Detector Upgrades for the High Luminosity Large Hadron Collider

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The Future of High Energy Physics: A New Generation, A New Vision
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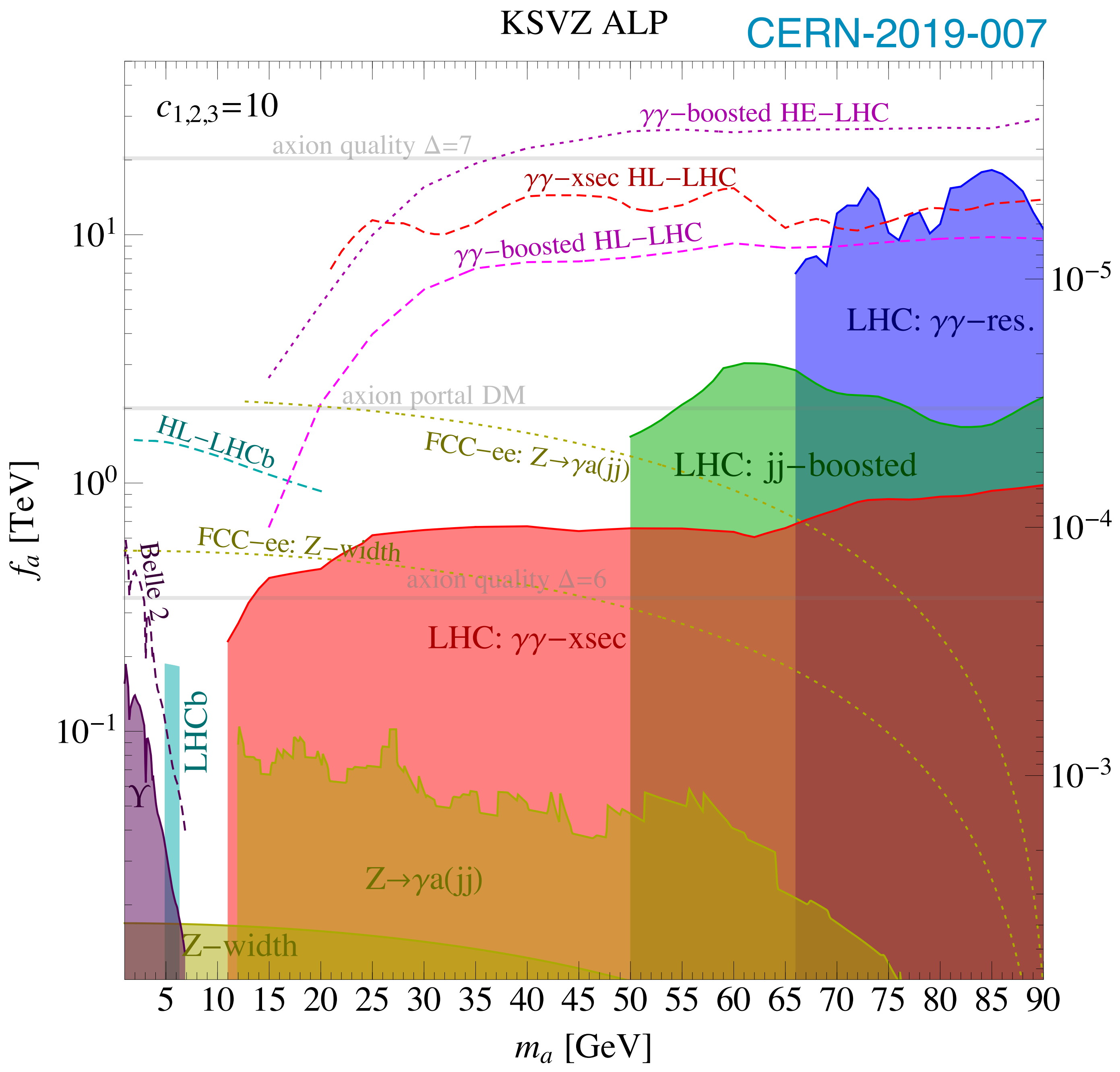
Outline

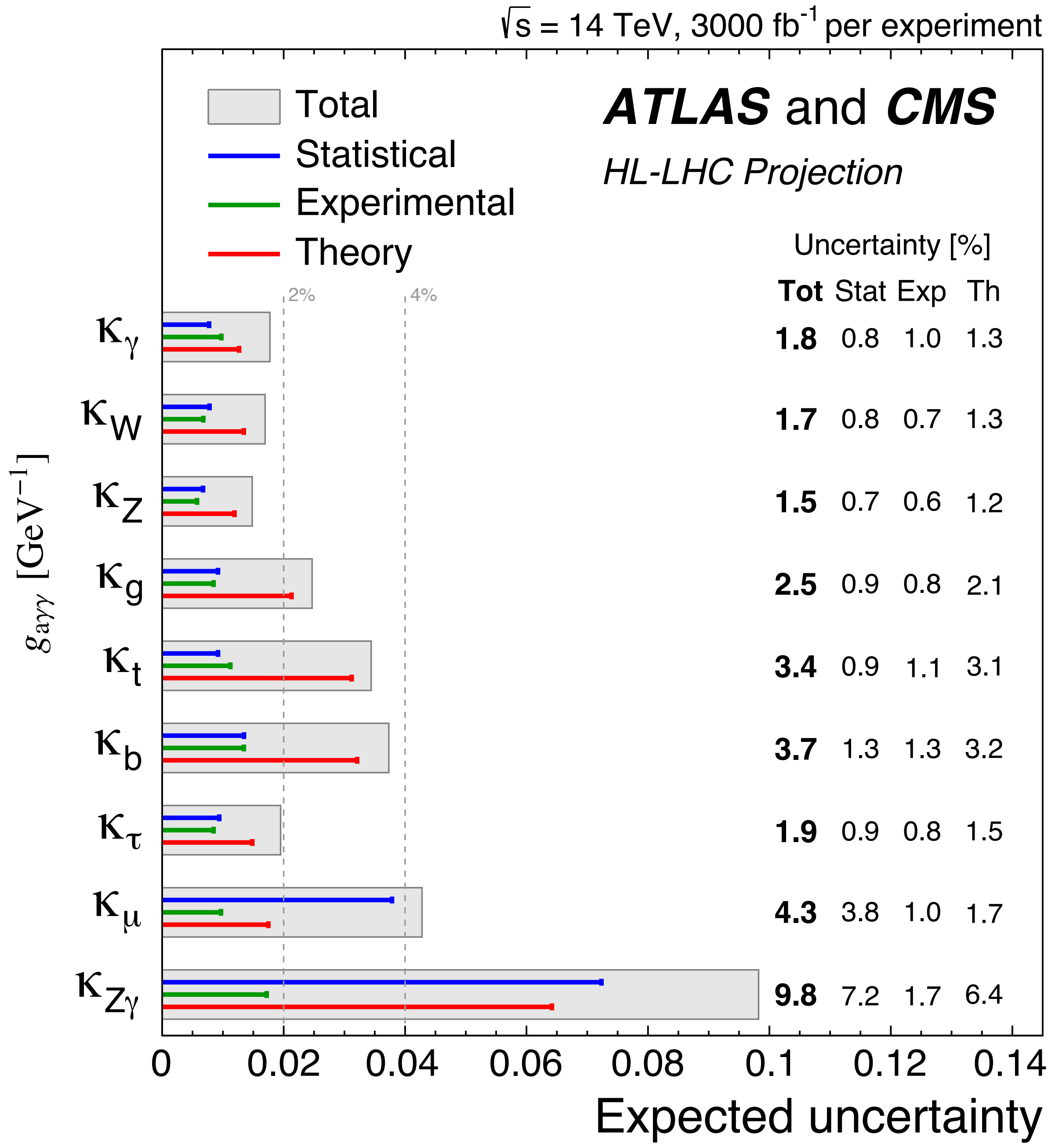
- Why the High Luminosity Large Hadron Collider (HL-LHC)?
- Challenges of the HL-LHC collision environment
- Detector design and technology requirements
- Highlights of the HL-LHC detector upgrades
  - Focus on CMS and ATLAS
- Conclusions

Why the HL-LHC?

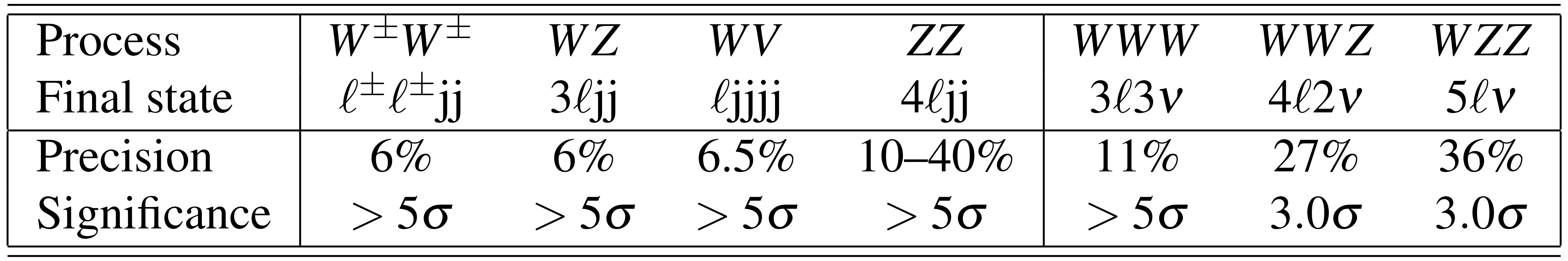
- Precision measurements of Higgs couplings: gauge, Yukawa, and self
- Higgs as a probe of physics beyond the Standard Model (BSM)
- Precision studies of electroweak symmetry via multiboson interactions or W mass measurement
- Rare BSM physics



CERN-2019-007



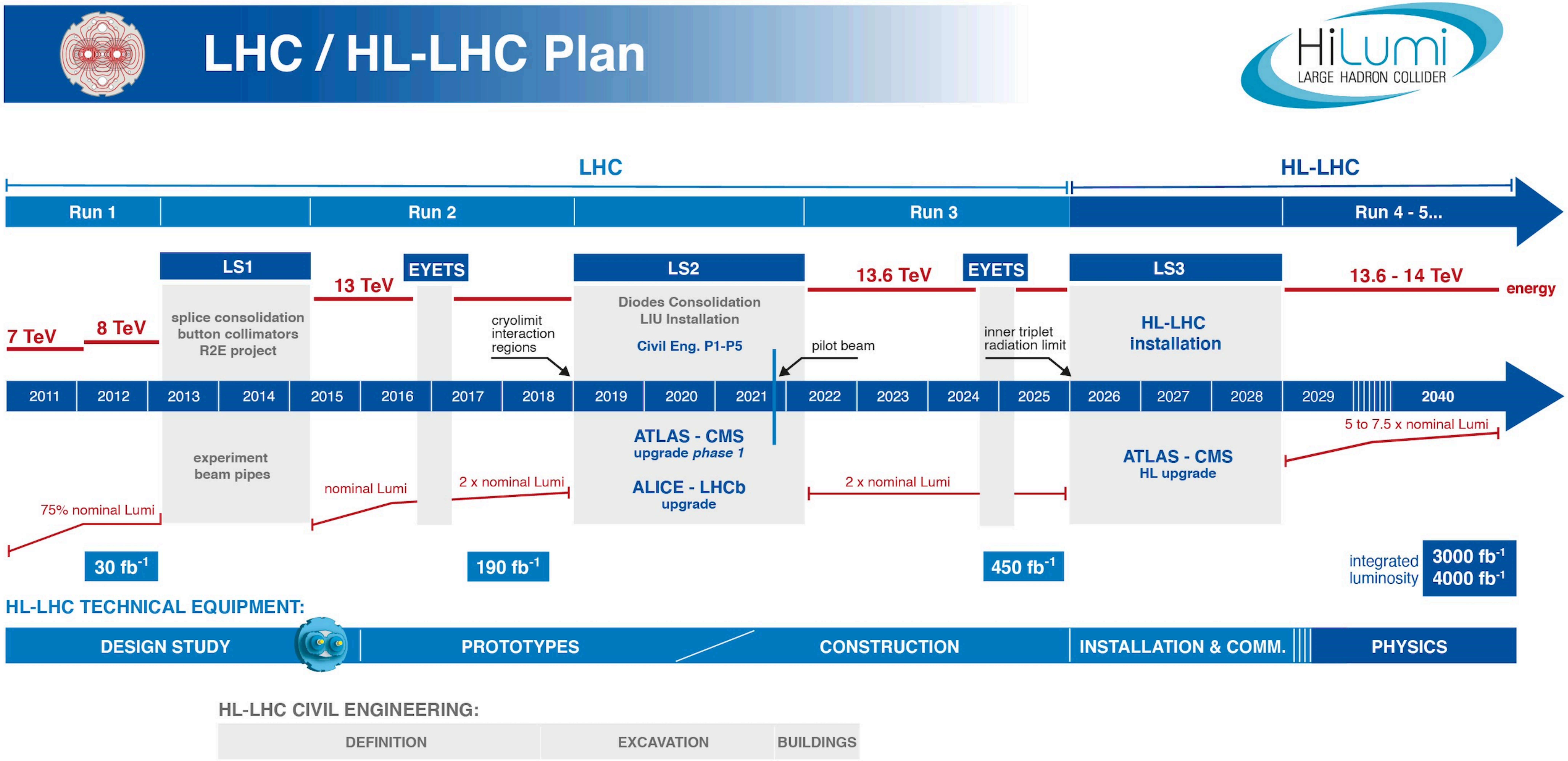
CERN-LPCC-2018-04



Process	$W^\pm W^\pm$	WZ	WV	ZZ	WWW	WWZ	WZZ
Final state	$\ell^\pm\ell^\pm$jj	3ℓjj	ℓjjjj	4ℓjj	$3\ell3\nu$	$4\ell2\nu$	$5\ell\nu$
Precision	6%	6%	6.5%	10–40%	11%	27%	36%
Significance	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	3.0σ	3.0σ

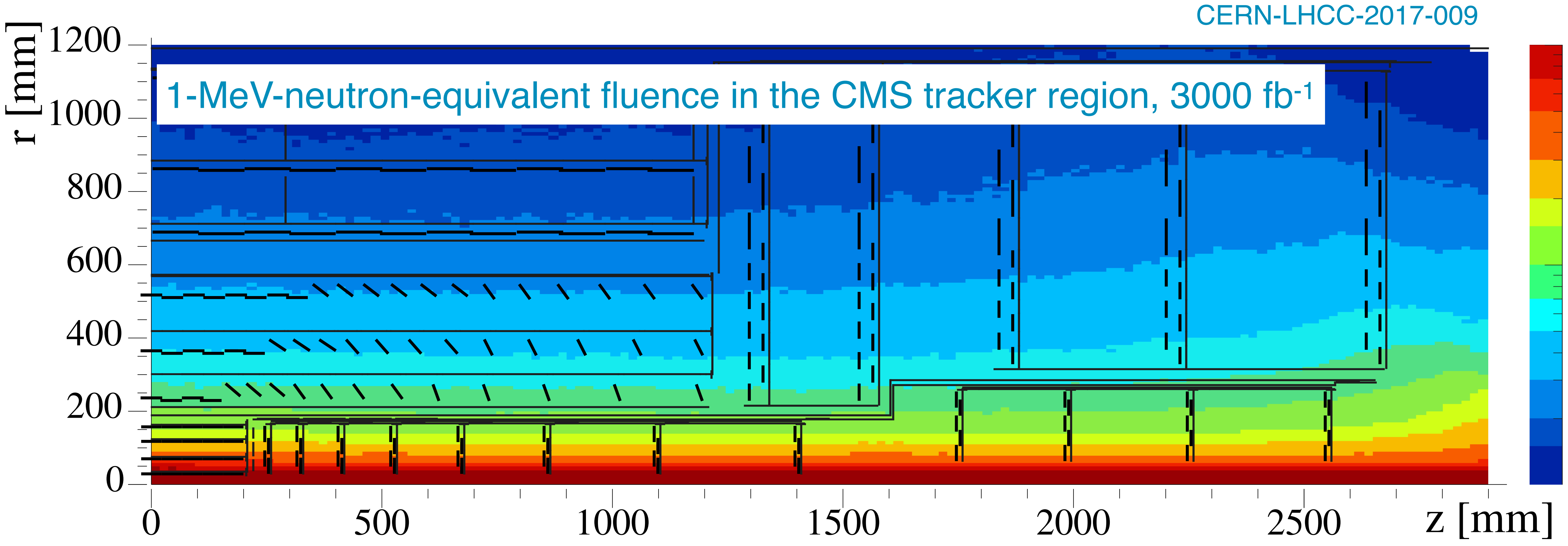
CERN-LPCC-2018-03

Why the HL-LHC?

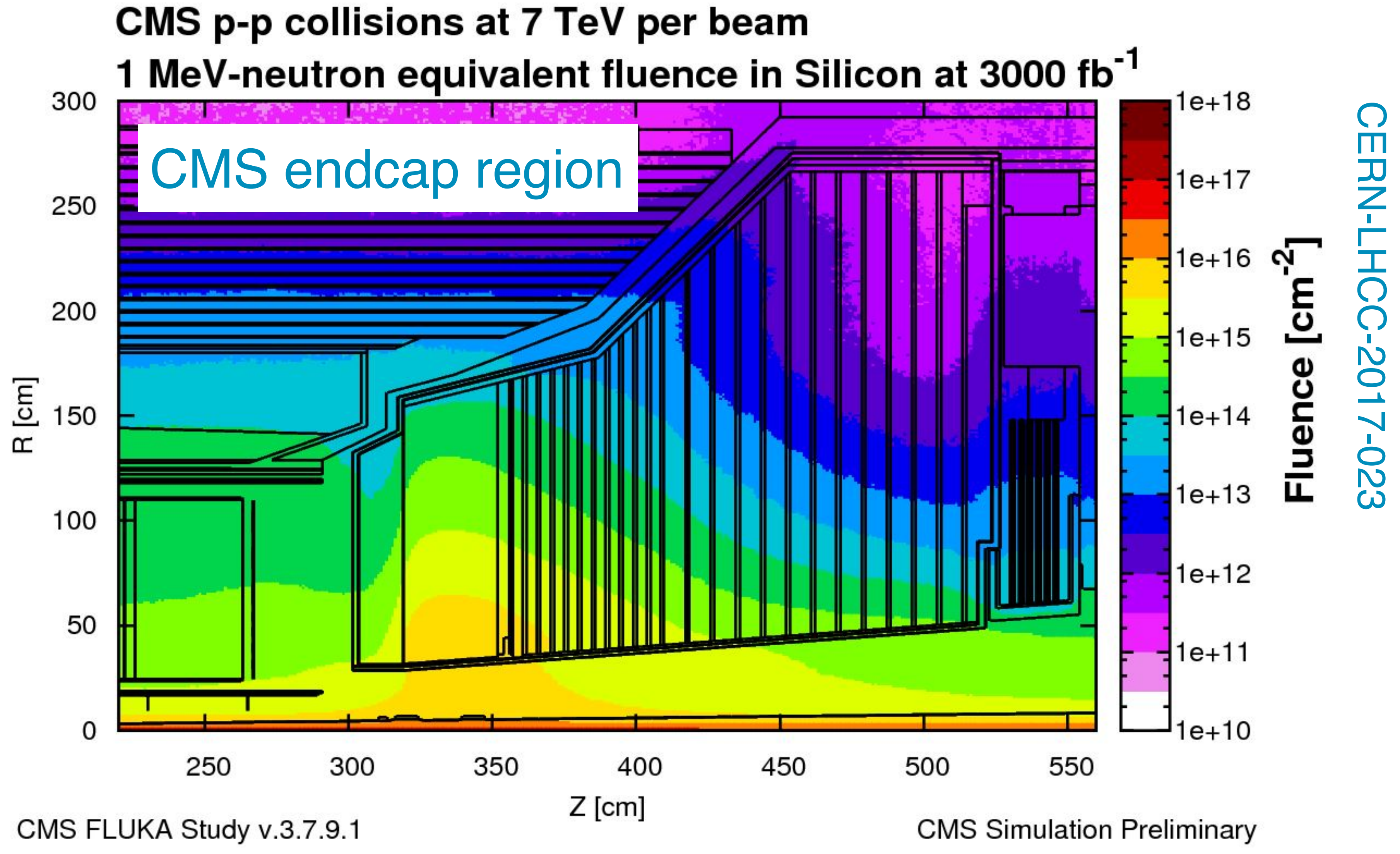


https://voisins.web.cern.ch/en/high-luminosity-lhc-hl-lhc

Challenges of the HL-LHC collision environment


CERN-LHCC-2017-009

1-MeV-neutron-equivalent fluence in the CMS tracker region, 3000 fb^{-1}


CMS p-p collisions at 7 TeV per beam

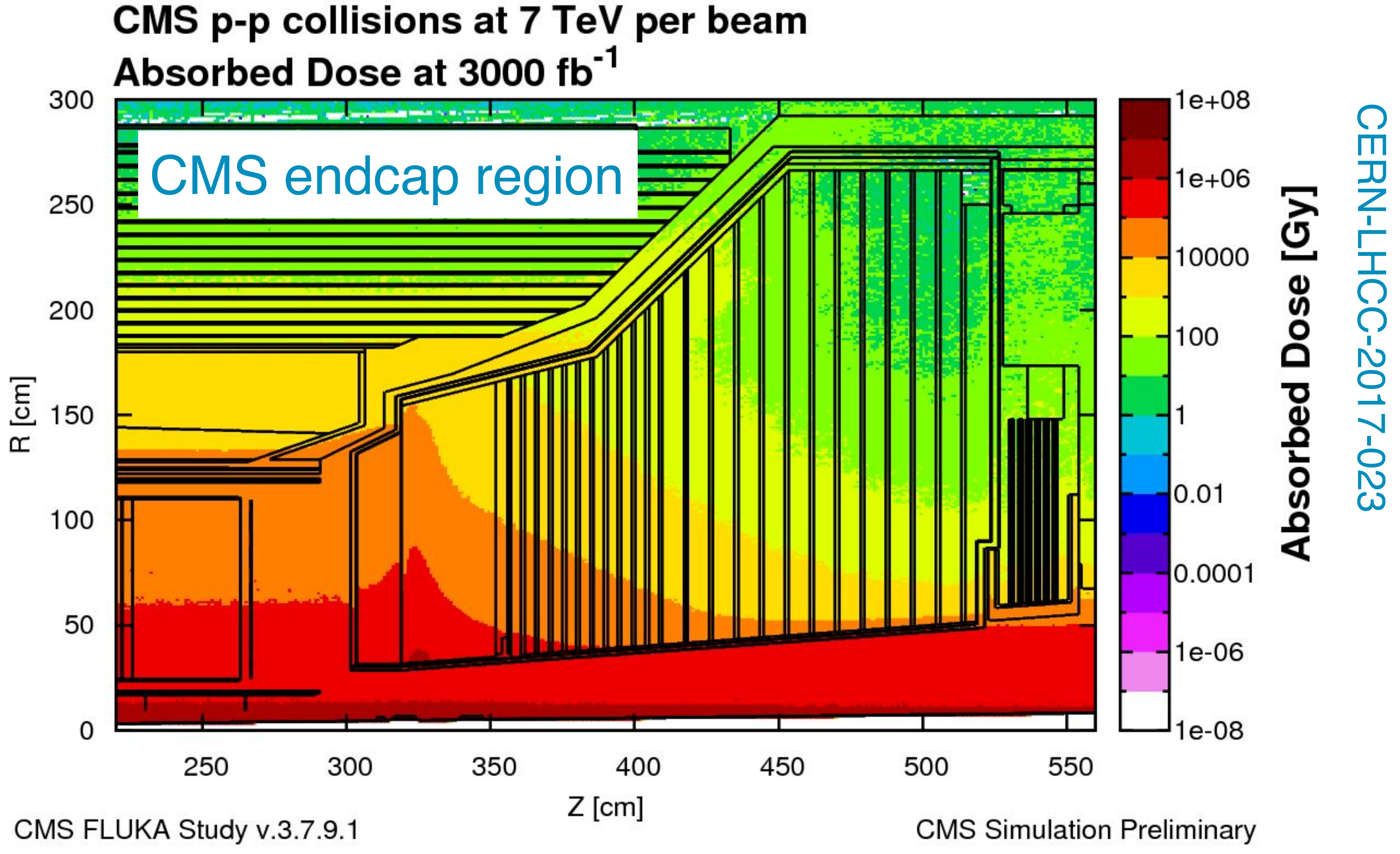
1 MeV-neutron equivalent fluence in Silicon at 3000 fb^{-1}

CMS endcap region

CERN-LHCC-2017-023

CMS FLUKA Study v.3.7.9.1

CMS Simulation Preliminary


CMS p-p collisions at 7 TeV per beam

Absorbed Dose at 3000 fb^{-1}

CMS endcap region

CERN-LHCC-2017-023

CMS FLUKA Study v.3.7.9.1

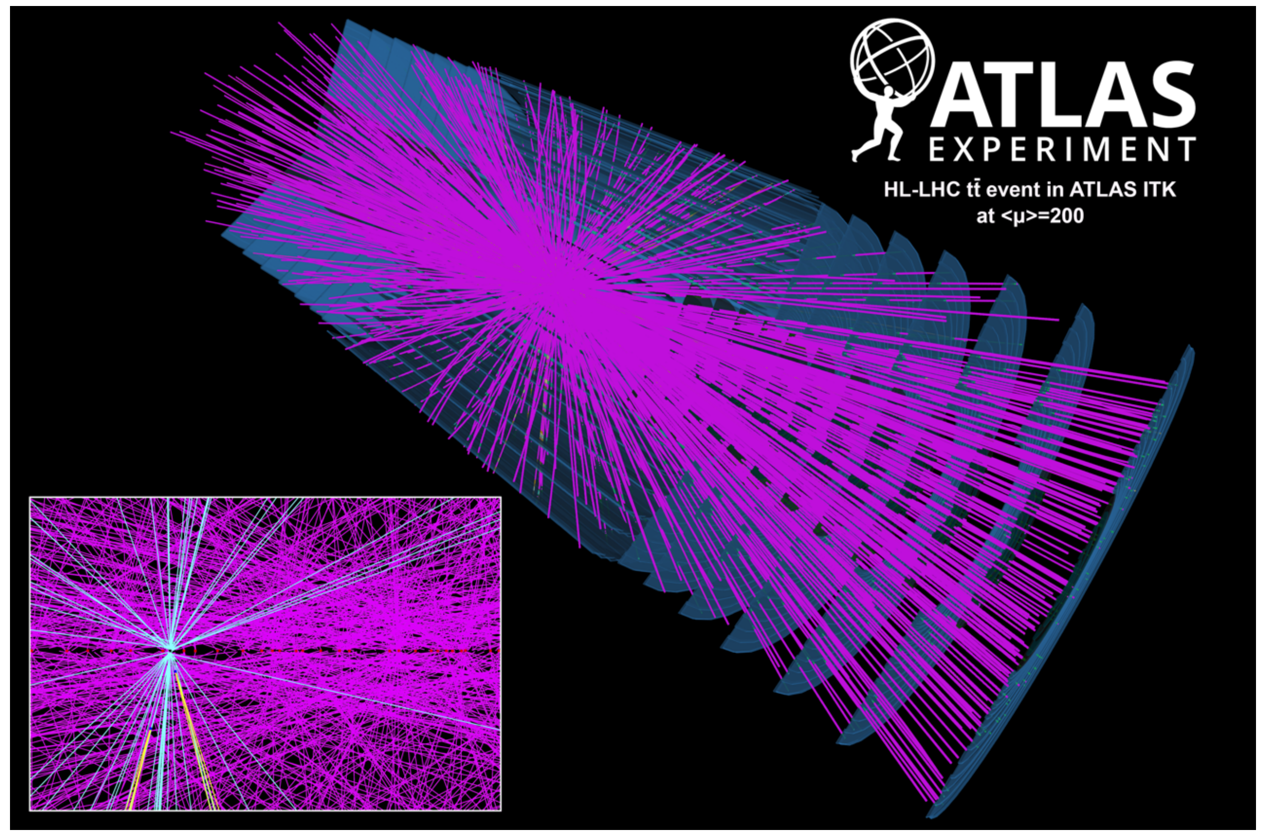
CMS Simulation Preliminary

	Baseline	Stretch
L_{inst} (cm^{-2} s^{-1})	5×10^{34}	7.5×10^{34}
L_{int} (fb^{-1})	3000	4000
Avg. pileup (PU)	140	200
Fluence* (n_{eq}/cm^2)	~2×10^{16} max	~2.5×10^{16} max
Dose* (MGy)	~12 max	~15 max

