Implementation of large imaging calorimeters

Roman Pöschl

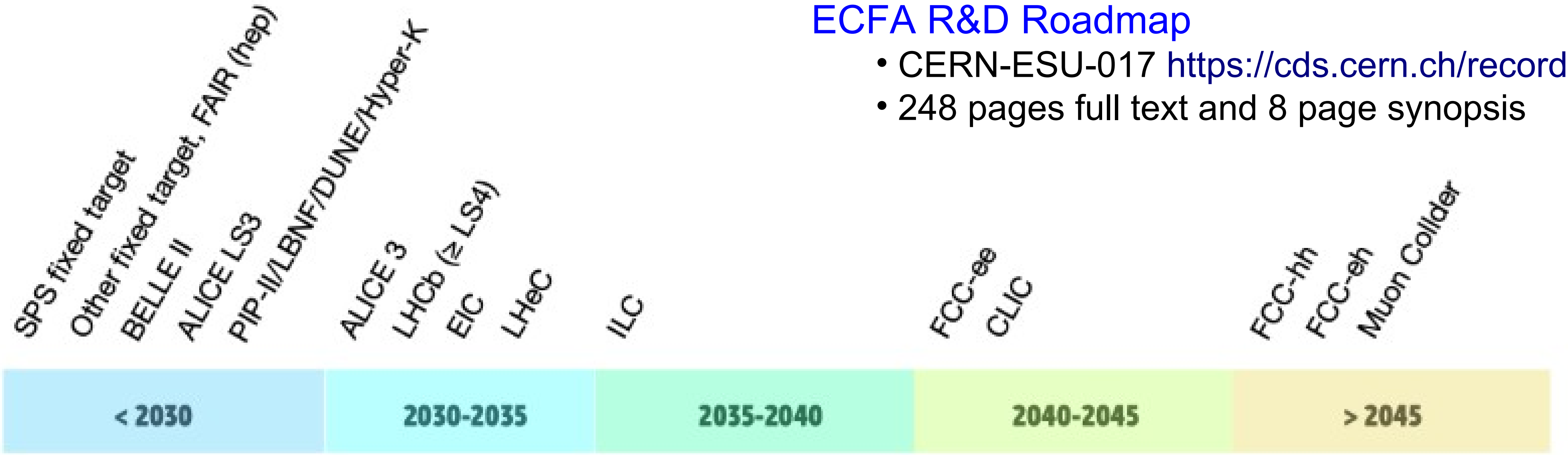
On behalf of the CALICE Collaboration

Seminar CPPM – April 2023

Supported by AIDA innova

The landscape

- The timeline for future projects and facilities

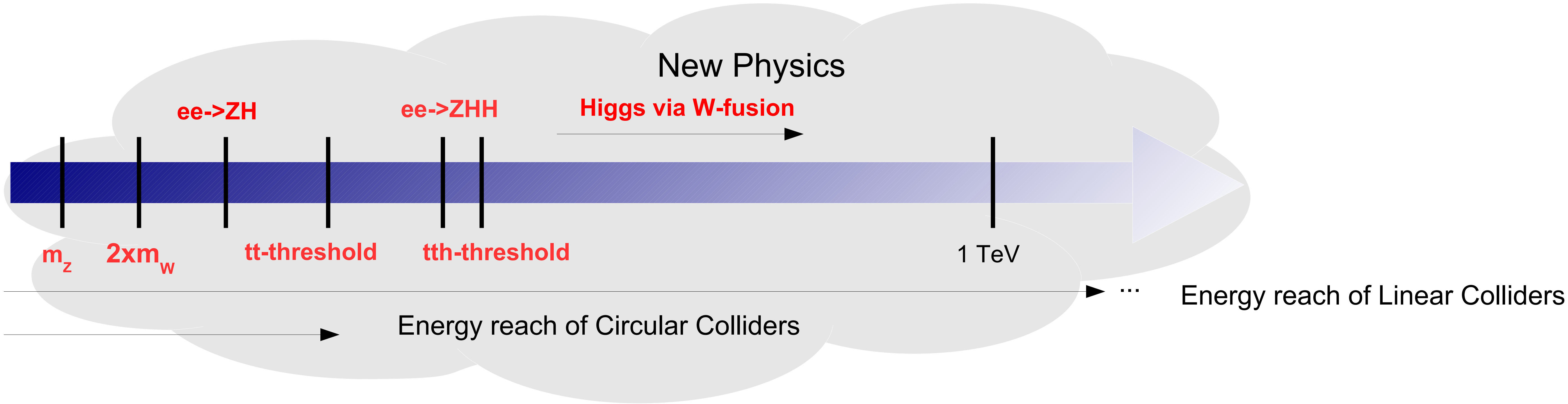


ECFA R&D Roadmap

- CERN-ESU-017 https://cds.cern.ch/record/2784893
- 248 pages full text and 8 page synopsis

- High energy e+e- colliders (ILC, FCC-ee, CEPC aka **Higgs Factories**) are among the **next major facilities in sight for particle physics**
- Therefore this seminar focuses on detector R&D relevant (mainly) for Higgs Factories

e+e- Physics program



New Physics

ee->ZH

ee->ZHH

Higgs via W-fusion

m_Z

$2xm_W$

tt-threshold

tth-threshold

1 TeV

… Energy reach of Linear Colliders

Energy reach of Circular Colliders

All Standard Model particles within reach of planned e+e- colliders

High precision tests of Standard Model over wide range to detect onset of New Physics

Machine settings can be “tailored” for specific processes

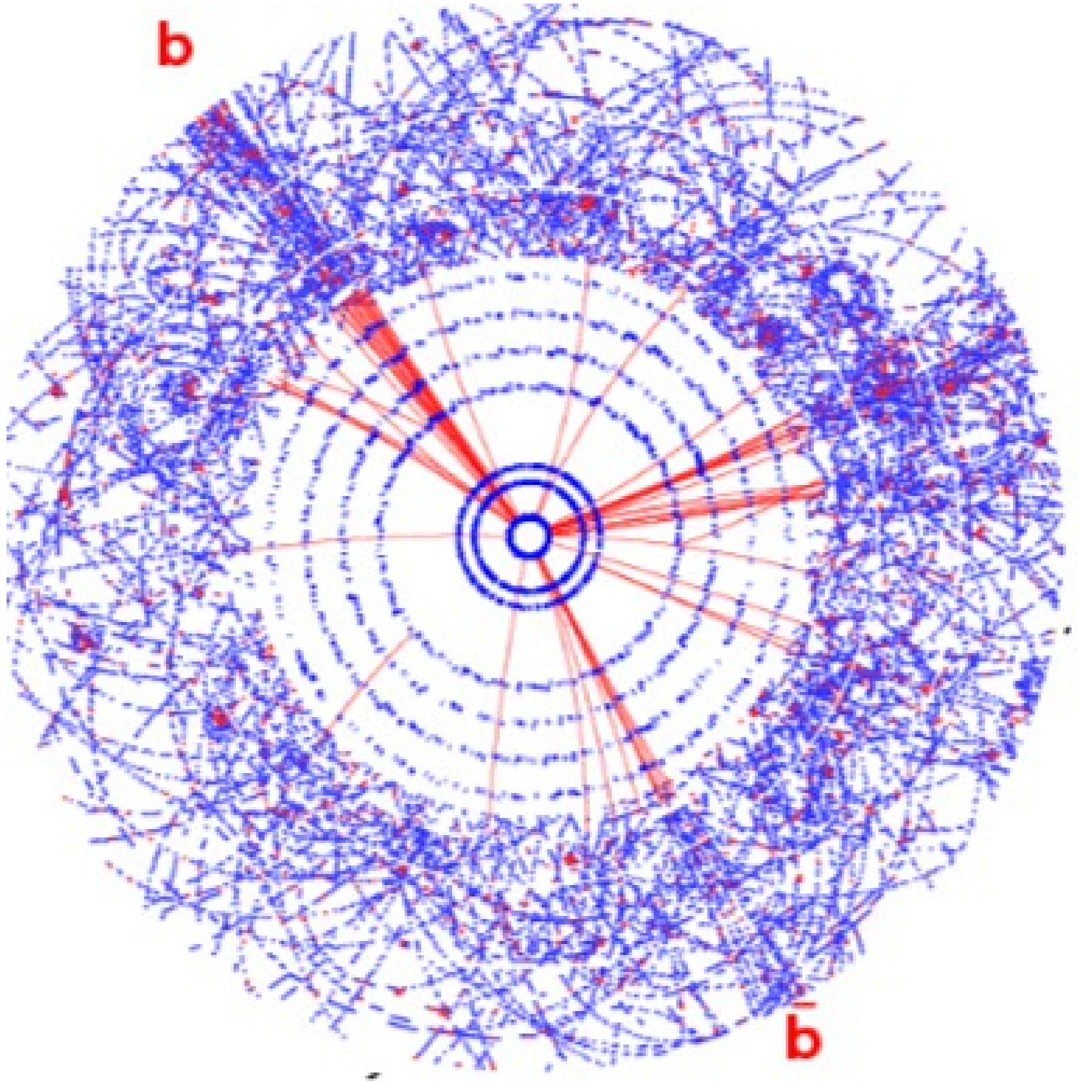
- Centre-of-Mass energy
- Beam polarisation (straightforward at linear colliders)

$$\sigma_{P,P'} = \frac{1}{4}\left[(1-PP')(\sigma_{LR}+\sigma_{RL})+(P-P')(\sigma_{RL}-\sigma_{LR})\right]$$

Background free searches for BSM through beam polarisation

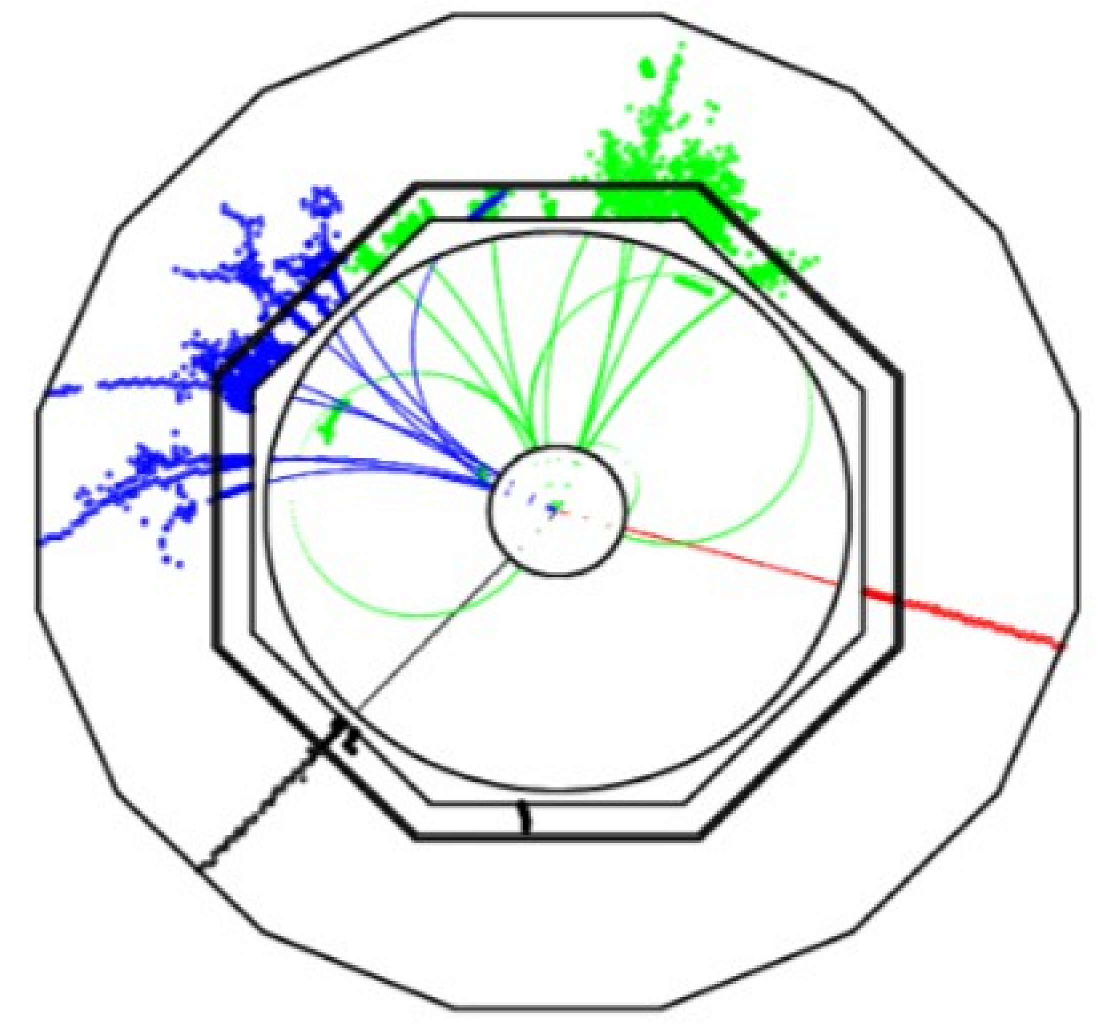
(Rough) Comparison – Hadron collisions ↔ e^+e^- collisions

Hadron-hadron collisions e.g. LHC



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

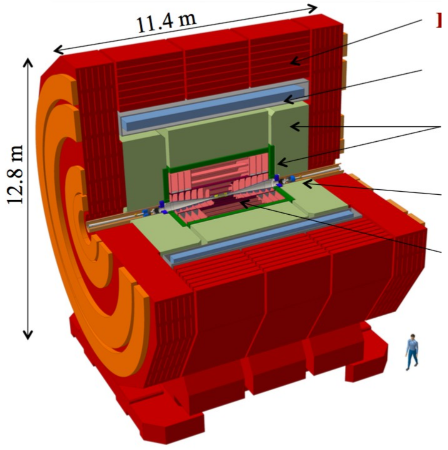
e^+e^--collisions

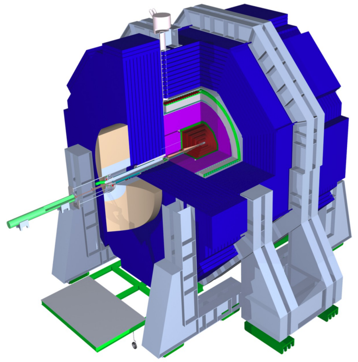


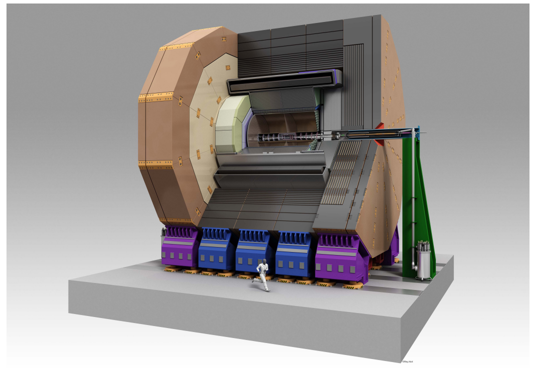
- Clean events
- No trigger
- Full event reconstruction

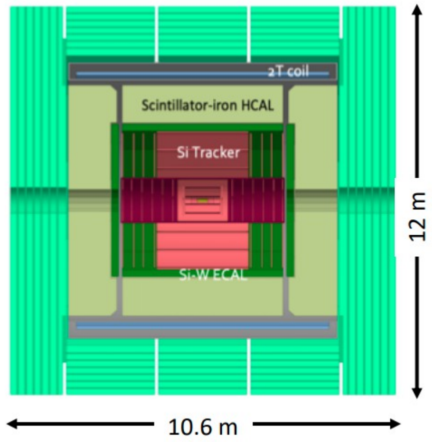
Detector systems – Target projects

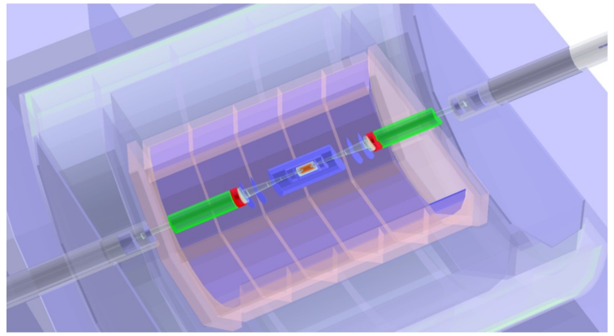
Detectors for Higgs Factories



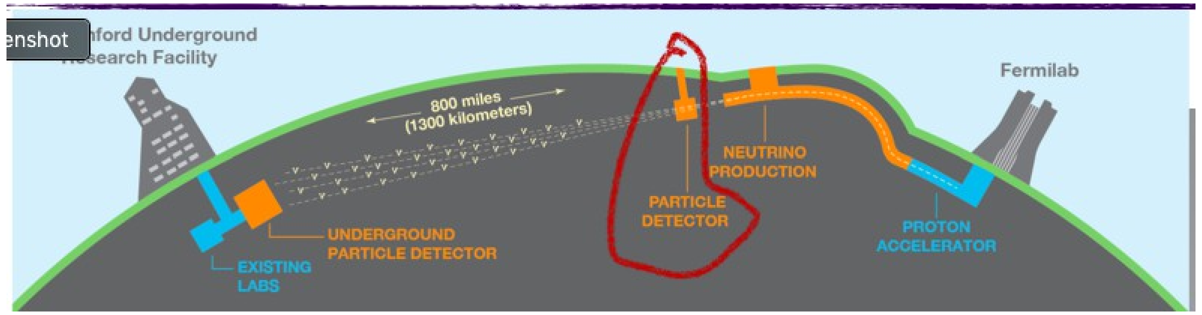








DUNE??

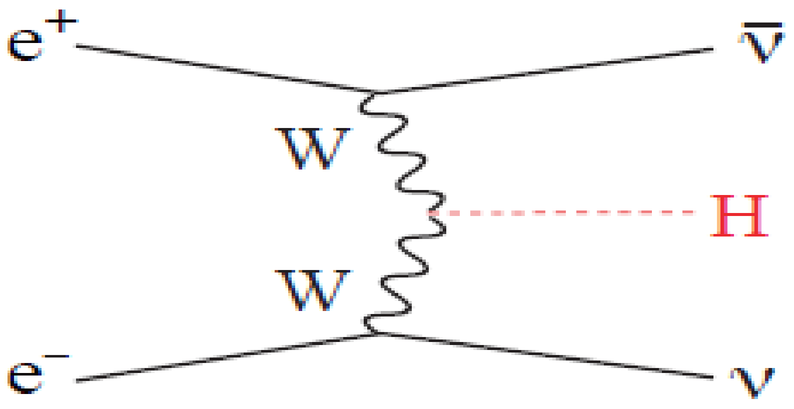


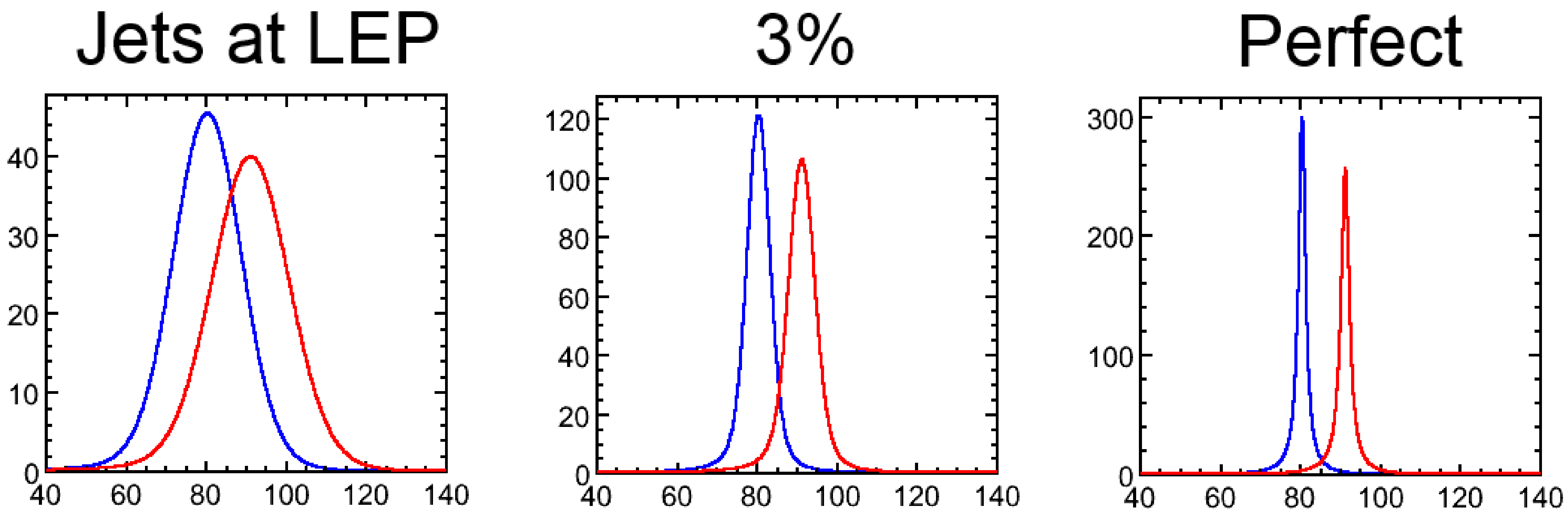
Near detector

Motivation for excellent jet energy measurement

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





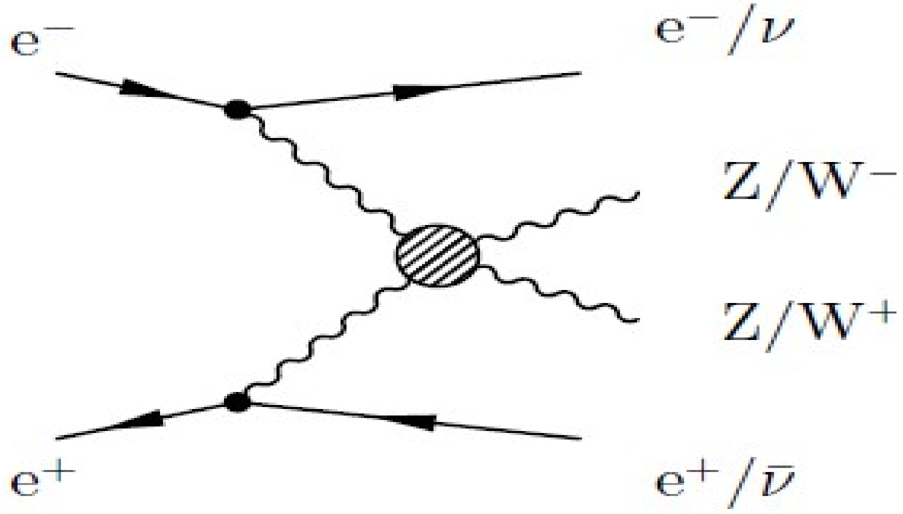


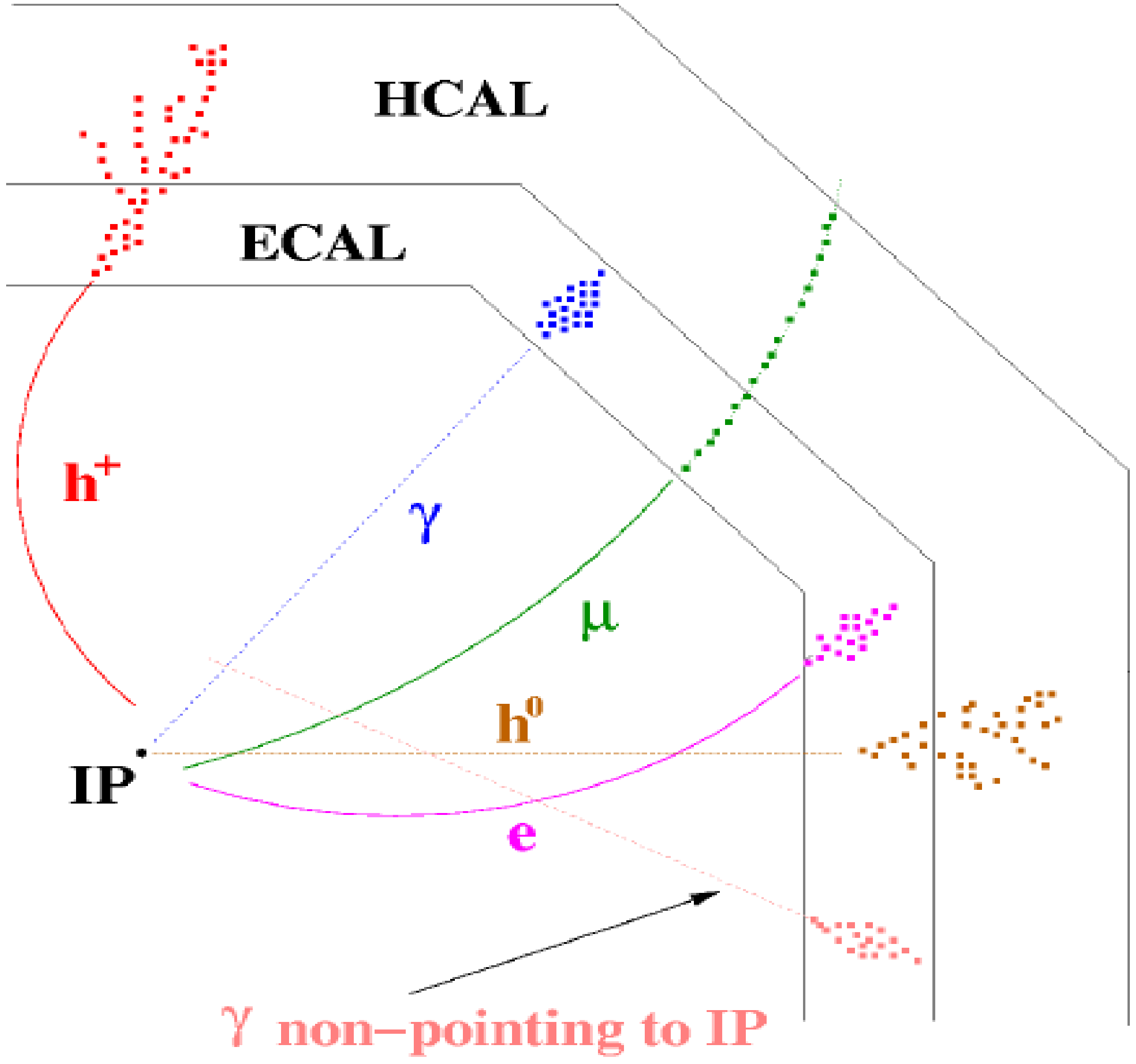
Figure by M. Thomson

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

Particle Flow Detector Layout

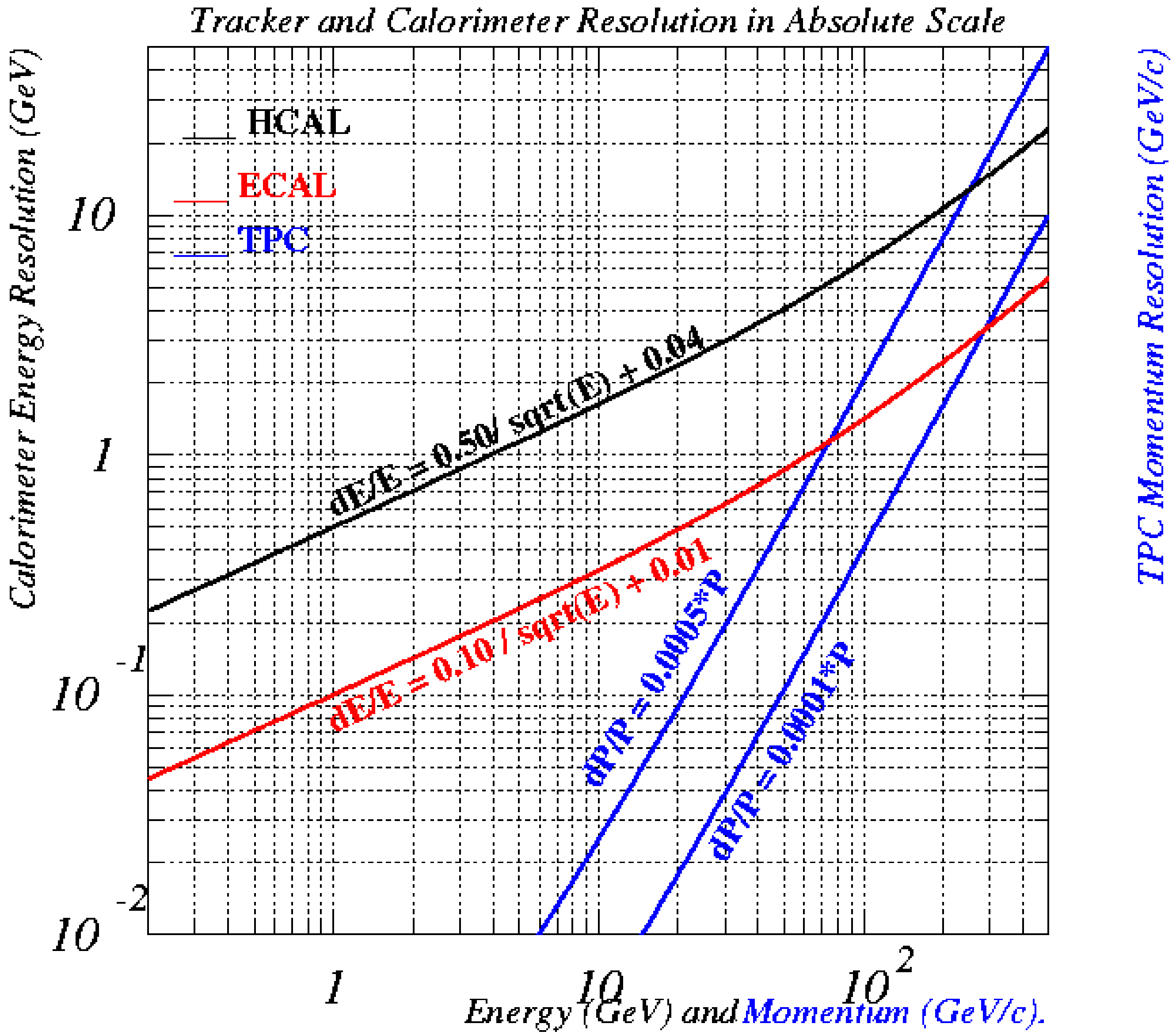
- Jet energy measurement by measurement of **individual particles**
- Maximal exploitation of precise tracking measurement

- Large radius and length
  - ➔ to separate the particles
- Large magnetic field
  - ➔ to sweep out charged tracks
- “no” material in front of calorimeters
  - ➔ stay inside coil
- Minimize shower overlap
  - ➔ Small Molière radius of calorimeters
- **high granularity of calorimeters**
  - ➔ to separate overlapping showers



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)



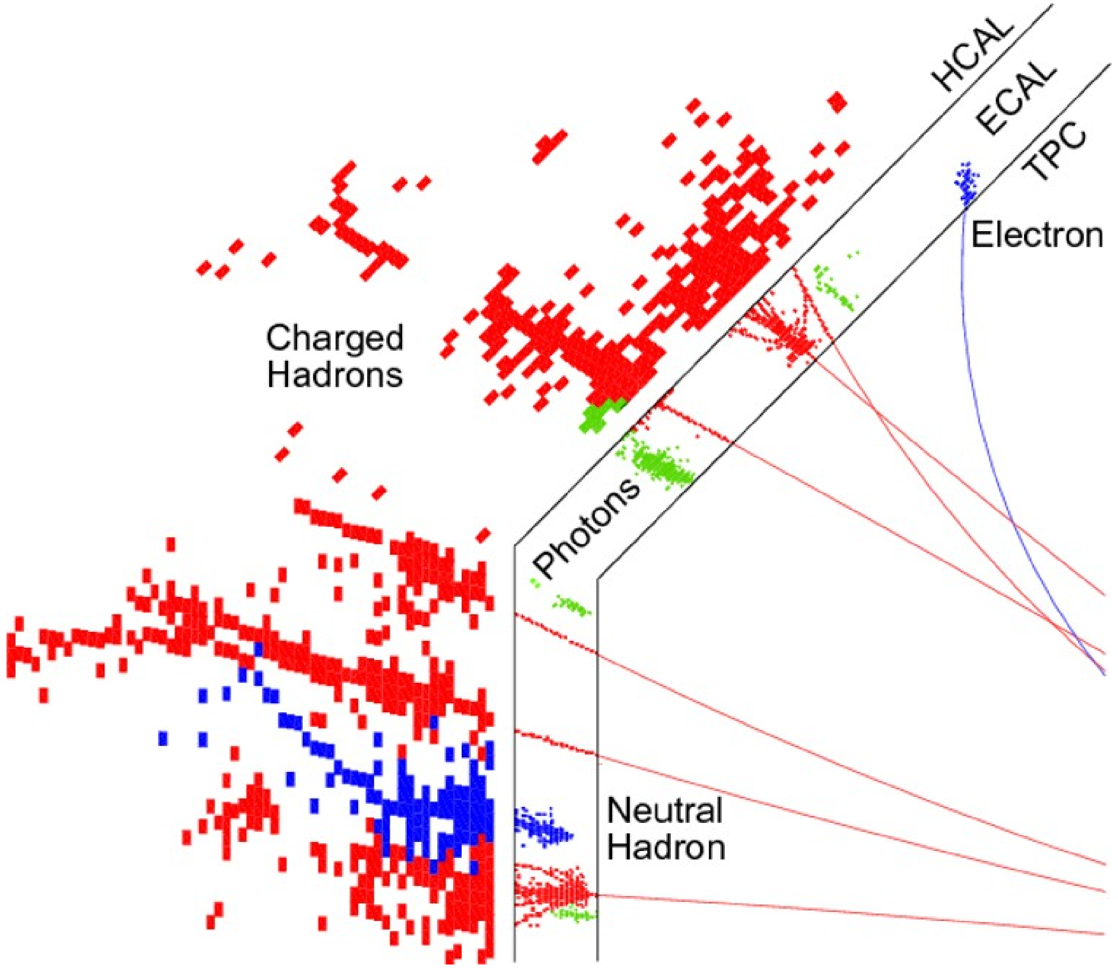
Jet energy carried by …

- Charged particles($e^{\pm}$, $h^{\pm}$,$\mu^{\pm}$): 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

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

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

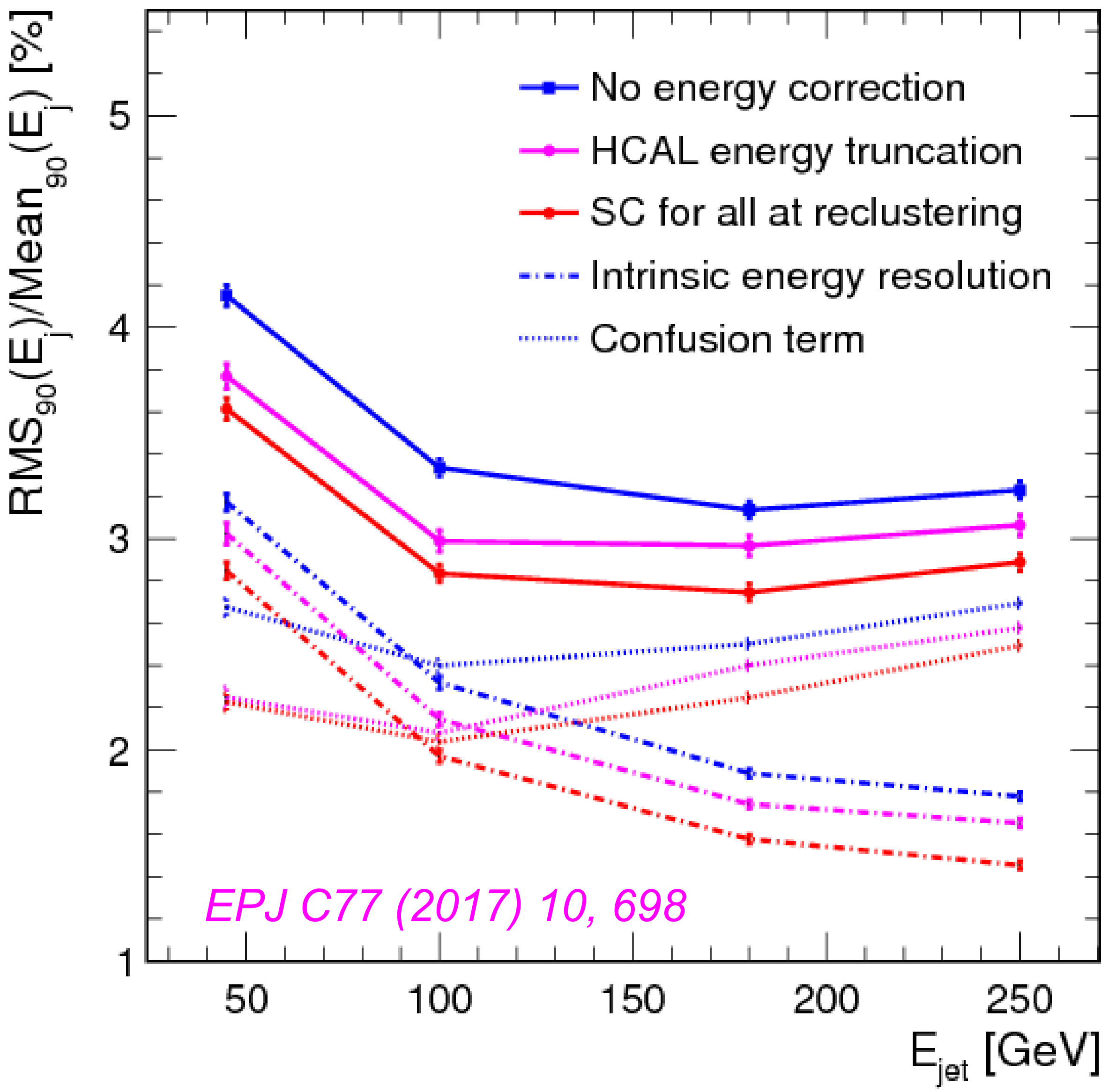
☐ **Confusion Term**

Need to minimize the confusion term as much as possible !!!

