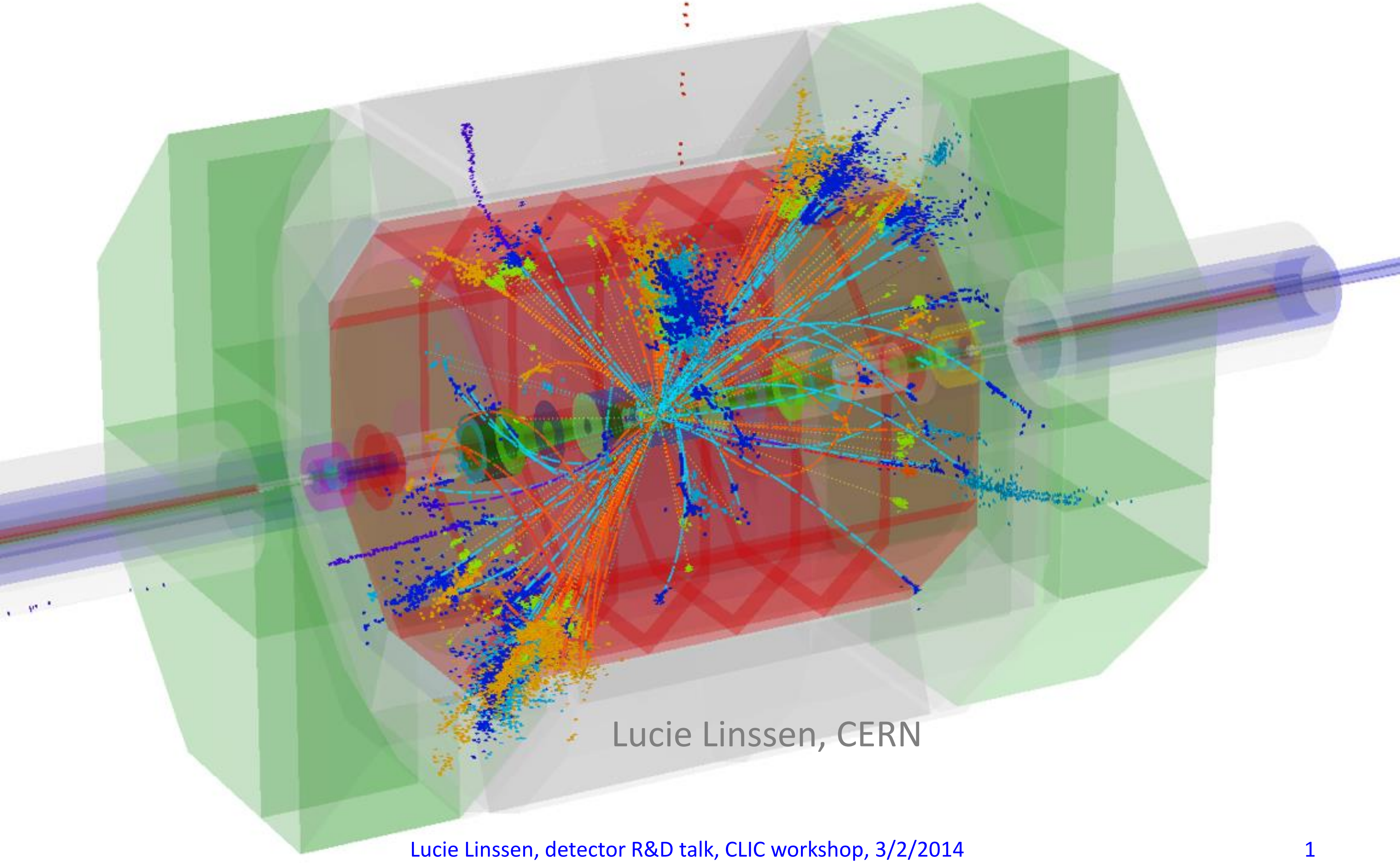
detector R&D challenges for energy frontier physics



Lucie Linssen, CERN

Outline

- Detector requirements at hadron and lepton colliders
- Challenges/technologies in vertex/tracking detectors
- Challenges/technologies in calorimetry
- Possible common development areas
- Outlook

In ~20 minutes:
Impossible to pay justice to the broad spectrum of detector R&D;
Impossible, also, to cover pp en e+e- options in a balanced way;
My apologies

Sources

Material used for this talk was taken from:

ECFA High Luminosity LHC experiments workshop, Aix-les-Bains, 2013
http://indico.cern.ch/conferenceDisplay.py?confId=252045

FHC Hadron Collider physics and experiments, indico
https://indico.cern.ch/categoryDisplay.py?categId=5258
In particular detector talks by D. Fournier and W. Riegler

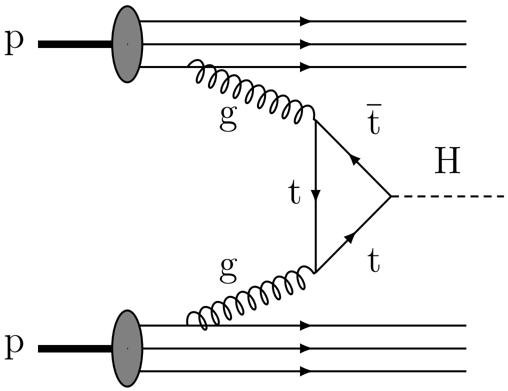
LCWS13, linear collider workshop, Tokyo, 2013
http://www.icepp.s.u-tokyo.ac.jp/lcws13/

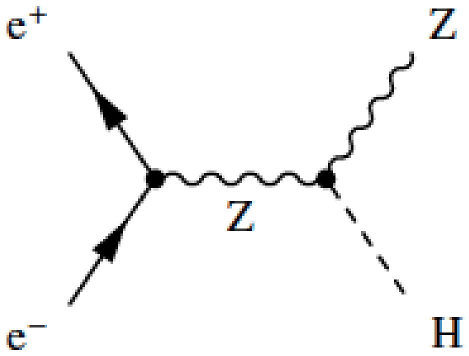
CLIC CDR (vol 2), Physics and Detectors at CLIC,
CERN-2012-003, arXiv:1202.5940

CLIC CDR (vol 3), The CLIC Programme: towards a staged e^+e^- Linear Collider exploring the Terascale, CERN-2012-005, http://arxiv.org/abs/1209.2543

With apologies for not having asked individual permissions

hadron vs. lepton colliders





p-p collisions	e^+e^- collisions
Proton is compound object → Initial state not known event-by-event → Limits achievable precision	e^+/e^- are point-like → Initial state well defined ($\sqrt{s}$ / polarization) → High-precision measurements
Circular colliders feasible	Linear Colliders (avoid synchrotron rad.)
High rates of QCD backgrounds → Complex triggering schemes → High levels of radiation	Cleaner experimental environment → trigger-less readout → Low radiation levels
High cross-sections for colored-states	Superior sensitivity for electro-weak states

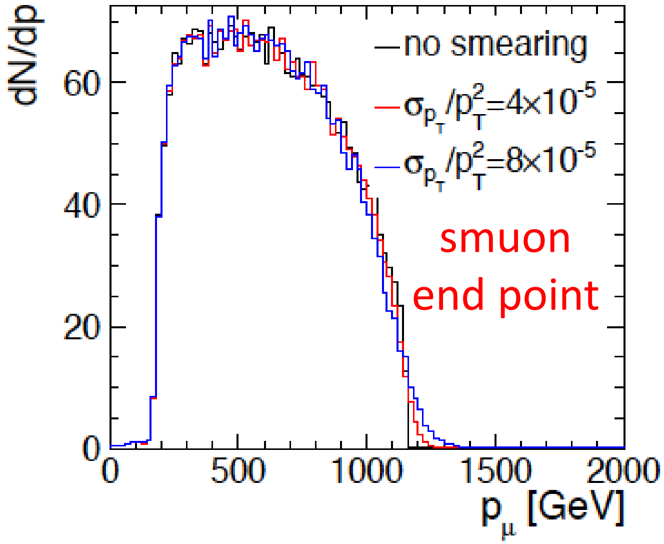
CLIC physics aims => detector needs

★ momentum resolution:

e.g. Smuon endpoint

Higgs recoil mass, Higgs coupling to muons

$$\sigma_{p_T}/p_T^2 \sim 2 \times 10^{-5}\,\mathrm{GeV}^{-1}$$

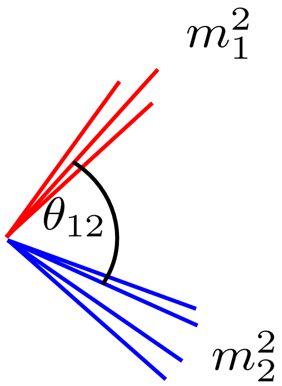


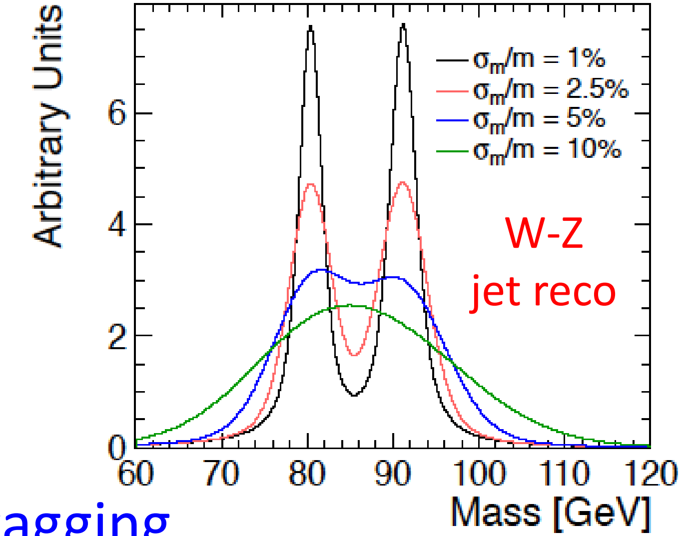
★ jet energy resolution:

e.g. W/Z/h di-jet mass separation

$$\frac{\sigma_E}{E} \sim 3.5 - 5\,\%$$

(for high-E jets)





★ impact parameter resolution:

e.g. c/b-tagging, Higgs BR

$$\sigma_{r\phi} = 5 \oplus 15/(p[\mathrm{GeV}]\sin^{\frac{3}{2}}\theta)\,\mu\mathrm{m}$$

★ angular coverage, very forward electron tagging

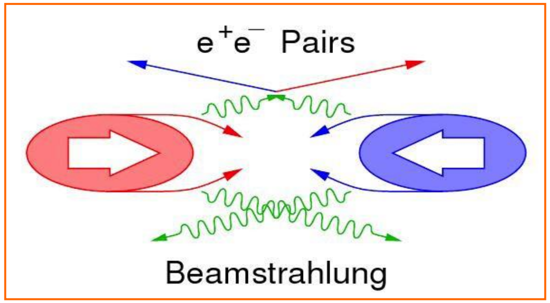
+ requirements from CLIC beam structure and beam-induced background

CLIC machine environment

	CLIC at 3 TeV
L ($cm^{-2}s^{-1}$)	5.9×10^{34}
BX separation	0.5 ns
#BX / train	312
Train duration (ns)	156
Rep. rate	50 Hz
σ_x / σ_y (nm)	≈ 45 / 1
σ_z (μm)	44

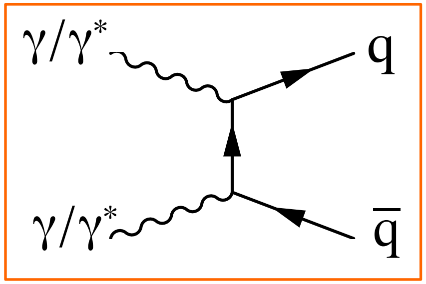
Drives timing requirements for CLIC detector

very small beam size



Beam related background:

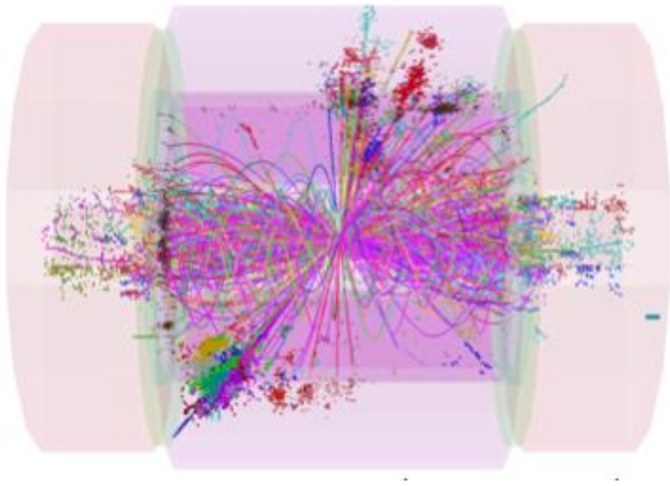
- Small beam profile at IP leads very high E-field
  - **Beamstrahlung**
    - Pair-background
      - High occupancies
    - γγ to hadrons
      - Energy deposits

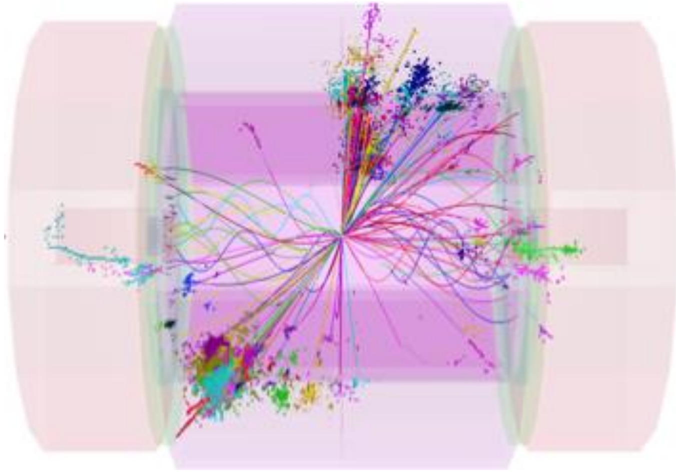


CLIC conditions => impact on detector

CLIC conditions => impact on detector technologies:

- **High tracker occupancies => need small cell sizes**
  (beyond what is needed for resolution)
  - Small vertex pixels
  - Large pixels in intermediate regions
  - Limited strip length in tracker
- **Bkg energy => need high-granularity calorimetry**
- **Bkg suppression => overall need for precise hit timing**
  - ~10 ns hit time-stamping in tracking
  - 1 ns accuracy for calorimeter hits
- **Low duty cycle**
  - Triggerless readout
  - Allows for power pulsing
    - => less mass and high precision in tracking
    - => high density for calorimetry





$e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}b\bar{t} \rightarrow 8$ jets

Challenges in LC detector R&D

Combined requirements lead to the following challenges:

Vertex and tracker

Very high granularity
Dense integration of functionalities
  Including ~10 ns time-stamping
Super-light materials
Low-power design + power pulsing
Air cooling

ultra – light

Calorimetry

Fine segmentation in R, phi, Z
Time resolution ~1 ns
Ultra – compact active layers
Pushing integration to limits
Power pulsing

ultra – heavy
and compact

detector requirements HL-LHC

Maintain performance at full sensitivity for discovery and precision measurements at low p_T, under severe pile-up conditions

Pileup

<PU> ≈ 50 events per crossing by LS2
<PU> ≈ 60 by LS3
<PU> up to 140 for lumi-leveling at $5\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at HL-LHC
(accounting for uncertainty and bunch-to-bunch variations)

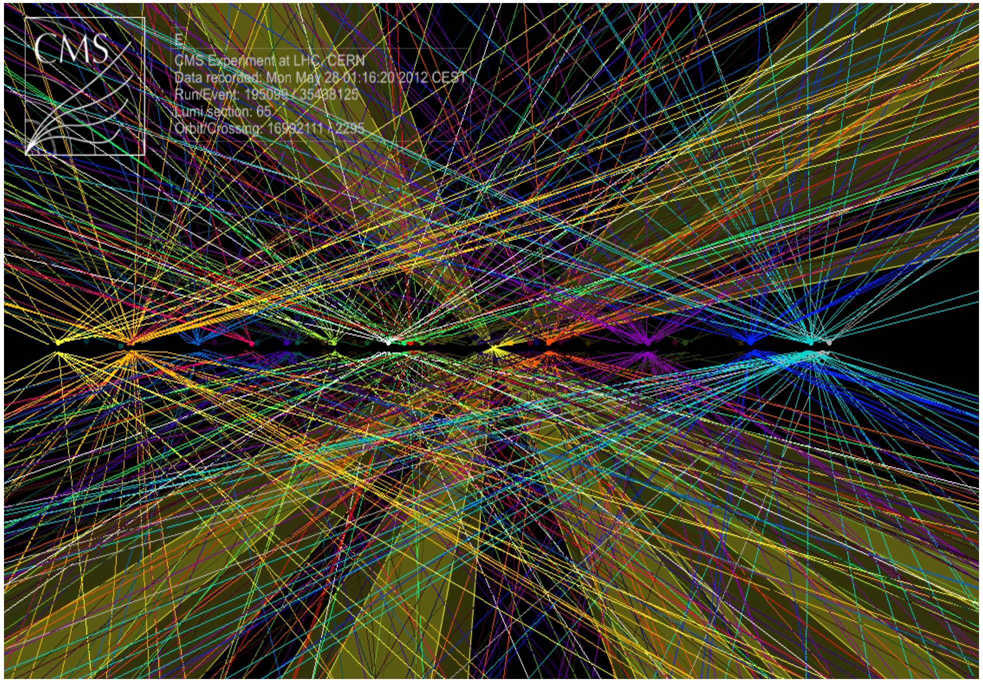
Radiation damage

Performance longevity after 300 fb^{-1}
Replace elements with limited lifetime

Extend performance to larger η

Profit from detector technology advances

Enhance trigger + DAQ



comparison CLIC ⇔ LHC detector

In a nutshell:

CLIC detector:

- **High precision:**
  - Jet energy resolution
    - => fine-grained calorimetry
  - Momentum resolution
  - Impact parameter resolution
- **Overlapping beam-induced background:**
  - High background rates, medium energies
  - High occupancies
  - Cannot use vertex separation
  - Need very precise timing (1ns, 10ns)
- **“No” issue of radiation damage (10^{-4} LHC)**
  - Except small forward calorimeters
- **Beam crossings “sporadic”**
- **No trigger, read-out of full 156 ns train**

LHC detector:

- **Medium-high precision:**
  - Very precise ECAL (CMS)
  - Very precise muon tracking (ATLAS)
- **Overlapping minimum-bias events:**
  - High background rates, high energies
  - High occupancies
  - Can use vertex separation in z
  - Need precise time-stamping (25 ns)
- **Severe challenge of radiation damage**
- **Continuous beam crossings**
- **Trigger has to achieve huge data reduction**

from HL-LHC to FHC

Some very (!) first assessments about extrapolation from LHC to FHC

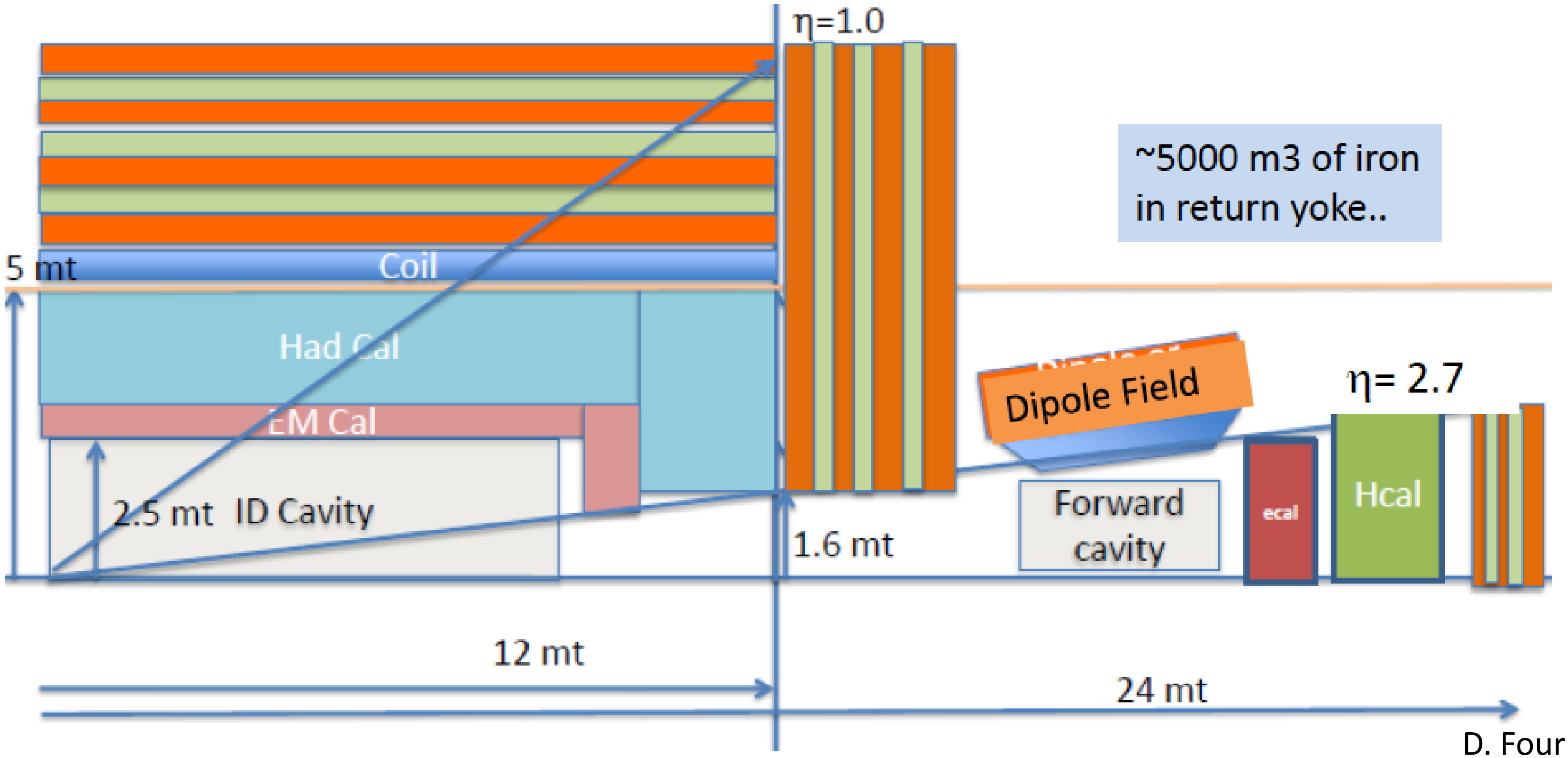
What are the changes the detectors have to cope with ?

