Niels Bohr Institute
University of Copenhagen

Towards FCC Detector Conceptual Design

XV Latin American Symposium on High Energy Physics, 8 November 2024

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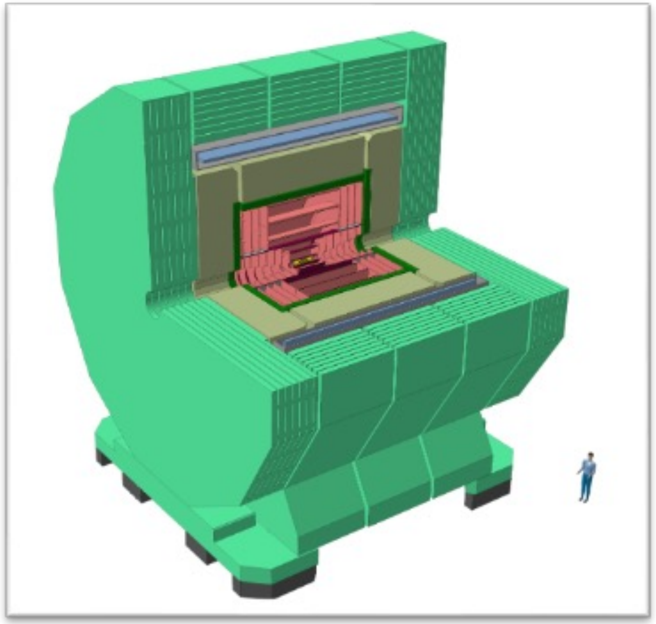
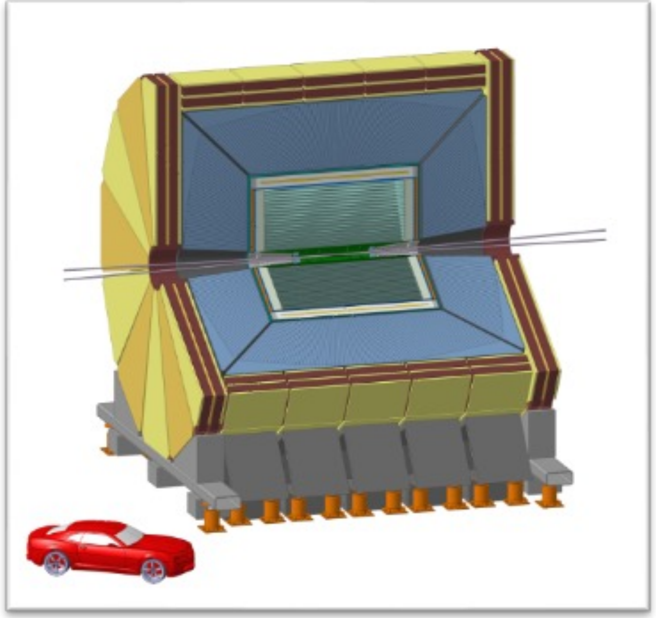
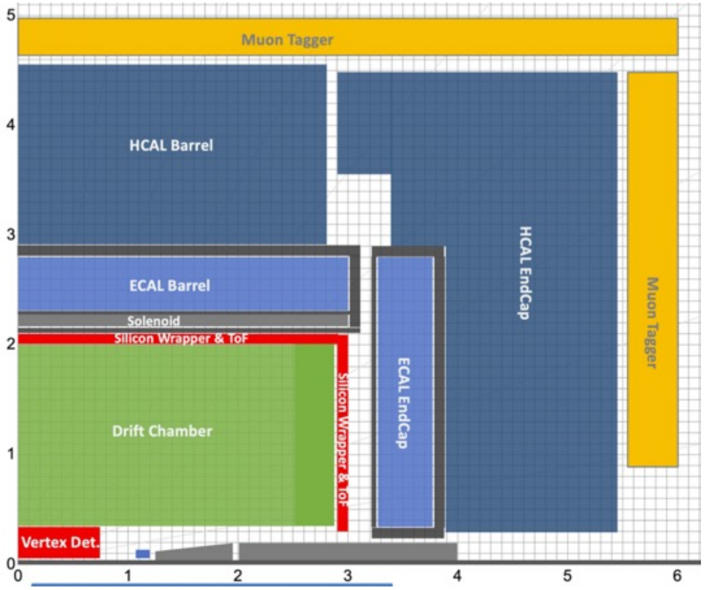
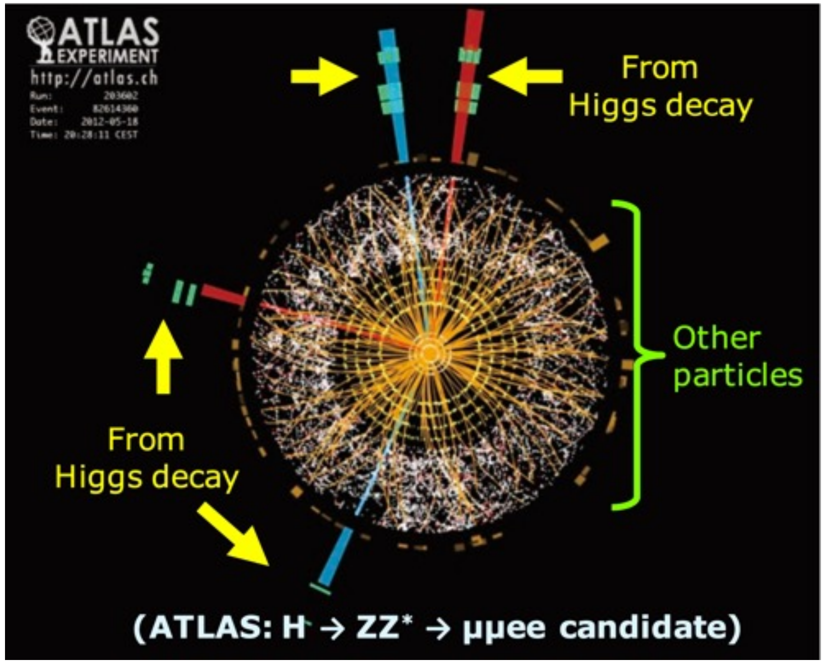




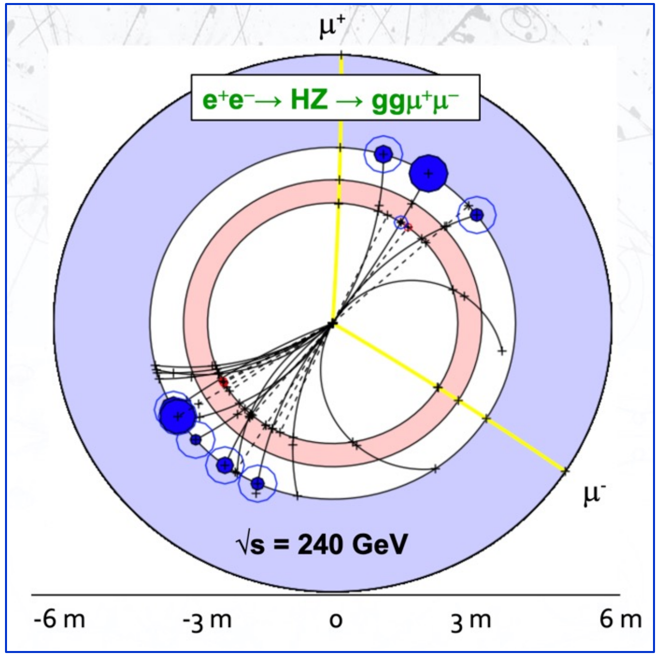


Introduction - pp versus e^+e^-

Higgs event in pp



Higgs event in e^+e^-



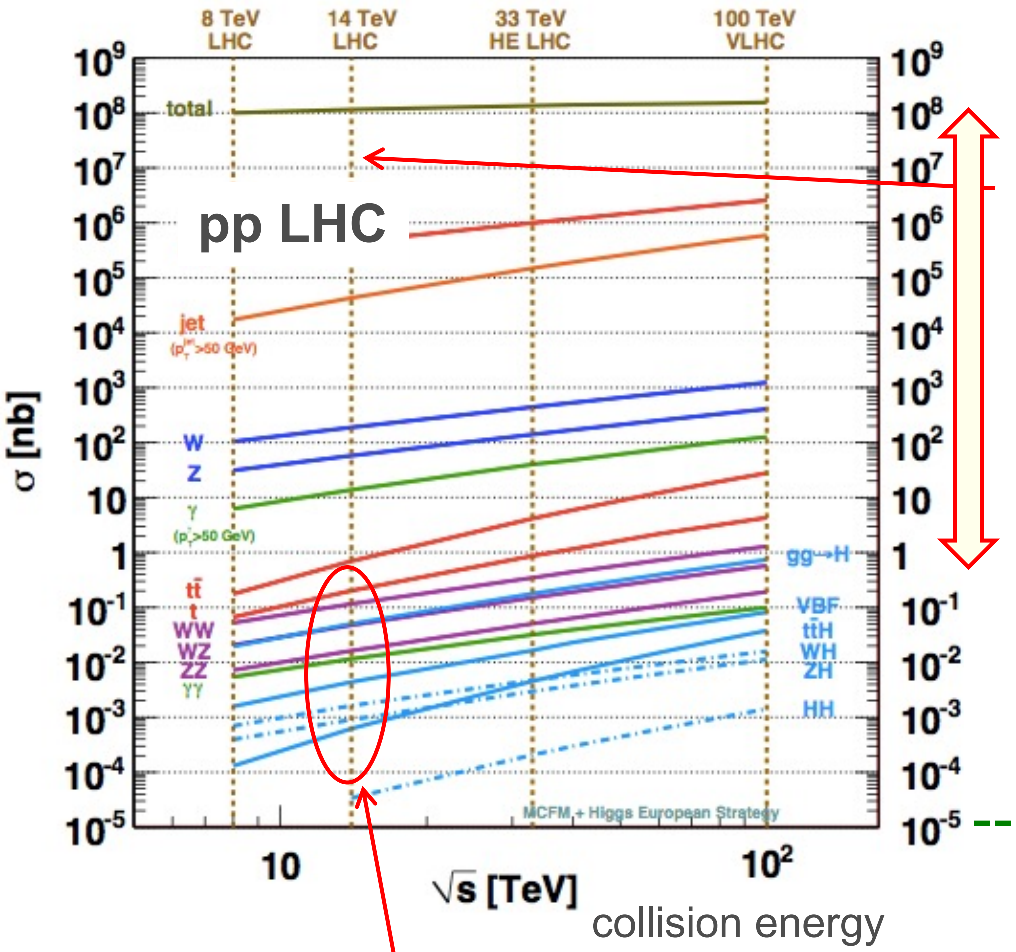
pp: look for striking signal in large background

- 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

- No pileup, no underlying event
- Clean experimental environment
  - Trigger-less readout
  - Low radiation levels
- Superiour sensitivity for electro-weak states
- Large indirect mass reach
- S/B ≈ 1

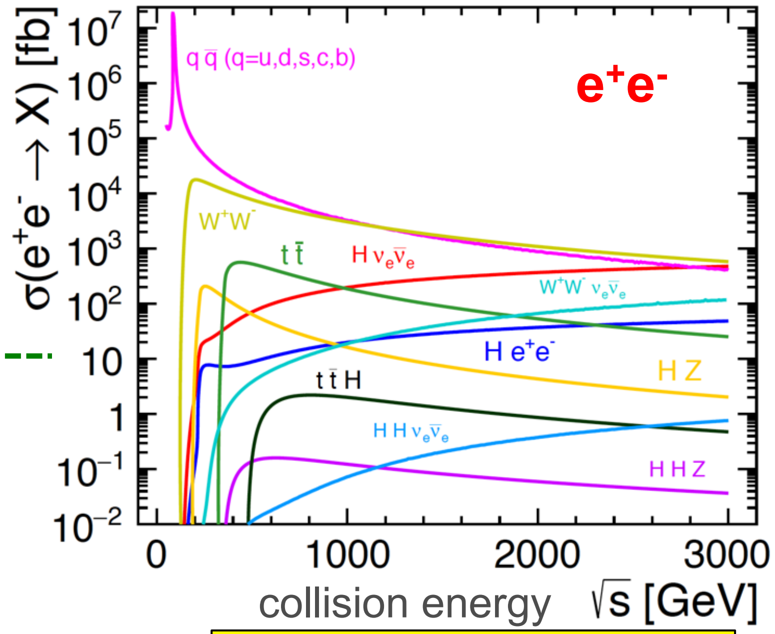
pp versus e^+e^- : Cross Section Comparison



LHC total cross section factor > 100 million !!

e^+e^-: Extremely clean environment
⇒ High precision

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



e^+e^- events are "clean"

