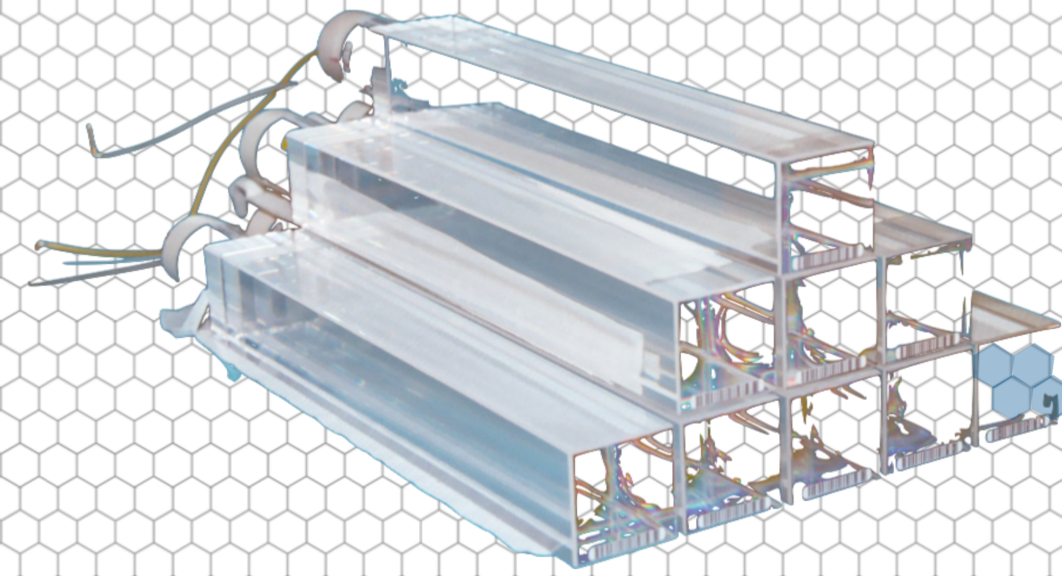
Arabella Martelli (CERN)



CALORIMETRI FASE 2

Performance e impatto sulla fisica

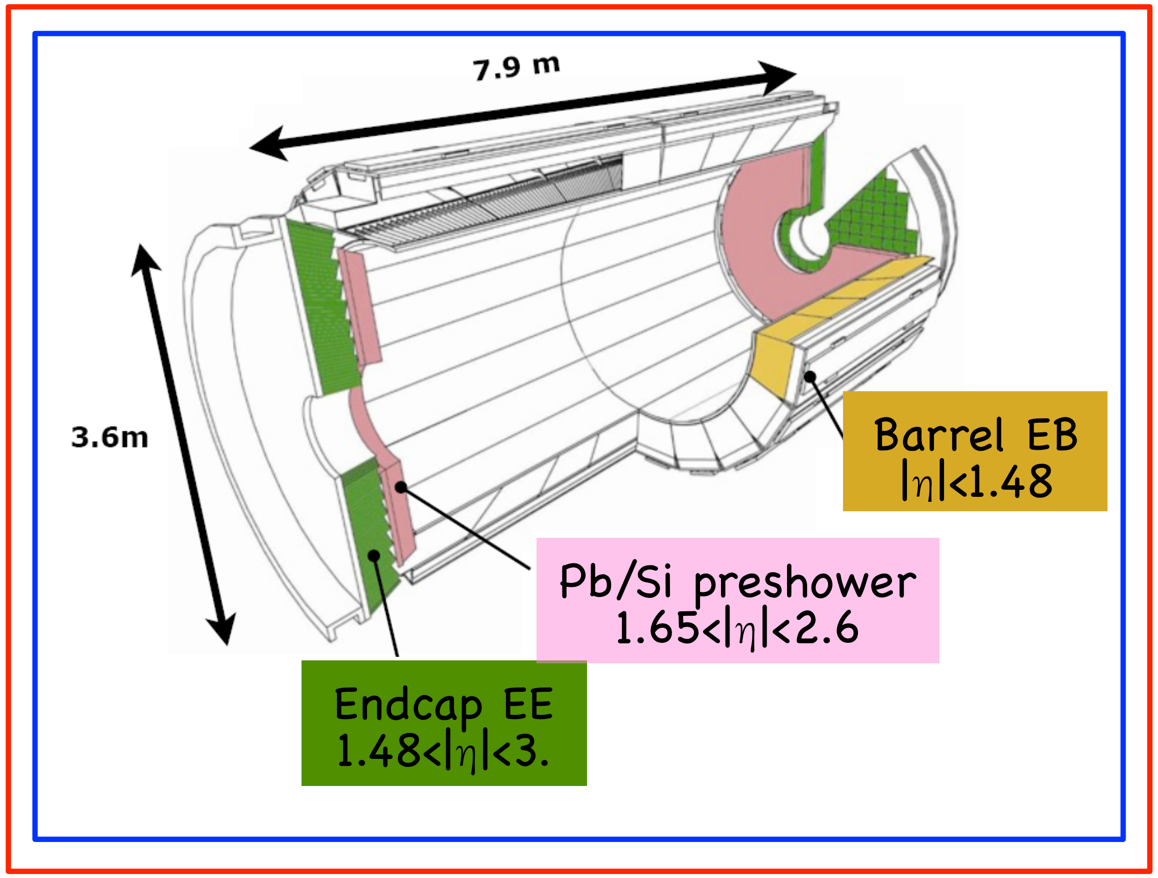
CMS Italia 2017

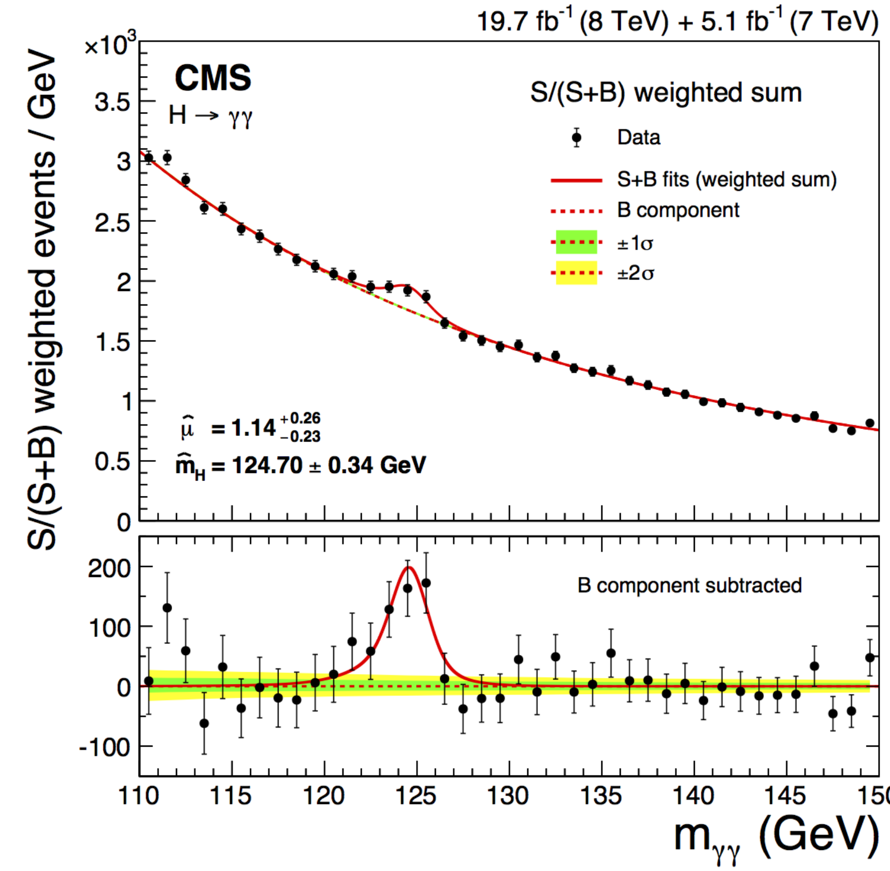
29 November to 01 December 2017 - Piacenza

Calorimetry from Phase1 to Phase2

- **Crucial role of calorimeters for physics in Phase1**

  => energy resolution for H$\gamma\gamma$ benchmark channel





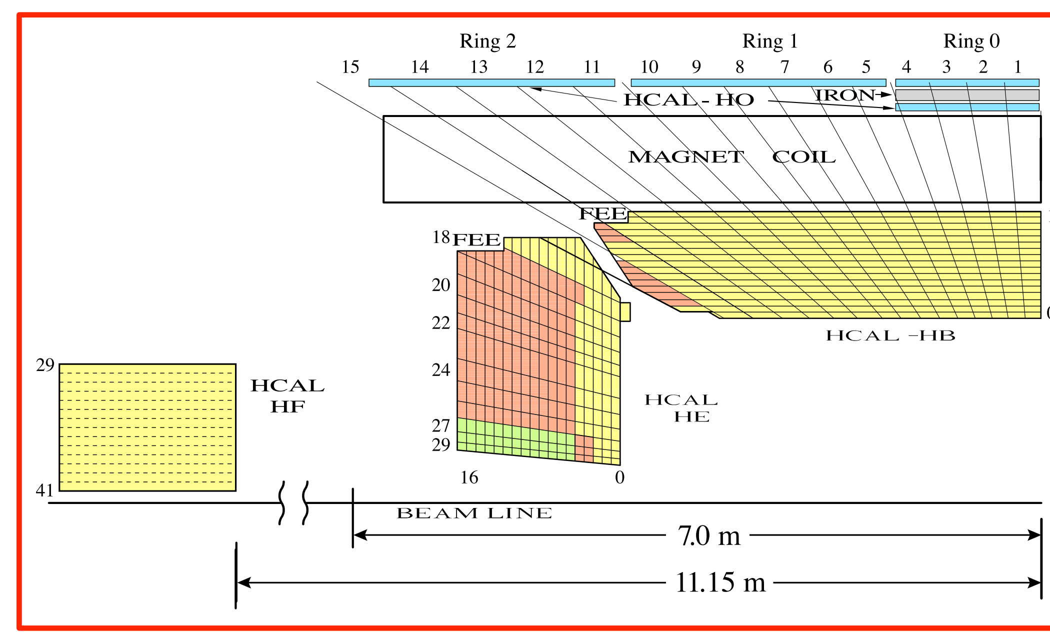
- Important also for electrons, Jets, MET

  => acceptance, trigger, reconstruction, ID

  => to be exploited in combination with tracker info

  - Key elements for Physics in Phase2

    => likely more important than providing excellent energy resolution



Physics in Phase2

- **Ingredients to pursue searches and precision SM measurements**
  - **boosted topologies => increase granularity** for reconstruction/ID of collimated objects
  - **forward boosted production => good performance at high η** coverage/reconstruction/ID/resolution + complement tracker upgrade (|η|<4 and reduced material budget)
  - **exploit VBF production => jet reco/ID also at trigger level**

- **High luminosity**
  - **high pileup => need clever ideas to select good events** in harsh HL-LHC environment
  - **higher rate => refurbish triggers** (hardware and software) to profit from more data
  - **high radiation => rad hard technologies**

- Overall CMS upgrade plan to achieve the goal
  => tracker + muon chambers + precision timing (see previous talks)
  - calorimetry: discussed here

The calorimetry upgrade program

- Physics requirements for operation at high luminosity drive the upgrade choices
  => Maintain Run2 performance also at HL-LHC + improve (where possible)

- Assure radiation hardness of components
  => **replace damaged detectors** (EE + ES + HCAL endcaps)
  => **operate EB colder** to reduce APD noise (18 °C to 9 °C, option for 6 °C)
  => **SiPMs in HCAL barrel** to replace HPDs

- Account for high demanding L1: 12.5μs latency and 750kHz rate
  => new on-detector and off-detector electronics

- **Exploit precision timing**

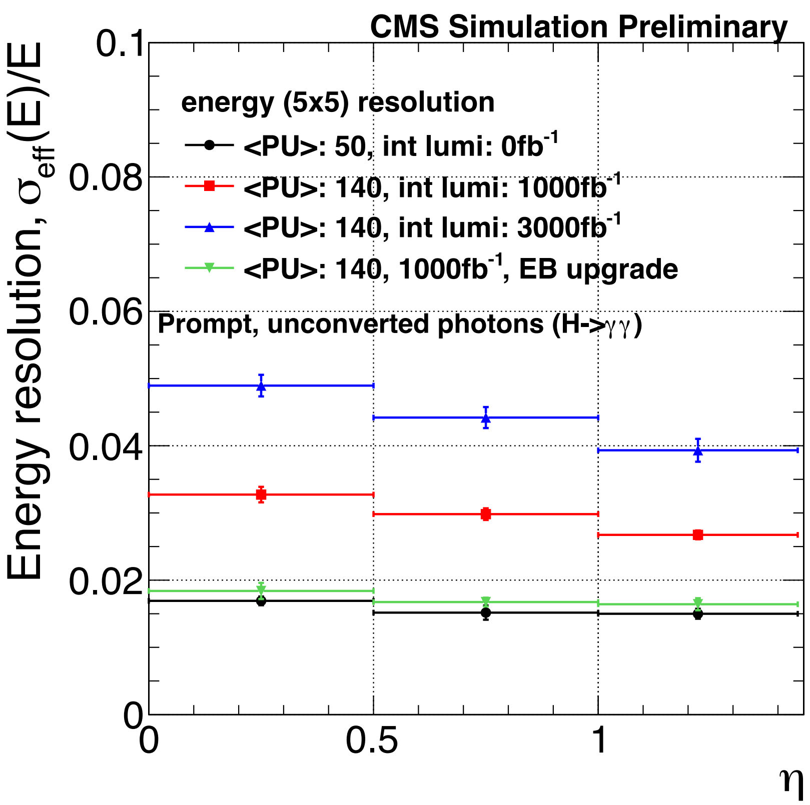
- **Increase granularity**

- Phase2 detector upgrade, both a challenge and an opportunity

ECAL BARREL for Phase2

- New electronics and operation at lower temperature (same crystals, same APDs)

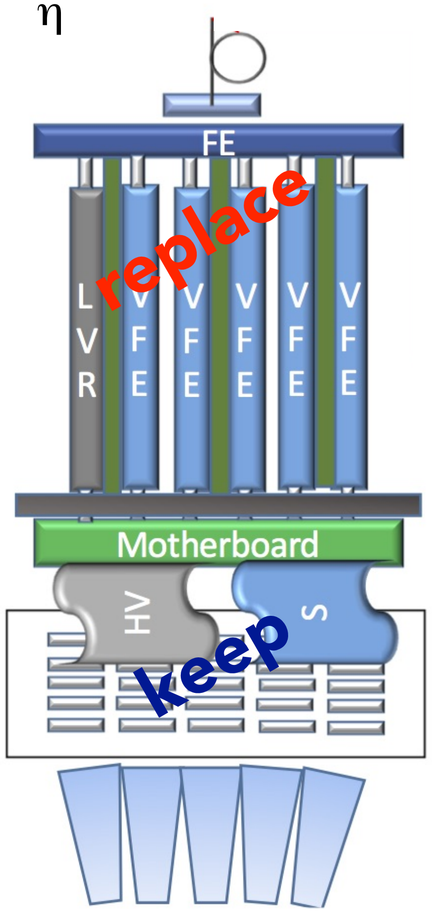
  => with upgraded detector,
  maintain good energy resolution
  at high PU and 300fb^{-1}



- **Main element is the upgrade of the electronics: FE and VFE**
- **Phase1: VFE preamplifiers provide shaping of signal & digitization**

  => Replacement with trans-impedance-amplifiers (TIA)
  - Digital design focused on achieving optimal time resolution
  - Two gain ranges (G1,G10) & 2 TeV dynamic range with 50 MeV LSB
- **Phase1: FE providing TPG with 5x5 crystals granularity**

  => FE moved off-detector



- Baseline for upgrade studies: adopt same reconstruction as in Phase1

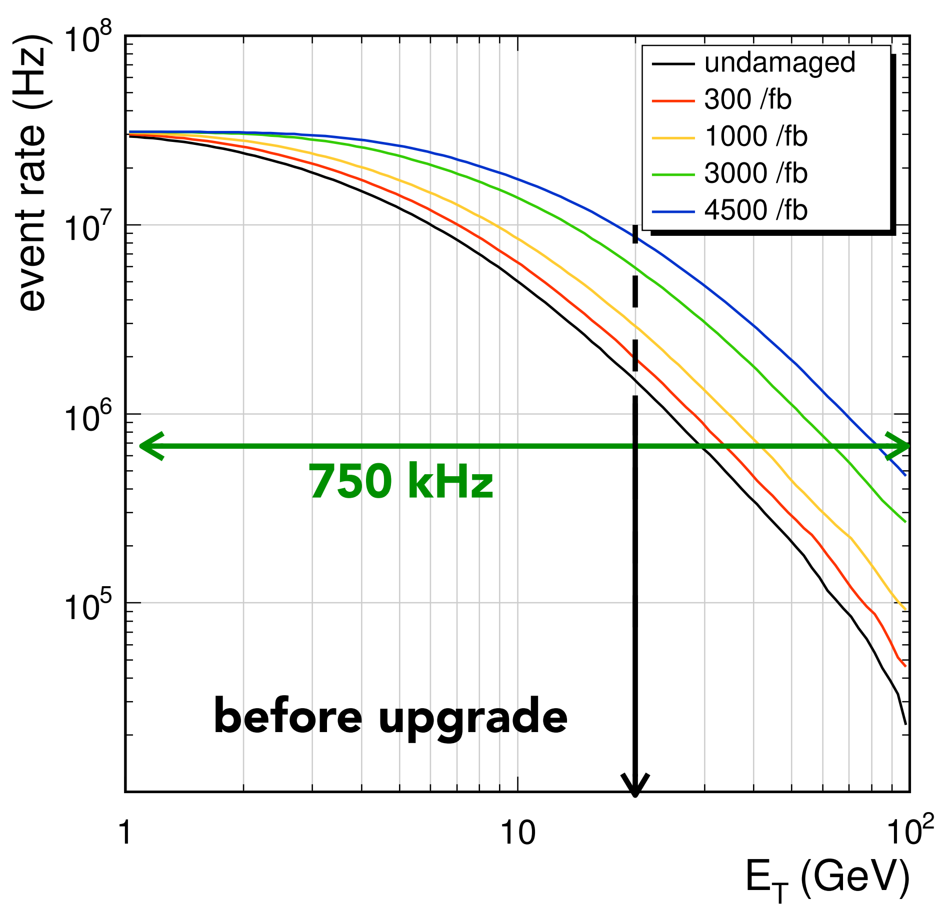
  => optimisation needed for PU mitigation and integration in particle-flow

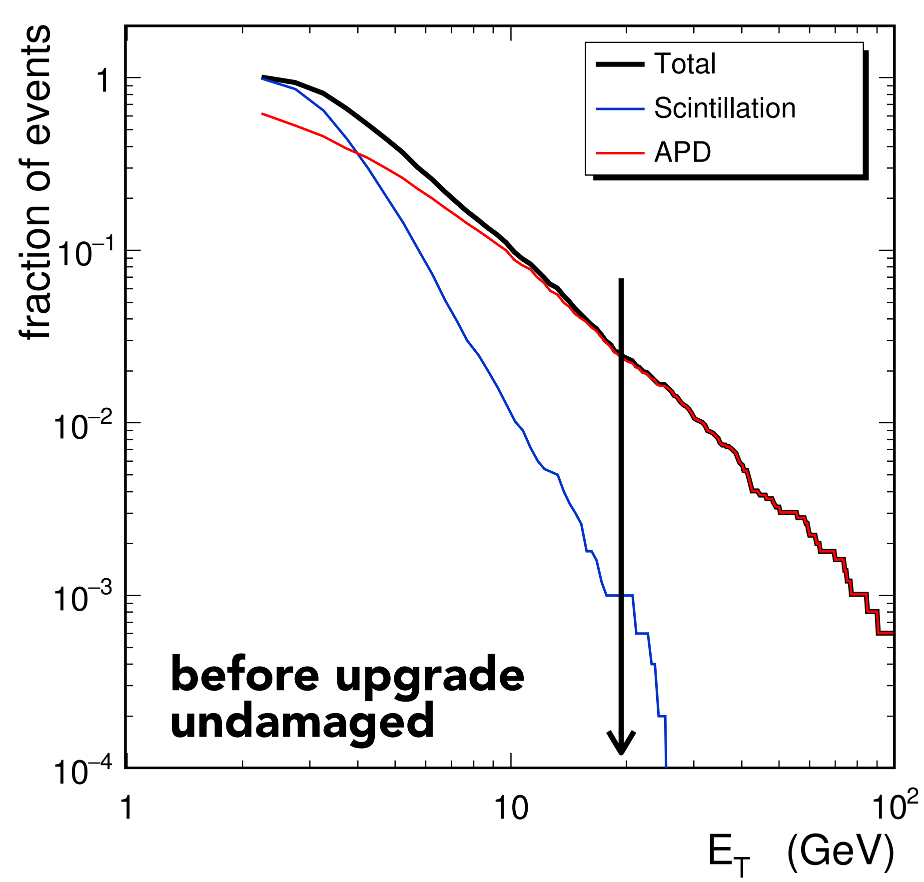
APD spikes in EB

- **Phase1: VFE preamplifiers provide shaping of signal & digitization**

- Opportunity to **improve the spike rejection online** and offline
  => rate from APD spikes already critical during current operations

- Projection at 200PU with Phase1 VFE electronics (43ns shaping time)
  - rate above max threshold for E_T > 20GeV
  - rate dominated by "spikes", scintillation (genuine signal) contribution at permill level



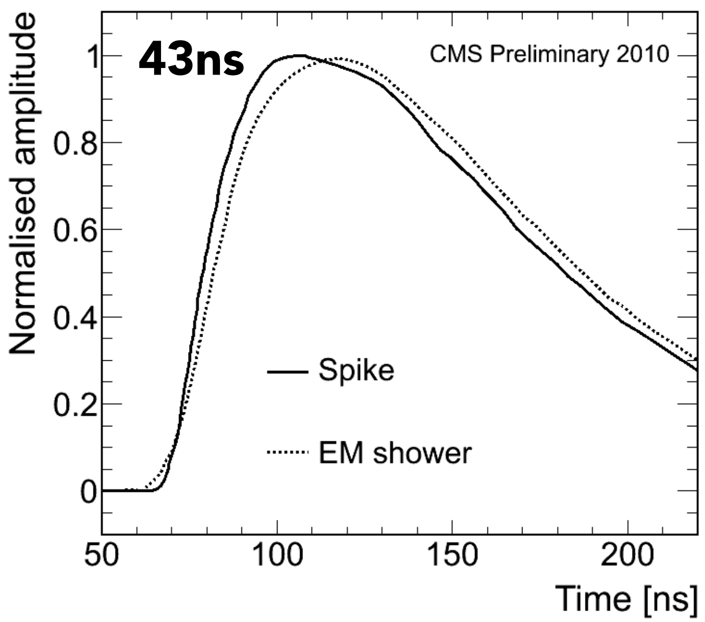


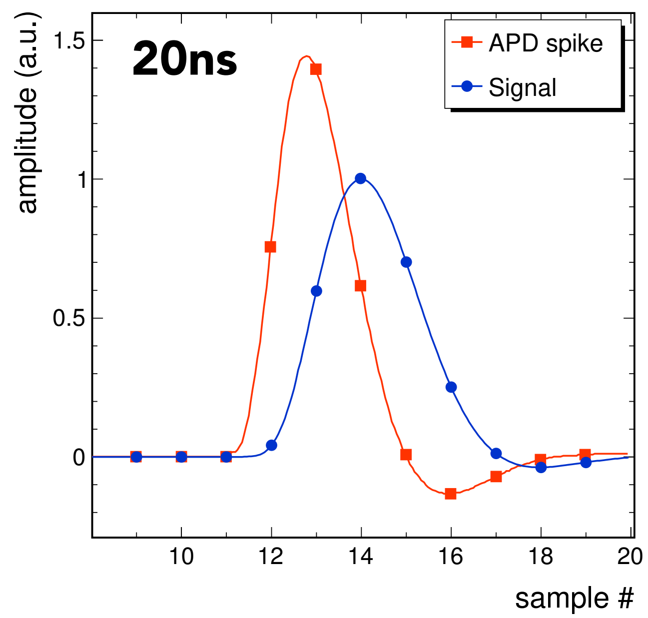
spikes = hit with ≥ 50% energy from APD

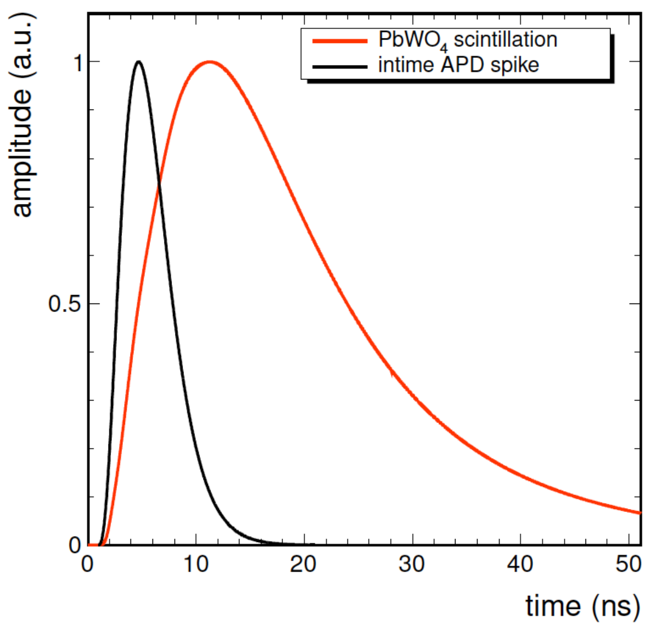
(new VFE) faster shaping time

- 20ns shaping time for **spike rejection**
  - exploit intrinsic difference peaking time between APD and scintillation

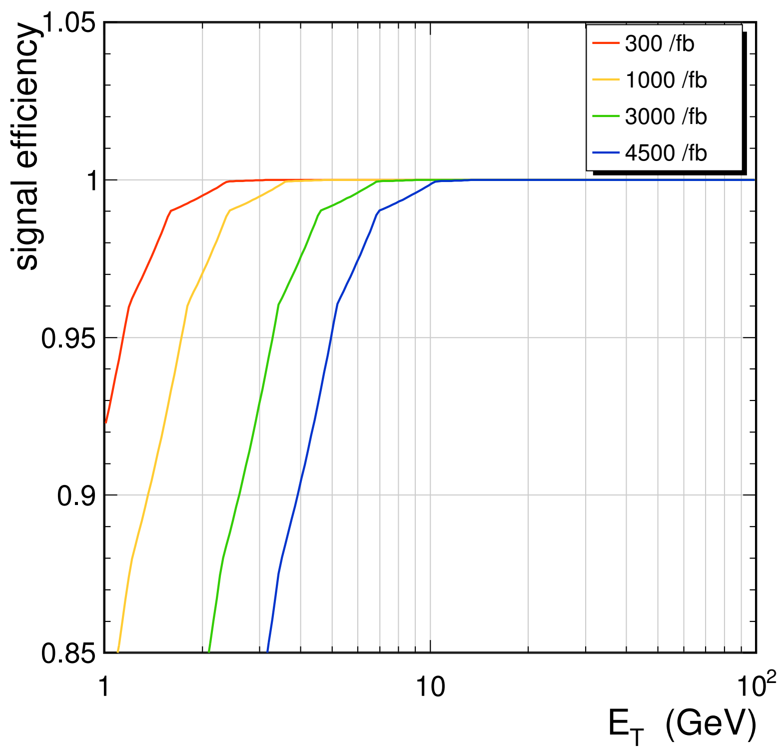
new discrimination based on pulse shape

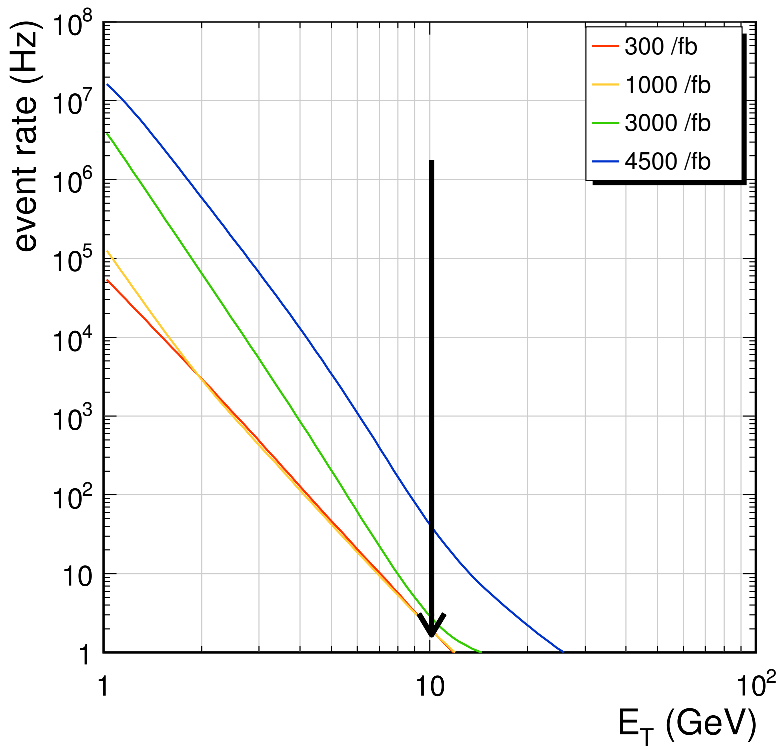






- E_T>10GeV full efficiency and rate from spike < few Hz (above few MHz before upgrade)

