** 963 (2021)
  DOI: 10.1140/epjp/s13360-021-01894-y

Will also be reporting from recent presentations by A. Lusiani:

- *Tau Physics at FCC*, 6th FCC Physics Workshop, Liverpool, Jan 2022
- *Tau Lifetime measurements at FCC-ee*, 6th FCC Physics Workshop, Krakow, Jan 2023
- *Detector Requirements from Tau Physics*, FCC Week, London, Jun 2023

τ Polarisation Measurement



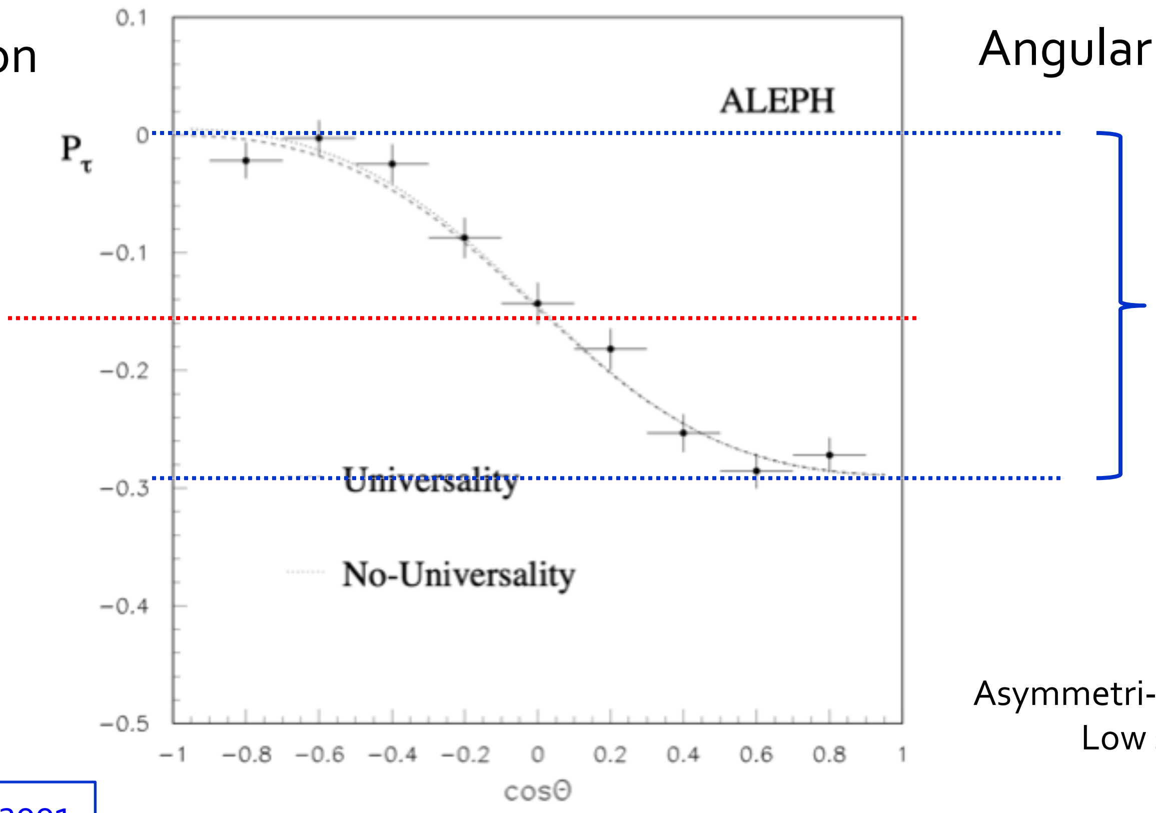


Example: Aleph at LEP

Mean polarisation

Angular dependence

$\mathcal{A}_\tau$



$\mathcal{A}_e$

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

Asymmetri-like measurement:
Low systematics

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

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

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

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
  - Most importantly, internally between **h+nπ⁰** states => **Photon** and **π⁰** reconstruction
- Reconstruction of kinematic variables
- Selection efficiency and backgrounds as function of kin. variables

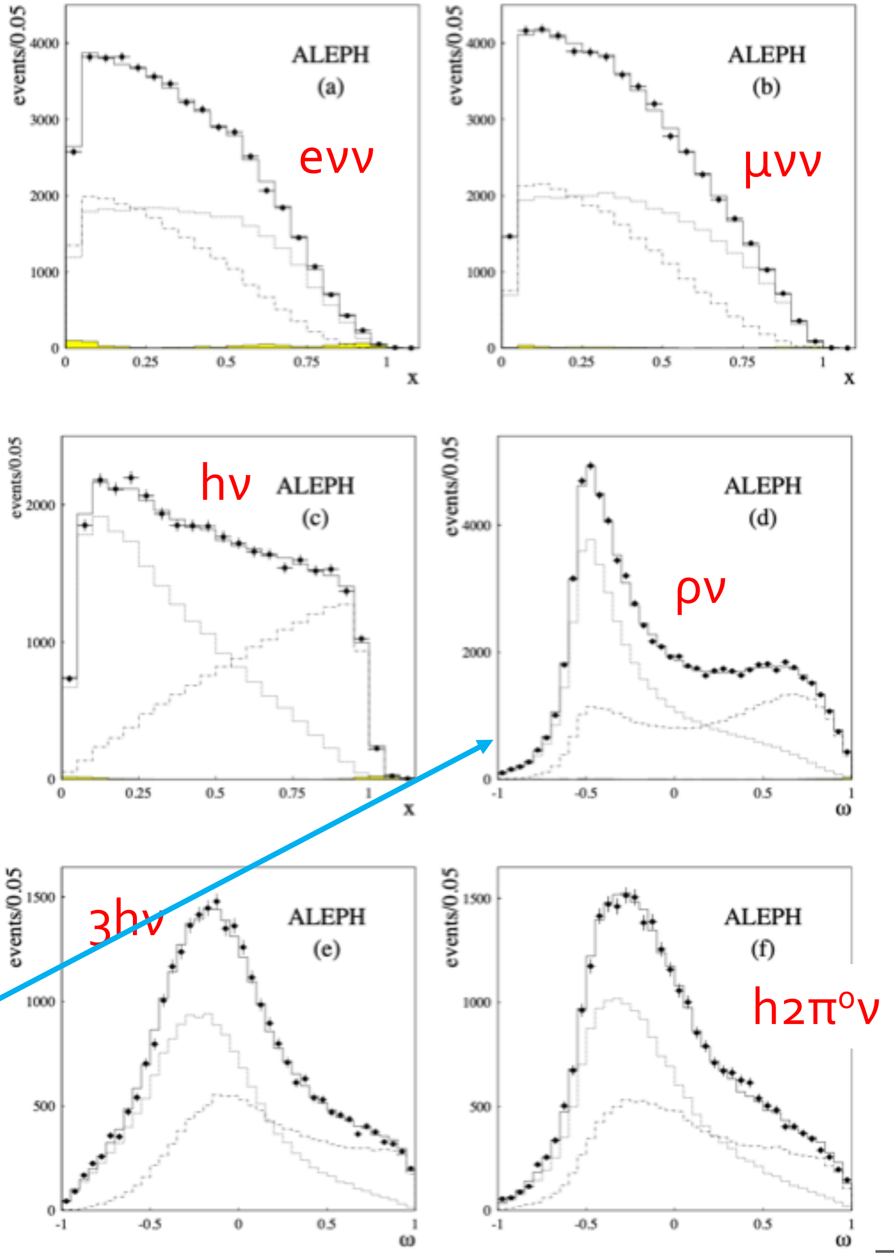
Important example (highest sensitivity) : $\tau^- \rightarrow \rho^-\nu \rightarrow \pi^-\pi^0\nu$

- Here polarisation is extracted from two angles

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

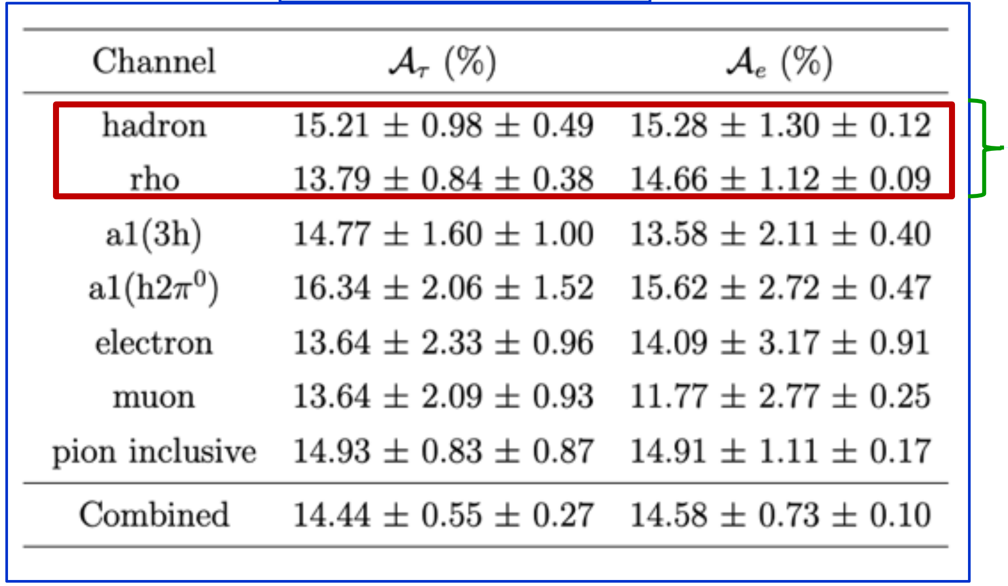
$\pi^-\ \pi^0$ energy sum difference

Combined into 1D "optimal observable"



