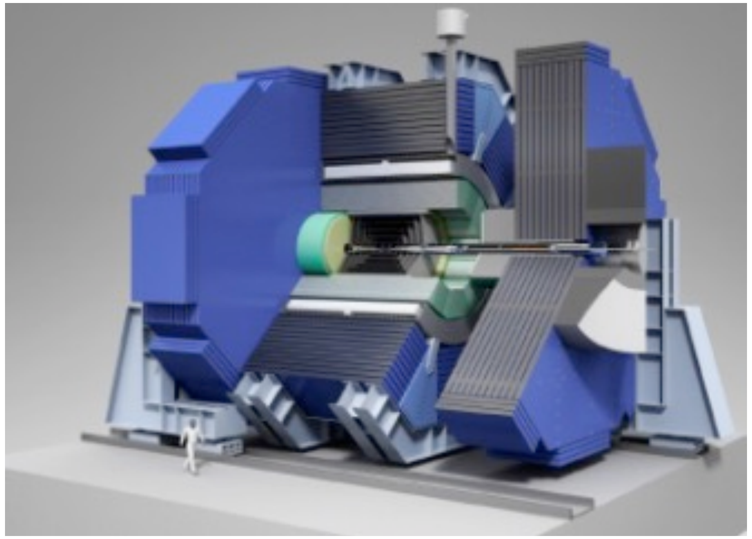
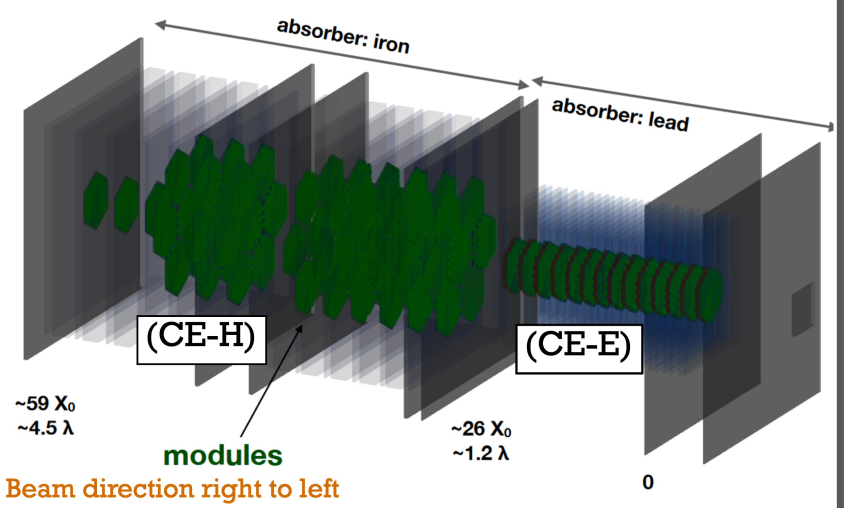
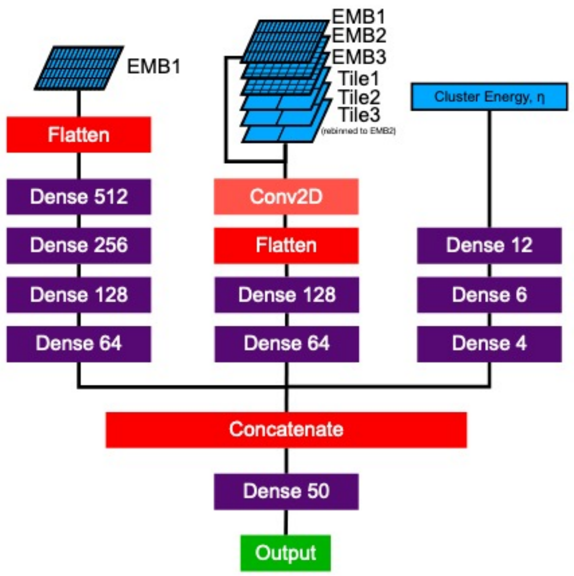


ILC Silicon Detector (SiD) Conceptual Design



CMS High Granularity Calorimeter (HGCAL) test beam



Machine learning for detector reconstruction

Detector R&D for the ILC

David Miller, University of Chicago

Preface: What this talk *will not be*

Complete overview of **all detector R&D for the International Linear Collider (ILC)**

Comparison of different **detector concepts** and **design choices**

Advocacy for or against **detector concepts conceived of for ILC**

Preface: What this talk *will be*

Incomplete and **naïve personal** perspective on **progression** of technologies, with input from ***Maxim Titov***

Context for evaluating developments and progress in calorimetry in particular

(see also Gerald Grenier's talk on SDHCAL specifically!)

Highlights of **recent progress** on long-term development efforts

My comments on **novel approaches** to interpreting and leveraging modern calorimeter measurements

Historical interlude (1982)

8 September, 2021

C.W. Fabjan (CERN) & T. Ludlam (BNL)
Annual Review of Nuclear and Particle Science (1982)

386 FABJAN & LUDLAM

Table 8 Future role of absorptive spectroscopy

Source of particles	Physics emphasis	Calorimeter properties	Technical implications
pp ($p\bar{p}$) collider collider	Rare processes: high p_T, lepton, photon production manifestations of heavy quarks, $W^{\pm}$, Z^0, . . .	4π coverage with e.m. and hadronic detection; high trigger selectivity	Approach intrinsic resolution in multicell device; control of inhomogeneities, stability
e^+e^- collider	Complex, high-multiplicity final states (multijets, electrons in jet, neutrinos)	Precision measurements of total, visible energy and momentum	Very high granularity; particle identification
Secondary beams $p \gtrsim 1$ TeV/c	Similar to first entry; with increasing energy, stronger emphasis on global features	Calorimeter becomes primary or sole spectrometer element	High granularity, high rate operation
Penetrating cosmic radiation; proton decay	Detailed final-state analysis of events with extremely low rate	Potentially largest detector systems ($\gtrsim$10,000tons) with very fine grain readout	Ultra-low-cost instrumentation

Slide credit: Maxim Titov , EPS-HEP 2021

Enormous breadth and depth to R&D community

- **Large collaborations:** CALICE, LCTPC, FCAL
- Collection of many efforts such as **vertex R&Ds**
- Individual **group R&D** activities
- Efforts currently **not directly included in the concept groups** (ILD, SiD, CLICdp), which may become important for LC in future

VIP

SOI

RPC Muon

LCTPC

Silicon ECAL (ILD)

Silicon ECAL (SiD)

CMOS MAPS

GEM DHCAL

ChronoPixel

CLICPix

Scintillator HCAL

FPCCD

DEPFET

KPIX

TPAC

RPC DHCAL

SDHCAL

Dual Readout

FCAL

Scintillator ECAL

https://zenodo.org/record/4496000

Linear Collider Collaboration: Detector R&D Liaison Report

- "Publicize" particular technology and to provide an update of the recent R&D efforts (through ~2020)
- Provides a "snapshot" for a given technology, without information on manpower needs and financial resources to reach project milestones.
- Provides an entry point for new groups in order to help them learn about the current landscape of ILC R&D efforts
- No specific technology choices are made in order keep various options open for specific sub-detector technologies
  - advantage that technologies can be further advanced until the project is approved.

