Detector Requirements and Concepts for FCC-ee

Martin Aleksa

- FCC-ee Introduction
- Physics Requirements
- Proto Detectors

Based on:

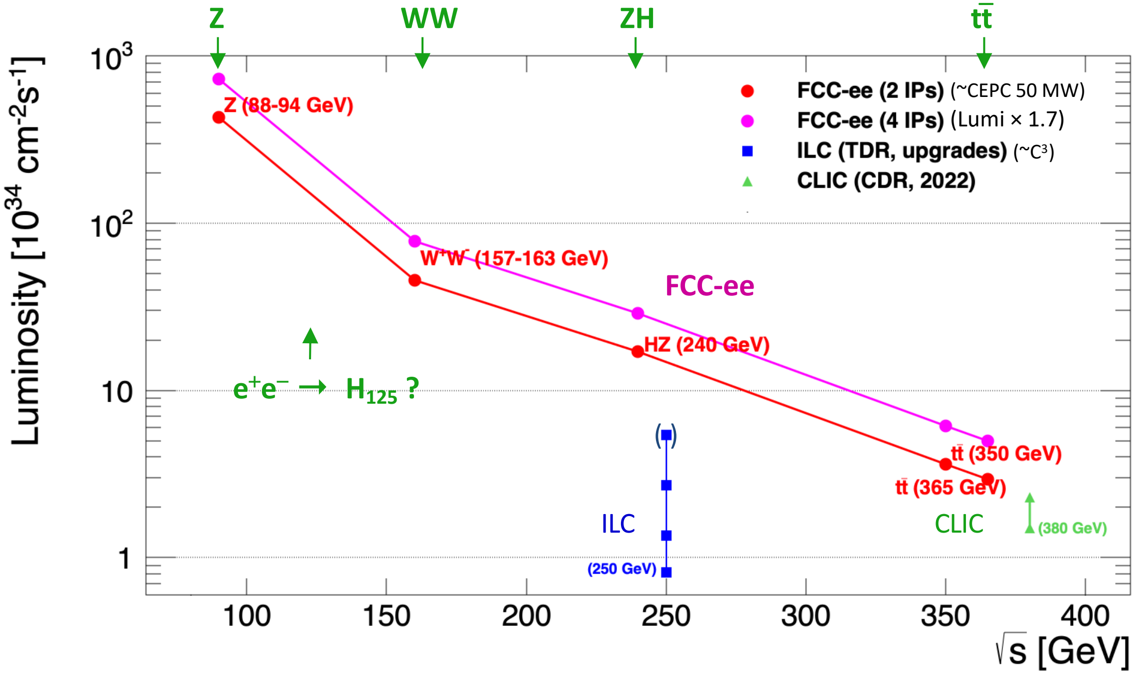
- First Annual US FCC Workshop at BNL (https://www.bnl.gov/usfccworkshop/)
- FCC Week in London (https://indico.cern.ch/event/1202105/)
- Noble-Liquid Calorimeter Group Meetings (https://indico.cern.ch/category/8922/)

Introduction & Detector Requirements

e^+e^- Collider Options

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	~8000	$e^+e^- \rightarrow H_{125}$]	Never done	< 100 keV

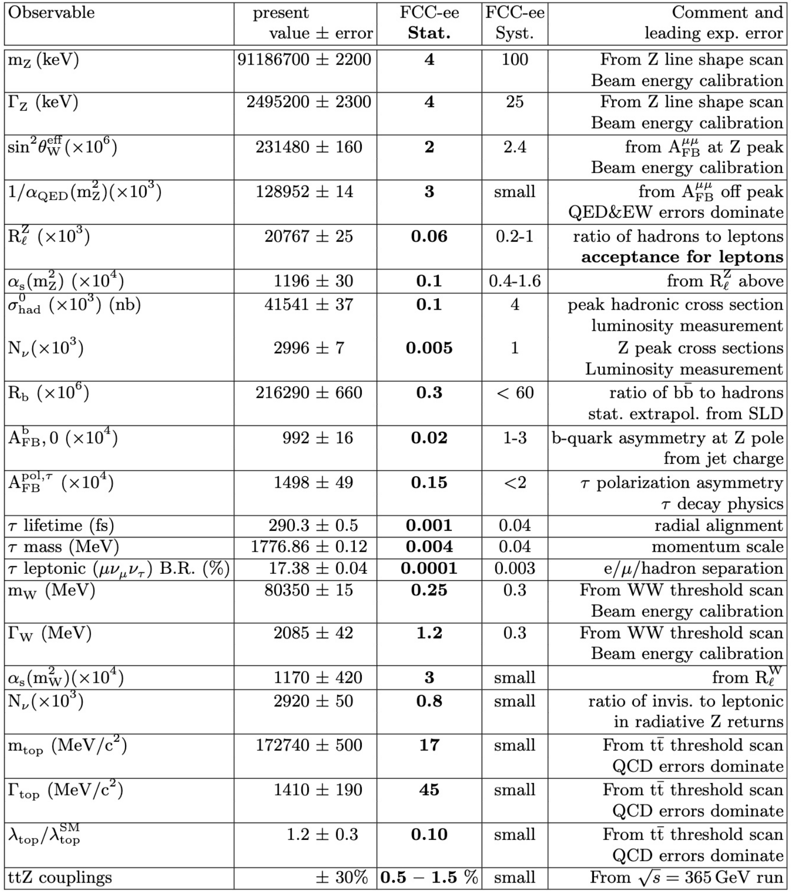


FCC-ee: ultimate precision with

- **~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**
  - 10-20 times more than ILC
- **~1 500 top quarks / day**

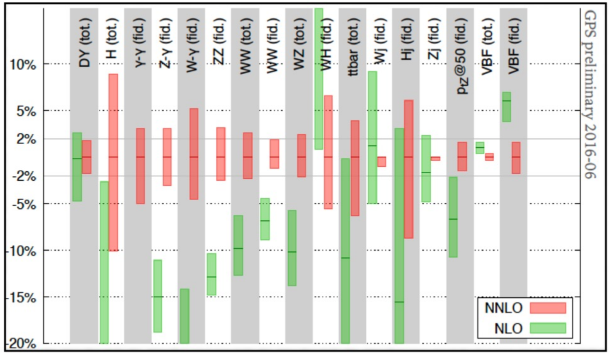
… in each detector

The Challenge – High Precision Measurements



Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. 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
$\sin^2\theta_W^{\text{eff}} (\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
σ_{had}^0 $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu (\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{\text{pol},\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization 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
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu (\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\text{top}}/\lambda_{\text{top}}^{\text{SM}}$	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

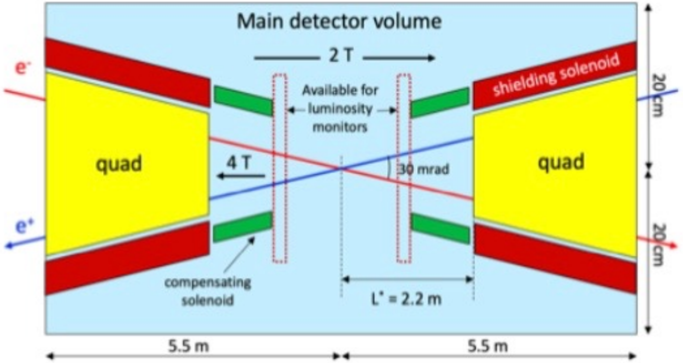
- **FCC-ee EWPO measurements with unprecedented statistical precision**
  - e.g. 6 x 10^{12} hadronic Z decays at Z-pole
  - **Statistical precision** for EWPOs measured at the Z-pole is **typically 500 times smaller than the current uncertainties**
- **→ Systematic uncertainty dominant!**
- **→ Can achieve indirect sensitivity to new physics up to a scale $\Lambda_{\text{new physics}}$ of 70 TeV**
- **We therefore require:**
  - Better control of parametric uncertainties, e.g. PDFs, α_s,m_t,m_H
  - Higher order theoretical computations, e.g. N…NLO
  - Access to phase-space limited regions + understand correlations among bins in distributions
  - **Minimizing detector systematics**

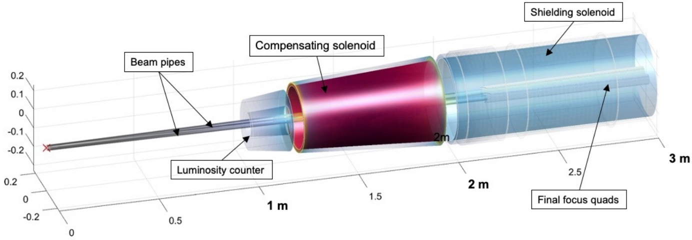


Experimental Challenges

- **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 ≤ 20 ns
  - Power management and cooling (no power pulsing as possible for linear coll.)
- **Extremely high luminosities**
  - High statistical precision – control of systematics down to 10^{-6} 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 $\lesssim 1$ μs 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, ...
- **More physics challenges**
  - Absolute luminosity measurement to 10^{-4} – luminometer acceptance to $\mathcal{O}(1\ \mu m)$ level
  - Detector acceptance to ~10^{-5} – acceptance definition to few micro-radians, hermeticity (no cracks!)
  - Precise momentum measurement through quasi-continuous resonant depolarisation (RDP) measurements → e.g. 50 keV at the Z pole
  - Stability of momentum measurement – stability of magnetic field wrt E_{cm} (10^{-6})

Central part of detector volume – top view





FCC-ee Physics Programme

”Higgs Factory” Programme

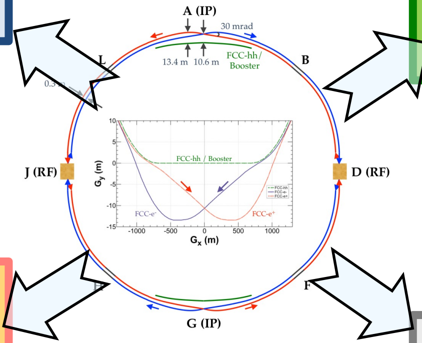
- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s} = 125$ GeV

Ultra Precise EW Programme & QCD

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

- $6\mathrm{x}10^{12}$ Z and $3\mathrm{x}10^{8}$ WW
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W^{eff}$, R^Z_ℓ, R_b, α_s, m_W, Γ_W,…
- $2\mathrm{x}10^{6}$ 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; $1.7\mathrm{x}10^{11}$ 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

Courtesy M. Dam

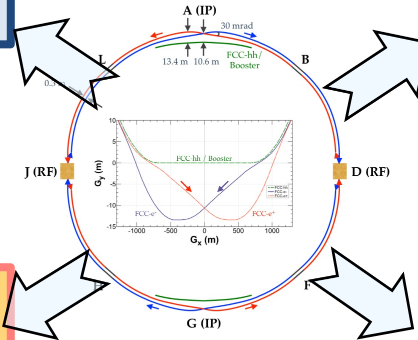
FCC-ee Detector Requirements

”Higgs Factory” Programme

- Momentum resol. at $p_T \sim 50$ GeV of $\sigma_{p_T}/p_T \simeq 10^{-3}$ commensurate with $\mathcal{O}(10^{-3})$ 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^{-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.



Courtesy M. Dam

Heavy Flavour Programme

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

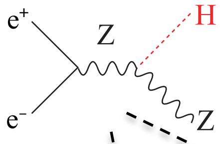
Feebly Coupled Particles - LLPs

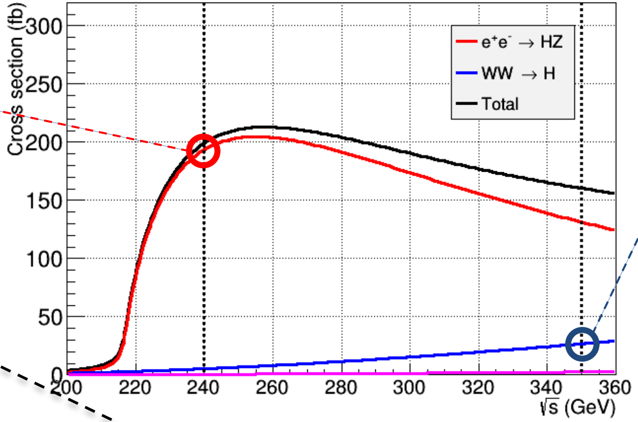
Benchmark signature: Z → νN, with N decaying late

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

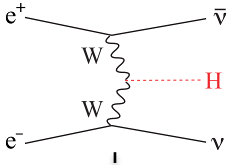
Higgs Factory: Higgs Production and Decay

Higgs-strahlung



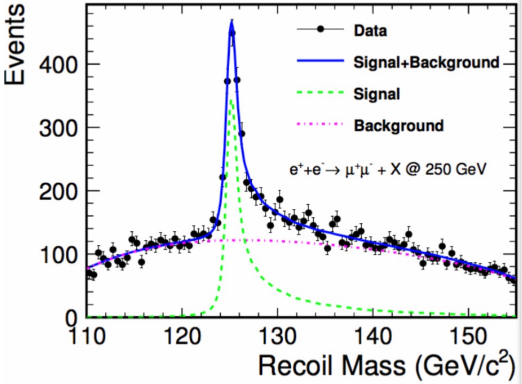


Boson fusion

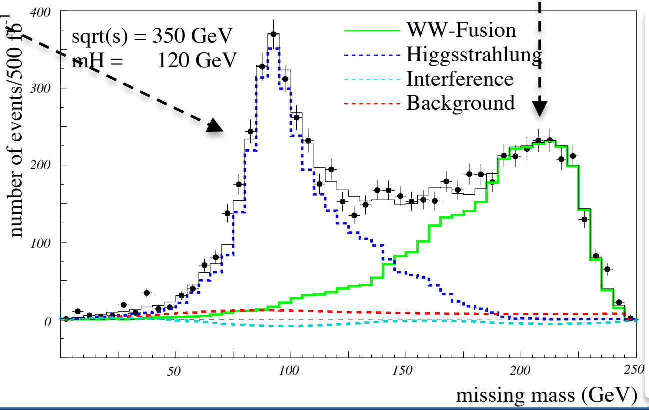


M_H = 125 GeV	SM BF
bb	56.1%
WW*	23.1%
gg	8.2%
ττ	6.3%
ZZ*	2.6%
cc	2.9%
γγ	0.2%
Zγ	0.15%
ss	0.1%
μμ	0.02%

flavour tagging



momentum resolution



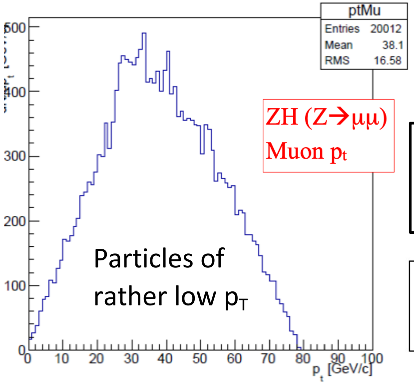
jet energy resolution

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



ZH (Z→μμ)
Muon p_t

Particles of rather low p_T

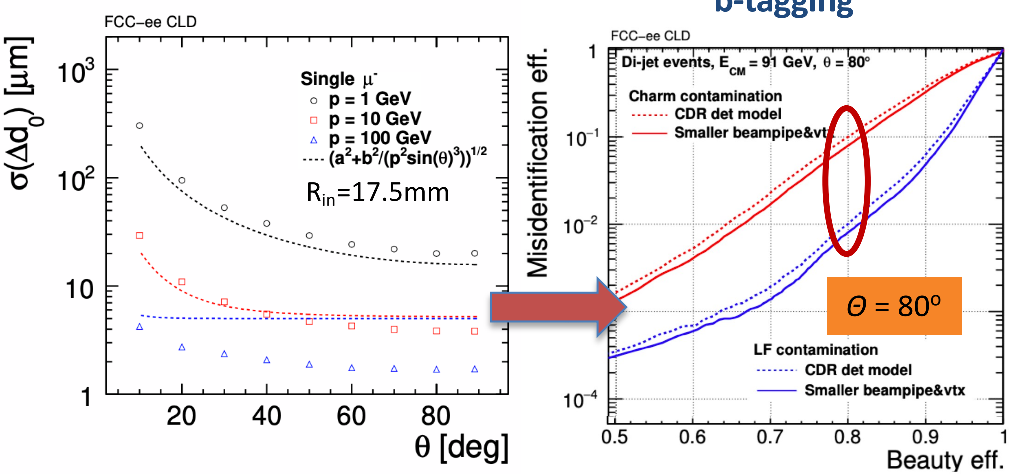
→ **Momentum resolution**
multiple scattering dominated

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

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

e.g. CLD flavour tagging

b-tagging



R_{in}=17.5mm

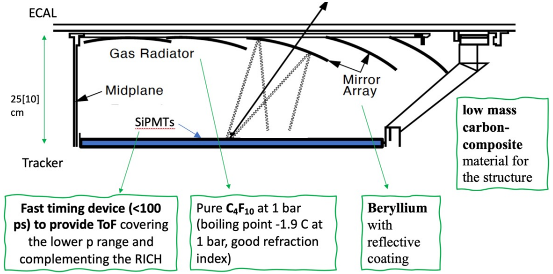
Θ = 80°

- → **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	12 mm

Particle Identification

- **PID capabilities across a wide momentum range** is essential for flavour studies and 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