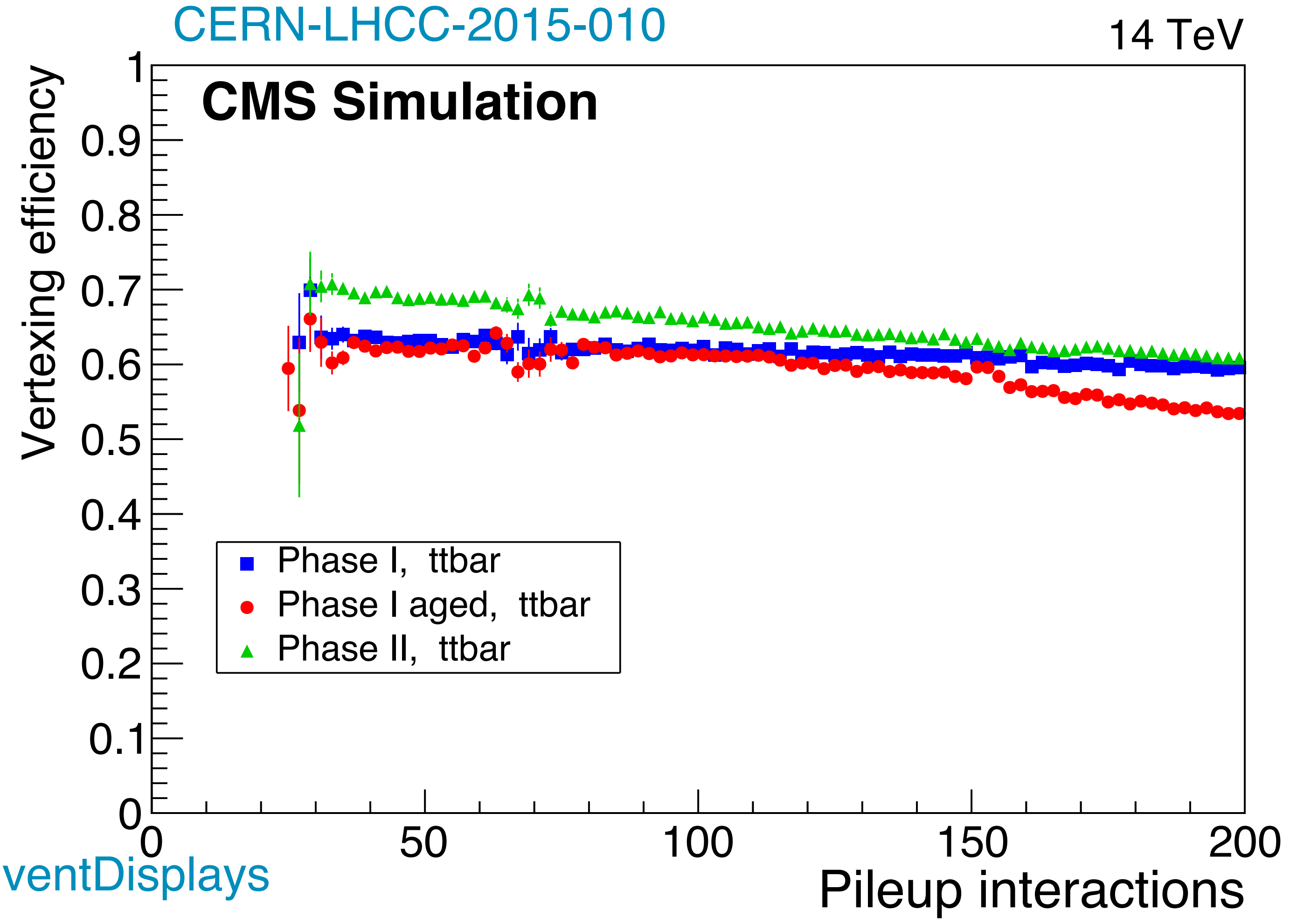
*In CMS, similar for ATLAS

Challenges of the HL-LHC collision environment

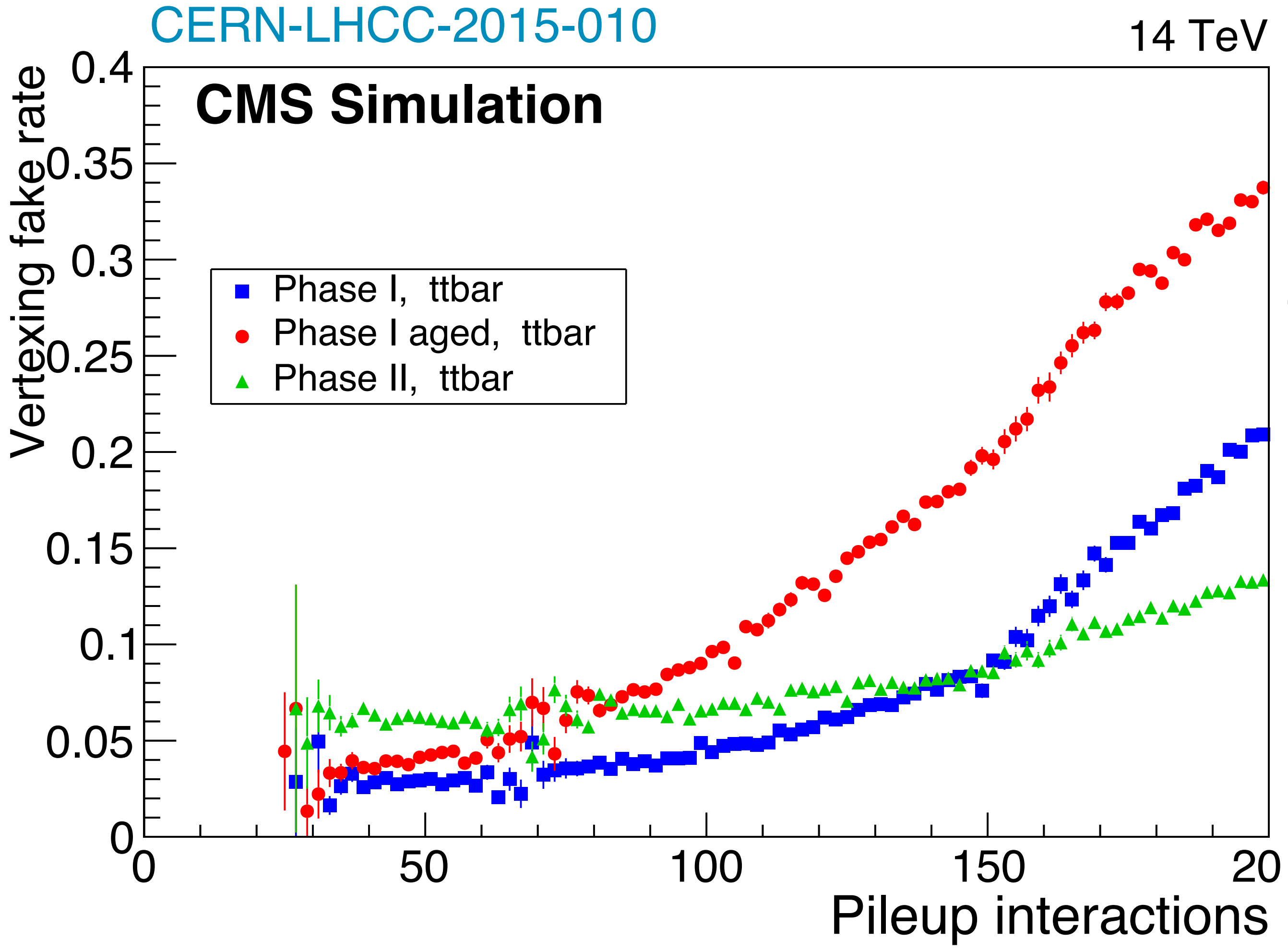
- <PU> = 140-200 pp interactions per 25 ns bunch crossing (BX)
    - Vertex and track reconstruction algorithms less discriminating
    - Existing trigger and readout bandwidth constraints imply tighter selection requirements to increase purity at the cost of signal acceptance



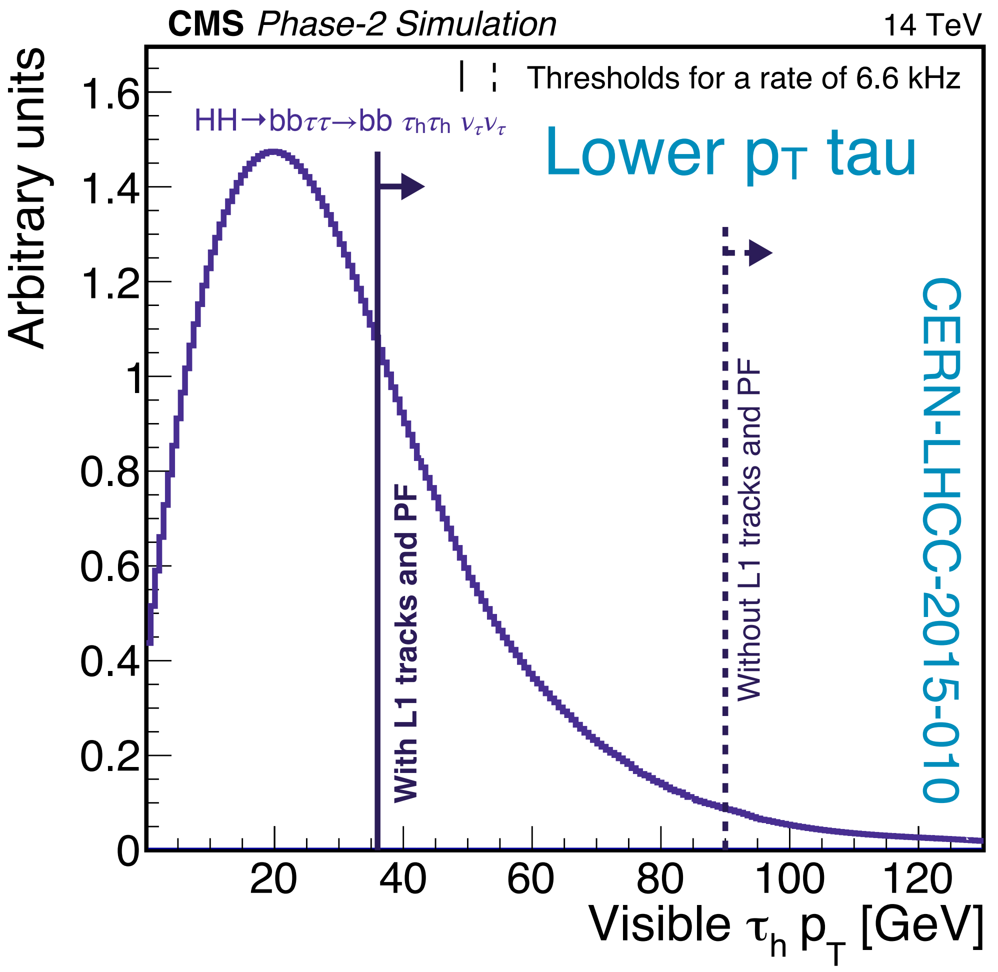
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradeEventDisplays



CERN-LHCC-2015-010



CERN-LHCC-2015-010



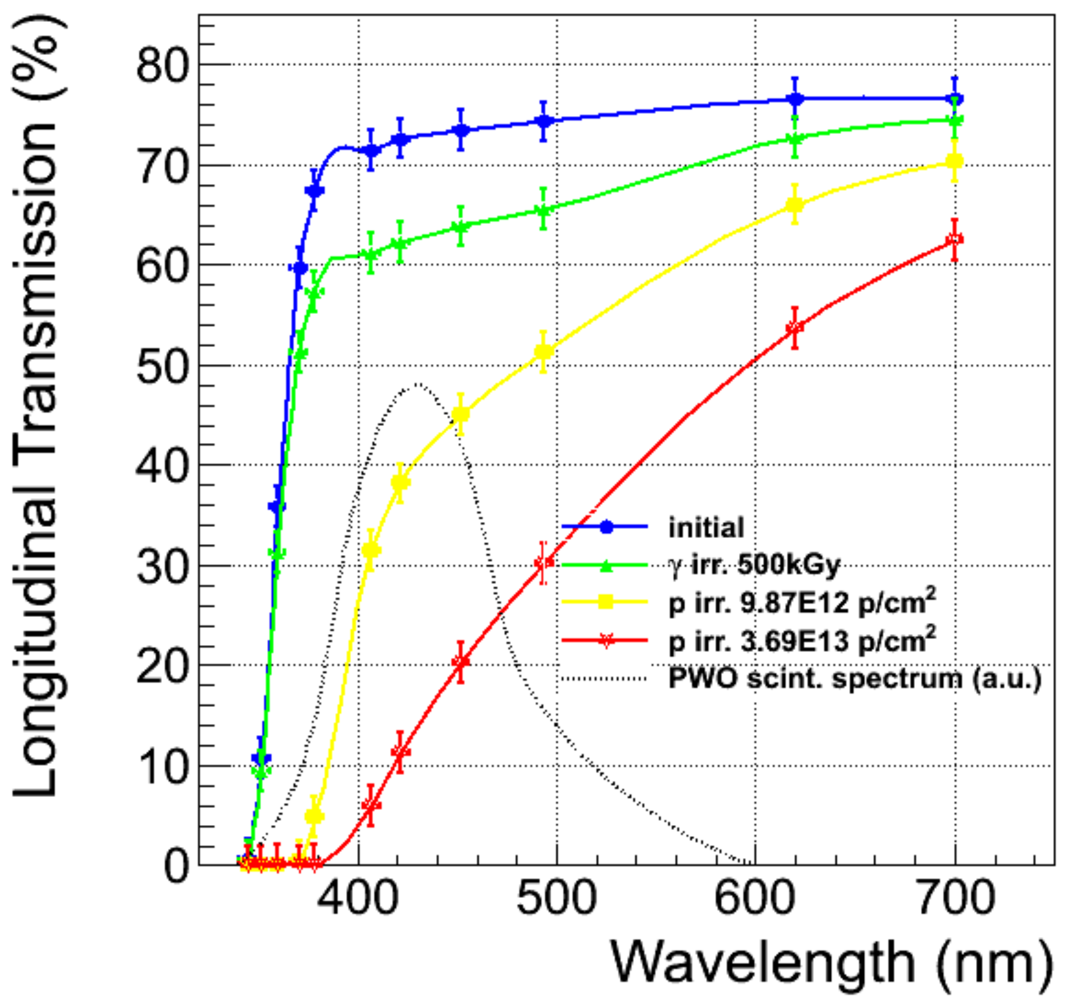
Lower p_T tau

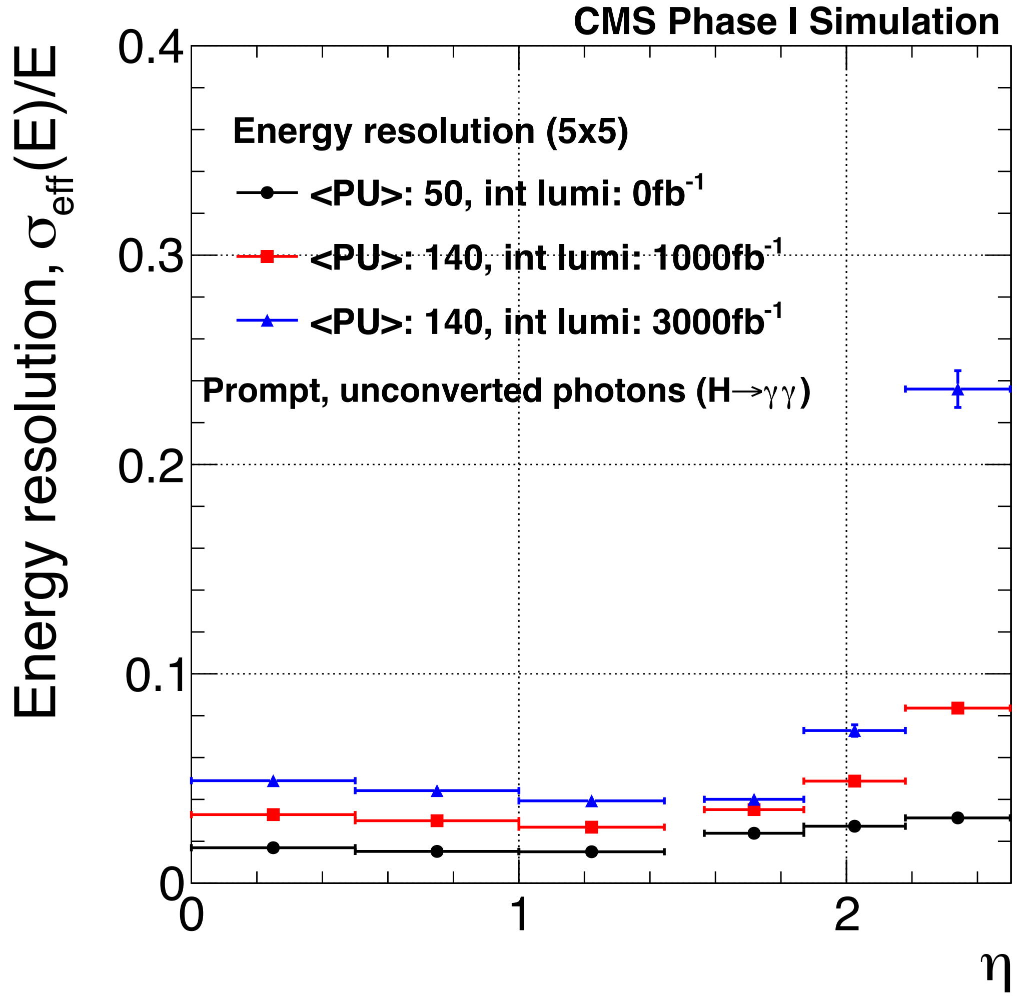
CERN-LHCC-2015-010

Challenges of the HL-LHC collision environment

- Accelerated aging in the general purpose detectors
  - Detector materials need to withstand another order of magnitude in dose and fluence
  - Need to maintain optically transparent materials (e.g. scintillators)
  - Need to manage leakage current and charge trapping in silicon sensors, dark count rate in silicon photomultipliers
  - Need to manage single event upsets in front end ASICs

CERN-LHCC-2015-010





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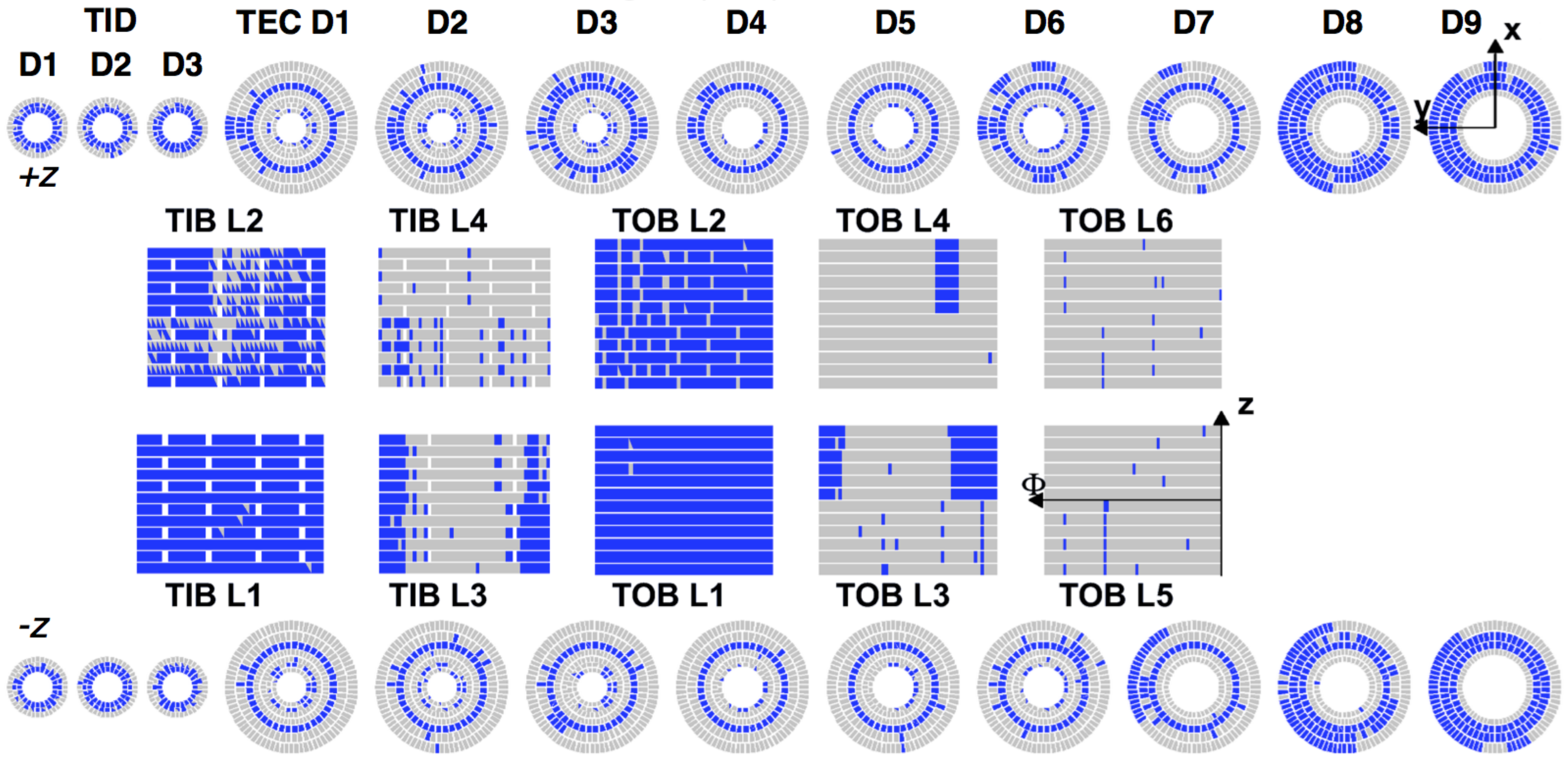
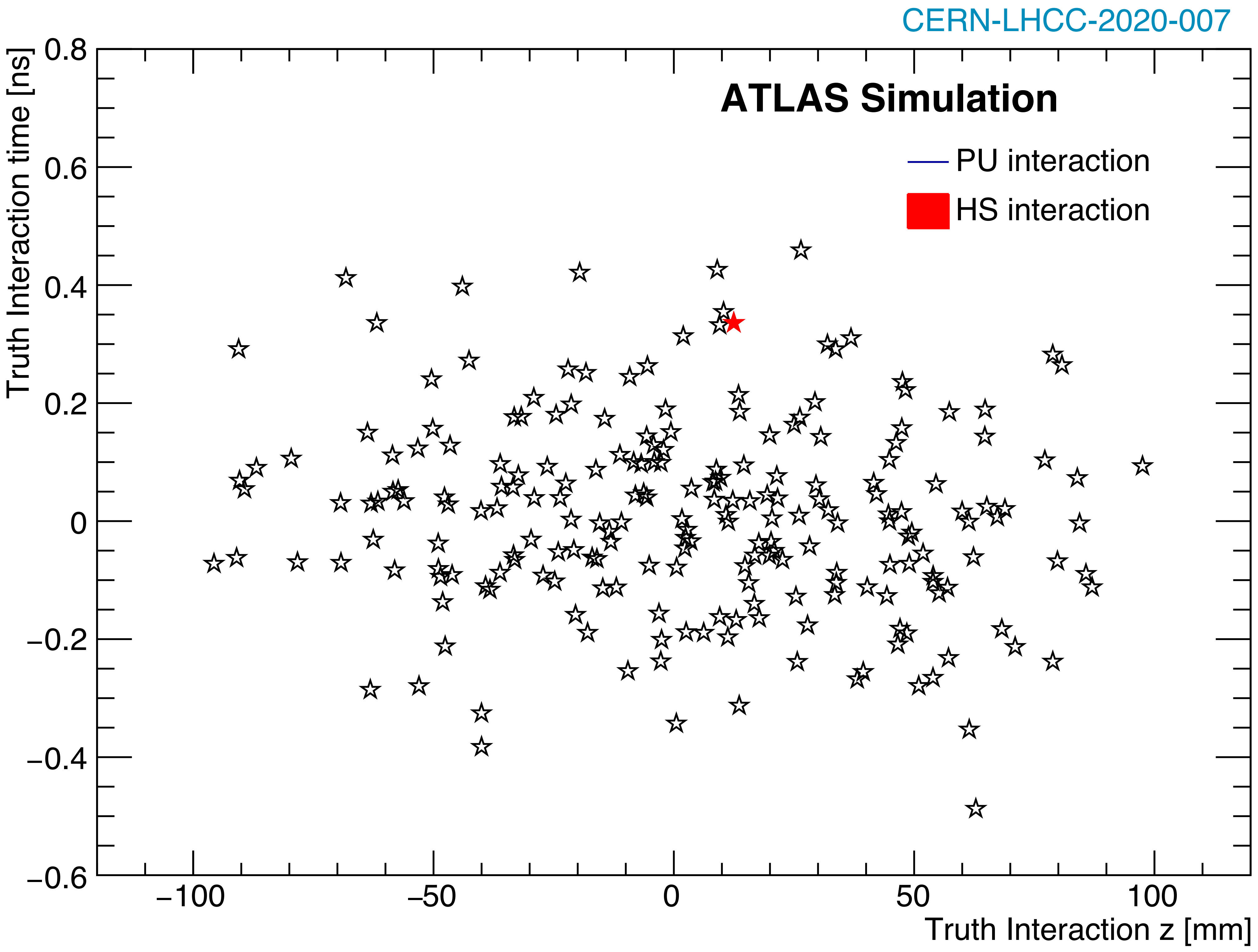


