Calorimetry for future experiments

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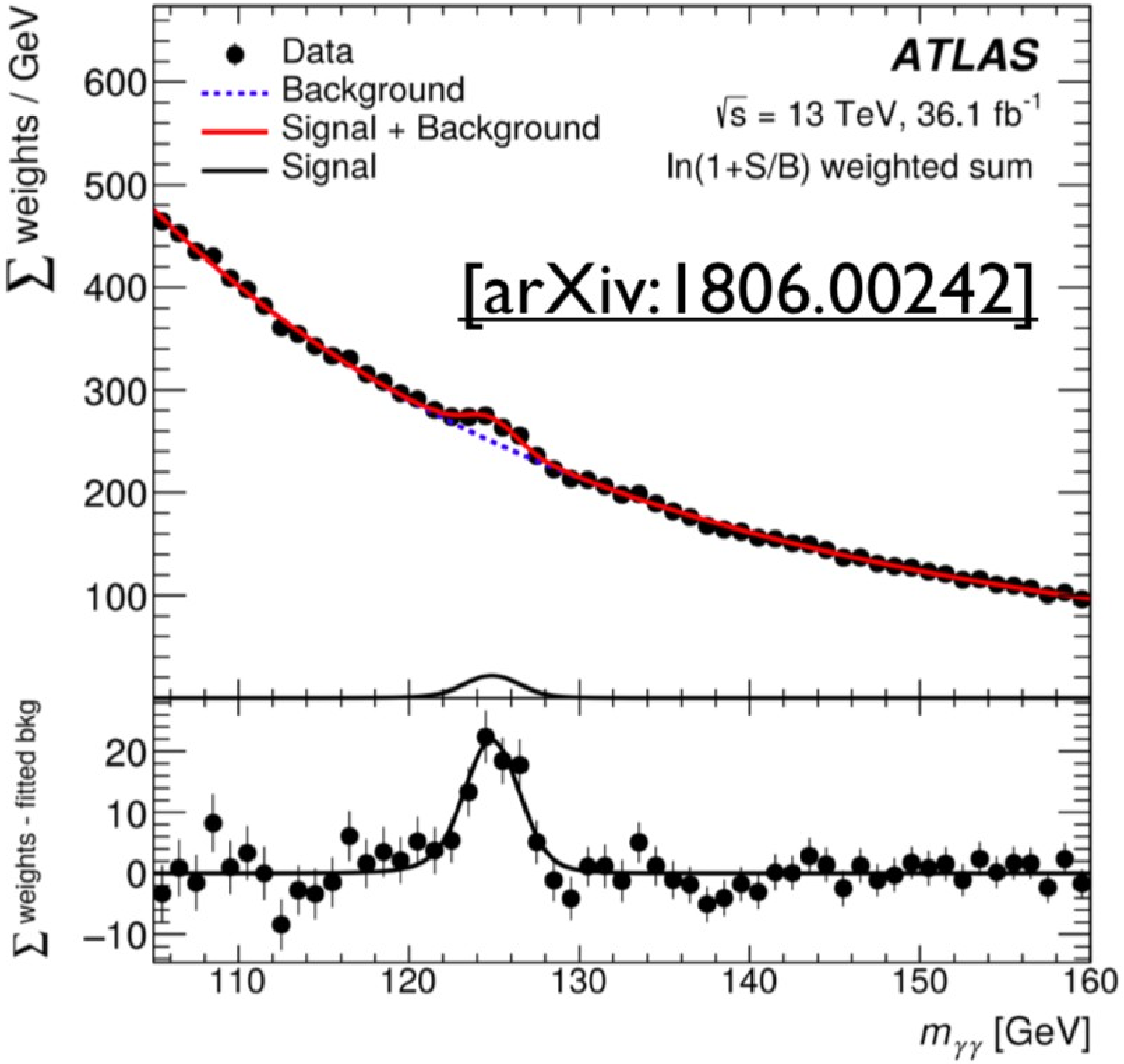
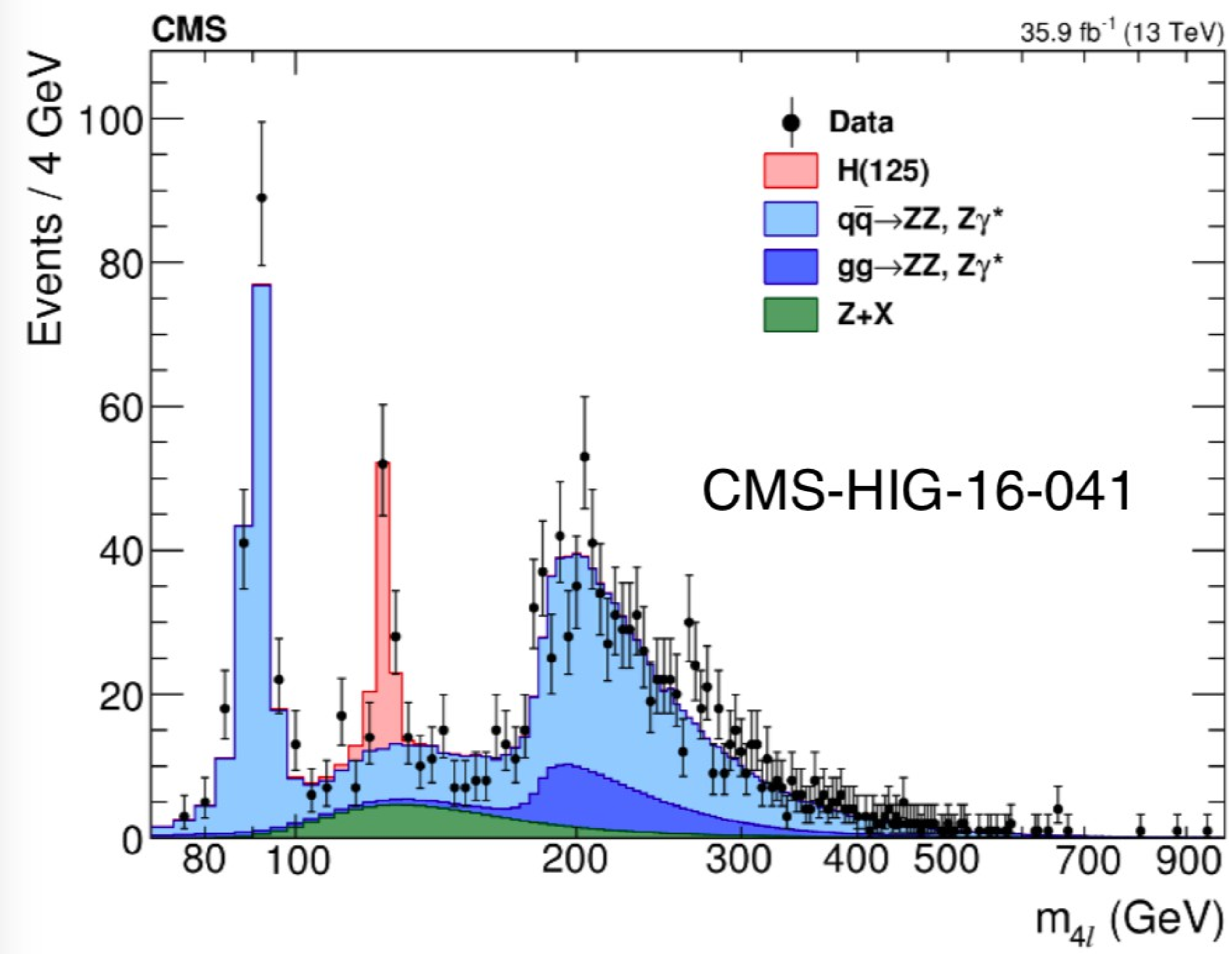
Instrumentation School in Particle, Nuclear and Medical Physics
iThemba LABS Western Cape South Africa– August/September 2023

Calorimeters @ LHC - Examples

H→γγ



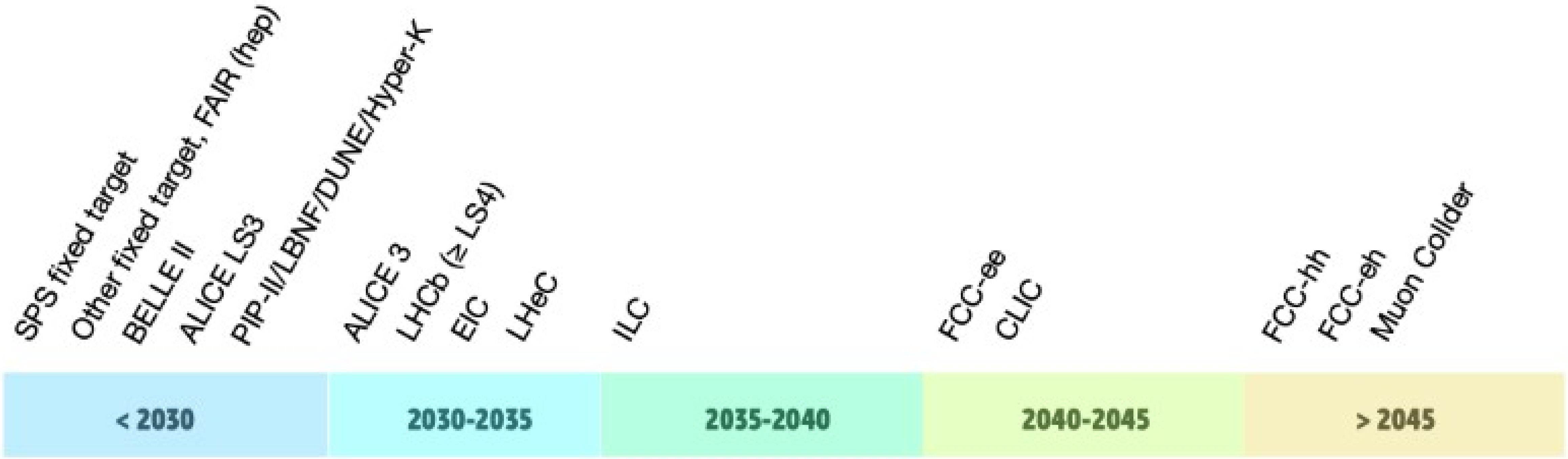
H→ZZ→llll



Higgs discovery based on particles that produce electromagnetic showers
=> Calorimeters played a crucial role for Higgs discovery

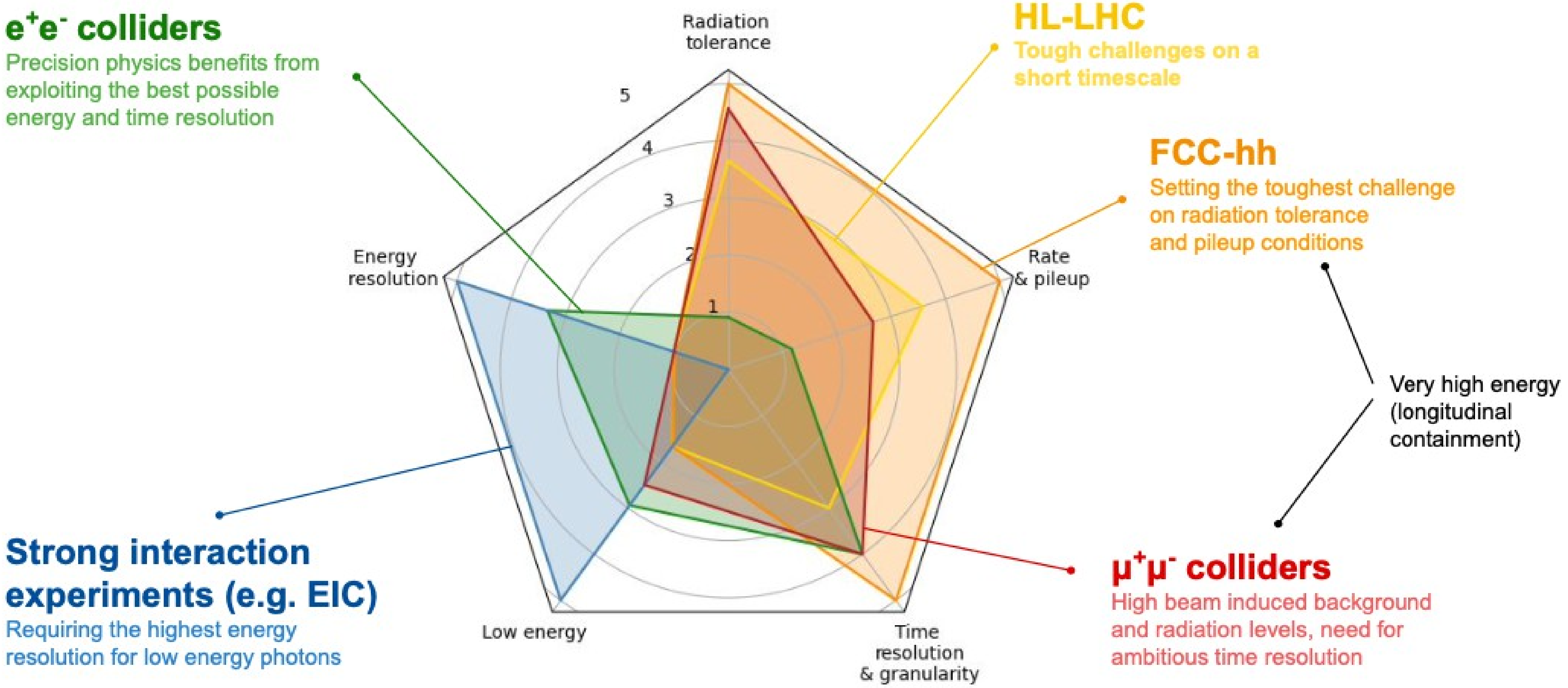
The landscape

- The timeline for future projects and facilities



From ECFA Detector R&D Roadmap (in print)
In sync with Update of European Strategy of Particle Physics (June 2020)

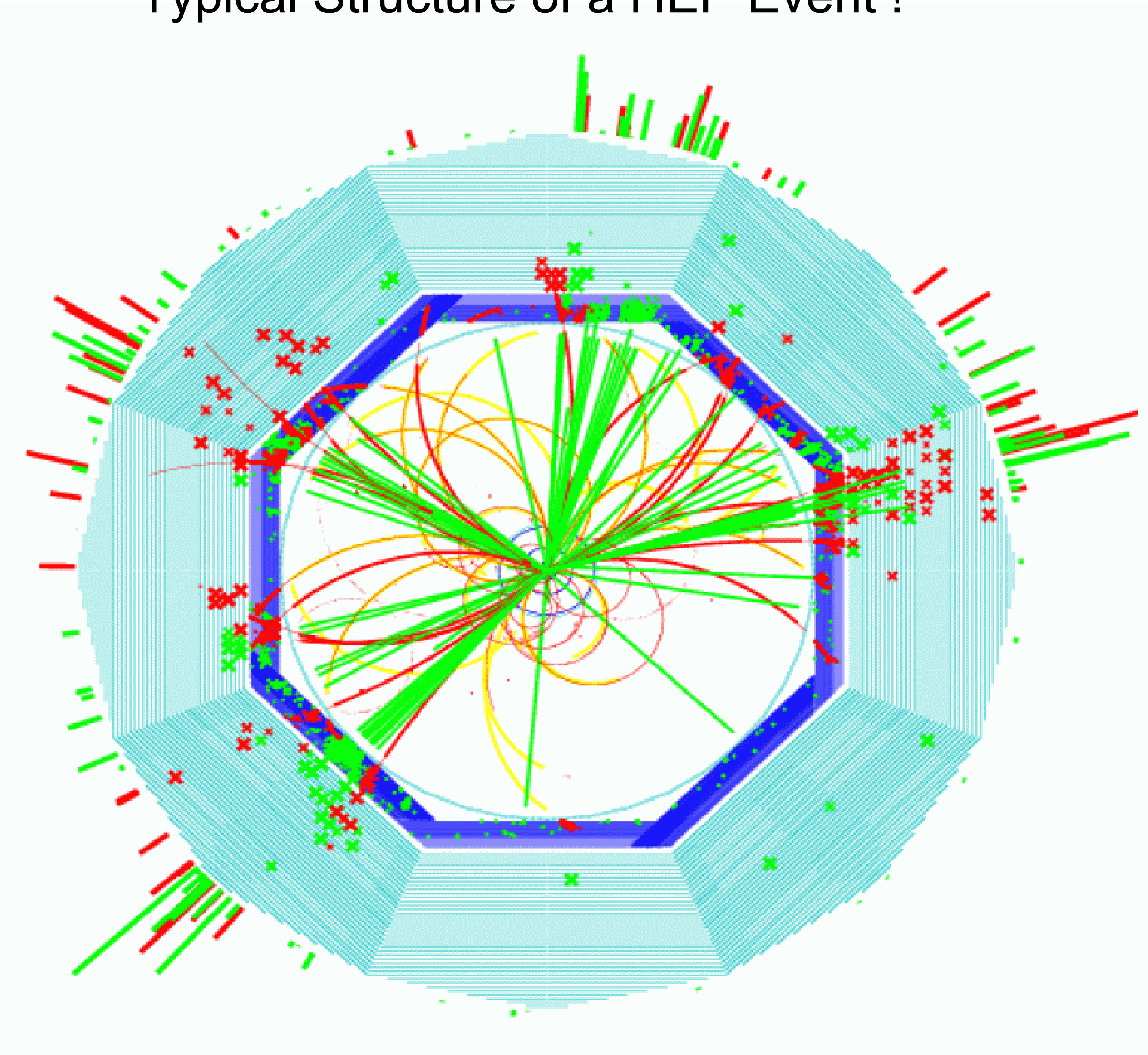
Requirements for calorimetry at future colliders



Inspired from https://indico.cern.ch/event/994685/

Collider Detector – Basic Structure

Event at the LC: …..
Typical Structure of a HEP Event !



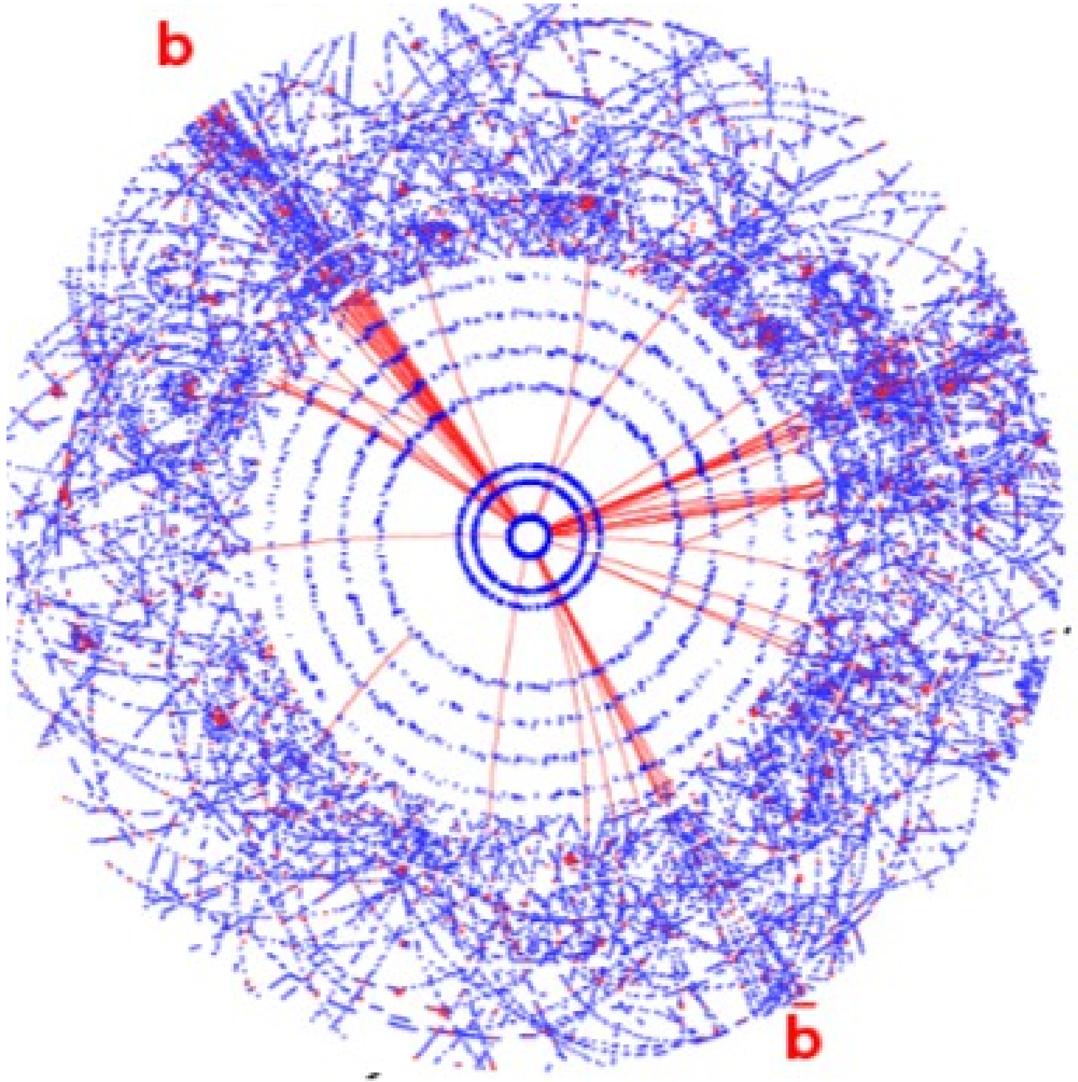
Vertex Detectors
Reconstruction of interaction point and decay vertices

Tracking Detectors
Reconstruction of charged particles in central and forward part

Calorimetry
Energy measurement in the outer (and forward) part
Subdivided in electromagnetic (ECAL) and Hadronic (HCAL) Calorimeters

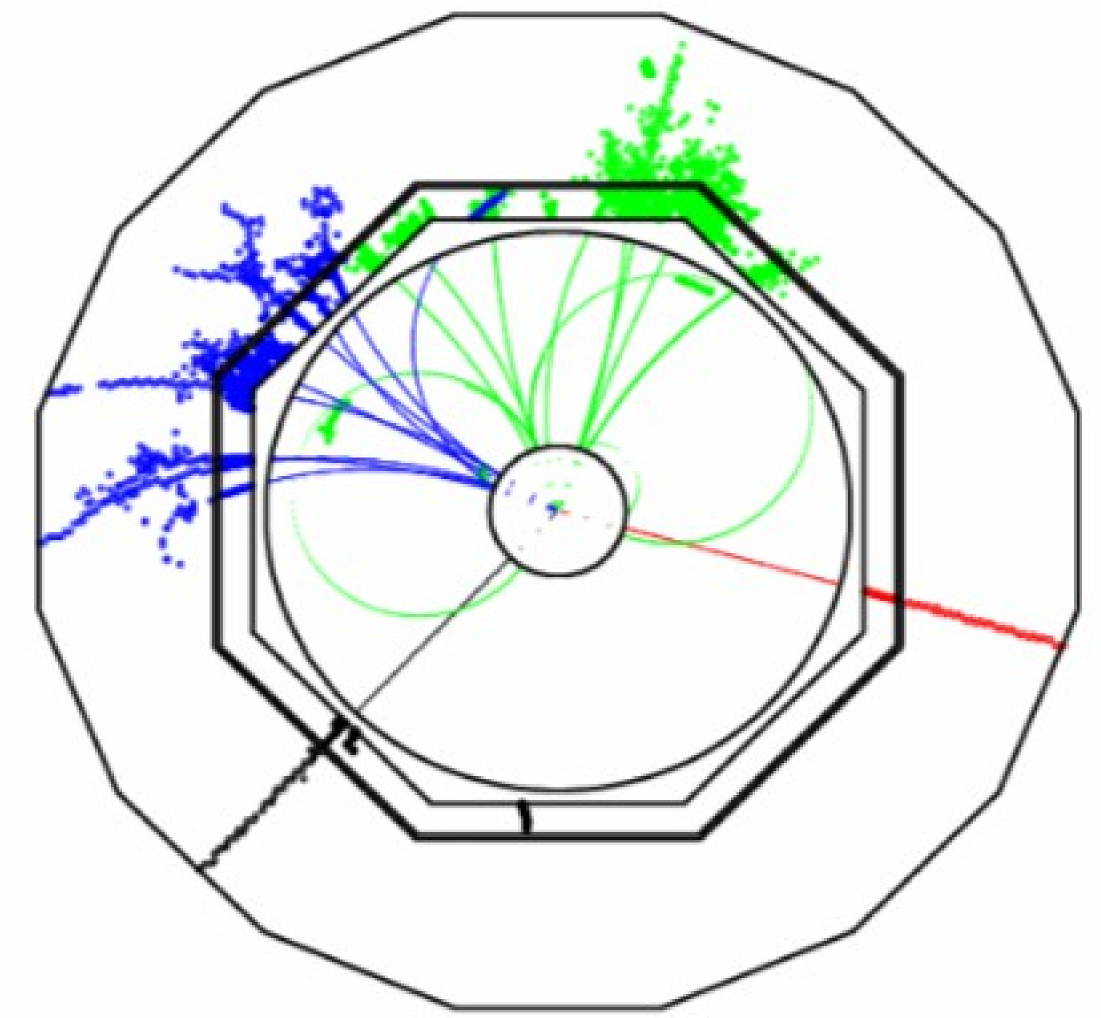
(Rough) Comparison – Hadron collisions ↔ e^+e^- collisions

Hadron-hadron collisions e.g. LHC



- Busy events
- Require hardware and software triggers
- High radiation levels

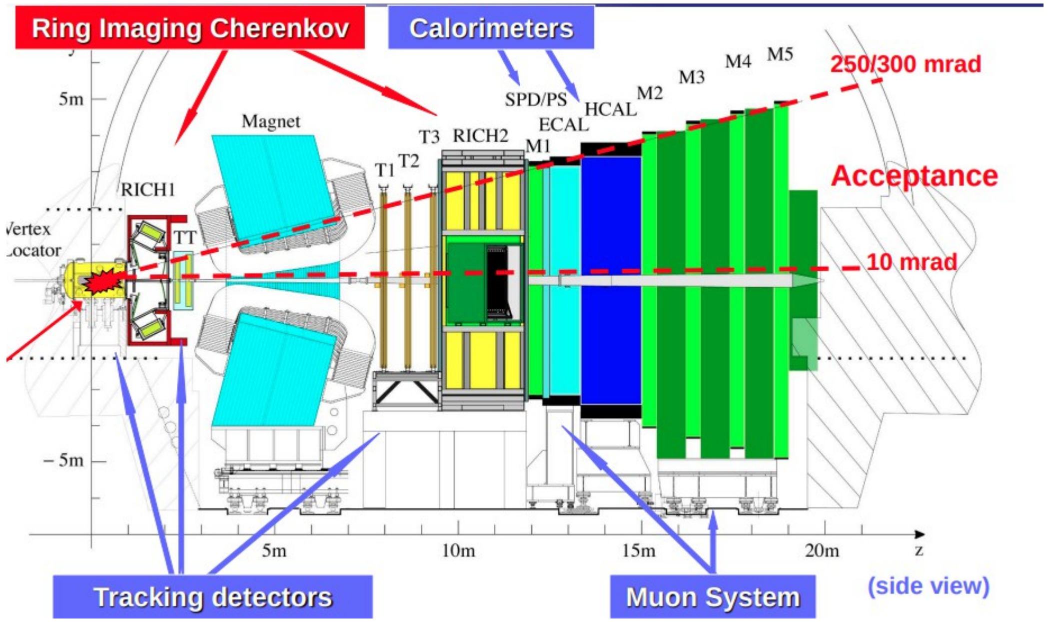
e^+e^--collisions



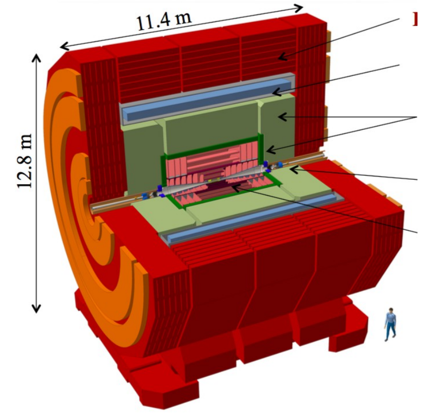
- Clean events
- No trigger
- Full event reconstruction

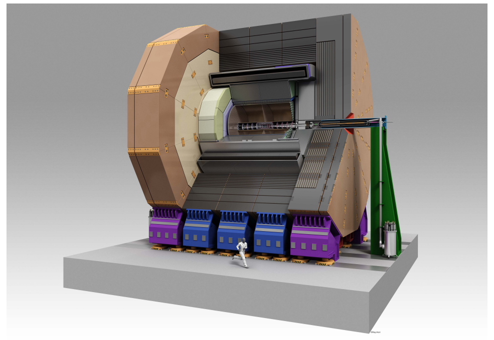
Main Target Projects of Detector R&D

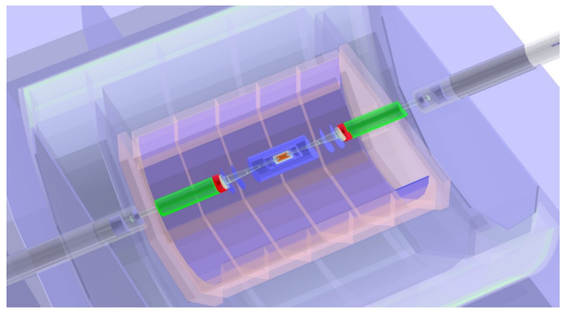
HL-LHC after LS4

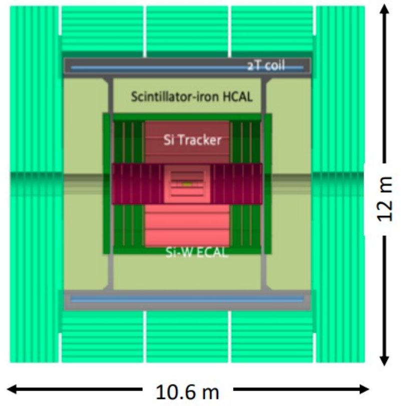


Higgs Factories

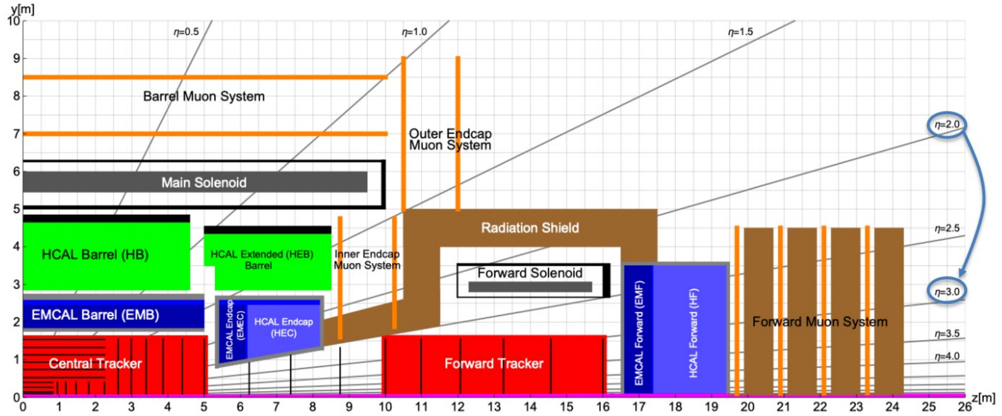




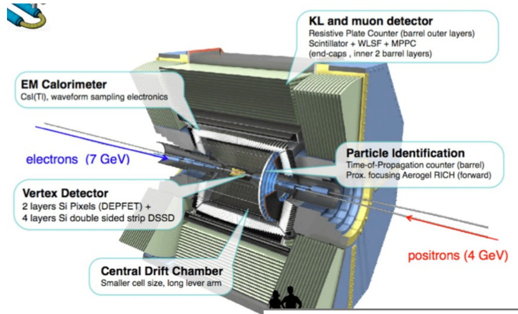


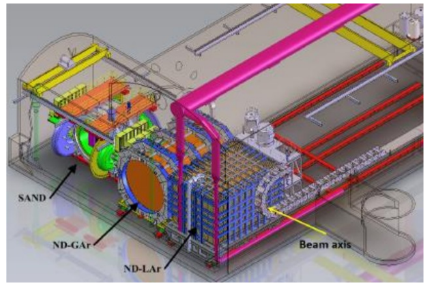


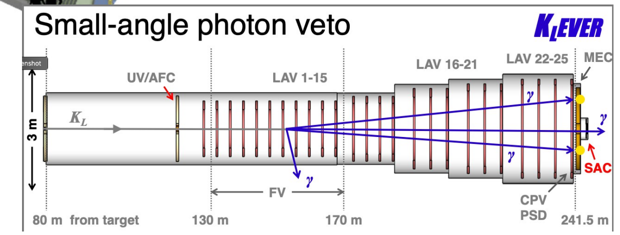
Future hadron colliders (including eh colliders)



