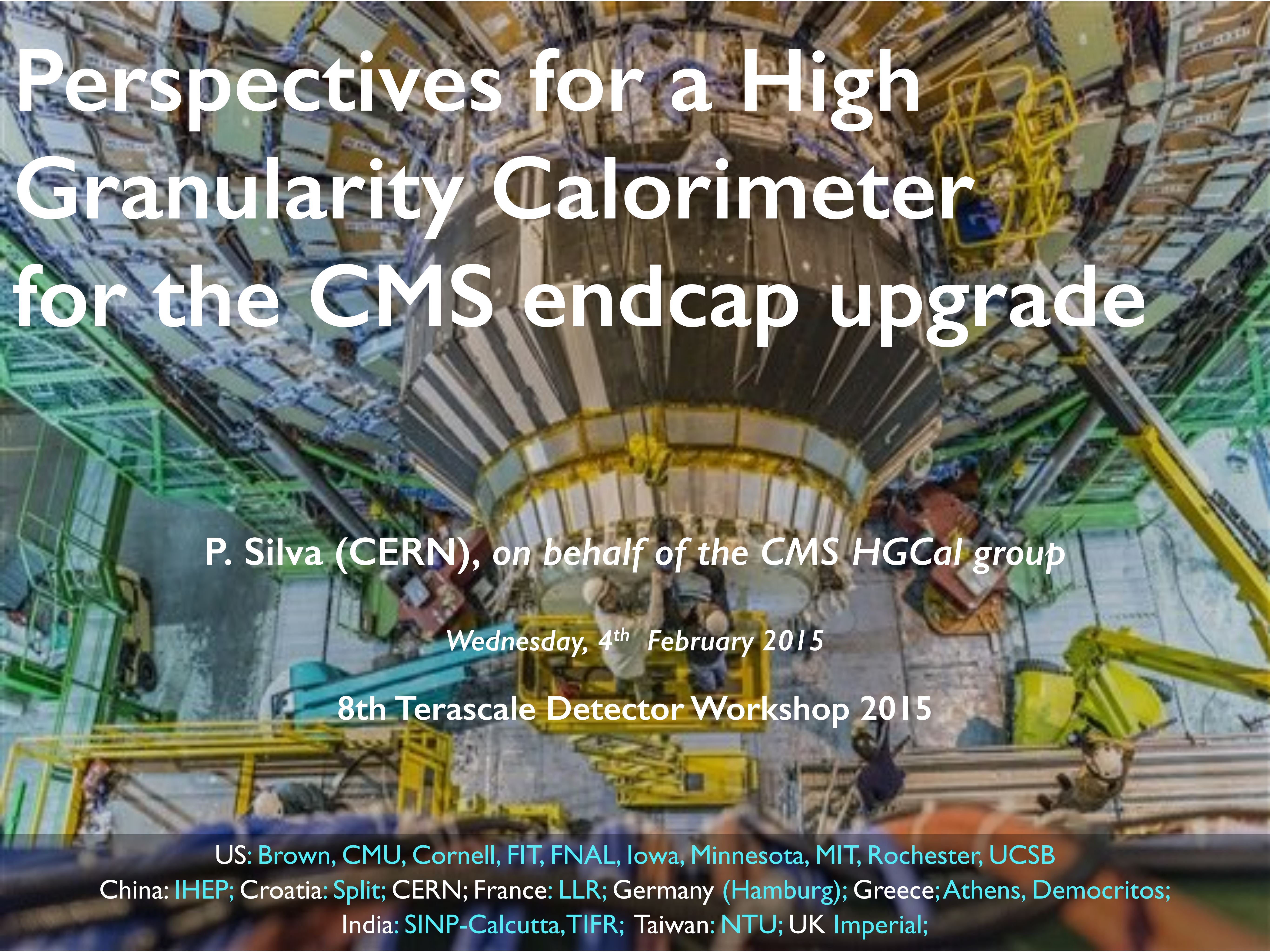


Perspectives for a High Granularity Calorimeter for the CMS endcap upgrade

P. Silva (CERN), *on behalf of the CMS HGCal group*

Wednesday, 4th February 2015

8th Terascale Detector Workshop 2015

US: Brown, CMU, Cornell, FIT, FNAL, Iowa, Minnesota, MIT, Rochester, UCSB
China: IHEP; Croatia: Split; CERN; France: LLR; Germany (Hamburg); Greece; Athens, Democritos;
India: SINP-Calcutta, TIFR; Taiwan: NTU; UK Imperial;

Outline

Experimental prospects at the High-Luminosity LHC

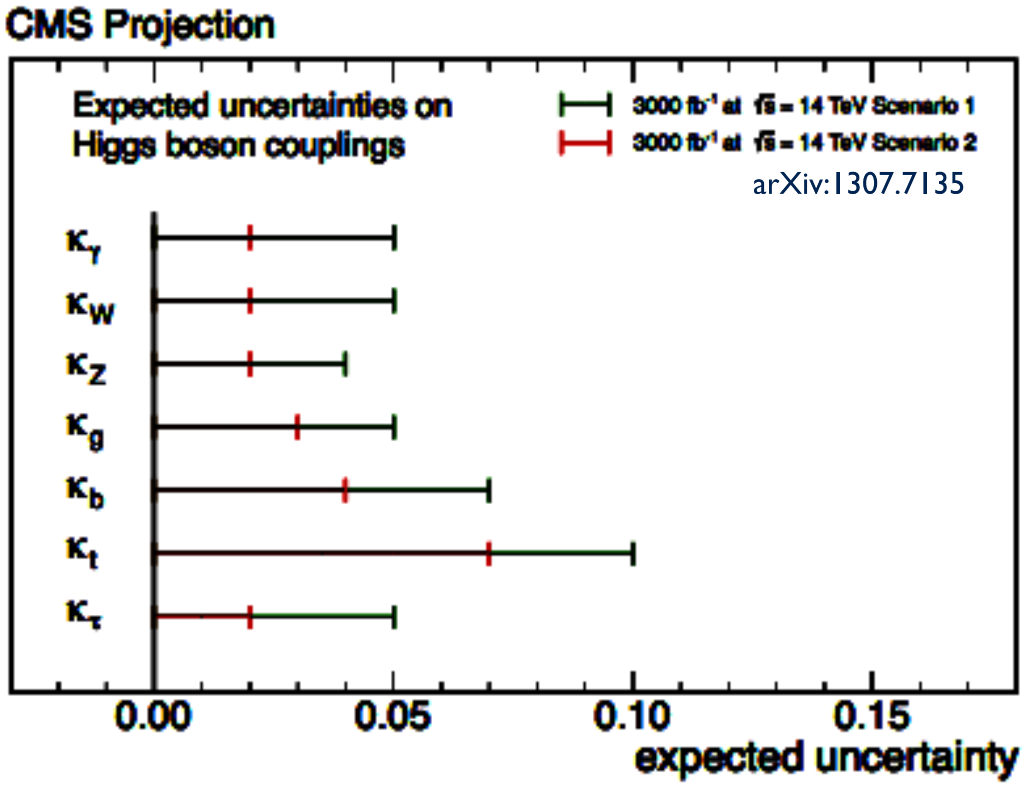
High-Granularity Calorimeter for CMS

Current performance estimates

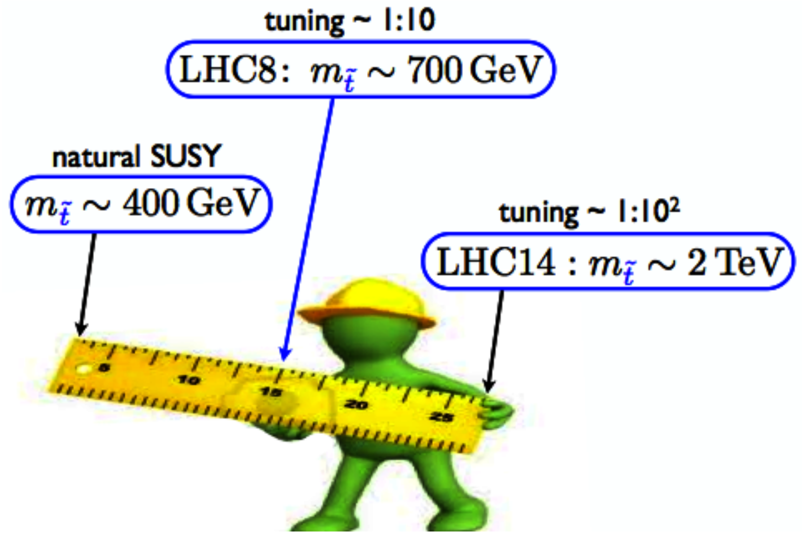
Conclusions

Physics at the HL-LHC

- **The HL-LHC will deliver us 3fb^{-1} of pp collisions per day**
  - leveled luminosity : 5 x 10^{34} cm^{-2} s^{-1} → **<PU>=140**
  - **3 ab^{-1} after 10 years** (2025-2035)
- **Higgs factory**
  - expect 2-10% uncertainty on Yukawa couplings
  - ~30% on self-couplings
  - test $V_L V_L \rightarrow V_L V_L$ unitarity
- …**but also ultimate precision** (as pp allows it) : B-, top-physics,…
- **Keep searching for new physics**
  - characterise Run II / III discoveries : dark matter? SUSY? new resonances?
  - push the energy frontier
  - uncover deviations from the SM or in rare processes

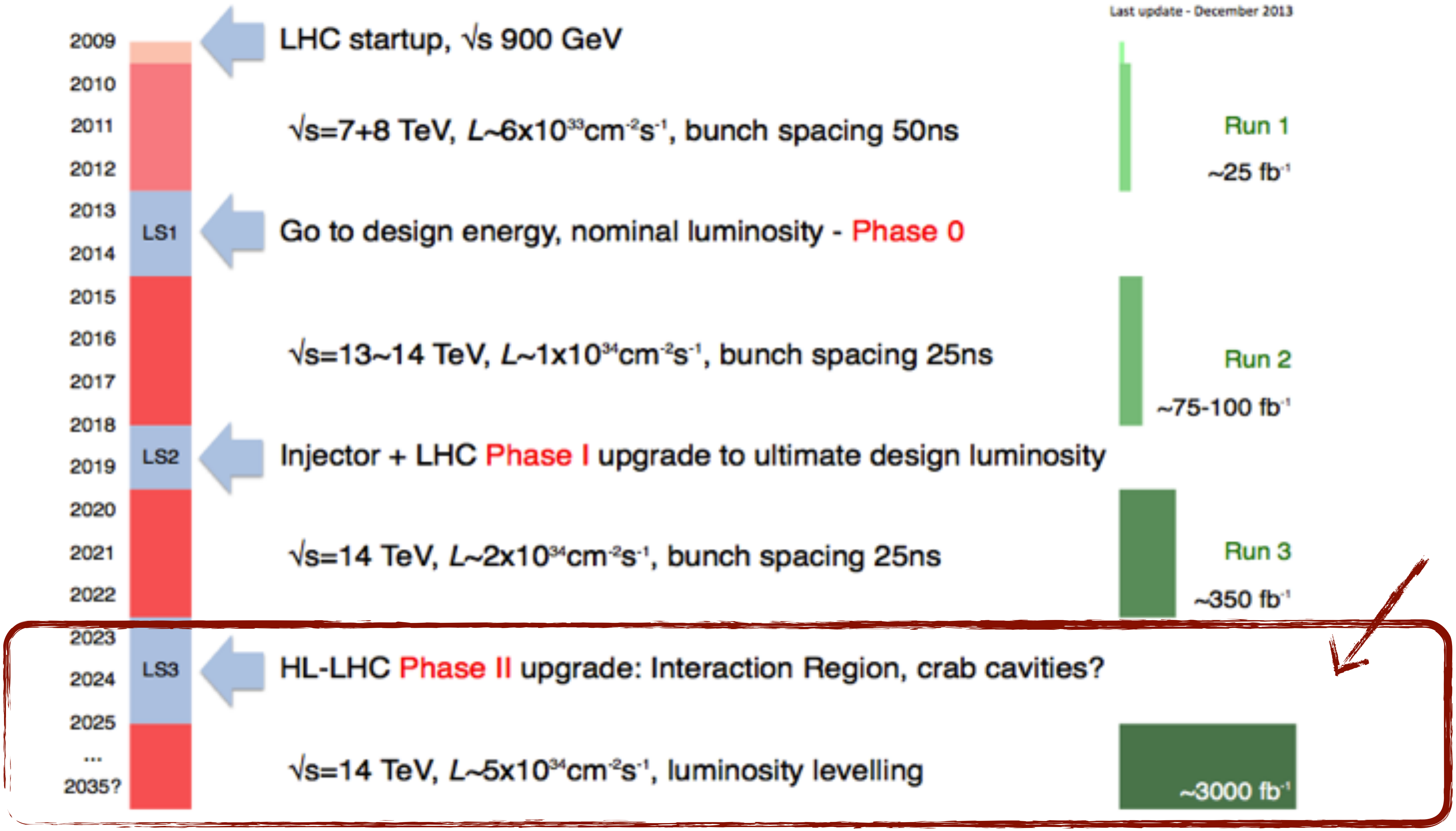


arXiv:1307.7135



(*) cartoon taken from G. Perez @TOPLHCWG May 2014

Machine schedule



LHC startup, $\sqrt{s}$ 900 GeV

$\sqrt{s}$=7+8 TeV, L~6x10^{33}cm^{-2}s^{-1}, bunch spacing 50ns

Go to design energy, nominal luminosity - Phase 0

$\sqrt{s}$=13~14 TeV, L~1x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns

Injector + LHC Phase I upgrade to ultimate design luminosity

$\sqrt{s}$=14 TeV, L~2x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns

HL-LHC Phase II upgrade: Interaction Region, crab cavities?

$\sqrt{s}$=14 TeV, L~5x10^{34}cm^{-2}s^{-1}, luminosity levelling

By now detectors are ready for Run II (pixels, electronics, trigger upgrades needed for Run III)

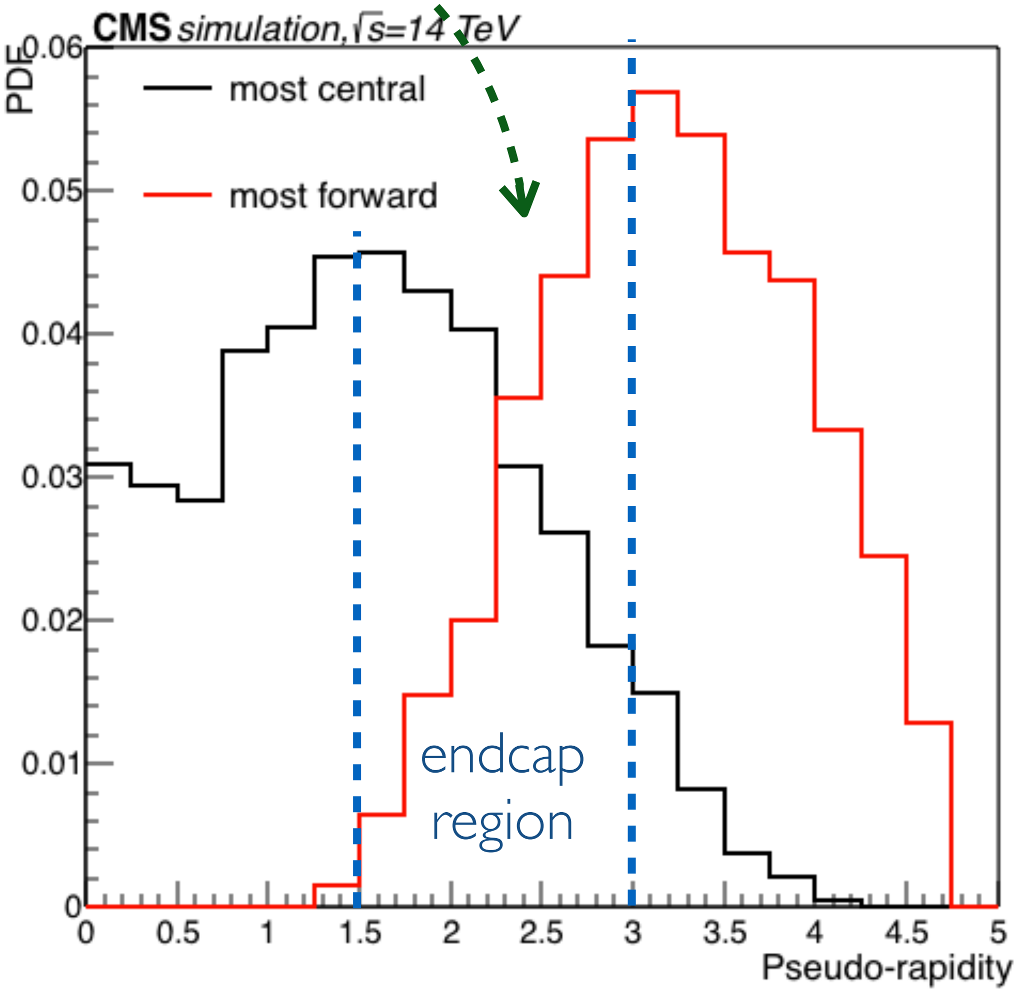
In the next slides will focus on the preparation for the HL-LHC

HL-LHC: requirements for the endcap calorimeters

- Use **global event description in the high pileup environment**
  - **good energy resolution** for e.m. and hadron showers - same or better than current detectors
  - **enable a powerful and flexible trigger**
  - **radiation hard**
  - **high efficiency and good resolution for VBF jets in acceptance**

- **Calorimeter design driven by physics performance**
  - high lateral and longitudinal granularity
  - small Moliere radius (radiation length) and interaction length
  - resolutions consistent with physics goals
  - good absolute and relative calibration
  - flexibility in creating L1 trigger primitives

Tag jets in VBF H→ττ



High-Granularity Calorimeter for CMS

Imaging particle flow calorimeter inspired by the ideas developed by the ILC- CLIC communities

CMS is investigating the usage of a high granularity calorimeter with ~6.5M channels of Si pad detectors.

Within CMS, the final decision on the endcap calorimeter technology will only occur end of March.

Why HGC?

- **Dense, high granular 3D sampling calorimeter** provides
  - unprecedented topological information and shower tracking capability
  - energy resolution well matched to boosted particles and jets in the endcap acceptance

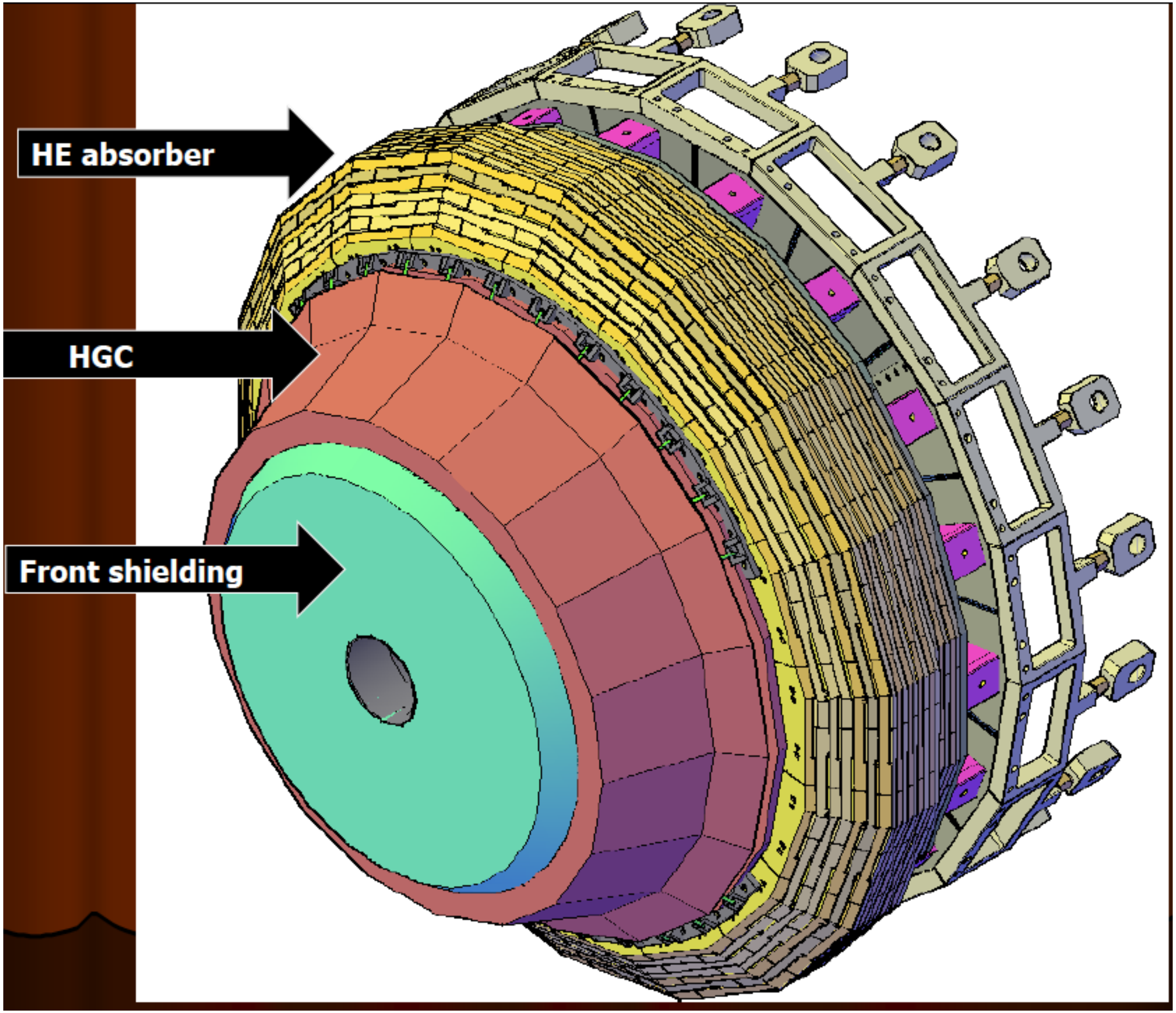
- **Exploit this potential for feature extraction and precision calorimetry**
  - Level-1 trigger and offline reconstruction with Particle Flow
  - unfold the effect of non-projective geometry by tracking showers
  - used 3D shower development to further improve e/γ identification
    as well has $\pi^{\pm}$ and neutral reconstruction in jets
  - apply pileup subtraction and measure shower energy using dynamic clustering

