HGCFC

HIGHTECH
High Granularity Hybrid Timing & Energy Detectors

Y. Sirois,
On behalf of HGCFC
colleagues from

LAL-CNRS Orsay
LLR-CNRS Palaiseau
SPP-CEA Saclay
SEDI-CEA Saclay

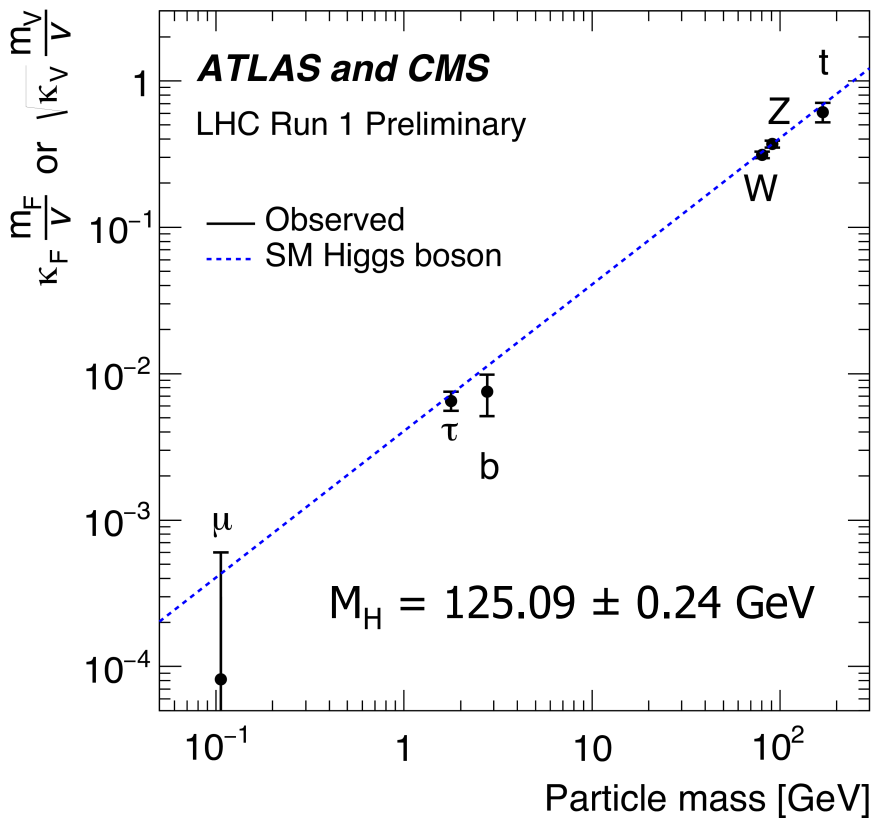
High **G**ranularity **C**alorimeter for **F**uture **C**ollider experiments

P2IO 7 June 2016

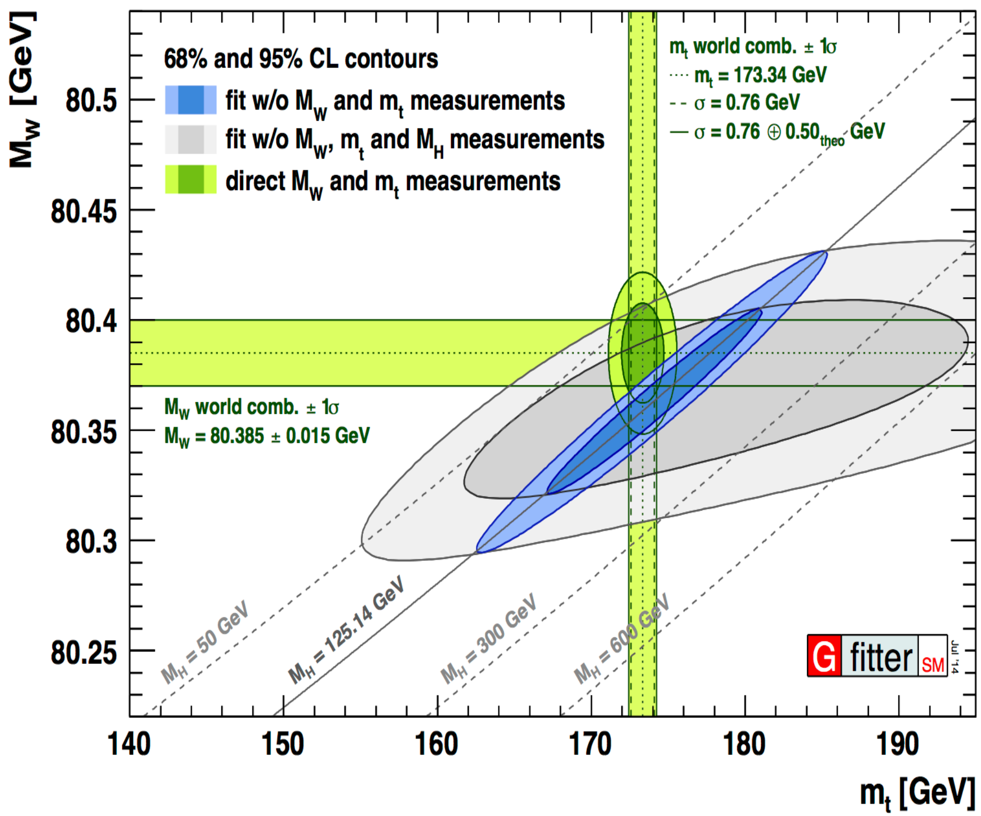

The Landscape

Physics Landscape: A Triumph …

2012: Discovery of the H Boson



Precision Electroweak Constraints



The SM and Higgs boson now firmly established !!!

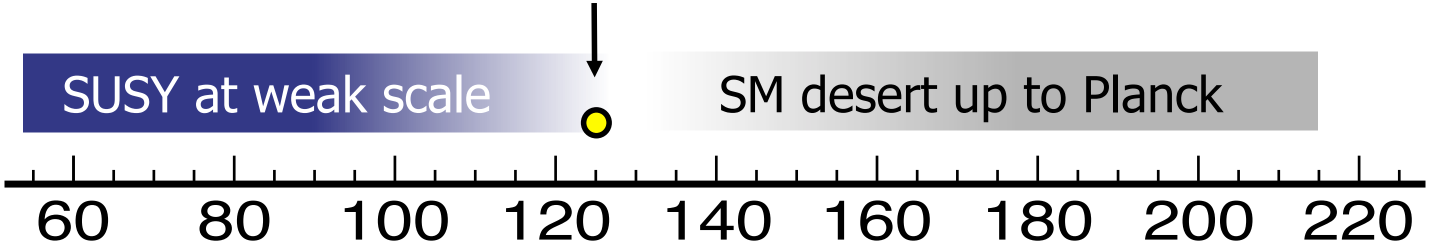
- Origin of interactions (gauge symmetries)
- Quantum origin of mass / short and long range forces
- Origin of particle families
- Early universe (and nature of vacuum) profoundly changed

… but a Paradoxical Triumph

For the first time time in the history of science, we have a theory in principle complete, consistent, and coherent at all scales … (< Planck scale)

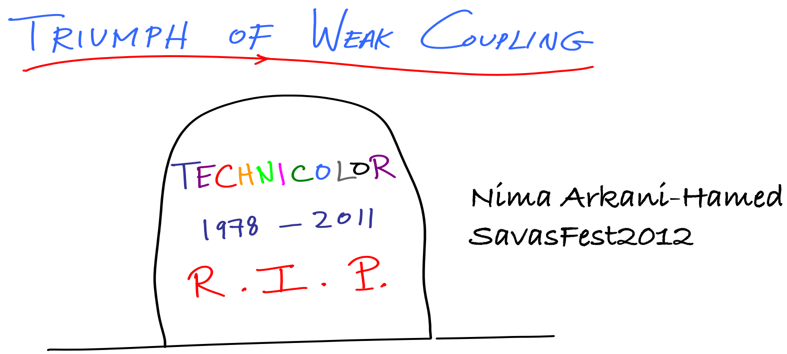
At the same time:

- The SM scalar sector is unstable / "improbable"
  (problem of hierarchy, instability of H boson mass, arbitrary Higgs potential)
- The flavour structure of the theory is not understood
- The matter-antimatter asymmetry in the universe is not understood
- The SM does not provide a candidate particle to explain Dark Matter



So far at the LHC:

NO Technicolor
NO New Z′, W′ Gauge bosons
NO Supersymmetry
NO Extra-dimensions



Higgs Boson

New Physics ?
Naturalness ?

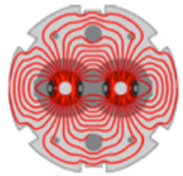
Ready to decide of future ?

New
Paradigm ?

? **FCC hh**
FCC eh

2011
2012
2013
2014

LHC RUN I



2015
2016
2017
2018

LHC RUN II

2019
2020
2021
2022
2023

LHC RUN III

2024
2025
2026
.
.
2035

HL-LHC

Intensive Detector R&D is **now**

irrespective of the collider options!!!

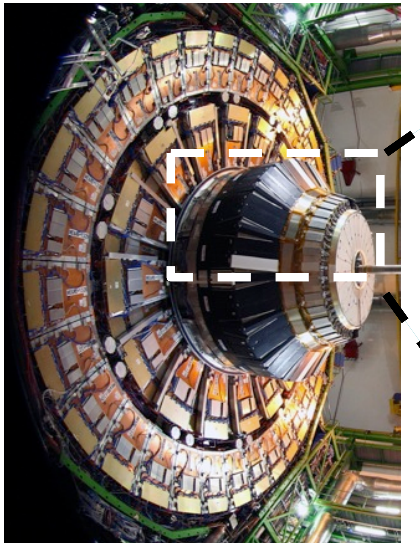
Precision measurements

ILC ee
? **CLIC ee**
FCC ee

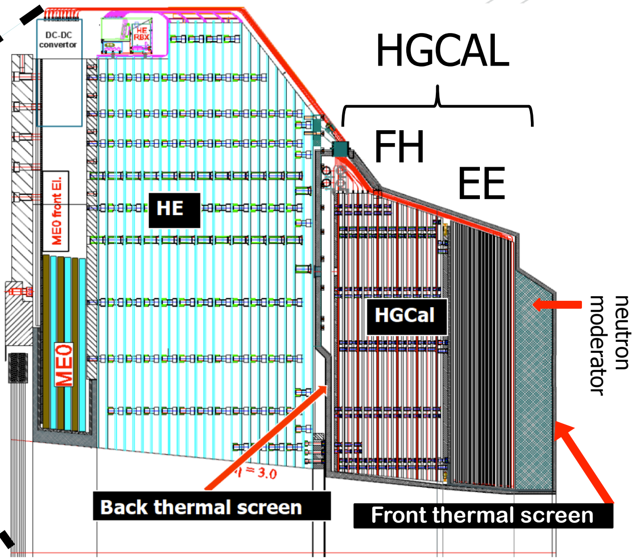
International Context: CMS @ LHC

Need to replace the forward calorimeter because of radiation damage

Current Endcap
$PbWO_4$ crystals



New high granularity Endcap
SiW Calorimeter design for HL-LHC



HGCAL =
EE+FH Highly granular

- **312** Cassettes,
- **44k** Wafers
- **100k** FE ASICS,
- **6M** Channels

- The CMS-LLR group, with help from Omega lab., is at the origin* of this ambitious CMS project selected in 2015

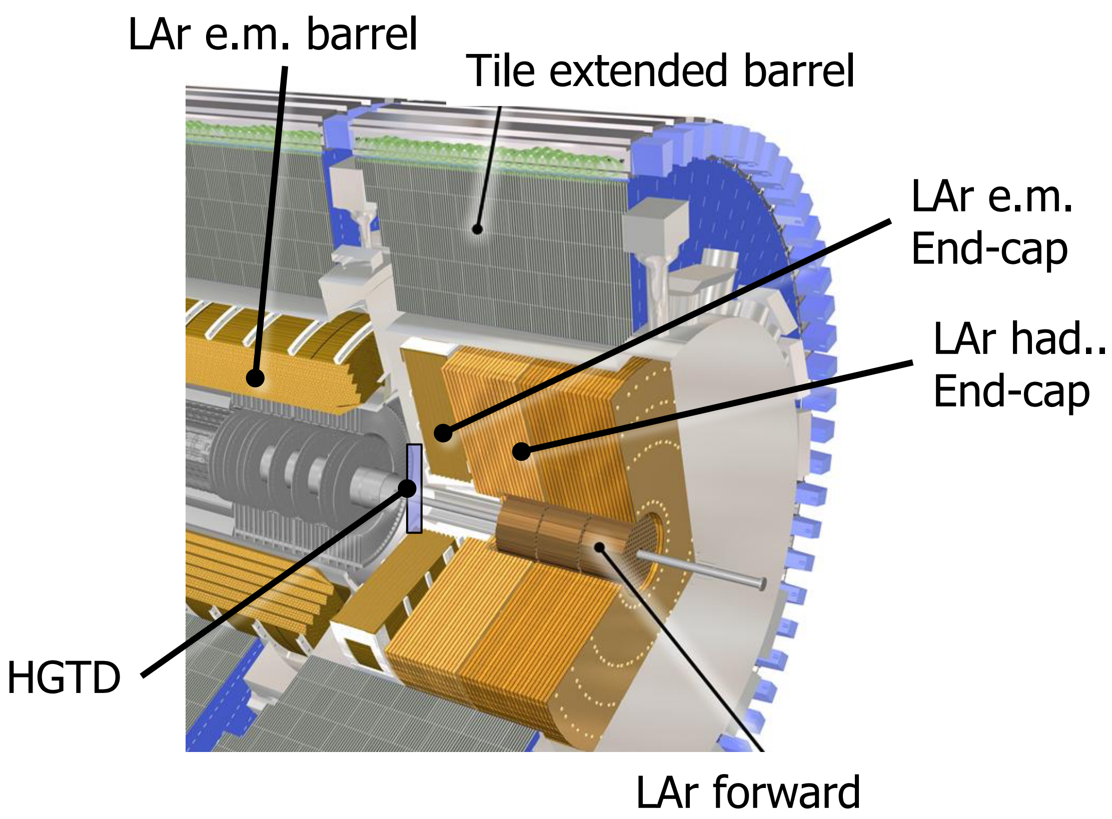
  * LLR polytechnique, CERN, U. Minnesota, IC London, UC Santa Barbara,

- The CMS HGCAL project now has ~ 100 members from 20 institutes among which 3 French IN2P3 and IRFU labs

Members of this P2IO Project have responsibilities in the HGCAL design and mechanics, trigger electronics, timing, and test beam measurements

International Context: ATLAS @ LHC

Need a dedicated "timing" forward detector to deal with pile-up at HL-LHC



The HGTD project started in 2015

Aim: 20-30 ps timing precision
for $(2.5<\eta<4.3)$

[coverage of actual so-called
Inner-wheel of the LAr forward
e.m. calorimeter]

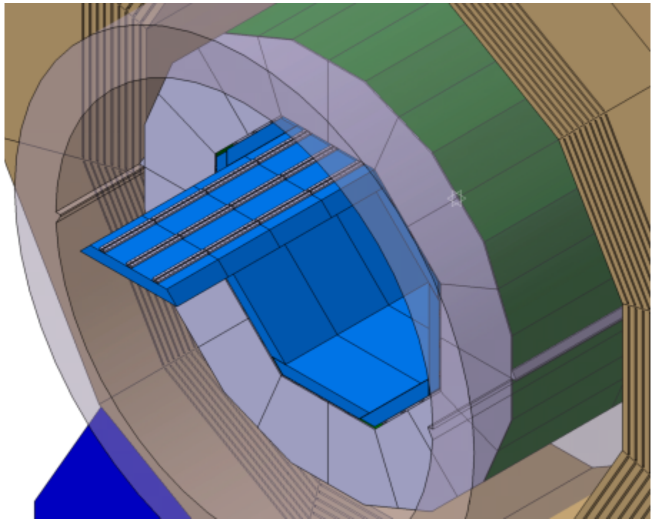
~ 4 layers in depth
~ 5x5 mm^2 transverse granularity
to optimize the timing resolution
versus the cell occupancy

- A Silicon High Granularity option is proposed by France (LAL, LPNHE, Omega, CCPM), US (Santa Cruz, BNL), and CERN

Members of this P2IO Project have responsibilities in the HGTD design, integration, simulation, and performances

International Context: CALICE @ ILC

Propose in CALICE a SiW-ECAL designed and optimized for the ILD



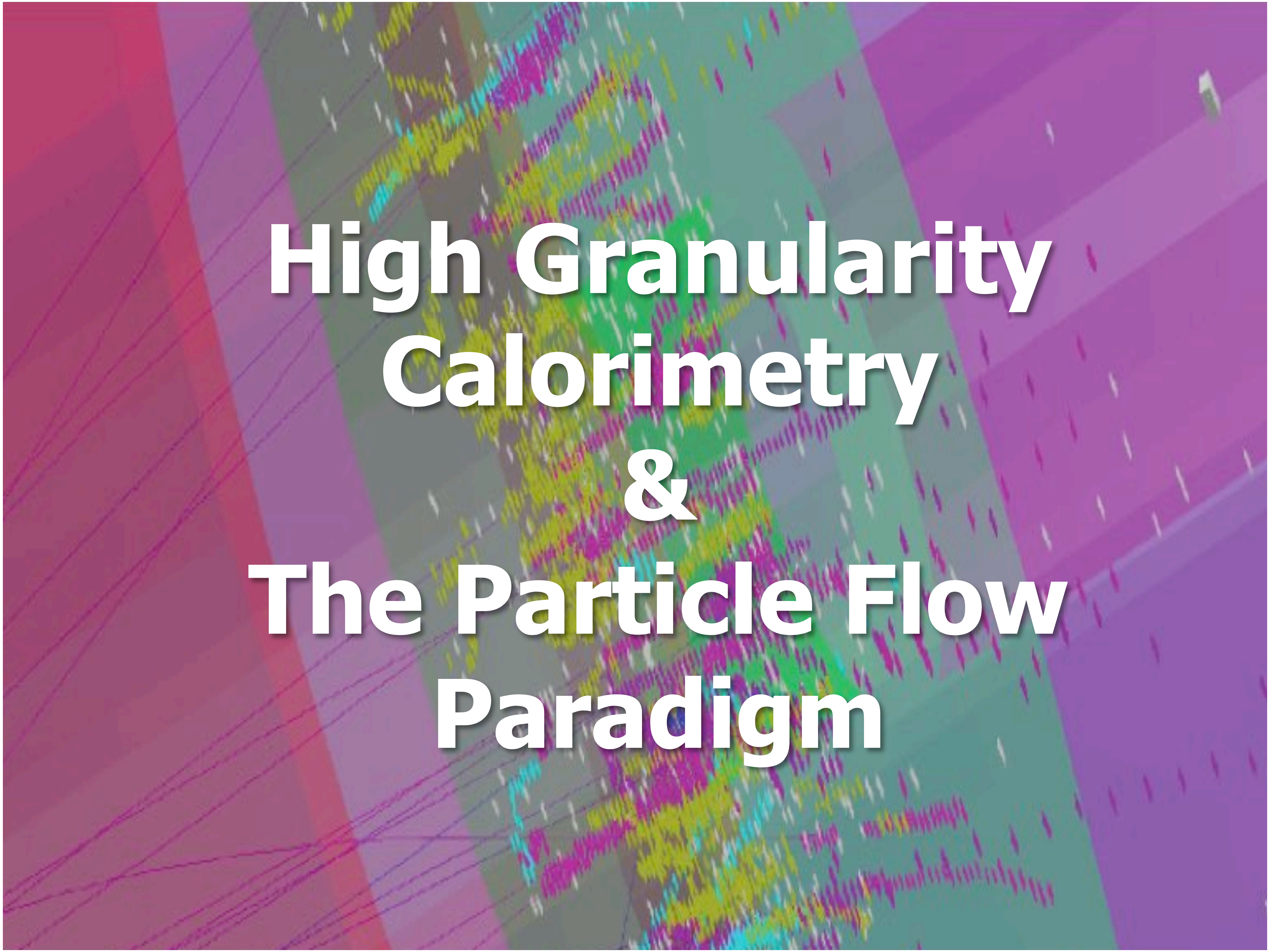
A highly integrated detector for high granularity and Particle Flow:

- **40** Barrel + **24** Endcap Modules
  - **9600** Cassettes
    - **~75k** PCBs
      - **300k** Wafers (2500 m²)
        - **1.2M** readout chips
          - **77M** Chan.

