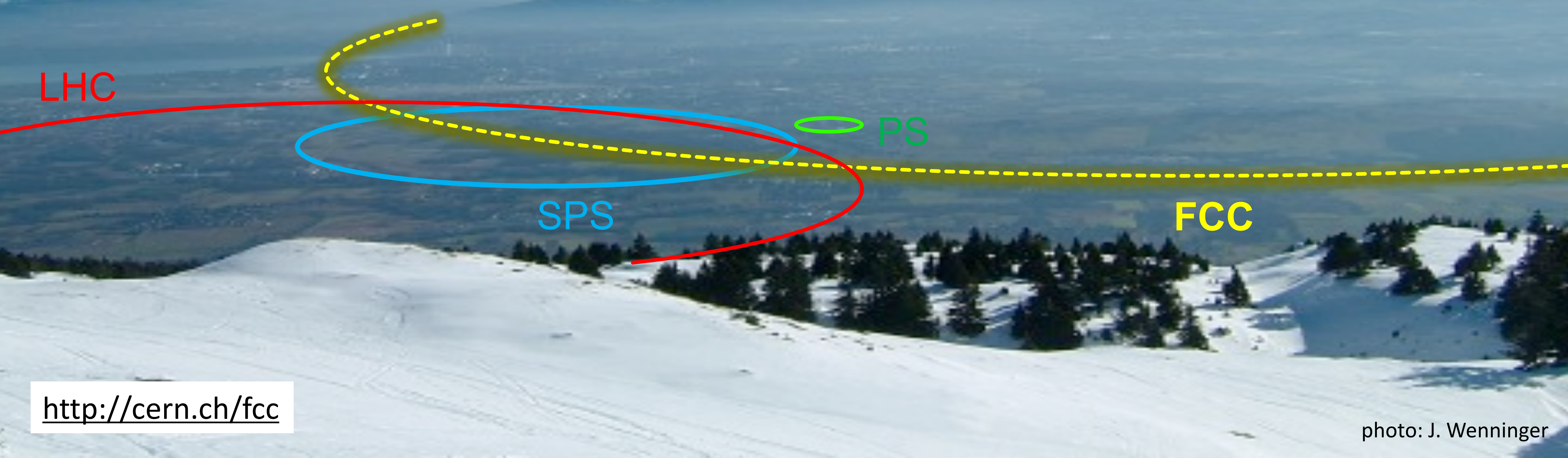
FCC-ee – also a tau factory!

Mogens Dam
Niels Bohr Institute



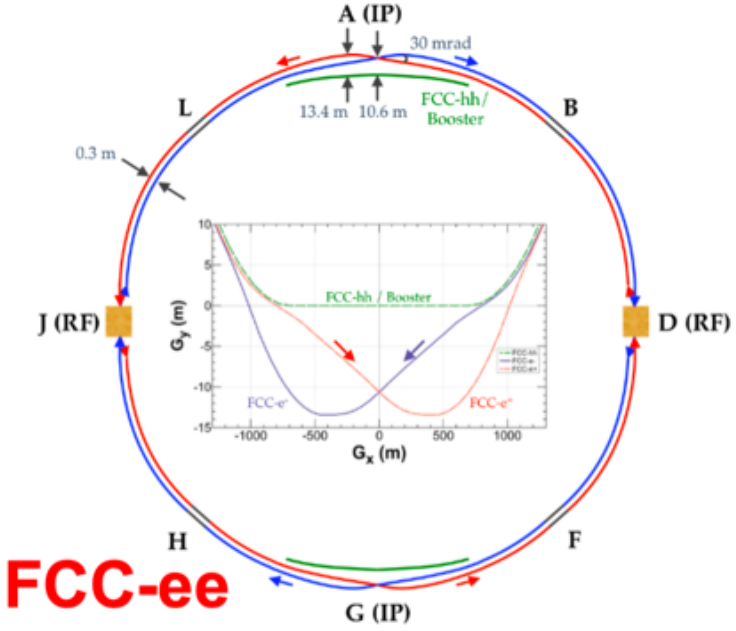
http://cern.ch/fcc

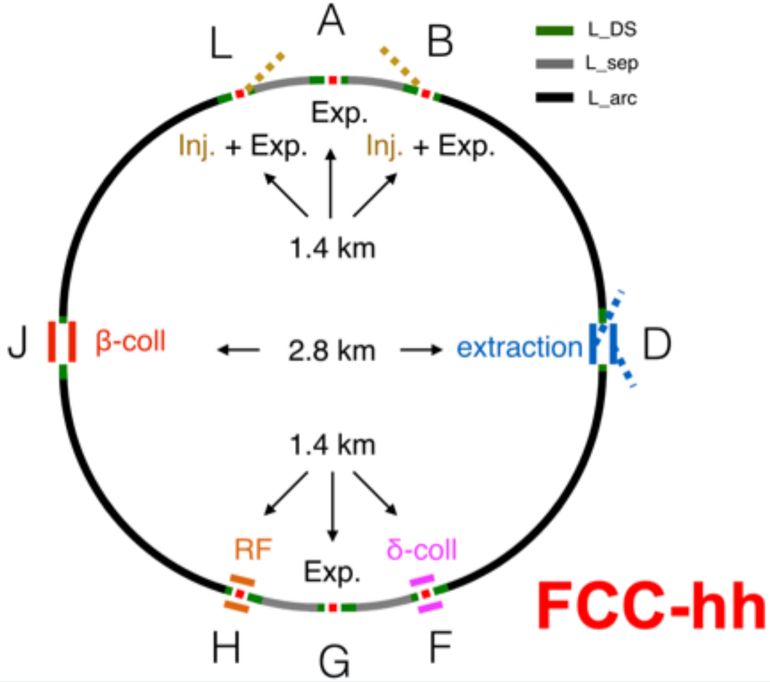
photo: J. Wenninger

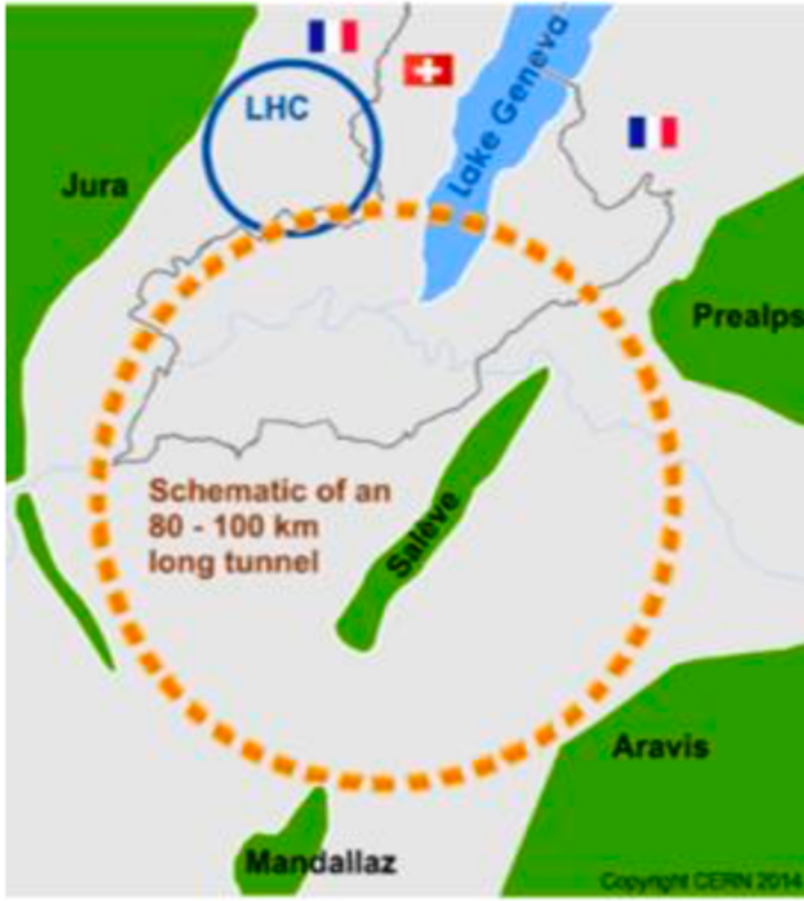
The FCC integrated program inspired by successful LEP – LHC programs at CERN

Comprehensive long-term program, maximizing physics opportunities

- **Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & and top factory at highest luminosities**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- Complementary physics
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after HL-LHC







The FCC integrated program inspired by successful LEP – LHC programs at CERN

and τ

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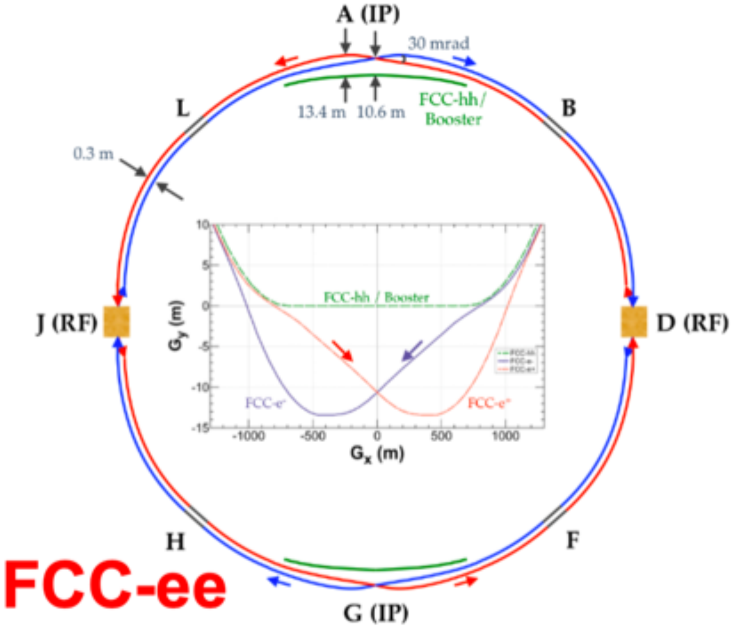
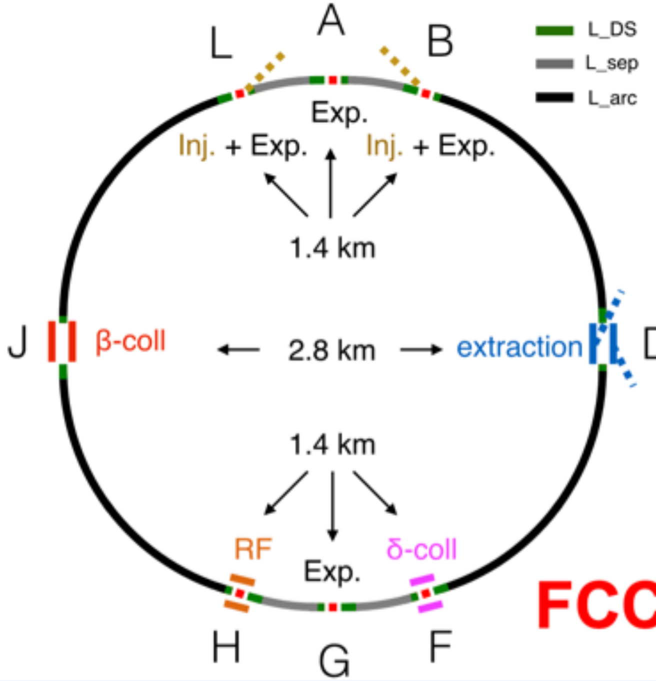
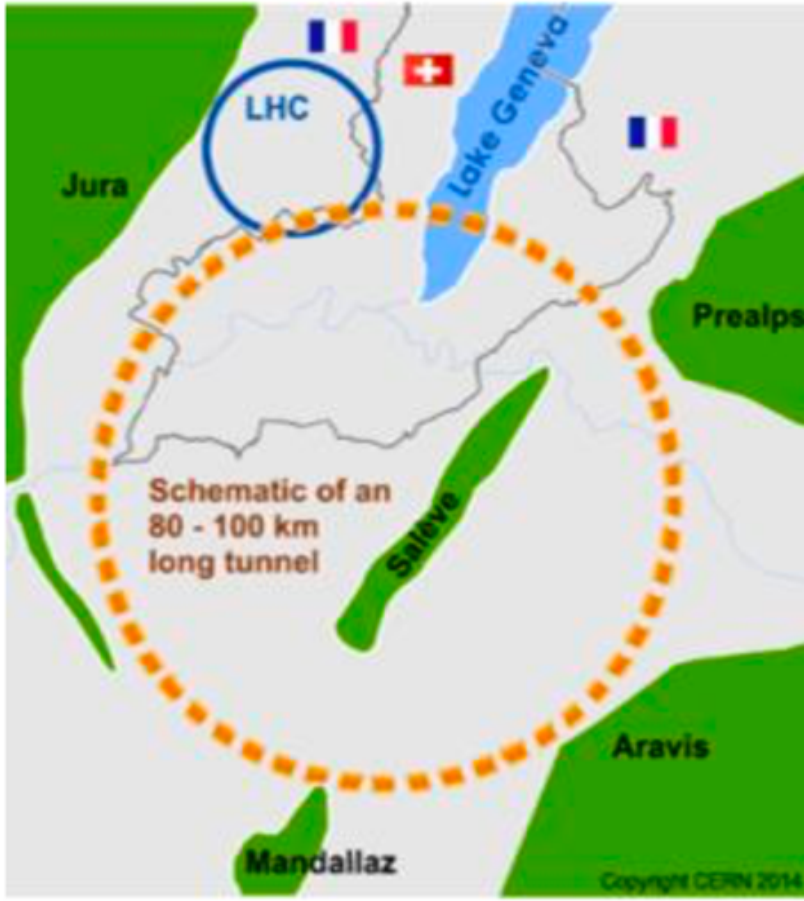


FCC-ee



FCC-hh



"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV, and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."

Feasibility study of the colliders (ee and hh) and related infrastructure

FCC is the highest priority future initiative (plan A)

European Strategy Update 2020

"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV, and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."

