Calorimetry: Requirements and Technology Challenges

17th Terascale Detector Workshop

Sven Menke, MPP München

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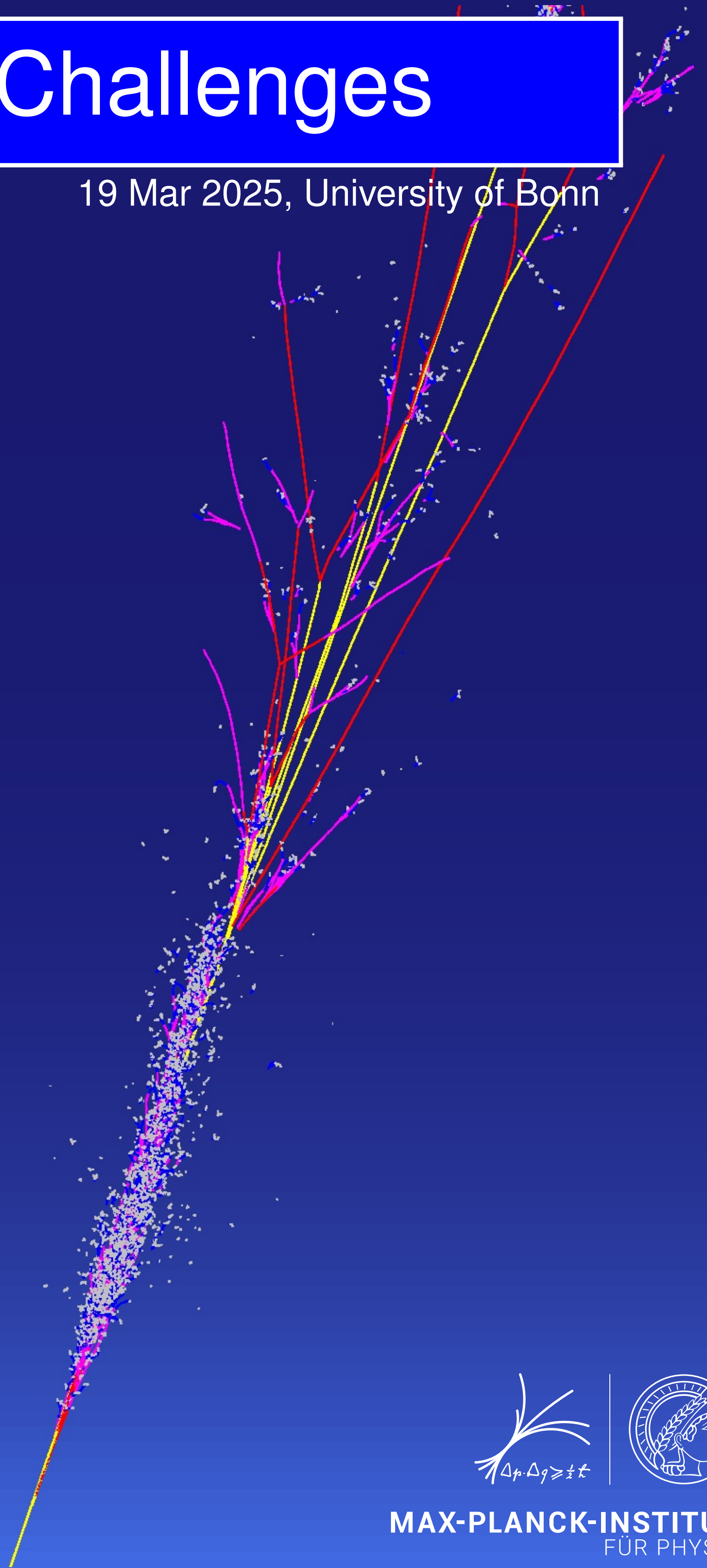
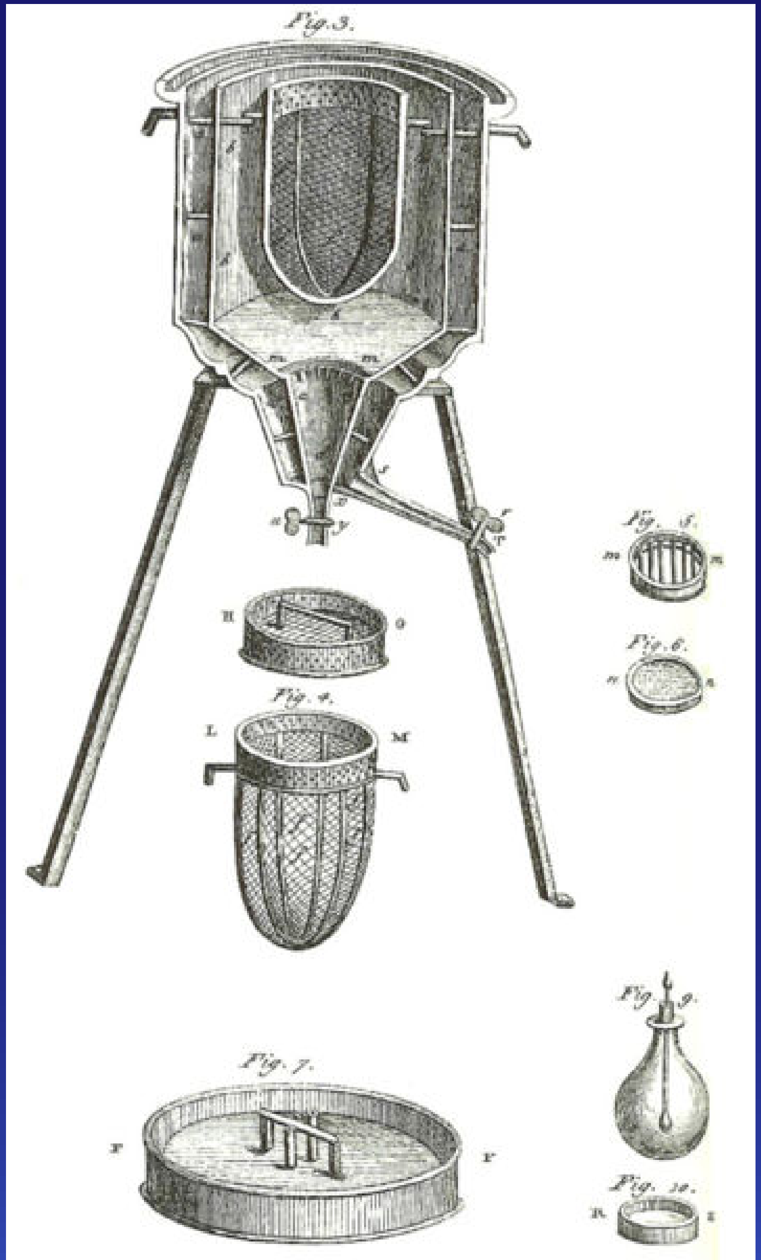
- Introduction
  - Calorimetry
  - Electromagnetic showers
  - Hadronic showers
- Calorimetry at the FCC-ee
  - FCC-ee physics and requirements
  - Detectors
    - CLD
    - IDEA
    - ALLEGRO
  - Calibration
- Conclusions



MAX-PLANCK-INSTITUT FÜR PHYSIK

- What is a calorimeter?
  - If you ask this question on WIKIPEDIA you get to see devices like the one shown here from 1782 by A. Lavoisier and P.-S. Laplace
  - i.e. devices to measure the heat of chemical reactions or physical changes or to measure heat capacity
- Not quite what we do in particle physics ...

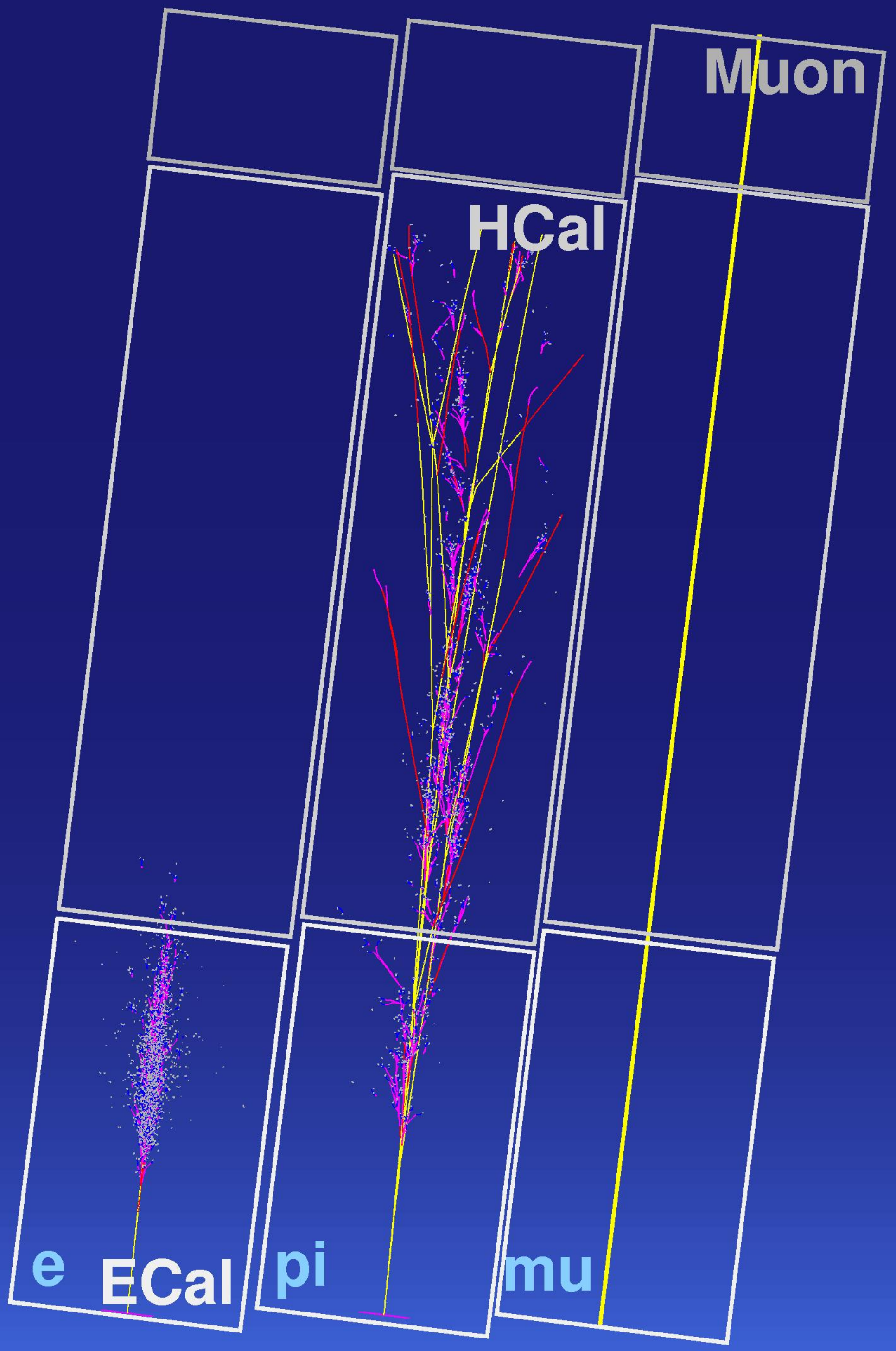
WIKIPEDIA



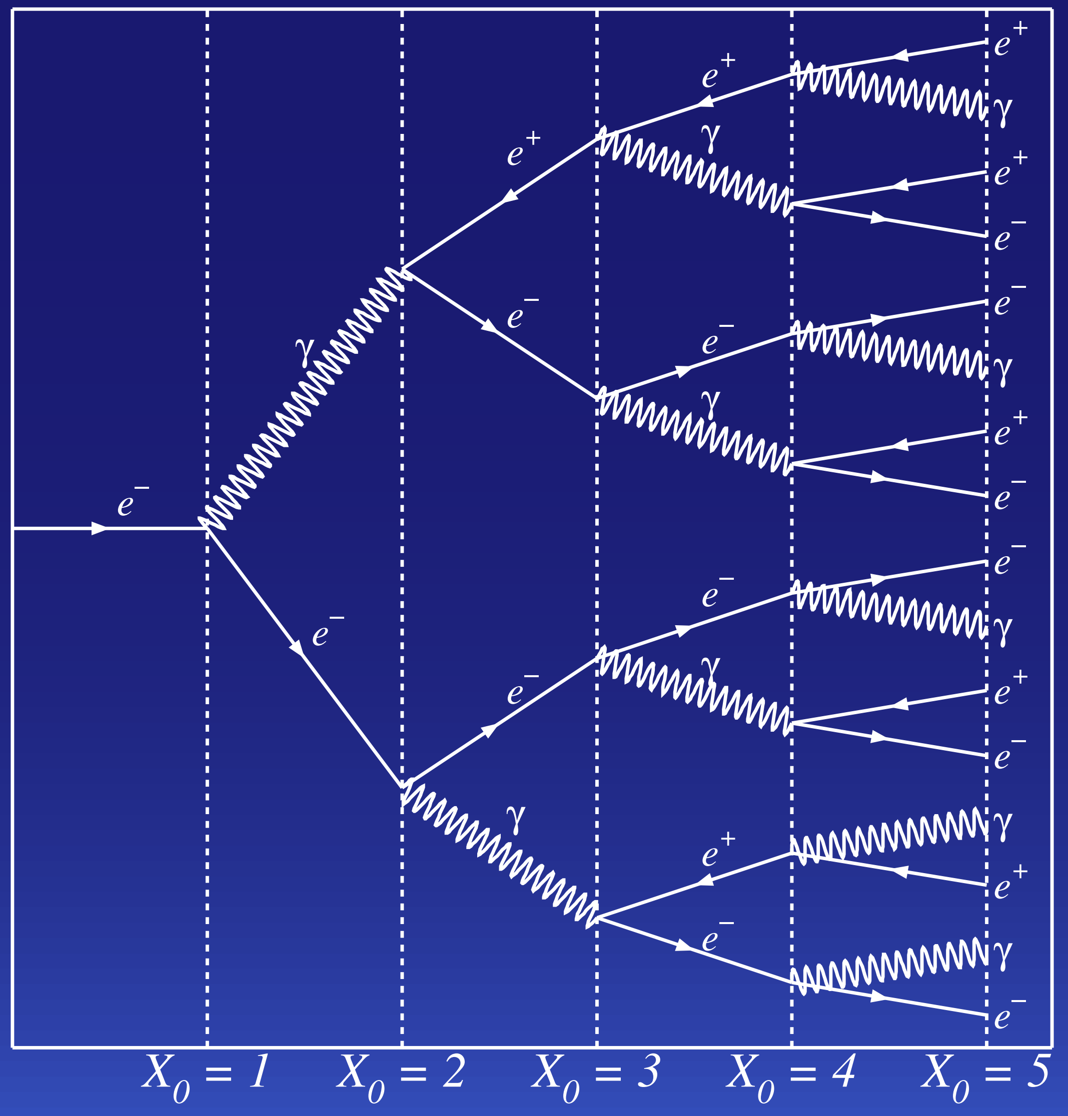
Ice-calorimeter from Antoine Lavoisier's 1789 Elements of Chemistry