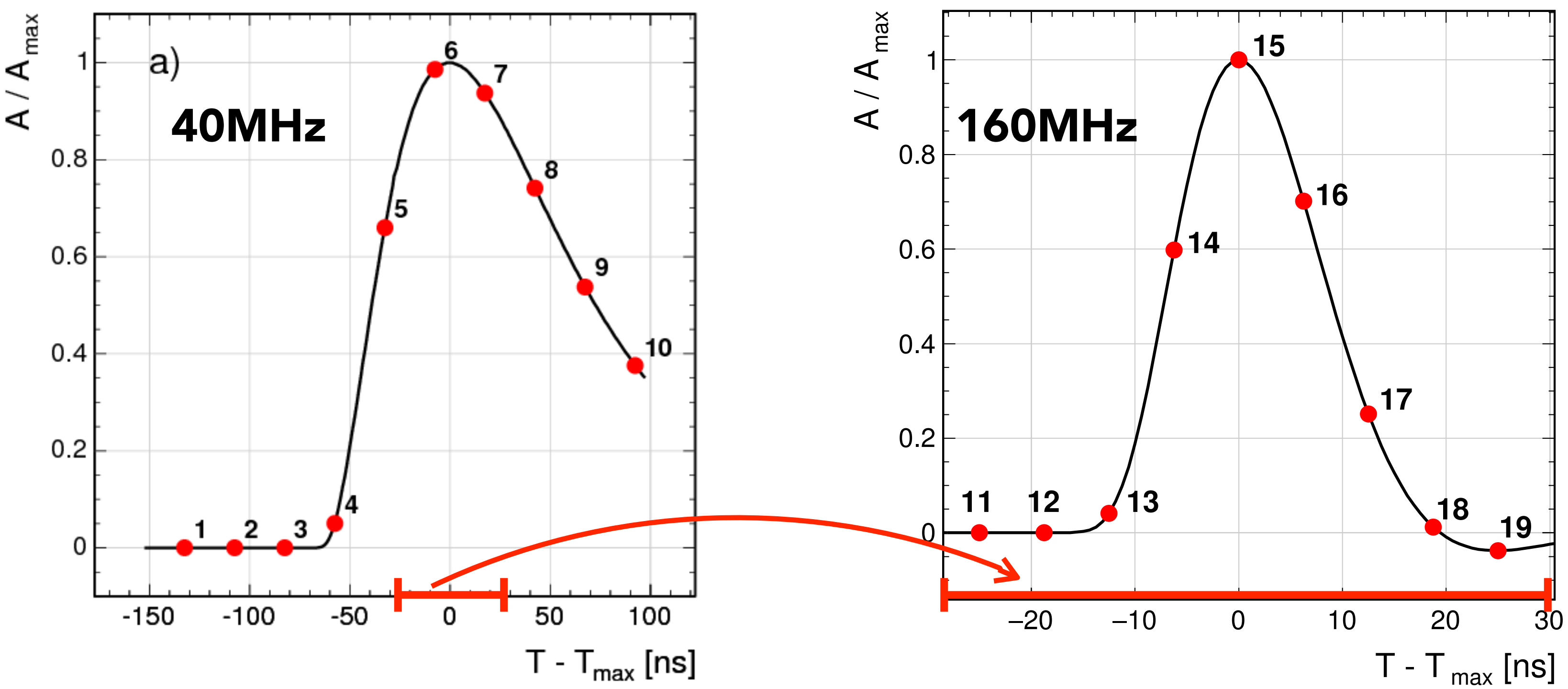




post upgrade with pulse shape discrimination

(new VFE) increased sampling readout

- x4 increase (160MHz) in readout sampling to allow **precision timing**
  - thanks also to reduced shaping time



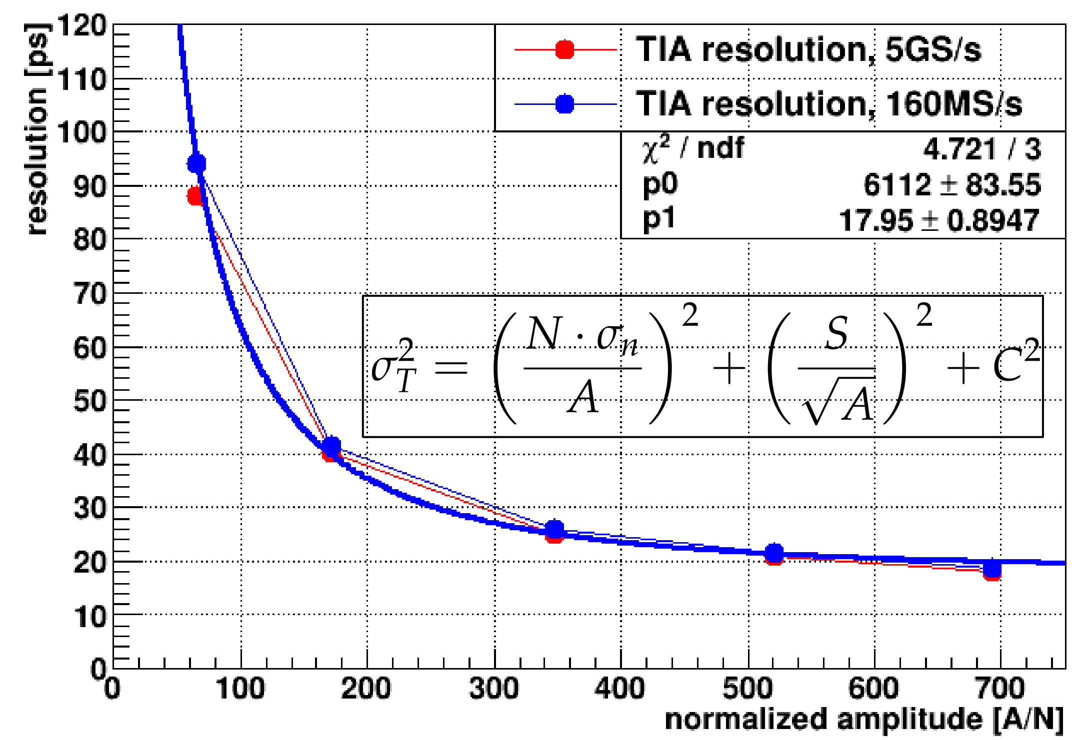
baseline for timing:
use ratio method (as Phase1),
from ratios of consecutive samples

- 160MHz enough to preserve precision timing
  - measurements at test beam using prototype TIA

    C ≈20ps and N ≈ 6ns/(S/N)

    where N ~7 with 200PU found in simulation

    30ps resolution at S/N = 250, @HL-LHC

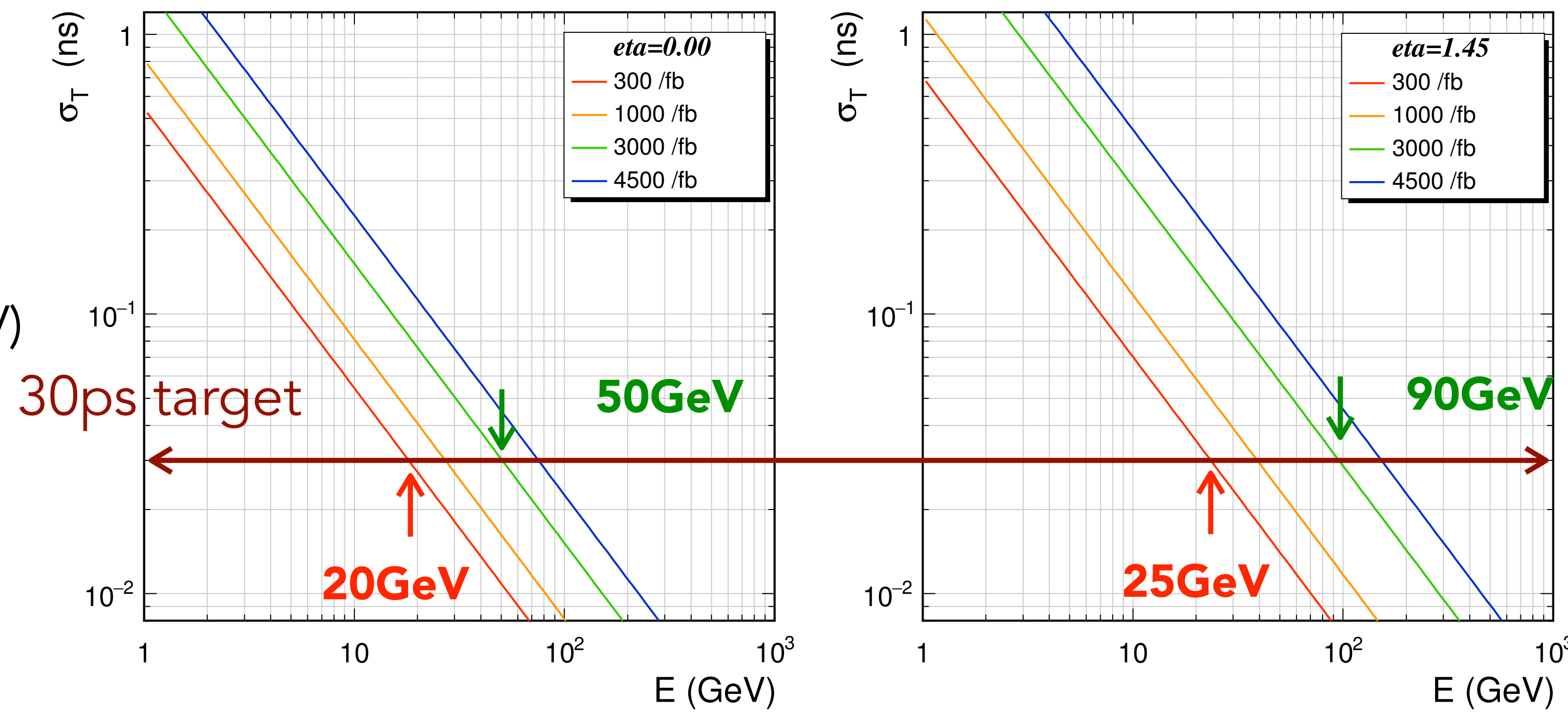


precision timing for EB

- Precision limited by noise contribution => expect lower S/N with radiation
  - larger APD noise
  - lower crystal transparency

30ps resolution at S/N = 250

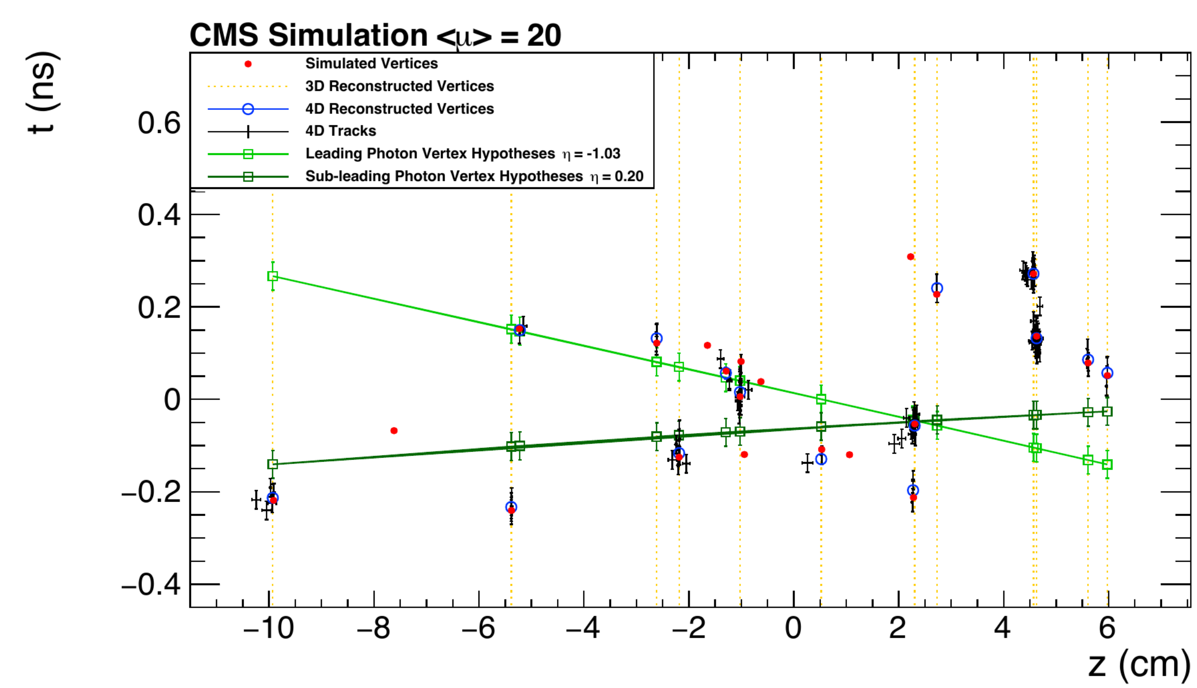
- 20GeV beginning (noise ≈100MeV)
- 50GeV end (noise ≈200MeV)



- **Impact of precision timing,**
  => in Hγγ help to triangulate the vertex in high PU

(see previous dedicated talk)

- Contribution from EB only
  => useful for high Δη
  => limited otherwise
  - 4D vertex for Δη <0.8
  - hermetic coverage



(new FE) increased granularity to L1

- **Phase1: FE providing TPG with 5x5 crystals granularity**

- Opportunity to **increase the granularity at L1 to the crystal level**
  - 61200 crystals in EB, [0.0174x0.0174] vs [0.087x0.087]

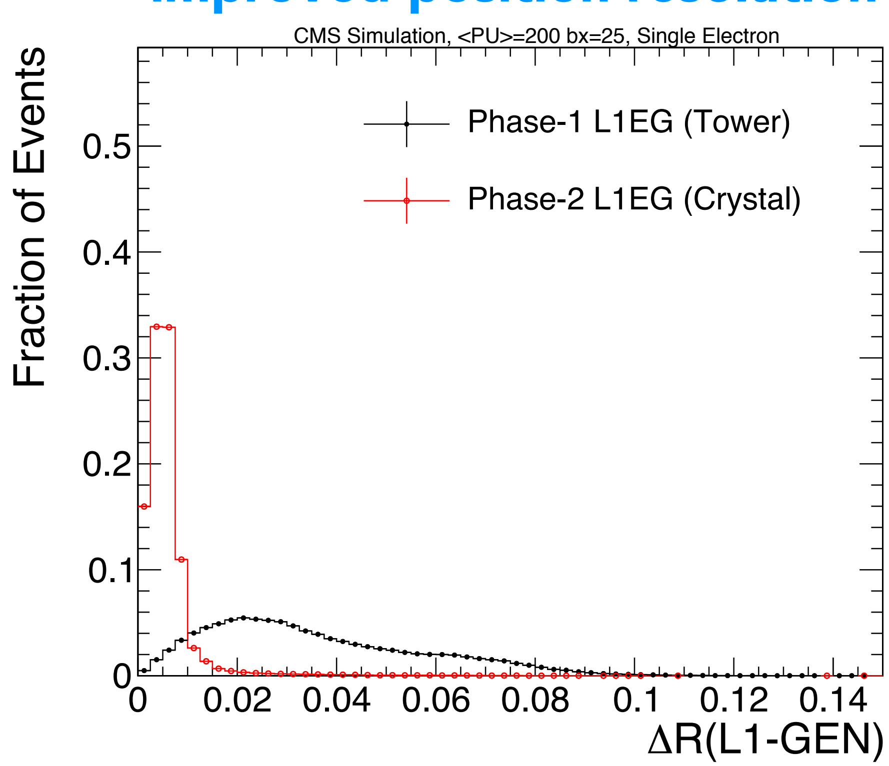
    => better isolation and position resolution for track-calo matching (track trigger)

    => topological spike tagging available at L1

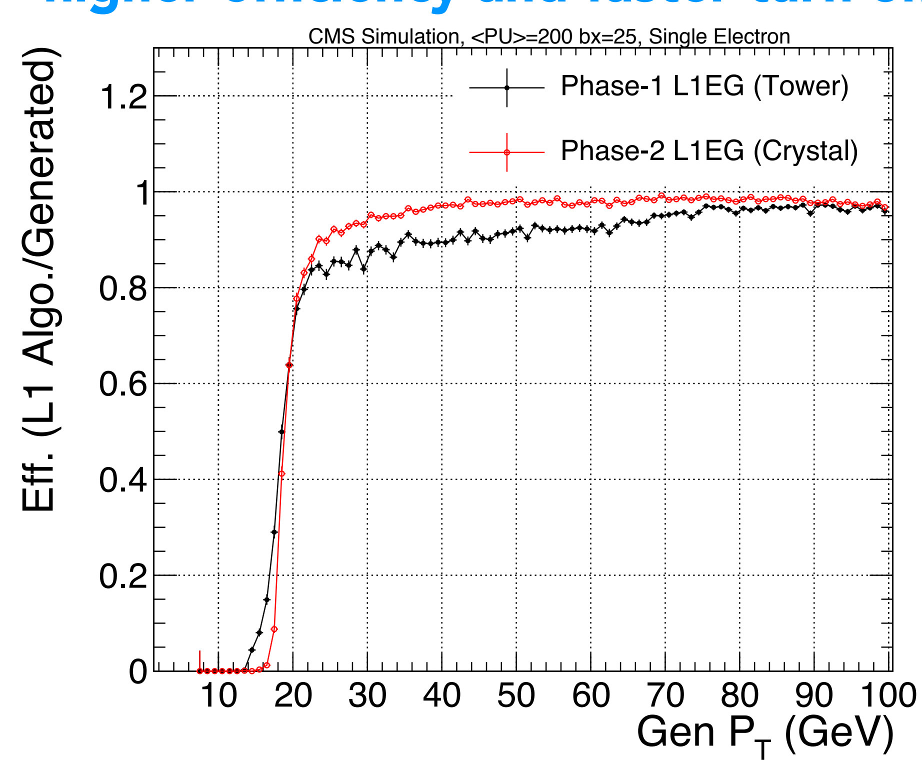
- L1 decision from EG+track trigger
  - EG inputs: pT > 1GeV crystal to seed cluster 3ηx5Φ + isolation in $E_{cluster}/E_{27x27}$
  - shower shapes in the 3x5 core crystals

- Performance based on single crystal information with electron gun

improved position resolution

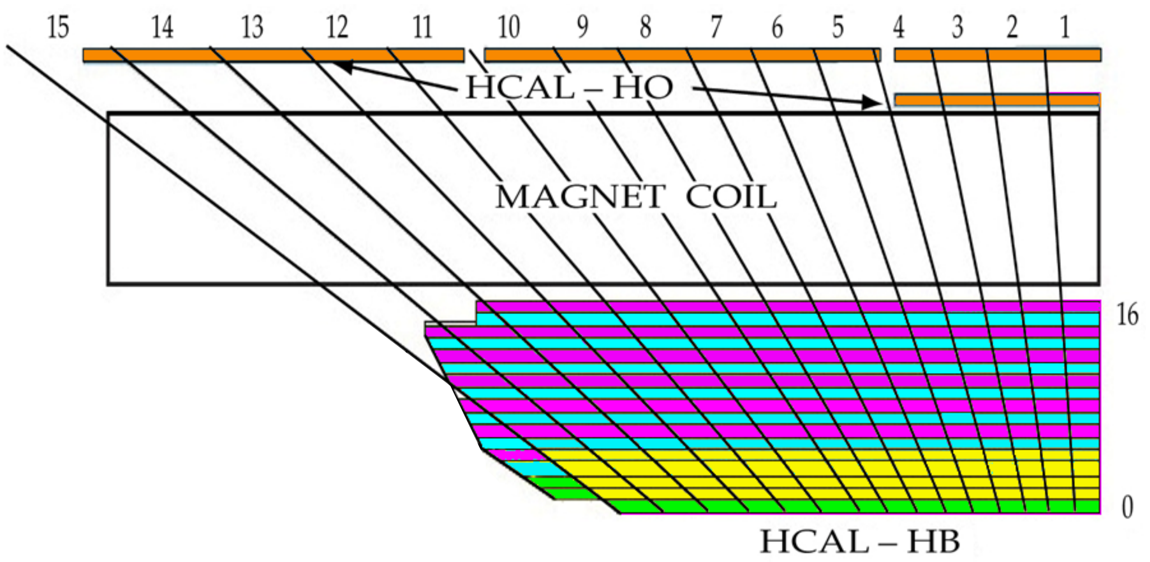


higher efficiency and faster turn-on

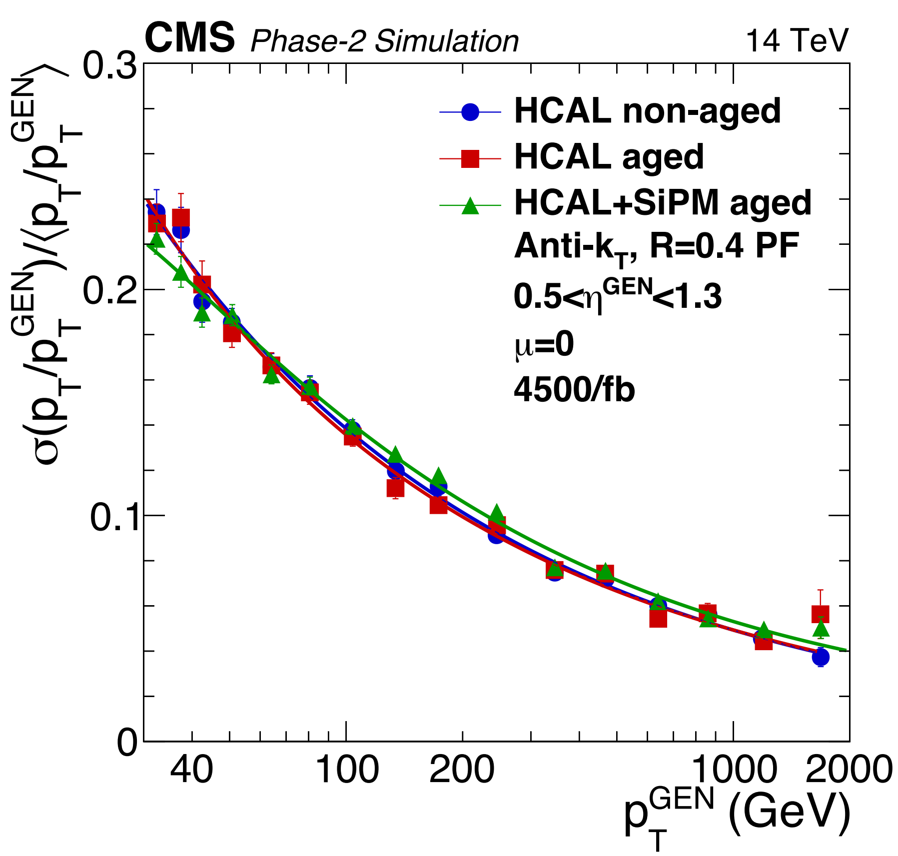


Hadron barrel for Phase2

- Replace light detector HPD with SiPM
  - data taken in early 2017 suggest that signal loss in hadron calorimeters is from radiation damage of HPD rather then scintillator



- **SiPM: high gain, higher S/N wrt HPD**
  (SiPM S/N≈4.5 for single photoelectron)
  => **possible segmentation in the barrel**
  - reduced response of individual tiles (better tolerance of radiation)
  - can mitigate individual losses at high lumi (high eta in particular)



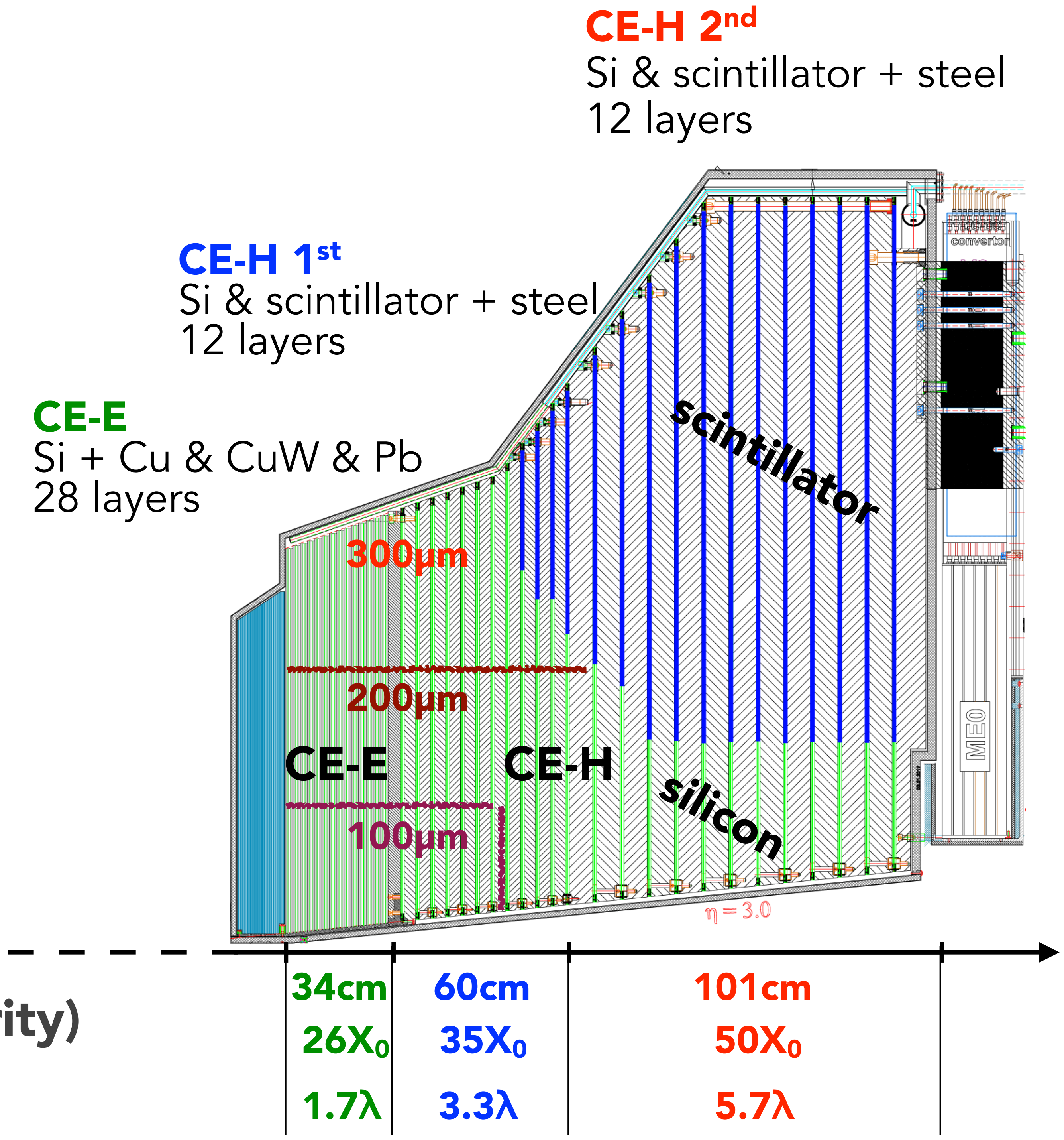
- Longitudinal segmentation
  => useful for particle-flow reconstruction
  - improved tracking for hadronic showers
  - shower profile, help in emg vs had showers
  - help pileup mitigation

Endcap calorimeters for Phase2

- **High Granularity Calorimeter: fine grain for a 3D shower reconstruction**
  => Silicon/scintillator sampling calorimeter, including both em and had parts

Key Parameters:
- **HGCAL covers 1.5 < η < 3.0**
- **Full system maintained at -30°C**
- **~600m² of silicon sensors**
- **~500m² of scintillators**
- **6M Si channels, ~22000 Si modules**
- Power at end of HL-LHC: ~110 kW per endcap

Active Elements:
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H



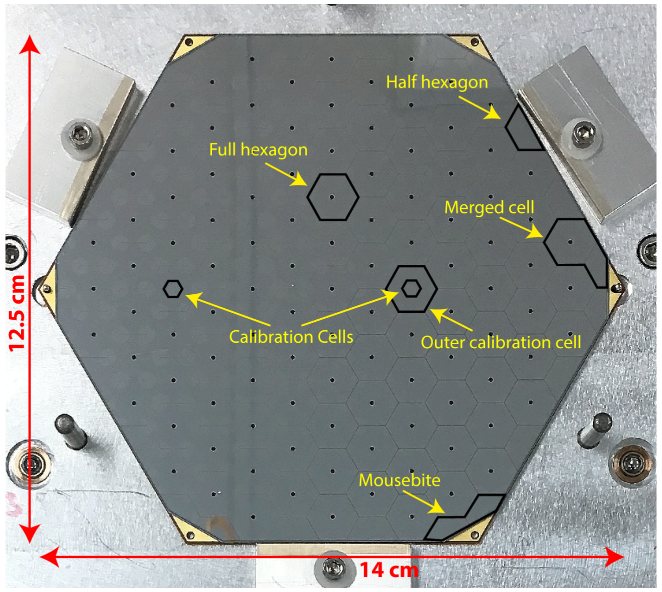
- **High granularity against congestion**
  - to help "features" extraction
  - suited for pf and imaging reconstruction

- **Silicon for radiation hardness (and granularity)**
  - radiation level similar to that experienced in the inner tracker

Silicon for high granularity

- **longitudinal** => can be made in thin layers + **transversal** => can be shaped in small pads

- **Hexagon shape choice**
  - cut from Si circular wafers => to save material and cost
  - geometry more natural to describe shower process
  - increase difficulty for readout electronics, due to non-standard shape



Example here
128 channels Si sensors (6″ wafer)
200μm depleted region, 1cm^2 cell-size

- Baseline choice:
  - 192 (or 432) channels from 8″ wafers, p-type

Active thickness (μm)	Cell size (cm^2)	Cell capacitance (pF)	Bulk polarity	Expected radiation fluence (n_{eq}/cm^2)
300	1.18	44	p / (n)	$1-5\times10^{14}$
200	1.18	65	p	$0.5-2.5\times10^{15}$
120	0.52	48	p	$0.2-1\times10^{16}$