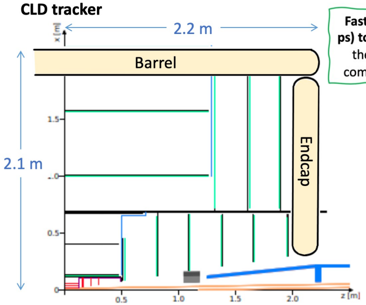
Fast timing device (<100 ps) to provide ToF covering the lower p range and complementing the RICH

Pure **C_4F_{10}** at 1 bar (boiling point -1.9 C at 1 bar, good refraction index)

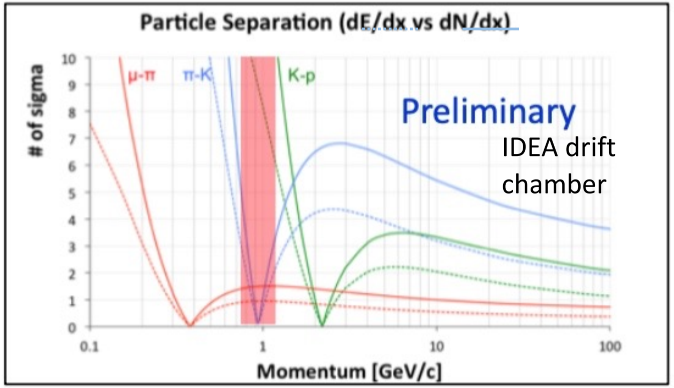
Beryllium with reflective coating

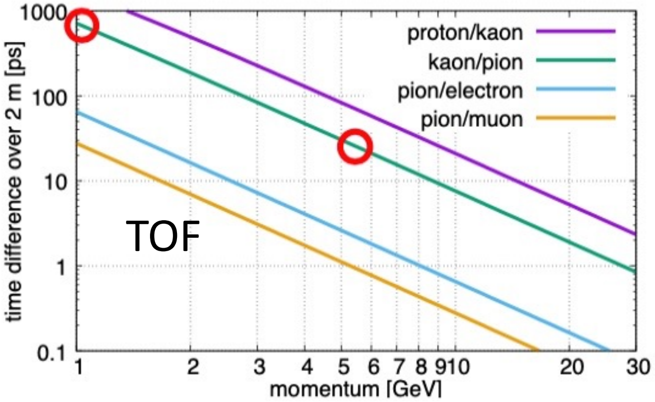
low mass carbon-composite material for the structure

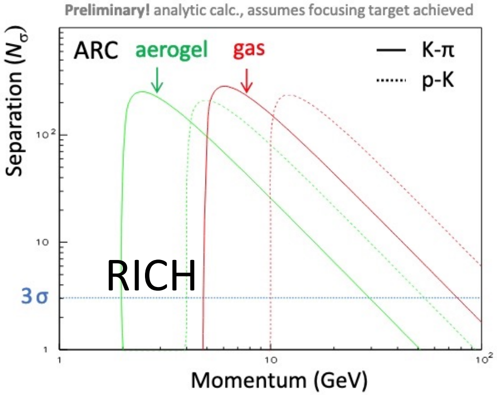
FCC Workshop, Feb. 2022



Possible RICH layout in an FCC-ee experiment







Calorimetry – Jet Energy Resolution

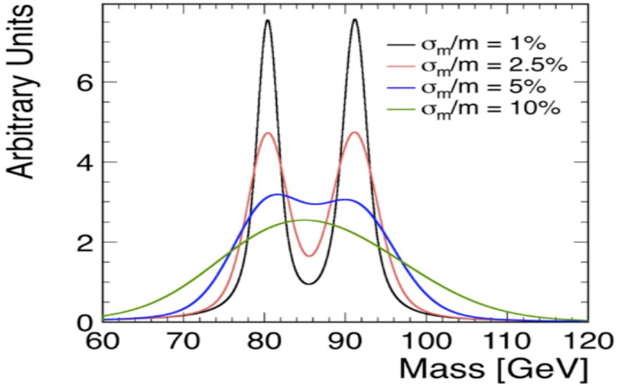
Energy coverage < 300 GeV : 22 X_0, 7λ
Precise jet angular resolution

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

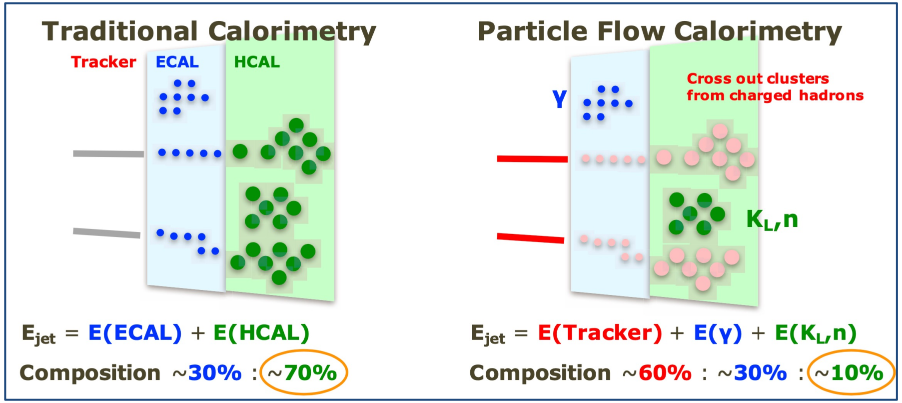
⇒ Mass reconstruction from jet pairs

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 $\sigma E/E \simeq 30\% / \sqrt{E\,[\mathrm{GeV}]}$, detector resolution is comparable to natural widths of W and Z bosons



How to achieve jet energy resolutions 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**

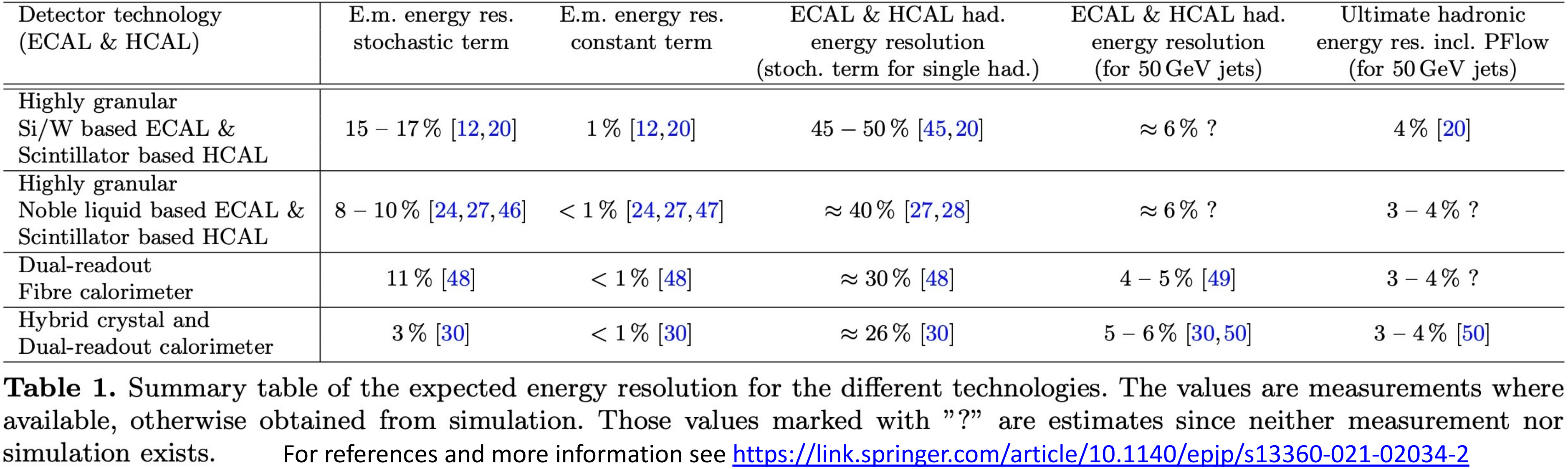


E_{jet} = E(ECAL) + E(HCAL)
Composition ~30% : ~70%

E_{jet} = E(Tracker) + E(γ) + E(K_L,n)
Composition ~60% : ~30% : ~10%

→ High granularity and/or dual read-out

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.

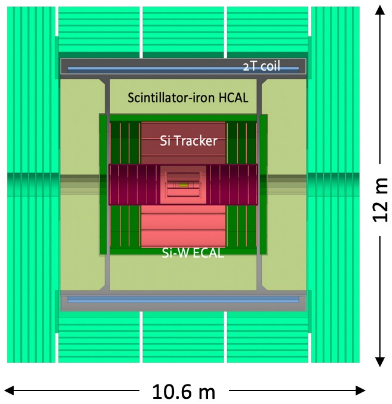
For references and more information see https://link.springer.com/article/10.1140/epjp/s13360-021-02034-2

- **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/π^0 separation** and measurement
- **Other concerns:** Operational stability, cost, ...
- **Optimisation ongoing for all technologies:** Choice of materials, segmentation, read-out, ...

Proto Detectors

FCC-ee Proto Detectors – Overview

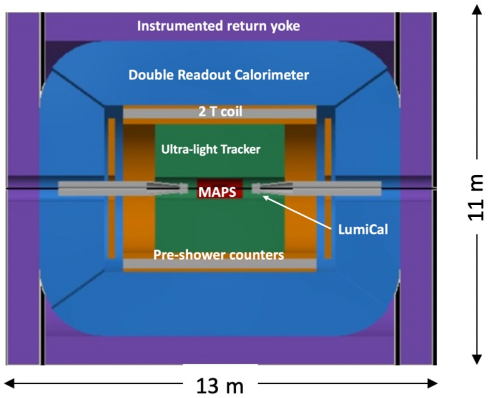
CLD



- Well established design
    - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker;
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
    - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
    - σ_p/p, σ_E/E
    - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
    - …

CDR

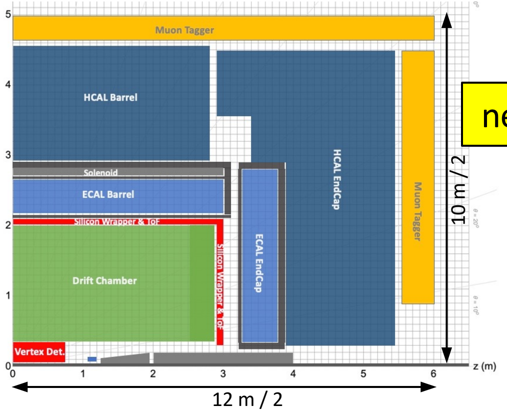
IDEA



- A bit less established design
    - But still ~15y history
- Si vtx detector; ultra light drift chamber w powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
    - Possibly augmented by crystal ECAL
- Muon system
- Very active community
    - Prototype designs, test beam campaigns, …

ALLEGRO (Noble Liquid ECAL based)

new

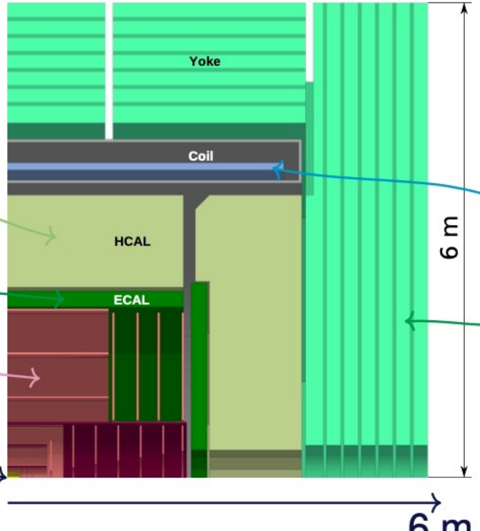


- A design in its infancy
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
    - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
    - Readout electrodes, feed-throughs, electronics, light cryostat, …
    - Software & performance studies

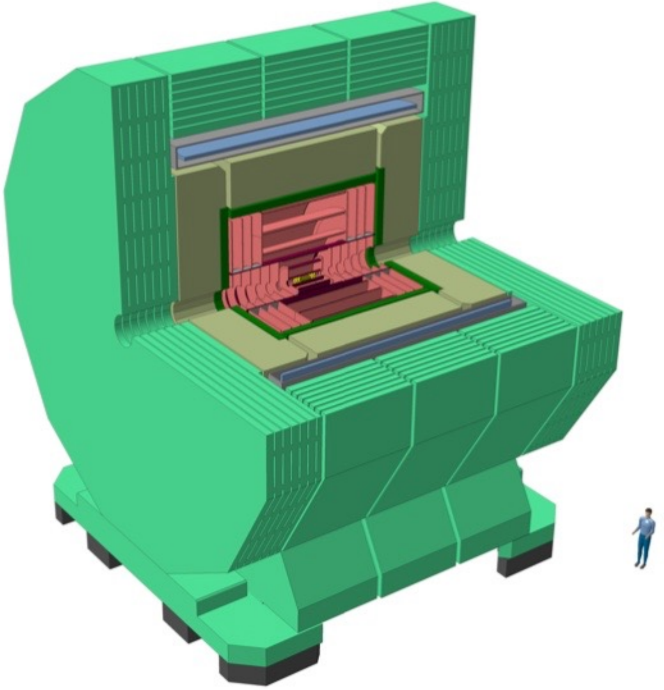
FCC-ee CDR: https://link.springer.com/article/10.1140/epjst/e2019-900045-4

CLD Detector Concept

General purpose detector for Particle Flow reconstruction
(based on the work for a detector at CLIC)



- 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
- Superconducting Solenoid of 2 T
- Iron Yoke with RPCs for Muon ID



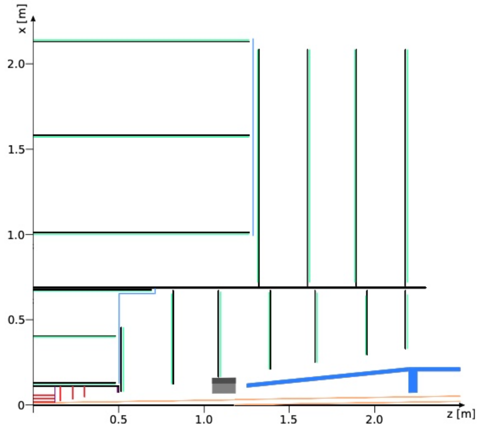
2 Tesla Solenoid Field (solenoid r=3.7m, L=7.4m)
Return yoke contains muon system with 6 equidistant layers

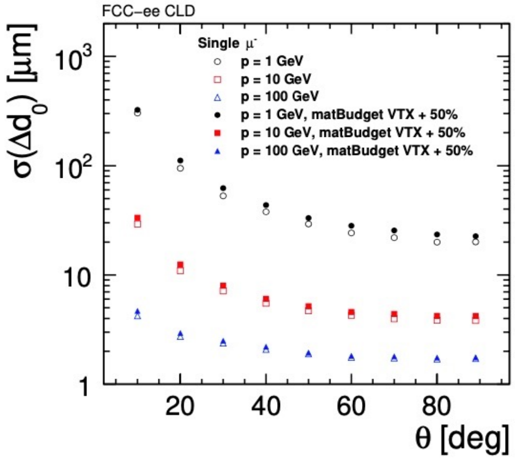
https://arxiv.org/abs/1911.12230

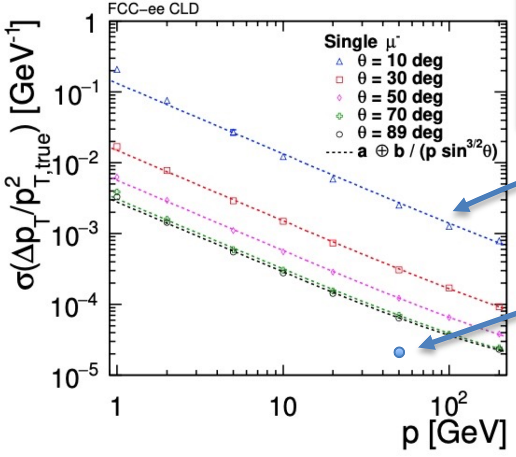
CLD Vertex Detector and Si Tracker

- **Silicon vertex detector:** precise vertex reconstruction
  - $25 \times 25\ \mu m^2$ pixels, 3 µm single point resolution, 50 µm silicon thickness
  - Double layers (0.3 % X_0 per detection layer), $R_{in} = 17.5$ mm
- **Inner and Outer Tracker**
  - 3 short and 3 long barrel layers, 7 inner and 4 outer endcaps
  - 200 µm Silicon thickness, 50 µm × 0.3 mm cell size, 7 µm × 90 µm single point resolution (except first inner tracker disk, $5\times5\ \mu m^2$)
  - At least 8 hits for $\theta > 8.5^o$
  - Material budget: 1.1 % – 2.2 % X_0 per layer (including overlaps)
  - Some studies for re-scaling were done, $R_{max} \in (2.1, 2.0, 1.9, 1.8)$

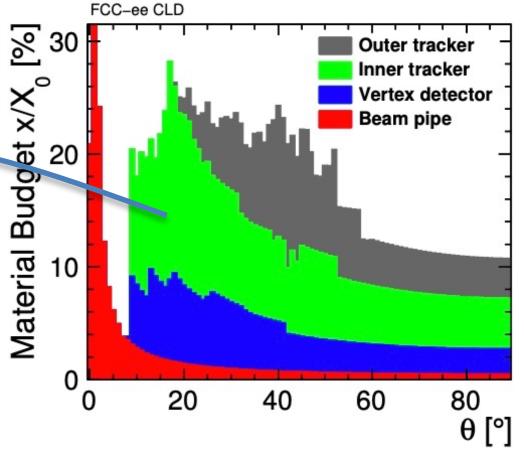
Multiple scattering limited
→ lighter Si tracker!?