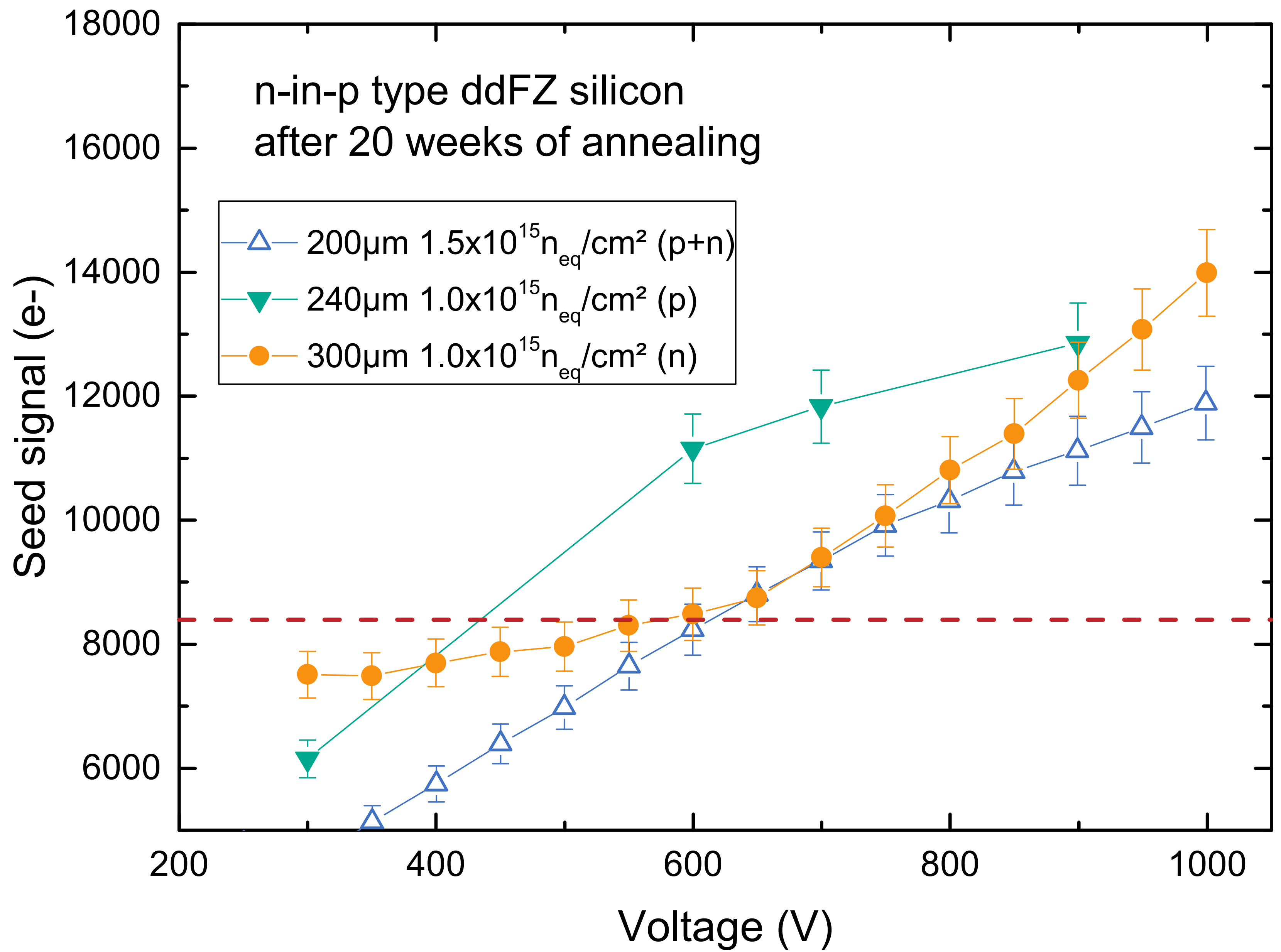
CERN-LHCC-2015-010

Detector design and technology requirements



- Fast, high throughput DAQ and trigger
  - ~100(LHC) → ~1000(HL-LHC) kHz trigger accept rate
  - ~4(LHC) → ~10(HL-LHC) µs trigger latency to permit more complex calculations ⇒ deeper buffers required in front and back end electronics
  - Optical link space constraints ⇒ more intelligence in the front ends
- O(50 ps) MIP timing resolution to discriminate interaction vertices in the same BX
- Higher channel granularity to reduce occupancy

Detector design and technology requirements



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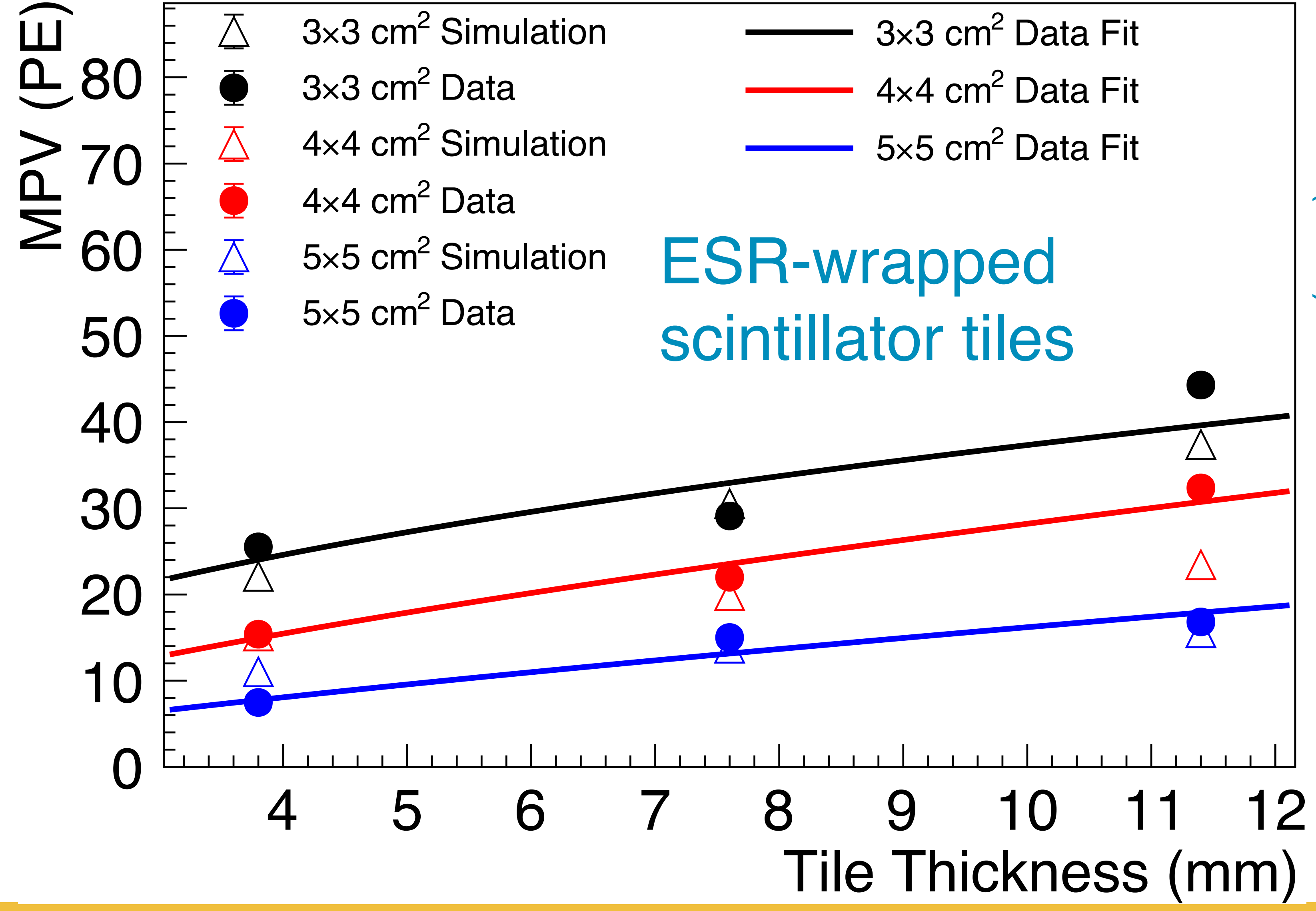
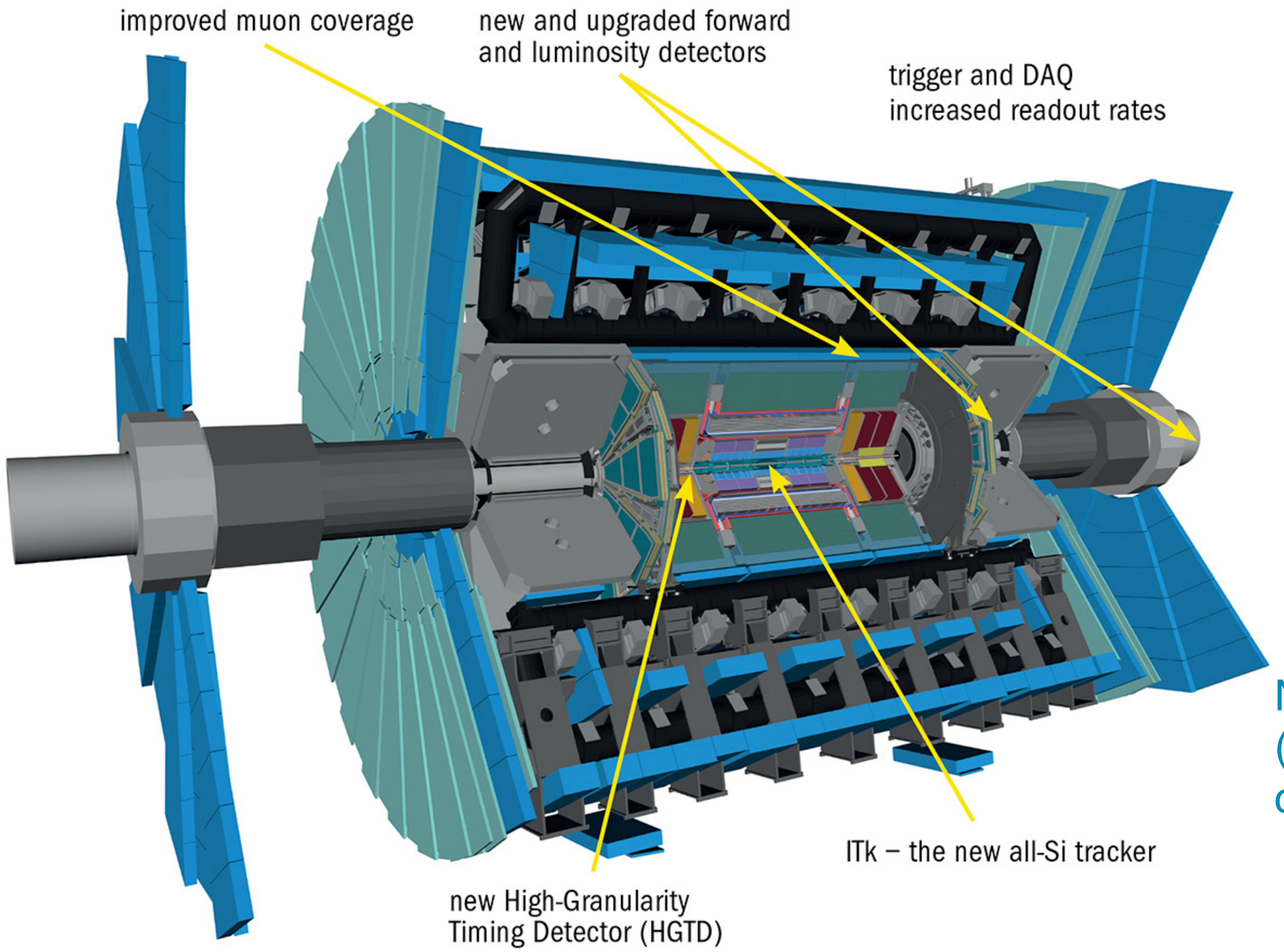


ESR-wrapped scintillator tiles

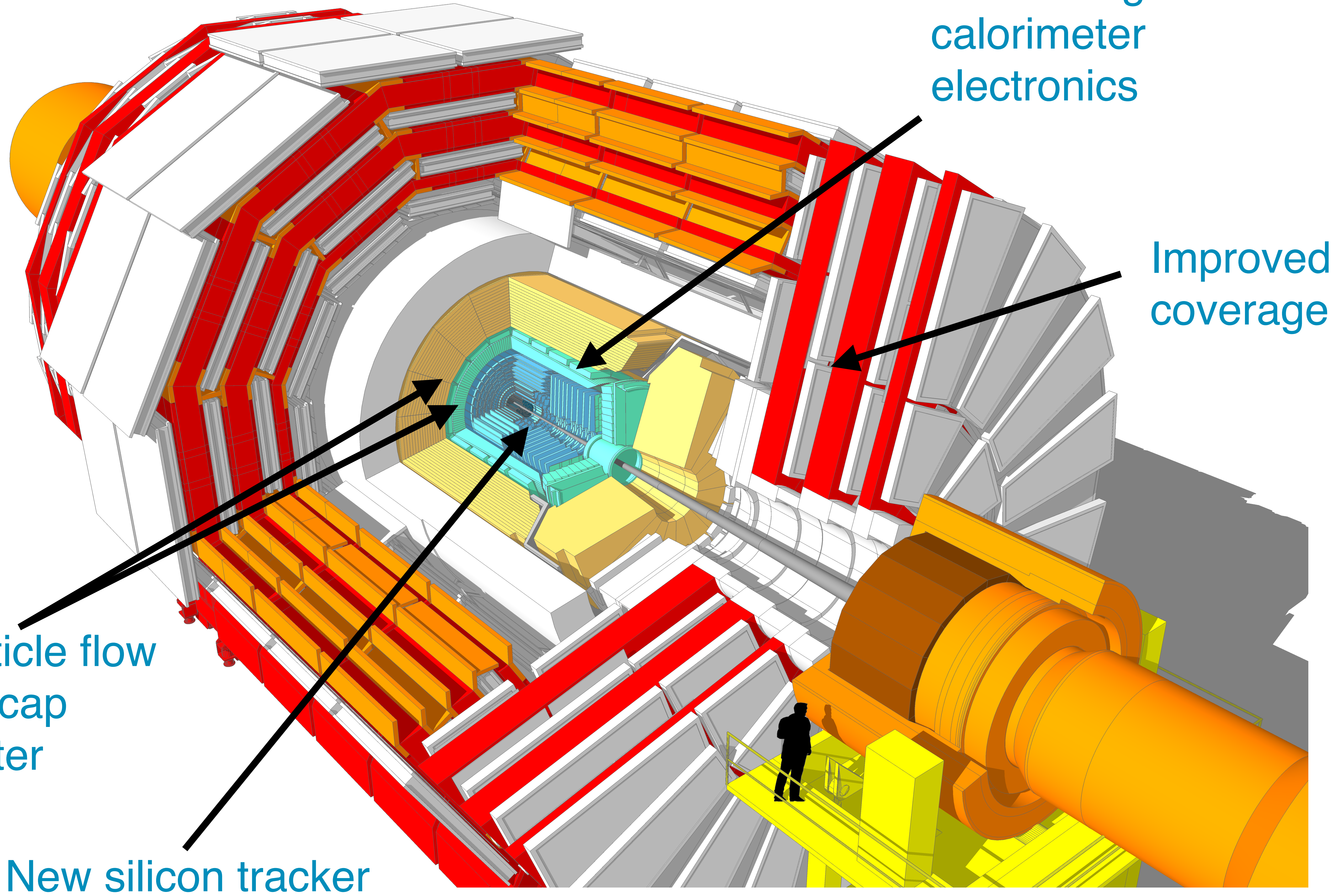
JINST **16** (2021) P07022

- More radiation-hard detector materials in the most critical locations: trackers, near the beam spot; and endcap calorimeter
  - Thinning of silicon sensors and cooling to around -30°C to reduce leakage current and signal loss
  - Mechanics to allow for future detector replacements
  - Power systems to support increased silicon bias voltage
  - Maximize light yield and transparency of scintillator systems

Highlights of the HL-LHC detector upgrades



https://cerncourier.com/a/a-new-atlas-for-the-high-luminosity-era/



Higher trigger accept rate and higher throughput DAQ

Upgraded barrel electromagnetic calorimeter electronics

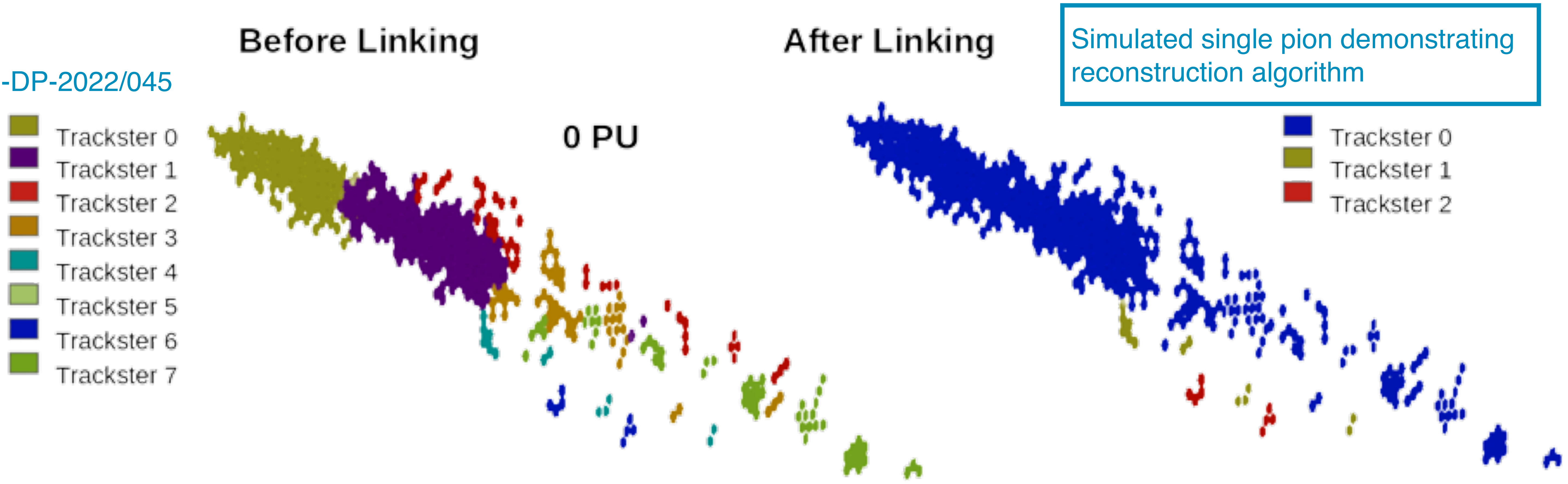
Improved muon coverage

New particle flow (PF) endcap calorimeter

New silicon tracker with track trigger

J. Phys.: Conf. Ser. **513** (2014) 022032

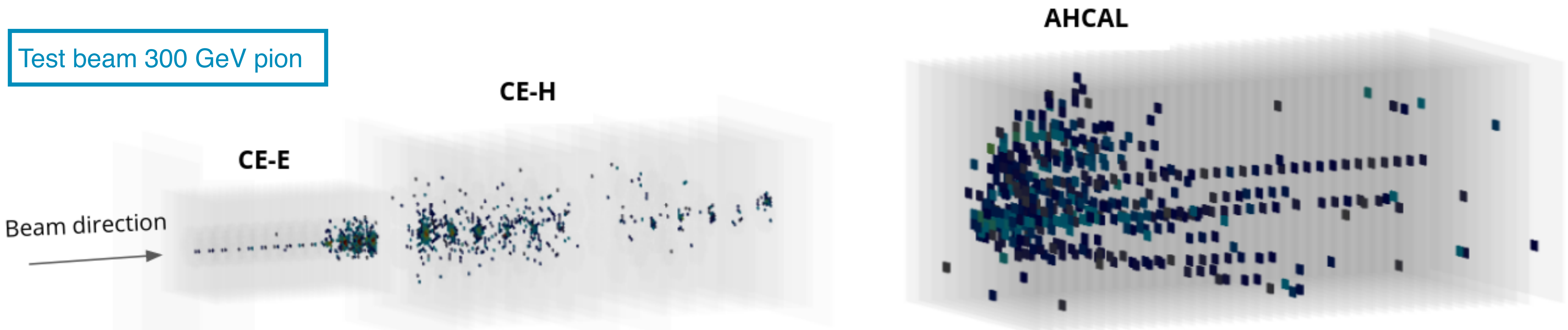
CMS High Granularity Calorimeter (HGCAL)



CMS-DP-2022/045

Simulated single pion demonstrating reconstruction algorithm

Test beam 300 GeV pion



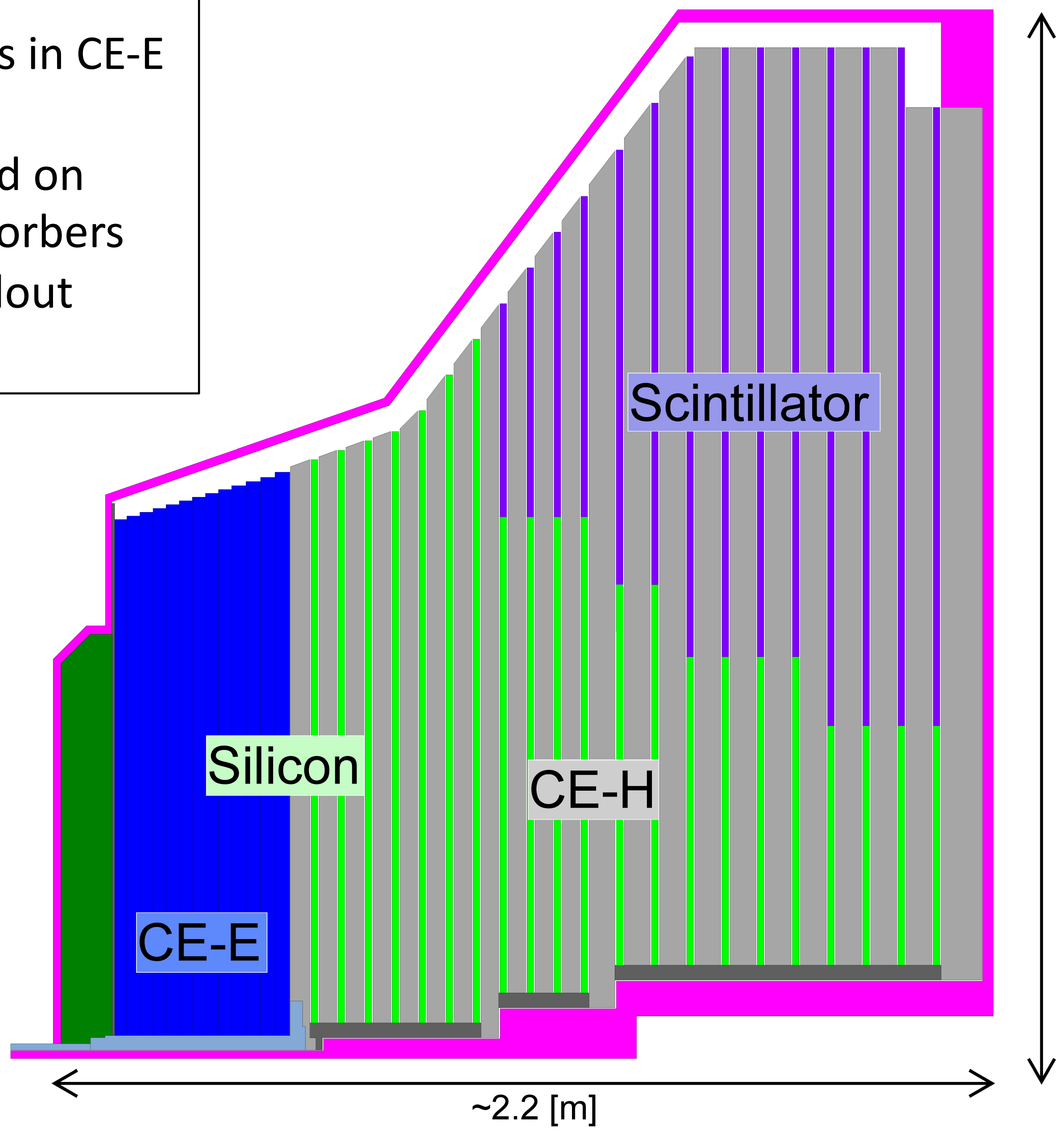
CMS-DP-2022/022

- Adapts CALICE developments for e^+e^- to use PF to reject PU and maintain good energy resolution for forward jets from vector boson scattering (VBS)
- Requires fine granularity to link the shower back to the original charged candidate of the jet

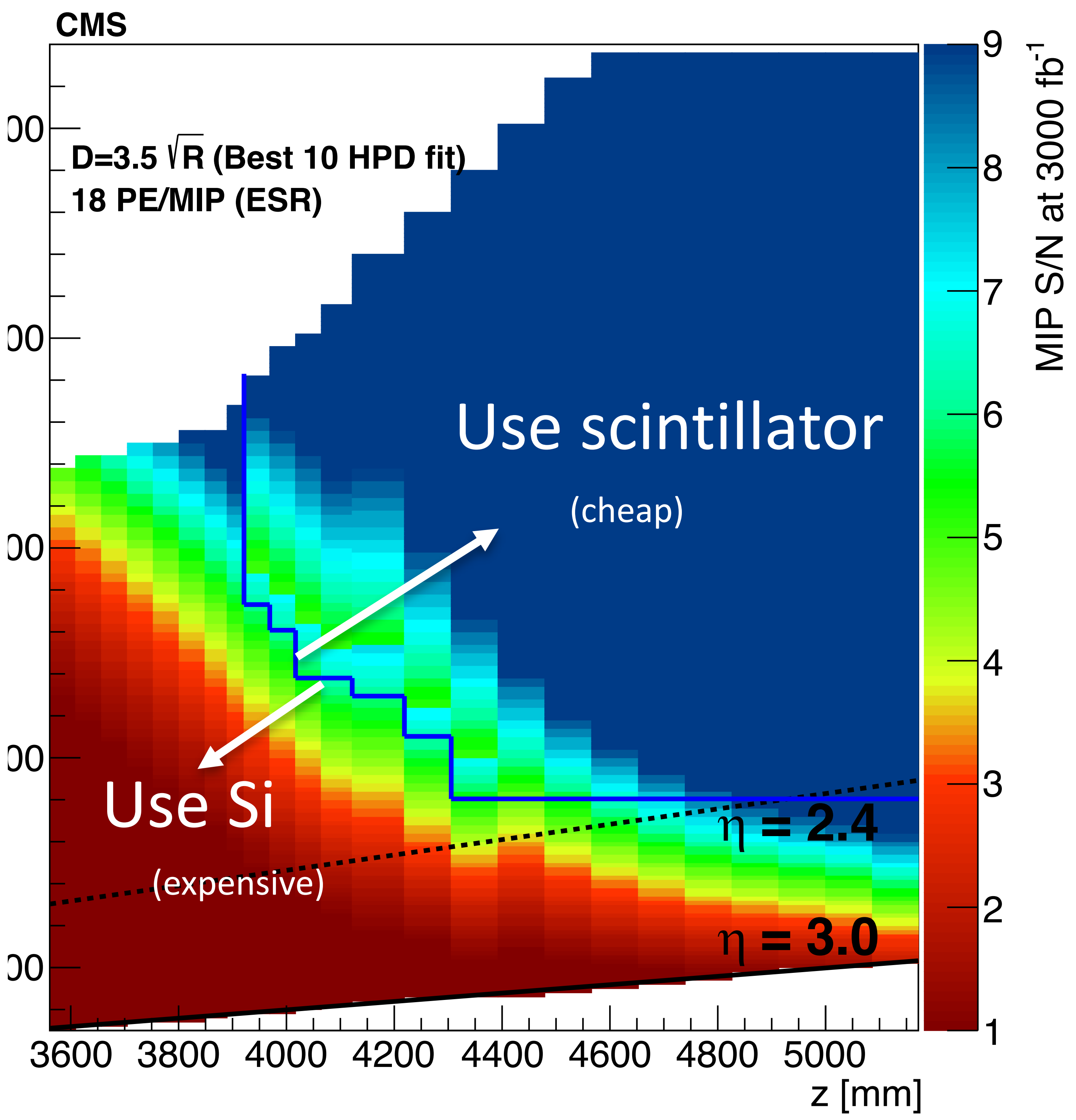
CMS HGCAL

Active Elements:
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with on-tile SiPM readout in low-radiation regions of CE-H

Key Parameters:
Coverage: 1.5 < |η| < 3.0
~215 tonnes per endcap
Full system maintained at -30°C
~620m^2 Si sensors in ~26000 modules
~6M Si channels, 0.6 or 1.2cm^2 cell size
~370m^2 of scintillators in ~3700 boards
~240k scint. channels, 4-30cm^2 cell size
Power at end of HL-LHC:
~125 kW per endcap

