ECFA

European Strategy Update

Detectors for Higgs Factories

Roberto Ferrari
INFN Pavia

Corfu2024 Workshop on Future Accelerators

Corfu, May 21, 2024

INFN
Istituto Nazionale di Fisica Nucleare
Sezione di Pavia

Credits

Most slides from Iacopo Vivarelli's talk ...

Credits

Most slides from Iacopo Vivarelli's talk ...

Interpretation is mine ...

Credits

Most slides from Iacopo Vivarelli's talk ...

Interpretation is mine ...

Of course ...

Credits

Most slides from Iacopo Vivarelli's talk ...

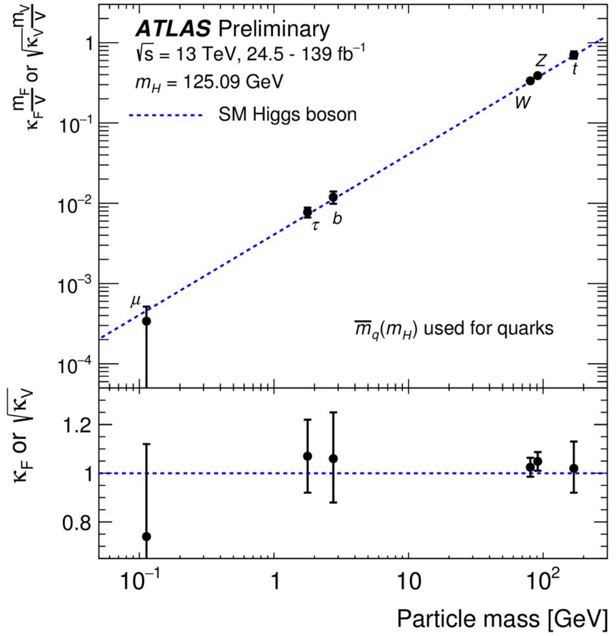
Interpretation is mine ...

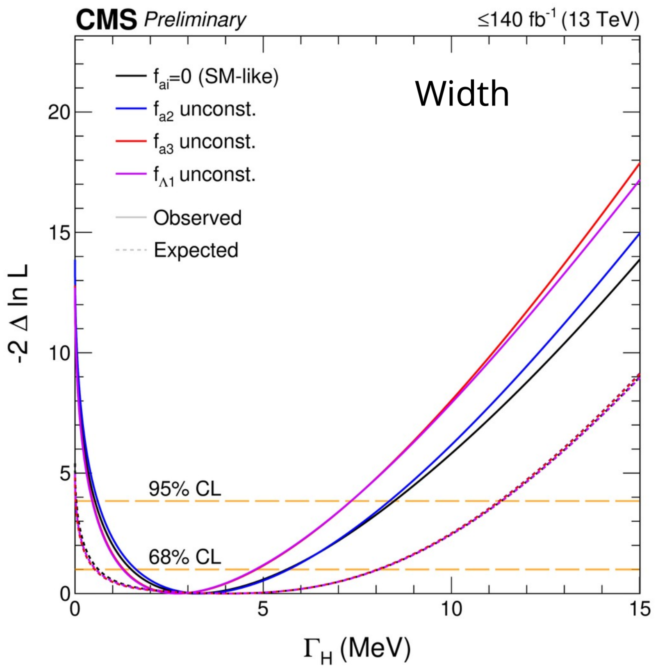
Of course ... mistakes are his

Physics we have

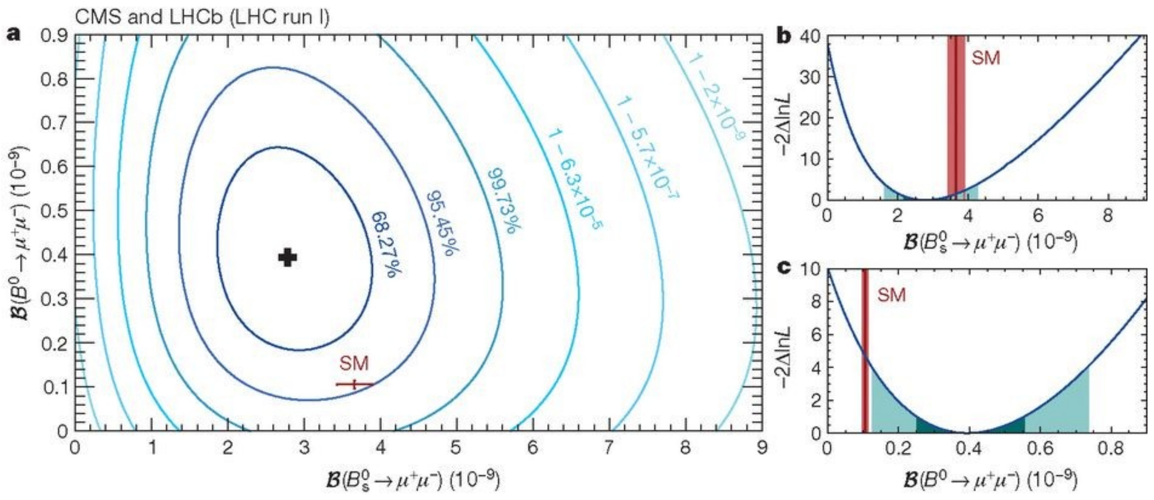
Istituto Nazionale di Fisica Nucleare
Sezione di Pavia

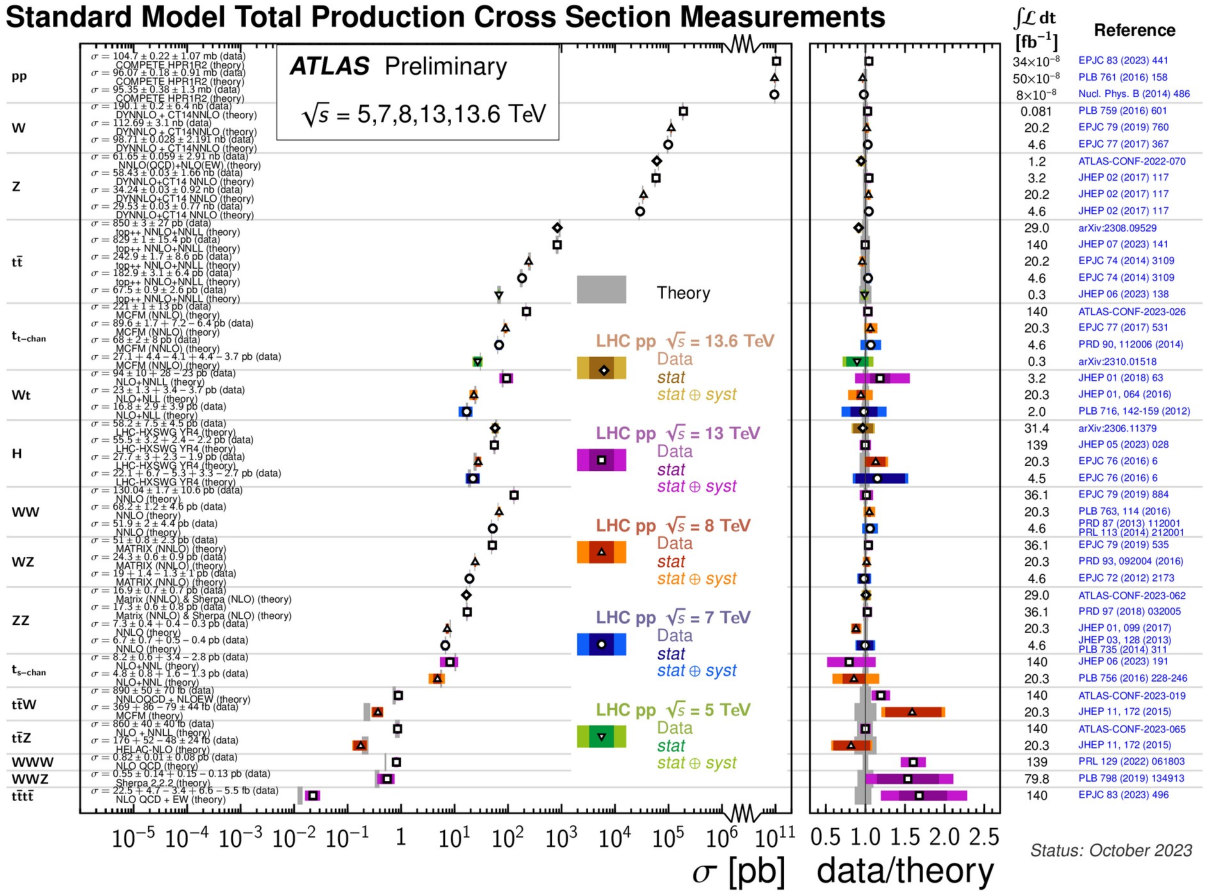
From LHC so far: **universe is very SM-like**





No significant deviation from SM with 140 fb^{-1} of pp collisions (not promising for BSM at HL-LHC)





Physics we need / we would like to have

Precision SM

- M_Z, Γ_Z, N_ν, R_l, A_{FB}, M_W, Γ_W
- α_S (with permille accuracy)
- Quark and gluon fragmentation
- NP QCD

BSM direct searches

ALPs, dark photons, Heavy Neutral Leptons, LLPs

Higgs physics

Higgs width, Higgs to invisible, (self-)couplings

Flavour Physics

- 10^{11} $\tau^+\tau^-$: tau-based EW observables, lepton universality
- 10^{12} *bb/cc* pairs: flavour observables and anomalies, CKM, CP, etc.

Top physics

M_{top}, Γ_{top}, EW top couplings

Numbers for FCC-ee – original slide from C. Grojean

Physics we need / we would like to have

Precision SM

- M_Z, Γ_Z, N_ν, R_l, A_{FB}, M_W, Γ_W
- α_S (with permille accuracy)
- Quark and gluon fragmentation
- NP QCD

EW factory (Z, WW)

Flavour Physics

- 10^{11} $\tau^+\tau^-$: tau-based EW observables, lepton universality
- 10^{12} *bb/cc* pairs: flavour observables and anomalies, CKM, CP, etc.

BSM direct searches

ALPs, dark photons, Heavy Neutral Leptons, LLPs

Higgs

Higgs physics

Higgs width, Higgs to invisible, (self-)couplings

Top

Top physics

M_{top}, Γ_{top}, EW top couplings

Numbers for FCC-ee – original slide from C. Grojean

Physics we need / we would like to have

Precision SM

- M_Z, Γ_Z, N_ν, R_l, A_{FB}, M_W, Γ_W
- α_S (with permille accuracy)
- Quark and gluon fragmentation
- NP QCD

EW factory (Z, WW)

Flavour Physics

- 10^{11} $\tau^+\tau^-$: tau-based EW observables, lepton universality
- 10^{12} *bb/cc* pairs: flavour observables and anomalies, CKM, CP, etc.

FCC-ee/ILC/CLIC

BSM direct searches

ALPs, dark photons, Heavy Neutral Leptons, LLPs

Higgs

Higgs physics

Higgs width, Higgs to invisible, (self-)couplings

Top

Top physics

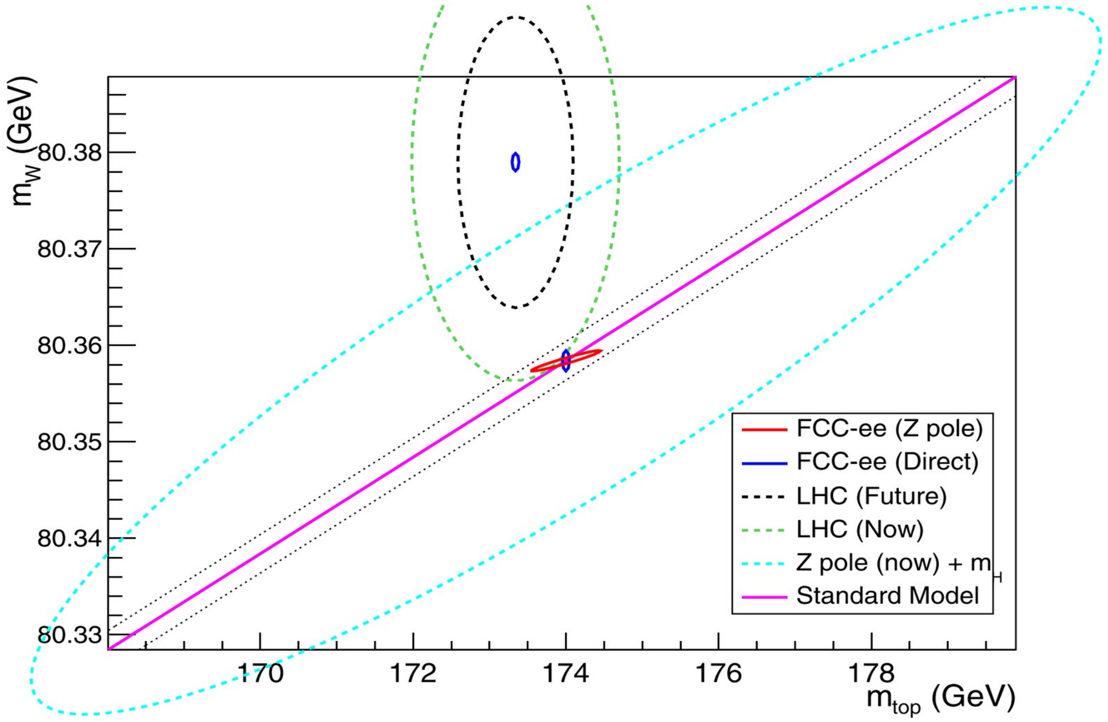
M_{top}, Γ_{top}, EW top couplings

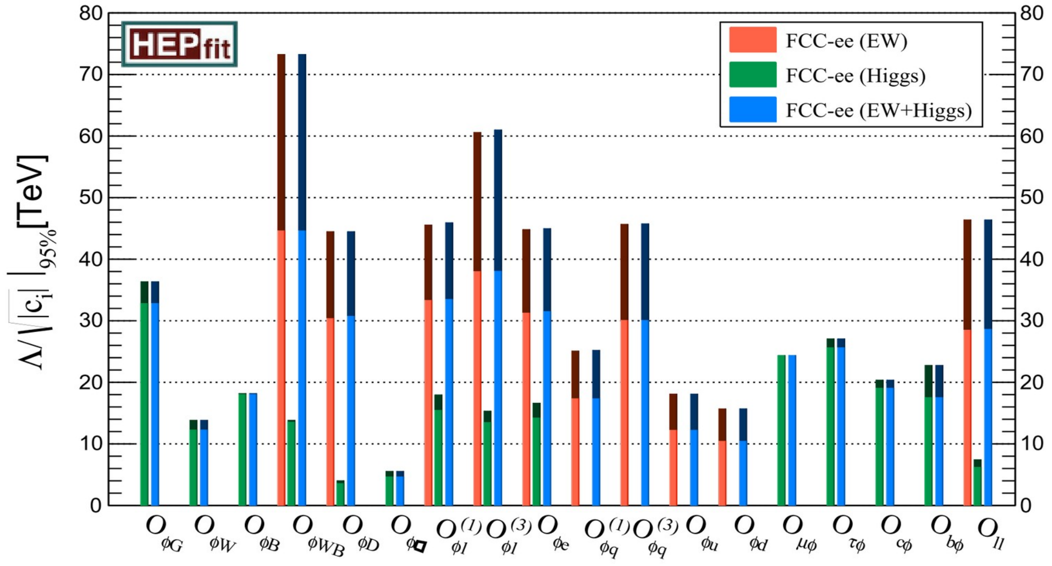
Numbers for FCC-ee – original slide from C. Grojean

Physics we need / we would like to have

Whole physics programme (not just "Higgs factory") makes the difference

- $\sin^2\theta_W$ (mainly from $A_{FB}^{\mu\mu}$)
- M_W, Γ_W to O(1 MeV)
- M_{top}, Γ_{top} at O(10-50 MeV)
- Auxiliary measurements ($\alpha_{QED}(M_Z^2)$, M_Z, Γ_Z, $\alpha_S(M_Z^2)$)
- Model-independent Γ_H, Higgs couplings, Higgs-to-invisible BR
- BSM models (ALPs, dark photons, light dark matter, …)





from FCC-ee CDR

Physics we need / we would like to have

FCC-ee/ILC/CLIC

EW factory (Z, WW)

Precision SM

- M_Z, Γ_Z, N_ν, R_l, A_{FB}, M_W, Γ_W
- α_S (with permille accuracy)
- Quark and gluon fragmentation
- NP QCD

Flavour Physics

- 10^{11} $\tau^+\tau^-$: tau-based EW observables, lepton universality
- 10^{12} *bb/cc* pairs: flavour observables and anomalies, CKM, CP, etc.

Particle ID, detector resolution, systematics, stability

Vertexing, Particle ID (tracking, calo)

BSM direct searches

ALPs, dark photons, Heavy Neutral Leptons, LLPs

Detector hermeticity, flexibility

Higgs

Higgs physics

Higgs width, Higgs to invisible, (self-)couplings

Tracking resolution (tagging), vertexing (flavour), jet resolution

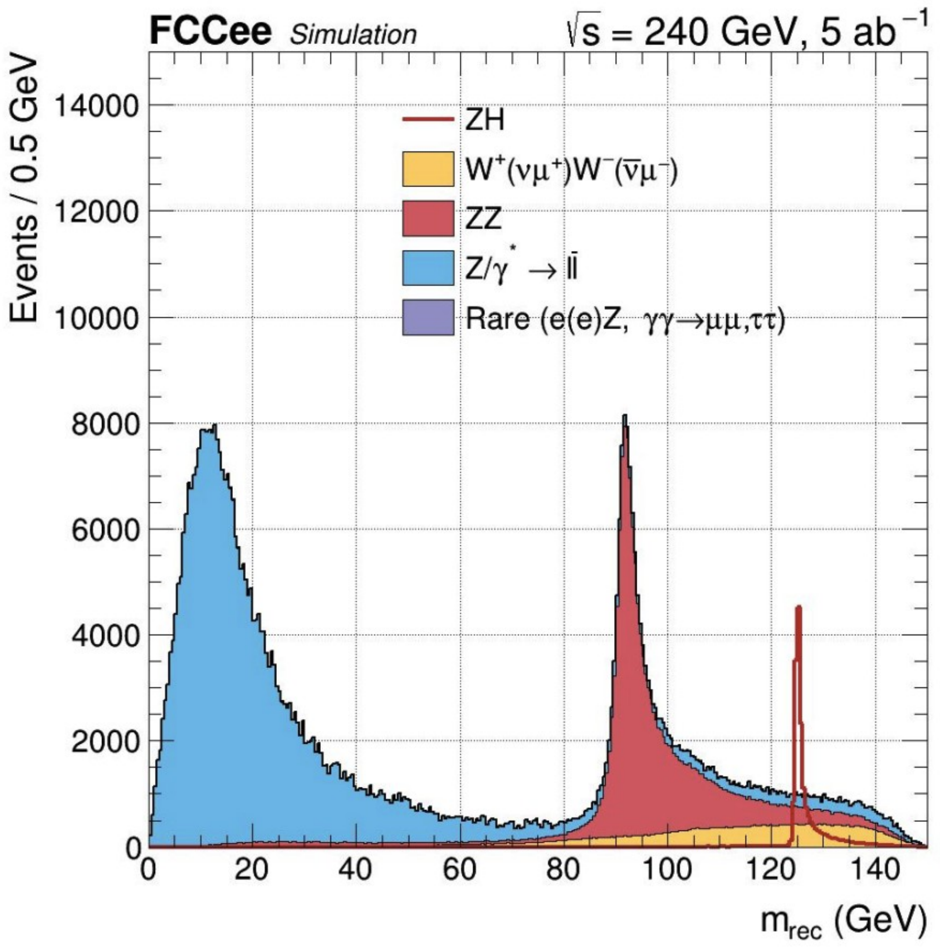
Top

Top physics

M_{top}, Γ_{top}, EW top couplings

Physics case drivers

- **Higgs boson tagging** and **BR into invisibles** sets requirements on:
  - Tracking performance
  - Material in the tracking volume
  - Magnetic field (and thickness of solenoid)
- Higgs boson BR sets requirements on **e, γ and jet energy and angular resolutions**
- Tagging sets requirements **on tracking and vertexing**
- Requirements grow as [more and more physics is explored]

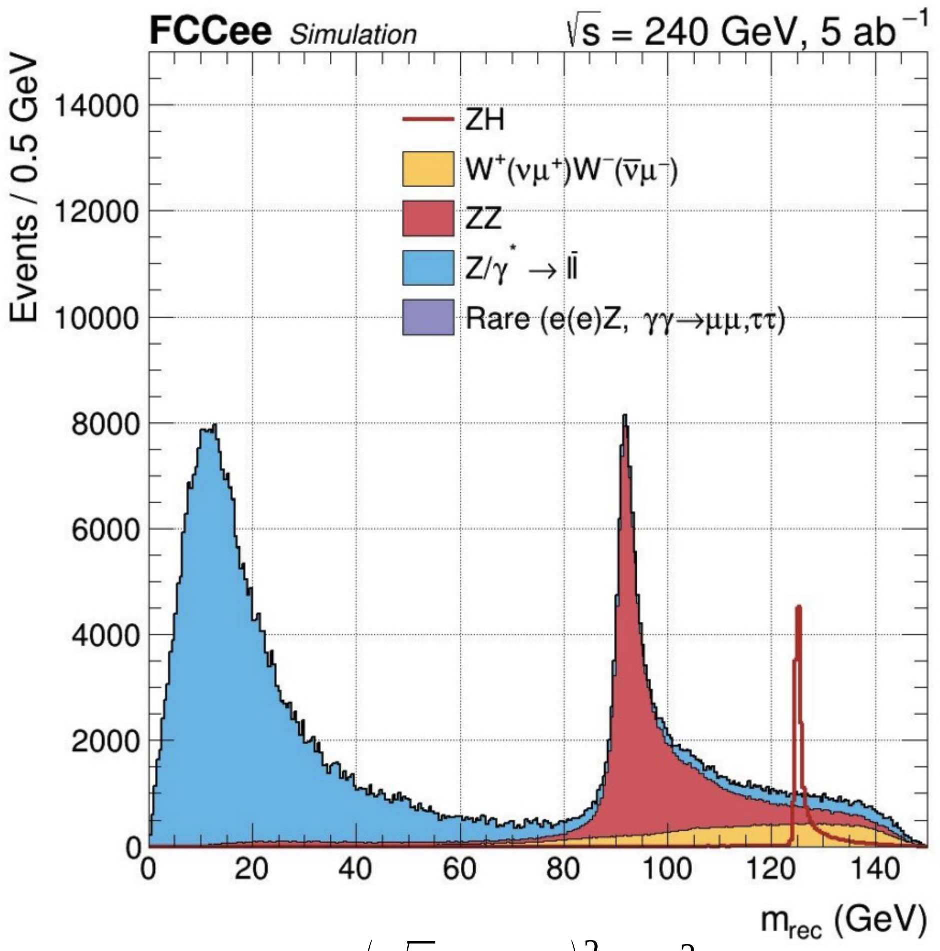


	Critical detector	Requirement	Comments
$ZH \to \ell^+\ell^- X$	Tracker	$\frac{\sigma(p_T)}{p_T^2} \sim \frac{0.1\,\%}{p_T} \oplus 2\cdot 10^{-5}$	But also precision EW, flavour, BSM
$H \to b\bar{b}, c\bar{c}$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 15(p\sin\theta^{\frac{3}{2}})^{-1}[\mu m]$	Additional case study: B→K*ττ
$H \to gg, q\bar{q}, VV$	ECAL, HCAL	$\frac{\sigma(E_{jet})}{E_{jet}} \sim 4\,\%$ (at $E_{jet} \sim 50$ GeV)	Also BSM and missing energy reconstruction
$H \to \gamma\gamma$	ECAL	$\frac{\sigma(E_\gamma)}{E_\gamma} \sim \frac{10-15\,\%}{\sqrt{E_\gamma}}$	But flavour physics may need better EM energy resolution

Benchmark physics channels for Higgs/Top/EW factories discussed in 2401.07564 will improve detector requirements by spring 2025

