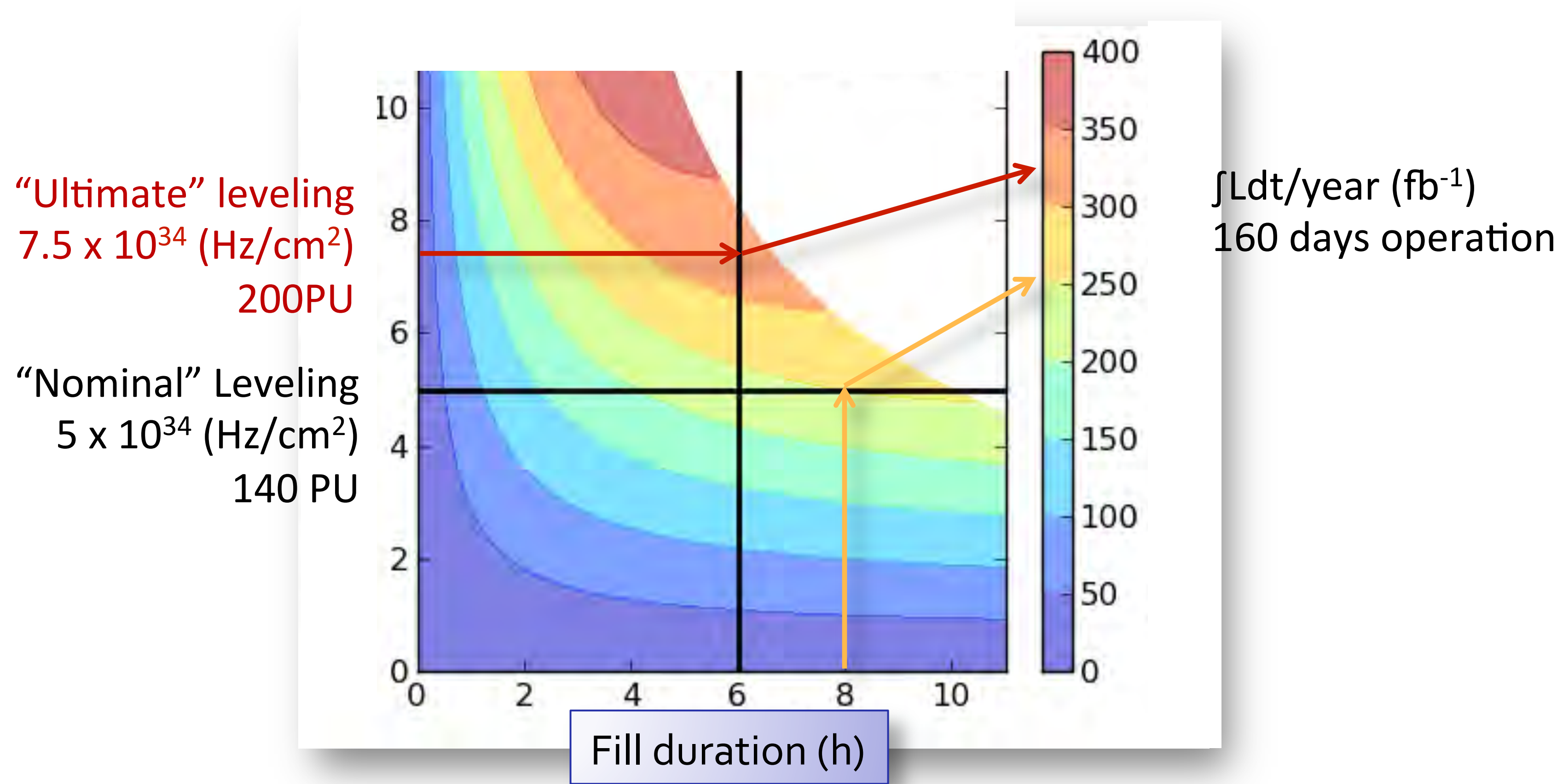
A High Granularity Silicon Calorimeter

CMS HL-LHC Upgrades

HL-LHC luminosity goals: Leveling vs nominal

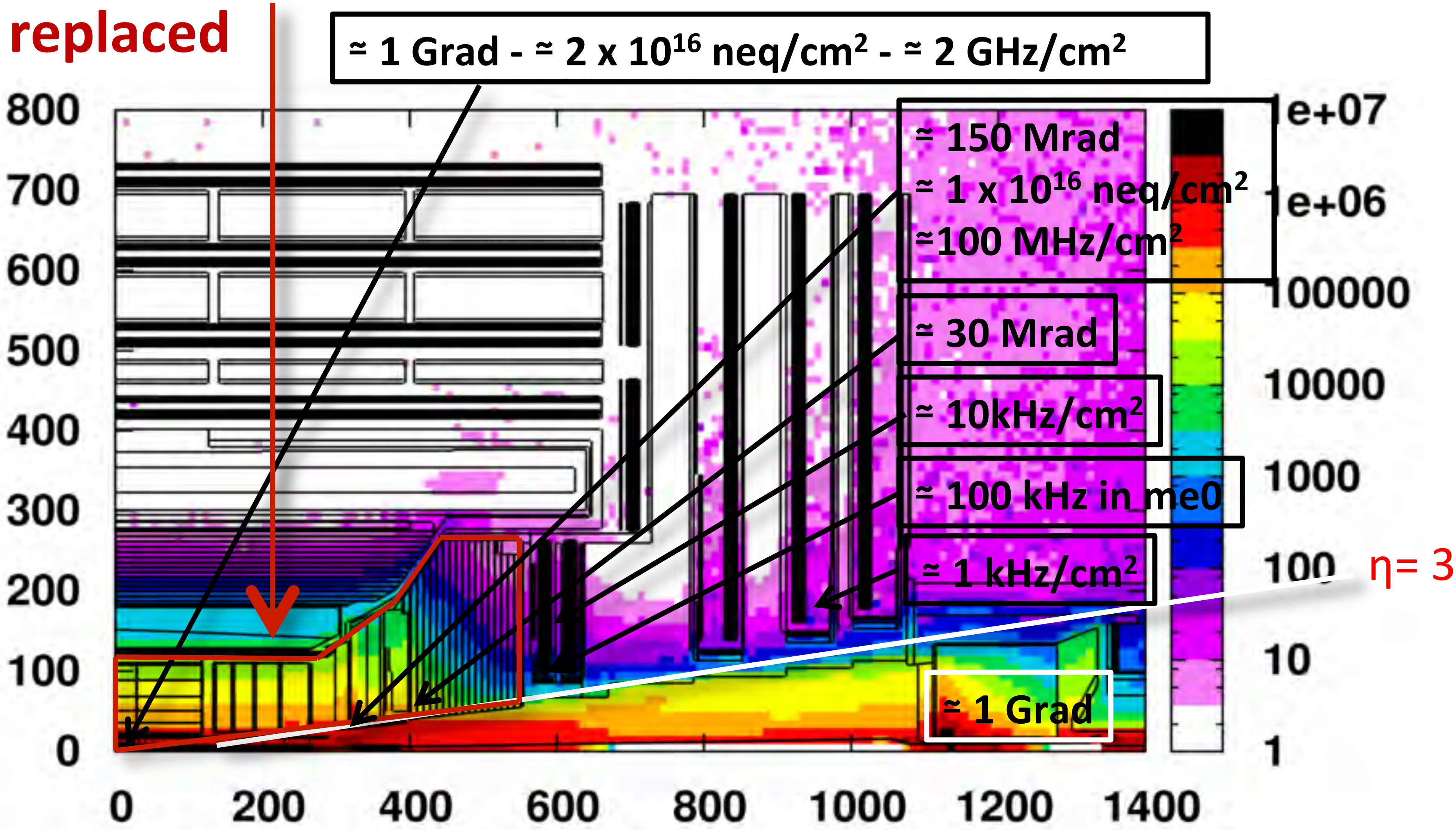


Ultimate luminosity represents ≃ 30% gain in operation time to reach expected additional integrated luminosity of ≃ 2500 fb^{-1}

Design for operation up to ~200 PU, with Phase-I equivalent performance at 140 PU, possible moderate degradation above 140 PU to 200 PU and radiation tolerance ≥ 3000 fb^{-1}

Phase 2 Radiation dose - neutron fluence - particle rates

- *3000 fb^{-1} Dose map in [Gy] simulated with MARS and FLUKA*
- *Numbers in boxes indicate maximum doses - neutron equivalent fluence - particle rates (for 5 x 10^{34} Hz/cm^2) seen by the various detectors*
- **Studies show that Tracker & End Cap Calo must be replaced**



CMS@HL-LHC

Muon system

- Complete RPC coverage in region $1.5 < \eta < 2.4$
- Add muon tagging $2.4 < \eta < 3$

Tracker

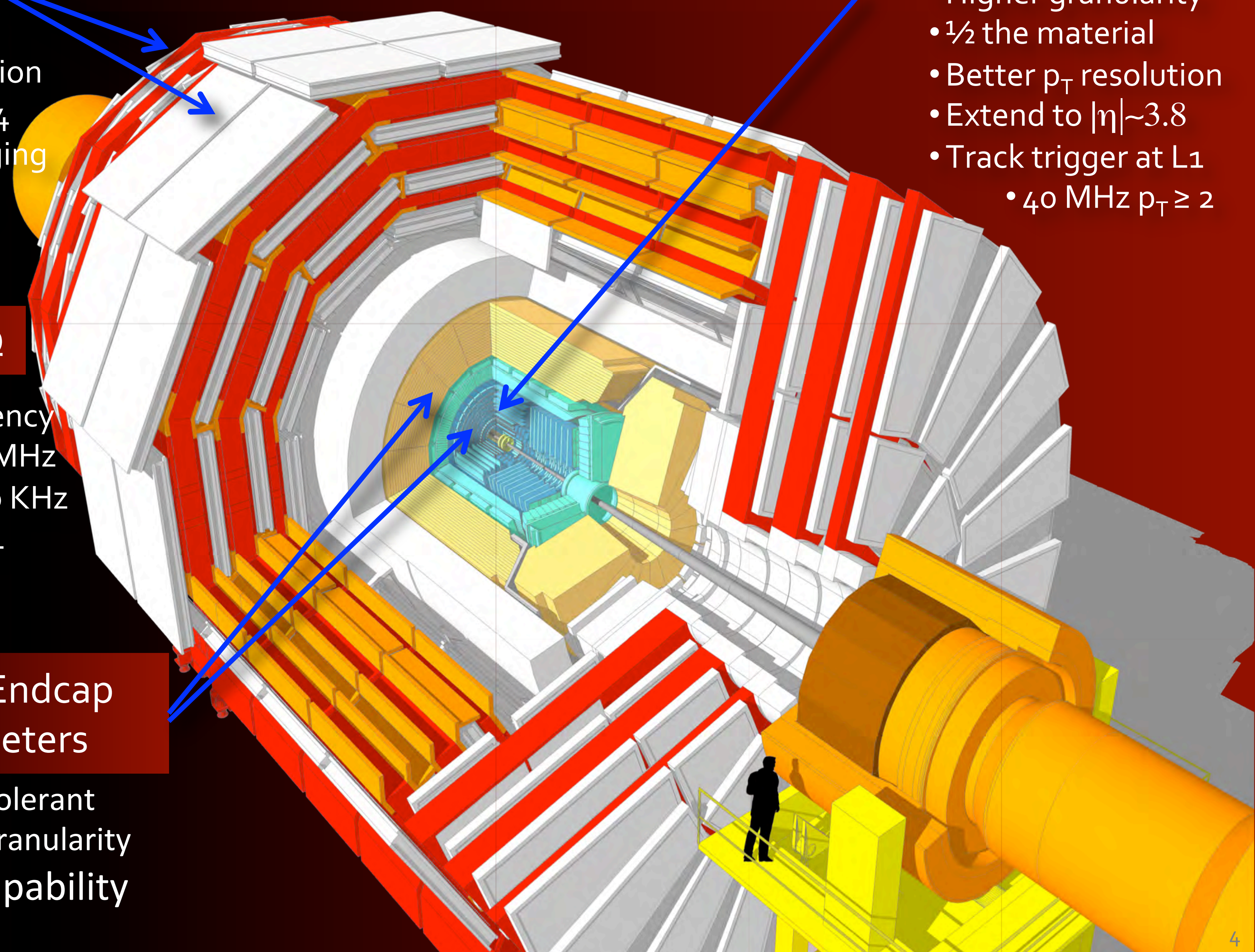
- Higher granularity
- ½ the material
- Better p_T resolution
- Extend to $|\eta| \sim 3.8$
- Track trigger at L1
  - 40 MHz $p_T \geq 2$

Trigger/DAQ

- 12.5 μs L1 latency
- L1 up to 0.75 MHz
- HLT up to ~10 KHz
- Tracking at L1

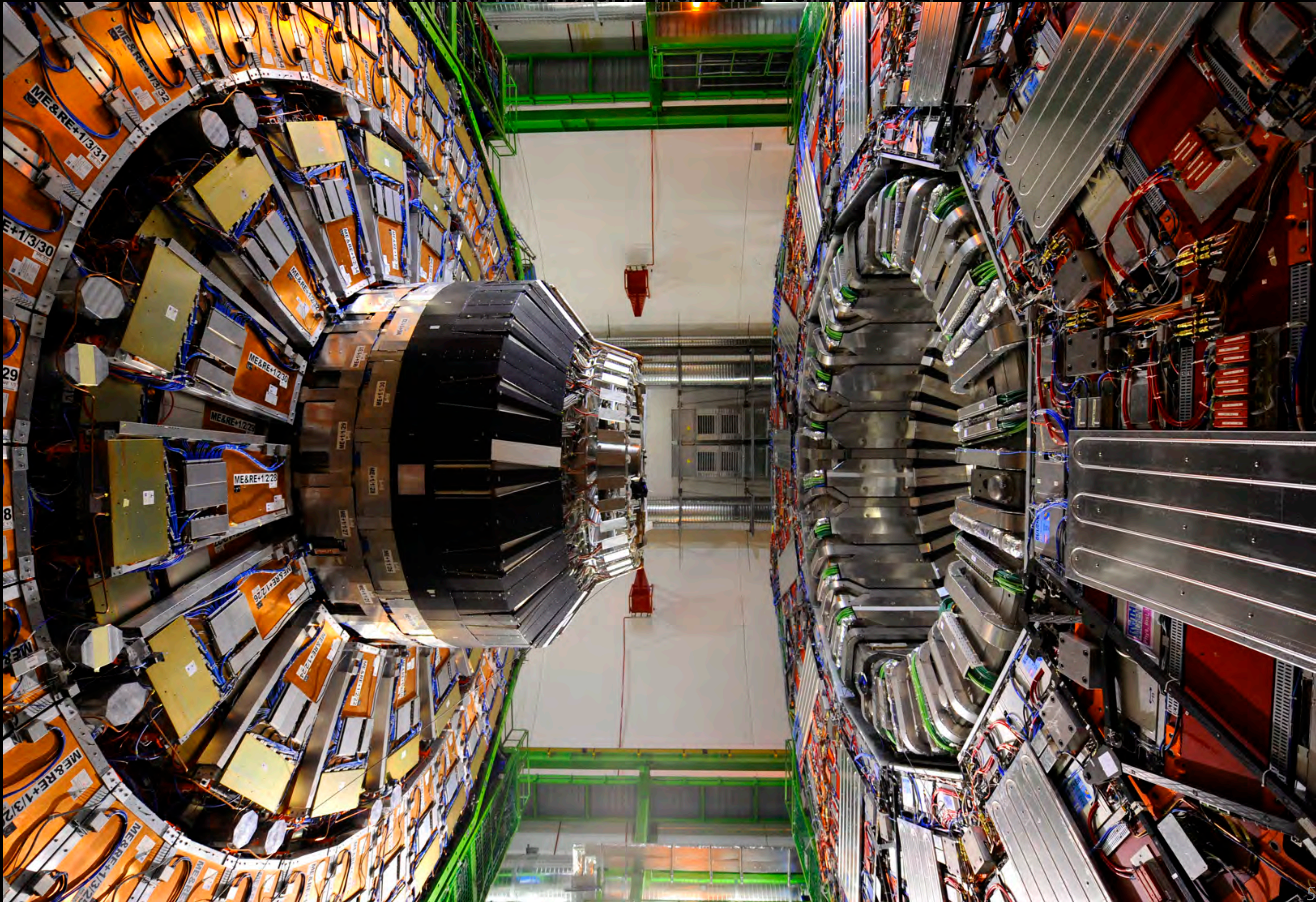
Replace Endcap Calorimeters

- Rad. Tolerant
- High granularity
- 3D capability



Upgrading the CMS Endcap Calorimetry

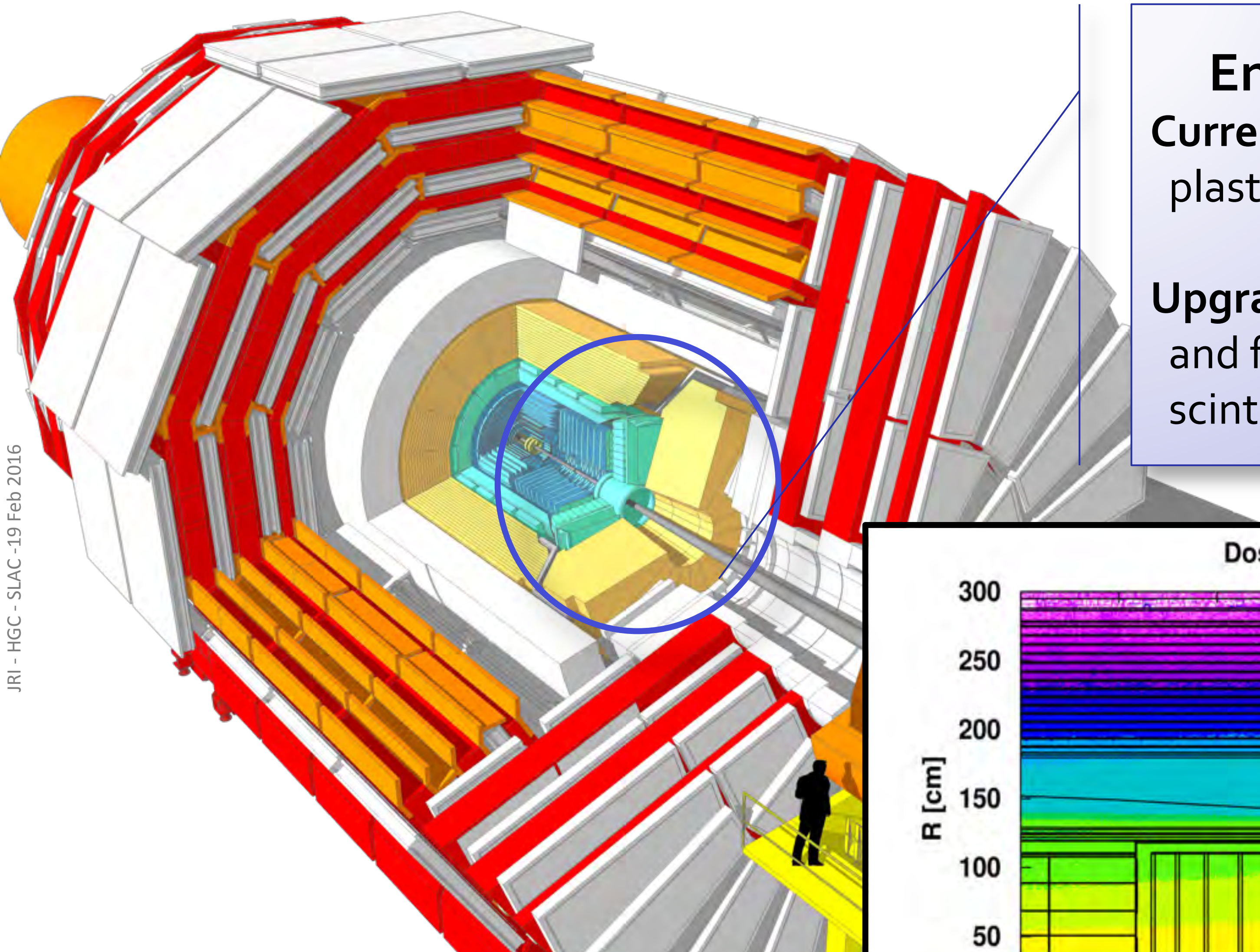
High Granularity and Backing Calorimeter