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



EPJ C77 (2017) 10, 698

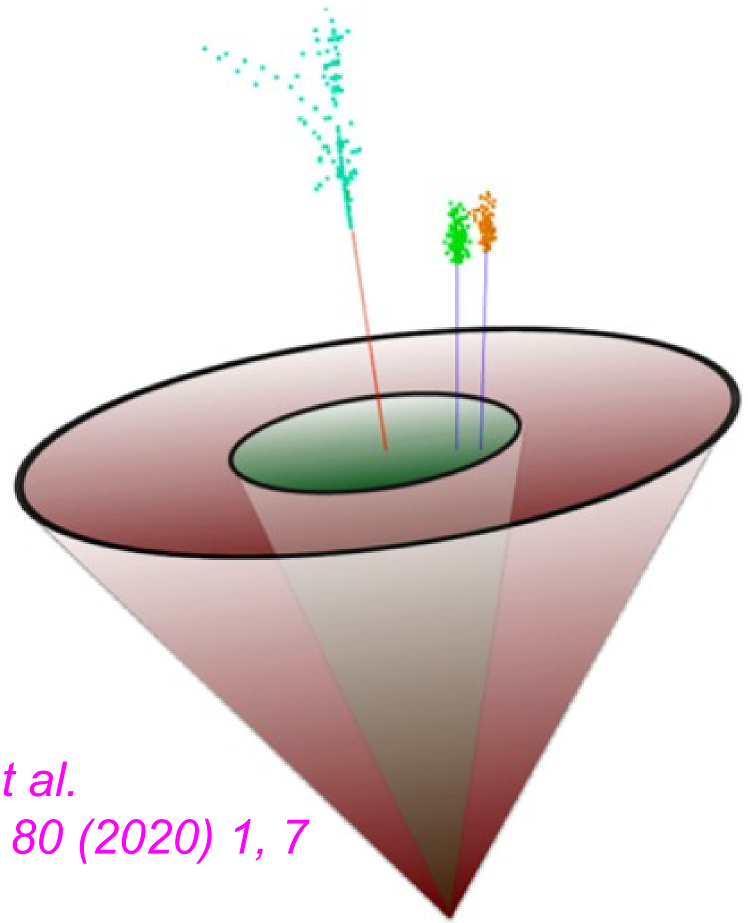
Study within ILD Concept

- 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

τ-lepton reconstruction – The major challenge for the Ecal



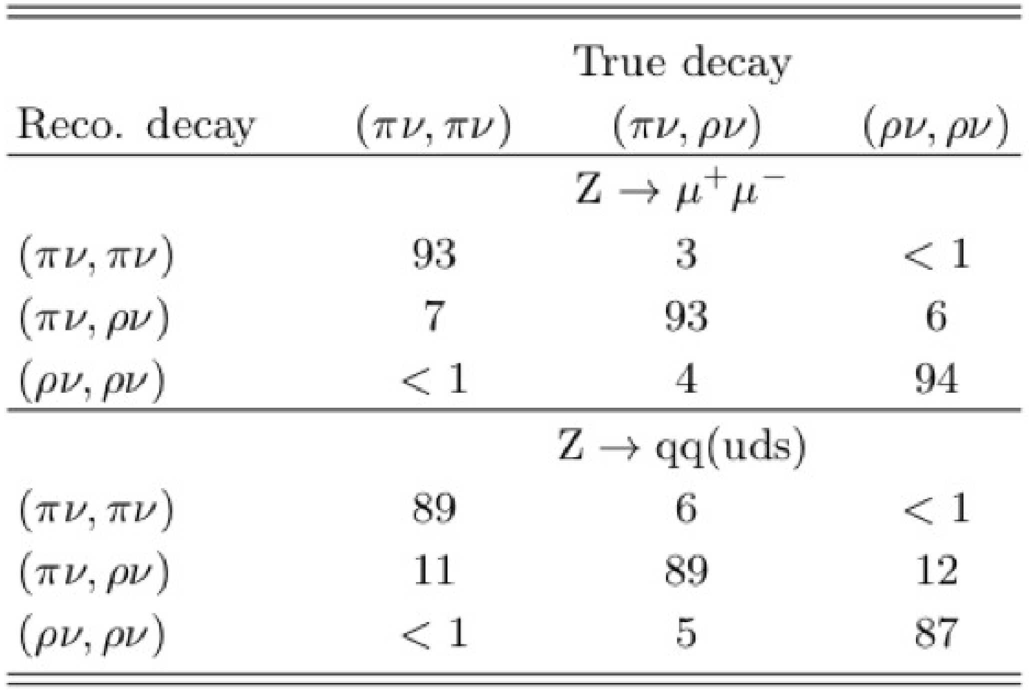
From D. Yu et al.
Eur.Phys.J.C 80 (2020) 1, 7

Available Tau Finders:

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

- Features on τ τ final 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

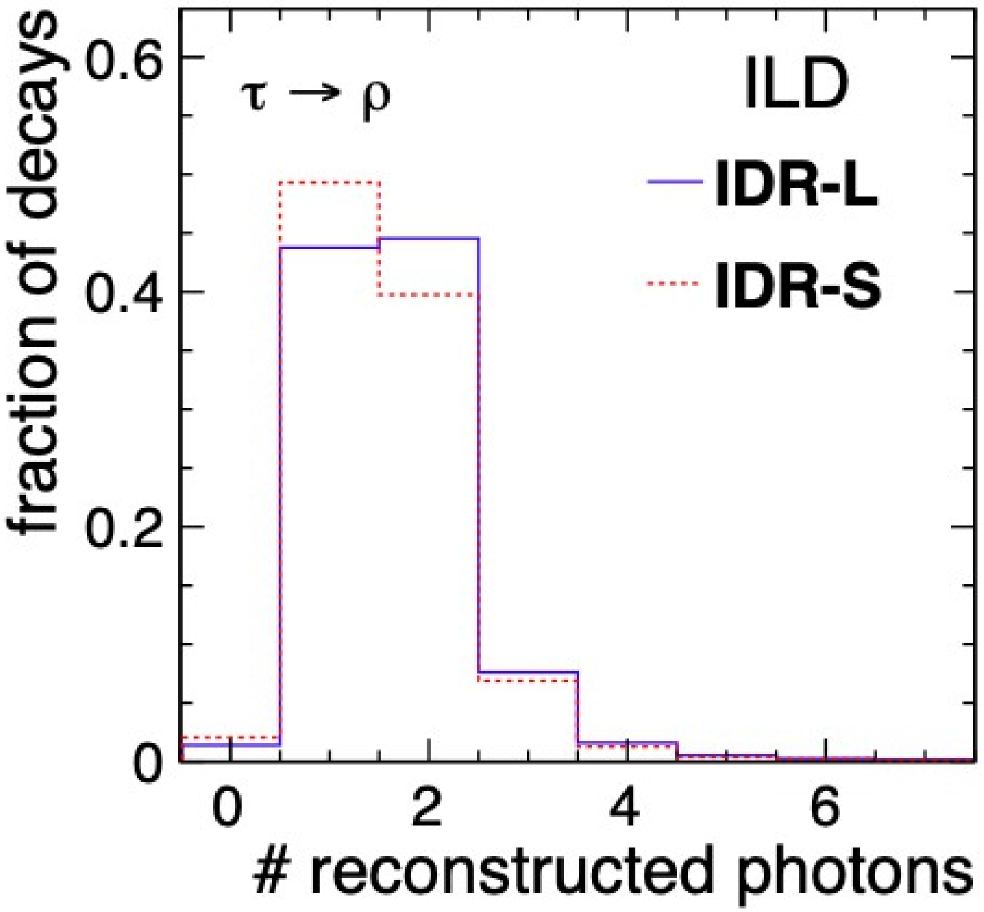


	True decay		
Reco. decay	$(\pi\nu, \pi\nu)$	$(\pi\nu, \rho\nu)$	$(\rho\nu, \rho\nu)$
	$Z \to \mu^+\mu^-$		
$(\pi\nu, \pi\nu)$	93	3	< 1
$(\pi\nu, \rho\nu)$	7	93	6
$(\rho\nu, \rho\nu)$	< 1	4	94
	$Z \to qq(uds)$		
$(\pi\nu, \pi\nu)$	89	6	< 1
$(\pi\nu, \rho\nu)$	11	89	12
$(\rho\nu, \rho\nu)$	< 1	5	87

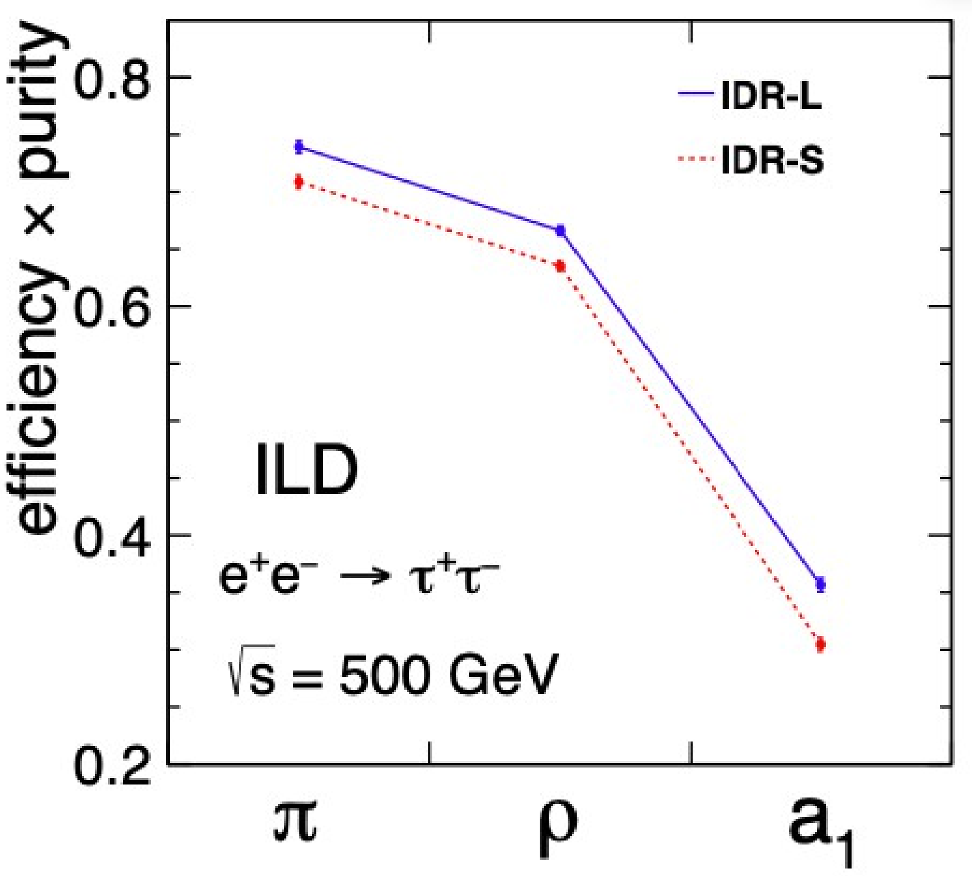
D.Jeans, G. Wilson
Phys.Rev.D 98 (2018) 1, 013007

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

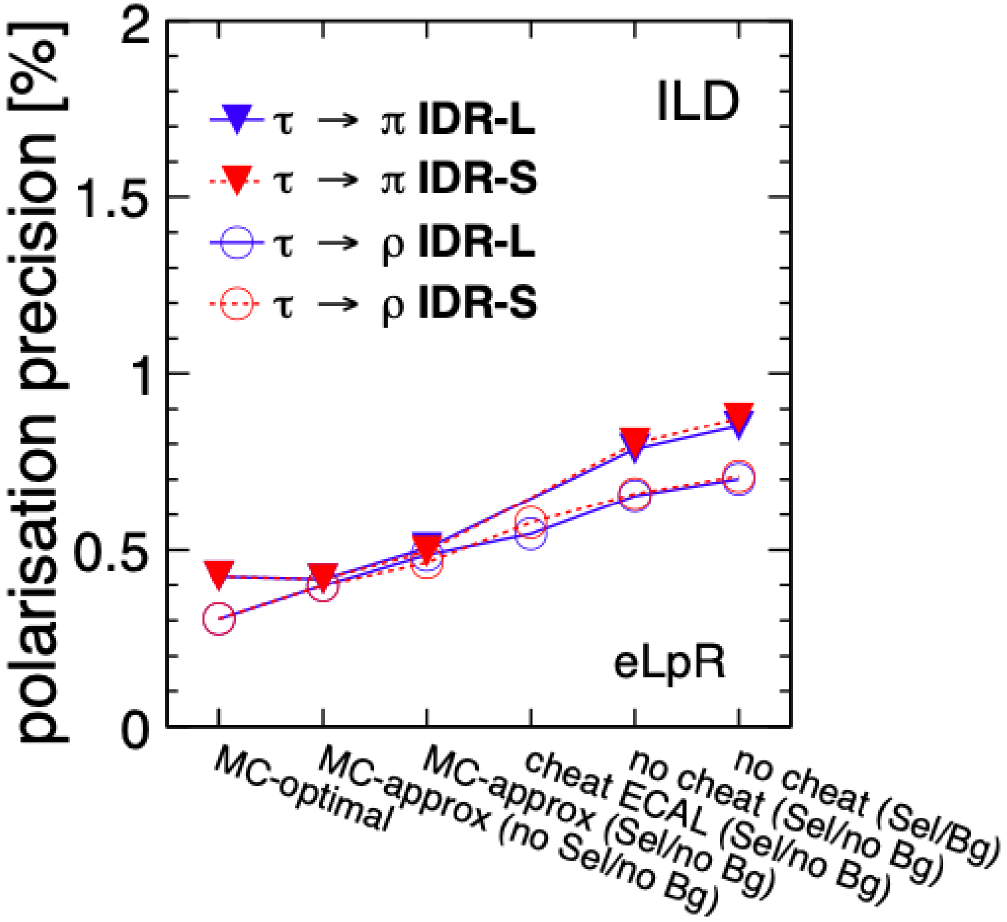
Recent study at 500 GeV for ILD IDR



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



- EfficiencyxPurity drops with increasing photon multiplicity



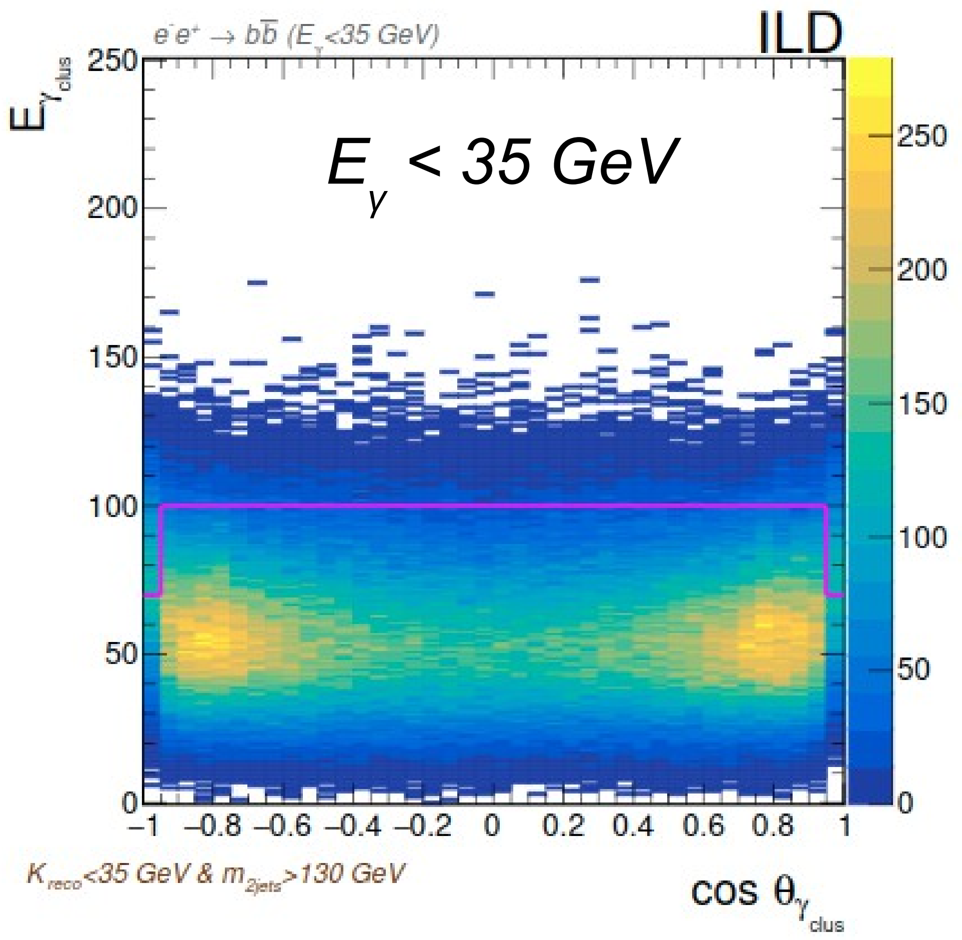
Precision of tau polarisation of order 0.3%-1%

- 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, higher granularity?

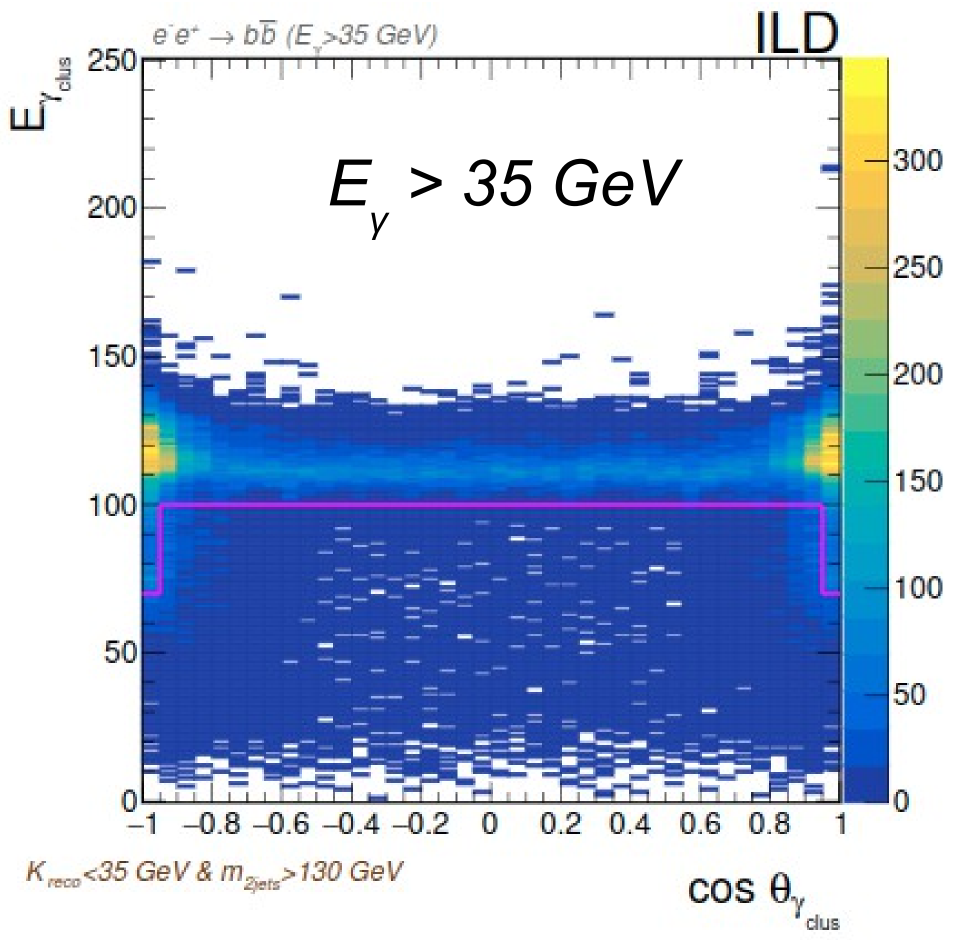
Measuring the ISR Photon in the Ecal

- 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

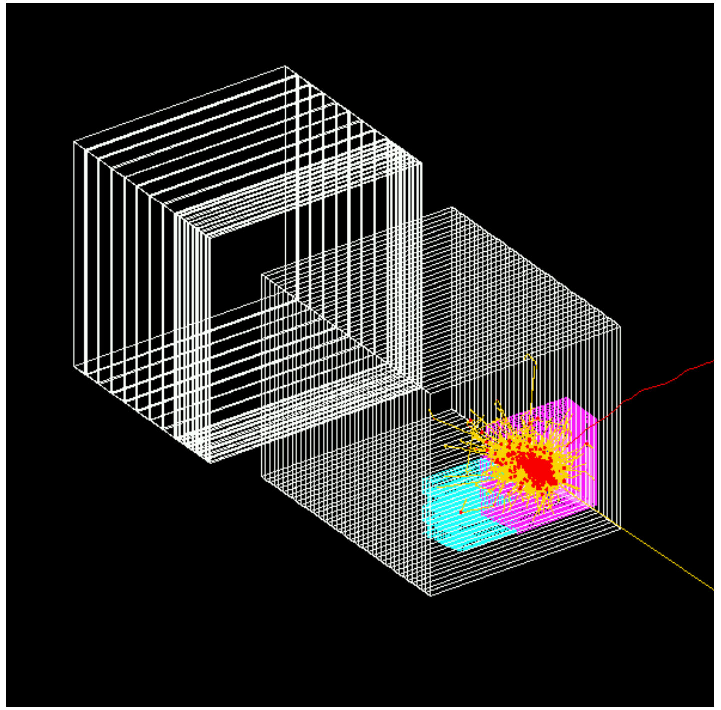


- Excellent photon ID in granular calorimeter is key
- Identification of ISR photon within detector (jet) reduces ISR background by nearly a factor of six
- Would be interesting to carry out this analysis with less granular calorimeters

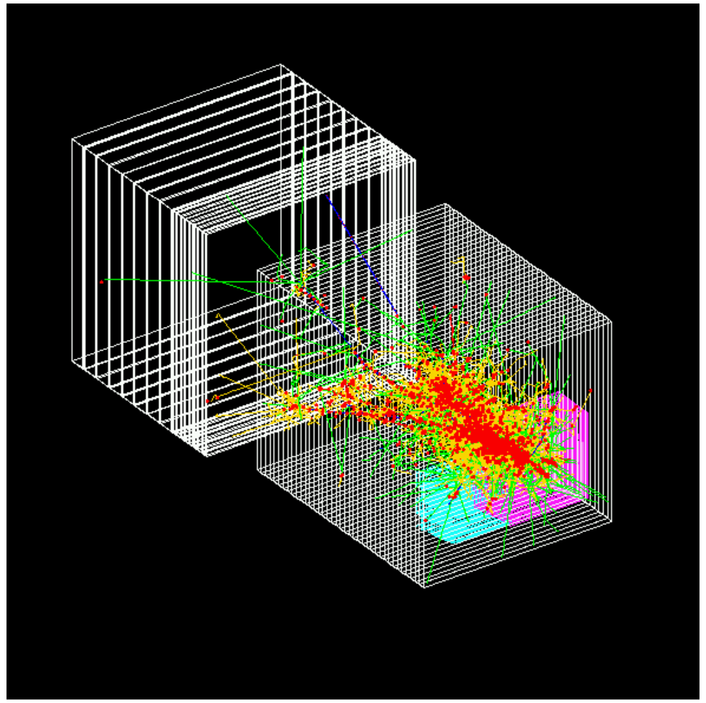
ILD: Irles, Richard, R.P.

Calorimetry and PFA in a nutshell

Electromagnetic Shower



Hadronic Shower



Characterized by
Radiation Length $X_0 \propto \frac{A}{Z^2}$
Molière Radius $R_M = \frac{21\,\mathrm{MeV}}{\epsilon_c} \cdot X_0$

Characterized by
Interaction Length: $\lambda_I = \frac{A}{N_A \sigma_{\pi N} A^{2/3} \rho} \propto A^{1/3}$

$$\boxed{\frac{\lambda_I}{X_0} \propto A^{4/3}}$$

=>

Choose material with large A for good photon/hadron separation

e.g. Tungsten in electromagnetic PFA Calorimeter

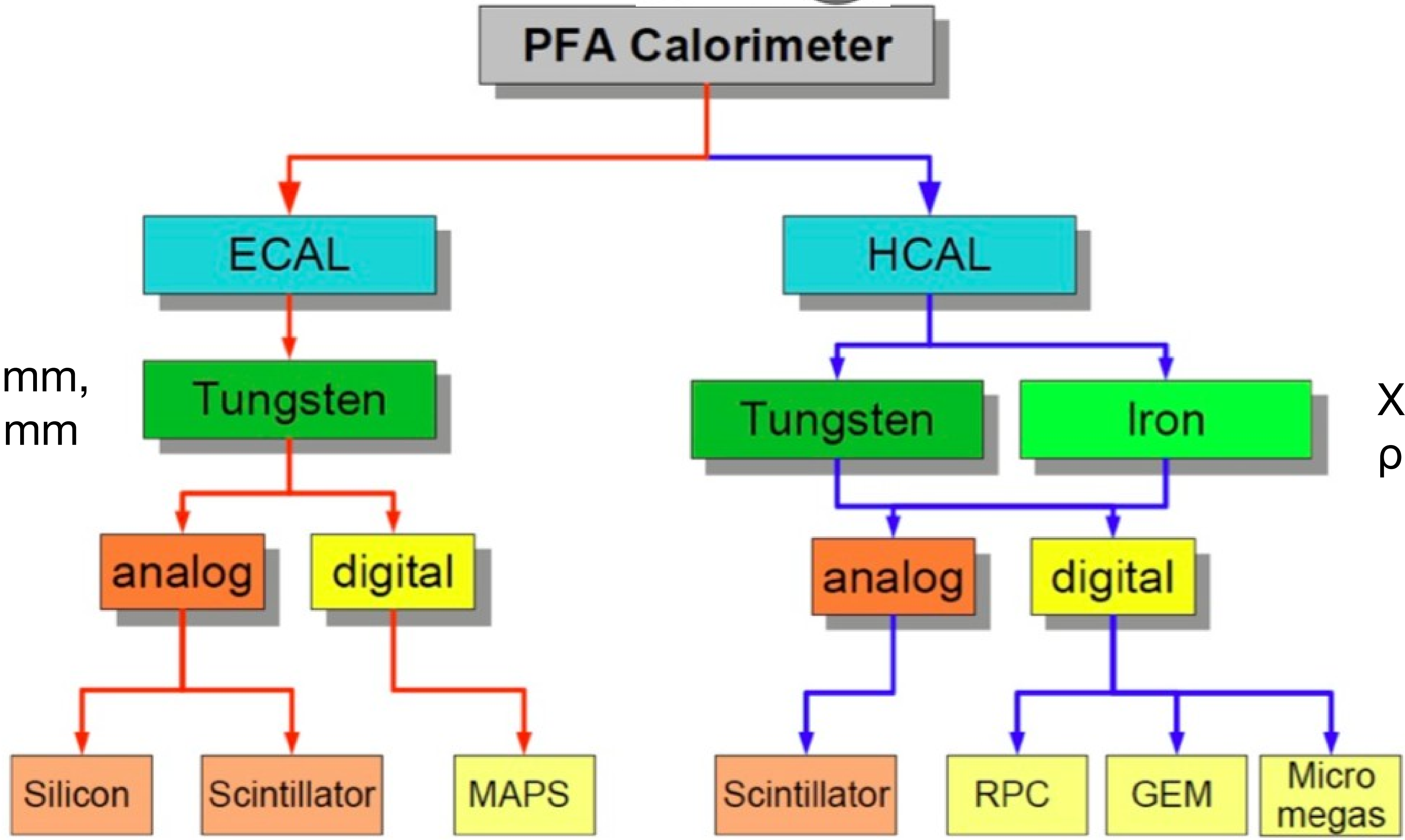
Choose lateral cell sizes to be smaller than Molière Radius of absorber

R_M(W) ~ 9mm => 0.5cm^3 segmentation in Ecal

Criteria lead to 10 – 100 Millions of detector cells in calorimeter

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

The CALICE Collaboration

Calorimeter R&D for large imaging calorimeters

~270 physicists/engineers from 62 institutes and 18 countries from 4 continents

- Integrated R&D effort
- Acceleration of detector development due to *coordinated* approach
- MOU 2005
  - IN2P3 among founding members, first Spokesperson Jean-Claude Brient

IN2P3 Groups working on Highly Granular Calorimeters

Silicon Tungsten Ecal

IN2P3 Groups:

IJCLab
LLR
LPC (until ~2012)
LPNHE
LPSC
OMEGA

Internationa partners

KEK (JP)
Kyushu University (JP)
IFIC (ES)
SKKU (SK)
CERN

Semi Digital Hcal

IN2P3 Groups:

I2PI
LPC (since ~2012)
LLR (until ~2013)
LAPP (until ~2015)
OMEGA

International partners

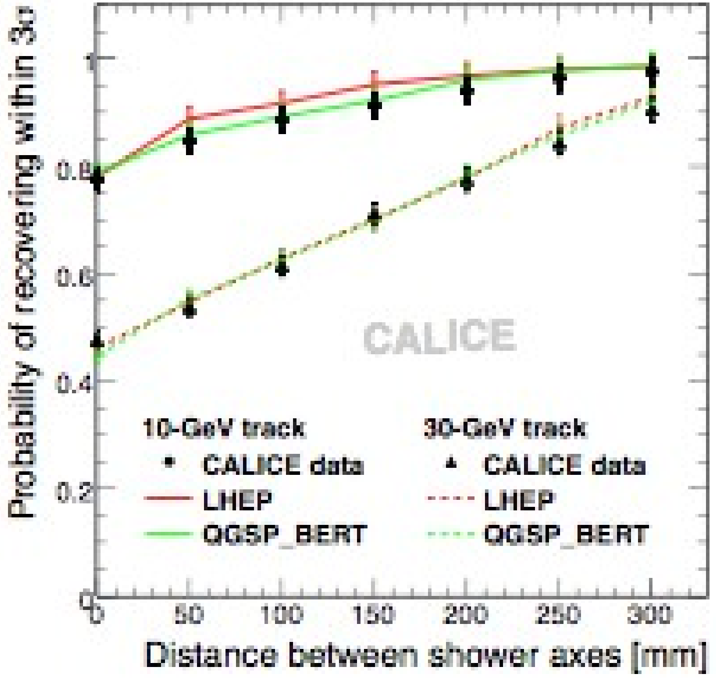
U Louvain (B)
U Ghent (B)
CIEMAT (ES)
SJTC (CN)
U Tunis (TN)

Steps of R&D

Physics Prototypes

2003 - 2012

JINST 6, P07005 (2011)



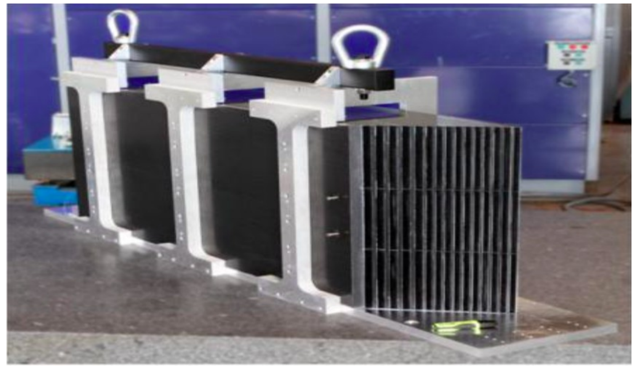
Proof of principle of granular calorimeters

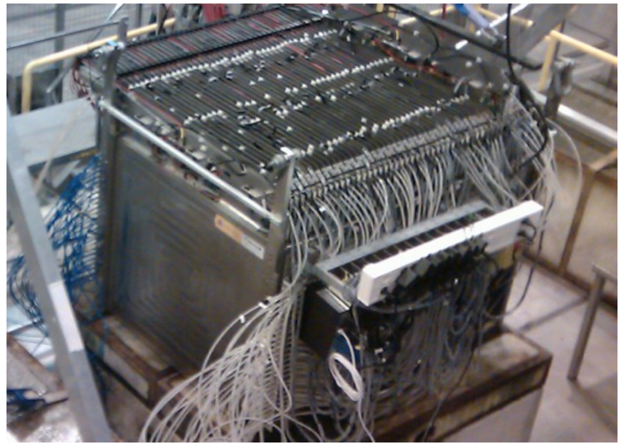
Large scale combined beam tests

Inspiration for CMS HGCAL

Technological Prototypes

2010 - ...



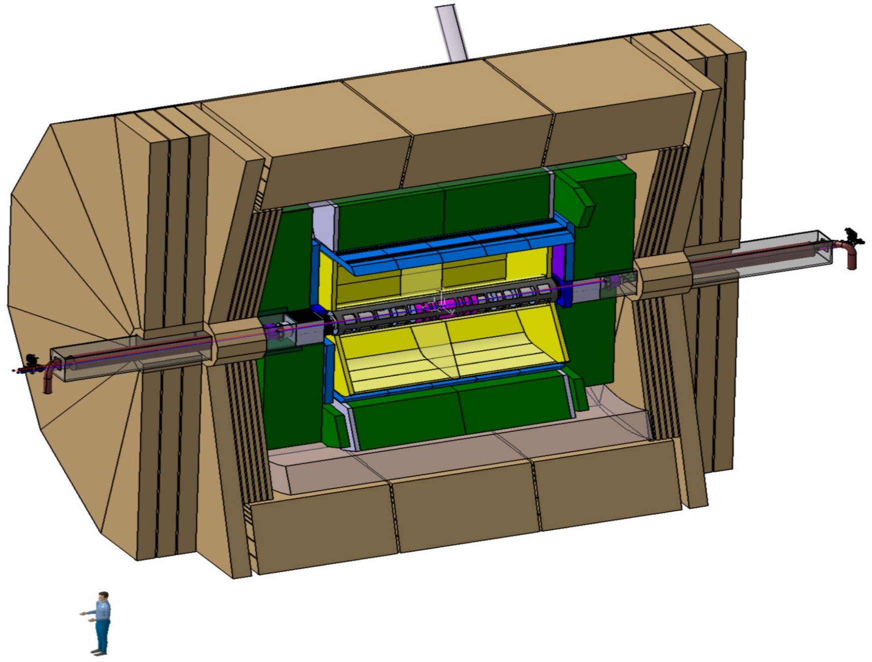


Engineering challenges

Higher granularity

Better sensitivity (lower noise)

Higgs Factory Detector



The goal
- Typically 10^8 calorimeter cells

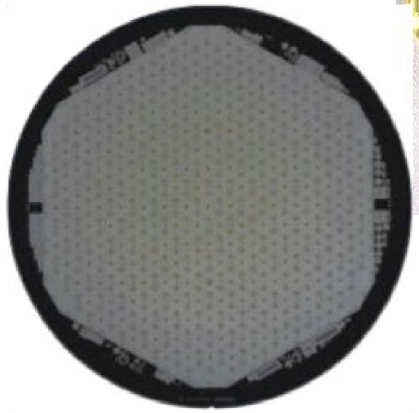
Compare:
- ATLAS LAr ~10^5 cells
- CMS HGCAL ~10^7 cells

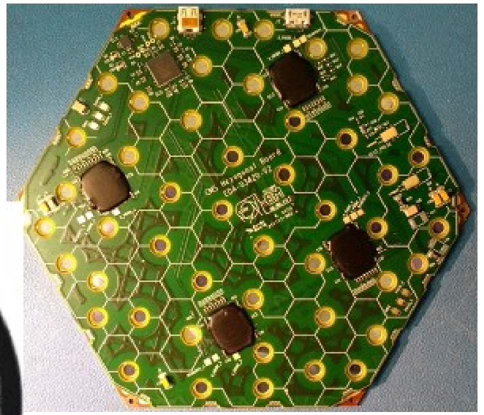
Current period

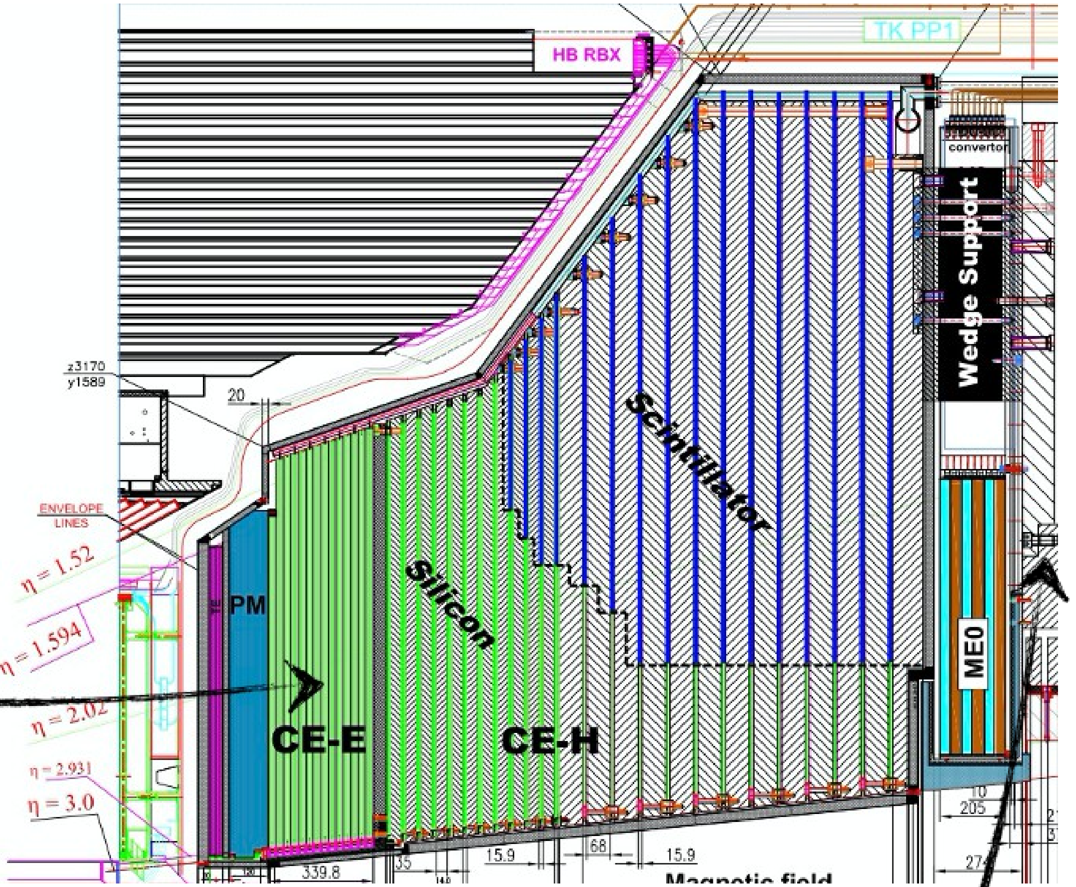
HL-LHC Upgrades

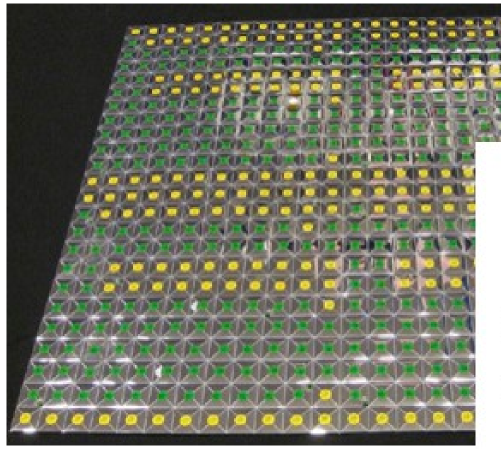
- The developments in CALICE have paved the way for a number of applications of highly granular calorimeters and related technologies in HEP

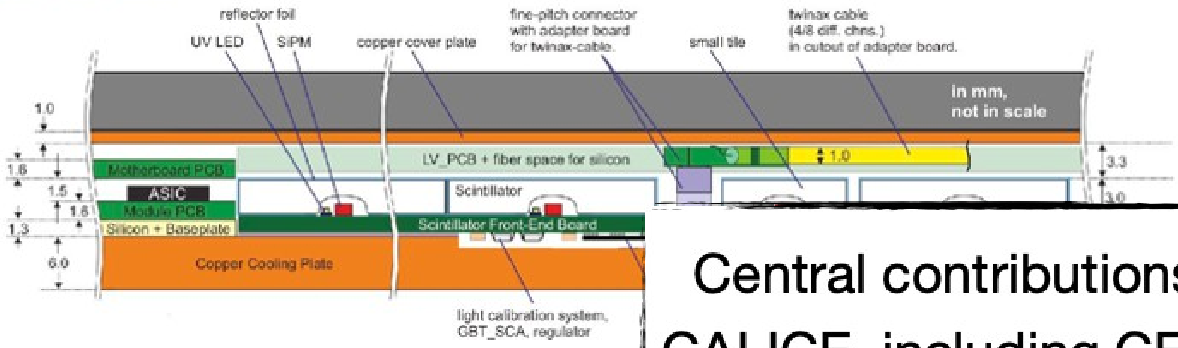
Most prominent: The CMS Endcap Calorimeter Upgrade HGCal









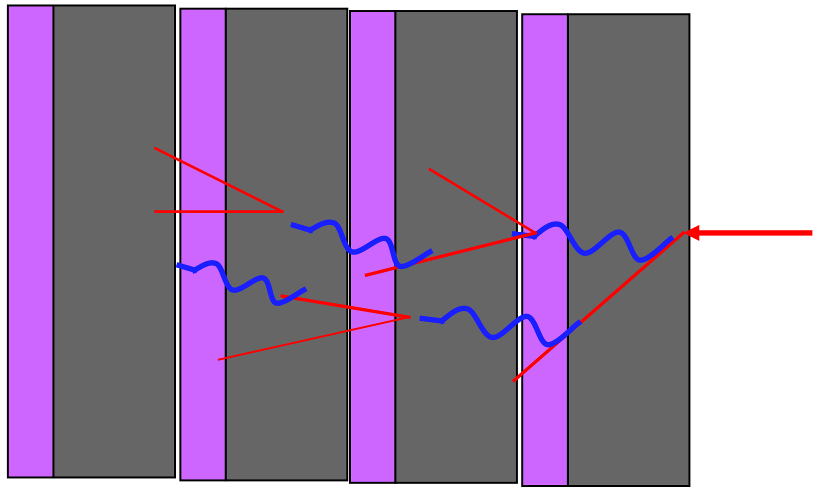


Central contributions by groups very active in CALICE, including CERN, DESY, LLR, OMEGA.

F. Simon

Calorimetry – Shower Measurement and Techniques I

Example: Sampling Calorimeters, Homogenous Calorimeters ➢ Homework



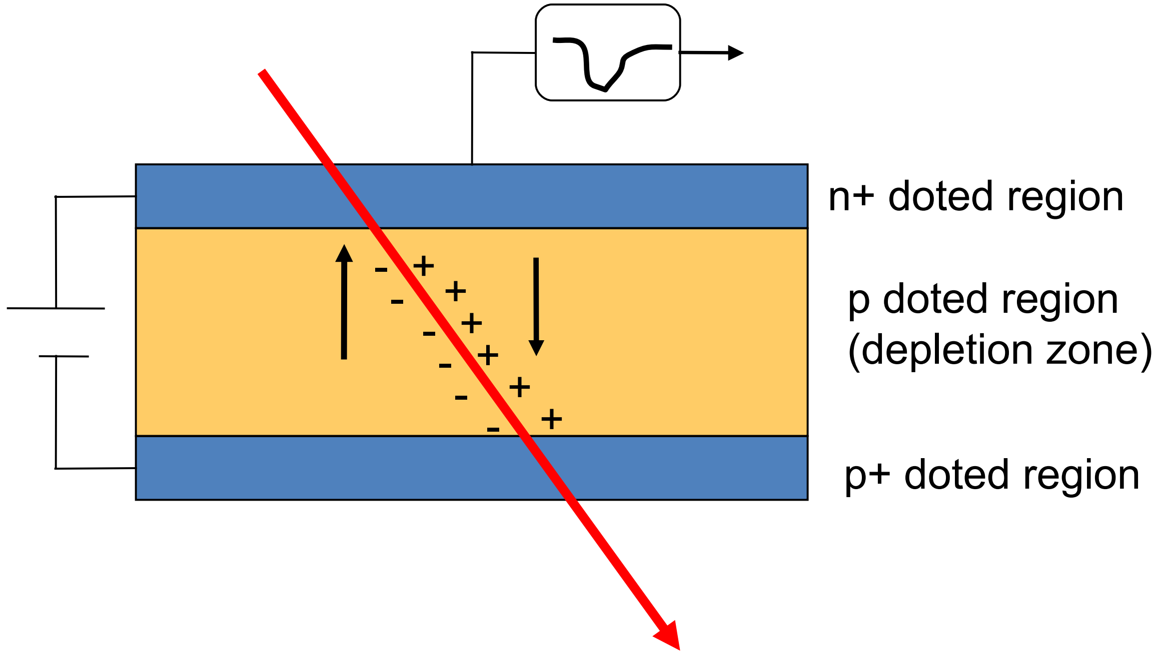
Alternating structure of Absorber and Sensitive medium

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

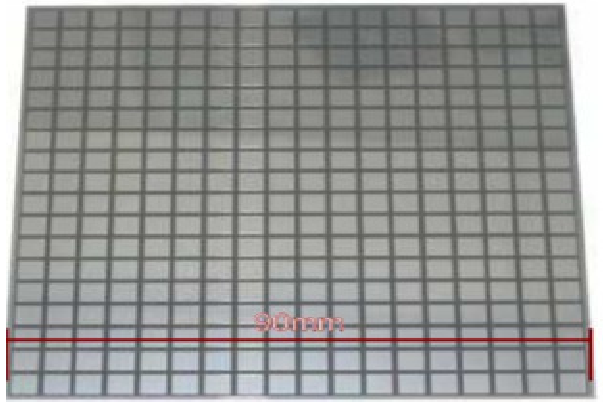
$$\boxed{\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E\,[\mathrm{GeV}]}} \oplus b \quad [\%]}$$

Master formula of calorimetry

- Sensitive medium I: Counters based on semi-conductor



Si Wafer for CALICE SiW ECAL

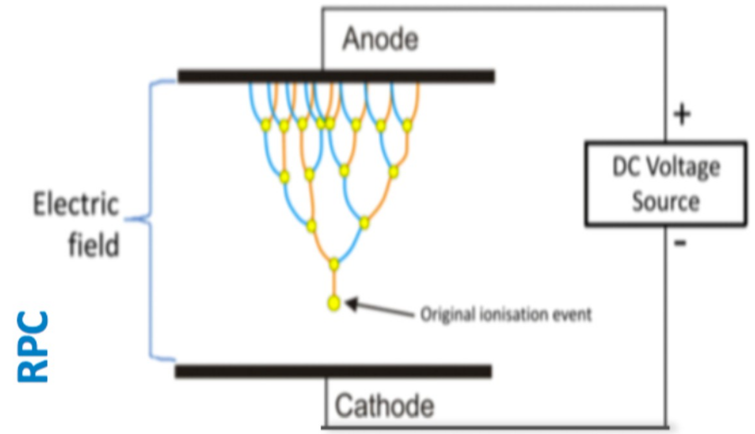


- Semi-Conductors allow for High level of segmentation
  - 5x5 mm^2 for SiW ECAL
- More for future calorimeters?
  - See above vertex detectors

Calorimetry – Shower measurement and Techniques II

- Sensitive Medium II: Gaseous Counters

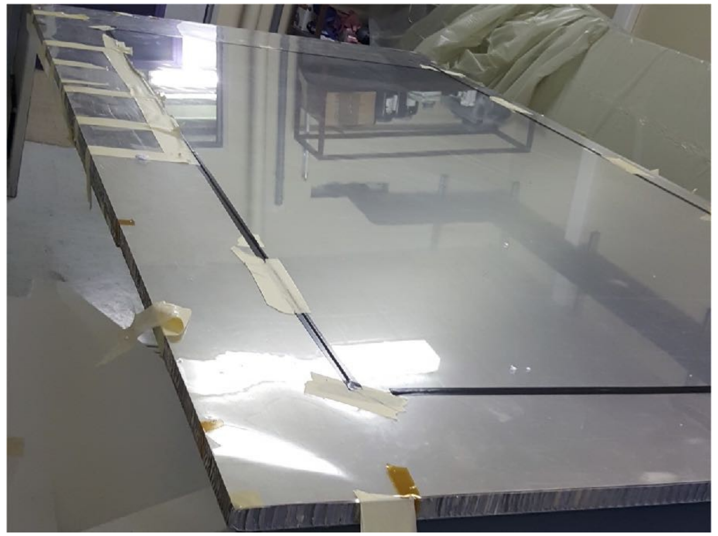
RPC = Resistive Plate Chamber



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

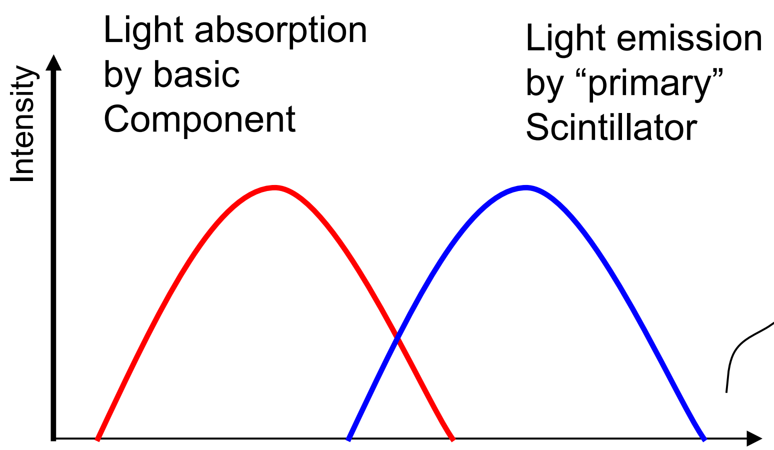
GRPC Chamber – CALICE SDHCAL



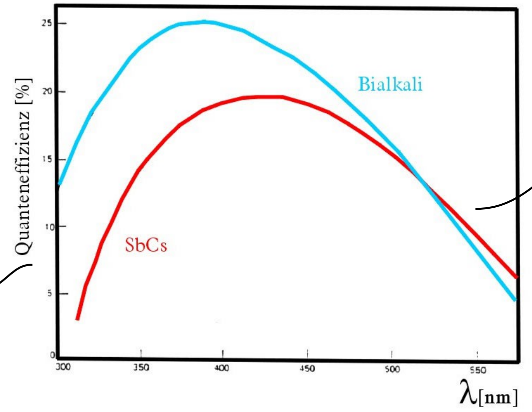
Lateral granularity 1x1 cm^2

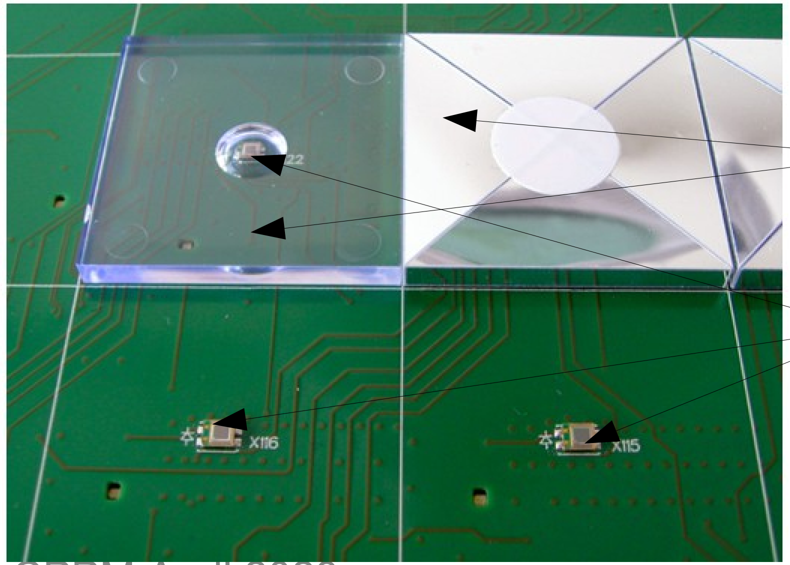
- Sensitive Medium III: Plastic Scintillators

Two Component
organic Material (Benzole Type)



Spectral sensitivity of Photocathodes





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

!

