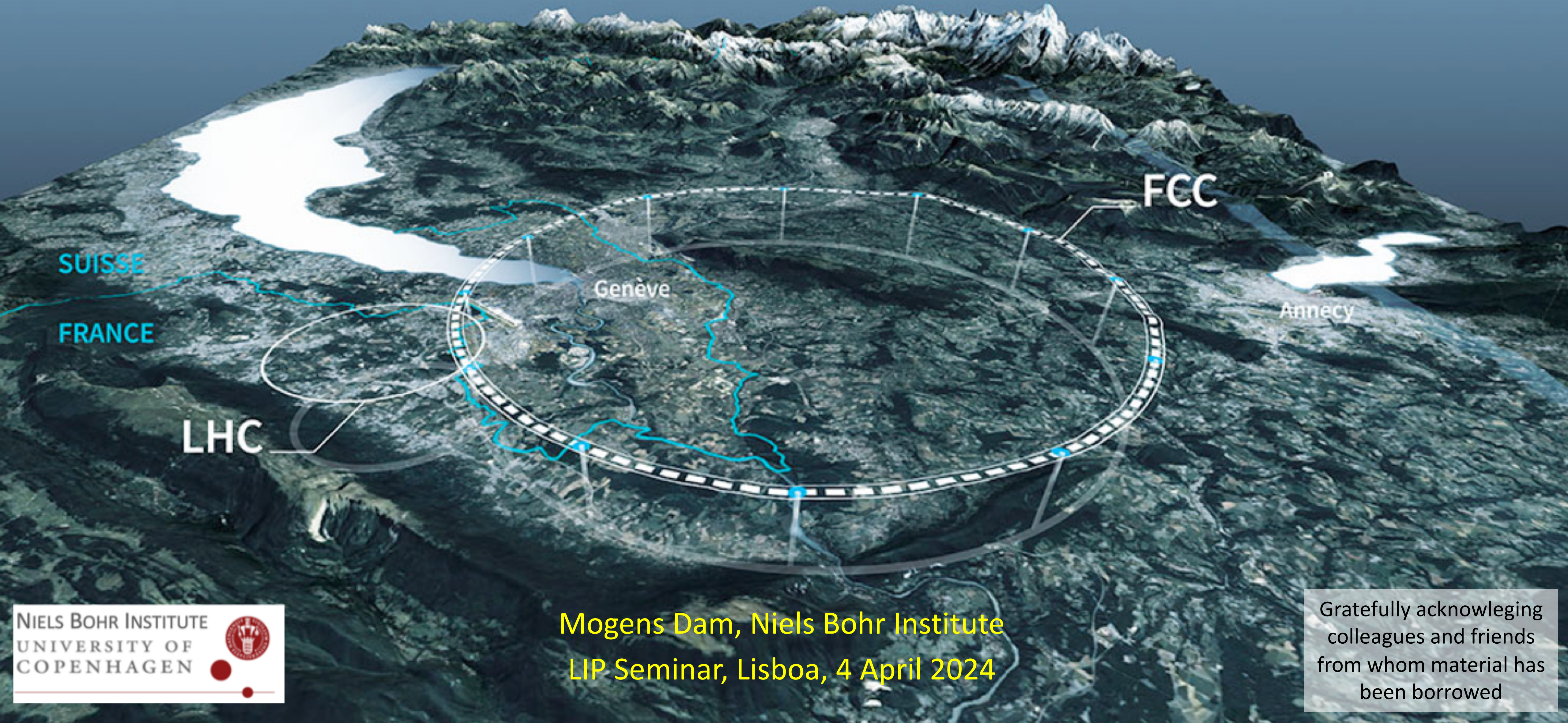
FCC-ee – Physics, Experiments and Detectors



Mogens Dam, Niels Bohr Institute

LIP Seminar, Lisboa, 4 April 2024

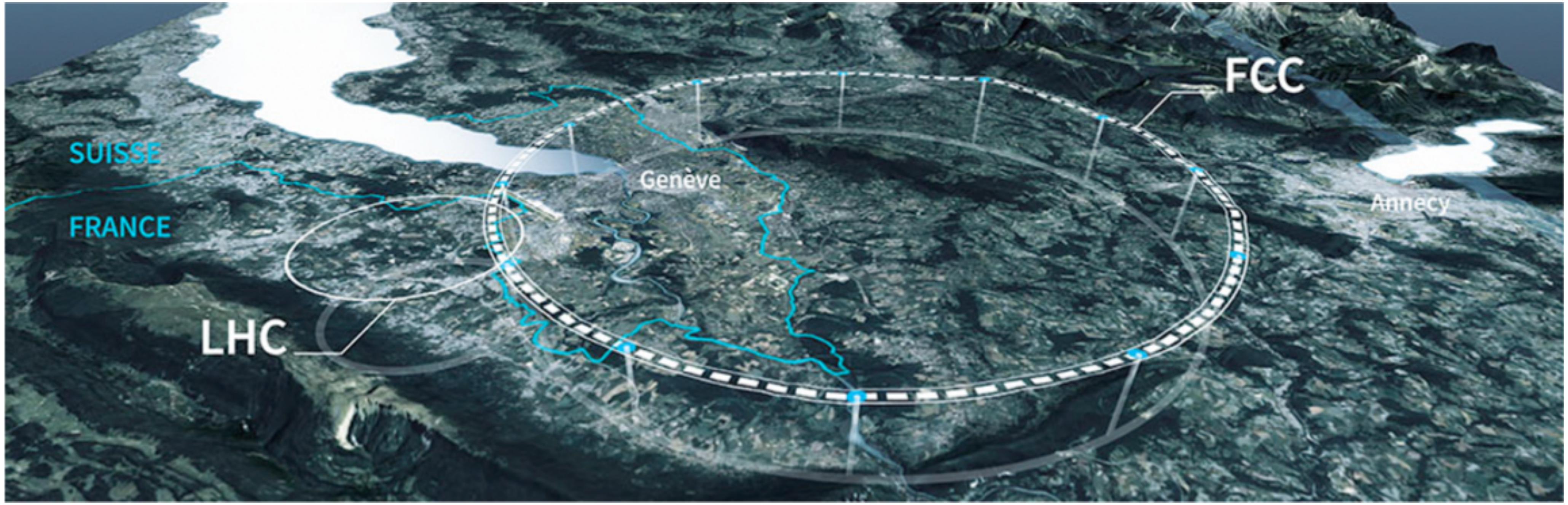
NIELS BOHR INSTITUTE
UNIVERSITY OF COPENHAGEN

Gratefully acknowleging colleagues and friends from whom material has been borrowed

FCC – Future Circular Collider at CERN

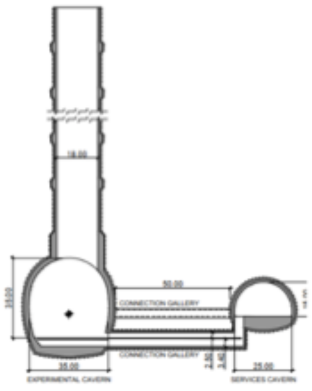
- A versatile, sequence of next-generation particle colliders housed in a 90-km ring
- Implelented in two stages
  - **Stage 1, Precision Frontier, FCC-ee :** electron-positron collisions at 90-365 GeV
    - Construction: 2030-2045 / Physics operation: 2045-2060
    - Precision tests of Standard Model → Indirect / low mass BSM sensitivity
  - **Stage 2, Energy Frontier, FCC-hh :** proton-proton collisions at ≥ 100 TeV
    - Physics operation: ∼ 2070
    - Maximaxing potential for BSM discovery → Direct high-mass BSM sensitivity

Complementary
Synenergetic
All-in-one facility

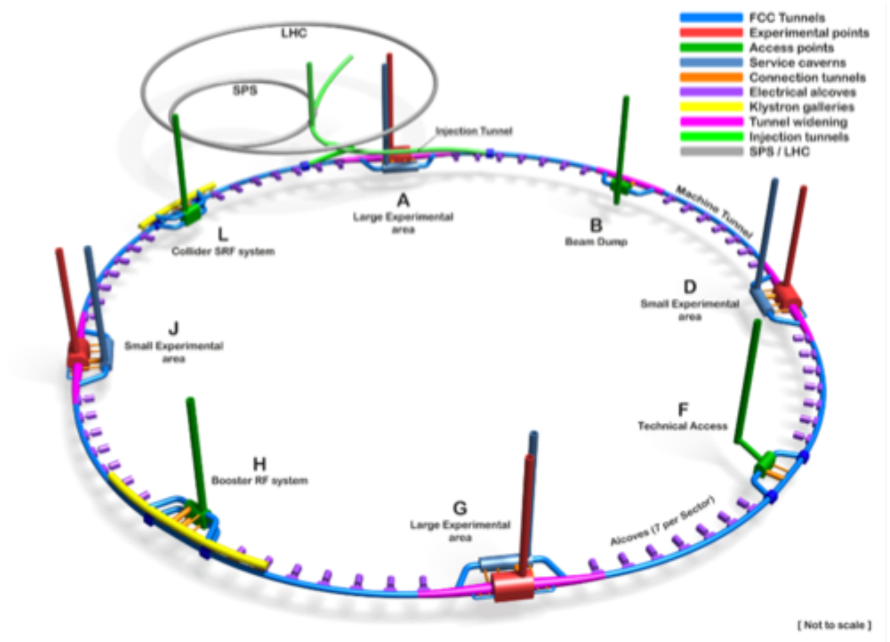


FCC Strengths

- Shared infrastructure
  - Using one tunnel and one set of caverns for both stages
    - 90.7 km ring, 8 surface points
    - 4 experimental areas
      - Accomodating the size of the CERN community

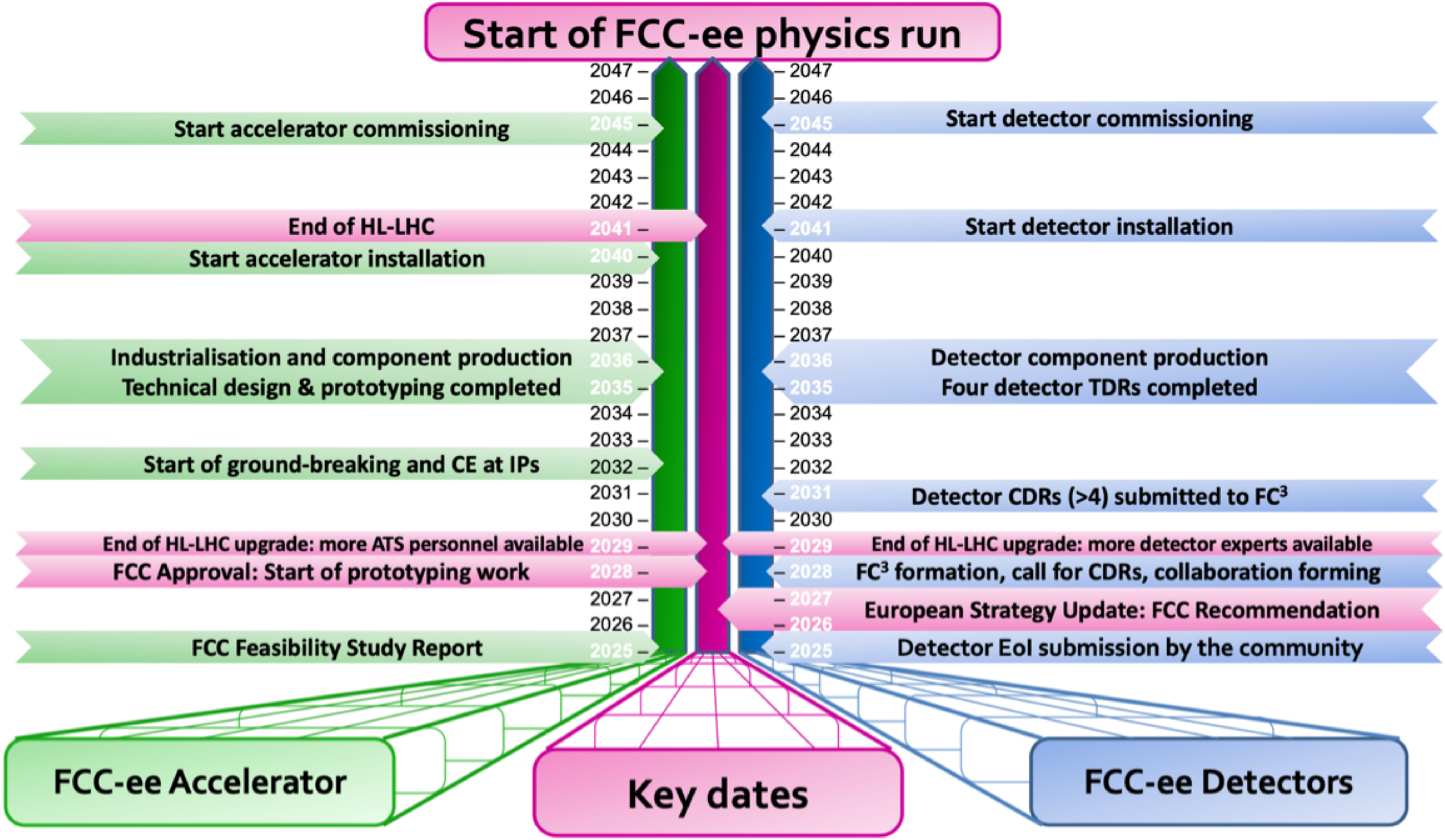


FCC

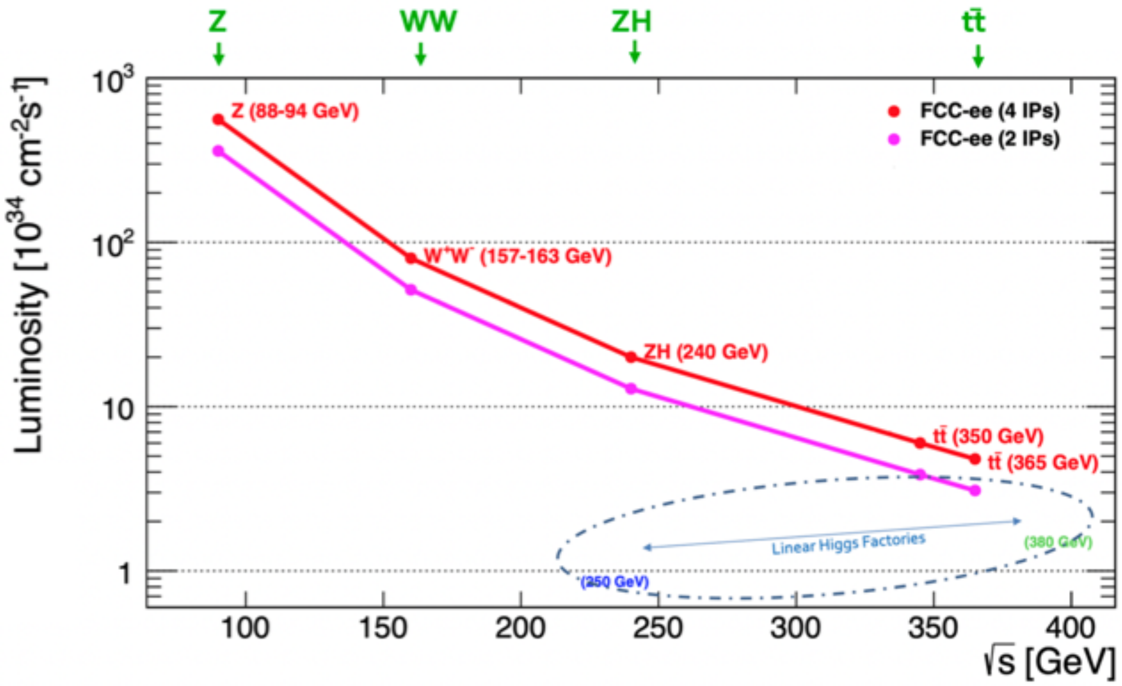


- Time scale
  - FCC-ee technology is mature → construction in parallel with HL-LHC operation
  - Physics operation few years after HL-LHC
  - Allows 20 years of R&D towards optimal and affordable FCC-hh high-field magnets
    - 16-20 Tesla

Possible Timeline



FCC-ee Luminosity and Conditions



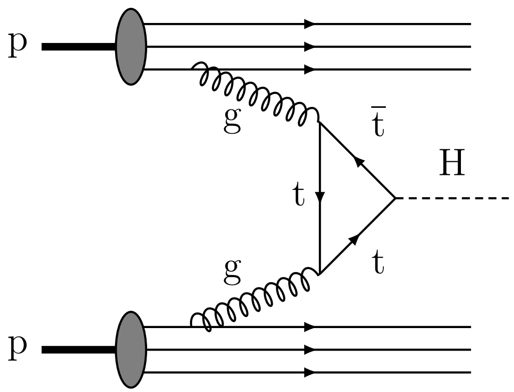
ZH maximum	$\sqrt{s} \sim 240$ GeV	3 years	10^6	$e^+e^- \to ZH$
$t\bar{t}$ threshold	$\sqrt{s} \sim 365$ GeV	5 years	10^6	$e^+e^- \to t\bar{t}$
Z peak	$\sqrt{s} \sim 91$ GeV	4 years	5×10^{12}	$e^+e^- \to Z$
WW threshold+	$\sqrt{s} \geq 161$ GeV	2 years	$> 10^8$	$e^+e^- \to W^+W^-$
[s-channel H	$\sqrt{s} = 125$ GeV	5? years	~5000	$e^+e^- \to H_{125}$]

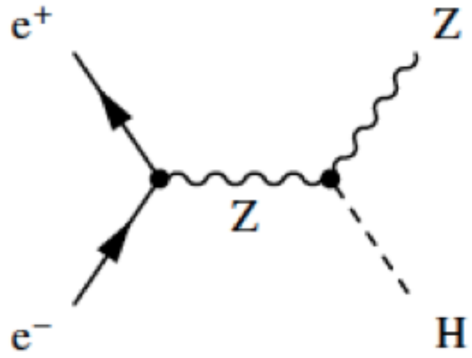
FCC-ee parameters		Z	W^+W^-	ZH	ttbar
√s	GeV	91.2	160	240	350-365
Luminosity / IP	10^{34} cm^{-2} s^{-1}	**140**	20	5.0	1.25
Bunch spacing	ns	25	160	680	5000
"Physics" cross section	pb	35,000	10	0.2	0.5
Total cross section (Z)	pb	70,000	30	10	8
Event rate	Hz	**100,000**	6	0.5	0.1
"Pile up" parameter [μ]	**10^{-6}**	2,500	1	1	1

Experimentally, Z pole most challenging

- Extremely large statistics
- Physics event rates up to 100 kHz
- Bunch spacing at 25 ns
  - "Continuous" beams, no bunch trains, no power pulsing
- No pileup, no underlying event …
  - …well, pileup of 2 x 10^{-3} at Z pole

