LHC detectors
Upgrades for HL-LHC

7th ENHEP School on High Energy Physics
26-31 January 2019
Ain Shams University Cairo - Egypt

Ludwik Dobrzynski

Laboratoire Leprince Ringuet - Ecole polytechnique - CNRS - IN2P3

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- Introduction
- Physics objectives
- Hadron collider detectors
- Detector upgrades for future searches
- Conclusion

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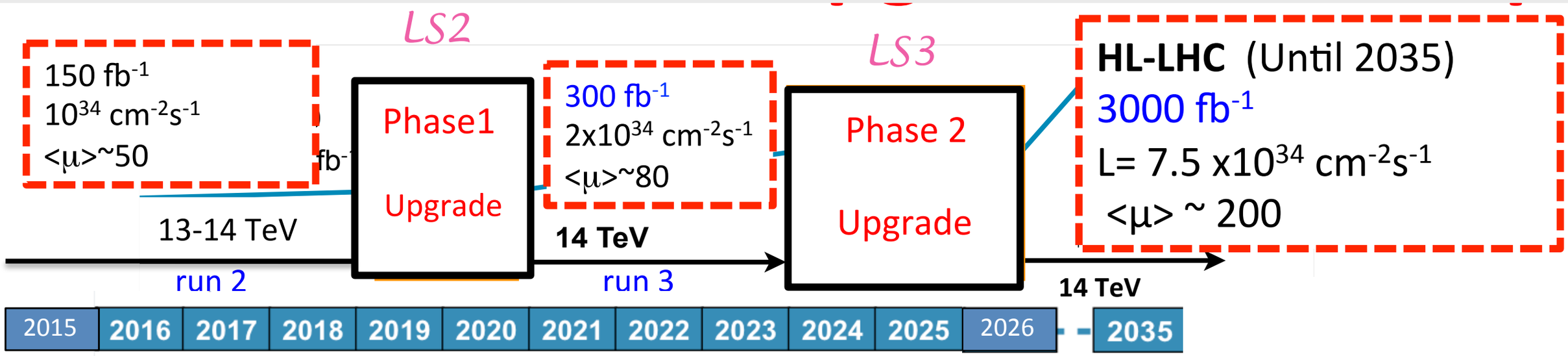
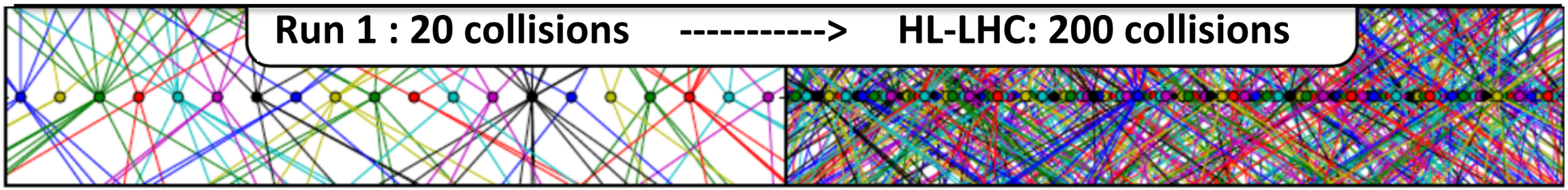
LHC ATLAS and CMS upgrades road map





Detector challenges:

- x 10 more radiation (~ 10^{16}neq/cm^2 ; 10 MGy)
- x 10 more pile-up
  - **Run1:** <μ>=20 ;<$n_{PU\ jets\ pT>30GeV}$> ~ 0.04
  - **HL-LHC:** x10 <μ>=200 ;<$n_{PU\ jets\ pT>30GeV}$> ~ 7.4 x185

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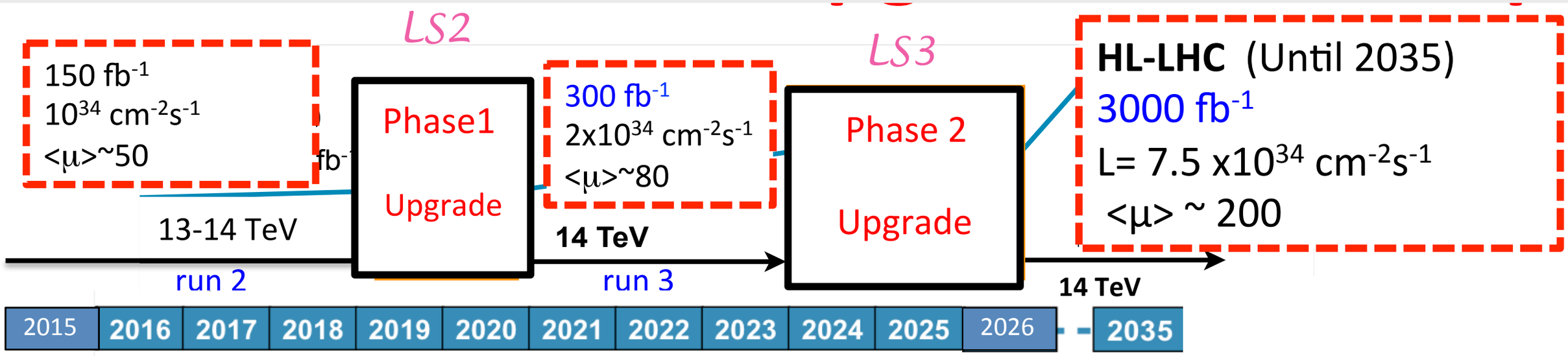

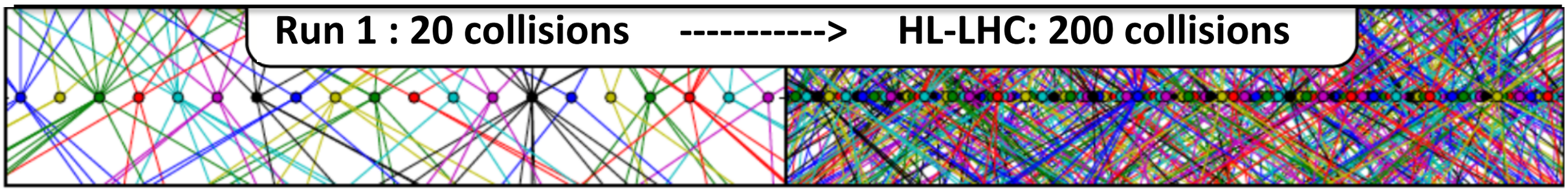

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Detector Upgrades needed to:

· *keep performance of the detector (tracking, b-tag, jet/Etmiss,...)*

. *Trigger rates acceptable with low P_T thresholds*

key issues: radiation tolerance and detector occupancy

Physics motivation at HL@LHC

- Electroweak symmetry Breaking
  - Higgs precision measurements (coupling and spin …)
  - Higgs rare and invisible decays (H@>μμ , H@>Zγ,…)
  - Top Yukawa coupling (tH)
  - Higgs self coupling (HH)
- Discovery of SM di-Higgs (HH) production is one of the main objective
  - as HH production will help us to measure the Higgs Boson self coupling, which determines the shape of the Higgs potential and helps us to understand the vacuum stability of the universe

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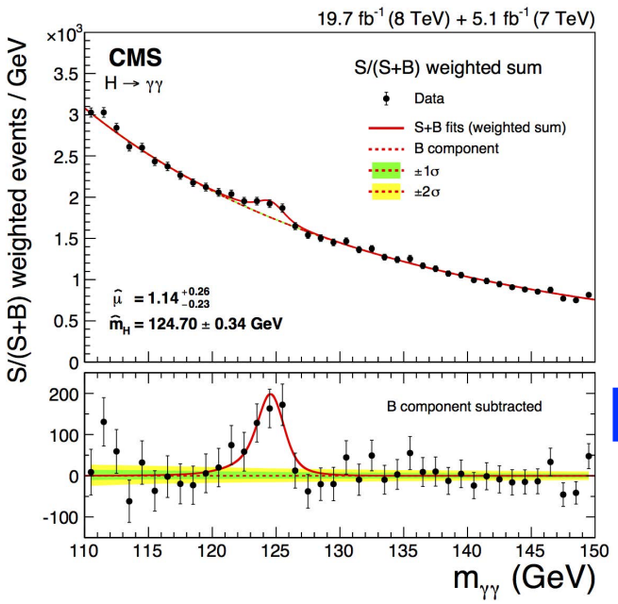
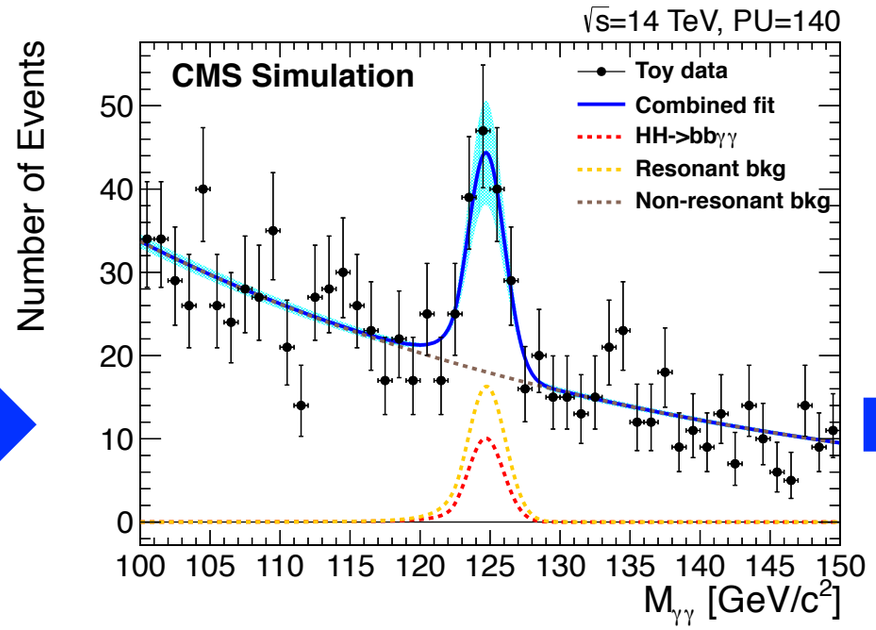
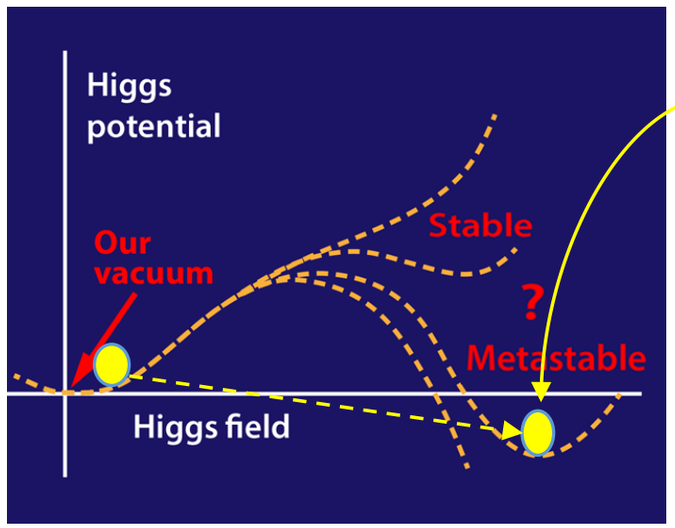


H(bb)H(γγ) discovery @ HL-LHC



Vacuum stability of Universe



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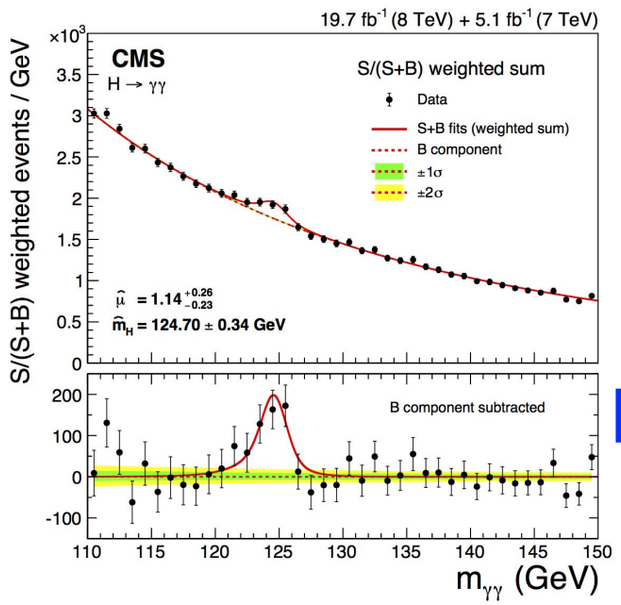

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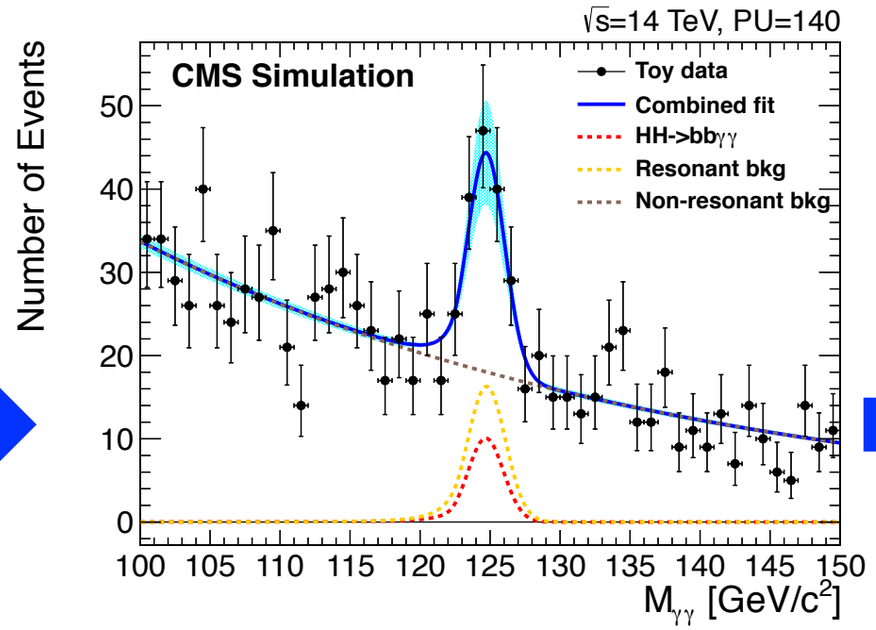

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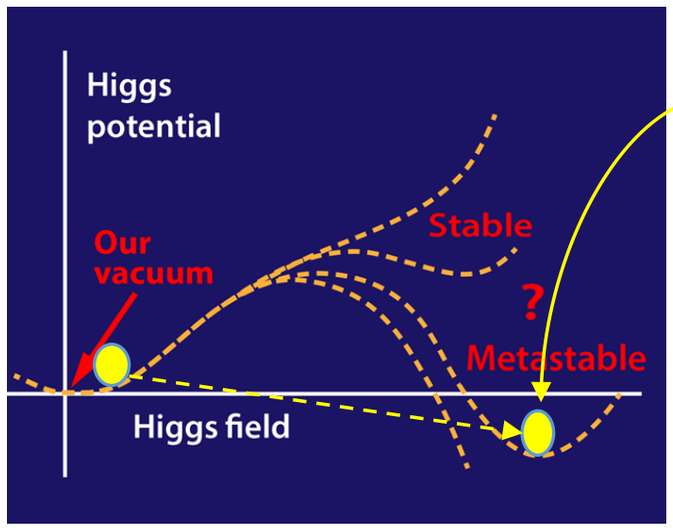

- *Beyond the Standard Model*
  - *Higgs sector (search for deviations from SM)*
  - *Dark mater*
  - *SUSY*
  - *Exotics*

Phase II Upgrade requirements

- Induced ageing due to Radiation imply
  - Replacement of tracker and part of calorimeters
- High pile-up in Run-4 imply
  - Upgrade of front-end and back-end electronics, trigger and DAQ
- Physics expectations
  - Access opportunities at 3/ab: Higgs; SUSY; SMP rare decays

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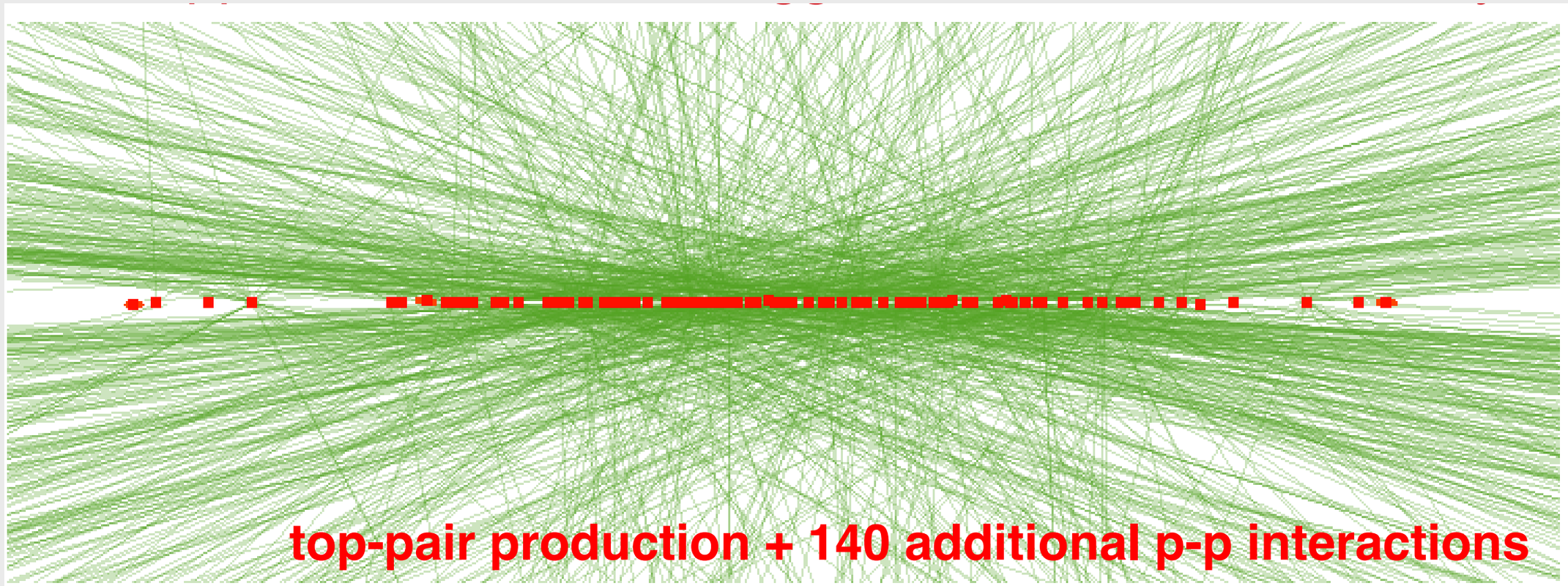

CMS Upgrade : Phase II Overview

Pixel detector:
- replace barrel layer 1 (guideline 250 fb-1 max lumi)
- replace all DCDC converters

Tracker
- Radiation tolerant, high granularity, low material budget
- Coverage up to $|\eta|=3.8$
- Track-trigger at L1

Install new **beam pipe** for phase II

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- New BE/FE electronics
- ECAL: lower temperature
- HCAL: partially new scintillator

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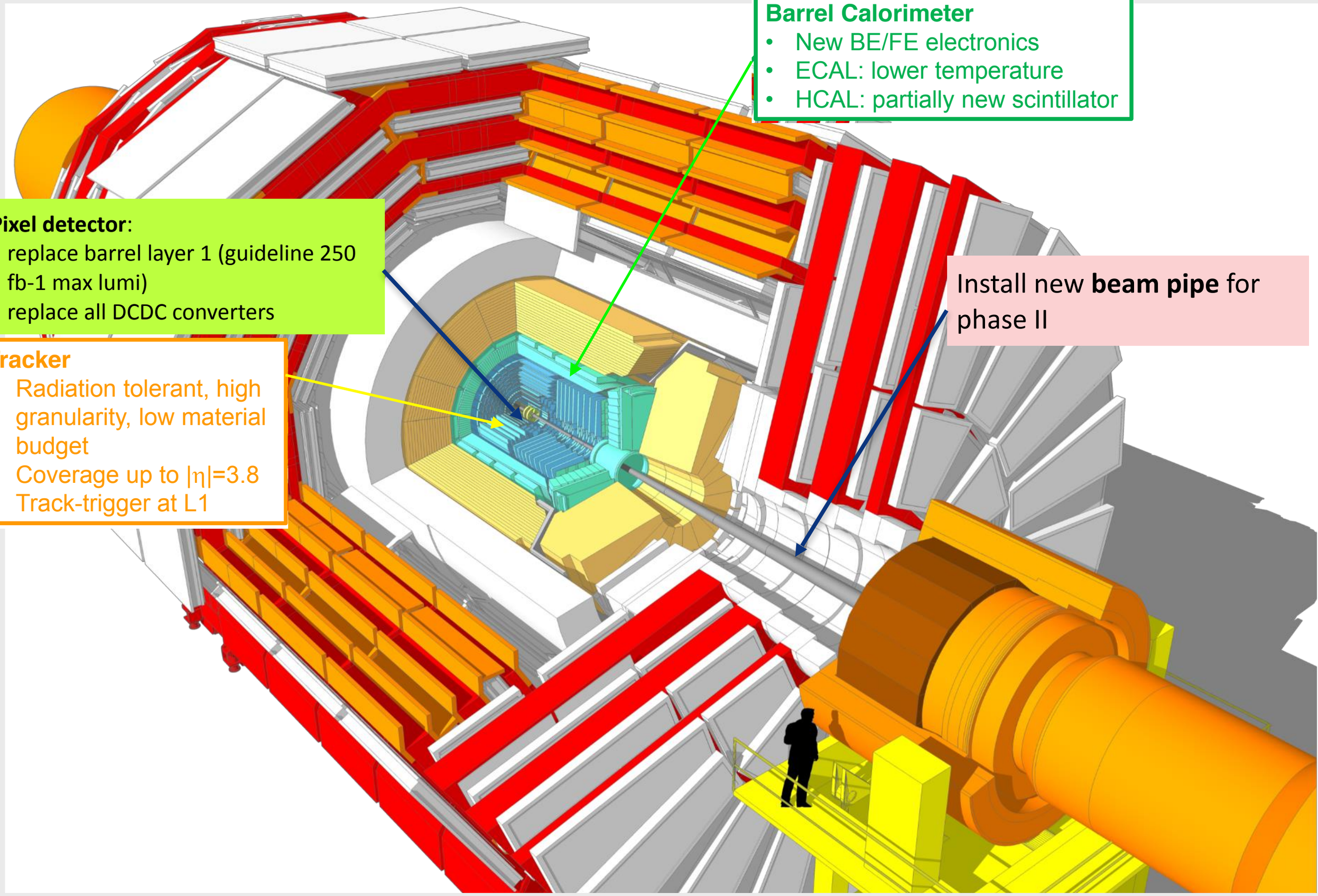

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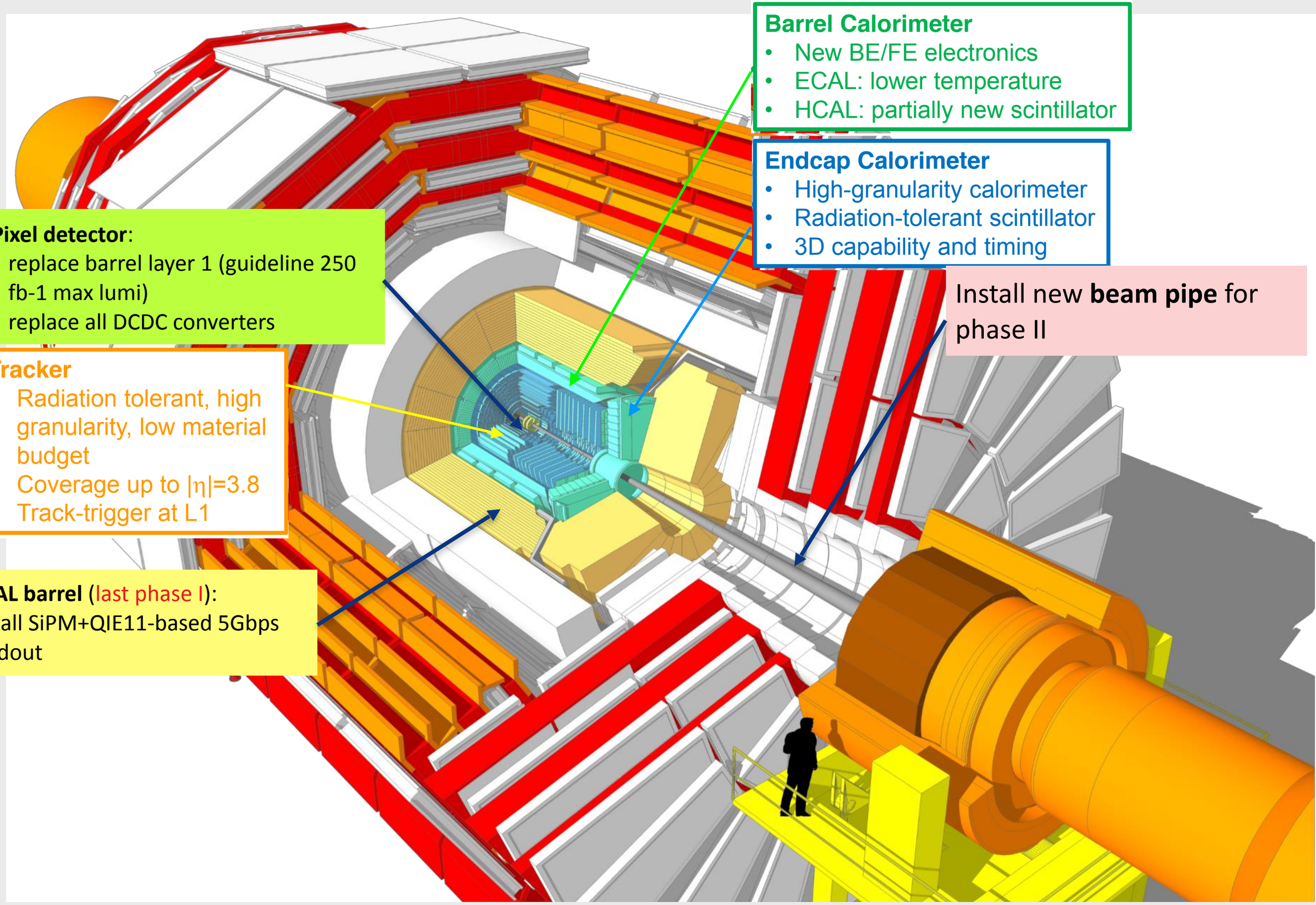

