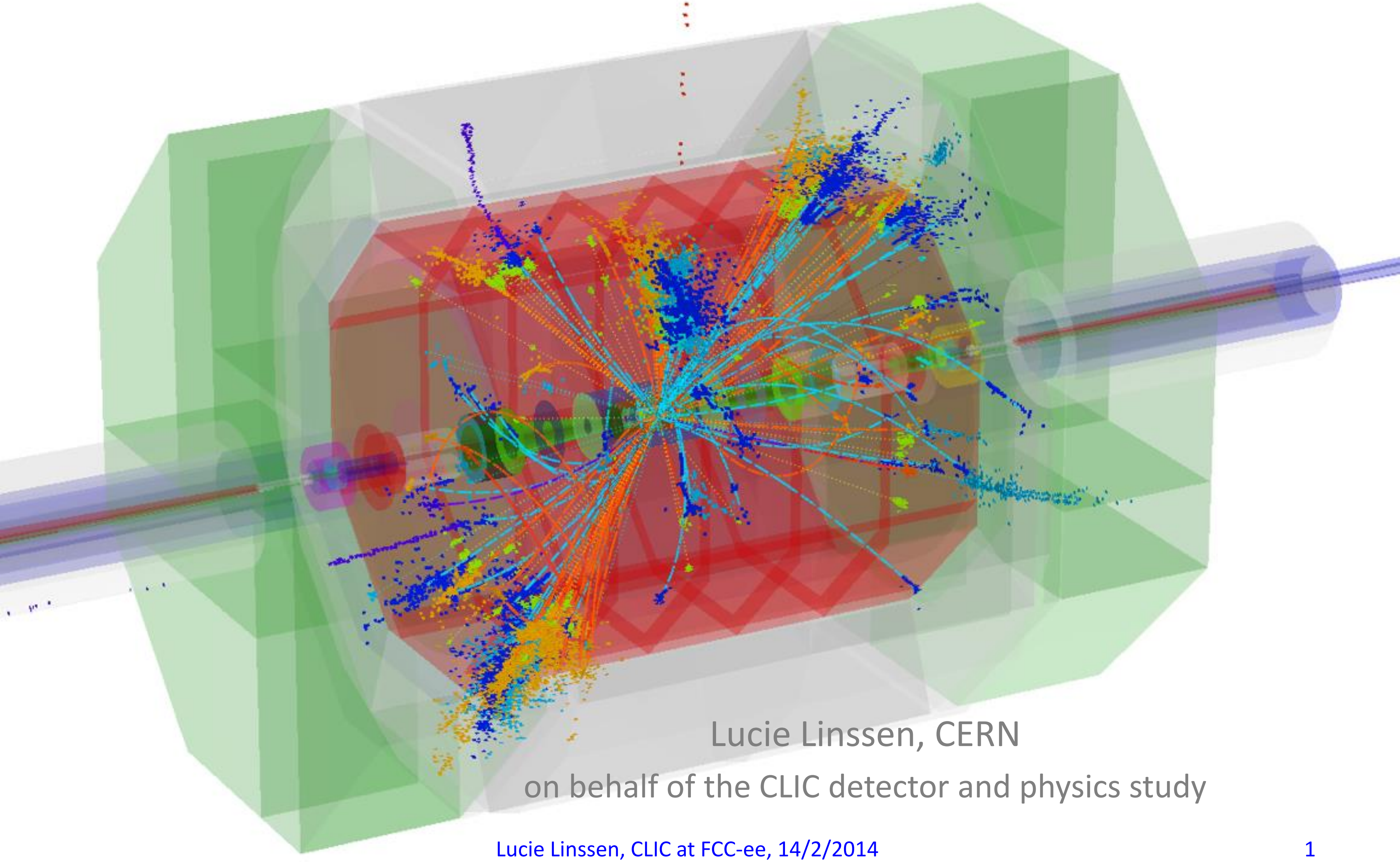
FCC-ee: possible synergies with CLIC detectors



Lucie Linssen, CERN

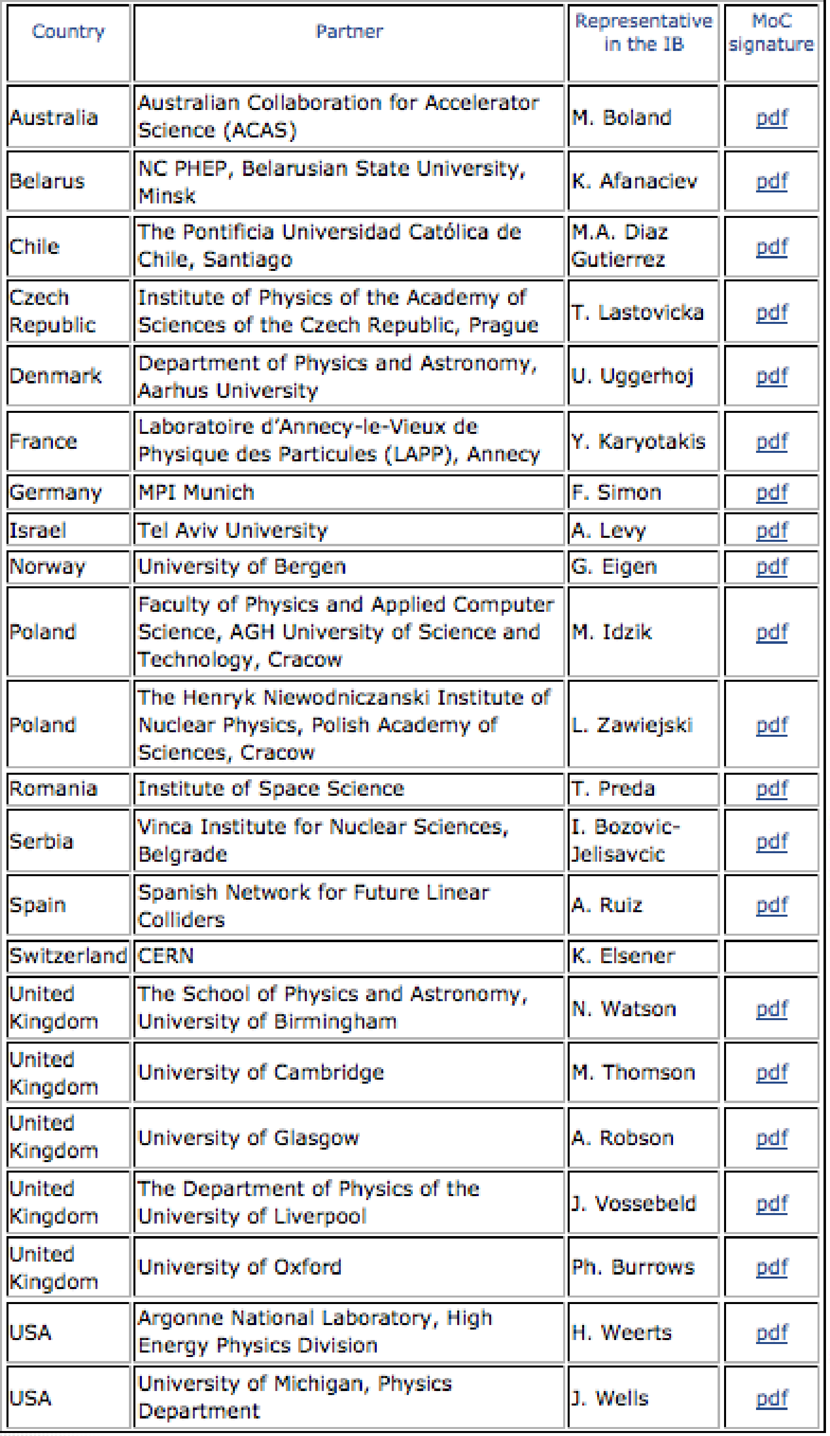
on behalf of the CLIC detector and physics study

Outline

- Detector requirements
- Challenges/technologies in vertex/tracking detectors
- Challenges/technologies in calorimetry
- Some considerations for FCC-ee
- Synergies
- Outlook

Apologies, some lack of time to prepare this talk.
In the future we can go one-by-one over individual items (e.g. performance requirements, technology choices, advantages-drawbacks, sharing of SW tools, collaboration on technology development.

Who are we ?



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

CLIC detector and physics study (CLICdp)

Light-weight collaboration structure

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

CLICdp: 22 institutes

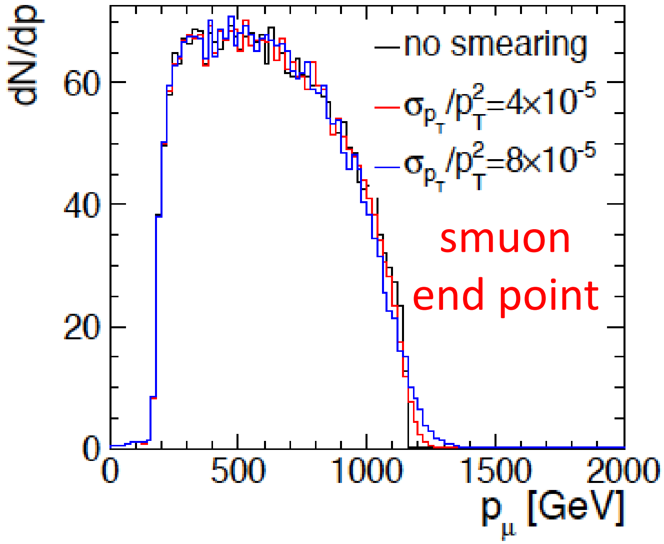
CLIC physics aims => detector needs

- ★ **momentum resolution:**

  e.g. Smuon endpoint

  Higgs recoil mass, Higgs coupling to muons

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



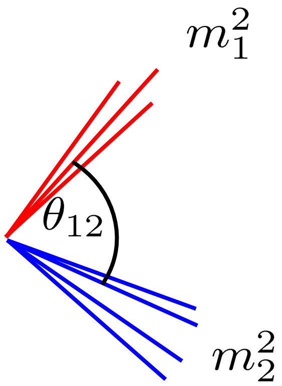
smuon end point

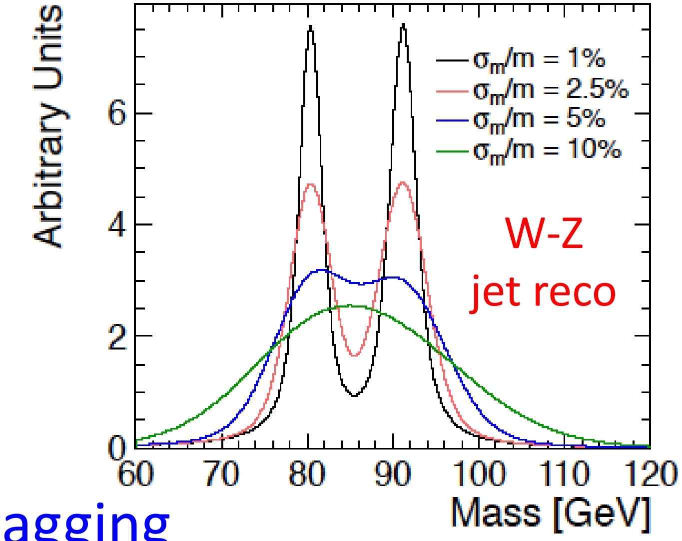
- ★ **jet energy resolution:**

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

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

(for high-E jets)





W-Z jet reco

- ★ **impact parameter resolution:**

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

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

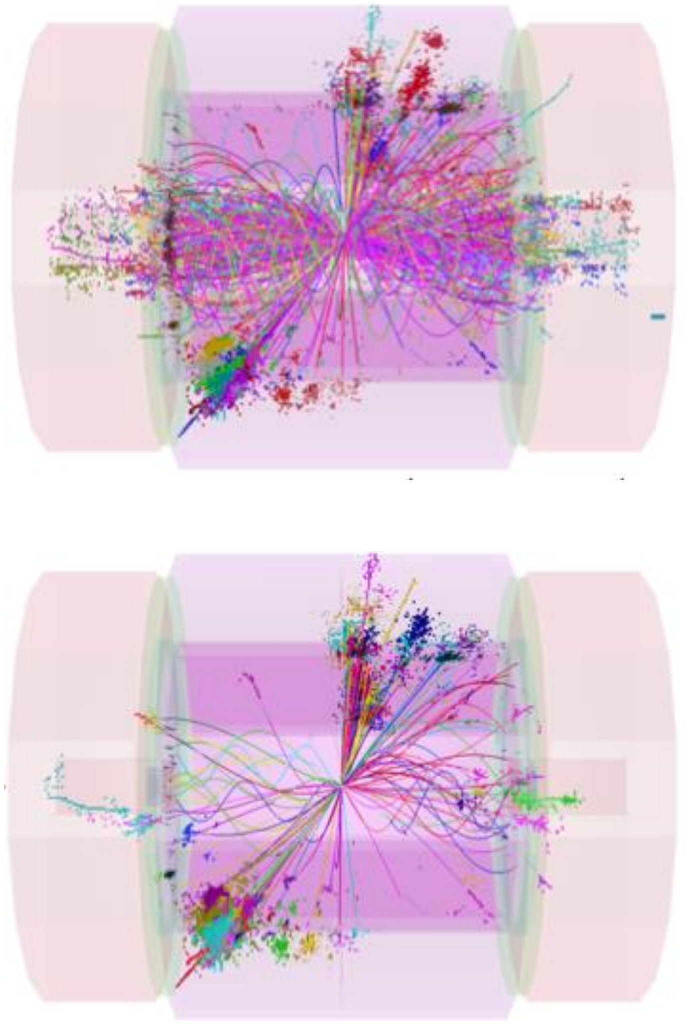
- ★ **angular coverage, very forward electron tagging**

+ requirements from CLIC beam structure and beam-induced background

CLIC conditions => impact on detector

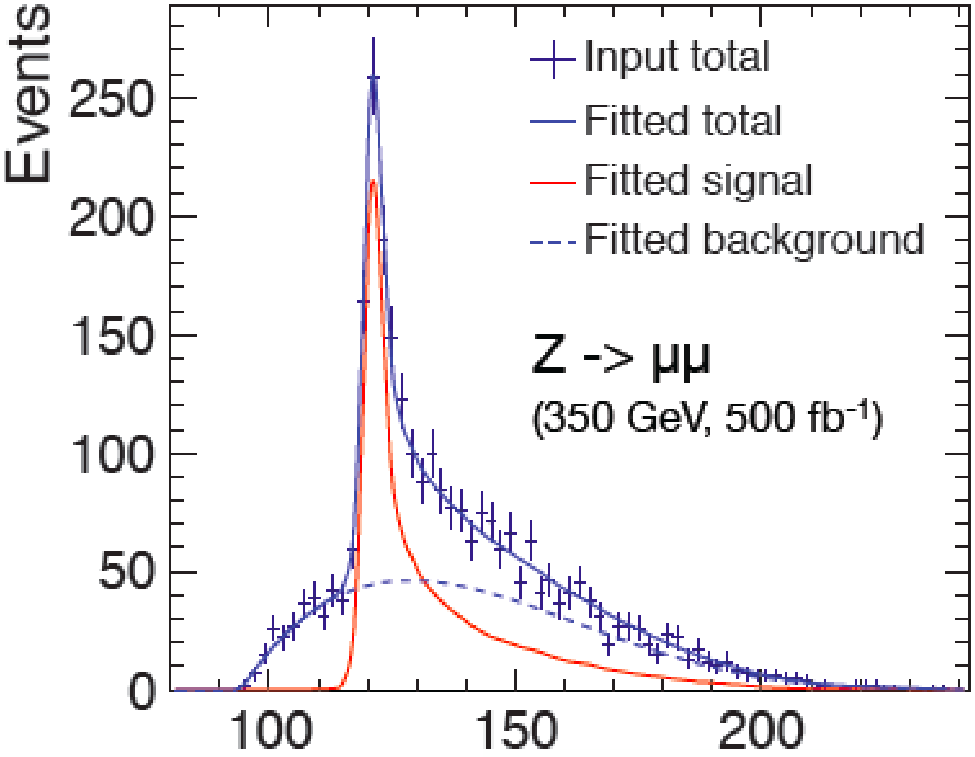
Beyond requirements for precision,
the CLIC beam conditions impact on detector requirements:

- **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**
    - for background suppression in data
- **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

