E I S A
European Institute for Sciences and Their Applications

Corfu Summer Institute
Hellenic School and Workshops on Elementary Particle Physics and Gravity
Corfu, Greece

NIELS BOHR INSTITUTE
UNIVERSITY OF COPENHAGEN

Detector Challenges for Higgs Factories

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Niels Bohr Institute, Copenhagen

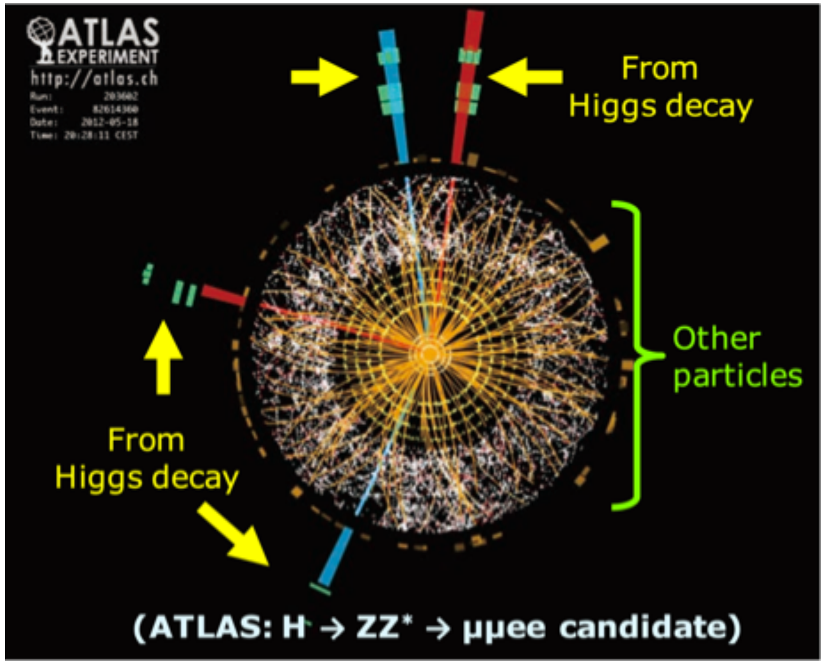
Workshop on Future Accelerators

APRIL 23 - APRIL 29, 2023

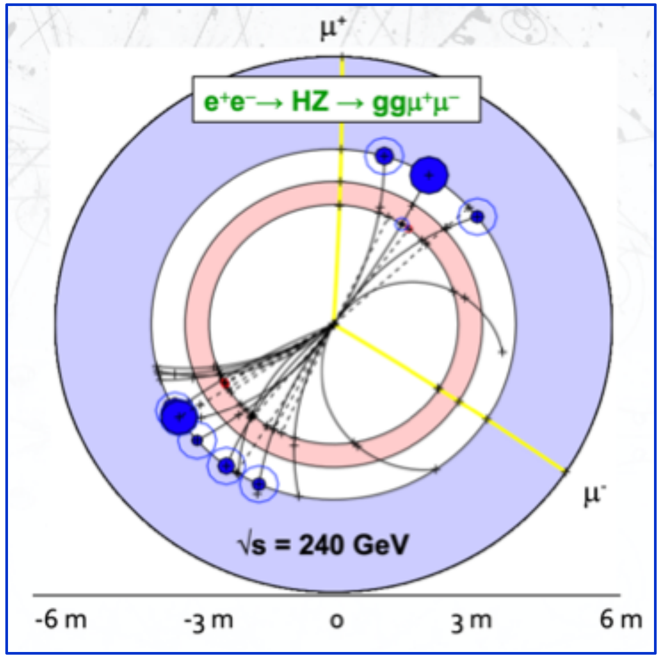
Gratefully acknowledging contributions and inspiration from my FCC colleagues

Prelude: pp vs. e^+e^-

Higgs event in pp



Higgs event in e^+e^-



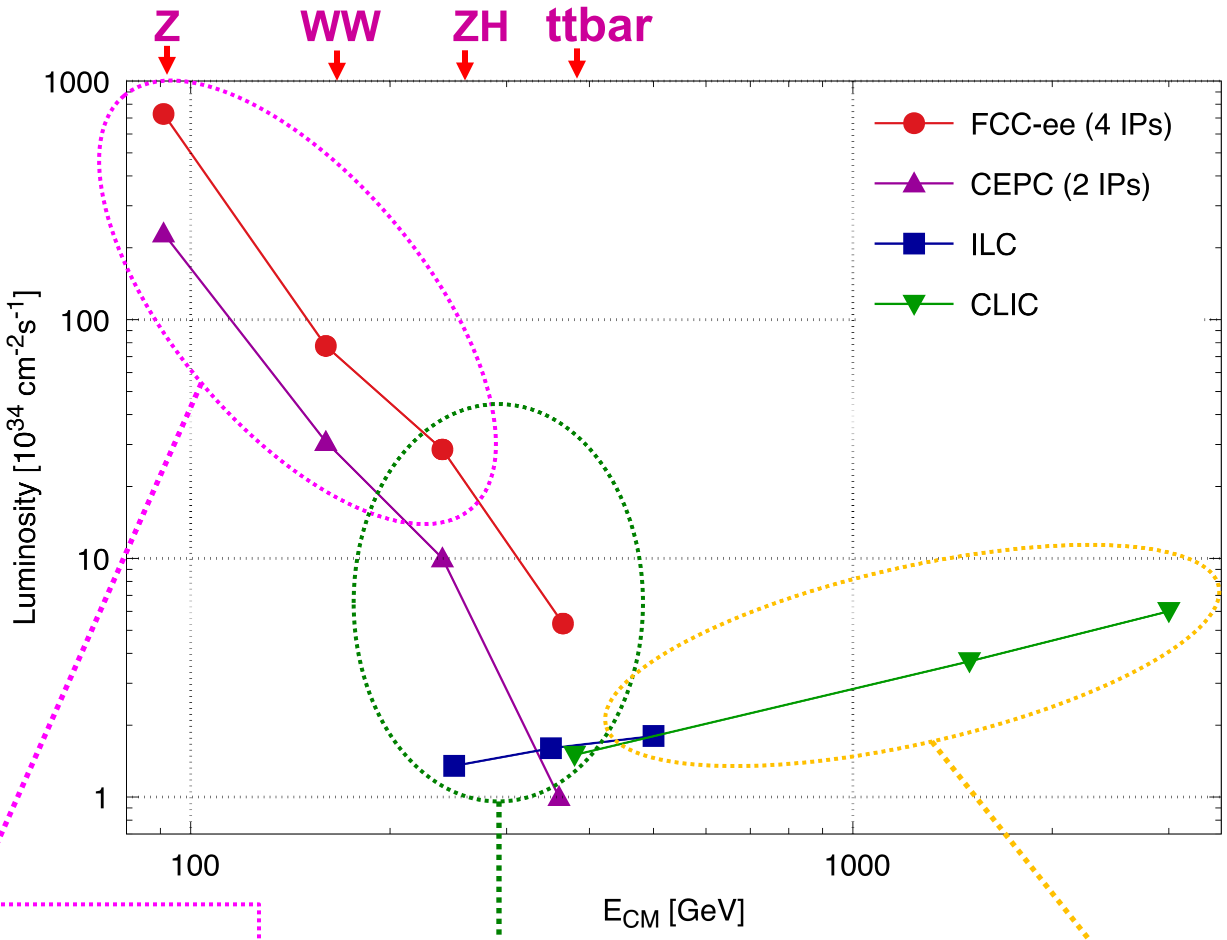
pp: look for striking signal in large background

- High rates of QCD backgrounds
  - Complex triggering schemes
  - High levels of radiation
- High cross-sections for coloured states
- High-energy circular pp colliders feasible
  - Large mass reach ➞ direct exploration
- S/B ≈ 10^{-10} before trigger; S/B ≈ 0.1 after trigger

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

- Clean experimental environment
  - Trigger-less readout
  - Low radiation levels
- Superiour sensitivity for electro-weak states
- Limited direct mass reach
- S/B ≈ 1 ➞ precision measurement
  - Exploration via precision

High-energy e^+e^- accelerator landscape

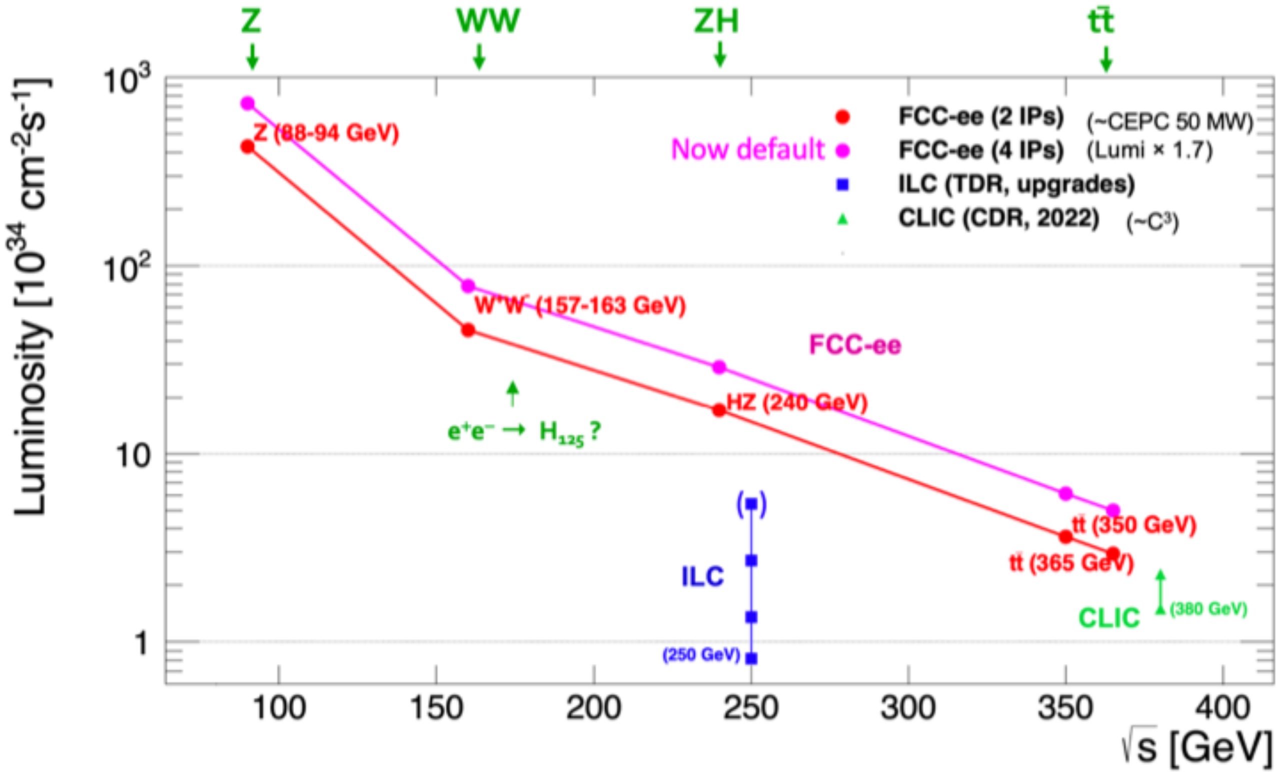


Circular colliders
Extremely high luminosities at lower energies:
Z, W, Higgs, and top factories

Overlap region, 240-380 GeV
Higgs Factories (and top)

Linear colliders
High centre-of-mass energies

e^+e^- Higgs (and EW & top) Factories



- From an experimental point of view, operation at the Z-pole is the most challenging
- Enormous Z-decay statistics drives detector design
  - ➢ Statistical precsion for EWPOs typically 300 times smaller than LEP (current) uncertainties
    - ➢ Need systematic uncertainties to match
  - ➢ Ultimate factory for heavy flavour: b, c, (s), τ
    - ➢ Need ultimate heavy flavour performance
  - ➢ Intensity frontier: Opportunity to directly observe new ”low mass” feebly interacting particles
    - ➢ Hermeticity, long lived particles, …

FCC-ee run plan with 4 IPs (now default) :

Numbers of events in 15 years, tuned to maximise the physics outcome

						$\sqrt{s}$ uncertainty
ZH maximum	$\sqrt{s} \sim 240$ GeV	3 years	2×10^6	$e^+e^- \rightarrow ZH$	Never done	2 MeV
$t\bar{t}$ threshold	$\sqrt{s} \sim 365$ GeV	5 years	2×10^6	$e^+e^- \rightarrow t\bar{t}$	Never done	5 MeV
Z peak	$\sqrt{s} \sim 91$ GeV	4 years	6×10^{12}	$e^+e^- \rightarrow Z$	LEP x 10^5	< 50 keV
WW threshold+	$\sqrt{s} \geq 161$ GeV	2 years	3×10^8	$e^+e^- \rightarrow W^+W^-$	LEP x 10^3	< 200 keV
[s-channel H	$\sqrt{s} = 125$ GeV	5? years	~7000	$e^+e^- \rightarrow H_{125}$]	Never done	< 100 keV

FCC-ee statistics:

- **~100 000 Z / second (!)**
  - 1 Z / second at LEP
- **~ 10 000 W / hour**
  - 20 000 W in 5 years at LEP
- **~ 1 500 Higgs bosons / day**
  - $\mathcal{O}(10)$ times more than ILC
- **~ 1 500 top quarks / day**

e^+e^- collider beam parameters

Linear

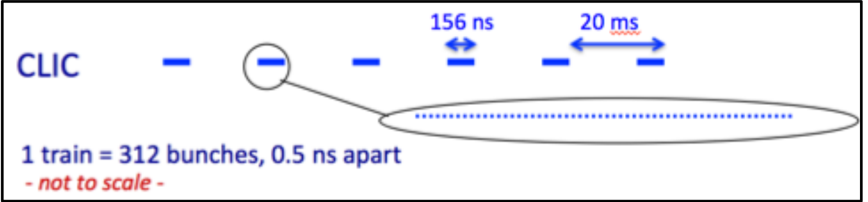
Parameter	ILC		CLIC		
	250 GeV	500 GeV	380 GeV	1.5 TeV	3 TeV
Luminosity L (10^{34}cm^{-2}sec^{-1})	**1.35** (2.7)	1.8	**1.5**	3.7	5.9
L > 99% of √s (10^{34}cm^{-2}sec^{-1})	1.0	1.0	0.9	1.4	2.0
Repetition frequency (Hz)	5	5	50	50	50
Bunch separation (ns)	554	554	0.5	0.5	0.5
Number of bunches per train	1312	1312	352	312	312
Beam size at IP σ_x/σ_y (nm)	515/7.7	474/5.9	150/2.9	~60/1.5	~40/1
Beam size at IP σ_z (μm)	300	300	70	44	44

ILC: Crossing angle 14 mrad, e^- polarization ±80%, e^+ polarization ±30%
CLIC: Crossing angle 20 mrad, e^- polarization ±80%

Very small beams + high energy => beamstrahlung

Very small bunch separation at CLIC drives timing requirements for detector

Very low duty cycle at ILC/CLIC allows for:
Triggerless readout
Power pulsing



Circular

	FCC-ee			
	Z	WW	Higgs	ttbar
√S [GeV]	**91.2**	**80**	**240**	**365**
Luminosity / IP (10^{34}cm^{-2}s^{-1}) [4IP]	**182**	**19.4**	**7.3**	**1.33**
no. of bunches / beam	15880	880	248	40
Bunch separation (ns)	**20**	**300**	1000	6000
Horizontal rms IP spot size [μm]	8	21	14	39
Vertical rms IP spot size [nm]	34	66	36	69

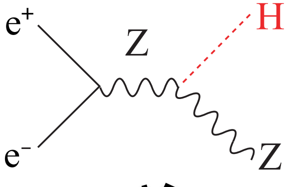
Beam transverse polarisation
=> beam energy can be measured to very high accuracy (~50 keV, 1ppm)

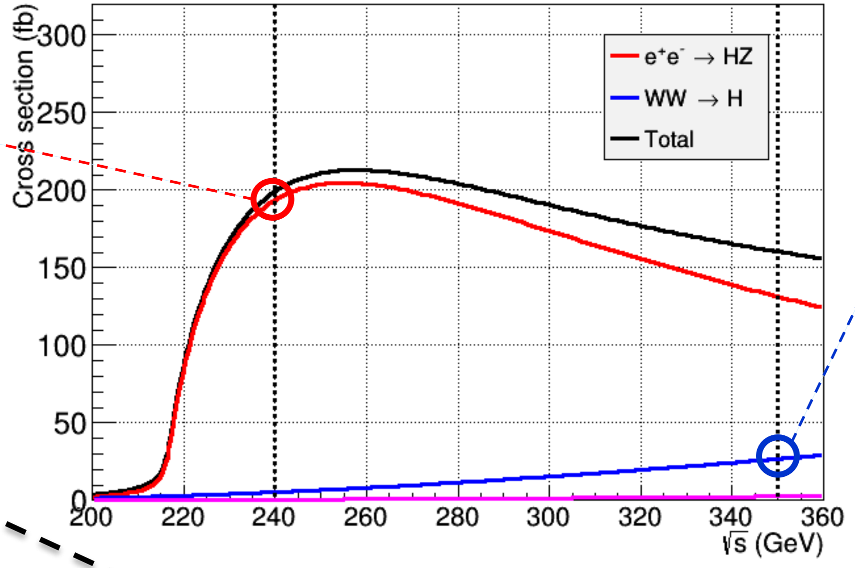
At Z-peak, very high luminosities and **very high e^+e^- cross section (40 nb)**
- ⇒ **Statistical accuracies at 10^{-4} -10^{-5} level** ⇒ **drives detector performance requirements**
- ⇒ **Small systematic errors required** to match
- ⇒ This also drives requirement on **data rates** (physics rates ~100 kHz)
- ⇒ Triggerless (streaming) readout likely possible