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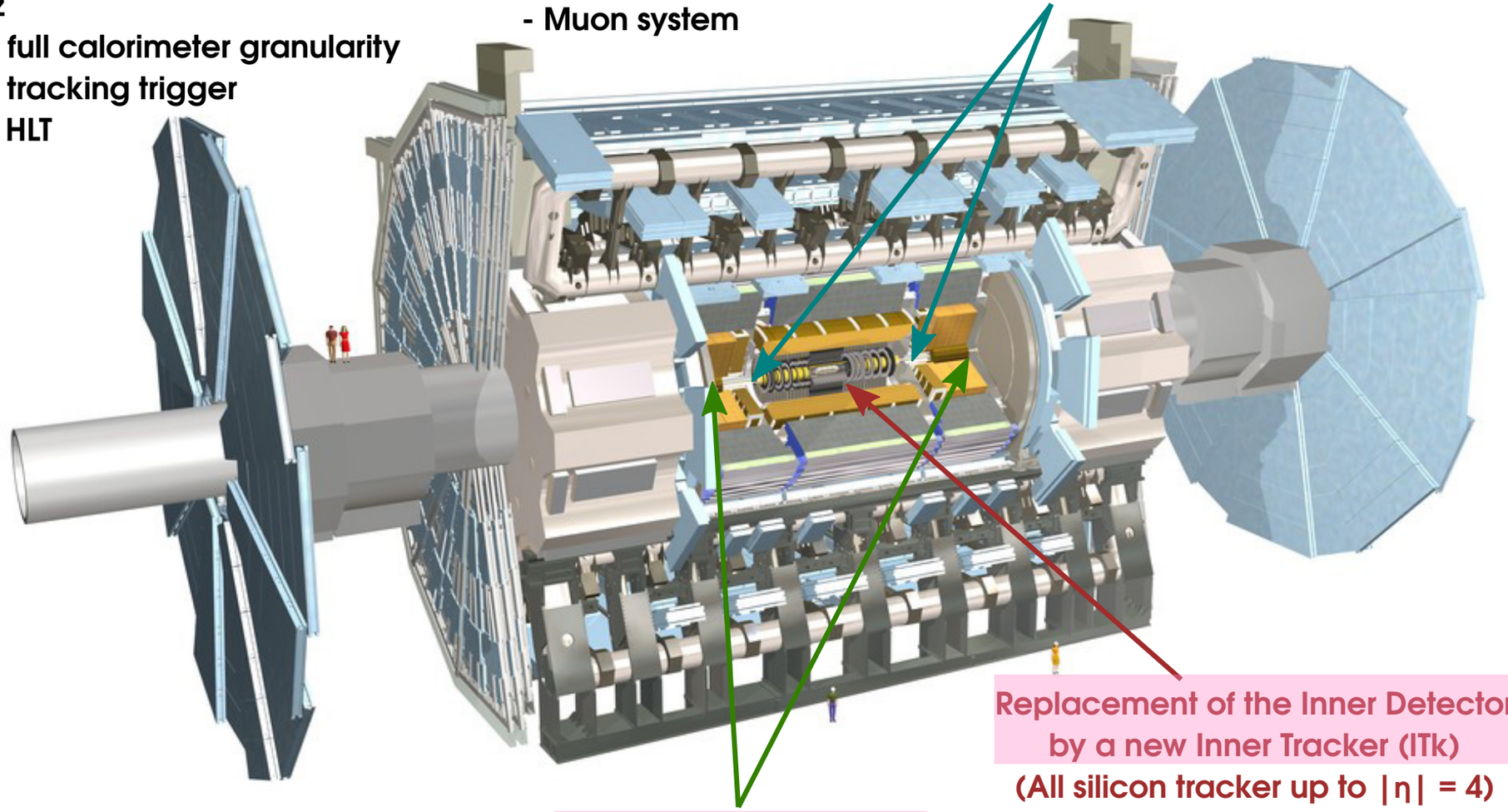
Trigger and DAQ
- Track-trigger at L1
- L1 rate ~ 750kHz
- HLT output ~ 7.5kHz

The upgraded ATLAS phase II detector

Upgraded Trigger and Data Aquisition system
- L0 @ 1MHz
- Access to full calorimeter granularity
- Hardware tracking trigger
- Improved HLT

Electronics Upgrade
- LAr calorimeter
- Tile Calorimeter
- Muon system

High Granularity Timing Detector (HGTD) 2.4 < |η| < 4



Replacement of the Inner Detector by a new Inner Tracker (ITk)
(All silicon tracker up to |η| = 4)

New Muons chambers in the inner Barrel region

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- To limit the computing time to associate 300,000 calorimeter hits to event objects
  - One needs to develop efficient reconstruction algorithms

CMS Tracker Upgrade for the HL-LHC
Expected performances

- ***The phase-2 tracker upgrade is necessary in order to maintain the detector performance***
- ***The new design will allow to keep tracking performance under a high pile-up and radiation environment***
- ***Tracks will be sent to the CMS level-1 trigger at 40 MHz***
- ***Design is well advanced***

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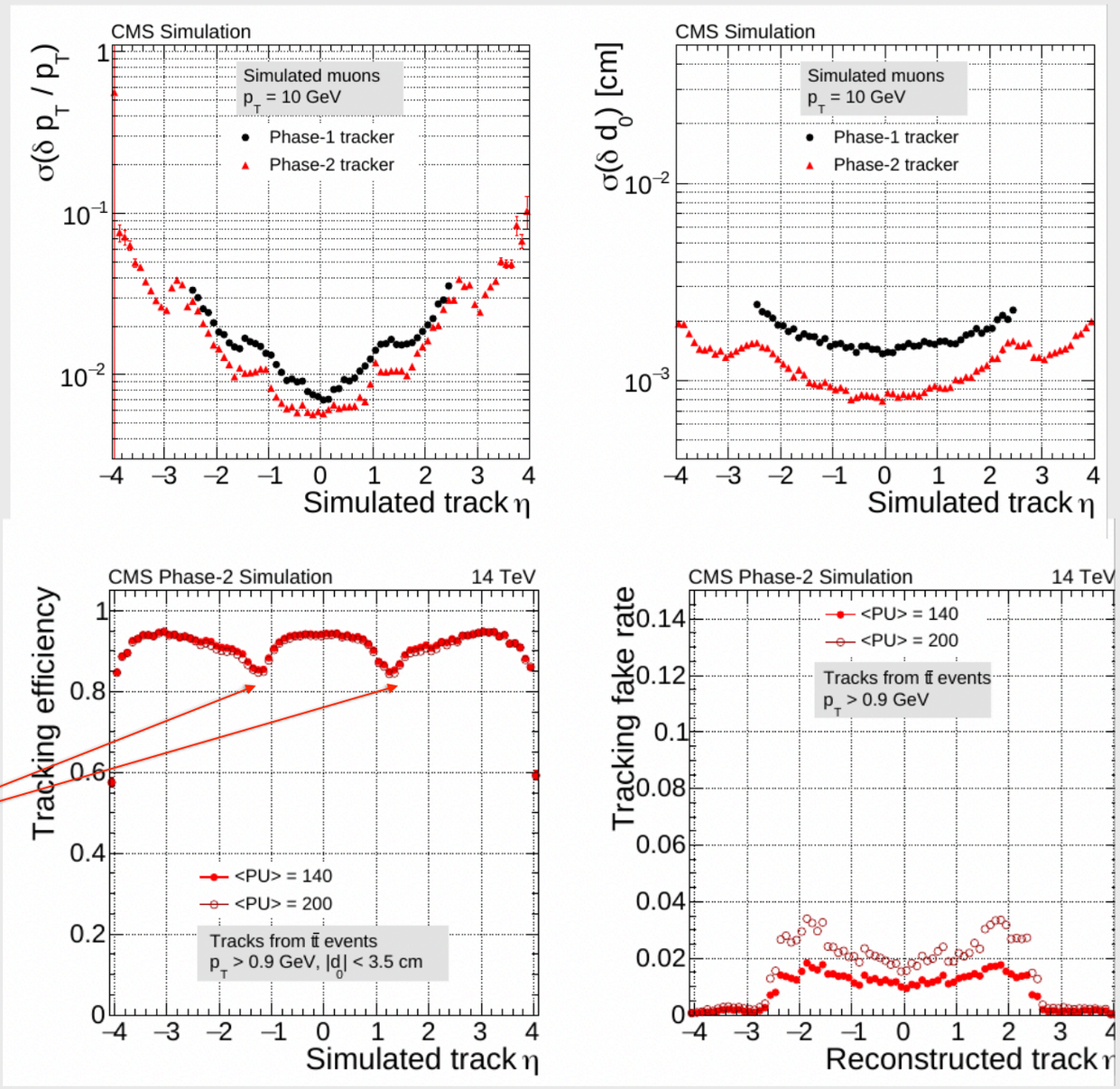
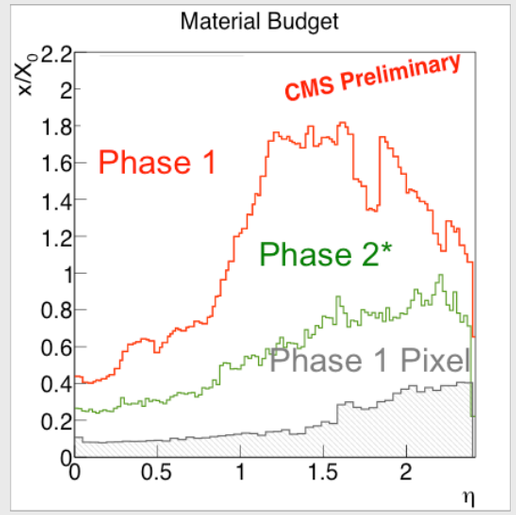
- *Full Monte-Carlo simulation*
  - *Signifcant improvement expected in p_T and d_0 resolution*
  - *90% tracking effciency for tracks from tt events with < 2% fake rate*
- *Work in progress!*
  - *Geometry is being optimized*
  - *Effciency at $|\eta| \sim 1.2$ is being addressed*



New Tracker requirements

- Radiation tolerance
- Increased granularity
- Improved 2-track separation
- Reduced material
- Robust pattern recognition
- Support for L1 trigger upgrade
- Extended tracking acceptance



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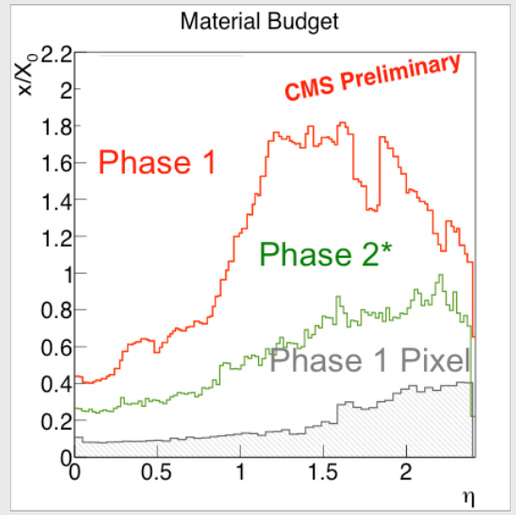

- Outer Tracker
  - Double-layer modules for trigger purpose
  - 6 barrel layers; 5 forward disks
  - Higher granularity
  - 4 times current detector
- Pixel Tracker
  - 10 forward disks, coverage up to
  - |eta|~3.8
  - Inner layer at 3cm from beam line
- Mechanics and Electronics requirements
  - Low material budget
  - Operations at -30C
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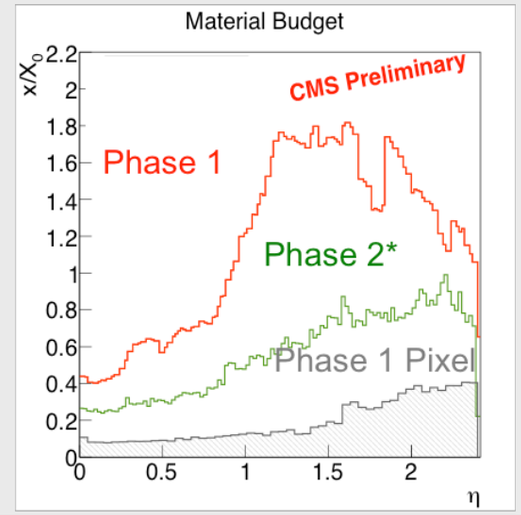

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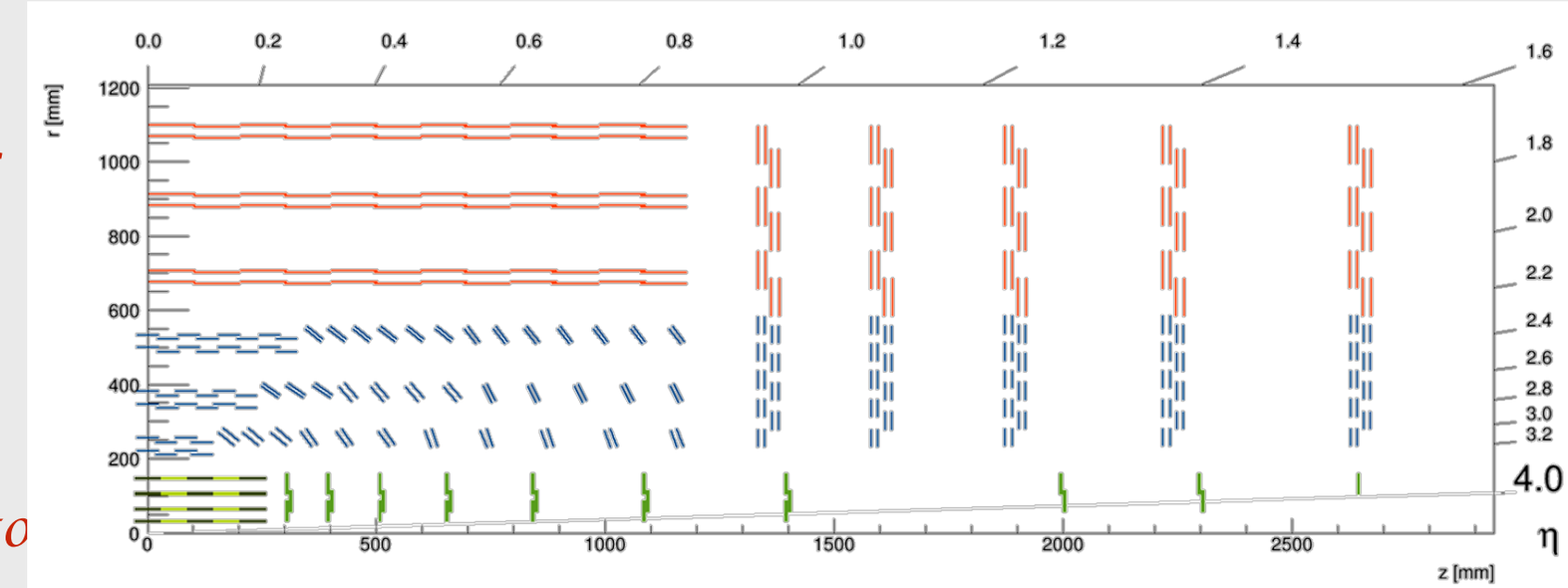

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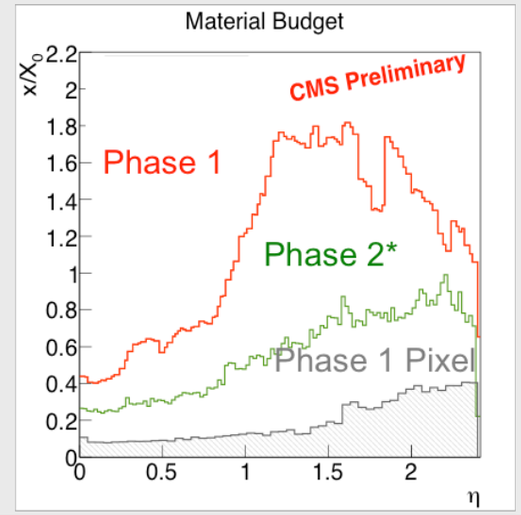

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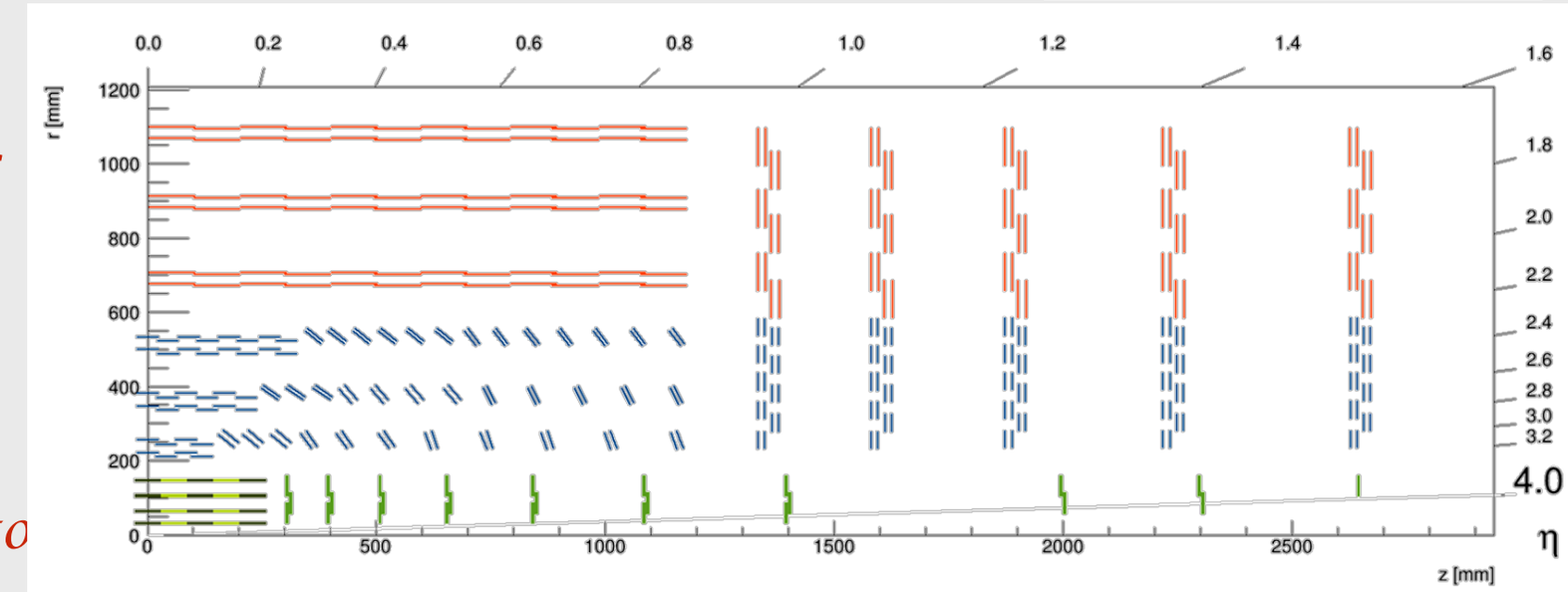
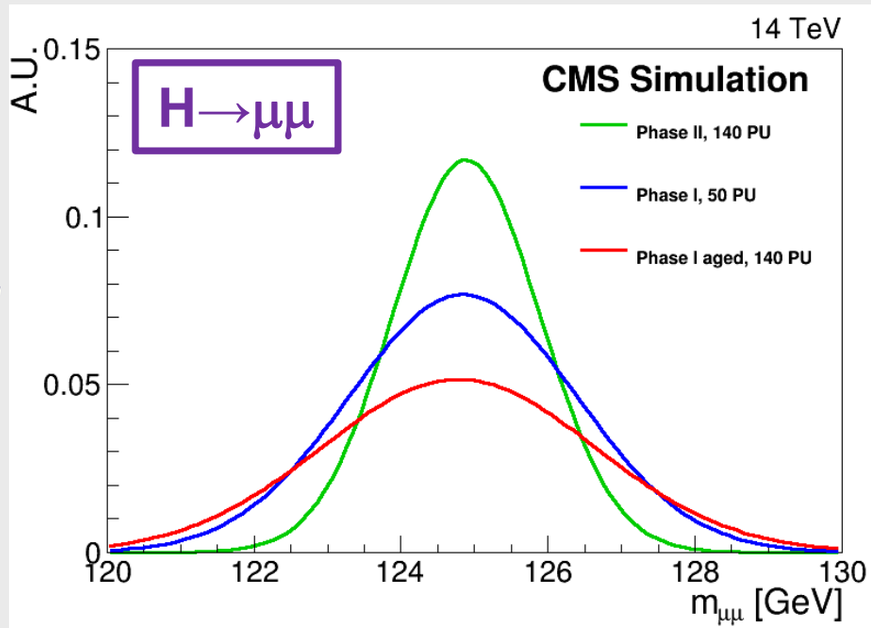
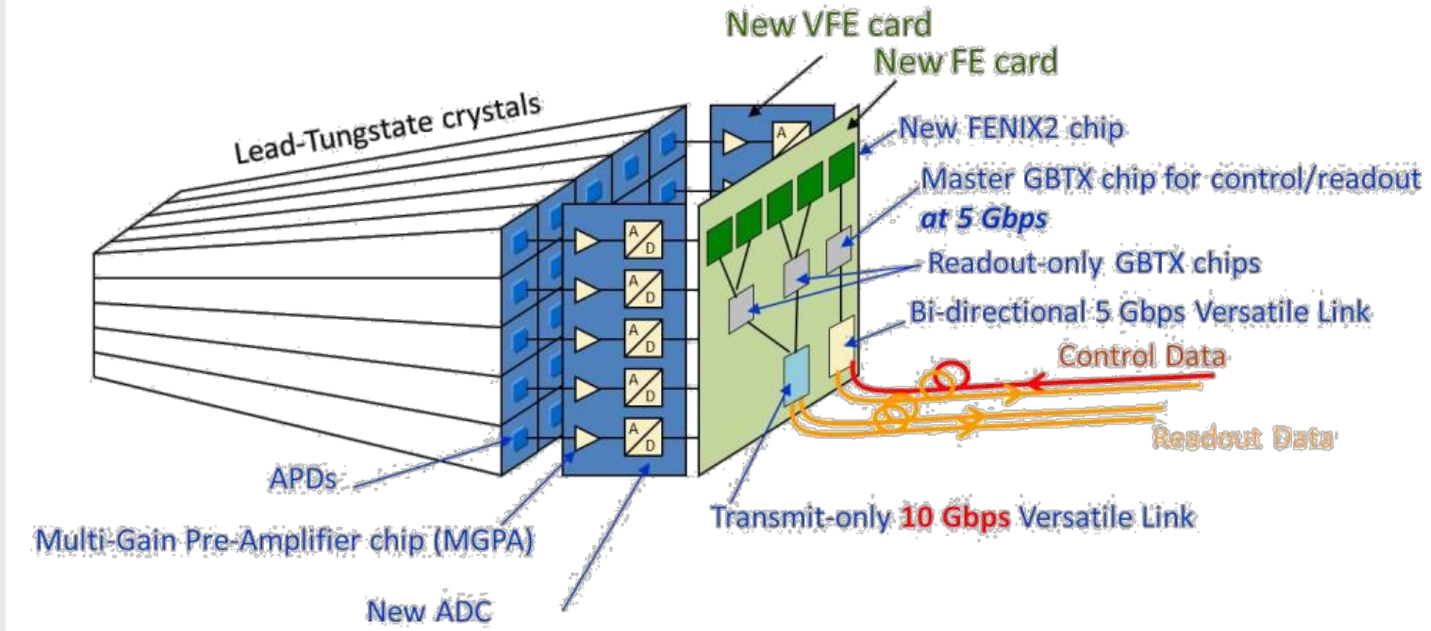