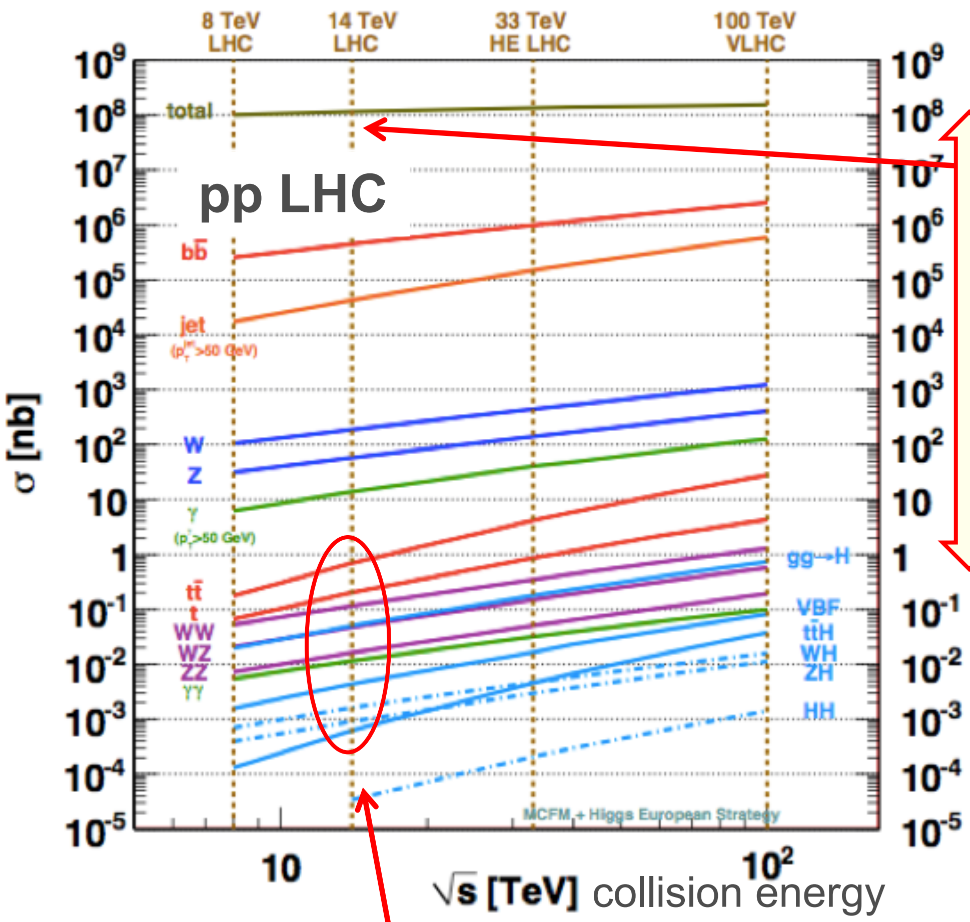
Reminder: pp vs. e^+e^- collisions (i)





p-p collisions	e^+e^- collisions
Proton is compound object → Initial state not known event-by-event → Limits achievable precision	**e^+/e^- are point-like** → Initial state well defined (*E*, ***p***) → High-precision measurements
High rates of QCD backgrounds → Complex triggering schemes → High levels of radiation	**Clean experimental environment** → Trigger-less readout → Low radiation levels
High cross-sections for **colored-states**	Superior sensitivity for **electro-weak states**

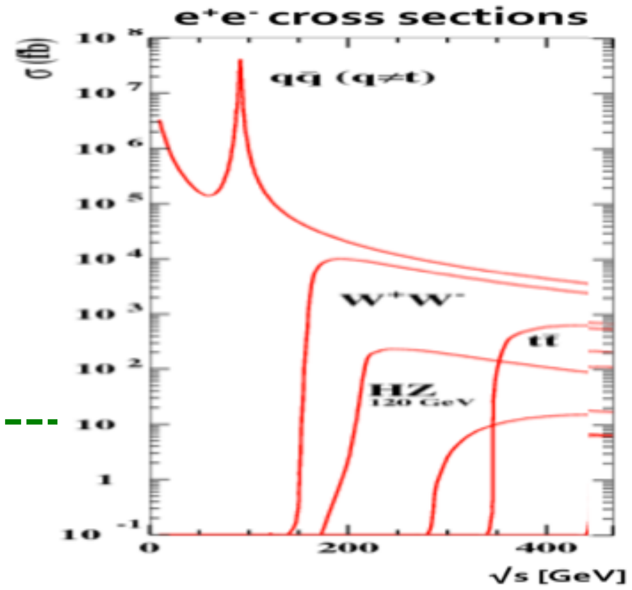
Reminder: pp vs. e^+e^- collisions (ii)



LHC total cross section factor > 100 million !!

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

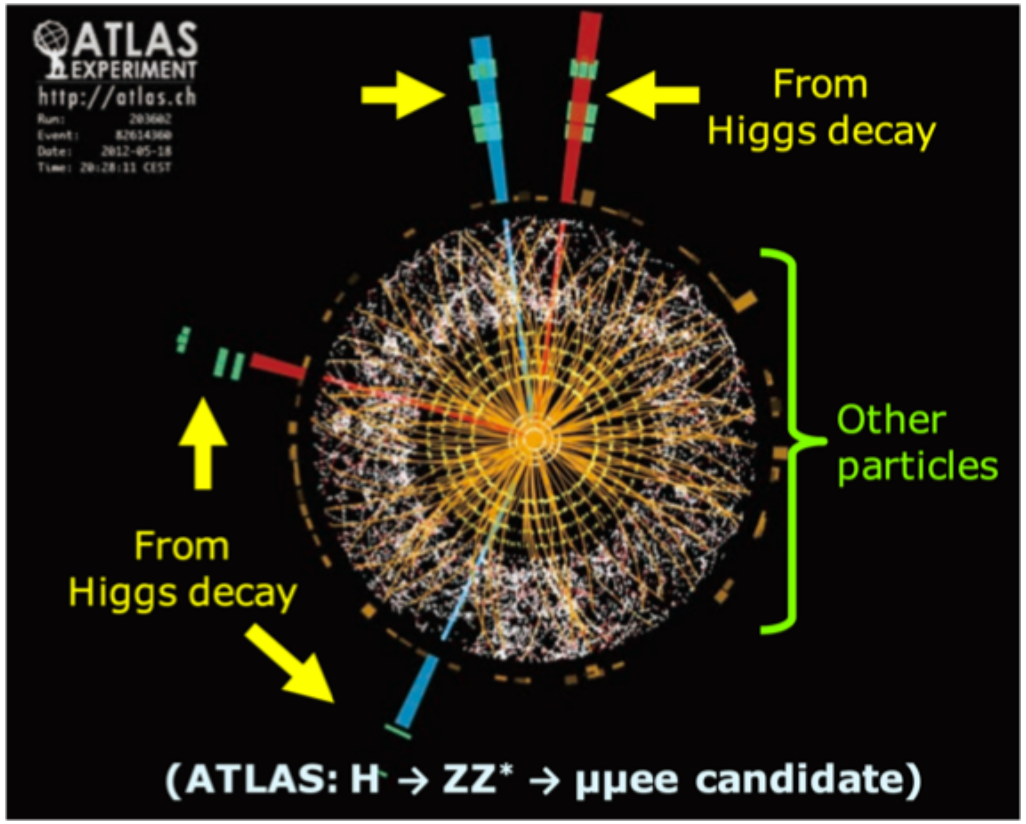
In e^+e^- collisions the total cross section equals the electroweak cross section.



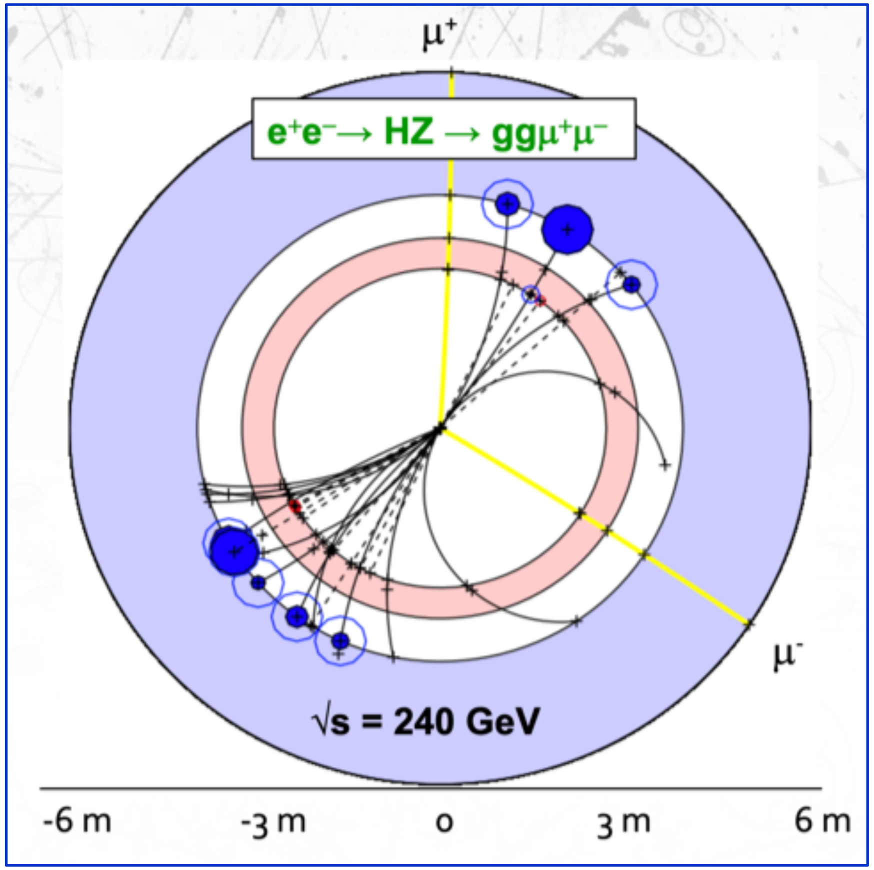
e^+e^- events are "clean"

Reminder: pp vs. e^+e^- collisions (iii)

Higgs event in pp



Higgs event in e^+e^-

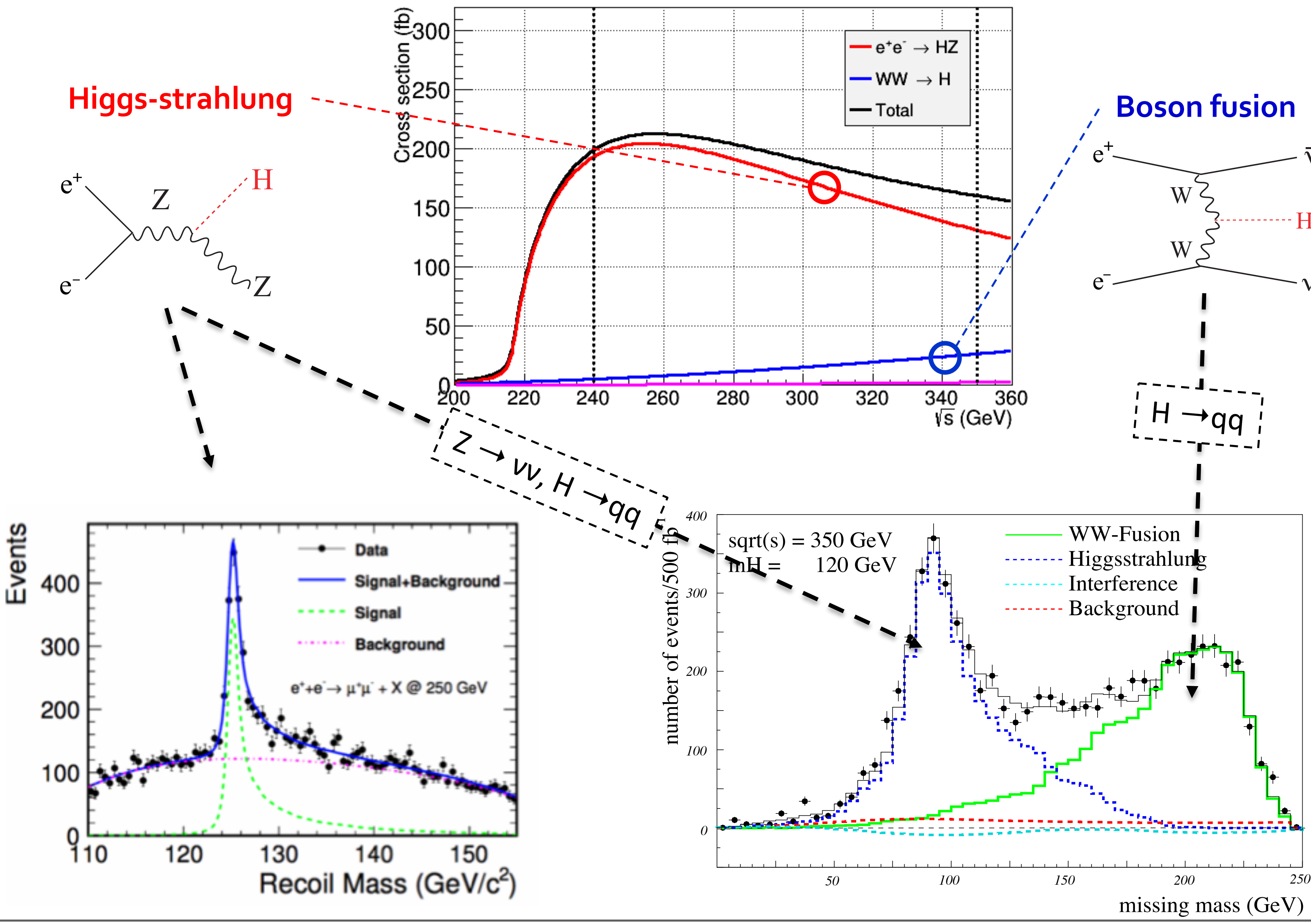


pp: look for striking signal in large background

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

Detector Requirements and Challenges

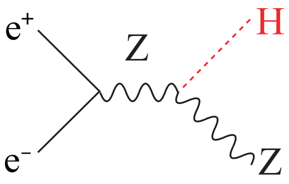
Higgs Factory: Higgs Production and Decay

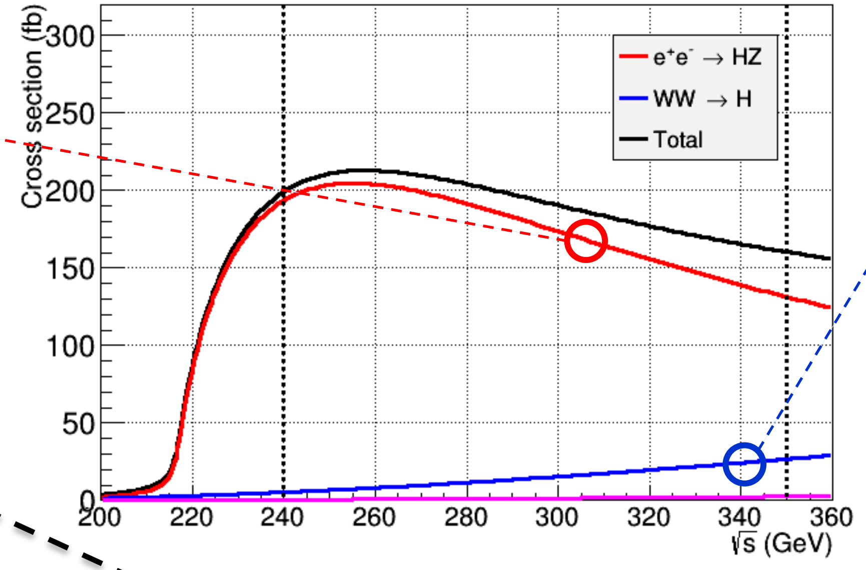


M_H = 125 GeV	SM BF
bb	56.1%
WW*	23.1%
gg	8.2%
ττ	6.3%
ZZ*	2.6%
cc	2.9%
γγ	0.2%
Zγ	0.15%
ss	0.1%
μμ	0.02%

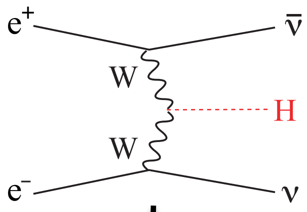
Higgs Factory: Higgs Production and Decay

Higgs-strahlung





Boson fusion



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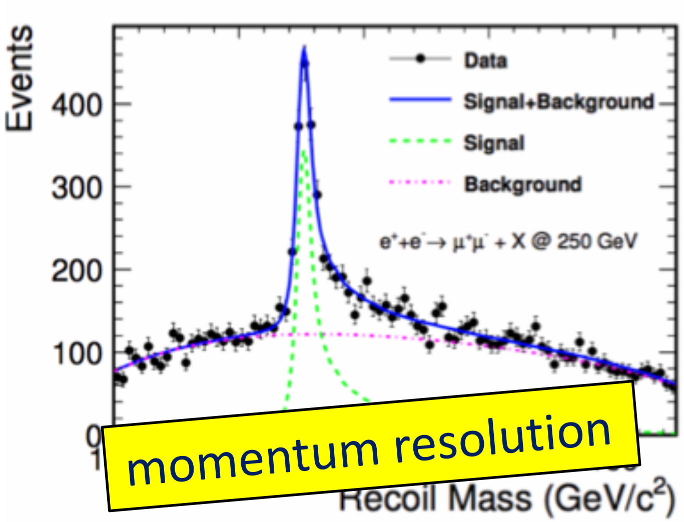
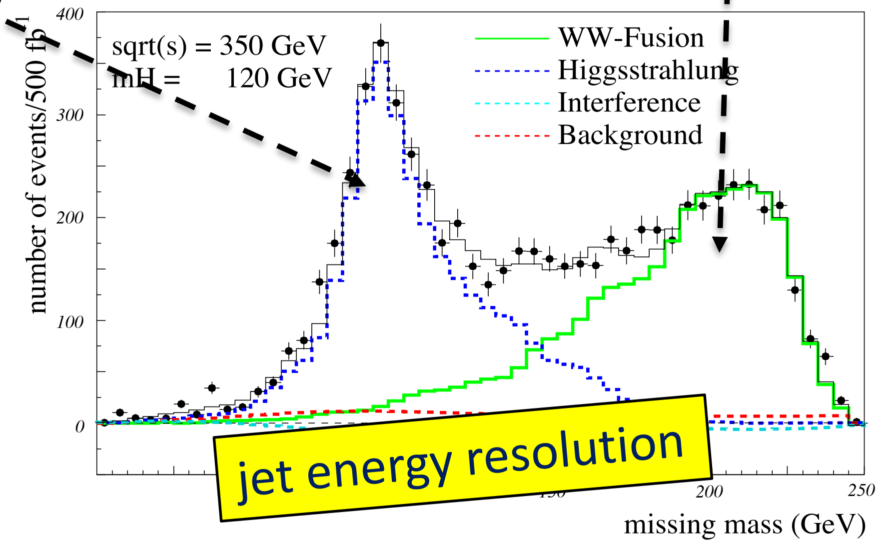
μμ	0.02%