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

Ultimate statistics/precision with

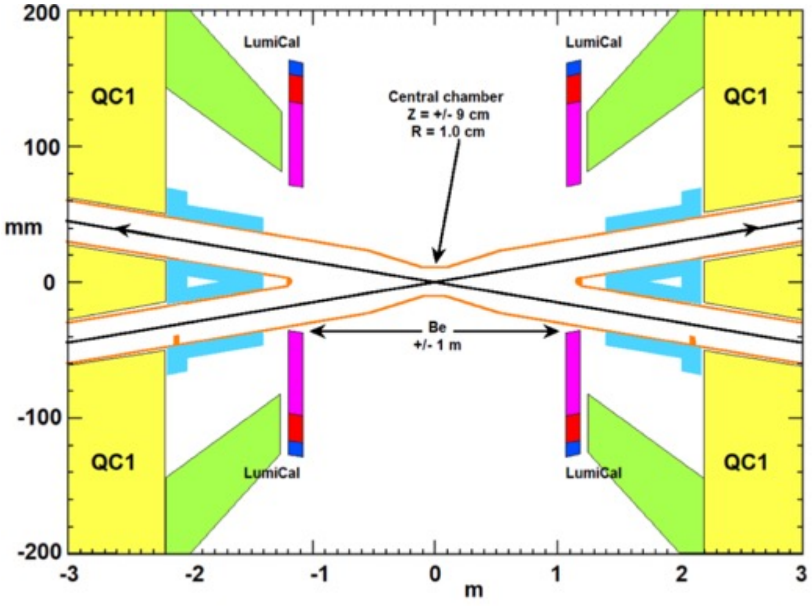
- ~50 000 Z / second
  - 1 Z / second at LEP
- ~10 000 W / hour
  - 20 000 W at LEP
- ~1 500 Higgs bosons / day
  - 10-20 times more then ILC
- ~1 500 top quarks / day

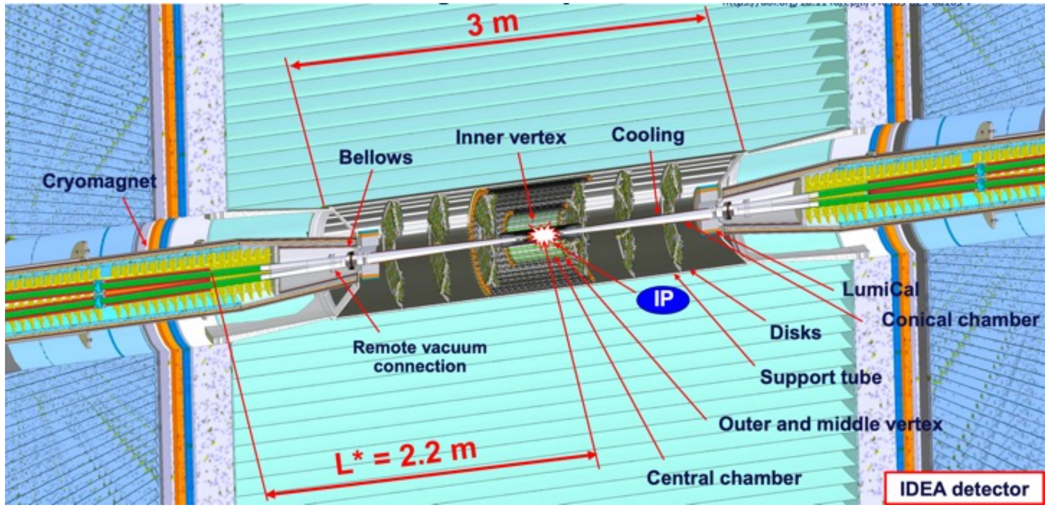
… in each detector

FCC-ee: Huge statistics
⇒ Systematic uncertainties dominant!

FCC-ee Experimental Challenges

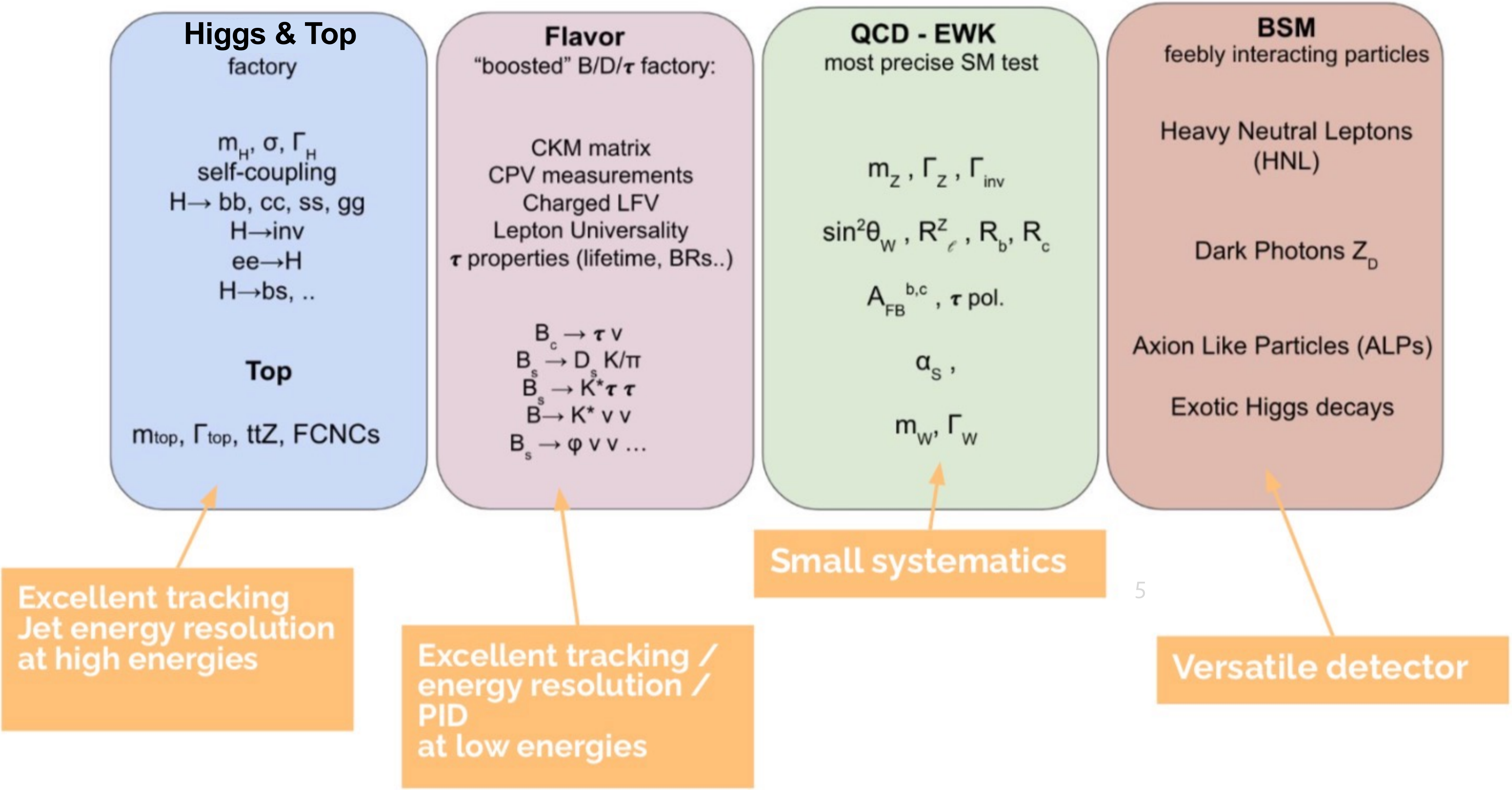
- **30 mrad beam crossing angle**
  - Detector B-field limited to 2 Tesla at Z-peak operation
  - Very complex and tightly packed MDI (Machine Detector Interface)
- **"Continuous" beams (no bunch trains); bunch spacing down to 20 ns**
  - Power management and cooling (no power pulsing as possible for linear colliders)
- **Extremely high luminosities**
  - High statistical precision – control of systematics down to 10^{-5} level
- **Physics events at up to 100 kHz**
  - Fast detector response
  - High occupancy in the inner layers and forward region (Bhabha scattering, $\gamma\gamma \rightarrow$ hadrons)
  - Beamstrahlung background
  - Strong requirements on sub-detector front-end electronics and DAQ systems
    - Is a trigger needed?
- **More physics challenges**
  - Absolute luminosity measurement to 10^{-4} – luminometer acceptance to $\mathcal{O}(1\ \mu m)$
  - Detector acceptance to ~10^{-5} – acceptance definition to $\mathcal{O}(10\ \mu rad)$, hermeticity (no cracks)
  - Stability of momentum measurement – stability of magnetic field wrt E_{cm} (10^{-6})