Physics case drivers

- **Higgs boson tagging** and **BR into invisibles** sets requirements on:
  - Tracking performance
  - Material in the tracking volume
  - Magnetic field (and thickness of solenoid)
- Higgs boson BR sets requirements on **e, γ and jet energy and angular resolutions**
- Tagging sets requirements **on tracking and vertexing**
- Requirements grow as more and more physics is explored



$$M_{rec} = \left(\sqrt{s} - E_{\mu\mu}\right)^2 - p_{\mu\mu}^2$$

	Critical detector	Requirement	Comments
$ZH \to \ell^+\ell^- X$	Tracker	$\frac{\sigma(p_T)}{p_T^2} \sim \frac{0.1\,\%}{p_T} \oplus 2 \cdot 10^{-5}$	But also precision EW, flavour, BSM
$H \to b\bar{b}, c\bar{c}$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 15(p \sin\theta^{\frac{3}{2}})^{-1}[\mu m]$	Additional case study: B→K*ττ
$H \to gg, q\bar{q}, VV$	ECAL, HCAL	$\frac{\sigma(E_{jet})}{E_{jet}} \sim 4\,\%$ (at $E_{jet} \sim 50$ GeV)	Also BSM and missing energy reconstruction
$H \to \gamma\gamma$	ECAL	$\frac{\sigma(E_\gamma)}{E_\gamma} \sim \frac{10-15\,\%}{\sqrt{E_\gamma}}$	But flavour physics may need better EM energy resolution

Benchmark physics channels for Higgs/Top/EW factories discussed in 2401.07564 will improve detector requirements by spring 2025

Typical detector @ e+e- collider

- Inner tracker with lowest possible mass and smallest possible inner radius
- Low-mass outer tracker for excellent momentum resolution at high energies
- Particle ID performance for flavour physics
- High granularity, high resolution calorimetry
- Large superconducting solenoid
- Muon system

Linear vs. circular specifics

Linear colliders:

- Bunch trains → allow power pulsing → cooling not needed
- Beamstrahlung:

  1) High magnetic field (> 3 T) desirable

     → lower tracking volume → solenoid could be outside calo volume

  2) Inner tracking radius limited to greater than some (~ 3) cm

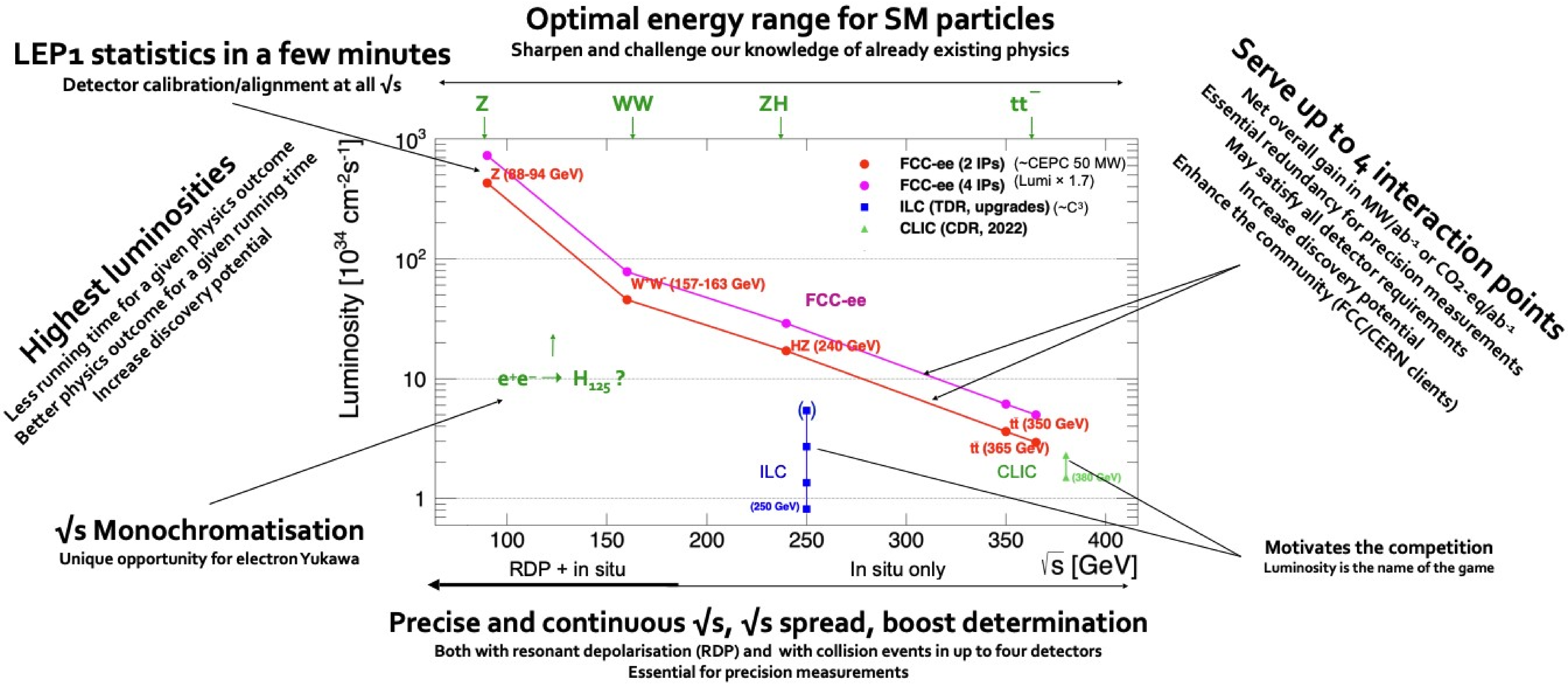
Circular colliders:

- Continuous running → cooling required
- Preserve beam emittance @ Z pole:
  - Magnetic field limited to 2 T max

    → larger tracking volume needed

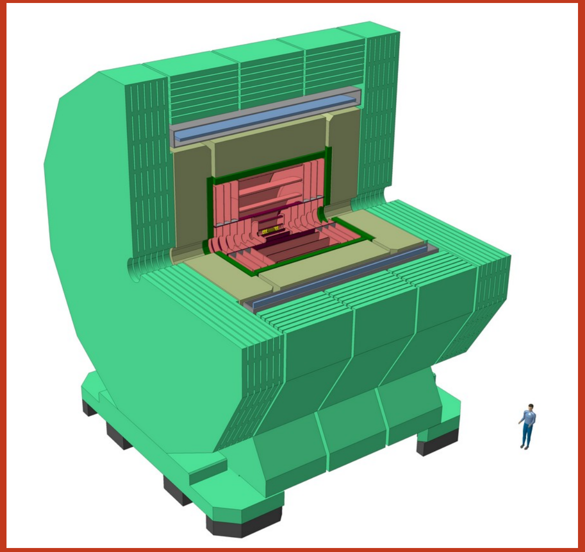
    → solenoid better inside calorimeter volume (or in between ECAL and HCAL)

A bit of advertising



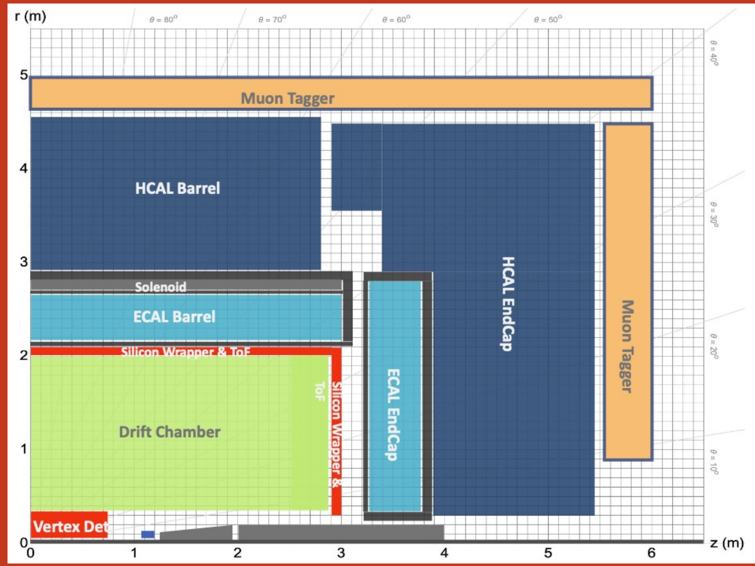
FCC-ee detectors

CLD (CLIC-like Detector)



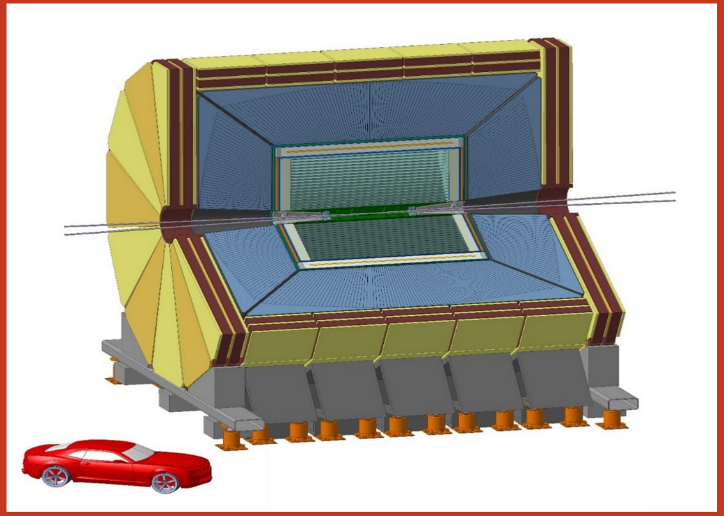
2 T solenoid **outside calo**
Full silicon tracker
SiW highly granular EM Calo
Sci-steel highly granular HAD Calo
RPC-based muon detector

ALLEGRO - A Noble-Liquid Ecal based



2 T solenoid **outside ECAL**
Tracking with ultra light drift chamber + Si Wrapper (improved tracking + timing)
LAr EM Calo + Sci-steel HAD Calo

IDEA - Innovative DEtector for e+e- Accelerators



2 T thin solenoid within calo
Si vertex detector
Tracking with ultra light drift chamber
Dual-readout calorimeter + preshower
MPGD (µRwell) based muon detector

- Beam crossing angle + need to keep vertical beam emittance low ⟹ **B field limited to 2 T @ Z pole**
- Lot of room for (even radical) changes
- Show already different approaches to tracking/calorimetry

Vertex detectors

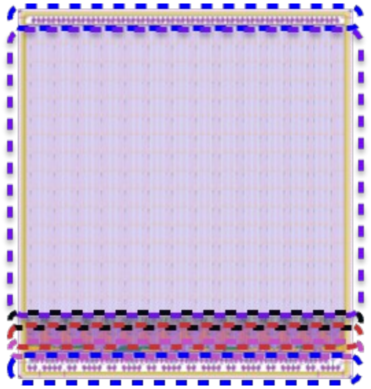
General requirements

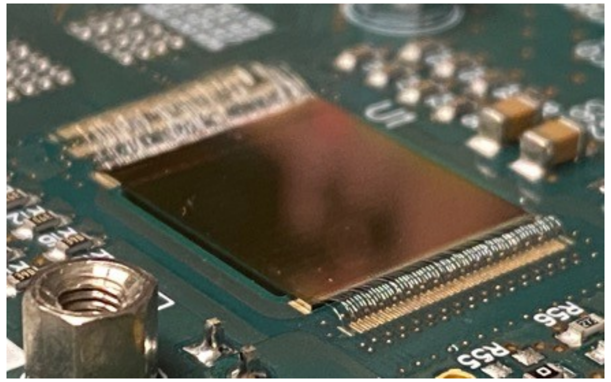
Flavour physics and tagging requires 3-5 μm → pixel size ~15 μm
Small material budget (0.1% of X_0/layer) → thickness ~ 50 μm
Low power consumption (especially inner layers) → 10-30 mW/cm^2

Solution: CMOS MAPS

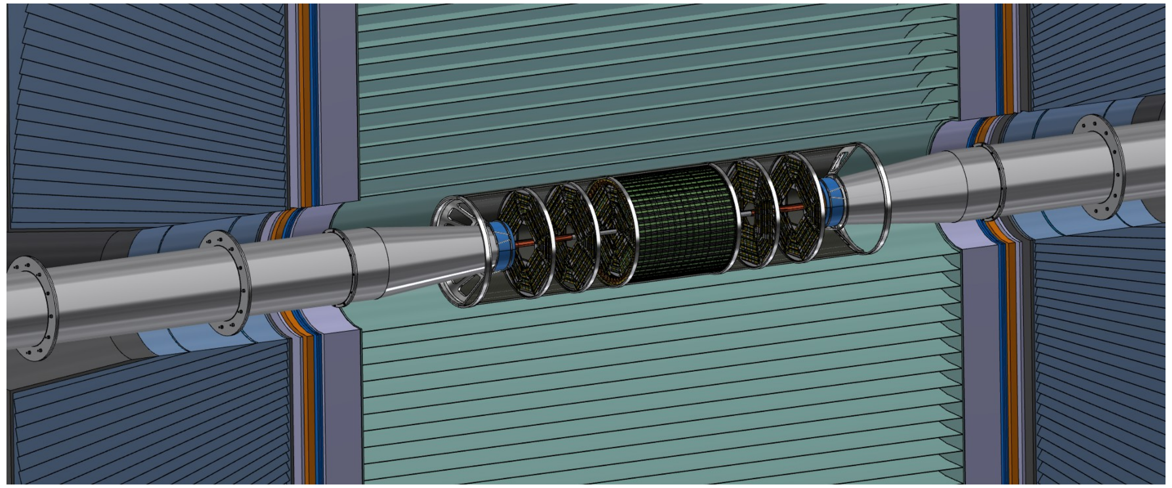
high spacial resolution and **small material** (integrated circuitery)
- Used in LHC upgrades (ALICE ITS, ATLAS ITK, etc.)
- No need for bump-bonding: allow smaller pixel size
- Overall affordable

ARCADIA

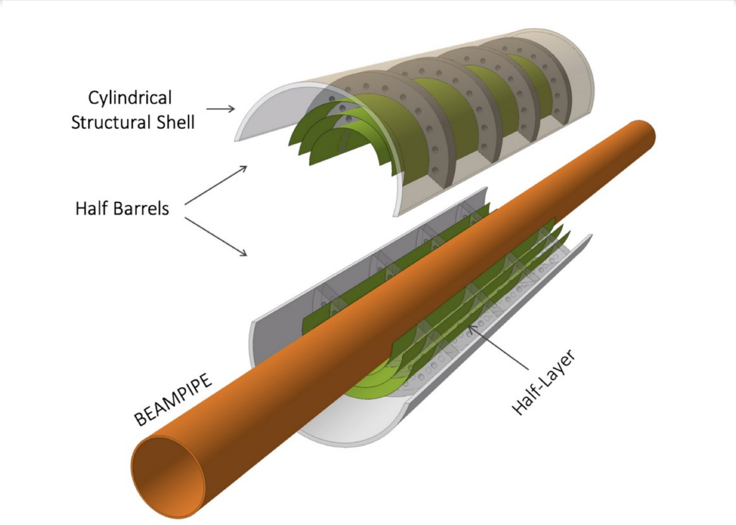




Bent silicon sensors (ALICE ITS3 R&D)



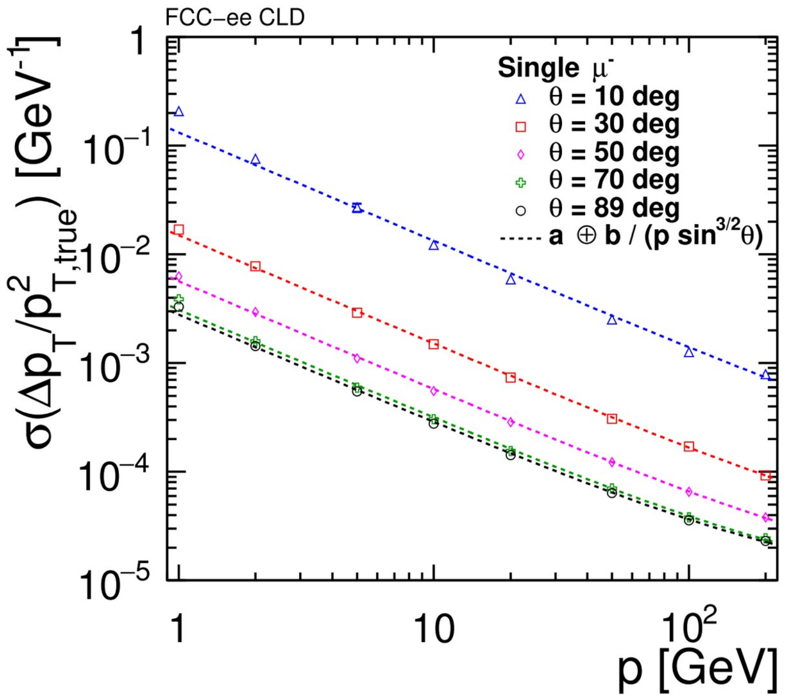
IDEA design

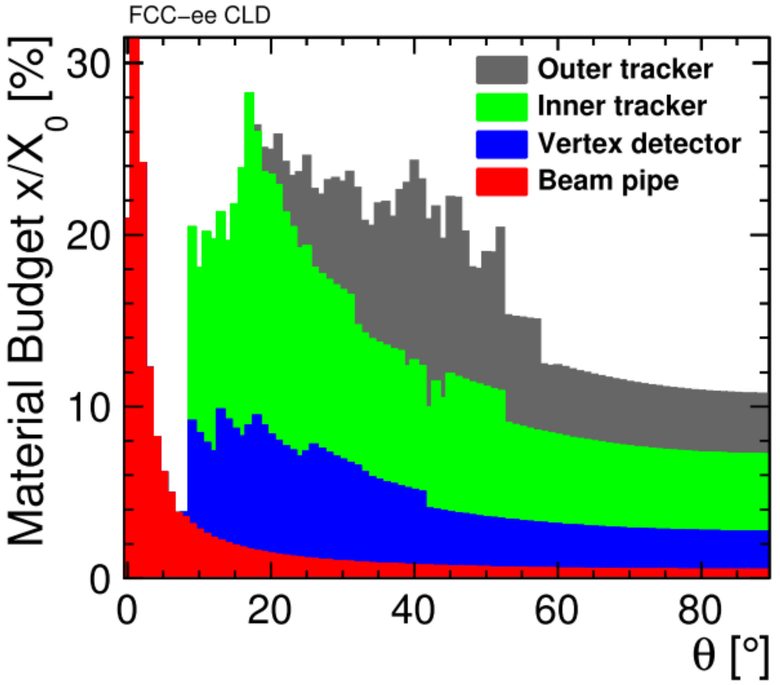


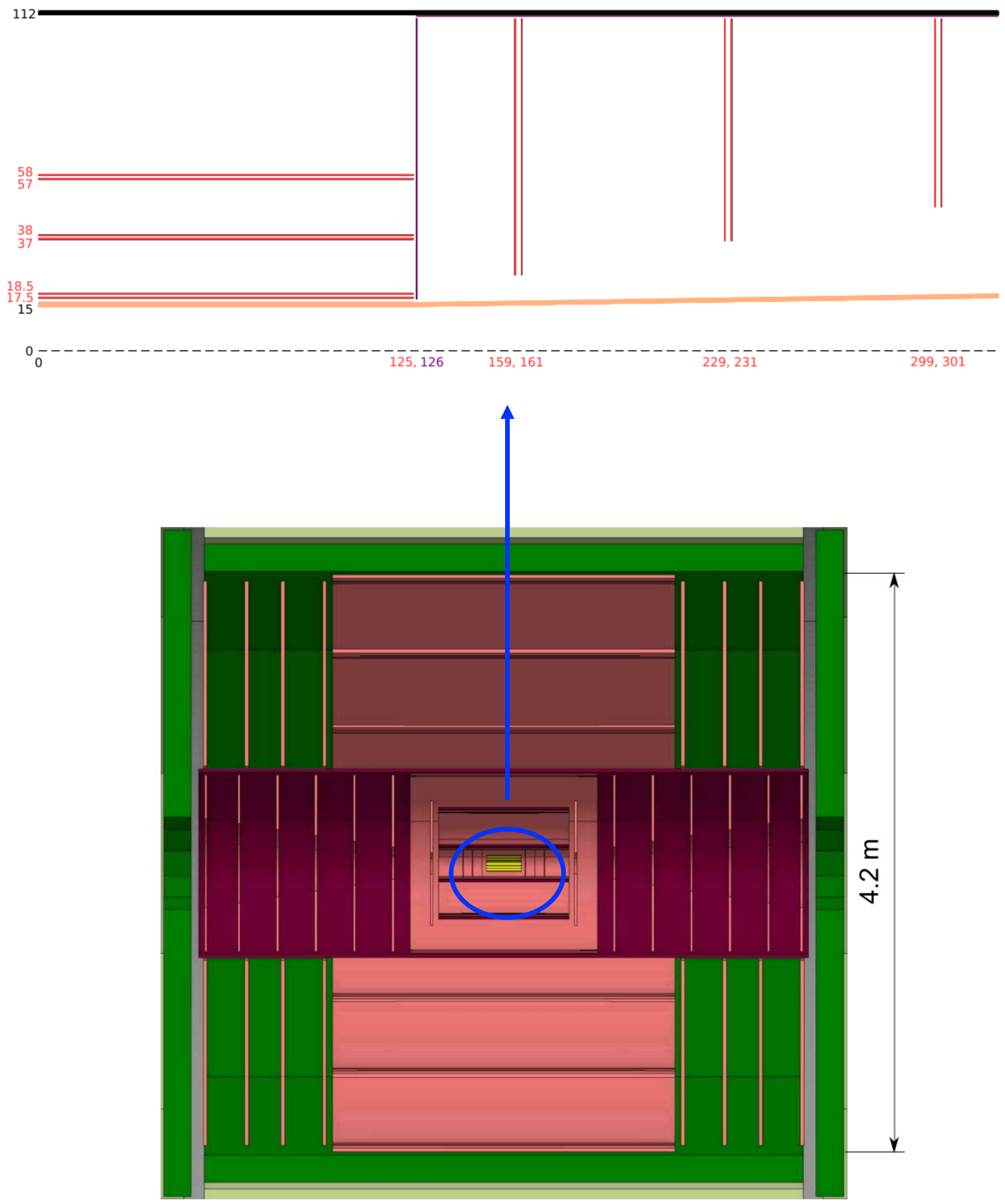
Full silicon tracking – CLD approach

VTX:
- Pixel size 25×25 μm² - 50 μm sensor thickness - aiming at 3 μm resolution
- Material and cooling benchmarked on ALICE ITS (LS2) upgrade design
- Power dissipation: 40 mW/cm² - water cooled

ID:
- Single point resolution 7×90 μm² (5×5 μm² in first layer)
- Inner tracker: barrel 3 layers, end-caps 7 disks
- Outer tracker: barrel 3 layers, end-caps 4 disks

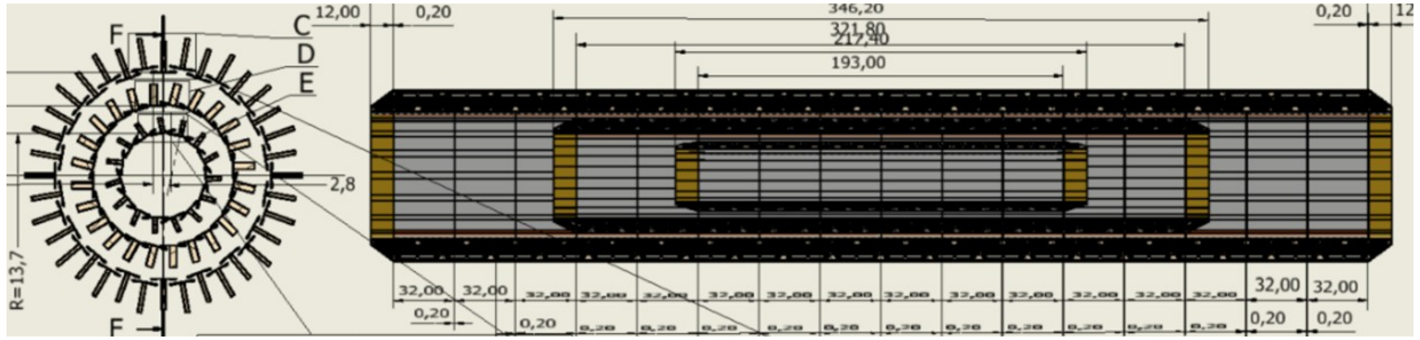






Light weight tracking - IDEA

Vertex technologies



Depleted Monolithic Active Pixel detectors

3 Inner Vertex (ARCADIA based):

- Lfoundry 110 nm process
- *50 µm thick*
- Dimensions:
- Power density 30 mW/cm^2
- **100 MHz/cm^2**

Target high granularity
Low power consumption required
- compromise with time-resolution

Precision points connecting vertex with Drift Chamber
Low-p_T tracking
Bunch-crossing ID

Middle and Outer Vertex plus disks (ATLASPIX3 based):

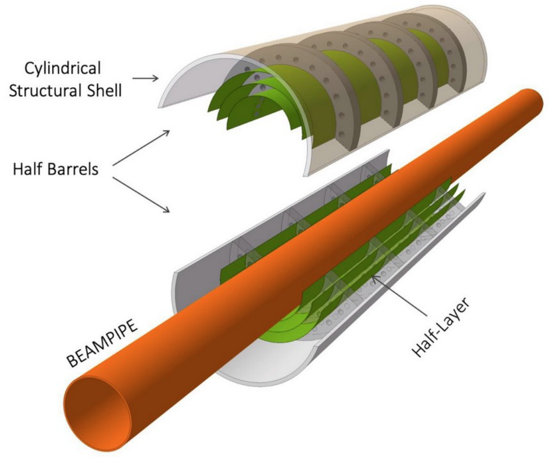
- TSI 180 nm process
- *50 µm thick*
- Module dimensions:
- Power density 150 mW/cm^2
- **Up to 1.28 Gb/s downlink**

Alternative: curved MAPS (inspired by ALICE ITS3 design)

~0.05% X/X_0 material budget per layer
5 times less than baseline option

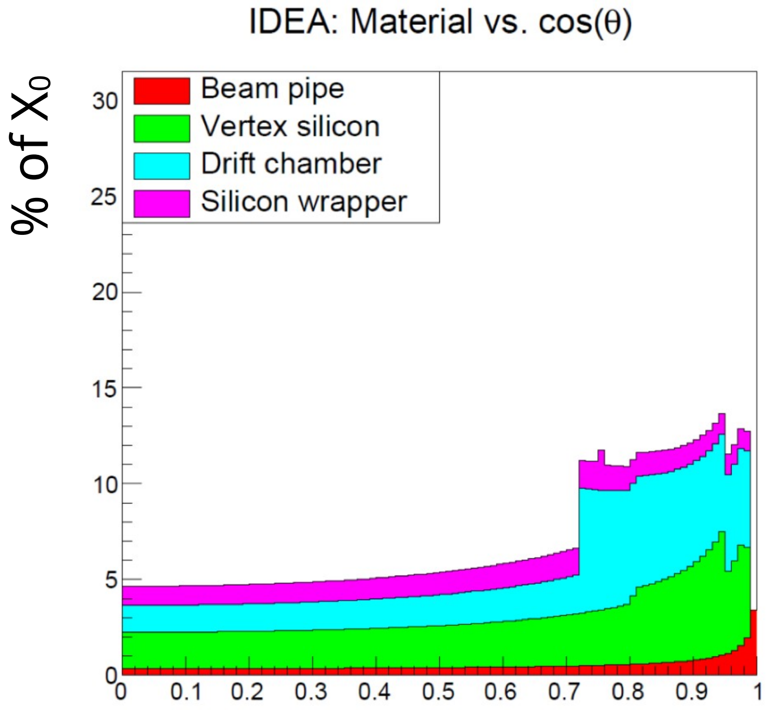
13.7 mm radius: mechanics ok, does electrically work?

