CMS
High Granularity
CALorimeter

Meeting the challenges of HL-LHC

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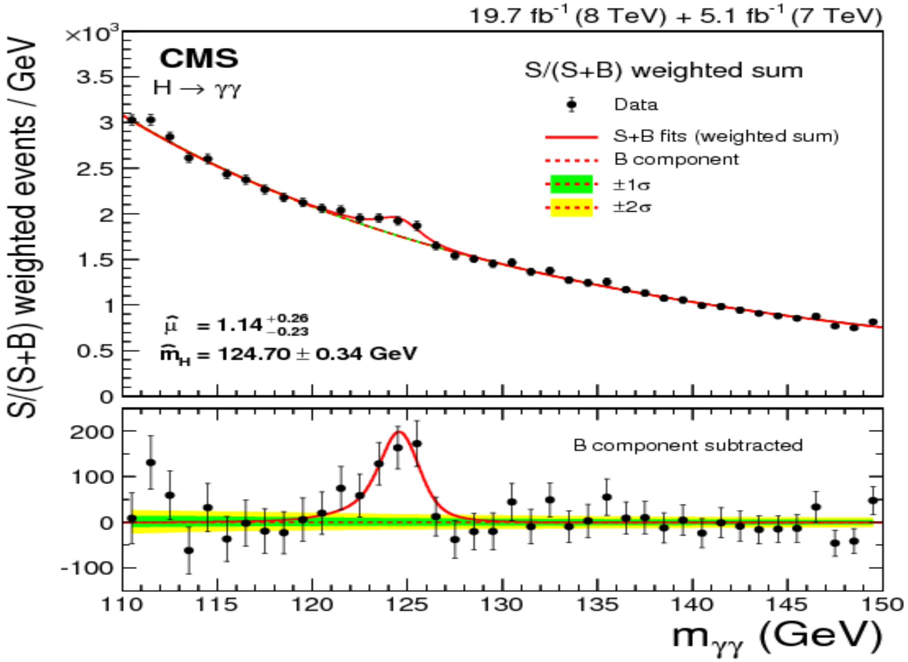
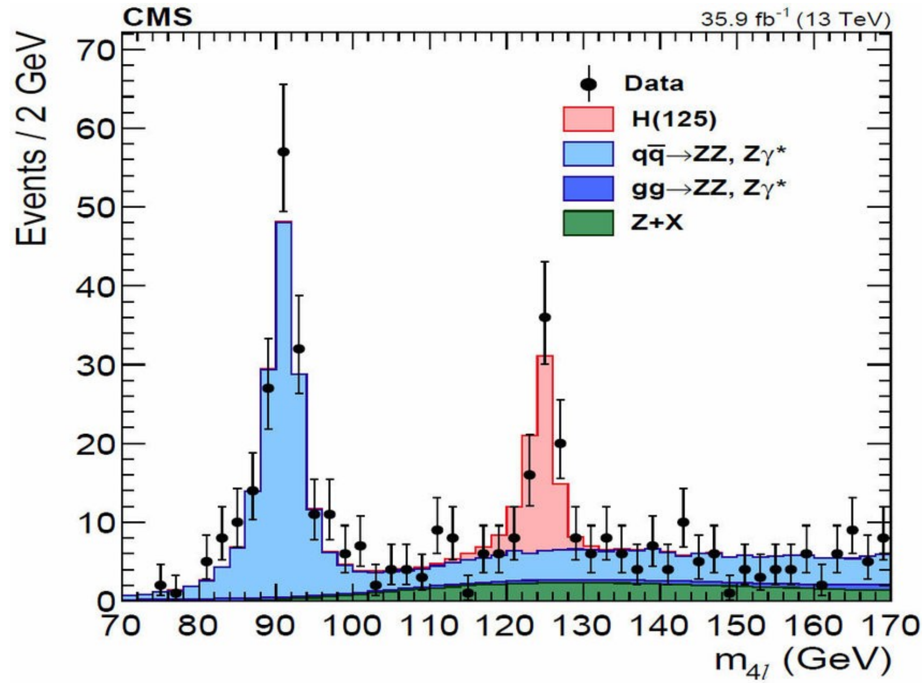
Outline

- *The stage for the High-Luminosity LHC*
  - *Challenges: Radiation & PU*
- *HGCAL:*
  - *From detectors to electronics*
  - *From data transmission to algorithm*
- *L1 triggering*
- *Timing*
- *Physics*

Why the High-Luminosity LHC ?

Higgs is so far the only major discovery @ LHC





Where are the other “leads” of LHC ?