- What is a calorimeter in high energy particle physics?
- In our experiments we want a calorimeter to measure:
  - the energy of a final state particle in a destructive way
    - thereby stopping the particle from entering detectors further out from the interaction region
  - where that particle is depositing its energy
    - to combined it with other particles and measurements
  - the type of the particle
    - electro-magnetic, hadronic or muonic
  - when that particle deposited its energy
    - to exclude reactions from background processes and to detect new long-lived particles
- Only one requirement (the first about the energy) has actually to do with heat
  - still, we don't actually measure the heat increase by the particle ...
- All other requirements mean that we can not exclusively optimise for energy resolution
  - still, we want to have the best energy measurement that does not compromise the other goals
- All the requirements are interdependent

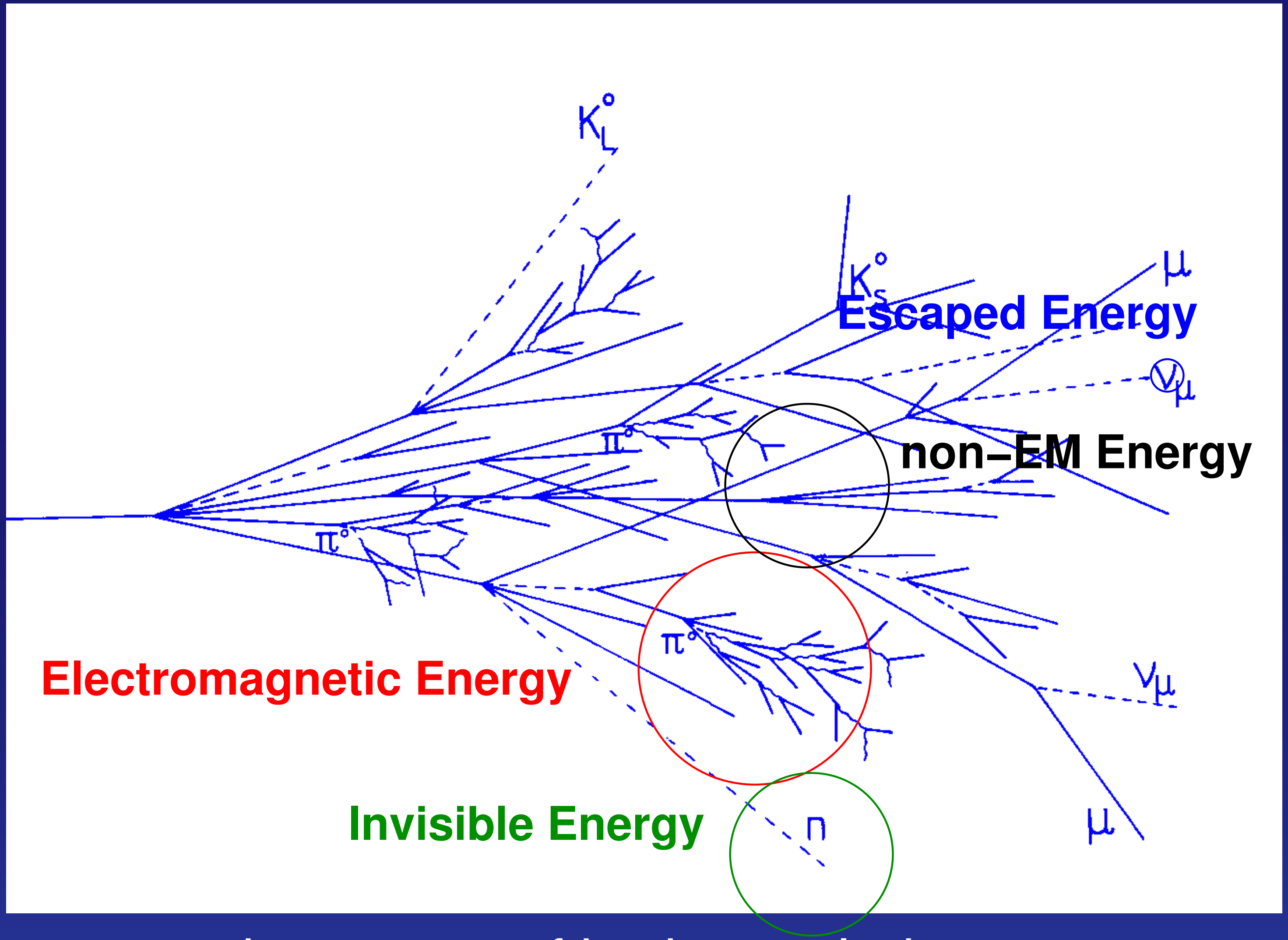
- electrons and photons are detected in the first part of the calorimeter (the electromagnetic calorimeter) by their electromagnetic showers
  - electrons also leave a track in the inner detector
- charged pions, neutrons and protons cause hadronic showers and are detected in both, the first (electromagnetic) and second (hadronic) part of the calorimeter
  - the charged pions and protons also leave a track in the inner detector
- muons do not initiate a shower and deposit ionising energy only, without being destroyed (stopped)
  - leave a track in the inner detector
  - and reach beyond the calorimeter to leave tracks in the muon system
- neutrinos do not interact (sufficiently) and escape
- Image shows simulation of three 50 GeV particles (electron, charged pion and muon) hitting steel
  - with all charged particles coloured proportional to their energy



- Simplified electromagnetic shower model (Rossi)
  - an electron with energy E_0 hits the calorimeter
  - each electron/positron radiates a bremsstrahlungs-photon after exactly one radiation length with half its energy
  - each photon converts after one radiation length in a e^+e^-–pair with half the photon energy each
  - after t radiation length the shower contains 2^t particles (e^+, e^-, γ with roughly similar abundances) each with the energy $E_0 / 2^t$
  - once the energy falls below a critical threshold $E_0 / 2^t < E_c$ the shower terminates
    - energy loss becomes larger than losses from Bremsstrahlung
    - for photons Compton-scattering becomes larger than pair-production
  - $t_{max} = \ln(E_0 / E_c) / \ln 2$
    - the shower depth is proportional to the logarithm of the original energy E_0
- $E_c \simeq O(10\,\mathrm{MeV})$ for typical calorimeter materials
- an em-shower with $E_0 = 100\,\mathrm{GeV}$ has $E_0 / E_c = 10000$ particles
  - number of particles at shower maximum is proportional to energy E_0
- its shower maximum is located at a depth of $t_{max} X_0 = X_0 \ln(E_0 / E_c) / \ln 2 = 13.3\,X_0$
  - the shower depth grows proportional to $\ln E_0$

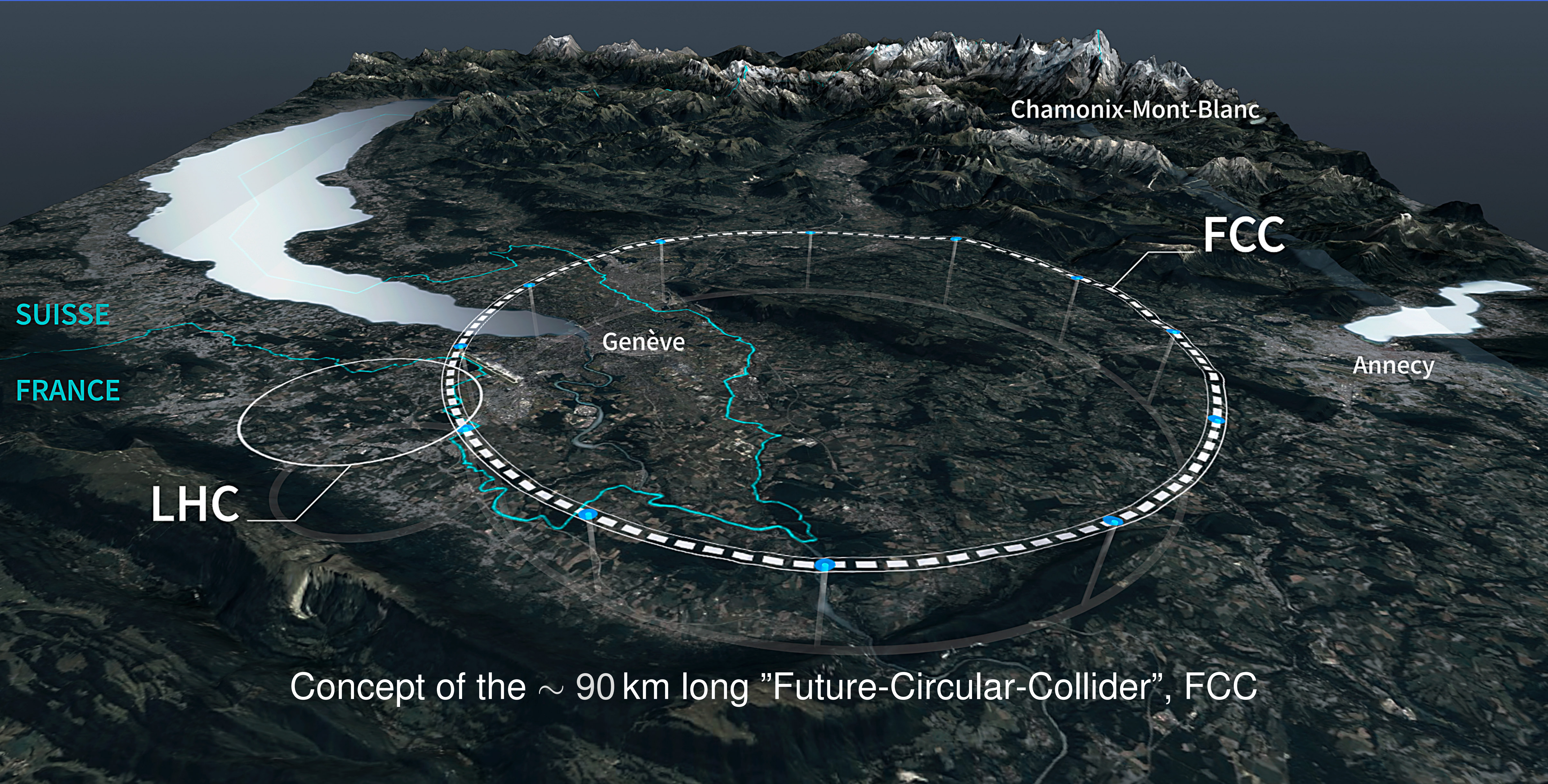


- In hadronic showers the nuclear interaction length (λ) takes the role the radiation length (X_0) has for em showers
  - $\lambda \simeq O(10)\, X_0$ for typical calorimeter materials
- A hadronic shower consists of
  - EM energy (e.g. $\pi^0 \to \gamma\gamma$) $O(50\,\%)$
  - visible non-EM energy (e.g. $\mathrm{d}E\,/\,\mathrm{d}x$ from $\pi^{\pm}, \mu^{\pm}$, etc.) $O(25\,\%)$
  - invisible energy (e.g. breakup of nuclei and nuclear excitation) $O(25\,\%)$
  - escaped energy (e.g. ν) $O(2\,\%)$
- each fraction is energy dependent and subject to large fluctuations



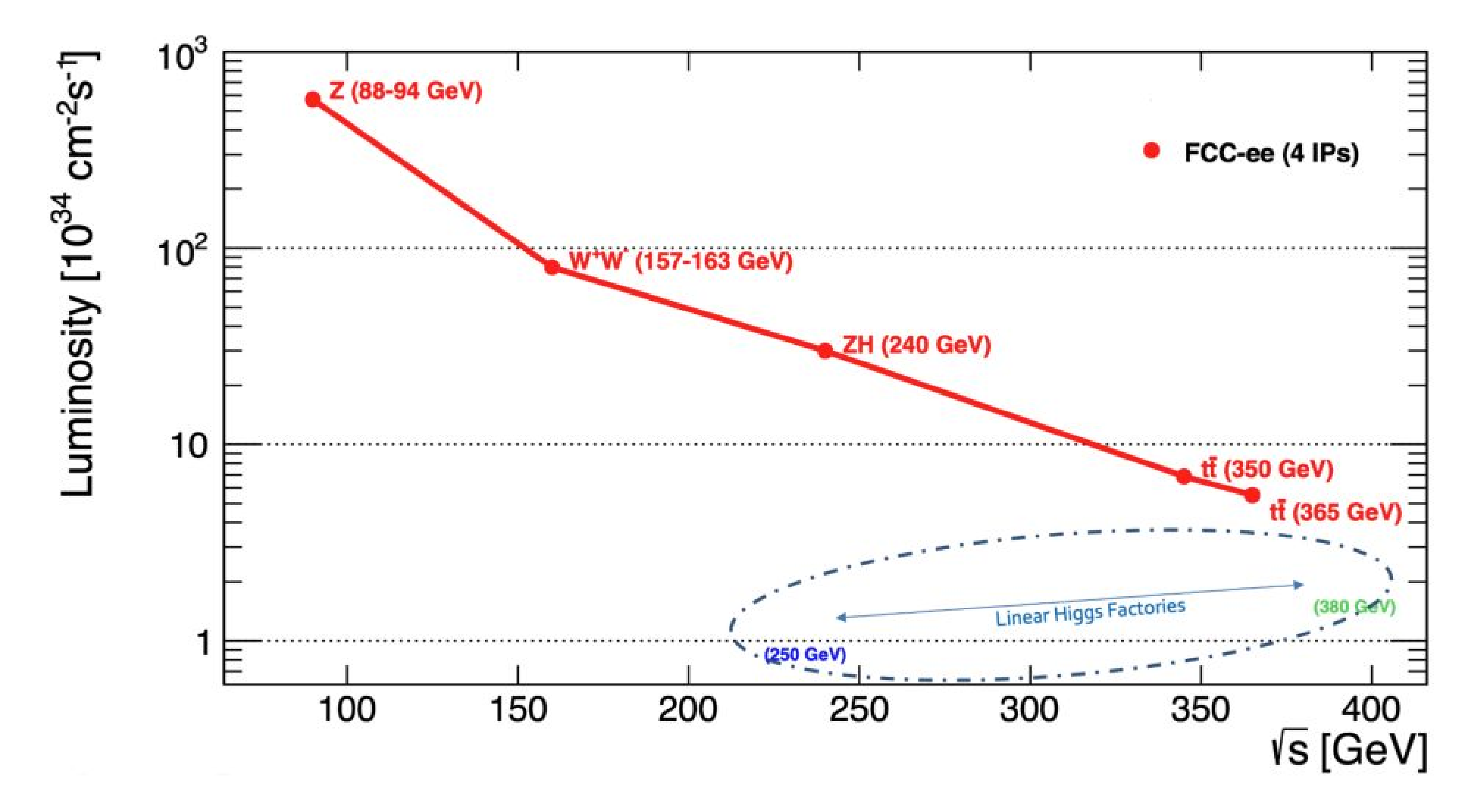
- invisible energy is the main source of the non-compensating nature of hadron calorimeters
- need to account for this either by construction (hardware compensation) or by hadronic calibration