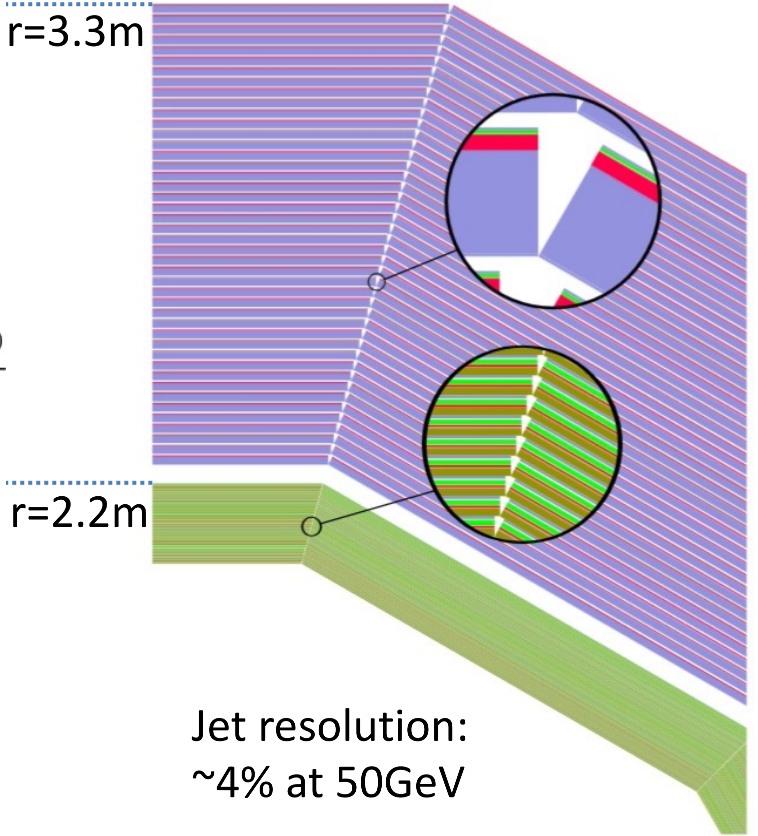
$\sigma_{pT}/p_T \simeq 10^{-3}$
@ 50GeV



CLD Calorimetry

- ECal (Si/W)
  - 40 layers, 1.9 mm tungsten absorber, 22 X_0
  - 0.5 mm thick silicon sensors with 5 × 5 mm^2 granularity
  - ECal optimisation studies
- HCal (Scintillator/Steel)
  - 44 layers, 19 mm steel absorber, 5.5 (+1) λ
  - 3 mm thick scintillator tiles with 3 × 3 cm^2 granularity

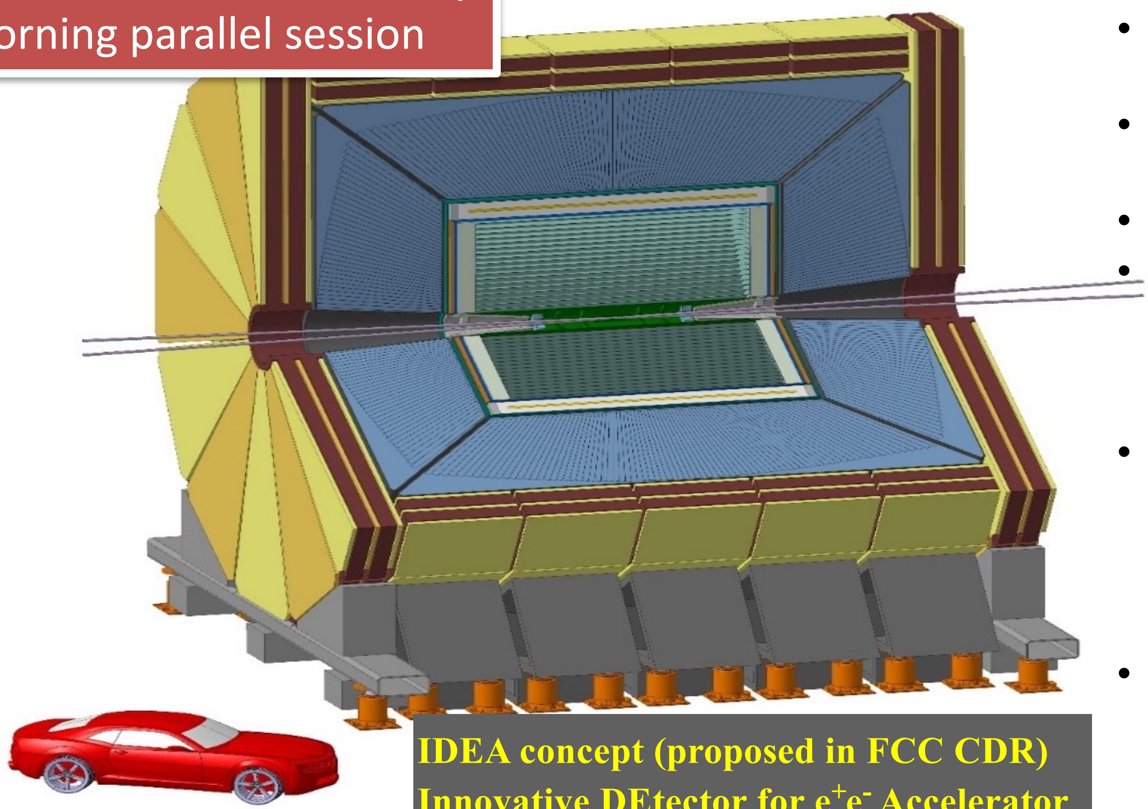
$$\frac{\sigma}{E} \approx \frac{16\,\%}{\sqrt{E}}$$



Jet resolution:
~4% at 50GeV

IDEA Detector Concept

→ See talks in the Tuesday morning parallel session



IDEA concept (proposed in FCC CDR)
Innovative DEtector for e^+e^- Accelerator

New, innovative concept

- Silicon vertex detector
  - 5MAPS layers, R=1.7-34cm
- Short-drift, ultra-light wire chamber
  - 112 layers, L=4m, R=35-200cm
- Silicon wrapper
- Thin and light solenoid coil inside calorimeter system (see back-up)
  - Coil: 2T, R=2.1-2.4m
  - $0.76X_0$, $0.16\lambda_{int}$
- Dual-readout calorimeter
  - 2m depth, $7\lambda_{int}$
  - Particle flow reconstruction
  - Option: crystal calorimeter in front for better EM resolution
- Muon system made of 3 layers of μ-RWELL detectors in the return yoke (see back-up)

https://pos.sissa.it/390/877/pdf

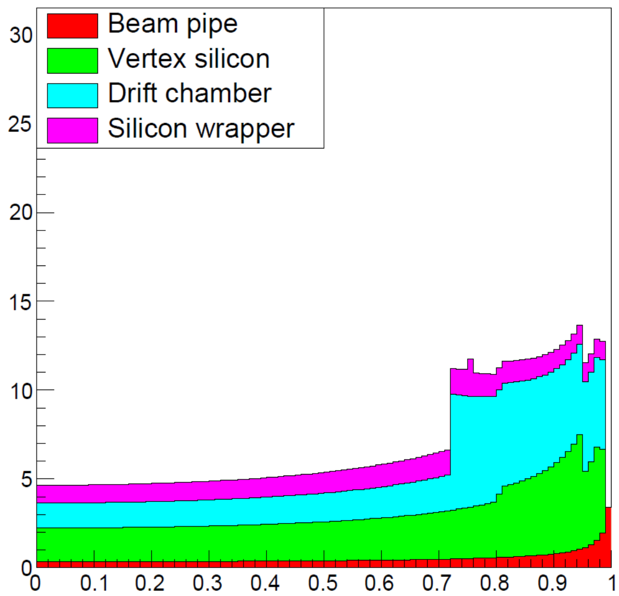
Vertex Detector & Momentum Measurement

Tracker: Z or H decay muons in ZH events have rather low p_T

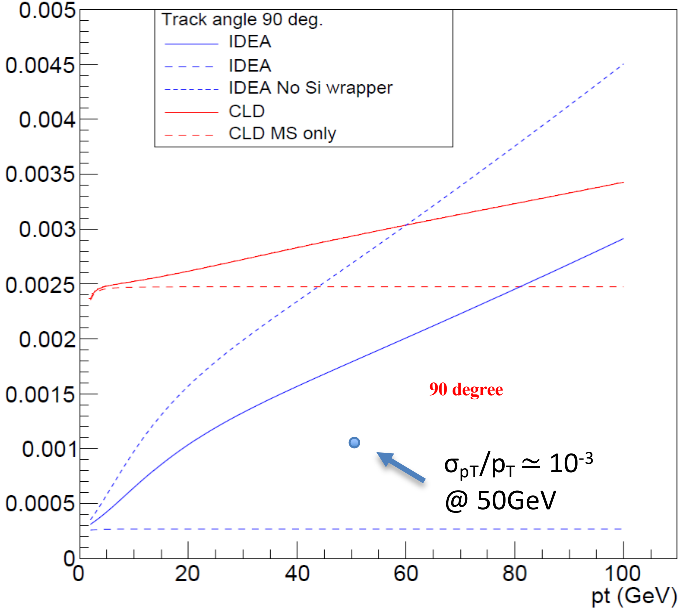
→ Transparency more important than asymptotic resol. → minimize material!

→ Very light vertex detector and drift chamber (see next slide and back-up)

IDEA: Material vs. cos(θ)



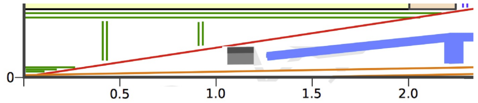
σ_{pt}/pt

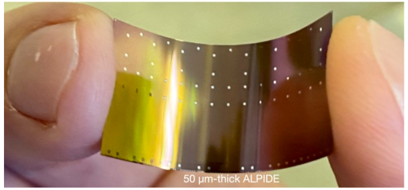


$\sigma_{pT}/p_T \simeq 10^{-3}$ @ 50GeV

Vertex Detector: Inspired by Belle II based on MAPS technology, using the ARCADIA R&D program

- 5MAPS layers, pixels 20 × 20 µm²
- Light
  - Inner layers: 0.3% X_0/layer
  - Outer layers: 1% X_0/layer
- Performance:
  - Point resolution of ~3 mm
  - Efficiency of ~100%
  - Extremely low fake rate hit rate



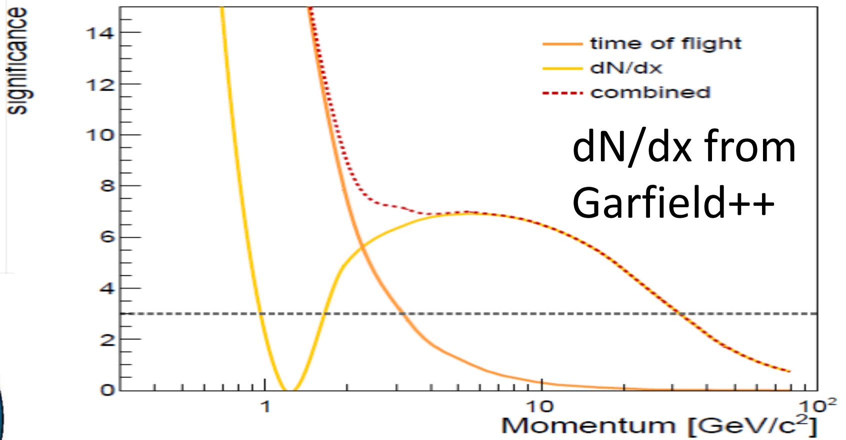


Courtesy of Magnus Mager, CERN

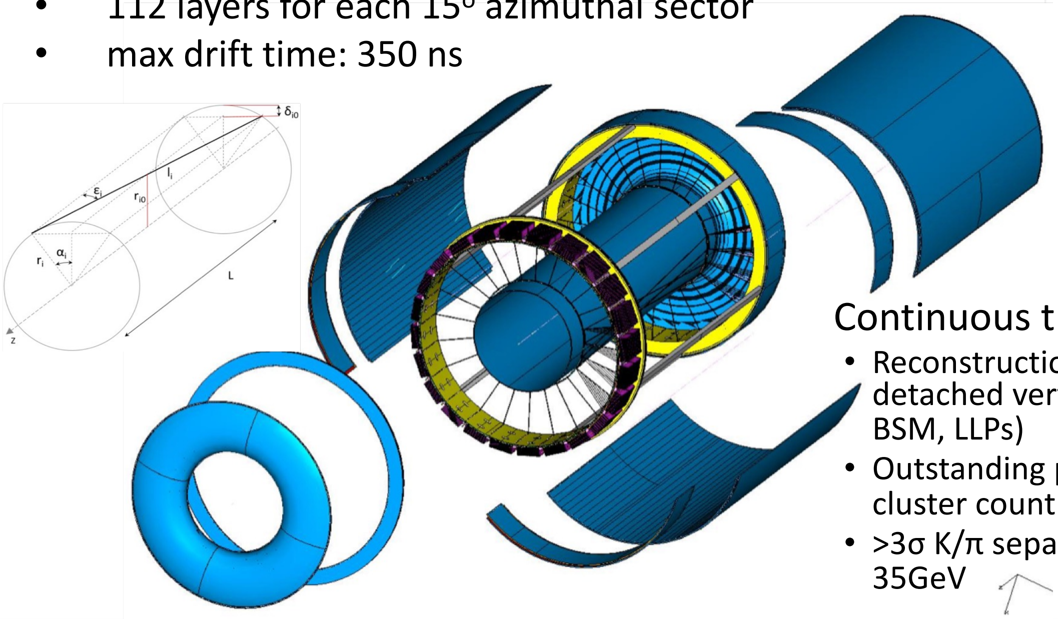
Drift Chamber

IDEA: Extremely transparent Drift Chamber

- Gas: 90% He – 10% iC_4H_{10}
- Radius 0.35 – 2.00m
- 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

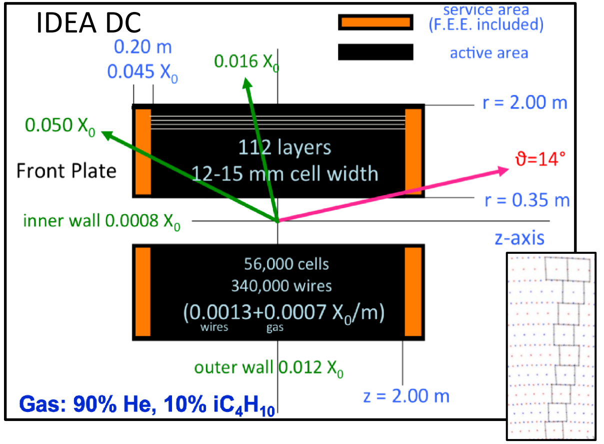


dN/dx from Garfield++

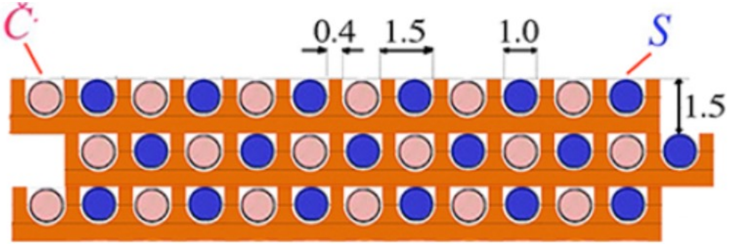


Continuous tracking:

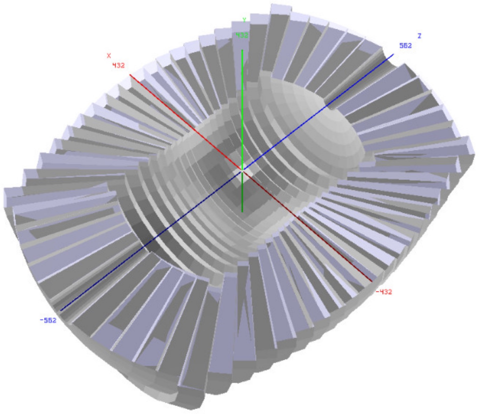
- Reconstruction of far-detached vertices (K^0_s, Λ, BSM, LLPs)
- Outstanding part. ID via cluster count. dN/dx or dE/dx
- >3σ K/π separation up to 35GeV



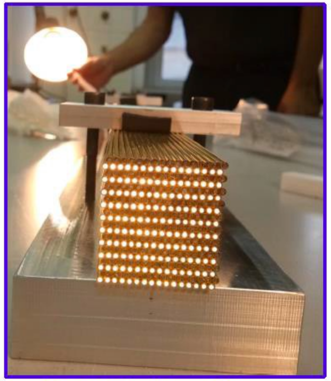
Dual Readout Calorimetry



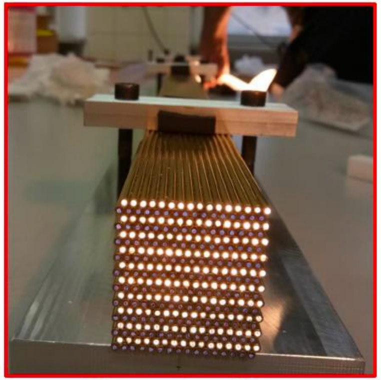
Alternate
- Scintillation fibres
- Cherenkov fibres



