FCC-ee – Experimental Challenge

NIELS BOHR INSTITUTE
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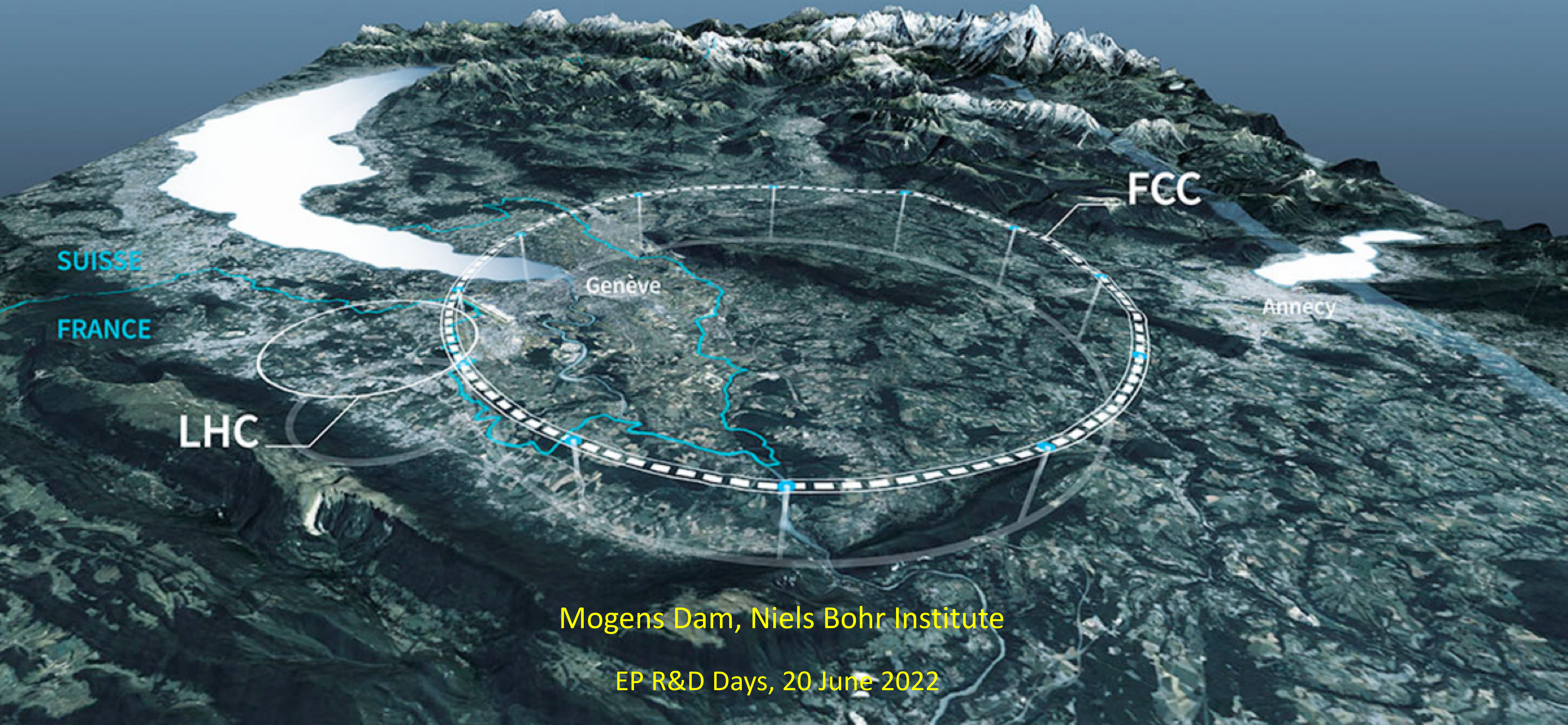


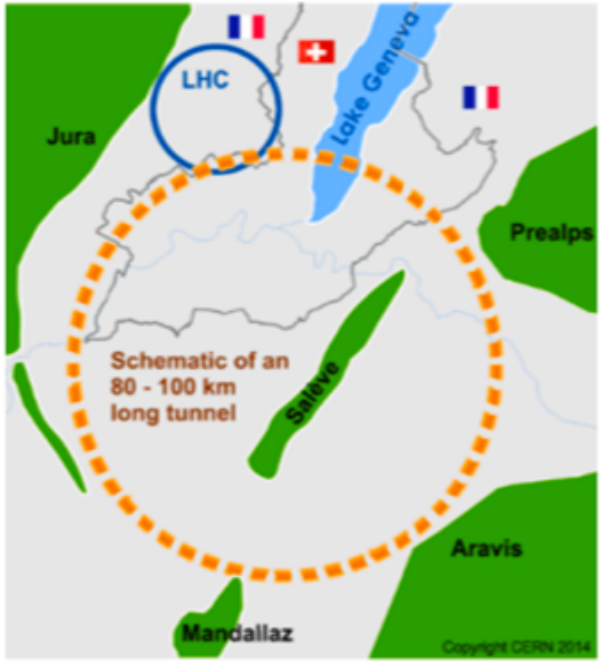
Mogens Dam, Niels Bohr Institute

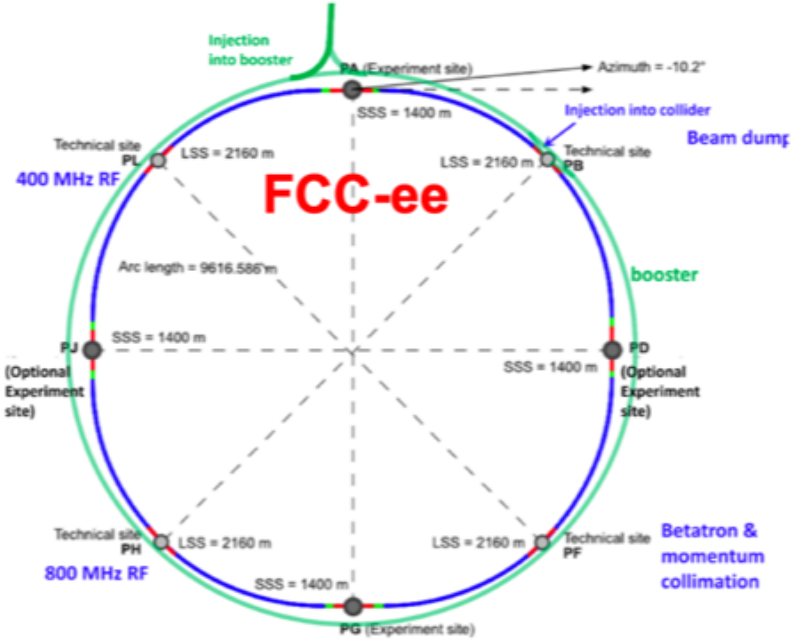
EP R&D Days, 20 June 2022

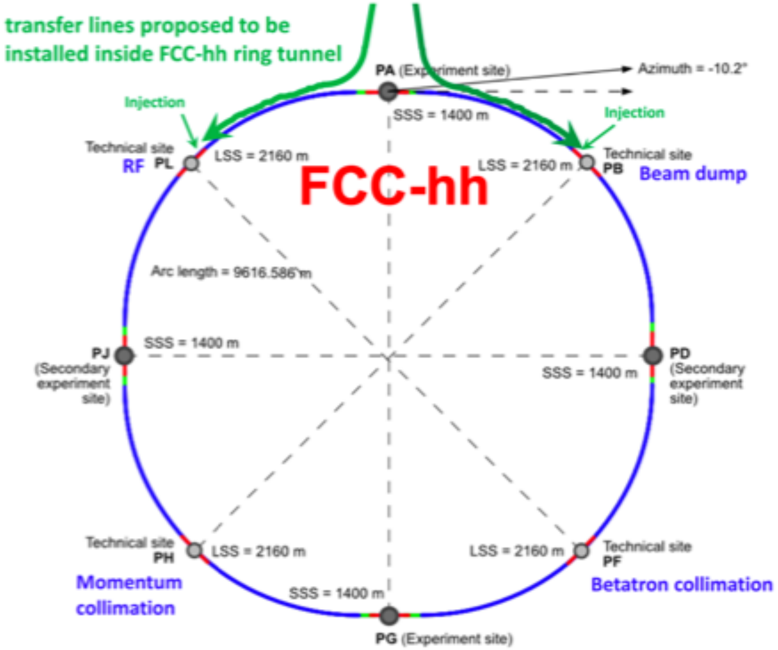
The FCC integrated program inspired by successful LEP – LHC programs at CERN

comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & 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 completion of the HL-LHC program

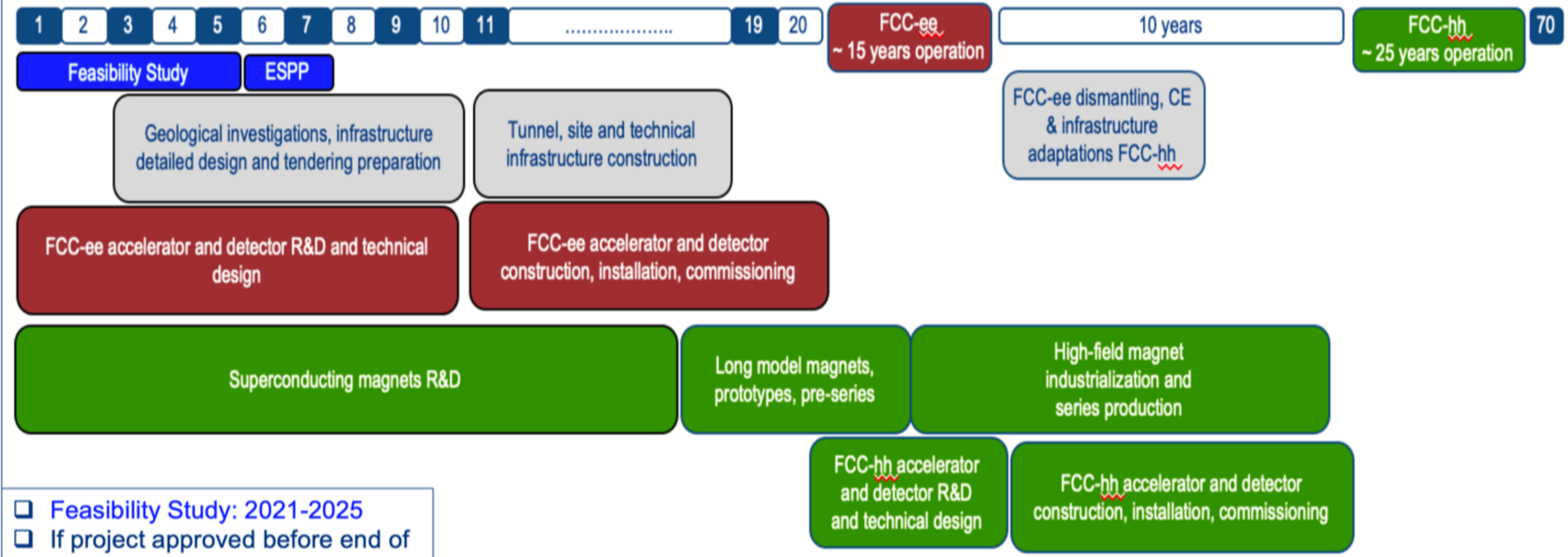






2020 - 2040 **2045 - 2060** **2070 - 2090++**

Timeline of the FCC integrated programme



1 2 3 4 5 6 7 8 9 10 11 .... 19 20

FCC-ee
~ 15 years operation

10 years

FCC-hh
~ 25 years operation

70

Feasibility Study

ESPP

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator and detector R&D and technical design

FCC-ee accelerator and detector construction, installation, commissioning

Superconducting magnets R&D

Long model magnets, prototypes, pre-series

High-field magnet industrialization and series production

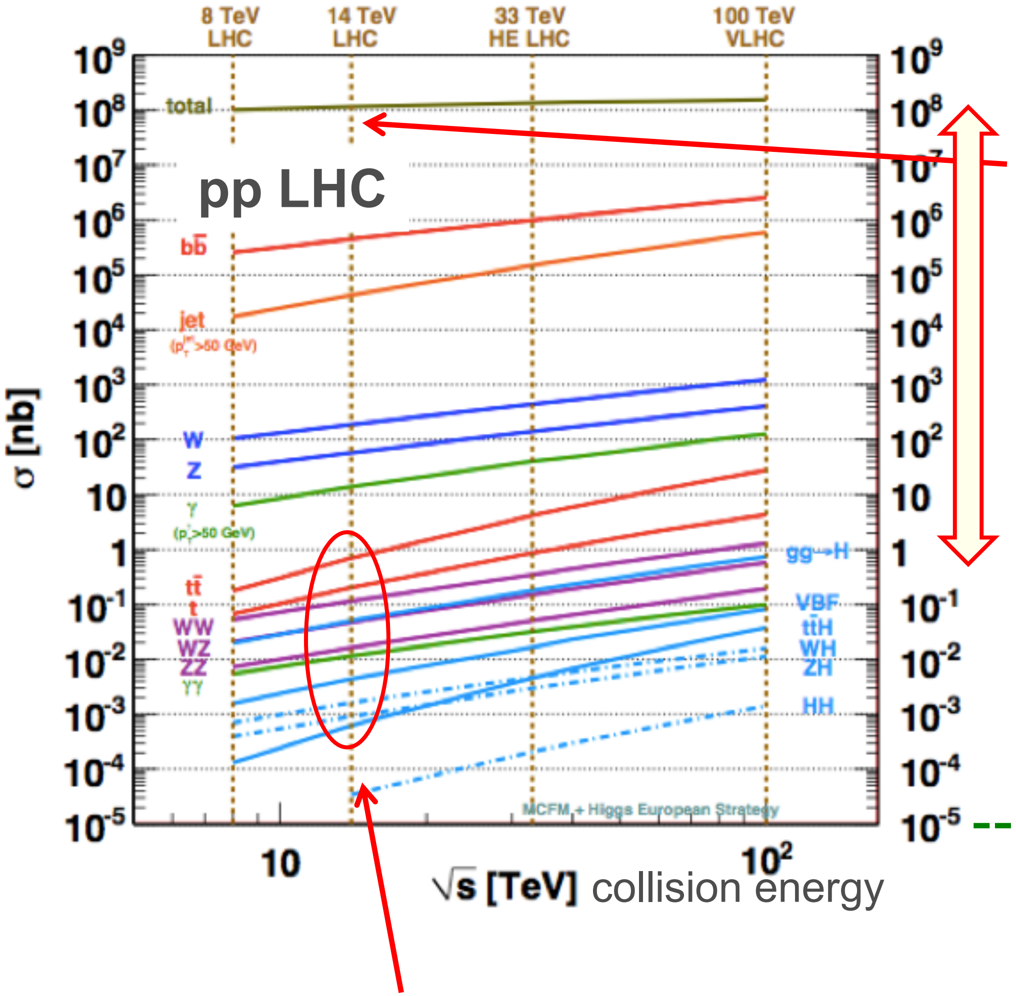
FCC-hh accelerator and detector R&D and technical design

