

New detectors for future challenges: the Allegro EM calorimeter

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DPhP, 23/02/2026



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

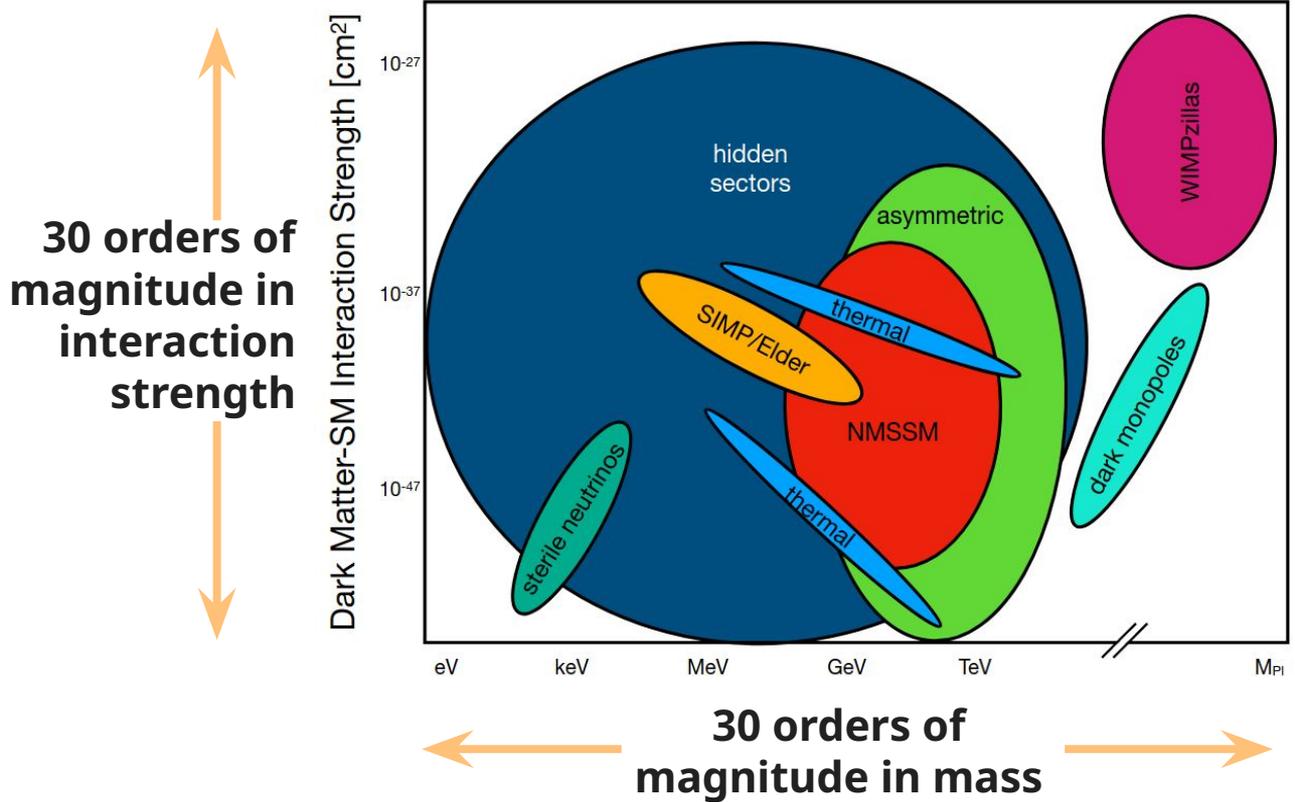
The SM is a huge success...

but

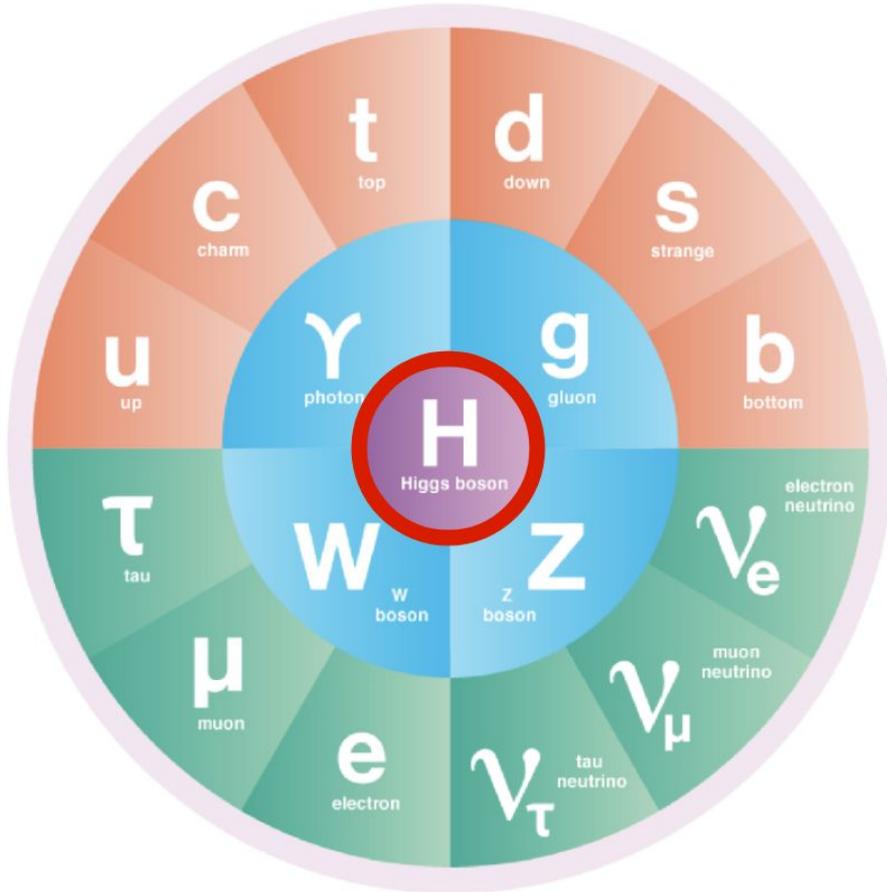
we have been so far **unlucky in getting answers to many questions !**

Dark Matter Landscape

Snowmass Dark Matter Report, [2209.07426](#)



Higgs Boson to the Rescue



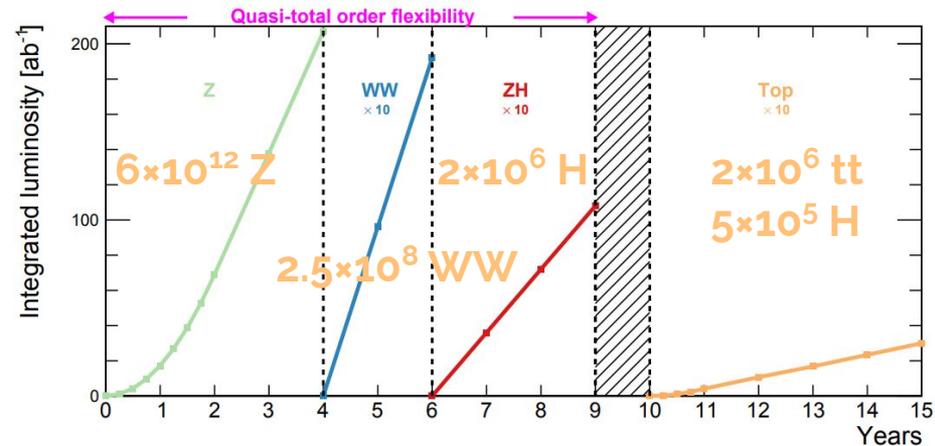
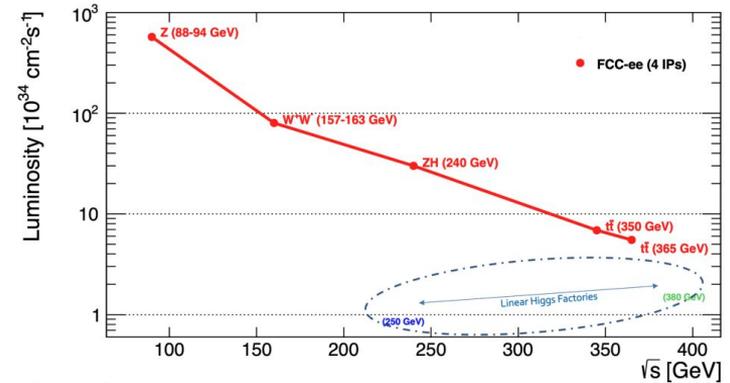
But we have been **lucky** in discovering a 125 GeV Higgs boson

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

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

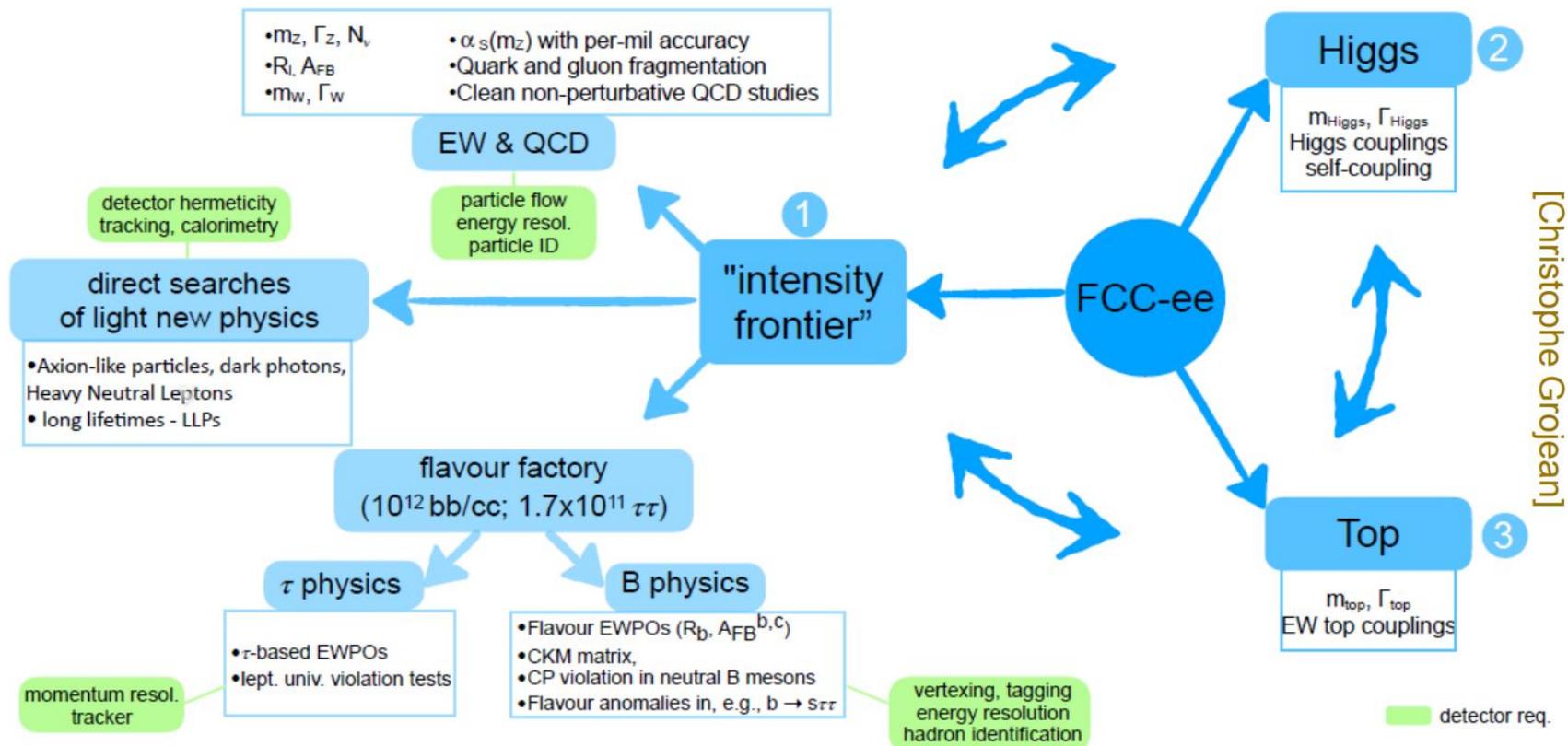
The FCC-ee project

- 90.7 km 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 successful for ESPPU
 - Huge work over 4 years !



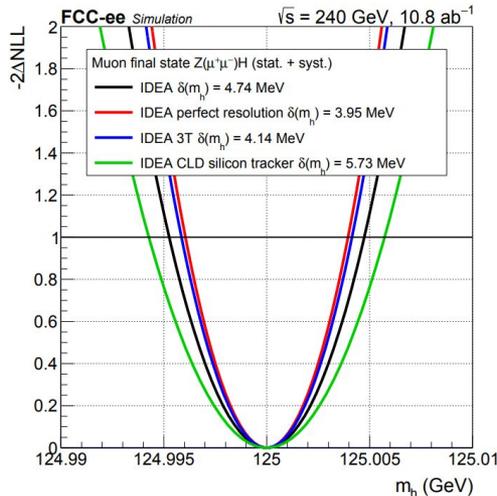
FCC-ee Physics Programme

Extremely broad ! Excellent complementarity with HL-LHC



Example: Higgs couplings and mass

- Higgs couplings
 - Per-mille precision on many of them
 - Start to be limited by SM parametric uncertainties, e.g m_b
 - $H \rightarrow ss$ at $\sim 2\sigma$!
 - HL-LHC still very important for couplings to top, photon, muon
 - FCC-ee: also get absolute couplings !



Coupling	HL-LHC	FCC-ee
κ_Z (%)	1.3*	0.10
κ_W (%)	1.5*	0.29
κ_b (%)	2.5*	0.38 / 0.49
κ_g (%)	2*	0.49 / 0.54
κ_τ (%)	1.6*	0.46
κ_c (%)	–	0.70 / 0.87
κ_γ (%)	1.6*	1.1
$\kappa_{Z\gamma}$ (%)	10*	4.3
κ_t (%)	3.2*	3.1
κ_μ (%)	4.4*	3.3
$ \kappa_s $ (%)	–	+29 –67
Γ_H (%)	–	0.78
$\mathcal{B}_{inv} (<, 95\% \text{ CL})$	$1.9 \times 10^{-2} *$	5×10^{-4}
$\mathcal{B}_{unt} (<, 95\% \text{ CL})$	$4 \times 10^{-2} *$	6.8×10^{-3}

- Higgs mass: down to 4 MeV !
 - < 10 MeV required for SM predictions to match couplings precision (e.g to Z and W)
 - 4 MeV needed for possible H pole running
 - Relies on excellent tracking resolution
 - High field magnet, gaseous tracker

Example: the ultimate EW precision

A real challenge for theory calculations and experimental systematics !

Observable	present value	present \pm uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	\pm 2000	4	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	\pm 2300	4	12	From Z line shape scan Beam energy calibration
$\sin^2 \theta_W^{\text{eff}} (\times 10^6)$	231,480	\pm 160	1.2	1.2	From $A_{\text{FB}}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\text{QED}}(m_Z^2) (\times 10^3)$	128 952	\pm 14	3.9 0.8	small tbc	From $A_{\text{FB}}^{\mu\mu}$ off peak From $A_{\text{FB}}^{\mu\mu}$ on peak QED&EW uncert. dominate
$R_\ell^Z (\times 10^3)$	20 767	\pm 25	0.05	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2) (\times 10^4)$	1 196	\pm 30	0.1	1	Combined $R_\ell^Z, \Gamma_{\text{tot}}^Z, \sigma_{\text{had}}^0$ fit
$\sigma_{\text{had}}^0 (\times 10^3)$ (nb)	41 480.2	\pm 32.5	0.03	0.8	Peak hadronic cross section Luminosity measurement
$N_\nu (\times 10^3)$	2 996.3	\pm 7.4	0.09	0.12	Z peak cross sections Luminosity measurement
$R_b (\times 10^6)$	216 290	\pm 660	0.25	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{\text{FB}}^{b,0} (\times 10^4)$	992	\pm 16	0.04	0.04	b-quark asymmetry at Z pole From jet charge
$A_{\text{FB}}^{\text{pol},\tau} (\times 10^4)$	1 498	\pm 49	0.07	0.2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	\pm 0.5	0.001	0.005	ISR, τ mass
τ mass (MeV)	1 776.93	\pm 0.09	0.002	0.02	estimator bias, ISR, FSR
τ leptonic ($\mu\nu_\mu\nu_\tau$) BR (%)	17.38	\pm 0.04	0.00007	0.003	PID, π^0 efficiency

m_W (MeV)	80 360.2	\pm 9.9	0.18	0.16	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2 085	\pm 42	0.27	0.2	From WW threshold scan Beam energy calibration
$\alpha_S(m_W^2) (\times 10^4)$	1 010	\pm 270	2	2	Combined $R_\ell^W, \Gamma_{\text{tot}}^W$ fit
$N_\nu (\times 10^3)$	2 920	\pm 50	0.5	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172 570	\pm 290	4.2	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate
Γ_{top} (MeV)	1 420	\pm 190	10	6	From $t\bar{t}$ threshold scan QCD uncert. dominate
$\lambda_{\text{top}}/\lambda_{\text{top}}^{\text{SM}}$	1.2	\pm 0.3	0.015	0.015	From $t\bar{t}$ threshold scan QCD uncert. dominate
$t\bar{t}$ couplings		\pm 30%	0.5–1.5 %	small	From $\sqrt{s} = 365$ GeV run

Outstanding Physics \Rightarrow Strong Requirements on Detectors

Higgs
factory

m_H, σ, Γ_H
self-coupling
 $H \rightarrow bb, cc, ss, gg$
 $H \rightarrow \text{inv}$
 $ee \rightarrow H$
 $H \rightarrow bs, ..$

Top

$m_{\text{top}}, \Gamma_{\text{top}}, ttZ, \text{FCNCs}$

Flavor
"boosted" B/D/ τ factory:

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

$B_c \rightarrow \tau \nu$
 $B_s \rightarrow D_s K/\pi$
 $B_s \rightarrow K^* \tau \tau$
 $B_s \rightarrow K^* \nu \nu$
 $B_s \rightarrow \phi \nu \nu ...$

QCD - EWK
most precise SM test

$m_Z, \Gamma_Z, \Gamma_{\text{inv}}$

$\sin^2 \theta_W, R_\ell^Z, R_b, R_c$

$A_{\text{FB}}^{b,c}, \tau \text{ pol.}$

$\alpha_S,$

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

Excellent knowledge
of detector:
Small systematics

Versatile detector
Photon pointing

**Plan A for CERN is FCC-ee
(ESPP draft, 2025)**

How to design FCC-ee Detectors ?

FCC-ee Detectors will be as challenging as LHC ones

But in different ways !

- Vertex detectors with small pixels, very close to IP
 - Large gaseous trackers at high rate, with PID capabilities
 - Minimal X_0 in front of calorimeters
 - High energy resolution for calorimeters
 - High granularity calorimeters
 - Precision positioning at 10 μ m level, stability
 - Very complex Machine-Detector Interface
- Low physics rate
 - Easier TDAQ
 - No issues from radiation damage
 - No need to measure TeV-scale particles

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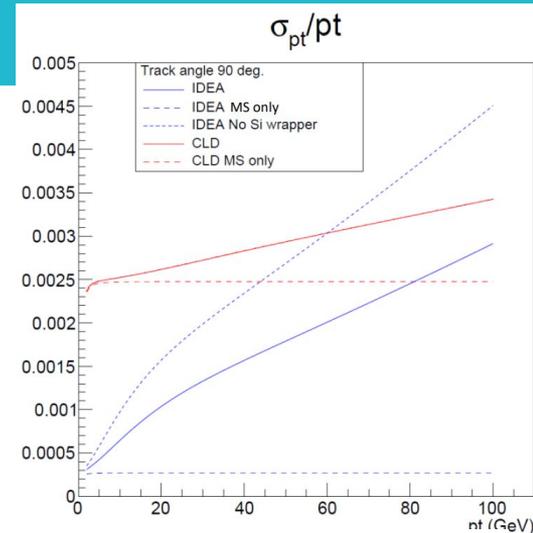
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 - **Well, actually...**
 - No issues from radiation damage
 - **Well, actually...**
 - No need to measure TeV-scale particles

Tracking performance

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

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

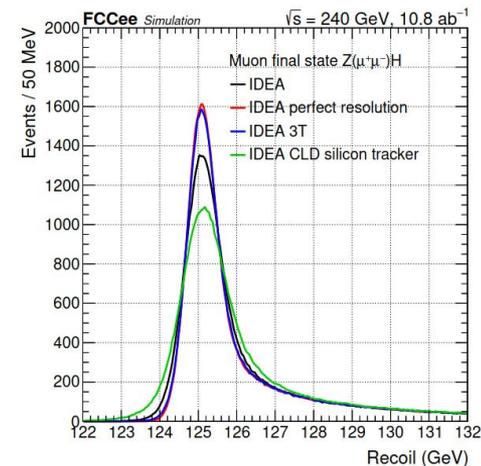
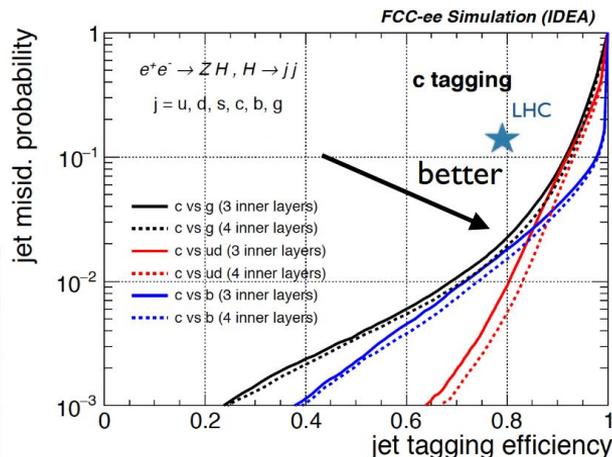
$$\frac{\Delta p_T}{p_T} \Big|_{m.s.} \approx \frac{0.0136 \text{ GeV}/c}{0.3\beta B_0 L_0} \sqrt{\frac{d_{tot}}{X_0 \sin \theta}}$$



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

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

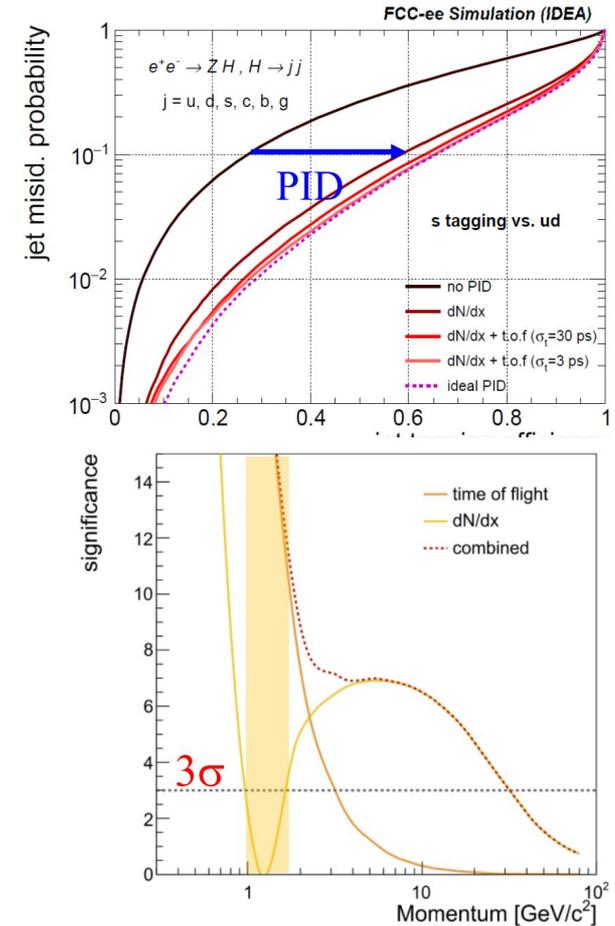
	r beam pipe	1 st VTX layer
ILC	12 mm	14 mm
CLIC	29 mm	31 mm
FCC-ee	10 mm	12 mm



Why PID ?

A must-have to complete the full Higgs, EW, Top programme

- Higgs physics
 - $H \rightarrow ss$ sensitivity driven by strange-tagging perf, depends a lot on PID performance
 - Flavour violating modes, e.g $H \rightarrow bs$
- SM parameters
 - Also depend on K identification / strange tagging
 - $V_{ts'}$, V_{bs}
- B physics
 - $B_s^0 \rightarrow D_s^\pm K^\mp$, $B \rightarrow K^* \nu \nu$, $B_s \rightarrow \phi \nu \nu$, ...
- Handles on PID
 - Gaseous trackers providing dE/dx or dN/dx
 - Time-of-flight with $O(10\text{ps})$ resolution
 - Cerenkov detectors (ARC concept)



Calorimeters for FCC-ee Physics

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 ?