Drivers for Endcap Upgrade

- Selected physics drivers
  - Jet reconstruction at 140 pileup (particularly for vector-boson-fusion and vector-boson-scattering studies)
  - Electron and photon reconstruction and id for Higgs ($H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow eell$) at 140 pileup
  - Missing transverse energy at high pileup, for dark-matter searches/studies
- Technical drivers
  - Very high radiation dose: current CMS endcap calorimeters lose > 90% of signal amplitude over large portions of detector if kept for HL-LHC era
  - Increased L1 readout rate (100 kHz increases up to 750 kHz) and longer L1 trigger latency (3 μs increases to 12.5 μs)

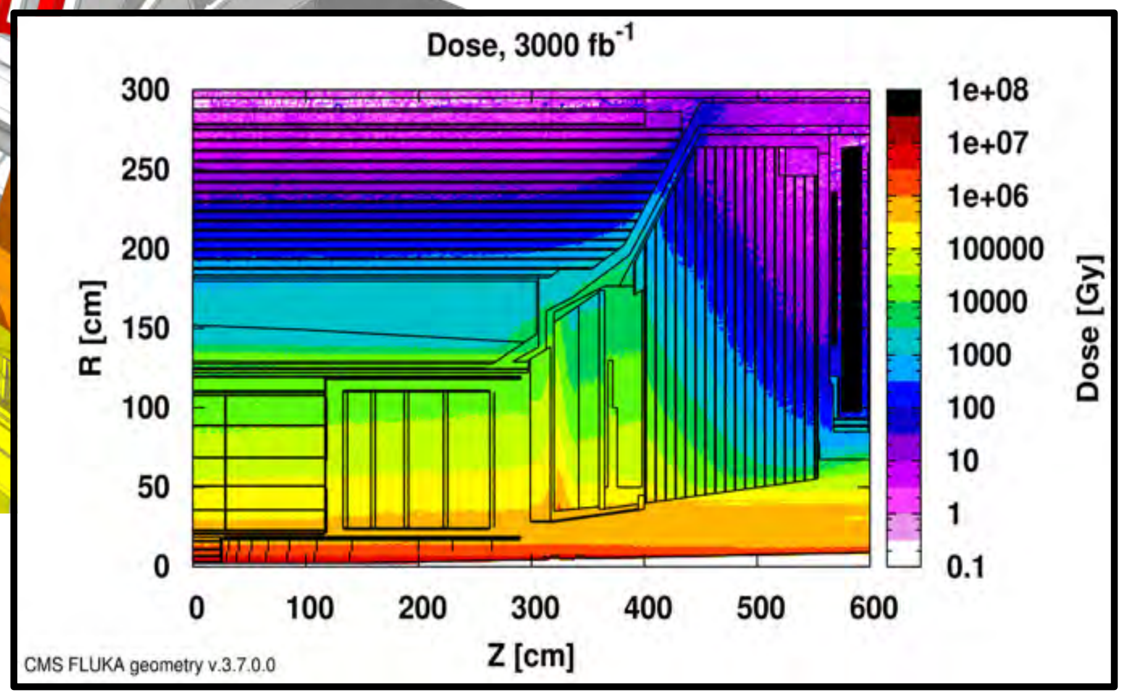
Overview of the Upgrade



Endcap Calorimetry

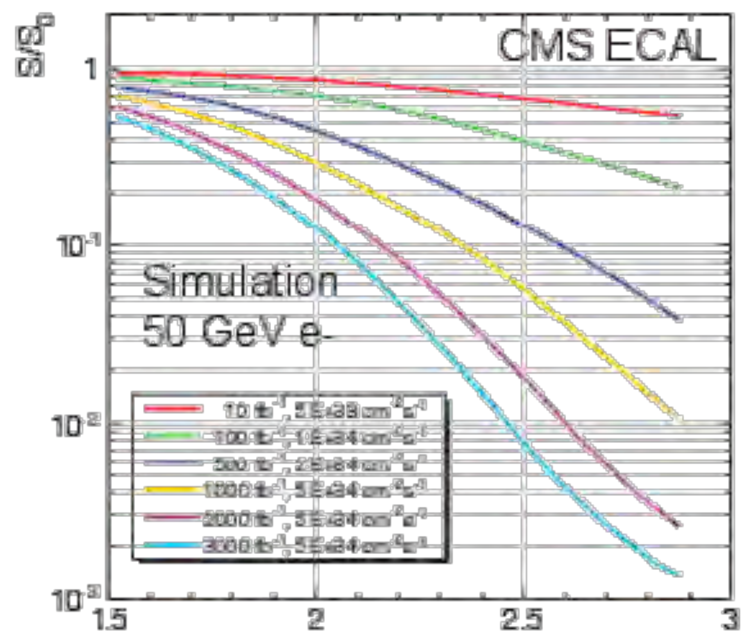
Current: $PbWo_4$ crystal ECAL+ plastic-scintillator/WLS HCAL

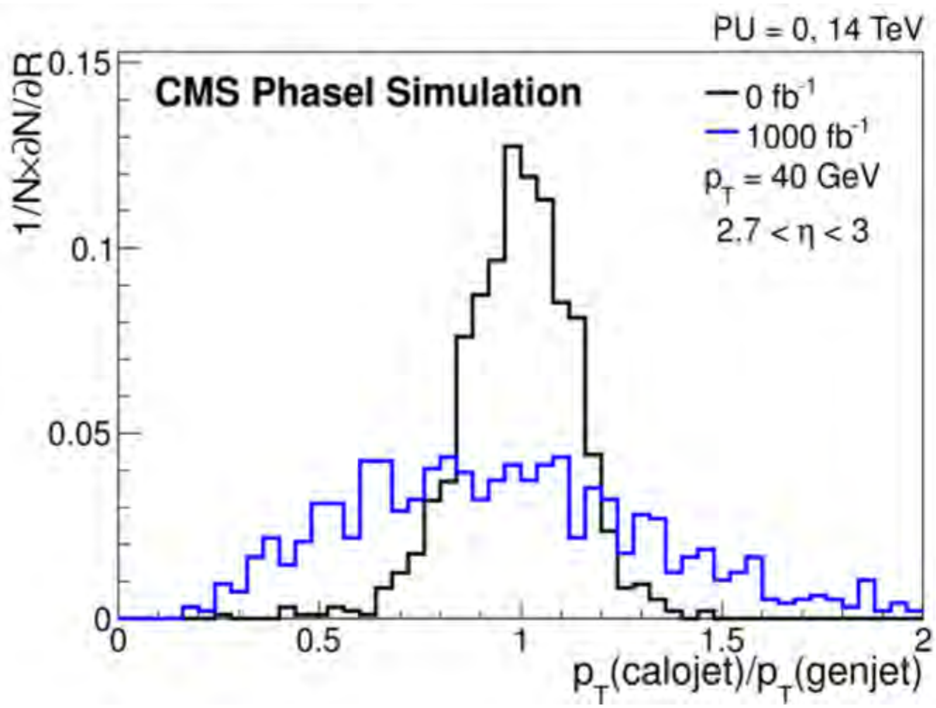
Upgrade: Silicon-based ECAL and front HCAL, plastic-scintillator/WLS back HCAL

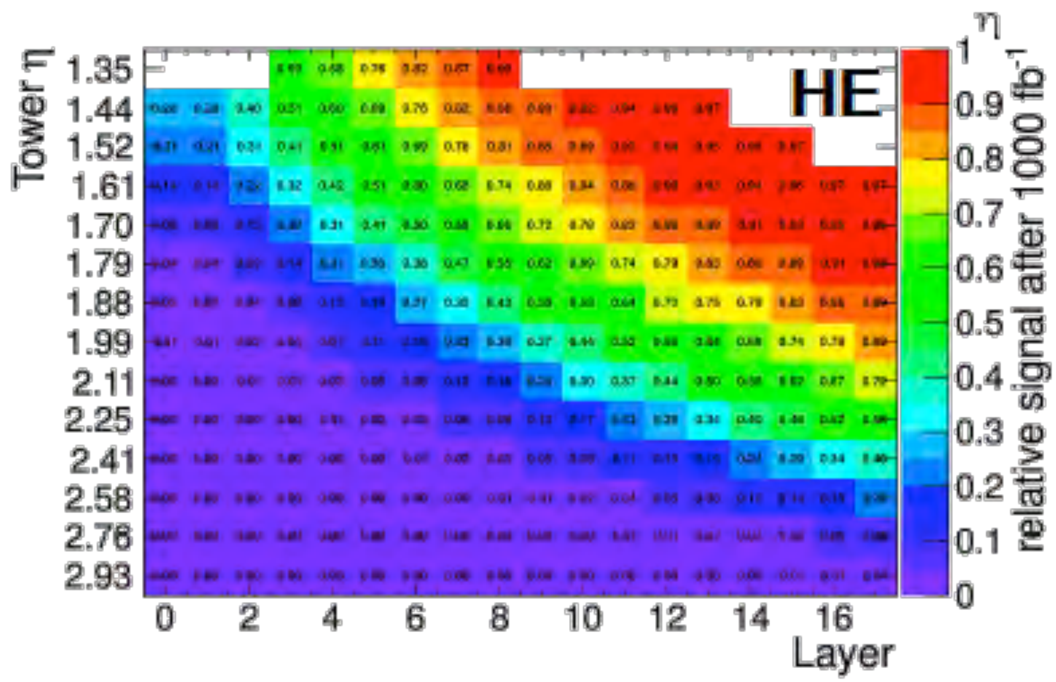


Motivation for the Upgrade

- Radiation damage will greatly reduce the energy resolution of the endcap calorimeters after 500 fb^{-1}
- Segmentation and performance is marginal for management of HL-LHC pileup conditions







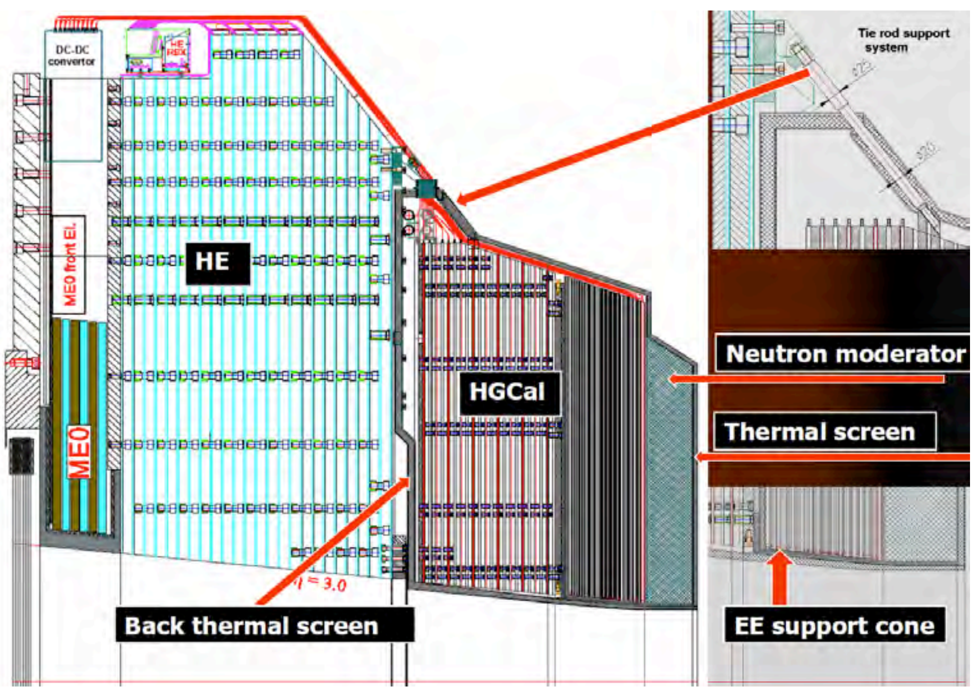
High Granularity (HGC) & Back Hadron (BH)

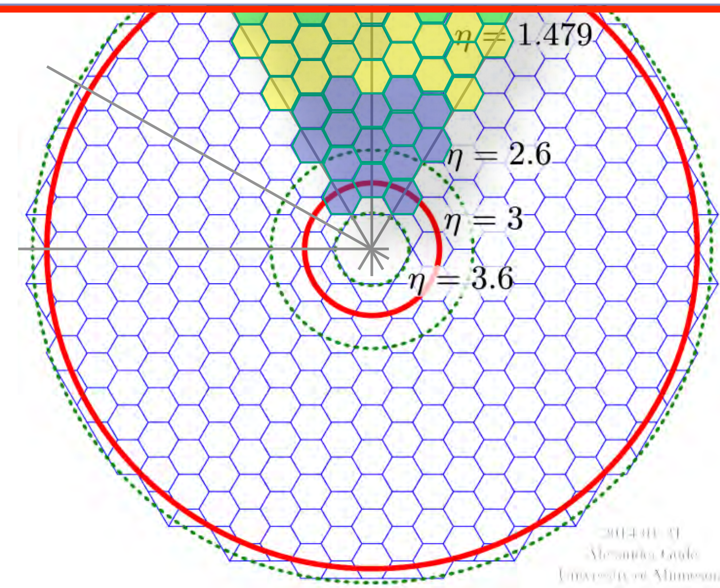
- 3D shower measurement in HGC
  - *Electromagnetic EE (26 X_0, 1.5λ): 28 layers of Silicon-W/Cu absorber*
  - *Front Hadronic FH (3.5 λ): 12 layers of Silicon/Brass*
  - *Back Hadronic BH (5 λ): 12 layers of Scintillator/Brass (2 depths readout)*

~20k channels → ~6.3M ch. @HL-LHC

Key parameters:

- *593 m² of silicon*
- *21,660 modules*
- *92,000 front-end ASICS.*
- *Power at end of life 115 kW.*



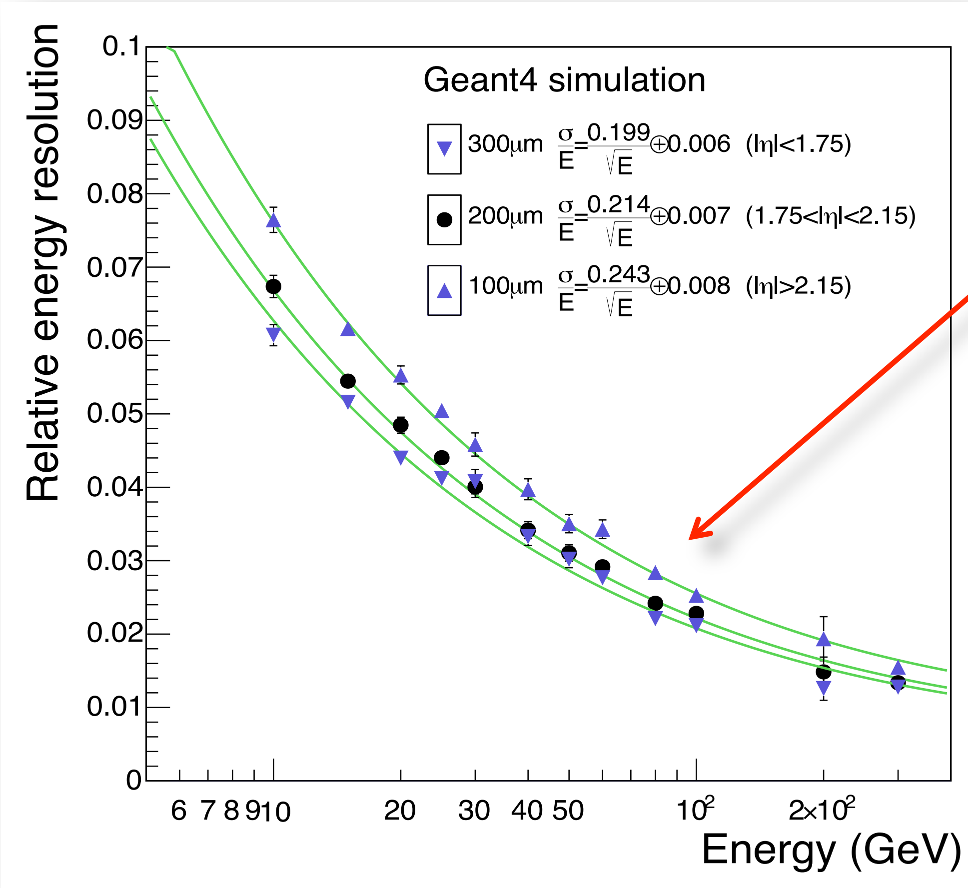


3 sensor active thicknesses 100-200-300 µm

0.5(1) cm² pads for 100(200/300) µm

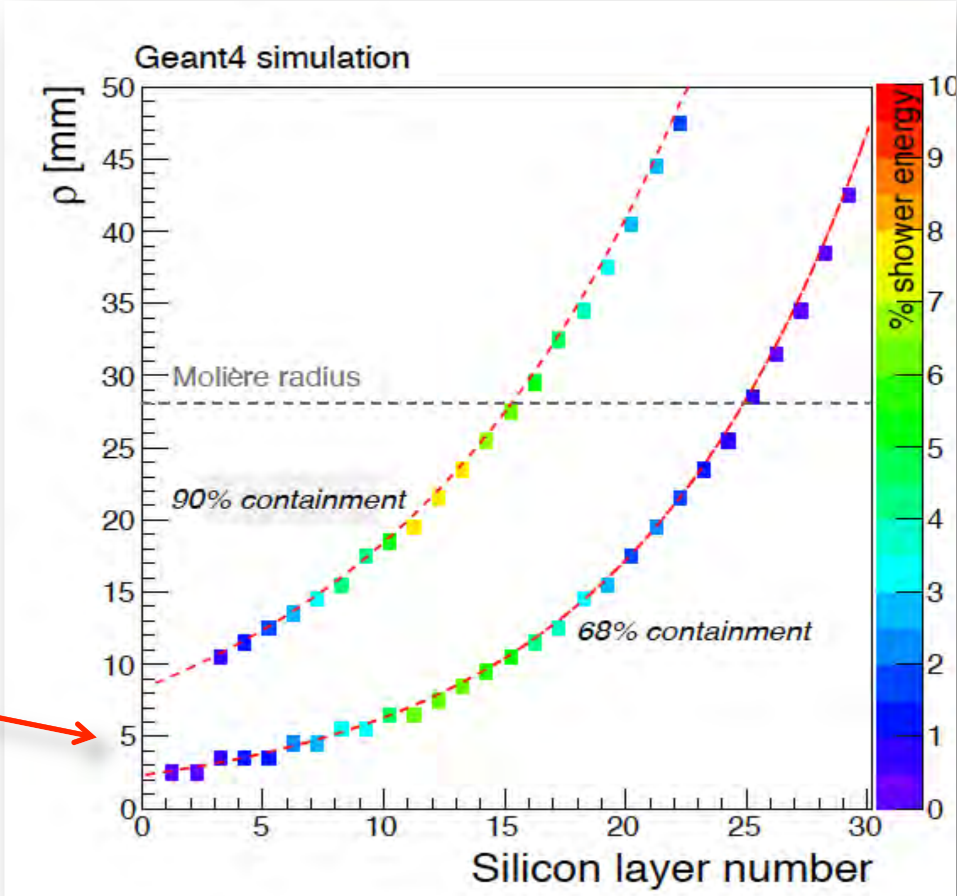
Si-HGC

EM Resolution, transverse shower size



Resolution has large stochastic term but low constant term

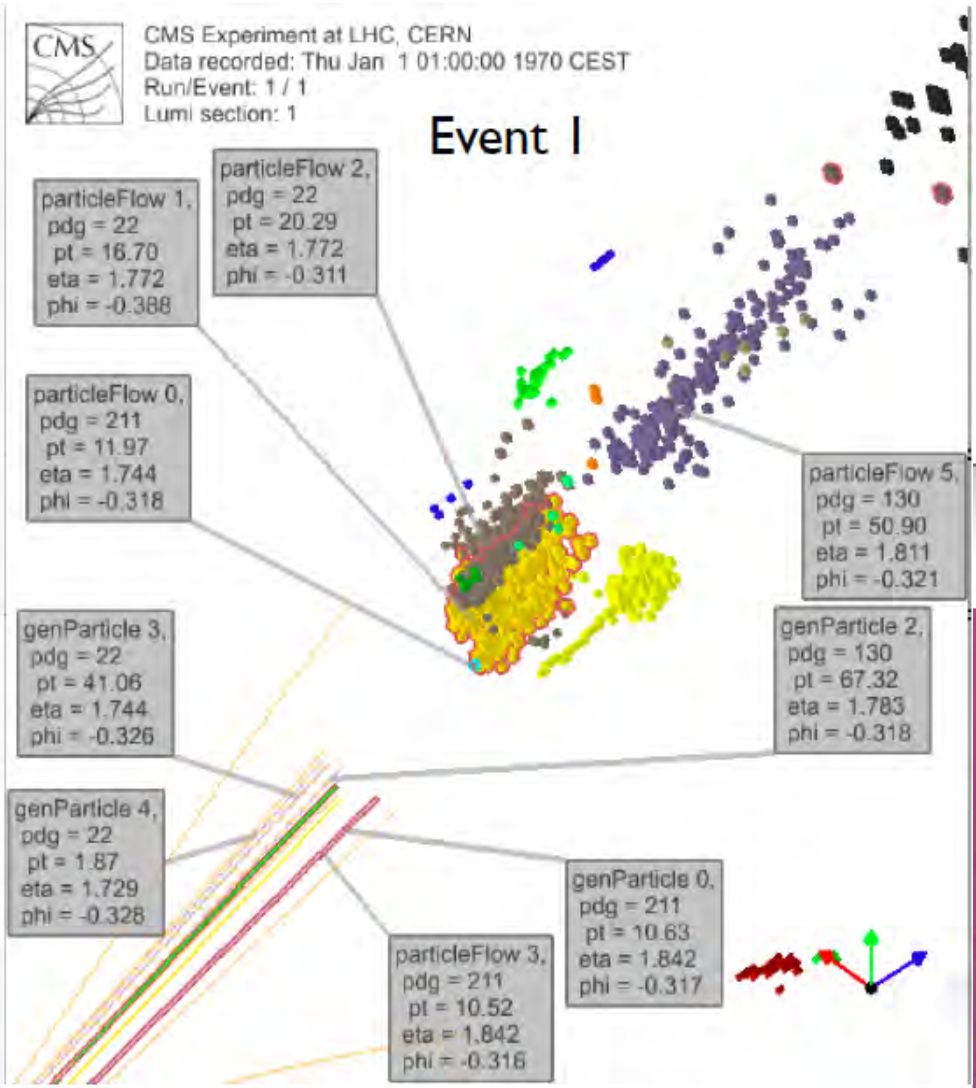
NB: In endcap E large even if E_T low



EM shower size is initially very small

NB: potential for good reconstruction of boosted objects and even for isolating neutral hadrons in HG hadronic layers