LINEAR COLLIDER COLLABORATION

DOI 10.5281/zenodo.4496000

Detector R&D Report

FINAL VERSION

doi:10.5281/zenodo.3749461

Editors

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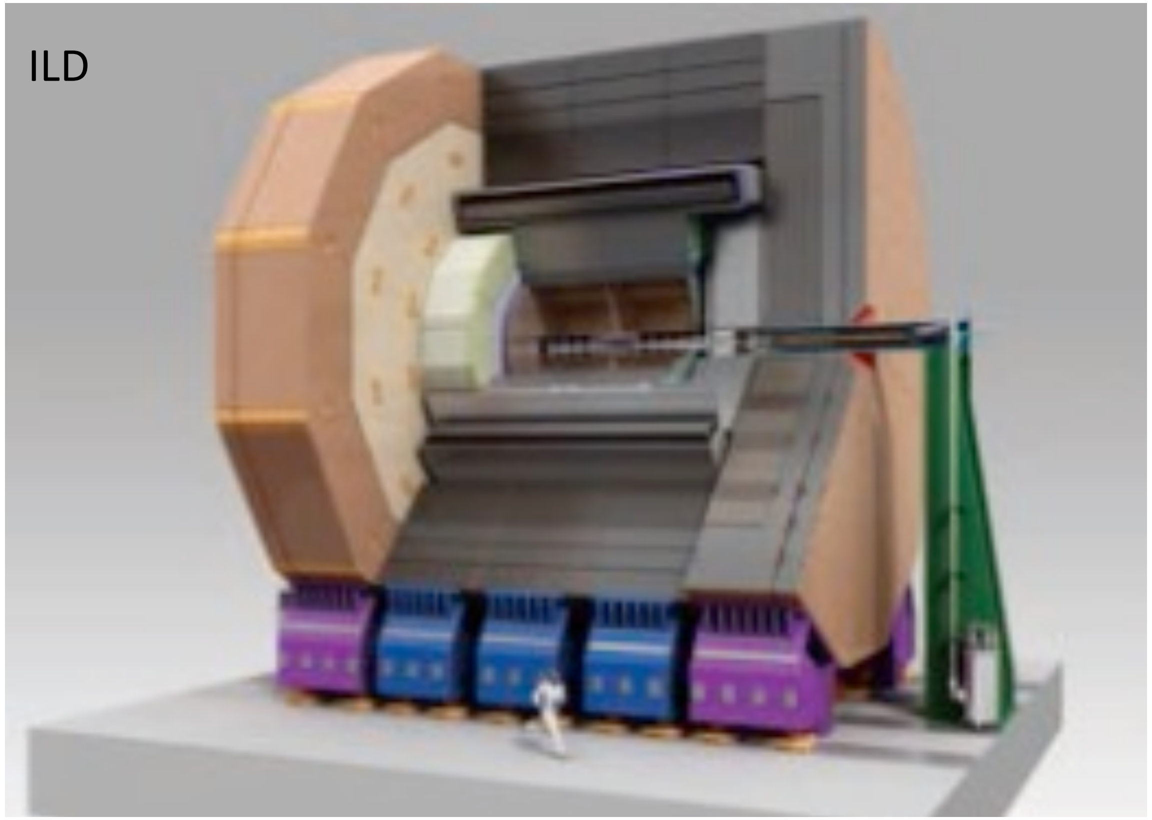
February 2, 2021

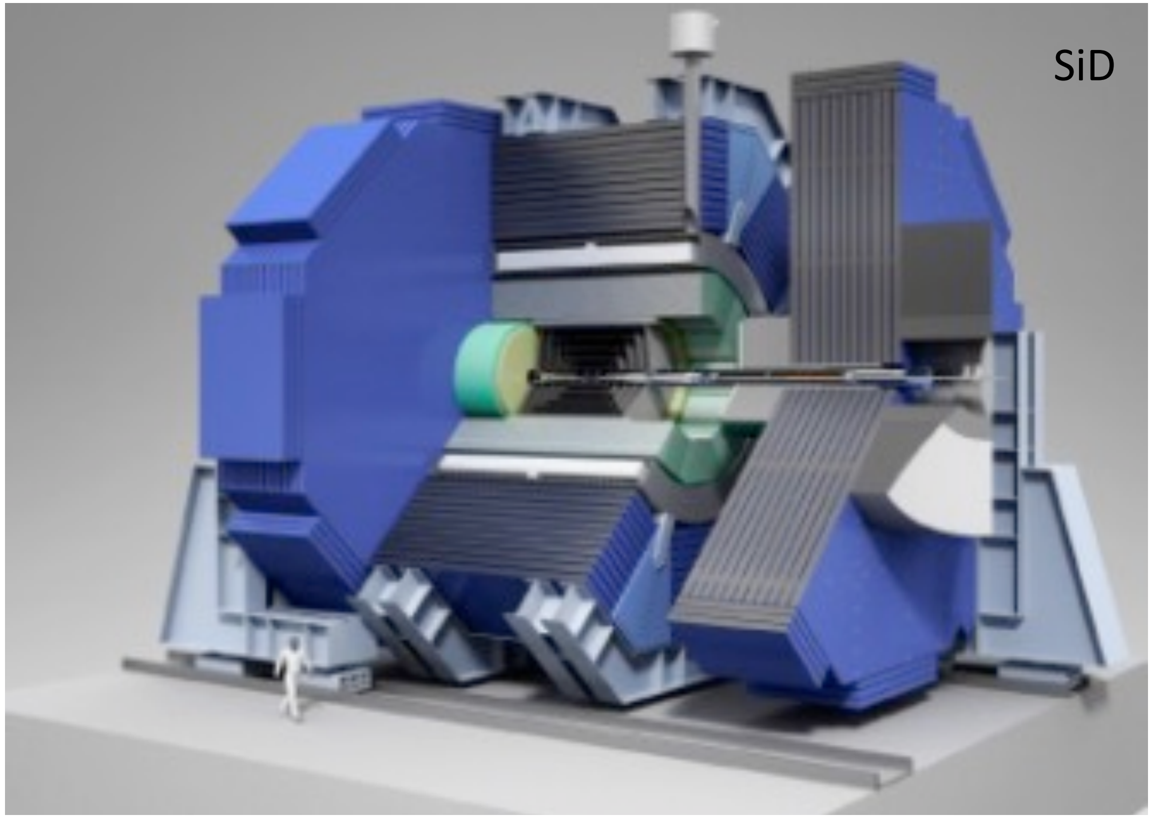
LINEAR COLLIDER COLLABORATION
Designing the world's next great particle accelerator

Slide credit: Maxim Titov , EPS-HEP 2021

ILC Detector Concept Groups: ILD and SiD

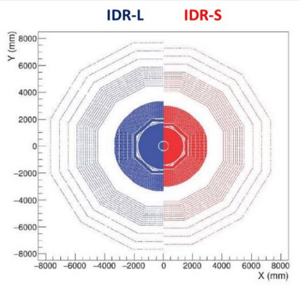
(ILD: International Large Detector and SiD: Silicon Detector)





ILC Detector Concept Groups: ILD and SiD

(ILD: International Large Detector and SiD: Silicon Detector)

ILD ("L" & "S")	SiD
Both optimized for PFA (*) Performance: ~ $B \cdot R_{ECAL,inner}^2$ (track separation @ ECAL)	
 **B = 3.5 T ("L") / 4 T ("S")**	**B = 5 T**
$R_{ECAL,inner}$ = 1.8 / 1.46 m	**$R_{ECAL,inner}$ = 1.27 m**
Si + TPC tracking Outer radius: 1.77 / 1.43 m	**Silicon Tracking only Outer radius: 1.22 m**

Slide credit: [Maxim Titov , EPS-HEP 2021]

(*) PFA: Particle Flow Analysis

Tracking and vertexing: complementary approaches

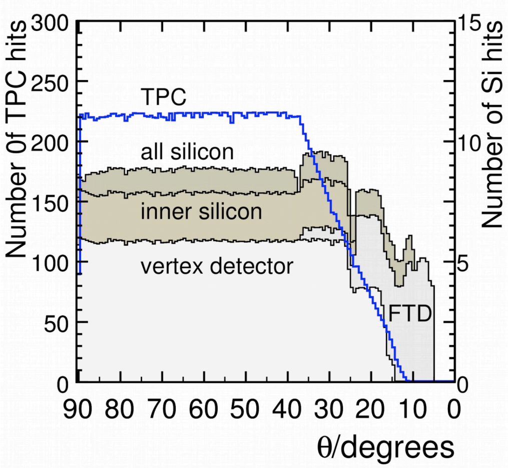
ILD: Silicon + Gaseous tracking

Vertexing

- long barrel of 3 double layers of silicon pixels

Tracking

- Intermediate Si-tracker (SIT, SET, FTD)
  - SIT/FTD: silicon pixel sensors (e.g. CMOS)
  - SET: silicon strip sensors
- Time Projection Chamber with MPGD-readout
  - High hit redundancy (200 hits / track)
  - dE/dx information for PID



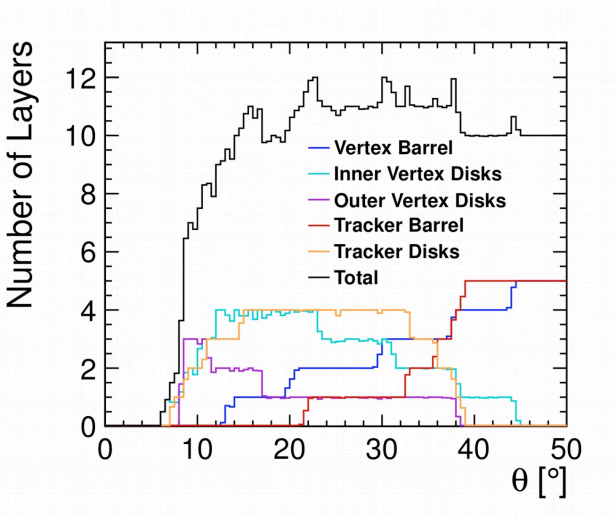
SiD: all-Silicon tracking

Vertexing

- short barrel of 5 single layers of silicon pixels

Tracking

- 5 layers Silicon-strip tracker
  - 25um strips
  - 50 um readout pitch
- Few highly precise hits (max. 12)
  - Robustness, single bunch time stamping