Collisions with **larger boost** => **need more forward coverage**
- Longer barrel ?
- Increased forward η-coverage (jet coverage up to η=6?)

Cope with **higher particle/jet energies for interesting physics**
- Larger tracker (muon system) radius and/or higher B-field
- Deeper calorimetry for less leakage (~2 Λ_i extra)
- (Muon energy loss)

Issues of background suppression and radiation levels 14 TeV => 100 TeV:
- 25% increase of pp cross section
- Charged multiplicity will go up by ~50%
- Average p_t will go up by ~1/3 (from 0.6 GeV to 0.8 GeV)
- One can expect factor 2 increase in fluence and dose levels at first pixel layer

first thoughts on FHC detectors



~5000 m3 of iron in return yoke..

D. Fournier et al.

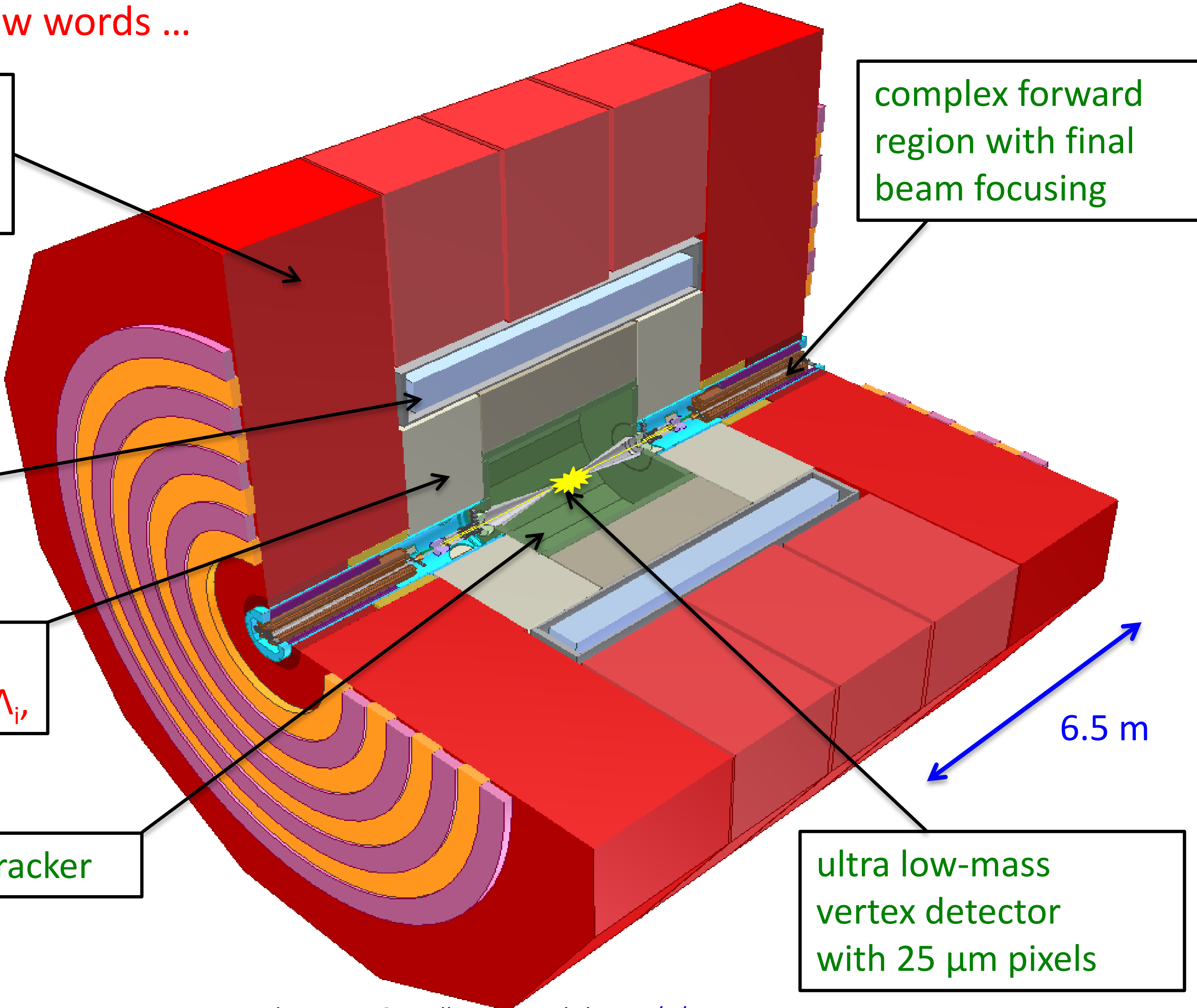
↑ a first iteration on dimensions:

- To achieve physics performance for high-E objects
- Increased forward coverage up to ~η=6
- without extrapolation on detector technology/precision capabilities

Room for smart ideas and use of new technologies !

CLIC detector concept

… in a few words …



return yoke with Instrumentation for muon ID

complex forward region with final beam focusing

strong solenoid 4 T - 5 T

fine grained (PFA) calorimetry, 1 + 7.5 Λ_i,

all-silicon tracker

ultra low-mass vertex detector with 25 µm pixels

Vertex/tracker technologies

Overall challenges:

More accuracy:

- Small cell sizes
- Low-mass
  - => Low power
  - => Interconnects: high-density + vertical

Integrated designs, including:

- Low-mass supports
- Cooling
- Power delivery
- Signal transmission

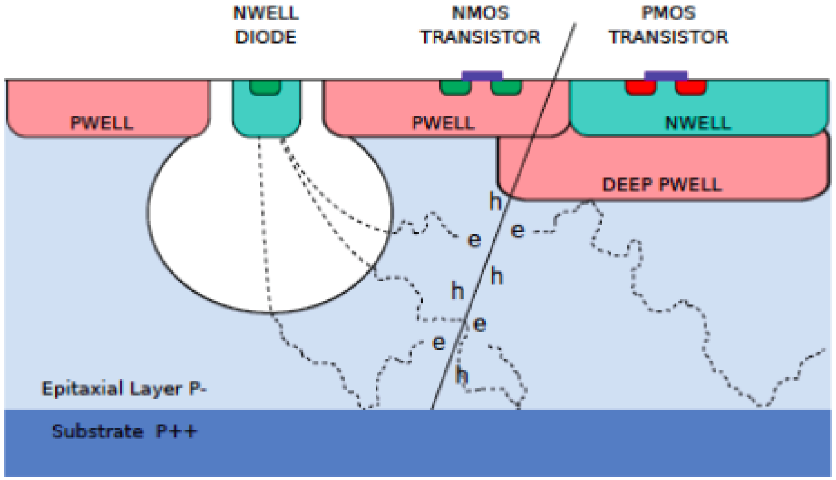
Manufacturability in large areas at low cost

Move away from most expensive elements (e.g. silicon sensors, bump-bonding)

Radiation hardness (for pp case)

A few technology examples on the next slides

Vertex detector: monolithic CMOS (ILC)



Monolithic sensor, CMOS process
high-resistivity in thin epitaxial layer

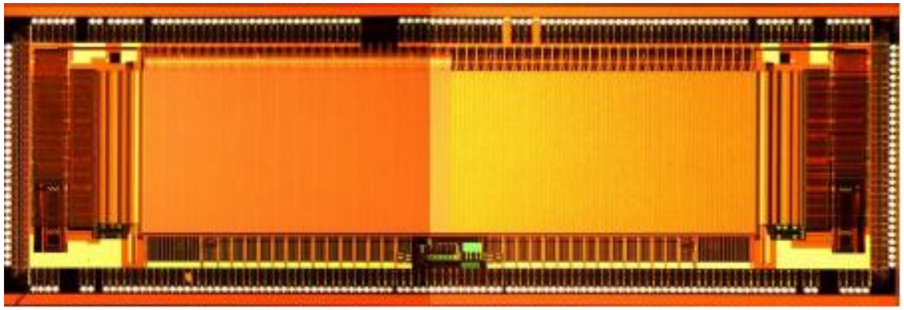
- Fast signal component (drift)
- Electronics integrated in pixel
- Rolling shutter read-out (coarse timing)
- Analog or digital readout possible

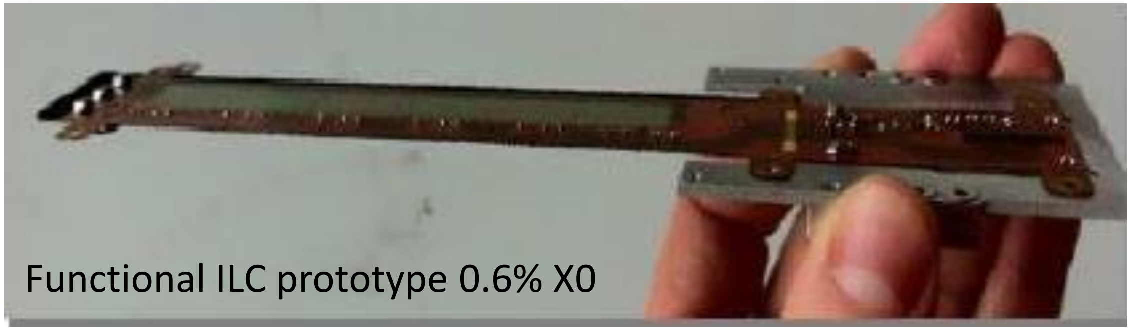
2 types of sensors for inner and outer layers

MIMOSA-30 : Dual sided readout out →

- 1 side for spatial resolution (16x16 µm pixel),
- 1 side for timing (~10µs, 16x64 µm pixel)

MIMOSA-31 : Larger pixel for reduced power consumption (35x35 µm)

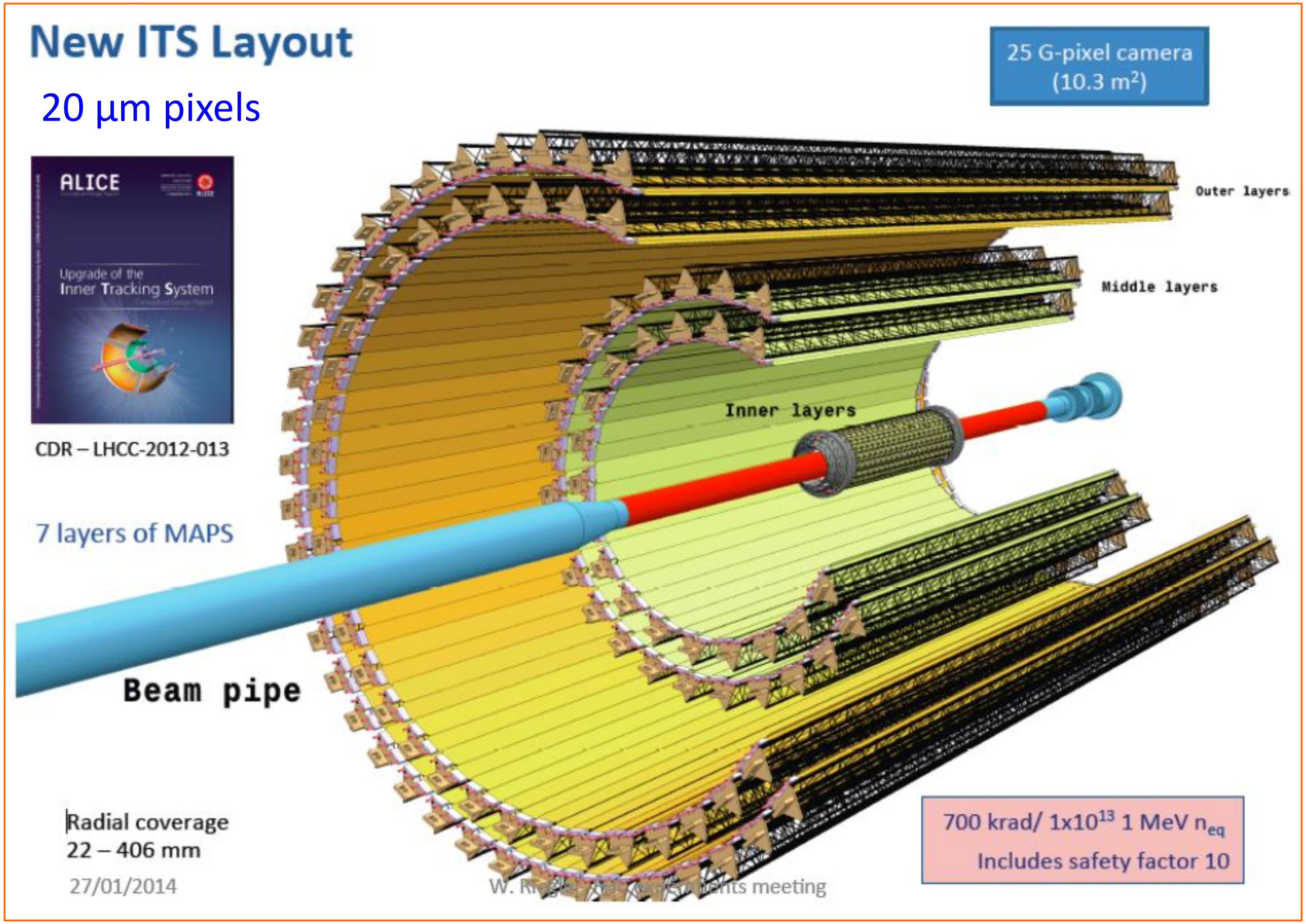




Functional ILC prototype 0.6% X0

Monolithic pixels => ALICE ITS

From ILC designs + RHIC detector to ALICE upgrade for 2018



New ITS Layout

20 µm pixels

25 G-pixel camera
(10.3 m^2)

CDR – LHCC-2012-013

7 layers of MAPS

Radial coverage
22 – 406 mm

700 krad/ $1x10^{13}$ 1 MeV n_{eq}
Includes safety factor 10

27/01/2014

W. R[illegible]ents meeting

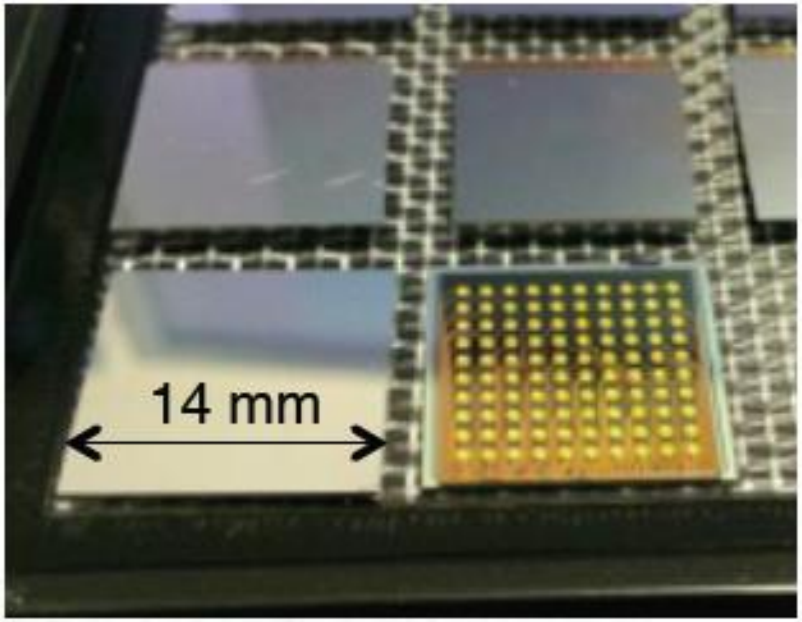
For CLIC and FHC would need increased rate and increased radiation hardness

Through Silicon Vias (TSV)

Through Silicon Via (TSV)

Vertical electrical connection passing through Si wafer

- eliminates need for wirebonds
- 4-side buttable chip/sensor assemblies
- large active surfaces => less material



- 240 µm TSV diameter
- wafers thinned to 120 µm
- 5 µm copper layer for TSV

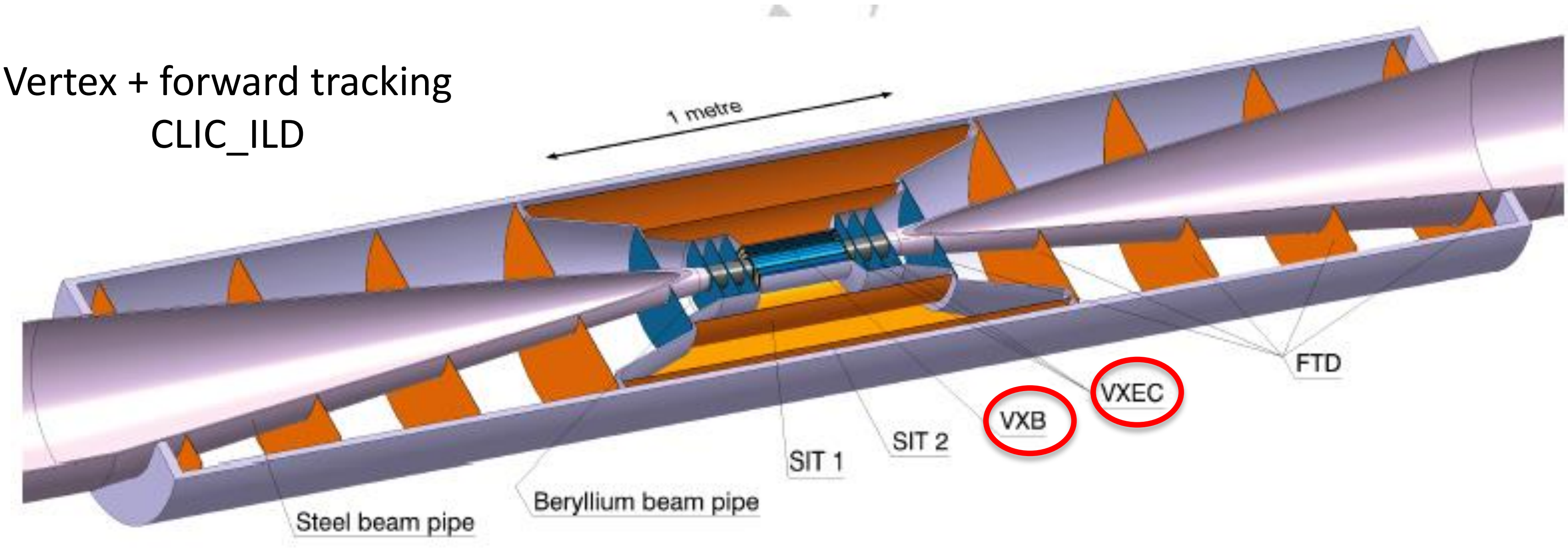
E.g. **Medipix TSV project** (ALICE / CLIC / ACEOLE / AIDA) with CEA-Leti