Feasibility study of the colliders (ee and hh) and related infrastructure

FCC is the highest priority future initiative (plan A)

Essential news for FCC

- June 2021:

  The FCC Feasibility Study (2021-2025) organization proposed to CERN council and approved unanimously

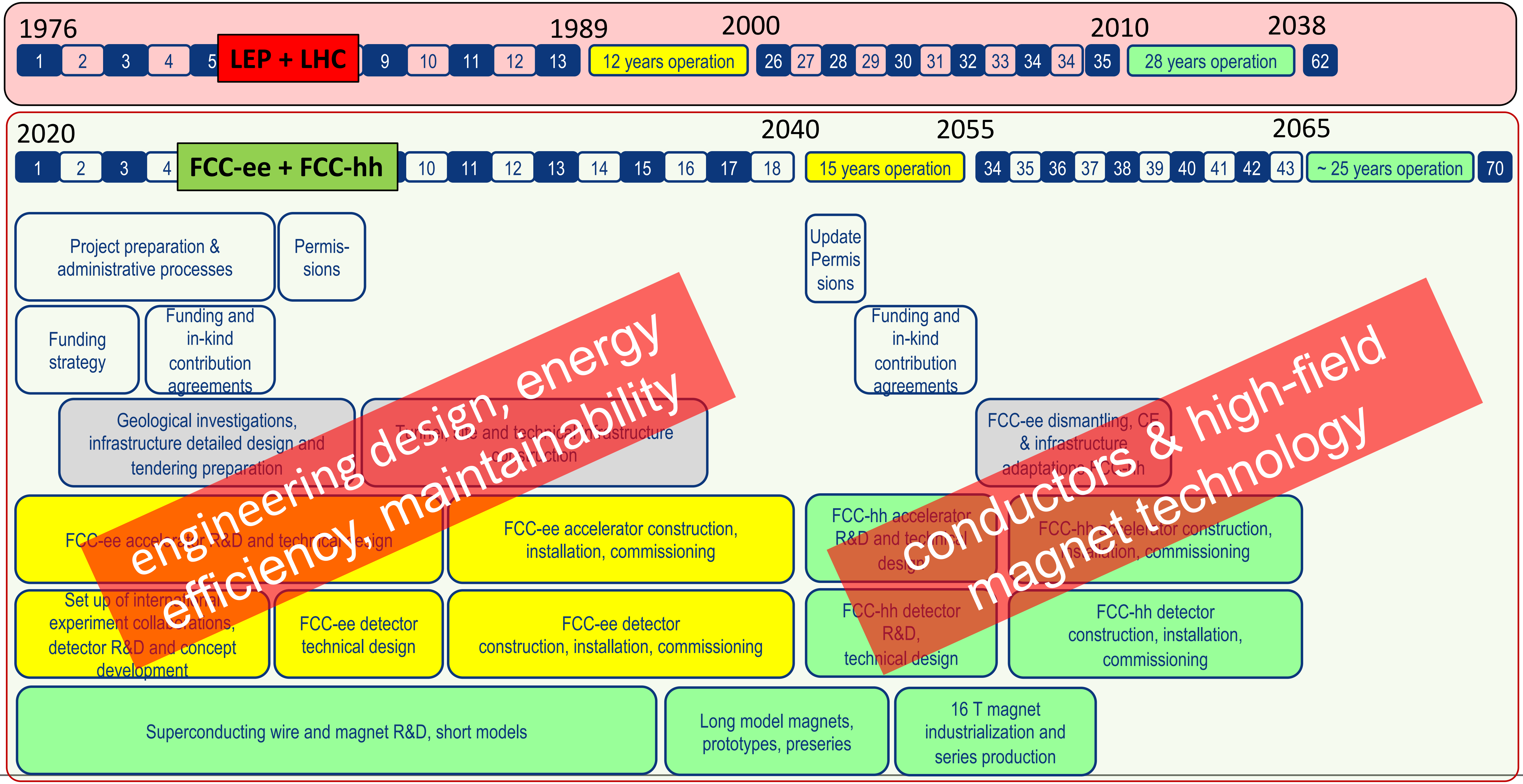
  - Council documents :
    - Organisational structure of the FCC feasibility study http://cds.cern.ch/record/2774006/files/English.pdf
    - Main deliverables and timeline of the FCC feasibility study http://cds.cern.ch/record/2774007/files/English.pdf

  "The focus will be on the tunnel and the first-stage collider (FCC-ee)"

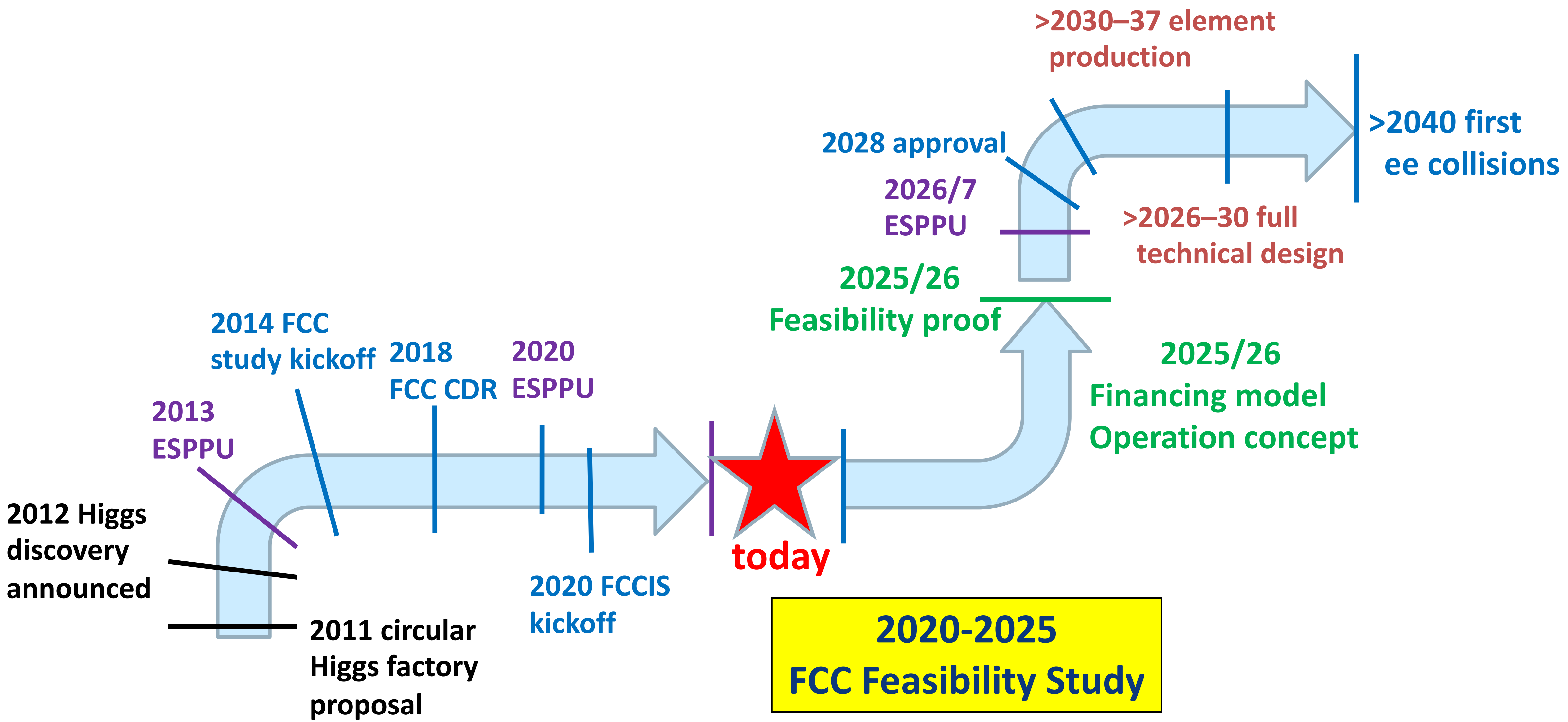
  - Intermediate review mid 2023, delivery of Feasibility Study Report (FSR) end 2025, first collisions 2040+
  - Stress importance of communication towards **scientific community,** governments and funding agencies, industries and general public
- Work has started on placement in Geneva area (France and Switzerland)
  - Reduce number of surface points from 12 to 8
    - This layout is consistent with later choice of 2 or 4IP for the e^+e^- collider
- In parallel, high field magnet R&D for FCC-hh will be carried out with high priority

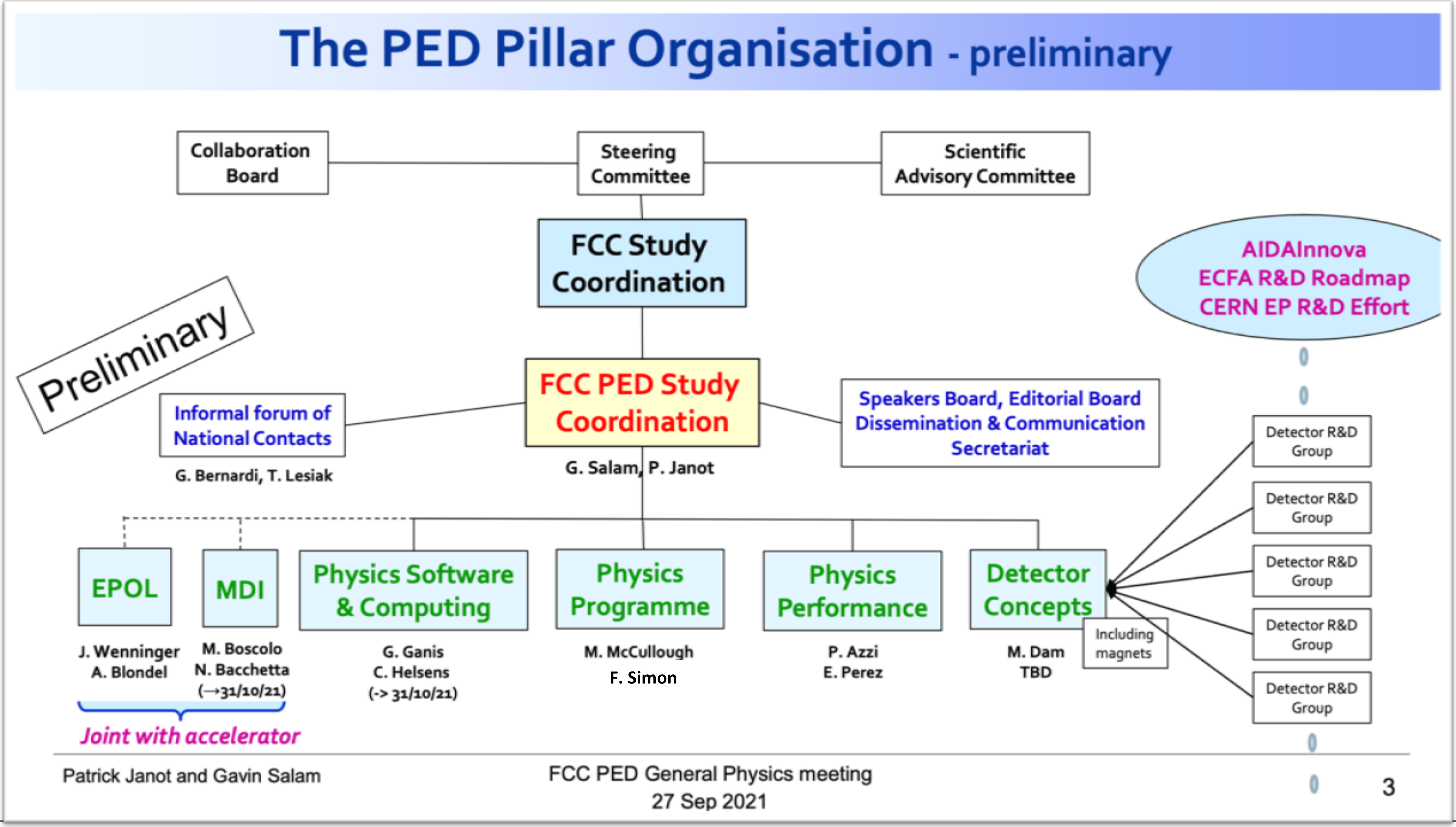
These events bring FCC-ee and FCC-hh one big step closer to reality

FCC-INT Timeline (compared to LEP + LHC)



FCC Roadmap towards FCC-ee




The PED Pillar Organisation - preliminary
Collaboration Board
Steering Committee
Scientific Advisory Committee
FCC Study Coordination
AIDAInnova
ECFA R&D Roadmap
CERN EP R&D Effort
Preliminary
FCC PED Study Coordination
G. Salam, P. Janot
Informal forum of National Contacts
G. Bernardi, T. Lesiak
Speakers Board, Editorial Board
Dissemination & Communication
Secretariat
Detector R&D Group
Detector R&D Group
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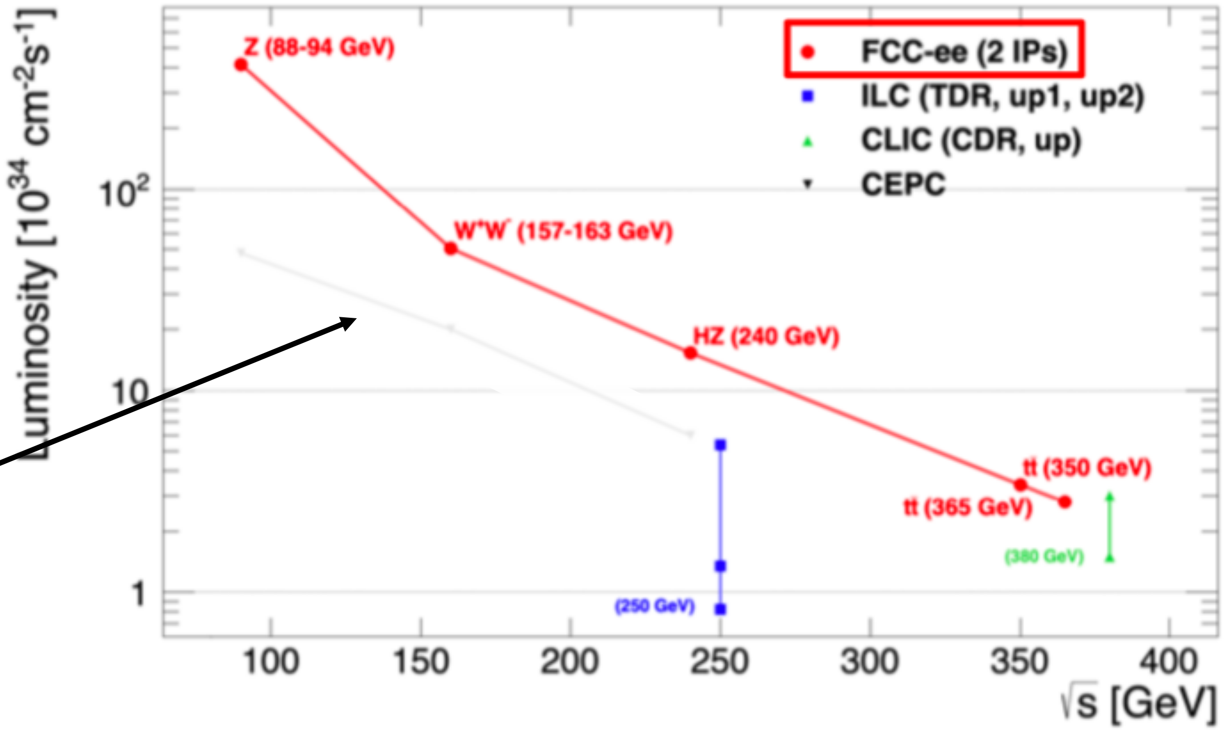
EPOL
J. Wenninger
A. Blondel
MDI
M. Boscolo
N. Bacchetta
(→31/10/21)
Physics Software & Computing
G. Ganis
C. Helsens
(-> 31/10/21)
Physics Programme
M. McCullough
F. Simon
Physics Performance
P. Azzi
E. Perez
Detector Concepts
M. Dam
TBD
Including magnets
Joint with accelerator
Patrick Janot and Gavin Salam
FCC PED General Physics meeting
27 Sep 2021
3