$Z \to \nu\nu$





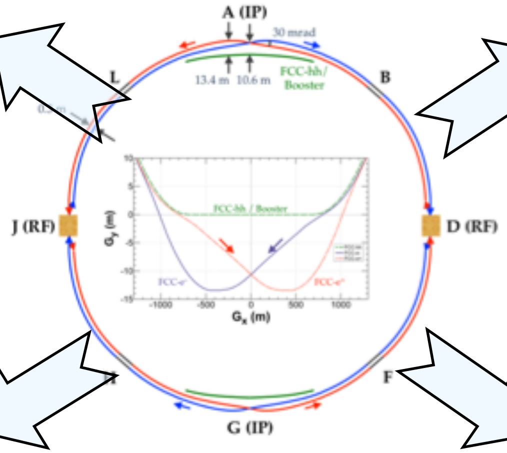
flavour tagging

FCC-ee – Wide Physics Programme

”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 w.r.t. 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

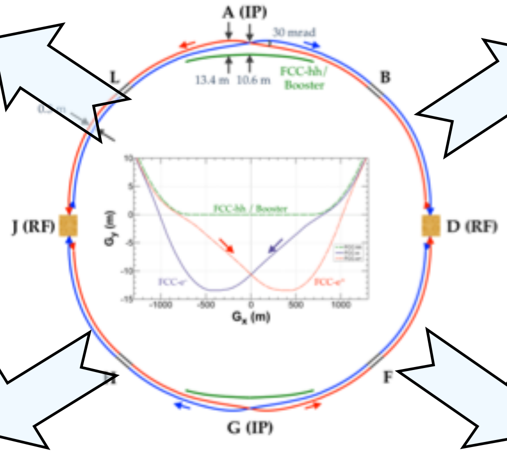
FCC-ee - Detector Requirements

”Higgs Factory” Programme

- Momentum resolution at $p_T \sim 50$ GeV of $\sigma_{pT}/p_T \simeq 10^{-3}$ 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, PID for s-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 flavour and tau physics (granularity)
- PID: K/π separation over wide momentum range for flavour 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

Main Experimental Challenge: High Precision Measurements

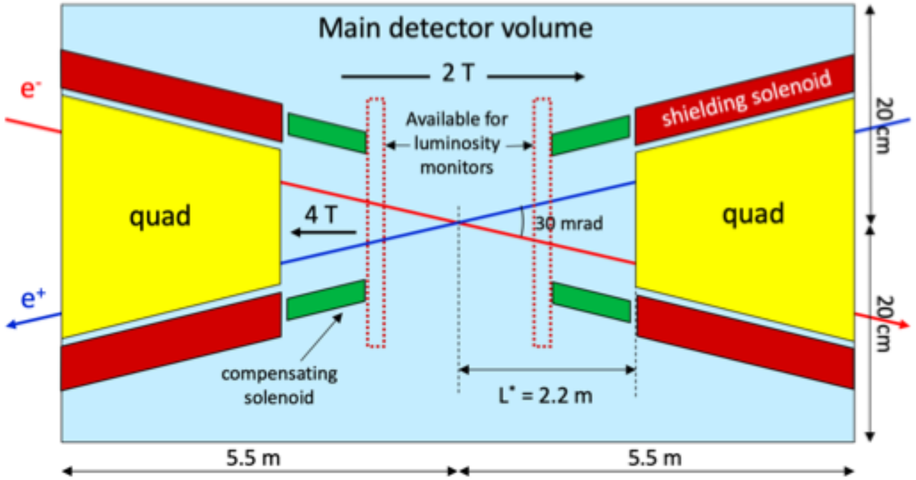
Observable	present value	±	error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
σ_{had}^0 $(\times10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross-section Luminosity measurement
$N_\nu(\times10^3)$	2996	±	7	**0.005**	1	Z peak cross-sections Luminosity measurement
R_b $(\times10^6)$	216290	±	660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ $(\times10^4)$	1498	±	49	**0.15**	<2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times10^4)$	1010	±	270	**3**	small	From R_ℓ^W
$N_\nu(\times10^3)$	2920	±	50	**0.8**	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172740	±	500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410	±	190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2	±	0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings		±	30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run

- FCC-ee EWPO measurements with unprecedented ***statistical*** precision
  - 5 x 10^{12} hadronic Z decays at Z-pole
    - Also flavour factory: 7×10^{11} Z → bb, 1.5×10^{11} Z → $\tau^+\tau^-$
  - **Statistical precision** for EWPOs is **typically 500 times smaller than the current uncertainties**
  - Systematic uncertainty will have to be reduced
  - Can achieve indirect sensitivity to new physics up to a scale $\Lambda_{\text{new physics}}$ of 70 TeV
- Require ***systematic*** precision to match
  - Comensurate control of parametric uncertainties, e.g. PDFs, α_s, m_t, m_H
  - Higher order theoretical computations, e.g. N…NLO
  - **Minimizing detector systematics**

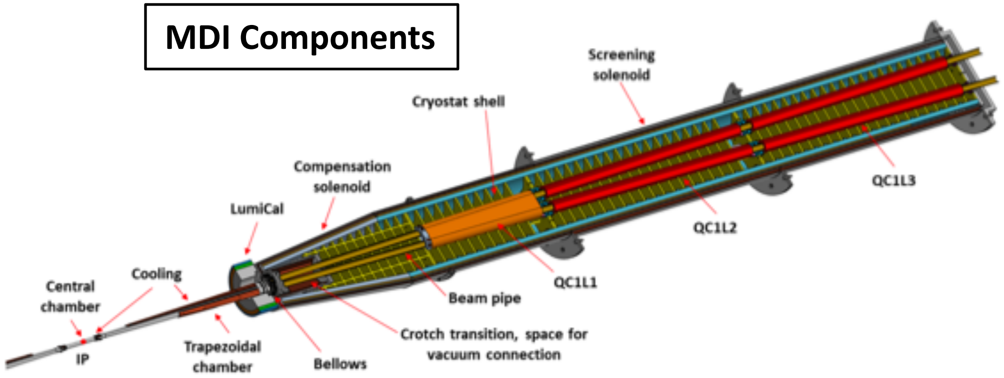
Experimental Challenges

- 30 mrad beam crossing angle
  - Detector B-field limited to 2 Tesla (at Z-peak operation)
  - Tightly packed MDI (Machine Detector Interface)
- "Continuous" beams (no bunch trains); bunch spacing down to 25 ns
  - Power management and cooling (no power pulsing as planned for linear colliders)
- Extremely high luminosities
  - High statistical precision -- control of systematics down to $\sim 10^{-5}$ level
  - Online and offline handling of $\mathcal{O}(10^{13})$ events for precision physics
    - "Big Data"
- Physics events at up to 100 kHz
  - Detector response time $\lesssim 1\ \mu s$ to minimise dead-time and event overlaps
  - 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



MDI Components



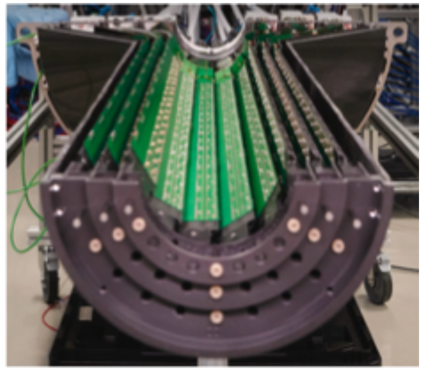
Detector elements and technologies

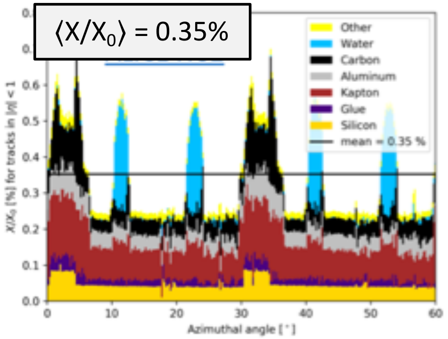
Vertex Detector

- Measurement of impact parameter, reconstruction of secondary vertices, flavour tagging, lifetime measurements
- Very strong development
  - **Lighter, more precise, closer**

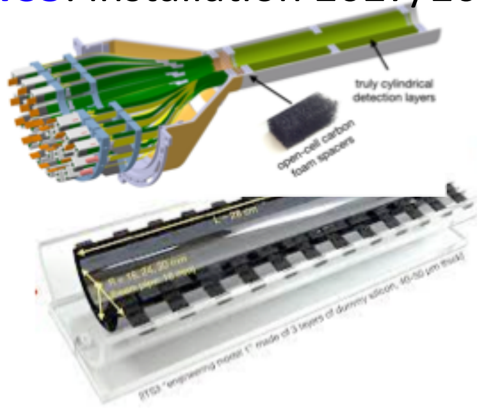
Strong ALICE Vertex detector development

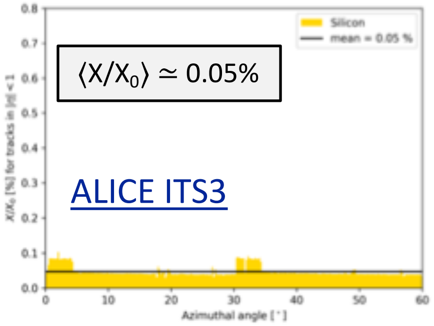
ITS2: installed in 2021





ITS3: installation 2027/2028

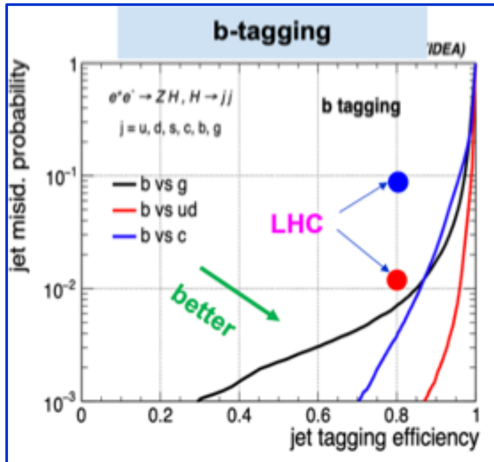




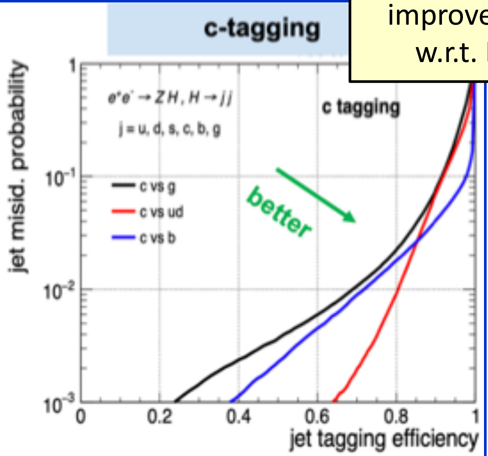
- Many conditions/requirements common between ALICE and FCC-ee
  - Moderate radiation environments
  - No need for picosecond timing
  - High resolution and low multiple scattering is key

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

Very substantial improvement w.r.t. LHC



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

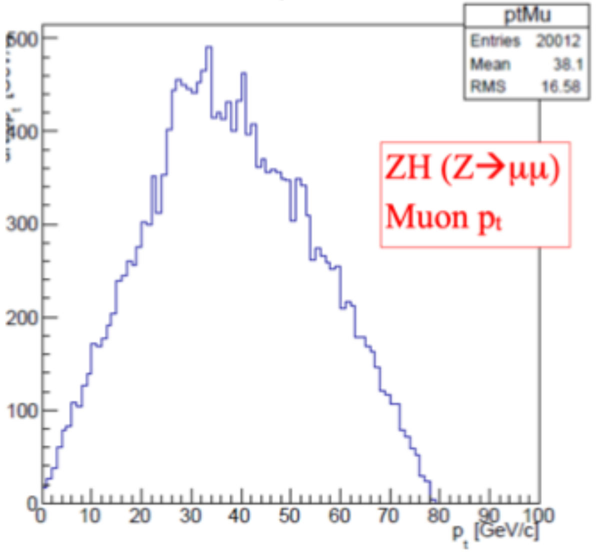


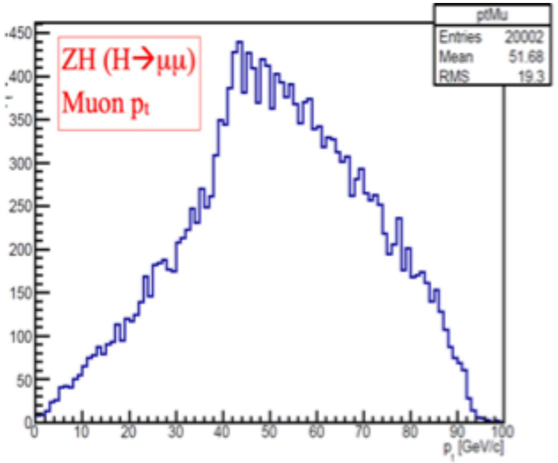
WP	Eff (c)	Mistag (g)	Mistag (ud)	Mistag (b)
Loose	90%	7%	7%	4%
Medium	80%	2%	0.8%	2%

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

Tracking Systems - Momentum measurement

Particles from Higgs production process are generally of moderate momentum





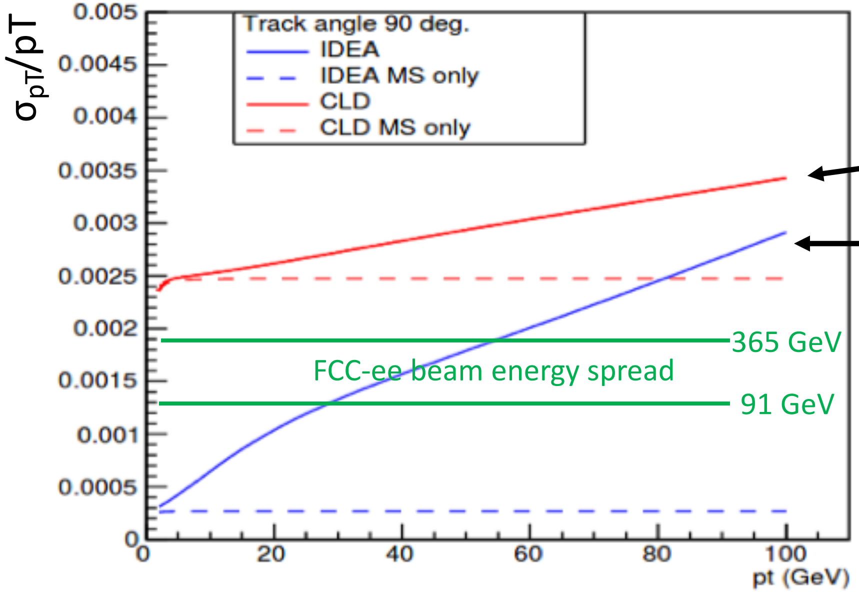
Momentum resolution tends to be multiple scattering dominated

⇒ Asymptotic resolution not reached

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

mult.scat

resolution



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

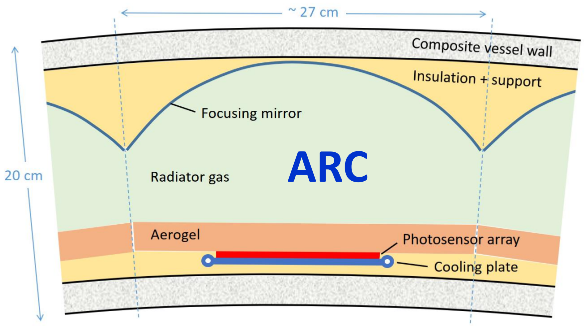
⇒ Detector transparency more important than asymptotic resolution ⇐

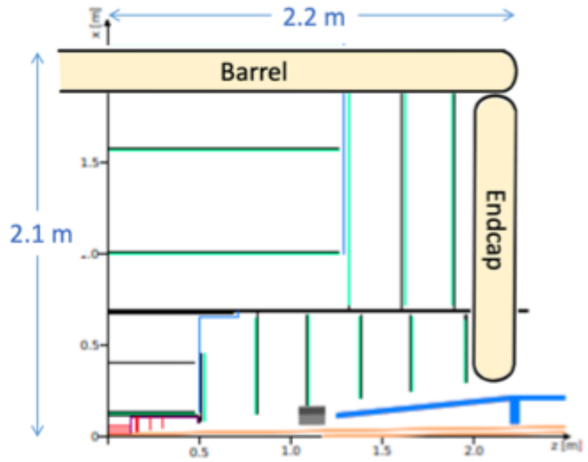
https://doi.org/10.1016/j.nima.2018.08.078

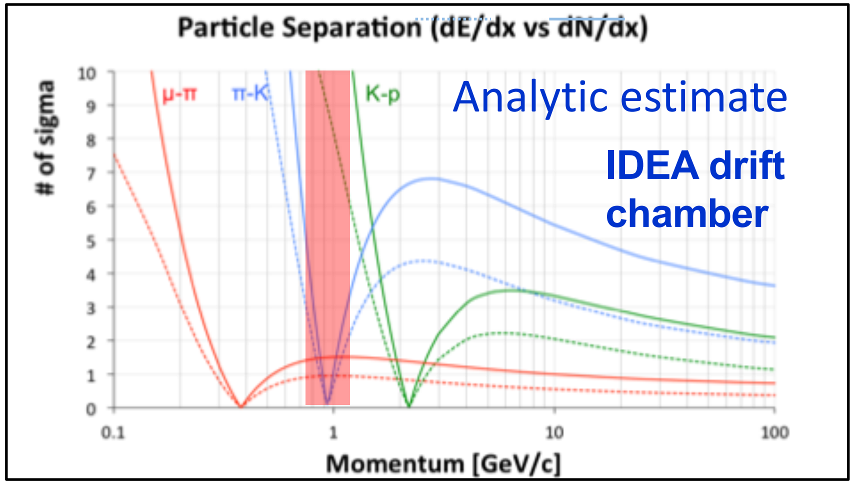
Particle Identification

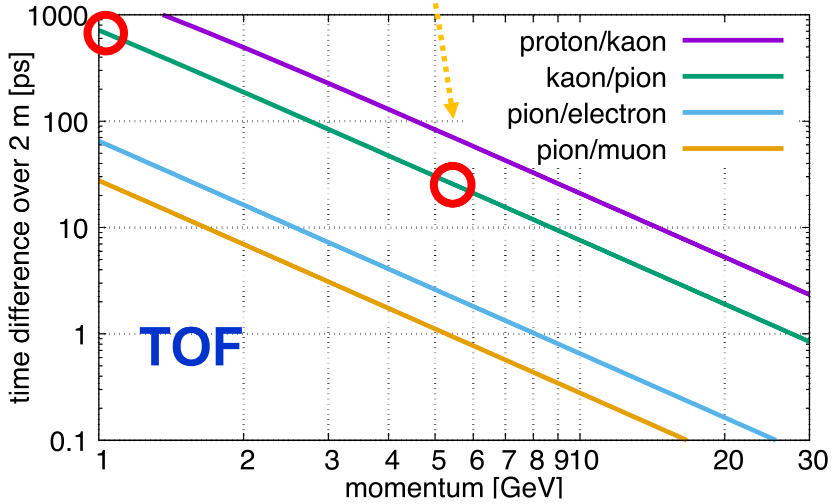
- **PID capabilities across a wide momentum range** is essential for flavour studies; will enhance overall physics reach
  - Example: important mode for CP-violation studies $B^0_S \rightarrow D^\pm_S K^\mp$ → require K/π separation over wide momentum range to suppress same topology $B^0_S \rightarrow D^\pm_S \pi^\mp$
- **E.g. IDEA drift chamber** promises >3σ π/K separation up to 35-100 GeV
  - 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 are also investigated (e.g. A pressurized RICH Detector – **ARC**)
  - could give 3σ π/K separation from 5 GeV to ~80 GeV