Slide credit: Maxim Titov , EPS-HEP 2021

Vertex Technologies: State-of-the-Art

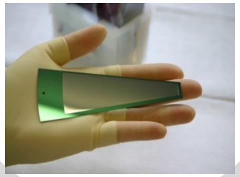
- Exploit ILC low duty cycle 0(10^{-3}): triggerless readout, power-pulsing
- Readout strategies:
  - continuous during the train with power cycling ⟶ mechanical stress from Lorentz forces in B-field
  - delayed after the train ⟶ ~5µm pitch or in-pixel time-stamping to reduce occupancy

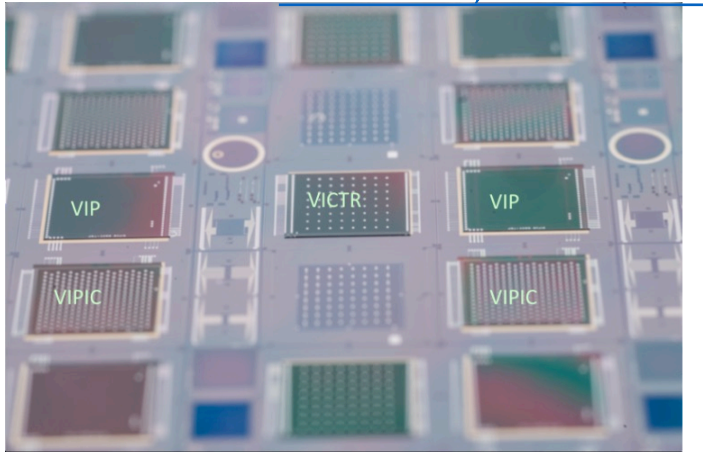
Physics driven requirements — **Running constraints** — **Sensor specifications**

- $\sigma_{s.p.}$ 2.8um ⟶ Small pixel ~16 µm
- Material budget 0.15% X_0/layer ⟶ Thinning to 50 µm
- ⟶ Air cooling ⟶ low power 50 mW/cm^2
- r of Inner most layer 16mm ⟶ beam-related background ⟶ fast readout ~1 µs
- ⟶ radiation damage ⟶ radiation tolerance ≤3.4 Mrad/ year, ≤$6.2\times10^{12} n_{eq}/(cm^2 year)$

Technology	FPCCD	DEPFET	SOI	CMOS	iLGAD
Added value (example)	Very granular	Low material budget	2 tier process (high density µcircuits)	Industry evolution	PID

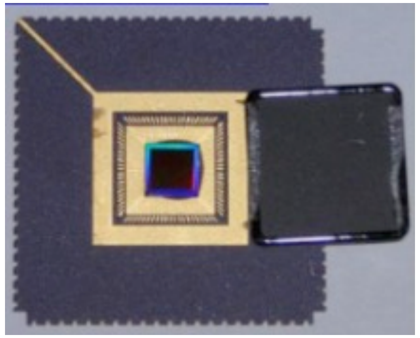
DEPFET: continuous readout, 75 / 50 um thick (Belle II)





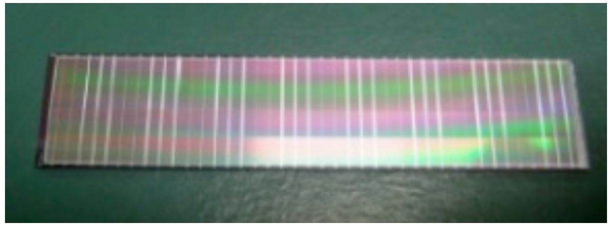
3D Integration (in-pixel data processing, on-hold): MWR in 2010, VIP(ILC)

Chronopixel: delayed readout, monolithic CMOS, 50 um thick

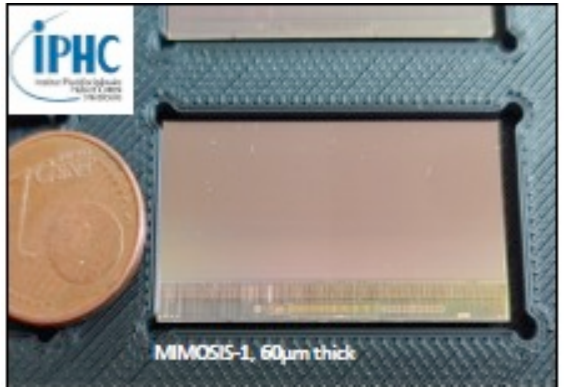


SOI: delayed / continuous readout; suited for 3D integration

Fine pixel CCD: delayed readout, 5 um pitch, 50 um thickness

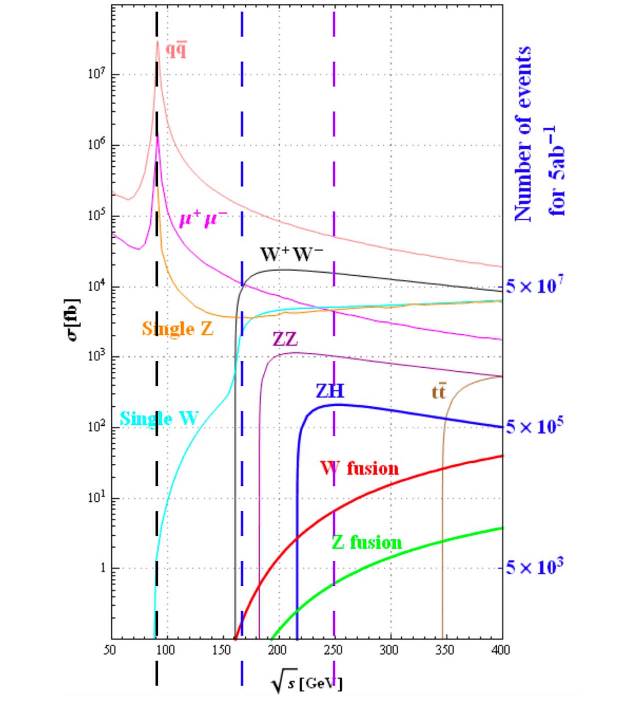


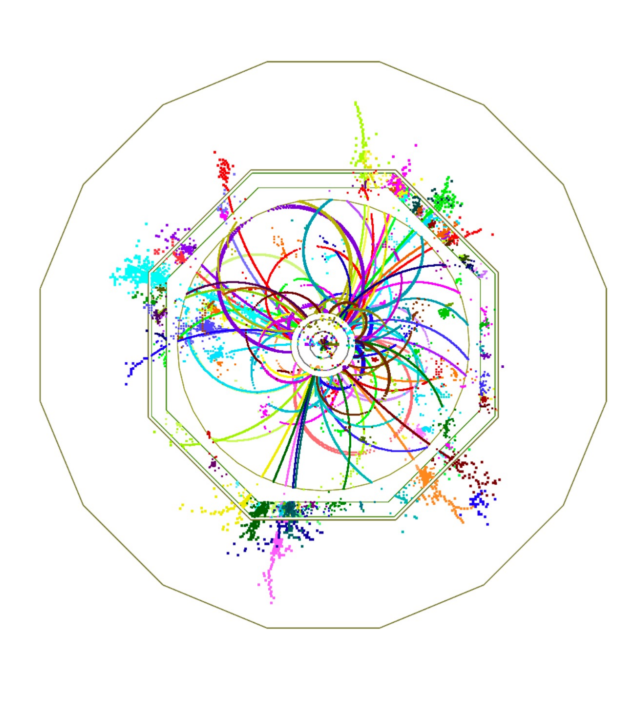
CMOS (CPS): continuous readout, stiching