Conceptual design

Backing HCAL 5.5λ

ECAL 25X_0

Front HCAL 3.6λ



Calorimeter concept

Electromagnetic calorimeter

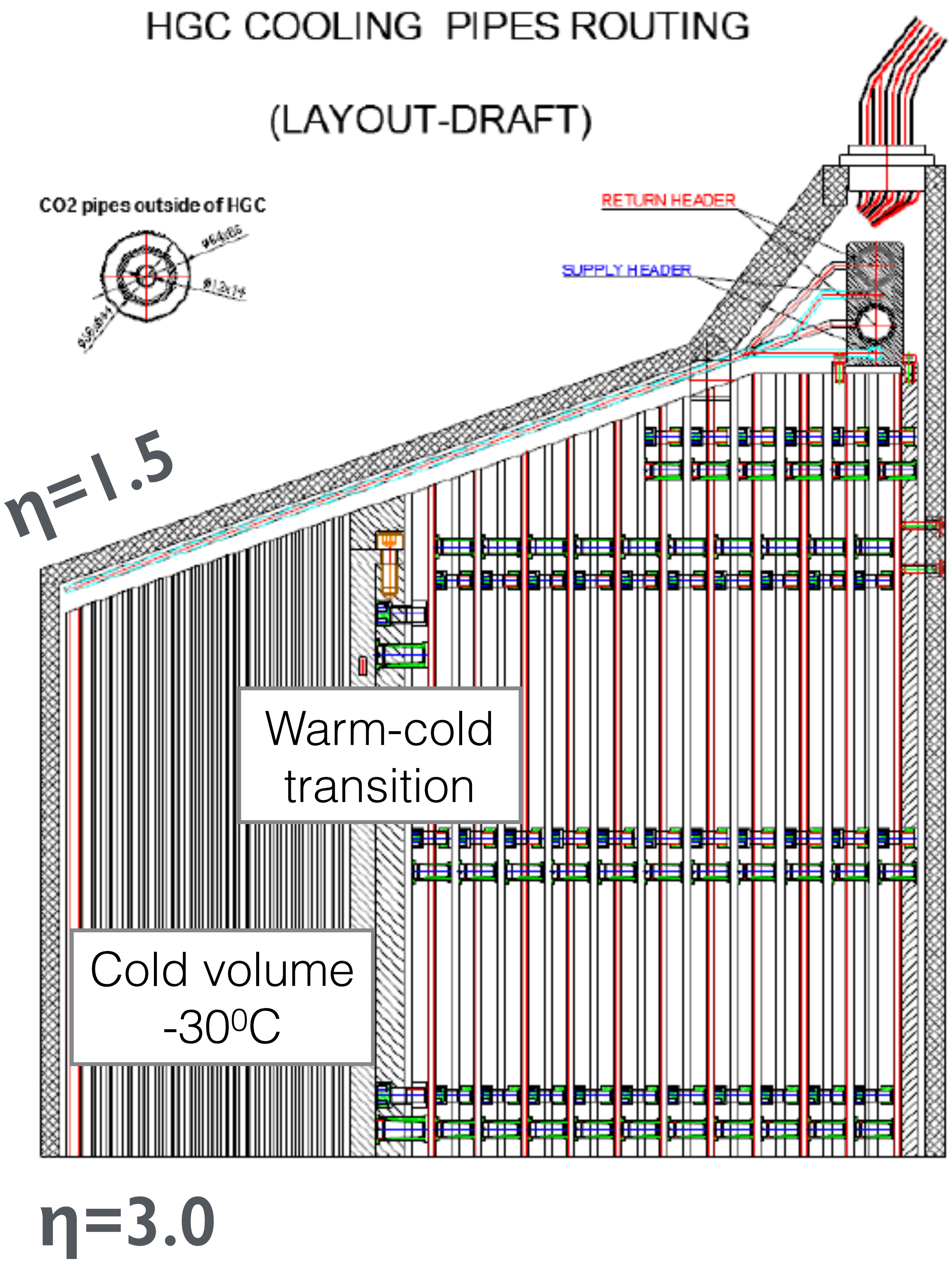
- 28 layers of W/Pb/Si
- total 25 X_0 / 1λ
- 3 sub-sections increasing X_0 ($10 \times 0.64 X_0 + 10 \times 0.88 X_0 + 8 \times 1.1 X_0$)
- cell size 0.5-1cm^2 = 4.8M channels

Front hadronic calorimeter

- 12 layers of Brass/Si (0.3λ)
- total 3.6λ
- cell size 1cm^2 = 1.96 M channels

Backing hadronic calorimeter

- 12 layers Brass/Scintillator (2 segments)
- total 5.5λ



Comparison with the Si tracker

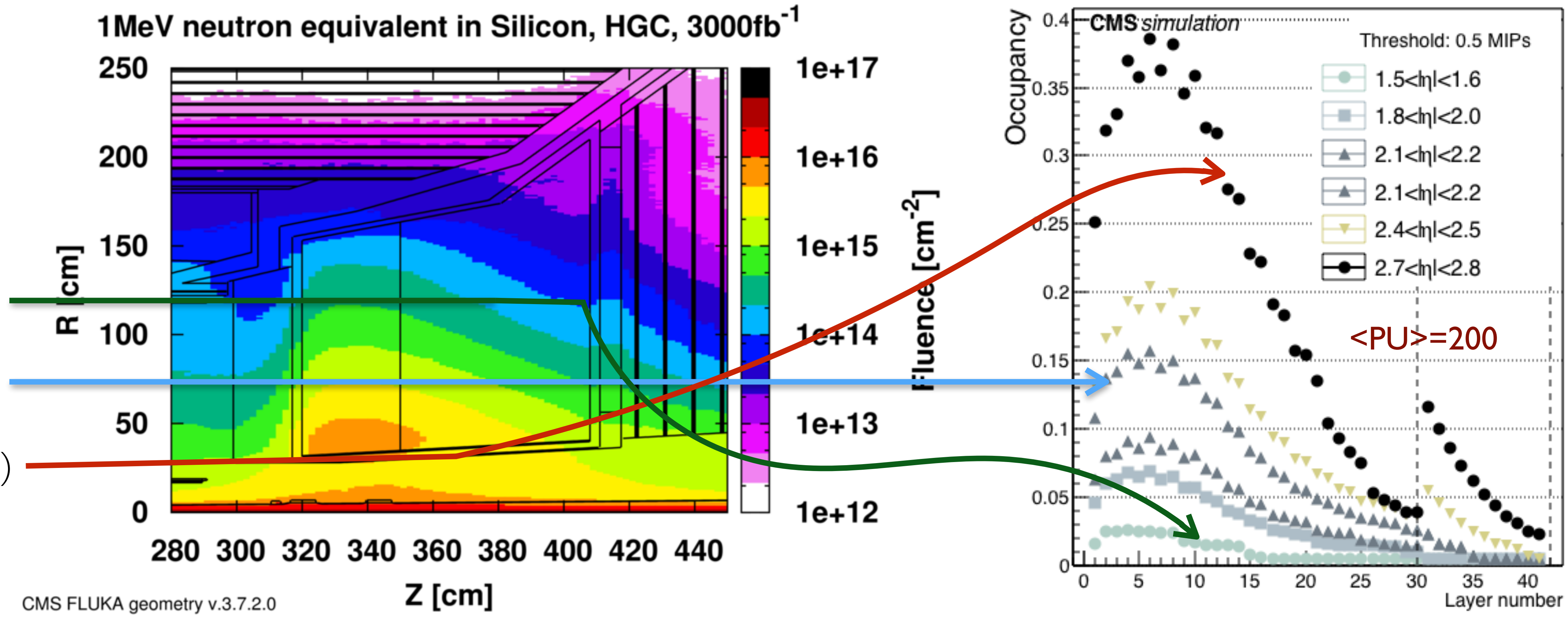
	Tracker	**Calorimeter**
Material budget	light materials wherever possible	dense, with small R_M
Services and support structures	care with placement	must not yield large gaps
Support and heat transport	carbon fiber/ Al-CF	W, Pb and or Cu
Radiation (main source)	charge hadrons	neutrons
geometry	fine strips	large area pad
Placement	precise	loose tolerance
Dynamic range	small	large
Cooling	operate at -30^{0}C (maintained with CO$_2$ cooling)	
Radiation levels	up to 10^{16} 1 MeV neutron equivalent	

Si width

300 μm (1cm^2)

200 μm (1cm^2)

100 μm (0.5cm^2)



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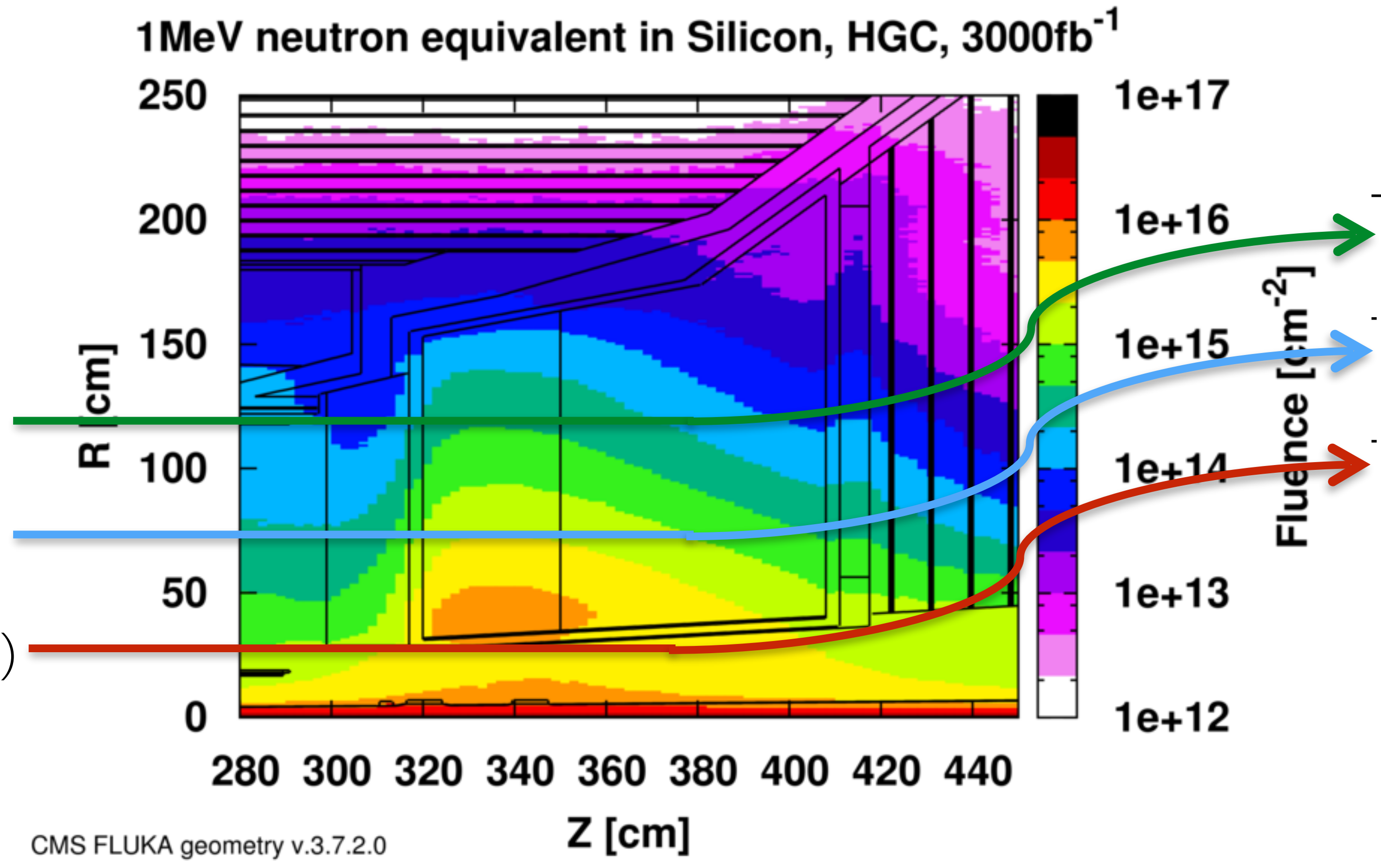
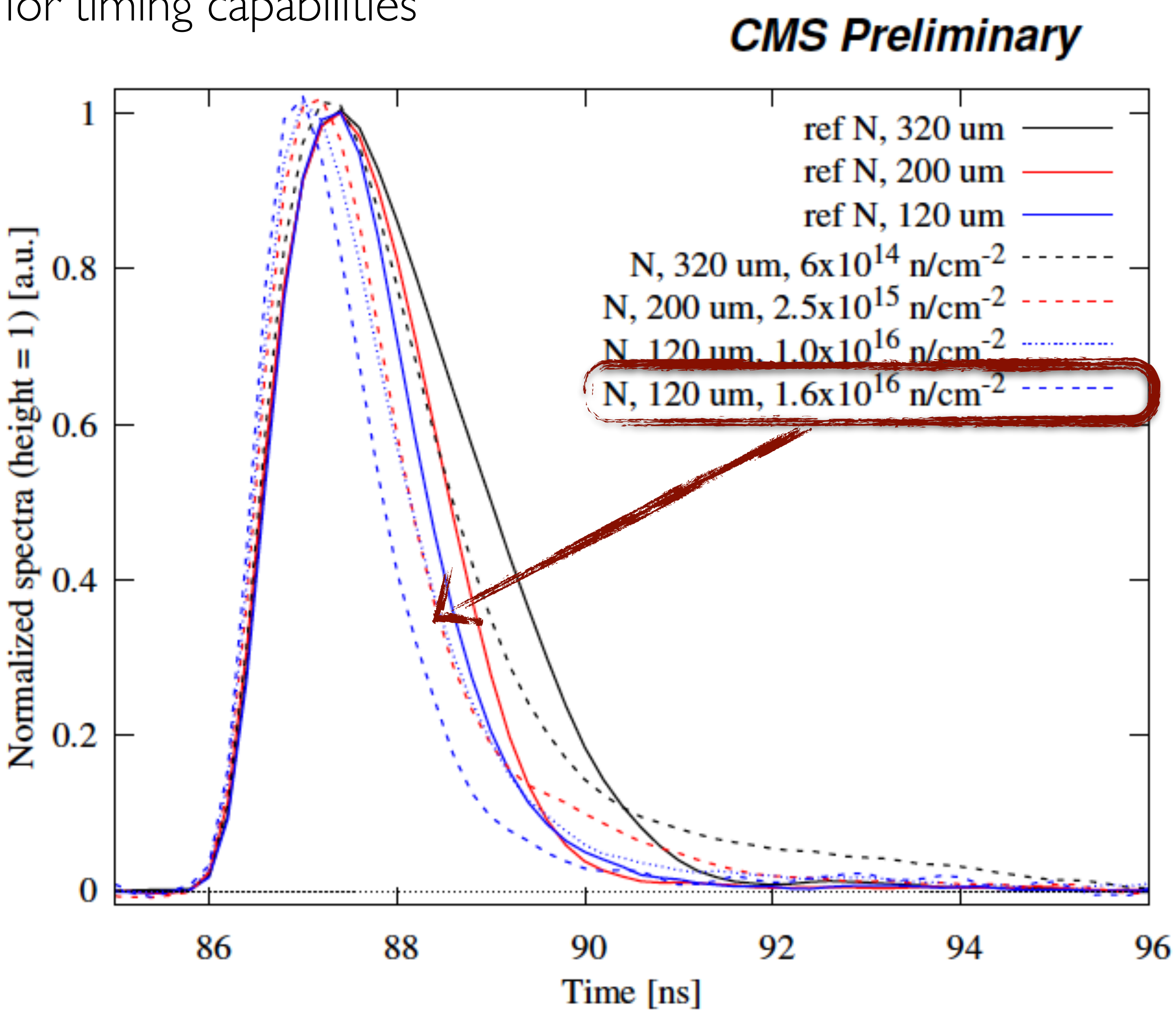


η	**E [GeV]** (p_T=150 GeV)	**<max ΔE>** [pC] *
1.8	466	9.8 pC
2.2	685	
3.0	1510	

** 1MIP=3.5 fC for 300 µm*
10pC=2850 MIP

Si sensors I

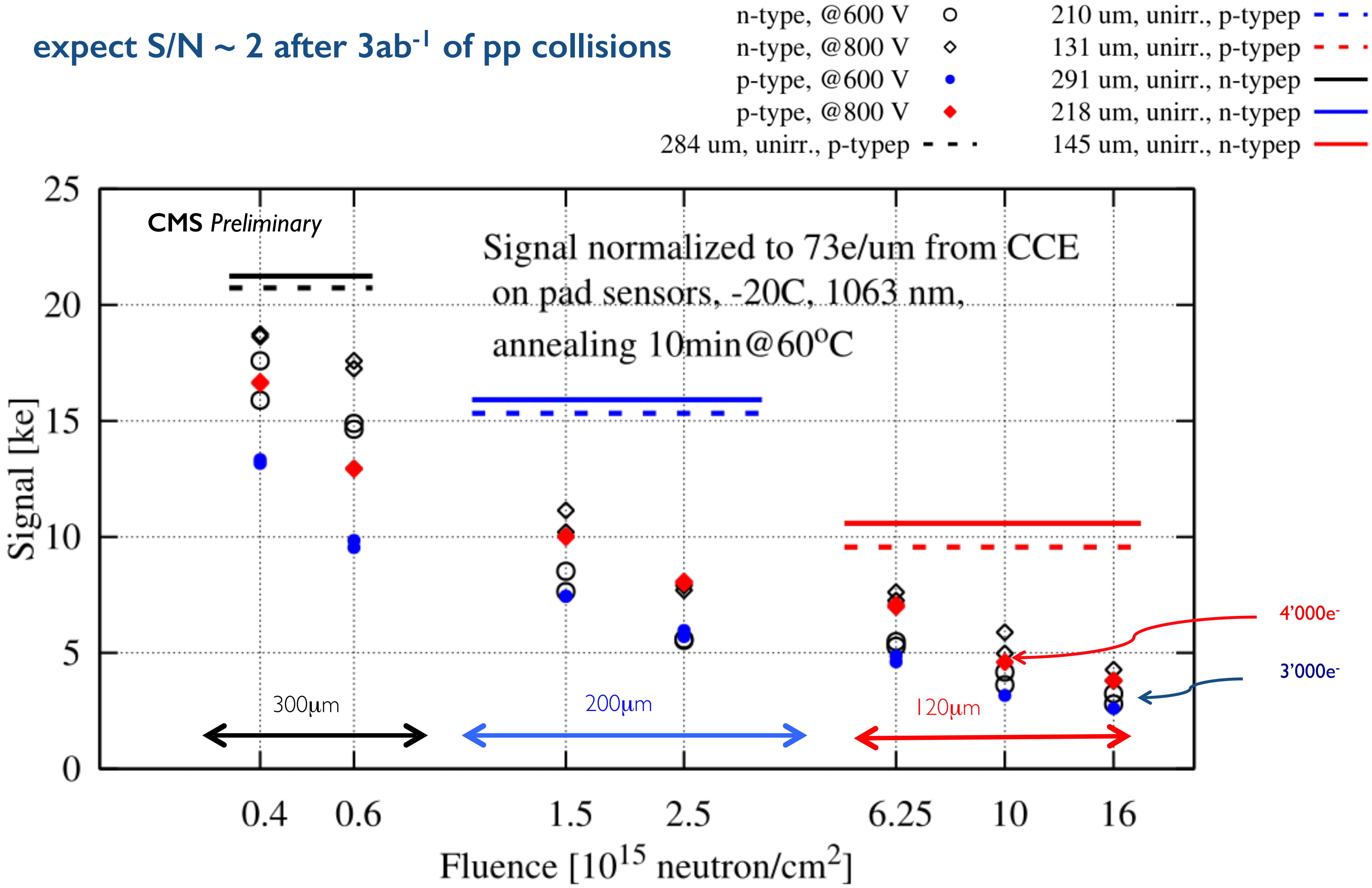
- Pulse shape before and after irradiation
  - p-in-n diodes, 600V bias, 50ps IR laser pulse λ=1060nm
- **After neutron irradiation: shorter pulse and rise time (width < 10ns)**
  - relevant for timing capabilities



1.5 higher dose with respect to the one expected after 3ab^{-1} at the HL-LHC

Si sensors II

- Fluence effect on charge collection efficiency
  - **expect S/N ~ 2 after 3ab^{-1} of pp collisions**