FCC-ee Conditions and Statistics

Have removed CEPC projection.
See talk by M. Ruan



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

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

Enormous statistics of Z bosons and of τ leptons

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

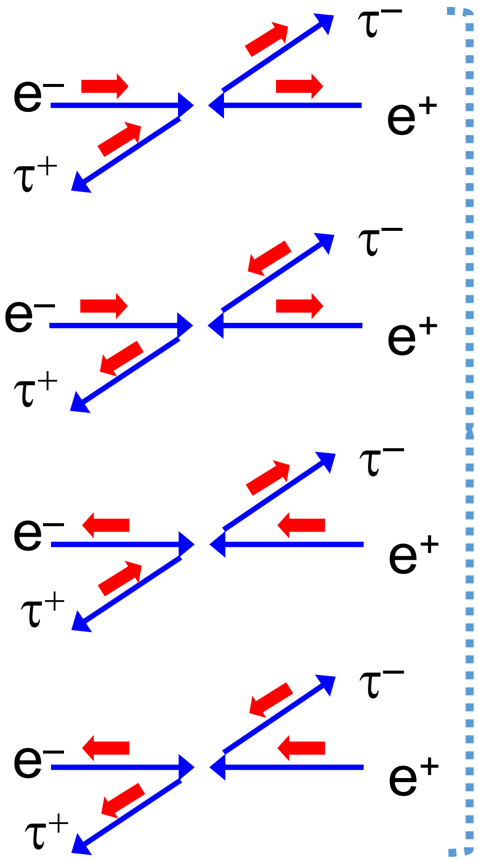
Outline

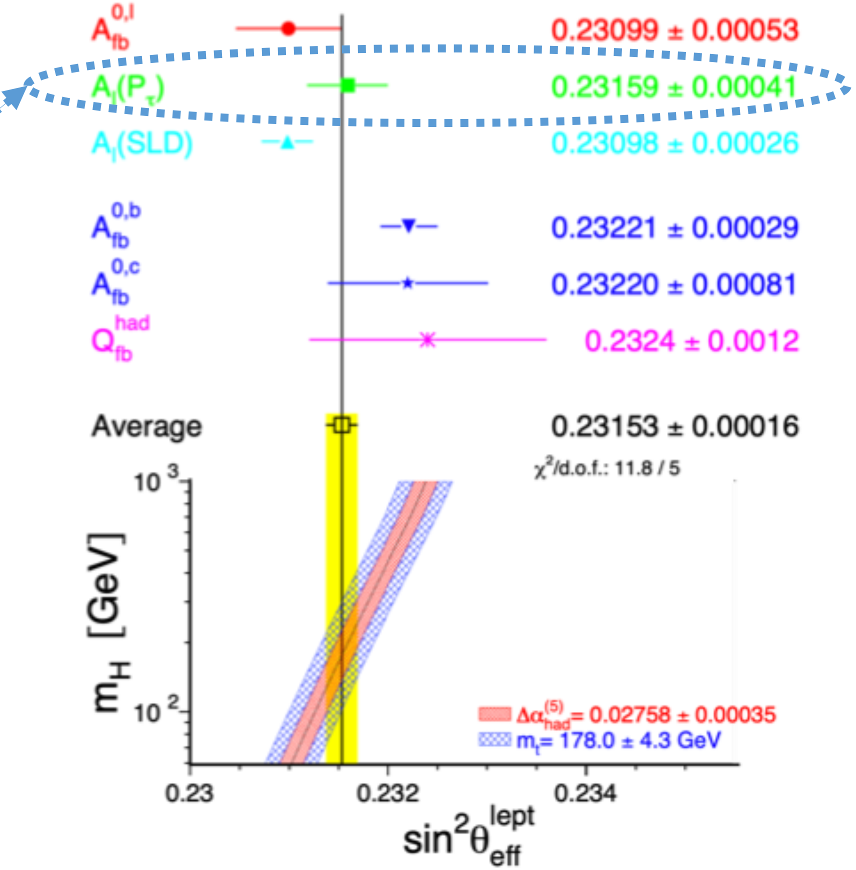
a. τ Polarisation Measurement
b. τ-lepton Properties and Lepton Universality
c. Lepton Flavour Violating Z decays
d. Lepton Flavour Violating τ decays
e. τ leptons in B decays

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 ← tau2018
- MD, *The τ challenges at FCC-ee,* *Eur. Phys. J. Plus* **136,** 963 (2021) DOI: 10.1140/epjp/s13360-021-01894-y
- Yasmine Amhis et al, *Prospects of $B_c \to \tau\nu$ at FCC-ee,* arXiv:2105.133330

τ Polarisation Measurement

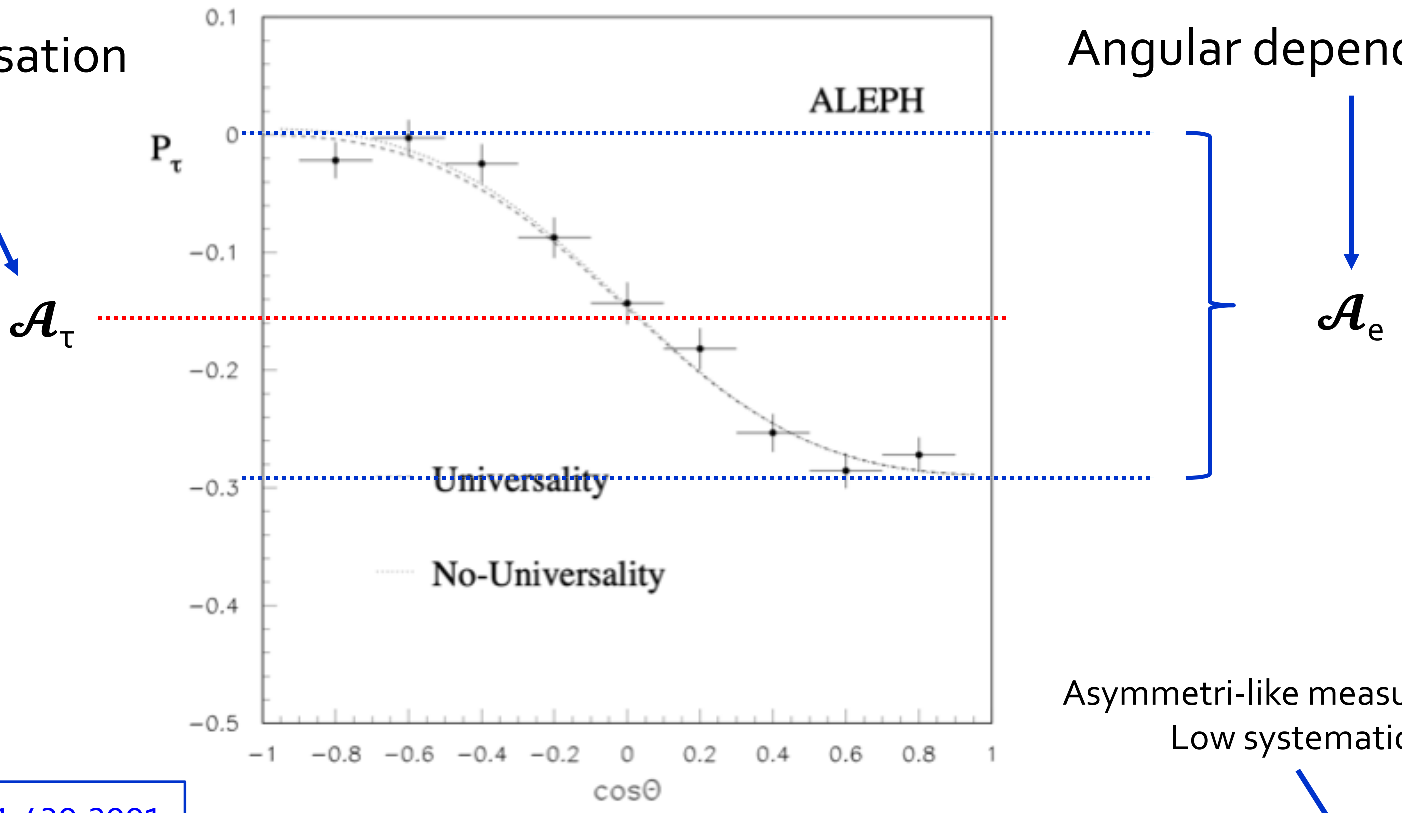




Example: Aleph at LEP

Mean polarisation

Angular dependence



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

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 $e^+e^- \to \tau^+\tau^-$ 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

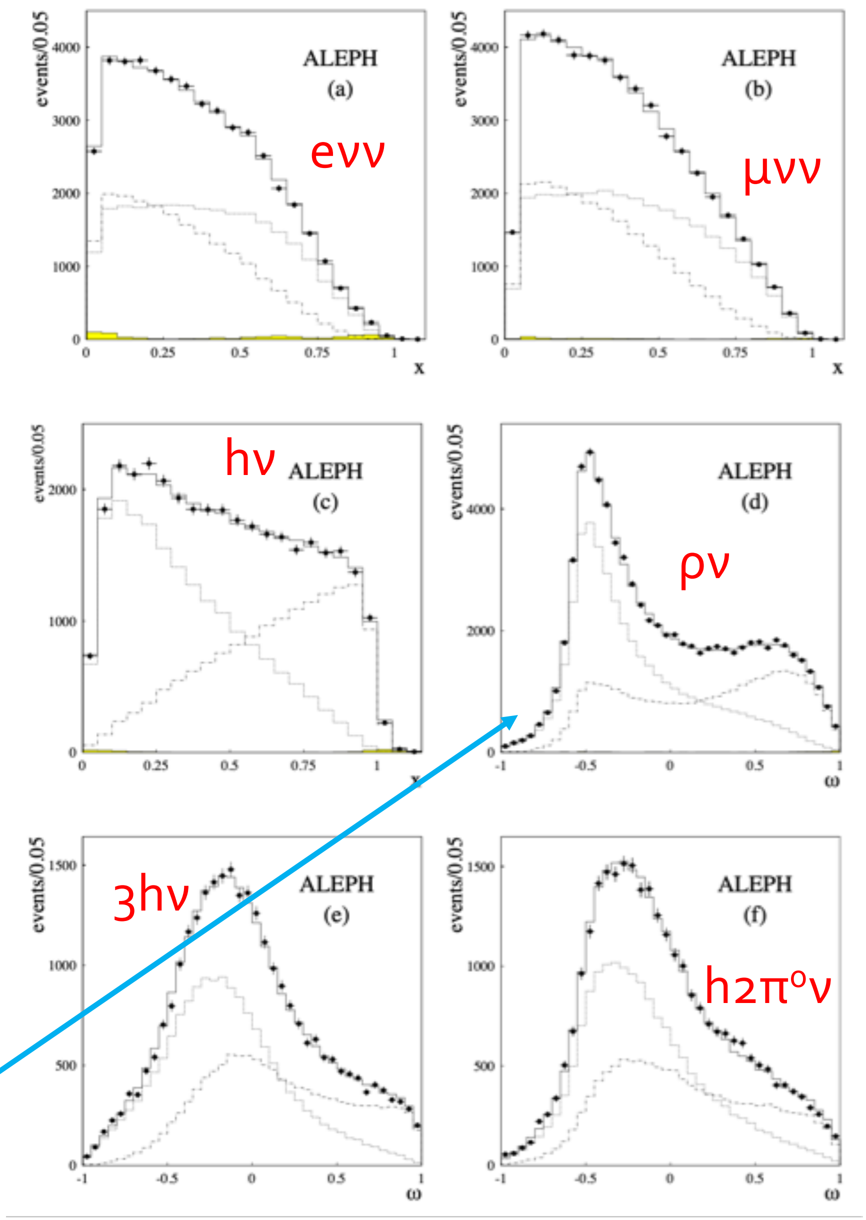
Example: $\tau^- \to \rho^-\nu \to \pi^-\pi^0\nu$

- Here polarisation is extracted from two angles

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

π^- π^0 energy sum difference

Combined into 1D "optimal observable"



Results and Precisions – case Aleph

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

Obtained results

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

Most precise channels

systematics

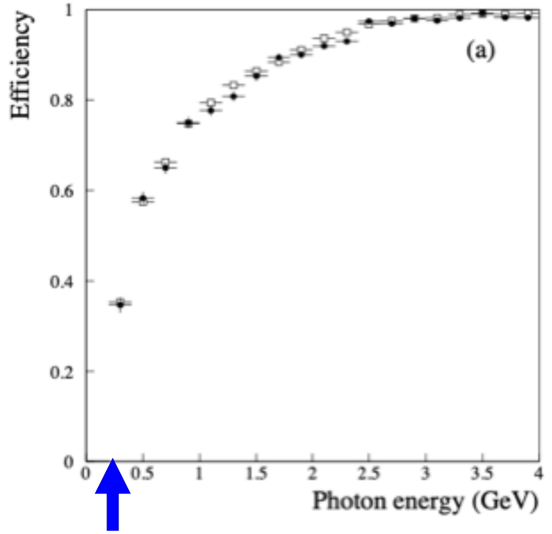
Source	h	ρ	$3h$	$h2\pi^0$	e	μ	Incl. h
			A_τ				
selection	-	0.01	-	-	0.14	0.02	0.08
tracking	0.06	-	0.22	-	-	0.10	-
ECAL scale	0.15	0.11	0.21	1.10	0.47	-	-
PID	0.15	0.06	0.04	0.01	0.07	0.07	0.18
misid.	0.05	-	-	-	0.08	0.03	0.05
photon	0.22	0.24	0.37	0.22	-	-	-
non-τ back.	0.19	0.08	0.05	0.18	0.54	0.67	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^{5-6} larger statistics: Need (much) reduced systematics

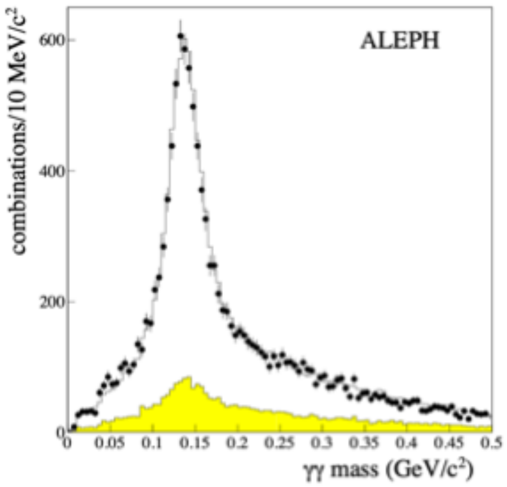
The single most important systematics (on the most precise channels) is due to photon and π^0 identification

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

Foton reconstruction efficiency.
Starting at 250 MeV



γγ mass of additional photons in hemispheres where one π^0 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

Measurement of muon polarisation ?

