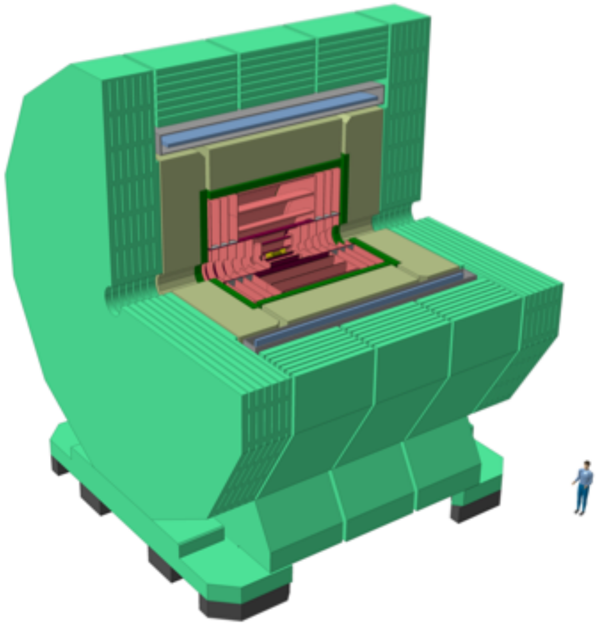
Experimental Challenges at Future circular e^+e^- colliders



Mogens Dam

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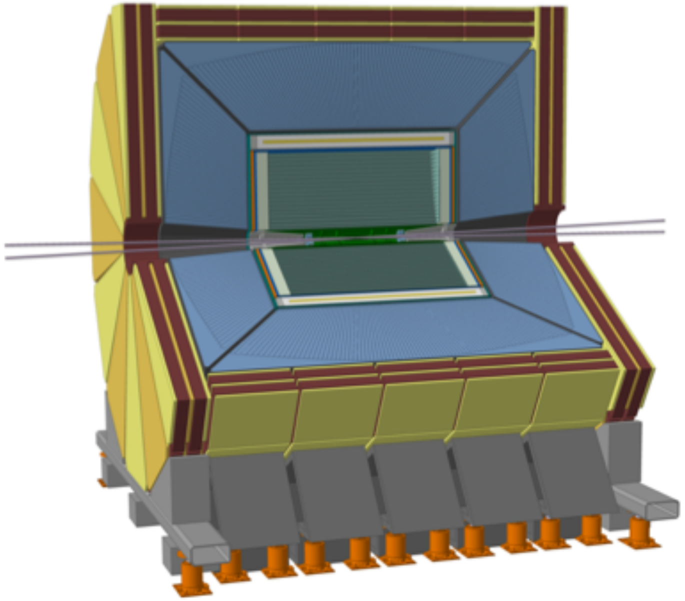
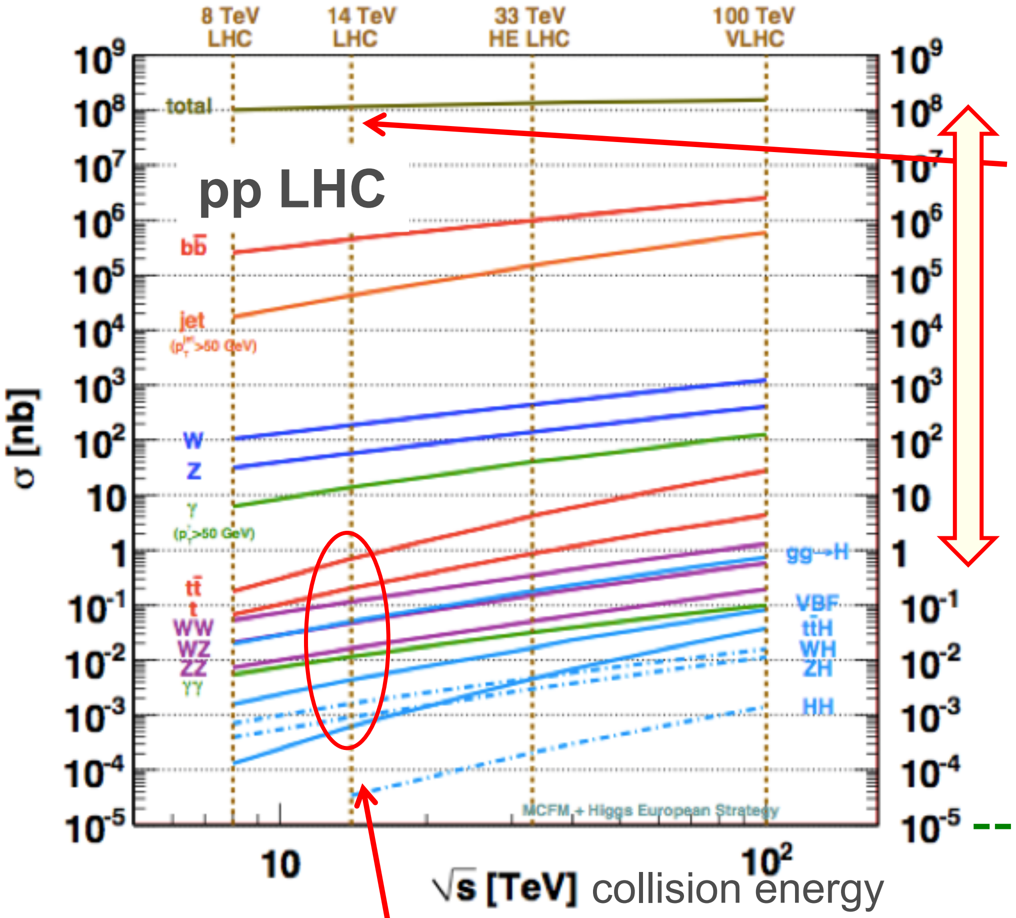


Mini Workshop on Particle Identification and
Associated Physics at e+e- Colliders

High Energy Physics HKUST IAS
Hong Kong, 14-15th January, 2021

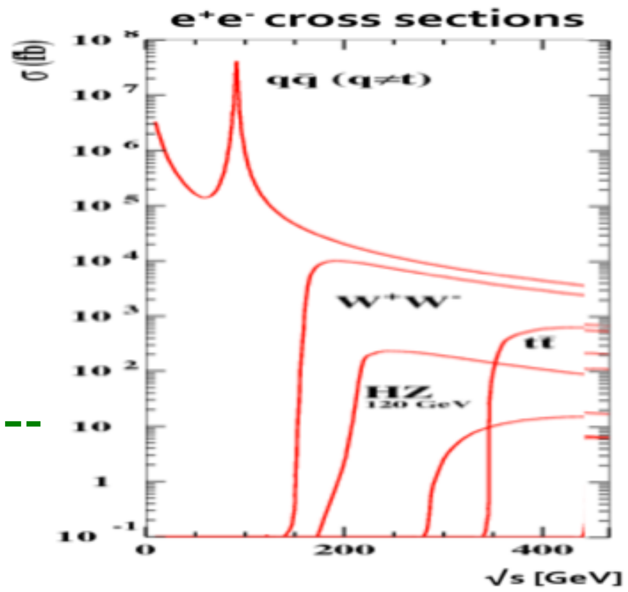
Advantages of e^+e^-



LHC total cross section factor > 100 million !!

At LHC, much of the interesting physics needs to be found among a huge number of collisions

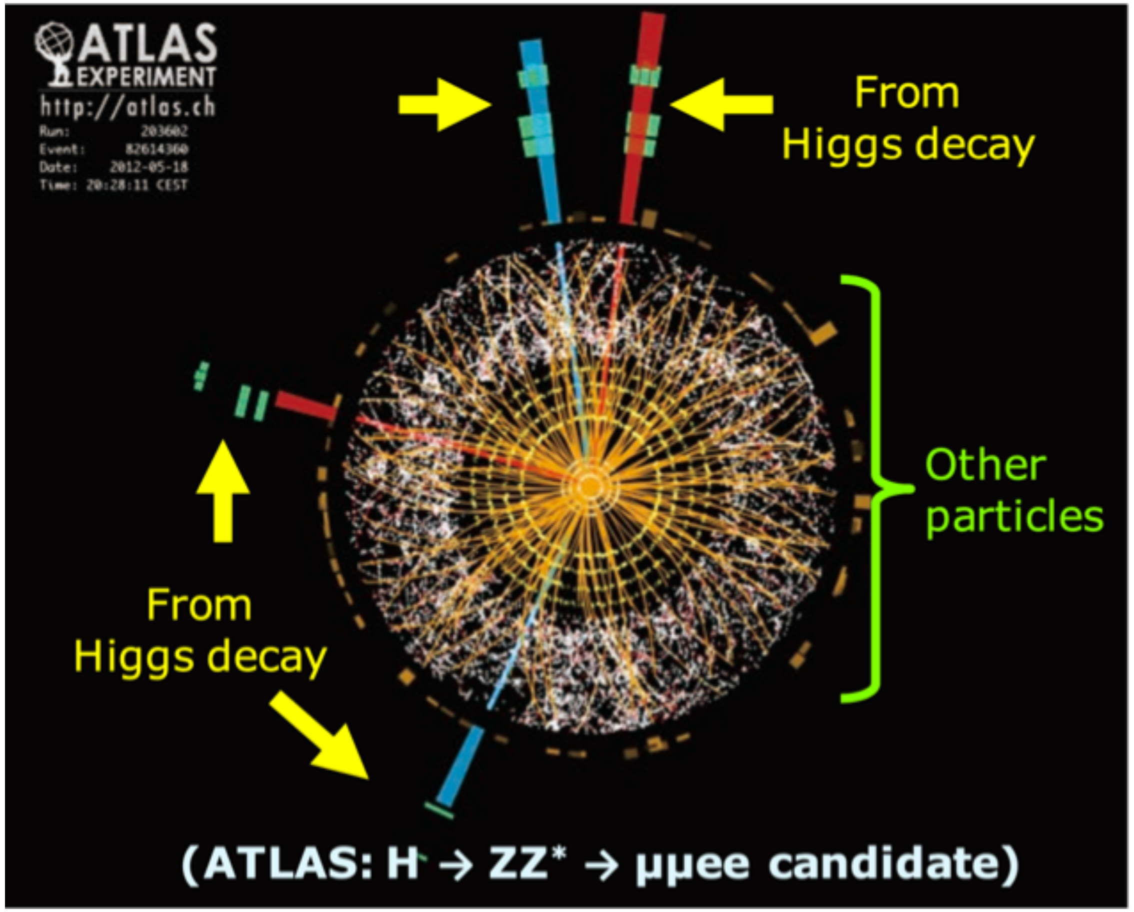
In e^+e^- collisions the total cross section ~ equals the electroweak cross section.