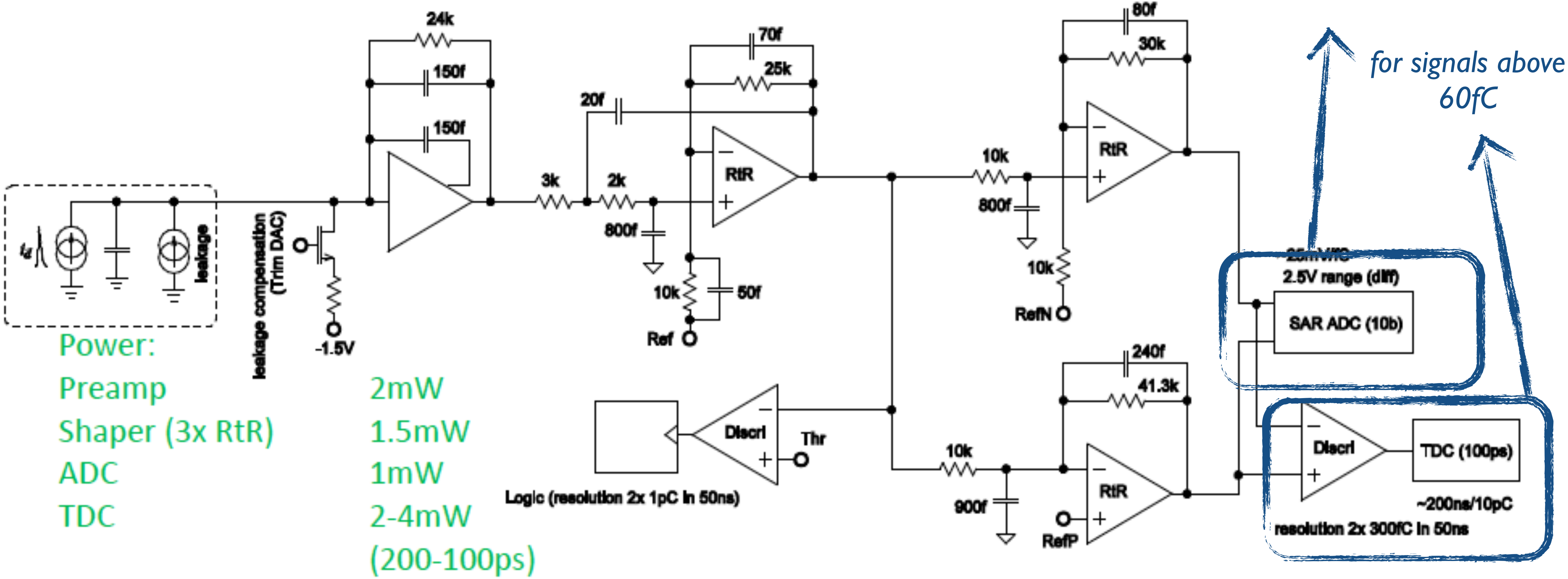


Front-end electronics I

- Input stage: cascode with PMOS input transistor with resistive feedback - 2mW @ 1.5V
- Leakage compensation with Trim DAC (negligible contribution to noise)
- Shaper: DC coupled, Sallen-Key low pass filter built with RtR amplifier
  - 3x400μW 2x10pF driving capability
  - peaking time 20ns (15ns after 1st stage four double pulse resolution)

for pulses up to 100fC

for signals above 60fC

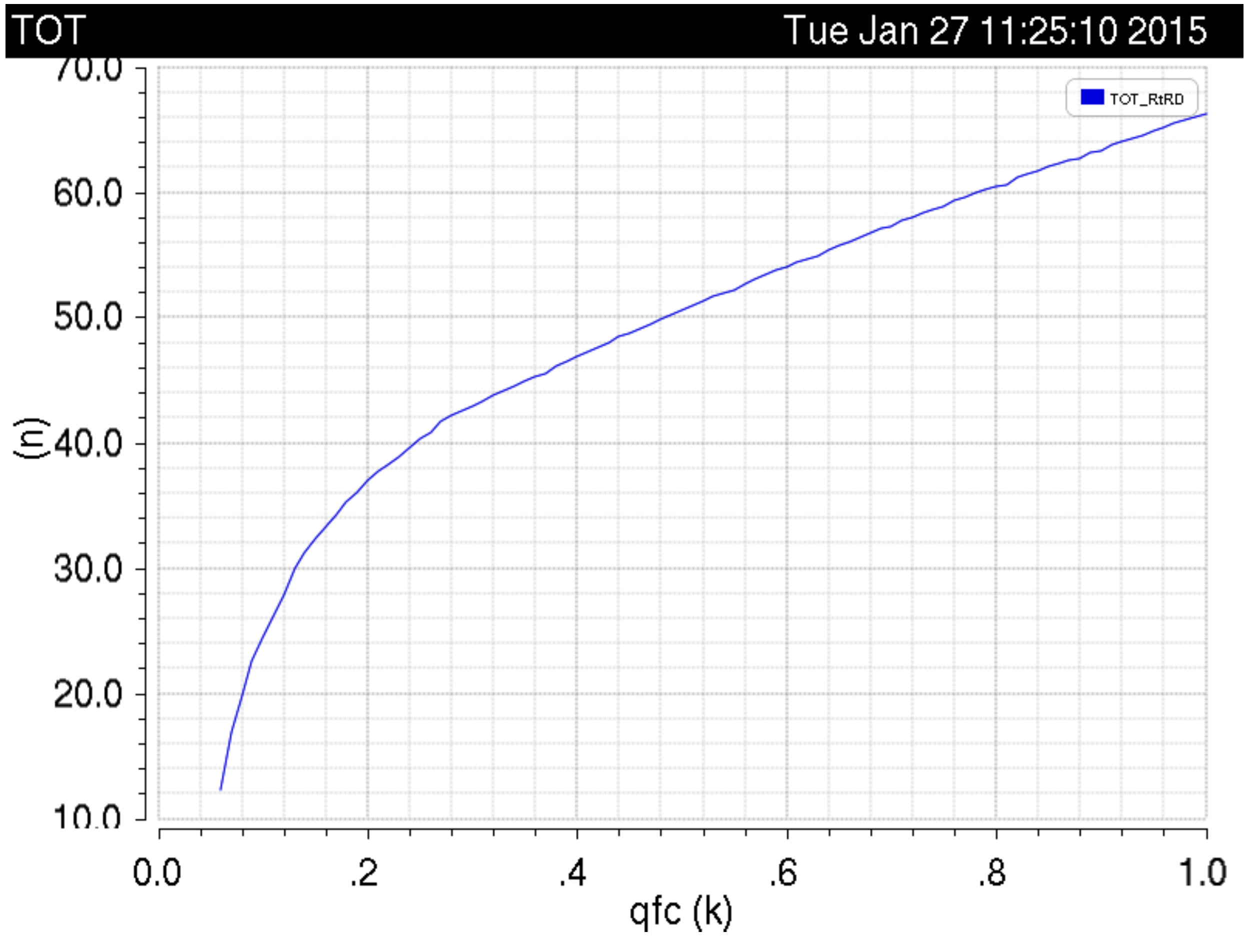


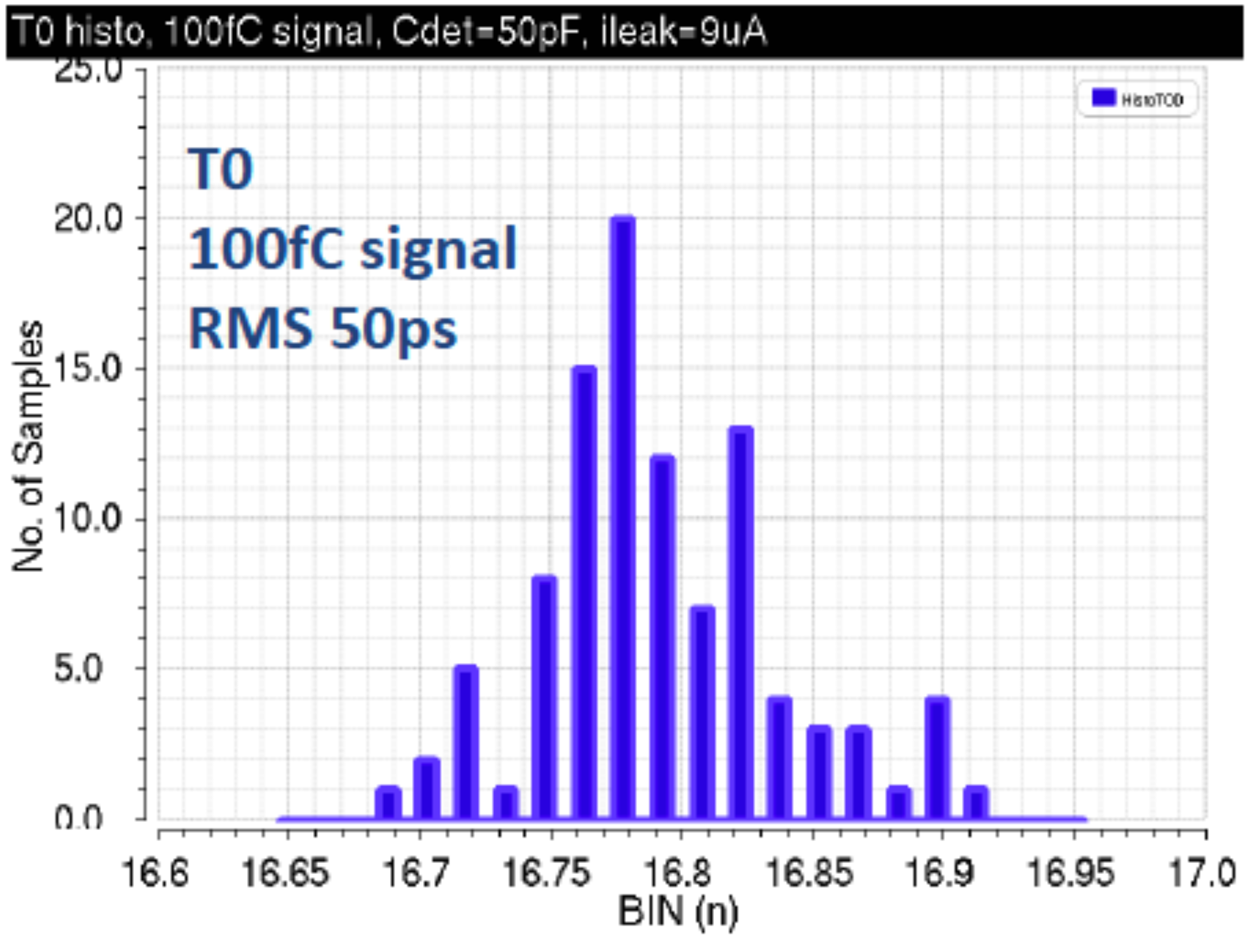
Power:

Preamp	2mW
Shaper (3x RtR)	1.5mW
ADC	1mW
TDC	2-4mW (200-100ps)

Front-end electronics II

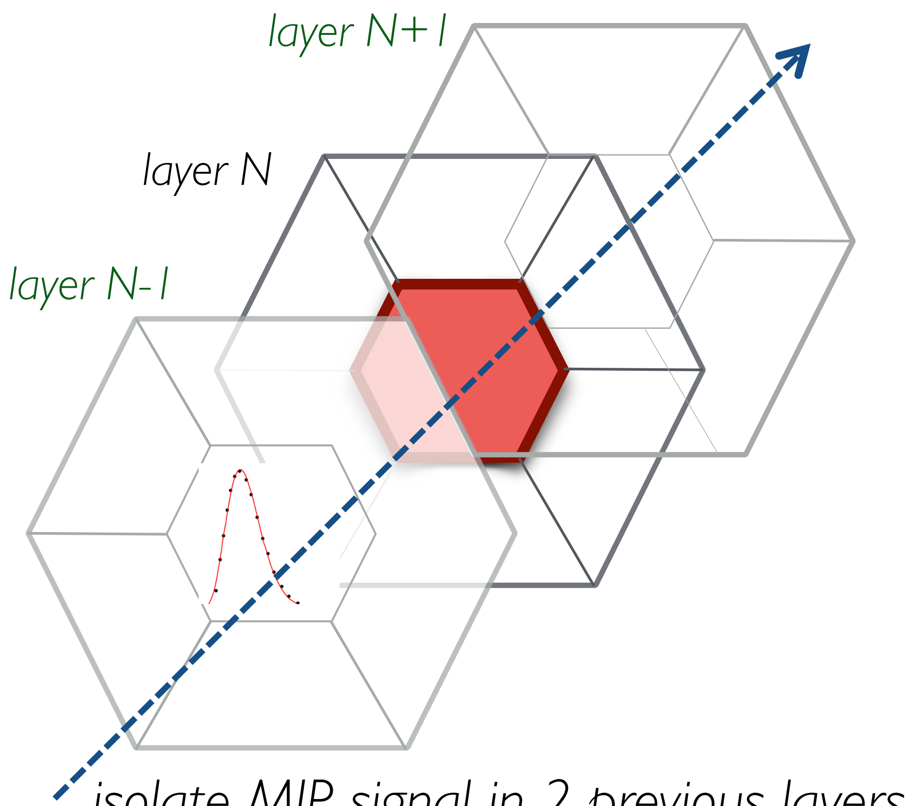
- Full SPICE simulation of the analog performance
    - **use time-over-threshold** (ToT) regime to provide low noise (~2k e$^-$) and cover full dynamic range
    - **potential for ~50ps timing** for cells in the core of showers with E_T>2-3 GeV
- **Dead-time** due to high energy, long ToT cells **from bunches previous to trigger**
    - preliminary estimates indicate both **small** fraction of cells (<10^{-4}) and degradation of the resolution
    - keep as back-up a low gain design (larger noise, ~11k e$^-$) without saturation



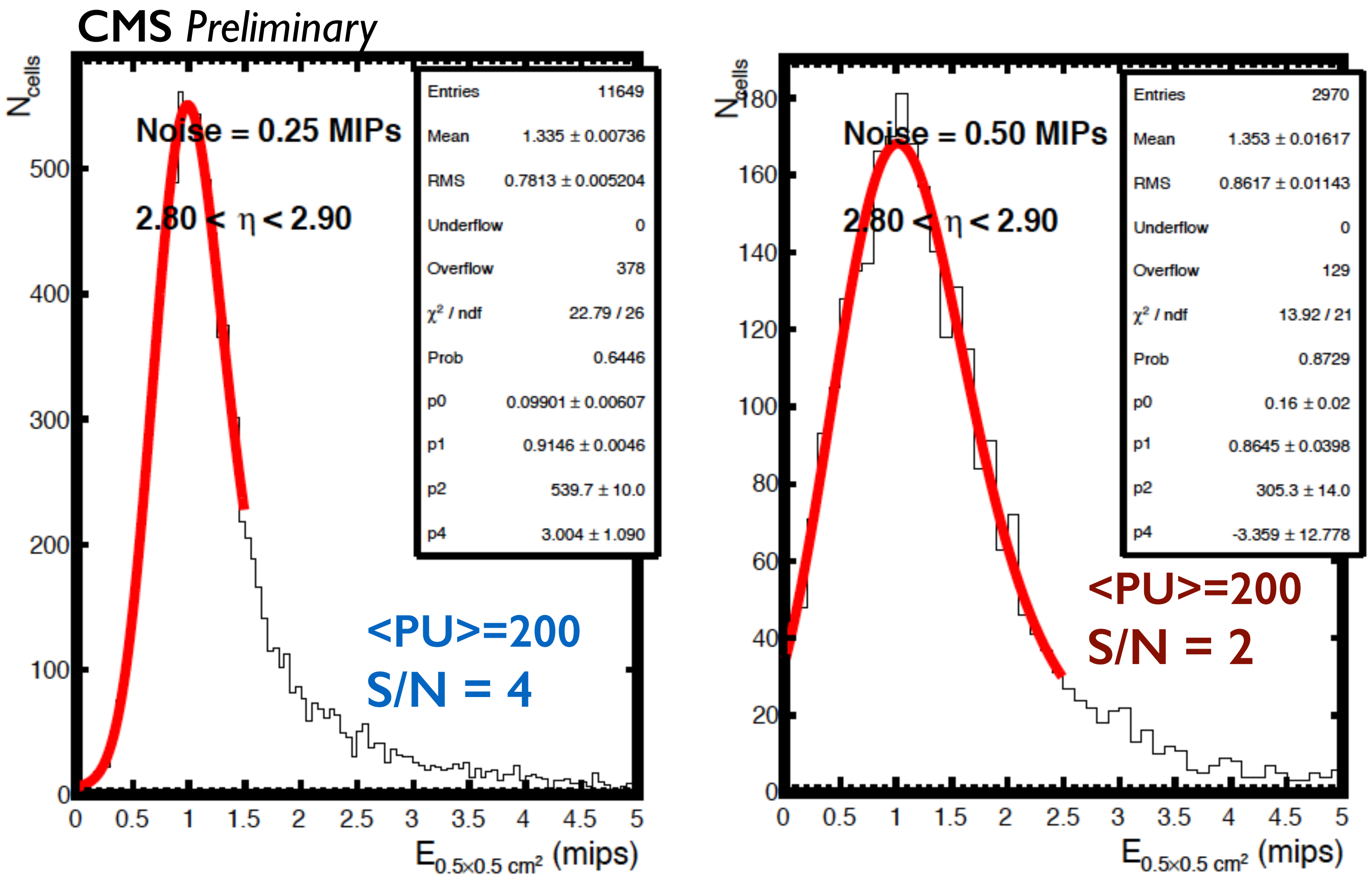


MIP calibration

- **Full calibration procedure developed:** full acceptance and expected life-time
  - pileup is rich in pions ➞ MIP-like deposits in calorimeter (before interaction)
  - tracking in the calorimeter allows for the isolation of clean MIP signals
  - calibration of charge possible with S/N=2
  - low noise cells provide local calibration with S/N>5
  - (same electronics as standard cells, but smaller area: use to study systematics)

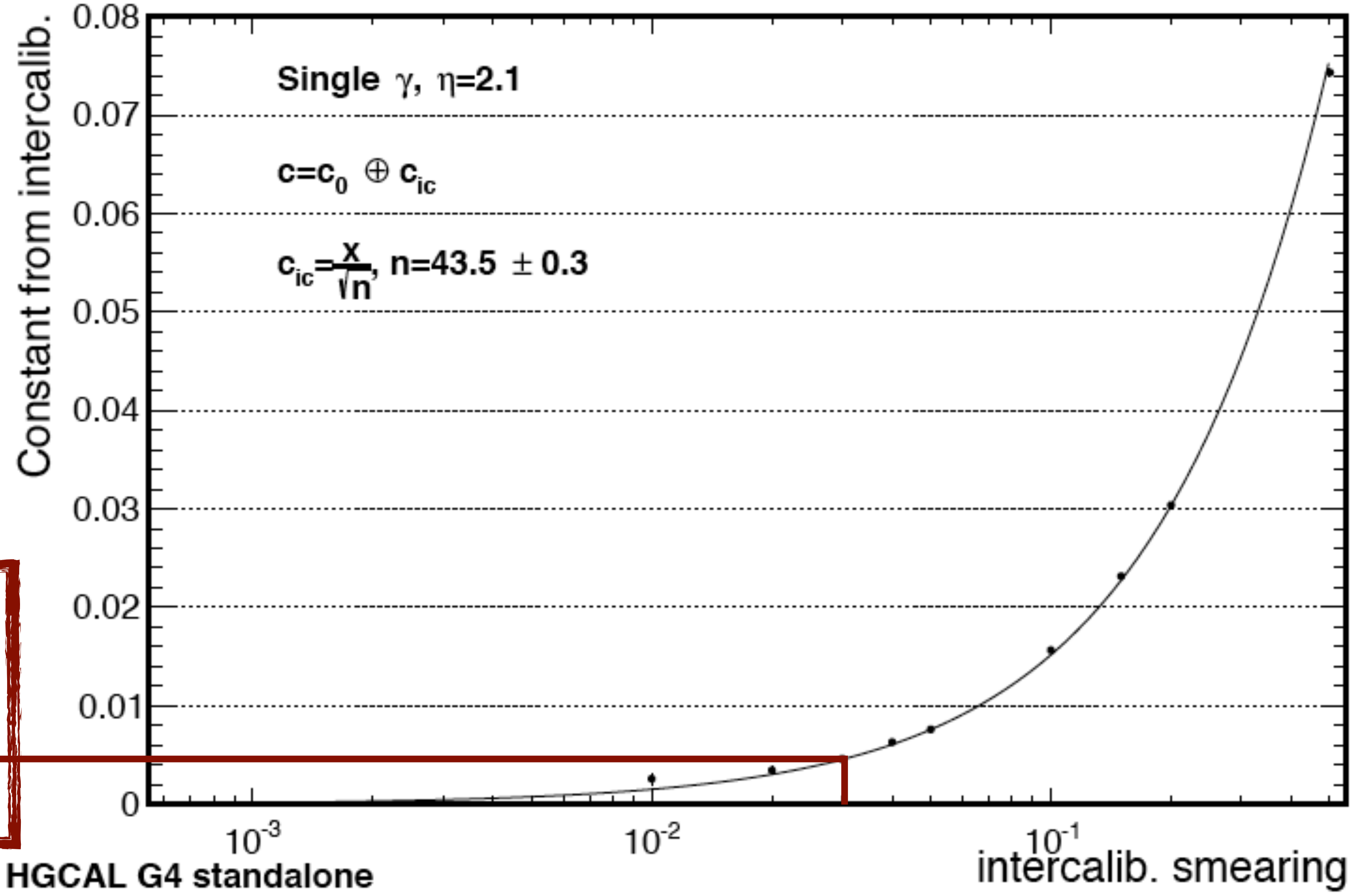


isolate MIP signal in 2 previous layers and 2consecutive layers



Cell inter-calibration and energy resolution

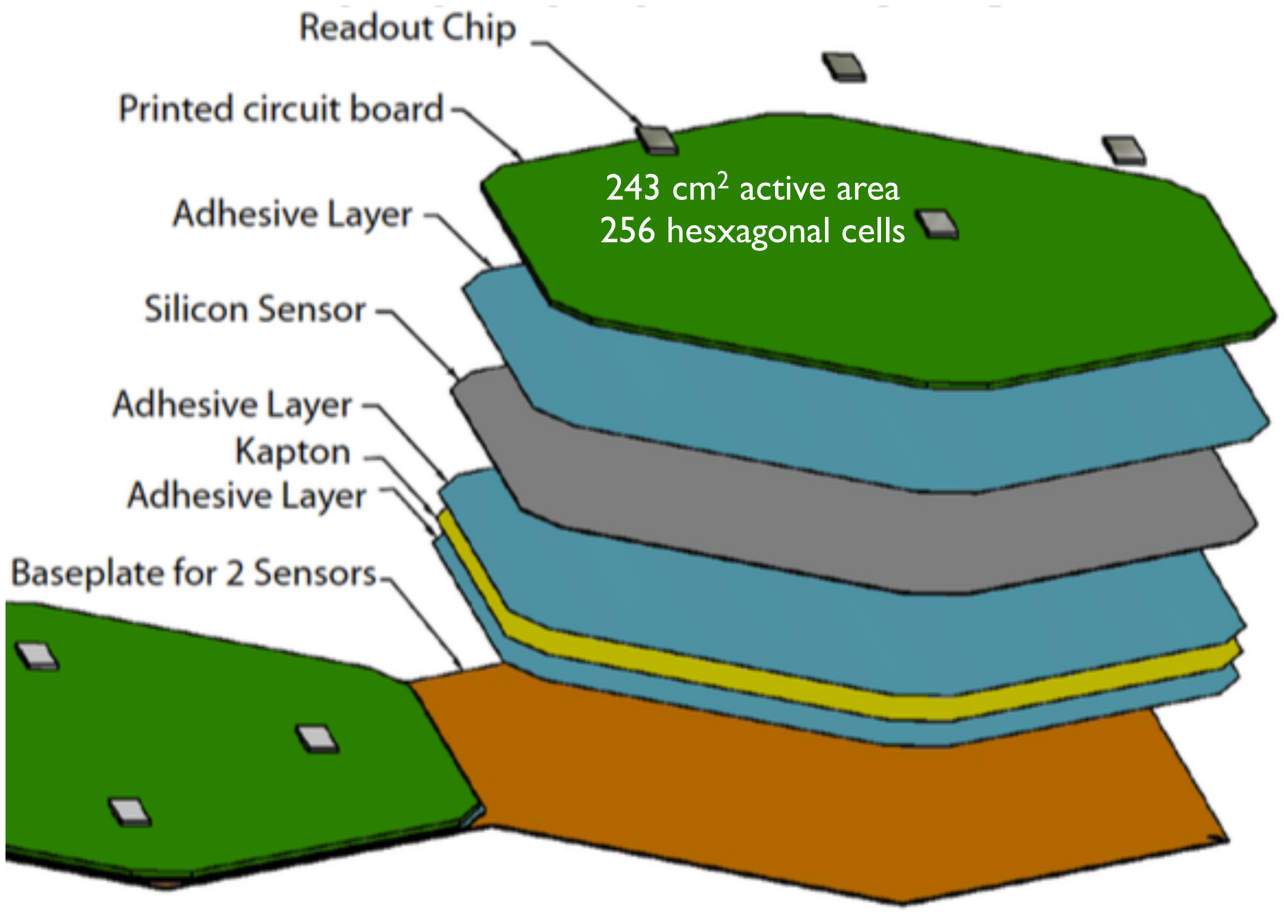
- As a sampling calorimeter resolution is dominated by fluctuations (stochastic term)
- Need to **achieve the smallest possible constant term on e/ɣ resolution**
  - aim to <3% uncertainty on inter-calibration of the charged collected in cells
  - need ~10^6 events if S/N>3 (~10^8 events towards the end of lifetime, at high η, when S/N~2)
  - notice that any triggered or recorded event is good for calibration purposes

