New detectors for future accelerators challenges: the Allegro detector concept

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Particle Physics: Where do we want to go ?

Dear Santa Claus,

We have been good these past decades. Please could you now bring us

- *a dark matter candidate*
- *an explanation for the fermion masses*
- *an explanation of matter-antimatter asymmetry*
- *an axion, to solve the strong CP problem*
- *a solution to fine tuning the EW scale*
- *a solution to fine tuning the cosmological constant*

Thank you, Particle Physicists

ps: please, no anthropics

Shamelessly stolen from Gavin Salam

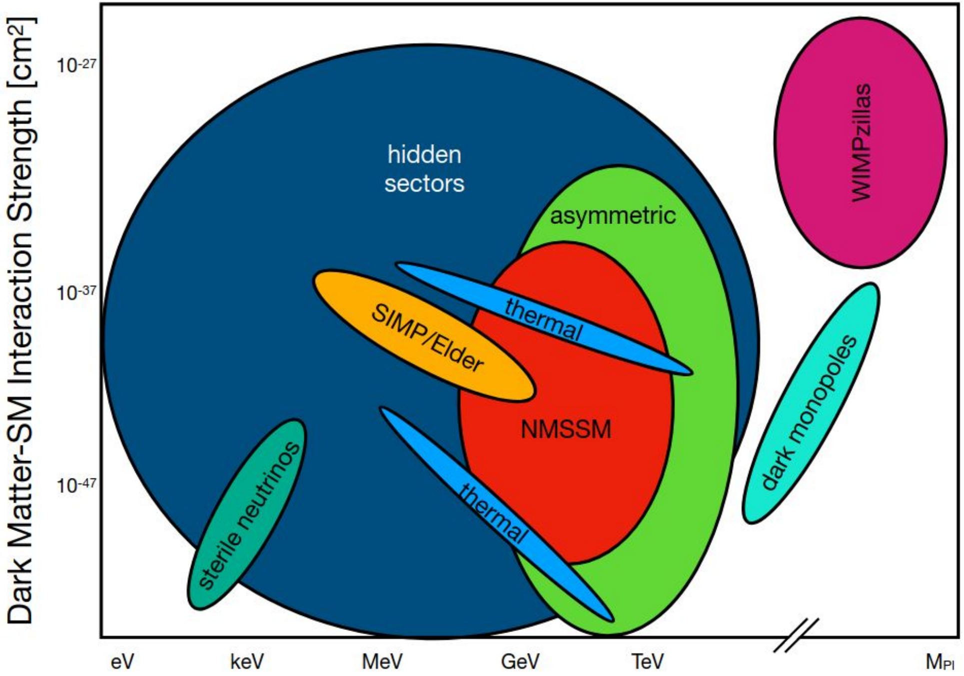
The SM is a huge success…

but

we have been so far unlucky in getting answers to many questions !

Dark Matter Landscape

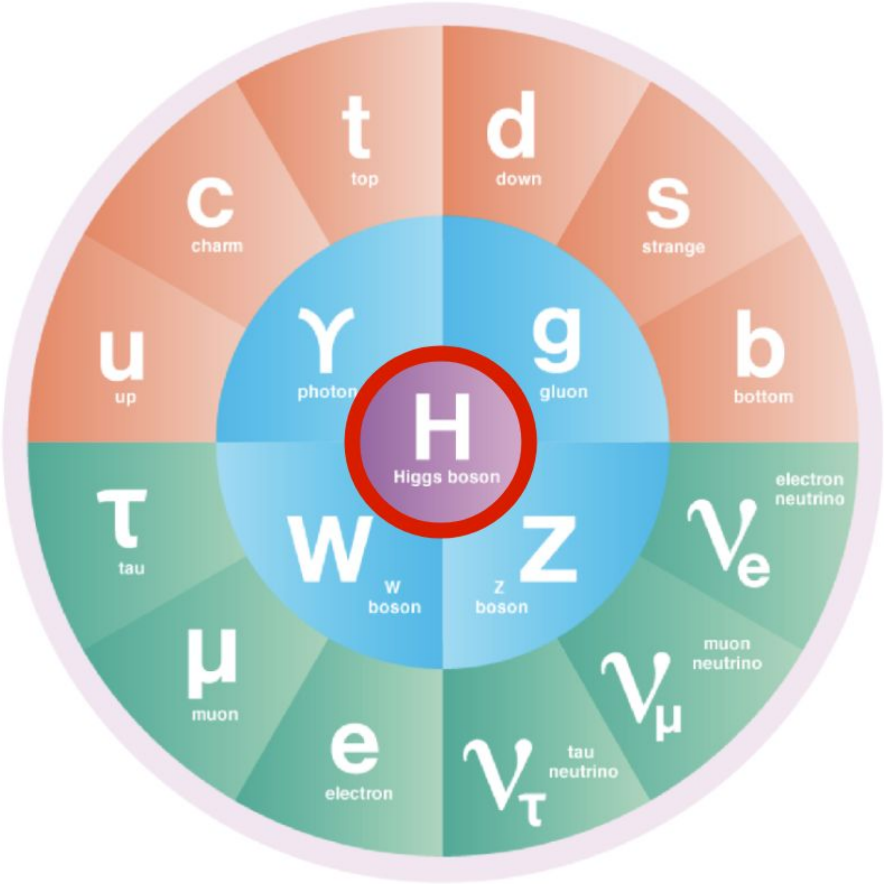
Snowmass Dark Matter Report, [2209.07426]



30 orders of magnitude in interaction strength

30 orders of magnitude in mass

Higgs Boson to the Rescue

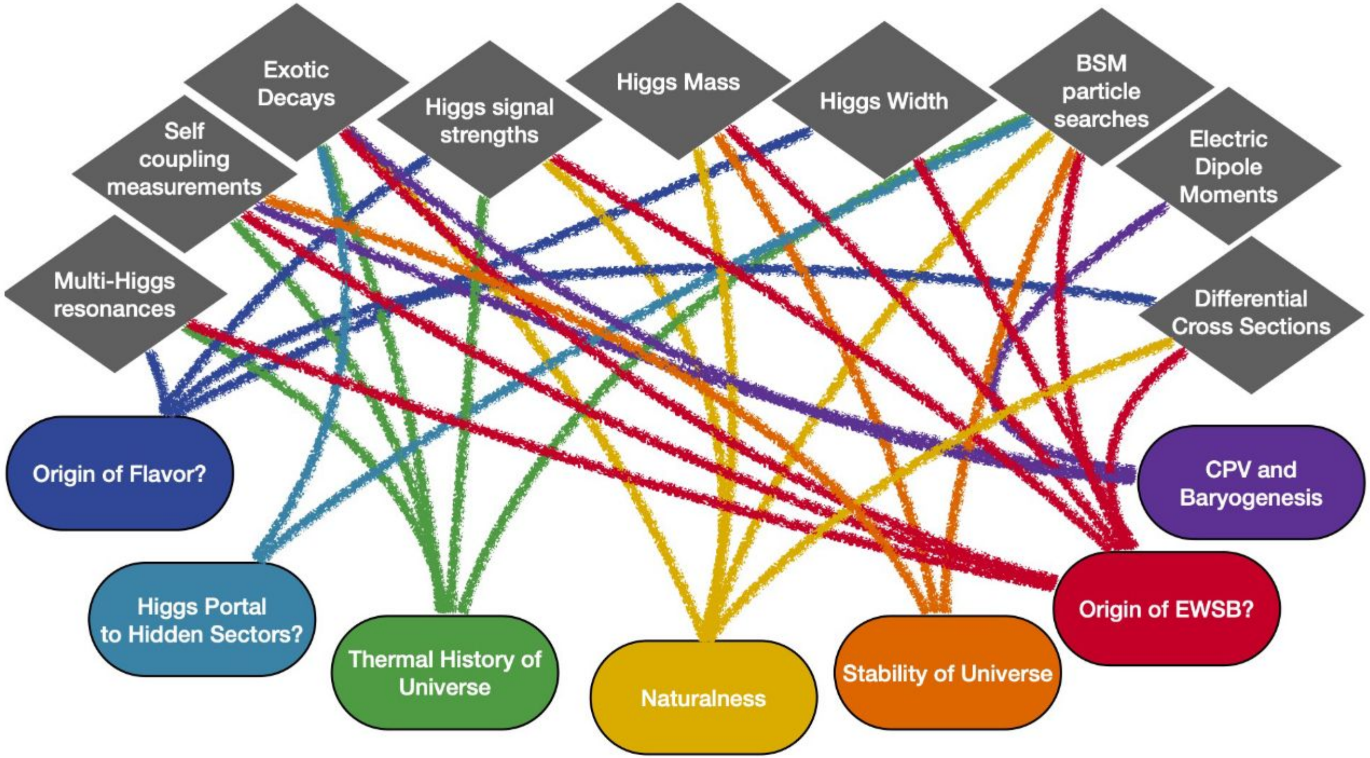


But we have been lucky in discovering a 125 GeV Higgs boson

It opens a door to the most mysterious part of the Standard Model

The Higgs Landscape

Links to many mysteries of the SM !



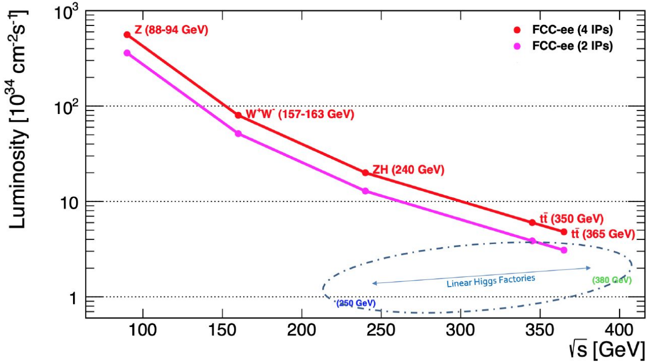
The next collider project should be an e^+e^- Higgs Factory (ESPP 2020)

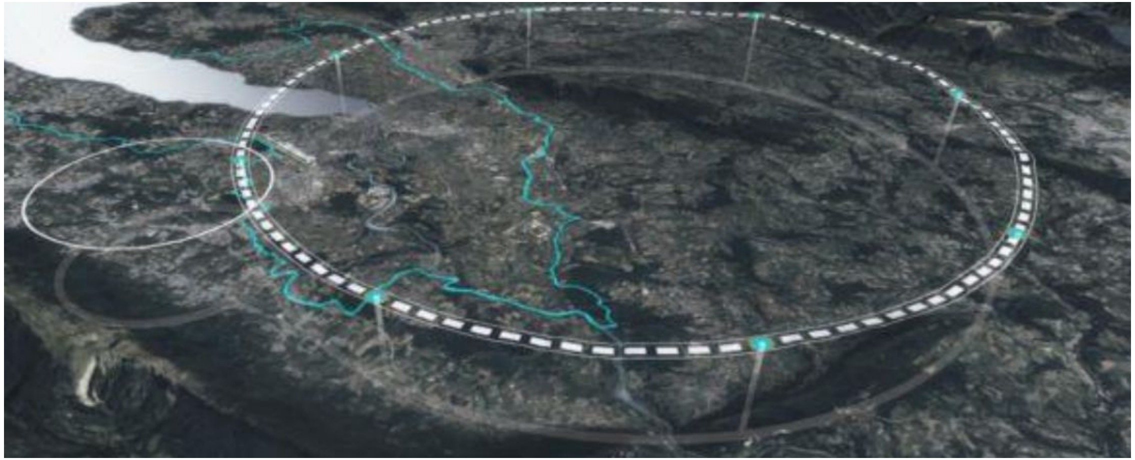
Desirable features of a worldwide HEP project ?