Calorimetry options

Many options on the table, for both Ecal and Hcal

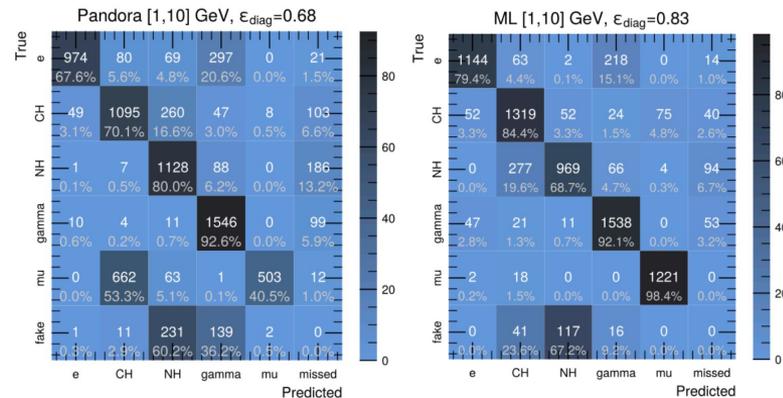
Detector technology (ECAL & HCAL)	E.m. energy res. stochastic term	E.m. energy res. constant term	ECAL & HCAL had. energy resolution (stoch. term for single had.)	ECAL & HCAL had. energy resolution (for 50 GeV jets)	Ultimate hadronic energy res. incl. PFlow (for 50 GeV jets)
Highly granular Si/W based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

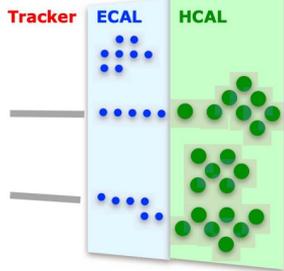
A quest for ultimate jet energy resolution

PFlow PFlow PFlow

- Target: $\sigma(E)/E = 30\%/\sqrt{E}$ (GeV)
 - Typical figure of merit: W/Z boson separation
 - Actual use: variety of hadronic measurements
- What granularity do we really need ?
- New calos concepts bring new ideas: crystals DR study ; GNN PFlow

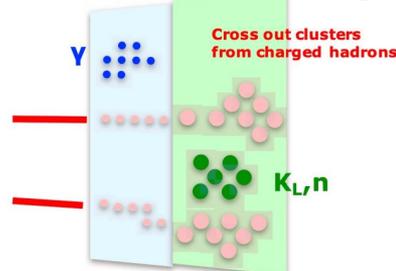


Traditional Calorimetry

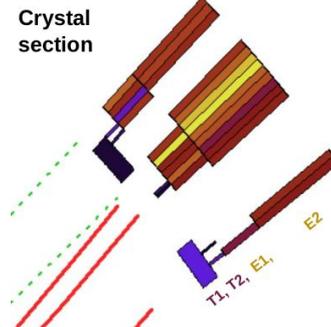


$E_{jet} = E(ECAL) + E(HCAL)$
 Composition $\sim 30\%$: $\sim 70\%$

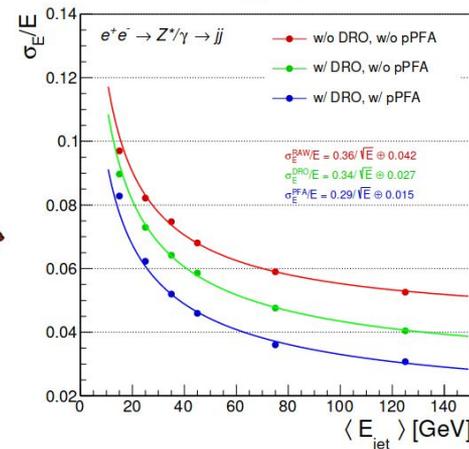
Particle Flow Calorimetry



$E_{jet} = E(Tracker) + E(Y) + E(KL,n)$
 Composition $\sim 60\%$: $\sim 30\%$: $\sim 10\%$



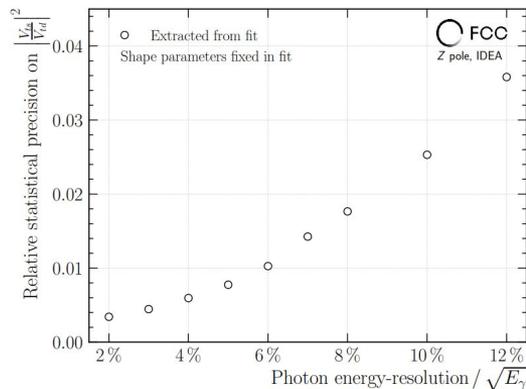
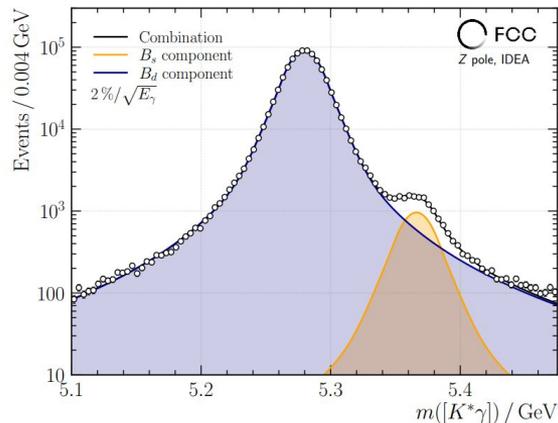
Jet energy resolution



EW factories unique challenges

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

- Some physics channels require very high EM resolution
 - e.g $B^0_{(s)} \rightarrow K^*\gamma$
- τ physics: reconstructing the decays
 - π^0 reconstruction and ID
 - Count close-by π^0
 - Granularity and resolution needed
- BSM, e.g ALP searches
 - Photon resolution, photon pointing



Recon \rightarrow Gen \downarrow	$\pi^\pm \nu$	$\pi^\pm \pi^0 \nu$	$\pi^\pm 2\pi^0 \nu$	$\pi^\pm 3\pi^0 \nu$	$\pi^\pm 4\pi^0 \nu$
$\pi^\pm \nu$	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. $\tau \rightarrow \pi^\pm \nu$ decays classified as each of the considered channels

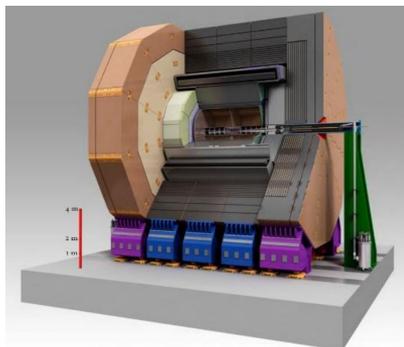
The ALLEGRO Detector Concept

Detector Concepts for FCC-ee

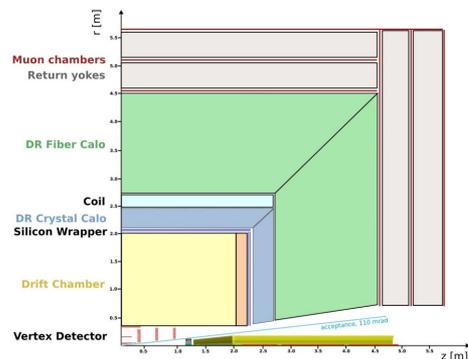
Concepts: Expressions of Interest as part of the FCC Feasibility Study

- Goal: design sub-detectors with **global performance** and **integration** into a real full detector in mind

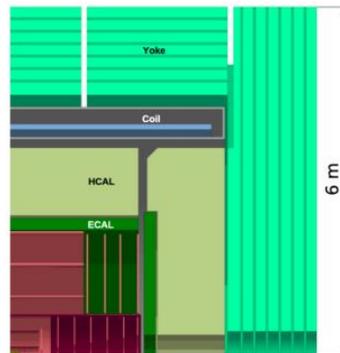
ILD



IDEA



CLD



ALLEGRO



- ALLEGRO is the least mature of the 4
 - Very open to options and new ideas at this stage

The ALLEGRO Detector Concept



**Noble Liquid
Ecal**

Lumical

MDI

**Steel -
Scintillator
Hcal**

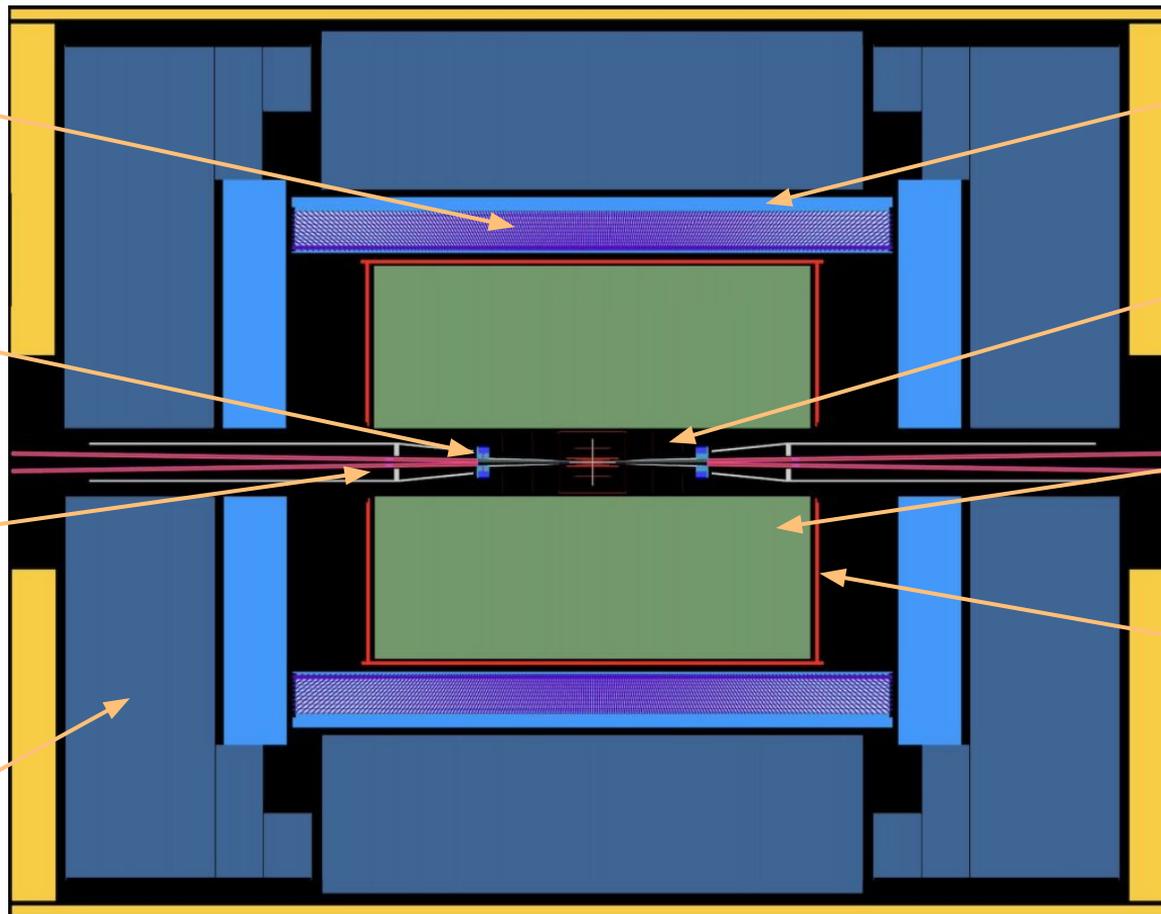
2T Solenoid

**Vertex
Detector**

Main tracker

**Silicon
Wrapper**

Muon Tagger



The ALLEGRO Detector Concept



Noble Liquid
Ecal

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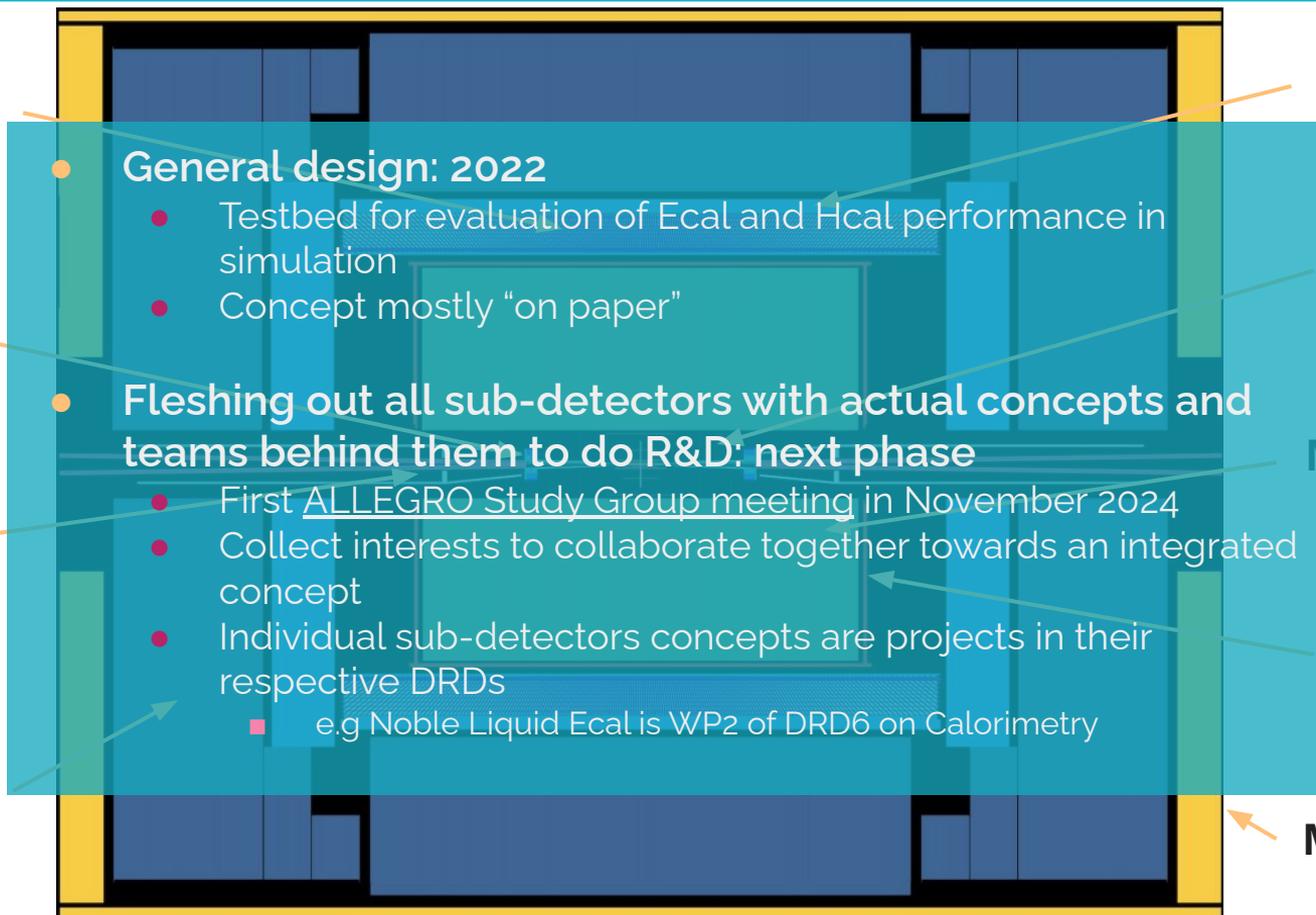
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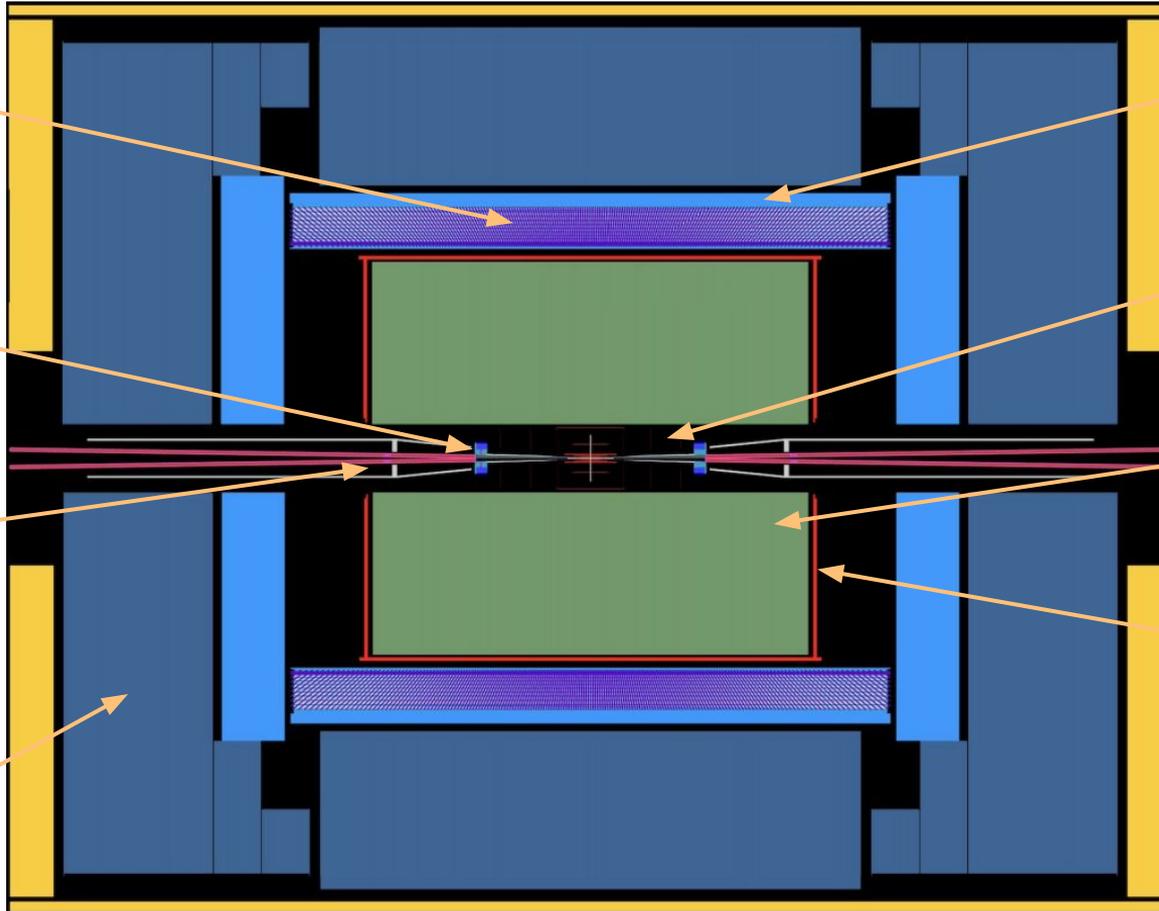


Noble Liquid Ecal

Lumical

MDI

**Steel -
Scintillator
Hcal**



2T Solenoid

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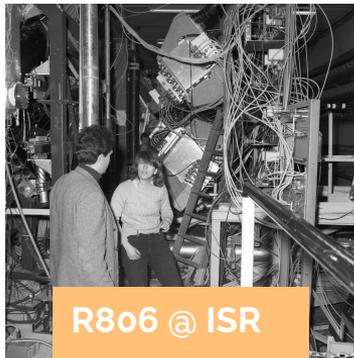
Main tracker

**Silicon
Wrapper**

Muon Tagger

Noble Liquid Calorimetry

Decades of successes in particle physics experiments



R806 @ ISR



DØ @ Tevatron



NA48 (LKr I)



ATLAS @ LHC

Checks all boxes for an excellent calorimeter at FCC-ee

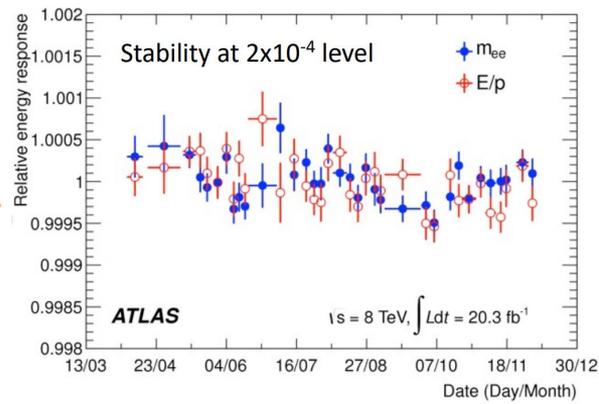
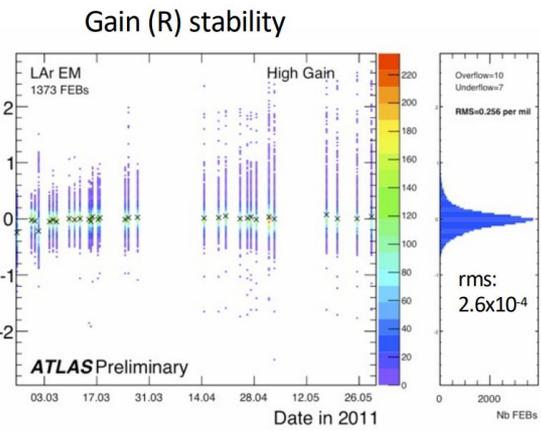
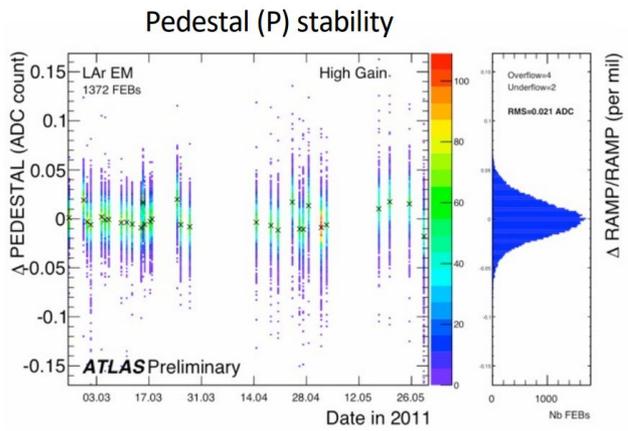
- **Excellent energy resolution**
 - $5 - 8\% / \sqrt{E}$
- **High granularity** achievable
 - Few 10^6 channels for Particle Flow Reconstruction
- Suitable for **low systematics**
 - Linearity, uniformity, long-term stability
 - Easy to calibrate

90 MeV systematics in
 $H \rightarrow \gamma\gamma$ mass
measurement with
ATLAS

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



Next-gen Noble Liquid Calorimetry for FCC-ee

Challenges for a next generation noble liquid calorimeter

- Reach **high granularity**
 - And optimize for physics: photon/ π^0 PID ; PFlow reconstruction
- Design for **improved energy resolution**
 - Including achieving **very low noise**
 - “Transparent” cryostat: **minimize amount of X_0** in front of calorimeter

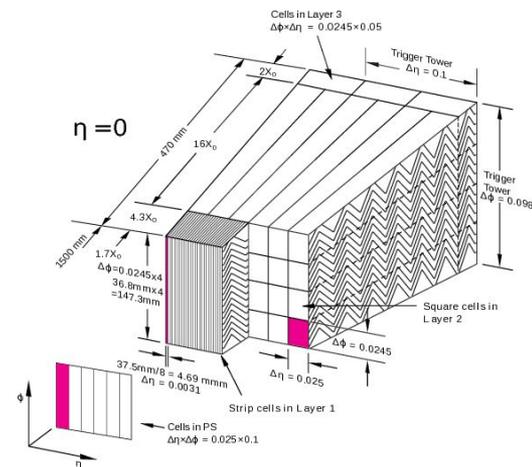
ALLEGRO Ecal R&D

- New design ideas to tackle these challenges
 - Study concepts for a barrel and for endcaps
 - Validate with prototypes in testbeam
 - Aim for post-LS3 (2029)
- Community of 20 institutes
 - Many already involved in ATLAS LAr
- Part of the DRD6 collaboration
 - WP2 on Noble liquid Calorimetry



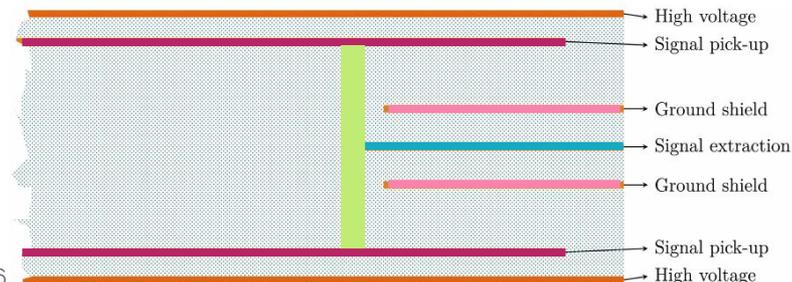
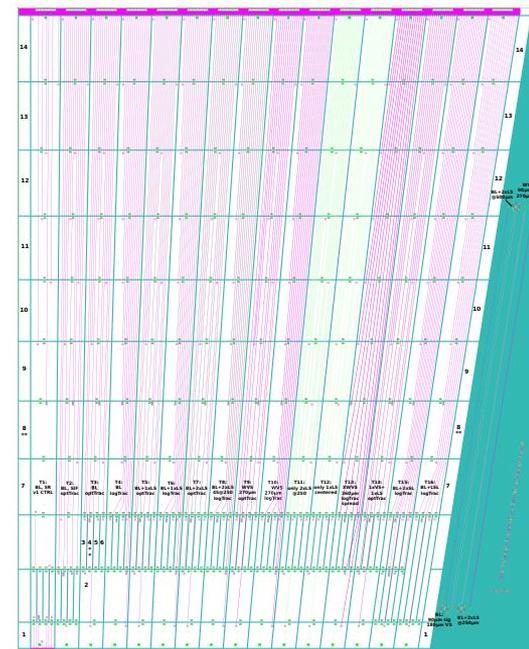
Granularity of Noble Liquid Calorimeters

- Calorimeter collects ionization charge
 - Granularity of the calorimeter
↔ granularity of the readout electrodes
- ATLAS: copper/kapton electrode
 - Traces to read out middle cells take real estate on back layer
 - Limits on longitudinal granularity
- FCC-ee requirements
 - High jet energy resolution needed
 - Particle flow algorithms take advantage of much finer granularity