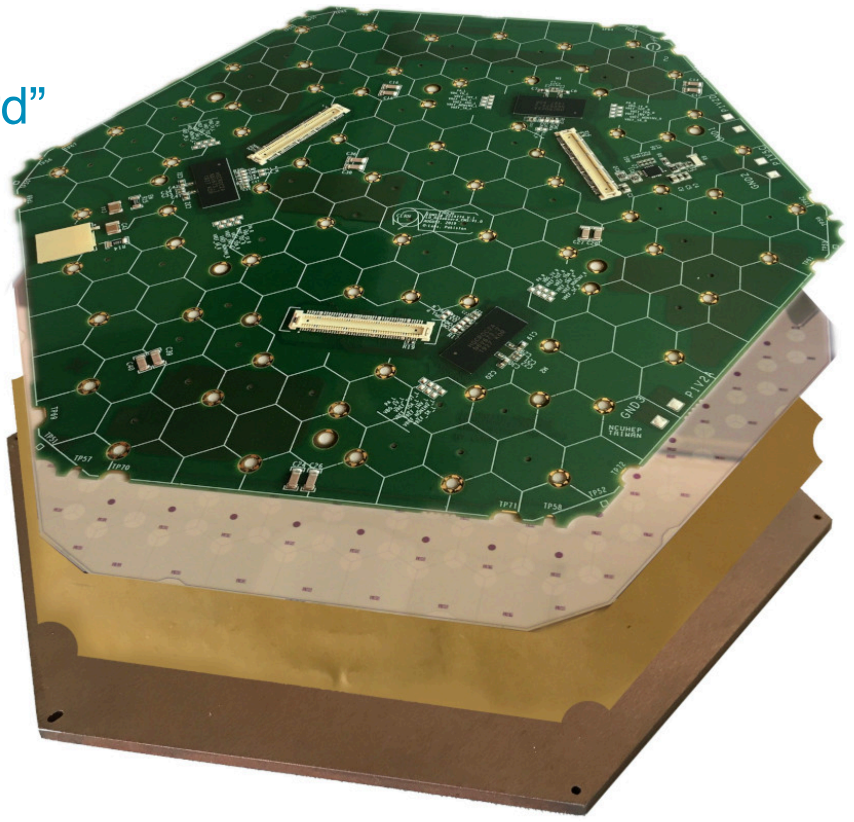


Simulated MIP S/N after 3000 fb^{-1} SiPM+scintillator aging



Electromagnetic calorimeter (**CE-E**): **Si**, Cu & CuW & Pb absorbers, 26 layers, 27.7 X_0 & ~1.5λ
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 21 layers, ~8.5λ

CMS HGCAL

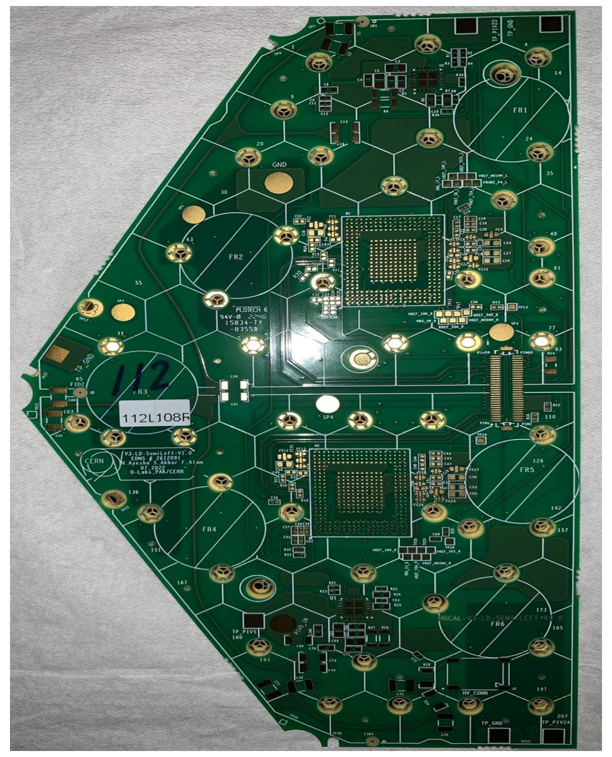


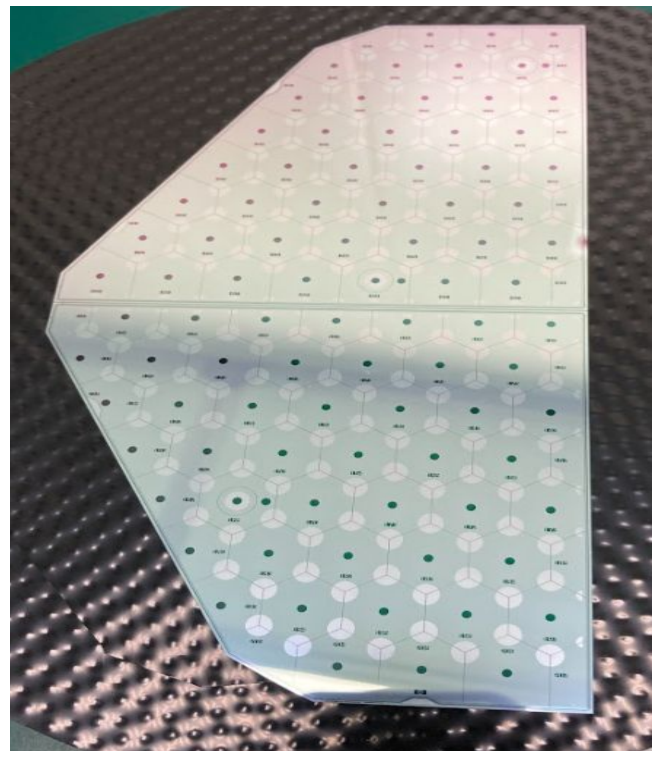
Readout "hexaboard"
Signal digitization, trigger primitive formation
Stepped through-holes for wirebonding

Sensor

Kapton insulation
Also carrying sensor backside bias

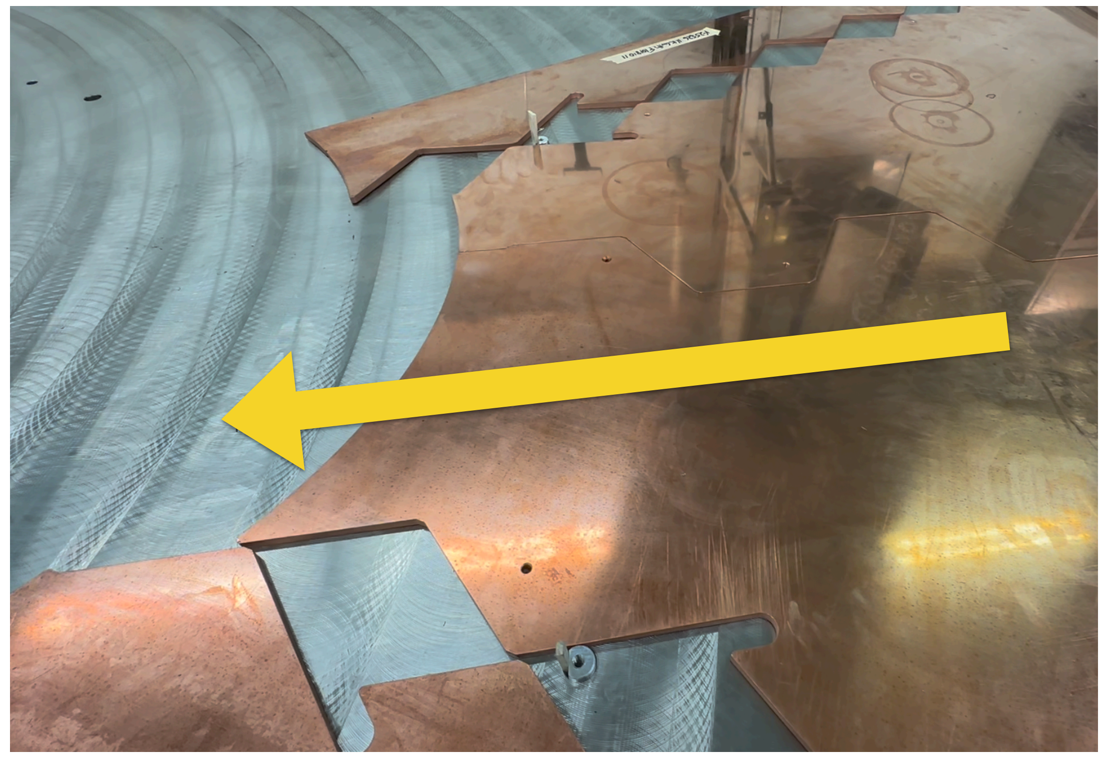
Baseplate
Connection to cooling plate
Part of absorber

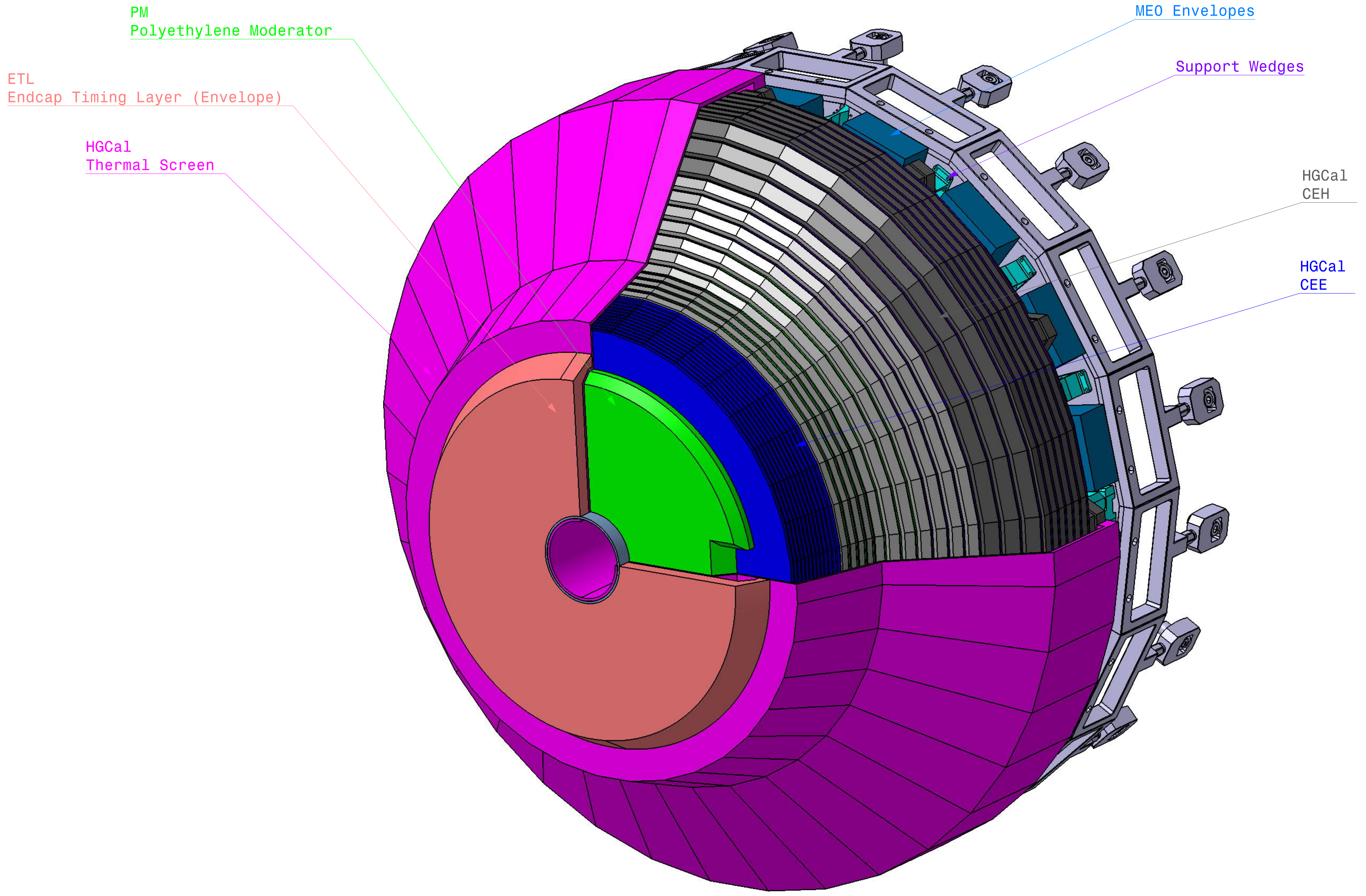




Prototype with irradiated SiPMs

CE-H insertion test

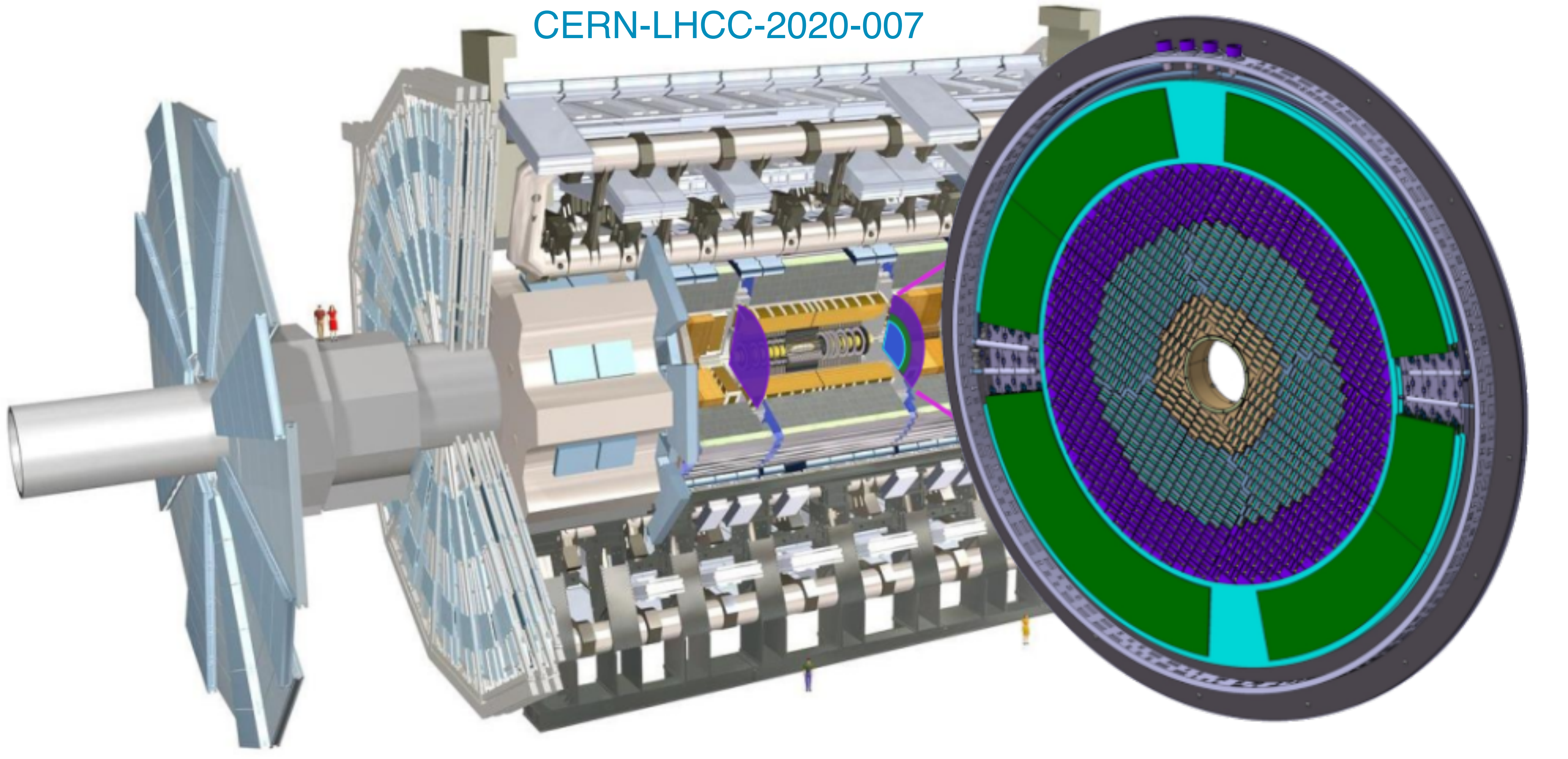




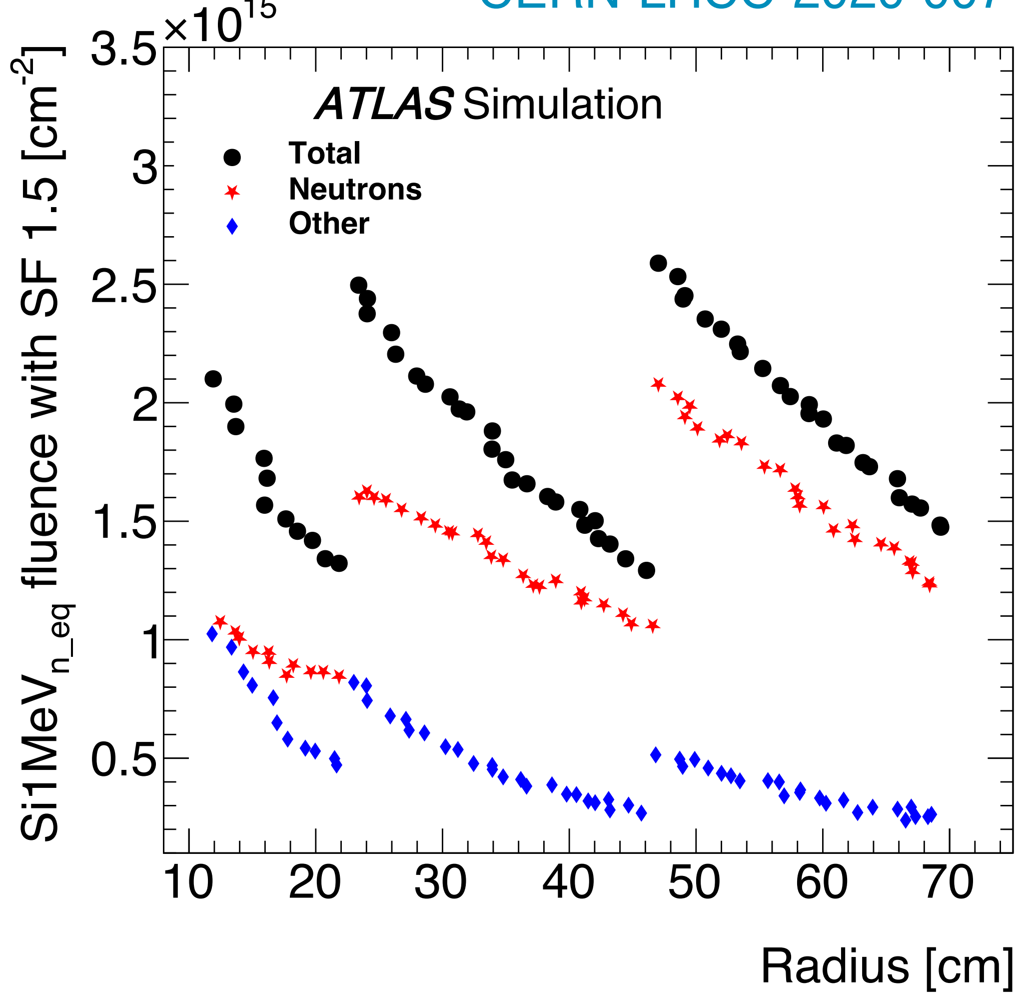
- Sensor and tile production underway
- Module production to begin late 2024

ATLAS High Granularity Timing Detector (HGTD)

- MIP time resolution 30 (start) - 70 (end) ps
- 2.4 < |η| < 4.0 to improve track z resolution in the forward region
- Doubles as a luminometer (target 1% uncertainty)
- Inner rings designed to be replaceable
- 350-550 V operating bias to achieve high S/N but avoid destructive breakdown



CERN-LHCC-2020-007



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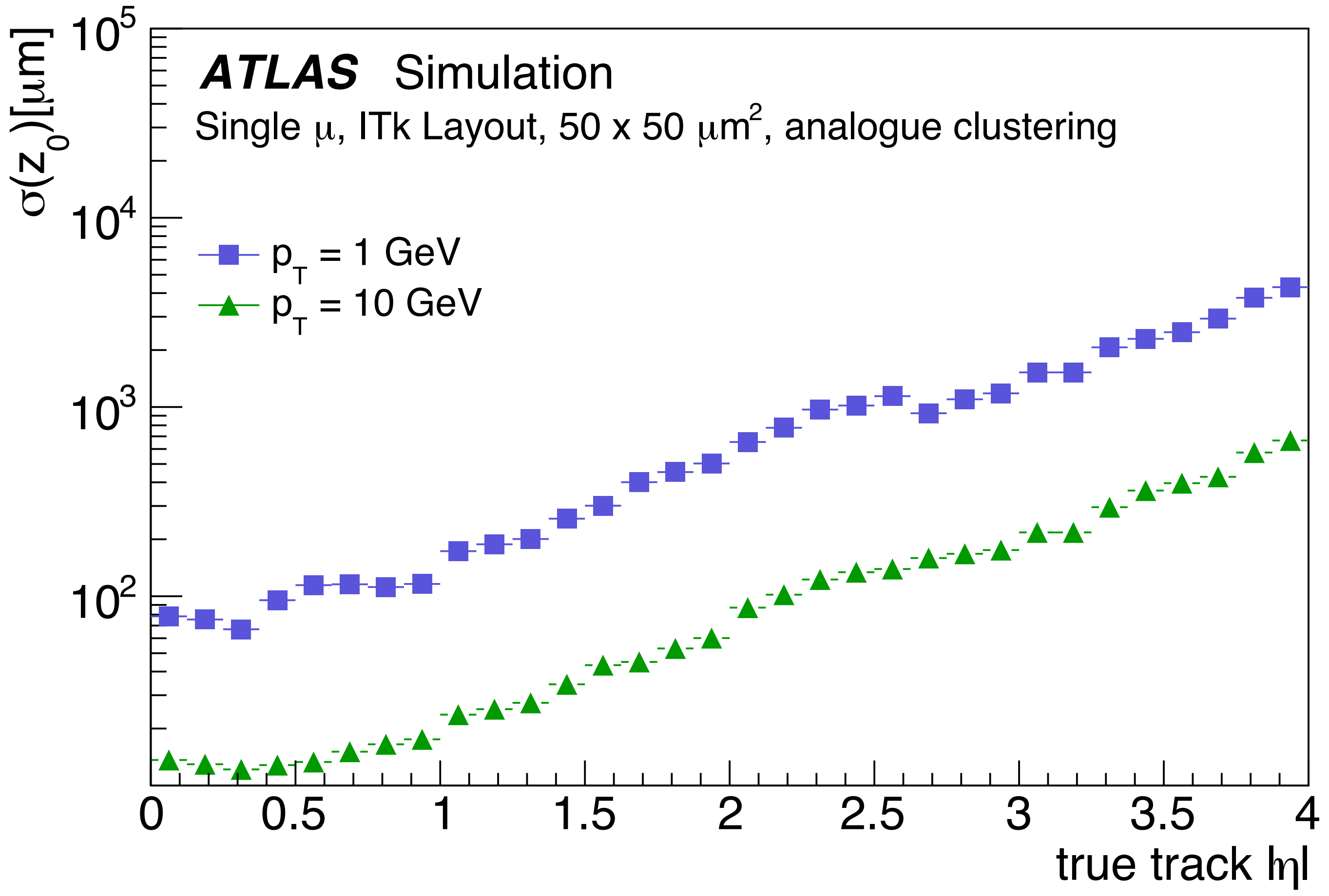
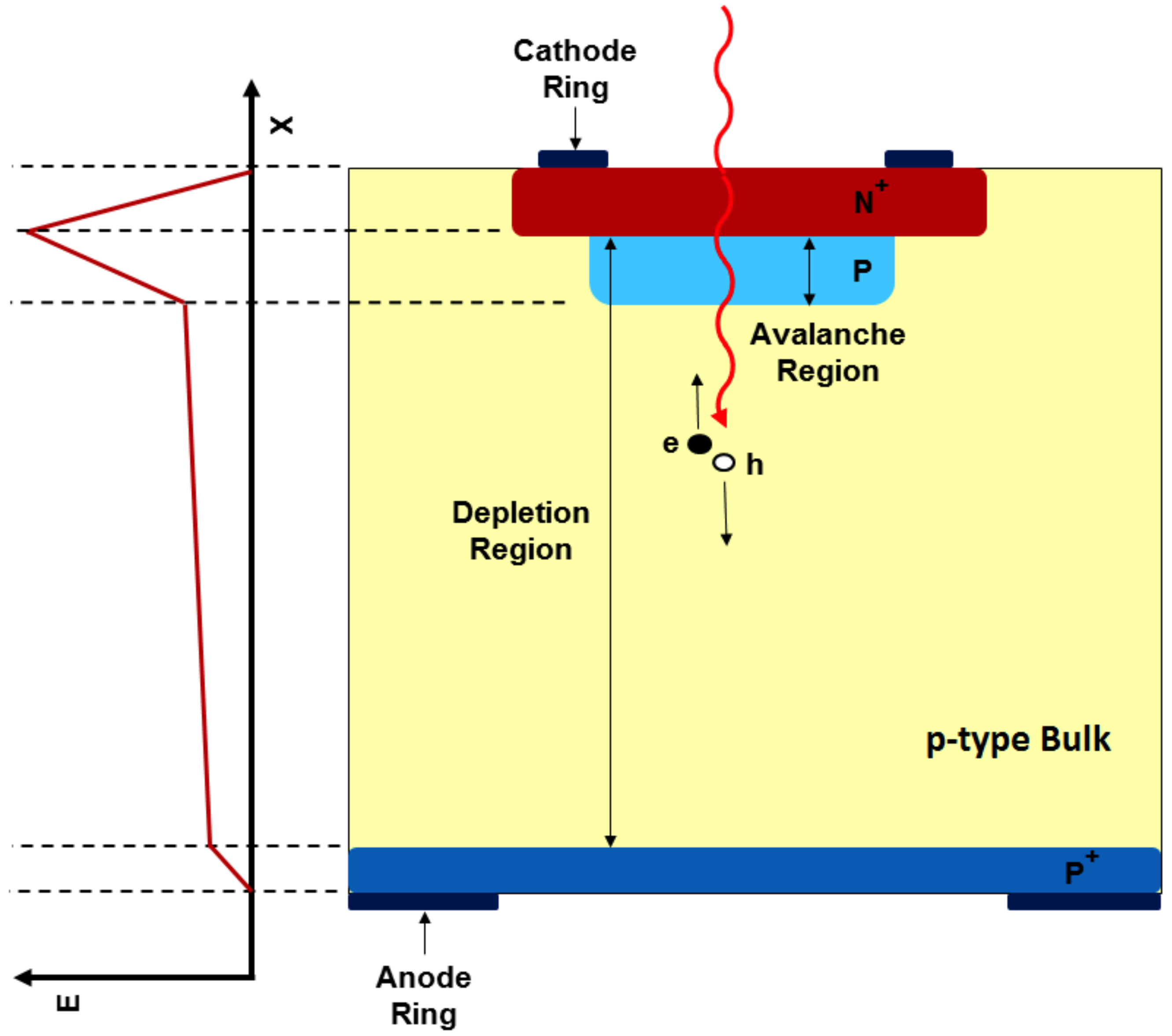