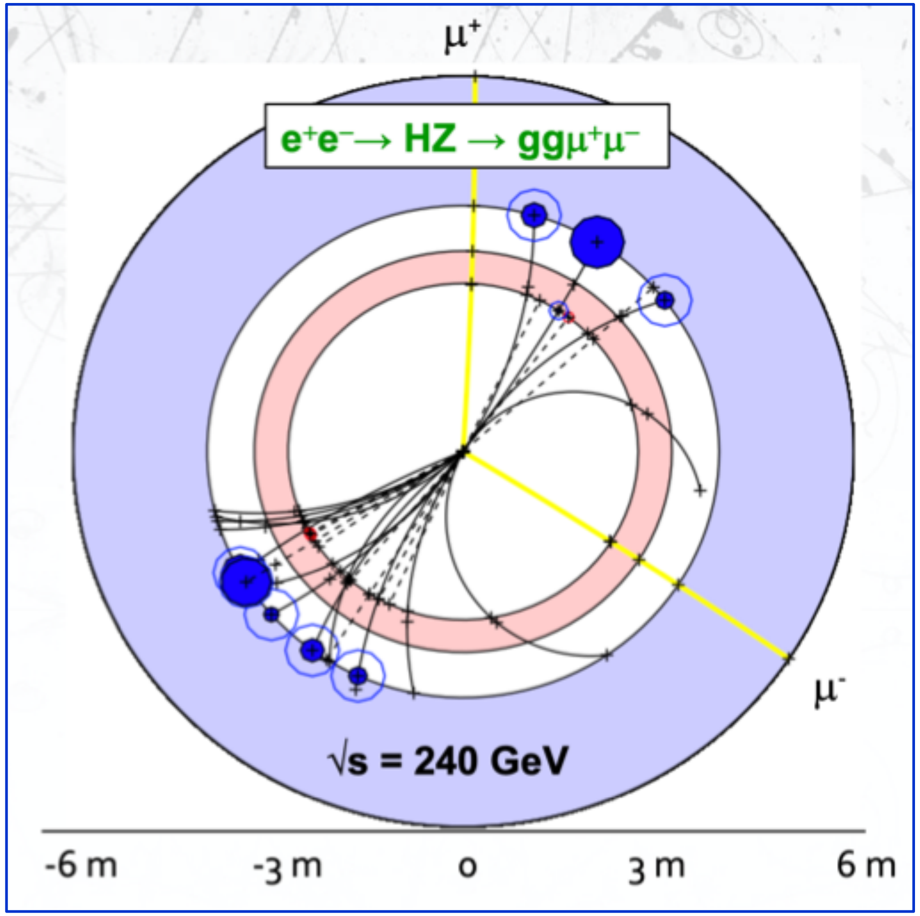


e^+e^- events are "clean"

- Partial vs. total cross section
- Clean experimental environment
- No pile-up, no underlying events
- Kinematic constraints
  - initial E, p known
- Low radiation level

Example: Higgs event in pp and e^+e^-





Proton-proton: look for striking signal in large background; high energy reach

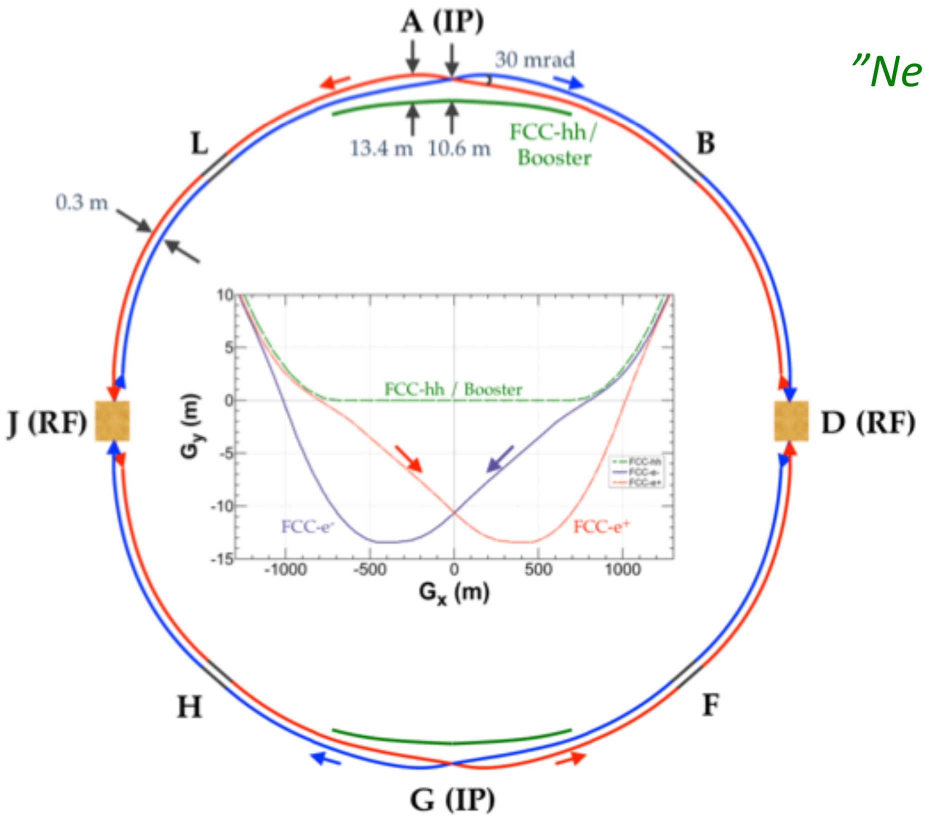
$e+e^-$: detect everything; measure precisely

FCC-ee and CEPC Accelerator Layouts

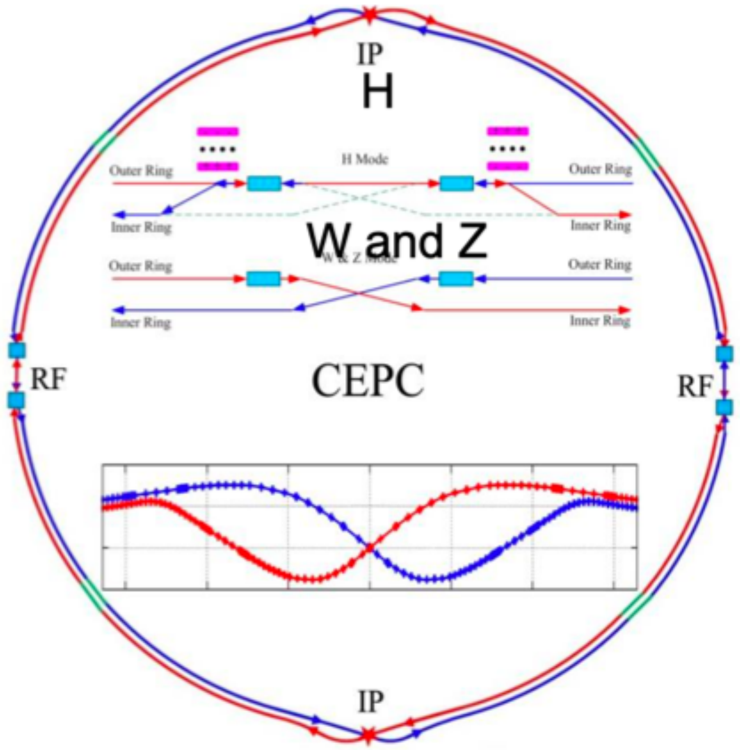
100 km accelerators

FCC-ee

CEPC

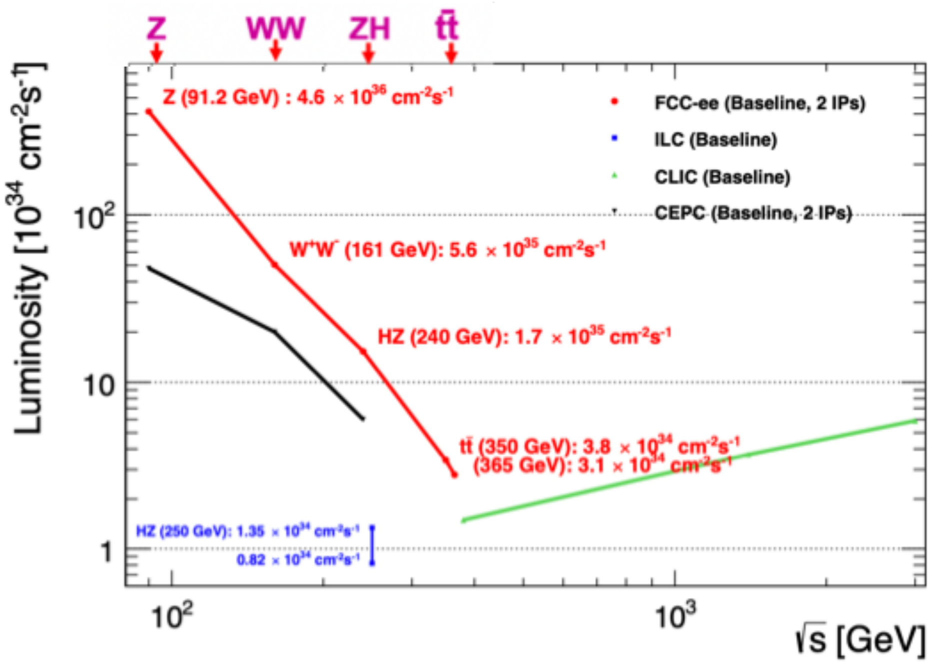


"Near-identical twins"