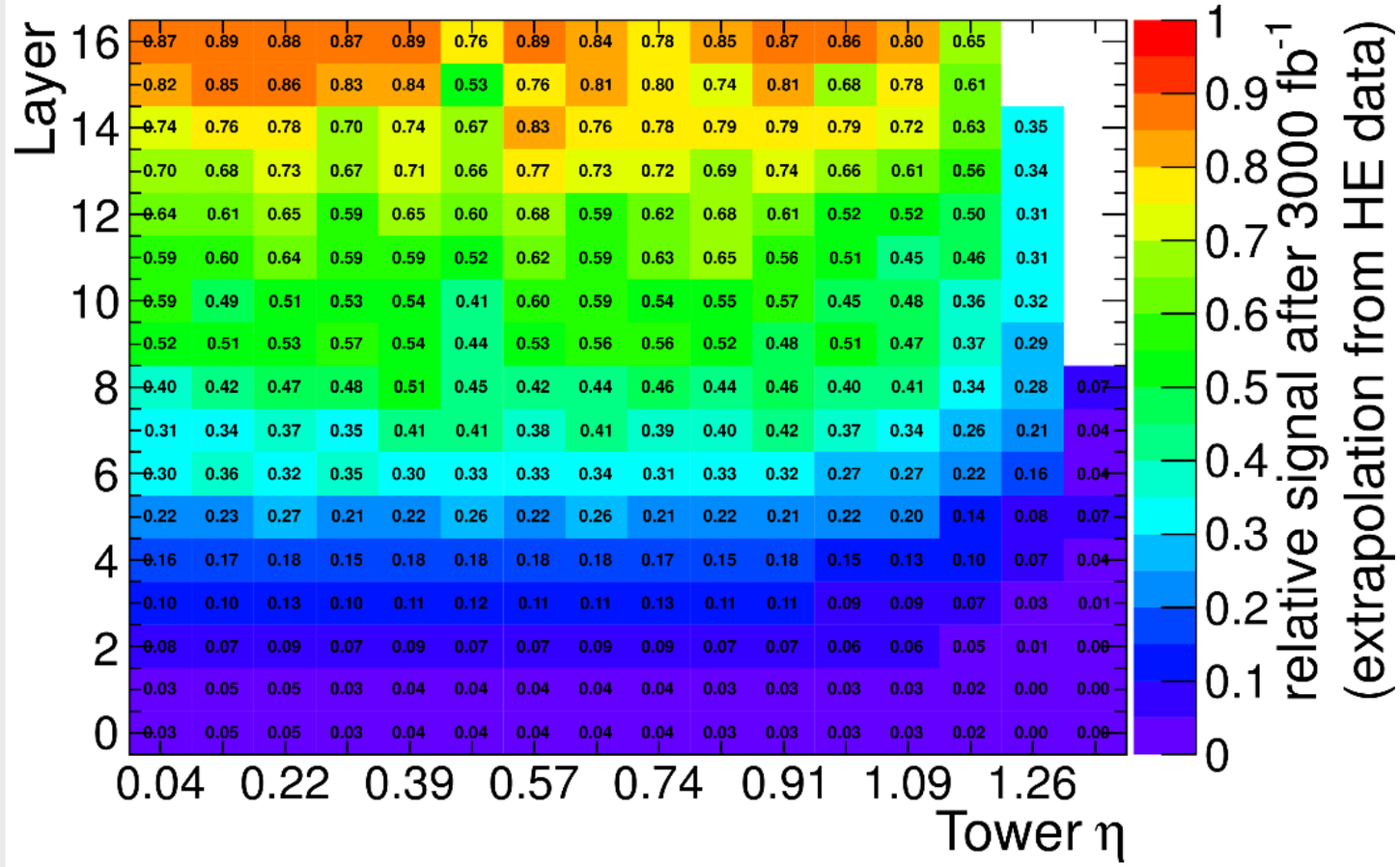
Higgs Physics



Barrel Calorimeters

- Electromagnetic Calorimeter
  - Homogeneous, $PbWO_4$
  - New front-end and back-end electronics to satisfy HL-LHC trigger requirements
  - Cooling to 8C and optimization of VFE (very-front-end) electronics to reduce noise
    - Interesting side-effect: cooling $PbWO_4$ increases its light output
- Hadronic Calorimeter
  - Plastic/brass sampling calorimeter
  - Replacement of inner layers with radiation-tolerant scintillator
  - New back-end electronics



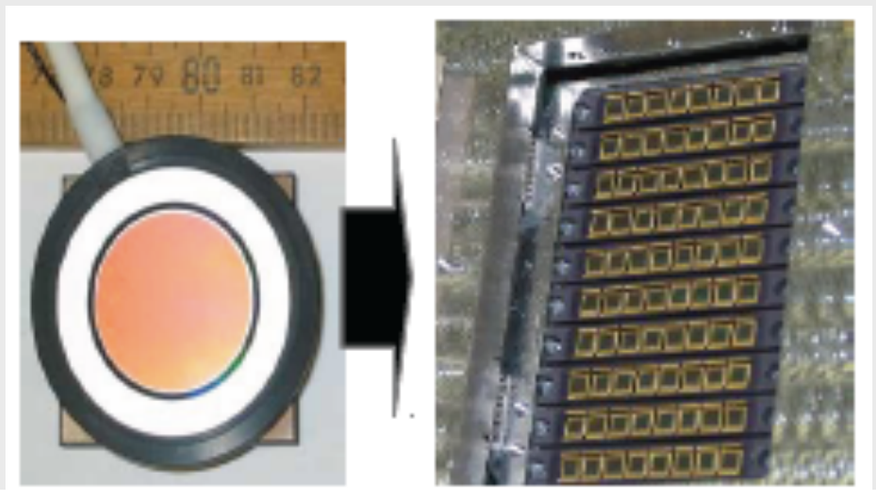


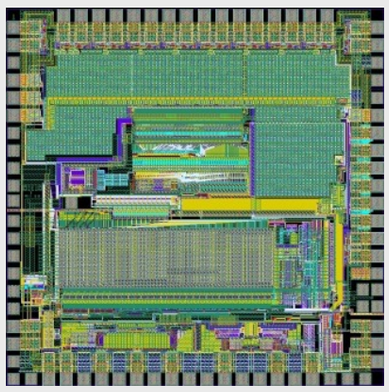
CMS HCAL Read-Out Upgrades

Installation during LS1(HO)/LS2(HB/HE)

HB/HE/HO

From HPD to SiPM's

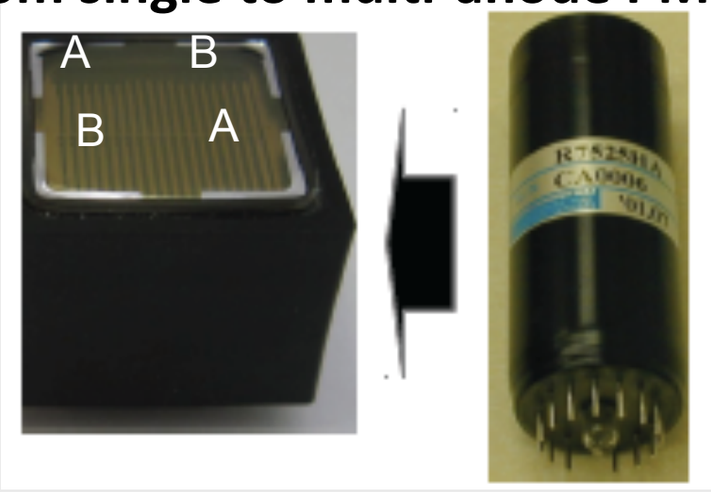


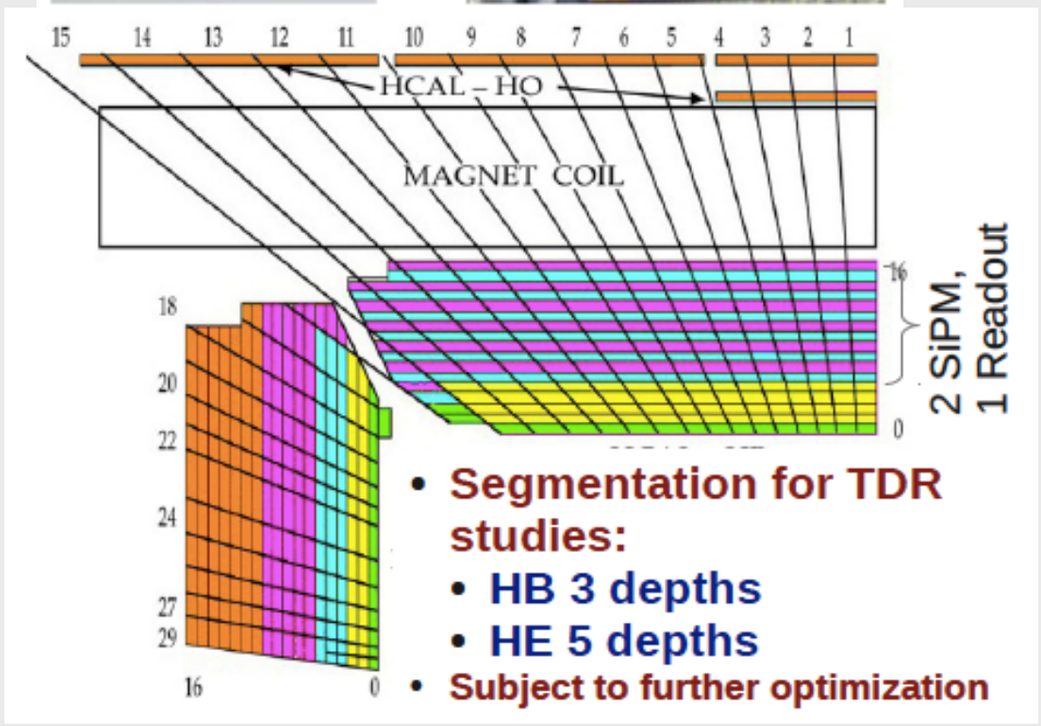


Installation during LS1

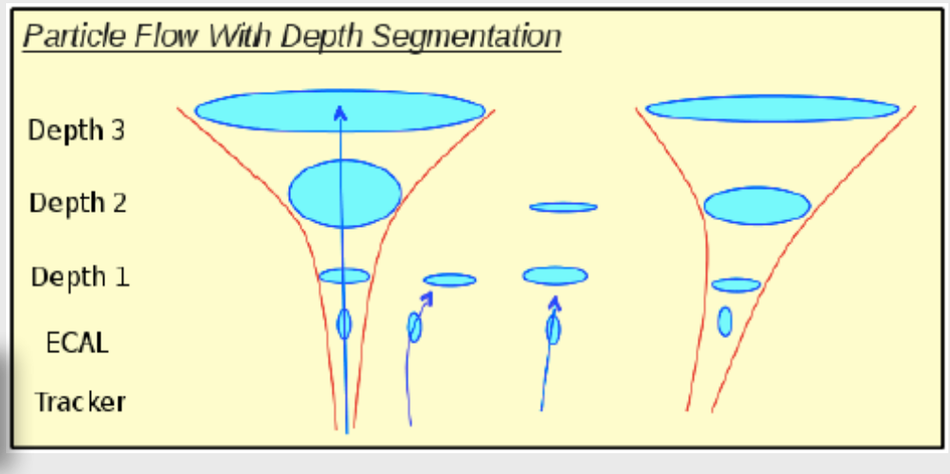
HF

From single to multi-anode PMT's

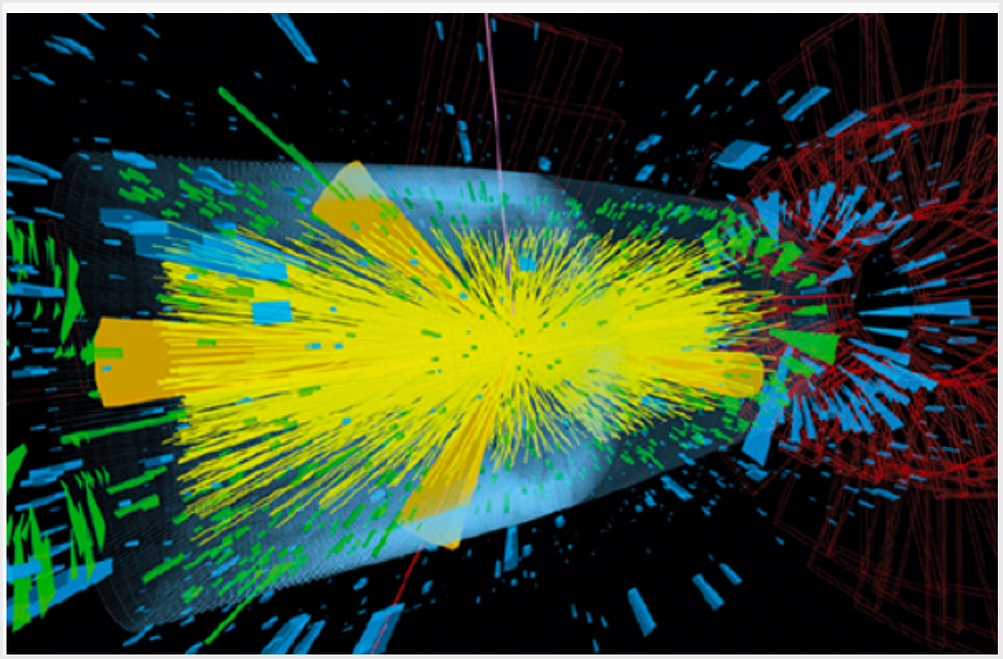


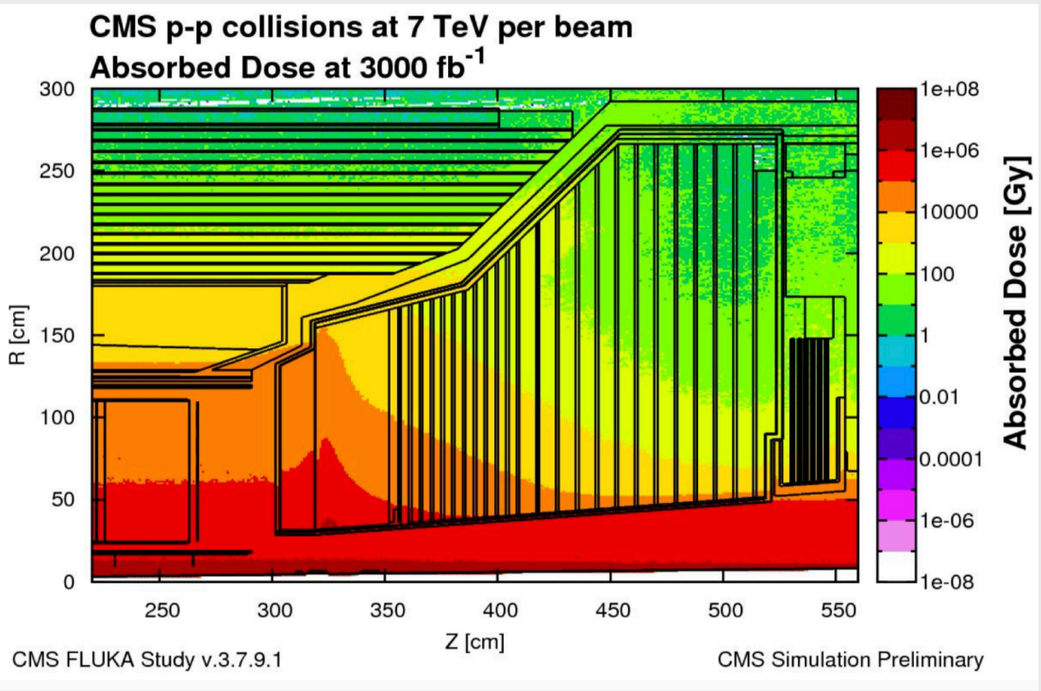


- Use SiPM's to increase HB/HE Depth Segmentation
- Improved PF Hadronic shower localization
- Provides effective tool for pile-up mitigation at high luminosity
- Mitigate radiation damage to scintillator & WLS fibers

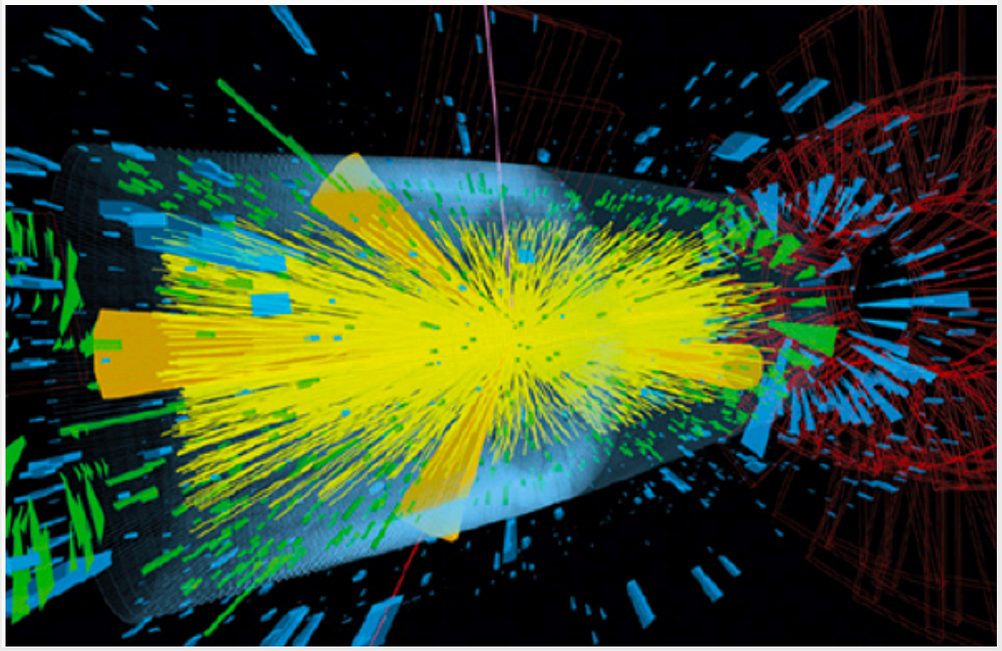


Depth segmentation: mitigate high pileup

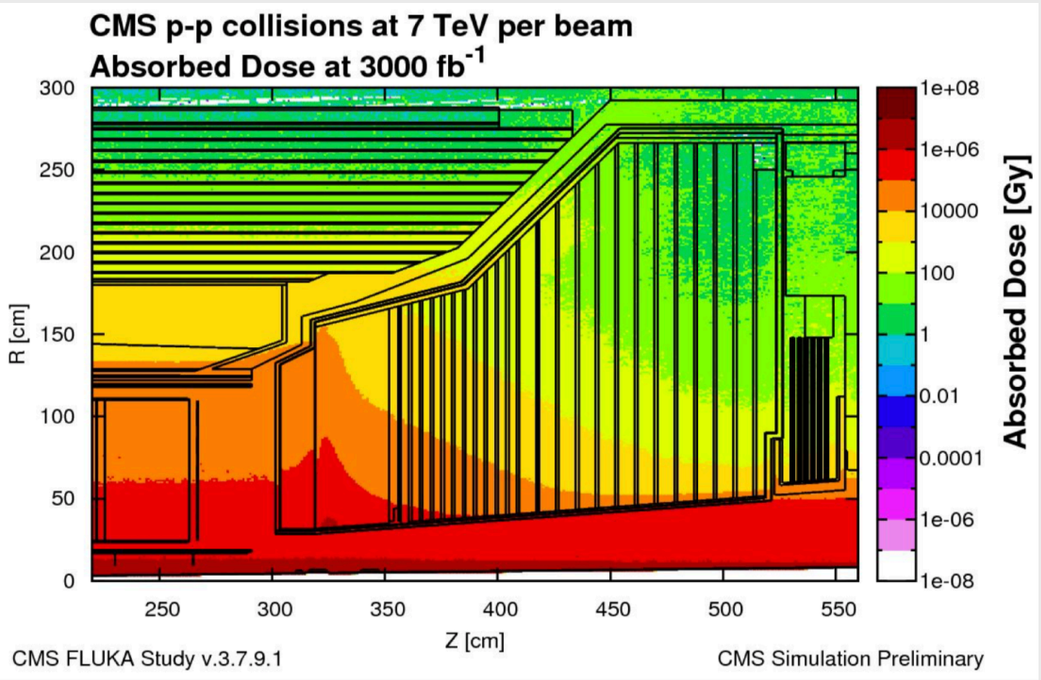



CMS p-p collisions at 7 TeV per beam
Absorbed Dose at 3000 fb-1
R [cm]
Z [cm]
Absorbed Dose [Gy]
1e+08
1e+06
10000
100
1
0.01
0.0001
1e-06
1e-08
CMS FLUKA Study v.3.7.9.1
CMS Simulation Preliminary

CMS CALORIMETER ENDCAP FOR THE HL-LHC



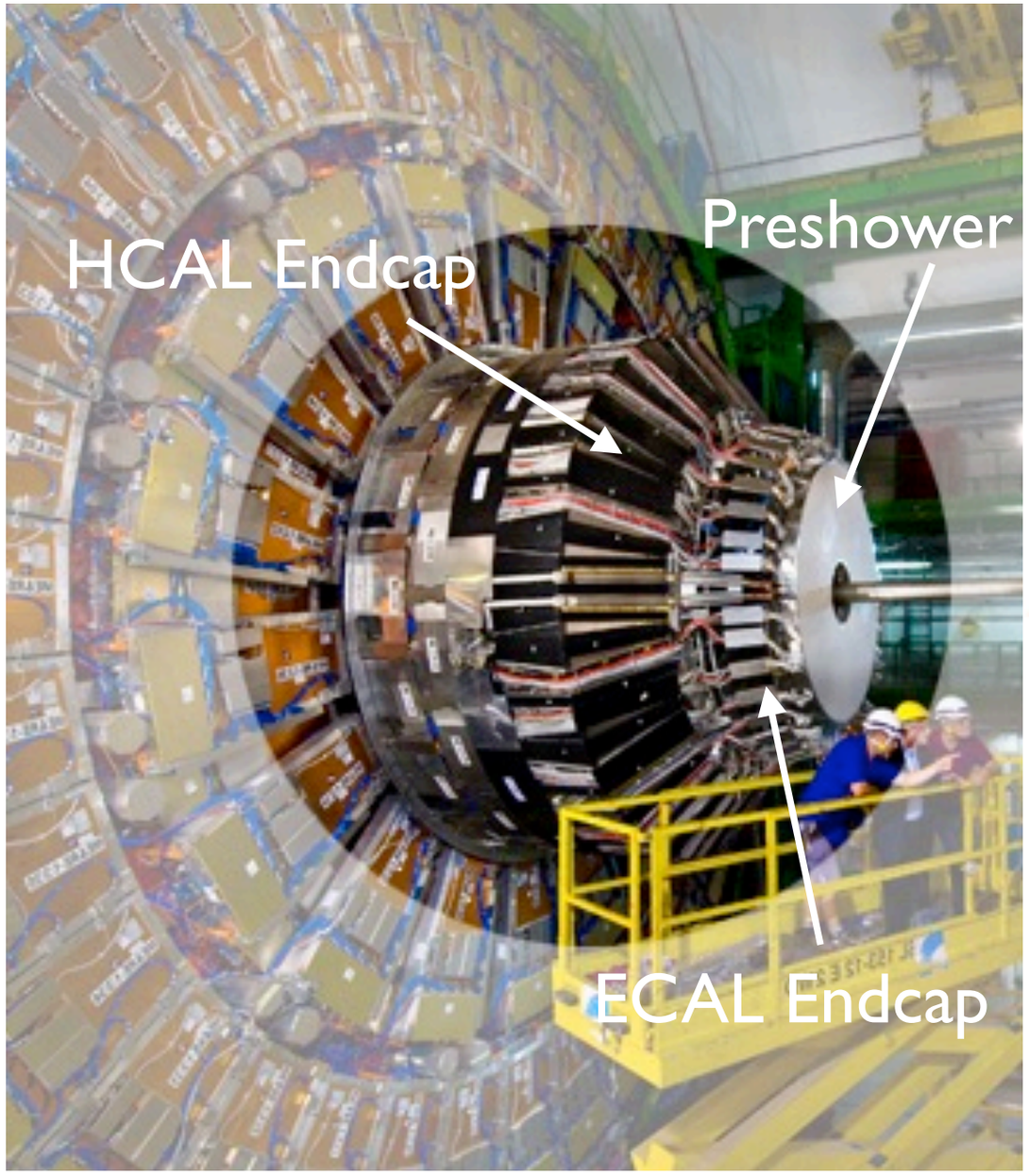
- *HL-LHC demanding environment of high radiation levels and large pileup <200> PU impose CMS Phase-2 Upgrades*
- *Current endcap calorimeters will need to be replaced*
  - *The Upgrade preserve or even improve sensitivity in the interesting and busy forward region for VBS/VBF*



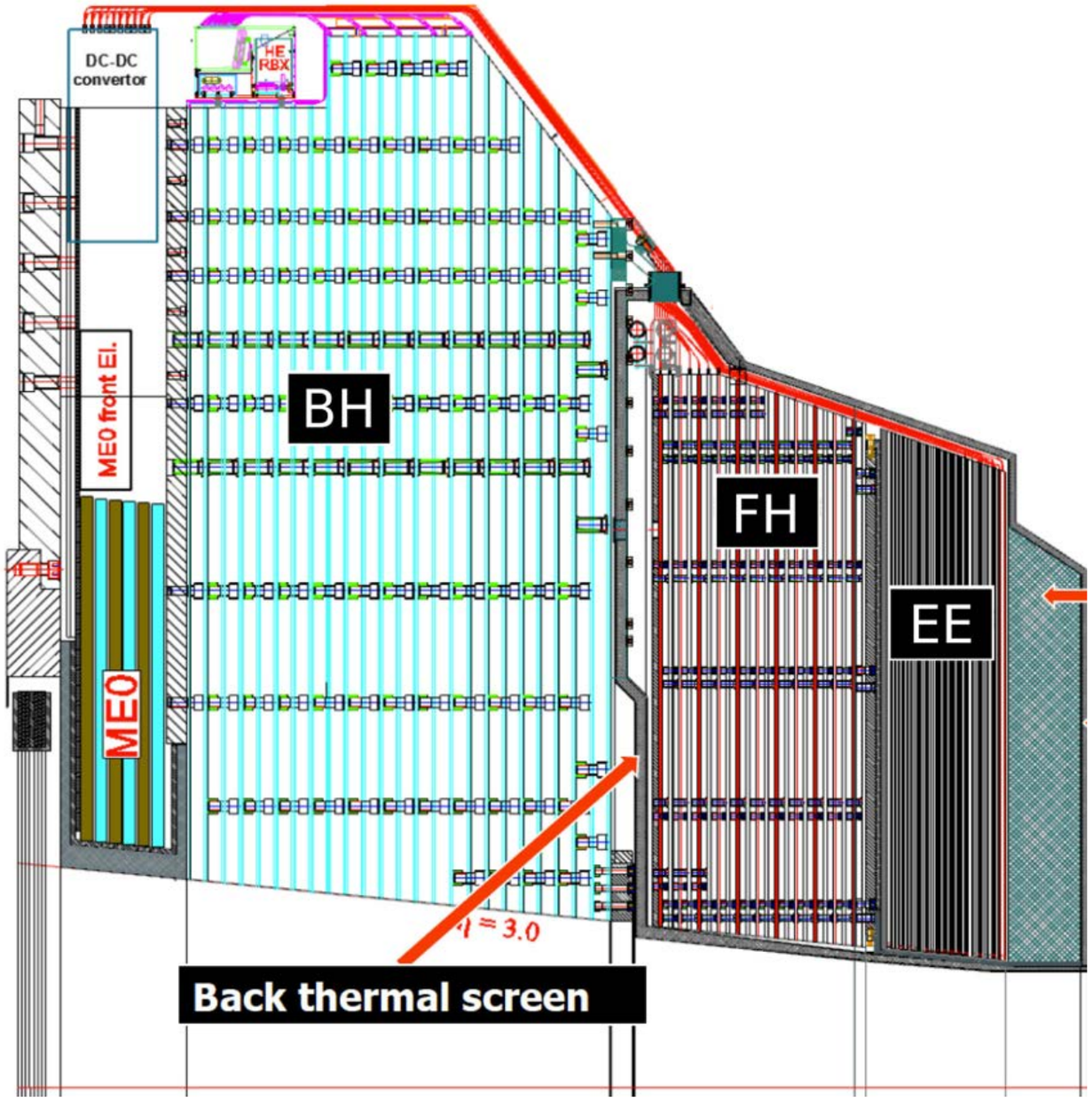
- *A High Granularity Calorimeter (HGCAL) will become the new Endcap (CE) Calorimeter:*
  - *Radiation hard technology based on a mix of silicon and scintillator detectors*
  - *High transverse and longitudinal granularity + timing (5D!) for enhanced particle flow reconstruction and ID/ pileup mitigation*