Results and Precisions – case Aleph

Obtained results

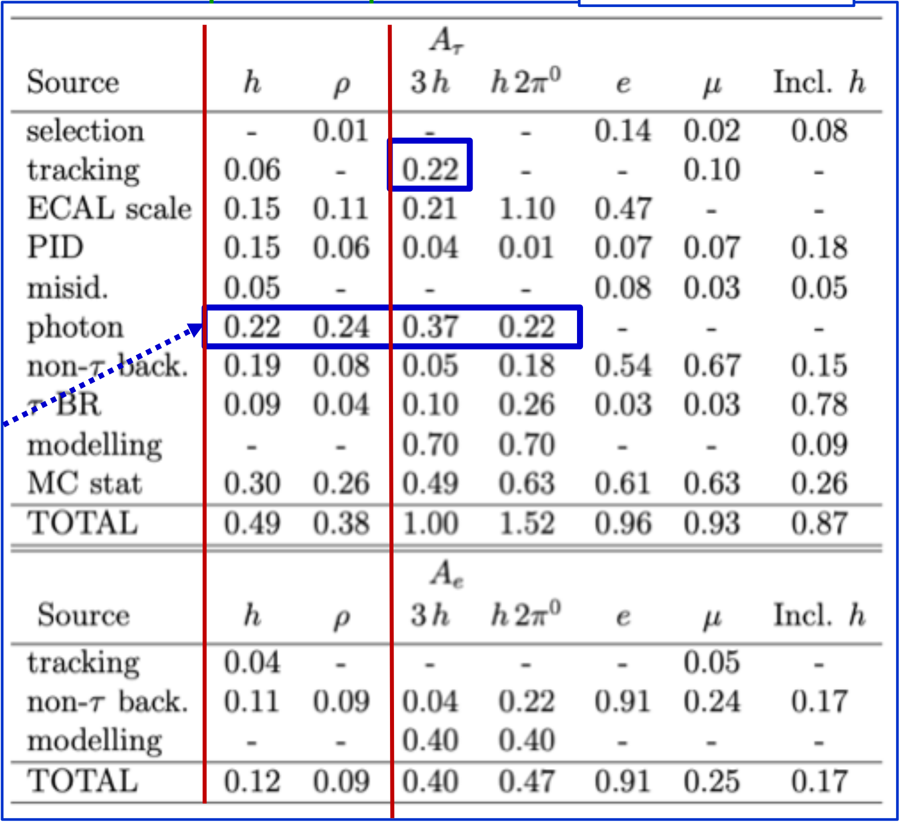


Channel	$\mathcal{A}_\tau$ (%)	$\mathcal{A}_e$ (%)
hadron	$15.21 \pm 0.98 \pm 0.49$	$15.28 \pm 1.30 \pm 0.12$
rho	$13.79 \pm 0.84 \pm 0.38$	$14.66 \pm 1.12 \pm 0.09$
a1(3h)	$14.77 \pm 1.60 \pm 1.00$	$13.58 \pm 2.11 \pm 0.40$
a1(h2π^0)	$16.34 \pm 2.06 \pm 1.52$	$15.62 \pm 2.72 \pm 0.47$
electron	$13.64 \pm 2.33 \pm 0.96$	$14.09 \pm 3.17 \pm 0.91$
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	$14.44 \pm 0.55 \pm 0.27$	$14.58 \pm 0.73 \pm 0.10$

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

Most precise channels

systematics



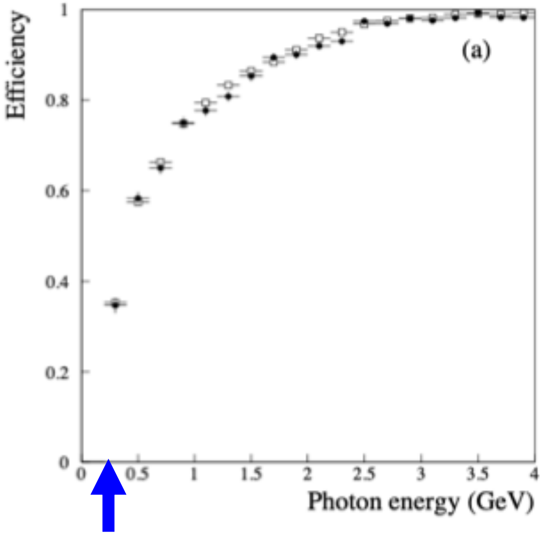
			A_τ				
Source	h	ρ	$3h$	$h2\pi^0$	e	μ	Incl. h
selection	-	0.01	-	-	0.14	0.02	0.08
tracking	0.06	-	0.22	-	-	0.10	-
ECAL scale	0.15	0.11	0.21	1.10	0.47	-	-
PID	0.15	0.06	0.04	0.01	0.07	0.07	0.18
misid.	0.05	-	-	-	0.08	0.03	0.05
photon	0.22	0.24	0.37	0.22	-	-	-
non-τ back.	0.19	0.08	0.05	0.18	0.54	0.67	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

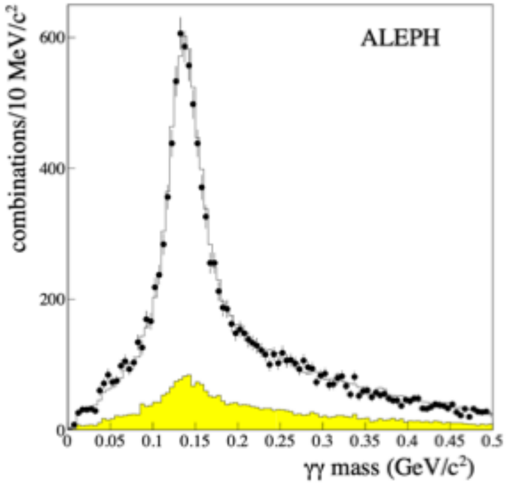
The single most important systematics (on the most precise channels) is due to photon and π⁰ identification

γ and π^0 reconstruction in τ decays – case Aleph

Foton reconstruction efficiency.
Taking off at 250 MeV



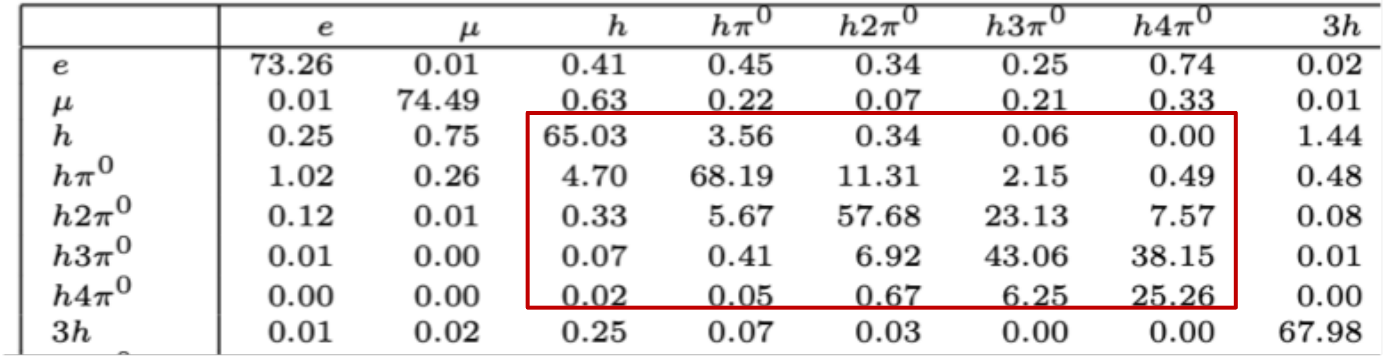
$\gamma\gamma$ mass of additional photons in hemispheres where one π^0 has been already identified



Migration matrix (part)

true/generated

reconstructed



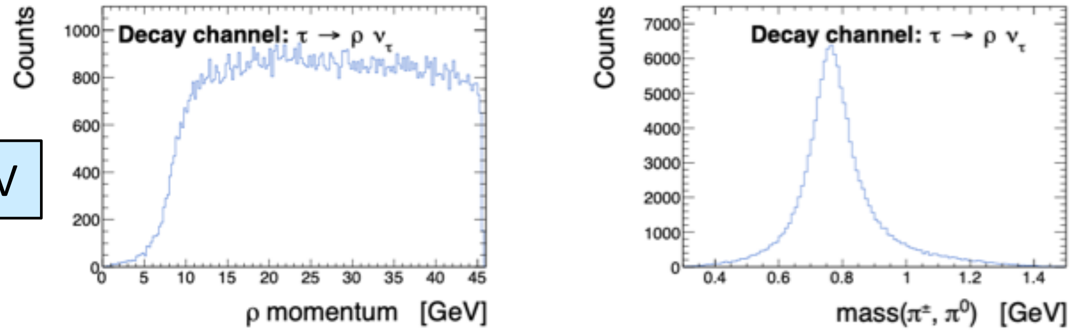
	e	μ	h	$h\pi^0$	$h2\pi^0$	$h3\pi^0$	$h4\pi^0$	$3h$
e	73.26	0.01	0.41	0.45	0.34	0.25	0.74	0.02
μ	0.01	74.49	0.63	0.22	0.07	0.21	0.33	0.01
h	0.25	0.75	65.03	3.56	0.34	0.06	0.00	1.44
$h\pi^0$	1.02	0.26	4.70	68.19	11.31	2.15	0.49	0.48
$h2\pi^0$	0.12	0.01	0.33	5.67	57.68	23.13	7.57	0.08
$h3\pi^0$	0.01	0.00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

Kinematics of $\tau \to \rho\nu \to \pi\pi^0\nu$

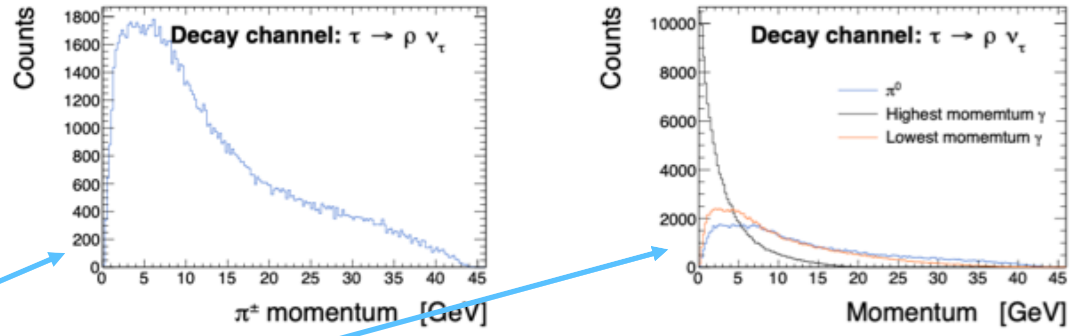
Decay modes	Branching fraction [%]
$e^- \bar{\nu}_e \nu_\tau$	17.82 ± 0.04
$\mu^- \bar{\nu}_\mu \nu_\tau$	17.39 ± 0.04
$h^- \nu_\tau$	11.51 ± 0.05
$h^- \pi^0 \nu_\tau$	25.93 ± 0.09
$h^- 2\pi^0 \nu_\tau$	9.48 ± 0.10
$h^- 3\pi^0 \nu_\tau$	1.18 ± 0.07
$h^- 4\pi^0 \nu_\tau$	0.16 ± 0.04
3 prongs	15.20 ± 0.06