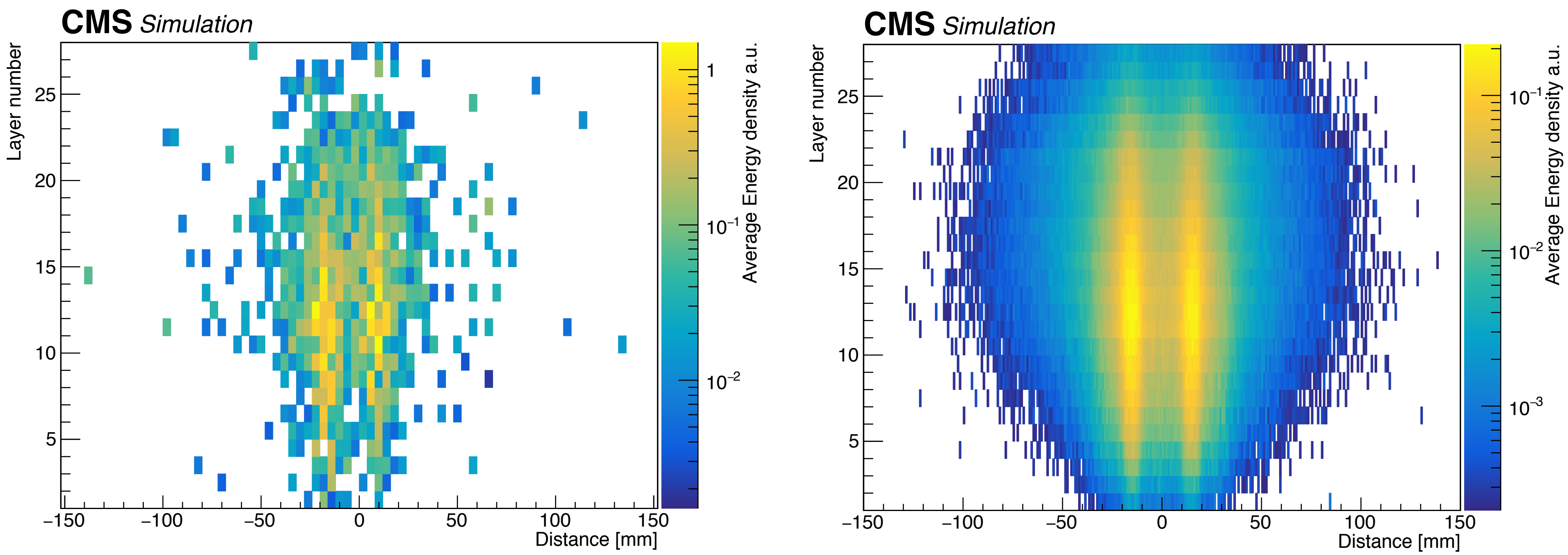
Si thickness (μm)	**300**	**200**	**120**
Area (m^2)	245	181	72
Largest lifetime dose (Mrad)	3	20	100
Largest lifetime fluence (n_{eq}/cm^2)	6×10^{14}	2.5×10^{15}	1×10^{16}
Largest outer radius (cm)	~ 180	~ 100	~ 70
Smallest inner radius (cm)	~ 100	~ 70	~ 35
Cell size (cm^2)	1.18	1.18	0.52
Initial S/N for MIP	11	6	4.5
Smallest S/N(MIP) after 3000 fb^{-1}	4.7	2.3	2.2

- **Cell size**
  - physics performance considerations as the lateral spread of the showers
  - constraints imposed to keep the cell capacitance within a reasonable range
    => guarantee ability to calibrate detector throughout its life

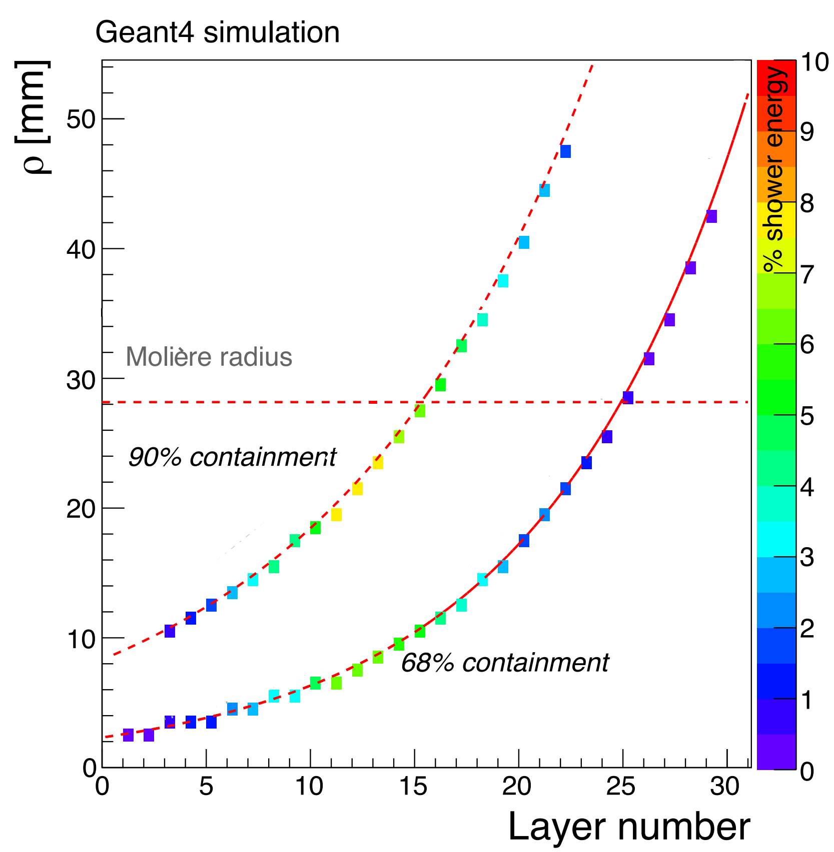
Advantage of high granularity

- Enhanced pattern recognition "imaging-calorimeter"
  - Good separation of nearby showers

14GeV pT photons at η 2.4 [80GeV] with ΔR 0.05 separation

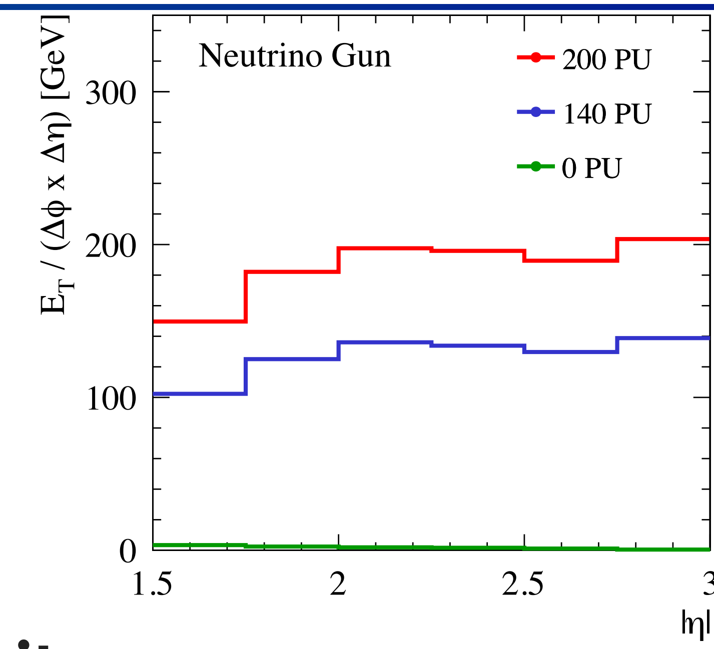


- Radial containment for photon shower
  - ~68% energy within 2.8cm around layer 15
  - spatial resolution < 1cm in first layers (at 0PU)



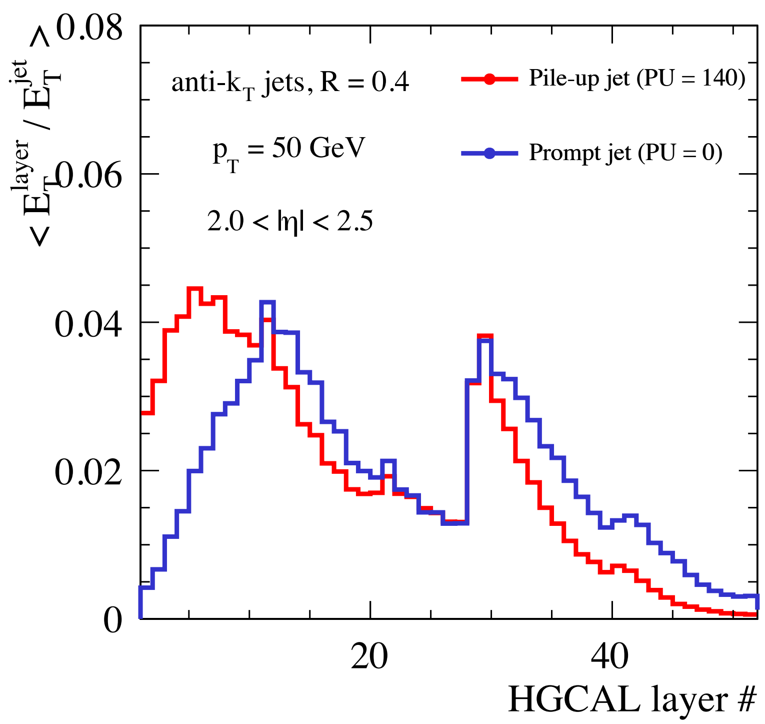
at high PU

- Energy deposition from pileup 200 is ~200GeV E_T per unit area
  => mandatory to exploit granularity and segmentation

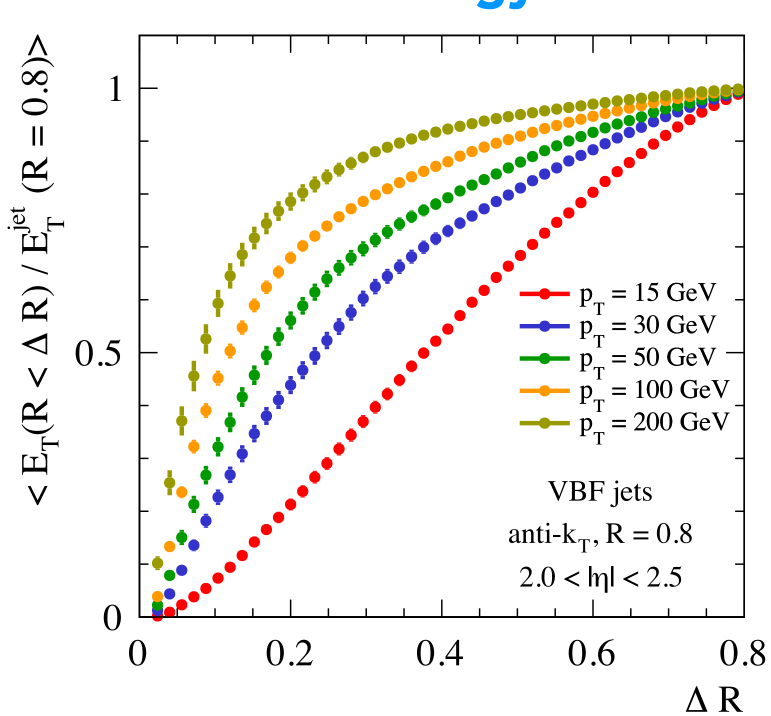


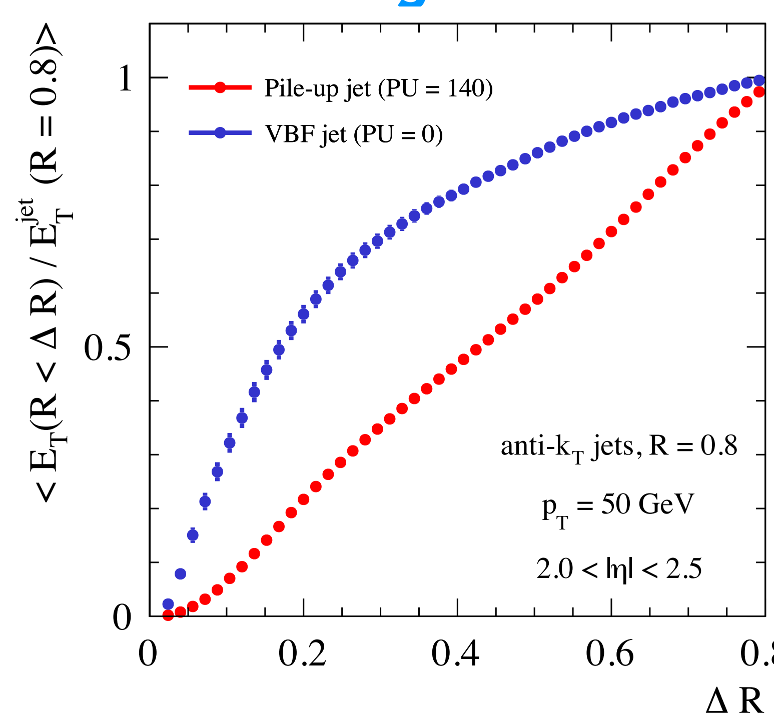
- Test reconstruction potential with calorimeter alone
  - Jet reconstructed with anti-kT on recHits
  - quark jets vs PU jets (mix gluon and soft jets clustered together)

- **Longitudinal segmentation helpful against pileup, also granularity**



balance is needed between integration of pileup energy and loss of energy out of the considered region



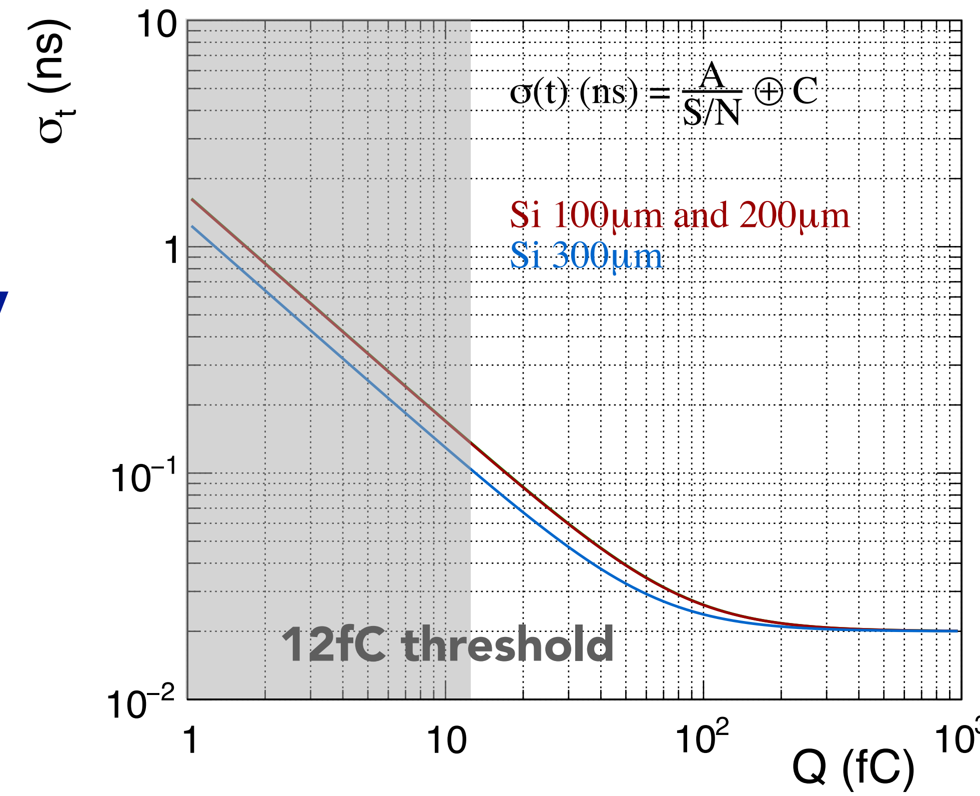


- **Indication to exploit a dynamic definition of R, layer dependent**
  => *development for coming years*

useful also for L1 (see later)

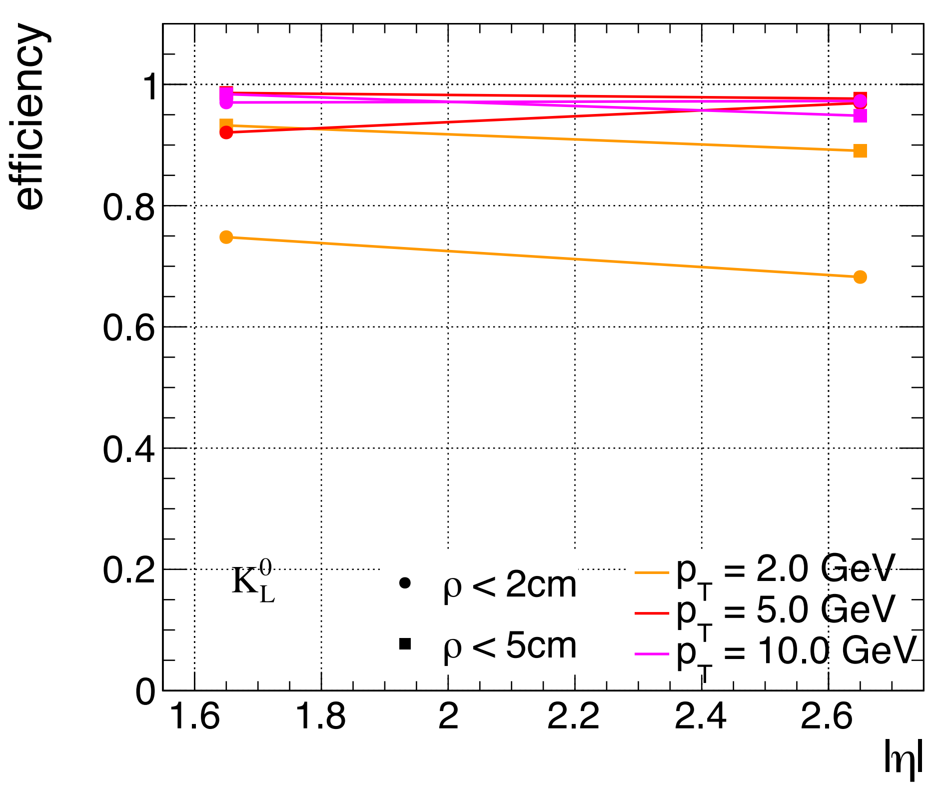
Precision timing

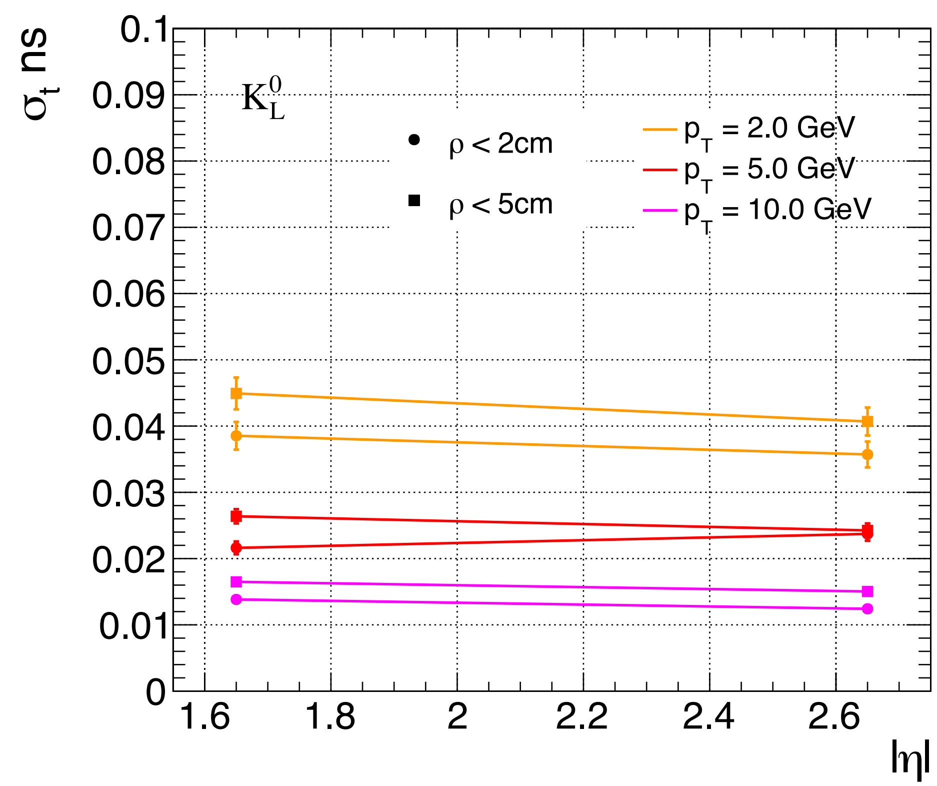
- Single cell performance (HGCROC + Si cell), from electronics simulation shows A = 5ns, C = 20ps



- **Precision timing for showers, exploiting hit multiplicity**

- Study based on the hits within ρ<2cm from shower axis
  - photon: 100% efficiency, σt ≤ 20ps for pT≥ 2GeV
    => electromagnetic component ≈ 30% for hadron showers
  - K^0_L: efficiency > 90%, σt ≤ 30ps for pT > 5GeV



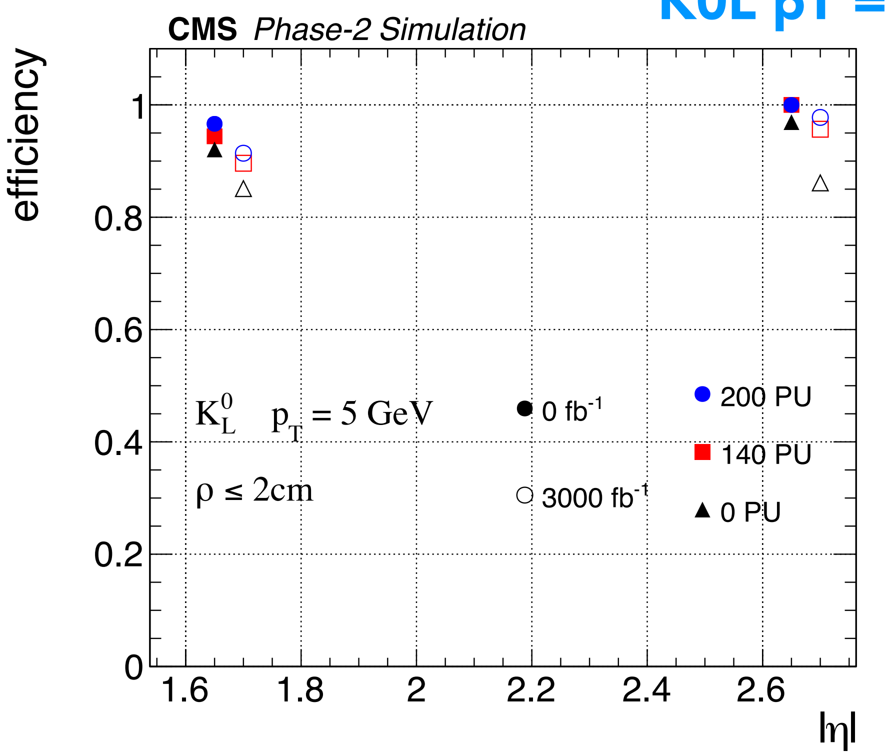


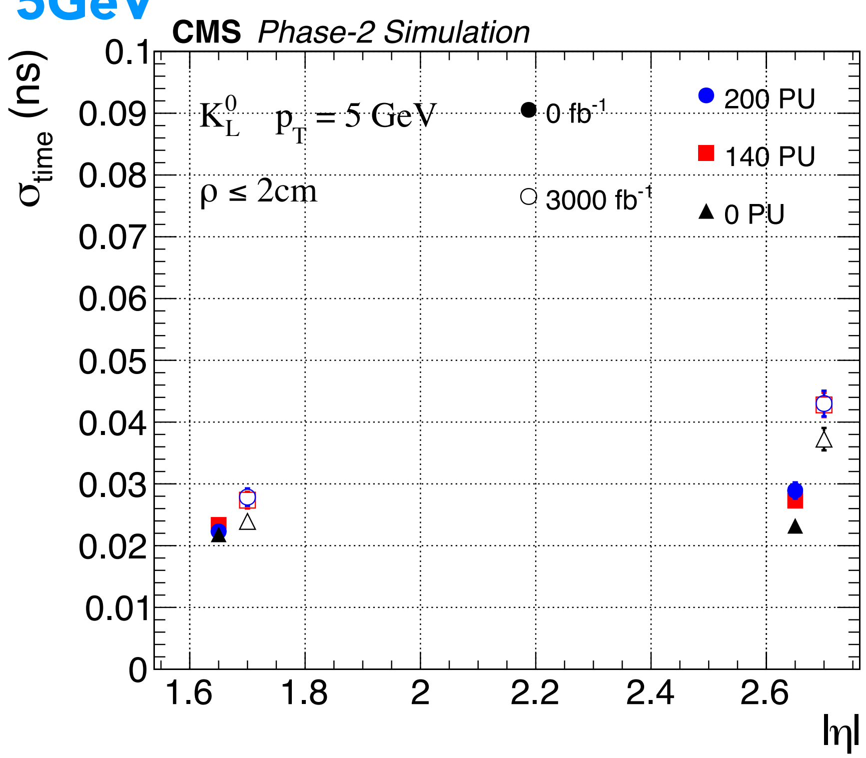
selections:
- consider events non interacting in the tracker volume
- require ≥ 3hits with time per shower

Precision timing

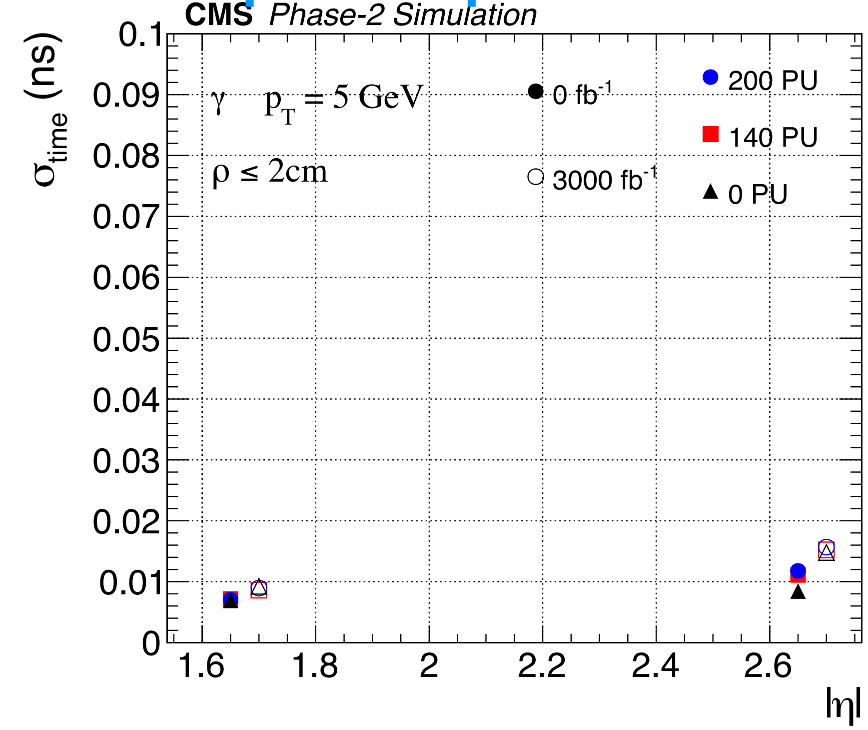
- **With pileup and aged detector: stable performance**

K0L pT = 5GeV





photons pT = 5GeV



- *Need to investigate timing in the reconstruction
  => possible benefits
  - 5D clustering: x,y,z, energy, time of single hits (HGCAL)
  - assist objects ID and shower separation (HGCAL)
  - test impact on pileup rejection and vertex ID, in combination with EB and MTD (global event)

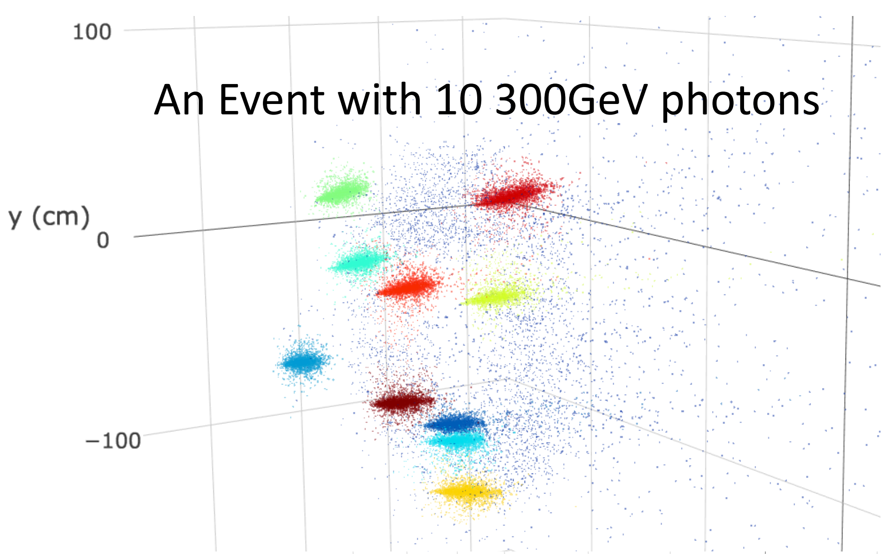
- ***caveat**: need to measure performance for single cell with realistic electronics
  - inputs used for studies

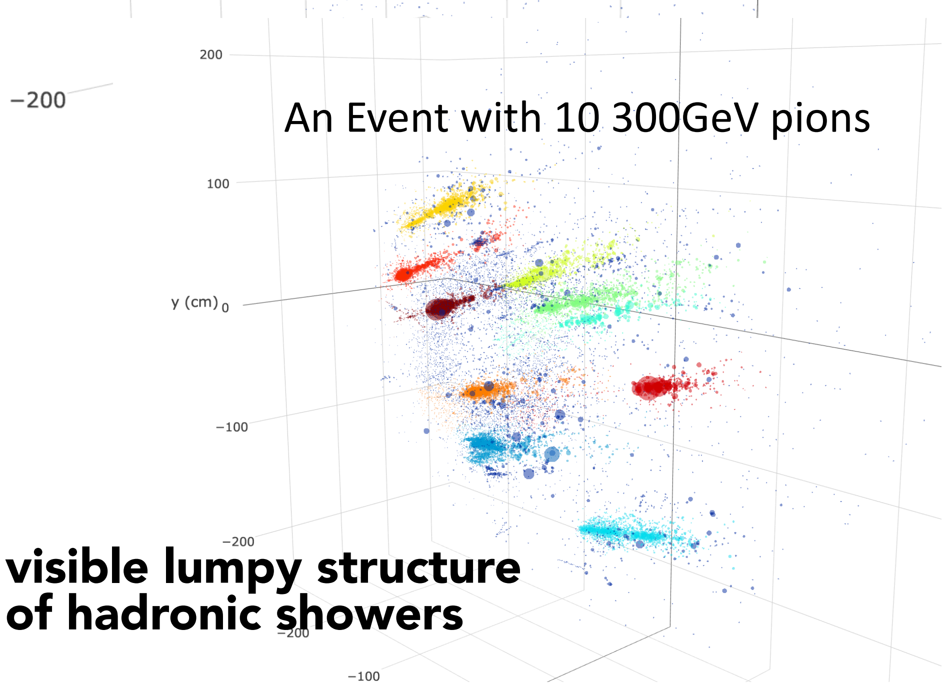
Reconstruction

- **Major impact on the detector performance: new detector = new reconstruction**
  => need is to separate individual particles in high pile-up environment