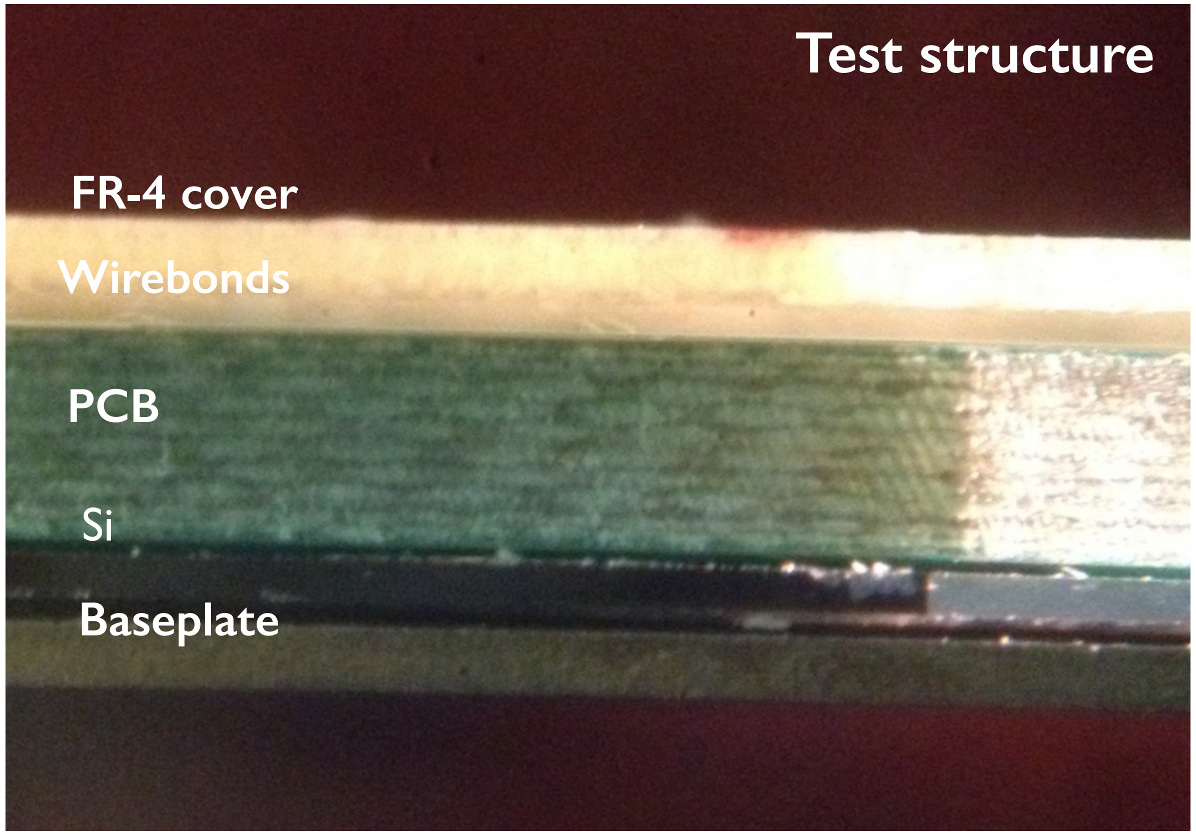


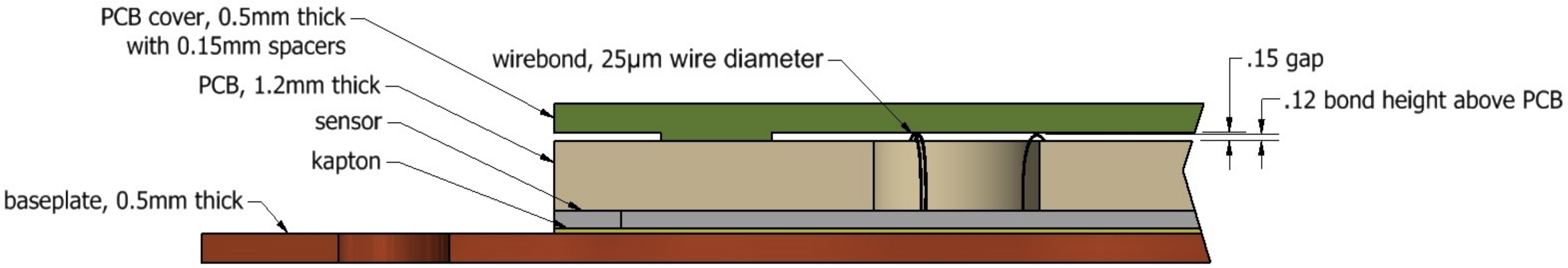
contribution to resolution is kept below 0.5% if the inter-calibration uncertainty is <3%

Silicon sensor module design

- Module design is **robust and suitable for large scale automated assembly**
  - current concept: 6” wafer 2-sensor backplate
  - full protection of sensor and wire bonds: mechanical stresses within safe limits

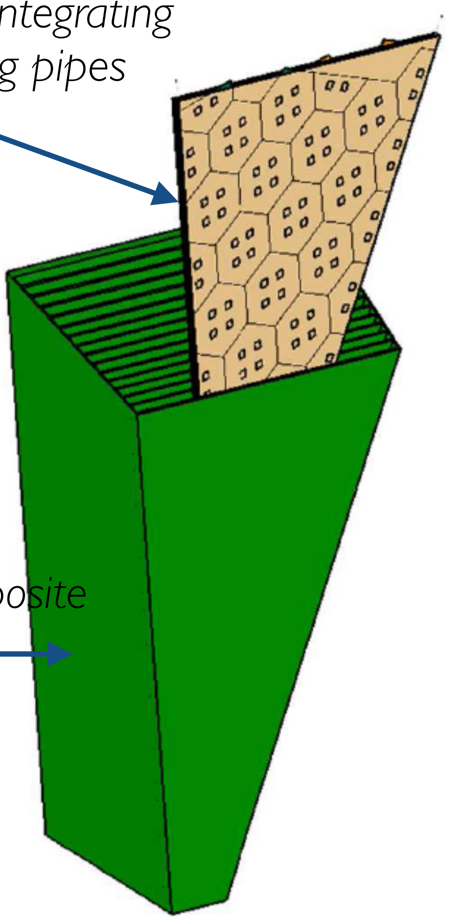






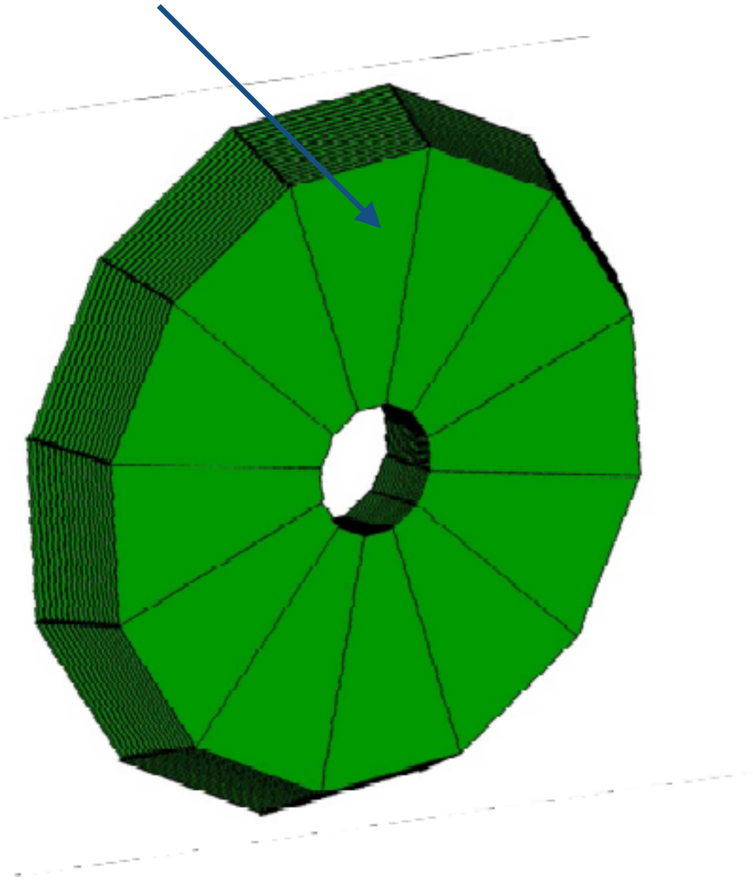
Mechanical design

<u>Cassettes</u> slid into slots
modules mounted on both
sides of 6mm Cu plate integrating
CO_2 capillary and cooling pipes

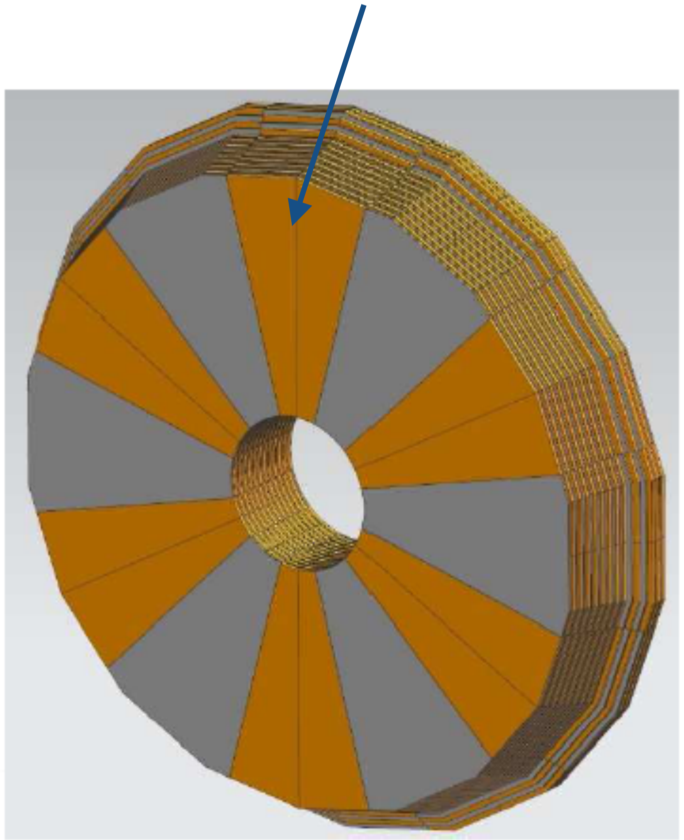


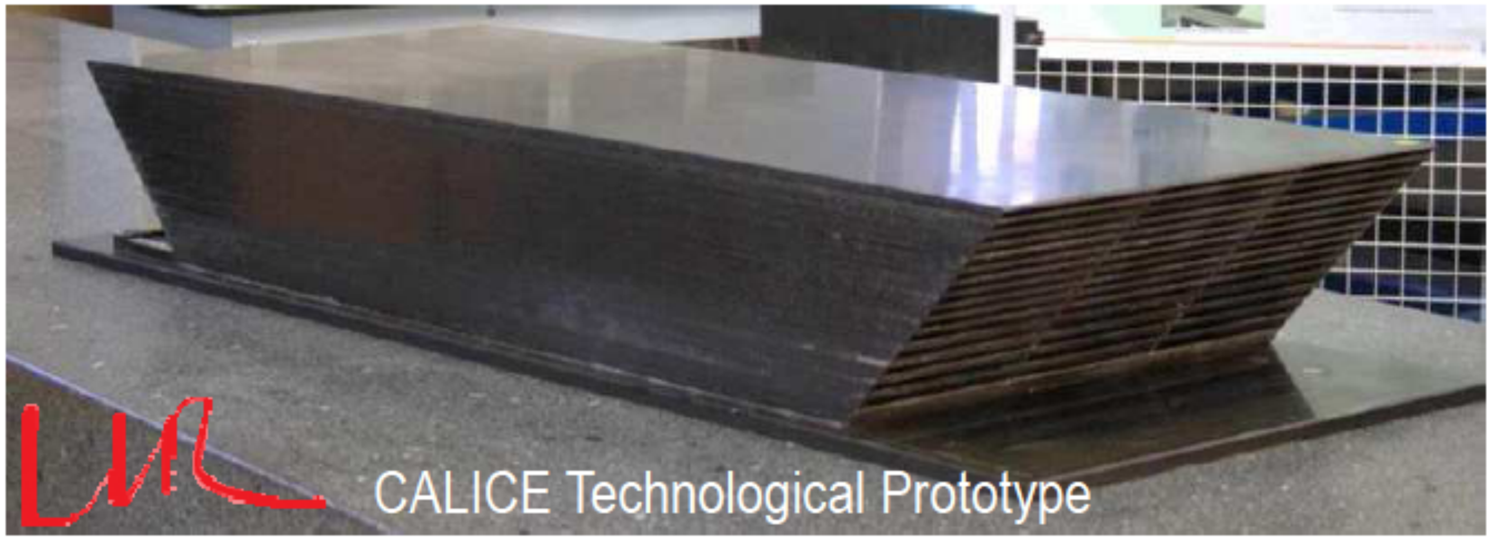
Alveolar structure
EE : Carbon Fiber/W composite
FH : Brass alveolar

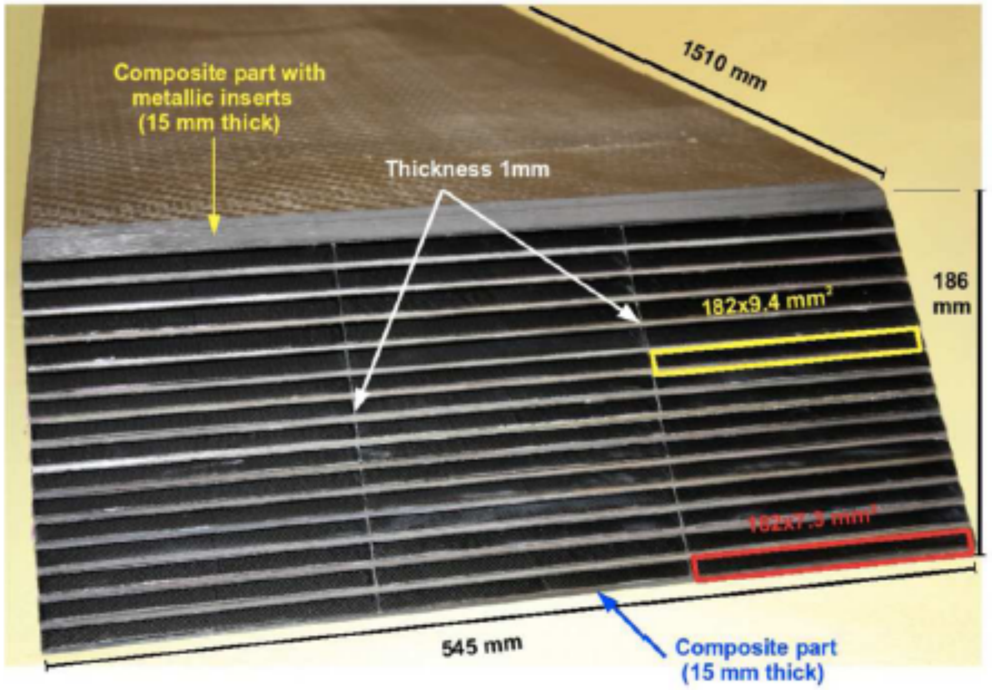
ECAL wedges to be glued together
form monolithic structure



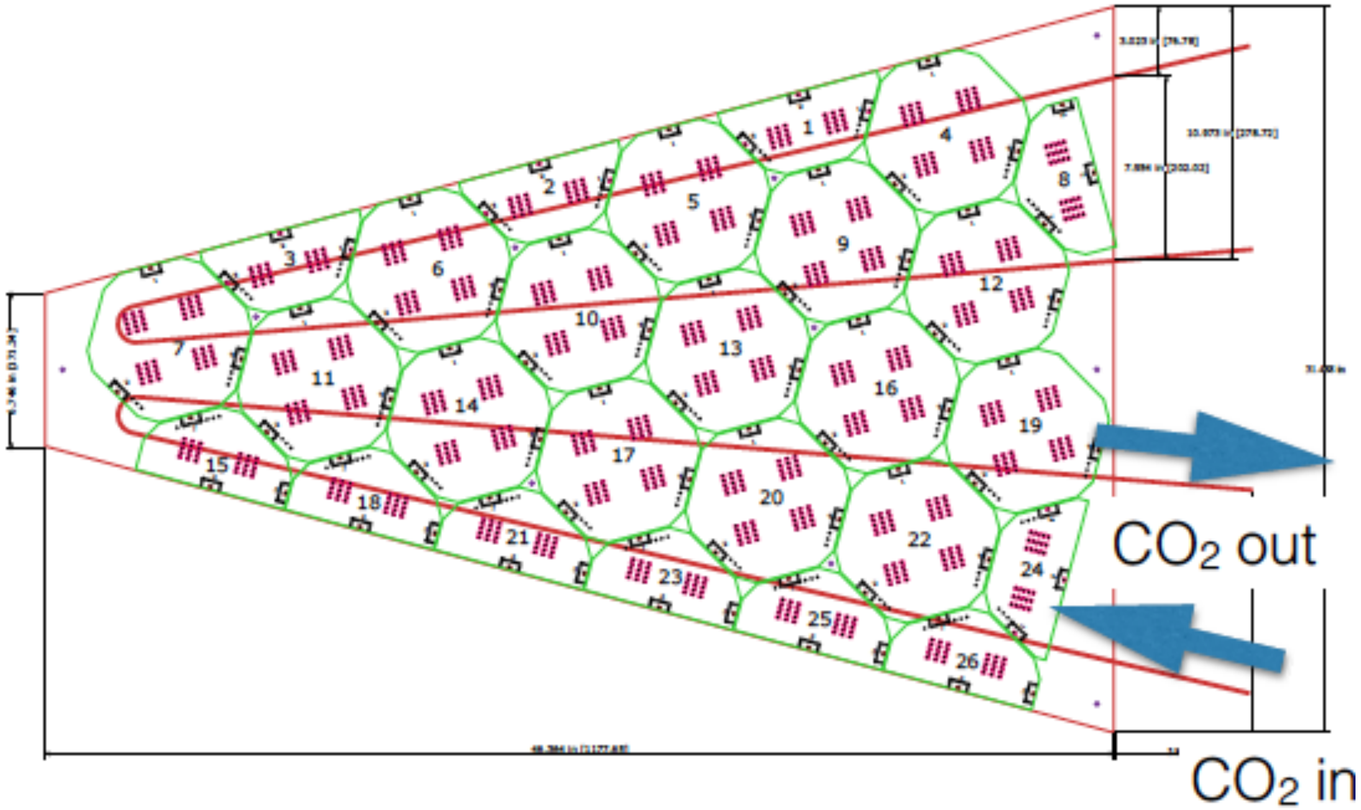
FH wedges bolted brass plate with
30^0 slots (based on current HE design)



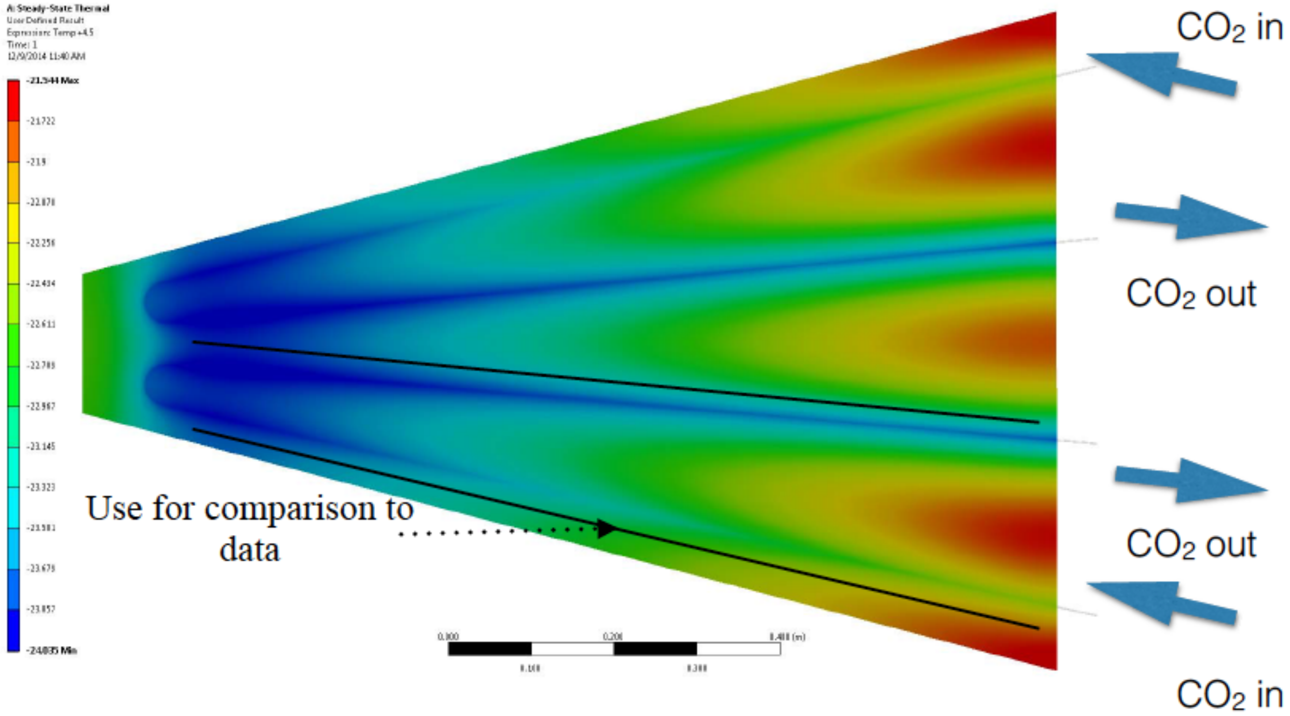




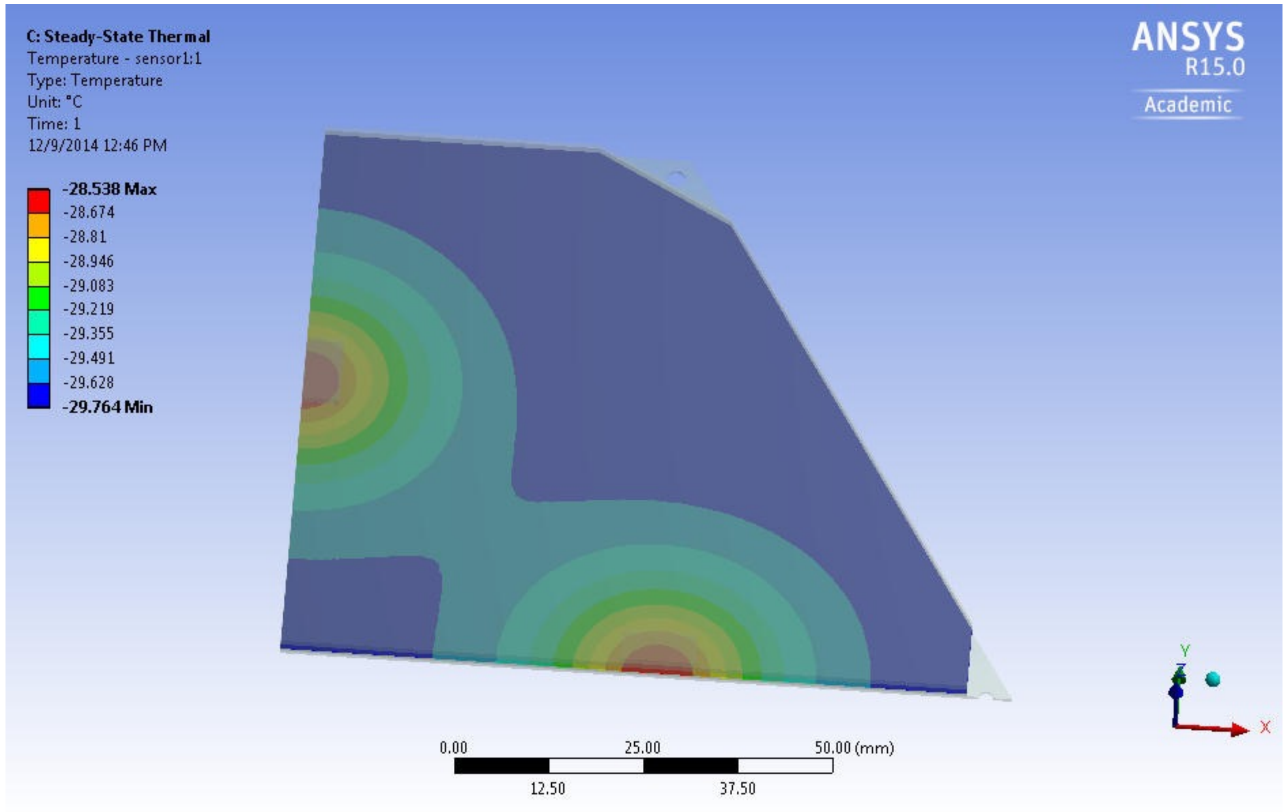
Si module cooling performance



- Thermally conductive epoxy between chips an PCB, regular epoxy on other adhesive layers
  - maximum sensor temperature: -28.5^{0}C
  - thermal gradient across sensor 1.3^{0}C
  - maximum temperature on PCB: -0.6^{0}C