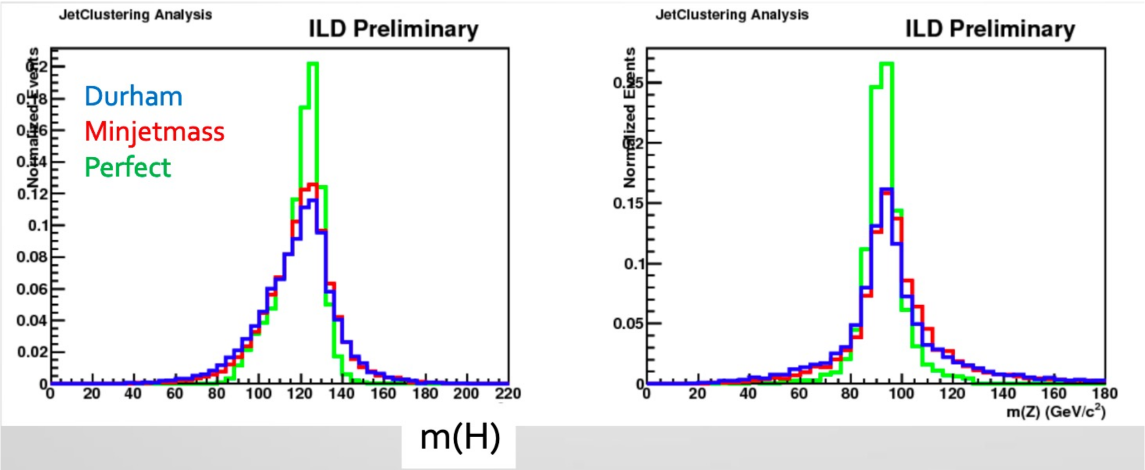


Calorimetry needs and opportunities at future linear e^+e^- colliders

- **Clear goal: Higgs processes**
  - In particular: *HZ*⟶jets
- **QCD measurements**
  - Including, jet shape and structure measurements, even at a 250 GeV ILC
- **Algorithmic considerations still critical**
  - Confusion terms in particle flow analysis (PFA) are very important
  - Jet clustering and pairing can degrade otherwise beautiful detector performance







(*) Also see: Manqi Ruan's talk at LCWS 2019

Masakazu Kurata's talk from Wed (17 Mar)

Developments* in the calorimetry *status quo*

** clearly, my own incomplete selection! Please comment on omissions you feel are important in Q&A!*

Shower profile and particle identification

- Particle flow: calo+tracker combined to understand the full event
- Precision Timing: shower particle time-of-flight precision of ~10—30 ps
- 5D Calorimetry: position (*x,y,z*), energy, time of signal ⟶ use all info

Active materials and photosensors

- Crystals and ceramics: ultrafast response times, extreme radiation hardness, cost reductions
- Ultraviolet response & transmission: Cerenkov signals for dual-readout

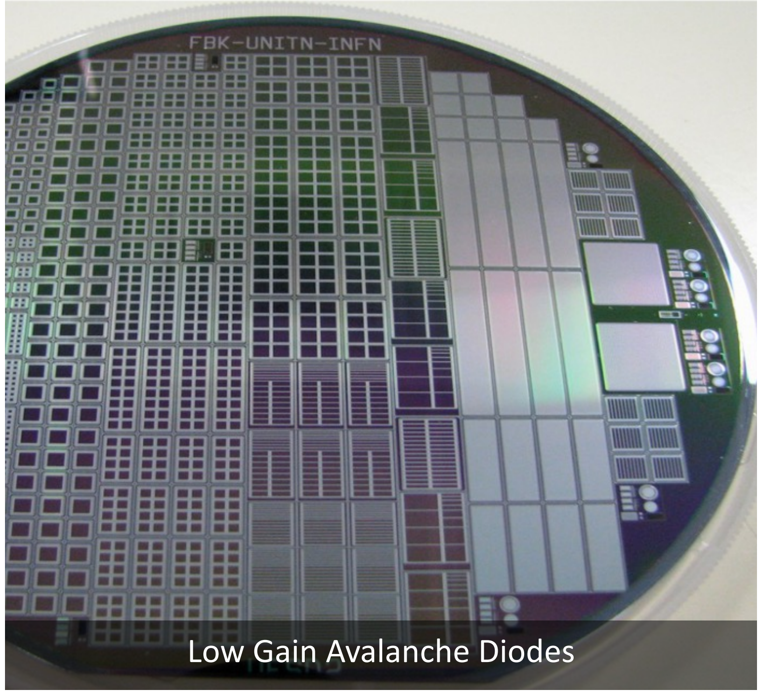
Monolithic active pixel sensor (MAPS) Technology

- Integrated sensor and readout technology with high voltage silicon

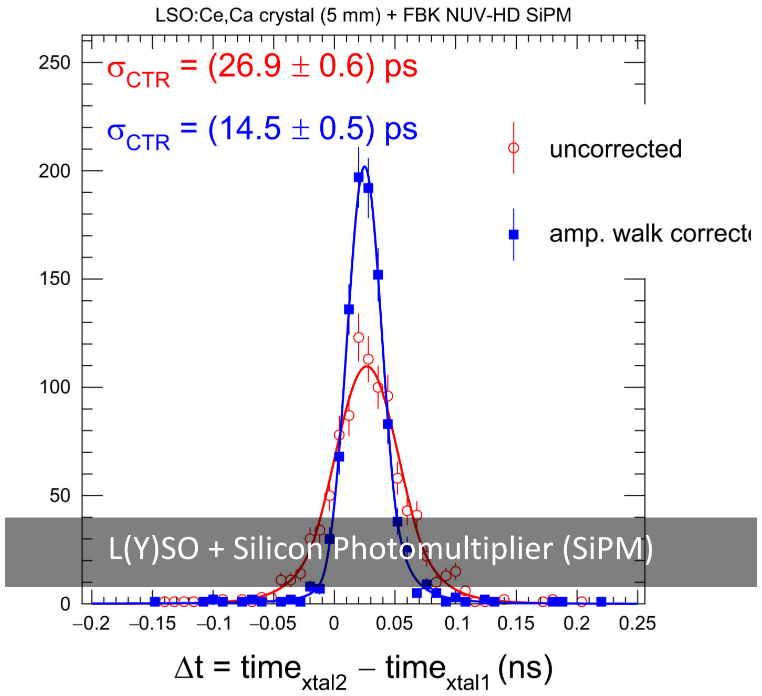
Powerful, fast, efficient readout electronics and powering

- Flexible and sophisticated on-detector electronics systems with FPGAs (field-programmable gate arrays) and SoC (System-on-Chip)
- Pulsed power systems with low duty cycle, greater physical density

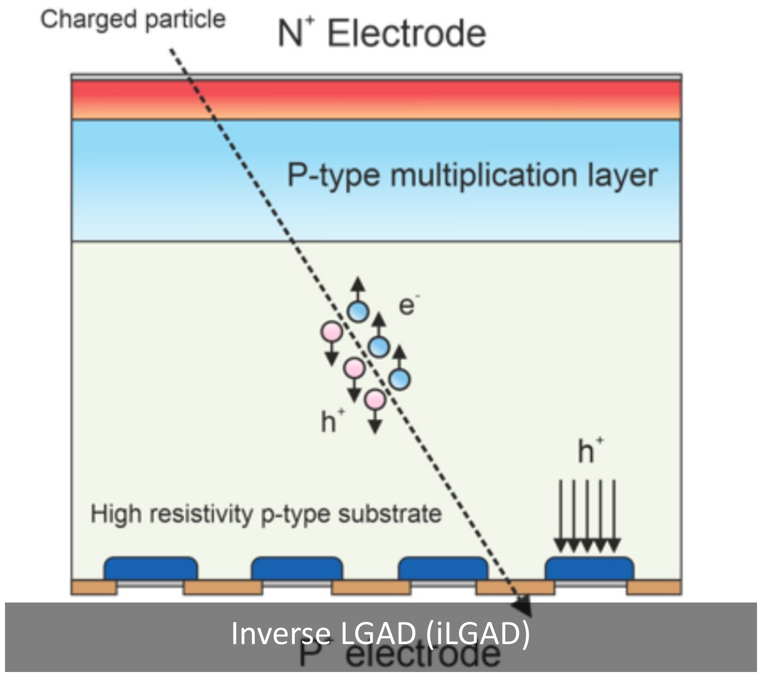
[Bohdan Dudar's talk at LCWS2021]



[NIMA 830 (2016) 30–35]



[Albert Doblas' talk at LCWS2021]