Energy = 45.6 GeV



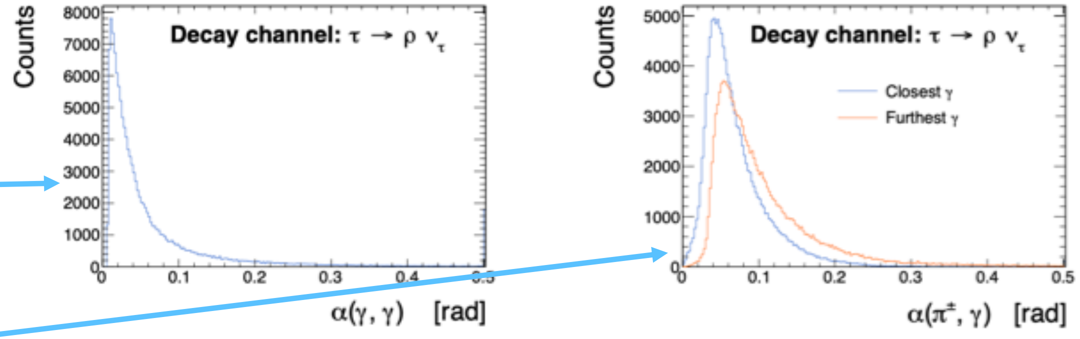
(a) Momentum of the ρ meson

(b) Invariant mass of the $\pi^\pm$ and π^0



(c) Momentum of the charged pion

(d) Momentum of the π^0 and its two daughter photons



(e) Opening angle between the photons from the $\pi^0 \to \gamma\gamma$ process

(f) Smallest and largest opening angle between the π^0 daughter photons and the $\pi^\pm$

Charged hadrons (π^- /K^-) over full momentum range

π^0 over full momentum range, many soft photons

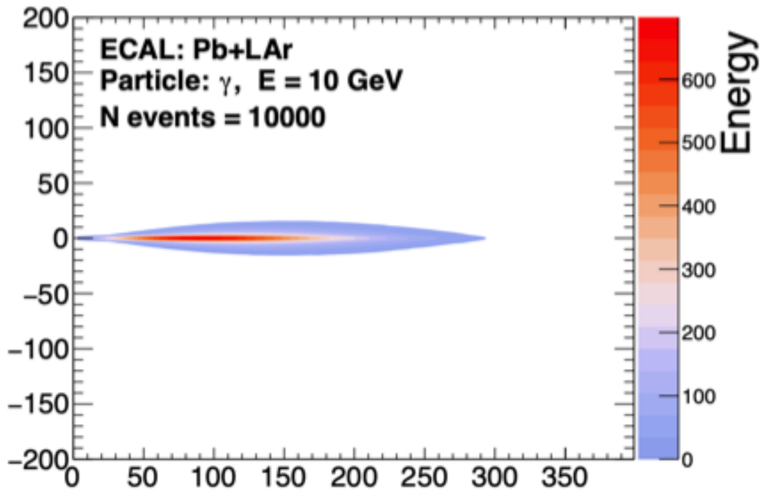
Photon-photon separation down to few mrad

π^- - photon separation typically 50 – 100 mrad (10-20 cm)

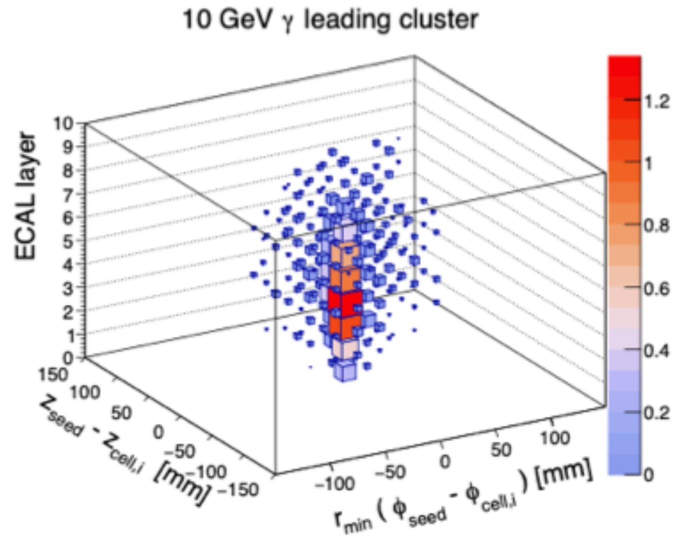
Full simulation study of a LAr Calorimeter

K. Wandall-Christensen, MSc thesis, Niels Bohr Institute, 2021

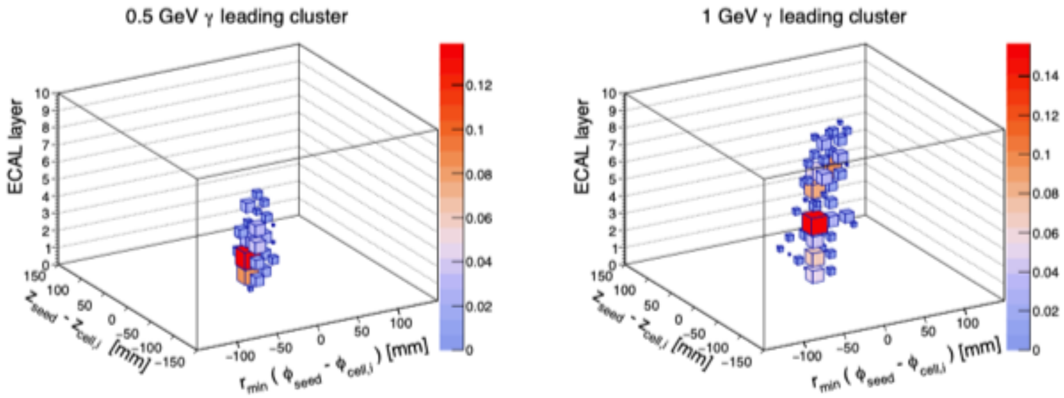
On average, EM showers are very smooth



Of course, shower-by-shower fluctuations

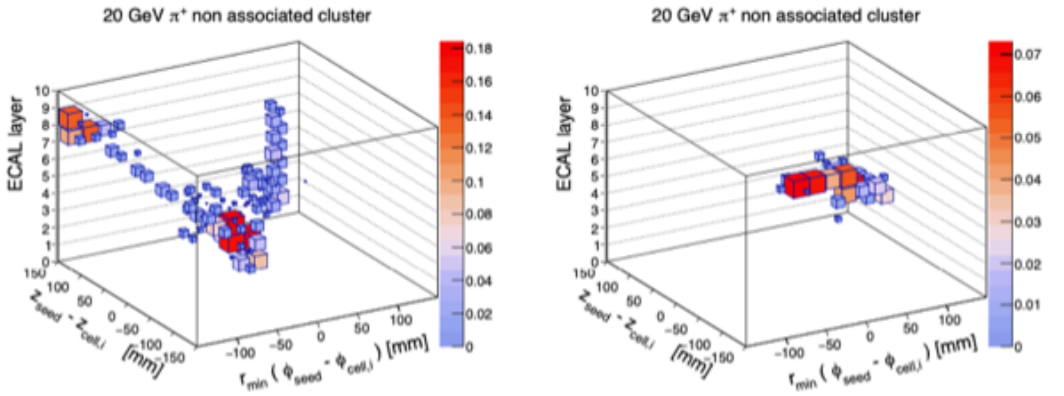


For soft photons, fluctuations become more important



(a) The leading cluster from a 0.5 GeV γ

(b) The leading cluster from a 1 GeV γ



(c) A fake photon cluster from a 20 GeV π^+

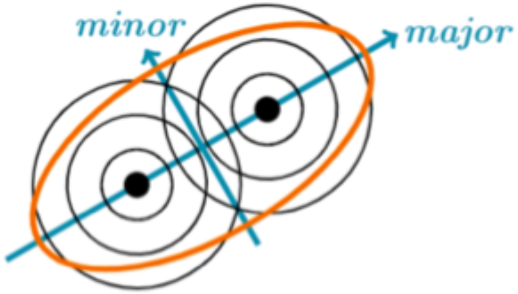
(d) A fake photon cluster from a 20 GeV π^+

Pattern recognition algo has to suppress fake photons from hadronic shower satellites

Example: photon/π^0 separation in a LAr Calorimeter

K. Wandall-Christensen, MSc thesis, Niels Bohr Institute, 2021

Shower moment analysis



$$M_{\text{clus}} = C \cdot E_{\text{clus}} \cdot \sqrt{major^2 - minor^2}$$

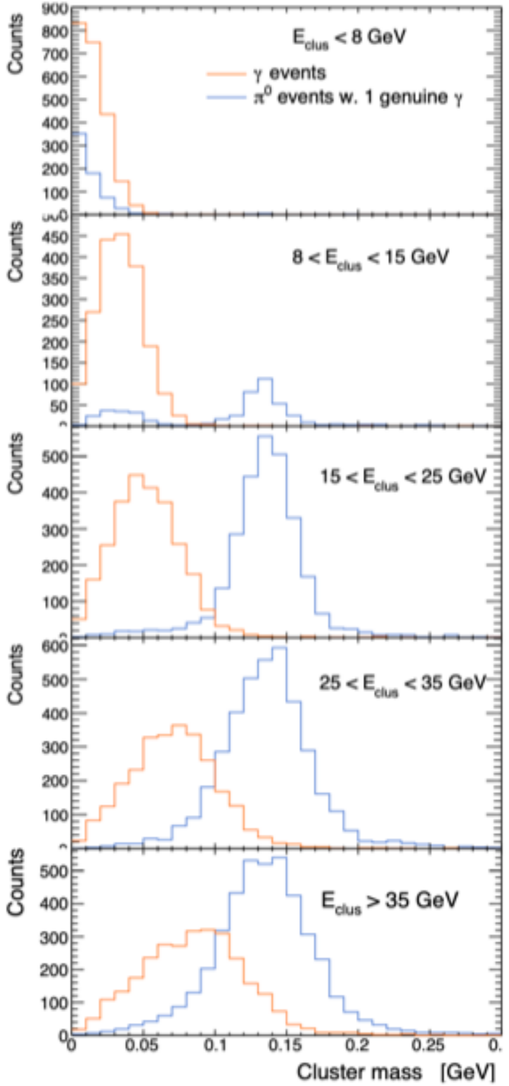
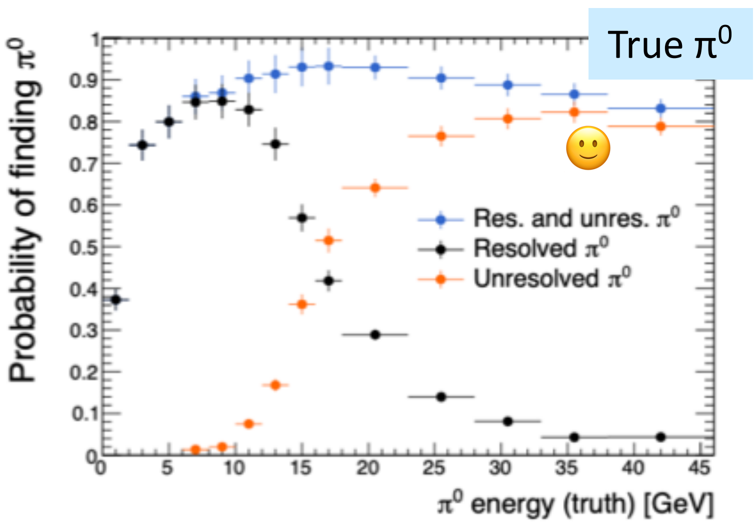
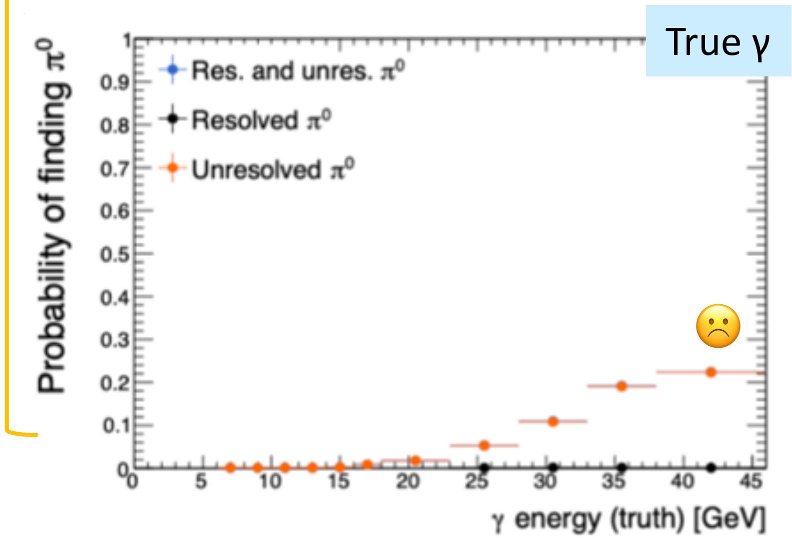