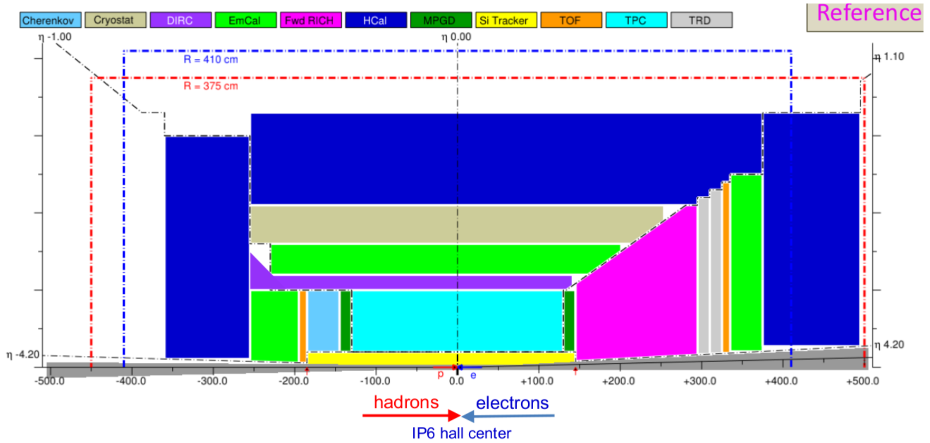
SuperKEKB, DUNE ND and Fixed Target



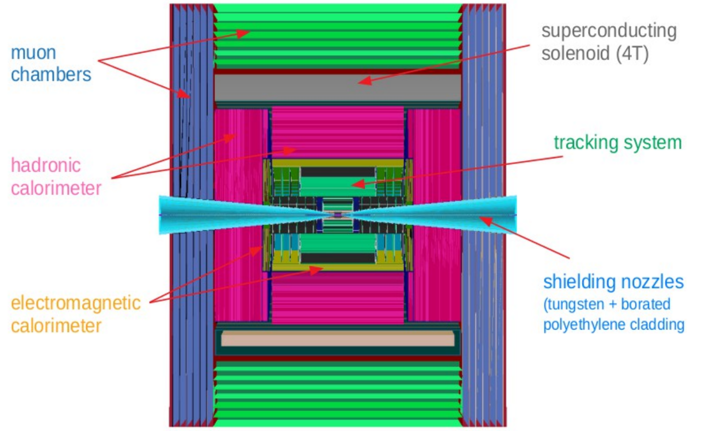




EiC

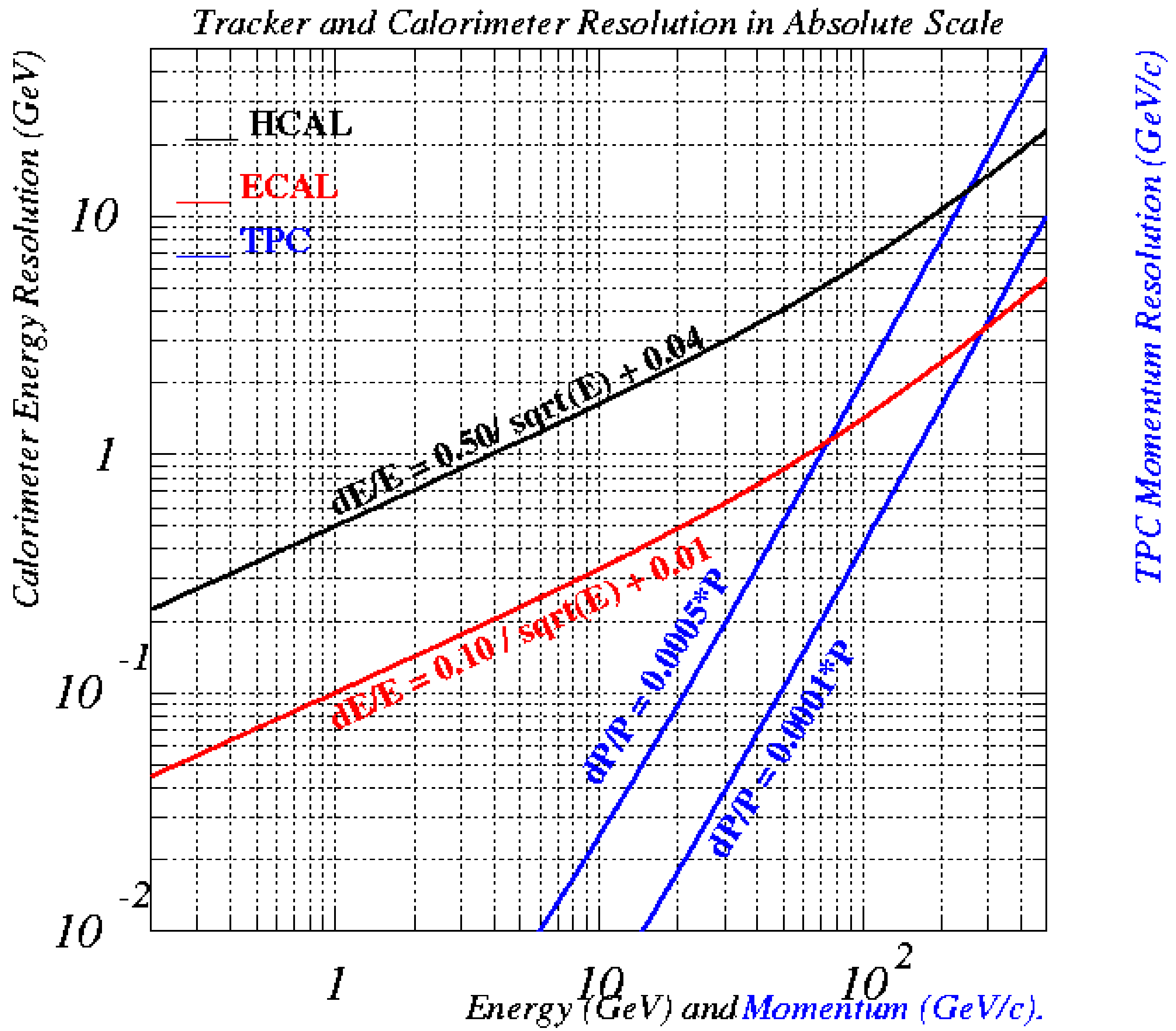


Muon Collider



Jet energy resolution

Final state contains high energetic jets from e.g. Z,W decays
Need to reconstruct the jet energy to the utmost precision !
Goal is around dE_{jet}/E_{jet} - 3-4% (e.g. 2x better than ALEPH)



Jet energy carried by …

- Charged particles (e±, h±,μ±65% :((
  Most precise measurement by Tracker
  Up to 100 GeV
- Photons: 25%
  Measurement by Electromagnetic
  Calorimeter (ECAL)
- Neutral Hadrons: 10%
  Measurement by Hadronic
  Calorimeter (HCAL) and ECAL

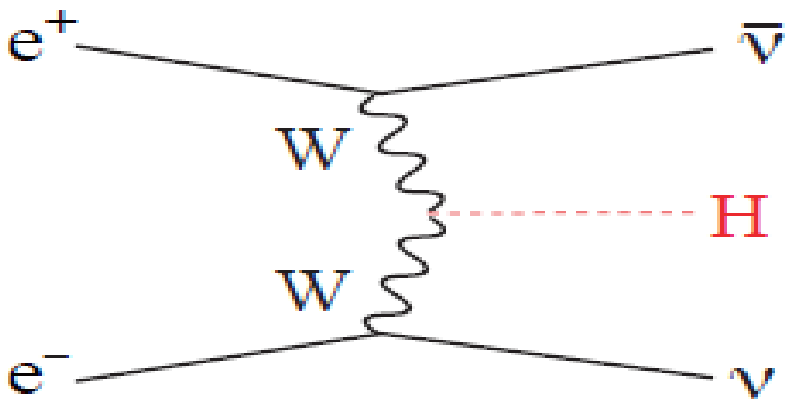
$$\sigma_{Jet} = \sqrt{\sigma^2_{Track} + \sigma^2_{Had.} + \sigma^2_{elm.} + \sigma^2_{Confusion}}$$

Motivation for excellent jet energy resolution

Examples:

- W Fusion with final state neutrinos requires reconstruction of H decays into jets

- Jet energy resolution of ~3% for a clean W/Z separation



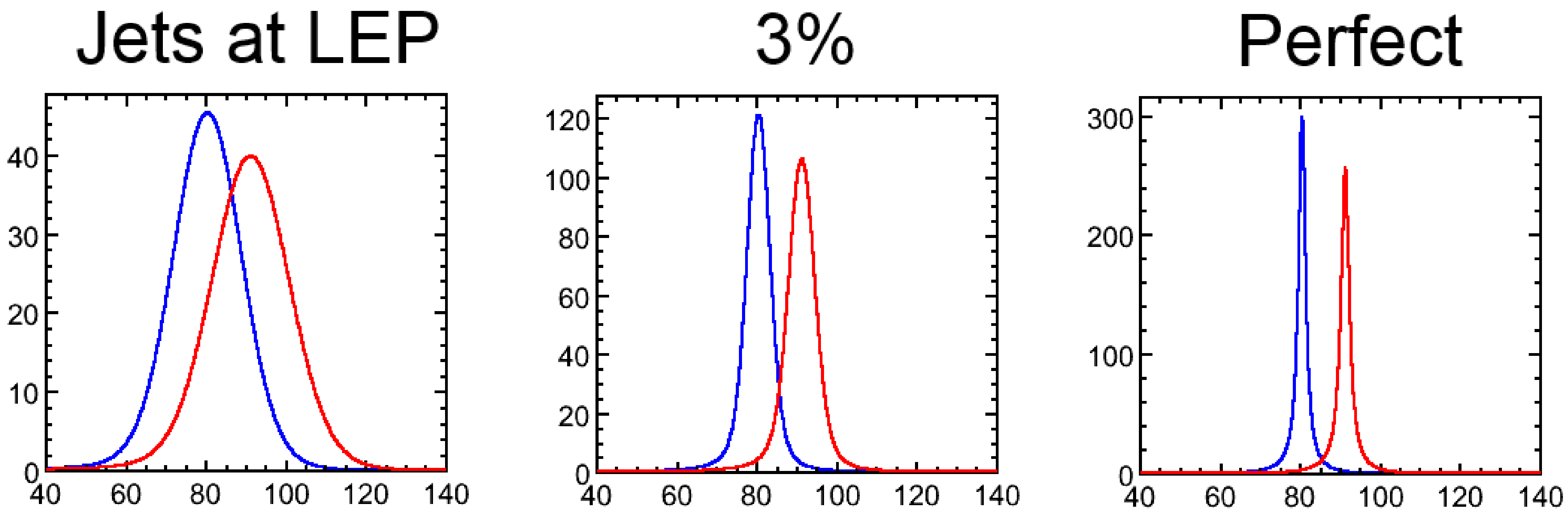
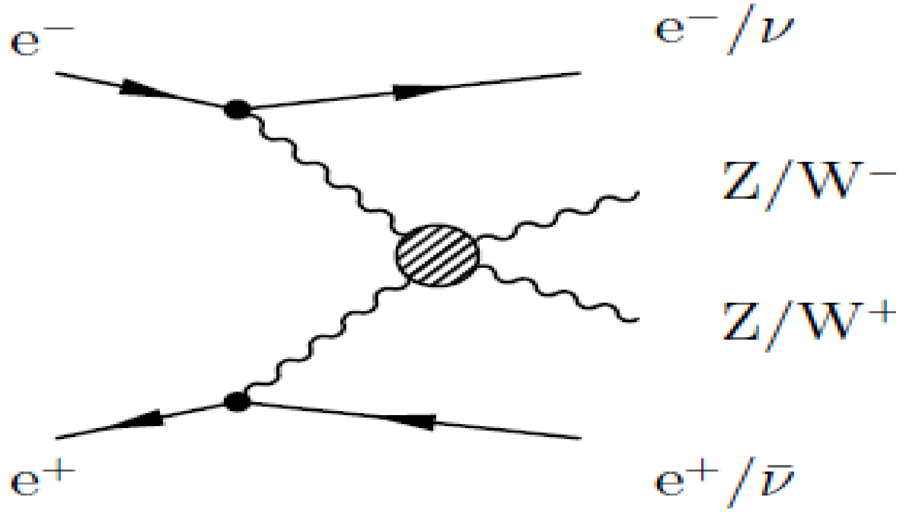


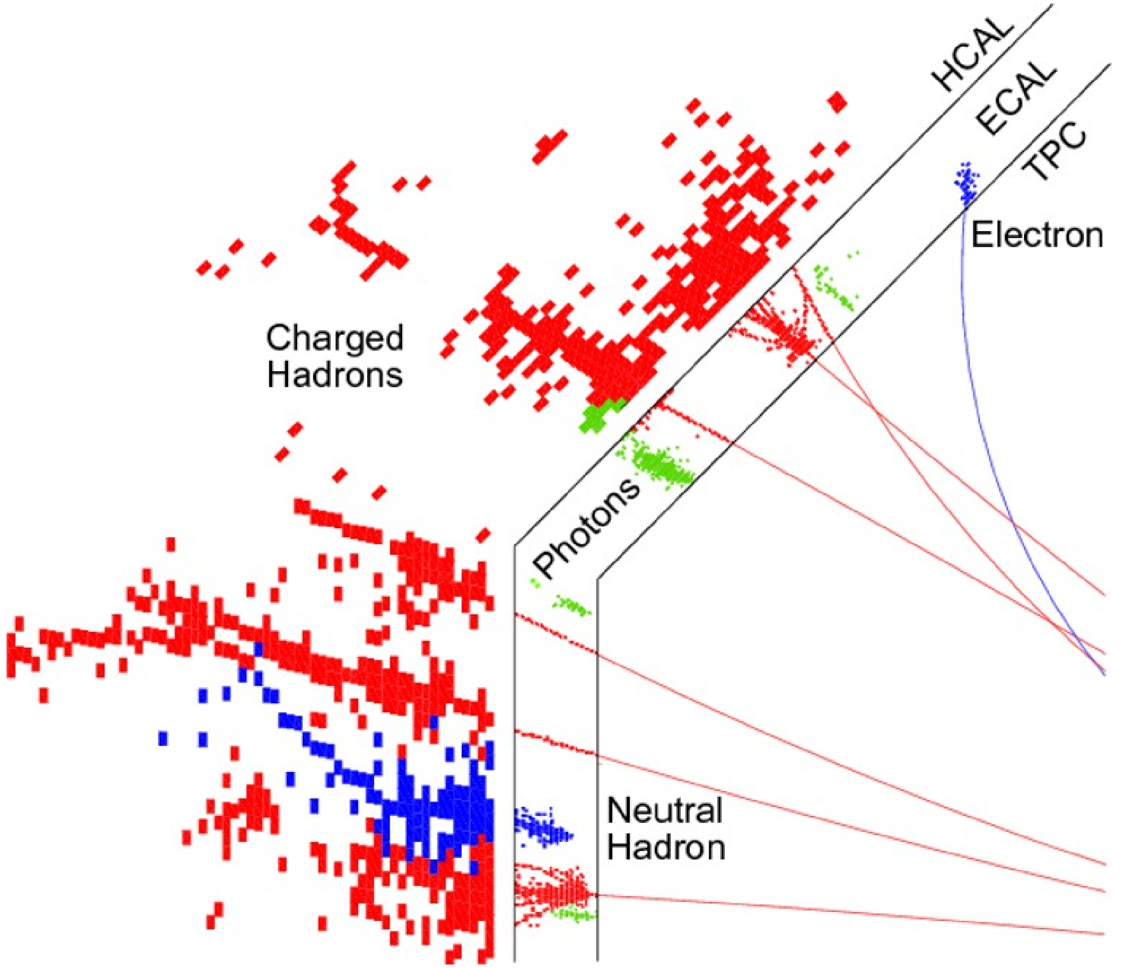
Figure by M. Thomson



Slide: F. Richard at International Linear Collider – A worldwide event

Jet energy resolution

- Particle flow
  - Base measurement as much as possible on measurement of charged particles in tracking devices
  - Separate of signals by charged and neutral particles in **highly granular calorimeters**



- Complicated topology by (hadronic) showers
- Overlap between showers compromises correct assignment of calo hits

→ **Confusion Term**

Need to minimize the confusionterm as much as possible !!!

Particle flow concept leads to calorimeter systems with up to 10^8 calorimeters cells

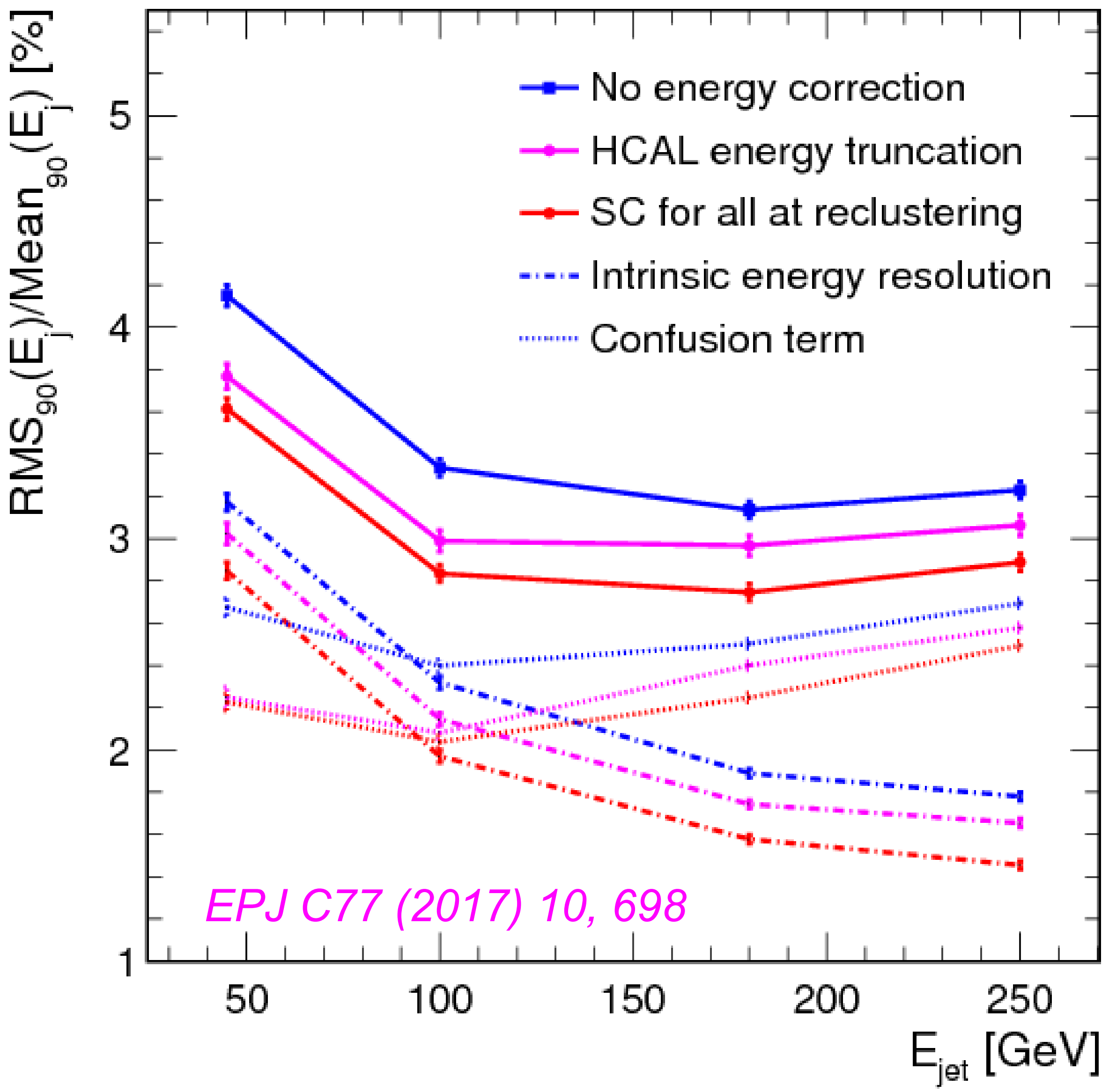
References for development of PFA concept and first comparisons between LEP results and prospects at TESLA/ILC:

J.C. Brient and H.Videau, arXiv:hep-ex/0202004 [hep-ex].

V.L. Morgunov, Proceedings, 10th International Conference, CALOR 2002, Pasadena, USA, March 25-29, 2002, pp. 70--84.

Jet energy resolution

Pandora PFA jet energy resolution



Study within ILD Concept

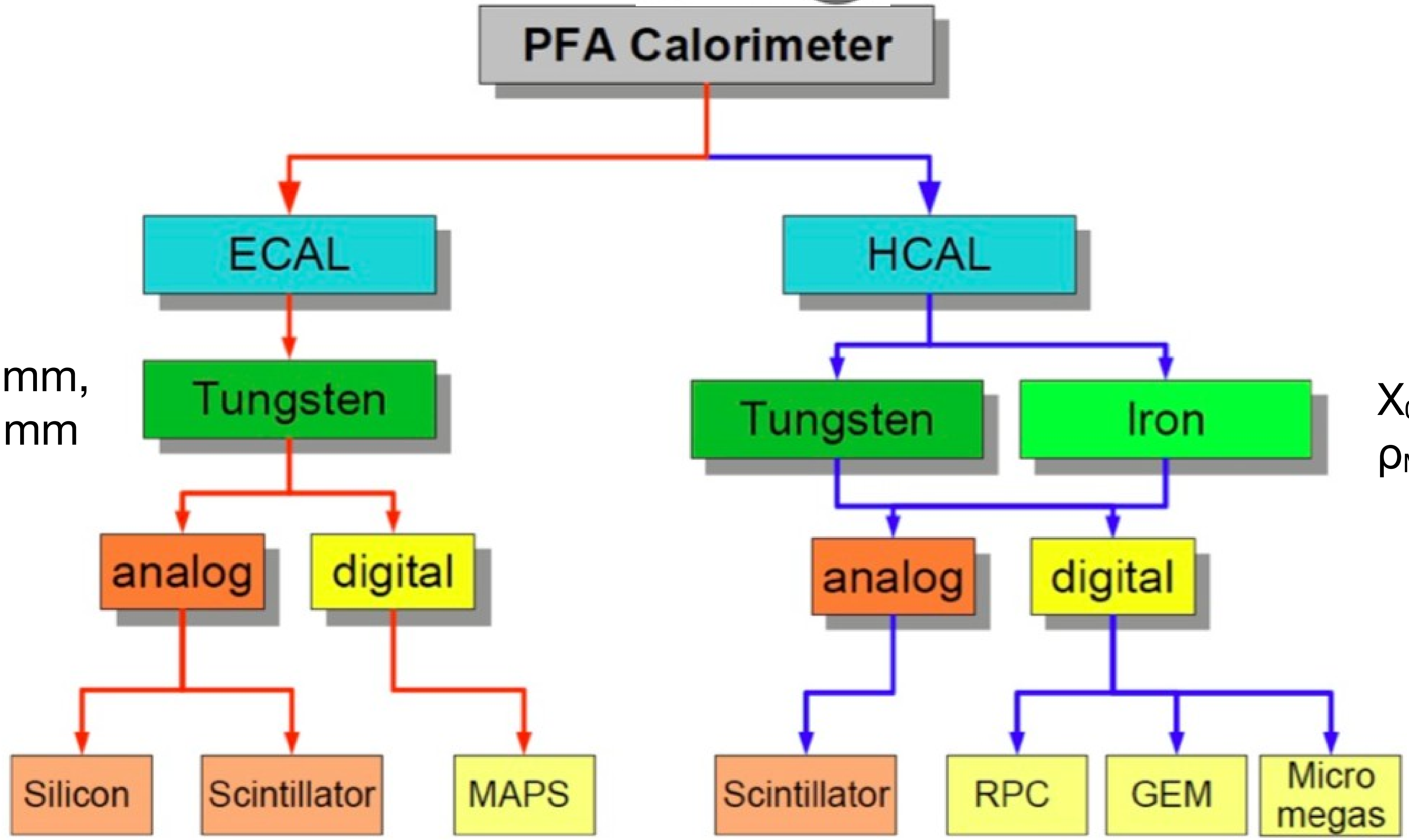
- Design goal: 30%/√E at 100 GeV
  - ~3-4% over entire jet energy range
- At lower energies < 100 GeV resolution is dominated by intrinsic calorimeter resolution
- At higher energies have more particles and higher boost
  - Smaller distance between particles
  - More overlap between calorimeter showers
  - Pattern recognition becomes more challenging

  => Confusion
- Note particularly the gain by software compensation
  - i.e. exploiting the wealth of information available through high granularity

PFAs ARBOR and APRIL are alternatives with similar performance

Calorimeters for PFA

Mainly organised within the CALICE Collaboration



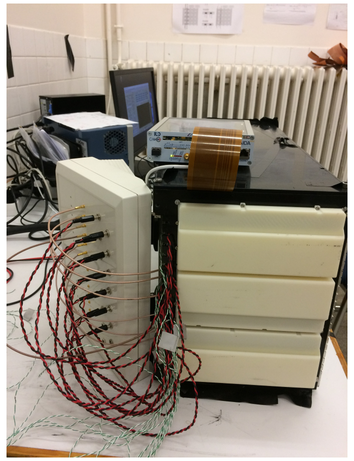
$X_0 \sim 3$ mm, $\rho_M \sim 9$ mm

$X_0 \sim 20$ mm, $\rho_M \sim 30$ mm

All projects of current future high energy colliders propose highly granular calorimeters

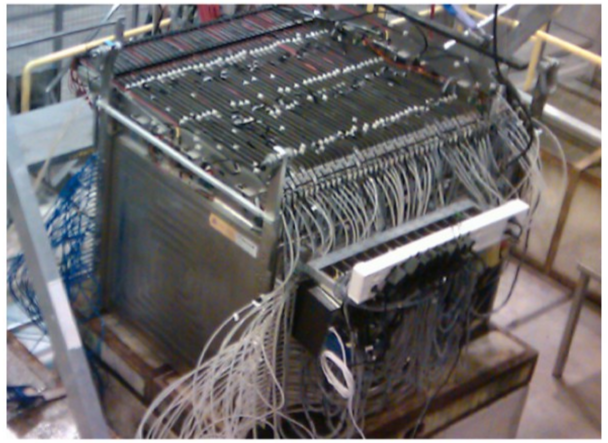
CALICE (Technological) Prototypes

ScECAL



SiECAL

AHCAL



SDHCAL

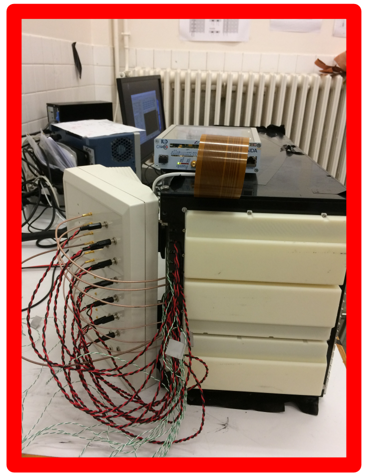
Name	Sensitive Material	Absorber Material	Resolution	Pixel size/mm^3	~Layer size**/cm^3	~Layer depth/X_0	~Layer depth/λ_I	# of Pixels/ layer	# of layers	Comment
ScECAL	Scintillator	W-Cu Alloy	Analogue, 12bit	5x45x2	23x22x0.5	0.73	0.03	210	32	2x16 x and y strips
SiECAL	Si	W	Analogue, 12bit	5.5x5.5x 0.3 (0.5, 0.65)	18x18x 0.24 (- 0.63)	0.6-1.6	0.02-0.06	1024	≥22	Can be run in different configs.
AHCAL	Scintillator	Fe*/W	Analogue, 12bit	30x30x3	72x72x2/ 1.4	1/2.9	0.11	576	38	Running with Fe and W
SDHCAL	Gas	Fe*	Semi-digital 2bit	10x10x6	100x100x 2.6	1.1	0.12	9216	48	

*Stainless Steel

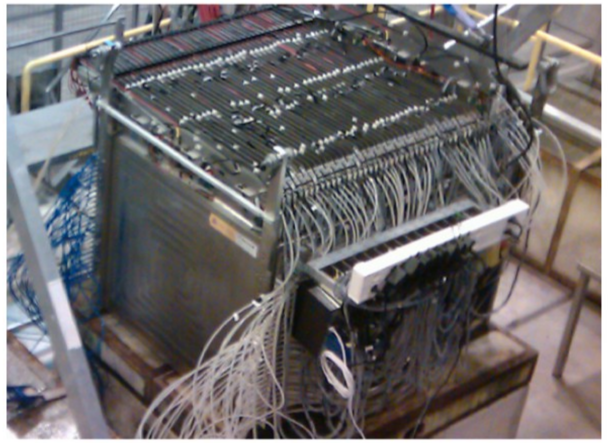
**Only absorber + sensitive material for z direction, air gaps, electronics discarded here (would add 5-10%)

CALICE (Technological) Prototypes


ScECAL


SiECAL


AHCAL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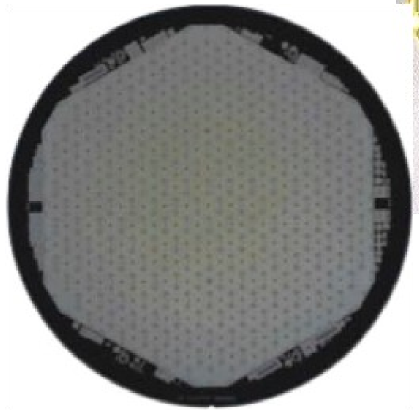
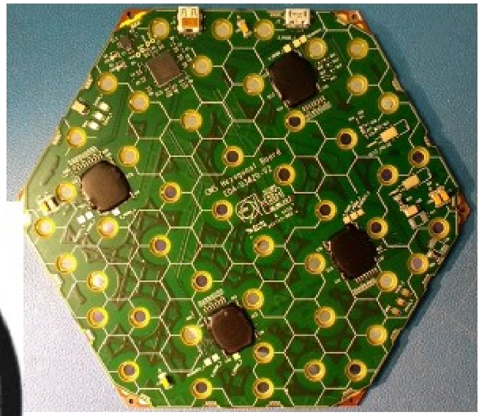
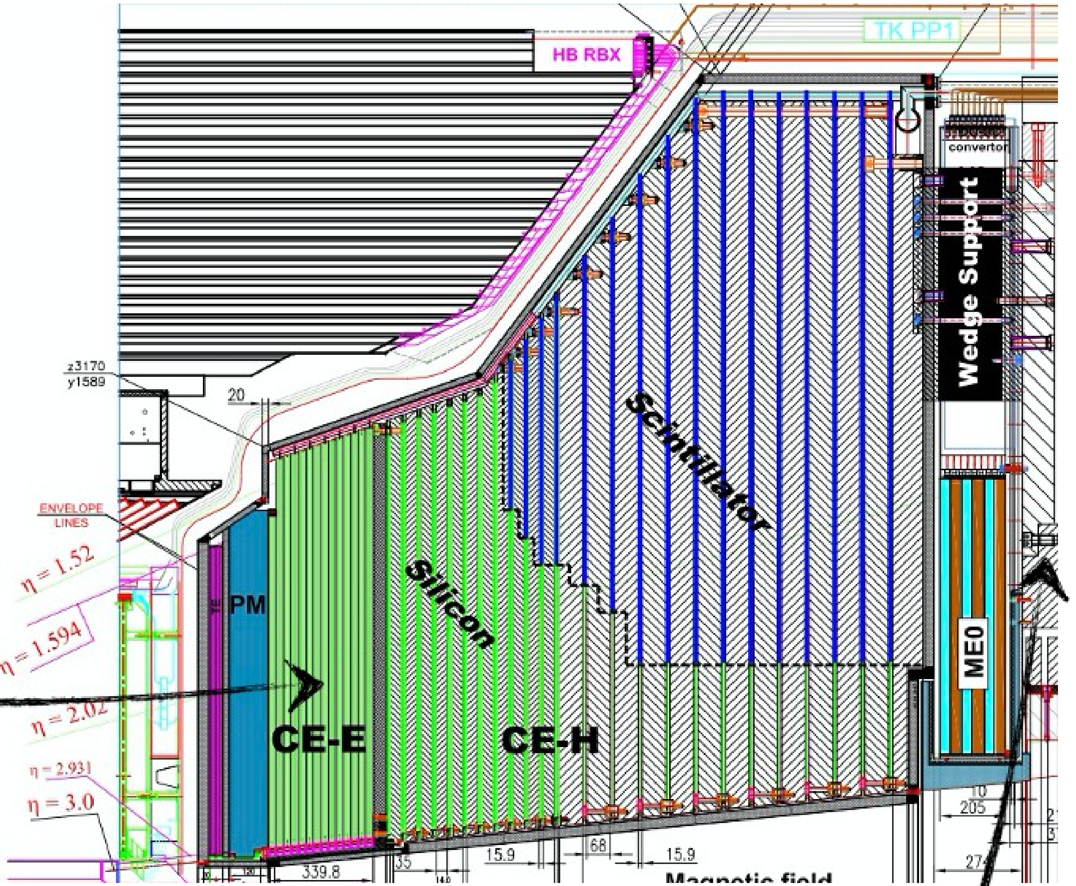
First Application in CMS

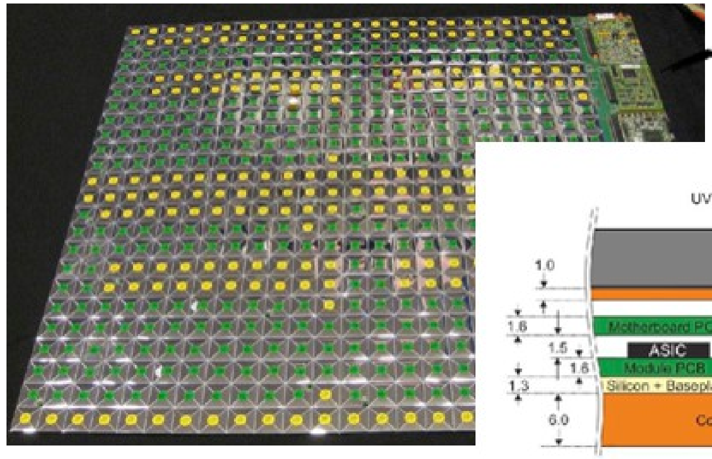
- The developments in CALICE have paved the way for a number of applications of highly granular calorimeters and related technologies in HEP

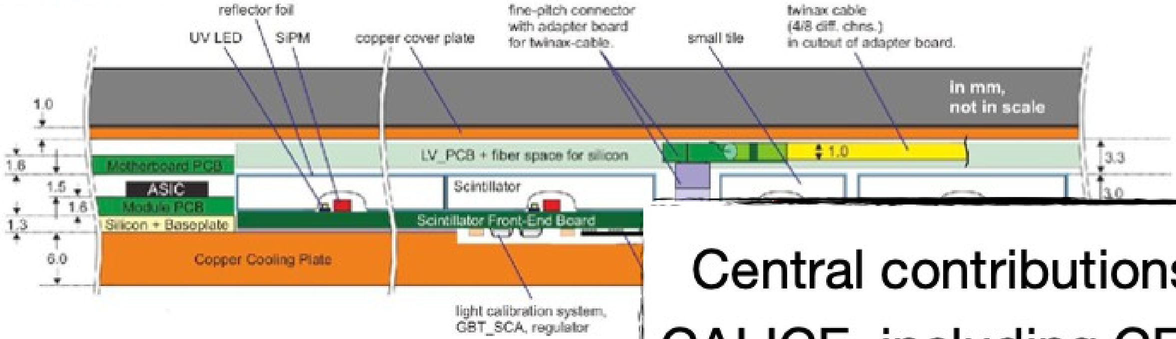
Most prominent: The CMS Endcap Calorimeter Upgrade HGCal







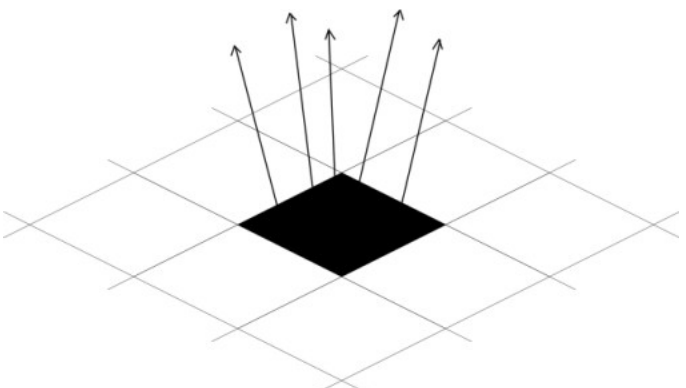




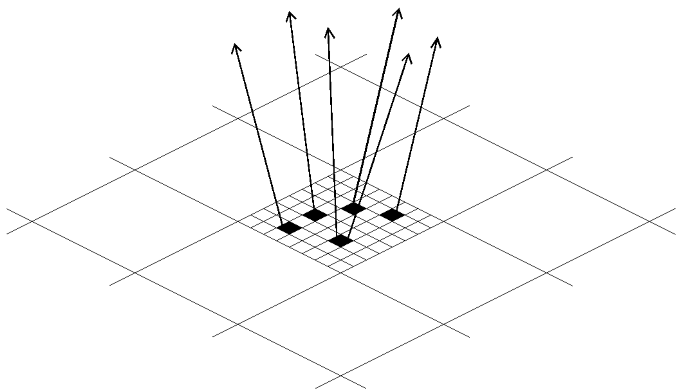
Central contributions by groups very active in CALICE, including CERN, DESY, LLR, OMEGA.