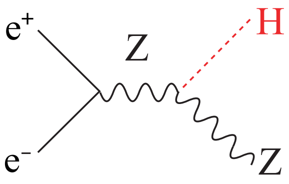
MDI region engineering has started

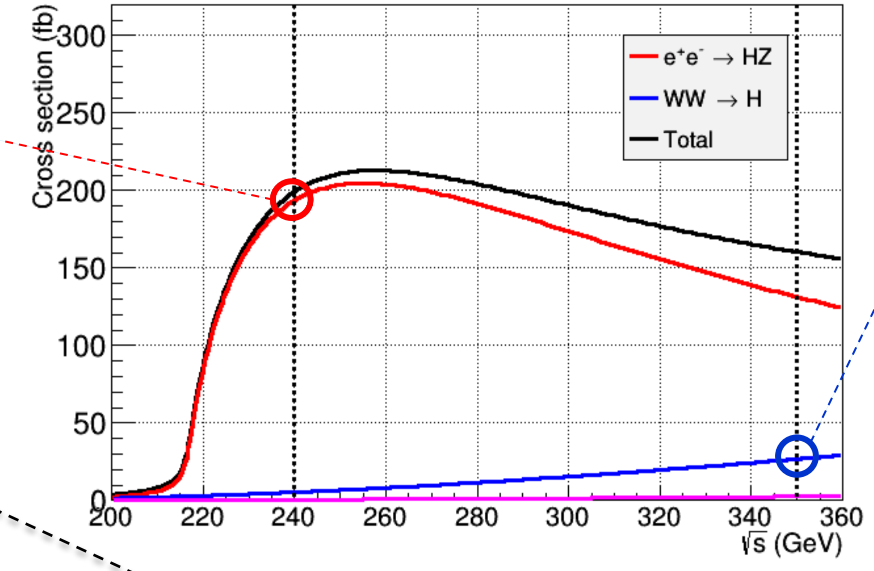
FCC-ee Physics Programme



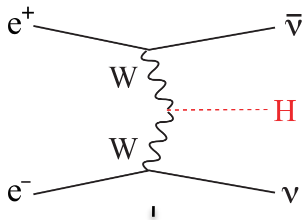
e^+e^-: Higgs Production and Decay

Higgs-strahlung

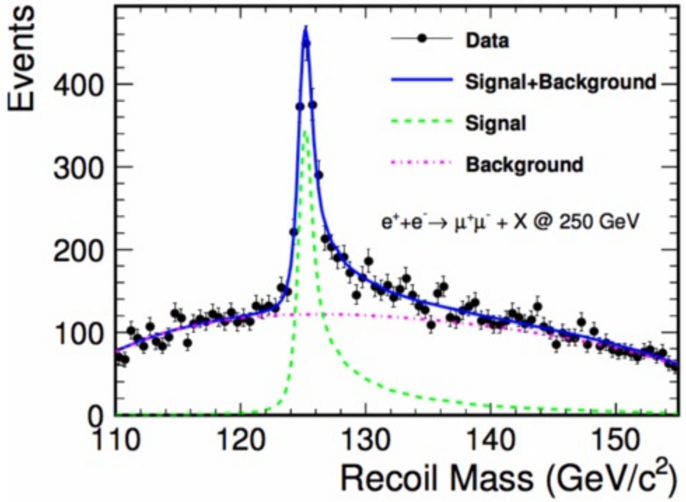




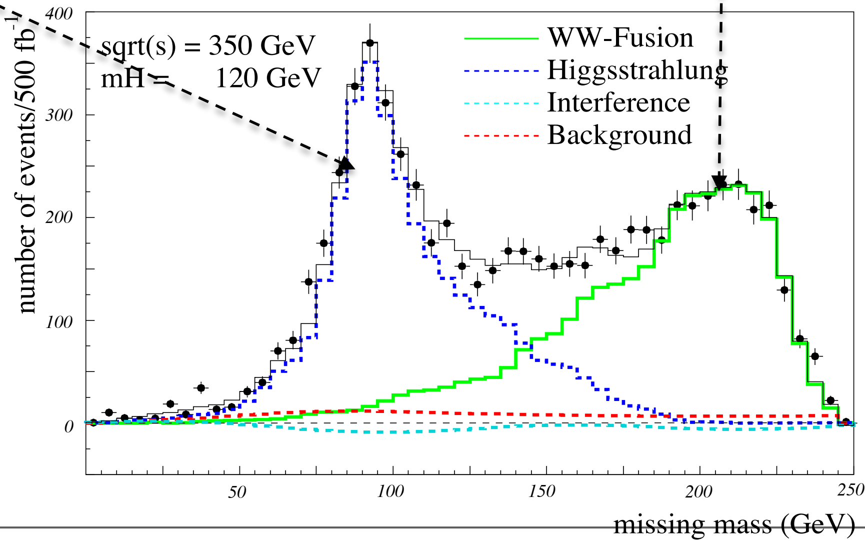
Boson fusion



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

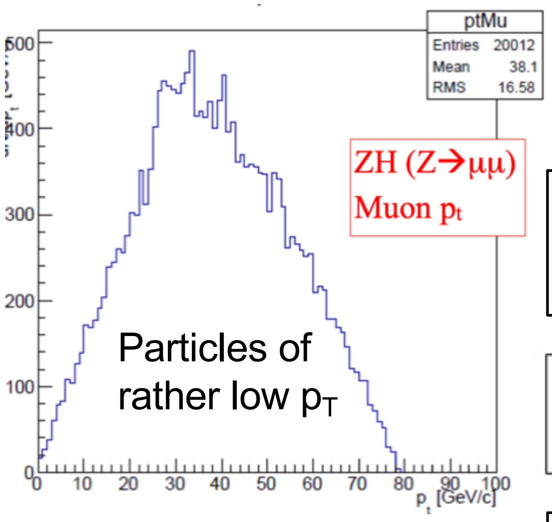
Vertex Detector and Tracking

Flavour Tagging:
Impact parameter "design goal"…

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

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

arXiv:1911.12230



→ Momentum resolution
multiple scattering dominated

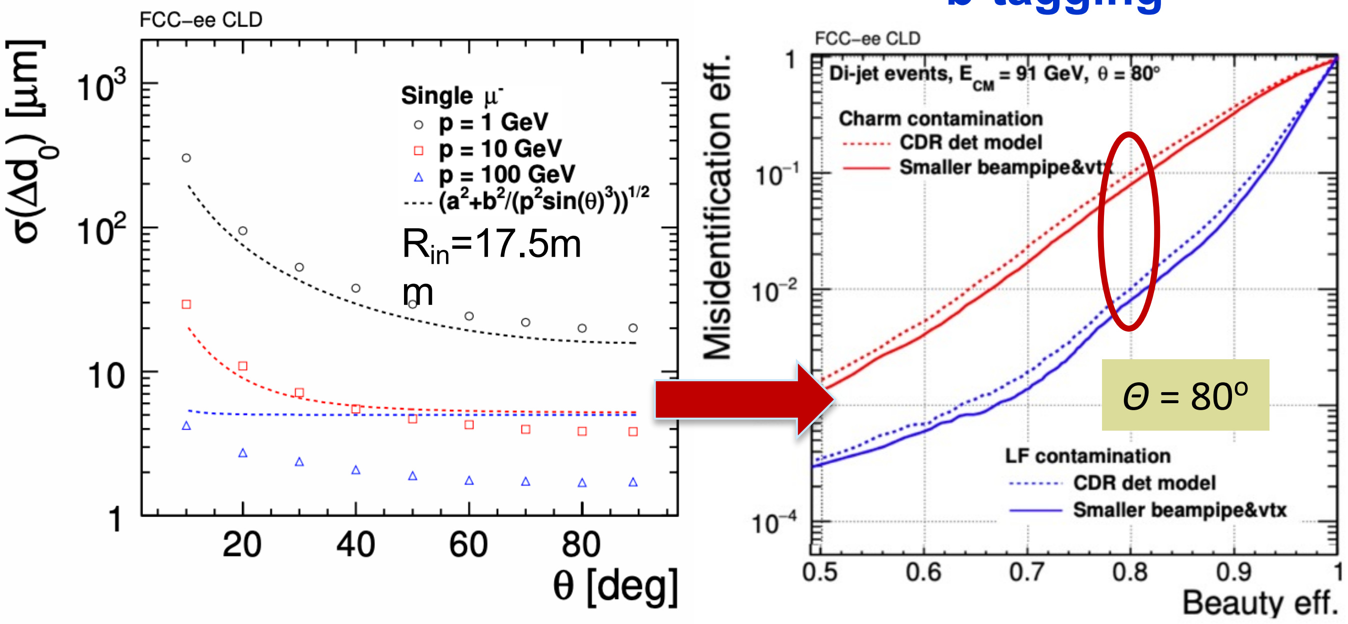
$$\sigma(p_T)/p_T^2 = a \oplus \frac{b}{p \sin\theta}$$

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

Ambitious goal: $\sigma_{pT}/p_T \simeq 10^{-3}$ @ 50GeV

e.g. CLD flavour tagging

b-tagging



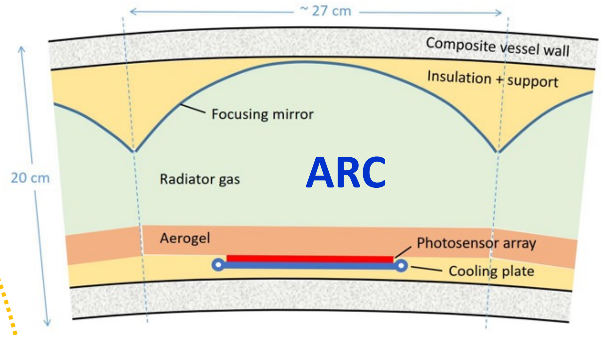
- **Flavour tagging – Vertex Detector: Lighter, more precise (smaller pixel size), closer to IP**
- **Momentum Resolution – Tracking Detector: The lighter the better**

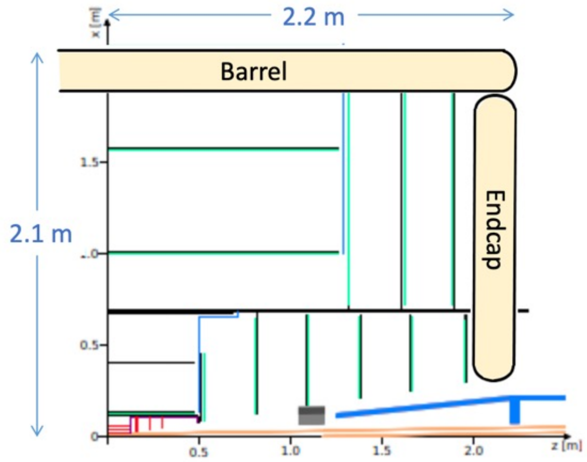
	r beam pipe	1st VTX layer
ILC	12 mm	14 mm
CLIC	29 mm	31 mm
FCC-ee	10 mm	13 mm

Particle Identification

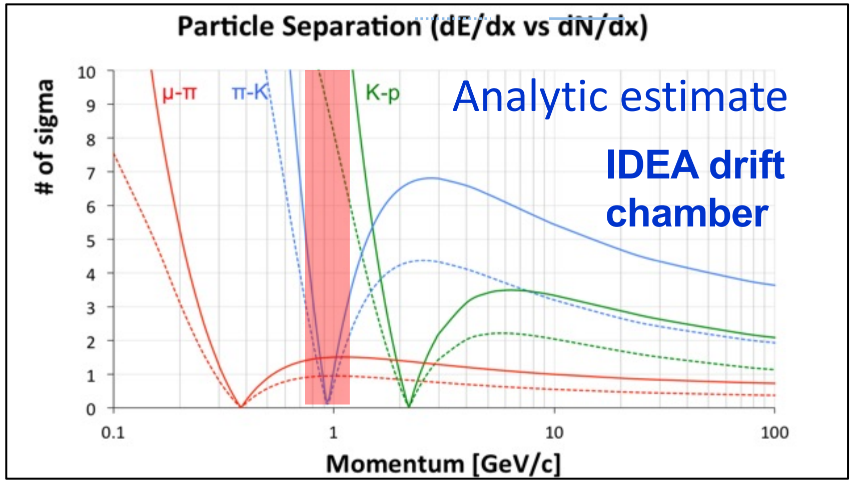
- **PID capabilities across a wide momentum range** is essential for flavour studies; will enhance overall physics reach
- **IDEA Drift Chamber** promises >3σ π/K separation up to 35-100 GeV
  - dE/dx cross-over window at 1 GeV, can be alleviated by unchallenging TOF measurement of δT ≲ 0.5 ns
- **Time of flight (TOF) alone** δT of ~10 ps over 2 m (LGAD)
  - could give 3σ π/K separation up to ~5 GeV
- **Alternative approaches**, in particular (gaseous) **RICH** counters also investigated (e.g. A pressurized RICH Detector – **ARC**)
  - could give 3σ π/K separation from 5 GeV to ~80 GeV

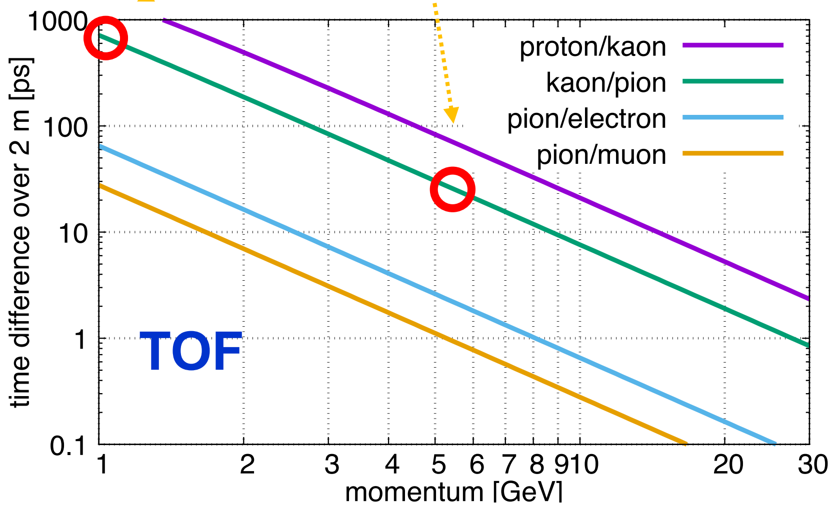
ARC: A possible RICH layout in an FCC-ee experiment

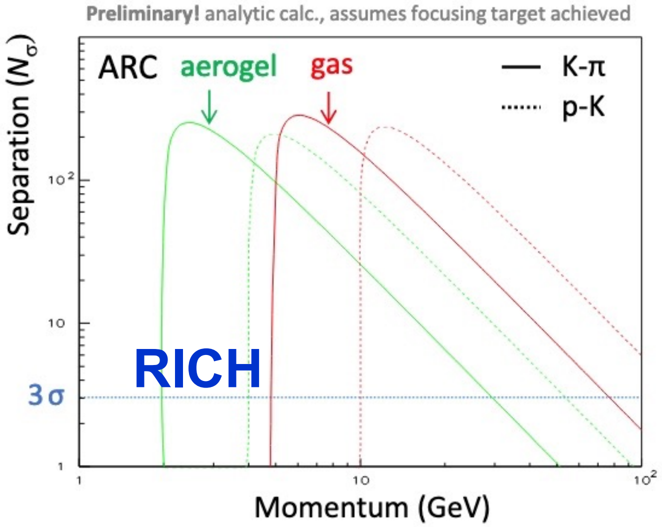




Compact & light!







Calorimetry

Energy coverage < 300 GeV → 22 X_0, 7λ
Precise jet angular resolution

Jet energy: $\sigma(E_{jet})/E_{jet} \simeq 30\% / \sqrt{E}$ [GeV] **?**

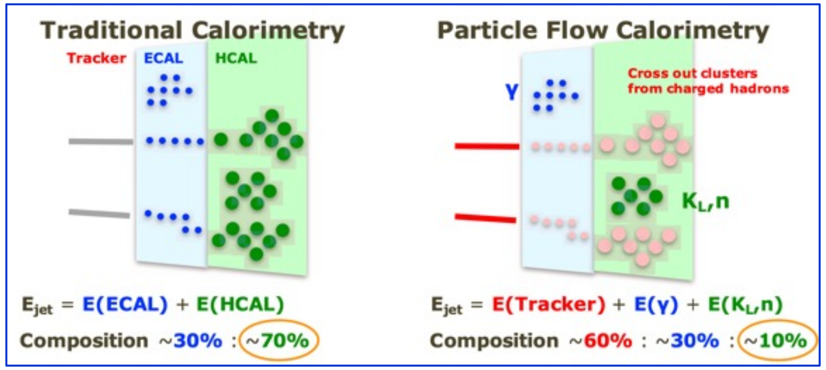
⇒ Mass reconstruction from jet pairs

Resolution important for control of (combinatorial) backgrounds in multi-jet final states with E_T^{miss}

How to achieve jet energy res. of ~3-4% at 50GeV:

- **Highly granular calorimeters**
- **Particle flow reconstruction and possibly in addition techniques to correct non-compensation (e/h≠1), e.g. dual read-out**

- **Excellent Jet resolution:** ≈ 30%/√E
- **ECAL resolution:**
  - **Higgs physics ≈ 15%/√E**
  - **For heavy flavour programme better resolution beneficial: → 8%/√E → 3%/√E**
- **Fine segmentation for PF algorithm** and powerful **γ/π⁰ separation** and measurement

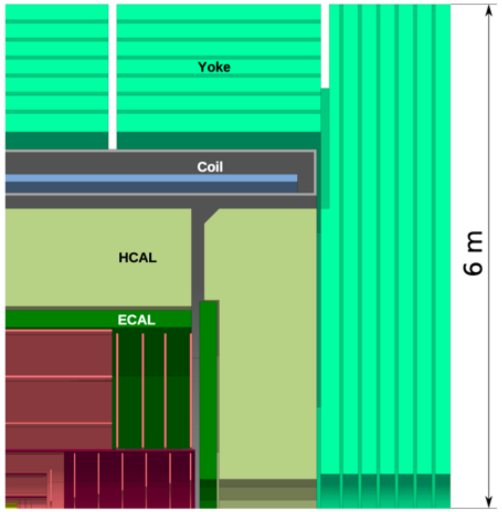


Detector technology (ECAL & HCAL)	E.m. energy res. stochastic term	E.m. energy res. constant term	ECAL & HCAL had. energy resolution (stoch. term for single had.)	ECAL & HCAL had. energy resolution (for 50 GeV jets)	Ultimate hadronic energy res. incl. PFlow (for 50 GeV jets)
Highly granular Si/W based 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]