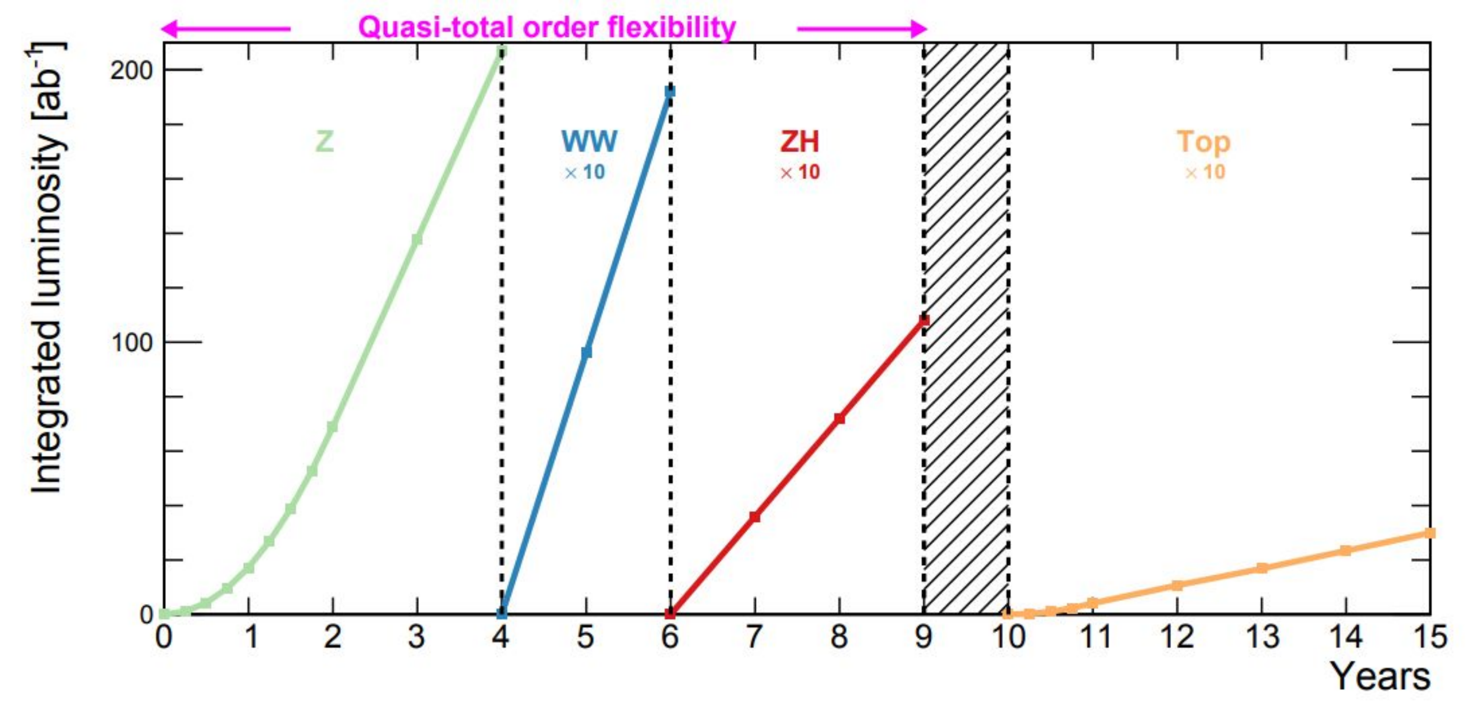
FCC-ee



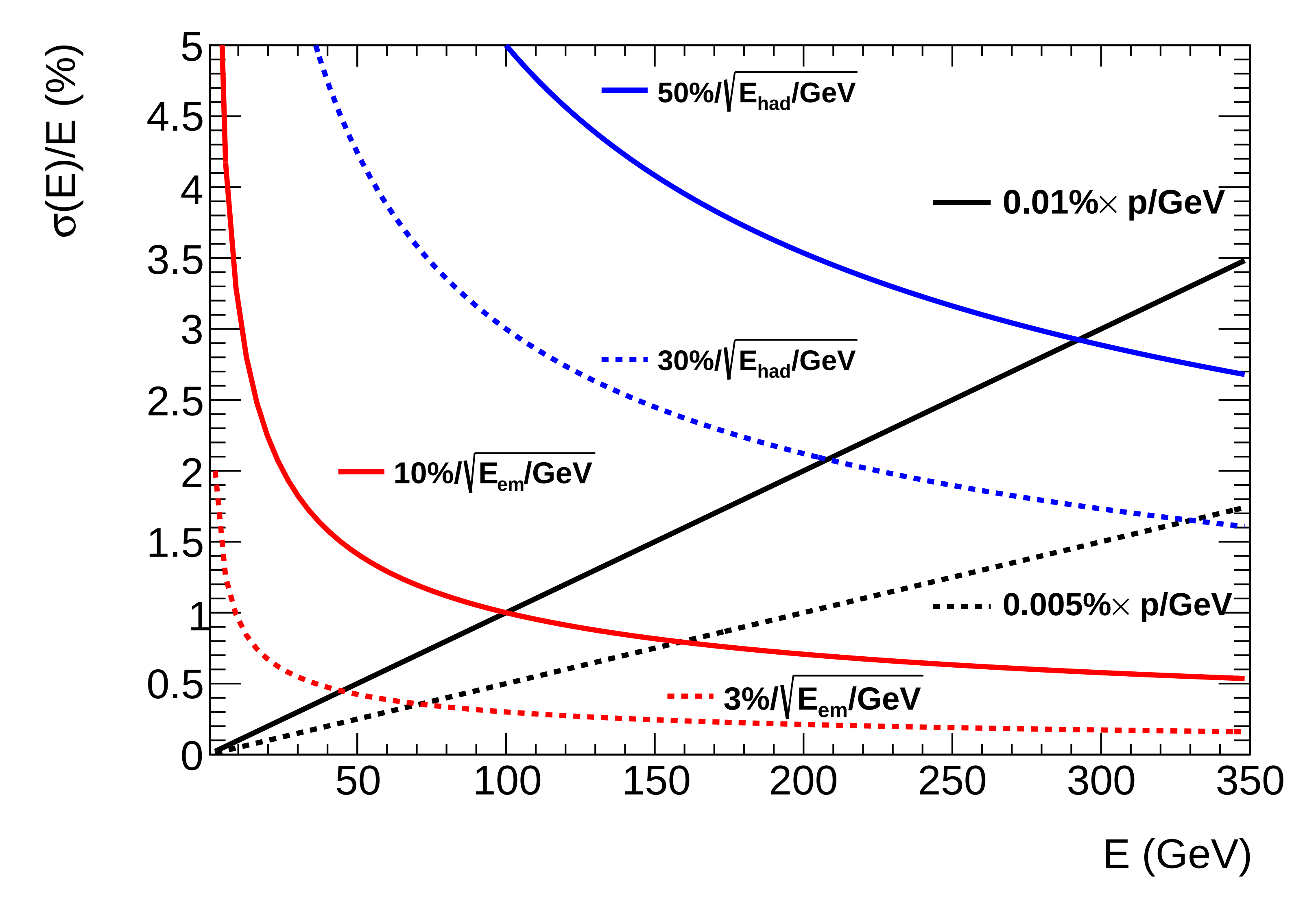
Concept of the $\sim$ 90 km long "Future-Circular-Collider", FCC

- $\sim$ 90 km circular e^+e^--collider
- 4 interaction regions
- physics at the Z-pole, WW-, ZH- and $t\bar{t}$-threshold
  - 6×10^{12} Z
  - 2.4×10^{8} WW
  - 1.5×10^{5} ZH
  - 2×10^{6} $t\bar{t}$
- highest lumi at the Z with $O(100\,\mathrm{kHz})$ trigger rate
  - entire LEP-1 program ($O(6\,\mathrm{M})$ hadronic Z for each experiment) every $\sim$ 2 minutes

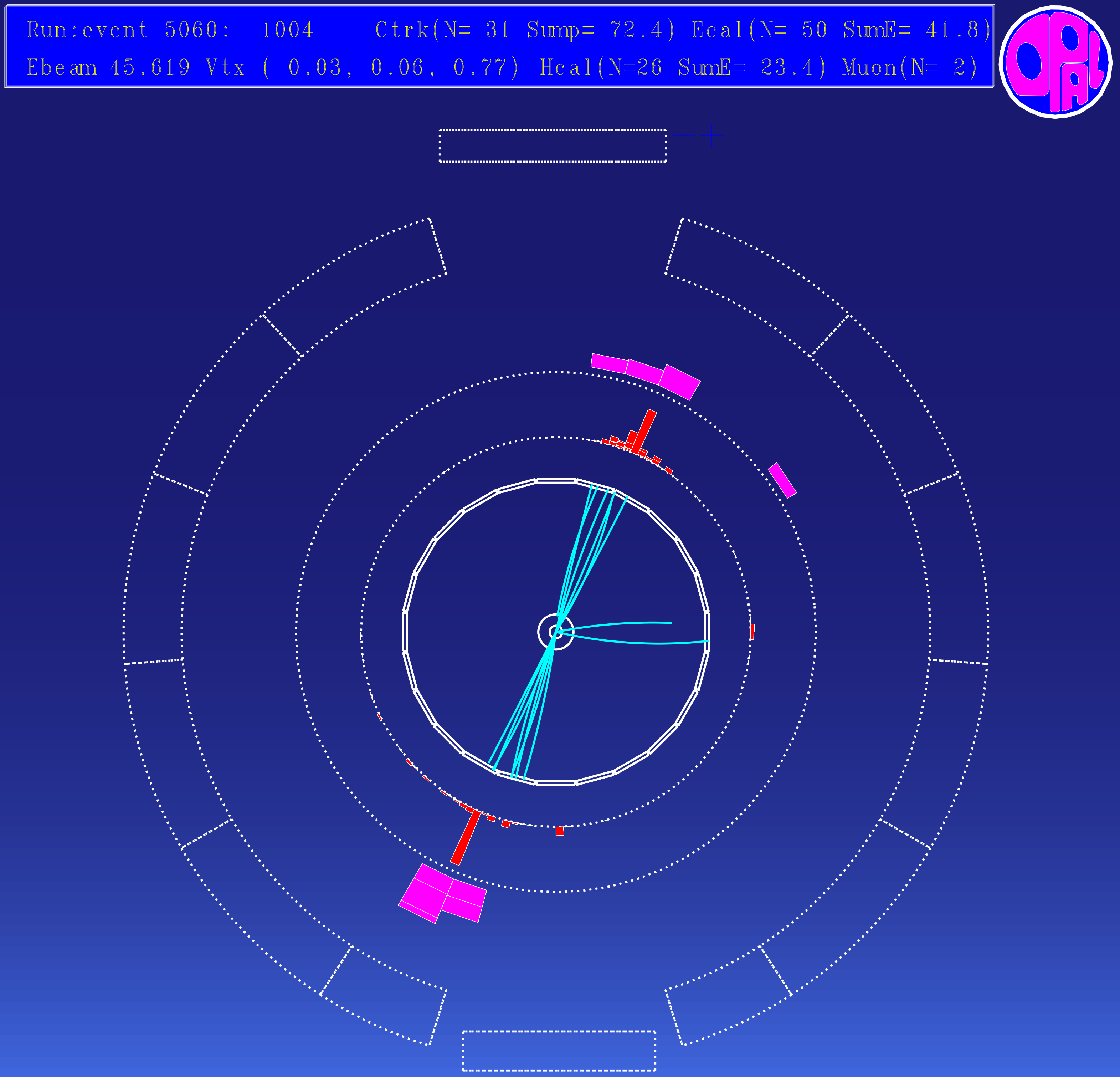




- e^+e^--collisions mean moderate energy
  - up to $O(100\ \text{GeV})$, not several TeV as for LHC
- Improving on the LEP-results for Z-physics and measuring the Higgs-couplings requires extremely high precision measurements
  - design detectors with `ParticleFlow` in mind
  - use tracker for any charged particle with $E < O(50\ \text{GeV})$
  - be able to separate the calorimeter signals from these charged particles from the neutral (hadronic) deposits
    ► need high transverse and longitudinal granularity in the calorimeters
  - separating γ from $\pi^0 \to \gamma\gamma$ is needed for example for hadronic τ-decays
    ► need even higher transverse granularity in the em-calorimeter
- With trigger rates of $O(100\ \text{kHz})$ at the Z-pole, the readout does not need to be particularly fast
  - but bunch crossings are only $O(20\ \text{ns})$ apart
  - so, still need accurate time resolution



- $Z^0 \to$ hadrons
  - $\sim$ 33 particles
  - $\sim$ 20 of them charged
  - $\sim$ 10 neutral pions (and other mesons decaying directly to $\gamma\gamma$)
  - $\sim$ 3 neutral hadrons ($\mathrm{n}, \mathrm{K_L}$)
- distributing the energy evenly over them in two jets
  - $E_{\mathrm{jet}} = (60.6\%_{\mathrm{track}} + 30.3\%_{\mathrm{em}} + 9.1\%_{\mathrm{had}})E_{\mathrm{jet}}$
  - $E_{\mathrm{jet}} = 10 \times 2.76\,\mathrm{GeV}_{\mathrm{track}} + 13.82\,\mathrm{GeV}_{\mathrm{em}} + 4.15\,\mathrm{GeV}_{\mathrm{had}}$
  - $\Delta E_{\mathrm{jet}} / E_{\mathrm{jet}} = 0.005\% \oplus 0.8\% \oplus 2.2\% = \mathbf{2.4\%}$ with ParticleFlow compared to
  - $\Delta E_{\mathrm{jet}} / E_{\mathrm{jet}} = 0.8\% \oplus 6.2\% = \mathbf{6.2\%}$ without
  - $\sqrt{2} \times 2.4\% = 3.4\%$ Z-mass resolution (vs. $\sqrt{2} \times 6.2\% = 8.8\%$)
- Image shows $Z \to$ hadrons event from OPAL (LEP-1, not a ParticleFlow optimised detector)



- $\tau \rightarrow \nu_\tau$ + hadrons
  - 1, 3 or 5 charged pions (or kaons)
  - 0 - 4 neutral pions
- need to separate the final states according to number of neutral pions
  - even number of charged + neutral pions: **vector** current
  - odd number of charged + neutral pions: **axial-vector** current
- channel cross-feed for $\tau \rightarrow \nu_\tau \pi^\pm + N\pi^0$ for OPAL (top) and a FCC LAr ECAL simulation (bottom)
  - need high granularity to separate close-by em showers
  - and only little material in front of the calorimeter

Reco / Gen	$\pi^\pm\pi^0$	$\pi^\pm 2\pi^0$	$\pi^\pm 3\pi^0$
$\pi^\pm\pi^0$	**82%**	17%	1%
$\pi^\pm 2\pi^0$	26%	**65%**	9%
$\pi^\pm 3\pi^0$	8%	57%	**35%**

S.Menke, PhD-thesis

Reco / Gen	$\pi^\pm$	$\pi^\pm\pi^0$	$\pi^\pm 2\pi^0$	$\pi^\pm 3\pi^0$	$\pi^\pm 4\pi^0$
$\pi^\pm$	**95.6%**	4.3%	0.1%	0	0
$\pi^\pm\pi^0$	3.7%	**90.2%**	5.9%	0.2%	0
$\pi^\pm 2\pi^0$	0.9%	12.8%	**78.0%**	8.1%	0.2%
$\pi^\pm 3\pi^0$	0.4%	3.7%	26.8%	**59.7%**	9.1%