For FCC-ee, investigating a 4IP layout

Running Conditions



CEPC and FCC-ee are near-identical machines. The reported differences in luminosity performance are mainly driven by technological/"political" choices:

- Different SR power loss: 100 vs 60 (33) MW
- CEPC choice to not go to tt threshold

Here report more ambitious FCC-ee numbers

Event statistics

5×10^{12} $e^+e^- \longrightarrow Z$

10^8 $e^+e^- \longrightarrow W^+W^-$

10^6 $e^+e^- \longrightarrow HZ$

10^6 $e^+e^- \longrightarrow tt$

FCC-ee parameters		**Z**	**W^+W^-**	**ZH**	**ttbar**
√s	GeV	91.2	160	240	350-365
Luminosity / IP	10^{34} cm^{-2} s^{-1}	**230**	28	8.5	1.7
Bunch spacing	ns	19.6	163	994	3000
"Physics" cross section	pb	35,000	10	0.2	0.5
Total cross section (Z)	pb	40,000	30	10	8
Event rate	Hz	**92,000**	8.4	1	0.1
"Pile up" parameter [μ]	**10^{-6}**	1,800	1	1	1

Experimentally, Z pole most challenging

- Extremely large statistics
- Physics event rates up to 100 kHz
- Bunch spacing at 20 ns
  - "Continuous" beams, no bunch trains, no power pulsing
- No pileup, no underlying event, …
  - …well, pileup of 2 x 10^{-3} at Z pole

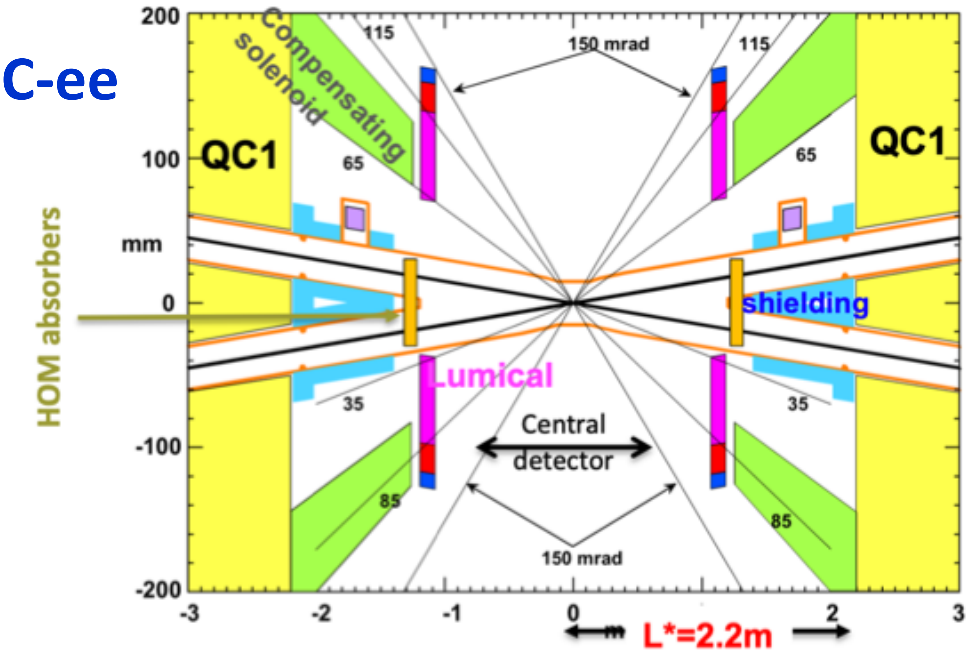
Experimental challenges

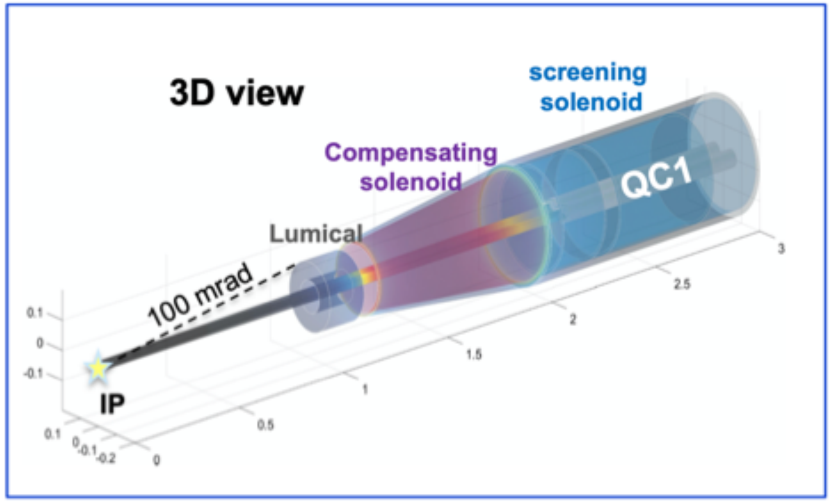
- Extremely high luminosities
  - High statistical precision => Challenge: beat down systematics to a commensutate $\mathcal{O}(10^{-5})$ level
  - Online and offline handling of $\mathcal{O}(10^{13})$ events for precision physics
    - ”Big Data”
- Physics events up to $\mathcal{O}$(100 kHz)
  - Strong requirements on front-end electronics and DAQ systems
    - Material budget: minimise mass of electronics, cables, cooling, …
- ”Continuous” beams (no bunch trains); bunch spacing at ~20 ns
  - Power management and cooling (no power pulsing)
- ~30 mrad beam crossing angle
  - Very complex Machine Detector Interface

- More physics challenges
  - Luminosity measurement to 10^{-4} – luminometer acceptance definition to $\mathcal{O}$(1 µm)
  - Detector acceptance to ~10^{-5} – acceptance definition to few 10s of µm, hermeticity (no cracks!)
  - b/c/g jets separation – primary importance for Higgs decays; flavour and τ physics: vertex detector precision
  - **Particle identification (π/K/p) without compromising detector performance and hermeticity – flavour and τ physics**

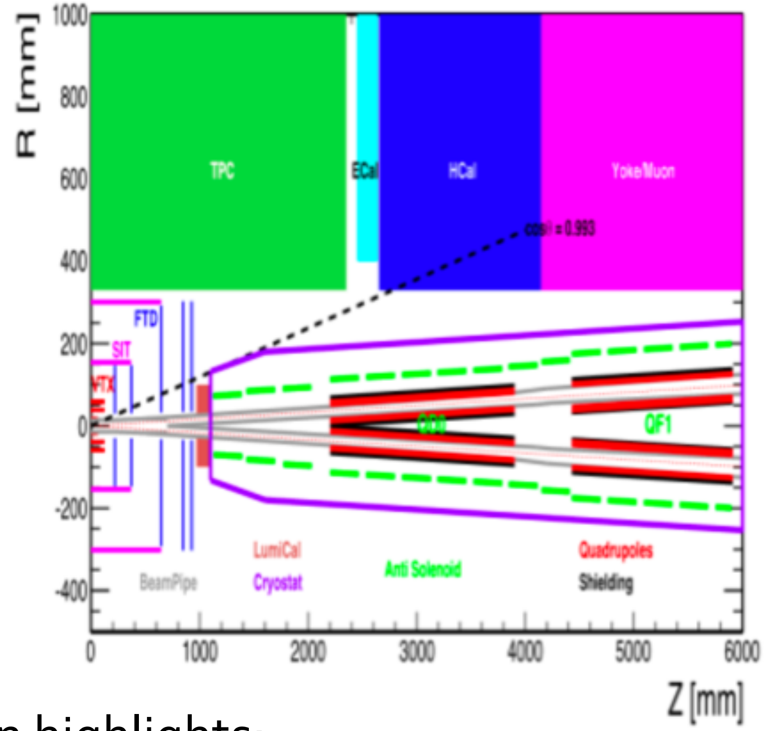
Machine Detector Interface - Interaction Region Layout