- The CALICE LAL and LLR groups involved in our P2IO project invented and designed the SiW-ECAL for the ILD

- The ILD has ~ 600 members and is composed of 68 institutes from 16 countries, among which 9 French laboratories from IN2P3 and IRFU

Members of this P2IO Project have responsibilities in the CALICE SiW-ECAL design, and the related project and coordination


High Granularity
Calorimetry
&
The Particle Flow
Paradigm

Evolution of Calorimetry Techniques

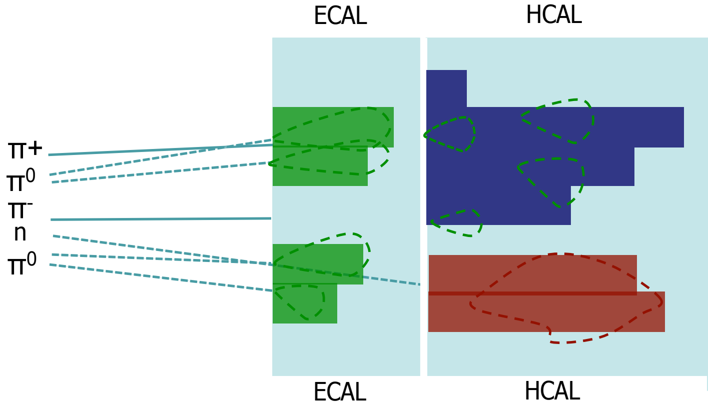
A Natural Evolution of Calorimetry Detector Techniques

- UA1/UA2, ZEUS ⇔ E measurement devices

1980's

Keyword: compensation

$$E_{jet} = E_{ECAL} + E_{HCAL}$$

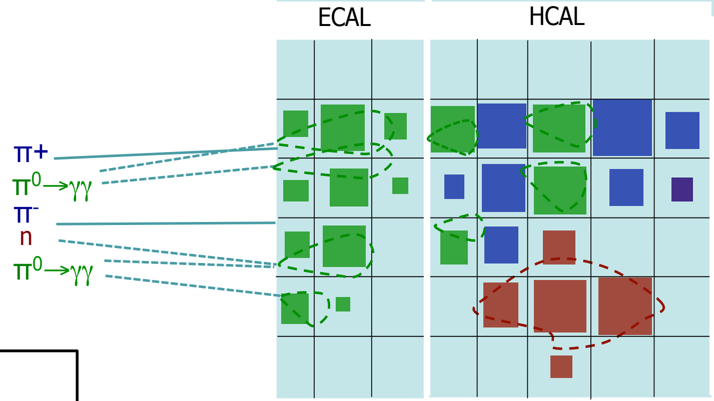


- H1/D0 ⇔ Eflow measurement devices

1990's

Keyword: segmentation

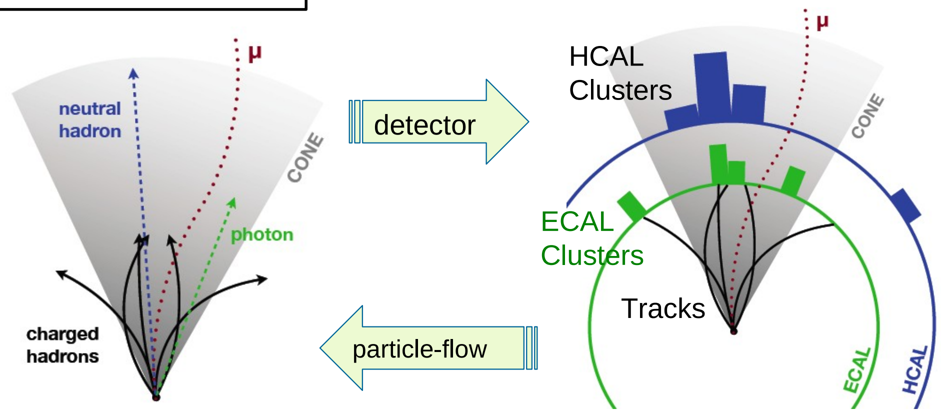
$$E_{jet} = \Sigma_{ijk} E^{i}_{ECAL} + E^{j}_{o} + W_j E^{j}_{h} + w_k E^{k}_{n}$$



- ALEPH/CMS ⇔ Particle Flow reconstruction

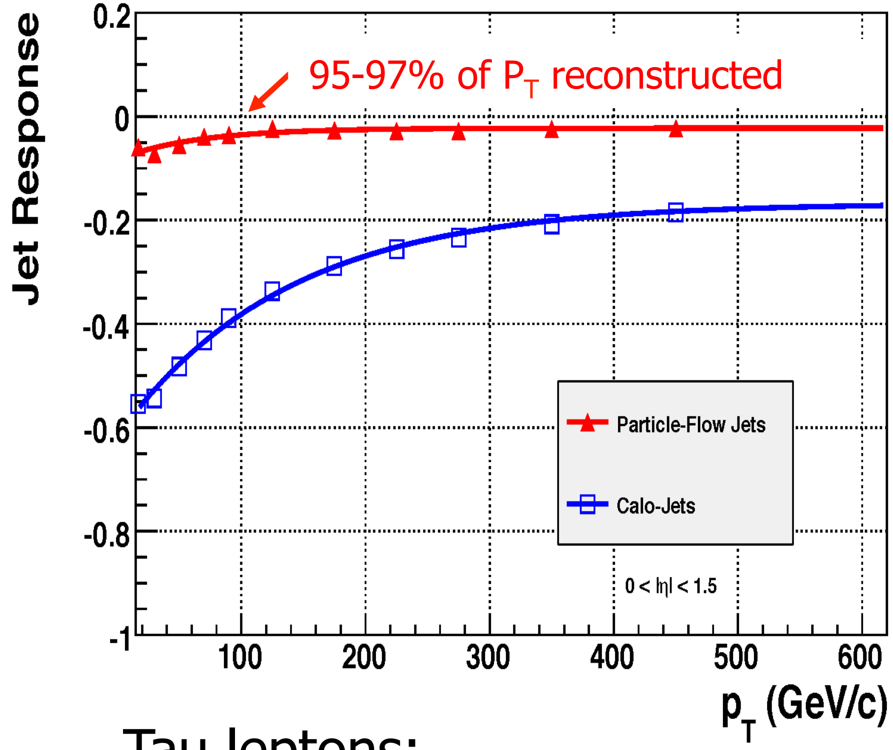
Keywords: tracking and granularity

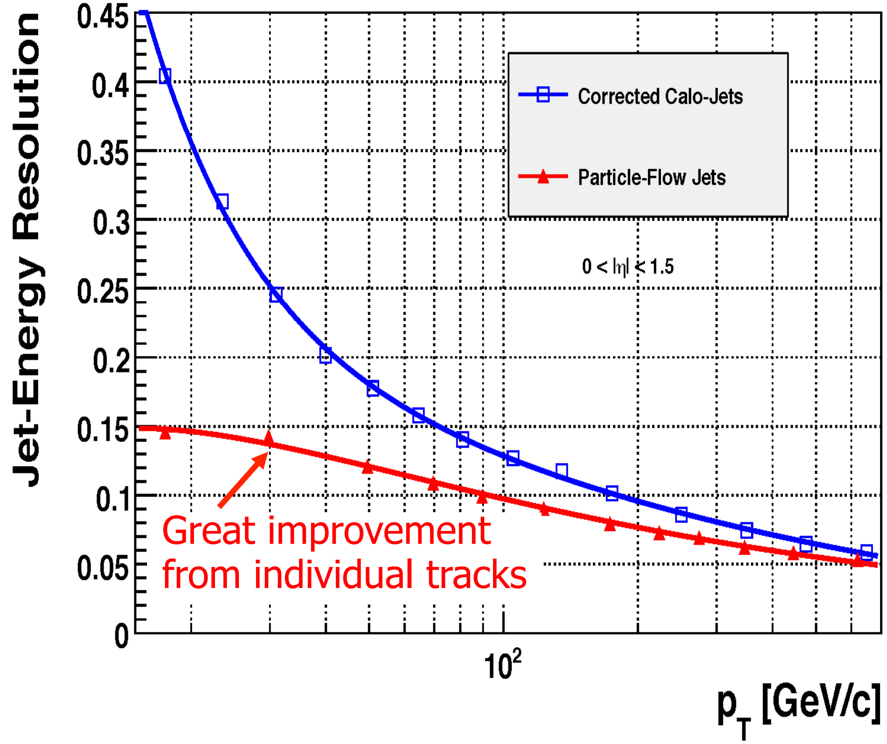
- Combine information from all sub-detectors.
- Provide an event description in the form of reconstructed particle candidates.



Experience with PFlow in CMS

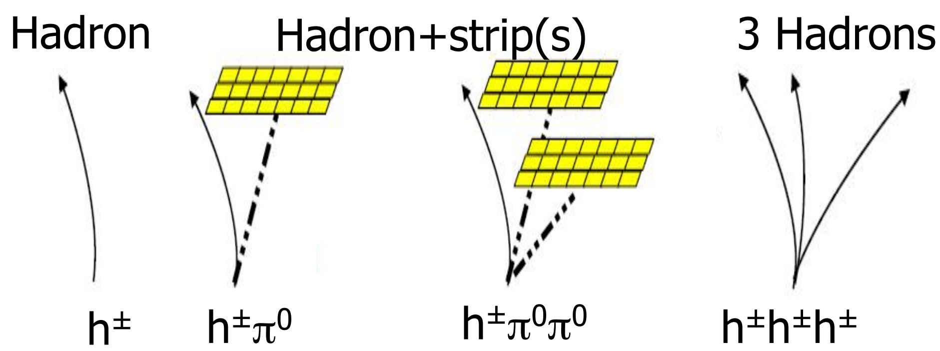
Jet measurement performances in CMS:





Tau leptons:

Also allows e.g. for optimal categorisation of t lepton « semi-hadronic » decays

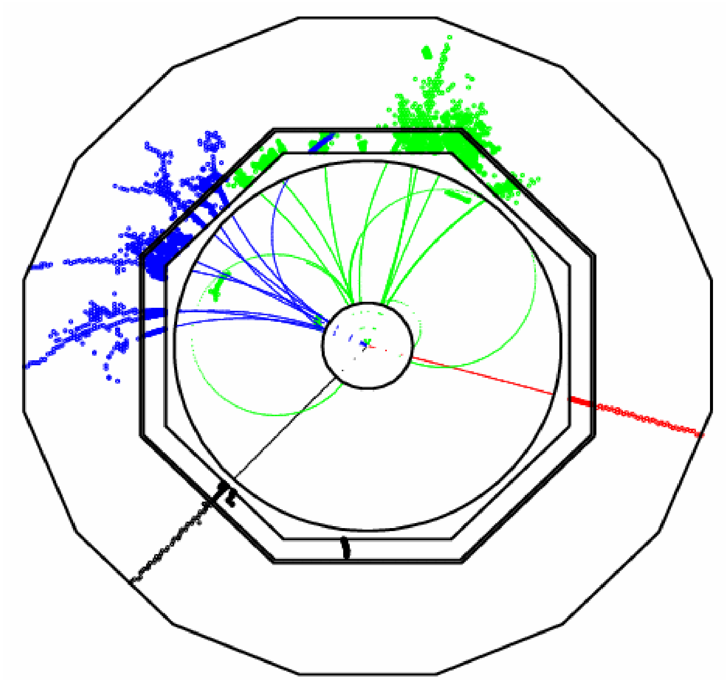


Pflow event reconstruction used for all CMS Physics Analyses

Particle Flow at Colliders

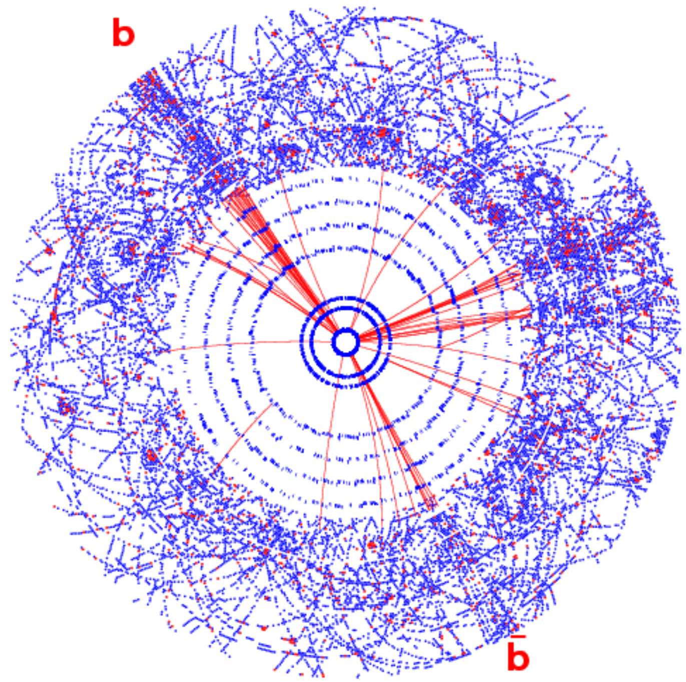
ILC

$e^+e^- \rightarrow H + Z;\ H \rightarrow bb;\ Z \rightarrow \mu\mu$



LHC

$pp \rightarrow H + X;\ \ H \rightarrow bb$



- Clean, low repetition rates
- Pulsed electronics
- No trigger / data reduction
- Reconstruct full particle patterns

- Messy, High rates (40 Mhz)
- Continuous readout
- Data reduction/trigger challenge
- Reconstruct constrained patterns

High Granularity at Colliders

Calorimetry for the ILC

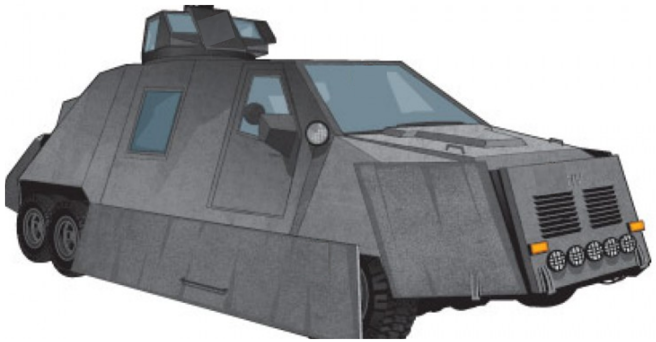
Initial Design:

SiD, ILD
Detector re-design/cost optimisation under way !

R&D on-going now !

Calorimetry for the HL-LHC

Has to survive in extremely harsh environment:



R&D on-going now !

Detector vs Running Costs

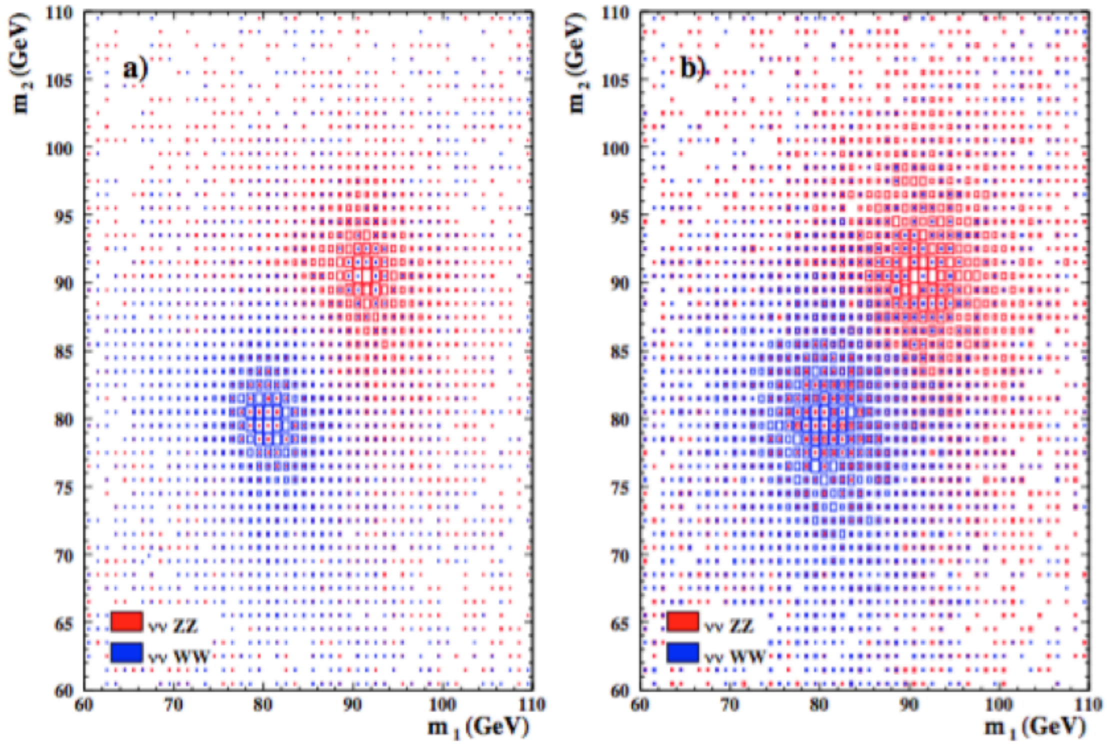
ILC

e.g. Tesla TDR p162

"For ZH, with H → WW, ZZ, the improvement in separation going from ΔE/√E = 30% to ΔE/√E = 60% is **equivalent to an increase of 30-40% in the luminosity**"

Running cost of ILC without manpower should be
~ 100-150 M€ / year

$e^+e^- \to \nu\nu WW$ and $e^+e^- \to \nu\nu ZZ$ events
for ΔE/√E = 30% and ΔE/√E = 60%