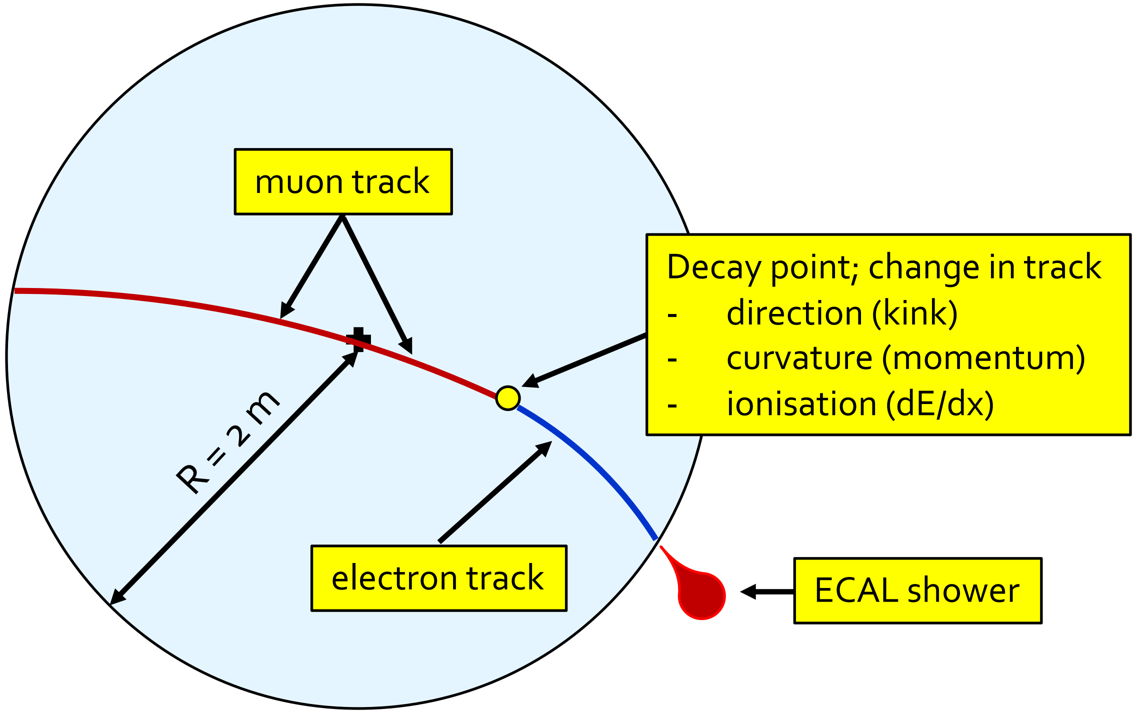
- Tau leptons decay, hence we can measure their polarisation
- But muons also decay
  - Look for events

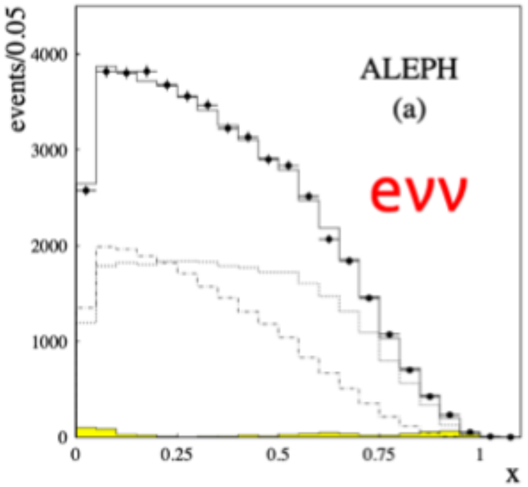
    $Z \rightarrow \mu\mu$ with one muon decaying $\mu \rightarrow e\nu\nu$

    - For FCC-ee statistics, 1.2 million decays per meter flight distance
  - For robust measurement, aim to measure track both before and after decay point
    - Complemented by calorimetric estimate of electron momentum
  - 1 million well reconstructed events will result in a measurement to a statistical precsion of

$$\delta P_{\mu} \simeq 0.0045$$

  - Slightly better than full tau polarisation measurement from LEP





Situation similar to this, but with ~ 30 times the statistics

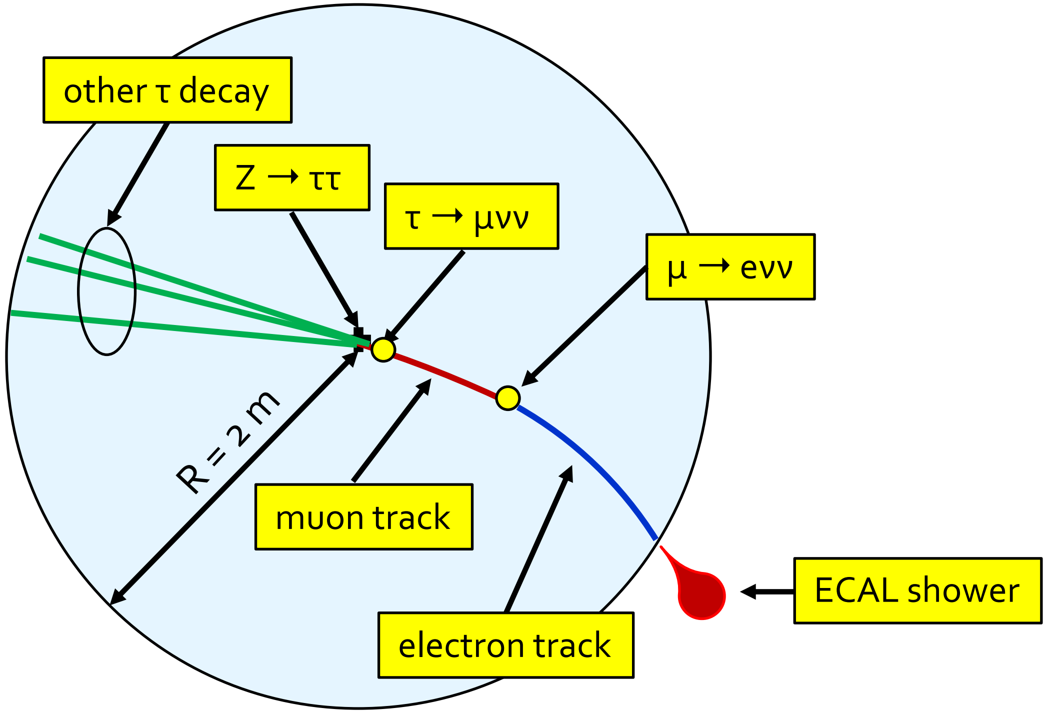
Lorentz structure of τ-decay amplitude ?

- Measure muon polarisation in decays

$Z \rightarrow \tau\tau$ followed by **$\tau \rightarrow \mu\nu\nu$** followed by **$\mu \rightarrow e\nu\nu$**

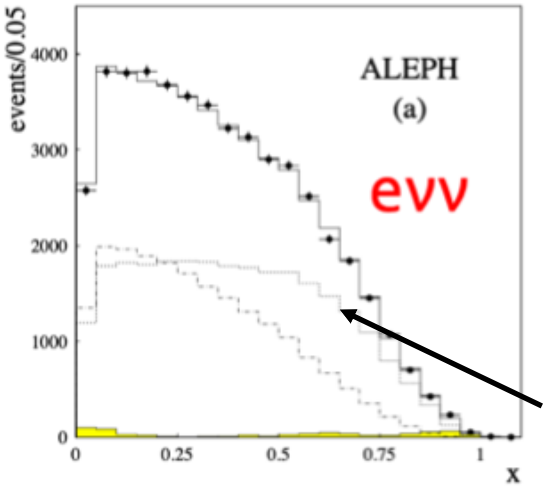
  - For FCC-ee statistics, few × 100,000 decays per meter flight distance

- Essential to measure sizeable track length both before and after decay point
  - Establish decay point / that decay actually happened
  - Measure momentum before & after decay point => $x = p_e / p_\mu$
  - Complemented by calorimetric estimate of electron momentum



- 100,000 well reconstructed events would result in a measurement to a statistical precsion of about

$\delta P_\mu \simeq 0.015$

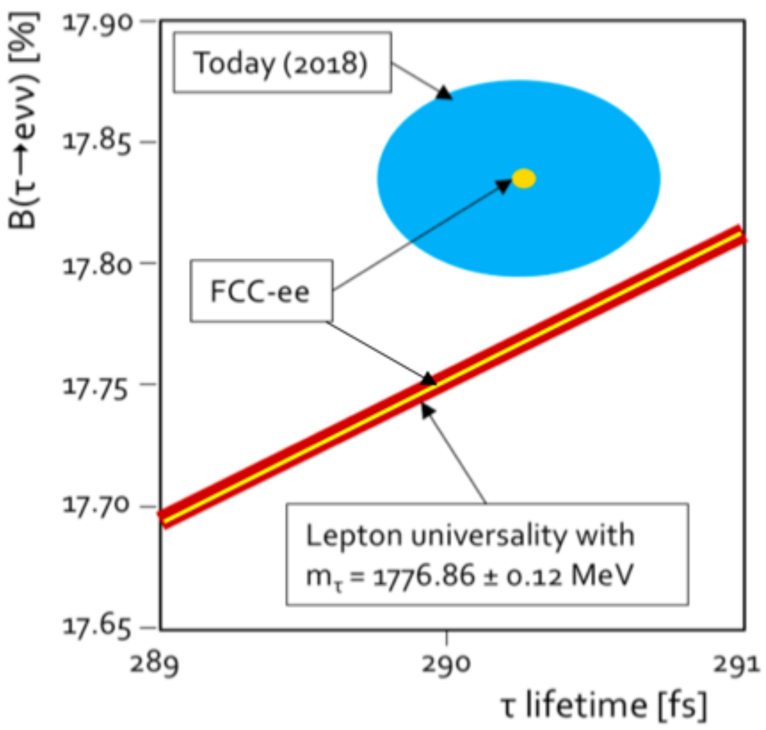


Situation similar to this with somewhat higher statistics

CC weak interaction (V-A): Expect to measure $P_\mu = -1$

τ-lepton properties and Lepton Universality

- Mass
- Lifetime
- Leptonic branching fractions



Lepton Universality - Universality of Fermi constant

The Fermi constant is measured in **μ decays** and defined by

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

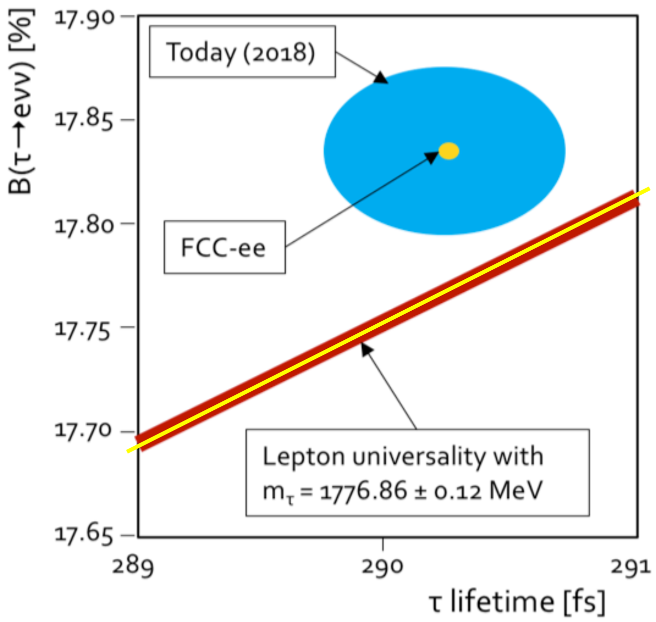
(known to 0.5 ppm)

Similarly, can define Fermi constant measured in **τ decays** by

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

(known to 1700 ppm)

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



Shown in yellow: "guestimates" on FCC-ee precisions

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

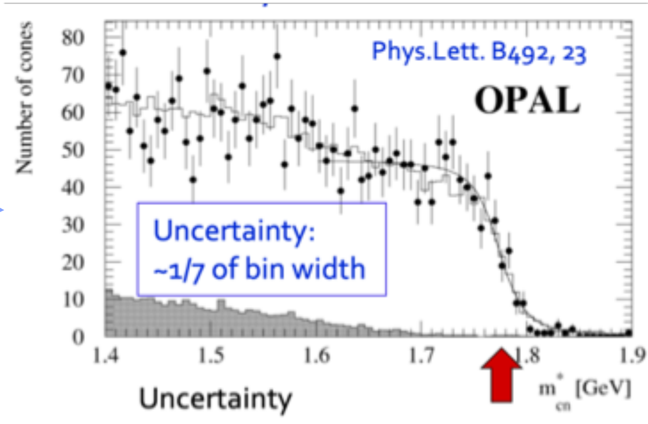
Today: 67 ppm BES | 1700 ppm Belle | 1700 ppm LEP

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
$\mathcal{B}$	No improvement since LEP (statistics limited) Depends primarily e^-/π^- (& e^-/ρ^-) separation	ECAL dE/dx