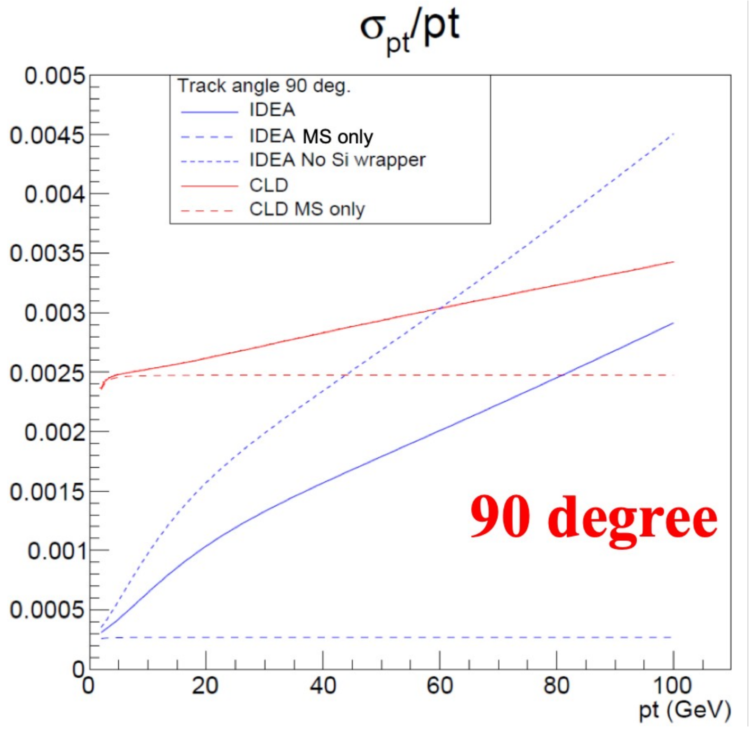
Active pixels < 95% of covered area (chip service zones)
Impact on physics?

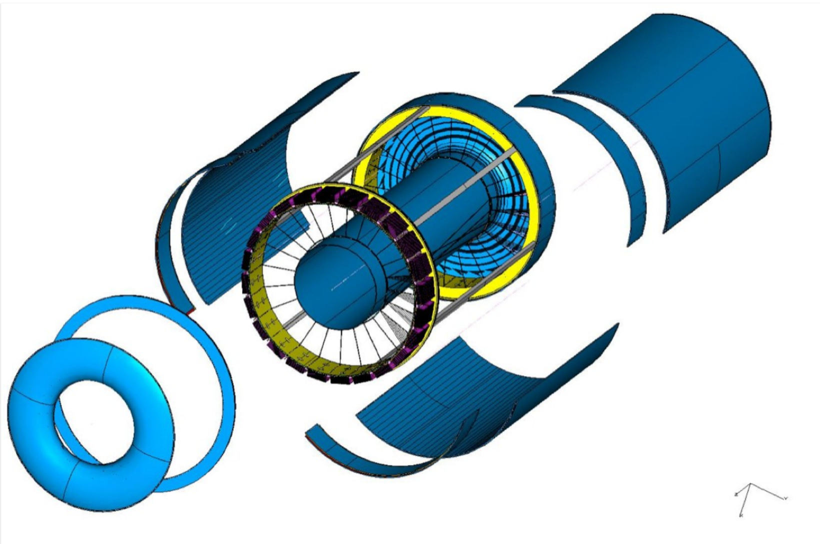


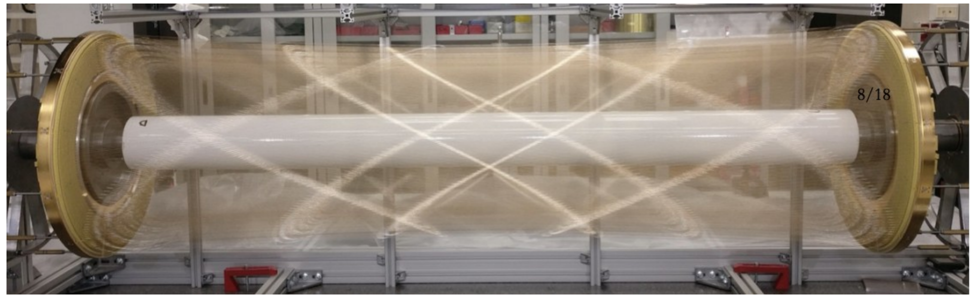
Light weight tracking - ALLEGRO

ALLEGRO: VTX similar to CLD
- Tracking with **drift chamber** (as in IDEA - similar in concept to MEG II chamber)
- Minimising multiple scattering, adding **only 2%** X_0 to material in front of calorimeter
- Drift time O(300 ns)
- Cluster counting (12.5 cm^{-1} clusters) **improves spacial resolution and dE/dx measurement**
- Single point precision (with cluster counting) better than ~ 100 μm, many points per track









Drift chamber

Total thickness: 1.6% of X_0 at 90°

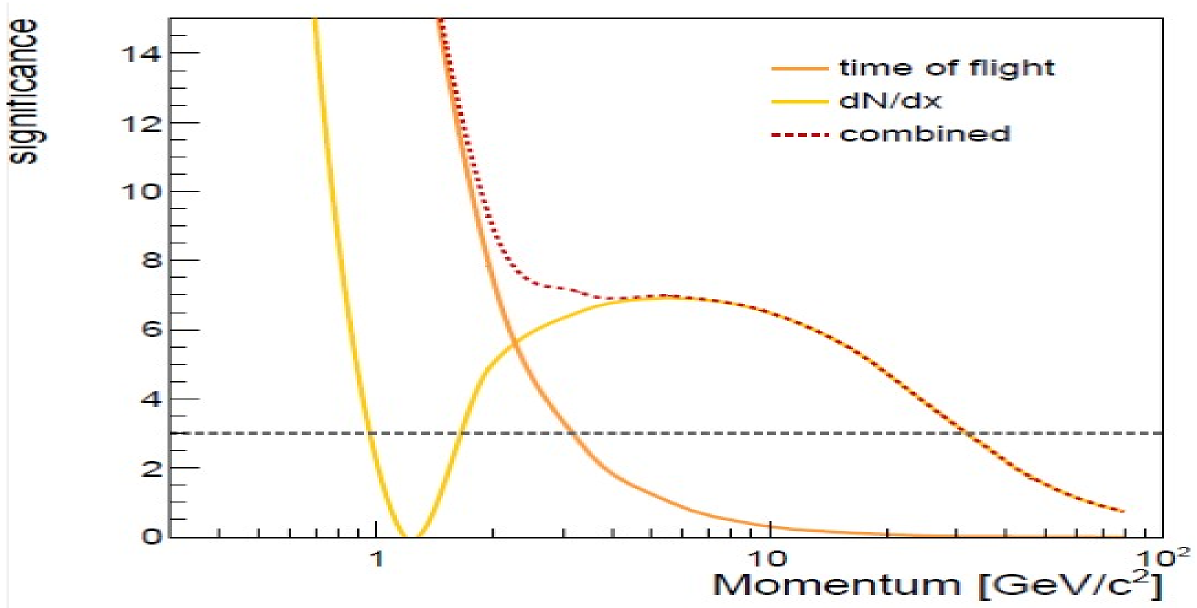
(W wires dominant contribution)

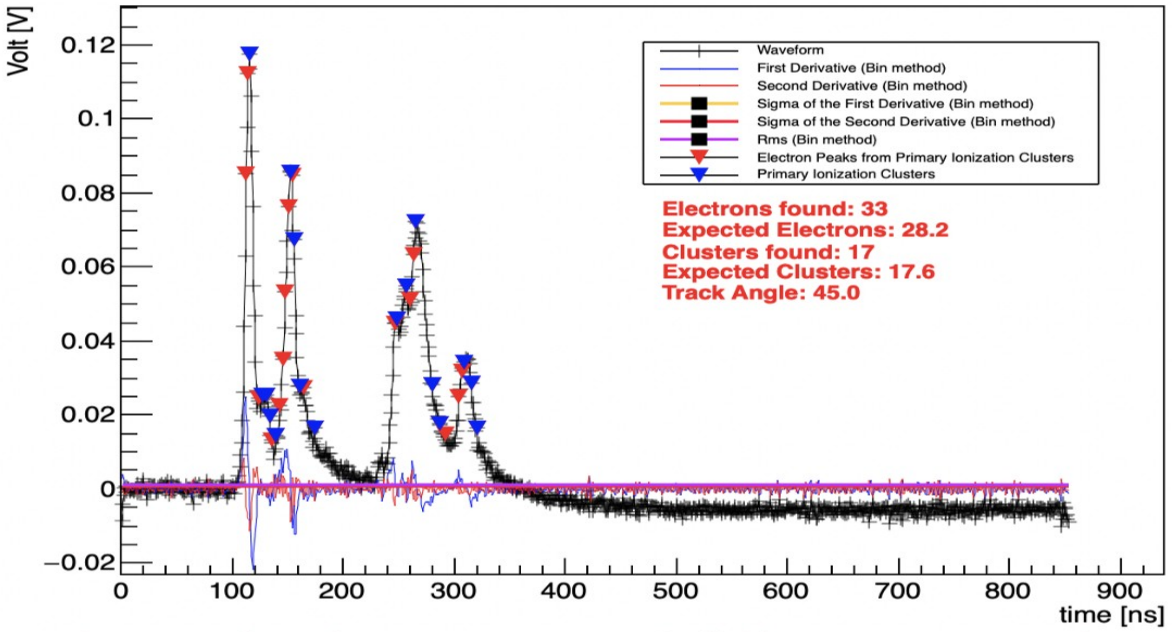
max drift time: 350 ns

σ_{xy} ~ 100 μm; σ_z < 1 mm

Open issues:

- Complete mapping of dN/dx data in all relevant background regions
  - Understand details of cluster counting performance
- Build large mechanical prototype
  - Inner radius R_{in} = 35 cm, outer radius R_{out} = 200 cm
  - Spoke (wire support) mechanical deformation due to wire mechanical tension
- Build full length functioning prototype with few cells
- Develop on-detector cluster counting electronics





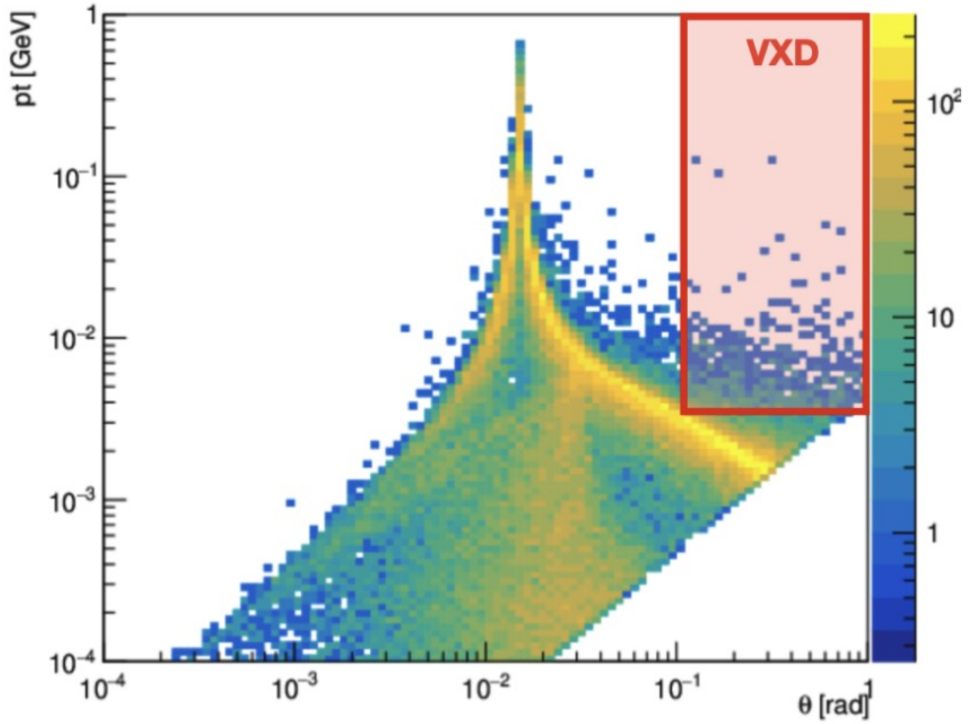
Sense Wire Diameter 10 um – Cell Size 1.0 cm – Track Angle 45° – 1.2 GSa/s – Gas Mixture He:IsoB 90/10 – 165 GeV

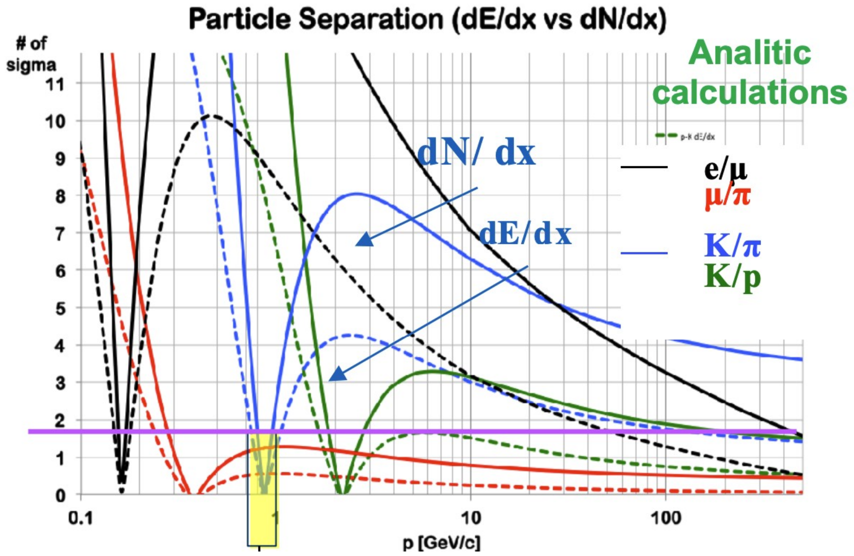
Challenges

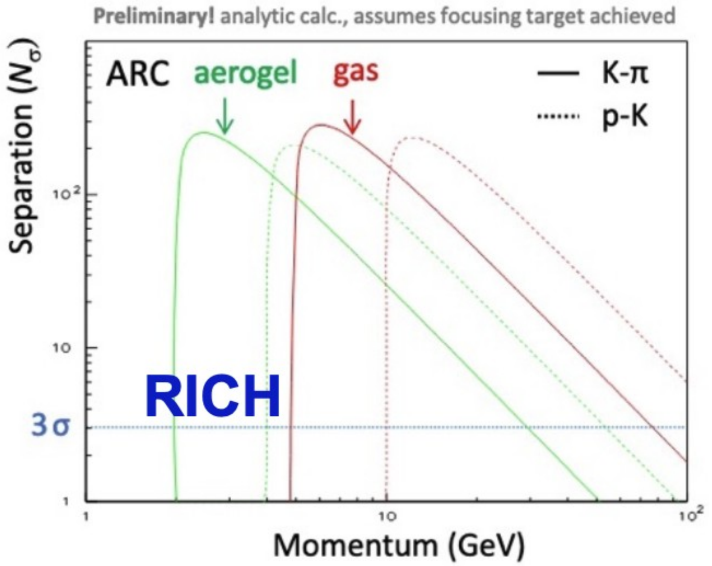
- Full silicon tracking:
  - **Keep material down**, despite cooling and services
  - Particle identification **may require additional detectors** (RICH?)

- Drift chamber:
  - Mechanical stability, cluster-counting compatible electronics

Taken from here





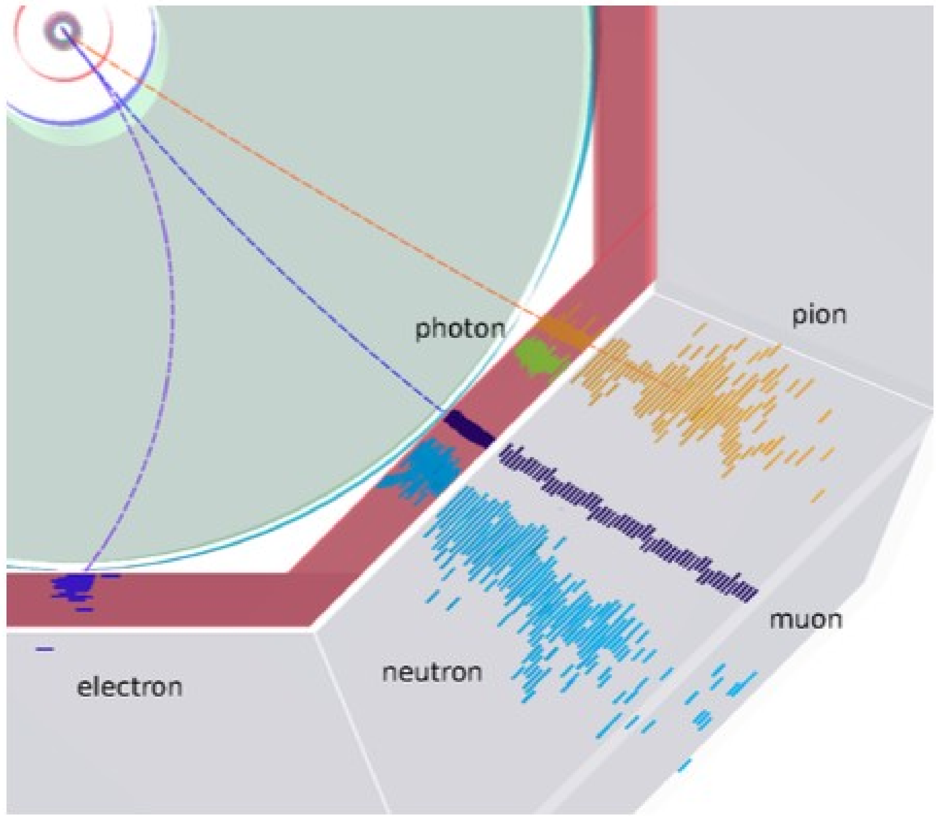


Detector occupancy driven by incoherent pair creation and synchrotron radiation photons

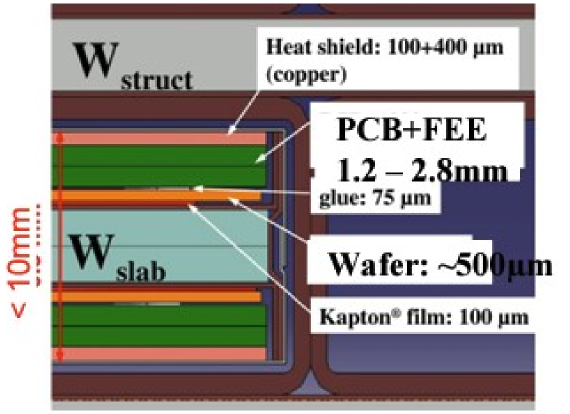
Estimated < 1% for full silicon detectors
Almost **NO GO** for TPC (see here)
OK (but need to **keep eye on**) for DWC

Particle-flow oriented calorimeters

- Basic idea: for charged particles, measure energy by **using tracker rather than calorimeter**
- Requirements: High granularity - compactness (small Molière radius)
- Drawbacks: confusion term (when calo-cluster subtraction goes wrong → tails in jet energy distributions)
- Studied in detail for linear colliders

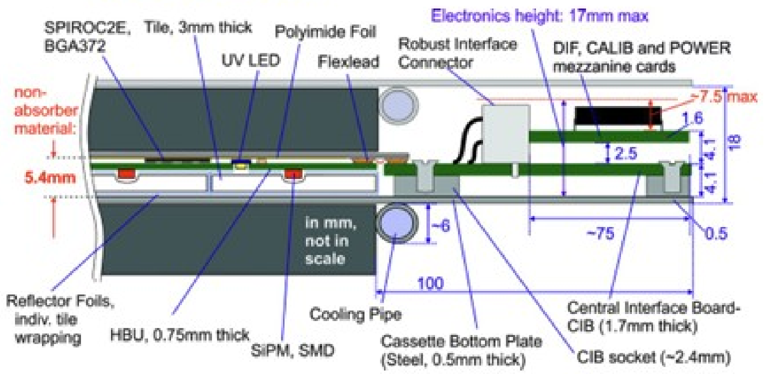


SiW ECAL



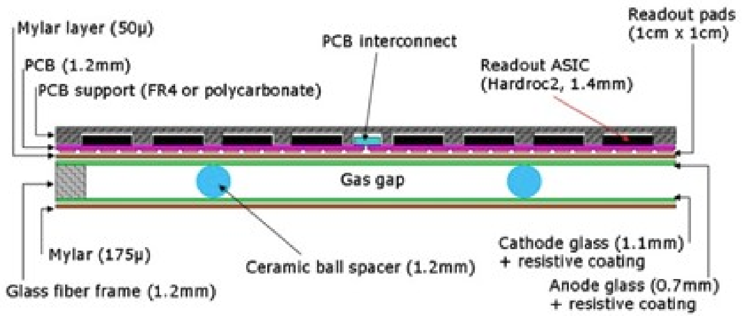
Active area: silicon PiN Diodes
Typical segmentation: 0.5x0.5 cm^2

Analogue Scintillator HCAL and ECAL



Scintillator tiles/strips + SiPM
Typical segmentation: 3x3cm^2

Semi Digital HCAL



Gas RPCs
Typical segmentation: 1x1cm^2

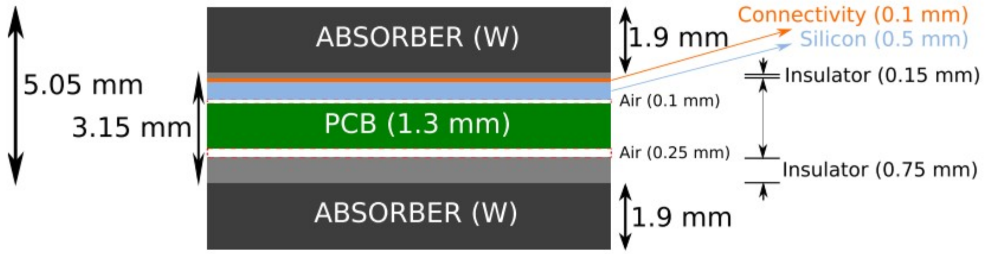
Challenges:

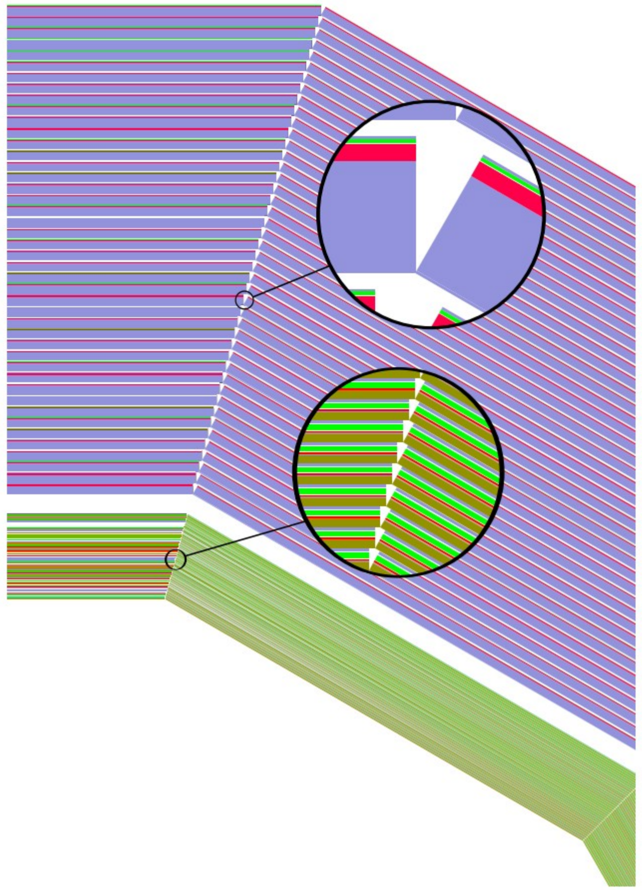
- Cooling despite challenging environment (no power pulsing possible)
- Large area of silicon detectors
- Timing for 5D particle flow?