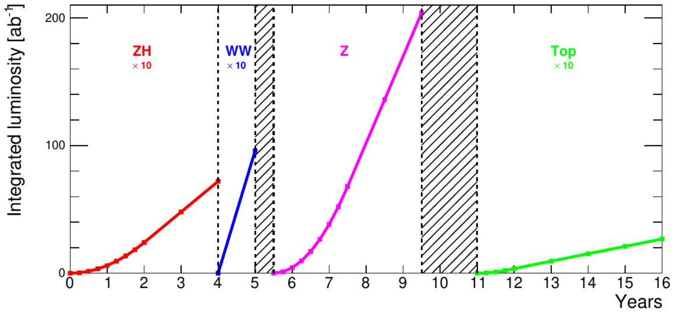
- An important target that is guaranteed to be reached (no-lose theorem)
- Exploration into the unknown by a significant factor in energy
- Major progress on a broad array of particle physics topics
- Likelihood of success, robustness (incl. multiple experiments)
- Cost-effective construction & operation, low carbon footprint

The FCC-ee project

- 90km circular collider at CERN: e^+e^-, then pp in long-term future
- High Luminosity: LEP every 2 minutes at Z pole
- 4 Interaction Points
- Feasibility Study being concluded
- Post-HL-LHC era: start in 20 years







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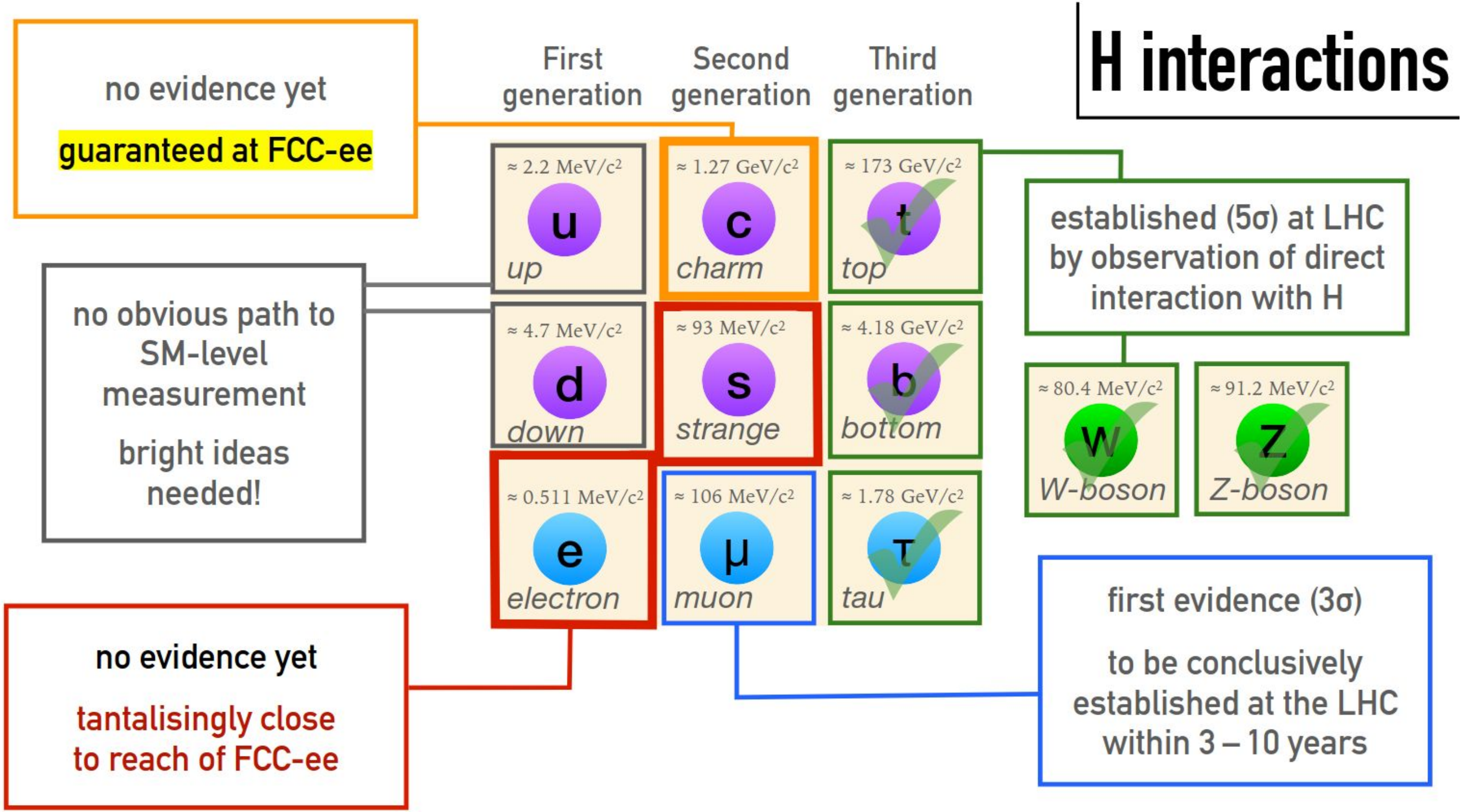
Studying the Higgs as a no-lose theorem



Studying the Higgs as a no-lose theorem

Electron Yukawa: does the Higgs mechanism explains chemistry ?

$$a_0 = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} = \frac{\hbar}{m_e c \alpha} \propto \frac{1}{y_e}$$

Higgs interactions and Higgs potential

$$\mathscr{L} = y H \psi \bar{\psi} + \mu^2 |H|^2 - \lambda |H|^4 - V_0$$

flavour (y) *naturalness* (μ^2) *stability* (λ)

cosmological constant (V_0)

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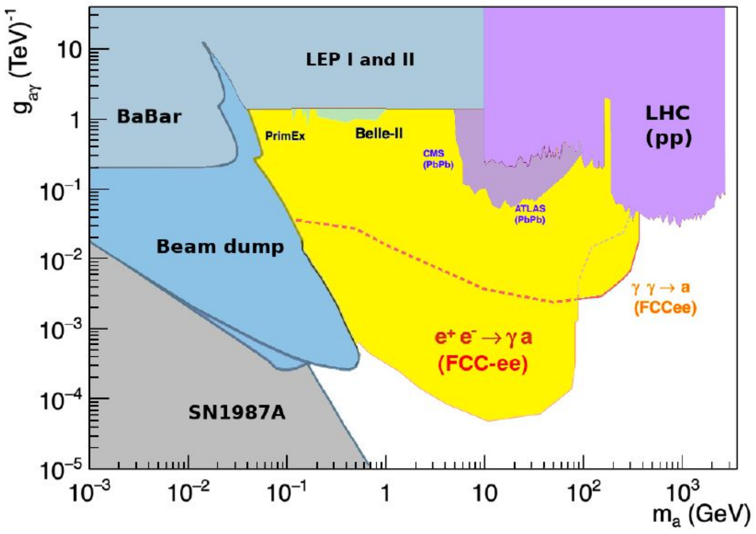
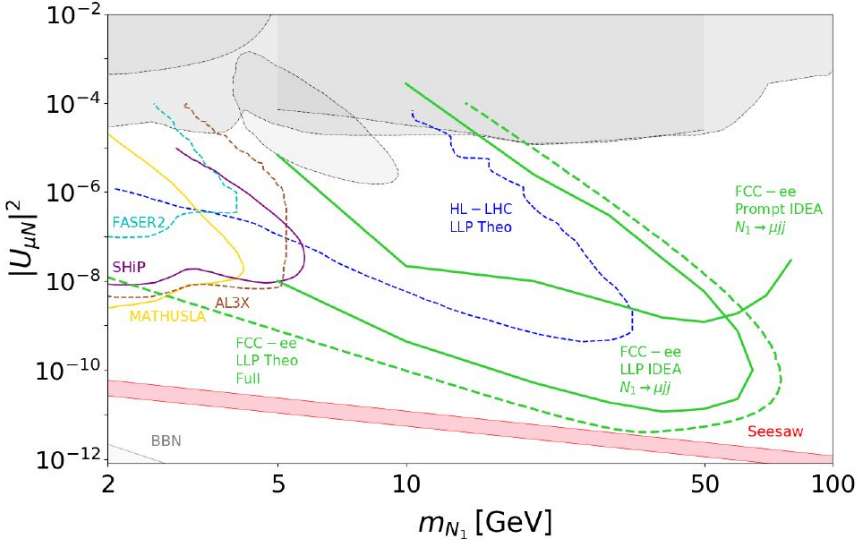
Exploring into the unknown

Complementary signatures wrt HL-LHC

Axions-like Particles



Heavy Neutral Leptons



- + Precision measurements will probe scales up to 40 TeV (through EFTs)

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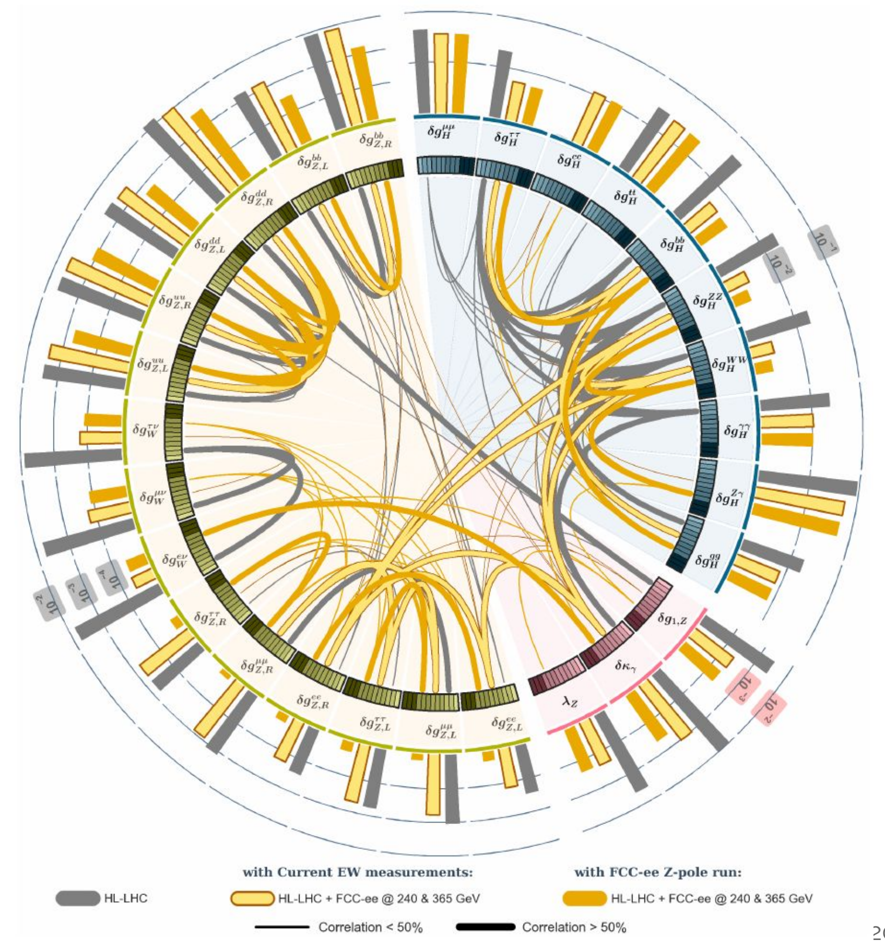
Complementarity of running energies

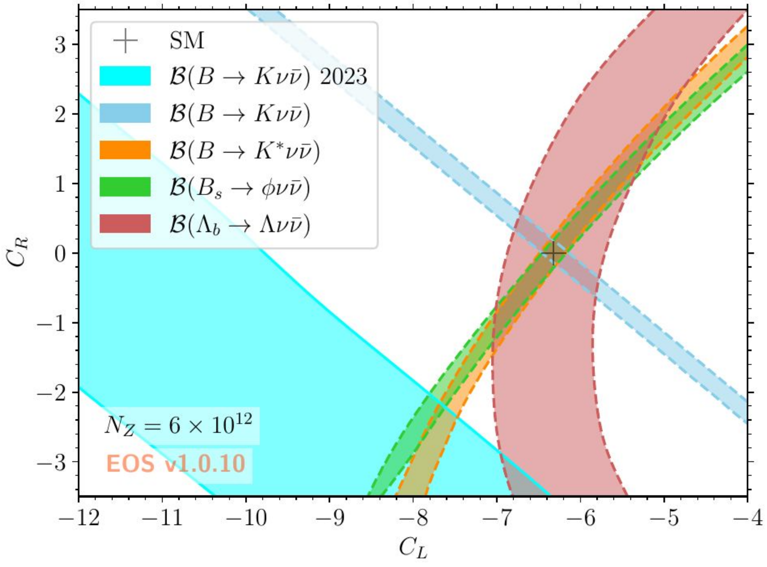


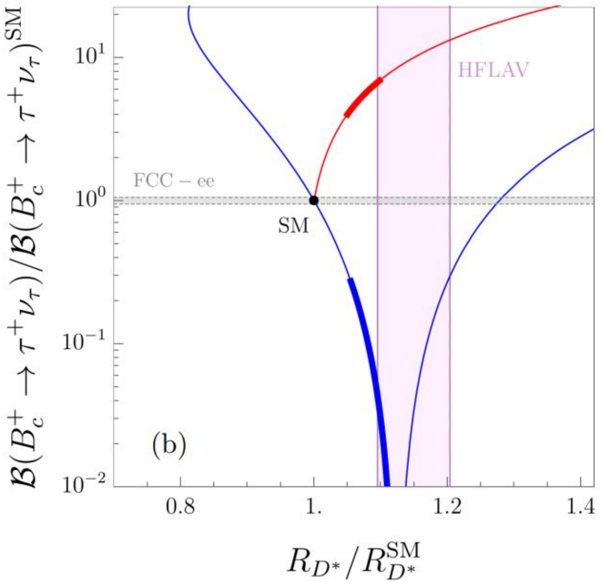
Expected constraints on Higgs/aTGC/EW EFT parameters

FCC-ee: a Flavour factory

10× bb and cc pairs wrt Belle 2 !