- Opportunity to develop/tune algorithms that best exploit the high level of information
- Some highlights, by using the calorimeter information on its own

direct 3D clustering

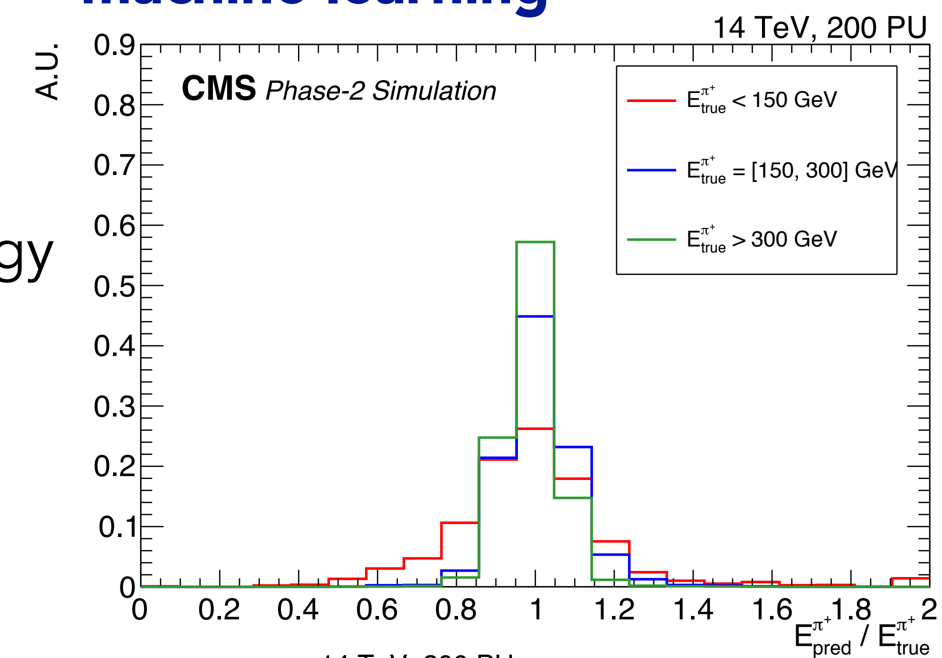


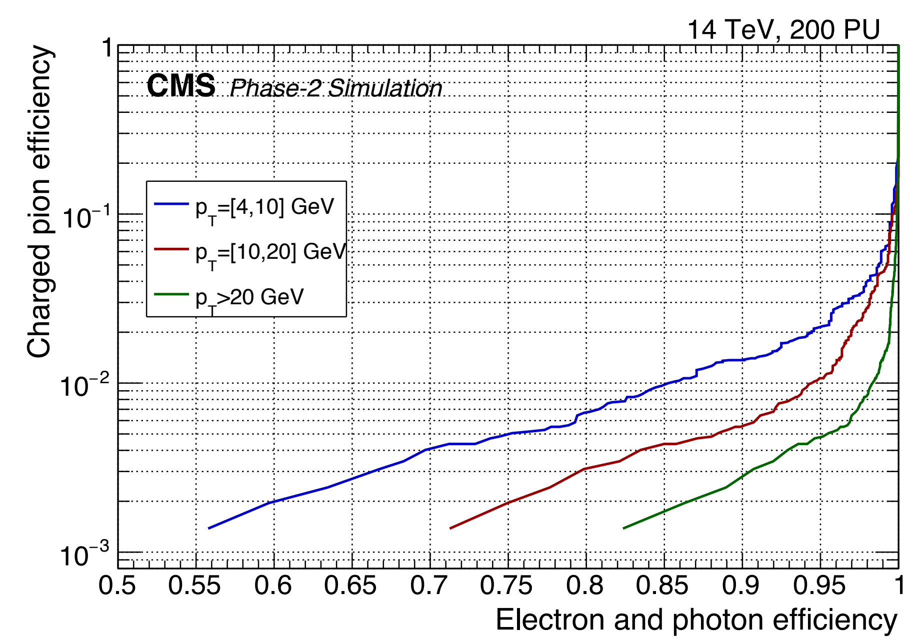


visible lumpy structure of hadronic showers

machine learning

pion energy resolution

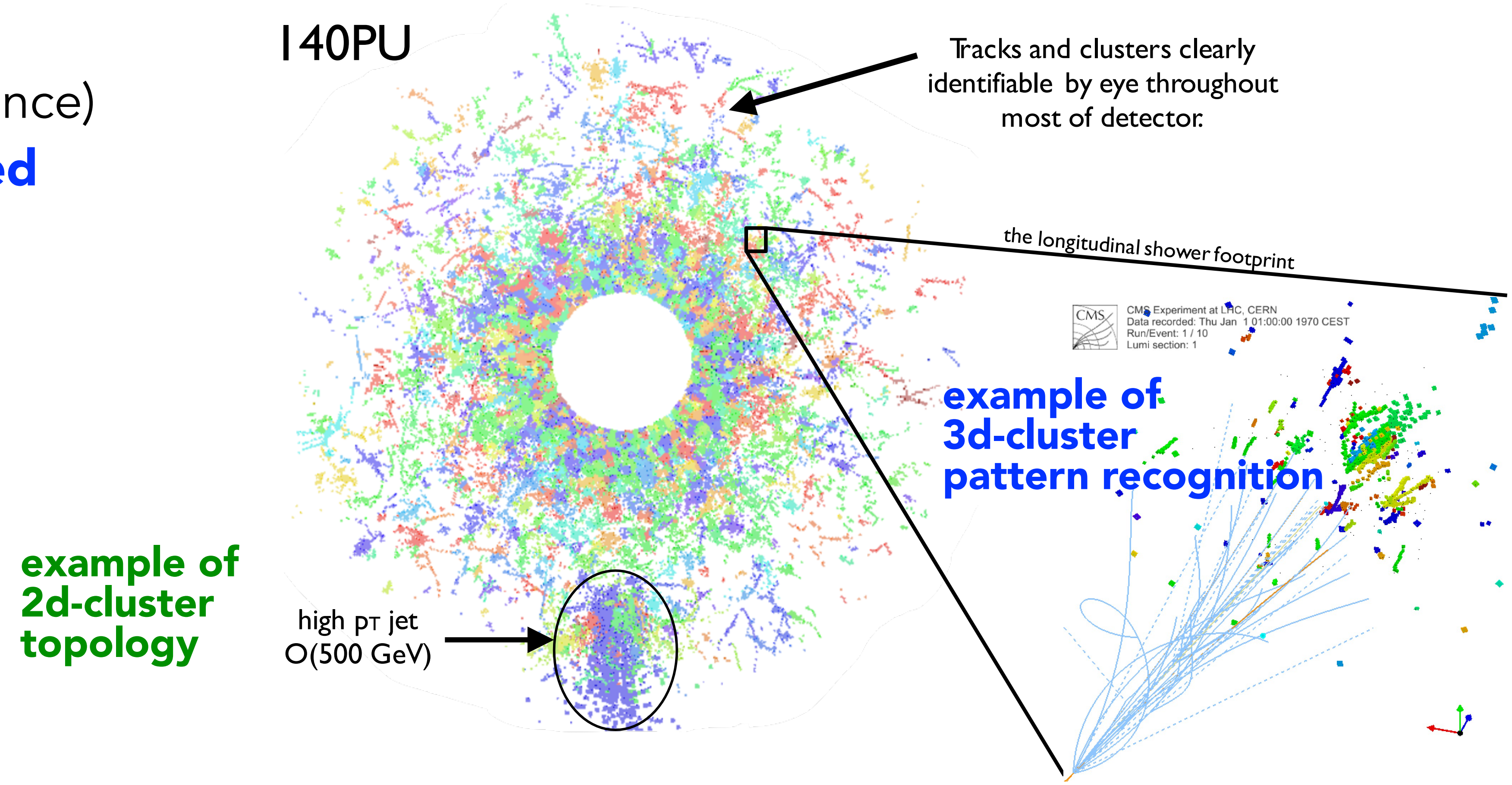




discrimination efficiency

3D imaging clustering*

- Algorithm best suited for the high granularity offered by the HGCal
- Current development in 2 steps:
  - builds **2d-clusters on each layer** based on the energy-density of the cells (energy and distance)
  - **associate 2d-clusters aligned** along the shower axis over different layers



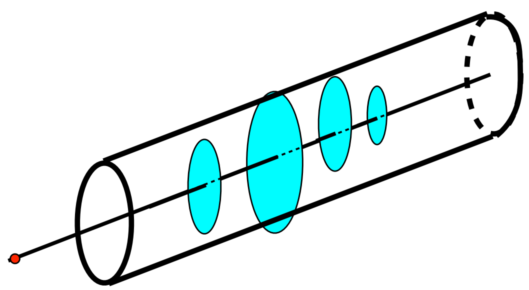
- Extendable to more than two dimensions:
  - direct 3D exploit full spatial correlation of the shower development
  - direct 3D + timing

* inspired by: [A. Rodriguez, A. Laio, "Clustering by fast search and find of density peaks", Science 344 (6191), 1492-1496. (June 26, 2014)]

3D imaging clustering

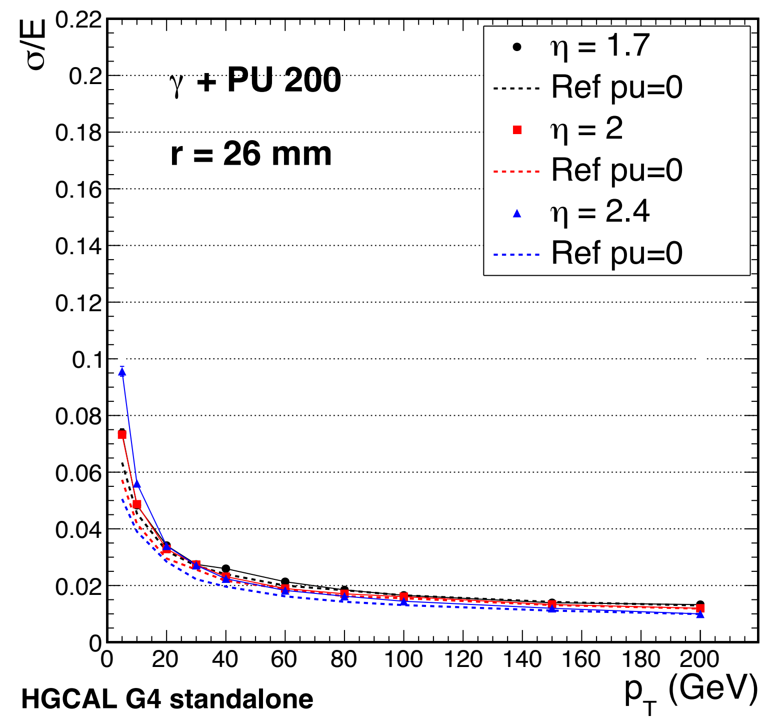
- Good performance for electromagnetic showers

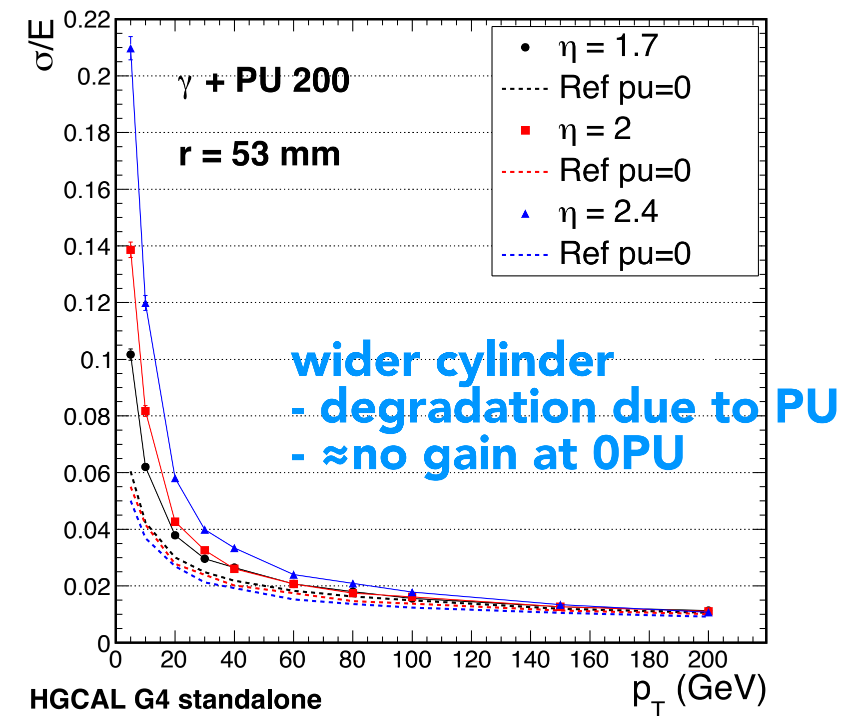
1single 3d-cluster per shower
(for non converting photons)



cylinder around 3d-cluster axis

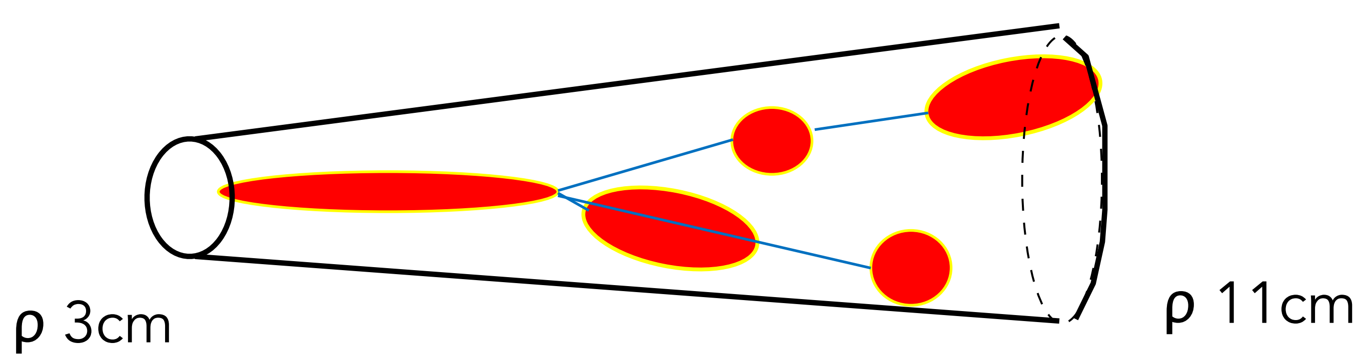
benefit of fine granularity



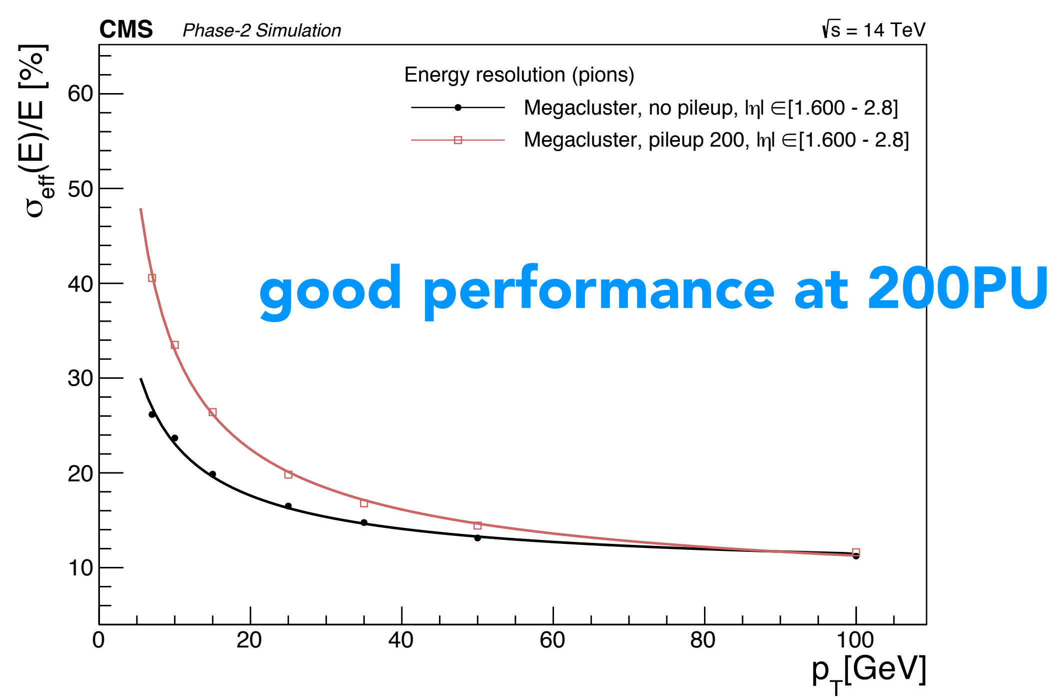


- Further collection of 3D lumpy clusters from hadronic showers

several 3d-clusters for hadron showers
(excluding interactions in the tracker)



truncated cone around seed 3d-cluster

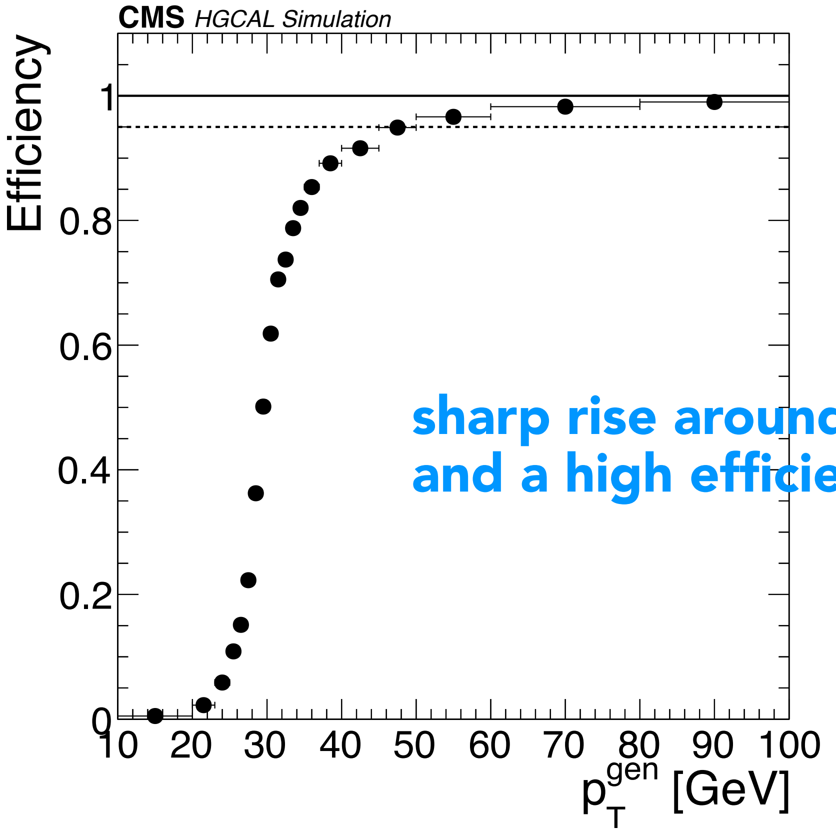


Trigger primitives L1

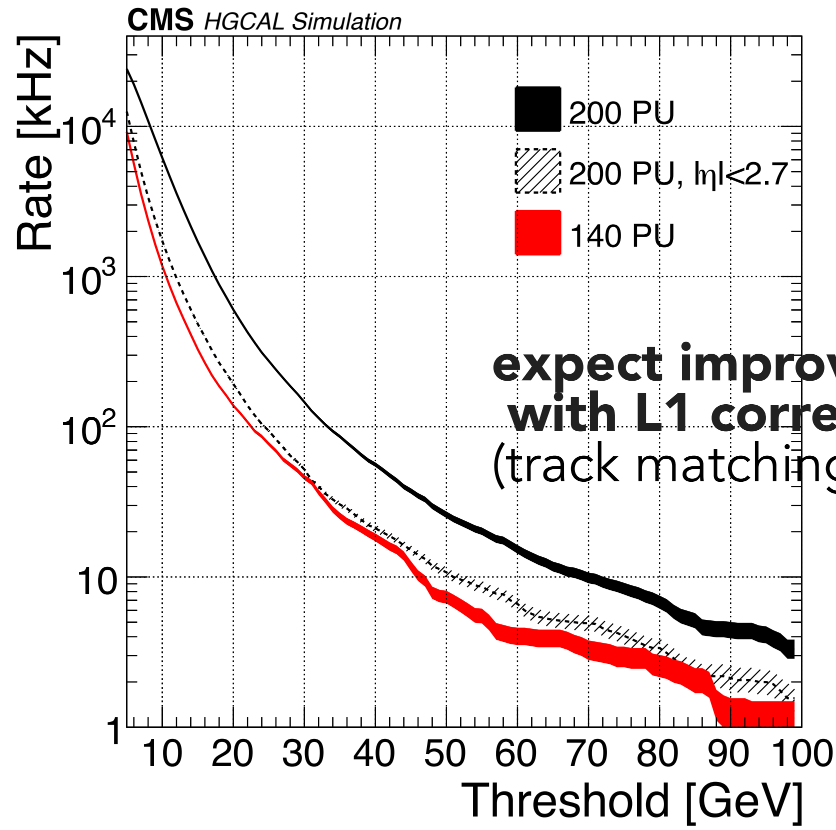
- 2-stage structure for TPG in off-detector BE dedicated boards
  => inputs from 14 layers from CE-E and all from CE-H readout for TPG
  - 1st => 2D cluster + η-φ E_T maps for $E_T \geq 2MIP_T$
  - 2nd => 3D cluster $E_T \geq 1$GeV sent to L1 correlator [1-400GeV full range, 100MeV precision] + extra cluster-variables for ID and energy corrections (length, start layer, maxE layer, width)

- TPG delivers primitives to the central L1 correlator
  => aim at 3D clustering running in FPGAs (*full development for coming years*)
  - currently in place for e/γ trigger, missing for jet trigger

- HGCAL-only performance for e/γ trigger (3D clustering on FPGA)



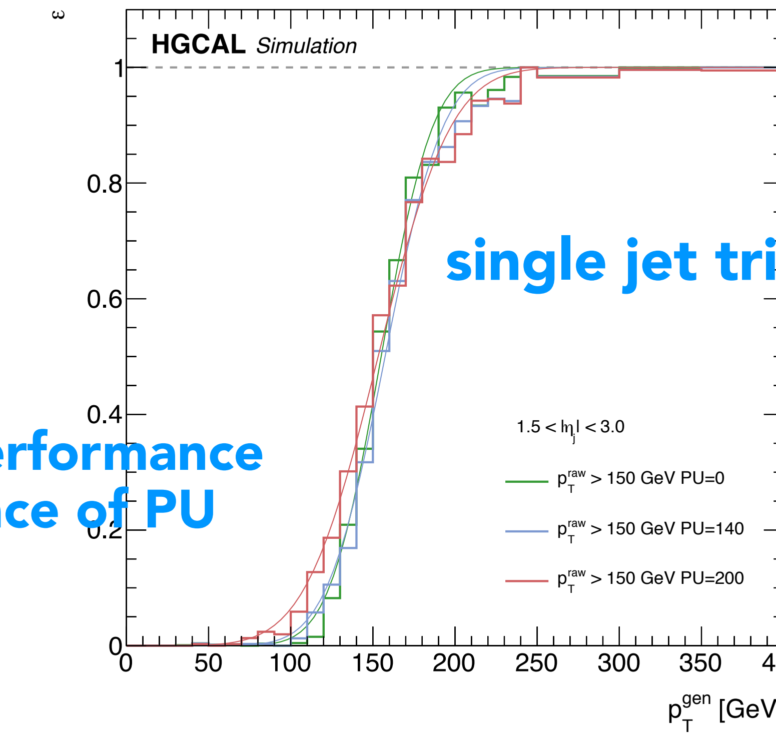
sharp rise around the threshold and a high efficiency above



expect improvement with L1 correlator (track matching, isolation…)

Trigger primitives L1

- Performance for jet trigger (running anti-k_T $\Delta R = 0.2$ on 3D clusters)
  => *need equivalent algorithm to run on FPGAs
  - correction for containment applied based on energy ratio in ΔR (0.1)/ΔR (0.2) and PU



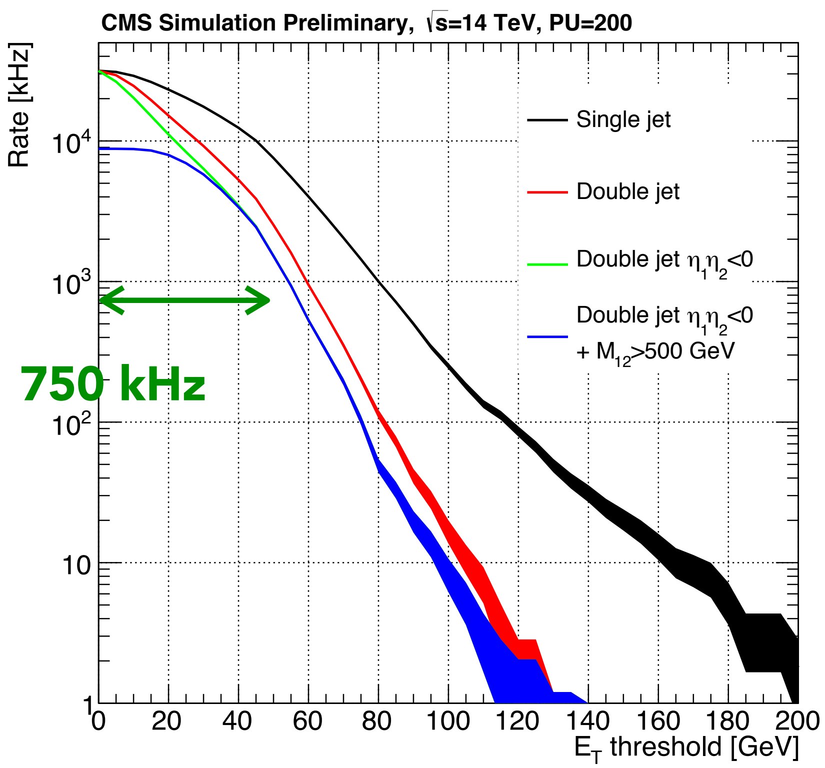
single jet trigger

stable performance in presence of PU

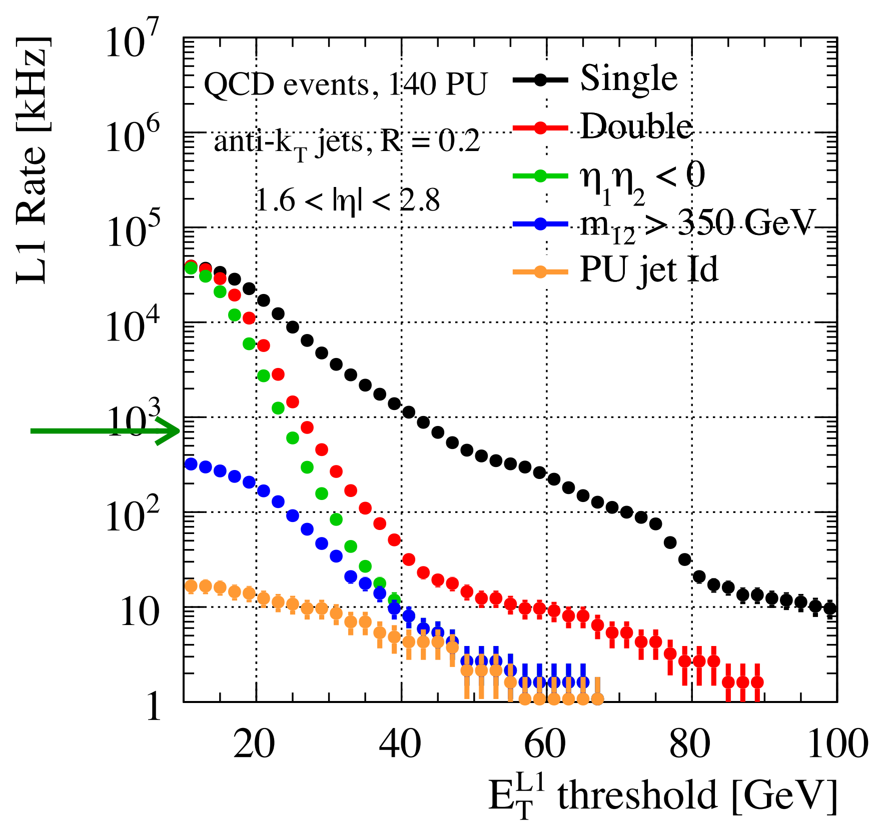
- Background jet rate and for for VBF tag jet topology
  => Segmentation and granularity help in the background rejection
  - PUjetID [Iso(0.1,0.4) + $E_{10layers}/E_{jet}$]

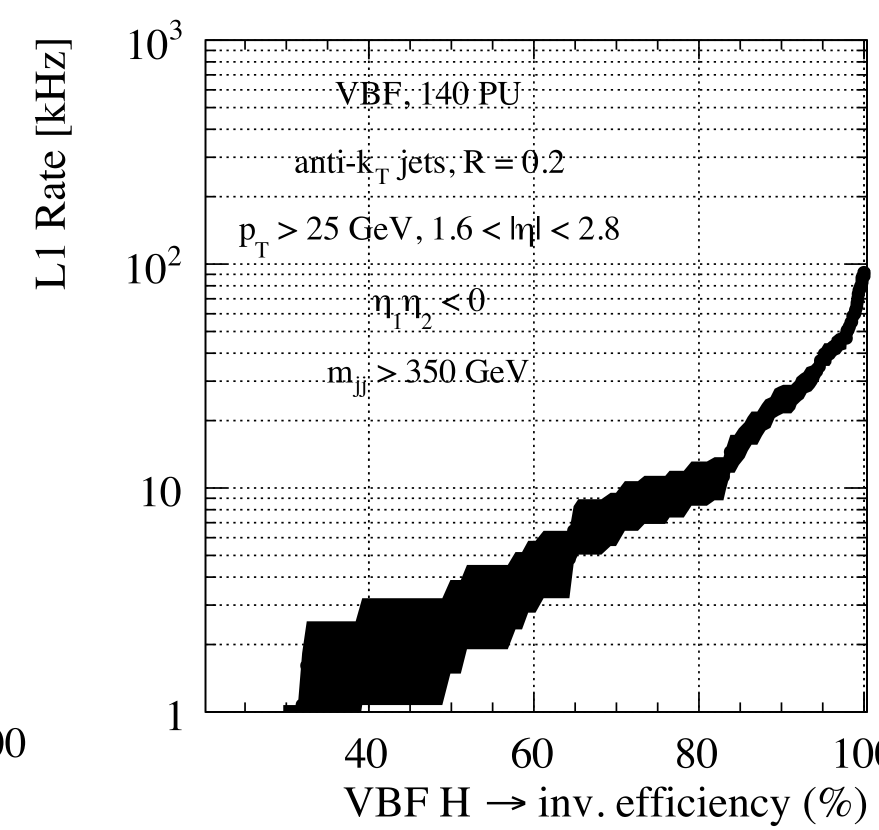
expect further improvement with L1 correlator