Beam-induced background, from beamstrahlung + synchrotron radiation
- Most significant at 365 GeV
- Well mitigated through MDI design and detector design

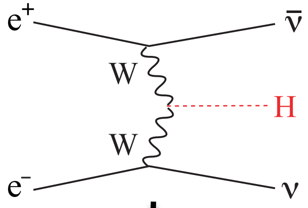
e^+e^- Higgs Factory: Higgs Production and Decay

Higgs-strahlung

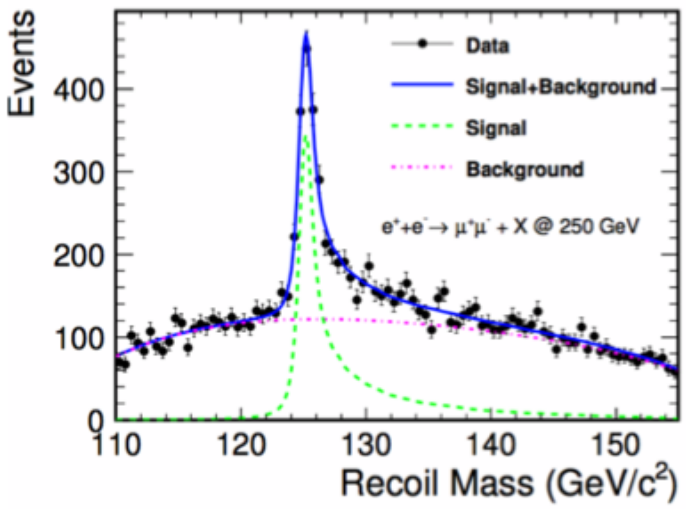




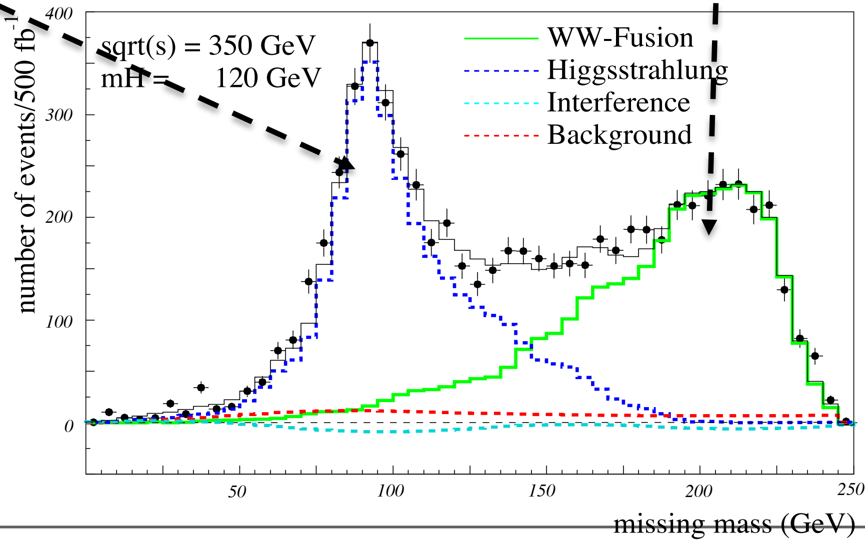
Boson fusion



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%



momentum resolution



jet energy resolution

flavour tagging

Particle ID

FCC-ee Physics Landscape

”Higgs Factory” Programme

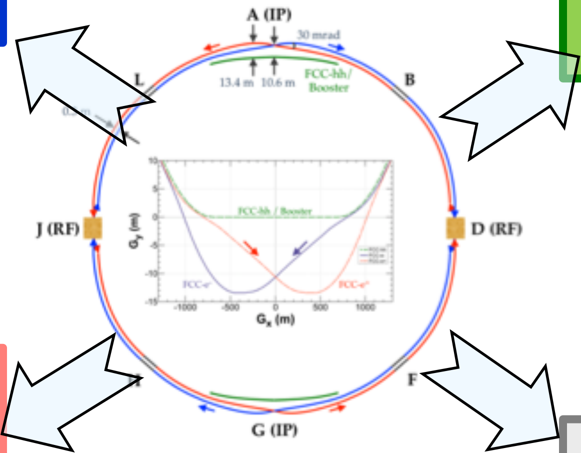
- At two energies, 240 and 365 GeV, collect in total
  - 2M HZ events and 125k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s} = 125$ GeV

Ultra Precise EW Programme & QCD

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

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

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



Heavy Flavour Programme

- Enormous statistics: 1.3×10^{12} bb, cc; 2.8×10^{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

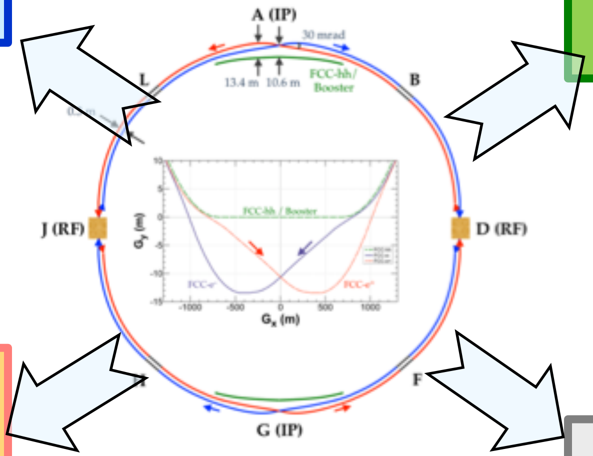
Detector Requirements in Brief

”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%/√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^{-5} - 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 √s meast.



Heavy Flavour Programme

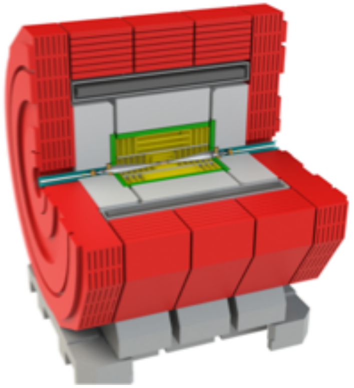
- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ √E level for invariant mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range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

Feebly Coupled Particles - LLPs

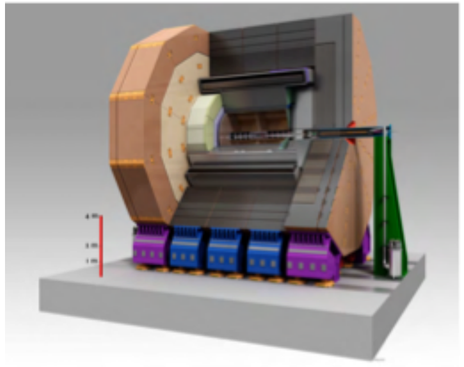
Benchmark signature: Z → νN, with N decaying late

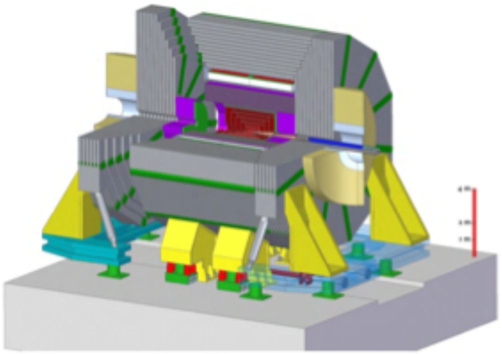
- Sensitivity to far-detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Precise timing for velocity (mass) estimate
- Hermeticity

High-energy e^+e^- Collider Detector Concepts



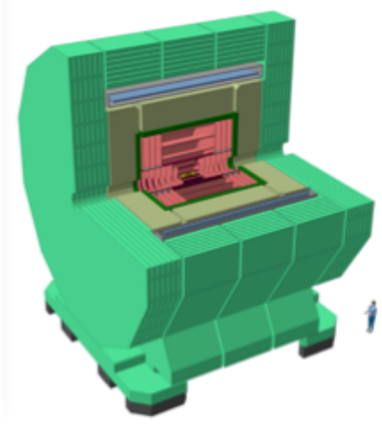
CLIC => **CLICdet**,
√s: 380 GeV, 1.5 TeV, 3 TeV



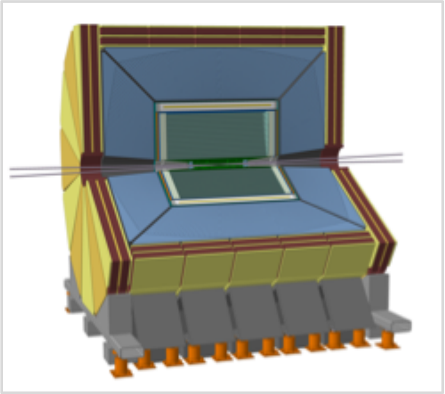


ILC => **ILD** and **SiD**:
√s: 250 – 500 GeV (1 TeV)

Strong solenoidal fields: 3.5 – 4 Tesla



Evolving concepts

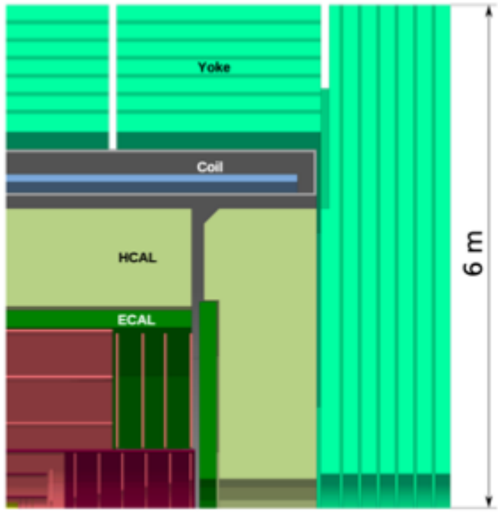


FCC-ee => **CLD, IDEA** and **LAr based concept**
√s: 90 - 365 GeV

Lower solenoidal fields: 2 Tesla
Beam has to survive crossing of field at 15 mrad angle

FCC-ee Evolving Detector Concepts Fast Overview

CLD



CDR

Conceptually extended from CLIC detector design

- Full silicon tracker
- High granularity silicon-tungsten ECAL
- High granularity scintilator-steel HCAL
- Instrumented return-yoke for muon detection
- Large 2 T coil surrounding calorimeter system

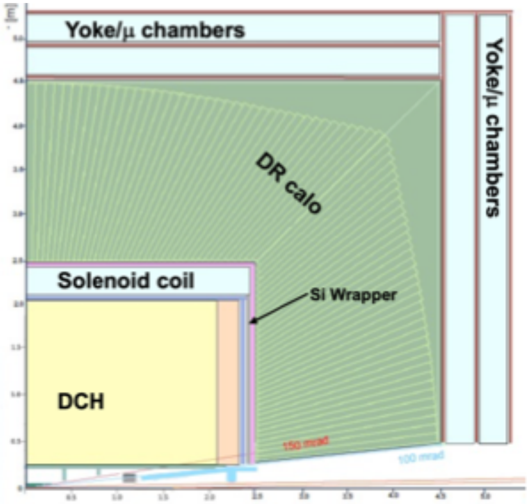
Engineering needed for adaptation to continous beam operation (no power pulsing)

- Cooling of Si-sensors & calorimeters

Possible detector optimisations

- Improved ECAL and momentum resolutions
- Particle identification (TOF and/or RICH)

IDEA



Specifically designed for FCC-ee (and CEPC)

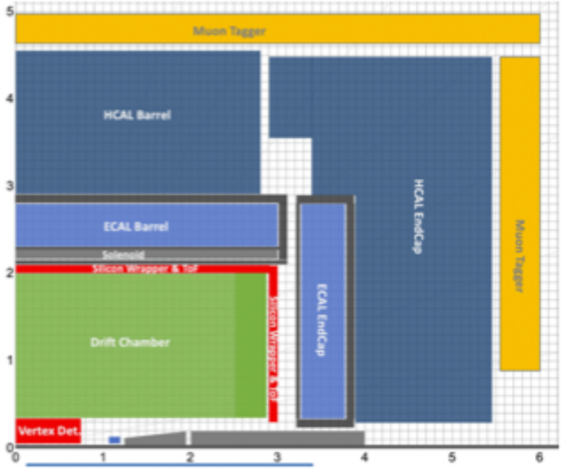
- Silicon vertex detector
- Low X_0 drift chamber with high-resolution particle ID via ionisation measurement
- Silicon wrapper around drift chamber
- Light, thin 2T coil inside calorimeter system
- Pre-shower detector based on MPGC
- Dual-readout calorimeter; copper -- scintilating + Cherenkov fibres
- Instrumented yoke with MPGC muon system

Possible detector optimisation

- Much improved EM energy resolution via crystal ECAL in front of coil

Noble-Liquid ECAL based

new



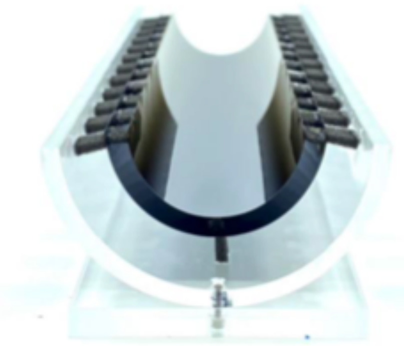
Specifically designed for FCC-ee, recent concept, under development

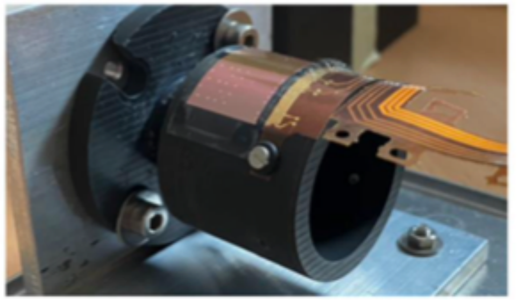
- Silicon vertex detector
- Low X_0 drift chamber with high-resolution particle ID via ionisation measurement
- Light, thin 2T coil inside same cryostat as ECAL
- High granularity Lead / Noble Liquid ECAL (LAr, possibly LKr)
- HCAL and muon systems to be specified

Vertex detector - Strong development: lighter, more precise, closer

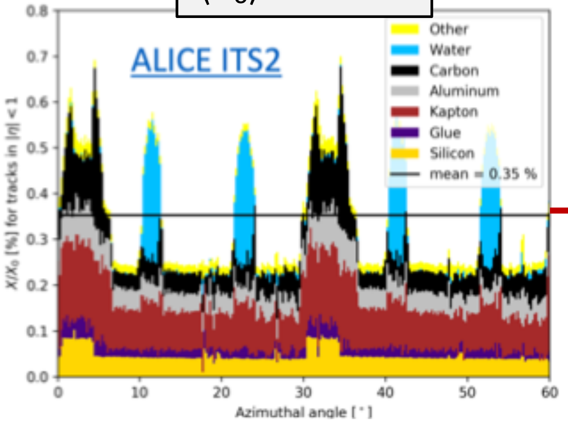
MAPS - Monolithic Active Pixel Sensors
- Readout electronics integrated in sensors

A. Ilg, L. Freitag,
6th FCC Physics Workshop

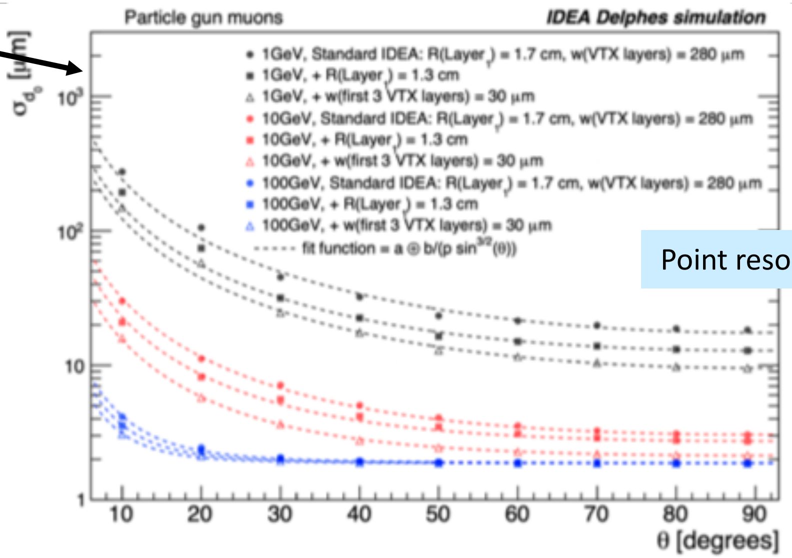




⟨X_0⟩ = 0.35%



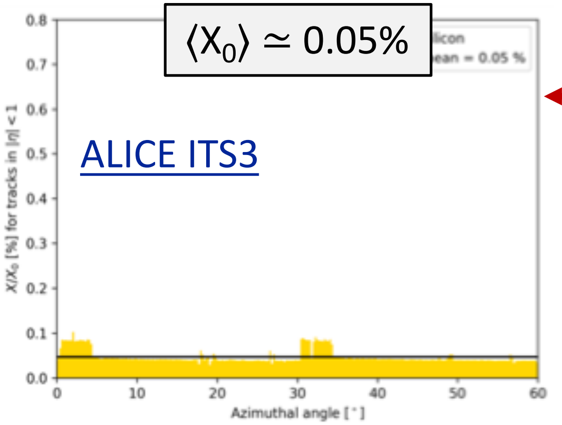
Closer, lighter: Substantial improvement in impact parameter resolution in particular at lower momenta