Particle species	B^0	B^+	B^0_s	Λ_b	B^+_c	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	370	370	90	80	2	720	200





The ultimate EW precision

A real challenge for theory calculations !

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
$\sin^2\theta_W^{eff} (\times 10^6)$	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
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
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	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
$\alpha_s(m_W^2)(\times 10^4)$	1010	±	270	**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)	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

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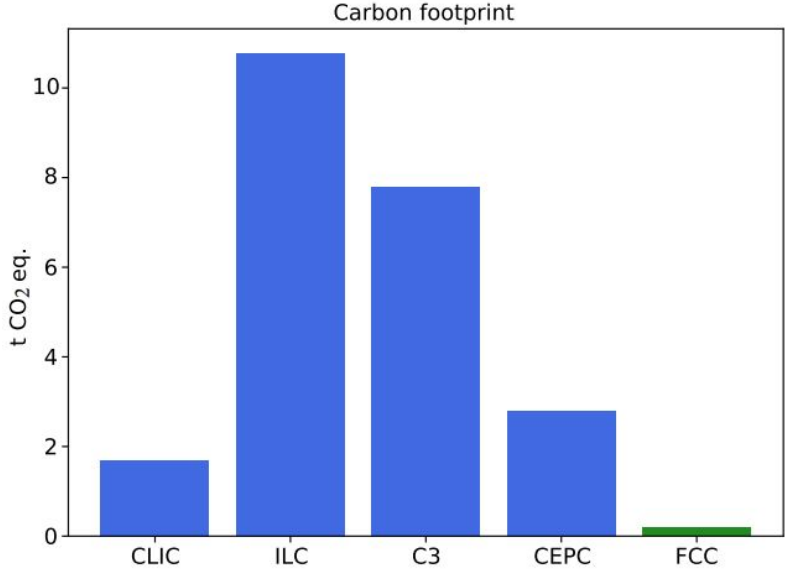
Few words on sustainability

- Among proposed Higgs Factories, FCC-ee has the lowest carbon footprint in operation
  - Fineprints apply
  - Electricity consumption of CERN during FCC-ee same as today with LHC
    - Energy-efficient klystrons, magnets
- As a large research infrastructure, it comes with potentially large impacts during construction
  - CERN takes it very seriously to reduce them as much as possible
    - e.g investigations on low-carbon concrete, use of excavated soil…
  - Tunnel construction amortized over 50+ years

Carbon footprint / Higgs boson



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Outstanding Physics ⇒ Strong Requirements on Detectors

Higgs
factory

m_H, σ, Γ_H
self-coupling
H→ bb, cc, ss, gg
H→inv
ee→H
H→bs, ..

Top

m_{top}, Γ_{top}, ttZ, FCNCs

Flavor
"boosted" B/D/τ factory:

CKM matrix
CPV measurements
Charged LFV
Lepton Universality
τ properties (lifetime, BRs..)

$B_c \to \tau \nu$
$B_s \to D_s K/\pi$
$B_s \to K^* \tau \tau$
$B \to K^* \nu \nu$
$B_s \to \varphi \nu \nu$ …

QCD - EWK
most precise SM test

m_Z , Γ_Z , Γ_{inv}

$\sin^2\theta_W$, R^Z_ℓ , R_b, R_c

$A_{FB}{}^{b,c}$, τ pol.

α_S ,

m_W, Γ_W

BSM
feebly interacting particles

Heavy Neutral Leptons (HNL)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

Excellent tracking
Jet energy resolution
at high energies

Excellent tracking /
energy resolution /
PID
at low energies

Small systematics

Versatile detector

A lot of fun for all detectors

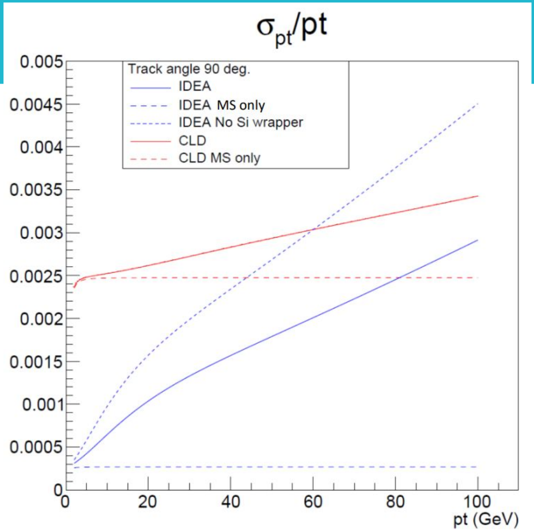
		Aggressive	Conservative	Comments
Beam-pipe		$\frac{X}{X_0} < 0.5\%$	$\frac{X}{X_0} < 1\%$	$B \to K^* \tau\tau$
Vertex		$\sigma(d_0) = 2 \oplus \frac{15}{p\sin^{3/2}\theta}\mu\mathrm{m}$ $\frac{X}{X_0} < 1\%$	-	$B \to K^* \tau\tau$ R_b, R_c
		$\delta L = 5\mathrm{ppm}$	-	$\delta\tau_\tau < 10$ ppm
Tracking		$\frac{\sigma_p}{p} < 0.1(0.2)\%$ at $\sqrt{s} = 90$ (240) GeV	-	$\delta M_H = 4$ MeV $\delta\Gamma_Z = 20$ keV $\mathrm{Z} \to \tau\mu$
		$\sigma_\theta < 0.1$ mrad	-	$\delta_{\mathrm{BES}} < 0.2\%$ for $\delta\Gamma_Z = 40$ keV
ECAL		$\frac{\sigma_E}{E} = \frac{3\%}{\sqrt{E}}$	$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}}$	$\mathrm{Z} \to \nu_e\bar{\nu}_e\gamma$
		$\Delta x \times \Delta y = 2 \times 2$ mm^2	$\Delta x \times \Delta y = 5 \times 5$ mm^2	τ polarisation boosted π^0 decays bremsstrahlung recovery
		$\delta z = 100$ µm, $\delta R_{\mathrm{min}} = 10$ µm (at 20°)	-	alignment tolerance for $\delta\mathcal{L} = 10^{-4}$ with $\gamma\gamma$ events
HCAL		$\frac{\sigma_E}{E} = \frac{30\%}{\sqrt{E}}$	$\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}}$	$\mathrm{H} \to s\bar{s}$, $c\bar{c}$, gg, invisible HNLs
		$\Delta x \times \Delta y = 2 \times 2$ mm^2	$\Delta x \times \Delta y = 30 \times 30$ mm^2	$\mathrm{H} \to s\bar{s}$, $c\bar{c}$, gg
Muons		low momentum (p < 1 GeV) ID	-	$B_s \to \nu\bar{\nu}$
Particle ID		3-σ K/π separation up to $p = 30$ GeV	-	$\mathrm{H} \to s\bar{s}$ $b \to s\nu\bar{\nu}$ ...
LumiCal		tolerance $\delta z = 100$ µm, $\delta R_{\mathrm{min}} = 1$ µm acceptance 50-100 mrad	-	$\delta\mathcal{L} = 10^{-4}$ target (Bhabha)
hermeticity		-	-	$\nu\bar{\nu}H$, H$\to$ invisible

Tracking performance

- Momentum resolution
  - Avoid large contribution from MS: the lighter, the better
- Flavour tagging: vertex detector
  - Closer to IP
  - Lighter
  - Smaller pixels

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

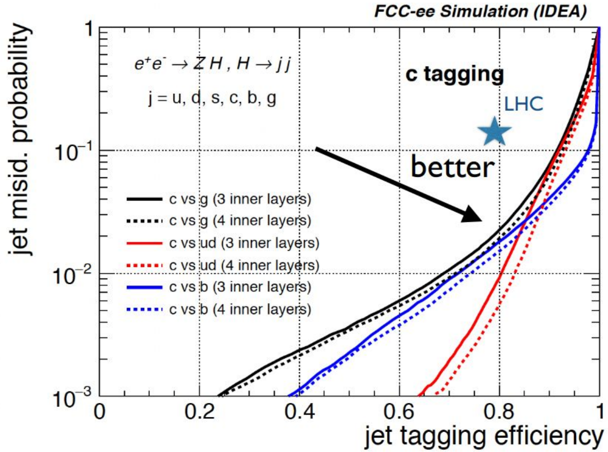
$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\, B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\,\sin\theta}}$$

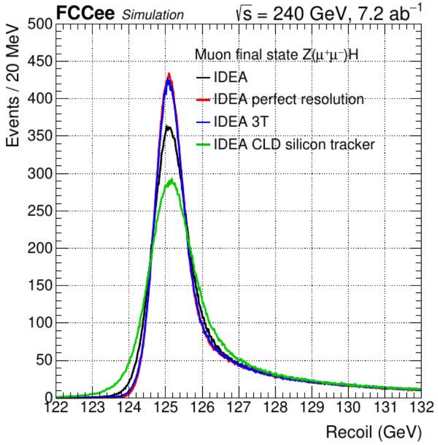


$$\sigma_{d_0} = a \oplus \frac{b}{p\sin^{3/2}\theta}$$

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

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

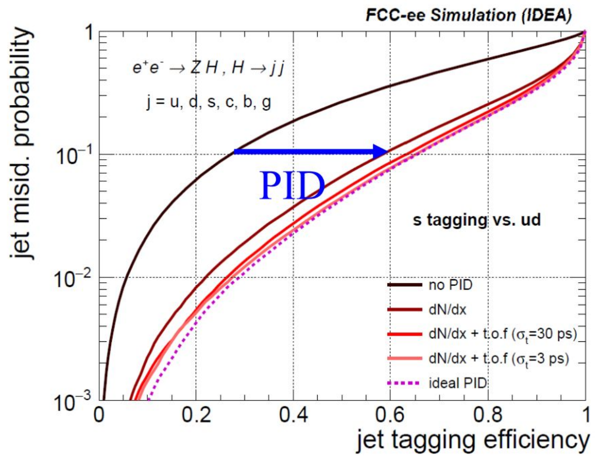


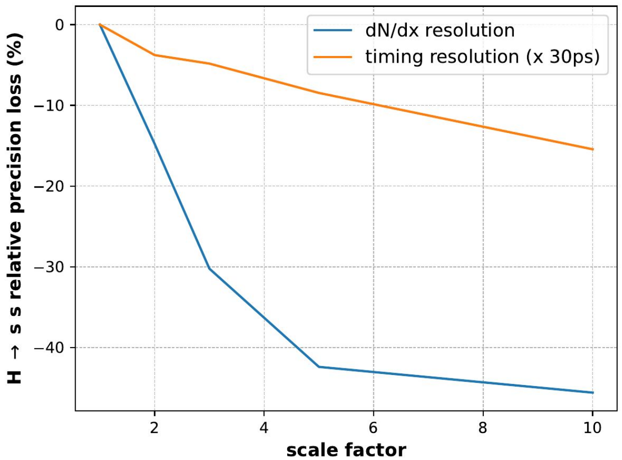


Why PID ?

A must-have to complete the full HET programme

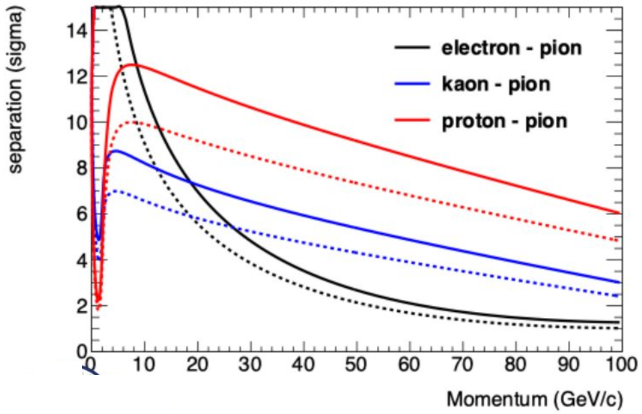
- Higgs physics
  - $H \to ss$ sensitivity driven by strange-tagging perf, depends a lot on PID performance
  - Flavour violating modes, e.g $H \to bs$
- SM parameters
  - Also depend on K identification / strange tagging
  - V_{ts}, V_{bs}
- B physics
  - $B^0_s \to D^{\pm}_s K^{\mp}$, $B \to K^* \nu\nu$, $B_s \to \phi\nu\nu$, ...