Illustration precision requirements

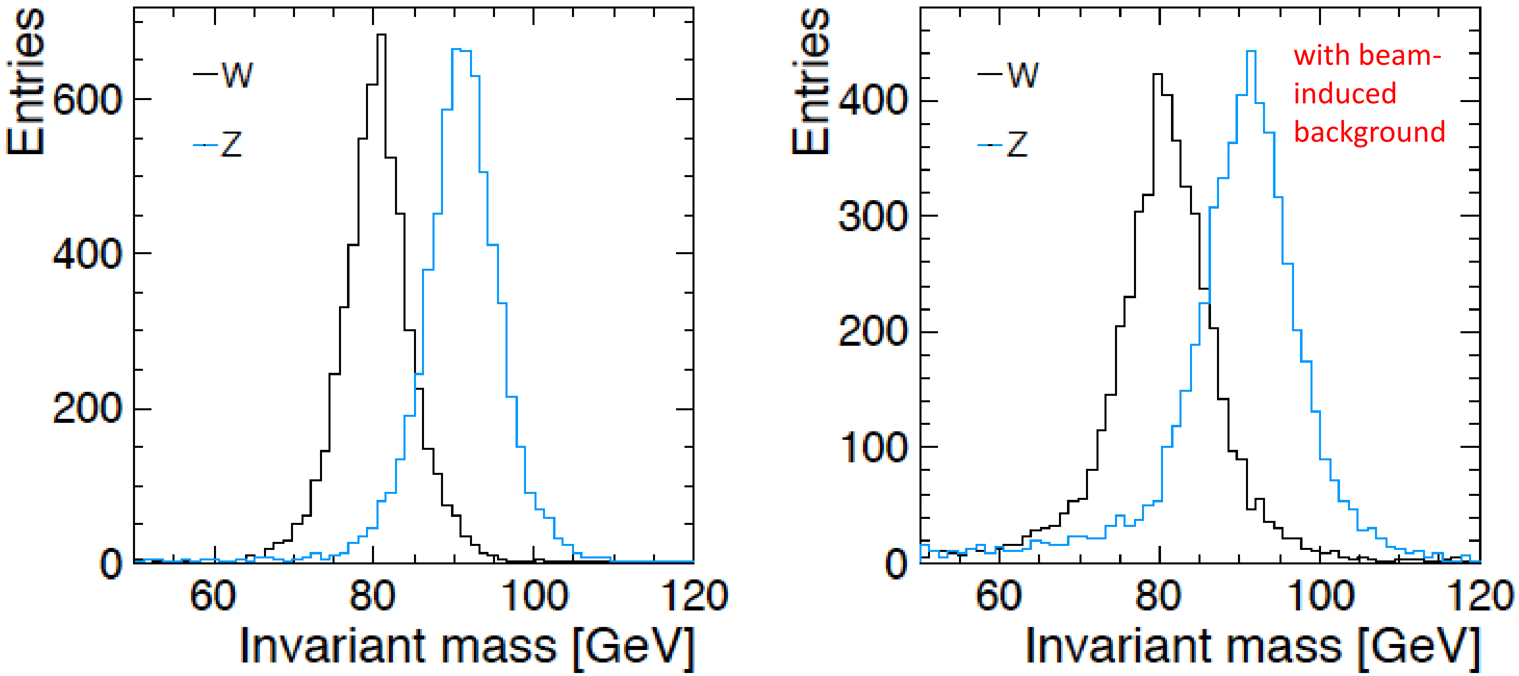


Momentum resolution helps to get:

- Excellent Higgs mass resolution
- Signal/(*physics* background)

W/Z separation in jj reconstruction (1)

Simulated WW => vvqq and ZZ => vlqq events



with beam-induced background

Figure 9: Mass distributions of reconstructed W and Z at an energy of 500 GeV, without background (left) and with 60 BX of background (right). Without background the separation is 2.2 σ. With 60 BX of background the separation drops to 1.8 σ. `Tight` PFO selection cuts are used for events with background.

Background suppressed through jet clustering and timing cuts of PFA particles

See: arXiv:1209.4039

W/Z separation in jj reconstruction (2)

Simulated events:

$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+W^-$$

$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 Z^0Z^0$$

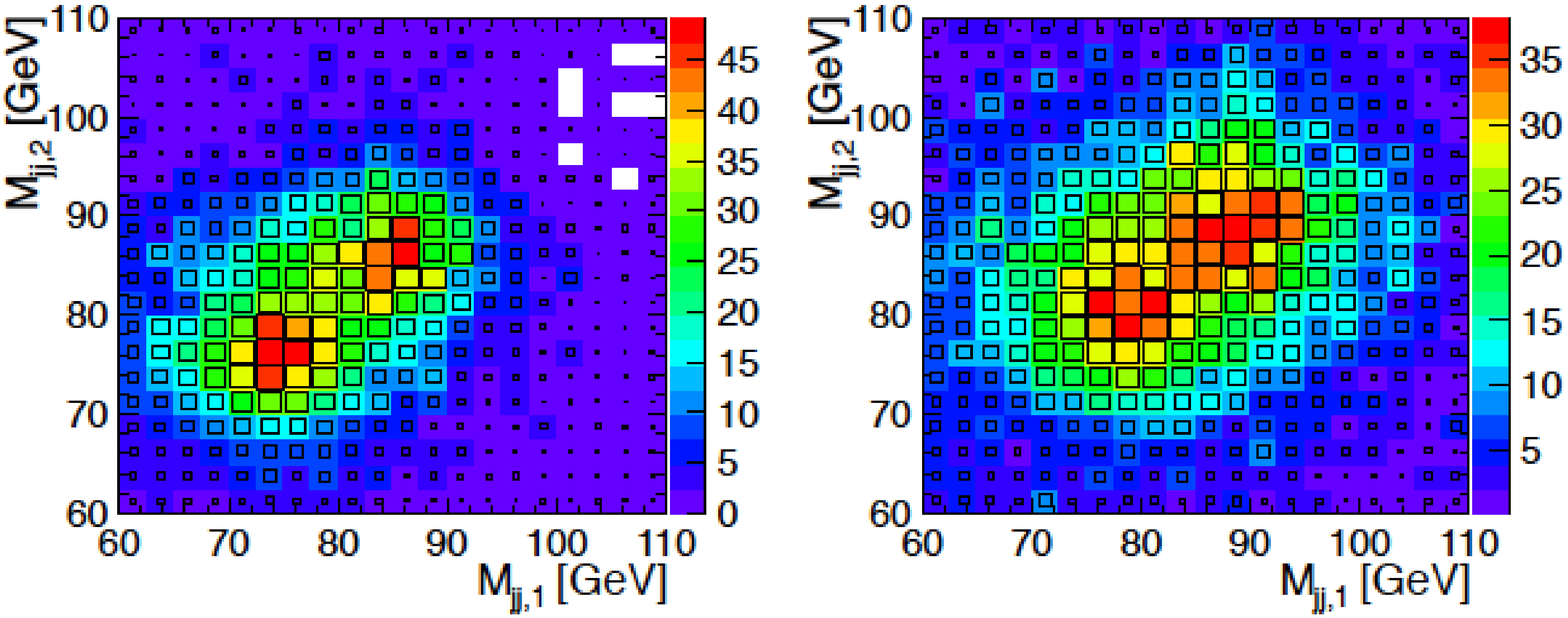


Figure 19: Separation of *W* and *Z* from the chargino decay without overlay (left) and with 60 BX of background (right) for CLIC_SiD.

See: LCD-Note-2012-028

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

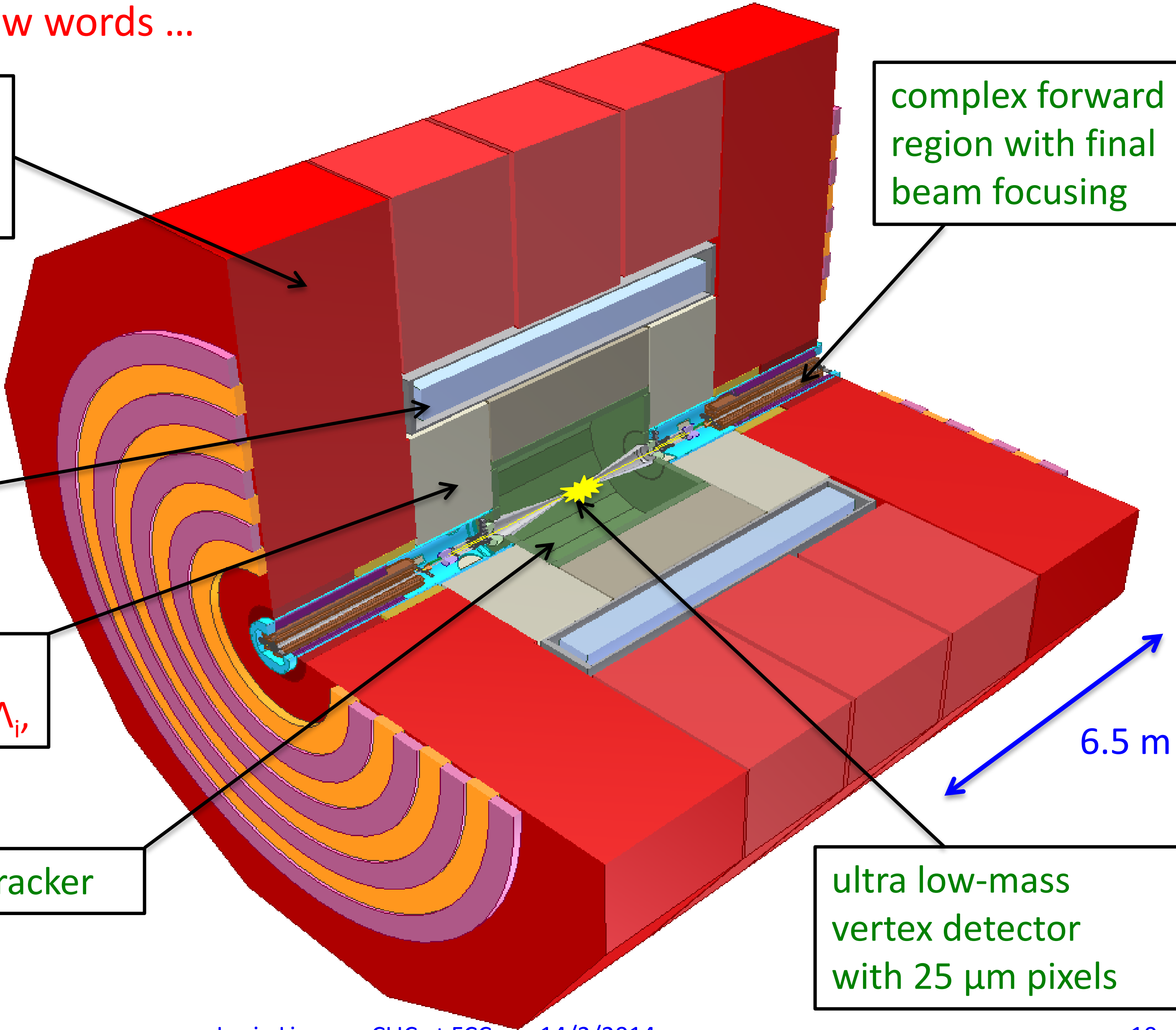
Calorimetry

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

ultra – heavy
and compact

CLIC detector concept

… in a few words …



return yoke with
Instrumentation
for muon ID

complex forward
region with final
beam focusing

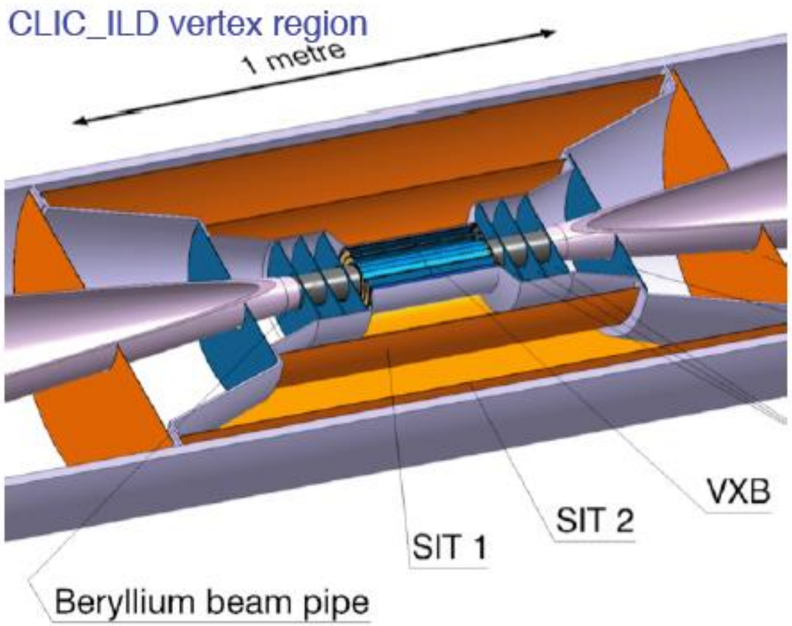
strong solenoid
4 T - 5 T

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

all-silicon tracker

ultra low-mass
vertex detector
with 25 µm pixels

CLIC vertex detector



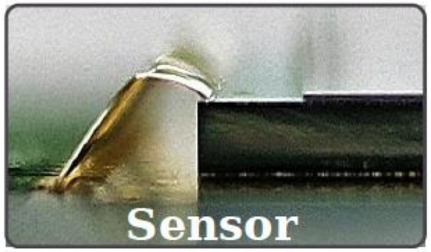
- ~25×25 µm pixel size => ~2 Giga-pixels
- 0.2% X_0 material per layer <= very thin !
  - Very thin materials/sensors
  - Low-power design, power pulsing, air cooling
  - Aim: 50 mW/cm^2
- Time stamping 10 ns
- Radiation level $<10^{11}$ $n_{eq}cm^{-2}year^{-1}$ <= 10^4 lower than LHC

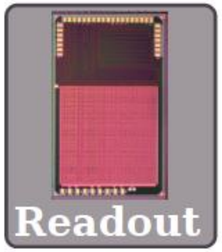
Challenges of CLIC vertex R&D => trend-setter for future detectors at other facilities

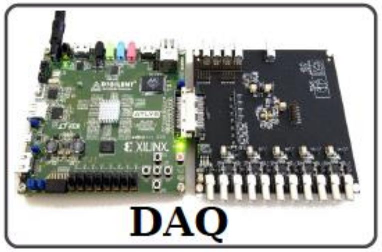
CLIC vertex detector R&D

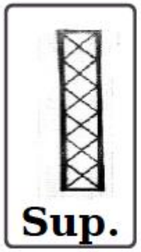
Aspects of Vertex R&D ongoing for CLIC => covering broad spectrum of technology areas

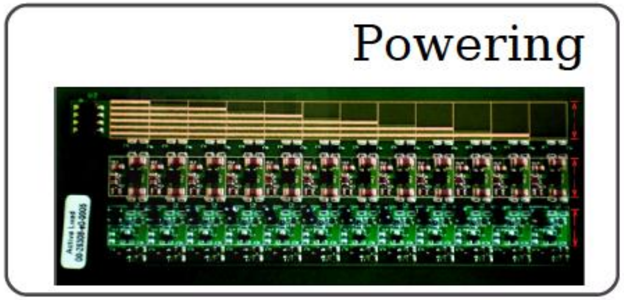

Simulations

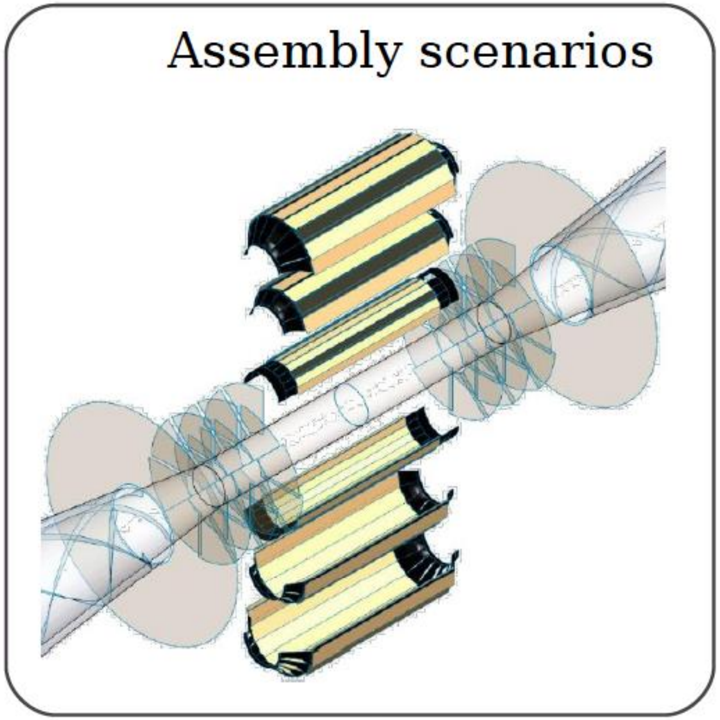

Sensor

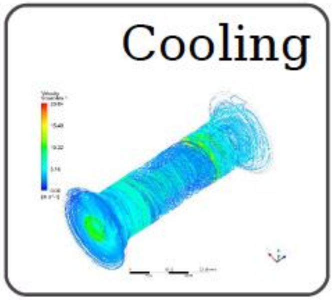

Readout

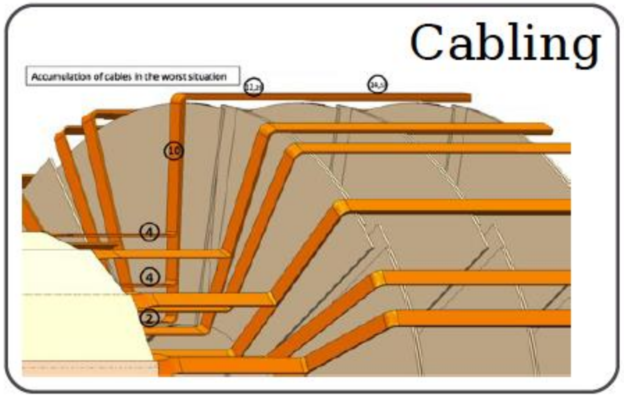

DAQ


Sup.