Newer DR calorimeter (bucatini calorimeter)



Scintillation fibers



Cherenkov fibers

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

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

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

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

Full GEANT4 simulation:

hadronic:

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

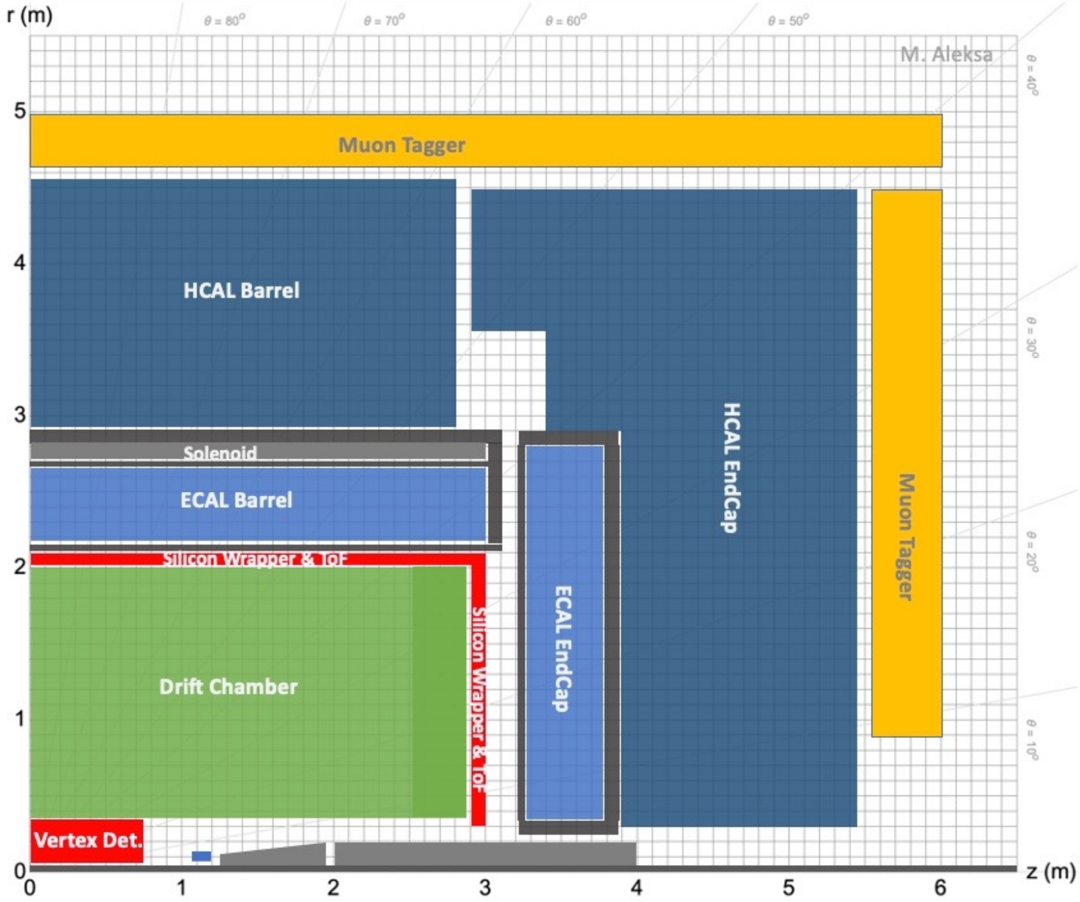
electromagnetic:

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

Crystal option:
20cm $PbWO_4$

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

ALLEGRO Detector Concept



ALLEGRO

- **A L**epton co**L**lider **E**xperiment with **G**ranular **R**ead-**O**ut

Vertex Detector:

- MAPS or DMAPS possibly with timing layer (LGAD)
- Possibly ALICE 3 like or similar to Belle II VTX upgrade

Drift Chamber (±2.5m active) similar to IDEA

Silicon Wrapper + ToF:

- MAPS or DMAPS possibly with timing layer (LGAD), Monolithic CMOS

High Granularity ECAL:

- Noble liquid + Pb or W
- Particle Flow reconstruction

Solenoid B=2T, sharing cryostat with ECAL, between ECAL and HCAL

- Light solenoid coil ≈ 0.76 X_0 (see back-up)
- Low-material cryostat < 0.1 X_0 (see back-up)

High Granularity HCAL / Iron Yoke:

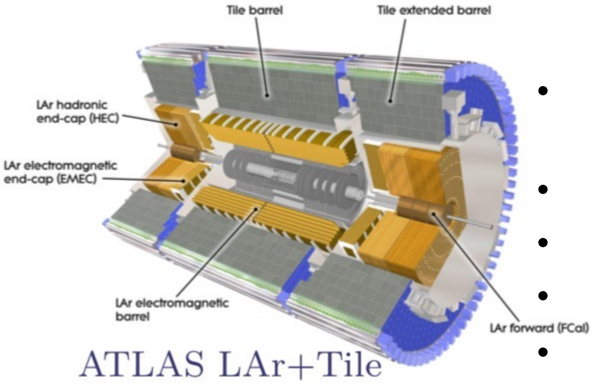
- Scintillator + Iron (particle flow reconstruction)
  - SiPMs directly on Scintillator or
  - TileCal: WS fibres, SiPMs outside

Muon Tagger:

- Drift chambers, RPC, MicroMegas

See talk at FCC Week 2022 in Paris

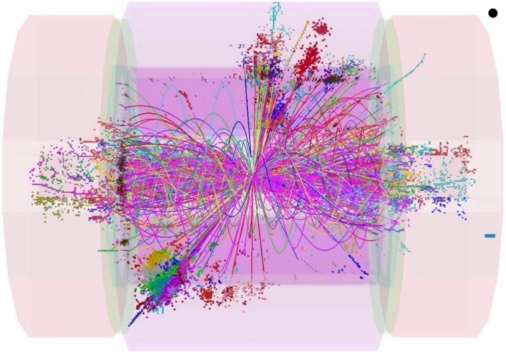
FCC Calorimetry



ATLAS LAr+Tile

arXiv:1305.4551

- Good intrinsic energy resolution
- Radiation hardness
- High stability
- Linearity and uniformity
- Easy to calibrate

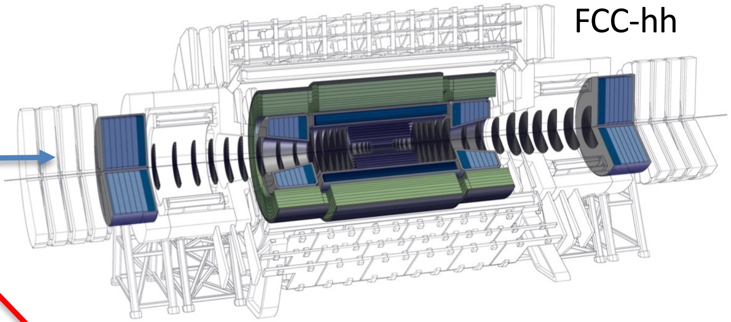


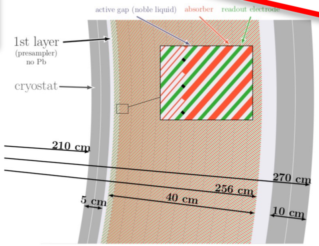
CLIC Detector

- High granularity
  - → Pile-up rejection
  - → Particle flow
  - → 3D/4D/5D imaging

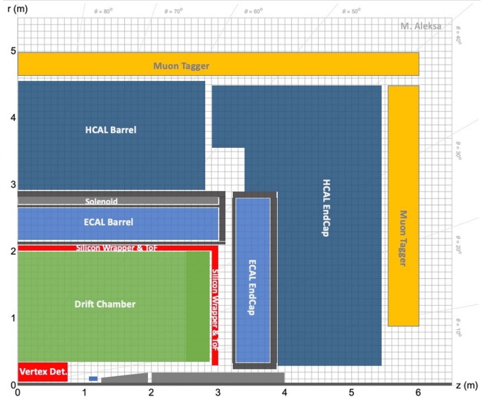
FCC Calorimetry

FCC-hh





FCC-ee



FCC-hh Calorimetry studies have been published at https://arxiv.org/abs/1912.09962

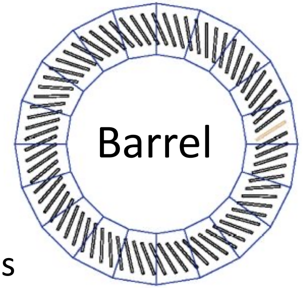
High Granularity Noble-Liquid Calorimeter

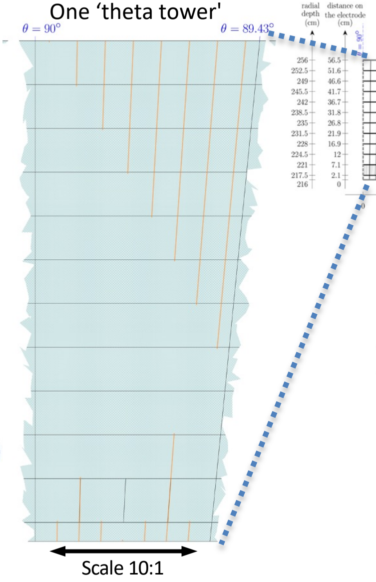
Baseline design

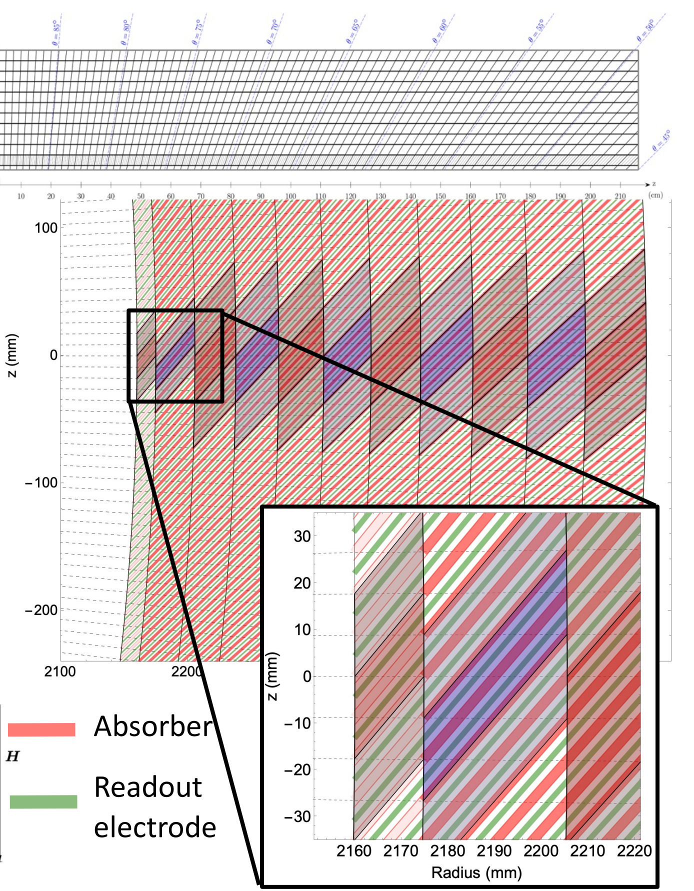
- 1536 straight inclined (50.4^o) 1.8mm Pb absorber plates
- Multi-layer PCBs as readout electrodes
  - → High granularity (very flexible – need to find optimum)
  - Ground shields to reduce cross-talk → increase detector capacitance 25 – 300pF per cell (impact on noise)
- 1.2 – 2.4mm LAr gaps
- 40cm 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

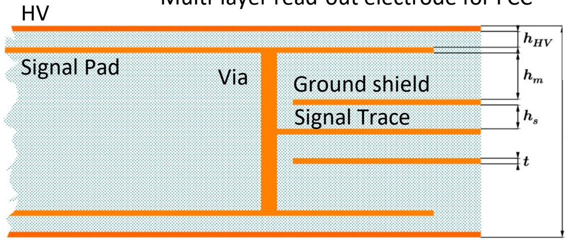
- LKr or LAr, W or Pb absorbers,
- Absorbers with growing thickn.
- Granularity optimization
- Al or carbon fibre cryostat
- Warm or cold electronics





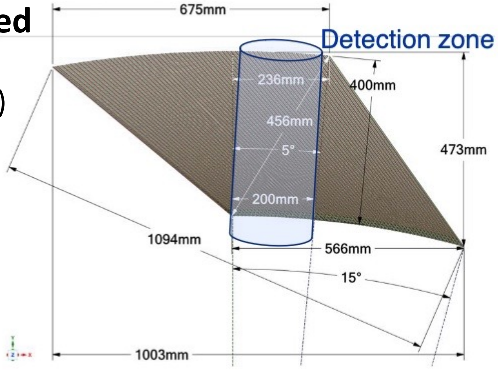


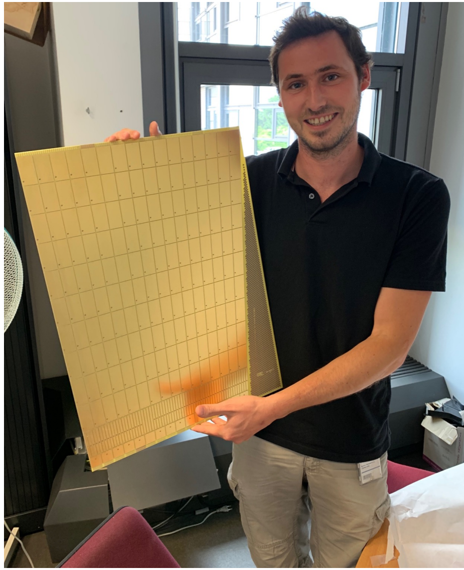
Multi-layer read-out electrode for FCC

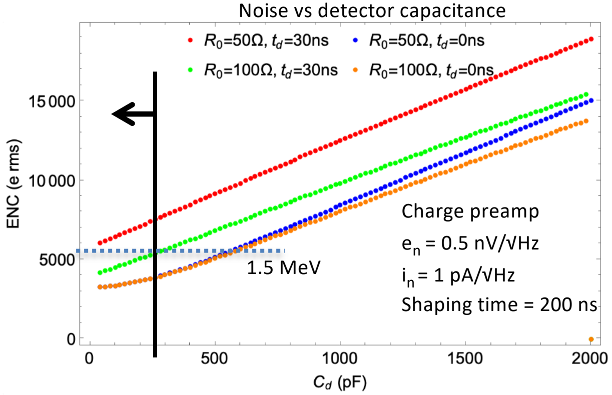


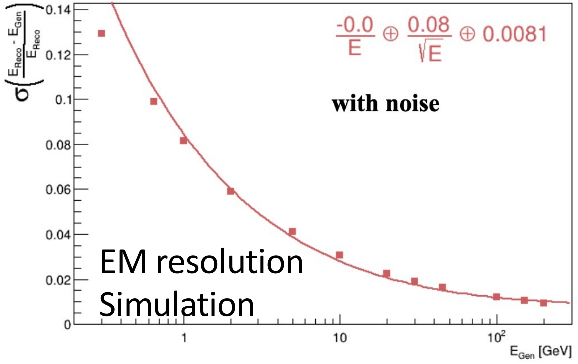
Challenges: Resolution, Noise and Crosstalk

- **EM resolution** with sampling term of 8 to 9%
- **Noise vs cross-talk challenge:** traces need to be shielded to minimize cross-talk → grounded shields increase detector capacitance and hence noise → need to find best compromise – **prototype electrode produced & measured**
  - **Noise** of < 1.5 MeV per cell for warm electronics and transmission lines of R_0 = 100 Ω and τ = 200 ns ($C_d \leq 250$ pF)
    - → MIP S/N > 5 reached for all layers
  - **Cross-talk** of < 1% for shaping times τ ≥ 20 ns
- **Next steps: Further optimization, then ≈64 absorber test module for testbeam measurements**

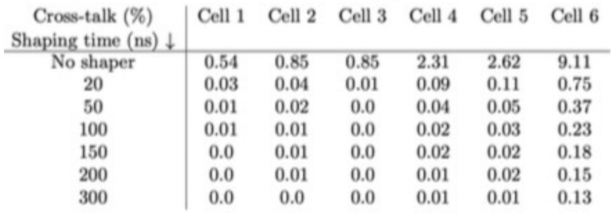








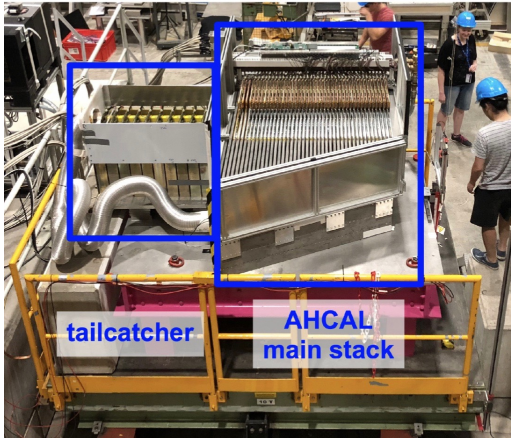
Simulated cross-talk 2 shields < 1% for τ ≥ 20 ns confirmed by measurements on prototype