K.Wandall-Christensen, Master-thesis

FCC-ee ► Detector Concepts

► CLD

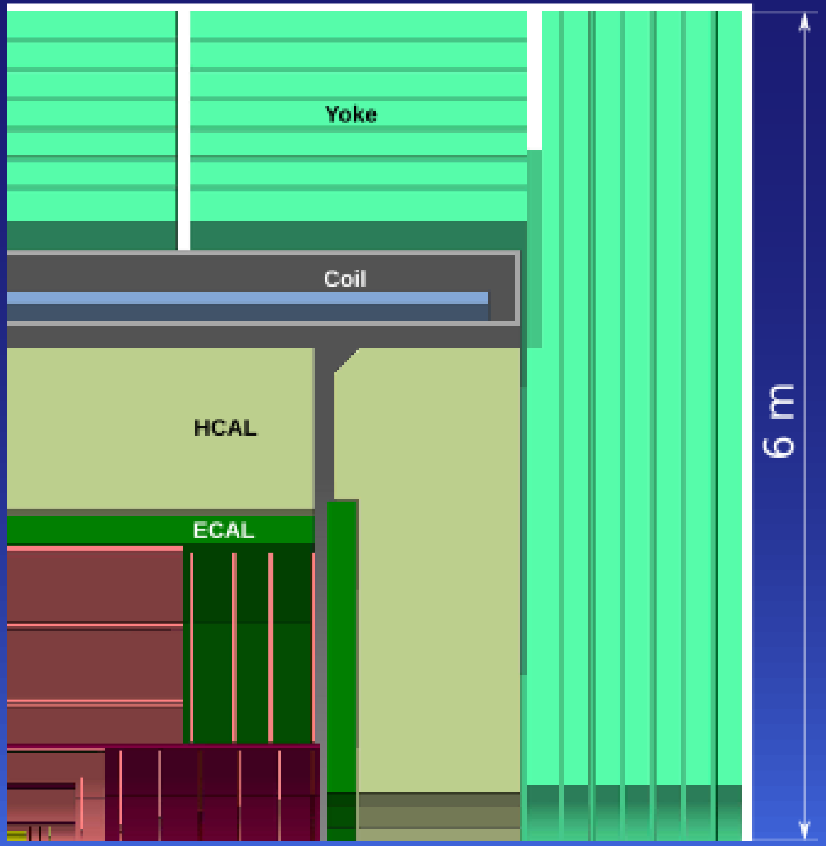
- **arXiv:1911.12230**
- based on CLIC detector design
- Full Si vertex detector and tracker
- coil outside calorimeters
- 3D-imaging high-granular calorimeter

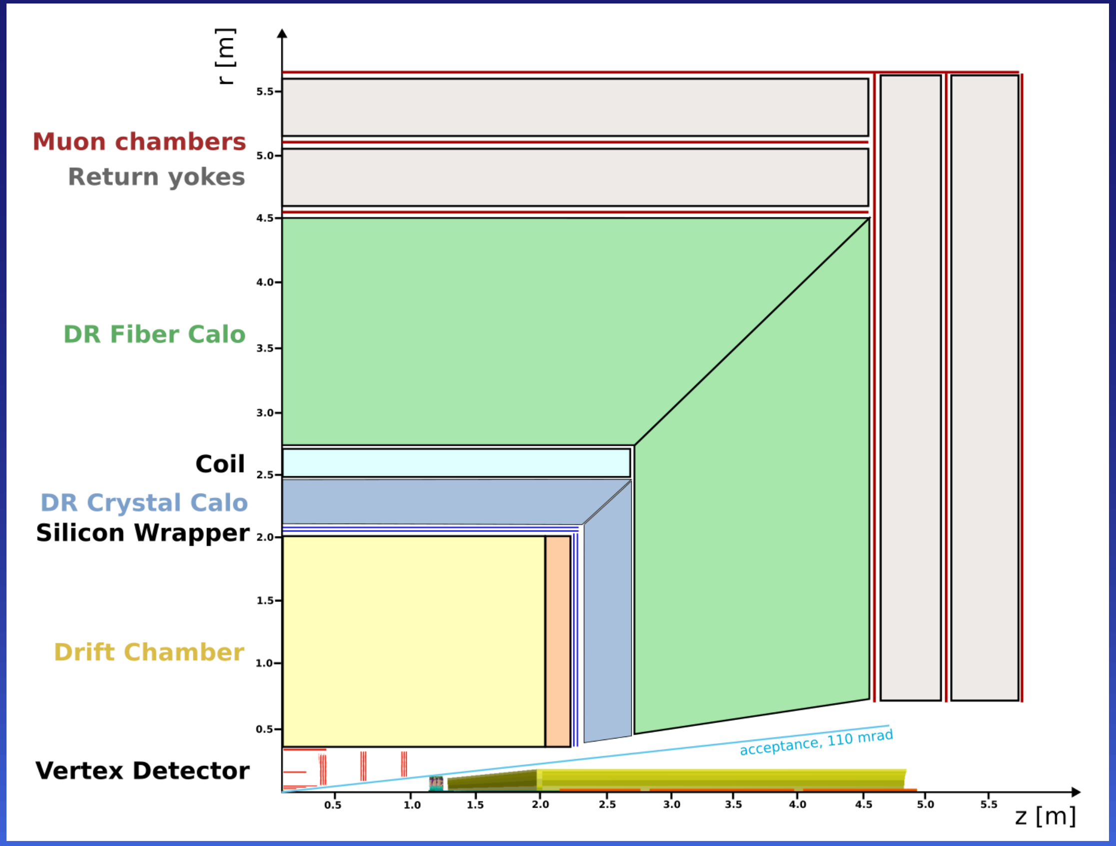
► IDEA

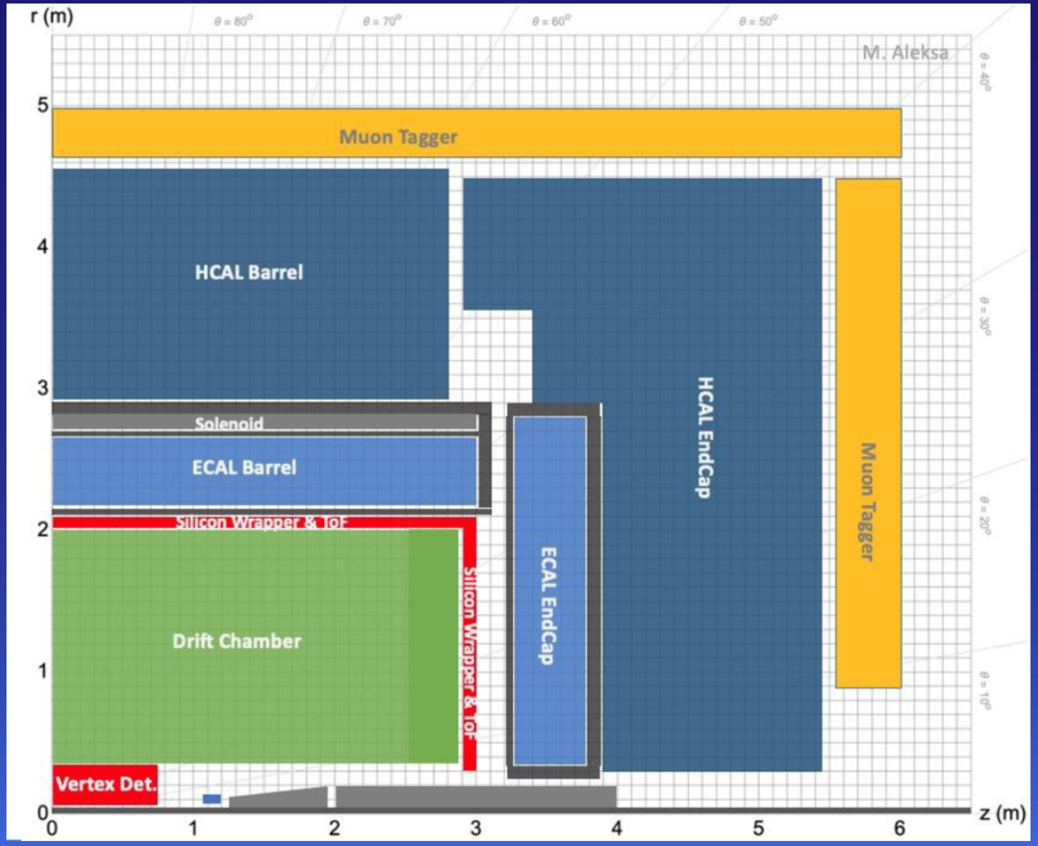
- **arXiv:2502.21223**
- Si vertex detector
- lightweight drift chamber with Si wrapper
- Dual-readout 2-layer EM crystal calorimeter in front of coil
- Dual-readout fibre-metal HAD sampling calorimeter

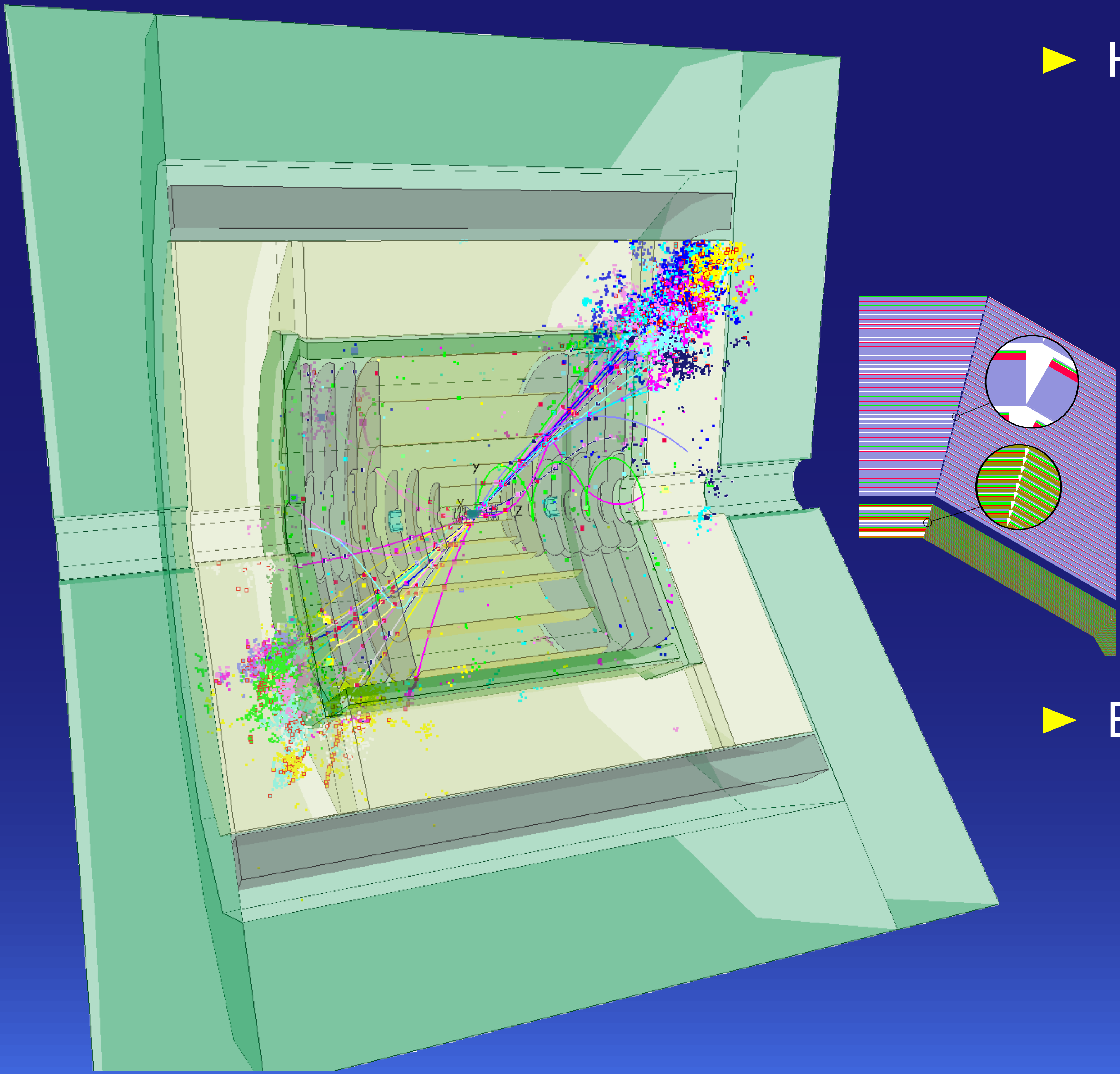
► ALLEGRO

- **arXiv:2109.00391**
- adapted from FCC-hh concept
- IDEA-like tracker
- high granular liquefied noble gas EM sampling calorimeter inside solenoid
- metal-scintillator tile HAD calorimeter





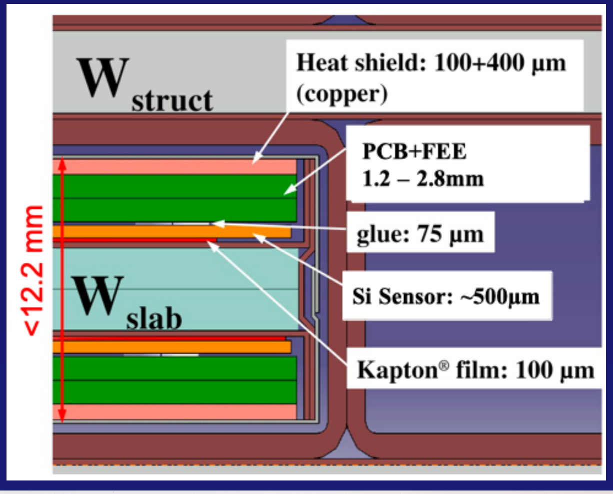


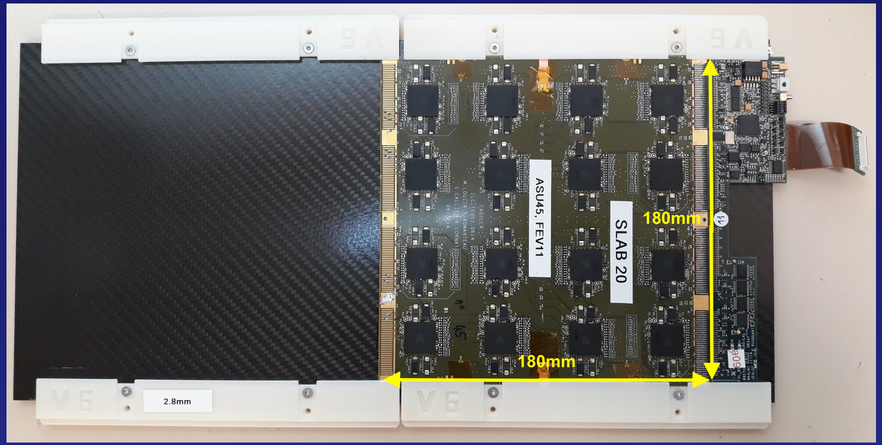


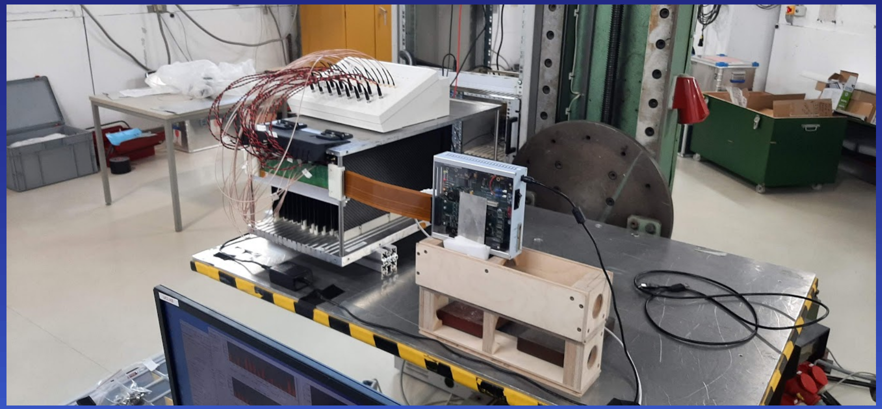
- HCAL
  - 44 sampling layers of 26.5 mm with 19 mm Fe-absorbers and 3 mm scintillator-readout ($\simeq 5.5\,\lambda$)
  - transverse granularity $30 \times 30\,\mathrm{mm}^2$ (4×10^6 barrel + 5.2×10^6 endcap channels)
- ECAL
  - 40 sampling layers of 5.05 mm with 1.9 mm W-absorbers and 500 μm Si-readout ($\simeq 22.5\,X_0$)
  - transverse granularity $5 \times 5\,\mathrm{mm}^2$ (99×10^6 barrel + 59×10^6 endcap channels)