- 130 nm IBM Medipix(RX) wafers, **via-last process**
- successful completion of first phase: *demonstrate feasibility*
- on-going second phase: *demonstrate good yield*
- Next phase: with Timepix3 and thin sensors

First Medipix3 Image taken with TSV assembly

CLIC vertex detector

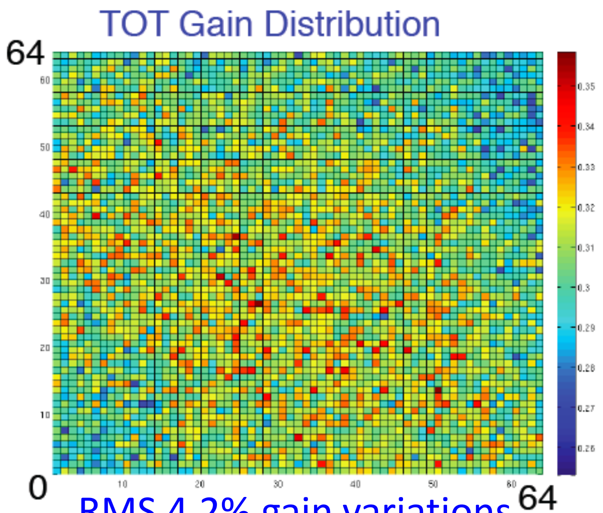
Vertex + forward tracking
CLIC_ILD



- ~25×25 µm pixel size => ~2 Giga-pixels
- 0.2% X_0 material per layer <= very thin !
  - Very thin materials/sensors
  - Low-power design, power pulsing, air cooling
  - Aim: 50 mW/cm^2
- Time stamping 10 ns
- Radiation level <10^{11} $n_{eq}cm^{-2}year^{-1}$ <= 10^4 lower than LHC

CLIC vertex detector R&D (1)

Hybrid approach pursued: (<= other options possible)
- Thin (~50 µm) silicon sensors
- Thinned high-density ASIC
  - R&D within Medipix/Timepix effort
- Low-mass interconnect
  - Micro-bump-bonding (Cu-pillar option)
  - Through-Silicon-Vias (R&D with CEA-Leti)
- Power pulsing
- Air cooling

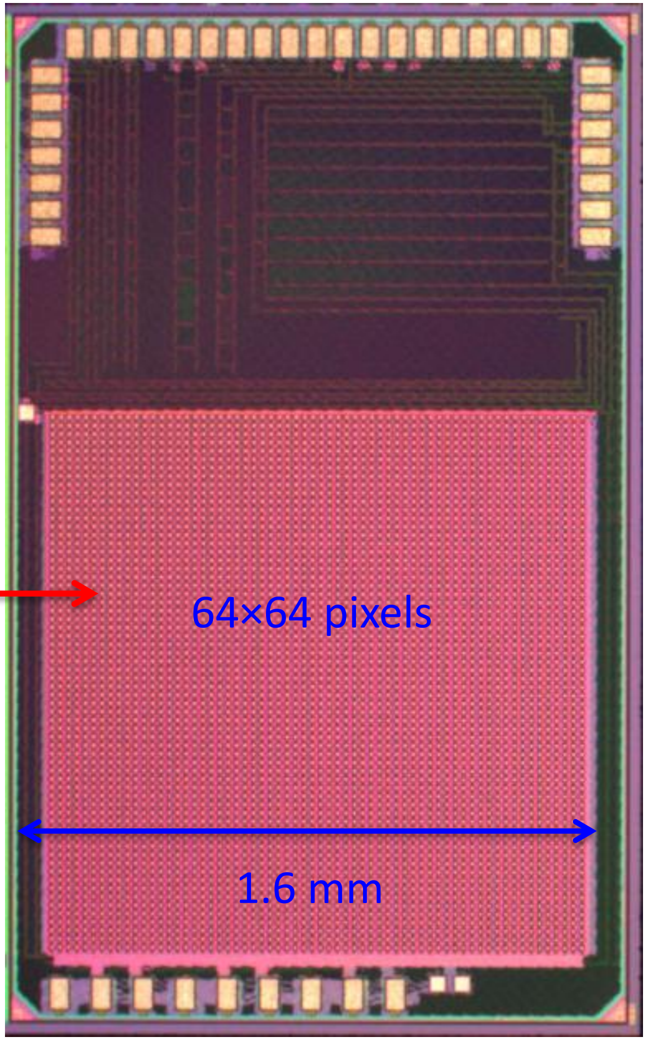


RMS 4.2% gain variations

CLICpix demonstrator

64×64 pixels, fully functional
- 65 nm technology
- 25×25 µm^2 pixels
- 4-bit ToA and ToT info
- Data compression
- Pulsed power: 50 mW/cm^2

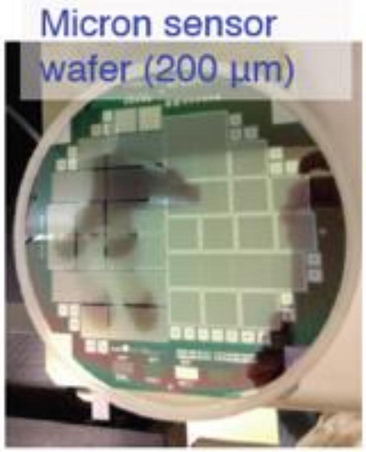
65 nm ASIC development
ATLAS, CMS, CLICdp => **RD53**



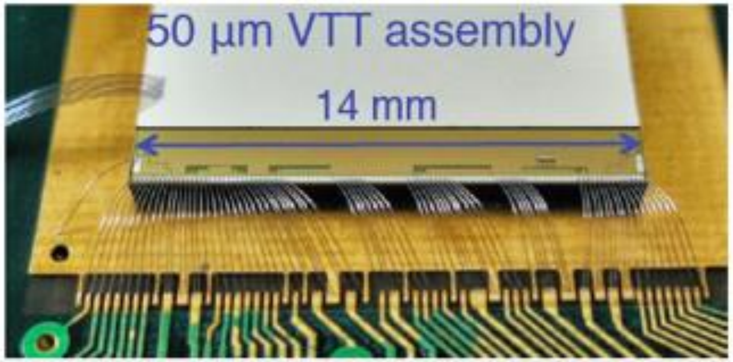
CLIC vertex detector R&D (2)

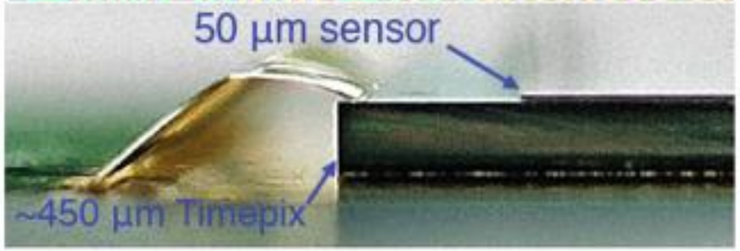
further ongoing R&D activities

thin sensors, down to 50 µm


Micron sensor wafer (200 µm)

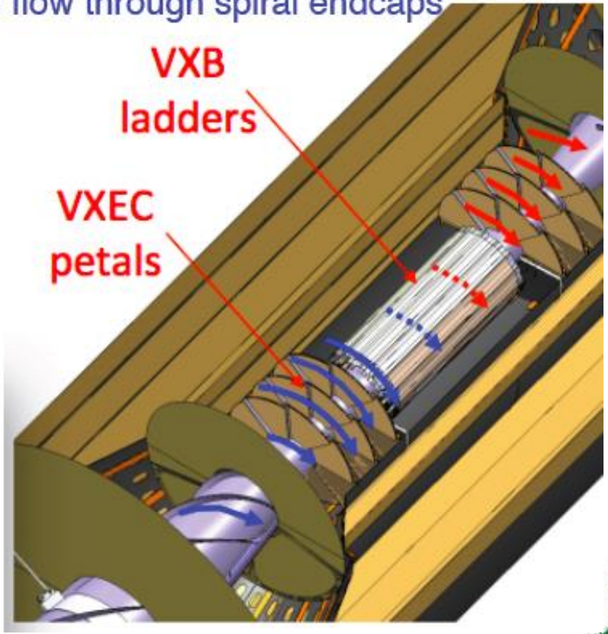

50 µm dummy wafer

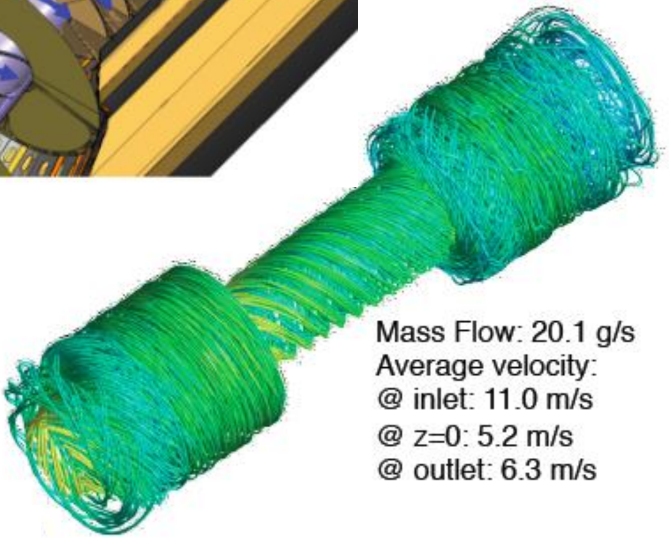

50 µm VTT assembly



power pulsing, air cooling, light supports

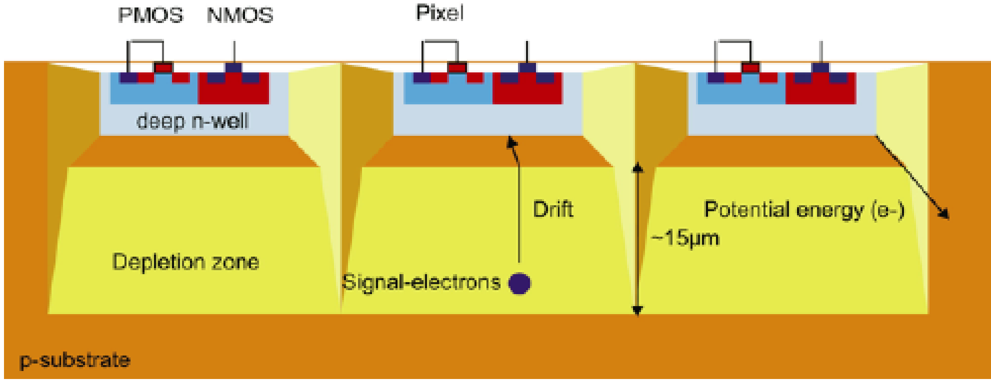
Air flow through spiral endcaps



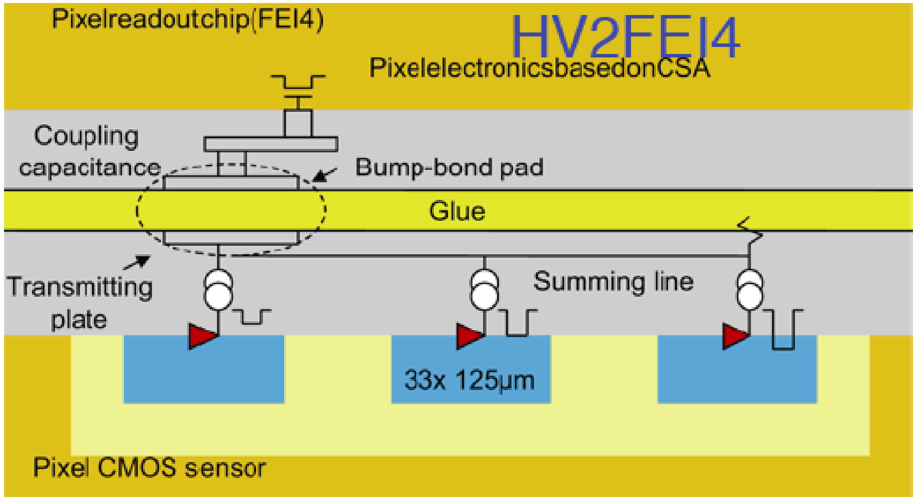

Mass Flow: 20.1 g/s
Average velocity:
@ inlet: 11.0 m/s
@ z=0: 5.2 m/s
@ outlet: 6.3 m/s

Watching other R&D, e.g. micro-channel cooling

Hybrid detector with HV-CMOS



HV-CMOS MAPS:
- 180 nm High Voltage process
- V_{bias} ~100 V, 10-20 µm depletion layer
- Integrated sensors, fast signal collection

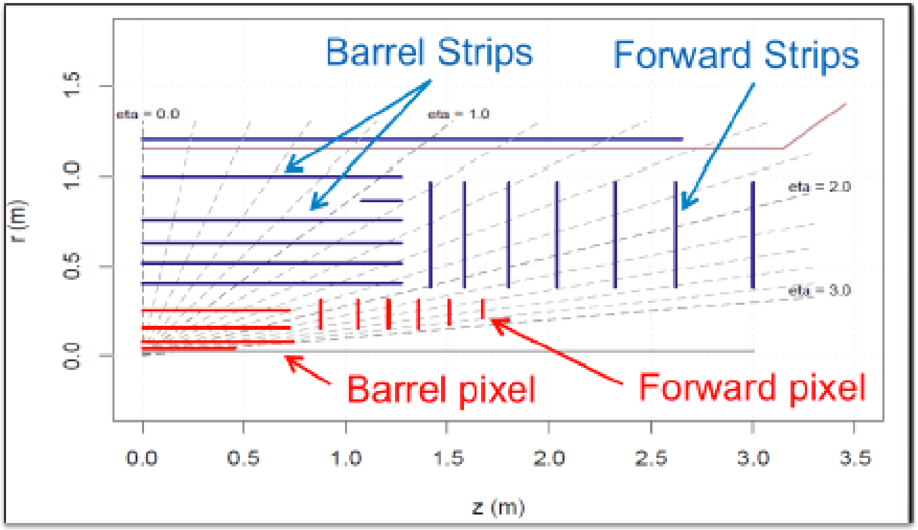


Hybrid option:

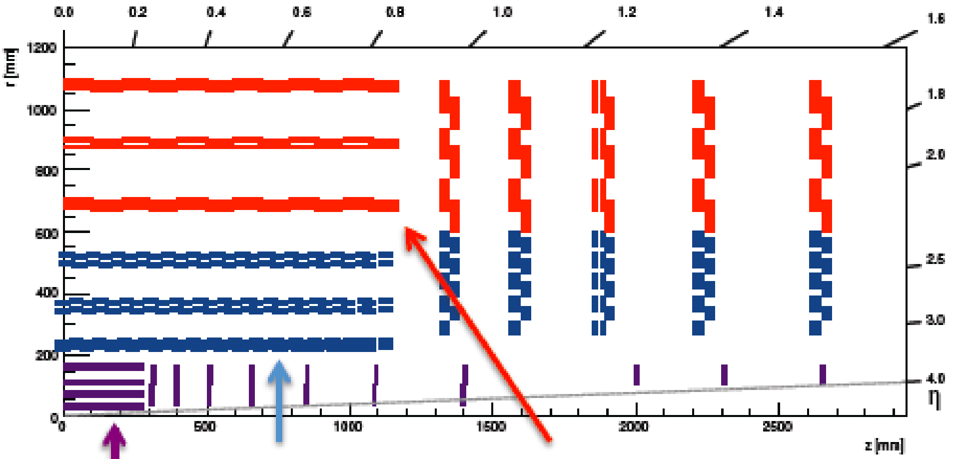
Capacitive Coupled Pixel Detector (CCPD)
- HV CMOs chip as integrated sensor+ amplifier
- Capacitive coupling to readout chip through layer of glue => no bump bonding
- Ongoing R&D with FEI4, Timepix, CLICpix

HL-LHC tracker upgrades

ATLAS design

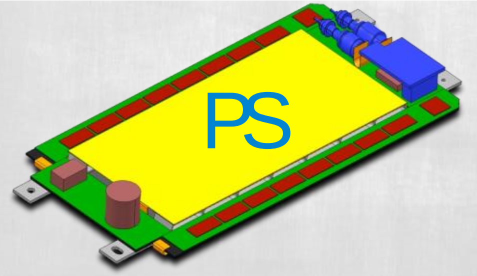


CMS design



Pixels - Macro-Pixel/Strip & Strip/Strip modules

Macro-pixel / Strip module



2.4 cm long strips + pixels
100 μm pitch
P = 5.01 W
~ 44 cm^2 active area

Upgrades	Area	Baseline sensor type
ALICE ITS	12 m^2	CMOS
LHCb VELO	0.15 m^2	tbd
LHCb UT	5 m^2	n-in-p
ATLAS Strips	193 m^2	n-in-p
CMS Strips	218 m^2	n-in-p
ATLAS Pixels	8.2 m^2	tbd
CMS Pixels	4.6 m^2	tbd

"large tracker pixels" also needed for CLIC
With smaller granularity and less mass

Calorimeter technologies

Overall challenges:

More accuracy:

- Shower reconstruction of particles within the jet
- Need hit-time accuracy
  - => ~1 ns for CLIC
  - => ~25 ns for LHC (ideally <200 ps for HL-LHC and FHC)

Integrated designs, involving:

- High density => little space for active layers
  - => ~2 mm in linear collider ECAL
  - => <7 mm in linear collider HCAL
- High channel count
- Low-power design
- Minimal space for cooling

Manufacturability in large areas at low cost

Radiation hardness (for pp case)

