EM Calorimeters
Design concepts overview

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Outstanding Physics ⇒ Strong Requirements on Detectors

Higgs
factory

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

Top

m_{top}, Γ_{top}, ttZ, FCNCs

→ Excellent tracking
Jet energy resolution
at high energies

Flavor
"boosted" B/D/τ factory:

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

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

→ Excellent tracking / energy resolution / PID at low energies

QCD - EWK
most precise SM test

m_Z, Γ_Z, Γ_{inv}

$\sin^2\theta_W$, R^Z_ℓ, R_b, R_c

$A_{FB}^{b,c}$, τ pol.

α_S,

m_W, Γ_W

→ Small systematics

BSM
feebly interacting particles

Heavy Neutral Leptons (HNL)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

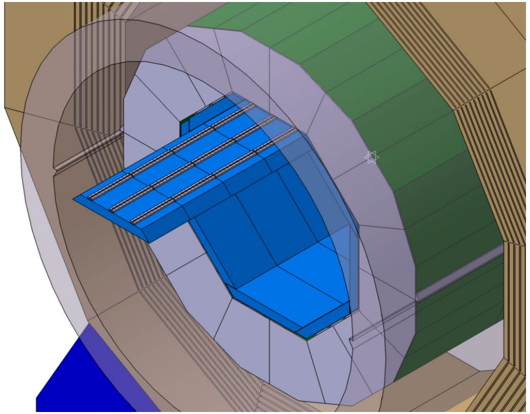
→ Versatile detector

WP1: SiW Ecal

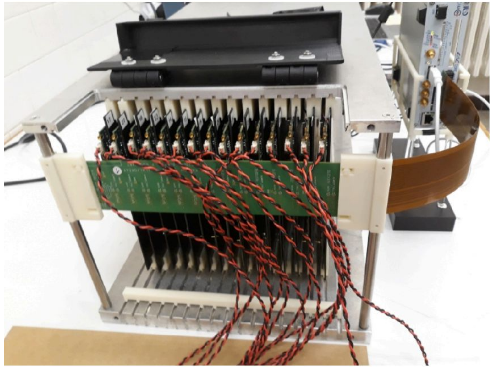
Vincent Boudry's Talk

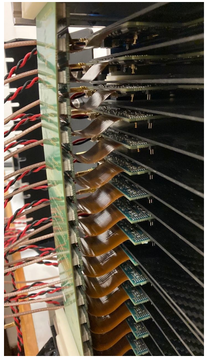
Baseline Ecal in ILD, CLD

- 30 layers, 2.8 mm tungsten absorber, 24 X_0
- 0.5 mm thick silicon sensors with 5×5 mm^2 granularity
- $O(10^8)$ cells
  - Super high granularity for PFlow reconstruction
  - Tight integration: compact and hermetic
- EM resolution ~17%/√E

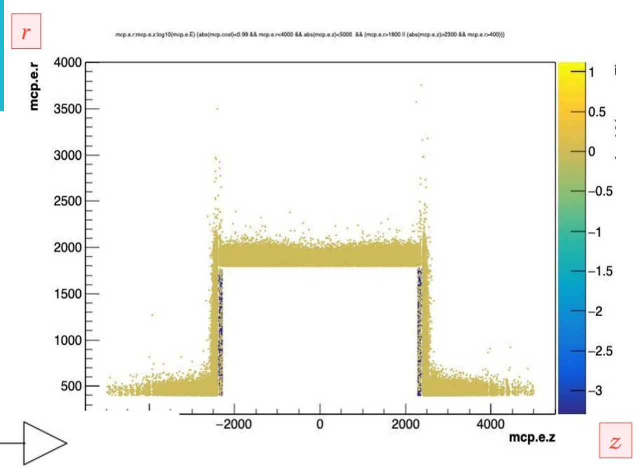


- Challenges:
  - Adaptation to FCC-ee (cooling, power)
  - Granularity re-optimisation ?
  - Study addition of timing
  - System aspects: design engineering module