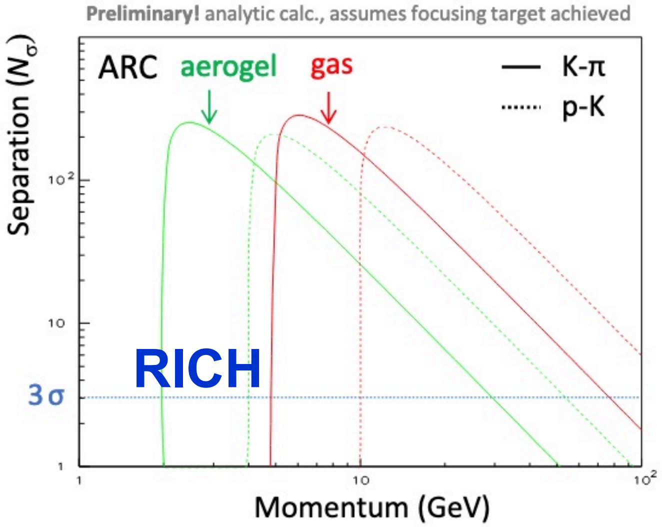
Possible RICH layout in an FCC-ee experiment











Calorimetry – Jet Energy Resolution

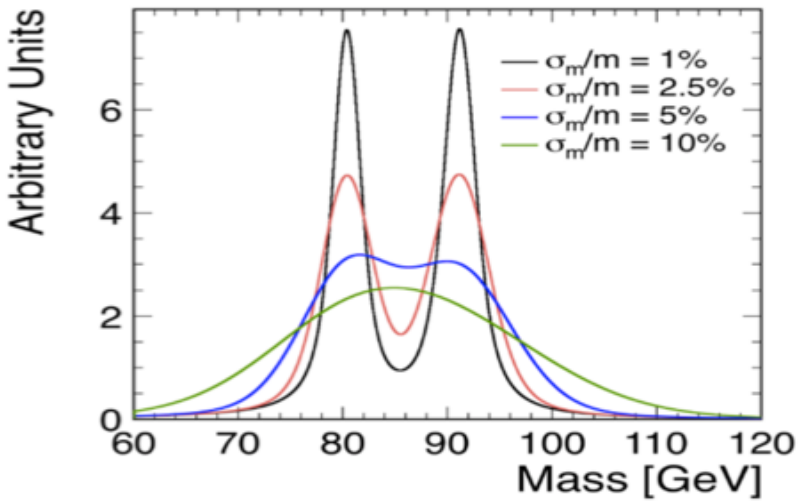
Energy coverage < 300 GeV : $22\ X_0$, 7λ
Precise jet angular resolution

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

⇒ Mass reconstruction from jet pairs

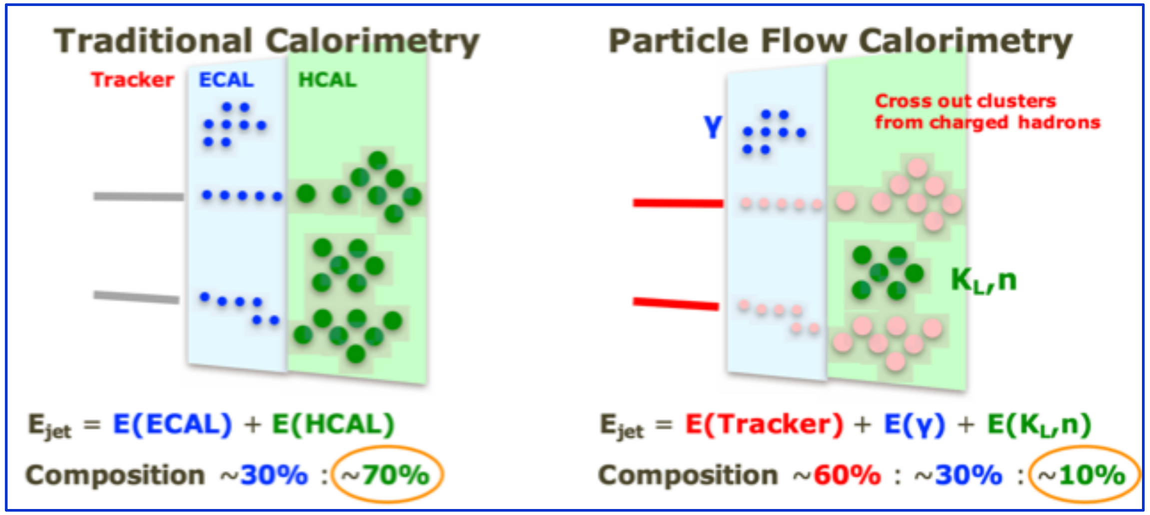
Resolution important for control of (combinatorial) backgrounds in multi-jet final states

- Separation of HZ and WW fusion contribution to ννH
- HZ → 4 jets, tt 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 possibly combined with techniques to correct for non-compensation (e/h ≠ 1), e.g. via *dual readout*



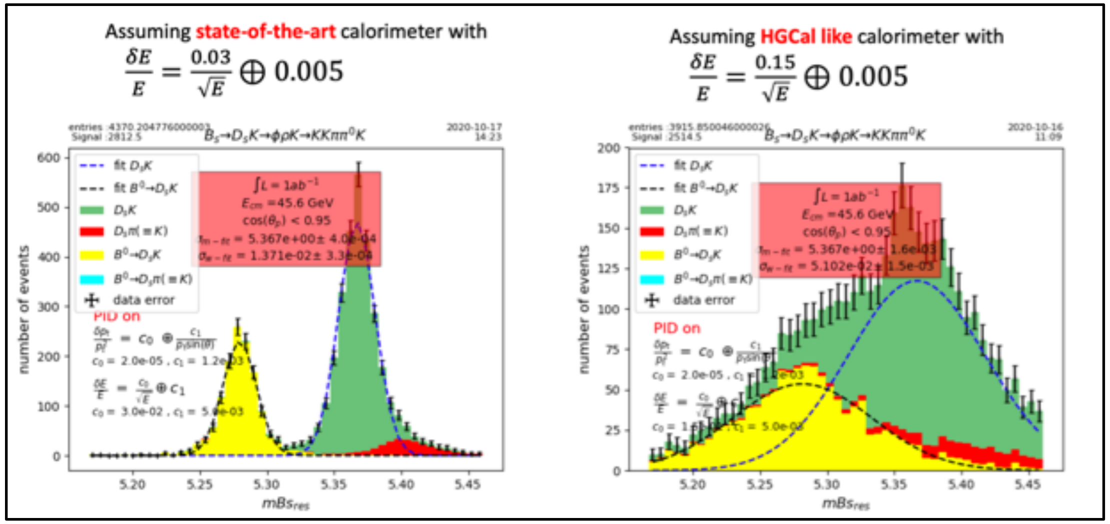
High granularity !
Possibly combined with dual readout

Incomplete list of requirements – all under study

- Energy resolution
  - Photons and neutral hadrons for PFlow
  - Electrons and charged hadrons for PID (E/p measurement)
- Dynamic range: 200 MeV – 180 GeV
  - For π^0 identification in flavour physics, sensitivity to photons down to few 100 MeV (as at LEP)
  - Much lower than at LHC
- Granularity: PID (γ vs. π^0), disentangle showers for Pflow
  - Requirement under study
- Hermeticity, uniformity, calibrability, stability
  - Low systematics for precision measurements
  - Complex engineering questions
- No need to be particularly fast
  - But can precise timing help in reconstricting showers?

Examples of specific requirements

- Much improved flavour and tau physics reach from improved ECAL energy and spatial resolution
  - For b-physics by making accesible exclusive channels with π^0's



  - For tau-physics, control of decay-mode migration matrix essential

LAr study

Recon → / Gen ↓	$\pi^\pm \nu$	$\pi^\pm \pi^0 \nu$	$\pi^\pm 2\pi^0 \nu$	$\pi^\pm 3\pi^0 \nu$	$\pi^\pm 4\pi^0 \nu$
$\pi^\pm \nu$	**0.9859**	0.0129	0.0008	0.0001	0.0003
$\pi^\pm \pi^0 \nu$	0.0351	**0.9338**	0.0300	0.0011	0.0001
$\pi^\pm 2\pi^0 \nu$	0.0084	0.1314	**0.8050**	0.0546	0.0003
$\pi^\pm 3\pi^0 \nu$	0.0031	0.0360	0.2673	**0.6138**	0.0792

Calorimetry – Overview of Technologies

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.

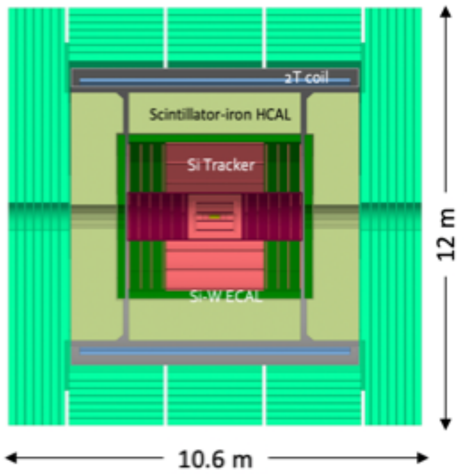
For references and more information see https://link.springer.com/article/10.1140/epjp/s13360-021-02034-2

- **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, …

Proto Detectors

Proto Detectors - Overview

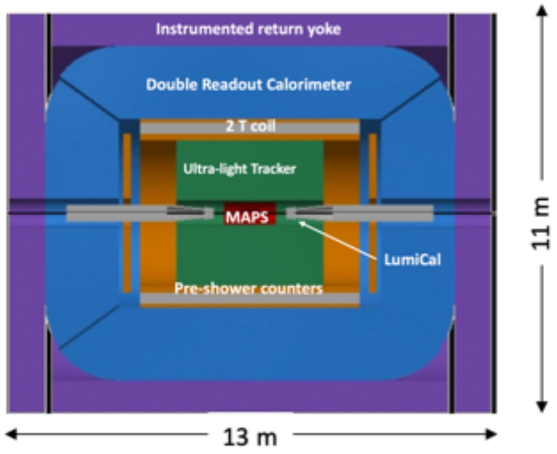
CLD



CDR

- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si VTX + tracker; CALICE-like calorimetry; large coil, muon system
- Engineering and R&D needed for
  - reduction of tracker material budget
  - operation with continous beam (no power pulsing: cooling of Si sensors for tracking + calorimetry)
- Possible detector optimizations
  - Improved σ_p/p, σ_E/E
  - PID: timing and/or RICH?
  - …

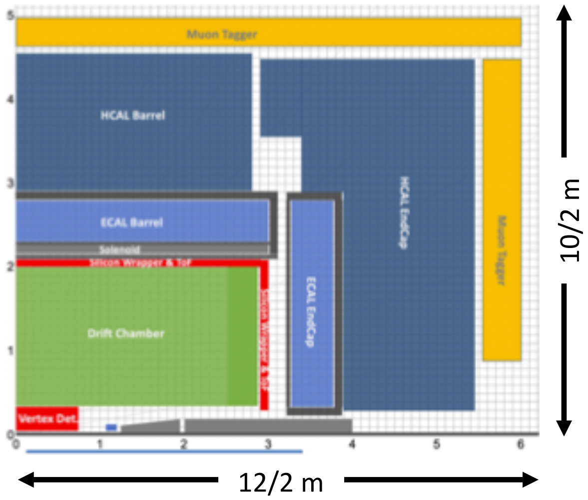
IDEA



- Less established design
  - But still ~15y history
- Si VTX detector; ultra light drift chamber w. powerfull PID; compact, light coil; monolitic dual readout calorimeter; muon system
  - Possibly augmented by crystal ECAL
- Active community
  - Prototype designs, test beams, …
  - Software

Allegro

new

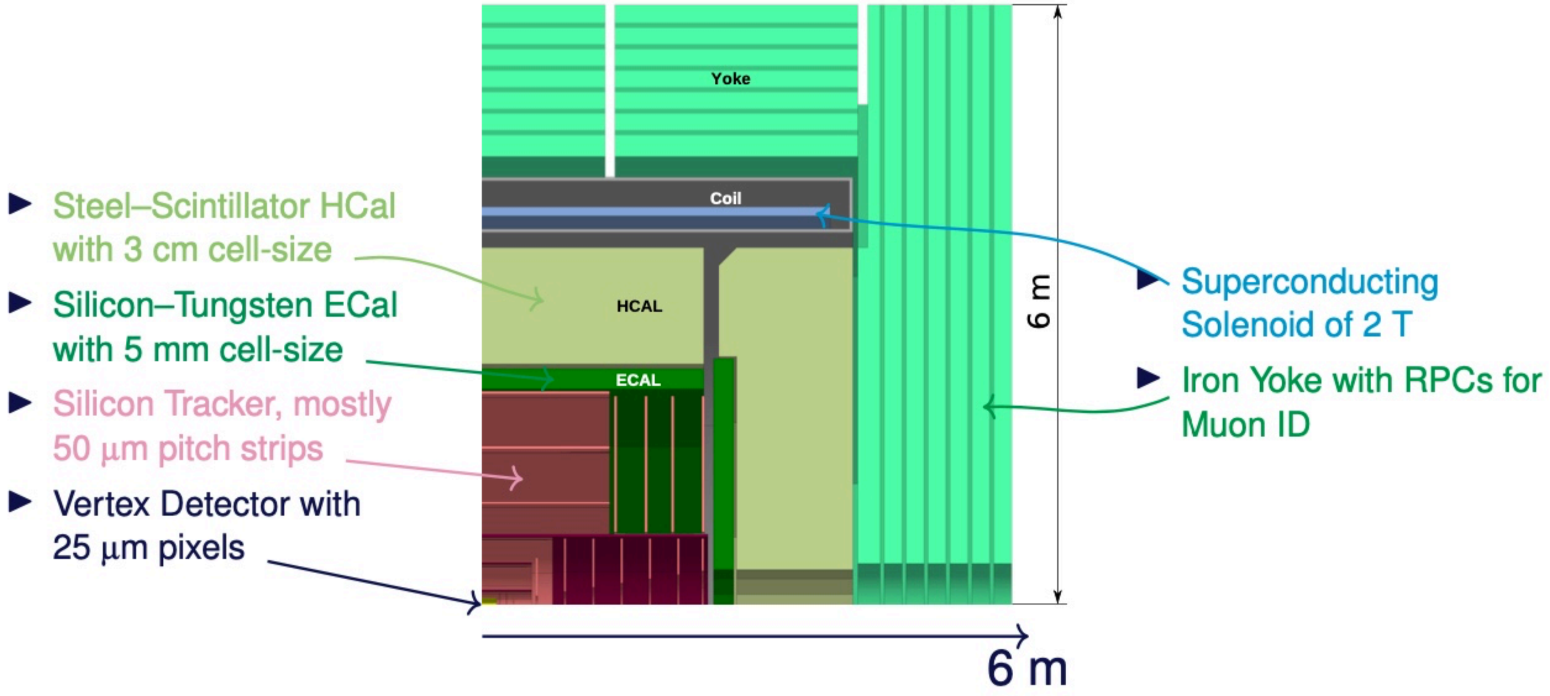


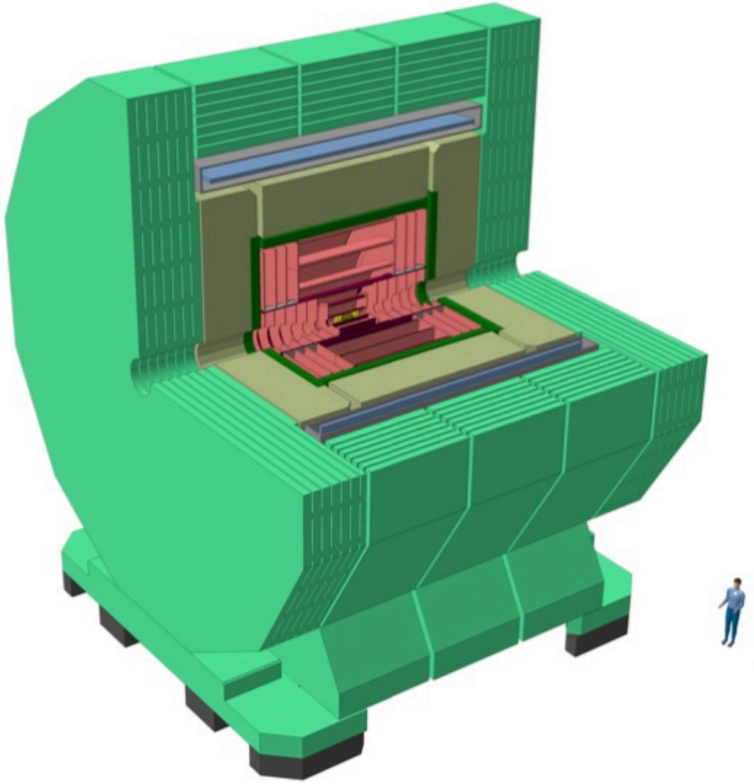
- A design in its infancy
- High granularity Noble Liquid ECAL is core
  - Pb+LAr (or denser W+LKr)
- Drift chamber; TileCal HCAL (a la ATLAS); muon system
- Coil inside same cryostat as LAr outside ECAL
- Active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