HL-LHC Endcap Calorimeter Upgrade

Current Endcap Calorimeter



High Granularity Endcap Calorimeter

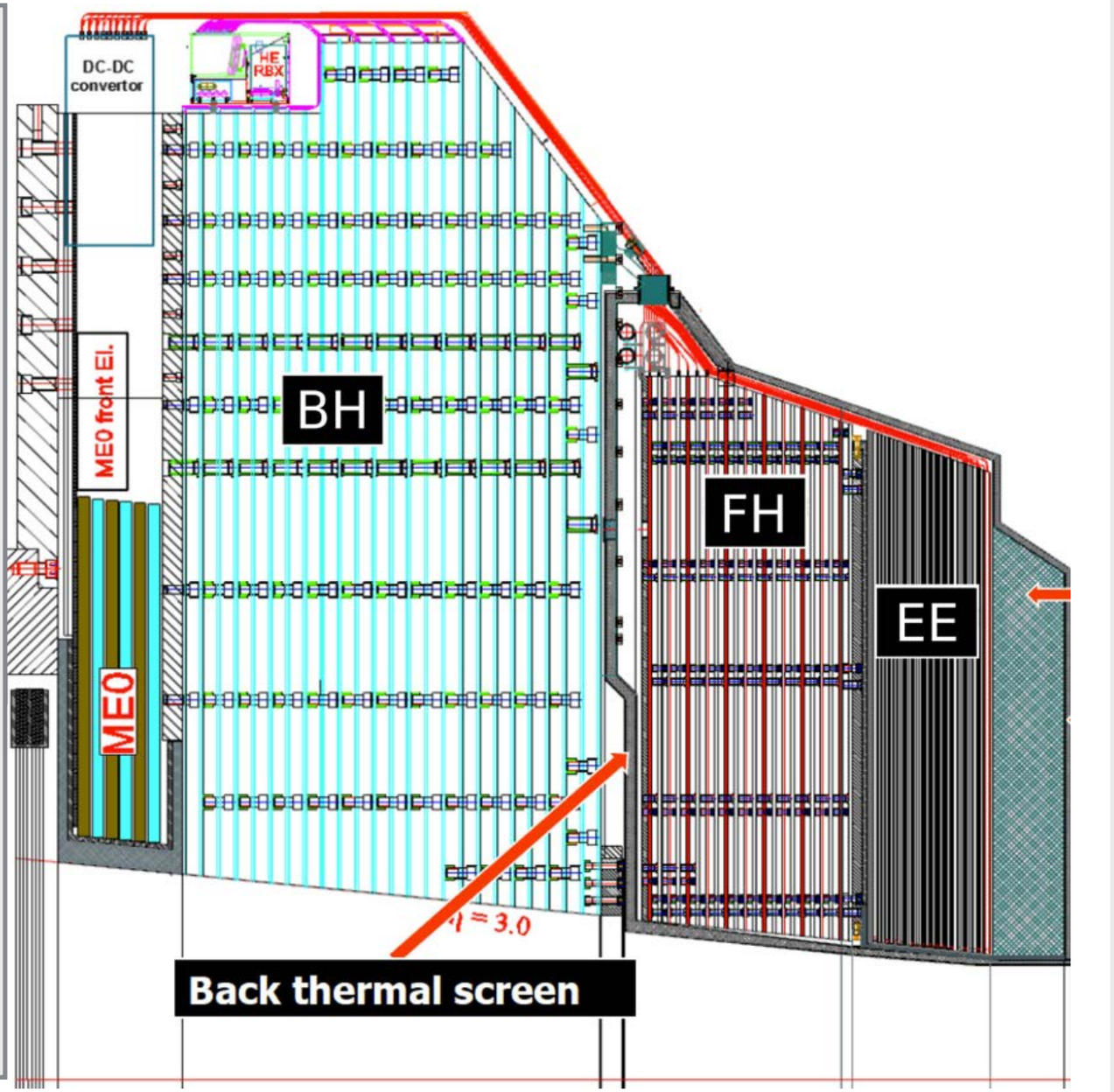


HL-LHC Endcap Calorimeter Upgrade

Current Endcap Calorimeter

High Granularity Endcap Calorimeter

- ★ *Challenging conditions push toward new exploratory model*
  - *High-granularity silicon- readout, based on ILC/CALICE detector*
  - *Si/W EE ($26X_0$, 1.5l); "28 layers"*
  - *Si/brass FH (3.5l)*
  - *Plastic scintillator/brass BH (5l)*
  - *A total of 52 layers*
- ★ *It imposes a high R&D activity on :*
  - *Radiation-tolerant "on-detector" electronics*
  - *Cold plastic scintillator*



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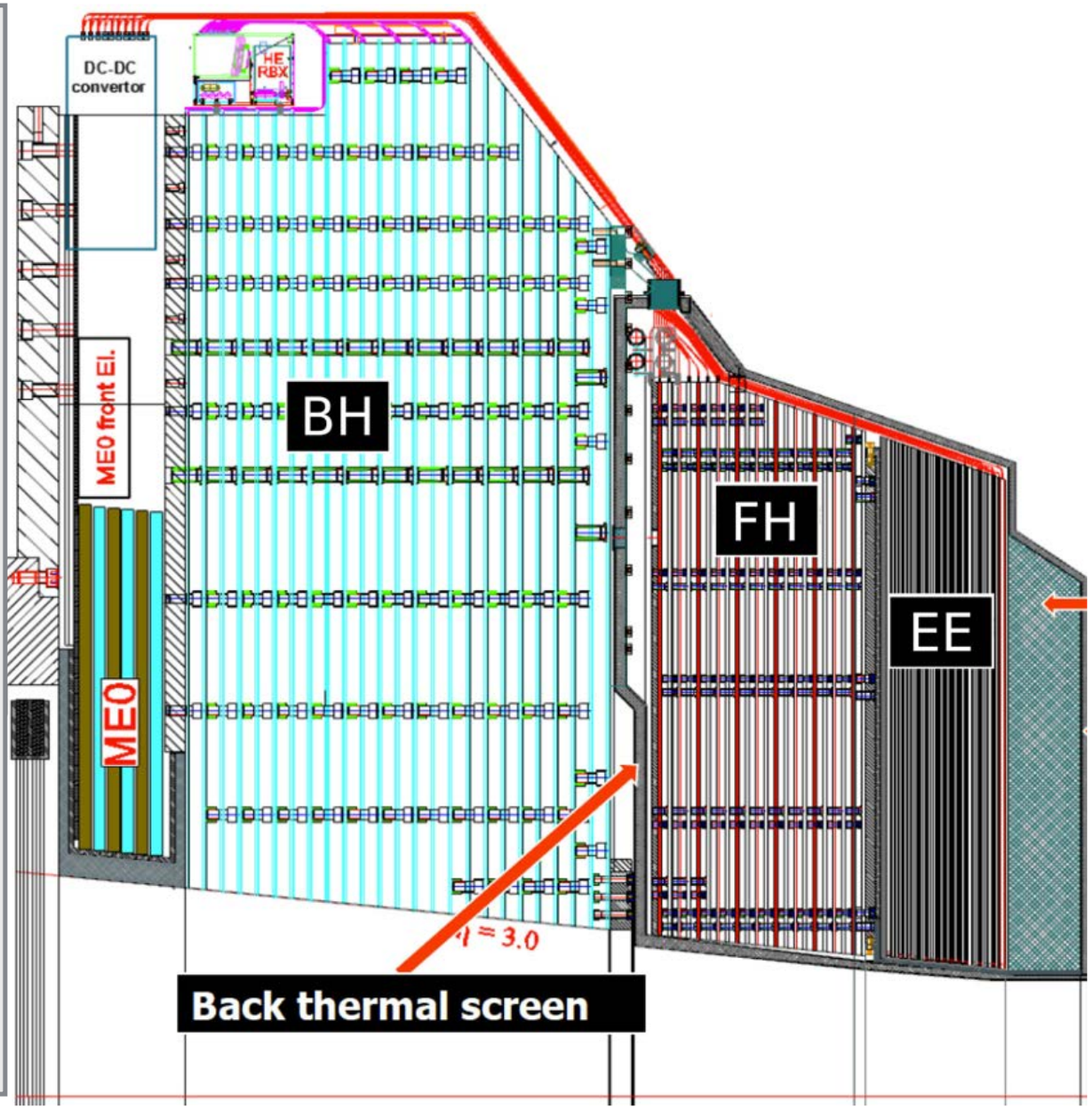
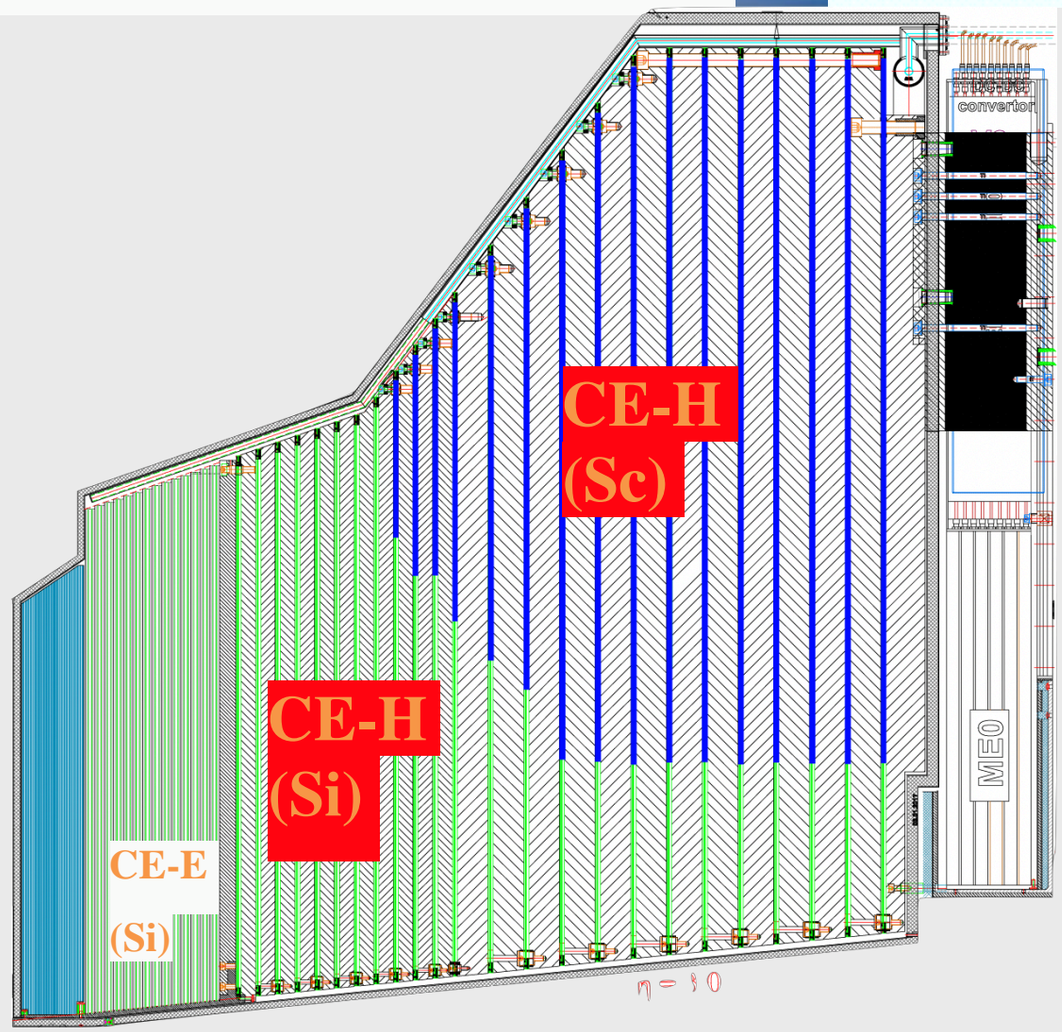


Such fine granularity enables precise particle flow techniques applied to calorimetry

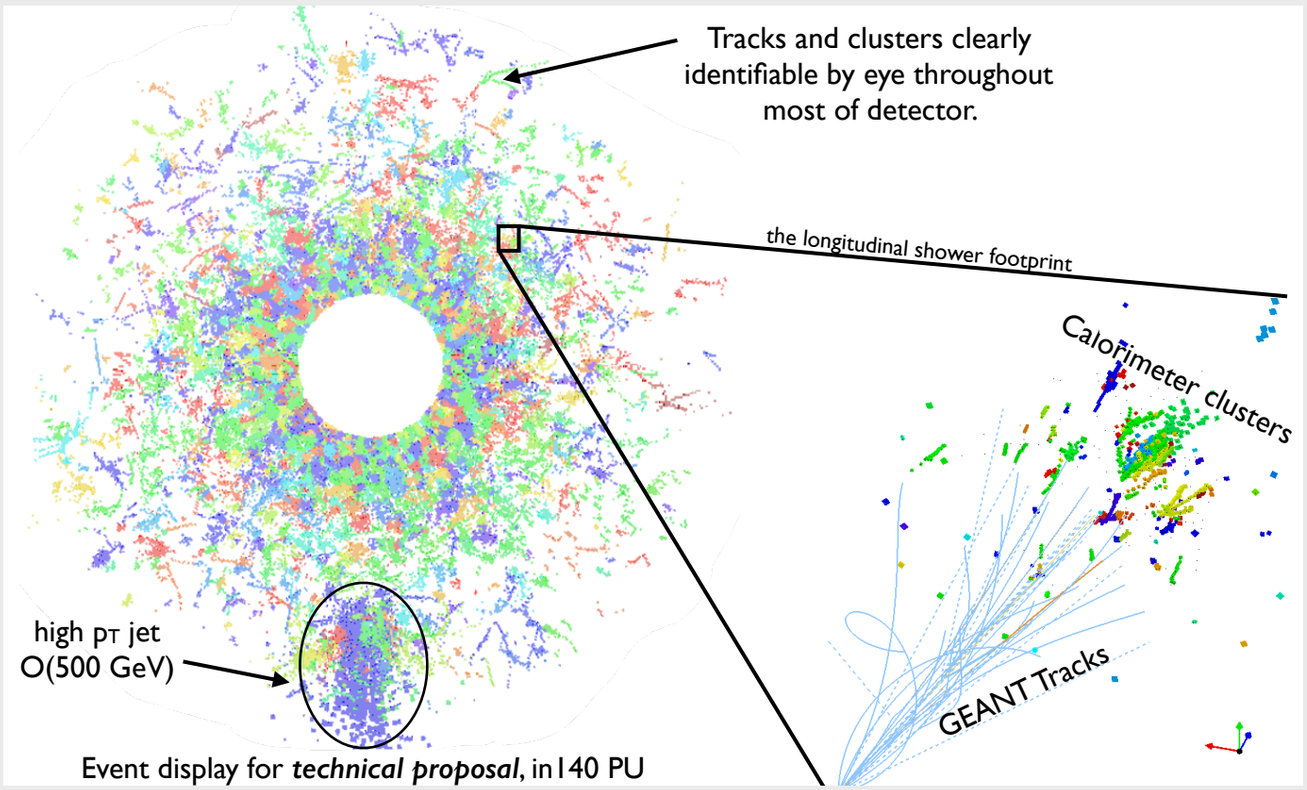
- ✦ *Now one can follow particles through the calorimeter layers*
- ✦ *Fine sampling brings robustness against pileup*

ENDCAP Calorimeter FOR THE HL-LHC

- The high luminosity and high granularity are a big challenge for the detector design:
  - Silicon/scintillator detectors in the high/low radiation regions
  - Triggering and reading data of >6M channels issued from 28 layers in the ECAL (CE-E) + 24 layers in the HCAL (CE-H) compartments



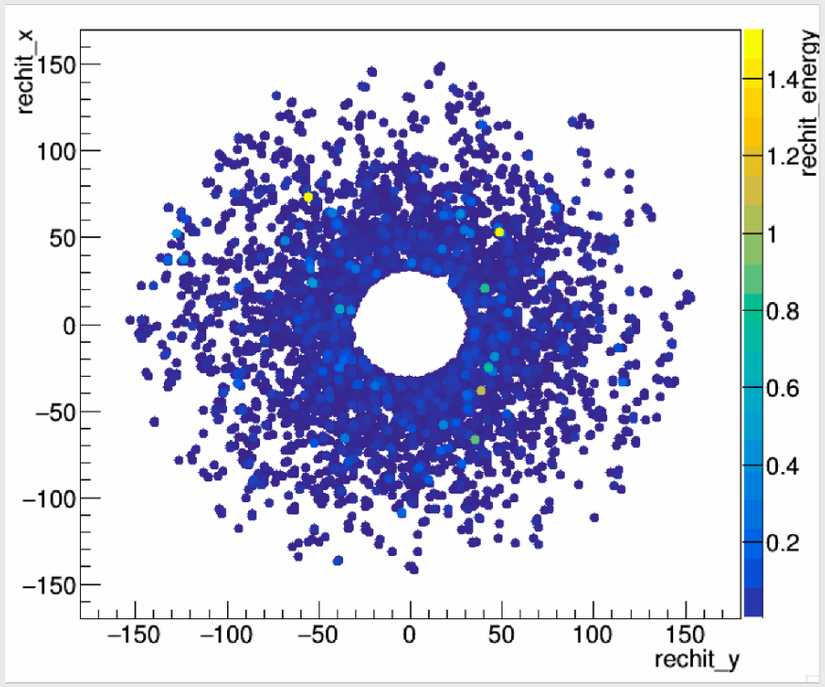
Imaging Showers with the HGCal



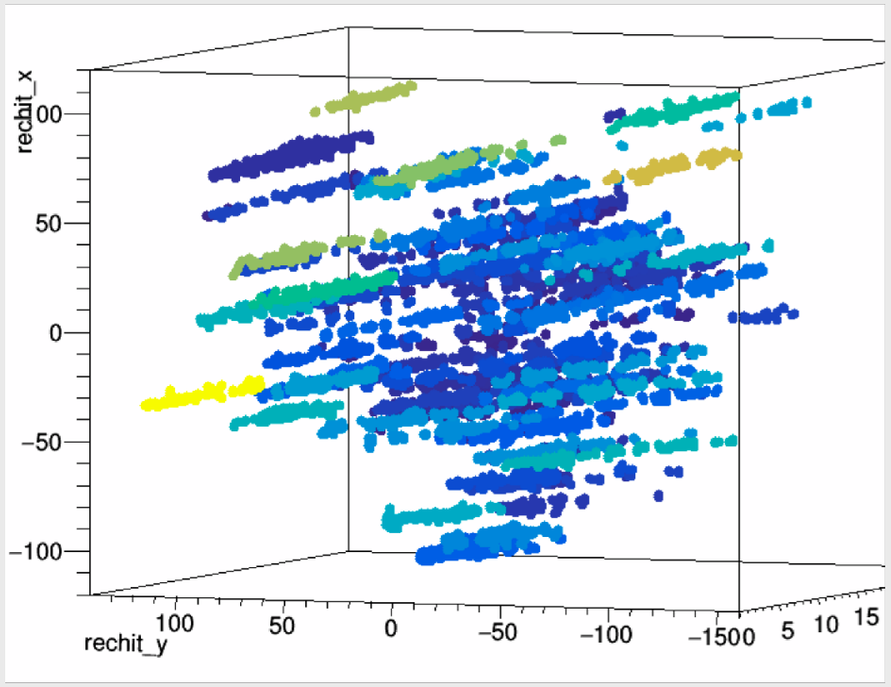
Endcap coverage: $1.5 < \lvert\eta\rvert < 3.0$		
Total	**Silicon sensors**	**Scintillator**
Area	600 m²	500 m²
Number of modules	27 000	4 000
Cell size	0.5 — 1 cm²	4 — 30 cm²
N of channels	6 000 000	400 000
Power	Total at end of HL-LHC: ~180 kW @ -30°C	

HGCAL objects reconstruction

- High occupancy and pileup induce big challenges for the particle reconstruction
  - But HGCAL is an 5D imaging calorimeter: 3D position, energy and time
  - ideal to perform Particle Flow
- The very first step is the clustering of the hits. Currently, the clustering is done in two steps:
  - 2D clustering in every layer using an energy density-based imaging algorithm
  - 3D clustering in an IP-pointing cylinder
- Great opportunity for novel tracking, clustering and imaging techniques!



All hits in layer 1 for a 200 PU event



Clustered hits for clusters with pt > 1 GeV

From (CHEP2018 : Artur Lobanov LLR — École polytechnique)

✦*Electrons are a 'standard candle' for Particle Flow:*

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HGCAL
ELECTRON IDENTIFICATION

- *Electrons are a 'standard candle' for Particle Flow:*

- *EM showers are compact (R ~ 3 cm), of known shape and associated with a track*
  - *3D information allows reconstruction of the shower axis (e.g. using Principal Component Analysis) and the measurement of shower shapes with an unprecedented precision*
  - *Axis pointing and association to a charge track will improves rejection of PU photons with respect to bremsstrahlung*

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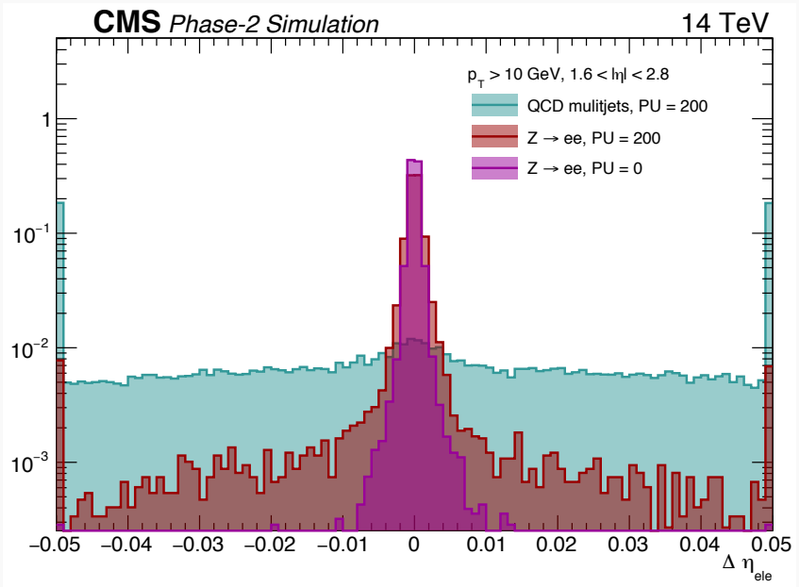
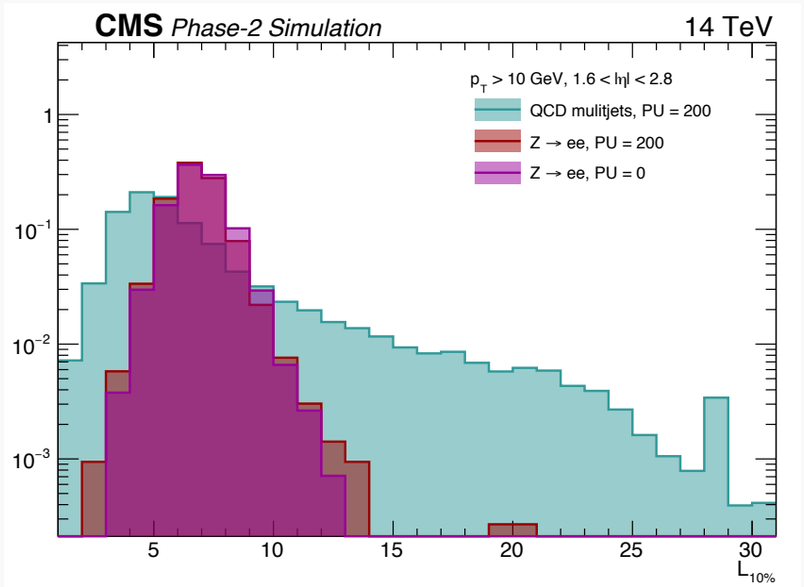
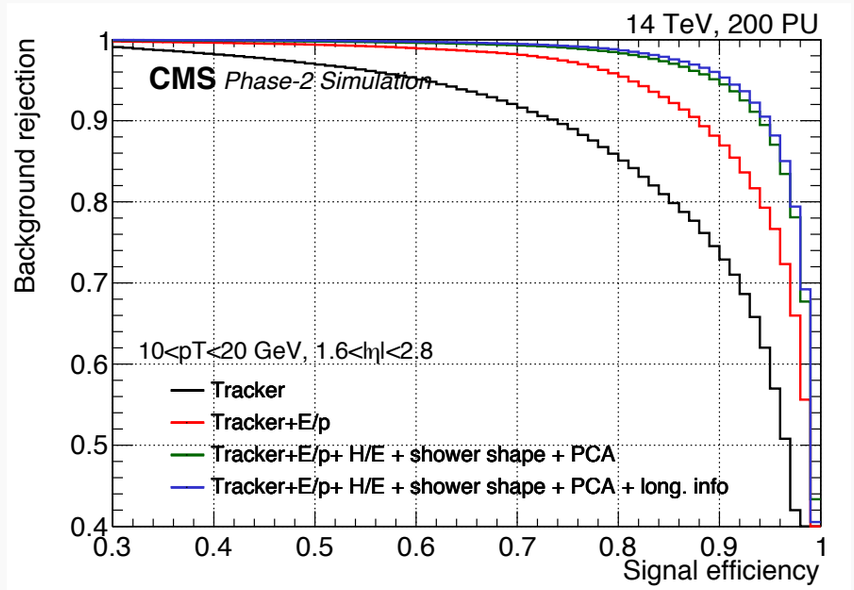