PU 200 anti-k_T on 3Dcluster



PU 140 and anti-k_T on recHits





Reconstruction vs performance

- Good potential for improved performance with upgrade elements (timing, granularity)
  => shown by calo-only based reconstruction (previous slides)

- **Important to tune particle-flow reconstruction**
  => physics performance can get maximum profit from the upgrade
  - true also for L1: high granularity expected to help L1 correlator with improved track-calo matching, isolation, particle ID
    => VBF production tag (critic for calo-only at 200PU)
    => help MET and HT triggers, that are then exploited to trigger soft lepton…

- **Reconstruction for the Phase2 detector is not optimal, several key points missing**:
  - tuned clustering in EB against pileup, clustering for hadron showers in HGCAL
  - exploit timing EB and HGCAL , exploit segmentation in HB
  - calibration of electromagnetic and hadronic objects
  - pf reconstruction for best track-calo-muon (timing) matching

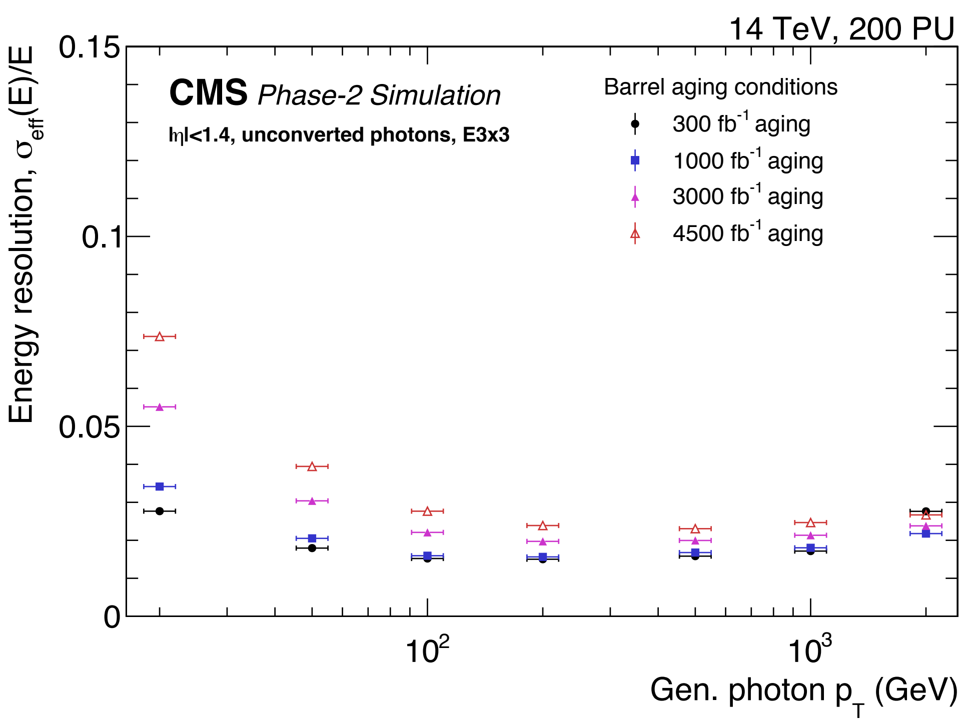
- Physics performance studies *very preliminary* (checks ongoing)
  => potential performance is satisfactory for physics

H-> γγ

very preliminary

- Good energy resolution for photons
- Vertex ID in high PU: benefit from timing (and VBF tag production)

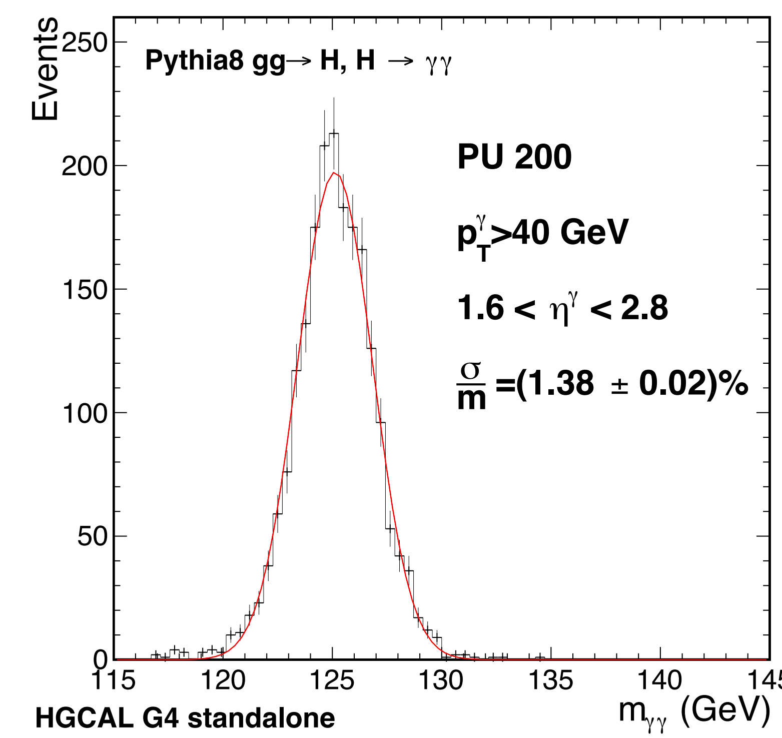
- Un-tuned clustering: consider 3x3 to minimize PU contamination
  => Run2 improved Mγγ resolution with MVA from 2.0 GeV to 1.0 GeV (E3x3, high R9)



expect Mγγ resolution - no MVA - EB

		300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}	4500 fb^{-1}
Unconverted photons (max 15)	0 PU	1.5 GeV	1.8 GeV	3.6 GeV	5.1 GeV
	200 PU	2.2 GeV	2.4 GeV	4.2 GeV	5.3 GeV
Unconverted photons (E3x3)	0 PU	1.7 GeV	1.8 GeV	2.7 GeV	3.4 GeV
	200 PU	1.9 GeV	2.0 GeV	2.8 GeV	3.6 GeV
All photons (max 15)	0 PU	2.0 GeV	2.3 GeV	3.8 GeV	5.2 GeV
	200 PU	2.8 GeV	2.9 GeV	4.3 GeV	5.6 GeV

expect same performance for γγ pairs in HGCAL



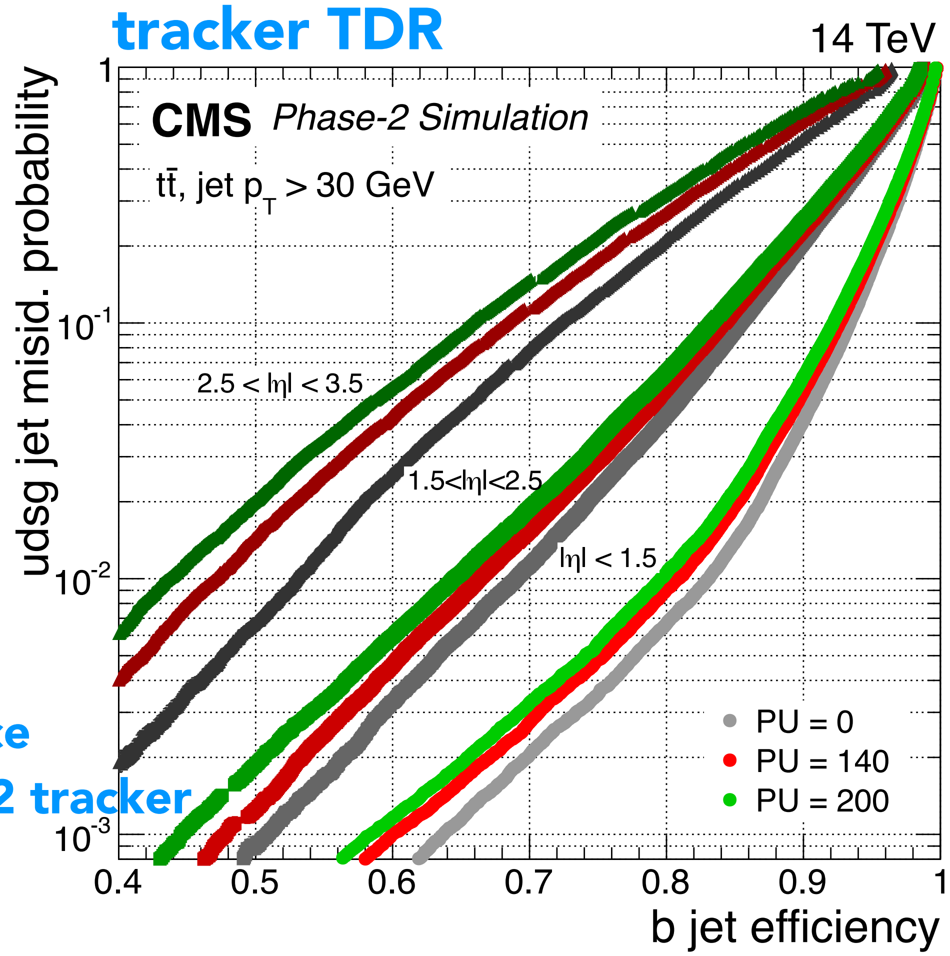
- Clear benefit for HH->γγbb, together with improved performance on b tag/acceptance

b tagging

very preliminary

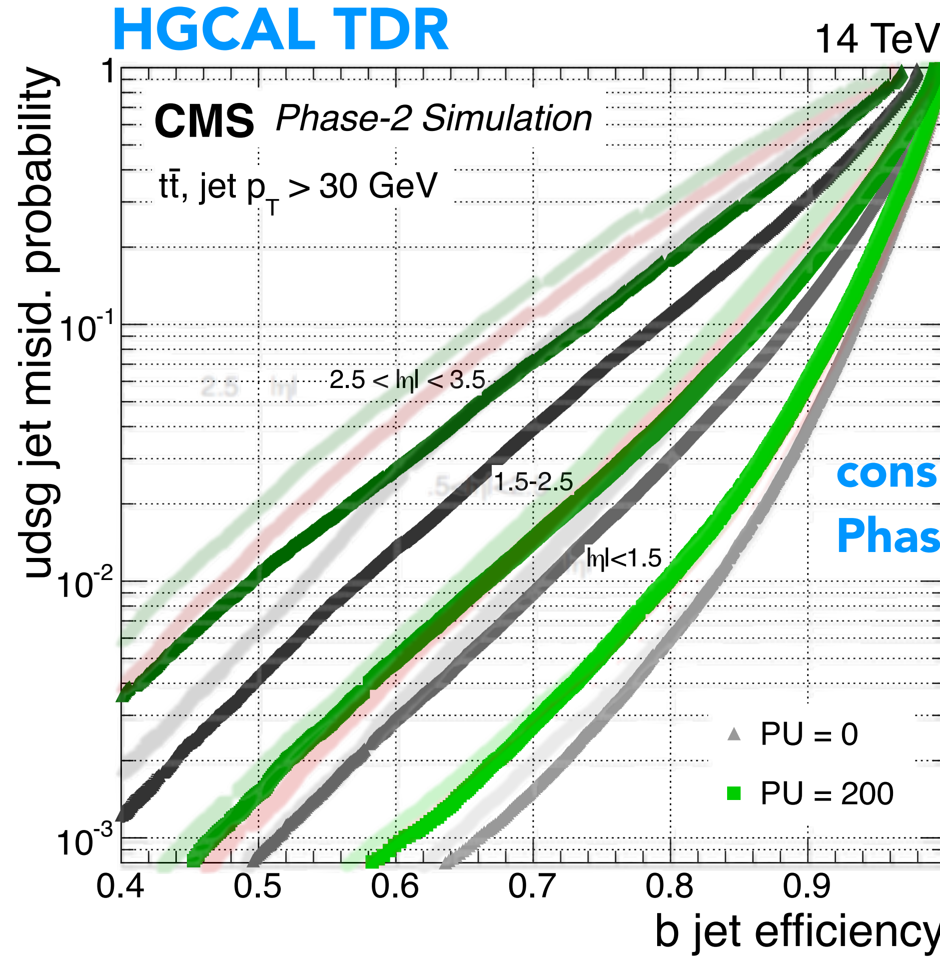
- Main impact from tracker performance
- **Improved particle-flow reconstruction can bring further gain**

tracker TDR



performance with Phase2 tracker

HGCAL TDR



consider also Phase2 calorimeters

=> particle-flow reconstruction currently used for HGCAL TDR studies

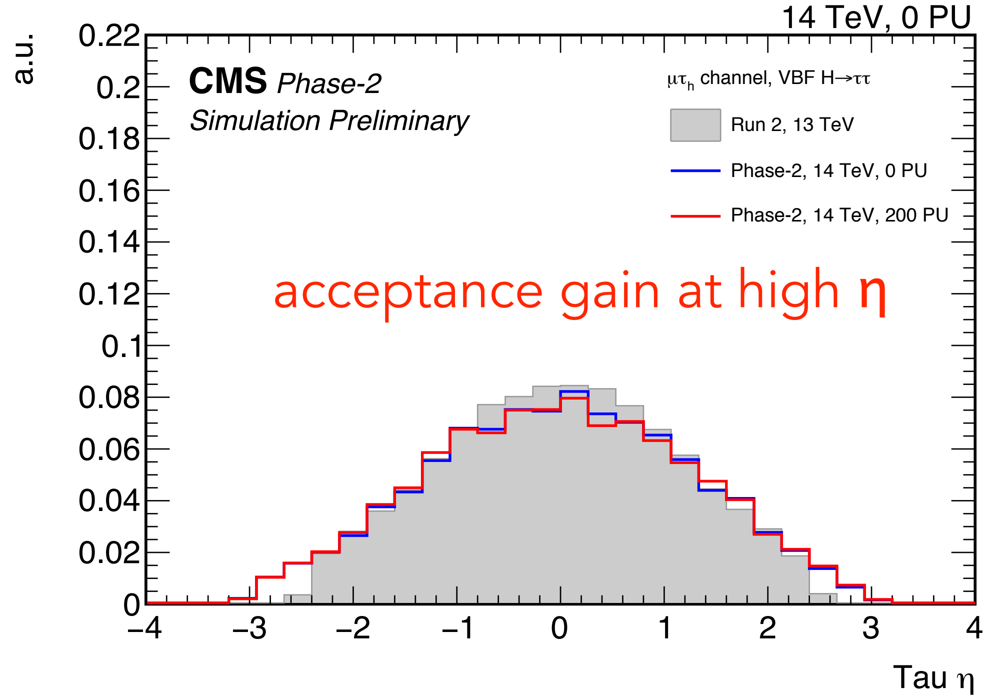
- ideal track-cluster matching + realistic merging of clusters
- **indication that the ingredients to improve the performance are available**

- Clear benefit for HH->γγbb
- Benefit also for HH->bbbb and for VH, ttH

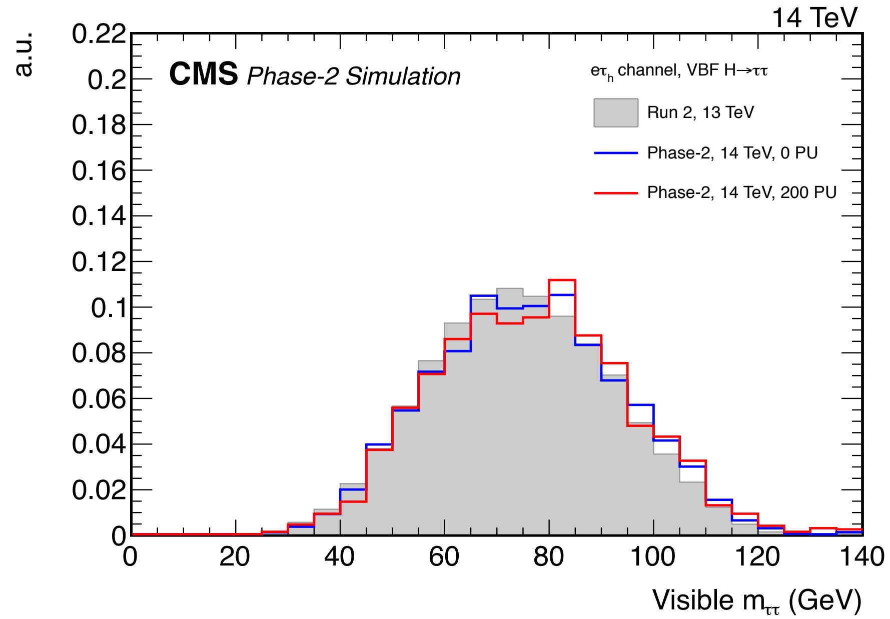
H->ττ

very preliminary

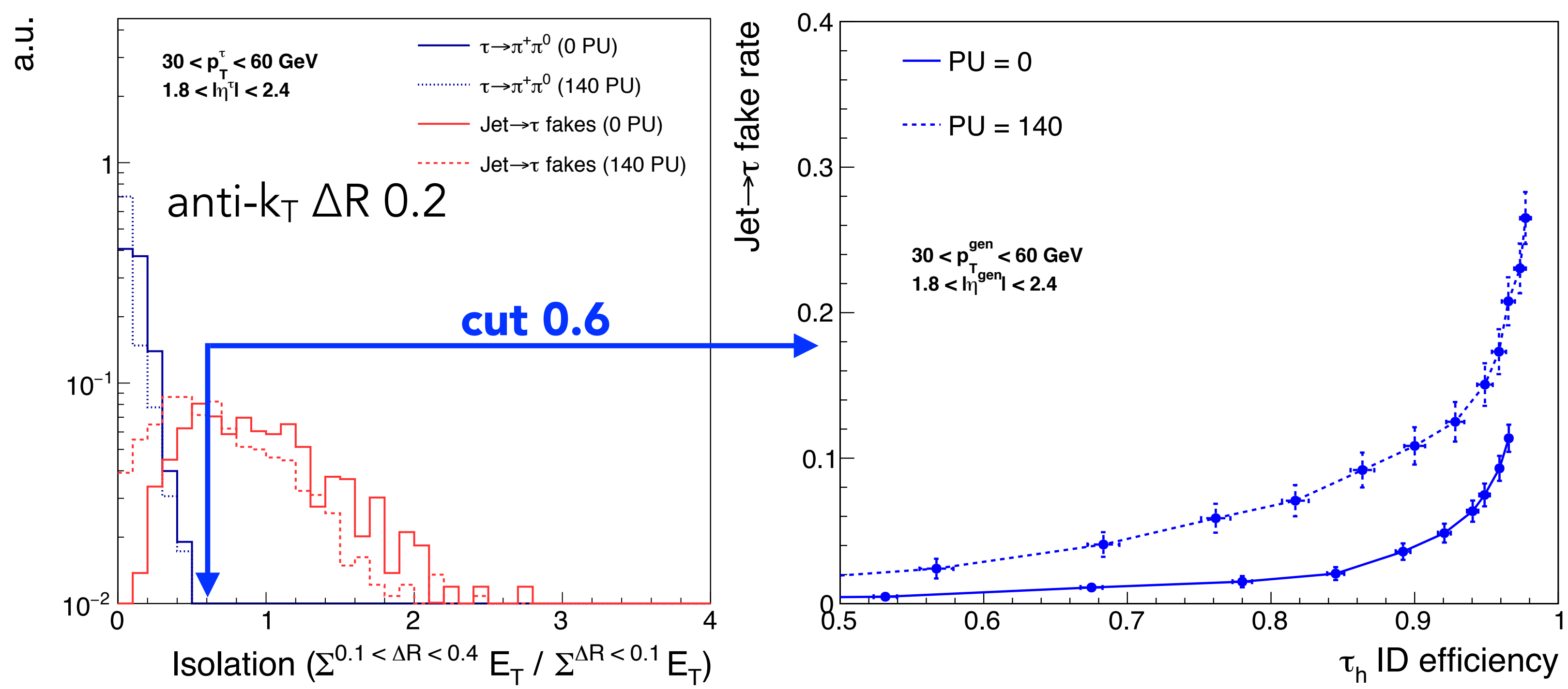
- Calorimeters relevant for the π^0 reconstruction
  - $\tau \to \pi^+\pi^0\nu_\tau$ (40% of hadronic decays mode)



- EB: maintain Run2 (50PU) performance also with 200PU



- HGCAL: exploit granularity => tau decay products are more collimated

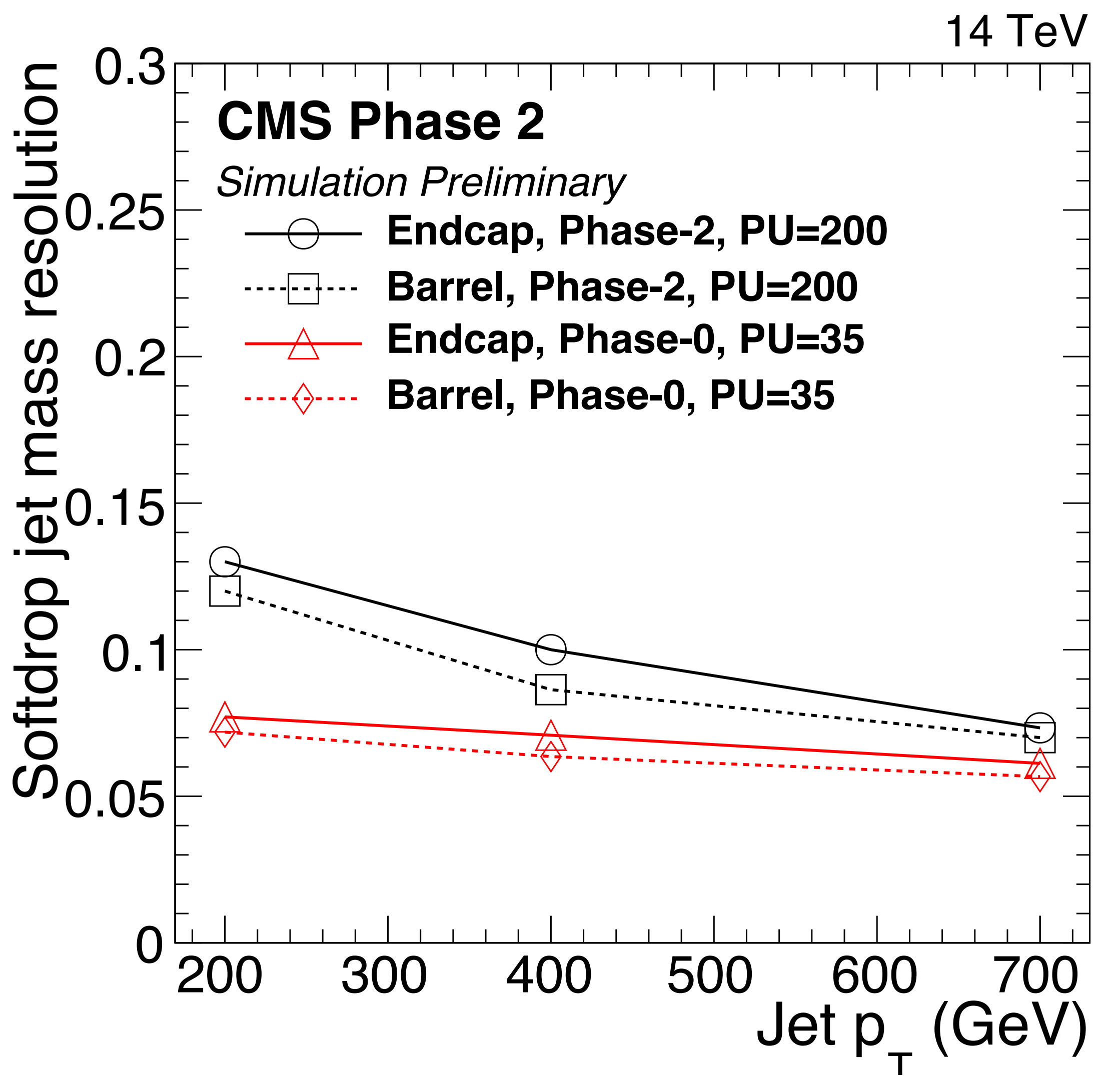


Tagging boosted topologies

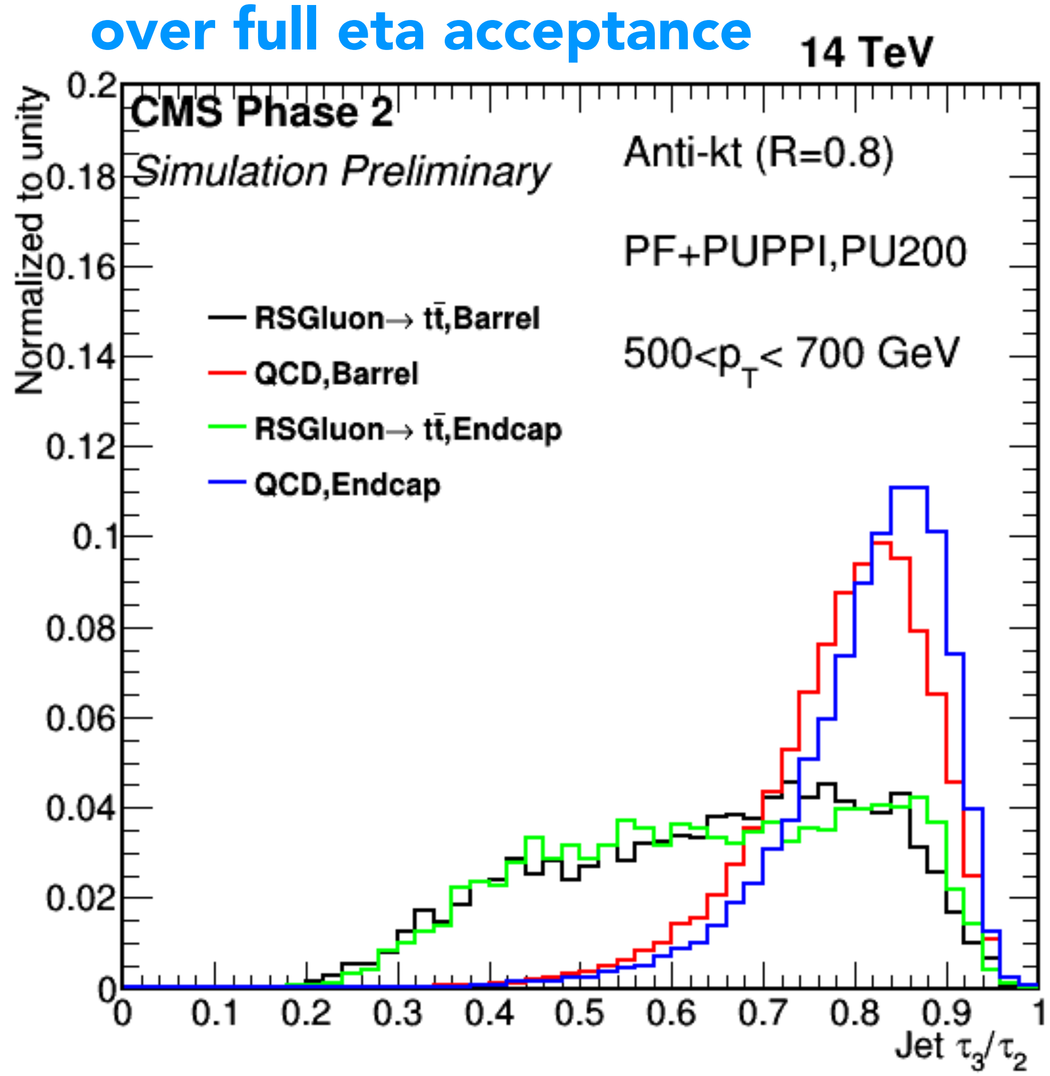
very preliminary

- High granularity helps to identify boosted W,Z,H and top from ordinary gluon/quark initiated jets
  - soft QCD radiation removed from the jet before calculating its invariant mass
  - n subjet axis within a fat jet

~same resolution 0 and 200 PU at high pT



same signal-background discrimination over full eta acceptance



In summary

- Granularity/segmentation and precision timing are expected to give a major improvement to objects reconstruction and ID, in 200PU

- Positive indications of detector performance
  - as obtained from preliminary reconstruction

- Improved particle-flow can bring major gain to physics performance
  => all the ingredients are there
  => the pf reconstruction (not fully in place) is definitely worth investing

- Phase2 calorimeters contribute to potential improved L1 trigger performance
  => improve and extent calo algorithms to provide the highest level of information to the L1 correlator
  => most of the tasks in charge of the L1 correlator

- **Very interesting phase to develop creative new ideas**
  => fundamental for (calorimeter performance) Physics results in 10years of HL-LHC

Reference

- TDR for Phase2 CMS detectors
  - HGCAL
  - barrel calorimeters
  - tracker

- Performance studies within the CMG-HGCAL group

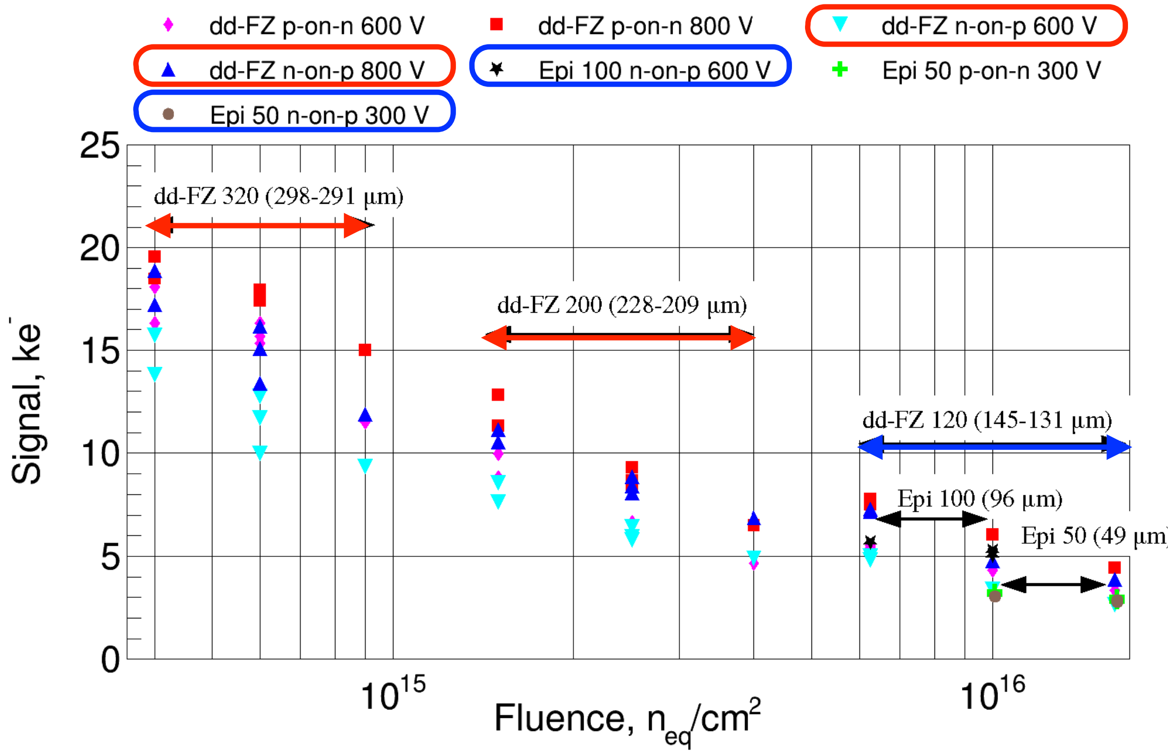
- Performance studies within the UPSG group