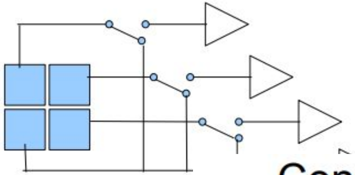




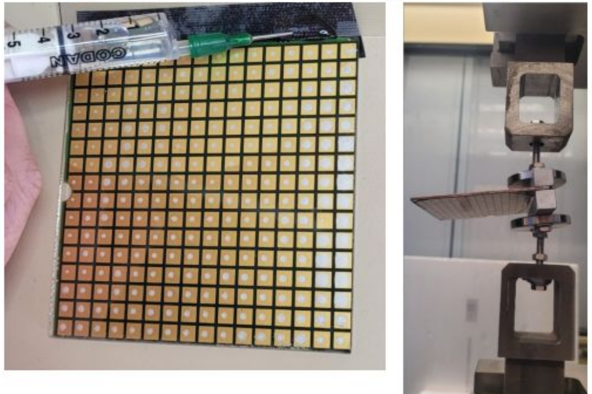
Latest News



- Work ongoing to study the implications of SiW in FCC-ee
- Estimation of expected fluxes in each layer of the calo
  - “CaloFlux” tool
  - Impact on rates and on power
- Re-optimization of number and thickness of layers (30 → 26)
- Granularity optimization: towards dynamic granularity ?
- Cooling studies
- Impact of timing in PFlow performance
- Improvements on hybridization



Conductive glue + filling (~invisible) on a glass plate



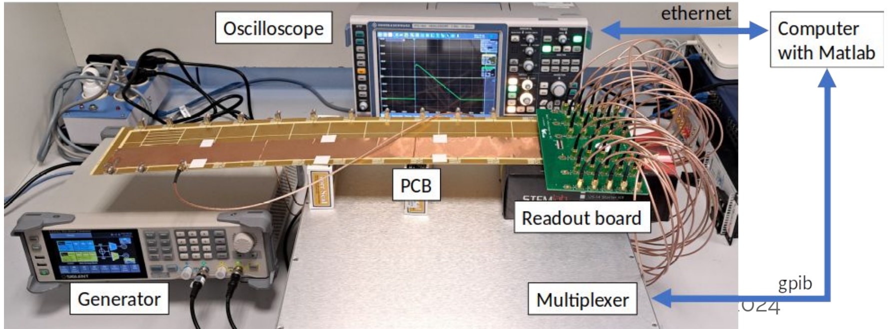
WP2: ALLEGRO ECal

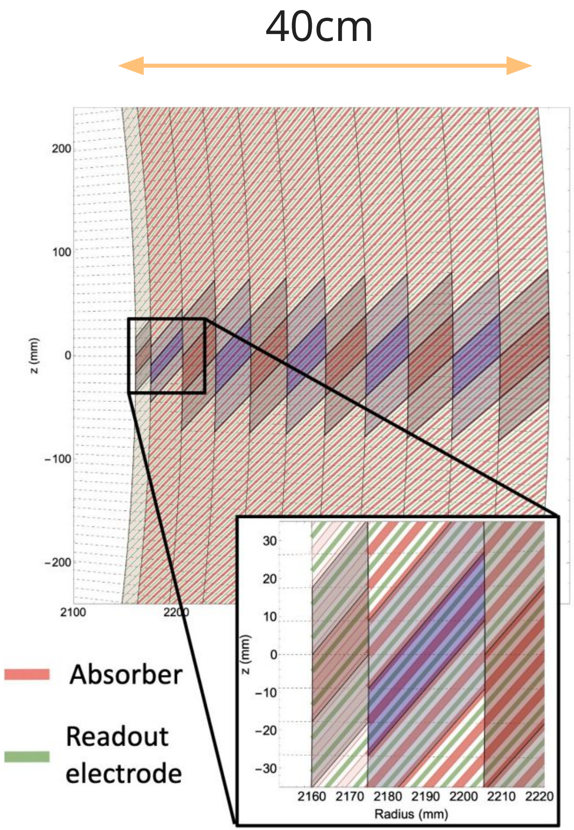
Farès Djama's Talk

Ecal for ALLEGRO Detector Concept

- High granularity (O(10^6) cells) noble liquid (LAr/LKr) Ecal using straight readout electrodes
  - Good compromise for granularity, resolution (5-8%/√E), stability, uniformity