Powering

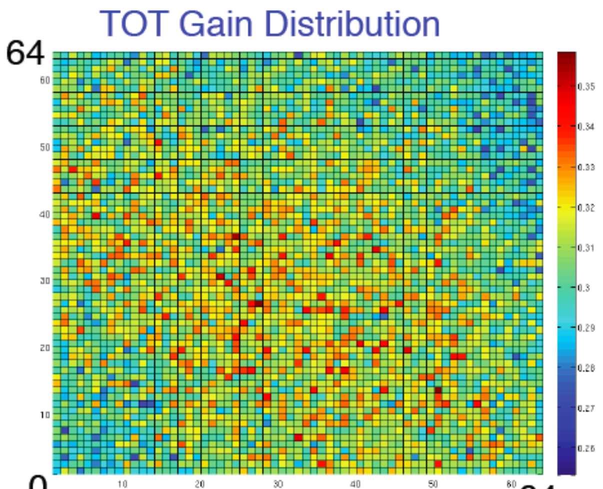

Assembly scenarios


Cooling


Cabling

CLIC vertex detector R&D (1)

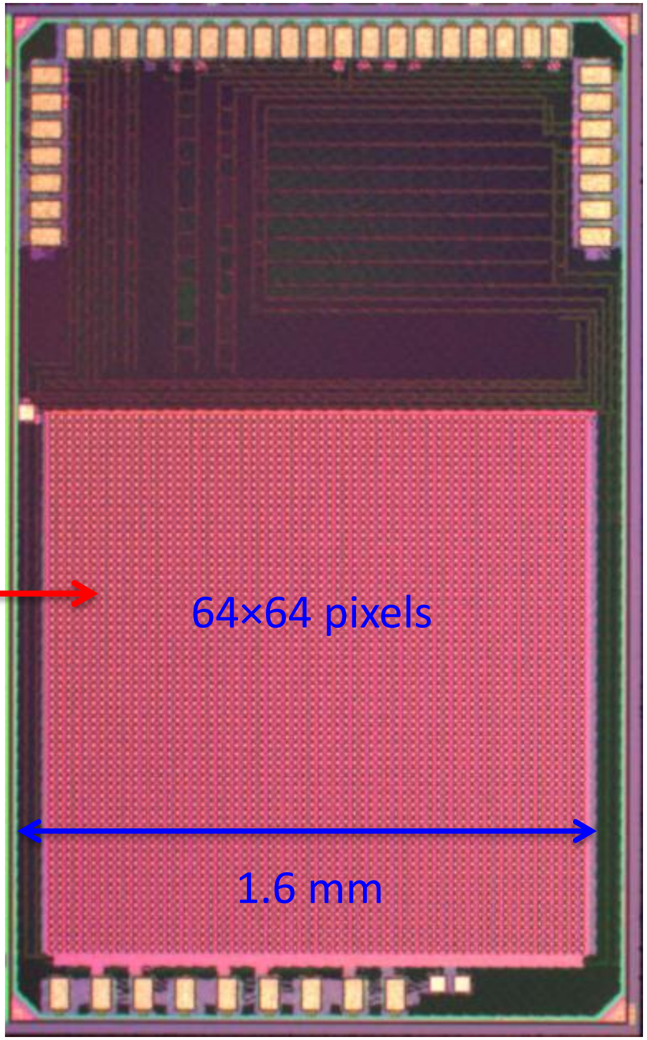
Hybrid approach pursued: (<= other options possible)
- Thin (~50 µm) silicon sensors
- Thinned high-density ASIC
    - R&D within Medipix/Timepix effort
- Low-mass interconnect
    - Micro-bump-bonding (Cu-pillar option)
    - Through-Silicon-Vias (R&D with CEA-Leti)
- Power pulsing
- Air cooling



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

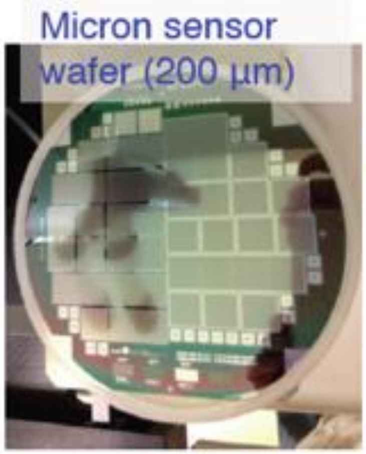


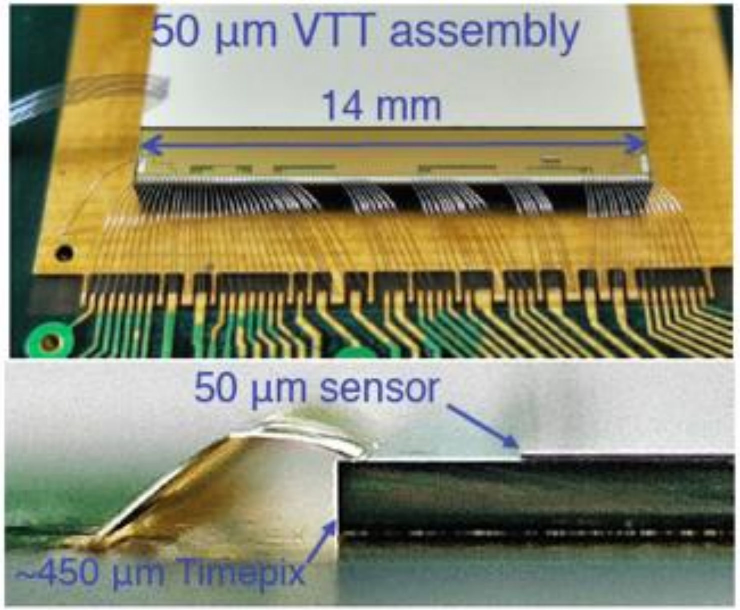
65 nm ASIC development
ATLAS, CMS, CLICdp => **RD53**

CLIC vertex detector R&D (2)

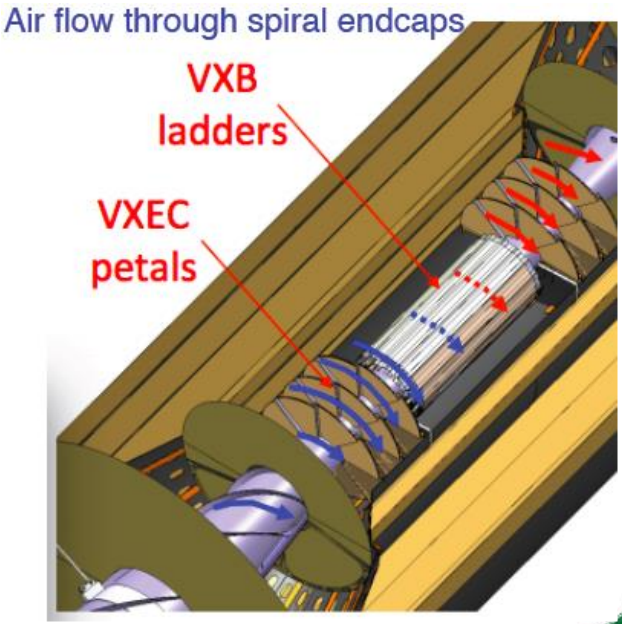
further ongoing R&D activities

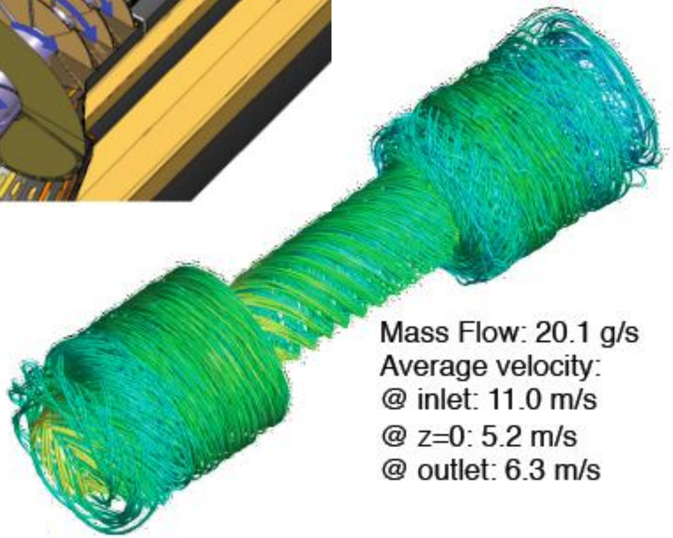
thin sensors, down to 50 µm





power pulsing, air cooling, light supports





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

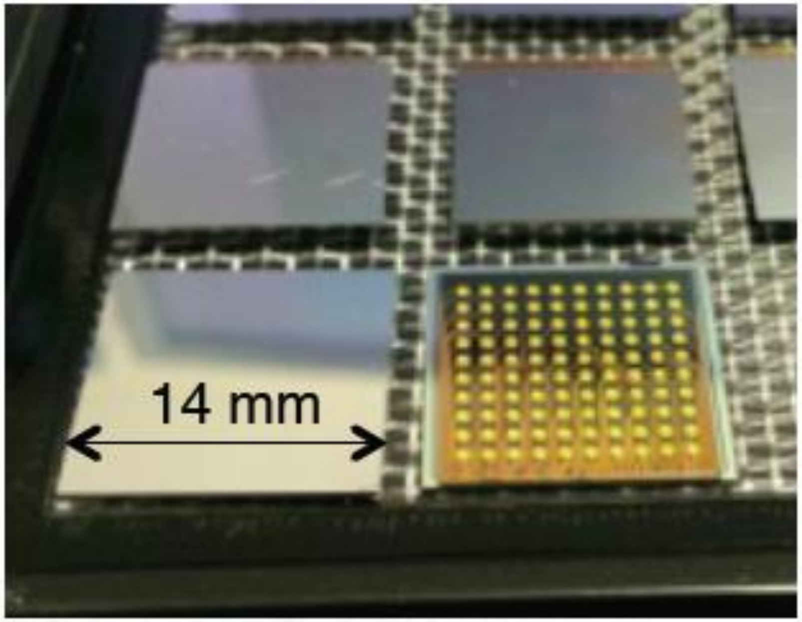
watching other R&D, e.g. **micro-channel cooling (NA62, LHCb-VeLo)**

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



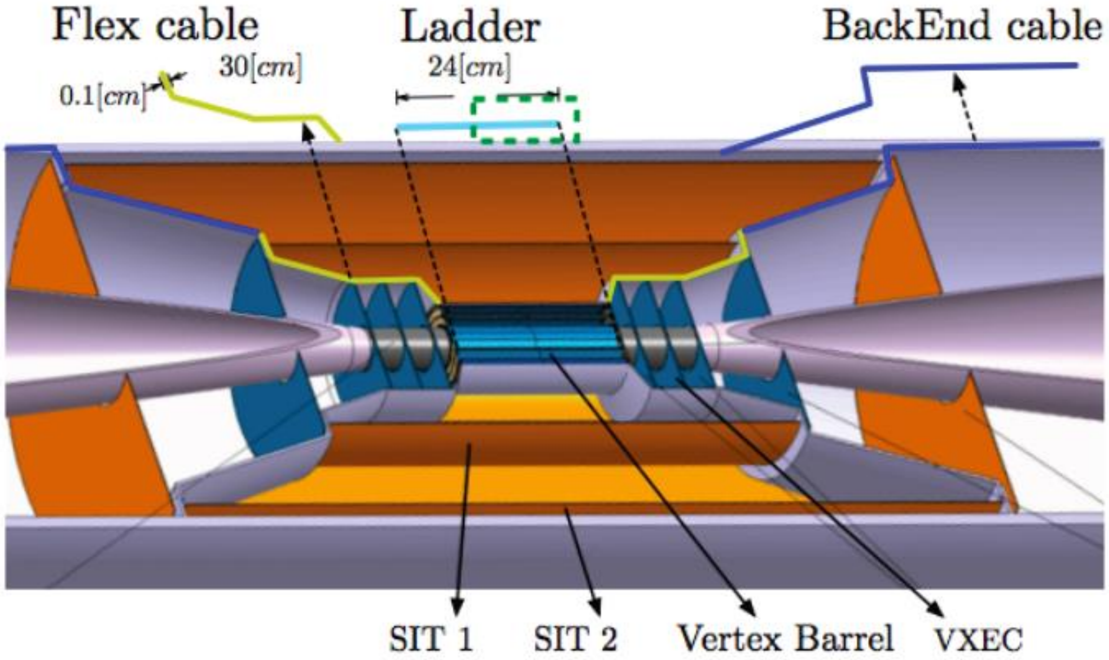
- 240 µm TSV diameter
- wafers thinned to 120 µm
- 5 µm copper layer for TSV

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 R&D: power pulsing

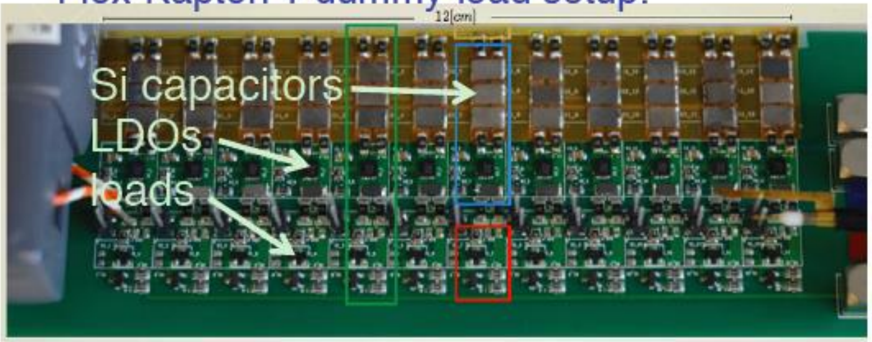


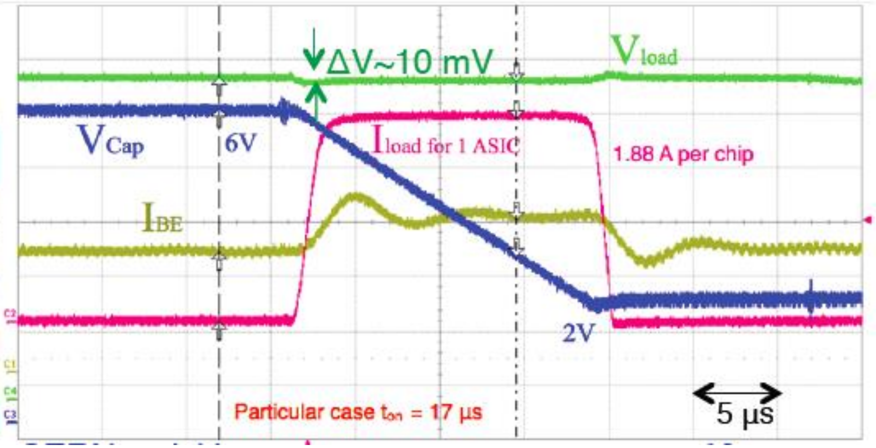
Even without power-pulsing, **reducing mass for powering components is important**

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:

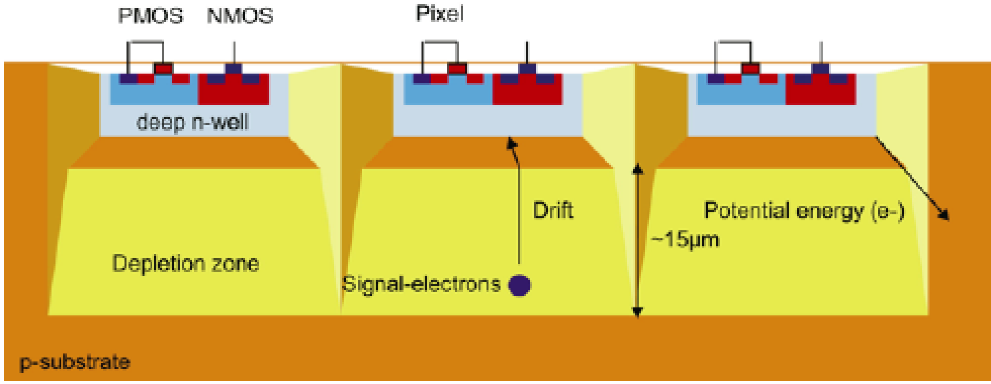




Hybrid detector with HV-CMOS

HV-CMOS MAPS:

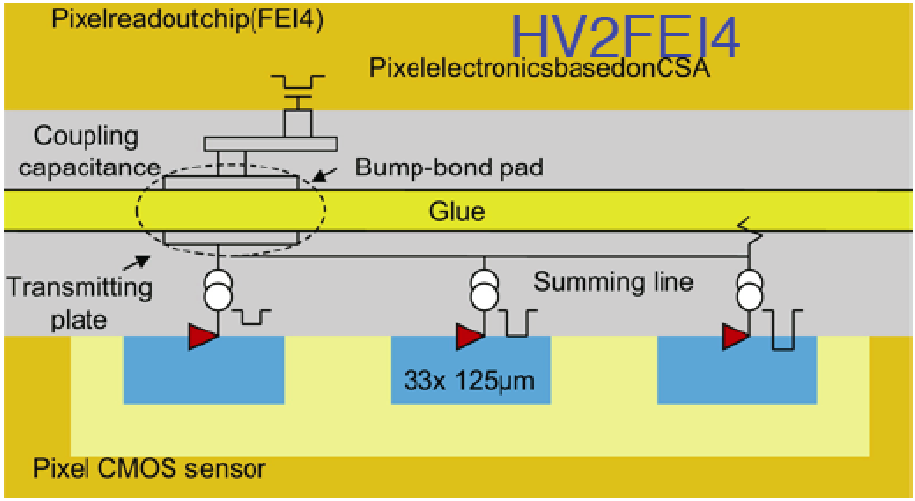
- 180 nm High Voltage process
- V_{bias} ~100 V, 10-20 µm depletion layer
- Integrated sensors, fast signal collection