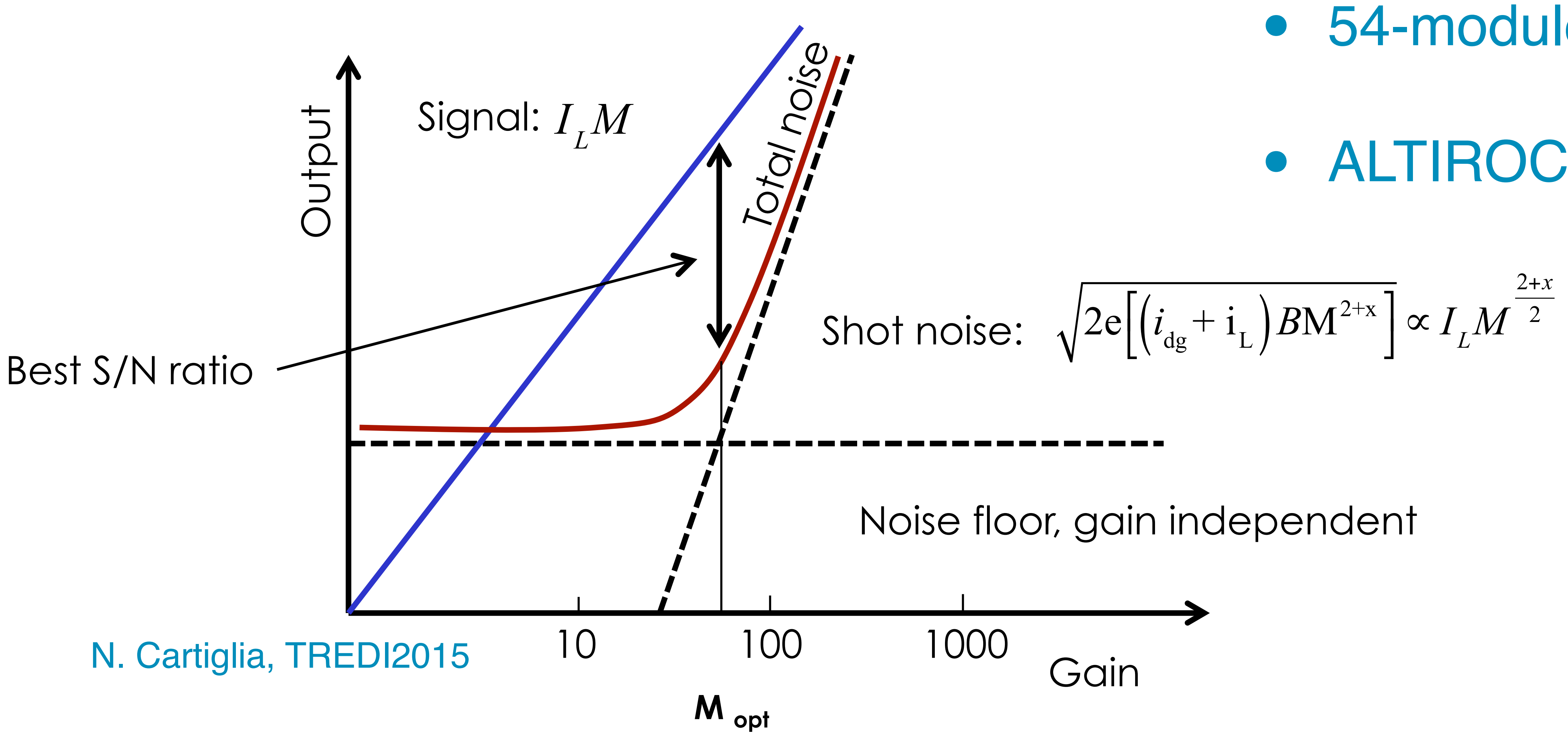
CERN-LHCC-2020-007

ATLAS HGTD

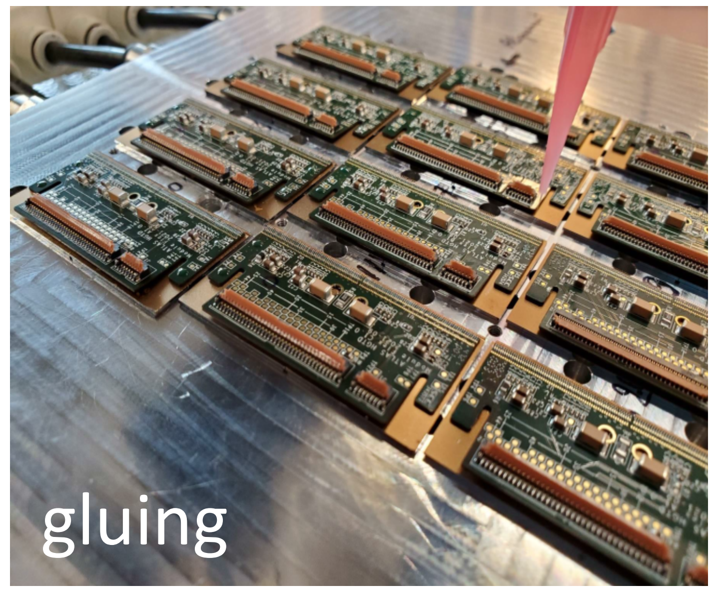


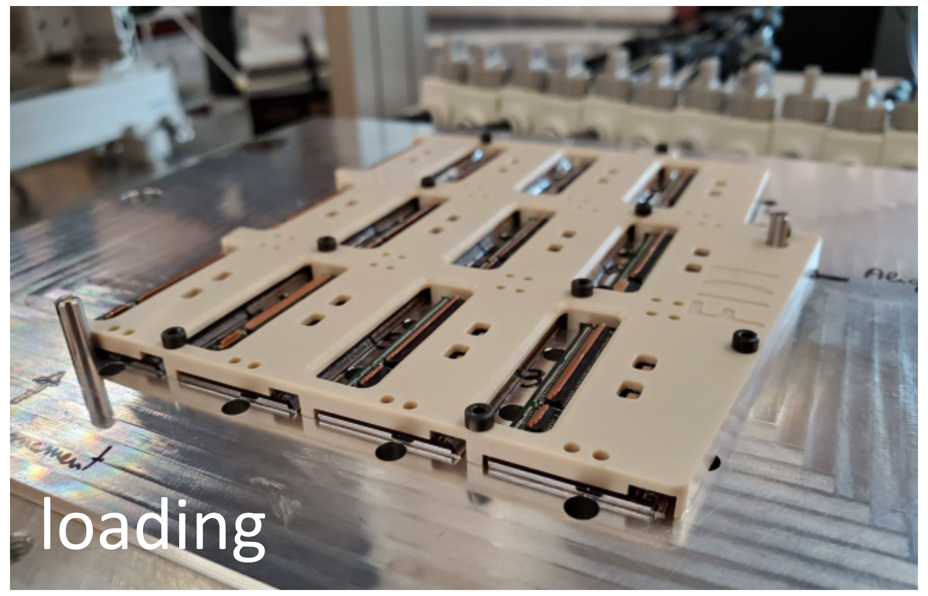
CERN-LHCC-2020-007

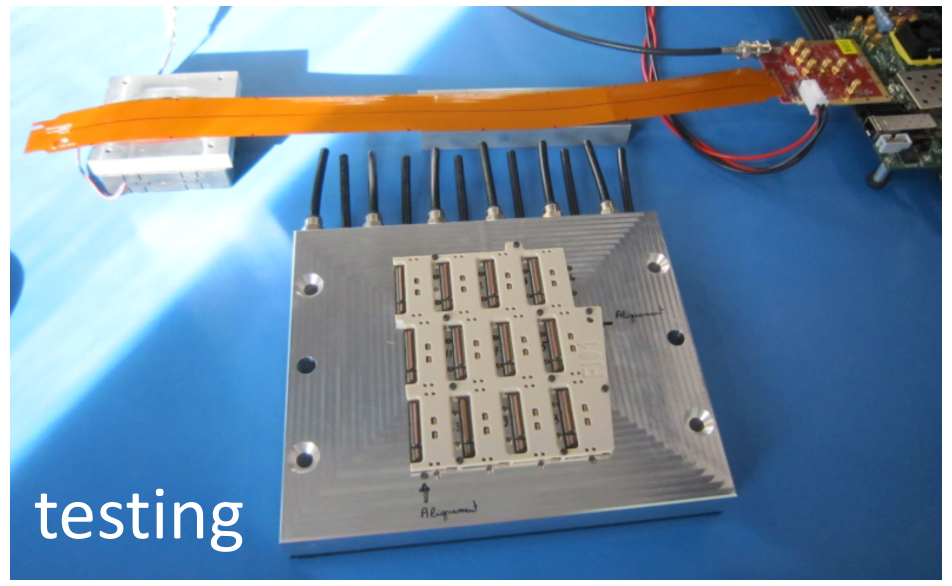
- Low-gain avalanche detectors (LGADs)
  - Reverse-biased silicon diodes with internal gain
  - 50 µm thickness with gain ~ 10
  - Engineered to maximize time resolution by minimizing jitter (sharp rise time from internal gain) and Landau noise (thin sensor)
  - Design frozen and already in pre-production
- 54-module demonstrators under construction, first tests underway
- ALTIROC3 front end readout chip in its last prototyping round



N. Cartiglia, TREDI2015



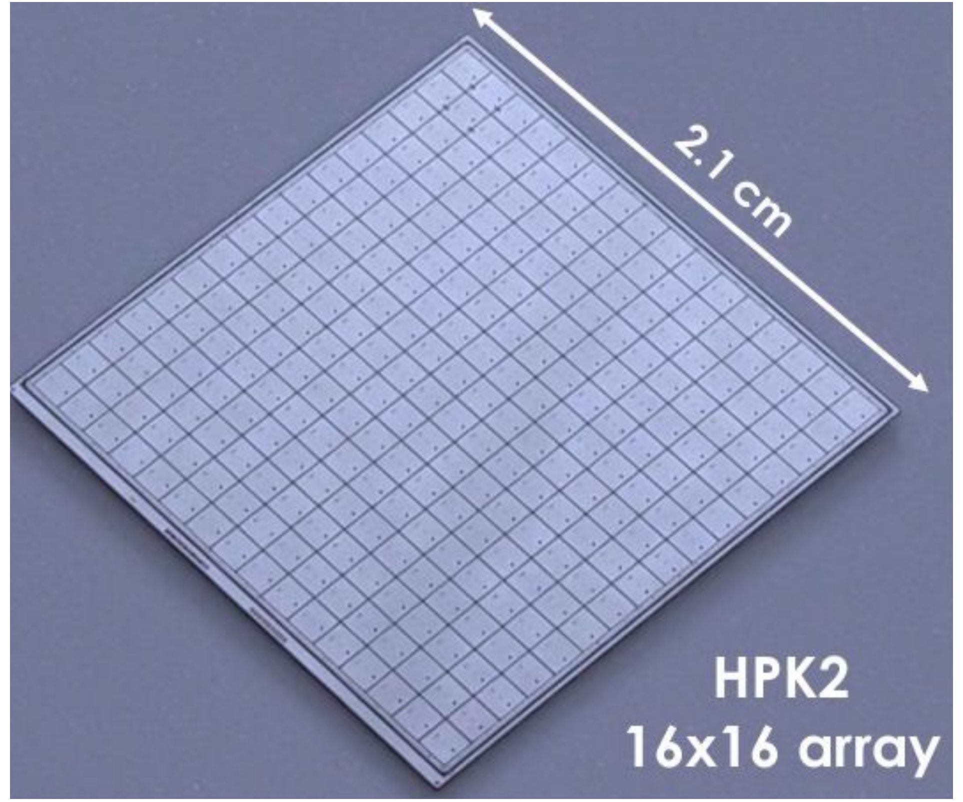




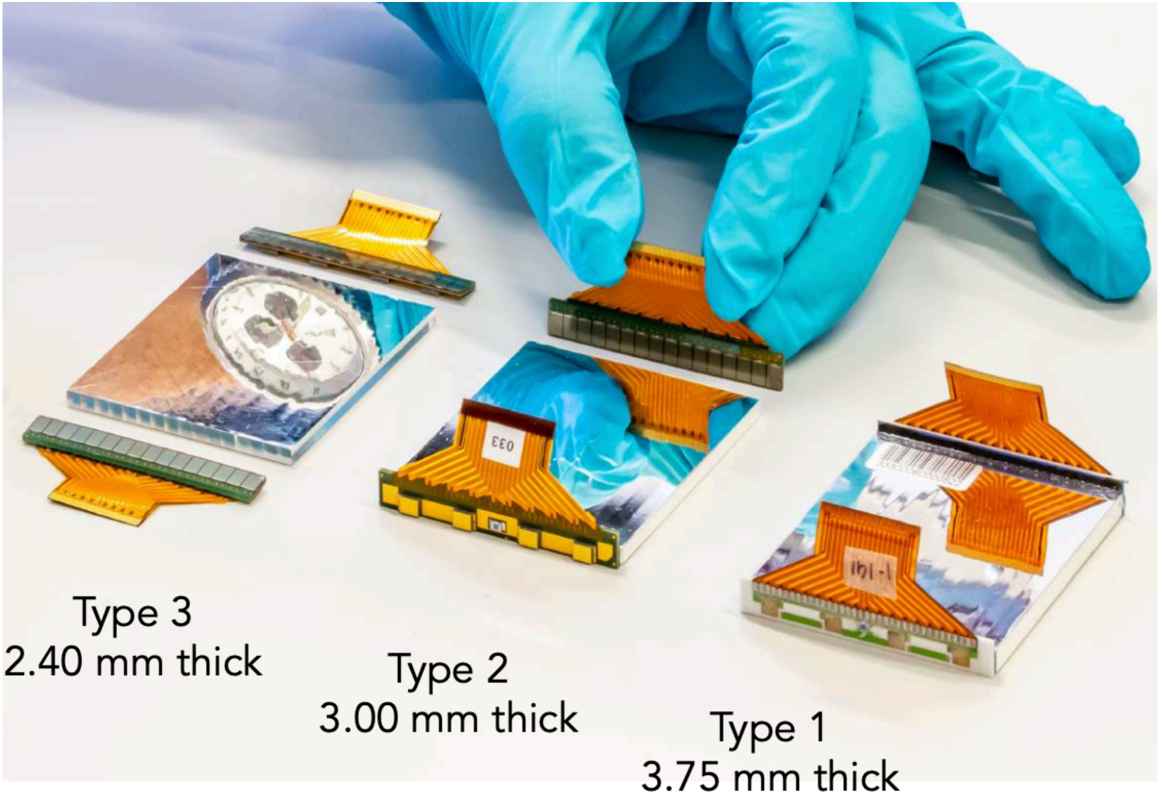
S. Terzo, VERTEX2023

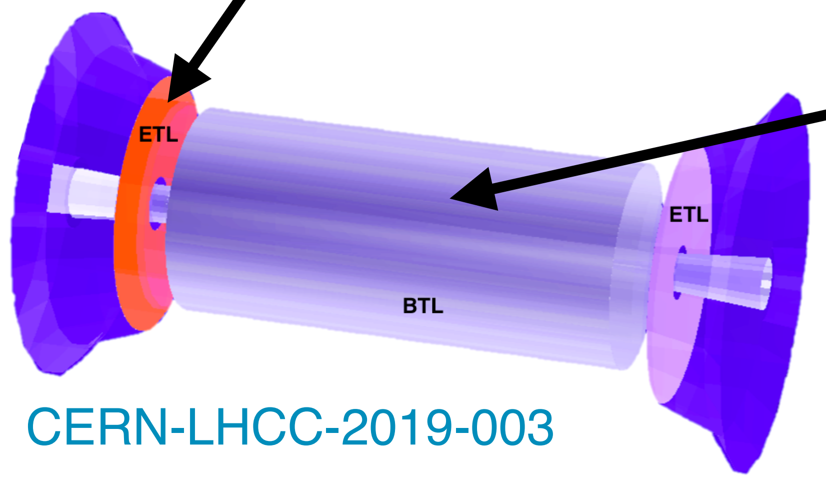
CMS MIP Timing Detector (MTD)

D. Spitzbart, LLWI2024



D. Spitzbart, LLWI2024





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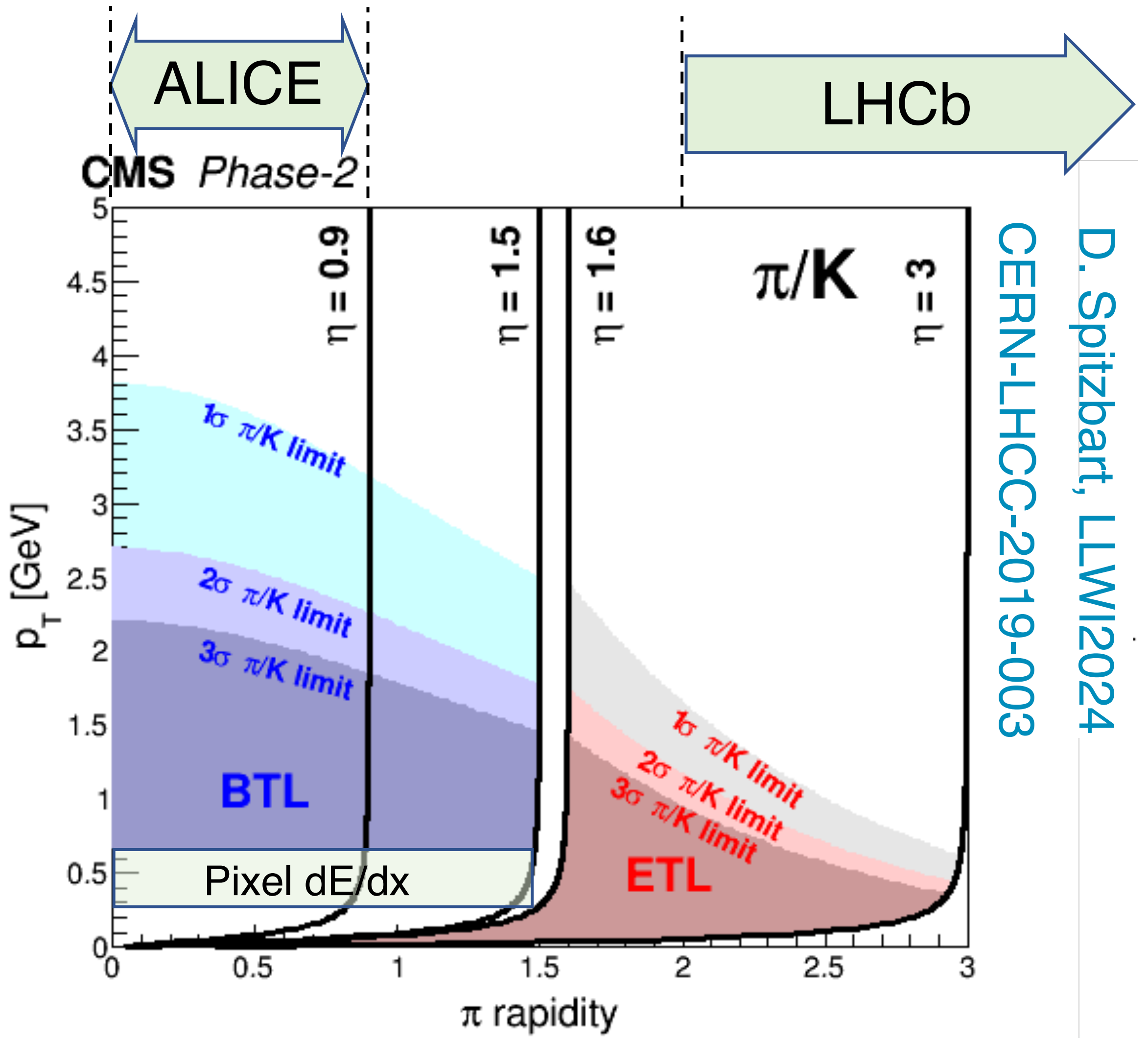


CERN-LHCC-2019-003

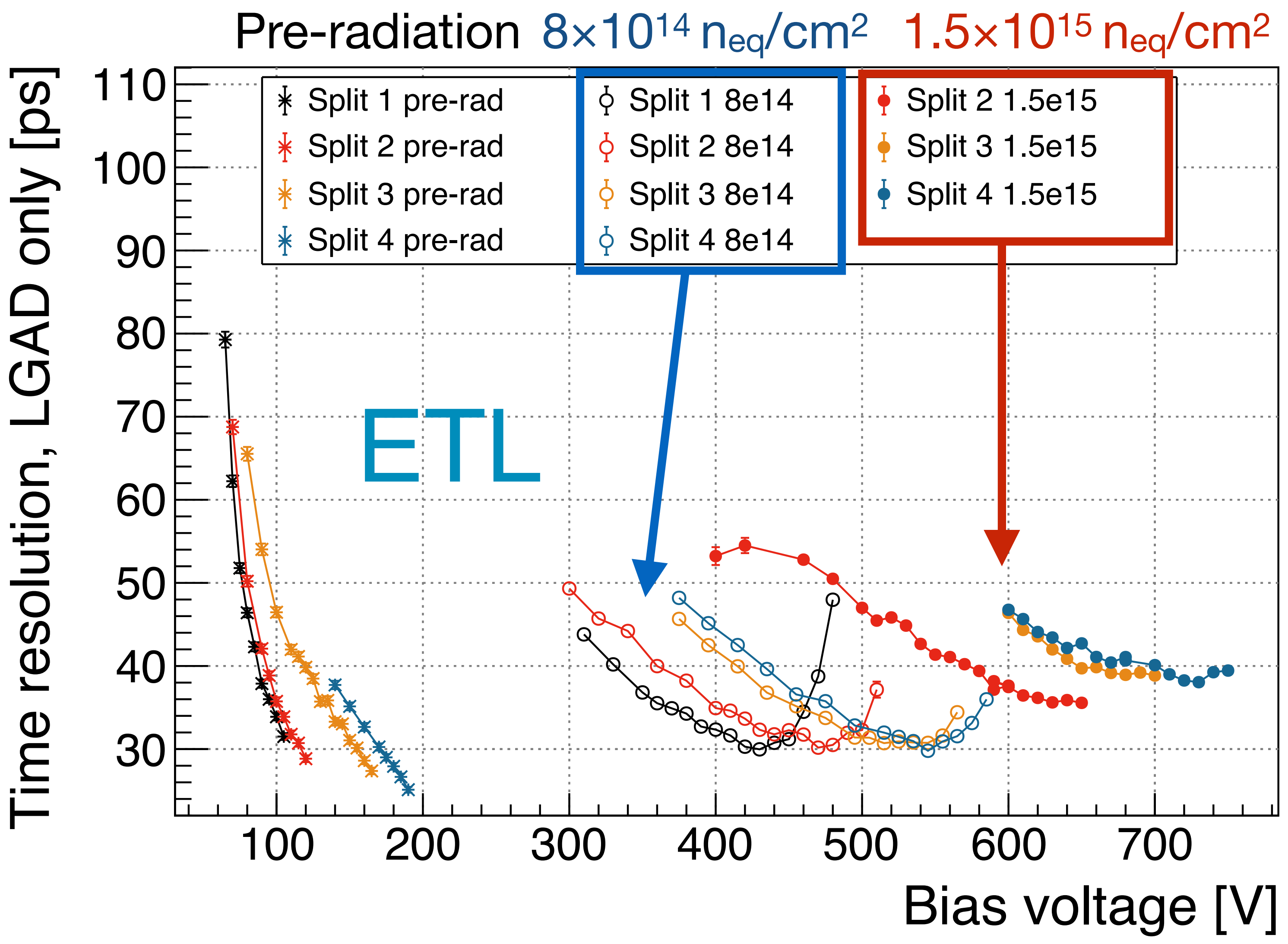
D. Spitzbart, LLWI2024

- |η| < 3, different from ATLAS HGTD
- Motivations
  - PU rejection and its impact on vertex association and isolation in many scenarios
  - Delayed BSM, time-of-flight discrimination of exotic heavy stable charged particles (HSCPs)
  - π/K separation for heavy ion physics

	Barrel Timing Layer (BTL)	Endcap Timing Layer (ETL)
Technology	LYSO crystal bars with SiPM readout	LGADs
|η|	<1.45	1.6-3.0
Surface area (m^2)	~38	~14
No. channels	332k	~8.5M
Fluence at 4 ab^{-1} (n_{eq}/cm^2)	2×10^{14}	2×10^{15} max

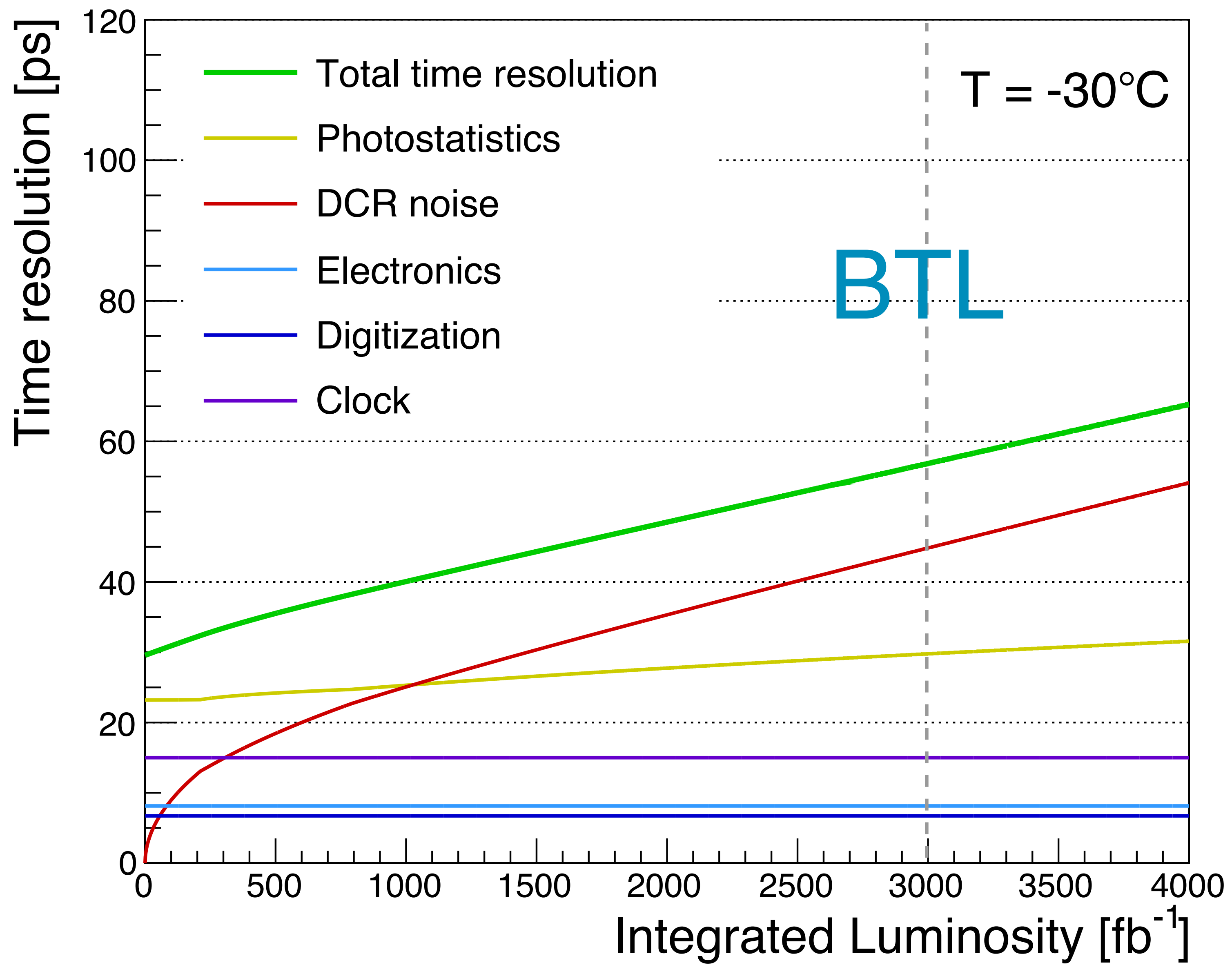
CMS MIP Timing Detector (MTD)