CLD Detector Concept

General purpose detector for Particle Flow reconstruction

- development of CLICdp detector concept developed for CLIC



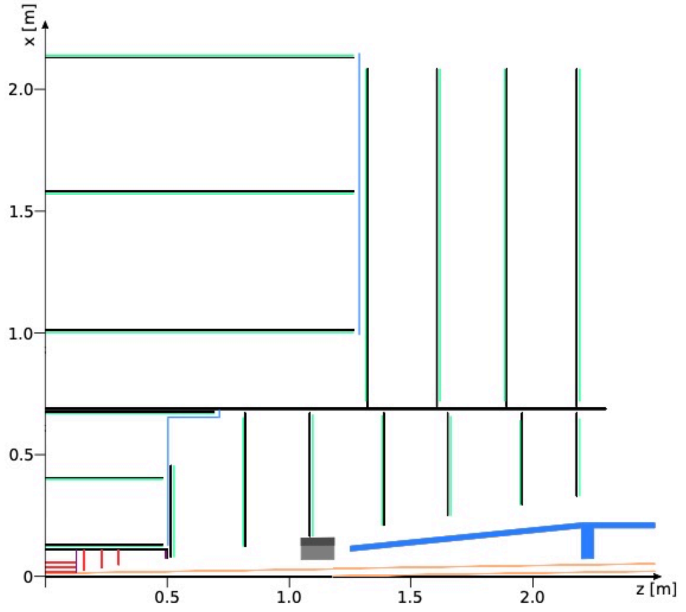


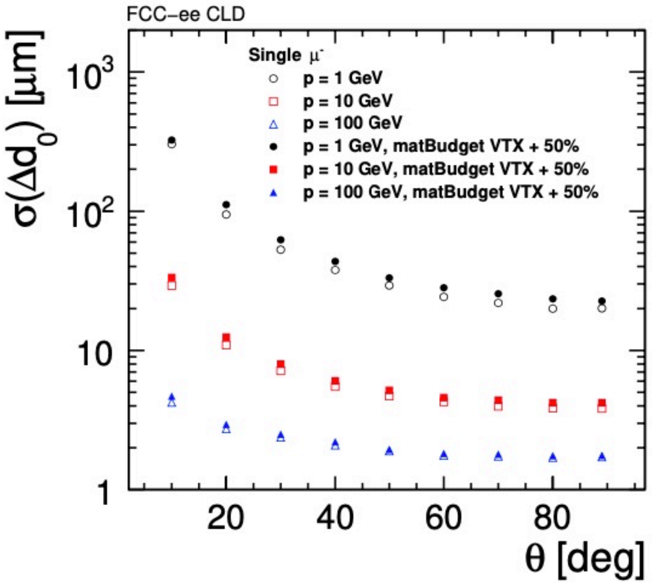
https://arxiv.org/abs/1911.12230 and FCC CDS vol. 2

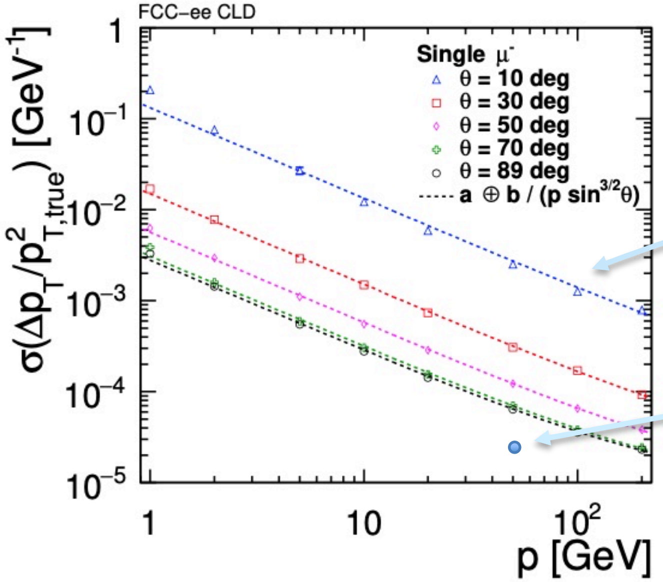
2 Tesla solenoidal field (solenoid ourside calorimetry, R=3.7m, L=7.4 m)
Return yoke contains muon system with 6 (7 in barrel) equidistant layers

CLD Vertex Detector and Si Tracker

- Silicon vertex detector: precise impact parameter measurement / vertex reconstruction
  - 25 x 25 µm pixels, 50 µm thickness, 3 µm single point resolution
  - Double layers (0.3% X_0 per detection layer), R_{in} = 17.5 mm (-> 12.5 mm with new, smaller beam pipe)
- Inner and Outer Silicon Tracker
  - 3 short and 3 long barrel layers, 7 inner and 4 outer endcaps
  - 200 µm sensor thickness, pixels for inner tracker disk, elsewhere strips
  - At least 8 hits for θ > 8.5°
  - Material budget: 1.1 – 2.2 % X_0 per layer (including overlaps)

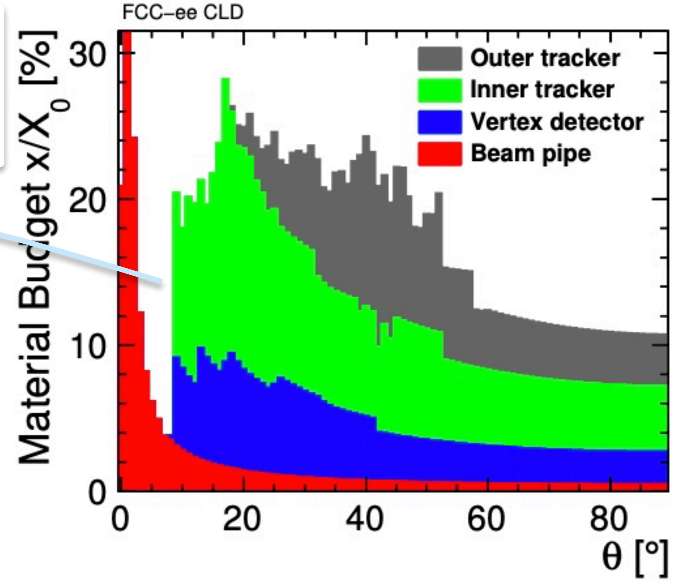






Multiple scattering limited
→ lighter Si tracker!?

$\sigma_{p_T}/p_T \simeq 1.5 \times 10^{-3}$
@ 50GeV (BES)

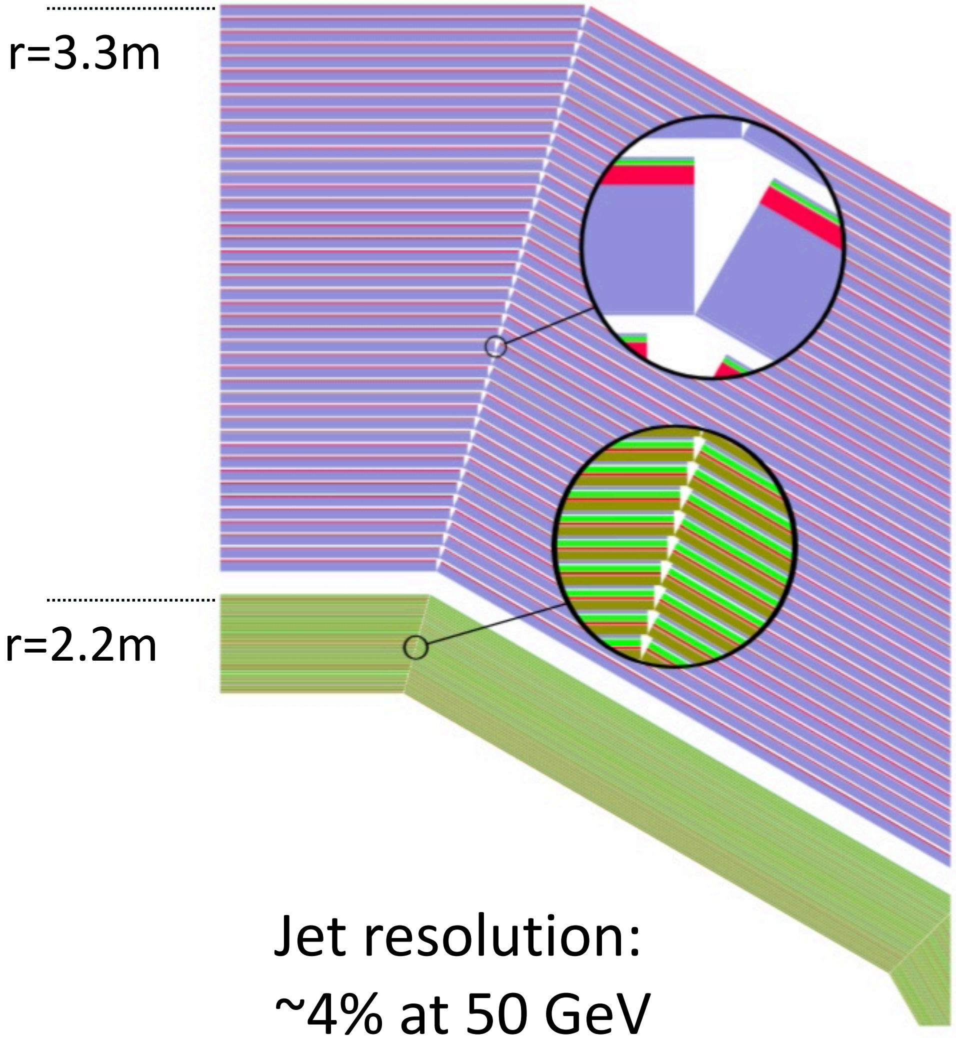


CLD Calorimetry

- ECAL (Si/W)
  - 40 layers, 1.9 mm tungsten absorber, 22 X_0
  - 0.5 mm thick Si sensors with 5 x 5 mm^2 granularity
  - ECAL optimisation studies

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

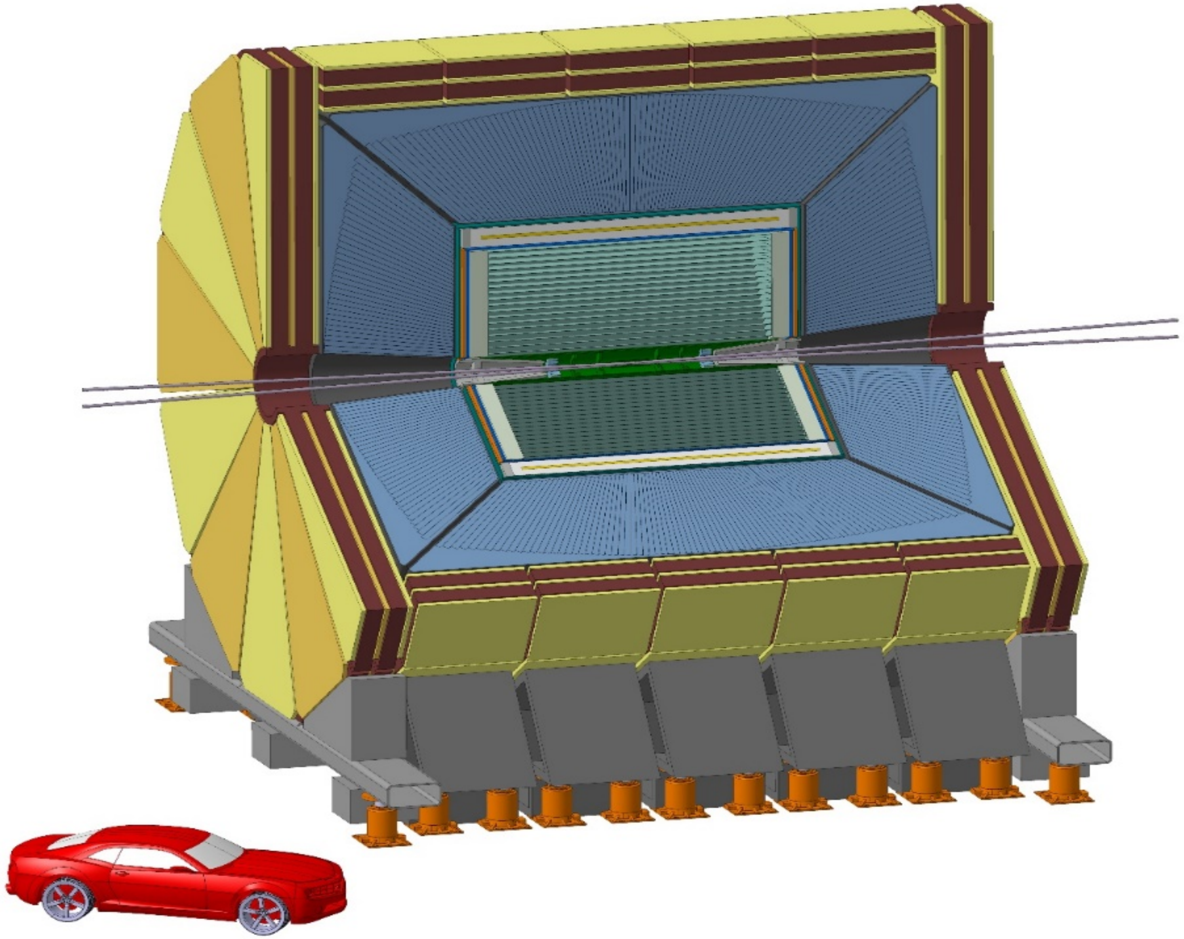
- HCAL (Scintillator/Steel)
  - 44 layers, 19 mm steel absorber, 5.5 (+1) λ
  - 3 mm thick scintillator tiles with 30 x 30 mm^2 granularity



Jet resolution:
~4% at 50 GeV

IDEA Detector Concept

IDEA, Innovative Detector for e^+e^- accelerator



FCC CDR vol. 2

Designed specifically for circular e^+e^- collider (FCC/CEPC)

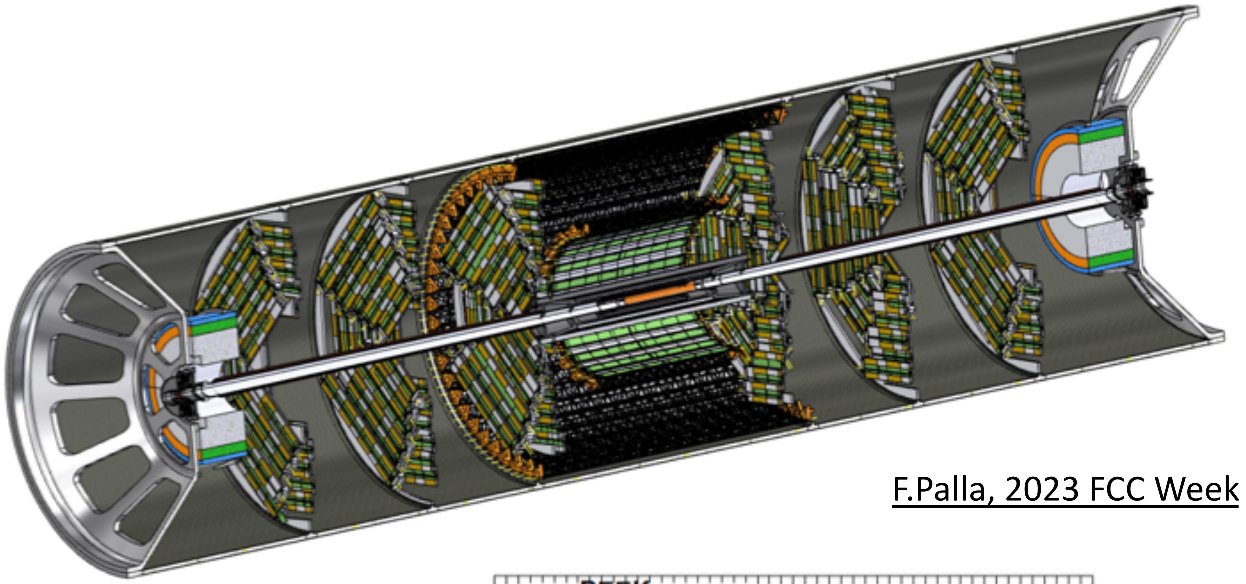
- Silicon vertex detector
  - 5 MAPS layers, 13-340 mm
- Short-drift, ultra-light wire chamber
  - 112 layers, L= 400 cm, R = 35-200 cm
- Silicon ”wrapper”
  - Precise spacepoint measurement in front of calorimeter
- Thin and light solenoid coil *inside* calorimeter system
  - Coil: 2 Tesla, R = 2.1-2.4 m
  - 0.76 X_0 , 0.19 λ_{int}
- Dual-readout calorimeter
  - 2 m depth, 7 λ_{int}
  - Particle flow reconstruction
  - Option: crystal ECAL (in front of coil) for better EM resolution
  - If no crystals: pre-shower detector in front of DR calorimeter
- Muon system
  - 3 layers of μ-RWELL detectors in return yoke