A few technology examples in the next slides

PFA calorimetry at CLIC

ECAL

Si or Scint. (active) + Tungsten (absorber)

cell sizes 13 mm^2 or 25 mm^2

30 layers in depth

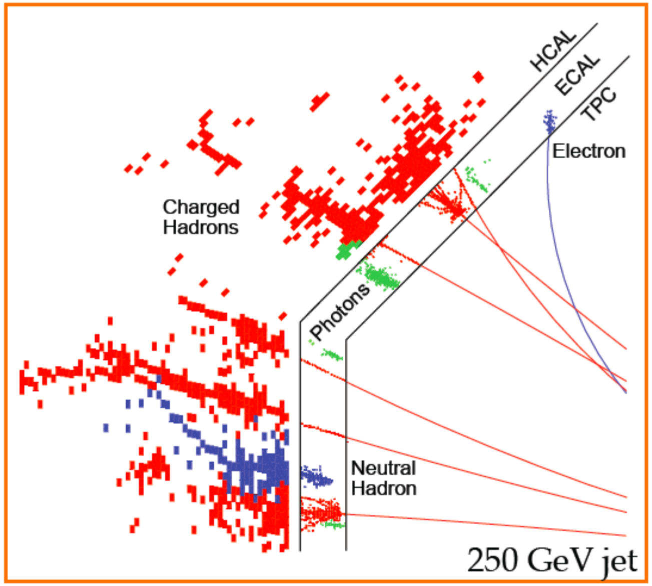
HCAL

Several technology options: scint. + gas

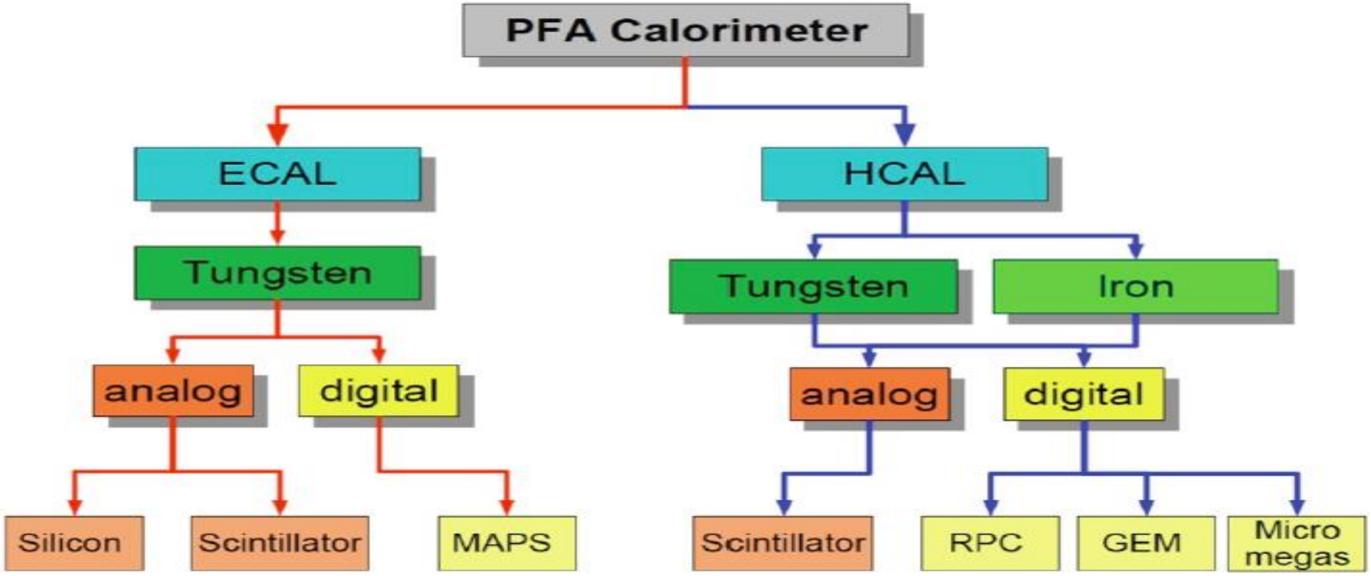
Tungsten (barrel), steel (endcap)

cell sizes 9 cm^2 (analog) or 1 cm^2 (digital)

60-75 layers in depth (HCAL depth ~7 Λ_i)



many technologies pursued



PFA Calorimeter

- ECAL
  - Tungsten
    - analog
      - Silicon
      - Scintillator
    - digital
      - MAPS
- HCAL
  - Tungsten
  - Iron
    - analog
      - Scintillator
    - digital
      - RPC
      - GEM
      - Micro megas

ECAL: Si-W (CALICE)

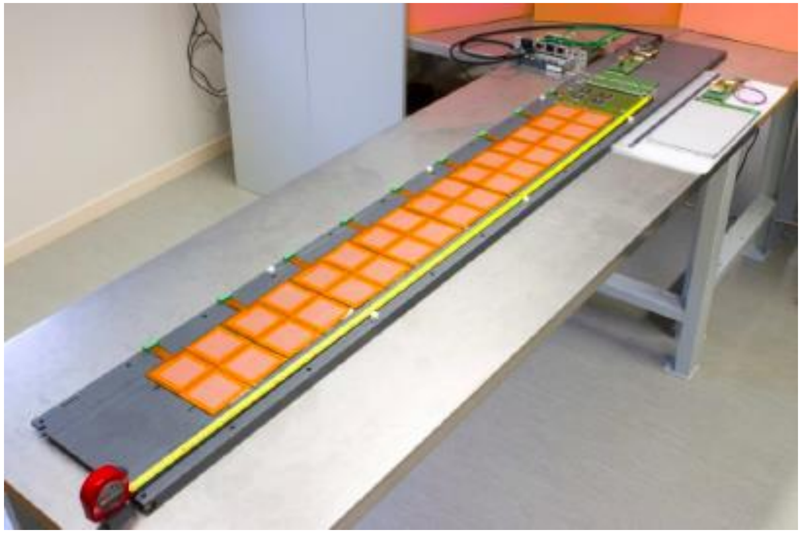
30 layers in depth

cell size 5.5x5.5mm^2

~100 M ECAL channels at ILC (ILD)

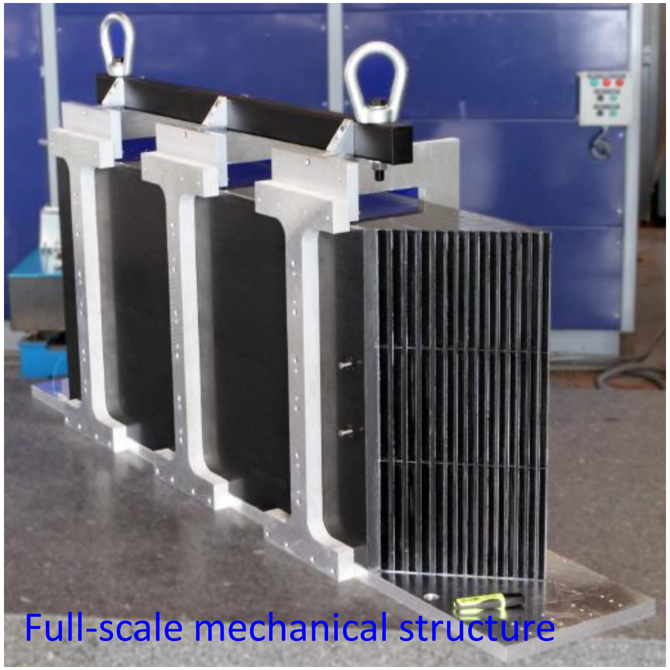
~2000 m^2 silicon

Successful beam tests

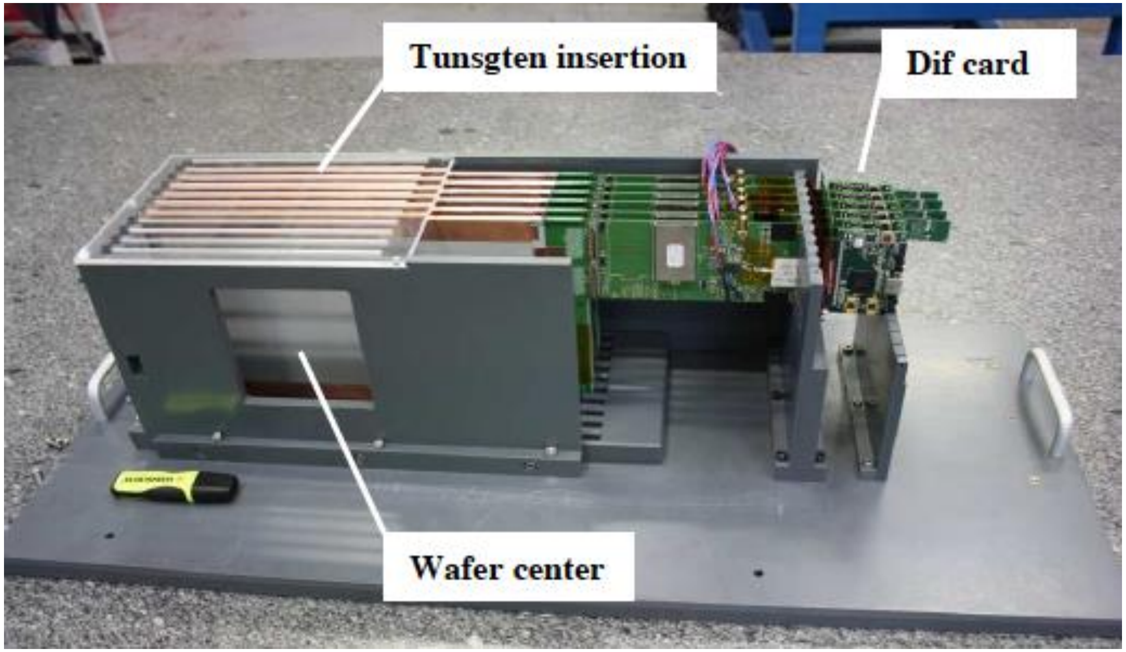


Currently: technological Si-ECAL prototype

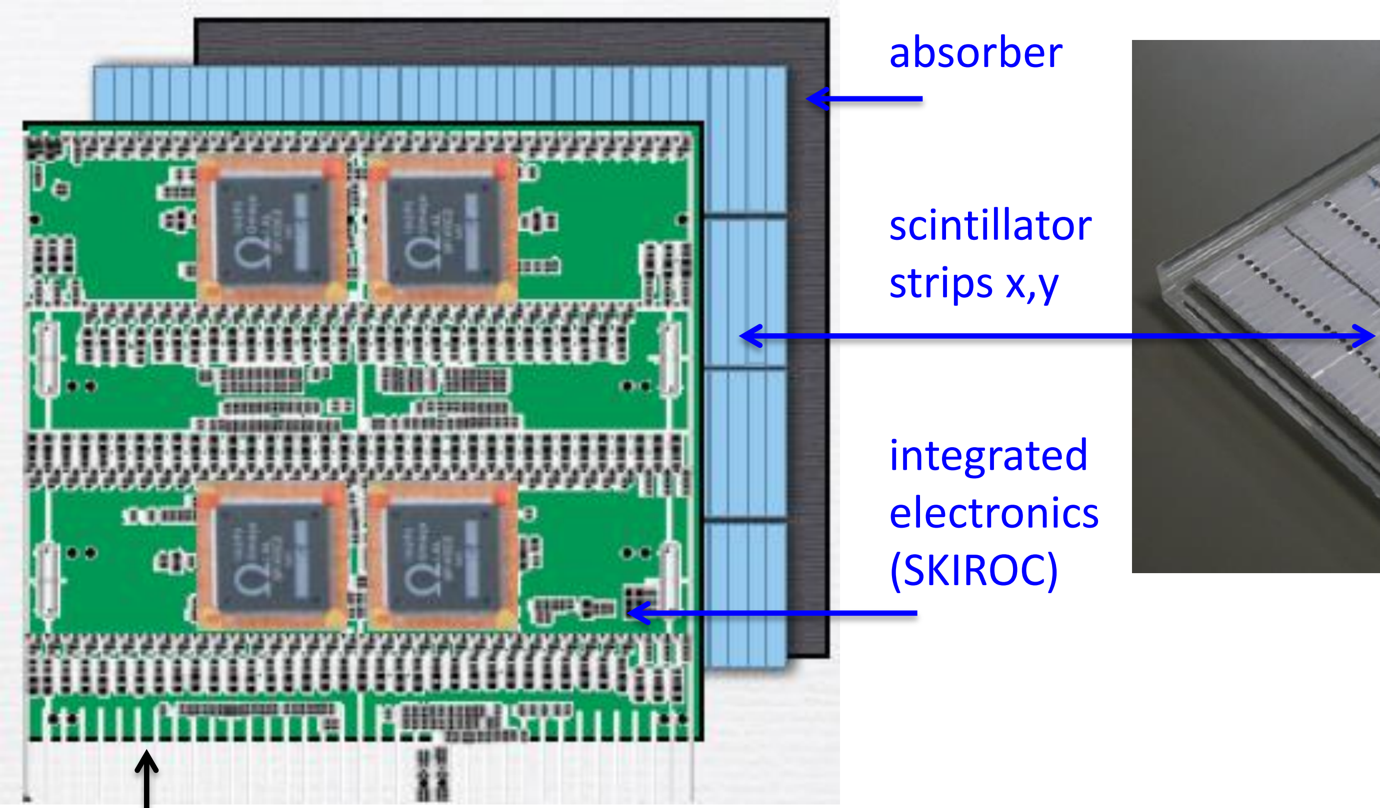
Real-scale detector integration model



Full-scale mechanical structure



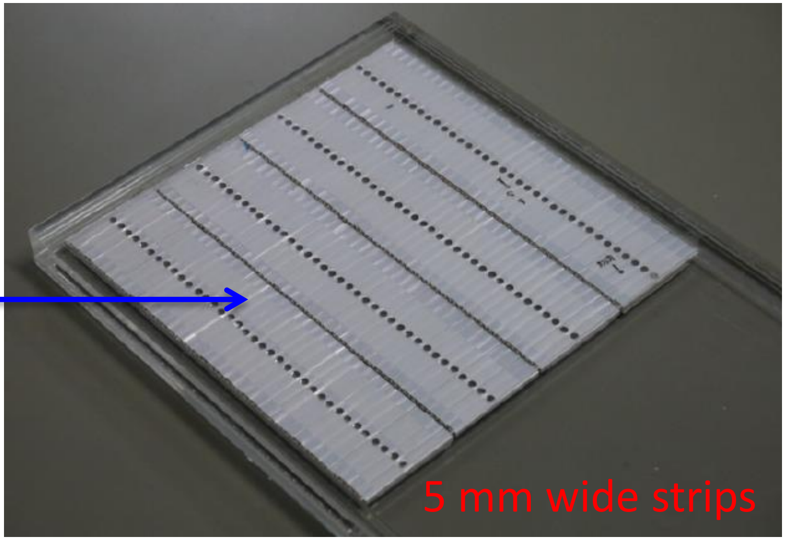
ECAL: Scint-ECAL (CALICE)



absorber

scintillator strips x,y

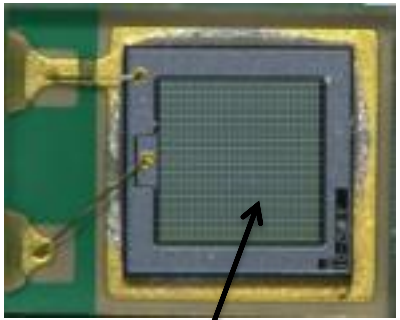
integrated electronics (SKIROC)



5 mm wide strips

Strips of 45*5*2 mm^3, 144 channels/ plane

Fully integrated modules, successful beam tests at DESY

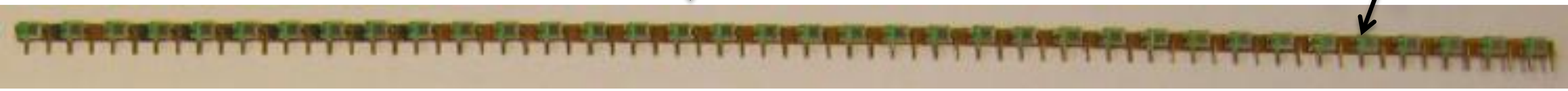


MPPC
1600 pixels
1×1 mm^2

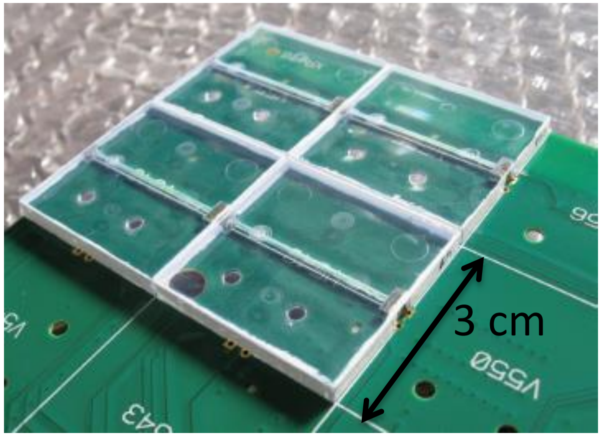
currently exploring SiPM with more pixels

1 cm

Row of MPPC (SiPM)



A-HCAL (CALICE)



3x3 cm^2 scintillator tiles with SiPMs

Integrated electronics (SPIROC chip)

LED SiPM calibration

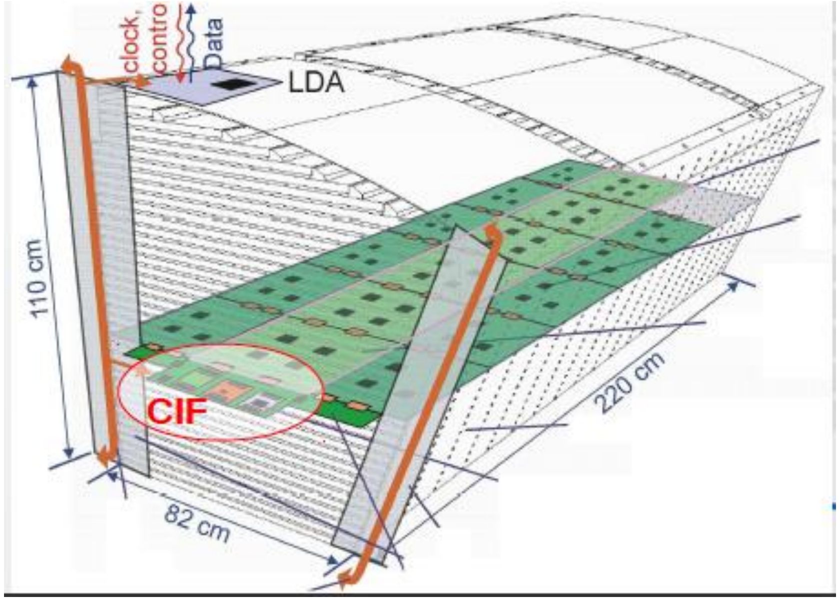
Power-pulsing

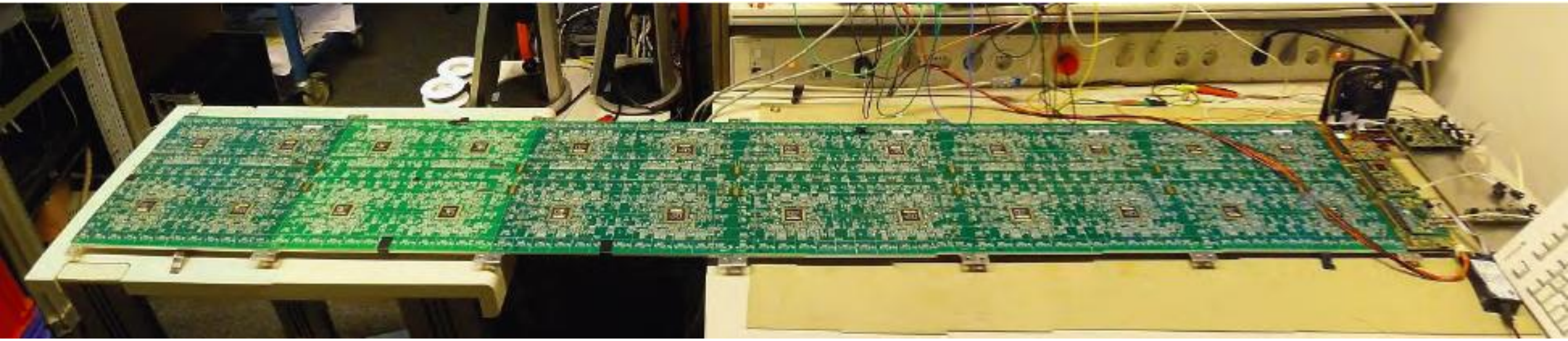
220 cm long modules

Active layer thickness of 5.4 mm

AHCAL 2nd generation fully integrated prototype

undergoing beam tests





digital DHCAL glass RPC’s (CALICE)