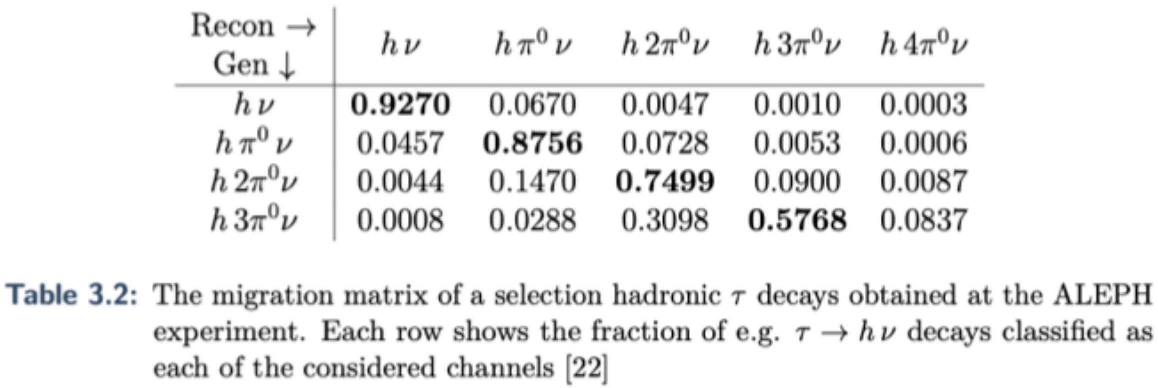
Figure 8.5: The cluster mass of single γ events (orange) and π^0 events with one genuine photon (blue)





Hadronic migration matrix – aleph and LAr Study

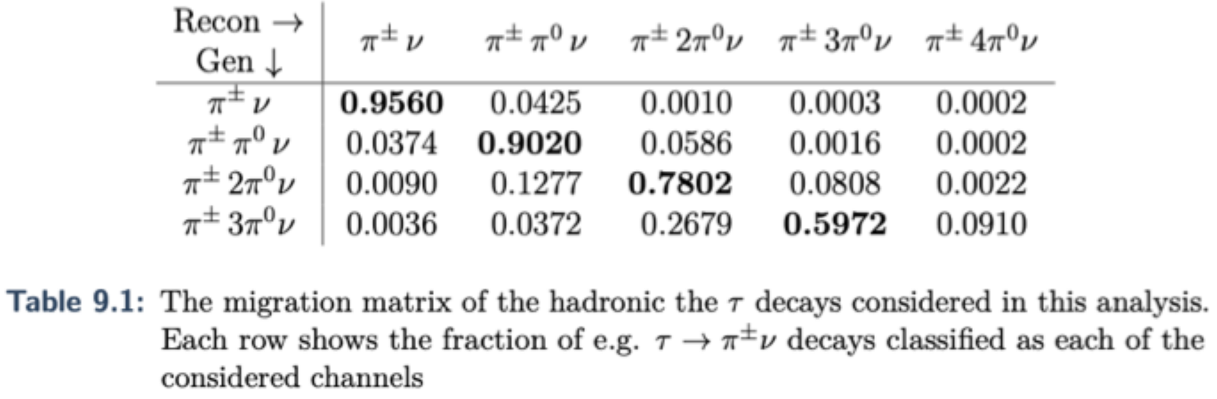
aleph



Recon → Gen ↓	$h\,\nu$	$h\,\pi^0\,\nu$	$h\,2\pi^0\nu$	$h\,3\pi^0\nu$	$h\,4\pi^0\nu$
$h\,\nu$	**0.9270**	0.0670	0.0047	0.0010	0.0003
$h\,\pi^0\,\nu$	0.0457	**0.8756**	0.0728	0.0053	0.0006
$h\,2\pi^0\nu$	0.0044	0.1470	**0.7499**	0.0900	0.0087
$h\,3\pi^0\nu$	0.0008	0.0288	0.3098	**0.5768**	0.0837

Table 3.2: The migration matrix of a selection hadronic τ decays obtained at the ALEPH experiment. Each row shows the fraction of e.g. $\tau \to h\,\nu$ decays classified as each of the considered channels [22]

LAr Study

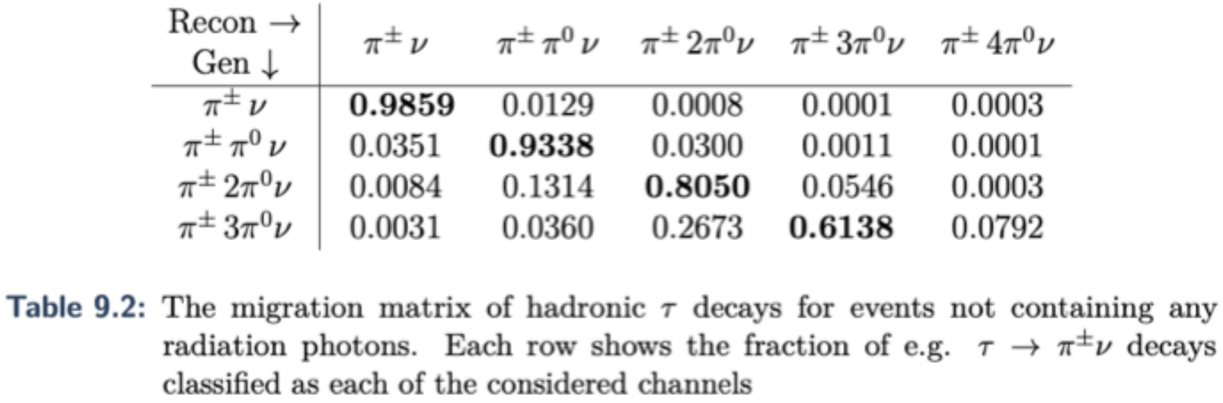


Recon → Gen ↓	$\pi^\pm\,\nu$	$\pi^\pm\,\pi^0\,\nu$	$\pi^\pm\,2\pi^0\nu$	$\pi^\pm\,3\pi^0\nu$	$\pi^\pm\,4\pi^0\nu$
$\pi^\pm\,\nu$	**0.9560**	0.0425	0.0010	0.0003	0.0002
$\pi^\pm\,\pi^0\,\nu$	0.0374	**0.9020**	0.0586	0.0016	0.0002
$\pi^\pm\,2\pi^0\nu$	0.0090	0.1277	**0.7802**	0.0808	0.0022
$\pi^\pm\,3\pi^0\nu$	0.0036	0.0372	0.2679	**0.5972**	0.0910

Table 9.1: The migration matrix of the hadronic the τ decays considered in this analysis. Each row shows the fraction of e.g. $\tau \to \pi^\pm\nu$ decays classified as each of the considered channels

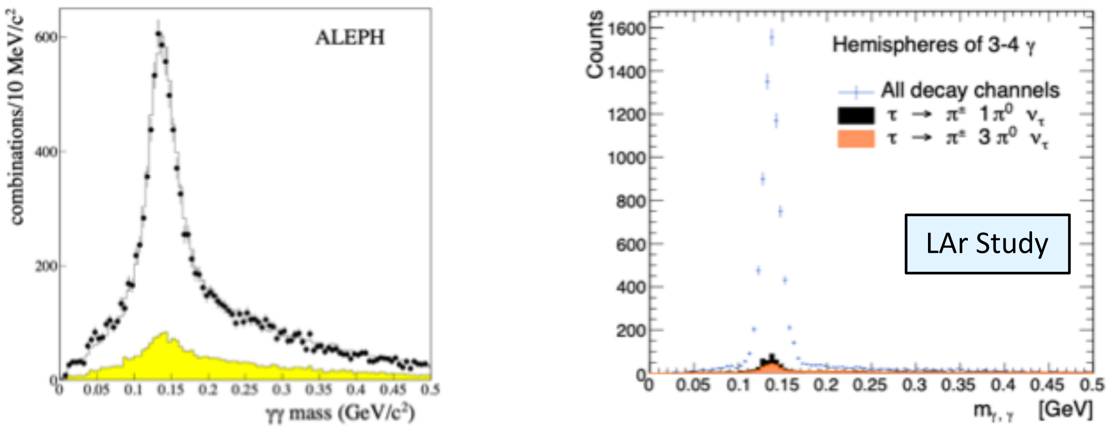
- Aleph was already pretty good
- LAr study points to possible improvements

LAr Study – no radiated photons



Recon → Gen ↓	$\pi^\pm\,\nu$	$\pi^\pm\,\pi^0\,\nu$	$\pi^\pm\,2\pi^0\nu$	$\pi^\pm\,3\pi^0\nu$	$\pi^\pm\,4\pi^0\nu$
$\pi^\pm\,\nu$	**0.9859**	0.0129	0.0008	0.0001	0.0003
$\pi^\pm\,\pi^0\,\nu$	0.0351	**0.9338**	0.0300	0.0011	0.0001
$\pi^\pm\,2\pi^0\nu$	0.0084	0.1314	**0.8050**	0.0546	0.0003
$\pi^\pm\,3\pi^0\nu$	0.0031	0.0360	0.2673	**0.6138**	0.0792