FCC-ee



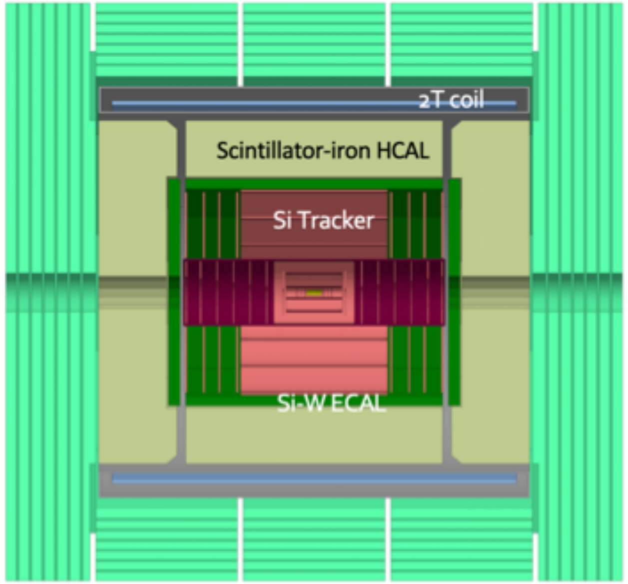


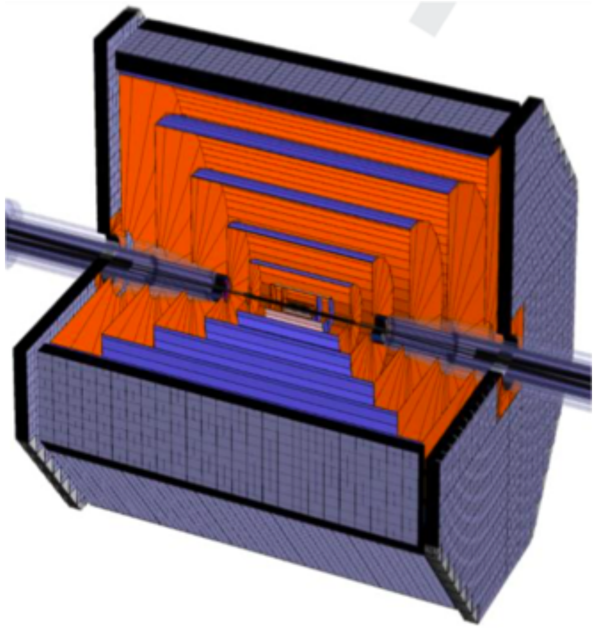
CEPC



- Design highlights:
  - Acceptance: ~100 mrad
  - Solenoid compensation scheme + quadrupole shielding
  - Beam pipe:
    - Warm, liquid cooled; Be in central region, then Cu
    - R = 15 mm in central region (investigating 10 mm)
    - SR masks, W shielding
      - **Backgrounds negligible everywhere (except at 365 GeV)**

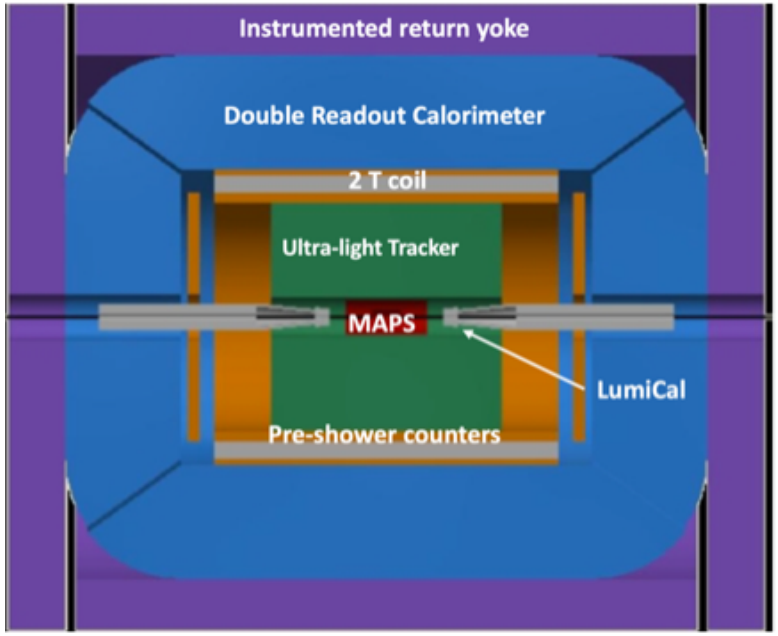
Complementary Detector Designs





FCC-ee: CLD

CEPC



Full Silicon Concepts

- Proven concept, understood performance:
  - All silicon vertex detector and tracker
  - 3D-imaging highly-granular calorimeter system
  - Coil *outside* calorimeter system

CEPC and FCC-ee: 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

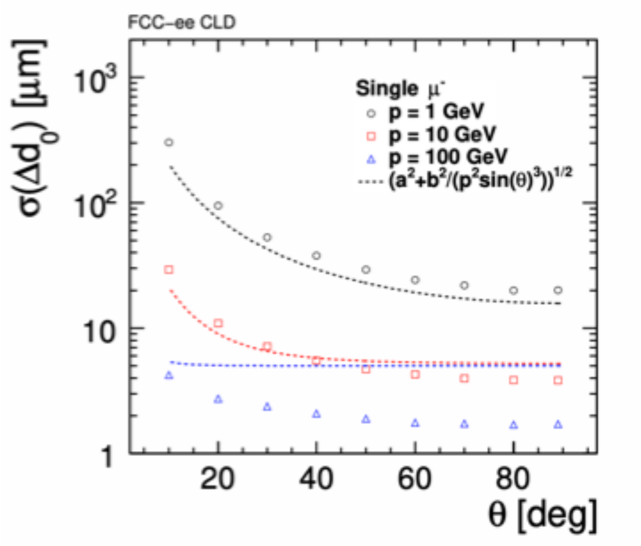
Experimental challenge: impact parameter resolution

Design goal…

$$\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2}\theta}$$

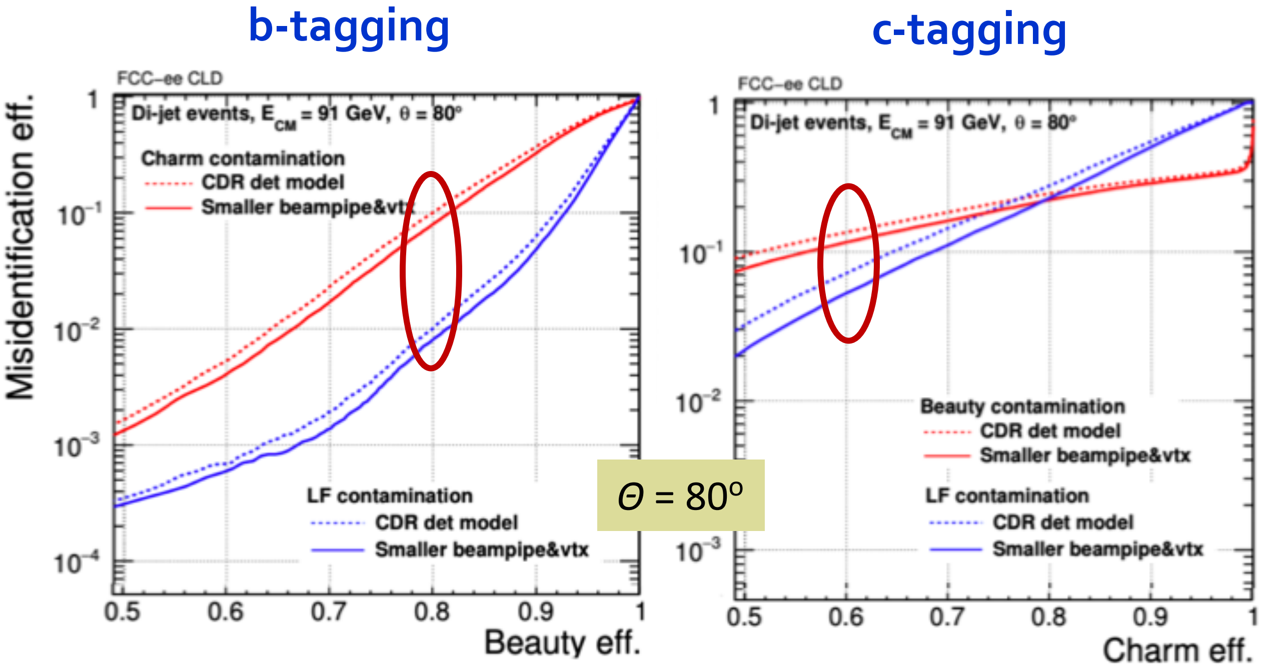
$$a \simeq 5\,\mu\mathrm{m}; \quad b \simeq 15\,\mu\mathrm{m\,GeV}$$

…satisfied in CLD full simulation study

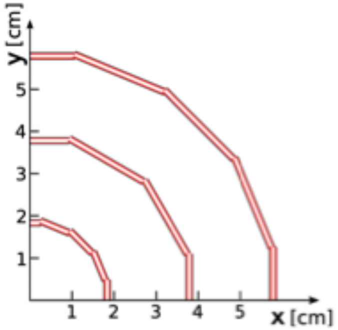


arXiv:1911.12230

CLD flavour tagging



- ❑ Single point accuracy of 3 μm
- ❑ Three very thin double sensor layers (50 μm Si) at radii 18, 37, 57 mm
  - ❖ 0.6% of X_0 for each double layer
- ❑ Beryllium, water cooled beam pipe at r=15 mm
  - ❖ 0.5% of X_0