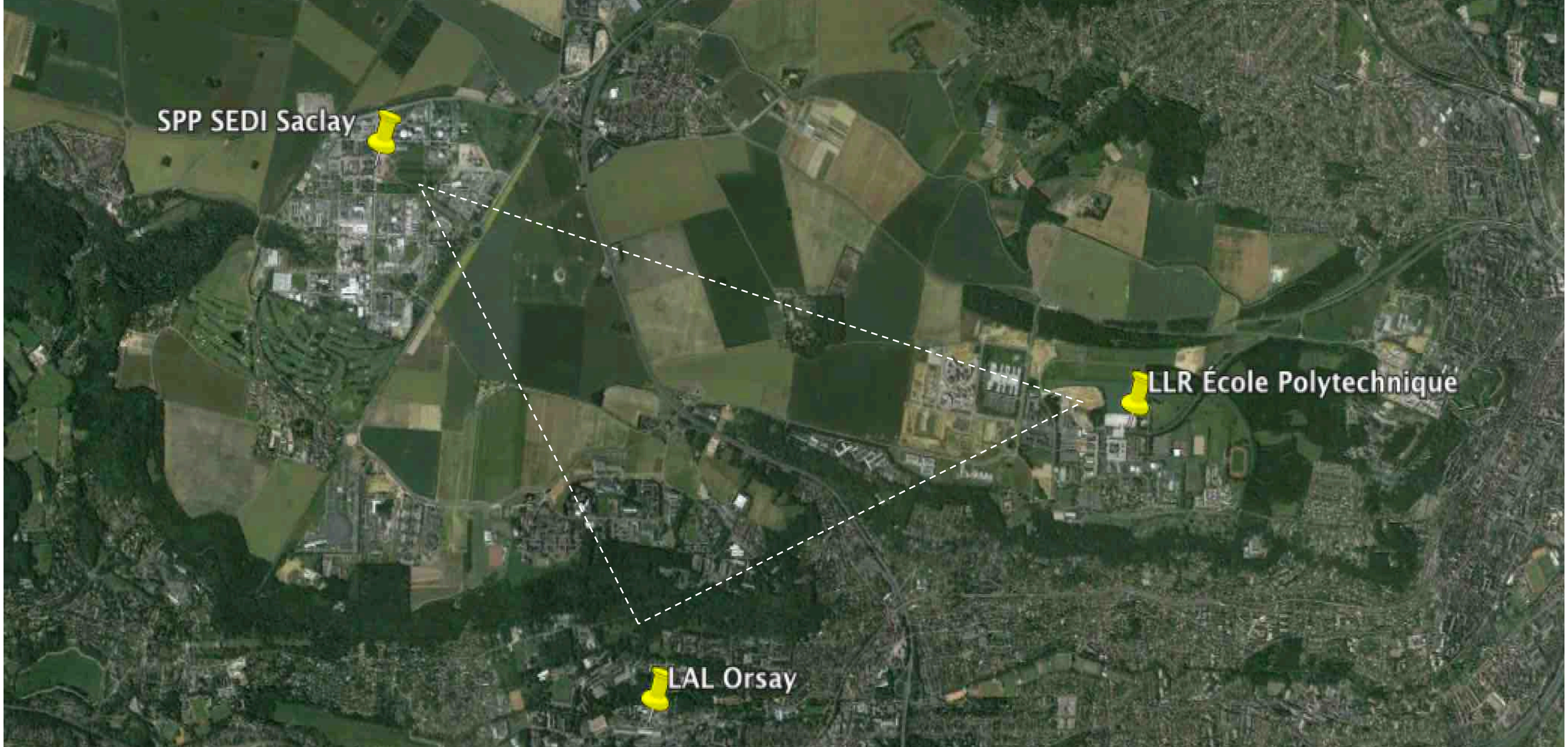


LHC

e.g. CMS M&O A+B = 18 M€ / year
LHC running costs (excluding manpower) ~ 300 M€ / year

But finding chunks of O(100) k€'s for necessary upgrade R&D has been extremely hard (e.g. almost impossible in France until 2015)

HIGHTEC© @ P2IO



- **Establish a strong collaboration on detector developments** between the 3 major HEP P2IO labs involved in 3 major experiments (ILD, ATLAS, CMS)

The New Generation: towards HIGHTEC

- The CALICE LAL and LLR groups involved in our P2IO project invented and designed the SiW-ECAL for the ILD
    - More than 10 years of developments
    - Technique and electronics validated in test beam
    - Full deployment of PFlow reconstruction techniques

- This made it possible to consider SiW Calorimetry for the HL-LHC !!!

This HGCFC Project aims at

- Leveraging our exceptional P2IO expertise on PFlow and High Granularity Calorimetry Techniques
- Built working prototypes for ILC and LHC
- Extend to high granularity hybrid time-energy calorimetry

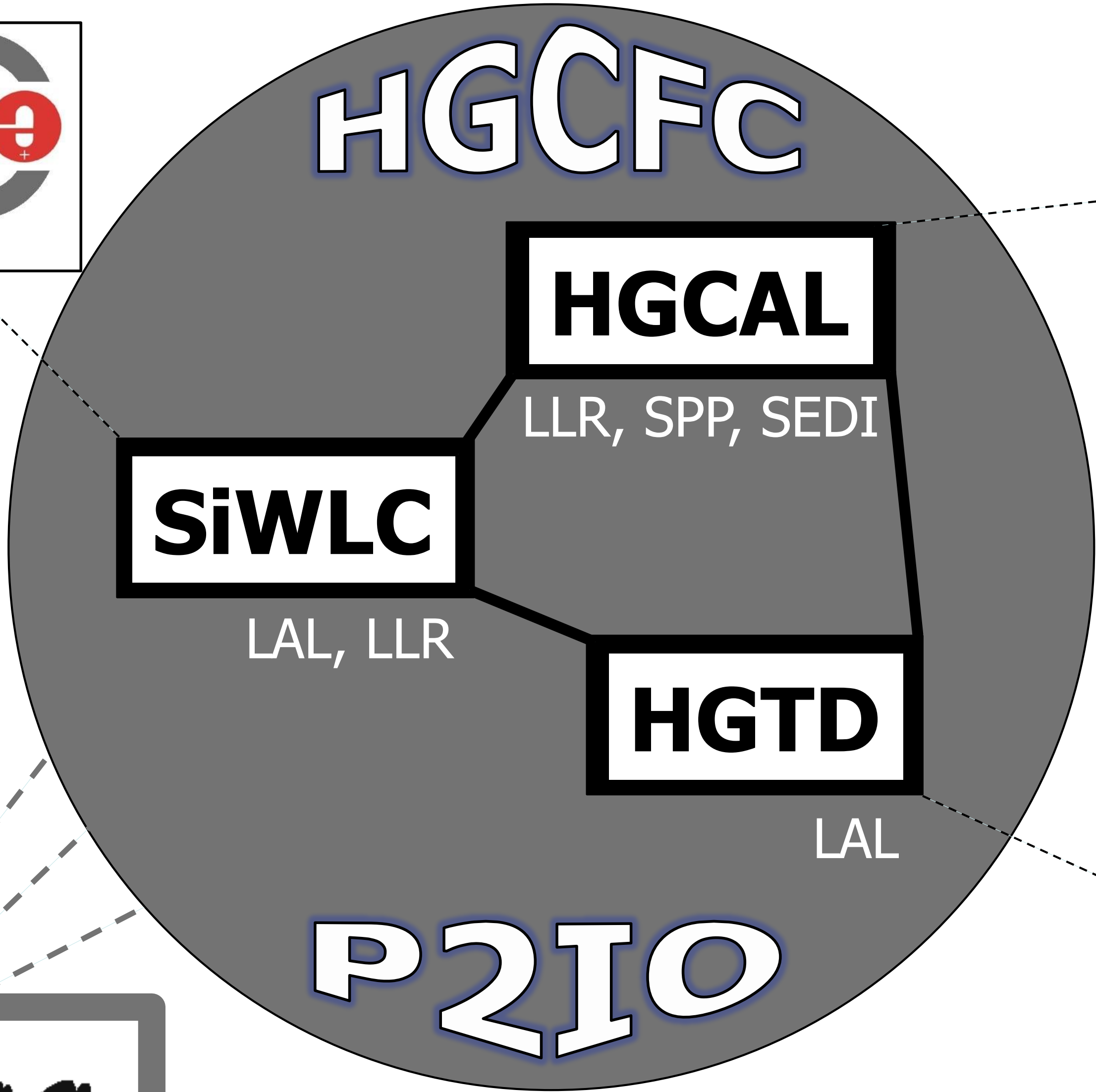
HIGHTEC

Detectors for the full deconvolution final state particles and **measurement of** their **E, Momenta, and Time of Flight**

The HIGHTEC Project at P2IO

CALICE
Calorimeter for ILC

CMS
LHC



LHC
ATLAS

Omega

LLR Palaiseau CNRS, LAL Orsay CNRS, SPP + SEDI Saclay CEA

HIGHTEC© Synergies @ P2IO

An optimisation of ressources

- The R&D developments needed for SiWLC, HGCAL, and HGTD have a lot in common and will greatly profit from this common HGCFC P2IO project
- This interest for a common effort and sharing of knowledge and know-how between physicist and engineers in this HGCFC project applies to each of the four main areas:

Mechanical Design: SiWLC, HGCAL, HGTD use similar C-Fibre techniques and engineering expertise for their reference designs

FE & BE electronics: SiWLC, HGCAL, HGTD each rely on variants of the Omega "SKIROC" type of FE chips
Also, digital electronics and data flow is a similar and major challenge

Clocks and Timing: Clock distribution and the study of the impact of timing for pile-up mitigation are common issues of HGCAL and HGTD

Performances & TB: Similar PFlow algorithms and clusterisation adapted to high granularity are major developments from same post-docs
Common beam tests are foreseen at CERN*

* A first SiWLC beam test at CERN organized with CMS HGCAL has occurred already in November 2014 at the initiative of P2IO groups !

A Unique Opportunity for P2IO

PFlow and the high granularity

- The **high granularity** « imaging » calorimetry techniques are mature enough following CALICE **pioneering work within P2IO since nearly a decade**
- High granularity devices are now proposed for the upgrade of the CMS forward calorimeter and for a forward timing detector for ATLAS
- The P2IO groups have gained world-wide recognition for their central contributions to the invention and realisation at LEP and LHC, of Particle Flow reconstruction techniques perfectly adapted to high granularity devices

Timing and the high granularity

- The timing requirements at HL-LHC imposes the deployment of "5D" devices combining highly granular calorimetry and timing measurements

Our P2IO HGCFC project proposes to promote and validate innovative HIGHTEC© detectors for future colliders

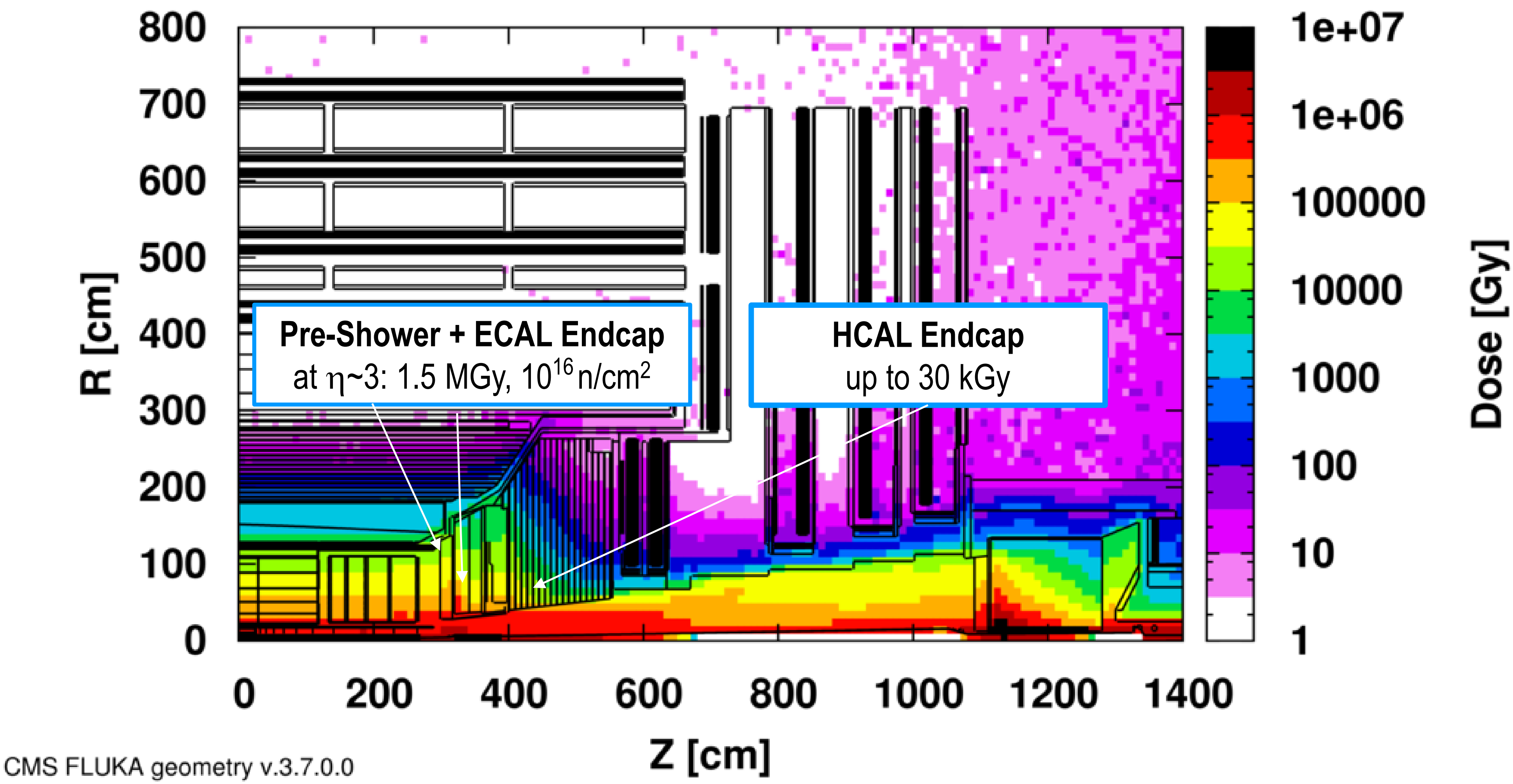
- This P2IO R&D for **Hi**gh **G**ranularity **H**ybrid **T**ime-**E**nergy **C**alorimetry© will guaranty world-wide visibility in a period of intense developments to arrive to operational solutions for the future ee (ILC, …) and pp (LHC, FCC) colliders

Recall: ATLAS & CMS TDRs + major HEP decisions expected within 4 years


Tolerance to Irradiation
Illustrating some of HIGHTEC challenges

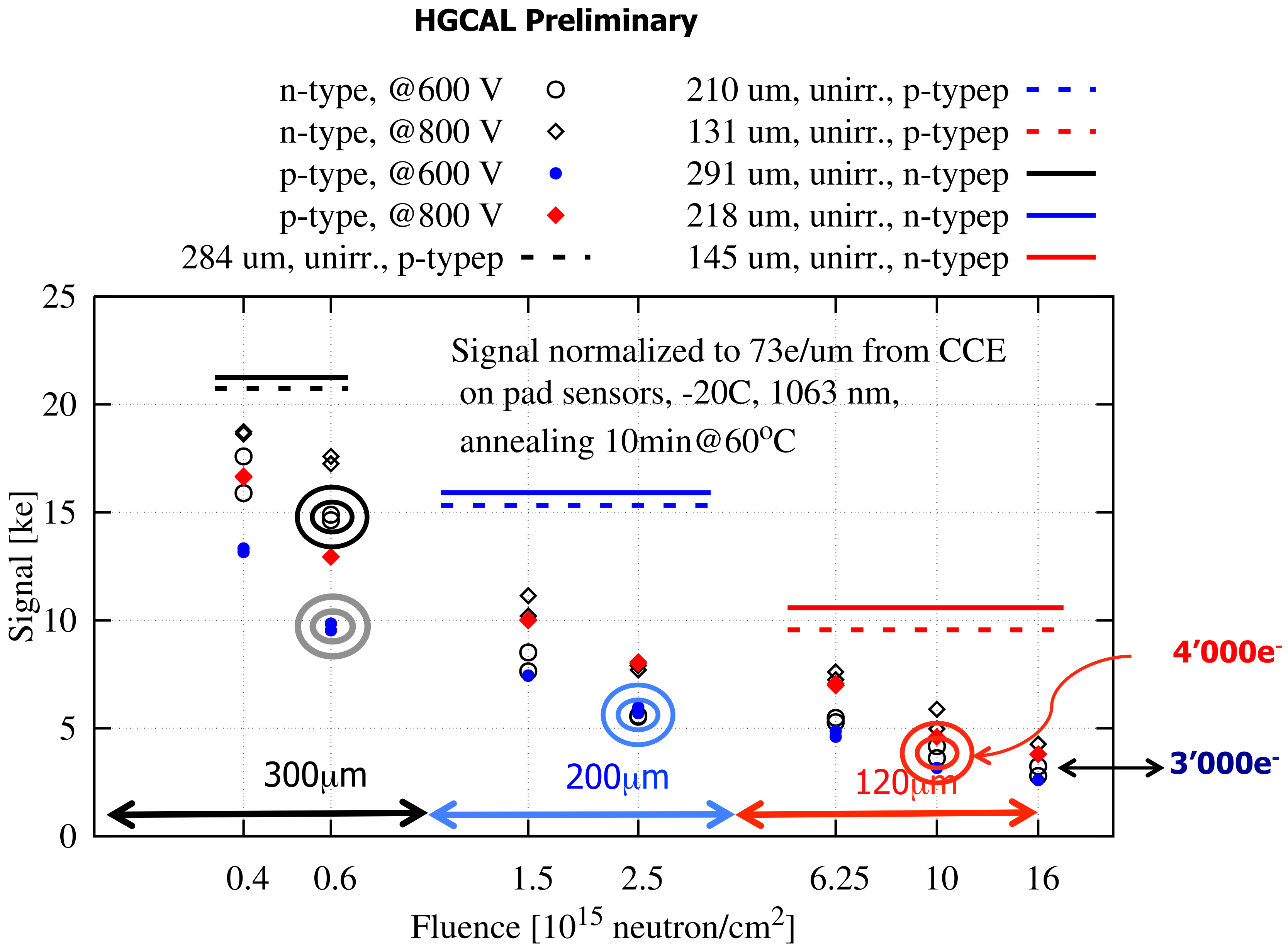
The HL-LHC Challenge 1: Radiation Damage

3000 fb-1 Absolute Dose map in [Gy] simulated with MARS and FLUKA



Need a radiation resistant ECAL in forward region

Radiation tolerance of Silicon Sensors (1)