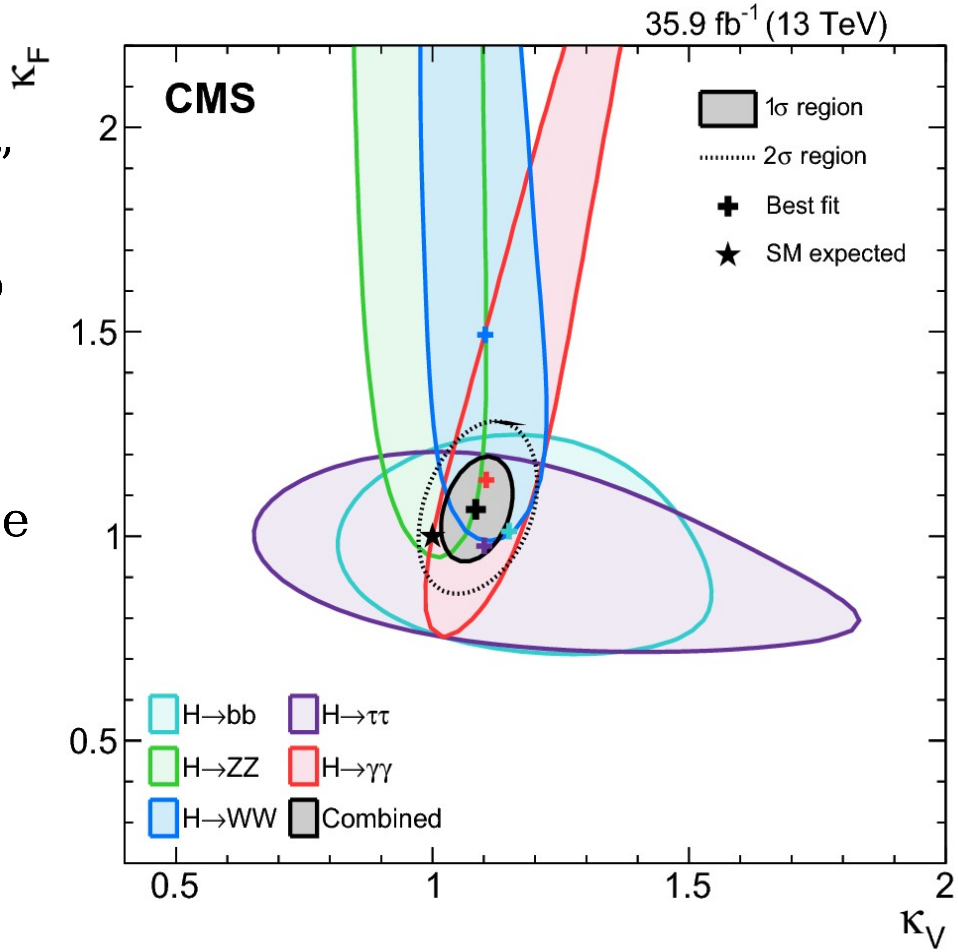
- Susy: so far the best cure to the hierarchy problem (of Higgs) in SM
  - So far not observed below ~1.5 TeV
- LeptoQuarks ?
- Universal Extra Dimensions ?
- Higher (Energy) Luminosity can shed light on mass regions sofar unexplored

Is Higgs a SM particle ?
Or does it belong to a bigger family of Higgs ?

In absence of direct observation of other Higgs bosons, the best "window" to answer the question is measuring the couplings of the observed Higgs to SM fermions/bosons

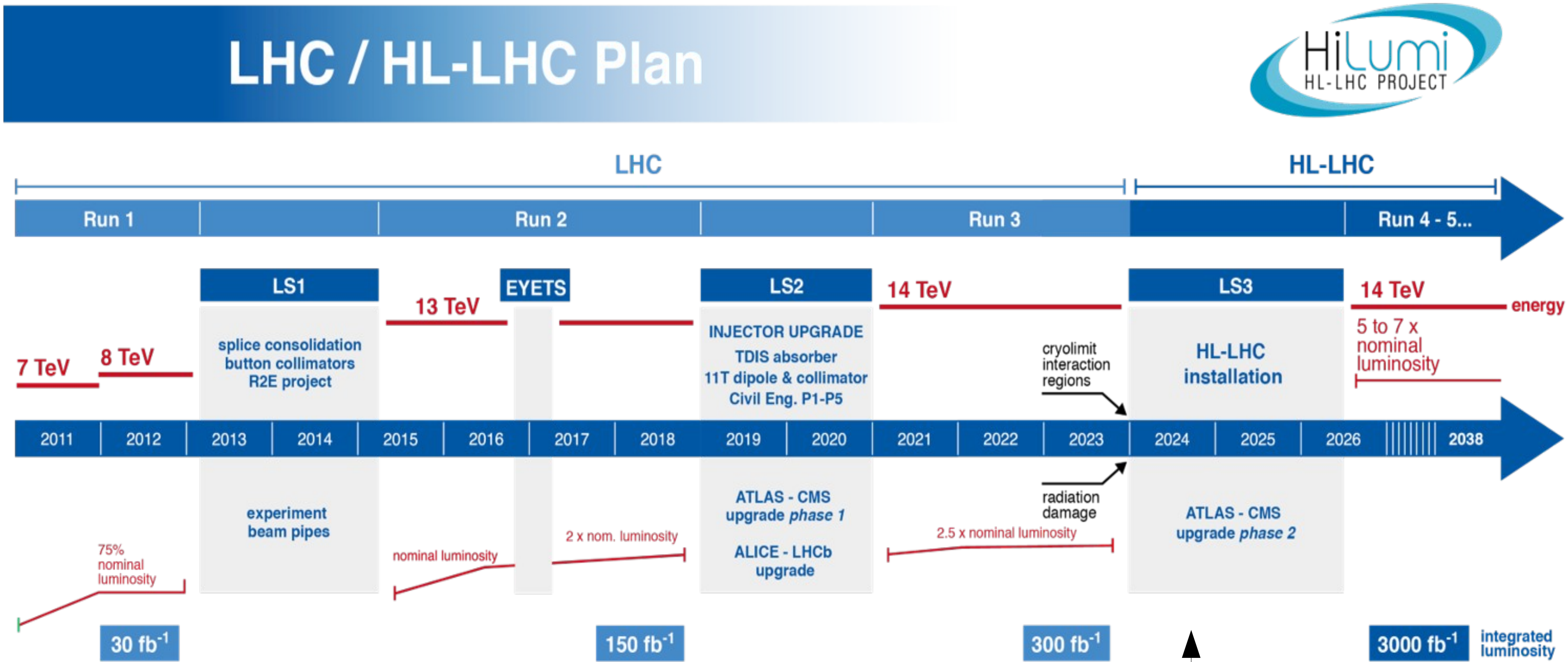
Given the collected data so far:
"I belong to standard model" seems the Higgs to say