Point resolution: 3 μm

- Thinned (20—40 μm) silicon sensors bent around beam pipe
- Stiching to 300 mm wafer scale design;
- Support by carbon foam ribs
- Low power consumption => Air cooling

⟨X_0⟩ ≃ 0.05%



	r beam pipe	1st VTX layer
ILC	12 mm	14 mm
CLIC	29 mm	31 mm
FCC-ee	10 mm	12 mm

Impact parameter resolution "design goal" …

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

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

… exceeded with
a = 1.9 μm
b = 11 μm GeV

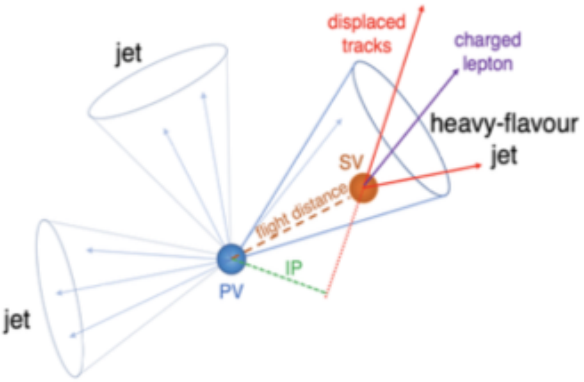
Vertex Detector - Heavy flavour tagging

Tagging methodology

Very substantial improvement wrt LHC

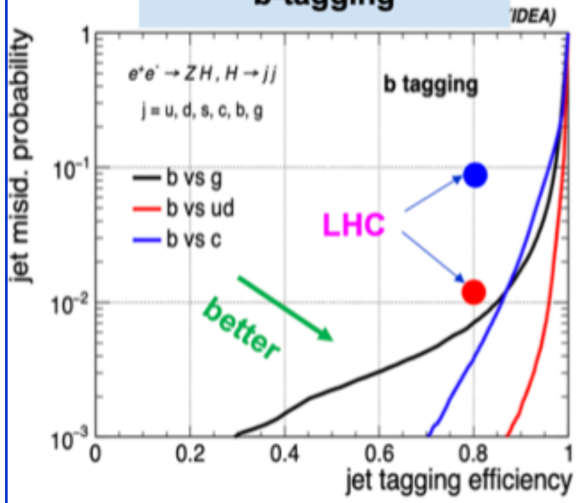
ML-based - ParticleNet
F.Bedeschi, M.Selvaggi, L.Goukas,
EPJ C 82 646 (2022) link

bottom/charm-tagging



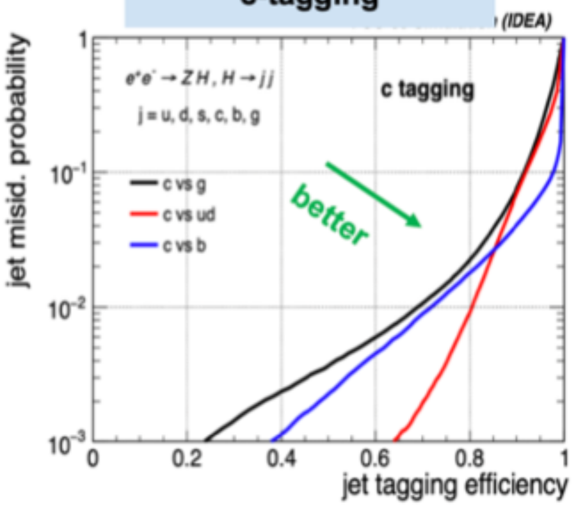
- Large lifetime
- Displaced vertices/tracks
- Large track multiplicity
- non-isolated e/μ

b-tagging



WP	Eff (b)	Mistag (g)	Mistag (ud)	Mistag (c)
Loose	90%	2%	0.1%	2%
Medium	80%	0.7%	<0.1%	0.3%

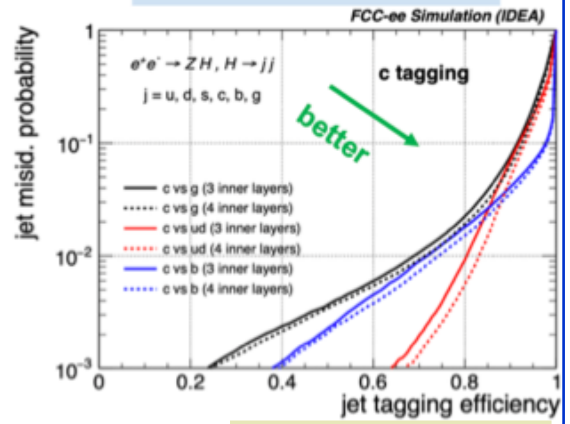
c-tagging



WP	Eff (c)	Mistag (g)	Mistag (ud)	Mistag (b)
Loose	90%	7%	7%	4%
Medium	80%	2%	0.8%	2%

c-tagging benefitting from extra layer

c-tagging [PIX layers]

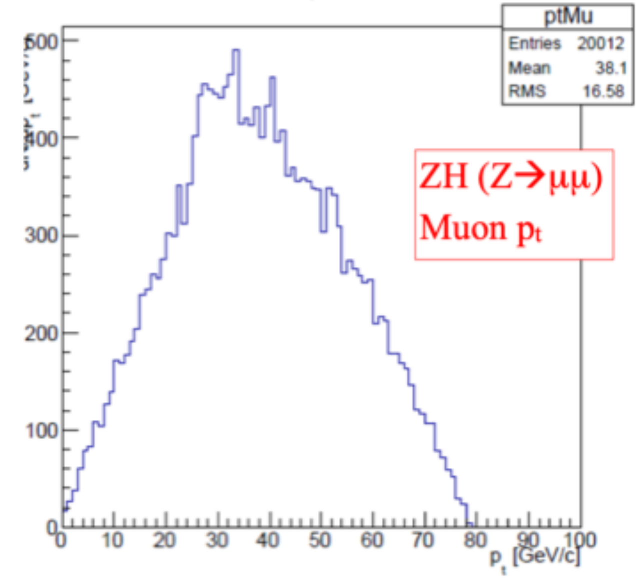


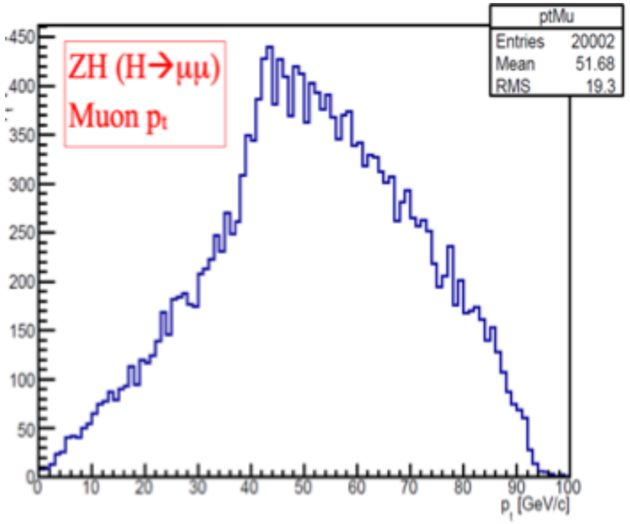
3 layers: closest at 15 mm
4 layers: add layer at 10 mm

- Additional pixel layer:
  - 2x improved BKG rejection in c-tagging
  - marginal/no improvement in b-tagging

Tracking - Momentum measurement (i)

Particles are generally of rather low p_T

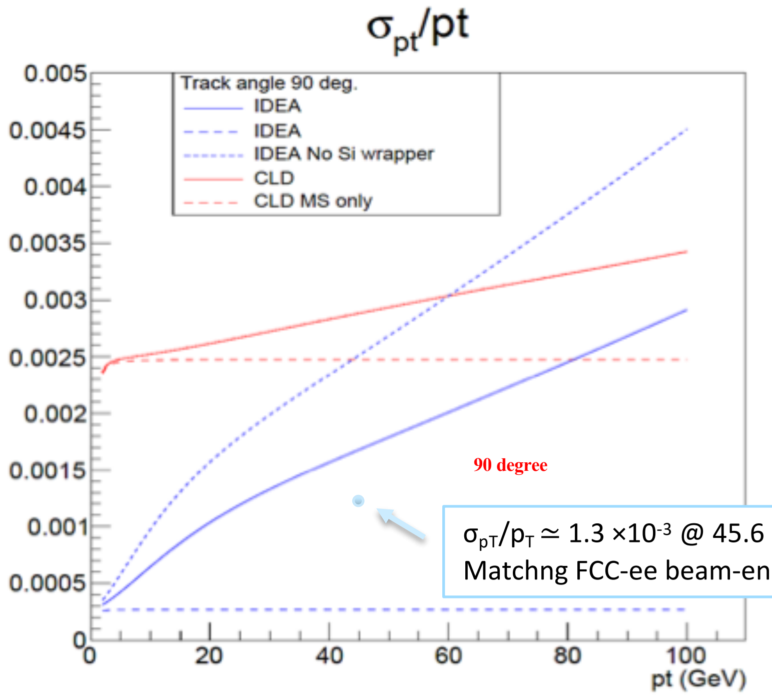




Momentum resolution is multiple scattering dominated

- Asymptotic resolution not reached

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



$\sigma_{p_T}/p_T \simeq 1.3 \times 10^{-3}$ @ 45.6 GeV
Matchng FCC-ee beam-energy spread

- CLD: Si tracker with total material budget of 11%
- IDEA: Drift Chamber as main tracking device with a material budget of 1.6%. Supplemented by VTX and Silicon ”wrapper” surrounding drift chamber.

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

Thinning of Si sensors helps (only) as √ of thickness

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

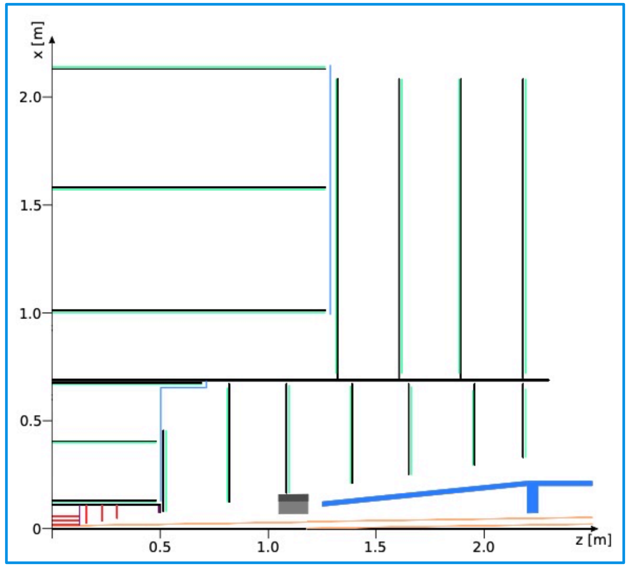
⇒ Detector transparency more important than asymptotic resolution ⇐

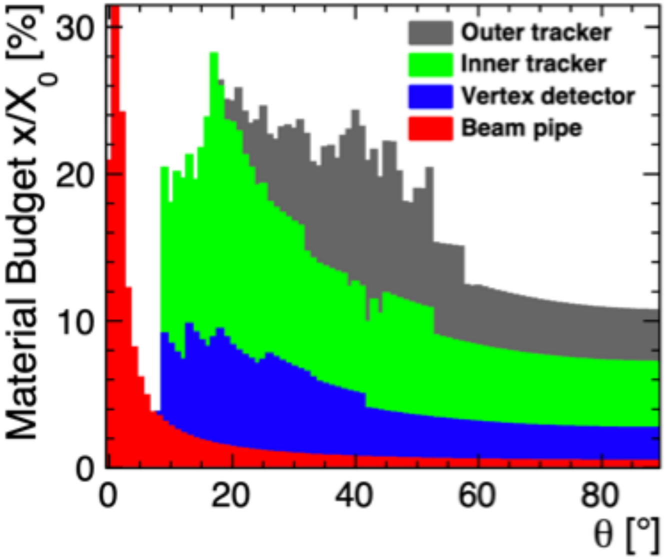
Tracking – Momentum measurement (ii)

Two solutions studied for CDR

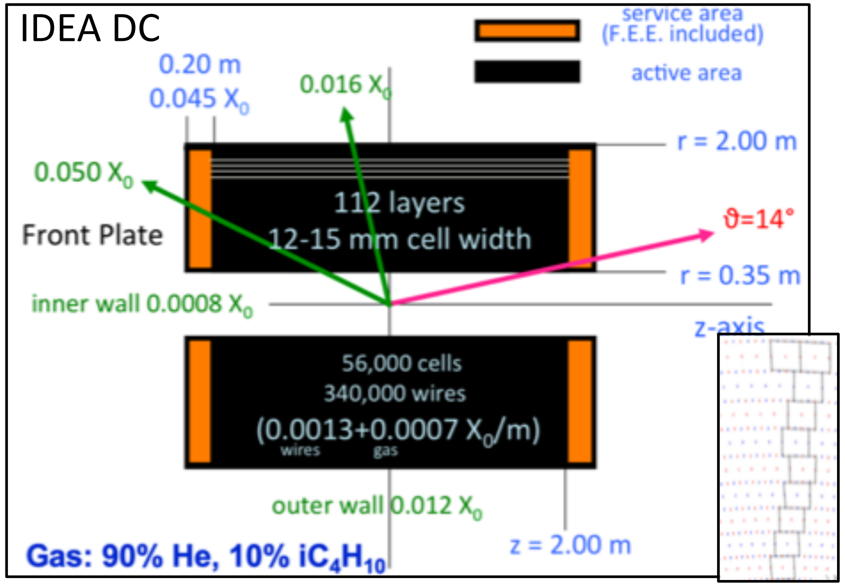
- **CLD**: All silicon: pixel VTX + strips tracker
  - ❑ VTX: 3 (3) barrel (fwd) double layers (.3% X_0 each)
  - ❑ Inner: 3 (7) barrel (fwd) layers (1.1-2.2% X_0 each)
  - ❑ Outer: 3 (4) barrel (fwd) layers (1.1-2.2% X_0 each)
  - ❑ Separated by support tube @ r= 675 mm (2.5% X_0)

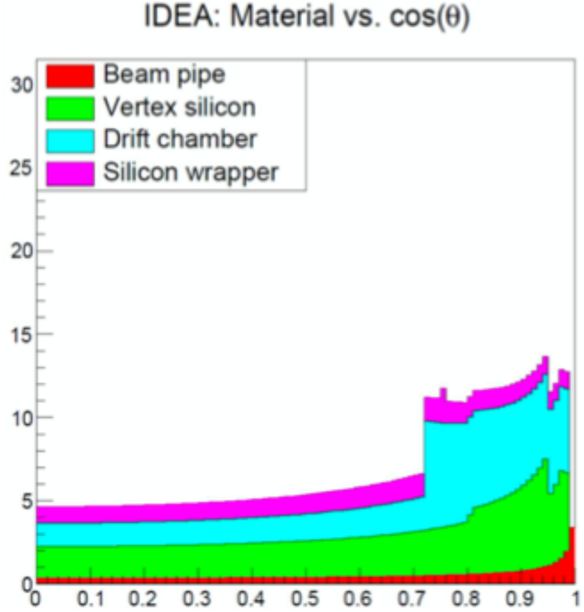
Multiple scattering limited
→ lighter Si tracker!?