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



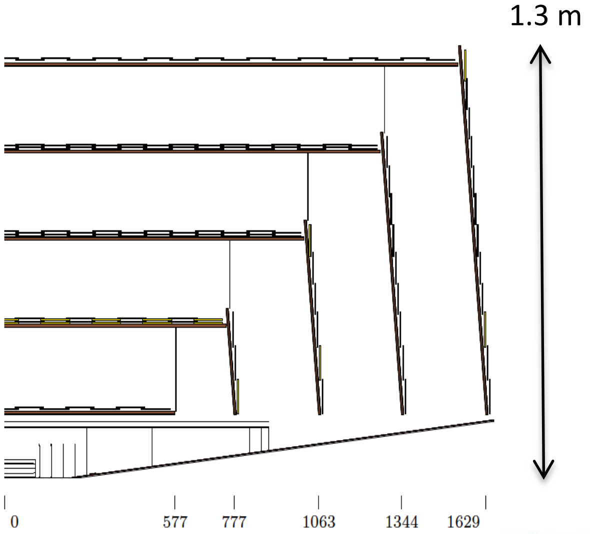
(HV-)CMOS is becoming increasingly relevant for vertex/tracking purposes
Holds promise for accurate + fast + thin devices
+ promise for cost-effectiveness on a large scale

Linear collider, Si-tracker R&D

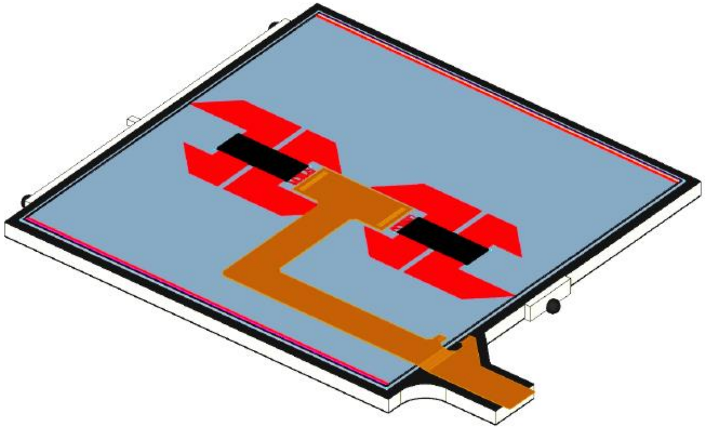
Silicon tracker for the Linear Collider

Better precision requires less mass

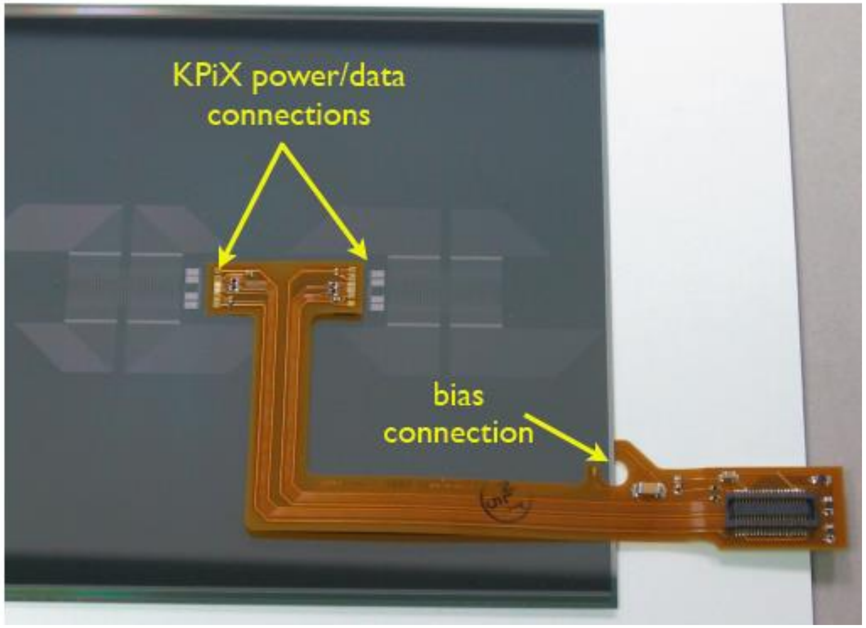
⇒ Aim for ~1% X_0 per layer



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)

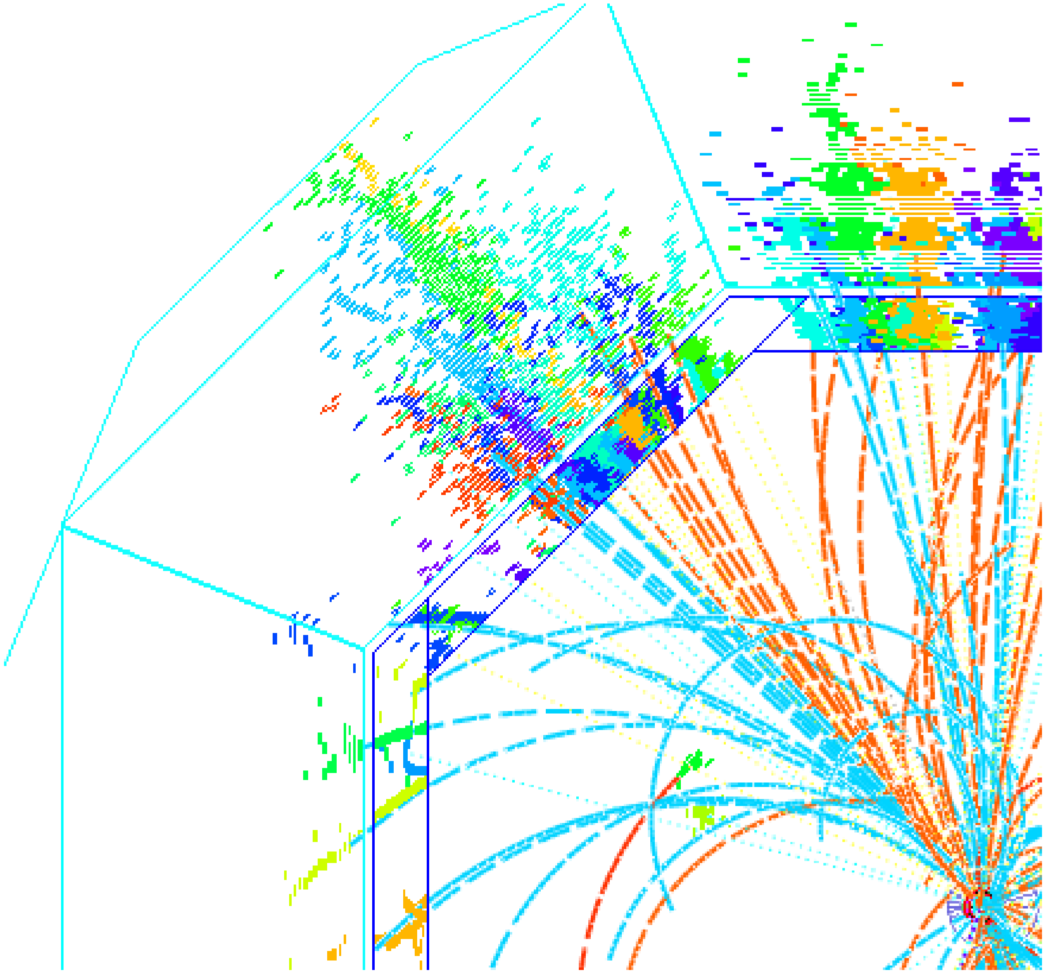
What is PFA?

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 !



PFA calorimetry at CLIC

ECAL

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

cell sizes 13 mm^2 or 25 mm^2

30 layers in depth

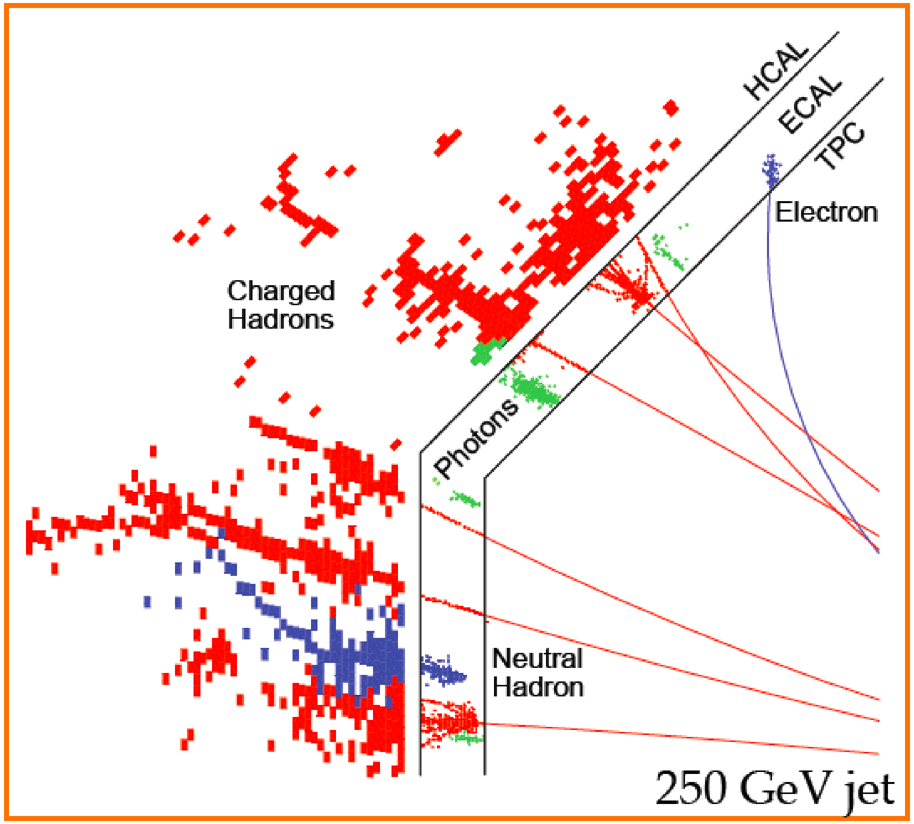
HCAL

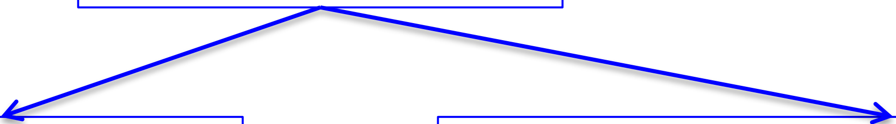
Several technology options: scint. + gas

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)





PFA =
Software + hardware

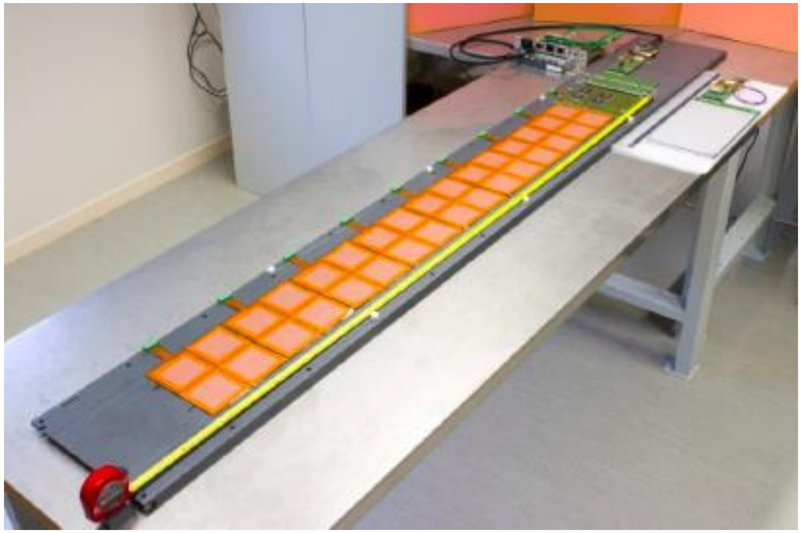
PandoraPFA software

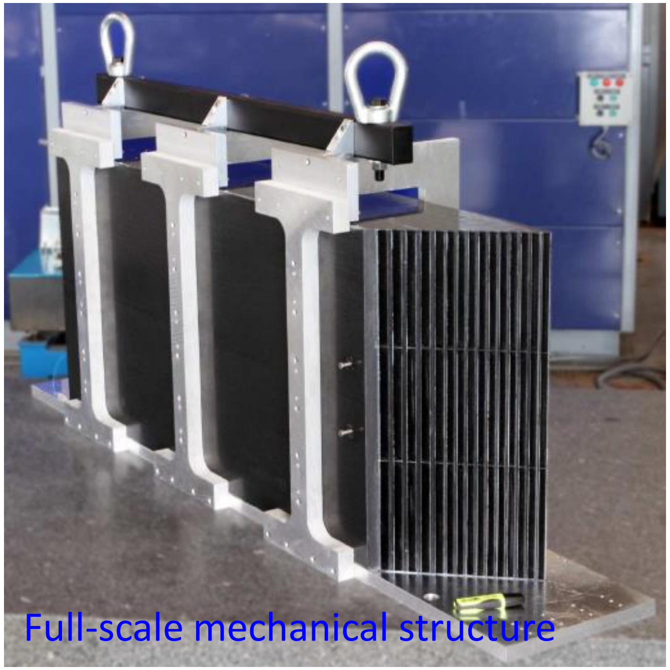
Many fine-grained calorimetry technologies
CALICE R&D collaboration

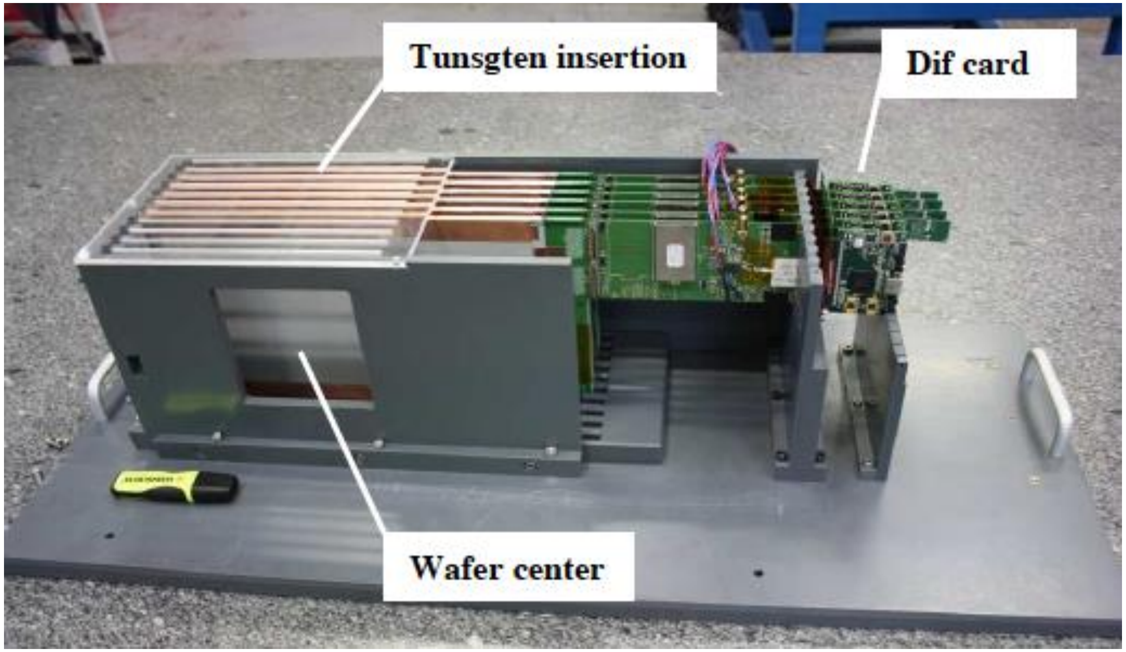
ECAL: Si-W (CALICE)

30 layers in depth
cell size 5.5x5.5mm^2
~100 M ECAL channels at ILC (ILD)
~2000 m^2 silicon
Successful beam tests