IDEA Vertex Detector

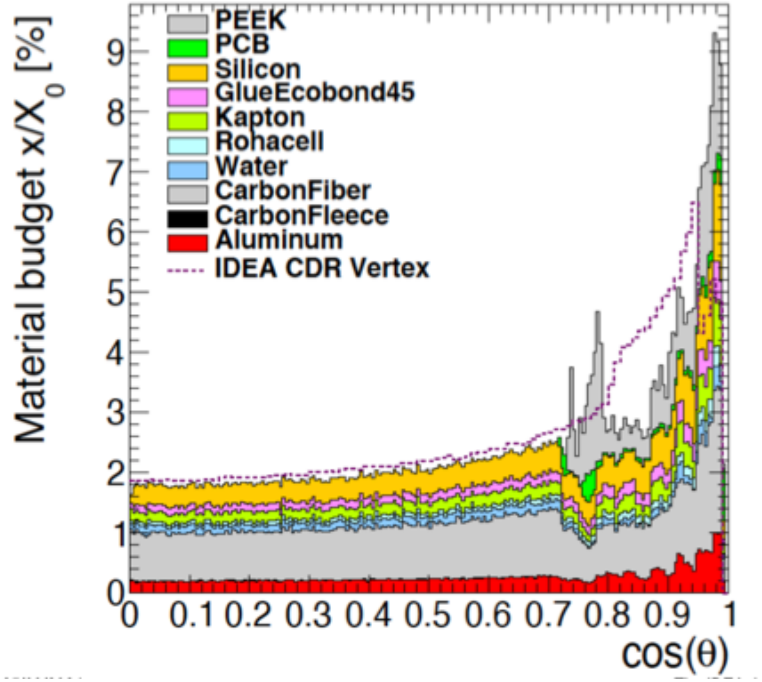
Vertex detector

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

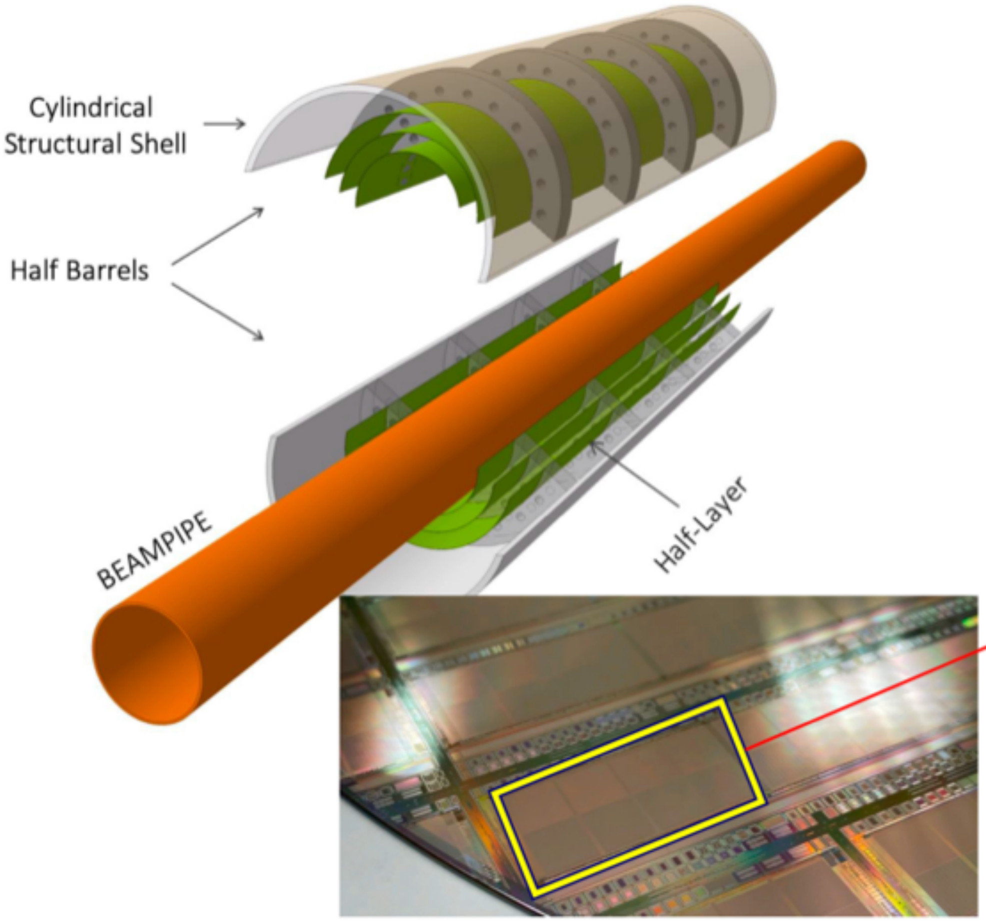


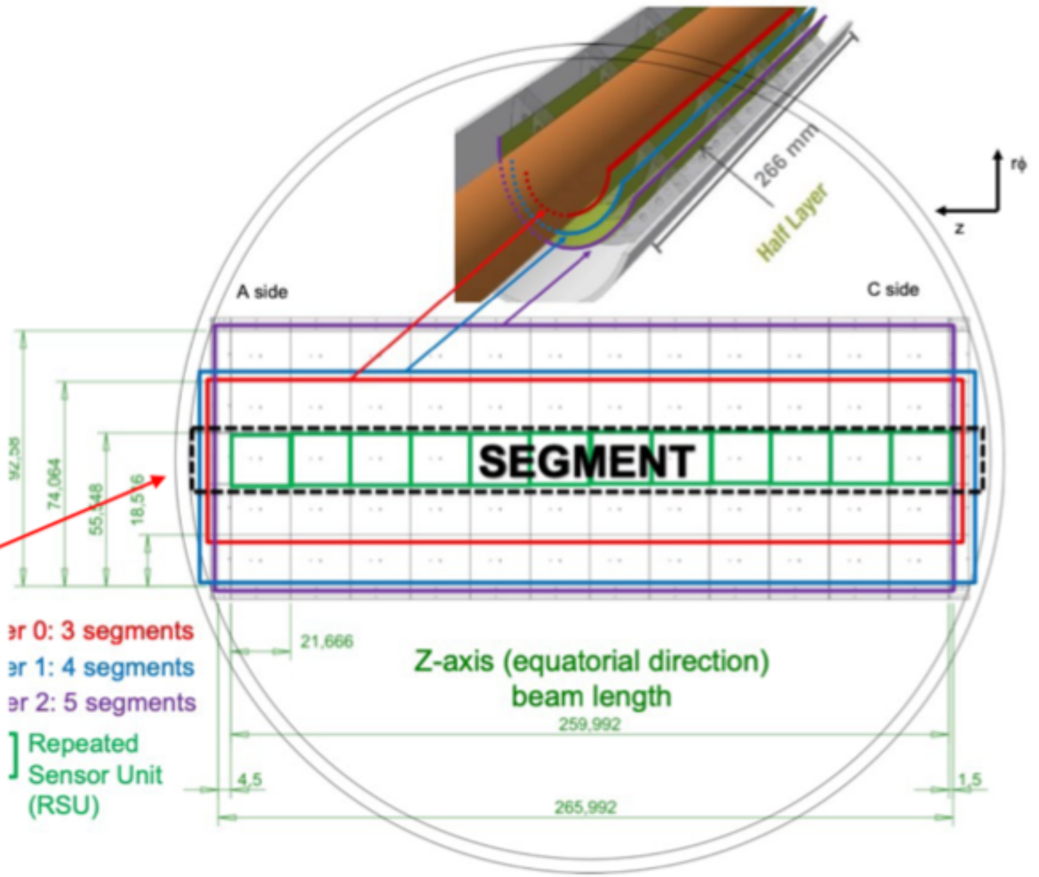
F.Palla, 2023 FCC Week



Proposed lighter concept with curved and stitched MAPS

F. Palla, 2nd Annual US FCC Workshop, 2024





Proposed layout using an ALICE ITS3 inspired design

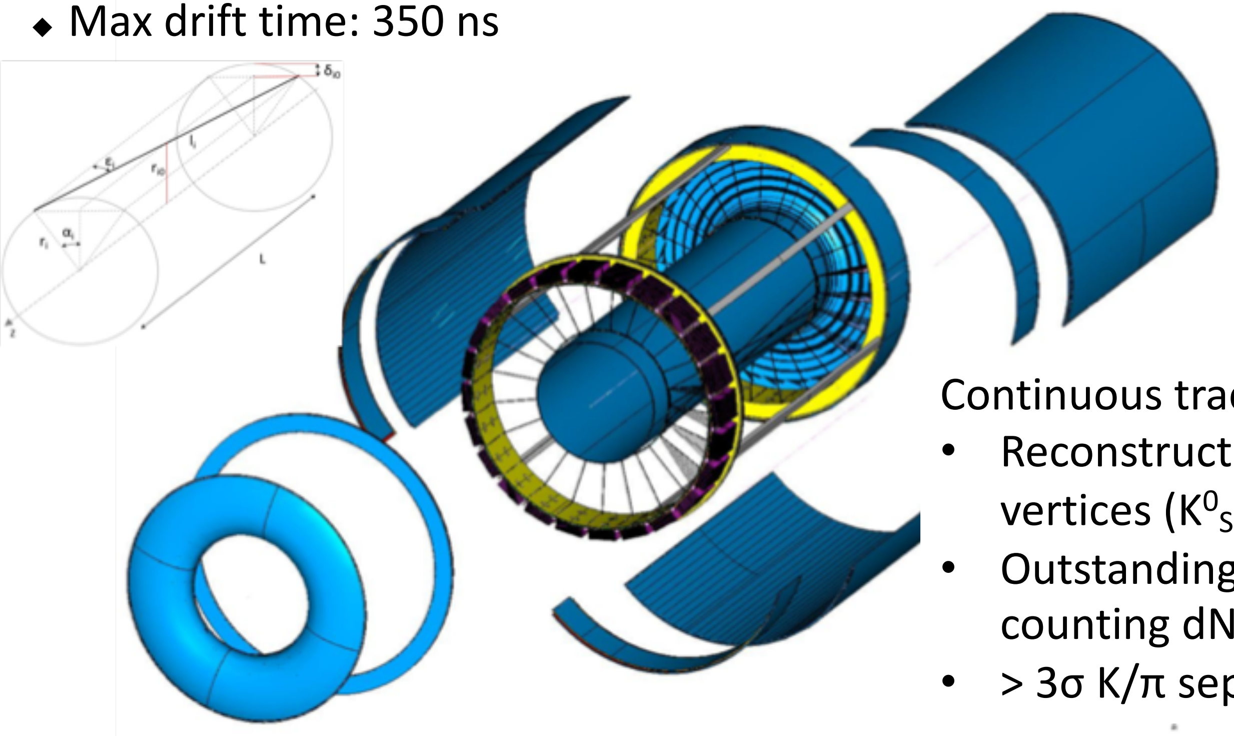
(~0.05 % X/X_0 material budget per layer – 5 times less than the Mid-Term one)

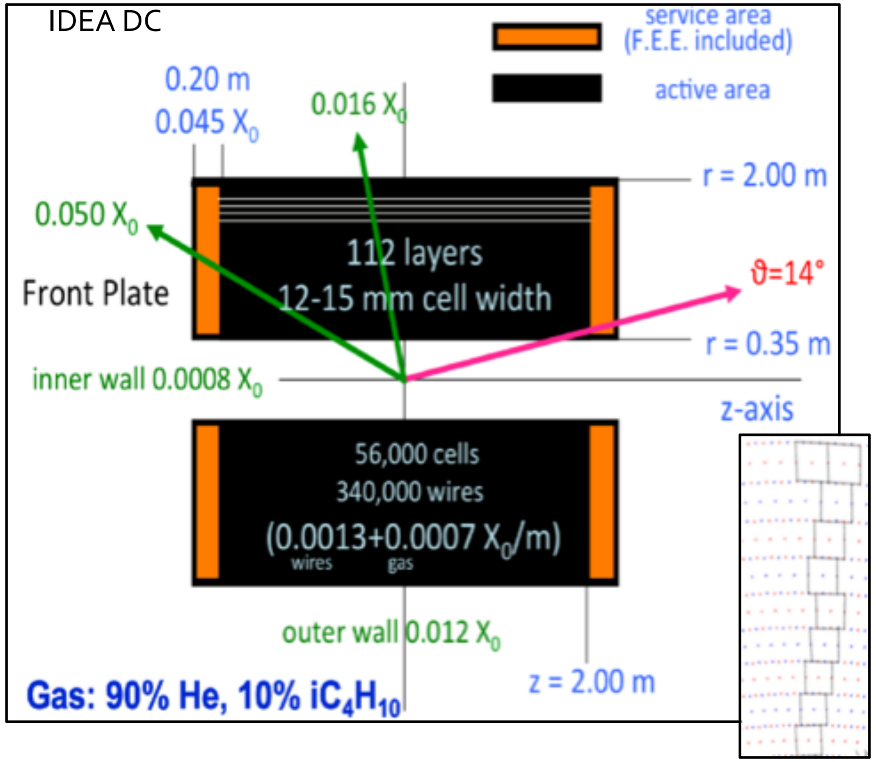
Multiple scattering term on impact parameter decrease by a factor of ~2

IDEA Drift Chamber

Extremely transparent Drift Chamber

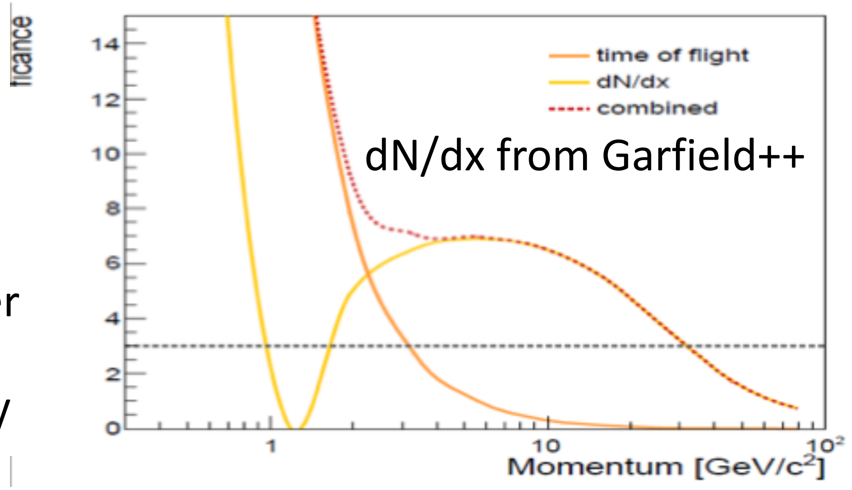
- Gas: 90% He – 10% iC_4H_{10}
- Radius: 0.35 – 200 cm
- Total thickness: 1.6% of X_0 at 90°
  - Tungsten wires dominant contributor
    - Possibility of using (gold-plated) carbon-fibre wires ?
- 112 layers for each 15° azimuthal sector
- Max drift time: 350 ns



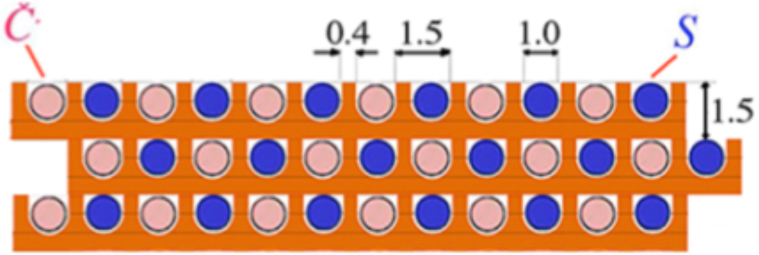


Continuous tracking:

- Reconstruction of far-detached vertices (K^0_S, Λ, BSM, LLPs)
- Outstanding particle ID via cluster counting dN/dx or dE/dx
- > 3σ K/π separation up to 35 GeV



Dual Readout Calorimetry



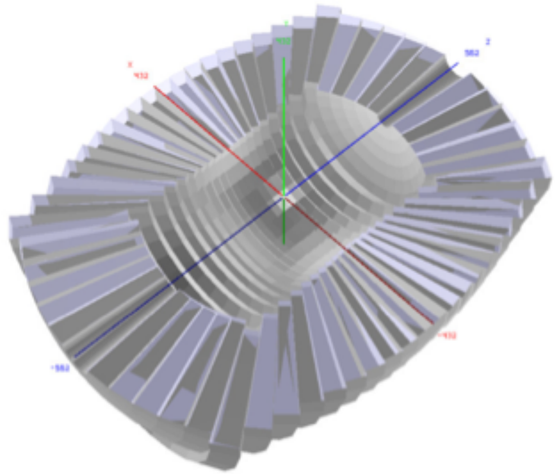
- Scintillation fibres
- Cherenkov fibres

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

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

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

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



GEANT4 simulation

Single hadron:

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

Electromagnetic:

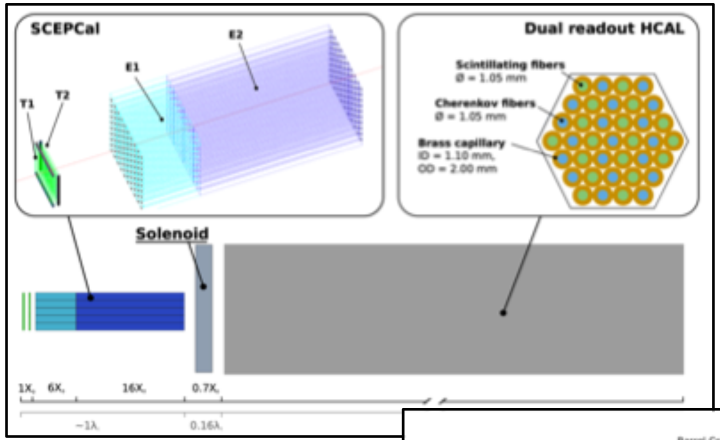
$$\frac{\sigma}{E} = \frac{13.0\%}{\sqrt{E}} + 0.2\%$$

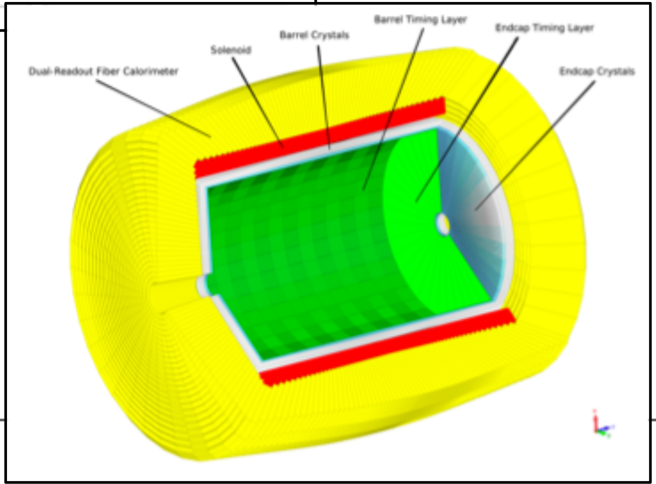
Crystal option: 20 cm $PbWO_4$

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

Crystal option

- Crystal ECAL in front of DR fibre calorimeter
- PbWO crystals – two longitudinal layers
  - 10 × 10 × [50 (front) + 150 (rear)] mm^3
  - Dual readout via separation of light spectrum (*S* vs. *C*)
- $\sigma_{EM} \approx 3\% / \sqrt{E}$





Allegro - Noble-Liquid ECAL Based Detector Concept

N. Morange, 2nd Annual US FCC Workshop, 2024

- Vertex Detector
  - MAPS or DMAPS possibly with timing layer (LGAD)
  - Possibly ALICE ITS3 like
- Drift Chamber
  - ± 2.5 m active
- Silicon wrapper + ToF
  - MAPS or DMAPS possibly with timing (LGAD)
- High Granularity ECAL
  - Noble Liquid (LAr possibly LKr) + absorber (Pb or W)
  - Particle Flow reconstruction
- Solenoid 2T outside ECAL, sharing cryostat with ECAL
  - Light solenoid coil = 0.75 X_0
  - Low-material cryostat < 0.1 X_0
- High Granularity HCAL / Iron yoke
  - Scintillator + Iron (particle flow reconstruction)
    - SiPMs directly on scintillators or
    - TileCal: WS fibres, SiPMs outside
- Muon System
  - Drift chambers, RPC, or Micromegas

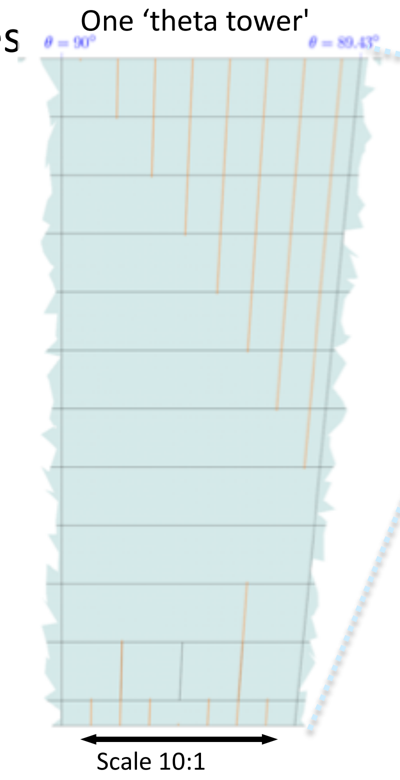
Allegro - High Granularity Noble-Liquid Calorimeter