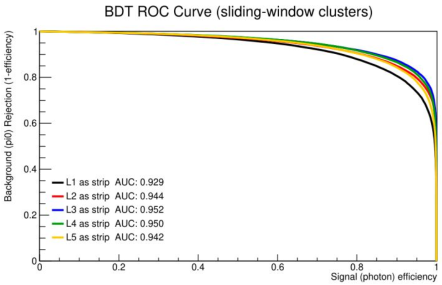
- Main R&D topics
  - Optimise design for performance based on simulations
  - R&D on electrodes and absorbers
  - Mechanical design
  - Cold and warm frontend electronics
  - Aim: testbeam module in 2028

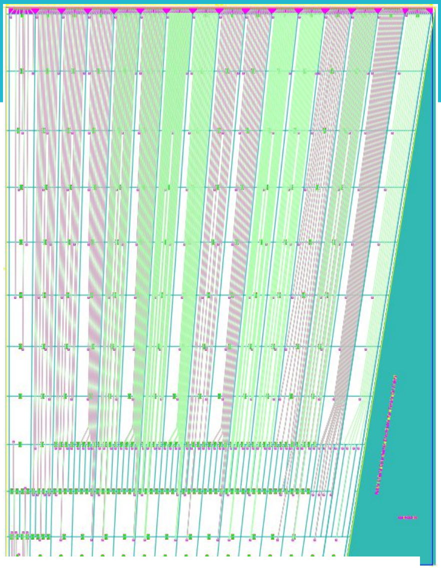


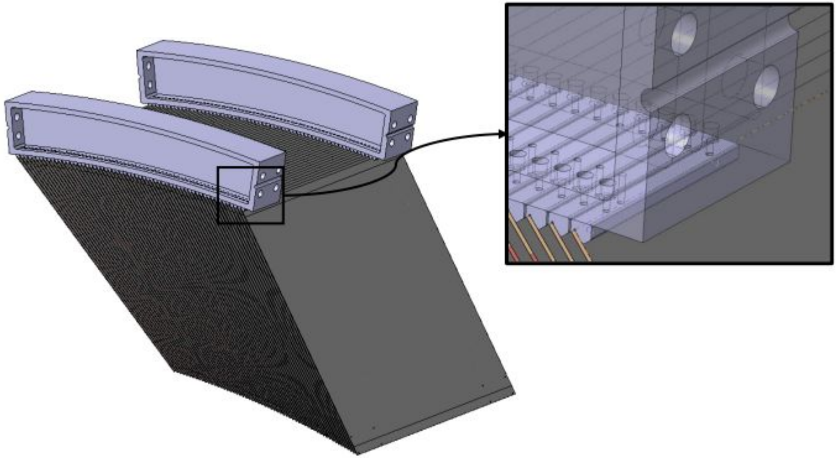


Latest News

- Extensive studies of electrode prototypes
  - Confirm cross-talk « 0.1% achievable
  - Inform trade-offs noise / cross-talk
- Preparation of next generation electrode protos
  - Features several design options to guide final design choices
- Progress on simulations
  - Photon / π^0 separation results guide granularity choices
- Mechanical design ongoing
  - Holding + precise positioning of absorbers and electrodes
  - Good progress towards testbeam module design