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

FCC-ee Detector Concepts Fast Overview

CLD



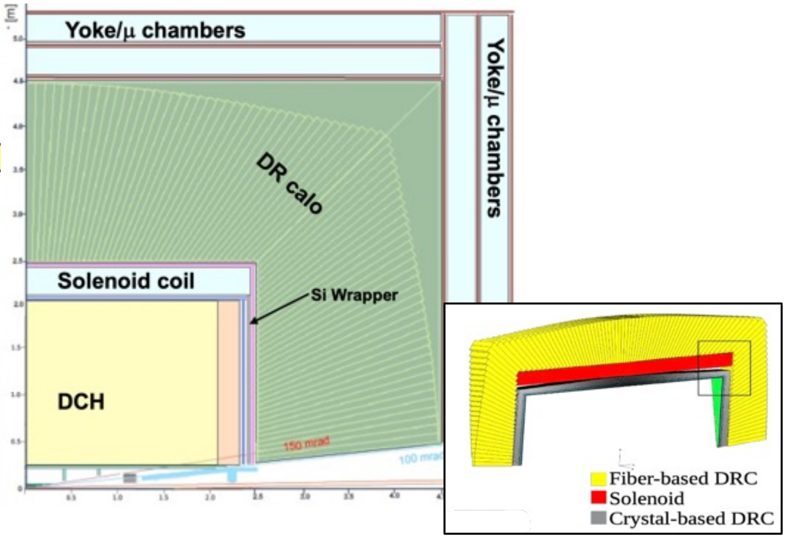
CDR

Conceptually extended from CLIC detector design
- Full silicon vertex detector + 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

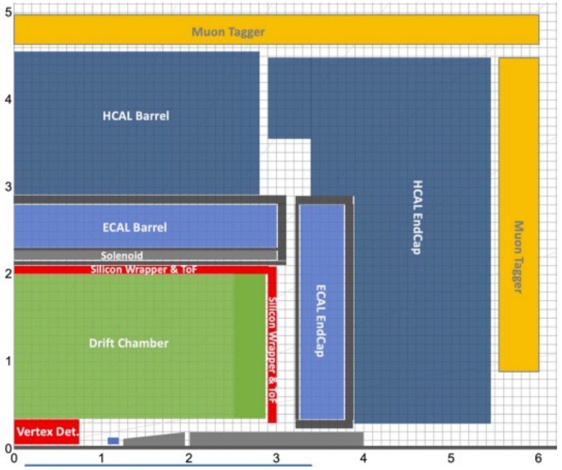
Possible detector optimisations
- Improved ECAL and momentum resolutions
- Particle identification (TOF and/or RICH)

IDEA



Specifically designed for FCC-ee
- Silicon vertex detector + "wrapper"
- Low X_0 drift chamber with high-resolution particle ID via ionisation measurement
- Crystal-based ECAL (now baseline)
- Light, thin coil
- Dual-readout calorimeter; radial scintilating + Cherenkov fibres
- Instrumented yoke with MPGC muon system

Allegro (Noble-Liquid ECAL based)

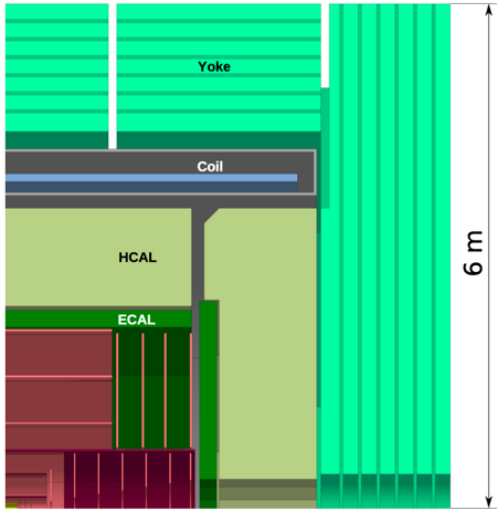


new

Specifically designed for FCC-ee, recent concept, under development
- Silicon vertex detector + "wrapper"
- Low X_0 drift chamber (possibly straw tracker) with high-resolution particle ID via ionisation measurement
- High granularity Noble Liquid ECAL as core
  - Pb/W + LAr (possibly denser W+LKr)
- Light, thin coil inside same cryostat as ECAL
- CALICE-like or TileCal-like HCAL
- Muon systems

FCC-ee Detector Concepts Fast Overview – Evolving!

CLD



CDR

Conceptually extended from CLIC detector design

- Full silicon vertex detector + tracker
- High granularity silicon-tungsten ECAL
- High granularit
- Instrumented
- Large 2 T coil s

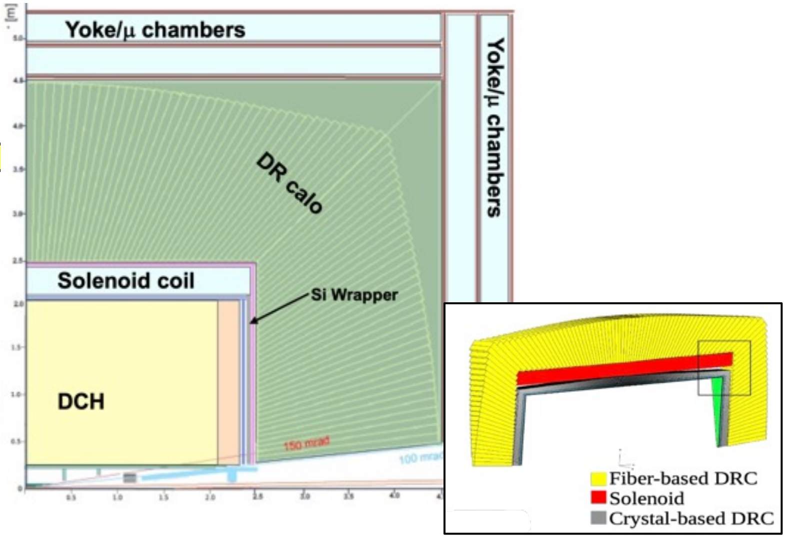
Engineering neede
beam operation (n

- Cooling of Si-se

Possible detector optimisations

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

IDEA

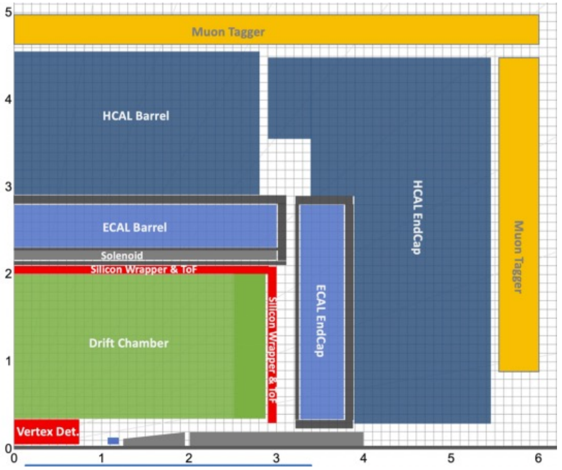


Specifically designed for FCC-ee

- Silicon vertex detector + "wrapper"
- Low X_0 drift chamber with high-resolution

Allegro (Noble-Liquid ECAL based)

new



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

- Silicon vertex detector + "wrapper"

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le ID via ionisation

uid ECAL as core
denser W+LKr)
cryostat as ECAL
HCAL
fied)

- At this stage these detector concepts are ideas and by no way fully worked out proposals of experiments
  - Such proposals will have to be worked out in the coming years (pre-TDR phase)
- At the end we are looking for at least 4 different experiments at FCC-ee satisfying the physics requirements
- → There is a lot of room for new ideas and new detectors – nothing is fixed yet

Work Ahead – Some Points of Attention

General: Develop 4 detector systems that match the performance set by physics benchmarks

- **Vertex Detector & MDI Region:**
  - Sensor technology exists (MAPS); light-weight support structures, low-material power and cooling infrastructure to be developed
  - Continue & strengthen engineering effort on MDI region, support of vertex detectors and LumiCal – develop MDI for all detector concepts
- **Tracking:**
  - Different proposals: Si tracker, drift chamber or straw tracker
  - Minimize material, start engineering of support structures, services, power, cooling…
- **Particle ID:**
  - Interesting idea to complement Si tracker with Cherenkov detector
  - Low GWP gases/gels for Cherenkov detectors
  - Precise timing (e.g. LGAD)
- **Calorimetry:**
  - Continue building prototypes of all proposed calorimeters; test beams
  - Define needed granularity, performance optimization
  - Engineering
- **Muon Tagger / Muon System:**
  - Need to optimise design for physics reach
  - Large area gas detectors, technology exists
  - Low GWP gases for gas detectors (e.g. RPC)
- **Software:**
  - Detector concepts existing in FCC SW, modular approach, can easily plug in new detectors, new ideas
  - Particle flow starting to work; needs tuning for each detector concept
- **Trigger and DAQ:**
  - Do we need a trigger or can we read out everything (keeping in mind power & cooling needs → more material)
  - Closely linked to studies of occupancies caused by background (Beamstrahlung, $\gamma\gamma \rightarrow$ hadrons, Bhabha scattering)
- **Detector Solenoid Magnets:**
  - Effort to re-establish availability of a reinforced aluminum-stabilized Nb-Ti conductors needed for FCC-ee, as well as to investigate novel HTS-based conductor technology and its implications
- **Cryostats:**
  - Further development of low-material carbon-composite cryostats as well as carbon fibre and aluminum honeycomb
  - Tightness of flanges to stainless steel feed-throughs
  - Tests of prototypes
- **Normalisation:**
  - Design of very compact LumiCal w. extreme $\mathcal{O}$(1 μm) geometrical precision, high rate.
  - Keep eye on $\mathcal{O}$(10 μrad) acceptance definition of forward detectors (tracking + calorimetry)

Extras

Vertex Detector

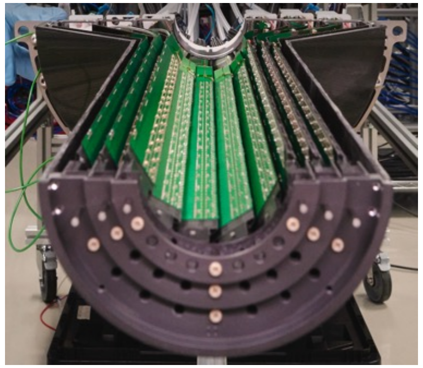
- Impact param., secondary vertices, flavour tag, lifetimes
- Very strong development: **Lighter, more precise, closer**

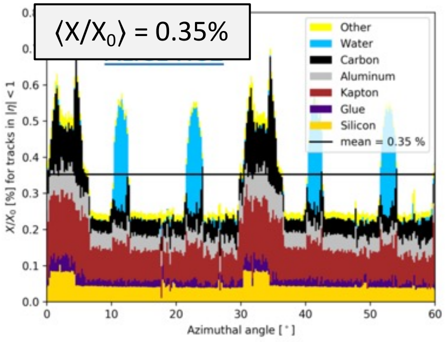
	r beam pipe	1st VTX layer
ILC	12 mm	14 mm
CLIC	29 mm	31 mm
FCC-ee	10 mm	13 mm

Strong ALICE Vertex detector development

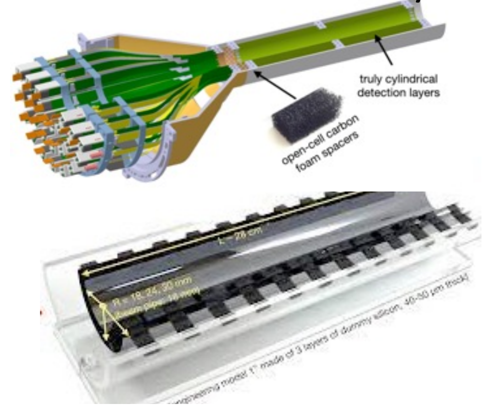
MAPS

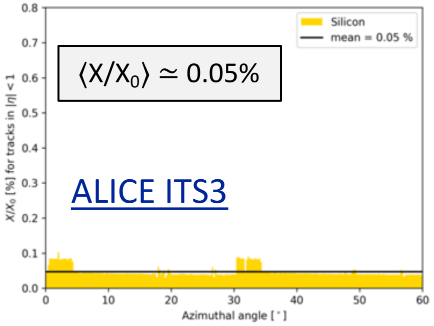
ITS2: installed in 2021





ITS3: installation 2027/2028



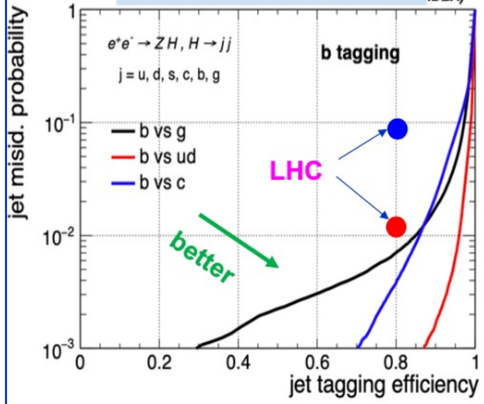


- Conditions/requirements largely common between ALICE and FCC-ee
  - Moderate radiation environments
  - No need for picosecond timing
  - High resolution and low multiple scattering is key

- Heavy flavour tagging results (FCC-ee simulation)
  - ML based: large lifetimes, displaced vertices/tracks, large track multiplicity, non-isolated e/μ