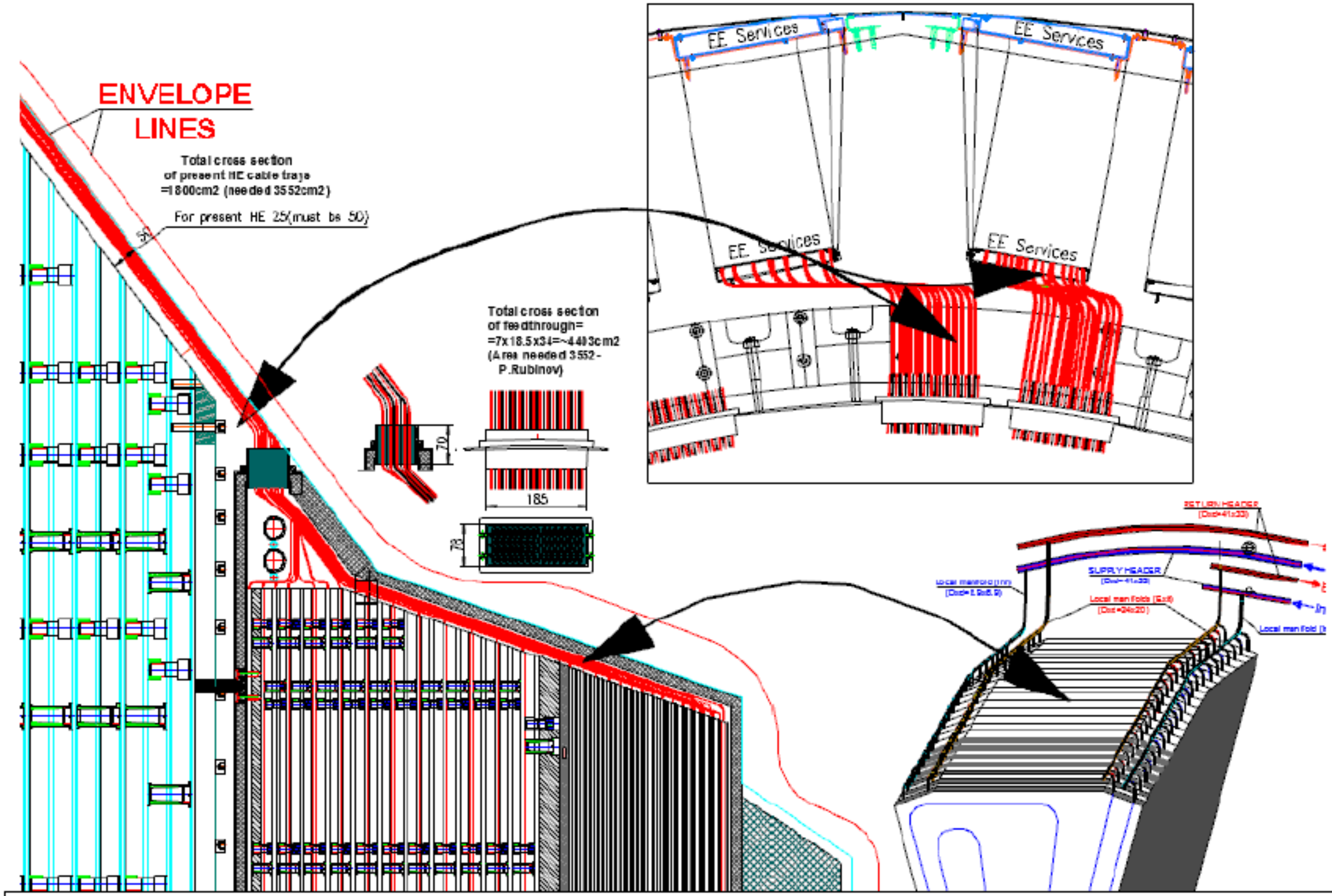


Use for comparison to data



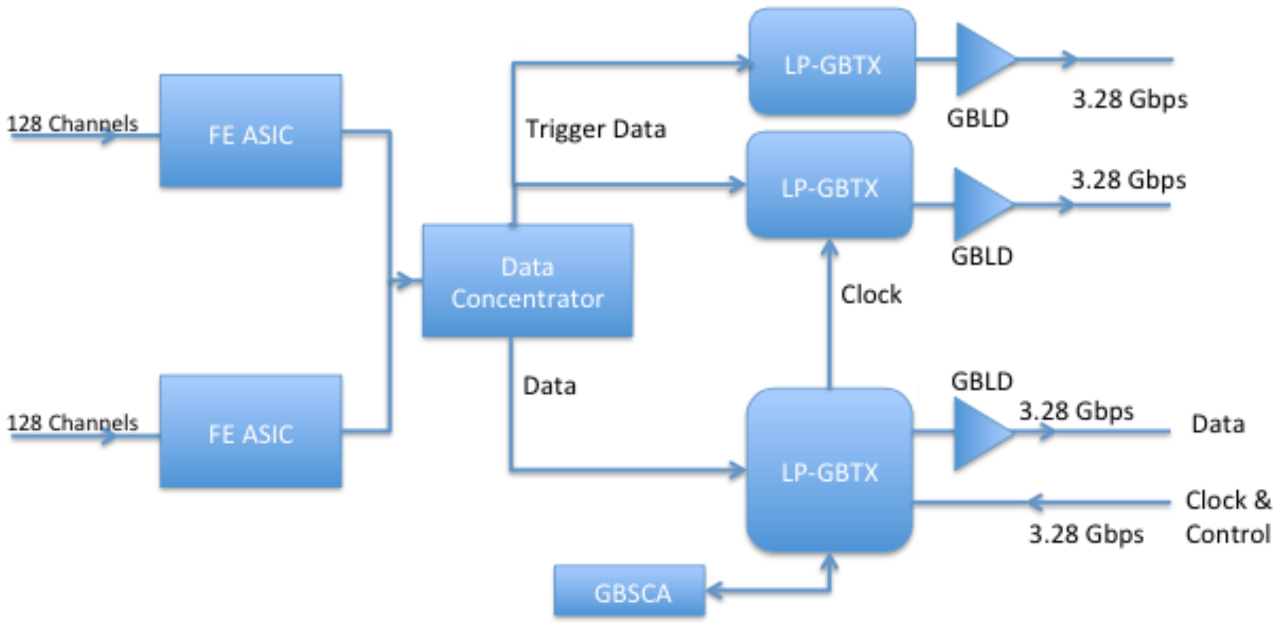
Integration in CMS

- Total power in cold volume ~125 kW (both end-caps) vs 240kW CO_2 total transfer line capacity
- Accommodate feed-through of HGC + 2-fold redundancy in case of CO_2 failure (~2k junctions /30^0 sector)



Conceptual solution from edge of cassette to back of HE

Front-end readout and trigger system

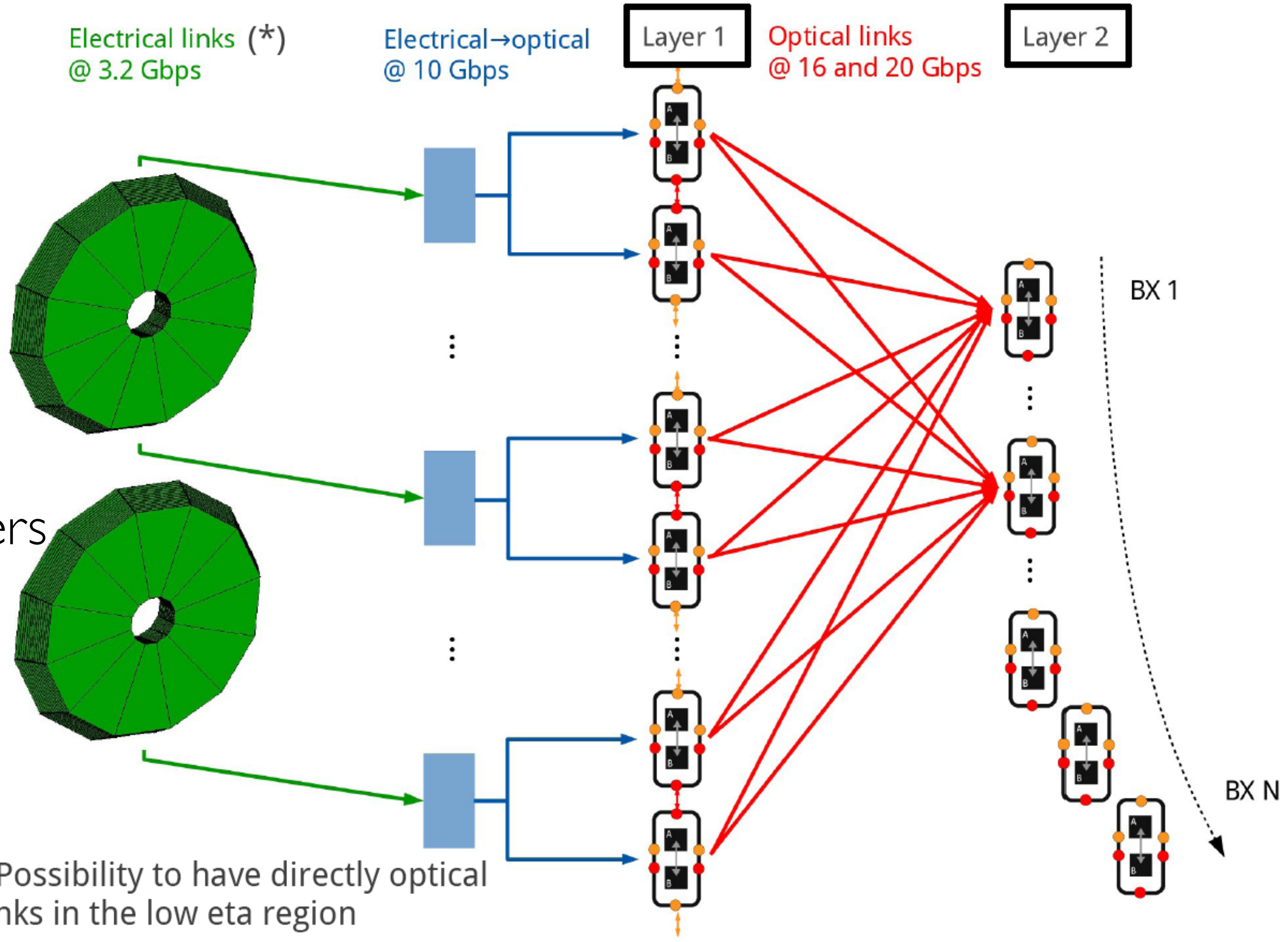


Concentrate data from two ASIC (2x128 ch)

Two low-power Gigabit transceiver (GBT)

- additional dedicated uni-direction links for trigger
- effective rate of 3.28 Gb/s

- Layer 1 - regional view
  - 2x2 sensor pad sums
  - identify interesting regions
  - cluster longitudinally in projective towers
- Layer 2 - global view
  - superclustering using all sub-detectors (+ tracker information)



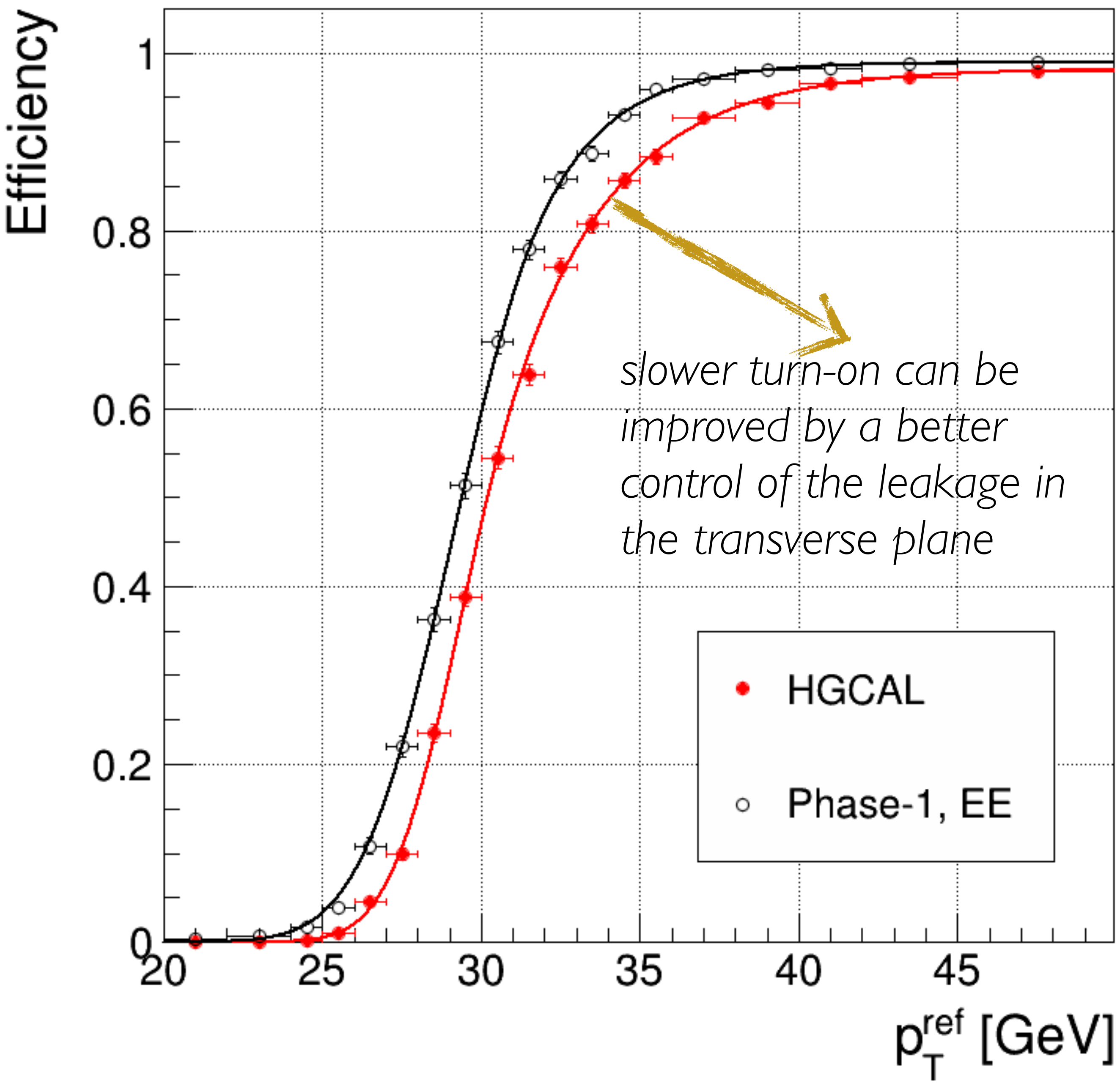
*Possibility to have directly optical links in the low eta region

Initial L1 trigger performance estimates for e/γ

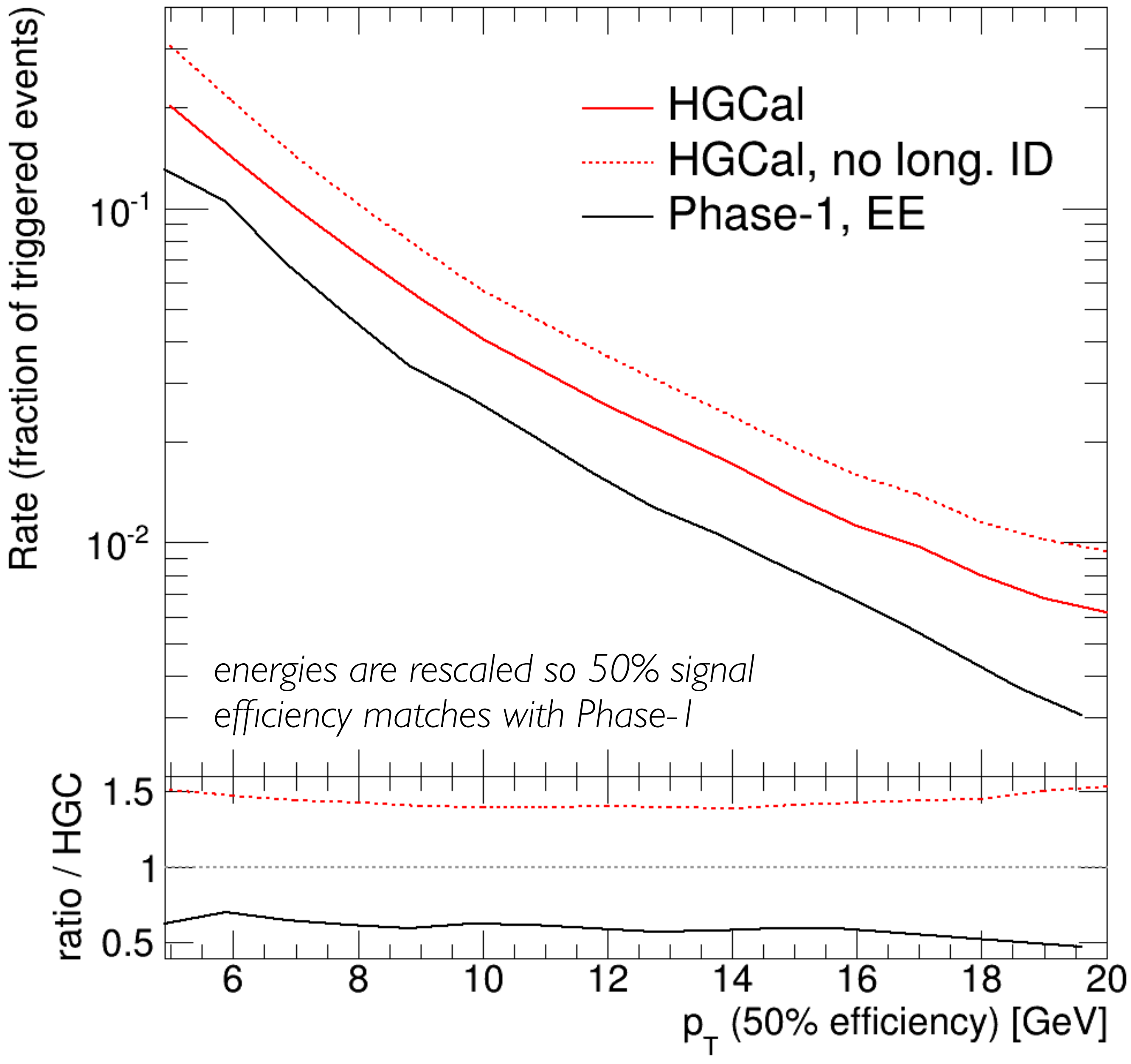
- Without longitudinal information observe "simple" scaling of rate with luminosity
  - drastic reduction effect from inclusion of shower longitudinal information at L1

Turn-on is comparable to Phase-I (PU=50) endcap

Single electron trigger rate under control with 140 PU



slower turn-on can be improved by a better control of the leakage in the transverse plane