CALICE SiW ECAL: a prototype for the CLD ECAL

- The CALICE collaboration tested several high granular absorber/readout options – mainly for future linear e^+e^- colliders
- a 15 layer SiW prototype with 15360 cells
- active electronics (SKIROC2a) with 64 channels, variable gain amplification, 12-bit ADC and 15-signal deep Switched Capacitor Array
- on-chip zero suppression: only signals above a threshold are sent to the ADC
- 1.5 mW per channel in continuous mode



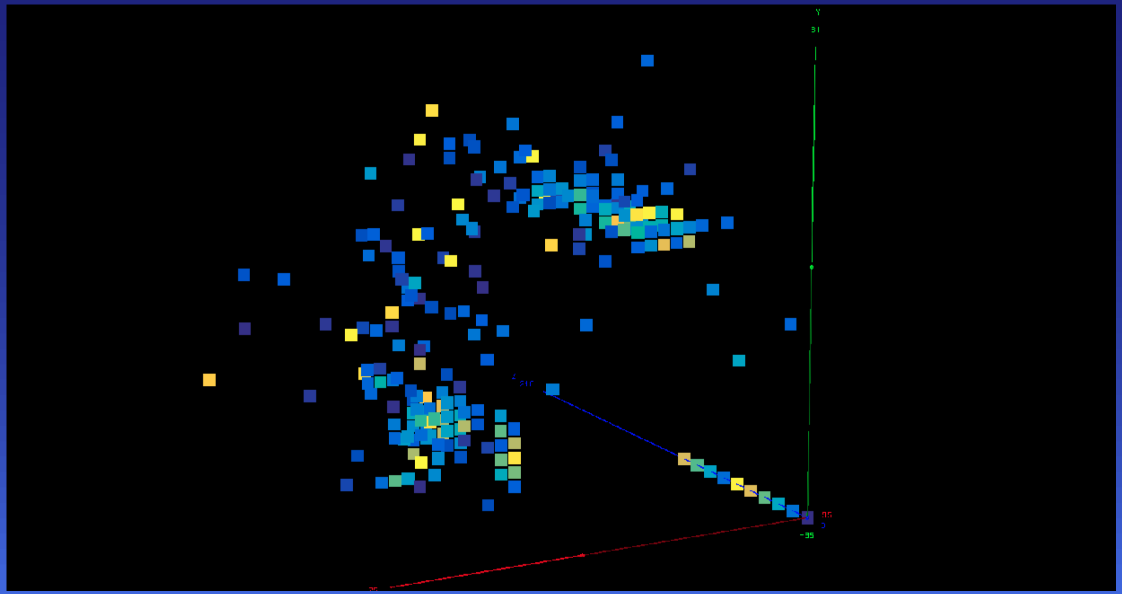




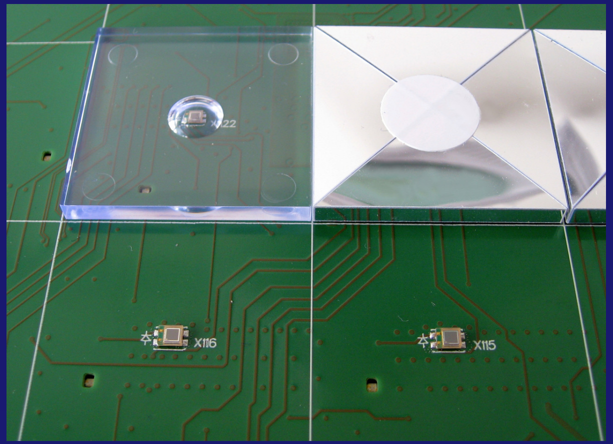
Challenges

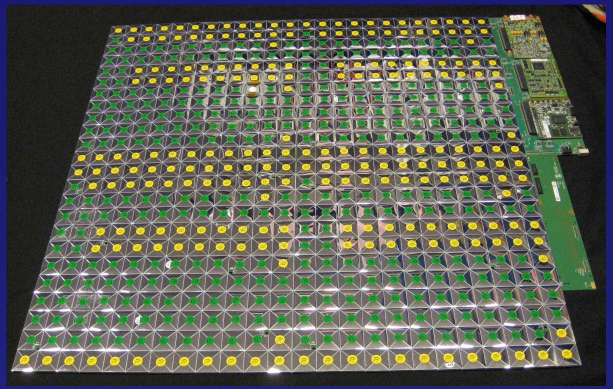
- uniformity: need calibration/monitoring of $O(100\ \mathrm{M})$ channels
- power: without pulsed operation need cooling for the electronics $O(150\ \mathrm{kW})$ for 100 M channels

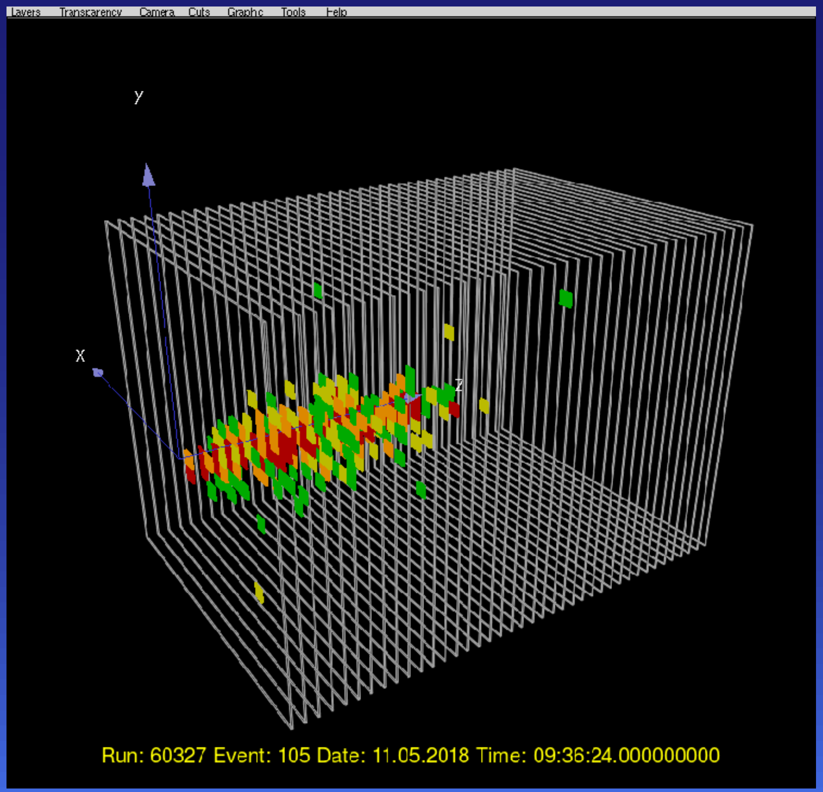
Excellent shower separation demonstrated

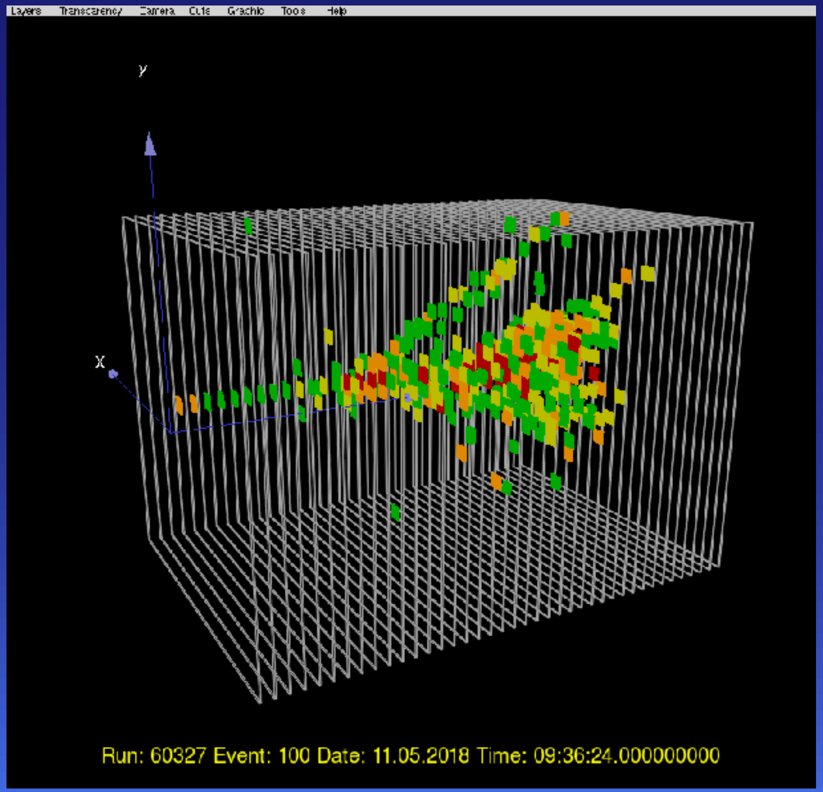


- CALICE AHCAL: a SiPM-on-tile calorimeter prototype
  - 38 active layers of $36 \times 36\,\mathrm{cm}^2$ holding 144 $3 \times 3\,\mathrm{cm}^2$ SiPMs controlled by 4 SPIROC2E ASICs
  - 21888 channels – again in pulsed-power operation mode (likely needs adjustment for FCC-ee)
  - Hamamatsu MPPC S13360-1325PE photon sensors in the centre dimple of polystyrene scintillator tiles
  - self-triggering
- em/had separation
  - is key for any `ParticleFlow` algorithm
  - electron shower (left) is compact with high energy density
  - hadron shower (right) has larger spread and low energy density