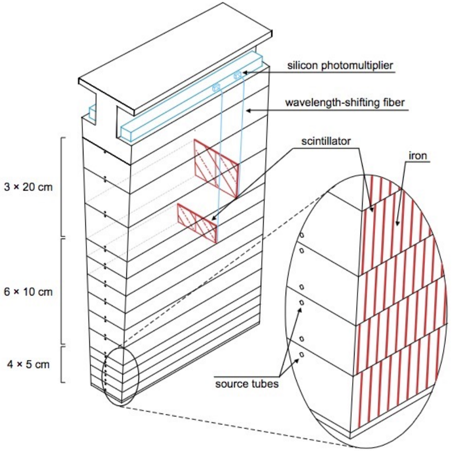
Cross-talk (%) Shaping time (ns) ↓	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
No shaper	0.54	0.85	0.85	2.31	2.62	9.11
20	0.03	0.04	0.01	0.09	0.11	0.75
50	0.01	0.02	0.0	0.04	0.05	0.37
100	0.01	0.01	0.0	0.02	0.03	0.23
150	0.0	0.01	0.0	0.02	0.02	0.18
200	0.0	0.01	0.0	0.01	0.02	0.15
300	0.0	0.0	0.0	0.01	0.01	0.13

HCAL for Noble-Liquid Based Concept

- **ATLAS TileCal inspired HCAL** has been implemented into FullSim, other **Sci/Steel options (CALICE like) will also be studied**
- **FCC-ee TileCal:**
  - 5mm steel absorber plates alternating with 3mm Scint.: 8 - 9.5λ
  - 128 modules in ϕ, 2 tile/module
  - 13 radial layers
  - $\Delta\eta = 0.025$ (grouping 3-4 tiles), $\Delta\phi = 0.025$
  - In the FCC-hh design there used to be Pb plates to improve the e/h ratio. Since the HCAL acts as return yoke, these Pb plates have been removed for FCC-ee.
  - FCC-ee TileCal geometry is available in SW - FCCDetectors
  - Work on optimisation of segmentation and reconstruction is in full swing
  - Started testing Sci tile + WLS fibre + SiPM readout
  - **ECAL + HCAL performance:** Sampling term of ~37% for $\pi^{\pm}$ → excellent starting point for particle flow reconstruction! → further improvement expected



CALICE AHCAL



TileCal

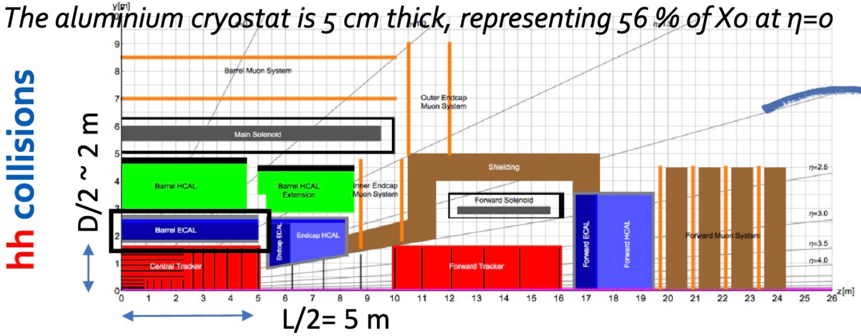
Thin Cryostats R&D at CERN

Thin cryostats (carbon fibre or honeycomb) under study, see presentation by M. Soledad

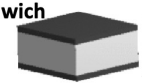
Presentation by M. Soledad at EP R&D Day, 2021

Baseline geometry, FCC-hh LAr barrel ECAL :

The aluminium cryostat is 5 cm thick, representing 56 % of Xo at η=0



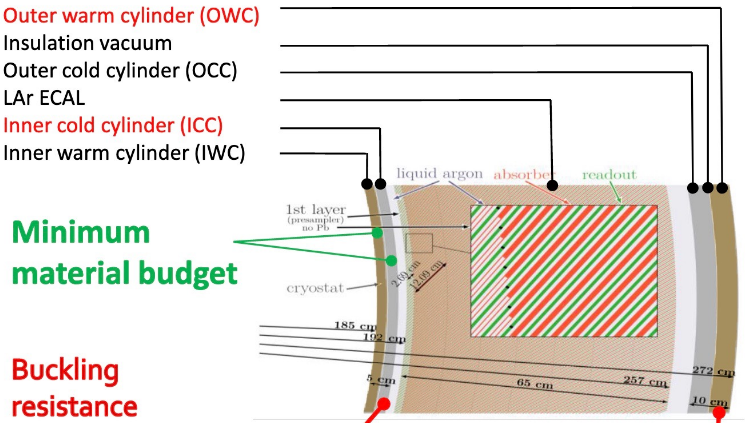
Sandwich



Skin [0,45,-45,90]s
Core : Al Honeycomb
Skin [0,45,-45,90]s

Radiation length X_0[mm]
Al = 88.9
HM CFRP = 260
Honeycomb Al= 6000

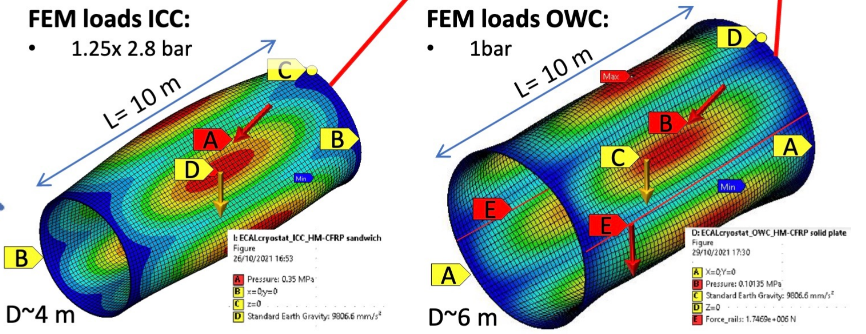
Criteria: Safety Factor = 2	Honeycomb Al				Solid shell			
	HM CFRP		Al		HM CFRP		Al	
	OWC	ICC	OWC	ICC	OWC	ICC	OWC	ICC
Material budget X/Xo	0.03	0.043	0.094	0.17	0.092	0.12	0.34	0.44
Xo % savings	-68%	-75%	REF	REF	-2%	-29%	262%	159%
Skin Th. [mm]	3.2	4.8	3.9	7.5				
Core Th. [mm]	32	38	40	40				
Total Th. [mm]	38.4	47.6	47.8	55	24	30.4	30	39
Thickness % savings	-20%	-13%	REF	REF	-50%	-45%	-37%	-29%



Outer warm cylinder (OWC)
Insulation vacuum
Outer cold cylinder (OCC)
LAr ECAL
Inner cold cylinder (ICC)
Inner warm cylinder (IWC)

Minimum material budget

Buckling resistance



FEM loads ICC:

- 1.25x 2.8 bar

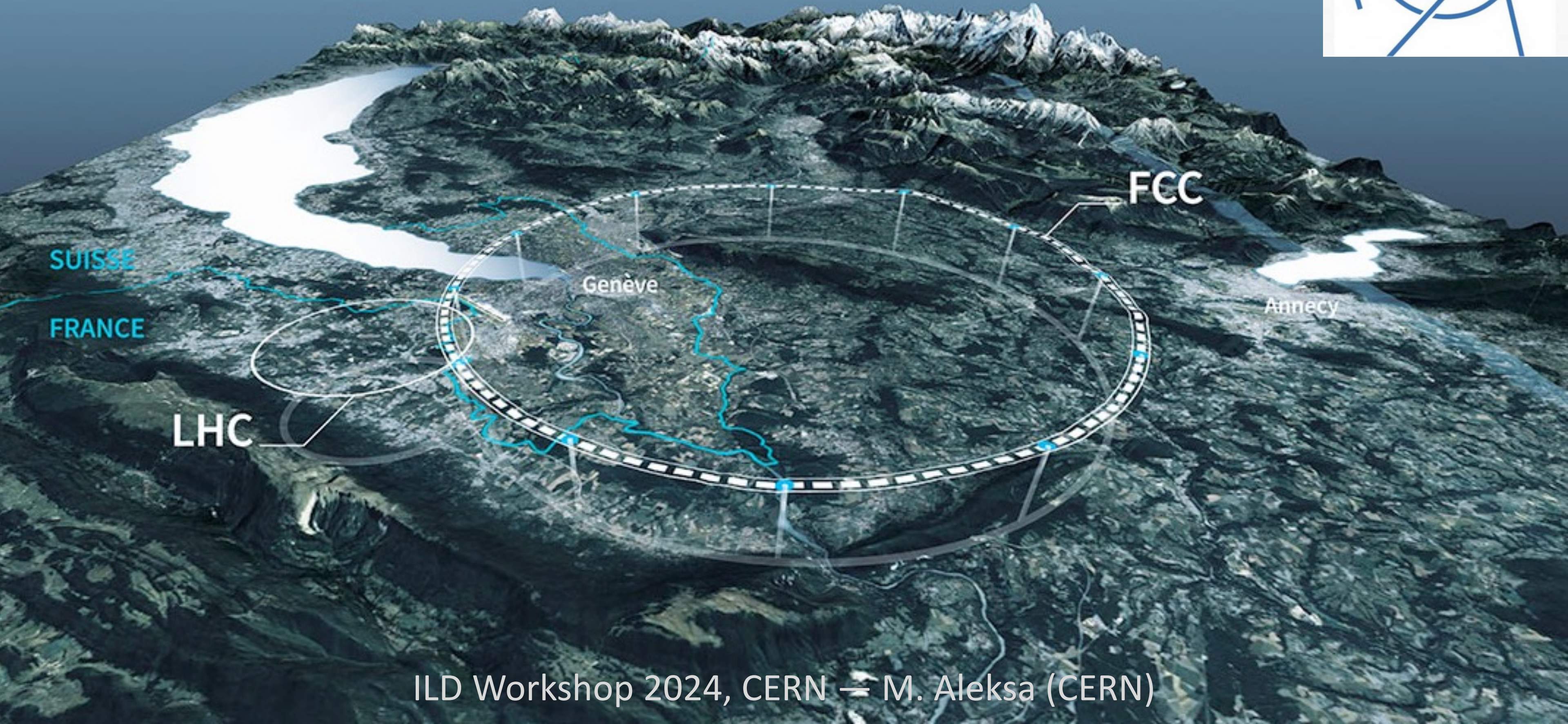
FEM loads OWC:

- 1bar

Conclusions

- FCC-ee has an enormous physics potential
  - Unprecedented factory for Z, W and Higgs bosons; for top, beauty, and charm quarks; and for tau leptons
  - Possibly also factory for BSM particles!!
- Instrumentation to fully exploit the physics potential is challenging and exciting
  - FCC-ee can host (up to) four experimental collaborations
  - Full exploitation of physics potential via N ”general purpose” experiments, possibly complemented by M dedicated experiments (e.g. heavy flavour) → N+M ≤ 4
- For next ESPP, need to propose detector concepts that meet the experimental challenge
- Detector Concepts working group formed last year (e-group: FCC-PED-DetectorConcepts), monthly meetings: https://indico.cern.ch/category/15054/
- Detector R&D for FCC-ee is a rich field totally orthogonal to challenges at HL-LHC
- Strong European effort (ECFA) on setting up Detector R&D Collaborations
- Many interesting questions and research topics ahead of us – ideal time to join in!
- The roadmap ahead of us: approval of the project in 2028, and the proposal of four detectors in ~2032!!

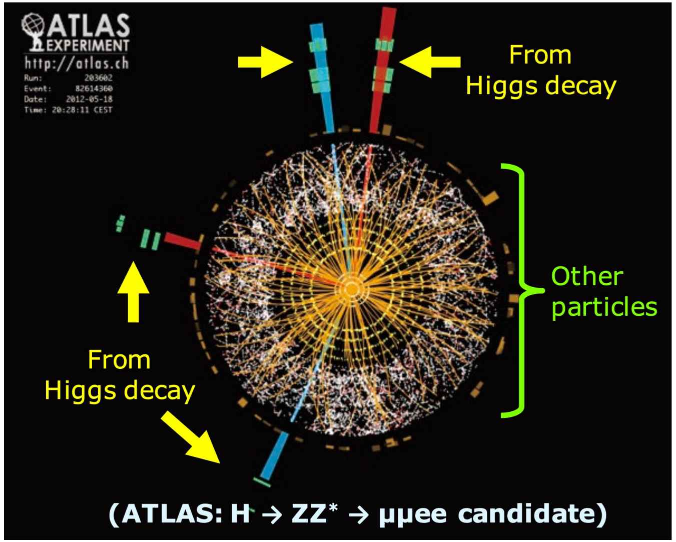
Thank You for Your Attention!



BACK-UP

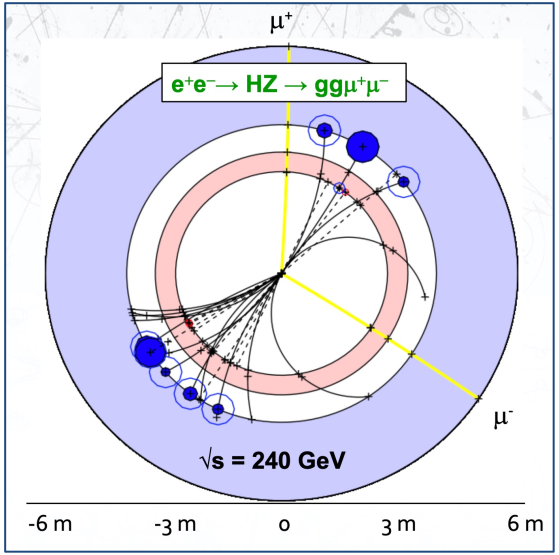
Introduction – pp versus e^+e^-

Higgs event in pp



(ATLAS: H → ZZ* → μμee candidate)

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 → exploration
- S/B ≈ 10^{-10} without trigger, S/B ≈ 0.1 with trigger

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

- Clean experimental environment
  - → Trigger-less readout
  - → Low radiation levels
- Superior sensitivity for electro-weak states
- Limited direct mass reach
- S/B ≈ 1 → measurement

Ultra-Thin Solenoid Magnet R&D at CERN

Thin solenoid magnet (studied for R=2.2m as developed for IDEA)
For ALLEGRO: Solenoid outside ECAL → R=2.8m (being studied, but results below for R=2.2m)

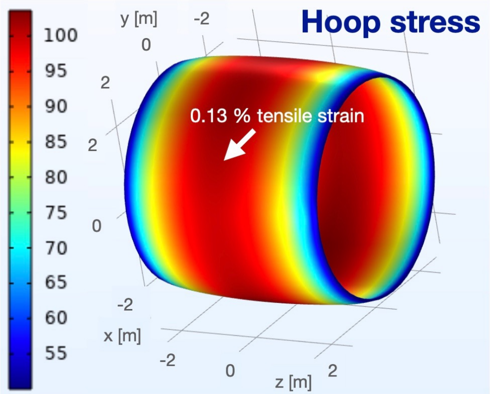
Presentation by N. Deelen at 5th FCC P&E WS

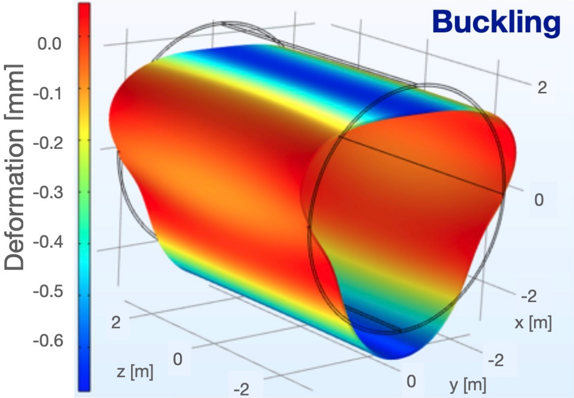
- Support cylinder with thickness of 12 mm
- Support cylinder material: aluminium 5083

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

- First mechanical analysis is promising

	Conductor	Support	
Parameter	Value	Value	Unit
Material	Ni-doped aluminium	Aluminium 5083	
Yield strength	147 (with NbTi) [3]	209 @ 4.2 K [4]	MPa
Young's modulus	75 x 10^3	81 x 10^3	MPa