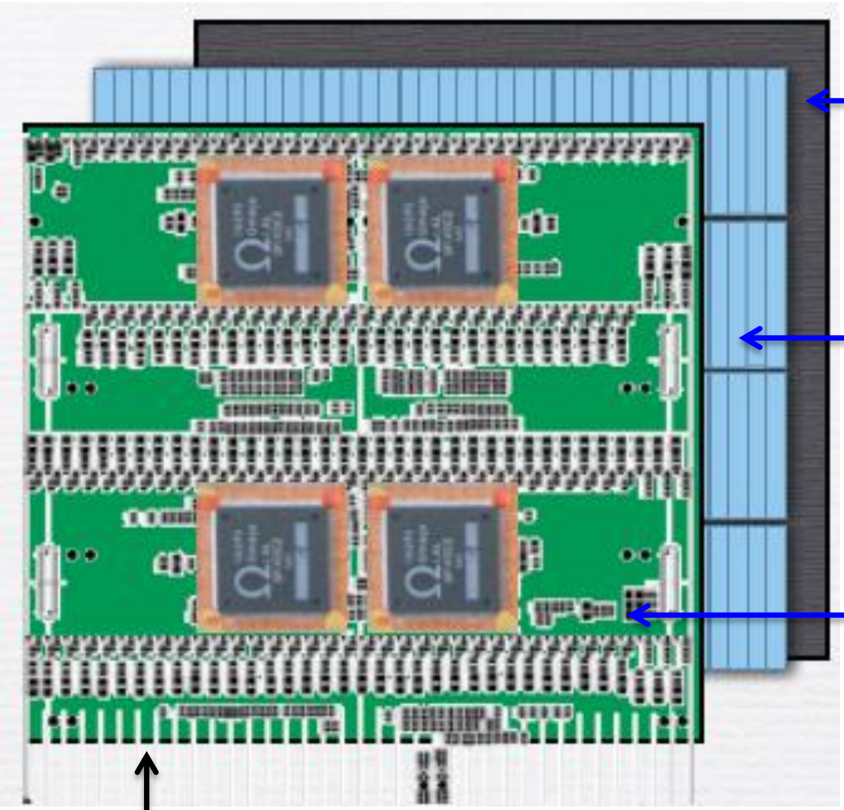
Currently: technological Si-ECAL prototype
Real-scale detector integration model




Full-scale mechanical structure



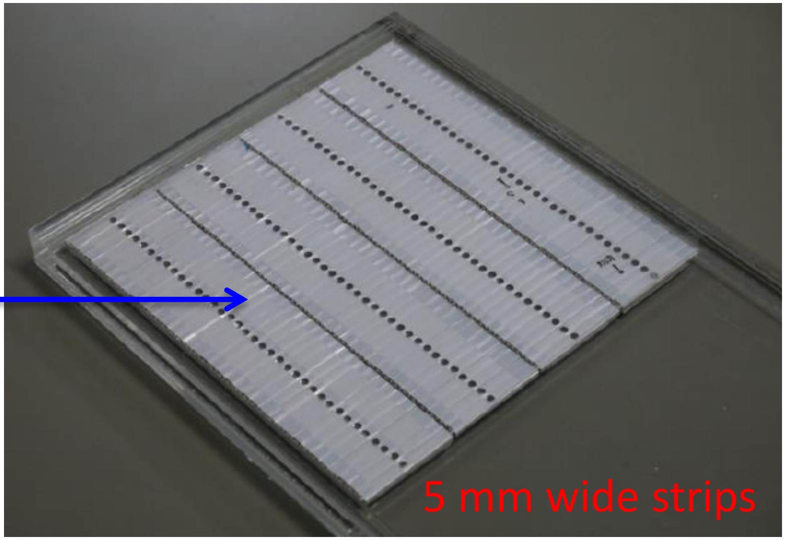
ECAL: Scint-ECAL (CALICE)



absorber

scintillator strips x,y

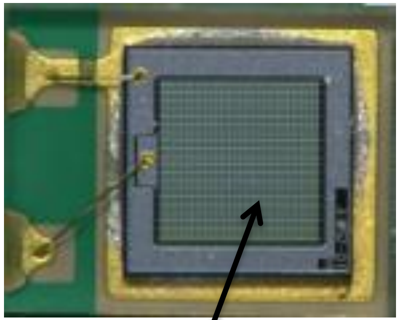
integrated electronics (SKIROC)



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

Fully integrated modules, successful beam tests at DESY

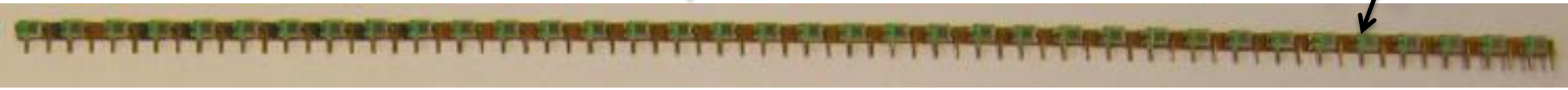
MPPC
1600 pixels
1×1 mm^2



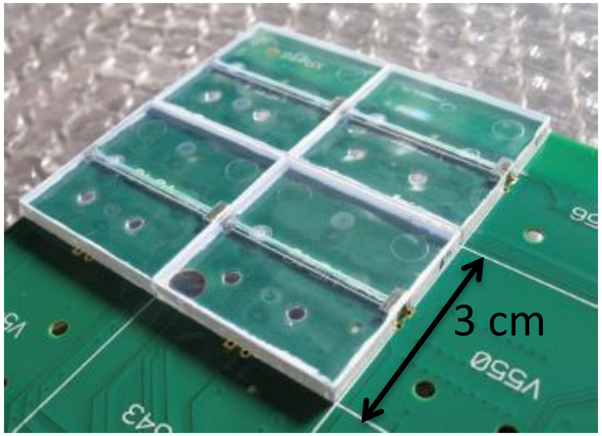
currently exploring SiPM with more pixels

1 cm

Row of MPPC (SiPM)



A-HCAL (CALICE)



3x3 cm^2 scintillator tiles with SiPMs

Integrated electronics (SPIROC chip)

LED SiPM calibration

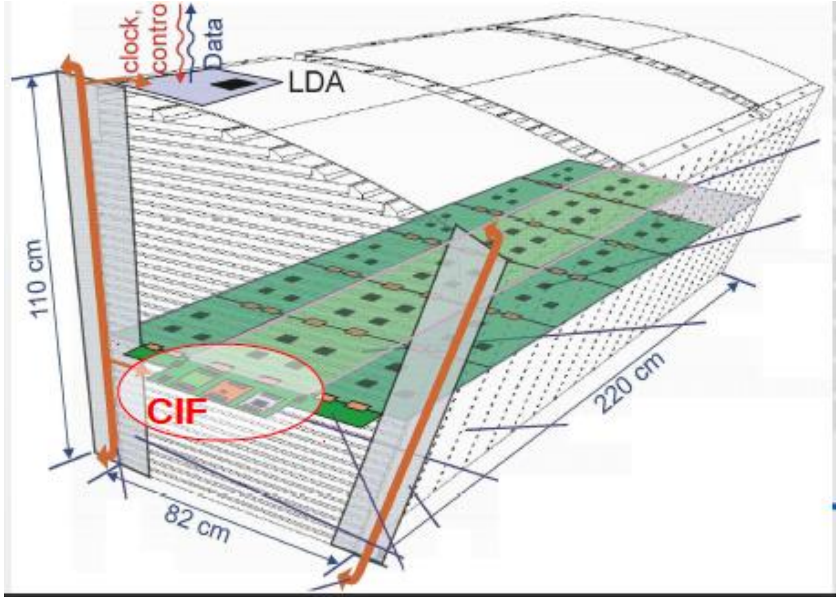
Power-pulsing

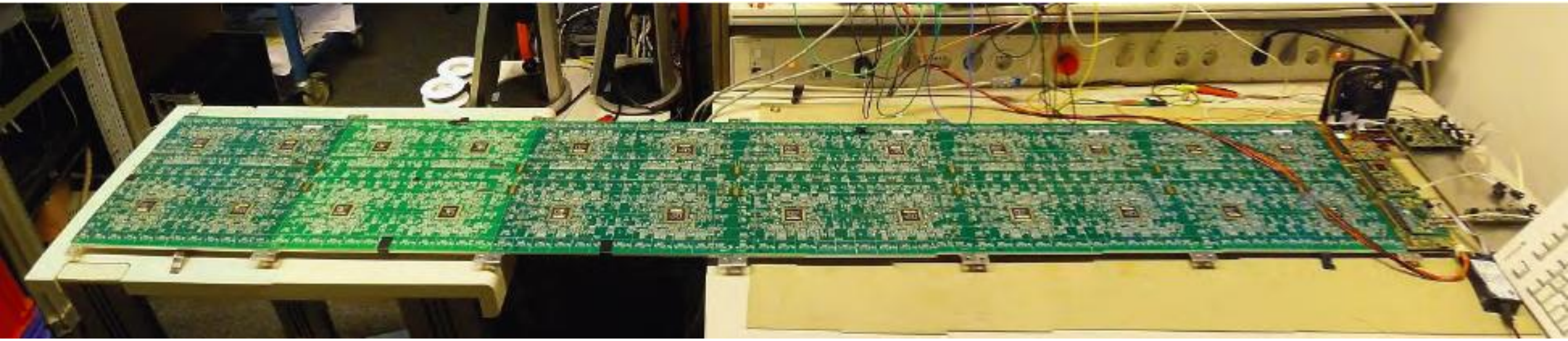
220 cm long modules

Active layer thickness of 5.4 mm

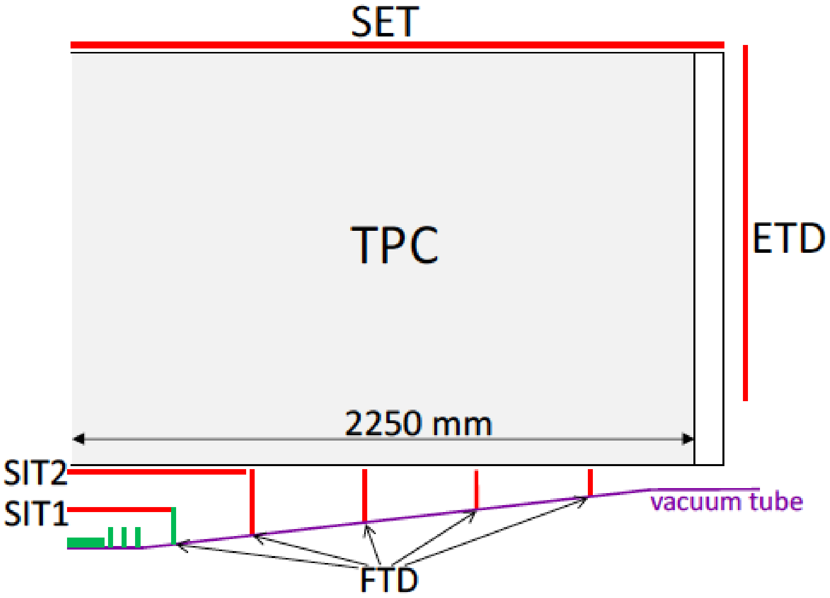
AHCAL 2nd generation fully integrated prototype

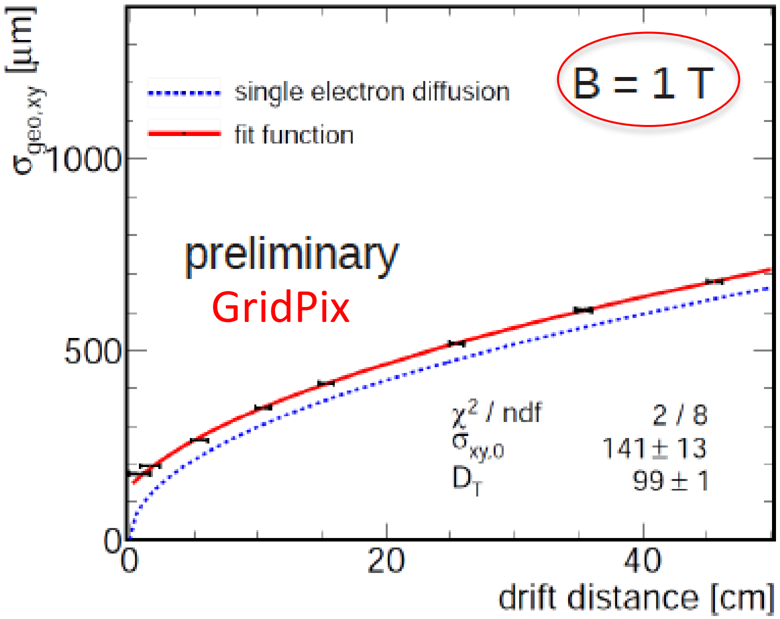
undergoing beam tests





Do you want a TPC for FCC-ee ? (1)





- Momentum resolution (B=4T):
  - TPC only : $\delta(1/p_T) \sim 8.\ 10^{-5}$ /GeV
  - SET+TPC+SIT+VTX: $\delta(1/p_T) \sim 2.\ 10^{-5}$ /GeV

⬋ TPC resolution dominated by diffusion ⬉
While resolution of Si detectors will profit from from technology advances.

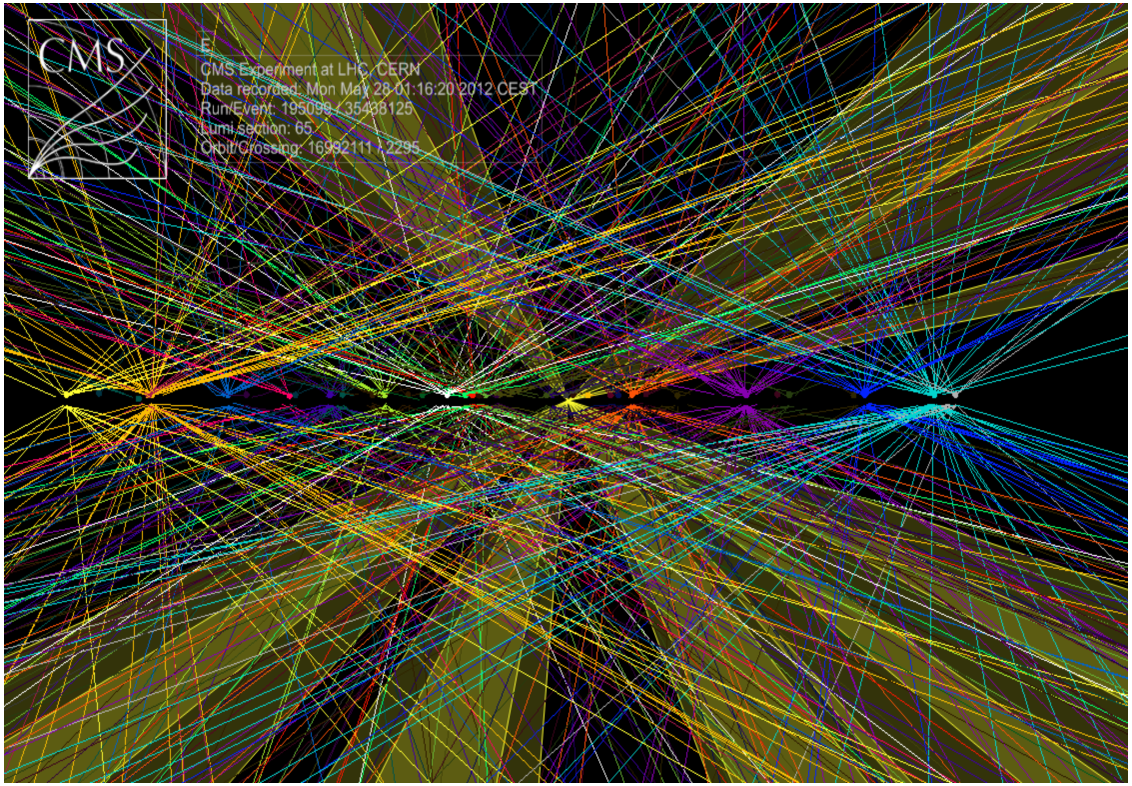
- #pads/#time buckets: ~2.10^6 / 1000 per endcap
- Pad size/#pad rows: ~1 mm x 4-6 mm / ~200 (standard readout) PAD

- Point resolution: in rϕ: < 100 µm ; in rz: ~ 0.5 mm
- 2-hit resolution: in rϕ: ~ 2 mm ; in rz: ~ 6 mm
- dE/dx resolution: ~ 5% (based on LEP TPC experience)

Do you want a TPC for FCC-ee ? (2)

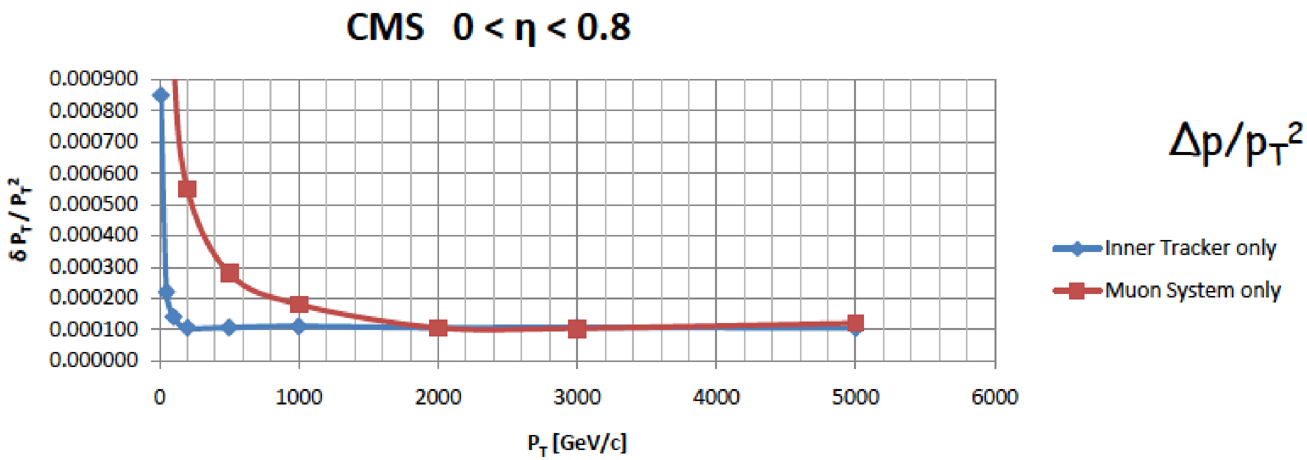
Issues at stake:

- Momentum resolution
- Pattern recognition
- Particle ID

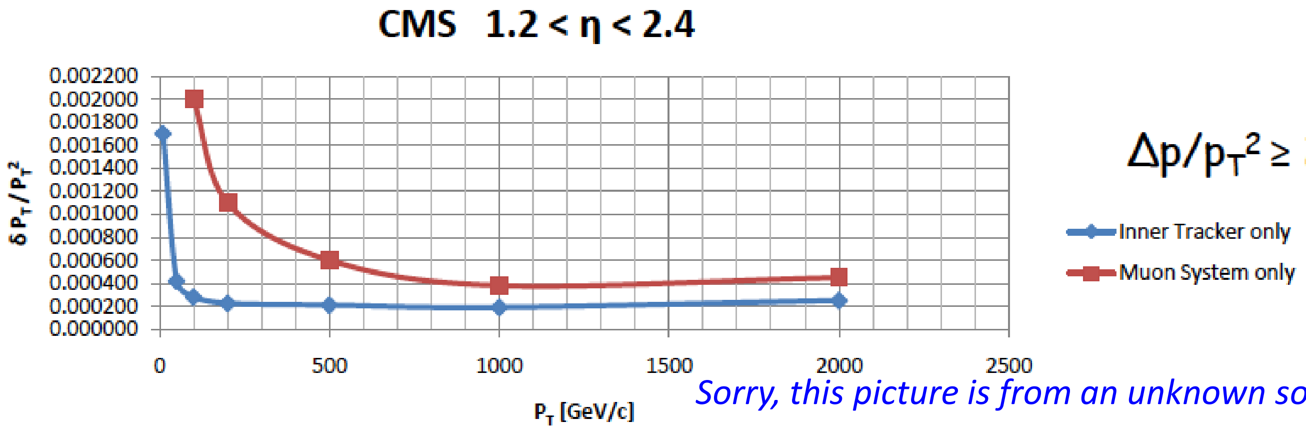


Given the tracking experience at LHC,
Do we need the TPC for pattern recognition ?

Muon system



$\Delta p/p_T^2 \geq 1 \times 10^{-4}$



$\Delta p/p_T^2 \geq 2\text{-}4 \times 10^{-4}$

Sorry, this picture is from an unknown source

Like for CLIC => muon momentum is measured precisely in the tracker

- Better muon momentum precision expected wrt LHC case
- **=> Instrumented yoke is for muon ID only**

Software tools

Linear Collider community => common software suite

Flexible geometry description
- DD4hep

Full simulation in Geant4
- Overlay of beam-induced background

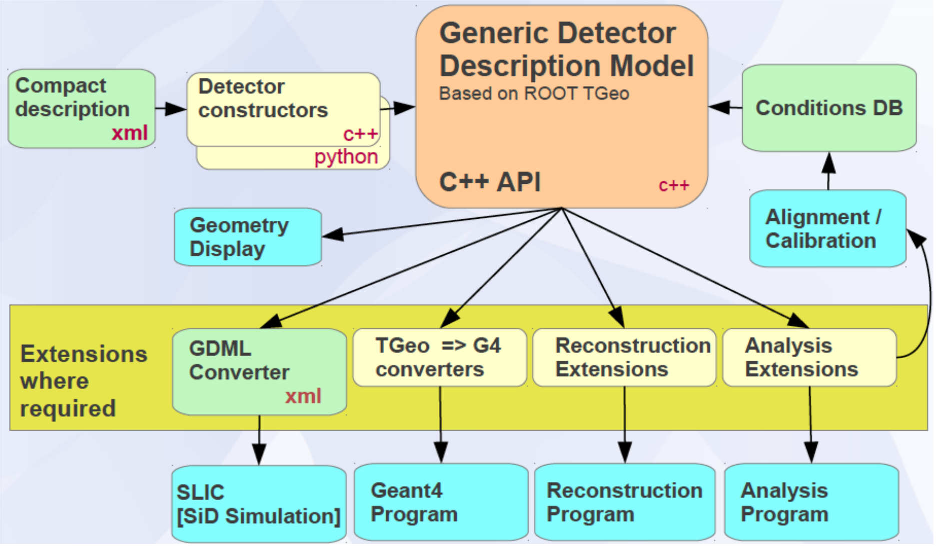
Tracking
- TPC tracking
- Silicon tracking

Particle-flow analysis
- PandoraPFA

Flavour tagging
- LCFI+

+ **Grid production** tool “ILCDIRAC”
(derived from LHCb grid tool)

DD4hep – The Big Picture



DD4hep, developed under AIDA
Modular detector description: Geometry, materials, visualization, readout, alignment, etc.

Software suite developed and maintained by ILC+CLIC
(DD4hep will also be used by FCC-he)
Can probably be shared with other activities (in full or per module)

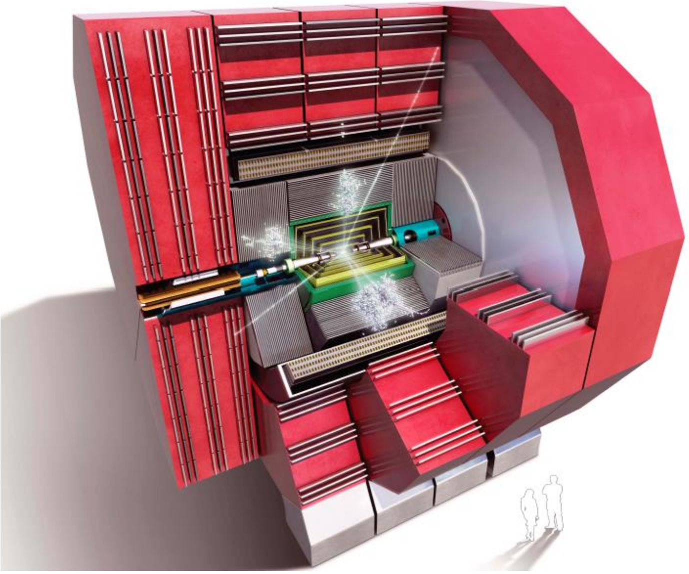
Summary/outlook

Since LEP-times, lots of advances in detector technologies

Challenging detector R&D ongoing for CLIC and for other facilities

FCC-ee => join (!) and profit from these developments

Be ambitious, there is still some time !



thank you

SPARE SLIDES

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)

These general challenges are largely common to CLIC, ILC, HL-LHC, FCC

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
  - => <25 ns for FCC?

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

These general challenges are largely common to CLIC, ILC, HL-LHC, FCC

CLIC machine environment

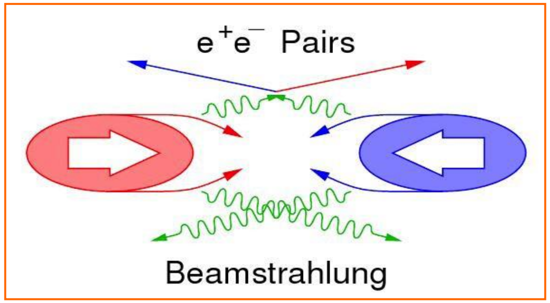
	CLIC at 3 TeV
L ($cm^{-2}s^{-1}$)	5.9×10^{34}
BX separation	0.5 ns
#BX / train	312
Train duration (ns)	156
Rep. rate	50 Hz
σ_x / σ_y (nm)	≈ 45 / 1
σ_z (μm)	44

Drives timing requirements for CLIC detector

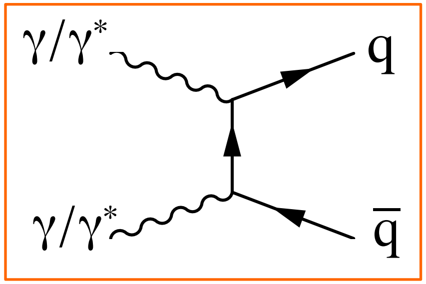
very small beam size

Beam related background:

- Small beam profile at IP leads very high E-field

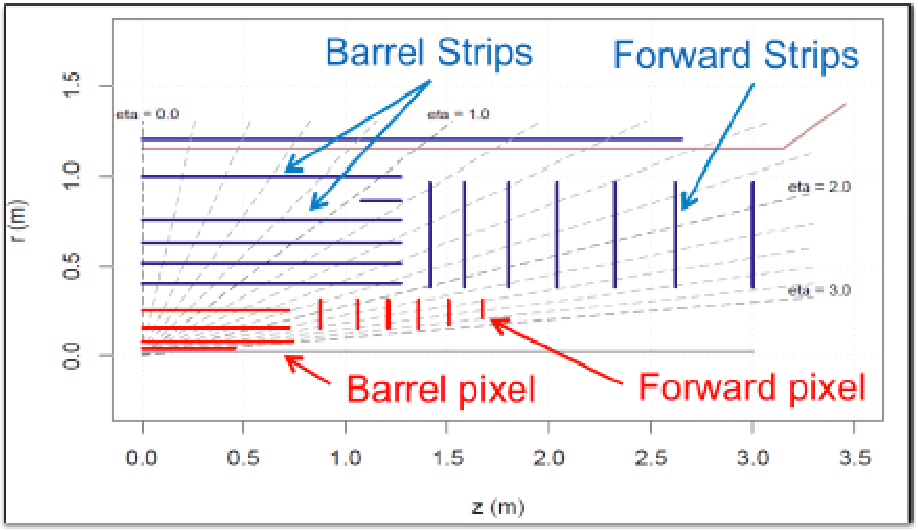


- **Beamstrahlung**
  - Pair-background
    - High occupancies
  - γγ to hadrons
    - Energy deposits (~19 TeV in calorimeter)

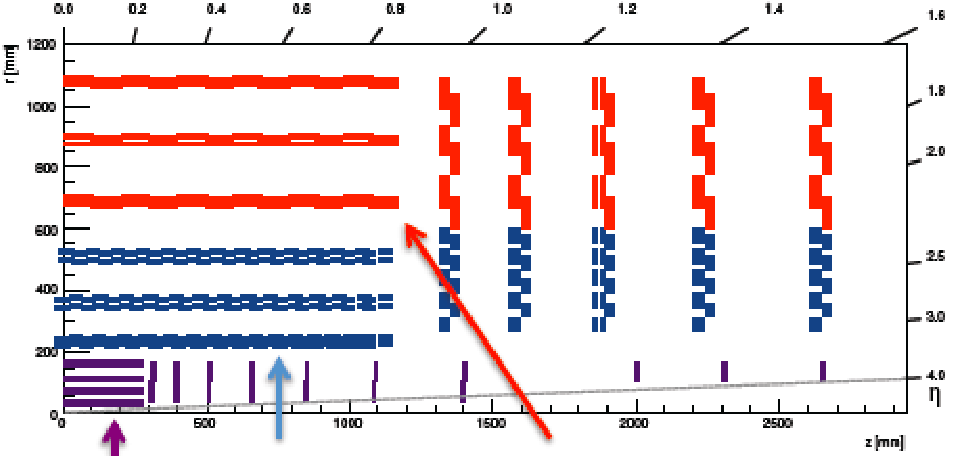


HL-LHC tracker upgrades

ATLAS design



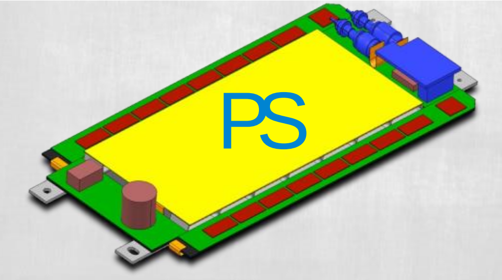
CMS design



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

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

Macro-pixel / Strip module



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

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

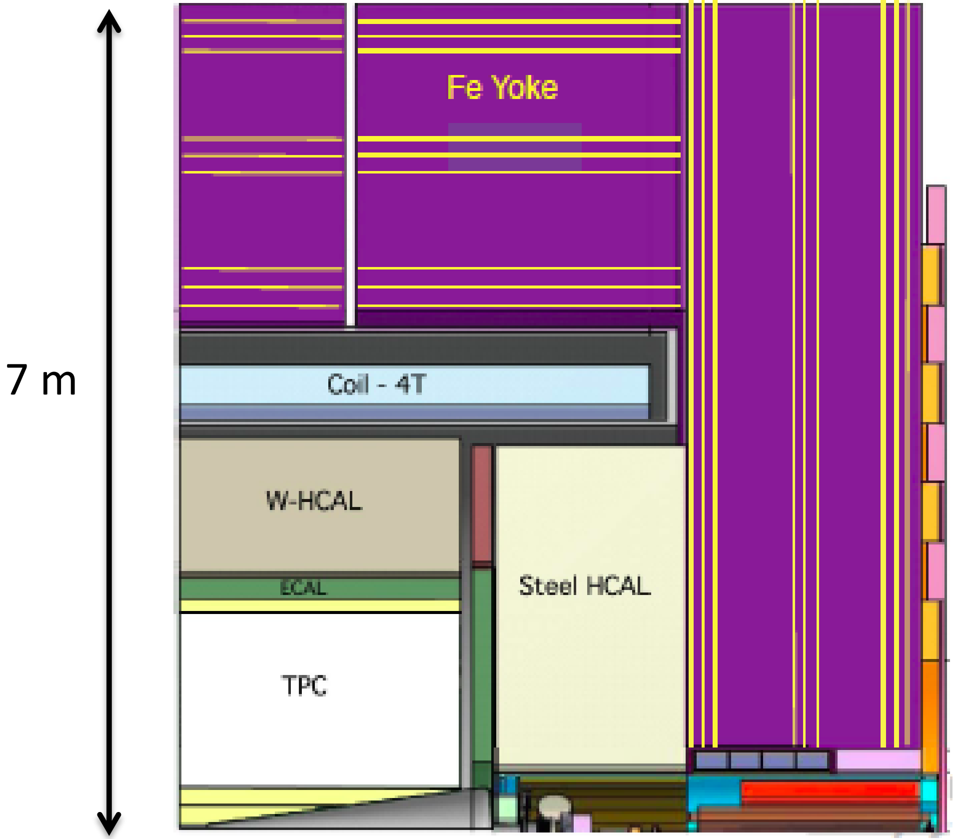
CLIC_ILD and CLIC_SiD

Two general-purpose CLIC detector concepts

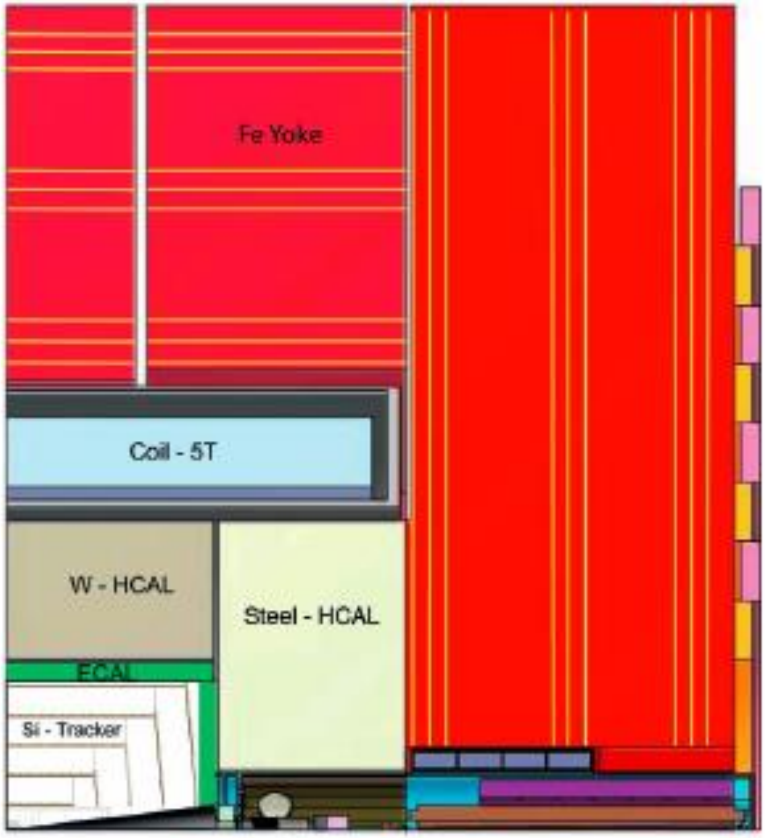
Based on initial ILC concepts (ILD and SiD)