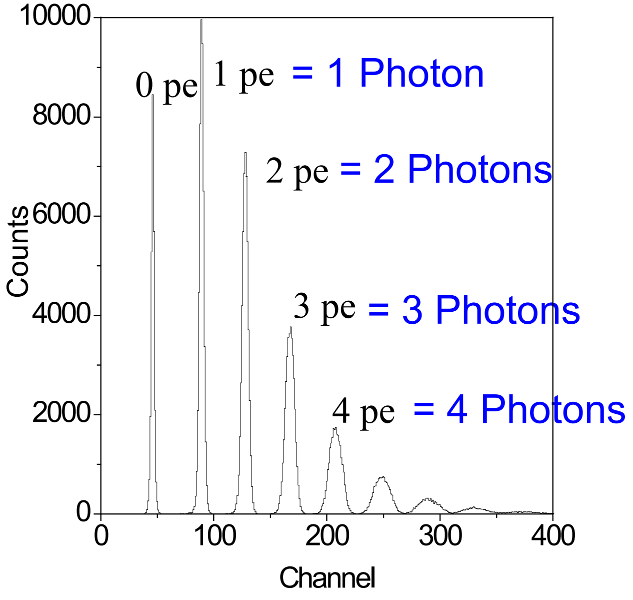
Silicon Photomultipliers

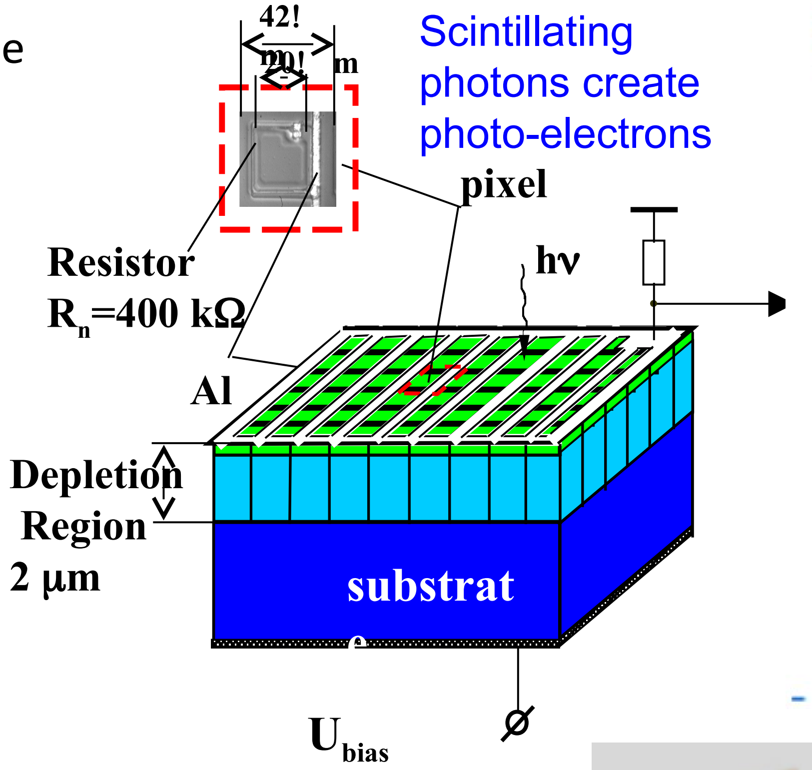
Basics

- A pixelated solid state Geiger counter (semi-conducting)
  - Several 1000 pixels on 1mm²
  - Gain 10**6, efficiency 10..15%
  - At 50 V typical bias voltage

Single photon signals

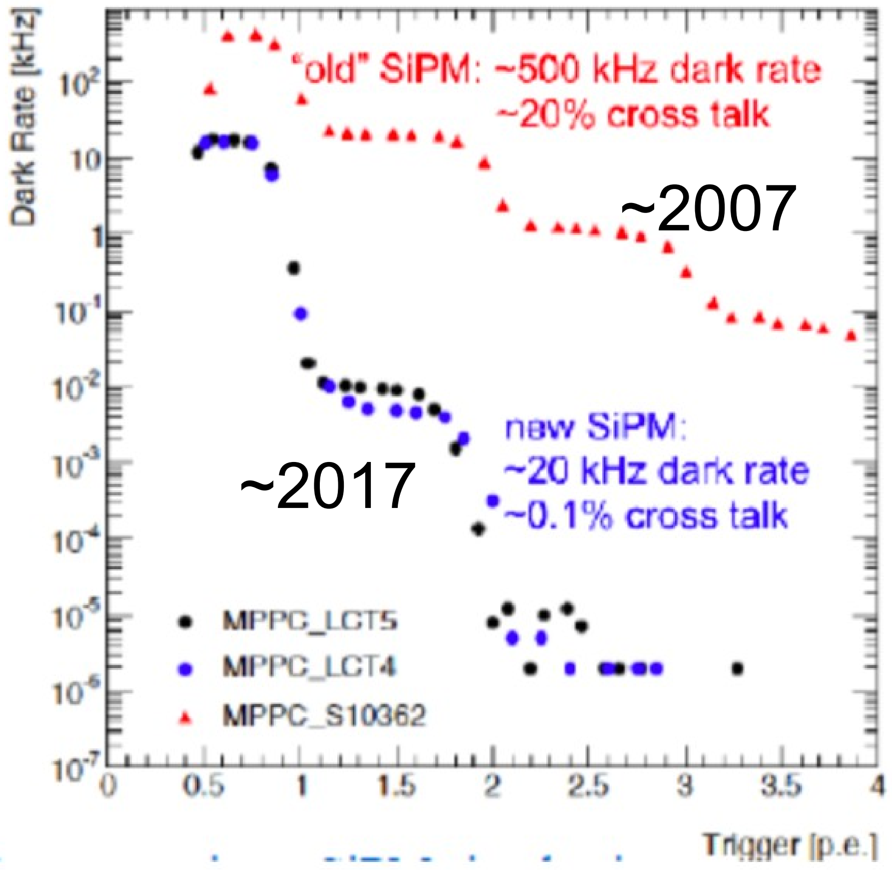
Signal - analog sum

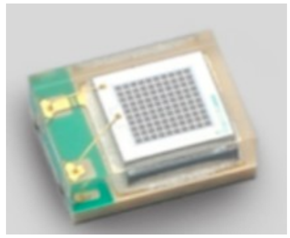




Scintillating photons create photo-electrons

Development over the years

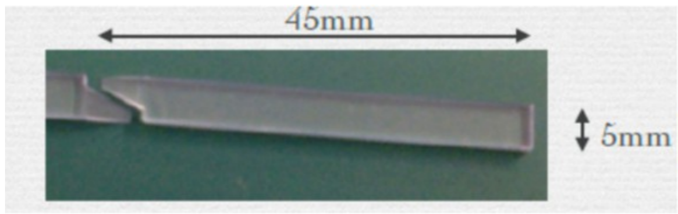




Huge step in quality of SiPM in last decade
- ~Since 2003 MePHI/Pulsar (RU)
- ~Since 2006 Hamamatsu
- Recently Chinese producers

Silicon photomultipliers have many applications Inside and outside of particle physics

- Calorimeters for future e+e- colliders
  Tile Hcal, Dual readout,
  Scintillator Ecal

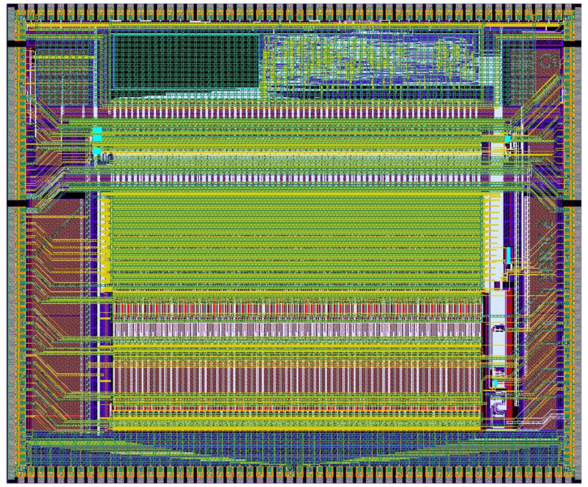


- HL-LHC Calorimeters

- Medical applications
  e.g. Endoscopy

ASICs – The "ROC Family"

SKIROC
(for SiW Ecal)



SiGe 0.35µm AMS,

Size 7.5 mm x 8.7 mm, 64 channels

High integration level

(variable gain charge amp,

12-bit Wilkinson ADC, digital logic)

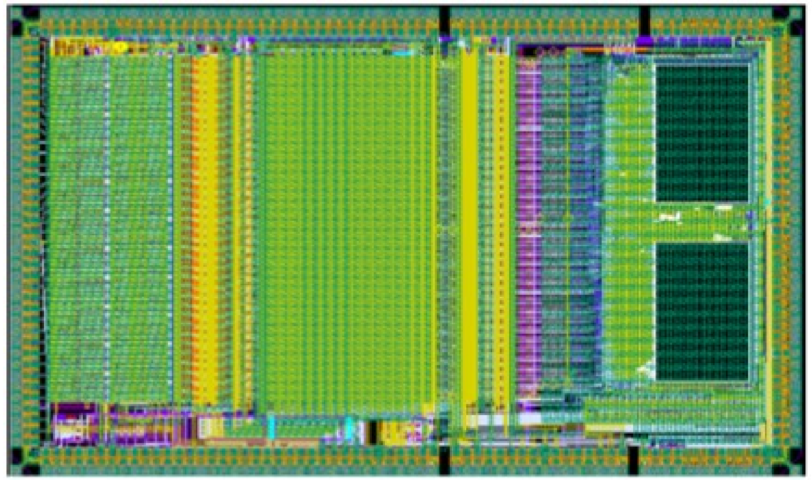
Large dynamic range (~2500 MIPS)

low noise (~1/10 of a MIP, 400 fC)

Auto-trigger at ½ MIP

Low Power: (25µW/ch) power pulsing

SPIROC
For optical readout, Tiles + SiPM



Variant of SKIROC

36 channels, 15 bit readout

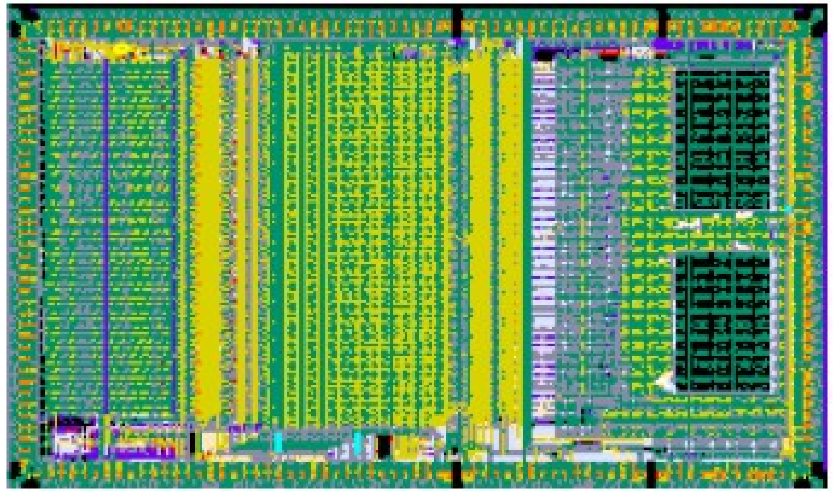
Auto-trigger down to ½ p.e,

80 fC for G=1x10^6

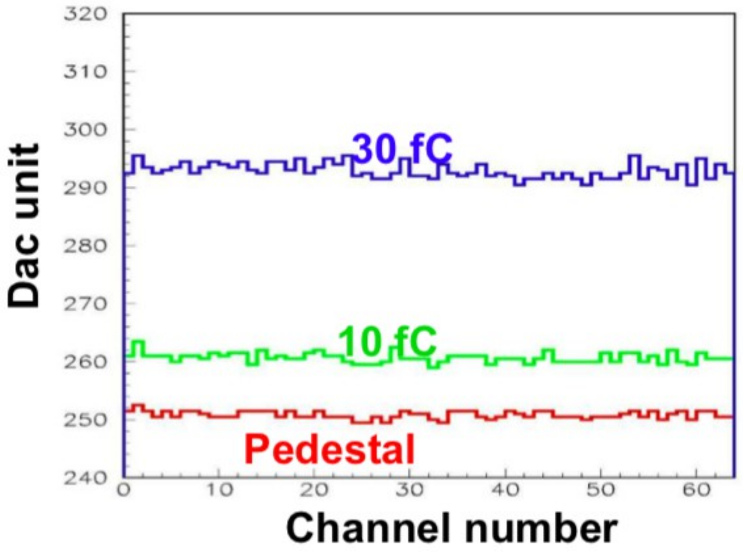
Timing to ~ 1ns

Low Power: (25µW/ch) power pulsing

HARDROC
For gaseous r/o - GRPC



64 Channels with three thresholds

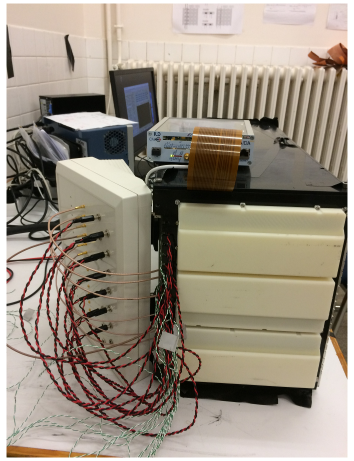


Power pulsing

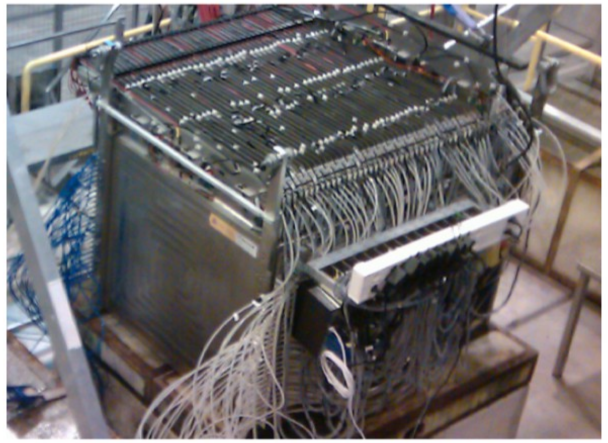
Variant for Micromegas: MICROROC

CALICE (Technological) Prototypes


ScECAL


SiECAL


AHCAL

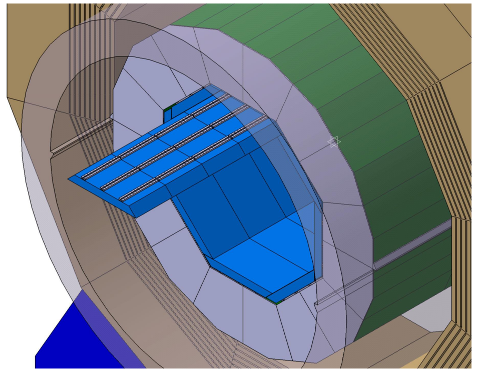

SDHCAL

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

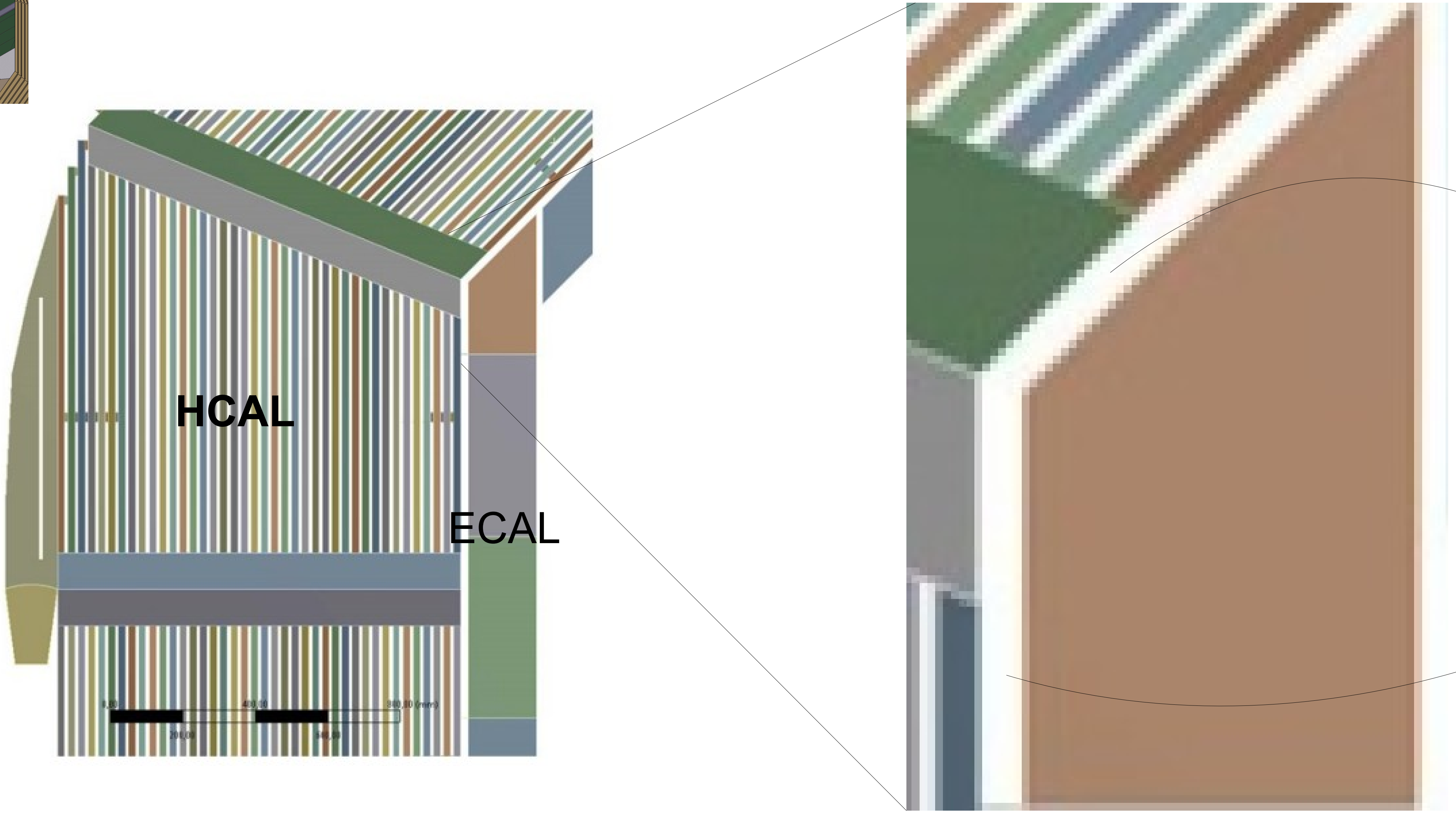
**Only absorber + sensitive material for z direction, air gaps, electronics discarded here (would add 5-10%)

Requirements on compactness



- Successful application of PFA requires calorimeters to be inside the magnetic coil

  => Tight lateral and longitudinal space constraints



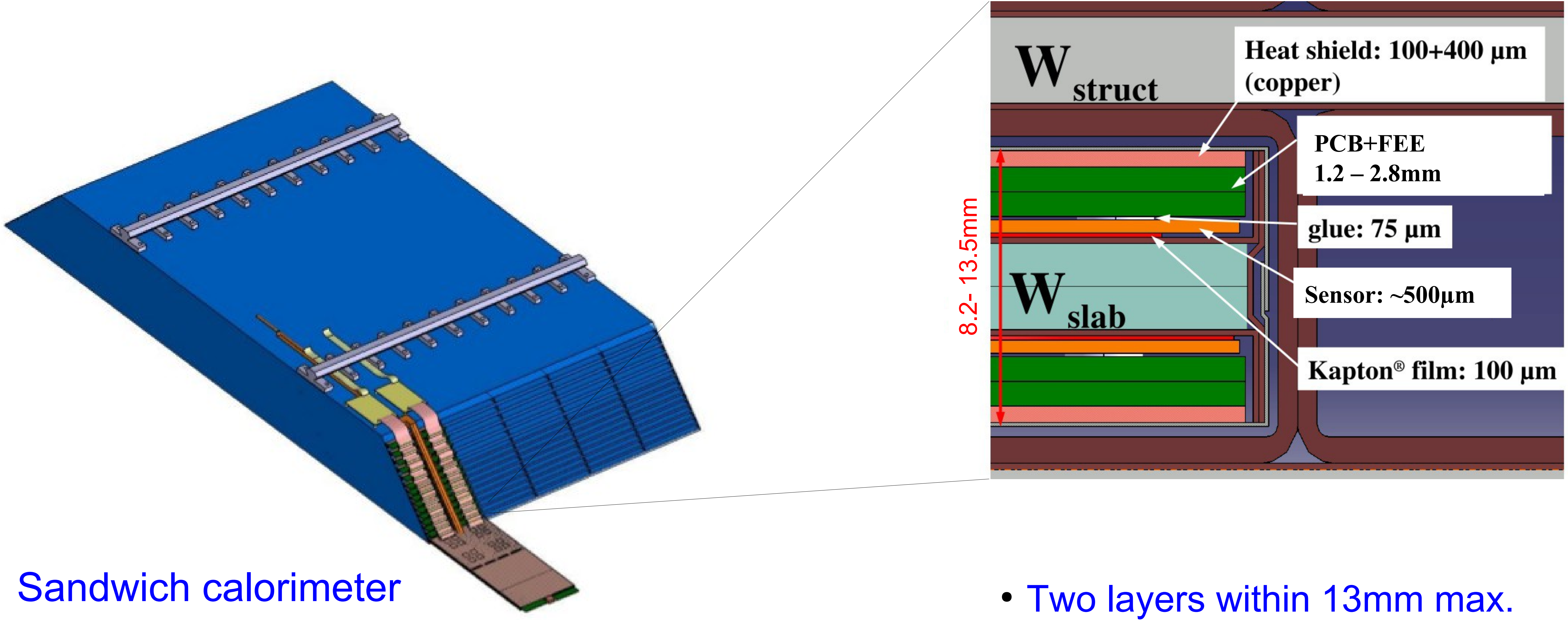
40-70mm for services as readout, cooling and power

~200mm for up to 30 layers with 10-20 kcells each

Calorimeter has to be conceived as one device with electromagnetic and hadronic sections

Silicon Tungsten electromagnetic calorimeter – Example ILD

Ecal alveolar structure

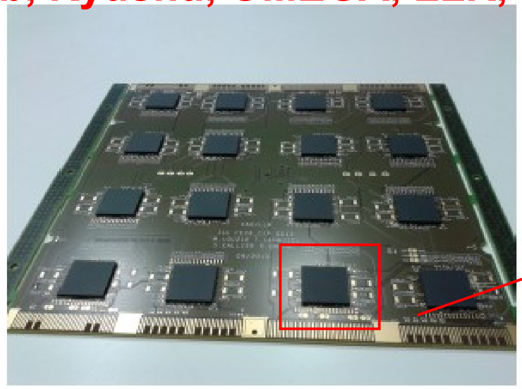


Sandwich calorimeter
26 layers (+/- 4)
Thickness: ~20cm, 24 $X_0/1\lambda_I$
Pixel size ~5x5 mm^2
Expected elm. energy resolution 15-20%/√E

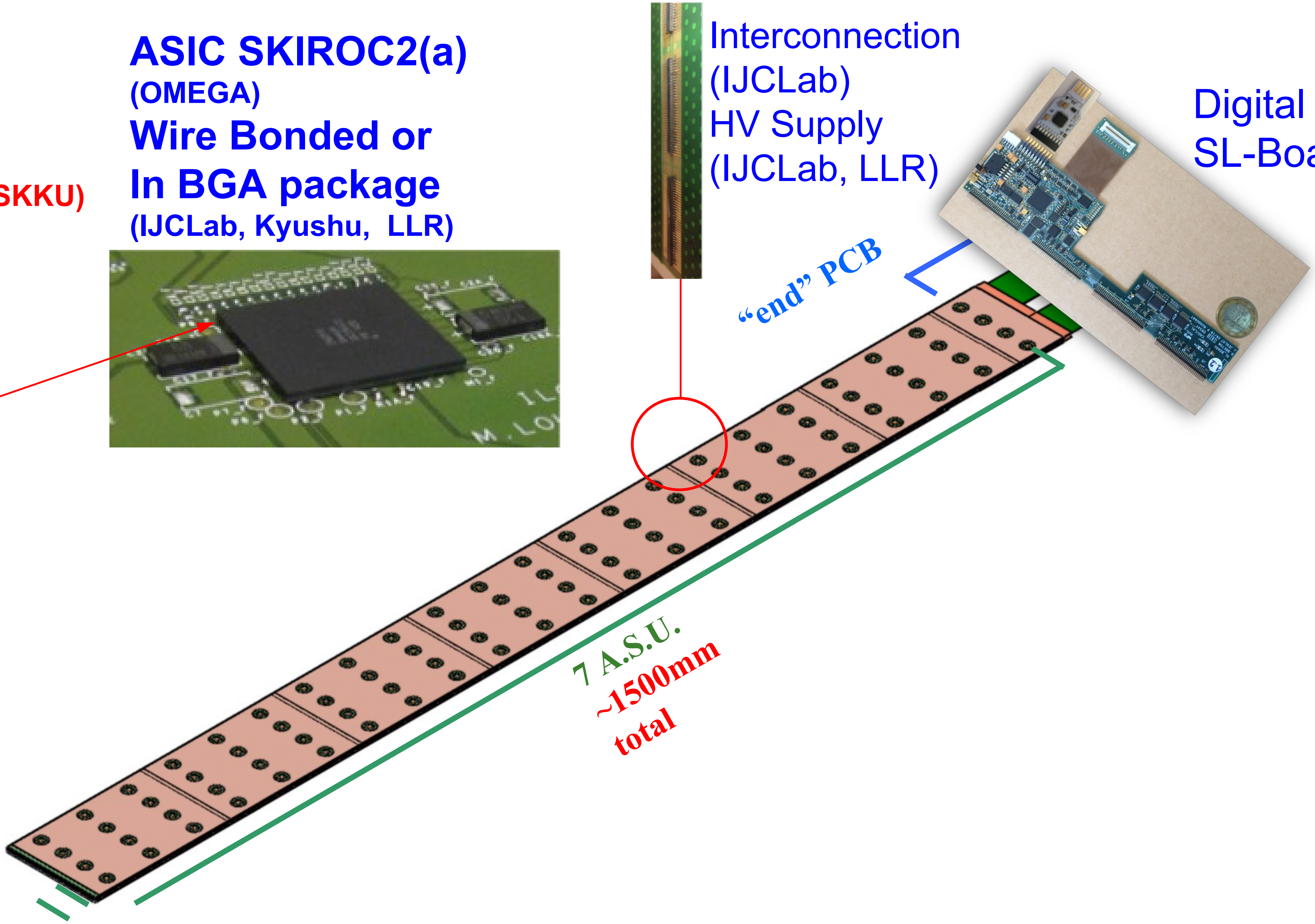
- Two layers within 13mm max.
- Key feature: Embedded electronics

SiW Ecal Technological prototype – Elements of (long) layer

ASIC+PCB+SiWafer
=ASU
Size 18x18 cm^2
(IJCLab, Kyushu, OMEGA, LLR, SKKU)



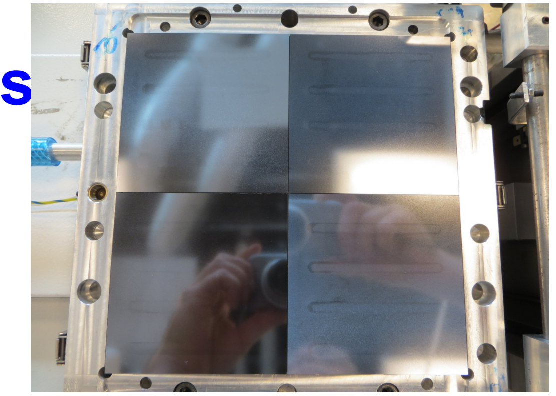
ASIC SKIROC2(a)
(OMEGA)
Wire Bonded or
In BGA package
(IJCLab, Kyushu, LLR)



Interconnection
(IJCLab)
HV Supply
(IJCLab, LLR)

Digital readout
SL-Board (IJCLab)

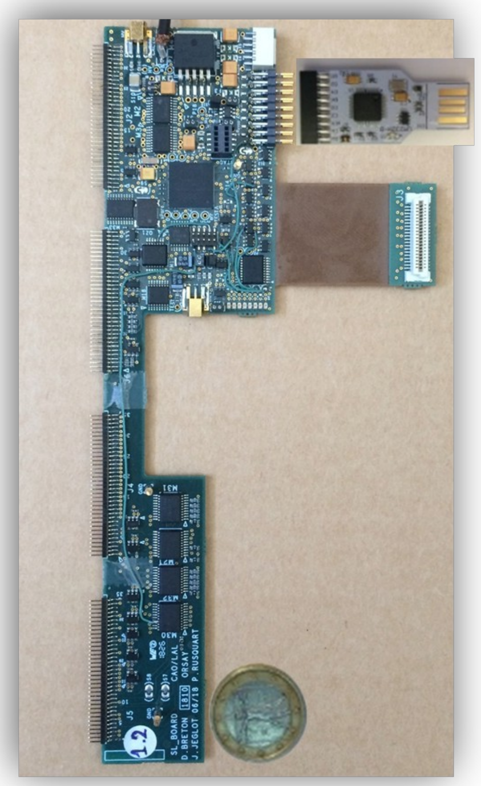
Si Sensors
glued
onto PCB
Pixel size
5.5x5.5 mm^2
(LPNHE, IFIC)



The beam test set ups comprised mainly **short layers** consisting of one ASU and a readout card each

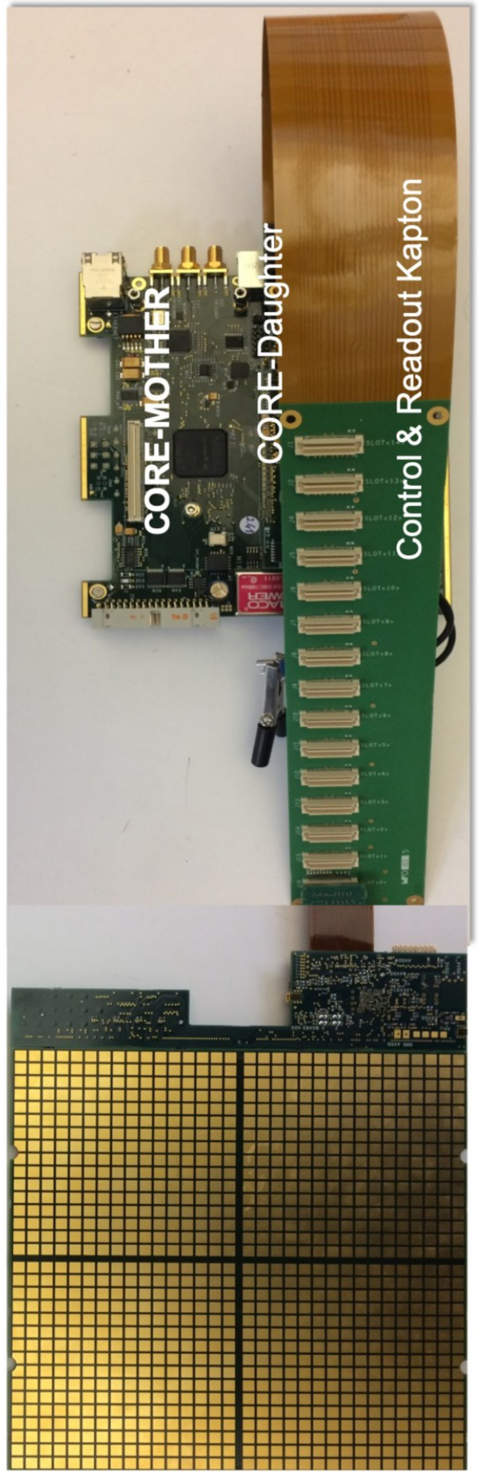
Compact readout

Current detector interface card (SL Board)
and zoom into interface region

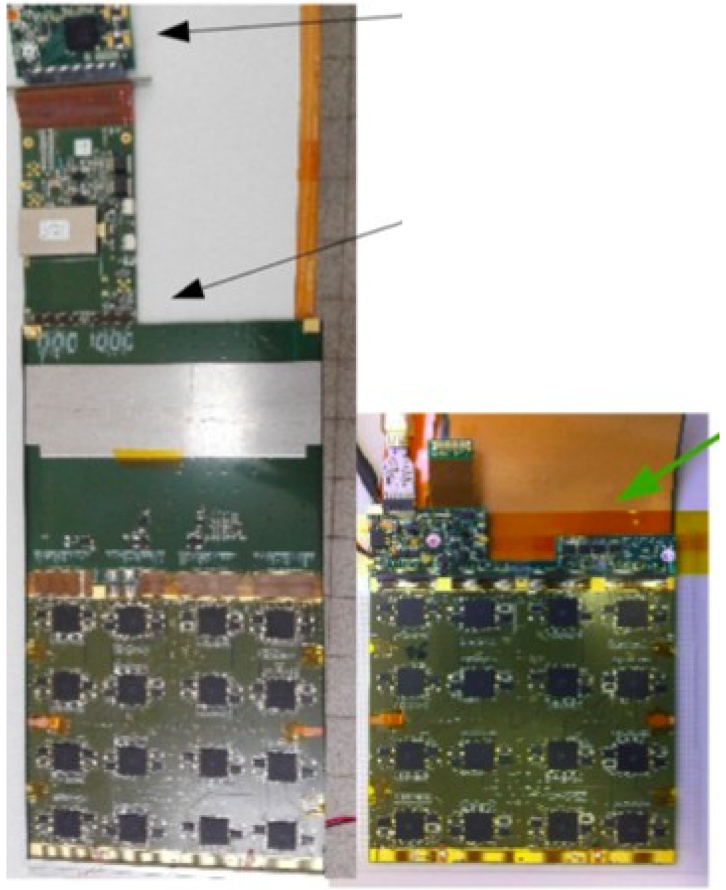


SL Board

Complete readout system



For reference
Comparison old/new r/o system



Deliverable of AIDA-2020 and HIGHTEC

"Dead space free" granular calorimeters put tight demands on compactness

- Current developments in for SiW ECAL meet these requirements

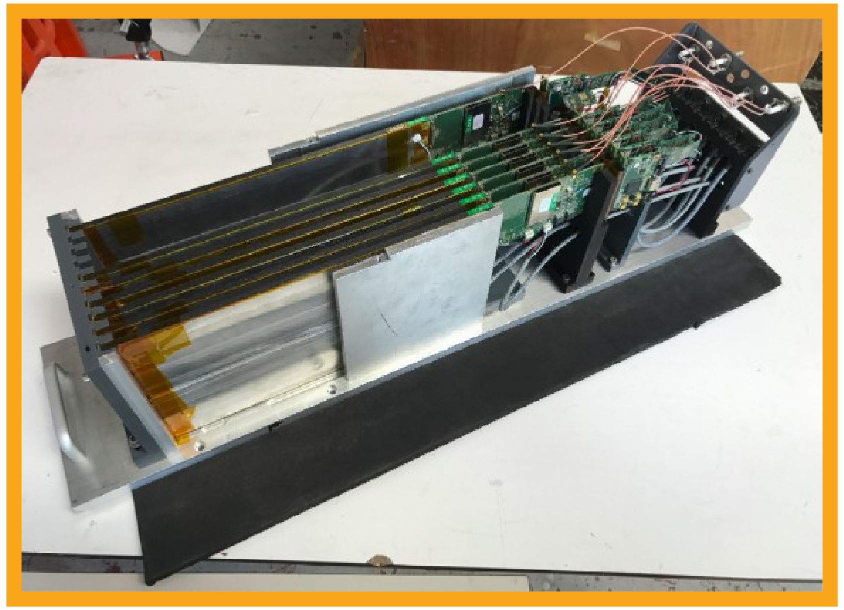
System allows to read column of 15 layers <-> to be expected in ILD

- Important that full readout system goes through scrutiny in beam tests

Readout piloted by performant firmware

SiW ECAL Technological Prototype – Development phases

≤ 2018



> 2018

Up to 7 short layers (18x18x0.5cm^3)

- Up ~10 X_0

1024 channels per layer => 7186 cells

Technical tests at “MIP level”