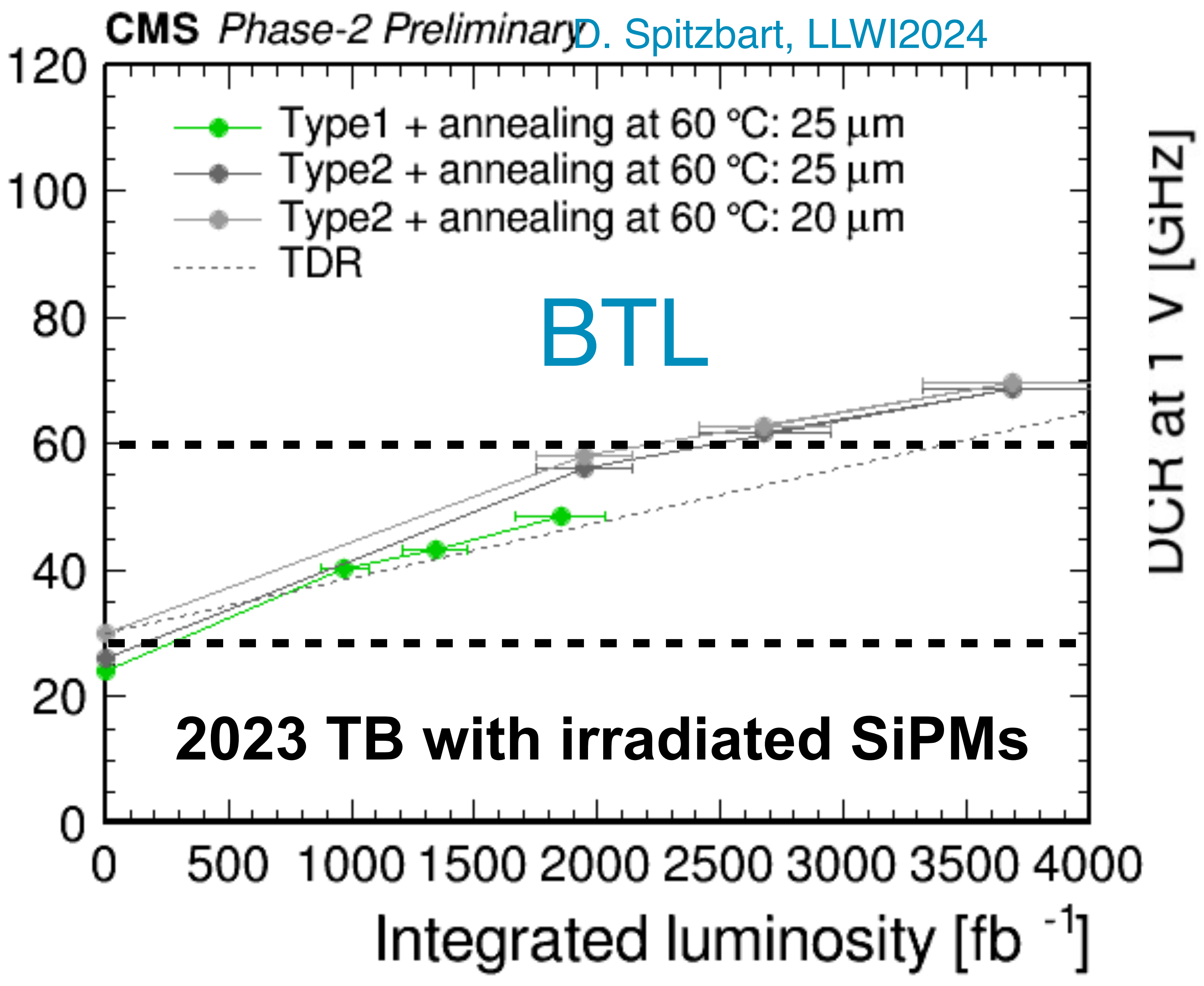
- LYSO+SiPM time resolution better than 70 ps till end of life
  - BTL readout chip (TOFHIR2) contribution ~13 ps
- LGAD time resolution better than 50 ps at end of life with 600 V bias (limit of safe operation)
  - ETL readout chip (ETROC) contribution < 40 ps



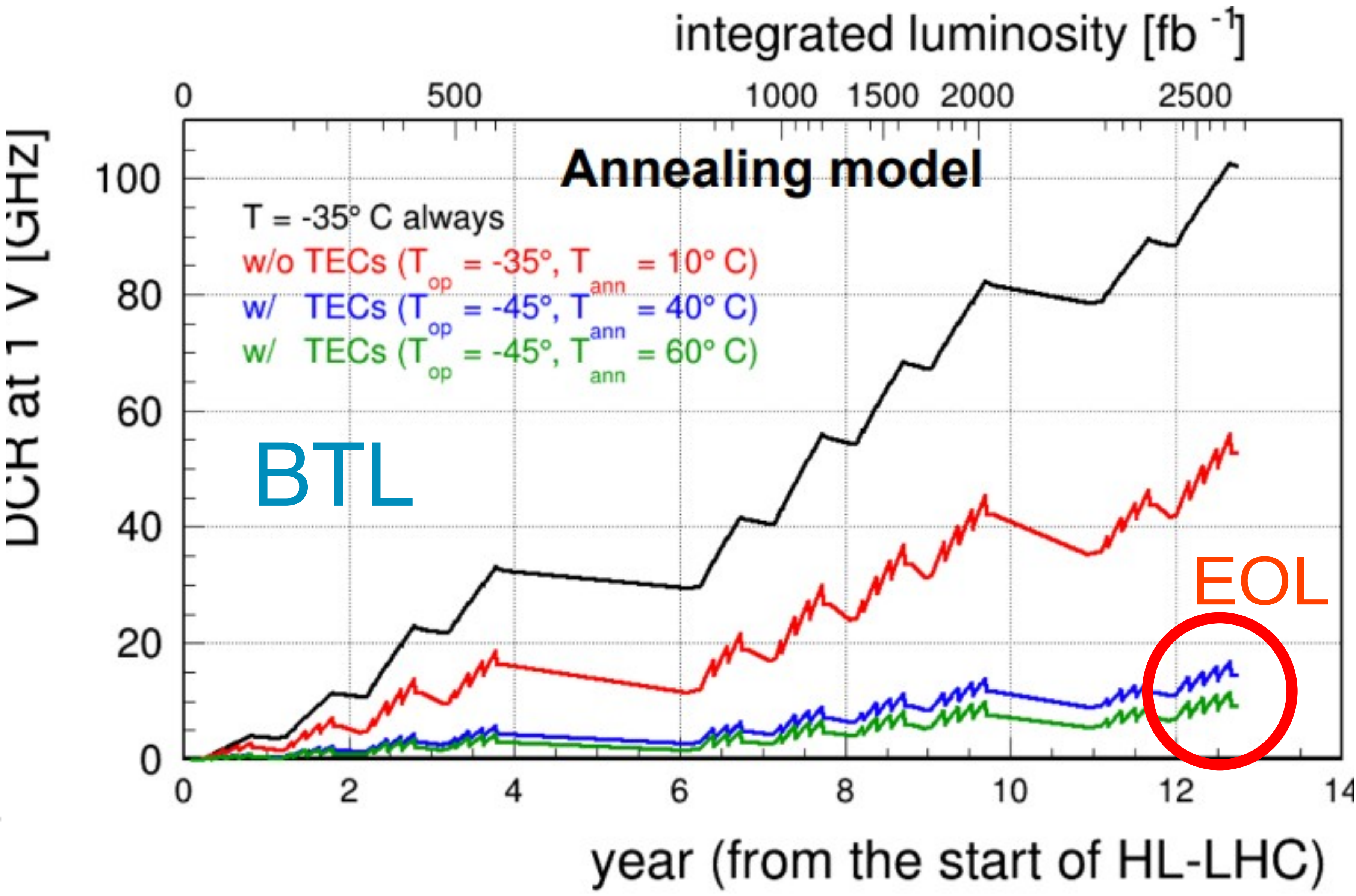
D. Spitzbart, LLWI2024

CERN-LHCC-2019-003



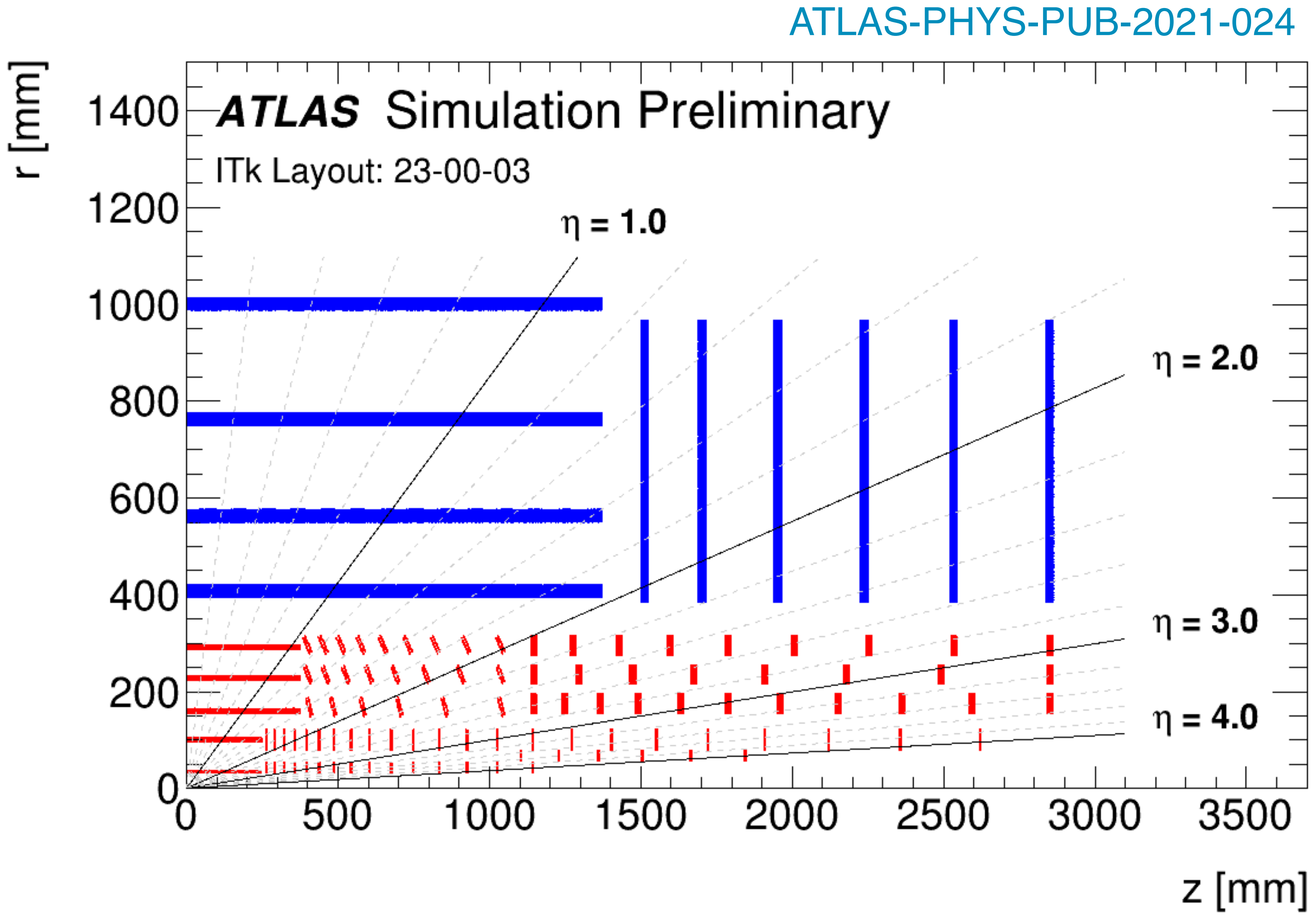


D. Spitzbart, LLWI2024

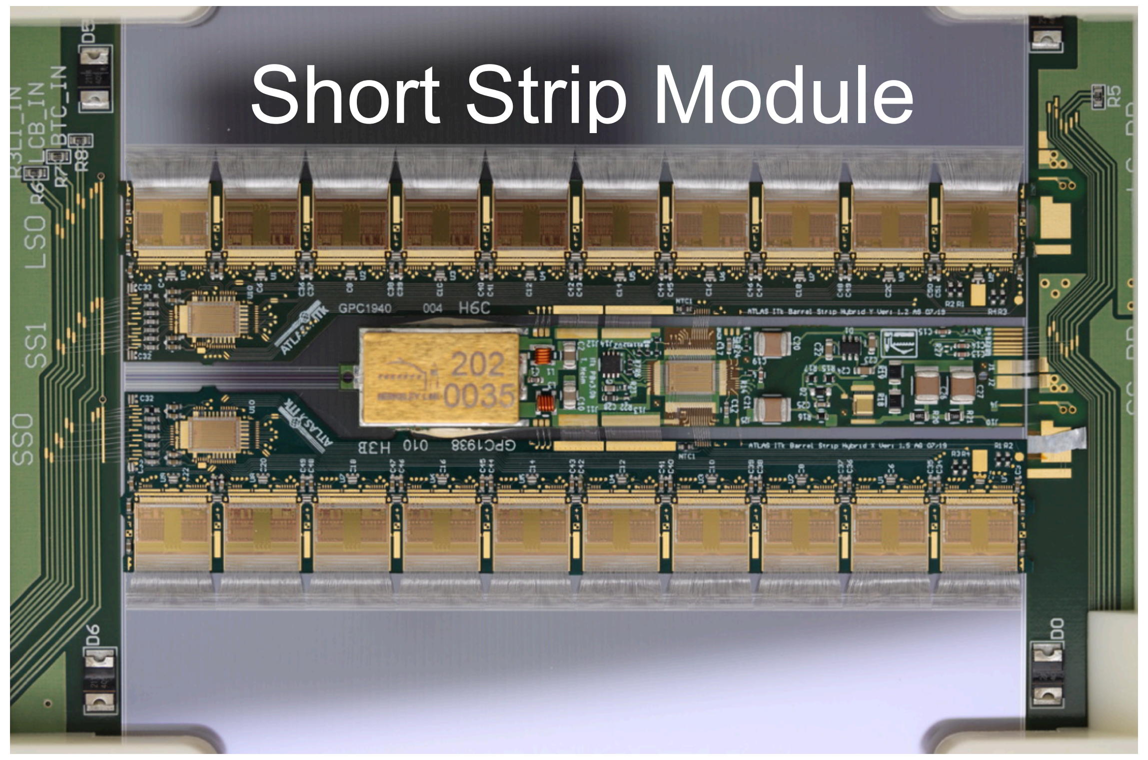


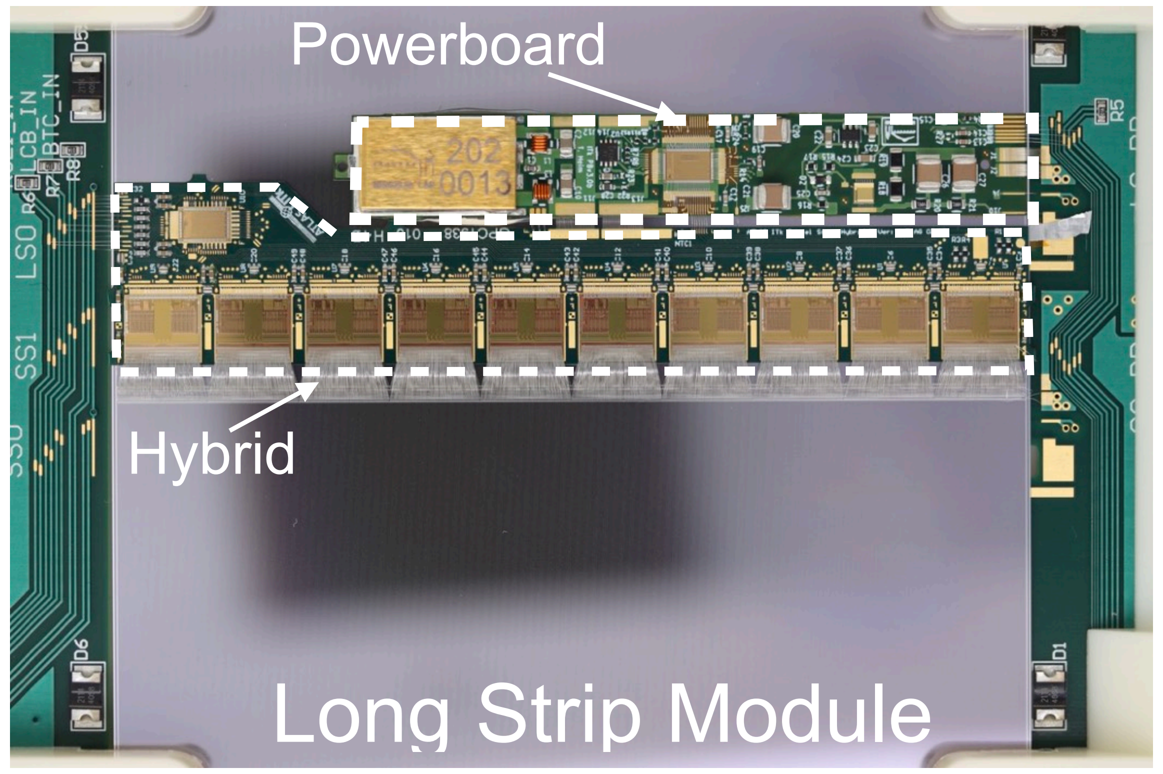
D. Spitzbart, LLWI2024

ATLAS Inner Tracker (ITk)



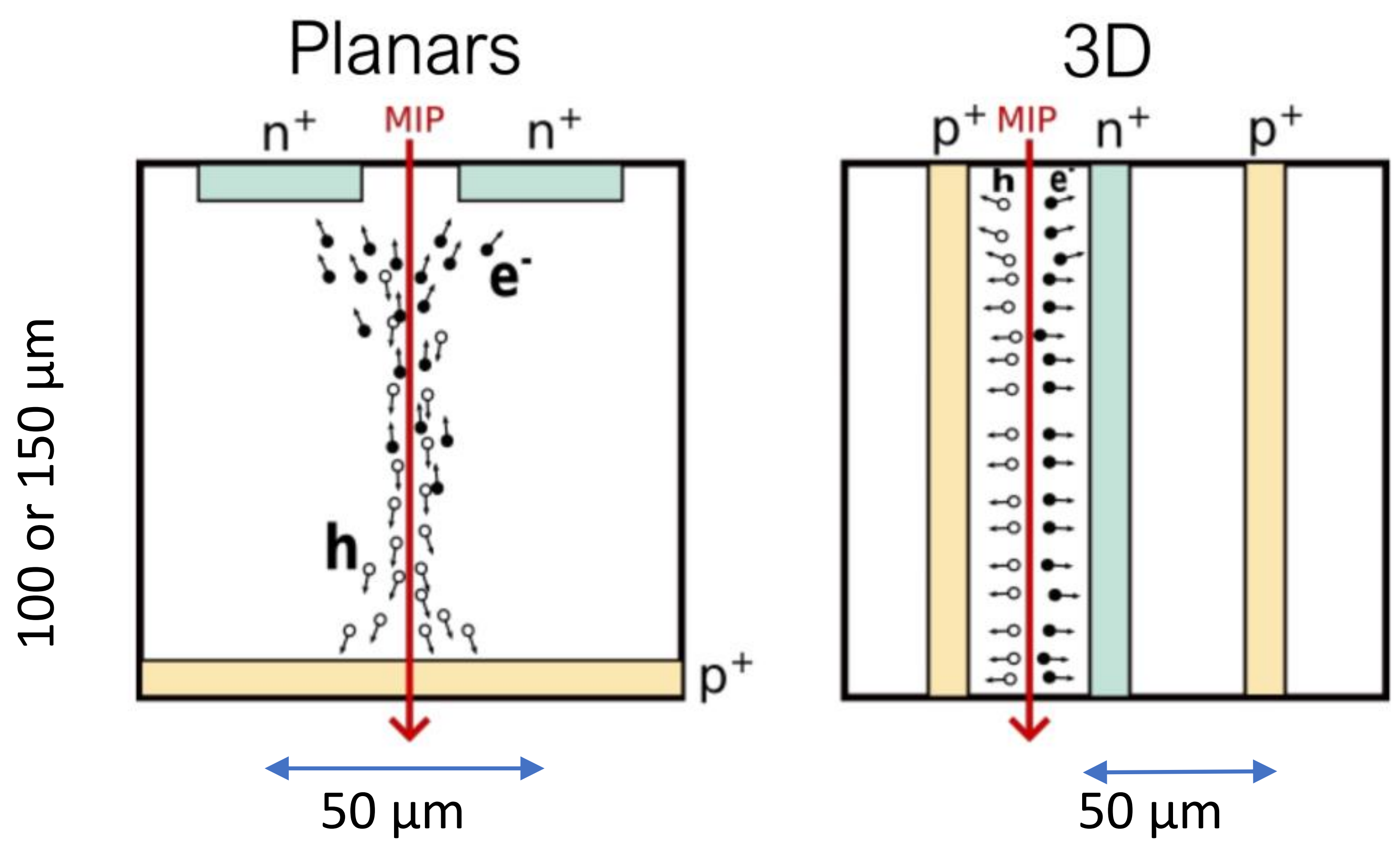
G. Iakovidis, HSTD13



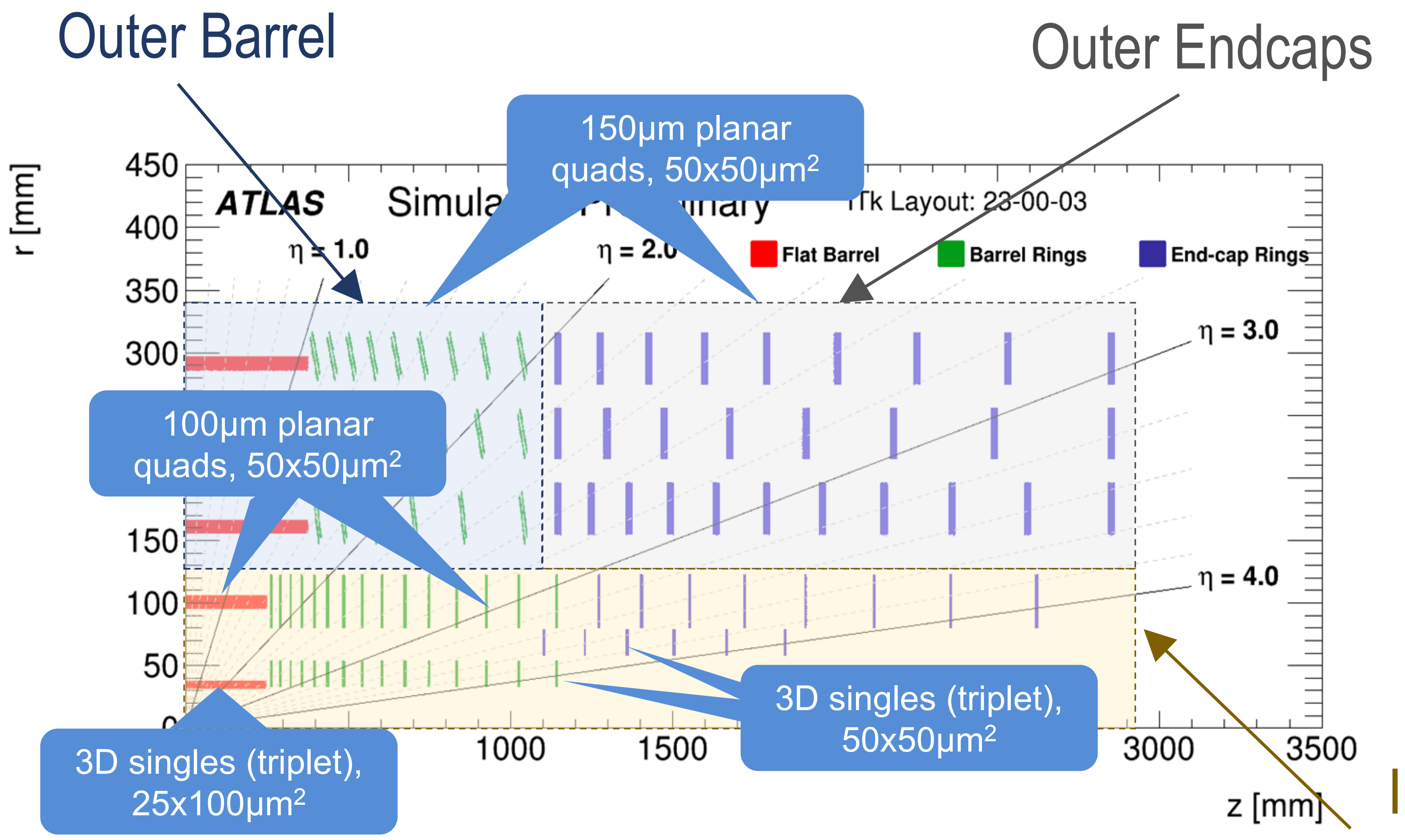


- Mixed silicon/transition-radiation tracker replaced with all-silicon tracker
- |η| < 4, same as CMS, with at least 9 hits per track to facilitate VBS jet identification
- Tilt of some endcap pixel sensors to improve track finding and reduce multiple scattering
- Layers 0 and 1 to be replaced after 2000 fb^{-1}; layers 3-5 survive to 4000 fb^{-1}
- CO$_2$ cooling, serial powering in pixel detector, and carbon fiber structures to minimize mass