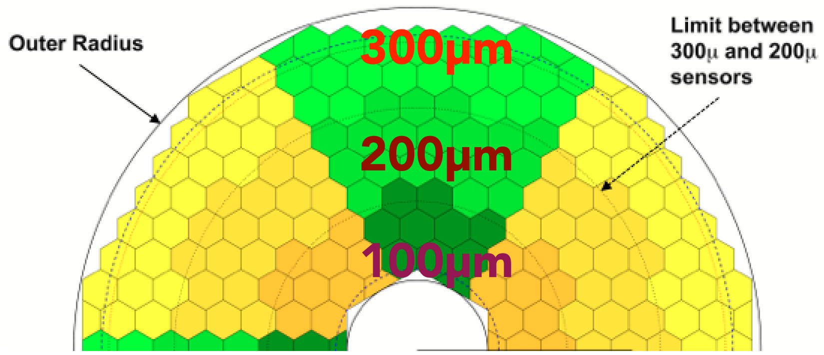
- DISCLAIMER: many plots are just preliminary and/or not the most updated

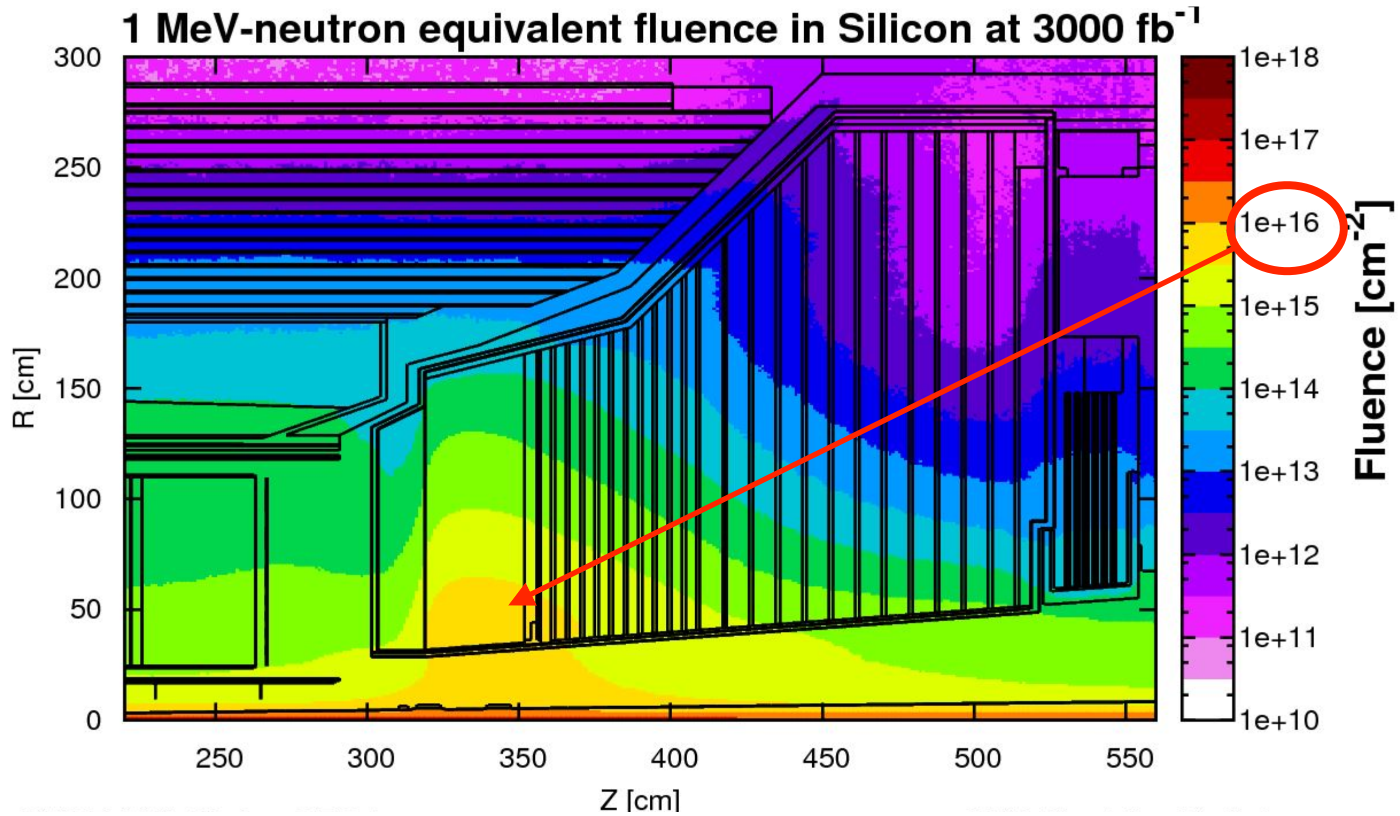
BACKUP

Silicon for radiation hardness

- Silicon can sustain high radiation levels
  - Fluence at η=3 in HGCAL ~ same as pixel inner layer => profit from extensive R&D in the past 20 years for Trackers and Pixels
  - complementary studies for neutrons irradiation up to 10^{16} n/cm^2 Fluence dominated by charged hadrons in the tracker, while by neutrons in the HGCAL







- Radiation effects are well understood and reproducible and can be partly mitigated by low T operation (-30 °C for full HGCAL)

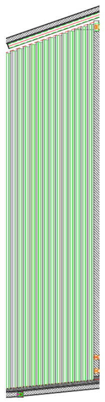
Longitudinal segmentation

- Chosen design a full disk option for all the 3 sections
  - with full disks of active material alternating full disks of absorber

CE-E

14 double-sided layers
=> 28 total sampling

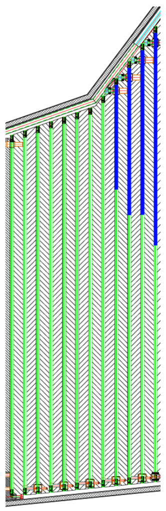
absorbers:
- Cu (6mm) + Cu/W (1.4mm)
- Pb (2mm) with SS clad (2x 0.3mm)



CE-H 1st

12 single-sided layers
=> 12 total sampling

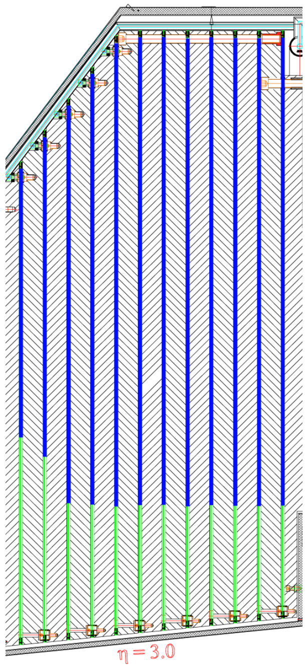
absorbers:
- Cu (6mm) + Cu/W (1.4mm)
- SS (35mm)

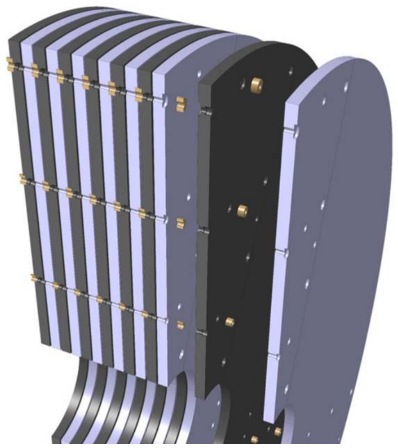


CE-H 2nd

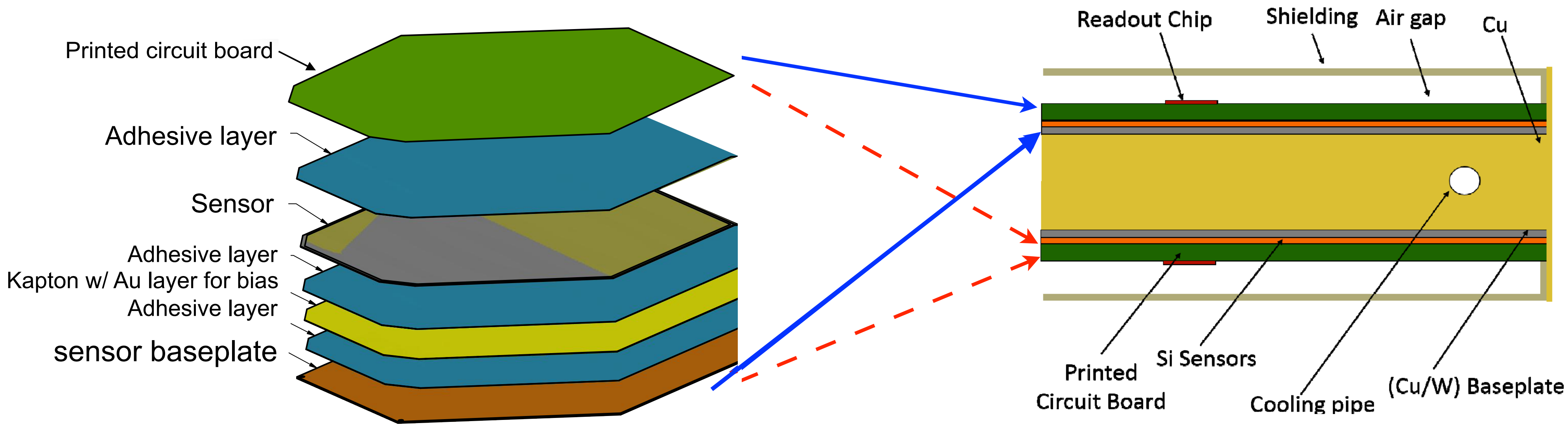
12 single-sided layers
=> 12 total sampling

absorbers:
- Cu (6mm)
- SS (68mm)





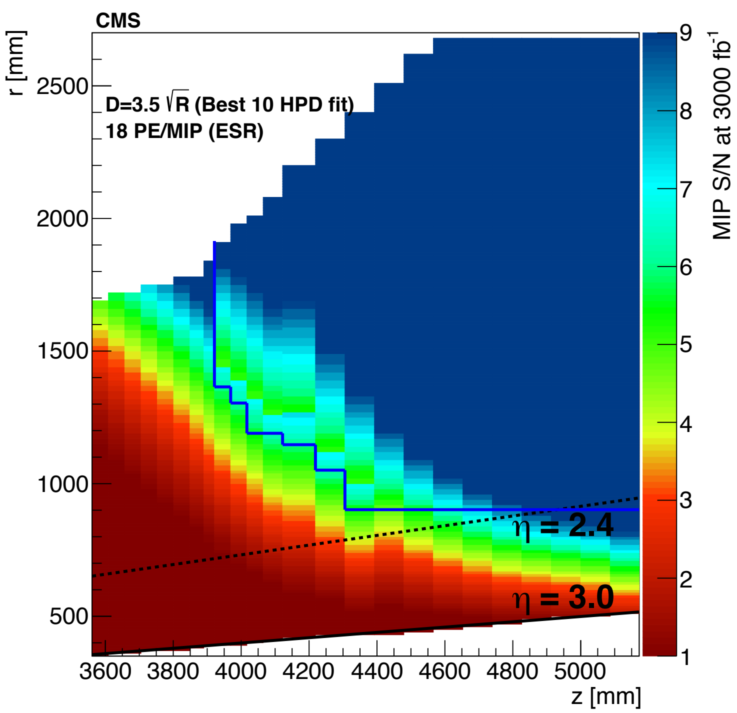
- Example of cassette structure for Si module in EE section:
  - is built up on either side of a 6 mm-thick copper cooling-plate



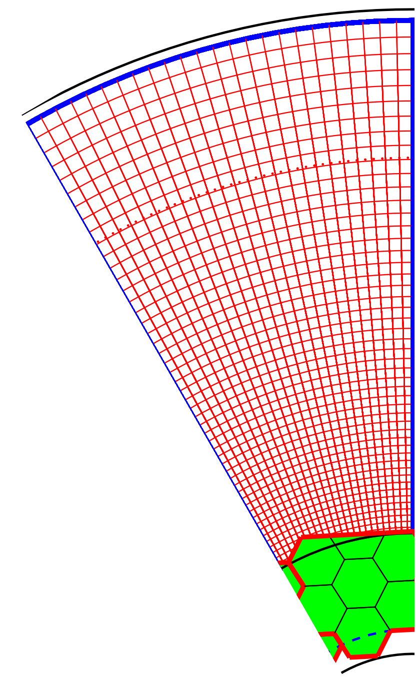
Longitudinal segmentation

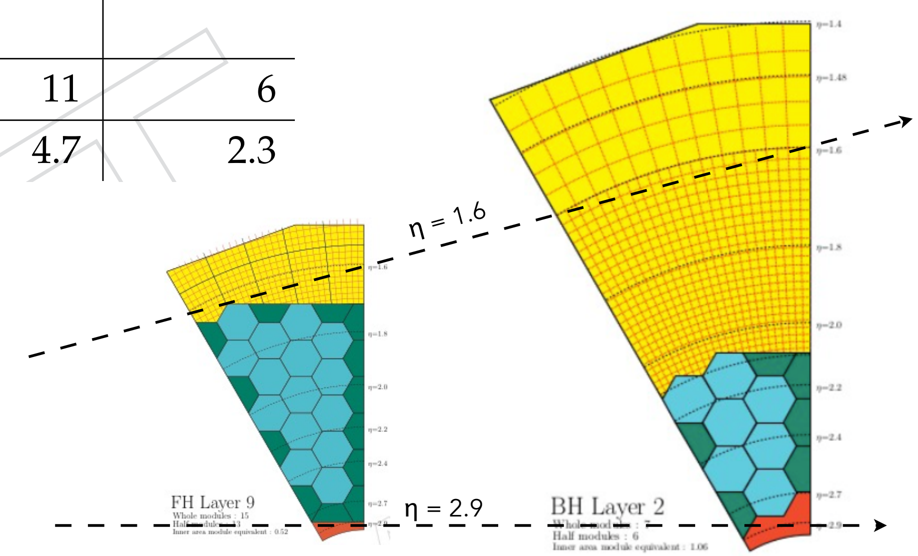
- Mixed scintillator-silicon geometry to guarantee calibration with MIPs throughout its life

- Plastic scintillator tiles used in low radiation area, with cell size function of R:
  - to maximize signal at highest radiation where SiPM noise is bigger
  - match the EB 5° cells and $4 cm^2$ trigger cells in the Silicon HGCAL
  - guarantee Silicon coverage for $|\eta| > 2.4$



	Scintillator	Si	Si
Sensor thickness	3 mm	300 μm	200 μm
Area (m^2)	480	71	15
Largest lifetime dose (Mrad)	< 0.3	30	100
Largest lifetime fluence (n_{eq}/cm^2)	8×10^{13}	6×10^{14}	2.5×10^{15}
Largest outer radius (cm)	~ 235	~ 160	~ 100
Smallest inner radius (cm)	~ 90	~ 80	~ 45
Cell size (cm^2)	2×2 to 5.5×5.5	1.18	1.18
Initial S/N for MIP	$\gg 5$	11	6
Smallest S/N(MIP) after 3000 fb^{-1}	5	4.7	2.3

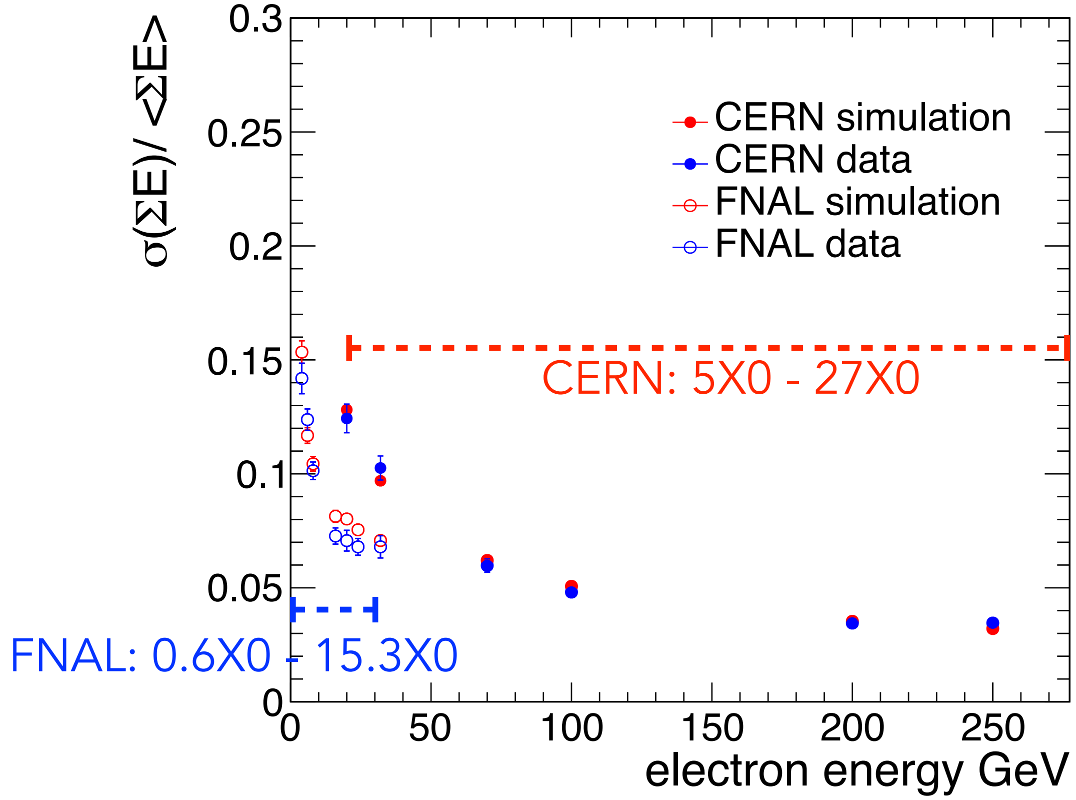


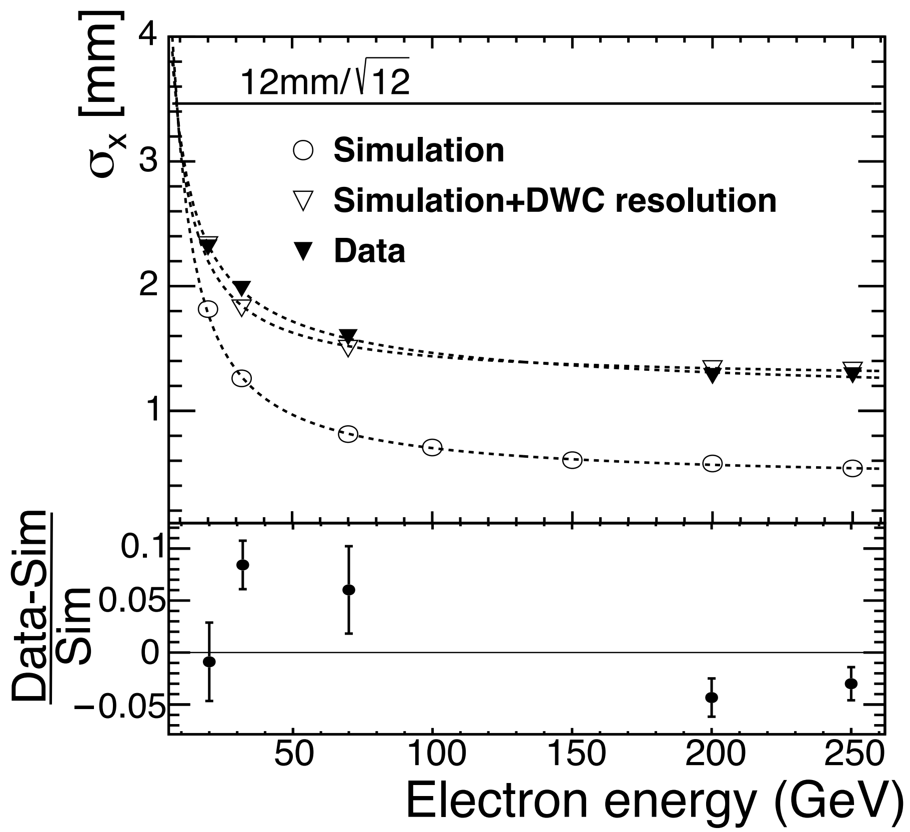


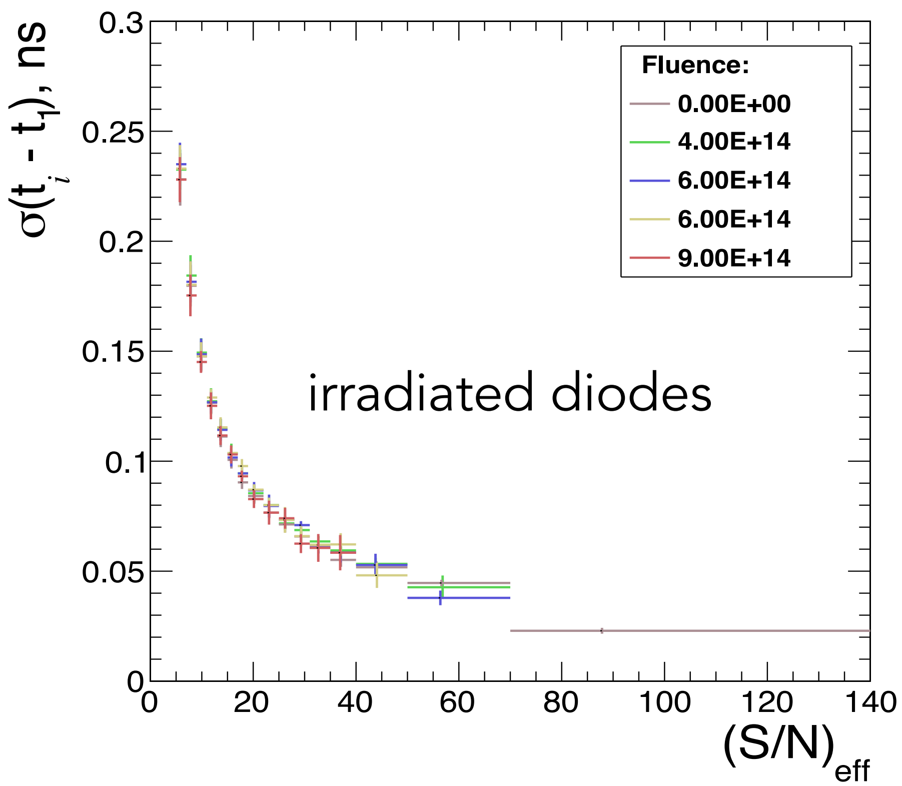
- Scintillator readout with SiPMs coupled directly to scintillating tiles
  => same SiPM as for Barrel HCAL upgrade => profit from experience and tests

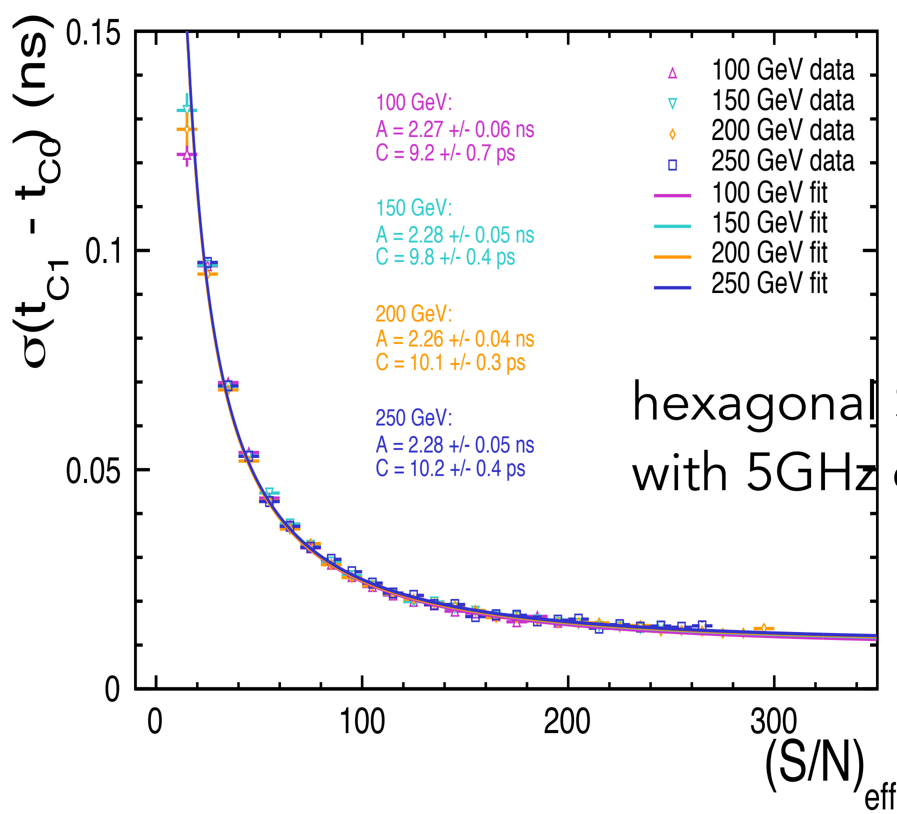
HGCAL beam test

- 2016 campaign: test Si (200μm) performance with electron showers





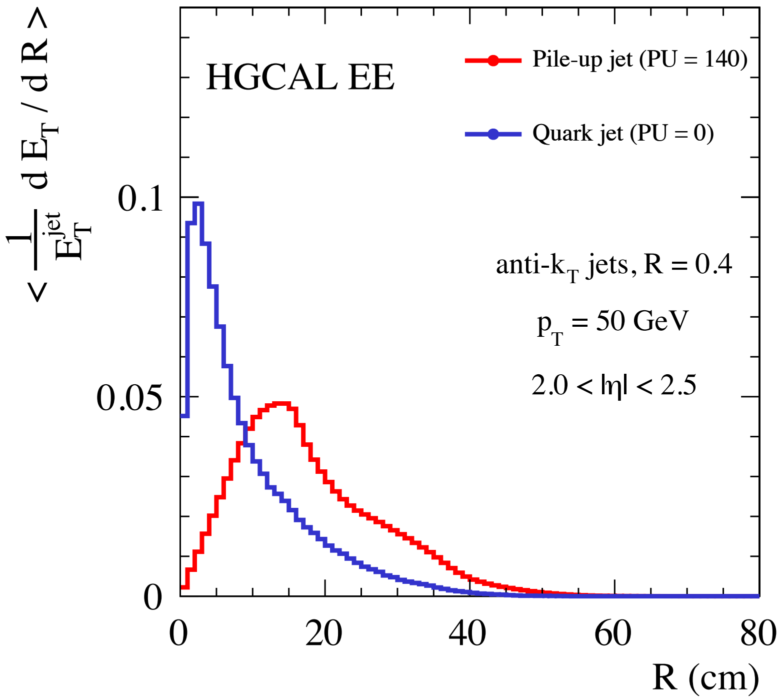


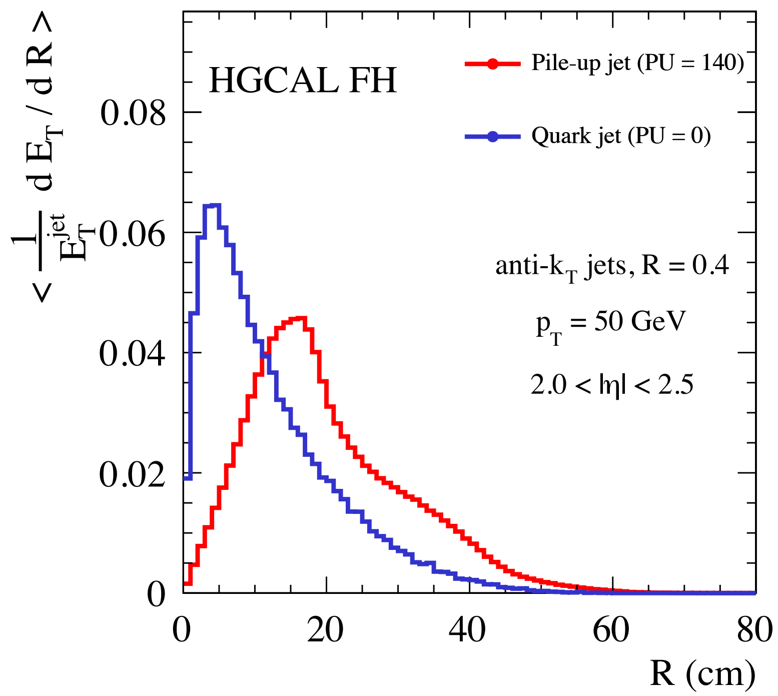


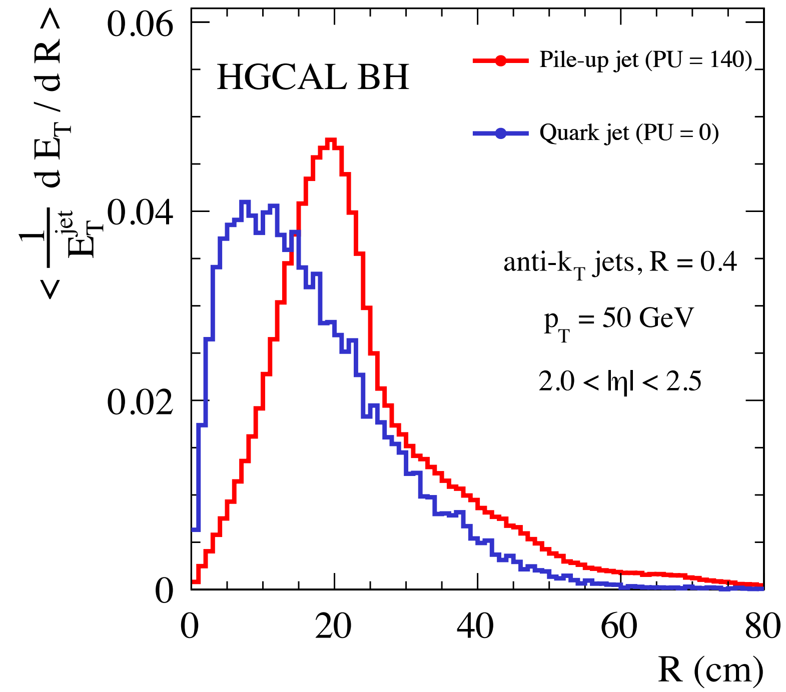
hexagonal Si module with 5GHz digitizer

Jets from calorimeter alone

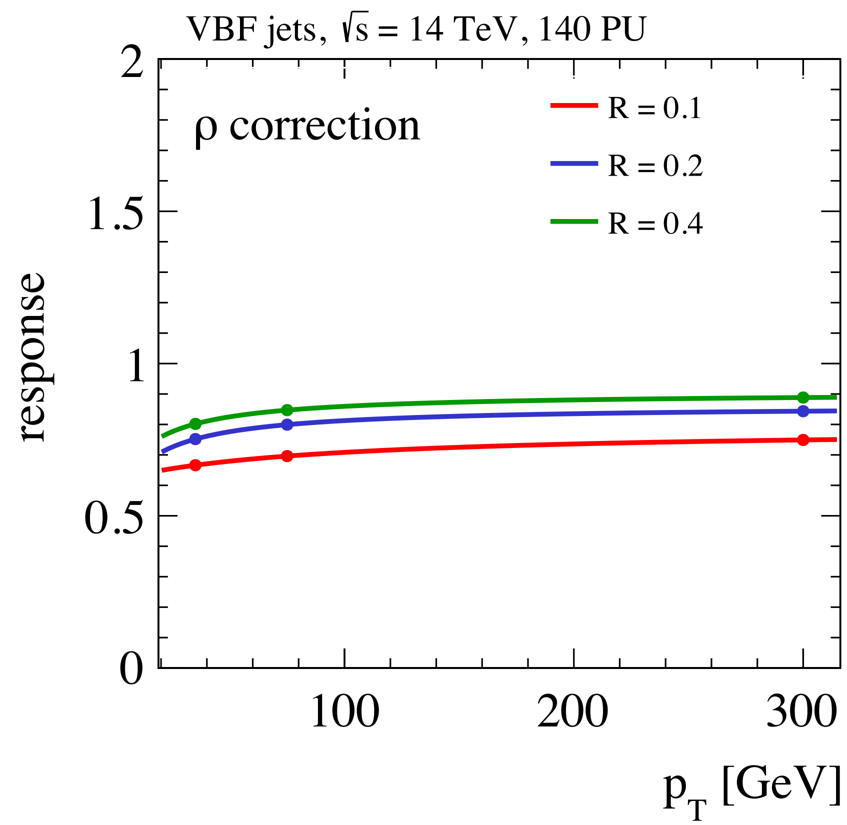
- Radial profile of jets in the 3 HGCAL sections