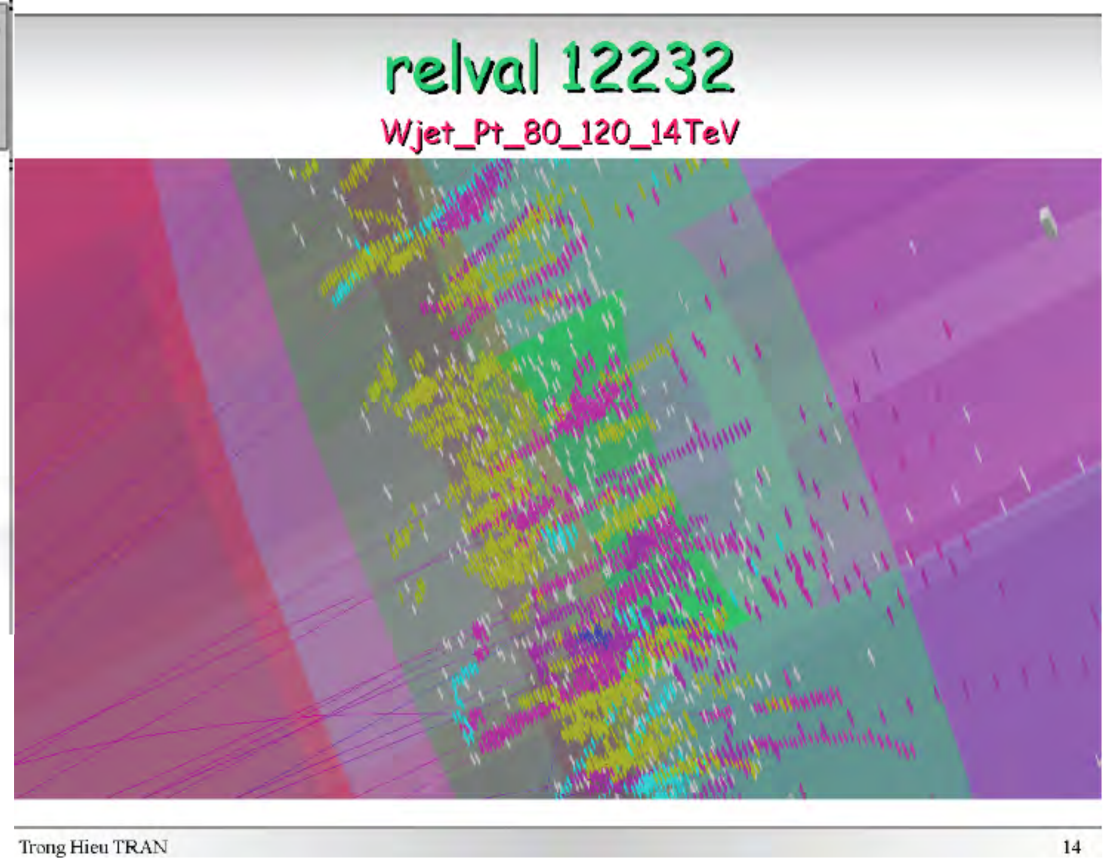
Si-HGC Event Displays



Si-HGC extends Tracking into Calorimeter

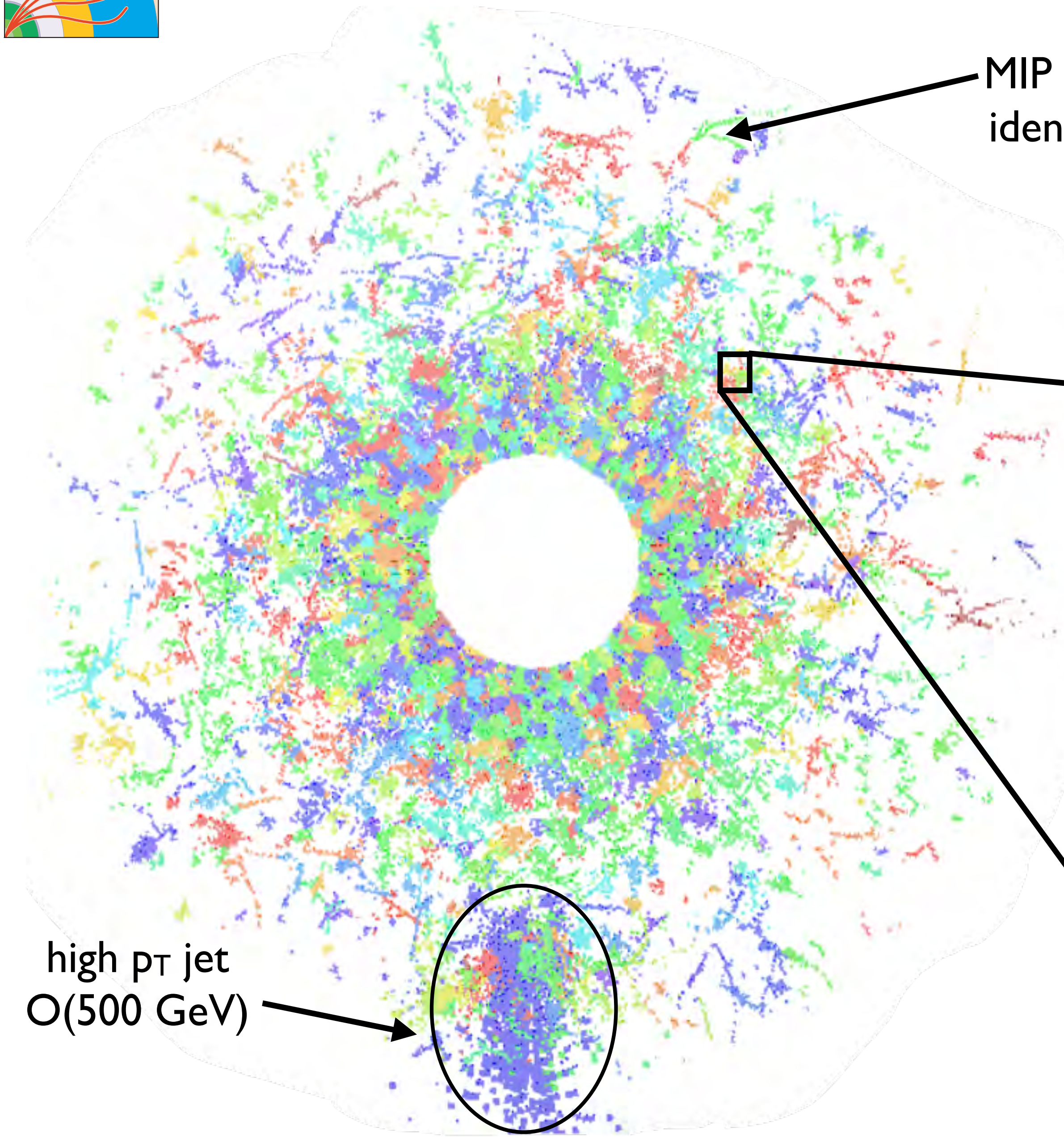
Provides good cluster energy resolution,
very detailed topological information
and excellent two-particle cluster resolving power

Ideally suited for Particle Flow reconstruction
in a high particle density environment



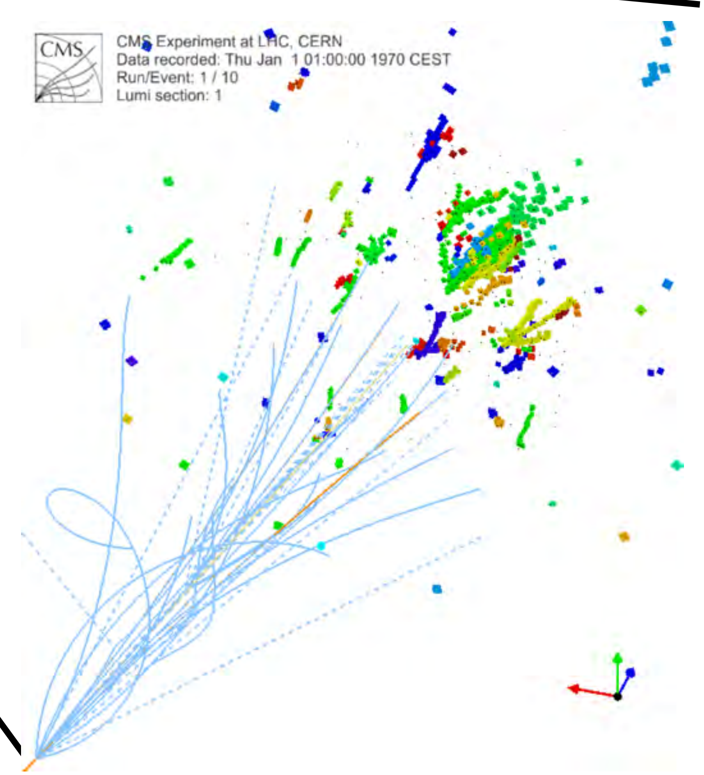
Showers with the HGCal

MIP tracks and clusters clearly identifiable by eye throughout most of detector.



high p_T jet
O(500 GeV)

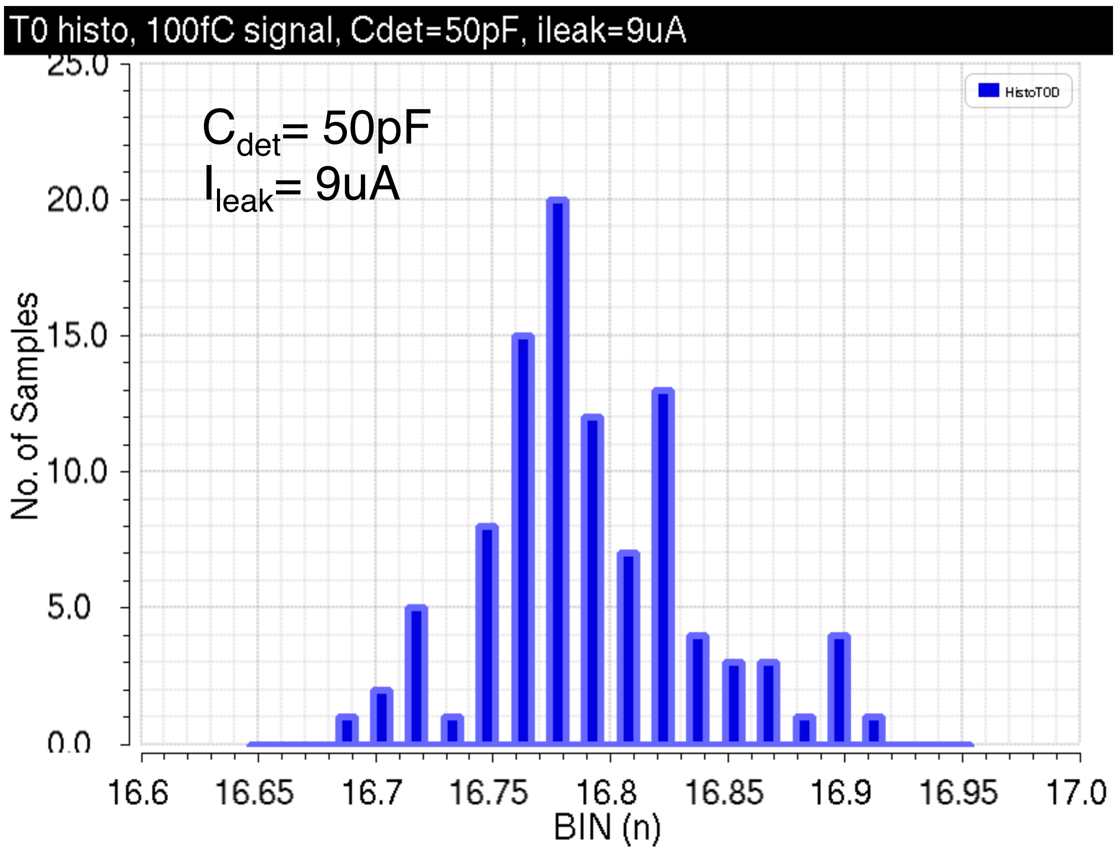
the longitudinal shower footprint



In this talk I will be discussing recent results with PandoraPFA integrated in CMSSW (CMSPandora), some of the road to getting there, and the road still to go.

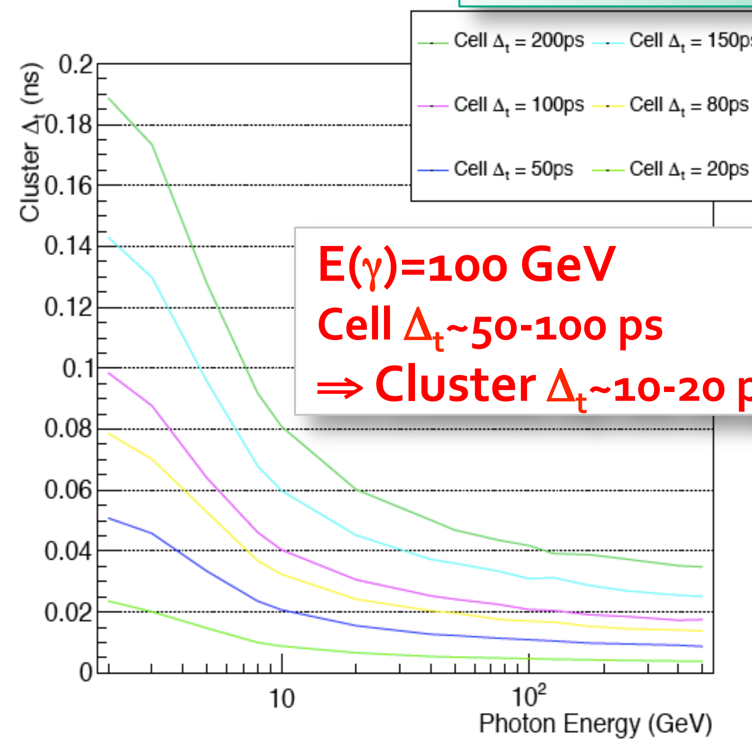
Precision Timing

T_0 for 100fC signal RMS 50ps

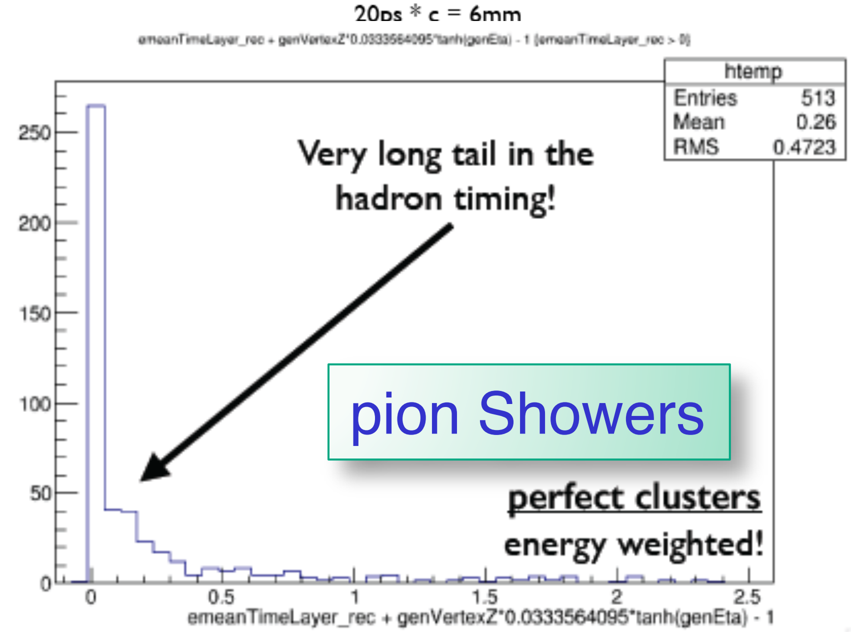


Potential to assist in the removal of pileup and location of interaction vertices

em showers



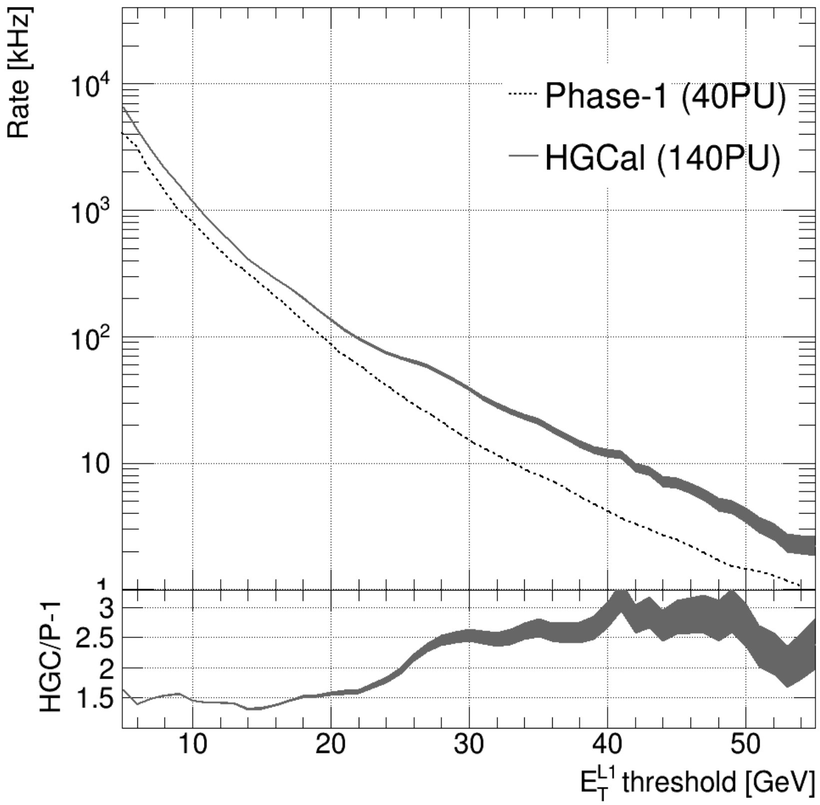
Δt is 68% effective RMS
20ps * c = 6mm

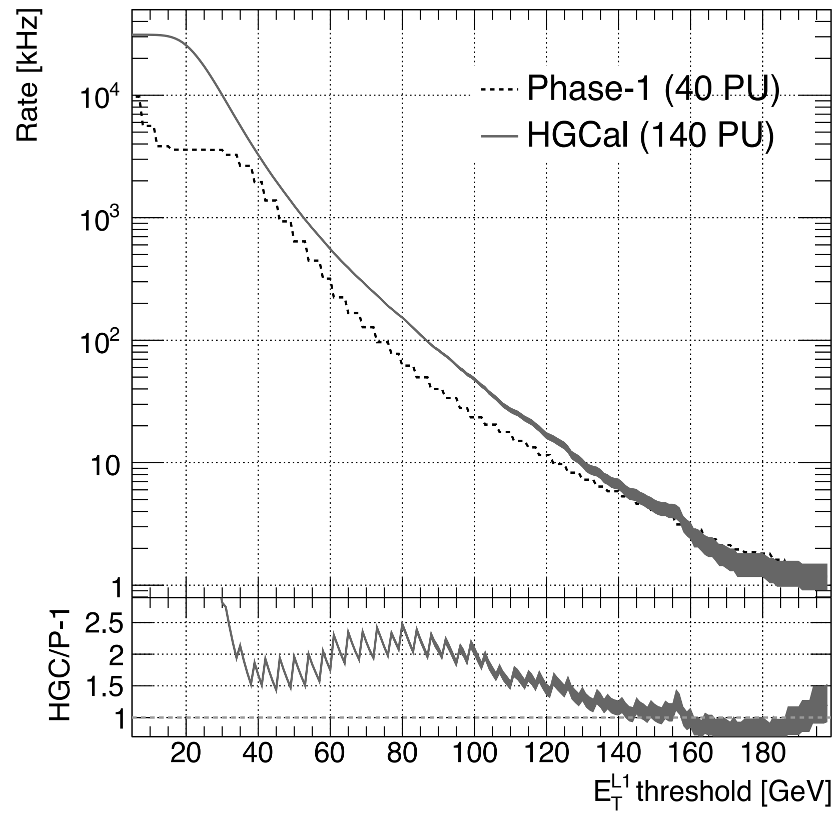


HGC Trigger performance

Expect improvements compared to present detector, particularly benefit where no (or less efficient) Track-Trigger (e.g γ, & VBF/S jets beyond η = 2.4)