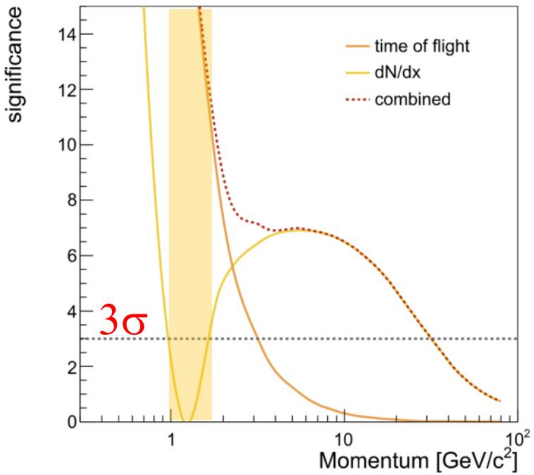


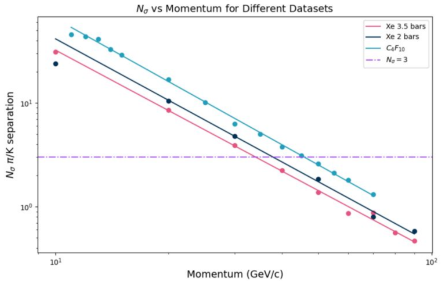


PID detectors

- Gaseous detectors
  - dE/dx or cluster counting measurements
  - Studies of TPC, Straw Tracker, Drift chamber
  - Need dedicated electronics / signal processing
- Fast detectors for time-of-flight measurements
  - Using e.g LGAD technologies
  - few ps – 10 ps resolution
  - Used in “silicon wrapper” layers after gaseous tracker, in front of calorimeter
    - Great complementarity
- Dedicated detector: ARC concept
  - 3σ K/π separation up to 45 GeV







Calorimeters for HET factories

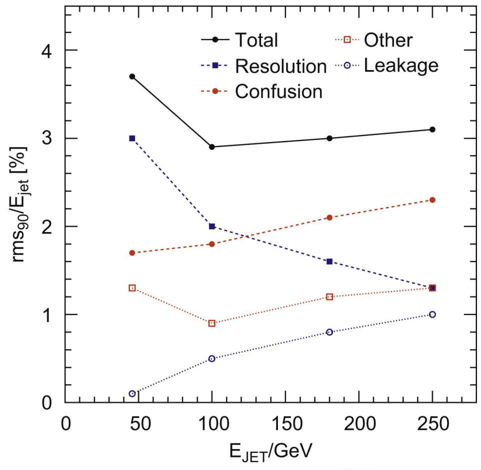
An extensive set of requirements

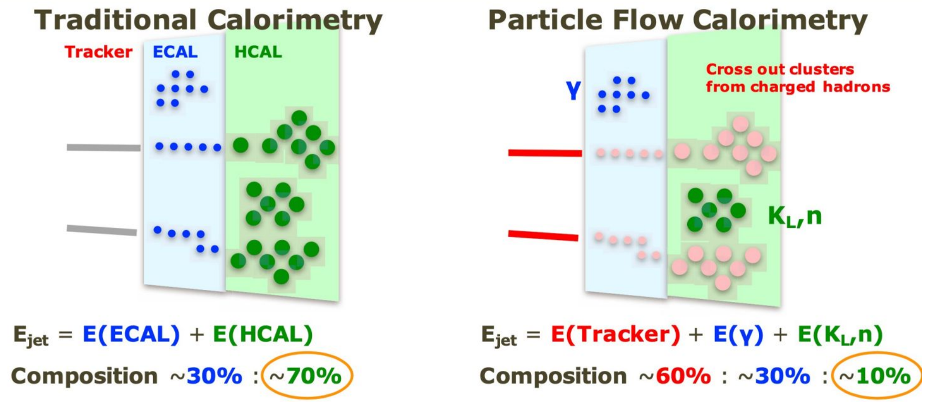
- Energy resolution: “only” for photons and neutral hadrons
  - But: ideally photons as low as 200 – 300 MeV
- Dynamic range: 200 MeV – 180 GeV
  - vs LHC: 6 TeV jets !
- Granularity: PID, disentangle showers for PFlow
  - But: how granular exactly ?
- Hermeticity, uniformity, calibrability, stability
  - Low systematics for precision measurements
  - Complex system-level engineering questions
- No need to be particularly fast
  - But: can precise timing help in reconstructing showers more accurately ?

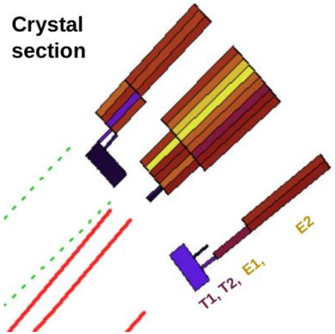
A quest for ultimate jet energy resolution

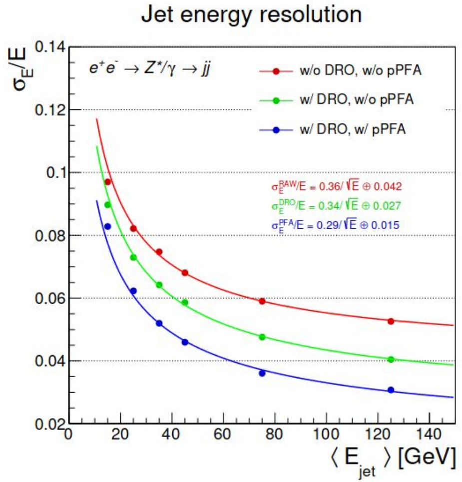
PFlow PFlow PFlow

- Target: σ(E)/E = 30%/√E (GeV)
  - Typical figure of merit: W/Z boson separation
  - Actual use: variety of hadronic measurements
- What granularity do we really need at HET Factories ?
- New calos concepts bring new ideas (crystals DR study)









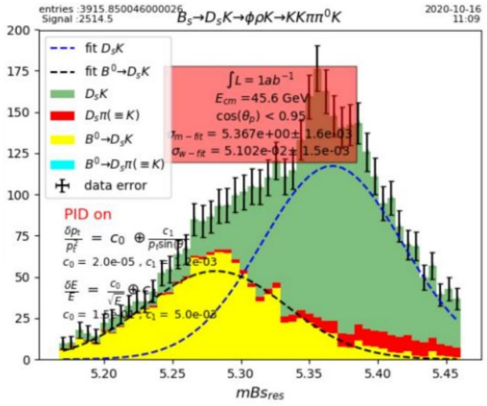
EW factories unique challenges

FCC-ee: O(10^{11}) B and τ at 45 GeV !!!

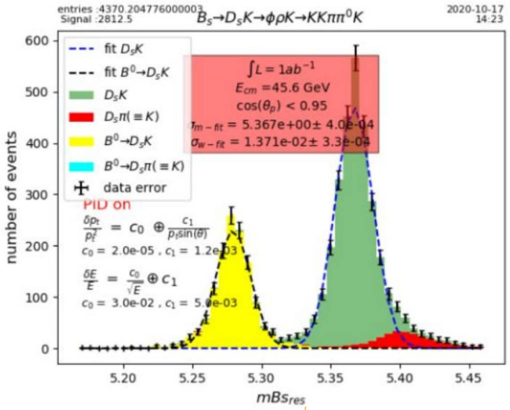
- Some physics channels require very high EM resolution

- τ physics: reconstructing the decays
  - Means π^0 reconstruction and ID
  - Count close-by π^0
  - Granularity

- BSM, e.g ALP searches
  - Photon resolution, photon pointing



15%/√E



3%/√E

Recon → / Gen ↓	$\pi^\pm \nu$	$\pi^\pm \pi^0 \nu$	$\pi^\pm 2\pi^0 \nu$	$\pi^\pm 3\pi^0 \nu$	$\pi^\pm 4\pi^0 \nu$
$\pi^\pm \nu$	**0.9560**	0.0425	0.0010	0.0003	0.0002
$\pi^\pm \pi^0 \nu$	0.0374	**0.9020**	0.0586	0.0016	0.0002
$\pi^\pm 2\pi^0 \nu$	0.0090	0.1277	**0.7802**	0.0808	0.0022
$\pi^\pm 3\pi^0 \nu$	0.0036	0.0372	0.2679	**0.5972**	0.0910

Table: Each row shows the fraction of e.g. $\tau \to \pi^\pm \nu$ decays classified as each of the considered channels

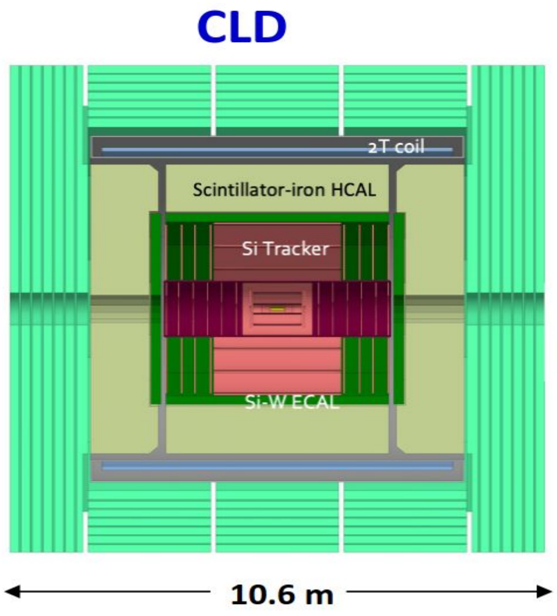
Calorimetry options

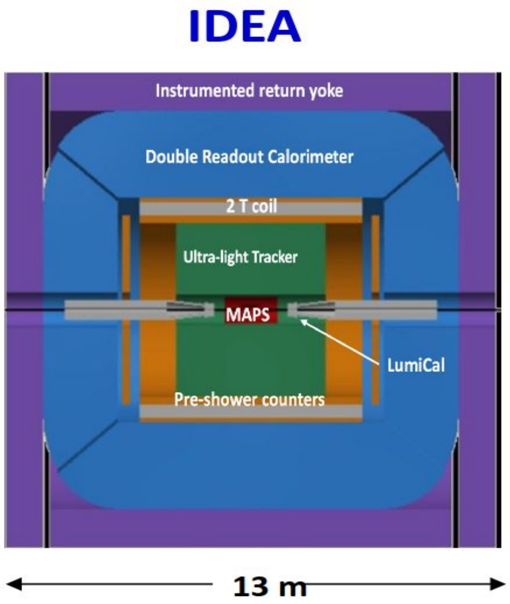
Many options on the table, for both Ecal and Hcal

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]

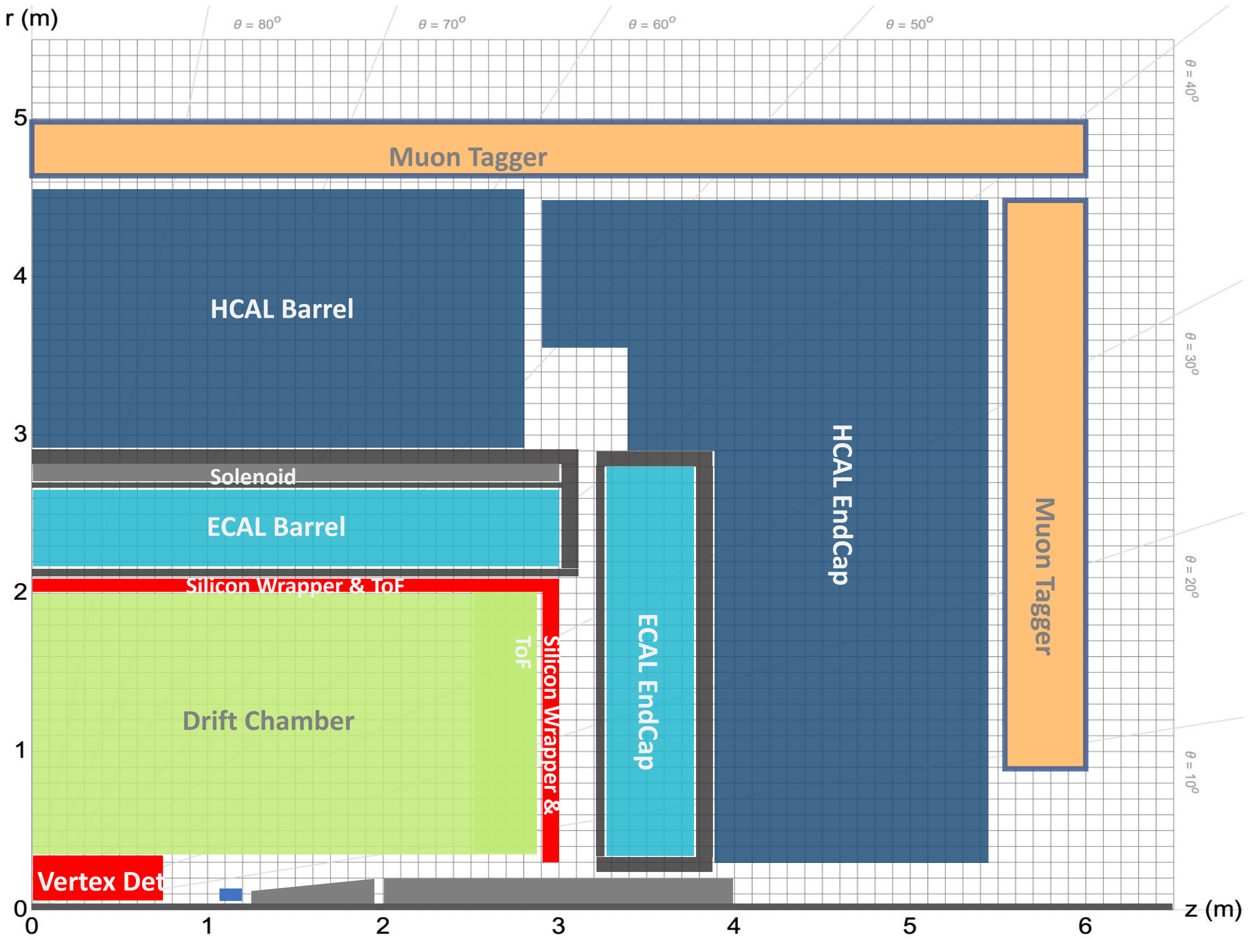
- All options feature good jet energy resolution
- Varying Ecal resolution ⇒ Highest EM resol required for B physics
- Varying segmentation: PFlow, shower shapes, cluster pointing
- Other characteristics: Operational stability, cost