FCC-hh accelerator and detector construction, installation, commissioning

- ❑ Feasibility Study: 2021-2025
- ❑ If project approved before end of decade → construction can start beginning 2030s
- ❑ FCC-ee operation ~2045-2060
- ❑ FCC-hh operation 2070-2090++

F. Gianotti

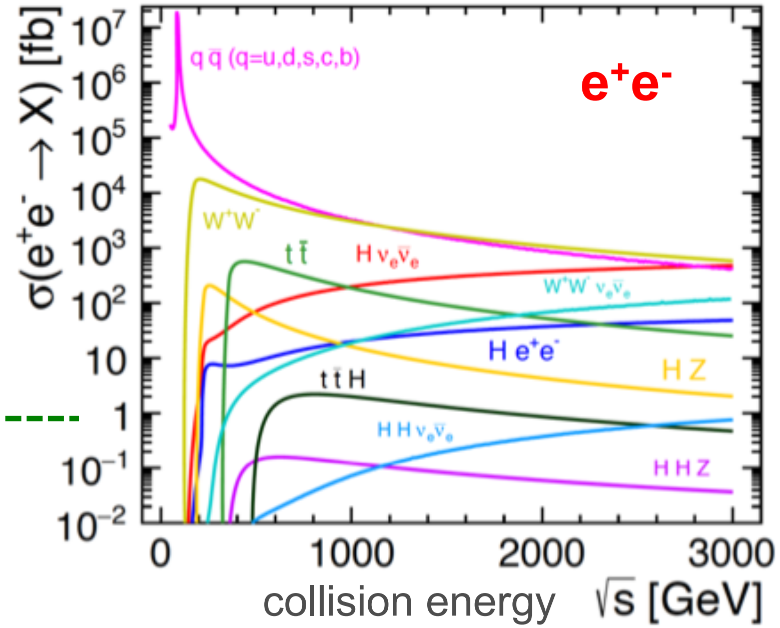
Prelude: pp collisions vs. e^+e^- collisions



LHC total cross section factor > 100 million !!

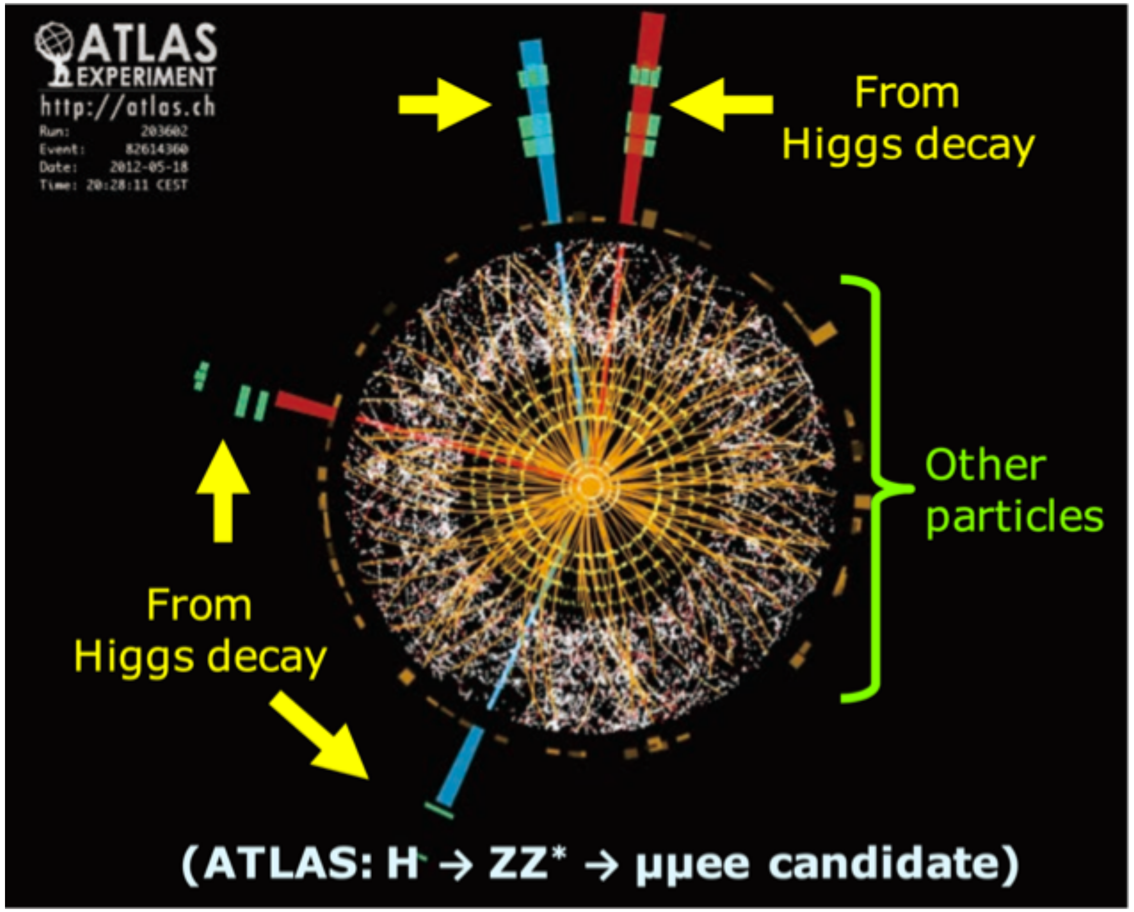
At LHC, much of the interesting physics needs to be found among a huge number of collisions

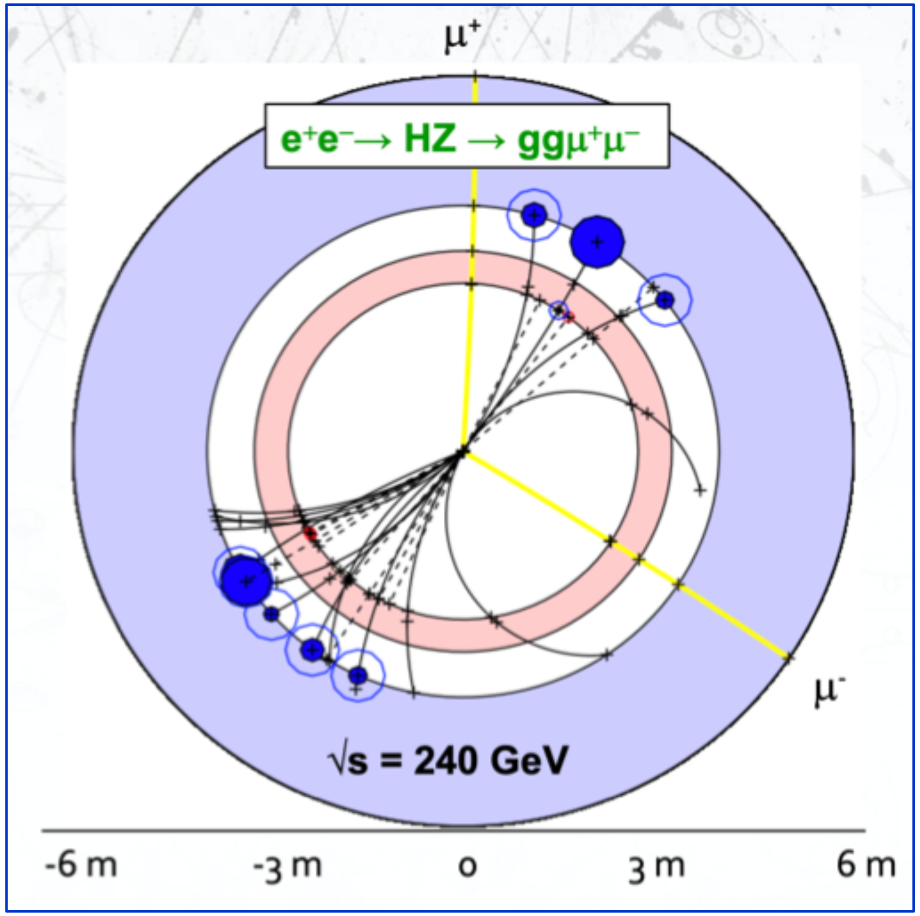
In e^+e^- collisions the total cross section ~ equals the electroweak cross section.



e^+e^- events are "clean"

Higgs event in pp and e^+e^-

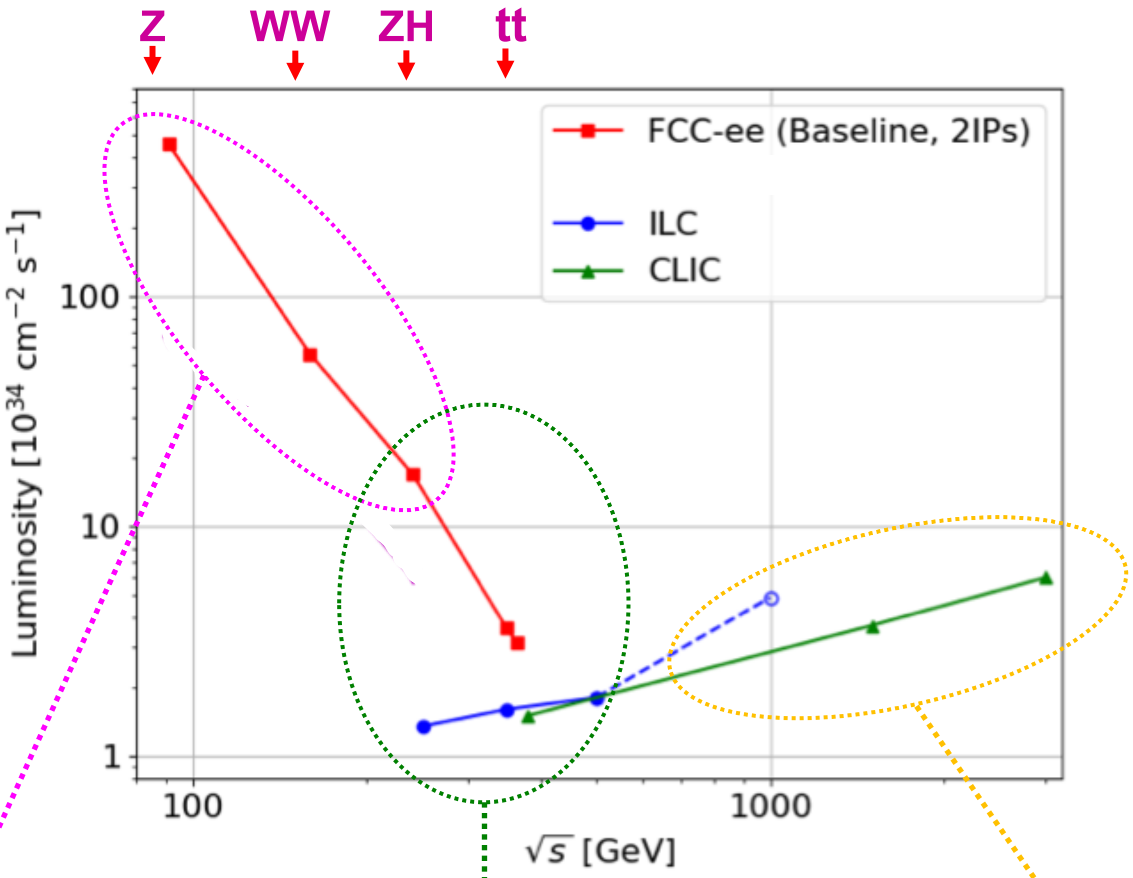




Proton-proton: look for striking signal in large background

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

High-energy e^+e^- accelerator landscape



Circular colliders:
Extremely high luminosities at lower energies:
Z, WW, Higgs factories