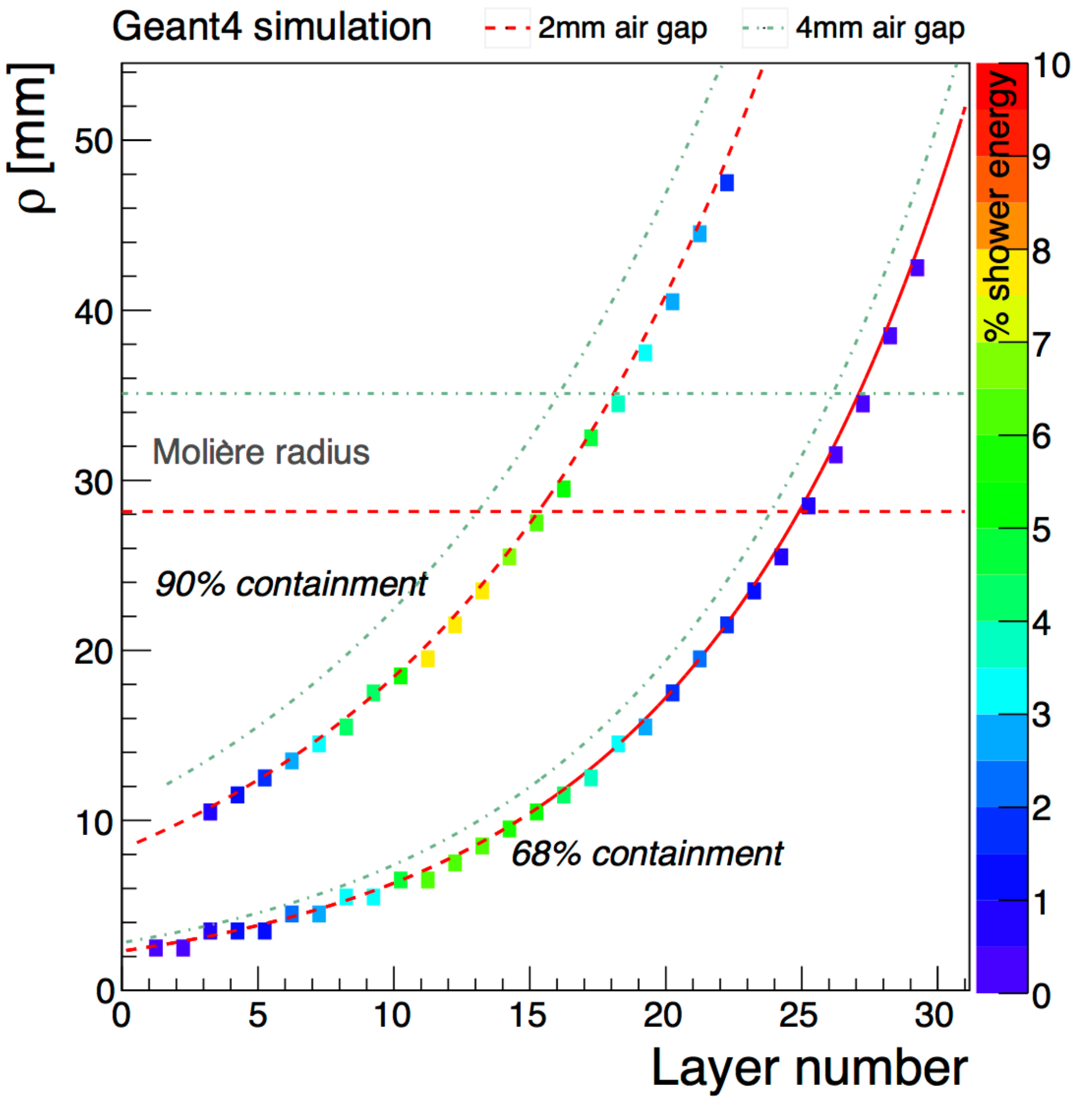
energies are rescaled so 50% signal efficiency matches with Phase-I

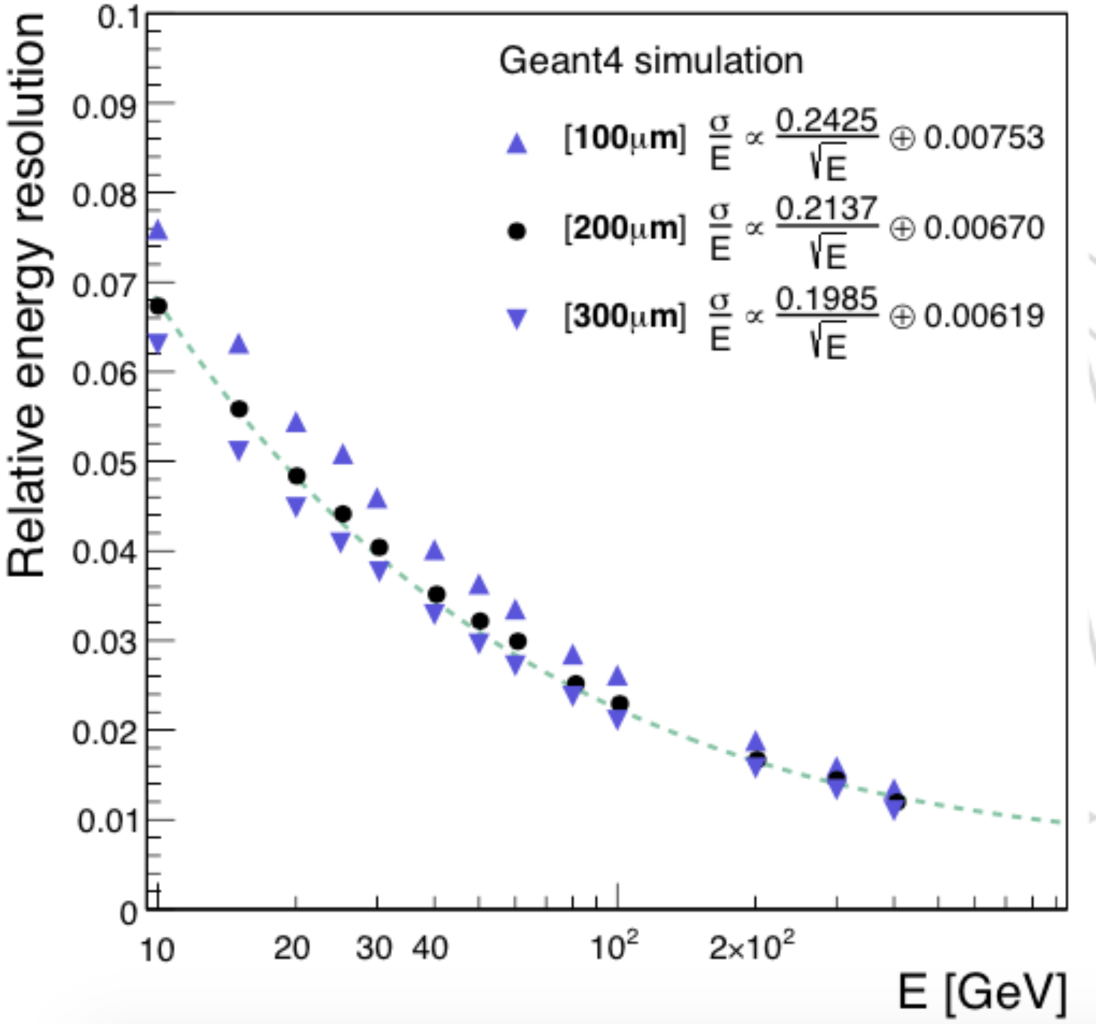
Current performance estimates

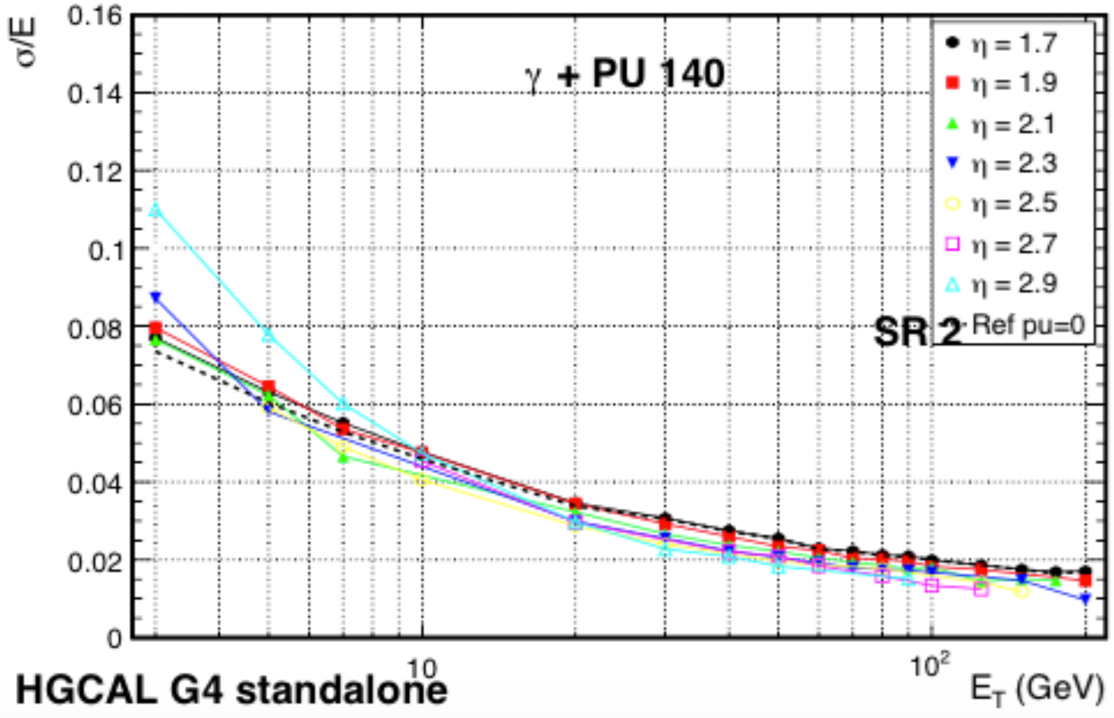
The following results are work in progress: no public document from CMS yet available .

Sharing these preliminary estimates to stimulate the discussion within the Terascale workshop community.

Baseline e/ɣ performance







- Resolution matching requirements for boosted objects
- Shower core is contained in a few cm (<R_M)
    - can use tight energy integration region with pileup
    - no significant loss of resolution
    - clustering based on OPAL SiW local maximum seeding

EPJC 14 (373-425) 2000

e.m. clusters have pointing capabilities

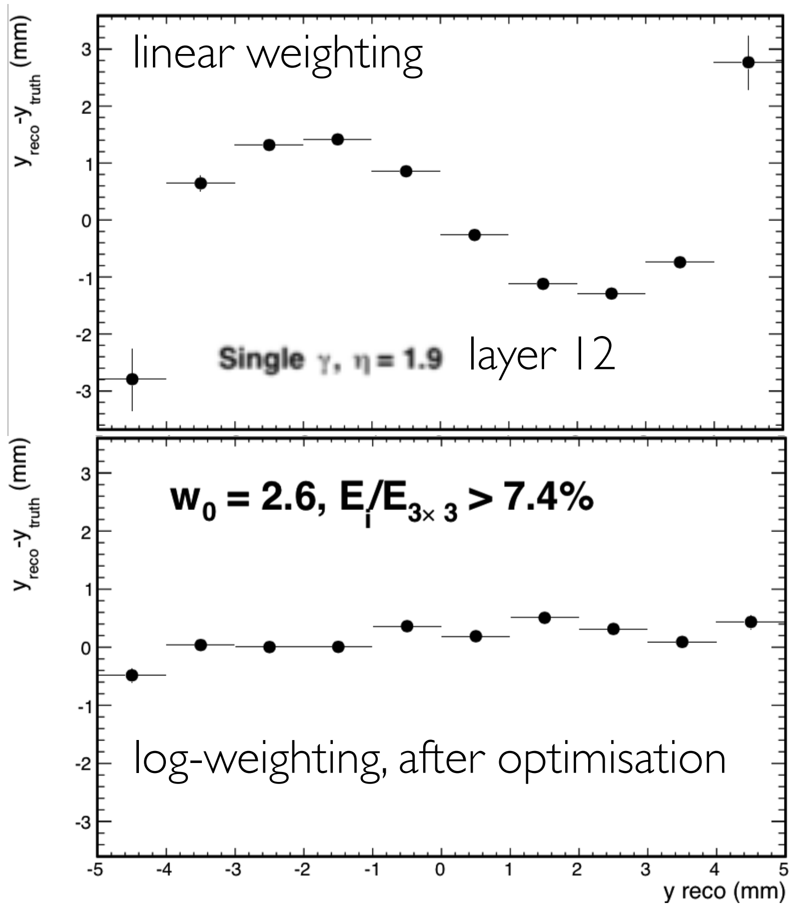
- Position estimate can be fine-tuned by scanning appropriate w_0
  - optimisation and resolution is pileup-independent
  - ~30% improvement in resolution with respect to linear weighting

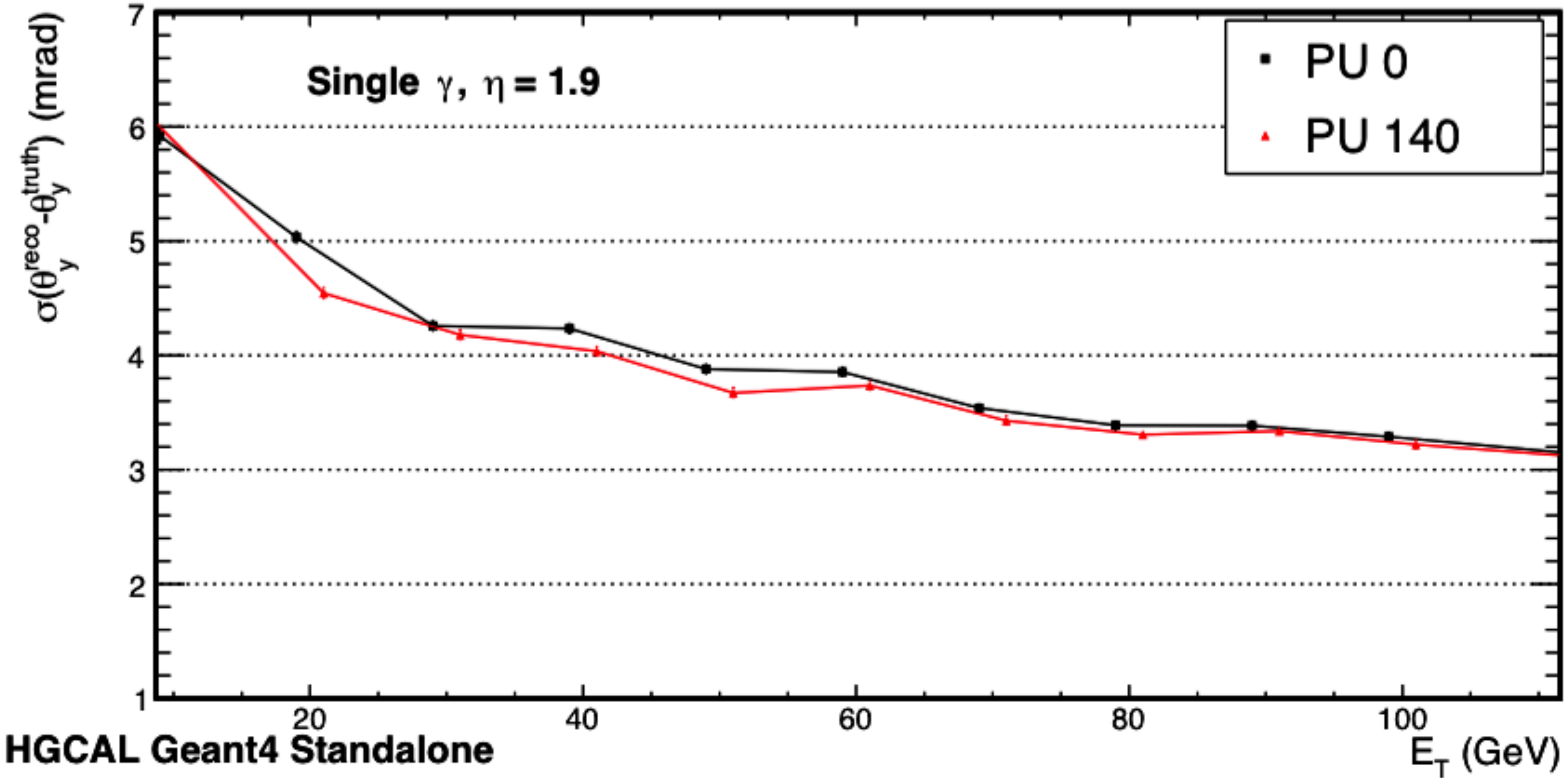
Current resolution:

$\sigma_\theta \simeq 4$ mrad

using the full information all layers

(at $\eta \sim 1.5 \rightarrow \sigma_z \simeq 3$cm)