F. Simon

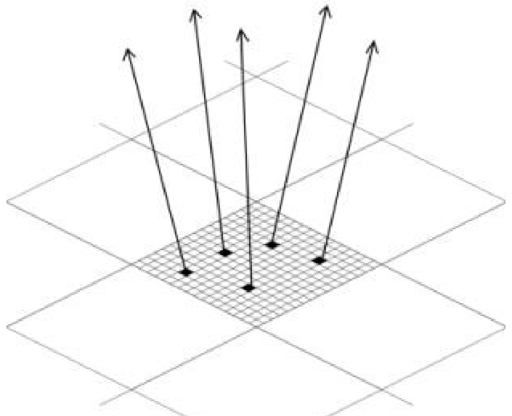
New Trends – Ultra High Granularity



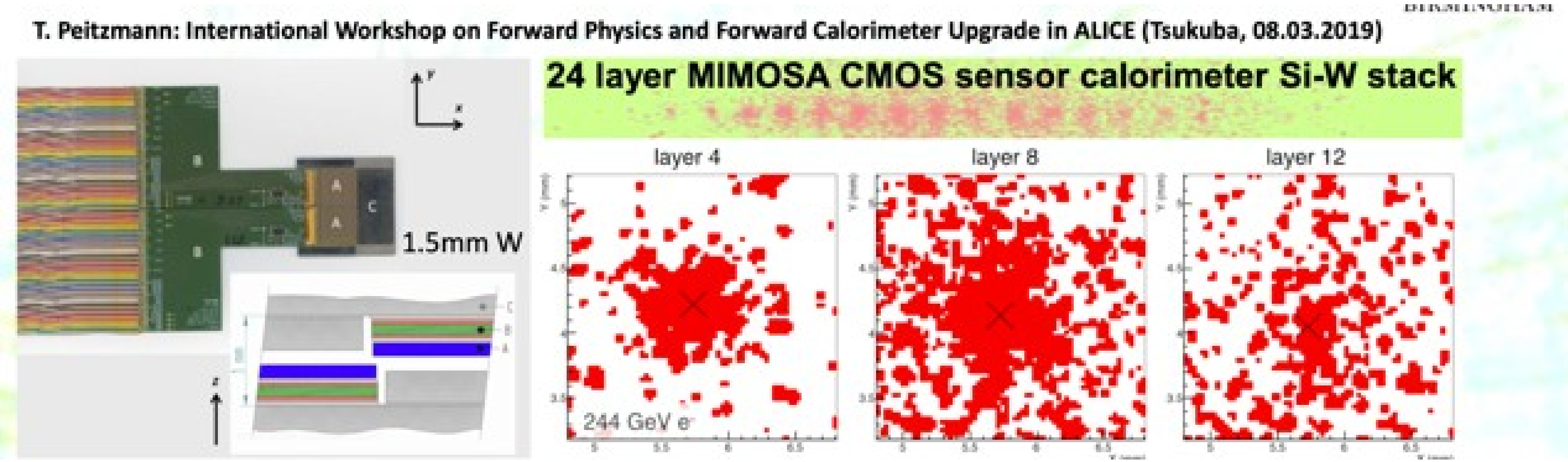
AECAL
Npixels<Nparticles



DECAL



DECAL
Npixels=Nparticles

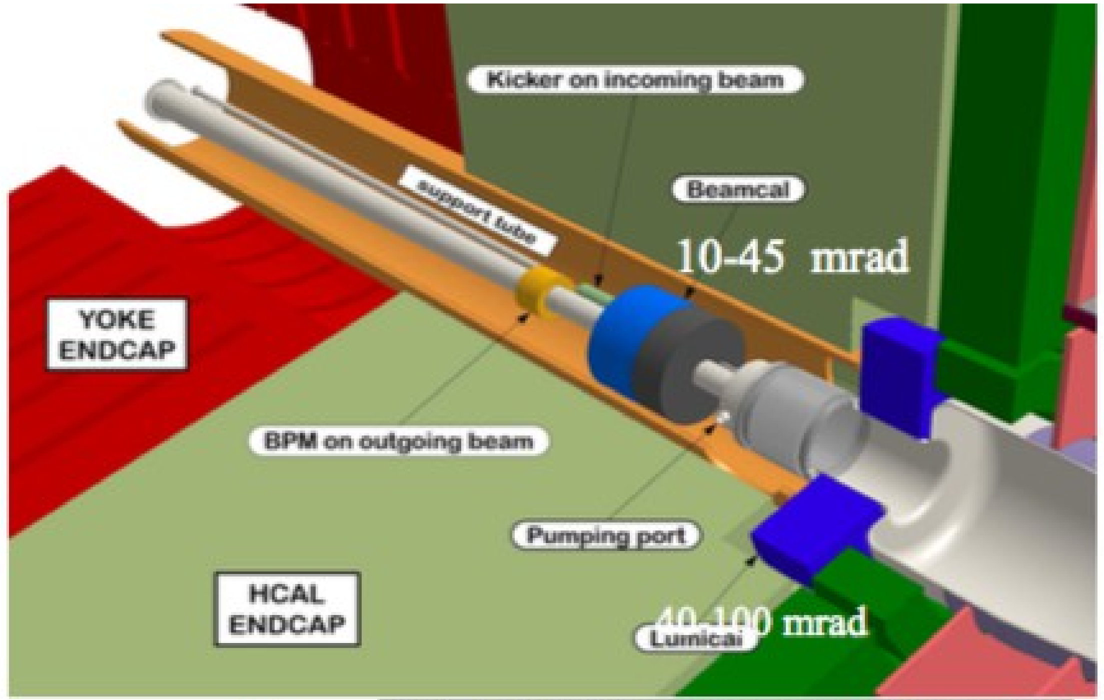


- CMOS Sensors for calorimetric approaches

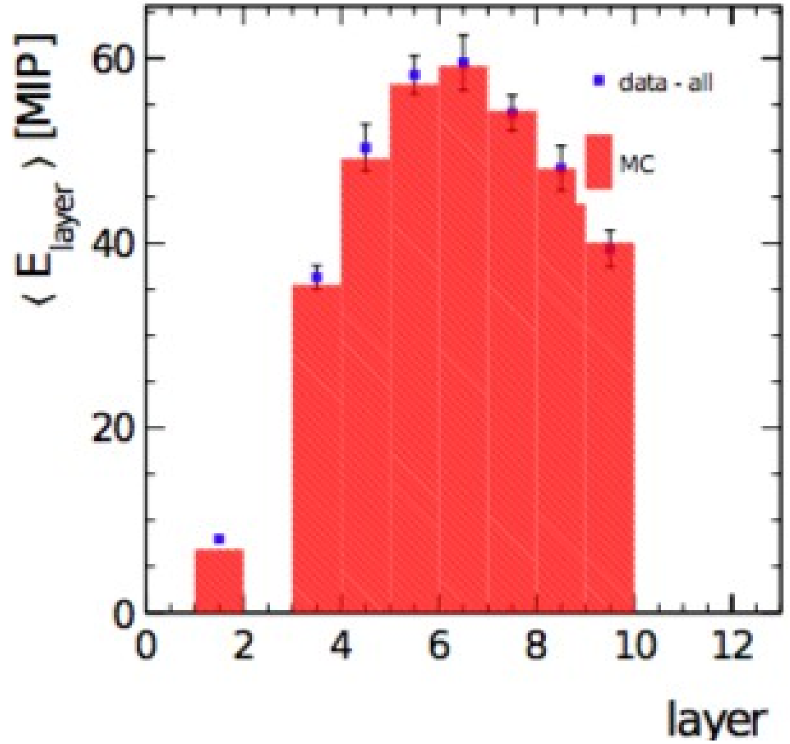
Forward calorimeters

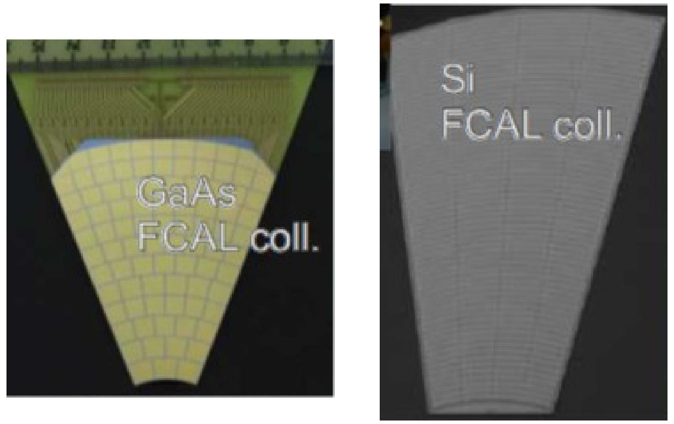
Forward calorimetry R&D for LC by FCAL:
LumiCal for measurement of luminosity (to a few permille as goal)

- BeamCal for very forward e or γ tagging
- Evaluating different r/o technologies
  - Radiation hardness
  - 2014 testbeam analysis finalized
    arXiv:1705.03885

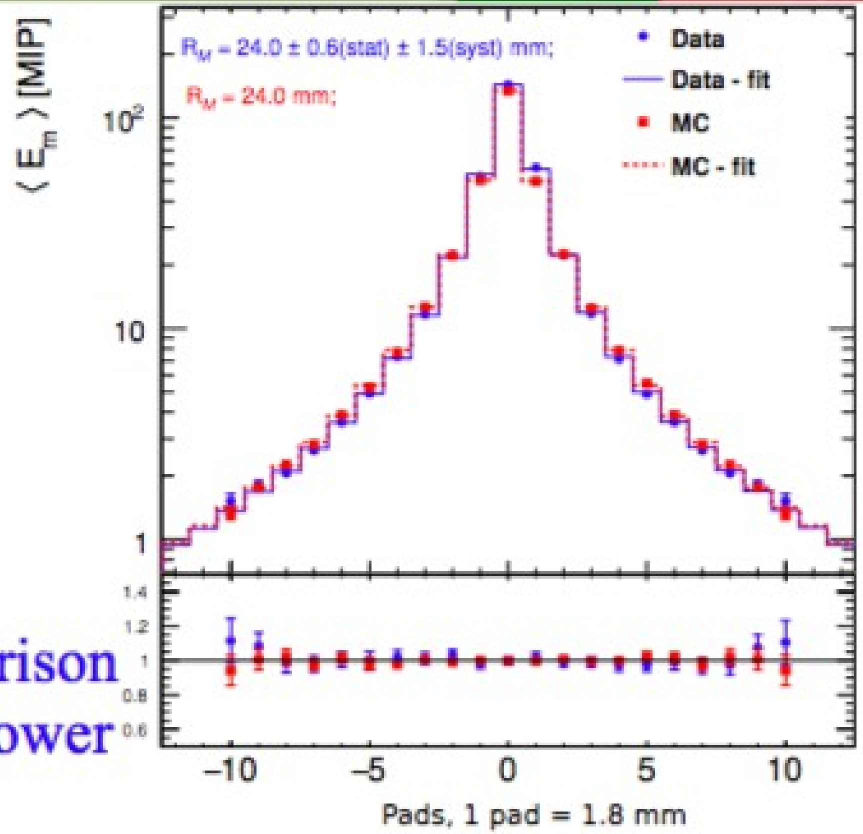


Data-MC comparison of longitudinal shower profile





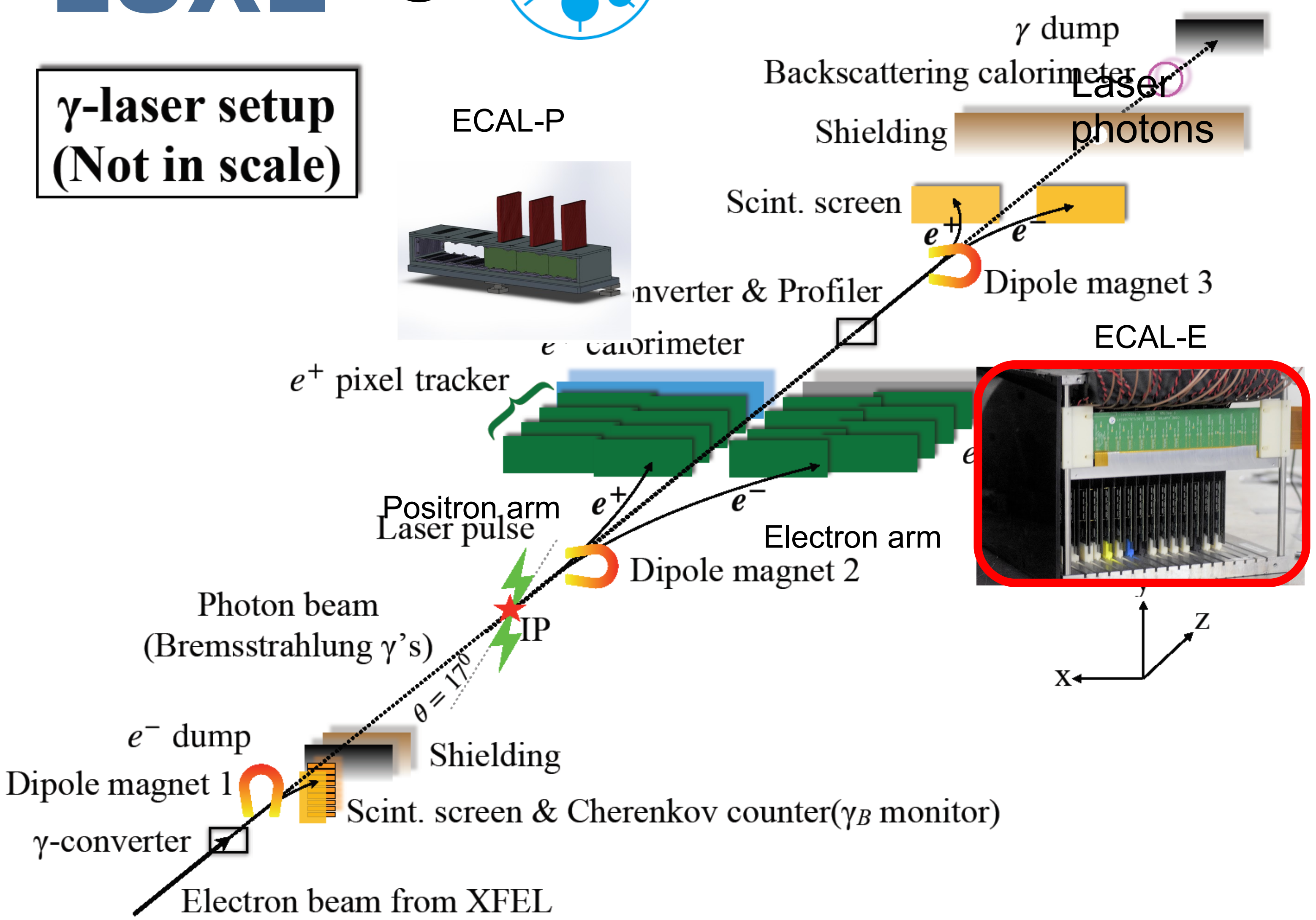
Semi-conductor counters



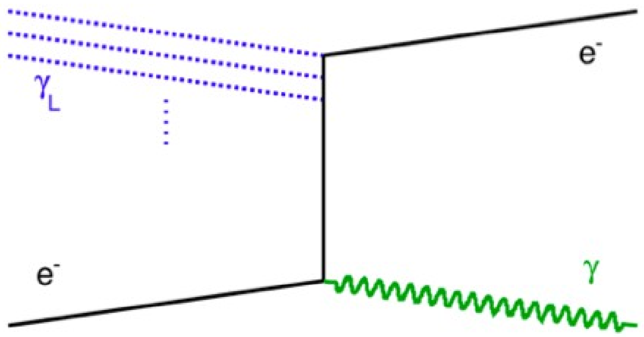
Data-MC comparison for transverse shower profile

Granular Calorimeters and Small Scale Experiments

LUXE @ DESY

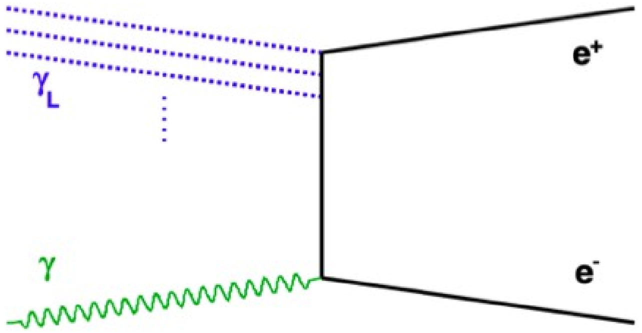


Compton scattering



Breit-Wheeler Process

Laser photons



- Goal of LUXE is to test QED in extreme environment using the DESY XFEL Beam
- Upshot for this lecture: Technologies introduced in previous slides ca also be applied in small experiments
  - ... Including the detector you're going to work with this afternoon
- What about experiments at iThemba LABS?

Future Noble Gas Calorimeters

- LAr Calorimetry is proven technology since a few decades
  ATLAS, H1, DO, NA31

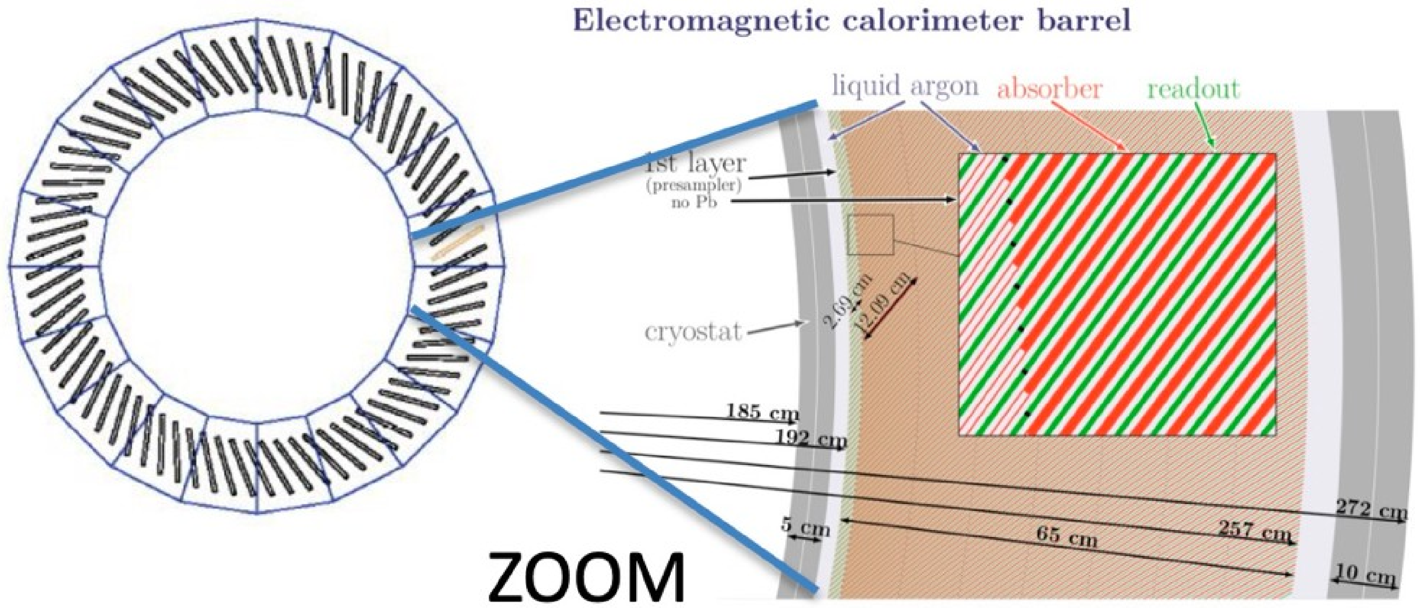
- Challenge is to make the technology “fit” for future hadron and lepton machines

- Design is driven by particle flow
  - ATLAS Jet-Energy resolution based on PFA
  - ~24% at 20 GeV and 6% at 300 GeV

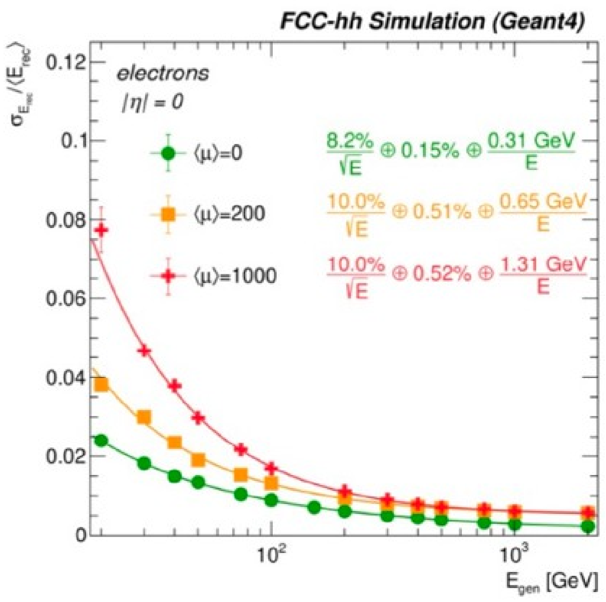
- => Increase of granularity
  - Goal: Factor ~10 w.r.t. ATLAS LAr Calorimeter
  - 220 kCells -> ~2 MCells

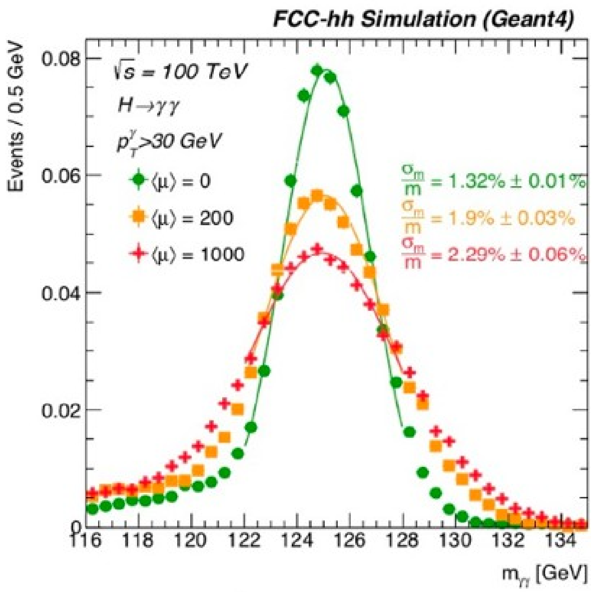
ATLAS LAr calorimeter

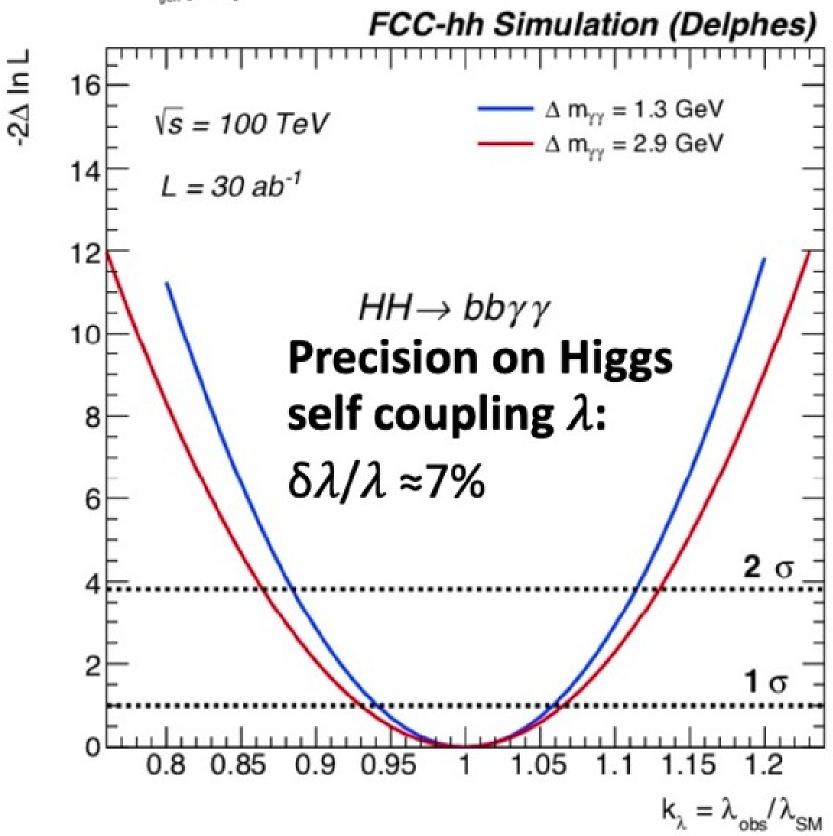
Example FCC-hh



- 2 mm absorber plates inclined by 50° angle;
- LAr gap increases with radius: 1.15 mm–3.09 mm;
- 8 longitudinal layers (first one without lead as a presampler);
- $\Delta\eta = 0.01$ (0.0025 in 2nd layer);
- $\Delta\varphi = 0.009$;



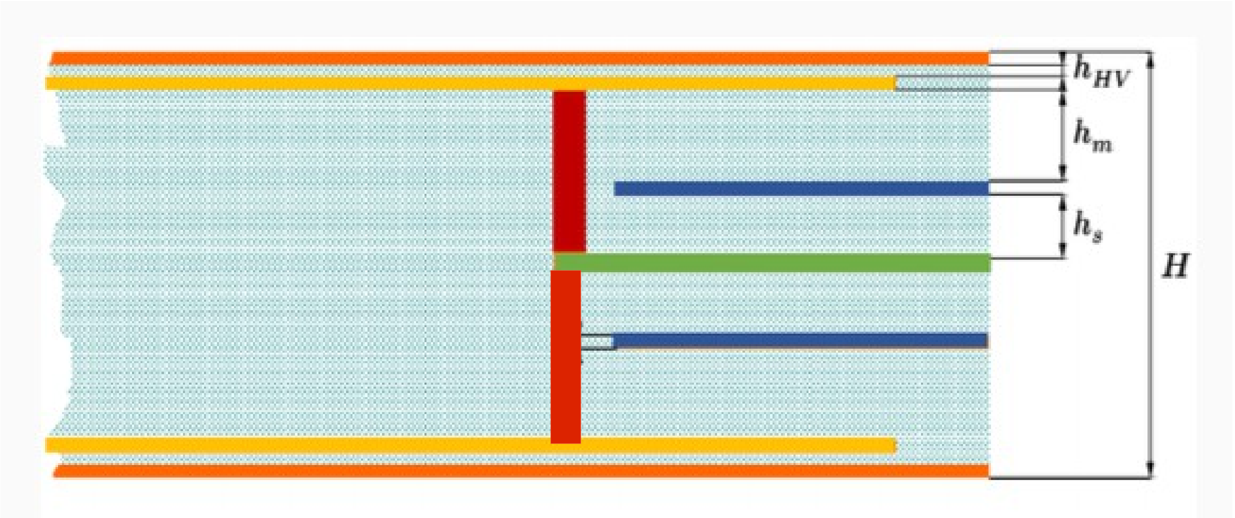




- **CDR Reference Detector: Performance & radiation considerations → LAr ECAL, Pb absorbers**
  - Options: LKr as active material, absorbers: W, Cu (for endcap HCAL and forward calorimeter)
- **Optimized for particle flow: larger longitudinal and transversal granularity** compared to ATLAS
  - 8-10 longitudinal layers, fine lateral granularity ($\Delta\eta \times \Delta\phi = 0.01 \times 0.01$, first layer $\Delta\eta=0.0025$),
  - → ~2.5M read-out channels
- Possible only with **straight multilayer electrodes**
  - Inclined plates of absorber (Pb) + active material (LAr) + multilayer readout electrodes (PCB)
  - Baseline: warm electronics sitting outside the cryostat (radiation, maintainability, upgradeability),
    - Radiation hard cold electronics could be an alternative option
- **Required energy resolution achieved**
  - Sampling term ≤ 10%/$\sqrt{E}$, only ≈300 MeV electronics noise despite multilayer electrodes
  - Impact of in-time pile-up at <μ> = 1000 of ≈ 1.3GeV pile-up noise (no in-time pile-up suppression)
  - →Efficient in-time pile-up suppression will be crucial (using the tracker and timing information)