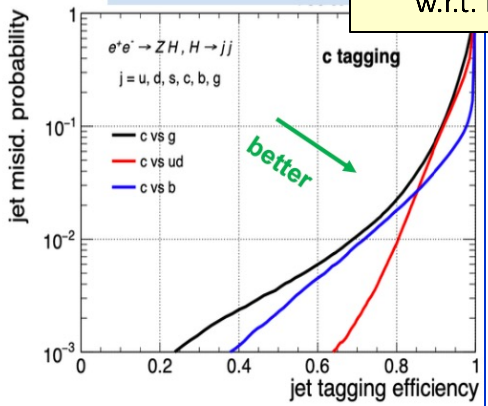
Very substantial improvement w.r.t. LHC

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



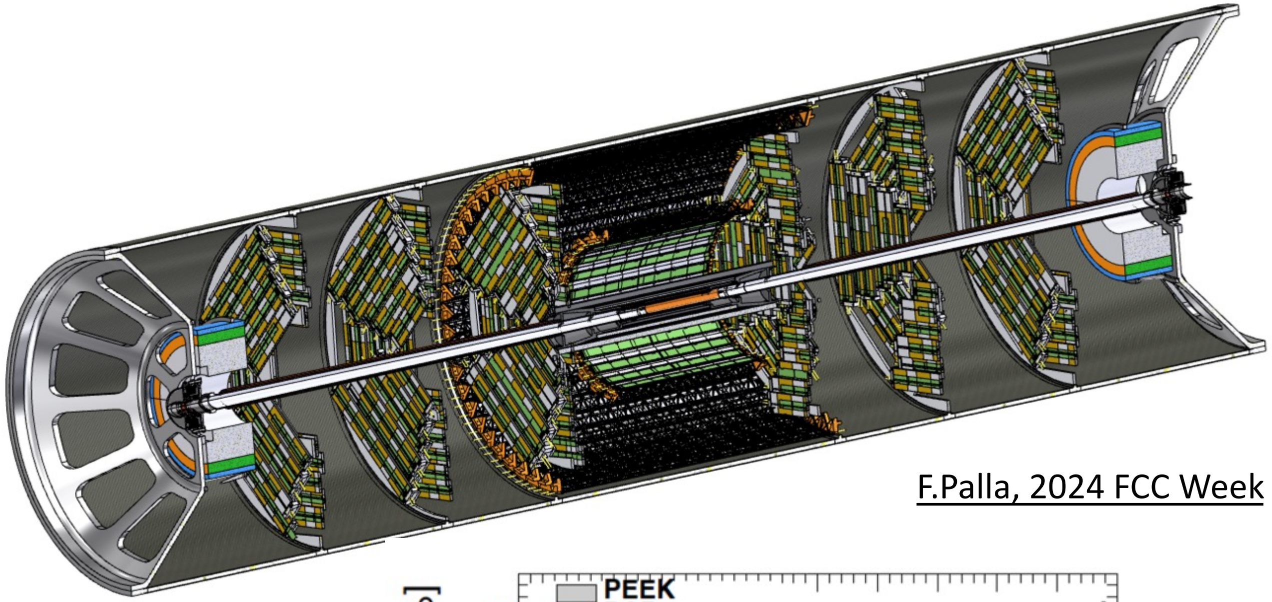
WP	Eff (c)	Mistag (g)	Mistag (ud)	Mistag (b)
Loose	90%	7%	7%	4%
Medium	80%	2%	0.8%	2%

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

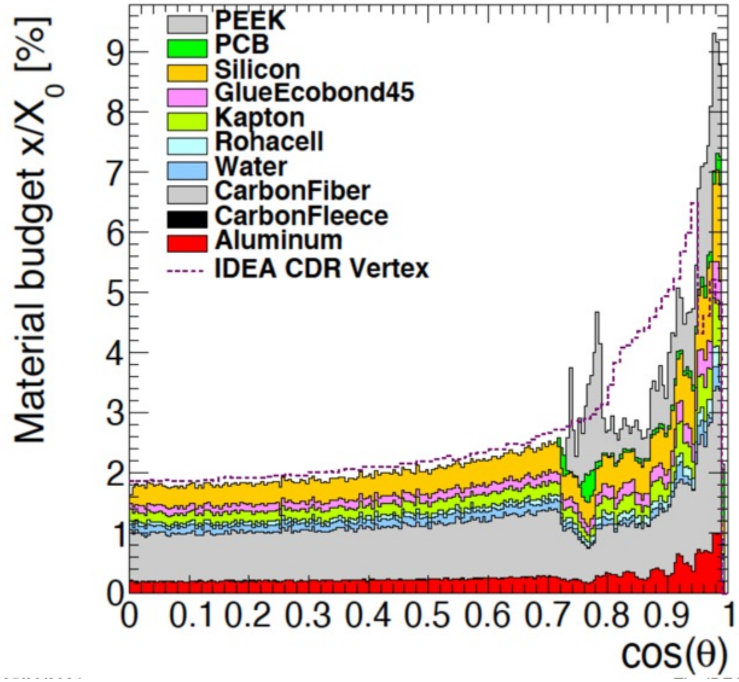
Recent development: IDEA Vertex Detector Design

Inspired by Belle II (and ALICE ITS) based on DMAPS (Depleted Monomithic Active Pixels) technology

- Inner Vertex (ARCADIA based)
  - Modules of 25 x 25 µm pixel size, 50 µm thick
  - 3 barrel layers at 13.7, 22.7, 33 mm
    - 0.3% X_0 per layer
  - Point resolution of ~3 mm
- Outer Vertex and disks (ATLASPIX3 based)
  - Modules of 50 x 150 µm pixel size, 50 µm thick
  - 2 barrel layers at 130, 315 mm; 2 x 3 disk layers
    - 1% X_0 per layer
- Performance
  - Efficiency of ~100%
  - Extremely low fake hit rate

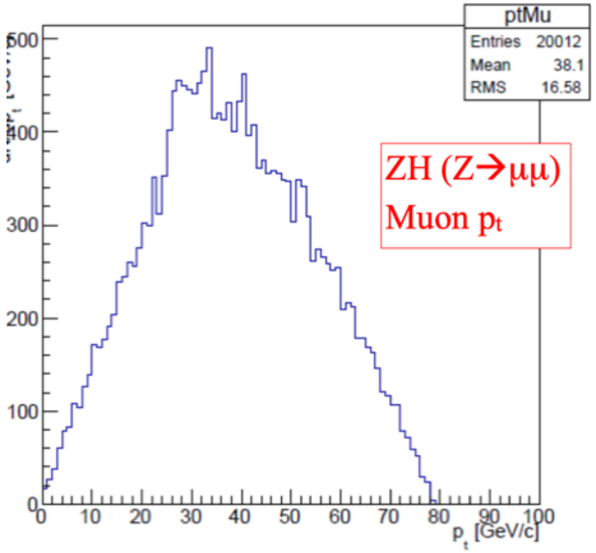


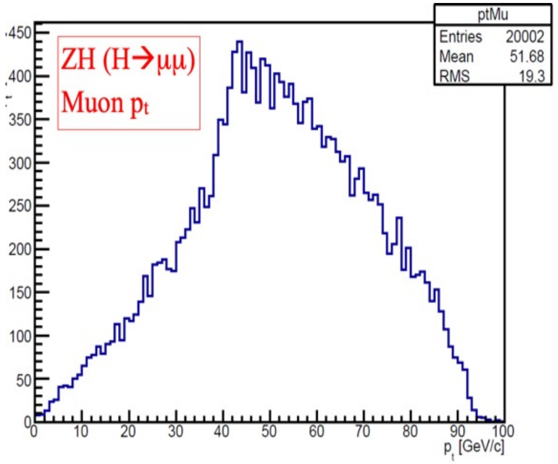
F.Palla, 2024 FCC Week



Tracking Systems - Momentum measurement

Particles from Higgs production process are generally of moderate momentum





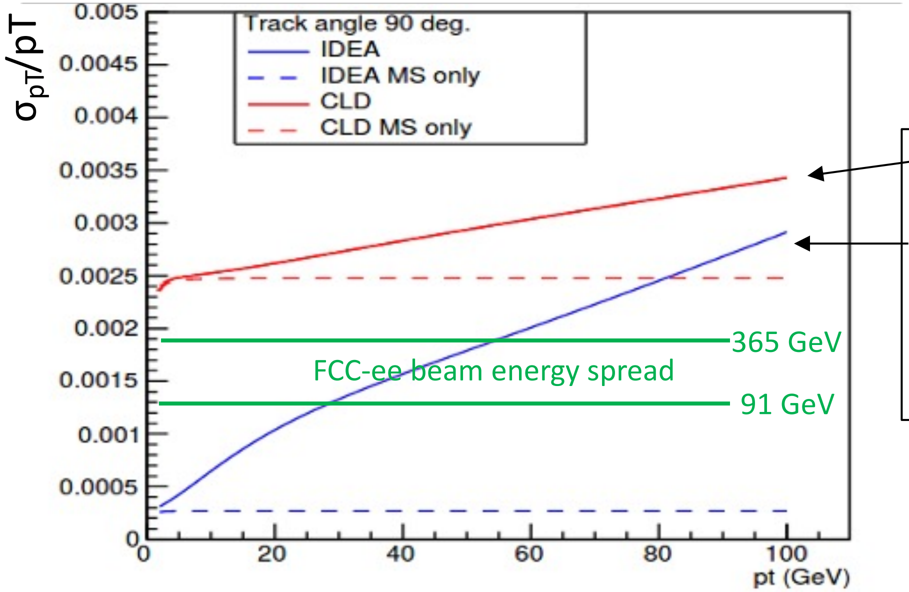
Momentum resolution tends to be multiple scattering dominated

⇒ Asymptotic resolution not reached

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

mult.scat (b)

resolution (a)



CLD: All-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.

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

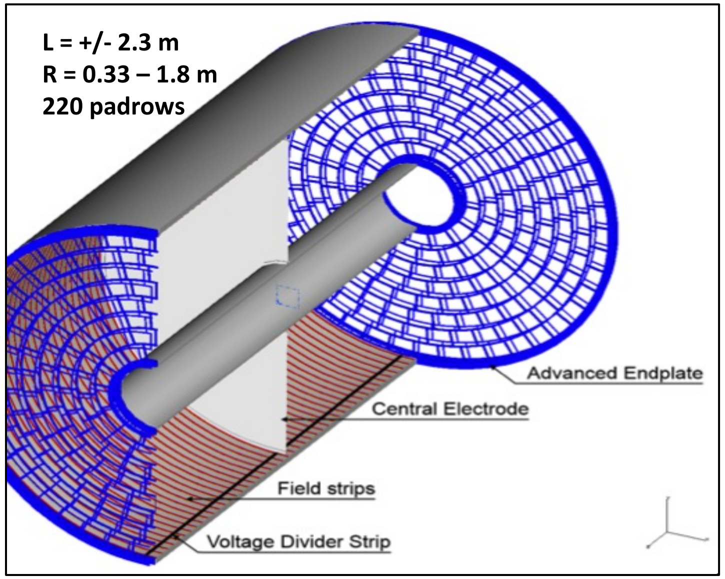
Thinning of Si sensors helps (only) as √ of thickness

⇒ Detector transparency more important than asymptotic resolution ⇐

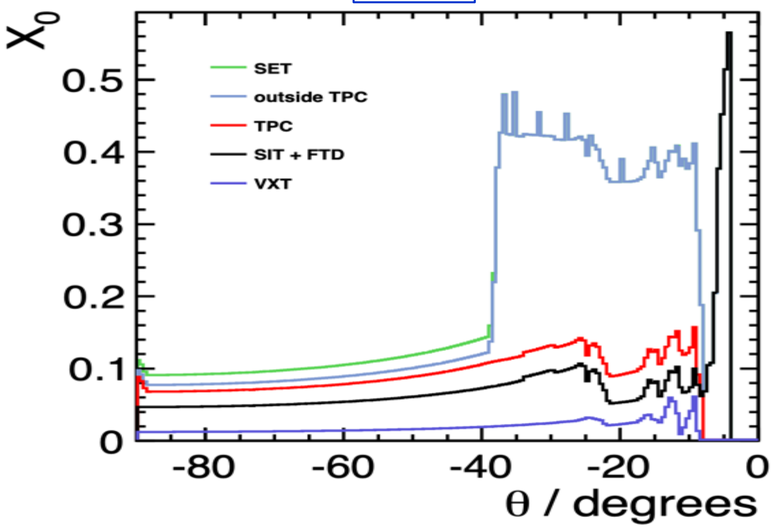
https://doi.org/10.1016/j.nima.2018.08.078