FCC-ee Detector Concepts





Allegro detector concept



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

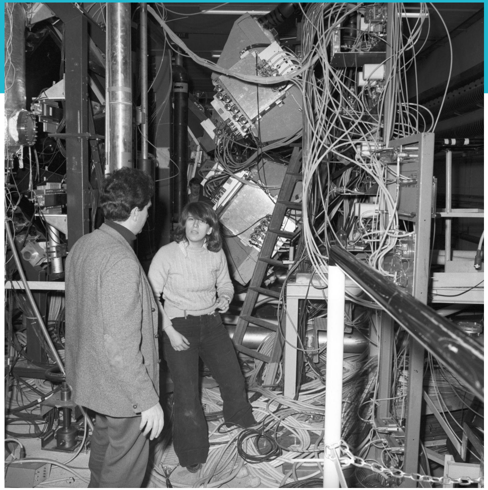
- **Vertex Detector**:
  - MAPS or DMAPS possibly with timing layer (LGAD)
  - Possibly ALICE 3 like?
- **Drift Chamber** (±2.5m active)
- **Silicon Wrapper + ToF**:
  - MAPS or DMAPS possibly with timing layer (LGAD)
- **Solenoid B=2T**, sharing cryostat with ECAL, outside ECAL
- **High Granularity ECAL**:
  - Noble liquid + Pb or W
- **High Granularity HCAL** / Iron Yoke:
  - Scintillator + Iron
    - SiPMs directly on Scintillator or
    - TileCal: WS fibres, SiPMs outside
- **Muon Tagger**:
  - Drift chambers, RPC, MicroMegas

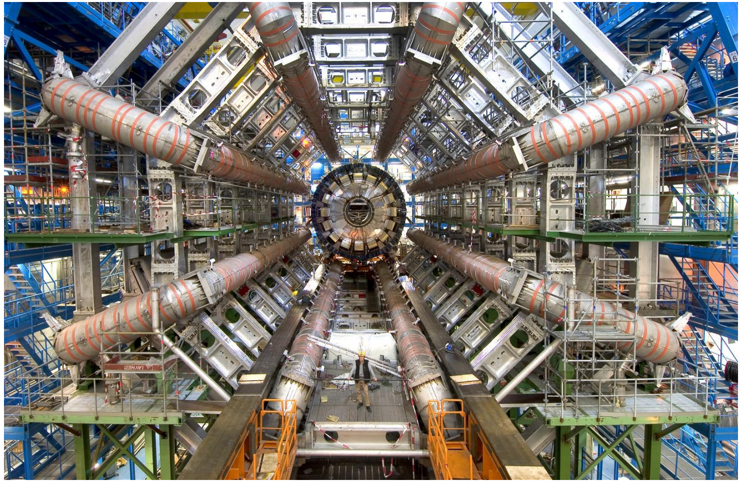
Noble liquid based Ecal

- Decades of success at particle physics experiments: from R806 to ATLAS
  - Mostly LAr, a bit of LKr
- An appealing option for FCC-ee
  - Good energy resolution
  - High(-ish) granularity achievable
  - Linearity, uniformity, long-term stability
  - Easy to calibrate

Excellent solution for small systematics

- Lots of interesting studies / R&D to do
  - Optimization for PFlow reconstruction
  - Achieving very low noise
  - Lightweight cryostats to minimize X_0
  - Designing for improved energy resolution





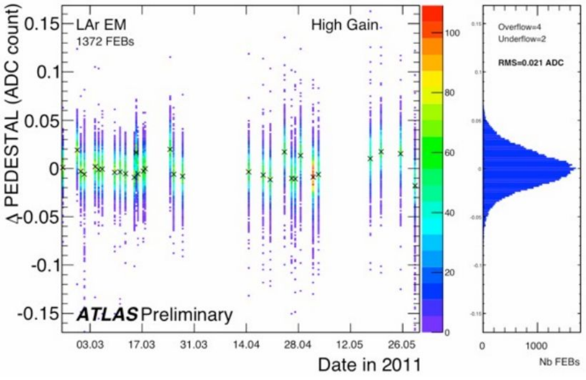
Example: Stability of ATLAS LAr Energy Scale

Noble-liquid calorimetry: High intrinsic stability

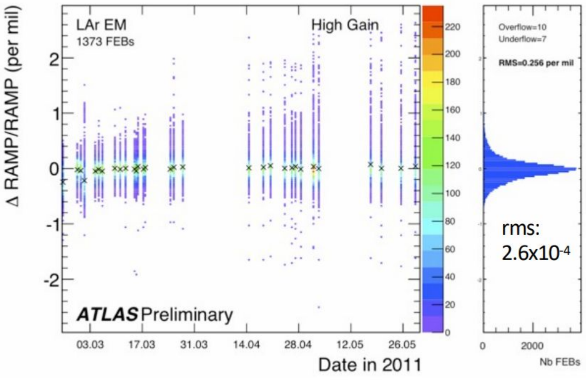
- Pedestal stability < 100 keV
- Gain stability 2.6×10^{-4}
- Parameters monitored in daily calibration runs
  - Changes in constants needed only about 1 / month

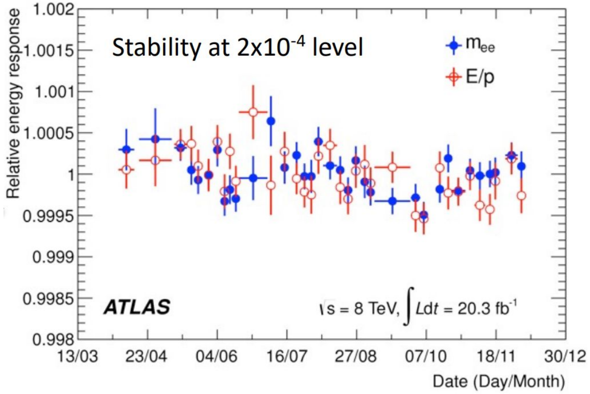
➢ **Stability of the energy scale of 2×10^{-4}**
  - Visible on $Z\rightarrow ee$ invariant mass and E/p

Pedestal (P) stability



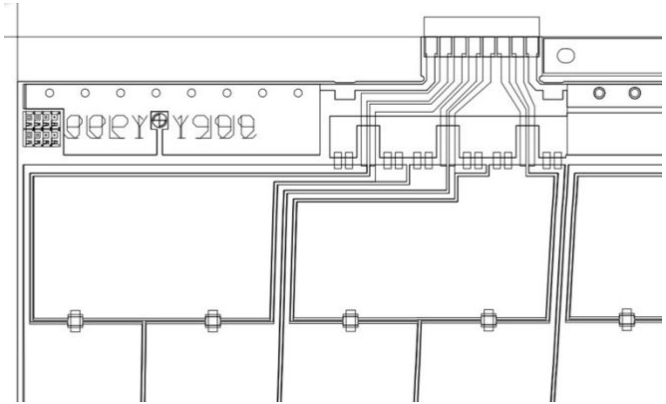
Gain (R) stability





Granularity of Noble Liquid Calorimeters

- Calorimeter design:
  - Granularity of the calorimeter
    ⇔ granularity of the electrodes
- ATLAS: copper/kapton electrode
  - Traces to read out middle cells take real estate on back layer
  - Cannot really increase granularity
- FCC-ee requirements
  - High jet energy resolution needed
  - Particle flow algorithms take advantage of much finer granularity
- **Solution for Noble Liquid calo for FCC**
  - Multi-layer PCB to route signals inside



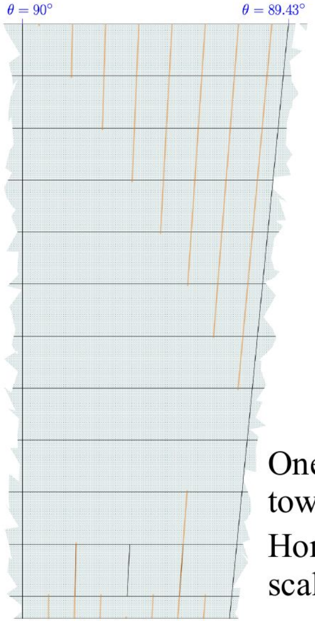
How to achieve high granularity ?

Aiming for ~ ×10 ATLAS granularity

- High granularity required for better PFlow performance (few million cells)
- >6 compartments to compensate LAr gap widening

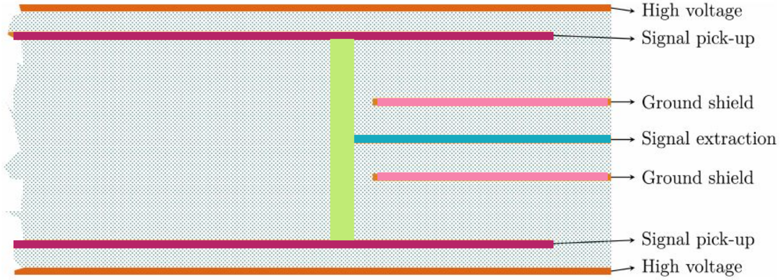
Implementation: multi-layer PCBs

- 7-layer PCB
  - Signal collection on **readout planes**
  - Transmission through **via**
  - Signal extraction on **trace**
  - **Ground shields** to mitigate cross-talk
- Challenges
  - Trade-off capacitance (noise) / cross-talk
  - Maximum density of signal traces ?
- Studies on simulations and prototypes



One theta tower

Horizontal axis scale 10:1



Allegro Barrel Design

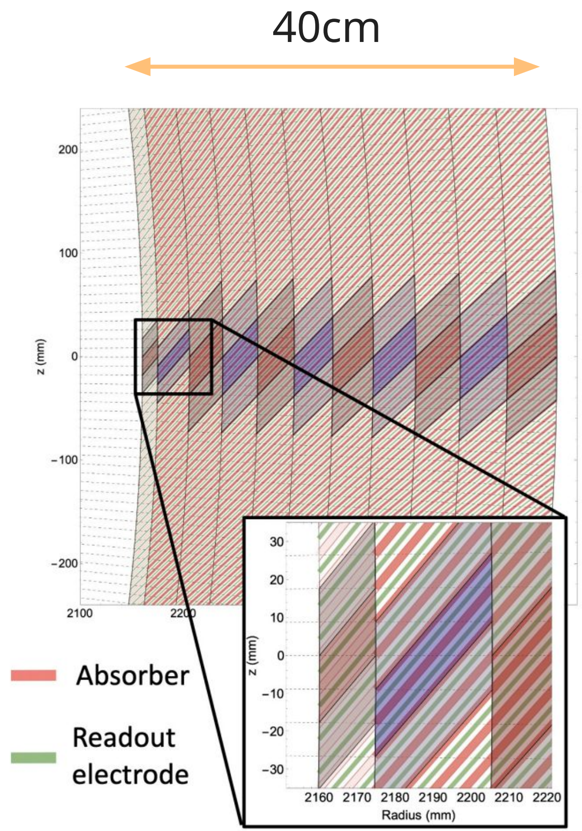
Design driven by the solution used for electrodes