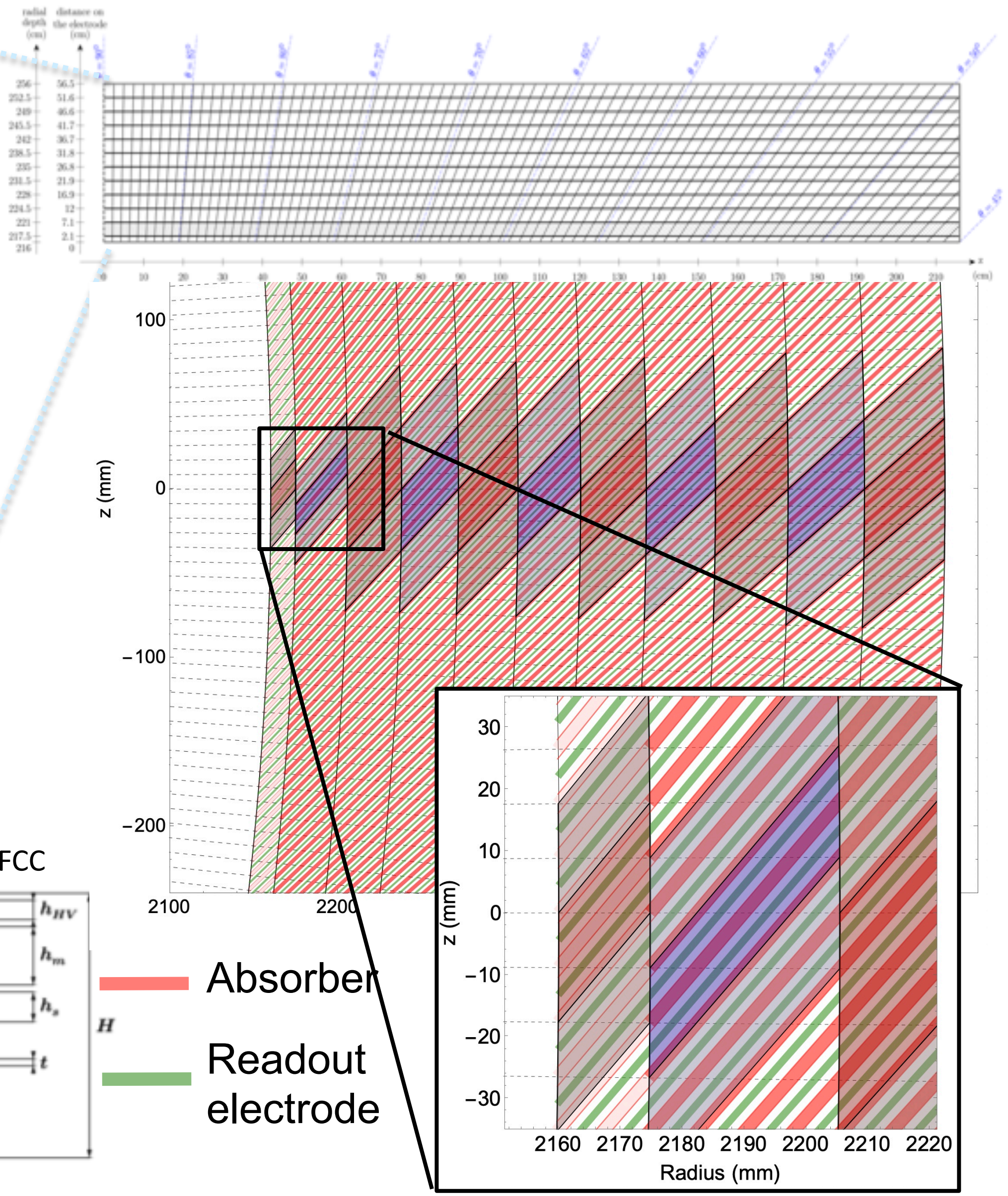
Baseline design

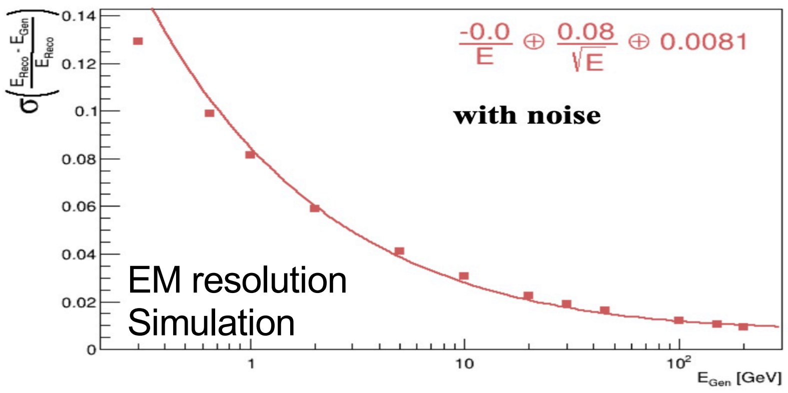
- 1536 straight inclined (50.4°) 1.8mm Pb absorber plates
- Multi-layer PCBs as readout electrodes
- 1.2 – 2.4mm LAr gaps
- 40 cm deep (≈ 22 X_0)
- Segmentation:
  - 11 longitudinal compartments
  - $\Delta\theta$ = 10 (2.5) mrad for regular (1st comp. strip) cells
  - $\Delta\phi$ = 8 mrad

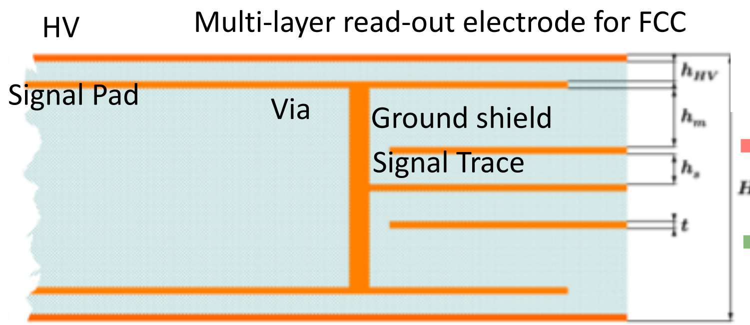
Possible options

- LKr or LAr active, W or Pb absorbers
- Absorbers with growing thickness
- Al or carbon fibre cryostat
- Warm or cold electronics







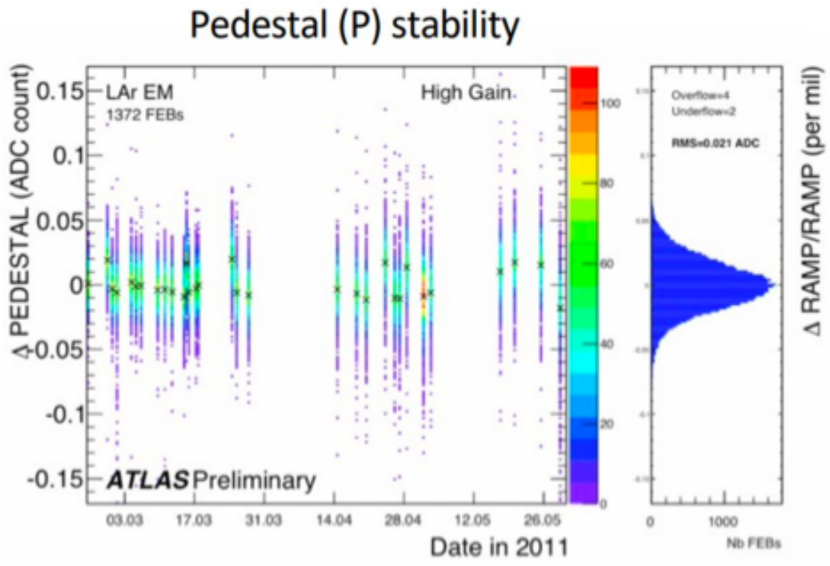


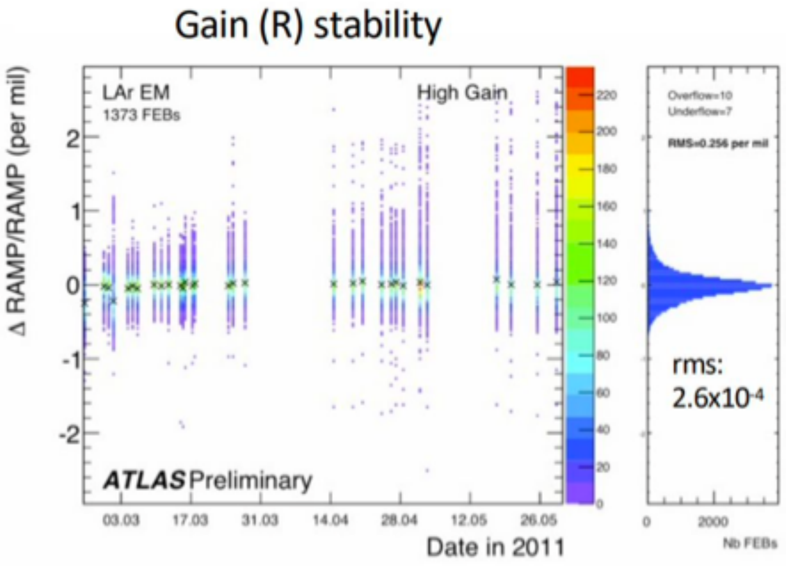
Example: Stability of ATLAS LAr Energy Scale

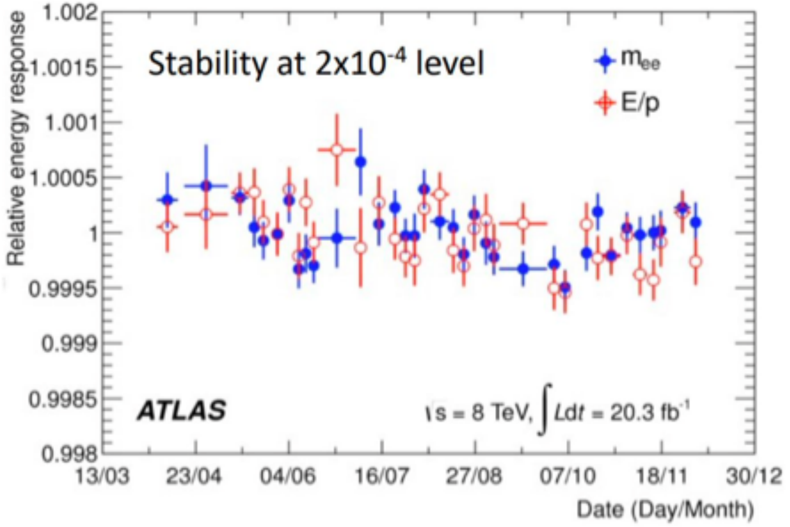
Noble-liquid calorimetry: High intrinsic stability

N. Morange, 2nd Annual US FCC Workshop, 2024

- Pedestal stability < 100 keV
- Gain stability 2.6×10^{-4}
- Parameters monitored in daily calibration runs
  - Changes in constants needed only about 1 / month
- ➢ Stability of the energy scale of 2×10^{-4}
  - Visible on Z→ee invariant mass and E/p





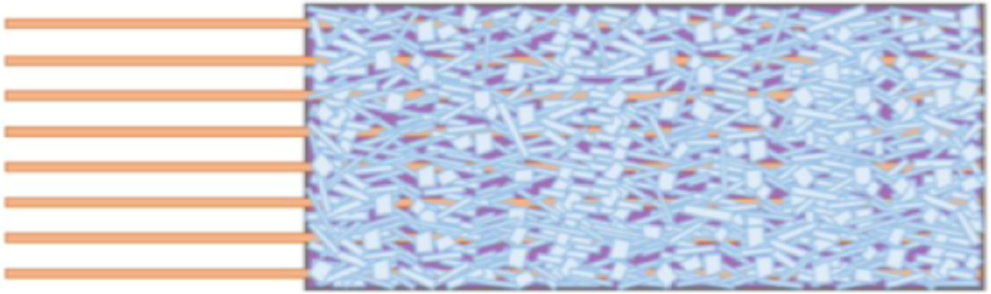


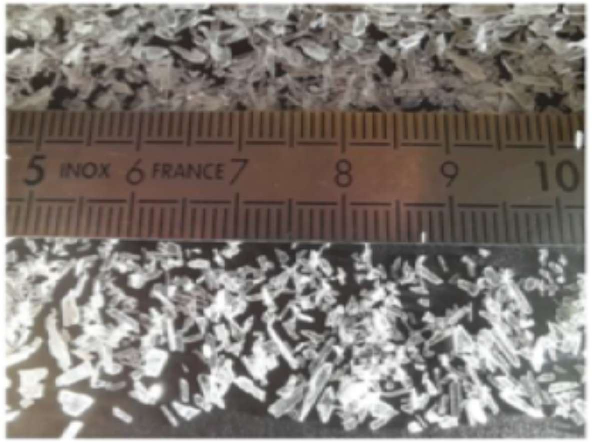
Other issues

Novel Calorimeter Concept - Granita

A novel type of calorimeter ~ next-gen shashlik

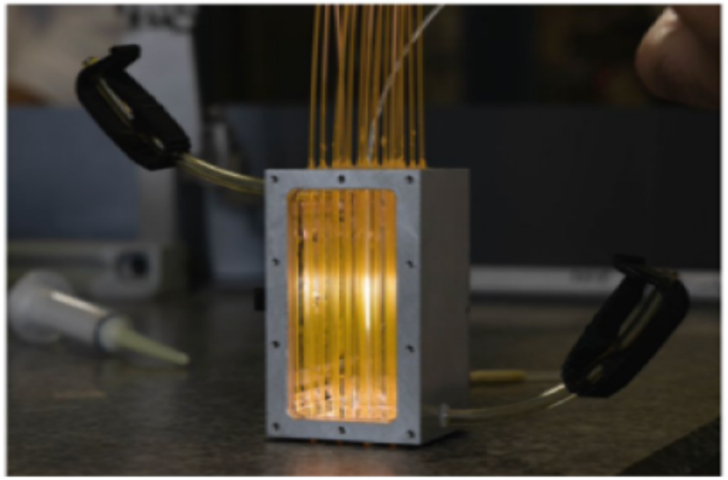
- Use grains of inorganic scintillating crystal readout by wavelength shifting fibers
  - Light spatially confined by refraction/reflections





- Excellent expected EM resolution: 2-3%/√E
  - Using BGO or $ZnWO_4$ crystals
  - First small 16-channel prototype used with cosmics

- Main R&D topics
  - R&D on crystal grains
  - Aim for larger prototype to validate on testbeam



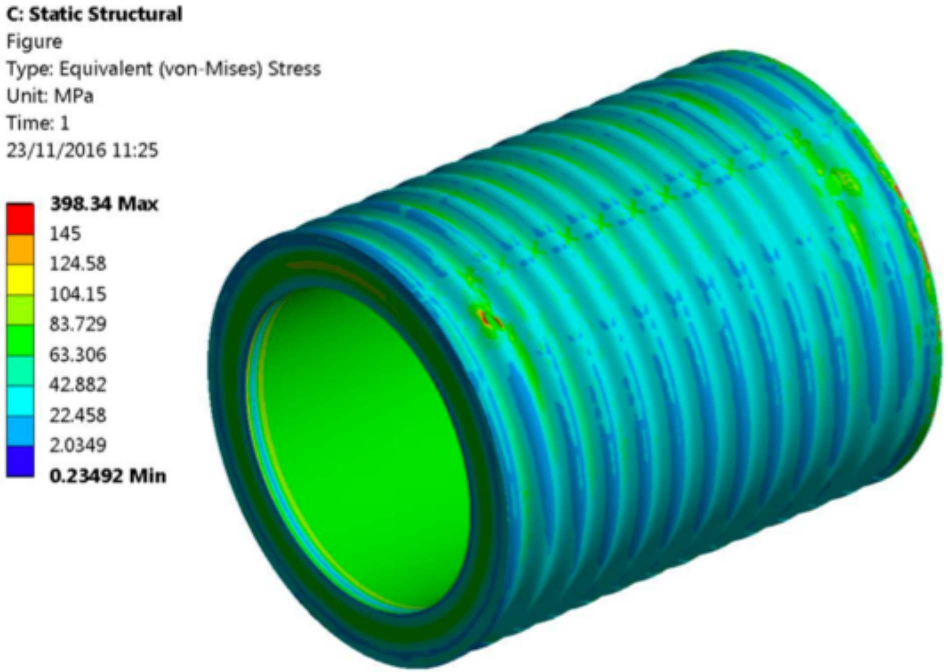
N. Morange (IJCLab) Second US FCC Workshop, 26/03/2024

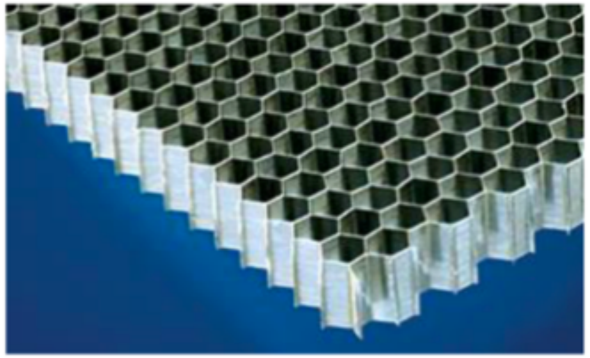
Thin, transparent Superconducting solenoid

Ultra light 2 T solenoid inside calorimetry

- Radial envelope 30 cm
- Single layer self-supporting winding (20 kA)
  - Cold mass: $X_0 = 0.47$, $\lambda = 0.09$
- Vacuum vessel (25 mm Al): $X_0 = 0.28$
  - Can be improved with new technologies
    - Corrugated plate: $X_0 = 0.11$
    - Honeycomb: $X_0 = 0.04$