Track-cluster deltaEta



First layer with 10% energy fraction

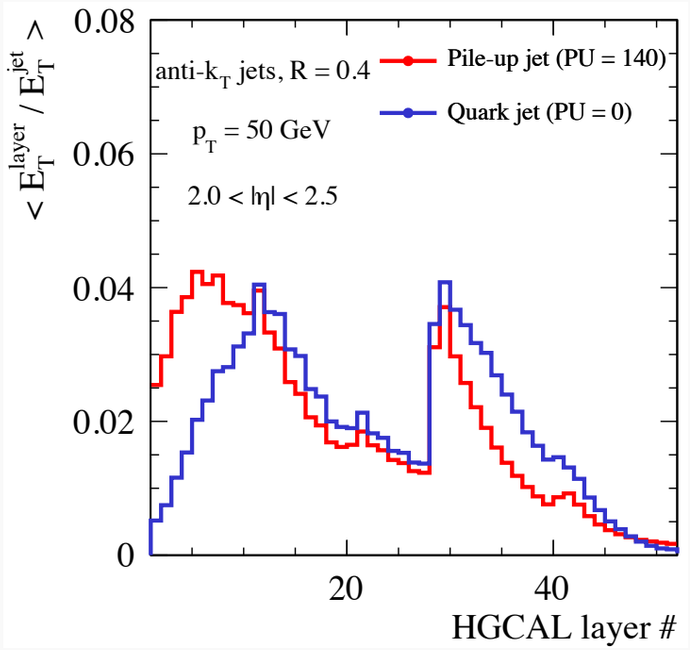


Electron ID for p_T in 10-20 GeV

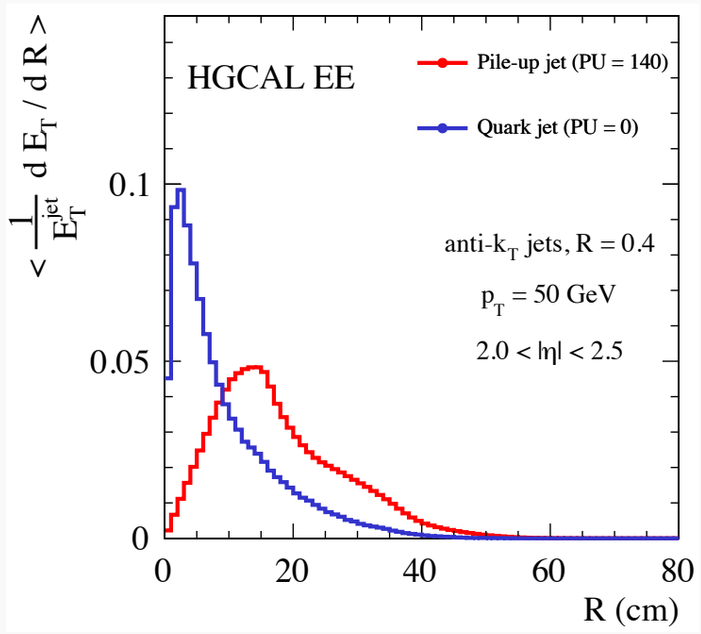
From (CHEP2018 : Artur Lobanov LLR — École polytechnique)

HGCAL JET IDENTIFICATION

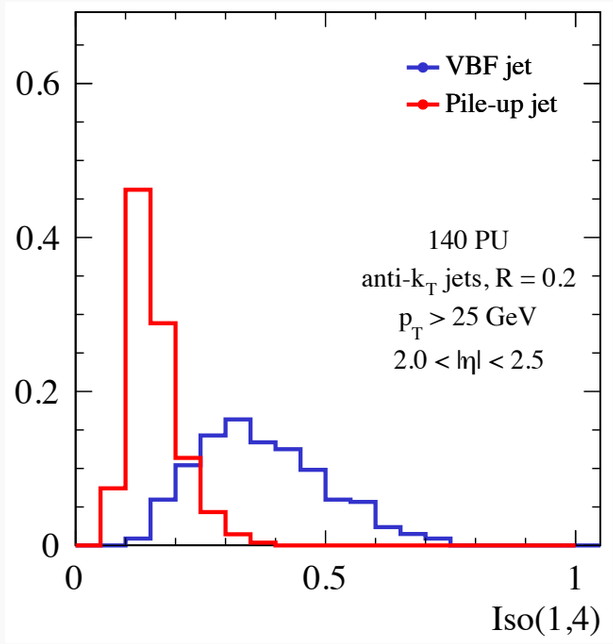
- *Using shape variables, the high granularity allows the separation of pileup jets as :*
  - *Pileup jets start to develop earlier in the calorimeter and are wider*
  - *Promising to resolve boosted jet topologies as VBF jets, top tagging, etc.*



Longitudinal energy profile



Radial jet profiles in the CE-E



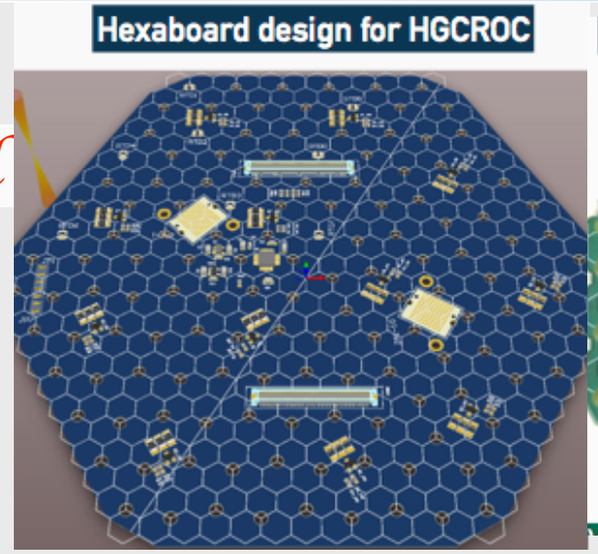
VBF vs PU jet isolation

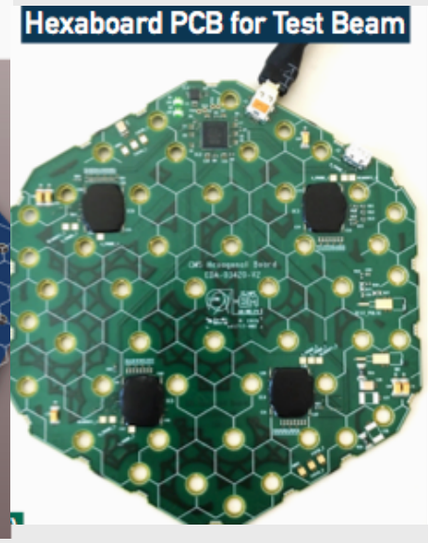
From (CHEP2018 : Artur Lobanov LLR — École polytechnique)

HGCAL FRONT-END ELECTRONICS

- Detector modules have 2 PCBs < 6mm thick:

1. PCB: "hexaboard" Wire-bonds to Si-sensor and very-FE ASICs
2. PCB: Motherboard for powering, data concentration, trigger generation and bi-directional communication





- Trigger/data transfer: low-power GBT links (lpGBT)

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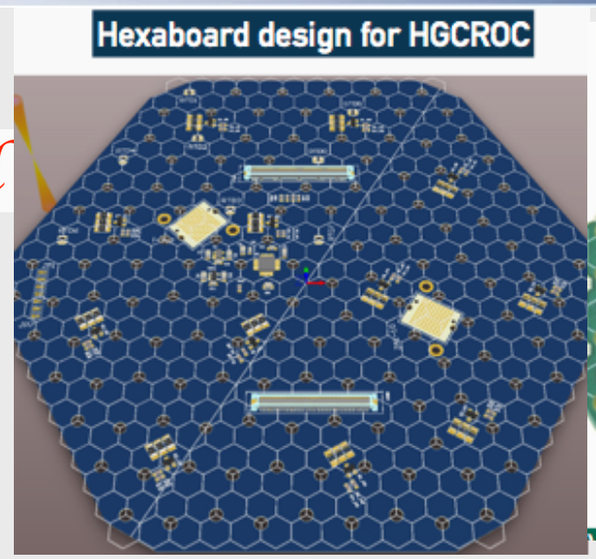
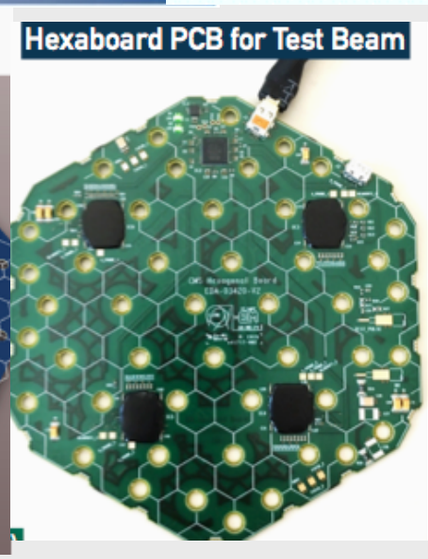
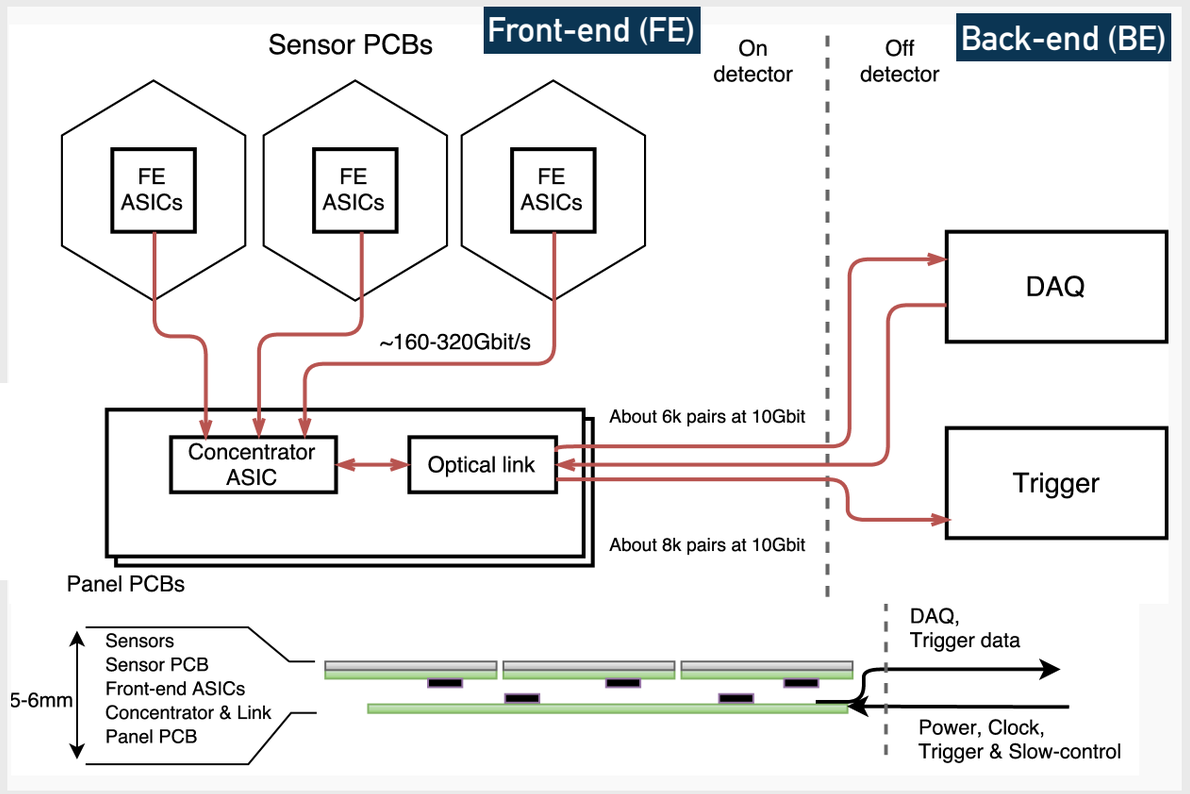




- Trigger/data transfer: low-power GBT links (lpGBT)

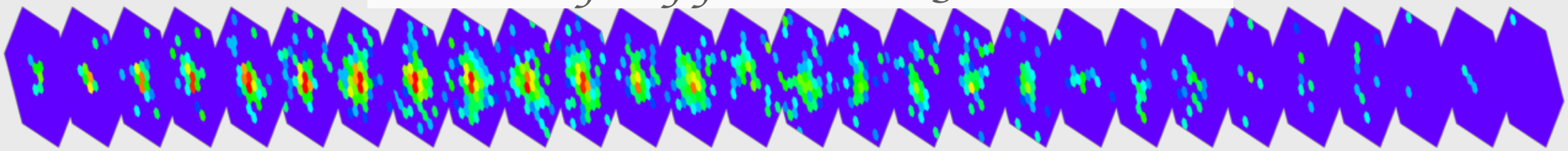
- The design and environment of the HGCAL impose several requirements
  - System on chip: charge, time, digitization, data and trigger processing, ...
  - Low power: < 15 W/channel
  - Low noise: < 2000 e^-
  - High radiation resistant : 10^{16} n_{eq} (1MeV eq.)/cm^2)
  - High speed readout: > 1 Gb/s
  - Same ROC (ASIC) for Si&SiPM



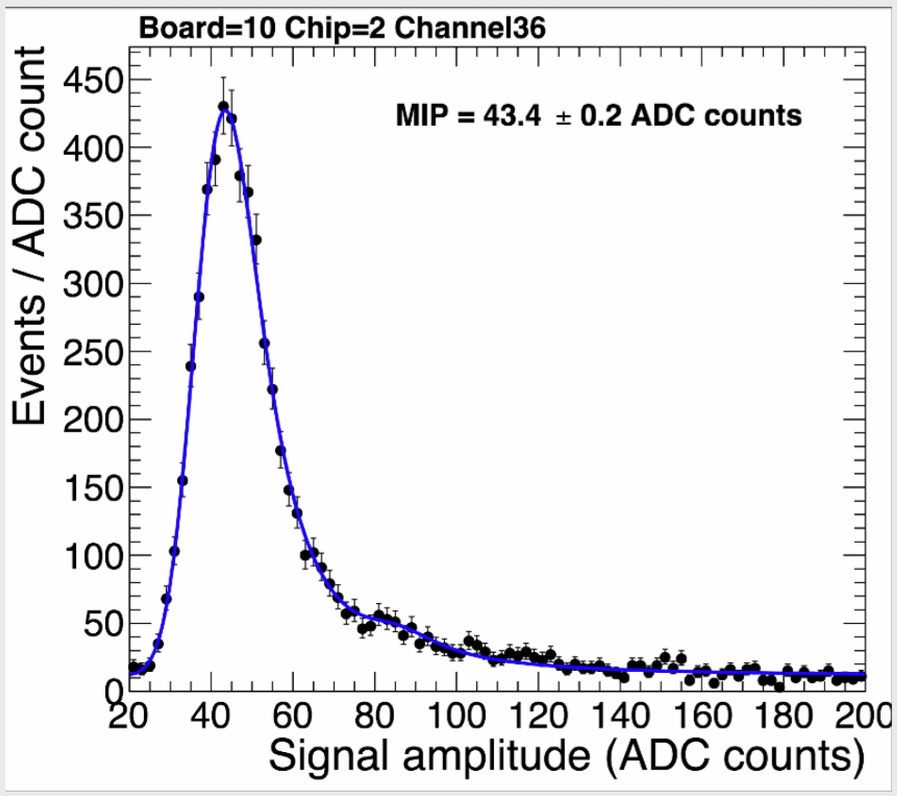
From (CHEP2018 : Artur Lobanov LLR — École polytechnique)

Beam test results (June 2018)

Event display for an 80 GeV electron



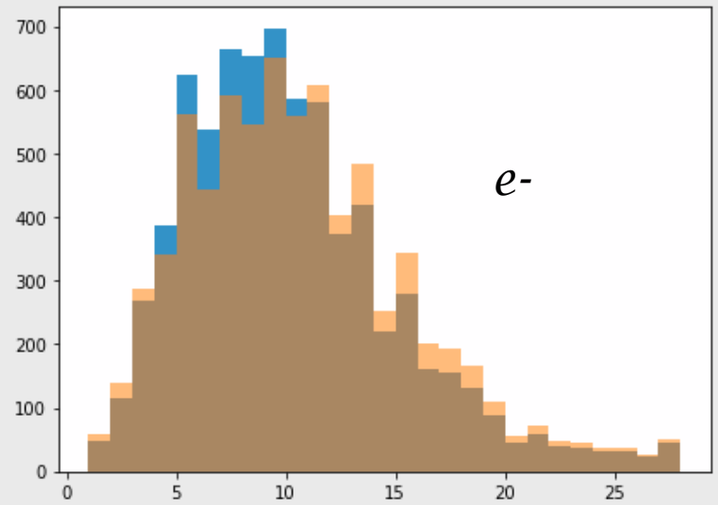
Muon MIP spectrum for a single channel

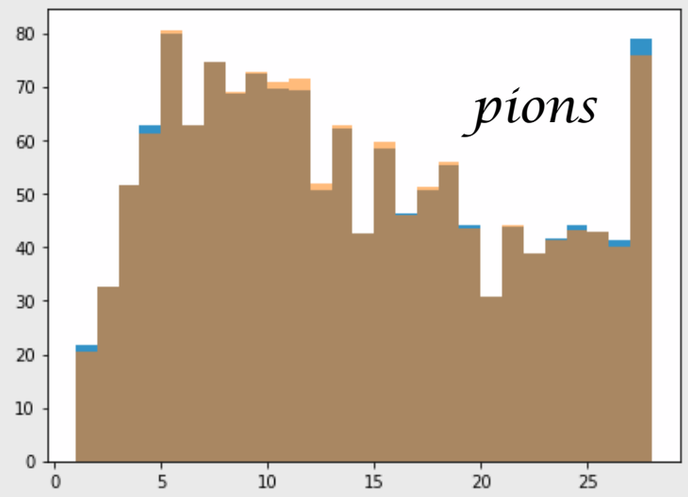


Preliminary results:

- *Clean MIP spectra for calibration*
- *electrons/pions longitudinal shower shapes are distinguishable*
- *Energy reconstruction works well even with preliminary calibration*
- *Basic agreement with Geant4 simulation for energy and multiplicity*

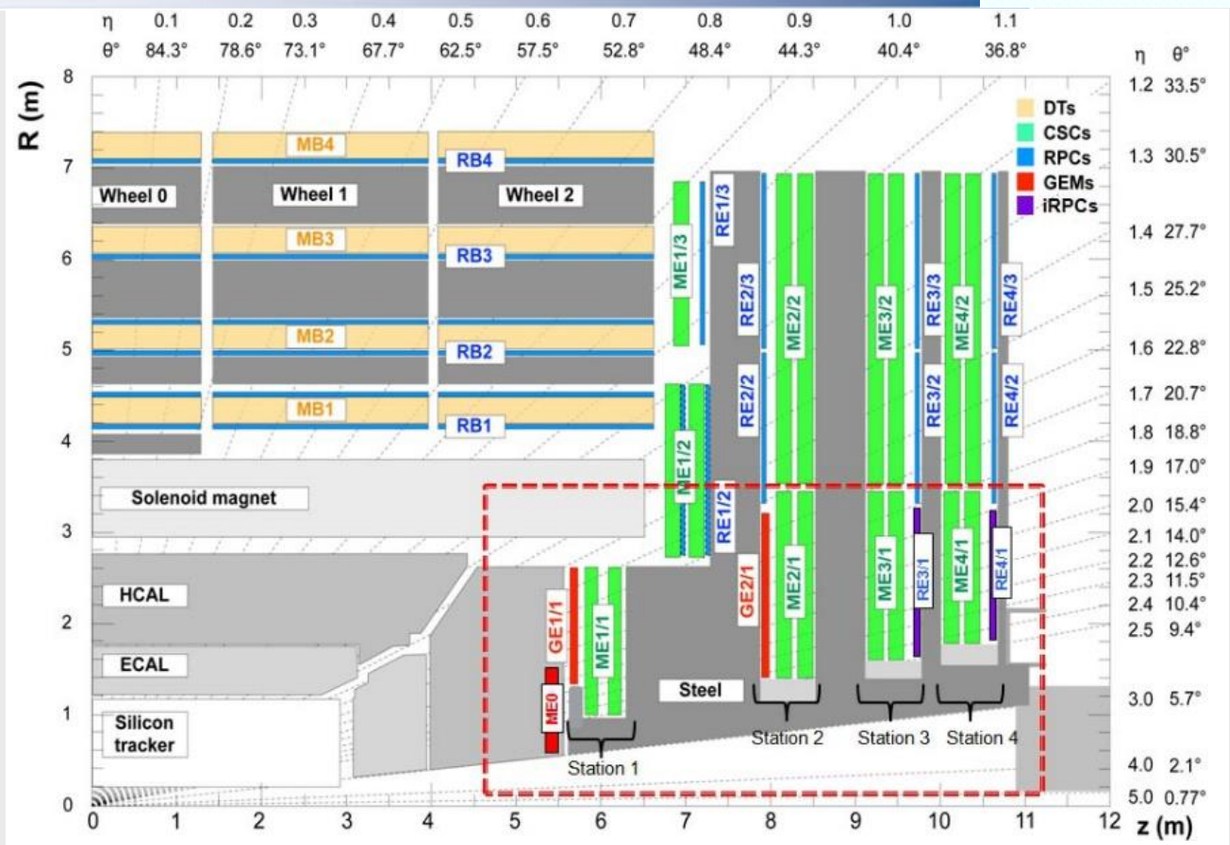
Longitudinal energy profiles

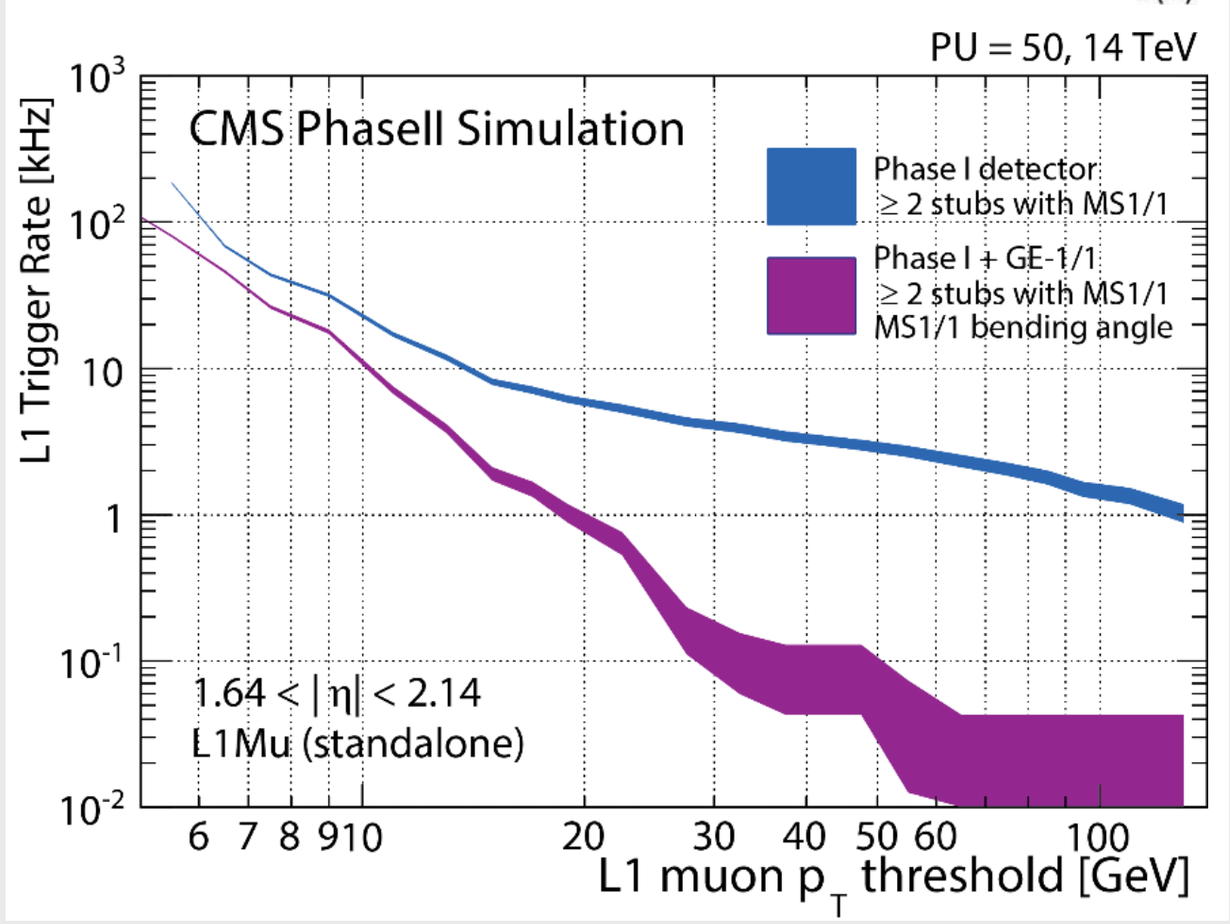




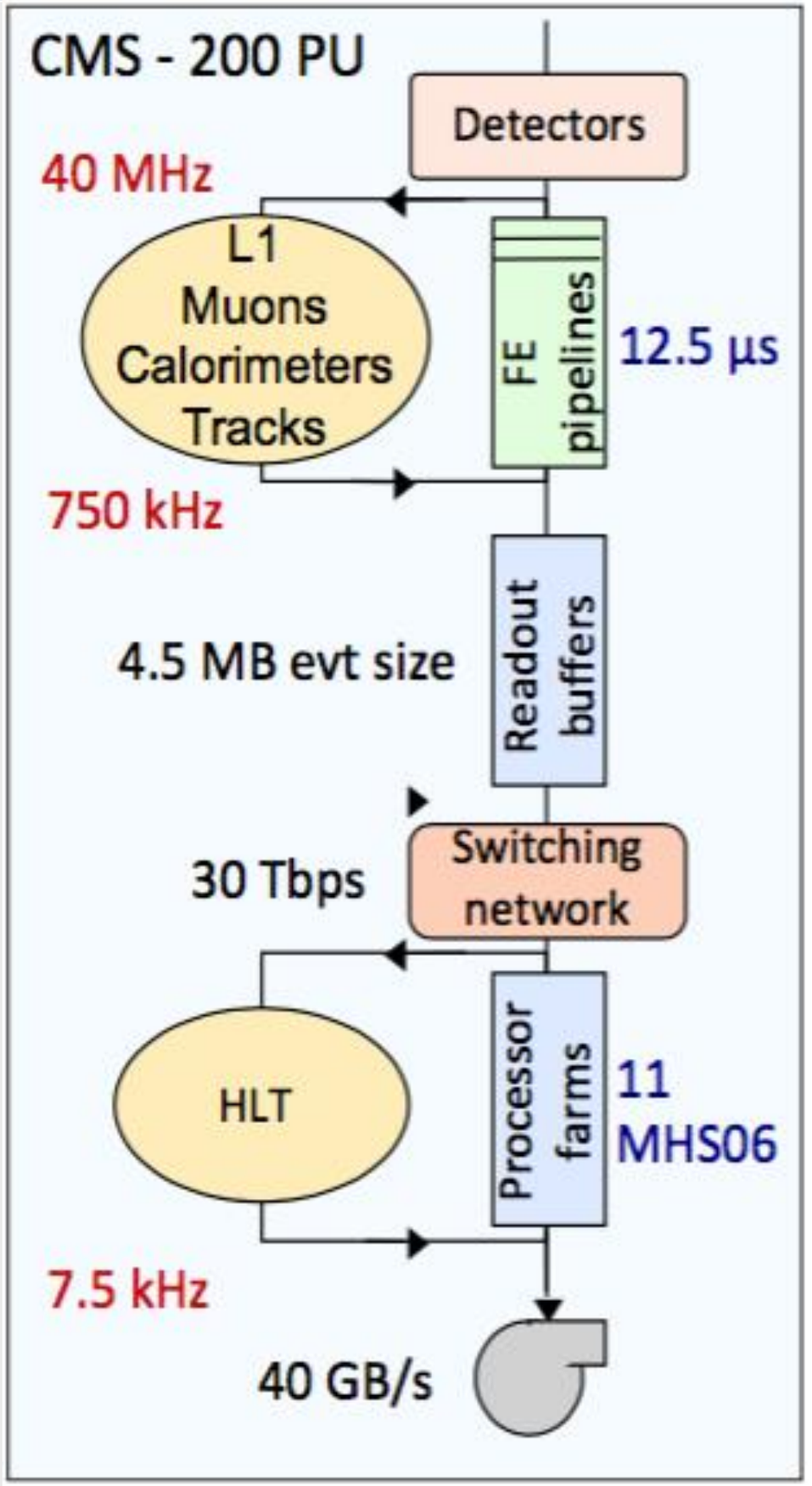
Muon System

- Extension of current muon system
  - Current chambers predicted to survive until end of HL-LHC
  - Complete coverage of RPC up to $|\eta|\sim2.4$ with fine-pitch chambers
- New GEM chambers
  - Improve trigger and reconstruction
  - Extend muon tagging to $|\eta|\sim3$
- Installation schedule
  - First GEM detector scheduled for installation during LS2 (2019-2020)
  - Fine-pitch RPC, Muon-Tagger chambers and second GEM station will be installed during LS3 (2024-2025)