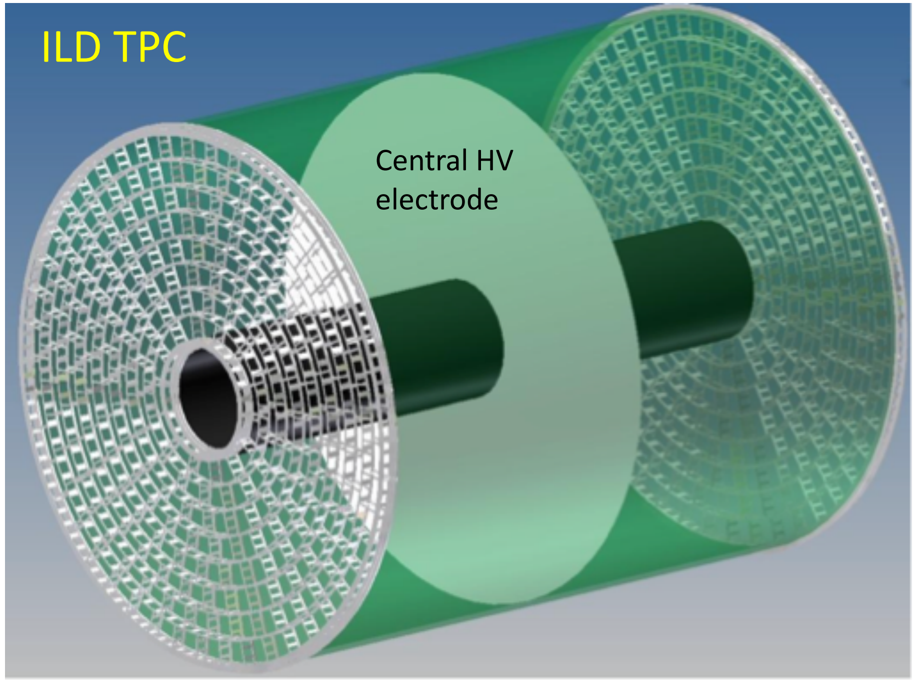


- **IDEA**: Extremely transparent Drift Chamber
  - ❑ Gas: 90% He – 10% iC_4H_{10}
  - ❑ Radius 0.35 – 2.00 m
  - ❑ Total thickness: 1.6% of X_0 at 90°
    - ❖ Tungsten wires dominant contribution
  - ❑ 112 layers for each 15° azimuthal sector
  - ❑ Max drift time: 350 ns
  - ❑ Full system includes Si VXT and Si "wrapper"
  - ❑ Continous tracking
    - ❖ Reconstruction of far-detached vertices (K^0_S, Λ, LLPs)



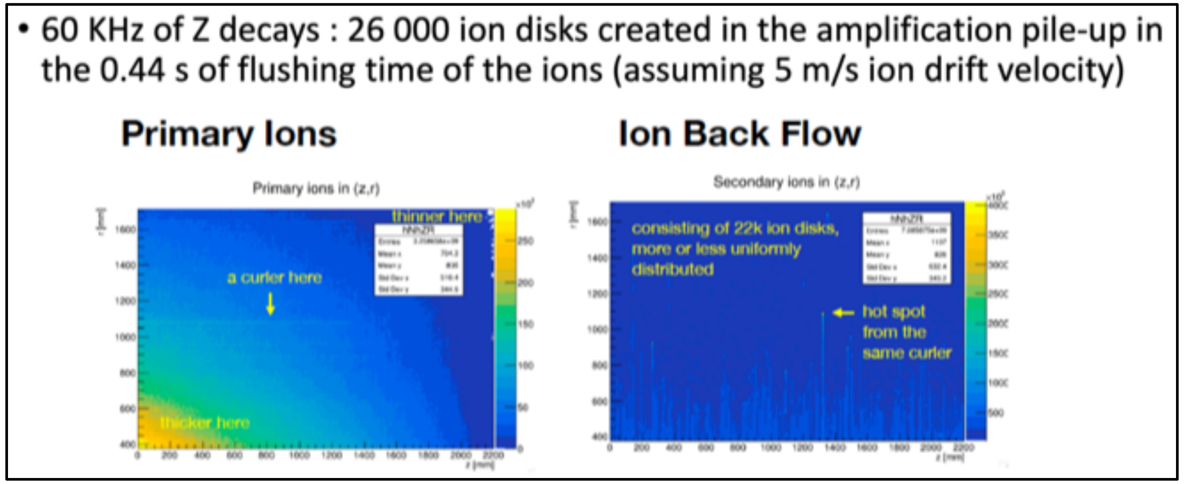


A TPC for FCC-ee ?



- Pros
  - Low material budget; powerfull dE/dx measurement
- Challenges at FCC-ee
  - Particularly at Z-pole, very high event rate of ~65 kHz
  - Continous beams; no gaps to ”clean” detector
    - Space charge from positive ions as at ALICE
  - Weaker solenoidal field than at linear colliders (2 T vs. 4T)
    - Weaker focussing of drifting electrons

- Ongoing studies within LCTPC Collaboration, link



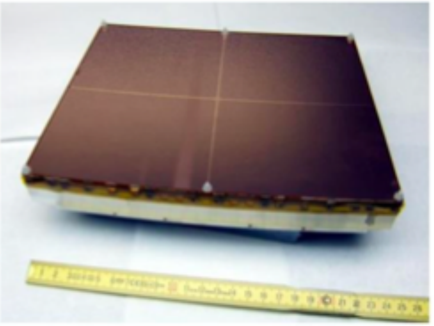
- 60 KHz of Z decays : 26 000 ion disks created in the amplification pile-up in the 0.44 s of flushing time of the ions (assuming 5 m/s ion drift velocity)

Primary Ions **Ion Back Flow**

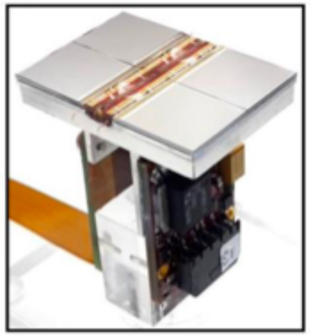
- TPC R&D – Three main options for readout under study

Micromegas

GEM



Gridpix



Calorimetry – Jet Energy Resolution

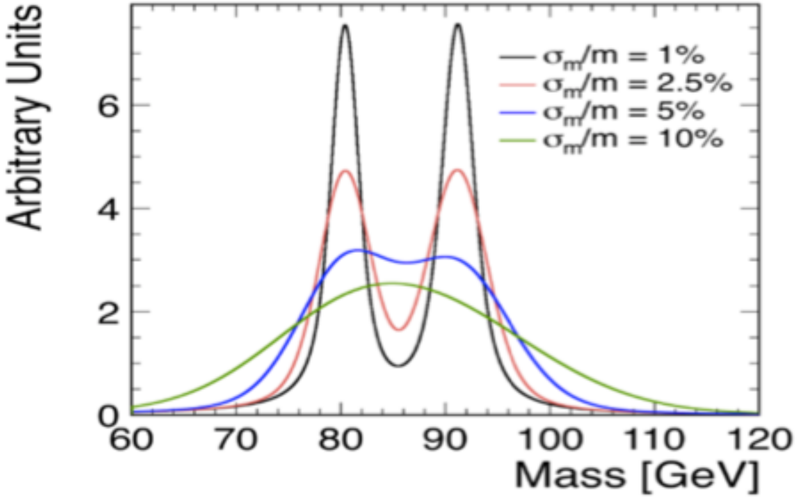
Energy coverage < 300 GeV : $22\ X_0,\ 7\lambda$

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

⇒ Mass reconstruction from jet pairs

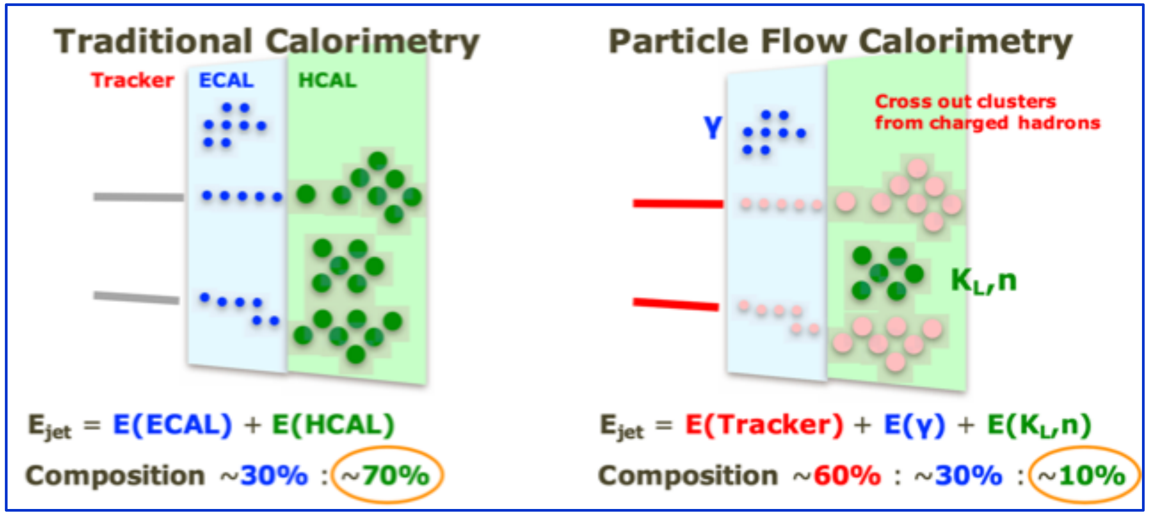
Resolution important for control of (combinatorial) backgrounds in multi-jet final states

- 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



How to reach jet energy resolutions of 3-4% at 50 GeV:

- **Highly granular calorimetes**
- **Particle Flow Analysis techniques**
- The above possible combined with techniques to correct for non-compensation (e/h ≠ 1), e.g. *dual readout*



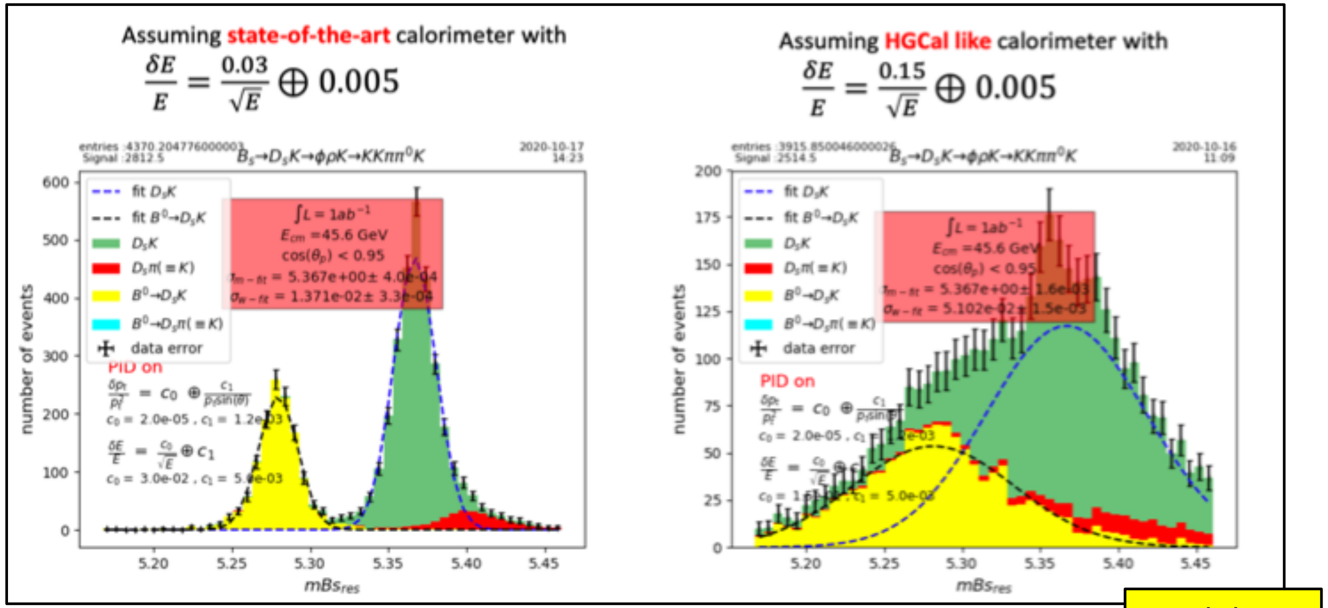
High granularity !
Possibly combined with dual readout

Calorimetry – ECAL Resolution

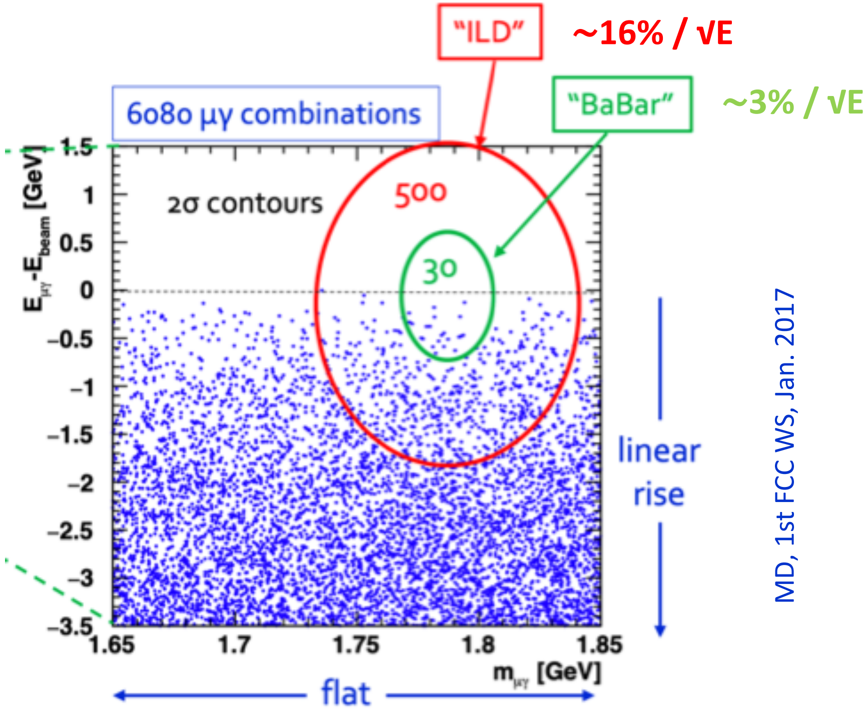
Much improved heavy flavour physics reach from improved ECAL resolution

For b-physics by making accesible exclusive channels with π^0's

Search limits for rare decays involving γ's.
- Here LFV decay $\tau \rightarrow \mu\gamma$
- ”BaBar” ~20 times better than ”ILD”



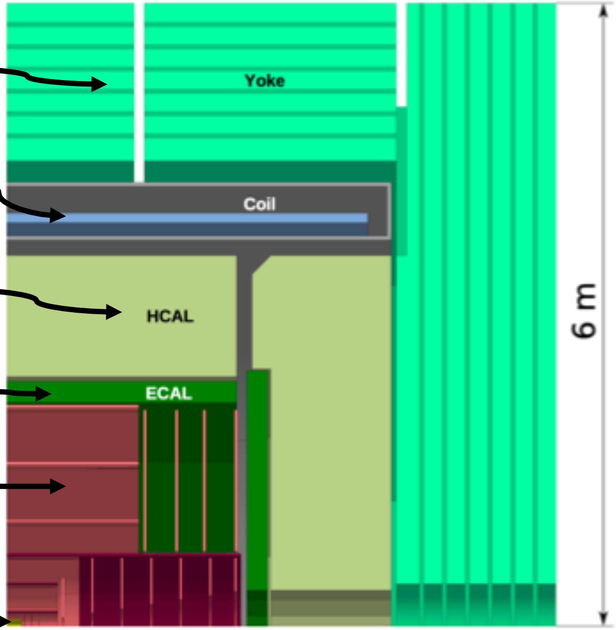
R. Aleksan



MD, 1st FCC WS, Jan. 2017

CLD Calorimetry

General purpose detector for Particle Flow reconstruction



- ➢ Return Yoke with RPCs for muon ID
- ➢ Superconducting Solenoid of 2 T
- ➢ Steel-Scintillator HCAL with 3 cm cell size
- ➢ Silicon-Tungsten ECAL with 5 mm cell size
- ➢ Silicon tracker mostly 50 µm pitch strips
- ➢ Vertex detector with 25 µm pixels

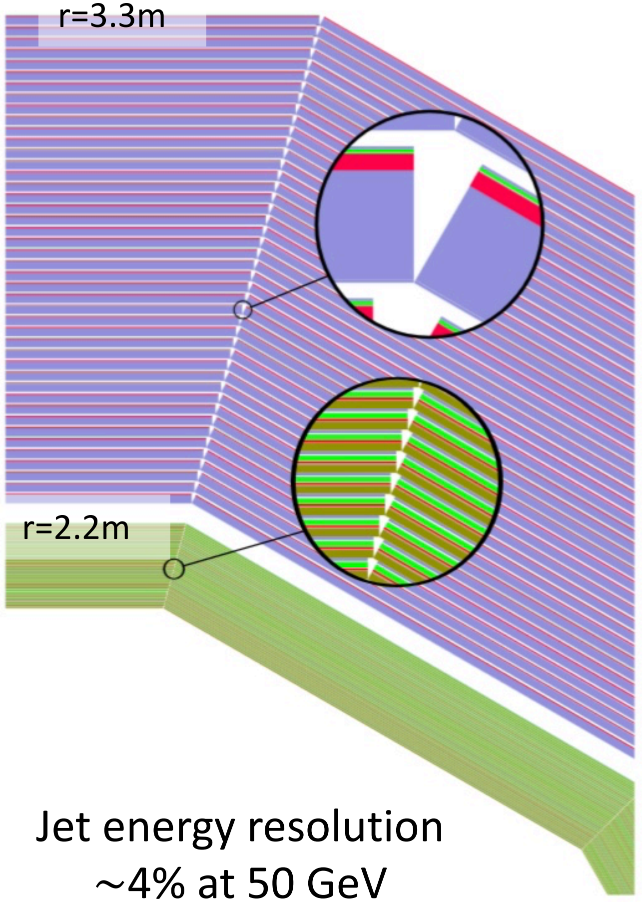
HCAL

- 44 layers, 19 mm steel absorber, 55 (+1) λ
- 3 mm thick scintillator tiles with 3×3 cm^2 granularity