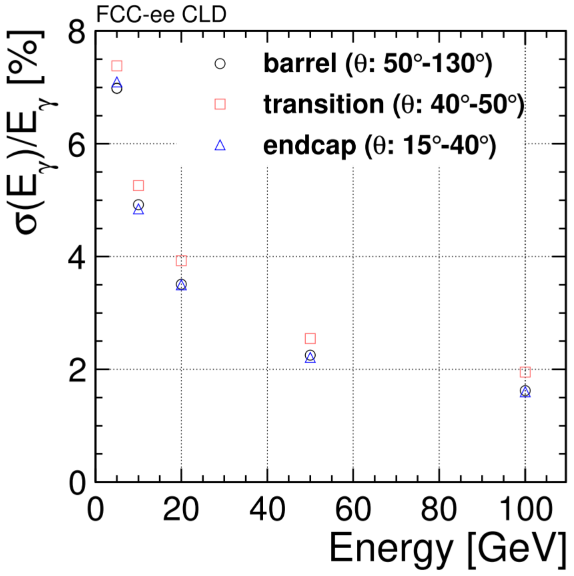
Calorimetry @ CLD

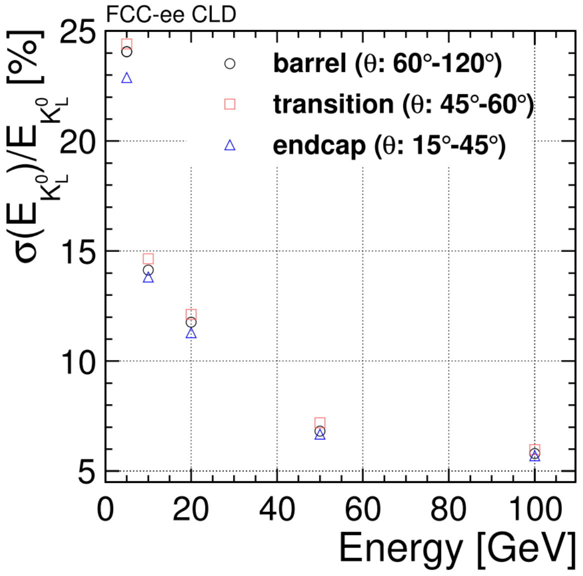
- CLD paradigm: calorimeter **optimised for particle flow** (emphasis on **granularity** rather than **quality of energy measurement**)

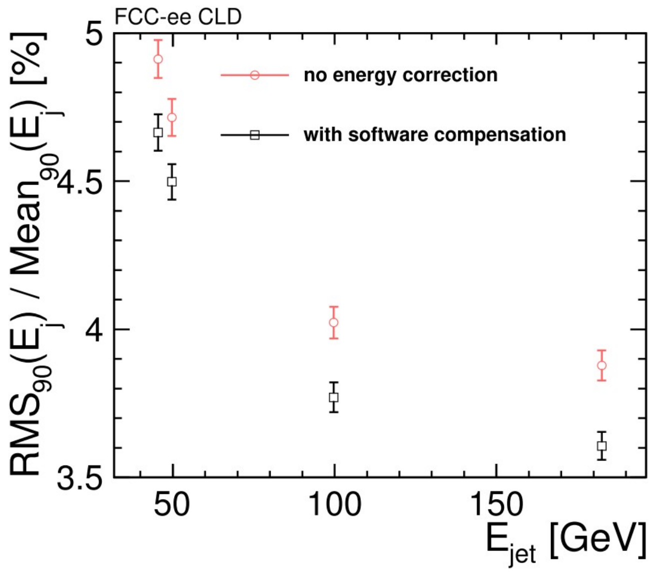
ECAL (CDR numbers - see here for optimisation studies):
Cell size 5×5 mm^2 with Si-W
40 layers - 5.05 mm thickness each
Total 20 cm, 22 X_0, ~ 1 λ_I
No power pulsing - cooling issue - part of optimisation process
HCAL:
Cell size 30×30 mm^2 scintillator-steel
44 layers - 26.5 thickness each
Total 117 cm, 5.5 λ_I







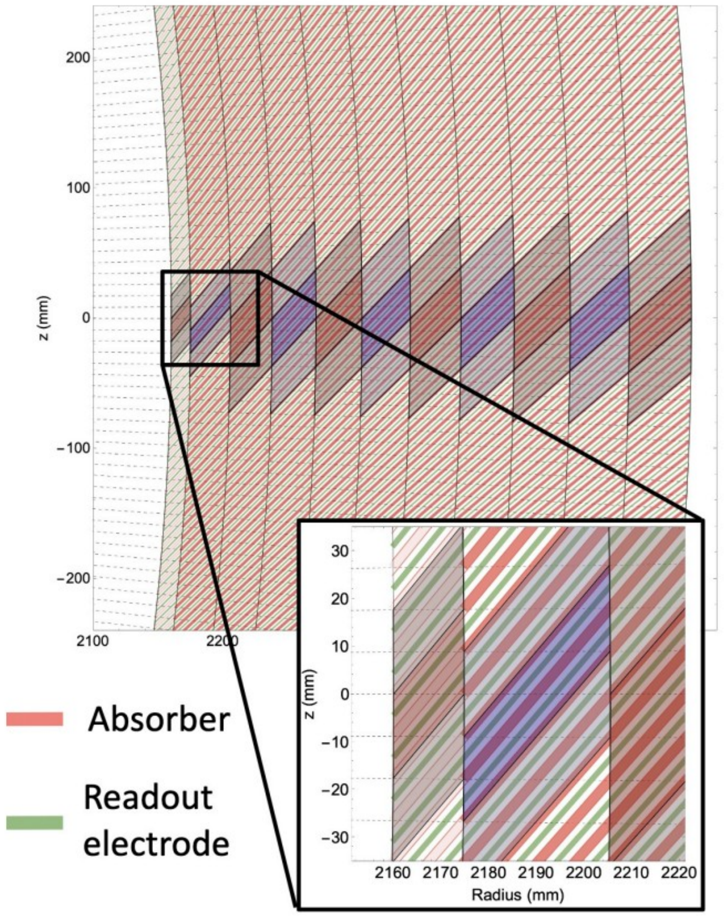




Calorimetry @ ALLEGRO

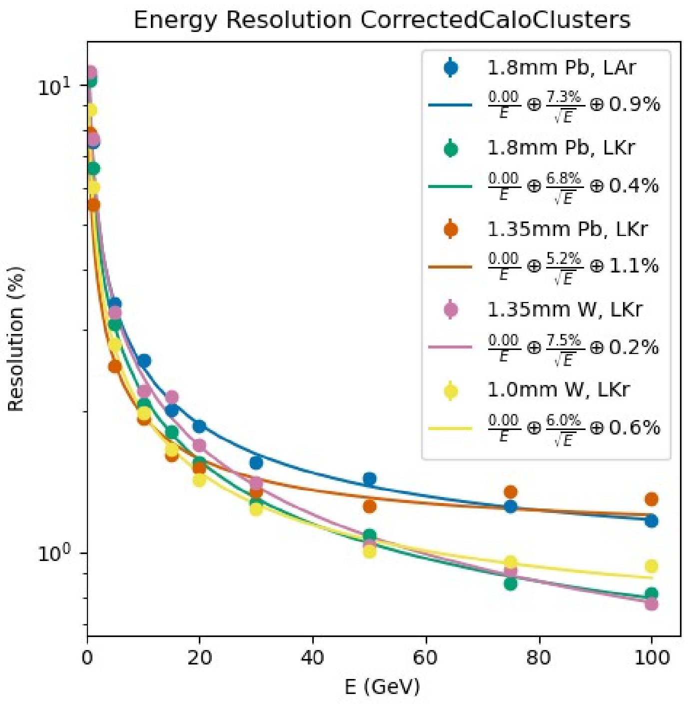
EM Calorimeter:

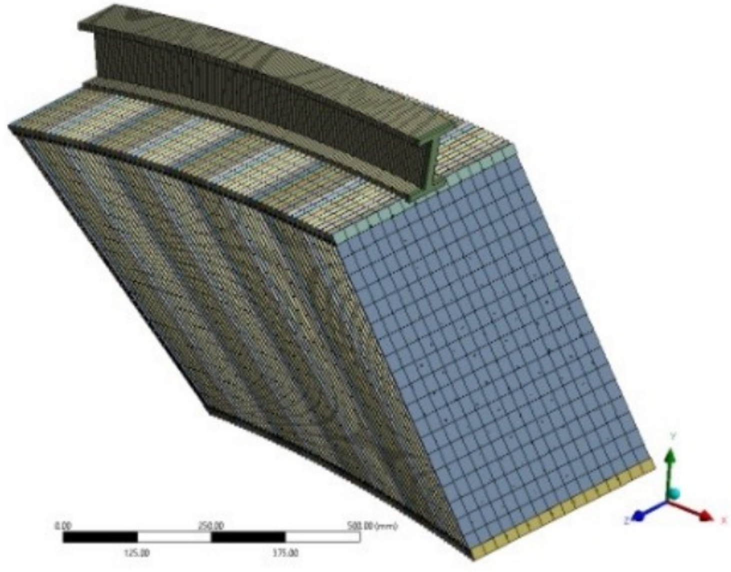
- Noble liquid calorimeters: good energy resolution, long-term stability, easy to calibrate
    - Ideas to **achieve high granularity** targeting particle flow
- Solution heavily inspired by ATLAS: LAr + copper - but different geometry

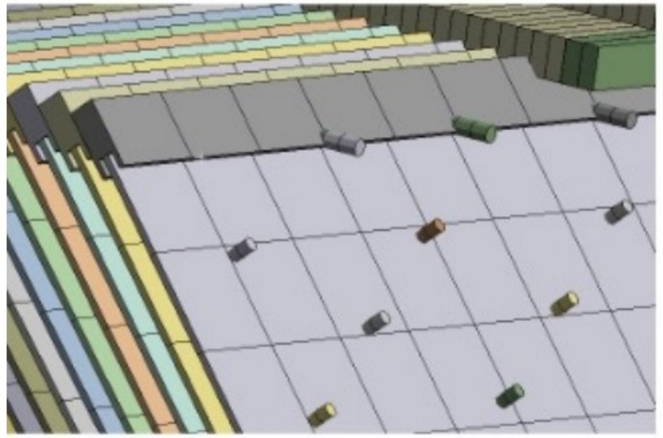


Hadronic section with increased granularity scintillator tile + steel (à la TileCal)

Material optimisation example







Calorimetry @ IDEA

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

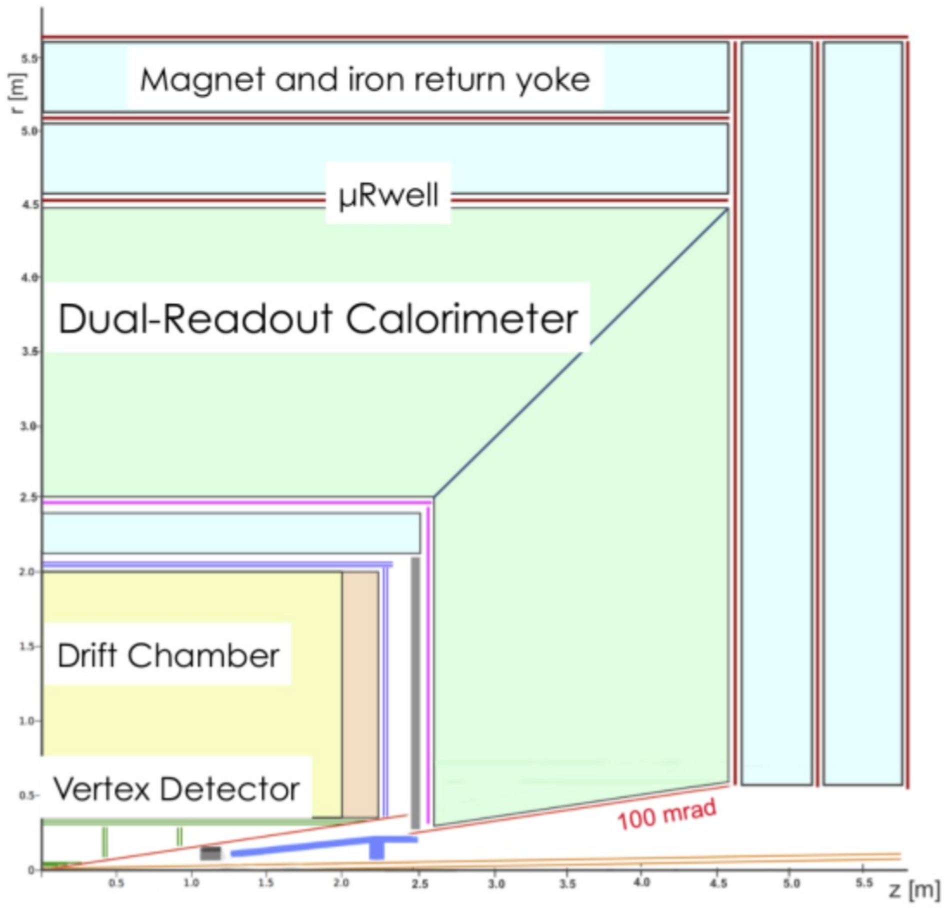
$$S = E[f_{em} + (h/e)_S(1 - f_{em})]$$

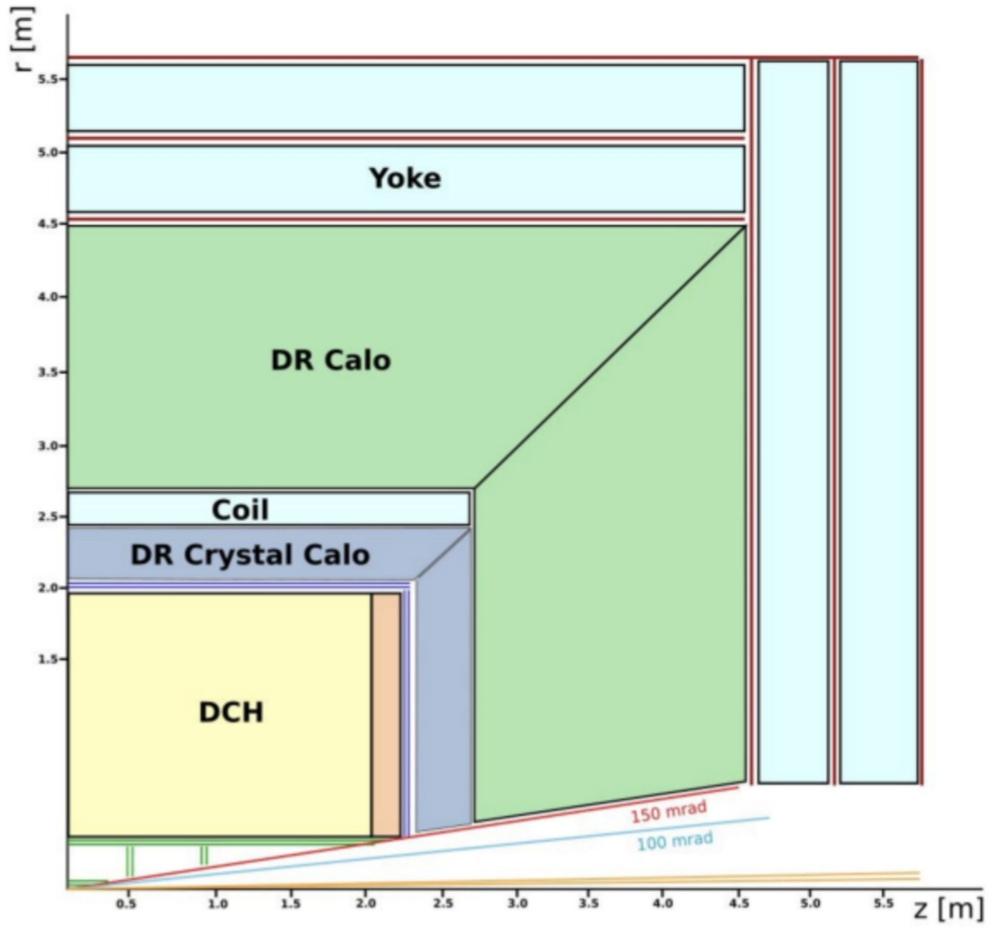
$$C = E[f_{em} + (h/e)_C(1 - f_{em})]$$

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

Two options currently under study:

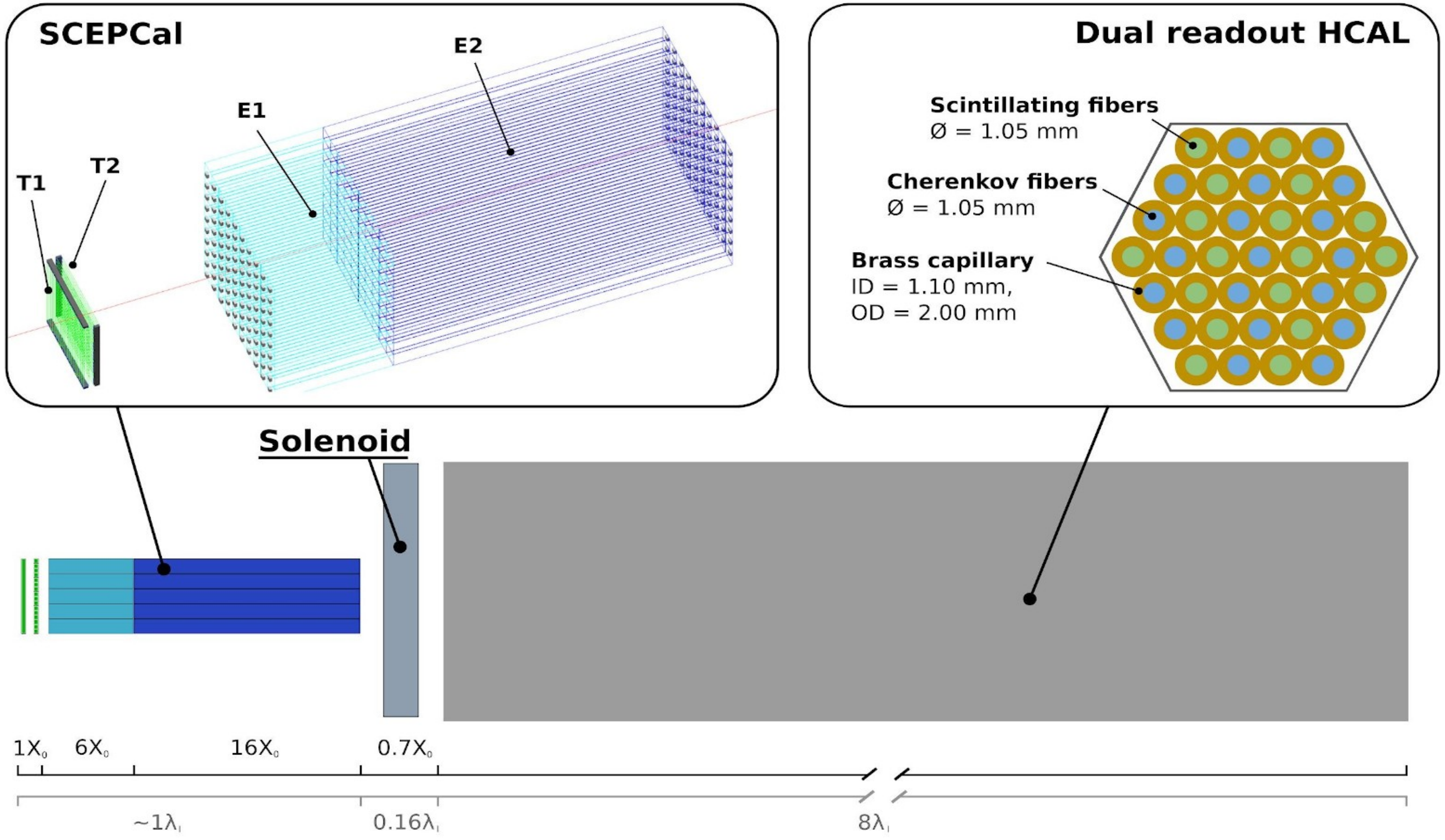
- Longitudinal unsegmented dual-readout fibre calorimeter (combined EM+HAD calorimeter)
- Dual-readout crystal (EM calo) + dual-readout fibre calorimeter (HAD calo) → boost flavour physics performance