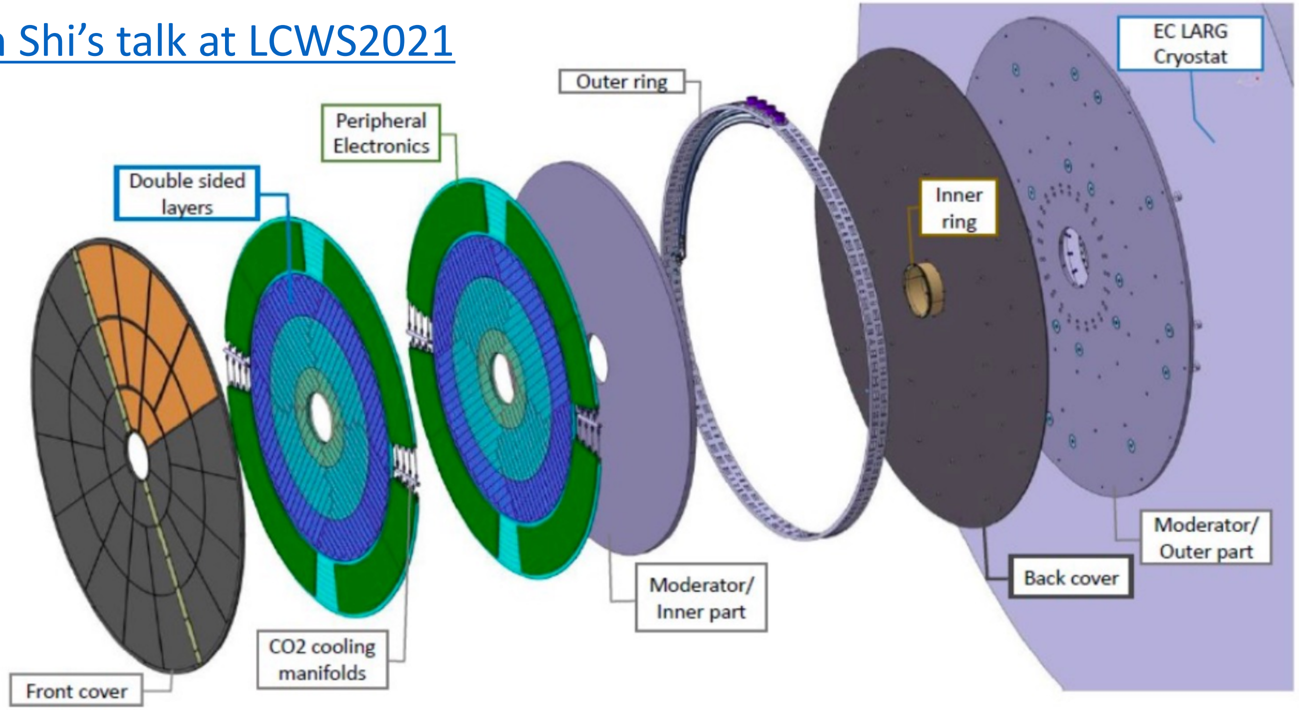


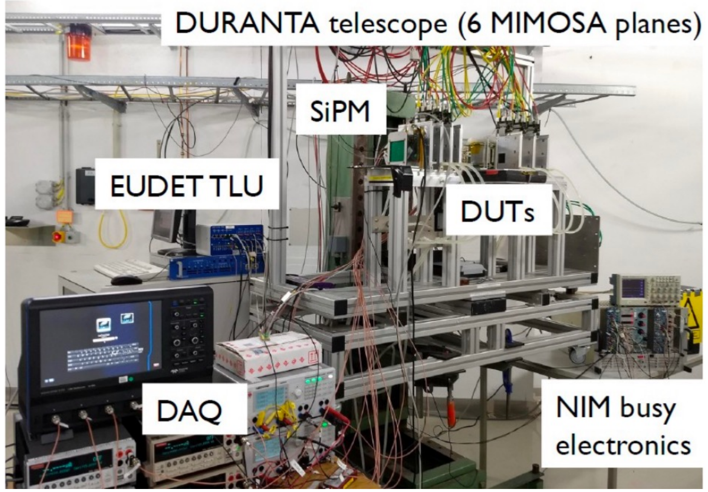
Fast timing
Nearly ubiquitous technology

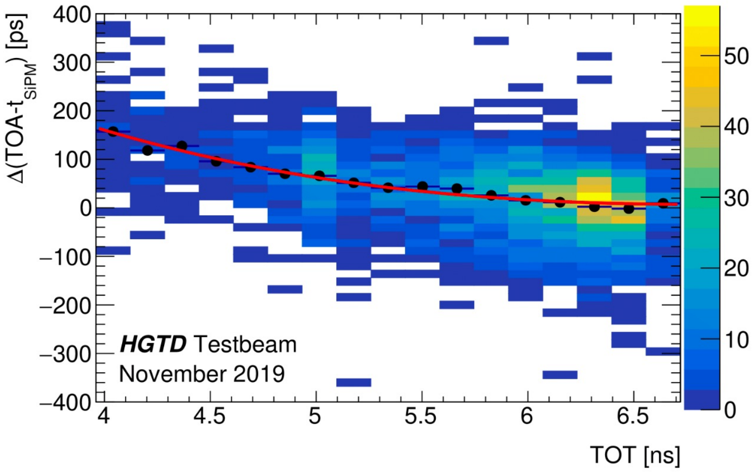
[Xin Shi's talk at LCWS2021]

ATLAS High Granularity Timing Detecyor (HGTD)

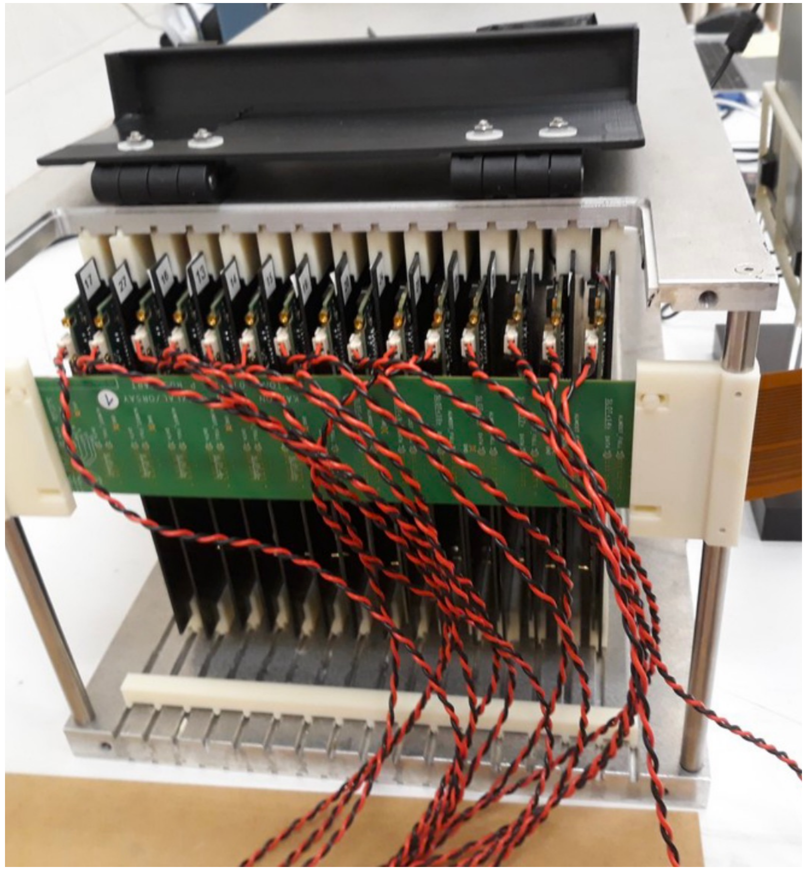
30—50 ps track resolution per track

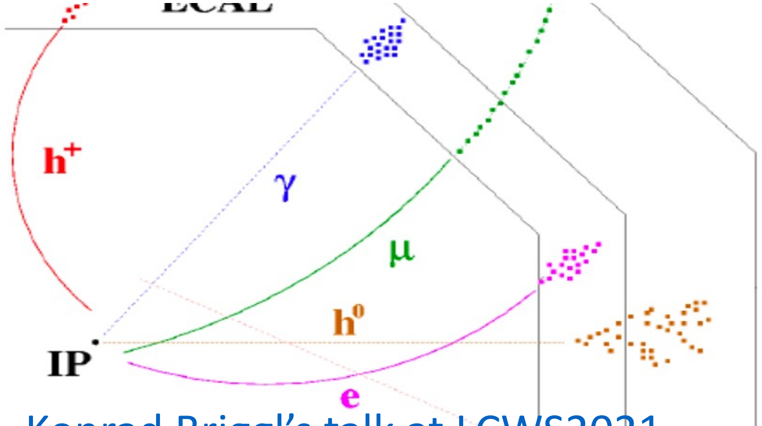






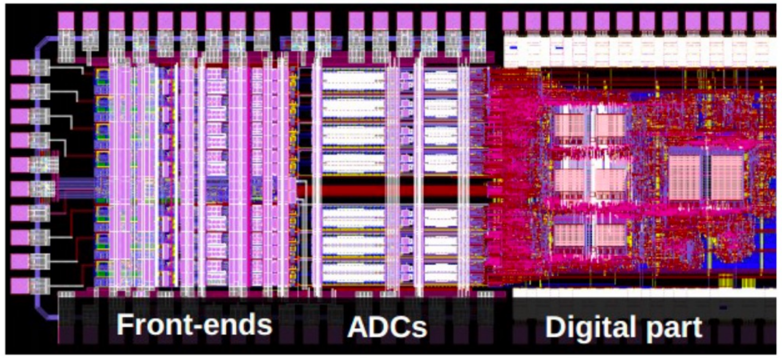
[Adrian Irles' talk at LCWS2021]