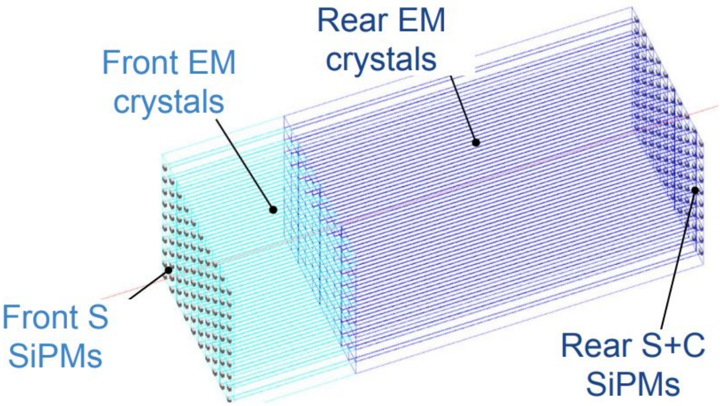


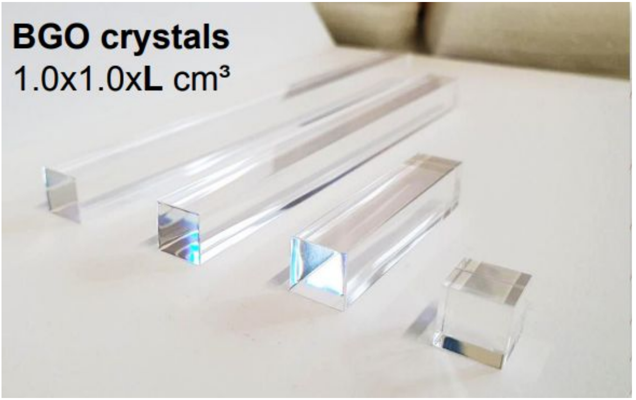
WP3: MAXICC / CalVision

Ecal for IDEA detector concept

- Homogeneous EM calorimeter based on segmented crystals with dual-readout
  - High density scintillating crystals with good cherenkov yield
  - Dedicated optical filters and SiPMs to readout S and C from same active element
  - Promise 3%/√E + DR capability

- Main R&D Topics
  - Identification of optimal crystals, optical filters and SiPM candidates
  - Proof-of-concept with lab measurements and prototypes
  - EM scale prototype for beam test

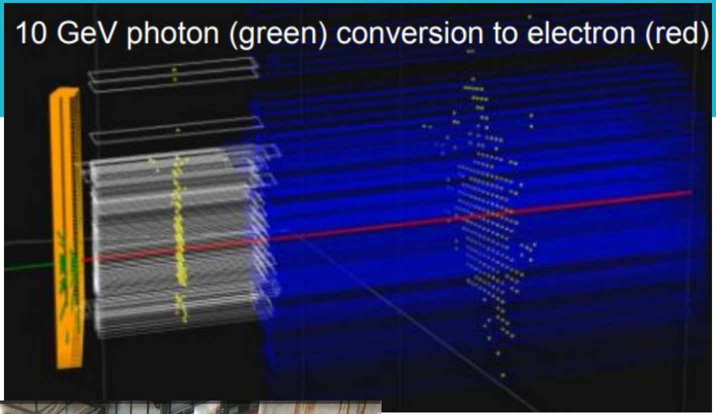


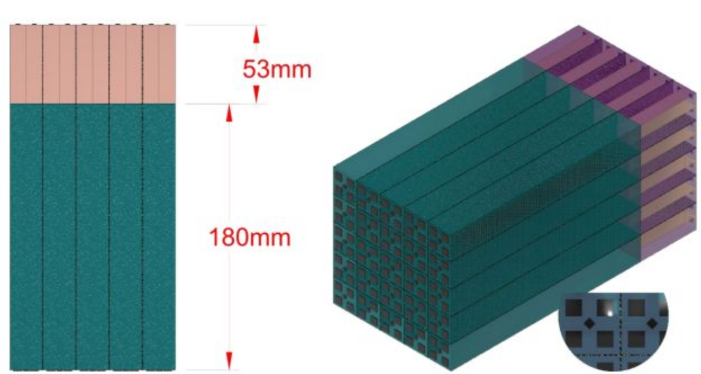


Latest News

Rapid progress in 2024 !

- Integration in key4hep making good progress
  - Digitization implemented
  - Resolution studies underway
  - Integration in IDEA fullsim ongoing
- Testbeam campaigns
  - FNAL 2023, DESY and CERN 2024
  - Understand photon modeling, improve optical coupling, understand Cerenkov yield
  - See Marcello's talk for details !
- Plans for 2025
  - Build two full containment prototypes (BGO and PWO)
  - Then testbeam end of September