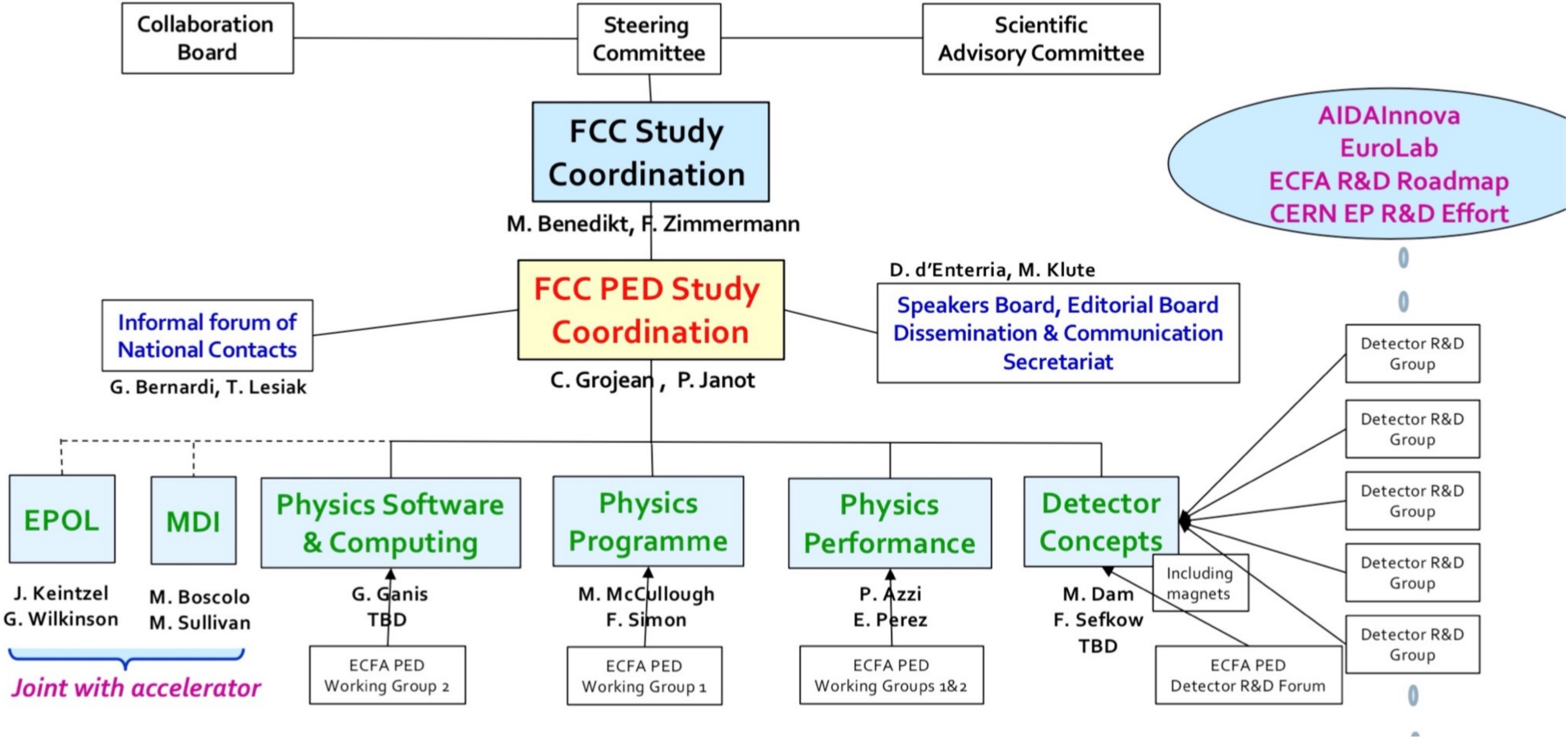


- Peak von Mises stress: **105 MPa**
- Peak tensile strain: **0.13 %**
- Peak shear stress: **0.5 MPa**
- Buckling of coil with simple **(pessimistic)** support, max. deformation: **0.7 mm**

See presentation by N. Deelen on this WS!

FCC Organisation & Detector R&D

The International FCC Organization



Collaboration Board

Steering Committee

Scientific Advisory Committee

FCC Study Coordination

M. Benedikt, F. Zimmermann

FCC PED Study Coordination

C. Grojean , P. Janot

Informal forum of National Contacts

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D. d'Enterria, M. Klute

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EuroLab
ECFA R&D Roadmap
CERN EP R&D Effort

EPOL

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G. Wilkinson

MDI

M. Boscolo
M. Sullivan

Joint with accelerator

Physics Software & Computing

G. Ganis
TBD

ECFA PED Working Group 2

Physics Programme

M. McCullough
F. Simon

ECFA PED Working Group 1

Physics Performance

P. Azzi
E. Perez

ECFA PED Working Groups 1&2

Detector Concepts

M. Dam
F. Sefkow
TBD

Including magnets

ECFA PED Detector R&D Forum

Detector R&D Group

Detector R&D Group

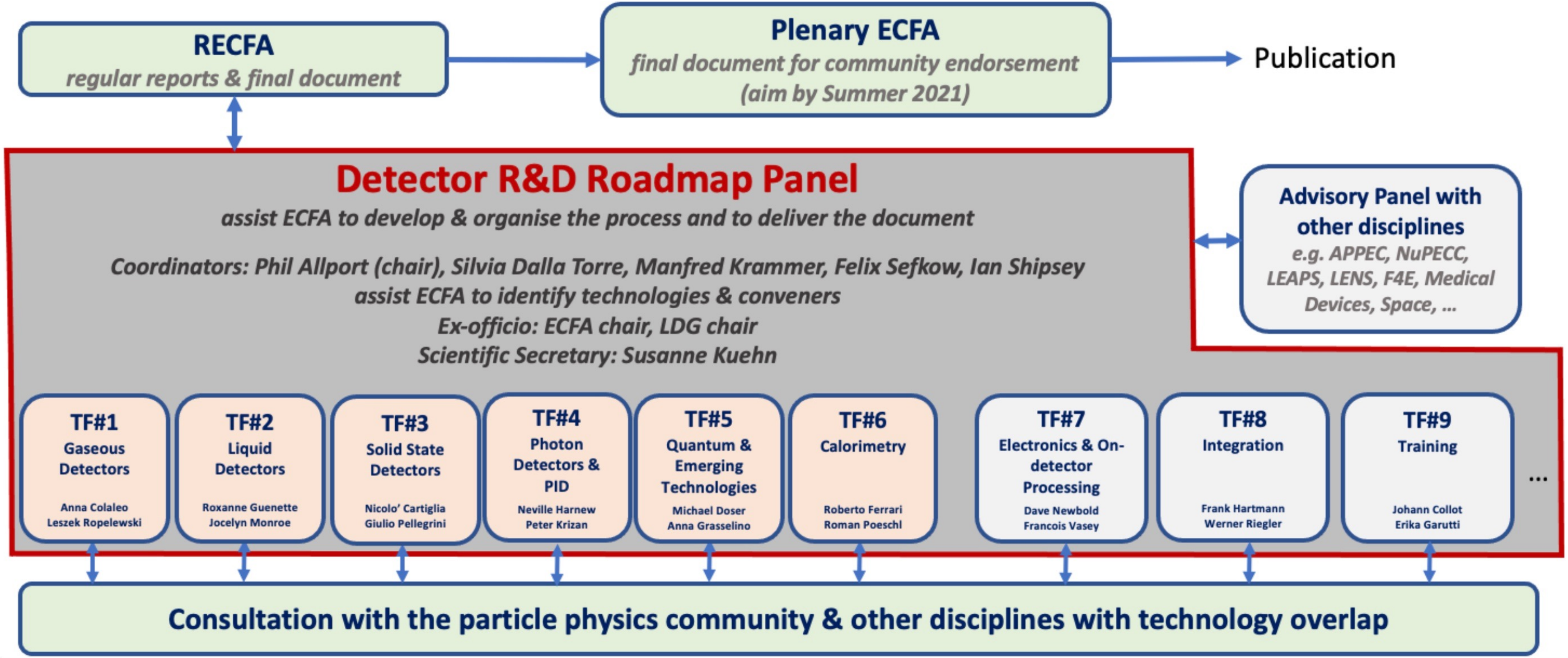
Detector R&D Group

Detector R&D Group

Detector R&D Group

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

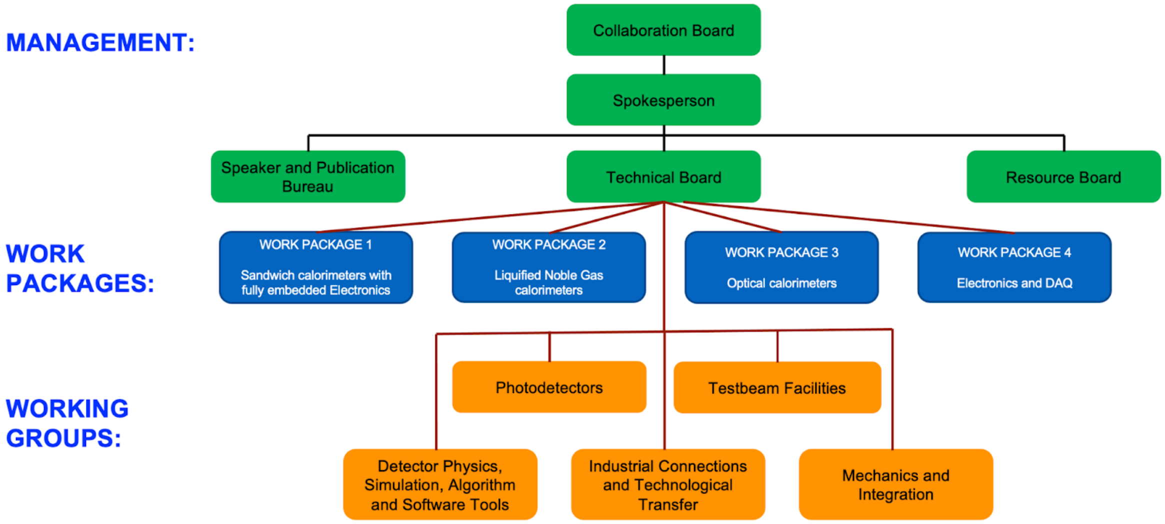
…

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.

DRD6 Proposal

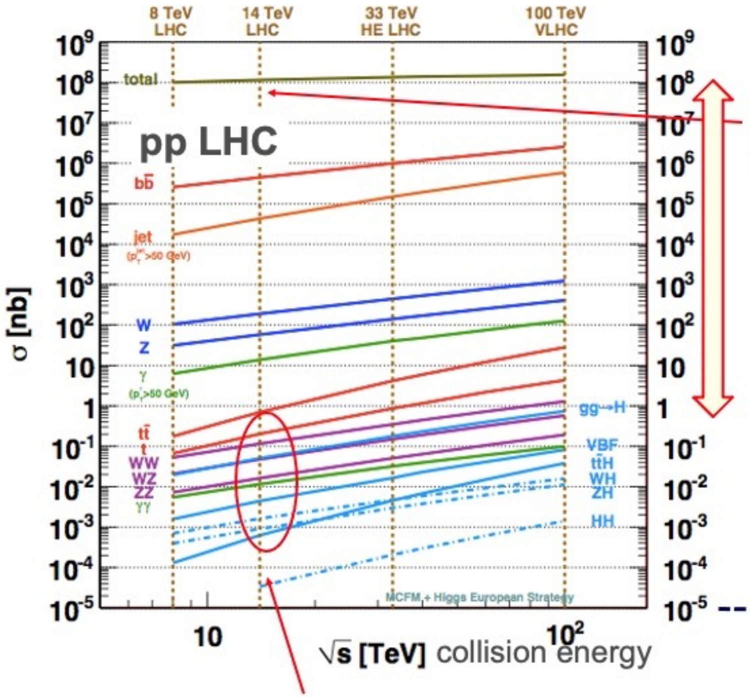
- **Detector R&D (DRD) collaborations** being set-up to implement the **ECFA Detector R&D Roadmap**
- **DRD6 on Calorimetry** with 4 work packages and several transversal activities (TB, Materials, SW, …)
  - Noble Liquid Calorimeter R&D part of work package 2 (18 institutes from 7 countries)
  - TileCal R&D part of work package 3 (7 institutes from 6 countries)
  - CALICE-like AHCAL part of work package 1 (10 institutes from 4 countries)
- **DRD Proposal** has been submitted, implementation beg. of 2024 (link)
- **Noble Liquid Calorimeter R&D (WP2)** joined by 18 institutes from 7 countries:
  - *O*(10-15) FTE expected during the next 5 years



Work Package 2 (noble-liquid calorimetry) **with 4 objectives**:

- Performance studies and optimization, optimization of granularity for particle flow, particle ID and displaced vertices
- Optimisation of read-out electrodes – further prototypes and then production of electrodes for test module
- Read-out electronics: warm electronics versus cold electronics
- Mechanical study of noble-liquid calorimeter in an experiment and design of a module for a testbeam to be built in 2027/2028.

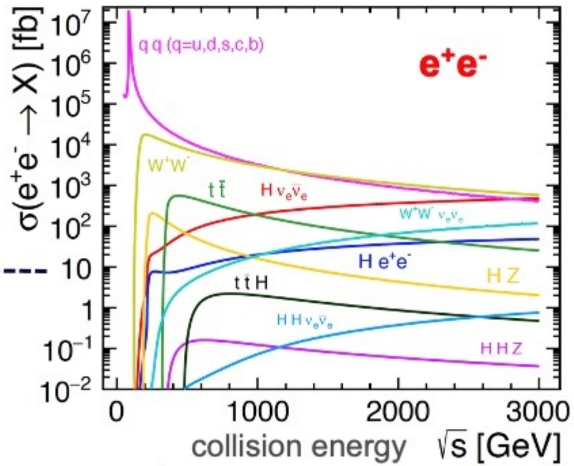
e^+e^- vs. pp Collisions – Cross Section Comparison



LHC total cross section factor > 100 million !!

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

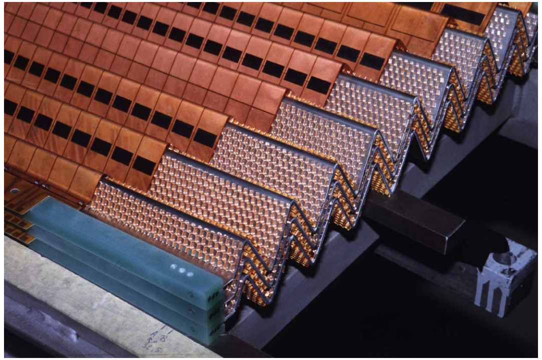
In e^+e^- collisions the total cross section ~ equals the electroweak cross section.

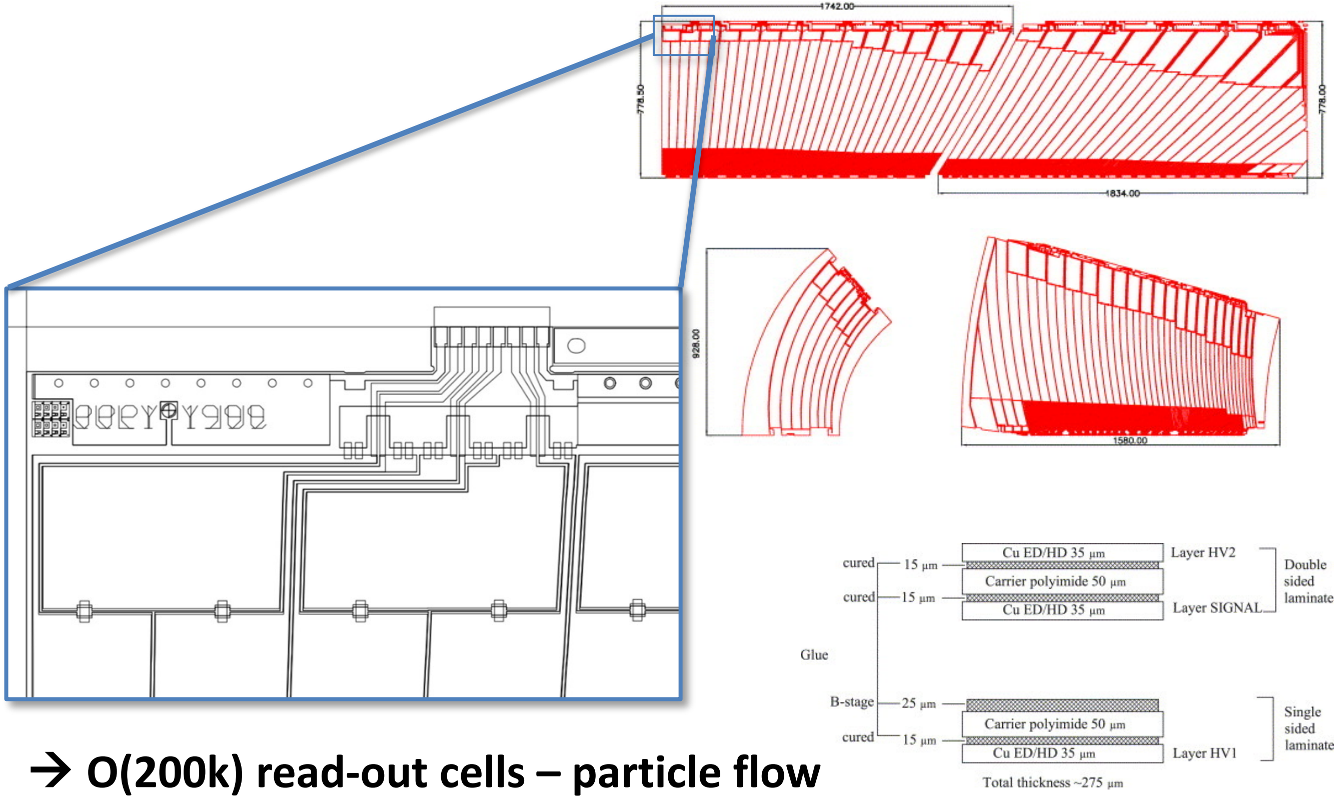


e^+e^- events are "clean"

Granularity – What are the Limits in ATLAS LAr?