Granularity of Noble Liquid Calorimeters

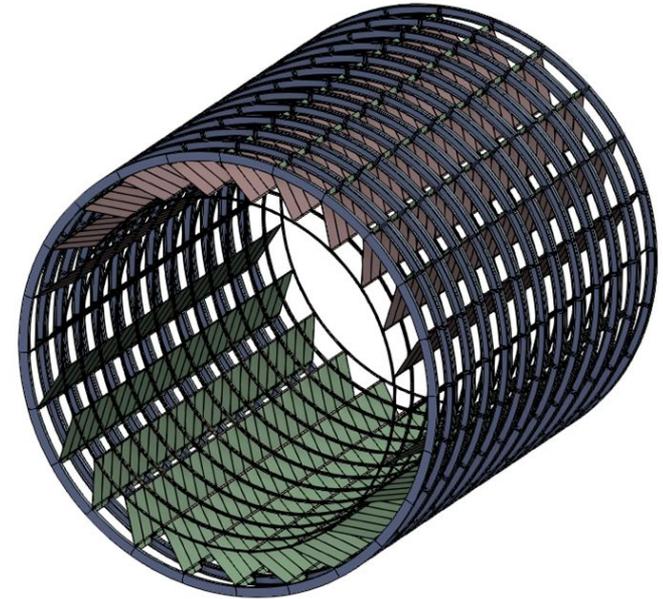
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- **Solution for Noble Liquid calo for FCC**
 - Multi-layer PCB to route signals inside
 - Allows for **~ ×10 ATLAS granularity**



Allegro Barrel Design

Design driven by the solution chosen for the electrodes

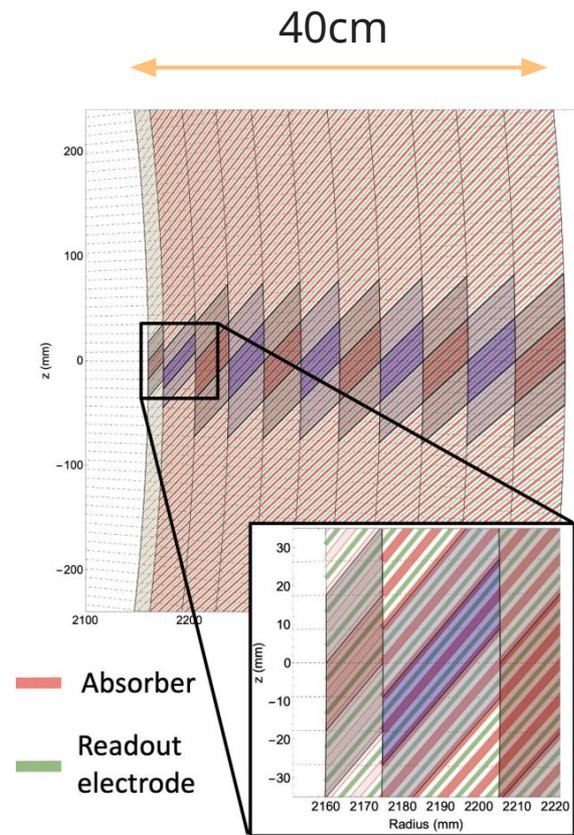
- Geometry description
 - 1536 **straight inclined** (50°) 1.8mm absorber plates
 - Segmented multi-layer PCBs as readout electrodes
 - 1.2 – 2.4mm LAr gaps ~20% sampling fraction
 - 40cm deep (**22 X₀**)
 - $\Delta\theta \times \Delta\phi = 10 \times 8$ mrad, 11 longitudinal layers
- PCBs as electrodes: great flexibility
 - Number of layers and granularity of each layer tuneable
 - Projective cells in θ and ϕ
- Active and passive material
 - Baseline: **Pb** for absorbers, **LAr** gaps
 - Options of **W** absorbers and **LKr** being investigated



Allegro Barrel Design

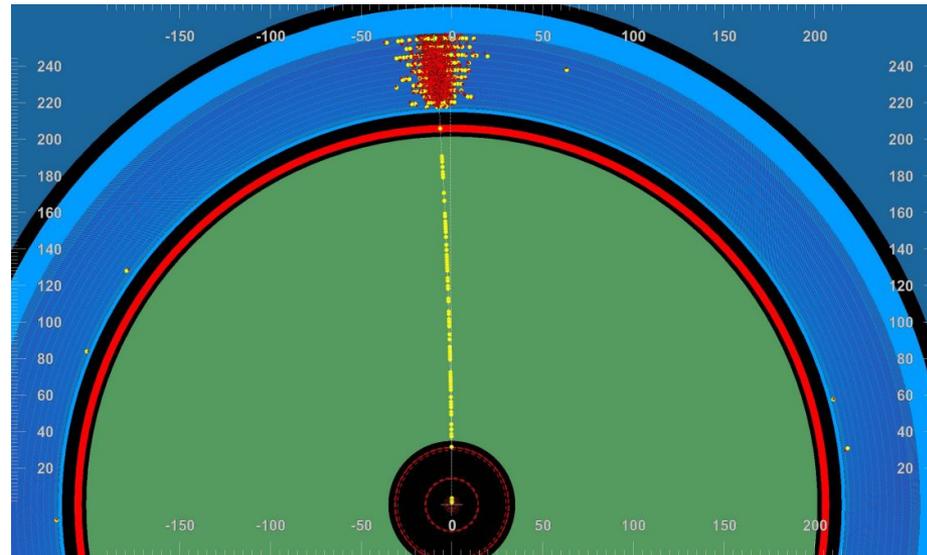
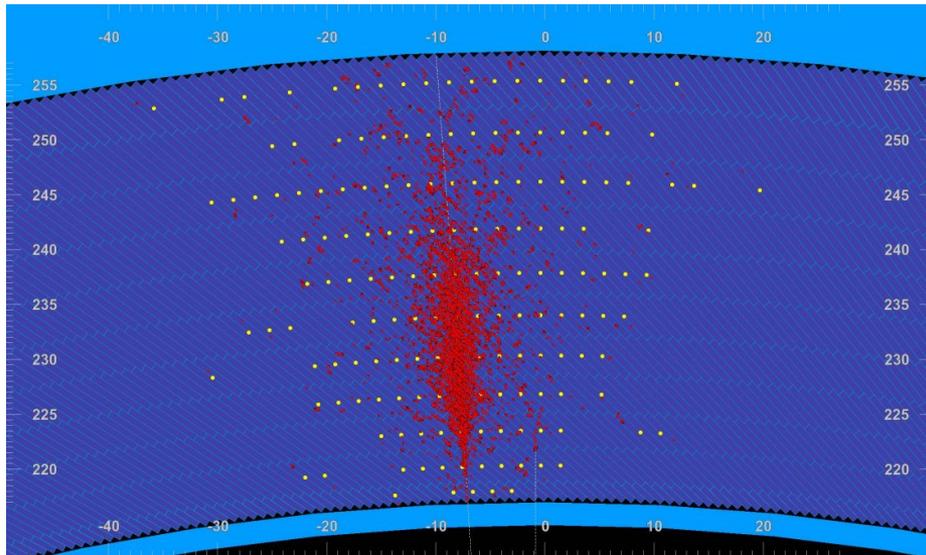
Design driven by the solution chosen for the electrodes

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 - Segmented multi-layer PCBs as readout electrodes
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Calorimeter Simulation

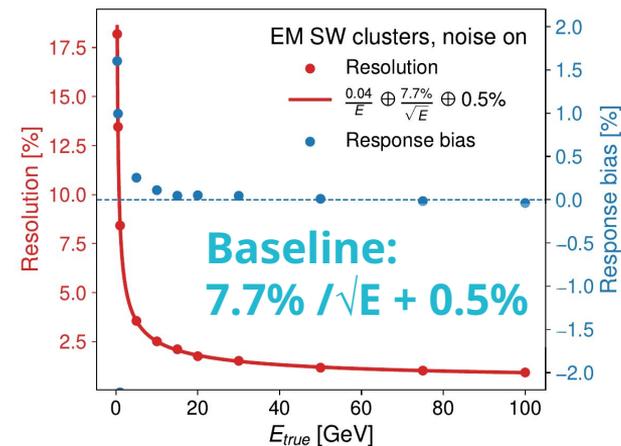
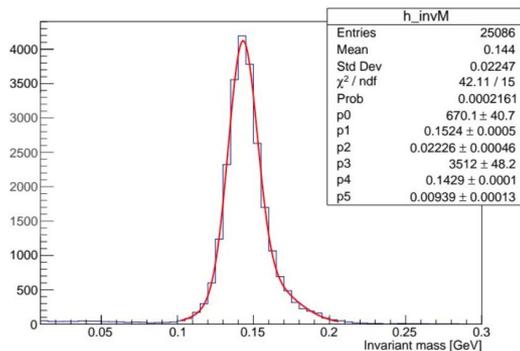
- Full calorimeter simulation implemented in Key4hep
 - (DD4hep/DDSim, EDM4hep, Gaudi)
 - Flexible enough to test easily new ideas



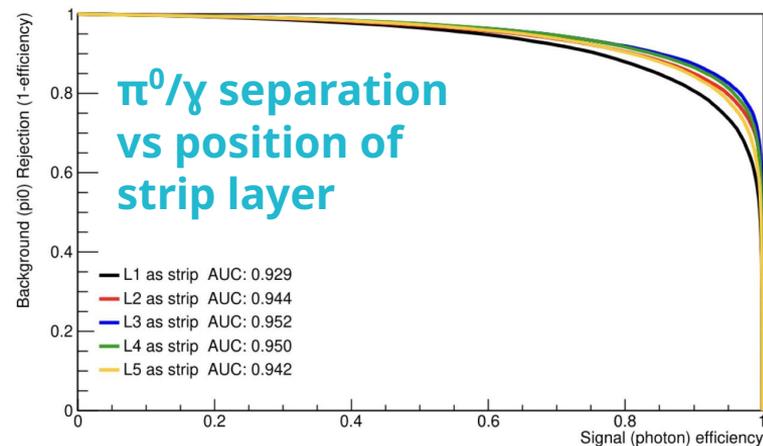
Simulations and design optimisation: granularity

- EM objects reconstruction using fixed-size or topo-clusters
 - Includes electronics noise and cross-talk effects
- Electron and photon energy reconstruction using BDT regression
- Studies on photon / π^0 classification
 - Allows to investigate EM granularity
 - Simple BDT for now ; GNN being developed
 - Physics case: hadronic τ decay modes

π^0 peak:
 $\sigma = 23$ MeV



BDT ROC Curve (sliding-window clusters)



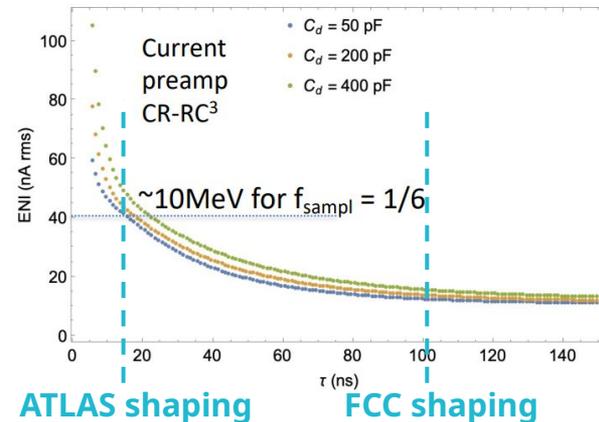
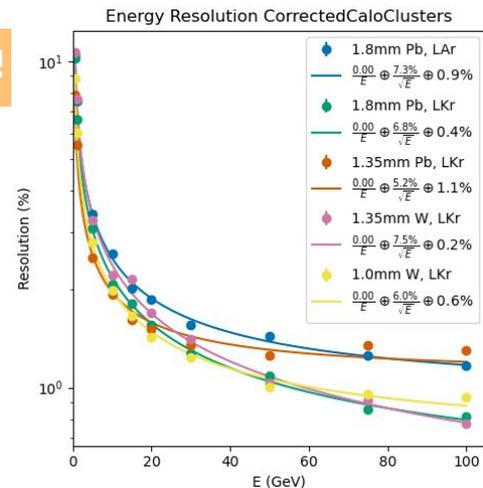
Energy resolution: design options and noise

Energy resolution: $\sigma(E)/E = a/E + b/\sqrt{E} + c \Rightarrow 3$ 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 \Rightarrow LKr, Pb \Rightarrow W
 - between **5%** and 7.5%
- **Noise term: readout electronics**
 - Req.: measurement of 200 MeV photons, $S/N > 5$ for MIPs

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

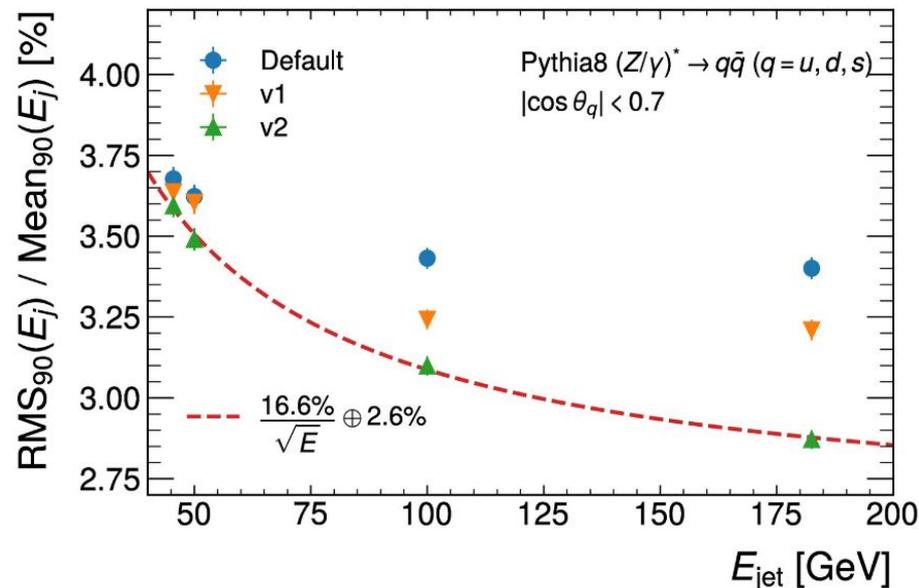
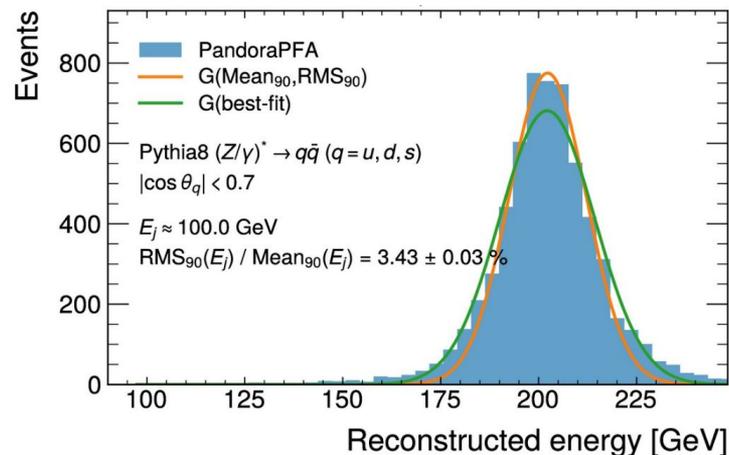
- Longer shaping time wrt ATLAS (200 ns)
- Cold frontend electronics in the cryostat will provide **noiseless readout**



Jet performance: particle flow reconstruction

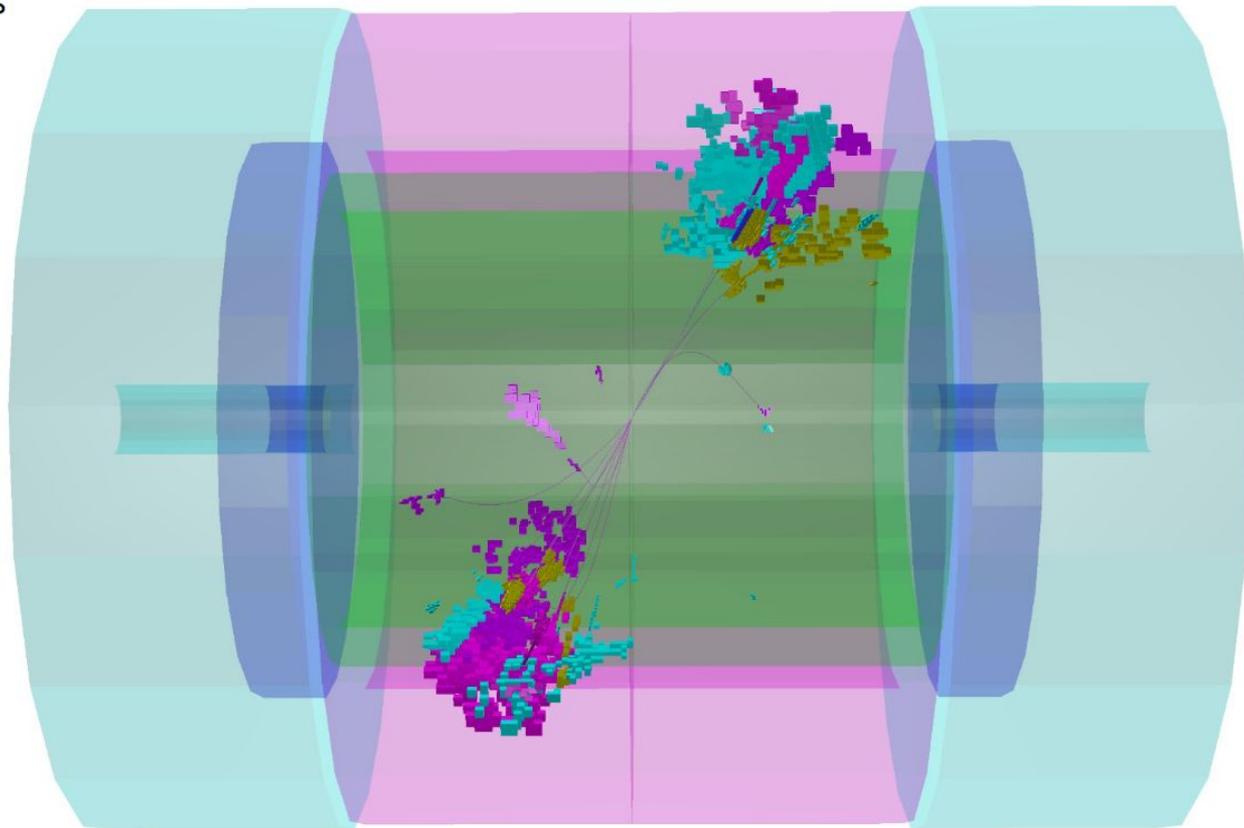
- Both Pandora PFA and GNN PFlow under development
- Very preliminary studies
 - True tracks used, no track reco
 - Lots of calibration constants and tuning to be done still
 - Typically clustering parameters

- **Very encouraging results**



100 GeV jets in ALLEGRO

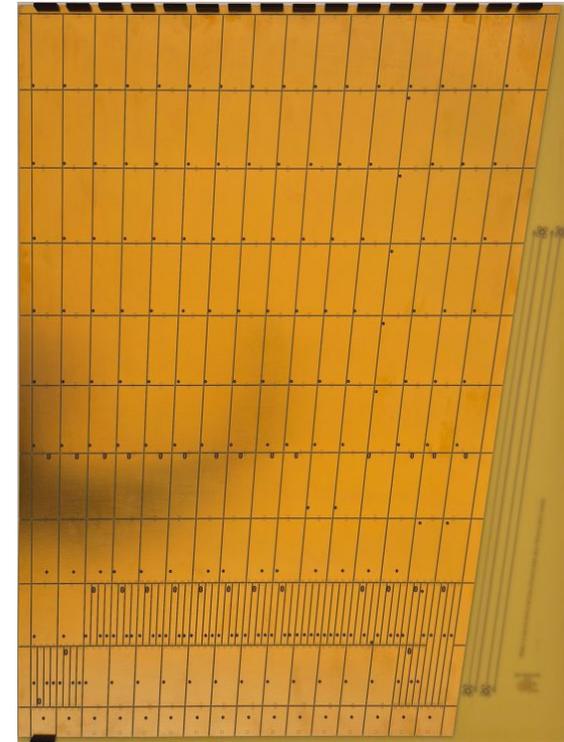
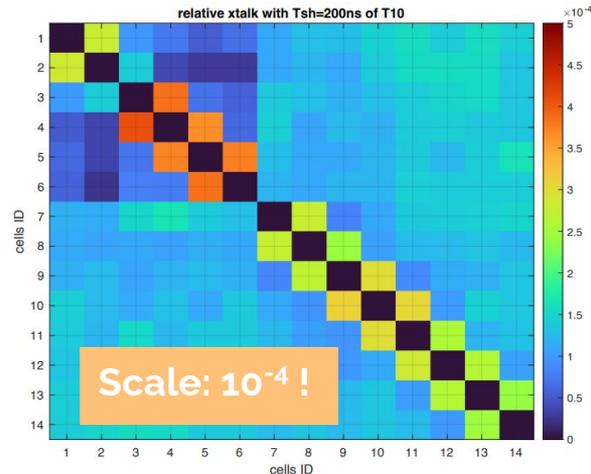
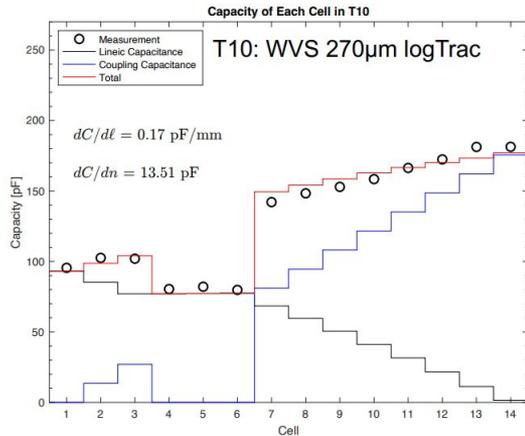
- Charged hadron associated hits
- Neutral hadron associated hits
- Photon associated hits



R&D on Electrodes

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

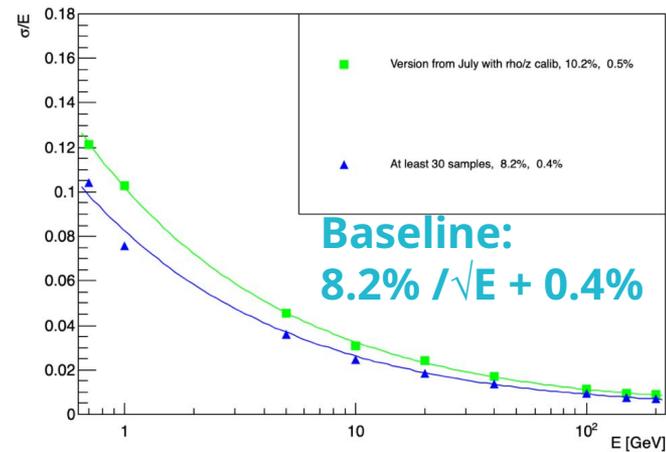
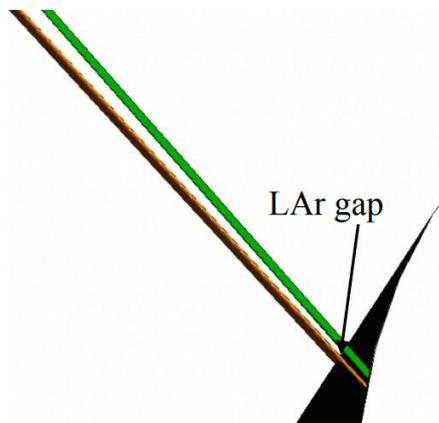
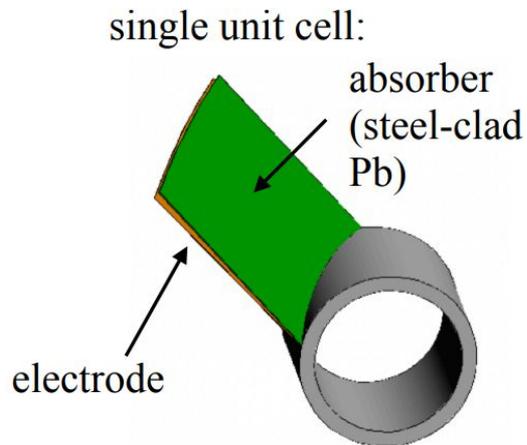
- Large-scale prototypes built with many design options
 - Especially for shielding of signal traces
- Conclusions so far
 - (sub)-**per-mille cross-talk achievable**
 - while keeping reasonable cell capacitances
 - Good agreement with FEM simulations
 - Holds up to 5 kV on outer layer