Tracking systems and material budgets

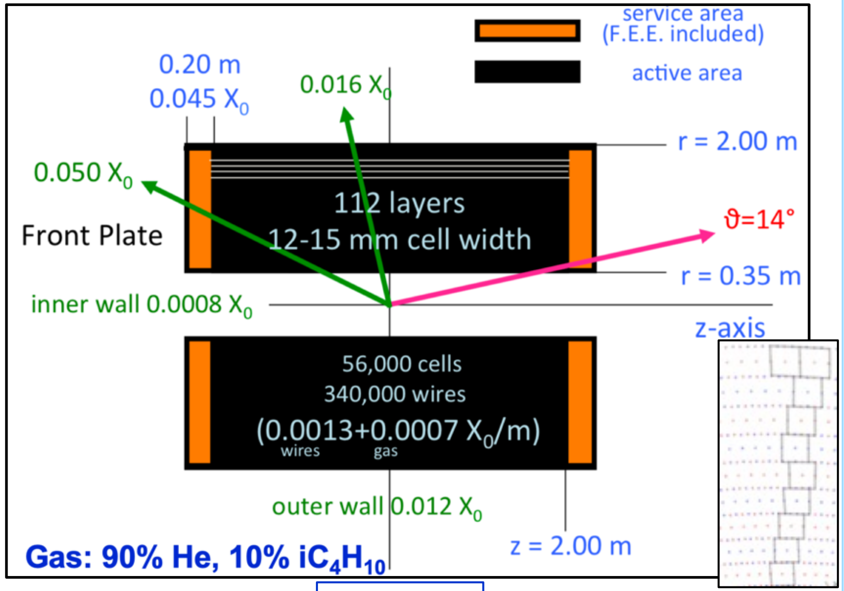
ILD TPC



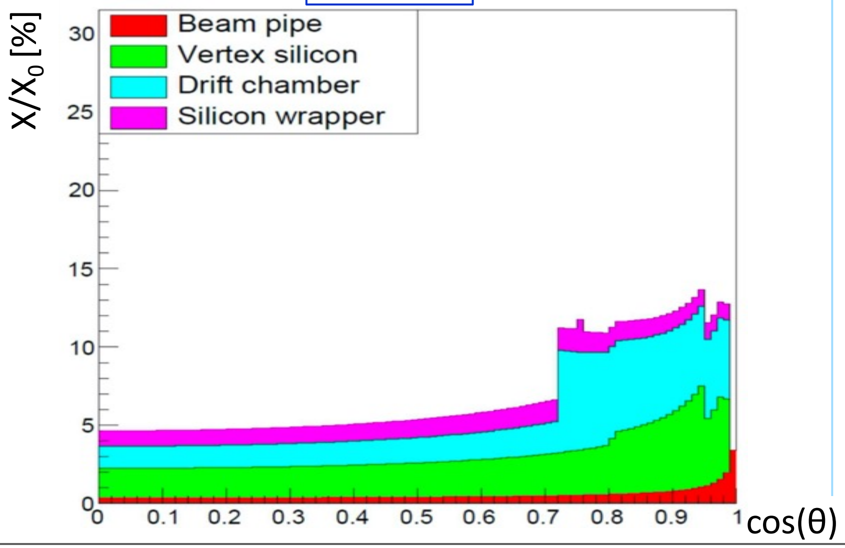
ILC TDR



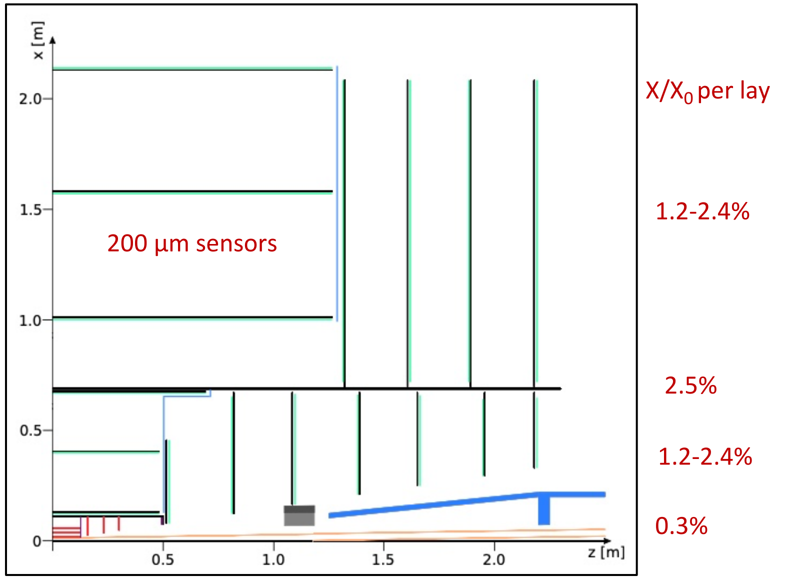
IDEA Drift Chamber



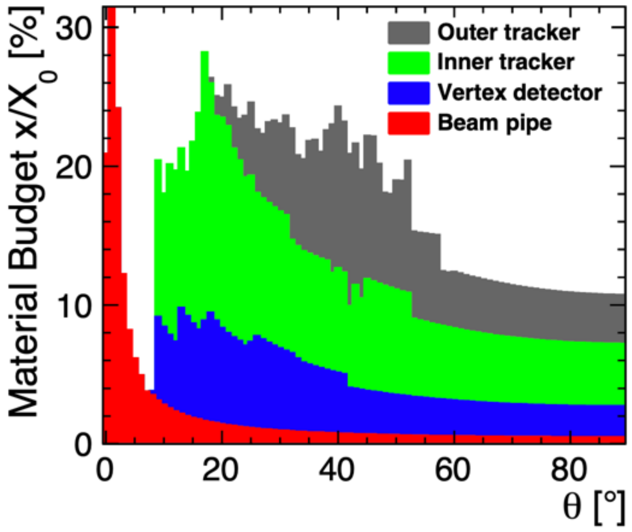
FCC-ee CDR



CLD - Full Silicon tracker

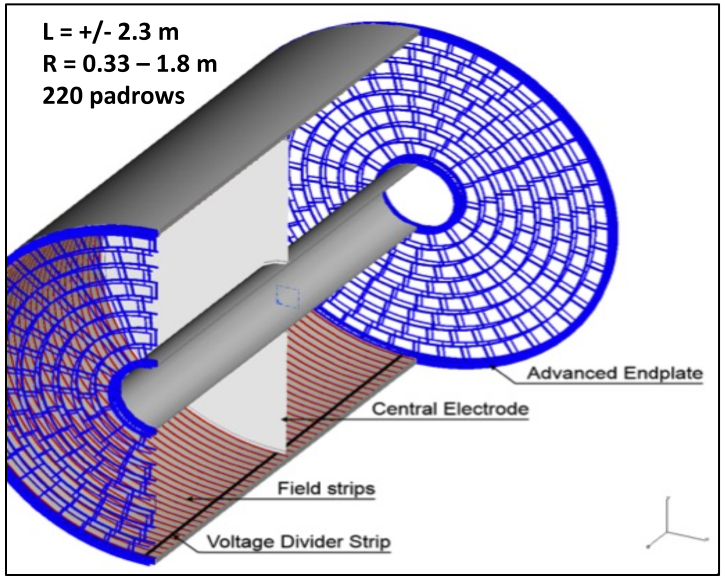


arXiv:1911.12230



Tracking system variants

ILD TPC



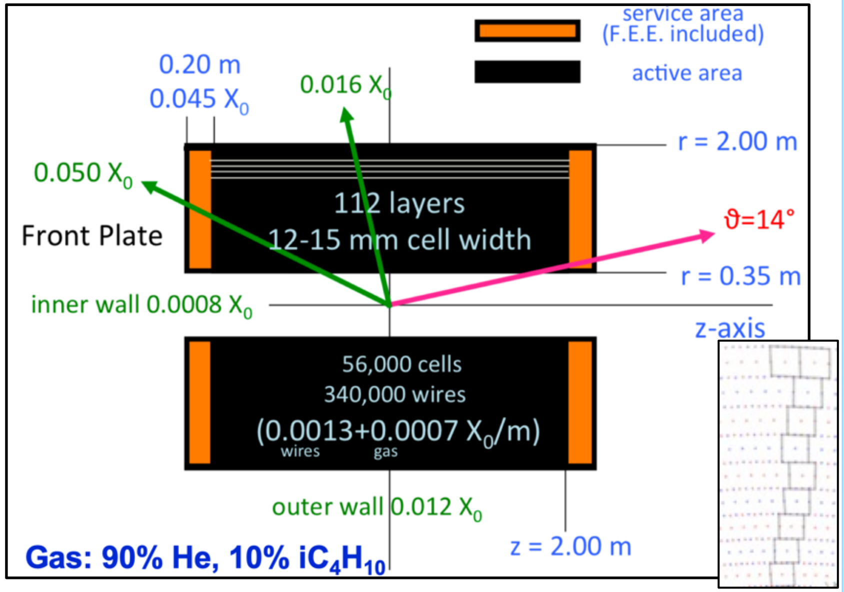
Pros:

- Low material budget (in barrel)
- Proven technologi, e.g. aleph and delphi at LEP
- Continous tracking; advantage for secondary vertex finding
- Particle ID via dE/dx measurement

Challenges:

- Not obvious if can be operated at ~100kHz FCC-ee event rate

IDEA Drift Chamber



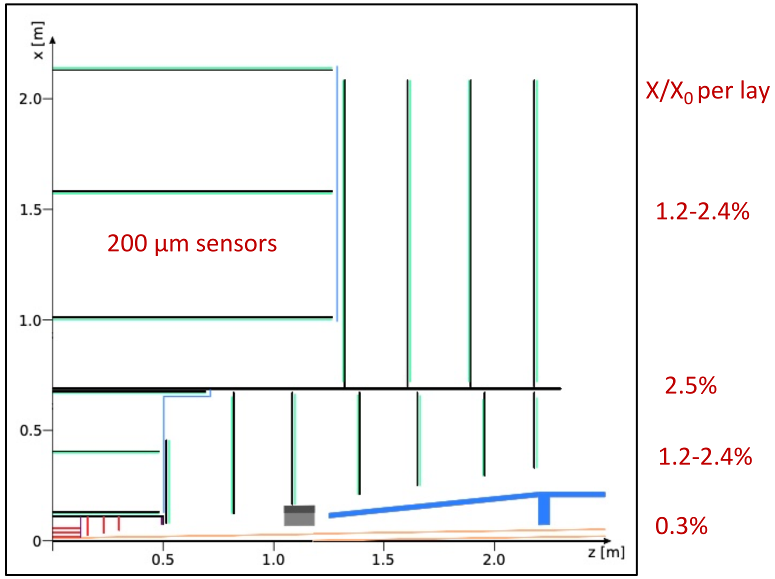
Pros:

- Very low material budget
- Proven technologi: KLOE at Daφne
- Continous tracking; advantage for secondary vertex finding
- Particle ID via dE/dx (dN/dx) measurement

Challenges:

- Need to prove operation at ~100 kHz FCC-ee physics rate and realistic backgrounds via full simulation studies

CLD - Full Silicon tracker



Pros:

- Very precise space points
- Proven technologi, e.g. LHC detectors
- No gas system

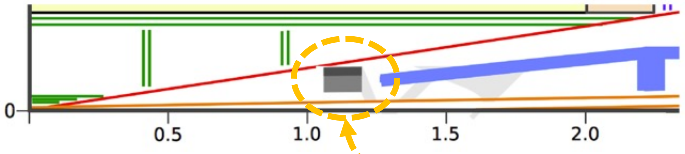
Challenges:

- No precise Particle Identification
  - Possibly TOF (or add RICH system)
- Optimisation of sensor thickness for lower material budget
- Design of (light) cooling system for operation at continous collisions

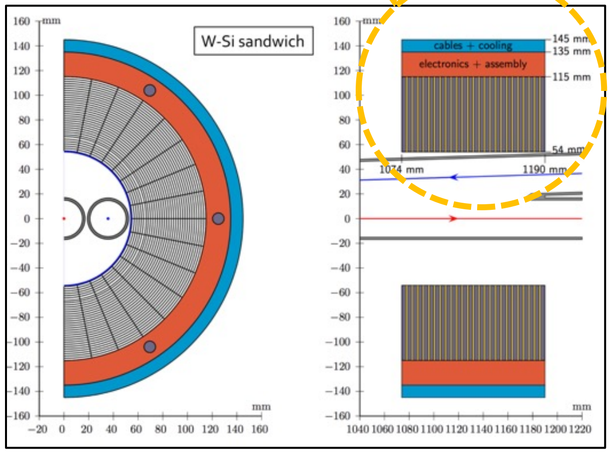
Normalisation

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)



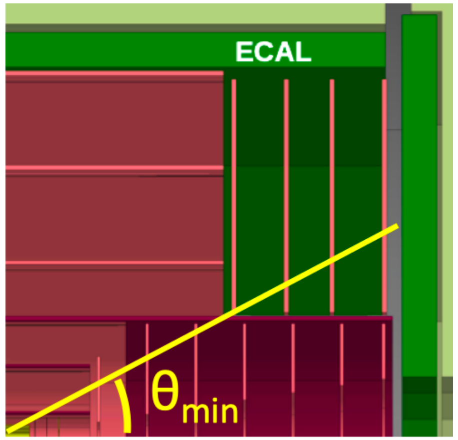
W-Si sandwich



- 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 $e^+e^- \to \gamma\gamma$
- $10^{-4} \Rightarrow$ control of acceptance boundary $\delta\theta_{min}$ to **$\mathcal{O}$(10 μrad)**
- 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 **$\mathcal{O}$(10 μrad)**
- No holes or cracks



A few words on Readout, DAQ, Data Handling

- In particular at Z-peak, challenging conditions
  - 50 MHz BX rate
  - 50 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)
    - 50-100 kHz of low angle Bhabhas; very compact detectors; avoid pile-up
- 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