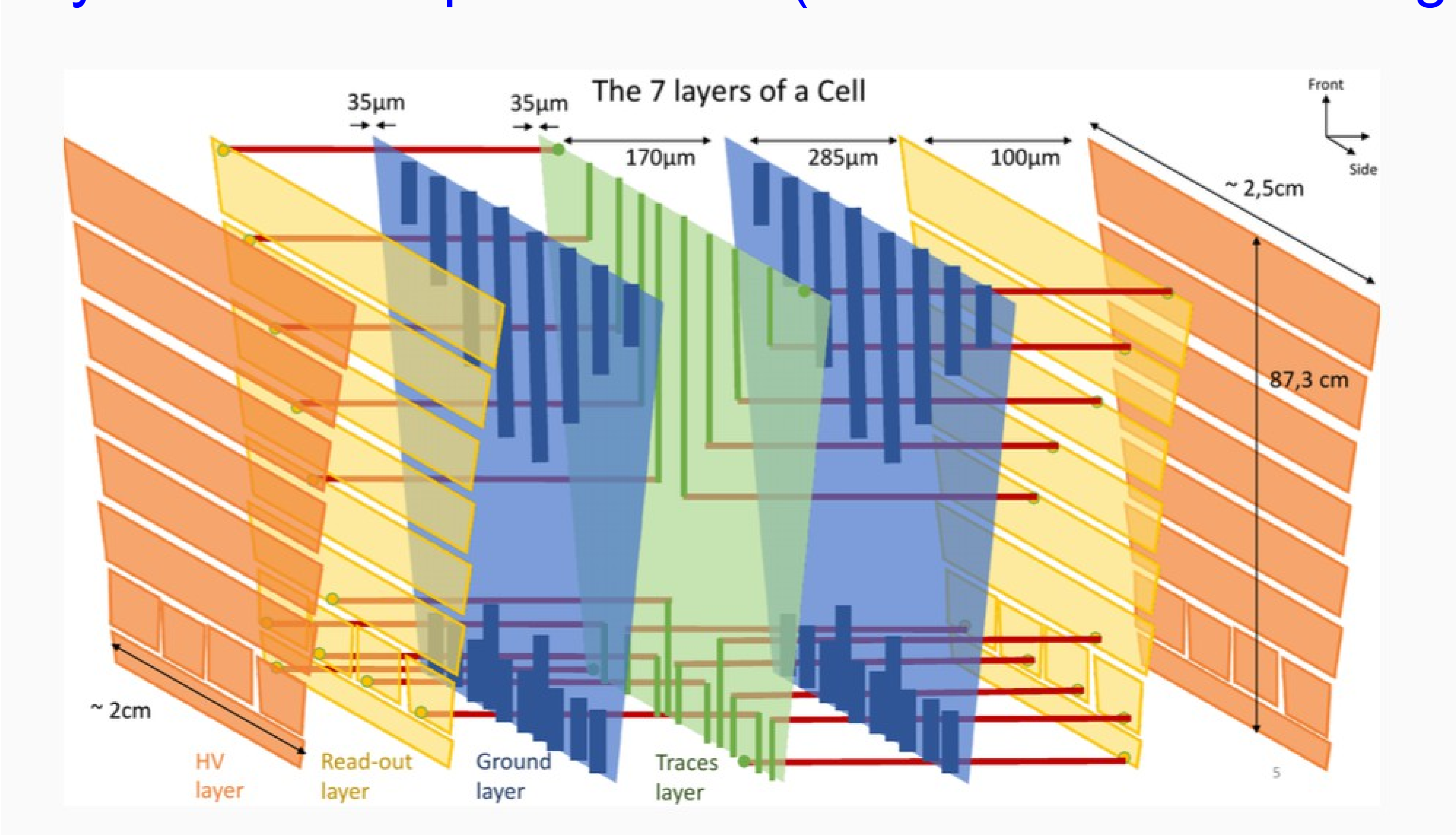
Future Noble Gas Calorimeters – How to increase the granularity

- Development of a multilayer PCB
  - HV Layer on both sides
  - Readout layer on both sides
  - Connected to signal trace



- One signal trace is economical solution to reduce signal traces
- Pick-up of signal from both sides increases S/N

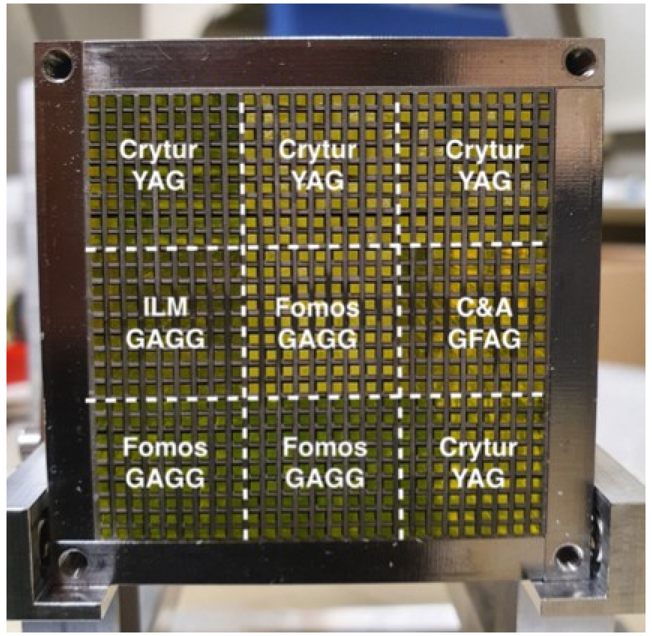
Multilayer PCB – Exploded view (attention FCC-hh design)

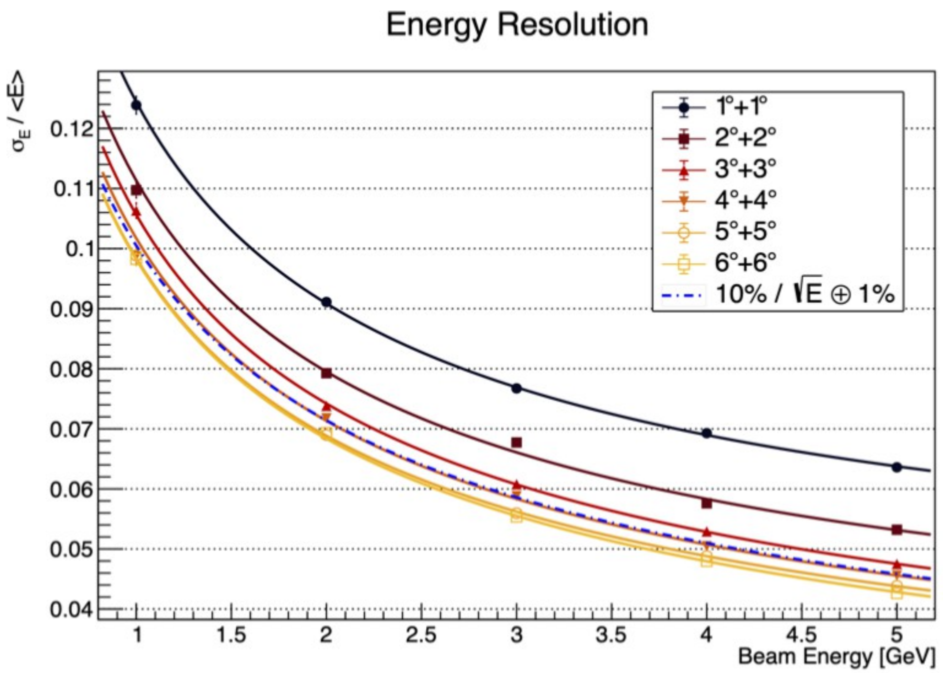


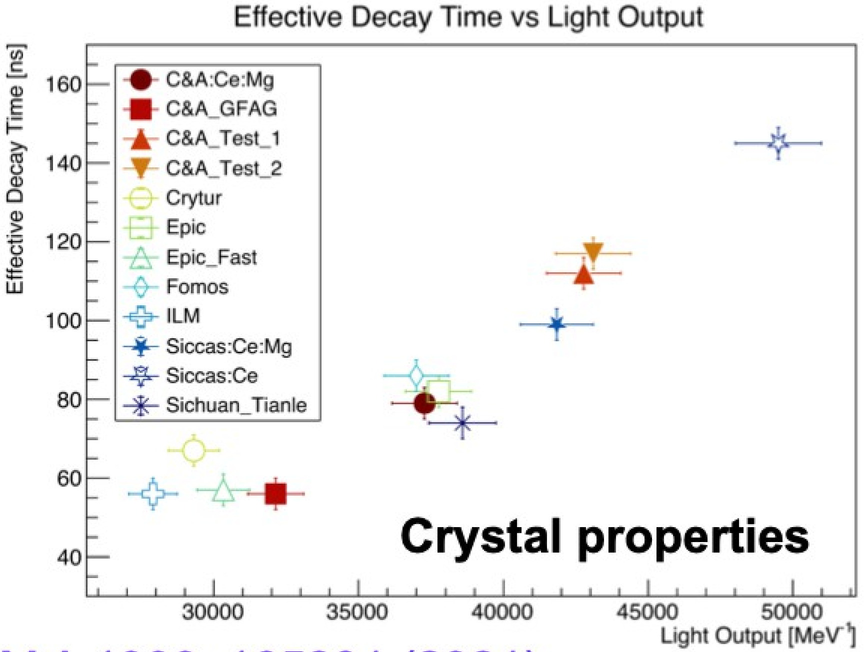
Challenges:

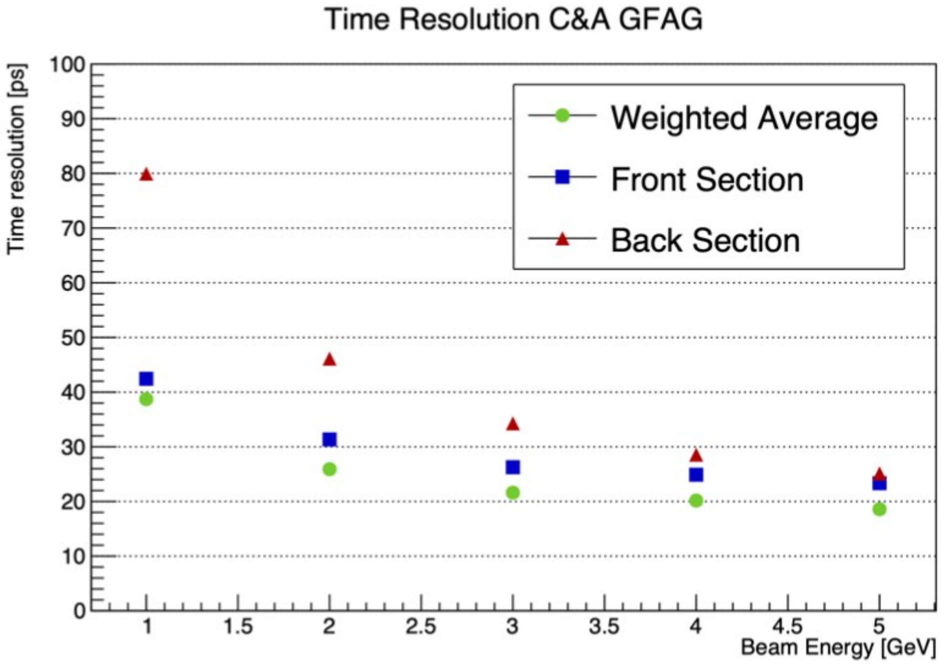
- Control number of signal traces
- Big number of capacitanes => Noise
  - Goal is 300 keV Noise for 200 pF cell (S/N > 5)
  - FCCee allows for higher integration times
  - Cold electronics?

Modern Fibre Calorimeter – SpaCal for LHCb









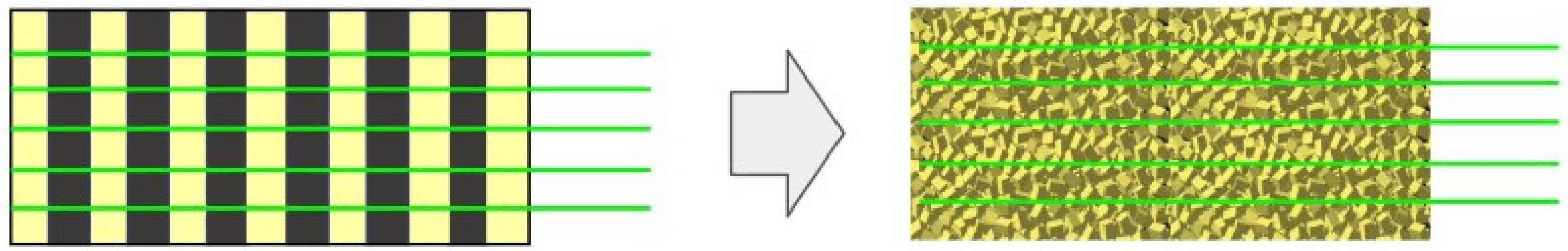
Another Idea– GRAINITA

GRAiNITA calorimeter

- **Ultra fine sampling opaque EM calorimeter** readout with WLS fibers
- Geant4 simulation of $ZnWO_4$ + CH_2I_2 cubes → **$\sigma_E/E \sim 2\%/\sqrt{E}$**
- Ongoing proof-of-concept with lab measurements and prototypes
- See presentation at FCC Italy-France Workshop [Ref]
  by M-H Schune (Université Paris-Saclay, CNRS-IN2P3)

Target application: e^+e^- colliders

Shashlyk-type calorimeter → GRAiNITA



$ZnWO_4$ grains

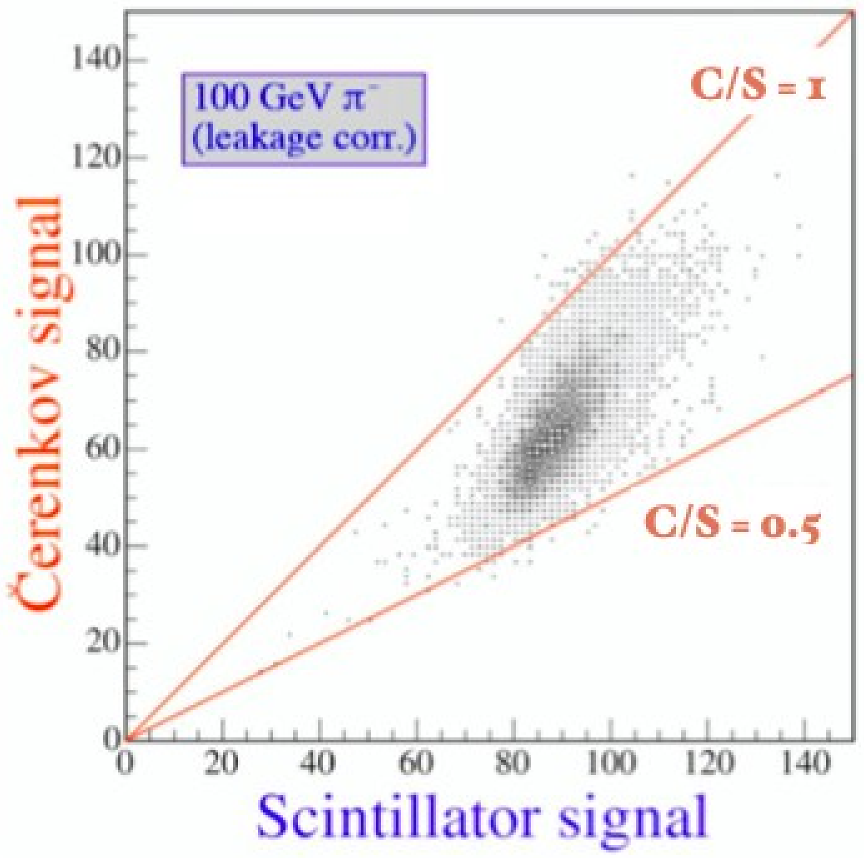
$ZnWO_4$ + propanol + Y11 WLS fibers

7

Dual Readout Calorimeter – The principla

- The **Dual-readout** concept: do not spoil em resolution to get **e/h=1** but **measure f_{em}** event by event → **eliminate effects of fluctuations in f_{em} on calorimeter performance**

- Use 2 different sampling processes: **Cherenkov light** (produced by relativistic particles and dominated by the e.m. shower component) and **scintillation light production** (for the total deposited energy):



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

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

e.g. if: (e/h) = **1.3(S)** vs **4.7(C)**

$$\frac{C}{S} = \frac{f_{em} + 0.21(1-f_{em})}{f_{em} + 0.77(1-f_{em})}$$

$$E = \frac{S - \chi C}{1 - \chi}$$

Universally valid!

with: $\chi = \dfrac{1-(h/e)_S}{1-(h/e)_C}$

χ is independent of both:

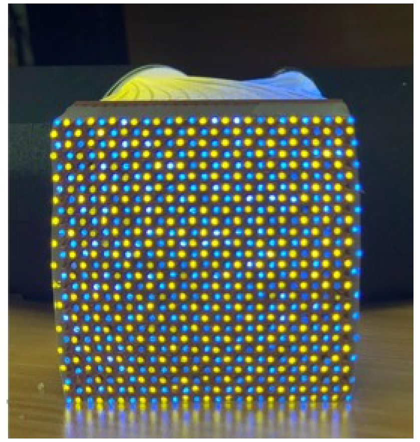
- Energy
- Type of hadron

M. Antonello, FCC-Week 2018

Dual readout calorimetry – Building Blocks

Fast signals

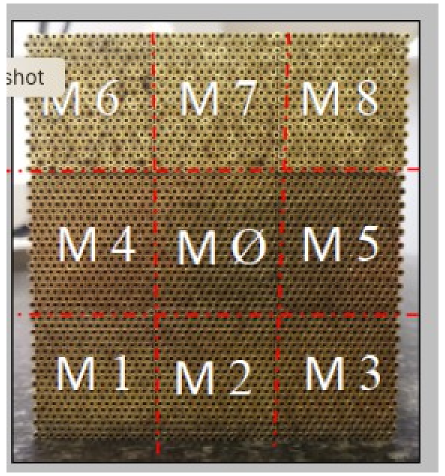
Slow signals



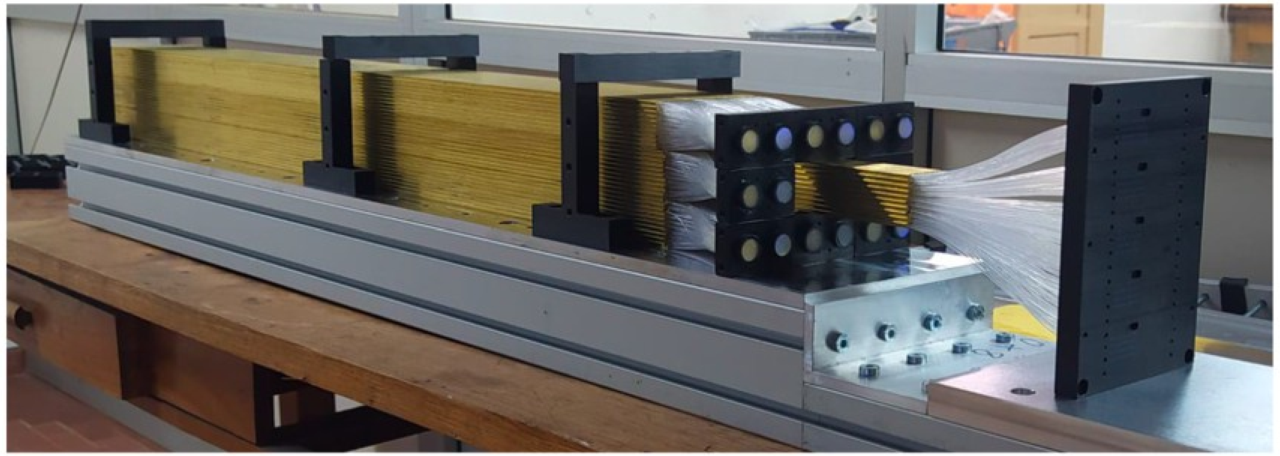
Dual readout to capture Electromagnetic and hadronic components of shower

Prototype development

- First step "electromagnetic prototype" 10x10x100cm^3
  - Qualification of
    - Assembly procedure
    - Readout systems



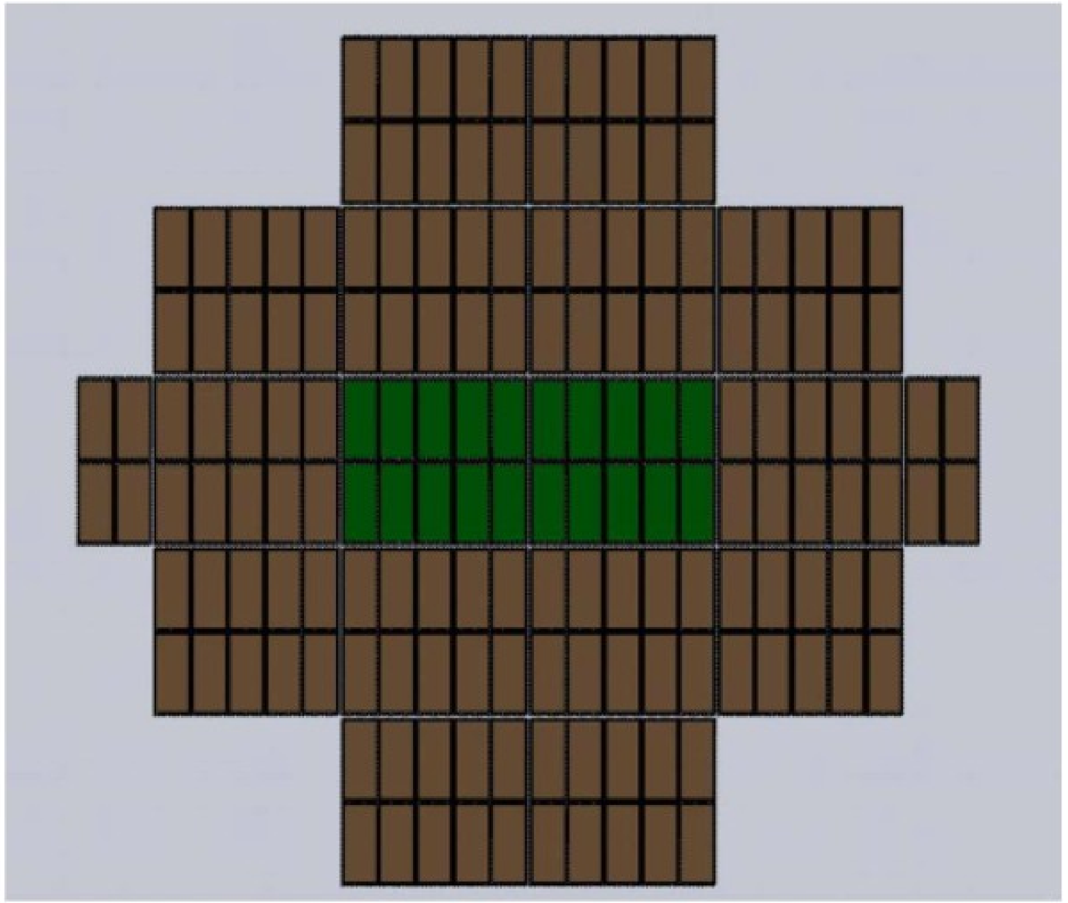
Stack of capillaries



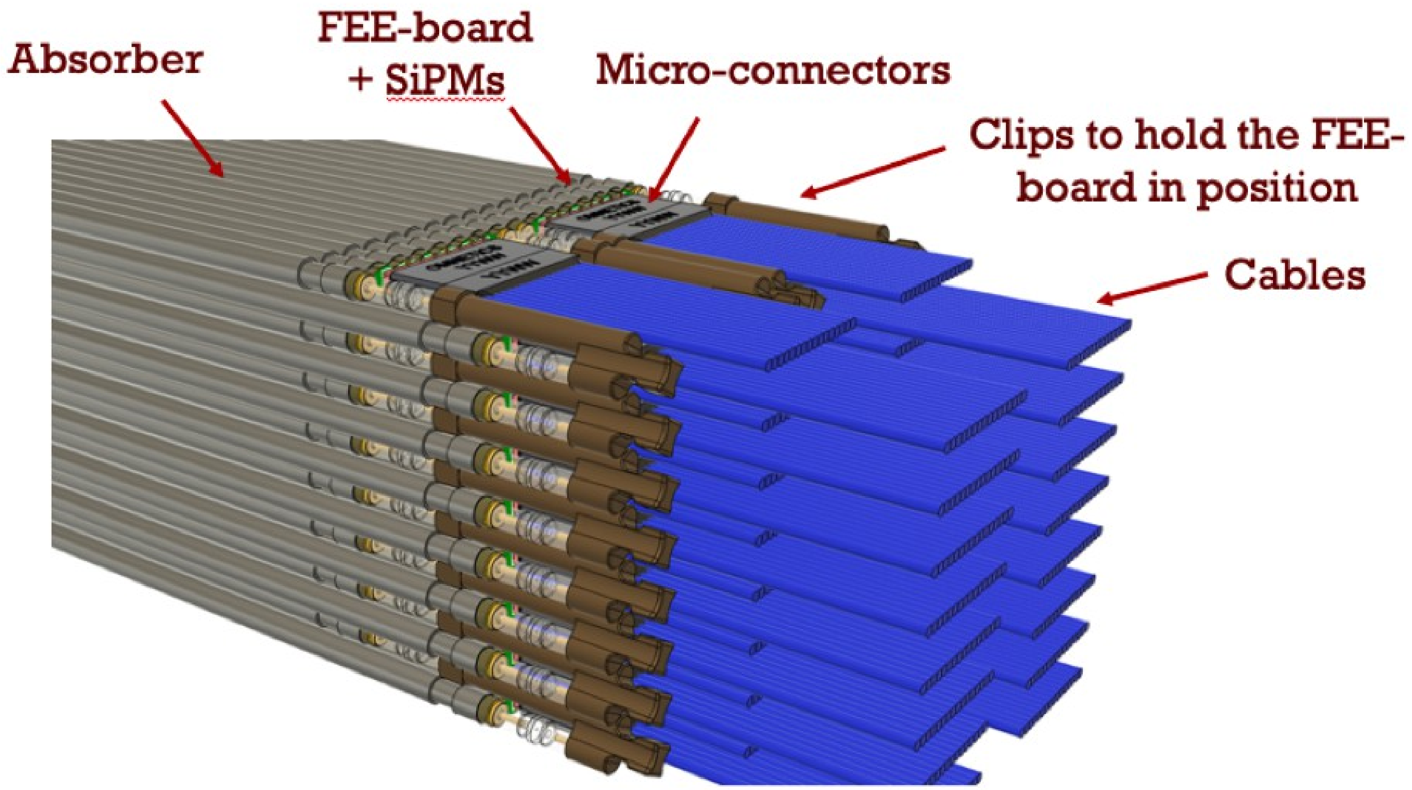
Outgoing fibres guided to readout plane

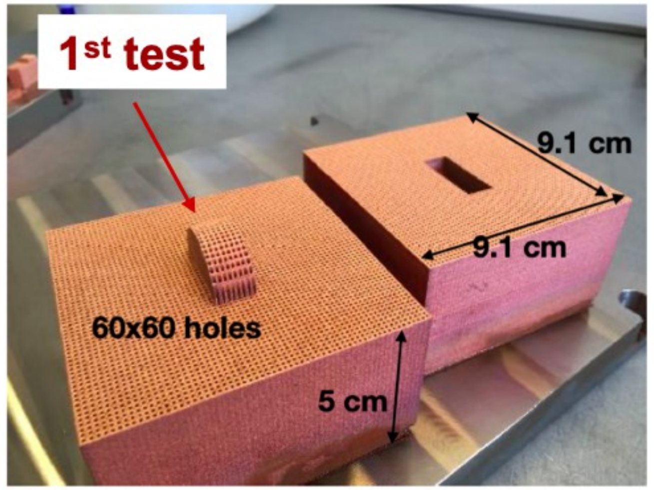
Dual readout calorimetry – Towards large prototype

Prototype with hadronic containment



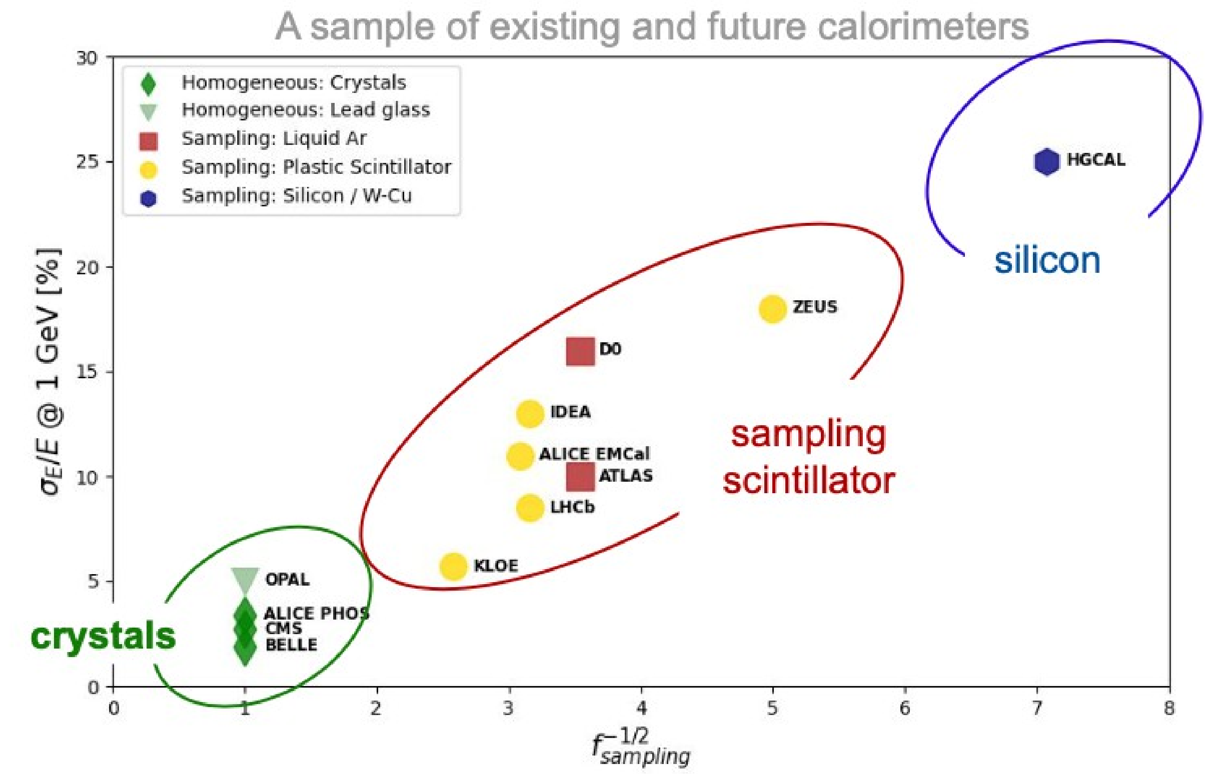
- $65x65x200\ cm^3$
- 17 modules in total
- 2 central modules equipped with SiPMs
- 15 modules equipped with PMTs



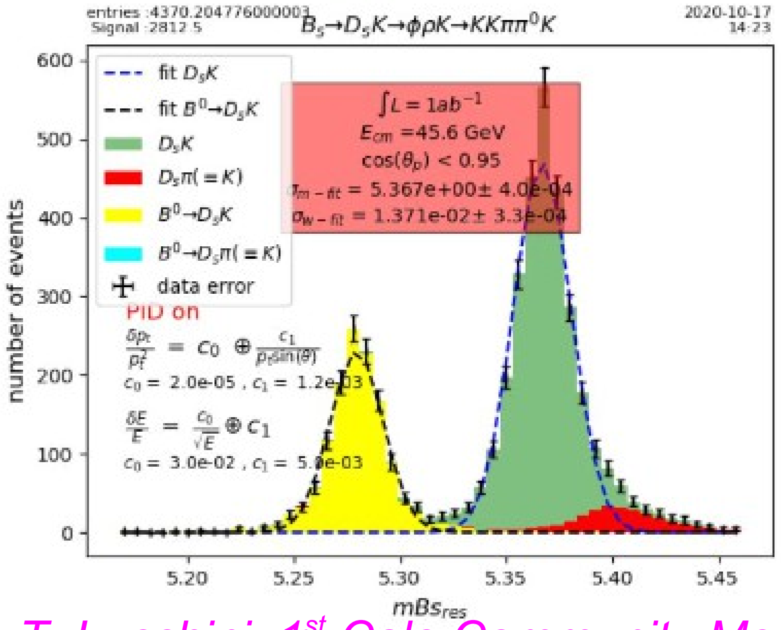


Sampling and Homogeneous Calorumeters

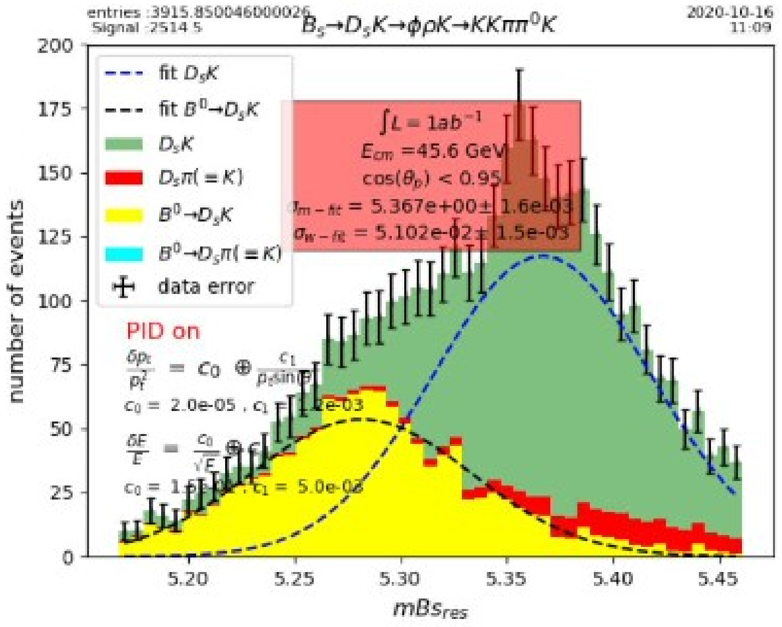
- So far we have concentrated on sampling calorimeters
  - i.e. Separation of sensitive and absorber medium
- Sampling leads to limitations in energy resolution 10-15%/√E
- (Most likely) homogeneous calorimeters semain the only Way to get to energy resolution of 1-5%/√E