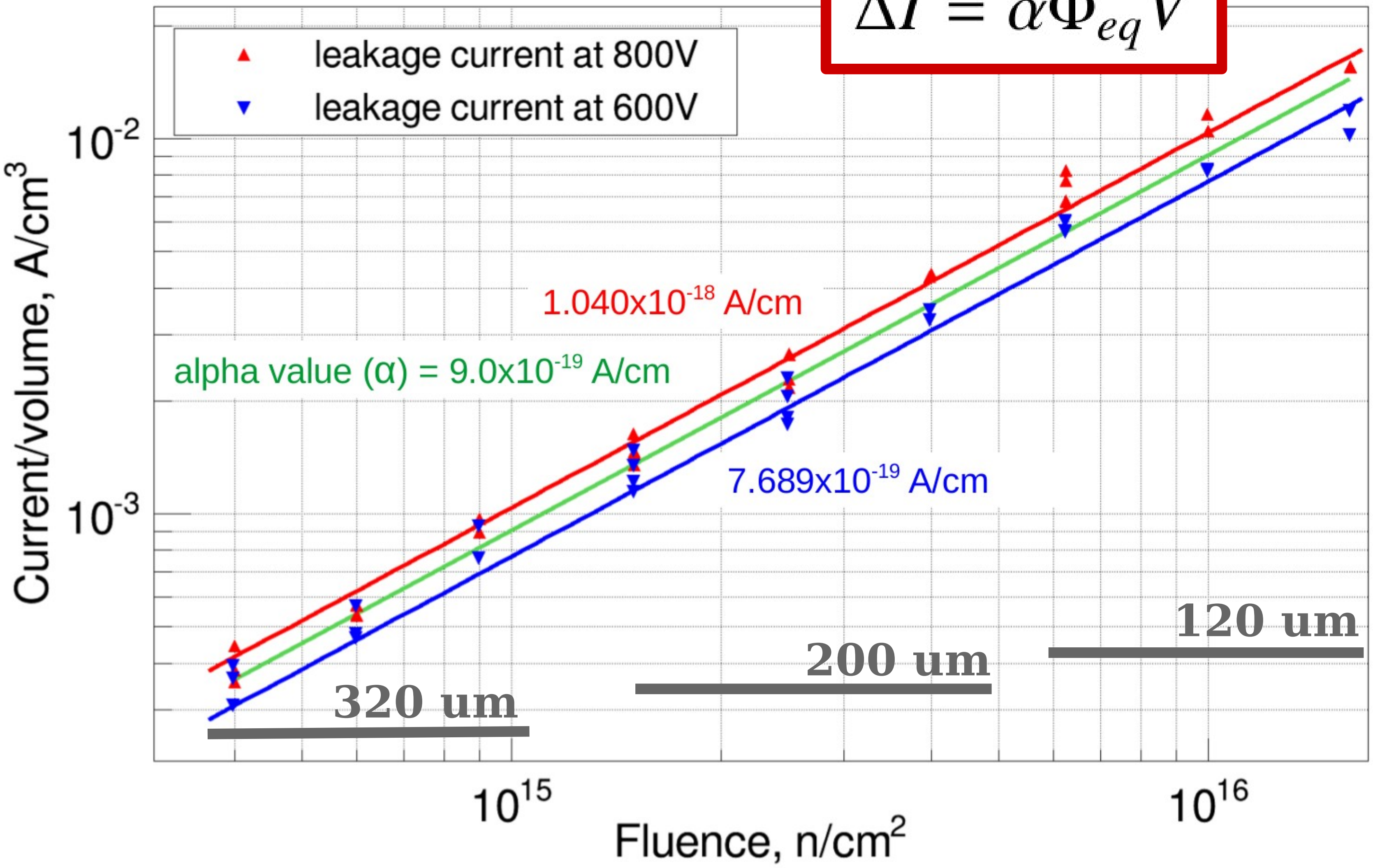


- Lower tolerance for ticker diodes and p-type diodes

Radiation tolerance of Silicon Sensors (2)

HGCAL Preliminary

$$\Delta I = \alpha \Phi_{eq} V$$



- Leakage current normalized by the volume of the diode ∝ fluence
- The current scales linearly with fluence even at very high fluence

HIGHTEC Design to Cope with Irradiation

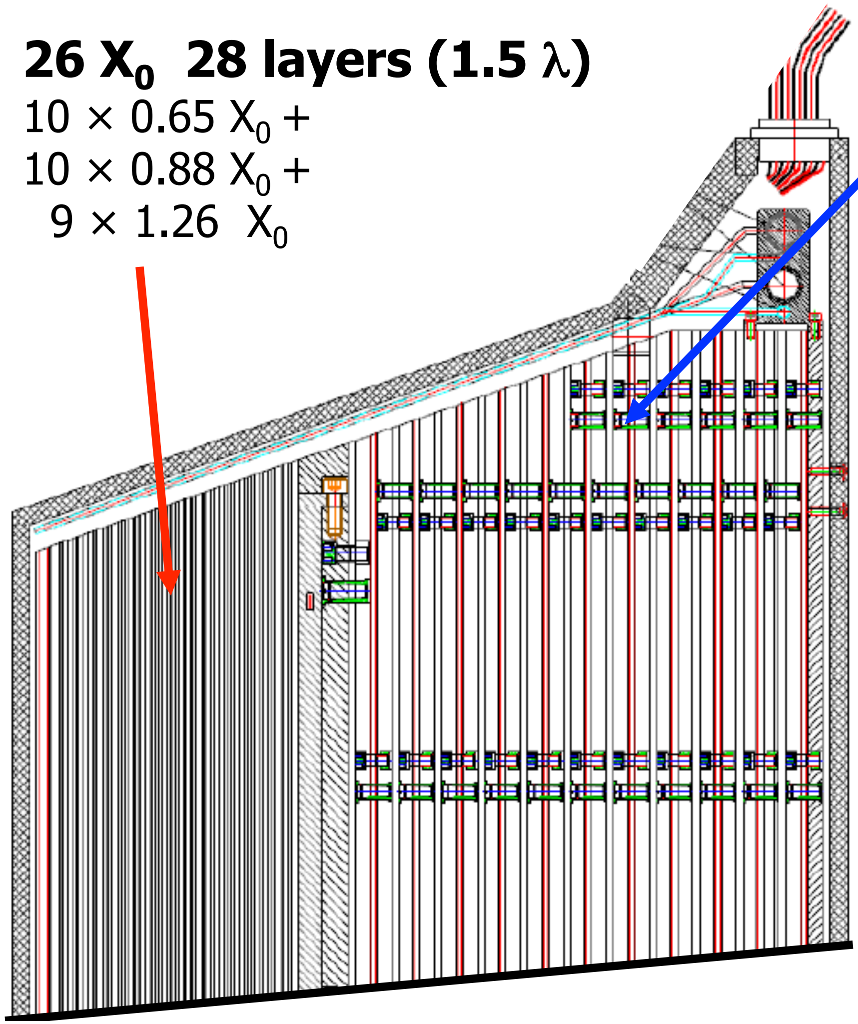
HGCAL Preliminary

Electromagnetic (EE)
Si/W+Cu

26 X_0 28 layers (1.5 λ)
10 × 0.65 X_0 +
10 × 0.88 X_0 +
9 × 1.26 X_0

Hadronic (FH+BH)
8.5 λ 14 layers

FHE : 12 layers × 0.3 λ +
BHE : 12 layers × 0.45 λ



To cope the irradiation / pile-up:

η dependent depletion of the Si
η dependent cell size

Thickness	300 μm	200 μm	100 μm
Maximum n fluence (cm^{-2})	6×10^{14}	2.5×10^{15}	1×10^{16}
Maximum dose (Mrad)	3	20	100
E-HG region	$\|\eta\| < 1.75$	$1.75 < \|\eta\| < 2.15$	$\|\eta\| > 2.15$
H-HG region	$R > 860$ mm	$R < 860$ mm	–
Cell size (cm^2)	1.05	1.05	0.53
Cell capacitance (pF)	40	60	60
S/N after 3000 fb^{-1}	9.6	4.9	2.4
Si wafer area (m^2)	323	161	117

- A "mip" signal above 3000 electrons can be maintained in the worse conditions expected at largest η (with very small effect on signal shape)

HIGHTEC Calibration

The calibration requires:

- Equalization of the cell-to-cell response (**inter-calibration**)
- Cell weights taking into account the absorber thickness
- Linearity of response extrapolated to high energy e/γ
- Absolute E scale for the showers using $Z \rightarrow ee$ as candlelight

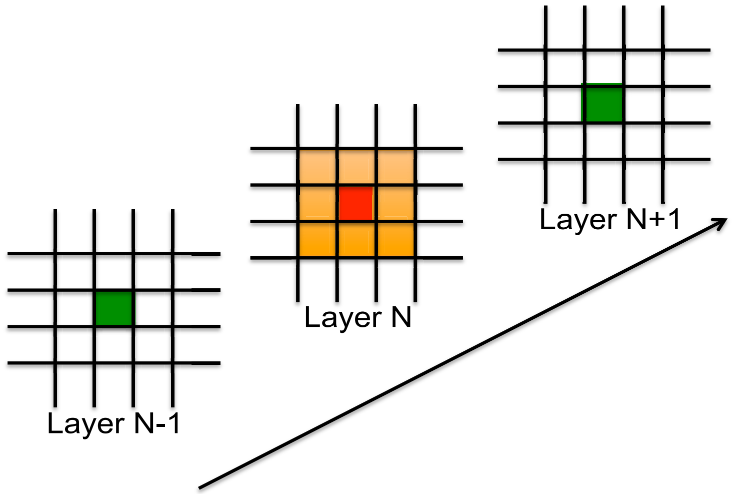
Inter-calibration requires:

3% precision on inter-calibration to maintain the constant term < 1%

Inter-calibration with « punch-through »:

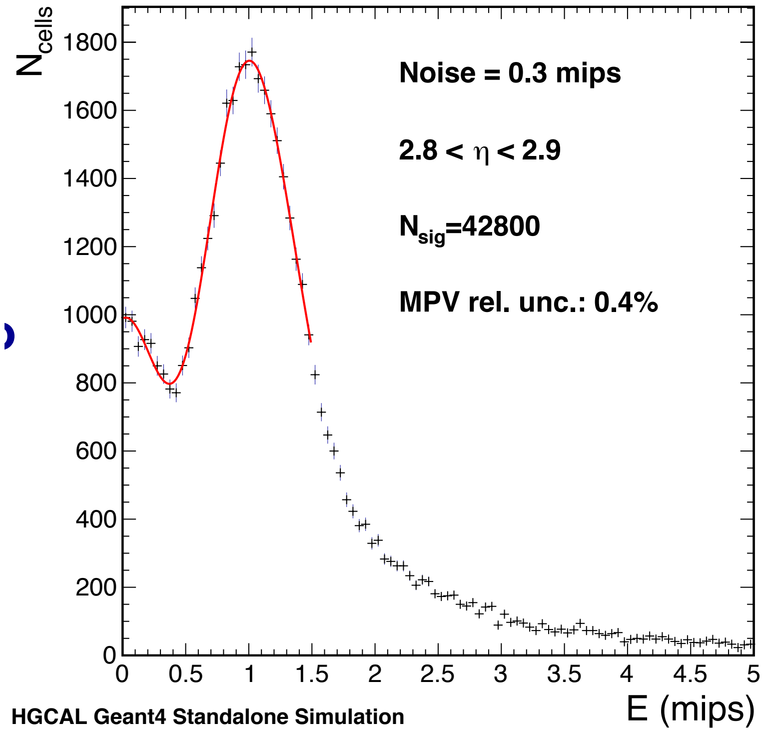
- For any cell, require no signal in 3x3 arrays of adjacent layers
- A single track mip in cell of layers ± 1 suffice for S/B > 2.5
- A mip track in layers ± 2 would work down to S/B > 1.7

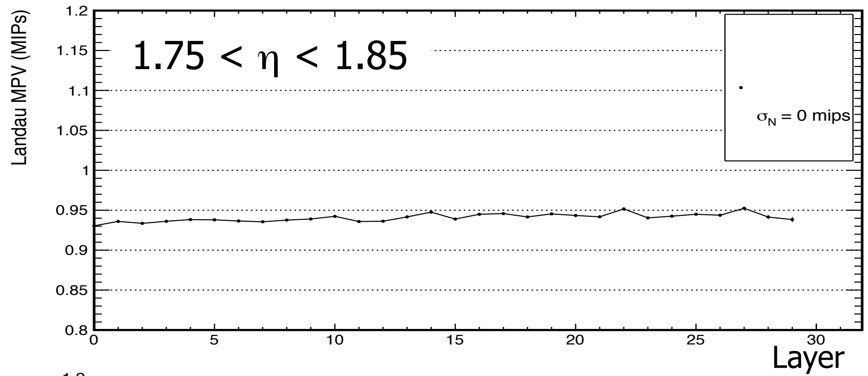
("worst case scenario" for actual design after 3000 fb^{-1})

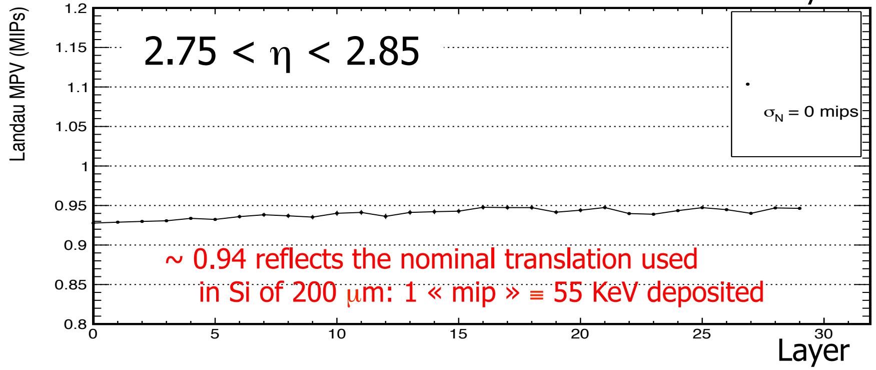


« Punch through » ≠ true mips

HIGHTEC Inter-calibration via punch-through







e.g. Need 1.5 M events to reach 3% precision with mip tracks in layers ± 1

For noise of 0.4 mip and <PU> = 140

Reachable ~ daily !

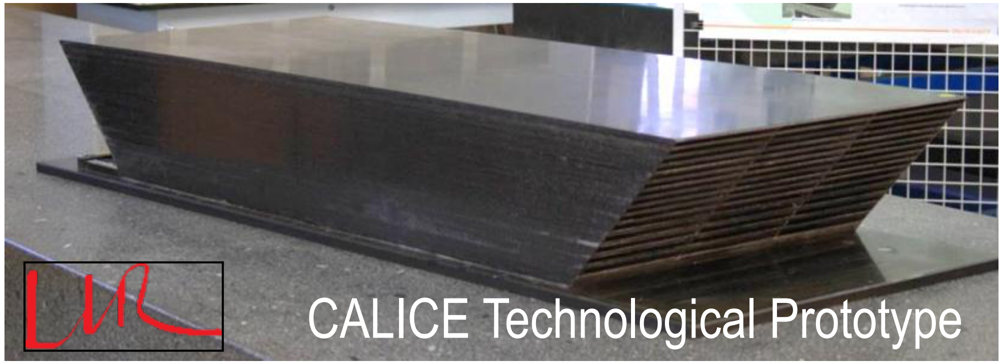
- Study response with using full G4 simulation of min. bias events
- Layer thickness defined by the track direction to nominal vertex

Inter-calibration stable at ± 1% for η ~ 1.8 et 2.8

Note: A standard charge injection circuit is realizable for residual non-linearity correction at channel-by-channel level

Impact on Mechanics Structures

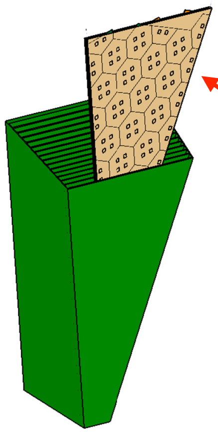
- The SiWLC, HGCAL, and HGTD relies on a similar C-Fibre/W structure inspired by the so-called "CALICE Technological Prototype" built at LLR



HGCAL Reference design

[CMS Technical Proposal]

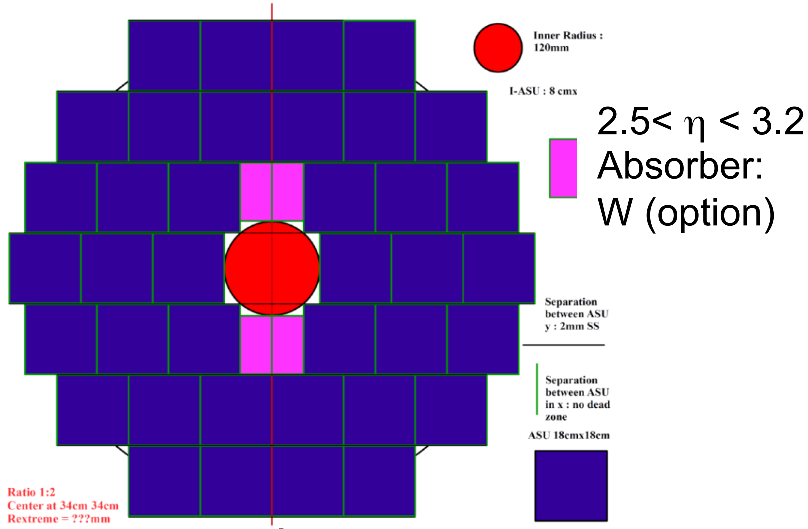
C-fibre/W Alveolar 30° "petals"
12 Petals assembled together



Cassettes
(heaxagonal Si active element,
FE, Cooling plates)
inserted in alveoli.

HGTD Reference design

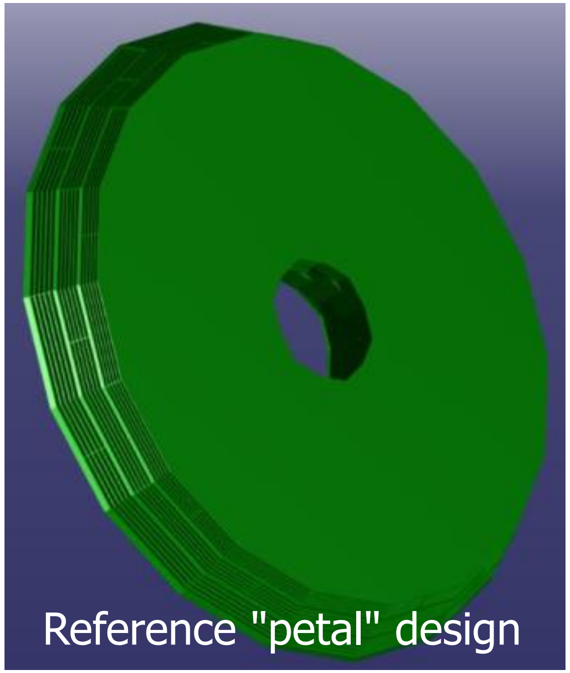
Rectangular Modules "à la" CALICE

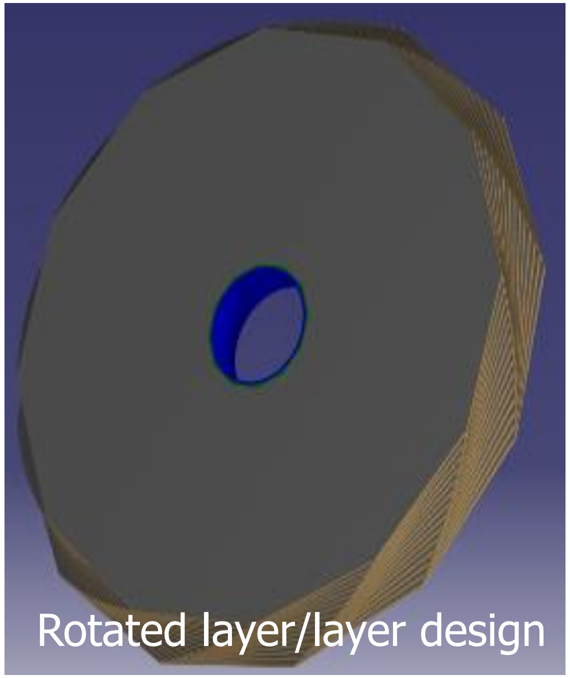


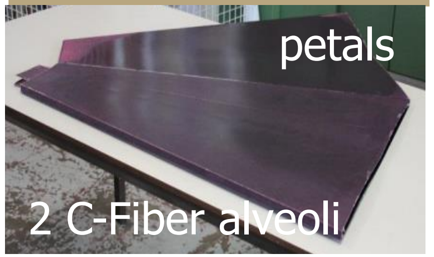
x-y view

Need to characterize the material (C-Fibre, various glues) tolerance to radiation and perform destructive tests.