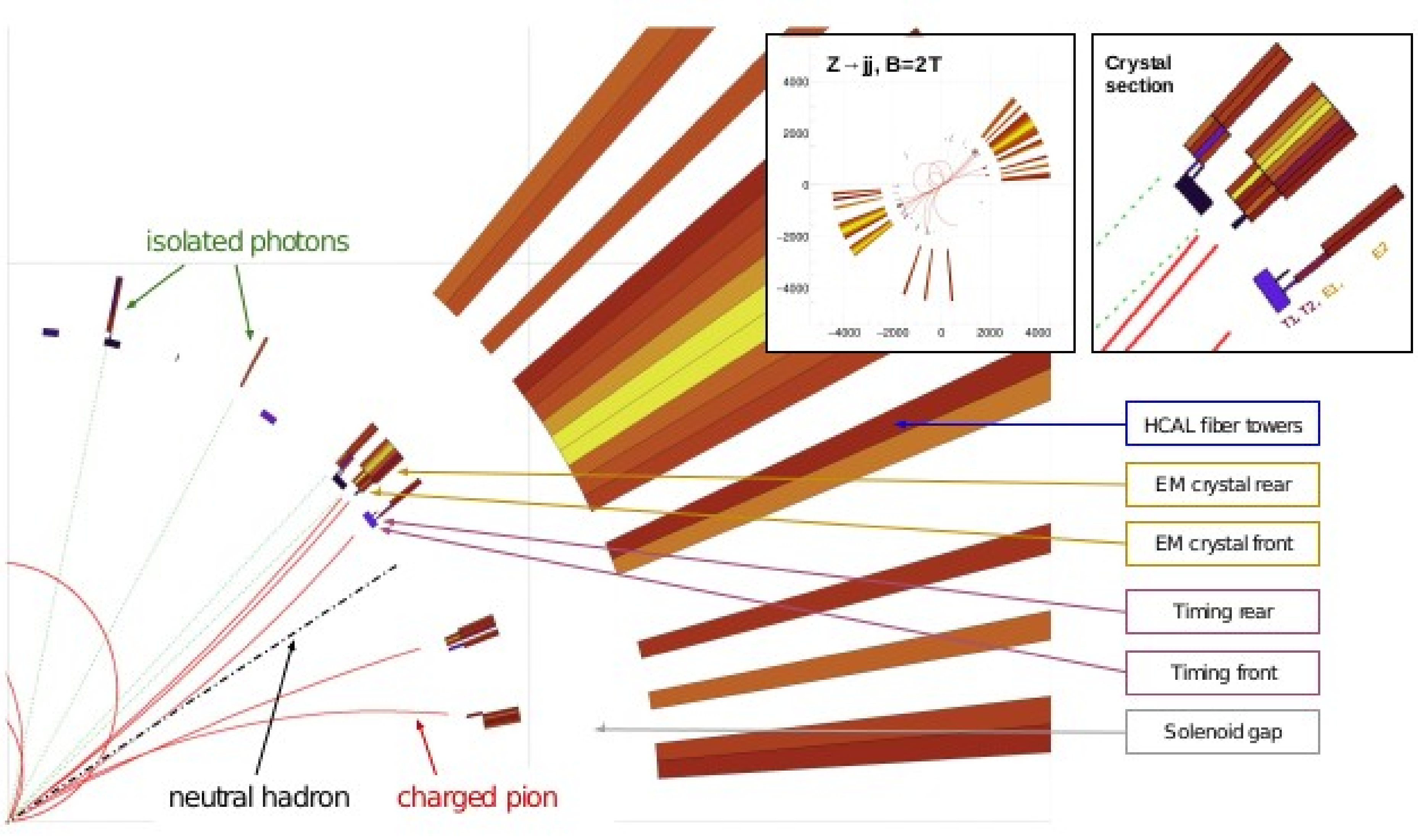


IDEA: dual readout + PFA

- ECAL ~20 cm $PbWO_4$
  - 2 layers: 6+16 X_0
  - DR with filters
  - $\sigma_{EM} \approx 3\% / \sqrt{E}$
- timing layer
  - LYSO:Ce crystals
  - $\sigma_t \sim 20$ ps
- HCAL layer
  - $\sigma_{HAD}/E \sim 26\%/\sqrt{E}$



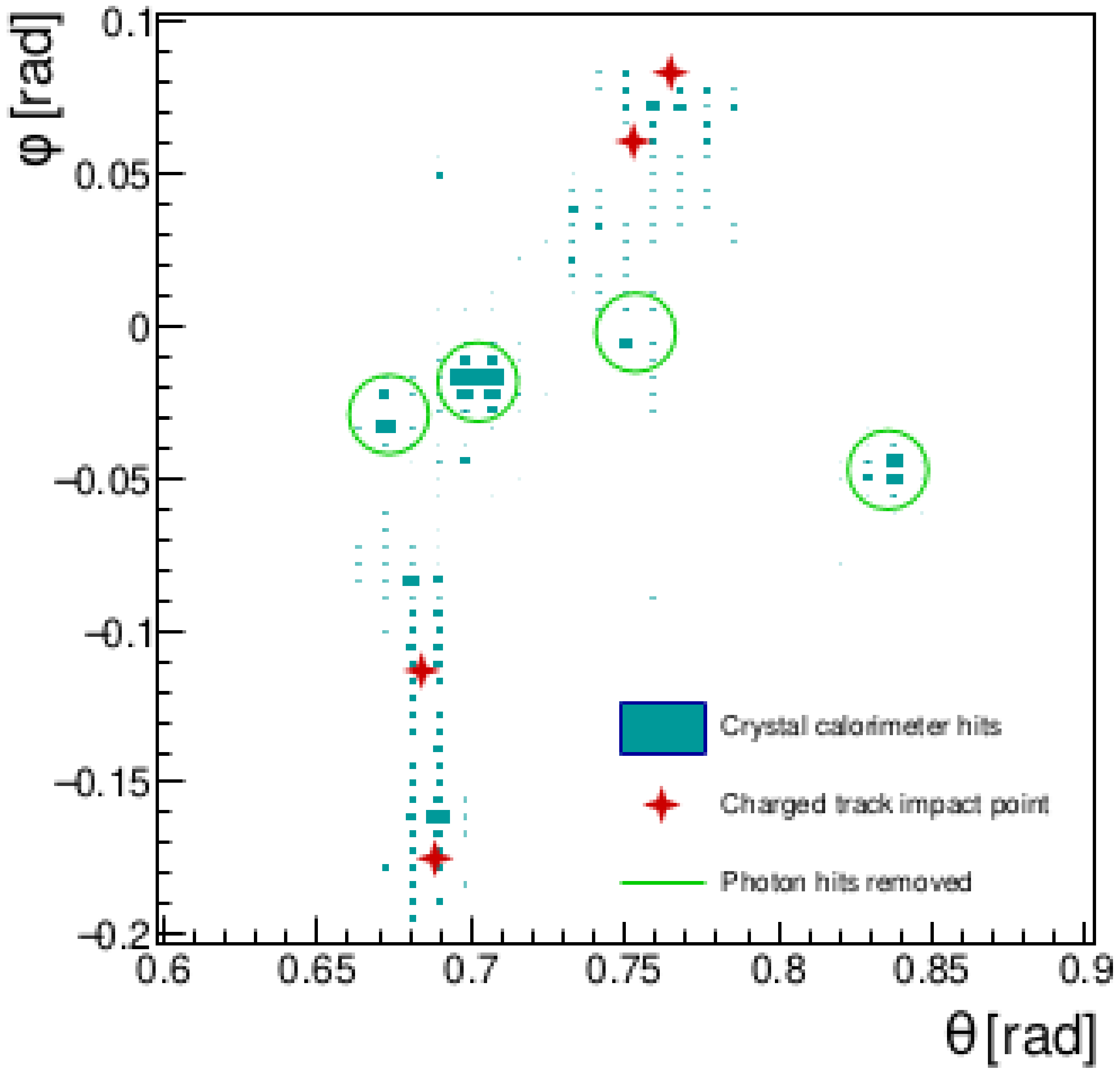
IDEA: dual readout + PFA



Geant4 simulation of Z→jj events:

- magnetic field ON but NO tracker
- Gaussian smearings of MC tracks according to expected IDEA tracker performance
- for each track extrapolate impact point
- remove and store tracks not reaching calo

IDEA: dual readout + PFA



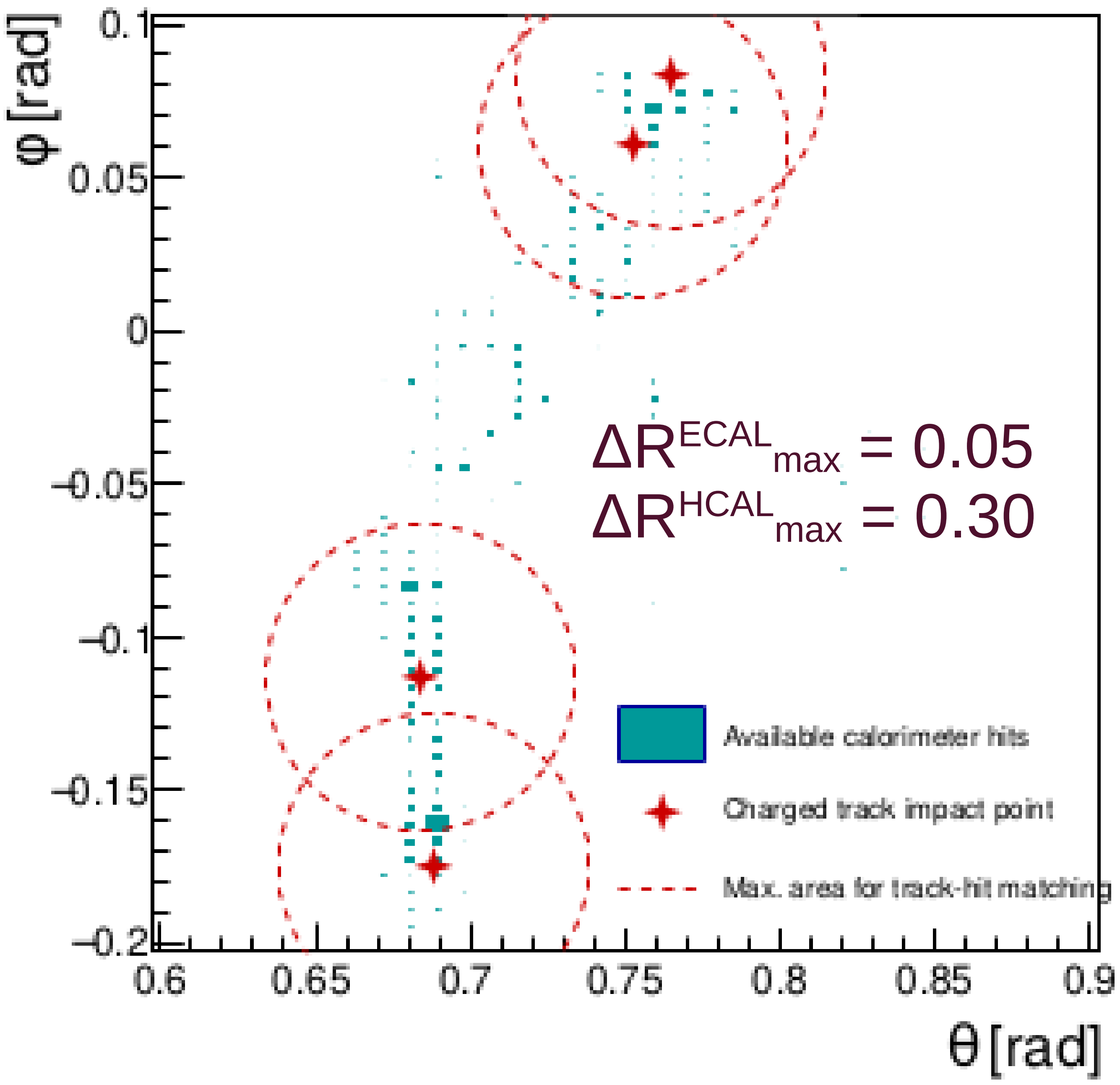
Geant4 simulation of Z→jj events:

- magnetic field ON but NO tracker
- Gaussian smearings of MC tracks according to expected IDEA tracker performance
- for each track extrapolate impact point
- remove and store tracks not reaching calo
- identify EM neutral clusters (photons) by cluster radius

$$R_{\text{transverse}} = \frac{E_{\text{seed}}}{\sum_i E_{\text{hit},i}(\Delta R_i < 0.013)}$$

- remove and store photons (R<0.9)

IDEA: dual readout + PFA



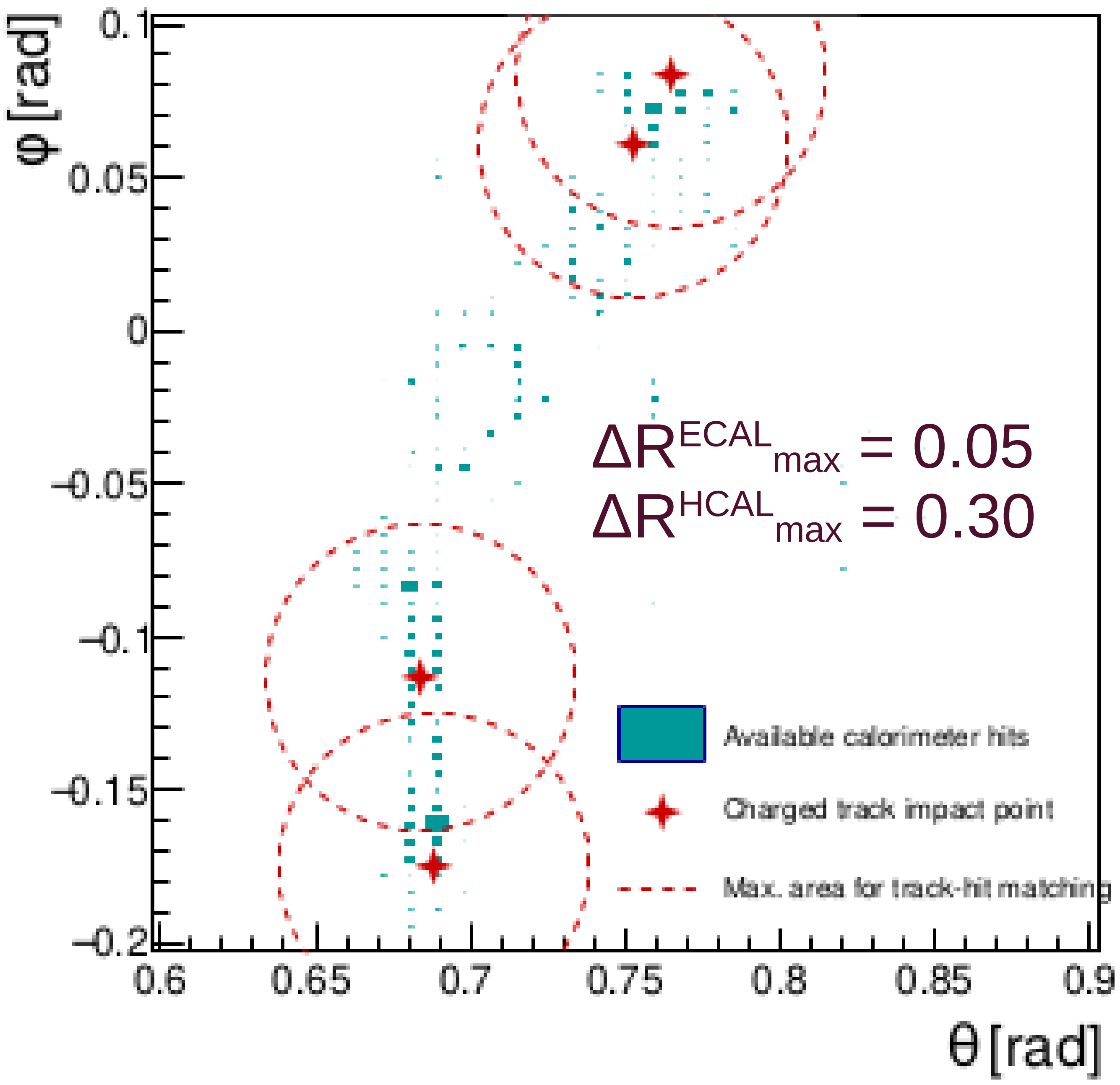
Geant4 simulation of Z→jj events:

- magnetic field ON but NO tracker
- Gaussian smearings of MC tracks according to expected IDEA tracker performance
- for each track extrapolate impact point
- remove and store tracks not reaching calo
- identify EM neutral clusters (photons) by cluster radius

$$R_{\text{transverse}} = \frac{E_{\text{seed}}}{\sum_i E_{\text{hit},i}(\Delta R_i < 0.013)}$$

- remove and store photons (R<0.9)
- for each track, rank calo hits by distance

IDEA: dual readout + PFA



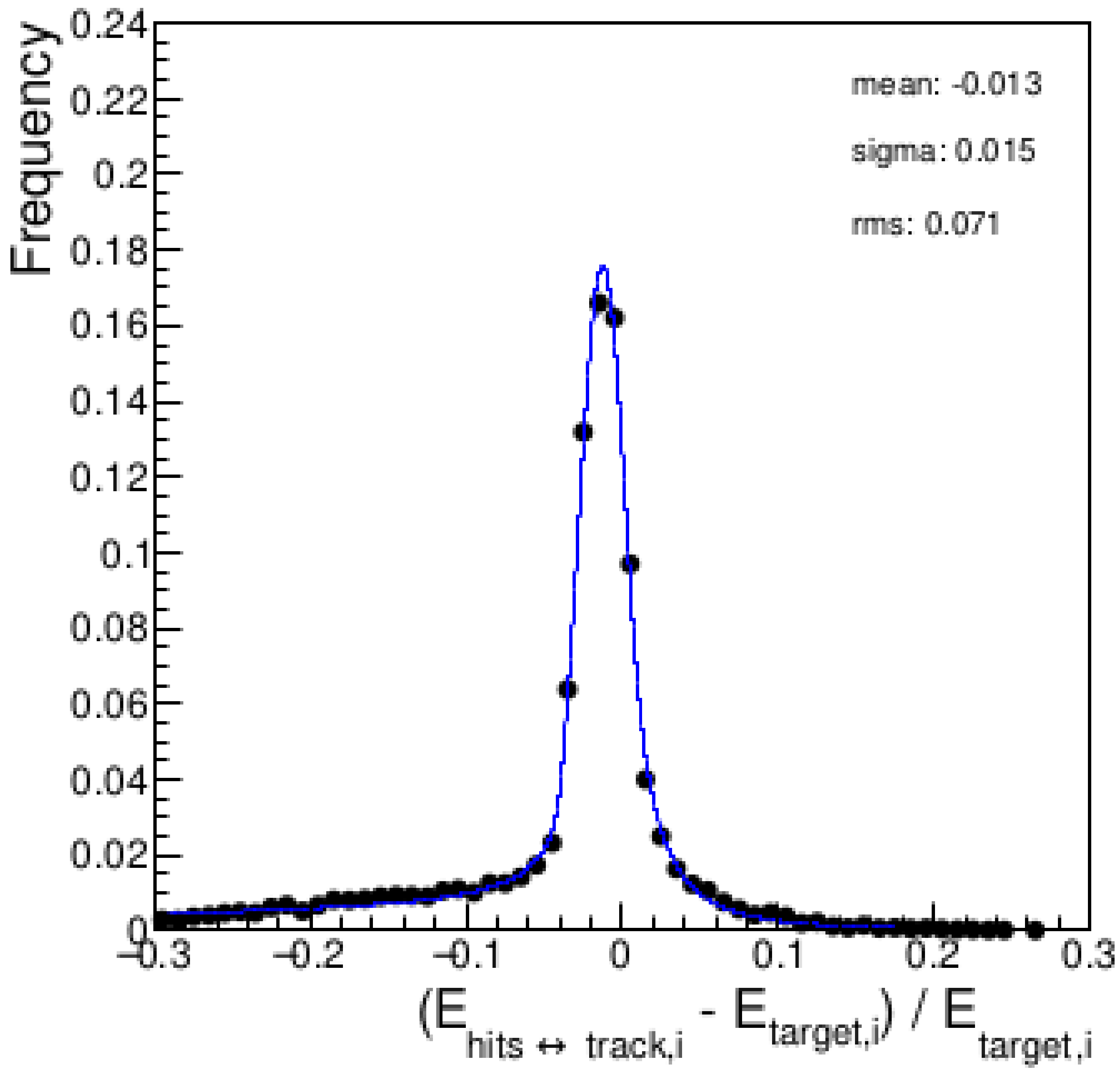
Geant4 simulation of Z→jj events:

- magnetic field ON but NO tracker
- Gaussian smearings of MC tracks according to expected IDEA tracker performance
- for each track extrapolate impact point
- remove and store tracks not reaching calo
- identify EM neutral clusters (photons) by cluster radius

$$R_{\text{transverse}} = \frac{E_{\text{seed}}}{\sum_i E_{\text{hit},i}(\Delta R_i < 0.013)}$$

- remove and store photons (R<0.9)
- for each track, rank calo hits by distance
- collect hits in cone

IDEA: dual readout + PFA



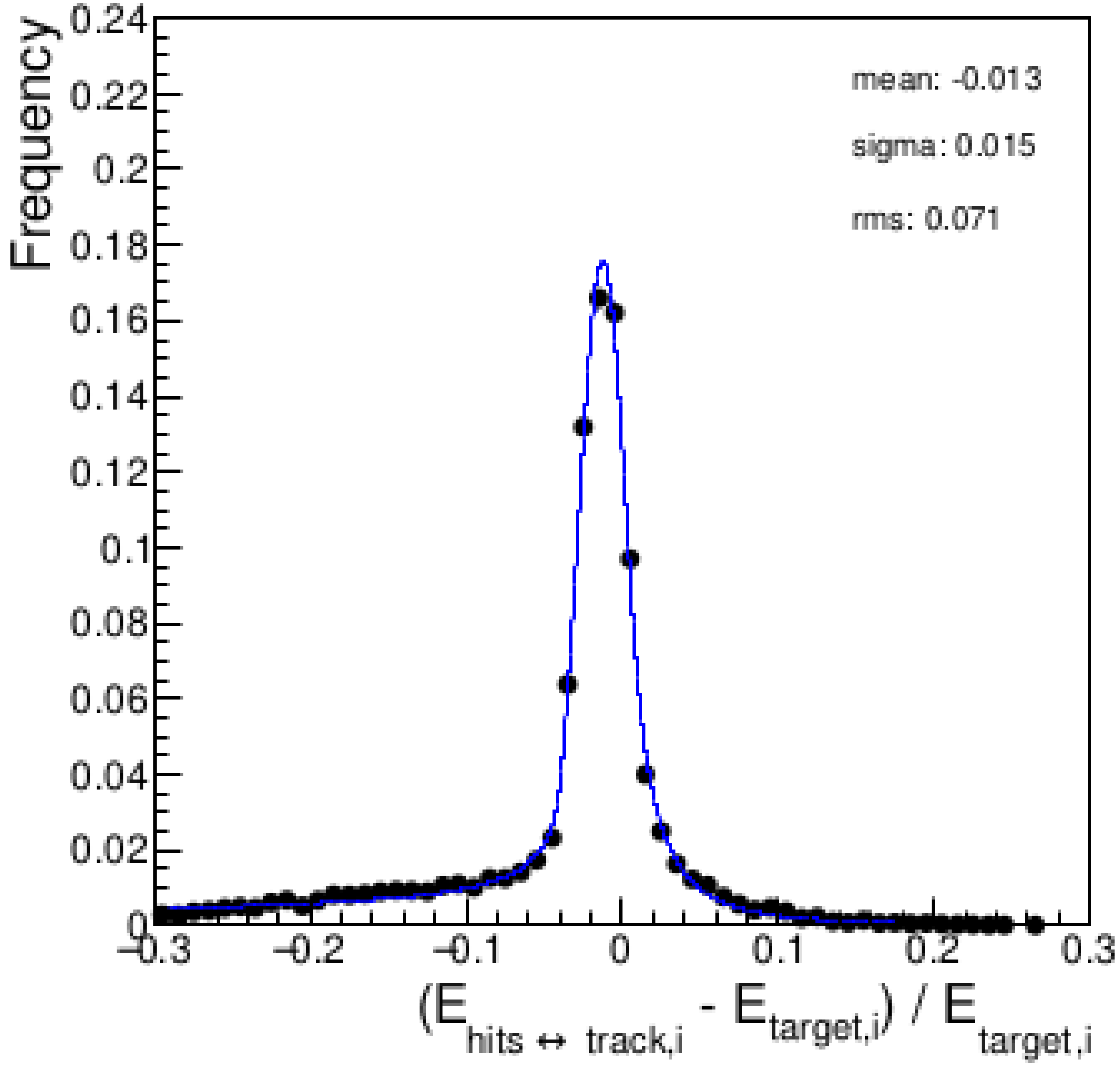
Geant4 simulation of $Z \rightarrow jj$ events:

- magnetic field ON but NO tracker
- Gaussian smearings of MC tracks according to expected IDEA tracker performance
- for each track extrapolate impact point
- remove and store tracks not reaching calo
- identify EM neutral clusters (photons) by cluster radius

$$R_{\mathrm{transverse}} = \frac{E_{\mathrm{seed}}}{\sum_i E_{\mathrm{hit},i}(\Delta R_i < 0.013)}$$

- remove and store photons (R<0.9)
- for each track, rank calo hits by distance
- collect hits in cone
- compare with E_{target}(track)

IDEA: dual readout + PFA



Geant4 simulation of Z→jj events:

- magnetic field ON but NO tracker
- Gaussian smearings of MC tracks according to expected IDEA tracker performance
- for each track extrapolate impact point
- remove and store tracks not reaching calo
- identify EM neutral clusters (photons) by cluster radius

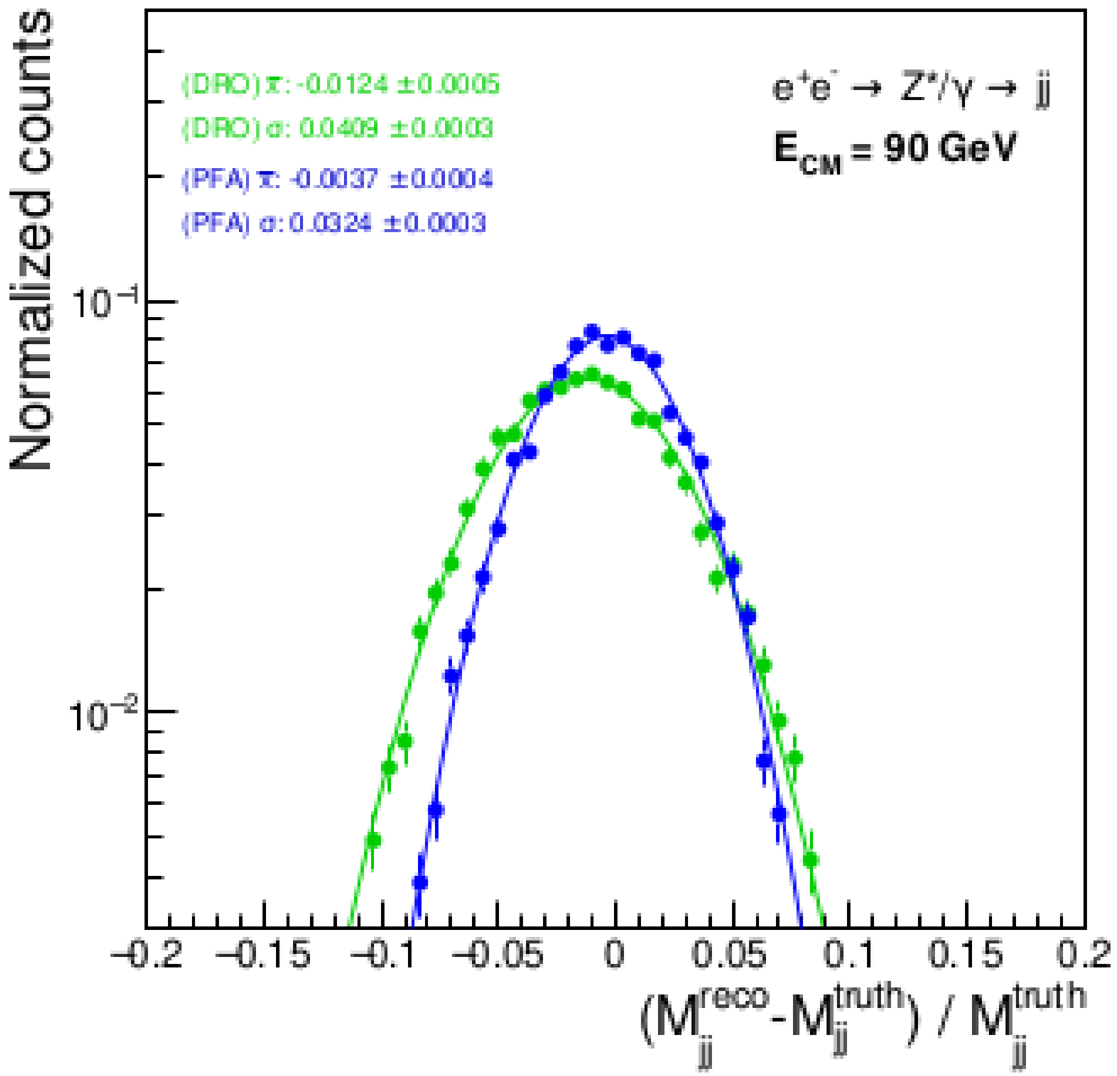
$$R_{\text{transverse}} = \frac{E_{\text{seed}}}{\sum_i E_{\text{hit},i}(\Delta R_i < 0.013)}$$

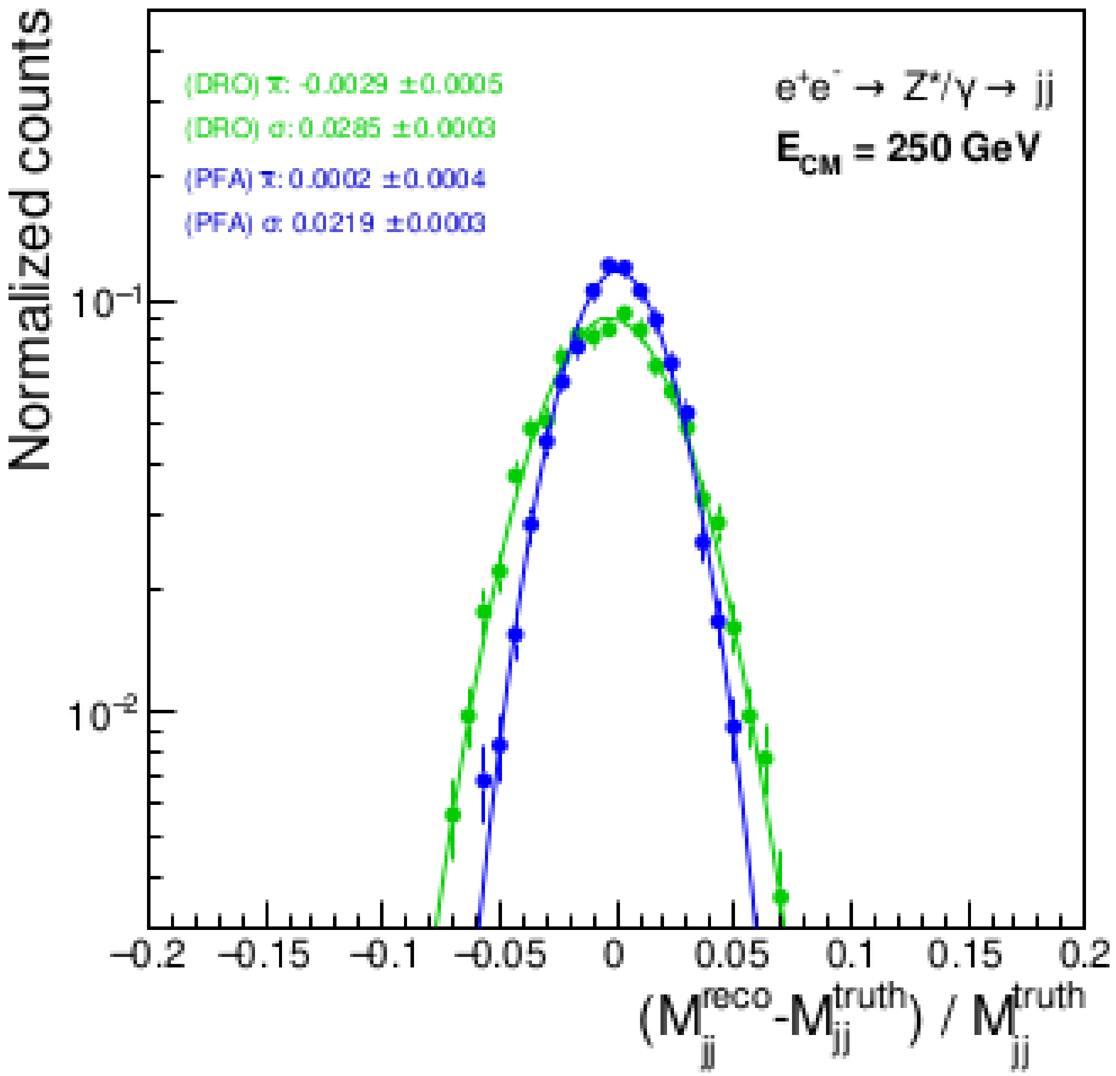
- remove and store photons (R<0.9)
- for each track, rank calo hits by distance
- collect hits in cone
- compare with E_{target}(track)
- if "good" agreement remove hits and track

IDEA: dual readout + PFA

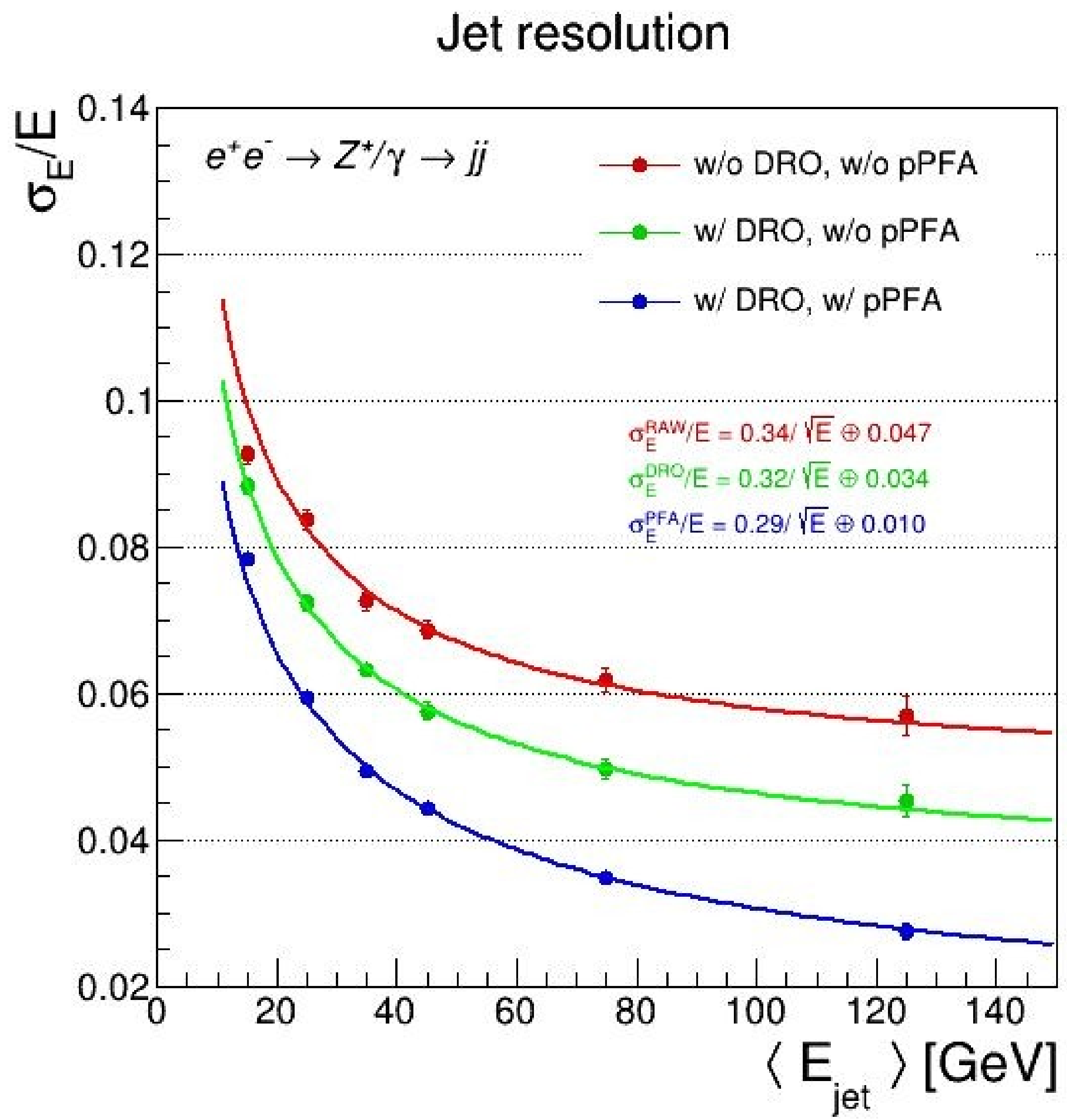
... continue

- apply k_t algorithm (e.g. Durham) for two jets





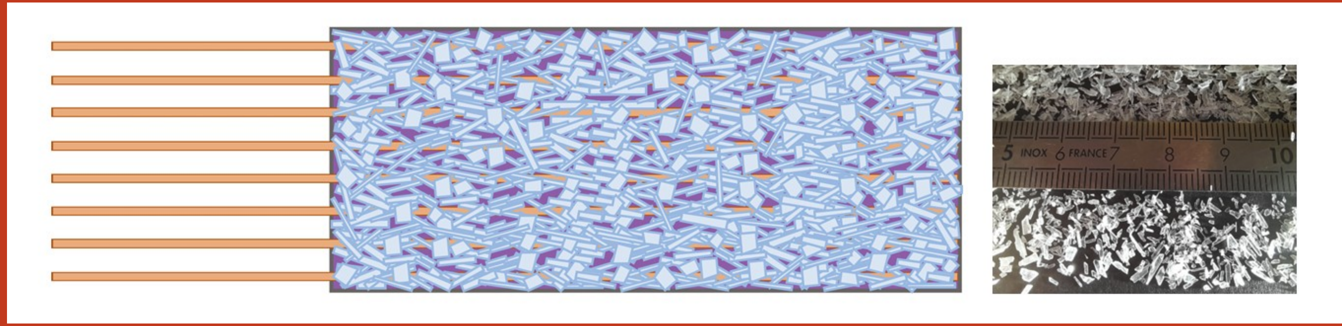
finally ...



Jet resolution
$e^+e^- \to Z^*/\gamma \to jj$
w/o DRO, w/o pPFA
w/ DRO, w/o pPFA
w/ DRO, w/ pPFA
$\sigma_E^{RAW}/E = 0.34/\sqrt{E} \oplus 0.047$
$\sigma_E^{DRO}/E = 0.32/\sqrt{E} \oplus 0.034$
$\sigma_E^{PFA}/E = 0.29/\sqrt{E} \oplus 0.010$
σ_E/E
$\langle E_{jet} \rangle$ [GeV]

Other ongoing R&D on calorimetry

GRAiNITA

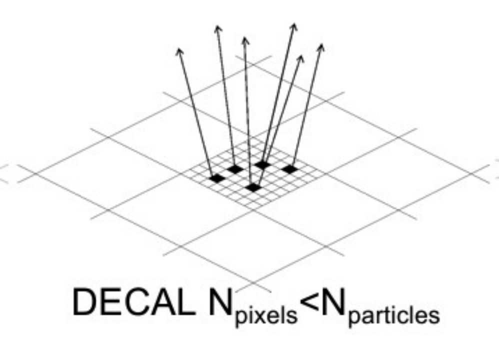


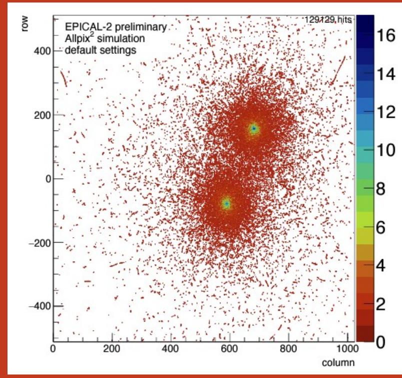
Scintillator grains and absorber suspended in liquid
Trapped light extracted with WLS fibres

High density EM calorimeter

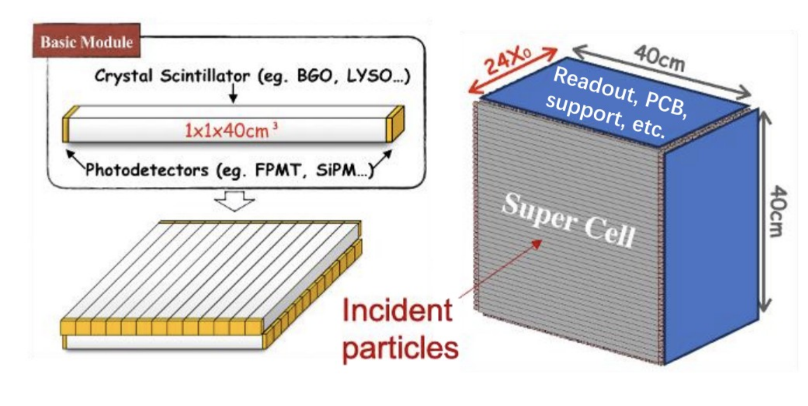
DECAL - Ultra-high granularity CMOS Ecal

High-density digital CMOS readout - count hits rather than measure energy



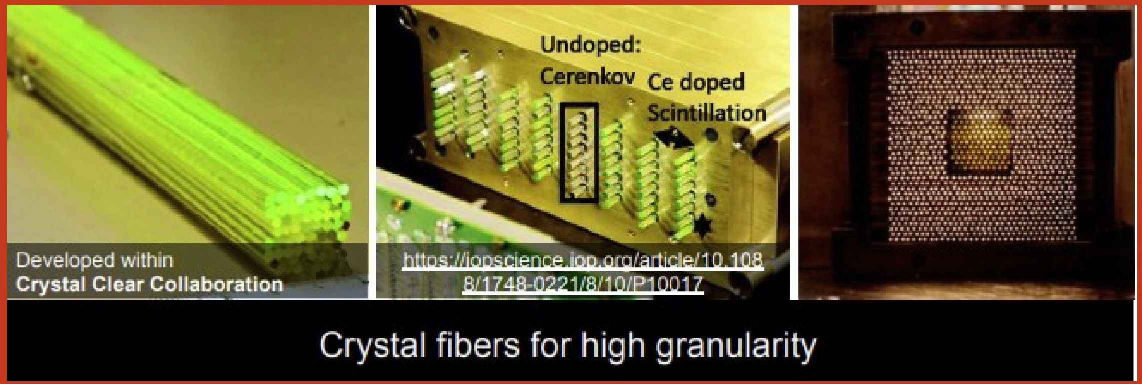


Crystal calorimeter for FCC-ee?

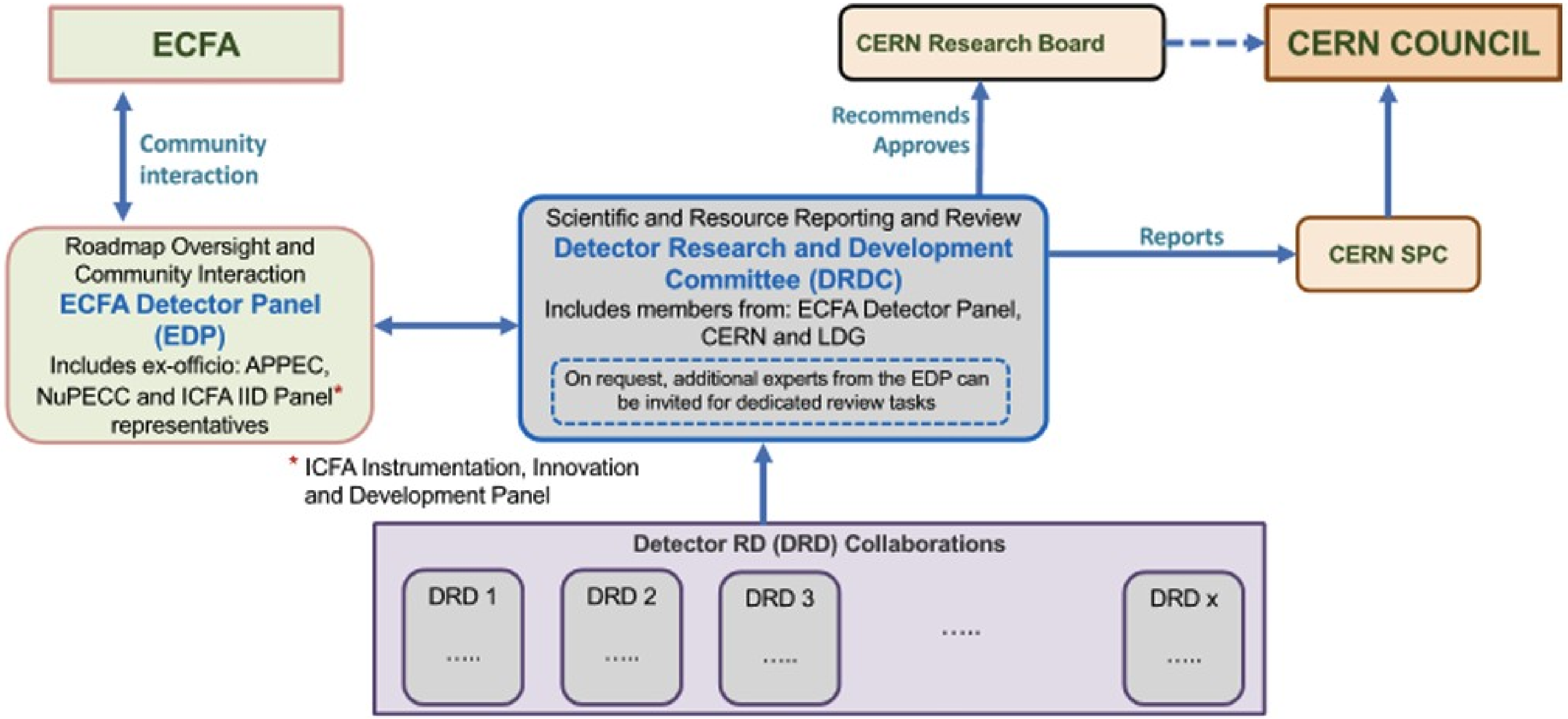


Traditionally achieve superb EM resolution but w/ limited granularity

Recent R&D shows potential for particle flow



Synergies: consortia and ECFA DRDs



- Lot of leverage done in past within **consortia and proto-collaborations**
- Challenges connected with detector R&D find **common framework** (aimed at increasing coherence and optimising resources) with ECFA DRDs

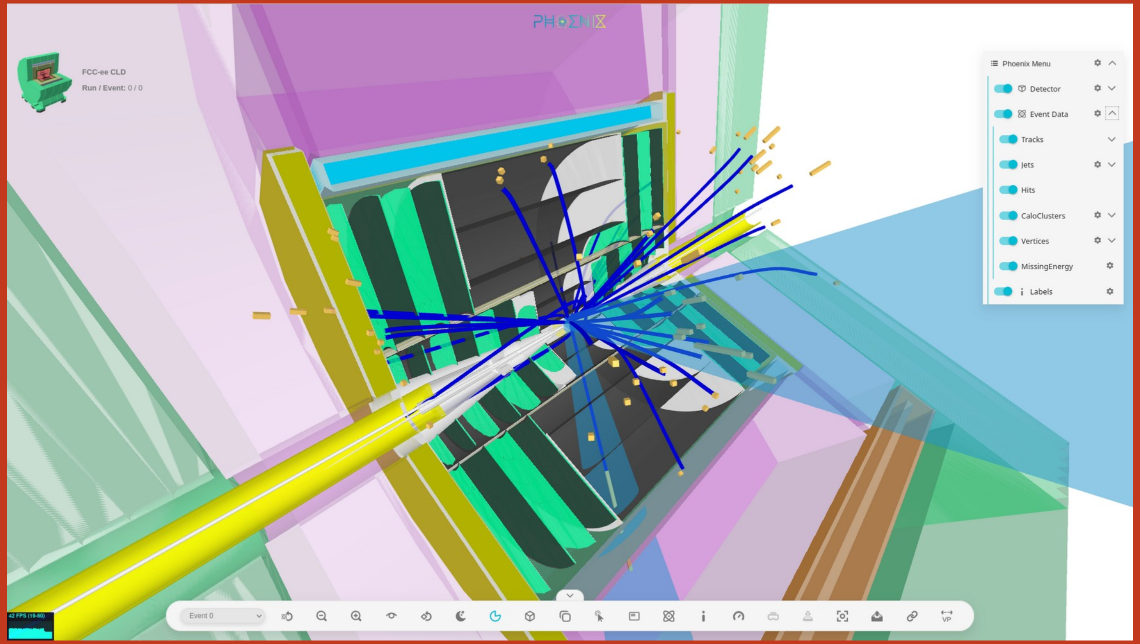
Synergies: common tools

- Nice sub-products of these collaborations already widely used

Key4HEP

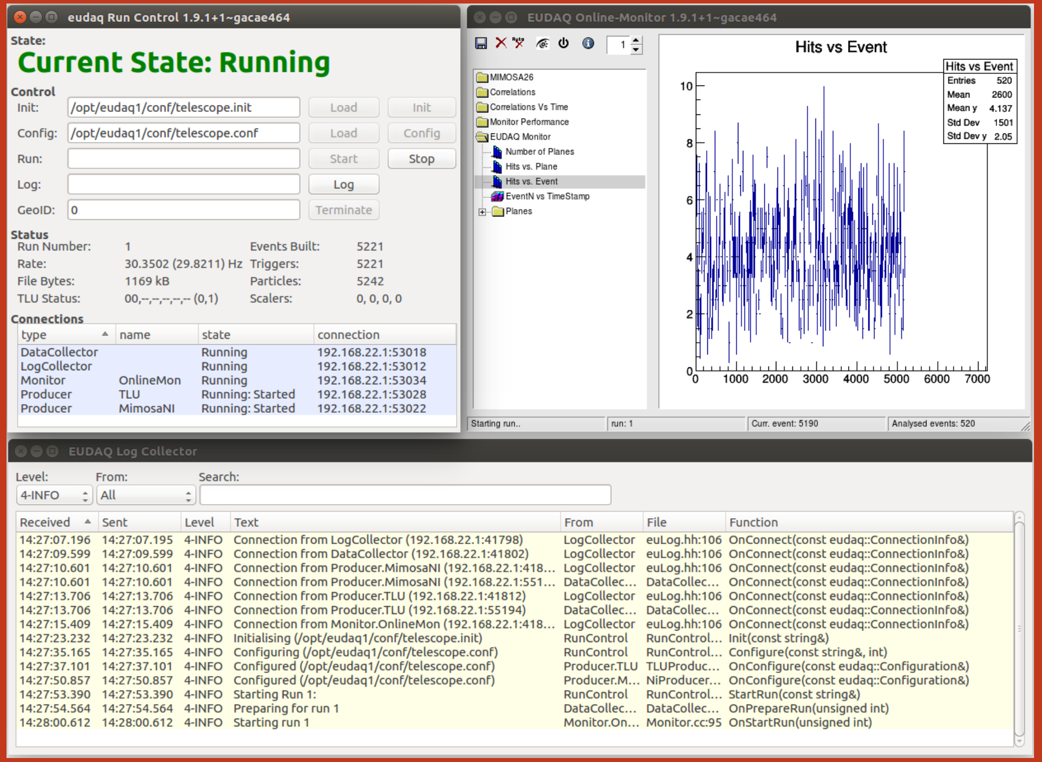
Common software framework used for FCC and for many of other future collider projects