- Trigger data: 2(2x2) pad sums (inner/outer) from alternate layers in EE/FH, full B

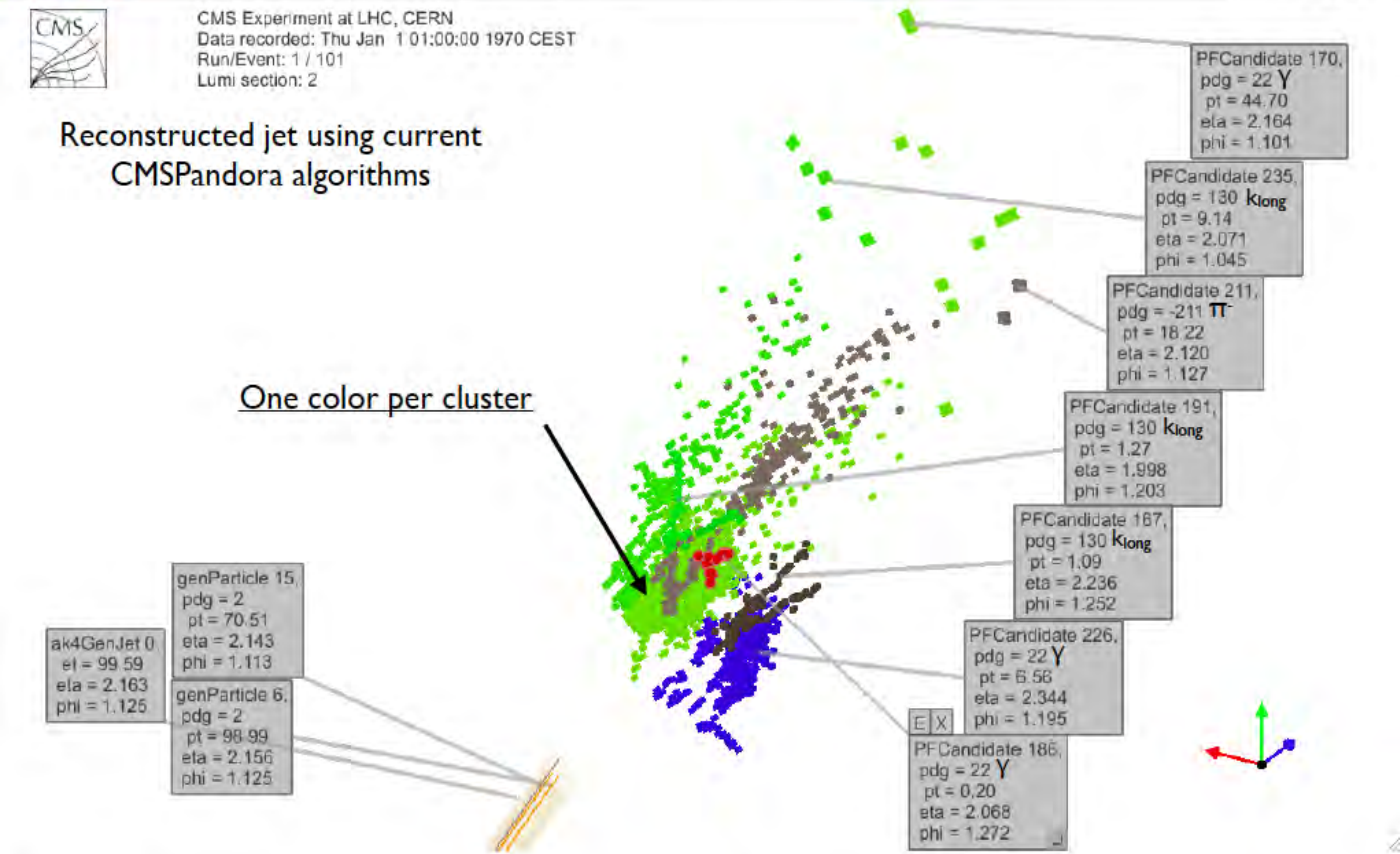




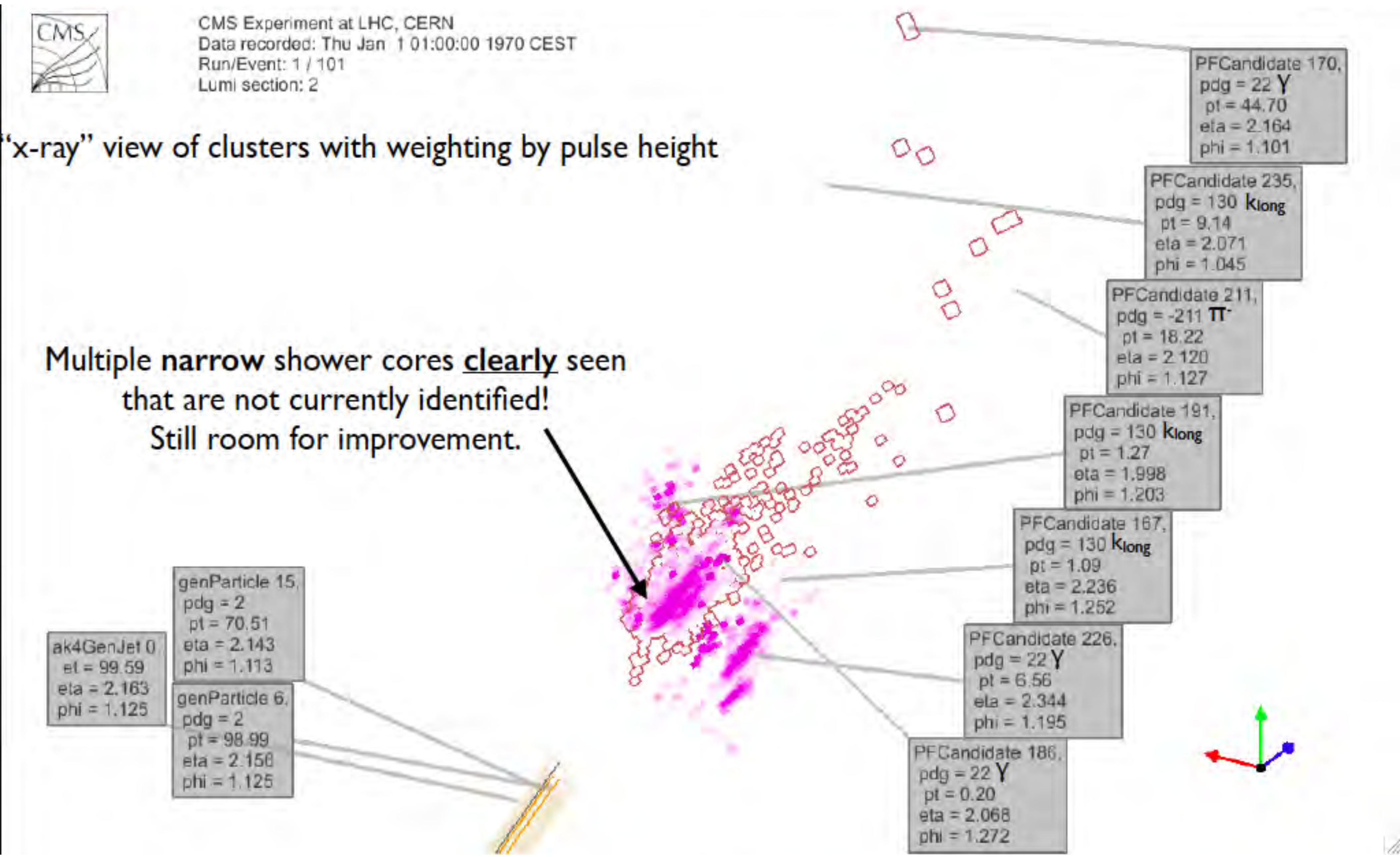
e/γ rate x 2.5 Phase-I (similar efficiency)

Jet trigger x 2 Phase-I

VBF Jets

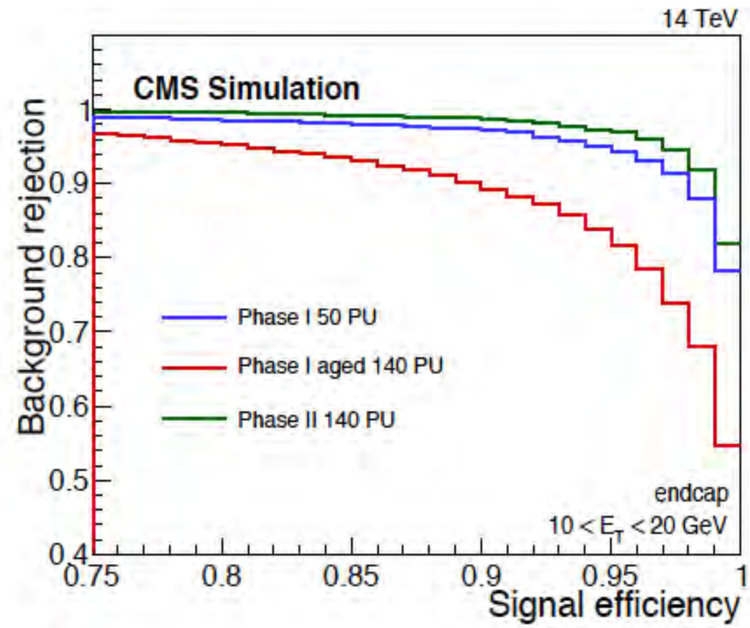

CMS
CMS Experiment at LHC, CERN
Data recorded: Thu Jan 1 01:00:00 1970 CEST
Run/Event: 1 / 101
Lumi section: 2
Reconstructed jet using current CMSPandora algorithms
One color per cluster
PFCandidate 170, pdg = 22 γ pt = 44.70 eta = 2.164 phi = 1.101
PFCandidate 235, pdg = 130 klong pt = 9.14 eta = 2.071 phi = 1.045
PFCandidate 211, pdg = -211 π- pt = 18.22 eta = 2.120 phi = 1.127
PFCandidate 191, pdg = 130 klong pt = 1.27 eta = 1.998 phi = 1.203
PFCandidate 167, pdg = 130 klong pt = 1.09 eta = 2.236 phi = 1.252
PFCandidate 226, pdg = 22 γ pt = 6.56 eta = 2.344 phi = 1.195
PFCandidate 186, pdg = 22 γ pt = 0.20 eta = 2.068 phi = 1.272
genParticle 15, pdg = 2 pt = 70.51 eta = 2.143 phi = 1.113
ak4GenJet 0 et = 99.59 eta = 2.163 phi = 1.125
genParticle 6, pdg = 2 pt = 98.99 eta = 2.156 phi = 1.125

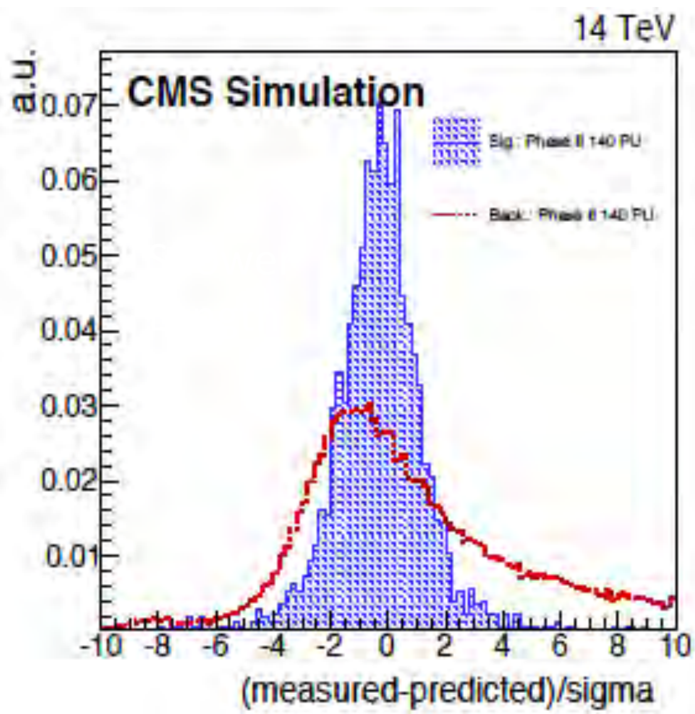
Ex. of untapped potential

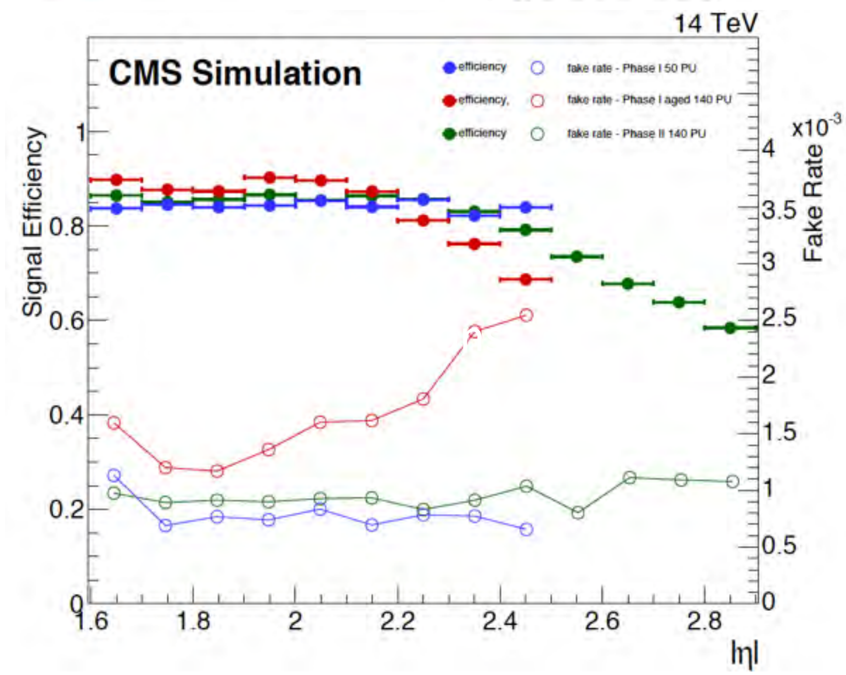


Performance for Electromagnetic Objects

- Electromagnetic object performance at high pileup is important for Higgs physics in the HL-LHC era
  - Access to low-momentum electrons allows broader use of H→ZZ→eell