3%/√E



15%/√E



CP violation studies with B_s decay to final states with low energy photons

[R.Aleksan et al., *Study of CP violation in B± decays to D0(D0)K± at FCCee,* arXiv:2107.05311]

M. T. Lucchini, 1st Calo Community Meeting

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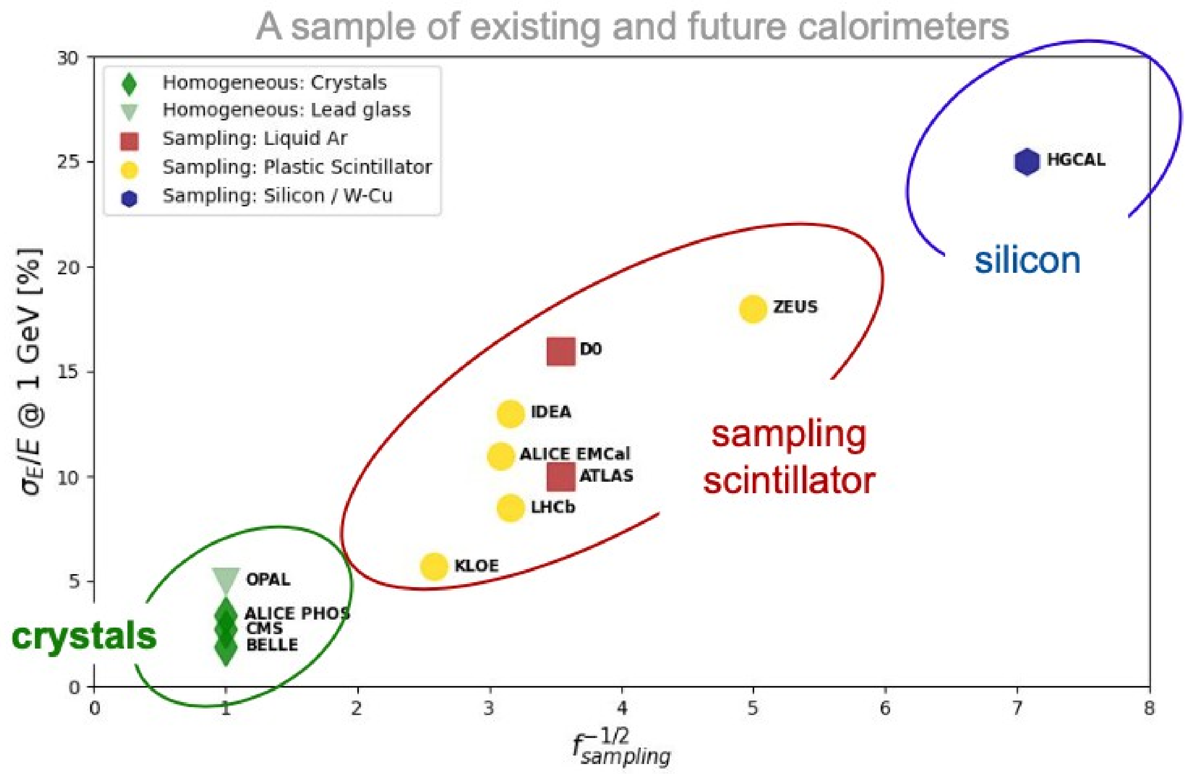
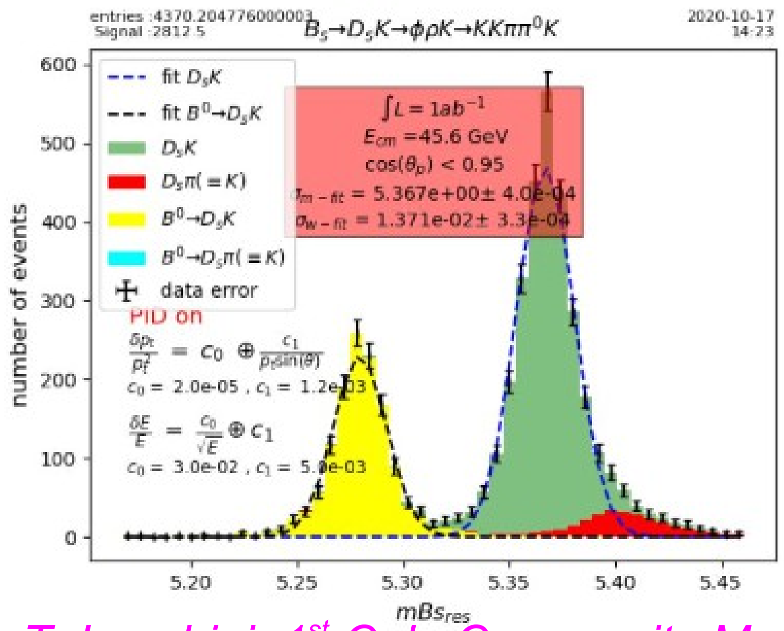
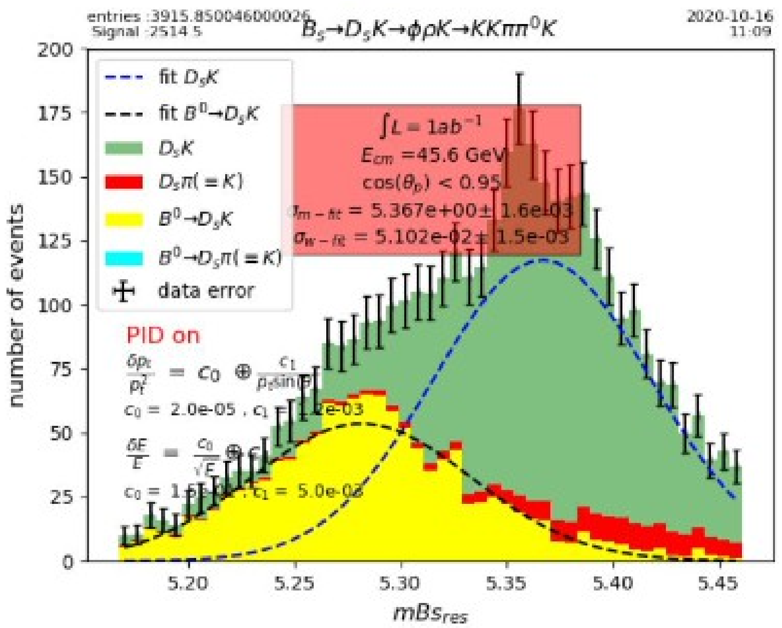


3%/√E



15%/√E



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M. T. Lucchini, 1st Calo Community Meeting

Future Homogeneous Calorimeters

Novel optical materials

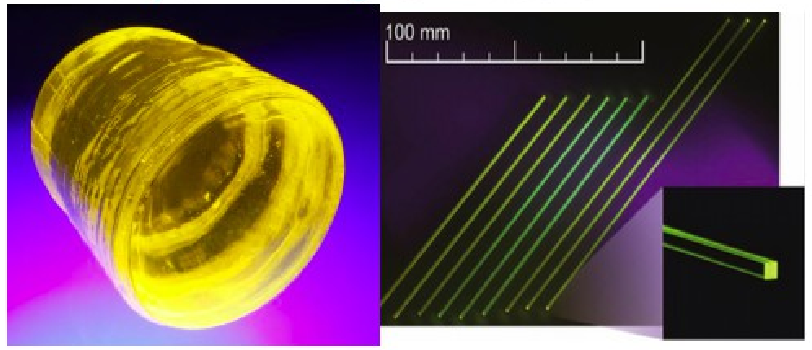
- Radiation hard optical materials with ultrafast timing response are required for new detectors in HEP, nuclear medicine and industry

- A time resolution below 30 ps or even in the sub ps domain requires a better understanding of the fast signal production mechanisms in detection materials

- Innovative test suites required for the combination of fast timing and radiation tolerance will be developed for the characterisation and classification of materials

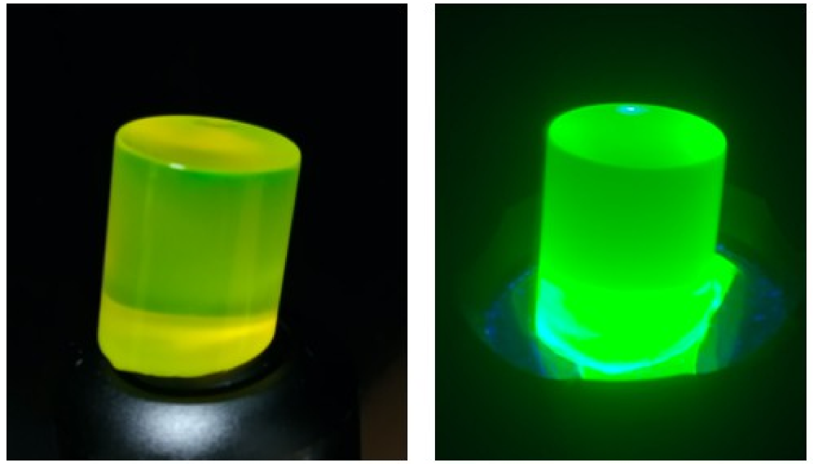
- Scalable and cost effective production techniques for the novel materials have to be explored together with the industrial partners

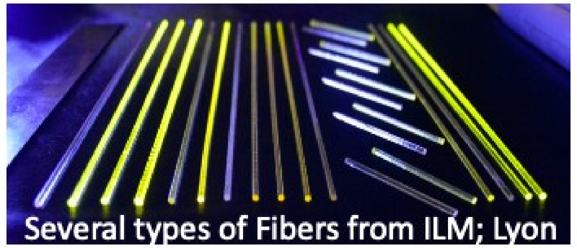
Crytur YAG ingots => fibers



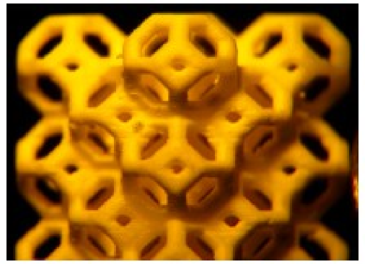
Crytur PWO crystals

GlasstoPower development on quantum materials





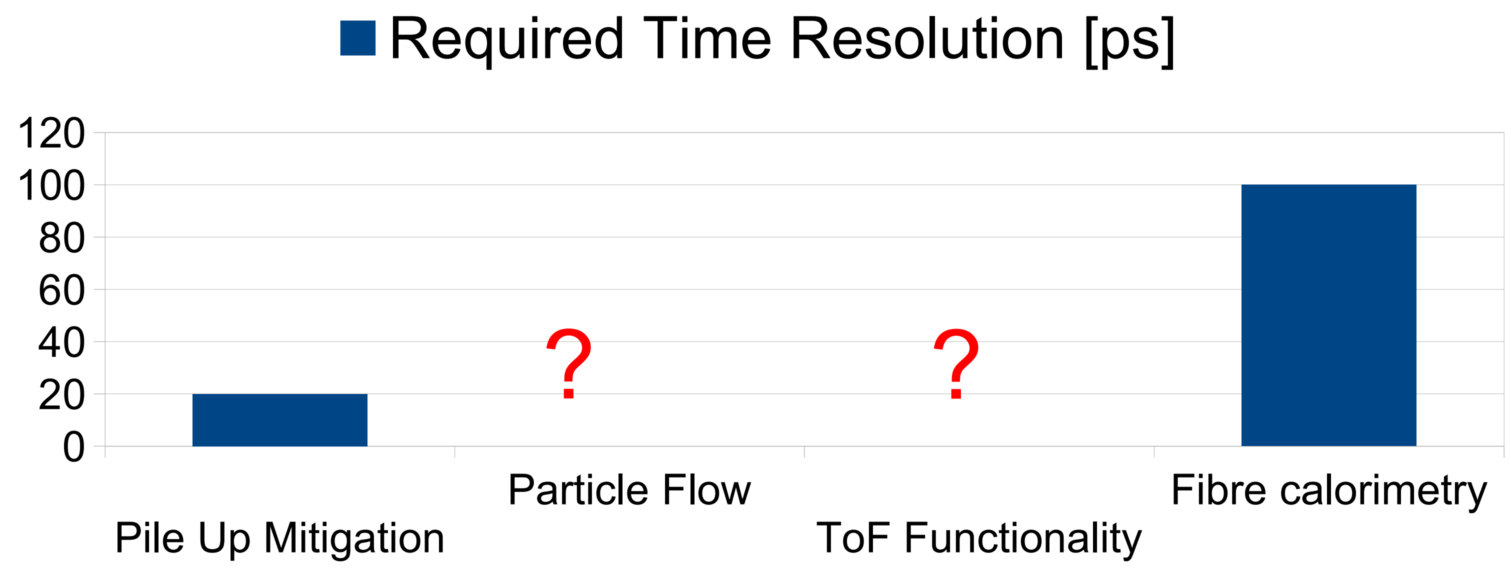
3 D printed garnet Crystals



Courtesy G. Dosovitskyi, Kurchatov Institute

Requirements on Timing

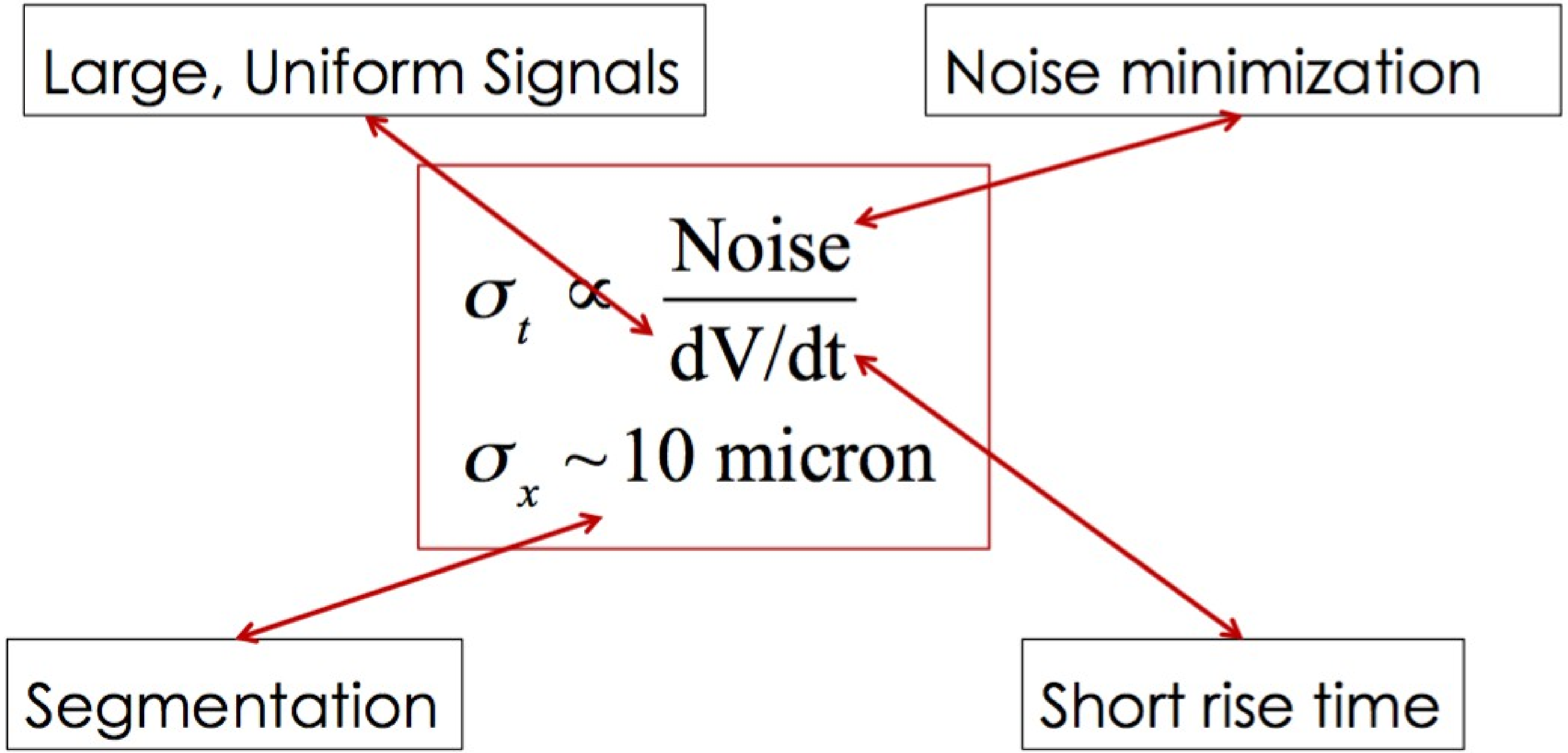
- Timing is a wide field
- A look to 2030 make resolutions between 20ps and 100ps at system level realistic assumptions
- At which level: 1 MIP or Multi-MIP?
- For which purpose ?
  - Mitigation of pile-up (basically all high rate experiments)
  - Support of PFA – unchartered territory
  - Calorimeters with ToF functionality in first layers?
    - Might be needed if no other PiD detectors are available (rate, technology or space requirements)
    - In this case 20ps (at MIP level) would be maybe not enough
  - Longitudinally unsegmented fibre calorimeters



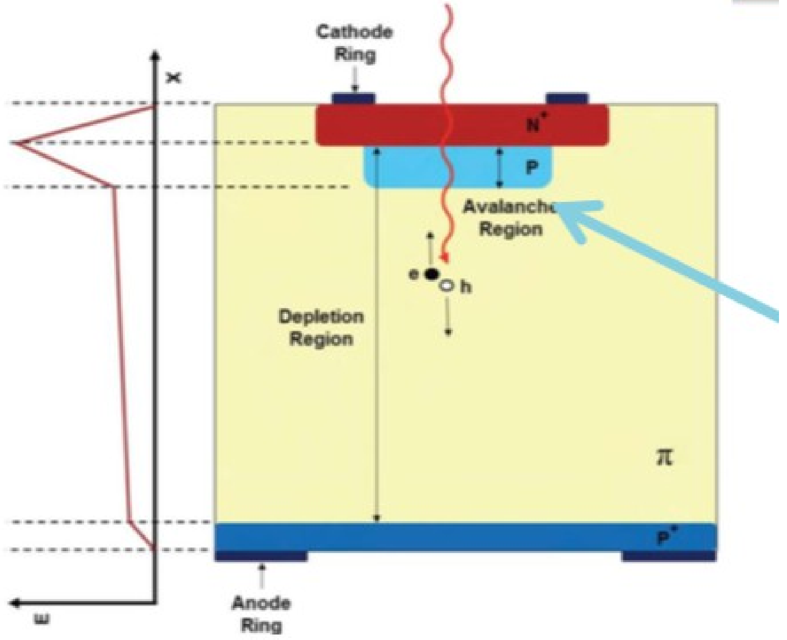
- Input sessions presented a wide field of application for precision timing
- A topic on which calorimetry has to make up it's mind
  - Remember also that time resolution comes at a price -> High(er) power consumption and (maybe) higher noise levels

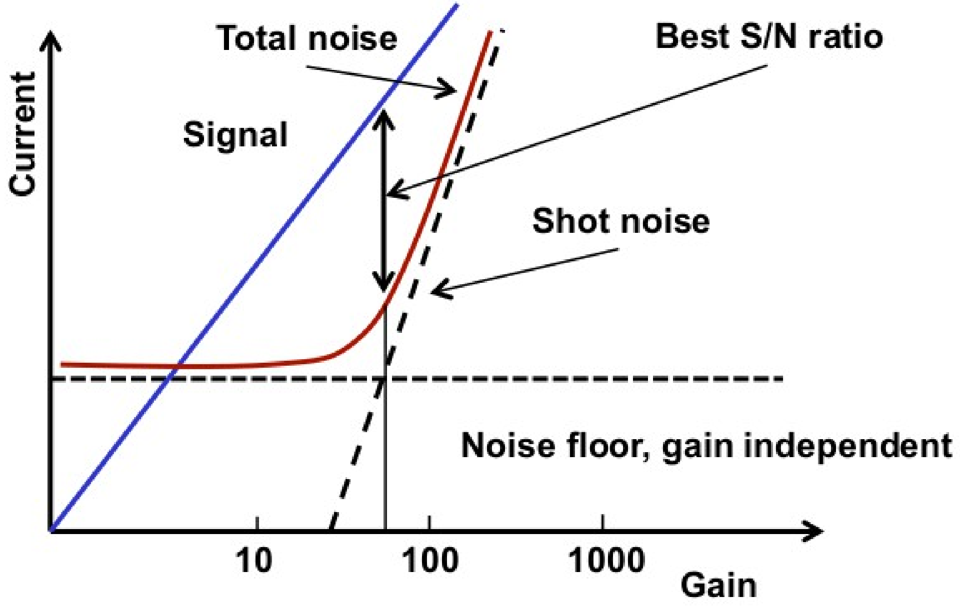
Timing – Some basic considerations

Pioneered by LHC Experiments, timing detectors may require adaptation for LC Experiments



LGAD

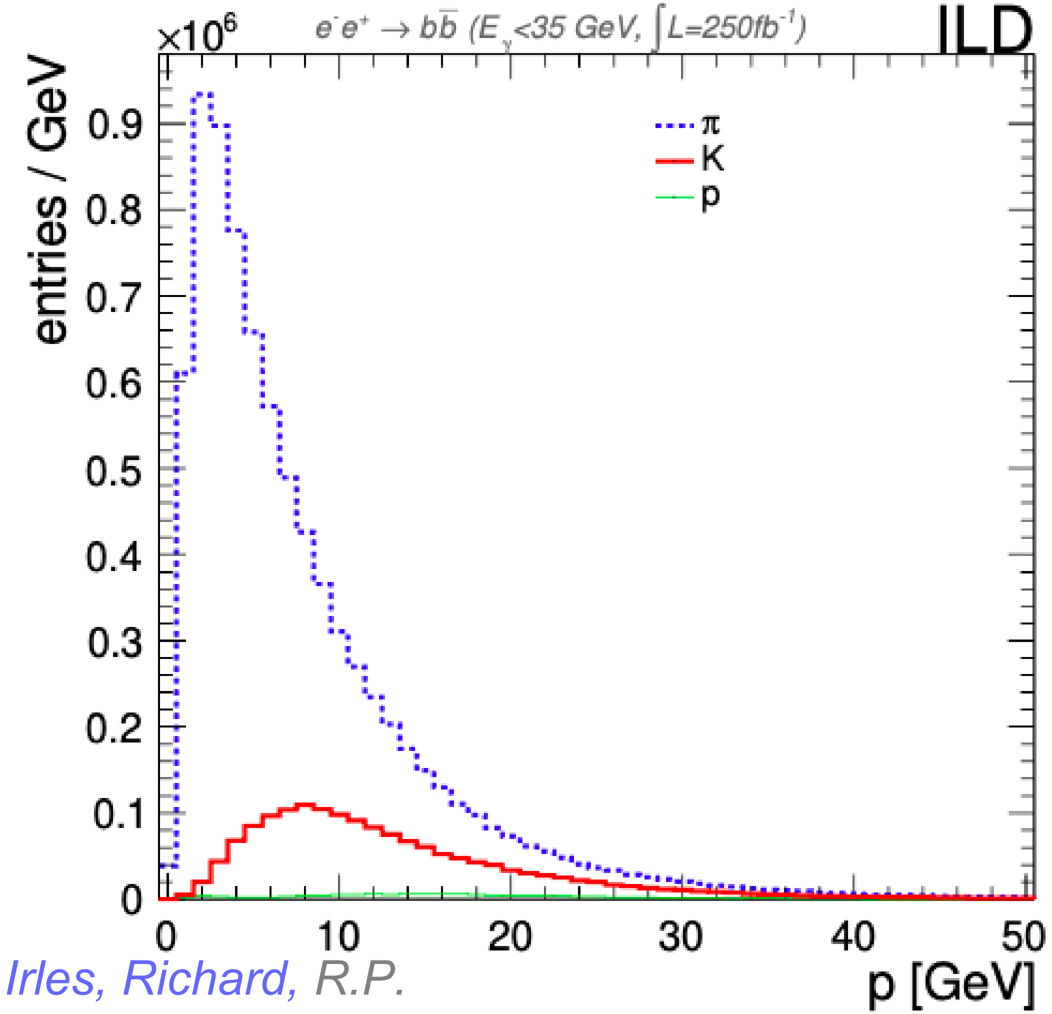




- Better dV/dt by "active" Si diodes ? => Low Gain Avalanche Detectors
  - LGADs applied for ATLAS HGTD and CMS ETD
  - Expect time resolution σ_t ~ 30-50ps
- Integration of LGADs into calorimeter volume may be one of the roads to follow

Calorimeters with ToF Functionality?

Momenta and abundance of pi/K/p in ee->bb @ 250 GeV



ILD: Irles, Richard, R.P.

Available time resolution with calos

Available "now"

Doable with Intensive R&D in 5-10 years

Requires a new breakthrough

Typical ToA at ILD Calos

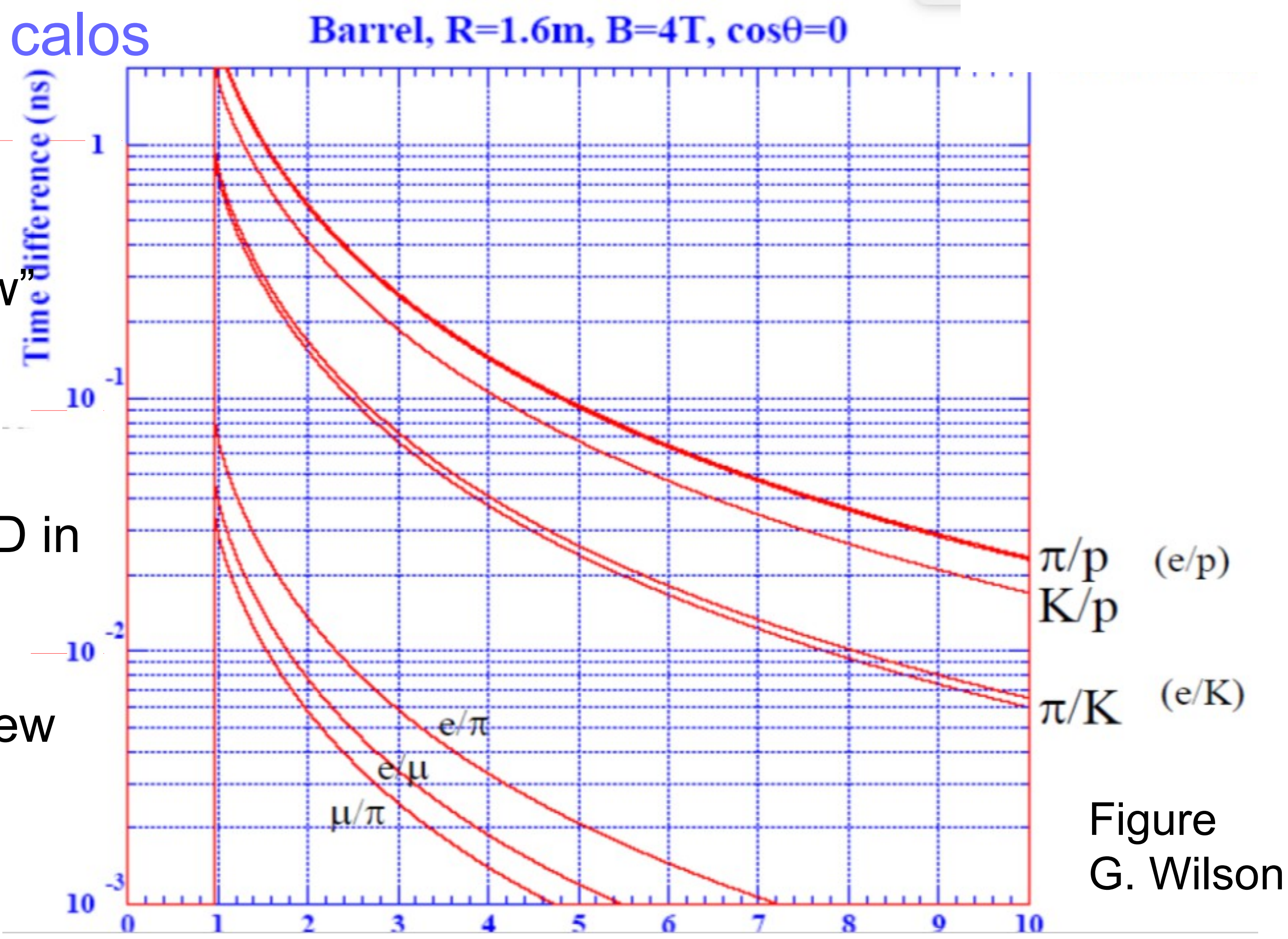
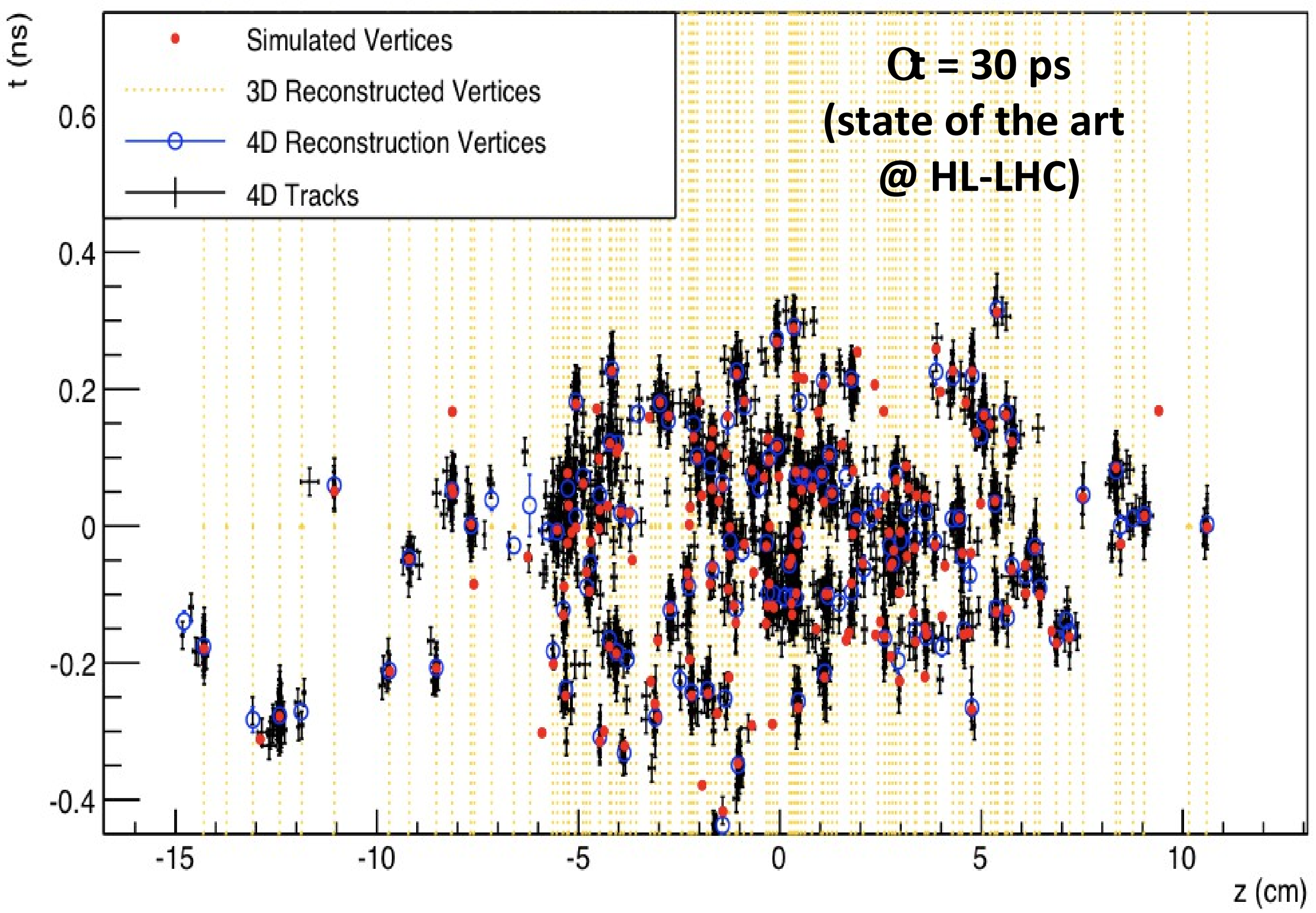


Figure G. Wilson

p[GeV]