First version of r/o system

15 short layers equivalent to 15360 readout cells

- Partially by ***recycling*** of ASUs from earliear stacks
- Up to 21 X_0

Overall size 640x304x246mm^3

Flexible mechanical structure to adapt to beam conditions

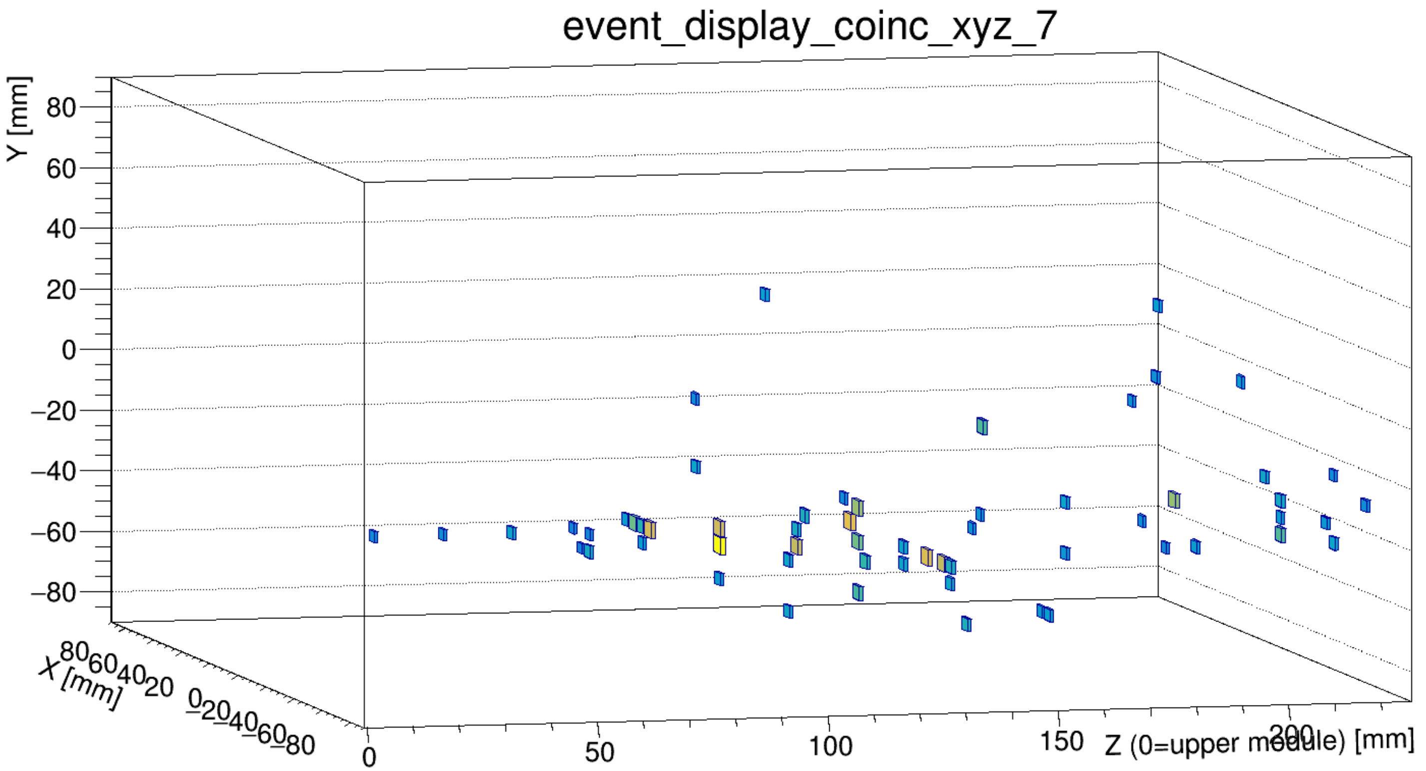
Commissioned 2020-2022

- ~450000 calibration constants for one ASIC feedback capa setting

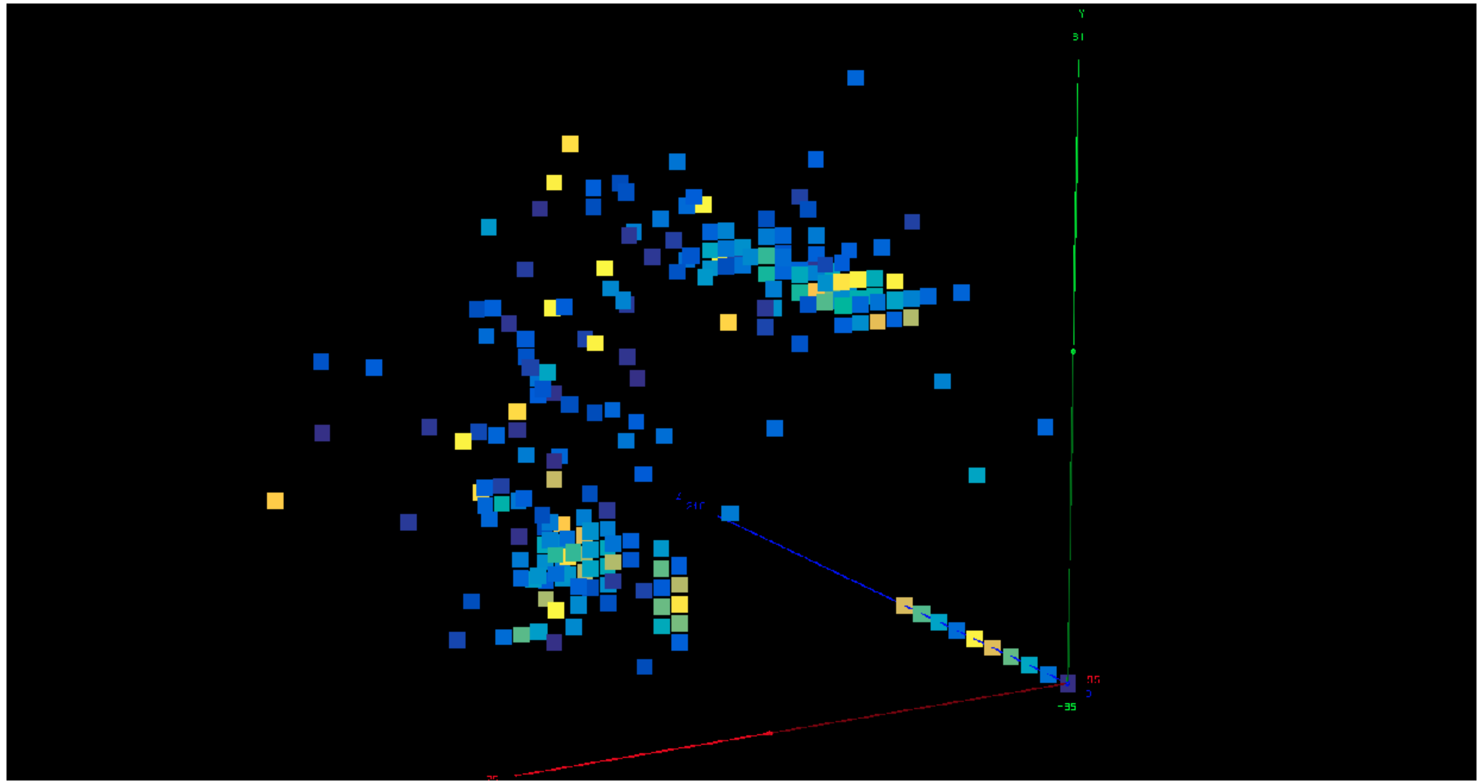
Testbeams (finally) in November 2021 and during 2022

SiW-ECAL Beam tests 2022 – Onlline/Offline Event Displays

First contained electron showers since physics prototype (2011)



J. Kunath (LLR)



Y. Okugawa (IJCLab)

Clear showers measured during beam test campaigns

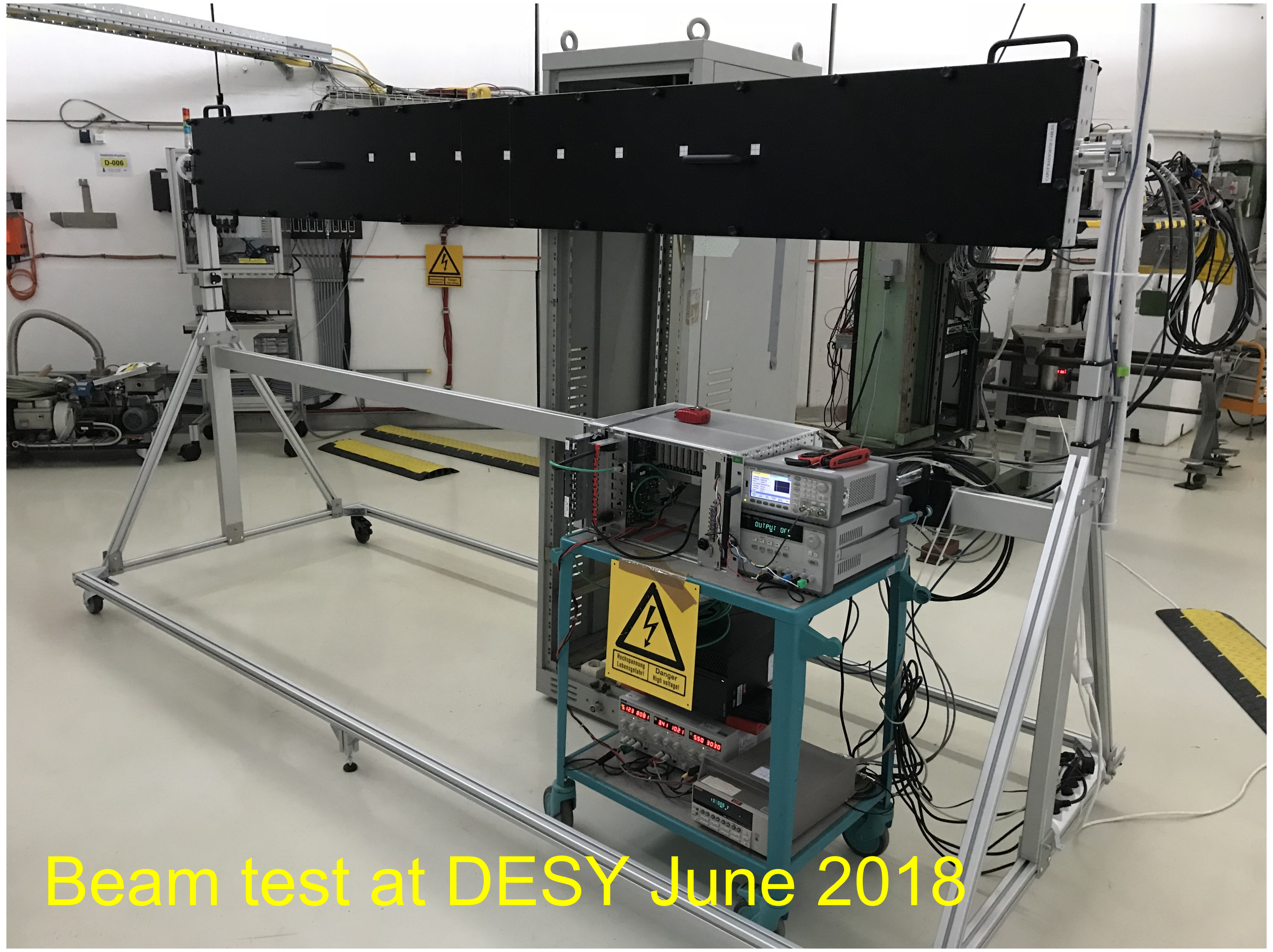
- Requires full event reconstruction
- These (and more) “high level” views are available already while a run is going on

“Particle separation continued”

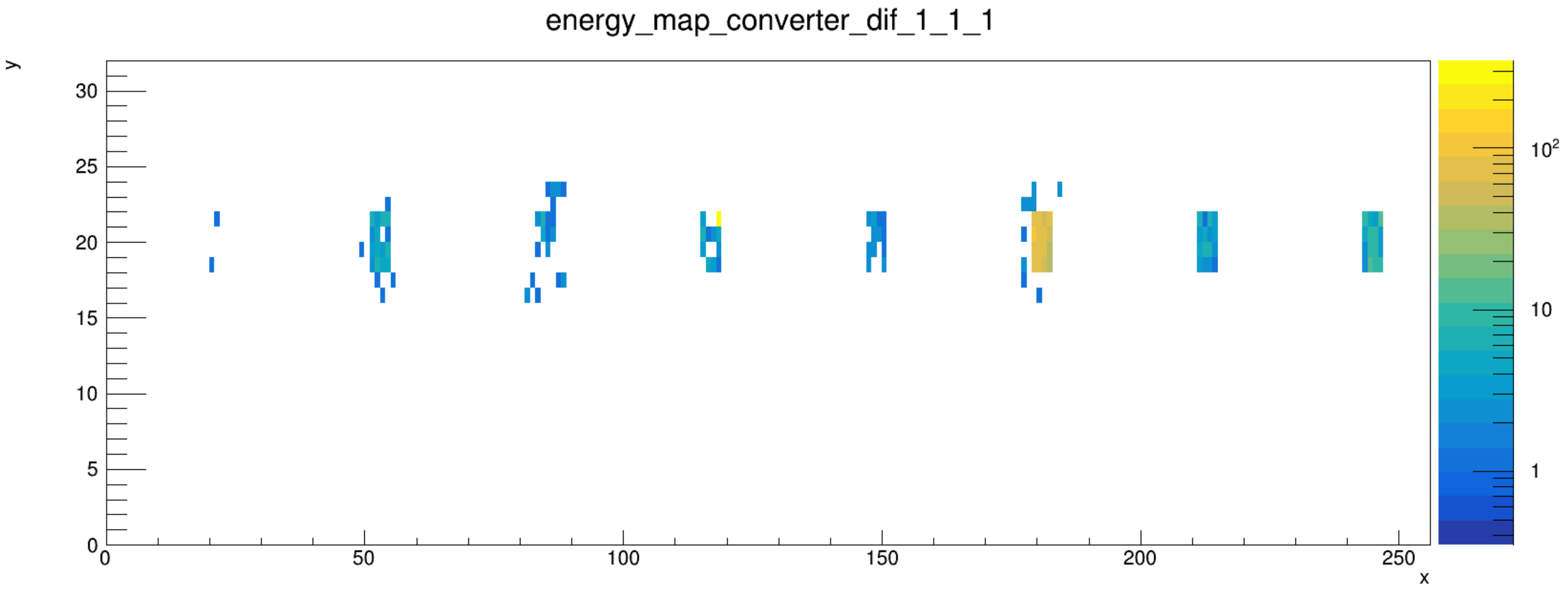
- Two electrons “seen” in 20 GeV e- run at CERN

(One of) Next step(s) – Slab long

Chain of
8 detection elements
~2m



Beam test at DESY June 2018



Encouraging results in first beam test in 2018

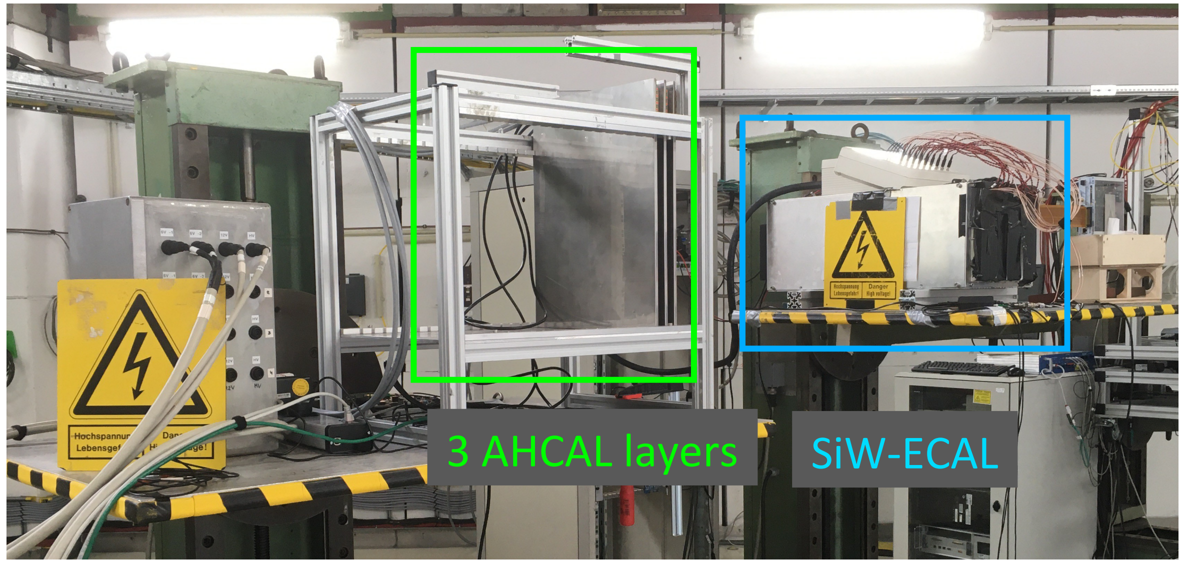
- Issues with signal drop towards extremities

- Long slab studies vital for all future applications

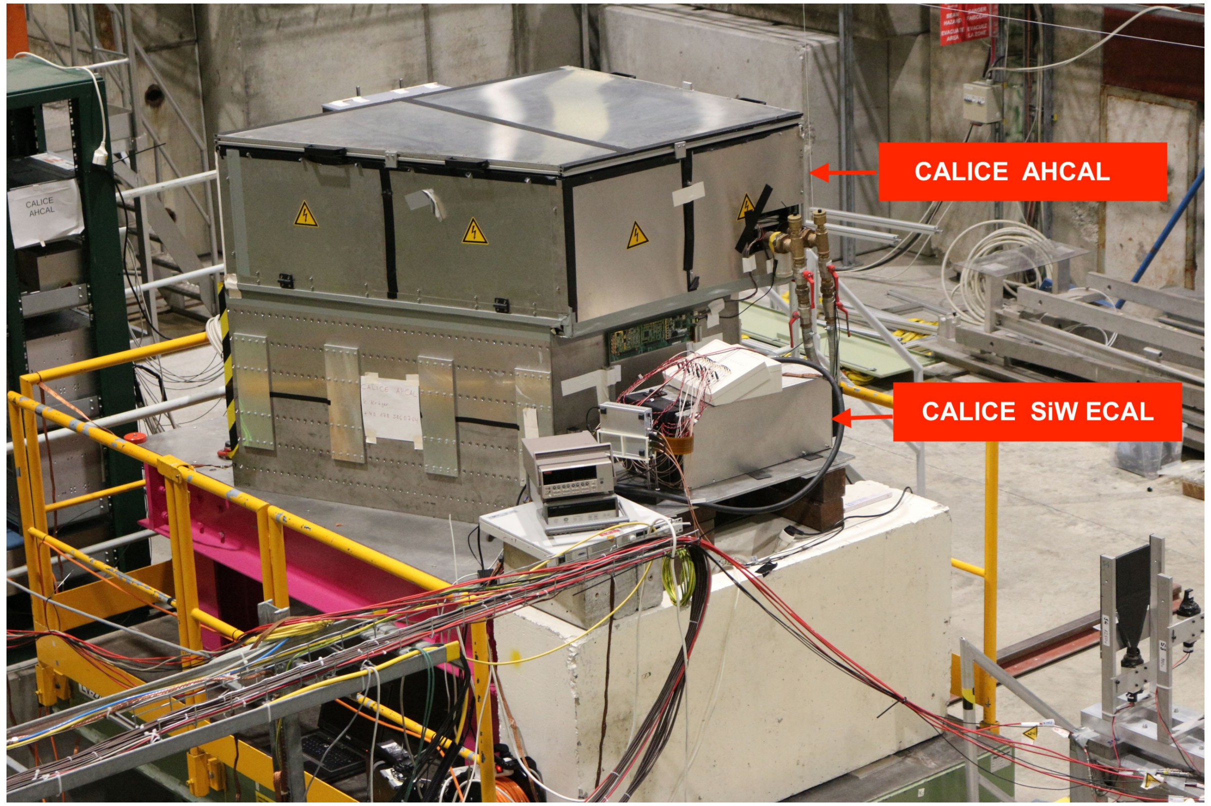
Common developments

CALICE meets DARK MATTER LAB

SiW-ECAL + AHCAL DAQ test @ DESY in March 2022



Common setup at CERN June 2022



15360 + 22000 (full analogue) readout cells

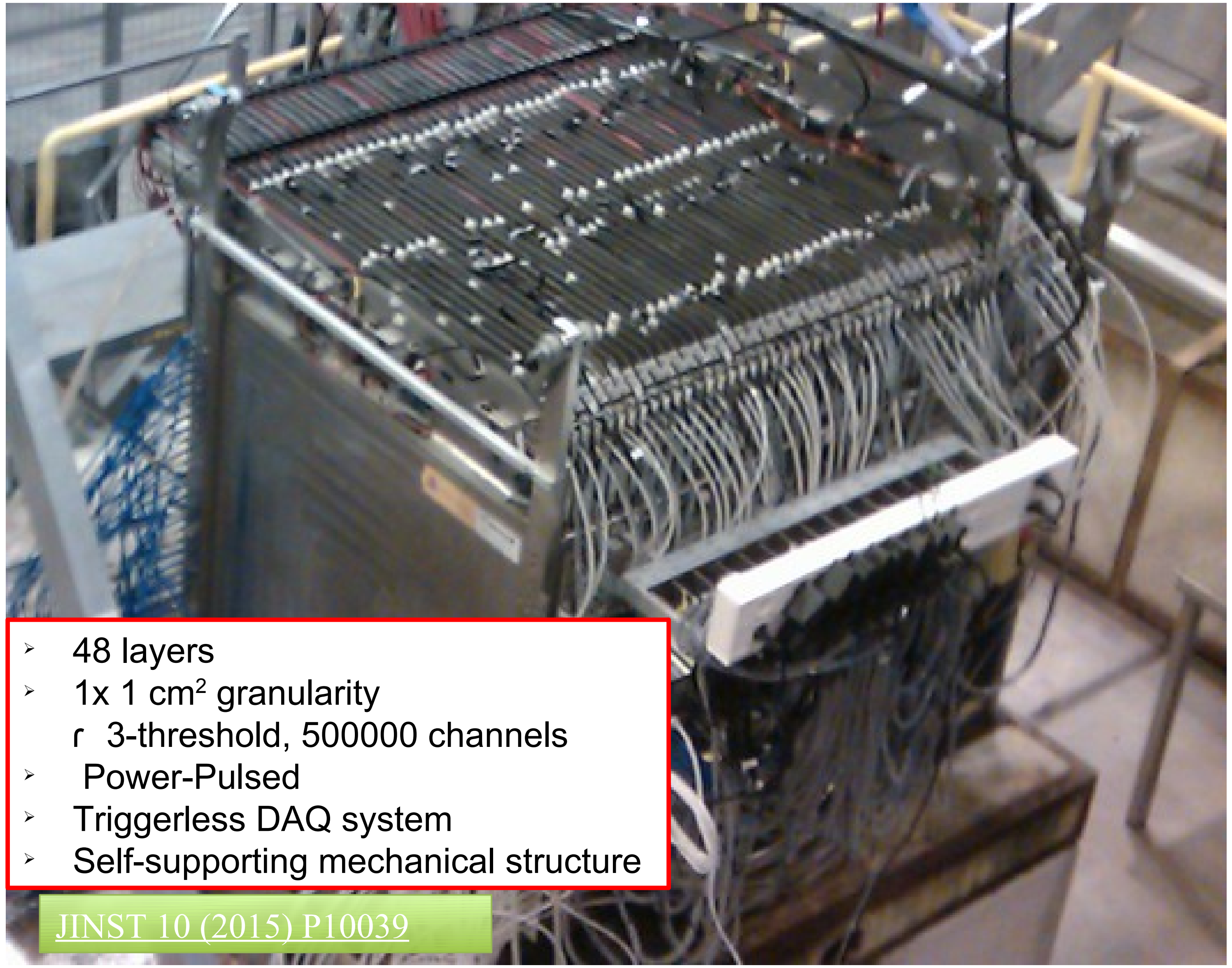
Successful synchronisation of data recorded with SIW-ECAL and AHCAL

- First step of ***knowledge transfer*** on compact readout system to AHCAL → AIDA innova

Common running makes full use of EUDAQ tools (developed within European projects)

Common data anlalysis ongoing

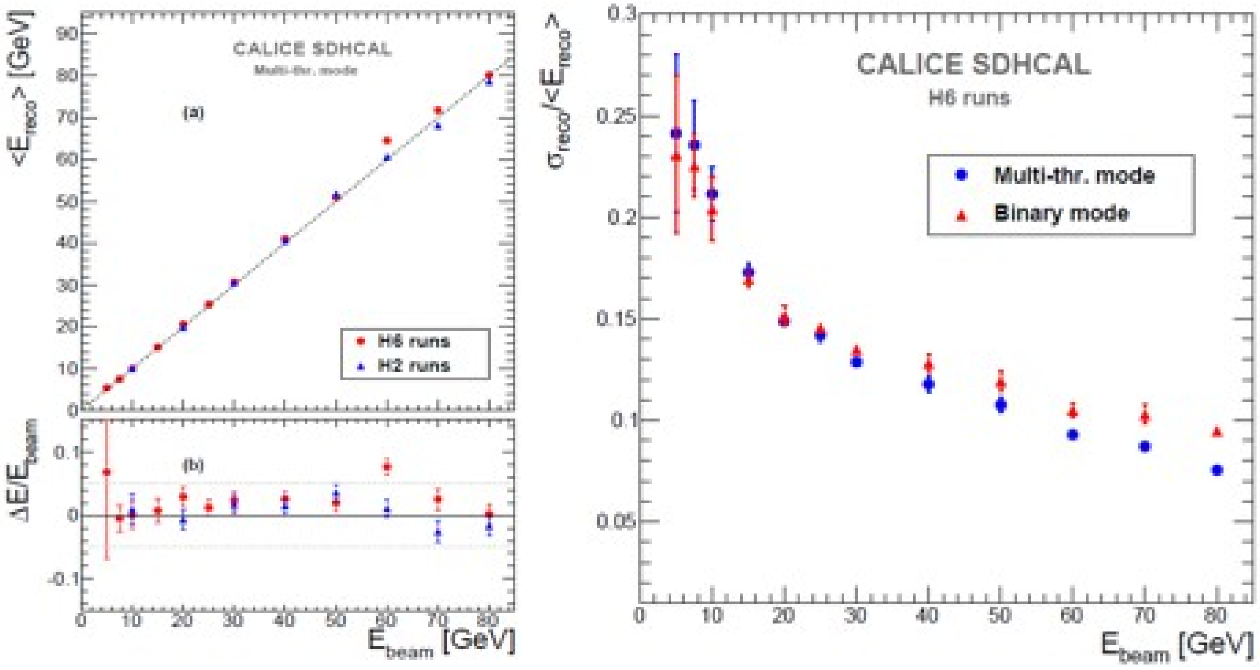
Semi-Digital HCAL – Technological Prototype

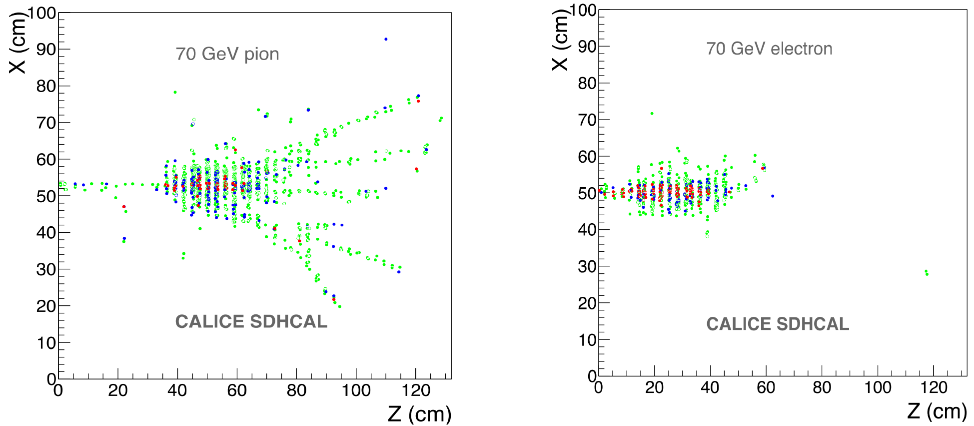


- 48 layers
- 1x 1 cm^2 granularity
  - 3-threshold, 500000 channels
- Power-Pulsed
- Triggerless DAQ system
- Self-supporting mechanical structure

JINST 10 (2015) P10039

JINST 11 (2016) P04001



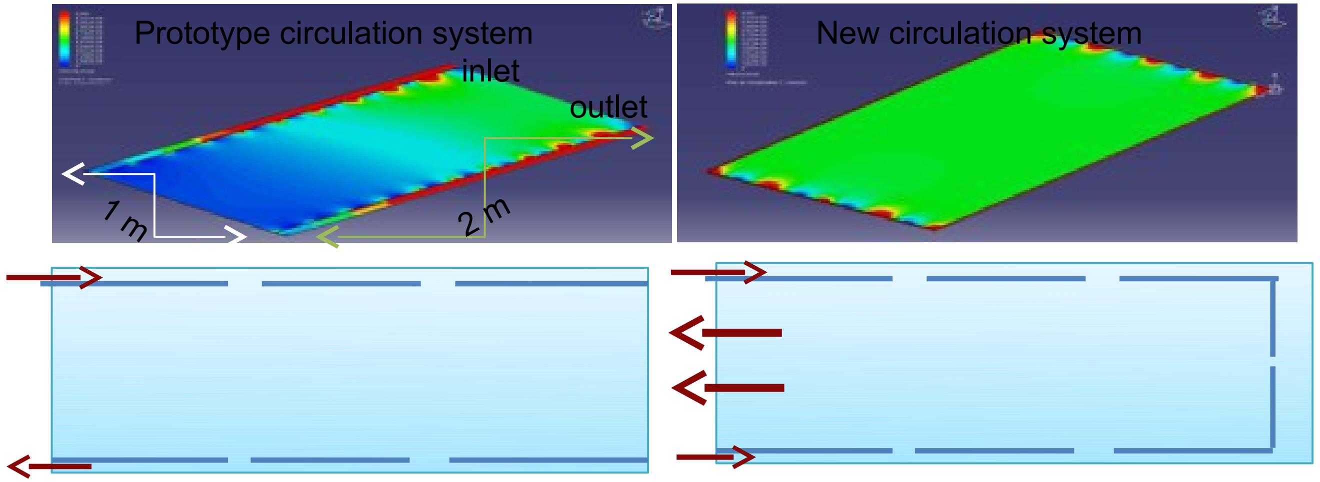


JINST 15 (2020) P10009

SDHCAL – Large Structures

- Detectors as large as 3x1m^2 need to be built
- Electronic readout should be the most robust with minimal intervention during operation.
- Mechanical structure with minimal dead zone
- Include time information **SDHCAL -> T-SDHCAL**

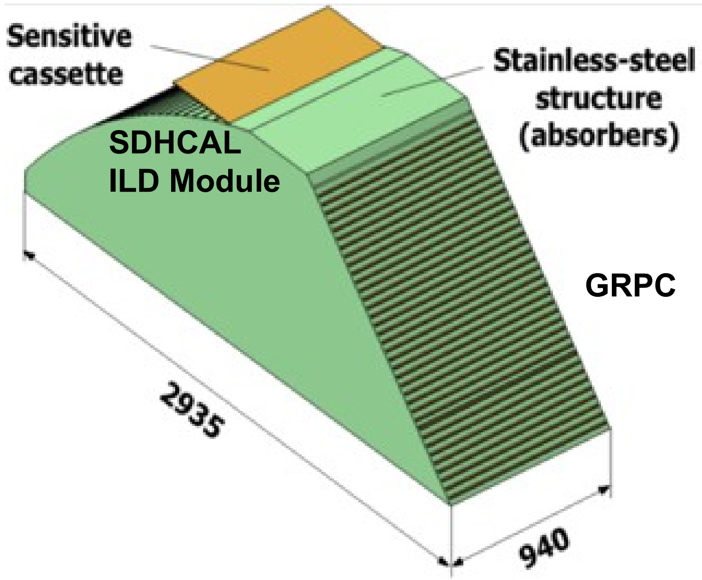
Large RPC detectors

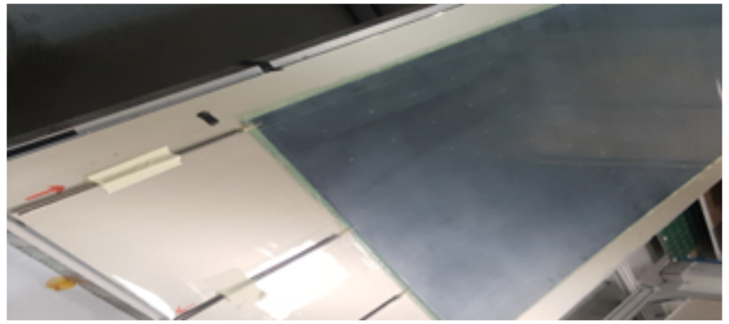


Large mechanical structure

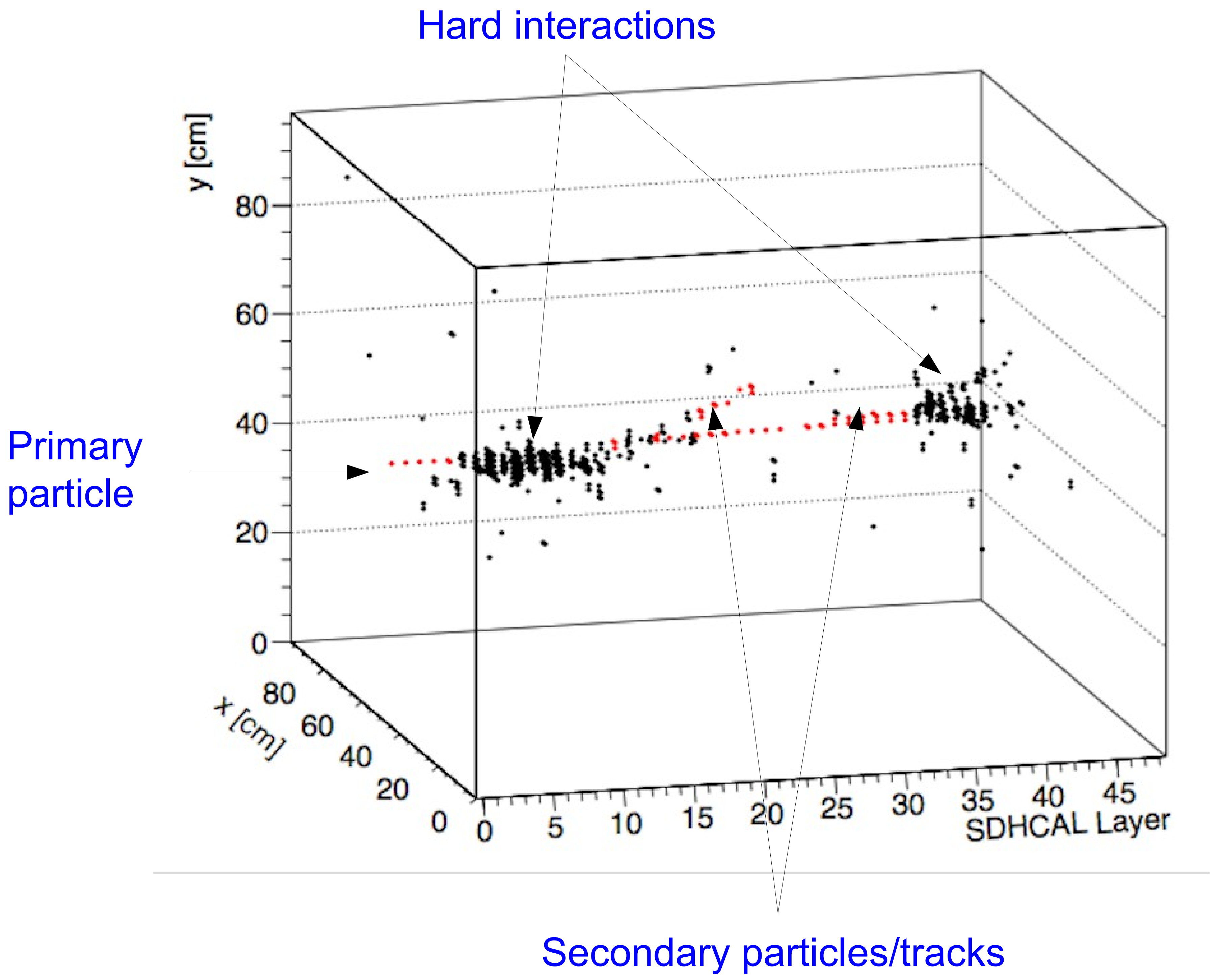
Flatness
Using roller leveling

Reduced dead zone
Using electron beam weilding



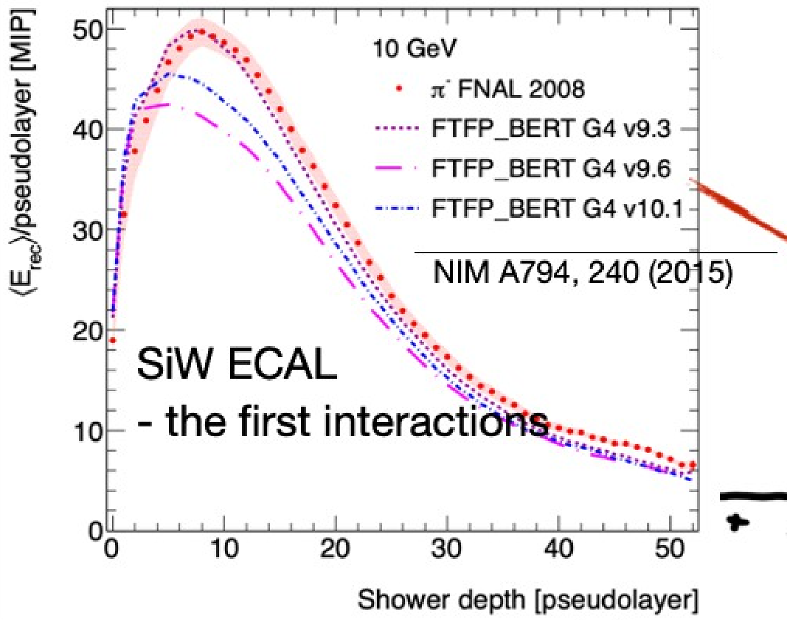


Granular Calorimeters – What do we see?



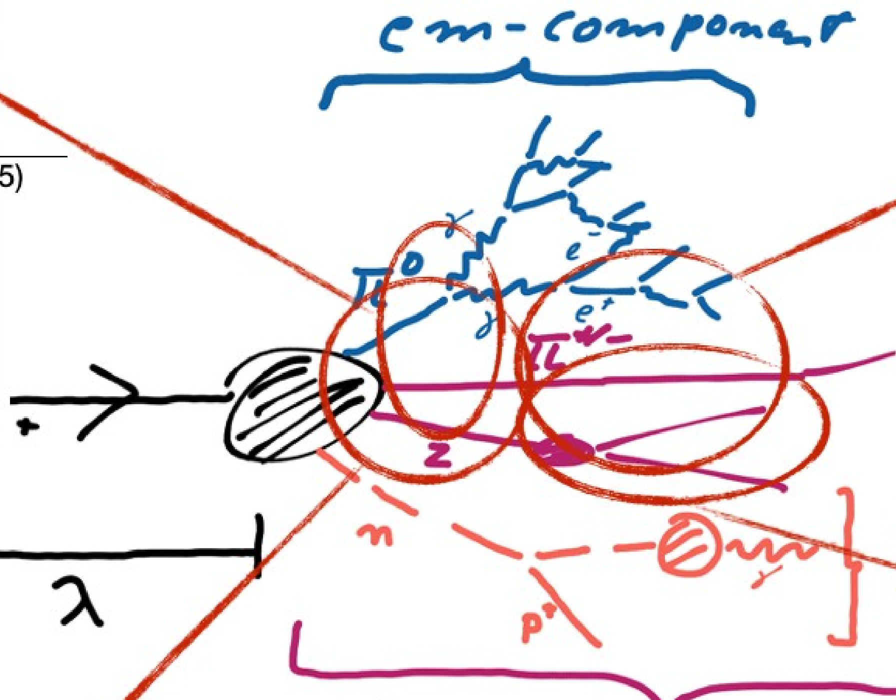
- Modern bubble chambers
- Revealing details of hadronic cascades
- Allows for tracking of particles in calorimetric volume
  - => particle separation for PFA
- Rich potential for application/development of modern pattern recognition algorithms

Exploiting the high granularity – Hadronic Cascades



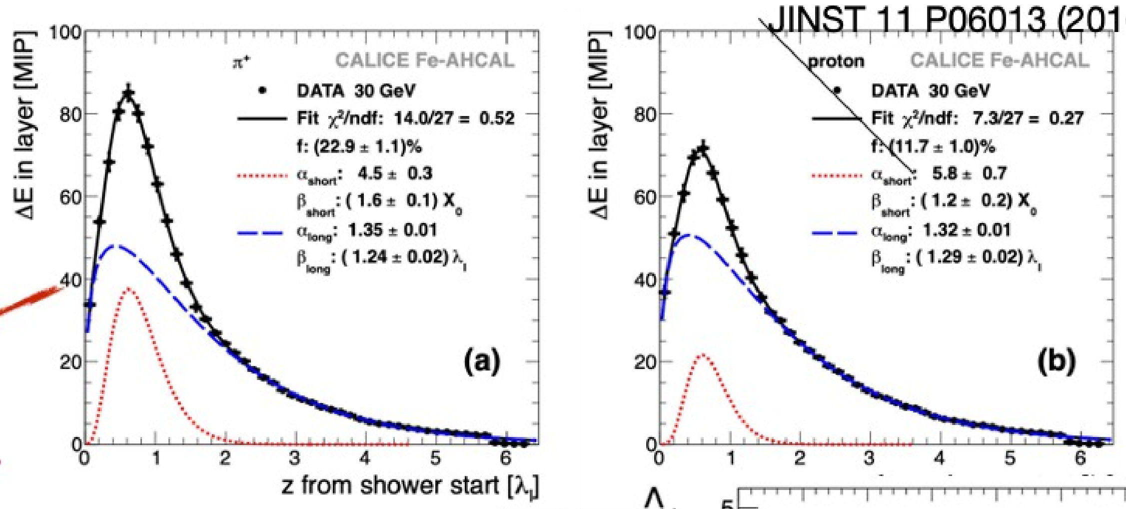
NIM A794, 240 (2015)

SiW ECAL
- the first interactions

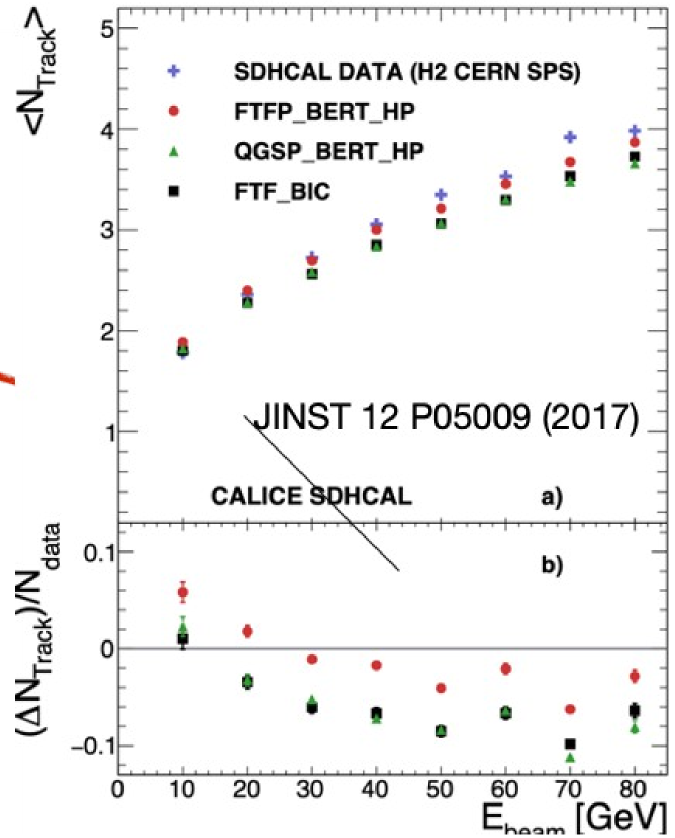


neutrons
→ late components

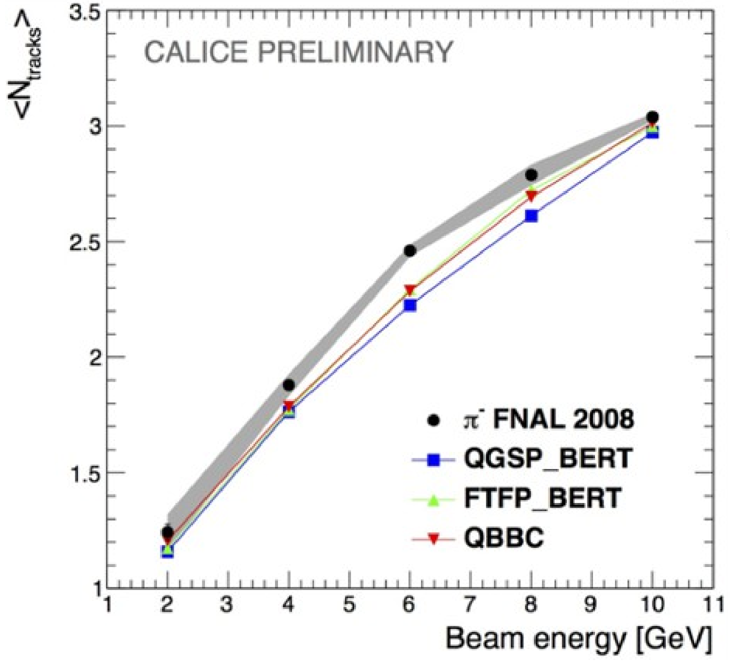
nponent

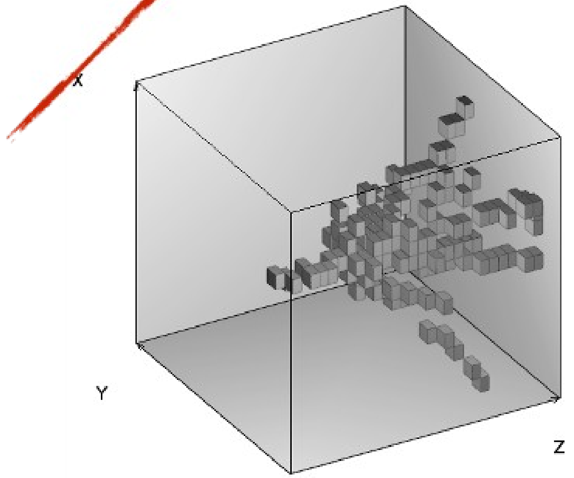


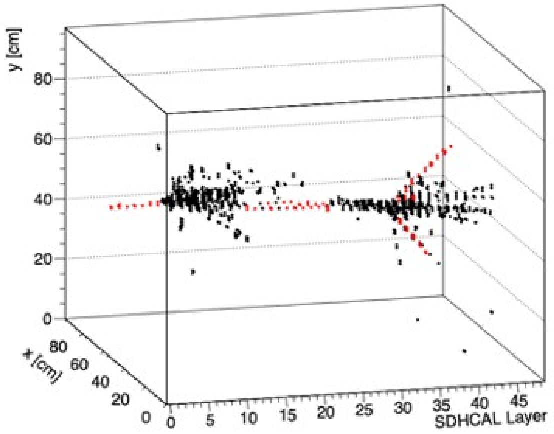
JINST 11 P06013 (2016)