ECAL

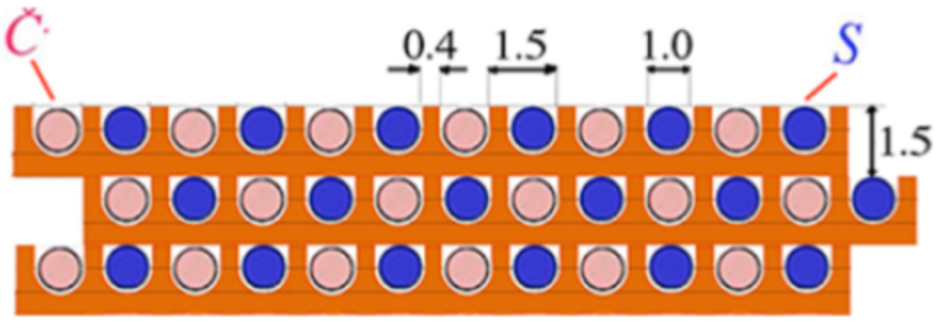
- 40 layers, 1.9 mm tungsten absorbers, 22 X_0
- 0.5 mm thick silicon sensors with 5×5 mm^2 granularity
- ECAL optimisation studies

$$\boxed{\frac{\sigma}{E} \approx \frac{16\,\%}{\sqrt{E}}}$$



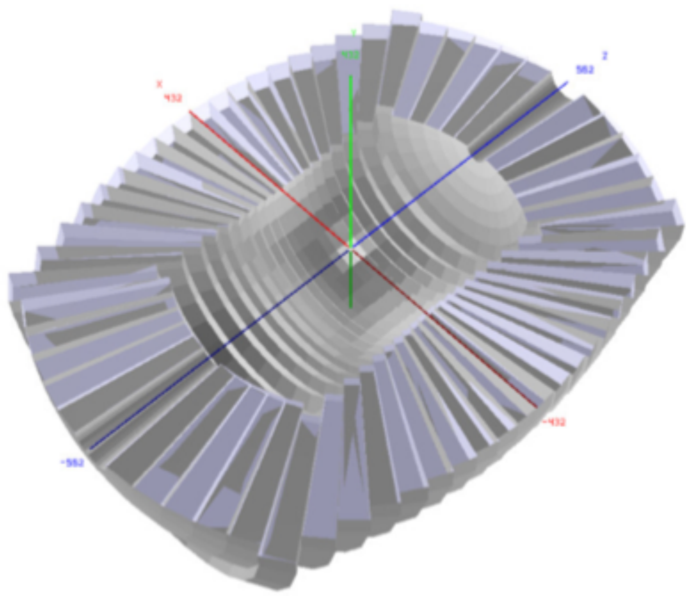
Jet energy resolution
~4% at 50 GeV

Dual Readout Calorimetry



Alternate

- Scintillation fibres
- Cherenkov fibres



- Measure simultaneously:
  - Scintillation signal (S)
  - Cherenkov signal (C)
- Calibrate both signals with e⁻
- Unfold event by event f_{em} to obtain corrected energy

$$S = E[f_{em} + (h/e)_S(1 - f_{em})]$$

$$C = E[f_{em} + (h/e)_C(1 - f_{em})]$$

$$E = \frac{S - \chi C}{1 - \chi} \quad \text{with:} \quad \chi = \frac{1 - (h/e)_S}{1 - (h/e)_C}$$

Full GEANT4 simulation:

Single hadron:

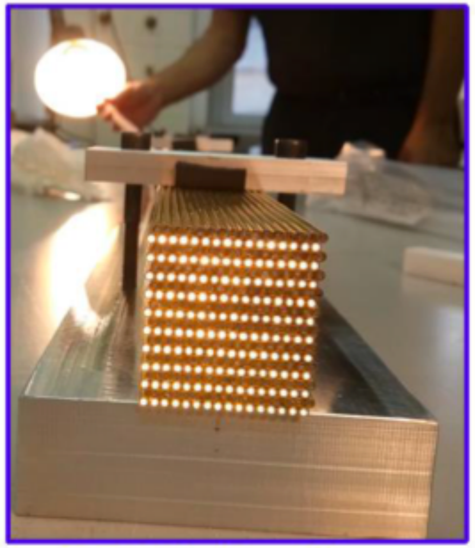
$$\frac{\sigma}{E} = \frac{31\%}{\sqrt{E}} + 0.4\%$$

Electromagnetic:

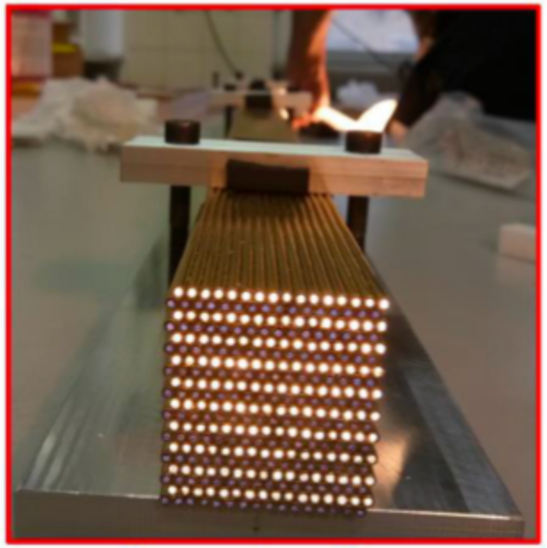
$$\frac{\sigma}{E} = \frac{13.0\%}{\sqrt{E}} + 0.2\%$$

Crystal option:
20 cm $PbWO_4$

$$\frac{\sigma}{E} \approx \frac{3\,\%}{\sqrt{E}}$$



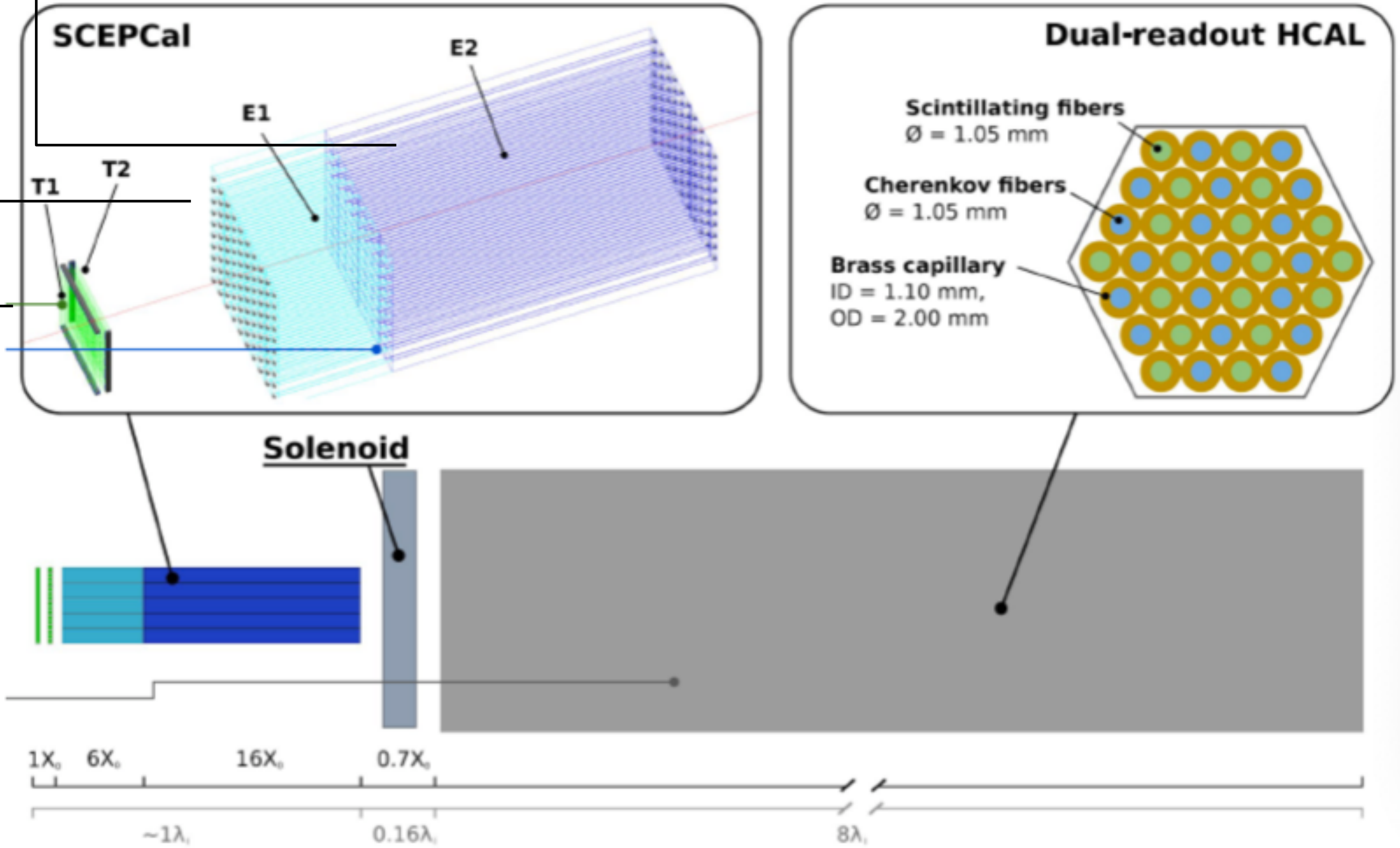
Scintillation fibers

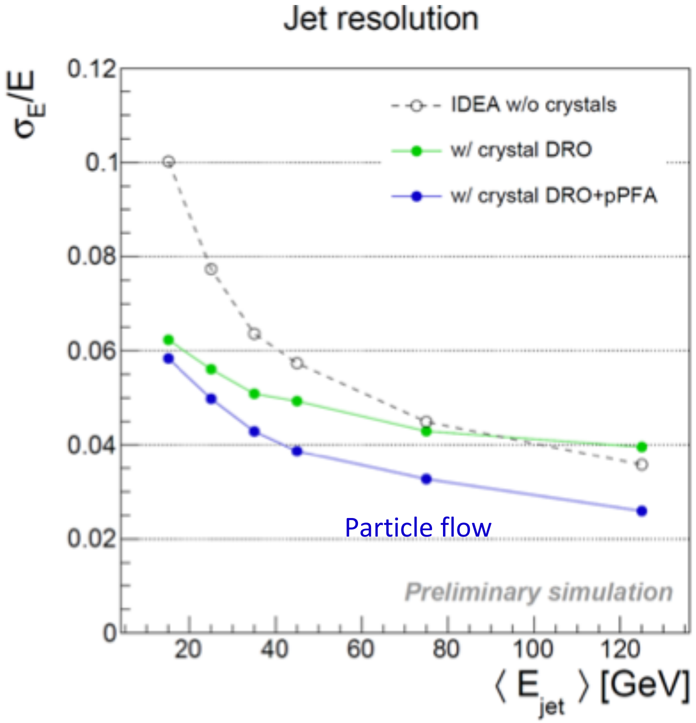


Cherenkov fibers

IDEA Crystal ECAL Option

- PbWO crystals
- Front segment 5 cm; ~5.4 X_0
- Rear segment for core shower
  - 15 cm; ~16.3 X_0
- 10 × 10 × 200 mm³ of crystals
- $\sigma_{EM} \approx 3\% / \sqrt{E}$
- Timing layer: LYSO 20—30 ps

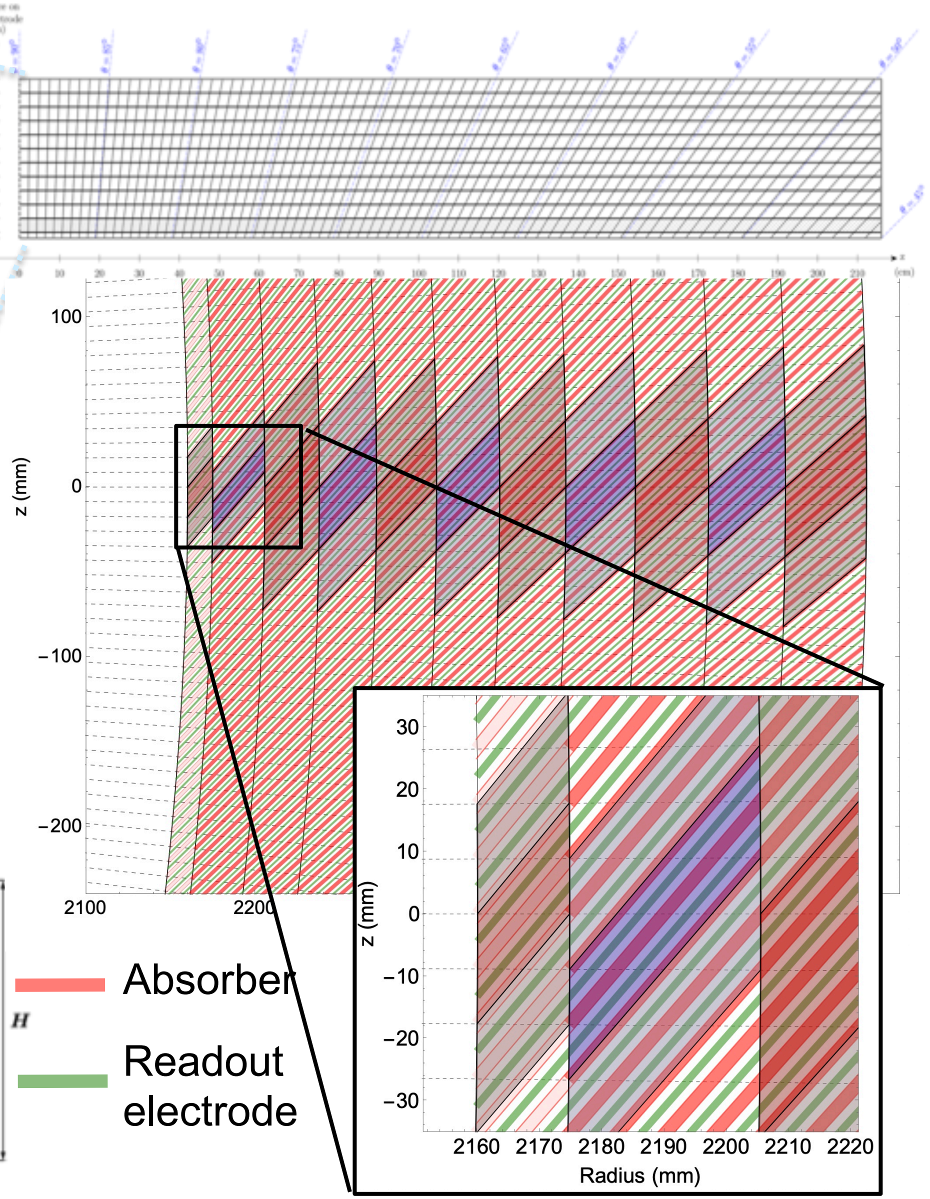




High Granularity Noble-Liquid Calorimeter

Baseline design

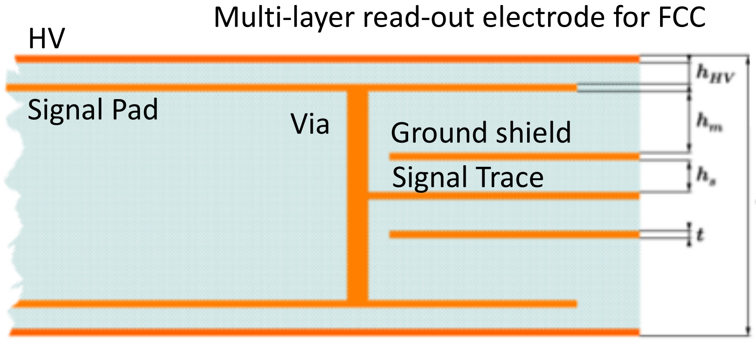
- 1536 straight inclined (50.4°) 1.8mm Pb absorber plates
- Multi-layer PCBs as readout electrodes
- 1.2 – 2.4mm LAr gaps
- 40 cm deep (≈ 22 X_0)
- Segmentation:
    - ❑ $\Delta\theta$ = 10 (2.5) mrad for regular (1st comp. strip) cells,
    - ❑ $\Delta\phi$ = 8 mrad
    - ❑ → cell size in strips: 5.4mm x 17.8mm x 30mm
- 11 longitudinal compartments
- Implemented in FCC-SW Fullsim