- 1536 **straight inclined** (50°) 1.8mm **Pb** absorber plates
- Multi-layer PCBs as readout electrodes
- 1.2 – 2.4mm **LAr** gaps (**LKr** seriously considered)
- 40cm deep (22 X_0)
- $\Delta\theta$ = 10 (2.5) mrad for regular (strip) cells, $\Delta\phi$ = 8 mrad, 11 longitudinal layers

Copper electrodes: lots of flexibility

- Number of layers and granularity of layers fully optimizable
- Projective cells

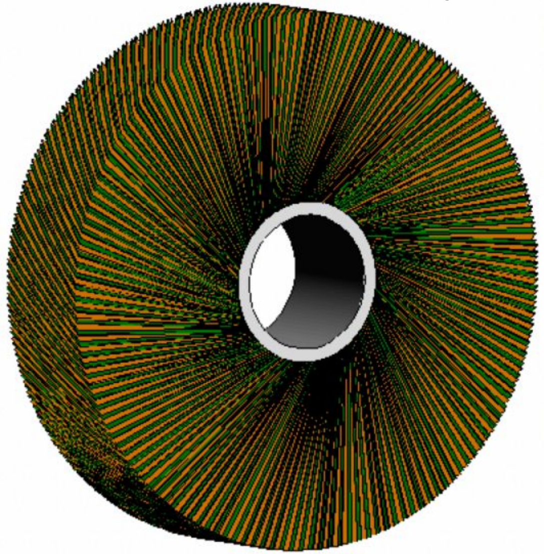
➢ **Lots of room for optimisation !**



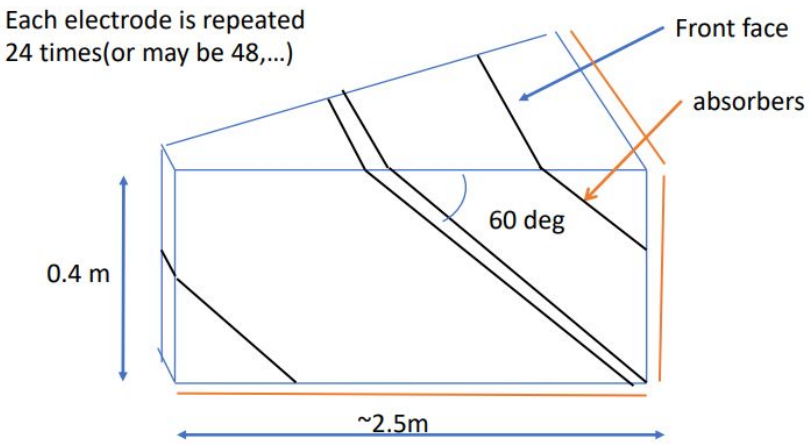
Designs for the endcaps: first ideas

Endcaps designs more complex than that of the barrel: very preliminary ideas !

- "Turbine" design
  - More similar to barrel design
  - Symmetric in ϕ
  - Issue: increase in the size of the Noble liquid gaps
  - Need to stack several cylinders



- XY / Pie wedge designs
  - Less symmetry in ϕ
  - Increase of LAr gaps under control
  - Many types of electrodes to draw and produce

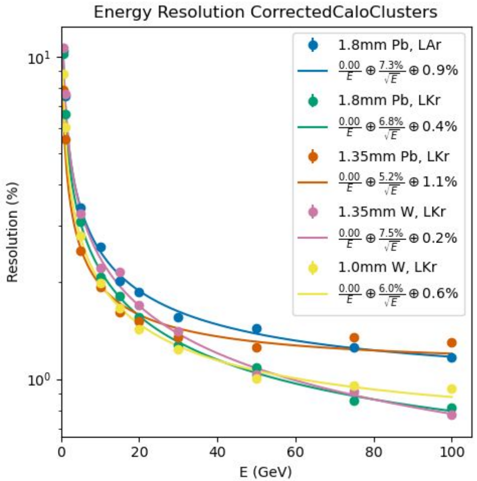


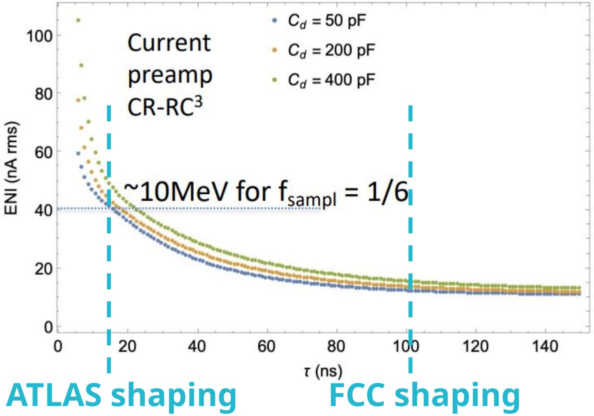
Energy resolution: design options and noise

Energy resolution: σ(E)/E = a/E + b/√E + c ⇒ 3 terms to optimise !

- Constant term
  - Hermeticity, low dead material, uniformity
- Sampling term: improve sampling fraction
  - Optimise gap size, sampling fraction, active and passive material
  - Explore LAr ⇒ LKr, Pb ⇒ W
    - between 5% and 7.5%
- Noise term: readout electronics
  - Want: measurement of 200 MeV photons, S/N>5 for MIPs
  - Longer shaping time wrt ATLAS (200 ns) helps a lot
  - Cold frontend electronics in the cryostat would provide noiseless readout

$$N \sim C_d \sqrt{\frac{4kT}{g_m \tau_p}}$$



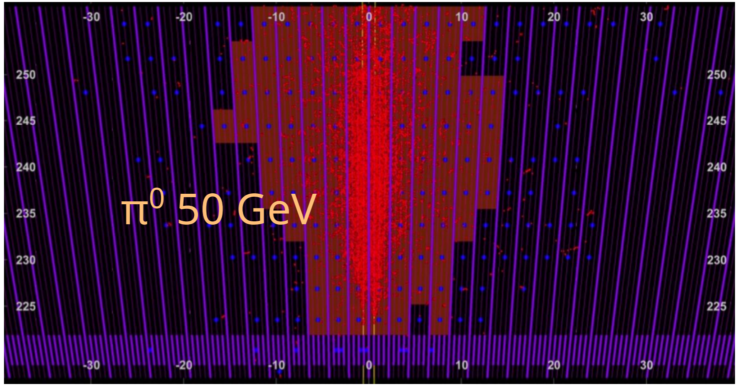


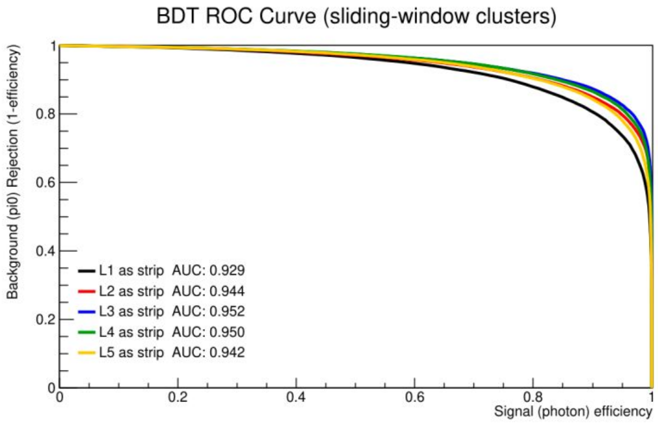
PID/PFlow: granularity optimisation

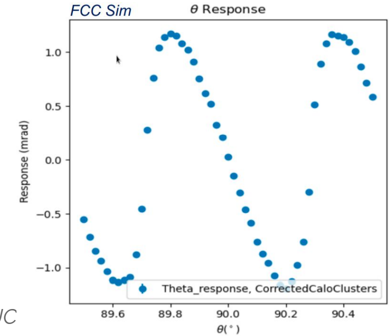
- Flexible geometry implemented in Full sim
  - Can study EM shower shapes
  - Benchmark: photon / π^0 separation
    - First consequence: position of "strips" layer
  - Ongoing: implementation of cross-talk effects

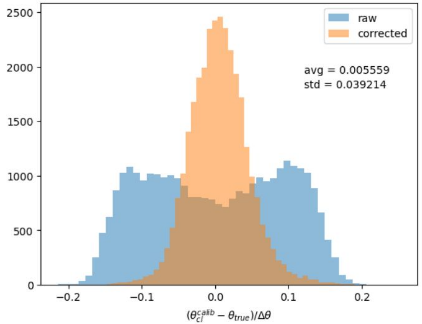
- Calibrations of reconstruction
  - Simple MVA energy regression of EM clusters
  - Cluster position calibration per layer
    - Allows pointing studies (⇒ ALPs)

- Particle Flow on its way
  - Using Pandora toolbox







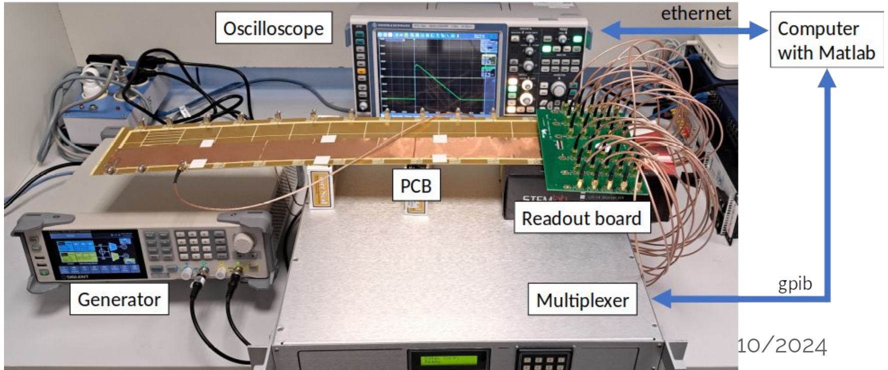


Electrodes prototypes

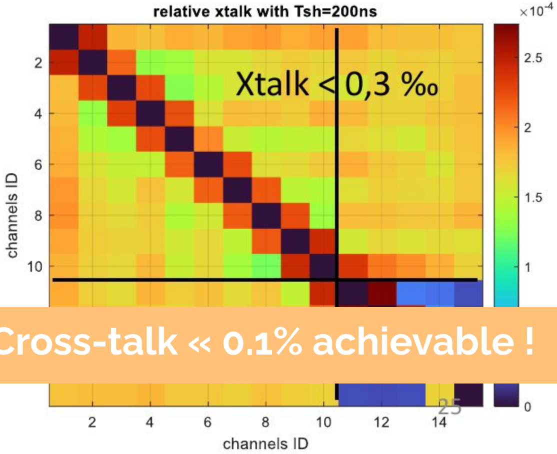
Explore tradeoffs: max granularity / capacitance (noise) / cross-talk

- First large-scale prototype at CERN
  - Explore many options for grounding, for shields
  - First layers readout at the front
  - Few per-mille cross-talk achievable with long shaping

- Latest prototype at IJCLab
  - All layers readout at the back
    - Best for material budget, worse for noise and cross-talk
  - New shielding ideas
  - Development of system for automated measurements



Tsh = 200ns

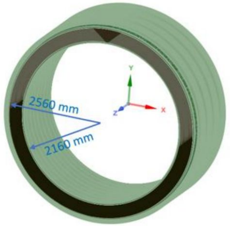


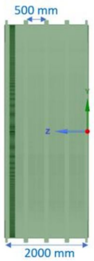
Cross-talk « 0.1% achievable !