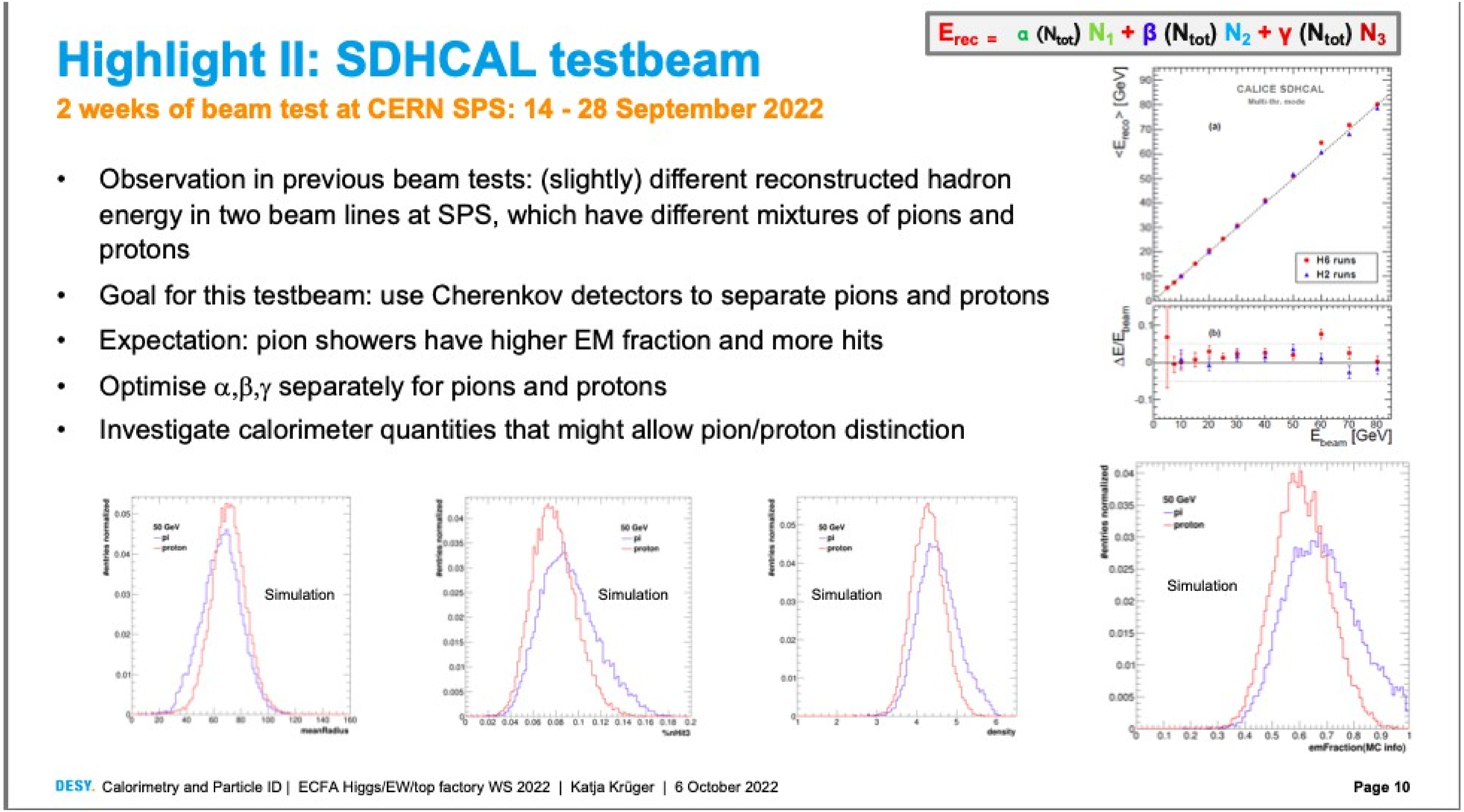
JINST 12 P05009 (2017)







SDHCAL – TB2022



$$E_{rec} = \alpha(N_{tot})\, N_1 + \beta(N_{tot})\, N_2 + \gamma(N_{tot})\, N_3$$

Highlight II: SDHCAL testbeam

2 weeks of beam test at CERN SPS: 14 - 28 September 2022

- Observation in previous beam tests: (slightly) different reconstructed hadron energy in two beam lines at SPS, which have different mixtures of pions and protons
- Goal for this testbeam: use Cherenkov detectors to separate pions and protons
- Expectation: pion showers have higher EM fraction and more hits
- Optimise α,β,γ separately for pions and protons
- Investigate calorimeter quantities that might allow pion/proton distinction

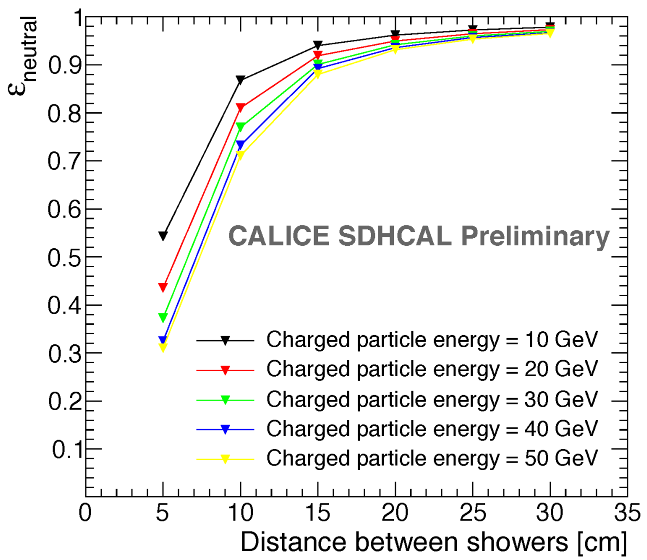
DESY. Calorimetry and Particle ID | ECFA Higgs/EW/top factory WS 2022 | Katja Krüger | 6 October 2022

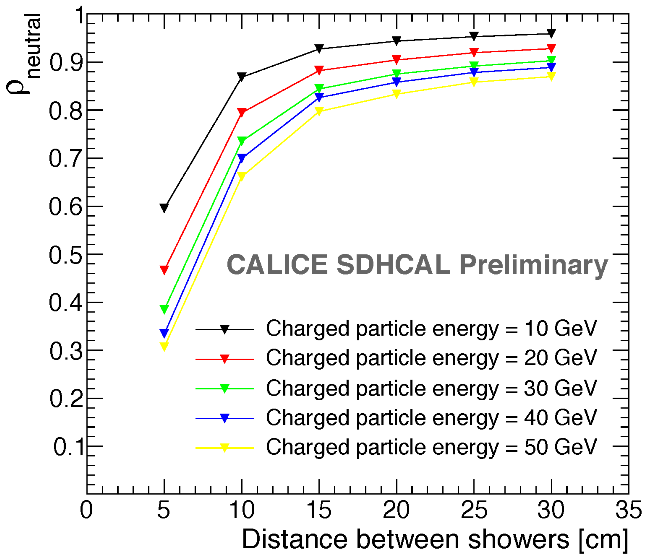
Page 10

From K. Krüger

Exploiting the high granularity – Particle Separation

SDHCAL: Separation of 10 GeV neutral hadron from charged hadron [CALICE-CAN-2015-001]

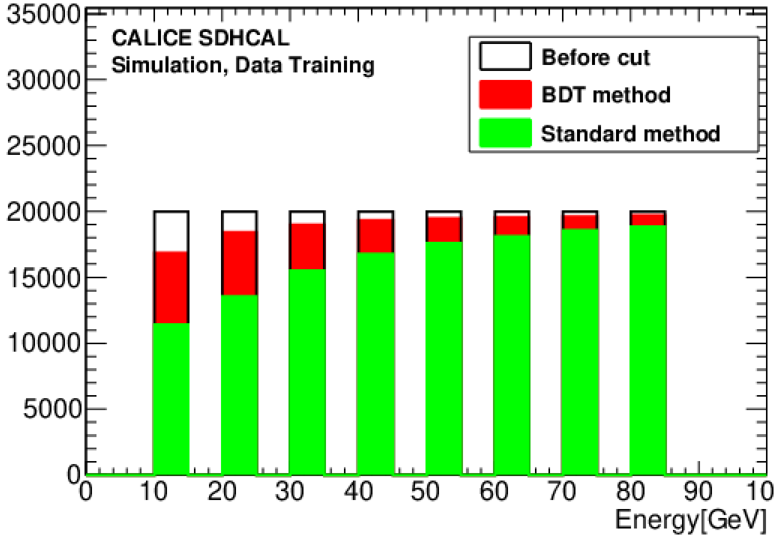


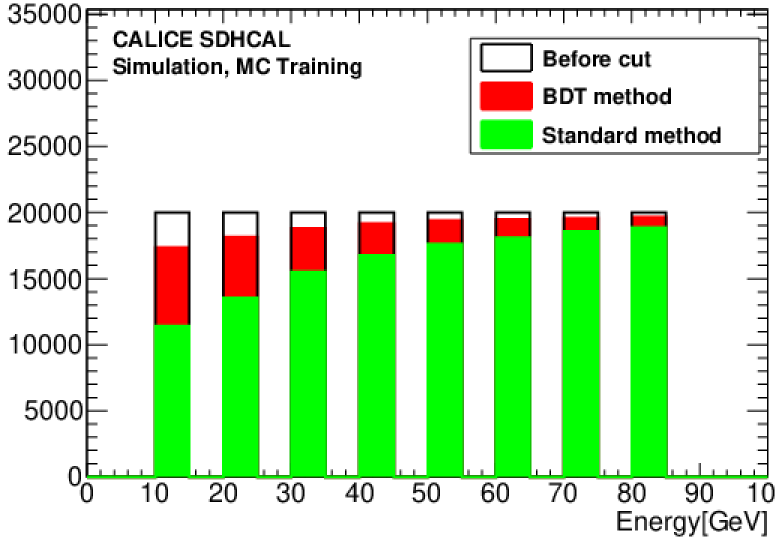


More than 90% efficiency (ε) and purity (ρ) for distances ≥ 15 cm

SDHCAL: Multi-variate analysis for Particle ID

[arxiv:2004.02972, accepted by JINST]

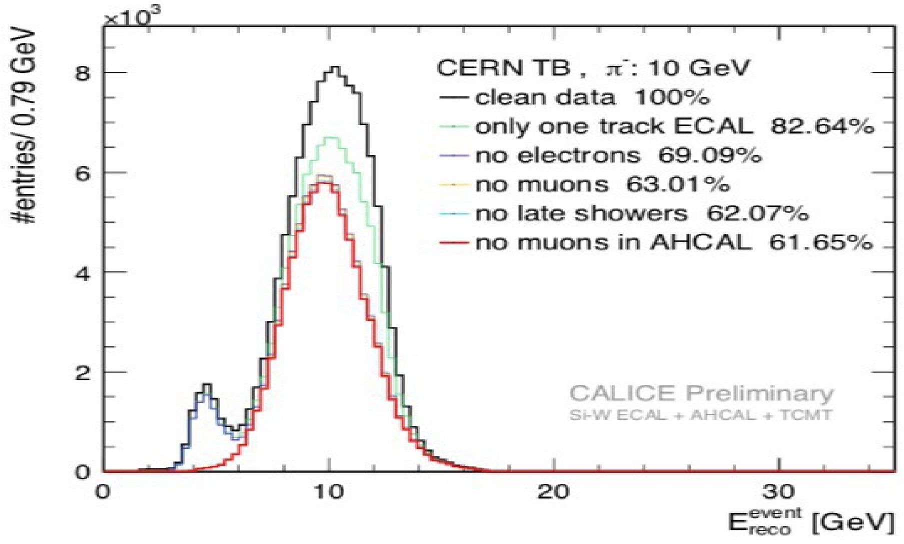




BDT enhance pion selection efficiency at small energies

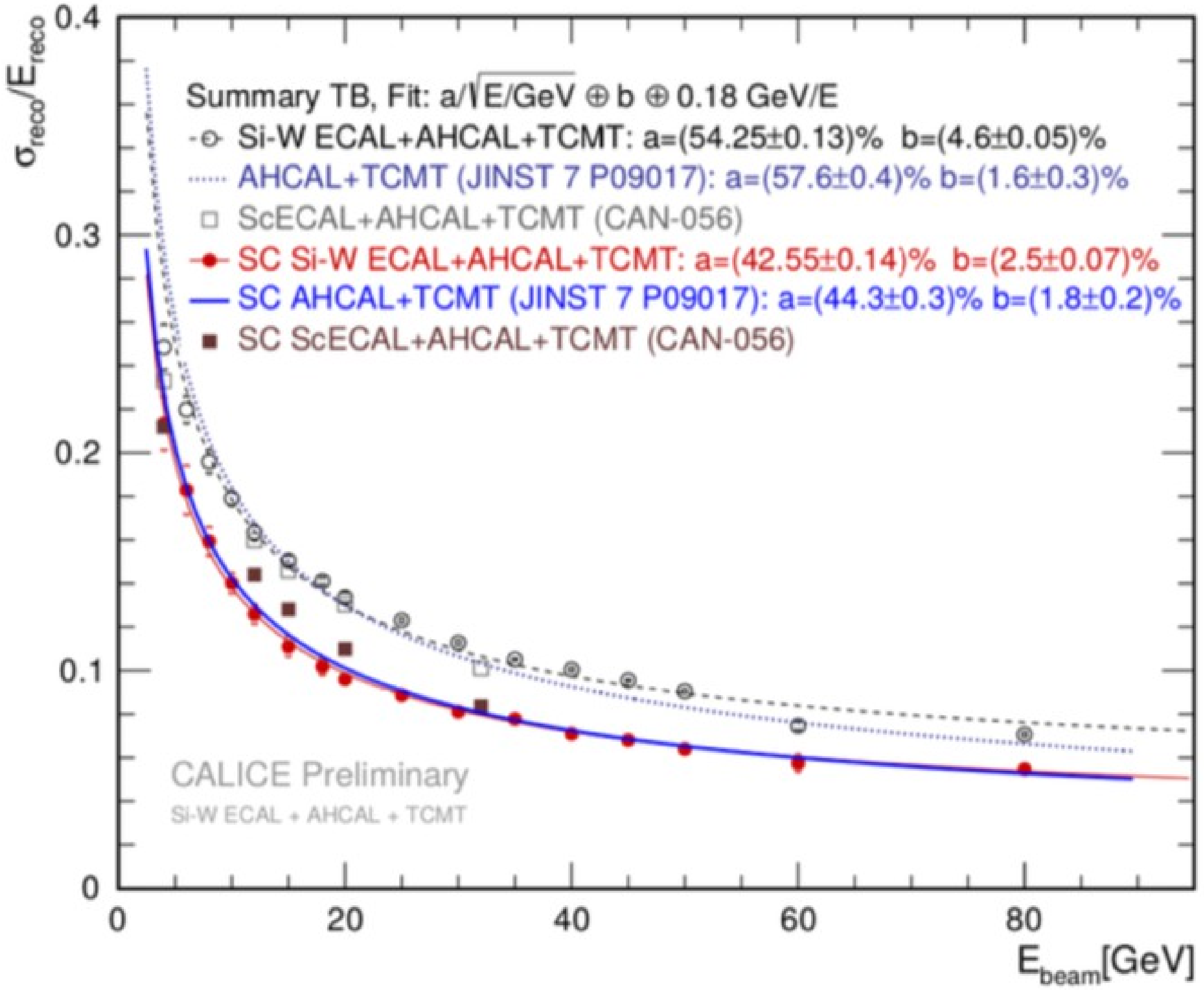
SiW ECAL: Tracking capabilities to select single π-events

[CALICE-CAN-2017-002]



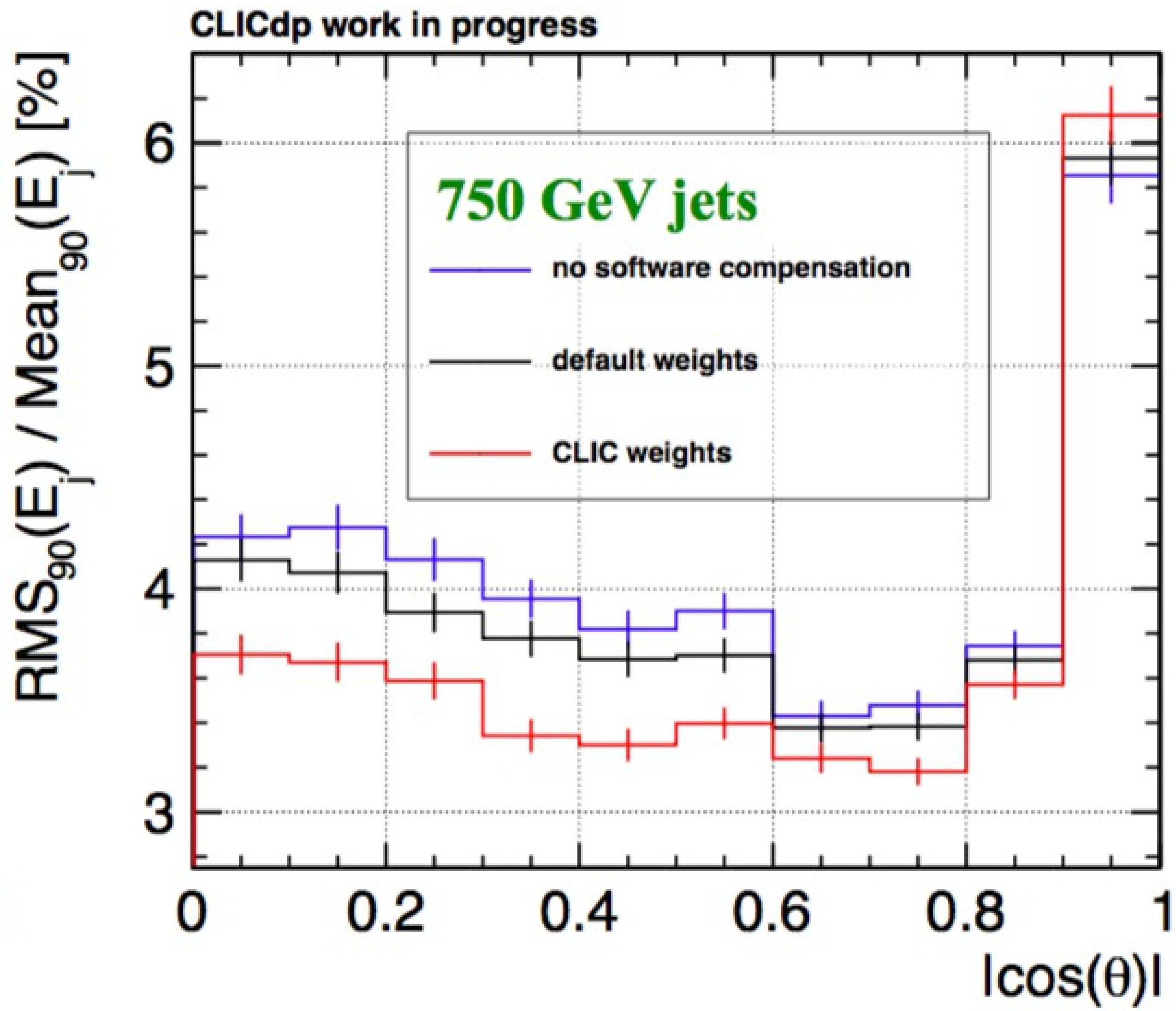
Exploiting the high granularity – Energy Resolution

Pion showers in combined CALICE beam tests



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

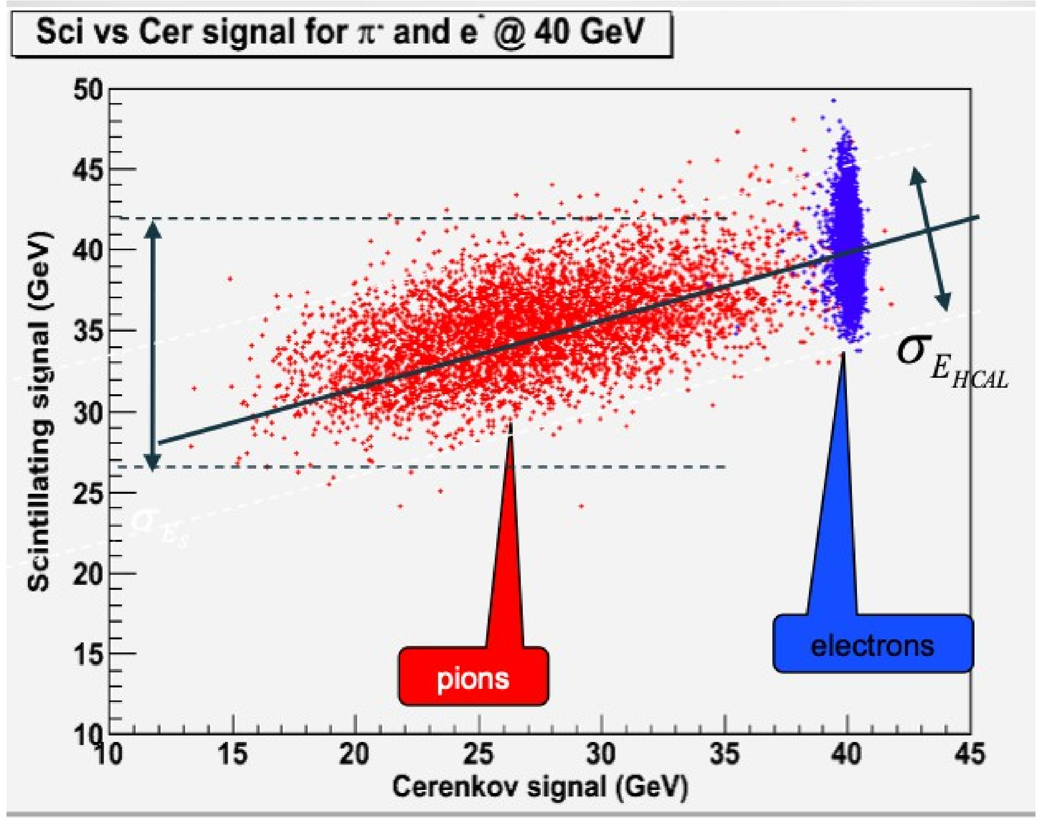
Jet analysis in CLIC



Software weighting improves jet energy resolution

New Trends – Dual readout goes highly granular

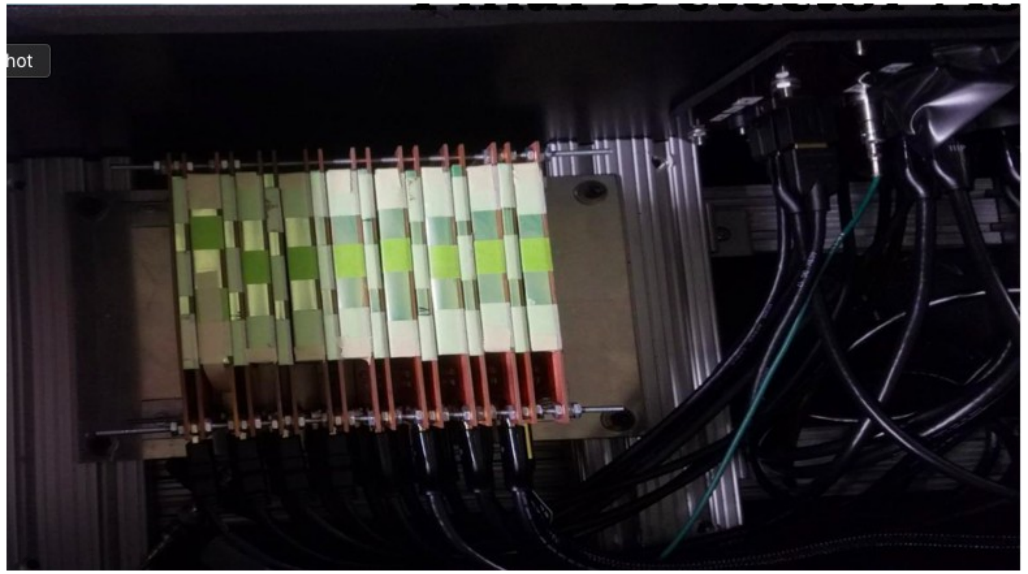
Principle of Dual Readout



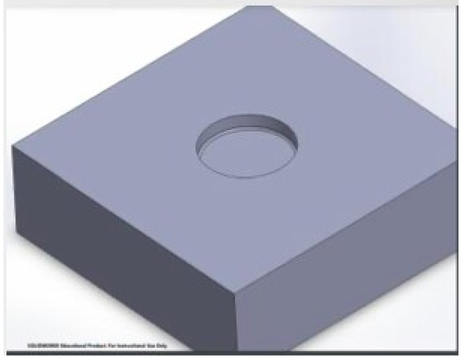
- Simultaneous readout of
  - Cerenkov Light from electromagnetic shower component
  - Scintillation light from Hadronic shower component

C. Gatto, CALICE TB Meeting

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



Next step:

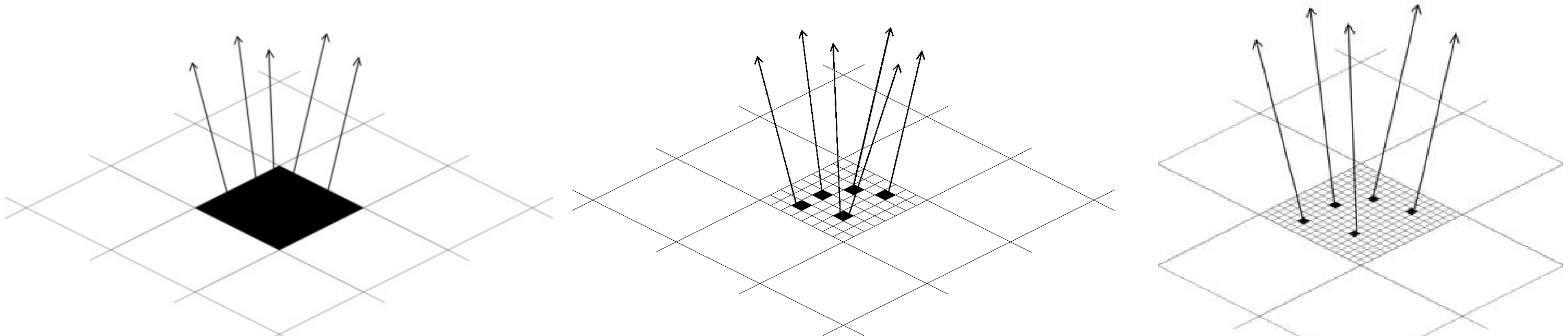


3x3 cm^2 Glass tile

3x3 cm^2 Plastic Tile

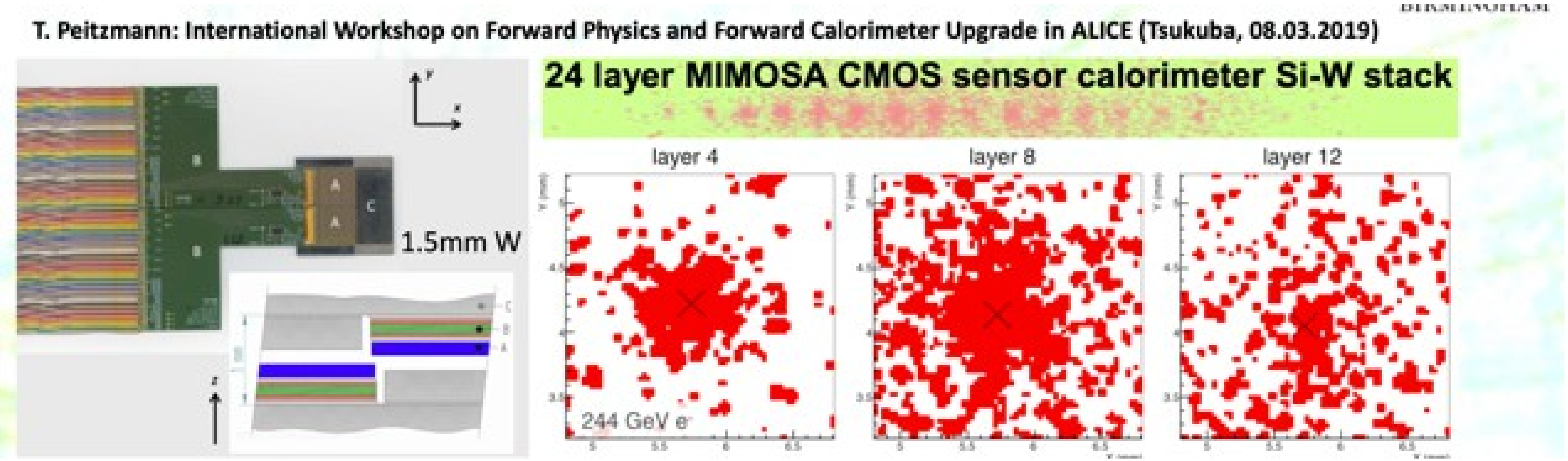
Dual Readout with “CALICE Size” tiles

New Trends – Ultra High Granularity


AECAL

DECAL
Npixels<Nparticles

DECAL
Npixels=Nparticles

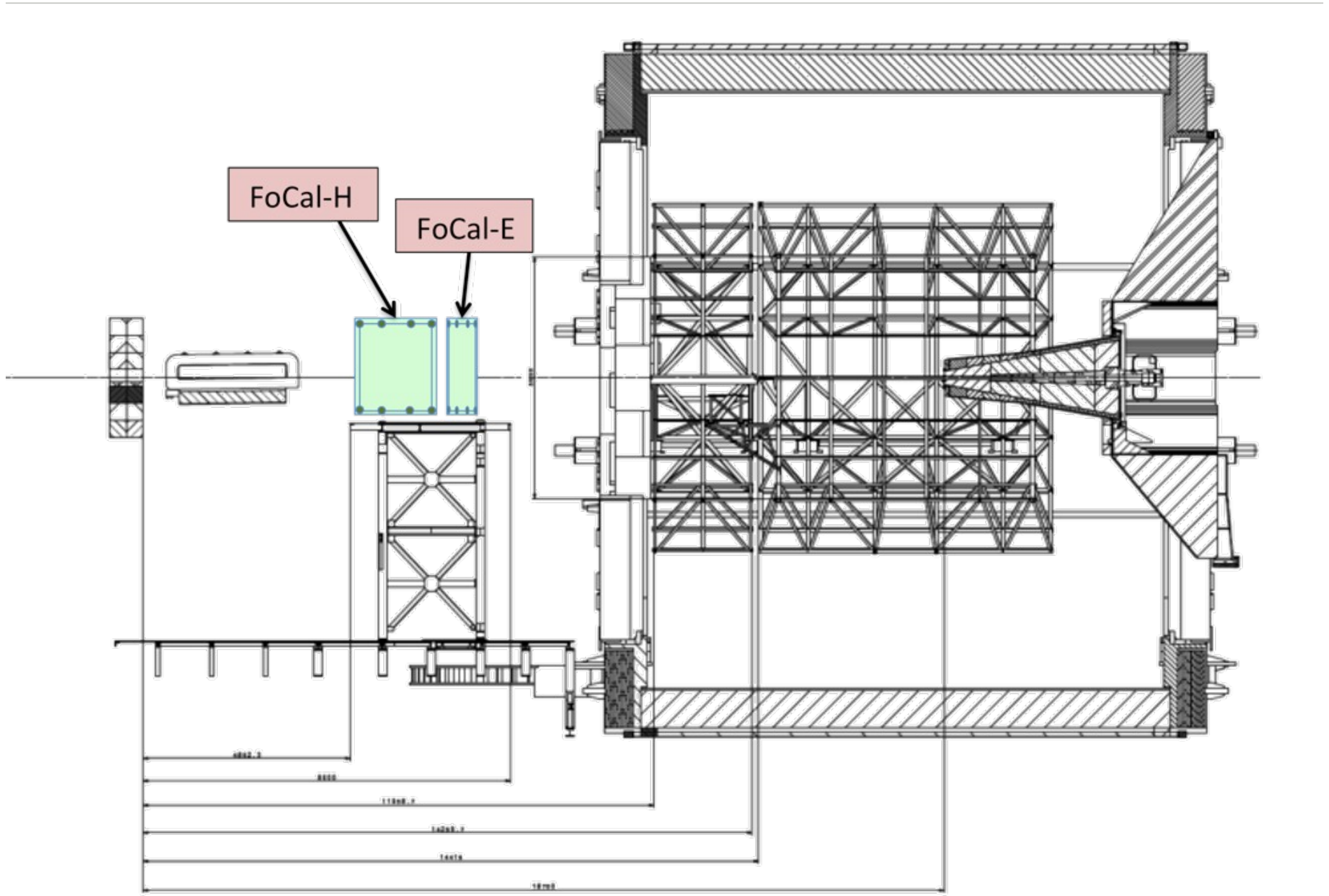

T. Peitzmann: International Workshop on Forward Physics and Forward Calorimeter Upgrade in ALICE (Tsukuba, 08.03.2019)

24 layer MIMOSA CMOS sensor calorimeter Si-W stack

- CMOS Sensors for calorimetric approaches
  - Synergies between LC Detector R&D and ALICE Detector Upgrade

MAPS ECAL

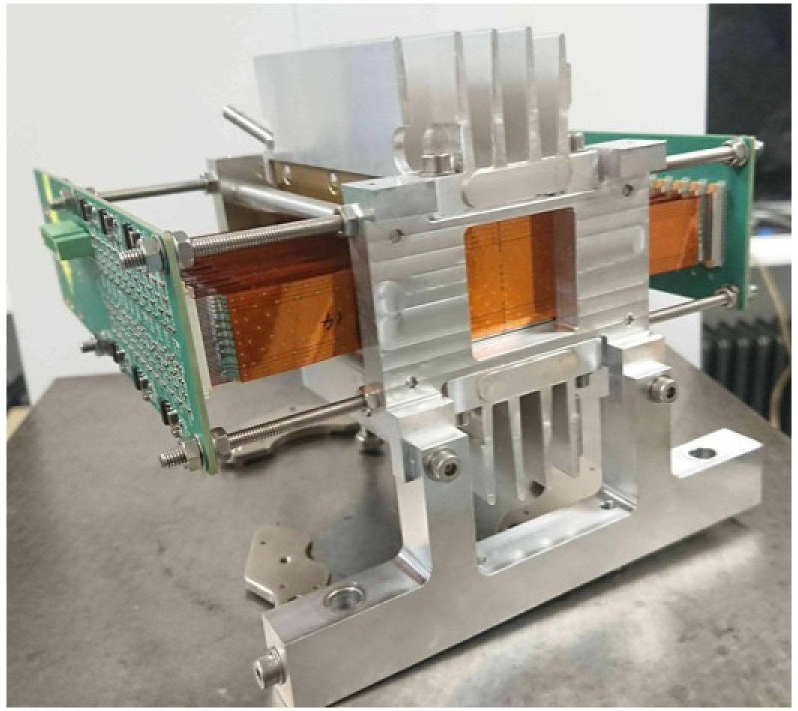
Ultrahigh granular calorimeter is under consideration for ALICE ...



... but also for SiD-ILC, FCC-hh

Numbers for FOCAL assuming ≈ $1\,\mathrm{m}^2$ detector surface

	LG	HG
pixel/pad size	≈ $1\,\mathrm{cm}^2$	**≈ $30\times30\,\mu\mathrm{m}^2$**
total # pixels/pads	≈ 2.5×10^5	**≈ 2.5×10^9**
readout channels	≈ 5×10^4	**≈ 2×10^6**



- Prototype with ALPIDE
- Arxiv:2209.02511

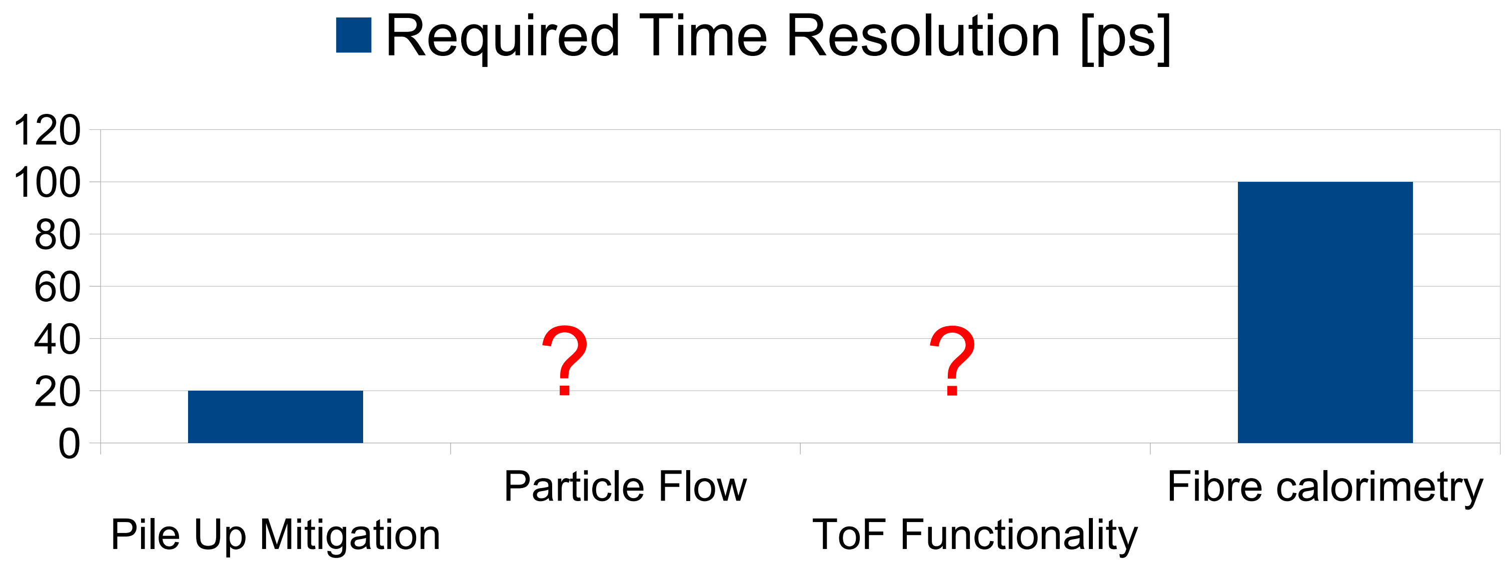
Timing ?

- 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?