Strong development:

- Lighter, more precise, closer
- 10 mm beam pipe under investigation

Accelerator	a (μm)	b ($\mu m \cdot GeV/c$)
LEP	25	70
SLC	8	33
LHC	12	70
RHIC-II	13	19
ILD	< 5	< 10

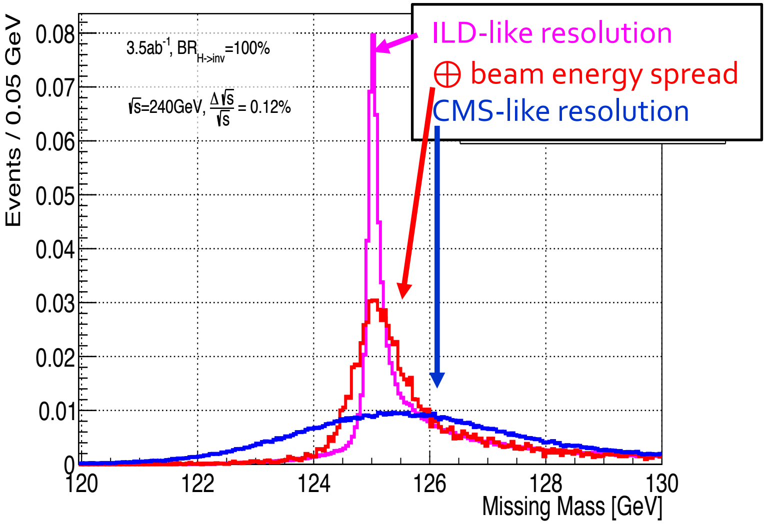
Experimental challenge: Momentum resolution (i)

Often, the "canonical" requirement is expressed as

$$\boxed{\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}\ \mathrm{GeV}^{-1}}$$

⇒ Mass reconstruction from lepton pairs in Higgs production

Reconstructed recoil mass in HZ with Z →$\ell^+\ell^-$



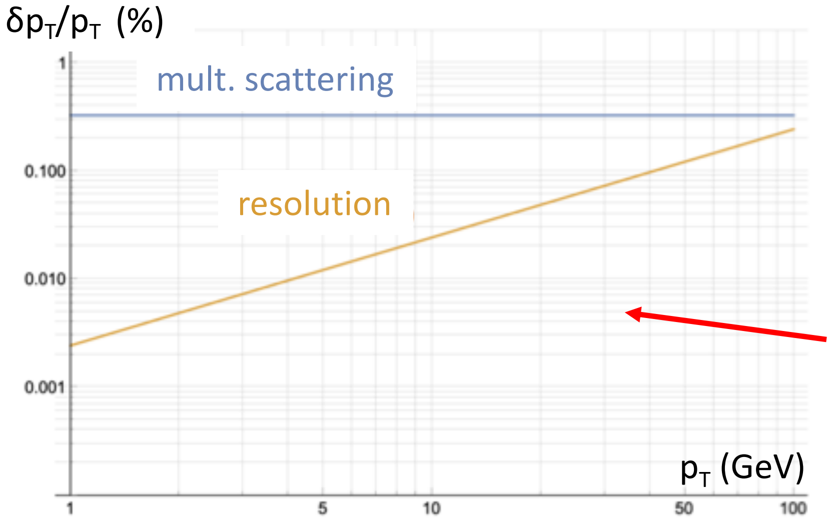
Eur.Phys.J. C77 (2017) no.2, 116

For FCC-ee, this matches well the beam energy spread of $\delta E/E \simeq 1\text{-}2 \times 10^{-3}$

In reality, there is of course a resolution term (*a*) and a multiple scattering term (*b*)

$$\boxed{\sigma(p_\mathrm{T})/p_\mathrm{T}^2 = a \oplus \frac{b}{p\sin\theta}}$$

For "standard" ultra-light detectors (e.g. full Si), multiple scattering dominates up to p_T of ~100 GeV



Here illustrated for the CLD detector at 90° :
Total material budget = 11% of X_0

From analytic expressions for track parameter resolutions.

Drasal, Riegler, https://doi.org/10.1016/j.nima.2018.08.078

$$\boxed{\left.\frac{\Delta p_T}{p_T}\right|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\, B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\,\sin\theta}}}$$

$$\boxed{\left.\frac{\Delta p_T}{p_T}\right|_{res.} \approx \frac{12\,\sigma_{r\phi}\,p_T}{0.3\,B_0 L_0^2}\sqrt{\frac{5}{N+5}}}$$

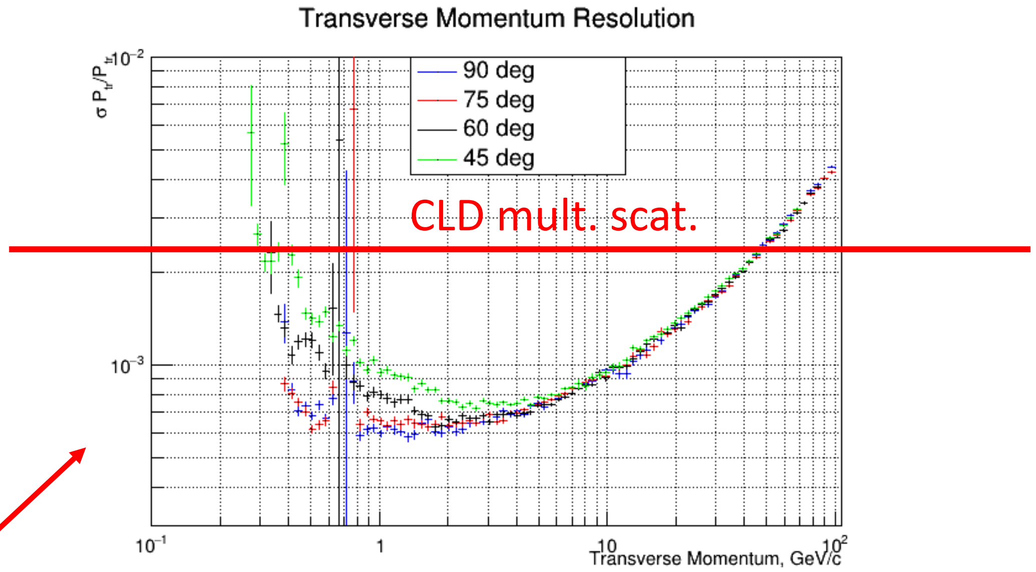
Momentum Resolution (ii)

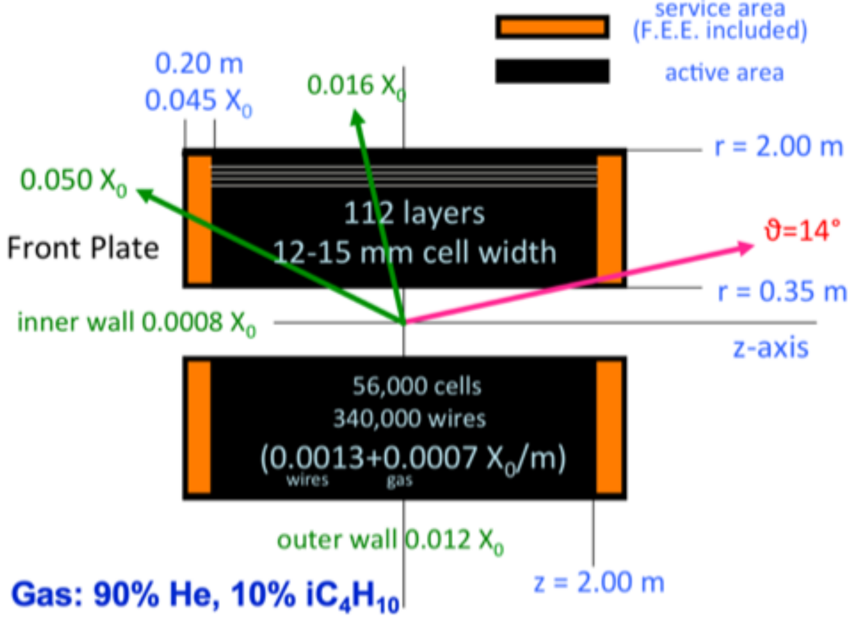
At CEPC/FCC-ee, very few tracks with $p_T > 100$ GeV.
Momentum measurements will be multiple-scattering limited

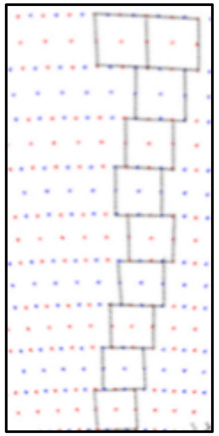
- Possible to reduce multiple scattering contribution?