ATLAS ITk



S. Passaggio, HSTD13


Outer Barrel

Outer Endcaps

150µm planar quads, 50x50µm²

100µm planar quads, 50x50µm²

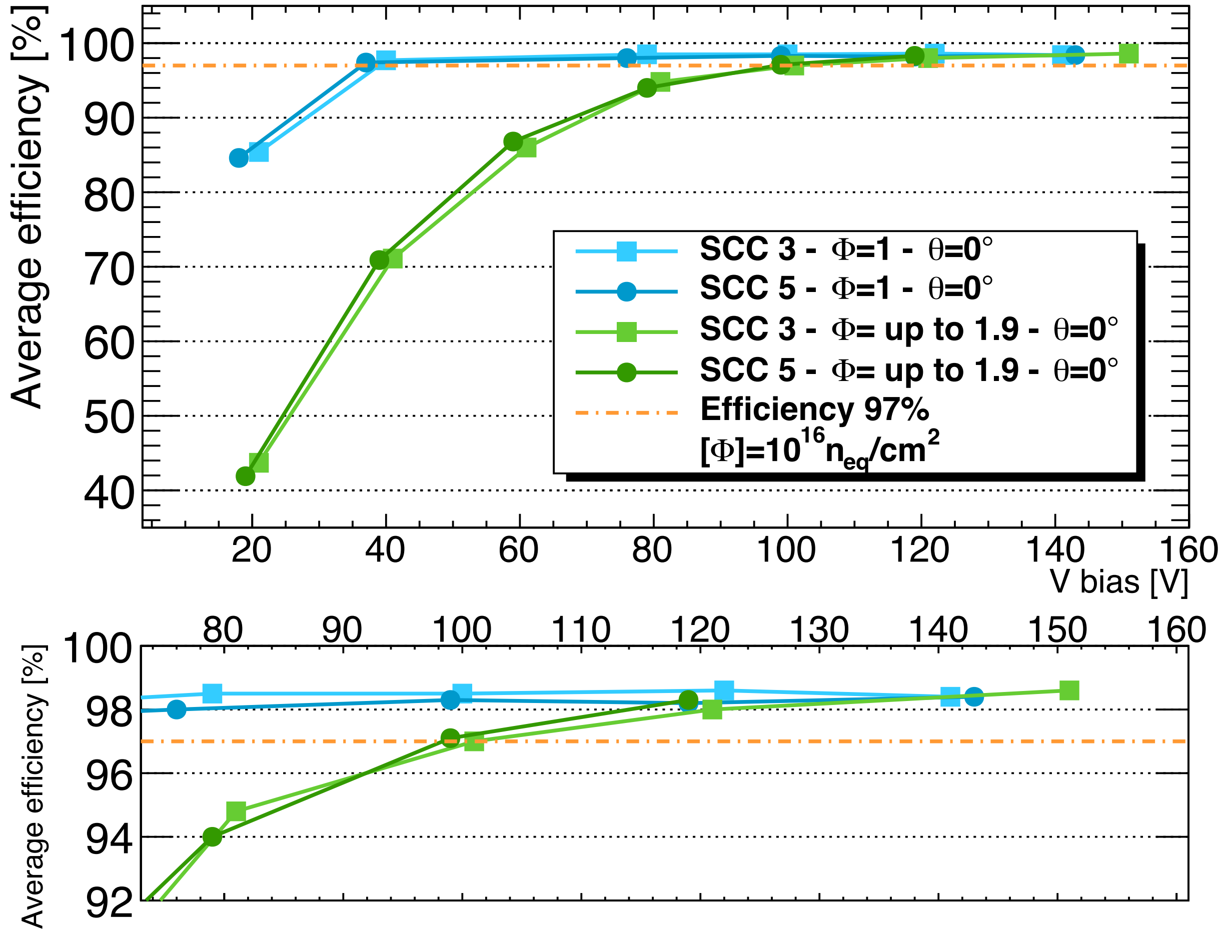
3D singles (triplet), 25x100µm²

3D singles (triplet), 50x50µm²

Inner System

S. Passaggio, HSTD13

ITK-2022-005

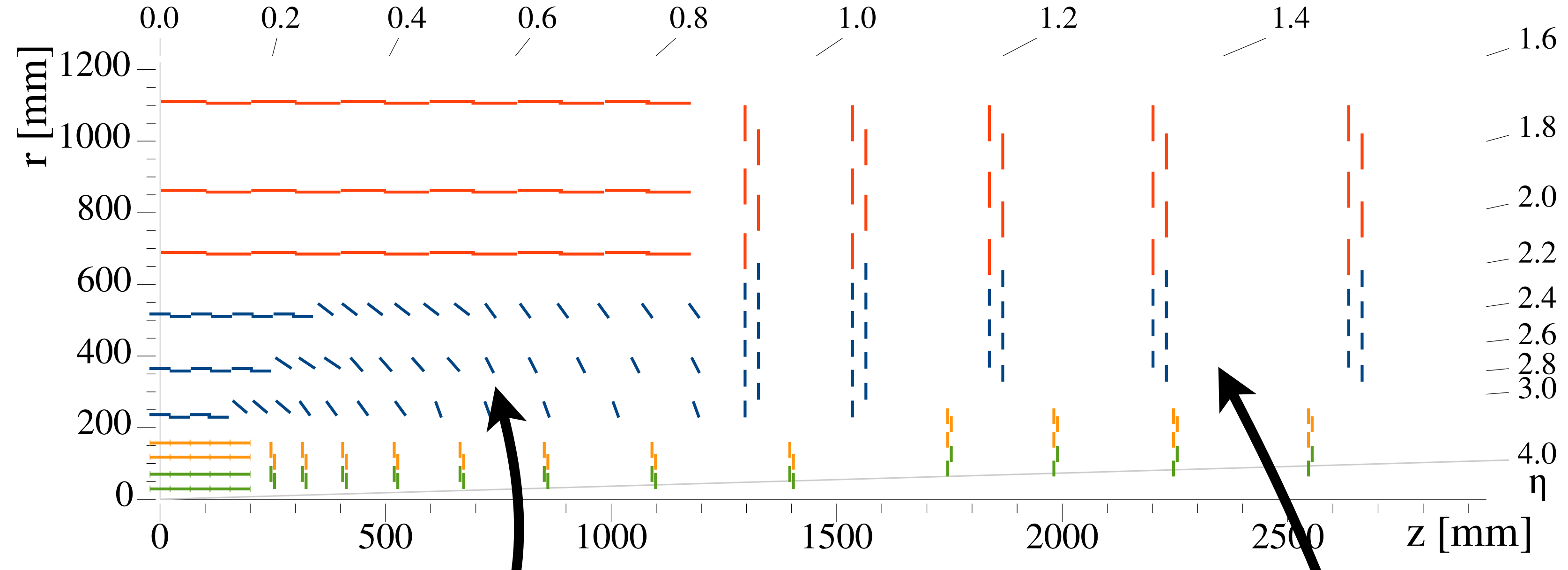


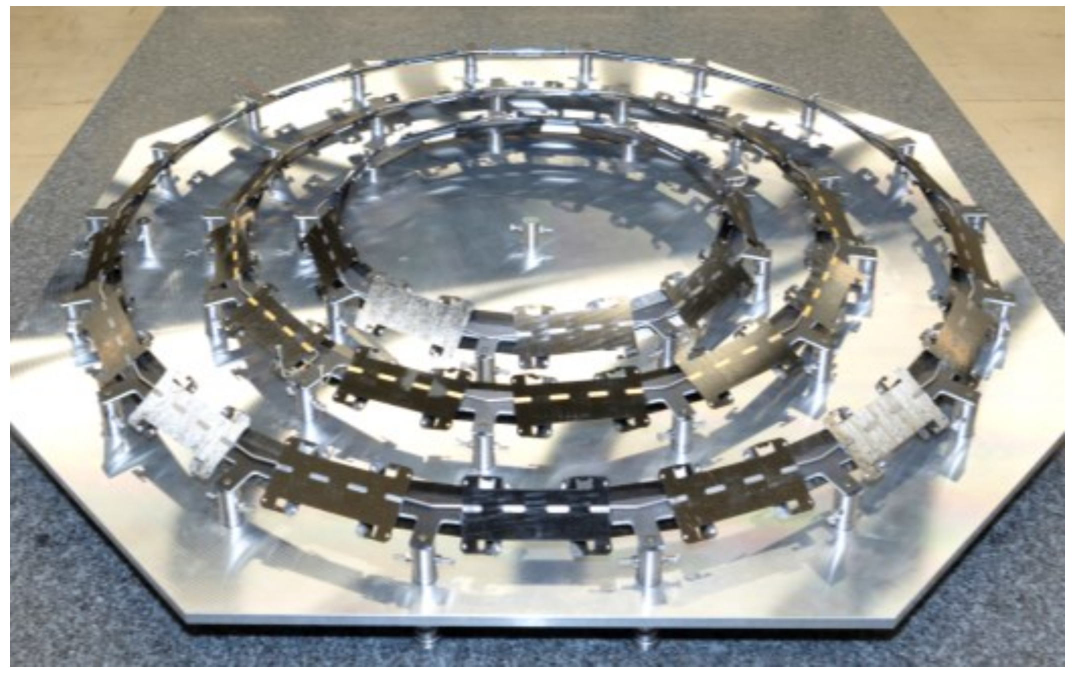
- Common CMS-ATLAS RD53 pixel readout chip in 65 nm technology
- 3D pixel sensors in “layer 0” for extreme radiation hardness
  - Shorter drift time ⇒ more charge collected before trapping ⇒ higher S/N
  - Good performance up to 1.9×10^{16} n_{eq}/cm^2
- Sensors production ongoing, other module components in pre-production, with planned completion 2027

CMS tracker

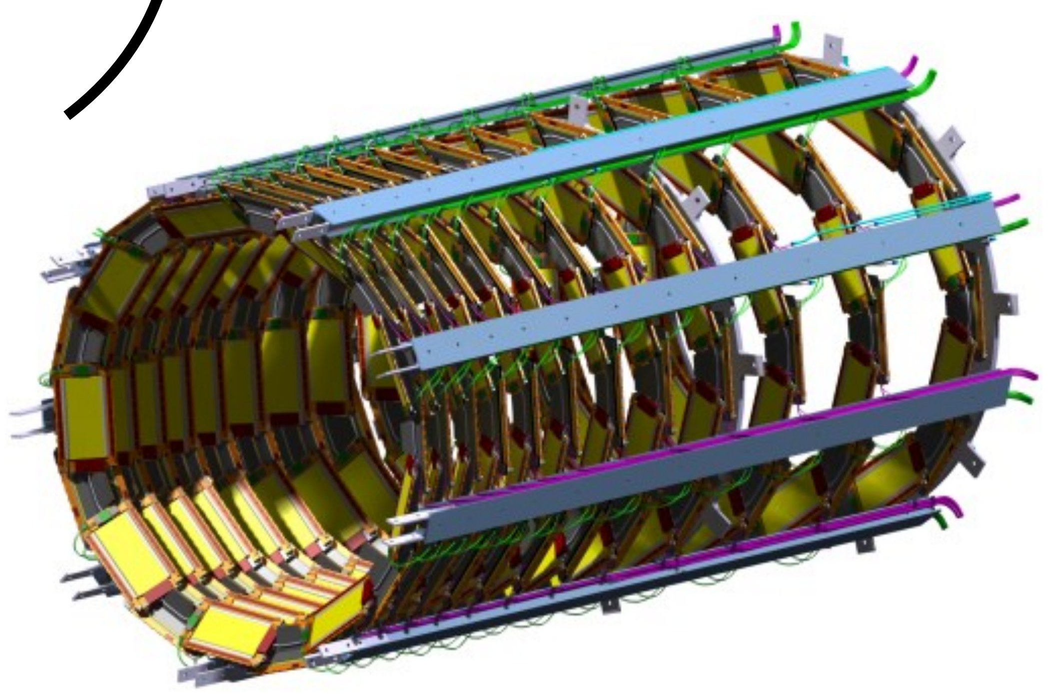
- 3D sensors in pixel layer 1, planar sensors elsewhere, as for ATLAS
- Tilted barrel section, like ATLAS, to minimize material and increase stub efficiency at high η
- Successful module prototyping will soon lead to pre-series orders
- Sensor production (long lead time) well underway

CERN-LHCC-2017-009

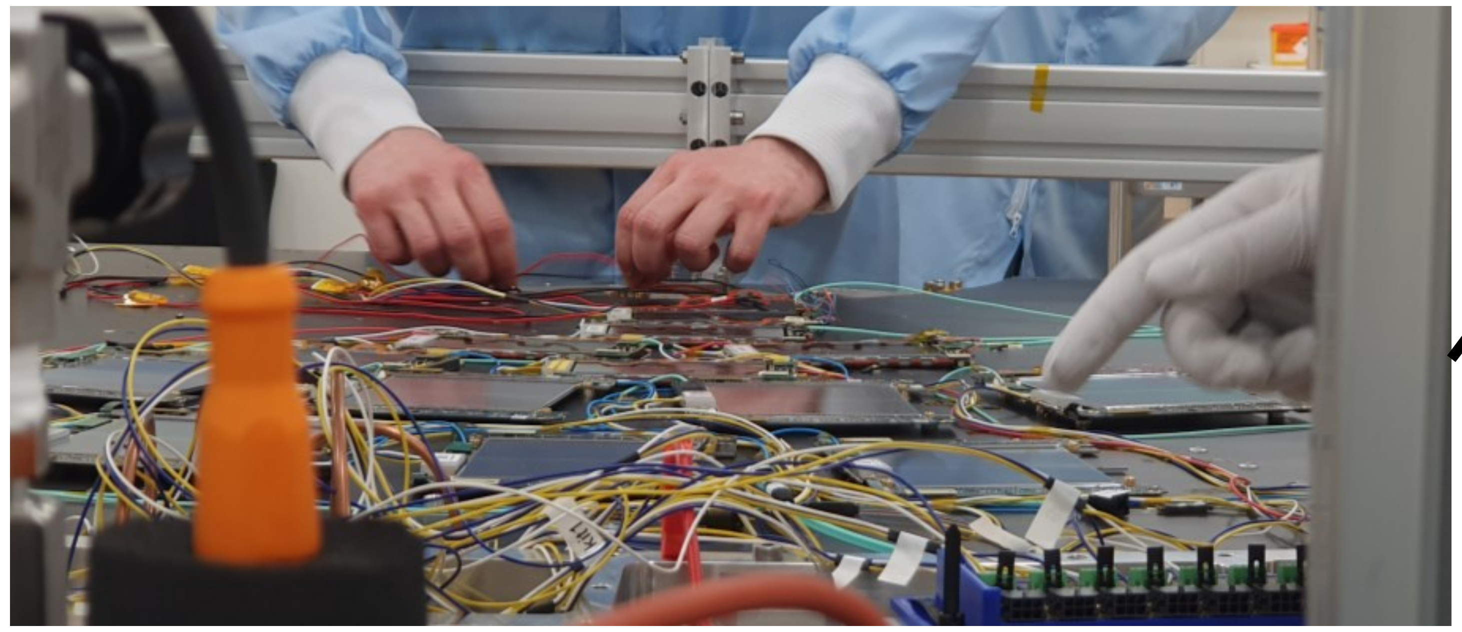




N. Roewert, HSTD13



N. Roewert, HSTD13



CMS tracker

- Level-1 track trigger to enable vertex finding, particle flow, and pileup reduction at the 40 MHz interaction rate
  - Double sided modules with tight tolerance on misalignment
  - Carbon fiber (CF) reinforced polymer stiffeners with good thermal conductivity
  - Al-CF spacers
- Binary strip readout, digitized pixel analog readout for better sensitivity to HSCPs

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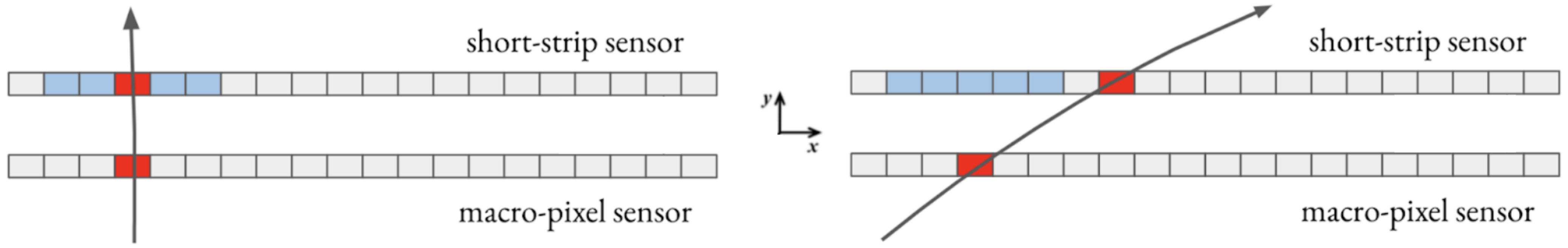
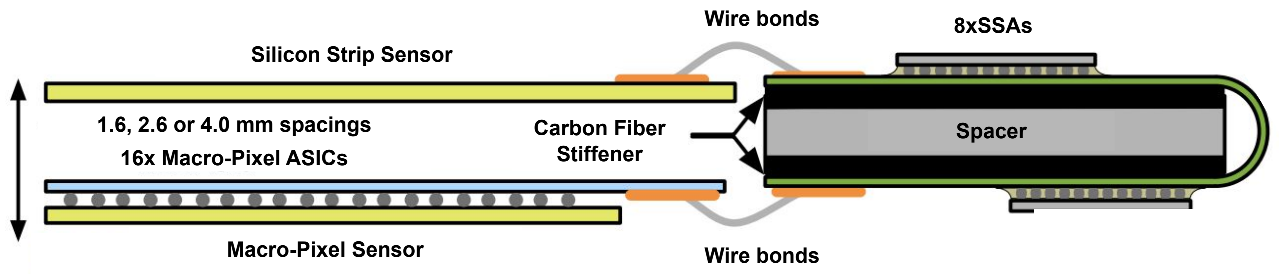
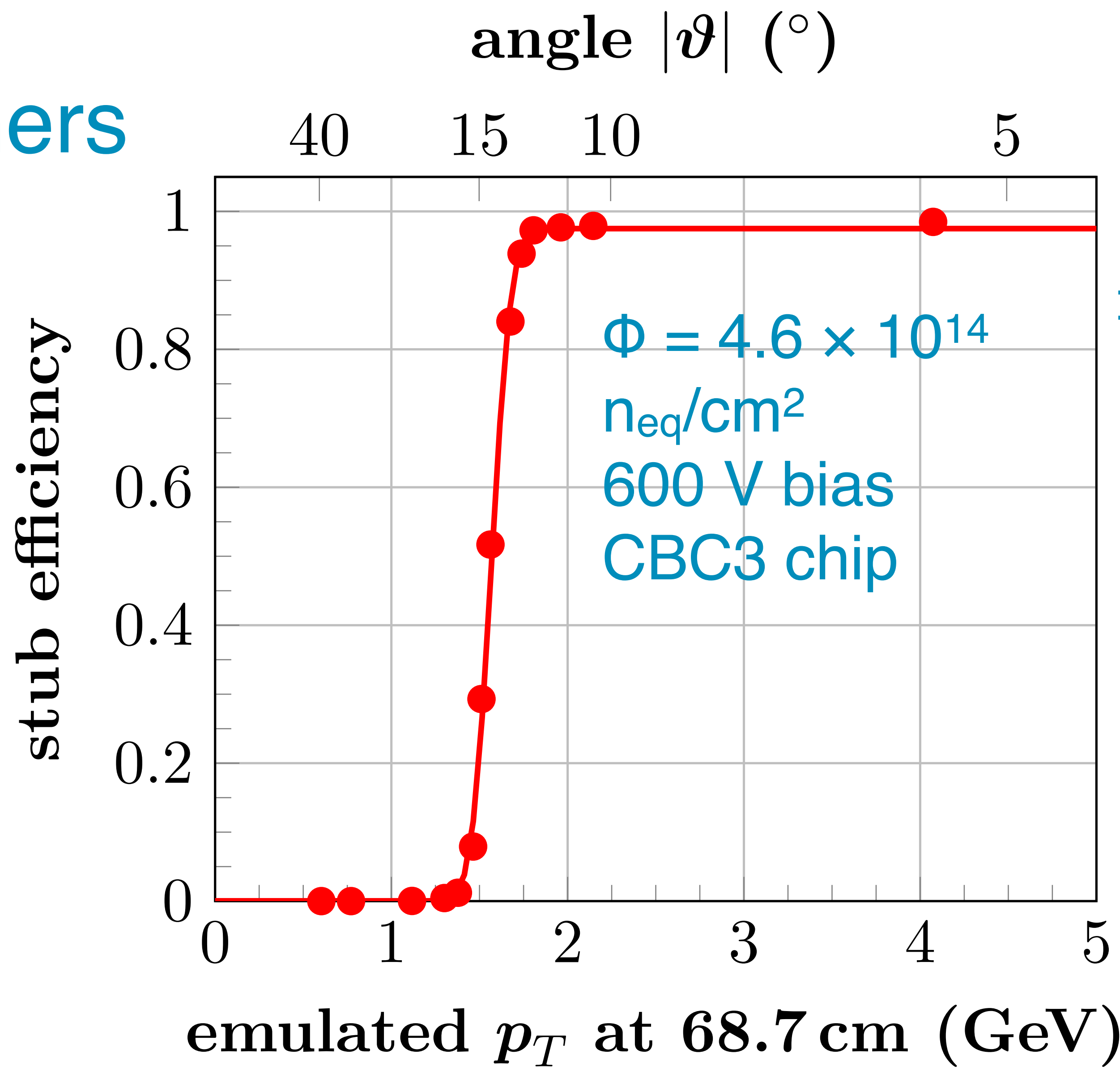


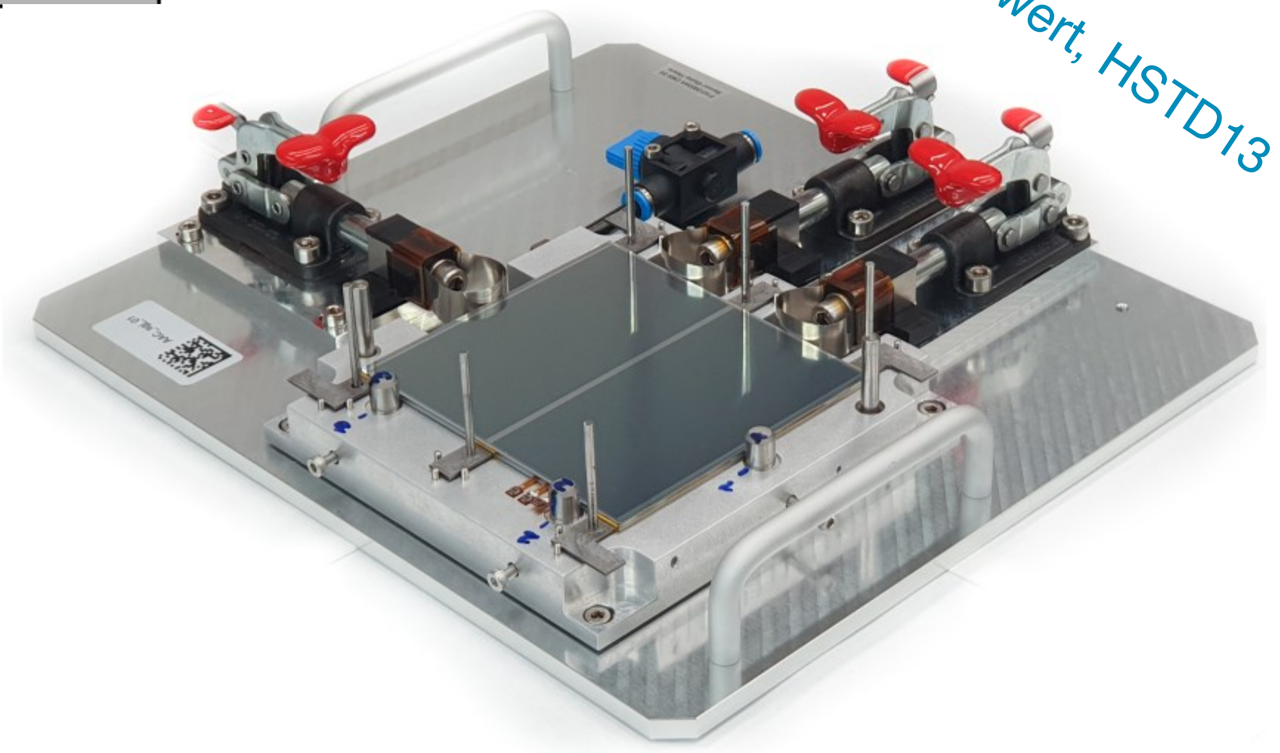




$\Phi = 4.6 \times 10^{14}$ n_{eq}/cm^2
600 V bias
CBC3 chip

R. Koppenhöfer, ETP-KA/2022-07

N. Roewert, HSTD13



Misalignment (controlled by jigs like this one) well within tolerances for stub finding

Trigger and DAQ

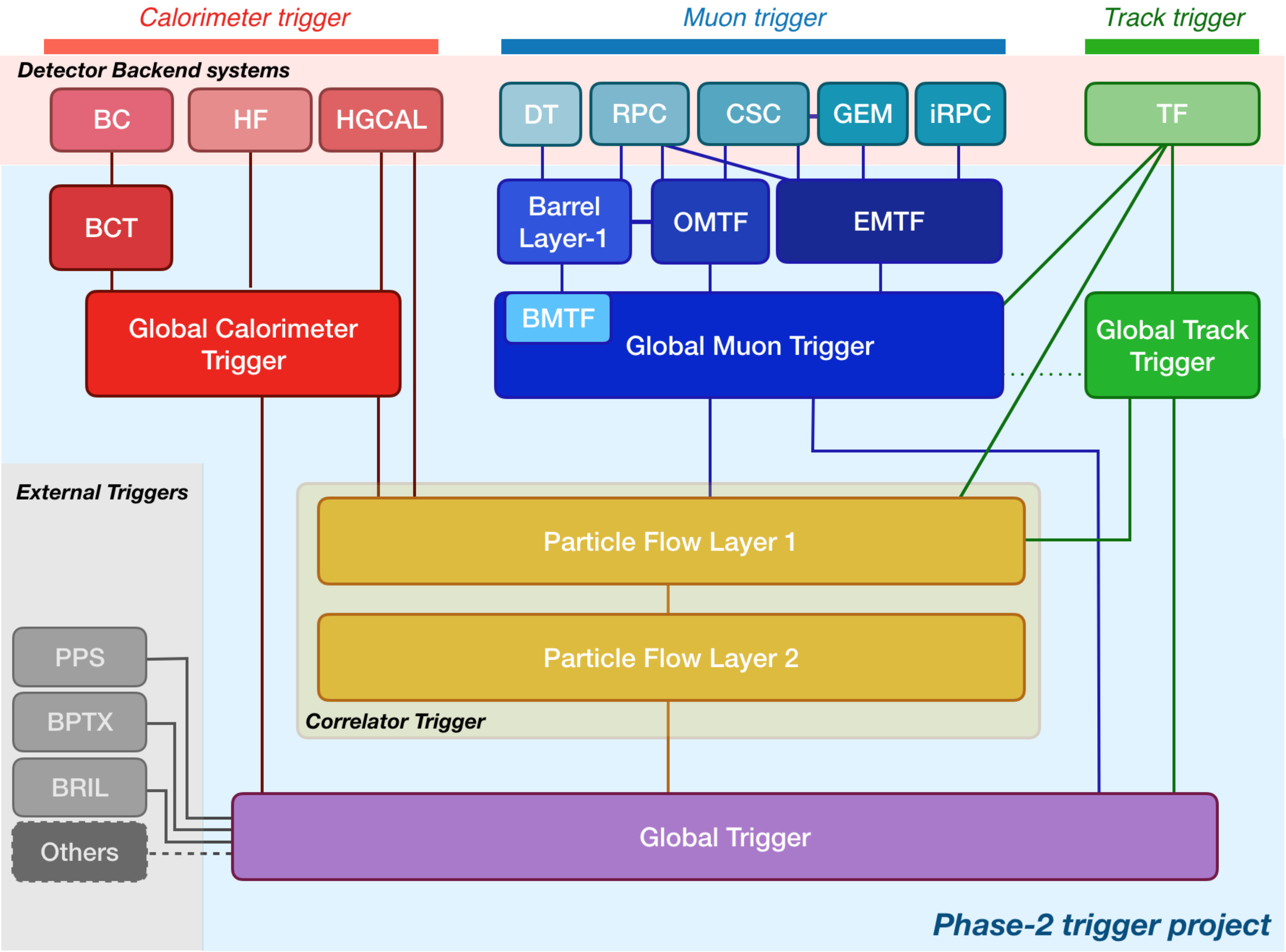
- Upgrades to calorimeter and muon system front end electronics to be compatible with high rate trigger

- Goal of keeping physics object p_T thresholds the same as currently

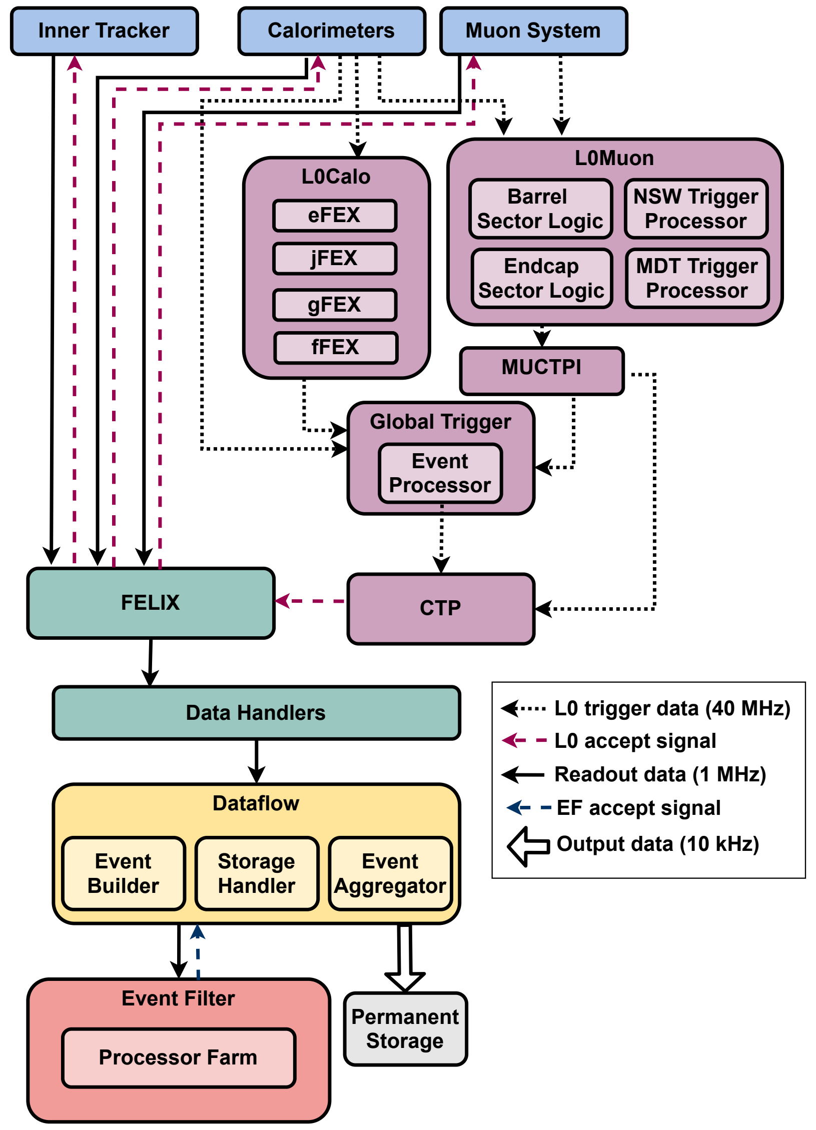
- Ability to use ML and PF in FPGA trigger boards