End-caps: turbine design

Turbine design: adaptation of barrel idea to end-caps regions

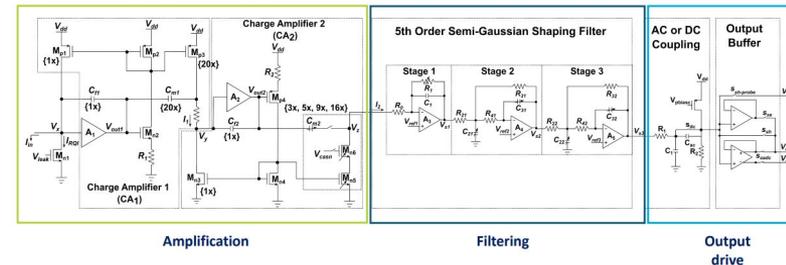
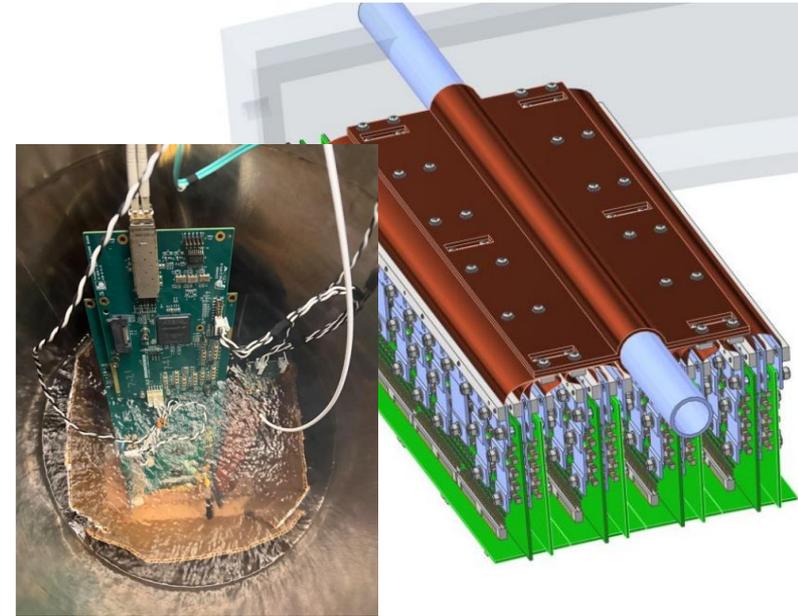
- Nice properties:
 - High sampling frequency
 - Uniformity in ϕ
 - Ability to read out solely from the high- $|z|$ face
 - Can be constructed with multiple copies of a small number of electrode/absorber designs



Readout electronics in the cold

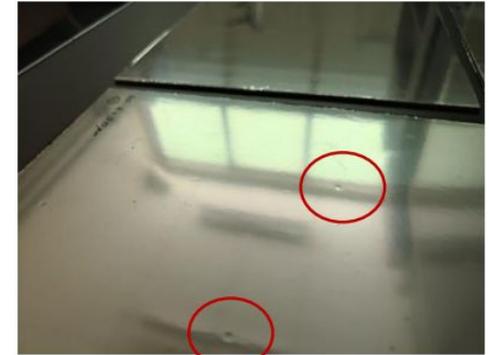
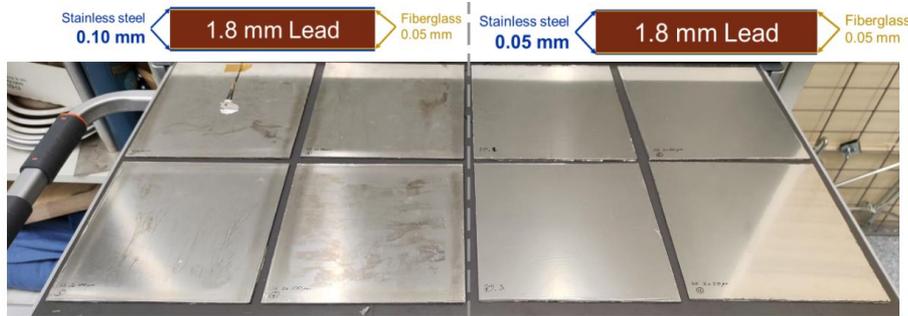
ALLEGRO Ecal barrel: ~2M channels

- Warm electronics outside of cryostat:
2M cables to route \Rightarrow avoid if possible
- Cold electronics: fewer cables, digital signals
 - But: needs room for boards + HV, powering and signal cables
 - Proposed solution inspired by DUNE electronics
 - Requires cooling system to dissipate heat
- Cold Frontend ASICs: two designs, based on Dune LArASIC or on CMS HGCROC
 - DUNE: turn a cryogenic-ready design into calorimeter application
 - CMS: turn a calorimeter chip into a lower-power, cryogenic-ready design
 - Tests of CALOROC to begin soon
 - First tests of CHARMS ASIC promising



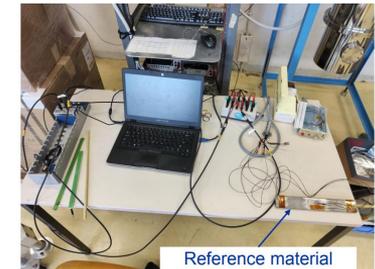
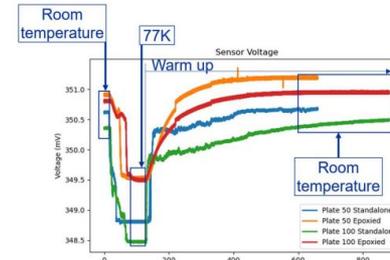
R&D on Absorbers

- Absorbers are 1.8mm lead plates sandwiched between stainless steel sheets, glued by prepreg
 - Absorbers fabricated with 0.1mm and 0.05mm SS sheets
 - Deformations appear in cold tests at 77K with 0.05mm sheets only



- CTE investigations
 - Deformations probably due to CTE differences
 - Investigated using strain gauges

- **0.1mm SS sheets is now default**
- **R&D conclusive !**

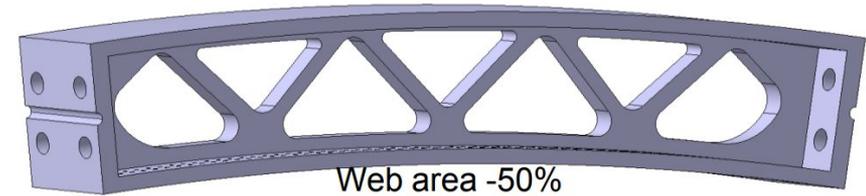


Reference material
Stainless steel sample

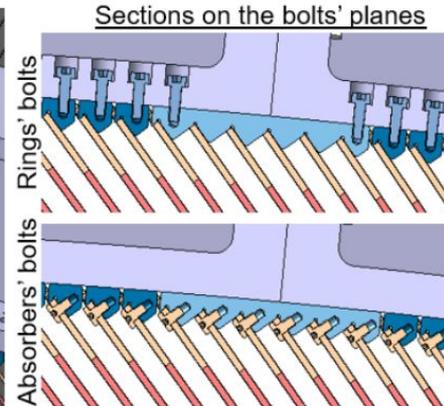
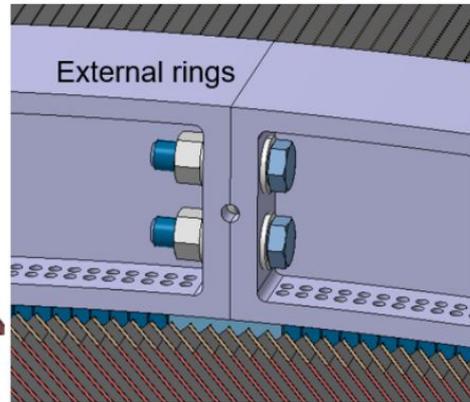
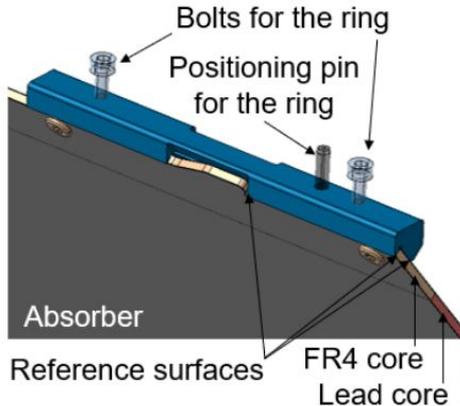
Support structures and general design

Compactness, rigidity, high precision in positioning

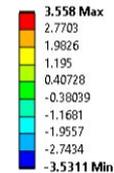
- How to hold the electrodes and absorbers ?
 - Overall structure is given by support rings, external and internal
 - Calculations to chose minimal beam size
 - High precision: need uniform LAr gaps
- Add constraints to route cables and pipes
 - ANSYS studies for hollow structure



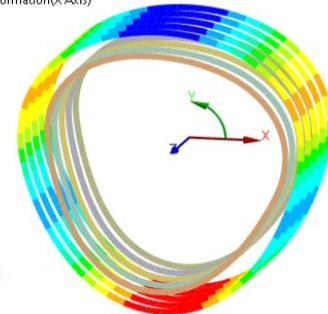
Radial displacement +15 %



D: v19.1 Gravity
Radial Deformation External Rings 1
Type: Directional Deformation(X Axis)
Unit: mm
CYLINDRICAL CS
Time: 1 s



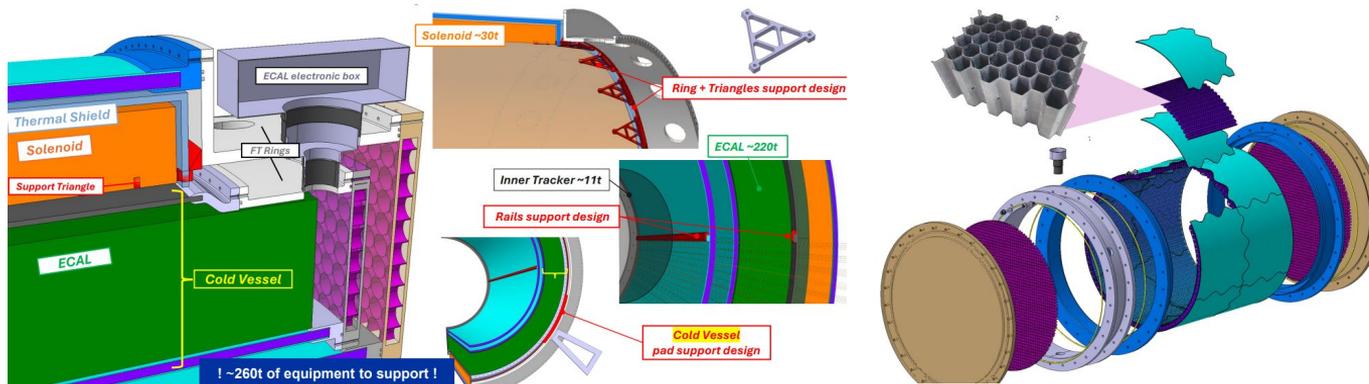
Scale x50



Transparent Cryostat for ALLEGRO Ecal

Minimal amount of $X_0 \Rightarrow$ Investigate solutions based on carbon fiber

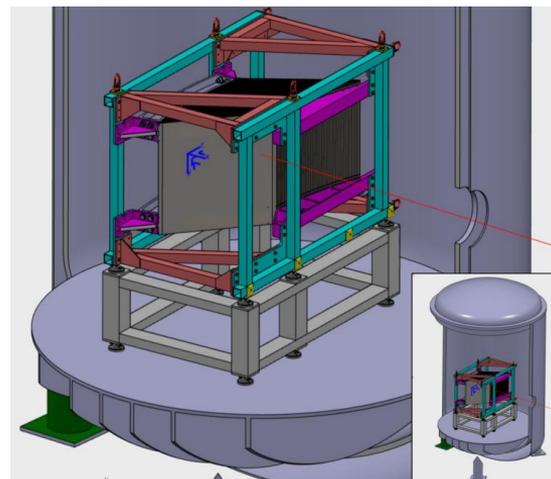
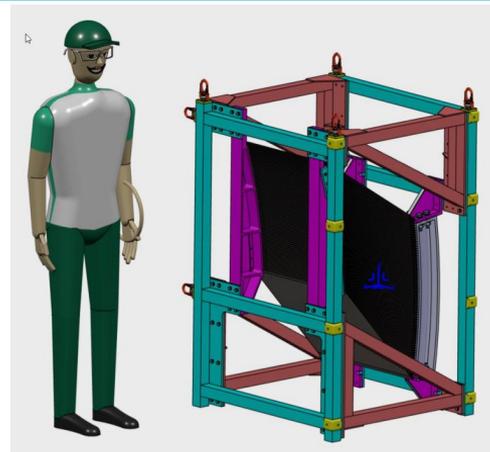
- Carbon cryostats developed for aerospace applications
 - But requirements quite different !
- R&D from component level to Engineering Models
 - **Sandwich Carbon layers + honeycomb: 3% X_0 / wall !**
- Design of a cryostat suitable for ALLEGRO in progress
 - With plans for demonstrators



Putting it all together: prototype module

Main goal of the R&D within 5 years

- Prototype representative of a calorimeter section
 - Full **containment of EM showers**
 - Realistic size of support beams
 - 64 electrodes, 65 absorber plates
 - ~5000 channels
- Advanced design of structure used for assembly and support
- Testbeams at CERN
 - Using existing cryostats
 - Post-LS3: 2029 – 2030
 - Coordination of calorimeter testbeams at DRD6 level



The ALLEGRO Detector Concept



**Noble Liquid
Ecal**

Lumical

MDI

**Steel -
Scintillator
Hcal**

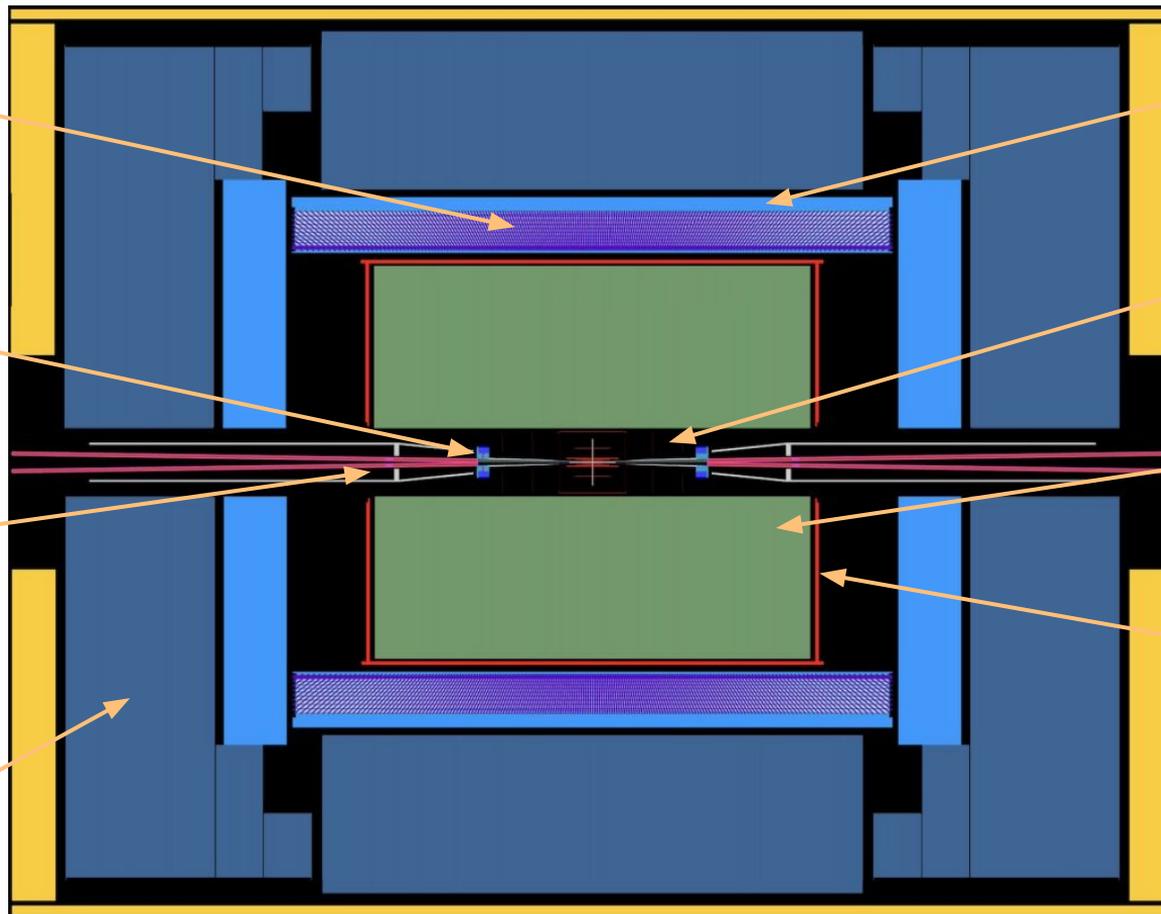
2T Solenoid

**Vertex
Detector**

Main tracker

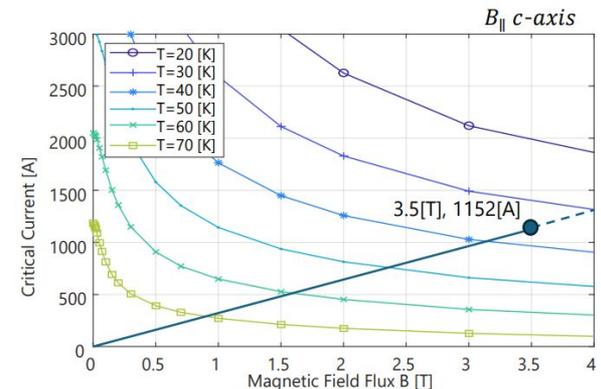
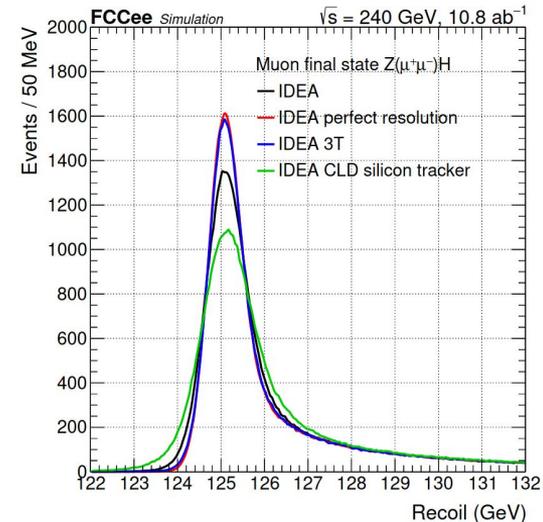
**Silicon
Wrapper**

Muon Tagger



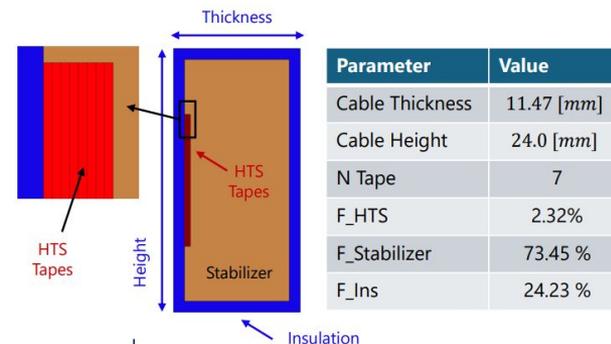
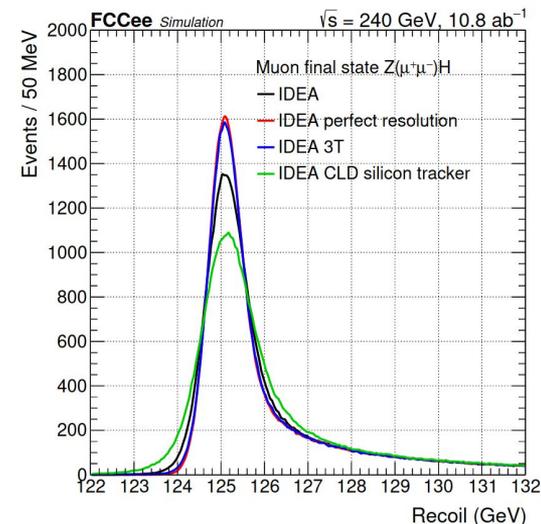
Next Generation Detector Magnets

- **Baseline is 2T solenoid**
 - Limit to 2T to not blow-up electron bunches at Z pole !
 - Current technology: Al-stabilized NbTi Rutherford cables
 - Well understood technology, affordable and good mechanical properties
 - **NOT Commercially available nowadays**
 - Required low temperature operation (< 5 K)
- **Physics would benefit from 3T at higher energies**
 - Higgs mass at ± 4.1 MeV
- **Studies begin ([IDEA detector concept](#)) for HTS 3T Detector solenoid !**
 - Increasing **Top** from 1.9 K to 15-20 K would increase the Cryogenic system efficiency by one order of magnitude!!!
 - Operate at 2T only for Z pole running
 - Cable concept: U Shape channel cable with Faraday Factory HTS REBCO Tapes
 - With AlTi stabilizer: solenoid ~ 12 cm thick, $1.5 X_0$



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**Steel -
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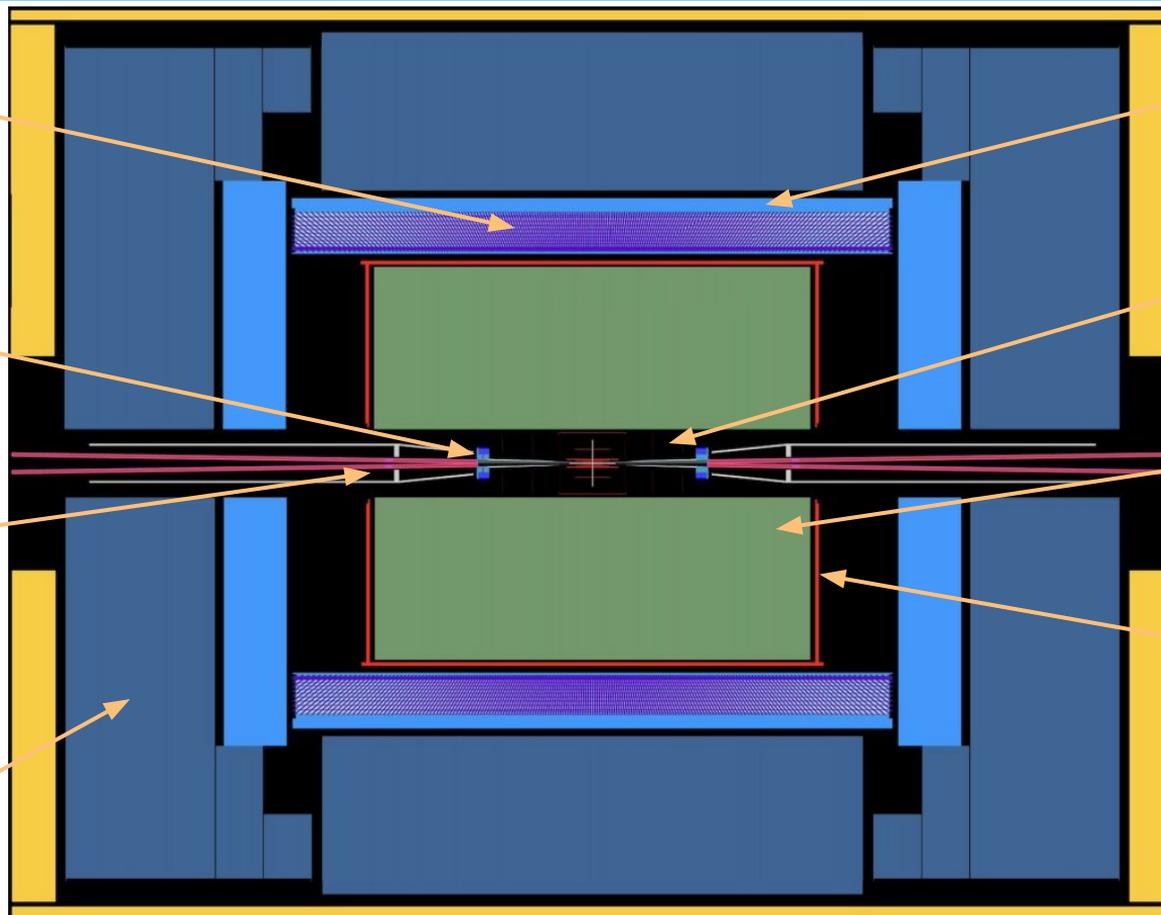
2T Solenoid

**Vertex
Detector**

Main tracker

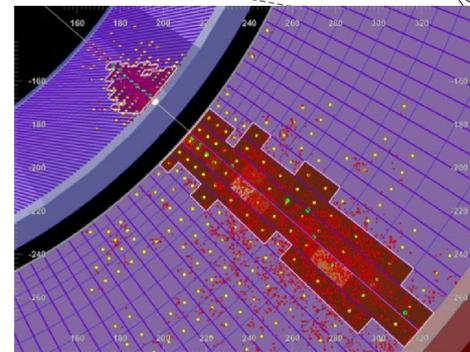
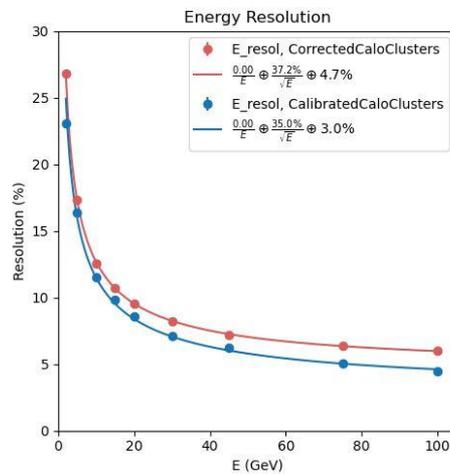
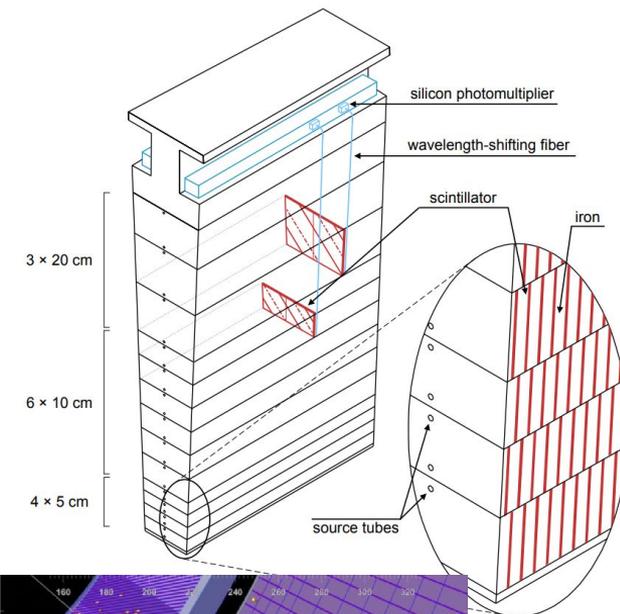
**Silicon
Wrapper**