Estimates of precisions ~ as presented at tau2018

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**			

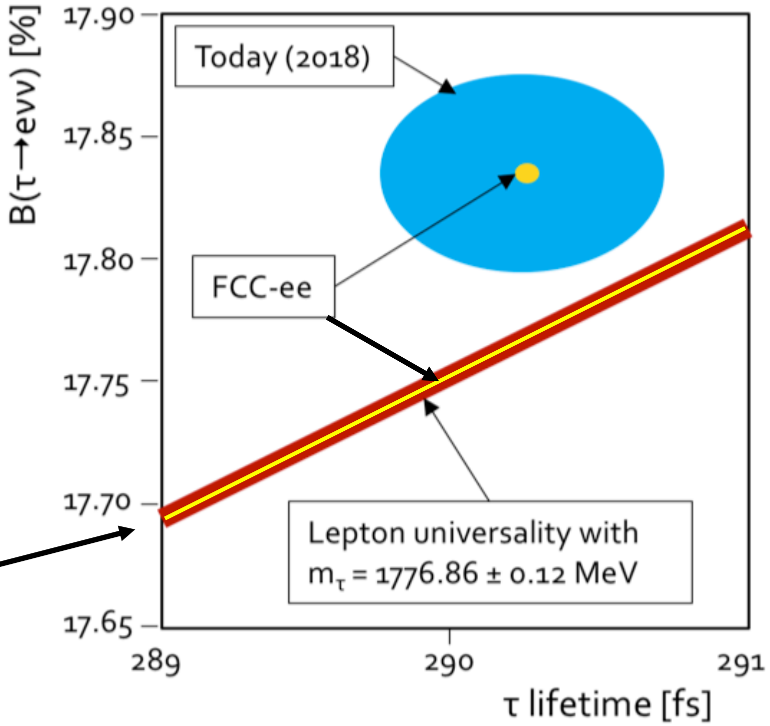


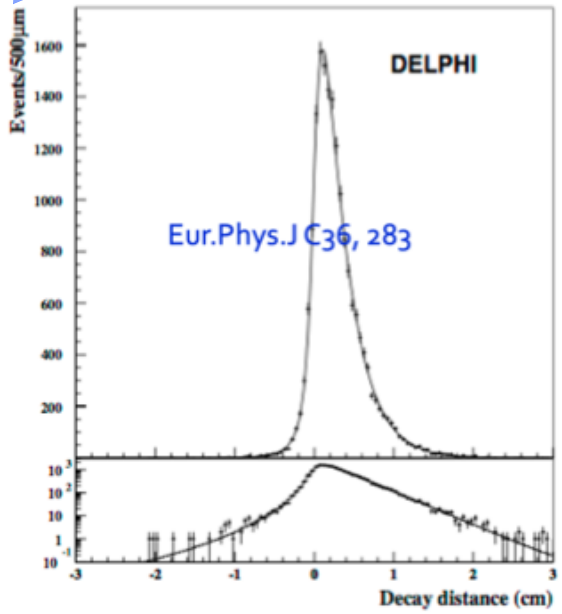
Lepton Universality Tests:

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 one order of magnitude or more**
$\lvert g_\tau/g_\mu \rvert$	$\Gamma_{\tau\to e} / \Gamma_{\mu\to e}$	1.0030 **± 0.0015**	

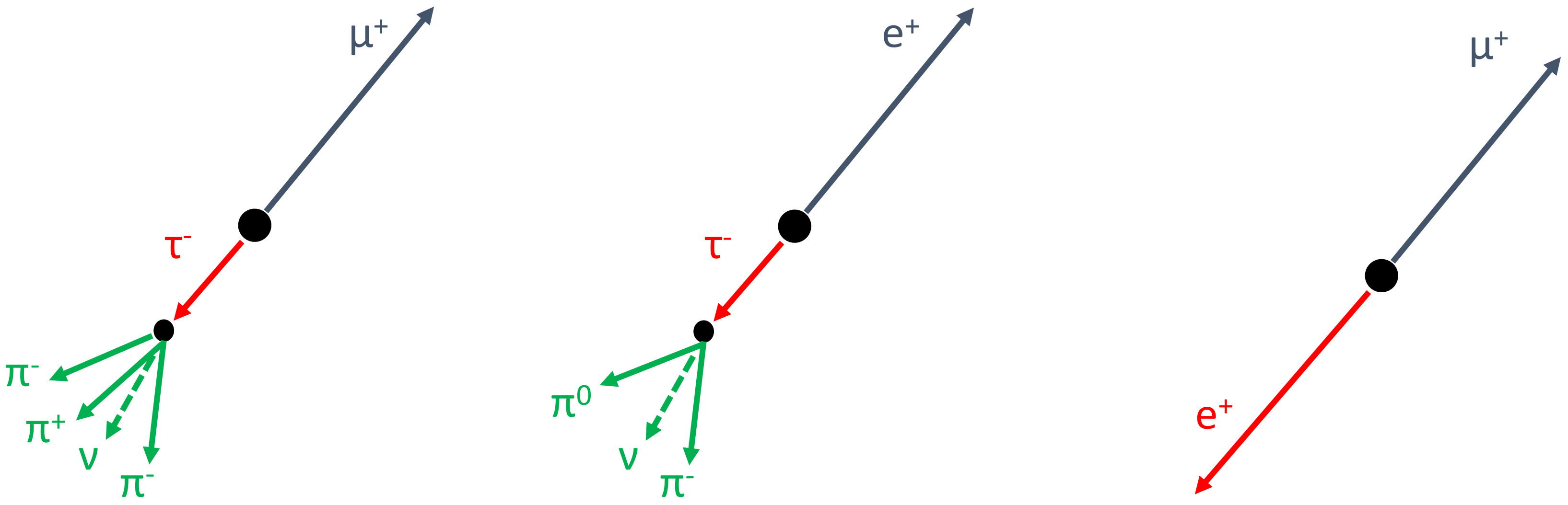
With the precise FCC-ee measurements of lifetime and BRs, m_τ could become the limiting measurement in the universality test

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

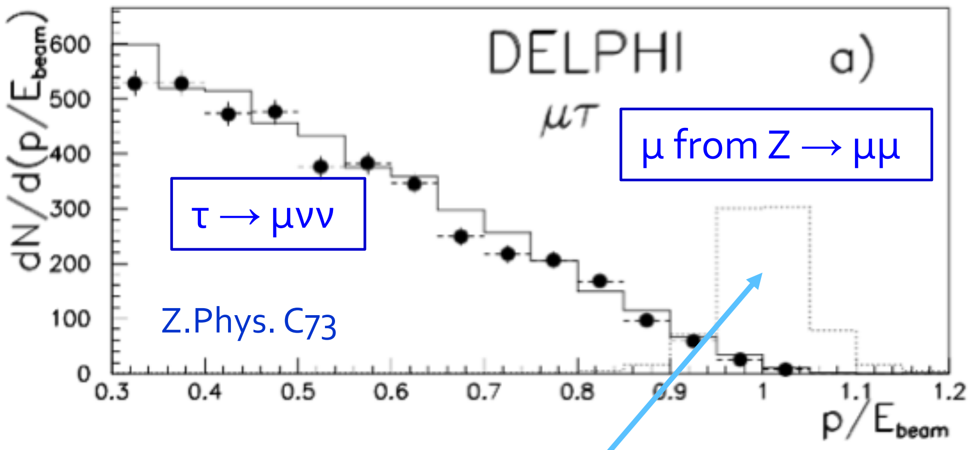




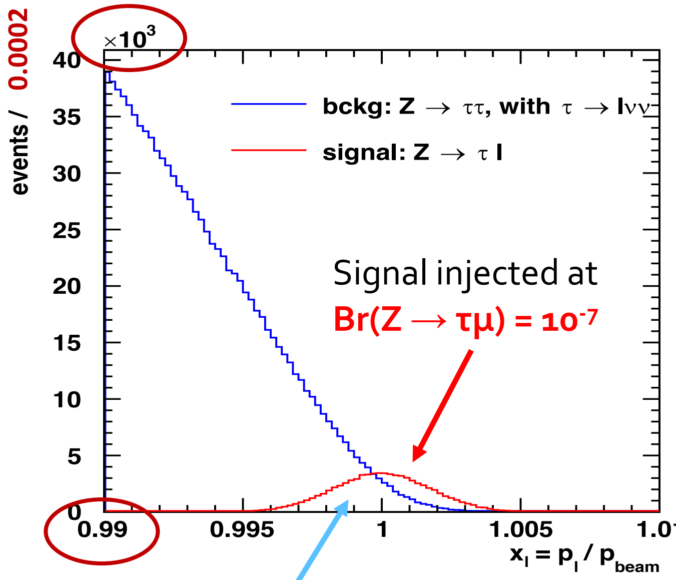
LFV Z decays



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



FCC-ee study with $5\mathrm{x}10^{12}$ Z decays



DELPHI momentum resolution at p_T = 45.6 GeV :

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

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

- 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:

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

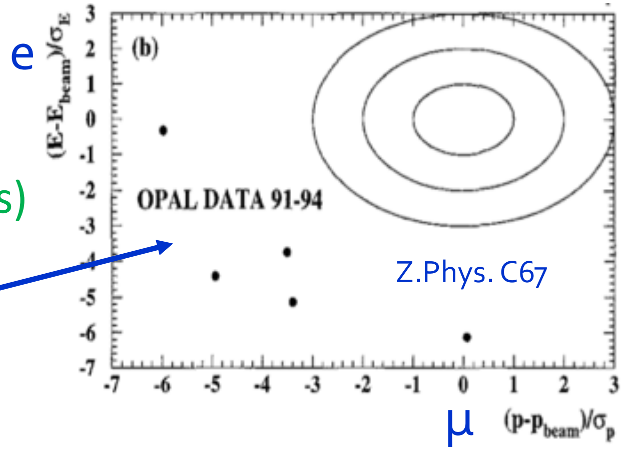
Findings:

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

BRs of ~10^{-9}

$Z \to e\mu$

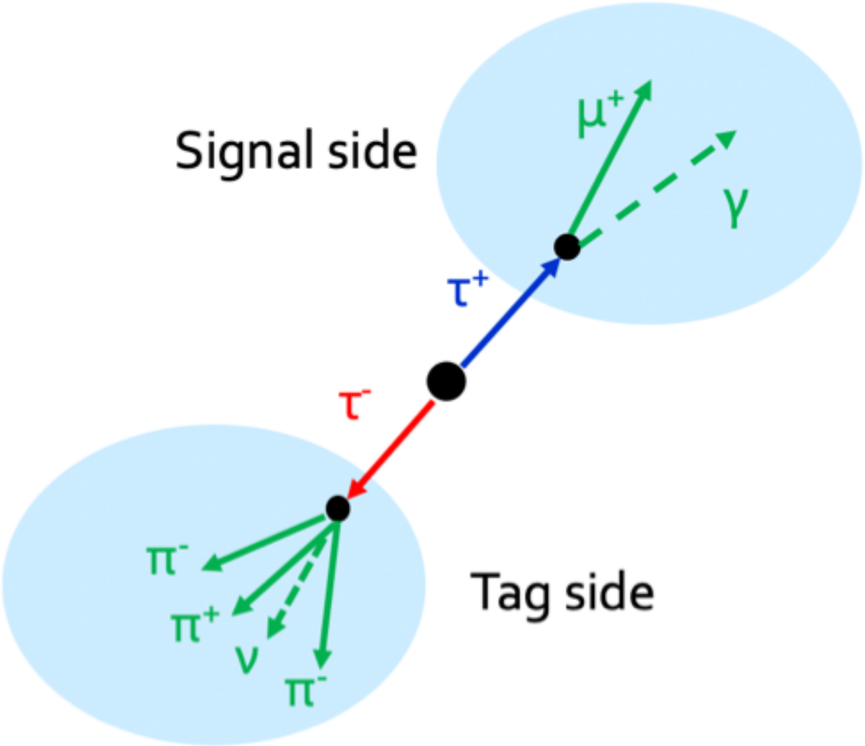
- Current limit:
  - **7.5 x 10^{-7} LHC/ATLAS** (20 fb^{-1}; no candidates)
  - **1.7 x 10^{-6} LEP/OPAL** (4.0 x 10^6 Z decays: no candidates)
- In e^+e^-, clean experimental signature:
  - Beam energy electron vs. beam energy muon

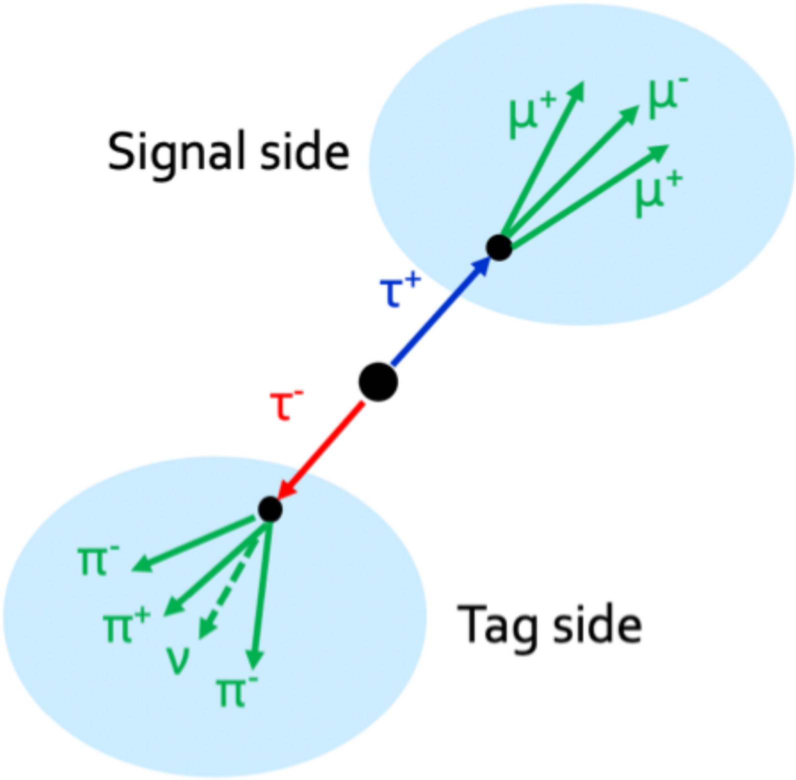


- Main experimental challenge:
  - **Catastrophic bremsstrahlung energy loss** of muon in electromagnetic calorimeter
    - Muon would deposit (nearly) full energy in ECAL: Misidentification $\mu \to e$
    - NA62: Probability of muon to deposit more than 95% of energy in ECAL: **4 x 10^{-6}**
    - 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 $P(\mu \to e)$
- 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 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