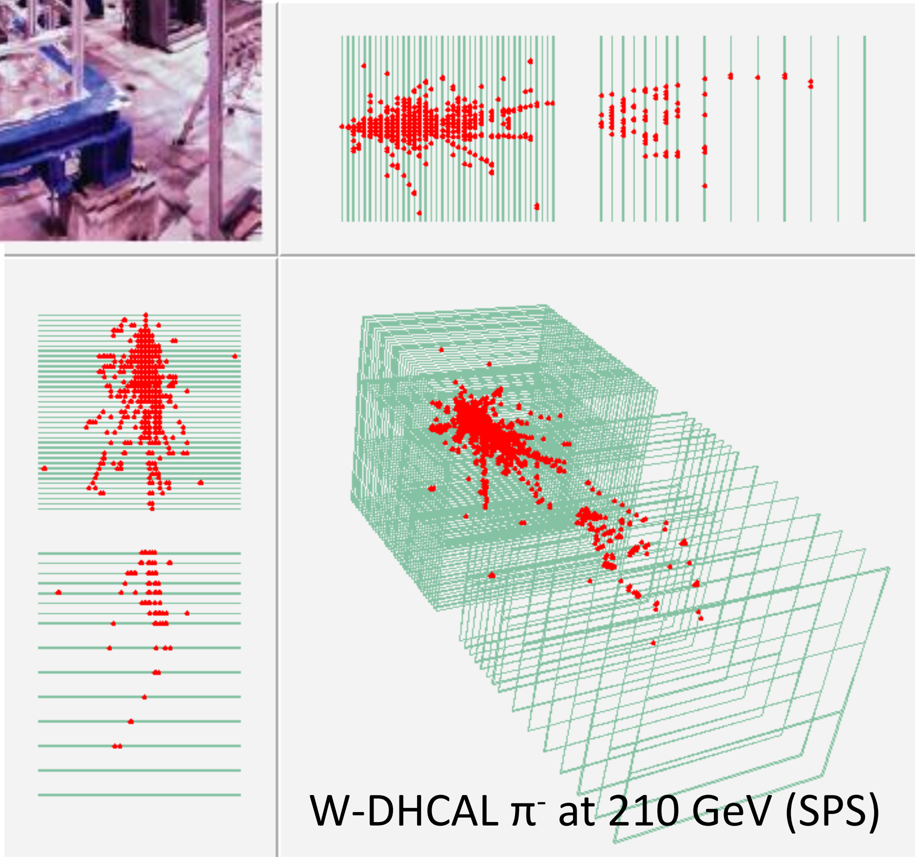
Steel DHCAL
Tungsten DHCAL
500’000 readout channels

54 glass RPC chambers, ~1m^2 each
PAD size 1×1 cm^2
Digital readout (1 threshold)
Fully integrated electronics
Total 500’000 readout channels

Ongoing R&D with lower-resistivity glass
for better rate dependence

Other large-scale protoypes:

- 1m^3 semi-digital HCAL with glass RPC’s
- 4 large (~1m^2) micromegas readout planes



W-DHCAL π^- at 210 GeV (SPS)

CLIC forward calorimetry

2 forward calorimeters: Lumical + Beamcal

Tungsten thickness 1 X_0, 40 layers

BeamCal sensors GaAs, 500 mm thick

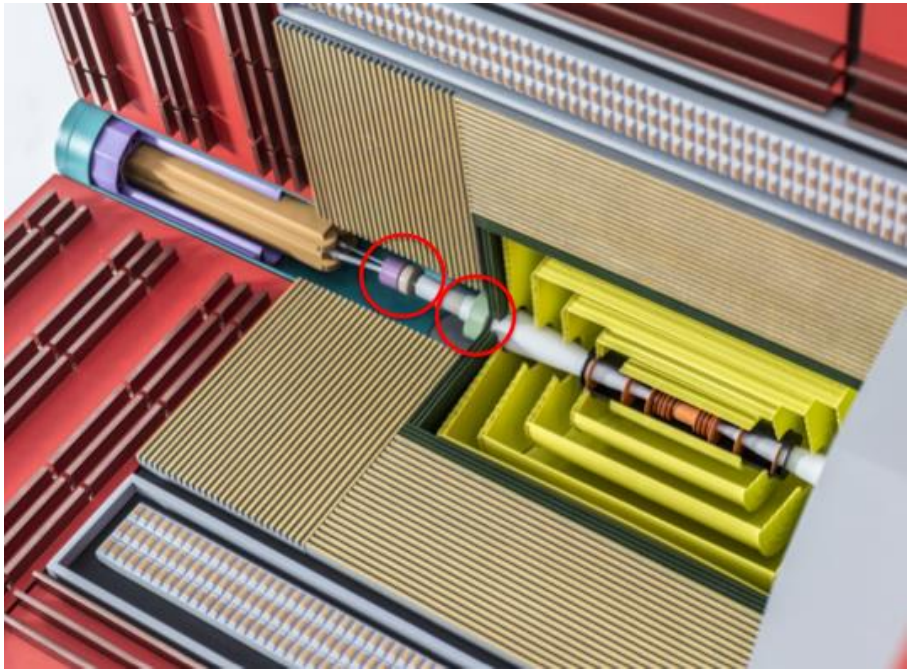
LumiCal sensors silicon, 320 mm thick

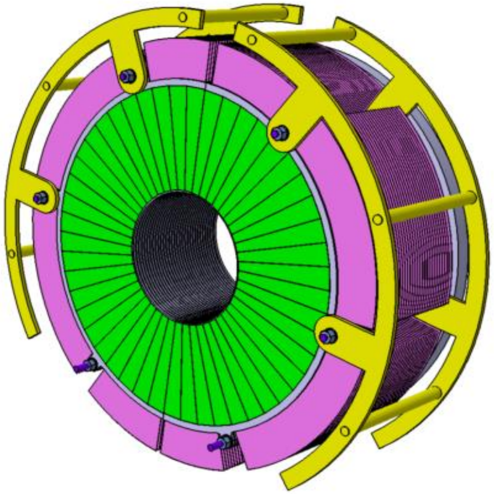
Readout at the outer radius

BeamCal angular coverage 10 - 40 mrad

LumiCal coverage 38 – 110 mrad

- doses up to 1 Mgy
- neutron fluxes of up to 10^{14} per year



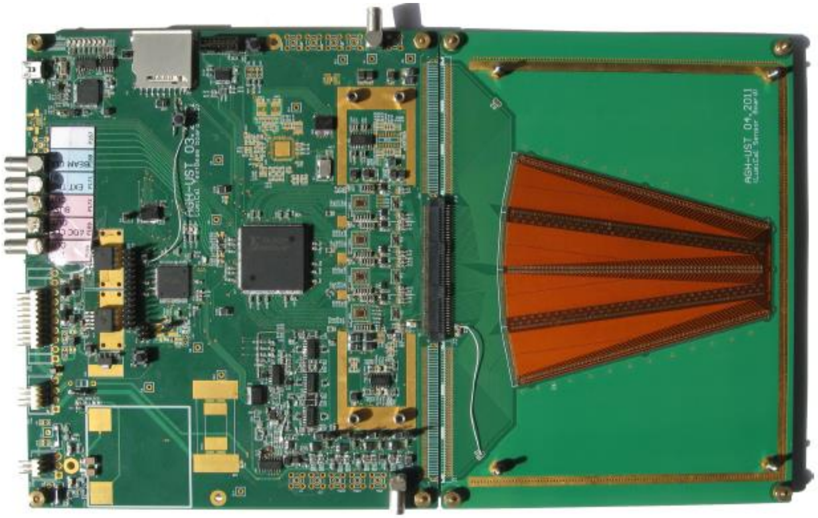


Very compact !

Active layer gap is 0.8 mm

Moliere radius 11 mm

high-radiation performance
=> collaboration with LHC beam monitors

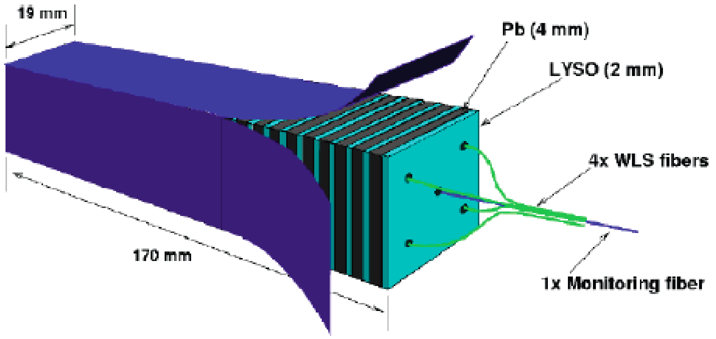


HL-LHC CMS end cap calorimetry

Potential replacement of the CMS end-cap calorimetry (EE+HE)

Main motivation:

- Radiation resistance
- Extension of the η-coverage (for jets from VBF)



Shashlik concept

Several detector options

They represent a nice illustration of recent technology advances

- **Shashlik design**
  - Radiation-hard scintillators (e.g. crystal scintillator for EE)
- **Dual fiber read-out**: scintillation & Cerenkov – following work of DREAM/RD52
  - using doped/crystal fibers => allows e/h correction
- **Fine-grained Particle Flow Calorimeter** – following work of CALICE
  - active layers GEM/Micromegas or Silicon => detailed jet reconstruction

Possible common pp/e^+e^- development areas

Non-exhaustive, to be completed

- **Vertex+tracking detector technology**
  - R&D in integrated hybrid detectors (including developments with HV-CMOS)
  - Advanced radiation-hard microelectronics
  - Interconnect technologies
  - Low-mass engineering
  - Low-mass detector cooling (e.g. microcooling options)
  - Detector powering
  - New low-mass solutions with small strips / large pixels
- **Fine-grained calorimetry**
  - Optimisation of jet energy resolution + bkg suppression with PFA
  - Compact, large area detectors
- **Overall detector engineering aspects and large+strong detector magnets**
- **Simulation tools and methods**
  - Flexible detector geometry descriptions for simulations in detector optimisation phase
  - PFA-like event reconstruction tools
  - Jet clustering

Summary/outlook

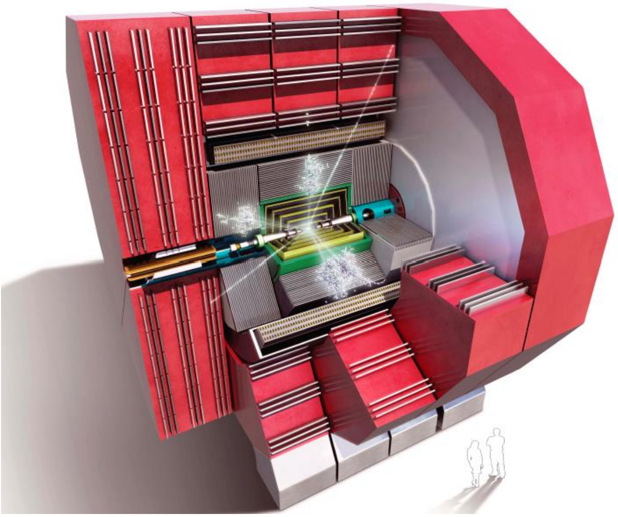
Many exciting detector R&D projects for high-energy e+e- and pp !

Collaborative efforts, creativity, perseverance and new technologies help to overcome challenges

When comparing e+e- with pp: many challenges are common, others diverge

In most cases, basic technology advances can be carried out in common

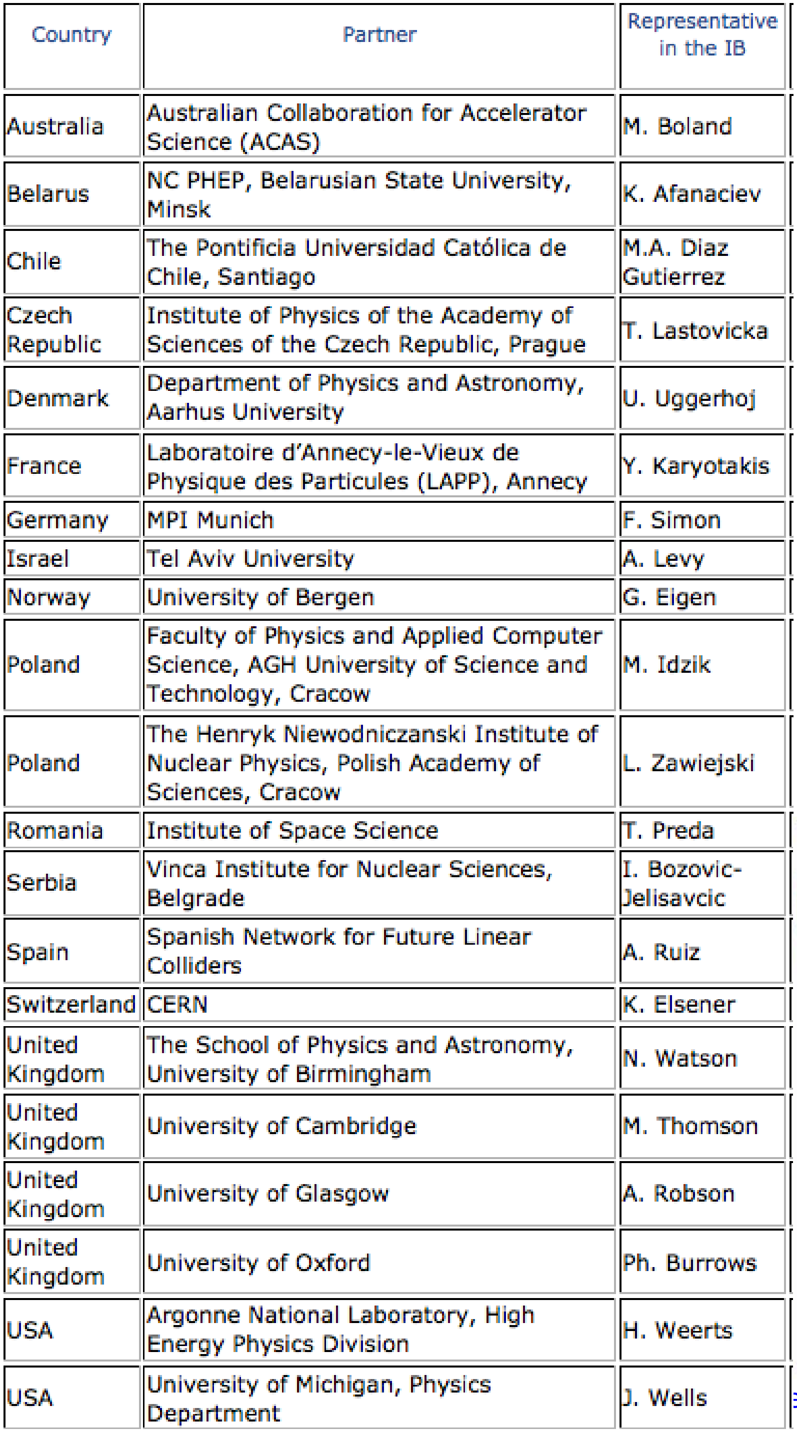
Implementations are nearly always application-specific



thank you

SPARE SLIDES

CLIC detector and physics study



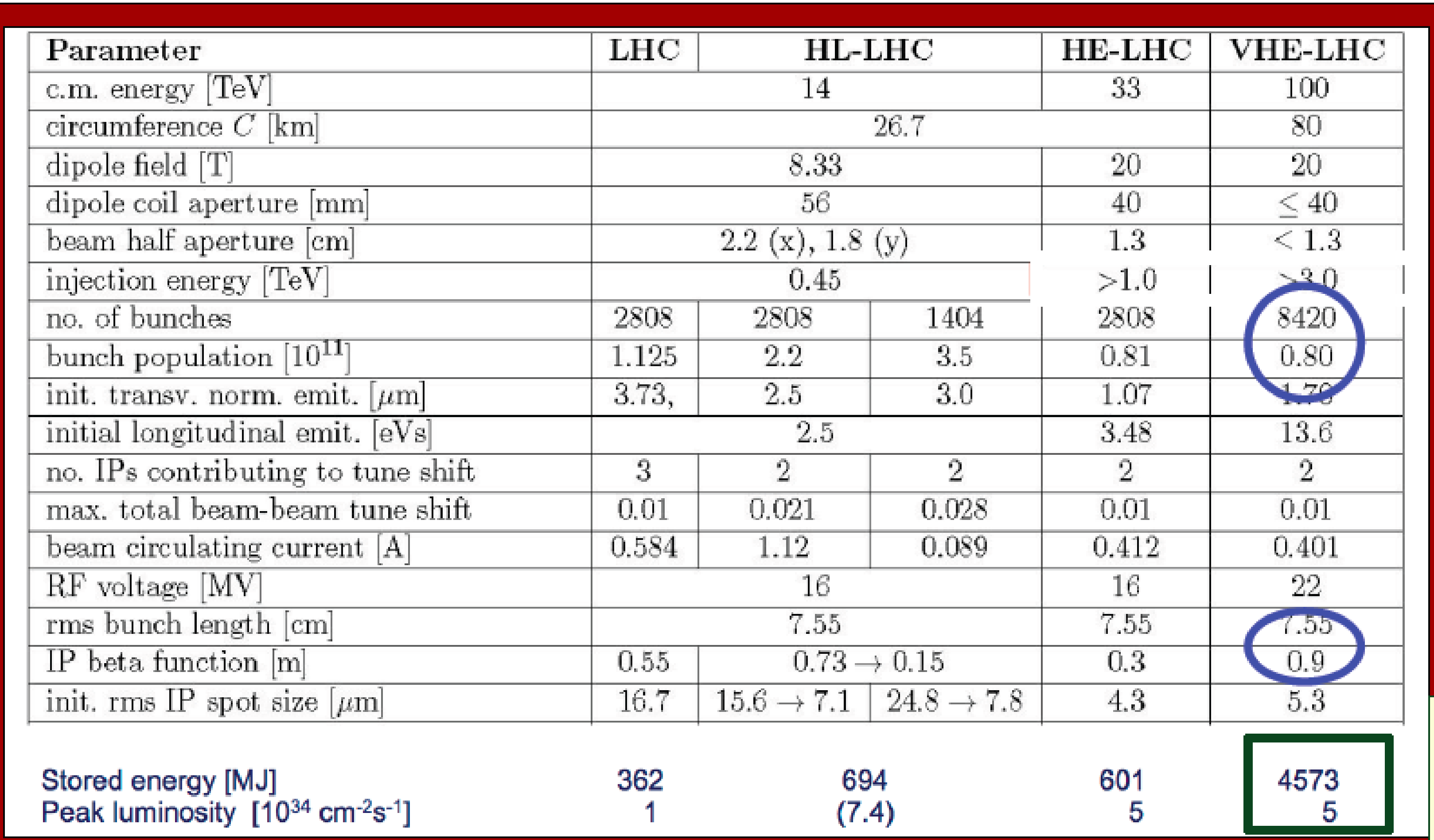
Country	Partner	Representative in the IB
Australia	Australian Collaboration for Accelerator Science (ACAS)	M. Boland
Belarus	NC PHEP, Belarusian State University, Minsk	K. Afanaciev
Chile	The Pontificia Universidad Católica de Chile, Santiago	M.A. Diaz Gutierrez
Czech Republic	Institute of Physics of the Academy of Sciences of the Czech Republic, Prague	T. Lastovicka
Denmark	Department of Physics and Astronomy, Aarhus University	U. Uggerhoj
France	Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Annecy	Y. Karyotakis
Germany	MPI Munich	F. Simon
Israel	Tel Aviv University	A. Levy
Norway	University of Bergen	G. Eigen
Poland	Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, Cracow	M. Idzik
Poland	The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow	L. Zawiejski
Romania	Institute of Space Science	T. Preda
Serbia	Vinca Institute for Nuclear Sciences, Belgrade	I. Bozovic-Jelisavcic
Spain	Spanish Network for Future Linear Colliders	A. Ruiz
Switzerland	CERN	K. Elsener
United Kingdom	The School of Physics and Astronomy, University of Birmingham	N. Watson
United Kingdom	University of Cambridge	M. Thomson
United Kingdom	University of Glasgow	A. Robson
United Kingdom	University of Oxford	Ph. Burrows
USA	Argonne National Laboratory, High Energy Physics Division	H. Weerts
USA	University of Michigan, Physics Department	J. Wells

Light-weight cooperation structure
No engagements, on best-effort basis
With strong collaborative links to ILC

http://lcd.web.cern.ch/LCD/Home/MoC.html

CLICdp: 21 institutes

pp table of comparison



Parameter	LHC	HL-LHC		HE-LHC	VHE-LHC
c.m. energy [TeV]	14			33	100
circumference C [km]	26.7				80
dipole field [T]	8.33			20	20
dipole coil aperture [mm]	56			40	≤ 40
beam half aperture [cm]	2.2 (x), 1.8 (y)			1.3	< 1.3
injection energy [TeV]	0.45			>1.0	>3.0
no. of bunches	2808	2808	1404	2808	8420
bunch population [10^{11}]	1.125	2.2	3.5	0.81	0.80
init. transv. norm. emit. [μm]	3.73,	2.5	3.0	1.07	1.79
initial longitudinal emit. [eVs]	2.5			3.48	13.6
no. IPs contributing to tune shift	3	2	2	2	2
max. total beam-beam tune shift	0.01	0.021	0.028	0.01	0.01
beam circulating current [A]	0.584	1.12	0.089	0.412	0.401
RF voltage [MV]	16			16	22
rms bunch length [cm]	7.55			7.55	7.55
IP beta function [m]	0.55	0.73 → 0.15		0.3	0.9
init. rms IP spot size [μm]	16.7	15.6 → 7.1	24.8 → 7.8	4.3	5.3
Stored energy [MJ]	362	694		601	4573
Peak luminosity [10^{34} cm^{-2}s^{-1}]	1	(7.4)		5	5

Average pile-up: ~140/xing

Assume:

Luminosity 5x10^{34} in 25ns or 5ns bunch spacing.