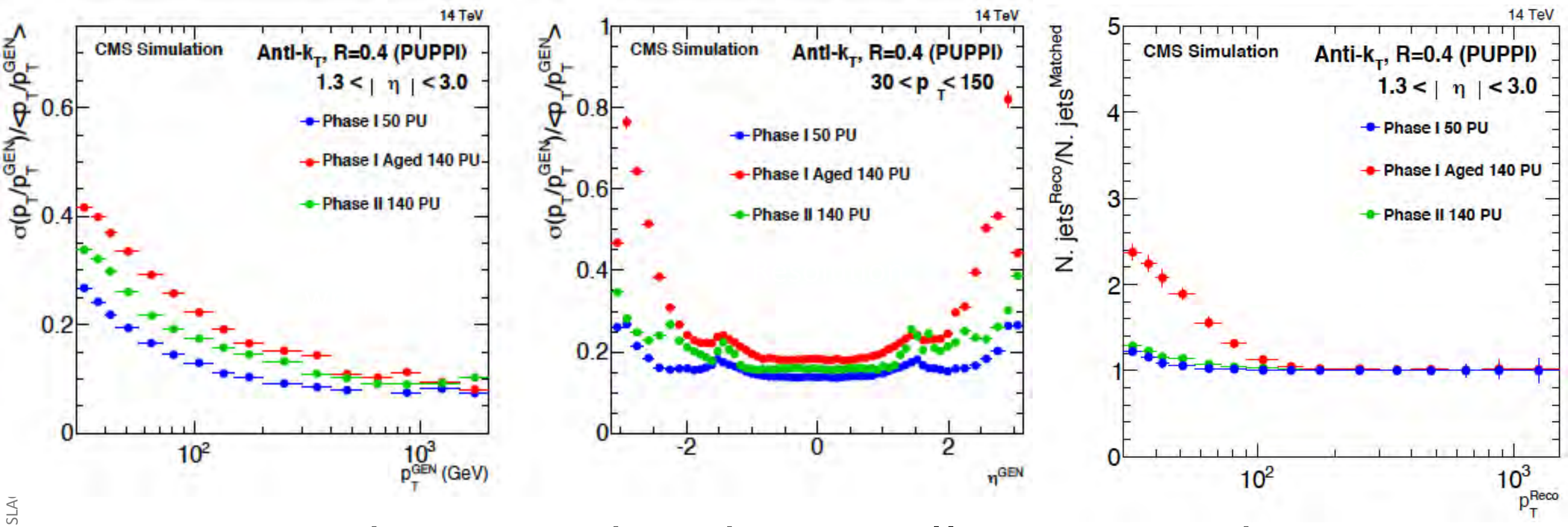






1.2

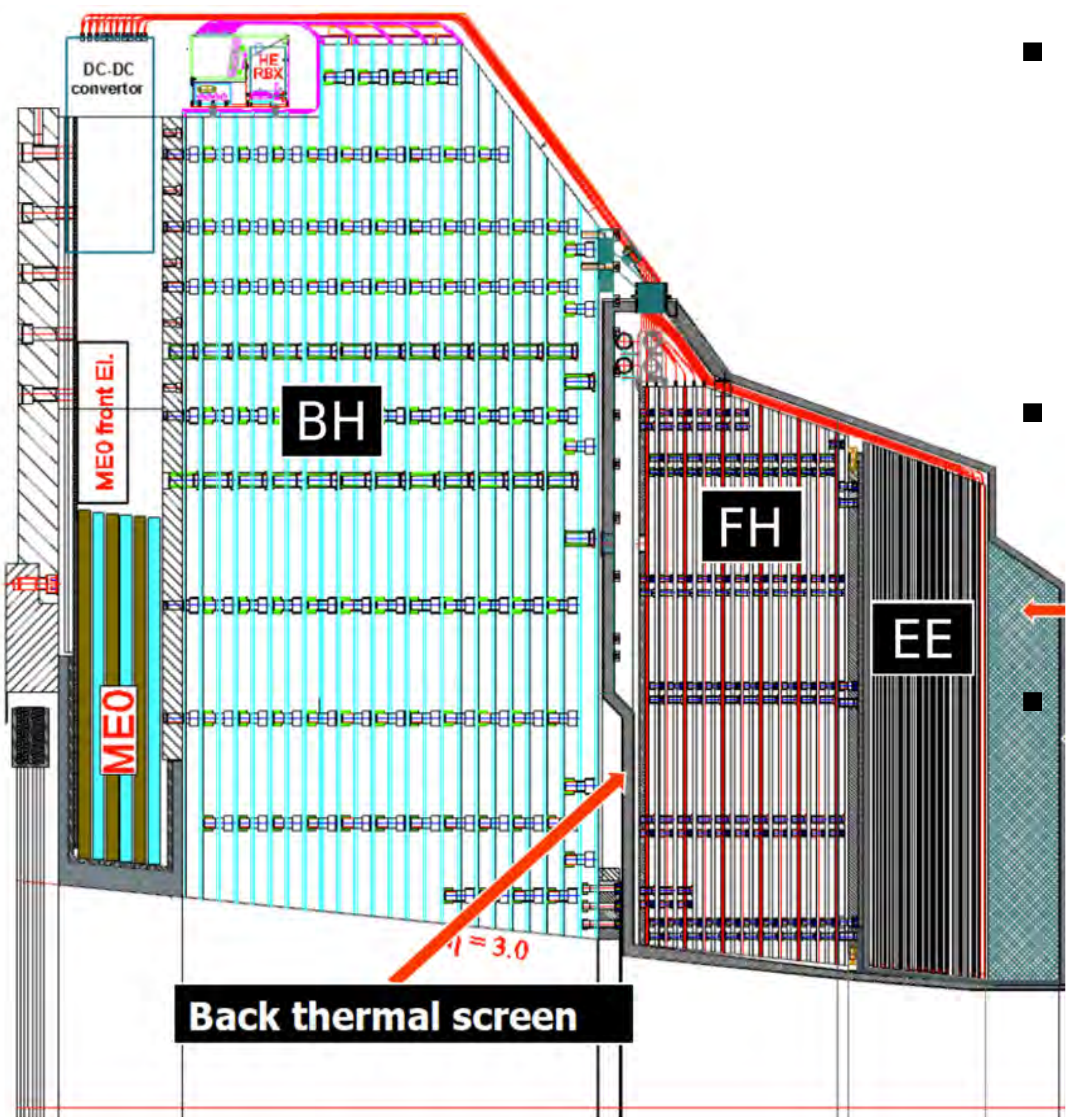
Performance for Jets



- For jets, the upgrade substantially restores the baseline performance of the detector, even at 140 PU
  - Low p_T region is important for vector-boson-fusion production of Higgs and other new particles, and crucial for vector boson scattering studies
  - Timing capability should further enhance pileup rejection

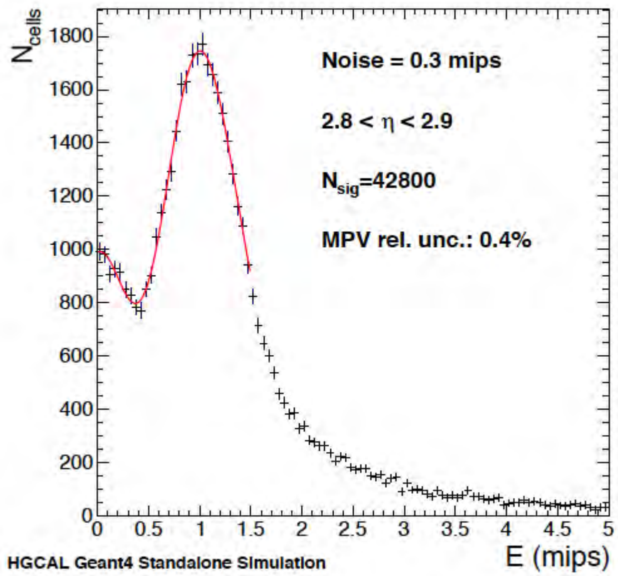
1.2

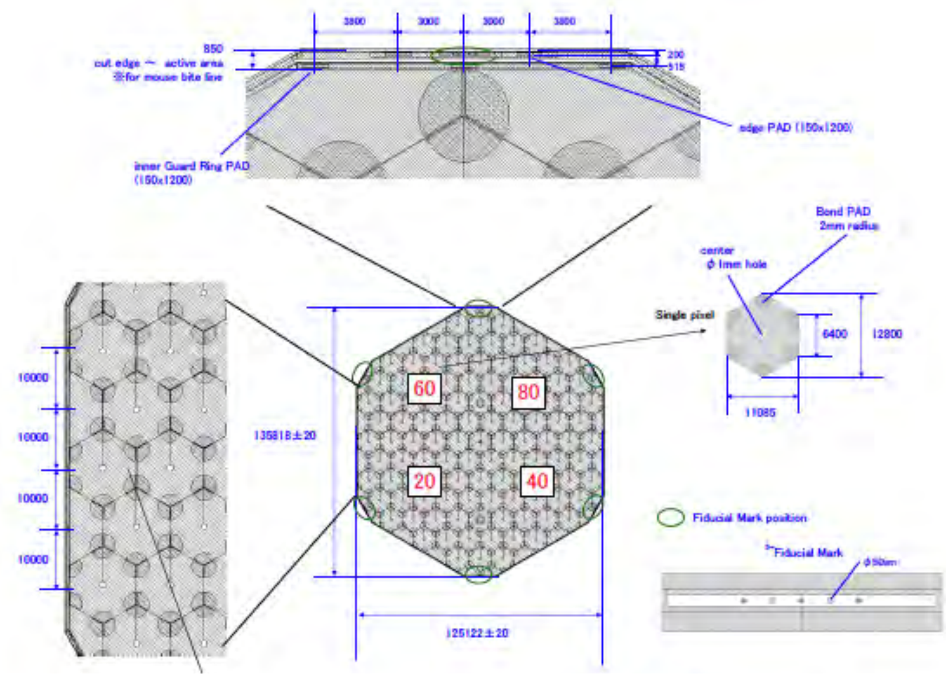
Conceptual design from Technical Proposal



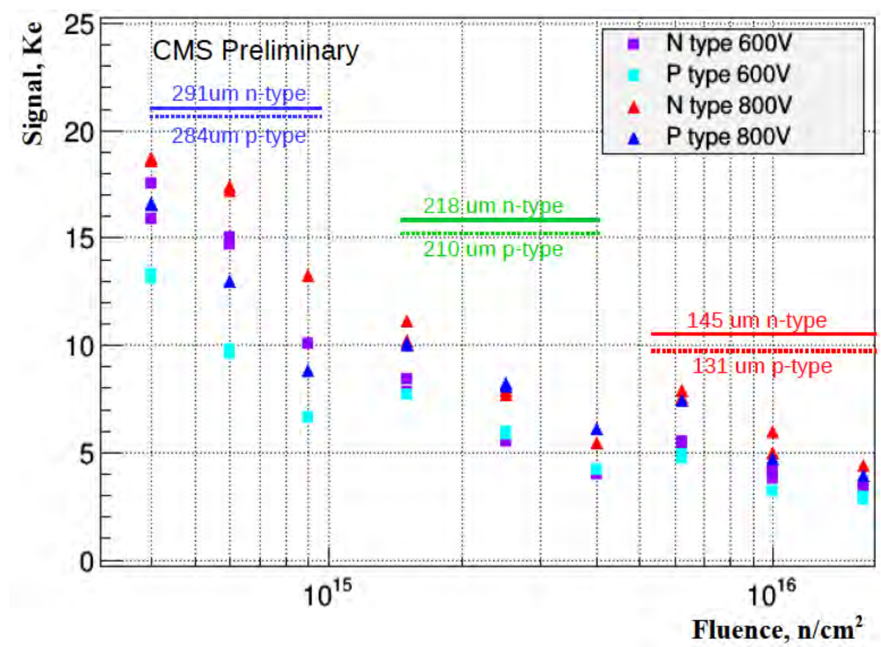
- Silicon/tungsten electromagnetic calorimeter (EE)
  - 28 layers with varying X_0 thickness (average 1.0)
- Silicon/brass hadron calorimeter (FH)
  - 12 sampling layers separated by 0.3 λ
- Scintillator/brass hadron calorimeter (BH)
  - 12 sampling layers

Calorimeter Silicon Sensors



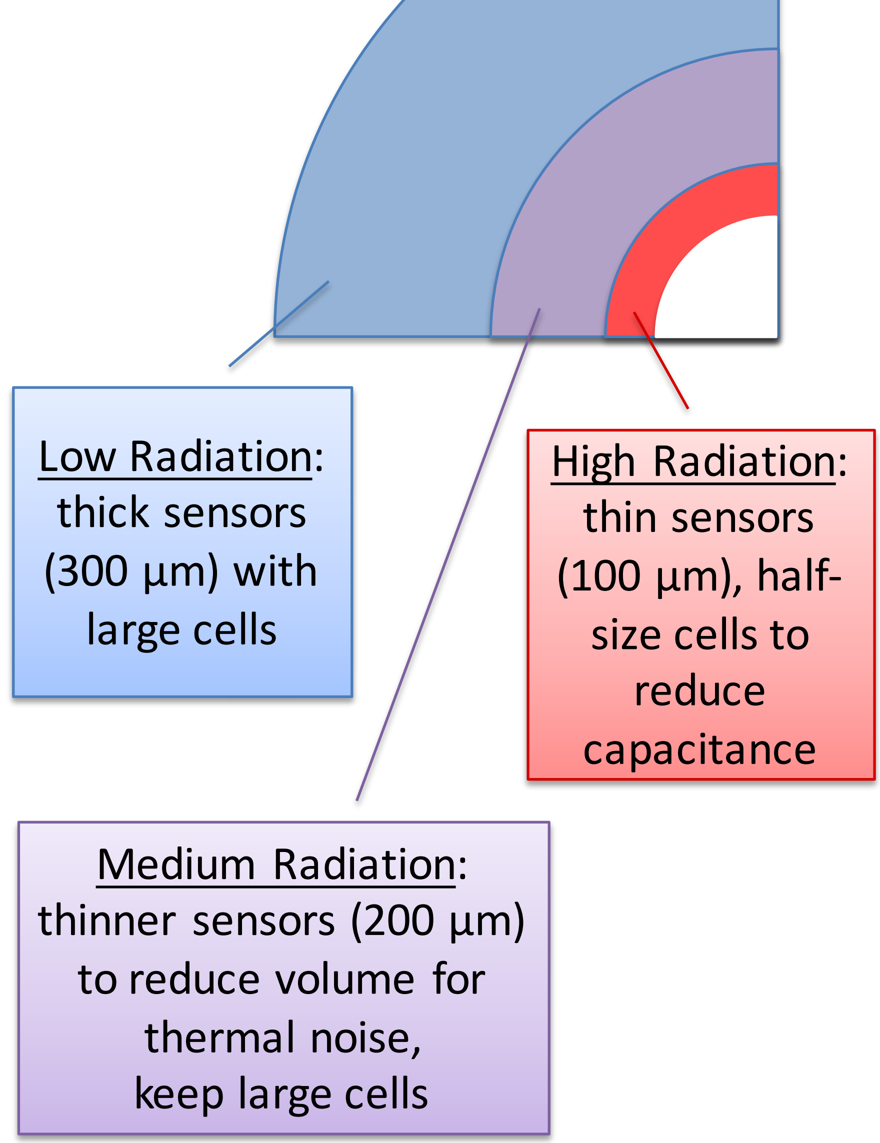


- Calorimeter sensor design is driven by balance of cost, radiation-damage and keeping pad capacitance low to control noise
  - Primary calibration/monitoring technique is based on MIP tracks in the detector
  - Three regions in detector with different active thickness (300, 200, 100 um) with 100 um sensors having smaller pad sizes



Sensor Status

- HPK 6″ 128 ch. p-on-n
  - sensors in hand @FNAL
  - FNAL 128 ch. probe card commissioned, now testing
- 6″ 256 ch. p-on-n design
  - Near final
    - Displaced pad contact enabling hole-free surface area for PCB components
- 8″ 128 ch. n-on-p
  - Finalized
    - Proceed with ordering prototypes from Infineon, HPK and Novati



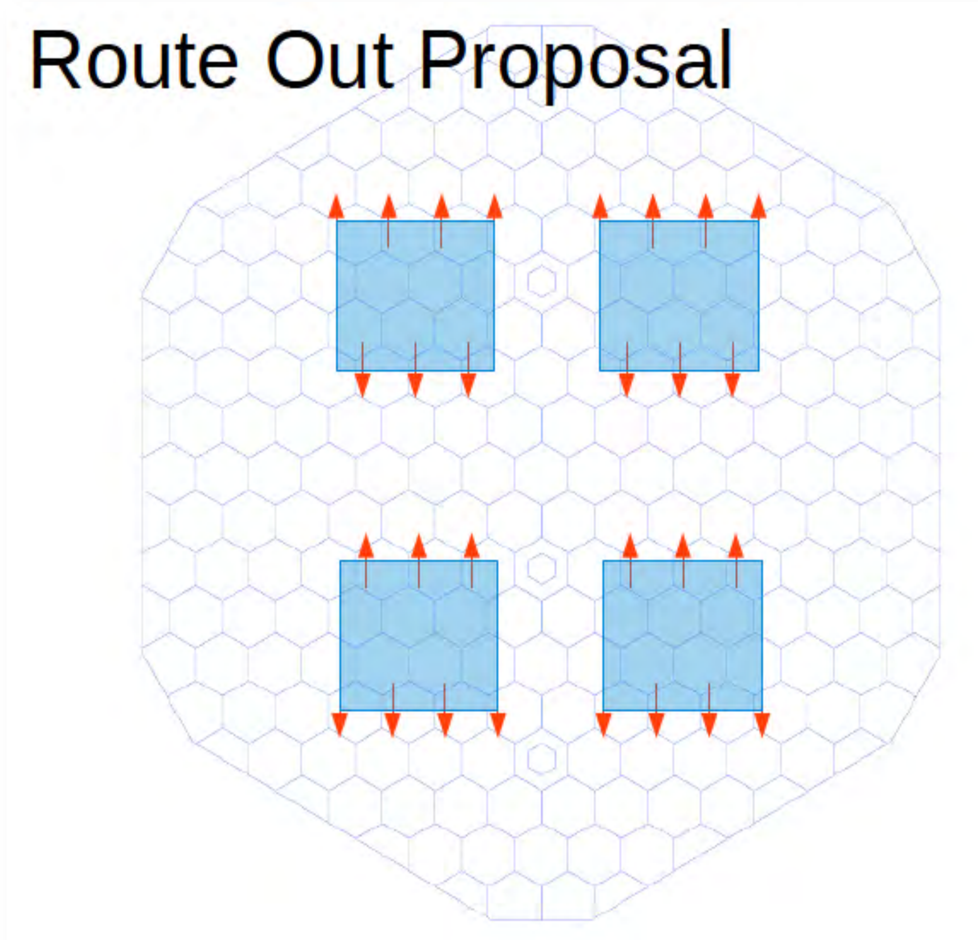
Study Noise & Coupling Capacitance for different inter-pad spacing - Sensors of 320 μm and 200 μm active thickness with 1cm^2 pads and 120 μm with 0.5 cm^2 pads

Adapted from M. Paulini – Talk at FNAL Director's review last week

Sensor news

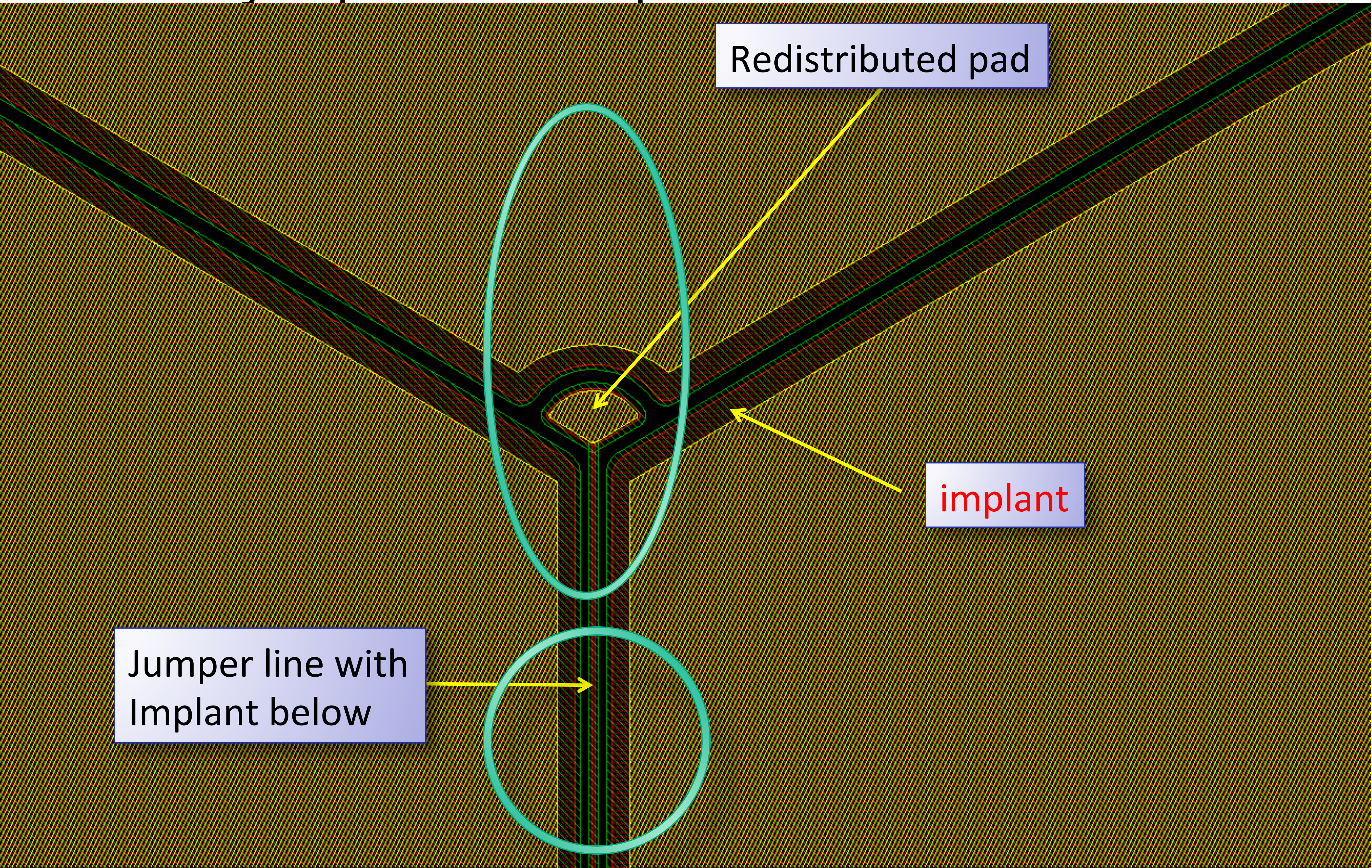
6" HPK 128 ch sensor at FNAL

- 256 ch. Sensor design with displaced pad contacts:
  - Simulations look very good!