Includes common **event data model**, tools for easy and portable **detector geometry handling**, consistent set of tags of **most used HEP software packages**



EUDAQ

Common data acquisition and online monitoring software, often used in conjunction with **common hardware** for beam monitor (EUDET), and data quality tools



Lost and found

Istituto Nazionale di Fisica Nucleare
Sezione di Pavia

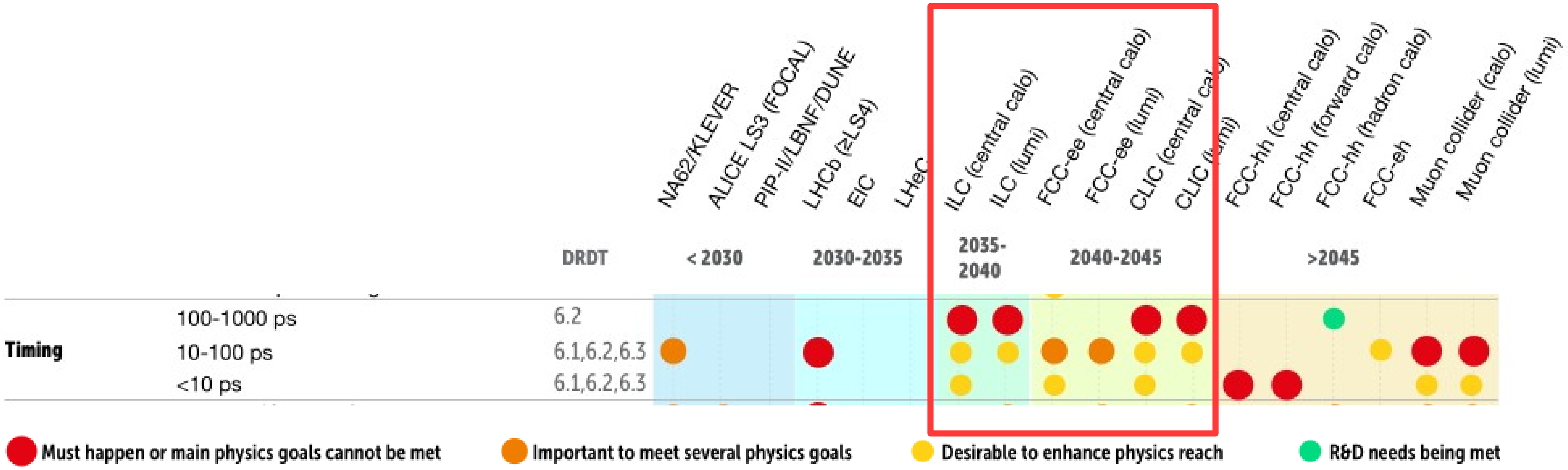
1. Timing

Timing

All detectors developments address timing issues:

- Trackers and muon chambers
- PID and ToF detectors
- Calorimeters

with sensitivities that cover quite different time domains → see table below for calorimeters (!)



Solid state detectors

INFN Istituto Nazionale di Fisica Nucleare Sezione di Pavia

"Technical" Start Date of Facility (This means, where the dates are not known, the earliest technically feasible start date is indicated - such that detector R&D readiness is not the delaying factor)				< 2030					2030-2035					2035-2040	2040-2045		> 2045		
				Panda 2025	CBM 2025	NA62/Klever 2025	Belle II 2026	ALICE LS3 1)	ALICE 3	LHCb (≳LS4) 1)	ATLAS/CMS (≳ LS4) 1)	EIC	LHeC	ILC 2)	FCC-ee	CLIC 2)	FCC-hh	FCC-eh	Muon Collider
Vertex Detector 3)	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.1 DRDT 3.4	Position precision σ_{hit} (μm)		≃ 5		≲ 5	≃ 3	≲ 3	≲ 10	≲ 15	≲ 3	≃ 5	≲ 3	≲ 3	≲ 3	≃ 7	≃ 5	≲ 5
			X/X_0 (%/layer)	≲ 0.1	≃ 0.5	≃ 0.5	≲ 0.1	≃ 0.05	≃ 0.05	≃ 1		≃ 0.05	≲ 0.1	≃ 0.05	≃ 0.05	≲ 0.2	≃ 1	≲ 0.1	≲ 0.2
			Power (mW/cm^2)		≃ 60			≃ 20	≃ 20			≃ 20		≃ 20	≃ 20	≃ 50			
			Rates (GHz/cm^2)		≃ 0.1	≃ 1	≲ 0.1		≲ 0.1	≃ 6		≲ 0.1	≃ 0.1	≃ 0.05	≃ 0.05	≃ 5	≃ 30	≃ 0.1	
			Wafers area (") 4)					12	12			12			12		12		12
		DRDT 3.2	Timing precision σ_t (ns) 5)	10		≲ 0.05	100		25	≲ 0.05	≲ 0.05	25	25	500	25	≃ 5	≲ 0.02	25	≲ 0.02
		DRDT3.3	Radiation tolerance NIEL (x 10^{16} neq/cm^2)							≃ 6	≃ 2						≃ 10^{2}		
			Radiation tolerance TID (Grad)							≃ 1	≃ 0.5						≃ 30		
Tracker 6)	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.1 DRDT 3.4	Position precision σ_{hit} (μm)						≃ 6	≃ 5		≃ 6	≃ 6	≃ 6	≃ 6	≃ 7	≃ 10	≃ 6	
			X/X_0 (%/layer)						≃ 1	≃ 1		≃ 1	≃ 1	≃ 1	≃ 1	≃ 1	≲ 2	≃ 1	
			Power (mW/cm^2)						≲ 100	≃ 100		≲ 100		≲ 100	≲ 100	≲ 150			
			Rates (GHz/cm^2)							≃ 0.16									
			Wafers area (") 4)						12			12		12	12	12	12		12
		DRDT 3.2	Timing precision σ_t (ns) 5)						25	≲ 25		25	25	≲ 0.1	≲ 0.1	≲ 0.1	≲ 0.02	25	≲ 0.02
		DRDT3.3	Radiation tolerance NIEL (x 10^{16} neq/cm^2)							≃ 0.3							≲ 1		
			Radiation tolerance TID (Grad)							≃ 0.25							≲ 1		
Calorimeter 7)	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.2	Timing precision σ_t (ns) 5)											≲ 0.05	≲ 0.05	≲ 0.05	≲ 0.02		≲ 0.02
		DRDT 3.3	Radiation tolerance NIEL (x 10^{16} neq/cm^2)														≳ 10^{2}		
			Radiation tolerance TID (Grad)														≃ 50		
Time of Flight 8)	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.2	Timing precision σ_t (ns) 5)				≃ 0.02		≃ 0.02		≲ 0.03	≃ 0.02	≃ 0.0		≲ 0.01		≲ 0.01	≃ 0.02	
		DRDT 3.3	Radiation tolerance NIEL (x 10^{16} neq/cm^2)														≃ 10^{2}		
			Radiation tolerance TID (Grad)														≃ 30		

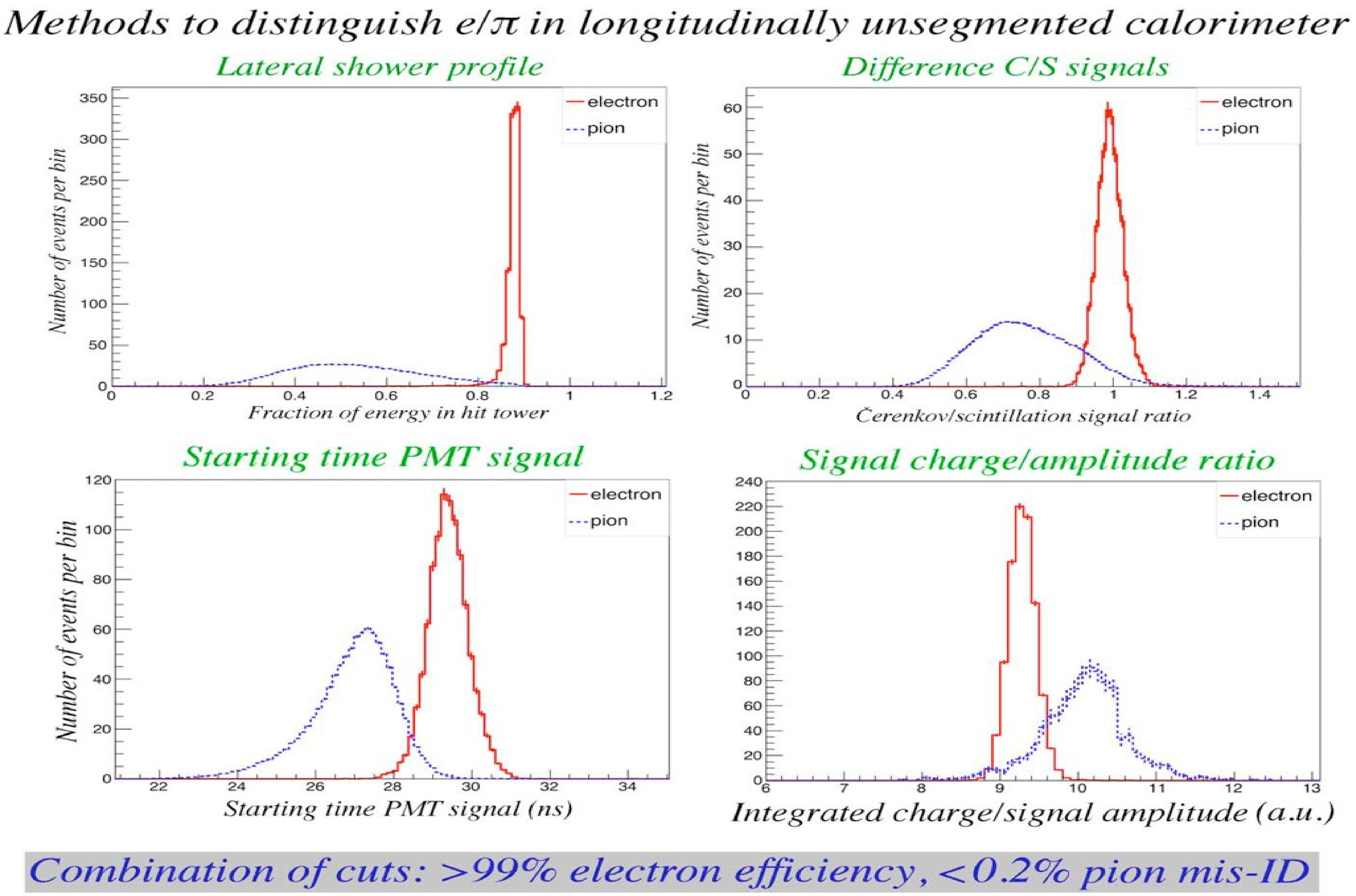
Impact of timing ... e/π discrimination

RD52 fibre-Pb dual-readout calorimeter

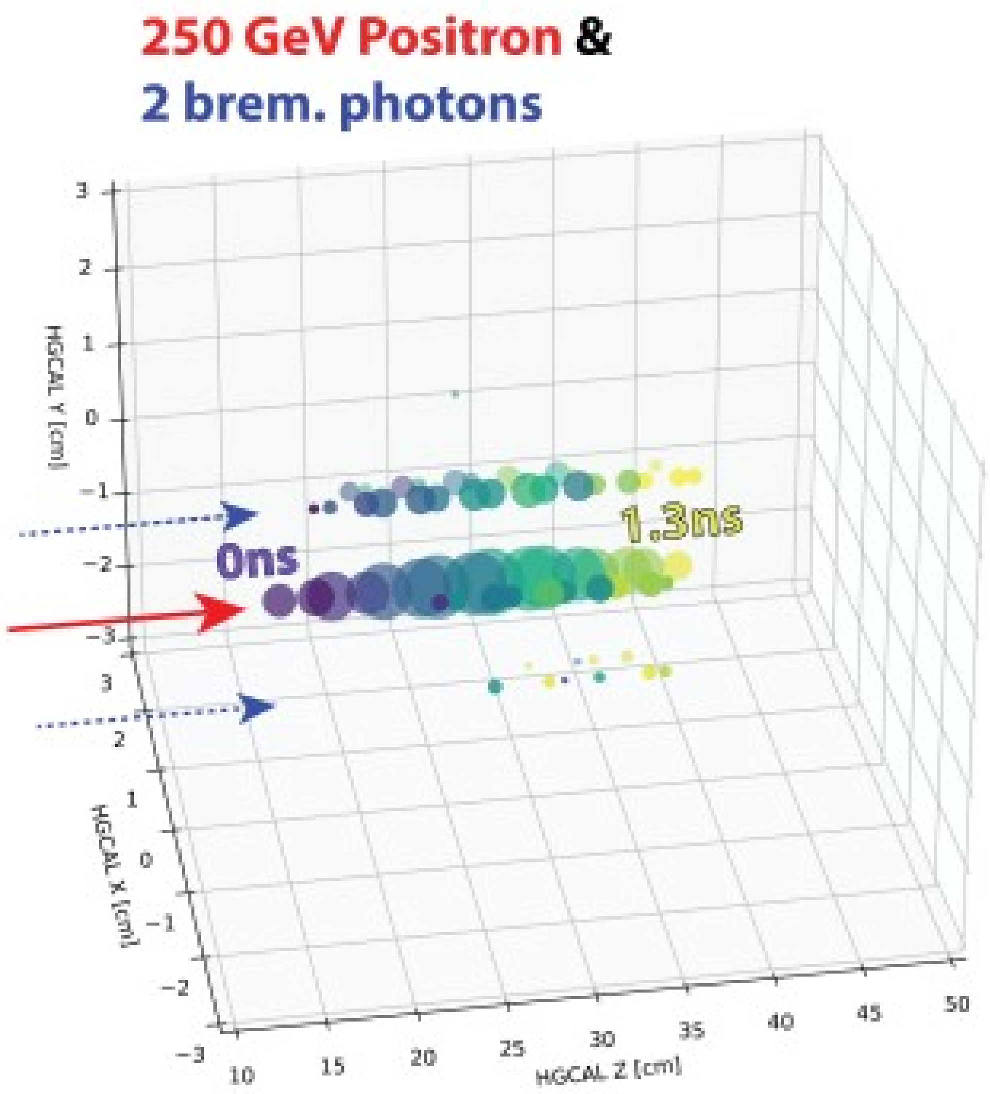
(60 GeV) e^- vs. π^-

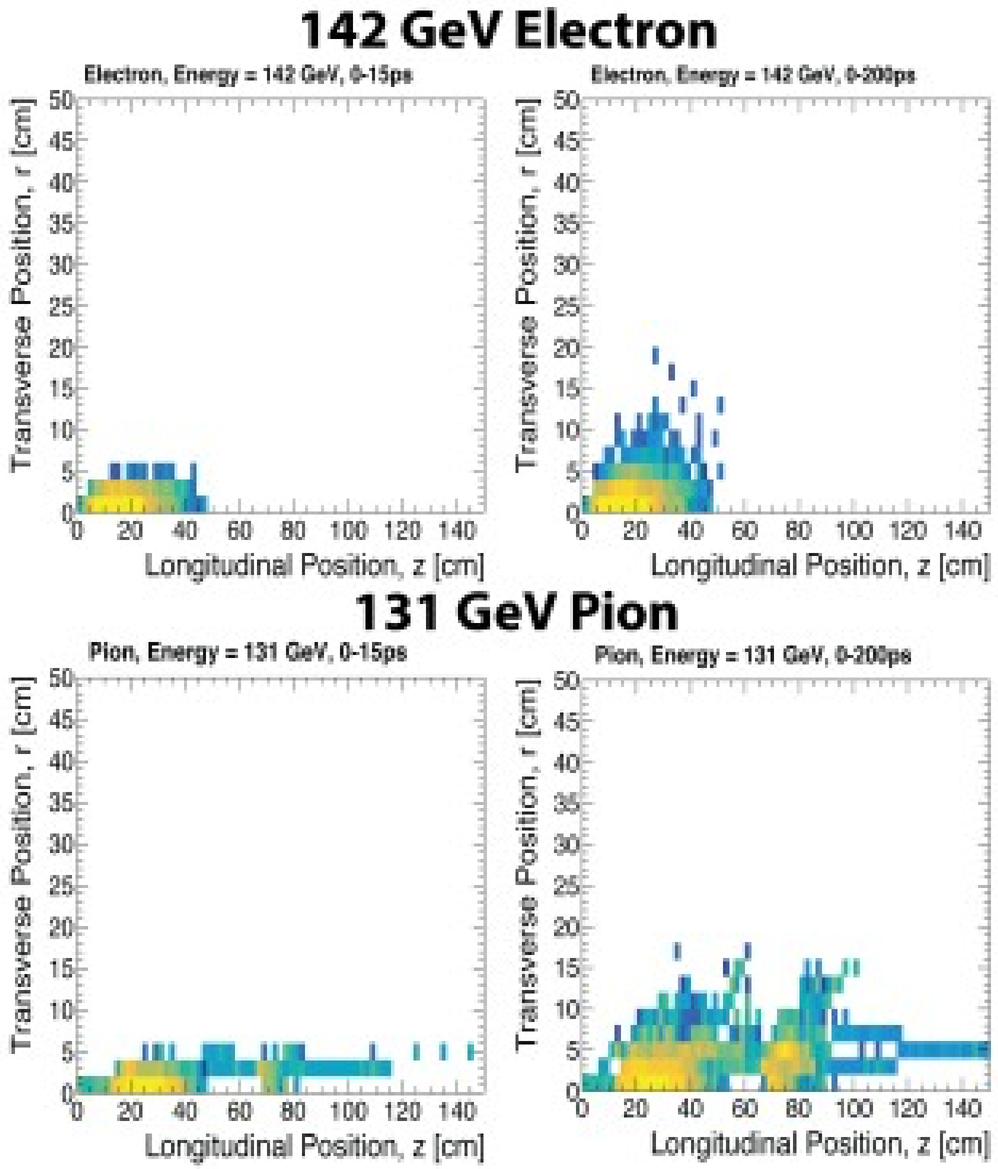
$\varepsilon(e^-) > 99\%$
$R(\pi^-) \sim 500$

NIM A 735 (2014) 120

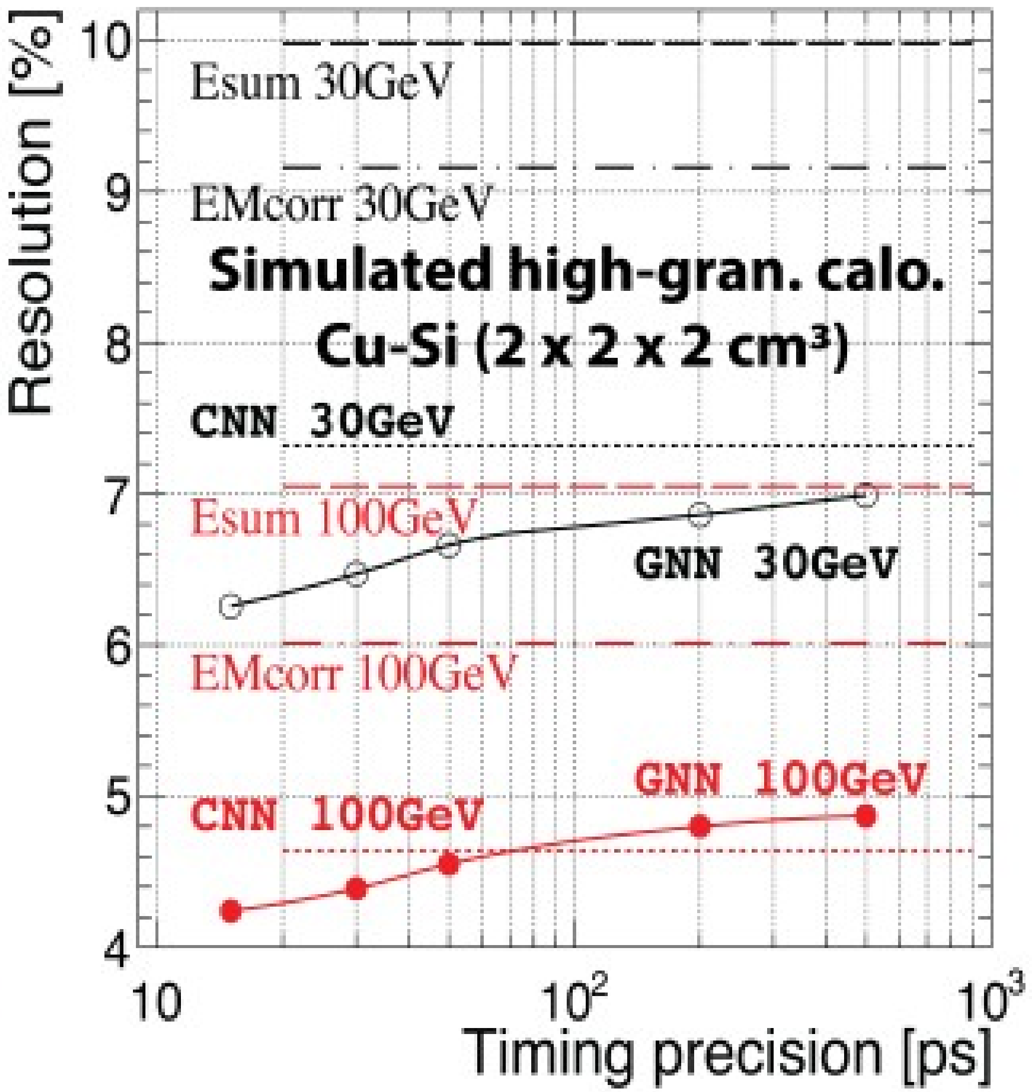


Impact of timing ... energy reconstruction





CMS HGCAL measurements



Highly granular Cu-Si calorimeter
30 & 100 GeV pion simulations

Impact of timing ... longitudinal segmentation

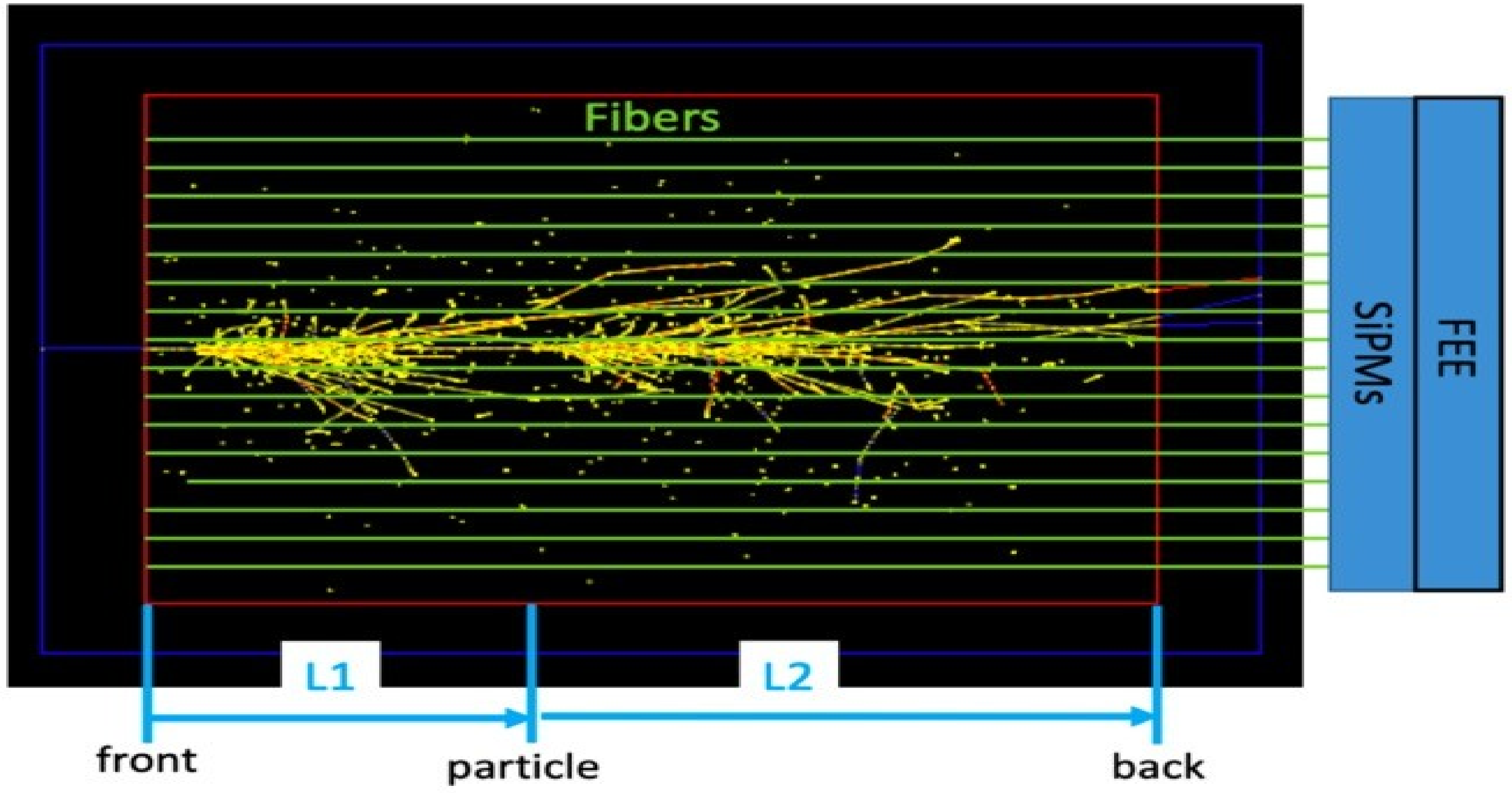


Table 1. The energy resolution of the 3D GNN reconstruction with various timing resolutions for longitudinal segmentation.