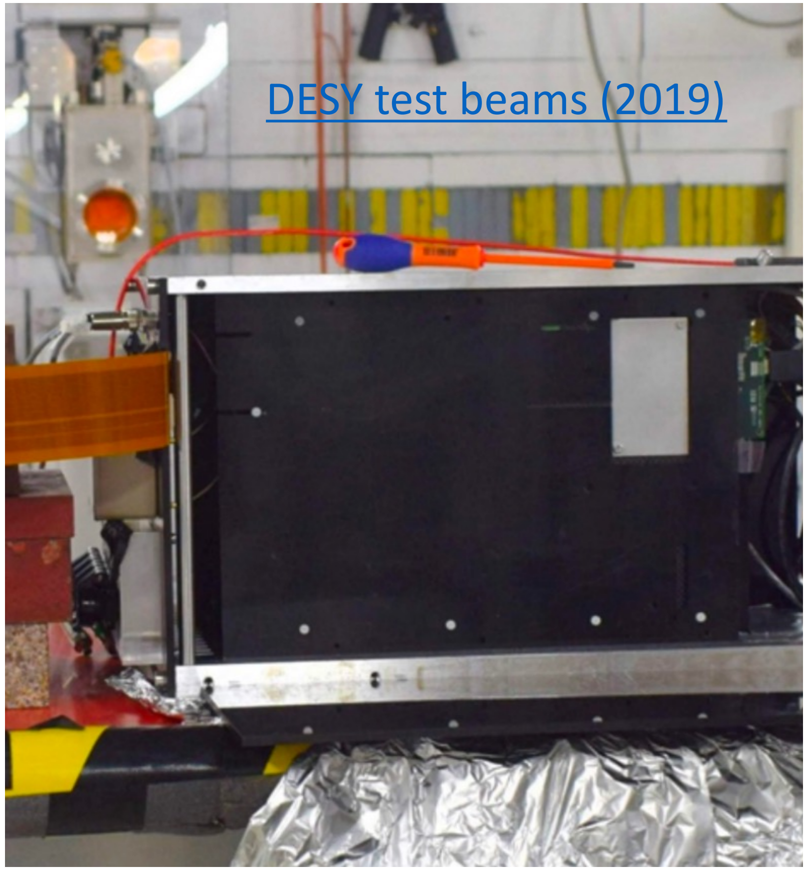


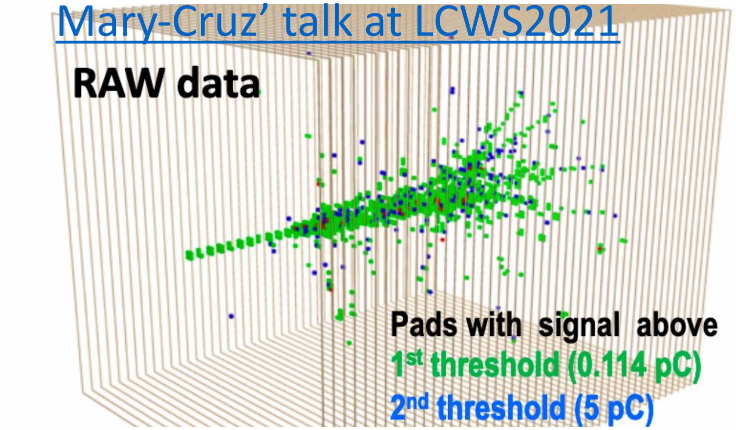


[Konrad Briggl's talk at LCWS2021]

7-channel KLauS4 prototype (2016)





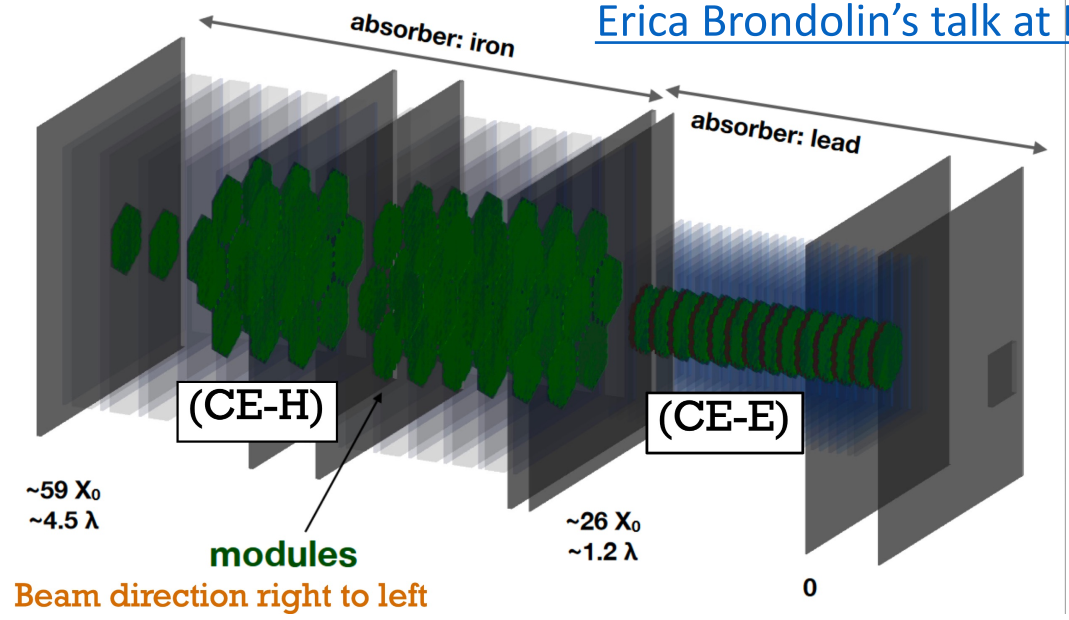


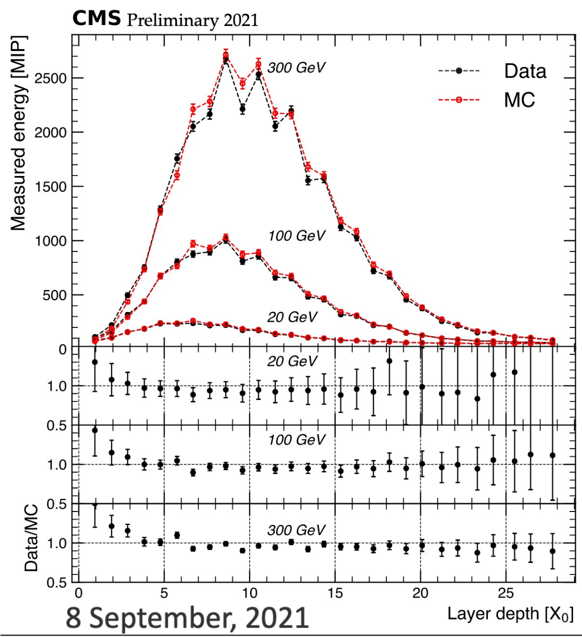
CALICE SiW ECAL, A/SDHCAL

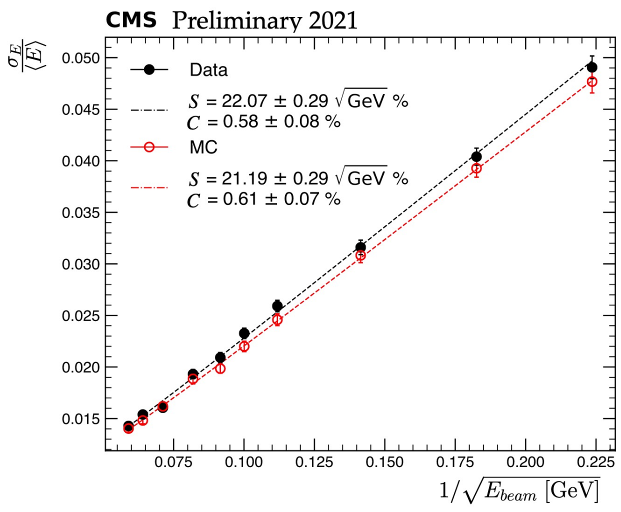
AHCAL: Steel+Scint.+SiPM
SDHCAL: Steel+Glass Resistive Plate Chambers