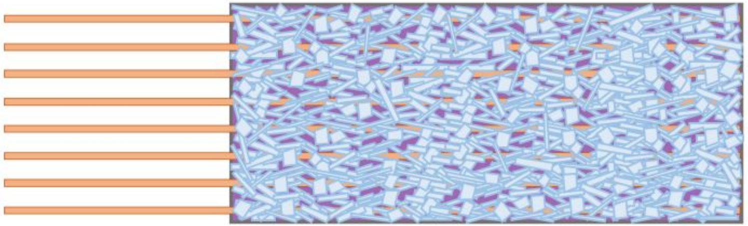


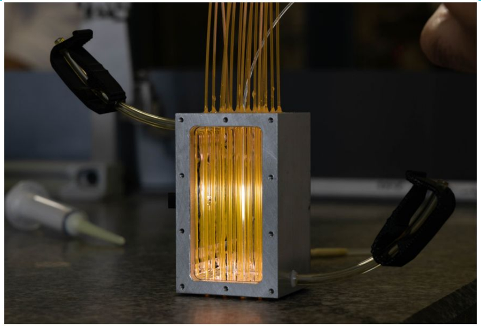
WP3: GRAiNITA

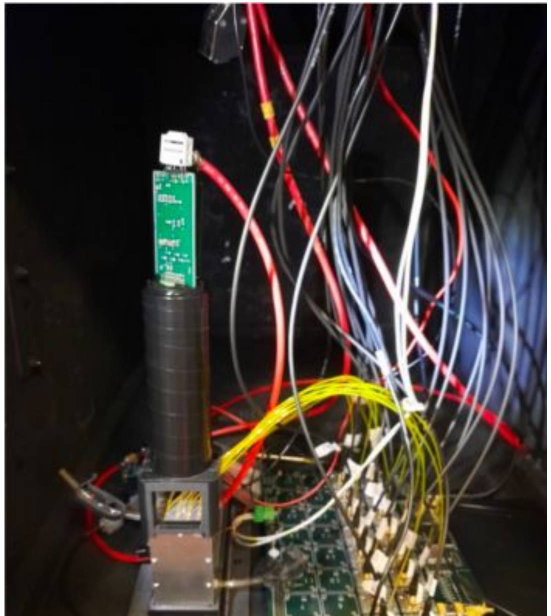
Marie-Hélène Schune's Talk

A novel type of calorimeter ~ next-gen shashlik

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





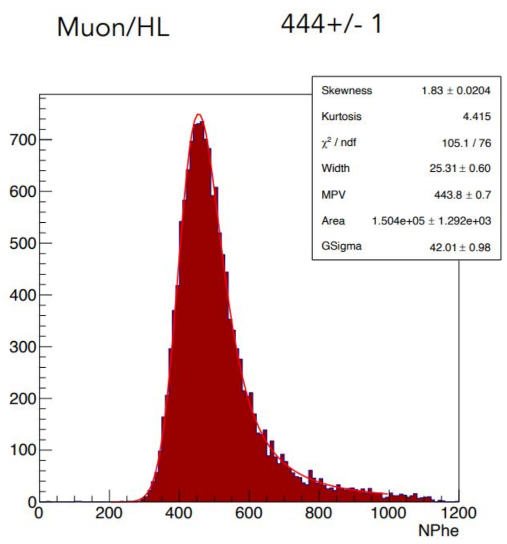


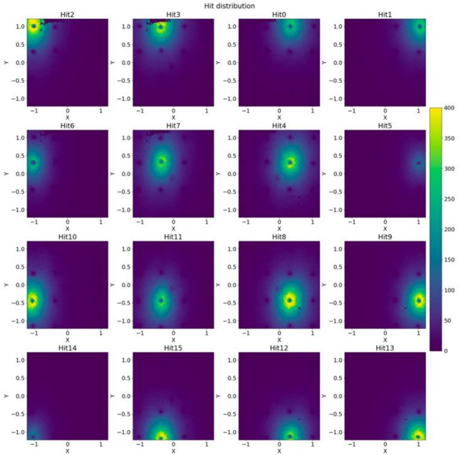
- Excellent expected EM resolution: 2-3%/√E
  - Using BGO or $ZnWO_4$ crystals
  - 16-channel prototype $ZnWO_4$ + liquid built in 2024 and tested with cosmics
- Main R&D topics
  - R&D on crystal grains
  - Aim for larger prototype to validate on testbeam