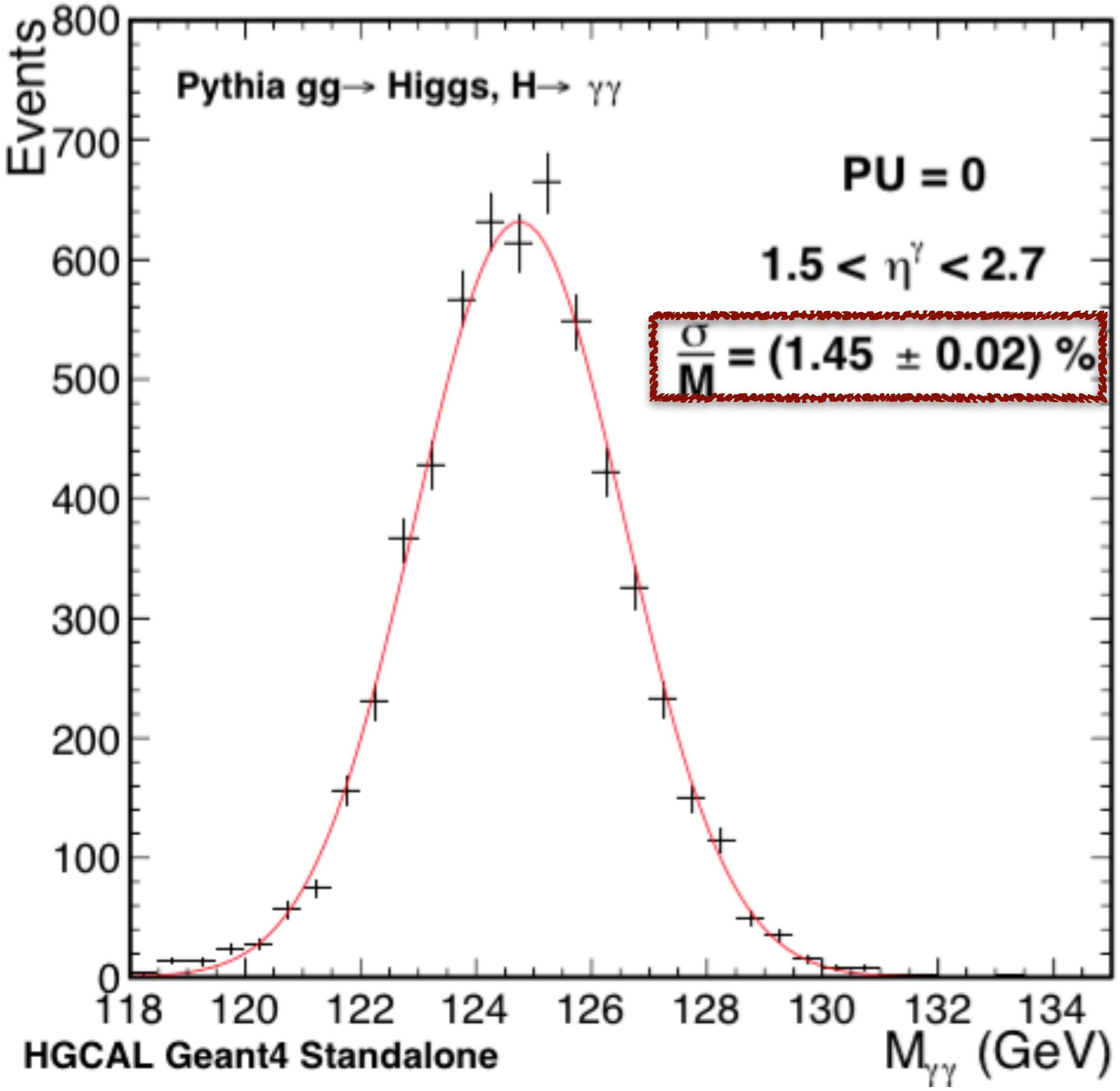


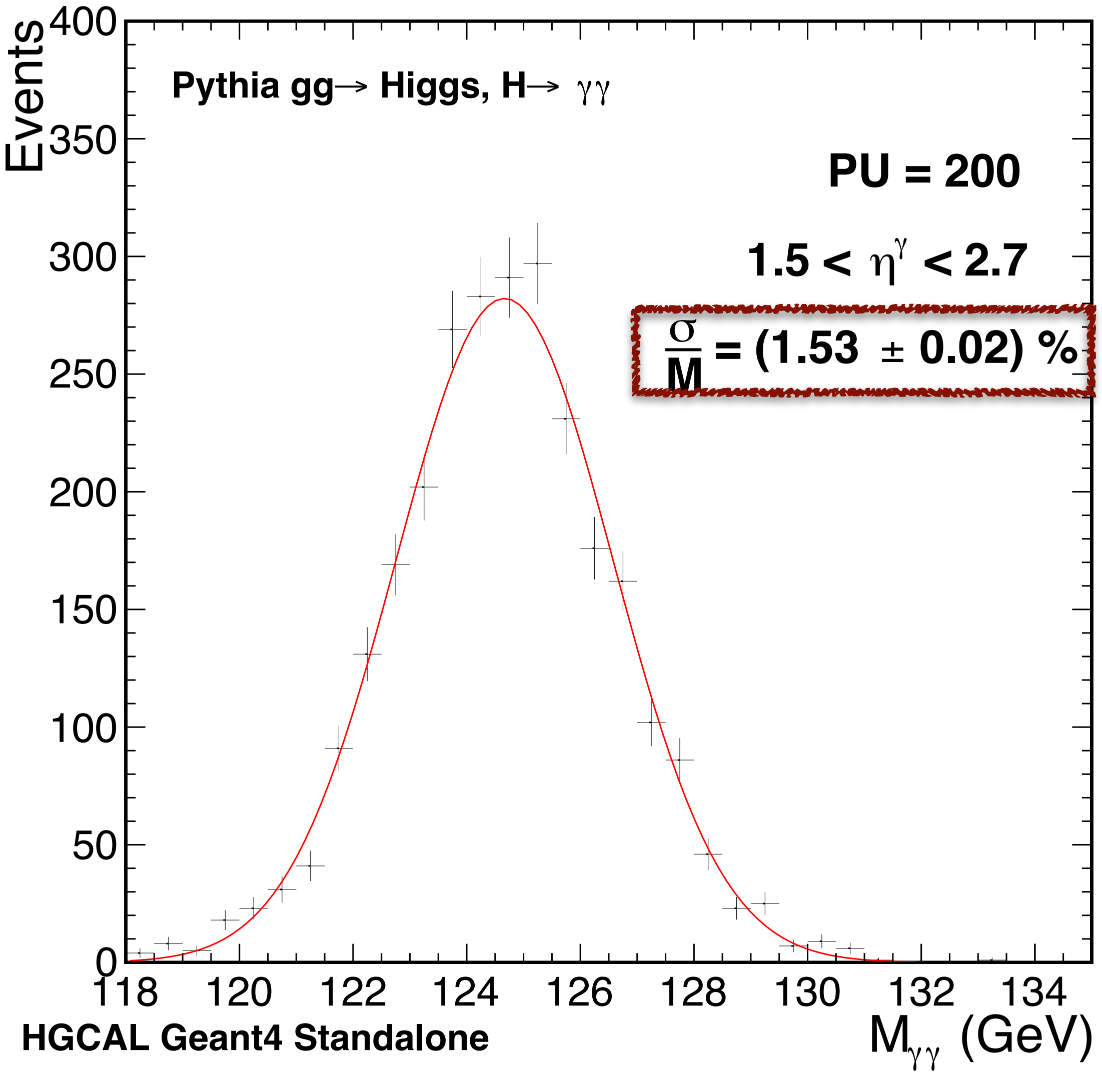


Current performance estimates

H→γγ performance

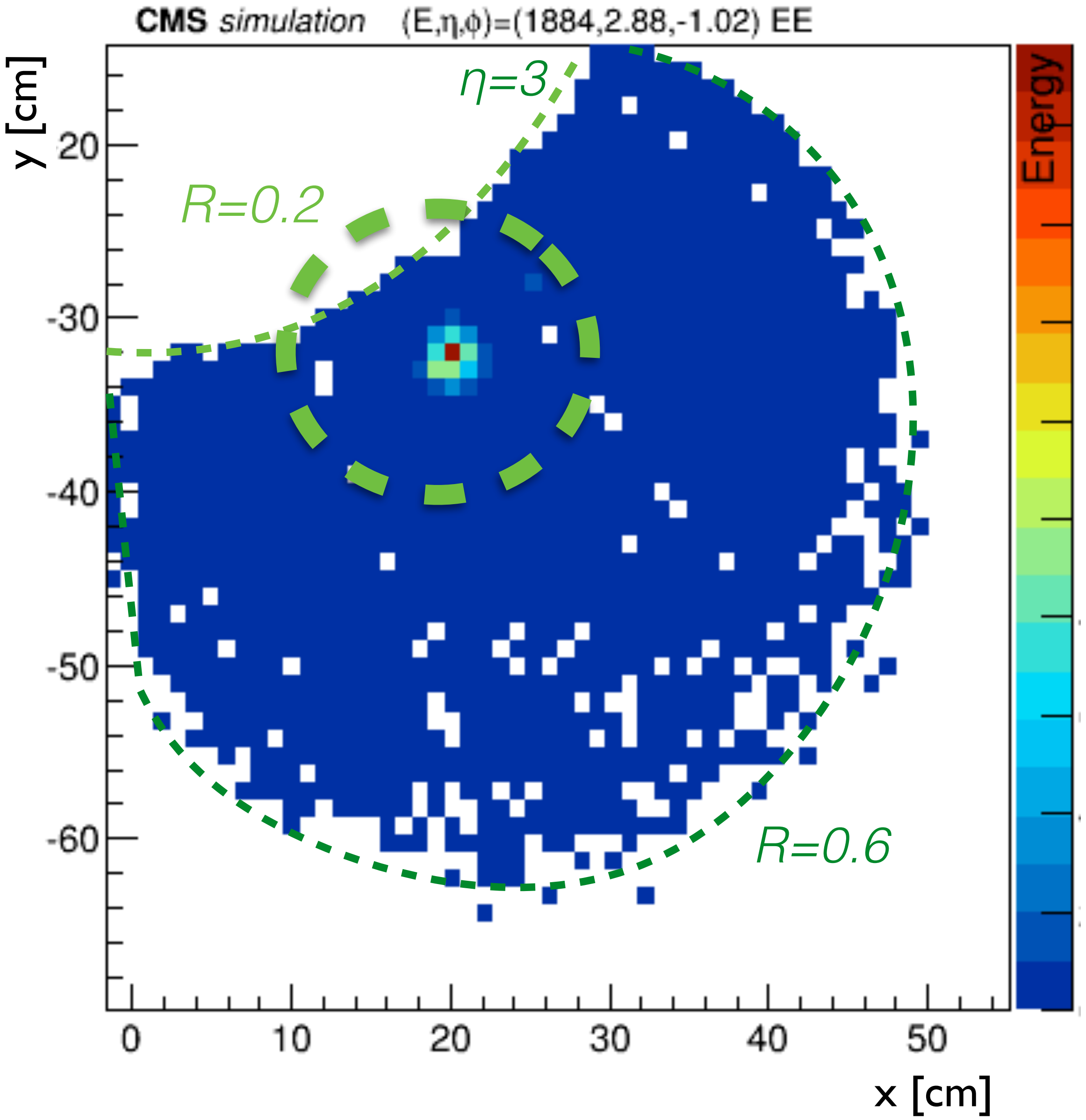
- Pileup subtraction + tuned calibration + vertex information recovery
    - **potential to recover PU=0 performance for H→γγ**
- Simulation of realistic pileup conditions with two endcap photons from Higgs decays
    - **resolution of ~1.5% with <PU>=200** (assuming vertex information successfully recovered)