- **In the ATLAS LAr calorimeter** electrodes have 3 layers that are glued together (~275µm thick)
  - 2 HV layers on the outside
  - 1 signal layer in the middle
- → **All cells** have to be connected **with fine signal traces** (2-3mm) to the edges of the electrodes
  - Front layer read at inner radius
  - Middle and back layer read at outer radius
- → **limits lateral and longitudinal granularity**
- → maximum 3 long. layers





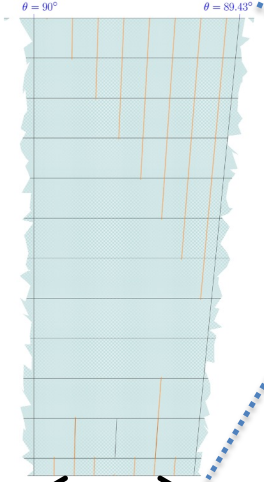
→ O(200k) read-out cells – particle flow reconstruction possible, but not optimal

Noble-Liquid Calo: How to Achieve High Granularity?

Realize electrodes as multi-layer PCBs (*H*=1.2mm thick), 5 to 7 layers

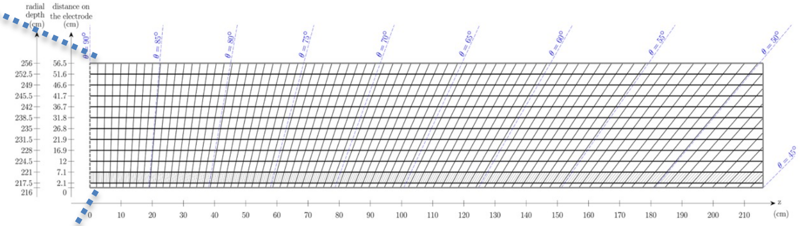
- HV and read-out
- Signal traces (width w_t) in dedicated signal layer connected with vias to the signal pads
- Traces shielded by ground-shields (width w_s , dist. h_s) forming 50Ω – 80Ω transmission lines
  - Optimizing between 0, 1 or 2 shield layers
- → capacitance between shields and signal pads C_s will add to the detector capacitance via the gap C_d
- → $C_{cell} = C_s + C_d \approx 25 – 300\text{pF}$
- The higher the granularity the more shields are necessary → C_s increases, C_d decreases (smaller cells)

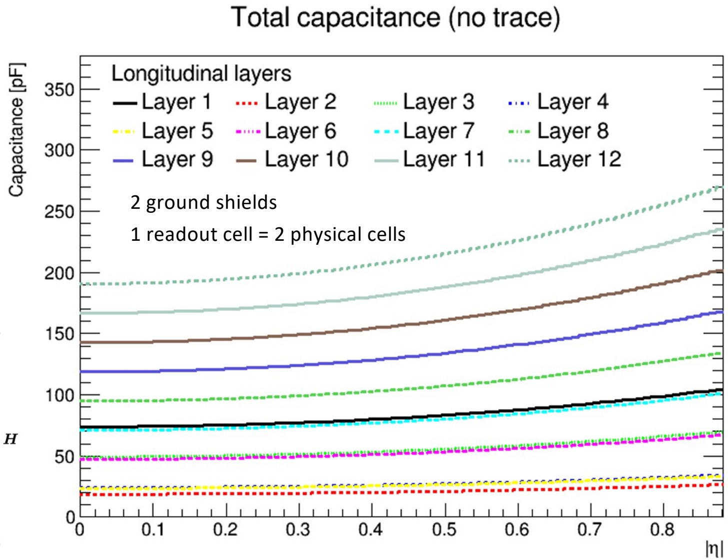
One 'theta tower'



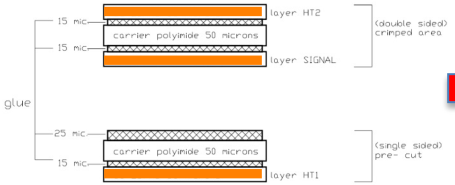
Scale 10:1

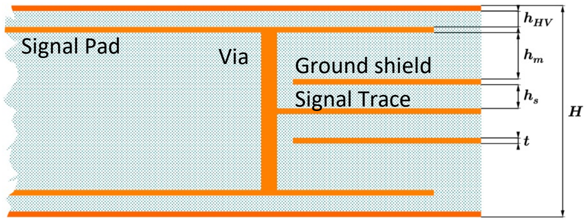
Multi-layer read-out electrode for FCC





ATLAS electrode





In principle any granularity realisable → cost in cross-talk and noise → careful optimization!

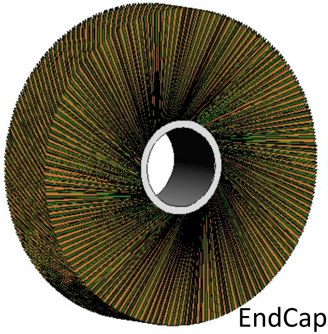
High Granularity Noble-Liquid Calorimeter

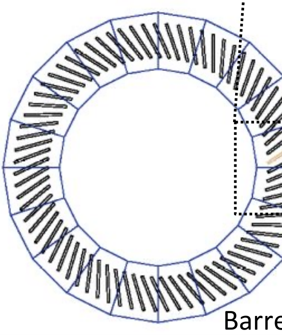
Baseline design

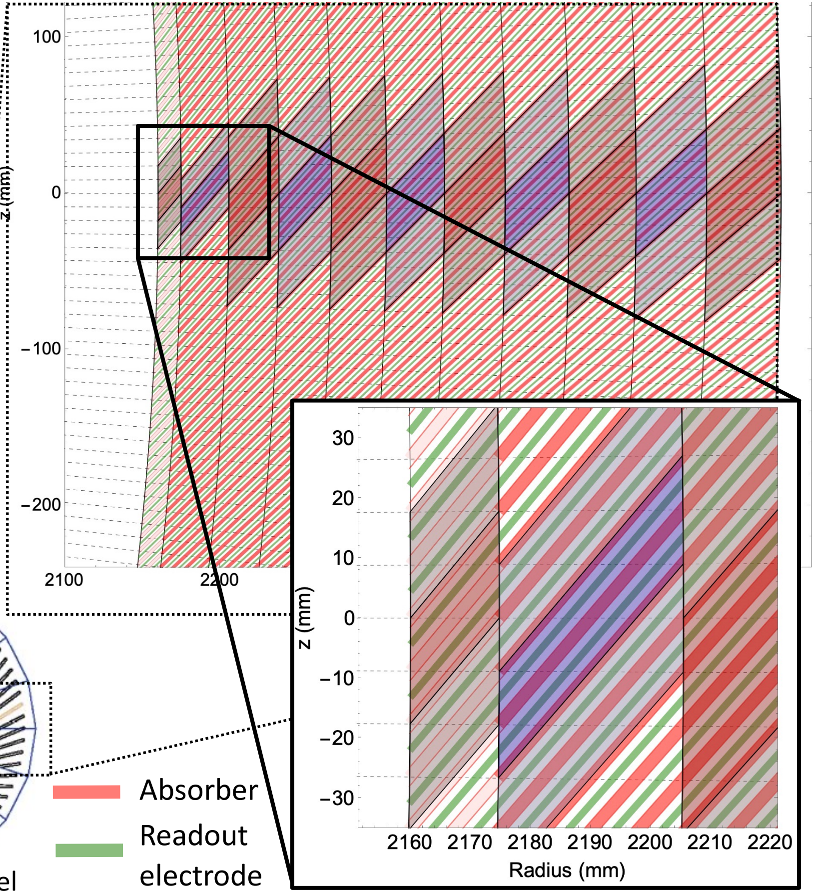
- 1536 straight inclined (50.4^o) 1.8mm Pb absorber plates
- R_i=216cm, R_o=256cm (small adjustments possible/probable)
- Multi-layer PCBs as readout electrodes
- 1.2 – 2.4mm LAr gaps
- 40cm deep (≈ 22 X_0)
- Segmentation:
  - $\Delta\theta$ = 10 (2.5) mrad for regular (1st comp. strip) cells,
  - $\Delta\phi$ = 8 mrad
  - → cell size in strips: 5.4mm x 17.8mm x 30mm
- 11 longitudinal compartments
- Implemented in FCC-SW Fullsim
- Exact radius and lateral and longitudinal segmentation subject to further optimization!

Possible Options

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

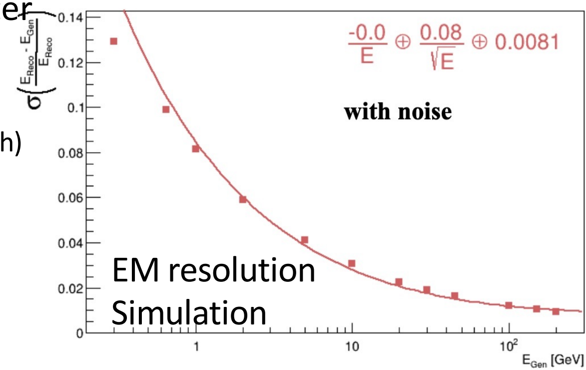






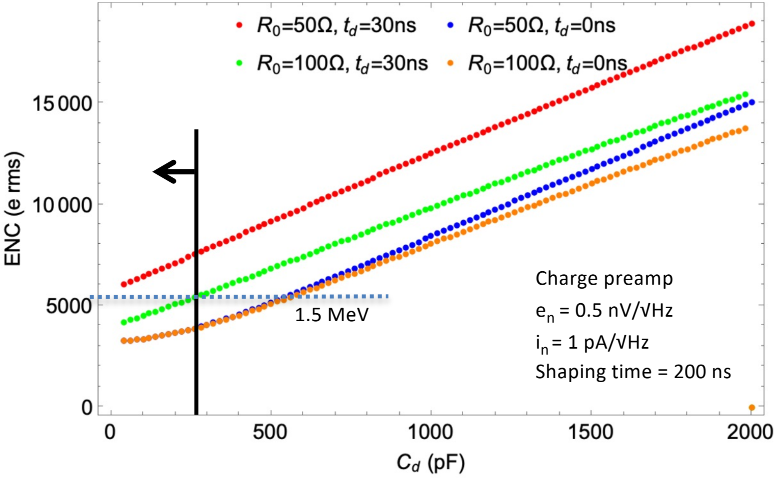
Challenges: Resolution, Noise and Crosstalk

- **Goal: EM resolution** with sampling term of 8-10% or better
  - Further **optimization** under study
    - Increasing sampling fraction,
    - Different absorber geometries (increasing thickness with depth)
    - Other active material (LAr/LKr)



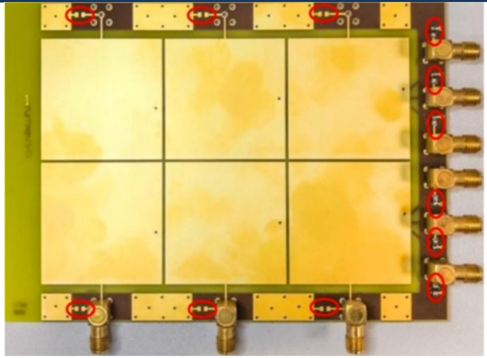
- **Noise vs cross-talk challenge:** traces need to be shielded to minimize cross-talk → grounded shields increase detector capacitance and hence noise → need to find best compromise – **prototype electrode produced & measured**
  - **Noise** of < 1.5 MeV per cell for warm electronics and transmission lines of R_0 = 100 Ω and τ = 200 ns ($C_d \leq 250$ pF)
    - → **MIP S/N > 5** reached for all layers using **warm electronics**
    - **With cold electronics noise** can be **further improved** substantially

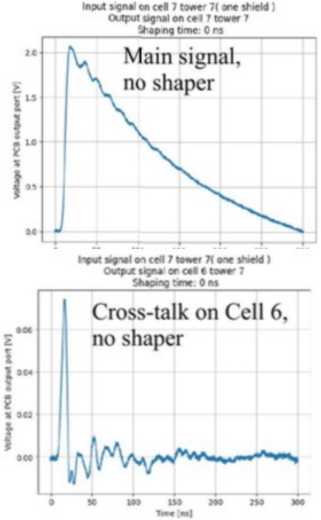
Noise vs detector capacitance

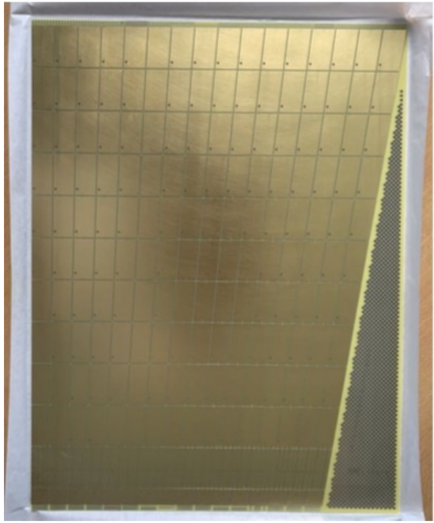


Prototype Electrodes

- **Small Scale Prototype Electrode** (IJCLab)
  - Detailed measurements of cell properties and cross-talk effects
    - Frequency behaviour
    - Good overall agreement with simulations on large frequency range
- **Larger Scale Prototype Electrode** (CERN)
  - 1:1 scale θ chunk: 16 towers with different layouts
    - Electrical tests with function generator, scope and software shaper
    - Sub-percent cross-talk easily achievable with > 50 ns shaping
- **New Prototypes Planned at IJCLab and CERN**

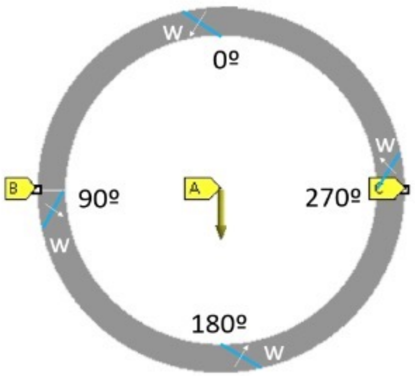




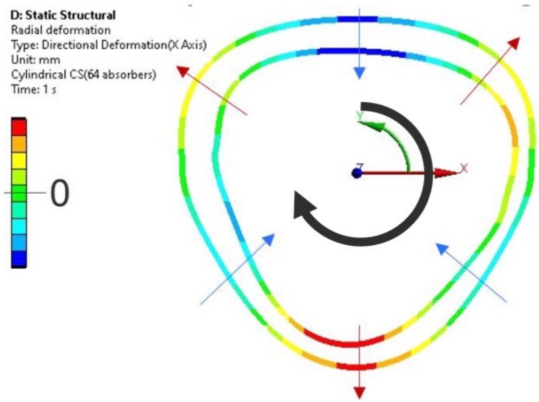


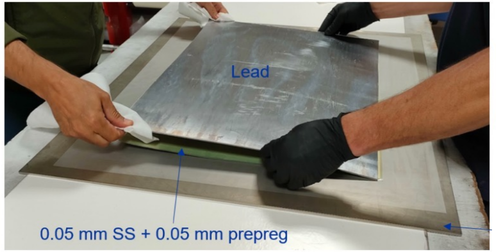
Noble-Liquid Calorimeter – Mechanical Studies

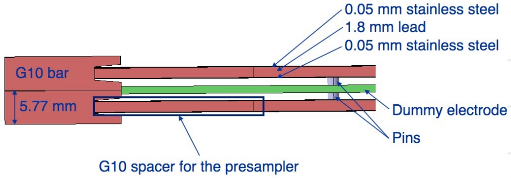
- Started to model **full barrel calorimeter**
- Defining **inner and outer rings** to hold barrel calorimeter
- Defining **spacers** between absorbers and electrodes – optimizing distance
- In order to verify assumed rigidity of absorbers building **feasibility prototype** and perform thermo-mechanical tests