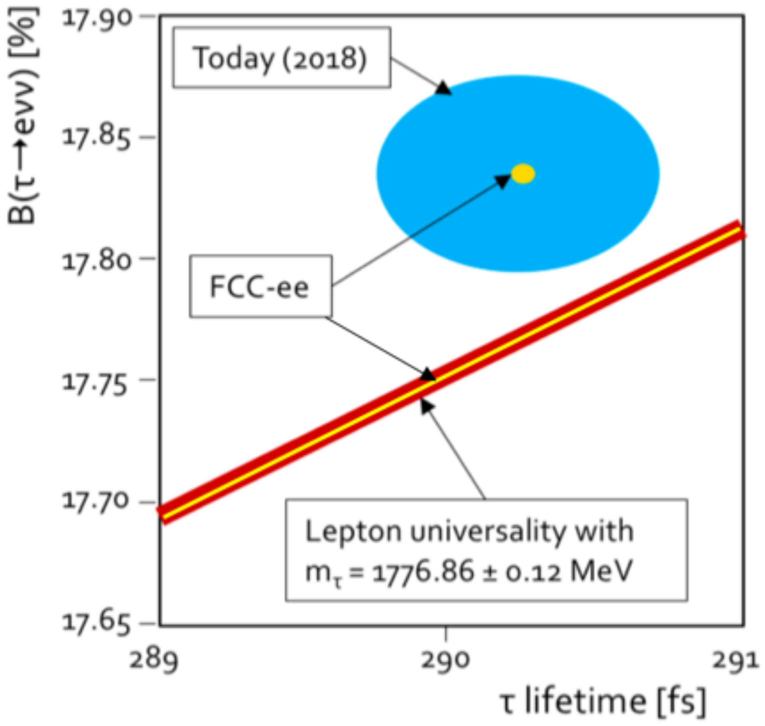
Table 9.2: The migration matrix of hadronic τ decays for events not containing any radiation photons. Each row shows the fraction of e.g. $\tau \to \pi^\pm\nu$ decays classified as each of the considered channels



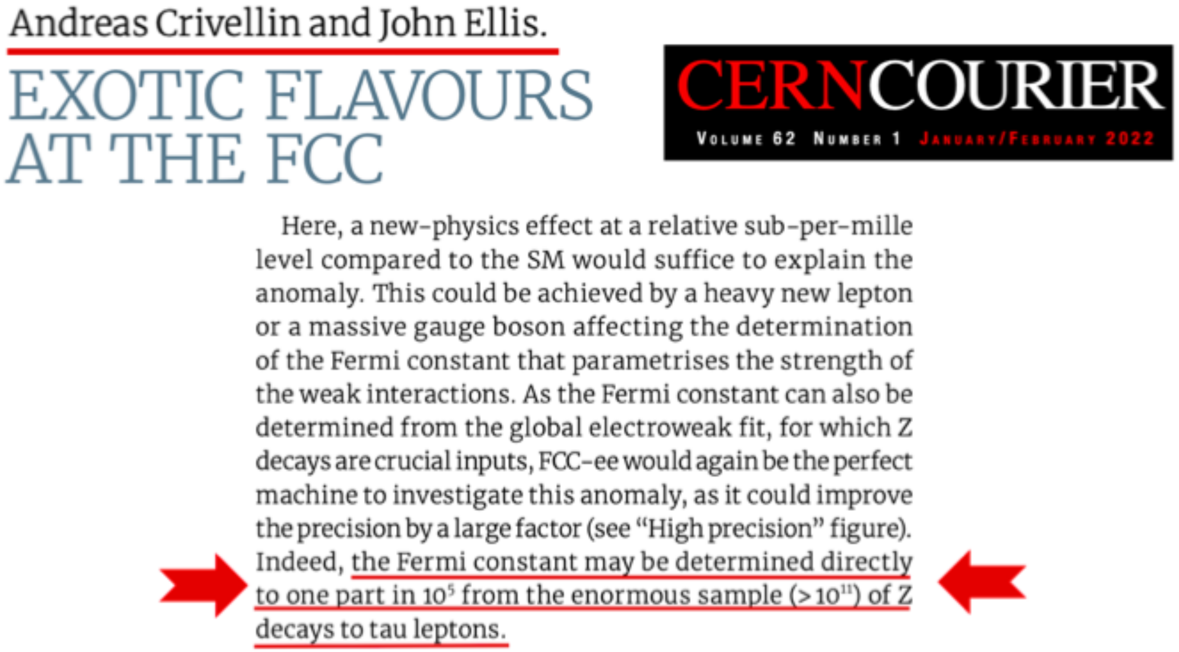
γγ mass of additional photons in hemispheres where one π° has been already identified

τ-lepton properties and Lepton Universality

- Mass
- Lifetime
- Leptonic branching fractions



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.

Fermi constant is measured in μ decays and defined by

$$G_F^{(e)} G_F^{(\mu)} = \frac{192\pi^3}{m_\mu^5\, \tau_\mu}$$

Assuming (e,μ) universality, the Fermi constant then is

$$G_F \equiv G_F^{(e)} = G_F^{(\mu)} = \sqrt{\frac{192\pi^3}{m_\mu^5\, \tau_\mu}}$$

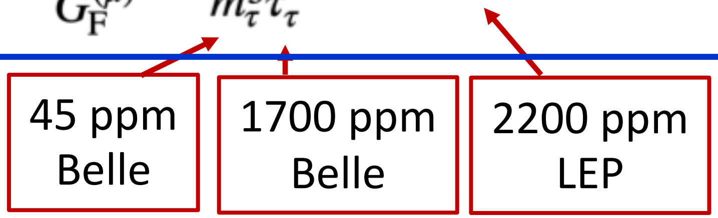
Experimentally known to 0.5 ppm (μ lifetime)

Similarly can define Fermi constant measured in τ decays

$$G_F^{(e)} G_F^{(\tau)} = \frac{192\pi^3 \mathscr{B}(\tau \to e\bar{\nu}\nu)}{m_\tau^5\, \tau_\tau}$$

Compare τ and μ based Fermi constanta

$$\frac{G_F^{(\tau)}}{G_F^{(\mu)}} = \frac{m_\mu^5 \tau_\mu}{m_\tau^5 \tau_\tau} \mathscr{B}(\tau \to e\bar{\nu}\nu)$$



Current precision:

45 ppm Belle

1700 ppm Belle

2200 ppm LEP

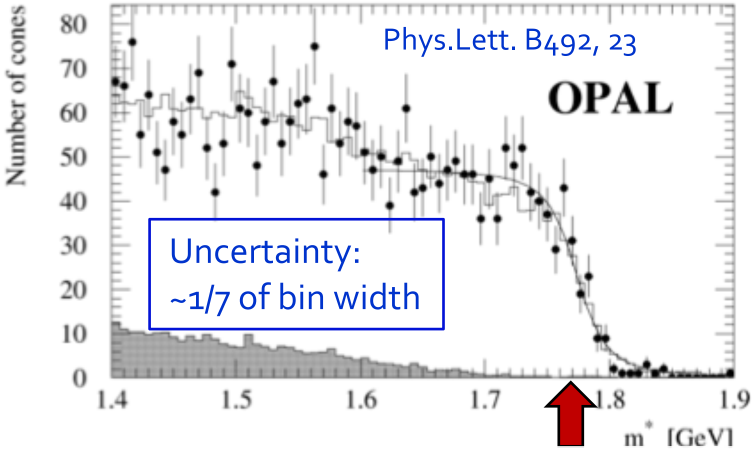
FCC-ee: Will see 5x10^{11} τ decays
Statistical uncertainties at the 10 ppm level
How well can we control systematics?

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

On the τ lifetime measurement, see link

Tau Mass

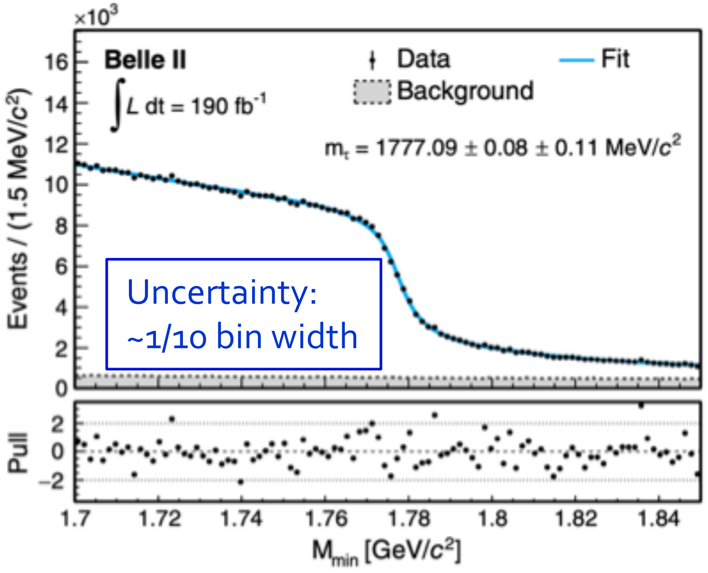
- **World average:** **m_τ = 1776.86 ± 0.12 MeV**
- Until recently, best in world: BES3 (threshold scan) $m_\tau = 1776.96\,^{+0.18}_{-0.21}\,(\text{stat.})\,^{+0.25}_{-0.17}\,(\text{syst.})$ MeV
- Best at LEP: OPAL m_τ = 1775.1 ± 1.6 (stat.) ± 1.0 (syst.) MeV
  - About factor 10 from world's best
  - 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 in analysis)
    - Dynamics of τ decay: 0.10 MeV



Phys.Lett. B492, 23

Uncertainty:
~1/7 of bin width

- Same method from Belle – new World's best
  - Systematics
    - Knowledge of beam energy.: 0.07 MeV
    - Reconstruction of charged particles : 0.06 MeV
    - Fit model: 0.04 MeV
    - Imperfections of simulation: 0.04 MeV