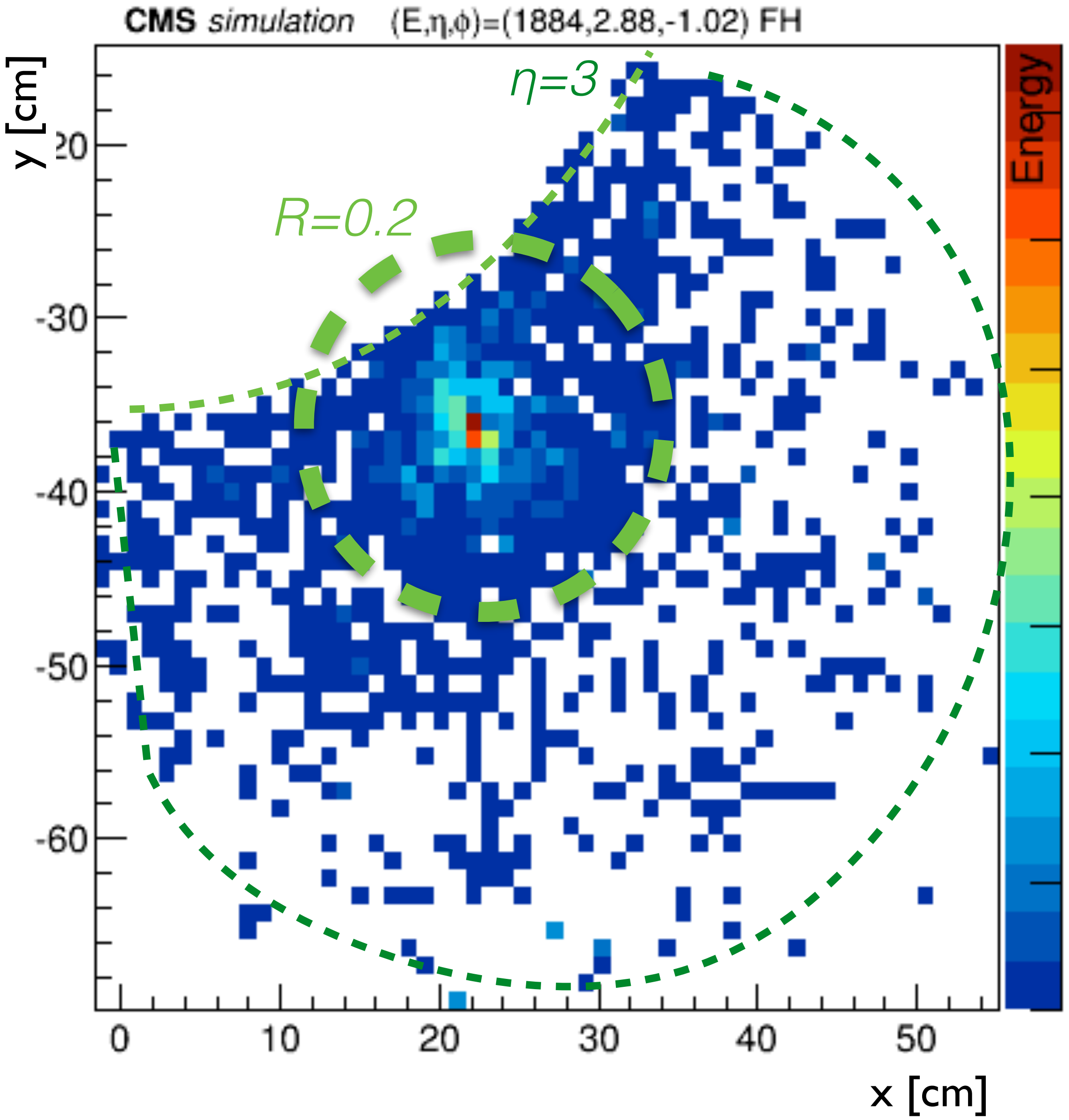


Towards physics performance: a VBF jet event

EE inclusive



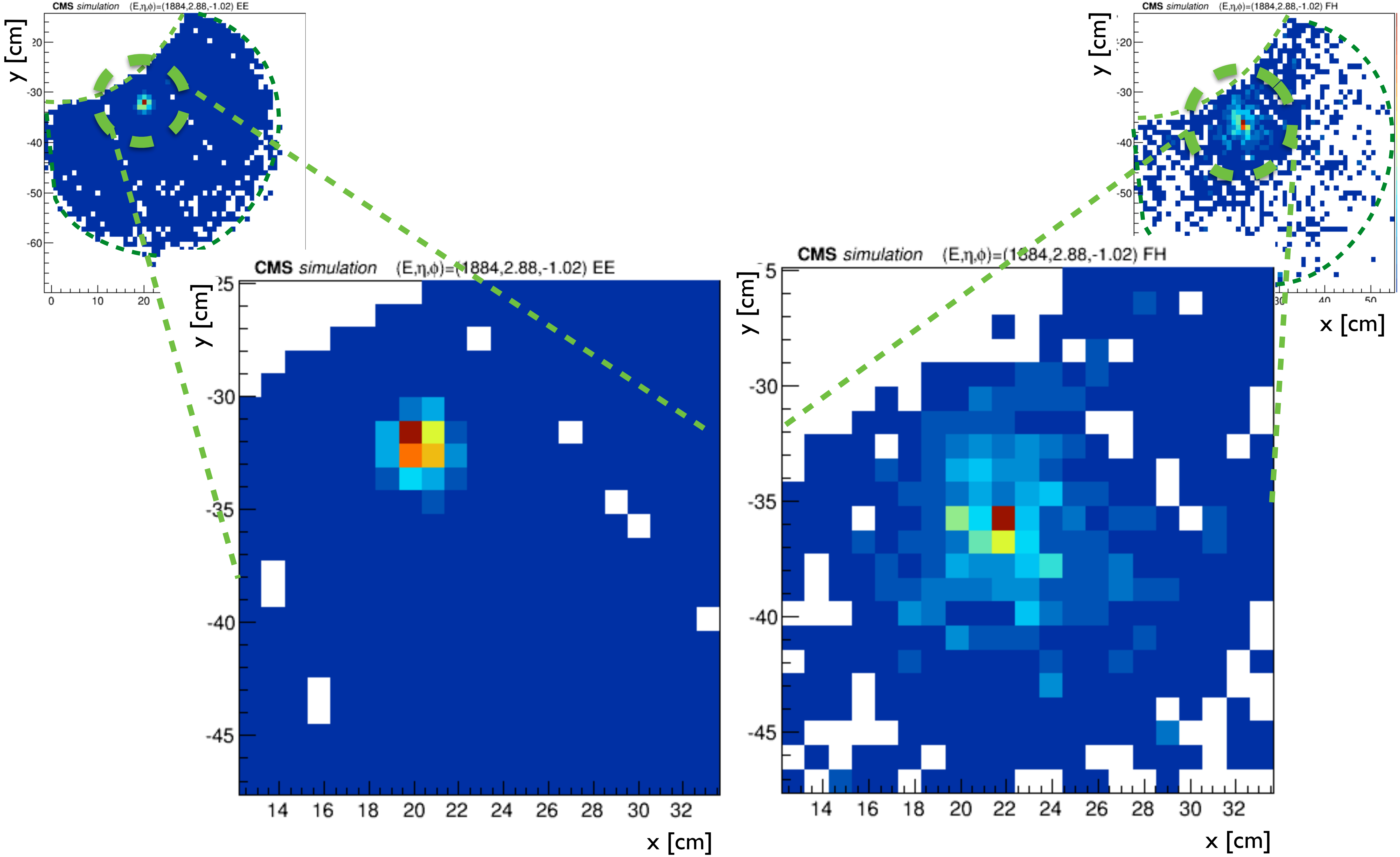
FH inclusive



Towards physics performance: a VBF jet event

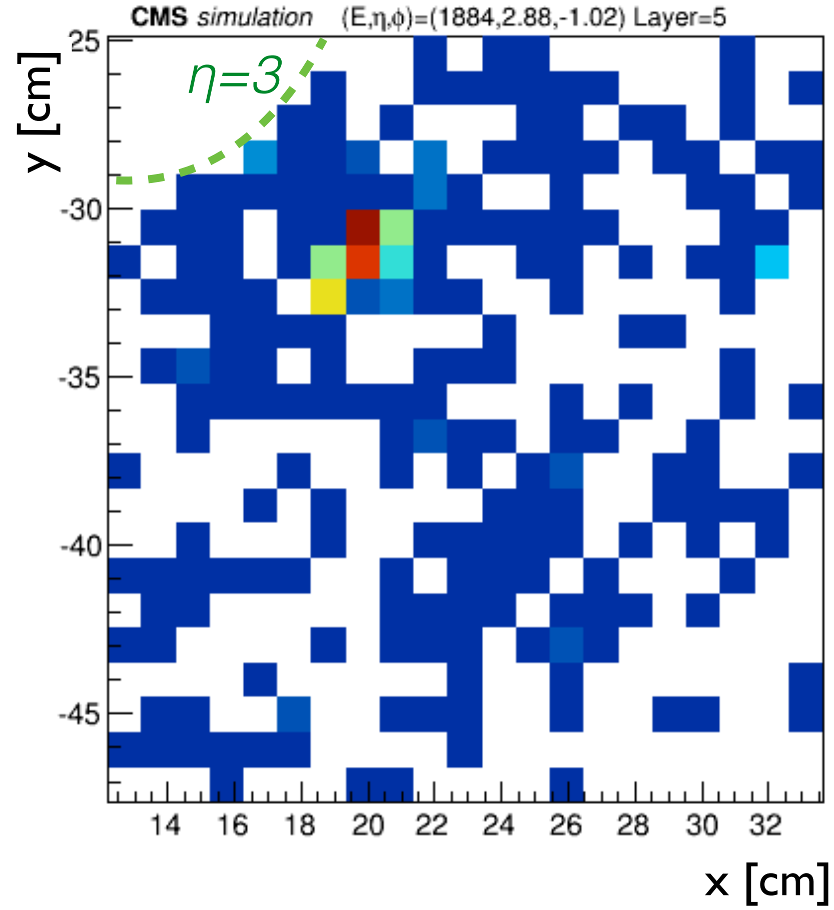
EE inclusive

FH inclusive

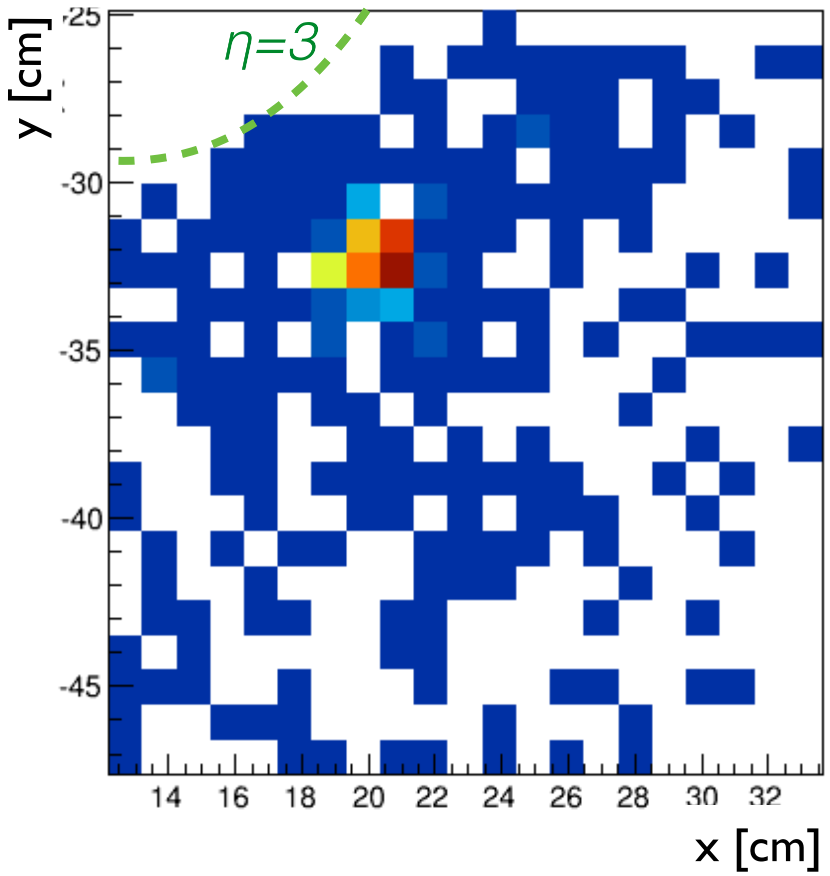


Towards physics performance: a VBF jet event

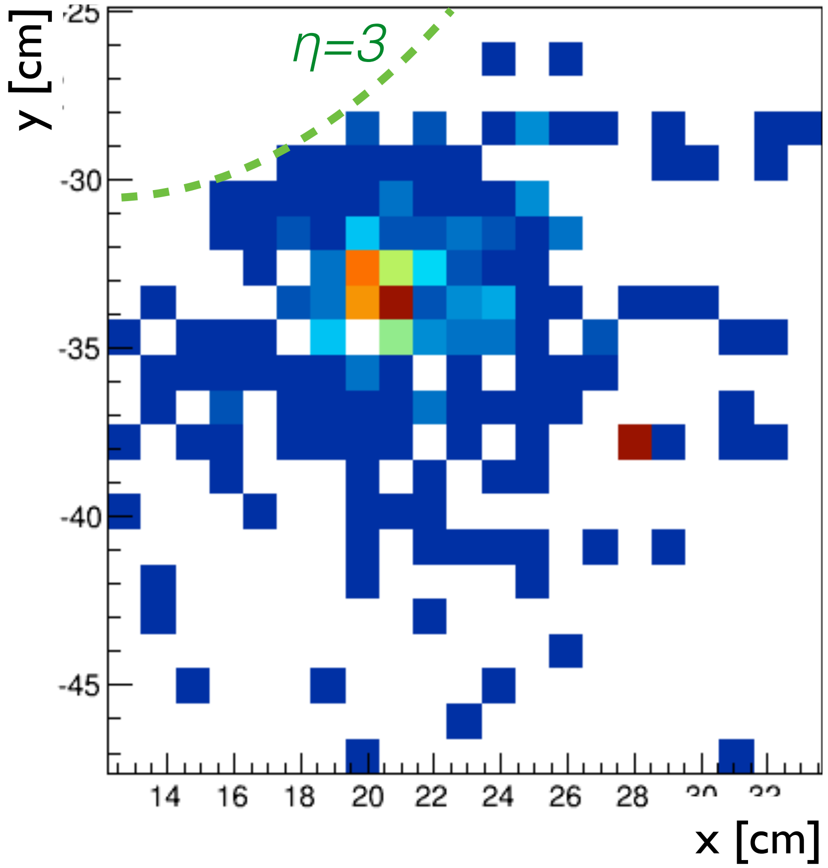
EE layer 5



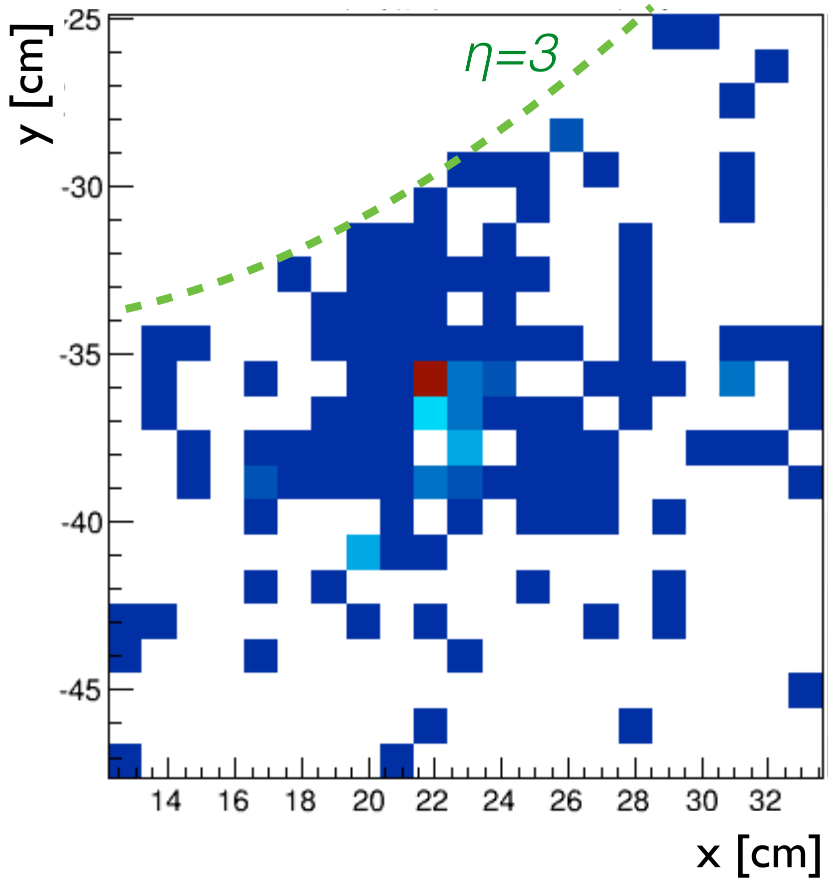
EE layer 15



EE layer 25

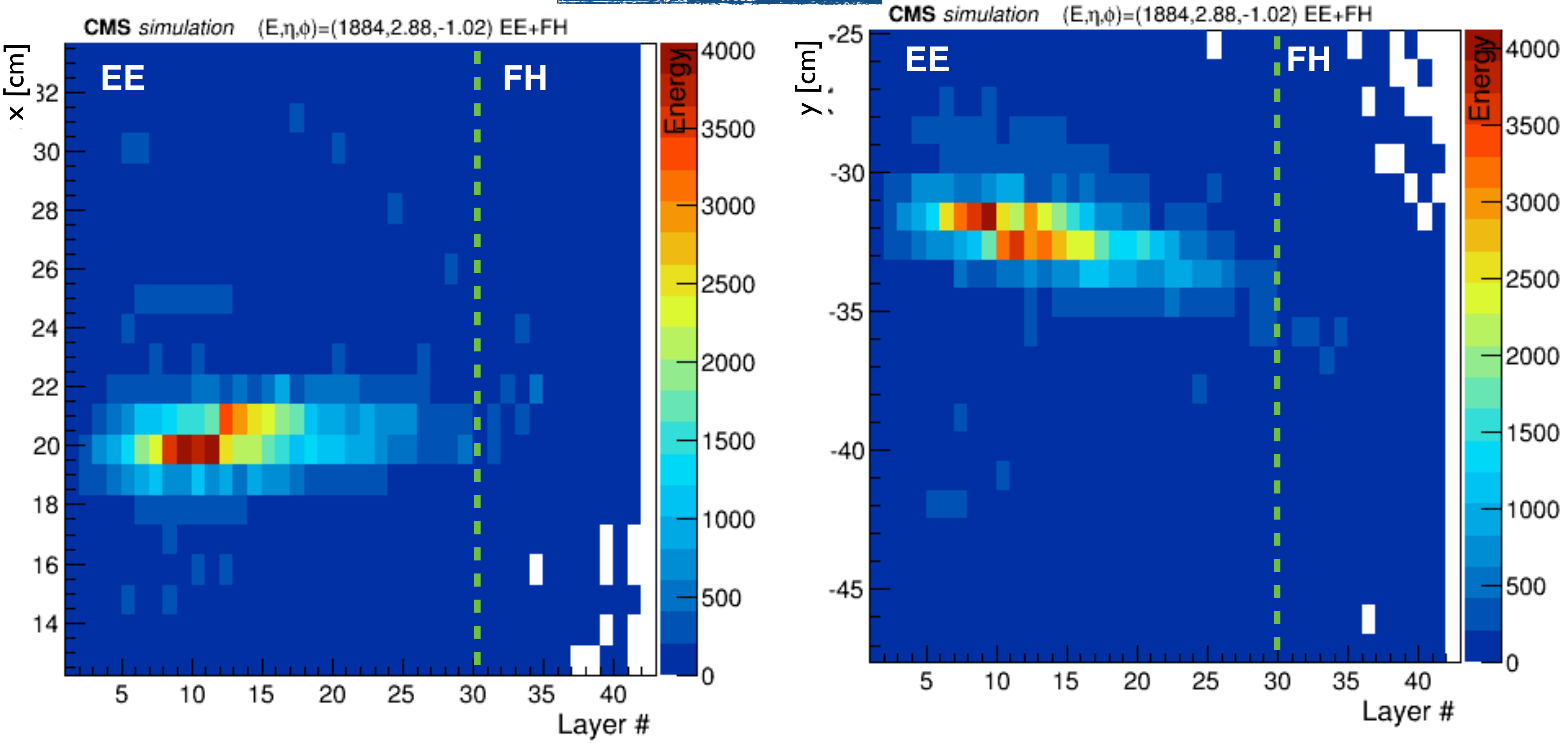


FH layer 5



Towards physics performance: a VBF jet event

EE+FH longitudinal slices



Pileup is in the first layers

Layer-by-layer : resolve showers

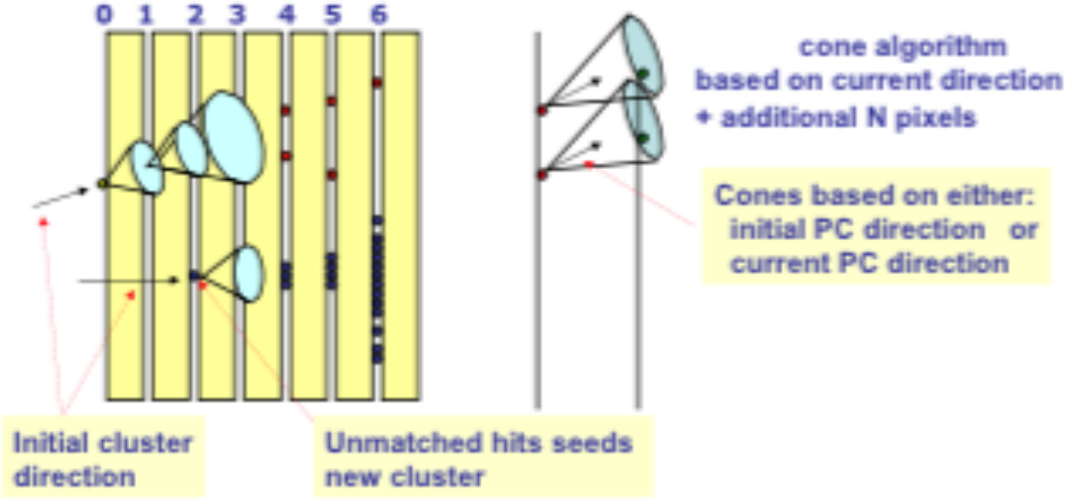
Track showers: point to primary vertex

Current performance estimates

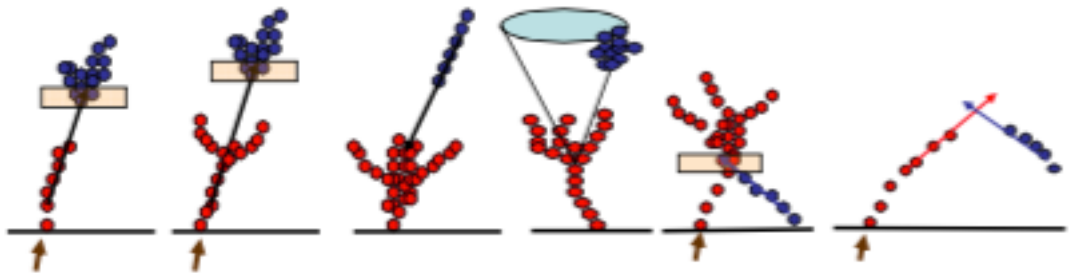
Particle flow and HGCal

- ~6M measurements to be correlated for reconstruction
  - group energy deposits according to shower evolution
  - clustering must follow particles/showers in calorimeter
  - resilience in dense pileup environment required
    clusters can't grow too much
- Reconcile tracking and calorimeter information
  - tame fluctuations in both calorimeter and tracker measurements
- Started to use the Pandora PFA - NIMA 611 (2009) 25-4
  - initially developed CLIC/ILC environments
  - adaptation of algorithm flow for pileup environment
  - initial ~1h/event brought down to 10min/event
- Very good out-of-the-box performance estimates with PU
  - first results being analysed, stay tuned!

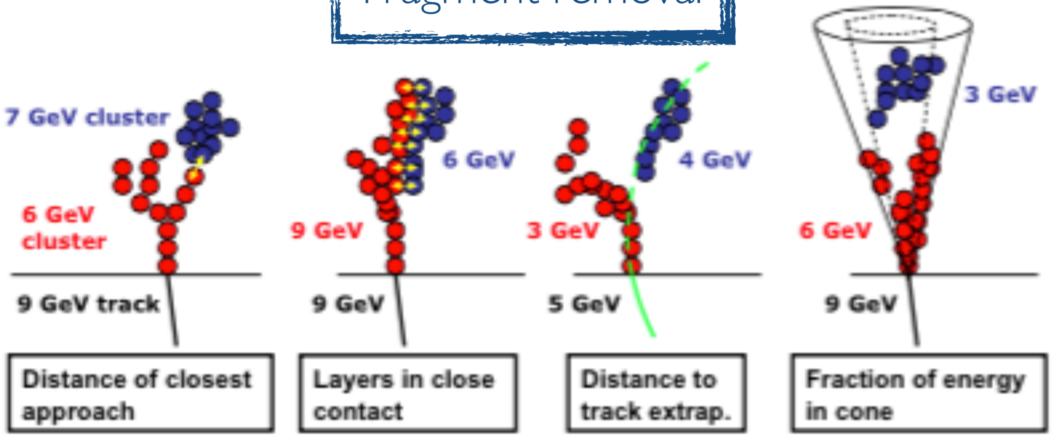
Iterative cone clustering



Topological association



Fragment removal



Conclusions

Conclusions

The HGCal concept as progressed over the past year to a viable conceptual design

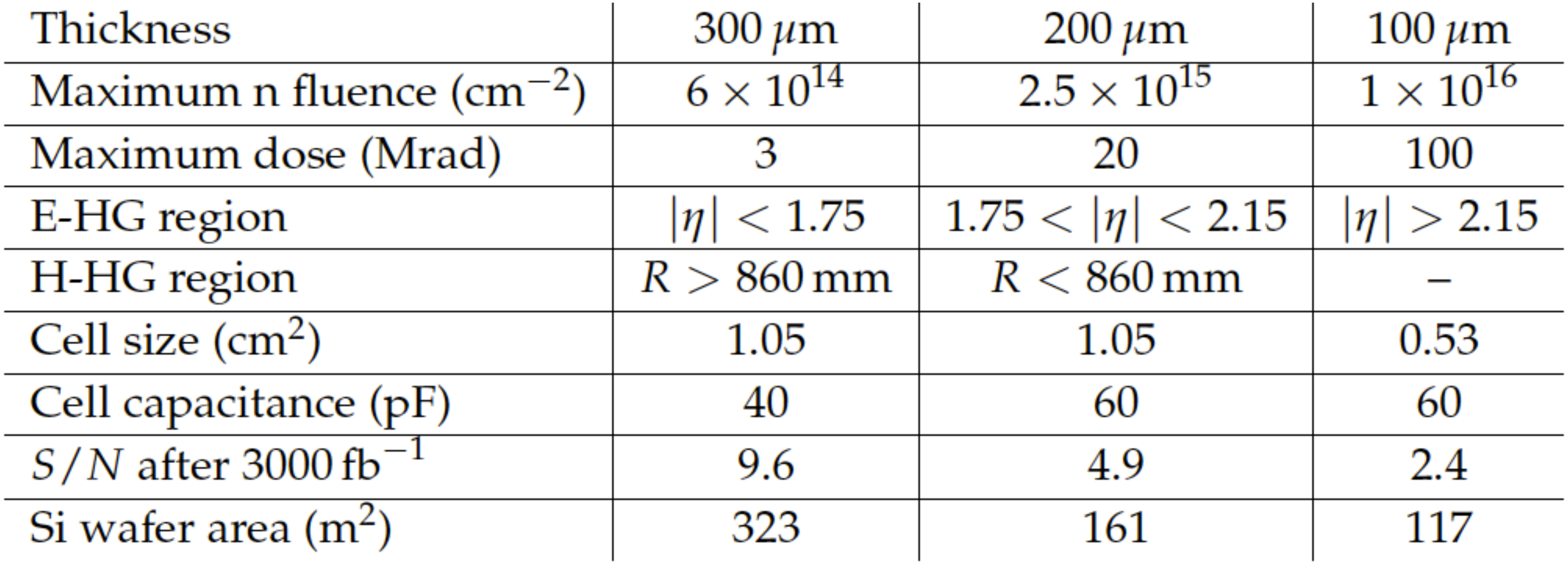
- **Already existing technologies enable production of sufficiently radiation hard components**
  - MIP sensitivity in the presence of pileup with viable in-situ calibration up to 3ab^{-1} at the HL-LHC
  - Good S/N, fast pulse and timing possibility for sufficiently energetic hits
- **Initial physics studies show that tracking shower paths as a function of depth enables**
  - unfolding the effect of non-projective geometry
  - measure the energy of the showers using dynamic clustering
  - estimate of localised energy densities to recover from fluctuations
  - measure high energy electron/photon shower directions to a few mrad
  - Currently studying jet reconstruction performance with the Pandora PF algorithm in 140-200PU

    very promising results already out of the box, with scope for improvement with further tuning

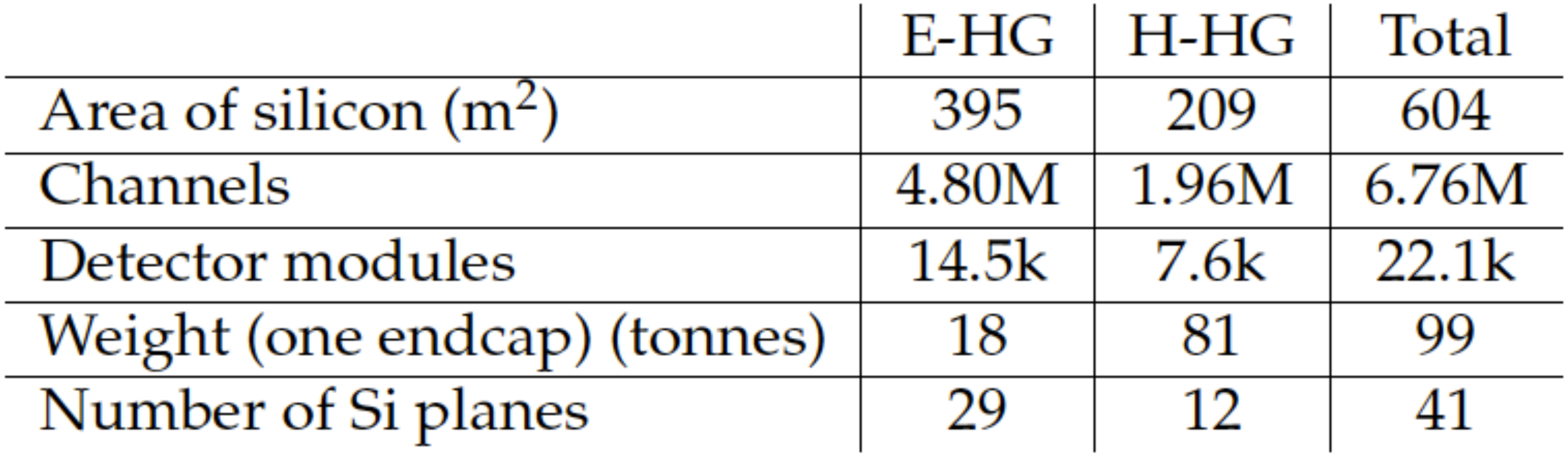
On track to enable efficient, robust, almost pileup-independent measurements at the HL-LHC

Backup

Calorimeter parameters



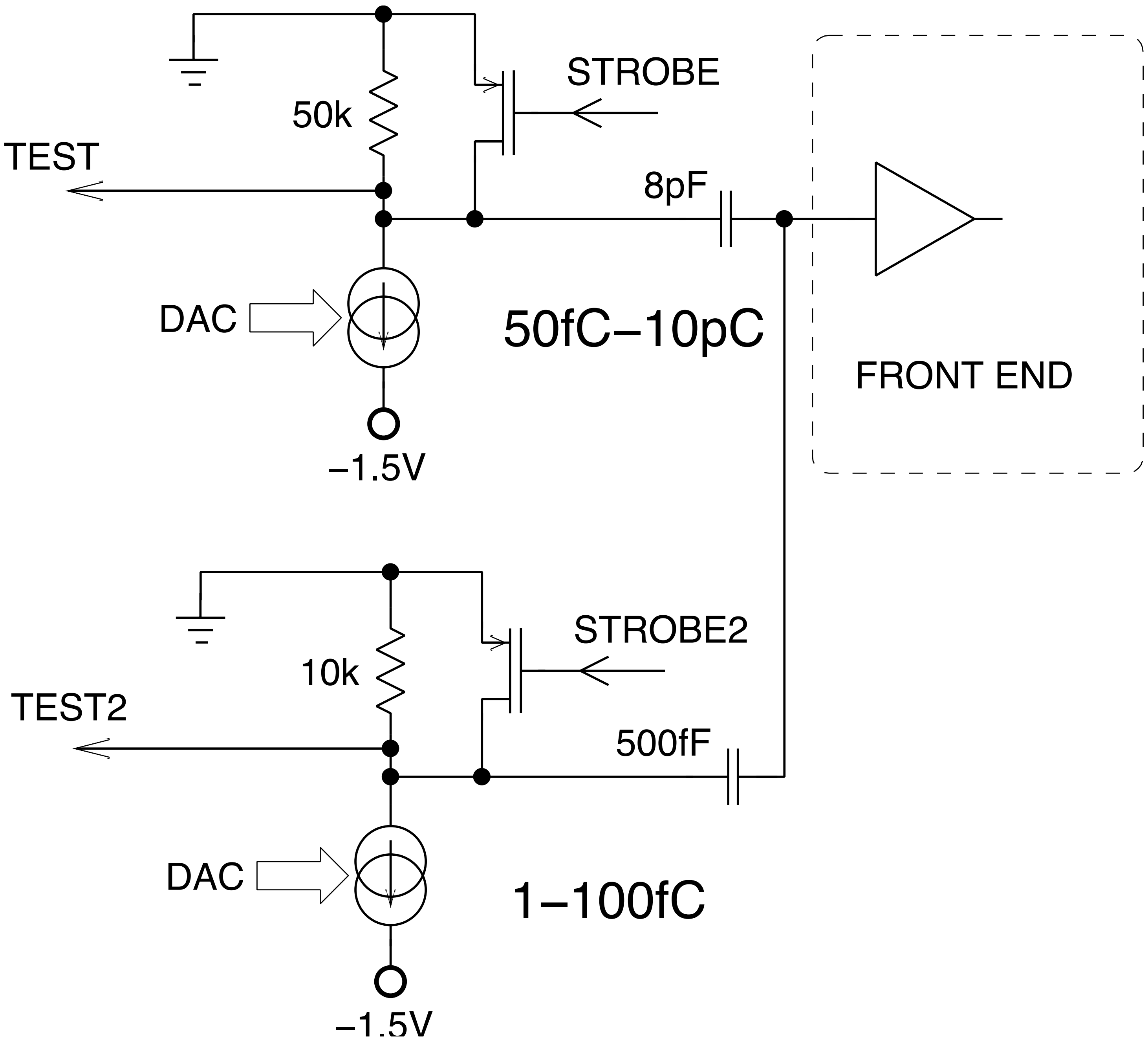
Thickness	300 μm	200 μm	100 μm
Maximum n fluence (cm^{-2})	6×10^{14}	2.5×10^{15}	1×10^{16}
Maximum dose (Mrad)	3	20	100
E-HG region	$\lvert\eta\rvert < 1.75$	$1.75 < \lvert\eta\rvert < 2.15$	$\lvert\eta\rvert > 2.15$
H-HG region	$R > 860$ mm	$R < 860$ mm	–
Cell size (cm^2)	1.05	1.05	0.53
Cell capacitance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



	E-HG	H-HG	Total
Area of silicon (m^2)	395	209	604
Channels	4.80M	1.96M	6.76M
Detector modules	14.5k	7.6k	22.1k
Weight (one endcap) (tonnes)	18	81	99
Number of Si planes	29	12	41

Charge injection calibration circuit

- Calibration can alternatively be achieved by means of charge injection in the front-end

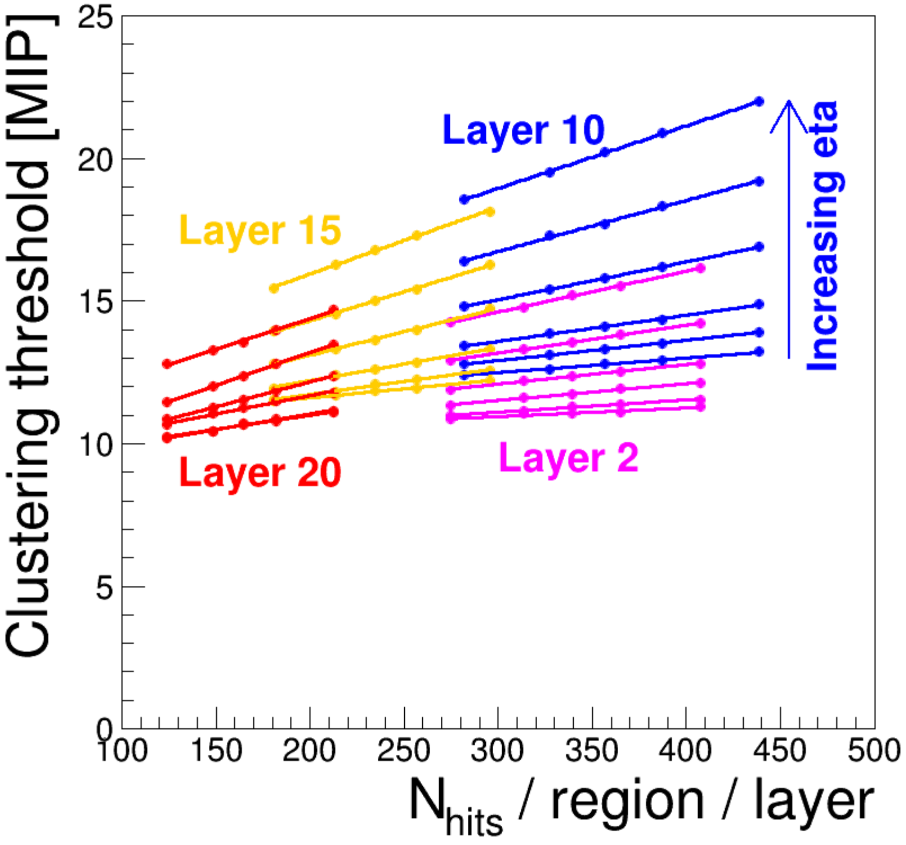


L1 Trigger performance

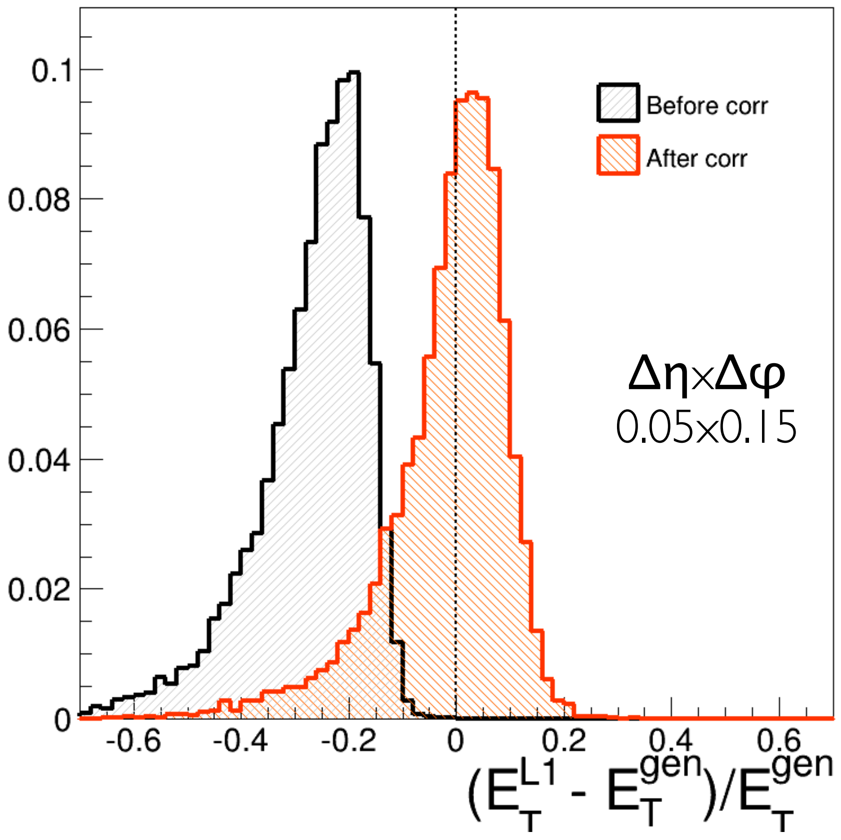
- Clustering algorithm shared between two layers
- **Seeding step :** build regions of interest from projective towers including layers 15-18 (~10 seeds/event)
- **Clustering step** : profit from expected transverse shower profile
- **Super-clustering** : corrected energy clusters sent to layer 2 and merged

PU removed layer-by-layer
Energy loss corrections applied

Threshold removes 95% of PU energy



Resolution and response recovered at L1



Simple / robust id based on long. information: shower start, max. and containment in EE