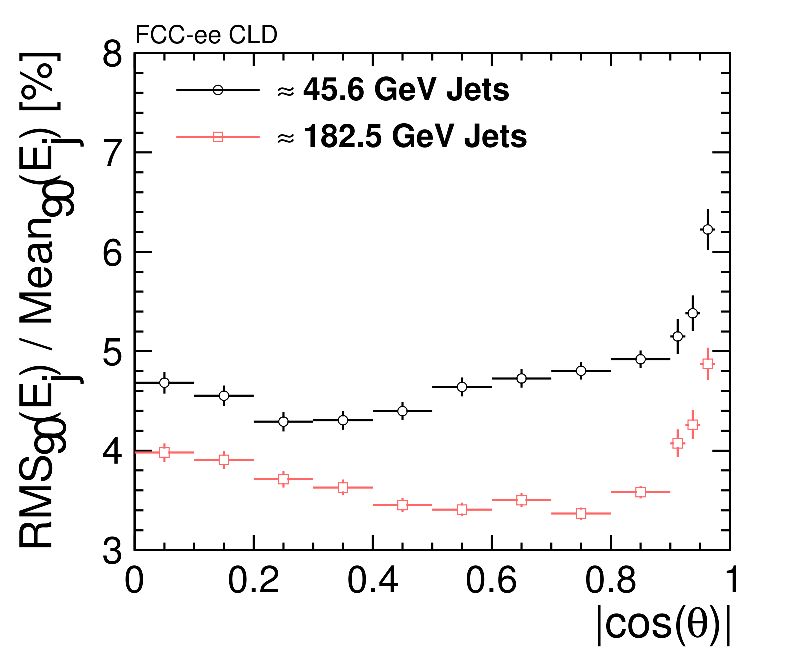


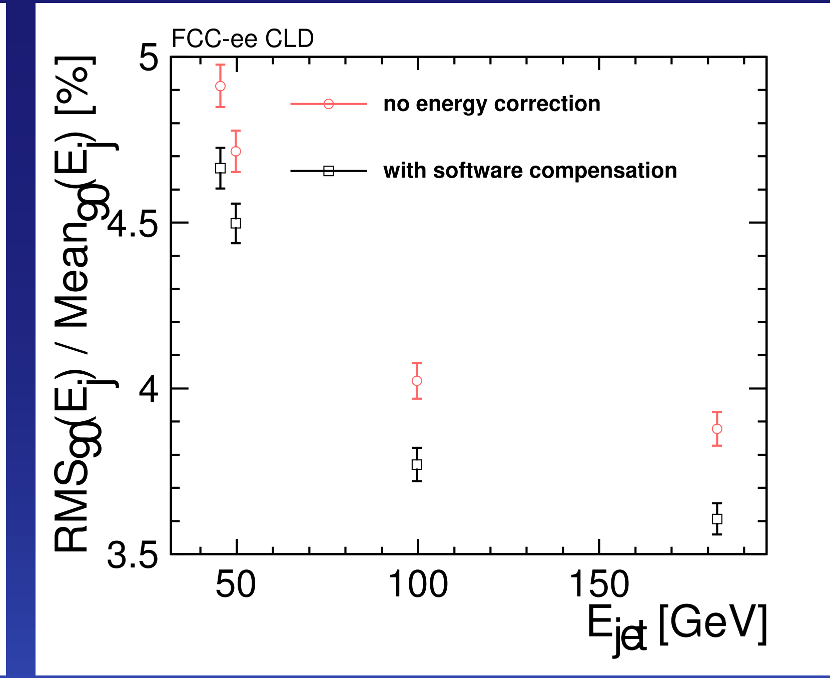


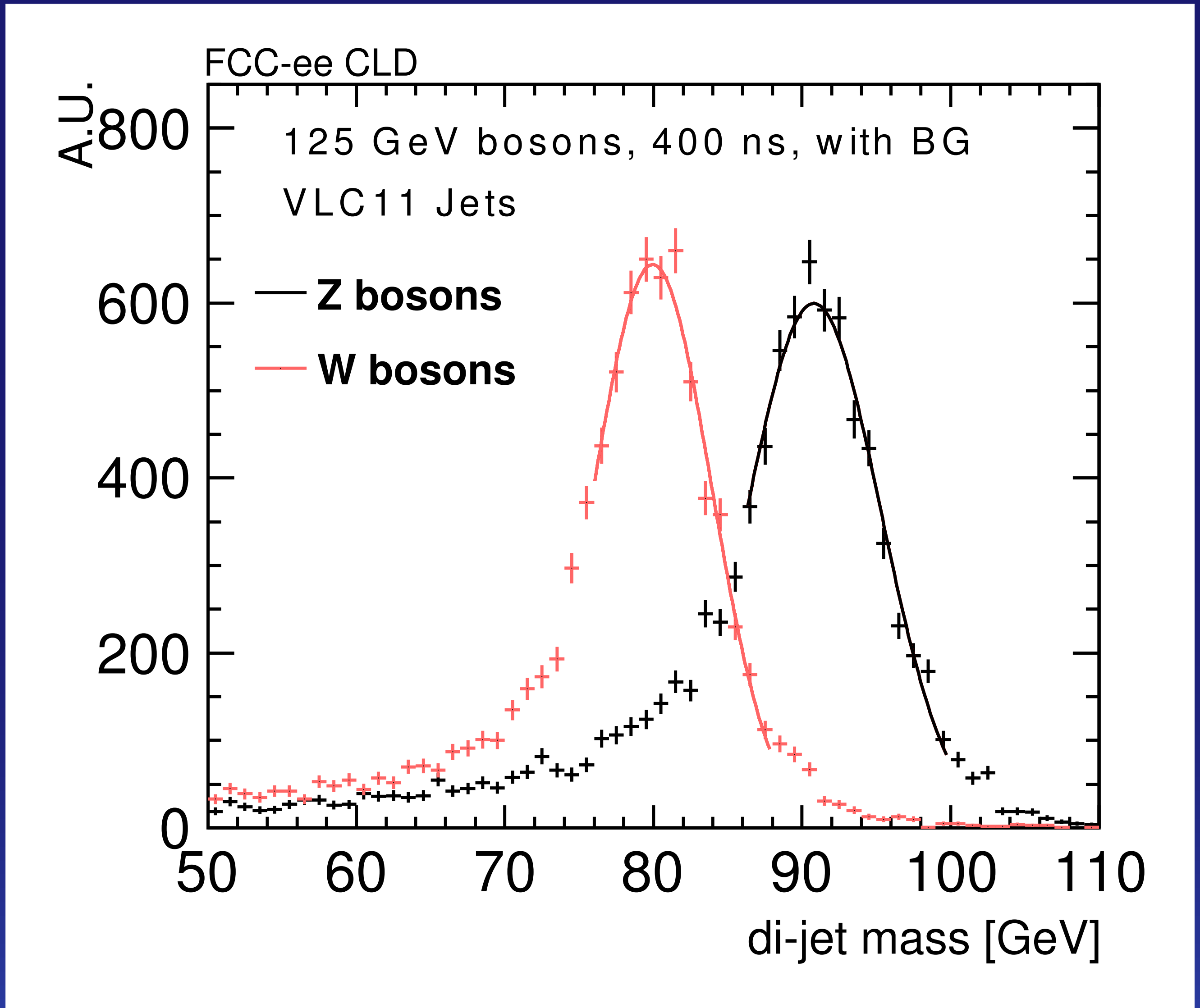


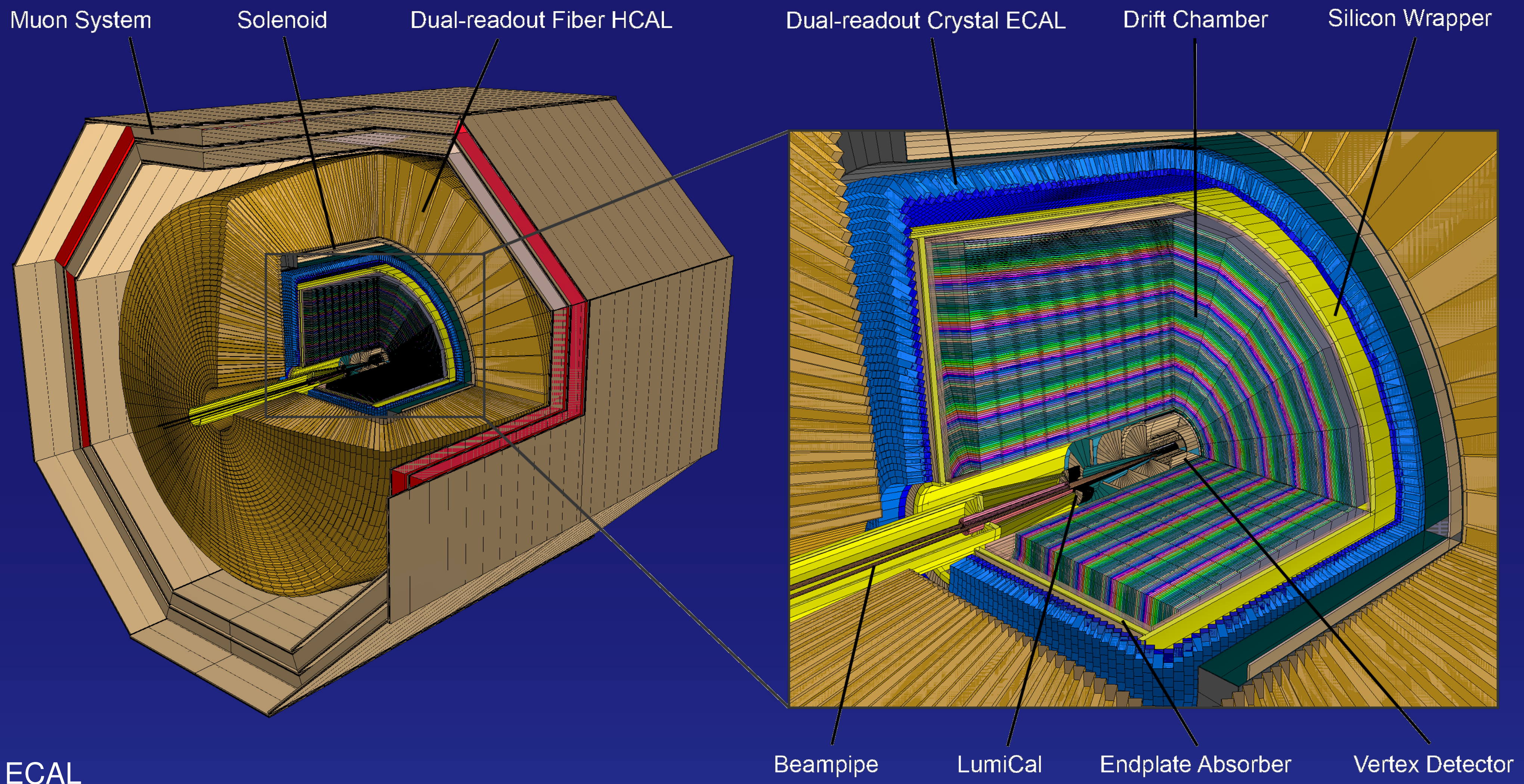


- Jet energy resolution for CLD using `PandoraPFA` (see e.g. **doi:10.1016/j.nima.2012.10.038**)
  - up to 4.5% resolution for hadronic jets at the Z-pole
  - software compensation (since $e/h > 1$) improves resolution by 5 - 7.5%
- W / Z separation
  - 125 GeV boson energy with incoherent pair-background at 365 GeV
  - 2.5 σ separation

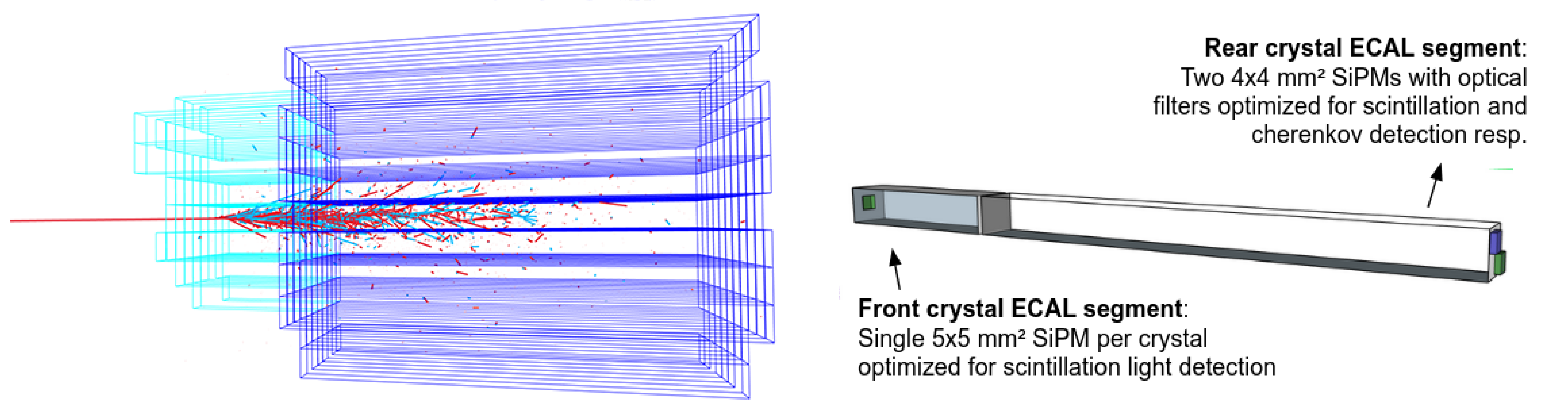




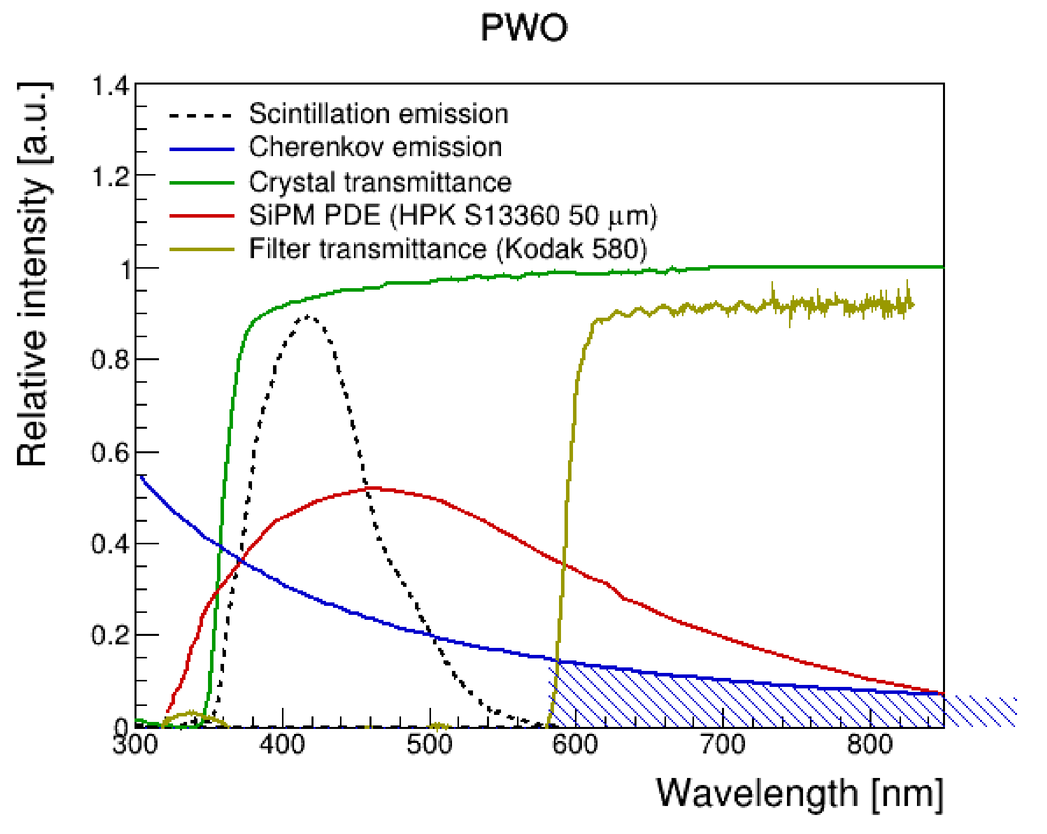




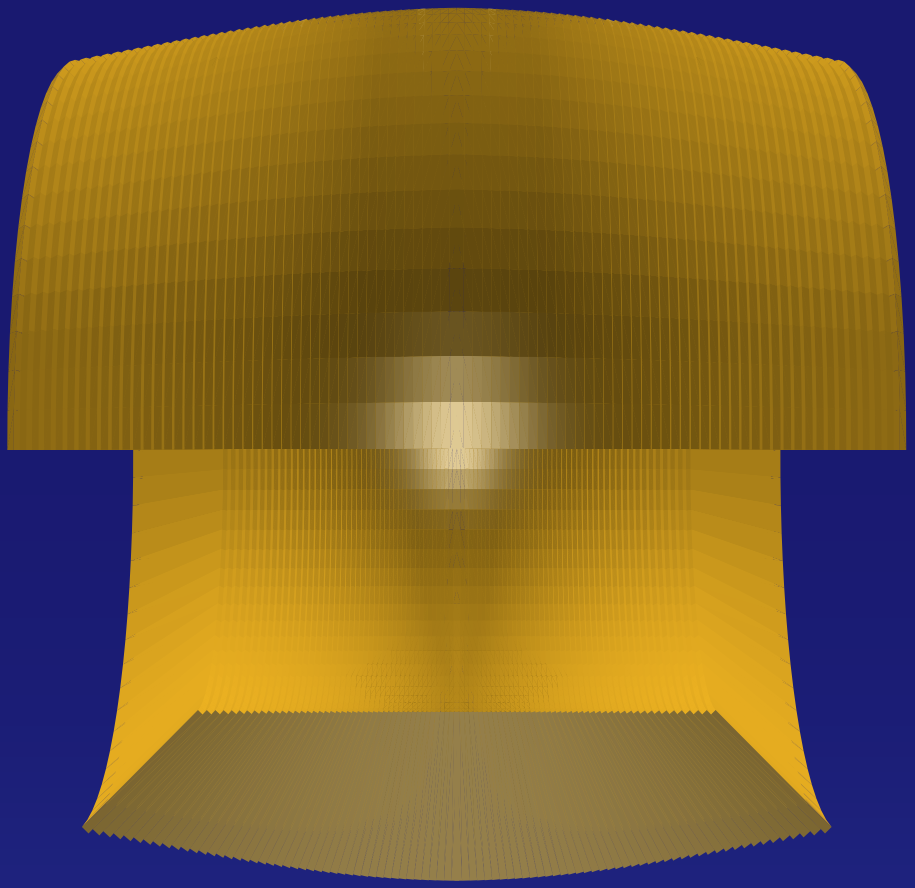
- ECAL
  - 2 layer crystal ECAL
  - $10 \times 10\,\mathrm{mm}^2$, $6X_0$ (front, E1) and $16X_0$ (back, E2) with 1 SiPM per crystal in E1 and 2 SiPM per crystal in E2 (dual readout)
  - 1.36×10^6 (barrel) and 0.25×10^6 (endcap) crystals
- HCAL
  - single layer dual readout fibre in metal sampling calorimeter
  - 60×10^6 (barrel) plus 20×10^6 (endcaps) fibres each with one SiPM – 8 SiPM feed one readout channel
  - longitudinal info possibly by timing