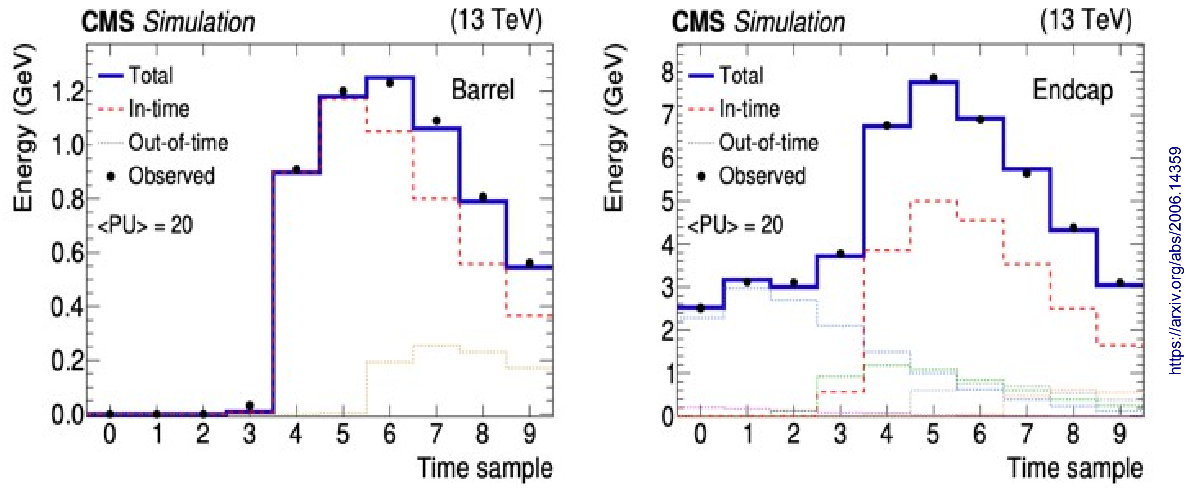
- Particle momenta (at 250 GeV) have peak below 10 GeV but long tail to higher energies
- Realistically ToF measurements will be (in foreseeable future) limited to particles below 10 GeV
  - Note that, apart from power consumption, in a final experiment one needs to control full system
- Momenta above 10 GeV require a real breakthrough and maybe even radically new approaches
  - Mandatory if ToF should work at and well above 250 GeV i.e. at Linear Collider Energies

Timing in calorimeters

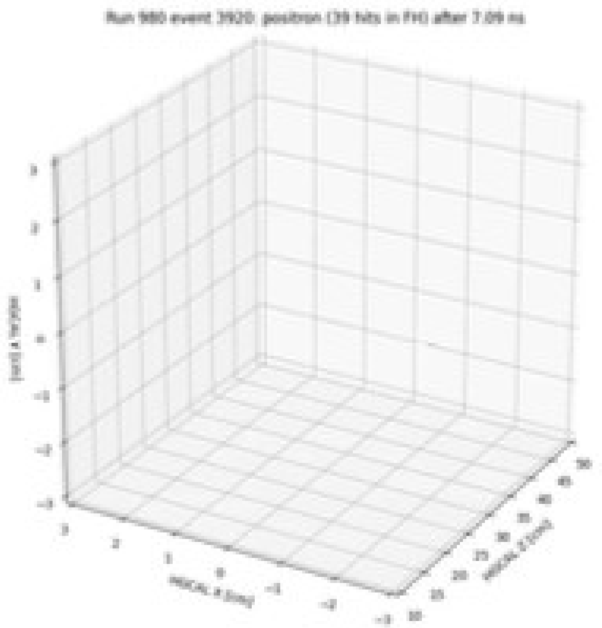


Red dots: 200 simulated vertices
Vertical yellow lines: 3D-reconstructed vertices (*i.e.* no timing info.) **Black crosses** and **blue open circles: 4D-reco inc. time information**

Many vertices that appear to be merged in the spatial dimension are clearly separated when time information (~30ps accuracy) is available

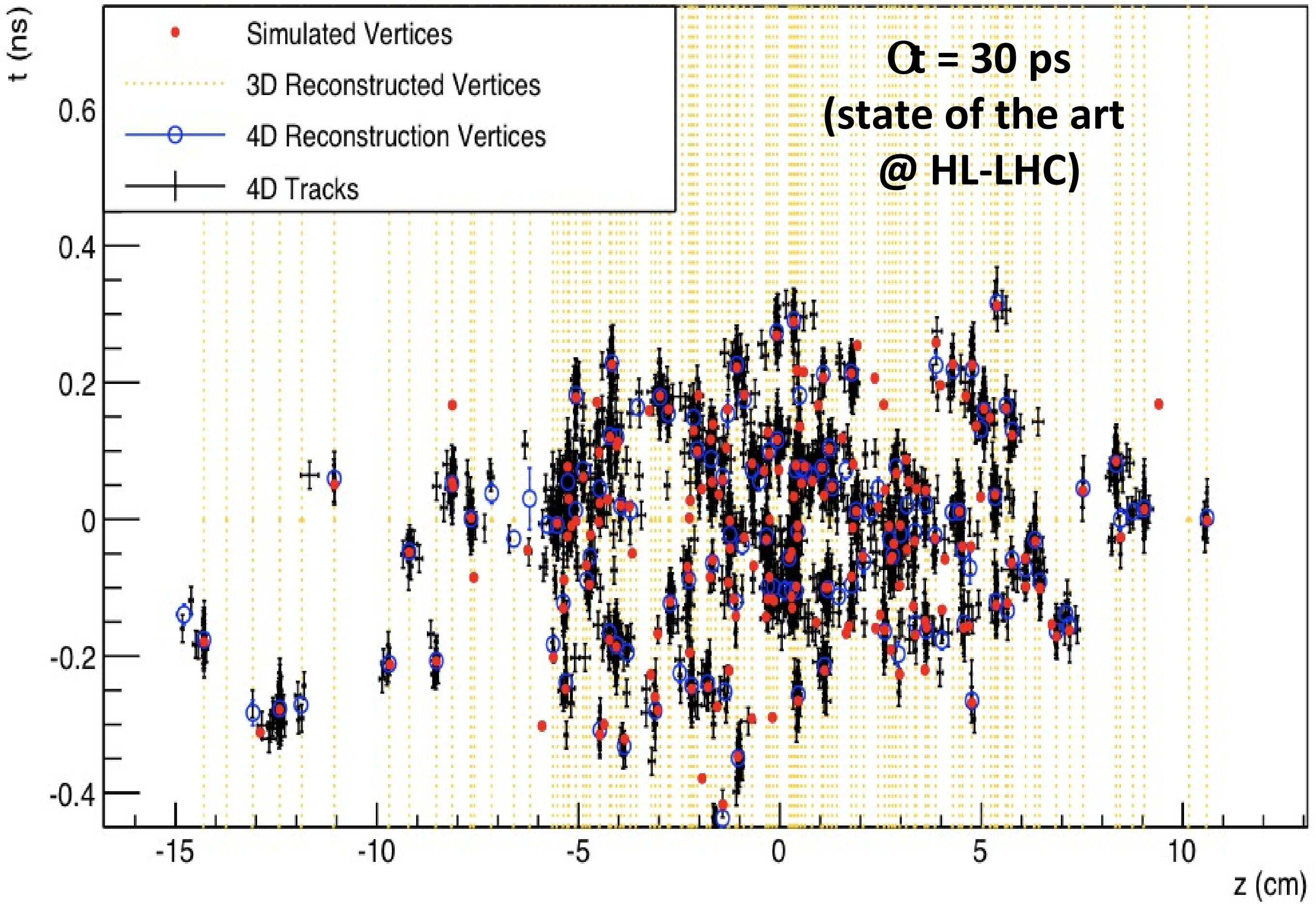


CMS ECAL uses template fits to in-time signal plus out-of-time signals to extract the best energy measurement



CMS HGCAL has measured **evolution of hadronic showers in the time domain** with ~80ps accuracy (50ps TDC binning)

Timing in calorimeters



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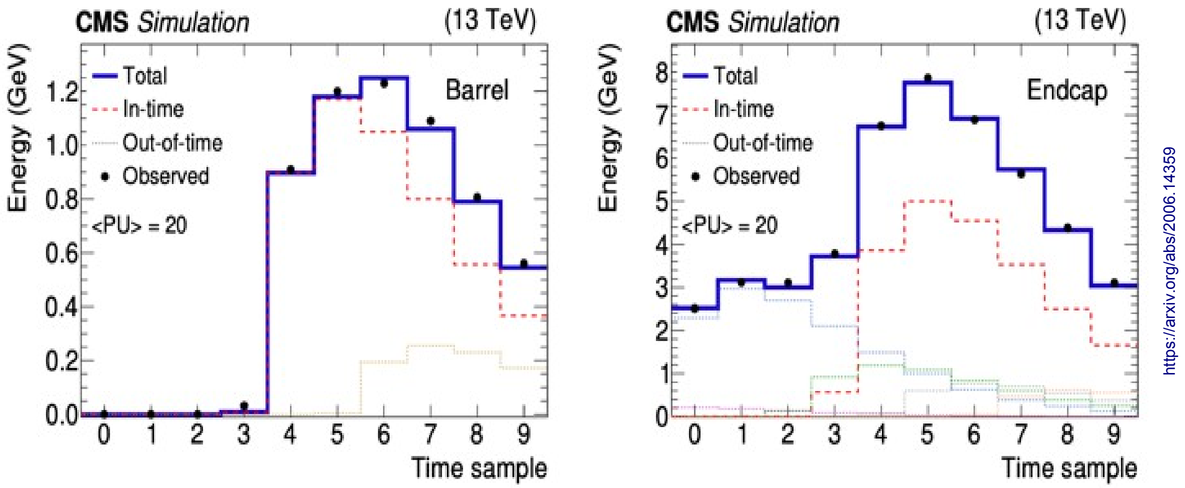

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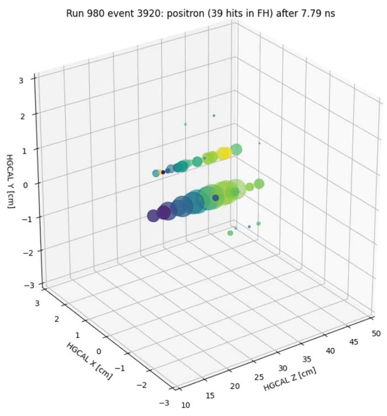
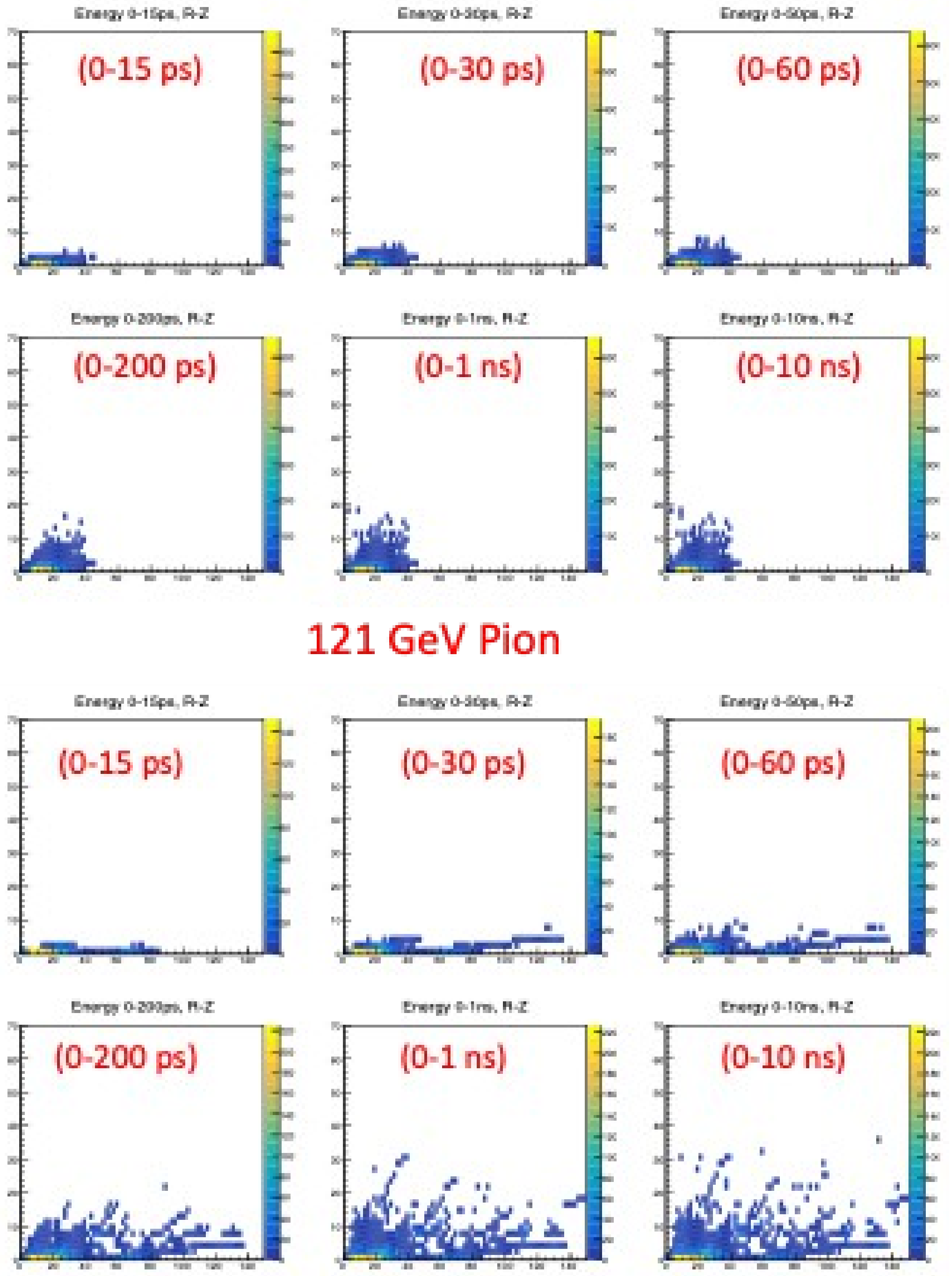
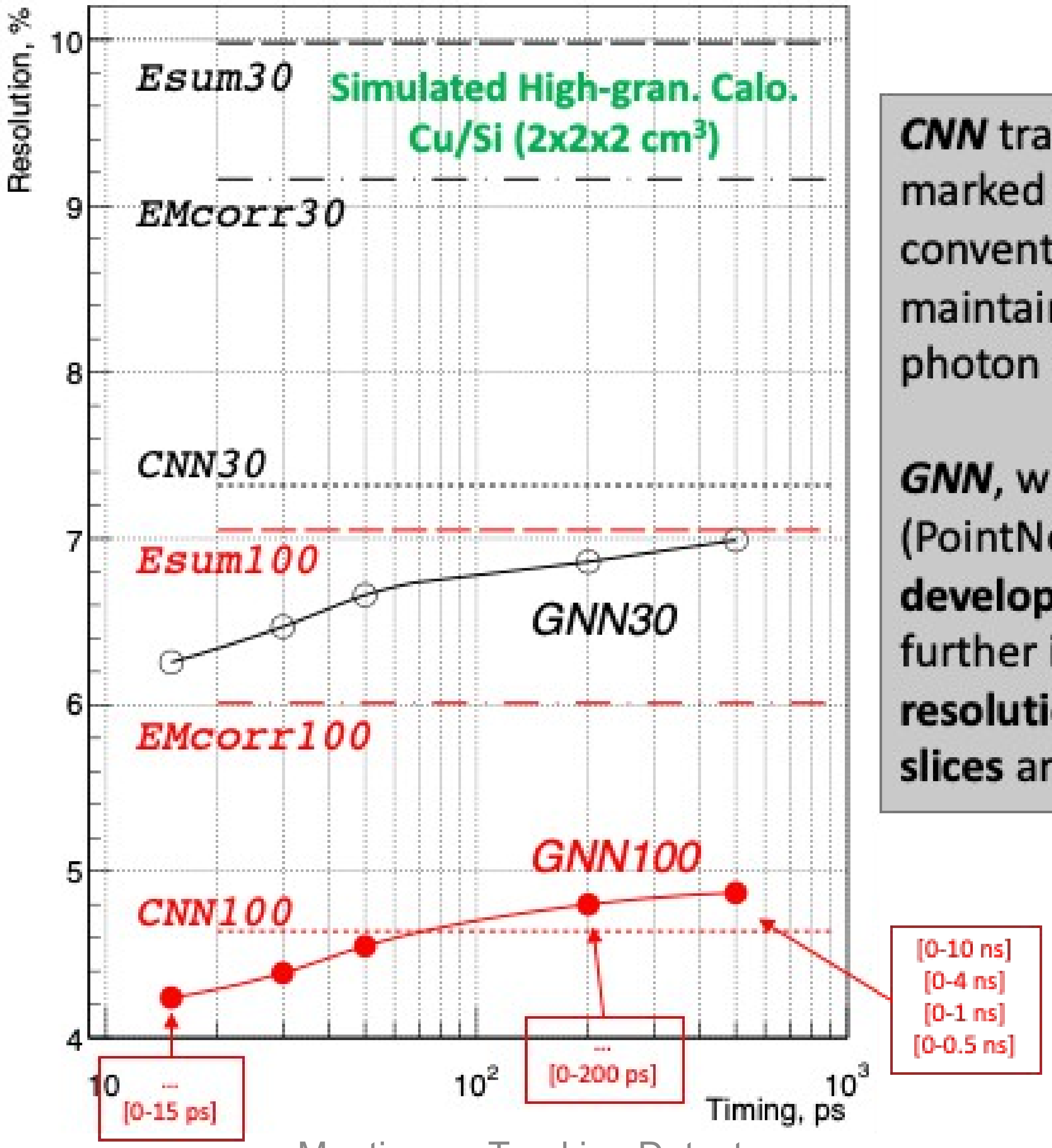


CMS HGCAL has measured **evolution of hadronic showers in the time domain** with ~80ps accuracy (50ps TDC binning)

Timing in calorimeters

Features that emerge in the time domain can help distinguish particle types and, with GNNs, enhance σ(E)/E





CNN trained on pions achieves marked improvement over the conventional approache while maintaining performance for photon reconstruction

GNN, with edge convolution (PointNet), **with shower development timing information** further **improves energy resolution** when **shorter time slices** are included

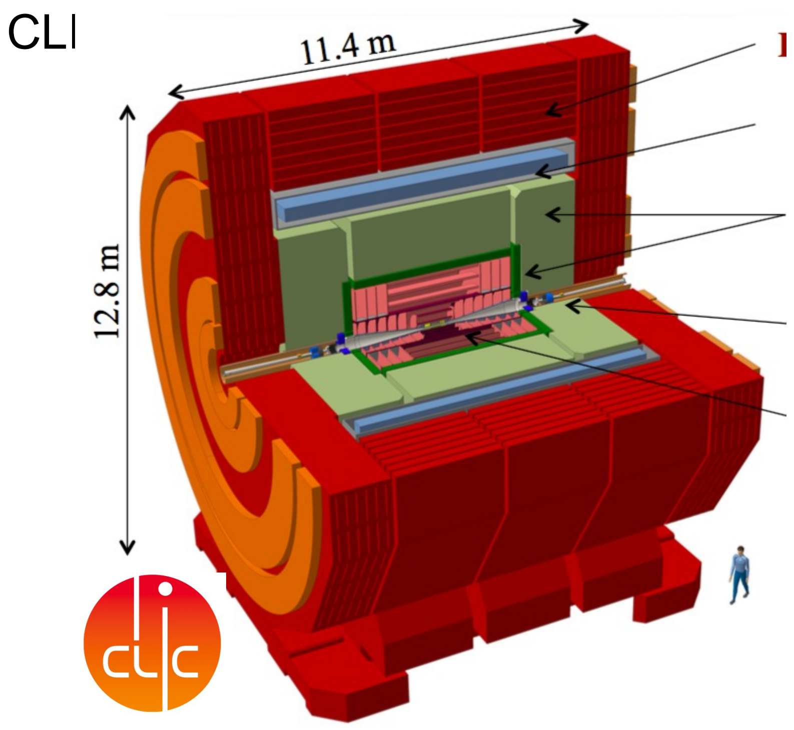
Summary and Conclusion

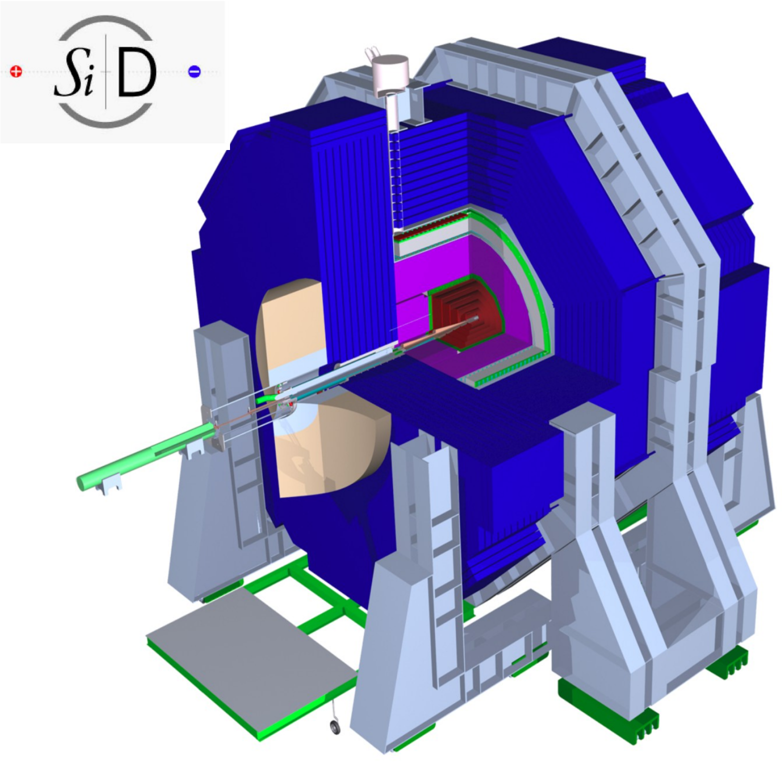
- I hope that this lecture serves as your entry point into the rich world of calorimeters
  - Two hpurs are not enough!!!
- Calorimeters are central objects of every particle physics experiments
- Calorimeters are a unique combination of sensitive materials, readout and engineering challenges
  - There is something interesting for everyone
- Not discussed today due to limited time
  - Data recorded with calorimeter prototypes allow for a detailed comparison between and e.g. Hadron
  - Shower models as implemented in GEANT4
  - (Granular) calorimeters are a rich field for modern pattern recognition algorithms
- There is a rich R&D programme for future calorimeters
  - ... that is waiting for your contributions

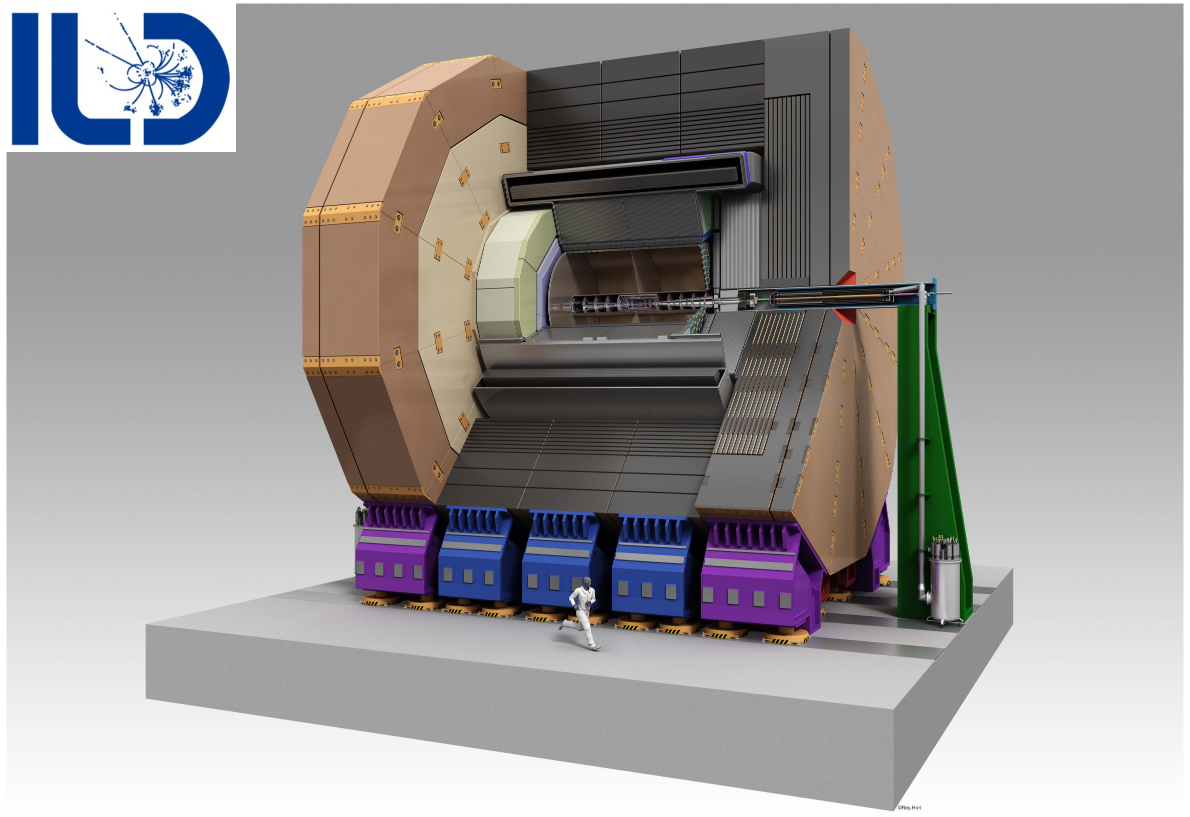
Backup

Detectors for Linear Colliders

e+e- detector concepts for linear colliders







B= 4T

B= 5T

B= 3.5T

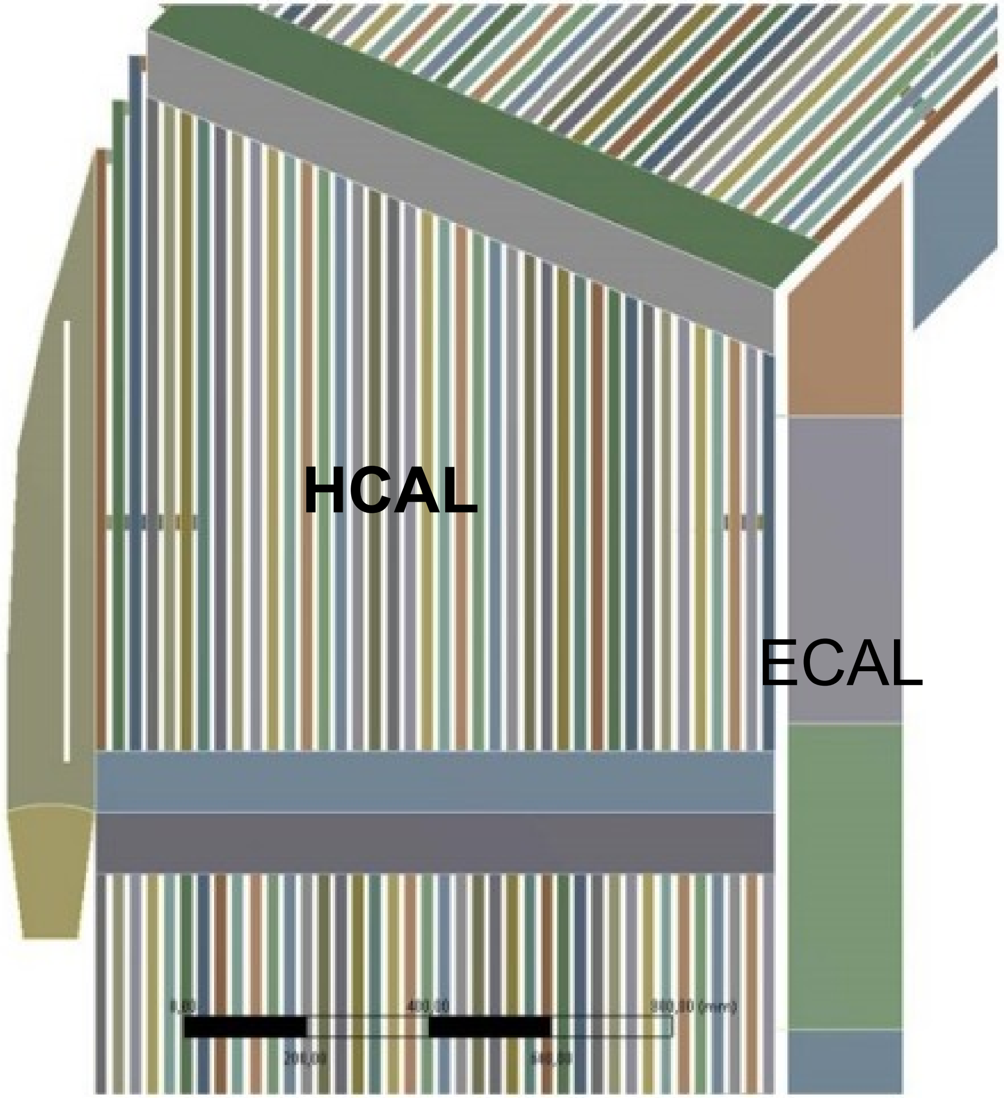
Highly granular calorimeters

Central tracking with silicon

Central tracking with TPC

Inner tracking with silicon

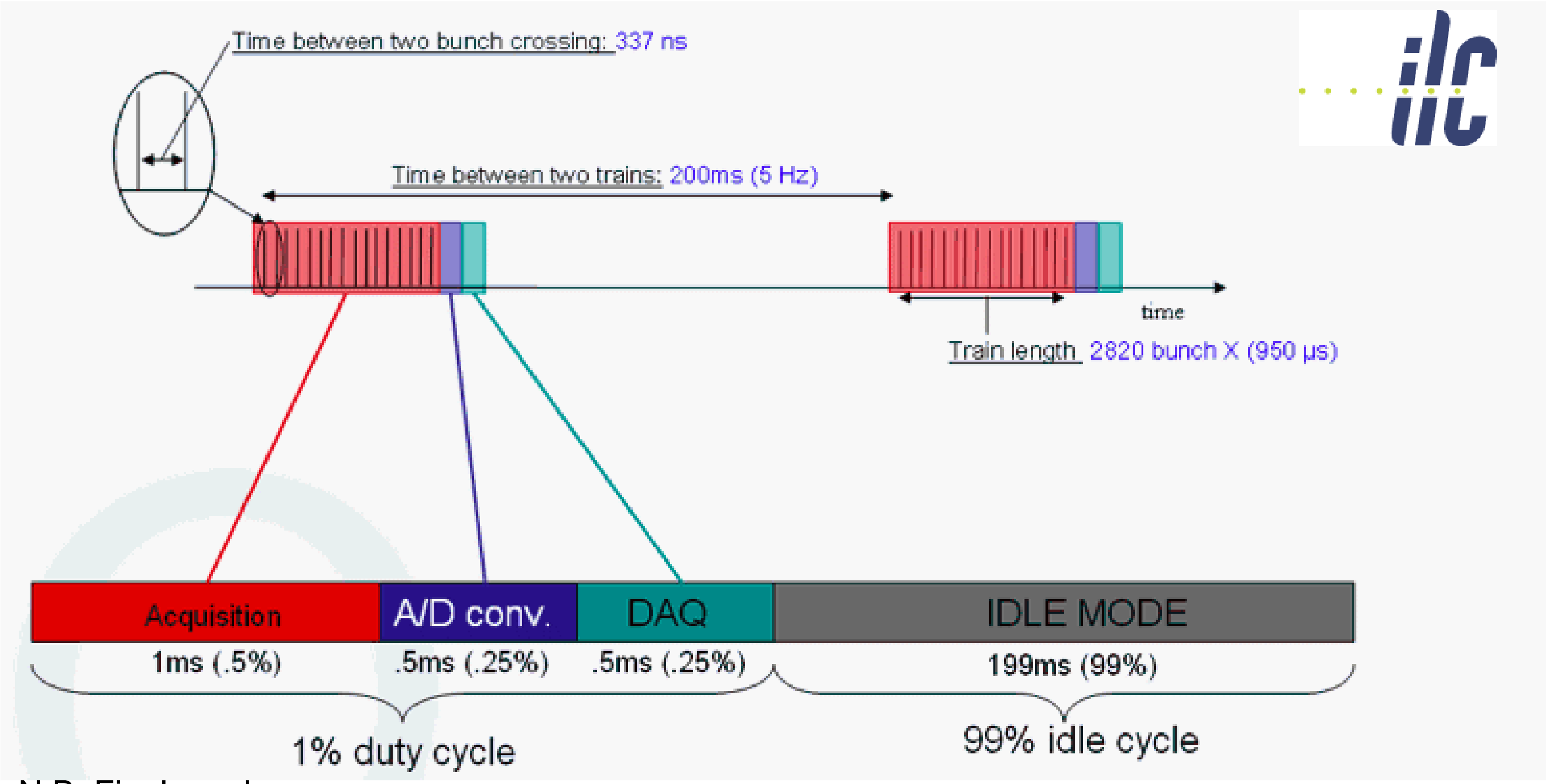
ILD concept and highly granular calorimeters



- ILD is particle flow detector
  - Implies goal to measure every particle of hadronic final state
  - Key components for PFA are highly granular calorimeters
- Calorimeter options in ILD
  - Silicon-Tungsten Ecal
    - 26-30 layers
    - Cell size 5.5x5.5mm^2, layer depth 0.6-1.6 X_0
  - Scintillator-Tungsten Ecal
    - 30 layers
    - Strip size 5x45 mm^2, layer depth 0.7 X_0
  - Analogue Hcal
    - 48 layers
    - Scintillating tiles: 30x30mm^2, layer depth 0.11λ_I
    - Absorber stainless steel
  - Semi-Digital Hcal
    - 48 layers
    - GRPC: 10x10mm^2, layer depth 0.12 λ_I
    - Absorber stainless steel

Beam Structure and Detector Operation

- Linear collider beams come in bunch trains
  - CLIC: repetition frequency 50 Hz, ILC: repetition frequency 5 Hz (minimum)



N.B. Final numbers may vary

- Power pulsing of electronics:

- Electronics switched on during > ~1ms of bunch train and data acquisition
- Bias currents shut down between bunch trains

Exploiting beam structure can/will lead to power economic operation of linear collider detectors

Detector requirements

Track momentum: $\sigma_{1/p} < 5 \times 10^{-5}$/GeV (1/10 x LEP)

(e.g. Measurement of Z boson mass in Higgs Recoil)

Impact parameter: $\sigma_{d0} < [5 \oplus 10/(p[GeV]\sin^{3/2}\theta)]$ μm (1/3 x SLD)

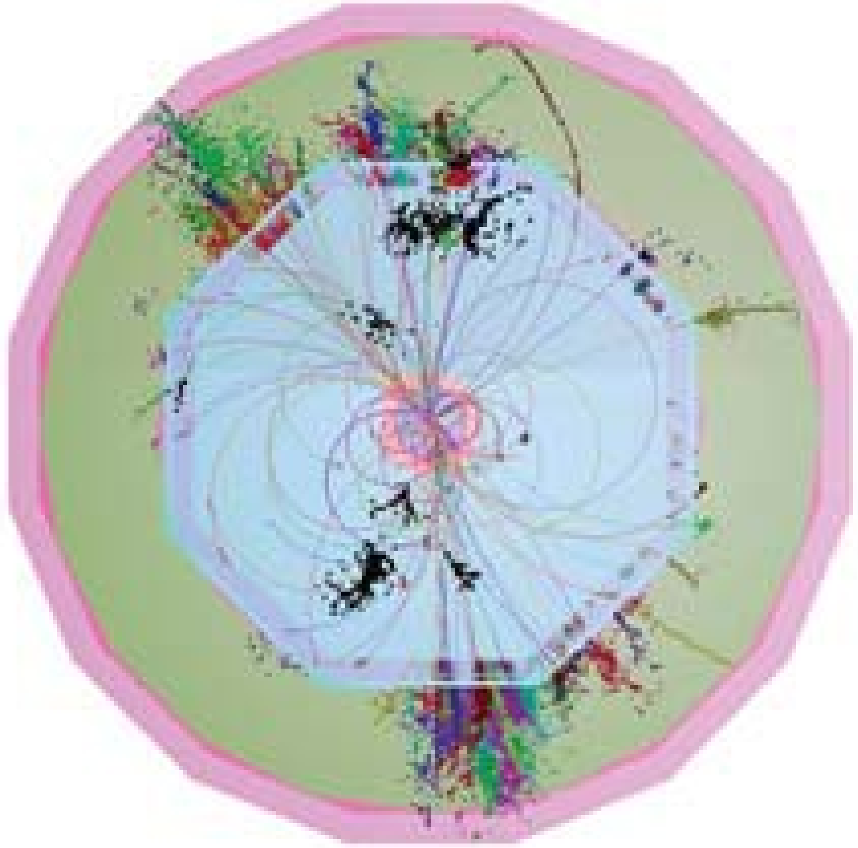
(Quark tagging c/b)

Jet energy resolution : $dE/E = 0.3/(E(GeV))^{1/2}$ (1/2 x LEP)

(W/Z masses with jets)

Hermeticity : θ_{min} = 5 mrad

(for events with missing energy e.g. SUSY)



Final state will comprise events with a large number of charged tracks and jets(6+)

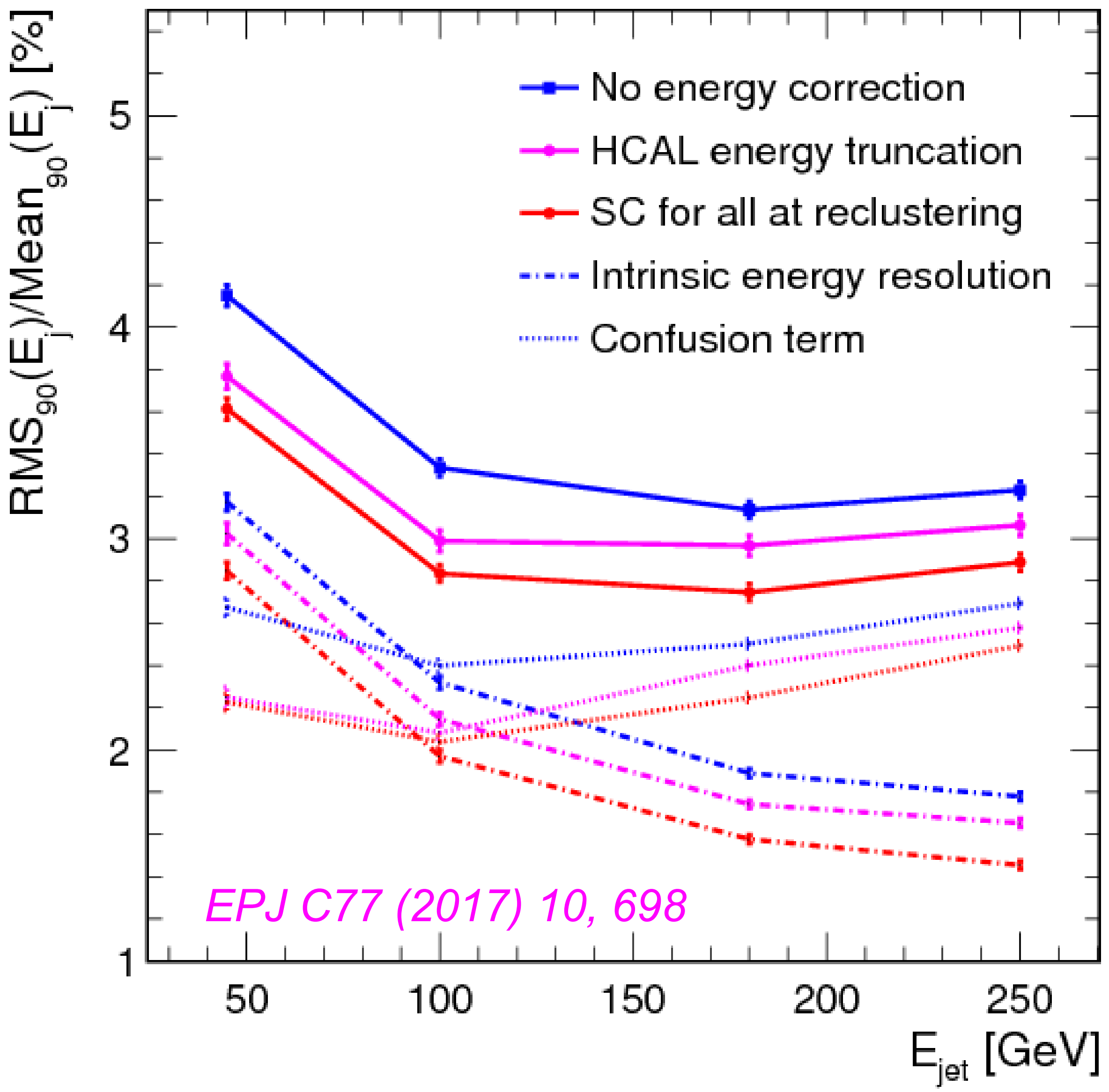
- High granularity
- Excellent momentum measurement
- High separation power for particles

Particle Flow Detectors

Detector Concepts: ILD, SiD and CLICdp

Jet energy resolution

Pandora PFA jet energy resolution



Study within ILD Concept

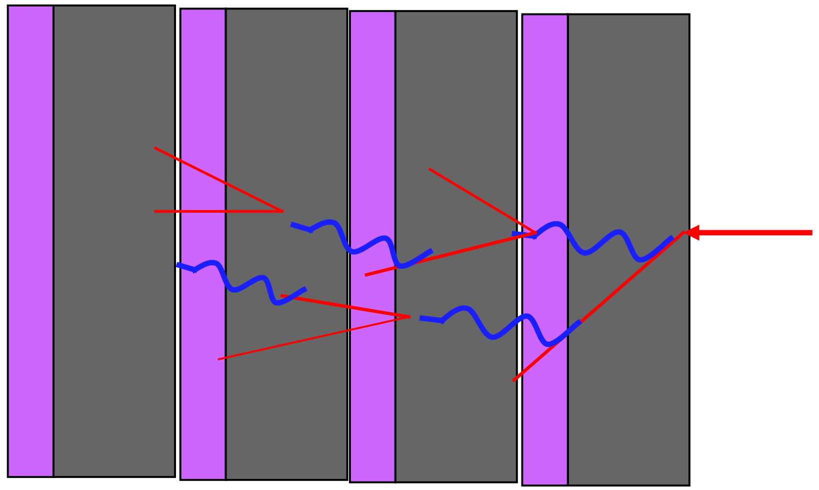
- Design goal: 30%/√E at 100 GeV
  - ~3-4% over entire jet energy range
- At lower energies < 100 GeV resolution is dominated by intrinsic calorimeter resolution
- At higher energies have more particles and higher boost
  - Smaller distance between particles
  - More overlap between calorimeter showers
  - Pattern recognition becomes more challenging

  => Confusion
- Note particularly the gain by software compensation
  - i.e. exploiting the wealth of information available through high granularity

PFAs ARBOR and APRIL are alternatives with similar performance

Calorimetry – Shower Measurement and Techniques I

Example: Sampling Calorimeters, Homogenous Calorimeters ➢ Homework



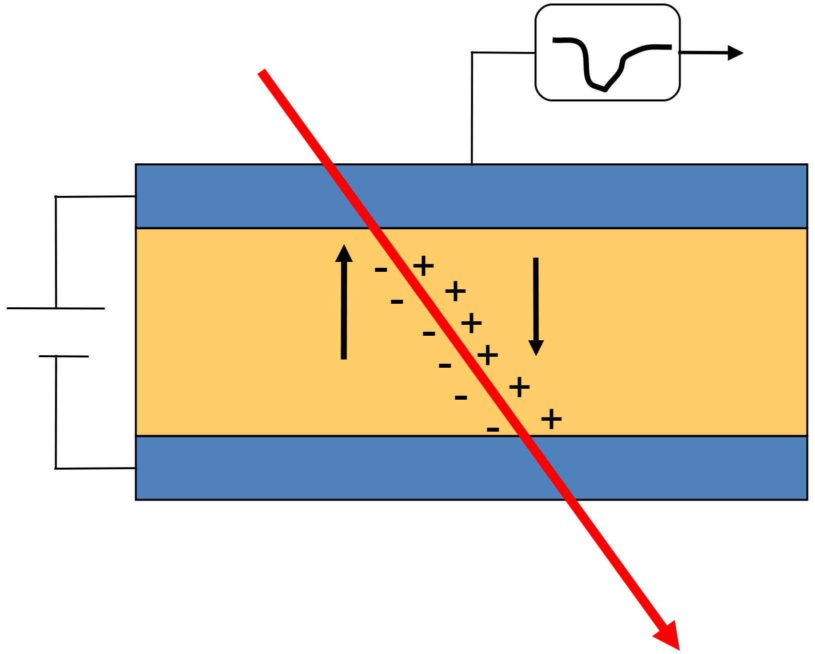
Alternating structure of Absorber and Sensitive medium

Only sample of shower passes active medium
Production of shower particles is statistical process
with N (t) ~ E ⇒ σ(E) ~ √E

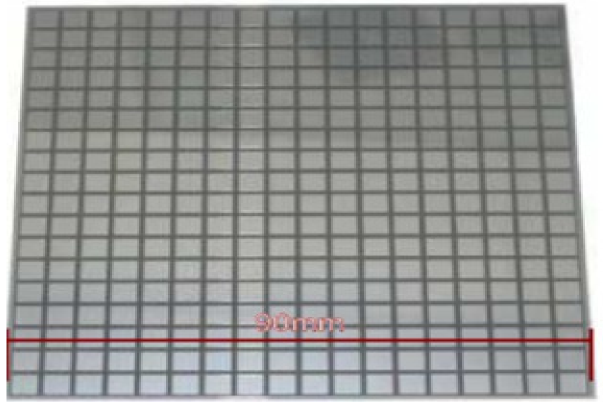
$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E\,[\mathrm{GeV}]}} \oplus b \;\; [\%]$$

Master formula of calorimetry

- Sensitive medium I: Counters based on semi-conductor



Si Wafer for CALICE SiW ECAL

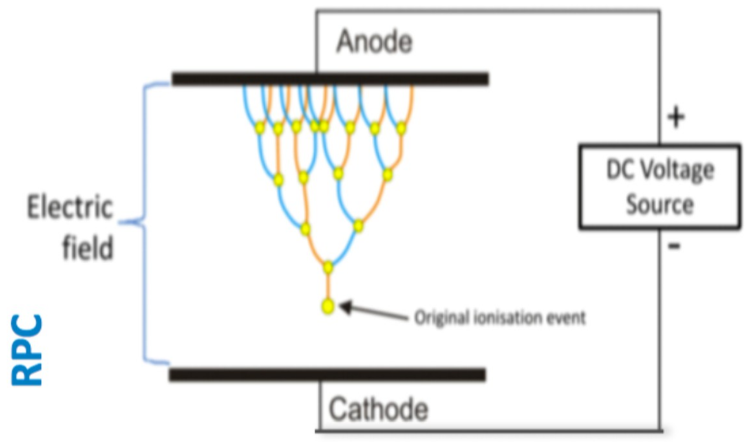


- Semi-Conductors allow for High level of segmentation
  - 5x5 mm^2 for SiW ECAL
- More for future calorimeters?
  - See above vertex detectors

Calorimetry – Shower measurement and Techniques II

- Sensitive Medium II: Gaseous Counters

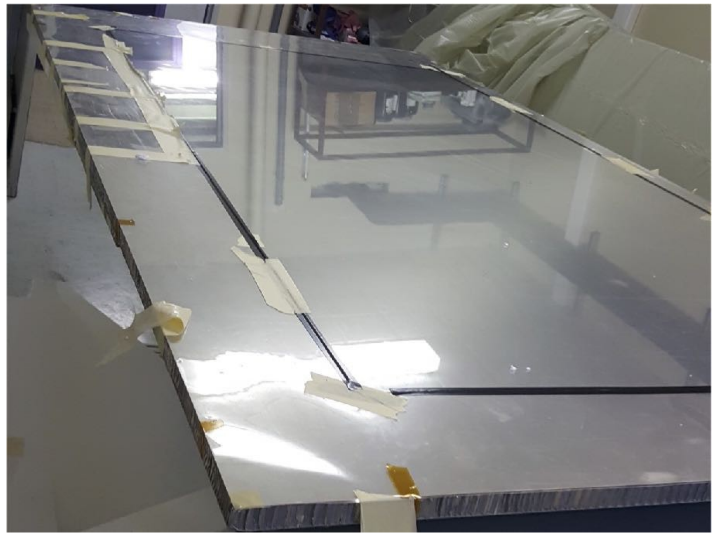
RPC = Resistive Plate Chamber



D. Boumediene

Primary Ionization in gas volume
Acceleration in strong electric field
– typically 5-10 kV between cathode and anode
Lots of secondary ionisation
Measurable charge

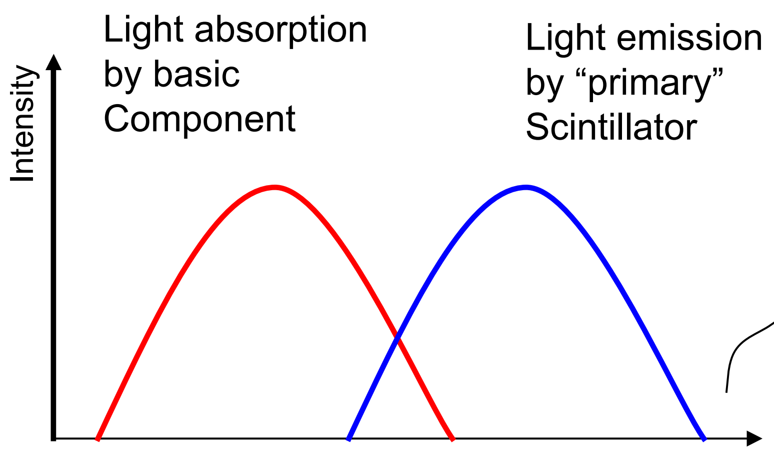
GRPC Chamber – CALICE SDHCAL



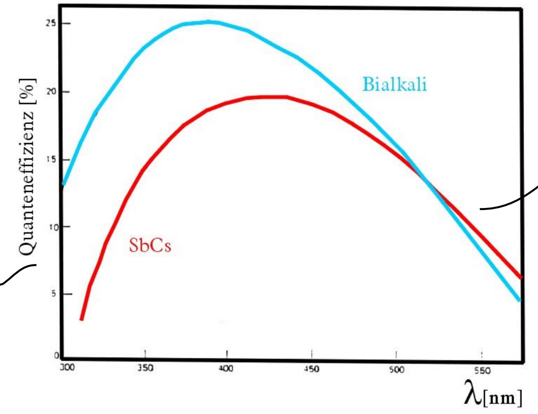
Lateral granularity 1x1 cm^2

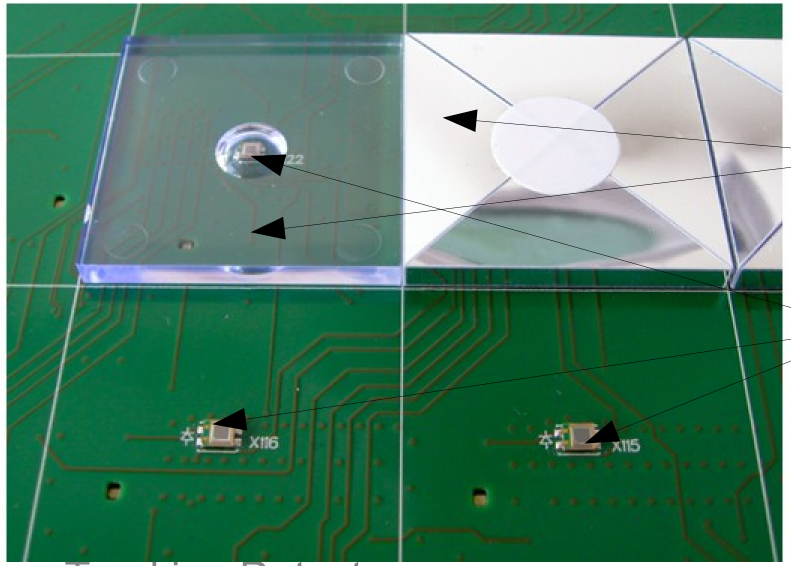
- Sensitive Medium III: Plastic Scintillators

  - Two Component organic Material (Benzole Type)



Spectral sensitivity of Photocathodes

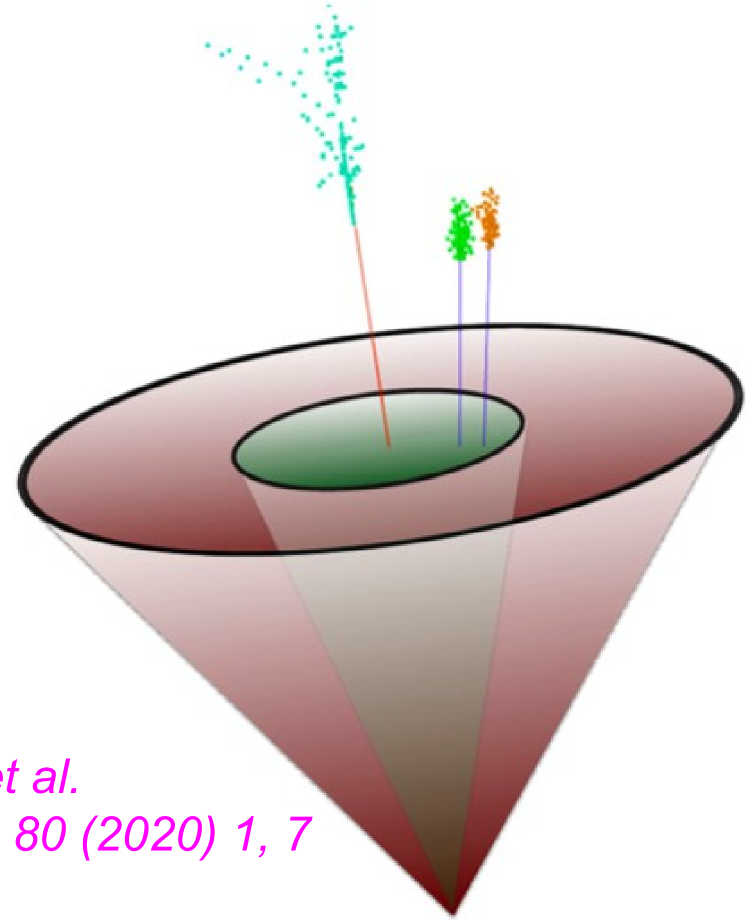




CALICE AHCAL with
- Scintillating Tiles (3x3cm^2) and
- Silicon Photomultipliers (SiPM)

!

τ-lepton reconstruction – The major challenge for the Ecal



From D. Yu et al.
Eur.Phys.J.C 80 (2020) 1, 7

Available Tau Finders:

- TAURUS (for CEPC)
- Tau-Finder in ILD Marlin

- Features on τ τ fnal states
  - Small multiplicity
  - => Can cut on small number of Particle Flow objects
- Assets of granular calorimeters
  - High granularity allows for counting of PFO
  - Clean separation of charged pion from photon clusters
  - Spatial resolution of close-by photons (at reasonable energy resolution)

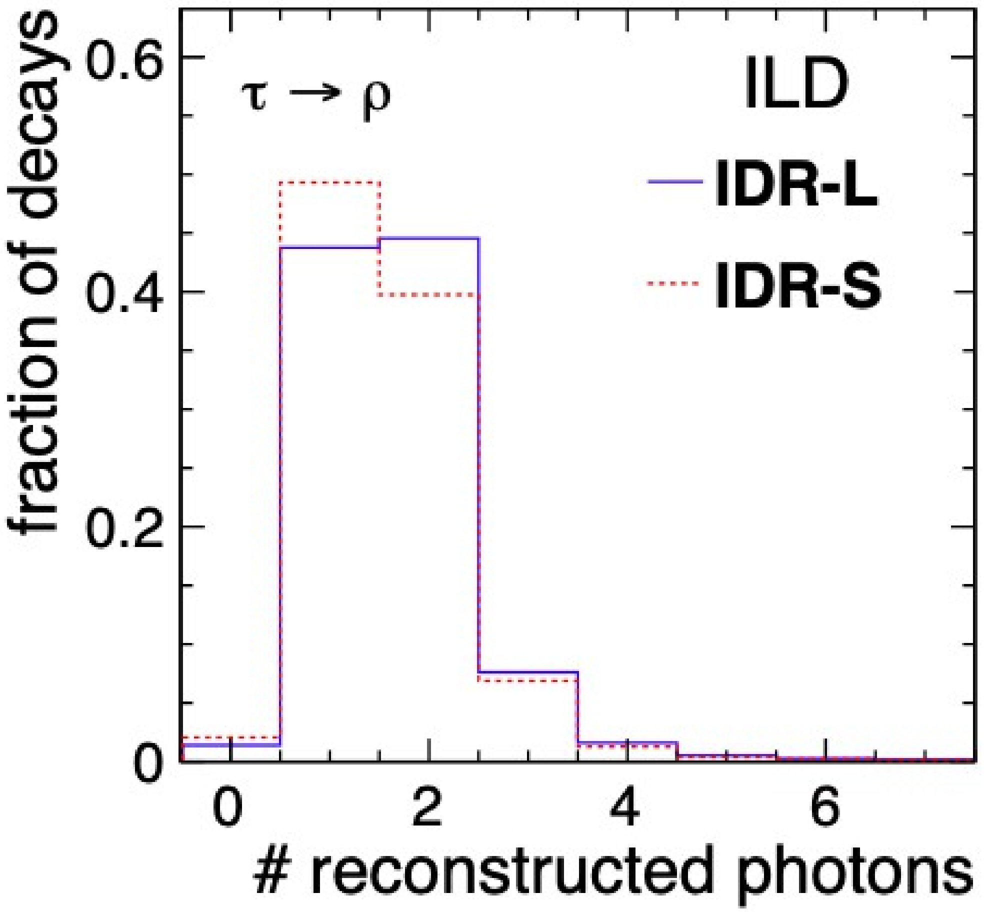
Migration of tau final states

Reco. decay	True decay $(\pi\nu,\pi\nu)$	$(\pi\nu,\rho\nu)$	$(\rho\nu,\rho\nu)$
	$Z\to\mu^+\mu^-$		
$(\pi\nu,\pi\nu)$	93	3	< 1
$(\pi\nu,\rho\nu)$	7	93	6
$(\rho\nu,\rho\nu)$	< 1	4	94
	$Z\to qq(uds)$		
$(\pi\nu,\pi\nu)$	89	6	< 1
$(\pi\nu,\rho\nu)$	11	89	12
$(\rho\nu,\rho\nu)$	< 1	5	87

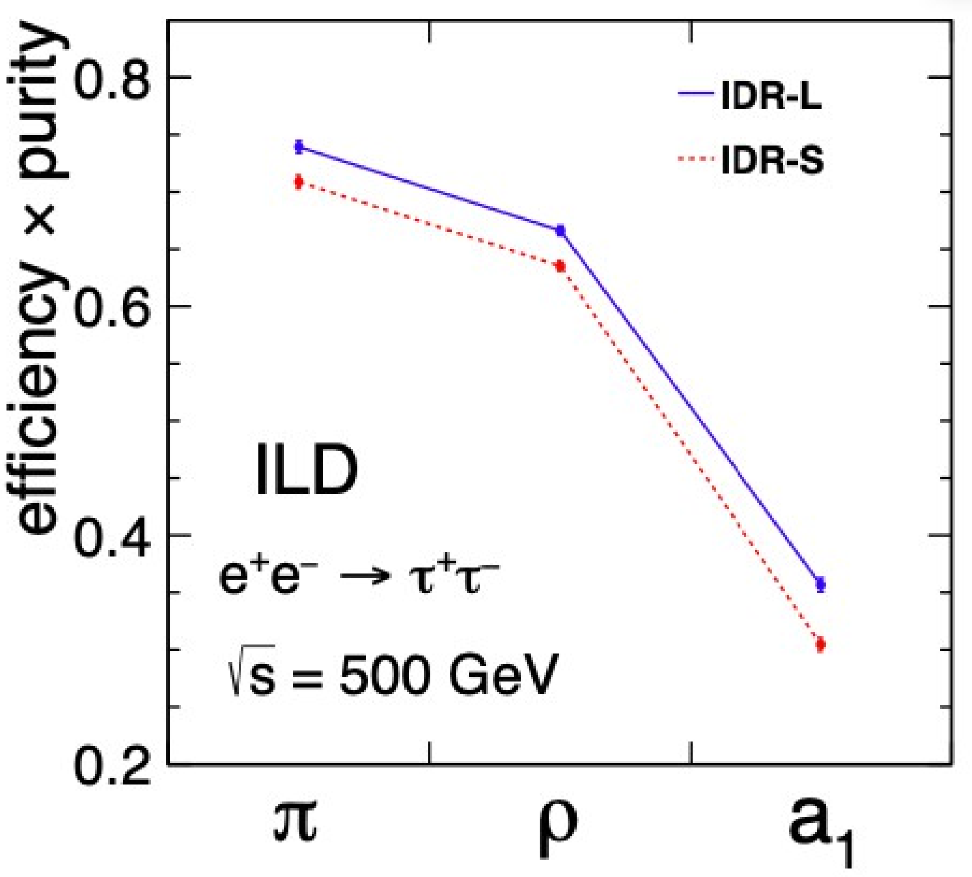
D.Jeans, G. Wilson
Phys.Rev.D 98 (2018) 1, 013007

$e^+e^- \to \tau^+\tau^-$

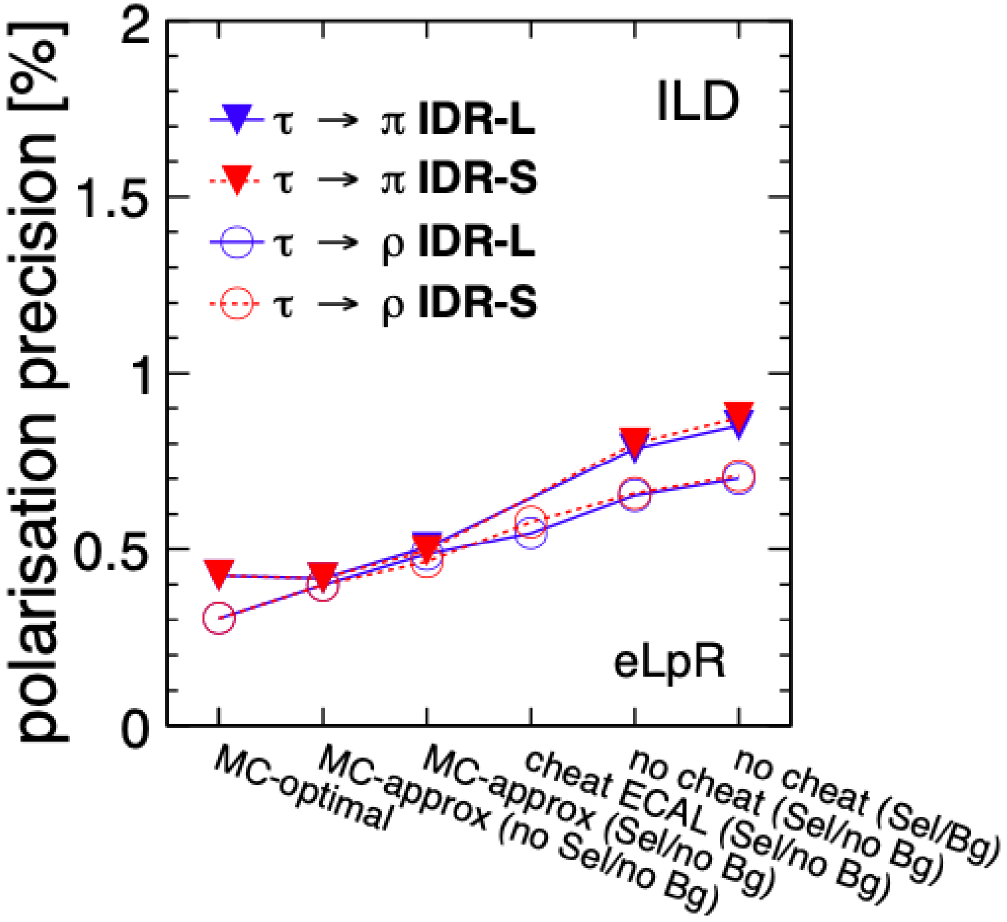
Recent study at 500 GeV for ILD IDR



- Photon separation gets involved at high energies
- Still often only one photon reconstructed



- EfficiencyxPurity drops with increasing photon multiplicity



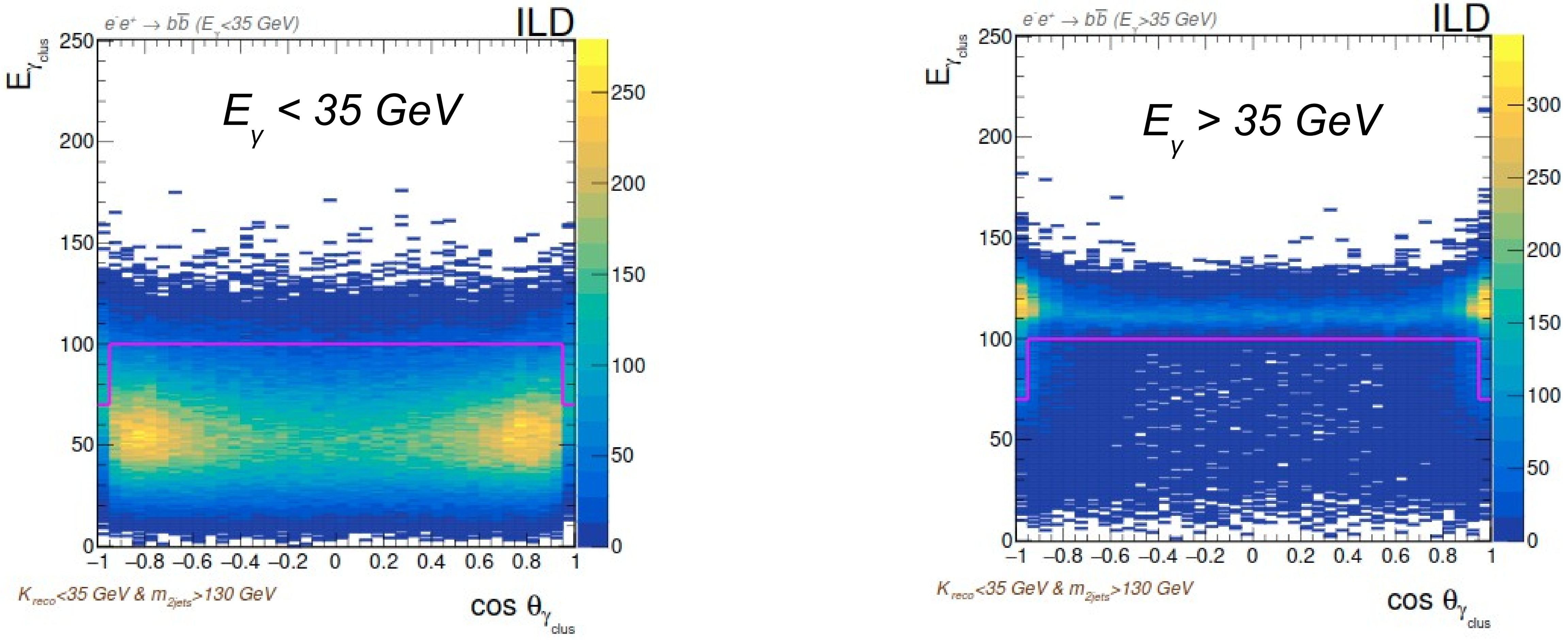
Precision of tau polarisation of order 0.3%-1%

- Close-by photons are challenge for highly granular calorimeters (in particular Ecal) at high-energies
- Ideal benchmark for detector optimisation
- Maybe still room for improvement, better algorithms?