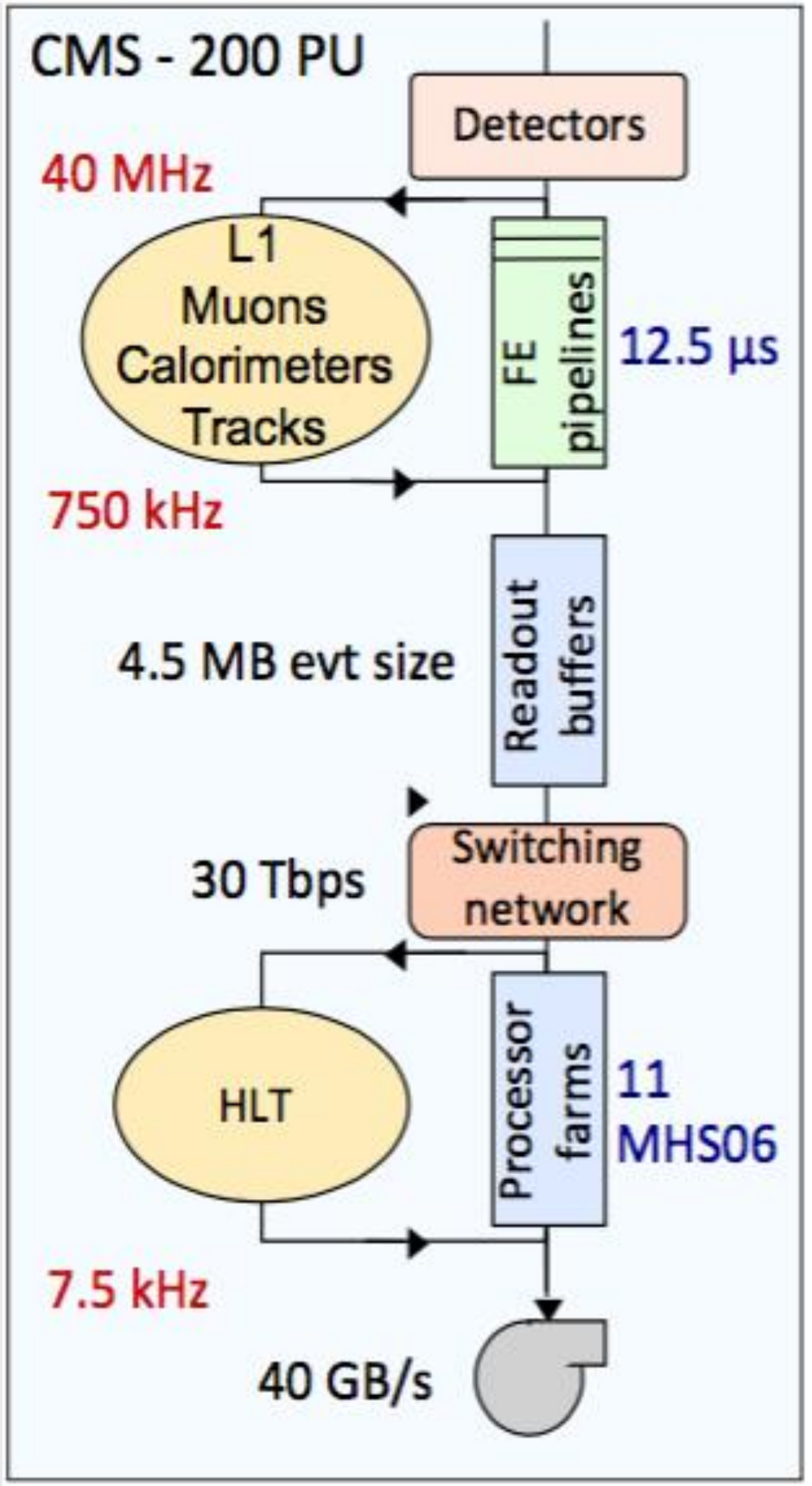


Trigger and DAQ



Trigger and DAQ

- L1 Trigger
  - Increase output to 750kHz, latency to 12.5μs, from 100kHz with 3.4μs latency
  - New track-trigger



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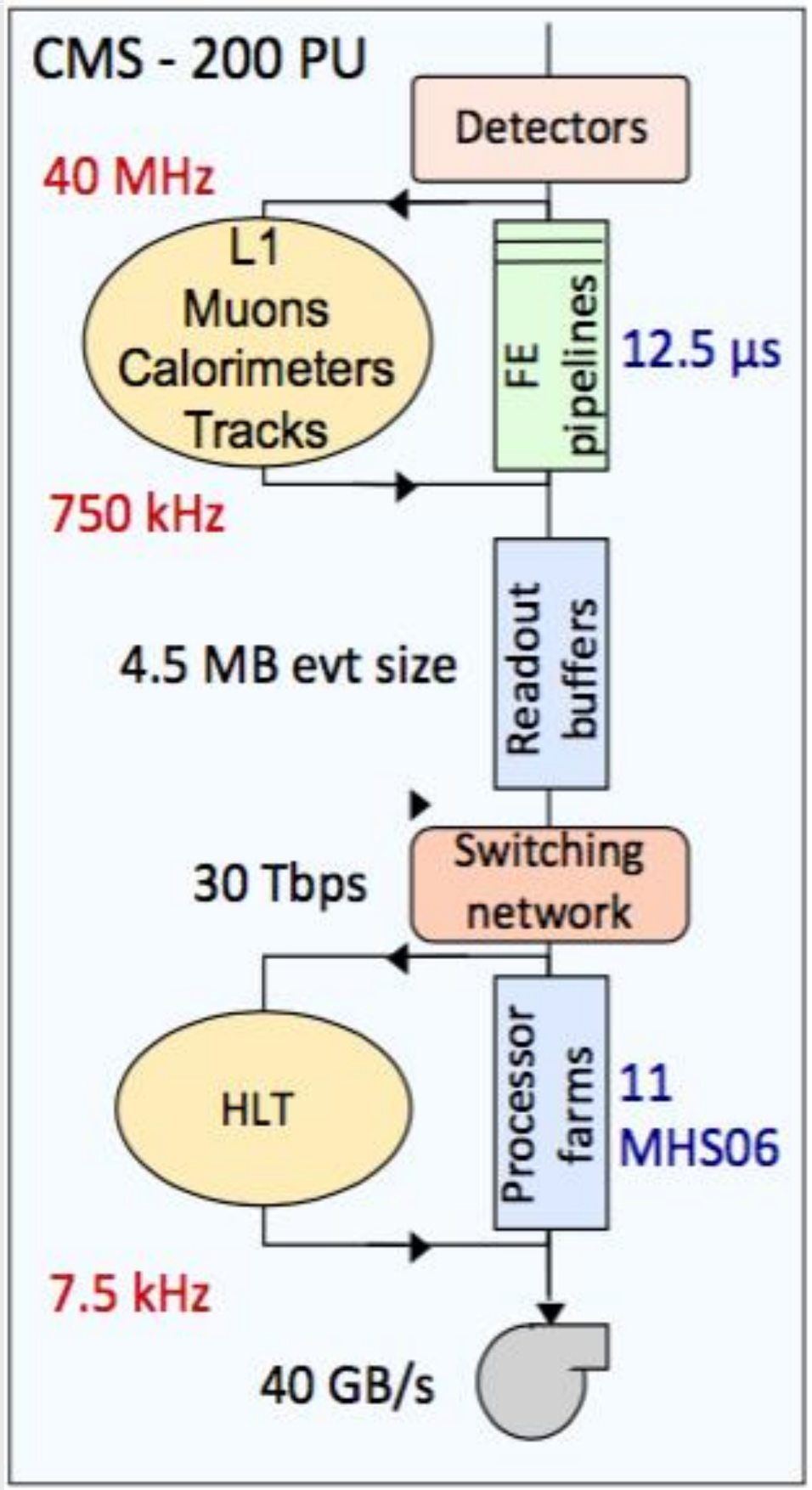
  - Output rate increase by ~1 to 7.5kHz



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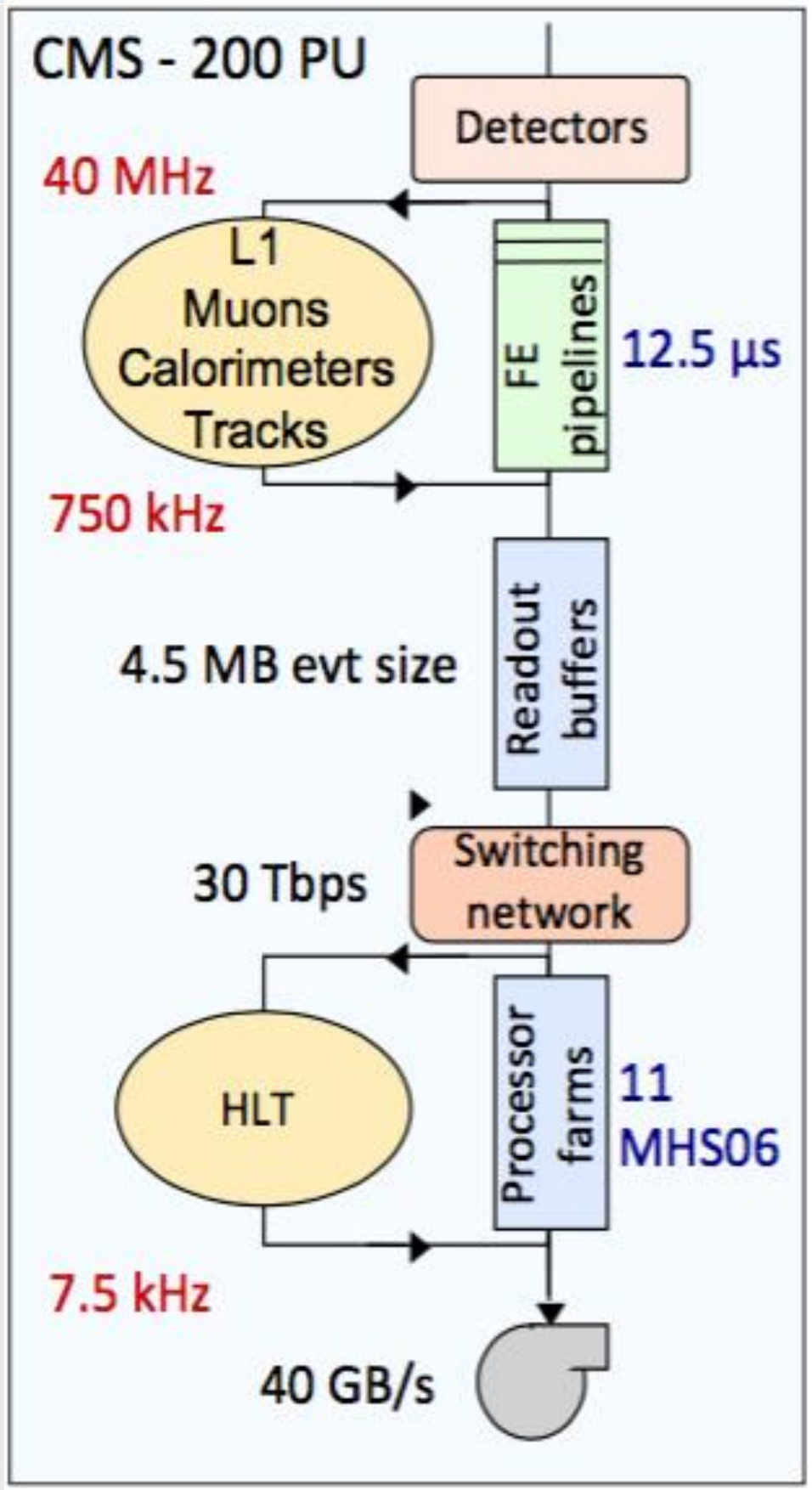
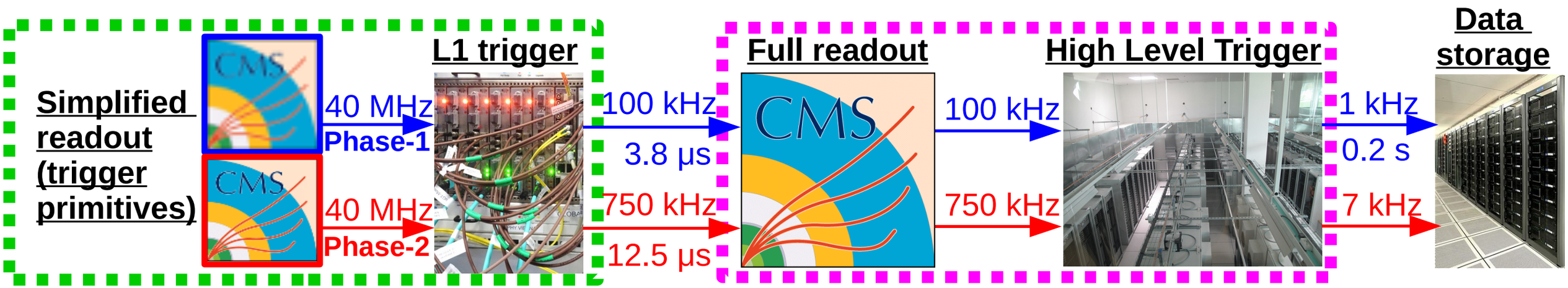
  - Output rate increase by ~1 to 7.5kHz
- DAQ
  - Increase bandwidth (800 links @ 100Gbps) to reach 30Tbps throughput



Summary : CMS trigger and Phase-2



Highlights of CMS Phase-2 trigger upgrade:

- larger L1 trigger rate / detector readout rate (100 kHz → 750 kHz);

- larger L1 trigger latency (3.8 µs→ 12.5 µs) →more sophisticated algo;

- more info at L1 trigger → L1 tracks, higher granularity;

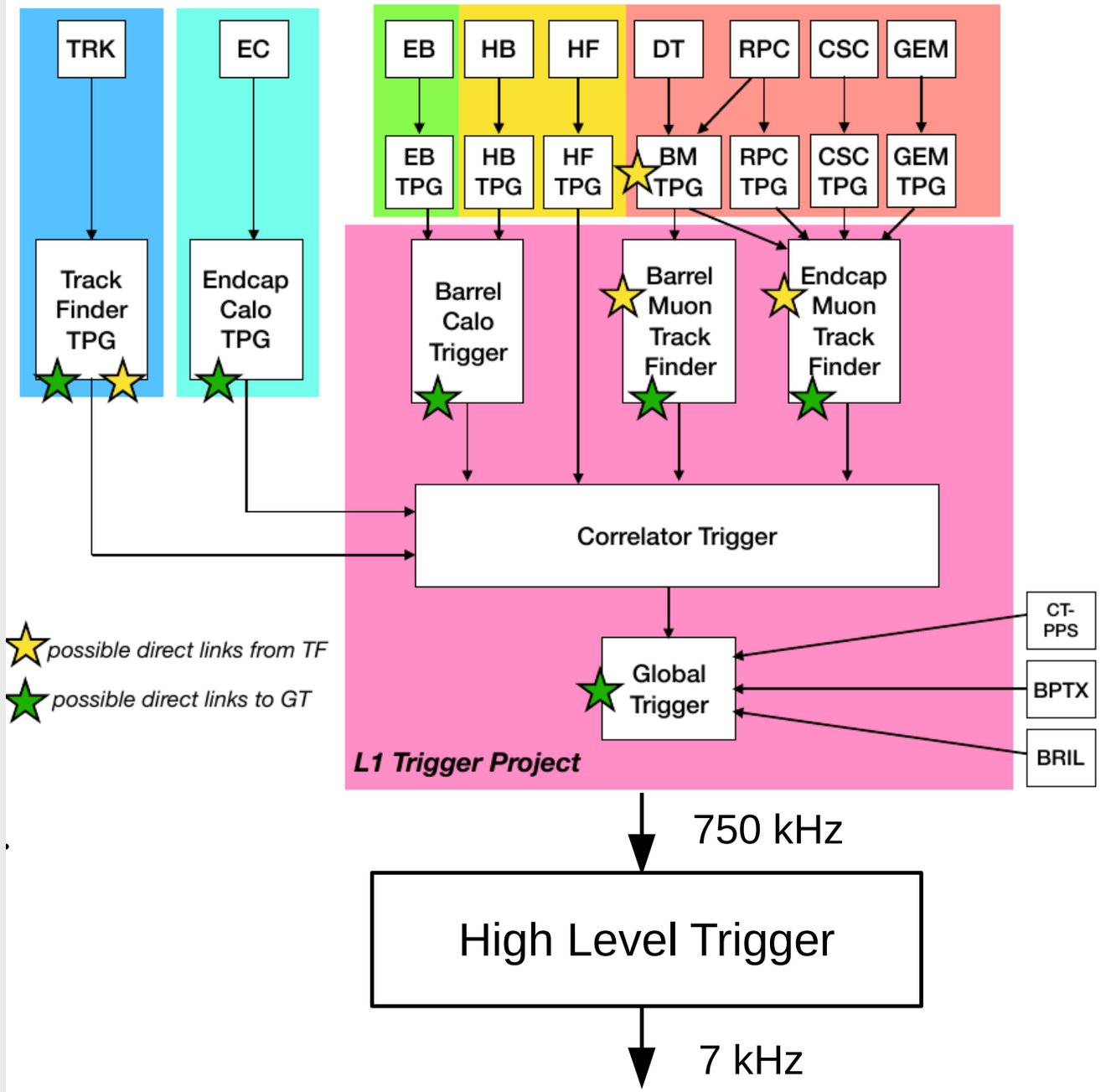
- larger HLT computing power to cope with larger rate and pile-up;

- more HLT output rate (1 kHz → 7.5 kHz)→more offline CPU power.

From ICHEP2018 (Silvio Donato (University of Zurich))

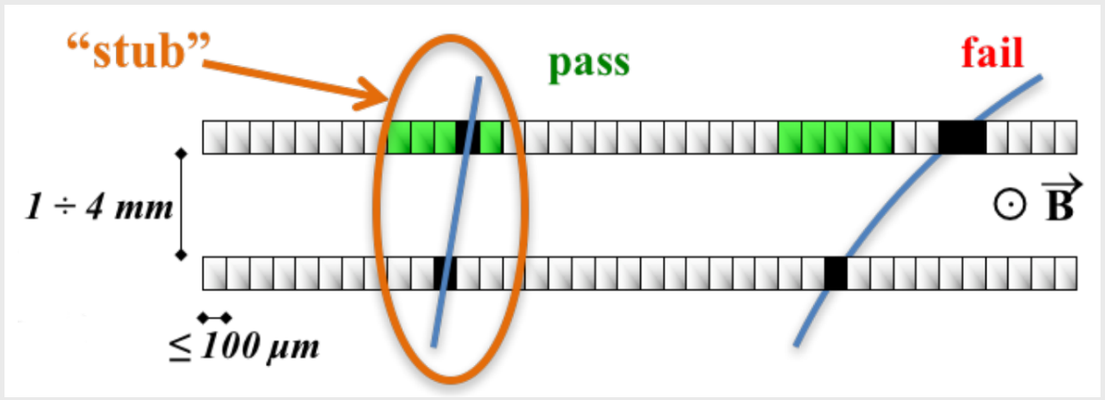
CMS L1 trigger at Phase-2

- Detector (simplified readout).
- Trigger Primitive Generator (TPG),
  - eg. track doublets.
- Combination of TPG,
  - eg. calorimetric tower.
- Correlater Trigger,
  - combine inputs from detectors;
  - possibility to run Particle Flow.
- Global Trigger → L1 decision.
- High Level Trigger.

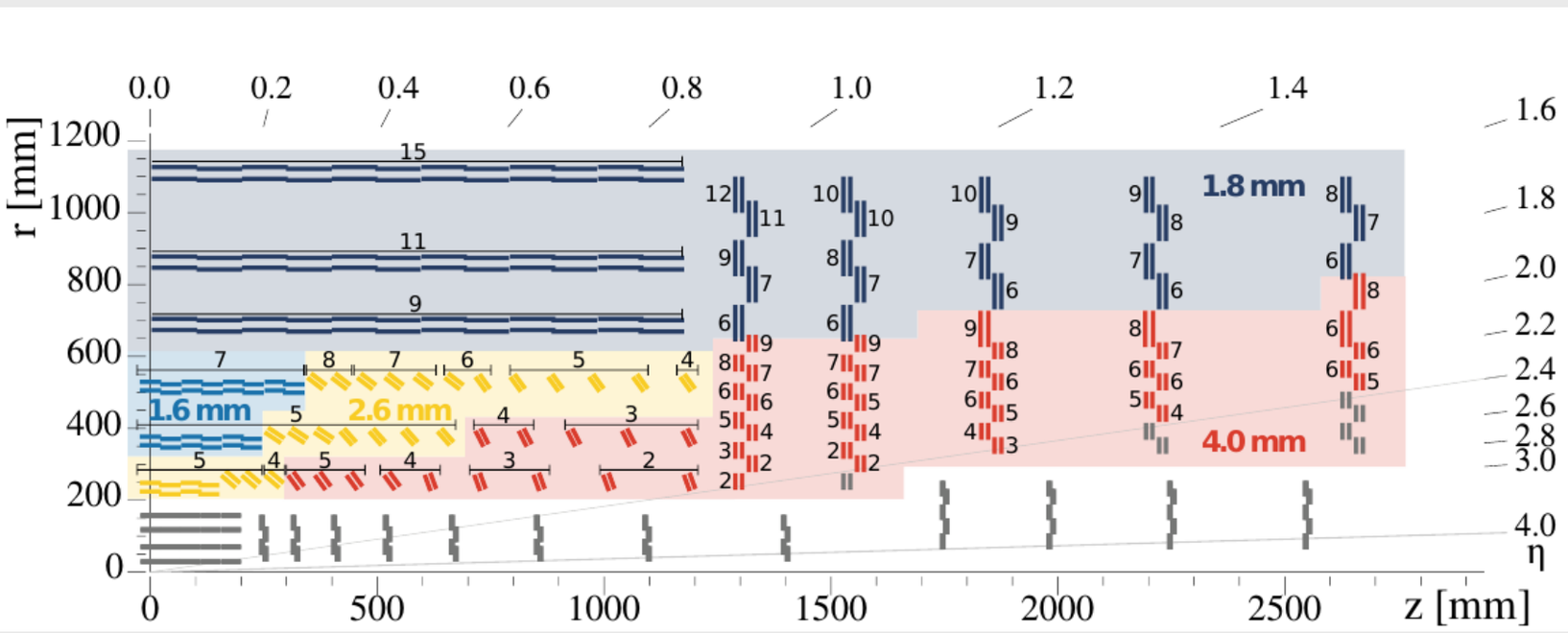


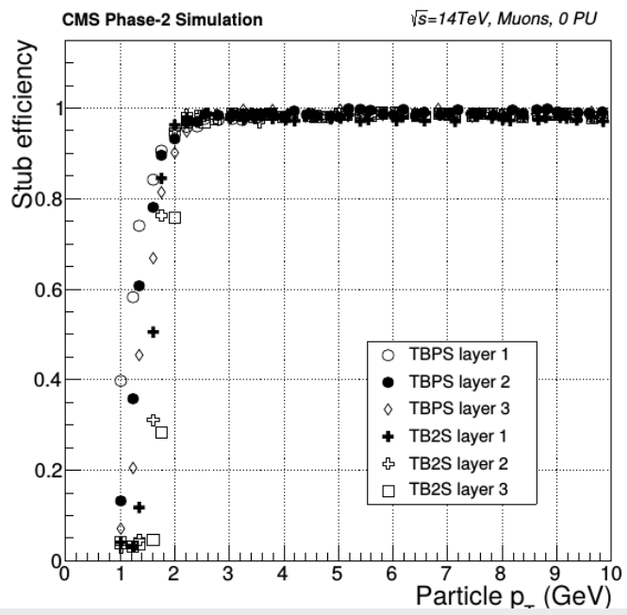
From ICHEP2018 (Silvio Donato (University of Zurich))

L1 trigger tracker



- CMS outer tracker trigger will be made of strip-strip and pixel-strip modules.
- Each pair looks for hit doublets compatible with a high pT track.
- About 15k doublets are expected to be reconstructed per event
- inducing 200 tracks on average with pT > 2 GeV @ 40MHz.