→ We need serious amount of data to challenge predictions of the SM



HL-LHC will enable precision measurements & observation of rare processes (SM or BSM) below current sensitivity

High Luminosity / Upgrades / Challenges



<PU>~21 <PU>~27 <PU>~50 **<PU>~200**

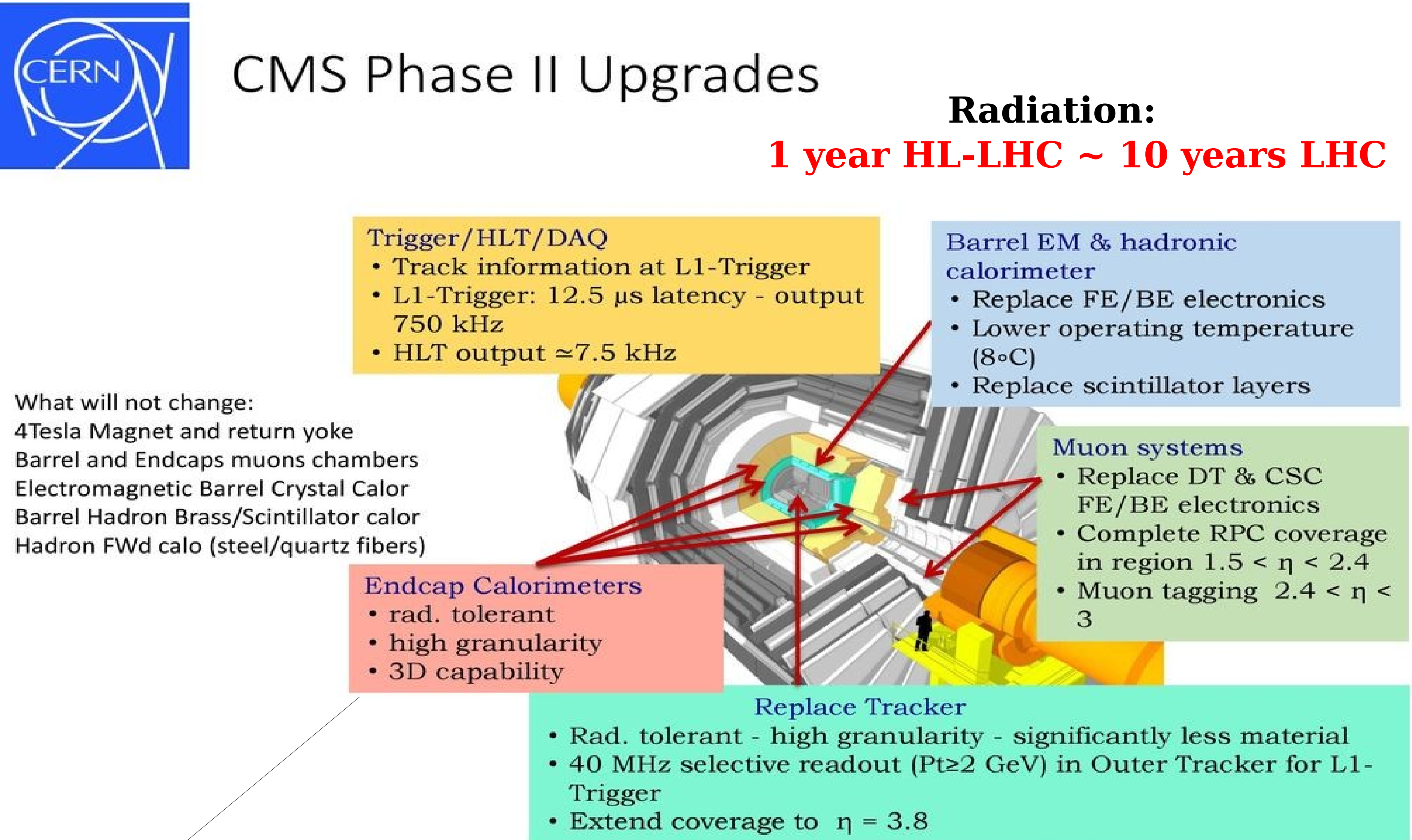
Peak Luminosity ~ 7.5×10^{34} $cm^{-2}s^{-1}$

High PU affects background rejection → need handle(s) to mitigate PU:
HGCAL

High Luminosity / Upgrades / Challenges

Radiation:

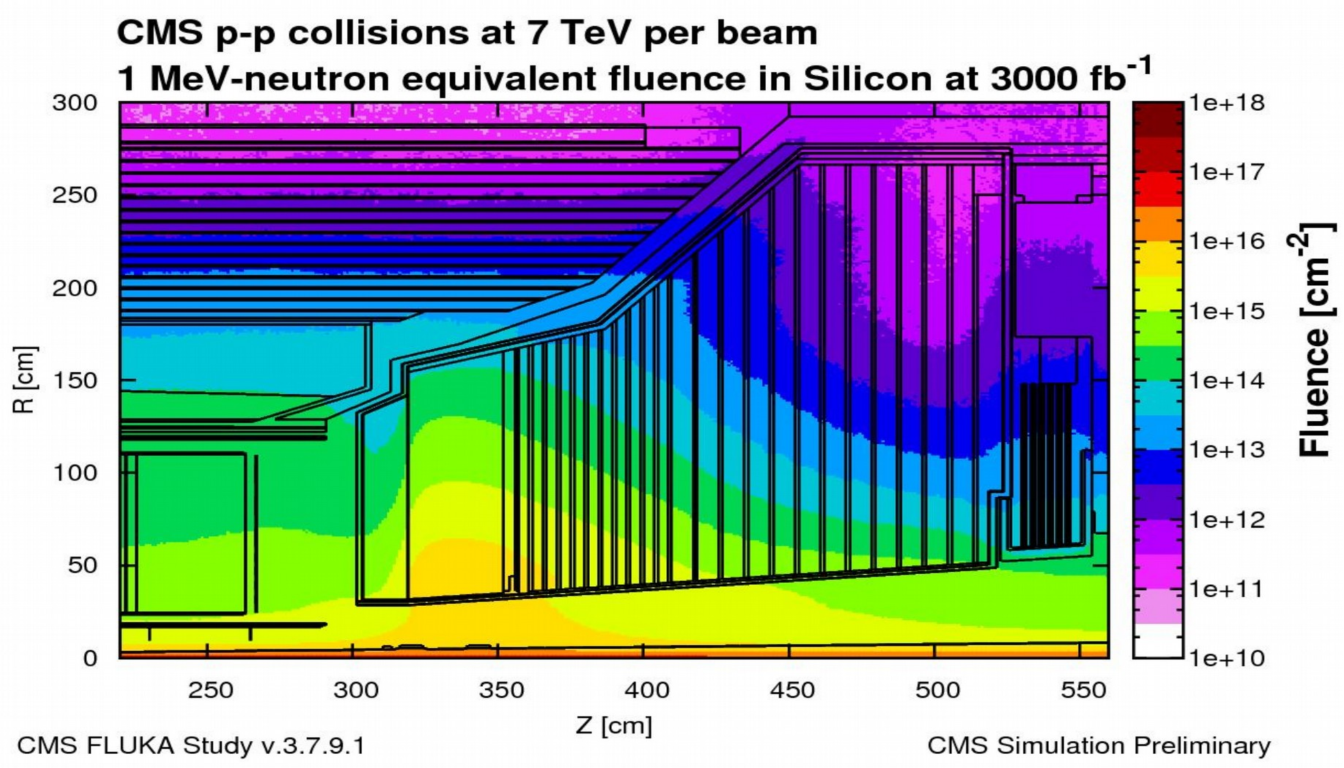
1 year HL-LHC ~ 10 years LHC



Endcap Calorimeter: Harsh radiation during HL-HLC
→ to be replaced by HGCAL

Radiation: challenge & solution

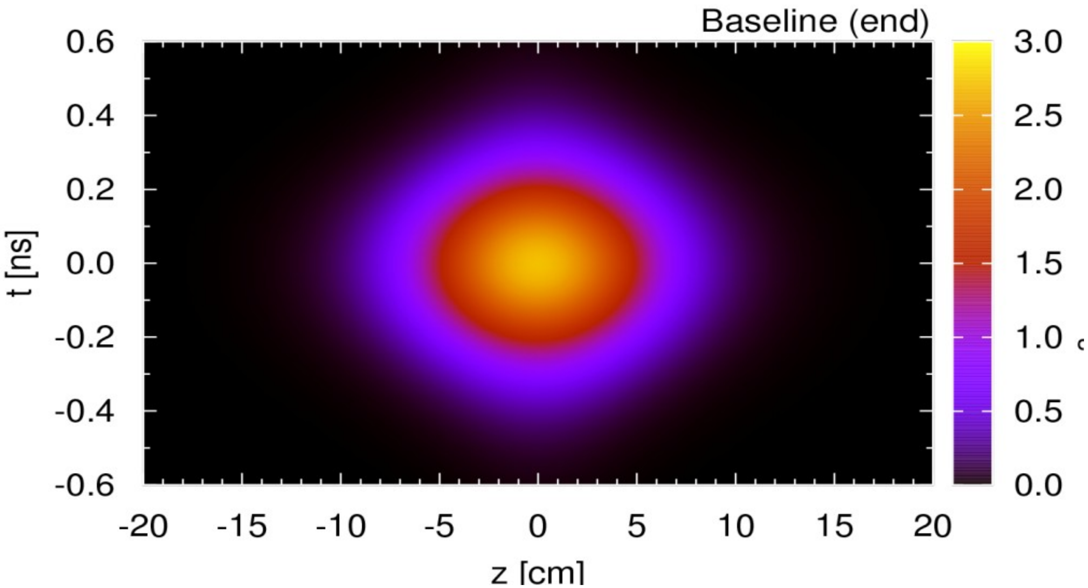
Present forward calorimeters: designed for an integrated luminosity of 500 fb^{-1}
→ Any replacement must have ability to withstand integrated radiation x10 higher than expected in original CMS design