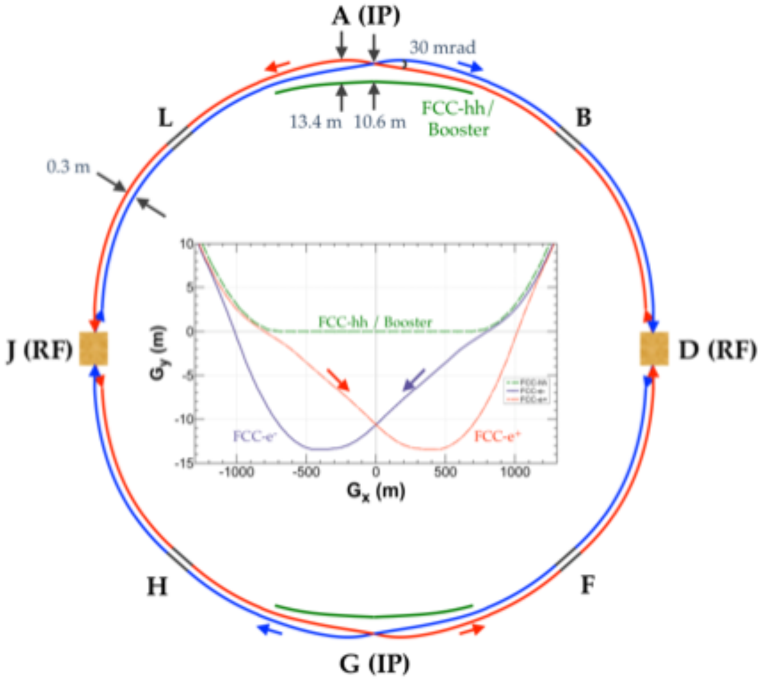
Overlap region, 240-380 GeV:
Higgs Factories

Linear colliders:
High centre-of-mass energies

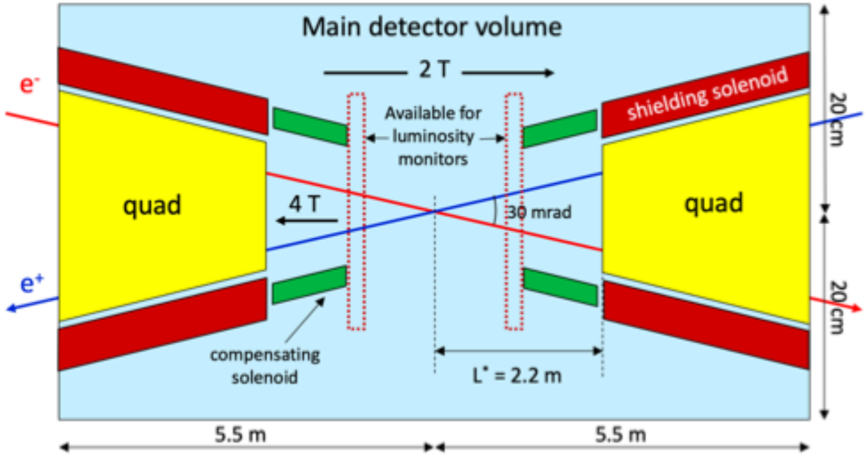
FCC-ee Experimental Challenges Overview

- 30 mrad beam crossing angle
  - Detector B-field limited to 2 Tesla
  - Very complex and tightly packed MDI (Machine Detector Interface)
- ”Continuous” beams (no bunch trains); bunch spacing down to 30 ns
  - Power management and cooling (no power pulsing)
- Extremely high luminosities
  - High statistical precision ⇒ control of systematics down to 10^{-5} level
  - Online and offline handling of $\mathcal{O}(10^{13})$ events for precision physics:

    ”Big Data”
- Physics events at up to 100 kHz
  - Fast detector response ($\lesssim 1\ \mu$s) to minimise dead-time and event overlaps (pile-up)
  - Strong requirements on sub-detector front-end electronics and DAQ systems
    - At the same time, keep low material budget: minimise mass of electronics, cables, cooling, …



Central part of detector volume – top view



FCC-ee Physics Landscape

"Higgs Factory" Programme

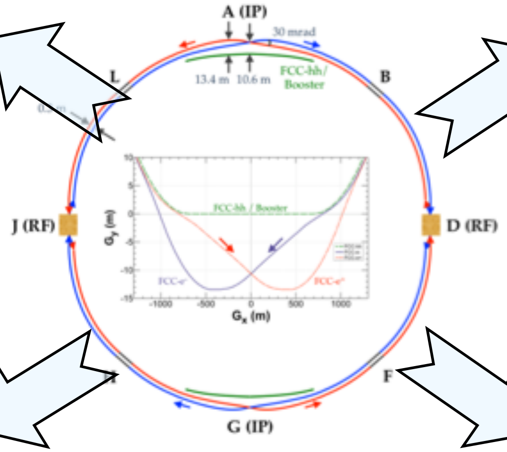
- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s} = 125$ GeV

Ultra Precise EW Programme & QCD

Measurement of EW parameters with factor ~300 improvement in *statistical* precision wrt current WA

- 5×10^{12} Z and 10^8 WW
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W^{eff}$, R^Z_ℓ, R_b, α_s, m_W, Γ_W,…
- 10^6 tt
  - m_{top}, Γ_{top}, EW couplings

Indirect sensitivity to new phys. up to Λ=70 TeV scale



Heavy Flavour Programme

- Enormous statistics: 10^{12} bb, cc; 1.7×10^{11} ττ
- Extremely clean environment, favourable kinematic conditions (boost) from Z decays
- CKM matrix, CP measurements, "flavour anomaly" studies, e.g. b → sττ, rare decays, CLFV searches, lepton universality, PNMS matrix unitarity

Feebly Coupled Particles - LLPs

Intensity frontier: Opportunity to directly observe new feebly interacting particles with masses below m_Z :

- Axion-like particles, dark photons, Heavy Neutral Leptons
- Signatures: long lifetimes – LLPs

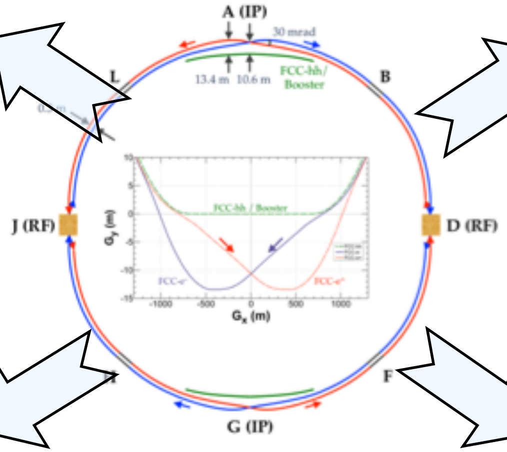
Detector Requirements in Brief

”Higgs Factory” Programme

- Momentum resolution at $p_T \sim 50$ GeV of $\sigma_{p_T}/p_T \simeq 10^{-3}$ commensurate with beam energy spread
- Jet energy resolution of 30%/$\sqrt{E}$ in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme & QCD

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution ”as good as we can get it”
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6} : stability of $\sqrt{s}$ meast.



Heavy Flavour Programme

- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ $\sqrt{E}$ level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

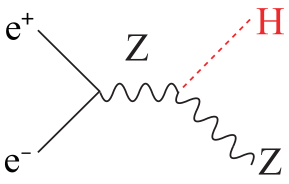
Feebly Coupled Particles - LLPs

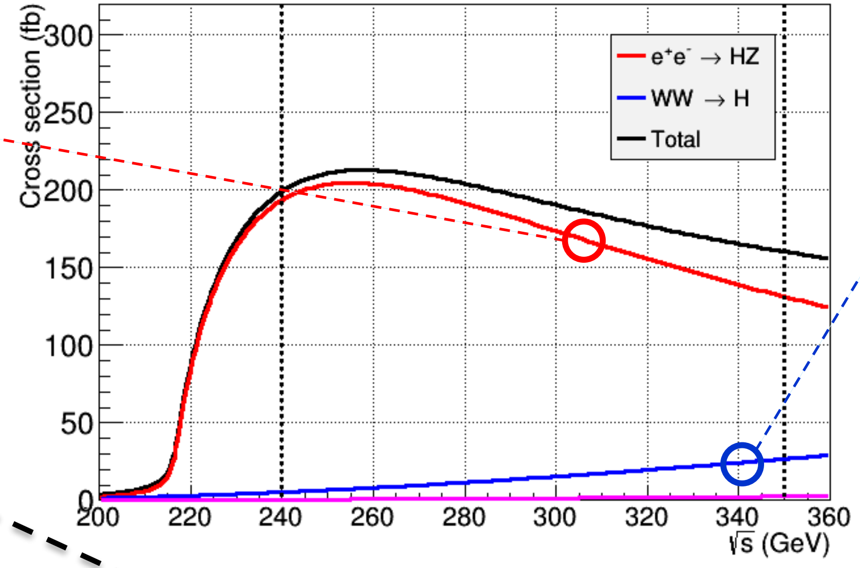
Benchmark signature: Z → νN, with N decaying late

- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Precise timing for velocity (mass) estimate
- Hermeticity

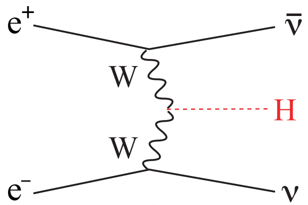
Higgs Factory: Higgs Production and Decay

Higgs-strahlung

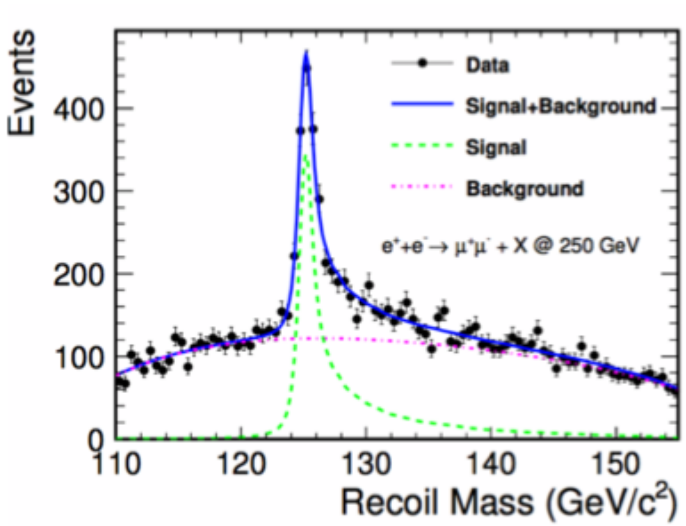


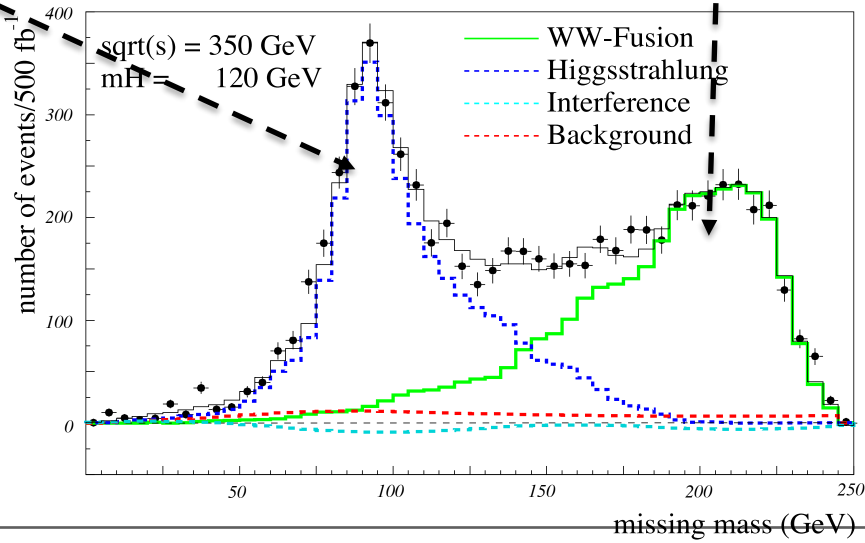


Boson fusion



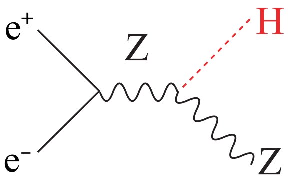
M_H = 125 GeV	SM BF
bb	56.1%
WW^*	23.1%
gg	8.2%
ττ	6.3%
ZZ^*	2.6%
cc	2.9%
γγ	0.2%
Zγ	0.15%
ss	0.1%
μμ	0.02%

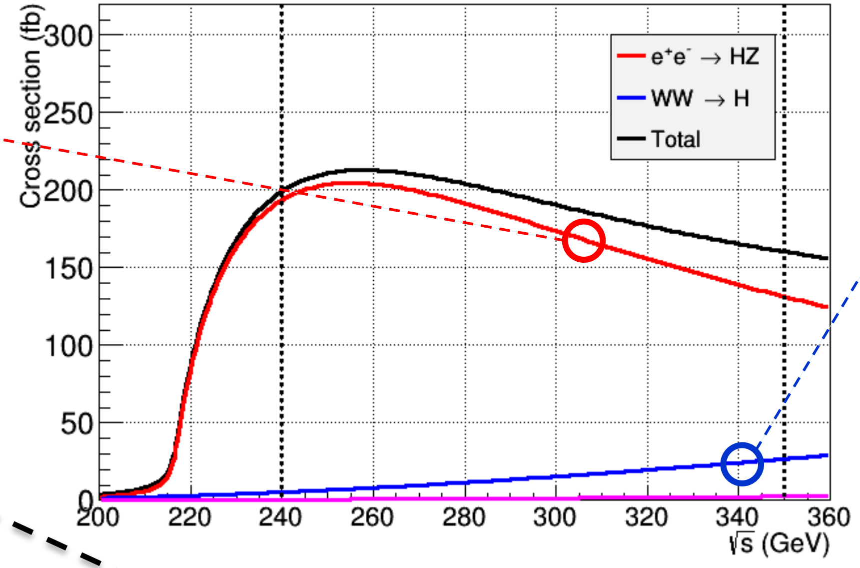




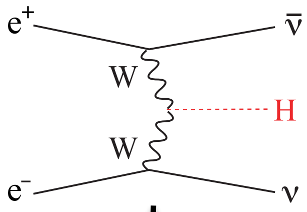
Higgs Factory: Higgs Production and Decay