IDEA Drift Chamber

- GAS: 90% He – 10% iC_4H_{10}
- Radius 0.35 – 2.00 m
- Total thickness: 1.6% (!) of X_0 at 90°
  - Tungsten wires dominant contribution to material
- Full tracker system includes Si VTX and Si "wrapper"







Further important benefit from reduced material:

- Minimize secondary interactions in material

For full Si tracker option, further thinning of Si sensors not very promising due to the √-behaviour

$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\, B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\,\sin\theta}}$$

Calorimetry – Jet Energy Resolution

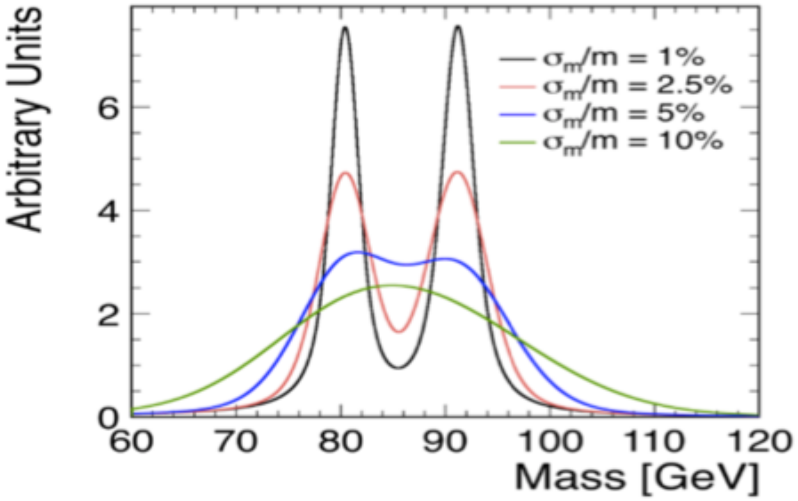
Energy coverage < 300 GeV : $22\ X_0,\ 7\lambda$

Jet energy: $\delta E_{jet}/E_{jet} \simeq 30\% / \sqrt{E}$ [GeV]

⇒ Mass reconstruction from jet pairs

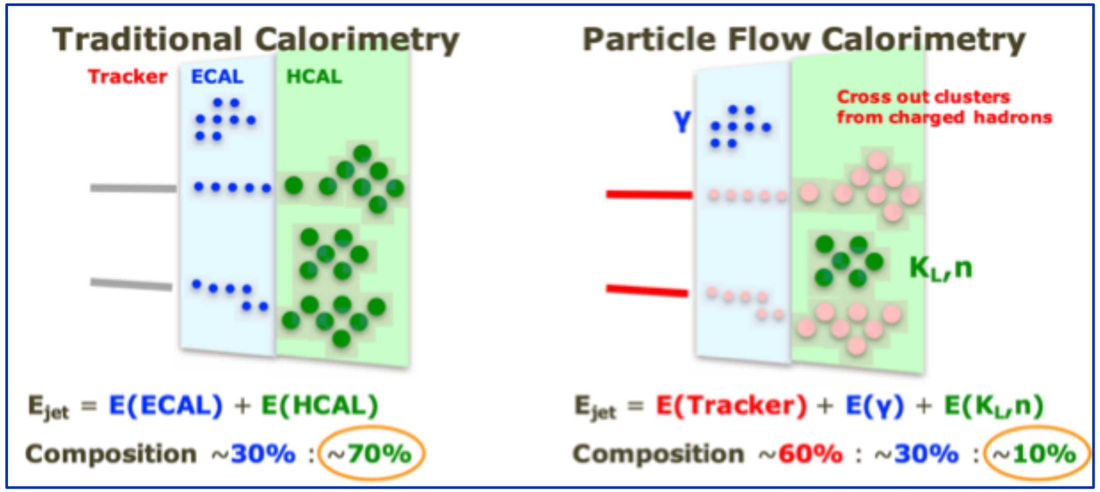
Resolution important for control of (combinatorial) backgrounds in multi-jet final states

- Separation of HZ and WW fusion contribution to ννH
- HZ → 4 jets, $t\bar{t}$ events (6 jets), etc.
- At $\delta E/E \simeq 30\% / \sqrt{E}$ [GeV], detector resolution is comparable to natural widths of W and Z bosons



To reach jet energy resolutions of ~3%, detectors employ

- **highly granular calorimeters**
- **Particle Flow Analysis techniques**



Technologies being pursued

a) **CALICE** like (ILC, CLIC, CLD)
  - ECAL: W/Si or W/scint+SiPM
  - HCAL: steel/scint+SiPM or steel/glass RPC

b) Parallel fiber **dual readout** calorimeter (IDEA)
  - Fine transverse, but no (weak) longitudinal segmentation

c) **Liquid Argon** ECAL + **Scintillating Tile** HCAL (ATLAS like)
  - Very fine segmentation, $\delta E_{EM}/E_{EM} \lesssim$ 8-9%

Calorimetry – ECAL Performance

ECAL energy resolutiuon parametrised as

$$\boxed{\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c}$$

with typically

technology	*a*	*b*	*c*
CALICE	15%	-	1%
Fiber DR	10%	-	1%
Lar	9%	-	-
Crystal	3-5%	-	0.5%

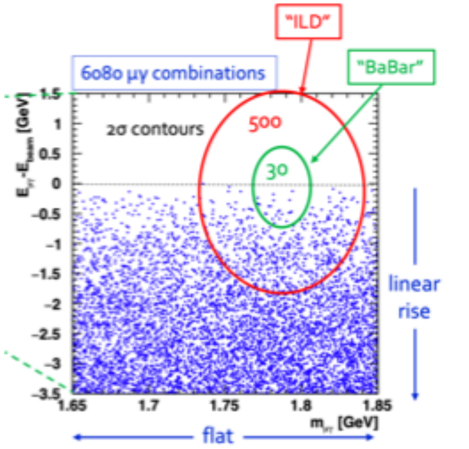
- CALICE-like resolution regarded sufficient at linear colliders with main emphasis on physics at 250-500 GeV
- An improved resolution may be advantageous for the 90-160 GeV FCC-ee programme

Finely segmented ECAL (transverse and longitudinal) is important for the precise identification of γ's and π^0's in dense topologies, e.g. τ and other heavy flavour physics

Examples:

a) Much improved search limits for rare decays involving γ's.

- Here LFV decay τ → μγ

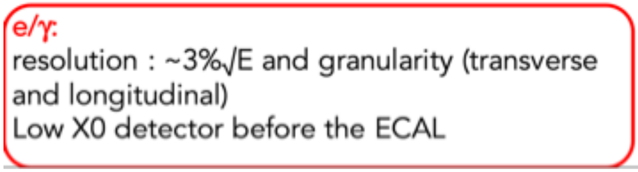


MD, 1st FCC WS, Jan. 2017

b) Much improved b-physics reach by making accesible exclusive channels with π^0's

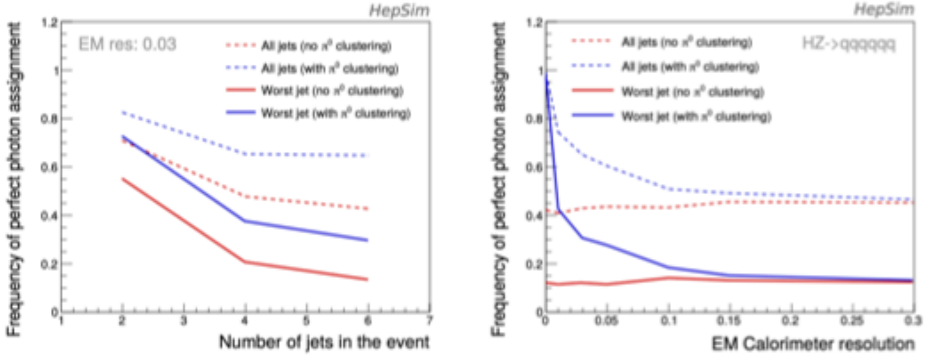
R. Aleksan in 4th FCC Workshop

From M-H. Schune's wish list, 3rd FCC WS, Jan. 2020



e/γ:
resolution : ~3%/√E and granularity (transverse and longitudinal)
Low X0 detector before the ECAL

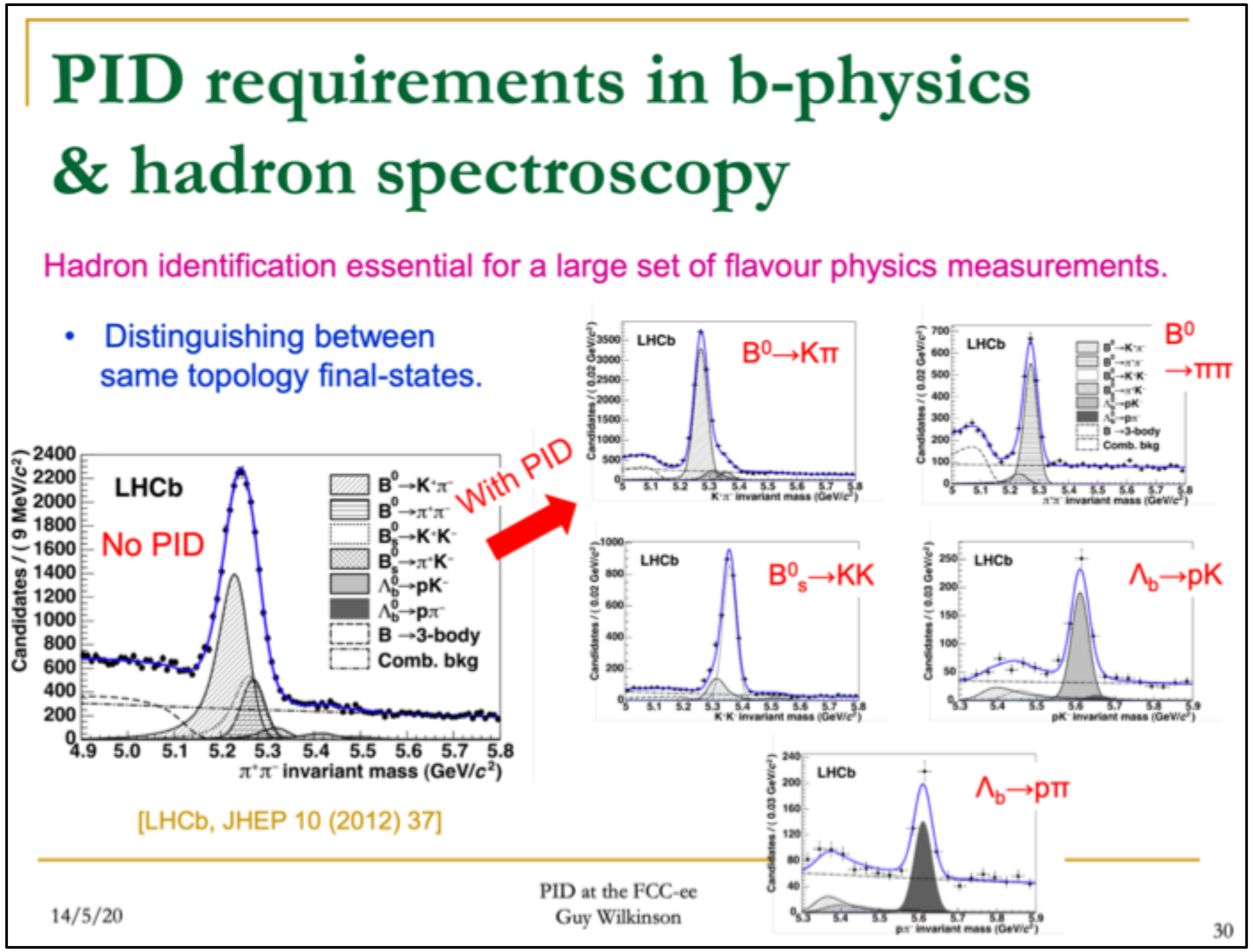
c) More precise jet definition in multijet events