Silicon sensors have adequate charge collection after submission to 1.5E16 neq/cm^2 (neq: number of 1 MeV equivalent neutrons), a fluence 50% higher than expected for an integrated luminosity of 3000 fb^{-1}

Pile-Up: profiles of a challenge

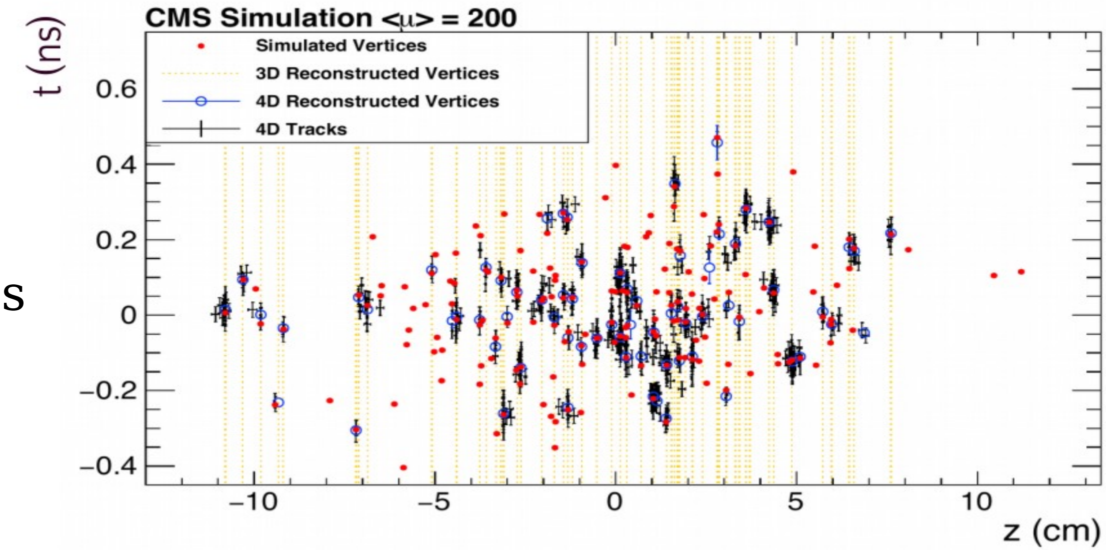
Space-time profile of the beam spot



- Interactions are spread over [100,200] ps

  Online selection ~ O(μs)

Space-time distribution of vertices



- Disentangle overlaping vertices with precise timing
  - Goal resolution: [20,30] ps

Profile of the aimed detector

- **Radiation tolerance:**
  - Fully preserve energy resolution after 3000 fb^{-1}
- **Fine lateral granularity:**
  - for low energy equivalent of electronics noise to give a high enough S/N to allow MIP calibration
  - help with shower separation & the observation of narrow jets
  - limit the region used for energy measurement: minimize inclusion of energy from PU particles
- **Fine longitudinal granularity:**
  - enable fine sampling of the longitudinal development of showers: provide good electromagnetic energy resolution (e.g. for $H \rightarrow \gamma\gamma$),
  - pattern recognition
  - discrimination against PU
- **Precision time measurement of high energy showers:**
  - precise timing from each cell with enough energy aids to reject energy from PU
- **Ability to contribute to the L1 trigger decision**

Is this asking too much ?

HGCAL: Overview

Electromagnetic part:

Active: Si sensors

Absorber: Cu/CuW/Pb

28 layers, 25 X_0, ~1.3 λ

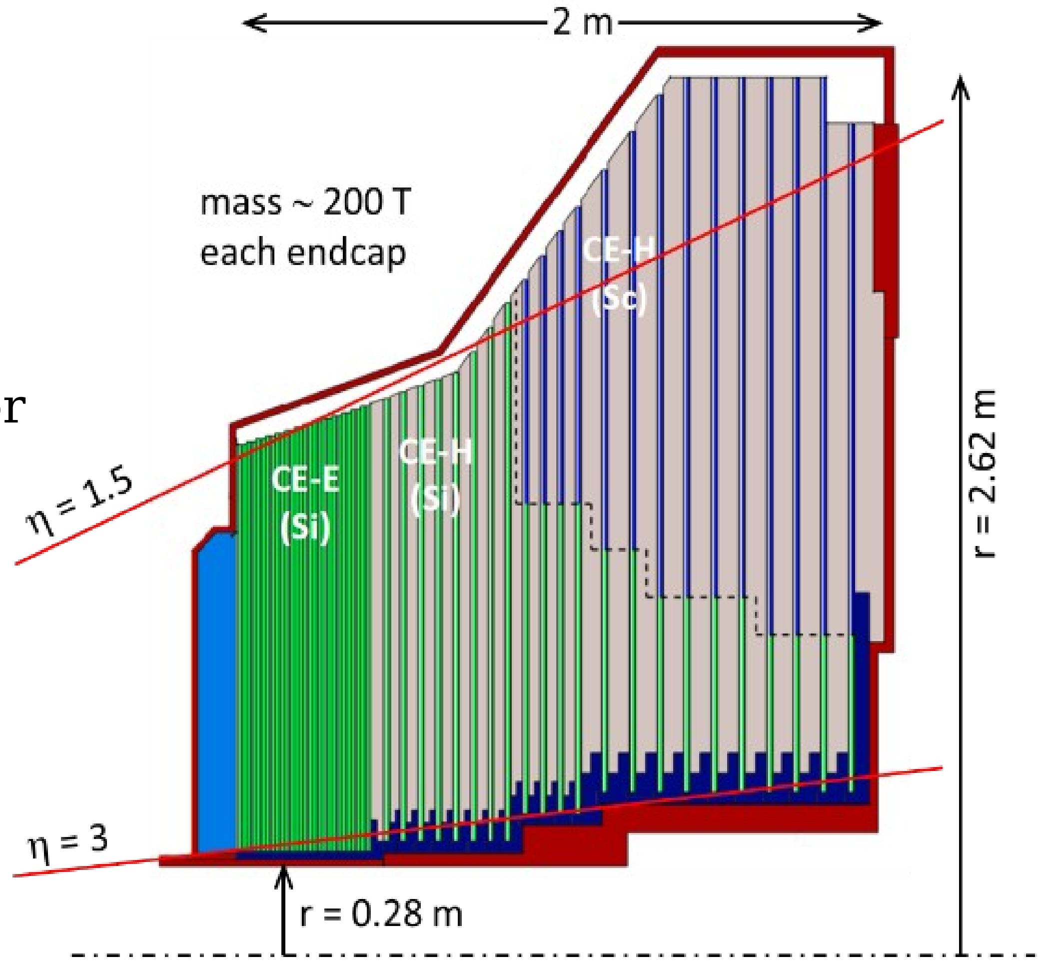
Hadronic part:

Active: $1.47<|\eta|<2.4$: Si-scintillator sensors (Sc)

$1.47<|\eta|<3$: Si sensors

Absorber: Steel

24 layers, ~7.2 λ

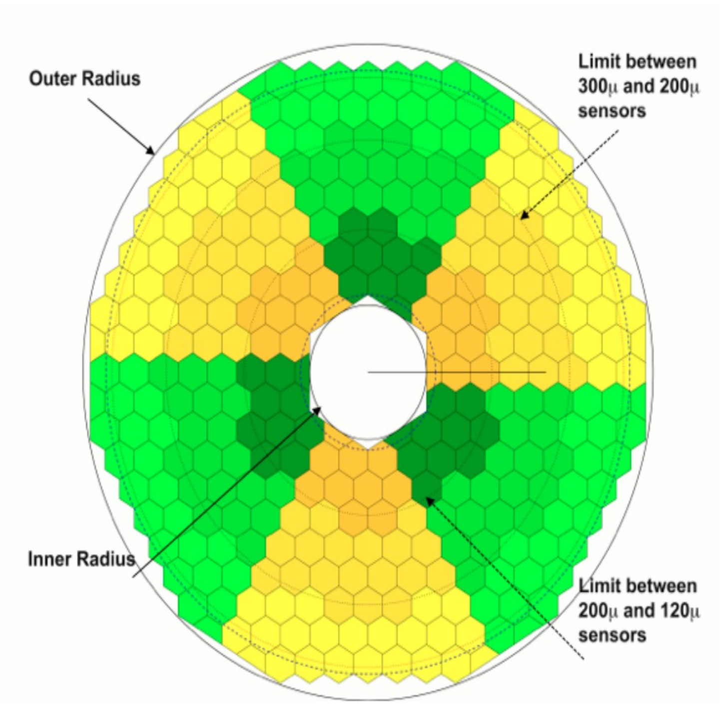


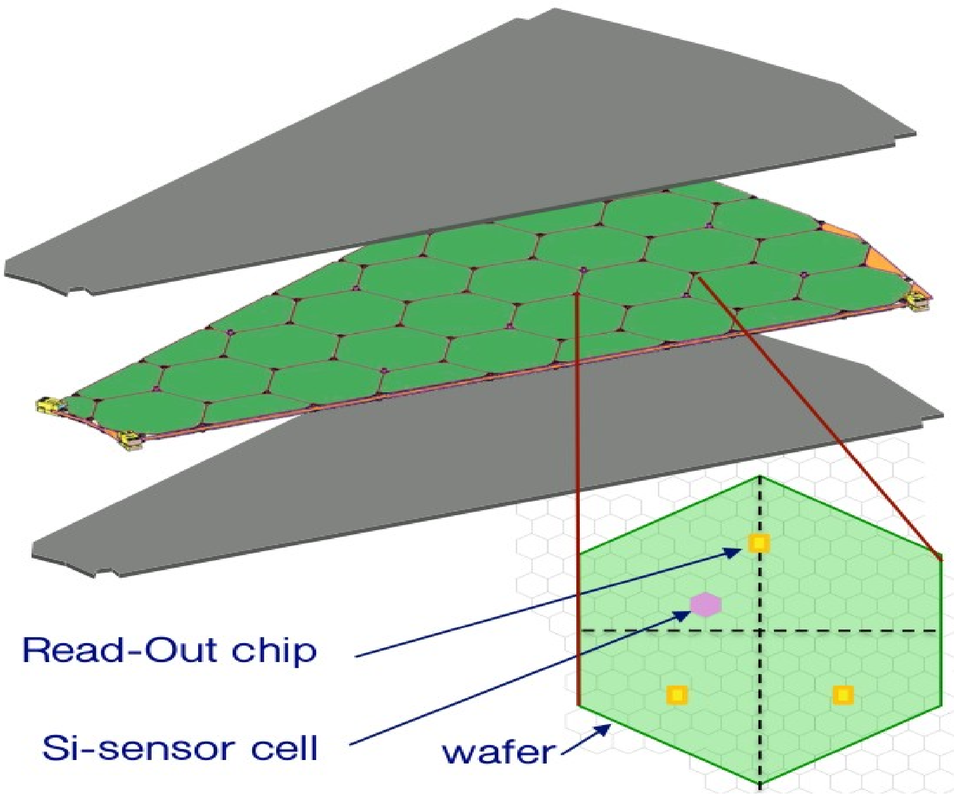
Main features:

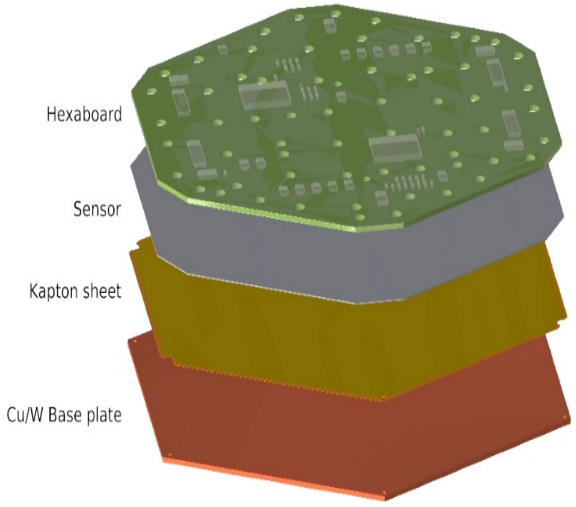
- $1.47 < |\eta| < 3$
- High radiation resistance
- Operation @ -30 C to limit Si leackage current & operate after radiation
- 6.1 M Si channels
- ~640 m^2 Si / ~370 m^2 Sc

HGCAL: detectors

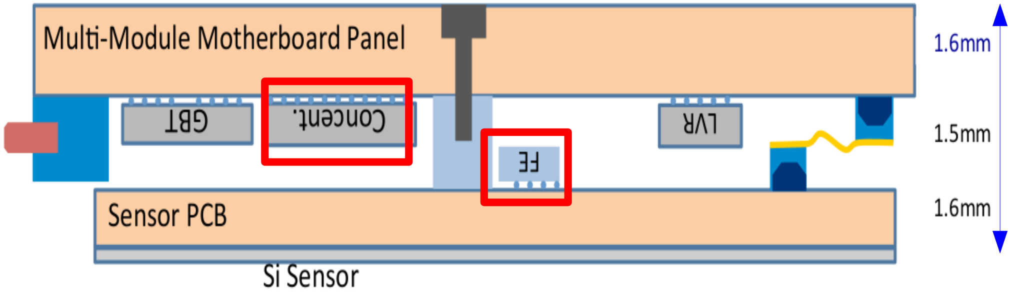
- Detection unit: hexagonal Si/Sc sensor cell
  - 3 thickness
- 1 hexagonal wafer: 192/432 cells 1/0.5 cm^2
  3/6 read-out chips
- Wafers assembeld in 30^o, 60^o cassettes
- Module = Wafer + PCB