Muon Tagger



Scintillating Tiles Hcal

- HCal inspired by ATLAS TileCal implemented in FCC Fullsim
 - Either with WLS (à la ATLAS), or with SiPM on Tiles (à la AHCAL)
 - Serves as return yoke
- Design
 - 5mm steel absorber plates alternating with 3mm Scintillating tiles: $8 - 9.5\lambda$
 - 128 modules in ϕ , 2 tiles/module, 13 radial layers
 - Optimisation of segmentation and reconstruction
- Prototype studies starting
- Performance
 - Ecal + Hcal combined clustering implemented
 - Single-pion resolution: $35\%/\sqrt{E}$



The ALLEGRO Detector Concept



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Ecal**

2T Solenoid

Lumical

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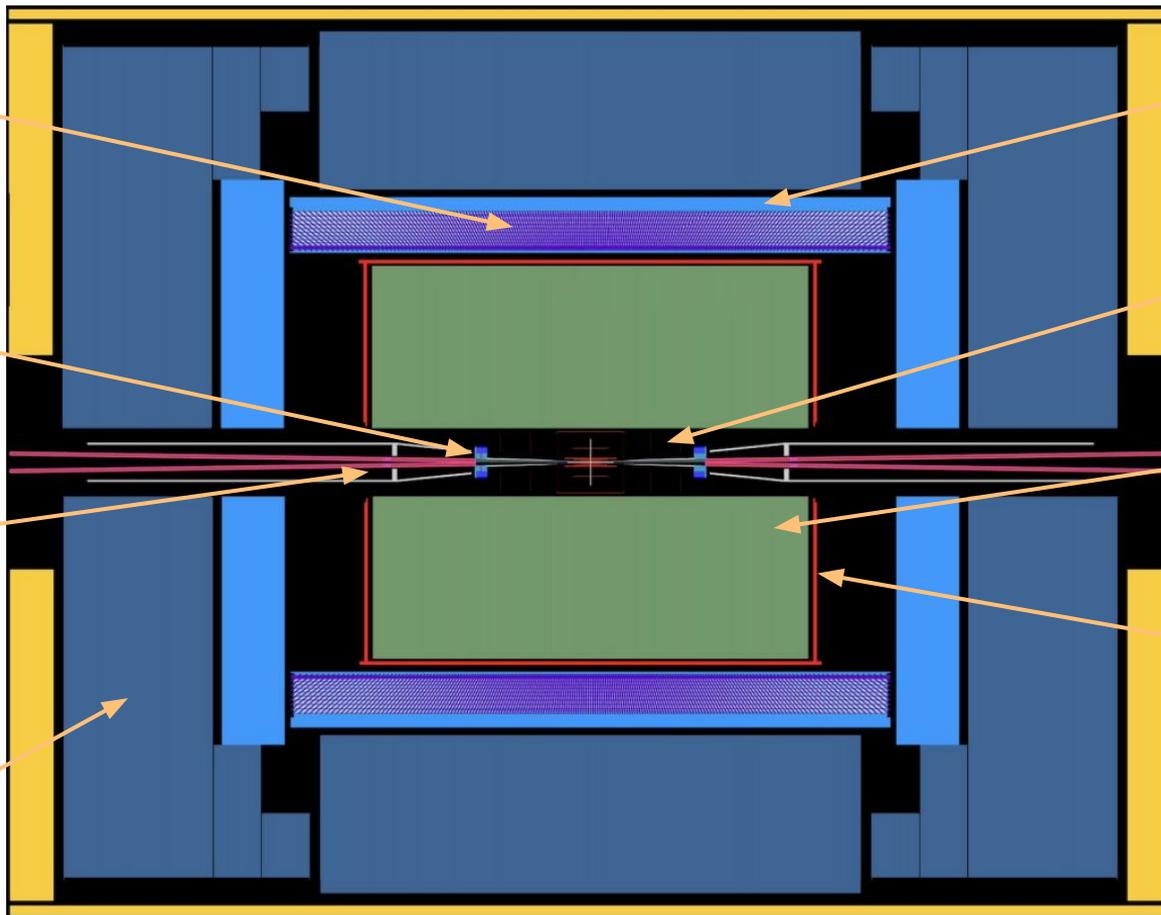
MDI

Main tracker

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Scintillator
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**Silicon
Wrapper**

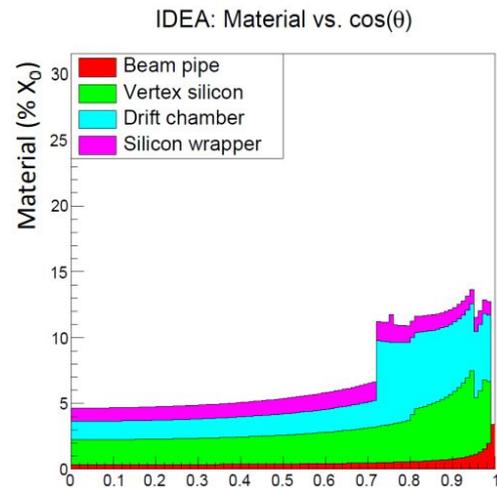
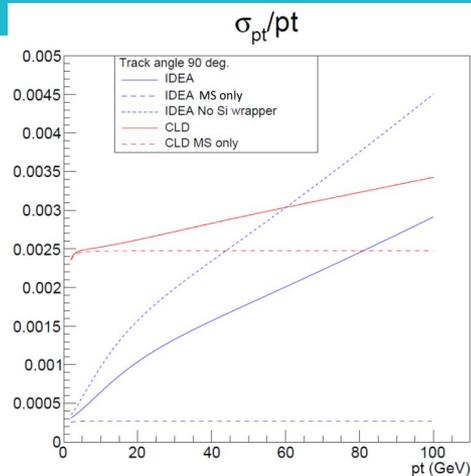
Muon Tagger



Vertex Detector

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
 - Extremely light: Inner layers: 0.1% X_0 / layer
 - Outer layers: 0.5 – 1% X_0 / layer
 - Designs using curved sensors



⚙️ No cabling, no piping in the active area

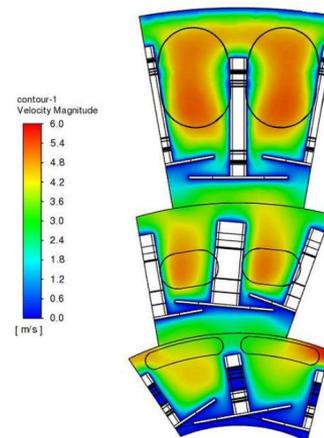
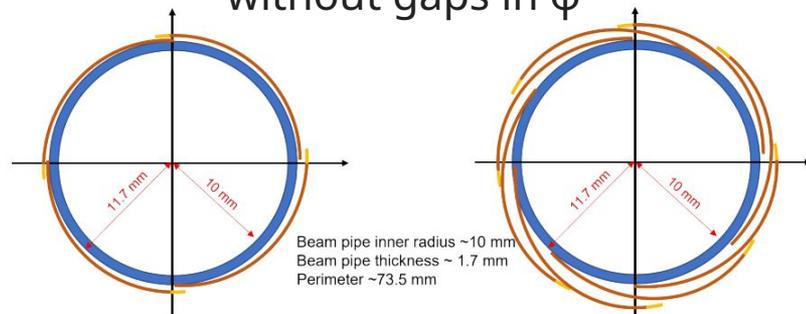


⚙️ Curved MAPS sensor

Vertex Detector

- Several CMOS processes available
 - e.g TPSCo 65nm
- Spatial hit resolution
 - $3\mu\text{m}$ per layer achievable with $15\mu\text{m}$ pitch or $25\mu\text{m}$ pitch with charge sharing
- Cooling
 - Study air-flow cooling to minimize X_0
 - Studied for IDEA Vertex Detector so far

FCC Seed: curved sensors without gaps in ϕ



The ALLEGRO Detector Concept



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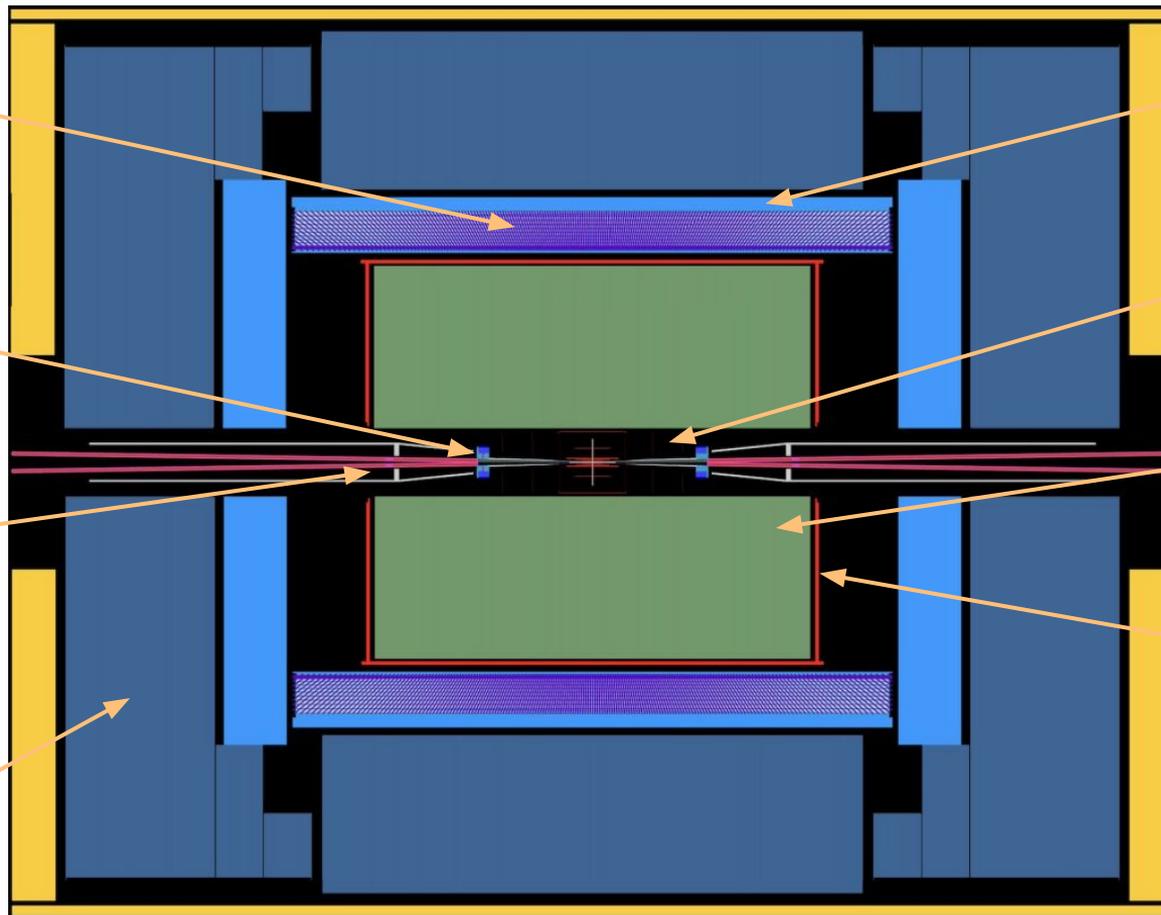
2T Solenoid

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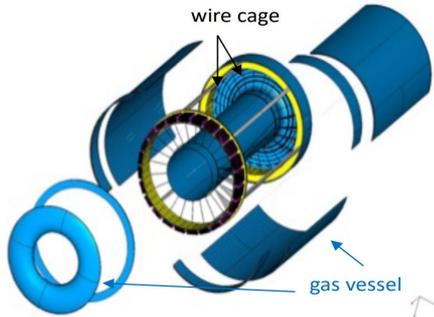
Muon Tagger



Drift chamber: IDEA design

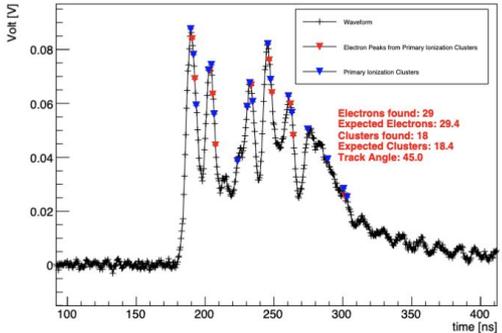
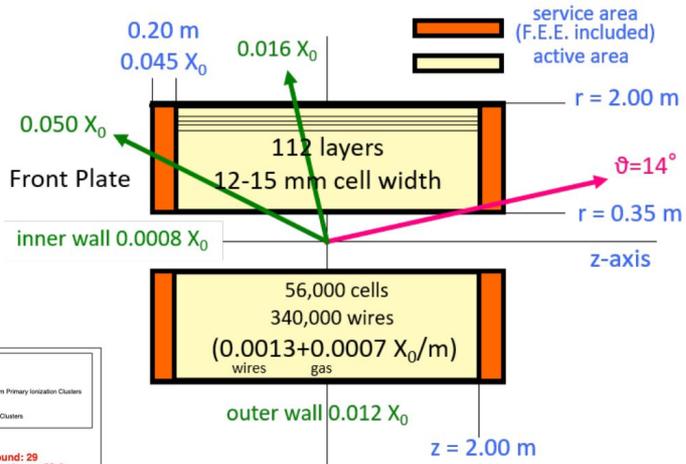
IDEA: Extremely transparent Drift Chamber

- Large volume:
 - $R_{in} = 0.35\text{ m}$, $R_{out} = 2\text{ m}$, $L = 4\text{ m}$
- 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 \Rightarrow fewer layers
 - Careful optimisation needed
- Expected resolution $\sigma_{xy} < 100\ \mu\text{m}$, $\sigma_z < 1\text{ mm}$
- Cluster counting for PID



tracking efficiency $\epsilon \approx 1$
 for $\vartheta > 14^\circ$ (260 mrad)
 97% solid angle

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



$\delta_{cl} = 12./\text{cm}$ for He/ iC_4H_{10} =90/10 and a 2m track $\rightarrow \sigma \approx 2.0\%$

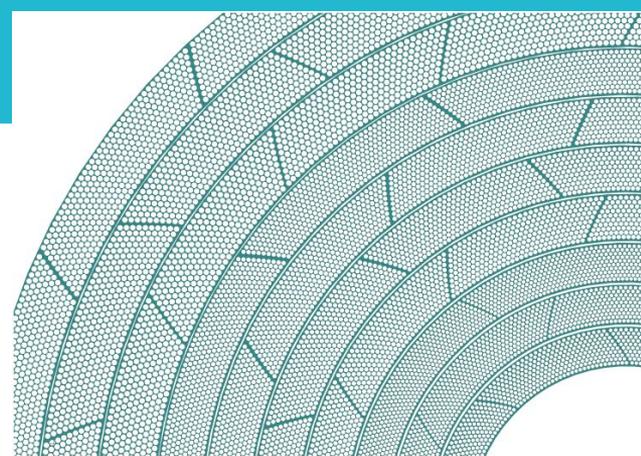
$$\frac{\sigma_{dN_{cl}/dx}}{(dN_{cl}/dx)} = (\delta_{cl} \cdot L_{track})^{-1/2} = N_{cl}^{-1/2}$$

Poisson

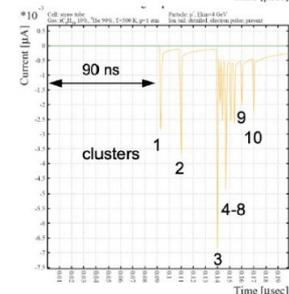
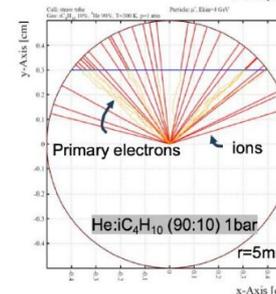
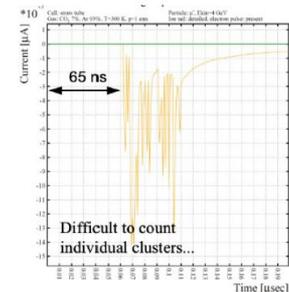
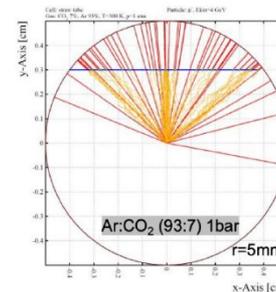
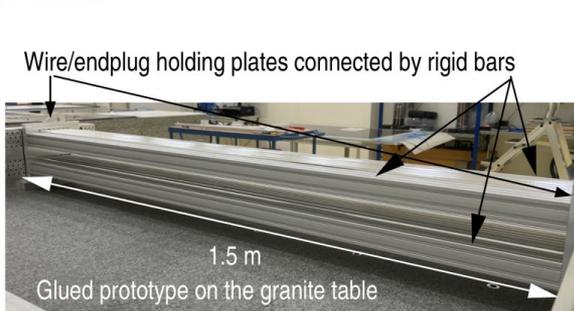
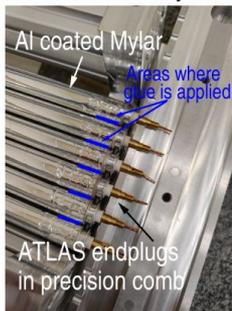
Straw Trackers Studies

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 dN/dx measurements



Chamber assembly at MPP Munich



The ALLEGRO Detector Concept



**Noble Liquid
Ecal**

2T Solenoid

Lumical

**Vertex
Detector**

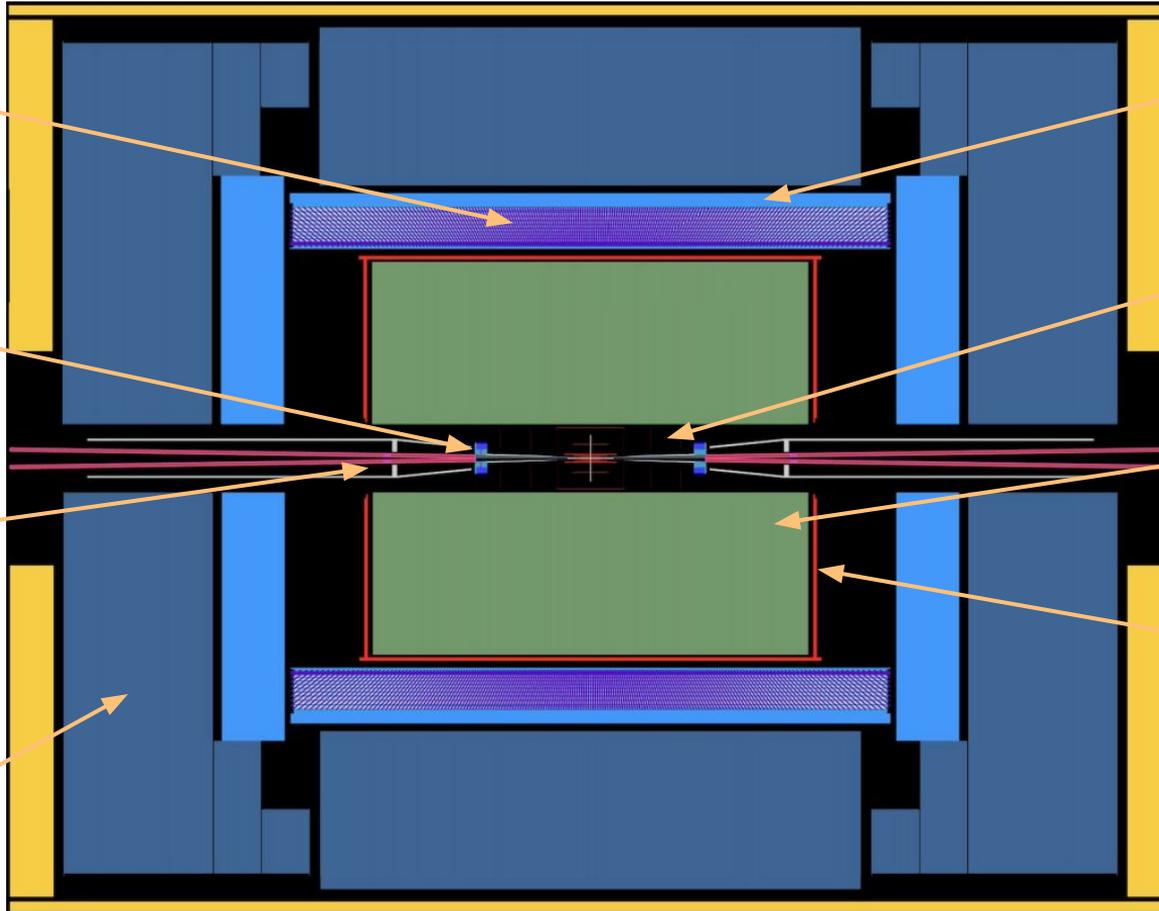
MDI

Main tracker

**Steel -
Scintillator
Hcal**

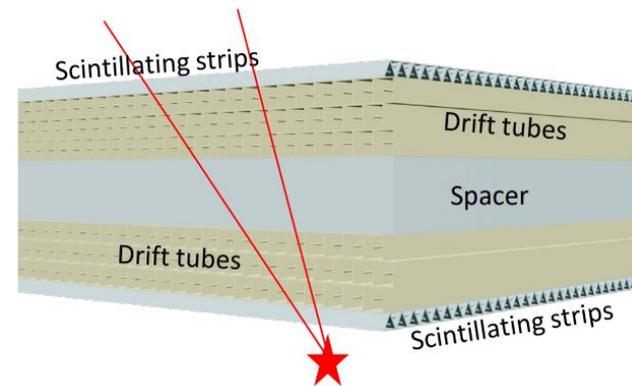
**Silicon
Wrapper**

Muon Tagger

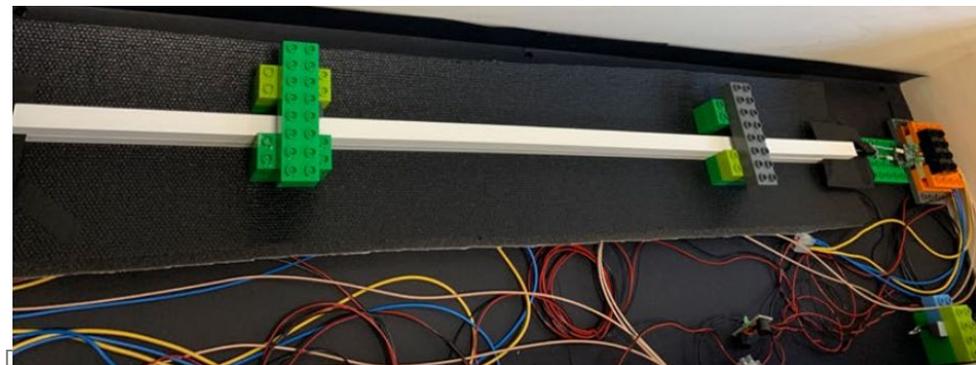
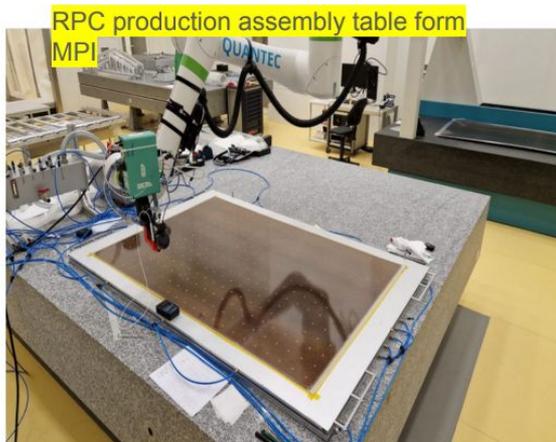


Muon Tagger

- Hcal acting as return yoke \Rightarrow very little B-field in muon system
 - Simple muon tagger, no spectrometer
- Many technologies proposed
 - RPCs, MDT, MicroMegas, scintillators
- Time-of-flight capabilities might be an advantage
 - Esp. for exotic searches (LLP)
 - Need more studies to make the case



Long-lived particle decay vertex away from IP



Conclusions

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

Detectors at FCC-ee will be **as challenging** as LHC detectors

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

A **noble-liquid based Ecal** is a **high-performance cost-effective** solution for a calorimeter at FCC-ee, and ongoing R&D aim to prove feasibility of the design