2008.00338

Figure 10. Frequency of events where photons are perfectly assigned to the corresponding jet as a function of the number of jets in the event, assuming a calorimeter resolution of $3\%/\sqrt{E}$ (left), and as a function of calorimeter EM resolution in the case of the $HZ \rightarrow q\bar{q}q\bar{q}q\bar{q}$ sample (right).

Experimental Challenge: Particle Identification



PID requirements in b-physics & hadron spectroscopy

Hadron identification essential for a large set of flavour physics measurements.

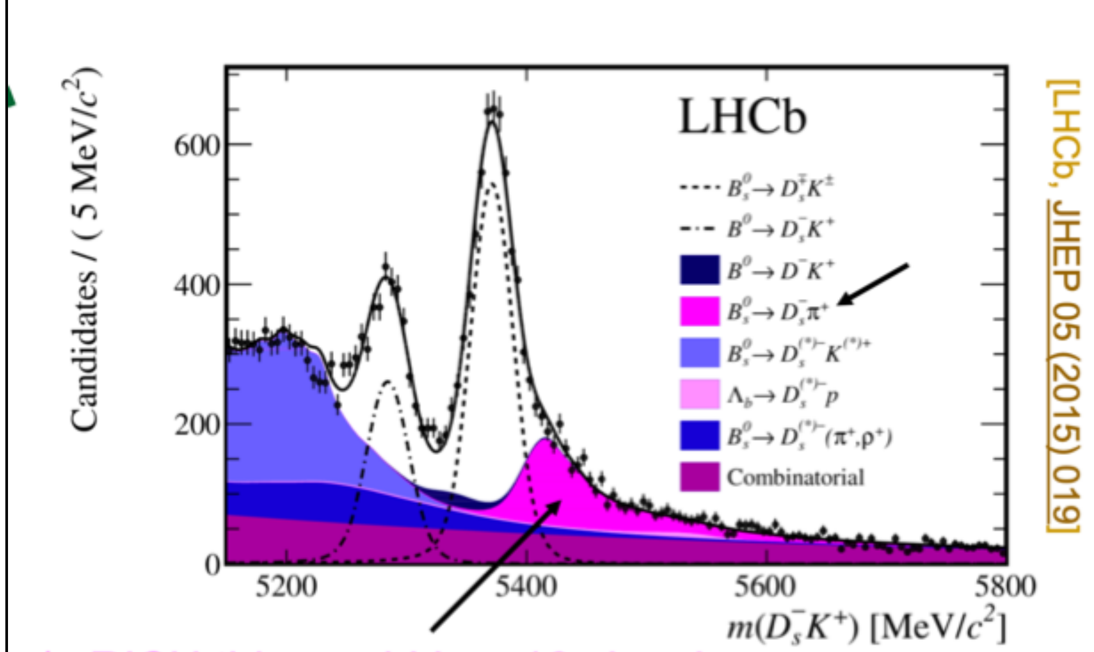
- Distinguishing between same topology final-states.

[LHCb, JHEP 10 (2012) 37]

14/5/20

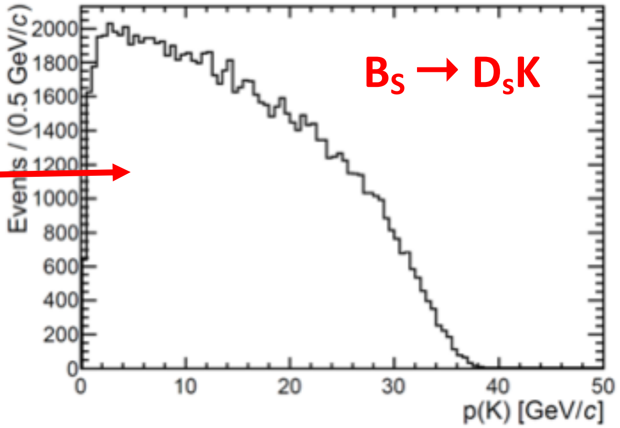
PID at the FCC-ee
Guy Wilkinson

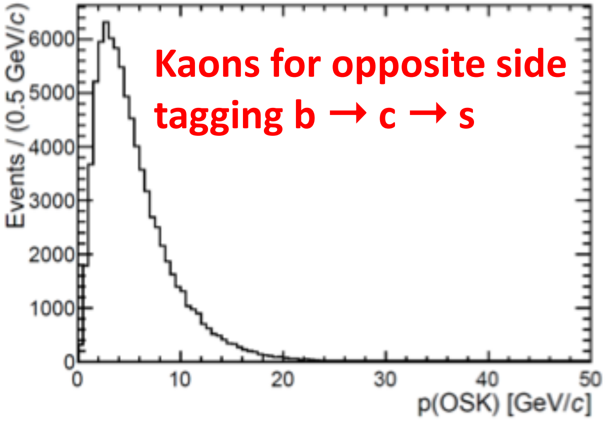
30



[LHCb, JHEP 05 (2015) 019]

w/o RICH this would be x10 signal





- For b physics, almost full momentum range interesting
- For separation of tau decay modes

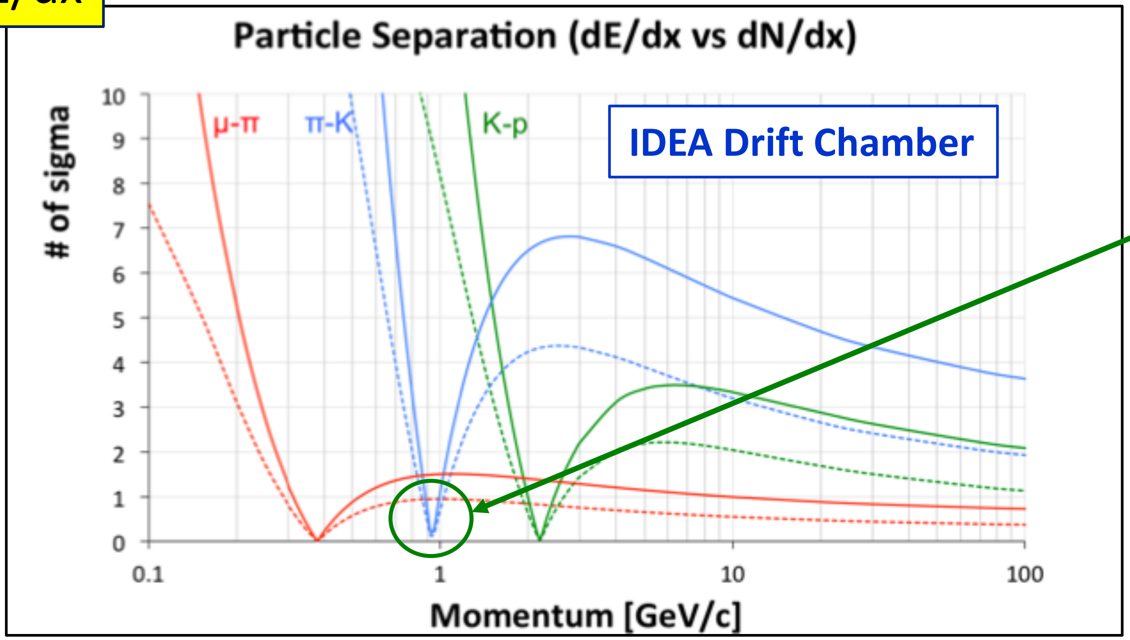
$\tau\to\pi\nu$ vs. $K\nu$; $\tau\to\rho\nu$ vs. $K^*\nu$