Debabrata Bhowmik's talk at LCWS2021
Erica Brondolin's talk at LCWS2021

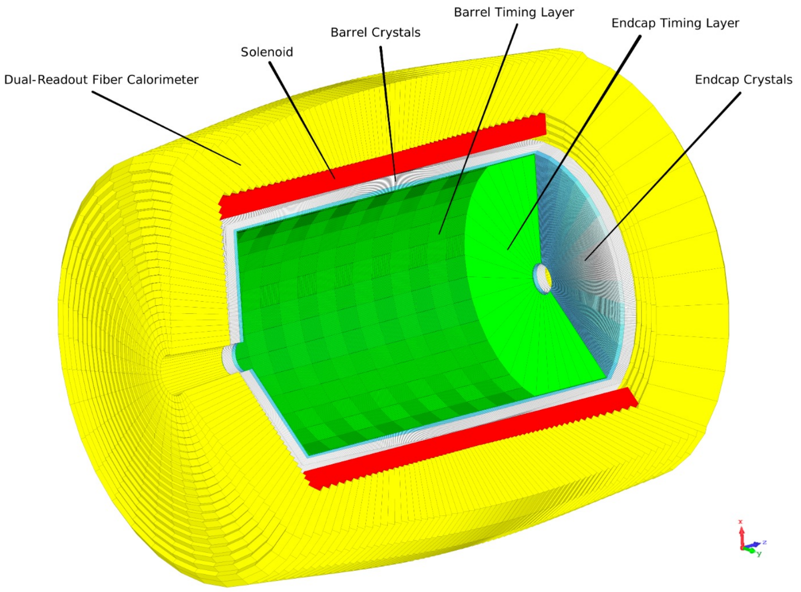
CMS HGCAL & ECAL

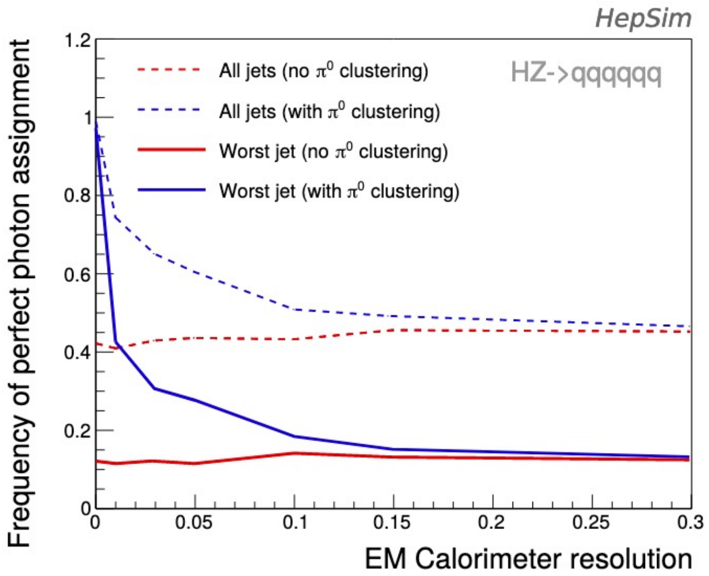


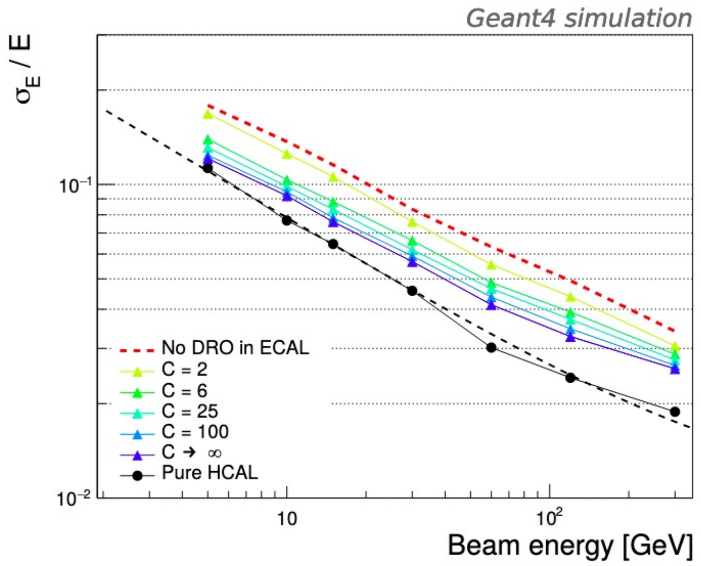




(*) See also: Stefano Agiro's talk on Tue (16 Mar)

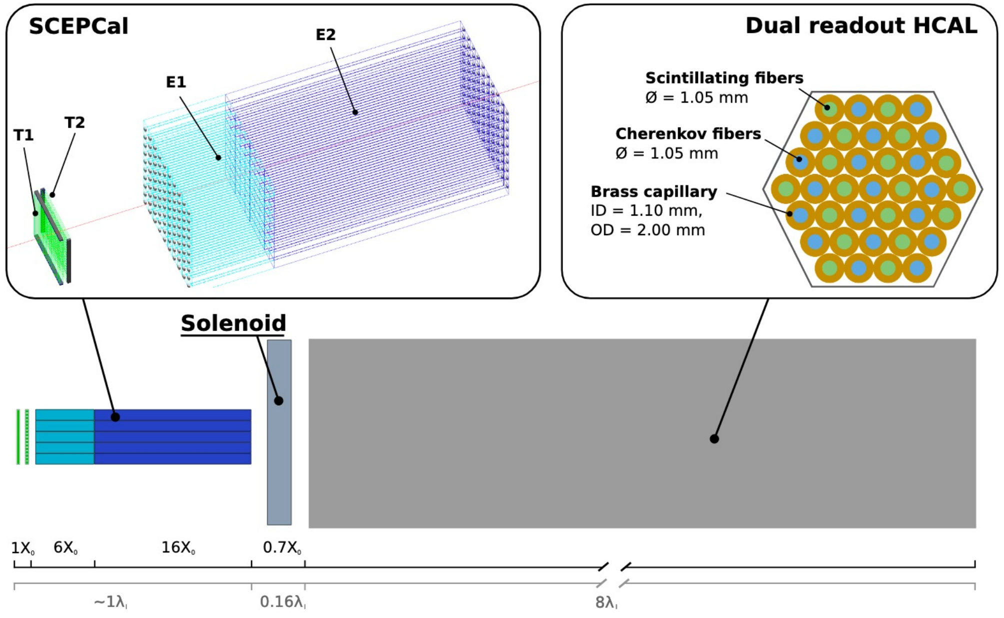






New ideas for crystal calorimetry

Coupled with dual-readout HCAL



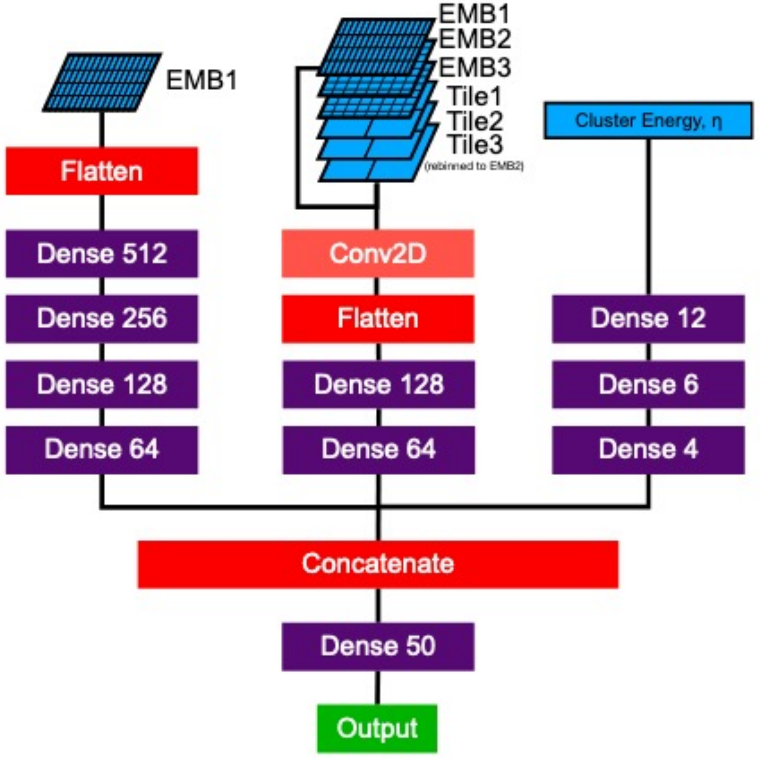
[2020 *JINST* **15** P11005](#)