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

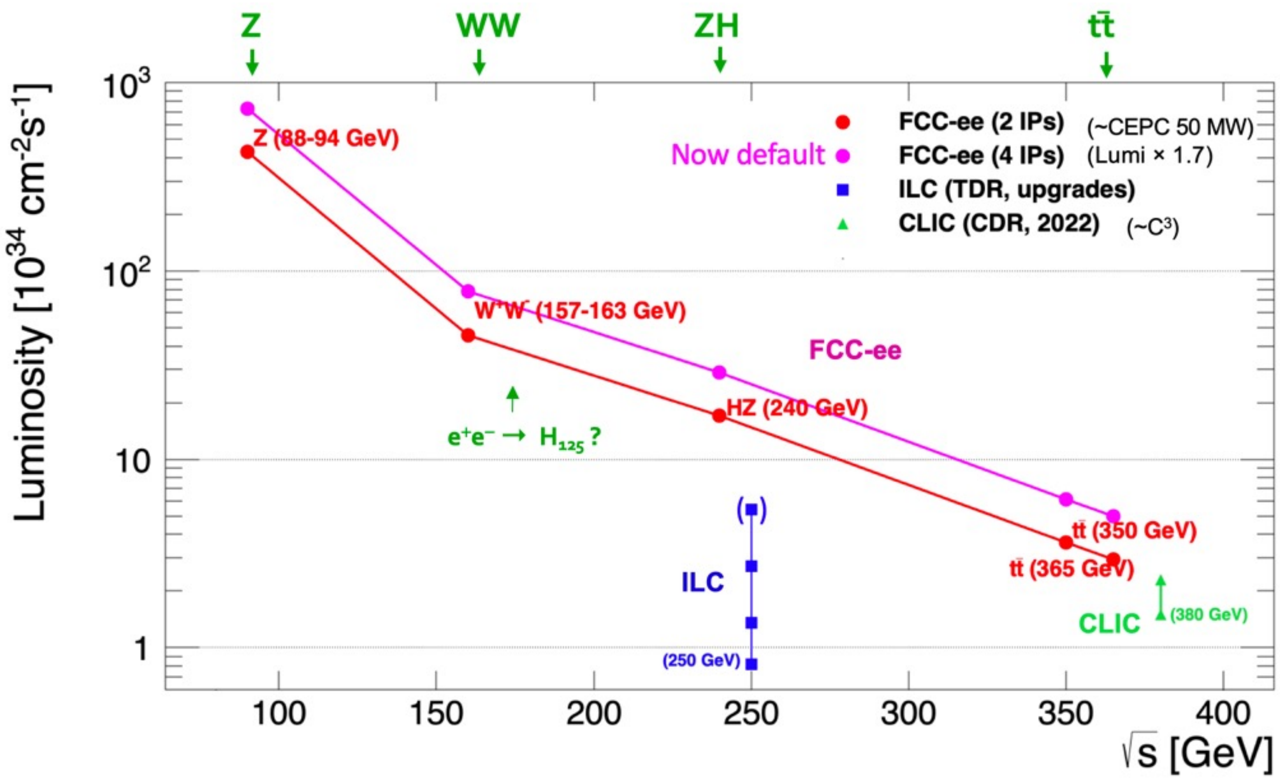
Detector optimization to be done for extremely rich physics capabilities especially at the Z pole with up to $5\text{x}10^{-5}$ Z decays: 10^{12} bb, cc, 2×10^{11} ττ, etc…

- Search for rare processes: Excellent acceptance definition, hermeticity, sensitivity to displaced vertices
- Luminosity measurement at 10^{-4} (abs), 10^{-5} (rel)
- Acceptance definition at ≤ 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^- 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

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

FCC-ee Physics Landscape

"Higgs Factory" Programme

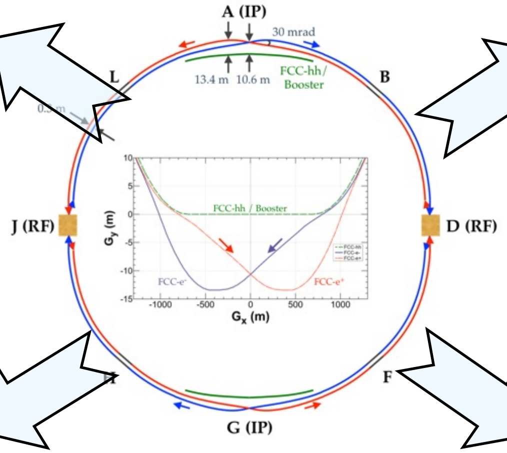
- At two energies, 240 and 365 GeV, collect in total
  - 2M HZ events and 125k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \to H$ @ $\sqrt{s}$ = 125 GeV

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

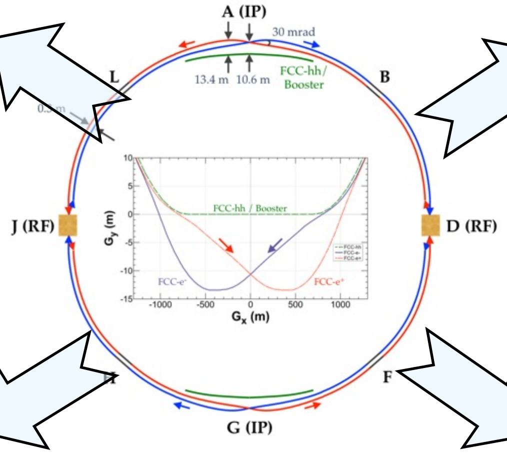
Detector Requirements in Brief

"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%/$\sqrt{E}$ 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^{-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 $\sqrt{s}$ meast.



Heavy Flavour Programme

- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ $\sqrt{E}$ level for 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

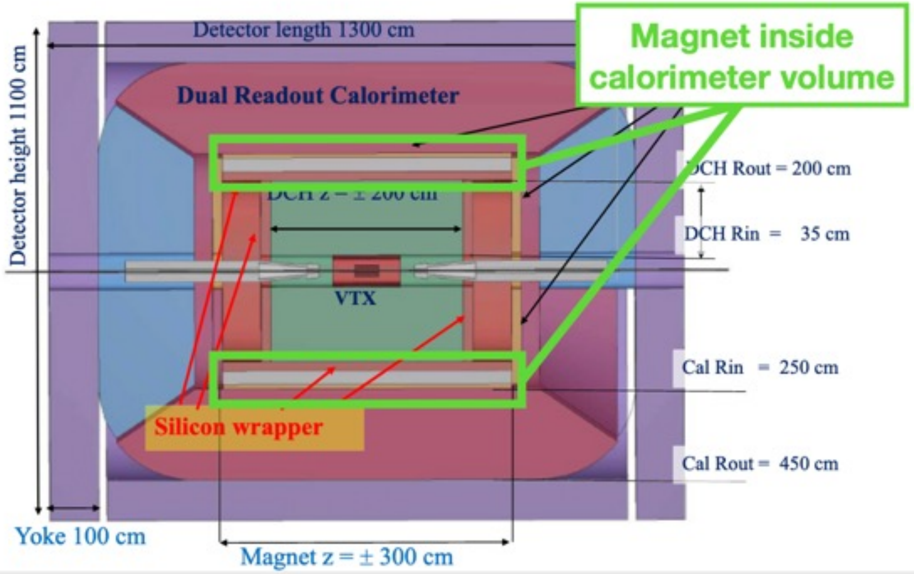
Benchmark signature: Z → νN, with N decaying late

- 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

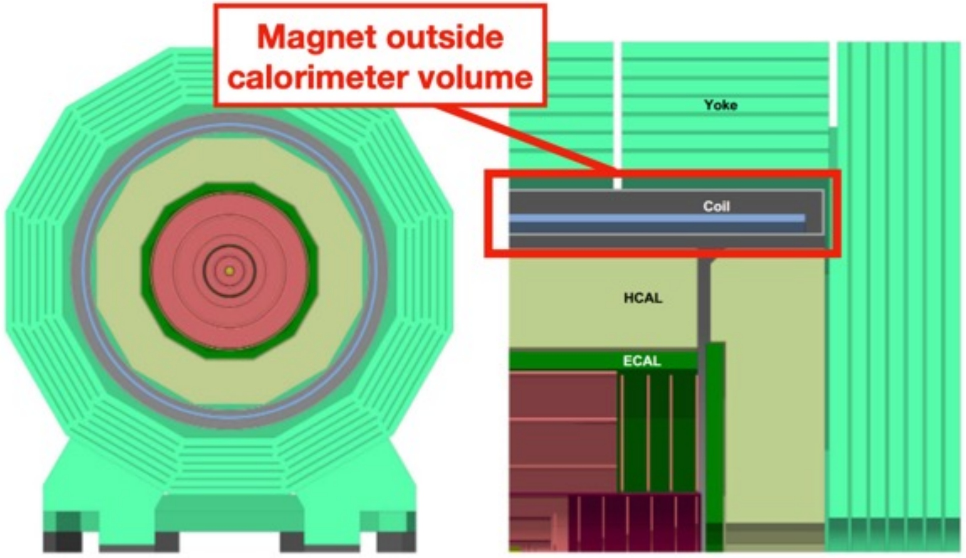
Solenoid Magnet

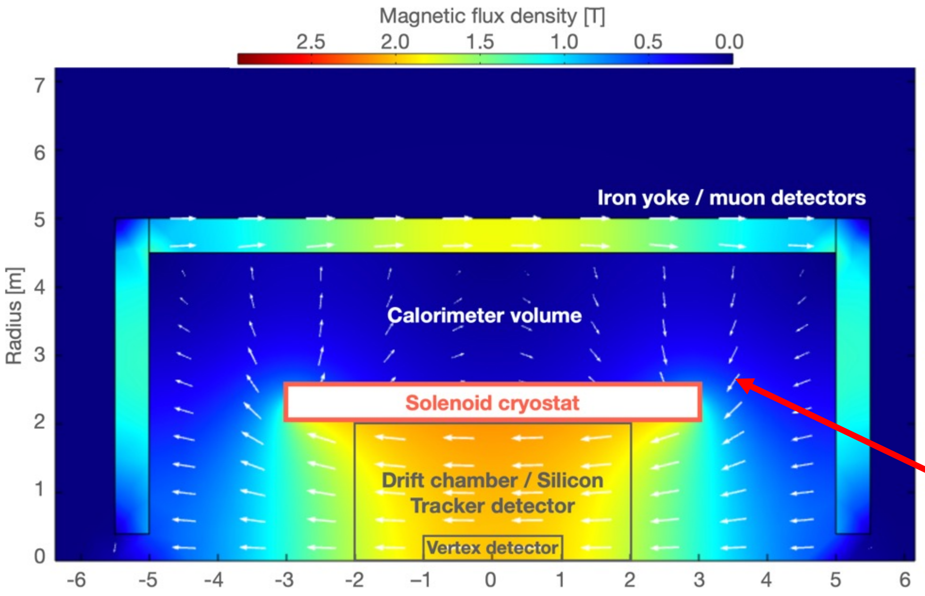
Nikkie Deelen,, FCC Workshop Feb. 2022

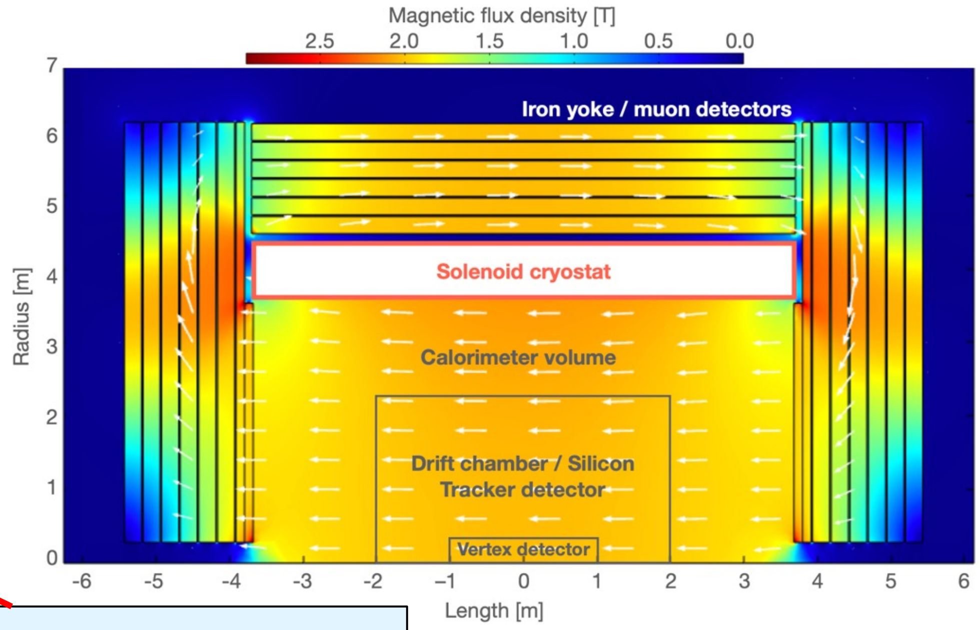
International Detector for Electron-positron Accelerators



CLIC-Like Detector



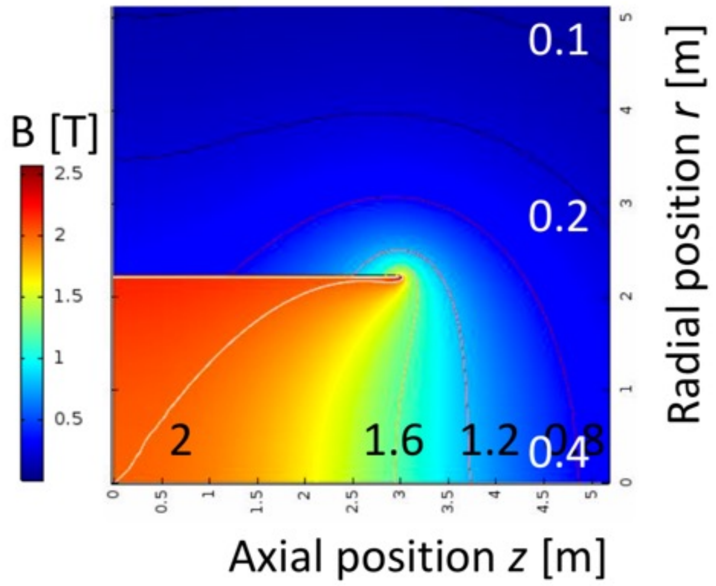




Transparency of the cold mass: 0.76 X_0
Energy density: ~14 kJ/kg [2]