full momentum range of interest

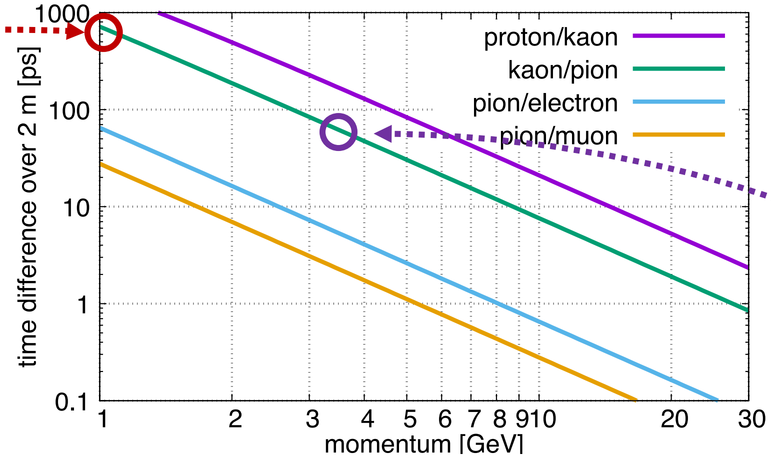
PID possibilities

- The IDEA Drift Chamber provides very powerful PID. Improved considerably by the use of *cluster counting*
  - ❑ Standard truncated mean dE/dx : **σ ≃ 4.2%**
  - ❑ Cluster counting : **σ ≃ 2.5%**

dE/dx



- ❑ >3σ π/K separation all the way up to 100 GeV
  - ❖ Except for cross-over window at ~1 GeV.



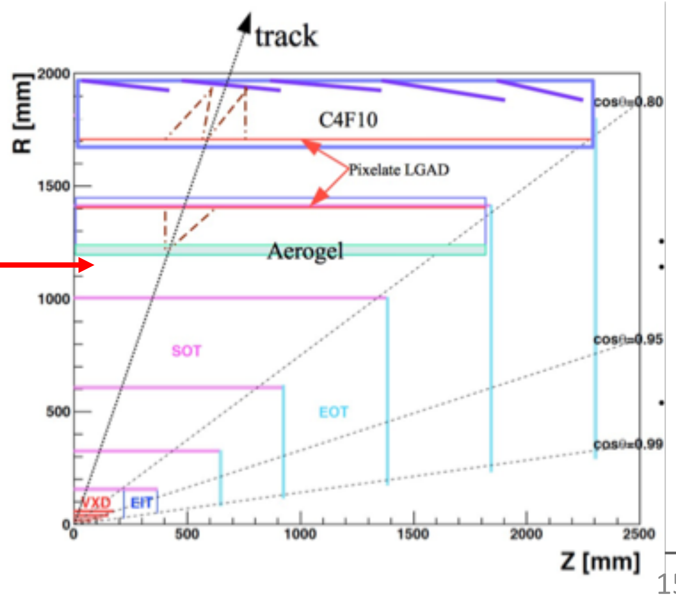
TOF

- ❑ Narrow dE/dx cross-over window at ~1 GeV, can be alleviated by unchallenging TOF measurement at r=2m of δT ≲ 0.5 ns
- ❑ TOF *alone* could give 3σ π/K separation up to a 3.5 GeV if measurement precision would be δT ~ 20 ps (LGAD, TORCH)

Cherenkov

Study of RICH counter for CEPC Full Silicon Detector

Also TORCH (LHCb) and TOP (BelleII): Essentially precise TOF devices: ~20 ps.



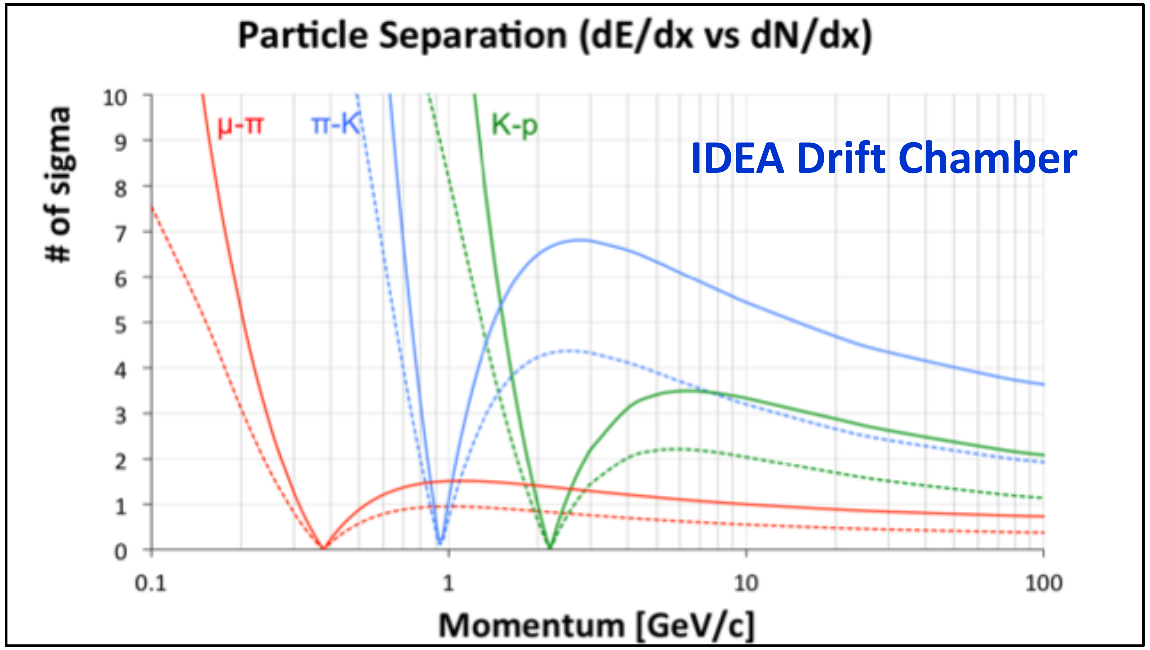
Outlook

- We know how to build detectors for e^+e^- Higgs and electroweak factories
  - Solid experience from LEP and from studies for Linear Colliders and for the CEPC and FCC-ee CDRs
- CEPC and FCC-ee circular colliders pose numerous additional challenges
  - Very high physics rates, continuous beams
    - Need for more cooling while keeping material budget at a minimum
    - Possibly need faster detectors and/or time stamping for BX identification
  - In particular at Z-pole, extremely large statistics
    - Beat down systematics as far as possible towards the very low statistical uncertainties
      - Acceptance definitions, efficiencies, momentum and angular resolutions, jet and ECAL energy resolutions, impact parameters and flight distances
  - The enormous Z sample makes CEPC/FCC-ee also the **ultimate heavy flavour factory: b, c, τ**
    - For full exploitation, need powerfull PID over large momentum range and precise γ/π^0 identification/separation
    - Benefits from very good (crystal-like) ECAL energy resolutions

Scope of this two day mini-workshop:

Identify the need for Particle Identification and point to possibly solutions

Extra: Personal remark - The Importance of Redundancy



- ”Calorimetric” particle identification (e/π, e/μ, π/μ) has several limiations, some of which stem directly from physics
  - ❑ Catastrophic muon energy loss ($\mu N \rightarrow \mu\gamma N$) early in ECAL happens at the ppm level and can make an muon appear as an electron
  - ❑ When charge-exchange process ($\pi^- p \rightarrow \pi^0 n$) happens early in ECAL, π^- may appear as an electron
  - ❑ The occurance of $\gamma \rightarrow \mu^+\mu^-$ or $\gamma \rightarrow \pi^+\pi^-$ in electromagnetic shower developments is rare, but does happen
  - ❑ …
- To measure these effects and to beat down PID uncertainties it is essential to have available a perpendicular, independent, nondestructive identification tool over the full momentum range
  - ❑ This is exactly what a powerful dE/dx measurement provides you!

Extras

Example of precision challenge: Universality of Fermi constant

The Fermi constant is measured in μ decays and defined by

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

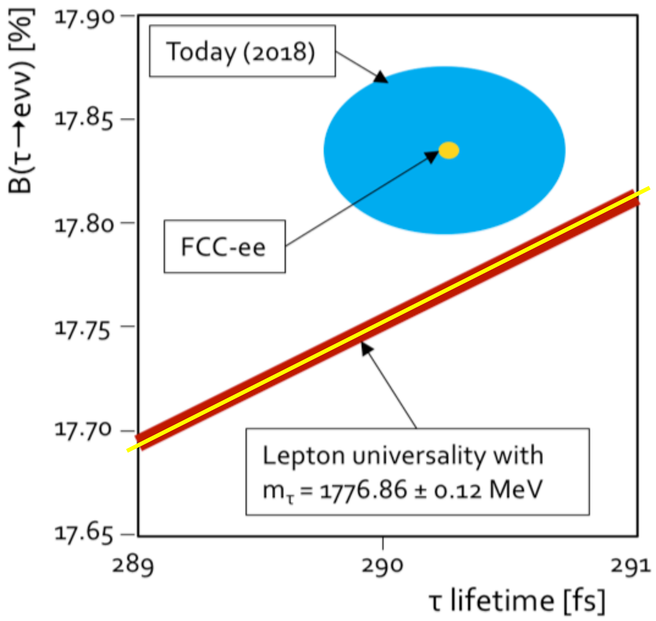
(known to 0.5 ppm)

Similarly can define Fermi constant measured in τ decays by

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

(known to 1700 ppm)

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



Shown in yellow: first guestimates on FCC-ee precisions

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

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