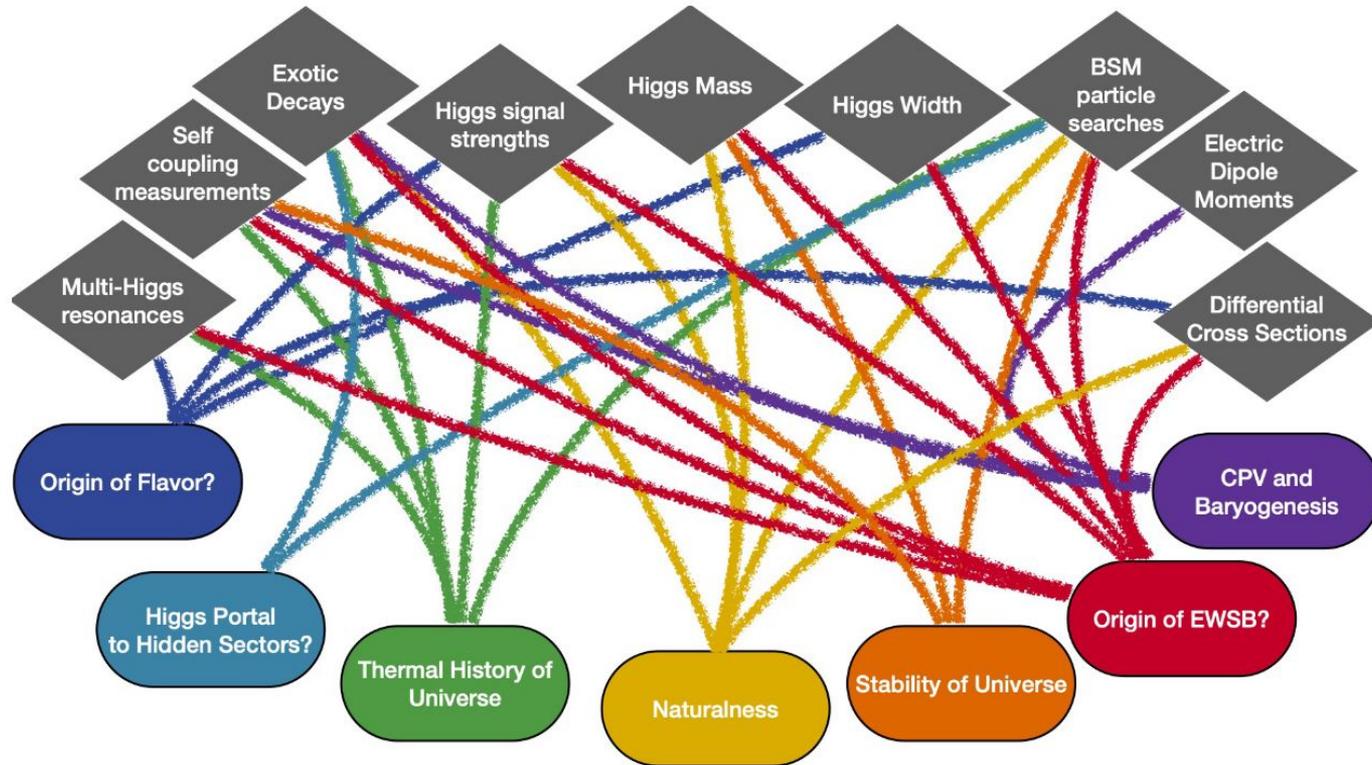
Additional Material

A lot of fun for all detectors

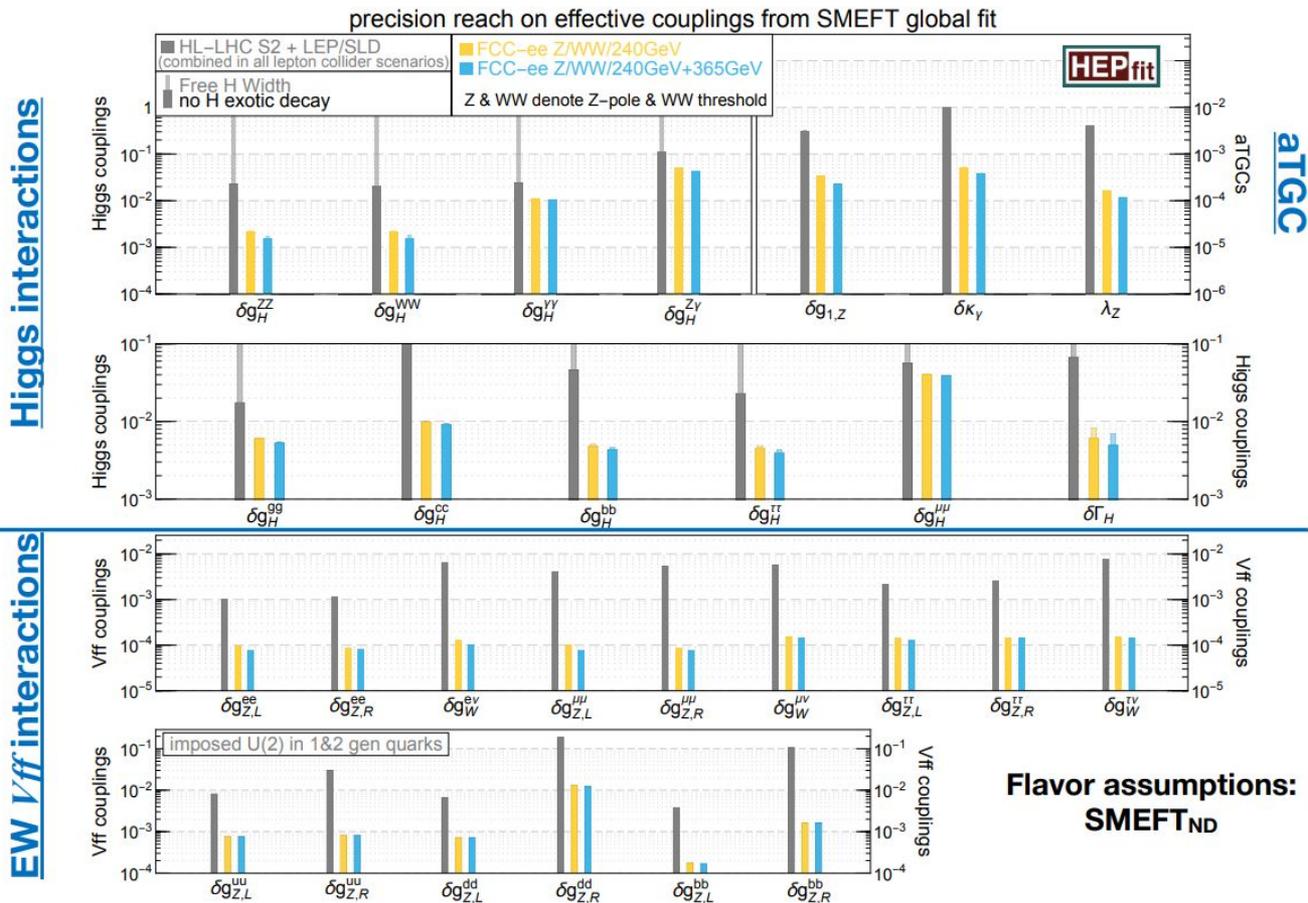
	Aggressive	Conservative	Comments
Beampipe	$X/X_0 < 0.5\%$	$X/X_0 < 1\%$	$B \rightarrow K^* \tau \tau$
Vertex	$\sigma(d_0) = 3 \oplus 15 / (p \sin^{3/2} \theta) \mu\text{m}$ $X/X_0 < 1\%$	–	$B \rightarrow K^* \tau \tau$ R_c
	$\delta L = 5 \text{ ppm}$	–	$\delta \tau_\tau < 10 \text{ ppm}$
Tracking	$\sigma_p/p < 0.1\%$ for $\mathcal{O}(50) \text{ GeV}$ tracks	$\sigma_p/p < 0.2\%$ for $\mathcal{O}(50) \text{ GeV}$ tracks	$\delta M_H = 4 \text{ MeV}$ $\delta \Gamma_Z = 15 \text{ keV}$ $Z \rightarrow \tau \mu$
	t.b.d.	$\sigma_\theta < 0.1 \text{ mrad}$	$\delta \Gamma_Z(\text{BES}) < 10 \text{ keV}$
ECAL	$\sigma_E/E = 3\%/\sqrt{E}$	$\sigma_E/E = 10\%/\sqrt{E}$	$Z \rightarrow \nu_e \bar{\nu}_e$ coupling, B physics, ALPs τ polarisation boosted π^0 decays bremsstrahlung recovery
	$\Delta x \times \Delta y = 2 \times 2 \text{ mm}^2$	$\Delta x \times \Delta y = 5 \times 5 \text{ mm}^2$	
	$\delta z = 100 \mu\text{m}$, $\delta R_{\min} = 10 \mu\text{m}$ ($\theta = 20^\circ$)	In-situ constraint with dilepton/diphoton events	alignment tolerance for $\delta \mathcal{L} = 10^{-5}$ with $\gamma\gamma$ events
HCAL	$\sigma_E/E = 30\%/\sqrt{E}$	$\sigma_E/E = 50\%/\sqrt{E}$	$H \rightarrow s\bar{s}, c\bar{c}, gg$, invisible HNLs
	$\Delta x \times \Delta y = 2 \times 2 \text{ mm}^2$	$\Delta x \times \Delta y = 20 \times 20 \text{ mm}^2$	$H \rightarrow s\bar{s}, c\bar{c}, gg$
Muons	low momentum ($p < 1 \text{ GeV}$) ID	–	$B_s \rightarrow \nu \bar{\nu}$
Particle ID	$3 \sigma K/\pi$ $p < 40 \text{ GeV}$	$3 \sigma K/\pi$ $p < 30 \text{ GeV}$	$H \rightarrow s\bar{s}$ $b \rightarrow s \nu \bar{\nu}, \dots$
LumiCal	tolerance $\delta z = 100 \mu\text{m}$, $\delta R_{\min} = 1 \mu\text{m}$ acceptance 50–100 mrad	–	$\delta \mathcal{L} = 10^{-4}$ target (Bhabha)
Acceptance	100 mrad	–	$e^+e^- \rightarrow \gamma\gamma$ $e^+e^- \rightarrow e^+e^-\tau^+\tau^-(c\bar{c})$

The Higgs Landscape

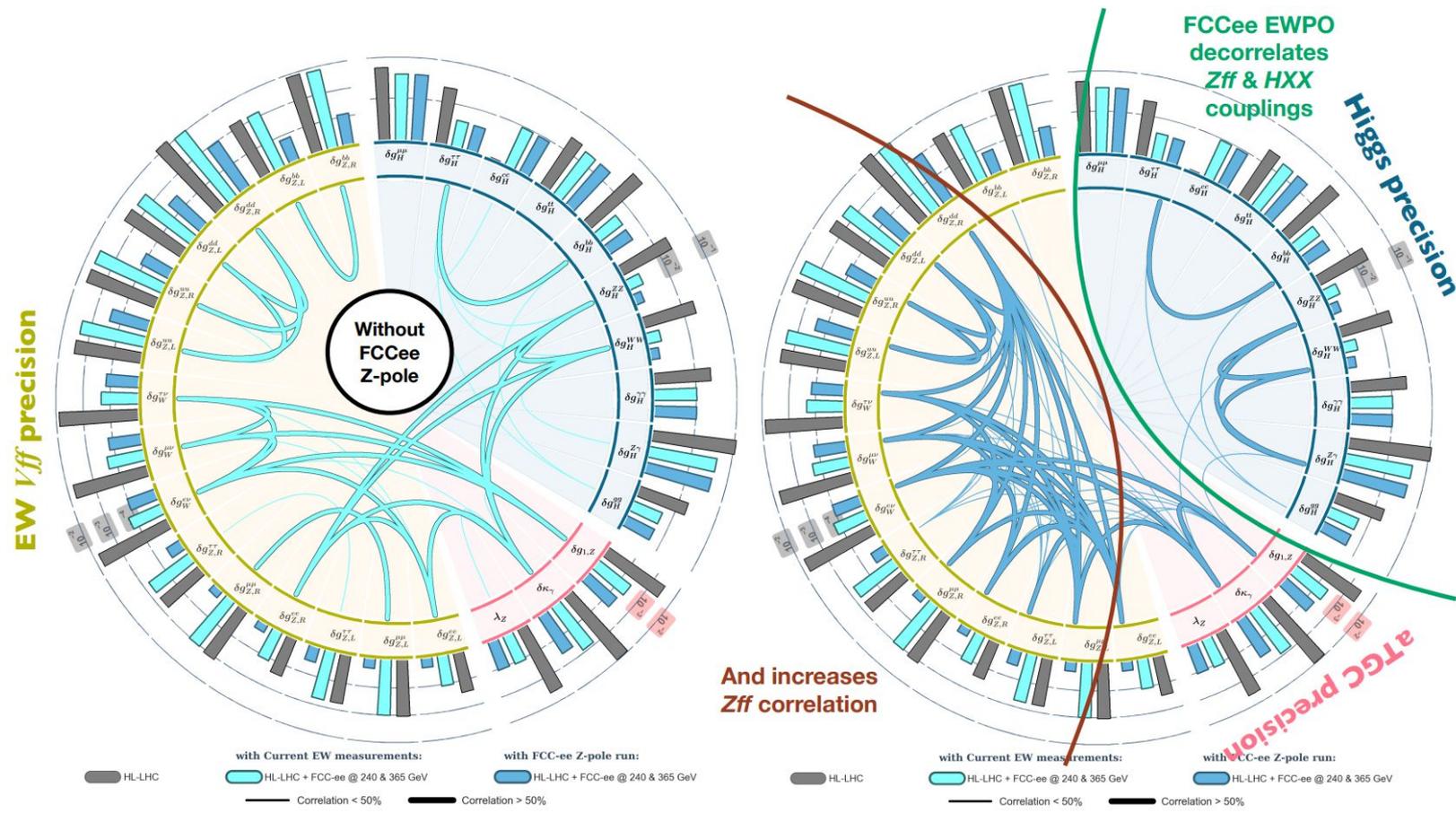
Links to many mysteries of the SM !



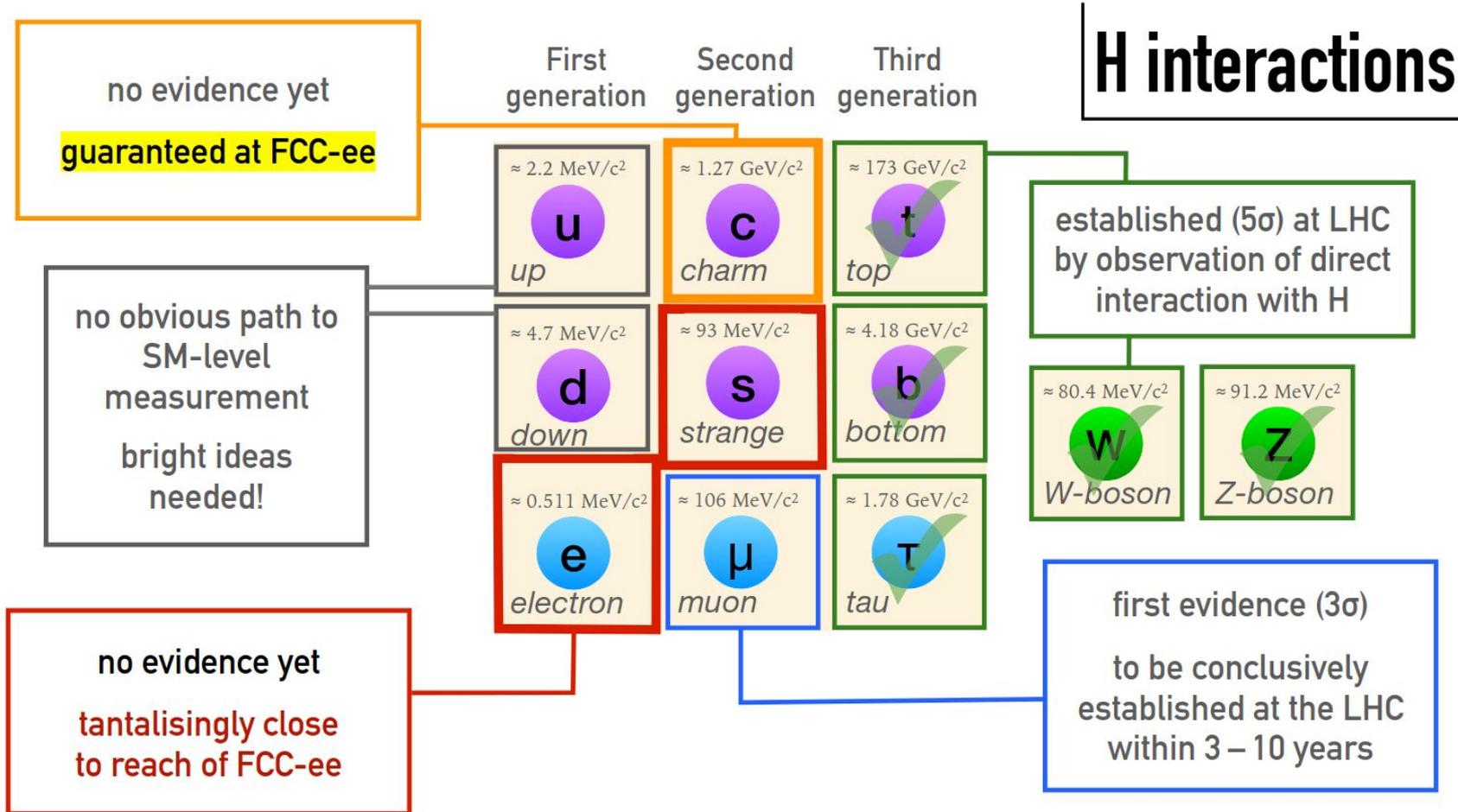
Higgs couplings in SMEFT Fit



Higgs Couplings: Complementarity between Energies



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

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

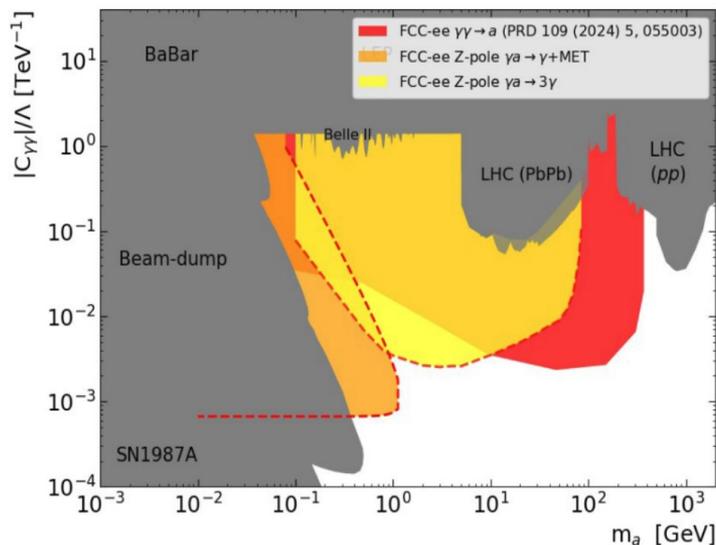
↑ ↑ ↑ ↑

flavour naturalness stability cosmological constant

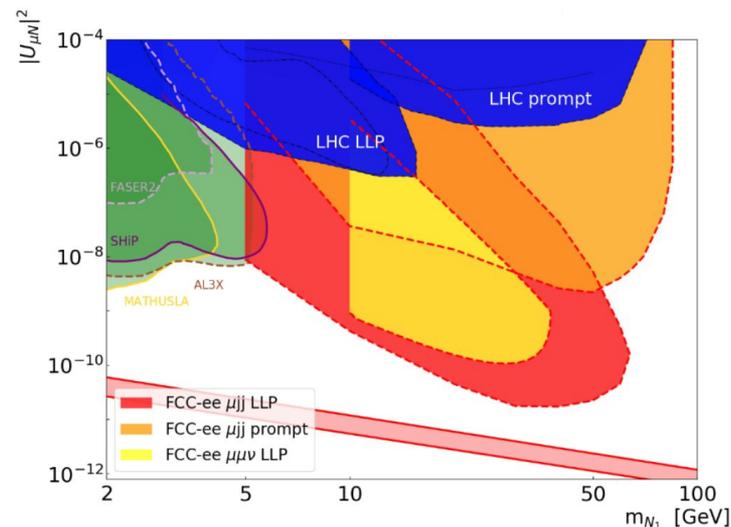
Exploring into the unknown

Complementary signatures wrt HL-LHC

Axions-like Particles



Heavy Neutral Leptons

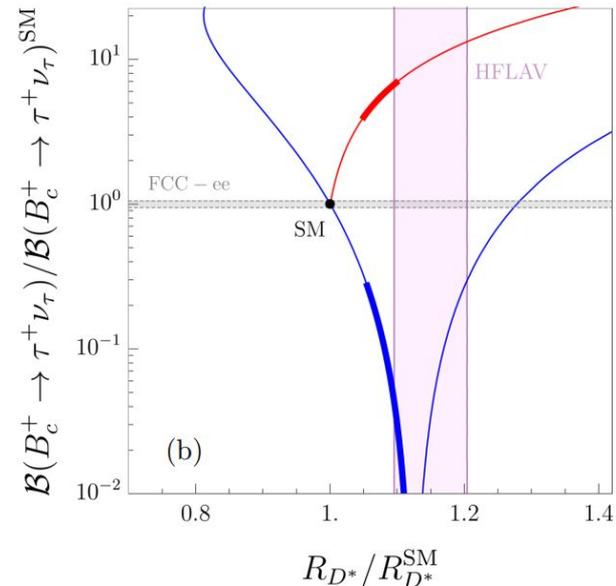
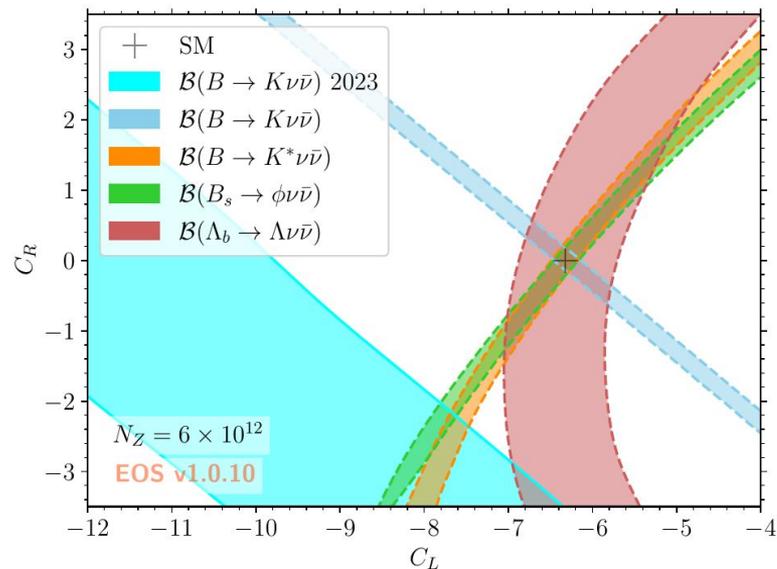


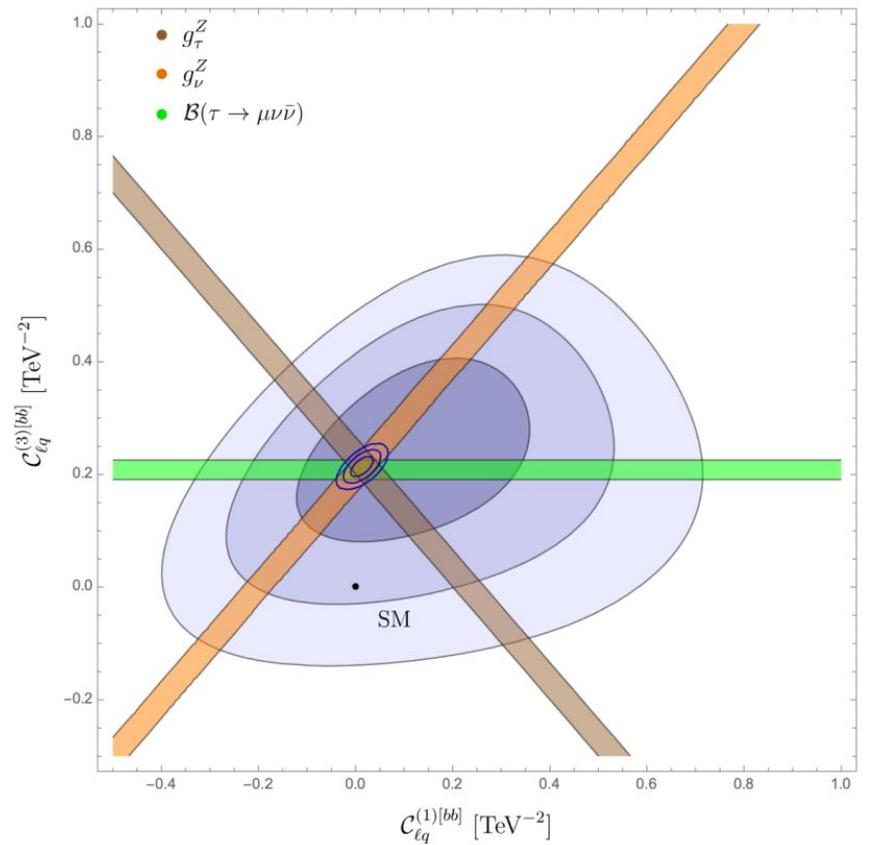
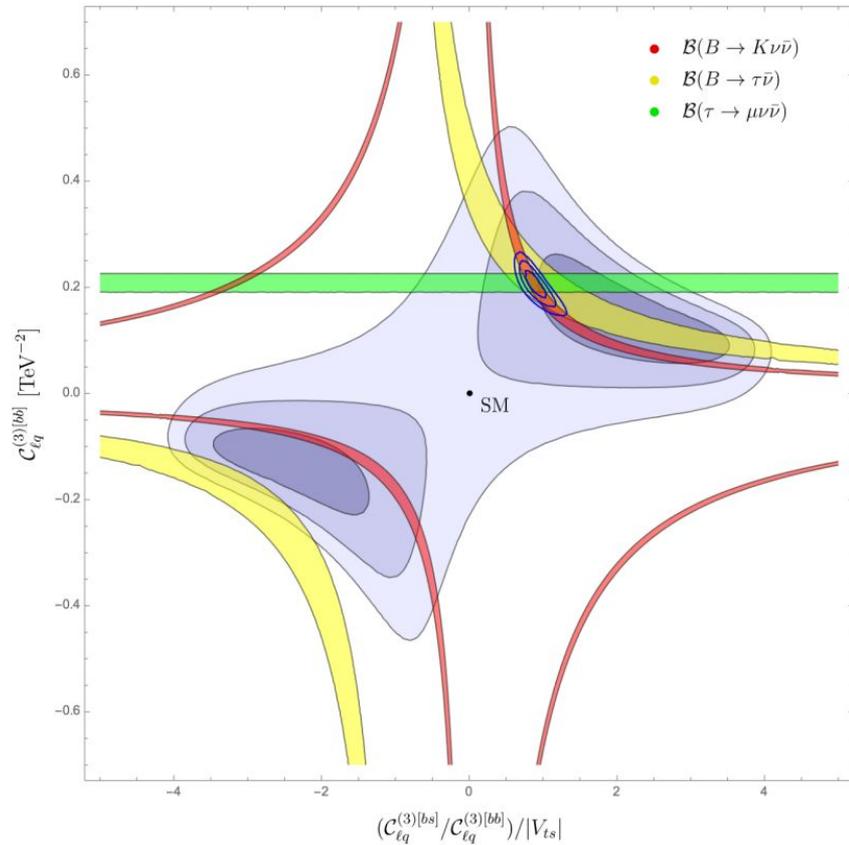
+ Precision measurements will probe scales up to 40 TeV (through EFTs)