Integrate 3000fb-1.

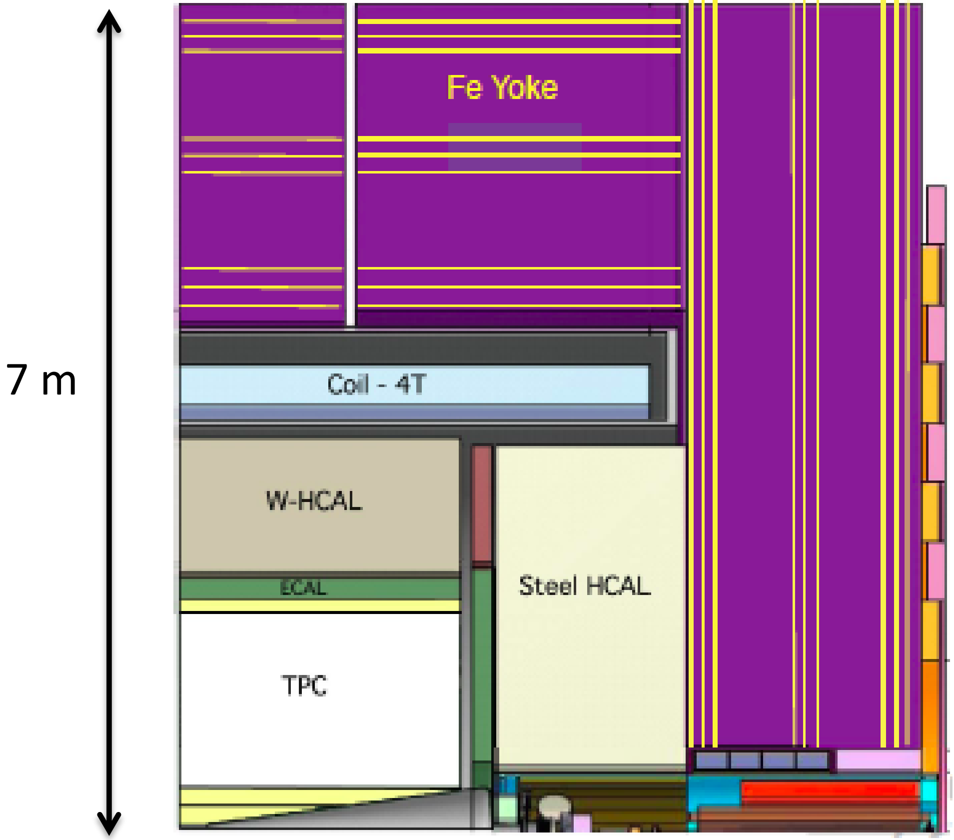
CLIC_ILD and CLIC_SiD

Two general-purpose CLIC detector concepts

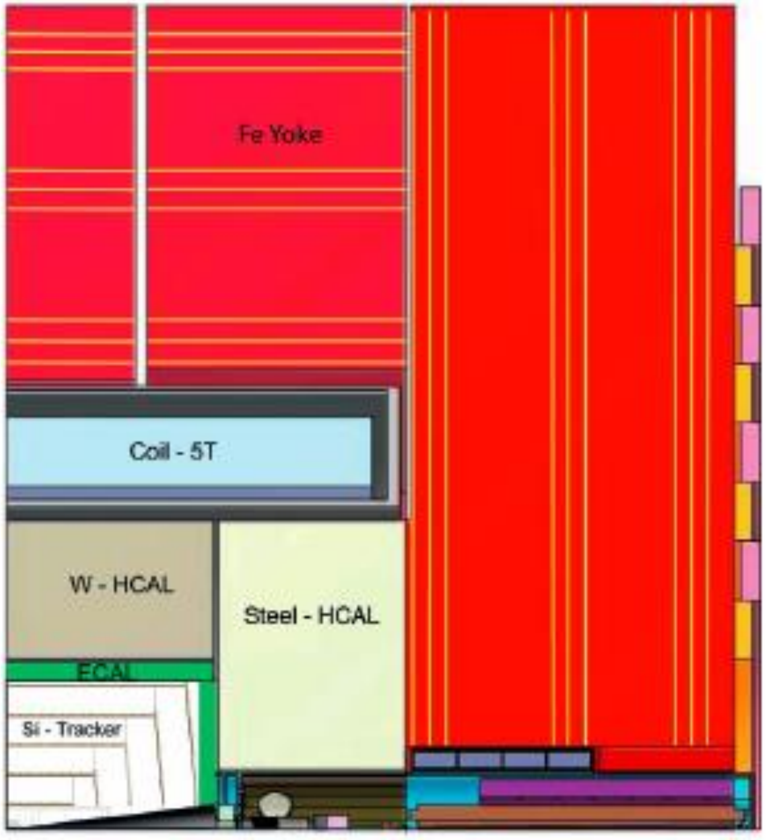
Based on initial ILC concepts (ILD and SiD)

Optimised and adapted to CLIC conditions

CLIC_ILD



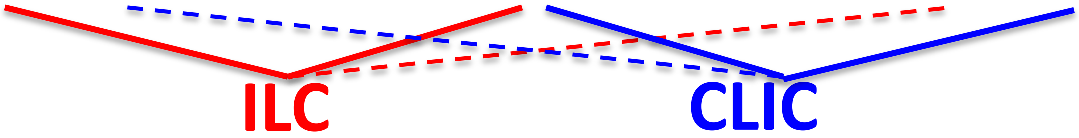
CLIC_SiD



Vertex detectors

Categories of candidate technologies

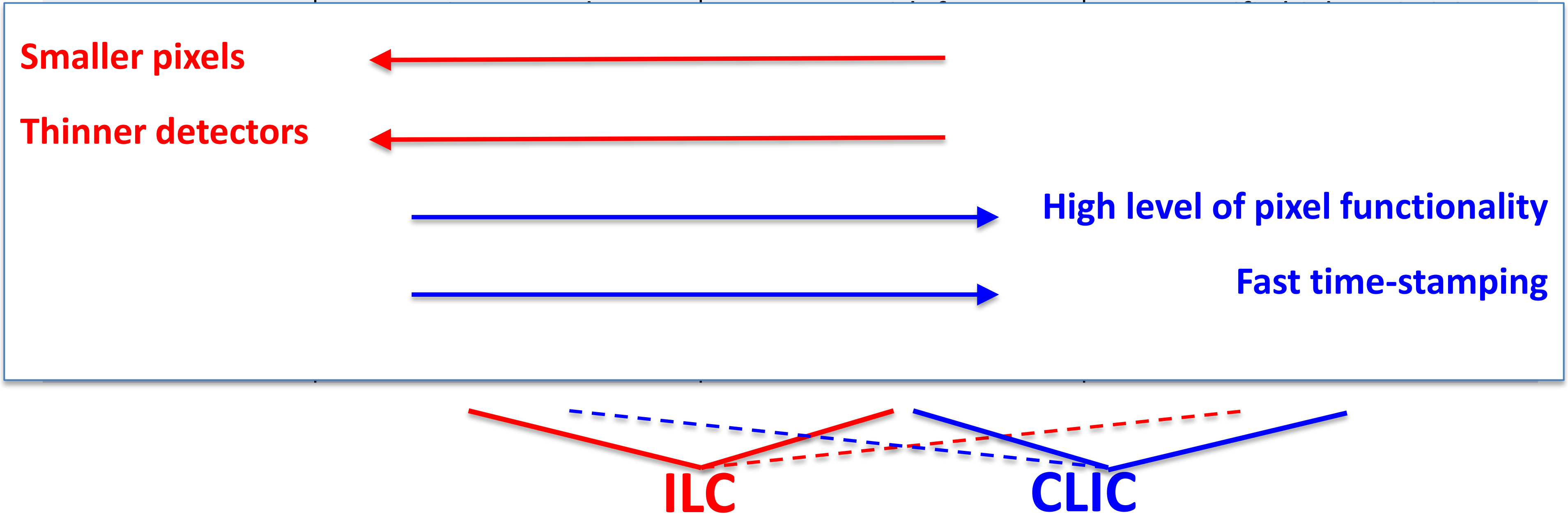
	Monolytic CMOS	**(3D) integrated**	**Hybrid pixel**
Examples	DEPFET, FPCCD, MAPS, HV-CMOS	SOI MIT-LL, Tezzaron, Ziptronix	CLICpix (TimePix3, Smallpix)
Technology	Specialised HEP processes, r/o and sensors integrated	Customized niche industry Processes with focus on Interconnectivity	Industry standard ASIC processes; HEP-specific high-resistivity sensors
Depletion layer	Partial	Partial or full	Full => large fast signals
Granularity	Down to 5 µm pixel size	Down to 5 µm pixel size	25 µm pixel size
Thickness	~50 µm total thickness achievable	~50 µm total thickness achievable	~50 µm sensor + ~50 µm r/o



Vertex detectors

Categories of candidate technologies

	Monolytic CMOS	(3D) integrated	Hybrid pixel
Examples	DEPFET, FPCCD, MAPS, HV-CMOS	SOI MIT-LL, Tezzaron, Ziptronix	CLICpix (TimePix3, Smallpix)
Technology	Specialised HEP processes, r/o and	Customized niche industry	Industry standard ASIC processes;

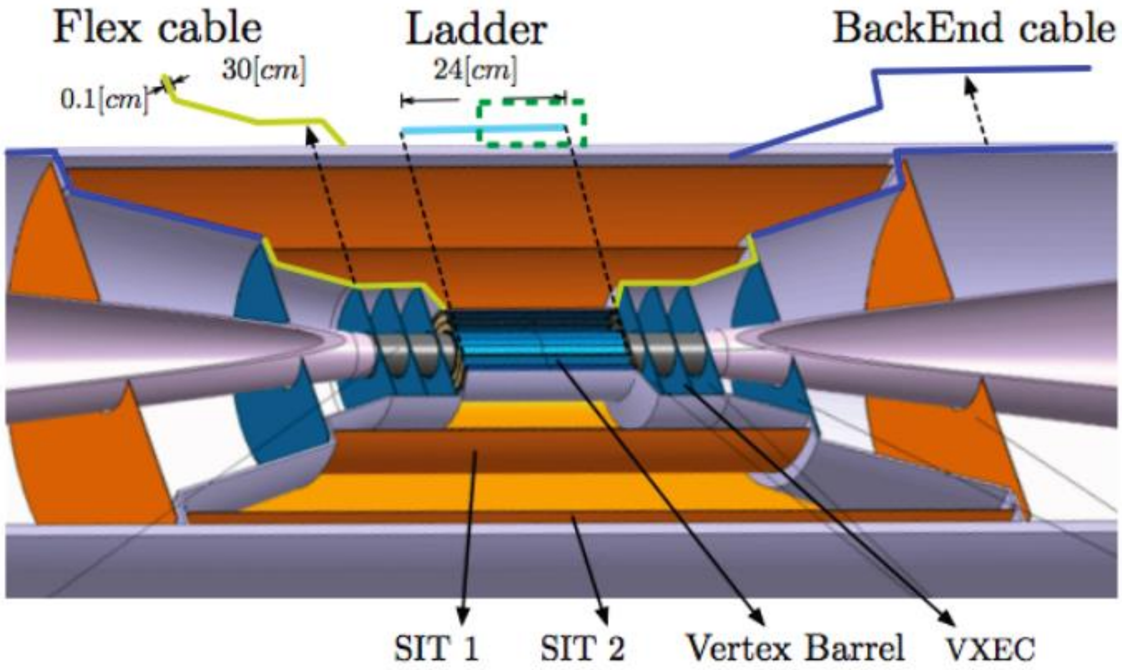

Smaller pixels

Thinner detectors

High level of pixel functionality

Fast time-stamping

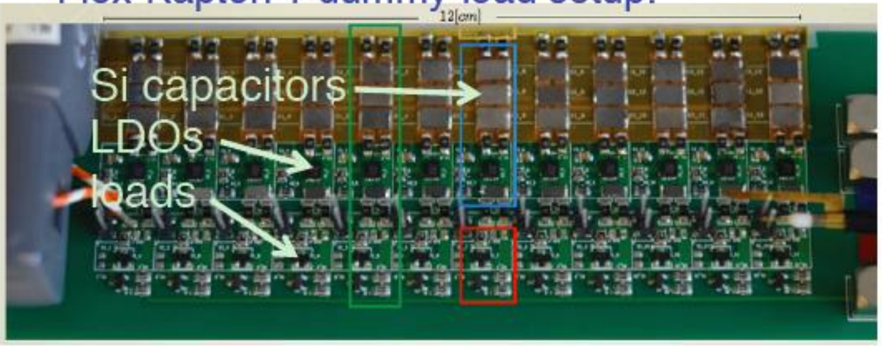
CLIC vertex R&D: power pulsing

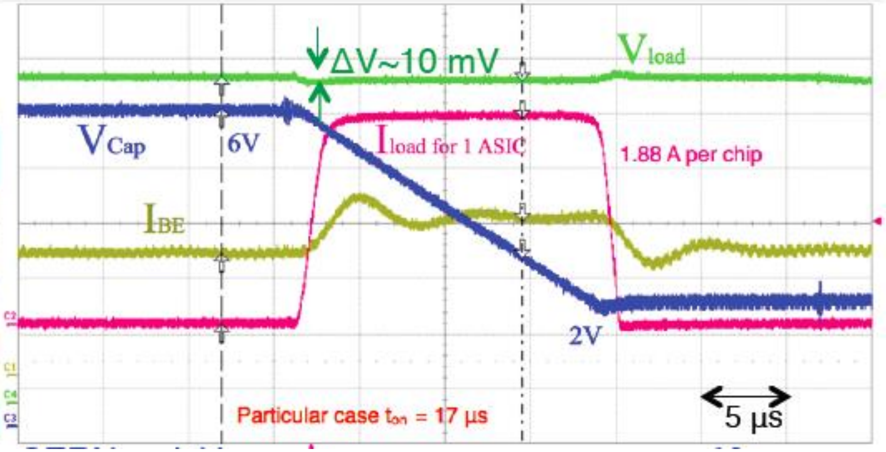


Power-delivery + pulsing

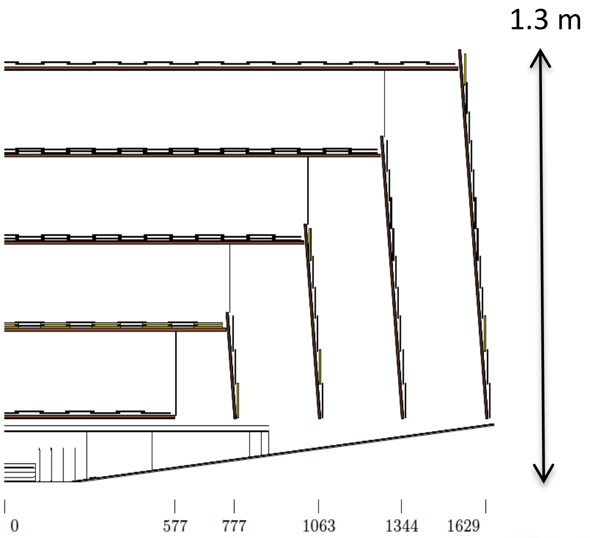
- low-mass Al-Kapton cables
- power pulsing with local energy storage and voltage regulation
- prototype for analog powering of CLICpix ladder:
  - I_{ladder}~20-60 mA; 10 mW/cm^2
  - voltage stability: ΔV~10 mV
  - 0.064% X_0 material contrib.
  - can be reduced to ~0.03% X_0

Flex-Kapton + dummy-load setup:



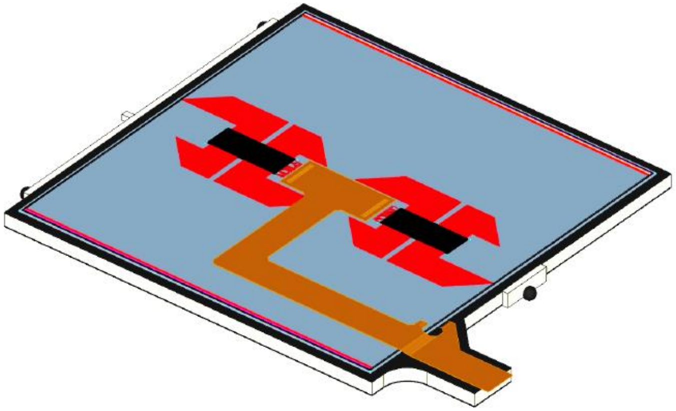


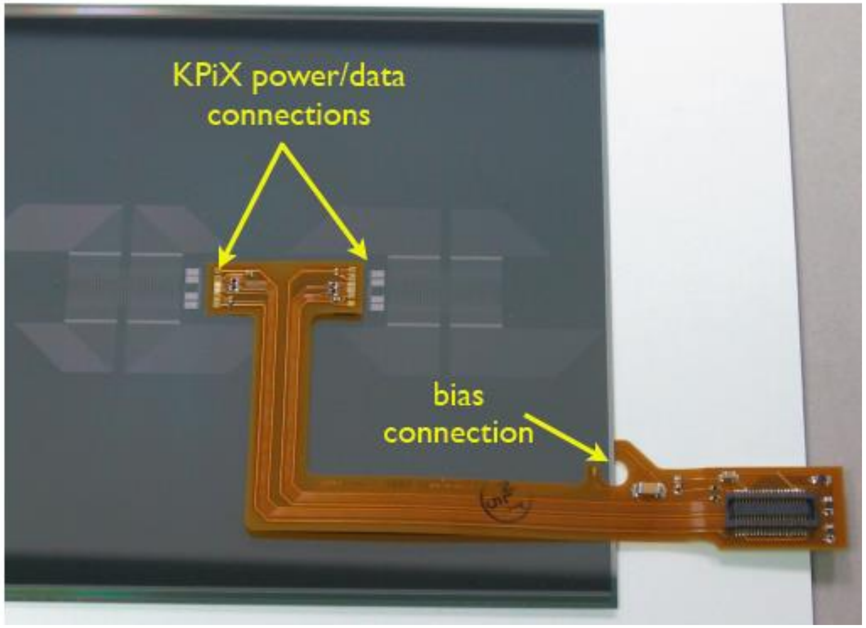
Linear collider, Si-tracker R&D



Silicon tracker for the Linear Collider
=> Aim for ~1% X0 per layer
⇒ Only limited R&D ongoing

SiD tracker module
"chip on sensor"





- 1024-channel KPIX chip
- Sensor with double metal-layer routing
- Connectivity via Kapton pig-tail cable

calorimetry and PFA

Jet energy resolution and **background rejection** drive the overall detector design

=> => fine-grained calorimetry + Particle Flow Analysis (PFA)