Measuring the ISR Photon in the Ecal

- Most ISR Photon are radiated collinearly but lead to a boost -> Check for acolinearity of dijet event
- Method doesn't work when photon is radiated into detector acceptance
  - ... and merged with a jet --> Busy environment

No or mild ISR — "Strong" ISR



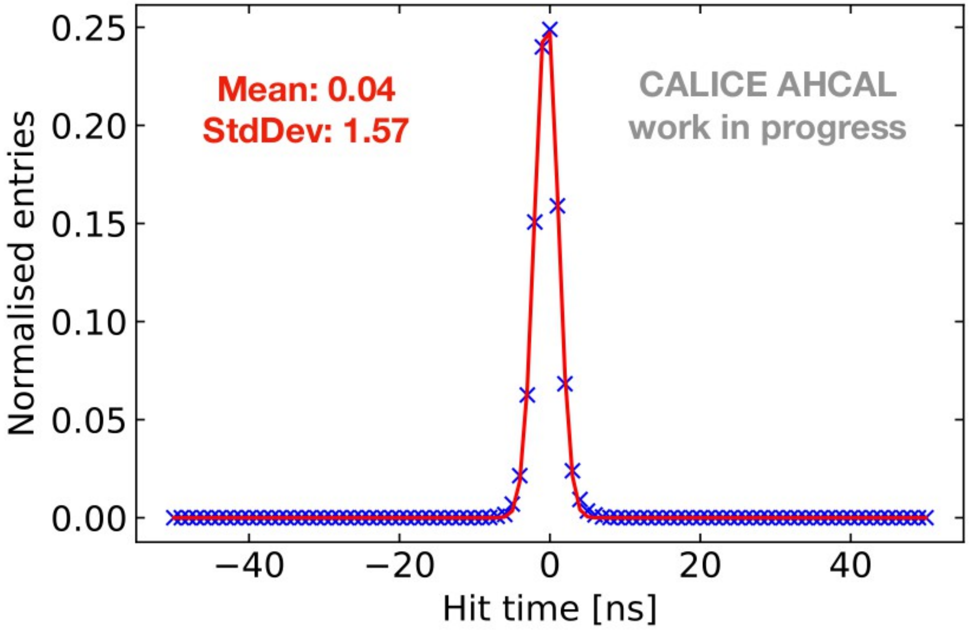
- Excellent photon ID in granular calorimeter is key
- Identification of ISR photon within detector (jet) reduces ISR background by nearly a factor of six
- Would be interesting to carry out this analysis with less granular calorimeters

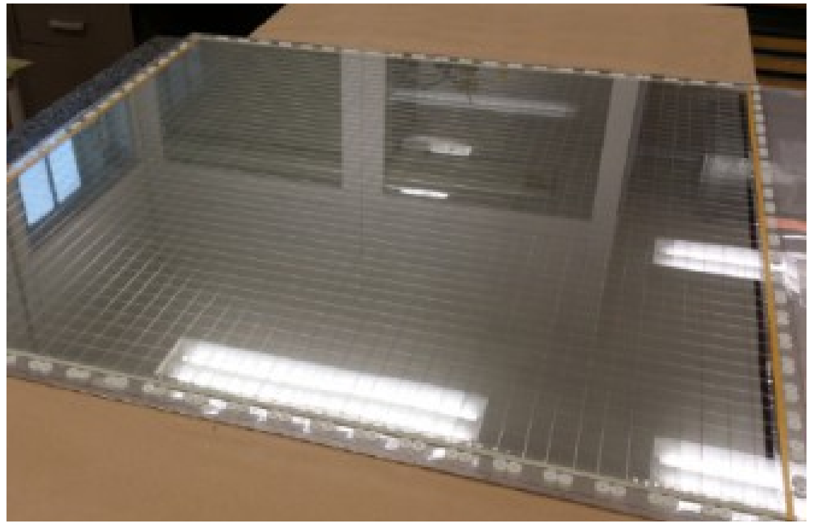
ILD: Irles, Richard, R.P.

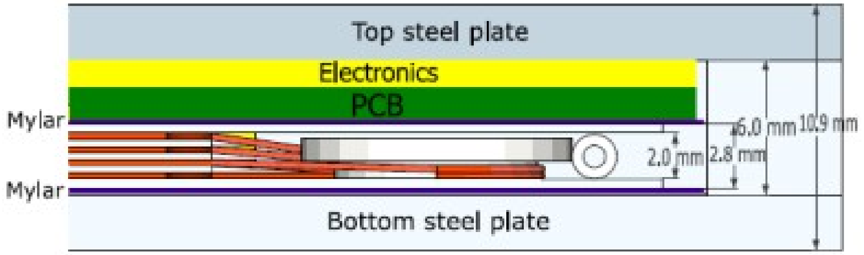
New Trends – Timing III

Hit time resolution:
Results from 2018 beam test of AHCAL with muons

Clock frequency 5 MHz,
Powering pulsing



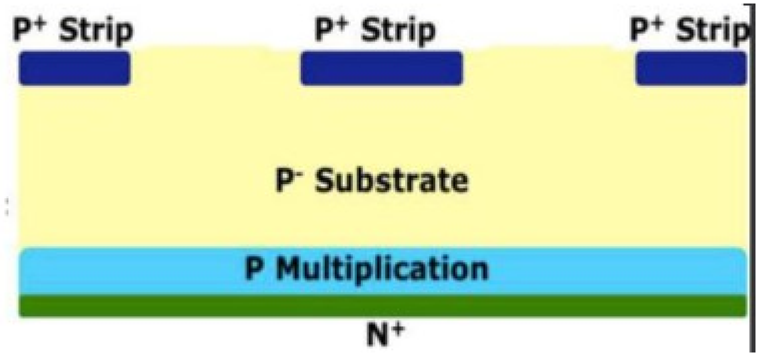




Under development:
GRPC with PETIROC

- < 20ps time jitter
- Developed for CMS Muon upgrade

Inverse APD as LGAD?

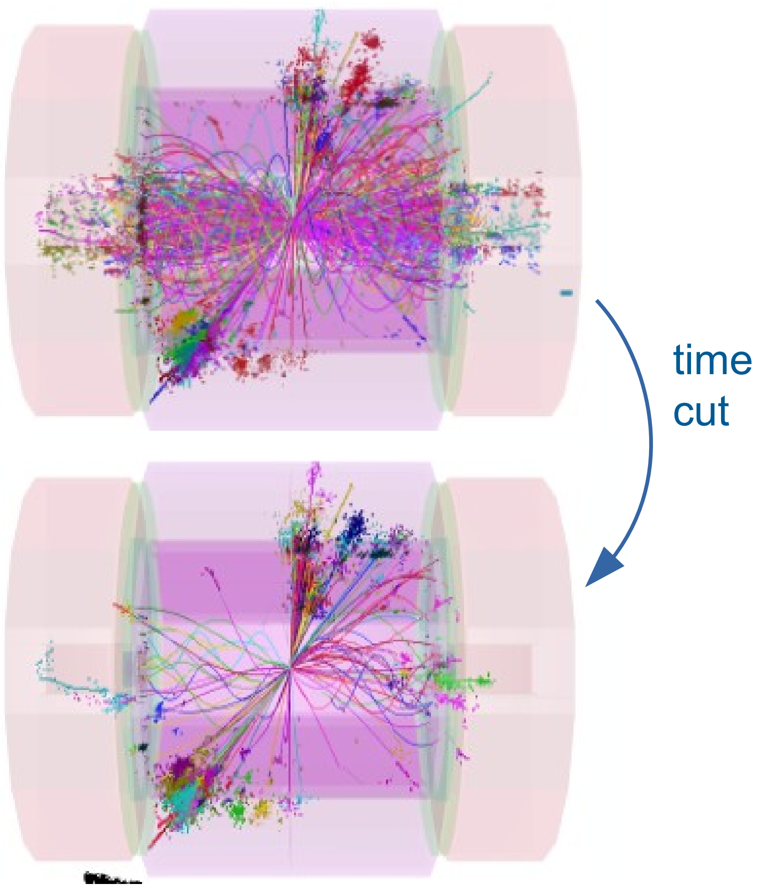


Inverse APD
by Hamamatsu

Gain ~ 50

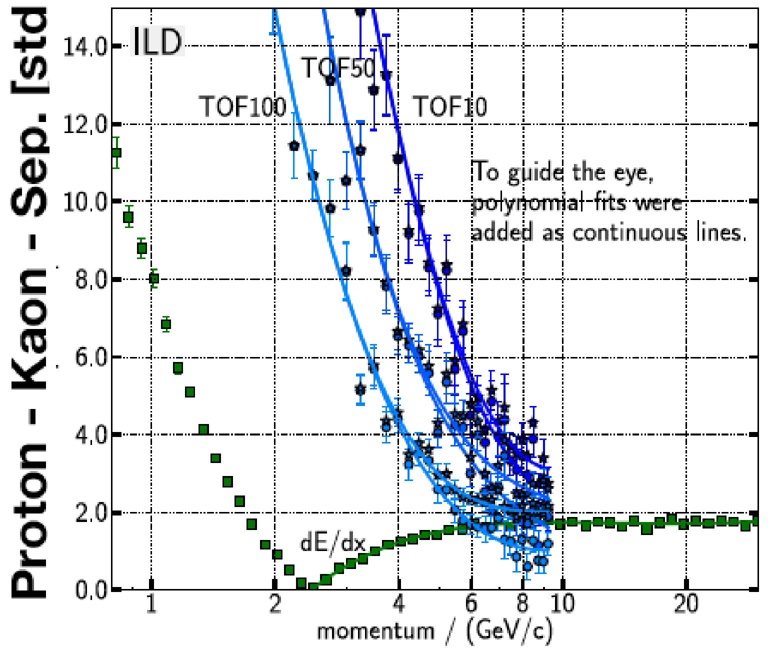
New Trends – Timing I

Cleaning of Events



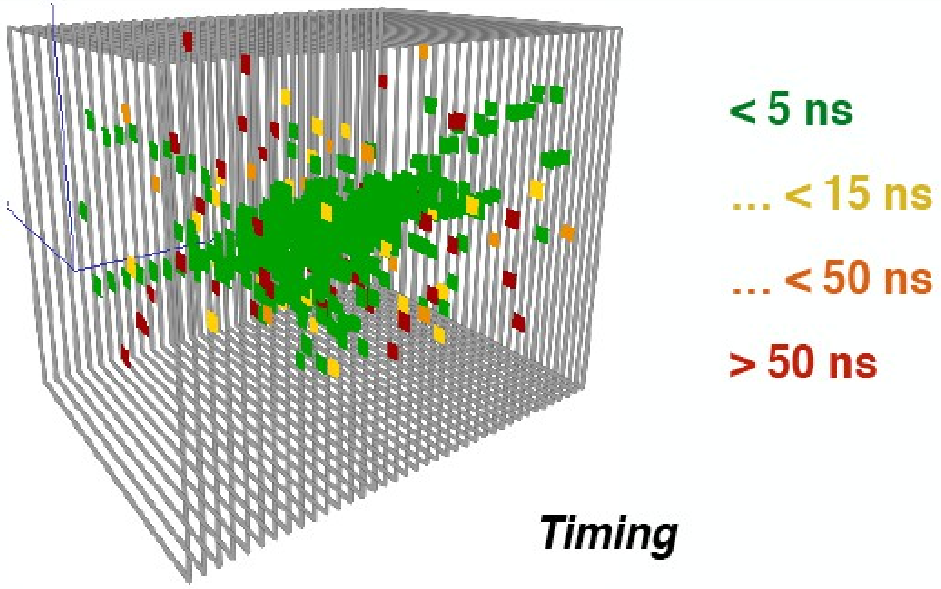
[CLIC CDR: 1202.5940]
adapted from L. Emberger

Particle ID by Time-of-Flight
- Complementary to dE/dx
  - here with 100ps on 10 ECAL hits



S. Dharani, U. Einhaus, J. List

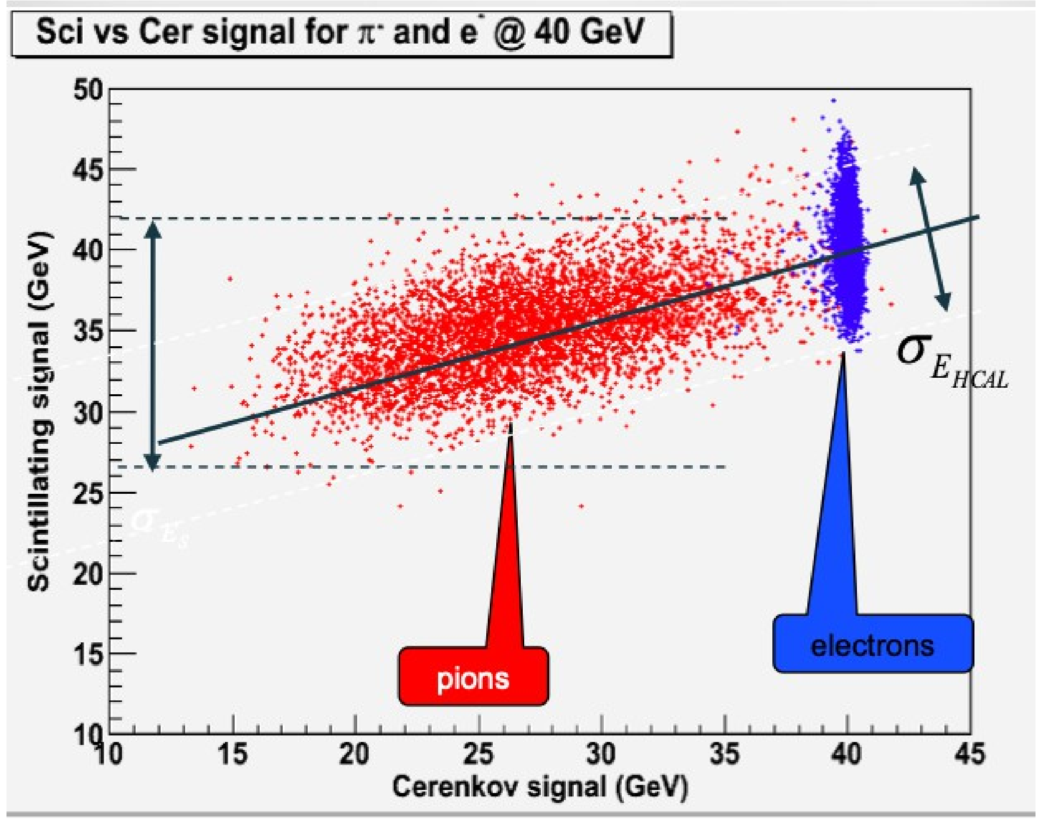
Ease Particle Flow:
- Identify primers in showers
- Help against confusion
- Cleaning of late neutrons & back scattering.



Ch. Graf

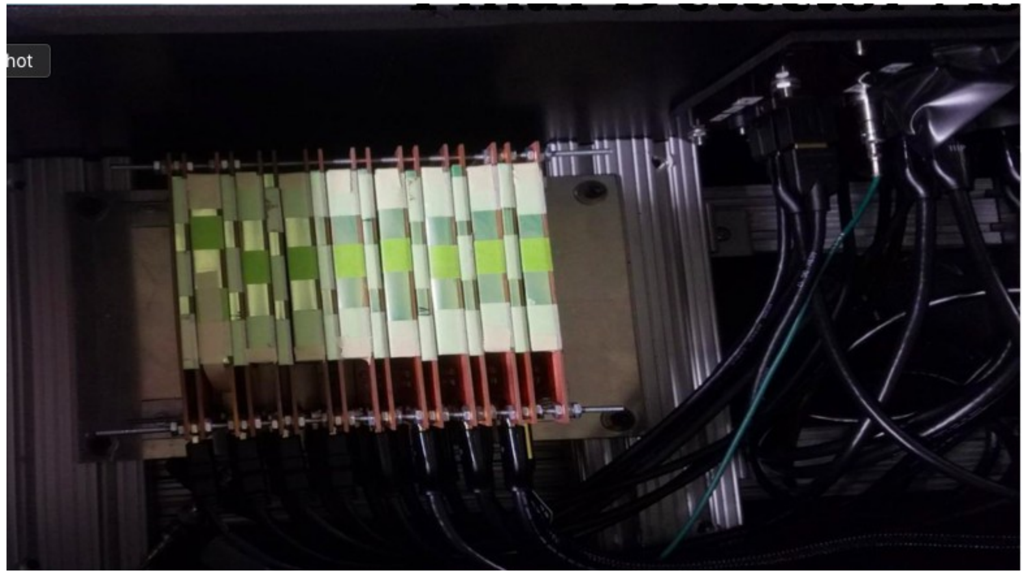
New Trends – Dual readout goes highly granular

Principle of Dual Readout

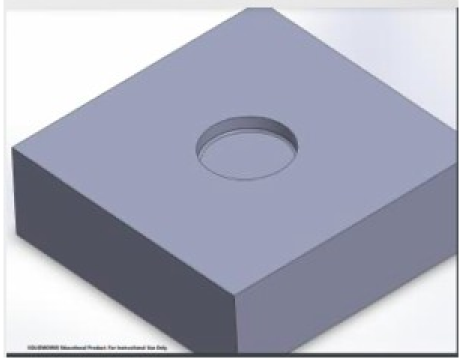


- Simultaneous readout of
  - Cerenkov Light from electromagnetic shower component
  - Scintillation light from Hadronic shower component

Adriano Beamtest with 10x10 cm^2 Glass (=Cerenkov) and Plastic scintillator (= Sc.) tiles



Next step:



3x3 cm^2 Glass tile

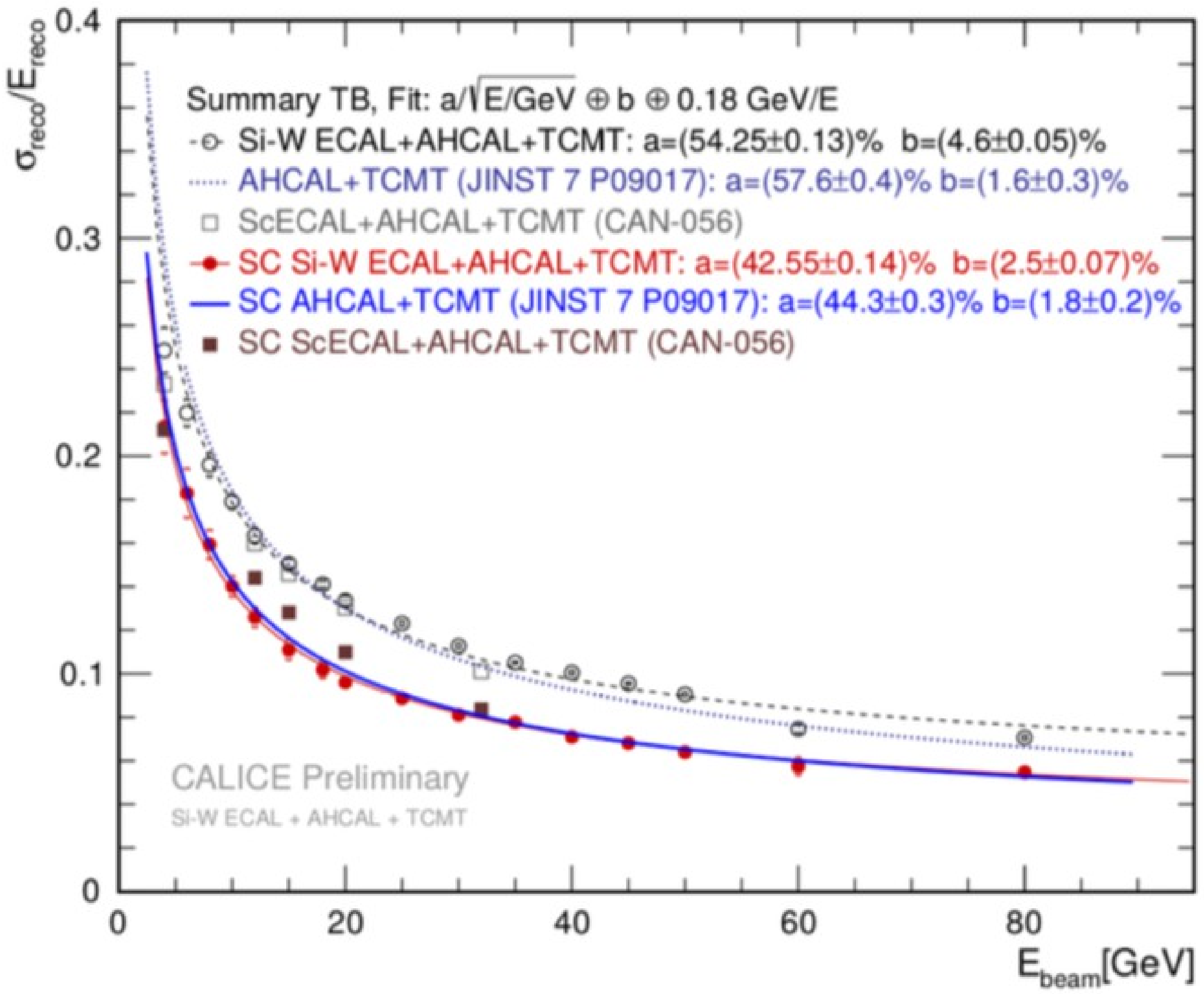
3x3 cm^2 Plastic Tile

Dual Readout with "CALICE Size" tiles

C. Gatto, CALICE TB Meeting

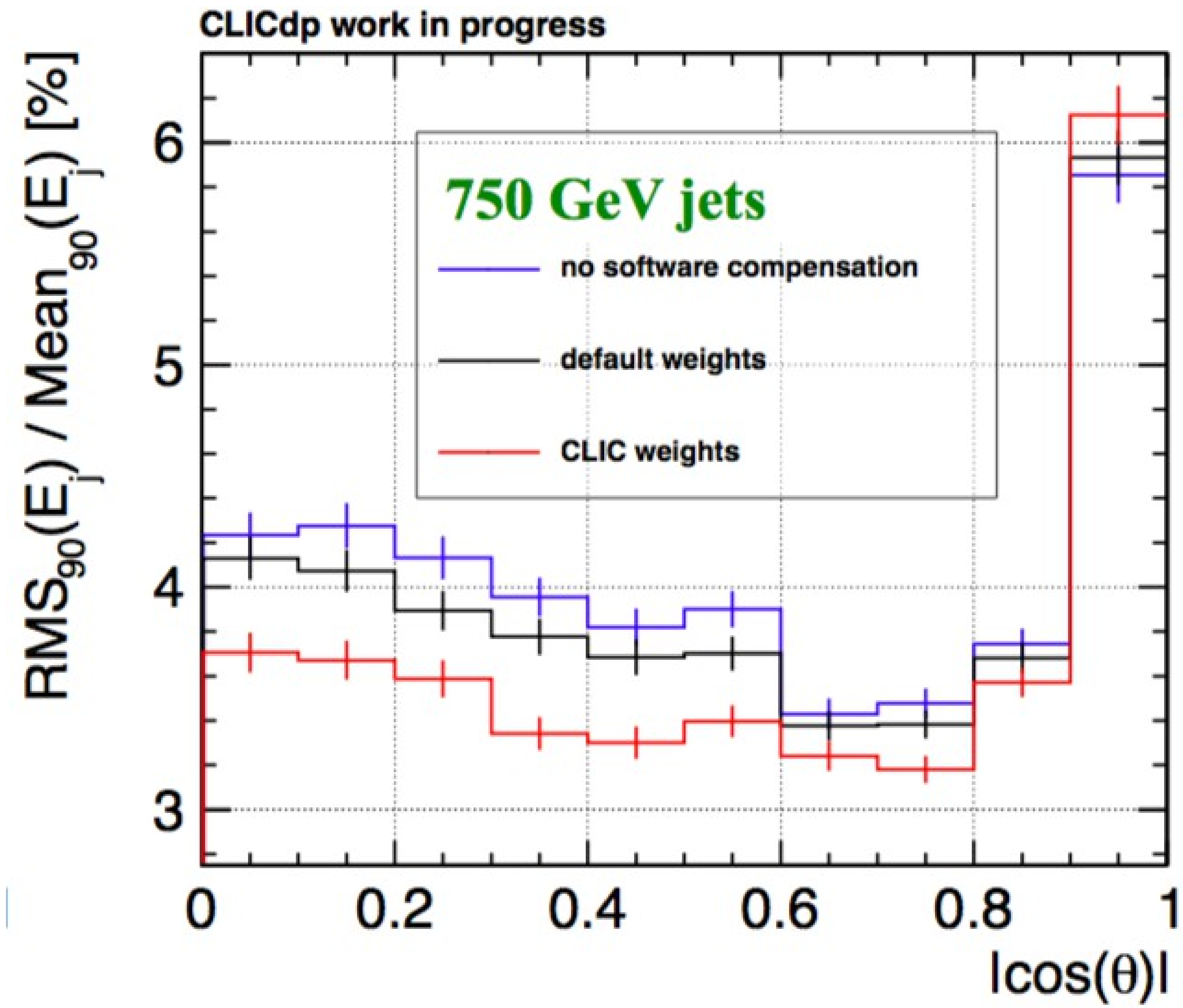
Hadronic and jet energy resolution with highly granular calorimeters

Pion showers in combined CALICE beam tests



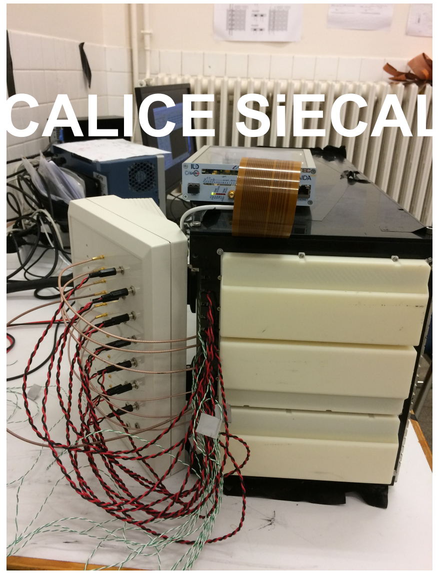
- Improvement by software compensation
  - i.e. Adequate weighting of energy depositions

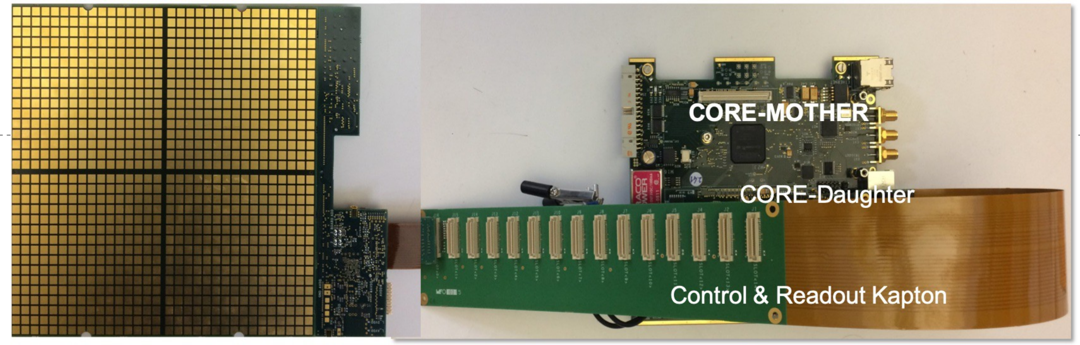
Jet analysis in CLIC

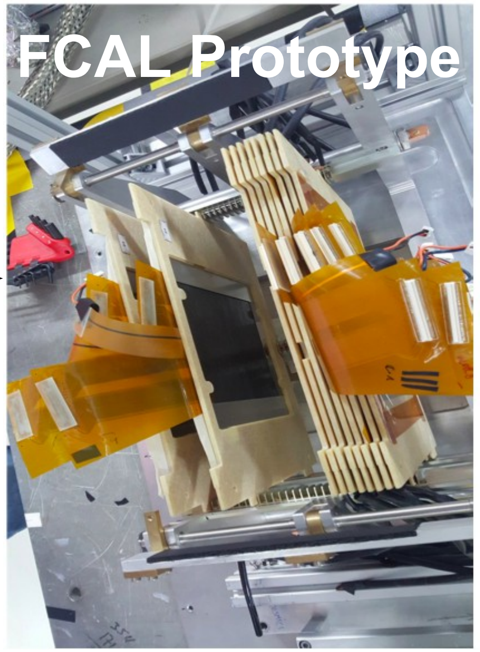


Software weighting improves jet energy resolution

The quest for hermeticity







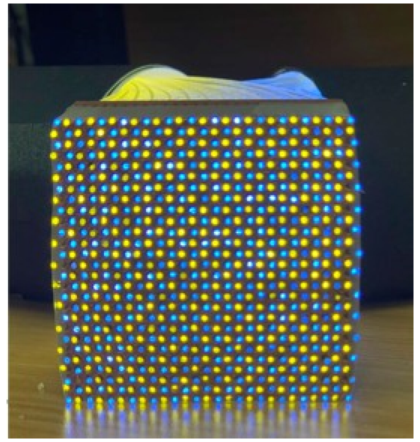
Adaptation of compact readout system
developed for SiW ECAL in AIDA2020
to other prototypes of granular calorimeters

Project timescales for new calorimeters

Project	~Earliest start of data taking	Current Calorimeter options					
		Solid state	Scintilling tiles/strips	Crystals	Fibre based r/o (including DR)	Gaseous	Liquid Noble Gas
HL-LHC (>LS4)	2030			✔	✔		
SuperKEKb (>2030)	2030			✔			
ILC	2035	✔	✔			✔	
CLIC	2040	✔	✔				
CEPC	2035	✔	✔	✔	✔	✔	✔
FCC-ee	2040	✔	✔	✔	✔	✔	✔
EiC	2030		✔	✔	✔		
FCC-hh	~2050						

Fast signals

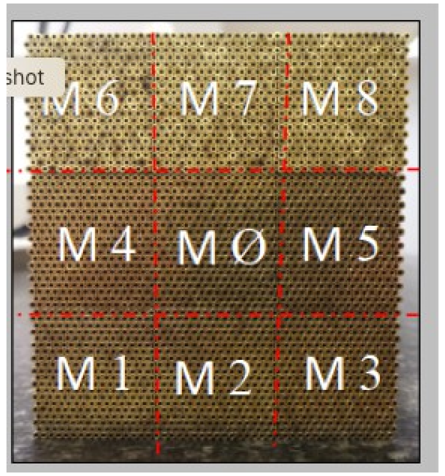
Slow signals



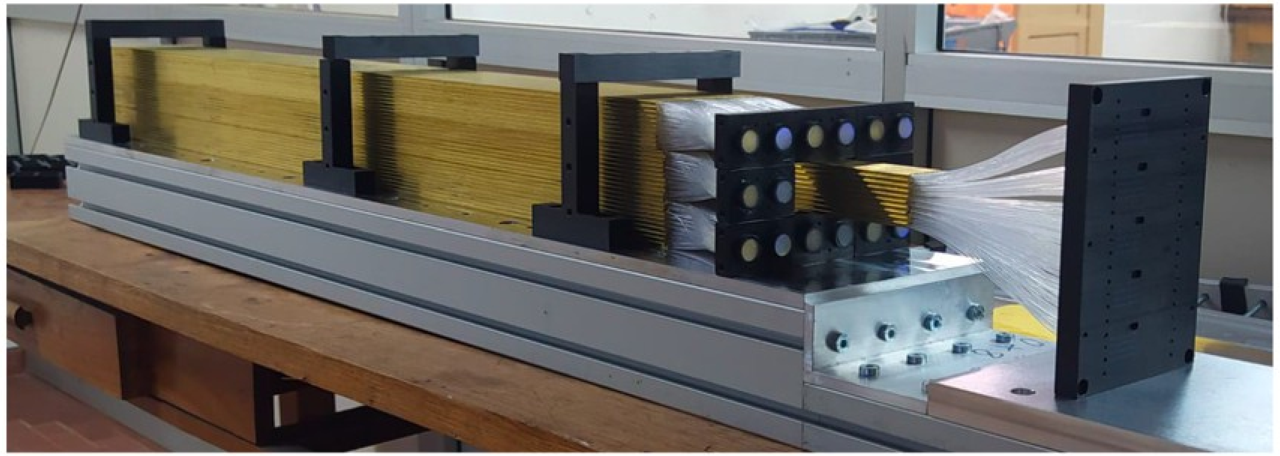
Dual readout to capture Electromagnetic and hadronic components of shower

Prototype development

- First step “electromagnetic prototype” 10x10x100cm^3
  - Qualification of
    - Assembly procedure
    - Readout systems



Stack of capillaries



Outgoing fibres guided to readout plane