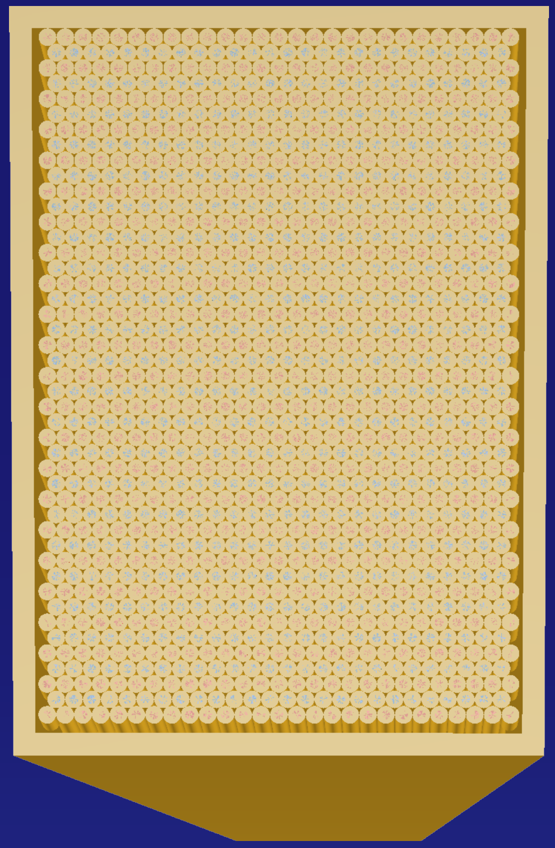


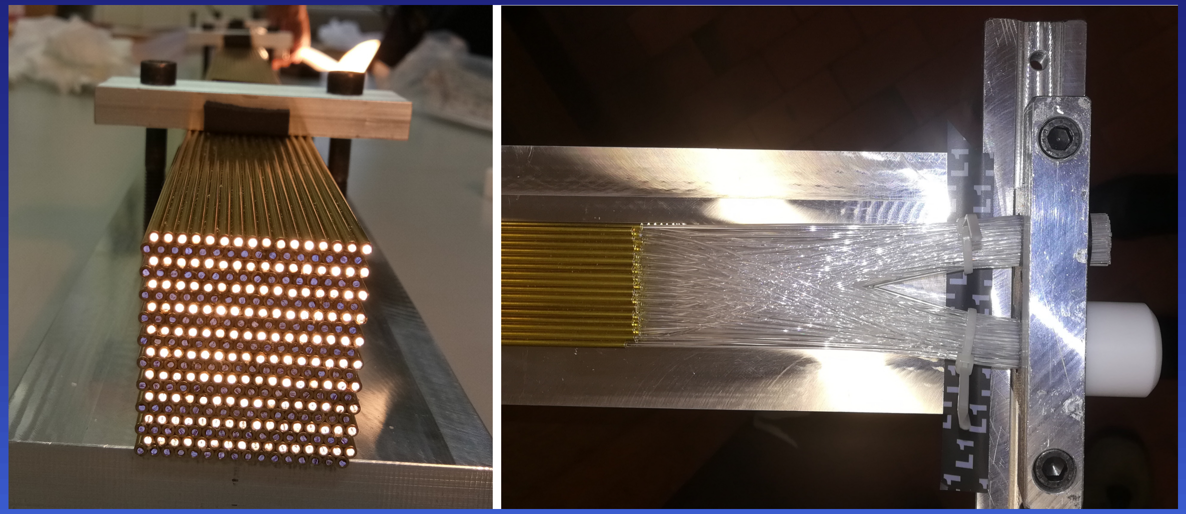
- Dual readout crystal ECAL with 2 longitudinal layers
  - scintillation light (S) is created by both, relativistic ($e^{\pm}$) and non-relativistic (hadronic) particles
  - Čerenkov light (C) is created by relativistic ($e^{\pm}$) particles only
  - single front SiPM collects mainly S (negligible amount of early showering hadrons)
  - 2 rear SiPM collect either Čerenkov light only (optical filter blocks scintillation light) or both S+C
  - allows to measure fluctuating em-component in hadronic showers ► to make $e/h = 1$



- Dual readout fibre HCAL
  - originally the only calorimeter for IDEA
  - decades of R&D by the DREAM collaboration (**http://www.phys.ttu.edu/ dream**)
  - dual readout by alternating S and C 1 mm diameter fibres with max. light yield in blue (S) or red (C)
  - tube metal could be brass or steel
  - S or C optimised individual SiPM's for each fibre
  - 8 SiPMs combined to one readout channel
  - allows measuring the em-component in hadronic showers
    - ► to make $e/h = 1$
- Images below show copper prototype with PM readout

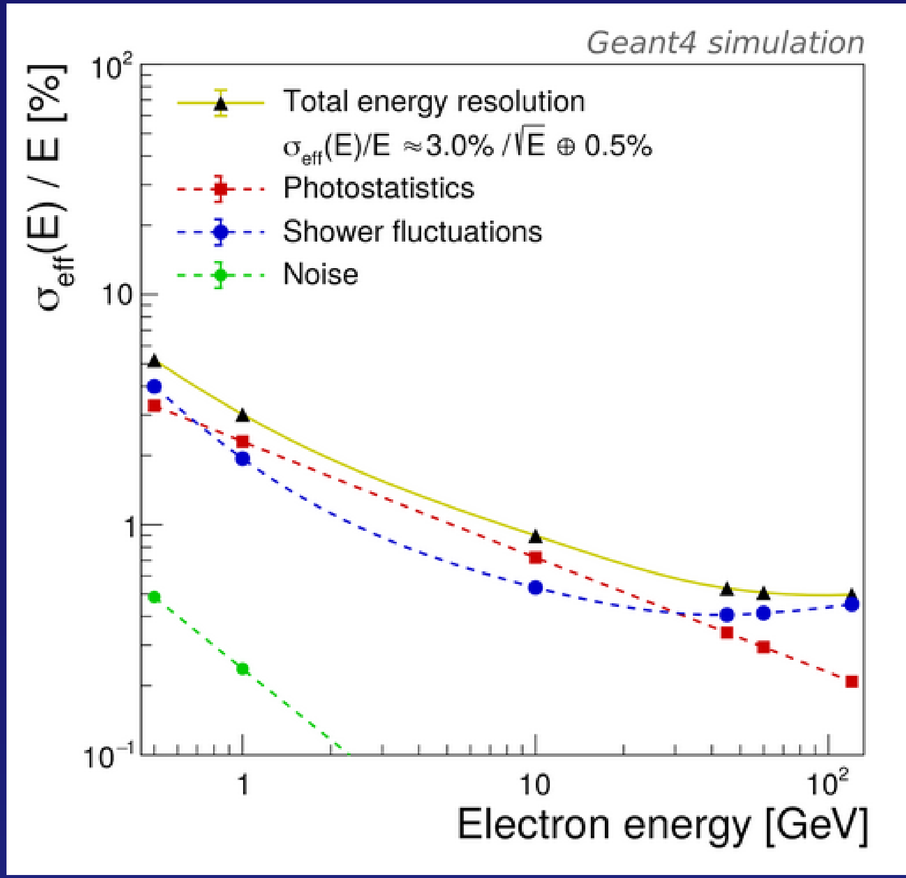




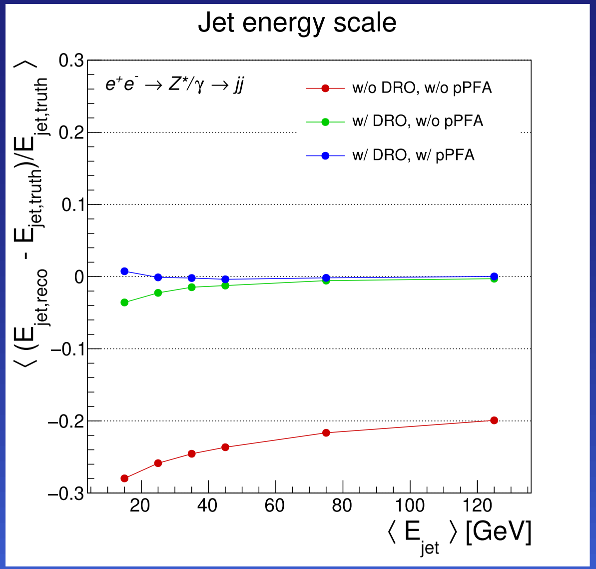


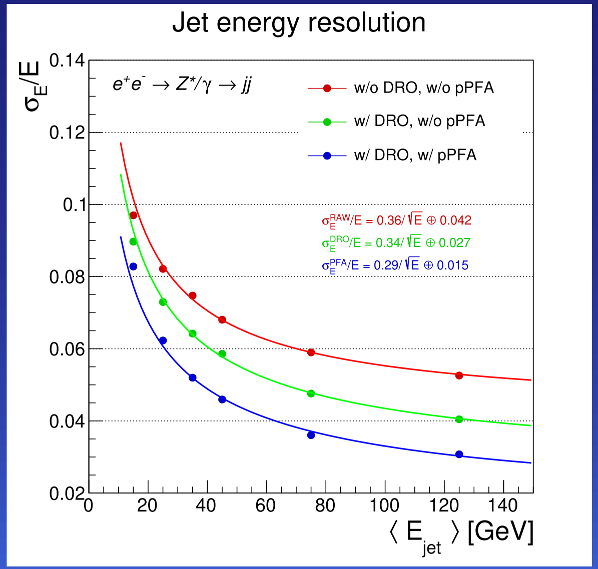
doi:10.1088/1748-0221/17/09/T09007

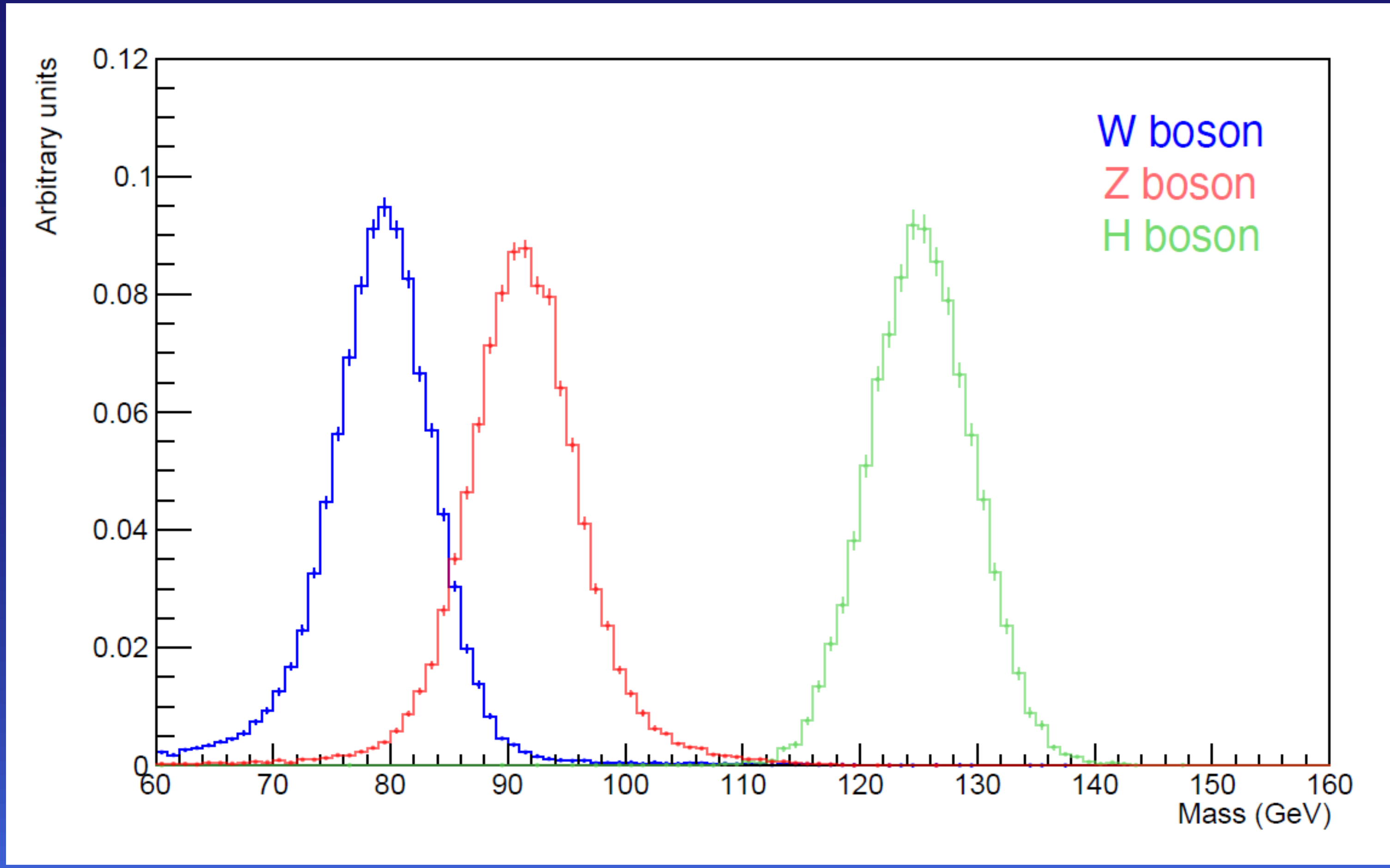
FCC-ee Detectors ► IDEA Jet Performance



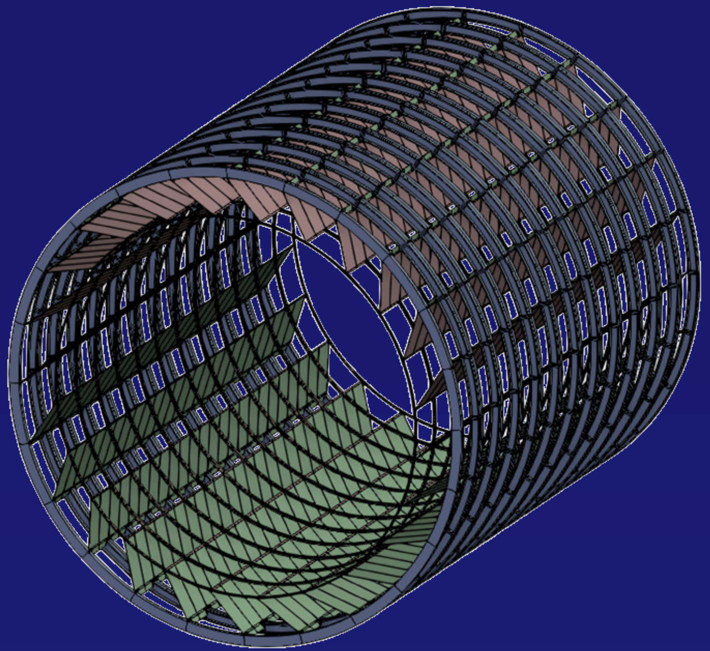
- ECAL performance
  - able to reach $\sigma_{\text{eff}}(E)\,/\,E \simeq 3.0\%\,/\,\sqrt{E} \oplus 0.2\%$
- Combined ECAL+HCAL+`ParticleFlow` performance
  - linerity and resolution for `S`-signal only (red), dual readout (`S` & `C`) (green) and dual readout with `ParticleFlow` (blue): $\sigma_{\text{eff}}(E)\,/\,E \simeq 29.0\%\,/\,\sqrt{E} \oplus 1.5\%$
  - separation of W/Z-bosons better than 2.5σ