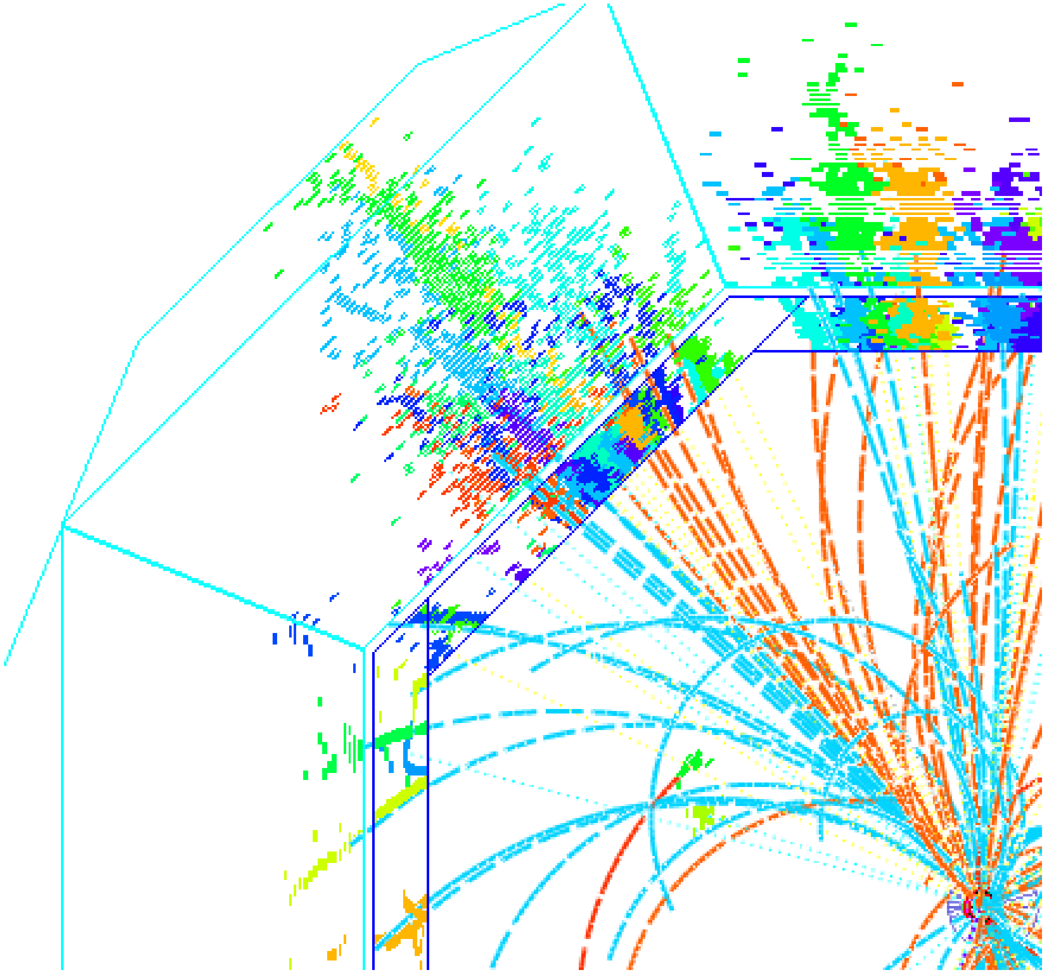
What is PFA?

Typical jet composition:
- 60% charged particles
- 30% photons
- 10% neutrons

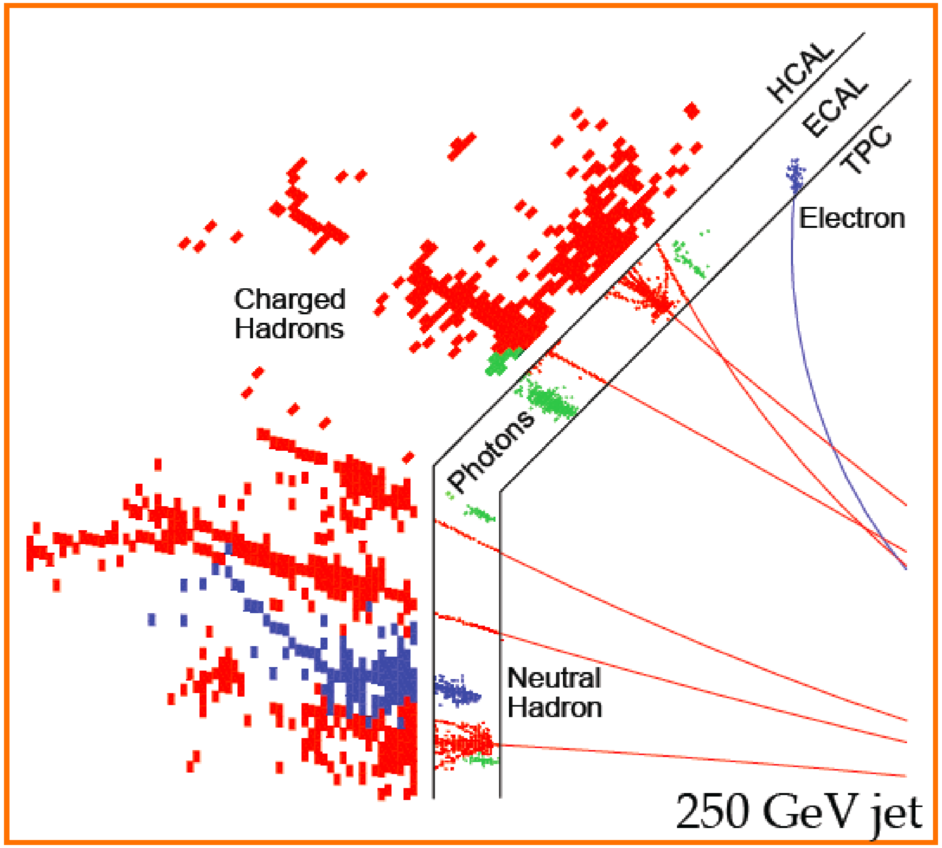
↓

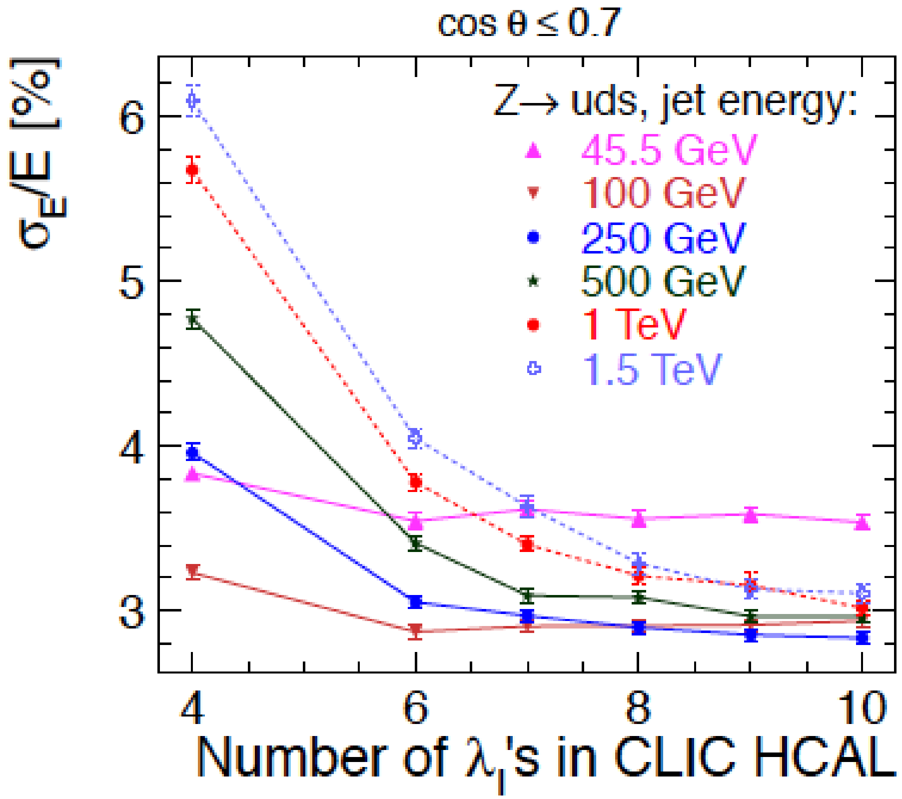
Always use the best info you have:
- 60% => tracker 🙂 🙂
- 30% => ECAL 🙂
- 10% => HCAL 🙁

Hardware + software !



calorimetry and PFA

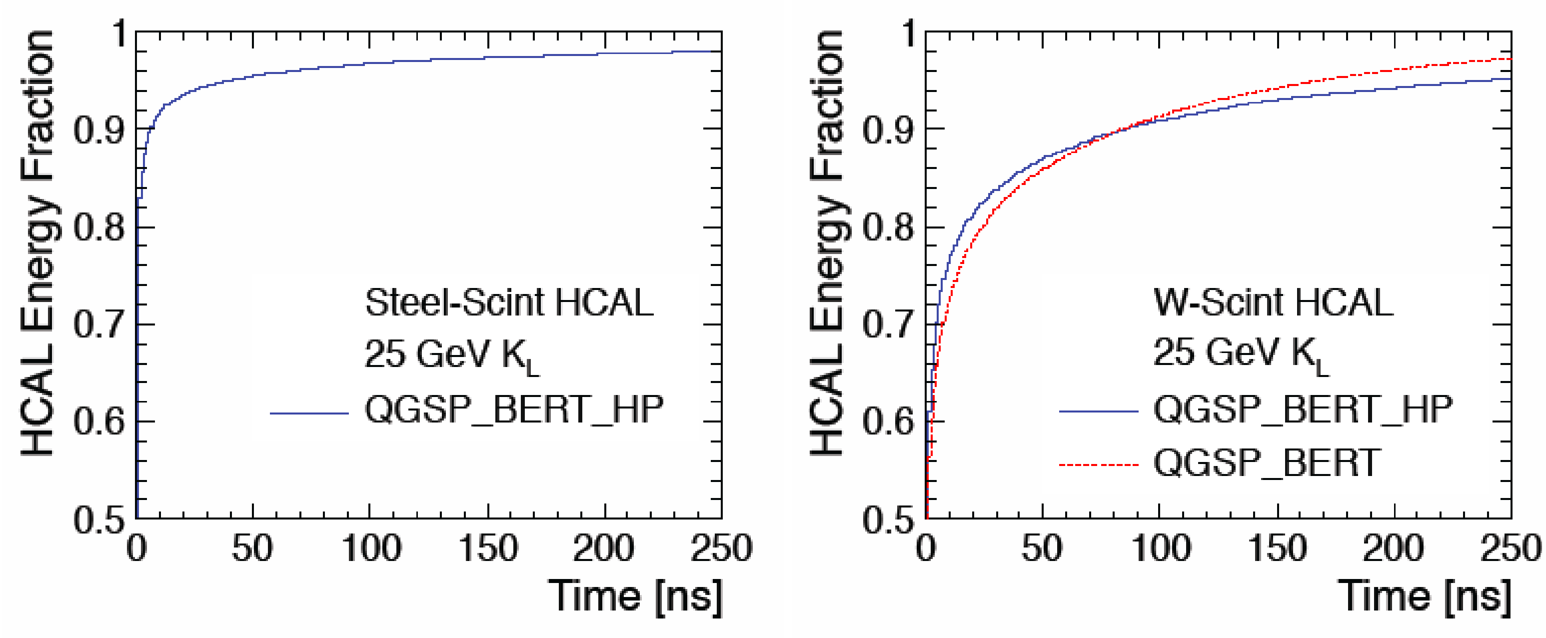




Simulated image
(gives good feeling of the granularity)

FPA-based simulation
(to determine depth of tungsten HCAL)

time development in hadronic showers

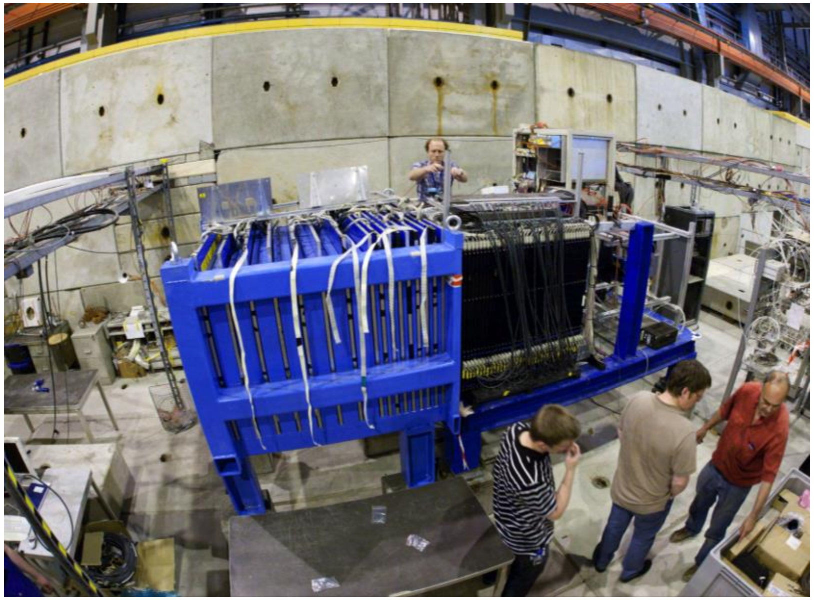


- In steel 90% of the energy is recorded within 6 ns (corrected for time-of-flight).
- In tungsten this takes almost ~100 ns. (depends on active material)
  - Response is slower due to the much larger component of the energy in slow neutrons.

➢ Need to integrate over ~100 ns in reconstruction, keeping out pile-up hits…

Analog HCAL: scintillator/tungsten

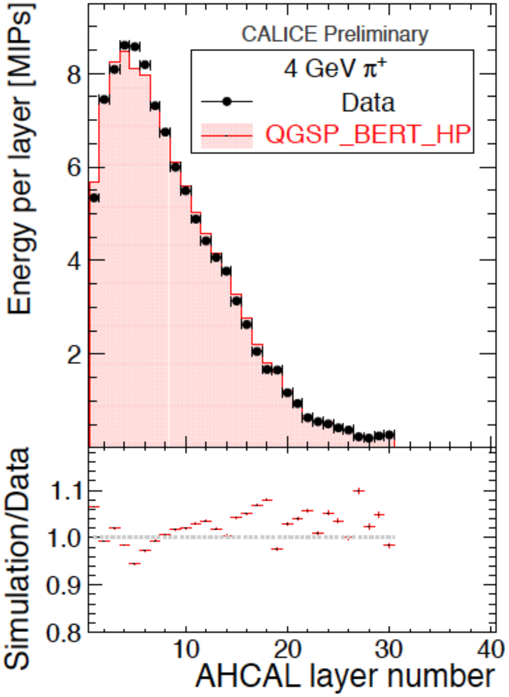
HCAL tests with 10 mm thick **Tungsten absorber** plates,
Tests in 2010+2011 with scintillator active layers, 3×3 cm^2 cells => analog readout



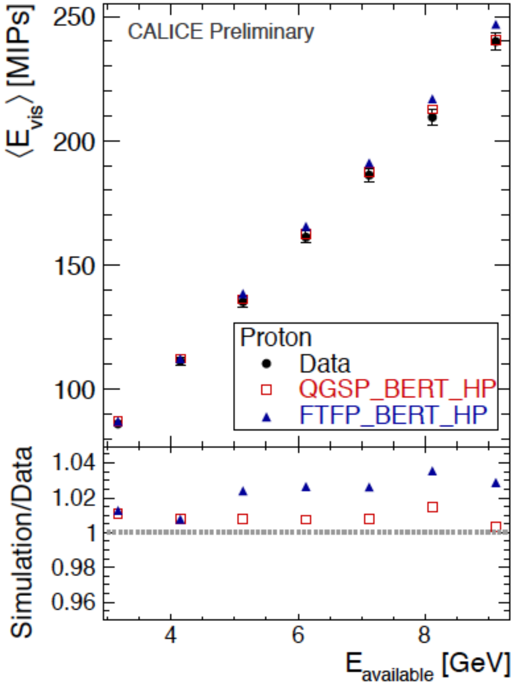
CERN SPS 2011

good agreement with Geant4

longitudinal shower profile, pions



visible Energy protons



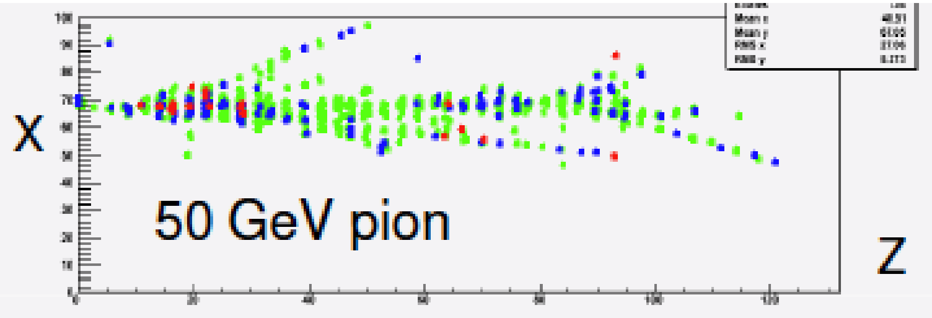
HCAL: SDHCAL (CALICE)

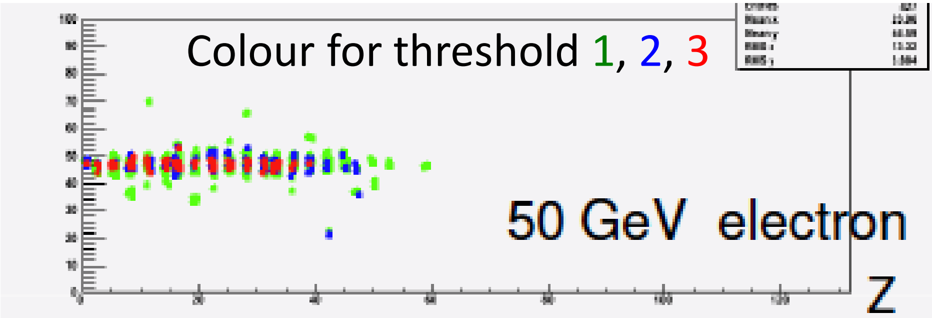
Steel SDHCAL
500'000 readout channels

~50 glass RPC chambers, 1m^2 each
PAD size 1×1 cm^2
Semi-digital readout (3 thresholds)
200 ns time-slicing
Fully integrated electronics

With power-pulsing !
Separate power-pulsing tests in 3T magnet
=> Stable signal response

Full SDHCAL stack **successfully tested**:
2012 (2011) CERN - ongoing
Steel absorber