Higgs-strahlung





Boson fusion



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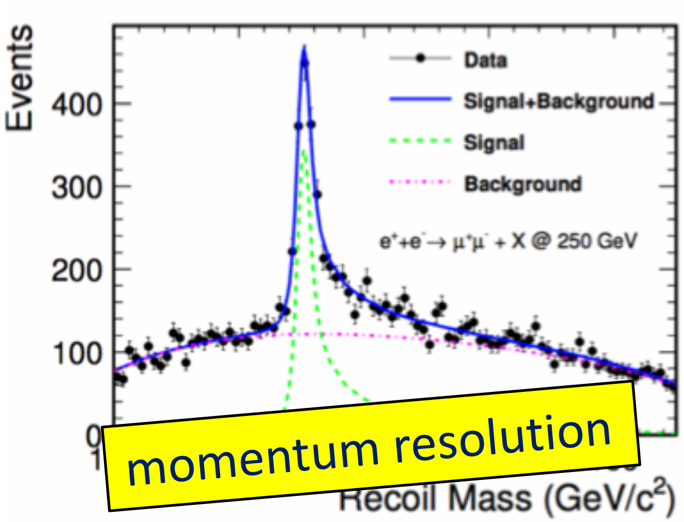
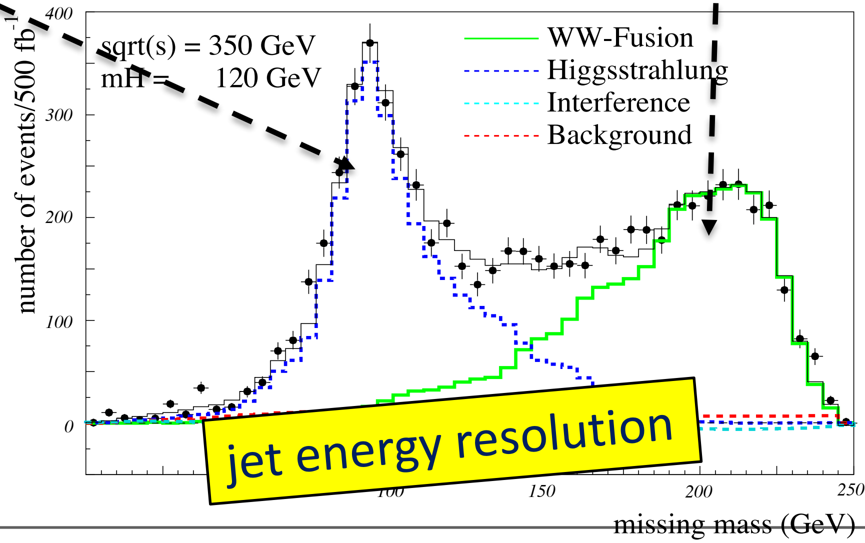


momentum resolution

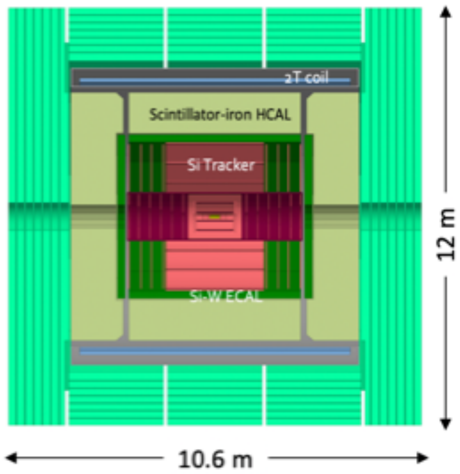


jet energy resolution

flavour tagging

Detector Concepts Fast Overview

CLD



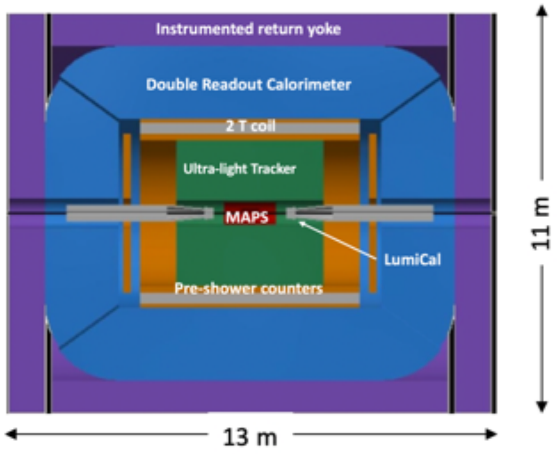
- Well established design
    - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker; CALICE-like calorimetry; large coil, muon system

- Engineering still needed for operation with continous beam (no power pulsing)
    - Cooling of Si-sensors & calorimeters

- Possible detector optimizations
    - σ_p/p, σ_E/E
    - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
    - …

CDR

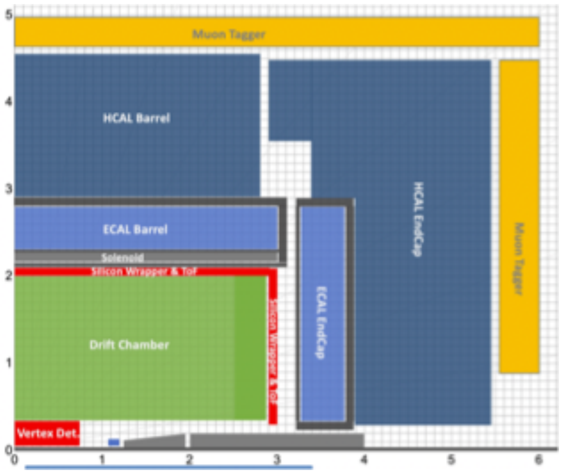
IDEA



- Less established design
    - But still ~15y history: ILC 4th Concept
- Si vtx detector; ultra light drift chamber w powerfull PID; compact, light coil; monolitic dual readout calorimeter; muon system
    - Possibly augmented by crystal ECAL

- Very active community
    - Prototype designs, test beam campaigns, …

Noble Liquid ECAL based



new

- A design in its infancy
- High granularity Noble Liquid ECAL is core
    - PB+LAr (or denser W+LCr)
- Drift chamber (or Si) tracking; CALICE-like HCAL; muon system.
- Coil inside same cryostat as LAr, possibly outside ECAL
- Very active Noble Liquid R&D team
    - Readout electrodes, feed-throughs, electronics, light cryostat, …
    - Software & performance studies

Flavour tagging, lifetime measurements

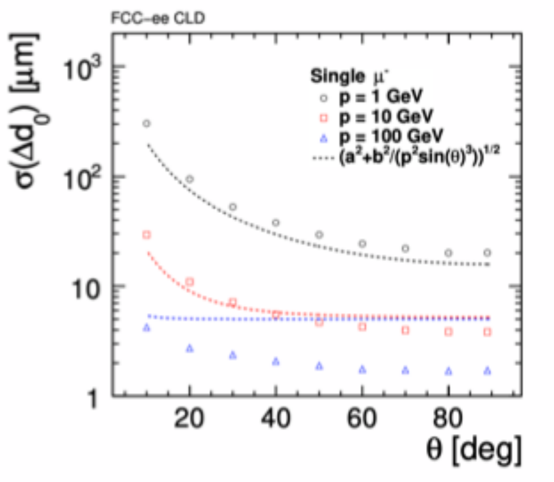
Impact parameter
”design goal”…

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

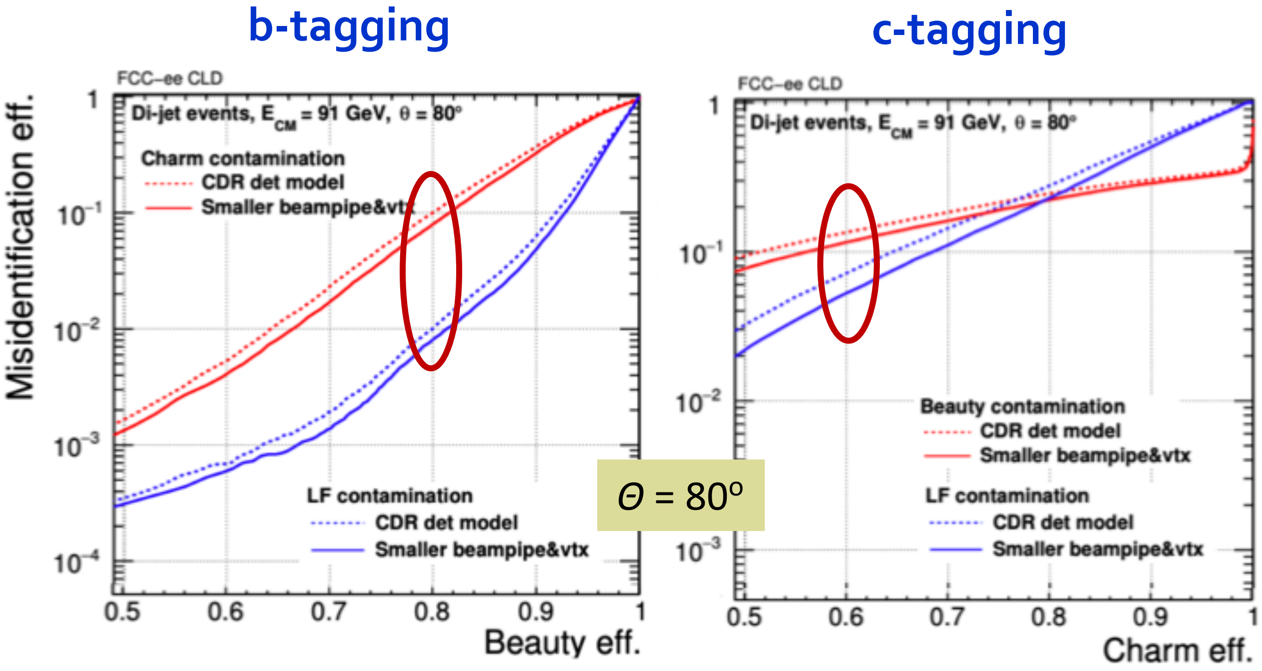
$$a \simeq 5\,\mu\text{m}; \quad b \simeq 15\,\mu\text{m}\,\text{GeV}$$

… satisfied in CLD full simulation study

arXiv:1911.12230



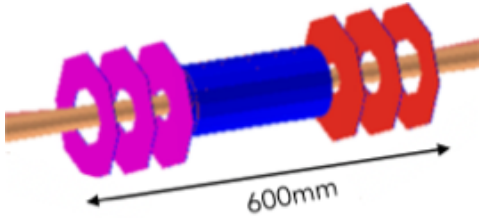
CLD flavour tagging

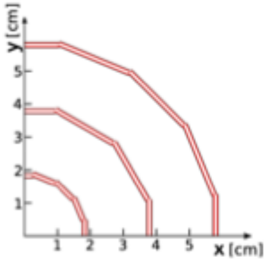

b-tagging

c-tagging

$\Theta = 80^{o}$

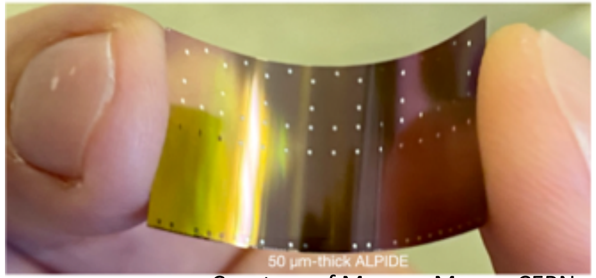
- Pixels size 25 × 25 μm^2; point accuracy of 3 μm
- Three thin double sensor layers (50 μm Si) at r= 18, 37, 57 mm
  - 0.6% of X_0 for each double layer
- Beryllium, water cooled beam pipe at r=15 mm (~0.5% of X_0)





Strong development: Lighter, more precise, closer

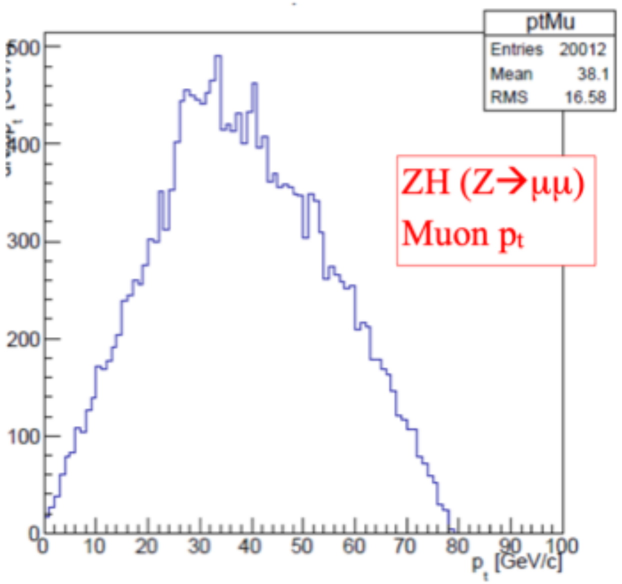
	r beam pipe	1^{st} VTX layer
ILC	12 mm	14 mm
CLIC	29 mm	31 mm
FCC-ee	15 (→ 10) mm	17 (→ 12) mm