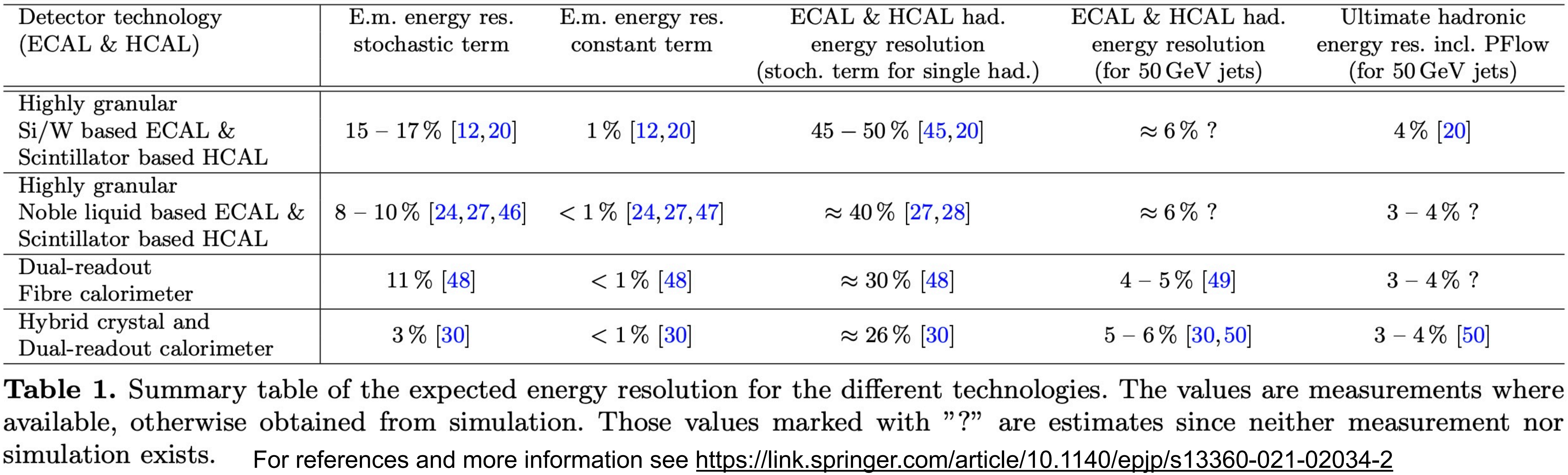
Possible options

- LKr or Lar, W or Pb absorbers
- Absorbers with growing thickness
- Granularity optimization
- Al or carbon fibre cryostat
- Warm or cold electronics

Multi-layer read-out electrode for FCC



Calorimetry



Detector technology (ECAL & HCAL)	E.m. energy res. stochastic term	E.m. energy res. constant term	ECAL & HCAL had. energy resolution (stoch. term for single had.)	ECAL & HCAL had. energy resolution (for 50 GeV jets)	Ultimate hadronic energy res. incl. PFlow (for 50 GeV jets)
Highly granular Si/W based ECAL & Scintillator based HCAL	15 – 17 % [12,20]	1 % [12,20]	45 – 50 % [45,20]	≈ 6 % ?	4 % [20]
Highly granular Noble liquid based ECAL & Scintillator based HCAL	8 – 10 % [24,27,46]	< 1 % [24,27,47]	≈ 40 % [27,28]	≈ 6 % ?	3 – 4 % ?
Dual-readout Fibre calorimeter	11 % [48]	< 1 % [48]	≈ 30 % [48]	4 – 5 % [49]	3 – 4 % ?
Hybrid crystal and Dual-readout calorimeter	3 % [30]	< 1 % [30]	≈ 26 % [30]	5 – 6 % [30,50]	3 – 4 % [50]

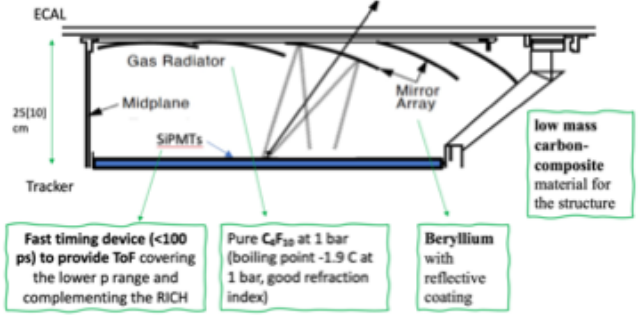
Table 1. Summary table of the expected energy resolution for the different technologies. The values are measurements where available, otherwise obtained from simulation. Those values marked with "?" are estimates since neither measurement nor simulation exists.

For references and more information see https://link.springer.com/article/10.1140/epjp/s13360-021-02034-2

- **Excellent Jet resolution:** ≈ 30%/√E
- **ECAL resolution:** Higgs physics ≈ 15%/√E; but for heavy flavour programme better resolution beneficial → 8%/√E → 3%/√E
- **Fine segmentation for PF algorithm** and powerful **γ/π⁰ separation** and measurement
- **Other concerns:** Operational stability, cost, …
- **Optimisation ongoing for all technologies:** Choice of materials, segmentation, read-out, …

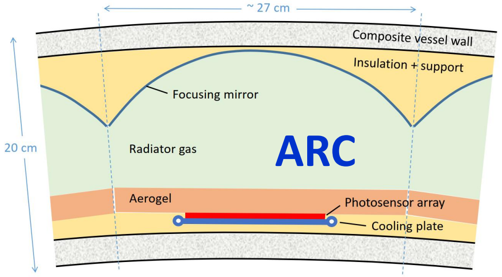
Particle Identification

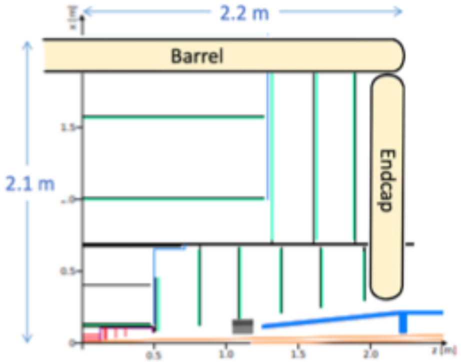
- **PID capabilities across a wide momentum range** is essential for flavour studies; will enhance overall physics reach
  - Example: important mode for CP-violation studies $B^0_S \rightarrow D^{\pm}_S K^{\mp}$ → require K/π separation over wide momentum range to suppress same topology $B^0_S \rightarrow D^{\pm}_S \pi^{\mp}$
- **E.g. IDEA drift chamber** promises >3σ π/K separation all the way up to 100 GeV
  - Cross-over window at 1 GeV, can be alleviated by unchallenging TOF measurement of $\delta T \lesssim 0.5$ ns
- **Time of flight (TOF) alone** δT of ~10 ps over 2 m (LGAD, TORCH)
  - could give 3σ π/K separation up to ~5 GeV
- **Alternative approaches**, in particular (gaseous) **RICH** counters are also investigated (e.g. A pressurized RICH Detector – **ARC**)
  - → could give 3σ π/K separation from 5 GeV to ~80 GeV

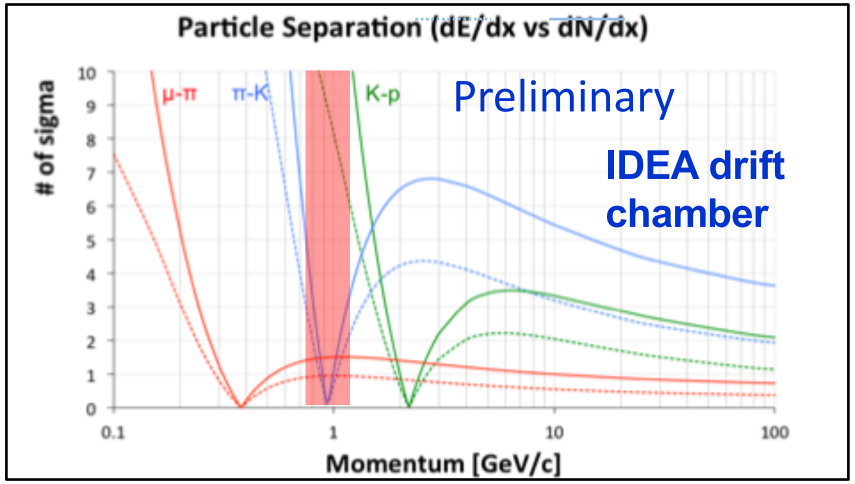


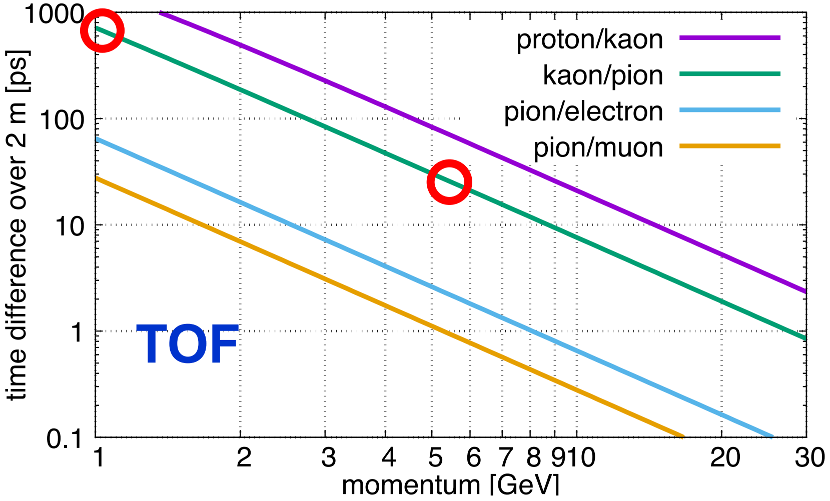
FCC Workshop, Feb. 2022

Possible RICH layout in an FCC-ee experiment

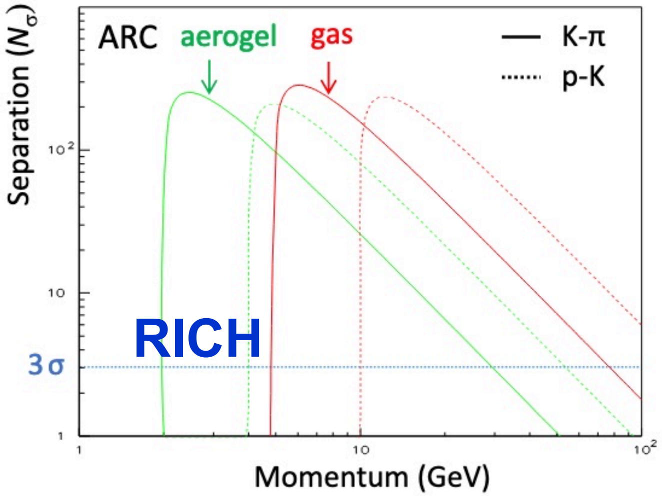








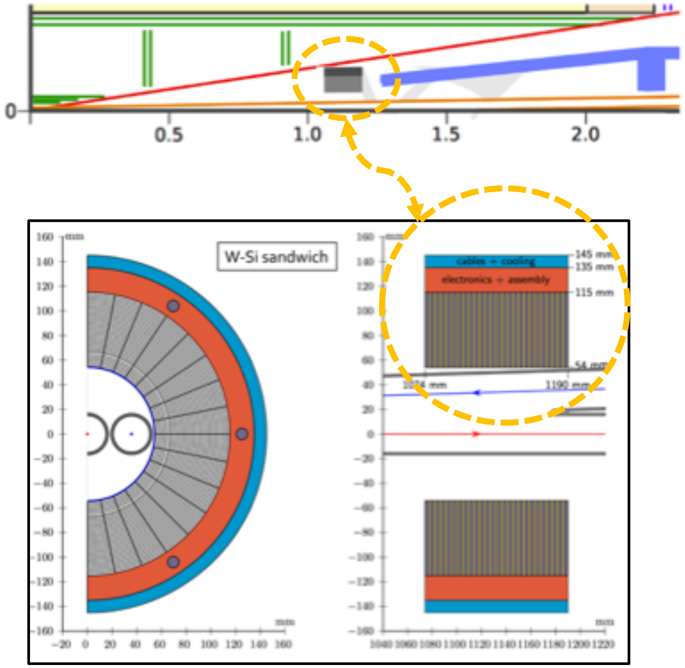
Preliminary! analytic calc., assumes focusing target achieved



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 $\lesssim 10^{-5}$

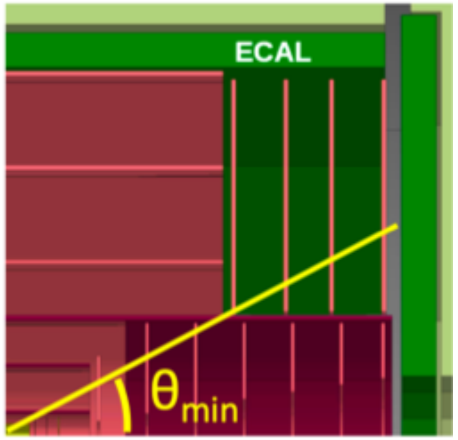
Luminosity Monitors (low angle Bhabha)



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

Complementary lumi process: large angle $e^+e^- \to \gamma\gamma$
- $10^{-4} \Rightarrow$ control of acceptance boundary $\delta\theta_{min}$ to **$\mathcal{O}(50\ \mu\text{rad})$**
- Possible bckg: $Z \to \pi^0\gamma \Rightarrow$ need to control $\mathcal{B}(Z\to\pi^0\gamma)$ to 10^{-7}

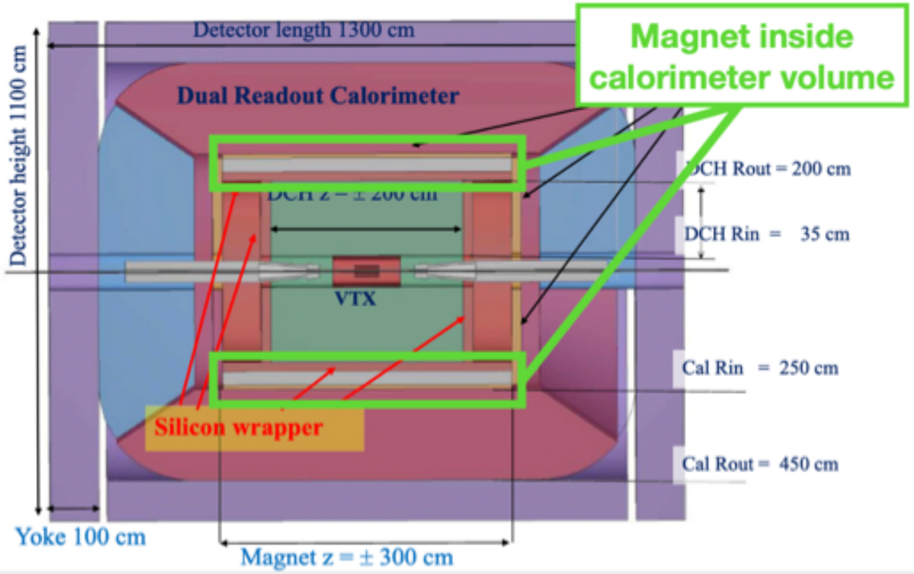
Acceptance of $Z \to \ell\ell$ to 10^{-5}
- Control of acceptance boundary $\delta\theta_{min}$ to **$\mathcal{O}(50\ \mu\text{rad})$**
- No holes or cracks