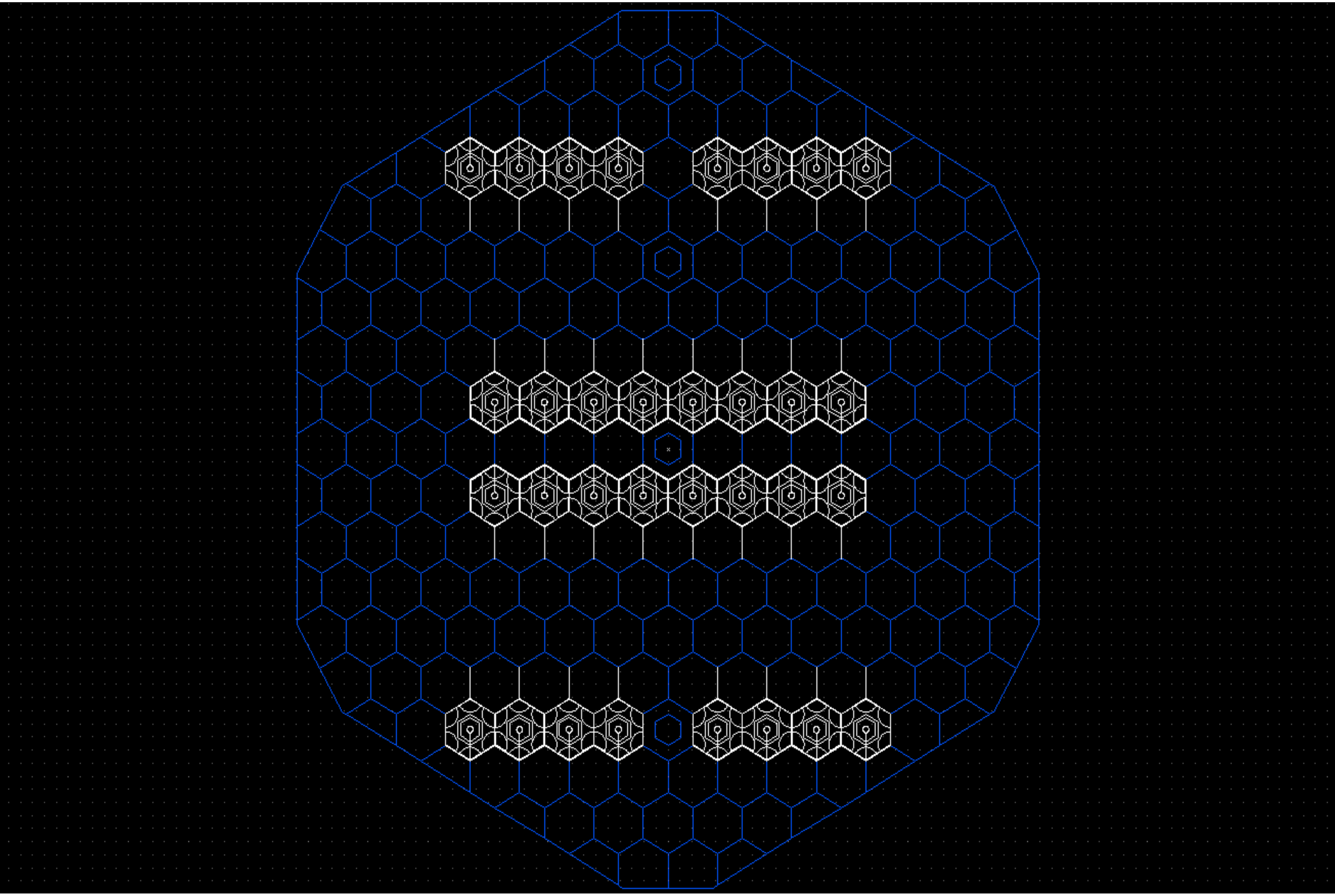


Jumper Close-up

- The jumpers have implants below the aluminum

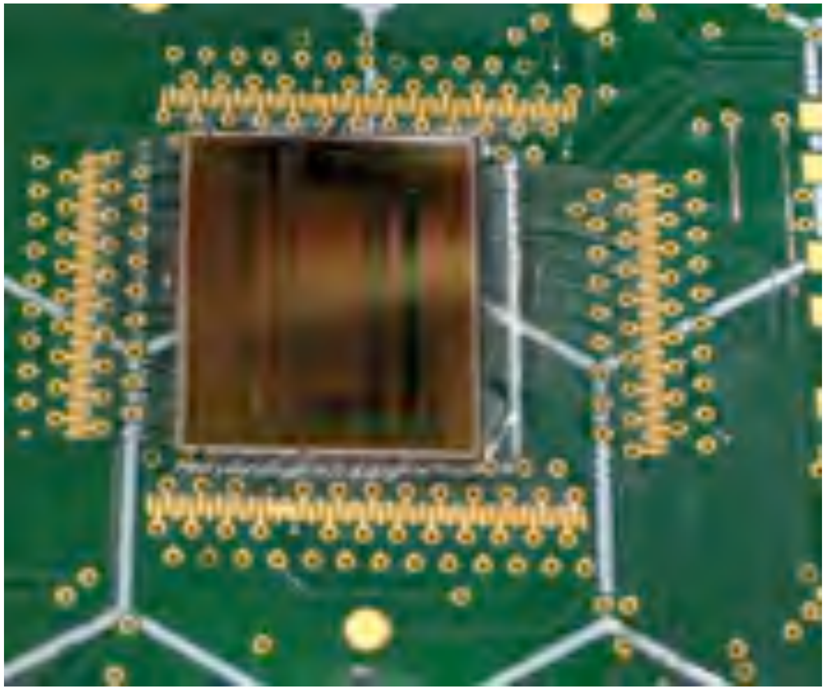


Current plan for jumper locations

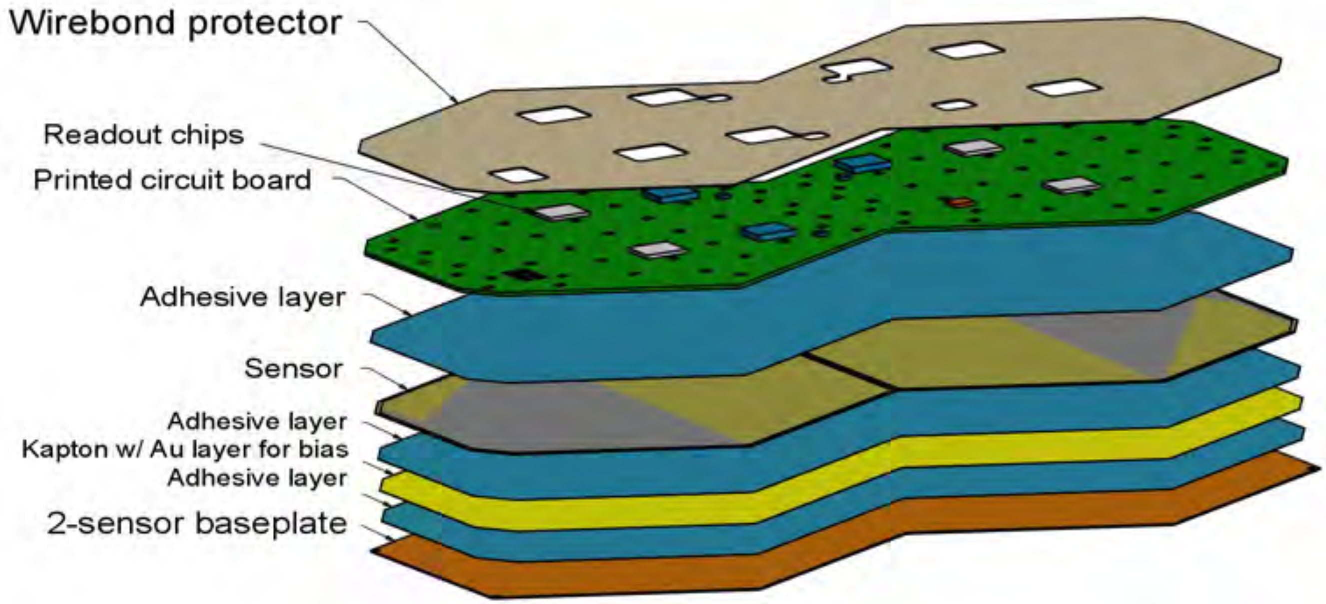


Status of other components

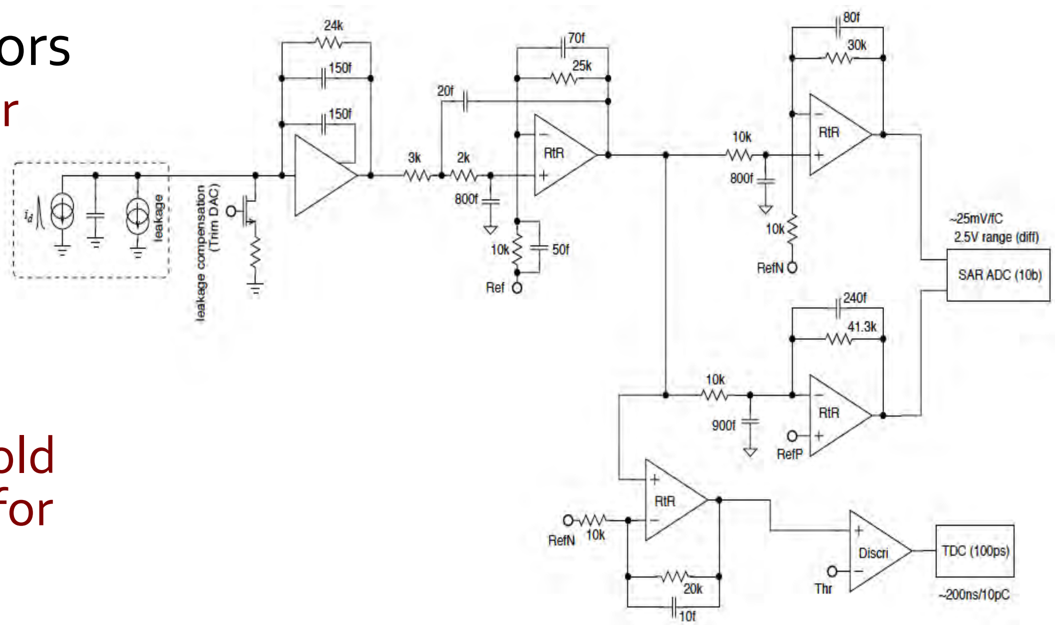
- Printed circuit board
  - 40 now being manufactured
    - Same company will load all components except SKIROCs
    - PCB will be 1.3 mm thickness (1.2 mm originally quoted)
- Other components
  - W/Cu Baseplates in hand
  - Au-plated Kapton in hand
  - Cover plates in progress
    - Using 3D CAD file of PCB with all components
    - First pieces expected end of Feb.
- Will be ready in time for test beam module production



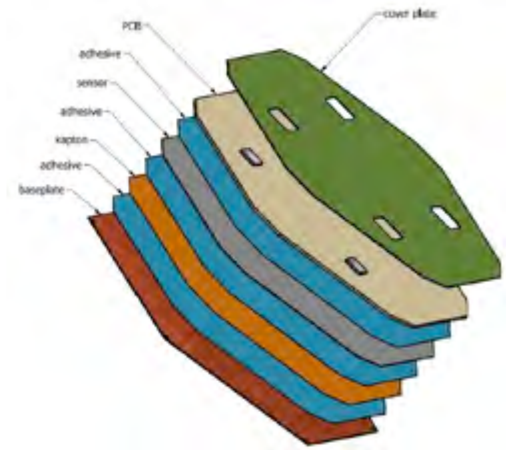
Silicon Calorimeter Modules

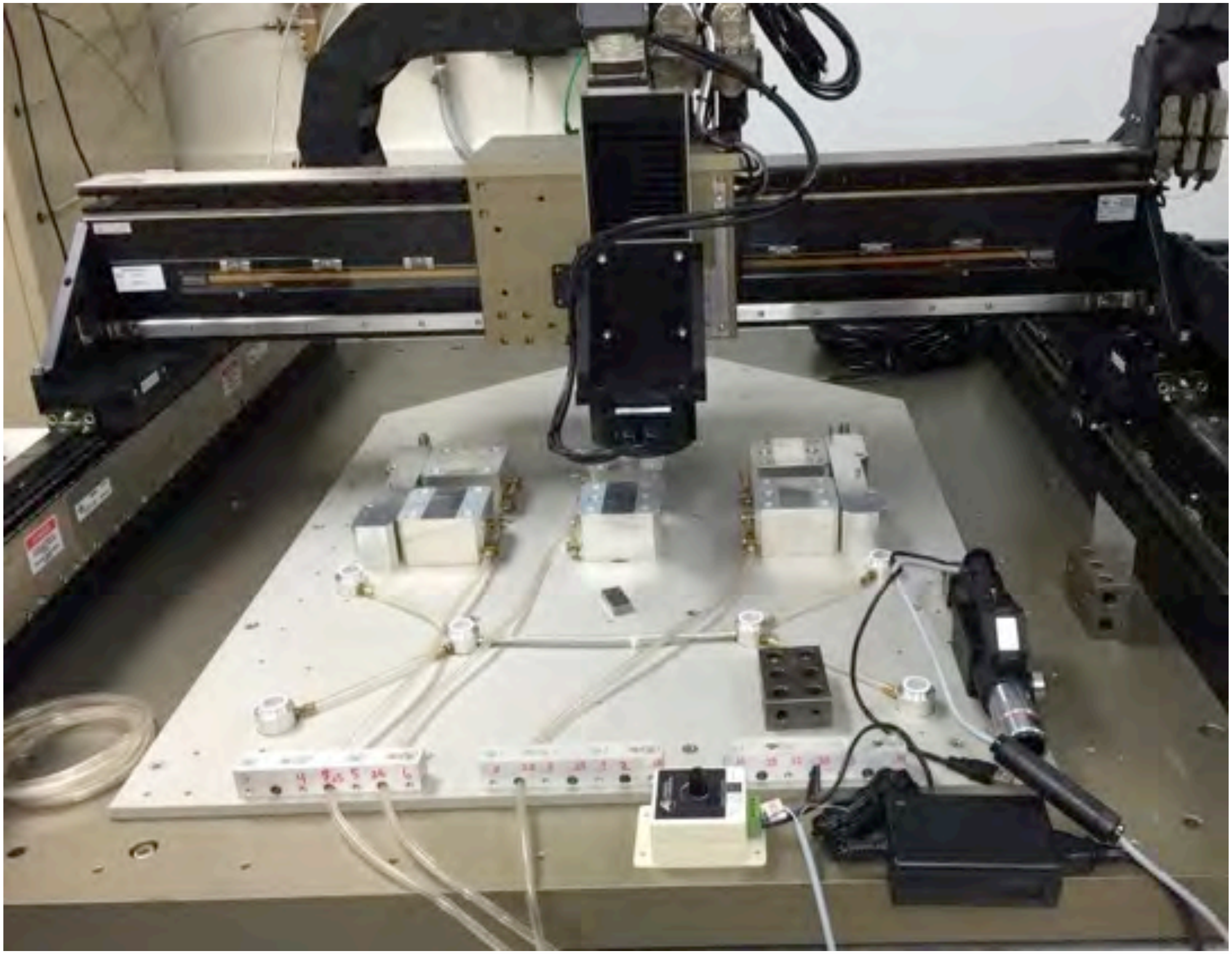


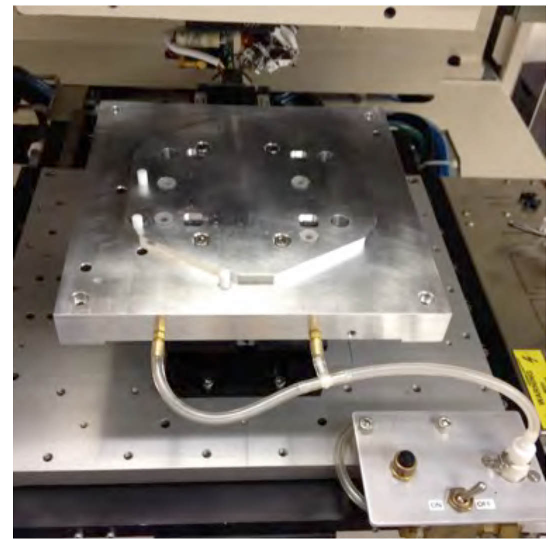
- Silicon modules combine two sensors
  - Construction simple relative to tracker modules – packaged ICs on standard PCBs rather than hybrids and HDIs
- Integrated readout chip contains trigger primitive calculation and L1 pipeline
  - Baseline ASIC uses Time-over-Threshold section and is capable of 50ps timing for EM showers



HGC Module Assembly Status





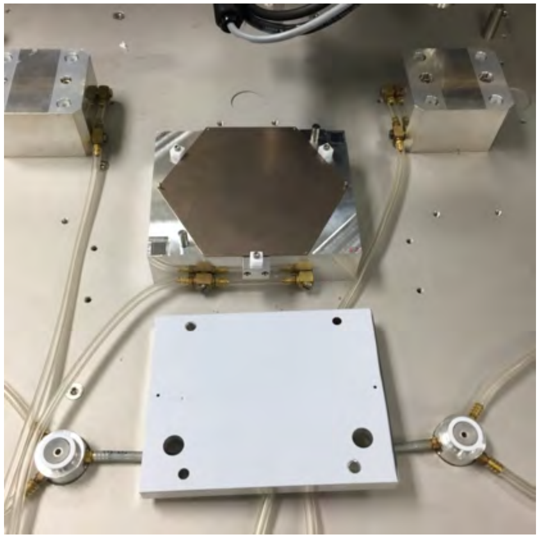


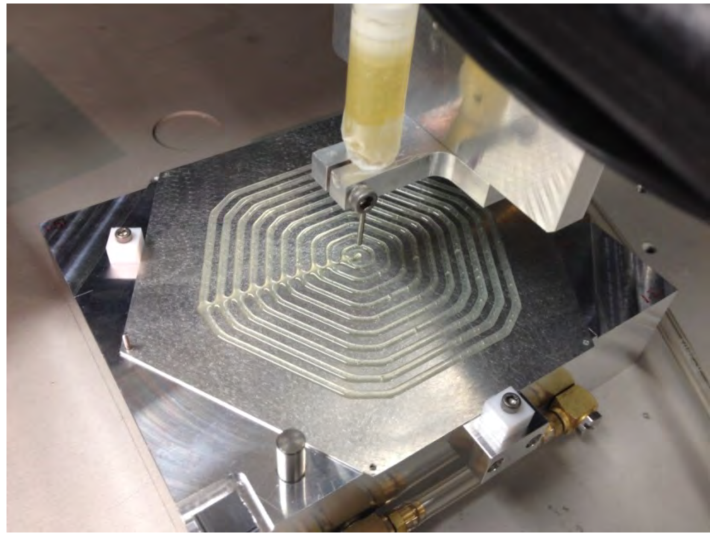
Modified 8"wire-bonding jig to accommodate 6" prototypes

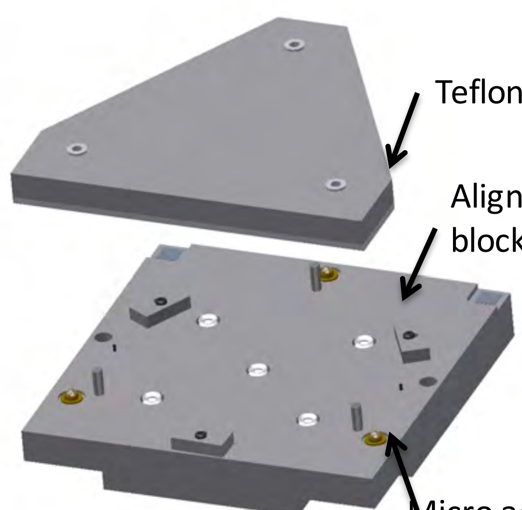
UCSB gantry refurbished, now up and running

- New LabVIEW interface: basic assembly functions being developed
- Nordson/EDF Ultimus V glue dispenser for the gantry in LabVIEW
- Full set of module assembly jigs in hand

Status of Module Assembly (1)