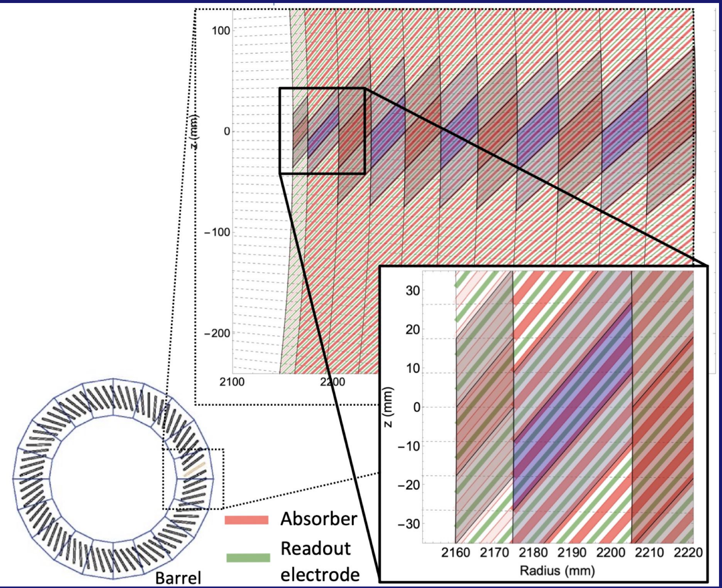


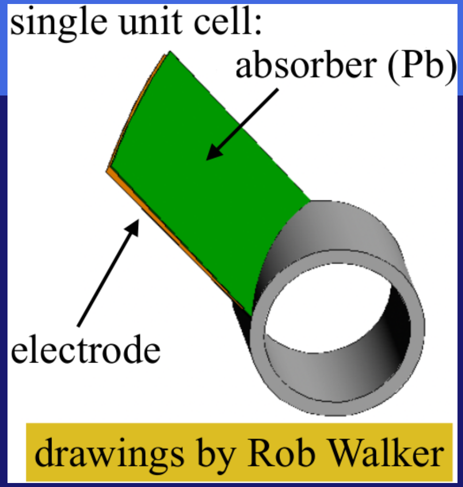




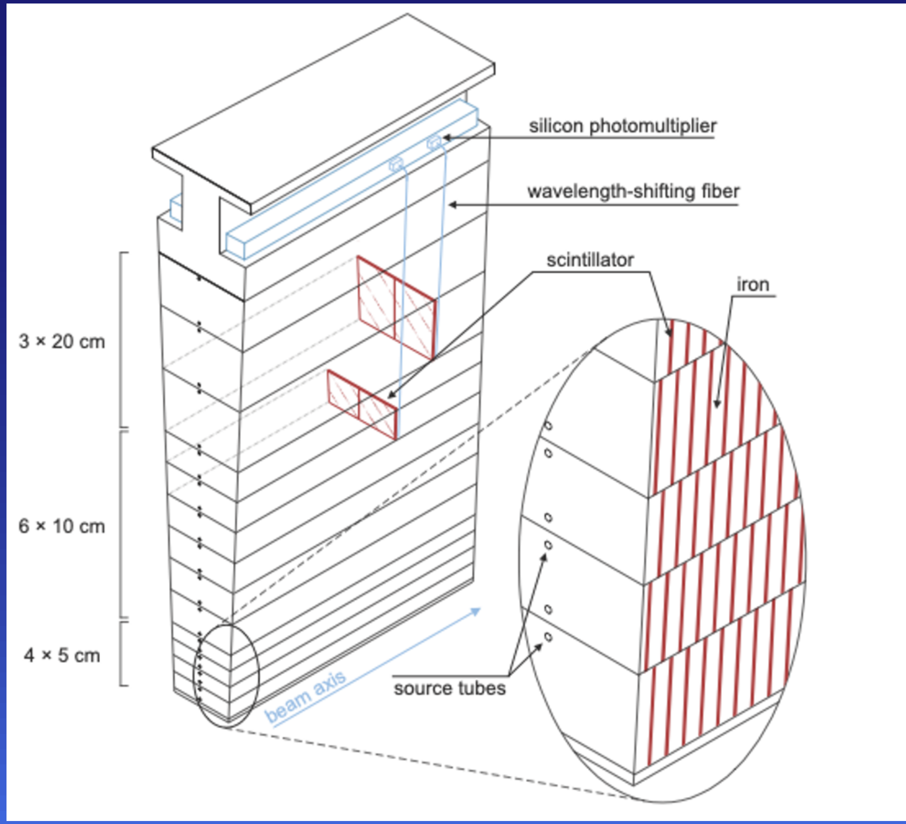
doi:10.1051/epjconf/202532000022







- **ECAL**
  - barrel (top left):
    - 1536 1.8 mm Pb plus 2 × 0.1 mm steel absorbers with 1.2 mm PCB spaced in 1.2 mm distance
    - tilted by 50° around cylinder axis
    - LAr gaps of 2 × 1.2 mm to 2 × 2.4 mm
    - 22 X_0, 11 longitudinal layers
    - $\Delta\phi$ = 8 mrad, $\Delta\theta$ = 10 mrad (2.5 mrad in strip cells)
    - $O(1.5 \times 10^6)$ readout channels
  - endcap (top right):
    - ”turbine”-design with absorbers rotated by 41° around r-axis
    - growing in thickness linear with r from initial 2.9 mm
    - PCB placed between adjacent absorbers
    - in three nested wheels with 144, 272 and 512 absorbers



- **HCAL (bottom left)**
  - current baseline is a steel-scintillator tile calorimeter (similar to ATLAS’ TileCal)

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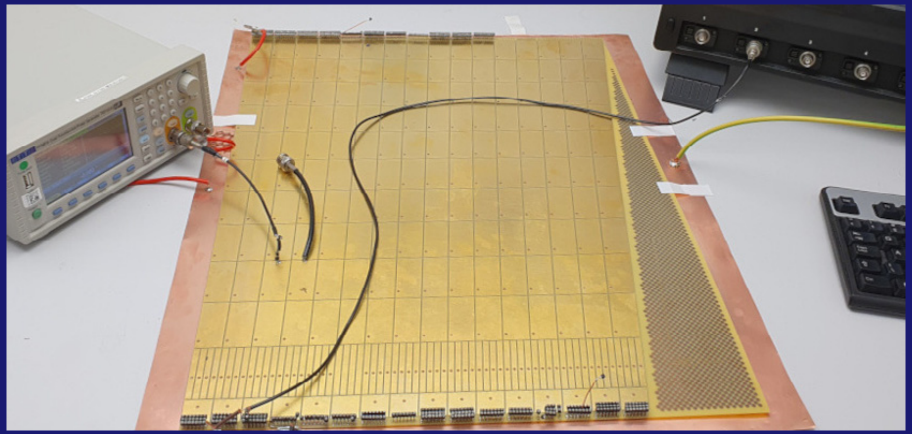
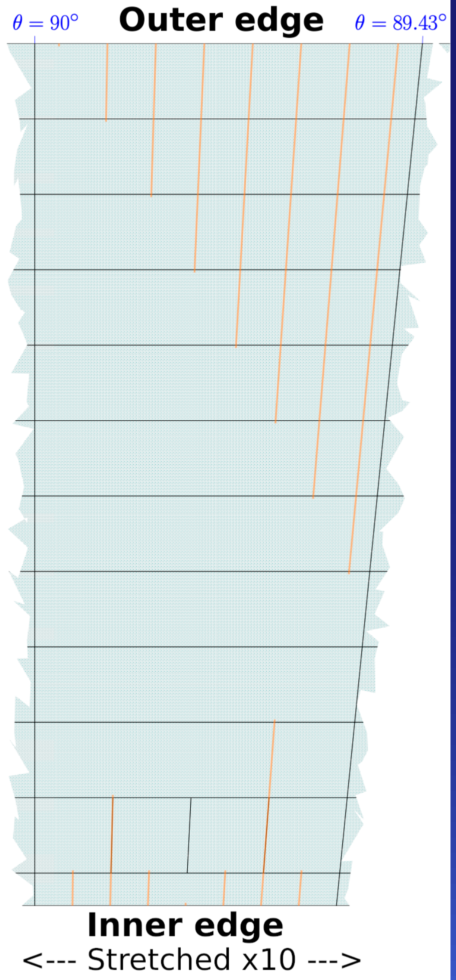
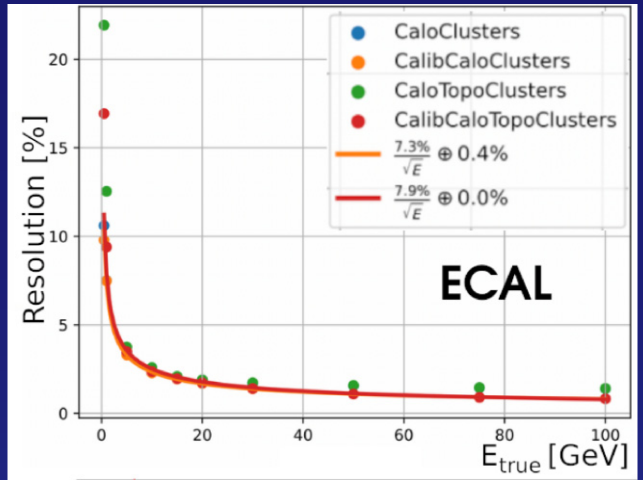
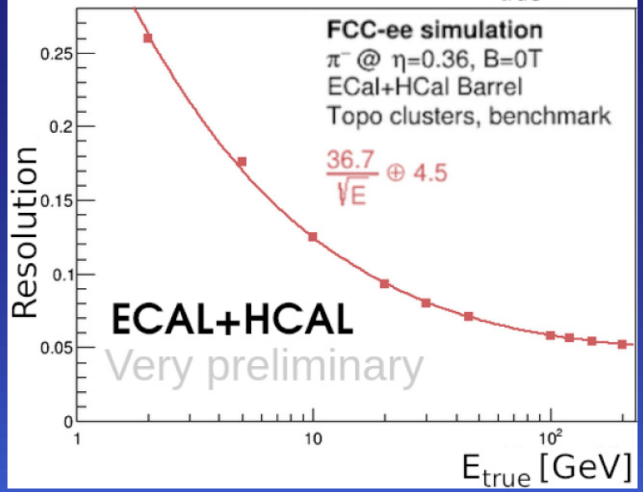
- ECAL prototype
  - 58 × 48 cm^2 electrode prototype has been produced and tested
  - division in 12 layers; front layer for presampling; second layer with finer strips (π^0 / γ-separation)
  - and 16 θ towers of 0.56° each
  - 7 layer PCB to route all signals out at r_{out}
- need to balance cross-talk and noise with granularity
- challenge is the number of signal cables to route out of cryostat
  - consider cold readout electronics inside the LAr
  - limited space inside the cryostat is a challenge
- encouraging first full simulation results on ECAL and ECAL+HCAL resolution



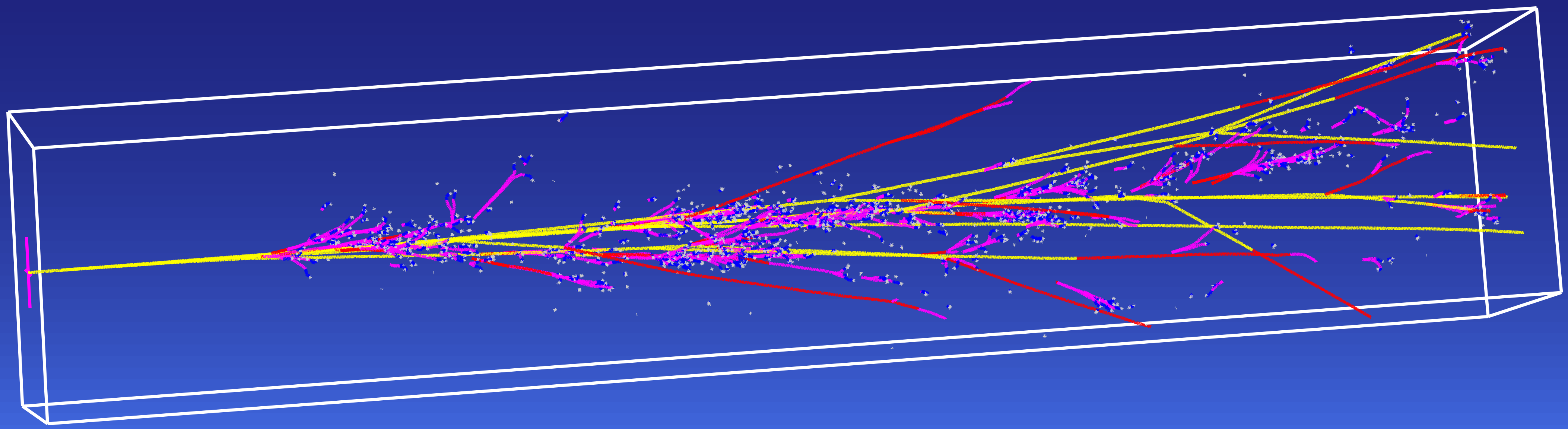






- Do we still need to cluster and calibrate calorimeter signals in times of `ParticleFlow`?
  - in `ParticleFlow` we want to reconstruct the energy from the measured $p_\perp$ in the tracker and the measured momentum direction θ, ϕ
  - the hadronic showers of these particles have an unknown em-fraction f_{em} – particle by particle and event by event!
  - the calorimetric response to hadrons is not constant! It varies with f_{em} – which is unknown
- $E_{reco} \sim f_{em} + (1 - f_{em}) / (e / h)$,

  with e / h the intrinsic response ratio of electrons to hadrons, typically $e / h > 1$



- This means you need to measure f_{em} for each hadronic shower in order to properly reconstruct its energy
  - dual readout calorimeters can do that by means of the two components measured per cell (scintillation light (em+had) and Čerenkov light (em only))
  - for non-compensating calorimeters you need to measure f_{em} from the shower shape:
    - dense sub-showers indicate the em component
    - less dense shower regions the rest
  - to judge dense vs. non-dense you need to group the energy measurements together – i.e. form clusters
  - it is relative to the cluster's total reconstructed energy on some (uncalibrated) scale that dense and non-dense sub-shower parts are identified
  - based on that distinction the energy-scale can be calibrated and unified – shower by shower and event by event
- Clustering (for determining f_{em}) and calibration (to get a uniform energy scale) need to be done before any part of the shower is subtracted

Conclusions

- FCC-ee will host a new generation of fantastic calorimeters
  - with unprecedented granularity ($O(10^6)$ - $O(10^8)$ readout channels)
- depending on the technology chosen there are many challenges
- calorimeters need to be linear
  - individual measurements proportional to deposited energy
  - regular calibration and monitoring of individual channels with $Z \to \mu^+\mu^-$ and $Z \to e^+e^-$
  - shower clustering of individual energy measurements to compensate $e/h > 1$ (or dual readout)
  - minimal amount of material in front of the calorimeters
  - maximal containment of all (em and had) showers
- readout electronics need to cope with the desired granularity
  - cooling and cables provide extra (unwanted) material
  - readout electronics take up extra (limited) space
- aim for excellent resolution
  - ensure shower separation by transverse and longitudinal granularity
  - regular calibration and monitoring of individual channels with $Z \to \mu^+\mu^-$ and $Z \to e^+e^-$ to ensure uniformity
  - calibration prior to ripping apart showers by `ParticleFlow`
- optimisation of the FCC-ee detector concepts in full swing
  - full Geant4-based simulations and tests with prototypes