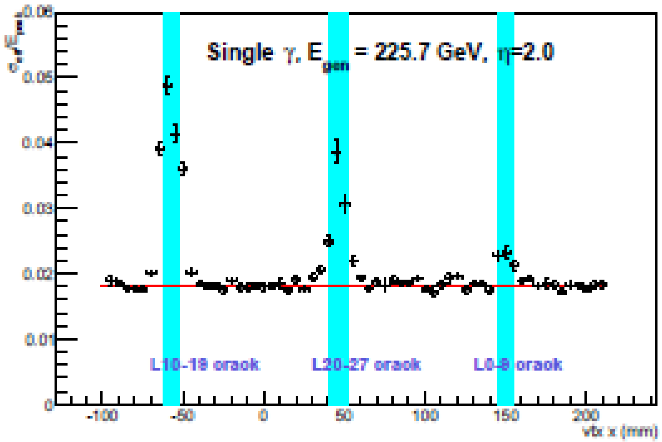
Mechanics Structures and Uniformity

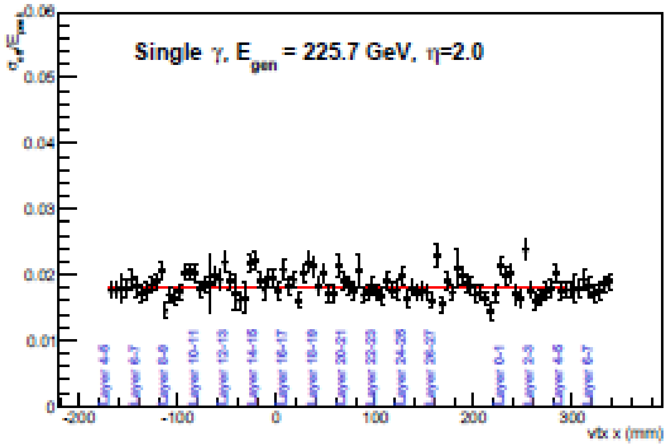




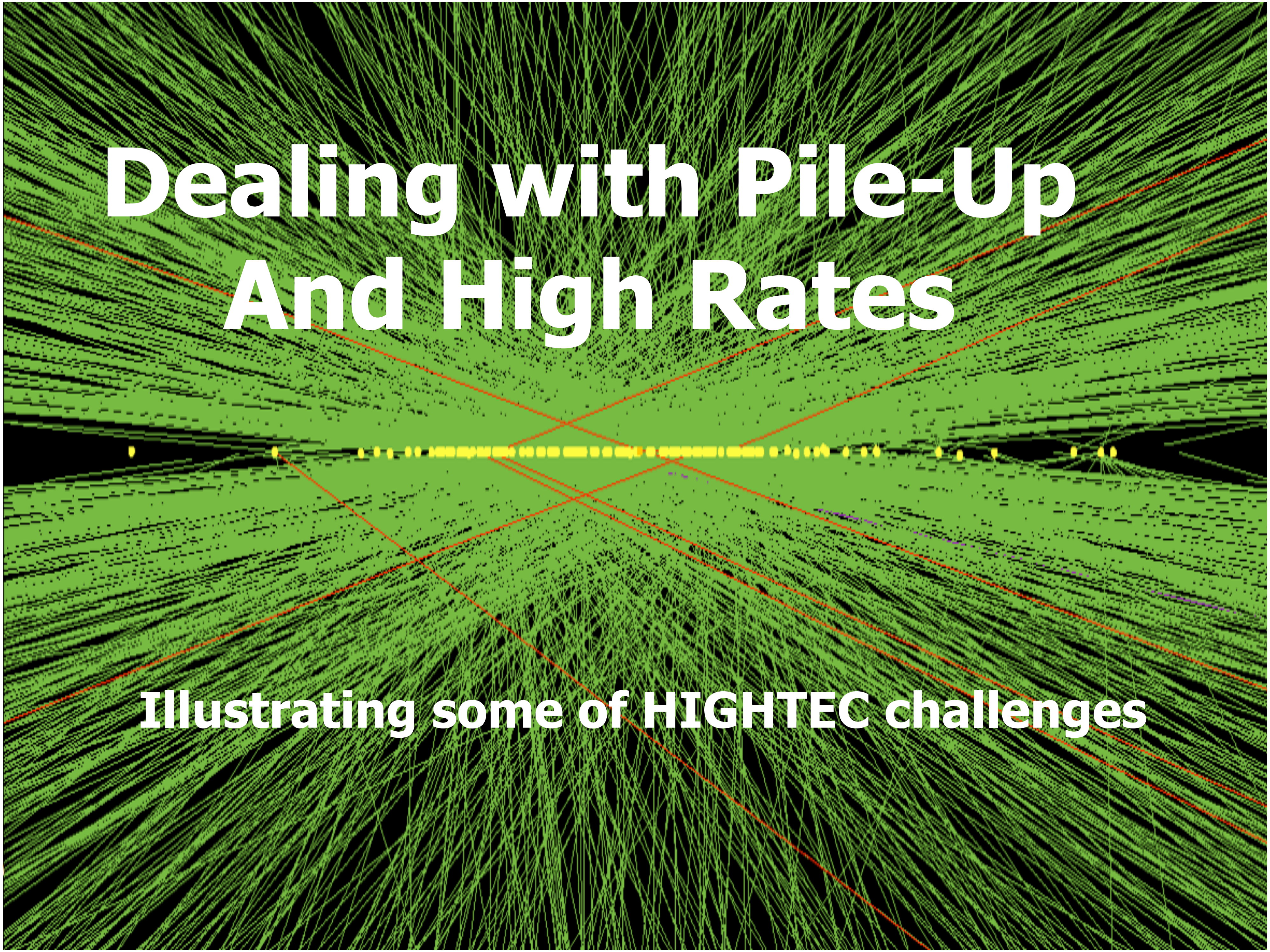


Various configurations simulated:



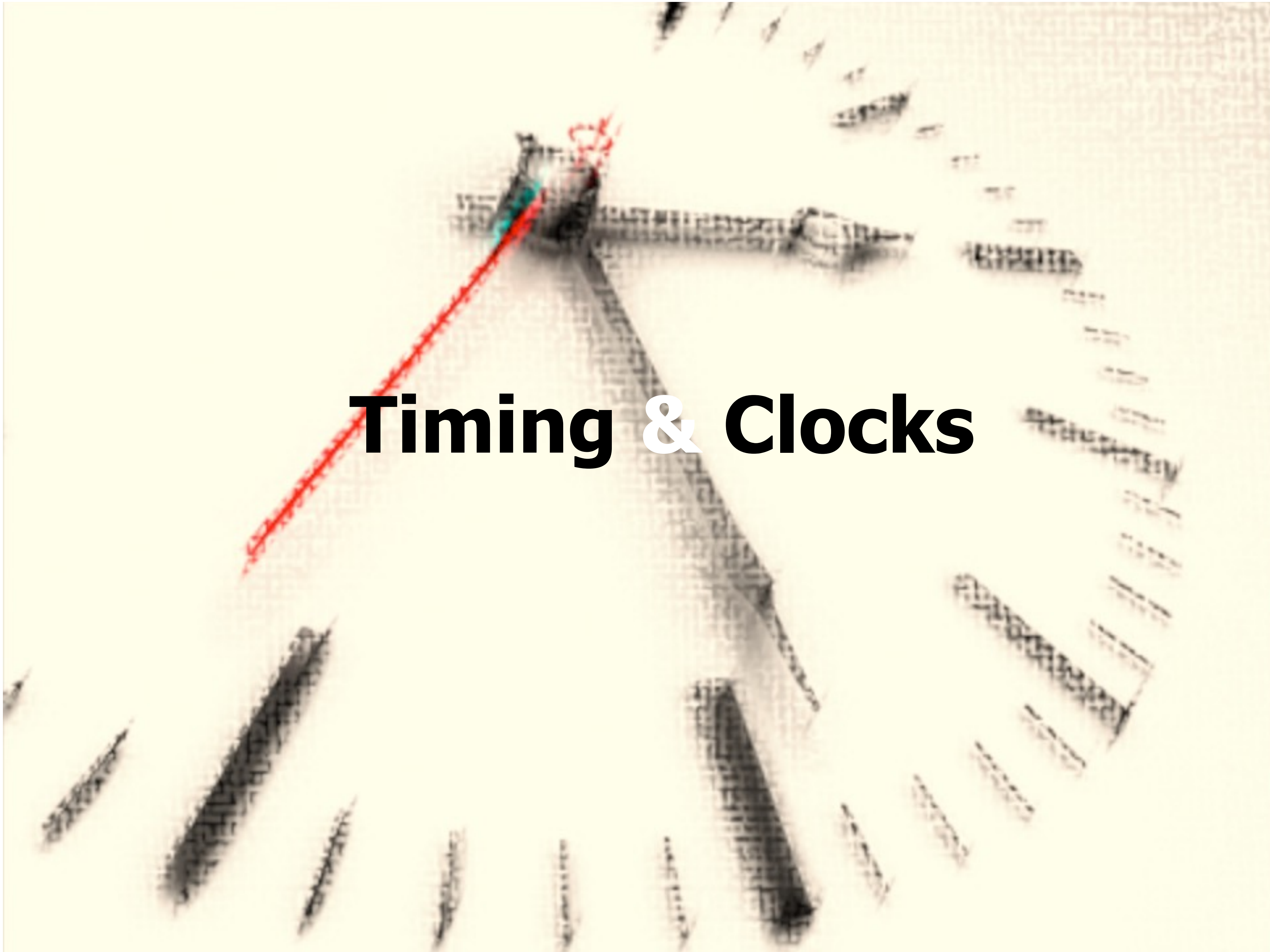


Dealing with Pile-Up And High Rates

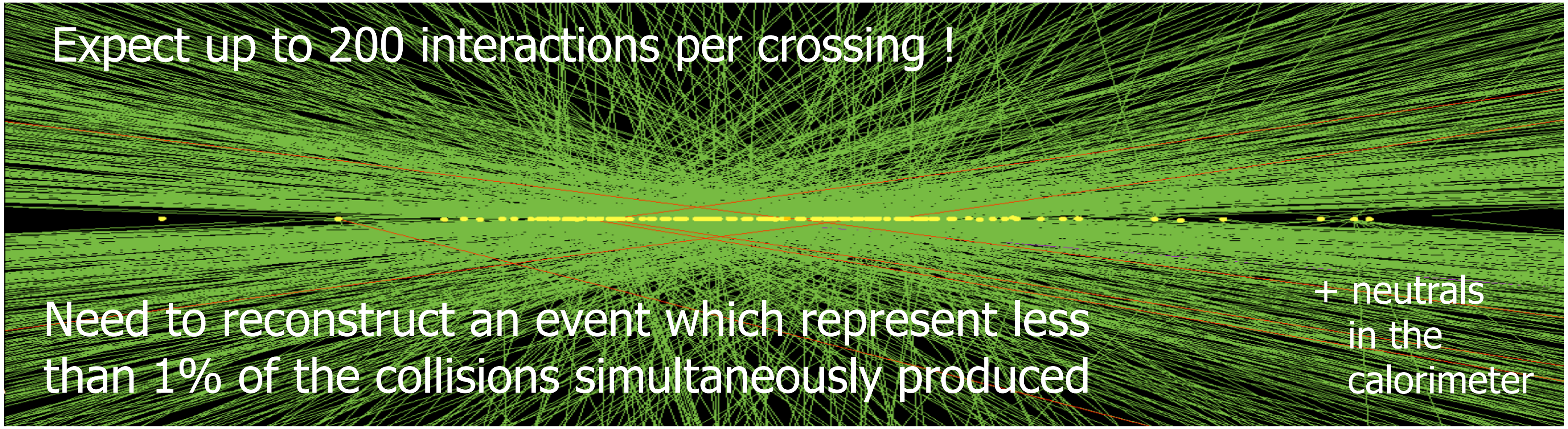


Illustrating some of HIGHTEC challenges

Timing & Clocks



Collisions Vertices at the HL-LHC



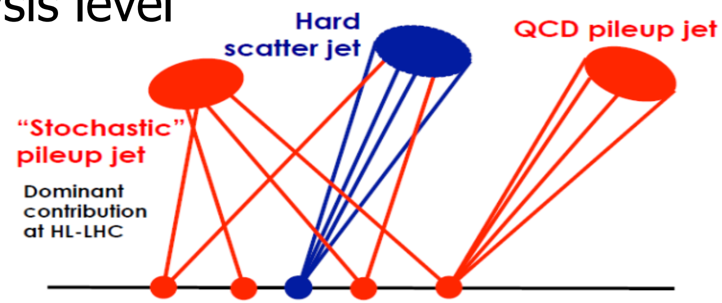
Spatial separation: Mean z-spacing of vertices down to ~ 500 μm

For a Poisson distributed probability per unit length for a beam interaction
- → spatial separation of two neighbouring vertices is exponentially falling
- → **significant overlap probability in vertex reconstruction**
- → PF algorithms start to fail in end cap region for <PU> ~200

Timing separation The RMS spread of vertices is ~ 150 ps

Goal: maintain or improve the performance of the forward detector at HL-LHC with <PU> ~ 200 at trigger or analysis level

Benchmark processes:
- Primary vertex for $H \rightarrow \gamma\gamma$
- VBF production with $X \rightarrow$ invis. against Z + jet & fake forward jets



Pile-Up Mitigation with Fast Timing

- PU effects can be mitigated via a determination of the interesting vertex
- Some (insufficient) mitigation possible via beam optics ("Crab-kissing")
- Fast timing for charge and neutral particles could allow to resolve a single bunch crossing
- The precision on timing for e.m. component of showers will improve with $\sqrt{N_{cell}}$, for N_{cell} with a signal above threshold ⇒ need O(30 ps) per cell

  e.g. $H \rightarrow \gamma\gamma$ have ~80 cells above ToT threshold with a largest signal in the cells in e.m. shower of E_T ~ 1.5 GeV

Clock Distribution

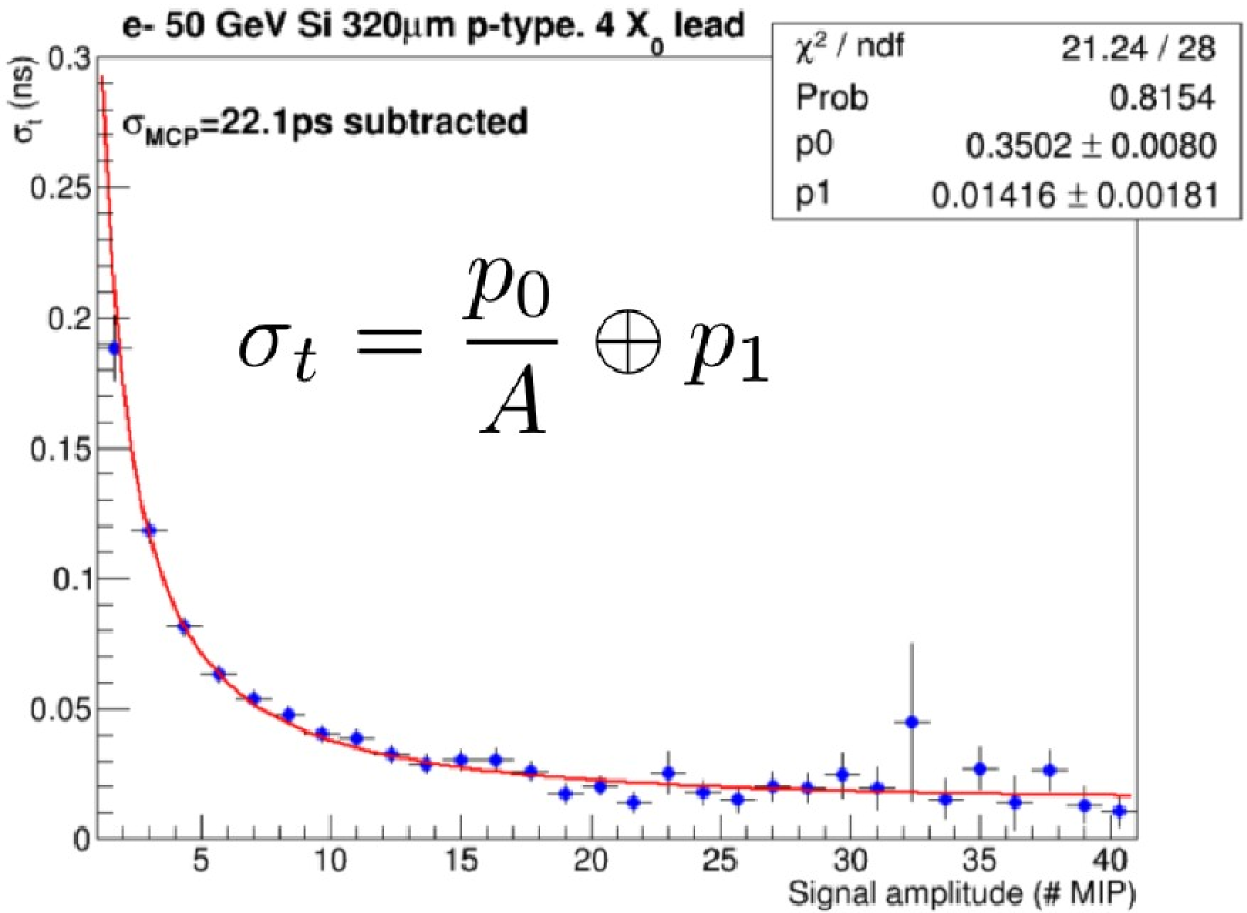
- The problem of the clock distribution is very similar in HGTD and HGCAL. The Clock Distribution R&D performed in particular for P2IO by HGCAL
- Different η covered by HGCAL ($1.5 < \eta < 2.5$) and HGTD ($2.5 < h < 5.0$) ⇒ possibly use different time measurement methods

  (e.g. LGAD for HGTD as more stringent precision requirements than "TOT" for HGCAL)
- Given the small intrinsic jitter of silicon detector, the precision on timing will be limited by the clock distribution