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

- **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
    - Presented at tau2018
  - From study (assuming 25% signal & background efficiency), projected BR sensitivity

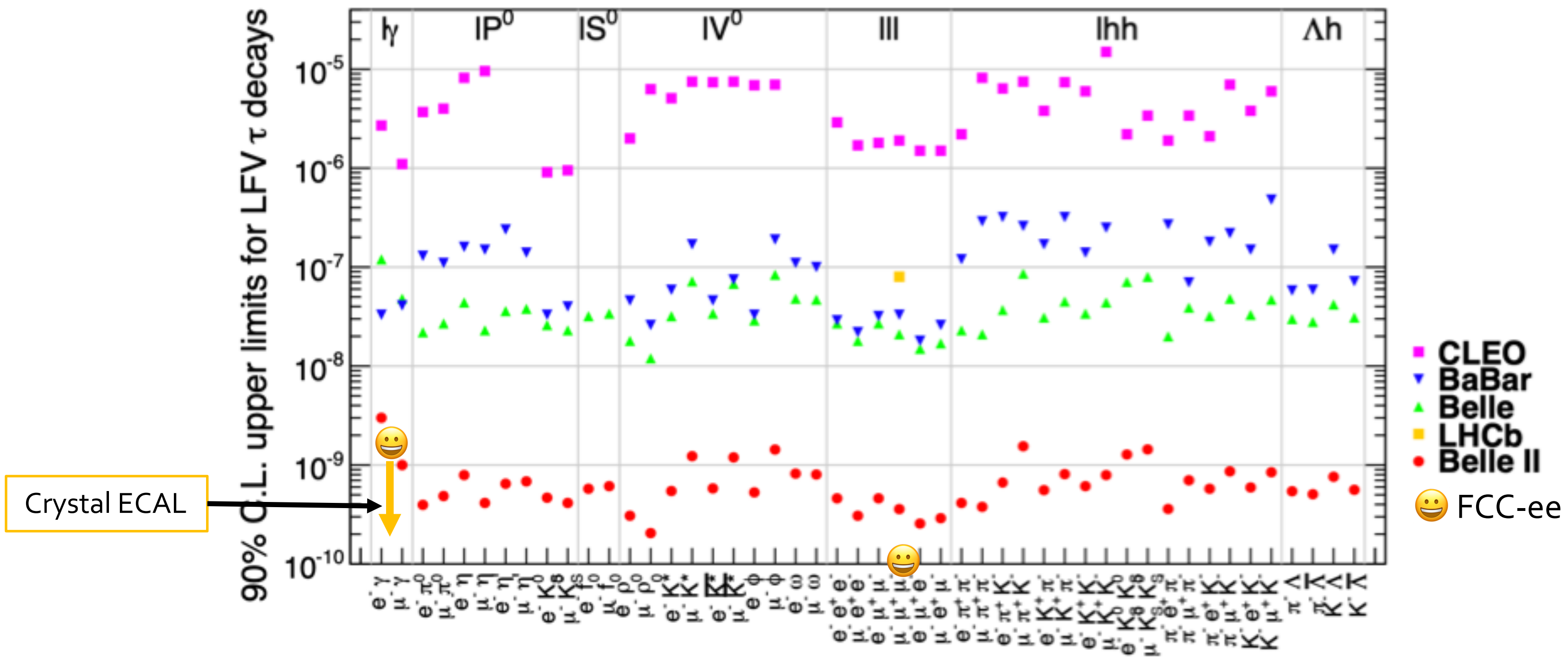
2×10^{-9}

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

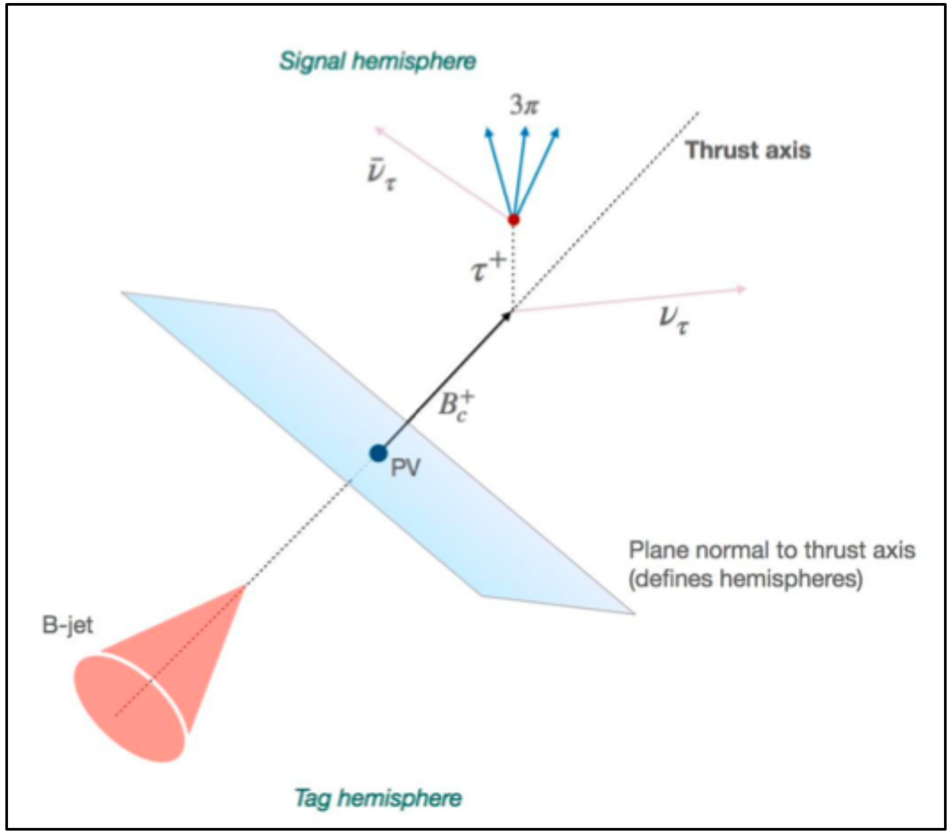
2008.00338

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

- 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 candidates
  - $\mu^-\mu^+\mu^-$: 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

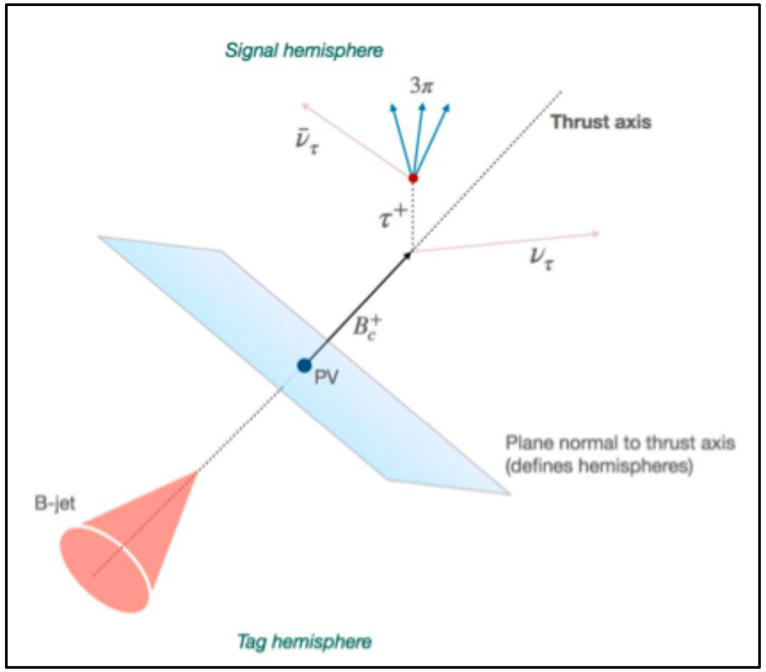


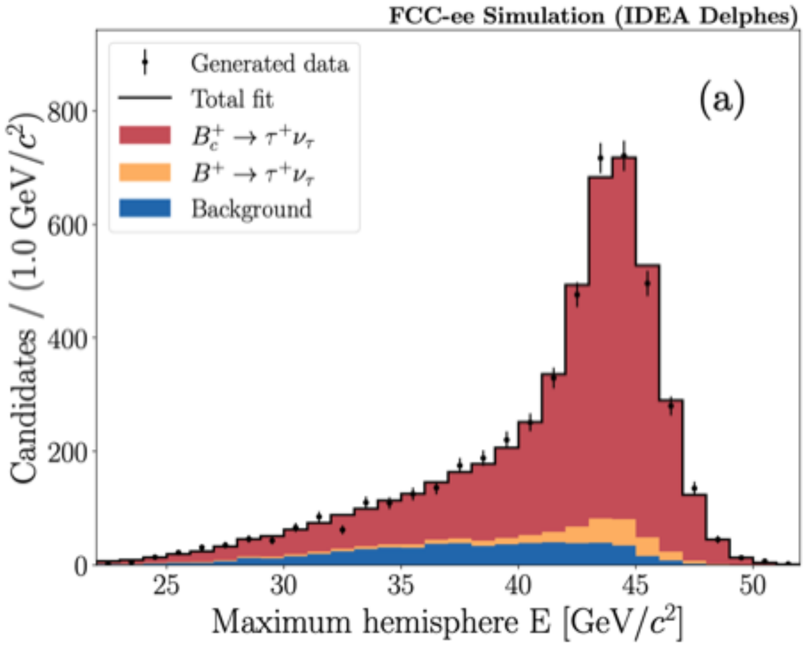
τ leptons in b decays

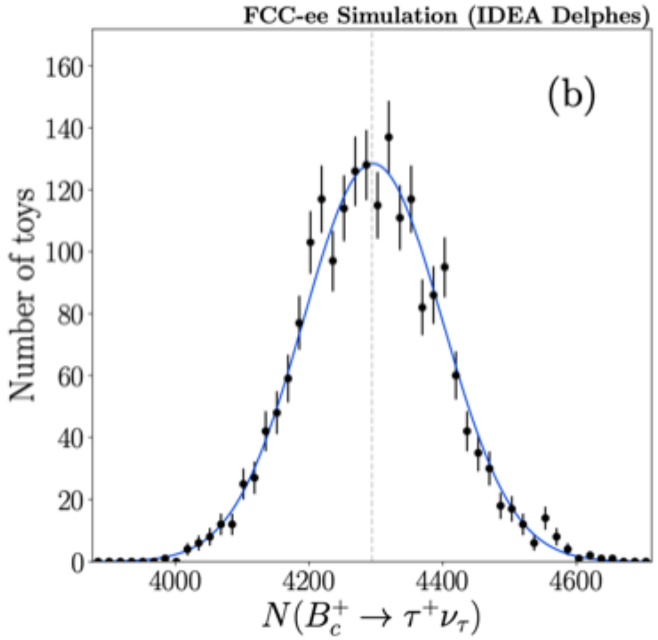


- $B_c \to \tau\nu_\tau$ process has same Feynman vertex factors as $b \to c\tau\nu_\tau$
  - Measurement of R(D) and R(D*) show ~ 3-4 σ tension in SM
- Exploit three-prong decay of τ
- Delphes simulation (IDEA Detector)
- Reject backgrounds from Z → bb/cc/qq using
  - Event level energy properties
  - Properties of the reconstructed 3π candidate
  - Two stage MVA approach

arXiv:2105.13330







- Toy dataset generated from signal and background PDFs
  - Signal measured with 2.4% precision

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 1-2 orders of magnitude down to at least $\mathcal{O}(10^{-4})$ level [$\mathcal{O}(10^{-4})$ statistically]
  - Substantial improvement in **τ lifetime**
  - Substantial improvement in **τ branching fractions**
  - Poential for improved measurement of **τ mass**
- Improved sensitivity to **lepton flavour violating Z decays** by factor **$\mathcal{O}(10^{3\text{-}4})$**
  - 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, …
- Prospects for very precise lepton universality τ lepton tests in b-physics
- And of course Higgs, etc…

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-, 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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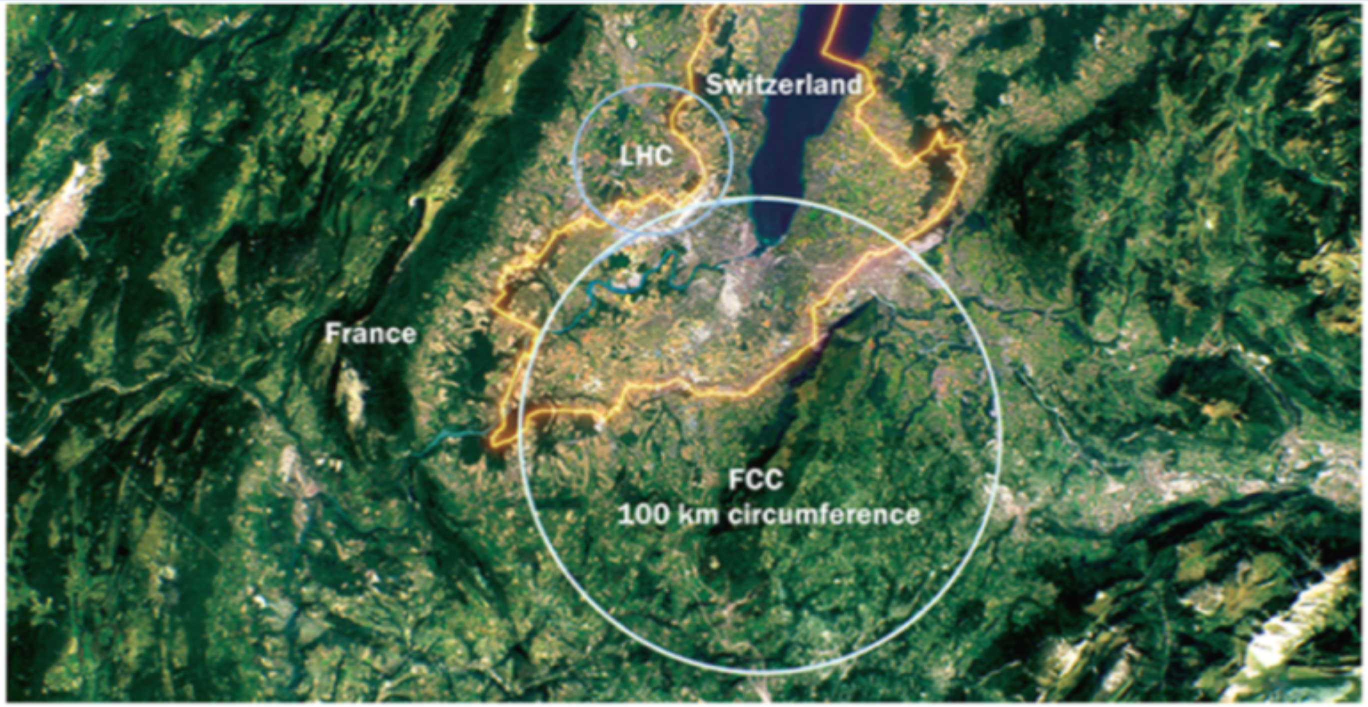
Design your detector with care!
Better start now

spares

FCC Feasibility Study (FS) 2021-2025

Fabiola Gianotti
FCC Week,
June 2021



- Tunnel: assess geological, technical, administrative, environmental feasibility → aim is to demonstrate there is no show-stopper for ~ 100 km ring in Geneva region
- Technologies: superconducting high-field magnets and RF accelerating structures; high-efficiency power production; energy saving and other sustainable technologies
- Funding: development of funding model for first-stage machine (tunnel and FCC-ee, total ~ 10 BCHF) and identification of substantial resources from outside CERN's budget
- "Consensus building": gathering scientific, political, societal support → communication campaign targeting scientists, governmental and other authorities, industry, general public