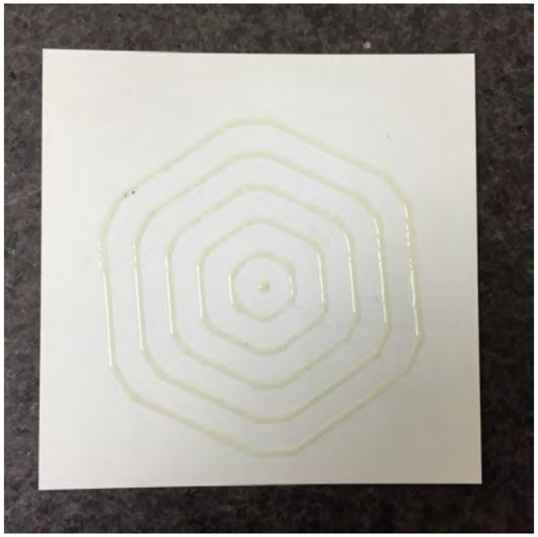


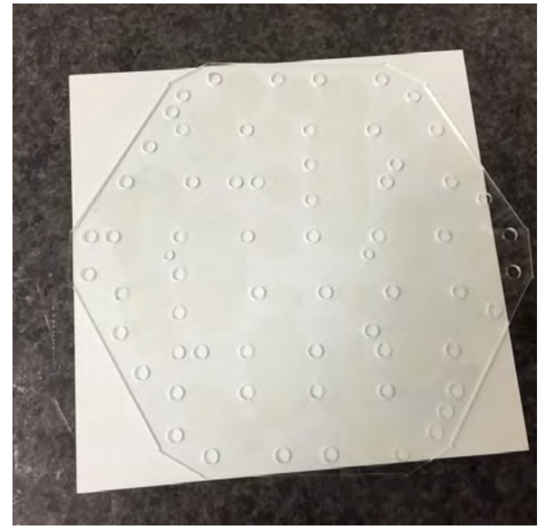


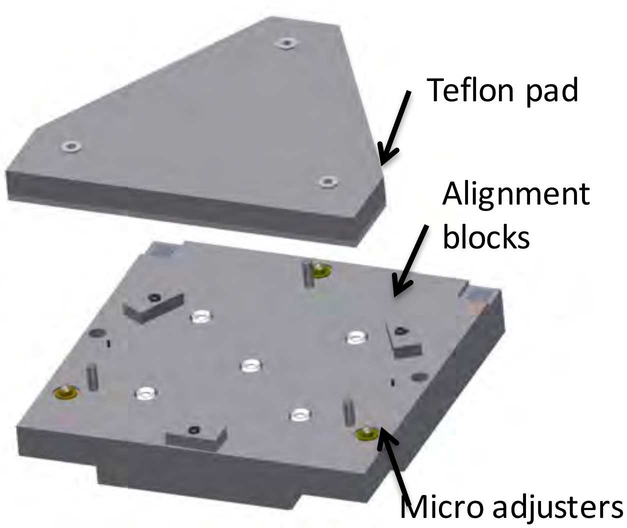


- Development of assembly and test procedures is the main R&D focus
- PCB layout work is ongoing
- Validation of epoxies and application steps are investigated for the test beam and pre-series modules

Status of Module Assembly (2)







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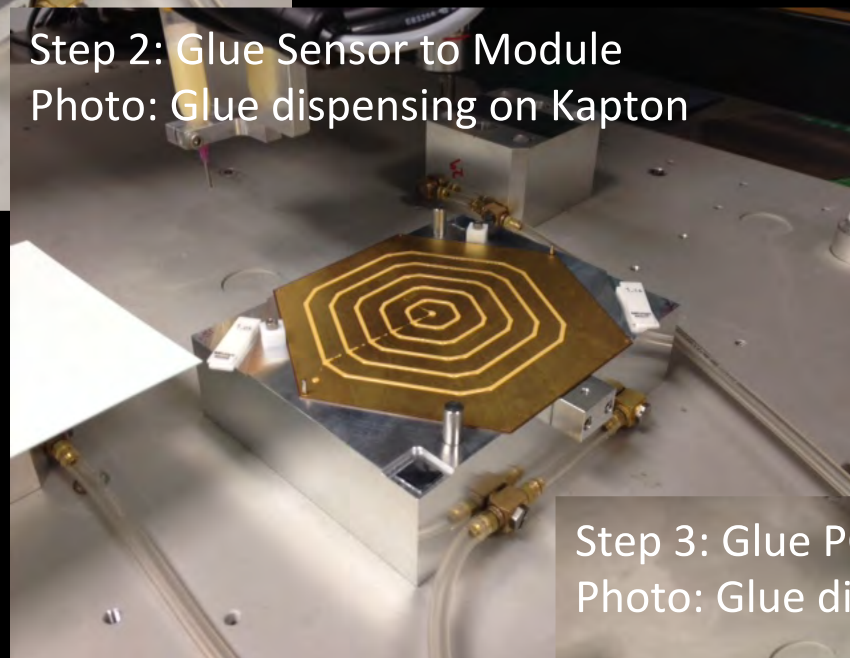
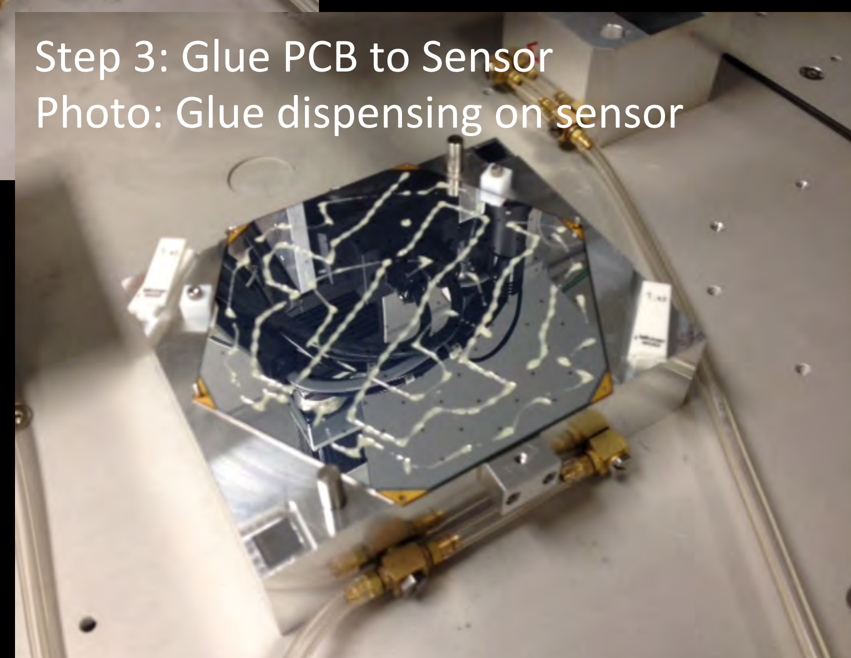
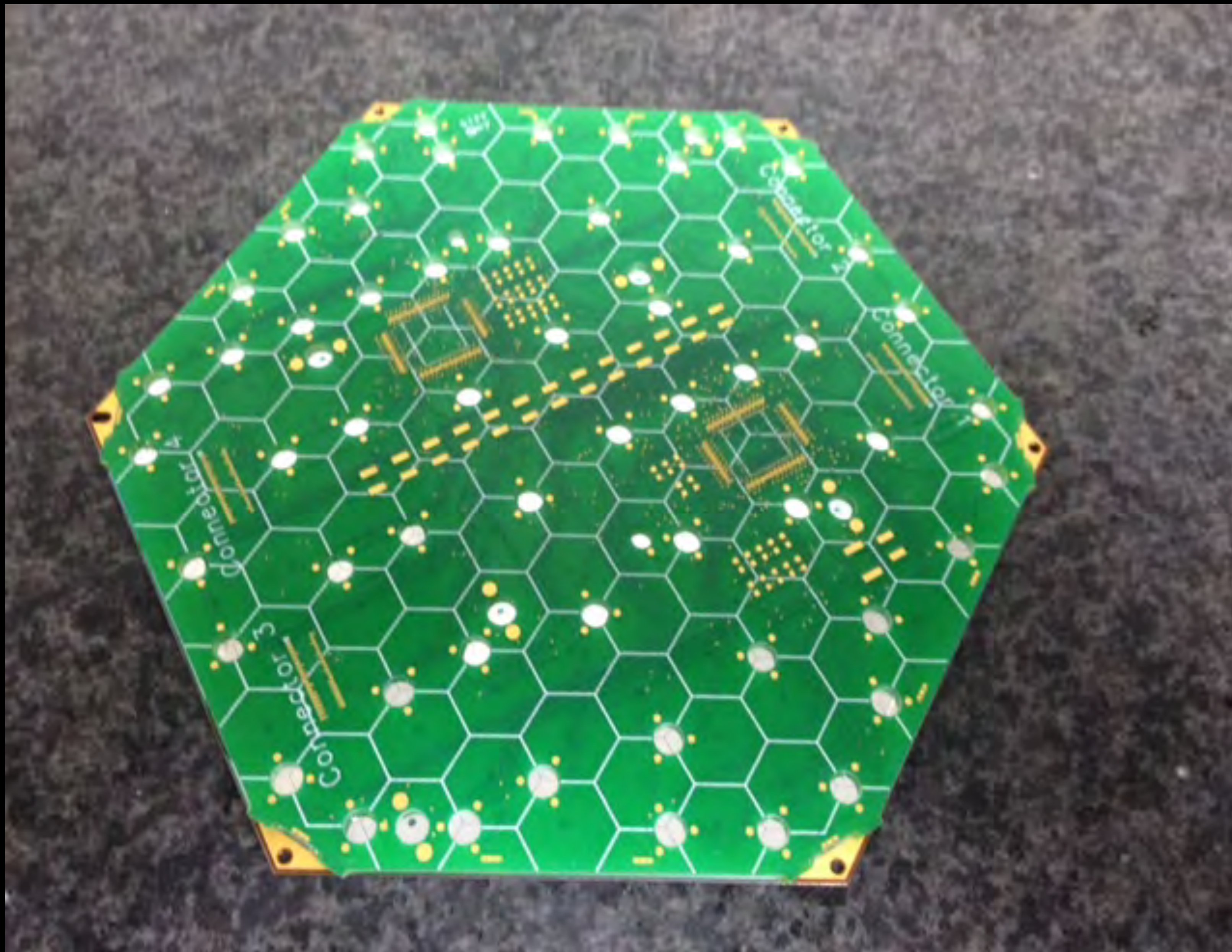
Assembly Steps

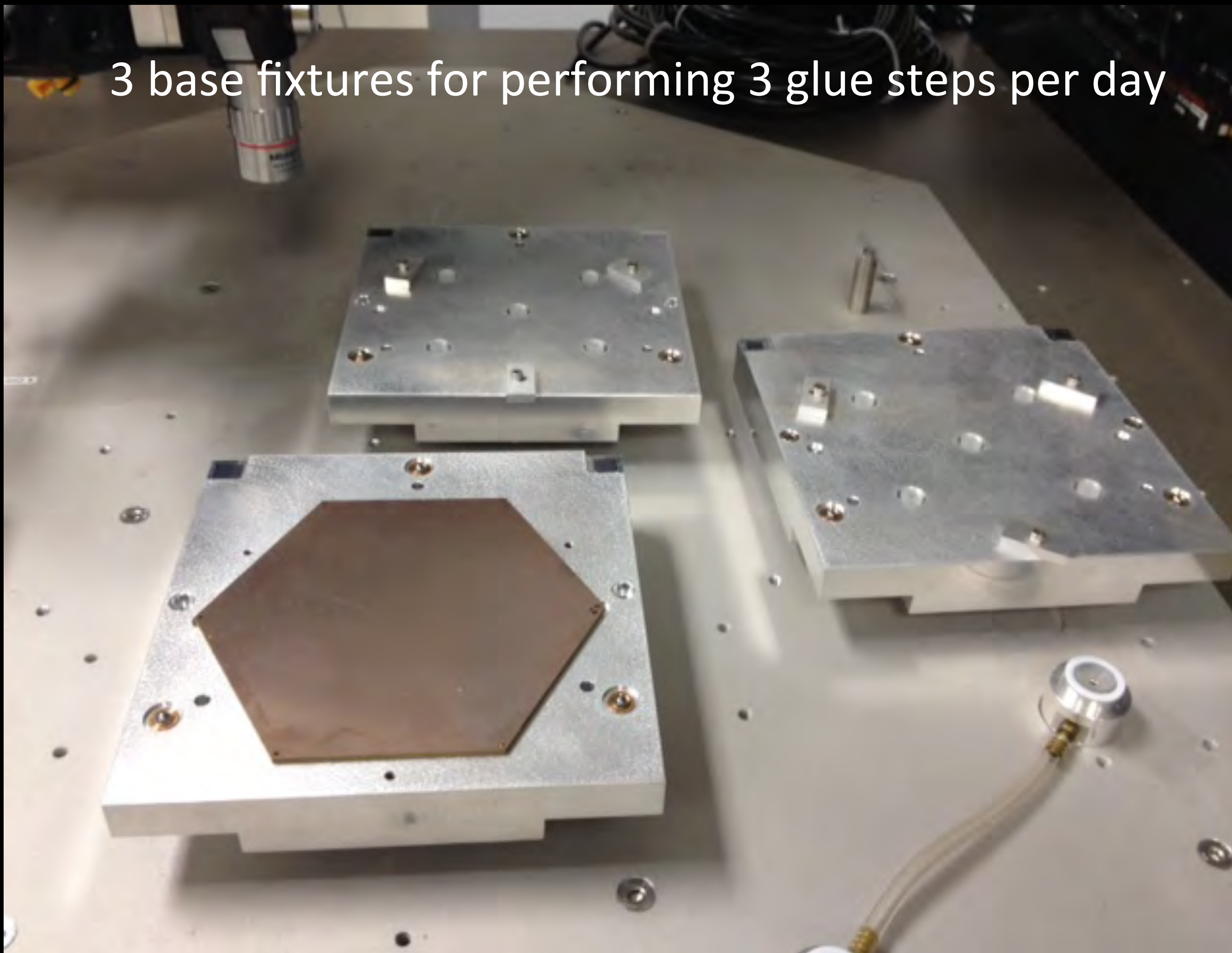




Finished (dummy) module



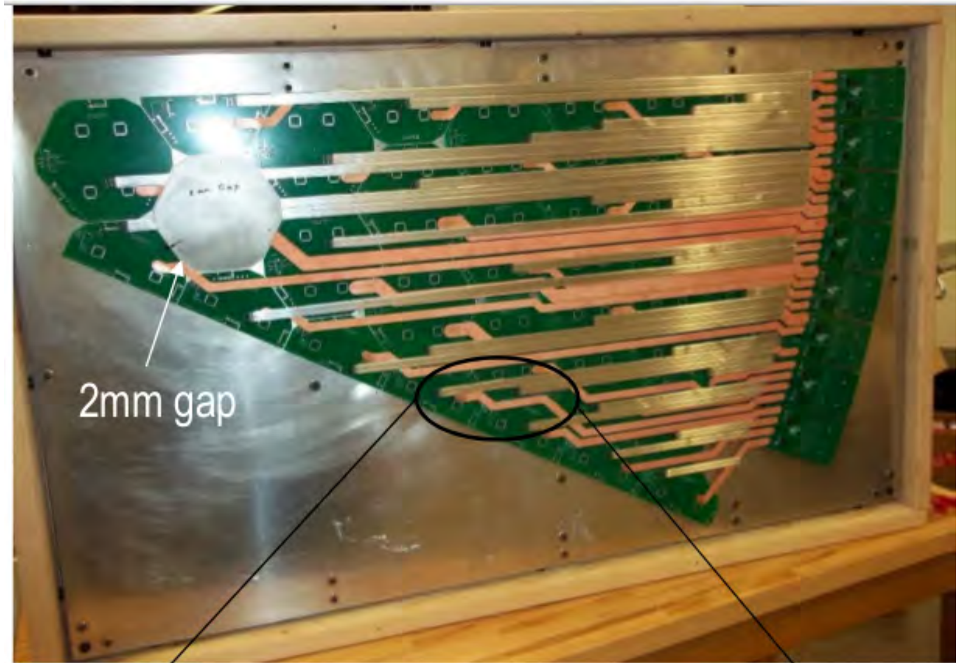
Module assembly fixtures

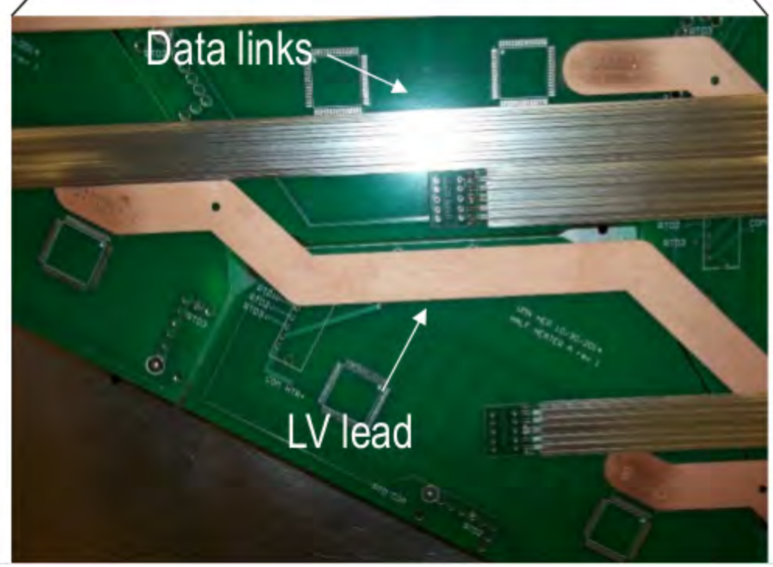


- **Current capacity**
  - 1 module per day
- **Need to double?**
  - CERN test beam schedule has advanced

Silicon Calorimeter Cassettes

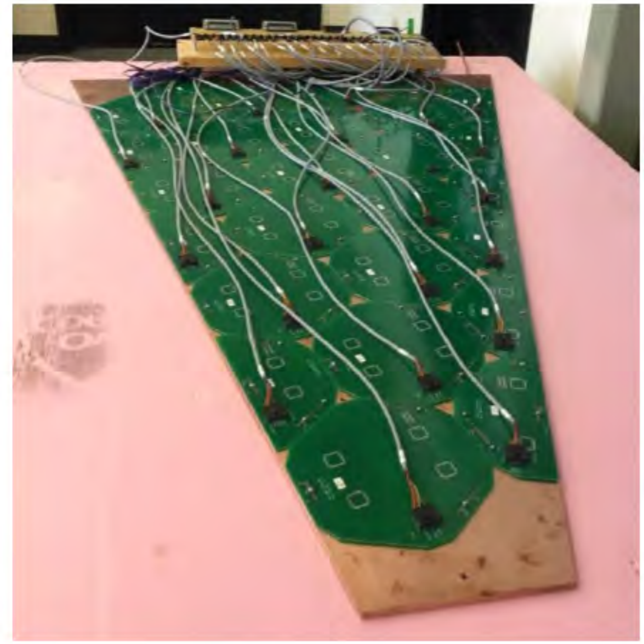
- Modules are integrated onto cassettes including CO_2 cooling pipes, PCBs which carry LV and high speed serial data streams
- Cassettes are inserted into the support matrix
  - Carbon-fiber+tungsten for EE
  - Brass plates for FH
- Cooling pipes, LV, HV, and readout are all integrated onto calorimeter which is then mounted as unit onto the CMS endcap yoke