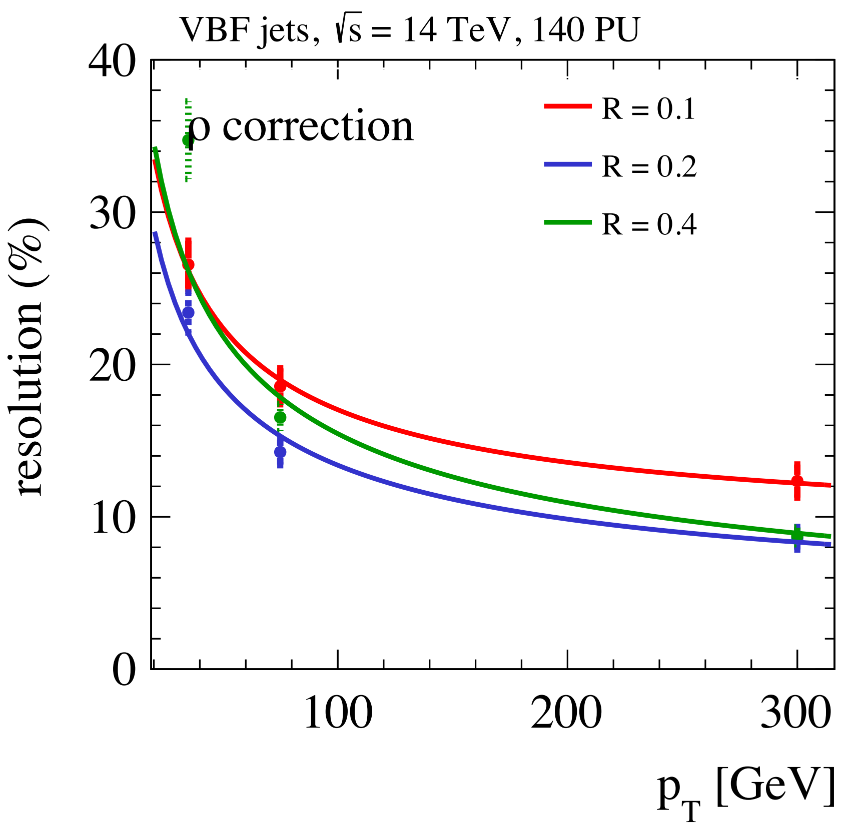






- Response and resolution for quark jets (small degradation, but compatible for gluon jets)

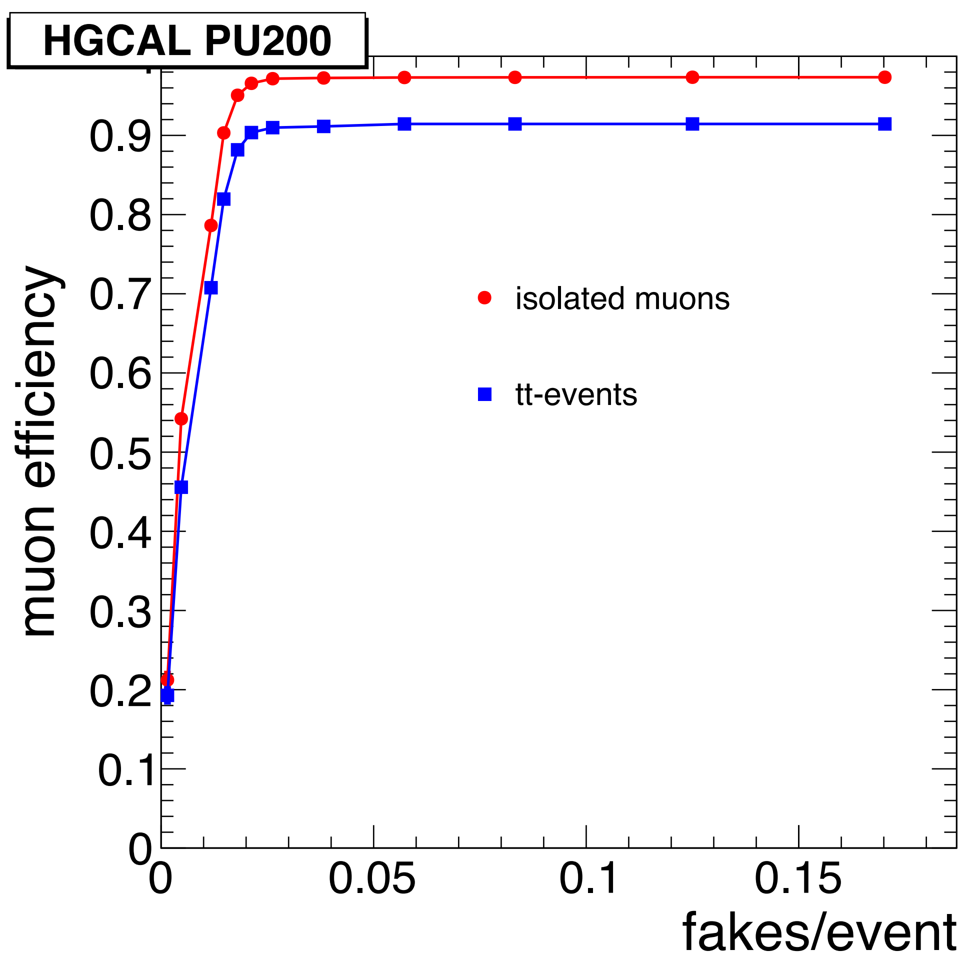


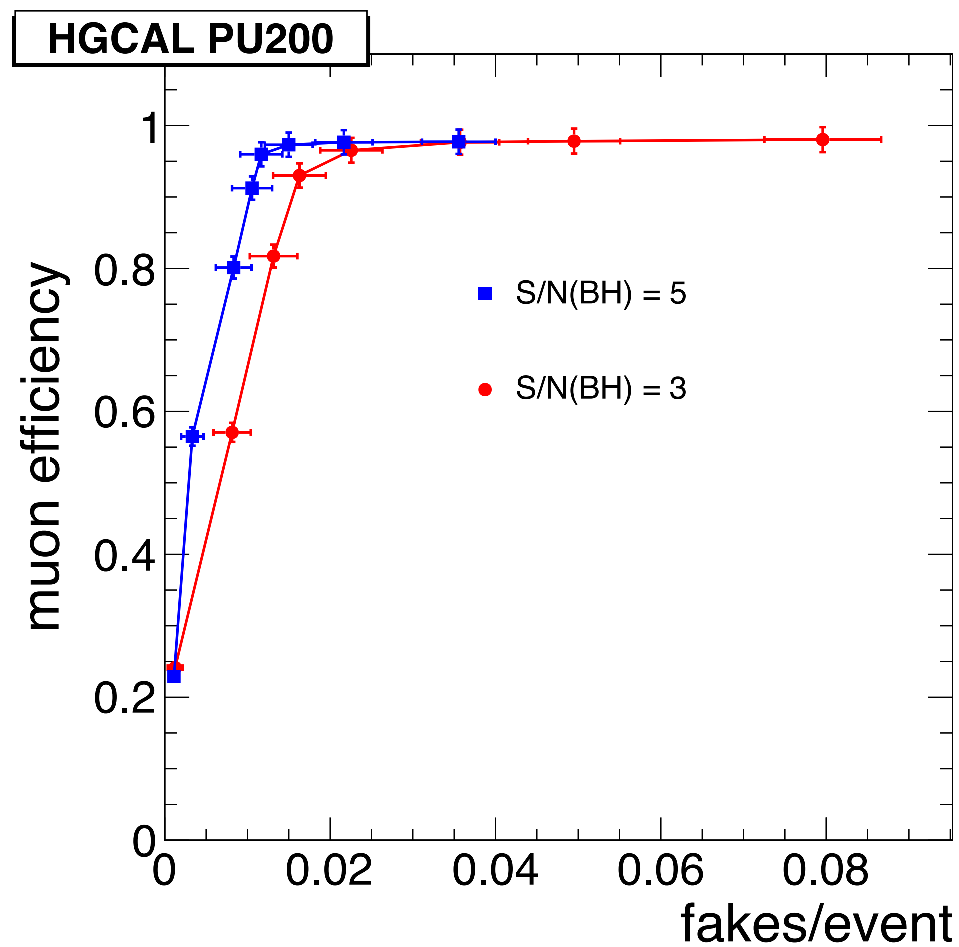


Muon ID (2 < |η| < 2.8)

- Match track propagation with signal in 1 or 1+6 cells
  - 0.5 < charge per cell < 3MIP and summed charge per layer < 3MIP
  - ask for a minimum of consecutive layers in BH

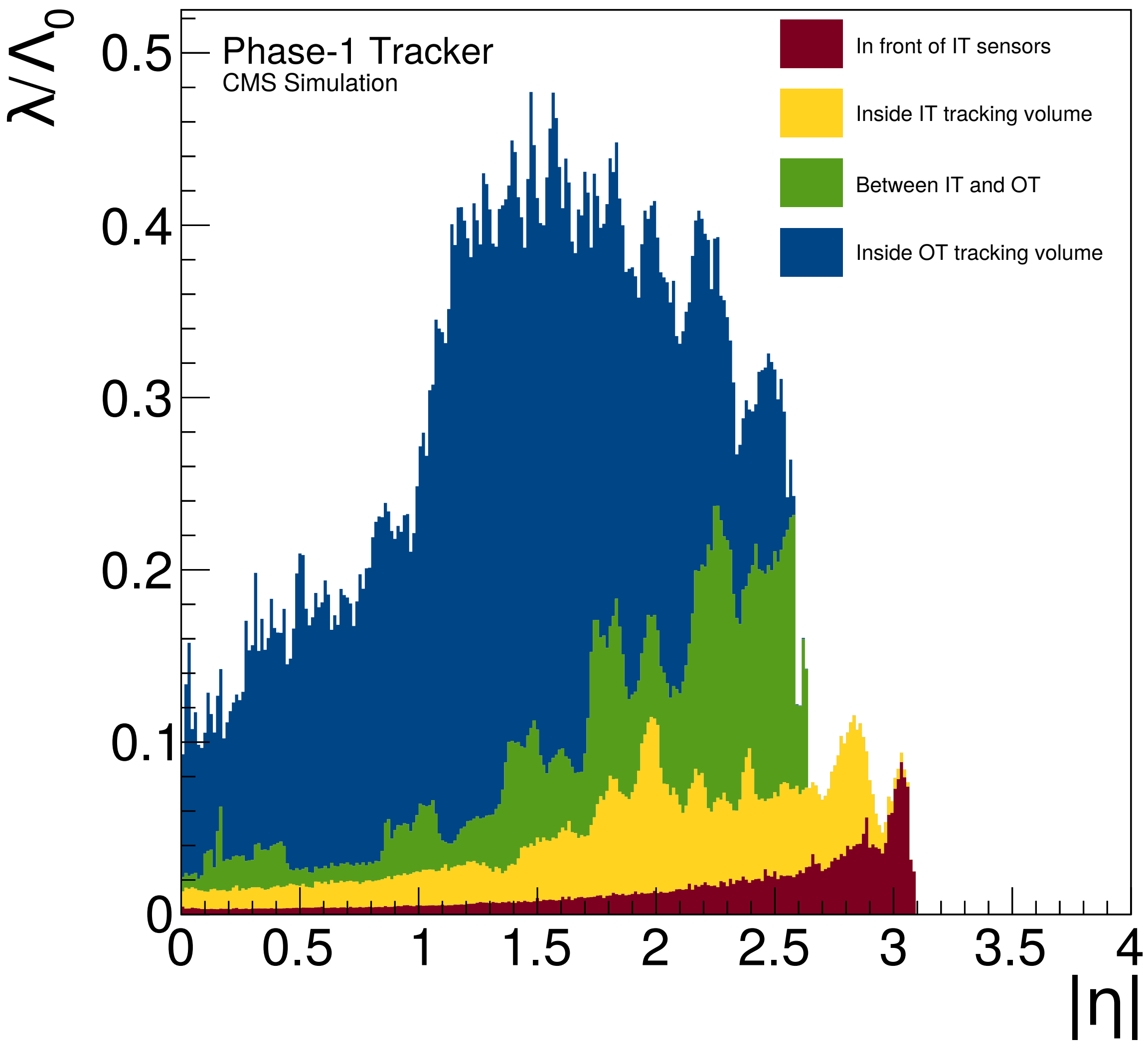
- Study with muons pT > 5GeV and plateau efficiency 97% (99% from tracking efficiency)
  - results solid against readout threshold (0.5MIP to 0.75MIP) and S/N with aged detector

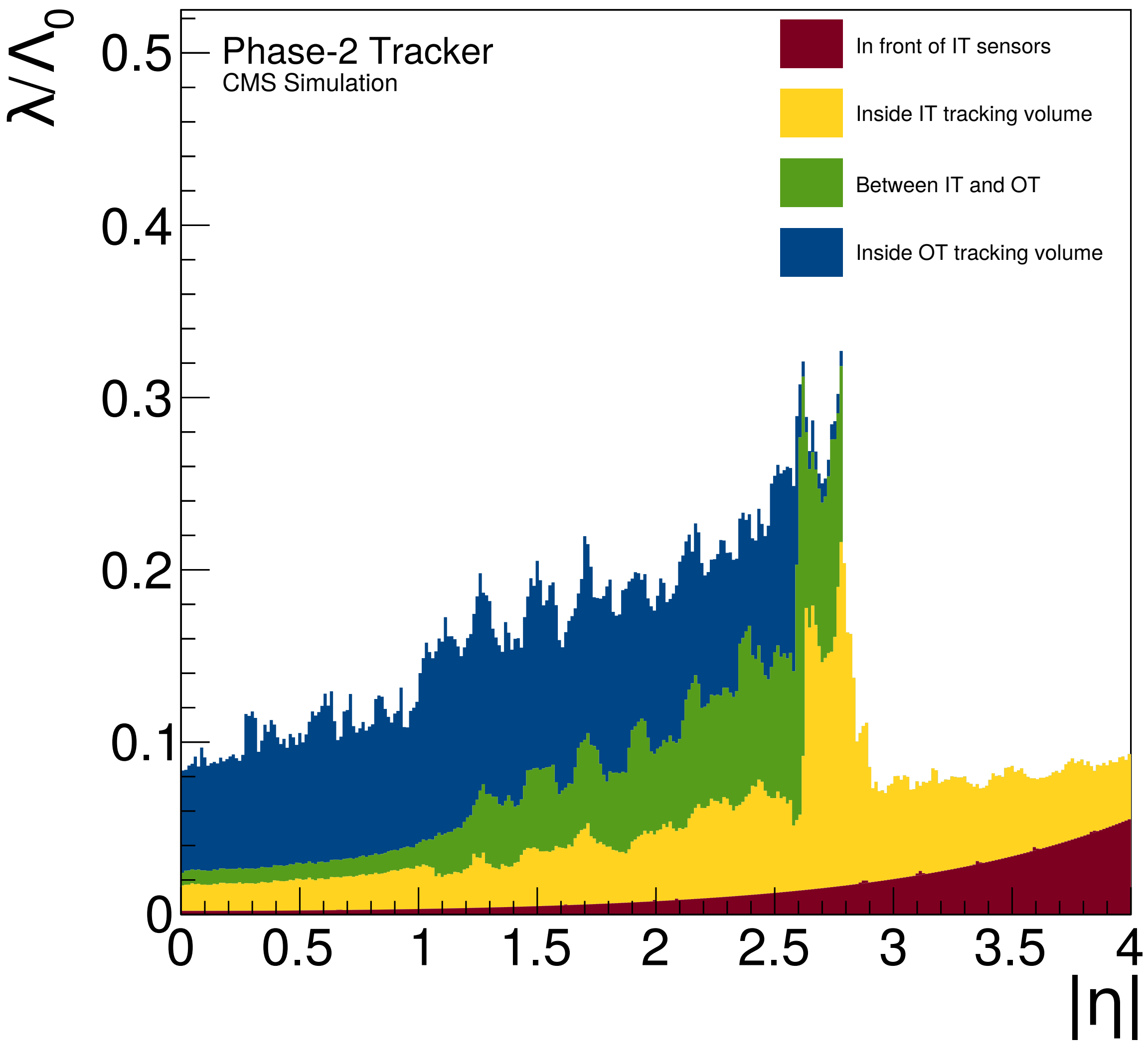




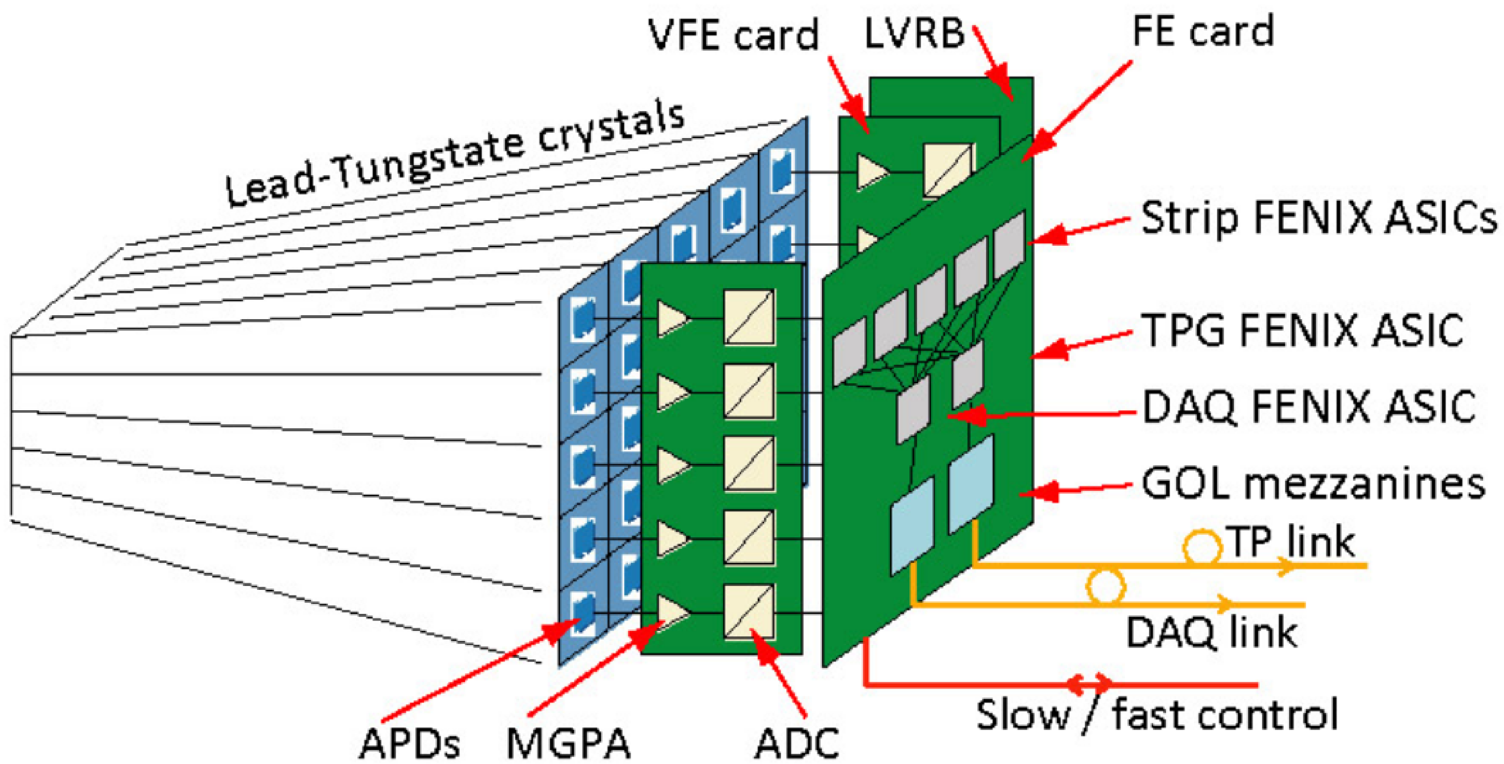
- Effect of slow neutrons evaluated with simulation and calculation with first principle => found negligible (≈ few permill probability)

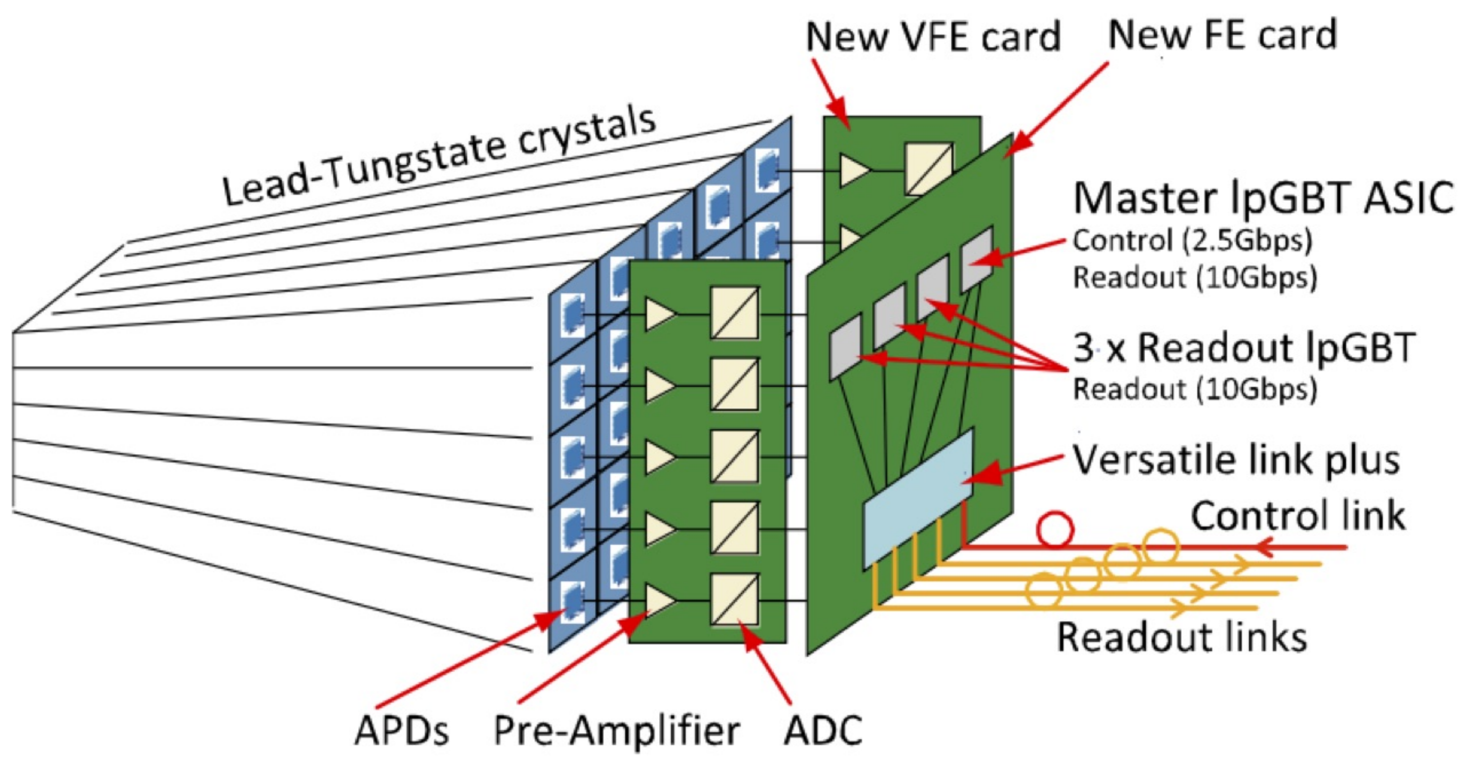
Tracker material budget





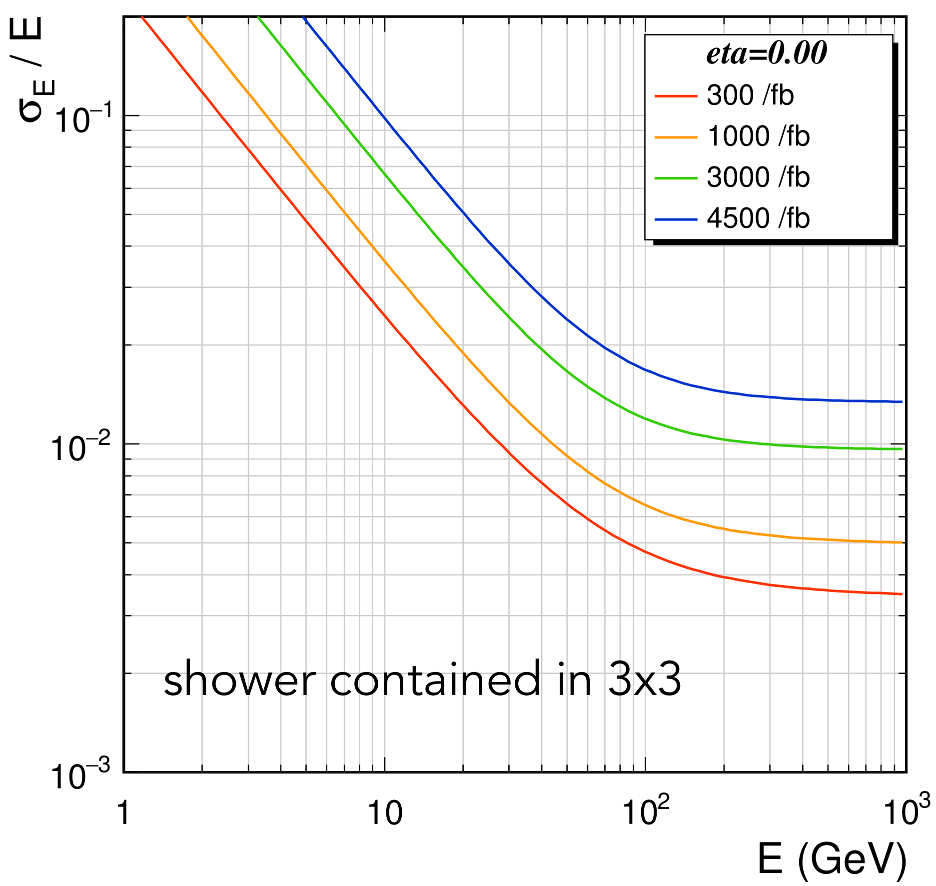
EB VFE and FE

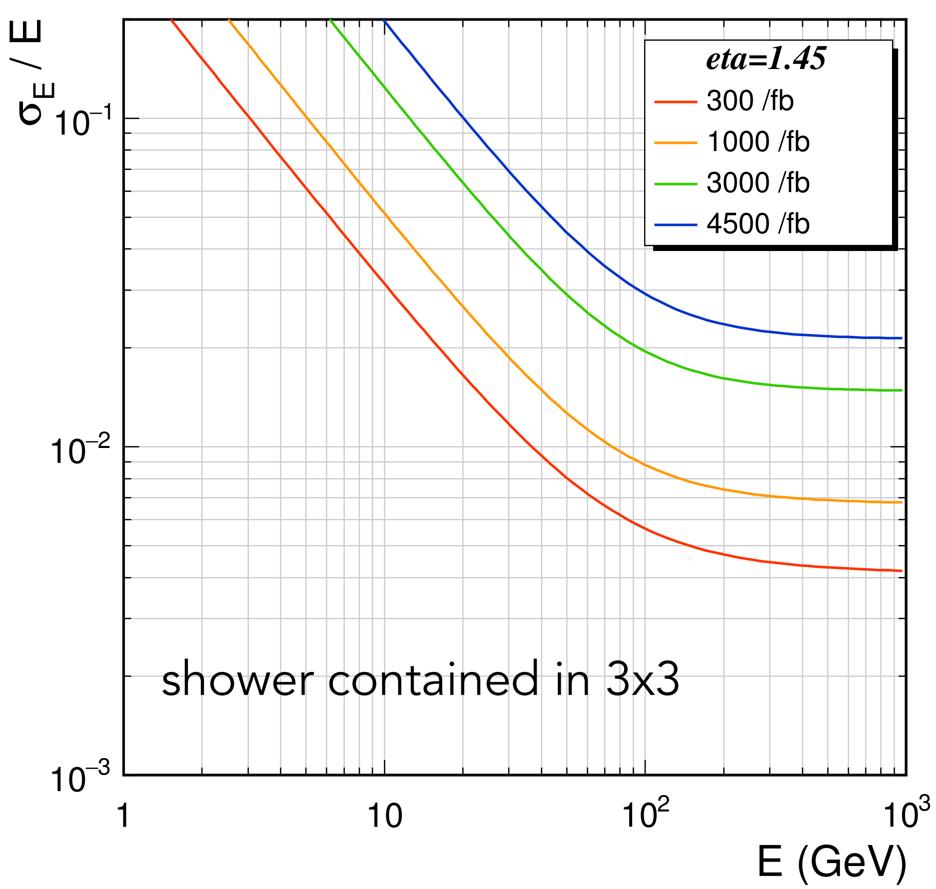

VFE card
LVRB
FE card
Lead-Tungstate crystals
Strip FENIX ASICs
TPG FENIX ASIC
DAQ FENIX ASIC
GOL mezzanines
TP link
DAQ link
Slow / fast control
APDs
MGPA
ADC