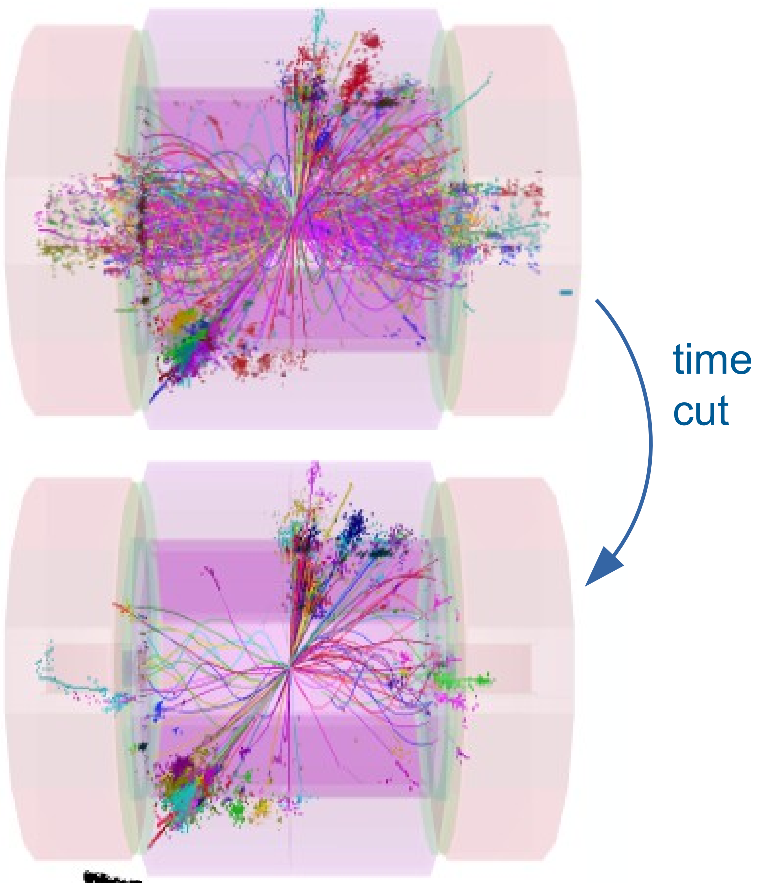
- For which purpose ?
  - •Mitigation of pile-up (basically all high rate experiments)
  - •Support of PFA – unchartered territory
  - •Calorimeters with ToF functionality in first layers?
    - •Might be needed if no other PiD detectors are available (rate, technology or space requirements)
    - •In this case 20ps (at MIP level) would be maybe not enough
  - •Longitudinally unsegmented fibre calorimeters



- 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

New Trends – Timing I

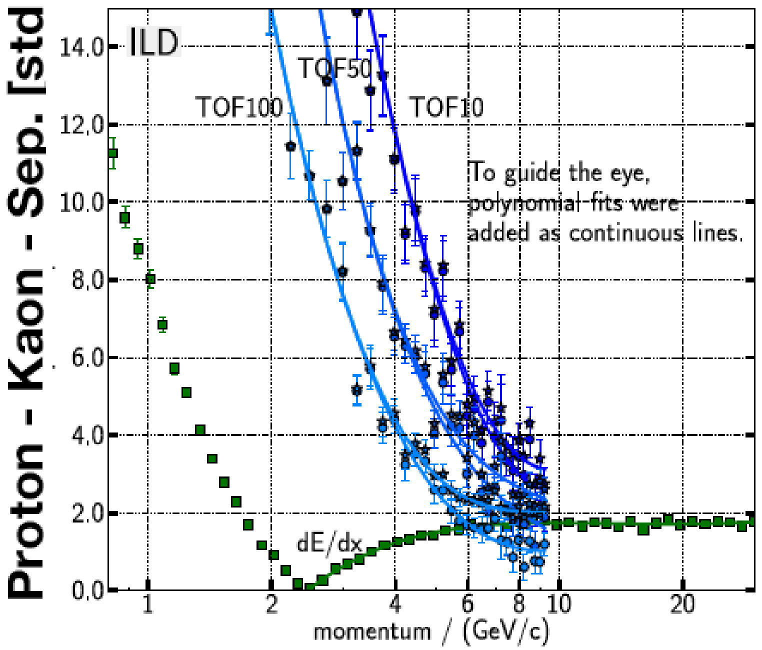
Cleaning of Events



[CLIC CDR: 1202.5940]
adapted from L. Emberger

Particle ID by Time-of-Flight

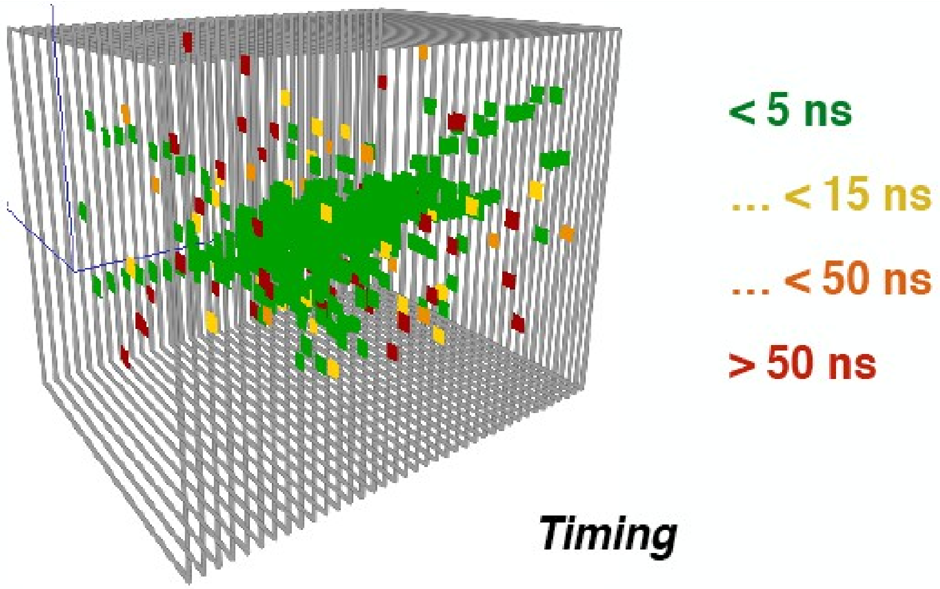
- Complementary to dE/dx
  - here with 100ps on 10 ECAL hits



S. Dharani, U. Einhaus, J. List

Ease Particle Flow:

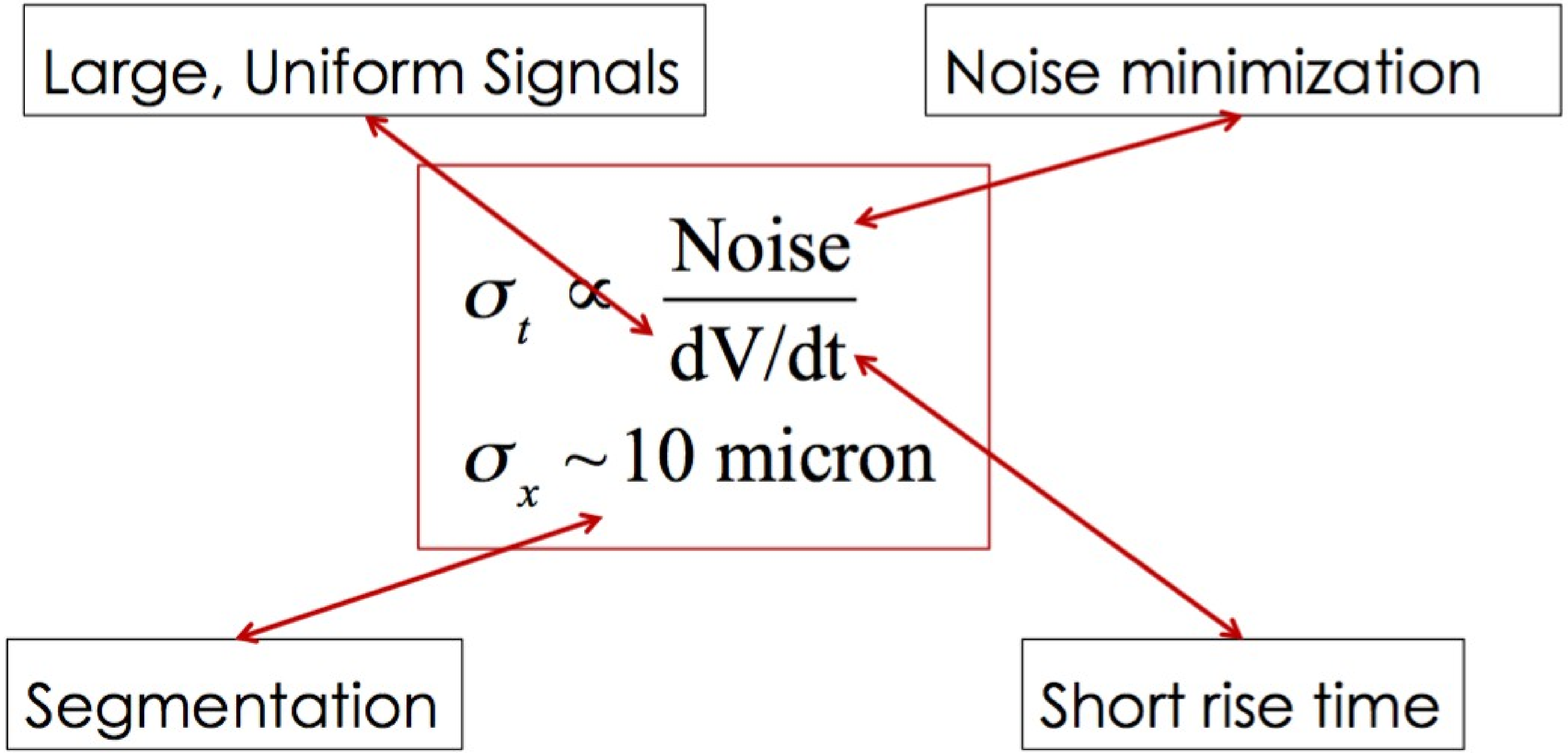
- Identify primers in showers
- Help against confusion
- Cleaning of late neutrons & back scattering.



Ch. Graf

New Trends Timing II

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



Large, Uniform Signals

Noise minimization

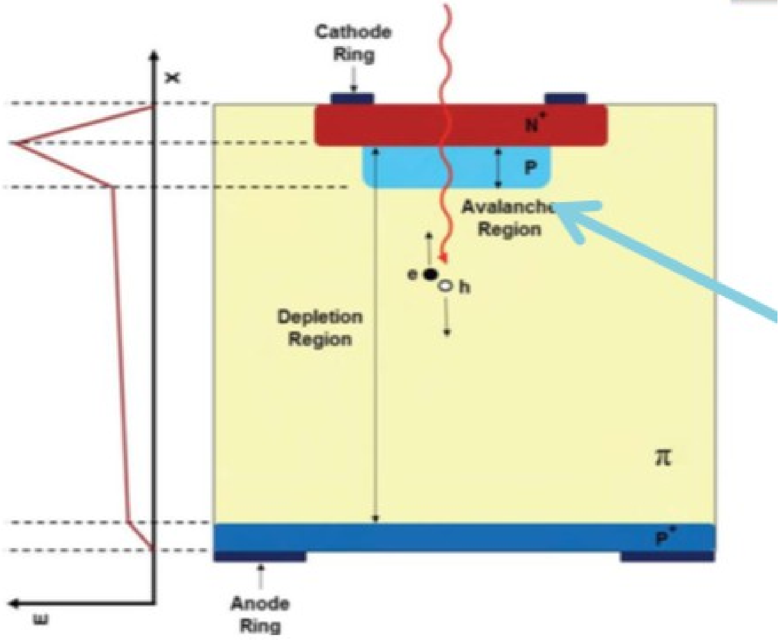
$$\sigma_t \propto \frac{\text{Noise}}{dV/dt}$$

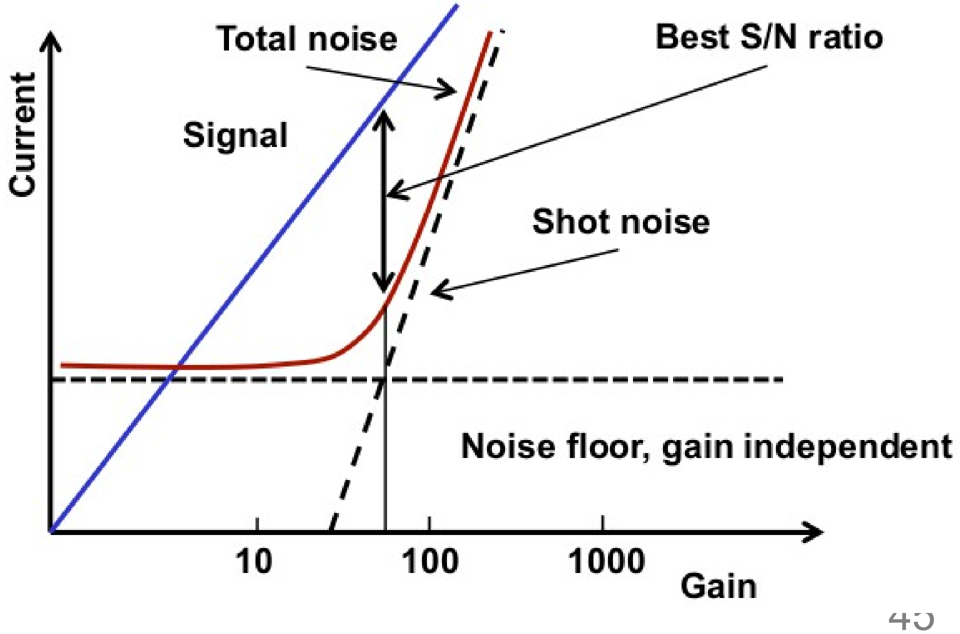
$$\sigma_x \sim 10 \text{ micron}$$

Segmentation

Short rise time

LGAD



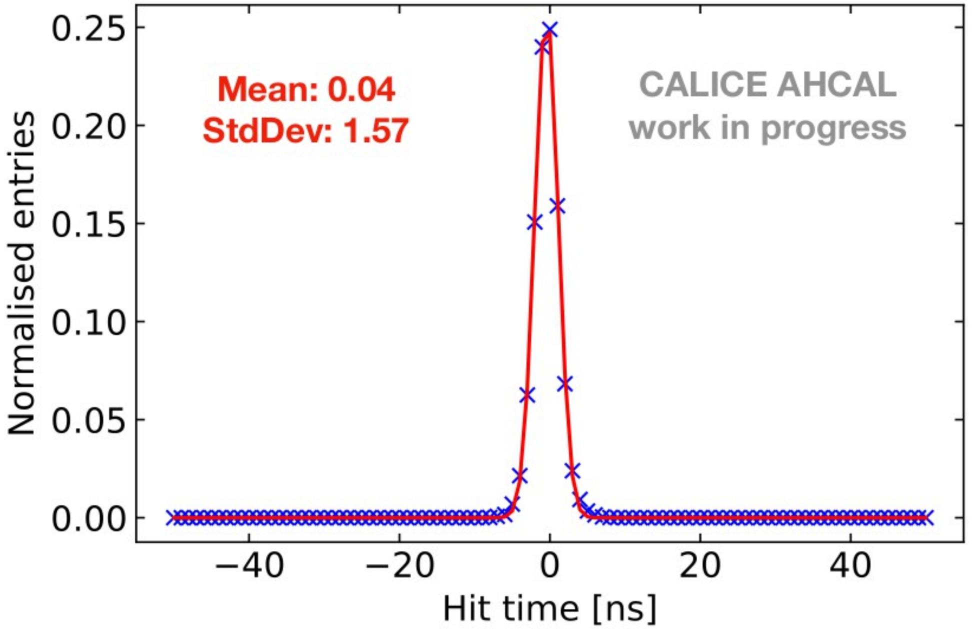


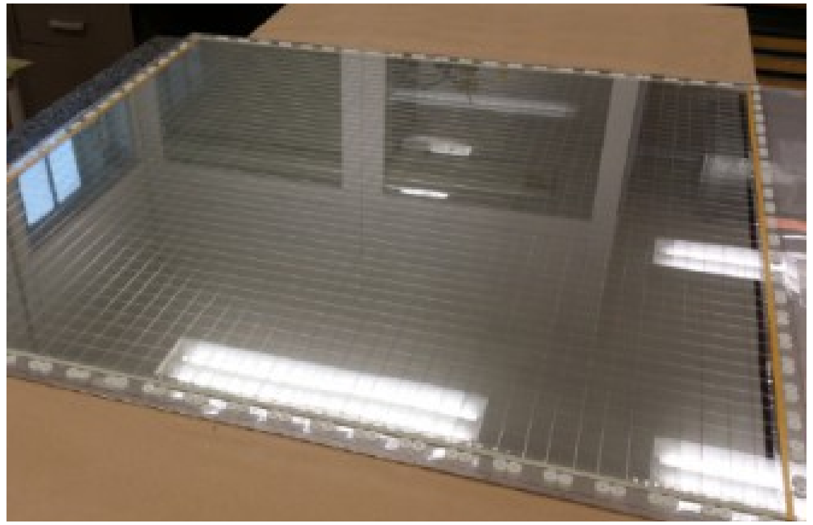
- Better dV/dt by “active” Si diodes ? => Low Gain Avalanche Detectors
  - LGADs applied for ATLAS HGTD and CMS ETD
  - Expect time resolution σ_t ~ 30-50ps
- Integration of LGADs into calorimeter volume may be one of the roads to follow

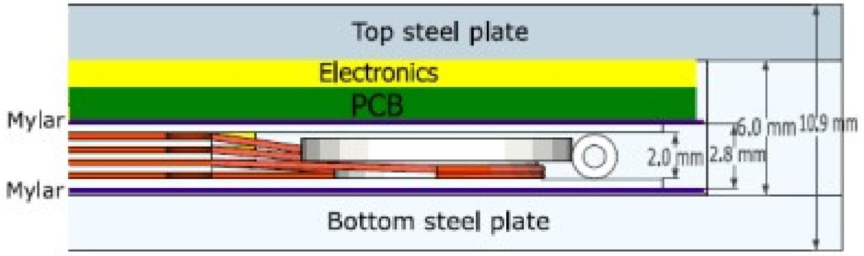
New Trends – Timing III

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

Clock frequency 5 MHz,
Powering pulsing



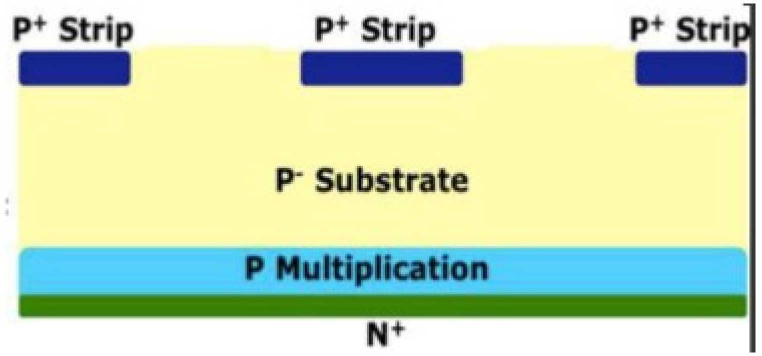




Under development:
GRPC with PETIROC

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

Inverse APD as LGAD?

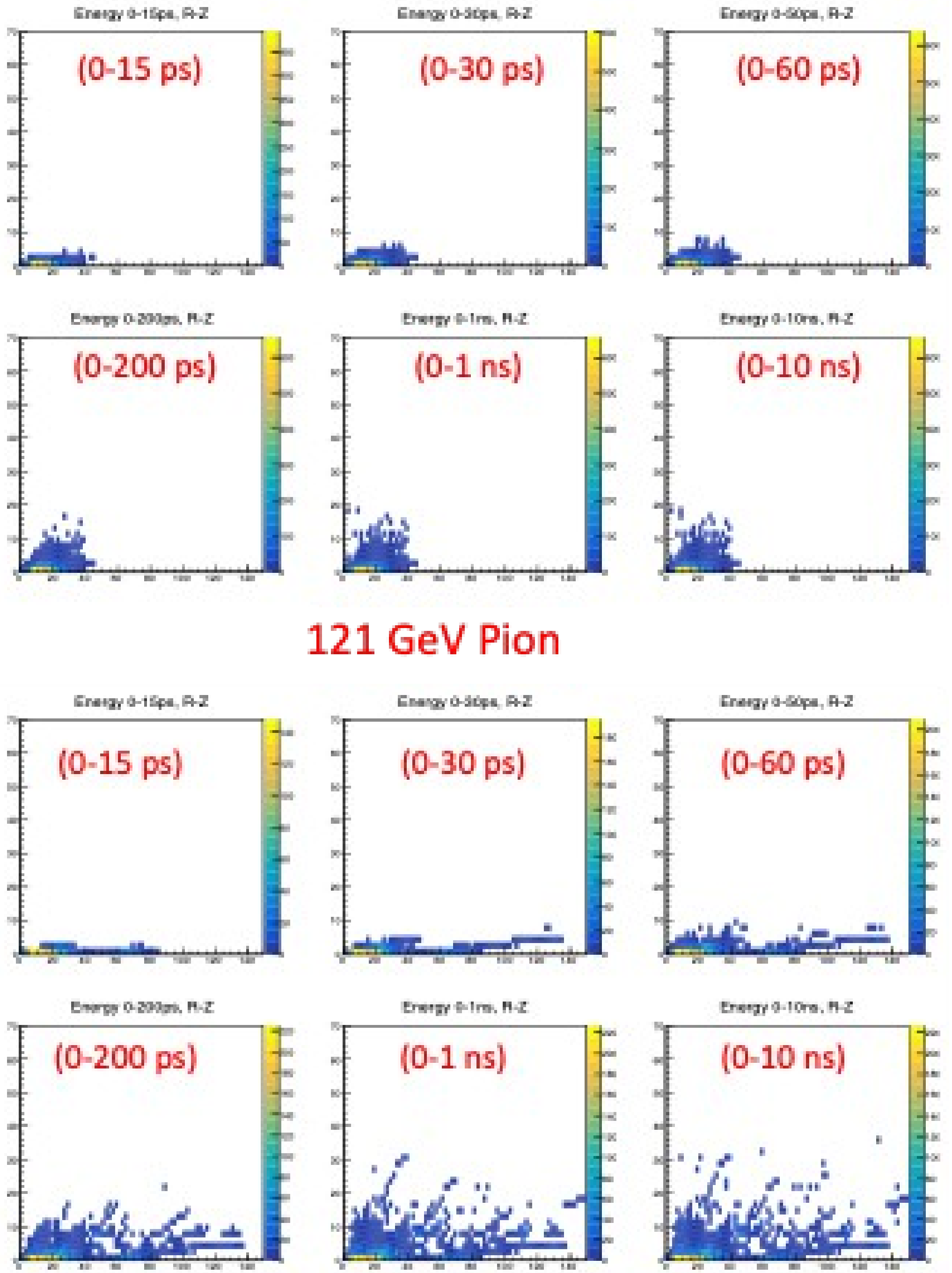


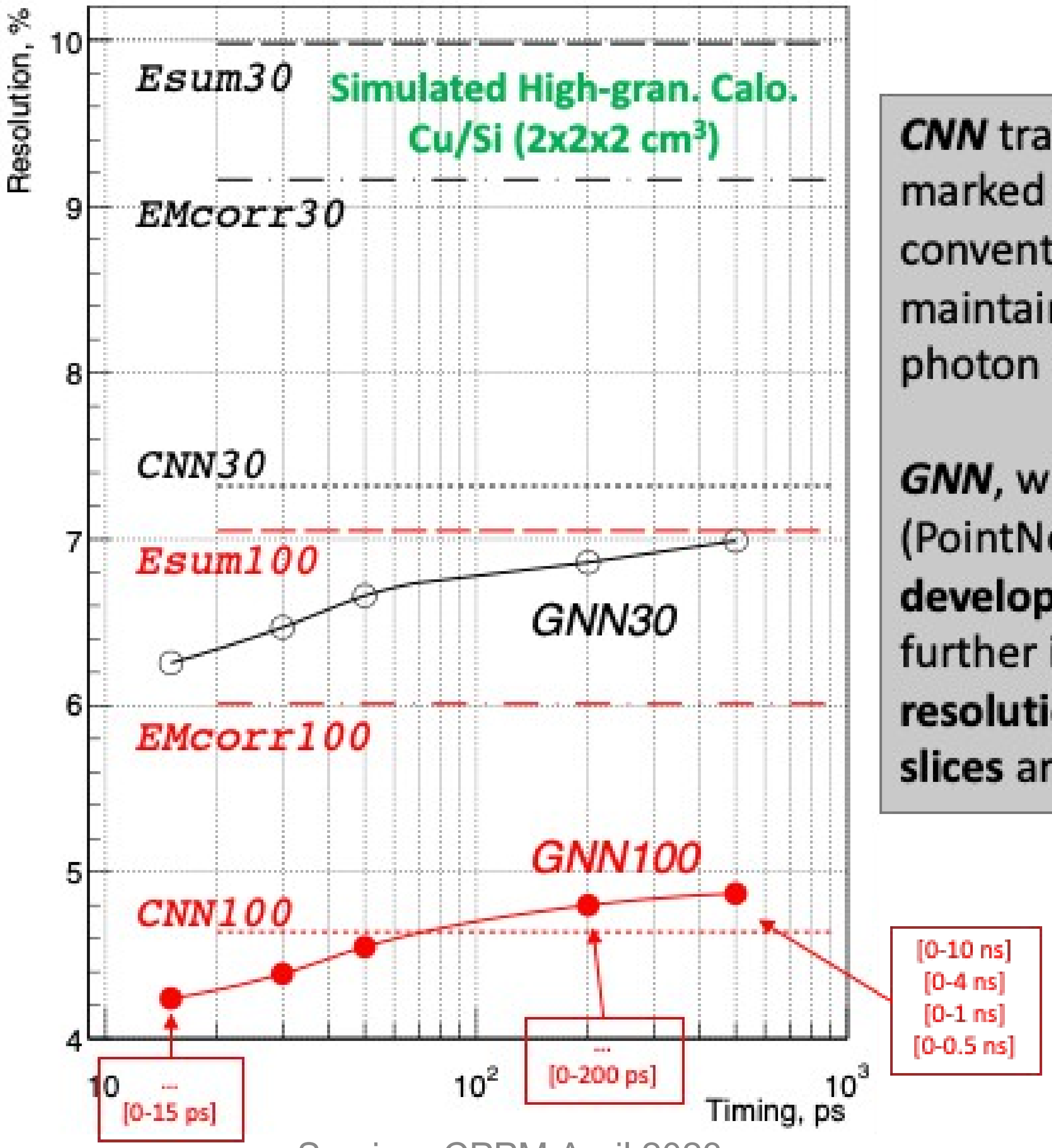
Inverse APD
by Hamamatsu

Gain ~ 50

Timing in calorimeters

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





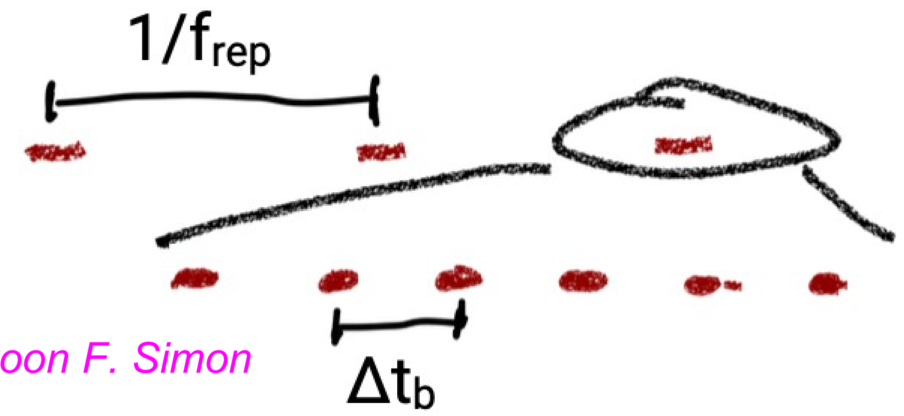
CNN trained on pions achieves marked improvement over the conventional approache while maintaining performance for photon reconstruction

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

arxiv:2108.10963

Operation mode- pulsed or continous

- Linear Colliders operate in bunch trains



Cartoon F. Simon

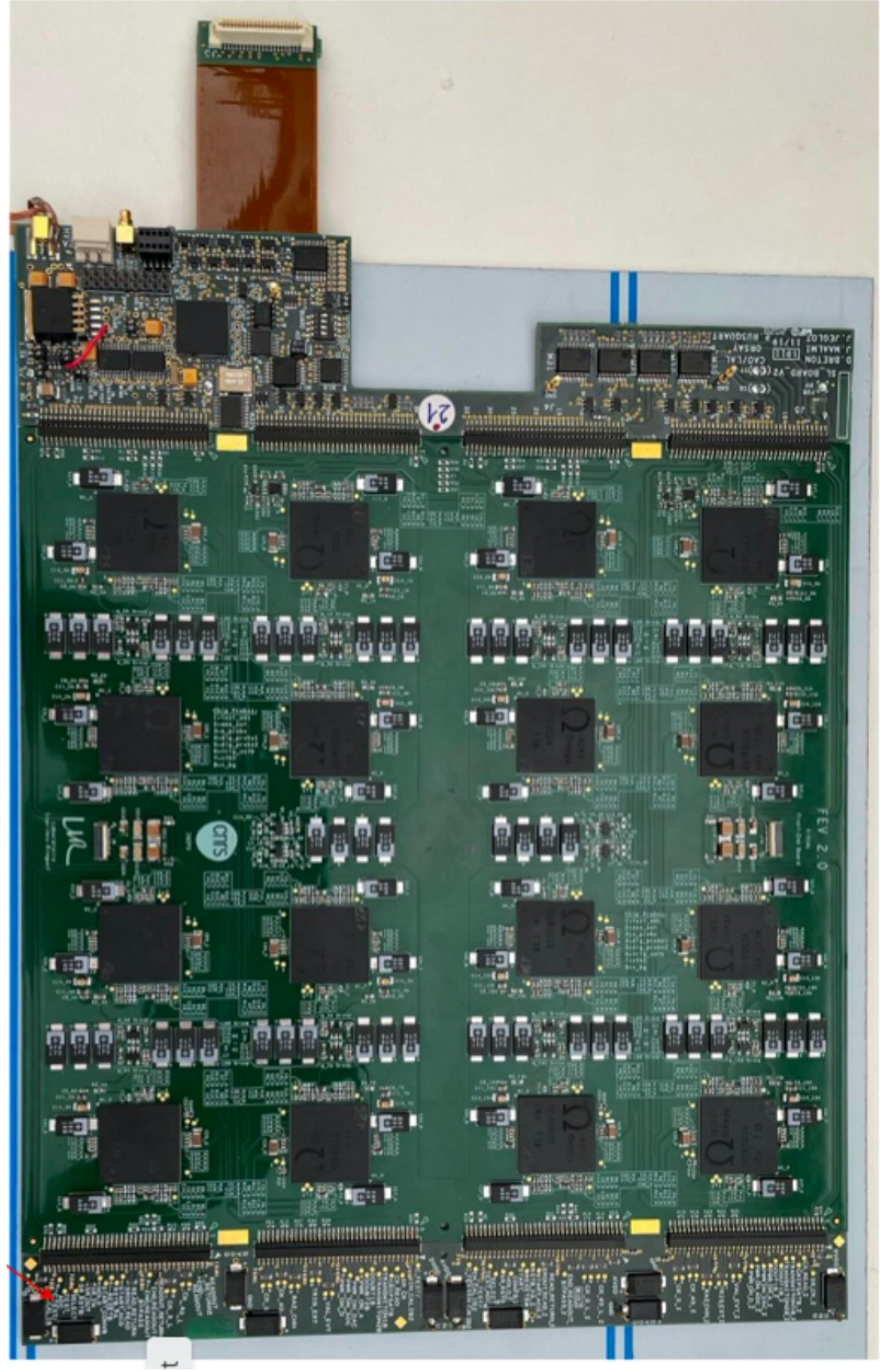
CLIC: Δt_b ~ 0.5ns, frep = 50Hz
ILC: Δt_b ~550ns, frep = 5 Hz (base line)

- Power Pulsing reduces dramatically the power consumption of detectors
  - e.g. ILD SiECAL: Total average power consumption 20 kW for a calorimeter system with 10^8 cells
- Power Pulsing has considerable consequences for detector design
  - Little to no active cooling
  - => Supports compact and hermetic detector design
- Have to avoid large peak currents
- Have to ensure stable operation in pulsed mode

- Upshot: Pulsed detectors face other R&D challenges than those that will be operated in “continuous” mode
  - Tendency: Avoid/minimise active cooling in also continuous mode

SiW ECAL PCB - New FEV 2.1

LLR, IJCLab, LPNHE, OMEGA



Improved Layout

- Better shielding of AVDD and AVDD PA plans and minimisation of cross-talk between inputs and digital signals.

Power Pulsing Mode: new philosophy

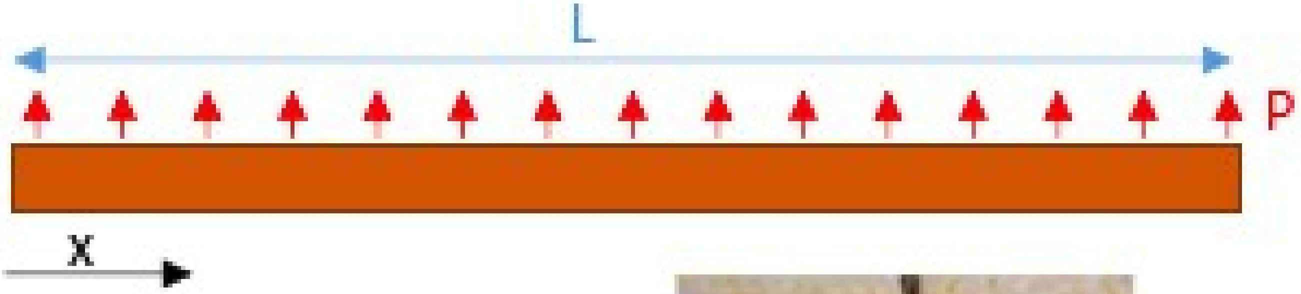
- limiting the current through a layber (current limiter present on the SL Board) to:
  - avoid driving high currents through the connectors and makes the current peaks **local** around the SKIROCs chips
  - avoid voltage drop along the slab
  - ensure temperature uniformity
- Large capacitors with low ESR for **local** energy storage (around each SKIROC chip)
- Generate **local** power supply with LDO (Low Drop Out) to avoid voltage variations

- 25 PCBs delivered beginning of March 2023

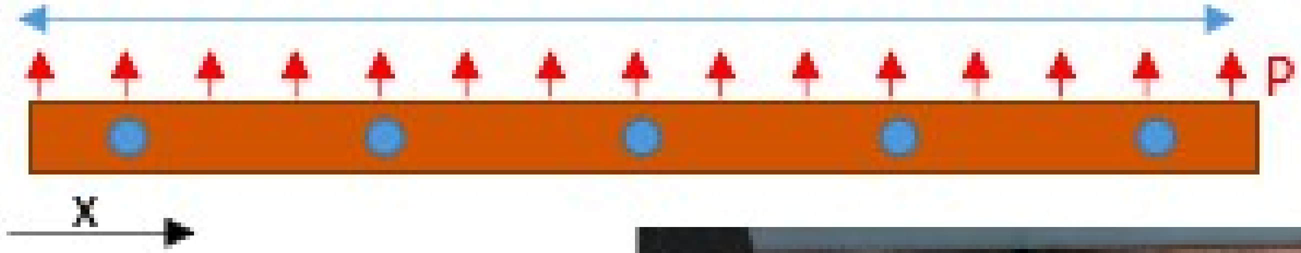
This board will enable us to finish the ongoing R&D, join the LUXE Experiment (see later) and be ready in case of ...

Active cooling?

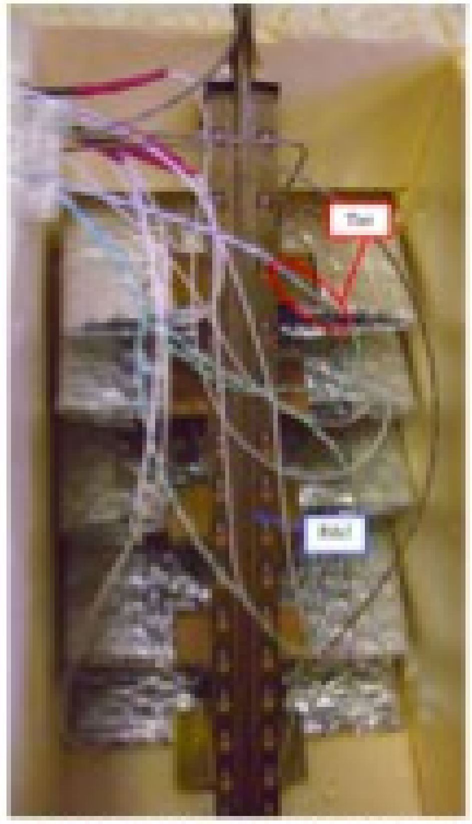
Passive cooling



Active cooling

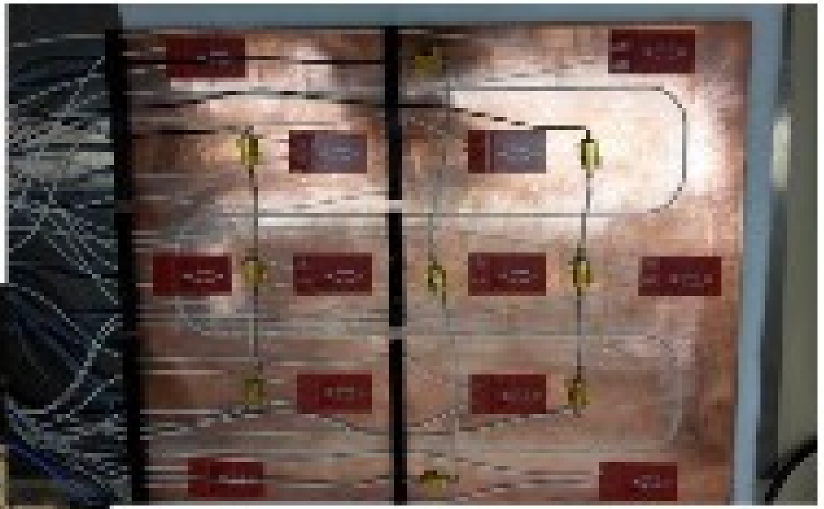


Passive cooling ramp example



Passive cooling ramp set up test

Active cooling set up test with water at room temperature



Active cooling test layout (400mm x 300mm x 3mm thick copper plate with 1,8OD pipes embedded)

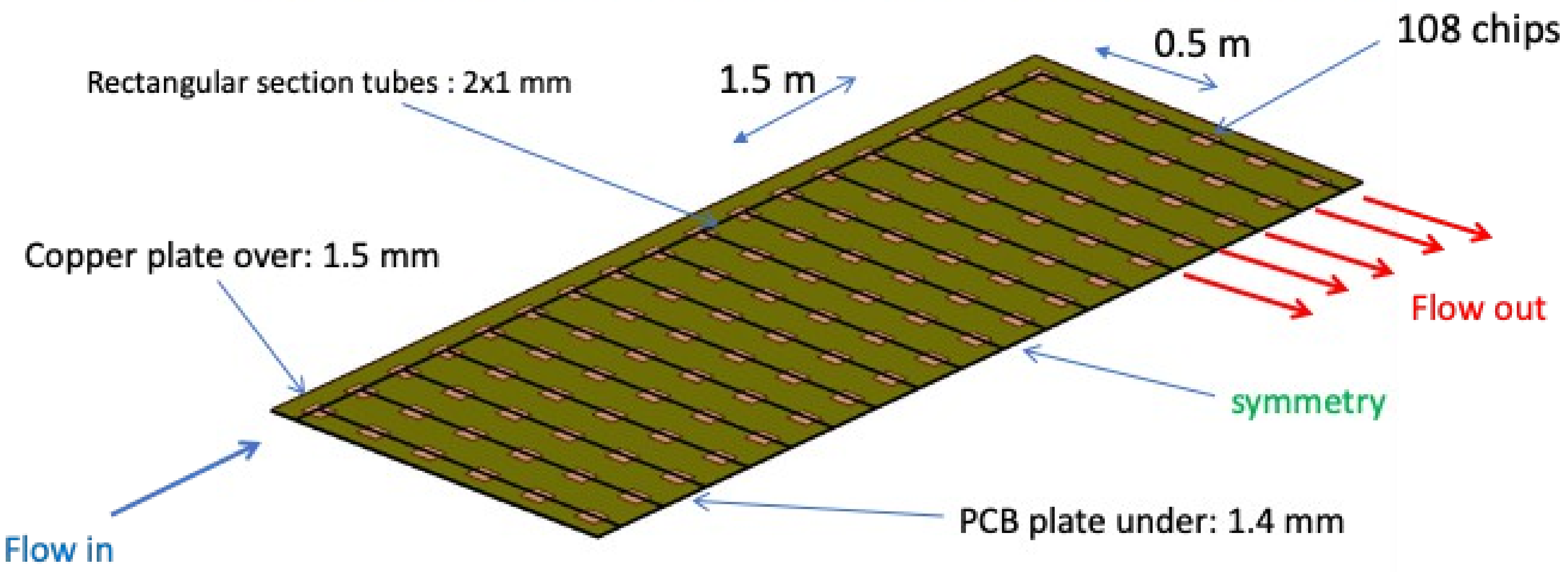
Cooling needs may be enhanced due to precision timing and will most likely be unavoidable at circular colliders

Large SDHCAL Module

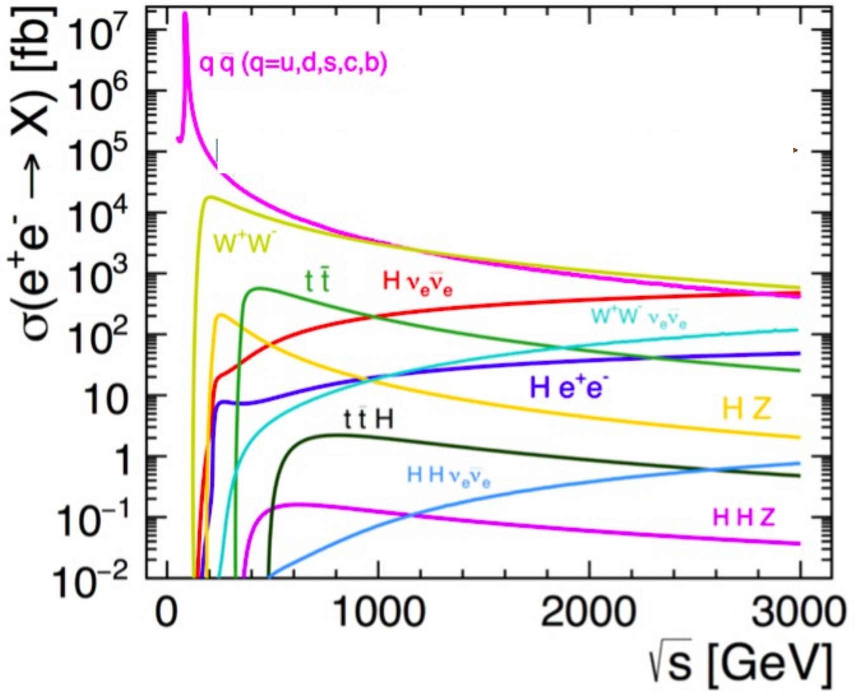
SDHCAL power consumption and cooling

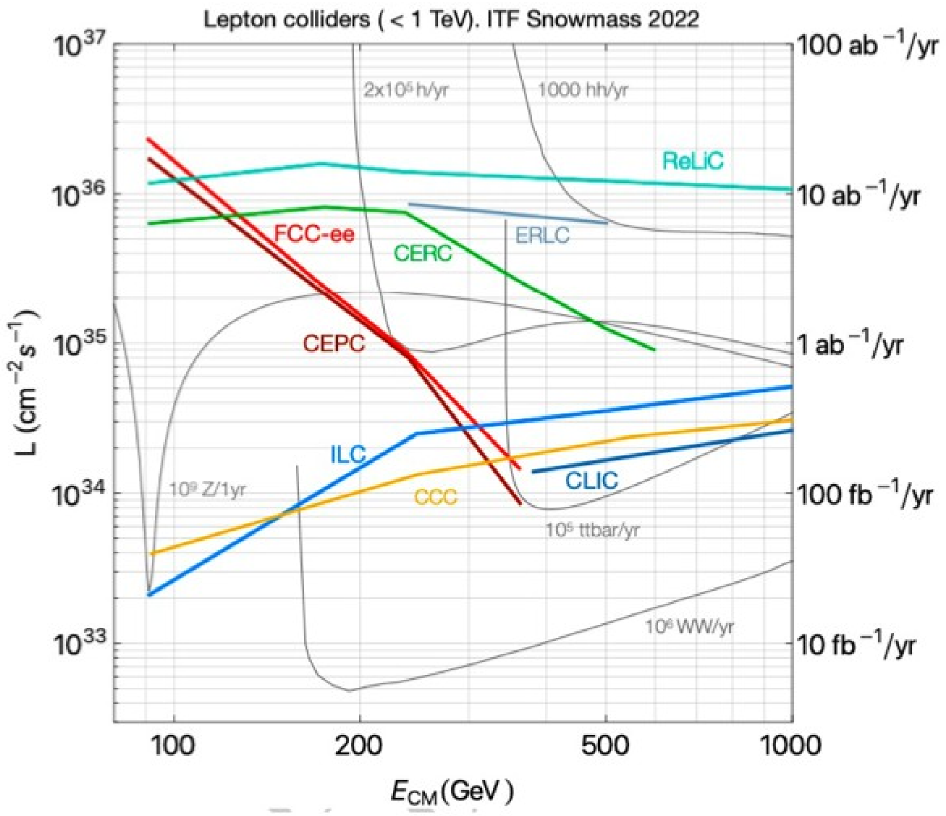
The duty cycles of CEPC/FCCee are different from that of ILC and no power pulsing is possible.
The power consumption is therefore increased by a factor of 100-200 with respect to ILC and active cooling is needed.
Lyon and Shanghai groups worked on a simple cooling system for SDHCAL based on using water circulating into copper pipes