Uncertainty:
~1/10 bin width

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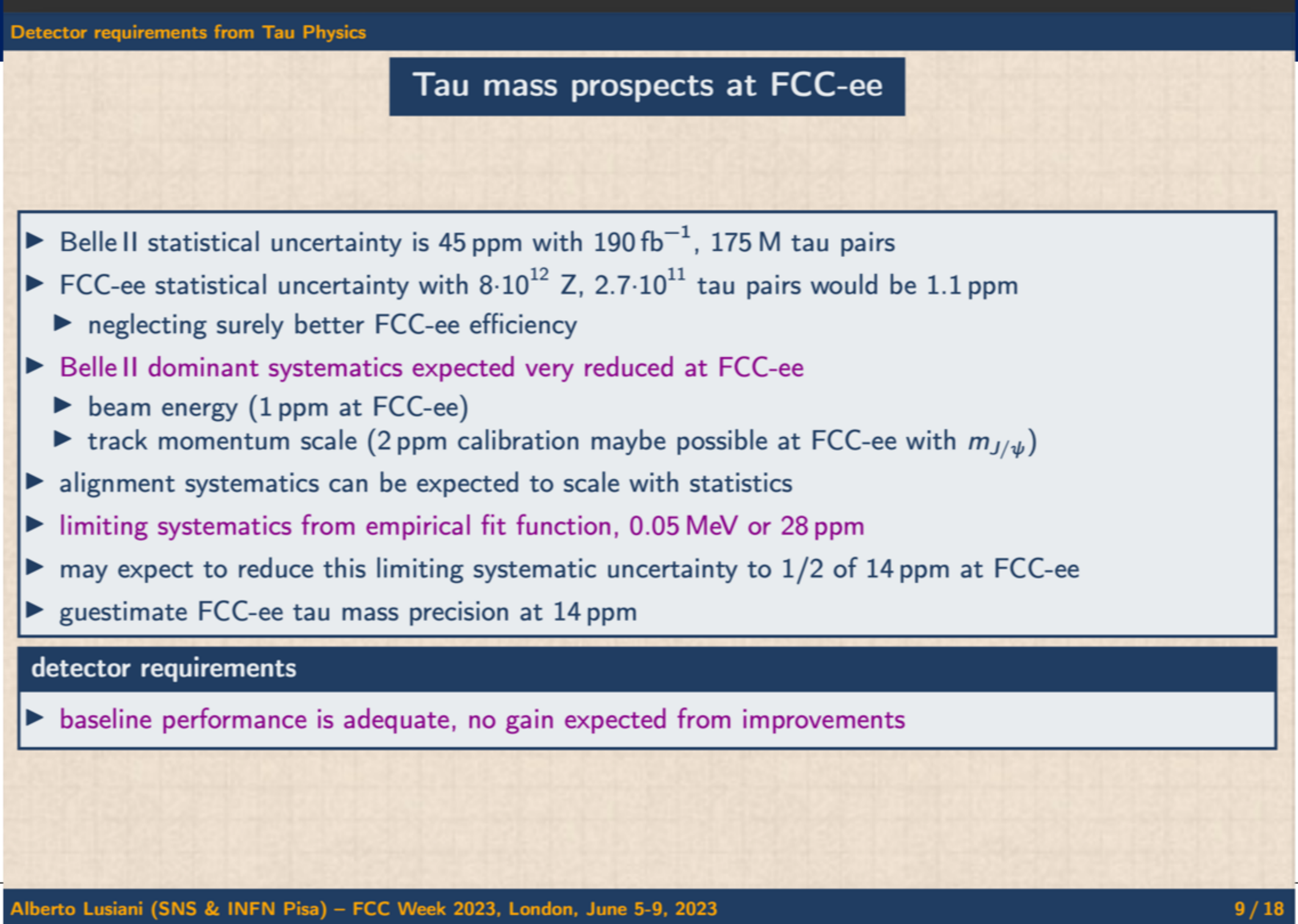
$$\boxed{m_\tau = 1776.61 \pm 0.08\,(\text{stat.}) \pm 0.11\,(\text{syst.})\ \text{MeV}}$$

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



Tau mass prospects at FCC-ee

- Belle II statistical uncertainty is 45 ppm with 190 fb^{-1}, 175 M tau pairs
- FCC-ee statistical uncertainty with $8{\cdot}10^{12}$ Z, $2.7{\cdot}10^{11}$ tau pairs would be 1.1 ppm
  - neglecting surely better FCC-ee efficiency
- Belle II dominant systematics expected very reduced at FCC-ee
  - beam energy (1 ppm at FCC-ee)
  - track momentum scale (2 ppm calibration maybe possible at FCC-ee with $m_{J/\psi}$)
- alignment systematics can be expected to scale with statistics
- limiting systematics from empirical fit function, 0.05 MeV or 28 ppm
- may expect to reduce this limiting systematic uncertainty to 1/2 of 14 ppm at FCC-ee
- guestimate FCC-ee tau mass precision at 14 ppm

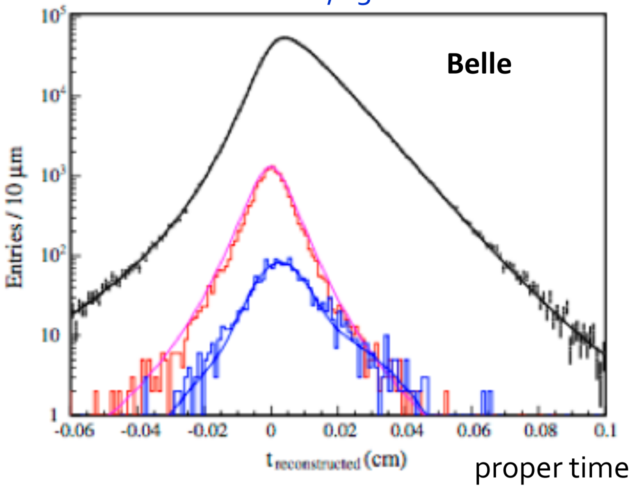
detector requirements

- baseline performance is adequate, no gain expected from improvements

Tau Lifetime

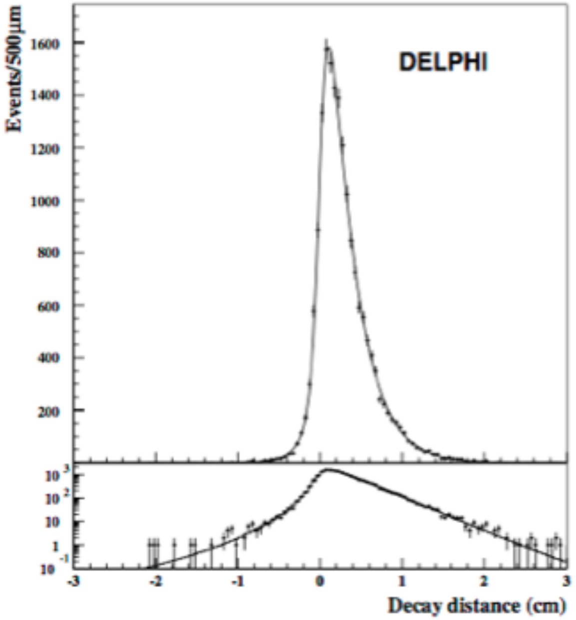
- **Current world average:** $\tau_\tau = 290.3 \pm 0.5$ **fs** **(1700 ppm)**
- **Best in world (**Belle): $\tau_\tau = 290.17 \pm 0.53_{stat} \pm 0.22_{syst}$ **fs**
  - ❑ Large statistics: 711 fb^{-1} @ Υ(4s): 6.3M $\tau^+\tau^-$ events
  - ❑ Use 3 vs. 3 prong events (1.1M events)
    - ❖ Reconstruct 2 secondary vertices + primary vertex
  - ❑ Measure flight distance ⇒ proper time
  - ❑ Dominant systematics: Vertex detector alignment to ~ **0.25 µm**
    - ❖ Vertex detector positioned 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 method (1v3)
  - ❑ Dominant systematics: Vertex detector alignment to **7.5 µm**
    - ❖ Alignment with data (qq events): statistics limited
  - ❑ Vertex detector: 7.5 µm point resolution at 63, 90, and 109 mm

PRL 112, 031801

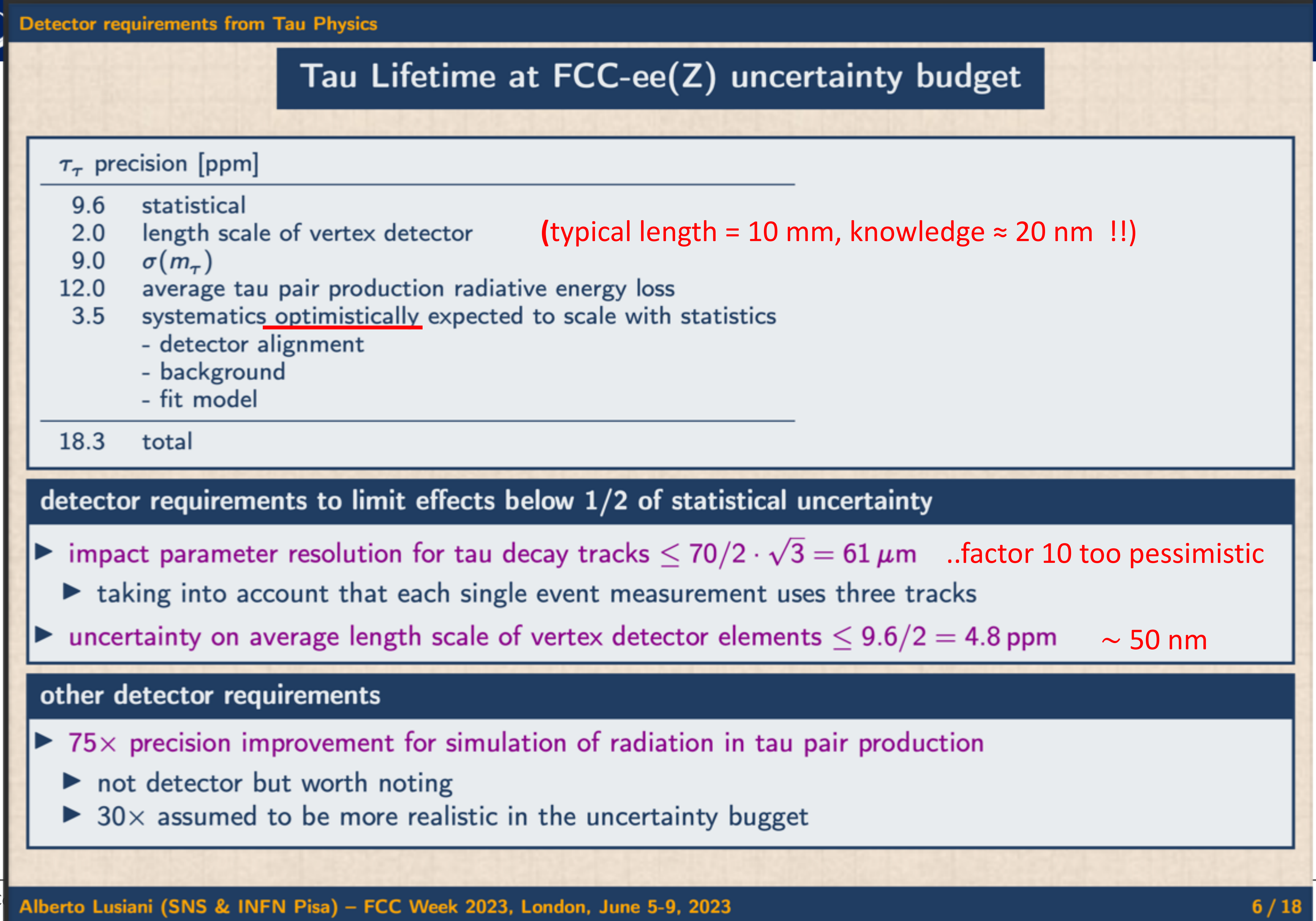


proper time

Eur.Phys.J C36, 283



MD comments in red



Detector requirements from Tau Physics

Tau Lifetime at FCC-ee(Z) uncertainty budget

τ_τ precision [ppm]		
9.6	statistical	
2.0	length scale of vertex detector	(typical length = 10 mm, knowledge ≈ 20 nm !!)
9.0	$\sigma(m_\tau)$	
12.0	average tau pair production radiative energy loss	
3.5	systematics optimistically expected to scale with statistics	
	- detector alignment	
	- background	
	- fit model	
18.3	total	

detector requirements to limit effects below 1/2 of statistical uncertainty

- impact parameter resolution for tau decay tracks $\leq 70/2 \cdot \sqrt{3} = 61\ \mu m$ ..factor 10 too pessimistic
  - taking into account that each single event measurement uses three tracks
- uncertainty on average length scale of vertex detector elements $\leq 9.6/2 = 4.8$ ppm $\sim$ 50 nm

other detector requirements

- 75× precision improvement for simulation of radiation in tau pair production
  - not detector but worth noting
  - 30× assumed to be more realistic in the uncertainty bugget

Alberto Lusiani (SNS & INFN Pisa) – FCC Week 2023, London, June 5-9, 2023 6 / 18

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
  - **$B(\tau \to e\nu\nu)$: 4400 ppm = [4000 (stat.) $\oplus$ 2000 (syst.)] ppm** ; **$B(\tau \to \mu\nu\nu)$: 4400 ppm = [4000 (stat.) $\oplus$ 1800 (syst.)] ppm**
- Three uncertainty contributions dominant in the Aleph measurement, all limited by stats, size of test samples, ...