→ Complete a Feasibility Study Report by end 2025

my emphasis

FCC-ee basic design choices

double ring e^+e^- collider ~100 km

follows footprint of FCC-hh,
except around IPs

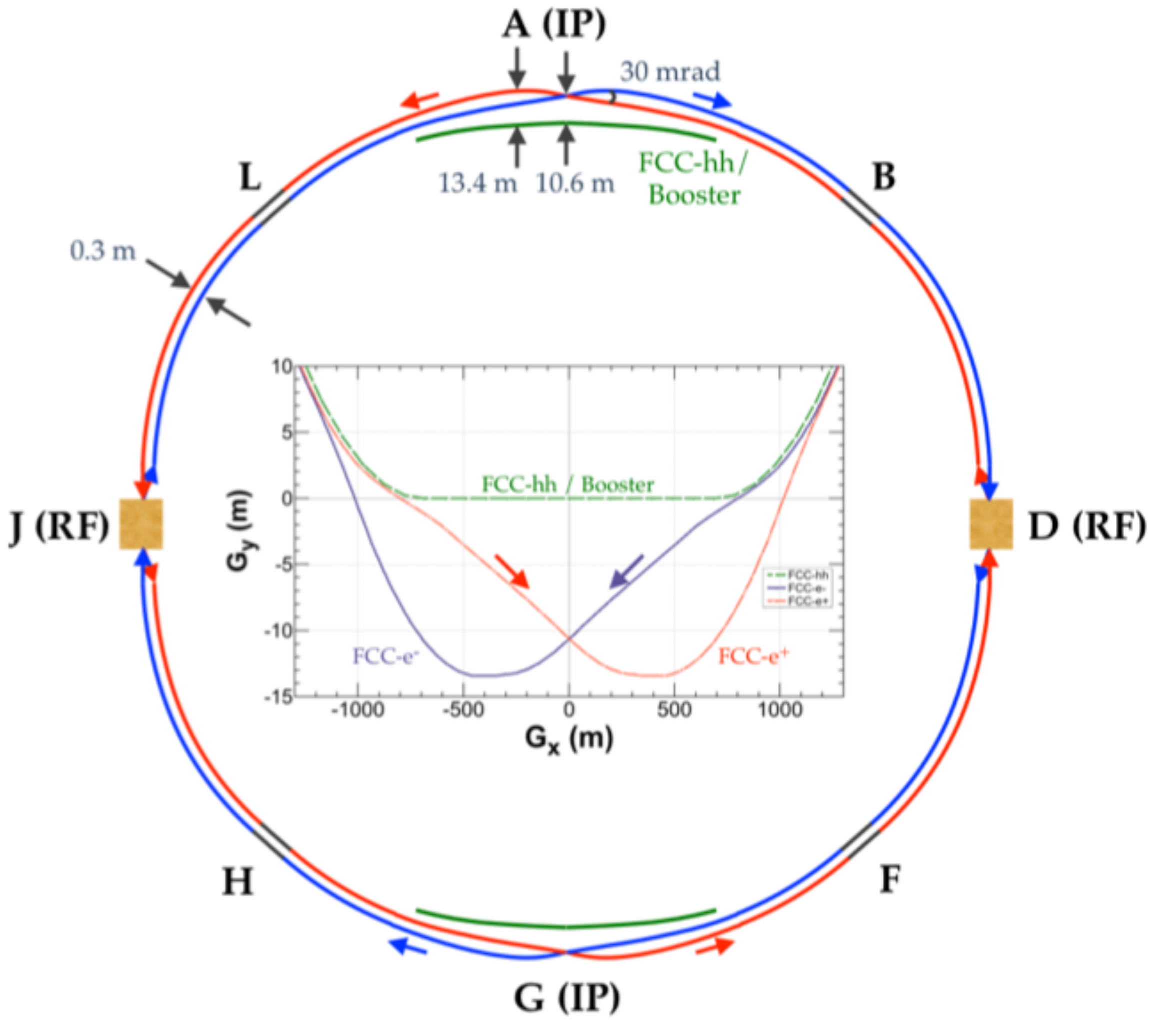
asymmetric IR layout & optics
to limit synchrotron radiation
towards the detector

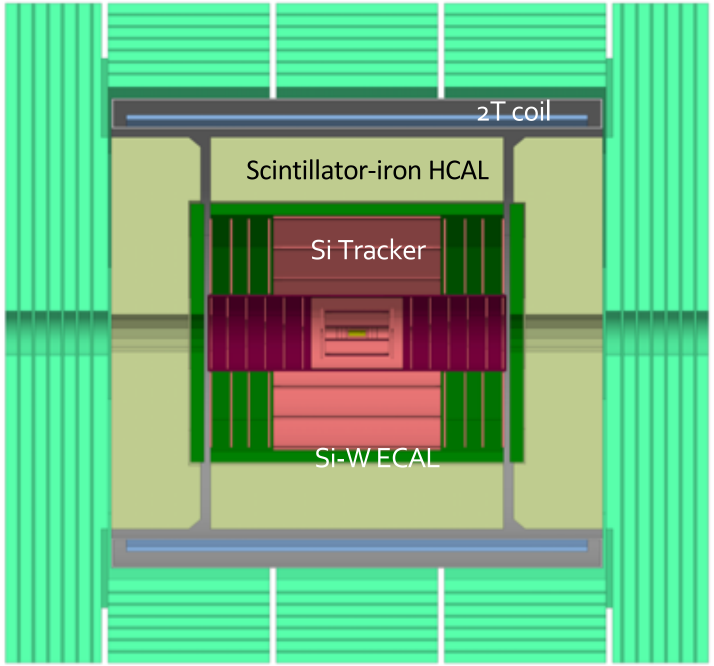
presently 2 IPs (alternative layout
with 4 IPs under study)

large horizontal crossing angle **30 mrad,**
crab-waist optics

synchrotron radiation power 50 MW/beam
at all beam energies

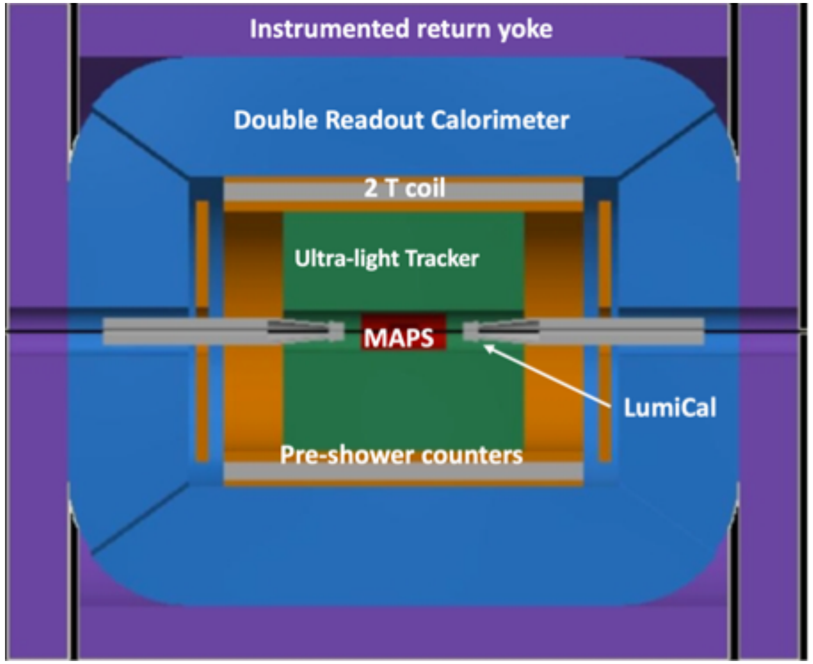
top-up injection scheme;
requires **booster synchrotron in collider tunnel**





CLD

- Consolidated option based on the detector design developed for CLIC
  - All silicon vertex detector and tracker
  - 3D-imaging highly-granular calorimeter system
  - Coil *outside* calorimeter system
- Proven concept, understood performance

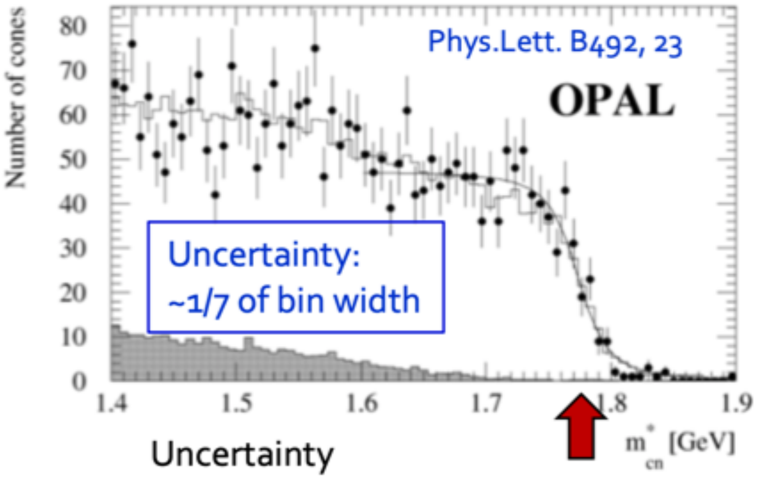


IDEA

- New, innovative, possibly more cost-effective design
  - Silicon vertex detector
  - Short-drift, ultra-light wire chamber
  - Dual-readout calorimeter
  - Thin and light solenoid coil *inside* calorimeter system

Tau Mass (i)

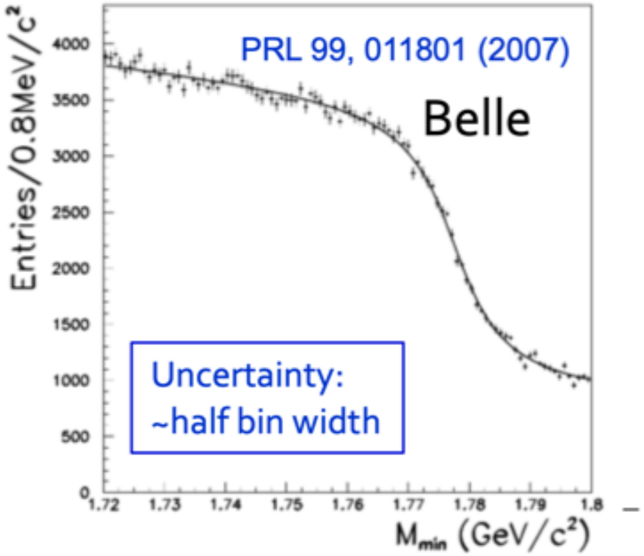
- **Current world average:** $m_\tau = 1776.86 \pm 0.12$ MeV
- Best in world: BES3 (threshold scan) $m_\tau = 1776.91 \pm 0.12\ (\text{stat.})\ ^{+0.10}_{-0.13}\ (\text{syst.})$ MeV
- Best at LEP: OPAL $m_\tau = 1775.1 \pm 1.6\ (\text{stat.}) \pm 1.0\ (\text{syst.})$ MeV
  - About factor 10 from world's 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, (perhaps even 7 prongs?)
  - Statistics 10^5 times OPAL: $\delta_{stat} = 0.004$ 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

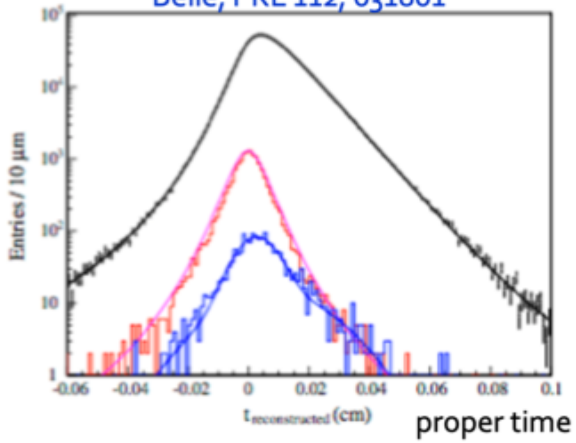
$$\delta_{syst} \lesssim 0.04 \text{ MeV}$$

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

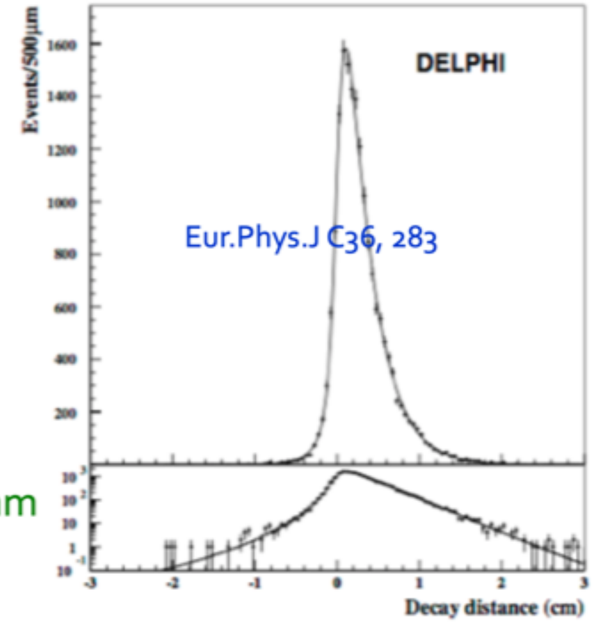
Tau Lifetime (i)