0.8 mW/chips with power pulsing → 80 mW/chips without power pulsing



Future direction of R&D - Impact of event rates





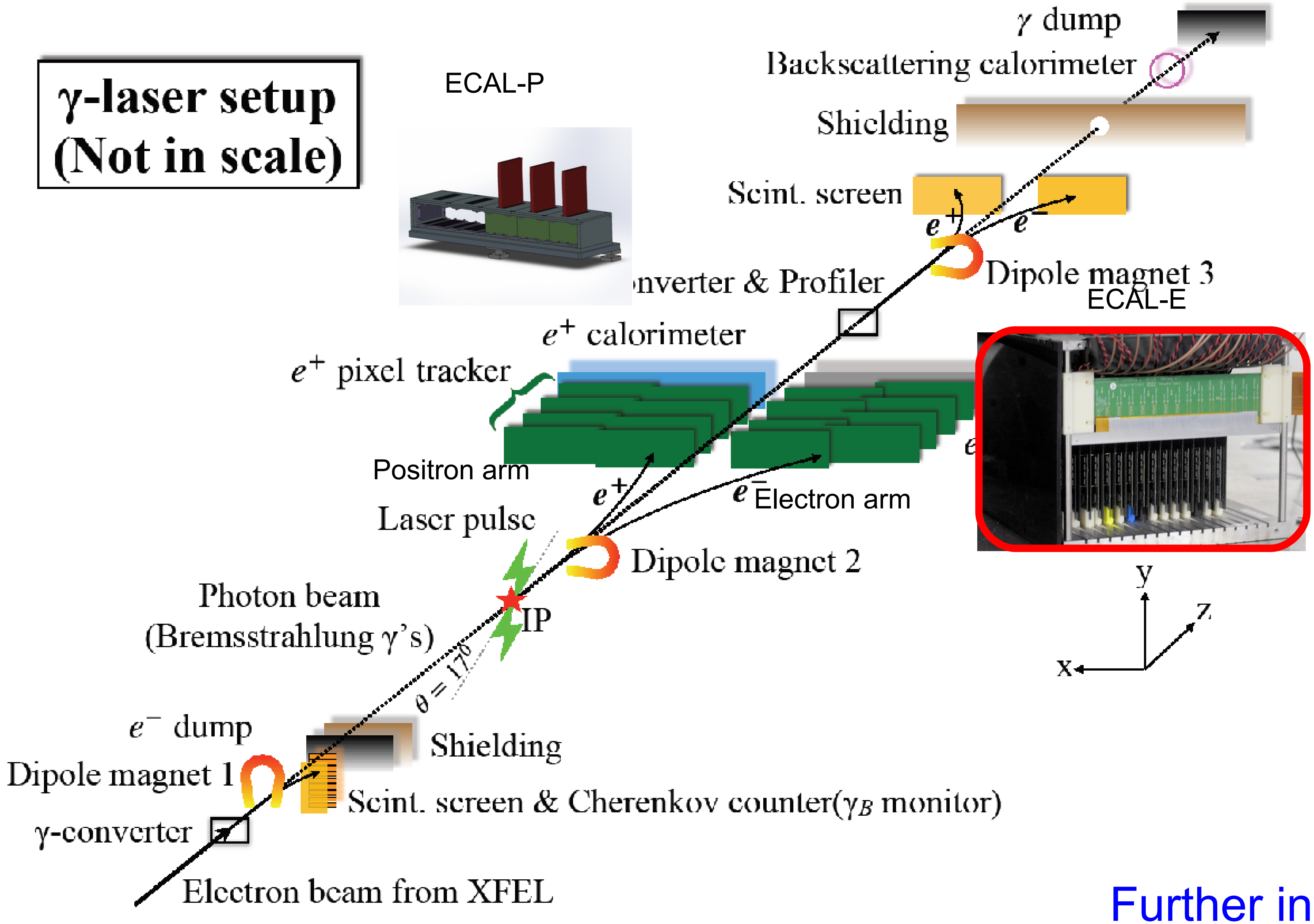
High energy e+e- colliders:

- Physics rate is governed by strong variation of cross section and instantaneous luminosity
- Ranges from 100 kHz at Z-Pole (FCC-ee) to few Hz above Z-Pole
- (Extreme) rates at pole may require other solutions than rates above pole

- Event and data rates have to looked at differentially
  - In terms of running scenarios and differential cross sections
  - Optimisation is more challenging for collider with strongly varying event rates
    - Z-pole running must not compromise precision Higgs physics

“Early Applications” of CALICE Technologies - LUXE

Laser Und Xfel Experiment – QED in extreme fields



CALICE meets LUXE

Granular calorimeters in positron and electron arms of spectrometer

- Our focus ECAL-E
- Main application electron measurement of Breit-Wheeler process in γ-laser setup
- Could also be used in early LUXE phase in case of delays of ECAL-P
  - Dark photon search next to γ dump could be further option
- Ideal application(s) of CALICE SiW Ecal technological prototype

Further interest by dark photon experiments EBES (KEK) and Lohengrin (Uni Bonn)

Summary and conclusion

- CALICE pioneered R&D on highly granular calorimeters
  - Large scale prototypes with rich set of results obtained in combined beam tests
  - Successful R&D inspired CMS to opt for a highly granular calorimeter for the LHC Phase 2 Upgrade
  - Further Spin-offs ALICE FOCAL, DUNE ND, Belle II CLAWS

- Technological prototypes address technological challenges of highly granular calorimeters
  - High level integration => dense detector layers
  - Collaboration allows to address common issues on readout and detector integration
  - Power pulsing requires further scrutiny
  - Versatile mechanics to avoid inactive detector zones
  - Timing capabilities studied and will be exploited further
  - Scale of prototypes will allow for producing new physics results to tune e,g. GEANT4
  - Ideal “playgground” for application of machine learning algorithms

- Ways forward (not mutually exclusive)
  - Finalise R&D for Linear Collider experiments
  - Common beam tests
  - Address new challenges at Circular Colliders

- Precious feedback from LHC Upgrades
  - System integration, timing, active cooling

- Application in small scale experiments (BES, LUXE, Lohengrin)

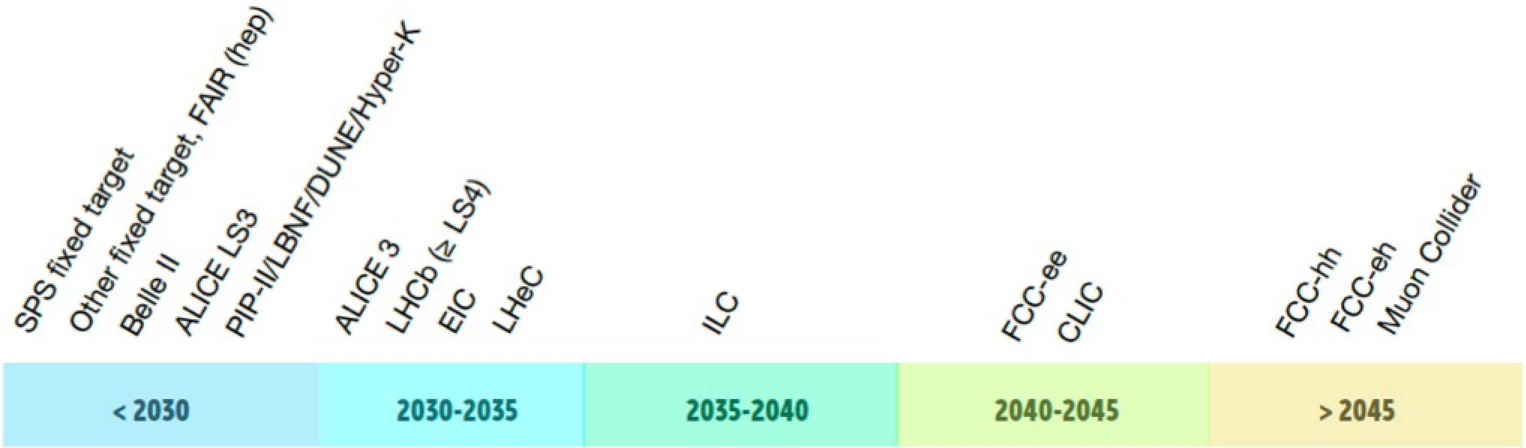
The roadmap document(s)

- ECFA R&D Roadmap
  - CERN-ESU-017 https://cds.cern.ch/record/2784893
  - 248 pages full text and 8 page synopsis

- Endorsed by ECFA and presented to CERN Council in December 2021

The Roadmap has identified
  - General Strategic Recommendations (GSR)
  - Detector R&D Themes (DRDT) for each of the taskforce topics
  - Concrete R&D Tasks

- Timescale of projects as approved by European Lab Director Group (LDG)



Guiding principle: Project realisation must not be delayed by detectors

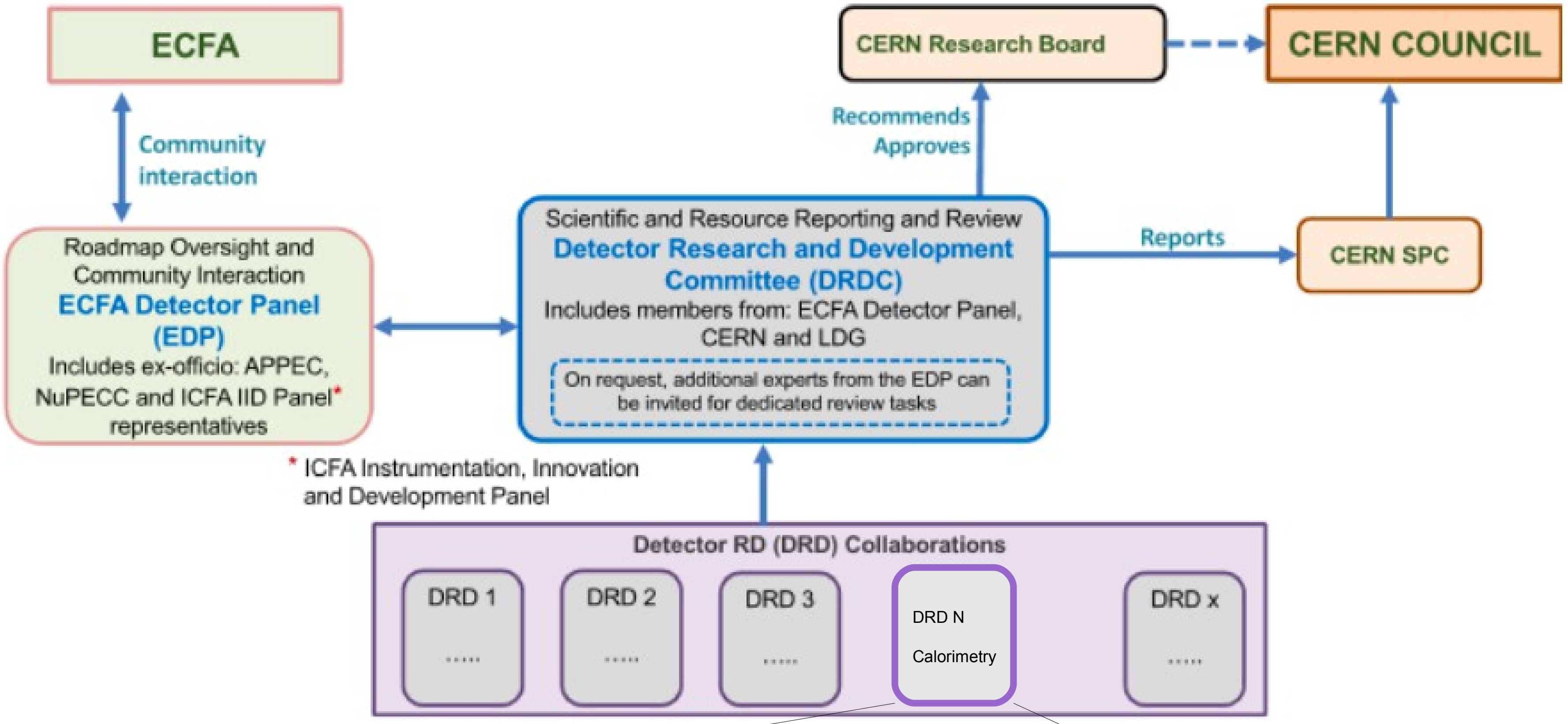
THE 2021 ECFA DETECTOR
RESEARCH AND DEVELOPMENT ROADMAP

The European Committee for Future Accelerators
Detector R&D Roadmap Process Group

Toward DRD Calorimetry

Proposed organisation scheme :

Endorsed by CERN Council in Sept. 2022



Roadmap Oversight and Community Interaction
ECFA Detector Panel (EDP)
Includes ex-officio: APPEC, NuPECC and ICFA IID Panel* representatives

Scientific and Resource Reporting and Review
Detector Research and Development Committee (DRDC)
Includes members from: ECFA Detector Panel, CERN and LDG

On request, additional experts from the EDP can be invited for dedicated review tasks

Detector RD (DRD) Collaborations

* ICFA Instrumentation, Innovation and Development Panel

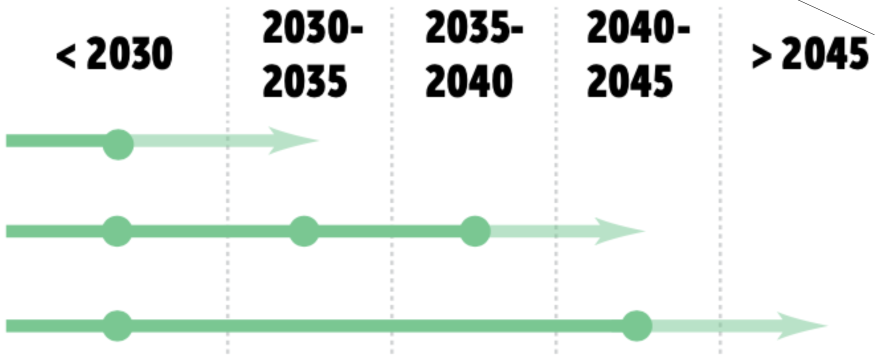
Research themes calorimetry:

Calorimetry

DRDT 6.1 Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution

DRDT 6.2 Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods

DRDT 6.3 Develop calorimeters for extreme radiation, rate and pile-up environments



Towards Implementation of DRD Calorimetry

- **Entry point, “DRD Calo indico page”: https://indico.cern.ch/event/1213733/**
  - Information on important events and access to relevant documents
  - Note also the Q&A Doc
  - 227 people from four regions registered so far

- 1st Community Meeting 12/1/23
  - https://indico.cern.ch/event/1212696/

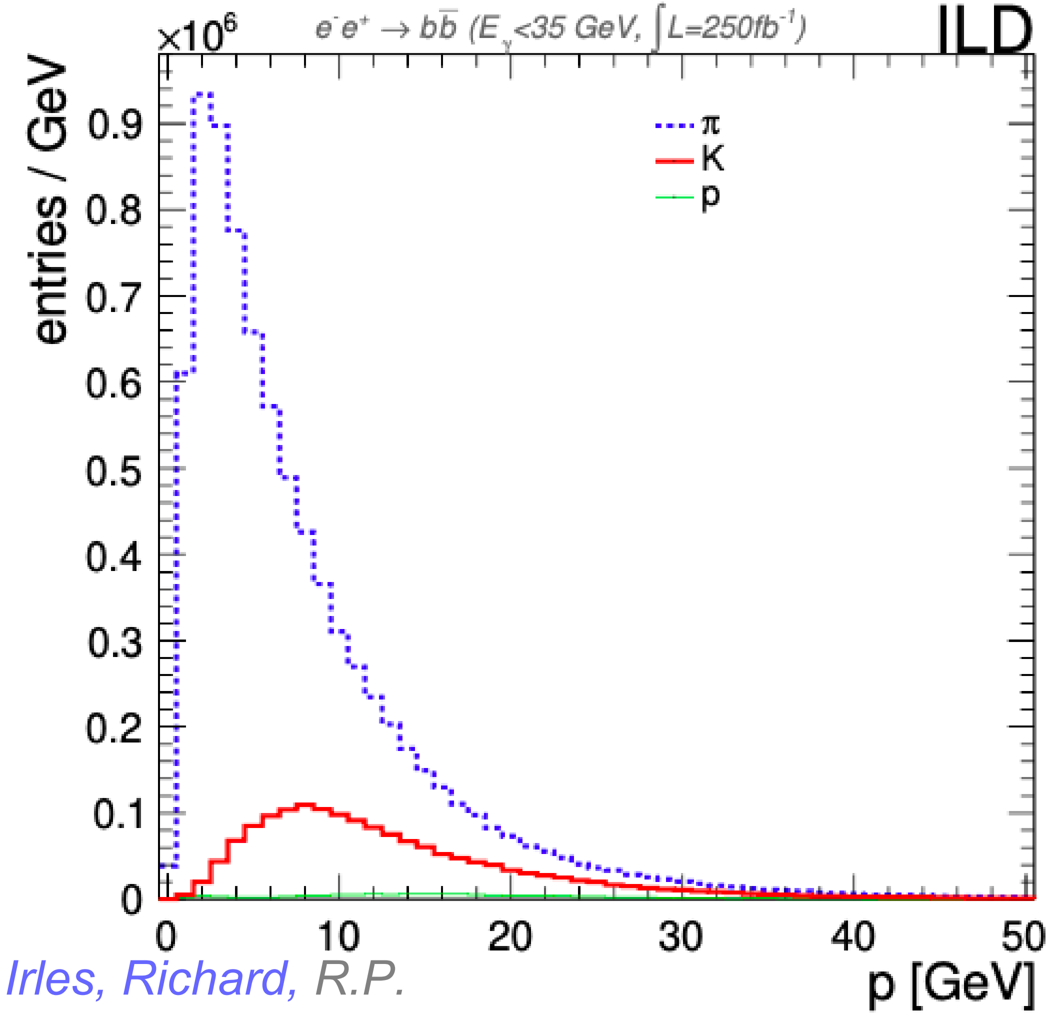
- Proposal phase until 1st of July 2023
  - **Input-proposals until latest 1st of April 2023**
  - 2nd Community Meeting 20th April at CERN
    - https://indico.cern.ch/event/1246381/
    - Summary of input-proposals (w/o disclosing confidential information)
    - Presentation/discussion of organisation of DRD Calorimetry (with focus on scientific aspects)
      - Guidance by existing R&D collaborations

  - Input-proposals will be condensed into a DRD on Calorimetry proposal until (around) 1st of June 2023
    - Further iteration with stakeholders, community and higher level bodies

Backup

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

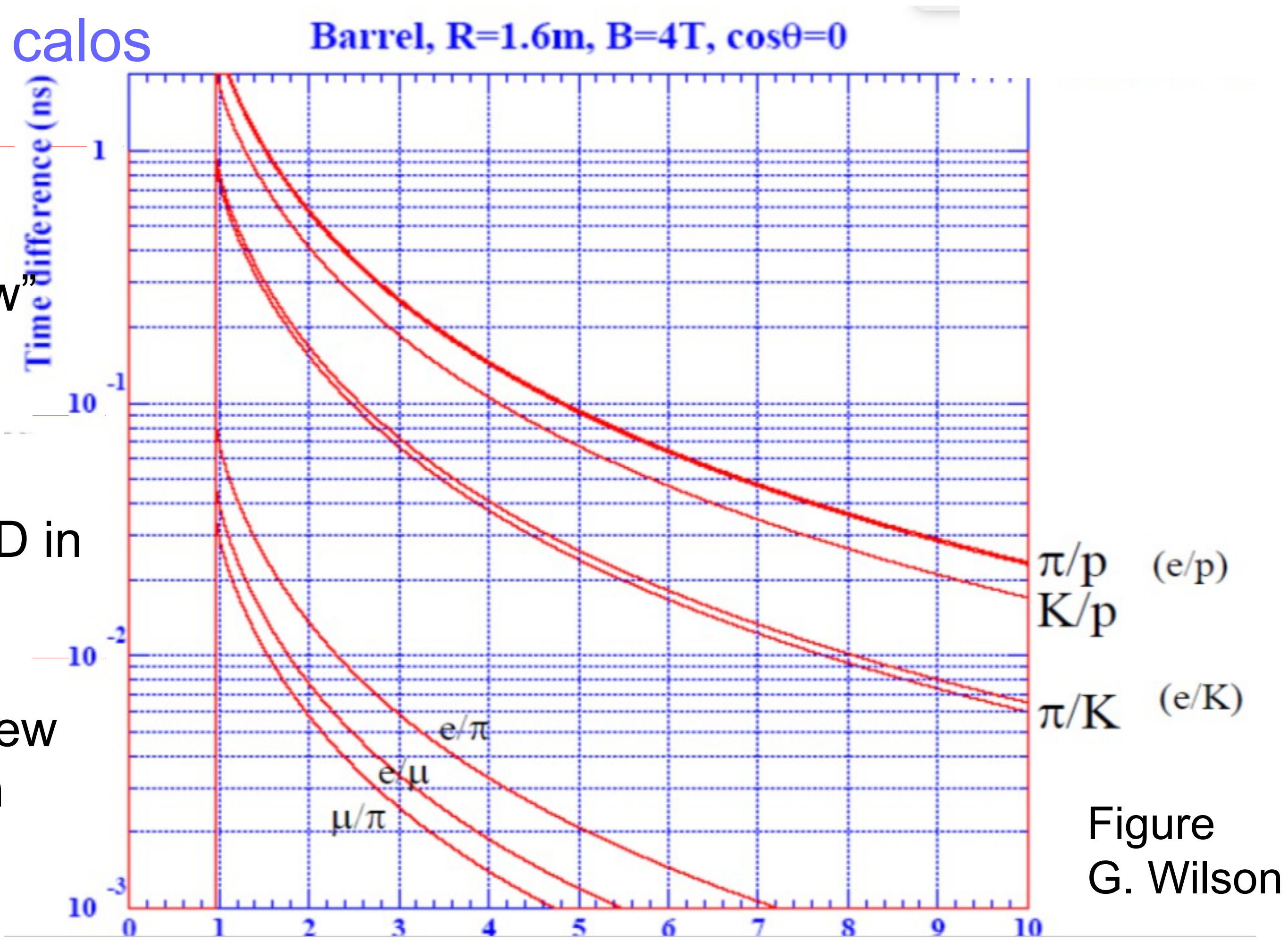
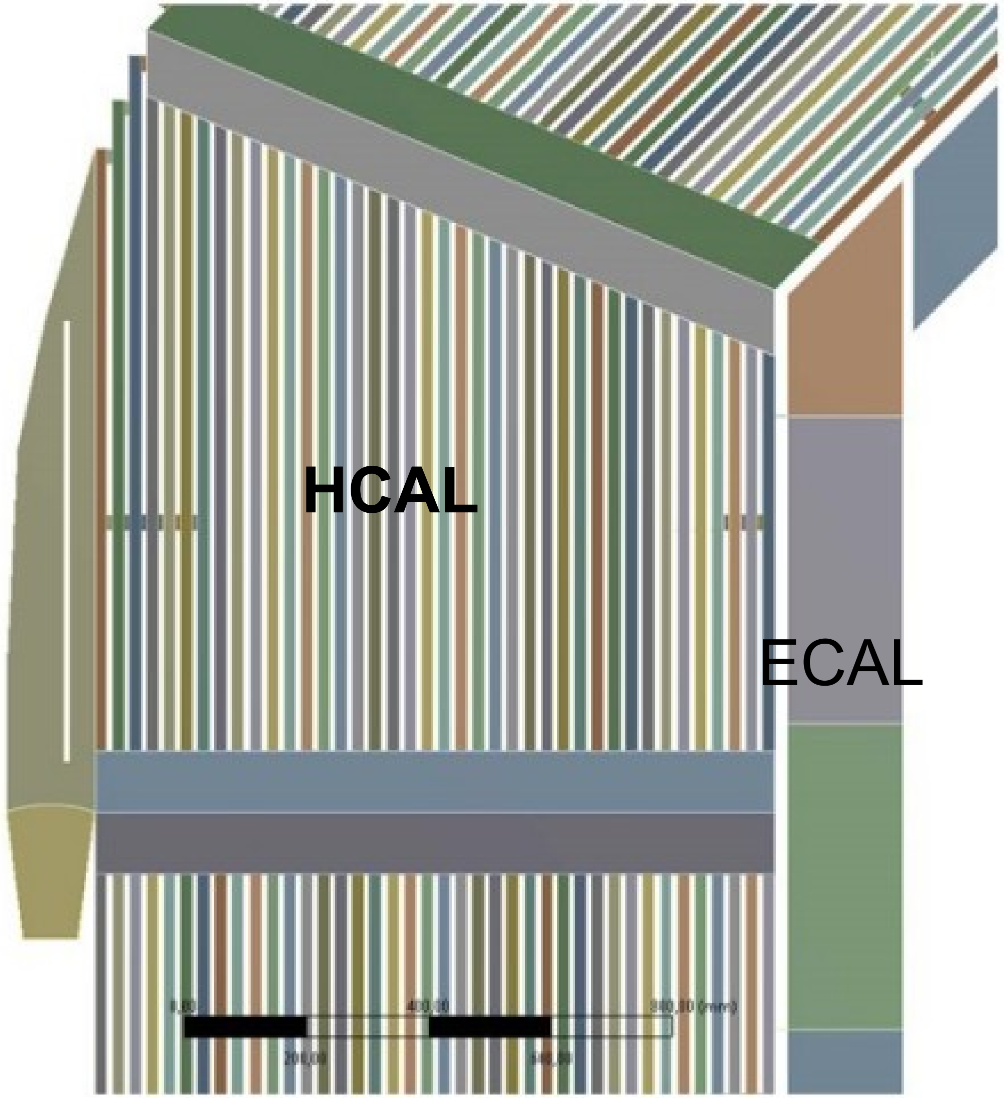


Figure G. Wilson

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

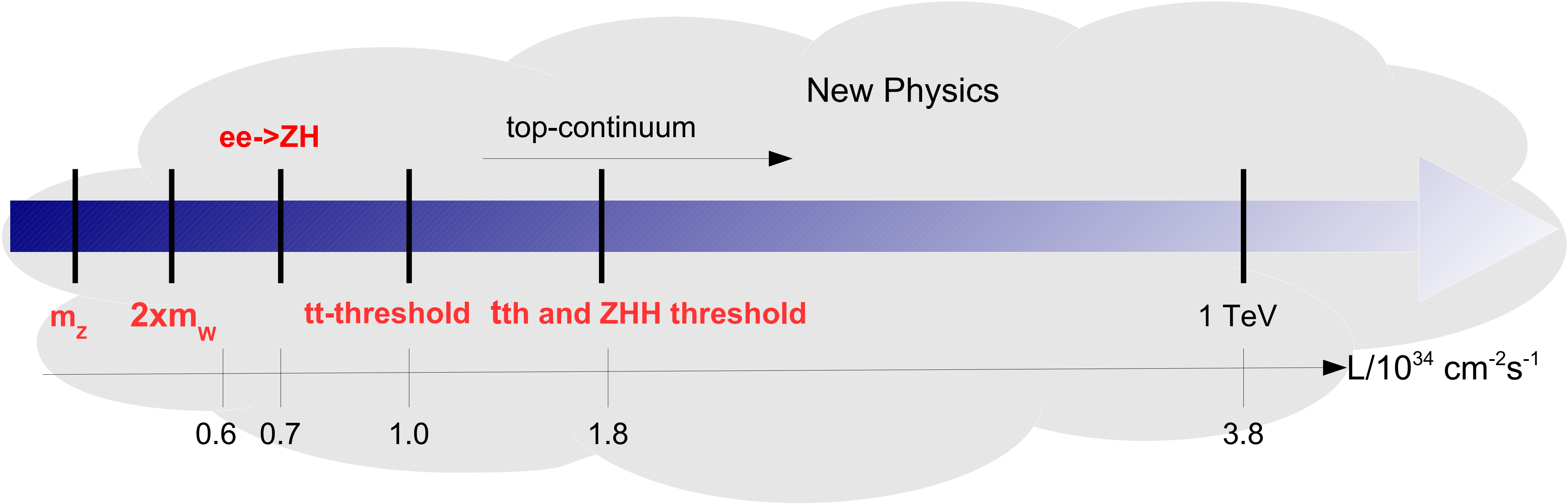
ILD concept and highly granular calorimeters



- 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

Lepton colliders physics program



All Standard Model particles within reach of planned linear colliders

High precision tests of Standard Model over wide range to detect onset of New Physics

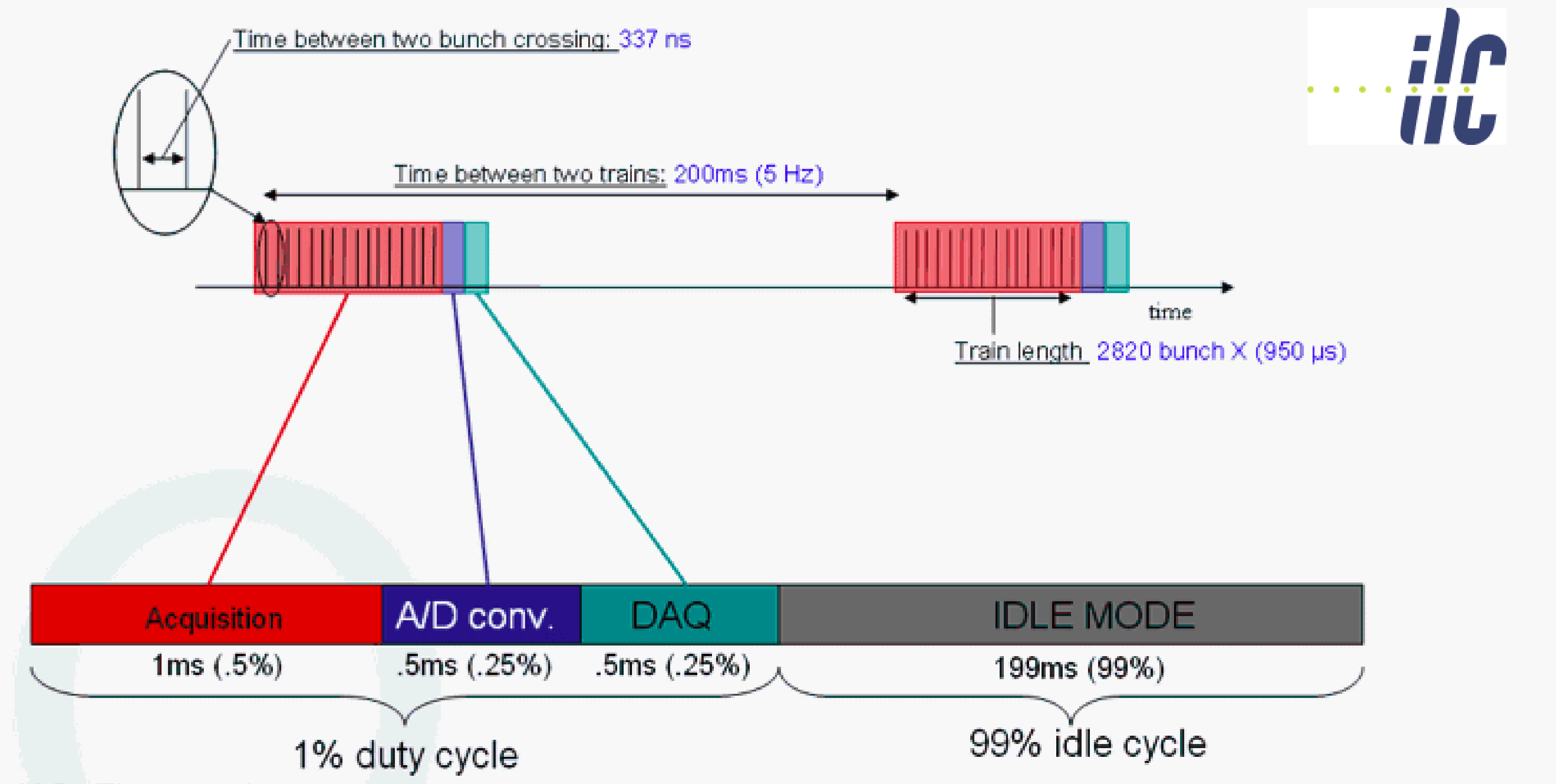
Machine settings can be "tailored" for specific processes
- Centre-of-Mass energy
- Beam polarisation (straightforward at linear colliders)

$$\sigma_{P,P'} = \frac{1}{4}\left[(1 - PP')(\sigma_{LR} + \sigma_{RL}) + (P - P')(\sigma_{RL} - \sigma_{LR})\right]$$

Background free searches for BSM through beam polarisation

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

Particle ID – Motivation and tools

Motivations:

- Tau reconstruction
- Distinction between Particle and anti-particle in ee->qq (as complement to vertex charge)
- Control of systematic errors In high precision measurements

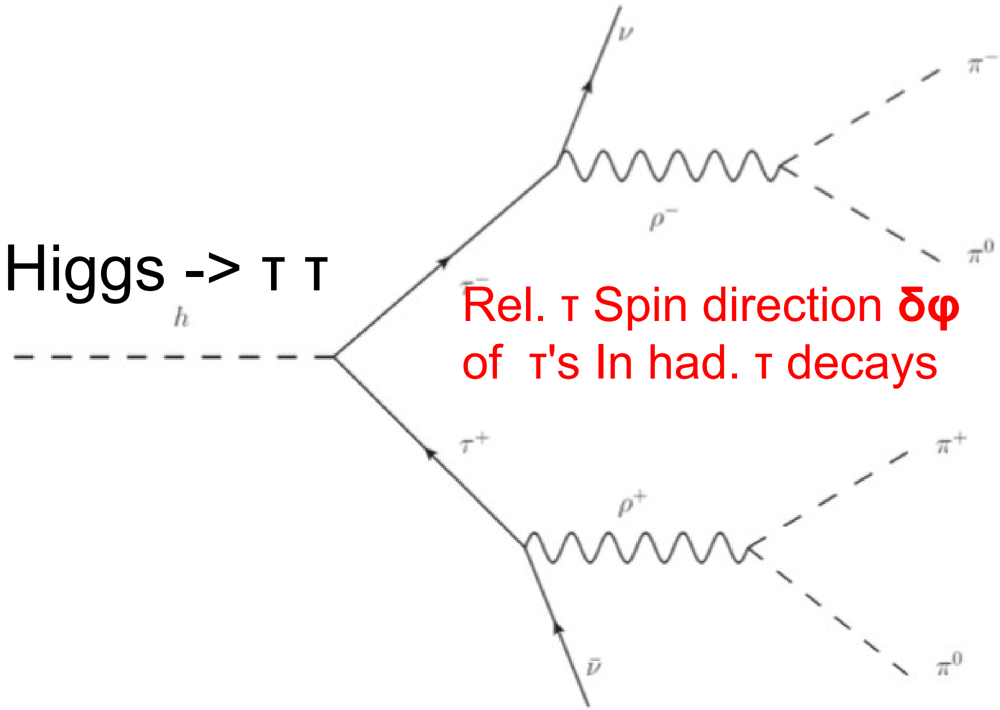
Particle Identity

Tools:

- Cerenkov counters
- Gaseous detectors via dE/dx
- ToF measurements
- Pattern recognition in granular calorimeters

$e^+e^- \to ZH(\to \tau\tau)$

Study @ 250 GeV



Higgs -> τ τ

Rel. τ Spin direction **δφ** of τ's In had. τ decays

- Polarisation of τ from analysis of decay products

- Prominently used τ decays

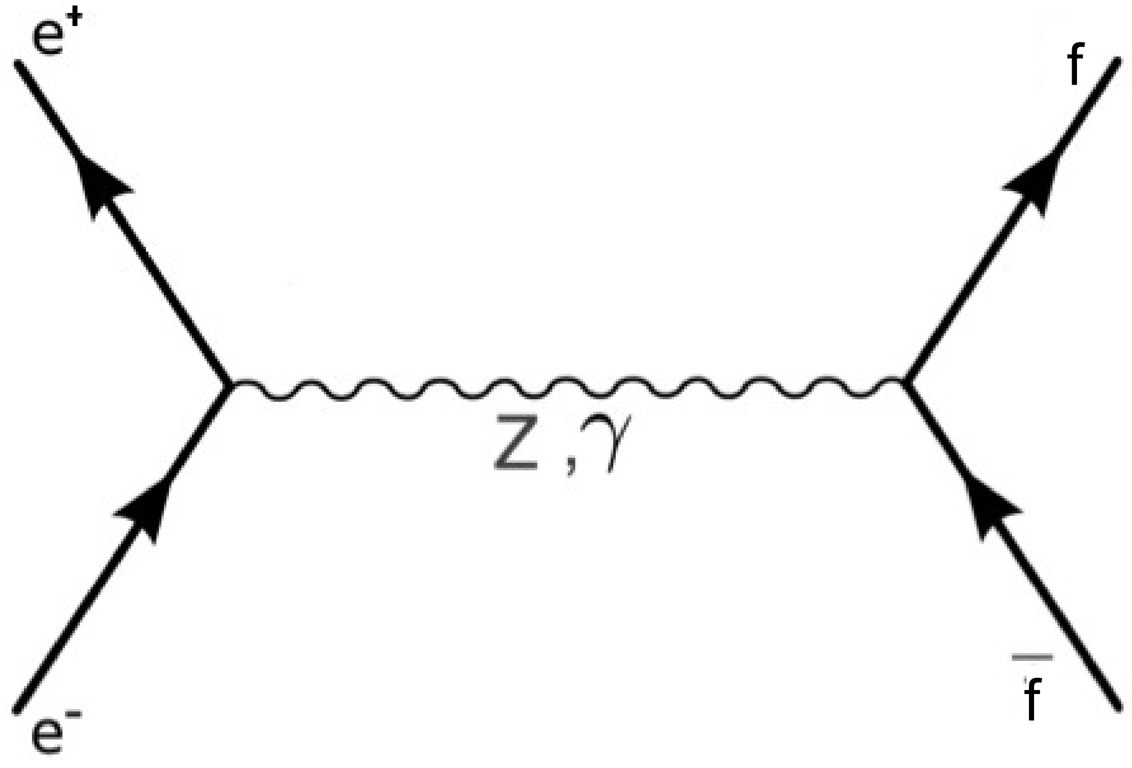
$$\tau^\pm \to \pi^\pm + \nu \, (\text{''}\pi\text{''})$$

$$\tau^\pm \to \pi^\pm + \pi^0 + \nu \, (\text{''}\rho\text{''})$$

$$\tau^\pm \to \pi^\pm + \pi^0 + \pi^0 + \nu \, (\text{''}a_1\text{''})$$

- Analysis requires (among others)
  - Clean photon/hadron separation
  - Tracker/Ecal/Hcal
- Separation of photons from π^0 in calorimeter
- Excellent testing ground to benchmark granular calorimeters

Two fermion processes



Differential cross sections for (relativistic) di-fermion production*:

$$\frac{d\sigma}{d\cos\theta}(e^-_L e^+_R \rightarrow f\bar{f}) = \Sigma_{LL}(1+\cos\theta)^2 + \Sigma_{LR}(1-\cos\theta)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^-_R e^+_L \rightarrow f\bar{f}) = \Sigma_{RL}(1+\cos\theta)^2 + \Sigma_{RR}(1-\cos\theta)^2$$

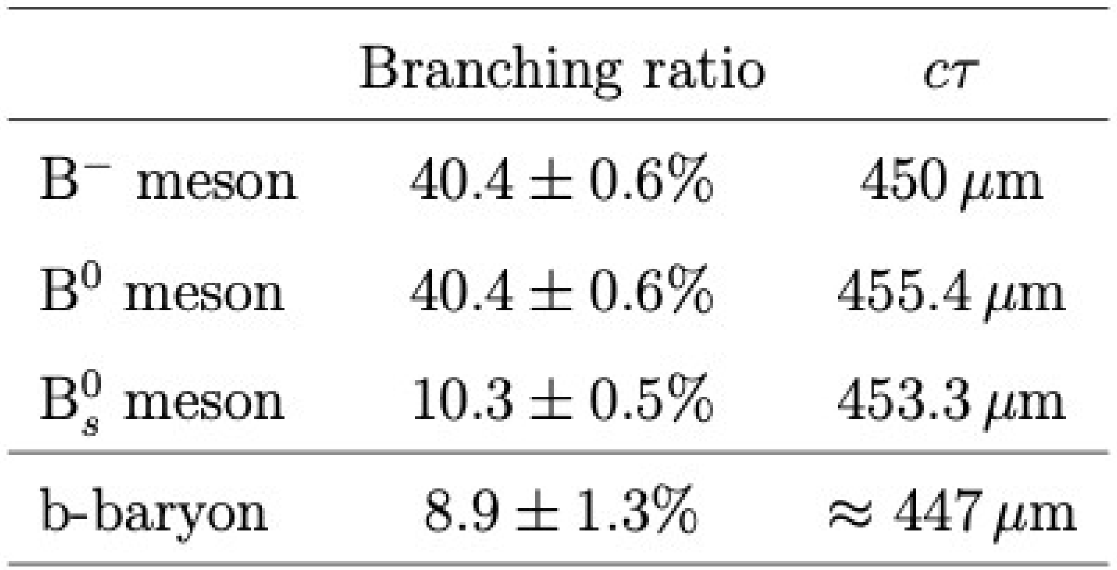
*add term ~$\sin^2\theta$ in case of non-relativistic fermions e.g. top close to threshold

- Σ_{IJ} are helicity amplitudes that contain couplings g_L, g_R (or F_V, F_A)
- Forward-backward in angle, general left-right in cross section
- **All four** helicity amplitudes for all fermions **only available with polarised beams**

At future e+e- colliders precisions of these processes will reach precision of O(0.1-0.5%)
Will concentrate today (mainly) on f= ,tb

Why Kaon Identification?