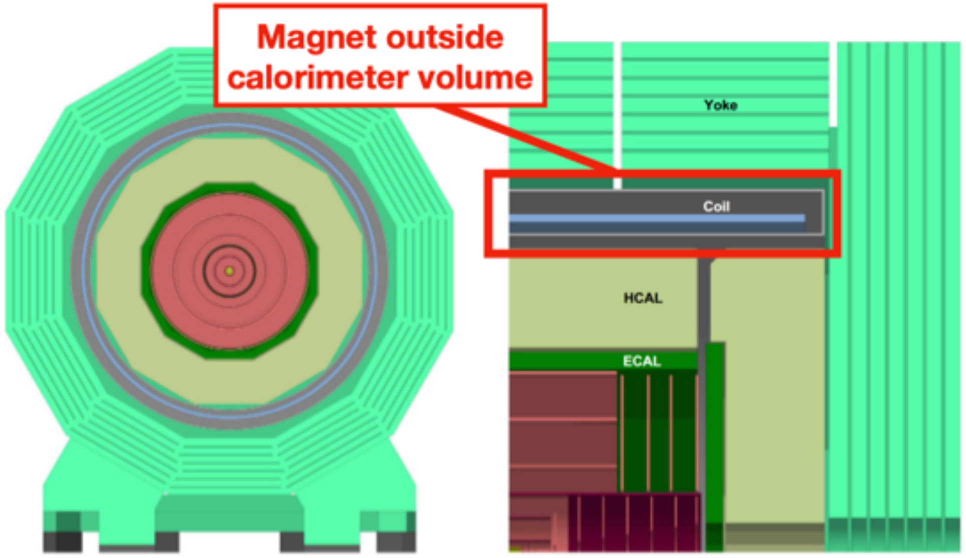
Solenoid Magnet

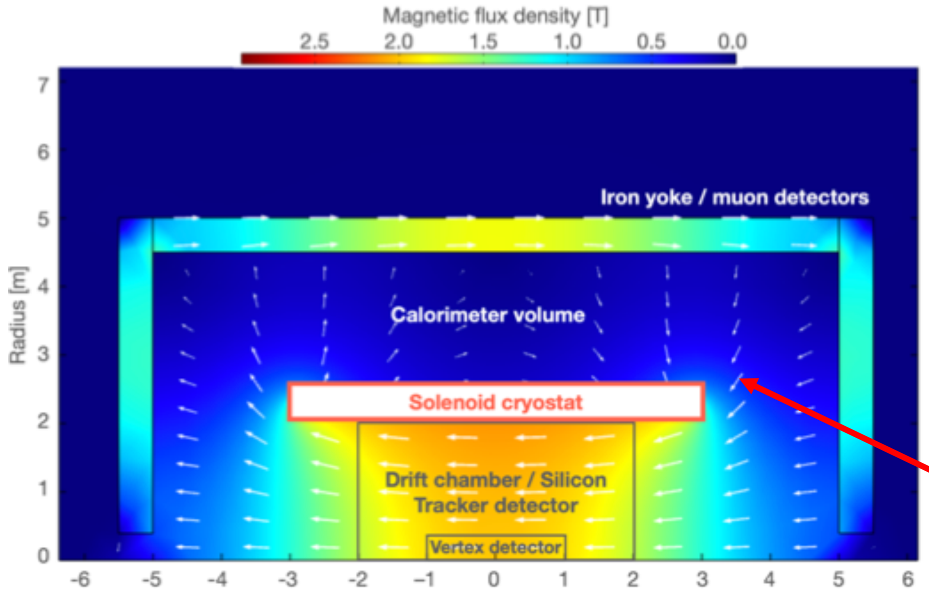
Nikkie Deelen,, FCC Workshop Feb. 2022

International Detector for Electron-positron Accelerators

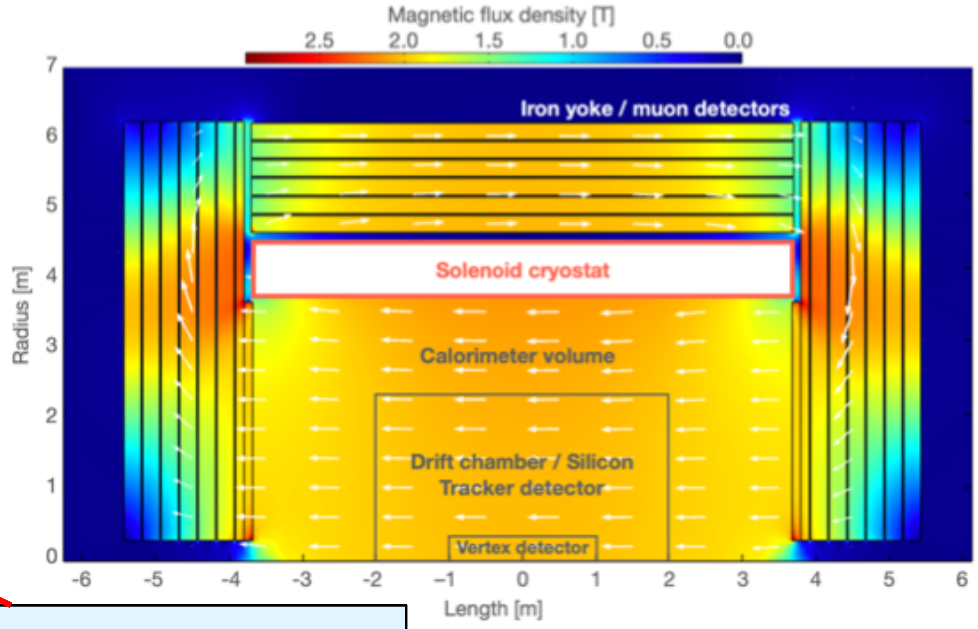


CLIC-Like Detector





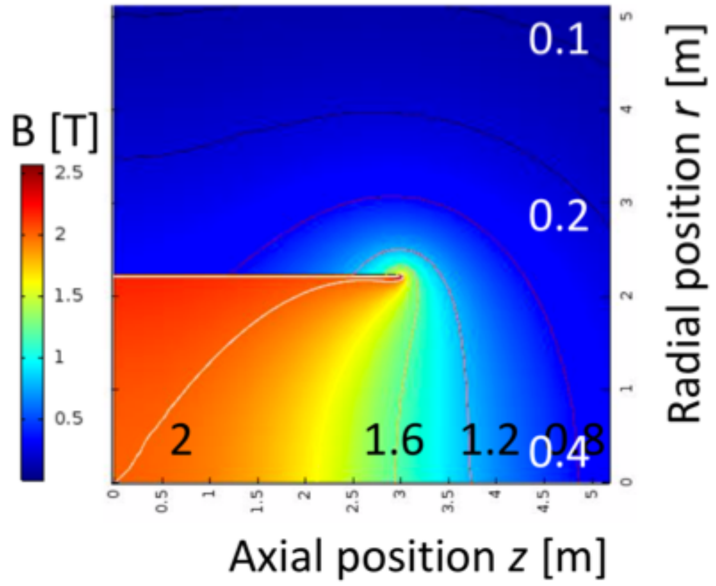
Transparency of the cold mass: 0.76 X_0
Energy density: ~14 kJ/kg [2]



For crystal IDEA:

- Hybrid solution; coil between ECAL and HCAL

2 T "light and thin" Solenoid inside Calorimeter



Property	Value
Magnetic field in center [T]	**2**
Free bore diameter [m]	4
Stored energy [MJ]	**170**
Cold mass [t]	8
Cold mass inner radius [m]	2.2
Cold mass thickness [m]	0.03
Cold mass length [m]	6

H. Ten Kate et al.

- **Objectives**
  - **Light**: certainly less than 1 X_0
  - **Thin**: As thin as possible for optimal tracker-to-calorimeter matching
- Self-supporting single layer coil
  - High yield strength conductor fully bonded
  - Thin Al support cylinder
- Coil composition
  - Aluminum (77 vol.%)
  - NbTi (5 vol.%) / copper (5 vol.%)
  - Glass-resin-dielectric films (13 vol.%)
- Radiation thickness (preliminary studies)
  - Cold mass: $X_0 \approx 0.46$
  - Cryostat (25 mm Al): $X_0 \approx 0.28$
  - Total $X_0 \approx 0.75$ achievable
  - Total radial envelope less than 30 cm
- Prospects for even lighter and thinner outer shell

reinforced

corrugated

honeycomb-like

A few words on Readout, DAQ, Data Handling

- In particular at Z-peak, challenging conditions
  - 50 MHz BX rate
  - 70 kHz Z rate + ~100 kHz LumiCal rate
  - Absolute normalisation goal 10^{-4}
- Different sub-detectors tend to prefer different integration times
  - Silicon VTX/tracker sensors: $\mathcal{O}$(μs) [also to save power]
    - Time-stamping will be needed
  - LumiCal: Preferential at ~BX frequency (20 ns)
    - Avoid additional event pileup
- How to organize readout?
  - **Hardware trigger** with latency buffering a la LHC ??
    - Probably not…
    - Which detector element would provide the trigger ?
  - **Free streaming** of self-triggering sub-detectors; event building based on precise time stamping
    - Need careful treatment of relative normalisation of sub-detectors – 10^{-5} level

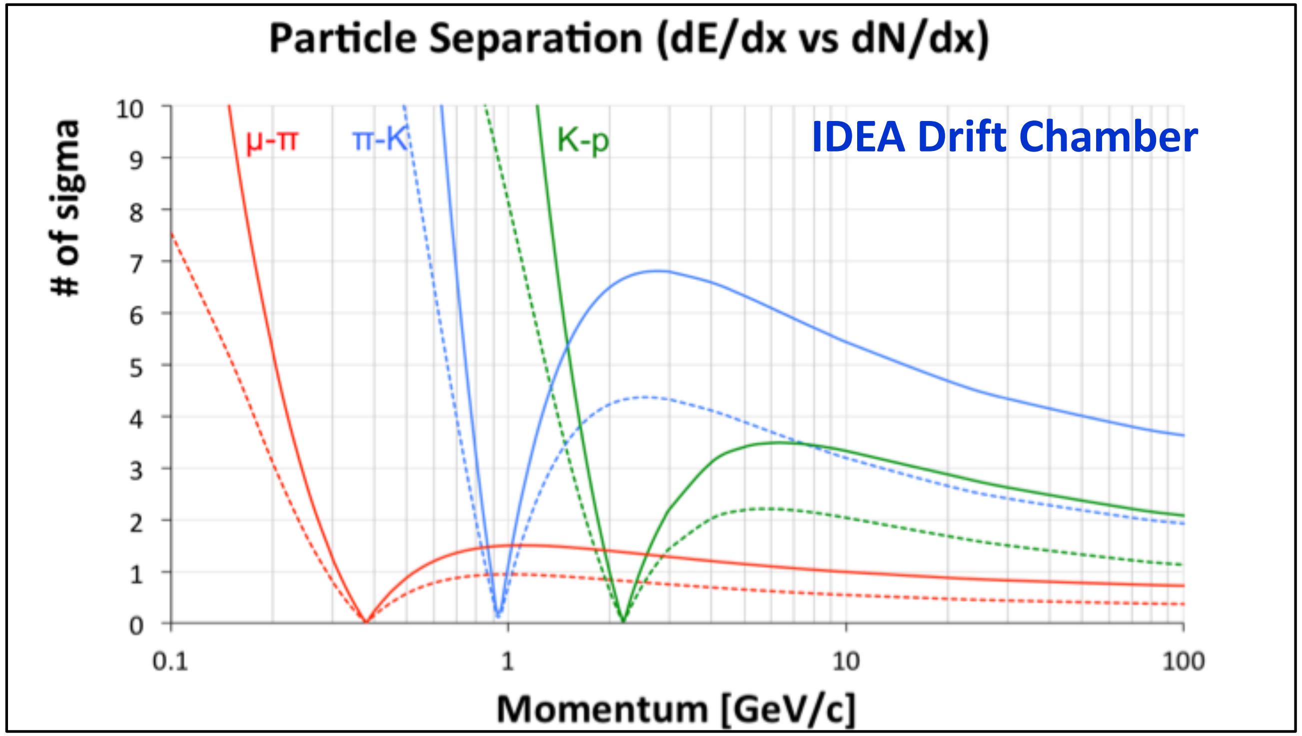
- Need to consider DAQ issues when designing detectors and their readout

- Off-line handling of $\mathcal{O}(10^{13})$ events for precision physics
  - … and Monte Carlo

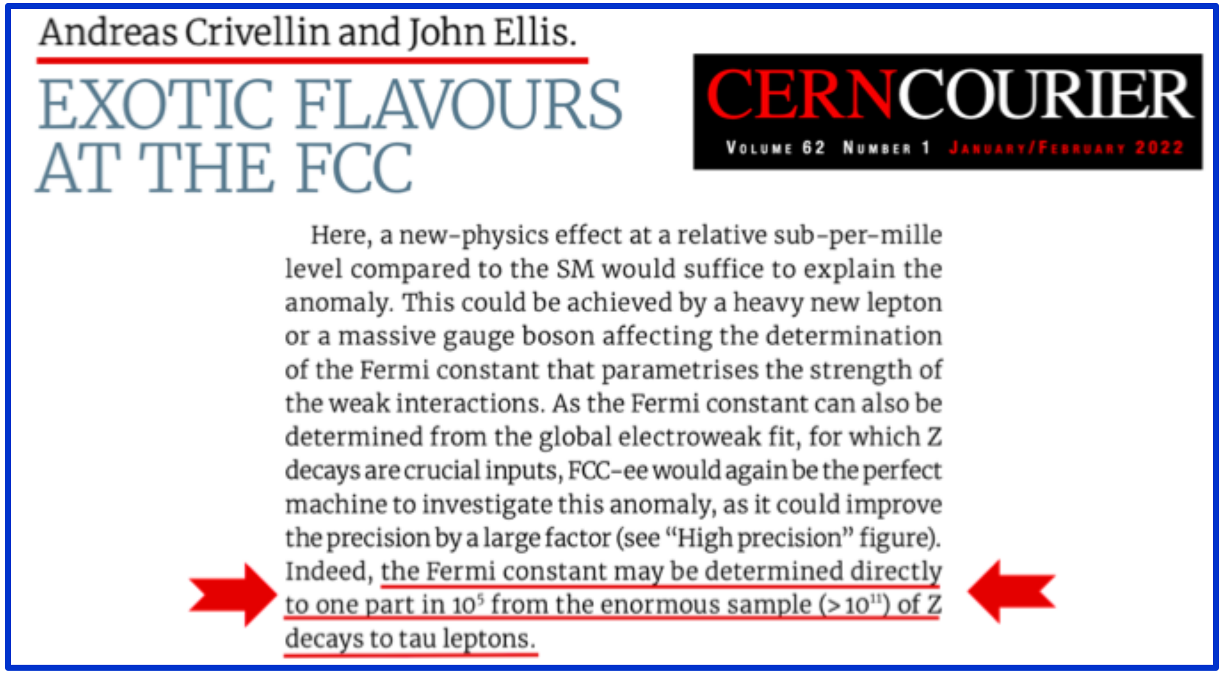
-LHCb DAQ upgrade
-Detectors at EIC

Redundancy, redundancy, redundancy

- For the control of systematic uncertaities, experimental redundancy is essential
  - Example: calorimetric separation of e/π, e/μ, π/μ
  - A powerful independent, non-destructive identification tool allows to establish clean test samples of e, π, μ to study their calorimetric response
  - This is what a powerful dE/dx measurement provides you!
    - As once at LEP and some day at FCC-ee



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

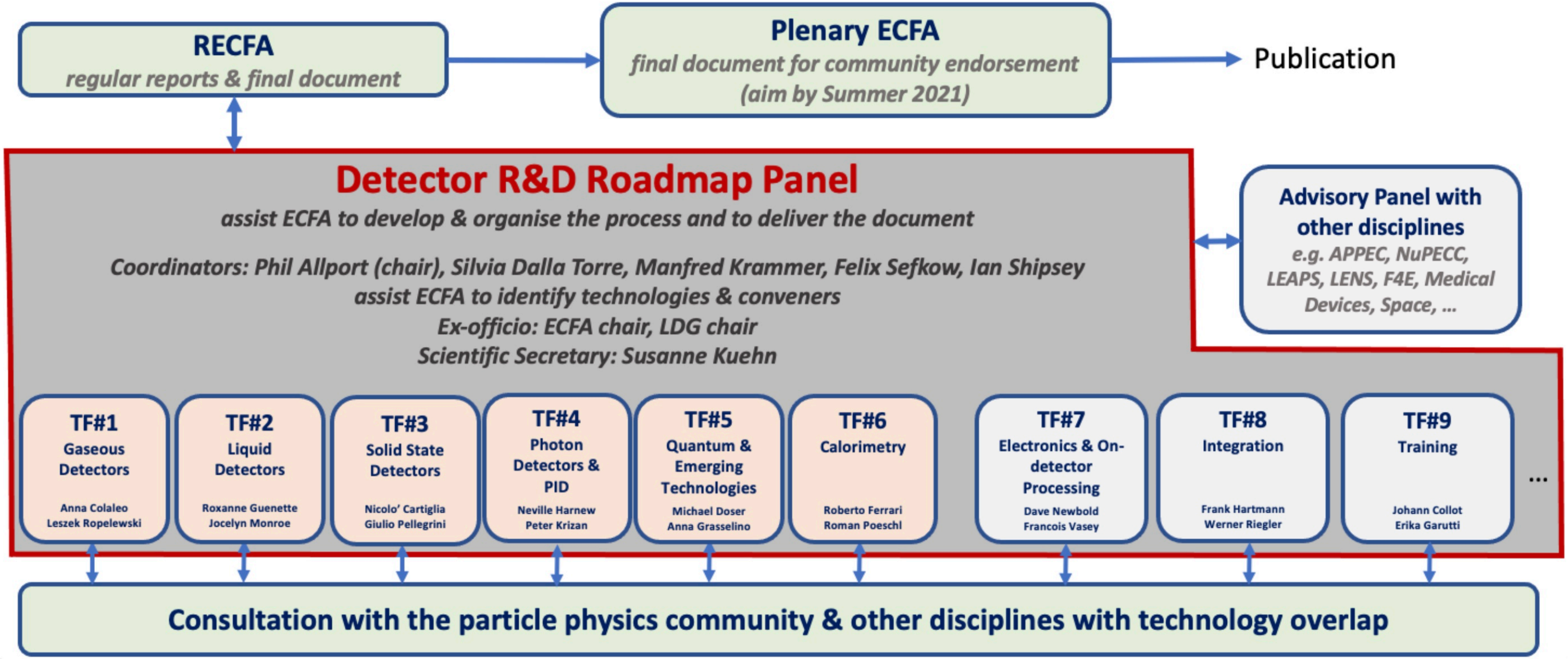
FCC-ee: Will see 5×10^{11} τ decays
Statistical uncertainties at the 10 ppm level
How well can we control systematics?