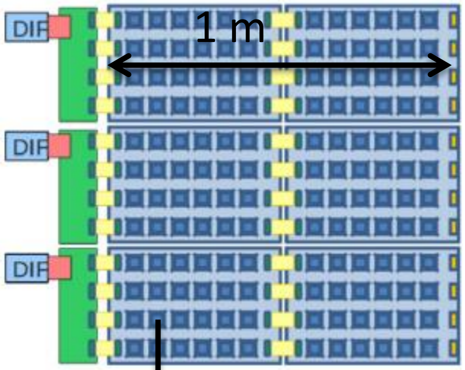

Colour for threshold 1, 2, 3

Calorimetry: Micromegas / GEM

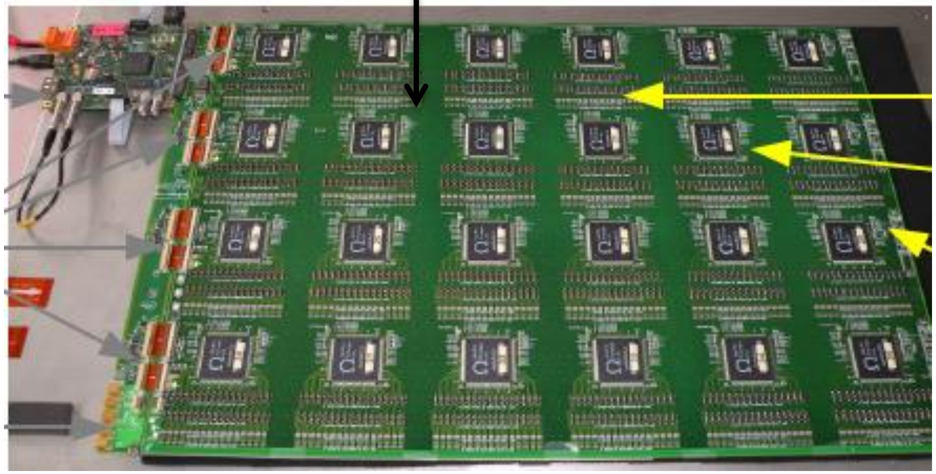
Micromegas

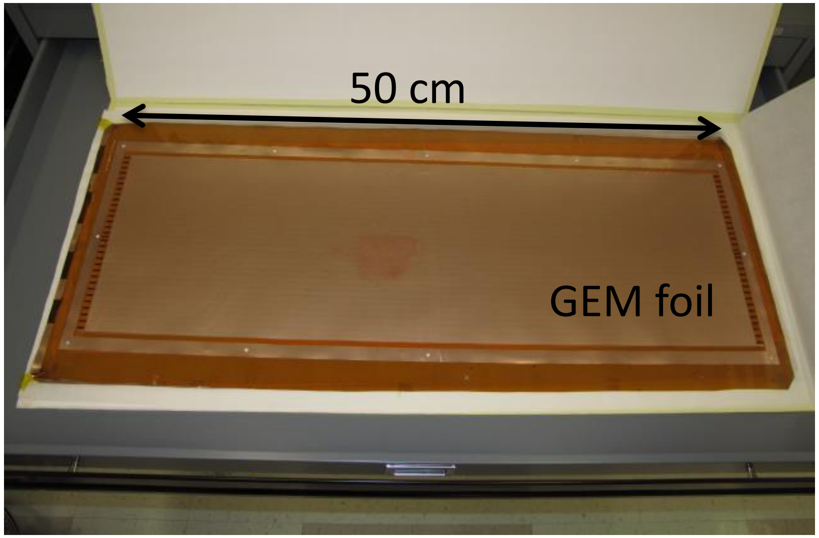
Two 1 m^2 chambers, multi-threshold readout

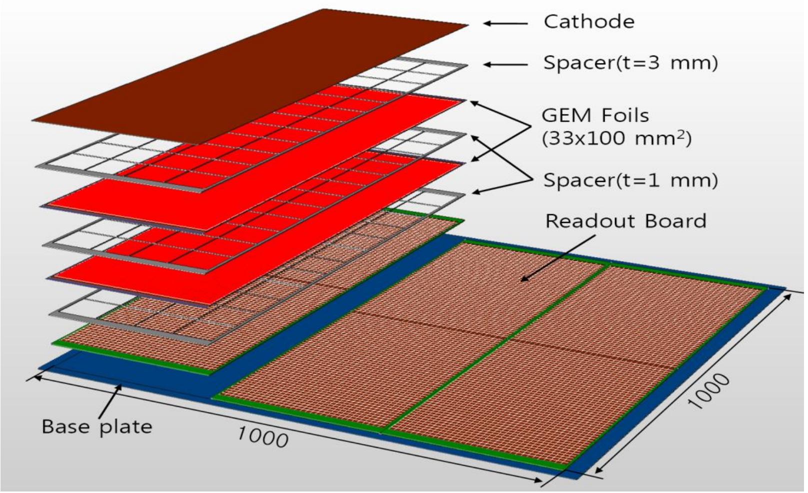
Successfully tested within SDHCAL stack, 2012



32x48 pads of 1 cm^2 on back side







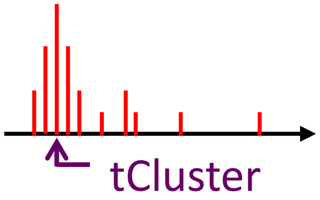
After successful tests with 30×30 cm **GEM chambers**, development towards of 1m^2 plane has started.

background suppression at CLIC

Triggerless readout of full train

t_0 physics event (offline)

- **Full event reconstruction + PFA analysis with background overlaid**
  - => physics objects with precise p_T and cluster time information
  - Time corrected for shower development and TOF
- **Then apply cluster-based timing cuts**
  - Cuts depend on particle-type, p_T and detector region
  - Allows to protect high-p_T physics objects



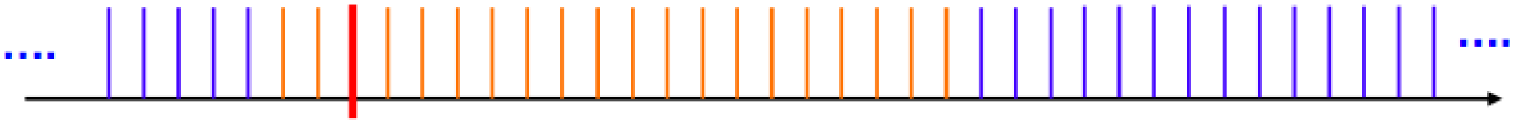
+

- **Use well-adapted jet clustering algorithms**
  - Making use of LHC experience (FastJet)

time window / time resolution

The event reconstruction software uses:

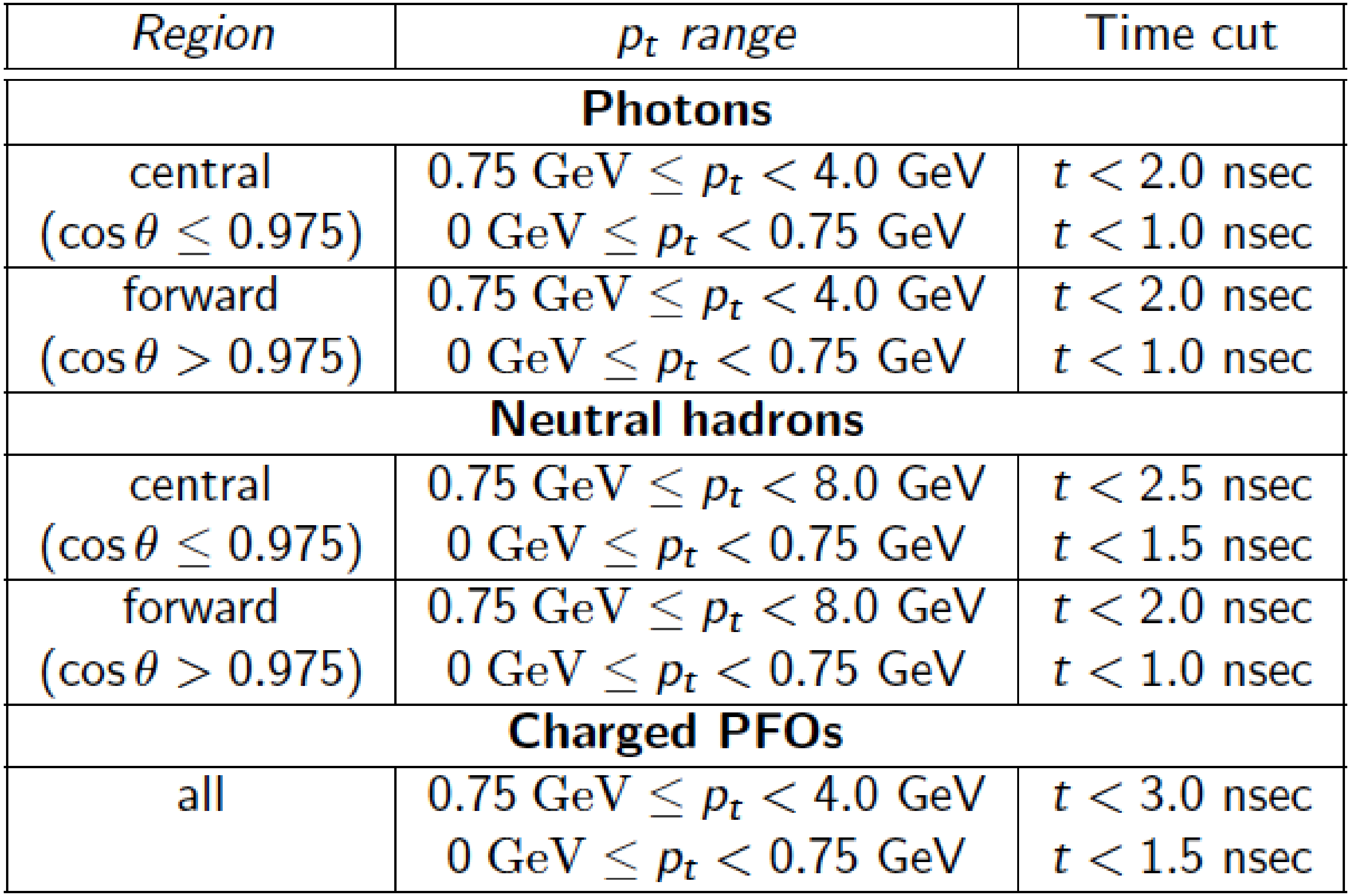
Subdetector	Reconstruction window	hit resolution
ECAL	10 ns	1 ns
HCAL Endcaps	10 ns	1 ns
HCAL Barrel	100 ns	1 ns
Silicon Detectors	10 ns	$10/\sqrt{12}$ ns
TPC	entire bunch train	n/a



t_0 physics event (offline)

Translates in precise **timing requirements** of the sub-detectors

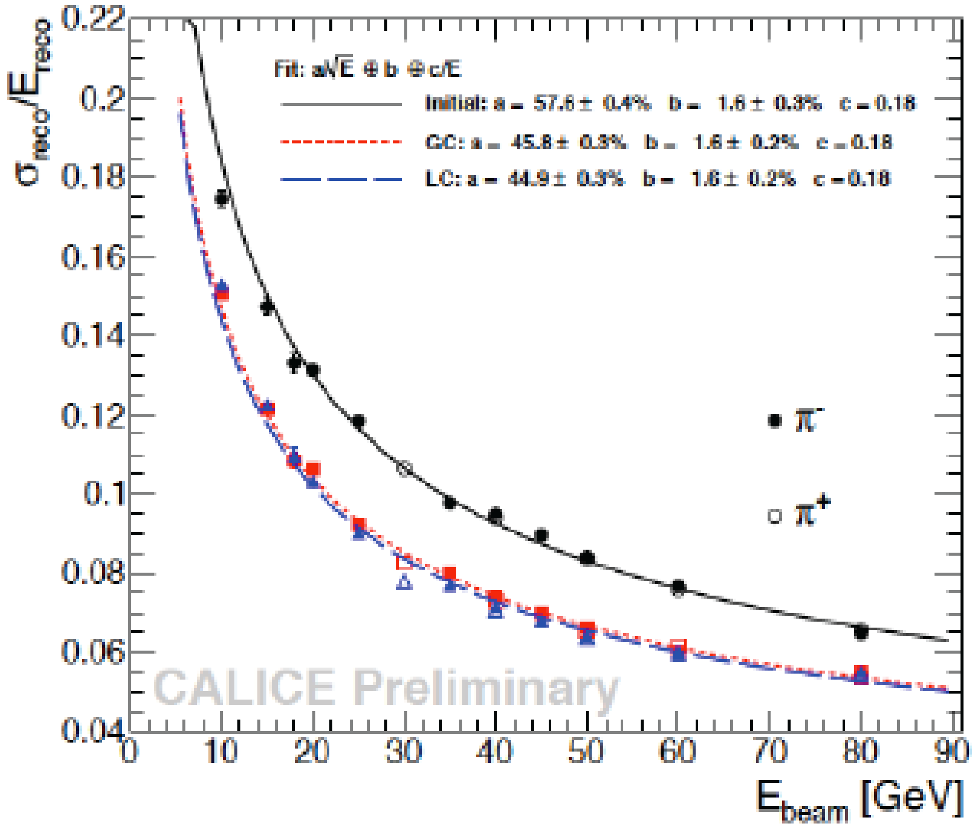
PFO-based timing cuts



Region	p_t *range*	Time cut
Photons		
central $(\cos\theta \leq 0.975)$	$0.75\ \text{GeV} \leq p_t < 4.0\ \text{GeV}$ $0\ \text{GeV} \leq p_t < 0.75\ \text{GeV}$	$t < 2.0$ nsec $t < 1.0$ nsec
forward $(\cos\theta > 0.975)$	$0.75\ \text{GeV} \leq p_t < 4.0\ \text{GeV}$ $0\ \text{GeV} \leq p_t < 0.75\ \text{GeV}$	$t < 2.0$ nsec $t < 1.0$ nsec
Neutral hadrons		
central $(\cos\theta \leq 0.975)$	$0.75\ \text{GeV} \leq p_t < 8.0\ \text{GeV}$ $0\ \text{GeV} \leq p_t < 0.75\ \text{GeV}$	$t < 2.5$ nsec $t < 1.5$ nsec
forward $(\cos\theta > 0.975)$	$0.75\ \text{GeV} \leq p_t < 8.0\ \text{GeV}$ $0\ \text{GeV} \leq p_t < 0.75\ \text{GeV}$	$t < 2.0$ nsec $t < 1.0$ nsec
Charged PFOs		
all	$0.75\ \text{GeV} \leq p_t < 4.0\ \text{GeV}$ $0\ \text{GeV} \leq p_t < 0.75\ \text{GeV}$	$t < 3.0$ nsec $t < 1.5$ nsec

Software compensation

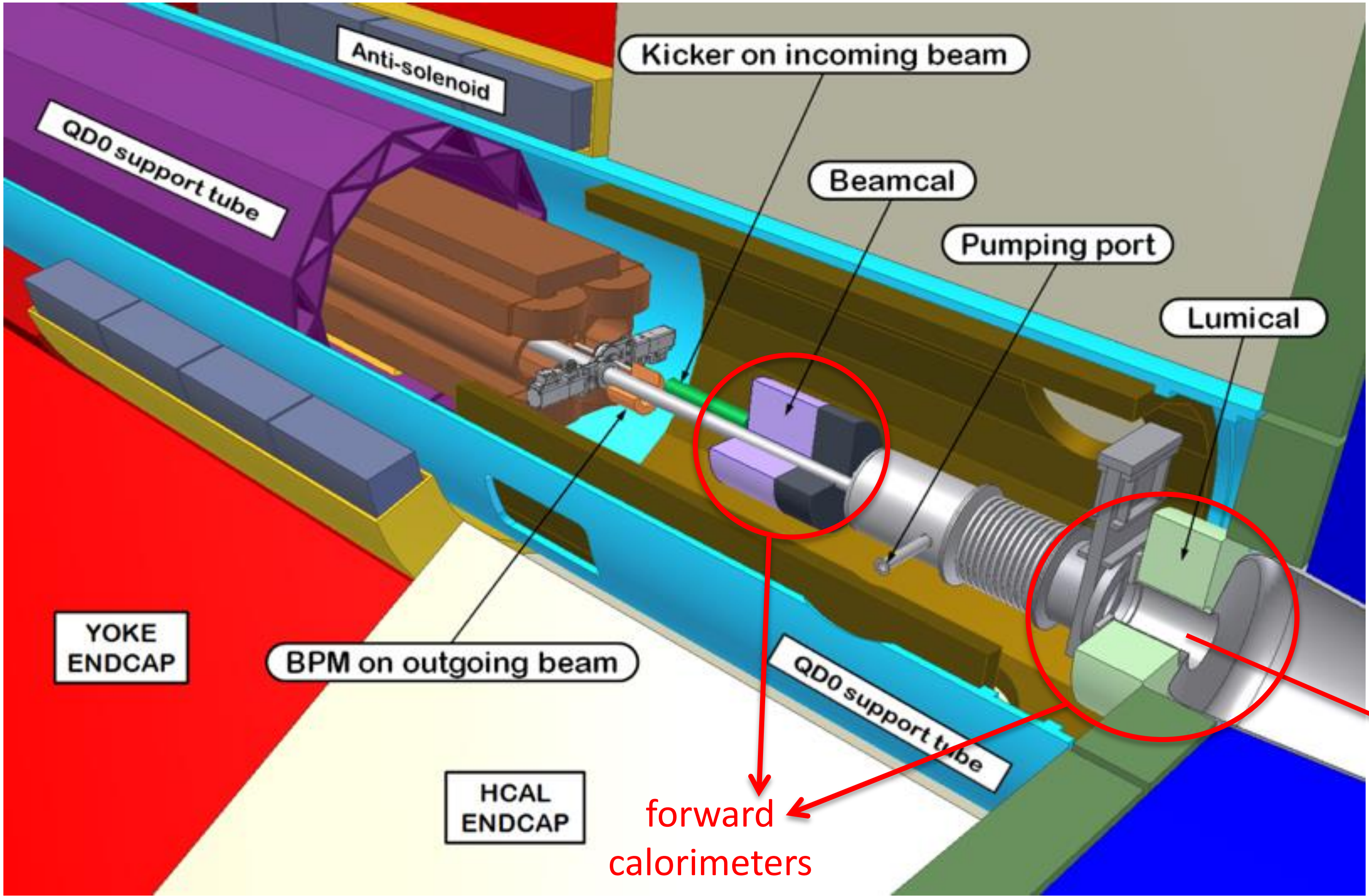
High granularity of the calorimeter can be used to distinguish between electromagnetic (dense) and hadronic (less dense) shower components



CALICE
Steel-AHCAL data

➔ Improved resolution (20% better) and linearity

details of forward detector region



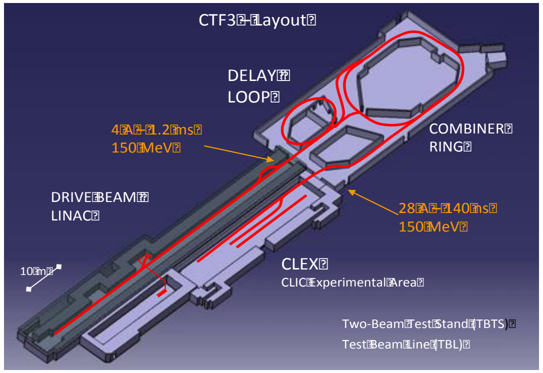
forward calorimeters “FCAL”

IP at ~2 m

CLIC strategy and objectives

2013-18 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.



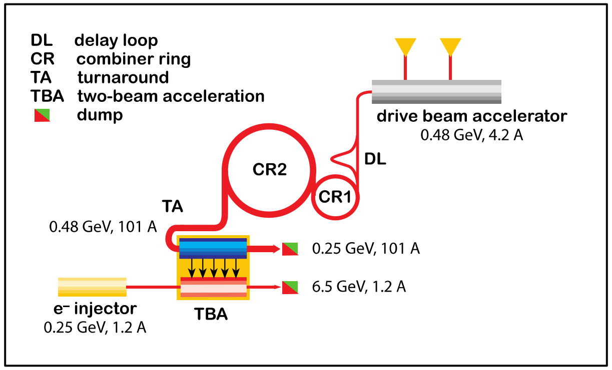
2018-19 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects), take decisions about next project(s) at the Energy Frontier.

4-5 year Preparation Phase

Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

Prepare detailed Technical Proposals for the detector-systems.



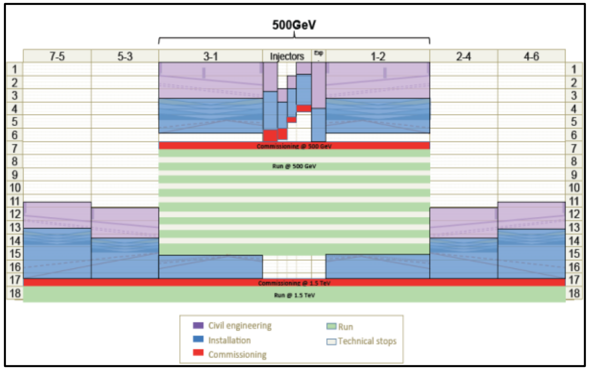
2024-25 Construction Start

Ready for full construction and main tunnel excavation.

Construction Phase

Stage 1 construction of CLIC, in parallel with detector construction.

Preparation for implementation of further stages.



Commissioning

Becoming ready for data-taking as the LHC programme reaches completion.

Lucie Linssen, detector R&D talk, CLIC workshop, 3/2/2014