Timing Resolution $\Delta(t)$, ps	Position Resolution $\Delta(z)$, cm	Energy Resolution σ/E, %
0	0.0	3.6
100	5.0	3.9
150	7.5	4.0
200	10.0	4.2

@ 100 GeV

w/ Cherenkov fibres only

Impact of timing ... ToA measurements (simulations)

Full SiPM signal sampled at 10 GHz

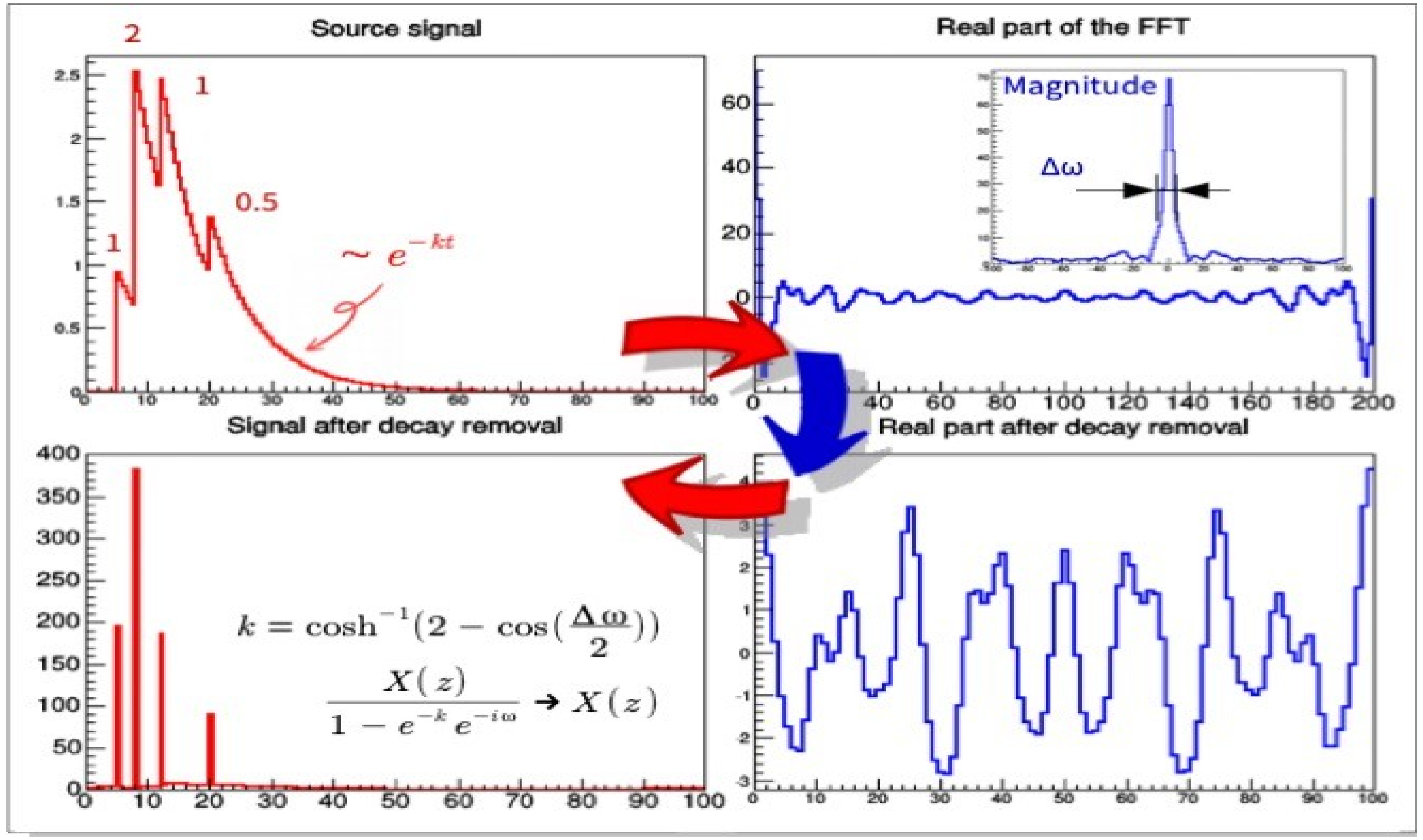
FFT used to mitigate exponential tail

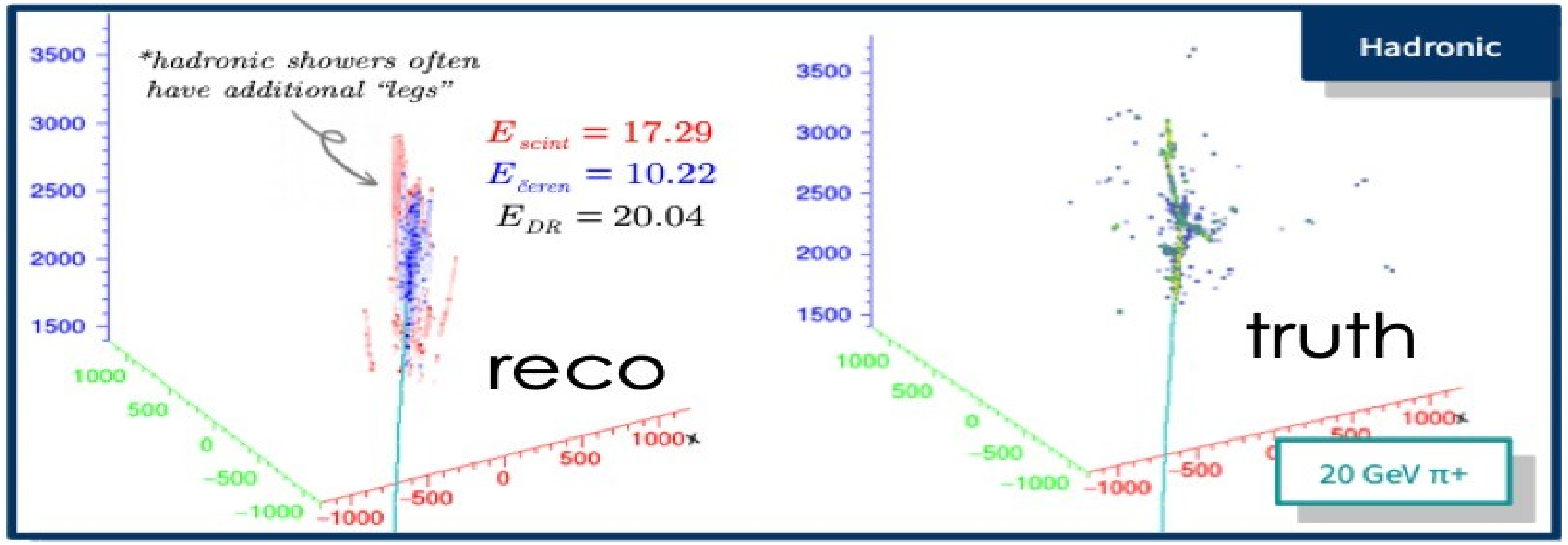
Unlocks full longitudinal information about energy deposit

Combined with DR information allows in-shower cluster identification

Time domain

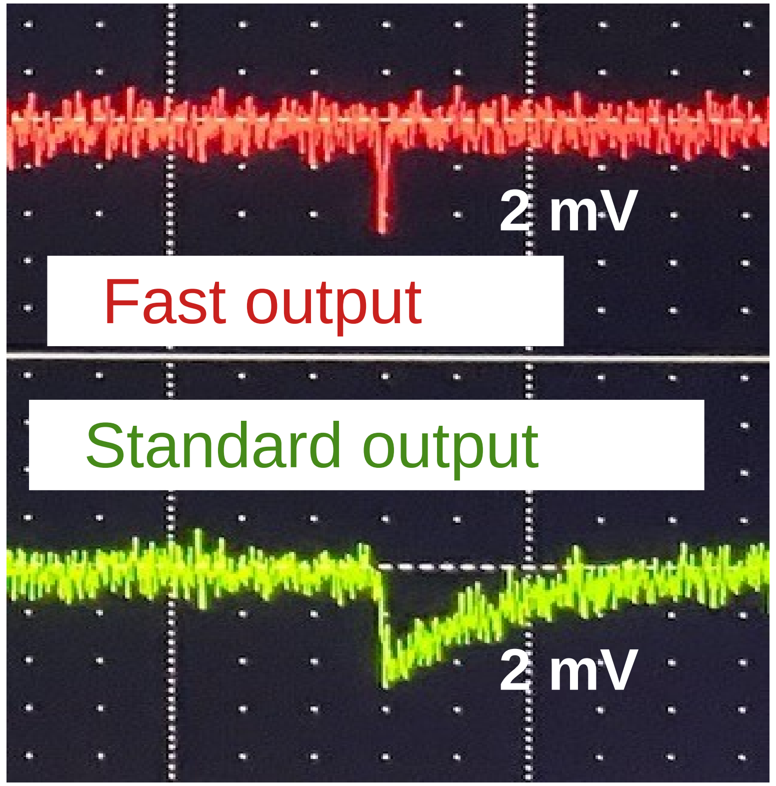
Frequency domain



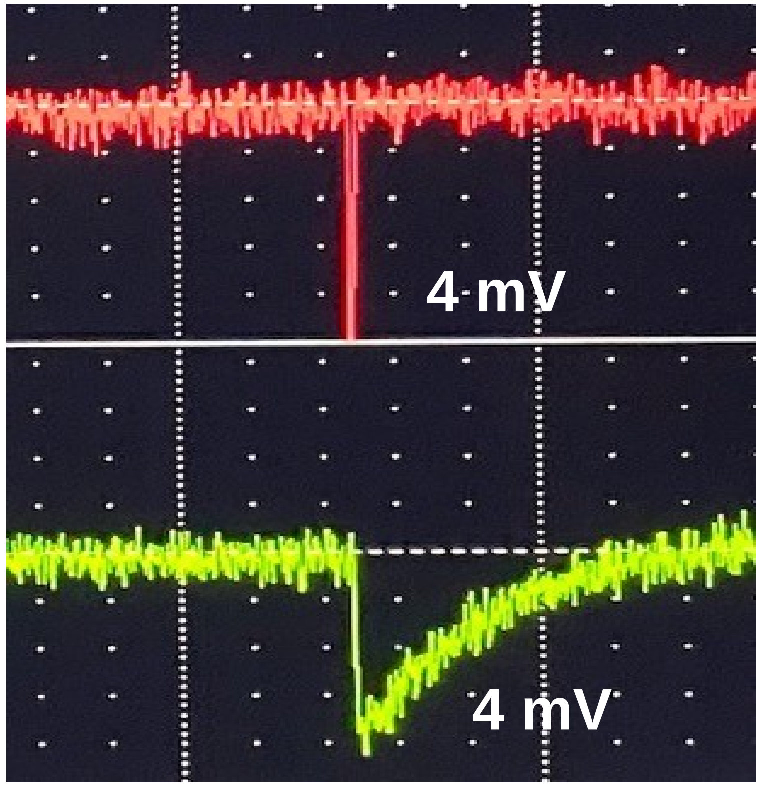


Waveform digitisation

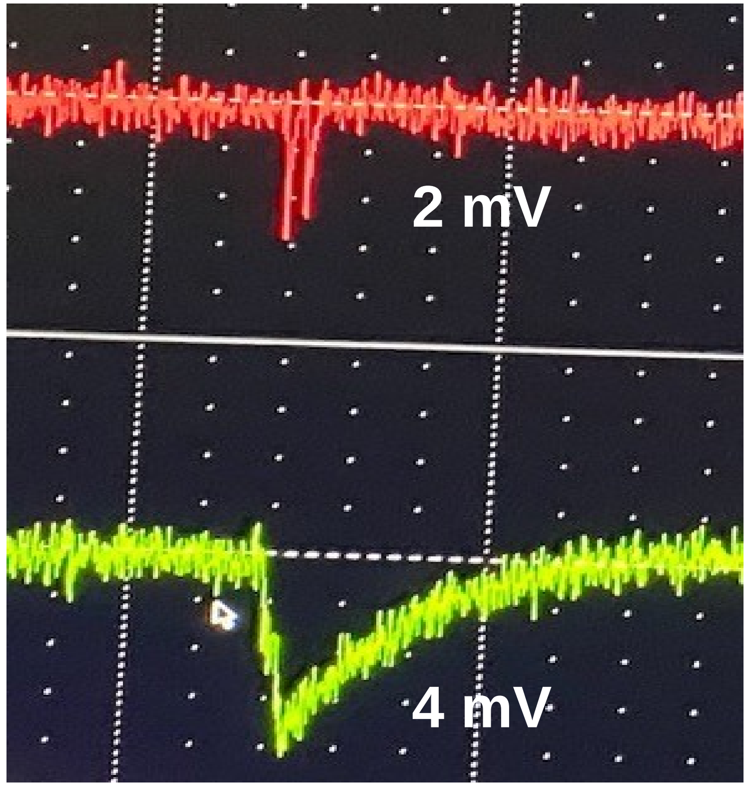
Results with SensL (MicroFC-30020SMT):
SiPM with both fast and standard output



One-photon event



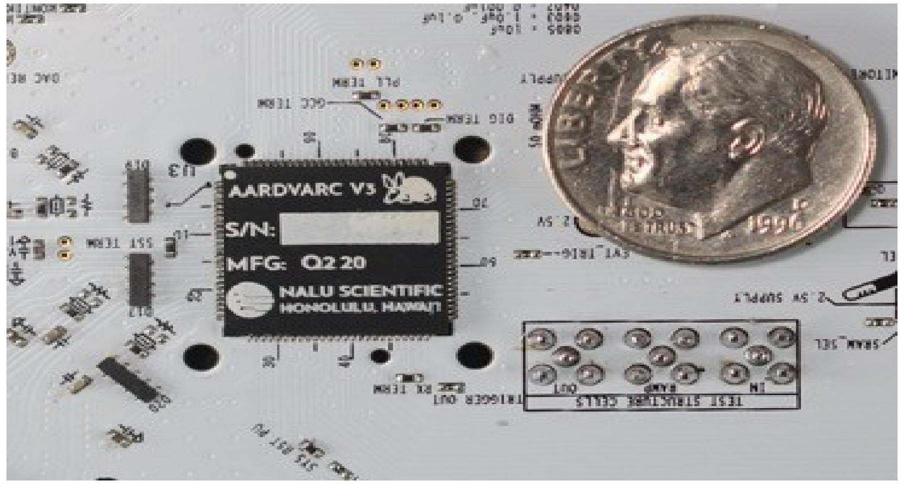
Two-photon event
(simultaneous)



Two-photon event
(5 ns apart)

NALU Scientific
AARDVARC v3

- Sampling rate 10-14 GS/s
- 12 bits ADC
- 4-8 ps timing resolution
- 32 k sampling buffer
- 2 GHz bandwidth
- System-on-Chip (CPU)



Lost and found

2. DNNs

DNNs

Significant performance improvements expected in many domains:

- Triggering (whenever needed)
- Data reduction (feature extraction)
- Final state identification
- Event reconstruction
- ...

DNNs at work – τ decay tagging

IDEA layout

→ information: fibre signal output (# p.e.)
(no time information)

3-class classification:
τ_{lep}, τ_{had}, QCD jet

8-class classification:
τ_0, τ_1, τ_2, τ_3, τ_4, τ_5, τ_6, QCD jet

[τ from Z → ττ decays]

3-class label	8-class label	
0	0	$\tau \rightarrow \mu\nu\nu$
0	1	$\tau \rightarrow e\nu\nu$
1	2	$\tau \rightarrow \pi\nu$
1	3	$\tau \rightarrow \pi\pi^0\nu$
1	4	$\tau \rightarrow \pi\pi^0\pi^0\nu$
1	5	$\tau \rightarrow \pi\pi\pi\nu$
1	6	$\tau \rightarrow \pi\pi\pi^0\nu$
2	7	$Z \rightarrow qq$ jets

DGCNN w/ geometrical information only

DGCNN optimised but w/o #pe as input feature

B field and material in

Truth BR \ Predicted BR	$\tau\to e\nu\nu$	$\tau\to\pi\nu$	$\tau\to\pi\pi^0\nu$	$\tau\to\pi\pi^0\pi^0\nu$	$\tau\to\pi\pi\pi\nu$	$\tau\to\pi\pi\pi\pi^0\nu$	$\tau\to\mu\nu\nu$	$Z\to qq$ jets
$\tau\to e\nu\nu$	90.36	4.07	2.21	0.03	0.00	0.00	3.34	0.00
$\tau\to\pi\nu$	2.57	86.24	5.39	0.25	3.59	0.17	1.57	0.22
$\tau\to\pi\pi^0\nu$	2.10	18.92	72.67	2.76	1.97	1.01	0.27	0.30
$\tau\to\pi\pi^0\pi^0\nu$	0.74	3.54	58.43	33.04	0.84	2.81	0.05	0.54
$\tau\to\pi\pi\pi\nu$	0.11	9.88	6.22	0.46	75.32	6.49	0.00	1.52
$\tau\to\pi\pi\pi\pi^0\nu$	0.11	1.49	9.30	2.90	38.28	43.75	0.05	4.12
$\tau\to\mu\nu\nu$	2.50	0.70	0.17	0.00	0.03	0.00	96.60	0.00
$Z\to qq$ jets	0.08	0.33	0.63	0.94	2.92	3.09	0.08	91.92

input: fibre coordinates only

avg accuracy: 73.7%

Truth BR \ Predicted BR	$\tau\to e\nu\nu$	$\tau\to\pi\nu$	$\tau\to\pi\pi^0\nu$	$\tau\to\pi\pi^0\pi^0\nu$	$\tau\to\pi\pi\pi\nu$	$\tau\to\pi\pi\pi\pi^0\nu$	$\tau\to\mu\nu\nu$	$Z\to qq$ jets
$\tau\to e\nu\nu$	96.95	0.79	0.62	0.03	0.00	0.00	1.58	0.03
$\tau\to\pi\nu$	3.09	89.03	3.48	0.41	2.02	0.39	1.44	0.14
$\tau\to\pi\pi^0\nu$	1.77	4.83	80.45	9.25	1.61	1.67	0.16	0.25
$\tau\to\pi\pi^0\pi^0\nu$	0.30	0.38	10.43	84.55	0.16	3.87	0.05	0.25
$\tau\to\pi\pi\pi\nu$	0.16	3.52	1.38	0.35	84.82	8.79	0.03	0.95
$\tau\to\pi\pi\pi\pi^0\nu$	0.11	0.24	1.98	2.60	10.19	82.60	0.08	2.20
$\tau\to\mu\nu\nu$	2.53	0.48	0.11	0.00	0.03	0.00	96.82	0.03
$Z\to qq$ jets	0.08	0.25	0.19	1.05	2.54	4.08	0.06	91.75

input: fibre coordinates + type

avg accuracy: 88.3% (w/ #p.e. 90.8%)

Where are we?

- Lot of work done, but way more ahead - not exhaustive list:
  - Detector concepts are **nice frameworks** - fresh ideas and redesign are **more than welcome**

    … and at FCC-ee there are 3 detector concepts and 4 IPs….
  - **New technologies** (timing for optimal particle flow? UV/digital light sensors for crystals/fibres?)
  - **Software is in development** (starting from detector simulations) - better software means more opportunities for improved physics requirements
- “Detector communities” fairly compact (o(20) people) - a lot of room for new collaborators)
  - Opportunities for **younger colleagues** (maybe while spending most of their time on LHC experiments):
    - Doing **“core” HEP detector/software work** after highly optimised LHC detectors
    - Talks and proceedings
    - Fundamental for “knowledge transfer” (forming future detector experts) → detector R&D need to be better “recognised” ... we form and loose people w/ quite impressive rate (my two cents)

Summary

- Work for definition of detectors for next high-energy collider is **in full swing**
- **FCC-ee** is gaining momentum also at international level (e.g. P5 endorsement and signing of SoI from US)
- Game of ideas (already at play for most, if not all, e+e- collider options):
  - **Full-silicon** or **ultra-low material** tracking? Calorimeter with **high granularity** or **high energy resolution?** Or both? **Lot of room for improvements!**
- International collaboration in detector R&D being shaped by **ECFA DRD initiative**
- Long time before first collisions
  - …but **big push happening now**! FCC-ee feasibility study + European Strategy update key ingredients for next steps

FCC-ee in pills

	Z pole	WW pole	ZH pole	Top pair pole
Beam energy (GeV)	45.6	80	120	182.5
Beam current (mA)	1270	137	26.7	4.9
Number of bunches	11200	1780	440	60
Luminosity (per IP - 10^{34} cm^{-2} s^{-1})	140	20	5	1.25
Integrated luminosity (per IP - ab^{-1}/year)	17	2.4	0.6	0.15
Planned running time	4	2	3	5

Which translates in

5×10^{12} Z (LEP $\times 10^5$)

$\sim 10^8$ WW (LEP $\times 10^4$)

2×10^6 H unprecedented at e^+e^-

2×10^6 $t\bar{t}$ unprecedented at e^+e^-