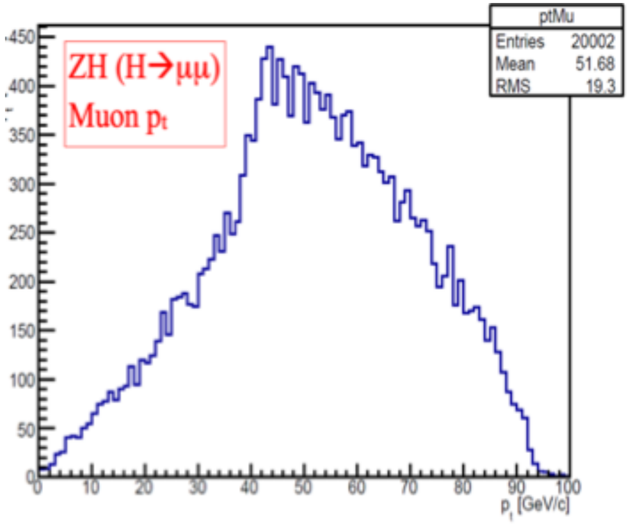


Courtesy of Magnus Mager, CERN

Momentum measurement

Particles are of rather low p_T





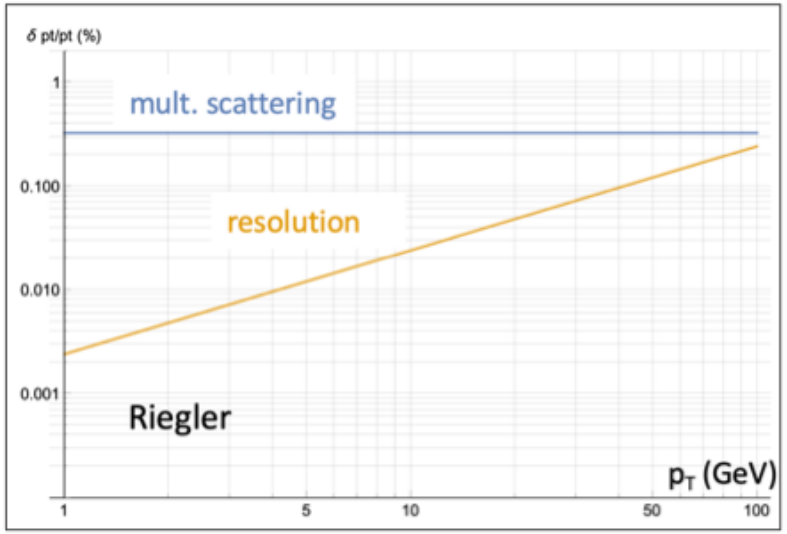
Momentum resolution tend to be multiple scattering dominated

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

- Asymptotic resolution not reached

Here illustrated by analytic calculation for CLD Si tracker at 90° :
Total material budget = 11% of X_0

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



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

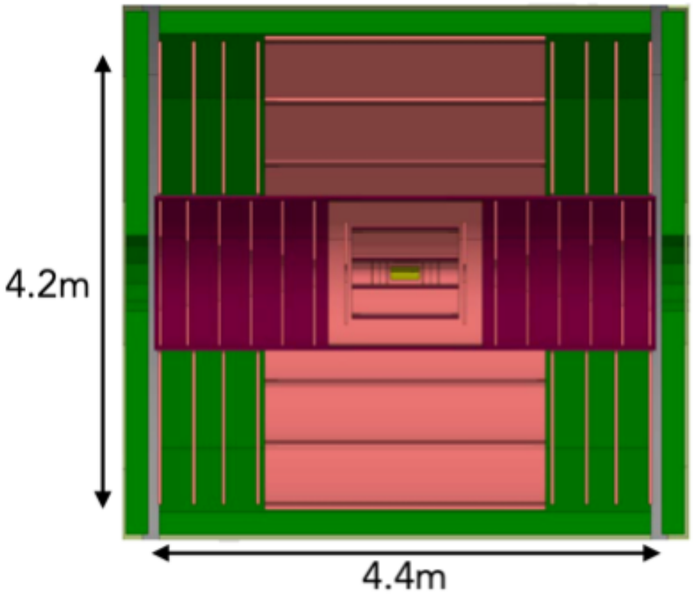
Thinning of Si sensors helps only as √ of thickness

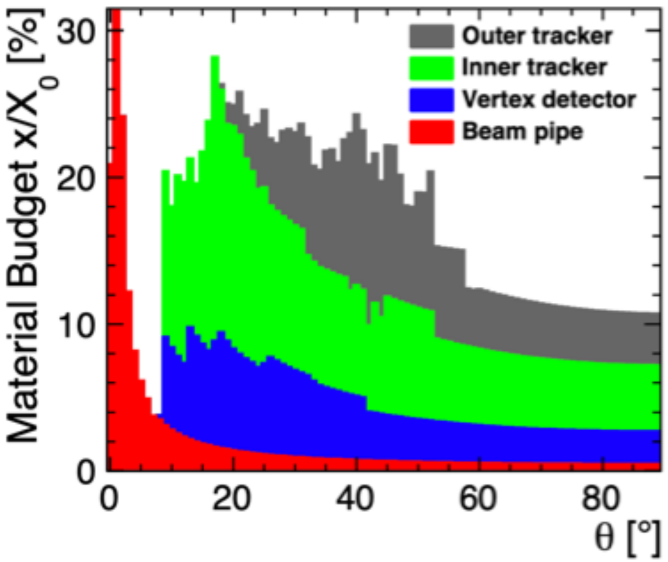
⇒ Detector transparency more important than asymptotic resolution ⇐

Tracking

Two solutions under study

- CLD: All silicon: pixel VTX + strips tracker
  - Inner: 3 (7) barrel (fwd) layers (1% X_0 each)
  - Outer: 3 (4) barrel (fwd) layers (1% X_0 each)
  - Separated by support tube @ r= 675 mm (2.5% X_0)

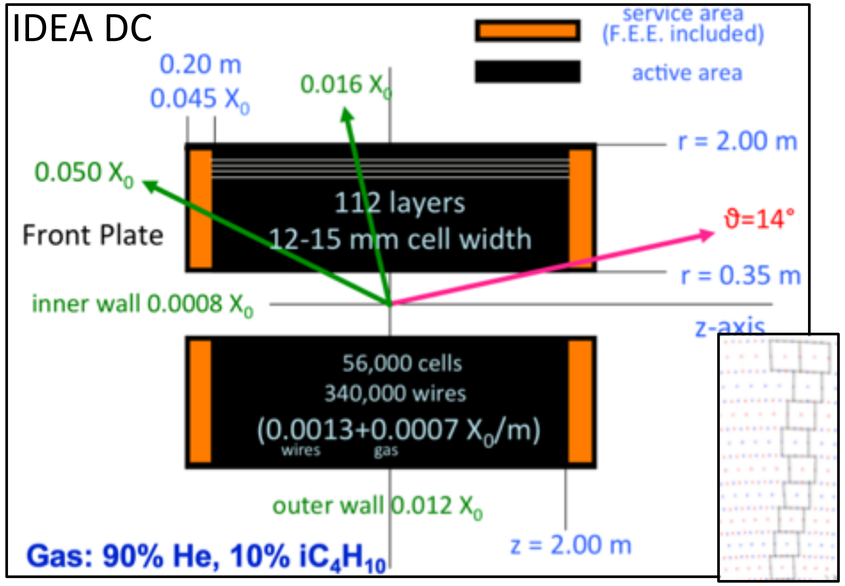


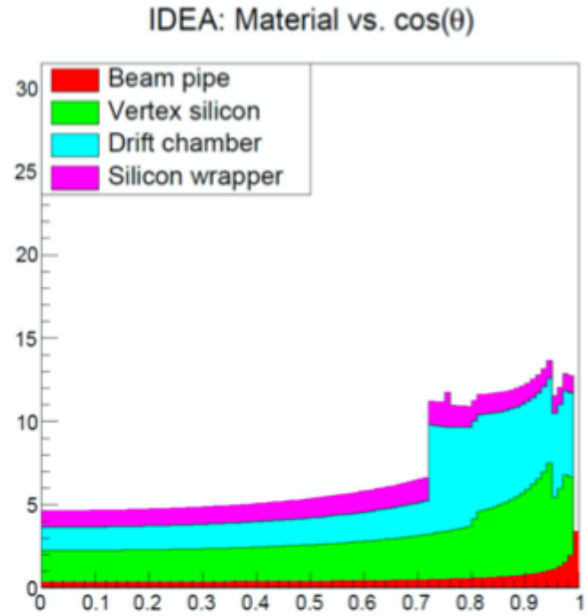


- IDEA: Extremely transparent Drift Chamber
  - GAS: 90% He – 10% iC_4H_{10}
  - Radius 0.35 – 2.00 m
  - Total thickness: 1.6% of X_0 at 90°
    - Tungsten wires dominant contribution
  - Full system includes Si VXT and Si "wrapper"

What about a TPC?

- Very high physics rate (70 kHz)
- B field limited to 2 Tesla
- Considered for CEPC, but having difficulties…





Calorimetry – Jet Energy Resolution

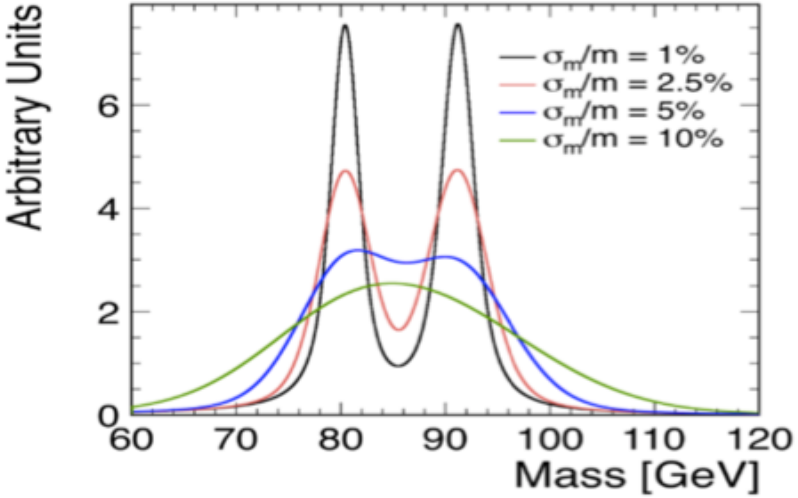
Energy coverage < 300 GeV : $22\ X_0$, 7λ

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

⇒ **Mass reconstruction from jet pairs**

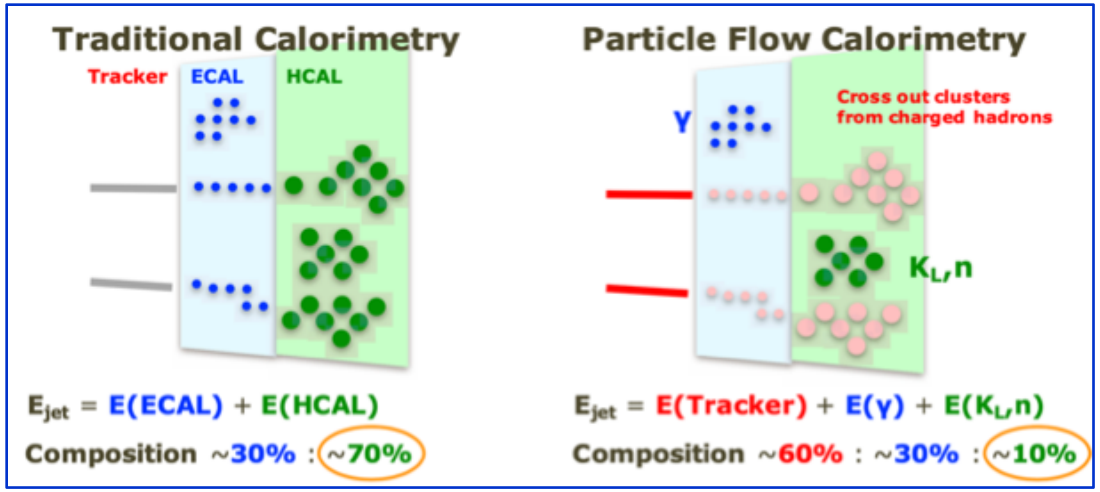
Resolution important for control of (combinatorial) backgrounds in multi-jet final states

- 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 – extremely fine segmentation (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 segmentation; some longitudinal inf. via timing

c) **Liquid Argon** ECAL + **CALICE-like** HCAL
  - Fine segmentation, high stability, $\delta E_{EM}/E_{EM} \sim$ 8-9%

Calorimetry – ECAL Performance

ECAL energy resolutiuon parametrised as

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

with typically

technology	a	b	c
CALICE	15%	-	1%
Fiber DR	10%	-	1%
LAr	8%	-	-
Crystal	3-5%	-	0.5%

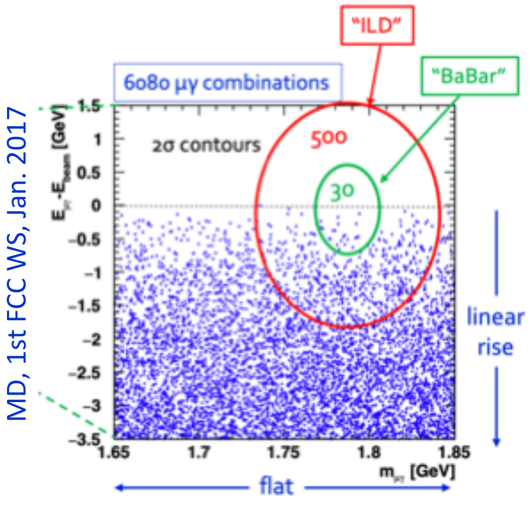
- CALICE-like resolution has been regarded sufficient at linear colliders with emphasis on physics at 250-500GeV
- An improved resolution may be advantageous for the 90-160 GeV FCC-ee programme

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.