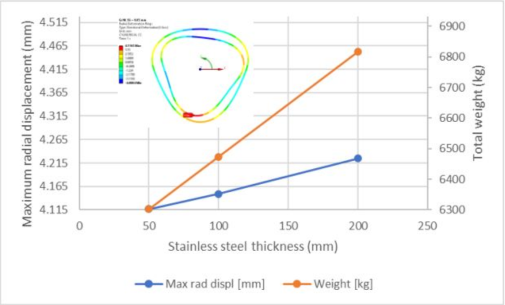
Mechanical studies

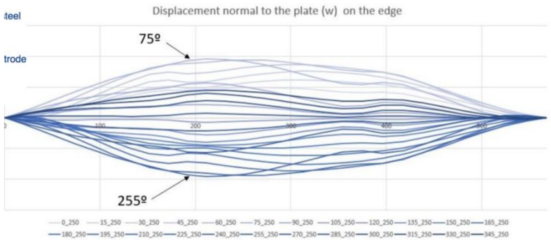
Simulation studies

- Model the full barrel
    - Define support structures, spacers
    - Study thickness of steel sheet
    - Simulations in warm and in cold



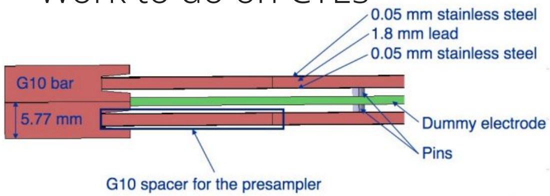


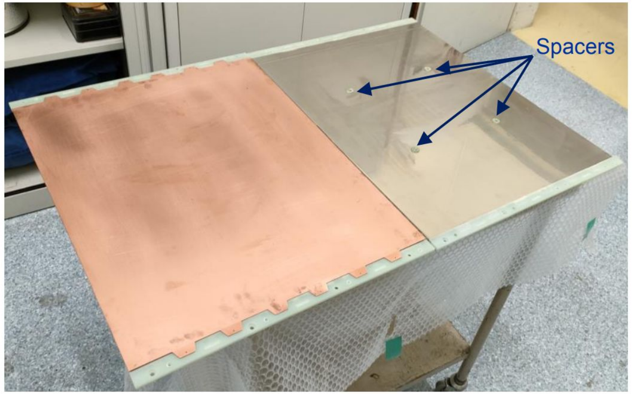




Absorbers prototypes

- First feasibility prototypes
    - Verify assumed rigidity
    - Thermo-mechanical tests in liquid nitrogen
    - Work to do on CTEs

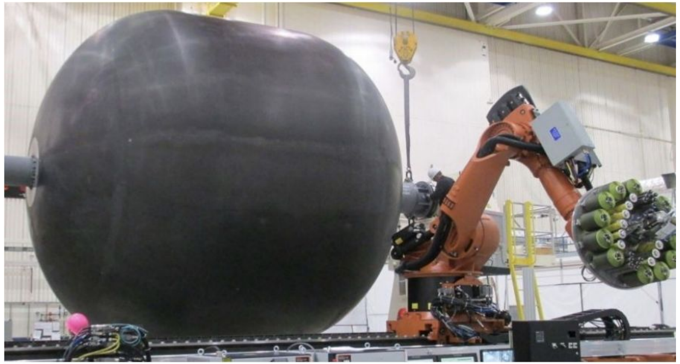




Cryostat and feedthroughs

Low mass cryostats

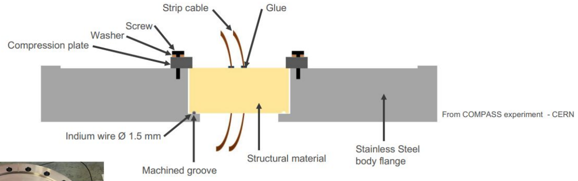
- Minimise dead material in front
  - Use of sandwiches with carbon fiber + Al honeycomb
  - Synergy with progress in aerospace
- CERN R&D: address CFRP/Metal interfaces
- Promises for **“transparent” cryostats**: few % of X_0 !

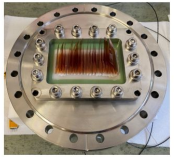


NASA’s lineless cryotank

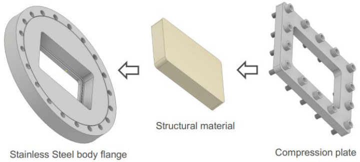
High-density feedthroughs

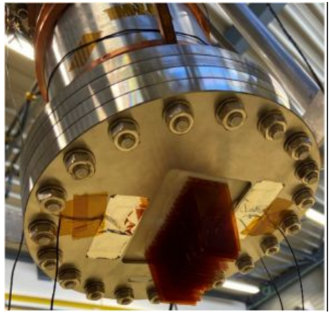
- Aim for ~ ×5 density and ~ ×2 area wrt ATLAS
- Successful R&D on connector-less feedthroughs at CERN
  - 3D-printed epoxy resins structures with slits for strip cables, glued to the flange
  - Leak tests and pressure tests at 300 K and 77 K





High-density flange sample to test

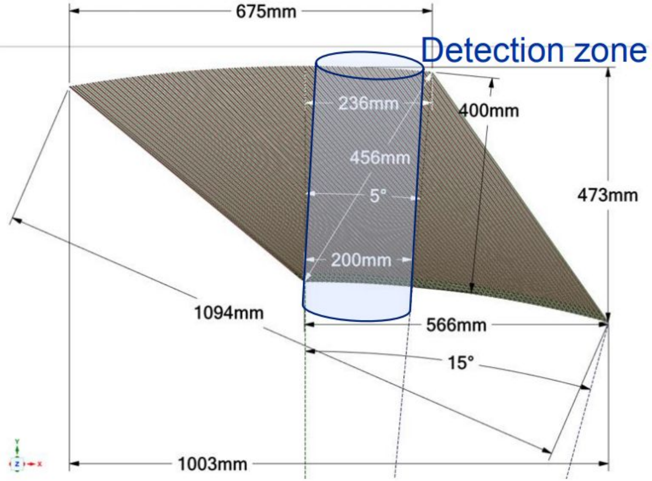




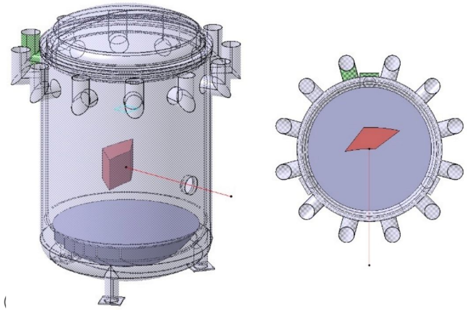
Towards a testbeam module

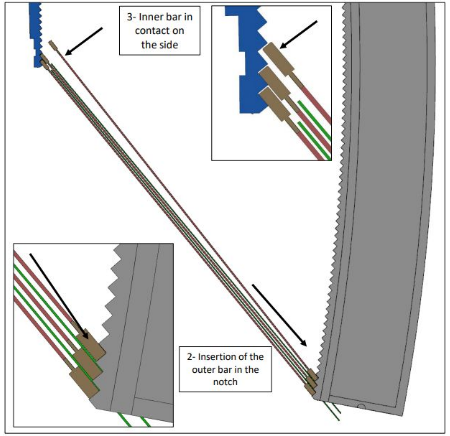
Plan to produce testmodule in the next four years

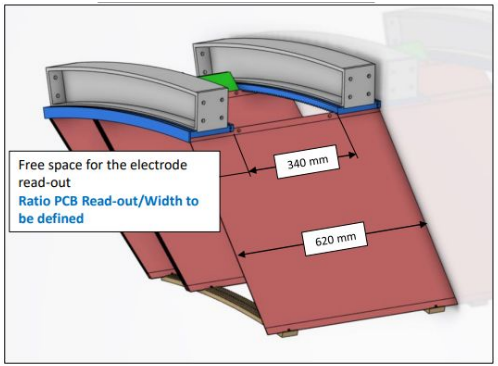
- Mechanical design of module (64 absorbers) has started
  - First finite element calculations performed
  - Designing solutions to stack then hold the layers together
- Work on finding / adapting testbeam cryostat



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

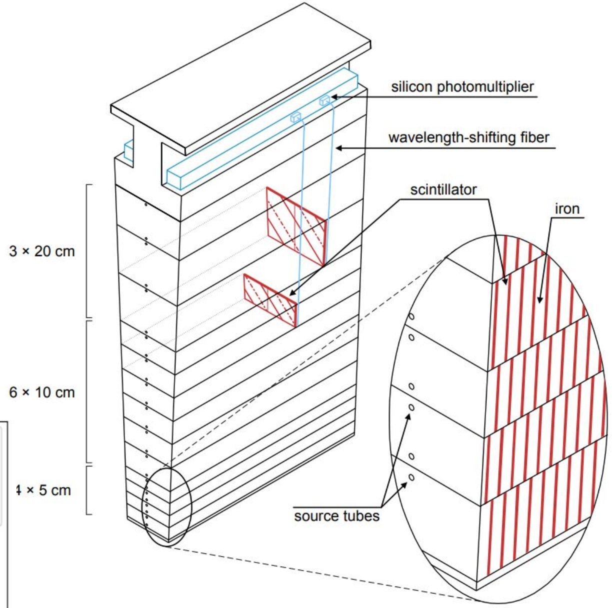


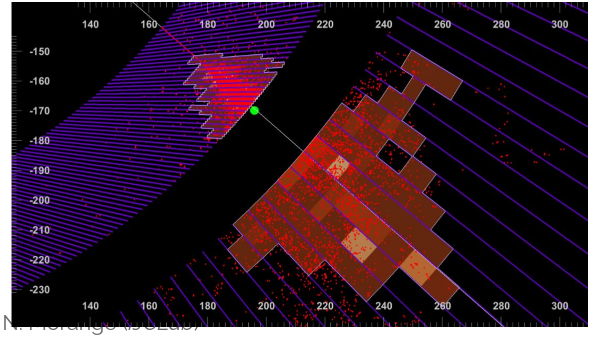


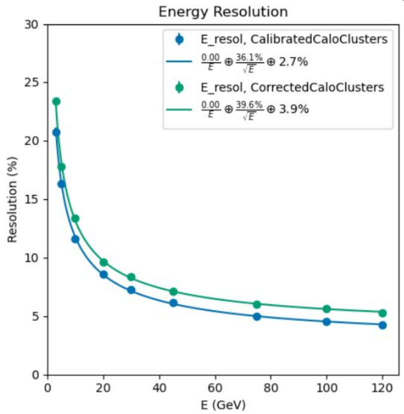


HCal for noble liquid based concept

- HCal inspired by ATLAS TileCal implemented in FCC Fullsim and studied so far
  - Other Sci/Steel options, e.g CALICE AHCAL will be studied as well
- Design
  - 5mm steel absorber plates alternating with 3mm Scint.: 8 - 9.5λ
  - 128 modules in ϕ, 2 tiles/module, 13 radial layers
  - Work on optimisation of segmentation and reconstruction is in full swing
  - Started testing Sci tile + WLS fibre + SiPM readout
- Performance
  - Ecal + Hcal combined clustering implemented
  - Single-pion resolution: 36%/√E



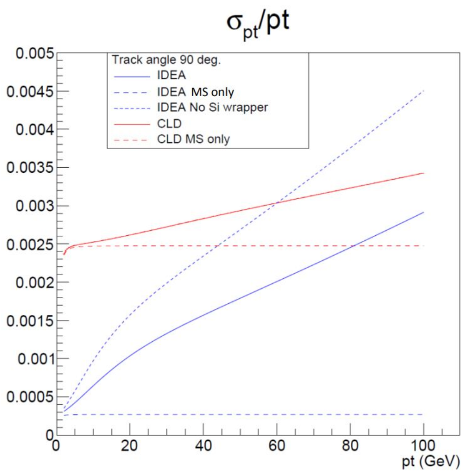


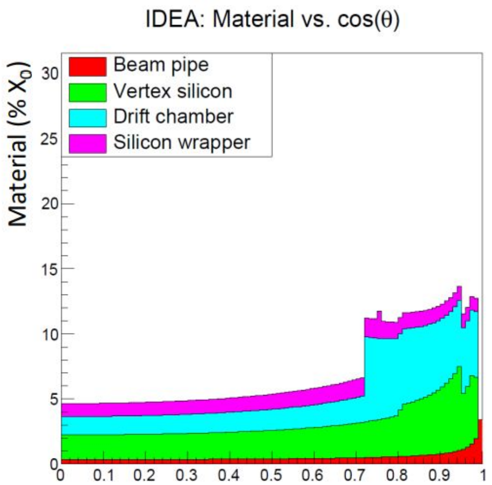


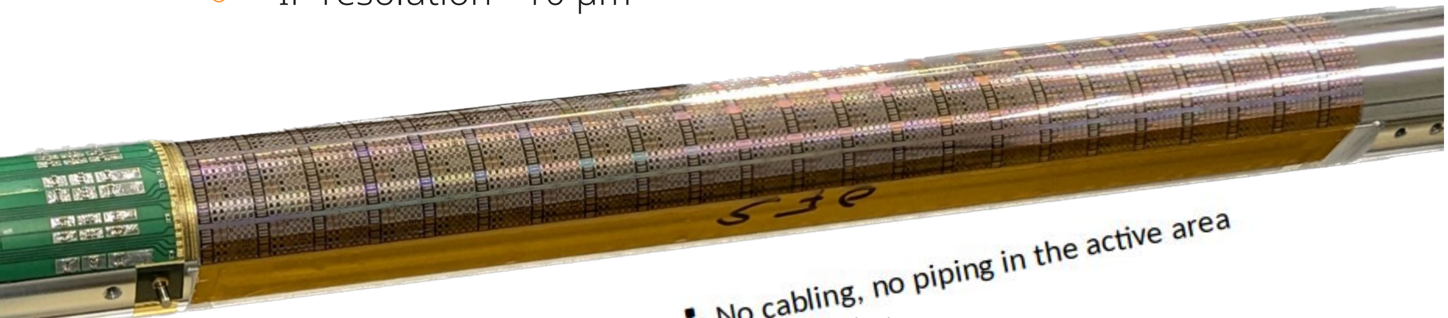
Vertex detector and momentum measurement