From ICHEP2018 (Silvio Donato (University of Zurich))

L1 ECAL barrel calorimeter

- *Large improvement of single e/g resolution in position and p_T.*

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L1 ECAL barrel calorimeter

- Large improvement of single e/g resolution in position and p_T.

- Electromagnetic barrel calorimeter will provide
  - Higher granularity: 5x5 crystal → single crystal.
  - Trigger Primitive Generator:
    - baseline: one for each 61200 crystals (E_T, time, spike flag);
    - possible clustering: 1000 clusters + unclustered energy info.

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L1 ECAL barrel calorimeter

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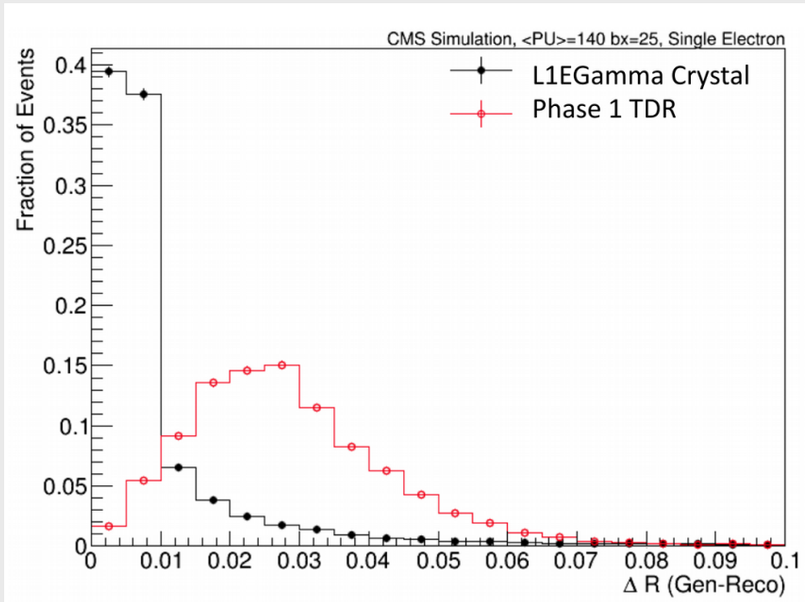
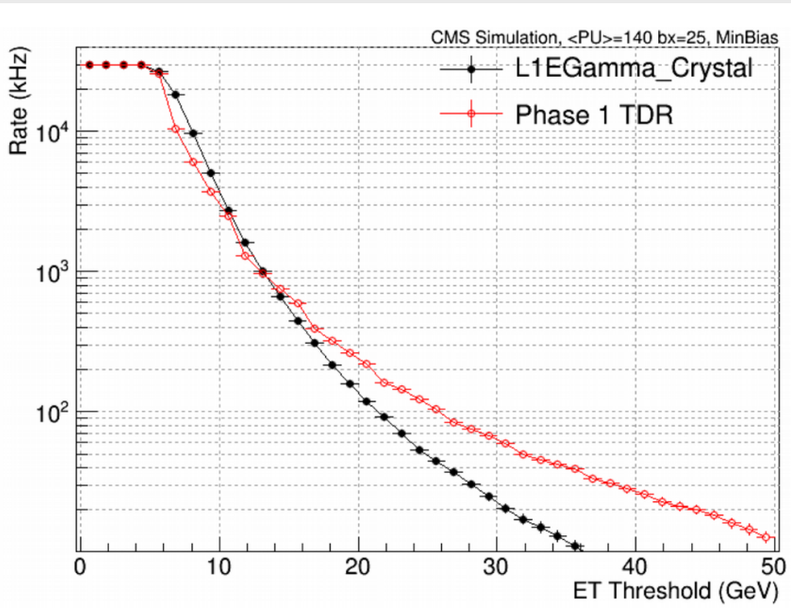
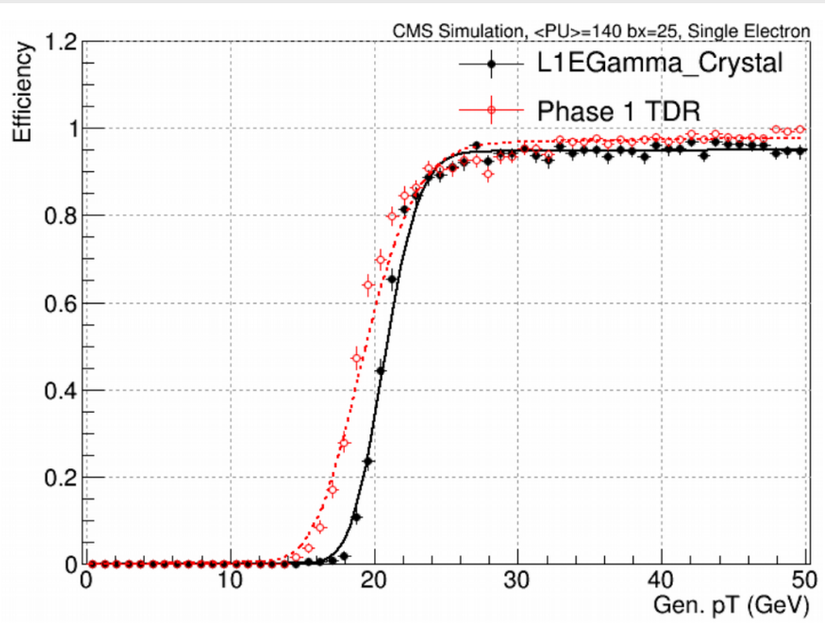


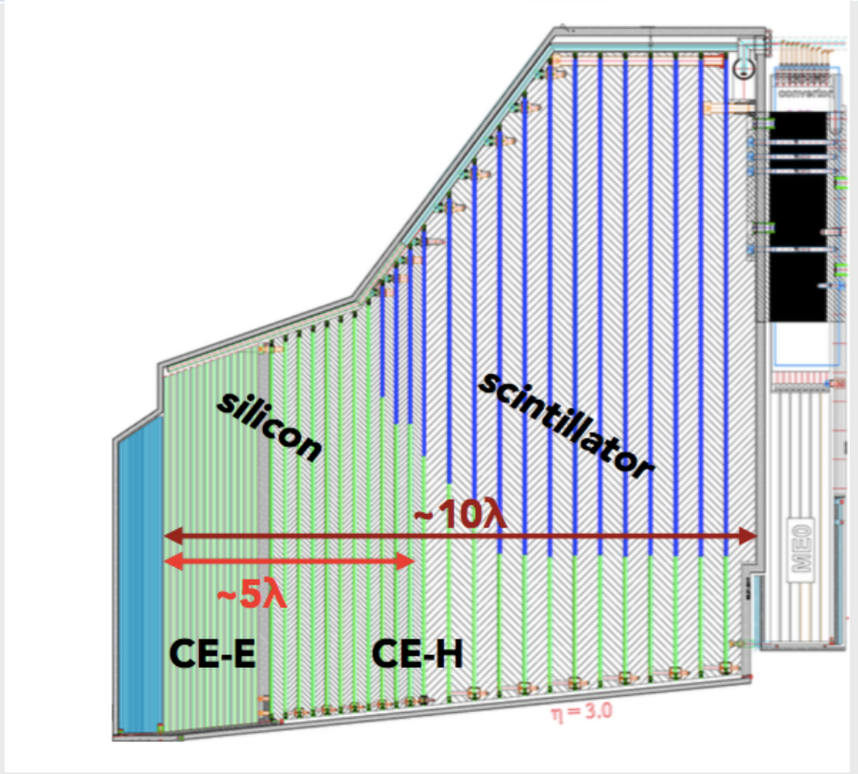




From ICHEP2018 (Silvio Donato (University of Zurich))

L1 trigger with HGCAL

- HGCAL in end-cap region has :
  - ~ silicon and scintillator as active material,
  - ~ 52 sensitive layers → 6M channels!
- Trigger cell granularity: 4 cm² silicon,
  - ~ 28 electromagnetic + 24 hadronic layers @ L1;
  - ~ trigger ready to read 900k channels.



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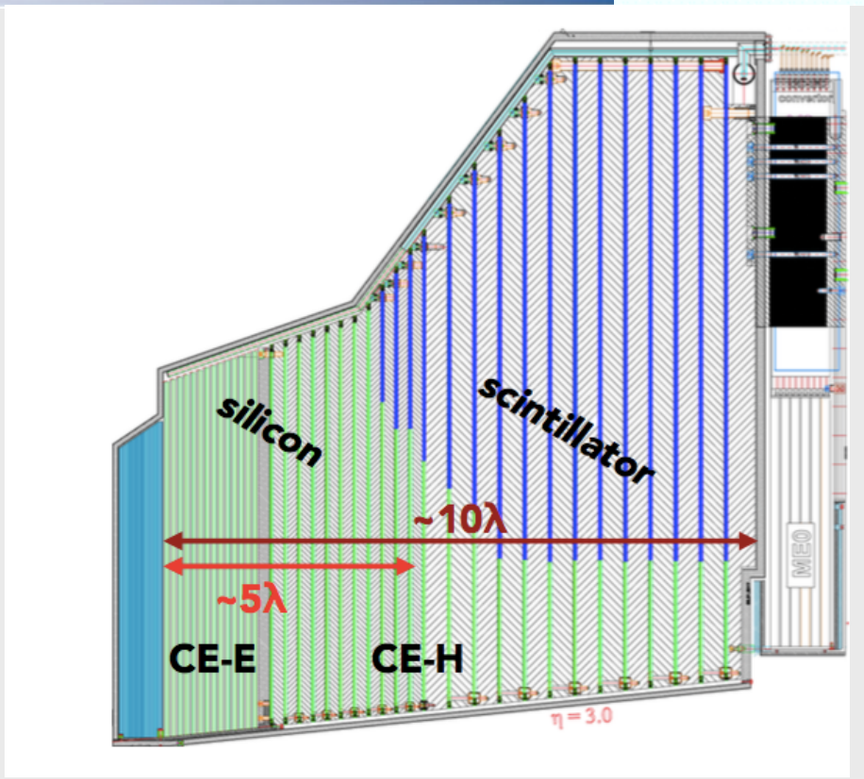

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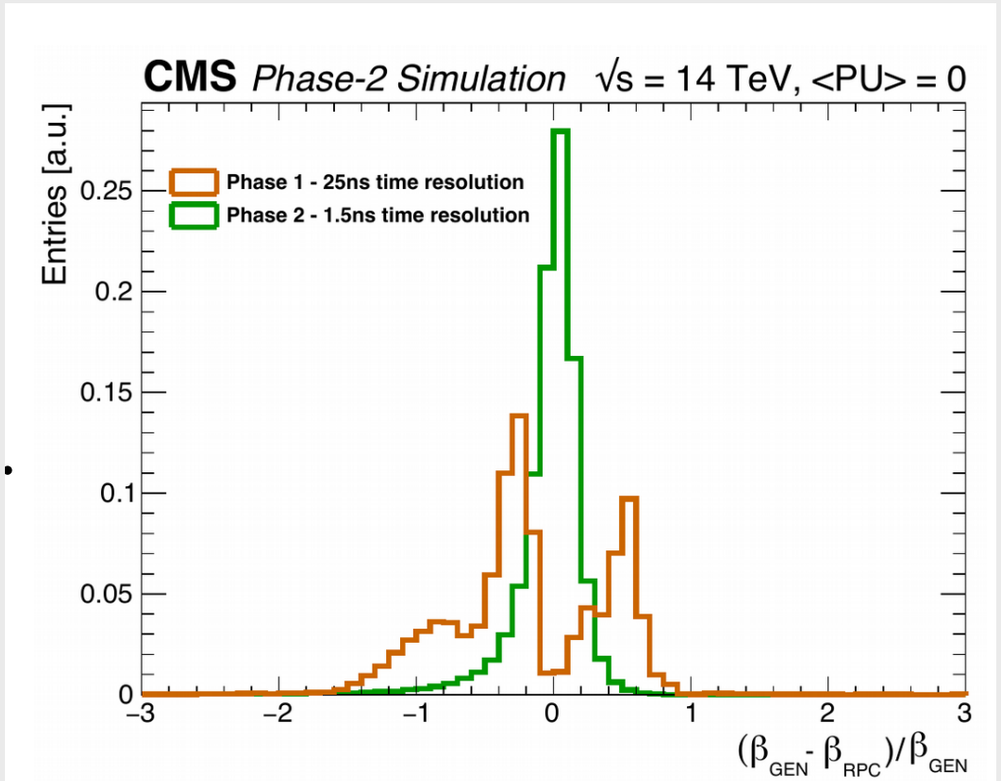
- Huge amount of data → zero suppression 2 MIP.
  - ~ Suppressed channels summed over large area
    → full coverage for ET miss, small bandwidth.
- Trigger Primitive Generator:
  - ~ 2D hits in each layer → combined in 3D clusters;
  - ~ ET, ETmiss fraction, shower position, quality, ...

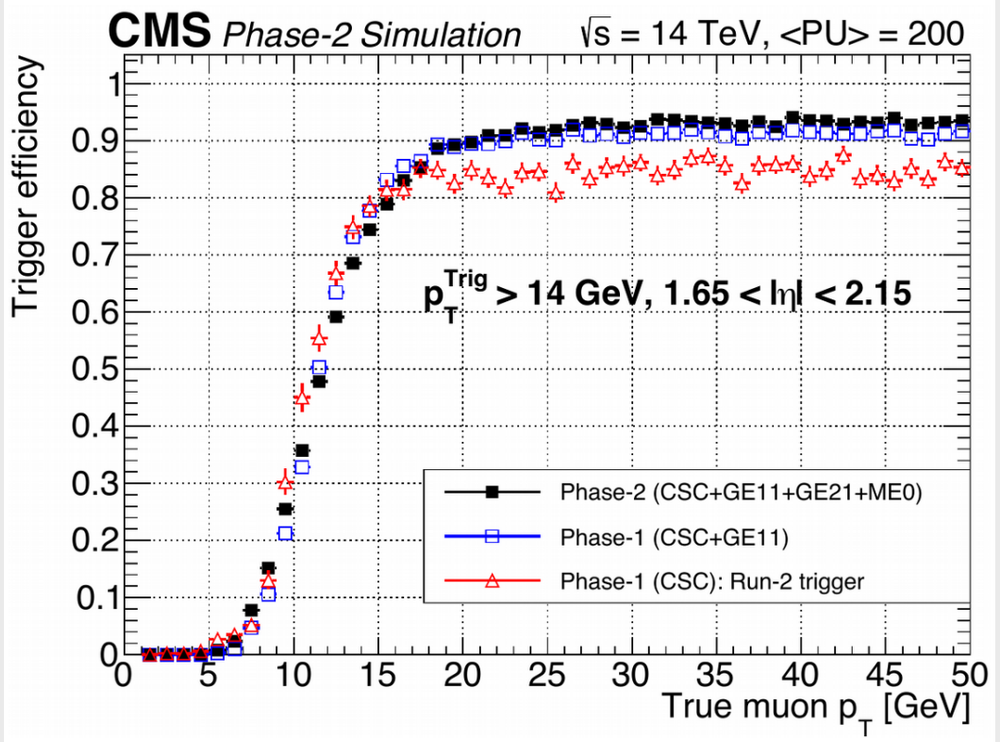
From ICHEP2018 (Silvio Donato (University of Zurich))

L1 muon detectors and trigger

- *Current:*
  - *DT + RPC, DT stub for triggering in barrel;*
  - *CSC + RPC, CSC stub for triggering in endcap.*
- *Improved RPC (iRPC) time res. 25 ns → 1.5 ns.*
- *Improved spatial resolution in DT.*
- *Combination DT + iRPC → better efficiency.*



- *New GEM detectors in endcaps:*
  - *combination with CSC to recover efficiency (GEM-CSC stub);*
  - *clusters send to L1 correlator trigger.*
- *L1 muons can be matched with L1 tracks in L1 trigger correlator → better p_T resolution.*



From ICHEP2018 (Silvio Donato (University of Zurich))

CMS L1 trigger potential

- Large improvement on muon p_T!
- Better electron and photon identification.
- Rate reduction from track isolation.
- Possibility to reject pile-up jet,
  - pile-up effect mitigation in MET triggers.

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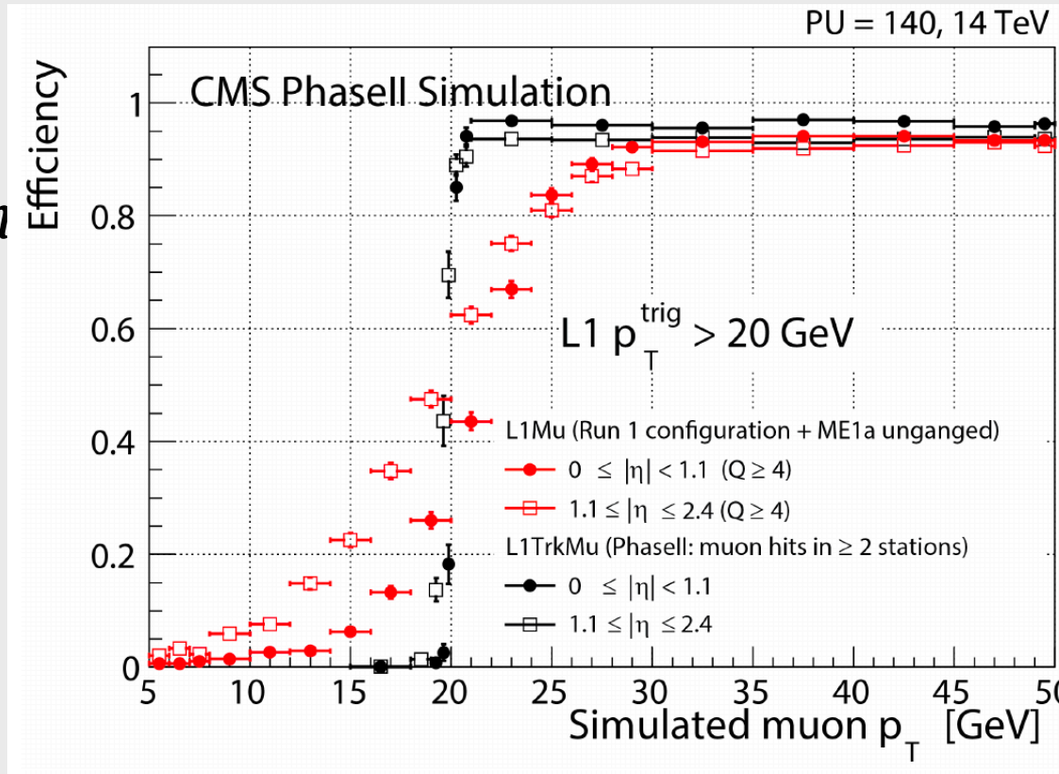

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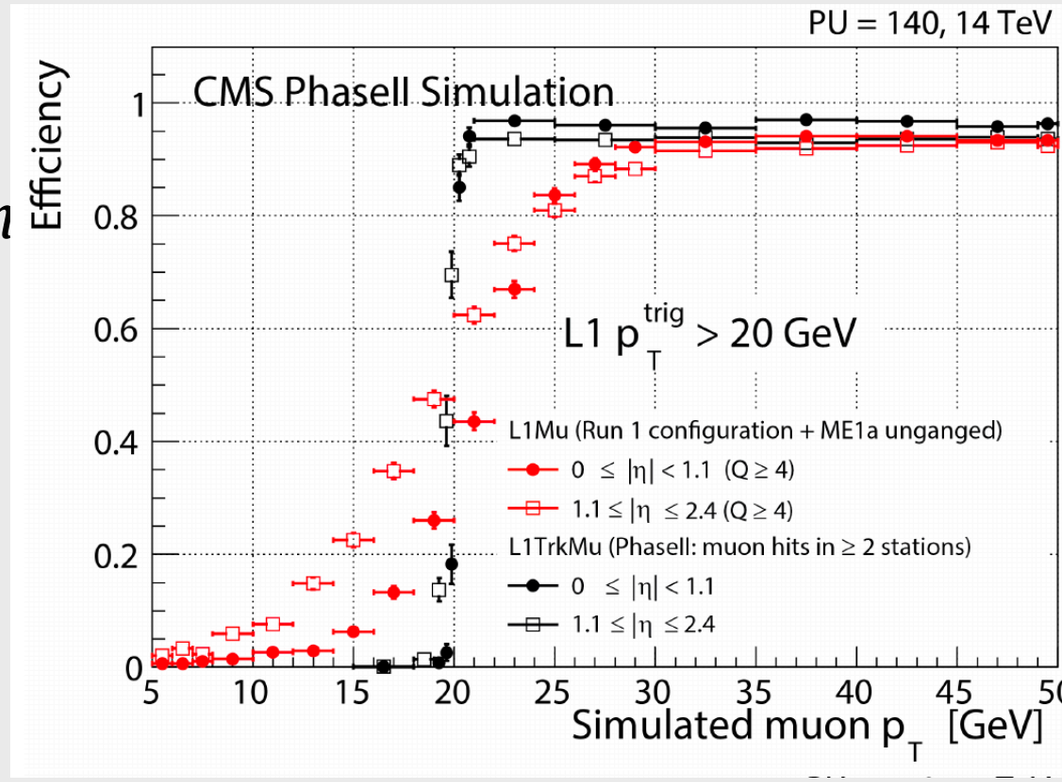