Optimised and adapted to CLIC conditions

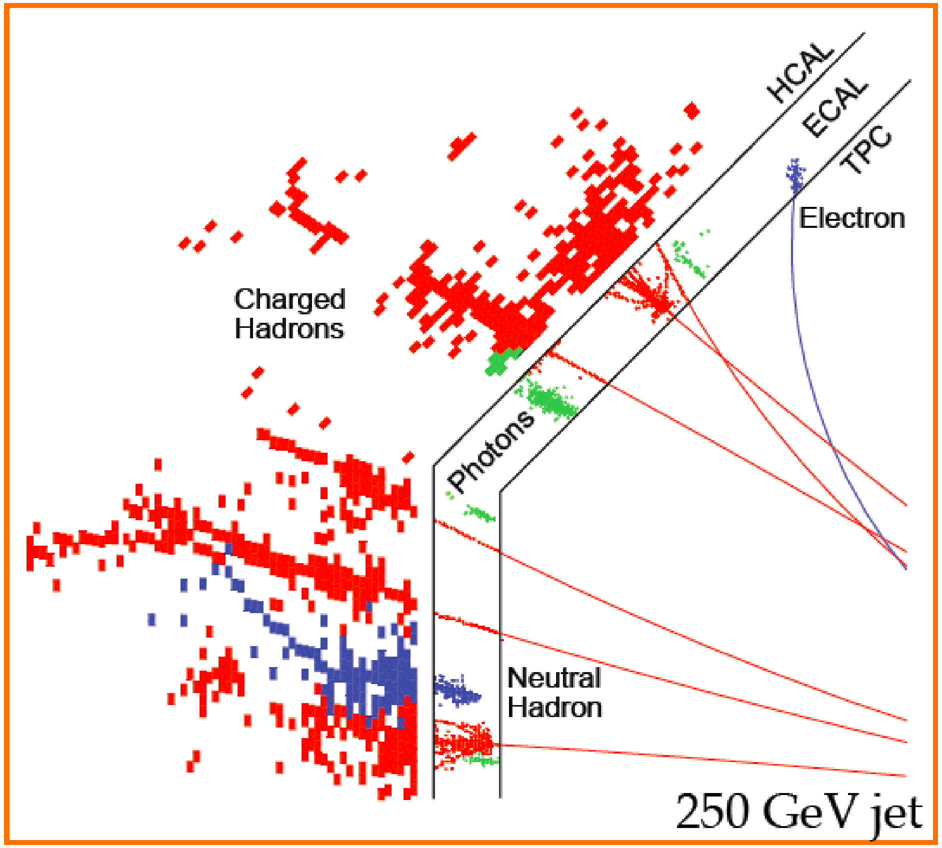
CLIC_ILD

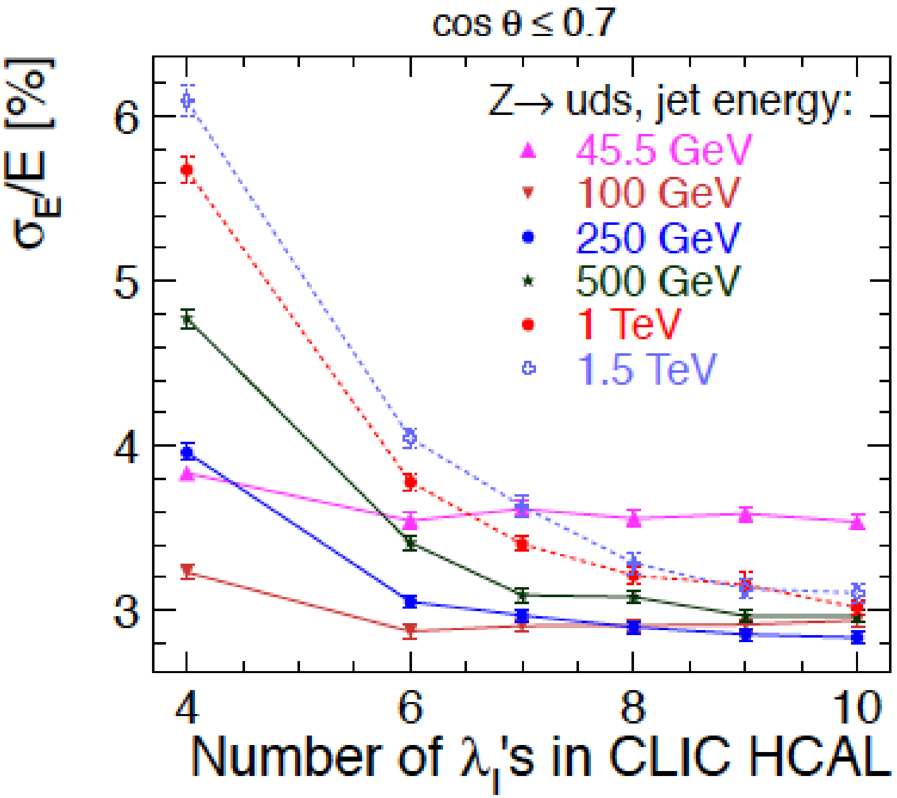


CLIC_SiD



calorimetry and PFA



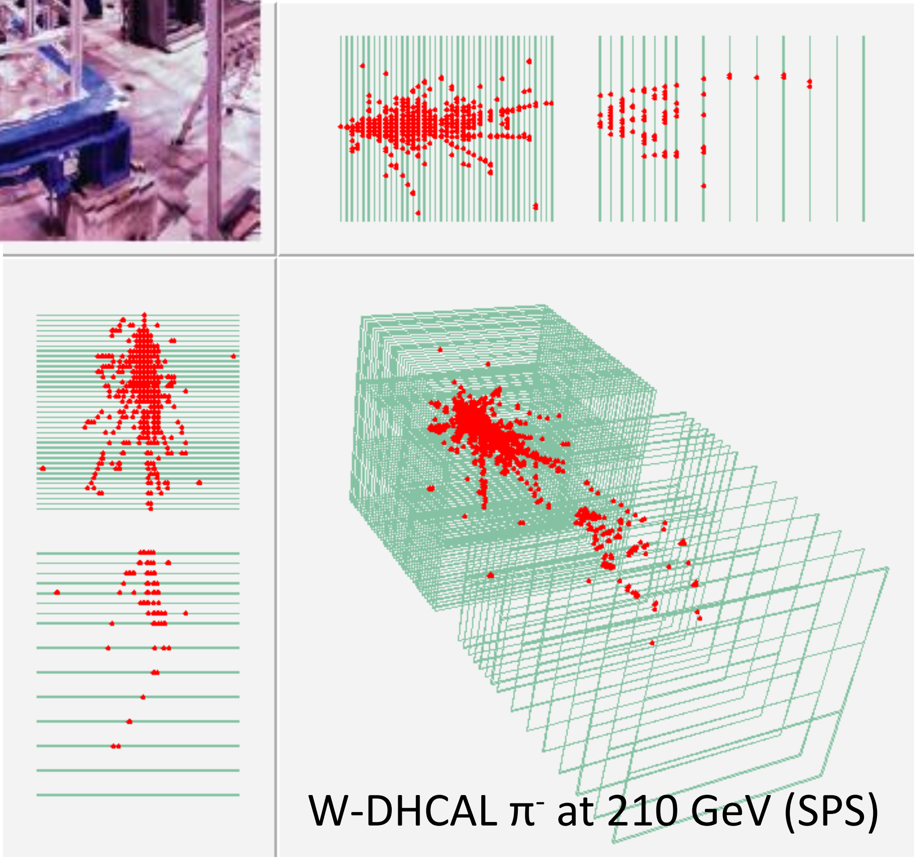


Simulated image
(gives good feeling of the granularity)

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

digital DHCAL glass RPC’s (CALICE)

Steel DHCAL
Tungsten DHCAL
500’000 readout channels



W-DHCAL π^- at 210 GeV (SPS)

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

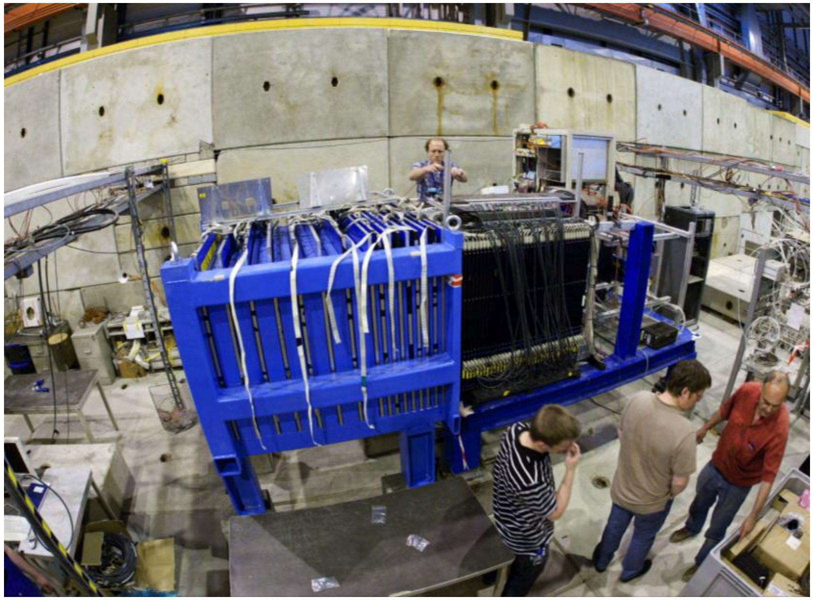
Ongoing R&D with lower-resistivity glass for better rate dependence

Other large-scale protoypes:

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

Analog HCAL: scintillator/tungsten

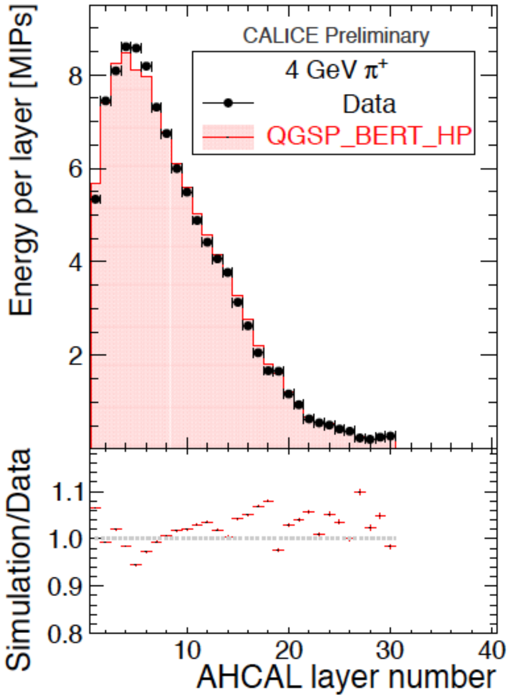
HCAL tests with 10 mm thick **Tungsten absorber** plates,
Tests in 2010+2011 with scintillator active layers, 3×3 cm^2 cells => analog readout



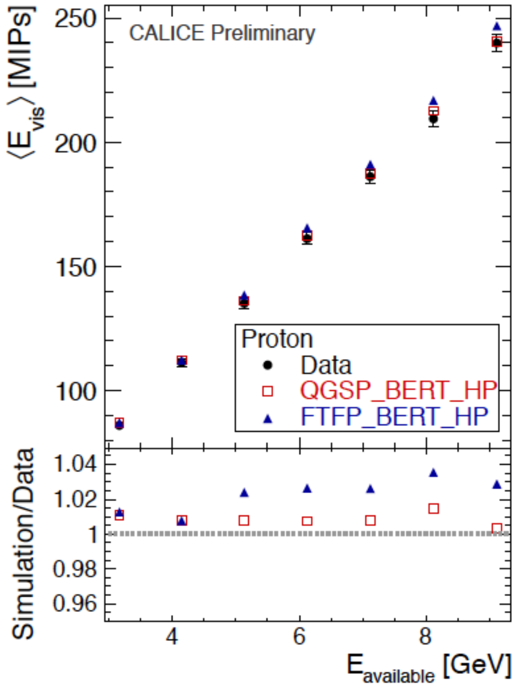
CERN SPS 2011

good agreement with Geant4

longitudinal shower profile, pions



visible Energy protons

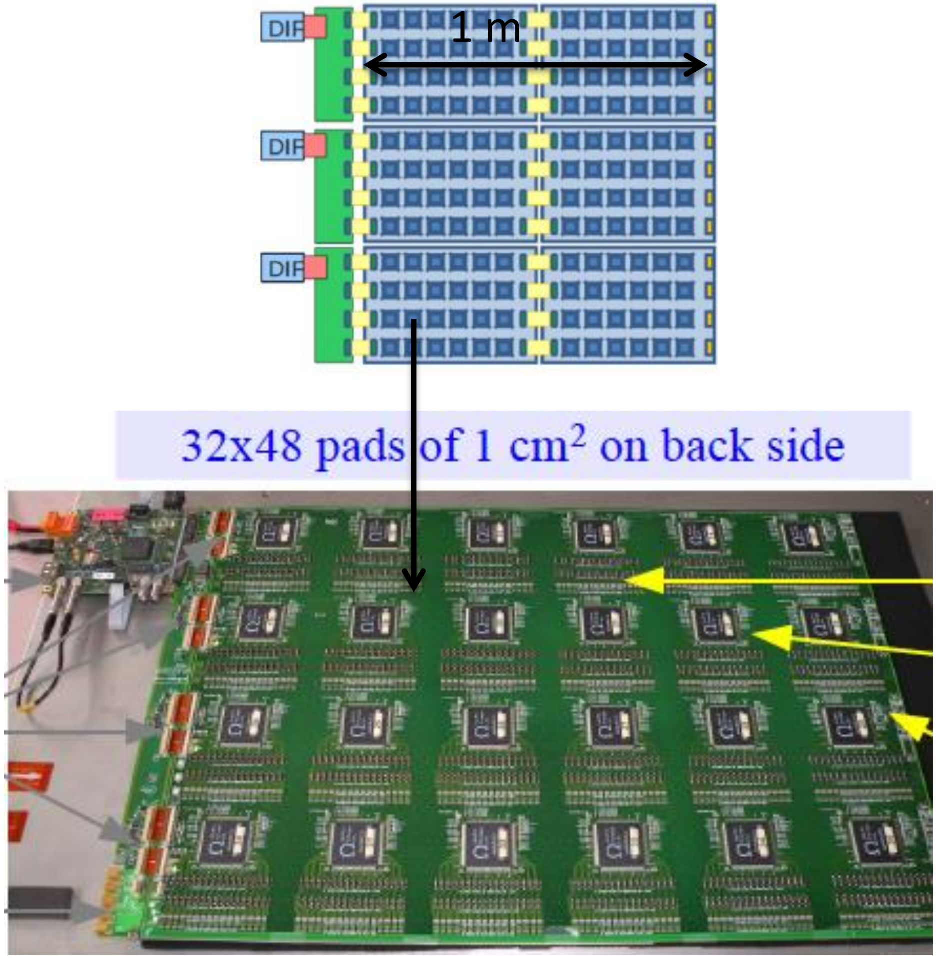


Calorimetry: Micromegas

Micromegas

Two 1 m^2 chambers, multi-threshold readout

Successfully tested within SDHCAL stack, 2012



32x48 pads of 1 cm^2 on back side

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

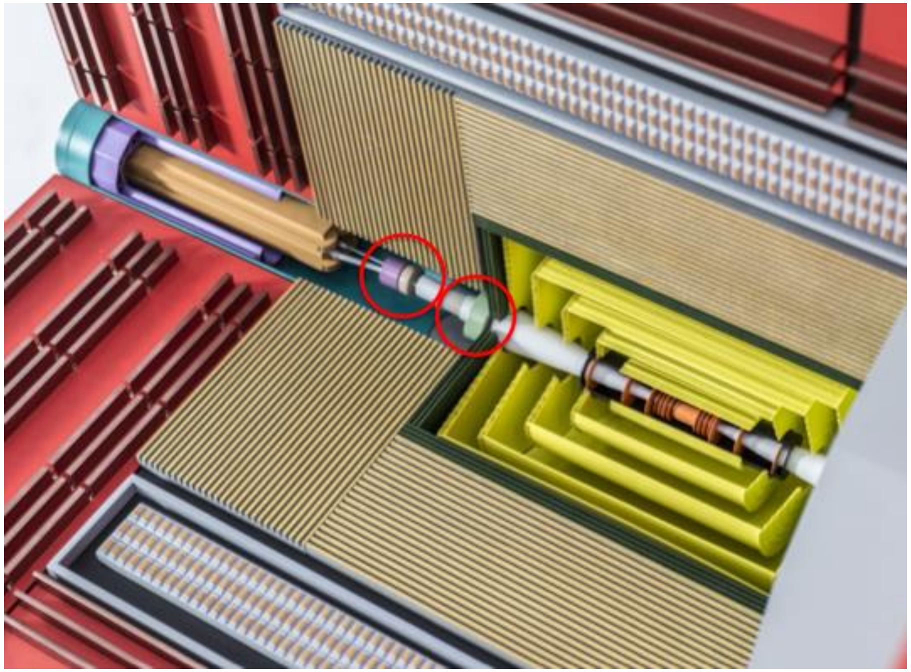
Readout at the outer radius

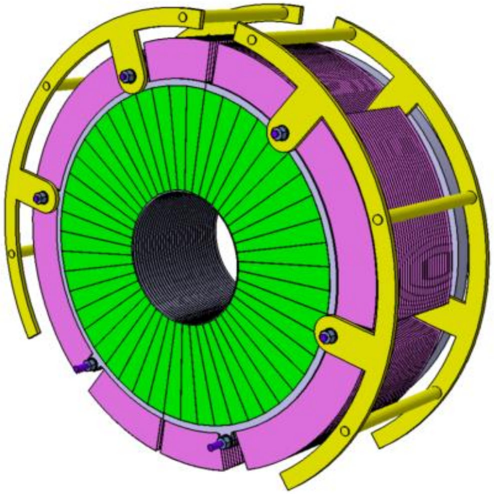
BeamCal angular coverage 10 - 40 mrad

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

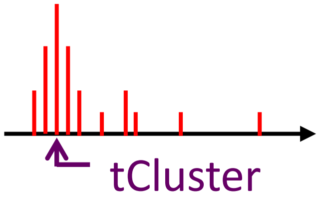
high-radiation performance

=> collaboration with LHC beam monitors

background suppression at CLIC

Triggerless readout of full train

- **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

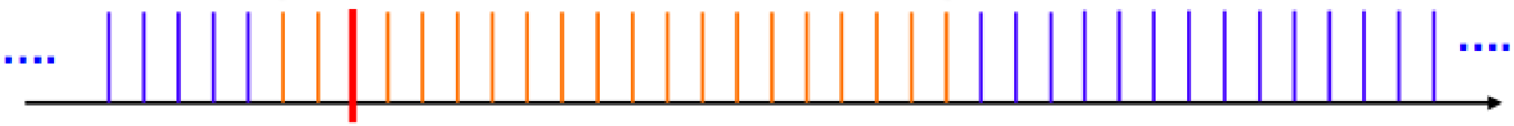
+

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

time window / time resolution

The event reconstruction software uses:

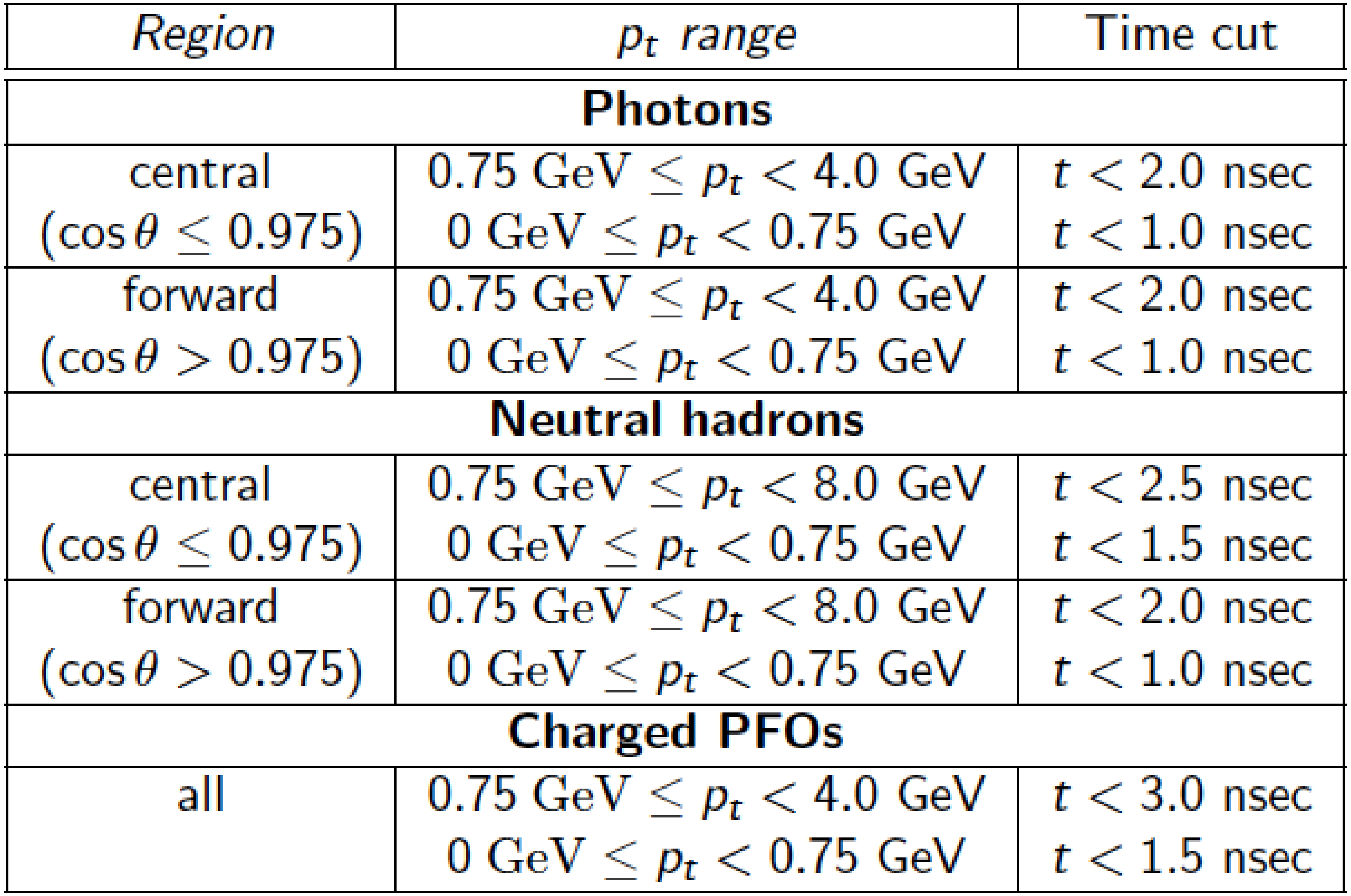
Subdetector	Reconstruction window	hit resolution
ECAL	10 ns	1 ns
HCAL Endcaps	10 ns	1 ns
HCAL Barrel	100 ns	1 ns
Silicon Detectors	10 ns	$10/\sqrt{12}$ ns
TPC	entire bunch train	n/a



t_0 physics event (offline)

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

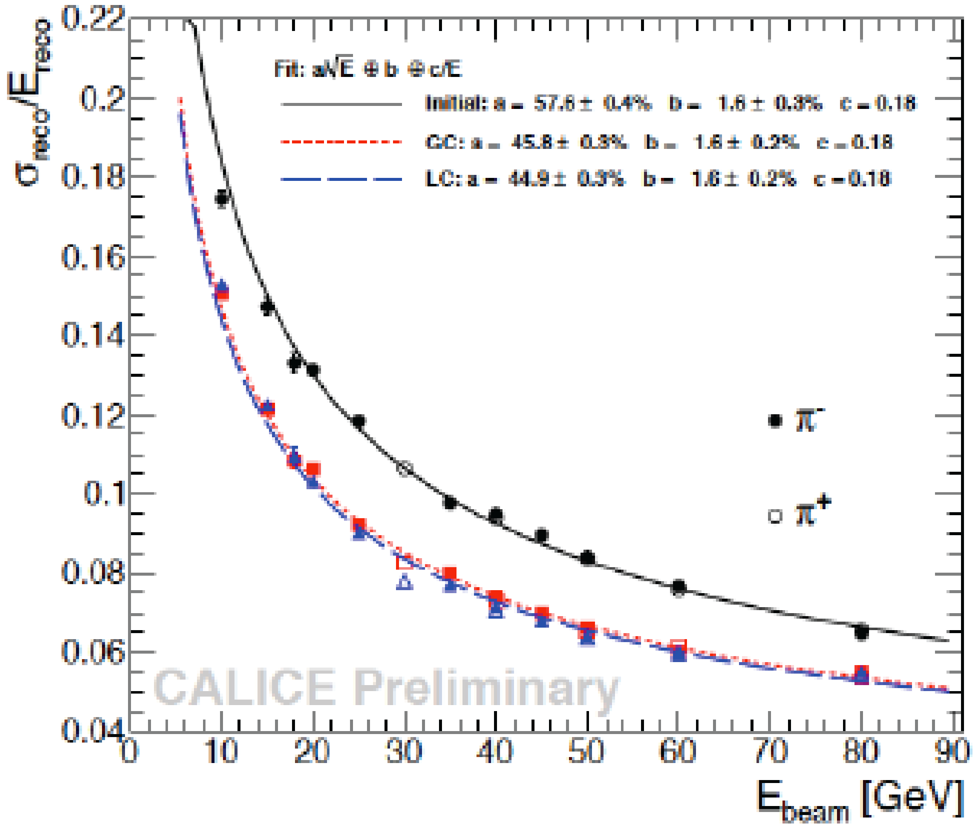
PFO-based timing cuts



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

Software compensation

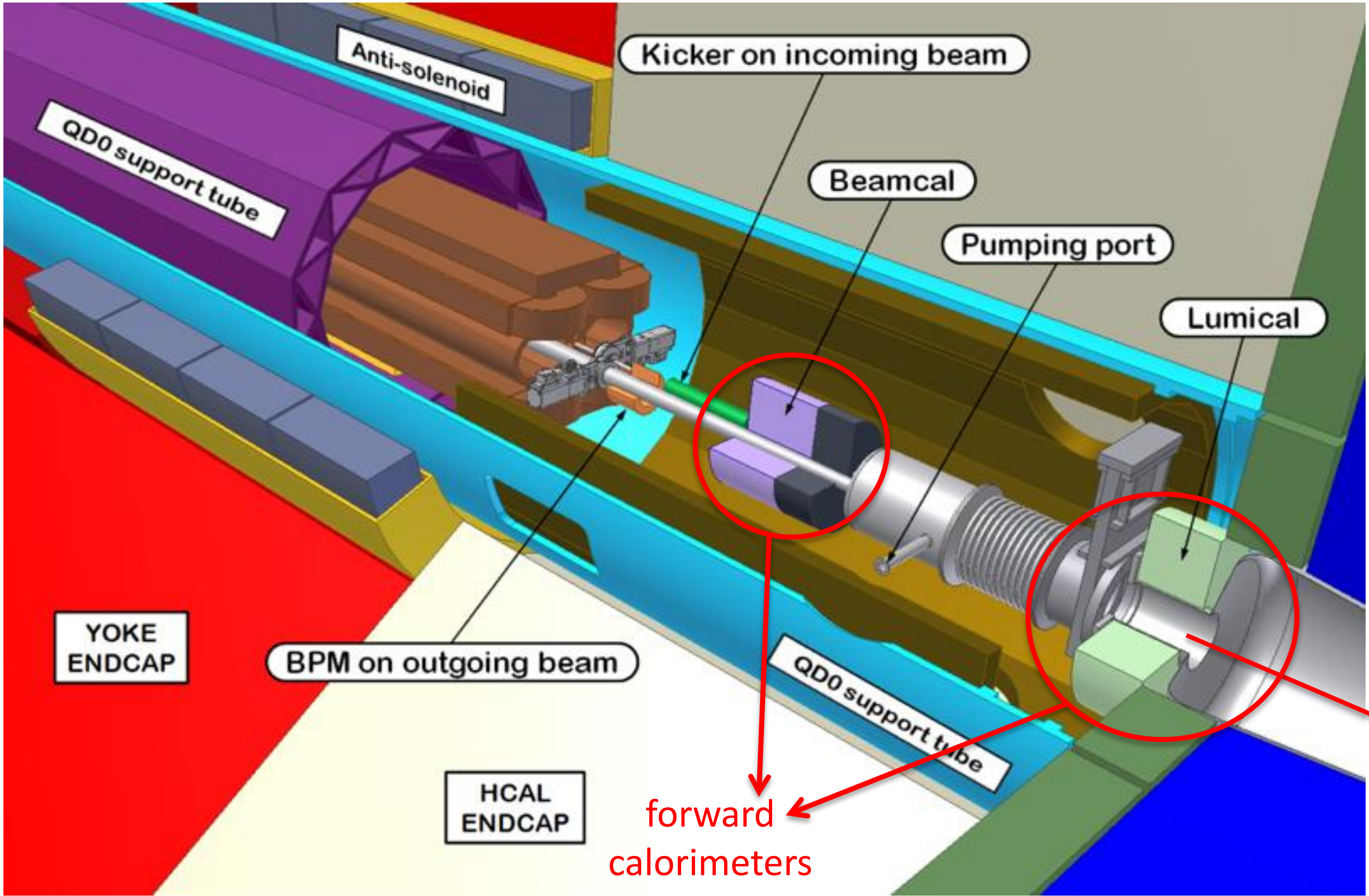
High granularity of the calorimeter can be used to distinguish between electromagnetic (dense) and hadronic (less dense) shower components



CALICE
Steel-AHCAL data

➔ Improved resolution (20% better) and linearity

details of forward detector region



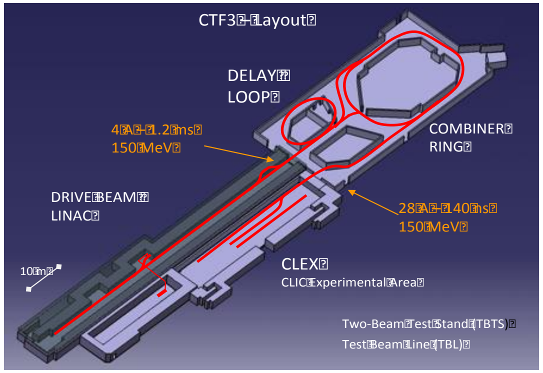
forward calorimeters “FCAL”

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.



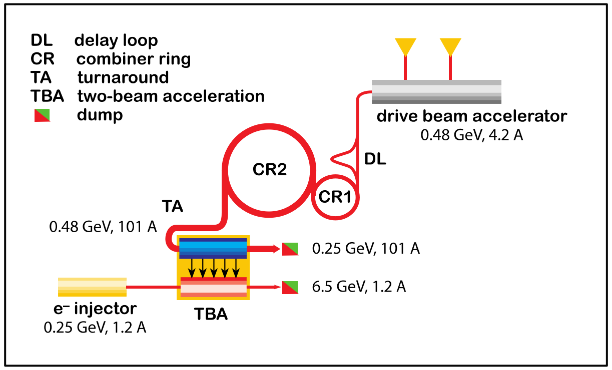
2018-19 Decisions

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.



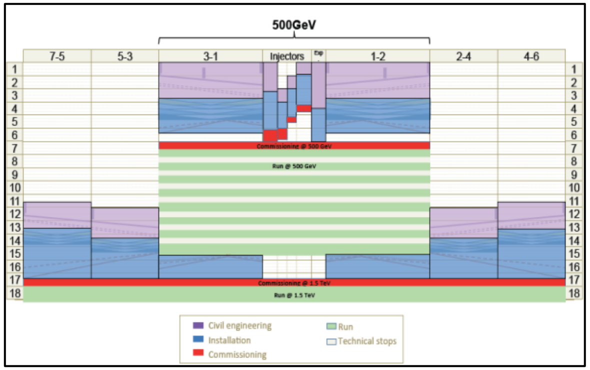
2024-25 Construction Start

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.

Sources

References :

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

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

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

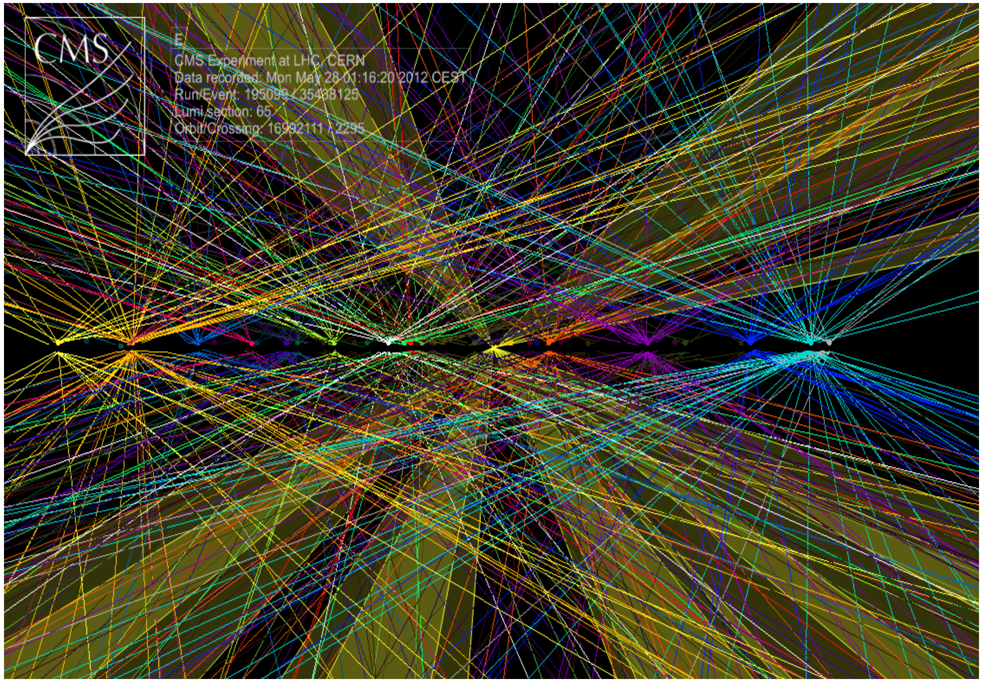
<PU> up to 140 for lumi-leveling at $5\times10^{34}\text{cm}^{-2}\text{s}^{-1}$ at HL-LHC

(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