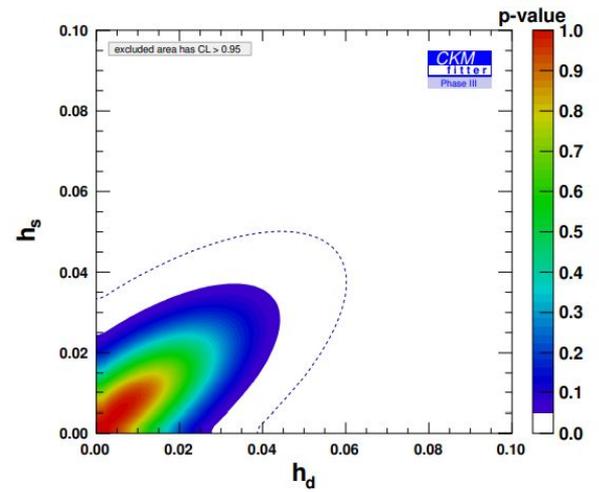
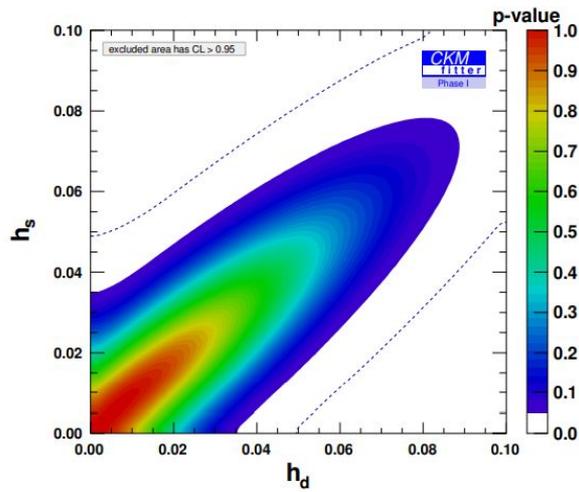
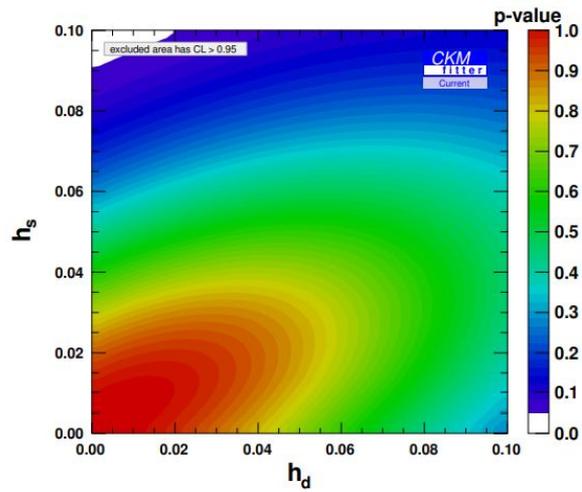
FCC-ee: a Flavour factory

10× bb and cc pairs wrt Belle 2 !

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







The ultimate EW precision

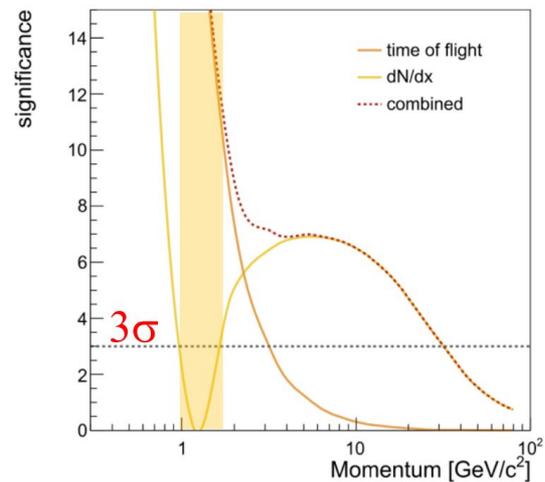
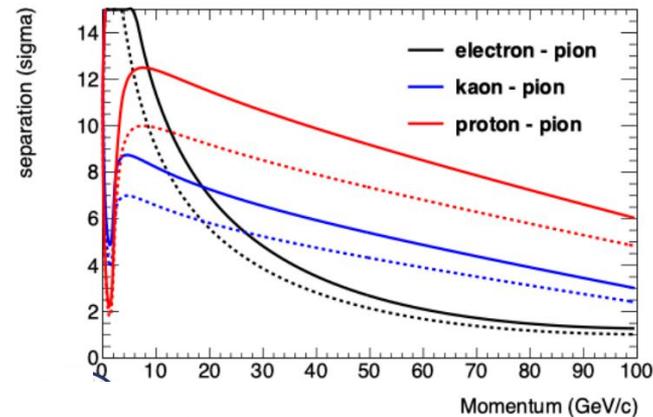
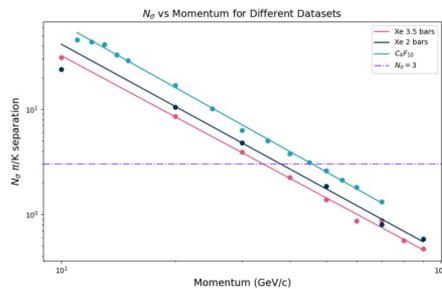
A real challenge for theory calculations !

Observable	present value	present \pm uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	\pm 2000	4	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	\pm 2300	4	12	From Z line shape scan Beam energy calibration
$\sin^2 \theta_W^{\text{eff}} (\times 10^6)$	231,480	\pm 160	1.2	1.2	From $A_{\text{FB}}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\text{QED}}(m_Z^2) (\times 10^3)$	128 952	\pm 14	3.9 0.8	small tbc	From $A_{\text{FB}}^{\mu\mu}$ off peak From $A_{\text{FB}}^{\mu\mu}$ on peak QED&EW uncert. dominate
$R_\ell^Z (\times 10^3)$	20 767	\pm 25	0.05	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2) (\times 10^4)$	1 196	\pm 30	0.1	1	Combined $R_\ell^Z, \Gamma_{\text{tot}}^Z, \sigma_{\text{had}}^0$ fit
$\sigma_{\text{had}}^0 (\times 10^3)$ (nb)	41 480.2	\pm 32.5	0.03	0.8	Peak hadronic cross section Luminosity measurement
$N_\nu (\times 10^3)$	2 996.3	\pm 7.4	0.09	0.12	Z peak cross sections Luminosity measurement
$R_b (\times 10^6)$	216 290	\pm 660	0.25	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{\text{FB}}^{b,0} (\times 10^4)$	992	\pm 16	0.04	0.04	b-quark asymmetry at Z pole From jet charge
$A_{\text{FB}}^{\text{pol},\tau} (\times 10^4)$	1 498	\pm 49	0.07	0.2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	\pm 0.5	0.001	0.005	ISR, τ mass
τ mass (MeV)	1 776.93	\pm 0.09	0.002	0.02	estimator bias, ISR, FSR
τ leptonic ($\mu\nu_\mu\nu_\tau$) BR (%)	17.38	\pm 0.04	0.00007	0.003	PID, π^0 efficiency

m_W (MeV)	80 360.2	\pm 9.9	0.18	0.16	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2 085	\pm 42	0.27	0.2	From WW threshold scan Beam energy calibration
$\alpha_S(m_W^2) (\times 10^4)$	1 010	\pm 270	2	2	Combined $R_\ell^W, \Gamma_{\text{tot}}^W$ fit
$N_\nu (\times 10^3)$	2 920	\pm 50	0.5	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172 570	\pm 290	4.2	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate
Γ_{top} (MeV)	1 420	\pm 190	10	6	From $t\bar{t}$ threshold scan QCD uncert. dominate
$\lambda_{\text{top}}/\lambda_{\text{top}}^{\text{SM}}$	1.2	\pm 0.3	0.015	0.015	From $t\bar{t}$ threshold scan QCD uncert. dominate
$t\bar{t}$ couplings		\pm 30%	0.5–1.5 %	small	From $\sqrt{s} = 365$ GeV run

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



Calorimetry options

Many options on the table, for both Ecal and Hcal

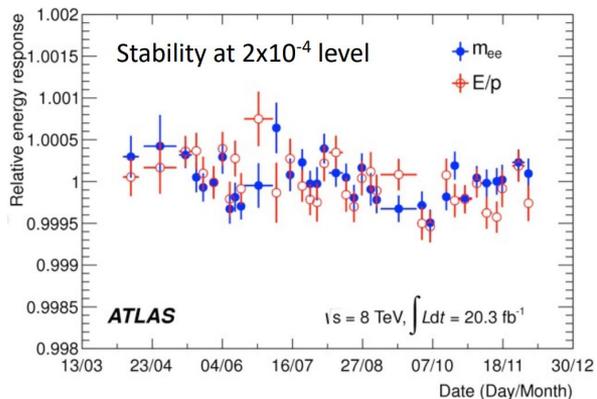
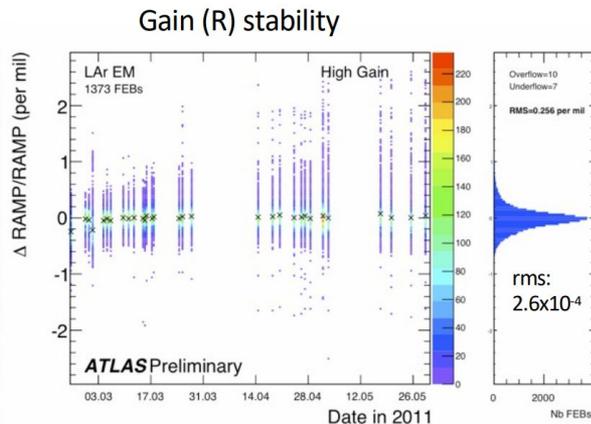
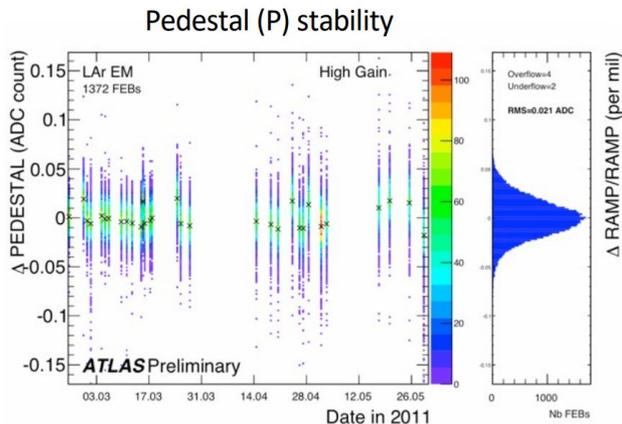
Detector technology (ECAL & HCAL)	E.m. energy res. stochastic term	E.m. energy res. constant term	ECAL & HCAL had. energy resolution (stoch. term for single had.)	ECAL & HCAL had. energy resolution (for 50 GeV jets)	Ultimate hadronic energy res. incl. PFlow (for 50 GeV jets)
Highly granular Si/W based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

Example: Stability of ATLAS LAr Energy Scale

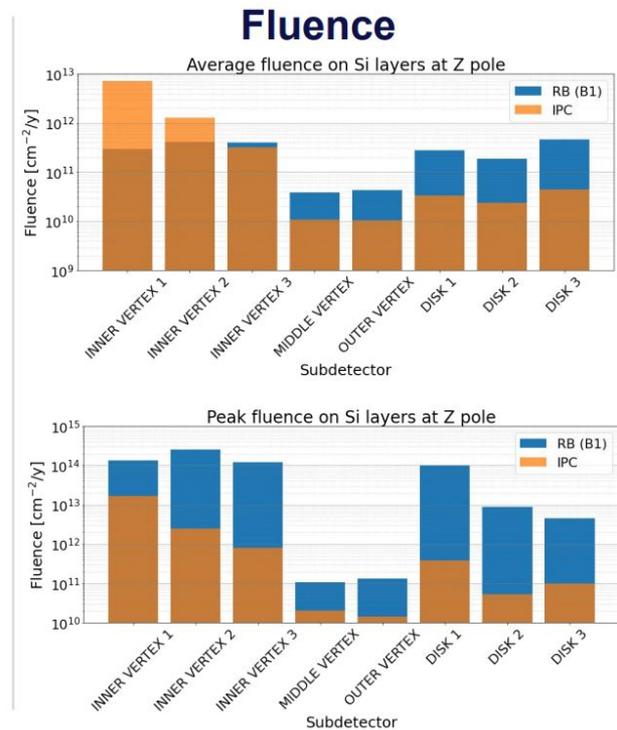
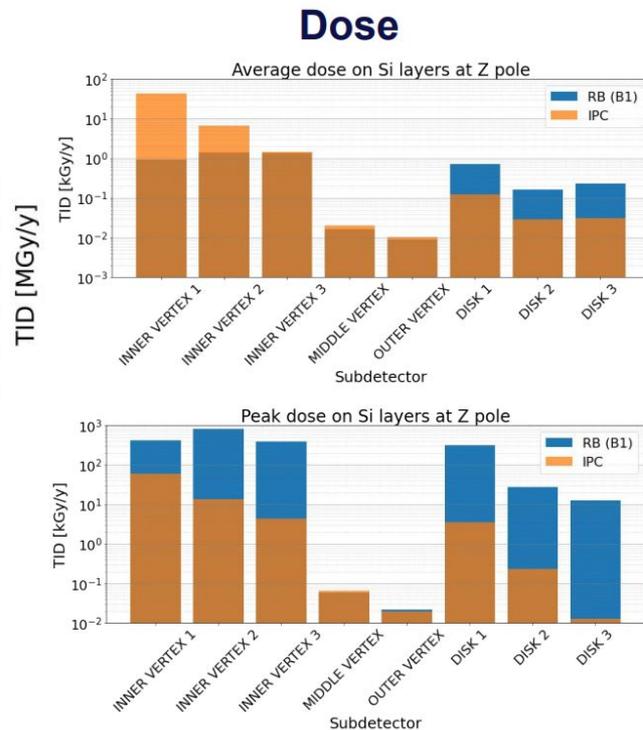
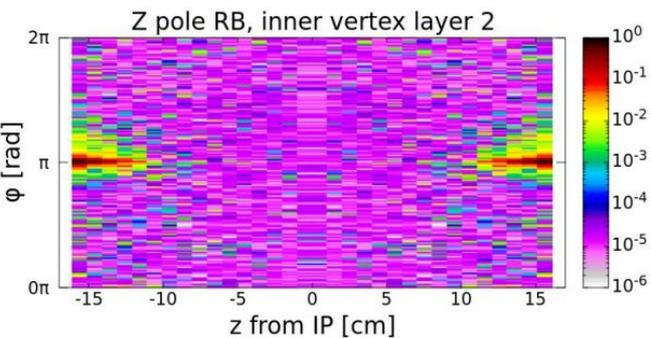
Noble-liquid calorimetry: High intrinsic stability

- 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



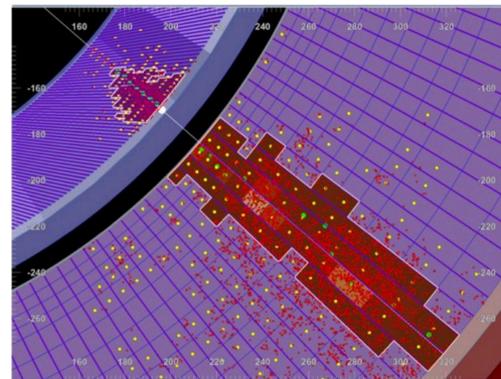
Radiation levels

Peak doses can be quite high !

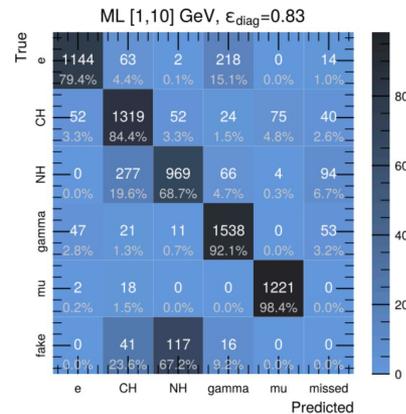


Simulations and design optimisation: granularity

- EM objects reconstruction using fixed-size or topo-clusters
 - Includes electronics noise and cross-talk effects
- Electron and photon energy reconstruction using BDT regression
- Studies on photon / π^0 classification
 - Allows to investigate EM granularity
 - Physics case: hadronic τ decay modes
- Next challenge: Particle Flow implementation
 - Key to performance of hadronic final states
 - Preliminary version of Pandora PFA running
 - Will also study state-of-the-art ML-based PFlow approaches

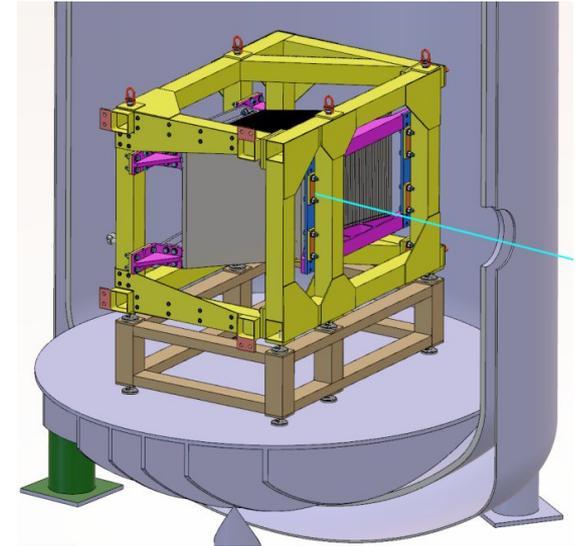


Cluster in ECal + Hcal



Conclusions

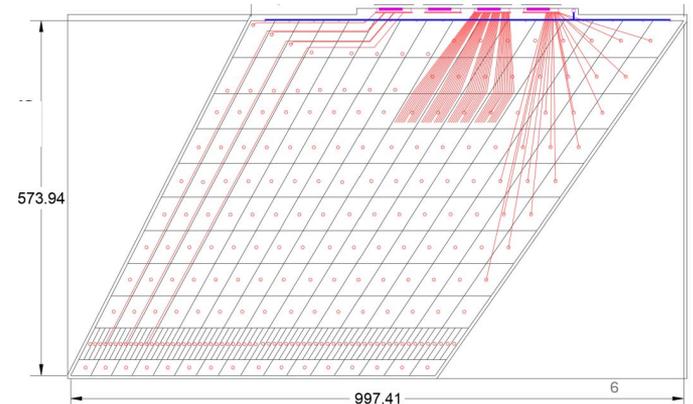
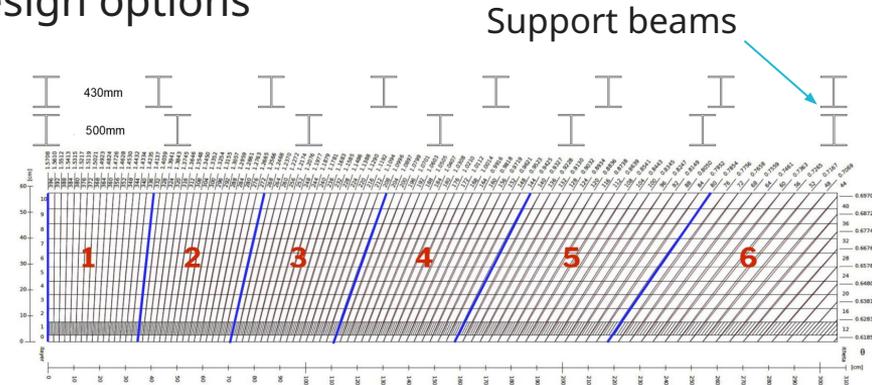
- Noble Liquid EM calorimetry is a very appealing solution for FCC-ee
 - Fulfils **all requirements** of the physics programme
 - Cost-effective
 - Significant progress in simulations to prove all important metrics
- Very active ALLEGRO Ecal R&D
 - As part of DRD6 collaboration
 - Working on all challenges to reach our performance goals
 - Design to be demonstrated by a prototype within 5 years
 - There is still plenty to do !
 - We are **always open to new collaborators !**



R&D on Electrodes

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

- Large-scale prototypes built with many design options
 - Especially for shielding of signal traces
- Conclusions so far
 - (sub)-**per-mille cross-talk achievable**
 - while keeping reasonable cell capacitances
 - Good agreement with FEM simulations
- Next challenges
 - Distribution of High Voltage (1 – 2 kV)
 - Will investigate resistive layers or resistive ink
 - Design of large electrodes at the end of the barrel
 - Do we still need projectivity ?