Latest News

Opportunity for testbeam in H2 at CERN

- ~4M pions, ~200k muons
- Confirmation of light confinement
- Confirmation of possibility of 1%/√E due to photon statistics
- First non-uniformity studies
  - 9% light yield difference for MIP close/far from a fiber
  - Seems enough for low constant term





Confirmation of light confinement

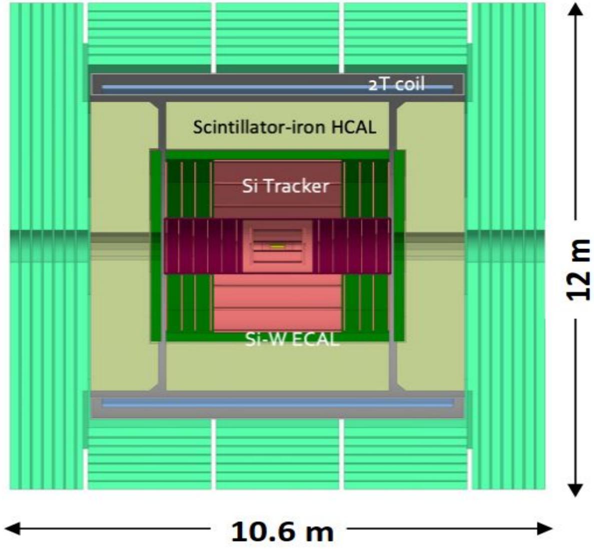
Conclusions / Discussion

- France and Italy communities strongly involved in EM Calos R&D
- Si-W, MAXICC and ALLEGRO Ecal all integrated in projected detector concepts
- Areas for collaboration identified through DRD6
  - Map to the Working Groups: Testbeams, Software
  - And electronics: frontend might be similar (Si-W, LAr), backend/DAQ should be harmonized as much as possible