Fast-timing and precise clock distribution is needed for PU mitigation

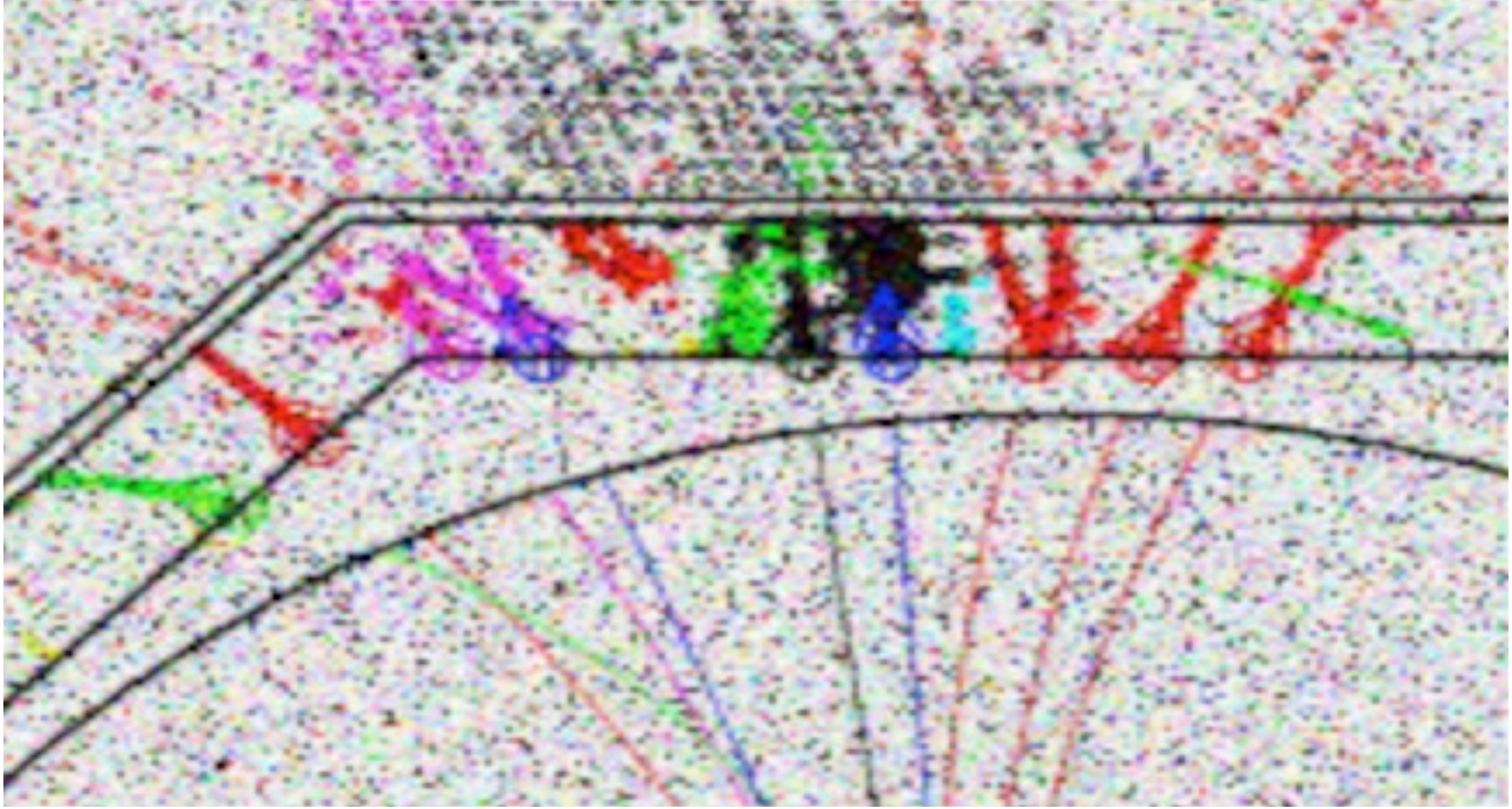
Test of Time Response in Beam

HGCAL Preliminary – Unirradiated Si PAD (July 2015)



- Timing resolution < 20 ps for a signal above 20 mips
- A single MIP signal is resolvable from noise
- Application of timing capabilities may allow to time-resolve showers (e.m. components) to mitigate pile-up

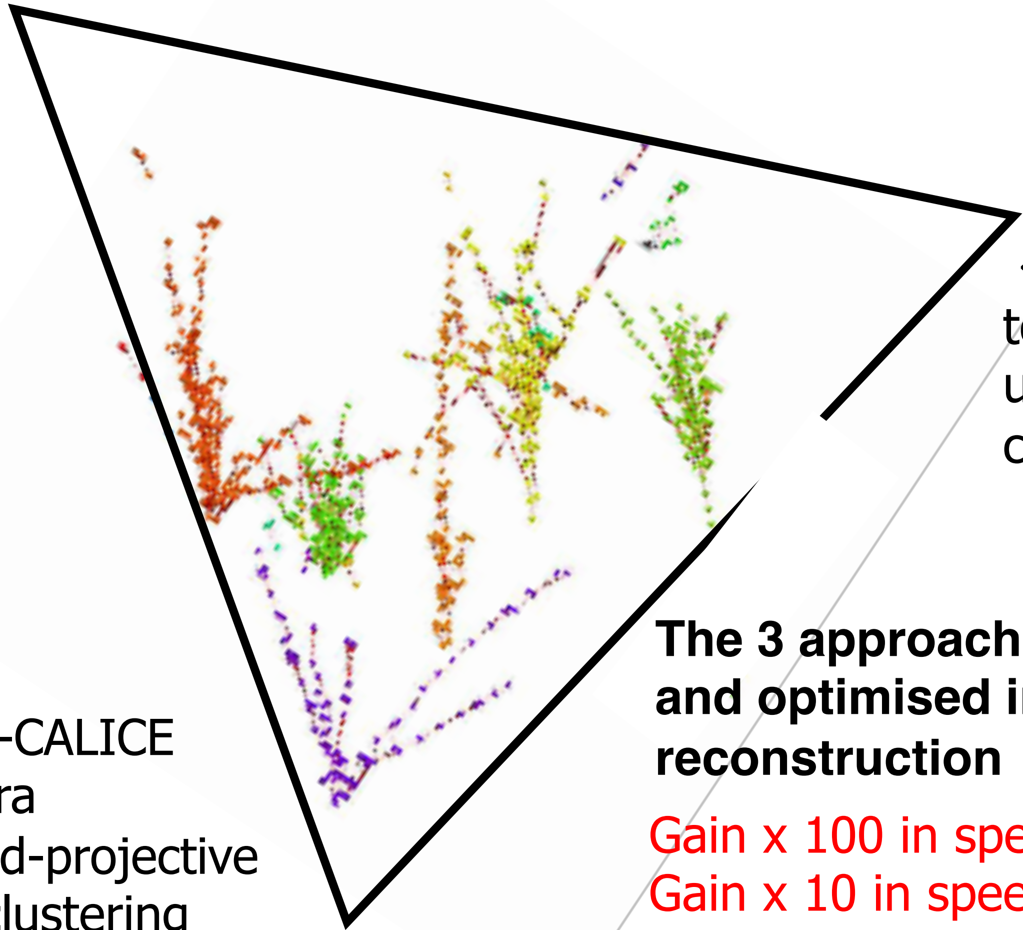
Reconstruction & Performances



Reconstruction Tools

- Strong synergy between SiWLC-CALICE and HGCAL-CMS established three existing methods successfully merged in CMS for HGCAL !

CMS PFlow
« Gaussian-mixture »
clustering from Run I



SiWLC-ECAL
« ARBOR »
topological
unconstrained
clustering

SiWLC-CALICE
Pandora
forward-projective
cone clustering

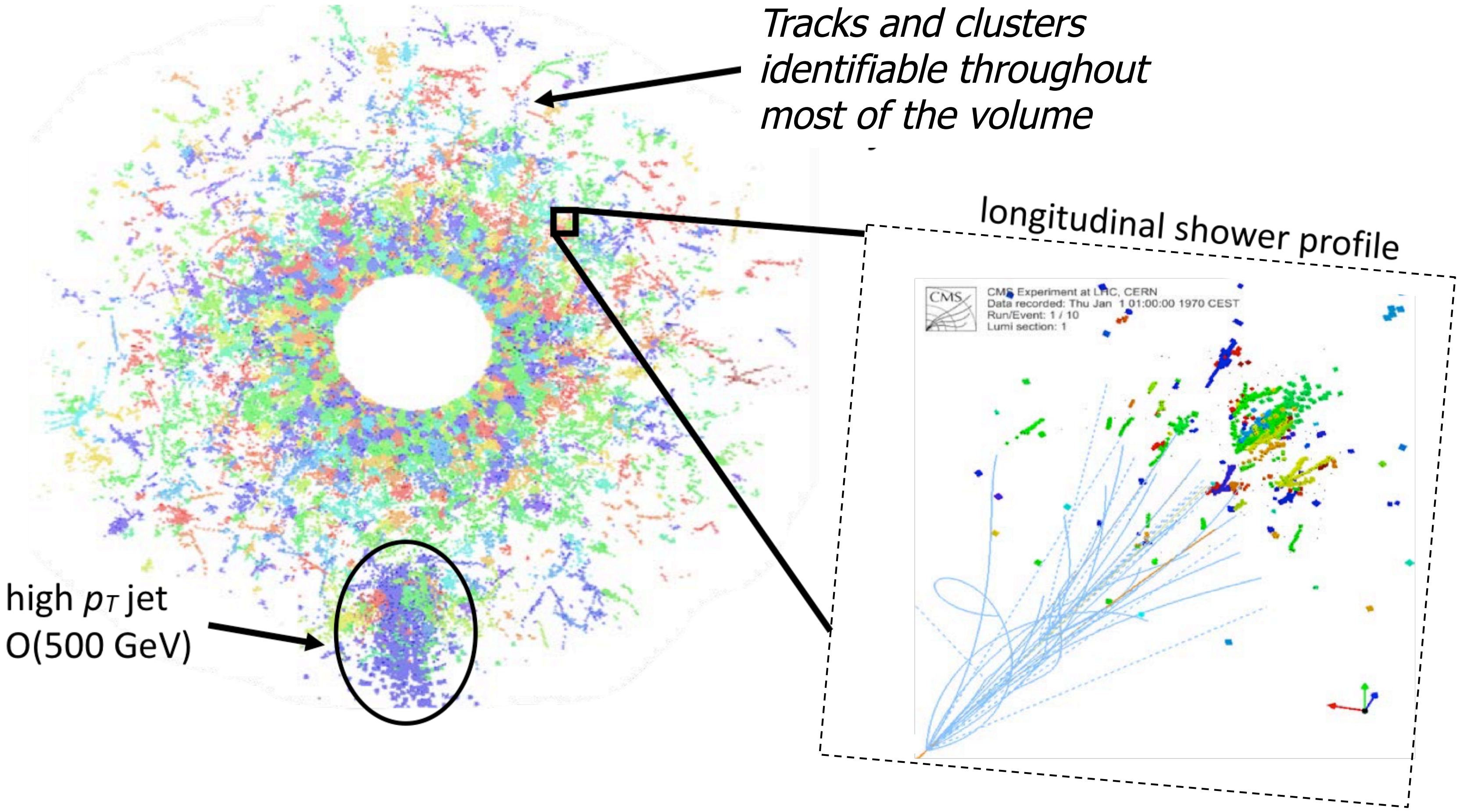
The 3 approaches are merged and optimised in the HGCAL reconstruction

Gain x 100 in speed for HGCAL !
Gain x 10 in speed for ARBOR !

- A next step is to introduce and make use of the timing information for e.m. shower components !

High Granularity at HL-LHC

The harsh environment at HL-LHC is a major challenge for calorimetry

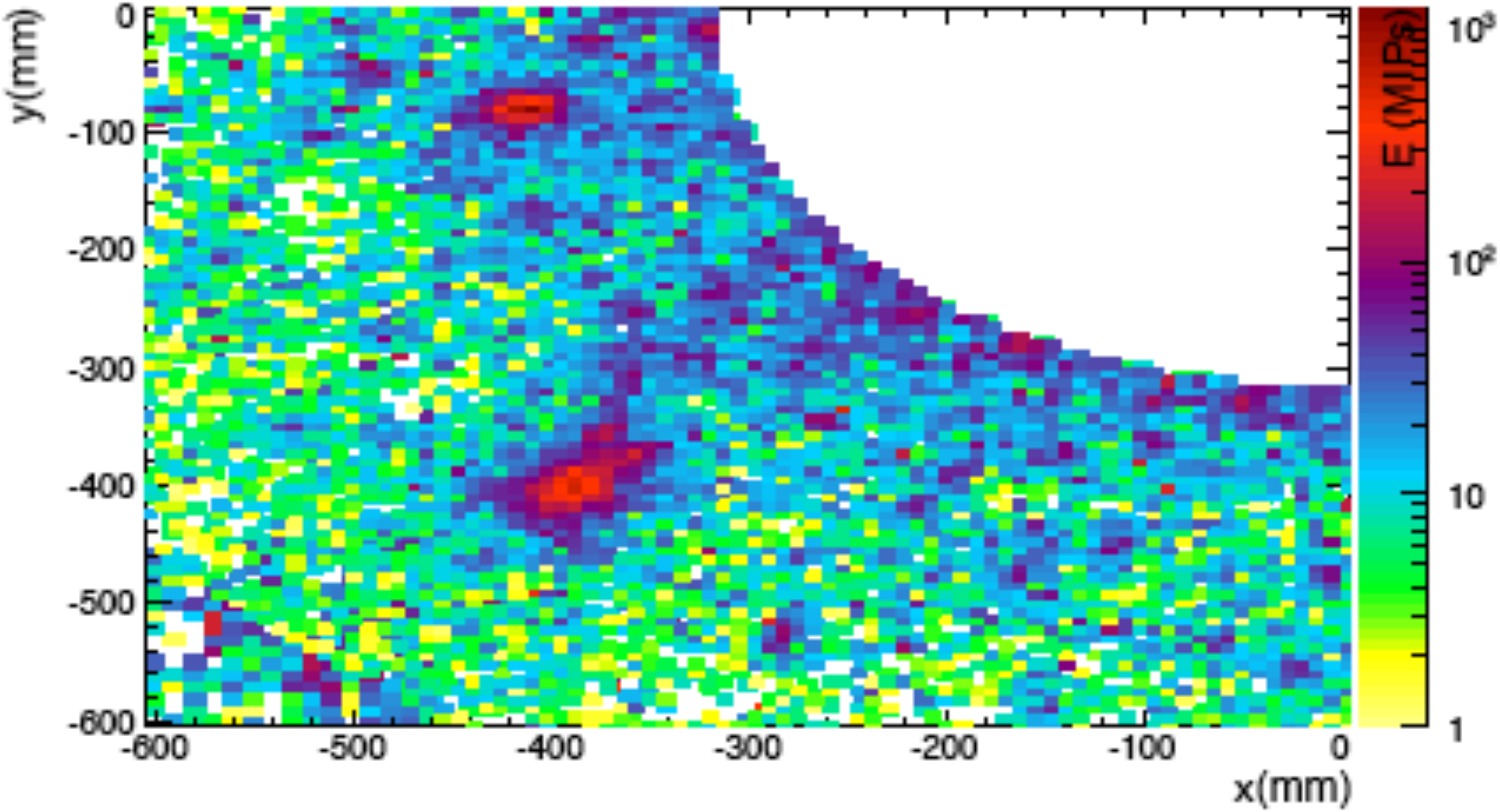


- Need to be complemented by timing with a resolution of O(20 ps) to fully disentangle contributions of an event

Exploiting Granularity

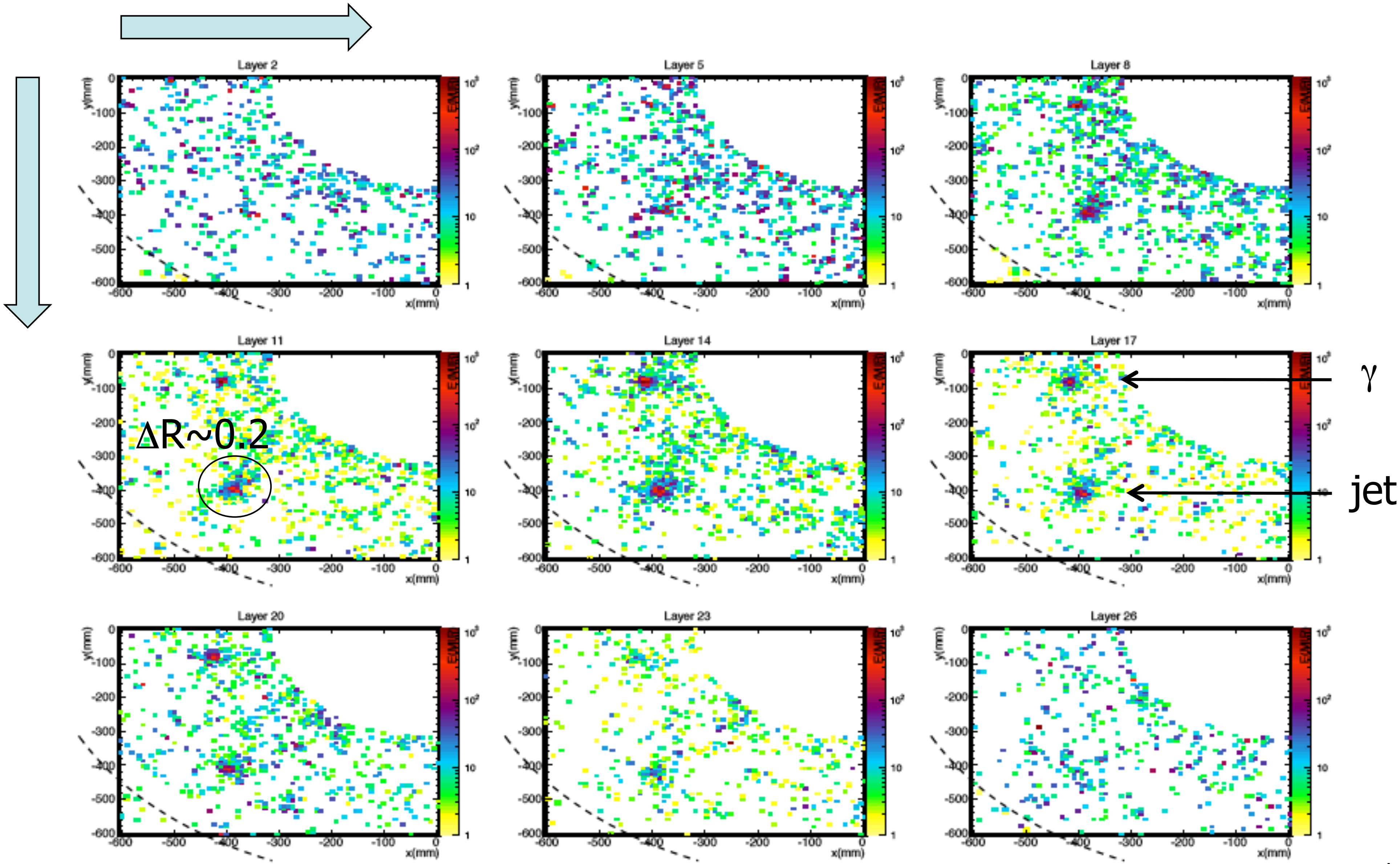
VBF H; H $\rightarrow \gamma\gamma$

Projected hits, event superposed with 140 PU:



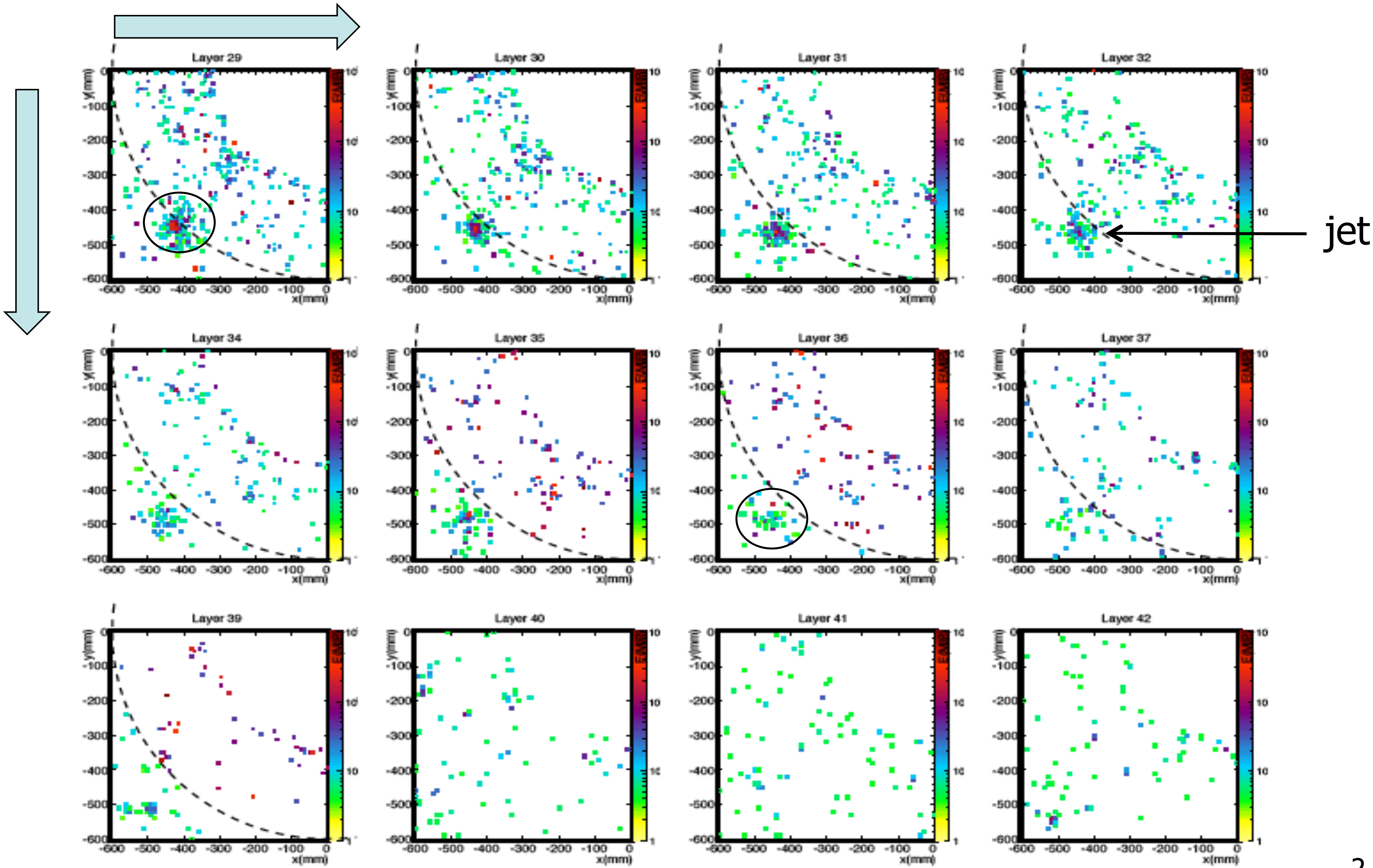
VBF H; H $\rightarrow \gamma\gamma$

Taking slices through the ECAL Section

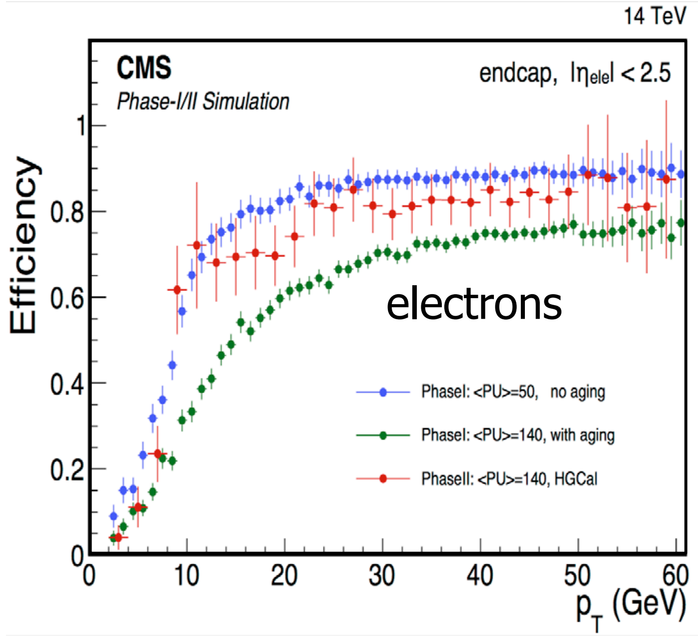


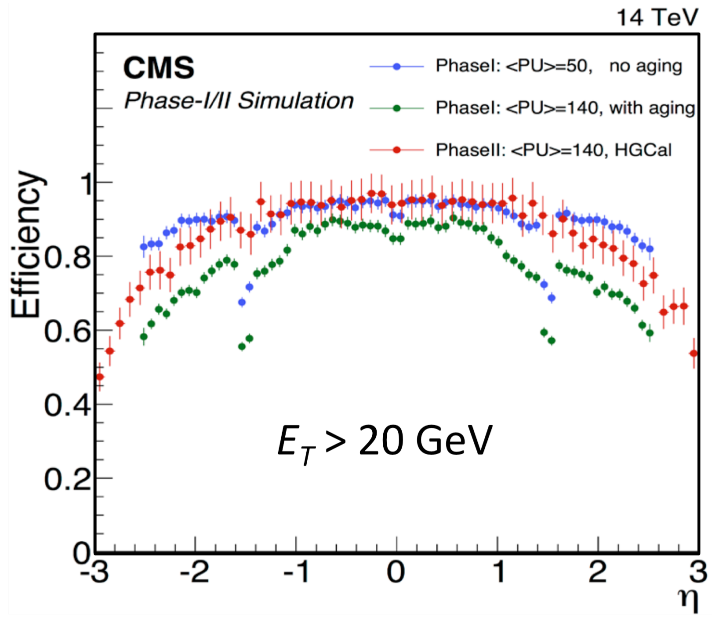
VBF H; H $\rightarrow \gamma\gamma$

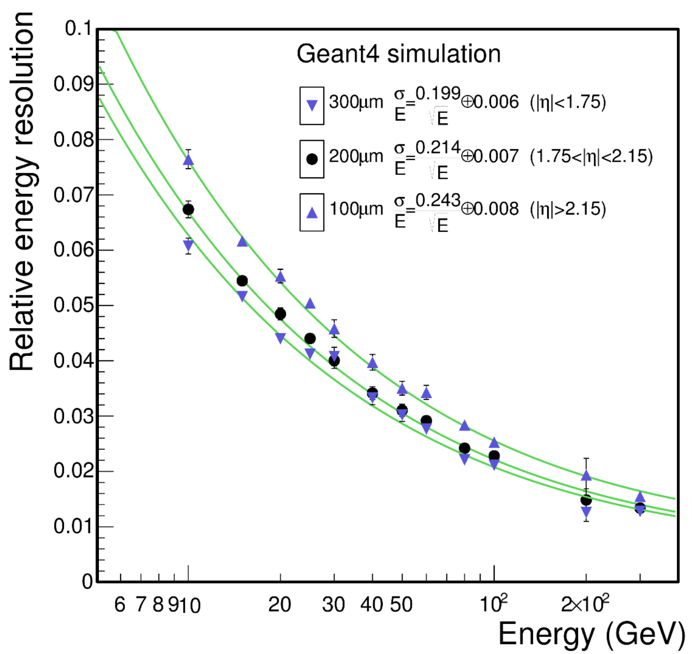
Taking slices through the HCAL Section

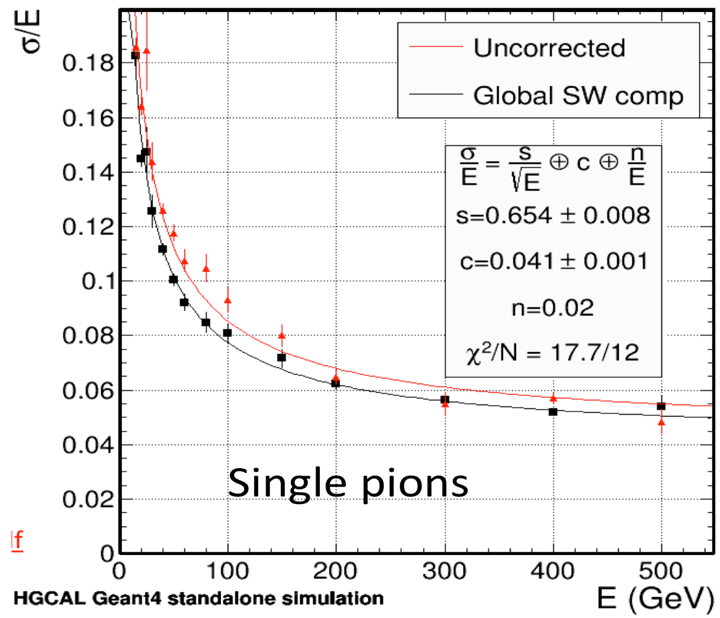


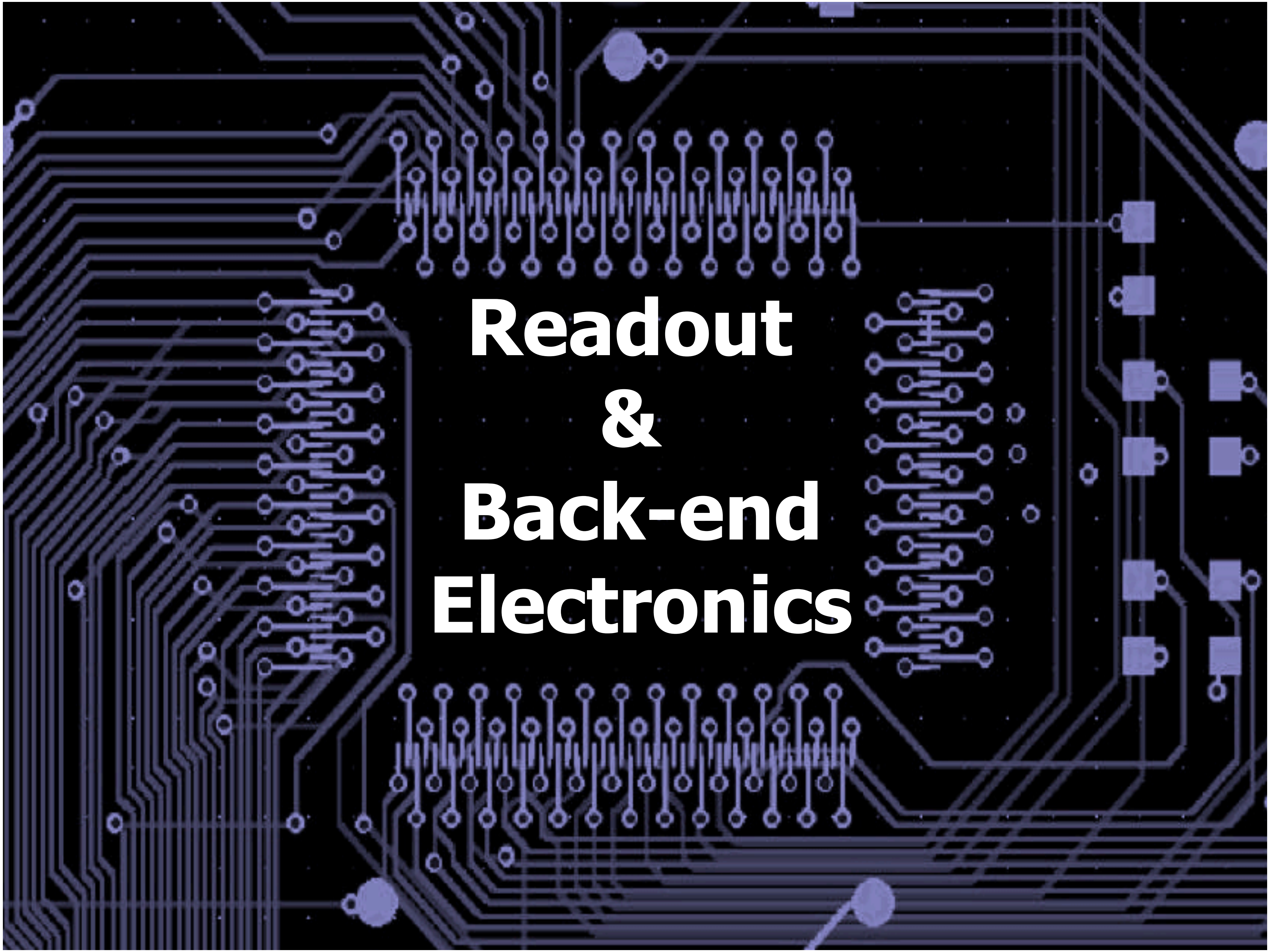
HGCAL Performance Simulations










Readout
&
Back-end
Electronics

Front-End Electronics

- The FE chips are among most challenging items for a HiGHTEC detector
- The IN2P3 profits from an exceptional micro-electronic lab. (Omega)

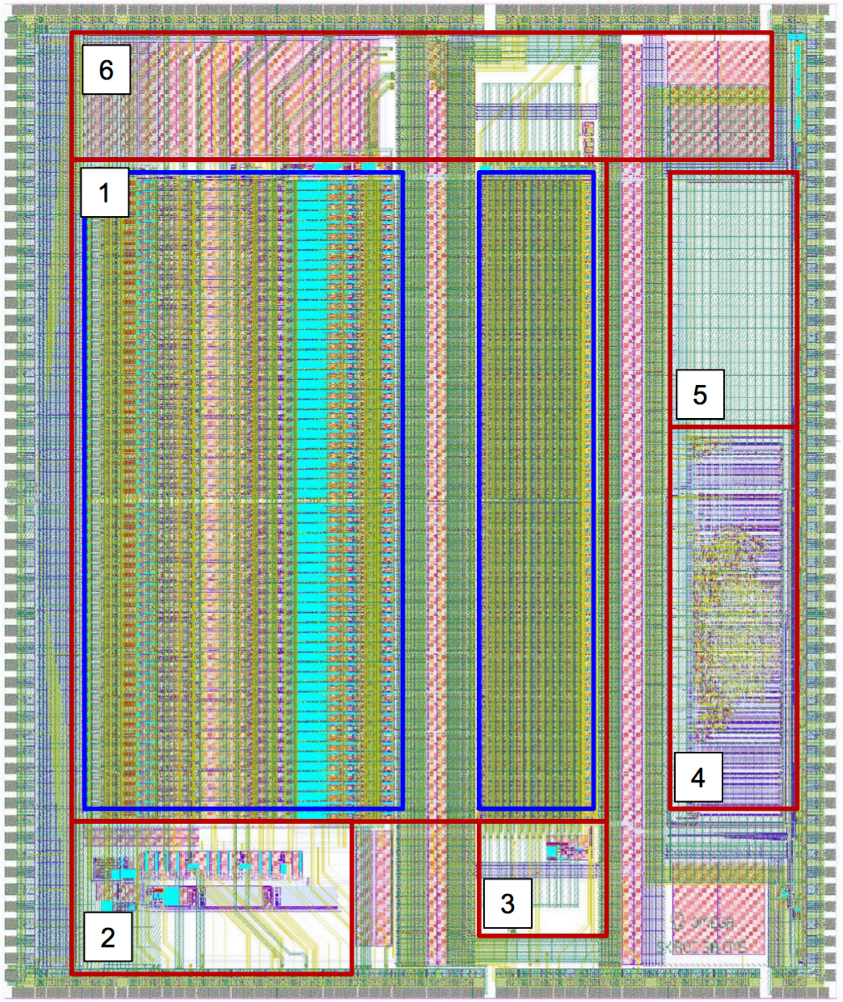
- Our SiWLC, HGTD, and HGCAL projects each rely on Omega for the FE chip

This is at the origin of strong synergies between the P2IO Groups

e.g. the same SKIROC-2 chip is used by SiWLC-CALICE (in power-pulsed mode) and for first tests in HGCAL-CMS.

The expertise was greatly profitable to design the first “SKIROC-CMS” ship (production launched last week !!!)

1 64 analog channels 2 DACs, bandgap
3 12-bits Wilkinson ADC 4 pure digital part
5 4k bytes RAM 6 decoupling capacitance



Readout and Back-End Electronics

- The HGTD-P2IO and HGCAL-P2IO will profit from the SiWLC Readout/DAQ experience with SKIROC chips on PCBs

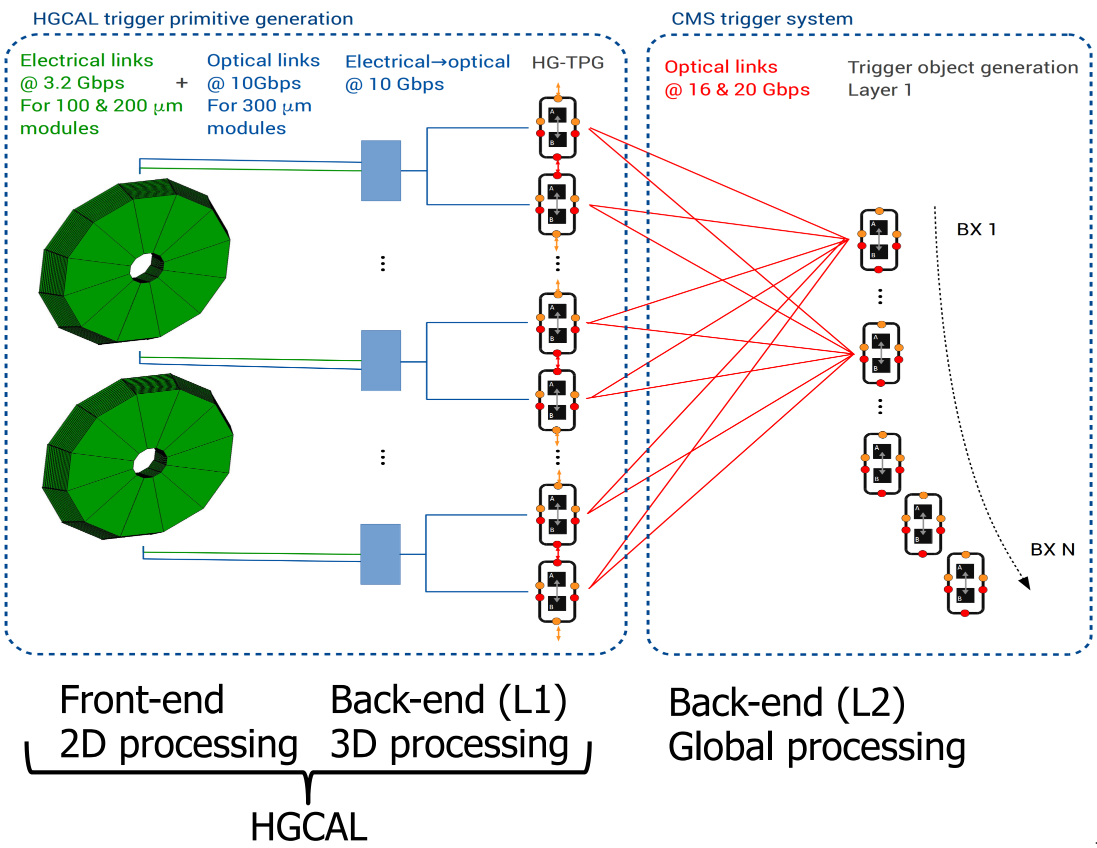
  e.g. → SiWLC plans a large scale DAQ design in synergy with ATLAS group
  → SKIROC-2 and SKIROC-CMS are pin-to-pin compatible and this may help re-use some of the SiWLC test tools

- Data Reduction and Trigger are a major challenge at the LHC with a lot in common between HGCAL and HGTD