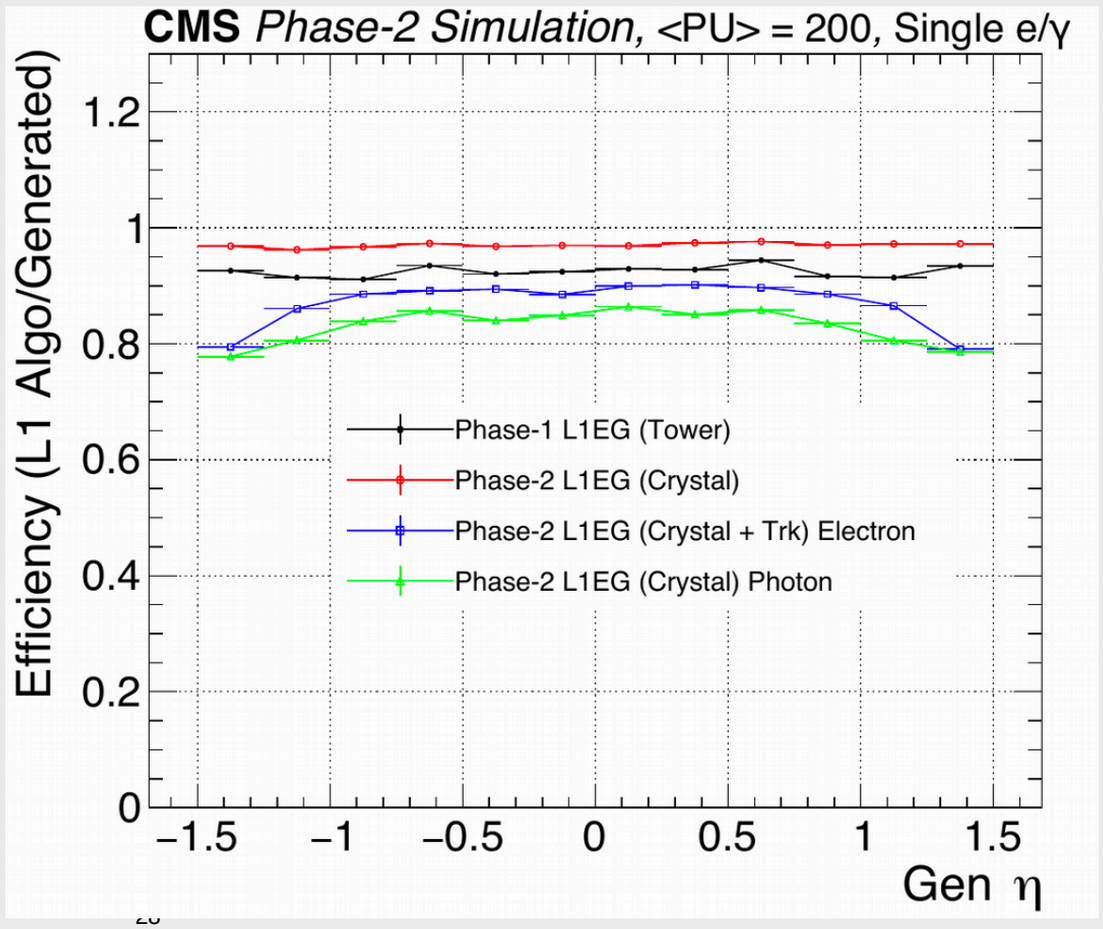

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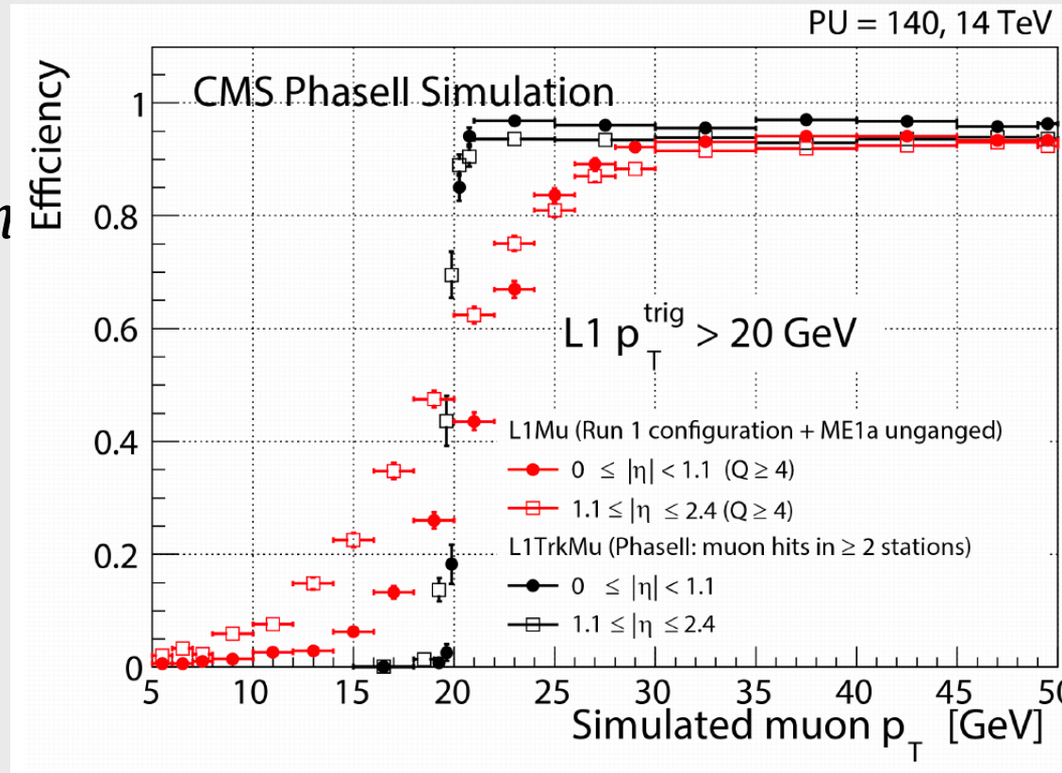
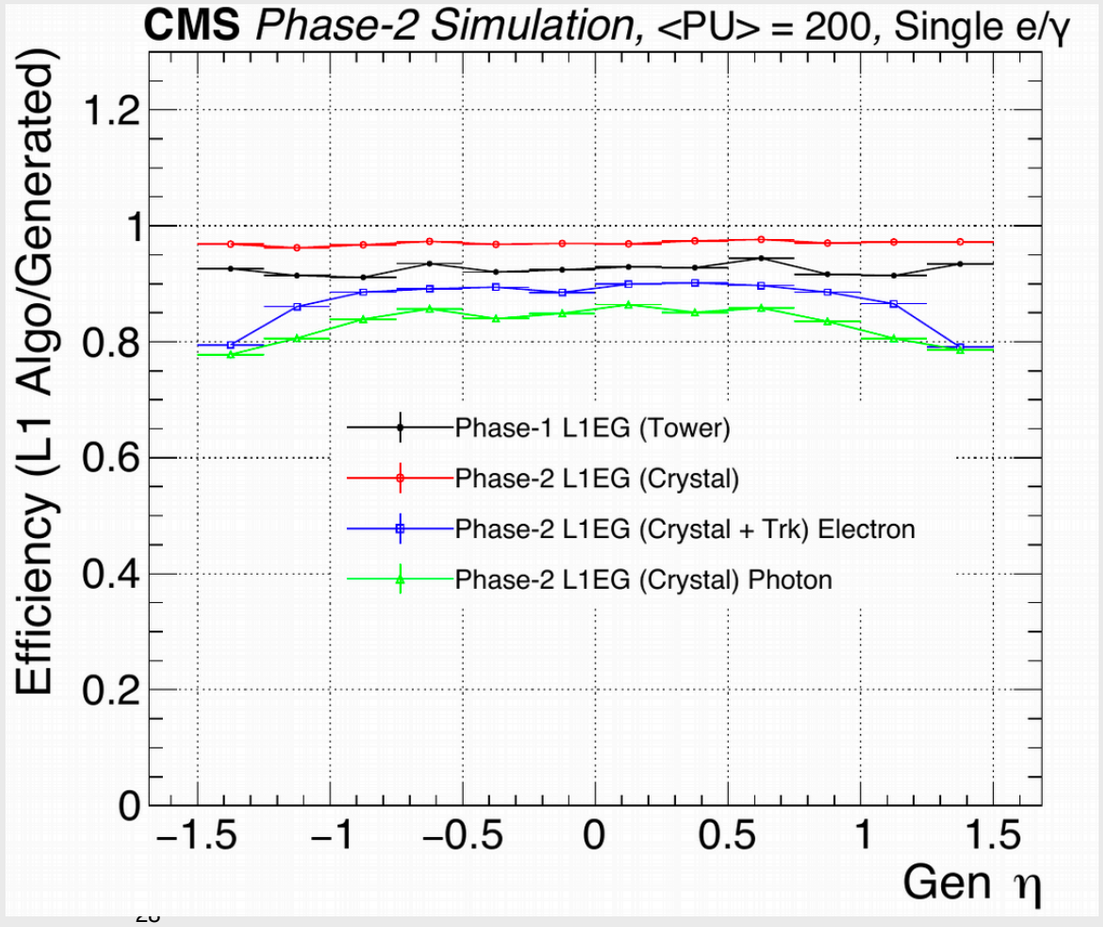
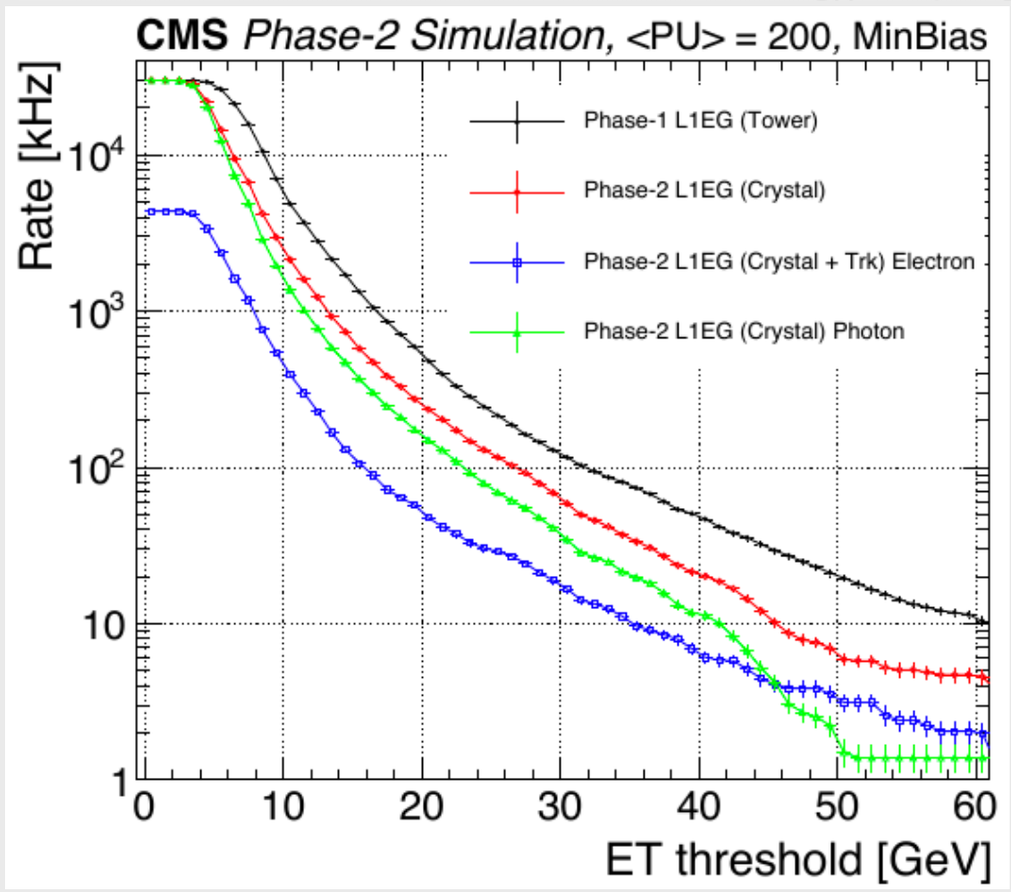


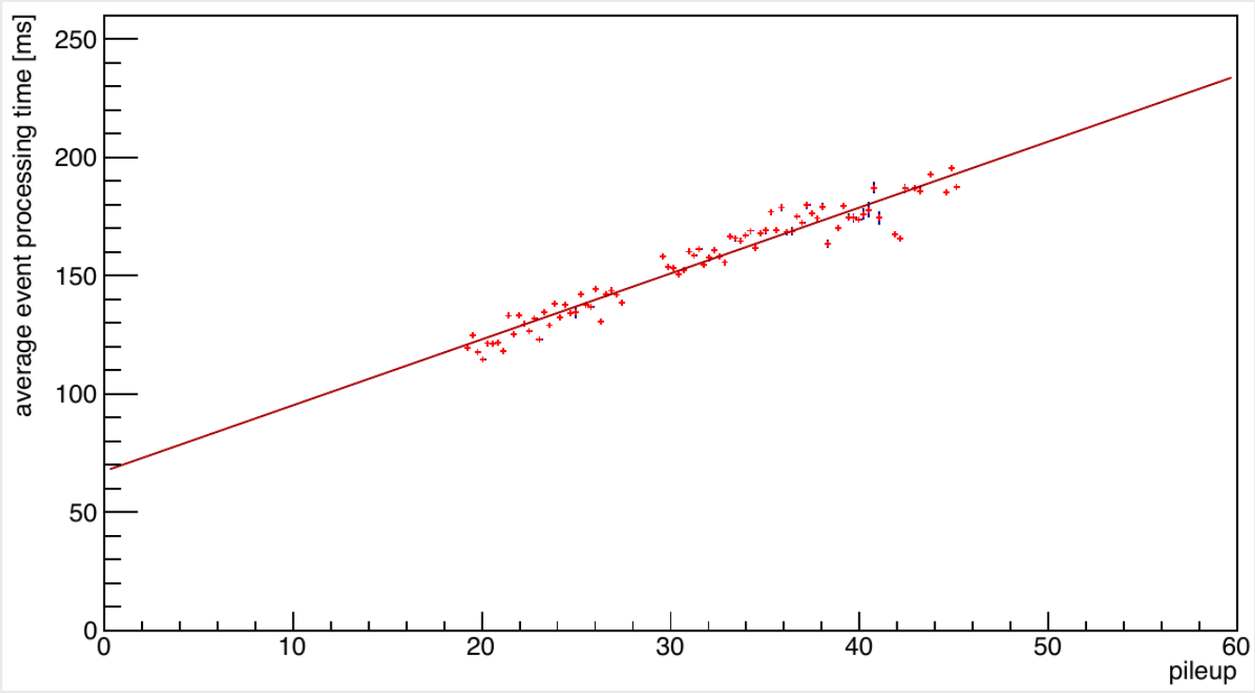




From ICHEP2018 (Silvio Donato (University of Zurich))

High Level Trigger

- The computing power required by the HLT will increase by a factor ~ x20:
  - x2.5 from larger pile-up;
  - x7.5 from larger L1 input rate.
- The expected HLT output rate will be about 7.5 kHz.



- The larger rates and event size increase both the DAQ bandwidth and storage throughput of about a factor 20.

CMS detector	LHC Run-2	HL-LHC Phase-2	
Peak ⟨PU⟩	60	140	200
L1 accept rate (maximum)	100 kHz	500 kHz	750 kHz
Event Size	2.0 MB [a]	5.7 MB [b]	7.4 MB
Event Network throughput	1.6 Tb/s	23 Tb/s	44 Tb/s
Event Network buffer (60 seconds)	12 TB	171 TB	333 TB
HLT accept rate	1 kHz	5 kHz	7.5 kHz
HLT computing power [c]	0.5 MHS06	4.5 MHS06	9.2 MHS06
Storage throughput	2.5 GB/s	31 GB/s	61 GB/s
Storage capacity needed (1 day)	0.2 PB	2.7 PB	5.3 PB

From ICHEP2018 (Silvio Donato (University of Zurich))

Trigger upgrade conclusions

- The HL-LHC is starting in eight years from now,
  - the expected luminosity is 7.10^{34} $cm^{-2}s^{-1}$ (pile-up ~ 200).
- The CMS trigger will be upgraded to cope with such a large luminosity:
  - L1 accept (detector readout) will increase its rate: 100 kHz → 750 kHz;
  - L1 trigger has access to more data from subdetectors.
- Expected big improvements from L1 tracks and higher granularity:
  - better muon pT resolution, track isolation, and electron/photon identification;
  - possibility to run Particle Flow at trigger level
- HLT computing power and IO throughput need to be upgraded:
  - usage of heterogeneous architectures is under study.

From ICHEP2018 (Silvio Donato (University of Zurich))

References

CERN-LHCC-2017-013: L1 Trigger upgrade, Interim TDR
CERN-LHCC-2017-009: Tracker upgrade, TDR
CERN-LHCC-2017-014: DAQ upgrade, Interim TDR
CERN-LHCC-2015-10: Technical Proposal

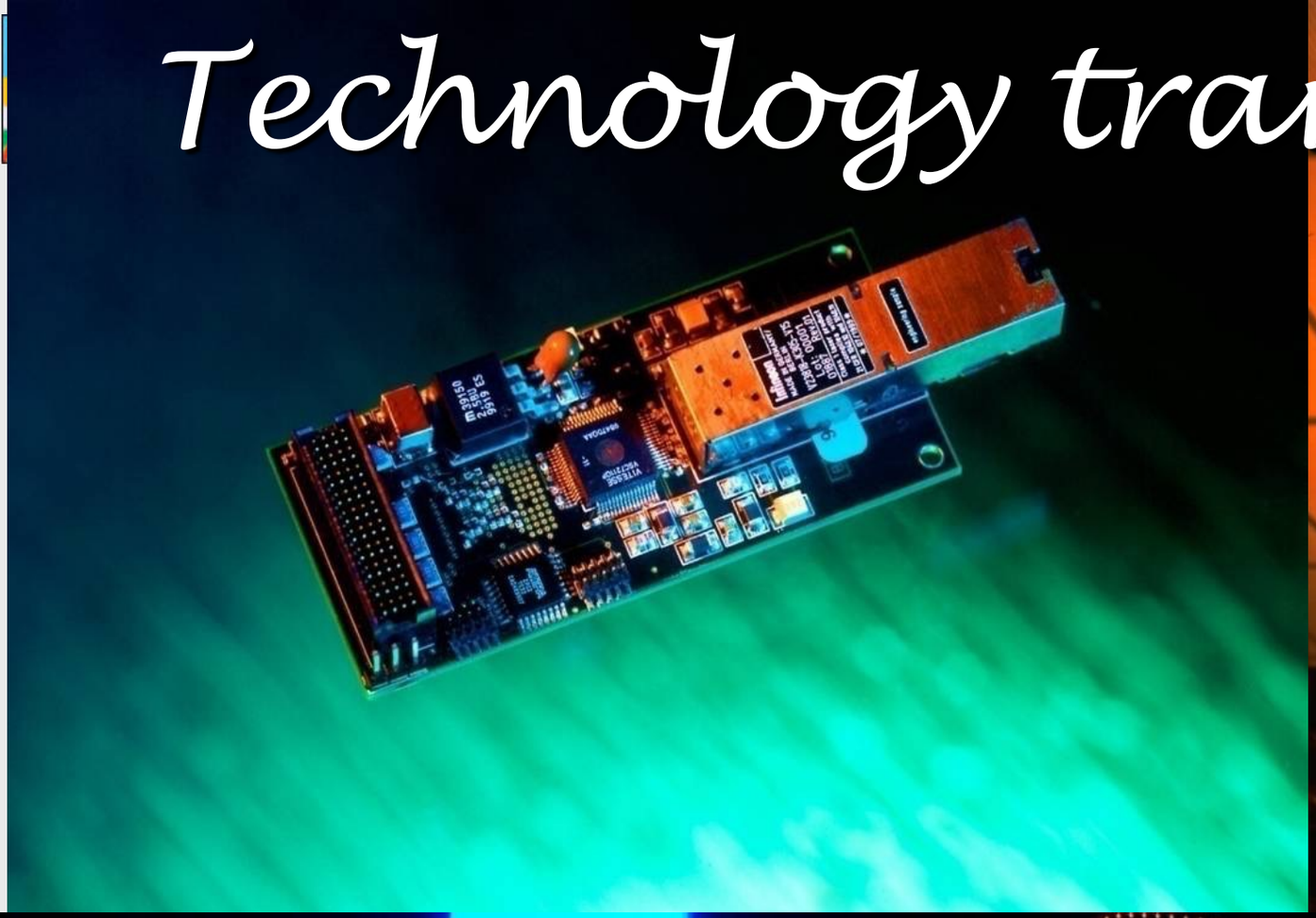
Concluding Remarks

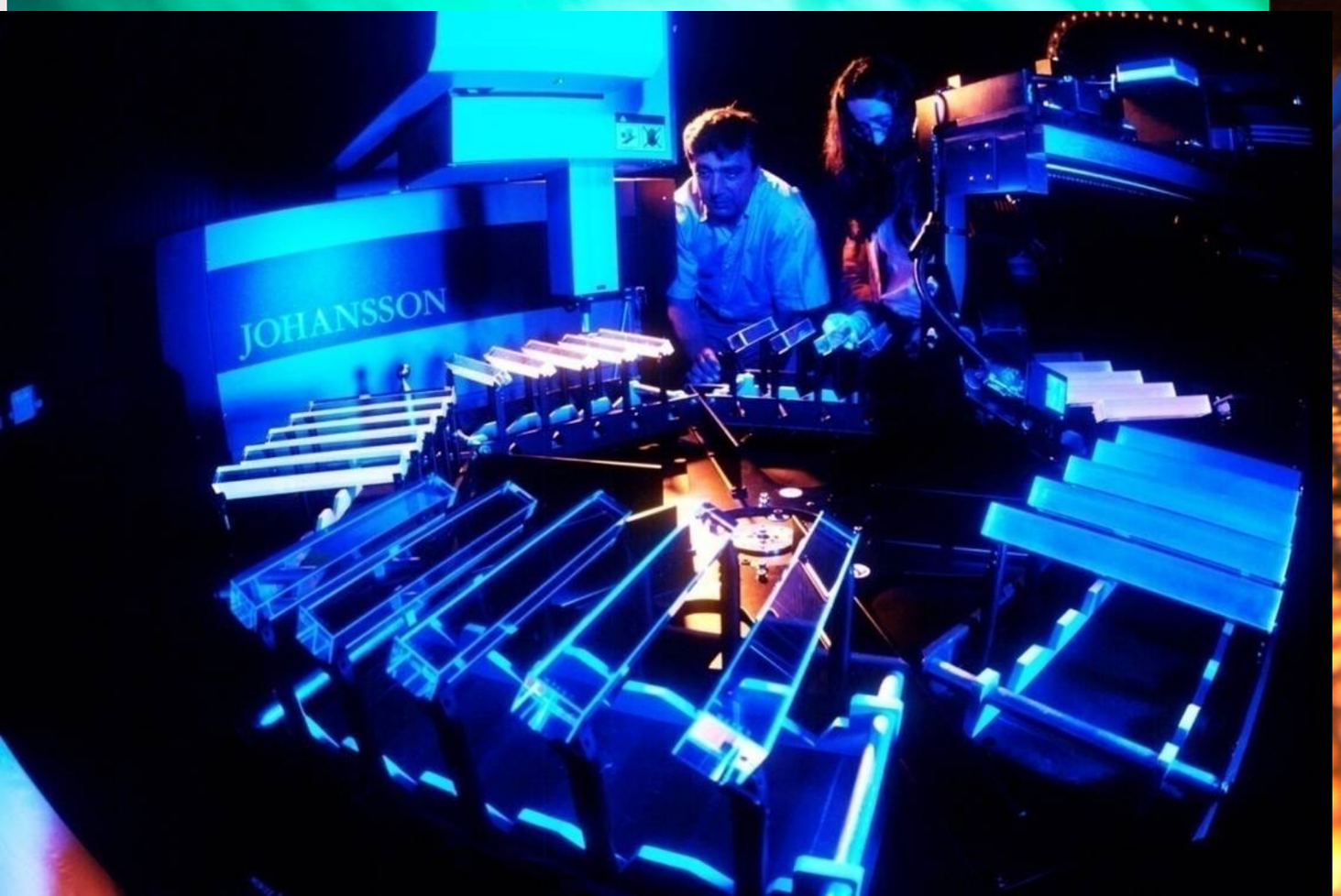
- *Upgrade projects are a continuous effort, overlapping with operations*
  - *Unique opportunity for training new physicists;*
  - *important to establish strong community to share knowledge of key personnel and ensure growth of next generation of physicists*
- *Phase-1 upgrade was used for RUN 2*
- *Phase-2 upgrade is in its initial stage*
  - *Very exciting R&D programs are on-going to define the future detectors*
- *The HL-LHC will open a new set of physics opportunities*
  - *A successful upgrade program is crucial to exploit them*

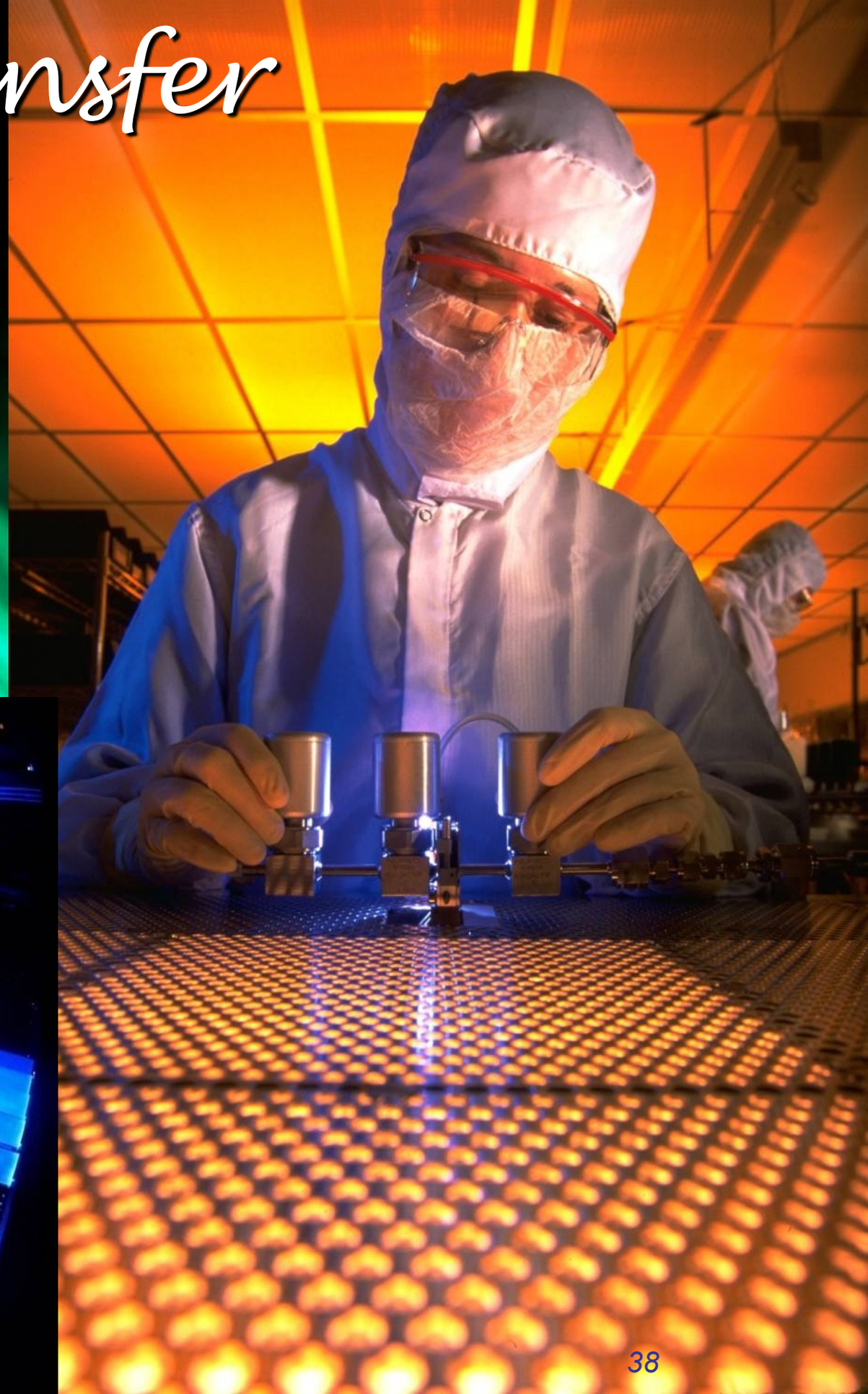
Final conclusions

- The LHC is world wide unique technological and scientific endeavour, comparable to the Space programmes.
- Twenty years spent on the design: R&D, prototyping, construction, assembly and commissioning gave to all experiments a huge volume of high energy collision data.
- The LHC has gradually rise the collision energy (now 13 TeV) and luminosity (now as high as 2 10^{34} $cm^{2}s^{-1}$
- The four major experiments ATLAS, CMS, ALICE and LHCb have taken high quality data operating extremely successfully, with very high efficiencies and generate hundreds of publications
- An upgrade programme prepare the detectors to accept and treat higher luminosities and extract new physics from large pile up background.
- The LHC will continue feed the world particle physics community for the next ~ 20 years

Technology transfer







CERN invented the WEB !!!