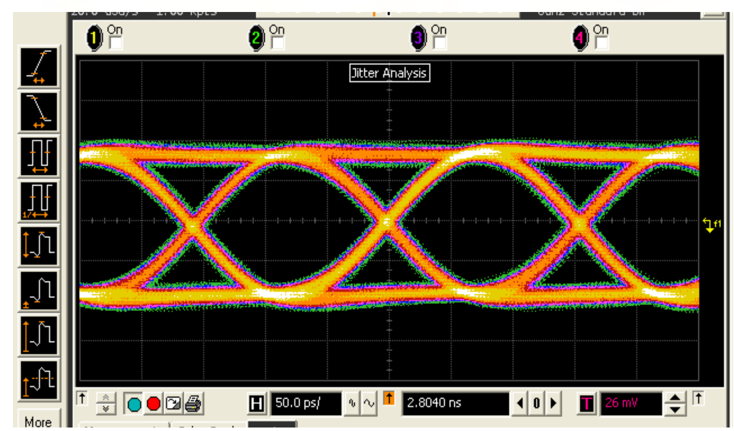




Development for Cassettes and Services

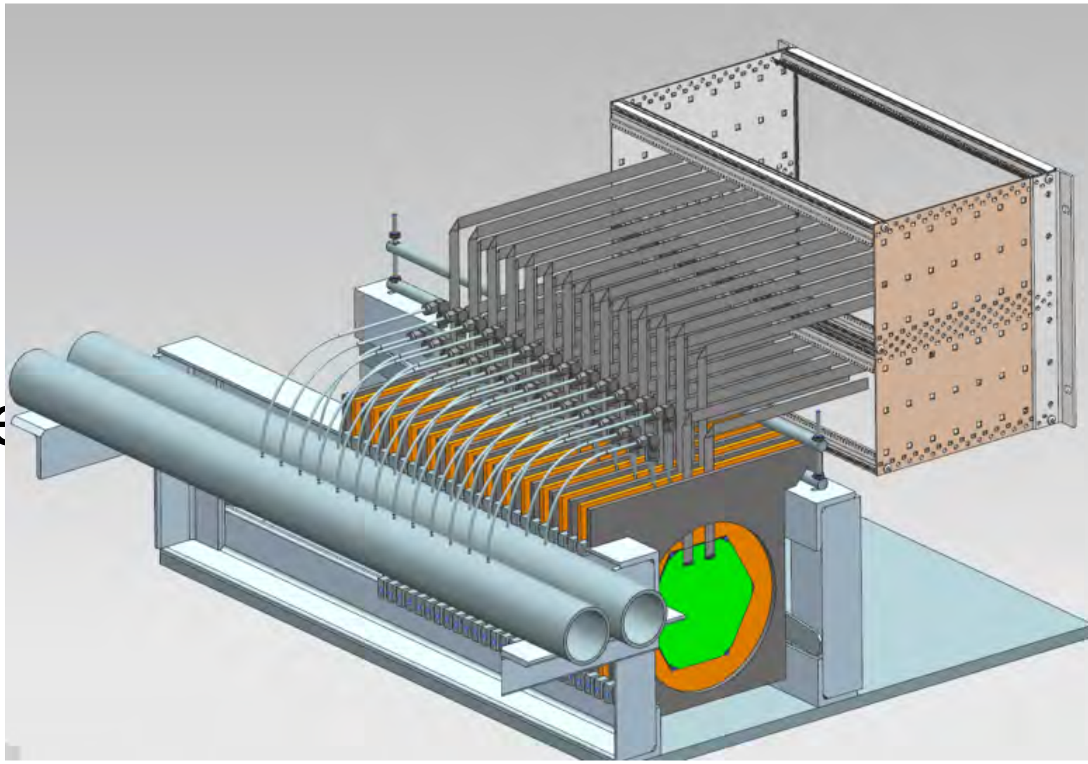
- To achieve a compact design, the cassettes should efficiently integrate as much of the services as possible
  - CO_2-based cooling including “flow-restrictors” required for system stability
  - DC-DC conversion, ideally at the edge of the cassette
  - Electrical/optical data conversion, behind the calorimeter or at the edge of the cassette
  - Services can have significant impact on design
- Cassette and services R&D will continue over the next few years leading to TDR





R & D overview

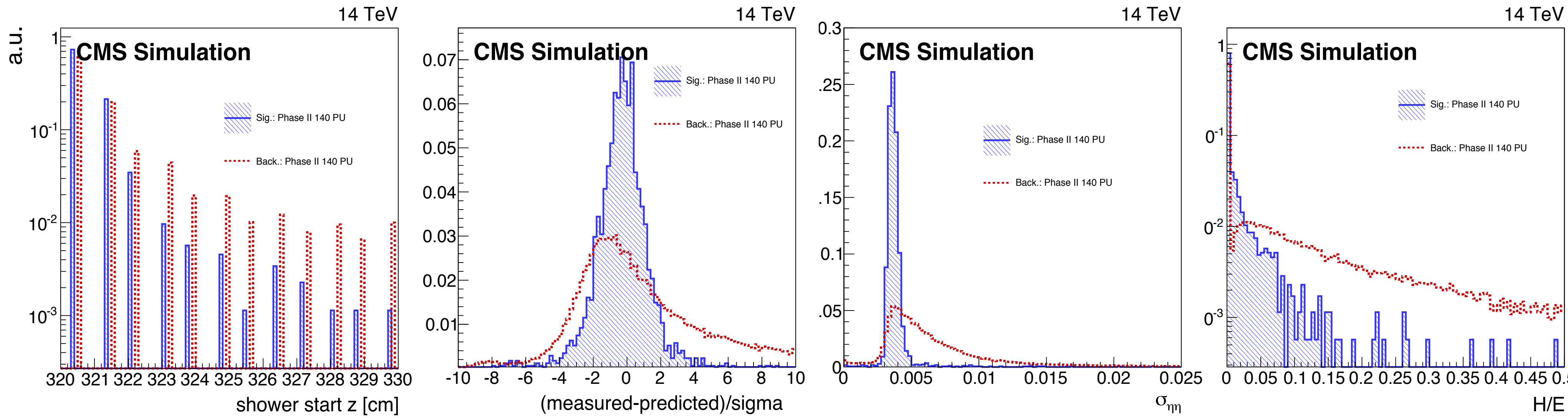
- Silicon calorimetry has been extensively studied in the ILC context by the CALICE collaboration and others
- For use in the HL-LHC environment, radiation and readout challenges must be addressed
  - Dedicated radiation studies have demonstrated the sensor functionality to the necessary fluence
  - Performance in a calorimeter will be tested in a series of beam tests beginning in the winter
- Radiation tests for scintillator technology are ongoing (low dose rate is essential for reliable results



The end

HGC e/γ new ID information, new ID variables

Shower start | Length compatibility | η width | H/E



Signal (blue) - background (red)

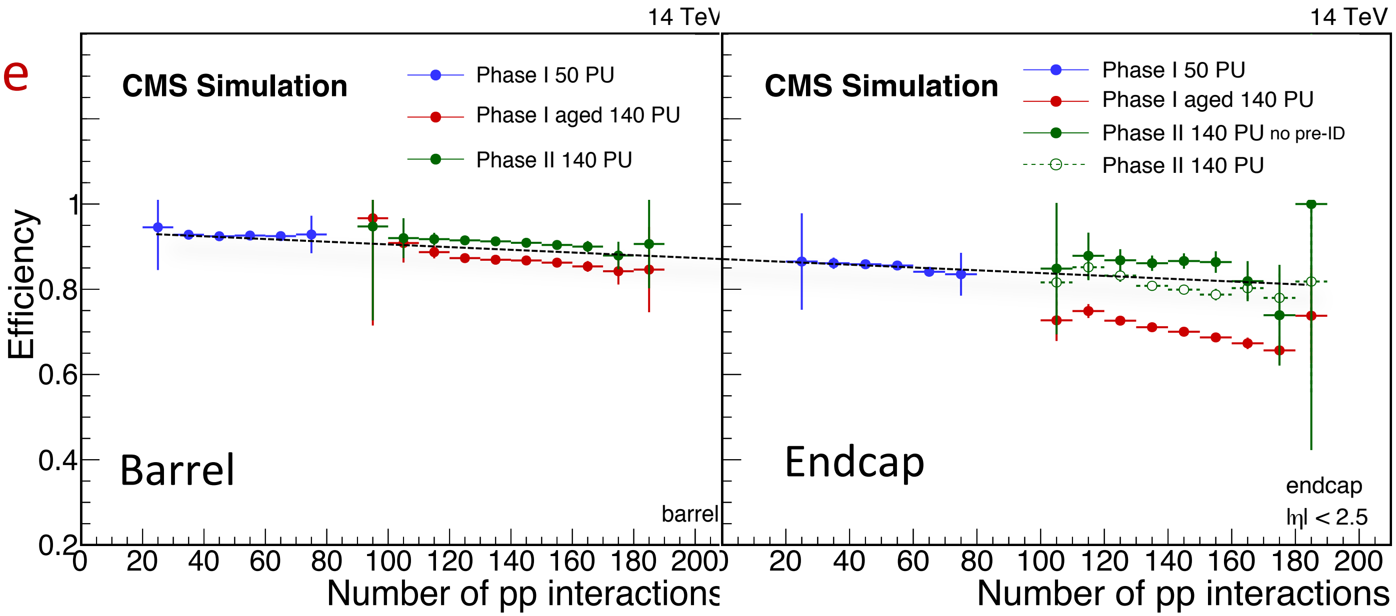
- And to mitigate PU use trans. granularity - cells in ≤ $1.5R_M$ - H/E in tight cone 0.05

**CMSSW software developments are at a very early stage, clustering, link to charged tracks and PU mitigation potential at layer level is far from being fully exploited in current studies*

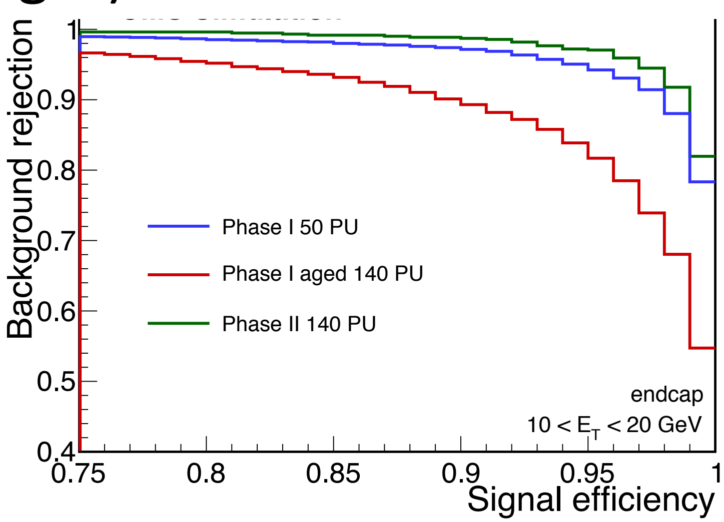
Electron and Photon performance

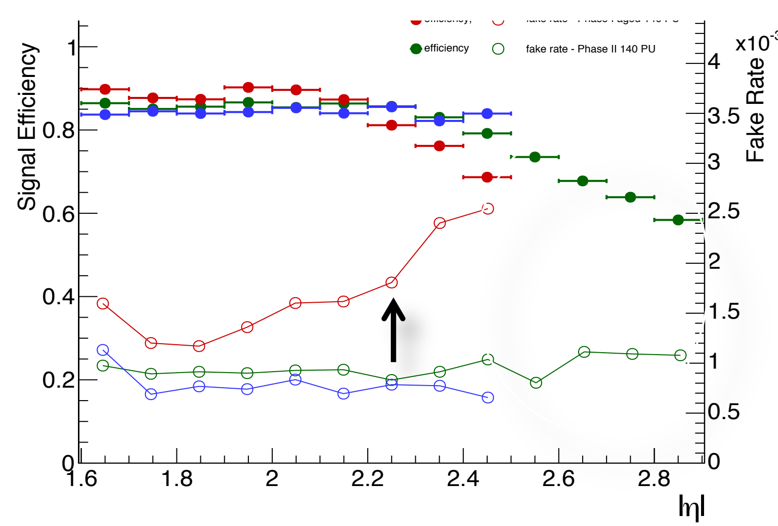
- Electron efficiency recovered with smooth decrease up to 200 PU

Z→ ee



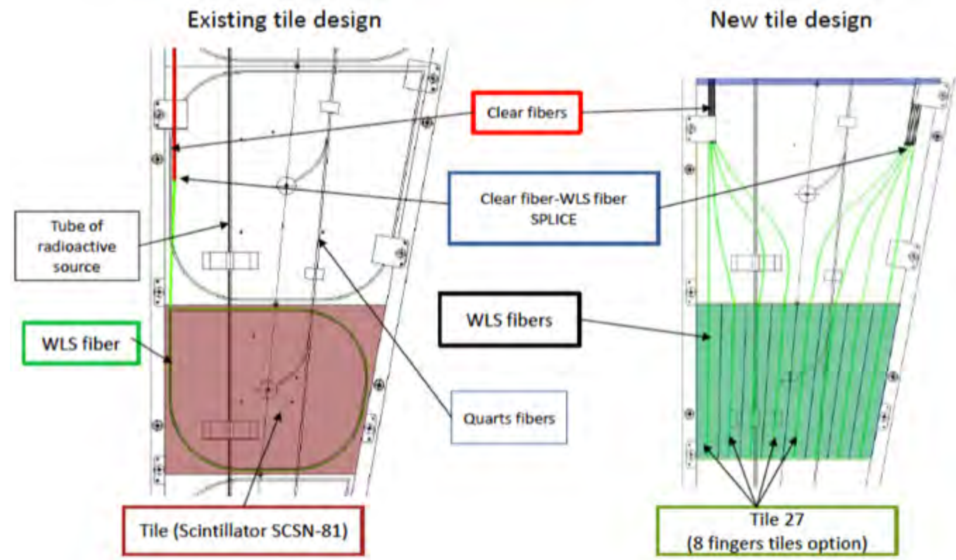
- BDT efficiency for DY electrons and for Jets (left) and BDT efficiency for γ and Jet fake rate for a WP at ≃ 85% efficiency (right)

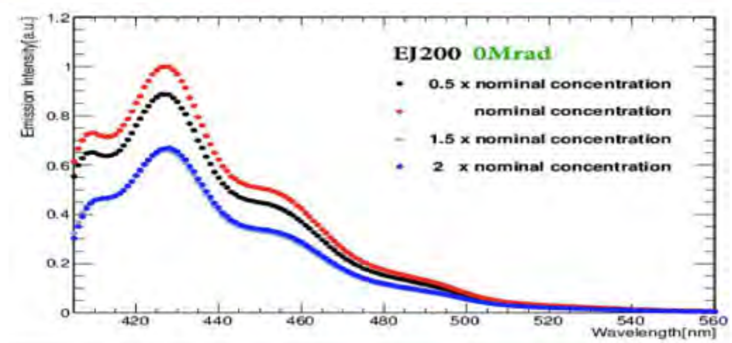


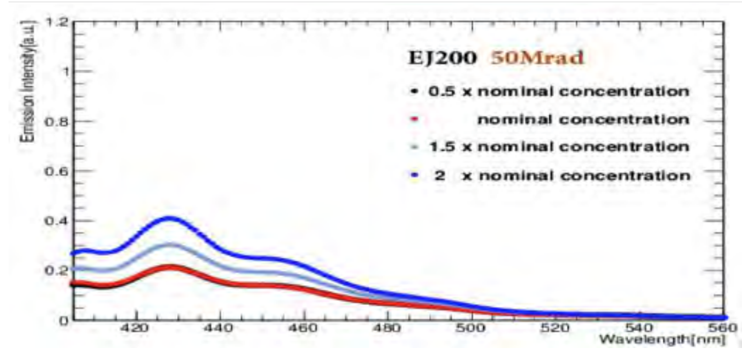


Backing Calorimeter

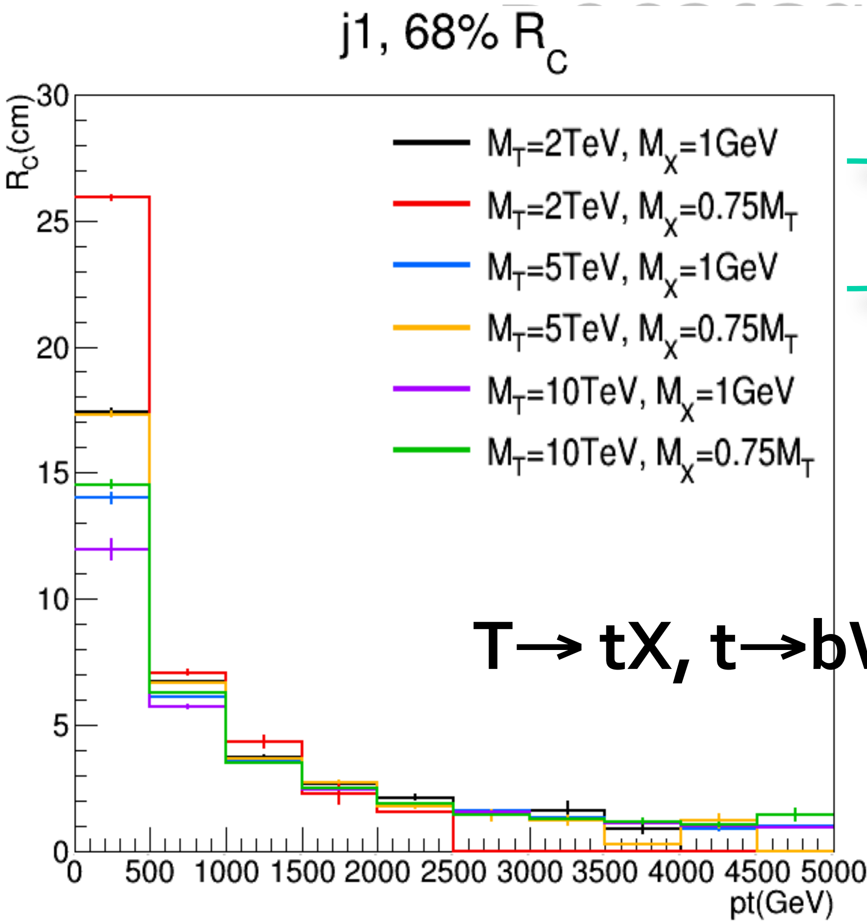
- Backing Hadron Calorimeter can be constructed quite similarly to existing HE: plastic scintillator tiles with WLS readout
  - Expected radiation dose is reduced by FH calorimeter absorbing the first 5 λ
  - Active materials with better radiation tolerance will be used
- To limit the duration of LS3 and simplify mechanics design, construct new electronics heavily based on Phase 1 upgrade which can be integrated with overall calorimeter construction





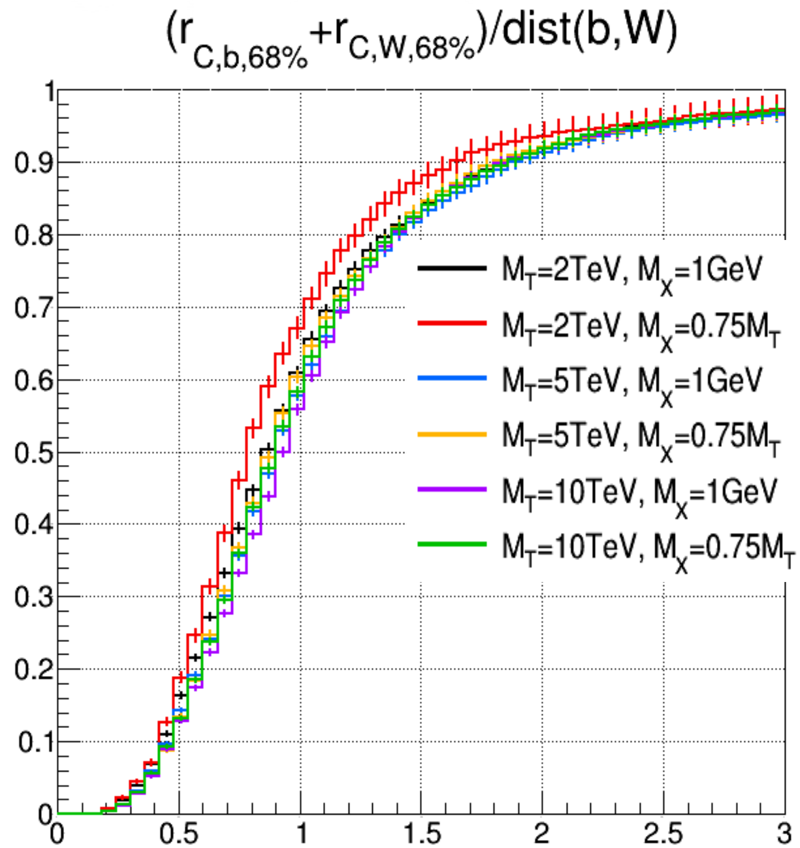


Boosted Objects: Substructure*



LHC

T→ tX, t→bW→bqq'



- Containment of 68%
  - Jet radius is a few cm for parton p_T above 500 GeV
- Compare size to separation
  - Sum of radii at 68% containment of b and 'W' daughters, over b-W separation:
    - Large overlap independent of mass
      - But relevant distance scale falls dramatically with p_T (see plot at left)

*From studies for 100 TeV pp collider

And 100 TeV