- Modern heterogeneous computing farms for software triggers

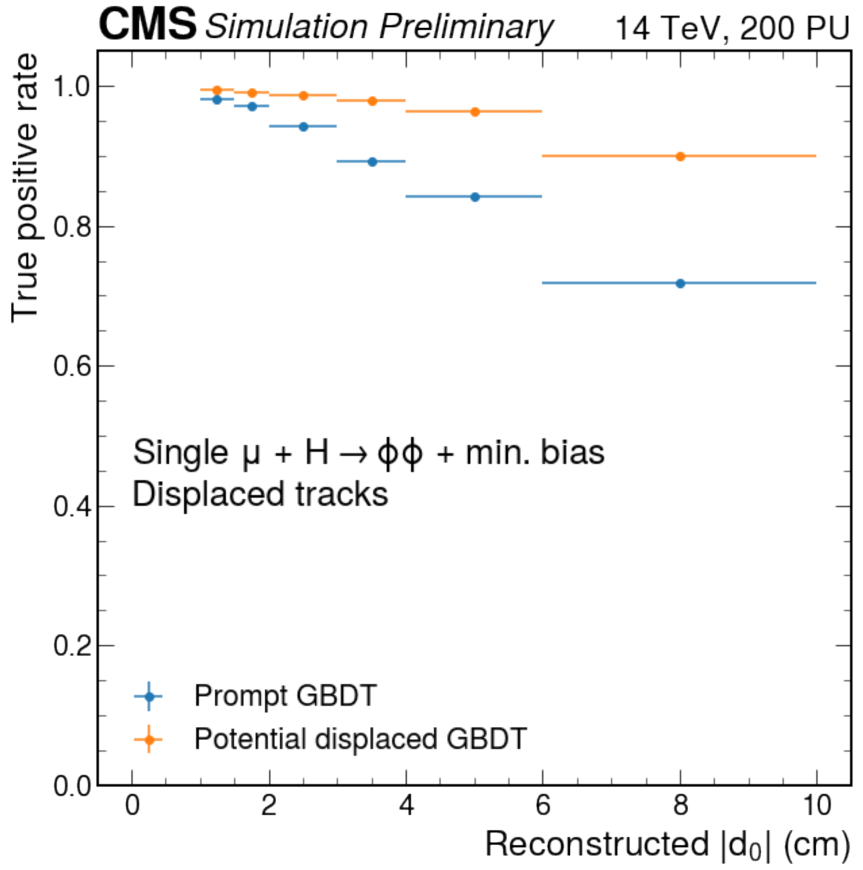
- Scouting for trigger monitoring and real-time analysis



CERN-LHCC-2020-004



CERN-LHCC-2022-004



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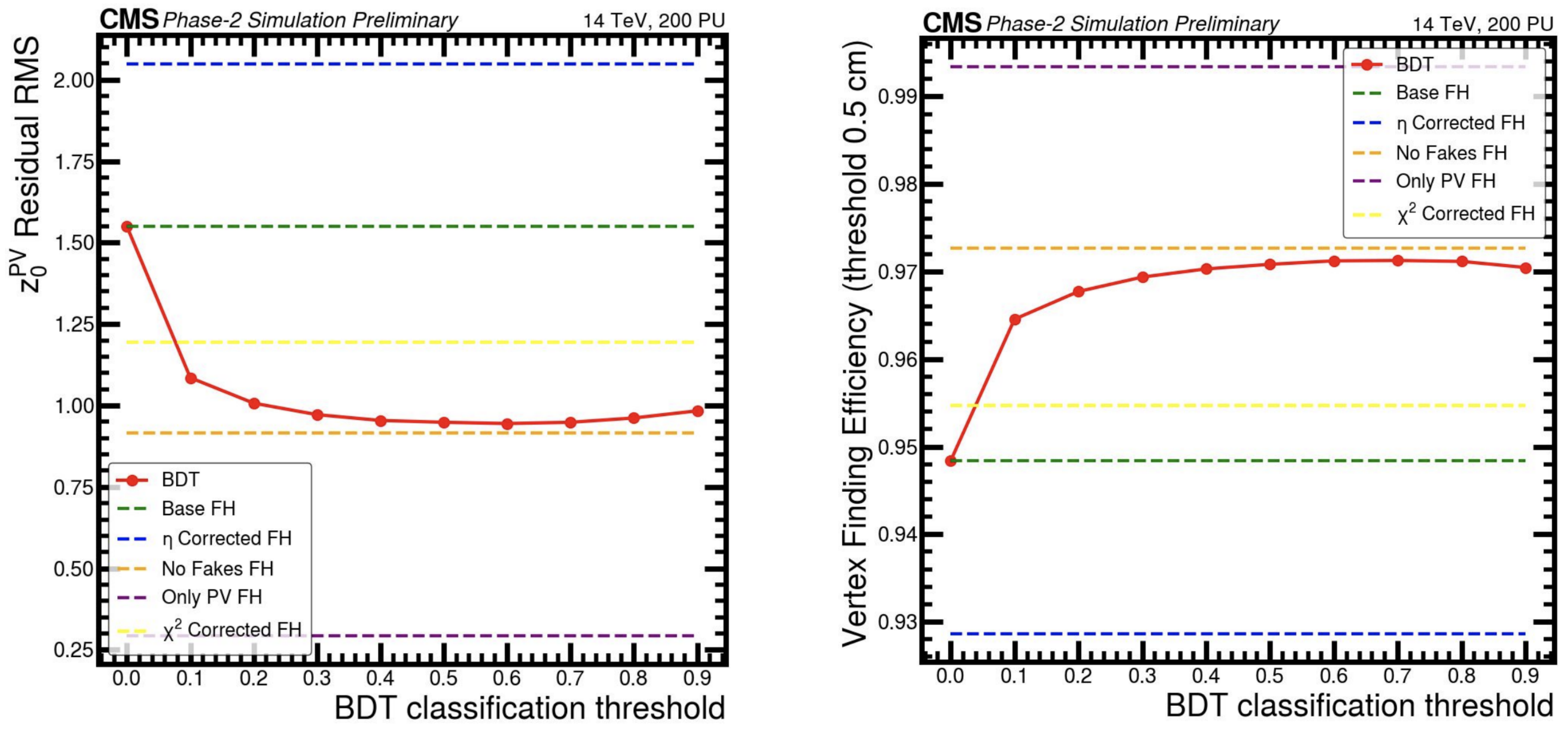


Conclusions

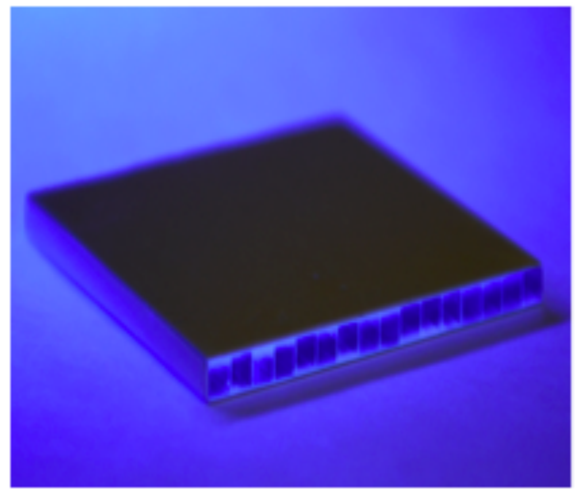
- The HL-LHC will measure the Higgs couplings and details of electroweak symmetry breaking not currently accessible
- To collect ~10 times more data than the LHC in about the same wall clock time, significant detector upgrades are necessary to
  - Effectively trigger on electroweak processes
  - Survive the radiation environment
- Enormous progress has been made to design, prototype, and construct detectors that meet these challenges

Backup

CMS MTD

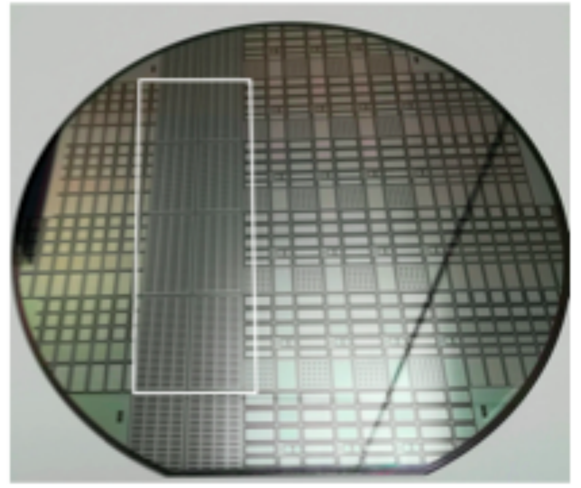
BTL: LYSO bars + SiPM readout:

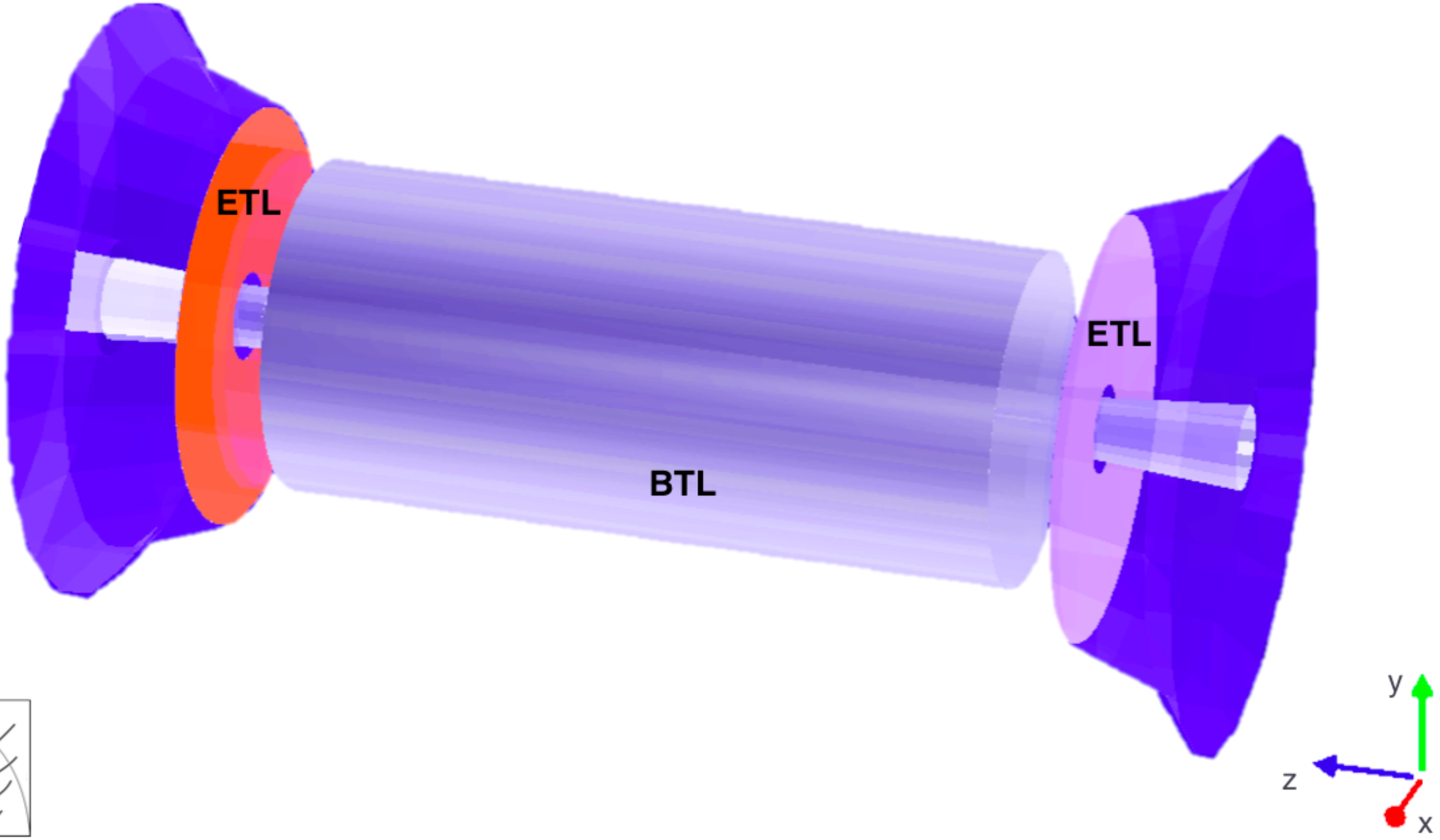
- TK / ECAL interface: |η| < 1.45
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: 2x10^{14} n_{eq}/cm^2



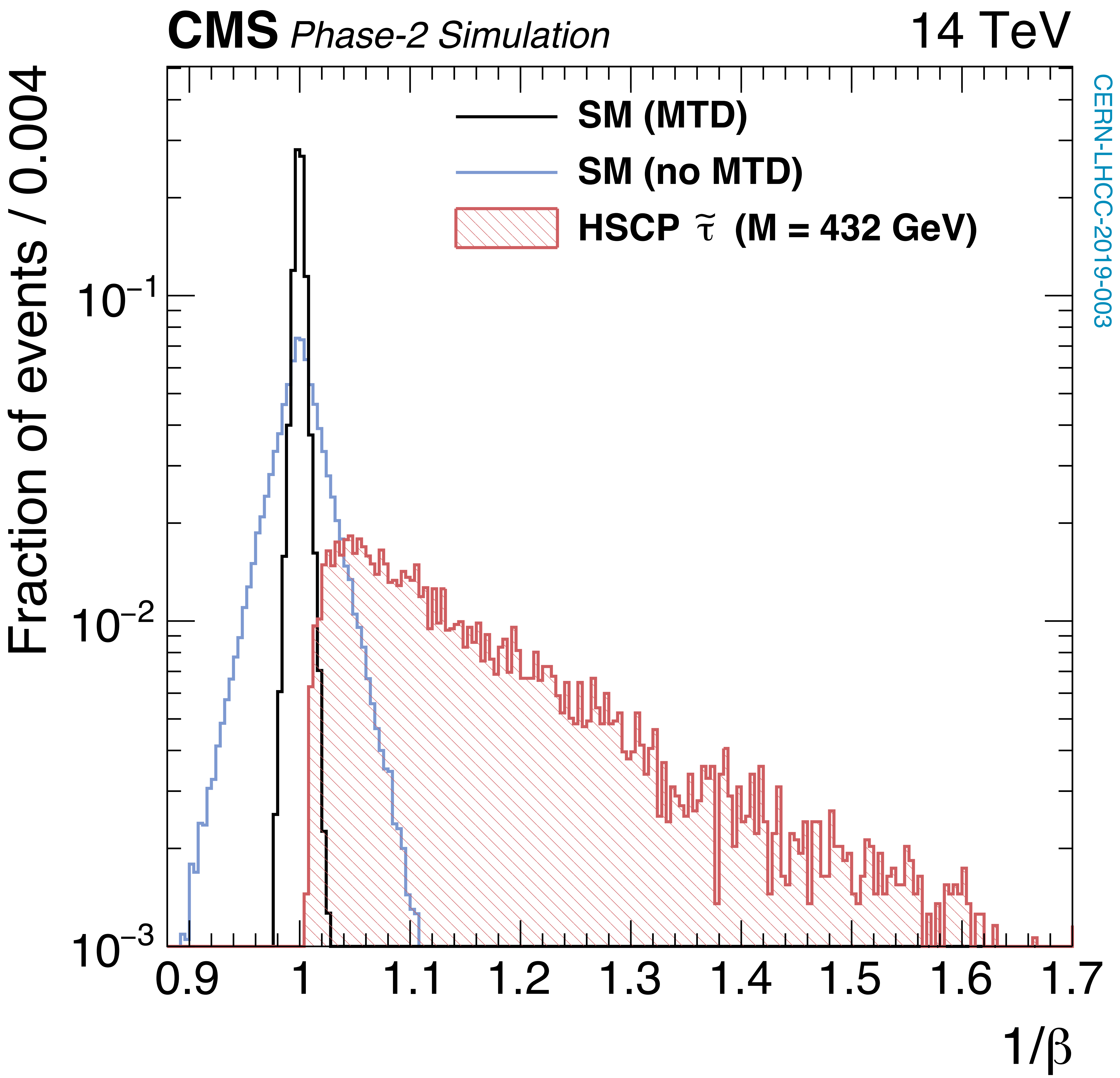
ETL: Si with internal gain (LGAD):

- On the CE nose: 1.6 < |η| < 3.0
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to 2x10^{15} n_{eq}/cm^2

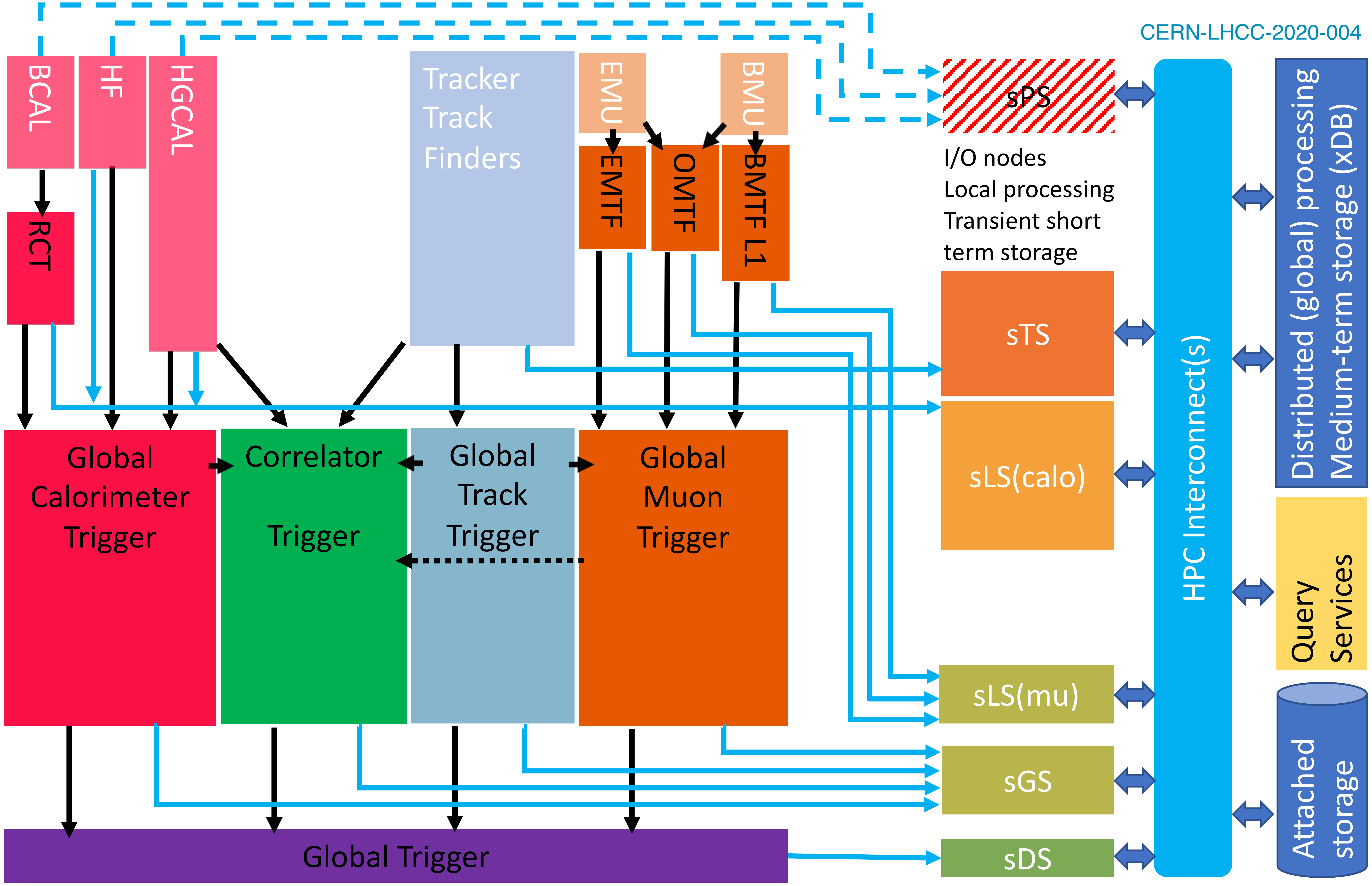




CMS MTD

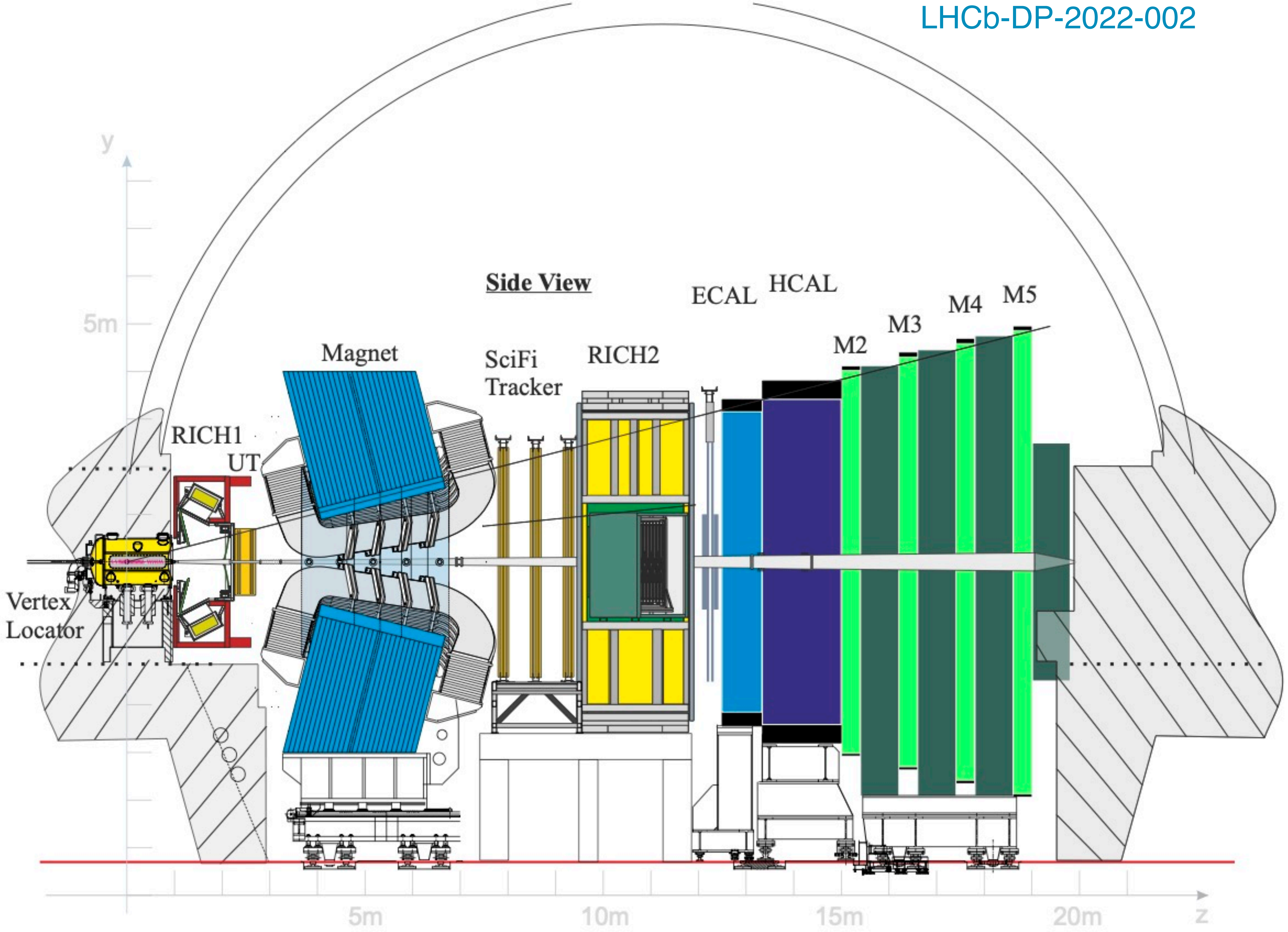

CMS *Phase-2 Simulation*
14 TeV
CERN-LHCC-2019-003
SM (MTD)
SM (no MTD)
HSCP $\tilde{\tau}$ (M = 432 GeV)
Fraction of events / 0.004
10^{-1}
10^{-2}
10^{-3}
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
$1/\beta$

CMS scouting system



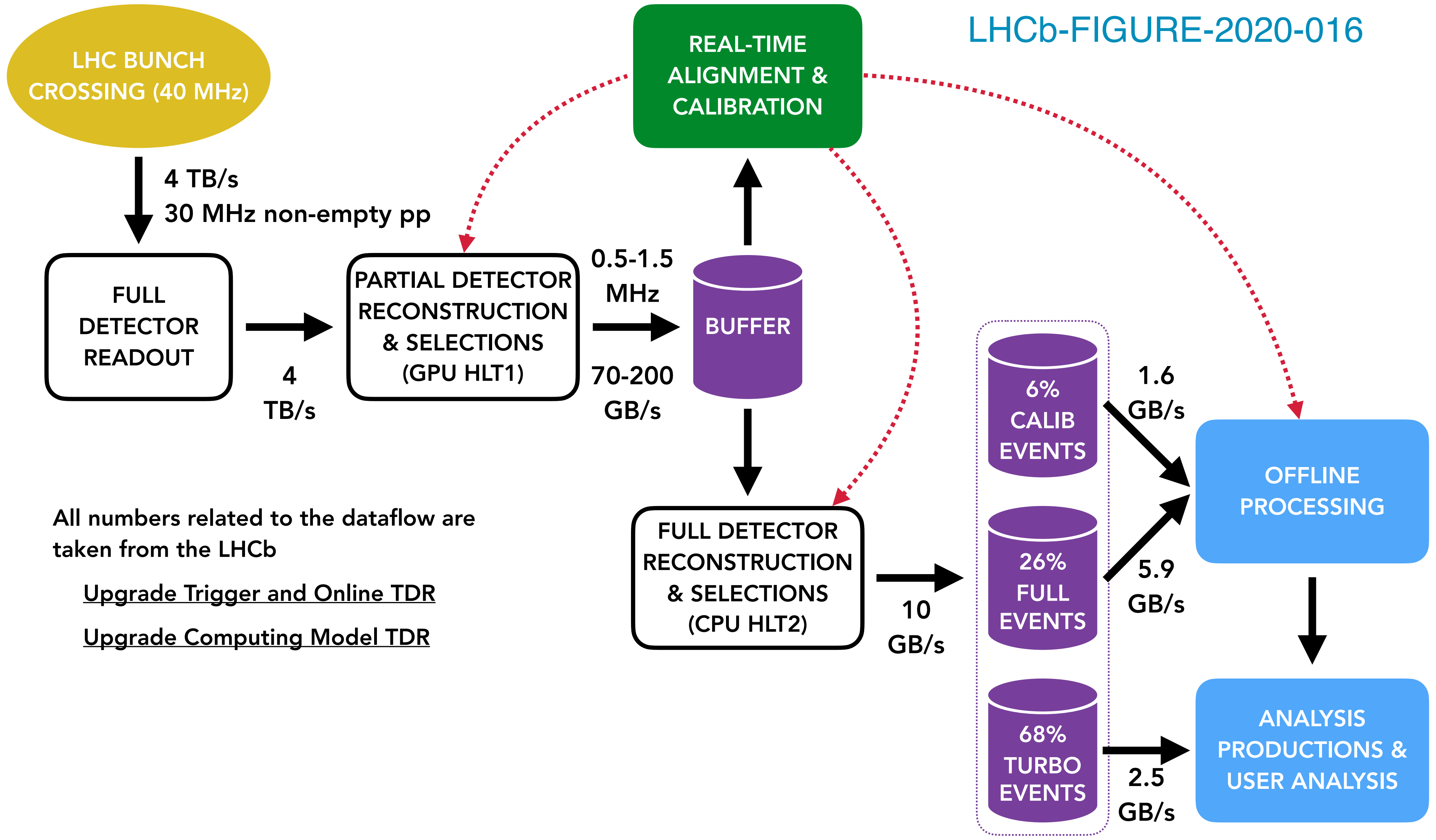
LHCb upgrades

LHCb-DP-2022-002



LHCb upgrades

- Upgrade to handle increased luminosity in Run 3 already active
- Highlights of Upgrade 1
    - Triggerless system (no L1 hardware trigger, only GPU/CPU event builder and high level trigger)
    - Real-time analysis: alignment and calibration applied at the HLT such that HLT objects are “offline” quality
    - Triggers must be highly analysis specific to reduce enormous background of events with loosely identified B hadrons
- CO_2 silicon microchannel cooling for the VELO which operates inside the beampipe (under vacuum) about 5 mm from the beamline



LHCb-FIGURE-2020-016

All numbers related to the dataflow are taken from the LHCb

Upgrade Trigger and Online TDR

Upgrade Computing Model TDR

LHCb-DP-2022-002