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

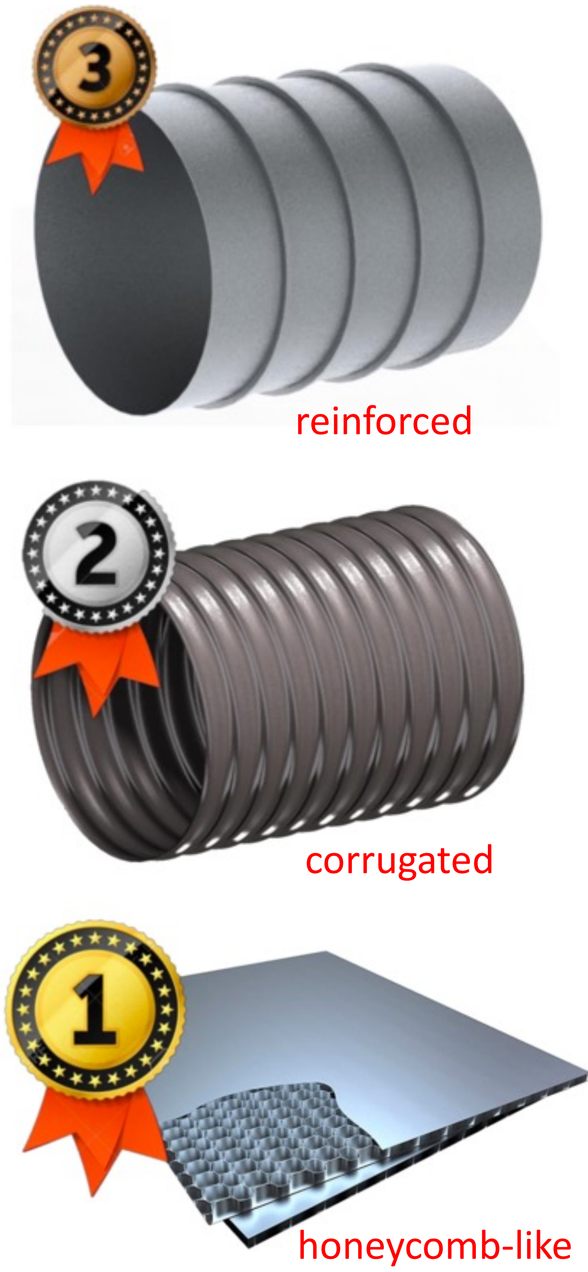
2 T "light and thin" Solenoid inside Calorimeter



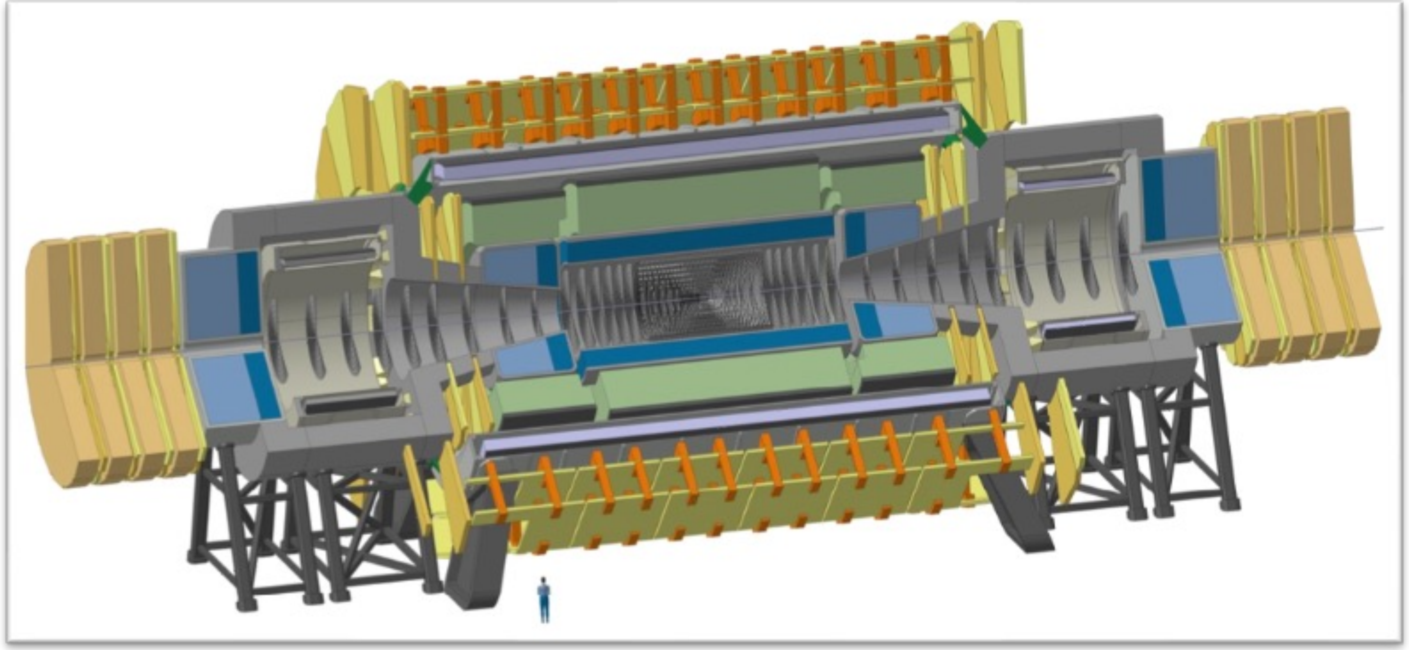
Property	Value
Magnetic field in center [T]	**2**
Free bore diameter [m]	4
Stored energy [MJ]	**170**
Cold mass [t]	8
Cold mass inner radius [m]	2.2
Cold mass thickness [m]	0.03
Cold mass length [m]	6

H. Ten Kate et al.

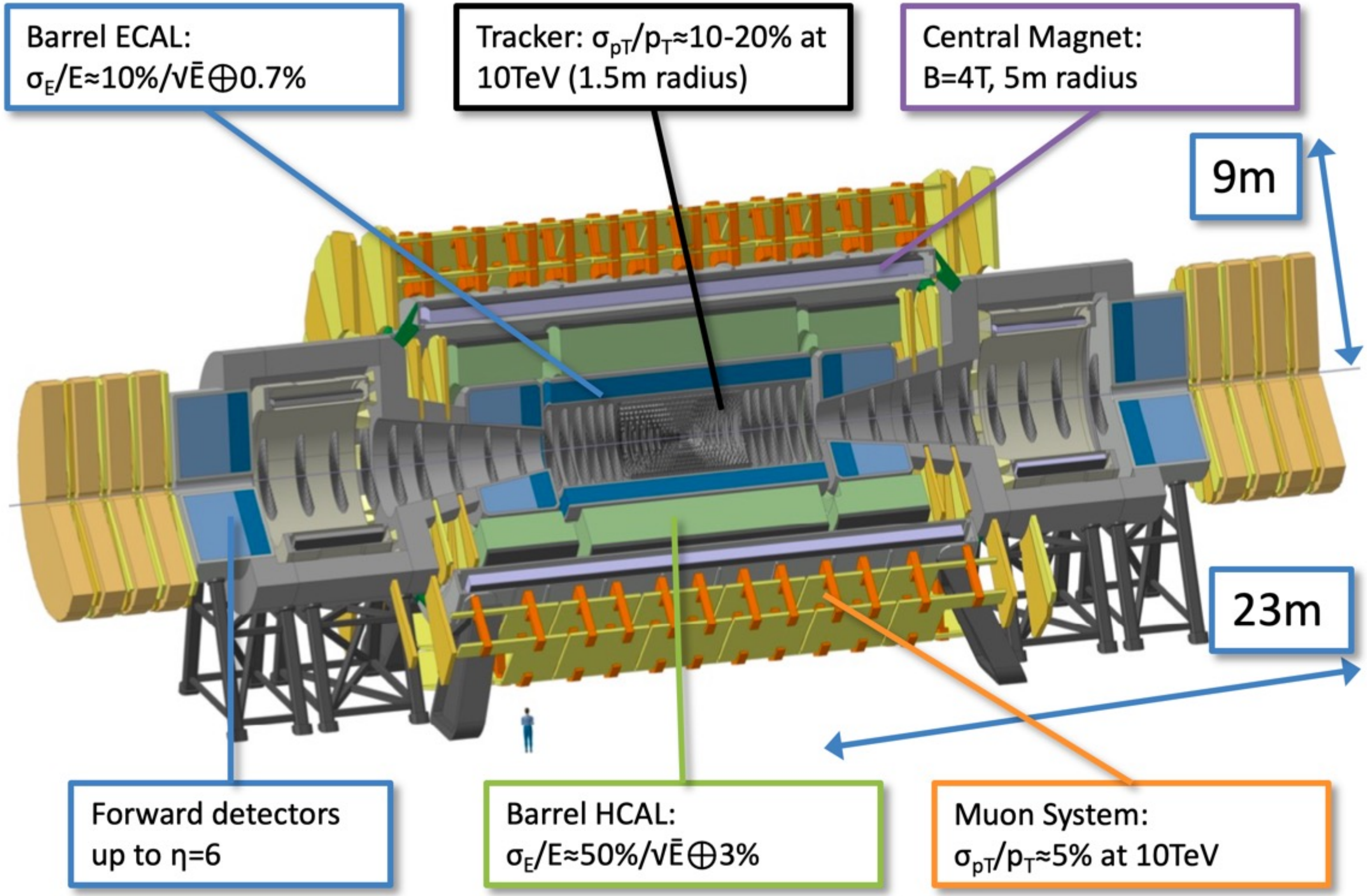
- **Objectives**
  - **Light**: certainly less than 1 X_0
  - **Thin**: As thin as possible for optimal tracker-to-calorimeter matching
- Self-supporting single layer coil
  - High yield strength conductor fully bonded
  - Thin Al support cylinder
- Coil composition
  - Aluminum (77 vol.%)
  - NbTi (5 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



FCC-hh

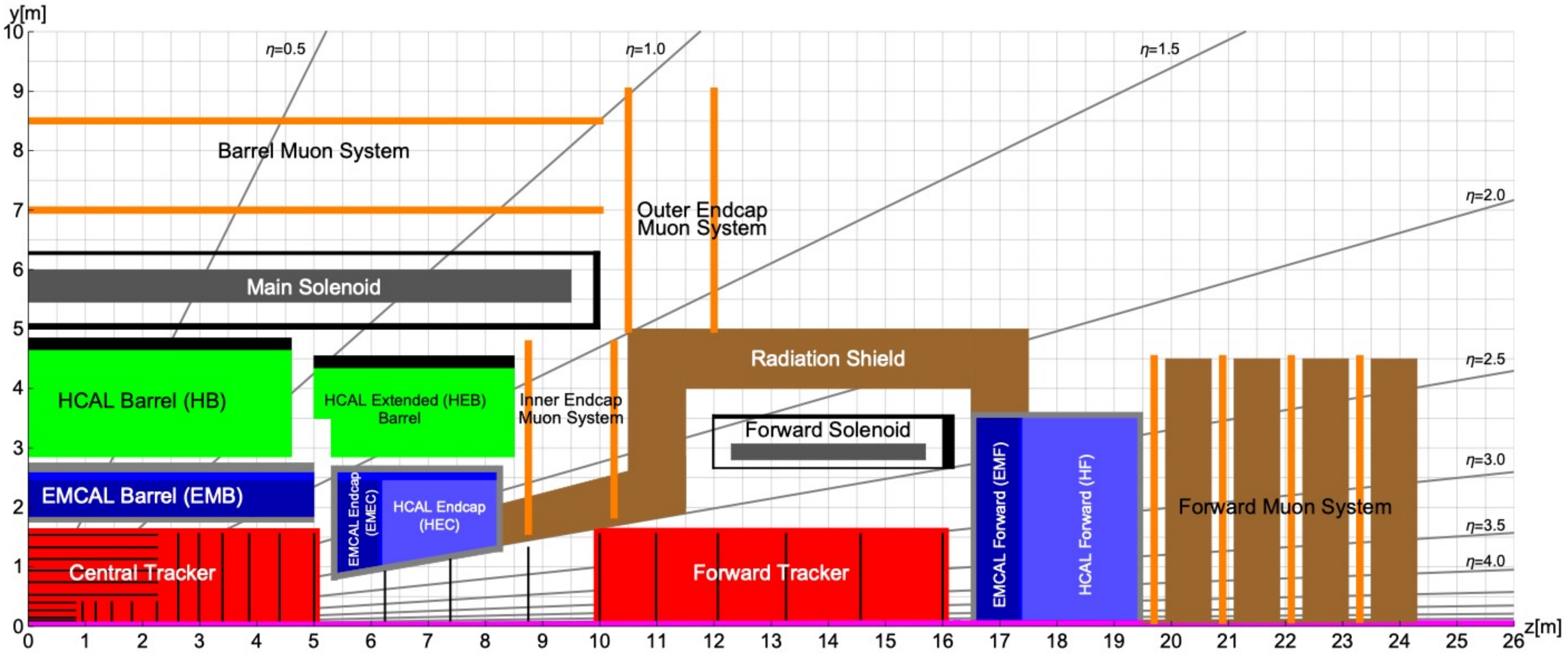


A Possible FCC-hh Detector – Reference Design for CDR



- **Reference design for an FCC-hh experiment for <u>FCC CDR</u>**
- Goal was to demonstrate, that an **experiment** exploiting the **full FCC-hh physics potential** is **technically feasible**
  - **Input for Delphes physics simulations**
  - **Radiation simulations**
- However, this is one example experiment, other choices are possible and very likely → A lot of **room for other ideas, other concepts and different technologies**

FCC-hh Detector - Reference Design for CDR



Forward solenoid adds about 1 unit of η with full lever-arm

Forward solenoid requires additional radiation shield to connect endcap and forward calorimeter