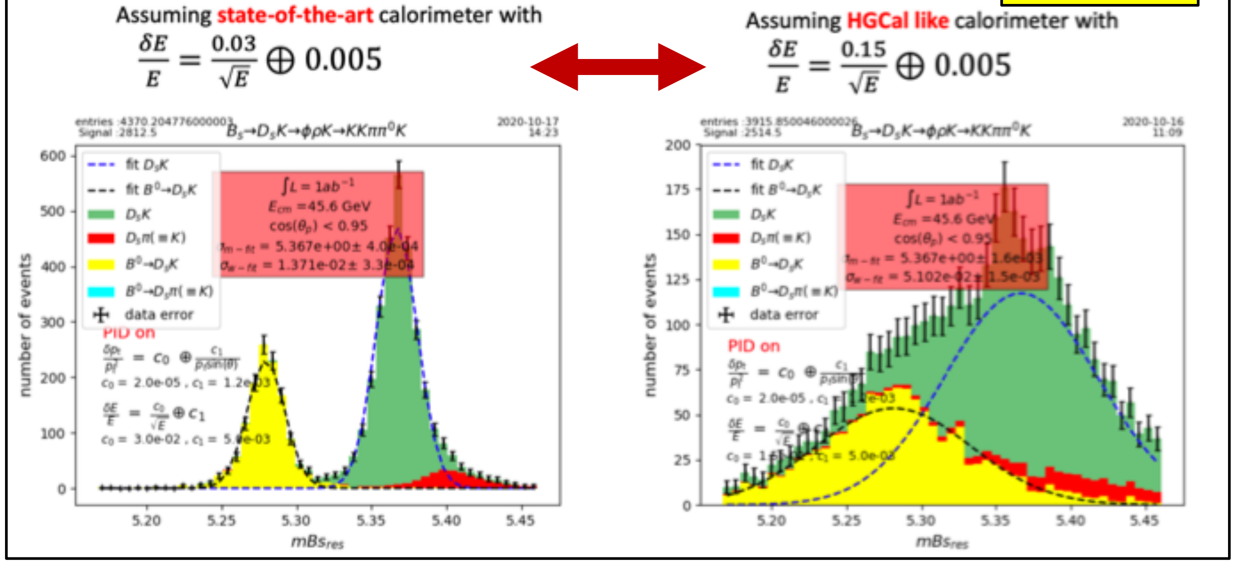
- Here LFV decay τ → μγ



MD, 1st FCC WS, Jan. 2017

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

R. Aleksan

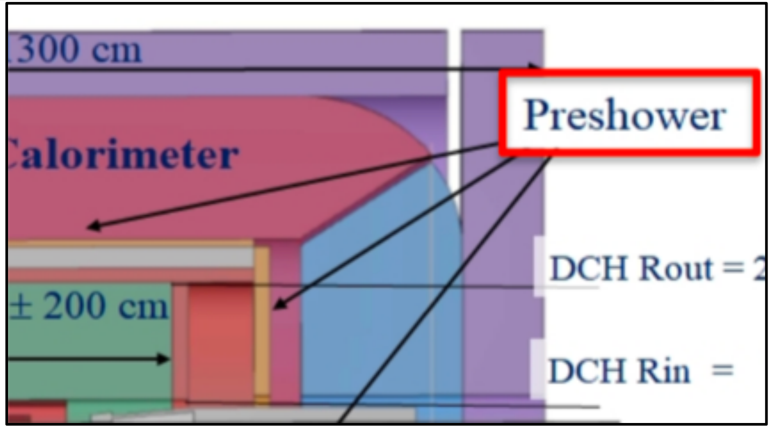

Assuming **state-of-the-art** calorimeter with $\frac{\delta E}{E} = \frac{0.03}{\sqrt{E}} \oplus 0.005$

Assuming **HGCal like** calorimeter with $\frac{\delta E}{E} = \frac{0.15}{\sqrt{E}} \oplus 0.005$

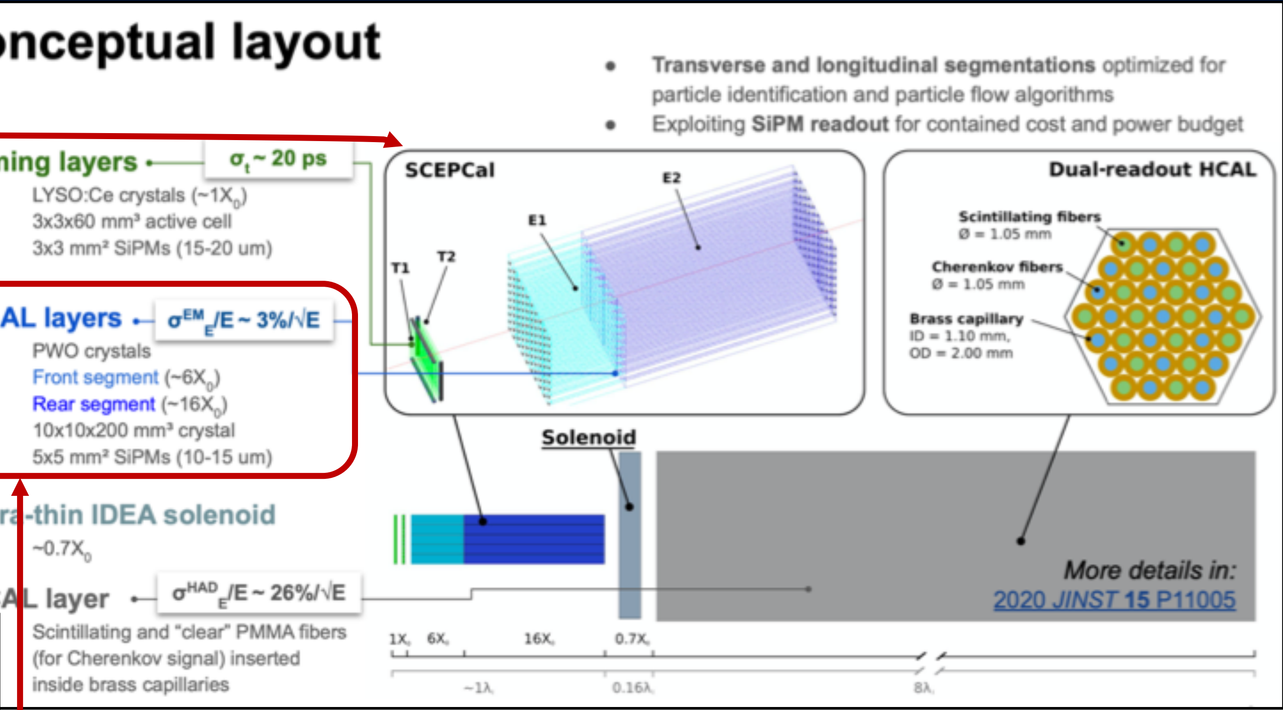
Crystals meet Spaghetti

M. Lucchini, FCC Workshop, Feb. 2022

IDEA Concept:
Monolitic calorimeter + preshower



Add crystals



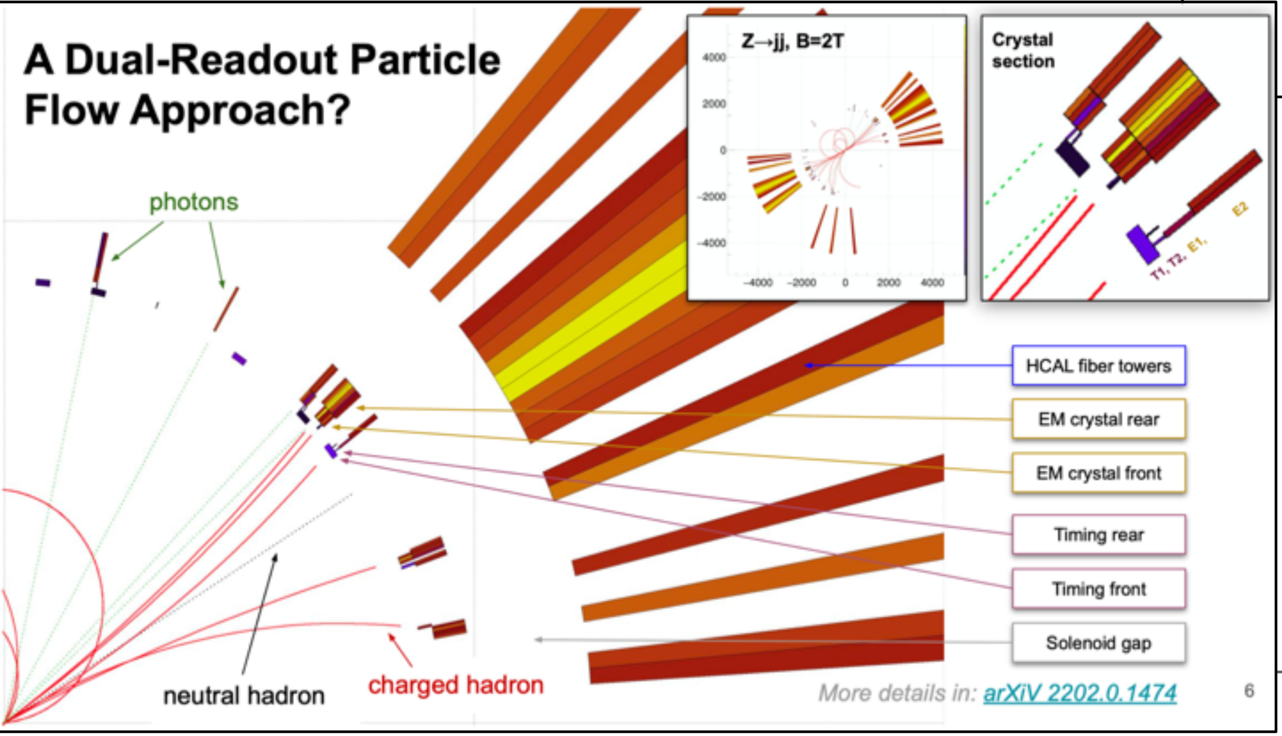
Conceptual layout

- **Transverse and longitudinal segmentations** optimized for particle identification and particle flow algorithms
- Exploiting **SiPM readout** for contained cost and power budget

- **Timing layers** — $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals (~$1X_0$)
  - 3x3x60 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- **ECAL layers** — $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
  - PWO crystals
  - Front segment (~$6X_0$)
  - Rear segment (~$16X_0$)
  - 10x10x200 mm³ crystal
  - 5x5 mm² SiPMs (10-15 um)
- **Ultra-thin IDEA solenoid**
  - ~$0.7X_0$
- **HCAL layer** — $\sigma^{HAD}_E/E \sim 26\%/\sqrt{E}$

  Scintillating and "clear" PMMA fibers (for Cherenkov signal) inserted inside brass capillaries

More details in: 2020 *JINST* 15 P11005

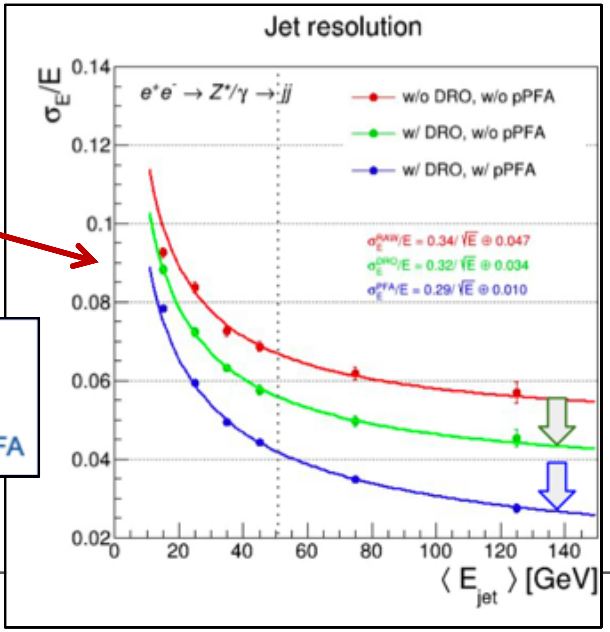


A Dual-Readout Particle Flow Approach?