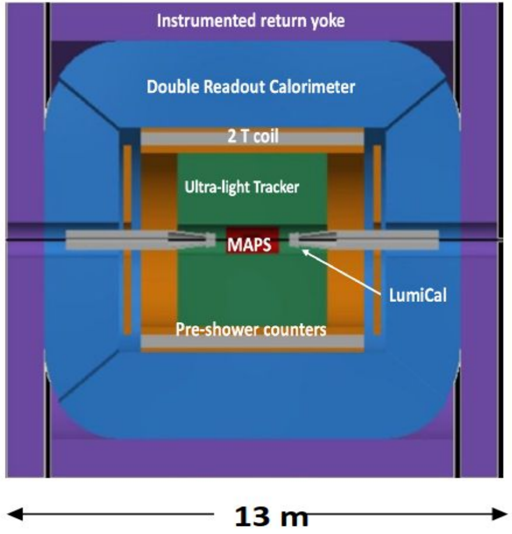
Supplementary Material

FCC-ee Detector Concepts

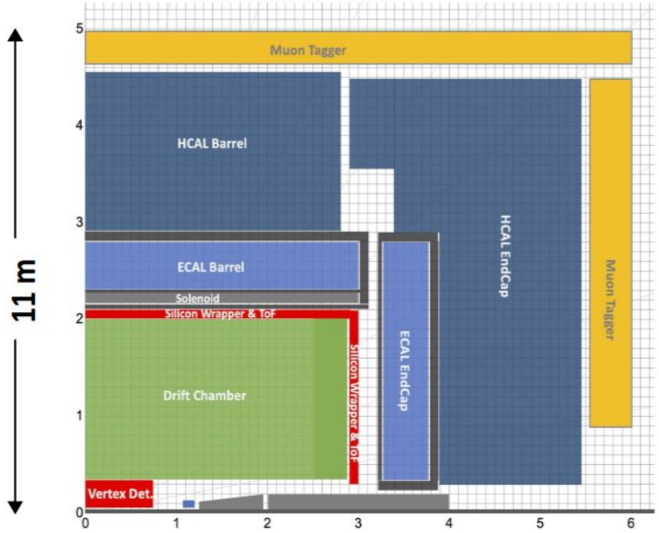
CLD



IDEA



ALLEGRO



Calorimeters for HET factories

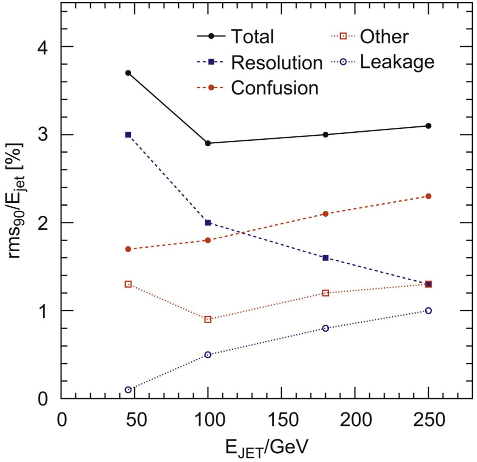
An extensive set of requirements

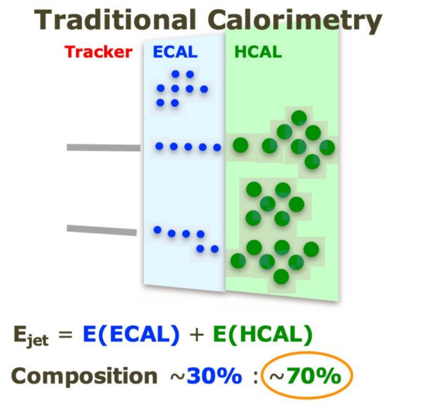
- Energy resolution: "only" for photons and neutral hadrons
  - But: ideally photons as low as 200 – 300 MeV
- Dynamic range: 200 MeV – 180 GeV
  - vs LHC: 6 TeV jets !
- Granularity: PID, disentangle showers for PFlow
  - But: how granular exactly ?
- Hermeticity, uniformity, calibrability, stability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

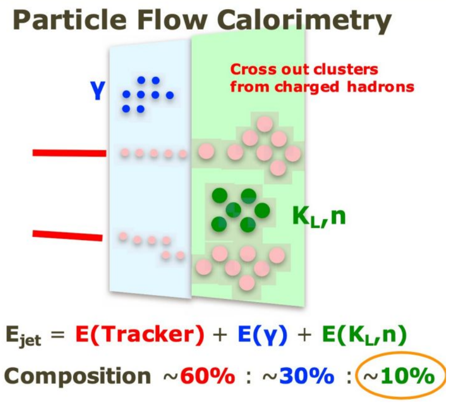
A quest for ultimate jet energy resolution

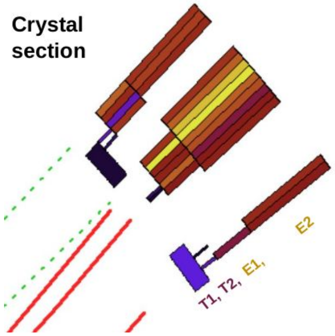
PFlow PFlow PFlow

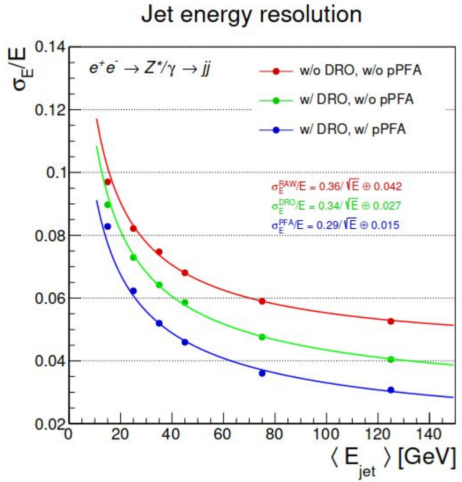
- Target: σ(E)/E = 30%/√E (GeV)
  - Typical figure of merit: W/Z boson separation
  - Actual use: variety of hadronic measurements
- What granularity do we really need at HET Factories ?
- New calos concepts bring new ideas (crystals DR study)