Courtesy of H. TenKate

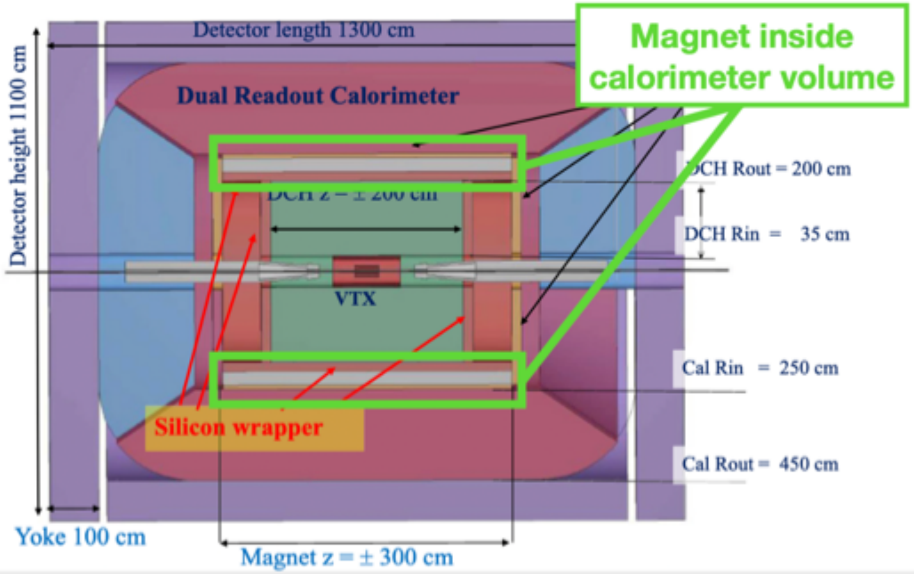




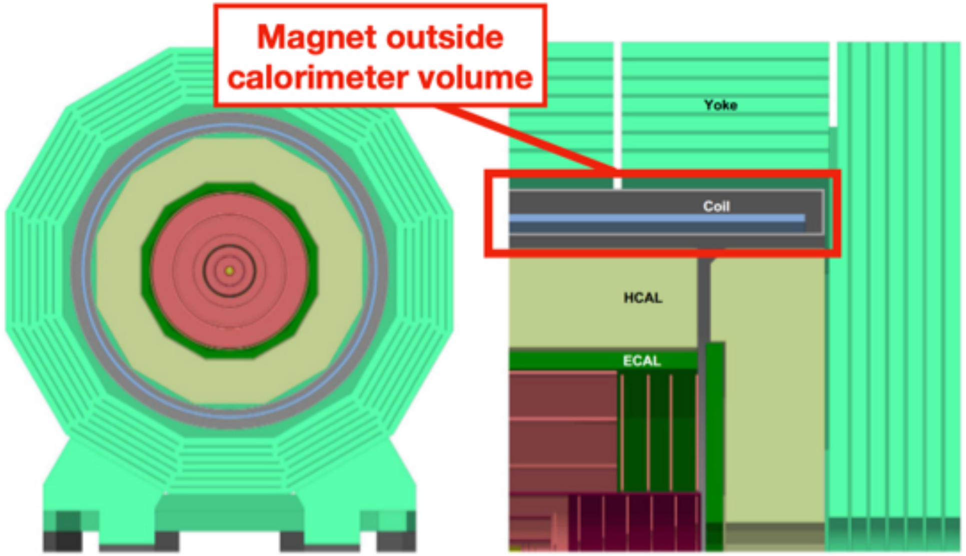
Solenoid Magnet

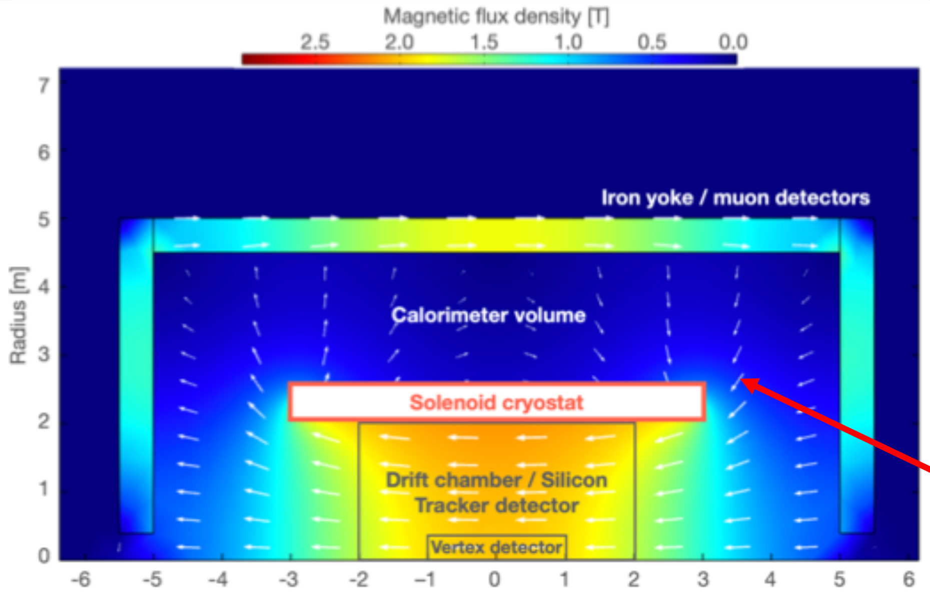
Nikkie Deelen,, FCC Workshop Feb. 2022

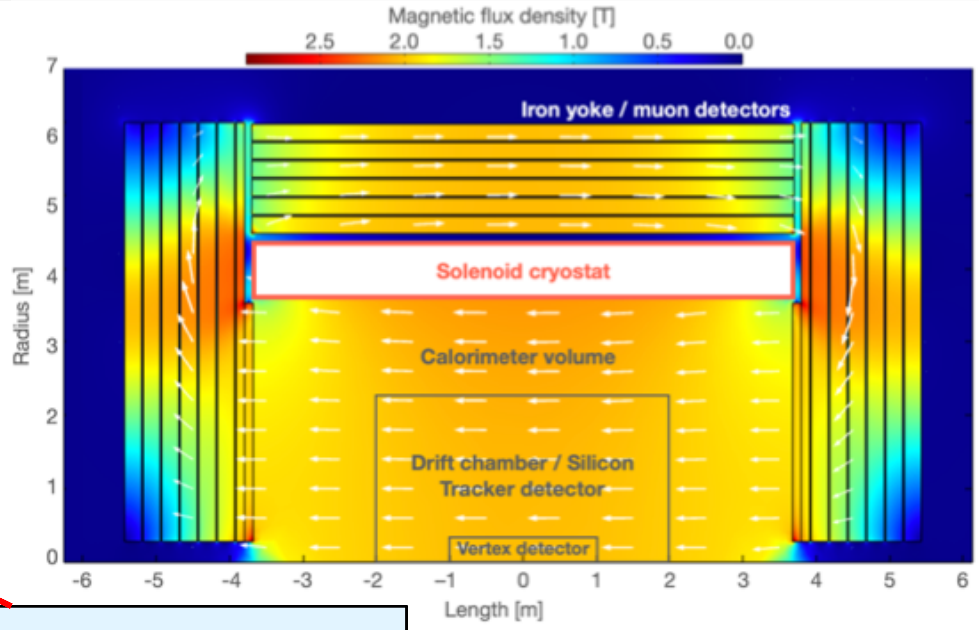
International Detector for Electron-positron Accelerators



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

A few words on Readout, DAQ, Data Handling

- In particular at Giga-Z operation, challenging conditions
  - 40 MHz BX rate
  - Physics rate at 100 kHz plus similar LumiCal rate
  - Absolute normalisation goal of 10^{-4} or better
- Different detector components tend to prefer different integration times
  - Silicon VTX/tracker sensors: $\mathcal{O}$(1 μs) [also to save power]
    - BX identification via time-stamping (at least at track level) will be needed
  - LumiCal: Preferential at ~BX frequency (25 ns)
    - Avoid additional event pileup
- How to organize readout?
  - **Hardware trigger** with latency buffering a la LHC ??
    - Probably not… or ???
    - Which detector element would provide the trigger to the required precision?
  - **Free streaming** of self-triggering sub-detectors; event building based on time stamping
    - Need careful treatment of relative normalisation of sub-detectors to 10^{-5} level

- Need to consider Trigger(?) & DAQ issues as an integral part of detector design
  - ”Thinking about the DAQ later” will very likely lead us into trouble
- Plus, need to plan for off-line handling of $\mathcal{O}(10^{13})$ events for precision physics
  - Plus Monte Carlo

Hardware trigger
- trigger buckets as in ATLAS/CMS

Free streaming
-LHCb DAQ upgrade
-Detectors at EIC

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 (light) BSM particles !!
- Development of instrumentation to fully exploit the physics potential is challenging and exciting
  - FCC-ee will host four experimental collaborations
- For next ESUPP, need to demonstrate that experimental challenge can be met by several Detector Concepts
- Work ongoing on three proto detectors with widely different technology choices
  - CLD (contacts: F. Simon, D. Dannheim), IDEA (contact: Paolo Giacomelli), and Allegro (contact: Martin Aleksa)
- Wide room for exploration of alternate ideas and solutions
- Work ongoing to implement proto detectors and their sub-detectors into Key4hep software framework
  - Allowing for optimisation studies

- Don't hesitate to join our exciting efforts!

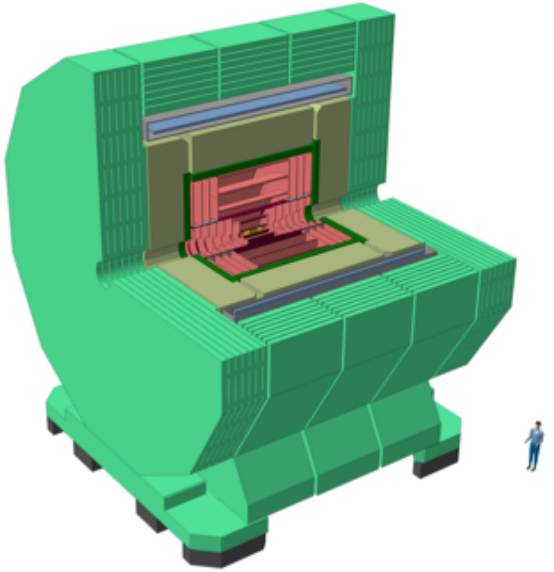
- Mailing lists:

  FCC-PED-DetectorConcepts@cern.ch

  FCC-PED-SoftwareAndComputing@cern.ch

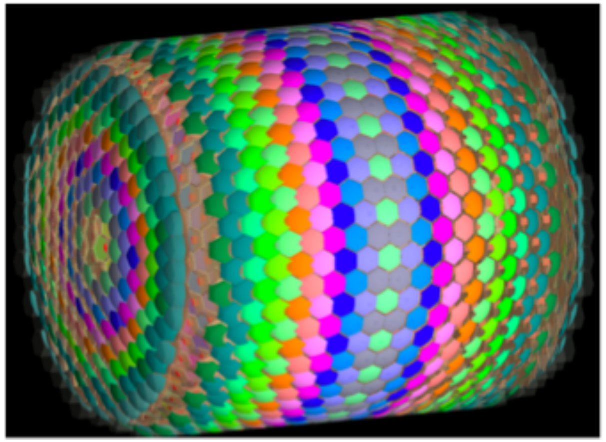
Extras

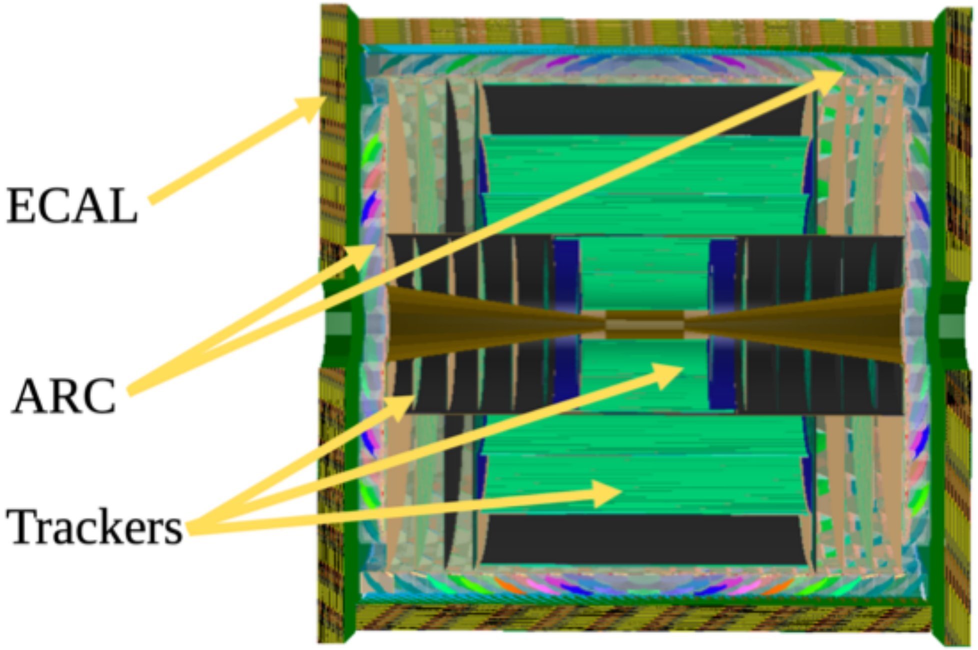
CLD - Software Implementation Status



- All CLD sub-detectors implemented in DD4hep
- Full simulation + reconstruction workflow available
  - Simulation through ddsim
  - Reconstruction through *Marlin*
    - Background overlay, digitization, conformalTracking, ParticleFlow (PandoraPFA), vertexing, and flavour tagging
    - Inhereted from ILD/CLICdet
- *Marlin* reconstruction based on LCIO data format but can be integrated in EDM4hep Gaudi workflows through *MarlinWrappers* + data format translation

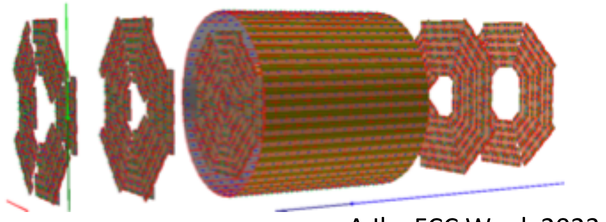
- RICH ARC detector finding its way into CLD full simulation



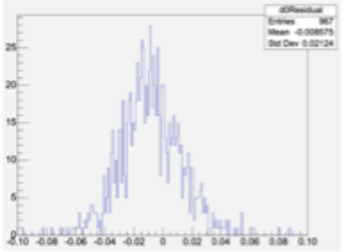


IDEA - Software Implementation Status

- Detailed DD4hep implementation of vertex detector being finalized
  - Sim, Digi, and Reco available
  - Silicon wrapper will be implemented based on the same detector builders

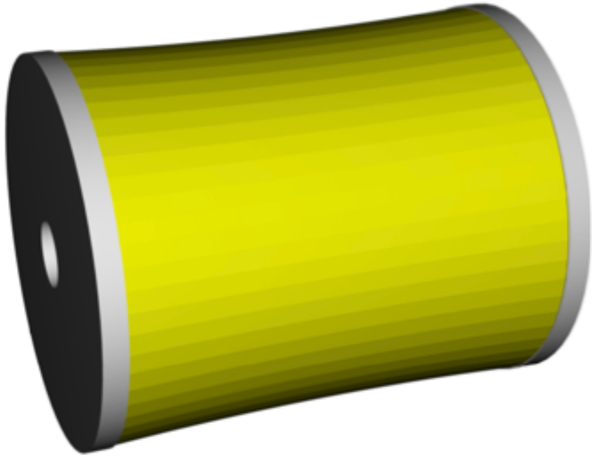


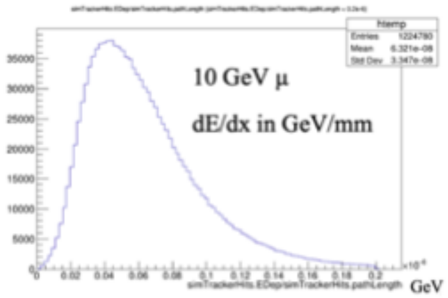
A.Ilg, FCC Week 2023



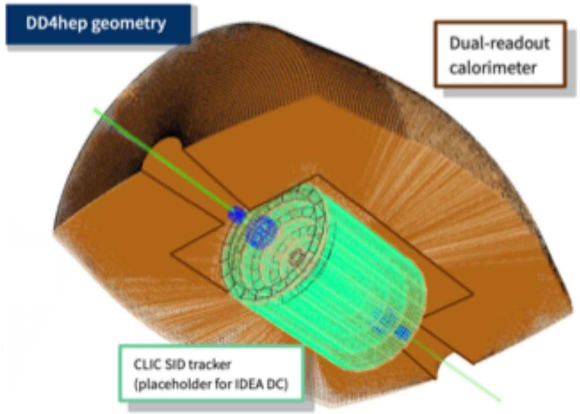
D_n resolution in mm.

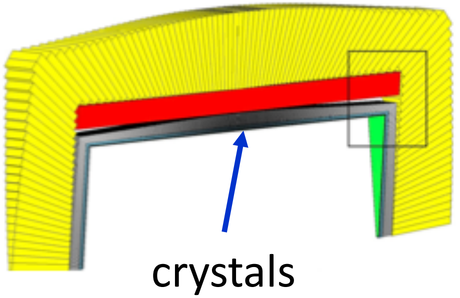
- Drift Chamber
  - Originally implemented in in plain Geant
  - Detailed DD4hep implementation under debugging and validation
    - Carbon fibre/Cu walls, sense + field wires, Au coating, Gas:He_90Isob_10
  - Next steps
    - Implementation of DCH reconstruction into Key4hep
    - Implementation of combined VXD + DCH tracking
      - Options: MarlinTracker, ACTS, ILD approach, BES III solution, native DCH tracking algorithm, …





- Dual readout calorimeter fully implemented in key4hep
  - Geometry, simulation, digitization, reconstruction
  - Next steps: integrate geometry in central repository, CPU optimisation
- Crystal ECAL detector description implemented in DD4hep
  - WIP: port code to central dual-readout repositiry, digi, reco, ParticleFlow

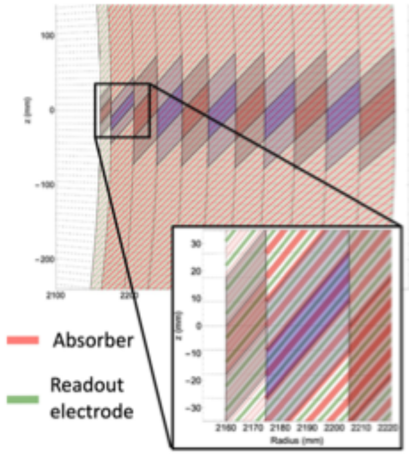


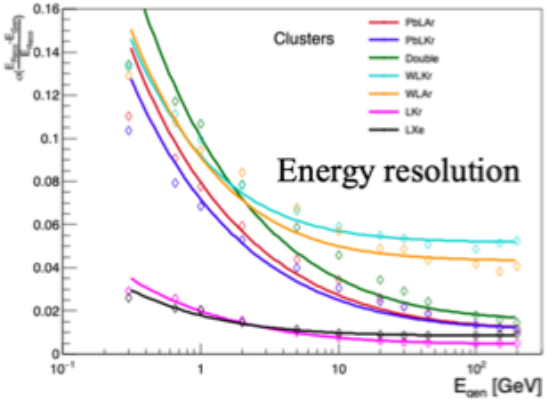


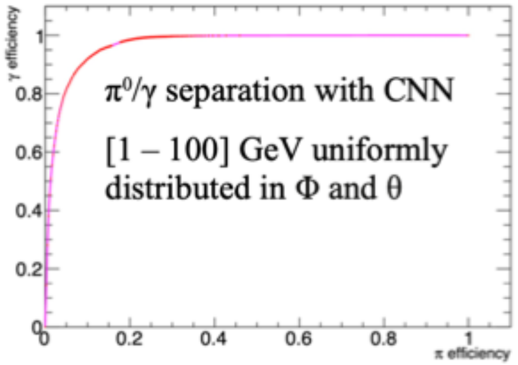
Allergo - Software Implementation Status

Current detector description in DD4hep

- Simplified VXD (CLD), to be updated to the detailed IDEA one
- Simplified drift chamber (no tracking available)
- **ECAL barrel fully implemented in Key4hep**
  - Inclined absorber plates that can be made trapezoidal
  - Cryostat, services, and solenoid material budget included
  - Calibration, noise, and clustering available as edm4hep native to Gaudi algorithms
  - Plug-and-play complant
    - Automatic rescaling upon geometry changes
  - First performance studies performed
  - Need Particle Flow to optimize granularity, requires tracks
    - Temperary hack: prepared detector config with CLD + LAr ECAL
    - Working on PandoraPFA integration
- ECAL endcaps under validation







B.Francois @ FCCWeek, 2023