More details in: arXiV 2202.0.1474

Excellent energy resolution for
- EM
- Jet via DR and pPFA algo

- crystals + IDEA w/o DRO
- crystals + IDEA w/ DRO
- crystals + IDEA w/ DRO + pPFA

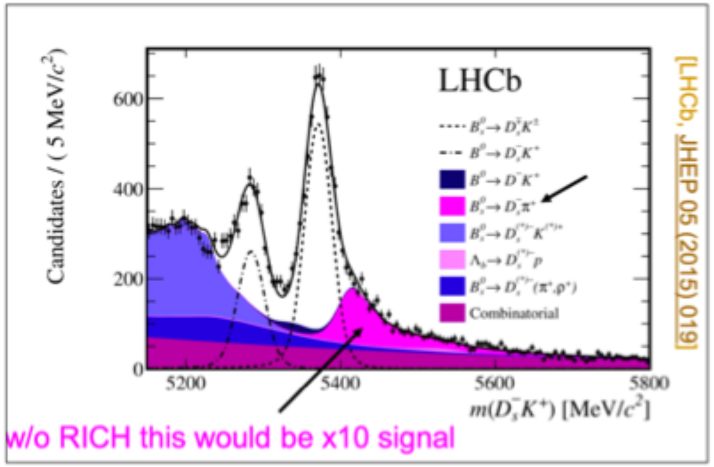


Experimental Challenge: Particle Identification

FCC-ee-Z has a very promising **heavy flavour programme** exceeding the Belle II statistics by a few orders

For heavy flavours, PID is essential Example of RICH in LHCb:

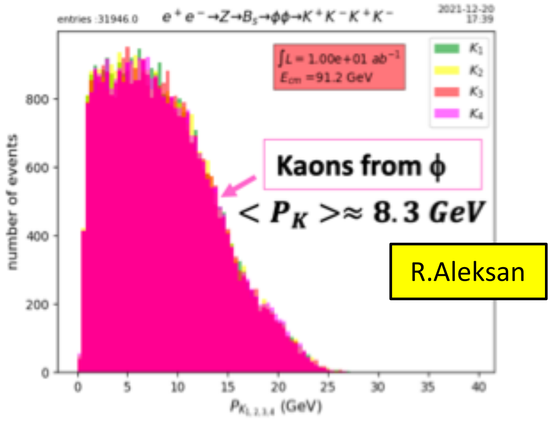
B physics



[LHCb, JHEP 05 (2015) 019]

w/o RICH this would be x10 signal

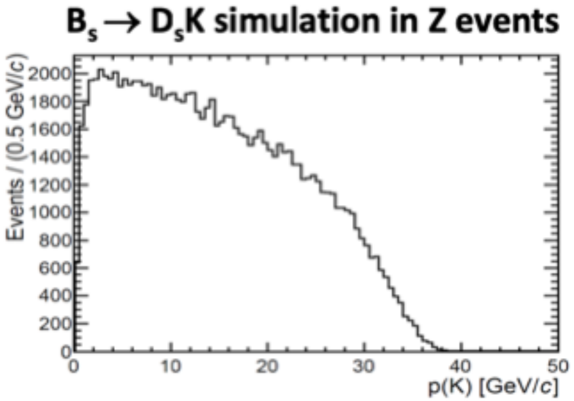
Efficient K/π separation needed over wide momentum range



Kaons from ϕ

$< P_K > \approx 8.3\ GeV$

R.Aleksan

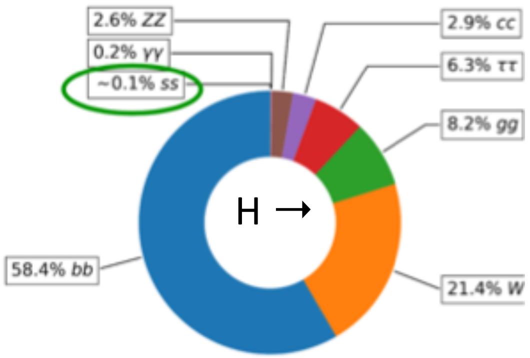


Likewise, **for tau physics**, K/π separation is needed up to 45 GeV needed for τ → πν vs τ → Kν separation.

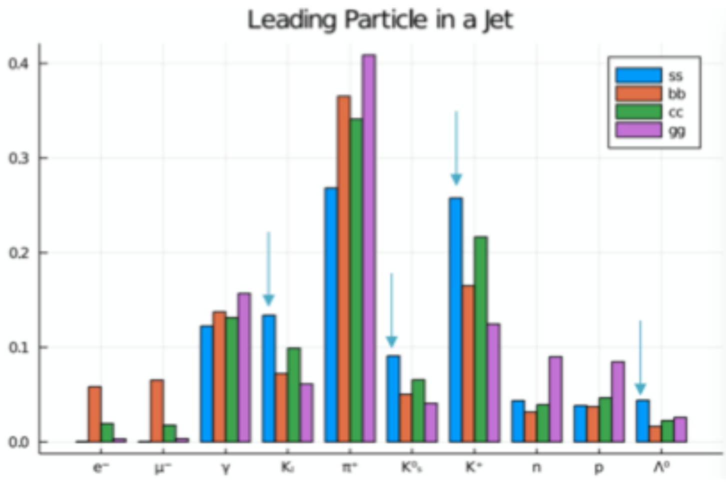
τ physics

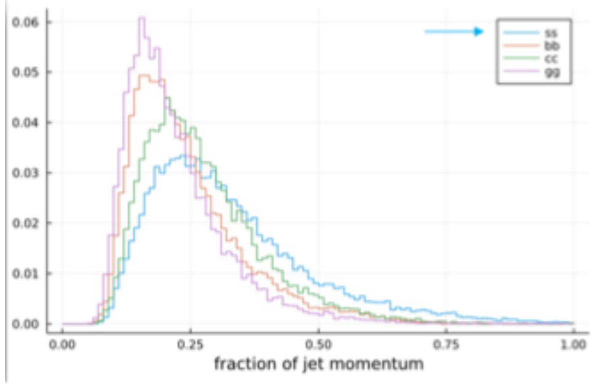
Strange tagging in Higgs decays:

- measure B(H->ss) (SM) and e.g. B(H->sb) (BSM)



Higgs physics





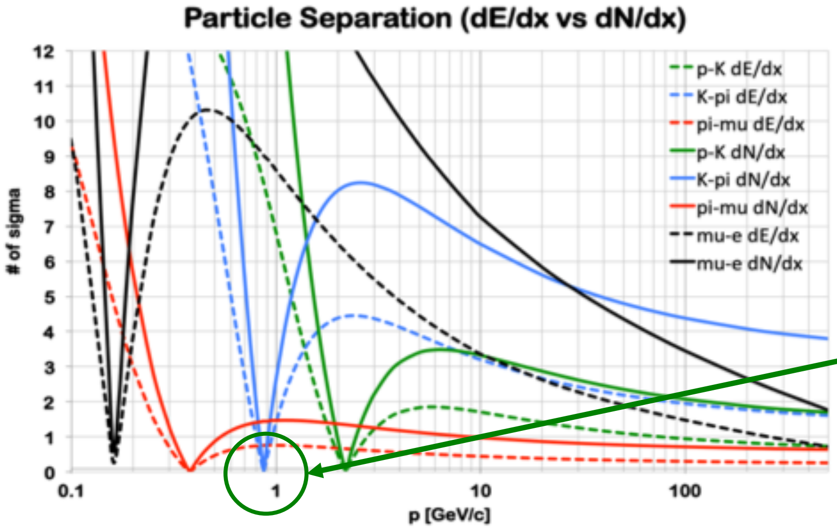
Need for K/π separation over wide range

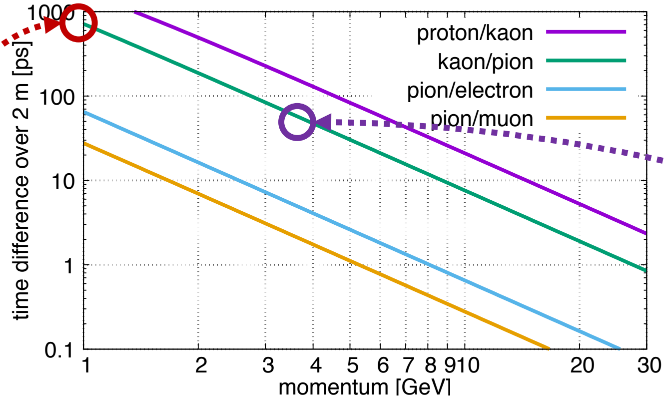
V. Cairo, FCC Workshop, 8 Feb. 2022

PID possibilities

IDEA Drift Chamber provides powerfull ionisation meast.
- Improved considerably by the use of cluster counting

Analytical calculation





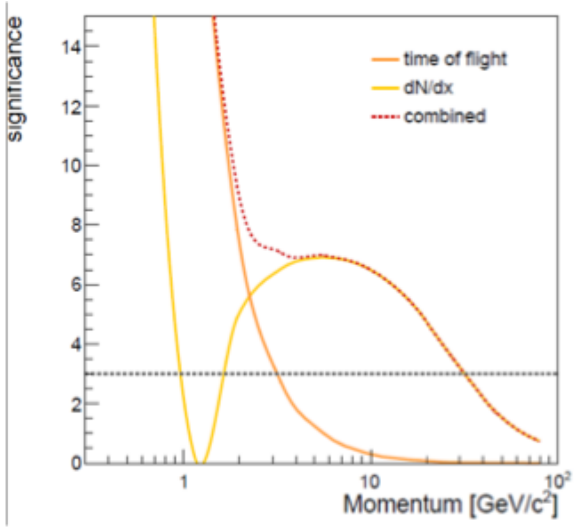
TOF

- ❑ Narrow dE/dx cross-over window at ~1 GeV, can be alleviated by unchallenging TOF measurement at r=2m of $\delta T \lesssim 0.5$ ns
- ❑ TOF *alone* could give 3σ π/K separation up to a 3.5 GeV for measurement precision of $\delta T \sim 20$ ps (LGAD, …)

Ionisation

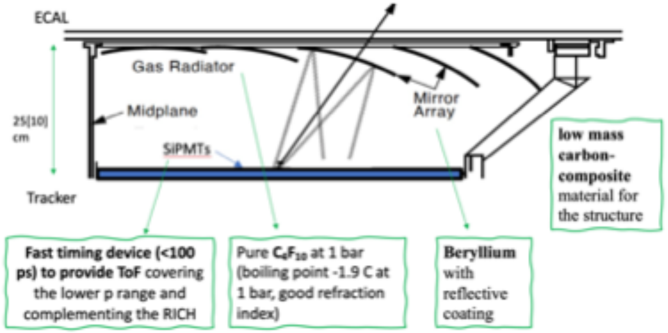
Garfield++ simulation gives somewhat less optimistic (but still good) results:
3σ K/π separation up to 35 GeV

Ongoing test beam campain to study dN/dx performance



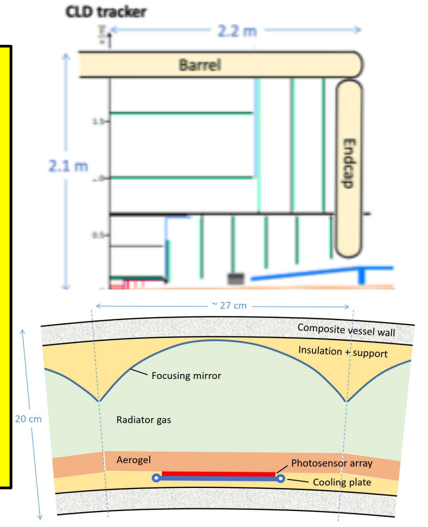
Cherenkov

Two studies of compact solutions have been presented



V. Cairo, FCC Workshop, 8 Feb. 2022

R.Forty, FCC Week, 1 July, 2021

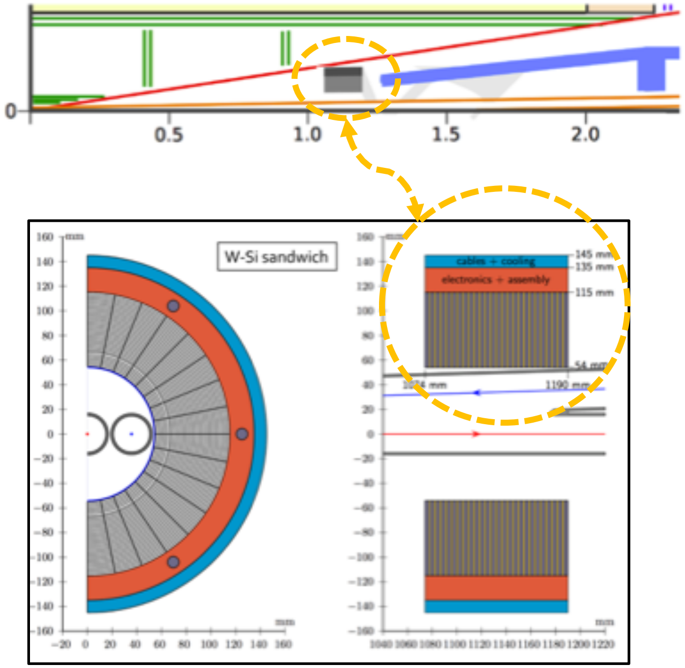


Normalisation Issues

Ambitious goals:

- Absolute luminosity measurement to $\lesssim 10^{-4}$
- Relative luminosity (energy-to-energy point) to $\lesssim 10^{-5}$
- Inter-channel normalisation (e.g. μμ/multi-hadronic) to $\lesssim 10^{-5}$

Luminosity Monitors (low angle Bhabha)



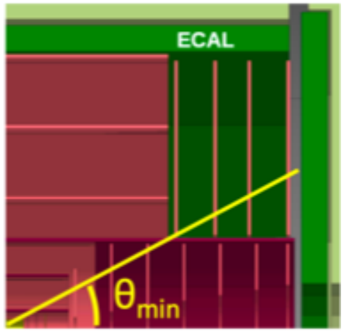
- ◆ Many R&D/engineering challenges
  - ❑ Precision on acceptance boundaries to $\mathcal{O}$(1 μm) !
  - ❑ Mechanical assembly, metrology, alignment
  - ❑ Support / integration in crowded and complex MDI area

Complementary lumi process: large angle $e^+e^- \rightarrow \gamma\gamma$

- ❑ 10^{-4} ⇒ control of acceptance boundary $\delta\theta_{min}$ to **$\mathcal{O}$(50 μrad)**
- ❑ Possible bckg: $Z \rightarrow \pi^0\gamma$ ⇒ need to control $\mathcal{B}(Z\rightarrow\pi^0\gamma)$ to 10^{-7}