Novel approaches to interpreting and leveraging modern calorimeter measurements

New paradigms on the horizon

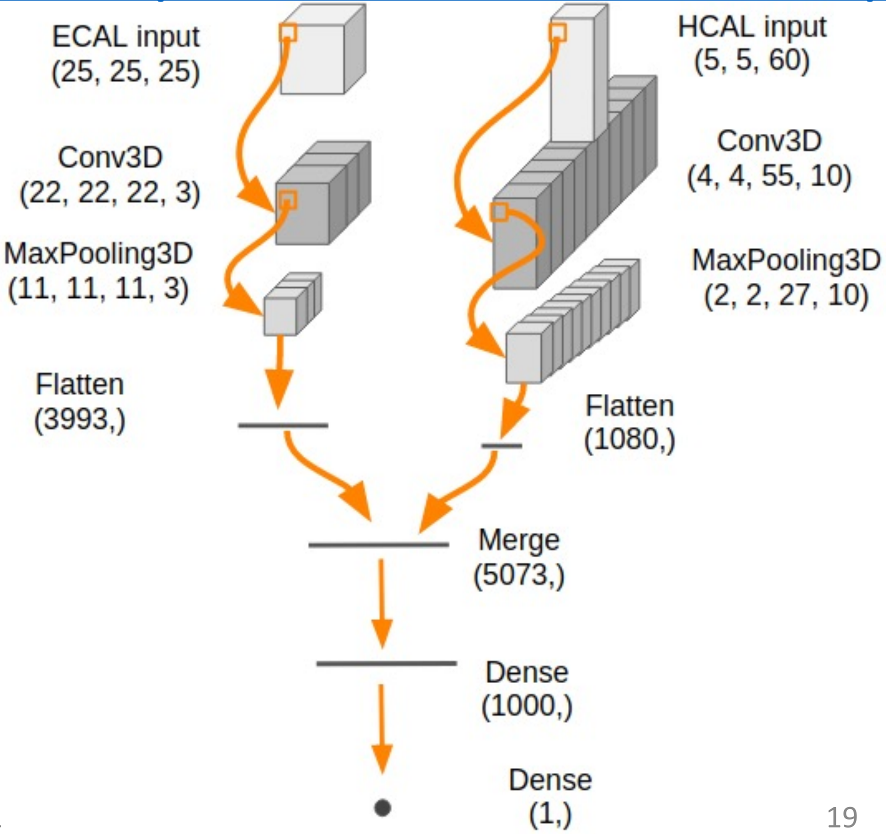
Deep Learning for Pion Identification and Energy Calibration with the ATLAS Detector

[ATL-PHYS-PUB-2020-018]



Calorimetry with deep learning: particle sim. and reco. for collider physics

[Belayneh, et al (arXiv:1912.06794, EPJC 80, 688 (2020))]



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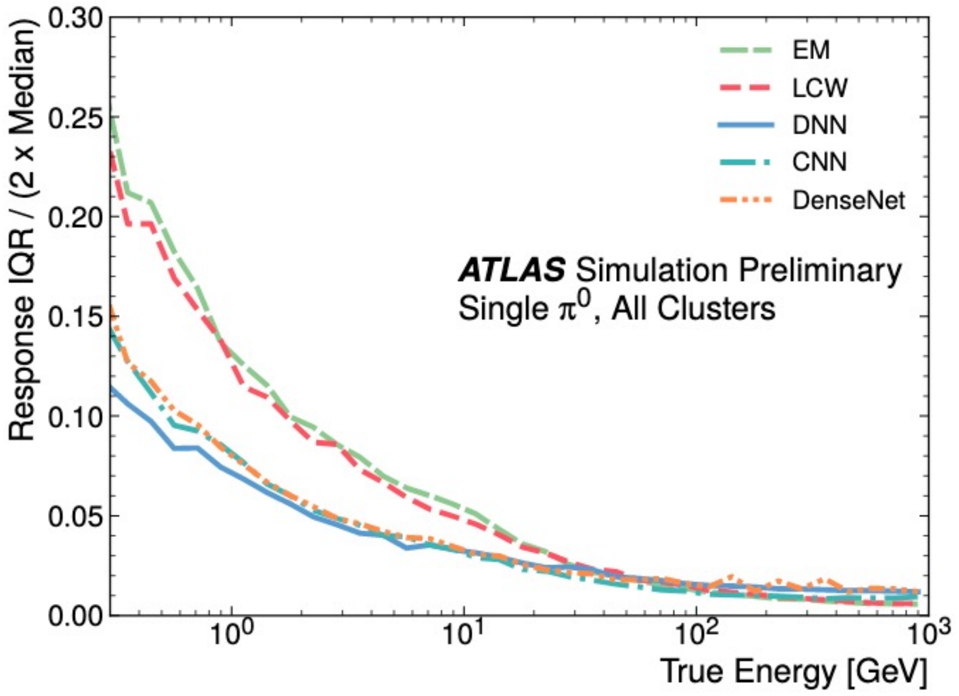

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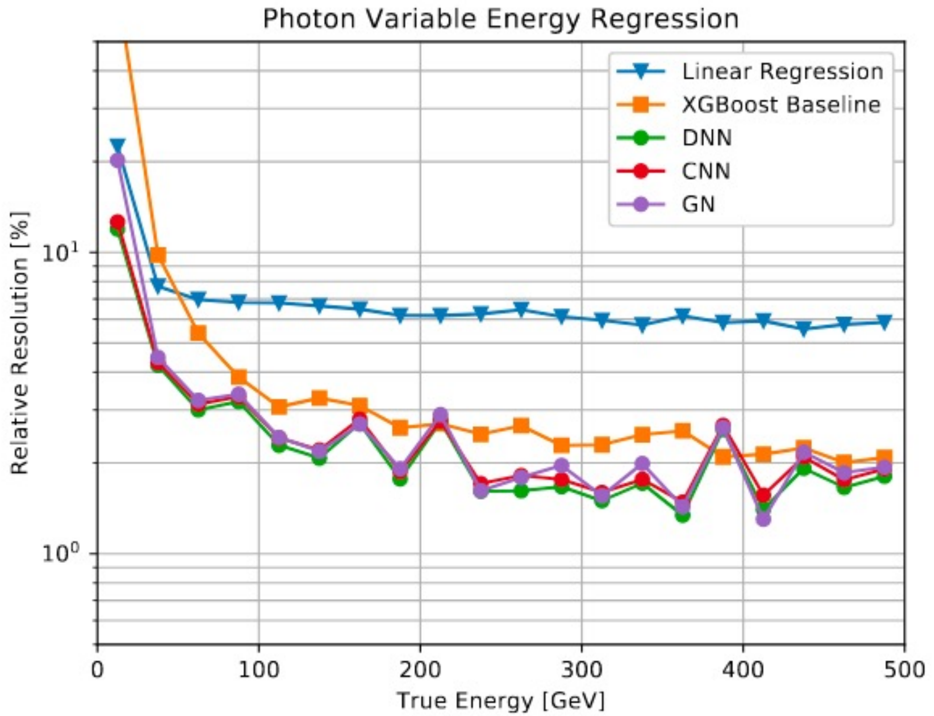

Summary & Conclusions

Huge breadth and depth of detector R&D for the ILC

- Well-established ILC Detector Concept groups with robust R&D efforts
- Collection of many efforts such as vertex R&Ds
- Individual group R&D activities

Decades of effort on new approaches to calorimetry are coming to fruition!

- Large-scale prototypes of many highly granular detector technologies for ECAL, HCAL, timing, and more
- Upgrades to existing calorimeter systems are being deployed and commissioned
- New ideas for optimizing and enhancing traditional calorimeter concepts

Interpretation and usage of detector information undergoing a renaissance!

- Flexible, powerful embedded electronics systems allow for complex on-detector processing
- High-dimensional data mining and machine learning are going to be extremely for various measurements and detector concepts should evaluate these ideas!