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

On the τ lifetime measurement, see link

ECFA Detector Roadmap Implementation

https://indico.cern.ch/event/957057/



RECFA
regular reports & final document

Plenary ECFA
final document for community endorsement
(aim by Summer 2021)

Publication

Detector R&D Roadmap Panel
assist ECFA to develop & organise the process and to deliver the document

Coordinators: Phil Allport (chair), Silvia Dalla Torre, Manfred Krammer, Felix Sefkow, Ian Shipsey
assist ECFA to identify technologies & conveners
Ex-officio: ECFA chair, LDG chair
Scientific Secretary: Susanne Kuehn

Advisory Panel with other disciplines
e.g. APPEC, NuPECC, LEAPS, LENS, F4E, Medical Devices, Space, …

TF#1 Gaseous Detectors
Anna Colaleo
Leszek Ropelewski

TF#2 Liquid Detectors
Roxanne Guenette
Jocelyn Monroe

TF#3 Solid State Detectors
Nicolo' Cartiglia
Giulio Pellegrini

TF#4 Photon Detectors & PID
Neville Harnew
Peter Krizan

TF#5 Quantum & Emerging Technologies
Michael Doser
Anna Grasselino

TF#6 Calorimetry
Roberto Ferrari
Roman Poeschl

TF#7 Electronics & On-detector Processing
Dave Newbold
Francois Vasey

TF#8 Integration
Frank Hartmann
Werner Riegler

TF#9 Training
Johann Collot
Erika Garutti

…

Consultation with the particle physics community & other disciplines with technology overlap

- Focus on the technical aspects given the EPPSU process as input.
- Development of a matrix, where for each Task Force the identified future science programmes that they will need to address in terms of the main technology challenges to be met and estimate the lead-time over which the required detector R&D programmes may be expected to extend.
- Create a time-ordered R&D requirements roadmap in terms of key capabilities not currently achievable.

Outlook

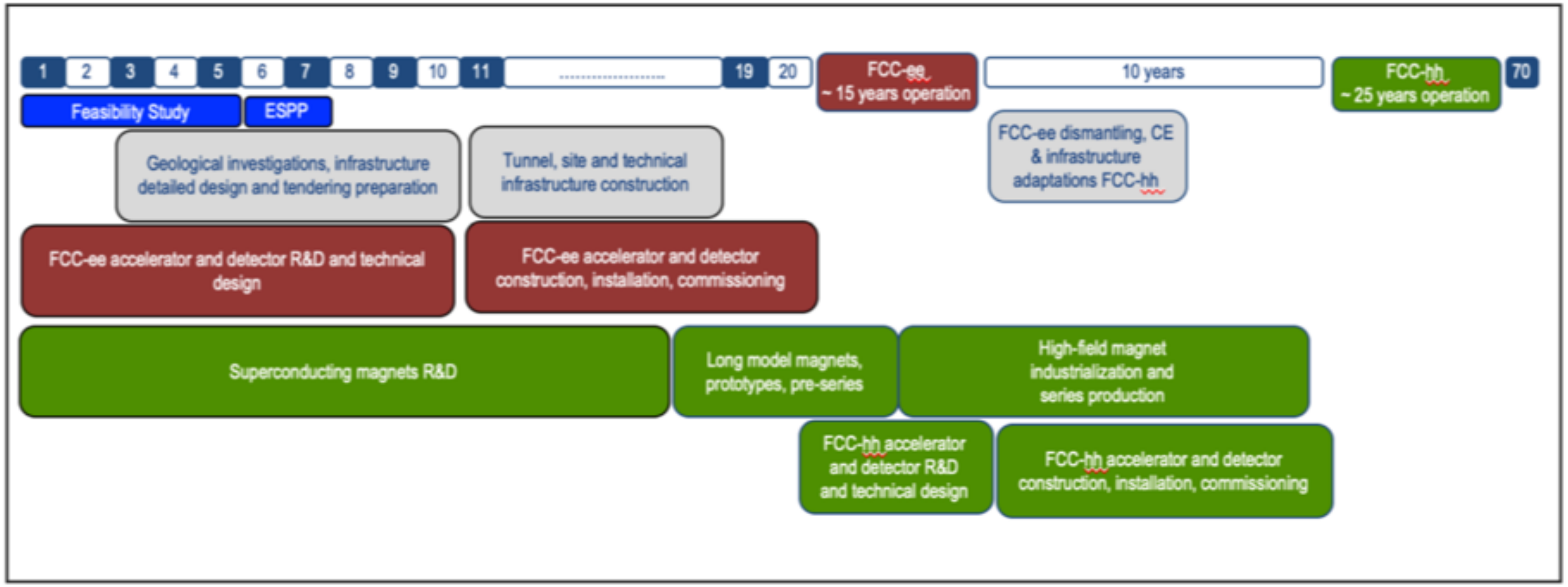
- European Strategy for Particle Physics: ***An electron-positron Higgs factory is the highest-priority next collider***
- FCC-ee is an excellent Higgs factory and offers much more
  - Unprecedented factory for Z, W and Higgs bosons; for top, beauty, and charm quarks; and for tau leptons
  - Possibly also factory for (feebly interacting) BSM particles !!
  - Possible timeline, see next slide
- Instrumentation to fully exploit the physics potential is challenging and exciting
  - FCC-ee can host four experimental collaborations
  - Many interesting challenges
    - Vertex detector, tracking, electromagnetic and hadronic calorimetry, particle identification, muon chambers
    - Normalisation issues
    - Overall detector layout including placement of coil
    - Readout, DAQ, data-handling
    - …

- For next ESPP, need to demonstrate that experimental challenges can be met by several Detector Concepts
- Detector Concepts group coordinating effort
  - CERN e-group: *FCC-PED-DetectorConcepts*

Please don't hesitate to join!

FCC estimated timeline

FUTURE CIRCULAR COLLIDER



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

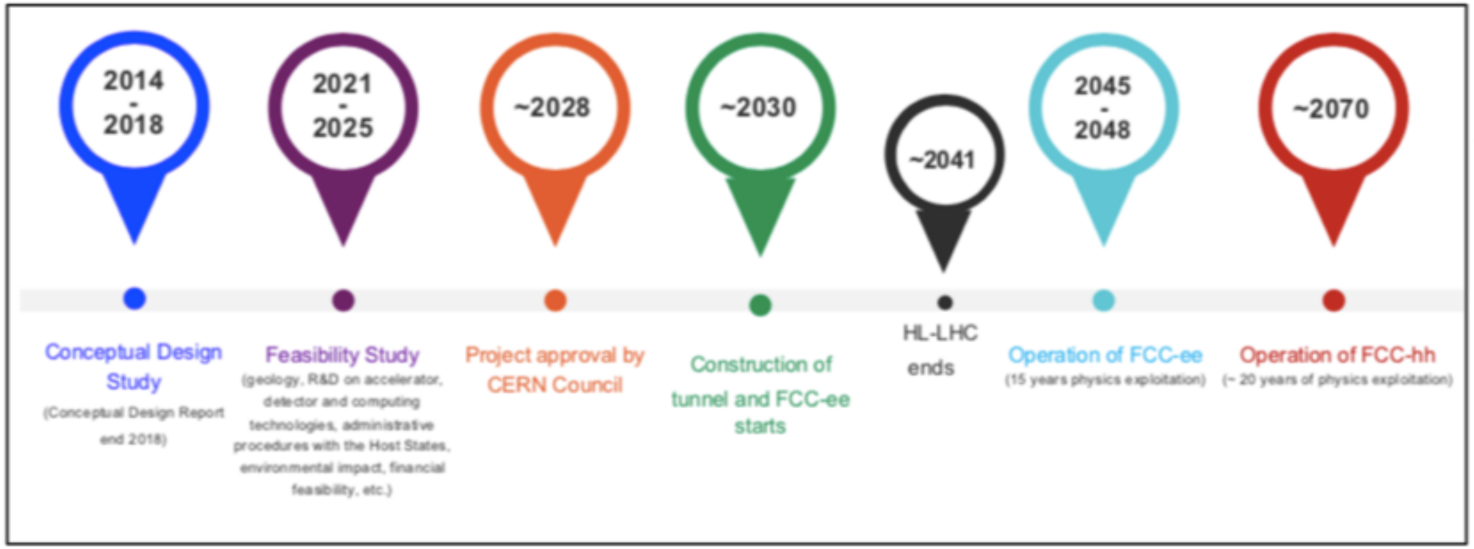
High-field magnet industrialization and series production

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

FCC-hh accelerator and detector construction, installation, commissioning

Technical schedule:
FCC-ee could start operation **in 2040 or earlier**

F. Gianotti, April 13, 2023



2014 - 2018
Conceptual Design Study
(Conceptual Design Report end 2018)

2021 - 2025
Feasibility Study
(geology, R&D on accelerator, detector and computing technologies, administrative procedures with the Host States, environmental impact, financial feasibility, etc.)

~2028
Project approval by CERN Council

~2030
Construction of tunnel and FCC-ee starts

~2041
HL-LHC ends

2045 - 2048
Operation of FCC-ee
(15 years physics exploitation)

~2070
Operation of FCC-hh
(~ 20 years of physics exploitation)

Realistic schedule takes into account:

- ☐ past experience in building colliders at CERN
- ☐ CERN Council approval timeline
- ☐ that HL-LHC will run until ~ 2041

→ **ANY future collider at CERN cannot start physics operation before 2045-2048** (but construction will proceed in parallel to HL-LHC operation)

Extras

Very high statistics Z factories - TeraZ

Running conditions:

- Extremely large statistics / statistical precision
  - …need small systematics (10^{-5}) to match
- Physics event rates up to 100 kHz
- Bunch spacing down to 20 ns
  - Continous beams, no power pulsing
- No pileup, no underlying event, …
  - …however, still pile-up at the 10^{-3} level

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	40,000	10	0.2	0.5
Total cross section (Z)	pb	40,000	30	10	8
Event rate	Hz	**92,000**	8,400	1	0.1
"Pile up" parameter [μ]	**10^{-6}**	1,800	1	1	1

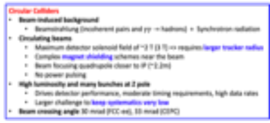
Detector optimization to be done for extremely rich physics capabilities especially at the Z pole with up to $5x10^{-5}$ Z decays: 10^{12} bb, cc, 2×10^{11} ττ, etc…

- Search for rare processes: Excellent acceptance definition, hermeticity, sensitivity to displaced vertices
- Luminosity measurement at 10^{-4} (abs), 10^{-5} (rel)
- Acceptance definition at $\leq 10^{-5}$
- Excellent b/c/gluon separation
- **PID**: TOF, dE/dx, Cherenkov?

The Z physics programme is still under development, in particular for rare processes and for heavy flavours:

- Detailed detector requirements still to be finalised, especially for PID.

e^+e^- colliders experimental conditions



Linear Colliders

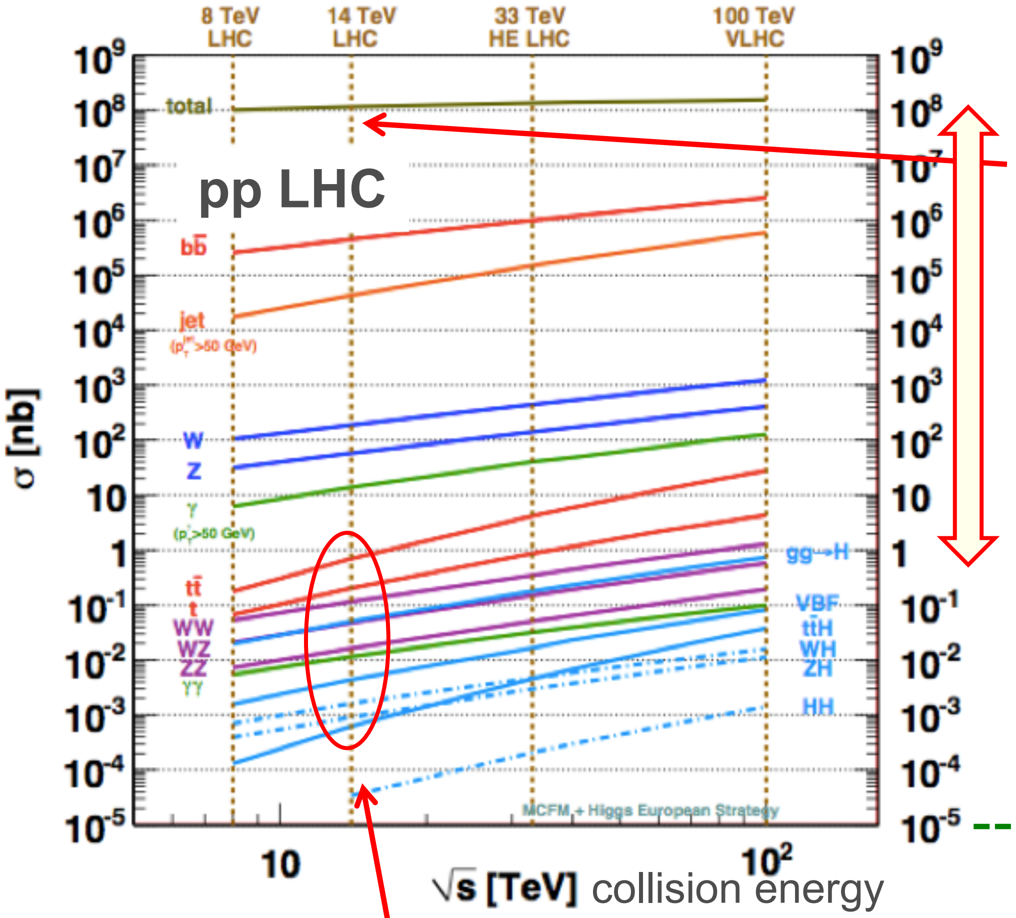
- **Beam-induced background**:
  - Beamstrahlung (incoherent pairs and $\gamma\gamma \rightarrow$ hadrons)
  - **High occupancies** in the detector => **small readout cells** needed
  - **O(1-5 ns) timing** required at CLIC
- **Low duty cycle**
  - **Power pulsing** of electronics possible
  - **Triggerless readout**
- **Beam crossing angle** 14 mrad (ILC), 20 mrad (CLIC)

Circular Colliders

- **Beam-induced background**
  - Beamstrahlung (incoherent pairs and $\gamma\gamma \rightarrow$ hadrons) + Synchrotron radiation
- **Circulating beams**
  - Maximum detector solenoid field of ~2 T (3 T) => requires **larger tracker radius**
  - Complex **magnet shielding** schemes near the beam
  - Beam focusing quadrupole closer to IP (~2.2m)

    } **Stronger engineering and layout constraints**
  - No power pulsing
- **High luminosity and many bunches at Z pole**
  - Drives detector performance, moderate timing requirements, high data rates
  - Larger challenge to **keep systematics very low**
- **Beam crossing angle** 30 mrad (FCC-ee), 33 mrad (CEPC)

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

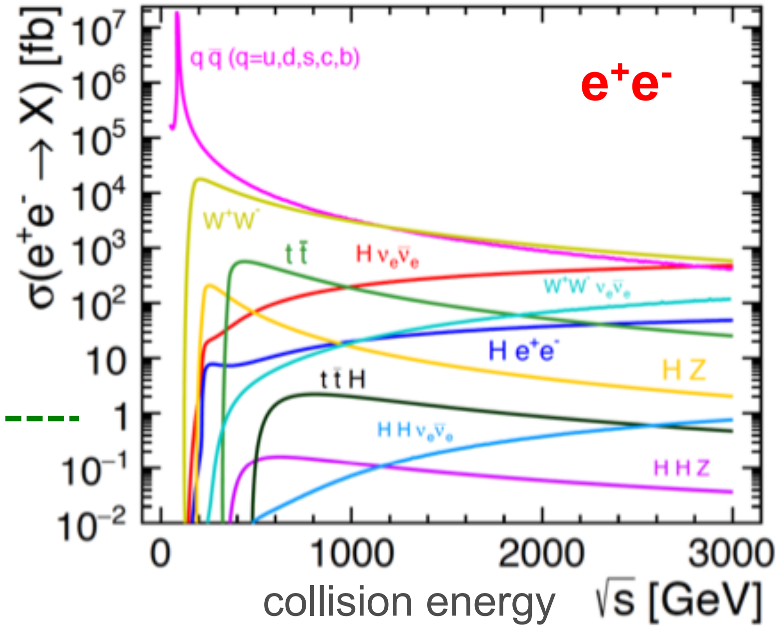


LHC total cross section

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"