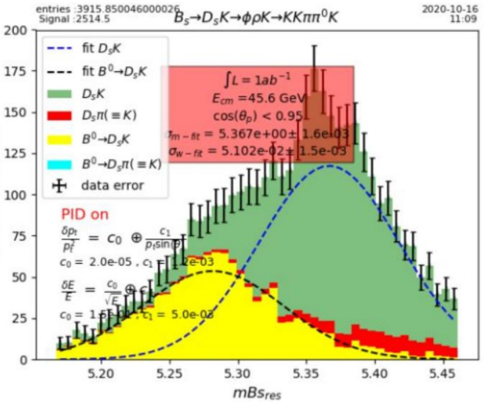
FCC unique challenges

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

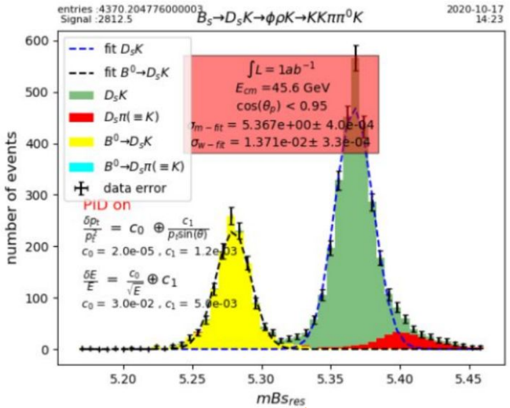
- Some physics channels require very high EM resolution

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

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



15%/√E



3%/√E

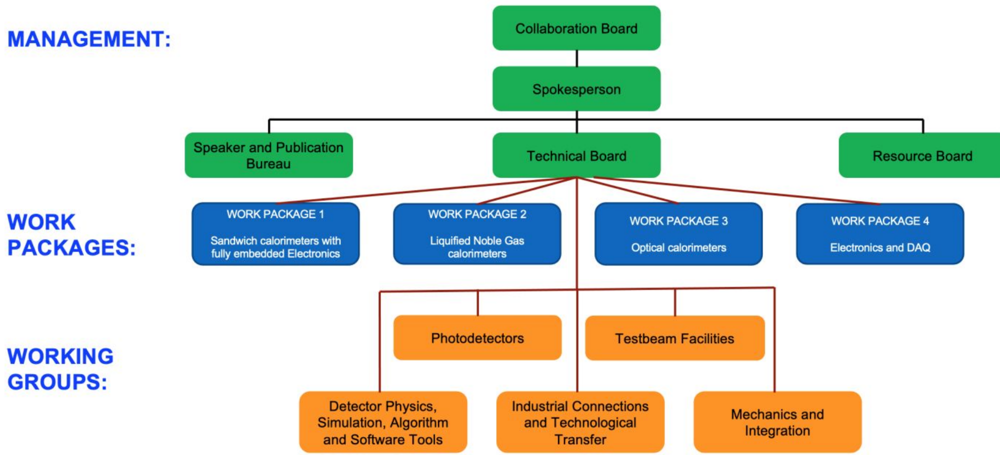
Recon → / Gen ↓	$\pi^\pm \nu$	$\pi^\pm \pi^0 \nu$	$\pi^\pm 2\pi^0 \nu$	$\pi^\pm 3\pi^0 \nu$	$\pi^\pm 4\pi^0 \nu$
$\pi^\pm \nu$	**0.9560**	0.0425	0.0010	0.0003	0.0002
$\pi^\pm \pi^0 \nu$	0.0374	**0.9020**	0.0586	0.0016	0.0002
$\pi^\pm 2\pi^0 \nu$	0.0090	0.1277	**0.7802**	0.0808	0.0022
$\pi^\pm 3\pi^0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

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

The home of calorimeter concepts: DRD6

Detector R&D (DRD) collaborations implement the ECFA Detector R&D Roadmap

- DRD6 on Calorimetry with 4 work packages and several transversal activities (TB, Materials, SW, ...)
- Many DRD6 calo projects aim at FCC
  - Presenting only **selected examples** to highlight main R&D directions
  - See last week's DRD6 meeting for details about the projects and the latest progress



- Mission:
  - Bring a diverse set of calorimeter technologies to a level of maturity such that they can be considered for a technology selection of future experiments
  - Maturity demonstrated with **full-scale prototypes**

A lot of fun for all detectors

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