Feasibility Study Report published on 31 March 2025

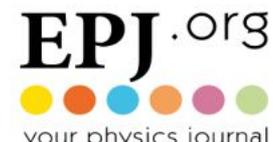
Structure: Three Volumes

- **Vol. 1: Physics, Experiments and Detectors**
- **Vol. 2: Accelerators, Technical Infrastructures, Safety Concepts**
- **Vol. 3: Civil Engineering, Implementation & Sustainability**

Input for the Update of European Strategy for Particle Physics

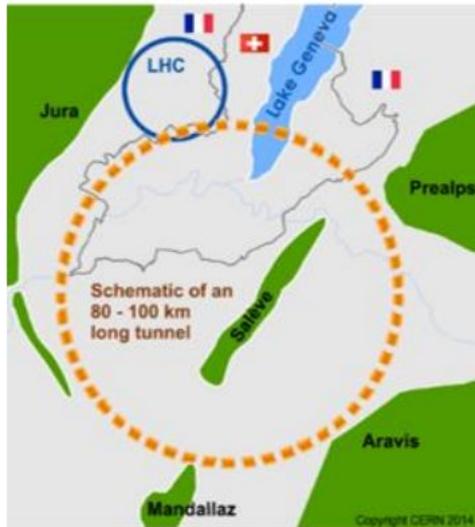
Three FSR volumes & other FCC-related input to 2025/26 European Strategy Update posted at <https://indico.cern.ch/event/1534205/>

prepared with Overleaf submitted for publication to EPJ (Springer-Nature) – FCCIS members

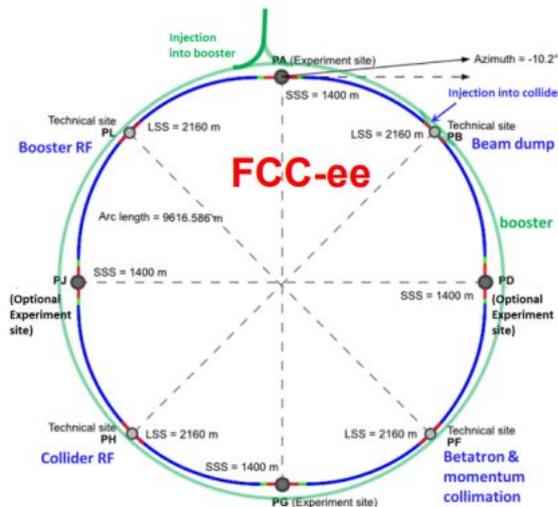


FCC integrated program – scope and timeline

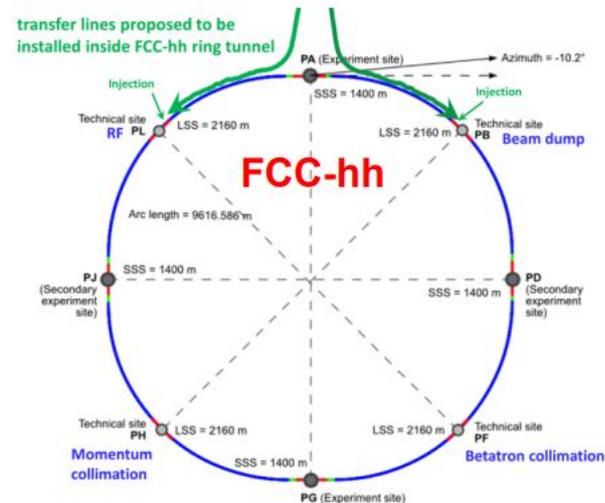
- stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities
- stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option
- highly synergetic and complementary programme maximising the physics opportunities
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC



2020 - 2045



2045 - 2065



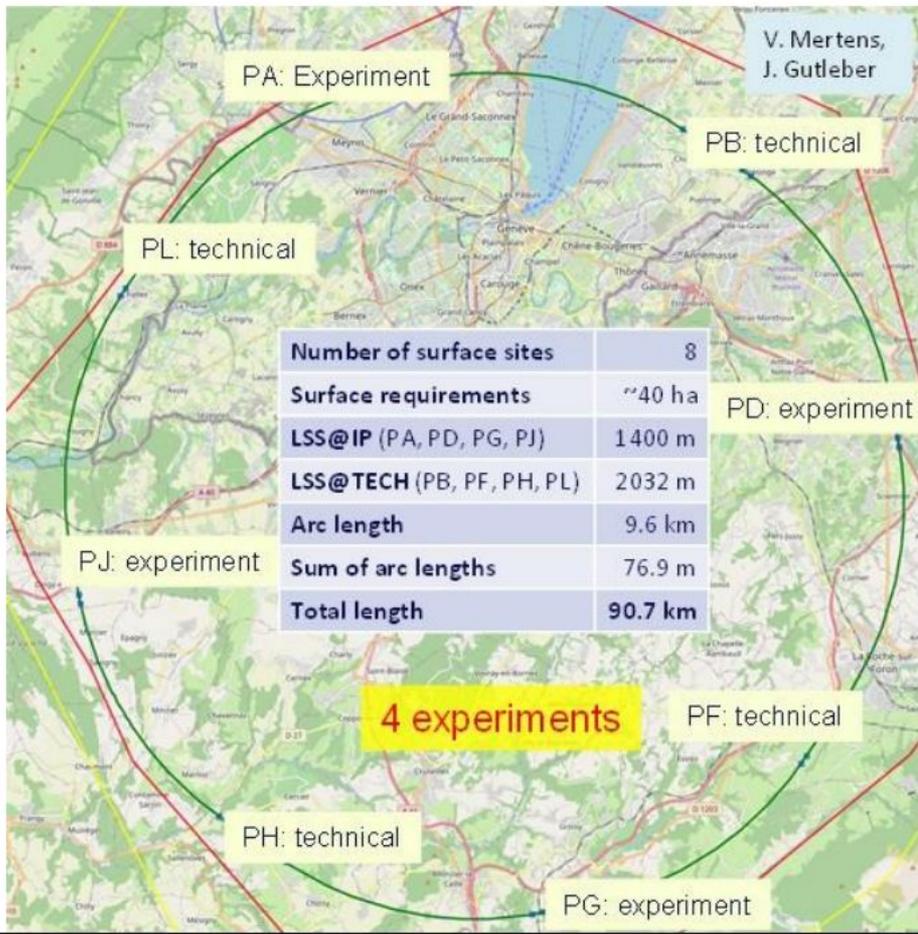
2070 - 2100

Reference layout and implementation: PA31 - 90.7 km

Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment**, (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

**Overall lowest-risk baseline:
90.7 km ring, 8 surface points,
4-fold symmetry**

- Reference layout was the basis for:
- **Surface sites optimisation** and **land reservation** with host states CH and FR
 - **Environmental initial-state study**



The ALLEGRO Detector Concept



**Noble Liquid
Ecal**

2T Solenoid

Lumical

**Vertex
Detector**

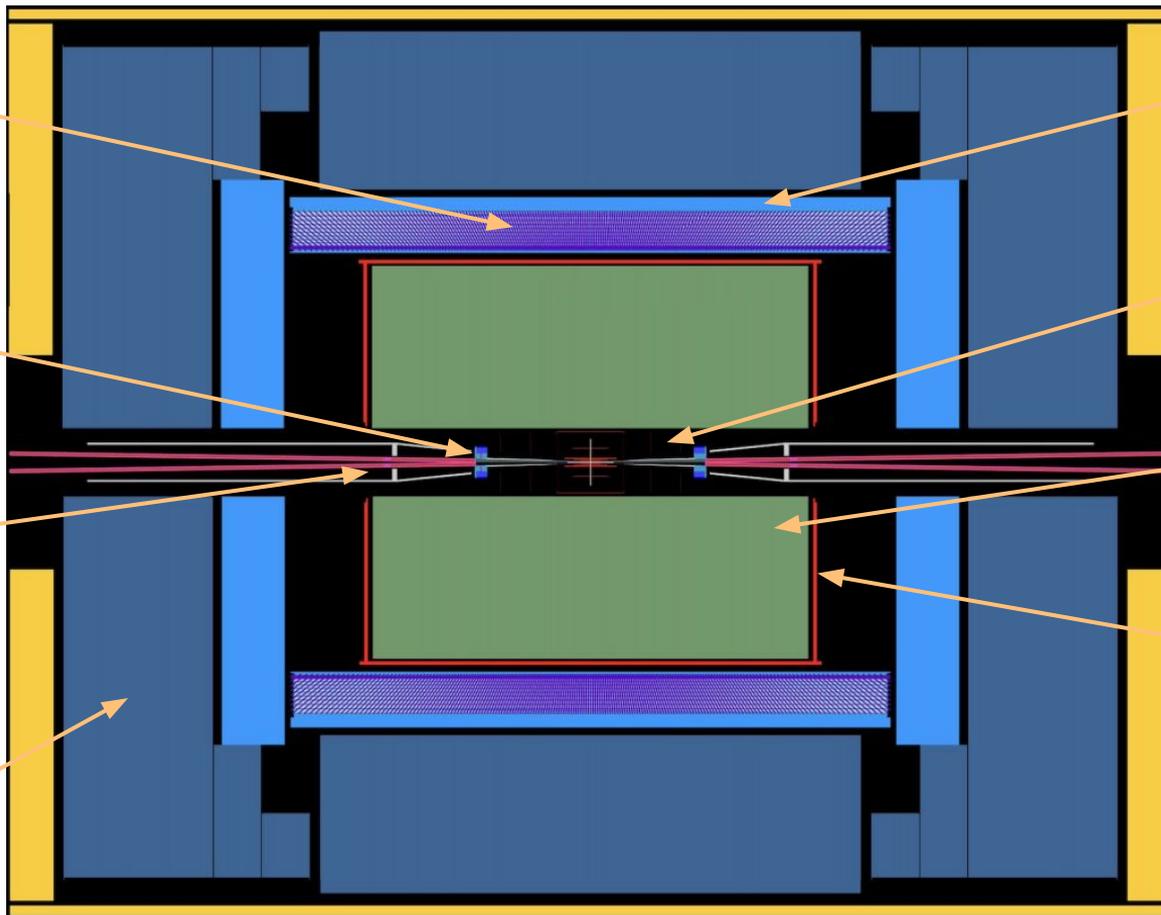
MDI

Main tracker

**Steel -
Scintillator
Hcal**

**Silicon
Wrapper**

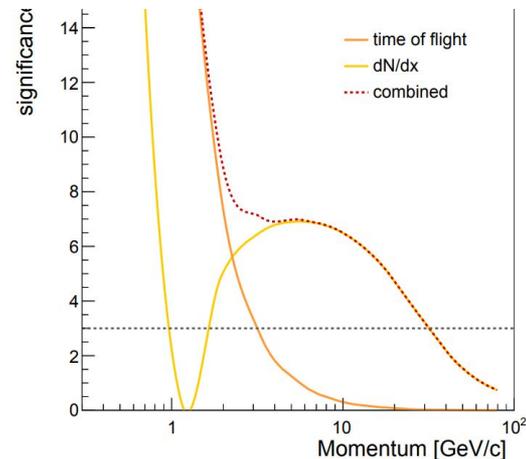
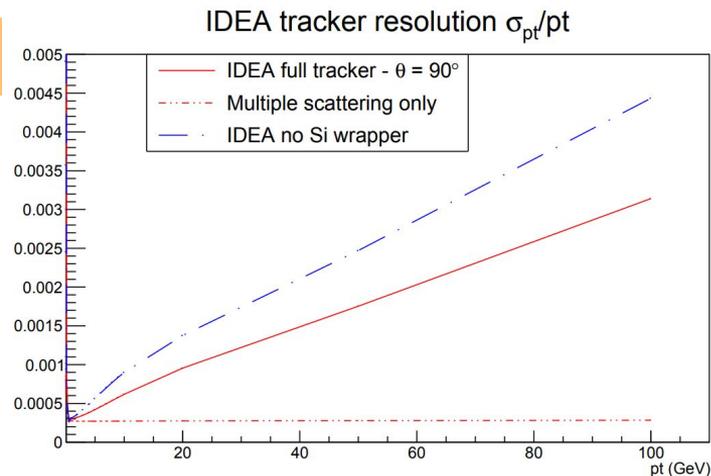
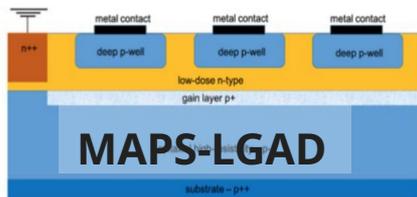
Muon Tagger



Silicon Wrapper

Add last precise tracking layer in front of calorimeter

- Two main goals
 - Last measurement point 'anchors' gaseous tracker and significantly improve high-pT resolution
 - Precise timing: provide ToF to complement dN/dx measurement for PID
 - aka: 4-D tracking
- Several technologies proposed
 - DMAPS, LGAD, AC-LGAD, LGAD-RSD
 - All aim few 10ps / layer
 - Design will learn from HL-LHC detectors



The ALLEGRO Detector Concept



**Noble Liquid
Ecal**

Lumical

MDI

**Steel -
Scintillator
Hcal**

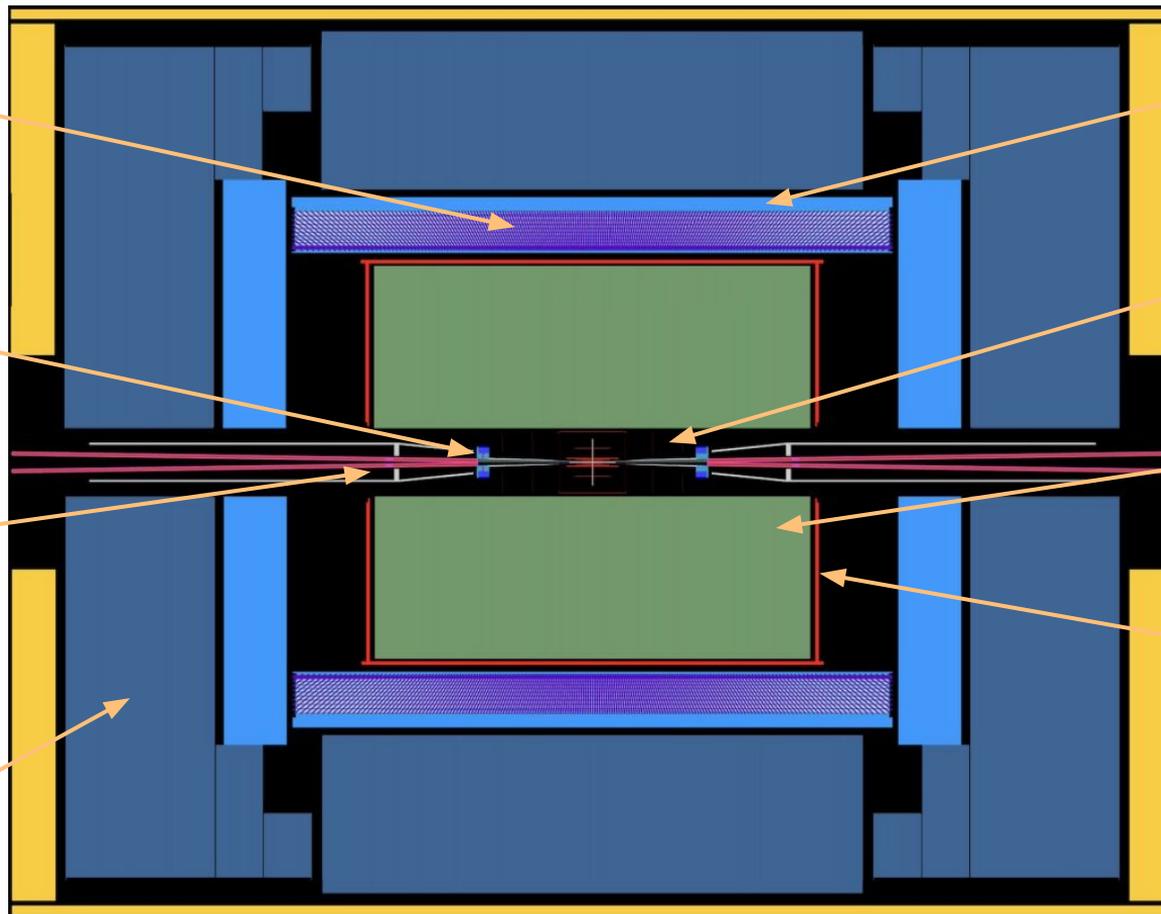
2T Solenoid

**Vertex
Detector**

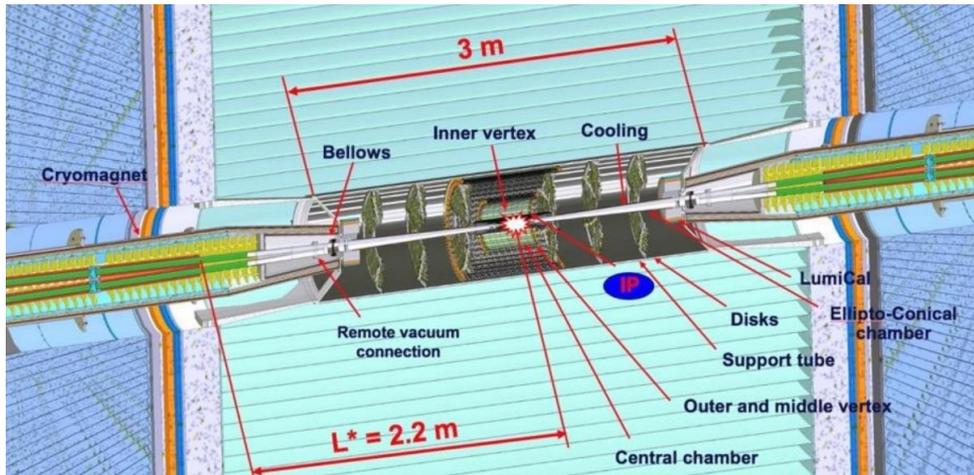
Main tracker

**Silicon
Wrapper**

Muon Tagger



- Goals:
 - Achieve target luminosity, despite detector B-field
 - Shielding from machine background (synchrotron radiation)
- Very delicate design
- Integration with vertex detector quite tricky
 - Studied for IDEA so far ; lessons apply to all detector concepts



The ALLEGRO Detector Concept



**Noble Liquid
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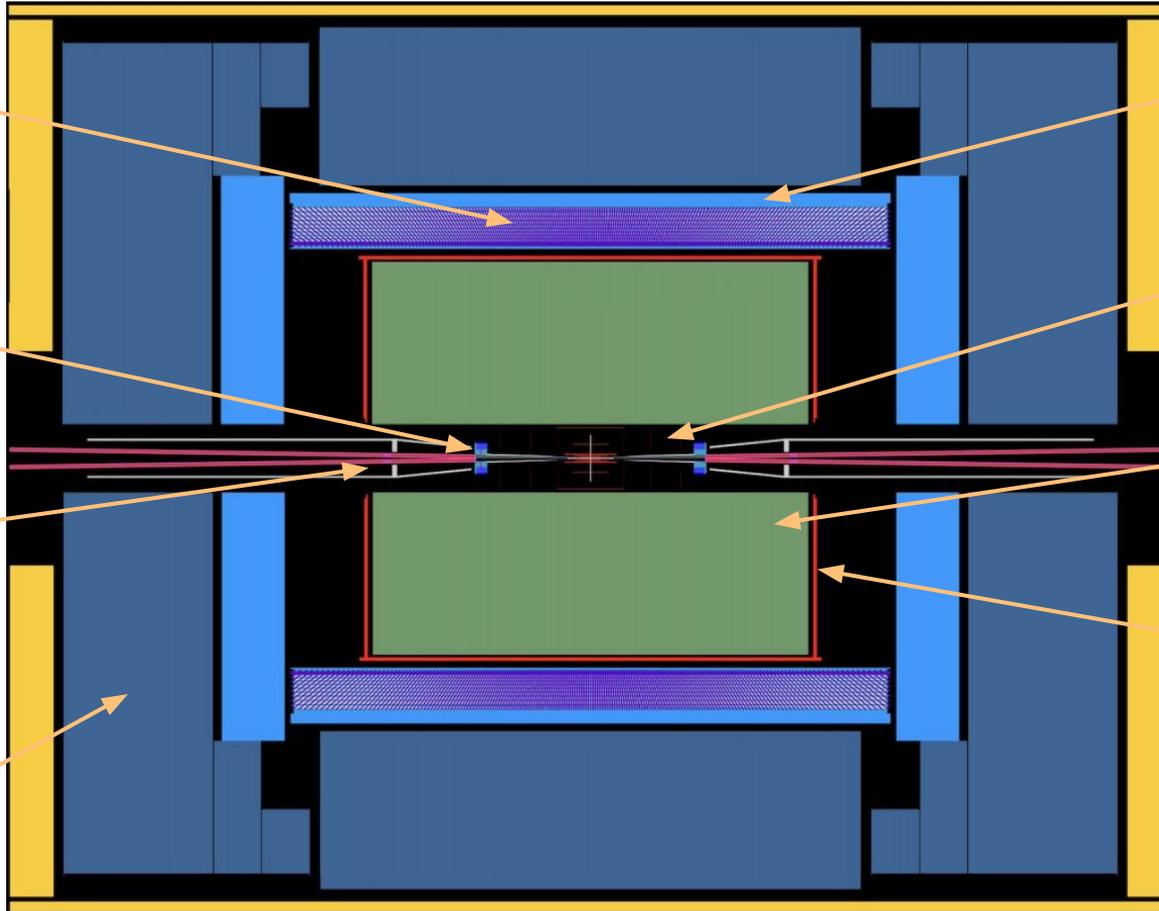
2T Solenoid

**Vertex
Detector**

Main tracker

**Silicon
Wrapper**

Muon Tagger



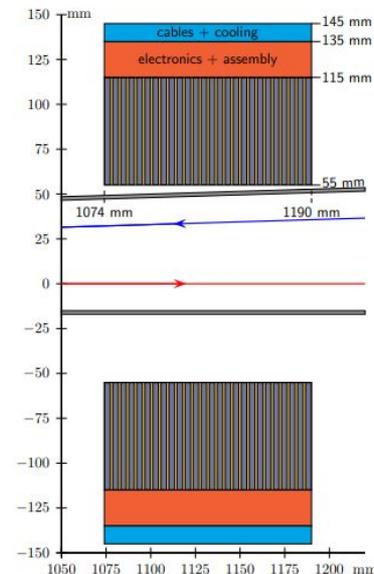
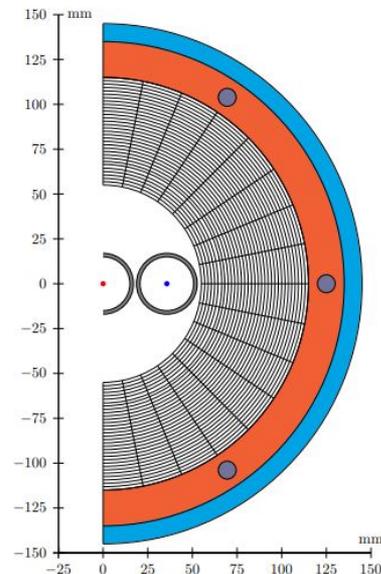
Goal: luminosity measurement at 10^{-4} !

- Challenging requirements

- Position and acceptance exquisitely well known ($\sim 10\mu\text{m}$ level)
- Fast response
- High granularity (count Bhabhas)

- Implementation concepts

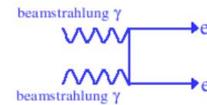
- Compact sandwich SiW calorimeters
 - 25 layers of 3.5mm W ($1 X_0$ each)
 - 26000 channels
- Quantum sensors (SNSPD)
 - Innovative solution based on superconducting nanowire detectors
 - Feasibility to be assessed



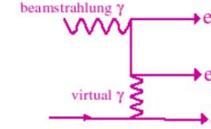
Physics rate: 200 kHz at Z pole / 40 MHz bunch crossing

- Initial thoughts: triggerless mode not too difficult
- But: very large backgrounds related to beam
 - Synchrotron Radiation
 - Incoherent Pairs Creation
 - Radiative Bhabhas (Brem)
 - Design of MDI very delicate: shieldings, back-scattering
- Occupancies actually not so small
 - Main issue for vertex detector and gaseous tracker
 - Work needed on frontend electronics to establish what can be done there
 - Significant reductions necessary to make readout rates manageable

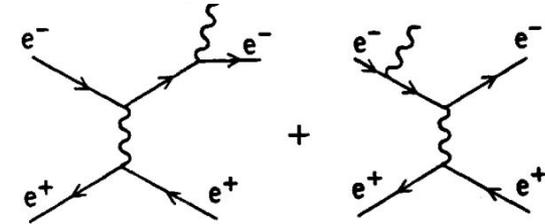
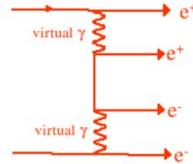
Breit-Wheeler



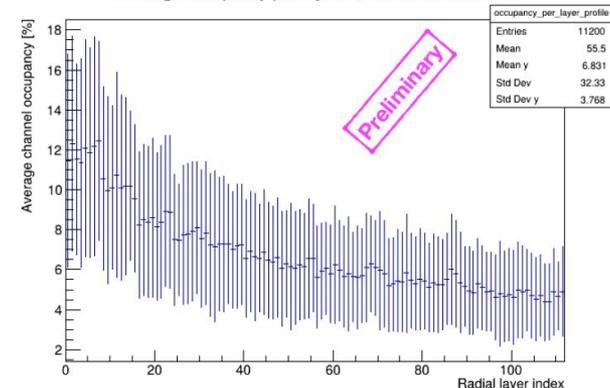
Bethe-Heitler



Landau-Lifshitz



Average occupancy per layer, 20 BXs ran 100 times



Home of detectors R&D: DRD Collaborations

8 Collaborations. Hosted at CERN. International research teams

DRD1: Gaseous Detectors

Large · Fast · eco-friendly gases · MPGD, e.g. GEMs

$\sigma \sim 25 \text{ ps}$ per track

PICOSEC: NIMA903 (2018) 317

SF₆

3M™ Resonant 5110 (CF₃CO₂CF₃) GWP <1

3M™ Resonant 1710 (CF₃CF₂) GWP 2130

DRD3: Semiconductor Det.

Monolithic CMOS · LGADs · radiation hardness · interconns.

SI-SEMICONDUCTOR DETECTORS

MONOLITHIC CMOS · LGADs · radiation hardness · interconns.

DRD6: Calorimetry

Energy resolution · High granularity · dual readout · particle flow · sandwich · optical

Homogeneous EM

Sampling EM

Sampling EM/Scal

DRD7: Electronics

ADC/TDC IP Blocks · Opto-electronics · packaging · power · extreme environments · COTS · intelligence on detector · foundry access

ADC/TDC IP Blocks · Opto-electronics · packaging · power · extreme environments · COTS · intelligence on detector · foundry access

DRD2: Liquid Detectors

for Neutrinos · Dark Matter · Ovbb

Noble Elements	Liquid Scintillators	Water Cherenkov
<ul style="list-style-type: none"> Argon & Xenon Ionisation charge & transport VUV Scintillation, light propagation & detection 	<ul style="list-style-type: none"> Visible Scintillation, light propagation Scintillator properties Isotope loading 	<ul style="list-style-type: none"> Cherenkov light, light propagation Doping for n-capture

DRD4: Photon detectors

vacuum, solid-state (SiPM), hybrid single-photon and SciFi detectors · applications in PID, RICH, tracking

radiator · photon detector · avalanche region · Collection Region

Hamamatsu R1286

DRD5: Quantum Sensors

Quantum dots · superconduct. nanowires · bolometers · TES · MMC · nuclear clocks

Applications in LEPP, first projects in HEPP happening

Intensity profile

Cherenkov profile

© Nature

DRD8: Mechanics

Ultra-thin beam pipes · CF foam and new materials · curved, retractable sensors · air & micro-channel cooling · eco-friendly cooling fluids · robots · augmented reality

Ultra-thin beam pipes · CF foam and new materials · curved, retractable sensors · air & micro-channel cooling · eco-friendly cooling fluids · robots · augmented reality