Reminder: Hadronisation modes of b-quark

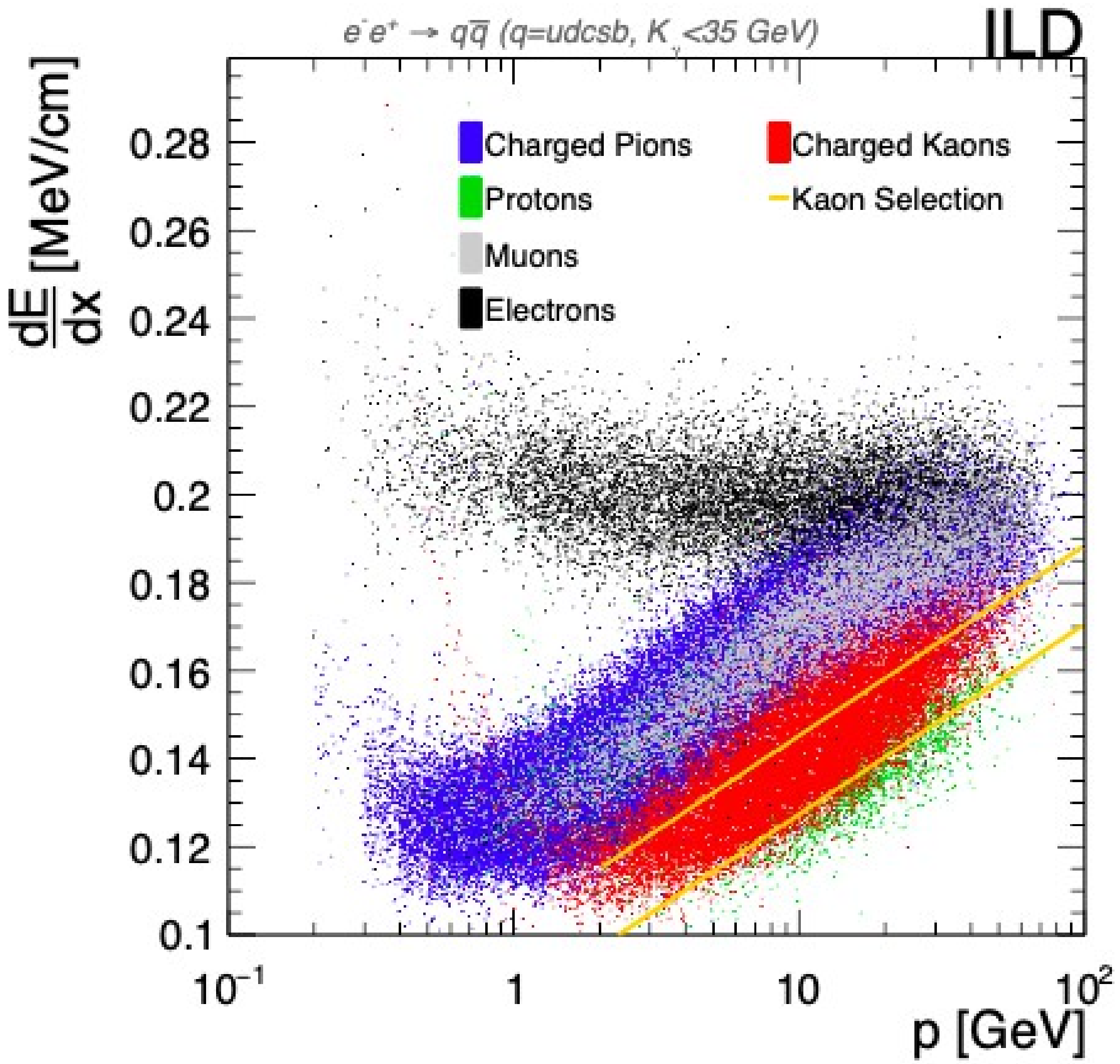


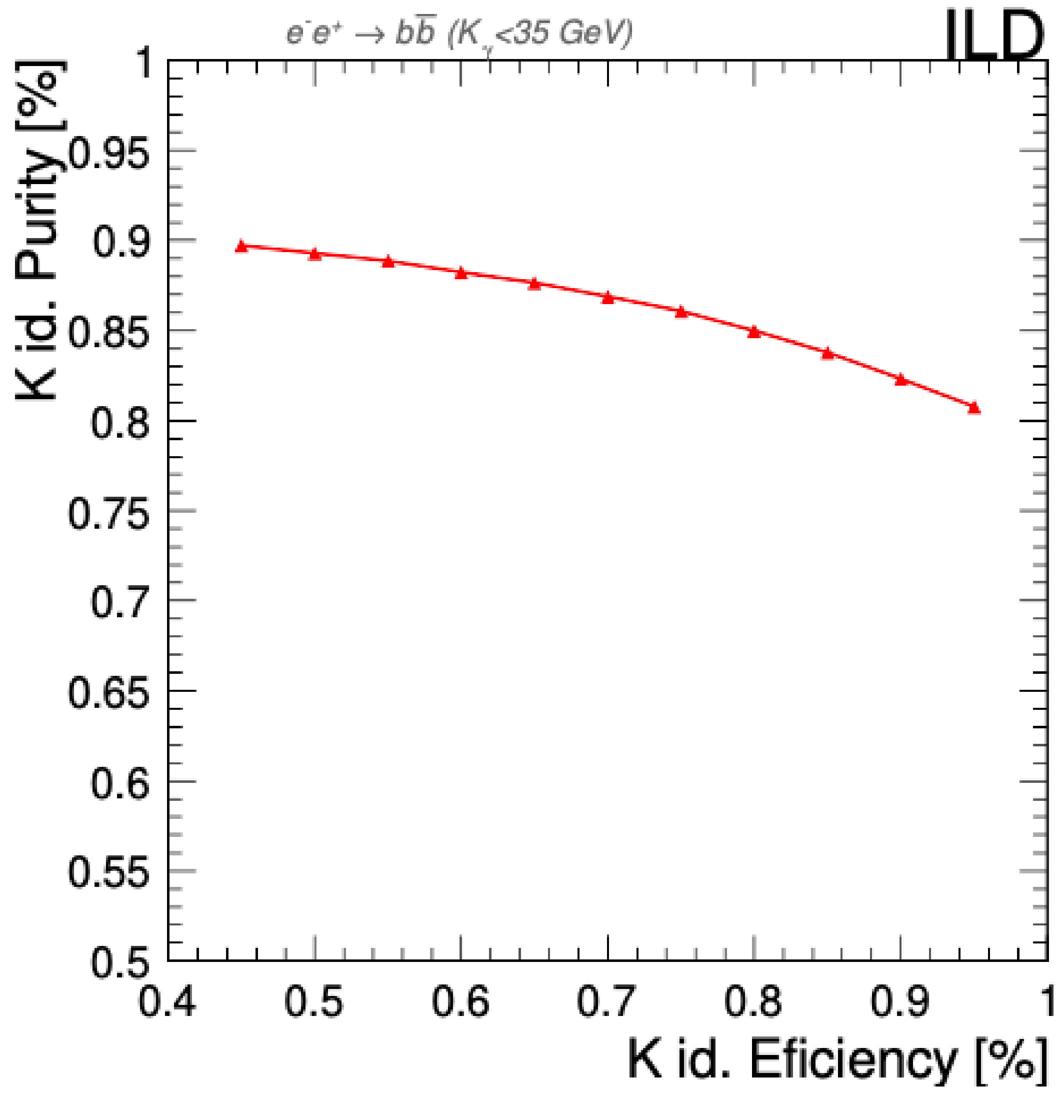
	Branching ratio	$c\tau$
B^- meson	$40.4 \pm 0.6\%$	$450\ \mu m$
B^0 meson	$40.4 \pm 0.6\%$	$455.4\ \mu m$
B^0_s meson	$10.3 \pm 0.5\%$	$453.3\ \mu m$
b-baryon	$8.9 \pm 1.3\%$	$\approx 447\ \mu m$

- First and intuitive tool to measure charge of b-quark is measurement of vertex charge from charged B-Mesons
  - Only 40% branching fraction
  - Efficiency for double tagged vertex charge is O(10%)
- ~80% of B-Mesons decay into Kaons with correct (b-quark) charge
- Kaons
  - ... as complement to vertex charge measurement
  - ... allow for using also neutral modes
  - Mismeasurement from BB-Oscillations can be corrected for in case of clean double tag

Kaon Identification – The “classical” way

ee->bb @ 250 GeV



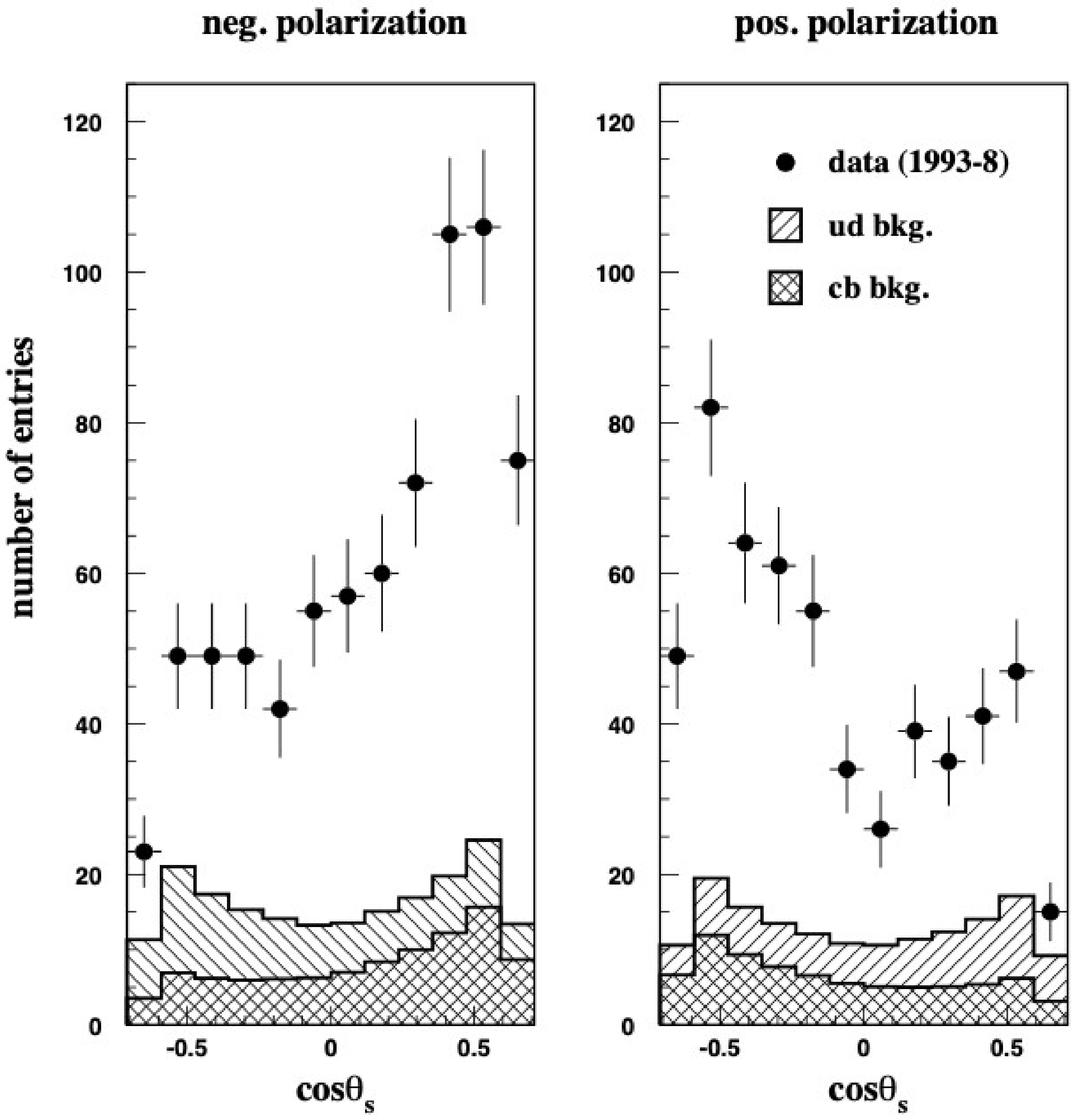


- Select Charged Kaons inside a strip in the dE/dx-p plane
- Choose “working point” as function of strip width (=> variation of efficiency and purity)

ILD: Irles, Richard, R.P.

And tomorrow ?

ee -->ss: SLD Analysis at Z Pole



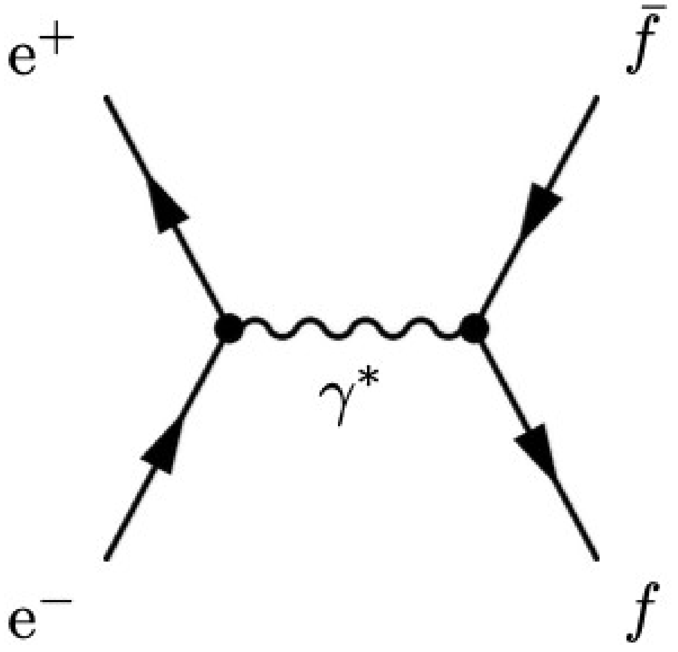
- Extend the heavy quark analyses to light quarks to get full picture
- Optimise vertexing and particle ID (i.e .Kaon ID) with full simulation studies

Photon ID for Precision Measurements

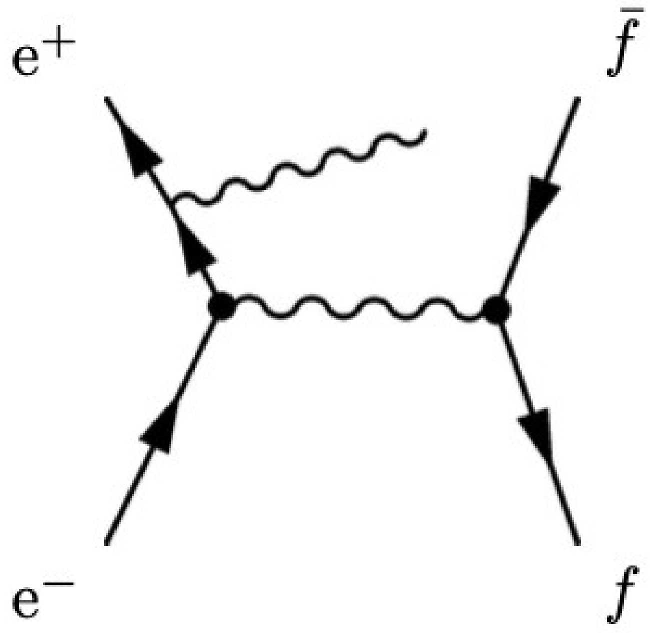
e.g. Precision observable: $R_b = \frac{N_{b\bar{b}}}{\sum N_{q\bar{q}}}$

On Z-Pole

Above Z-Pole



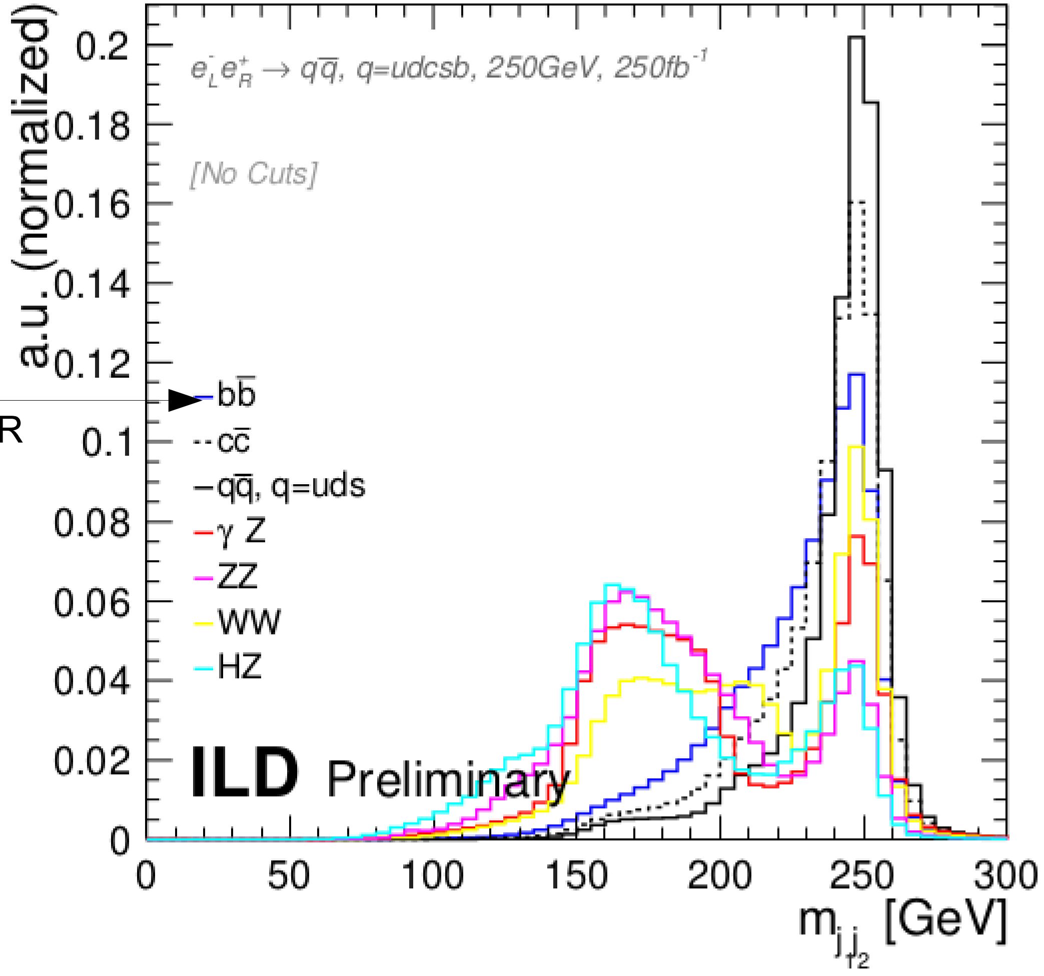
No ISR Photon

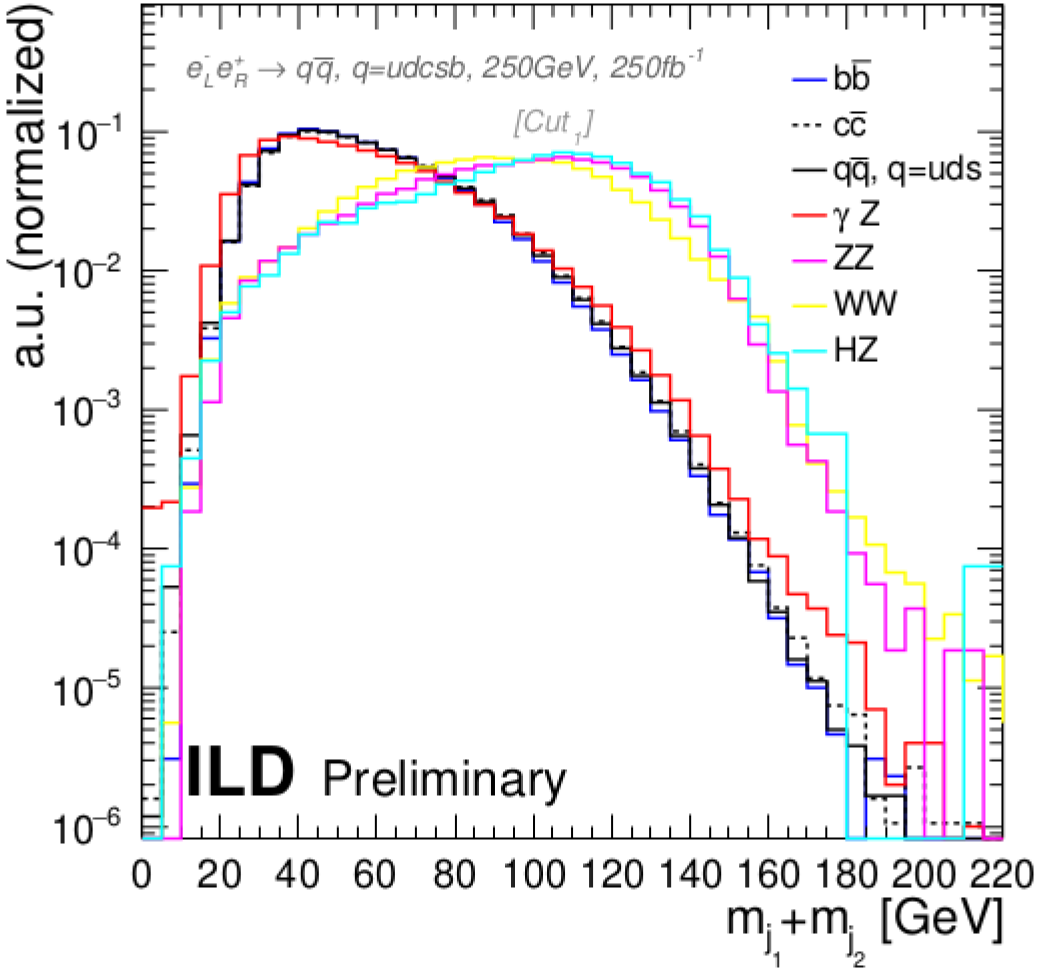


ISR Photon requires exact definition of phase space and careful **flavor Independent** Cuts

(Naive) selection cuts

Remark:
Here most of ISR has not been simulated





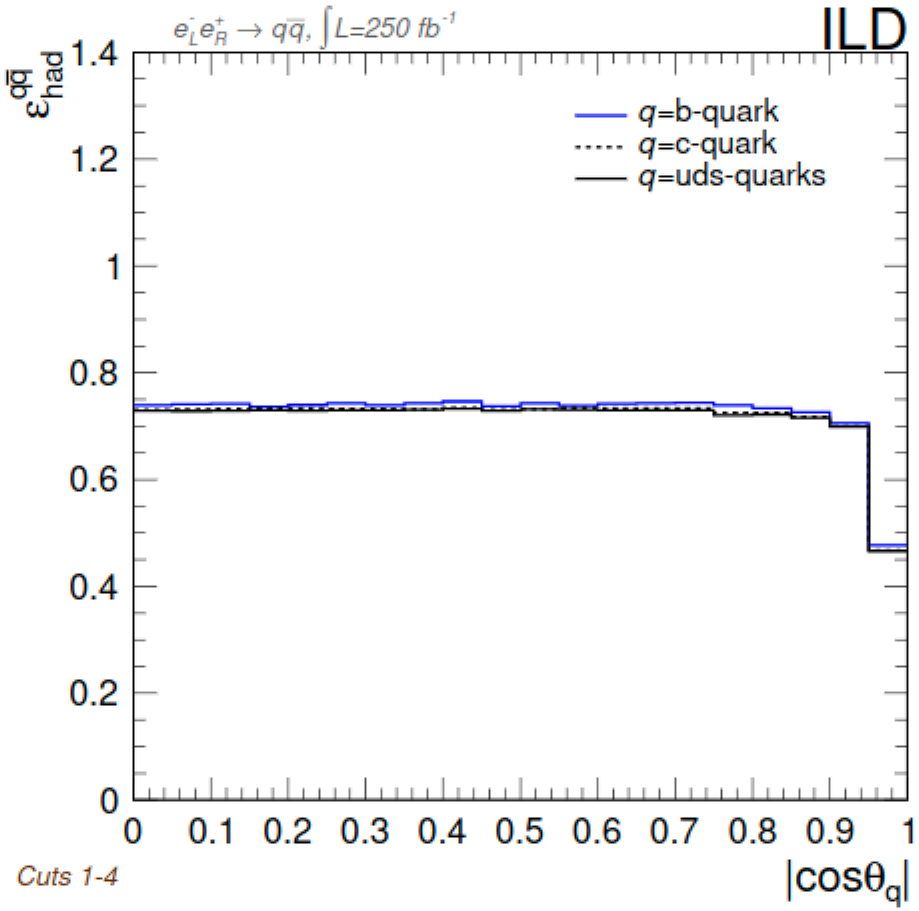
- Invariant Dijet mass
  - Flavor dependent spectrum

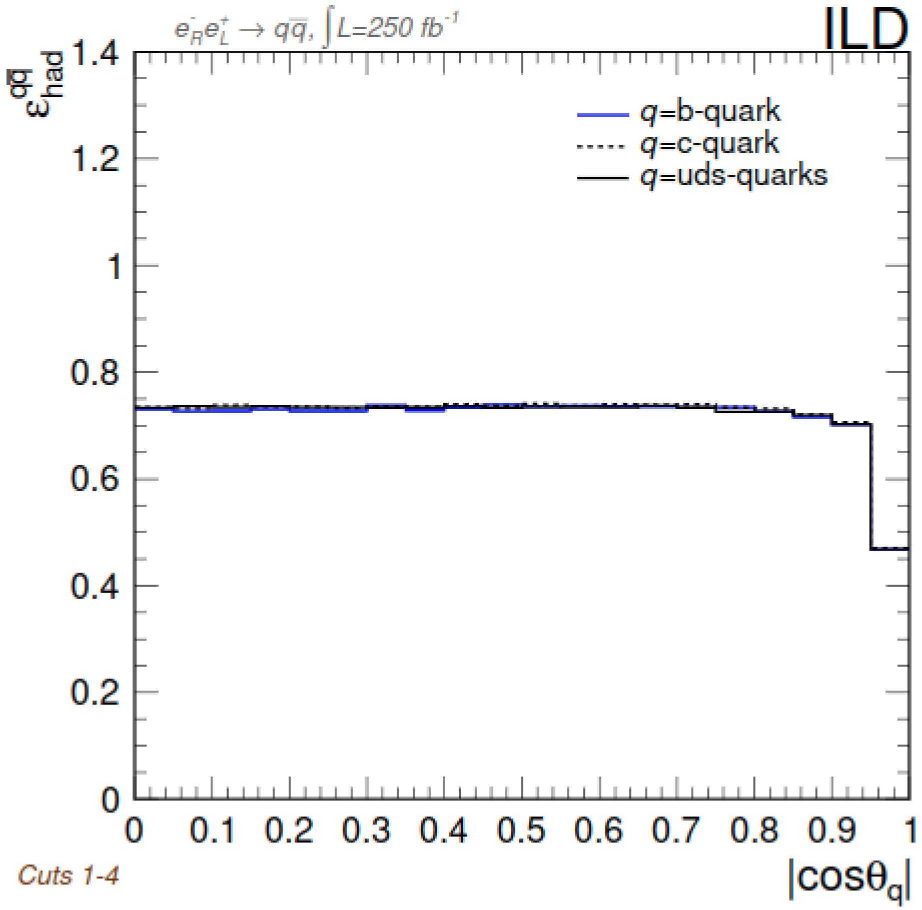
- Sum of jet masses
  - Mild flavor dependence

- Naive cut against radiative return would be on dijet masses
- (Hard) cuts on dijet mass introduce flavor dependence of normalisation of R_b
  - => Systematic error and dependence even on fragmentation functions of heavy quarks

ILD: Irles, Richard, R.P.

Efficiency of dijet event selection





- Flavor independent efficiency for dijet events
- Minimises systematic error in measurement of R_b

Summary and outlook

- Particle ID plays an important role for the precision physics program at a future lepton collider

- First order importance of granular calorimeters for τ decays
  - Particle counting
  - Disentangling of close-by final state particles

- Measuring of ISR Photons in jets important for flavor independent measurements of dijet events

- Future: Can precision timing in calorimeters replace a TPC or a Cerenkov Detector for particle ID?
  - Remark: For me this is an extremely important question that should, however, be addressed with a sense of realism.
  - I am skeptical that this will be possible above particle momenta of 10 GeV in foreseeable future

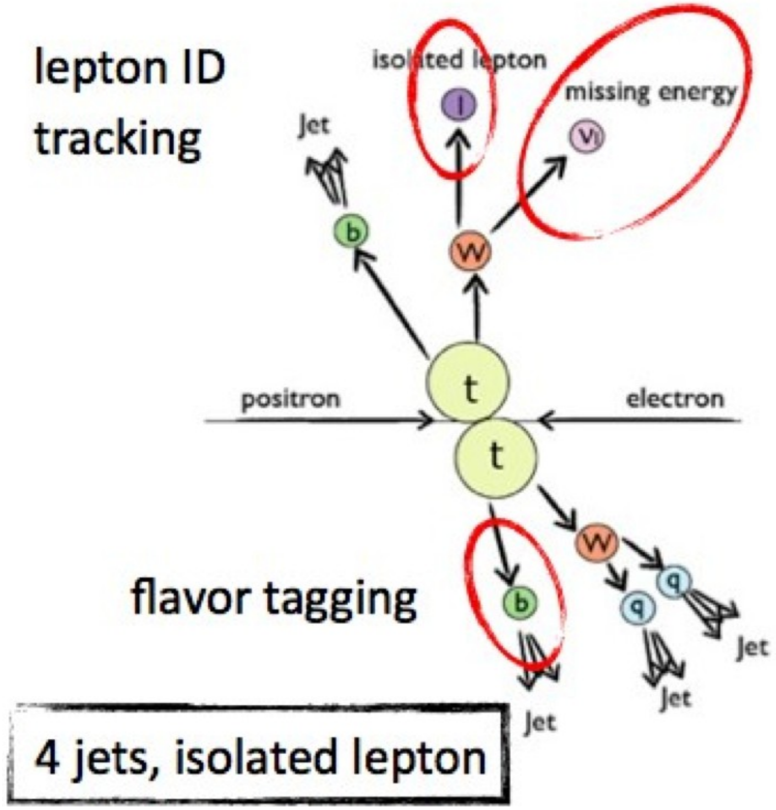
- Other applications not shown in my talk
  - B--> τν (Talk by D. Yu and Manqi Ruan in ILD Meeting)
  - Vertex constraints with π^0 from primary vertex (M. Kurata at IAS Conference 2018)

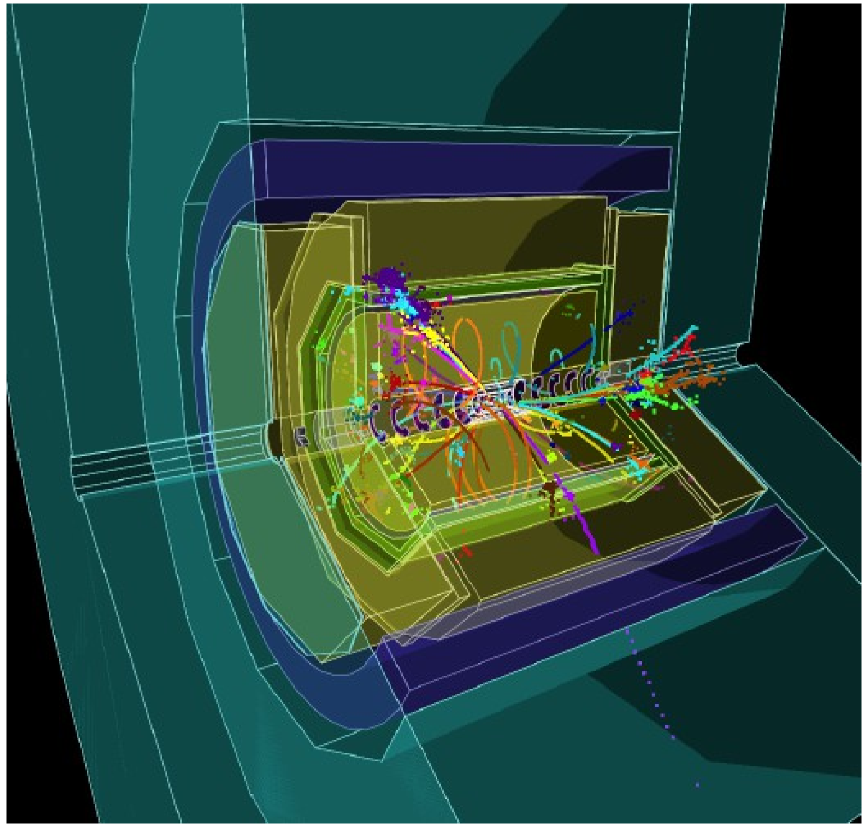
Elements of top quark reconstruction

Three different final states:

1) Fully hadronic (46.2%) → 6 jets
2) Semi leptonic (43.5%) → 4 jets + 1 charged lepton and a neutrino
3) Fully leptonic (10.3%) → 2 jets + 4 leptons

$$t\bar{t} \rightarrow (bW)(bW) \rightarrow (bqq')(b\ell\nu)$$





Final state reconstruction uses all detector aspects

Results shown in the following are based on <u>full simulation</u> of LC Detectors

Detector requirements

e+e- detector concepts for linear colliders
Preferred solution Particle Flow Detectors

CLIC Detector

SiD

ILD

B= 4T

B= 5T

B= 3.5T

Highly granular calorimeters

Central tracking with silicon

Central tracking with TPC

Inner tracking with silicon

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

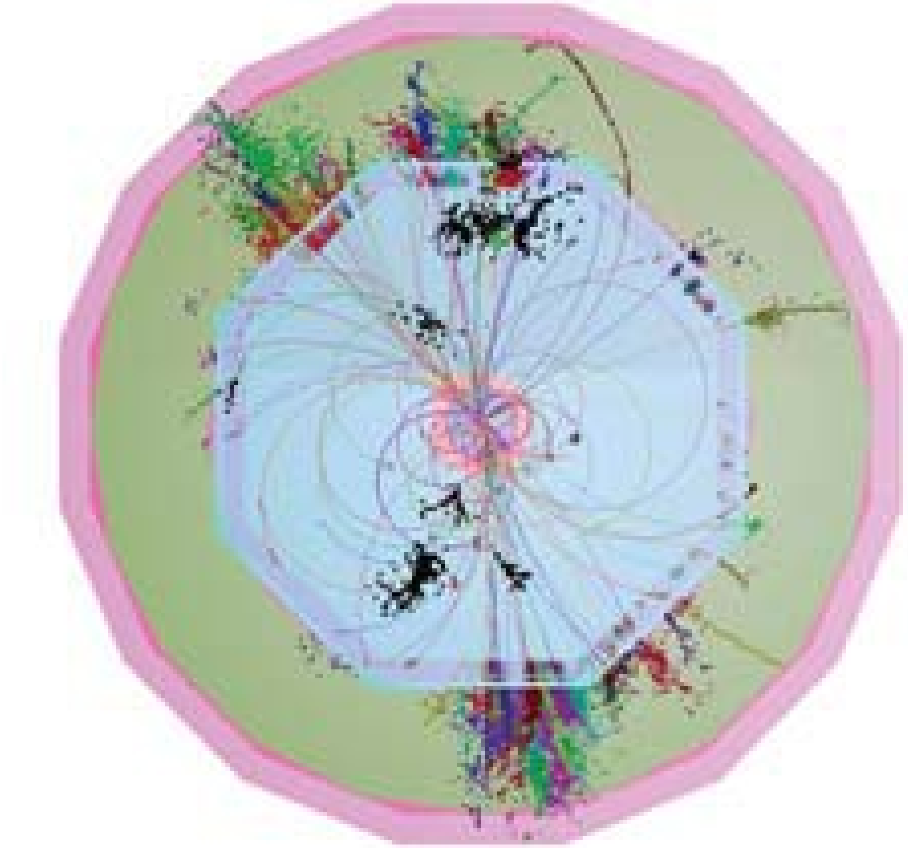
(Quark tagging c/b)

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

(W/Z masses with jets)

Hermeticity : $\theta_{min} = 5$ mrad

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



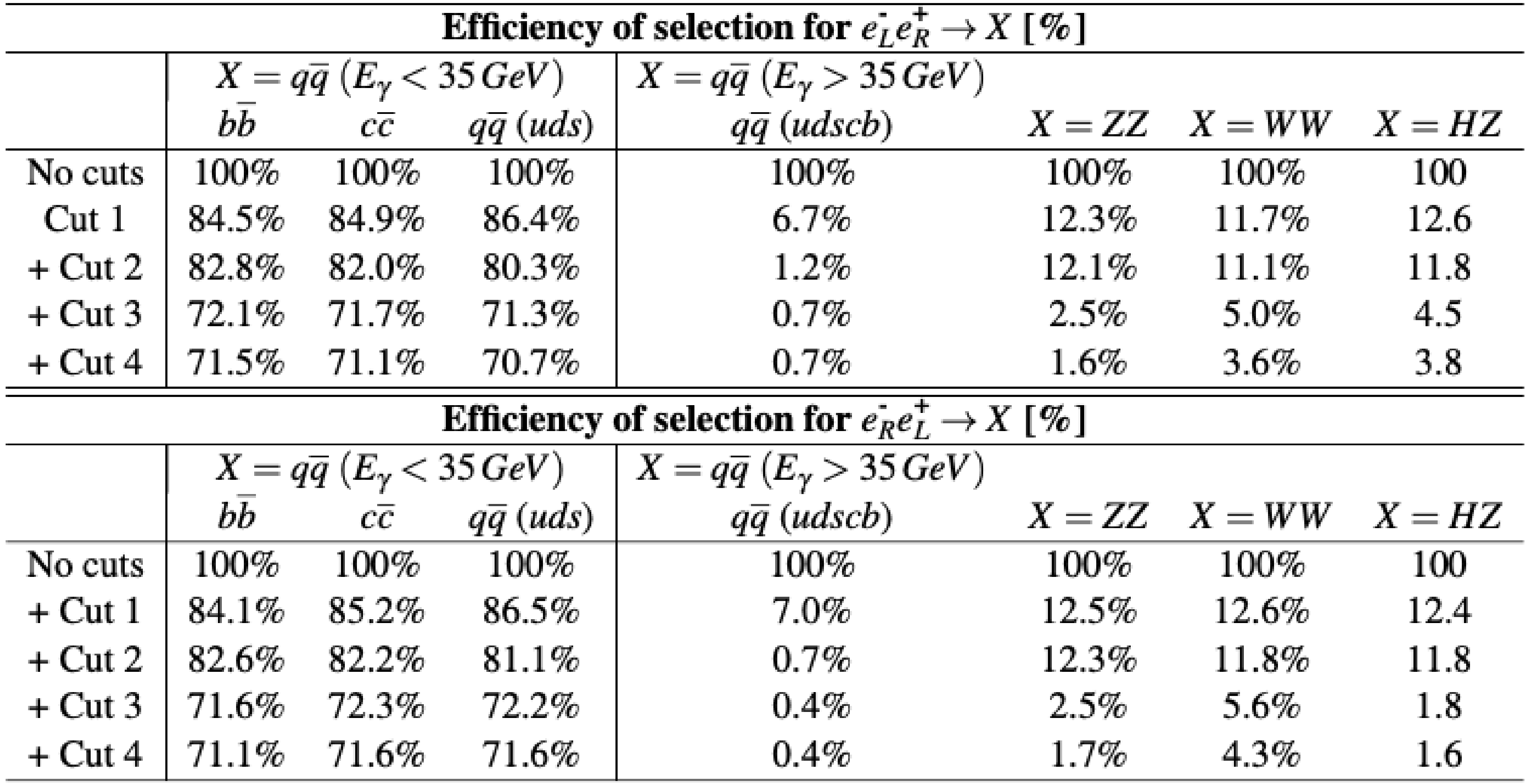
Final state will comprise events with a large number of charged tracks and jets(6+)

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

Particle Flow Detectors

Detector Concepts: ILD, SiD and CLICdp

ee->bb at 250 GeV



Efficiency of selection for $e^-_L e^+_R \to X$ [%]

	$X = q\bar{q}$ ($E_\gamma < 35\,GeV$)			$X = q\bar{q}$ ($E_\gamma > 35\,GeV$)			
	$b\bar{b}$	$c\bar{c}$	$q\bar{q}$ (uds)	$q\bar{q}$ ($udscb$)	$X = ZZ$	$X = WW$	$X = HZ$
No cuts	100%	100%	100%	100%	100%	100%	100
Cut 1	84.5%	84.9%	86.4%	6.7%	12.3%	11.7%	12.6
+ Cut 2	82.8%	82.0%	80.3%	1.2%	12.1%	11.1%	11.8
+ Cut 3	72.1%	71.7%	71.3%	0.7%	2.5%	5.0%	4.5
+ Cut 4	71.5%	71.1%	70.7%	0.7%	1.6%	3.6%	3.8

Efficiency of selection for $e^-_R e^+_L \to X$ [%]

	$X = q\bar{q}$ ($E_\gamma < 35\,GeV$)			$X = q\bar{q}$ ($E_\gamma > 35\,GeV$)			
	$b\bar{b}$	$c\bar{c}$	$q\bar{q}$ (uds)	$q\bar{q}$ ($udscb$)	$X = ZZ$	$X = WW$	$X = HZ$
No cuts	100%	100%	100%	100%	100%	100%	100
+ Cut 1	84.1%	85.2%	86.5%	7.0%	12.5%	12.6%	12.4
+ Cut 2	82.6%	82.2%	81.1%	0.7%	12.3%	11.8%	11.8
+ Cut 3	71.6%	72.3%	72.2%	0.4%	2.5%	5.6%	1.8
+ Cut 4	71.1%	71.6%	71.6%	0.4%	1.7%	4.3%	1.6

Table 3: Cut flow for the signal and background events.

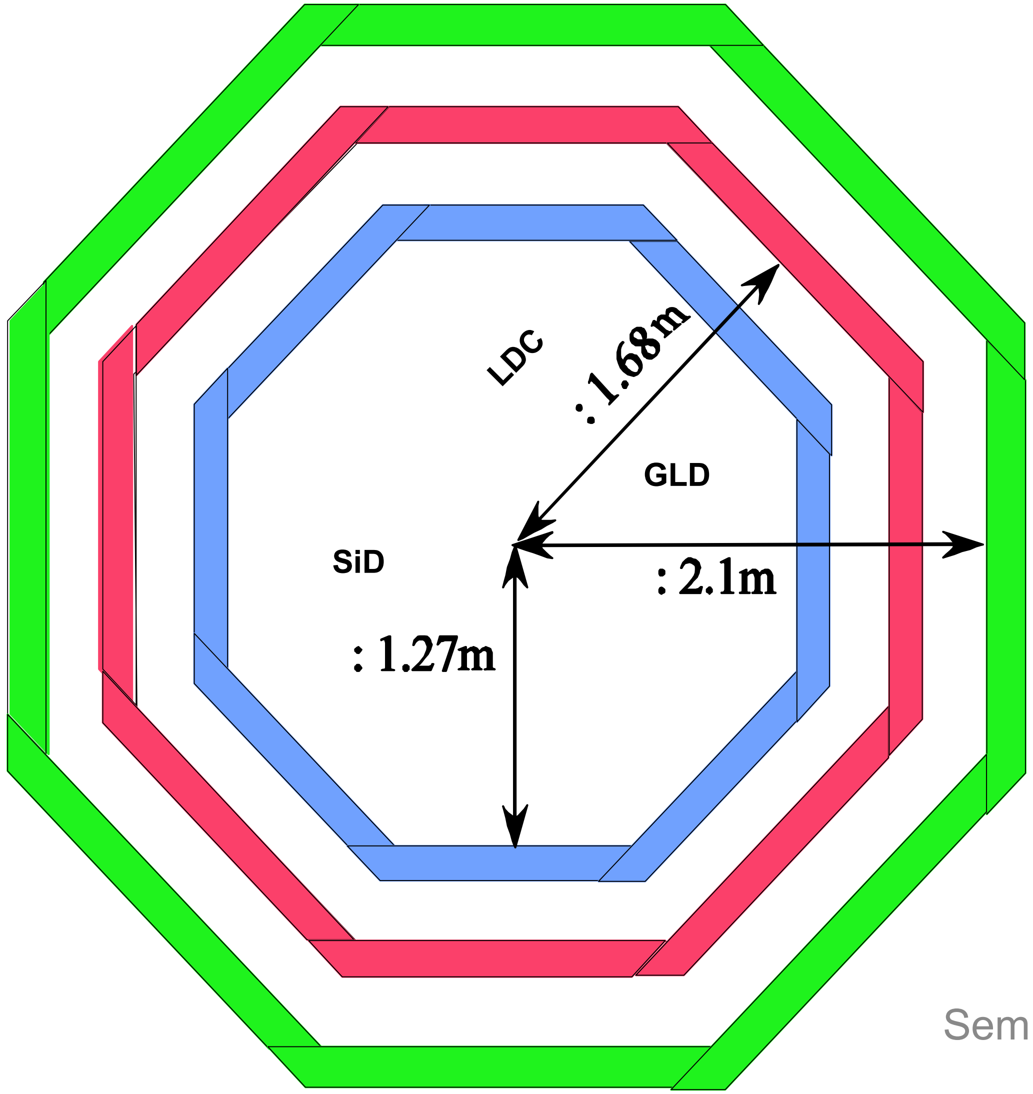
- Cut 1: Photon veto based on acolinearity
- Cut 2: Photon veto based on ISR photon reconstruction in detector volume

ILD concept and highly granular calorimeters

Concepts currently studies differ mainly in SIZE and aspect ratio

Relevant: inner radius of ECAL: defines the overall scale

ECAL end-view



- Figure of merit (ECAL):

  Barrel: $B\, R_{in}^2 / R_m^{effective}$

  Endcap: "B" $Z^2 / R_m^{effective}$

  R_{in} : Inner radius of Barrel ECAL

  Z : Z of EC ECAL front face

- Different approaches

  SiD: $B\, R_{in}^2$

  LDC: $B\, R_{in}^2$

  GLD: $B\, R_{in}^2$