- **Current world average:** $\tau_\tau = 290.3 \pm 0.5$ fs
- **Best in world** (Belle): $\tau_\tau = 290.17 \pm 0.53_{stat} \pm 0.22_{syst}$ fs
  - Large statistics: 711 fb^{-1} @ $\Upsilon(4s)$: 6.3×10^8 $\tau^+\tau^-$ 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



- **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 ($q\bar{q}$ 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!**

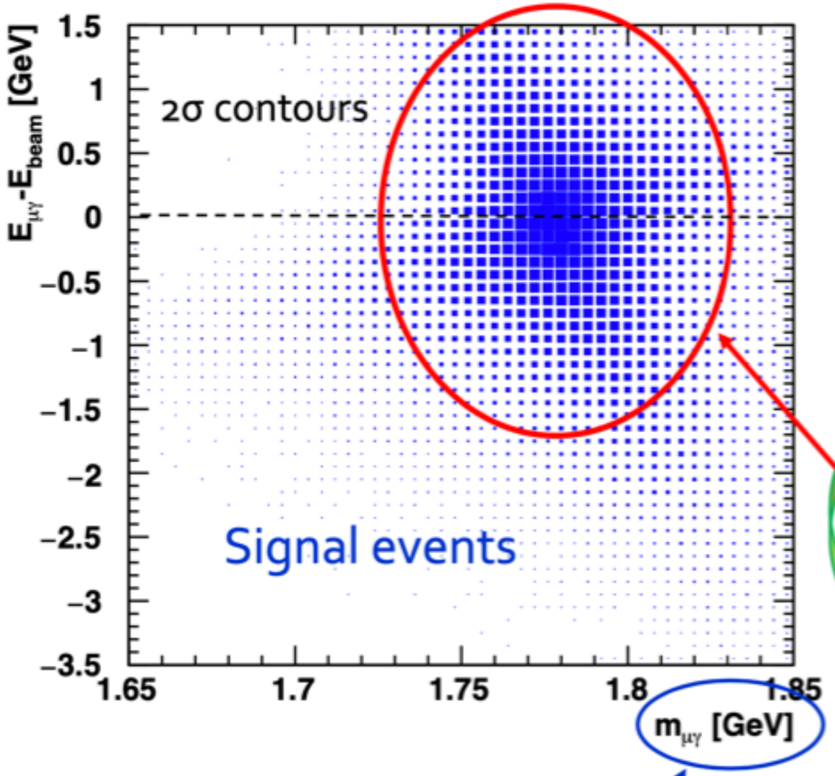
With the large statistics, will learn a lot. Suggest a factor 10 improvement wrt Aleph:

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

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

$\tau \to \mu\gamma$ 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]
  $\sigma(p_T)/p_T = 2\times10^{-5} \times p_T \oplus 1\times10^{-3}$
- 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 $\tau \to \mu\gamma$

$\sigma(m_{\gamma\mu}) = 26$ 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:

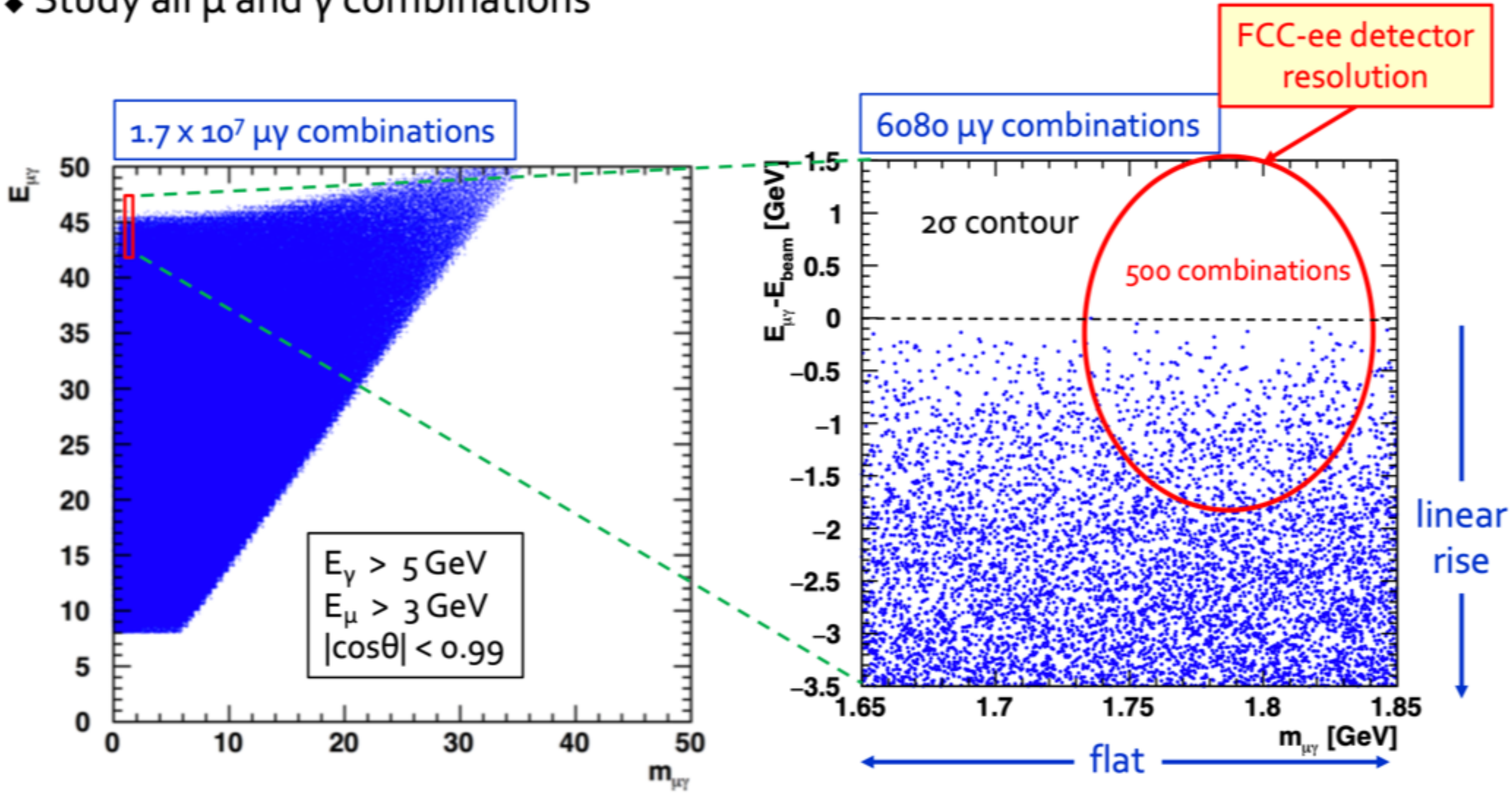
$$m_{\gamma\mu} = m_{raw} \times (E_{\gamma\mu}/E_{beam})$$

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 5×10^8 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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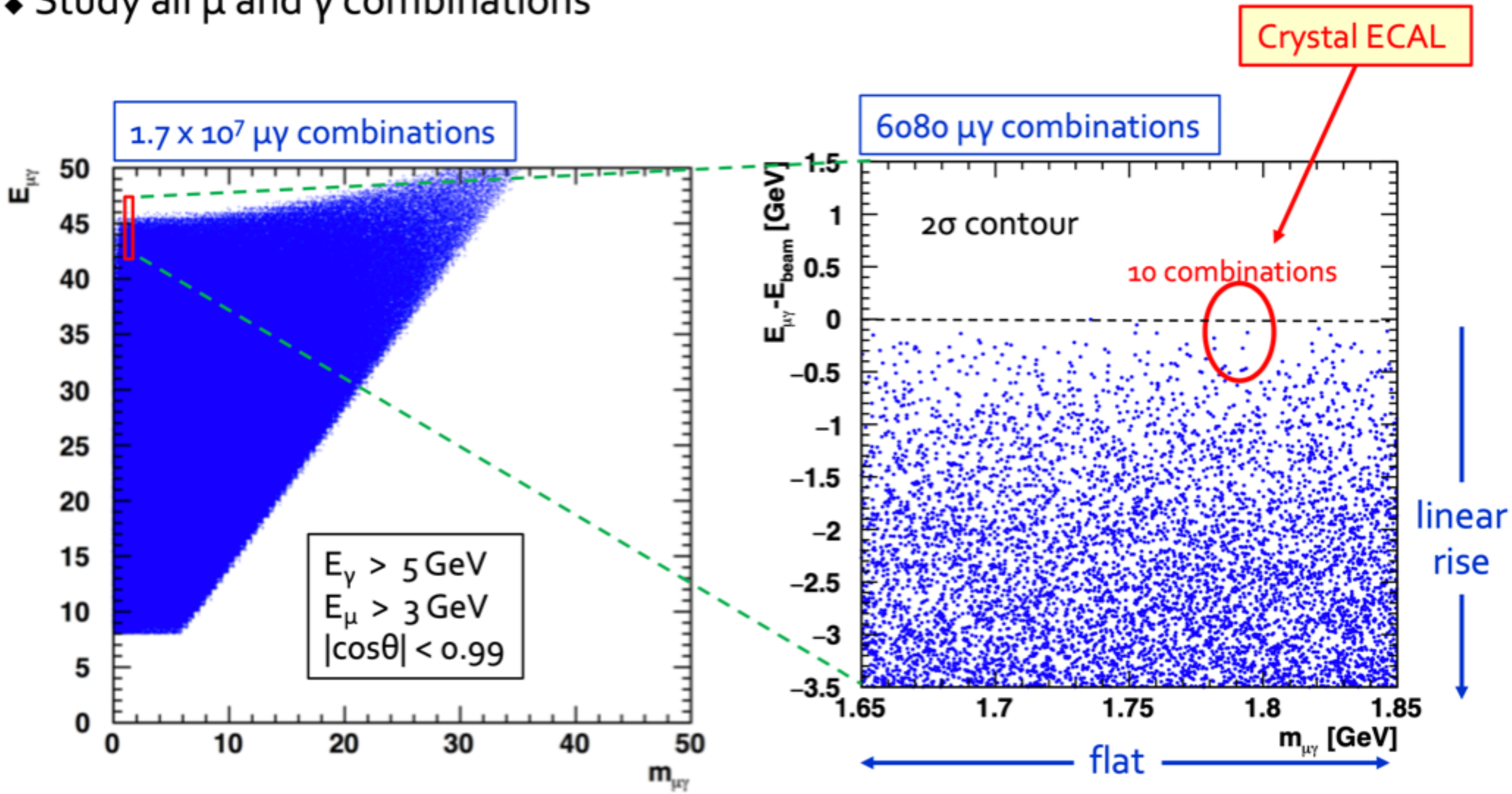
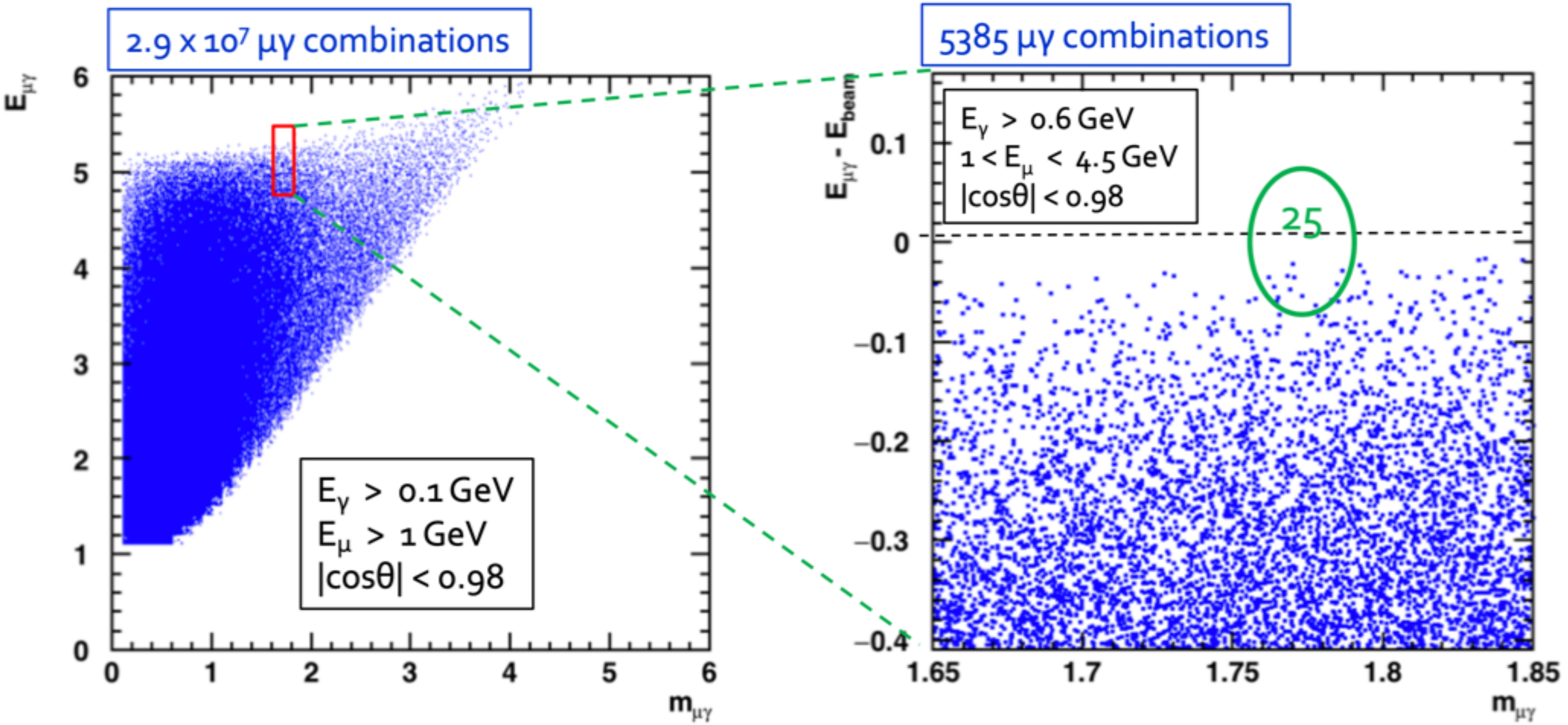


$\tau \to \mu\gamma$ Study – Check of method

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

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



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

Compare to my extrapolation of current BaBar limit: ~$3\text{-}4 \times 10^{-9}$

Agrees within a factor 2
Not too bad