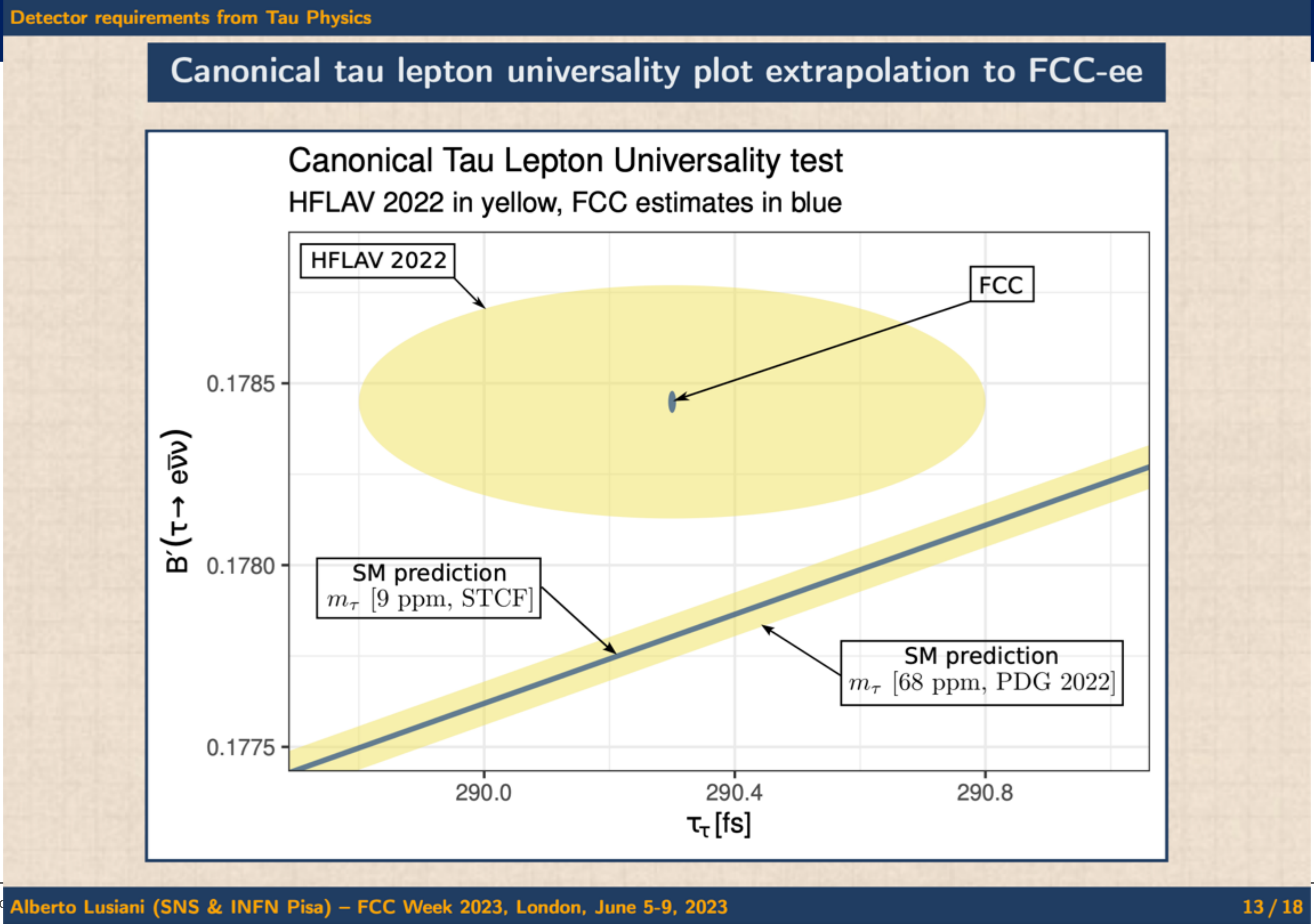
Selection efficiency:	1180	;	1150 ppm
Non-$\tau^+\tau^-$ background:	1630	;	1150 ppm
Particle ID:	1070	;	1200 ppm

- Prospects at FCC-ee
  - Enormous statistics ⇒ **5 ppm**
  - **Systematic uncertainty is hard to guestimate 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

With the large statistics, much will be learned. Suggest a factor 10 improvement wrt Aleph: ~190 ppm

⇒ **Key:** Overall detector design, including tracking, calorimetry, PID, muon system $\oplus$ redundancy

Canonical tau lepton universality plot extrapolation to FCC-ee



Canonical Tau Lepton Universality test

HFLAV 2022 in yellow, FCC estimates in blue

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 ($\gamma = 26$)
  - ❑ Boost is advantageous for many studies
- Potential for very precise $\sin^2\theta_W$ determination via **τ polarisation** measurement
  - ❑ ECAL performance crucial
- Improved **Lepton universality test** by about two orders of magnitude.
  - ❑ Expressed via tau decay based Fermi constant

$$\frac{\delta G_{\mathrm{F}}^{(\tau)}}{G_{\mathrm{F}}^{(\tau)}} = \left[5 \cdot \frac{\delta m_\tau}{m_\tau} \oplus \frac{\delta \tau_\tau}{\tau_\tau} \oplus \frac{\delta \mathcal{B}(\tau \to e\nu\nu)}{\mathcal{B}(\tau \to e\nu\nu)} \right]$$

$$= \left[(5 \cdot 14) \oplus 19 \oplus 190 \right] \ \text{ppm} \simeq 200 \ \text{ppm}$$

today, 2800 ppm

ECAL crucial

- ❑ Overall improvement by factor 14 w.r.t. current precision !!
- ❑ Still a long way way to go to 10 ppm …

Summary, detector requirements

τ physics sets very strong detector requirements; good benchmark for detector design

- **Vertexing**
  - ❑ Lifetime measurement to 10 ppm corresponds to 22 nm flight distance !
- **Tracking**
  - ❑ Two-track separation: collimated topoligies, 3-, 5-, 7-, 9- … prong decays
  - ❑ Extremely good control of momentum and mass scale
    - ❖ τ mass measurement
  - ❑ 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
  - ❑ Collimated topologies: Important to be able to separate γs from close-lying hadronic showers
- **Muon system:**
  - ❑ High efficiency, low background muon ID
- **PID**
  - ❑ Necessary for separation of π/K modes (0 – 45 GeV momentum range)
  - ❑ e/π separation at low momenta (where calorimetric separation is most difficult)
  - ❑ Even provides e/μ separation
  - ❑ **Redundancy**: Provides valuable handle to create test samples for study of calorimetry etc.

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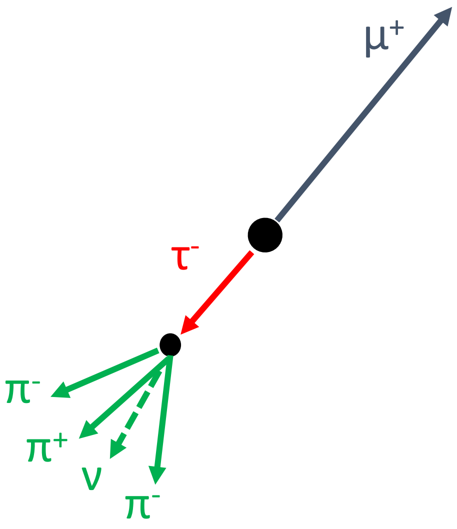
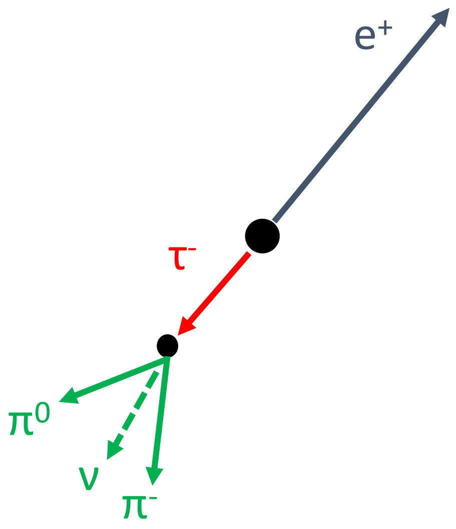
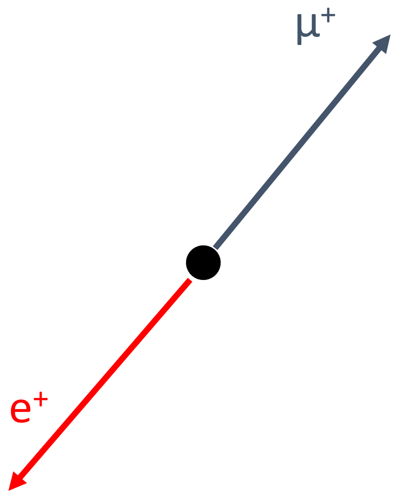
Design your detector with care!