Transparency key for high resolution

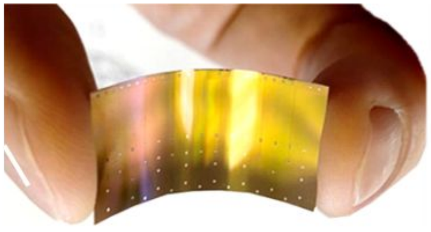
- Light vertex detector and tracker
  - Particle energies < 100 GeV: lower MS contribution required
- Vertex detector: MAPS-based
  - Similar to e.g Belle 2 or ALICE ITS3
  - Typically: 5 layers, 33 x 33 μm^2 pixels
  - Extremely light: Inner layers: 0.1% X_0 / layer
  - Outer layers: 0.5 – 1% X_0 / layer
  - IP resolution ~10 μm







No cabling, no piping in the active area



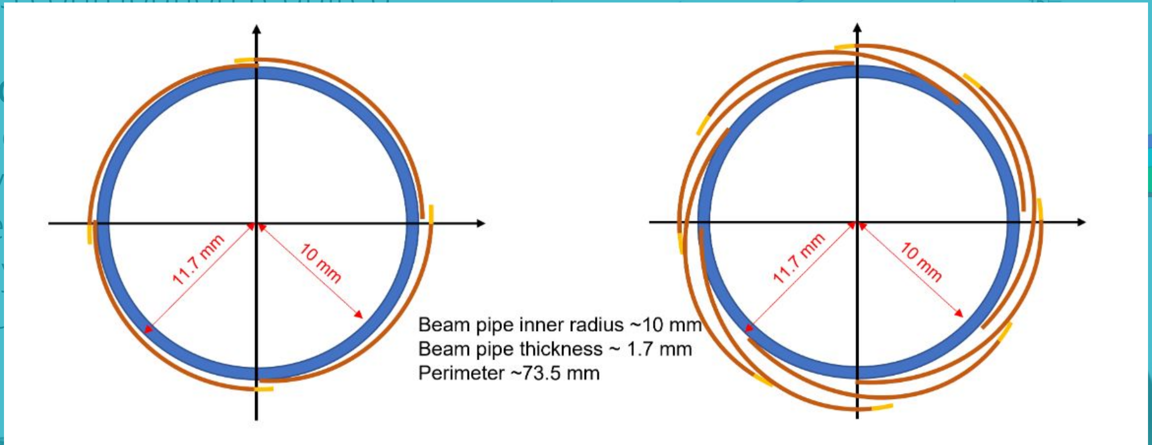
Curved MAPS sensor

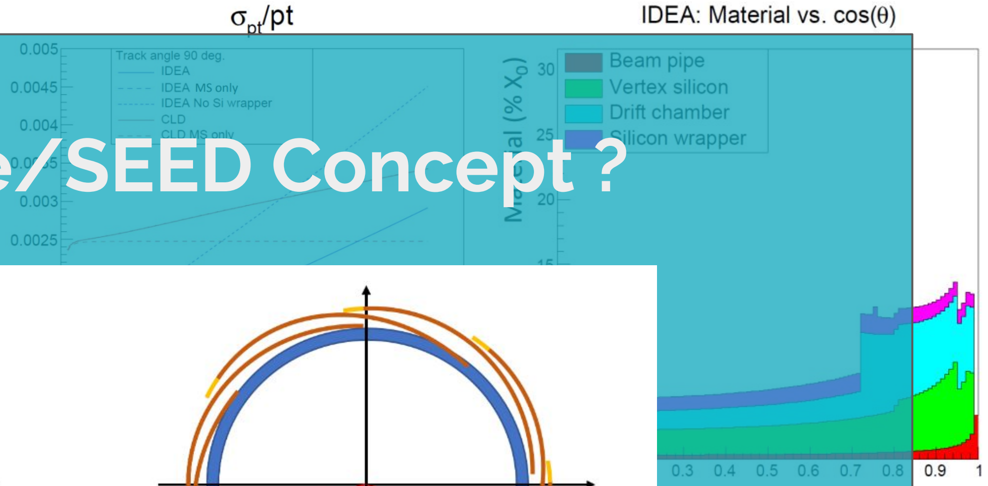
Vertex detector and momentum measurement

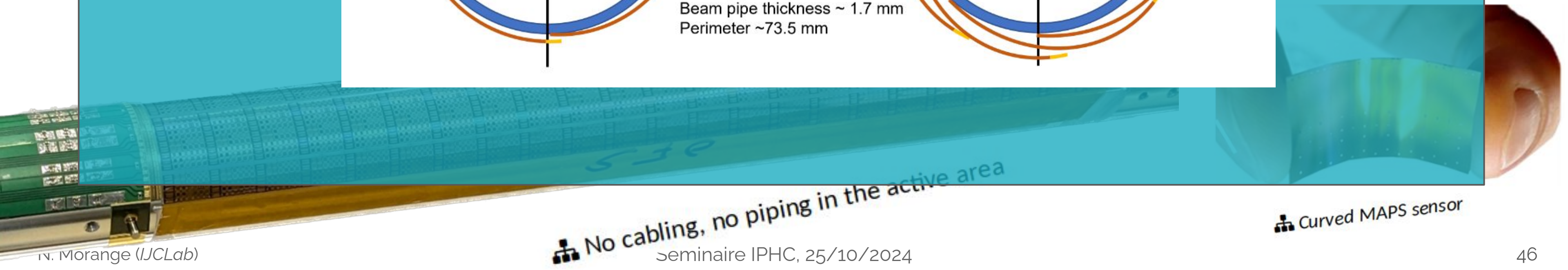
Transparency key for high resolution

- Light vertex detector and tracker
  - Particle energies < 100 GeV: lower MS contribution required
- Vertex detec
  - Similar t
  - Typically
  - Extreme
  - Outer la
  - IP resolu

Or: Schnecke/SEED Concept ?







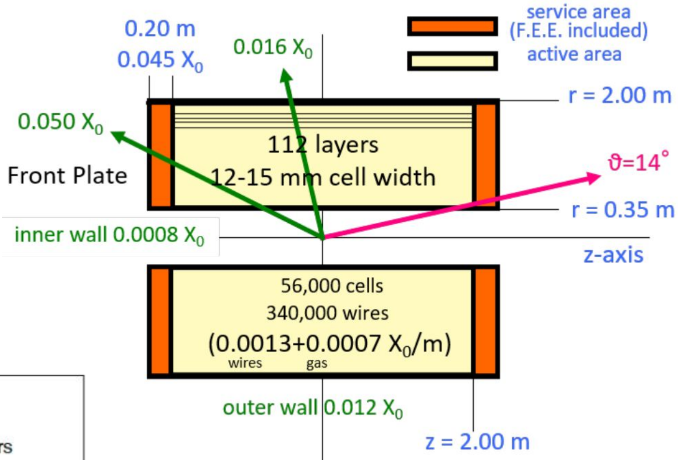
Drift chamber: IDEA design

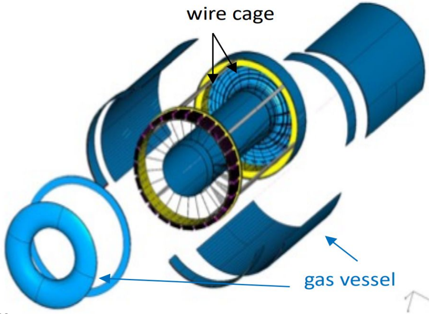
IDEA: Extremely transparent Drift Chamber

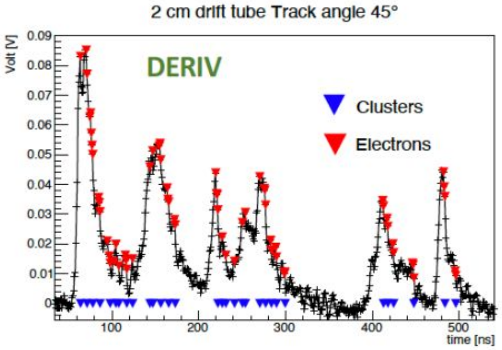
- Large volume:
  - Rin = 0.35 m, Rout = 2 m, L = 4 m
- Operating gas: He 90% - iC_4H_{10} 10%
- Full stereo:
  - 112 co-axial layers, at alternating-sign stereo angles ranging from 50 to 250 mrad
  - **Allegro**: Longer DC ⇒ fewer layers
    - **Careful optimisation needed**
- Expected resolution σ_{xy} < 100 μm, σ_z < 1 mm
- Cluster counting for PID

tracking efficiency ε ≈ 1 for ϑ > 14° (260 mrad)
97% solid angle

$0.016\ X_0$ to barrel calorimeter
$0.050\ X_0$ to end-cap calorimeter





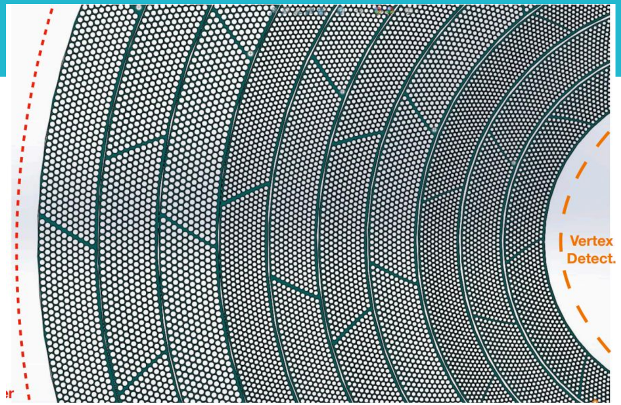


δ_{cl} = 12./cm for He/iC_4H_{10}=90/10 and a 2m track → **σ ≈ 2.0%**

$$\frac{\sigma_{dN_{cl}/dx}}{\left(dN_{cl}/dx\right)} = \left(\delta_{cl}\cdot L_{track}\right)^{-1/2} = N_{cl}^{-1/2}$$

Poisson

Straw Trackers Studies

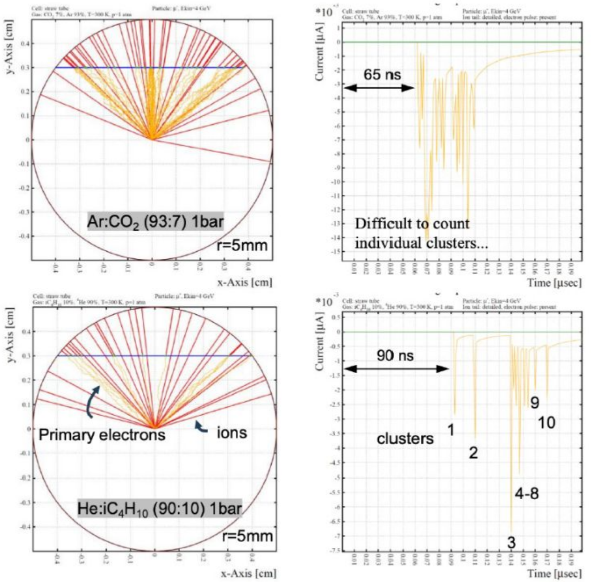


Very recent proposal as alternative to Drift Chamber

- Potential advantages:
  - Comparable resolution with greater design flexibility, PID
  - Operational robustness (broken wires)
  - Economical

- Many straw trackers built for recent experiments
  - GlueX, NA62, PANDA, Mu2e, DUNE ND...

- Interesting R&D paths
  - Overall detector design
  - Single tube production and assembly (minimize X_0)
  - Gas studies, electronics for dE/dx measurements



N_{straws}	R_{straw} [mm]	Material [X_0]	$\frac{\sigma_p}{p}$
100	9.7	1.3%	$0.52\% \oplus 0.15\% = 0.54\%$
112	8.7	1.5%	$0.49\% \oplus 0.16\% = 0.52\%$
200	4.9	2.5%	$0.36\% \oplus 0.21\% = 0.42\%$

N. $\Rightarrow$ Straw-tracker alternative fully competitive with the drift-chamber.

Conclusion

FCC-ee has an **outstanding** physics program and is the best project we can hope for after the LHC

It is unfortunately 20 years away

But remember: ATLAS and CMS were conceptualized > 15 years before they were built

Let's design our future detectors !

A noble-liquid based Ecal is a **high-performance cost-effective** solution for a calorimeter at FCC-ee

For all other subdetectors, we are looking for collaborators to move ALLEGRO from a drawing on paper to a real **detector concept** !