New VFE card
New FE card
Lead-Tungstate crystals
Master lpGBT ASIC
Control (2.5Gbps)
Readout (10Gbps)
3 x Readout lpGBT
Readout (10Gbps)
Versatile link plus
Control link
Readout links
APDs
Pre-Amplifier
ADC

ECAL energy resolution

- Energy resolution with upgraded detector

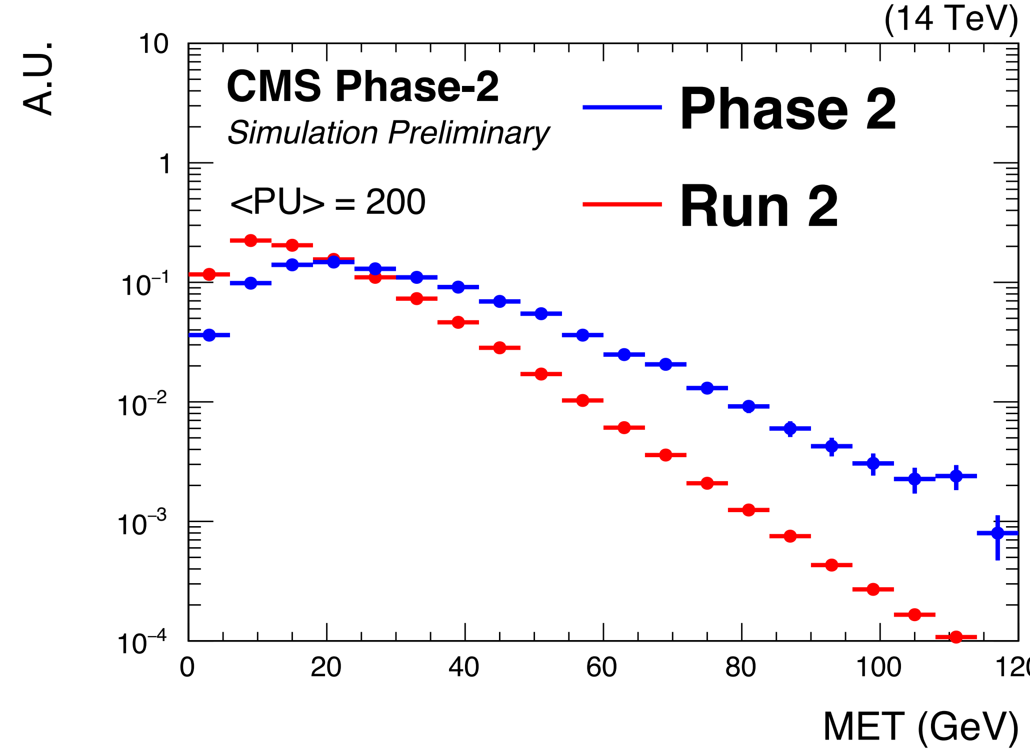


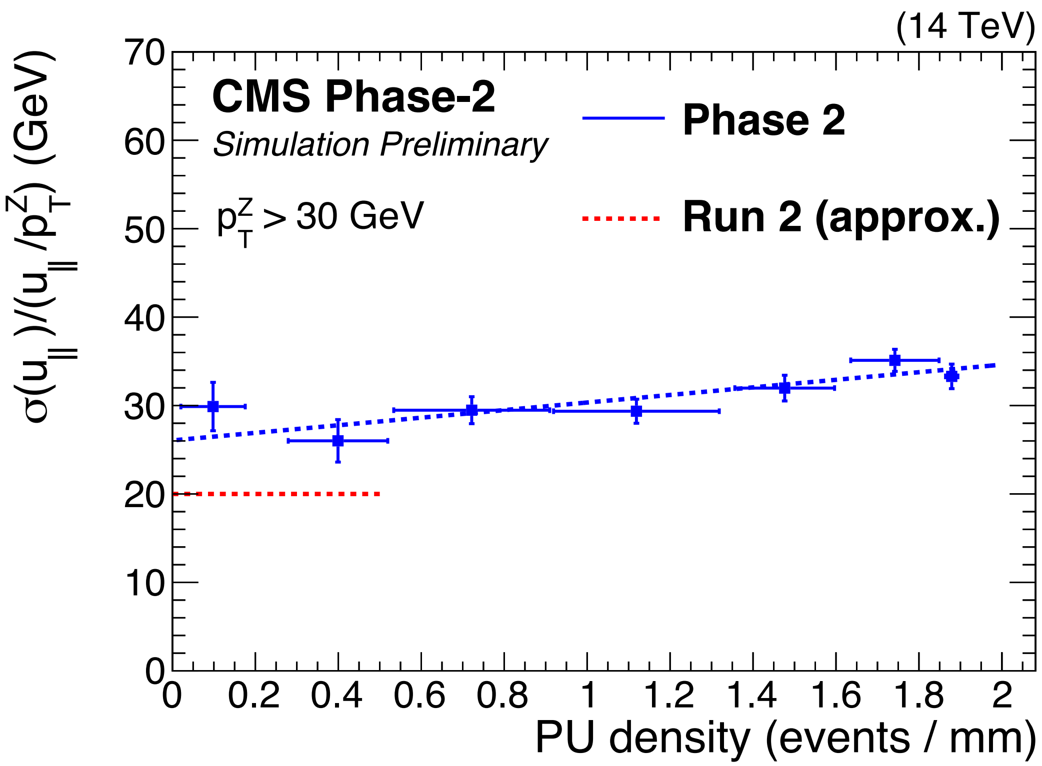


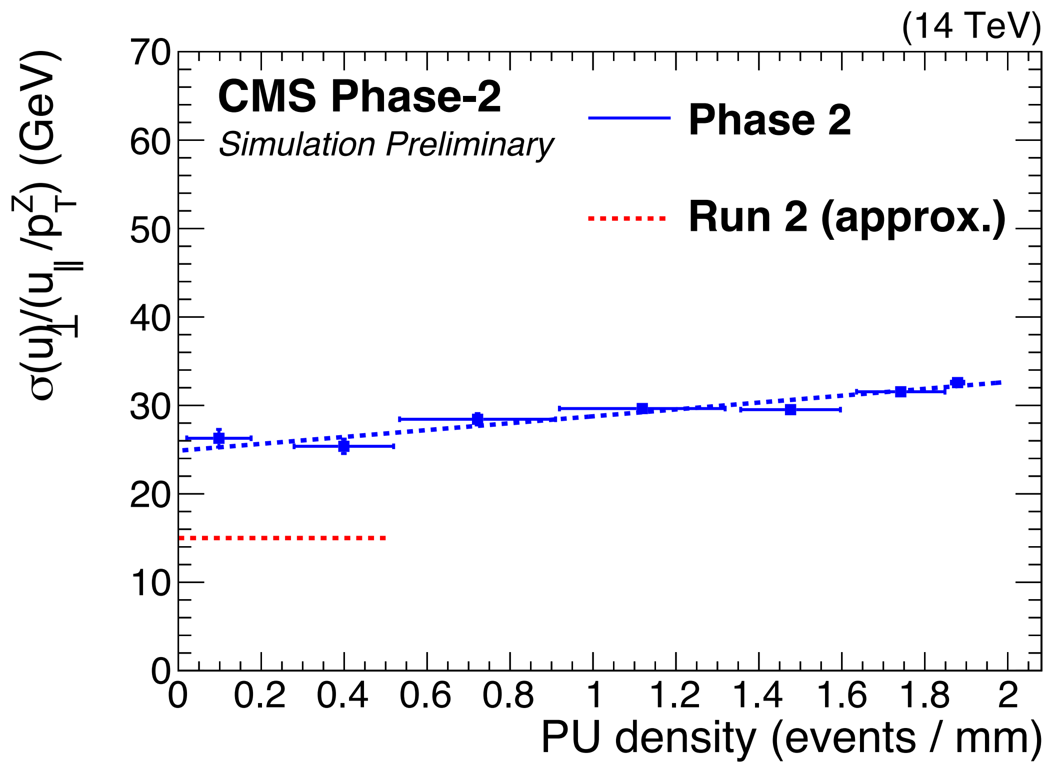
MET

- Expect worst performance from calo-only MET at PU 200
- Fundamental to tune reconstruction with full CMS information

Preliminary performance for PUPPI MET in Z->μμ events

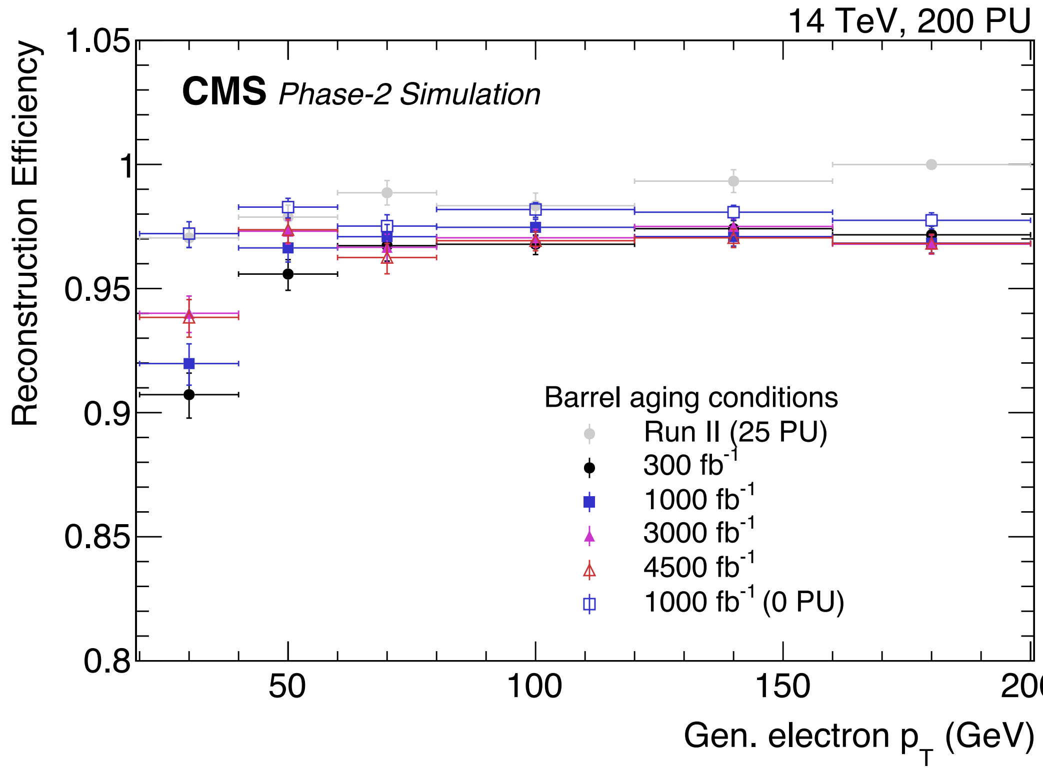


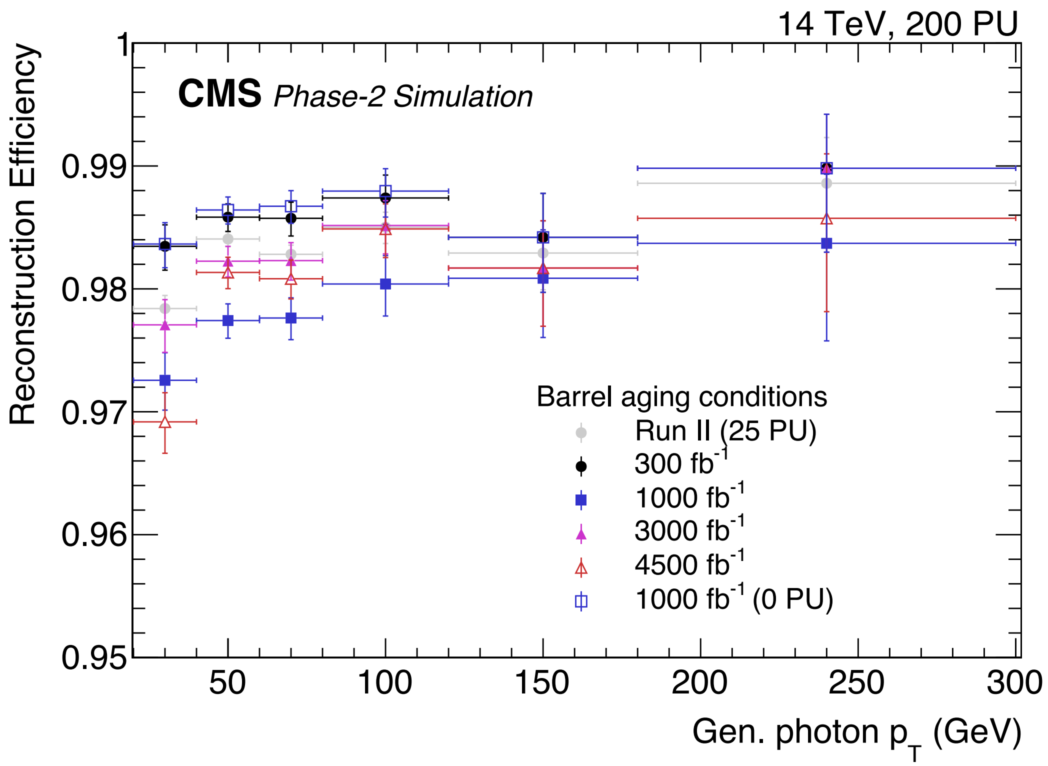




EB electron - photon performance

- Same performance as in Run2 at high pT
  => deficit for electrons at low pT, due to un-tuned reconstruction





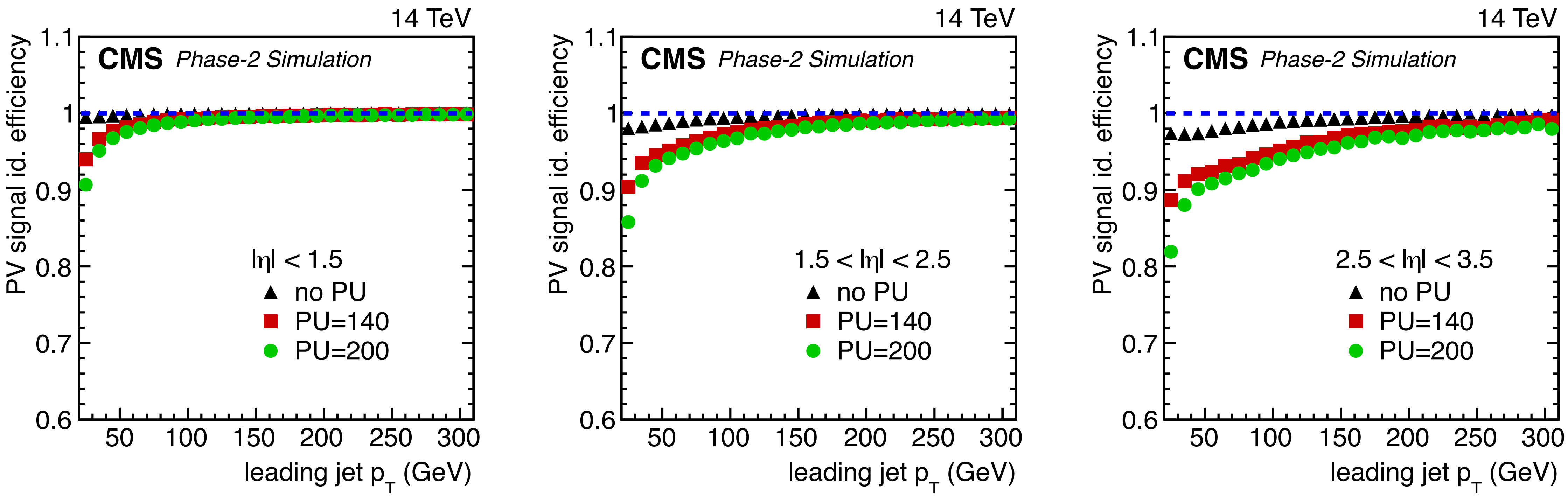
- Resolution for single photons

Detector conditions	Photon category	$\sigma_{\mathrm{eff}}(E)/E$ $p_T^{\gamma} = 50$ GeV	$p_T^{\gamma} = 100$ GeV
Pileup 200, 300 fb^{-1} ageing	E3×3, unconverted photons	1.8%	1.5%
	max15, all photons	2.5%	1.6%
Pileup 200, 1000 fb^{-1} ageing	E3×3, unconverted photons	2.1%	1.6%
	max15, all photons	2.7%	1.7%
Pileup 200, 3000 fb^{-1} ageing	E3×3, unconverted photons	3.0%	2.2%
	max15, all photons	4.8%	2.5%
Pileup 200, 4500 fb^{-1} ageing	E3×3, unconverted photons	3.9%	2.8%
	max15, all photons	6.0%	3.6%

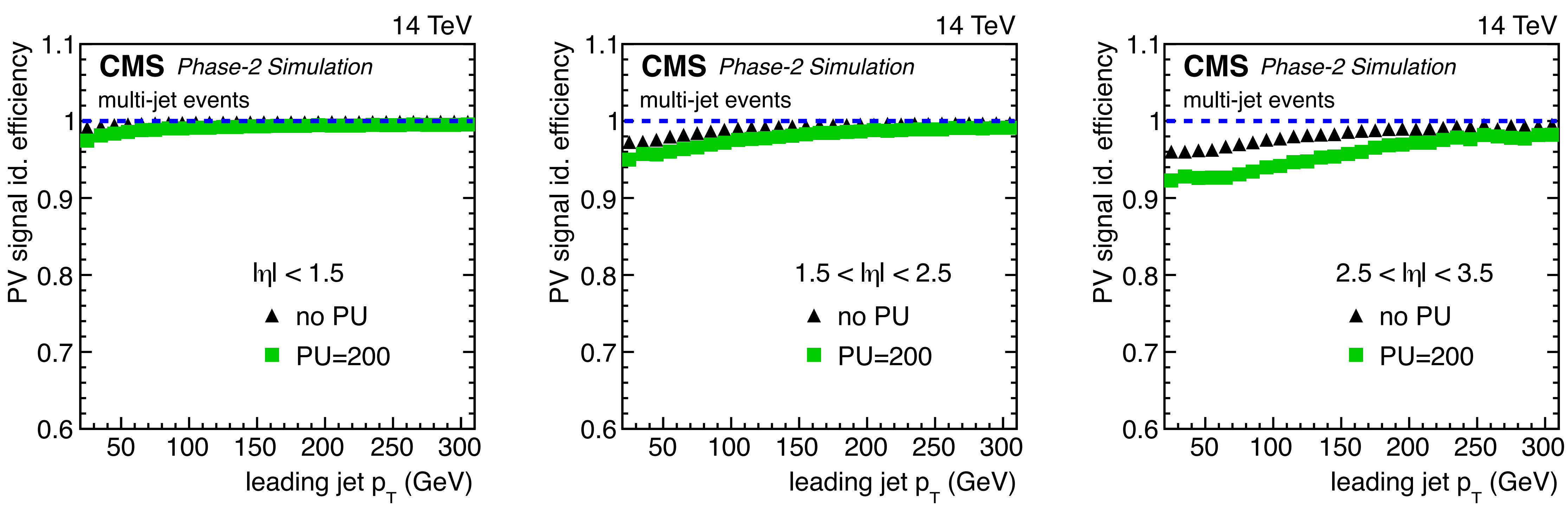
Vtx efficiency

- Gain at low pT, improved particle-flow (reject fakes) in particular at high eta

tracker TDR



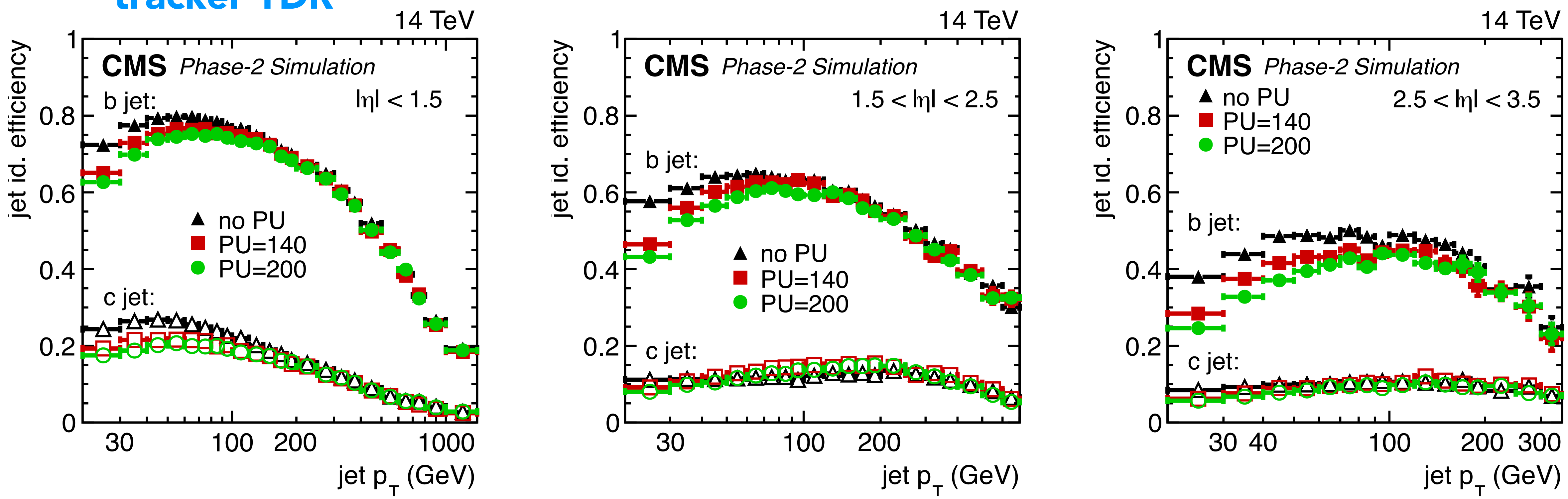
HGCAL TDR



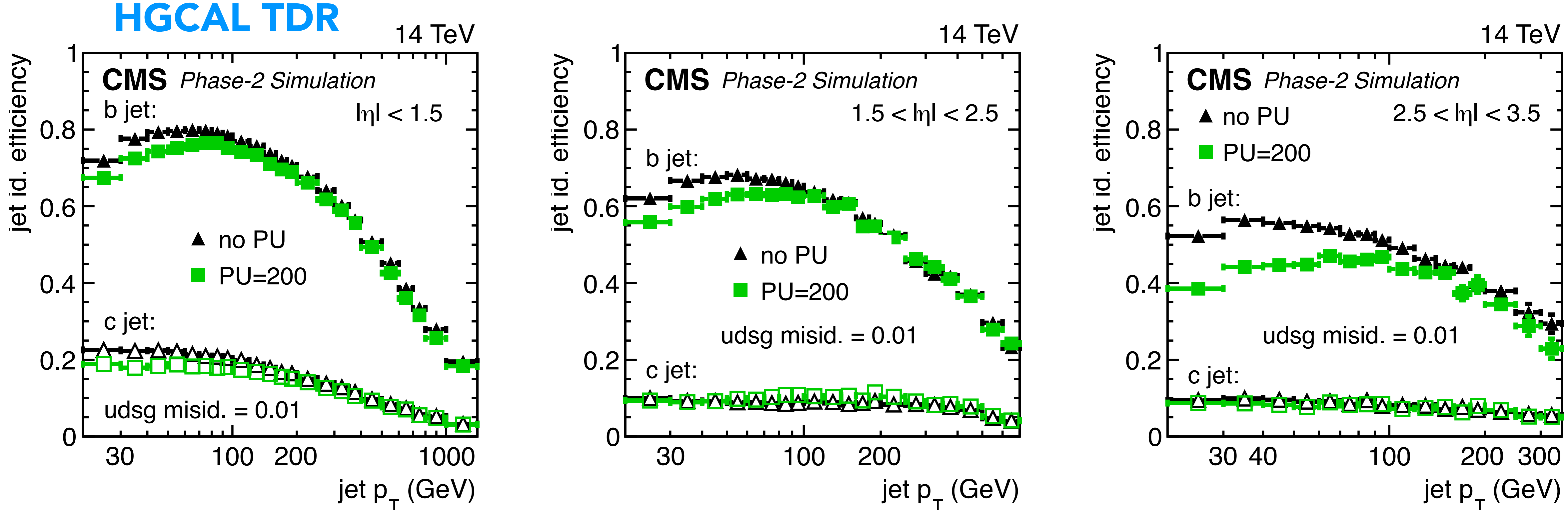
b/c tagging efficiency

- Improved efficiency with PU and at low pT, in particular in the very forward region

tracker TDR



HGCAL TDR

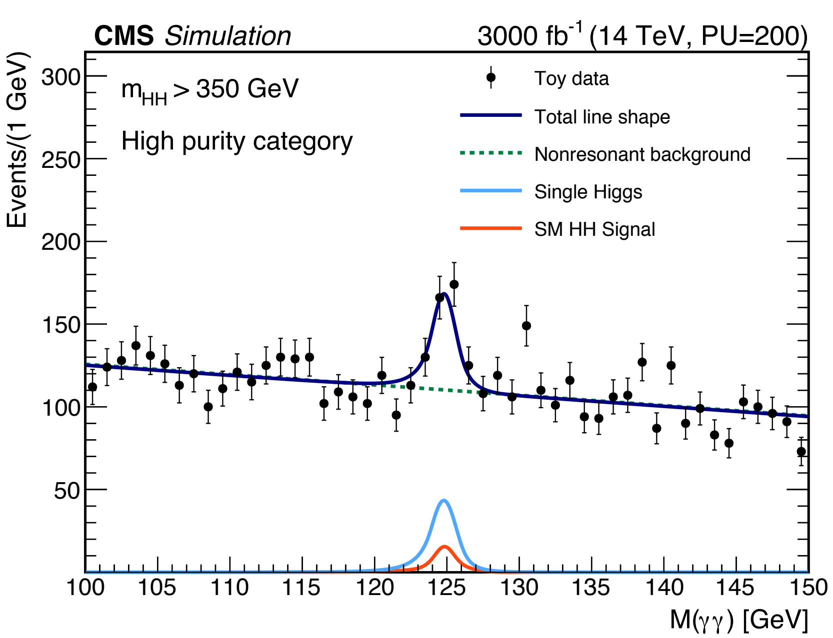


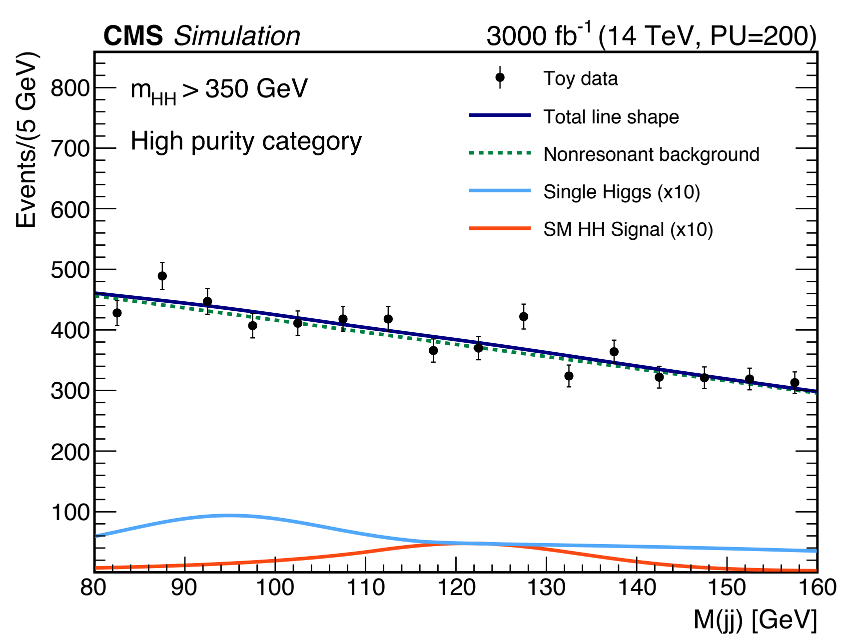
HH->γγbb (EB-TDR)

- Account for pileup to worsen the isolation efficiency, for both signal and background
  - a reduction of 2.3% in identification efficiency for prompt photons applied in the barrel
  - a 10% reduction has been applied in the endcaps

- b tagging efficiency from 69% to 74% per jet => increase of the signal efficiency by 15%, as well as of VH, ttH and bbH backgrounds

- The Mγγ observable allows to separate the signal from non-resonant background but not form resonant single H boson background
- The Mjj observable improves the separation between single H and HH signal





acceptance at high η can help the background rejection