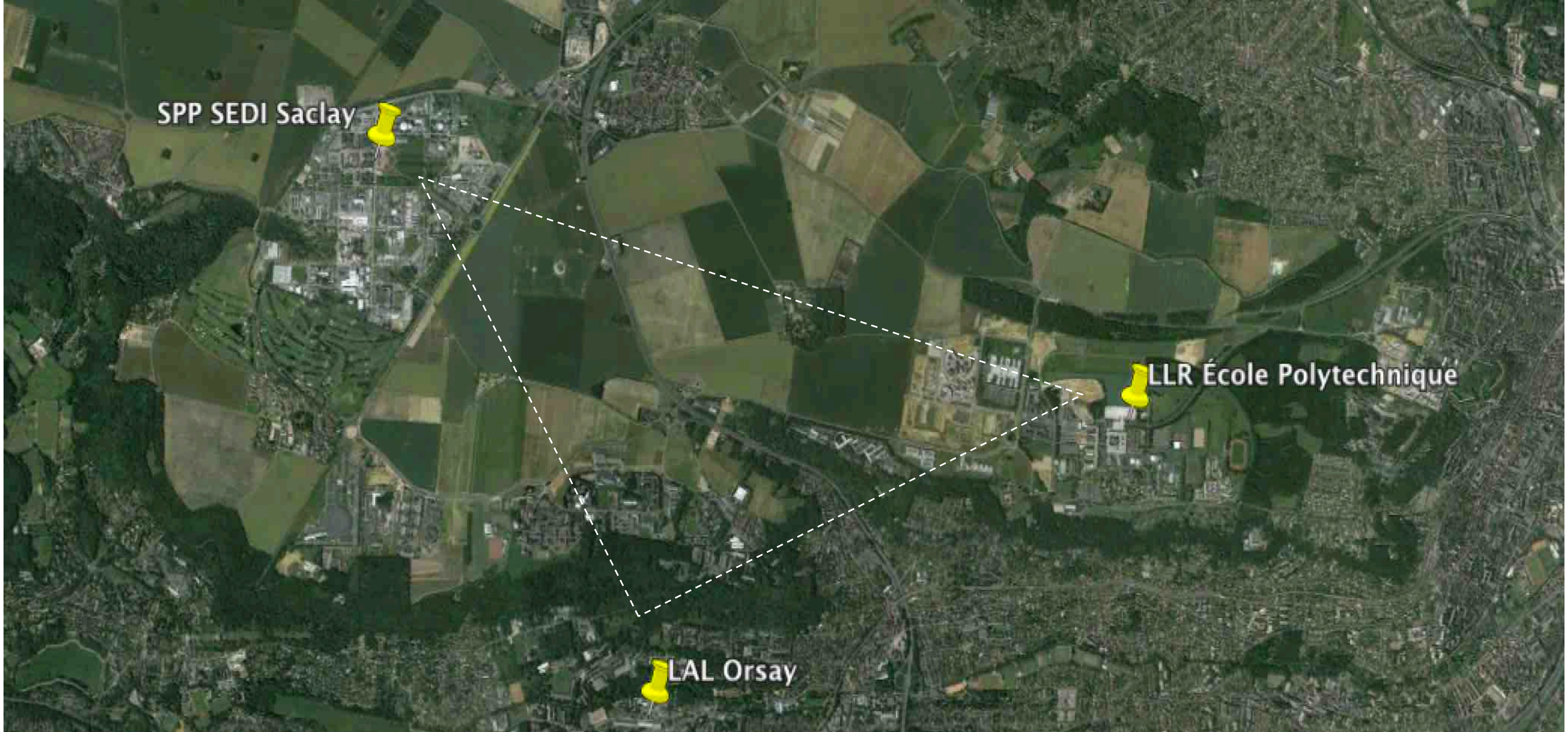
→ Need to preserve H boson signal while exploring TeV scale
→ Pile-up can severely affect the trigger

e.g. **CMS TP Architecture proposed by CMS-LLR:**

- Higher bandwidth
- Higher granularity (e/γ iso. and ID)
- Better PU control (longitudinal segmentation)
- Better combination of sub-detectors



HIGHTEC© @ P2IO

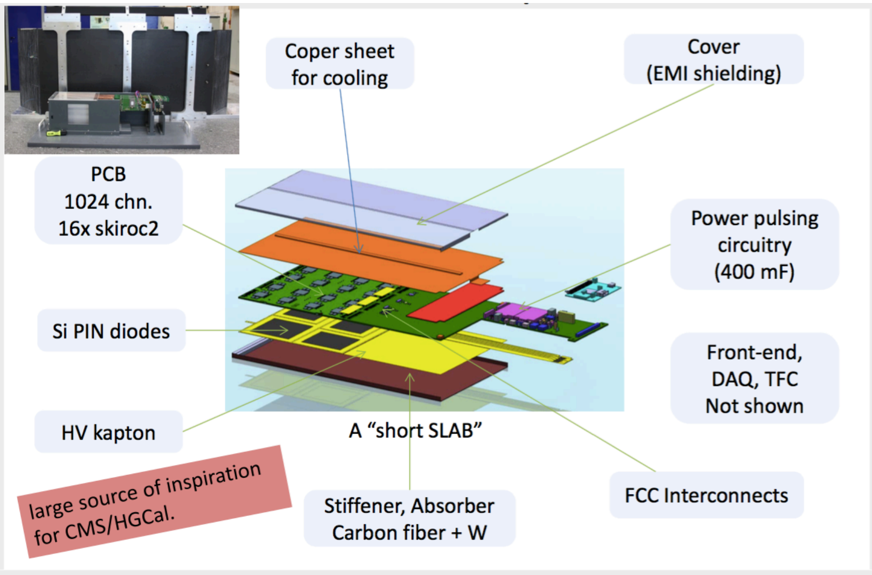


- **Establish a strong collaboration on detector developments** between the 3 major HEP P2IO labs involved in 3 major experiments (ILD, ATLAS, CMS)

SiWLC Status and Prospects

Past decade: Proof of principle
Now: Engineering challenges for the technological prototype

Short Cassettes

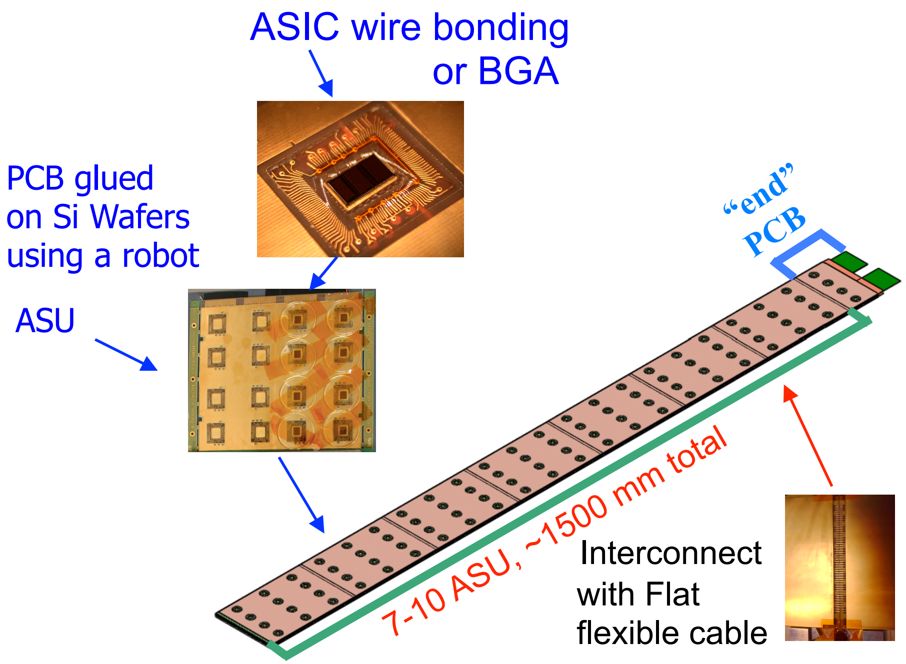


This P2IO project:

- Produce up to15 short cassettes for HGCFC beam tests
- Validation of concept under real conditions beam tests with SDHCAL for tests of PFlow
- Realise a Long cassettes as a most challenging R&D
- Also R&D in assembly process, PCB, Wafers

Long Cassettes

Several short ASUs (Active Sensors Units)
Similar layout for HGTD Task



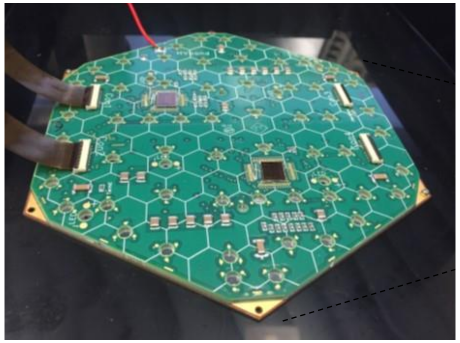
~10000 readout pads
~10000 interconnections
Current peaks >10 A for 2ms
Reliable signal propagation to be assured

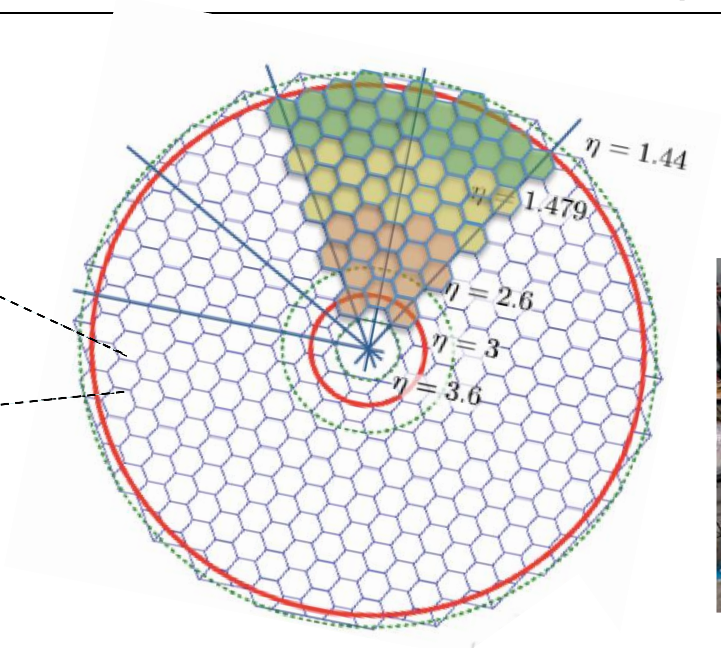
+ 1 post-doc

HGCAL Status and Prospects

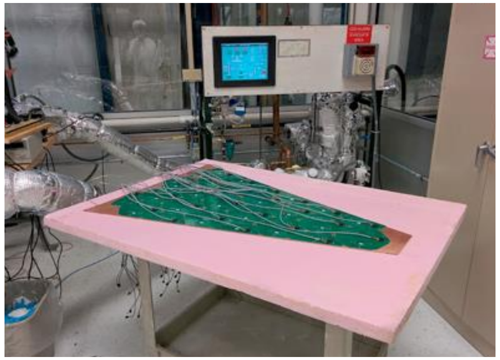
Project accepted in 2015; very fast start beyond TP thanks to CALICE R&D
… but different solutions for electronics, readout layers, trigger, etc.

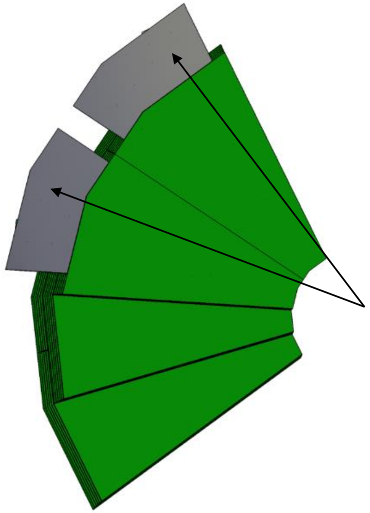
Hexagonal Si sensors
PCB, FE chip, on W/Cu





Successful cooling
tests and modeling
$\Delta T \sim 1 - 2$ °C





Cassettes with active
elements and CO_2
cooling inserted
in alveoli

Omega (IN2P3)

- New SKIROC-CMS chip produced for HGCAL prototype
- Test Vehicule for final FE chip in prod;

This P2IO project:

- Mechanical design, trigger strategy and electronics, clock distribution
- Technical prototype in test beam
- Trigger and reconstruction performances for physics

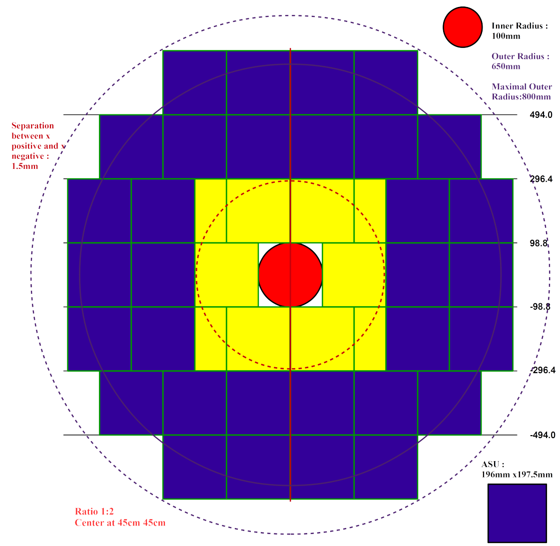
+ 2 post-docs

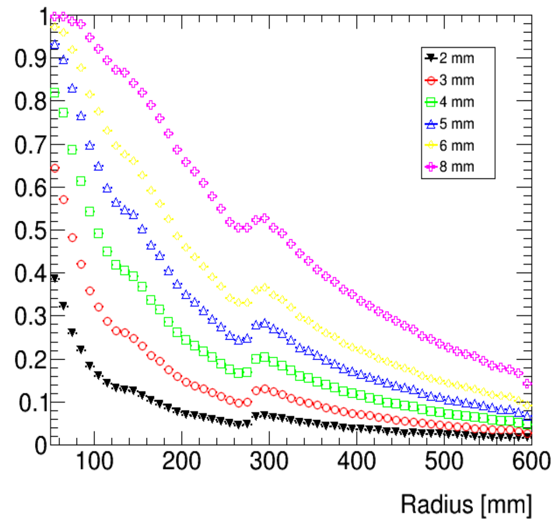
HGTD Status and Progress

Studies started on

Full simulation:

- Geometry: implemented in Geant4 framework of ATLAS
- Simulation of HITS on going
- Studies being performed (HIGHTEC):
  - Occupancy (minimum bias)
  - Muon, electron and jet performance/behaviour in HGTD





Electronics:

- Design of preamp done
- Study of CFD (Constant Fraction Discriminator) versus
  - Common interest ATLAS and CMS
- Submission in October 130nm CMOS

Personnel:

- Corentin Allaire (PhD thesis HIGHTEC)

Beam Tests & Performances

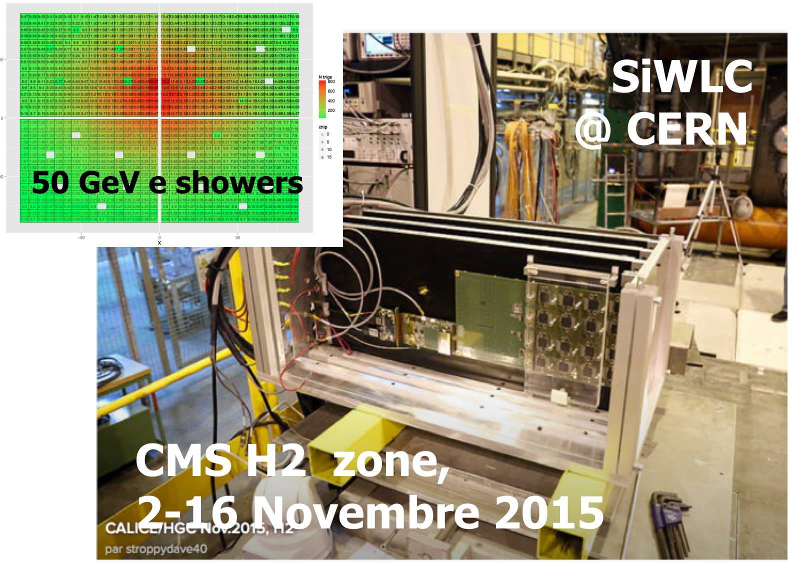
SiWLC : 2 weeks of test-beam at CERN on-going !!

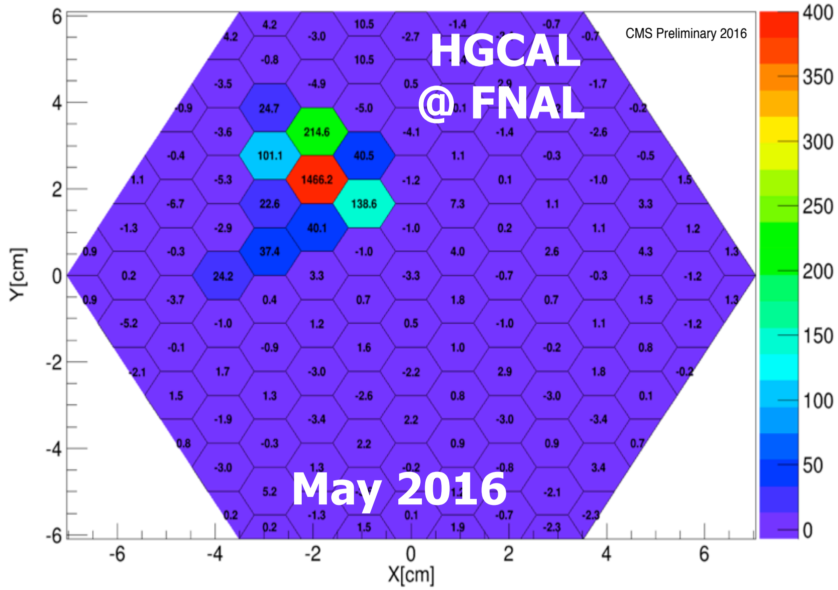
HGCAL : Test beam at CERN in August and November 2016

HGTD : Test beam at CERN for 3 weeks starting in October 2016

Goal: test sensor performance

- **50micron LGAD (glueing and wirebonding)**
- **130micron Pin Diode (glueing only)**
- **3mm x 3mm pads**
- **Discrete electronics for preamp and readout**





Test beam validation and performances are major goals of this project

Answers to Questions Raised Yesterday (1)

Concerning the sharing after budget cuts:

- P2IO budget 666 k€ (-26 %)

  45.0% SiWLC, 46.2% HGCAL, 8.7% HGTD

  56.7% hardware and 43.2% for manpower and travel funds

  Cut on hardware and 2 ½ year of post-docs
- Post-doc obtained for HGCAL (+ ILC Test beam) from X + IN2P3

  Most damaging: the missing ½ year of post-doc on HGCAL Timing

Expectations from P2IO:

- Possibility to review the situation in view of the milestones and decision of the CMS HGCAL Project which might affect the relative needs in terms of mechanics (which design chosen) vs intelligence (post-doc needs for timing or triggers)

High **G**ranularity **H**ybrid **T**ime-**E**nergy **C**alorimetry©
HIGHTEC

- This P2IO Project extends the concept of High Granularity Calorimetry to fully exploit also time capabilities motivated by the LHC applications
- The project will have a major international impact with three essential « HiGHTEC » realisations for applications at e+e- and hadronic colliders
- Large international collaborations are by nature rather hermetic. Mutualisation and exchanges are better initiated at "local" / national level across projects
- The impact of the groups on SiWLC, HGCAL, and HGTD will strongly profit from the synergy and expertise within P2IO

The LAL+LLR **SiWLC** groups in our P2IO project will construct, and validate in test beams, a first complete ECAL prototype that meets the requirements for a future e^+e^- collider experiment

The LLR, SPP, and SEDI **HGCAL** groups in our P2IO project will perform essential R&D on mechanics, trigger, and timing for the forward calorimetry to be deployed at High-Luminosity LHC

The LAL **HGTD** group in our P2IO project will perform essential R&D for the timing capabilities of a forward detector proposed for HL-LHC


Backup Réserve