spares

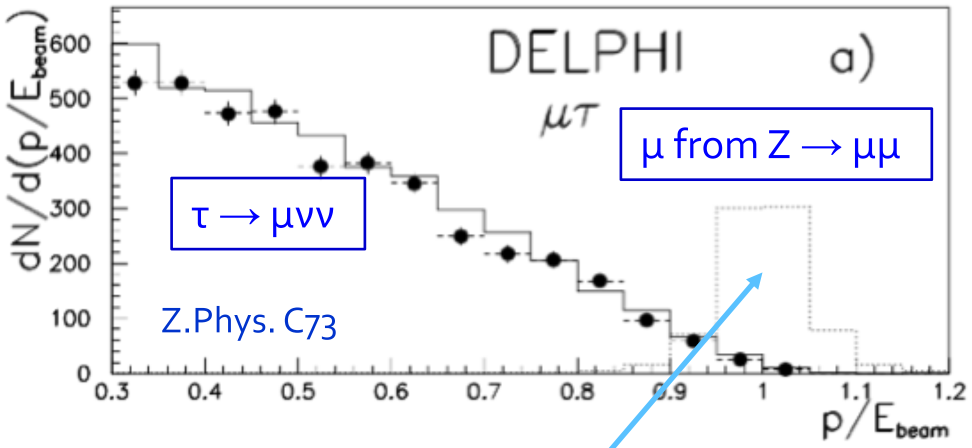
LFV Z decays







Z → eτ and Z → μτ

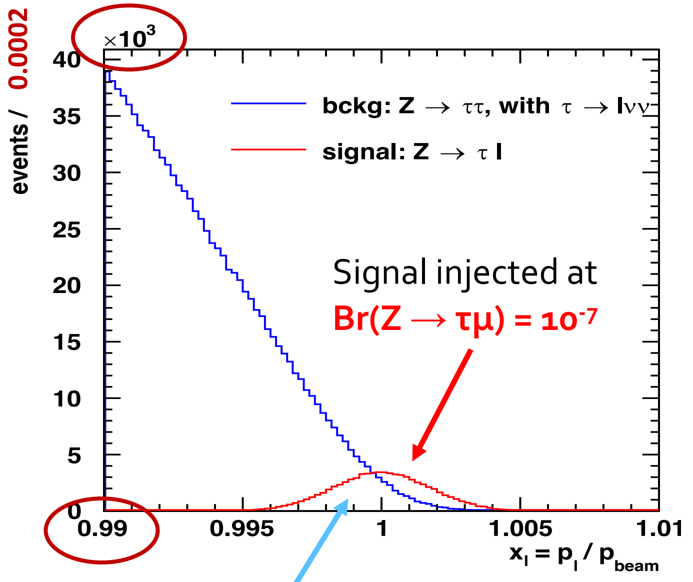


μ from Z → μμ

τ → μνν

Z.Phys. C73

FCC-ee study with 5×10^{12} Z decays



Signal injected at
Br(Z → τμ) = 10^{-7}

DELPHI momentum resolution at $p_T = 45.6$ GeV :

$\sigma(p_T)/p_T = 2.7 \times 10^{-2}$

Limit set at $\boxed{Br(Z \to \mu\tau) < 12 \times 10^{-6}}$

- Best at LEP
- World's best until recently:
  - ATLAS now at 9.5×10^{-6}

Assumed momentum resolution at $p_T = 45.6$ GeV including contribution (0.9×10^{-3}) from beam-energy spread:

$\sigma(p_T)/p_T = 1.8 \times 10^{-3}$

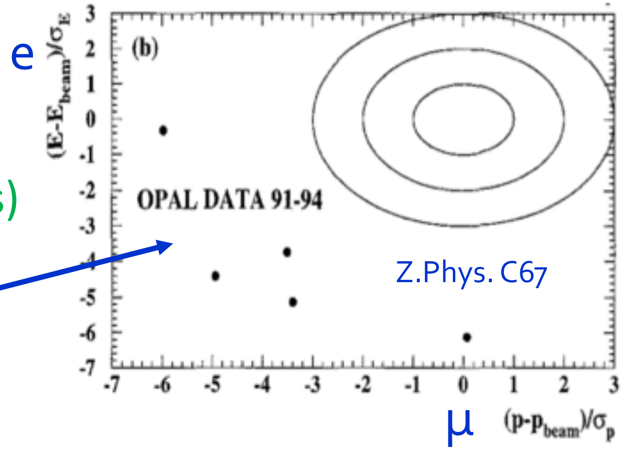
Findings:

- Sensitivity scales ~ linear in momentum resolution
- Irreducible background (from $\tau \to \mu\nu\nu$) ⇒ sensitivity $\propto 1/\sqrt{\mathcal{L}}$
- Similar sensitivity for Z → eτ
- Sensitivity for signals down to

$\boxed{\text{BRs of} \sim 10^{-9}}$

Z → eμ

- Current limit:
  - **7.5 x 10^{-7} LHC/ATLAS** (20 fb^{-1}; no candidates)
  - **1.7 x 10^{-6} LEP/OPAL** (4.0 x 10^{6} Z decays: no candidates)
- In e^+e^-, clean experimental signature:
  - Beam energy electron vs. beam energy muon

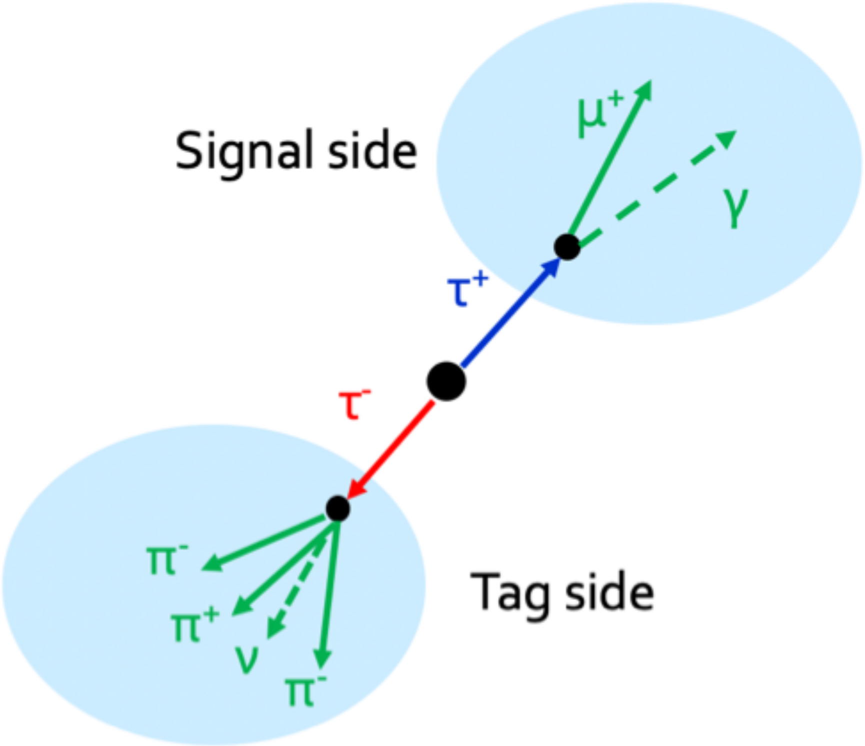


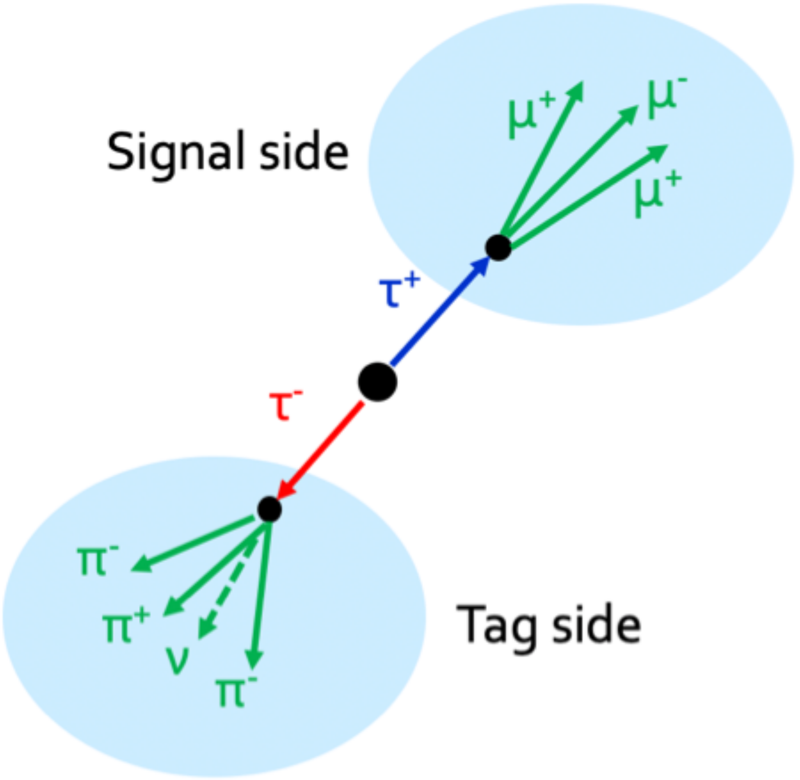
Z.Phys. C67

- Main experimental challenge:
  - **Catastrophic bremsstrahlung energy loss** of muon in electromagnetic calorimeter
    - Muon would deposit (nearly) full energy in ECAL: Misidentification μ → e
    - NA62: Probability of muon to deposit more than 95% of energy in ECAL: **4 x 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(μ → e)
- FCC-ee:
  - Misidentification from catastrophic energy loss corresponds to limit of about **Br(Z →eμ) ≃ 10^{-8}**
  - Possibly do $\mathcal{O}(10)$ better than that **Br(Z →eμ) ~ 10^{-9}** (probably even **10^{-10}** with IDEA dE/dx)

10^{-10} – 10^{-8}
sensitivity depending on
detector design and
performance

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

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

- **Current limits:**
  - ❑ **$Br(\tau^- \rightarrow e^-\gamma) < 3.3 \times 10^{-8}$** BaBar, 10.6 GeV; 4.8×10^8 $e^+e^- \rightarrow \tau^+\tau^-$: 1.6 expected bckg
  - ❑ **$Br(\tau^- \rightarrow \mu^-\gamma) < 4.4 \times 10^{-8}$** 3.6 expected bckg
- **Main background:** Radiative events (IRS+FSR), $e^+e^- \rightarrow \tau^+\tau^-\gamma$
  - ❑ $\tau \rightarrow \mu\gamma$ decay faked by combination of γ from ISR/FSR and μ from $\tau \rightarrow \mu\nu\bar{\nu}$
- **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, $e^+e^- \rightarrow \tau^+\tau^-\gamma$, performed
    - ❖ Presented at tau2018
  - ❑ From study (assuming 25% signal & background efficiency), projected BR sensitivity

$\boxed{2 \times 10^{-9}}$

  - ❑ With the recently suggested crystal ECAL, possible a factor of about 6-10 better

2008.00338

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

- Current limits:
  - All 6 combs. of $e^\pm$, $\mu^\pm$: Br ≲ 2×10^{-8} Belle@10.6 GeV; 7.2×10^8 $e^+e^- \rightarrow \tau^+\tau^-$: no candidates
  - $\mu^-\mu^+\mu^-$: Br < 4.6×10^{-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 **≲ 10^{-10}**
- Many more decay modes to search for when time comes. Need PID for most