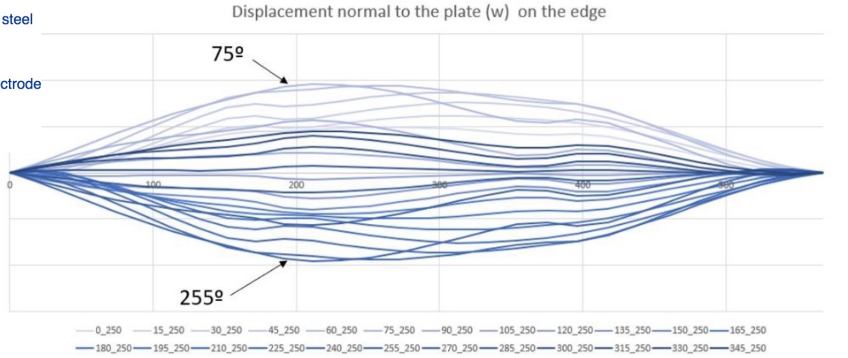


Radial and circumferential displacement of the rings



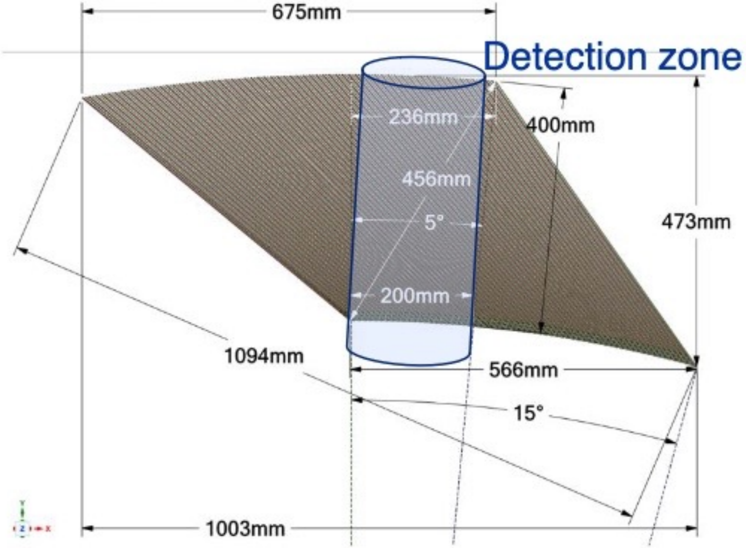




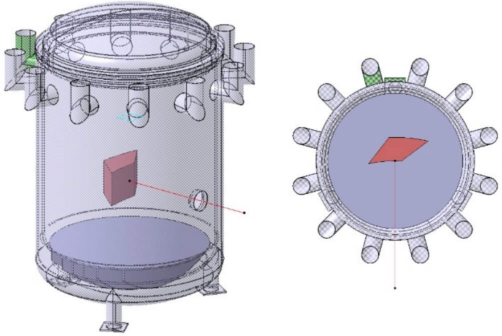


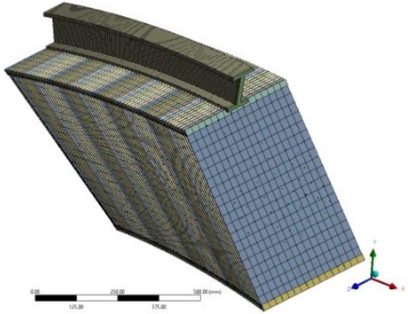
Noble-Liquid Calorimeter – Testbeam Module

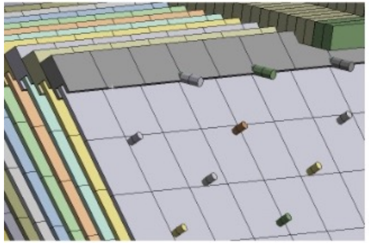
- Mechanical design of **testbeam module** (64 absorbers) has started
- **Finite element calculations** including
  - Rings and G10 bars
  - Absorbers and electrodes as shell (2D) elements using layers
  - Distance pins
  - Six M5 beams join electrodes and absorbers in each side (inner-outer)
- In parallel work on finding/adapting **testbeam cryostat**
- Plan to **produce testmodule** in the next four years

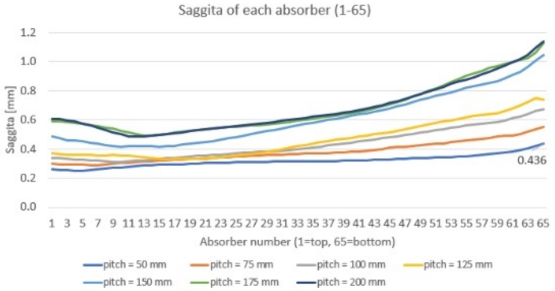


The cryostat available to make the test beam is the CRRP-00563.



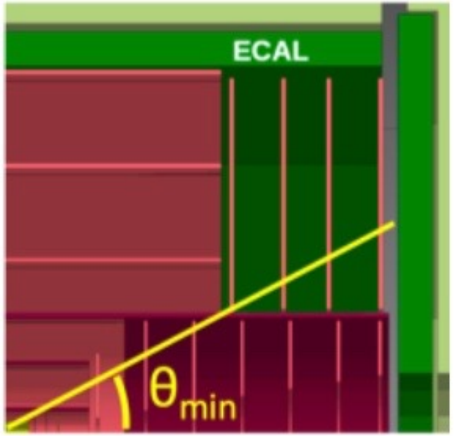




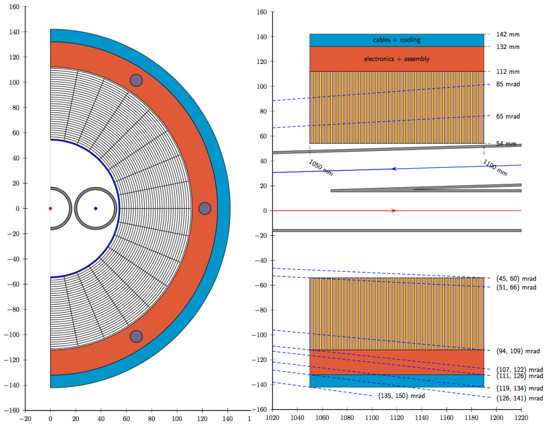


FCC-ee: Center of Mass Energy and Luminosity Measurement

- **Need to know < √s > precisely**
  - Key systematics for all mass measurements, and all EW observables.
  - FCC-ee, Z peak and WW threshold: exquisite precision on < √s > (100 keV at the Z, 300 keV at WW) thanks to quasi-continuous resonant depolarisation (RDP) measurements
    - Exploits the relation between the number of spin precessions per turn of transversely polarised e+/- and their energy
    - Very powerful, unique to circular machines - allows a meas. of M_Z to 100 keV



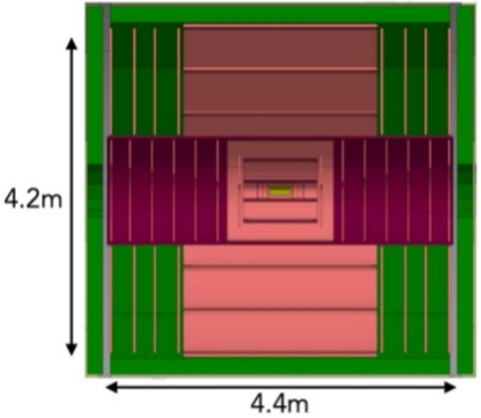
- **Luminosity Measurement: ambitious goals:**
  - Absolute luminosity measurement to $\lesssim 10^{-4}$
  - Relative luminosity (energy-to-energy point) to $\lesssim 10^{-5}$
  - Inter-channel normalisation (e.g. μμ/multi-hadronic) to $\lesssim 10^{-5}$
  - Luminosity measurement using low-angle BhaBha scattering, large angle $e^+e^- \rightarrow \gamma\gamma$ and Z → ll
    - Requiring extremely high precision on acceptance boundaries
    - O(1 μm) and O(50μrad)! → Very challenging!!

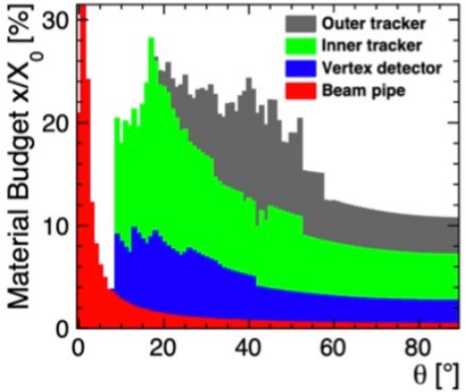


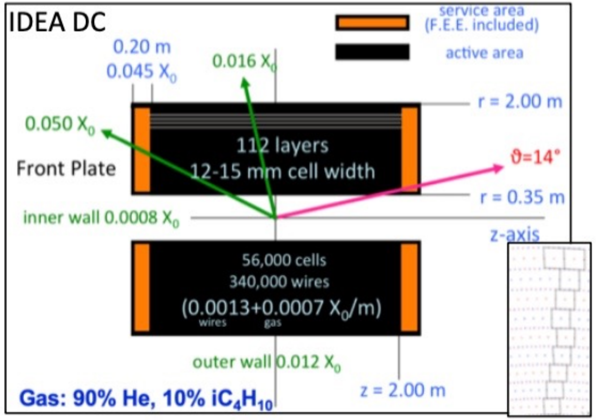
Tracking for FCC-ee

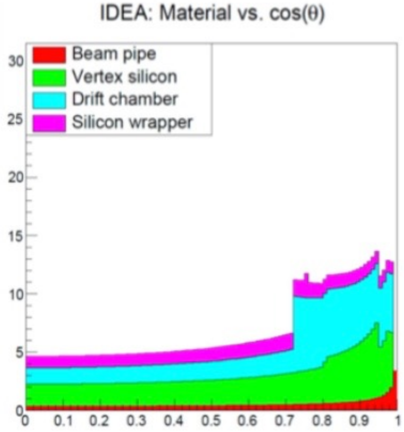
Two solutions under study

- **CLD:** All silicon pixel (innermost) + strips
  - Inner: 3 (7) barrel (fwd) layers (1% X_0 each)
  - Outer: 3 (4) barrel (fwd) layers (1% X_0 each)
  - Separated by support tube (2.5% X_0)
- **IDEA:** Extremely transparent Drift Chamber
  - GAS: 90% He – 10% iC_4H_{10}
  - Radius 0.35 – 2.00 m
  - Total thickness: 1.6% of X_0 at 90°
    - Tungsten wires dominant contribution
  - Full system includes Si VTX and Si "wrapper"
- **What about a TPC?**
  - Very high physics rate (70 kHz), field limited to 2T
  - Considered for CEPC, but having difficulties...



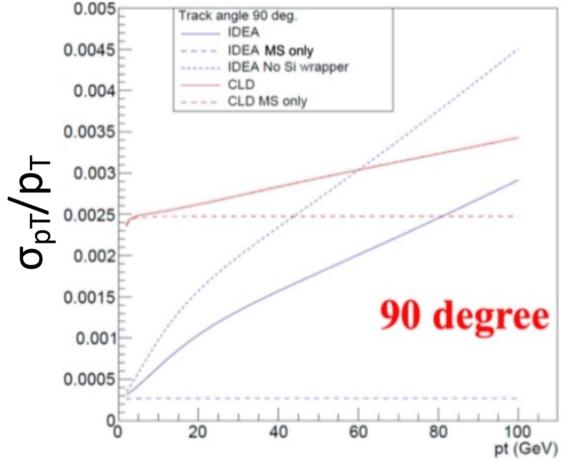


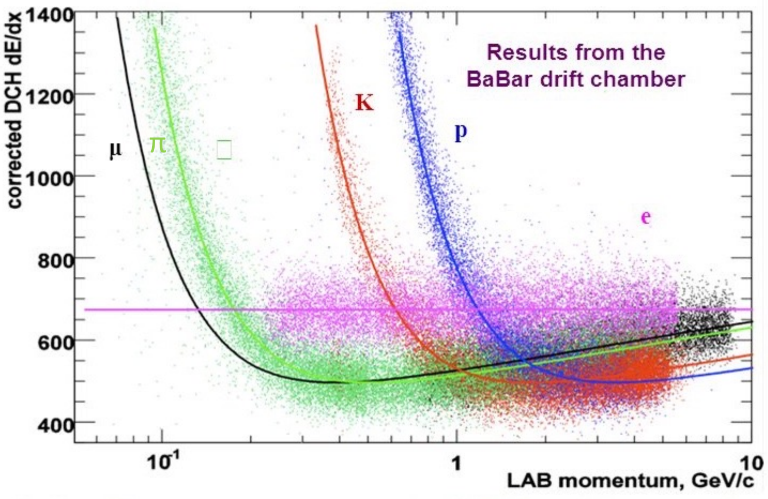


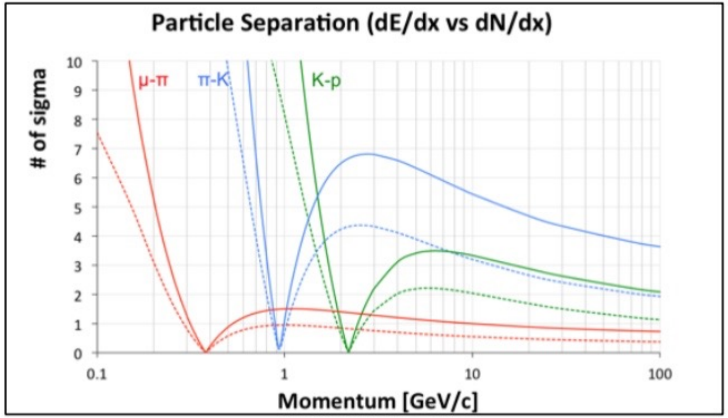


Drift Chamber

- **Drift chamber (gaseous tracker) advantages**
  - Extremely transparent: minimal multiple scattering and secondary interactions
  - Continuous tracking: reconstruction of far-detached vertices
    - K^0_S , Λ, BSM long-lived particles (LLPs)
  - Particle separation via dE/dx or cluster counting (dN/dx)
    - dE/dx much exploited in LEP analyses



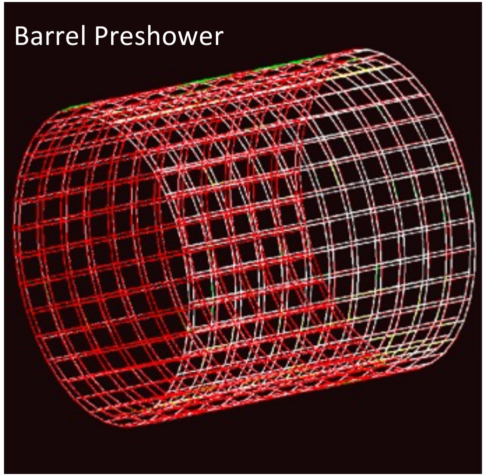




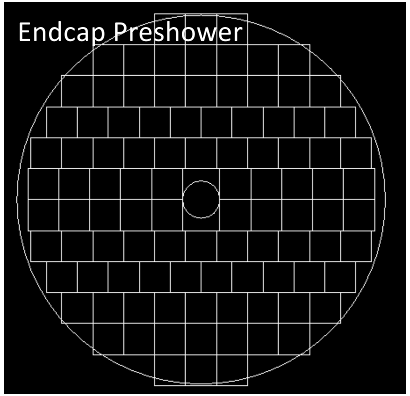
IDEA: Preshower and Muon Detector

Preshower Detector

- High resolution before the magnet to improve cluster reconstruction
- Efficiency > 98%
- Space Resolution < 100 mm
- Mass production
- Optimization of FEE channels/cost



Similar design for the Muon detector



Similar design for the Muon detector

Muon Detector

- Identifies muons and detects LLPs
- Efficiency > 98%
- Space Resolution < 400 mm
- Mass production
- Optimization of FEE channels/cost

Detector technology:

μ-RWELL, 50x50 cm^2 2D tiles to cover more than 4330 m^2

- **Preshower:**
  - pitch = 0.4 mm
  - FEE capacitance = 70 pF
  - 1.5 million channels
- **Muon Detector:**
  - pitch = 1.5 mm
  - FEE capacitance = 270 pF
  - 5 million channels

IDEA: µ-RWELL Technology

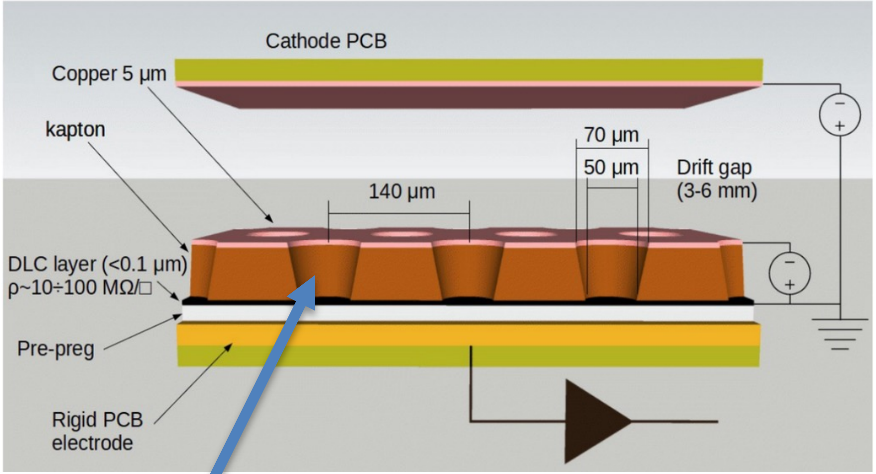
The µ-RWELL is composed of only two elements:

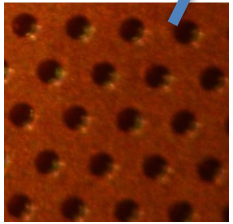
- µ-RWELL_PCB
- drift/cathode PCB defining the gas gap

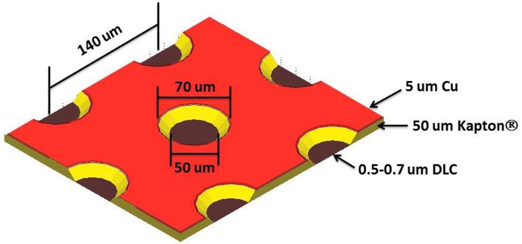
µ-RWELL_PCB = amplification-stage ⊕ resistive stage ⊕ readout PCB

µ-RWELL operation:

- A charged particle ionises the gas between the two detector elements
- Primary electrons drift towards the µ-RWELL_PCB (anode) where they are multiplied, while ions drift to the cathode
- The signal is induced capacitively, through the DLC layer, to the readout PCB
- HV is applied between the Anode and Cathode PCB electrodes
- HV is also applied to the copper layer on the top of the kapton foil, providing the amplification field







(*) G. Bencivenni et al., "The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD", 2015_JINST_10_P02008)