Acceptance of $Z \rightarrow \ell\ell$ to 10^{-5}

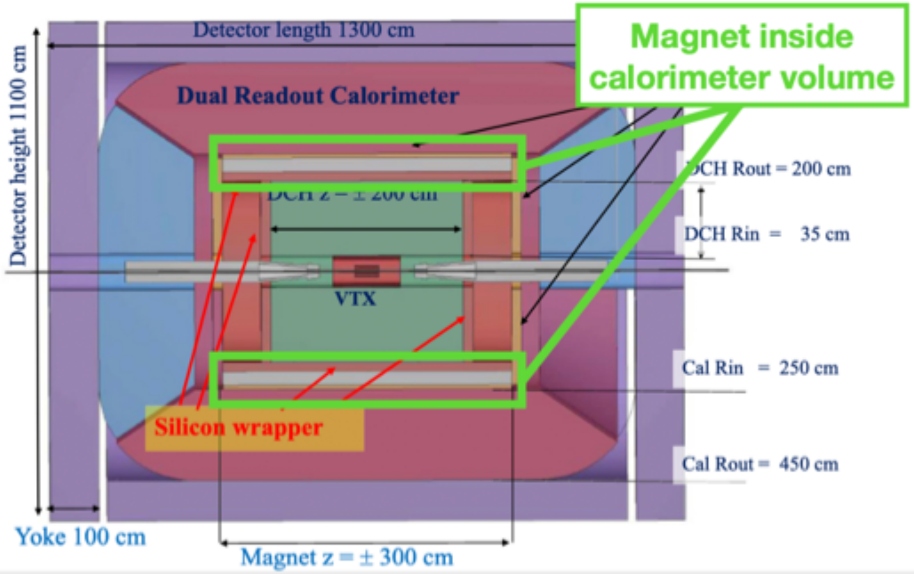
- ❑ Control of acceptance boundary $\delta\theta_{min}$ to **$\mathcal{O}$(50 μrad)**
- ❑ No holes or cracks
- ◆ Possible implementation: Precisely machined pre-shower device in front of forward calorimeter
  - ❑ Note 1: IDEA concept already includes pre-shower + Si wrapper
  - ❑ Note 2: CM and detector systems differ by a β=0.015 transverse boost



Solenoid Magnet

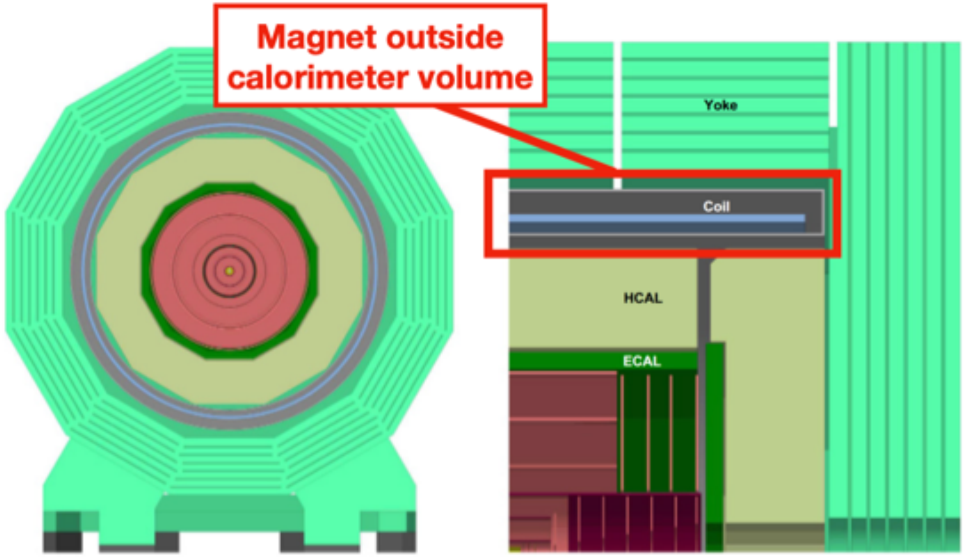
Nikkie Deelen,, FCC Workshop Feb. 2022

International Detector for Electron-positron Accelerators

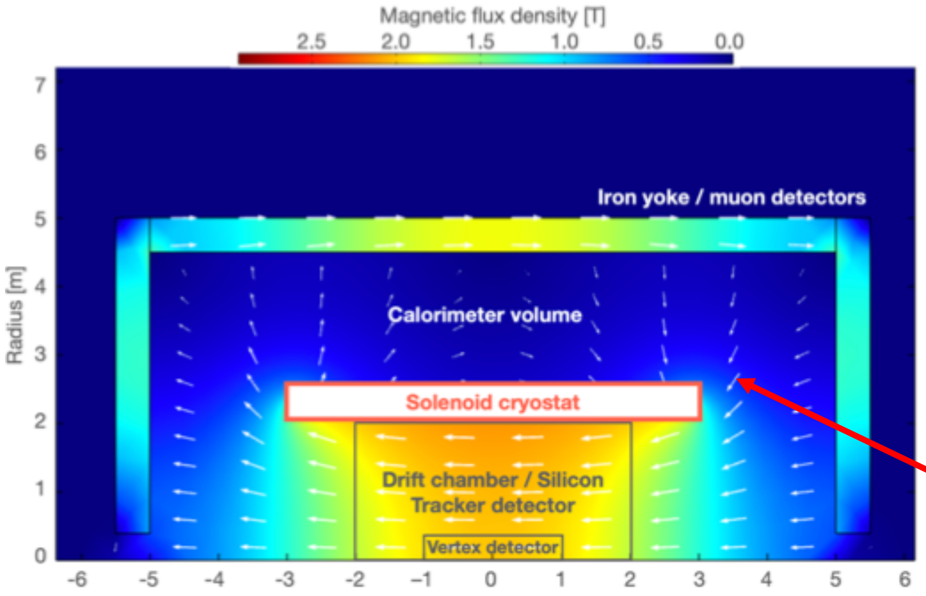


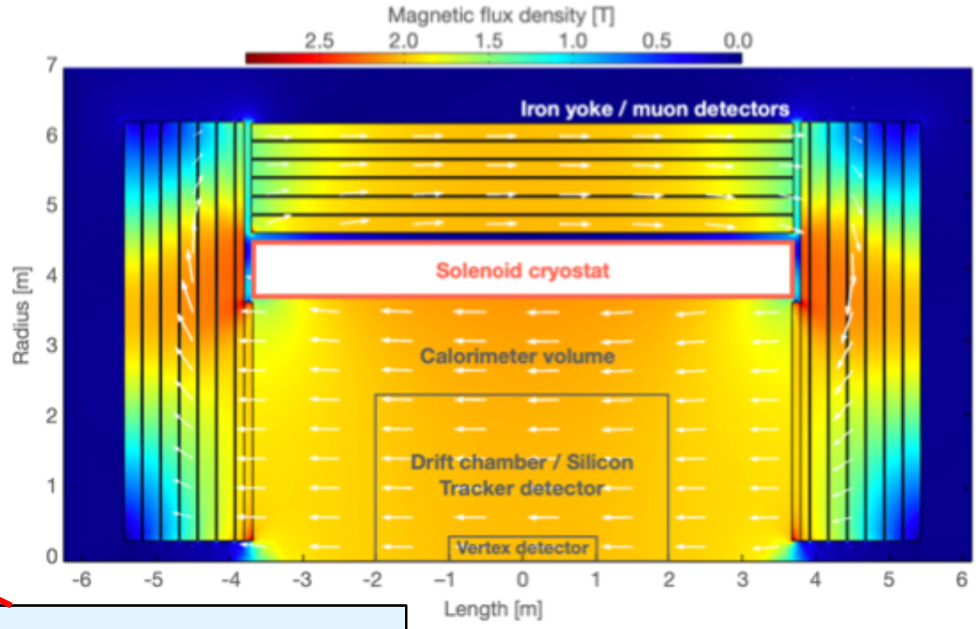
Magnet inside calorimeter volume

CLIC-Like Detector



Magnet outside calorimeter volume

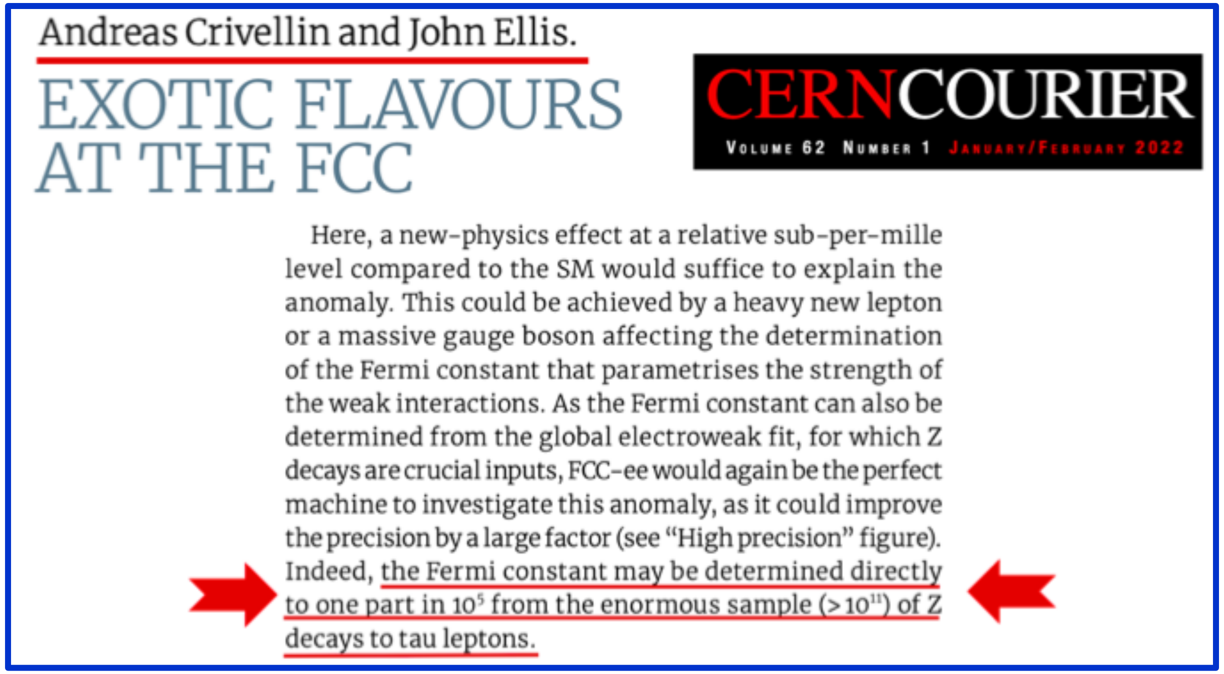




Transparency of the cold mass: 0.76 X_0
Energy density: ~14 kJ/kg [2]

For crystal IDEA:
- Hybrid solution; coil between ECAL and HCAL

Example of precision challenge: 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

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

Compare τ and μ based Fermi consants

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

Current precision:	67 ppm BES	1700 ppm Belle	2200 ppm LEP

FCC-ee: Will see 3×10^{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

Outlook

- FCC-ee has an enormous physics potential
  - Unprecedented factory for Z, W and Higgs bosons; for top, beauty, and charm quarks; and for tau leptons
  - Possibly also factory for BSM particles !!
- Instrumentation to fully exploit the physics potential is challenging and exciting
  - FCC-ee can host (up to) four experimental collaborations
  - Full exploitation of physics potential via N ”general purpose” experiments, possibly complemented by M dedicated experiments
    - e.g. heavy flavour
- For next ESUPP, need to demonstrate that experimental challenge can be met by several (N+M ≤ 4) Detector Concepts
- Detector Concepts working group formed early this year
  - Provide guidance for coherent detector R&D efforts to address FCC detector requirements
  - Establish forum, where progress, ideas, and results from individual R&D efforts and test-beam activities are presented, discussed and reviewed
  - Work as interface to MDI and accelerator groups
  - Management: MD, Philipp Roloff, Felix Sefkow
- Dedicated ”kick off” workshop at CERN this week, June 22-23 https://indico.cern.ch/event/1165167/
- e-group: *FCC-PED-DetectorConcepts*

Please don’t hesitate to join!

Extras

Example of precision challenge: Universality of Fermi constant

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

Current precision:

67 ppm
BES

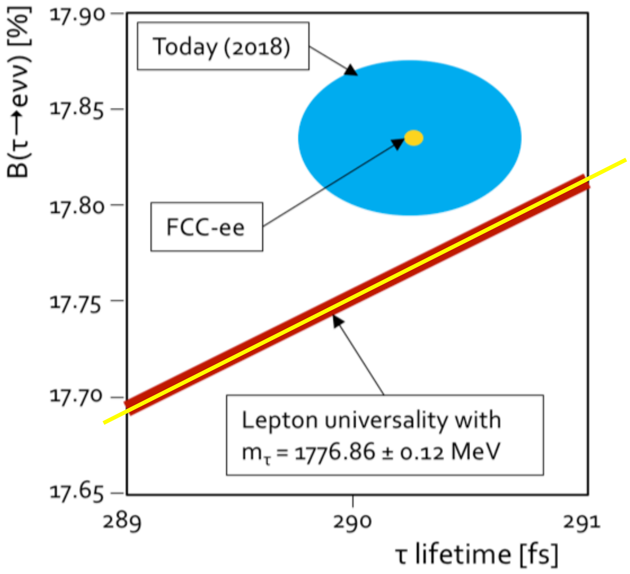
1700 ppm
Belle

2200 ppm
LEP

To current precision, data supports lepton universality.

- 1σ error ellipse (blue) consistent with mass (red)

Shown in yellow: first guestimates of FCC-ee precisions



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