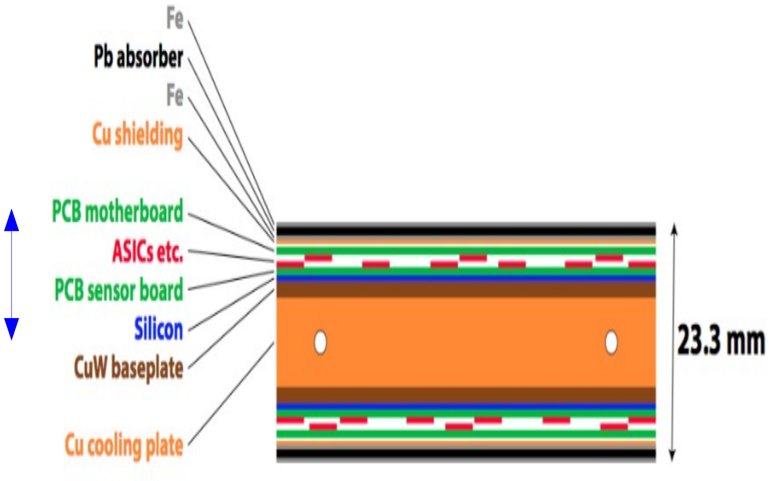


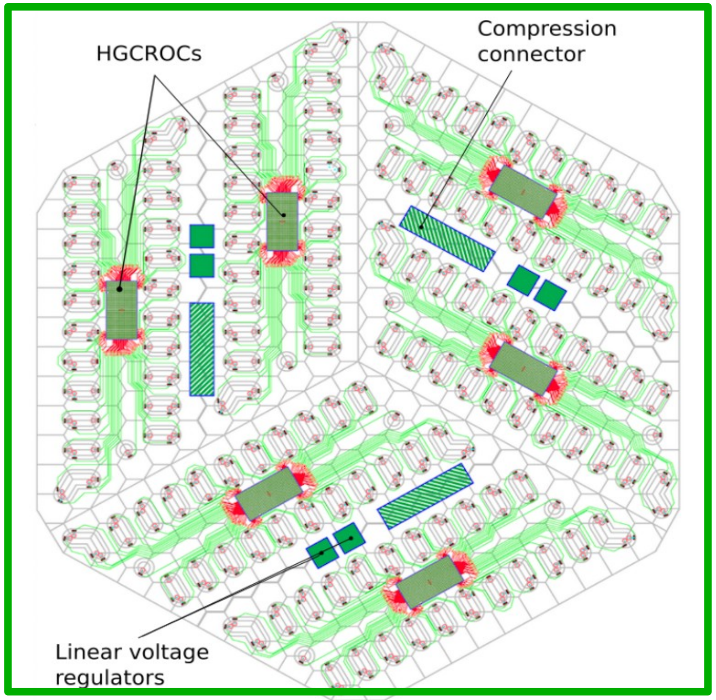




- PCB sensor: hexagonal, holding **FE ASICs**
- Mother-board: connecting 4 **modules**







Information's path in electronics:

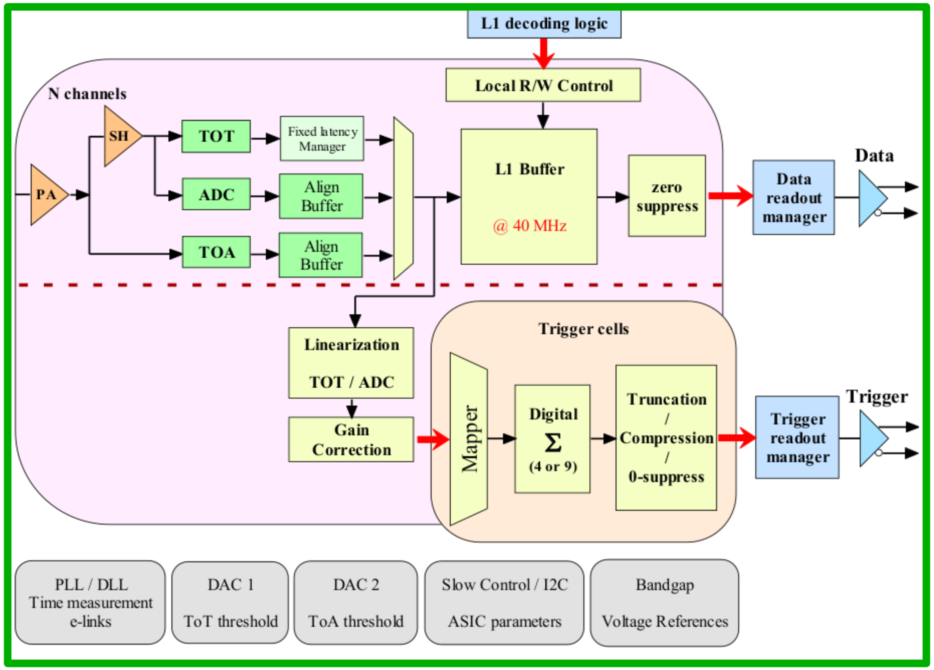
- Si/Sc → HGCROC:
  - Digitization of channels
- → PCB sensor → Connectors → Motherboard
- → Concentrator chip:
  - Conglomerates data from modules
  - 0 suppression
  - Formats → GigaBitTransiever → BE

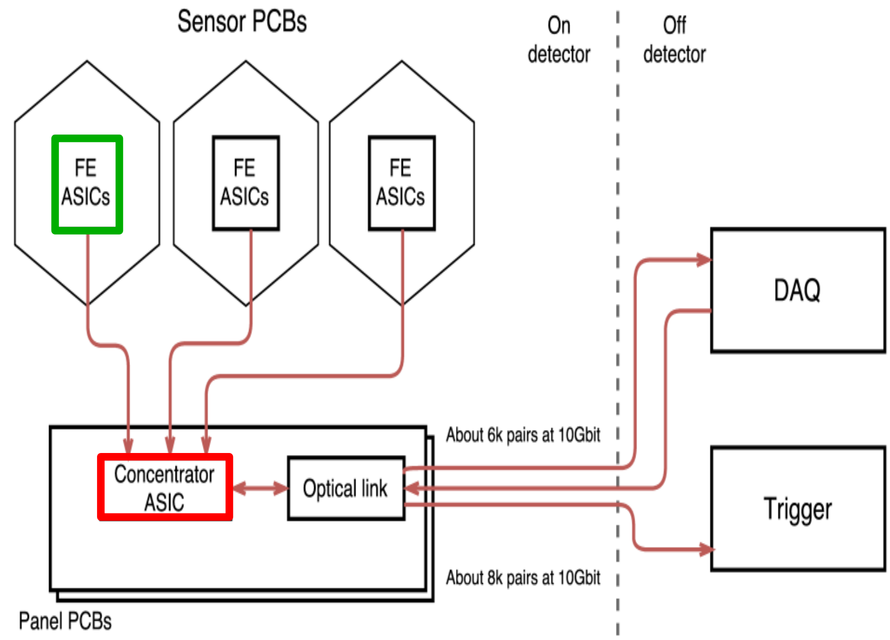
HGCAL: electronics & data transmission

Signal ∈ [MIP, O(TeV)]: ADC/TOT used for low/high signals

HGCROC:

- Digital sum of E(cell) in Trigger-Cell
- E(TC) truncation & compression





Concentrator:

- Reception, selection and transmission of trigger & data
- Transmits TCs & Global Sum

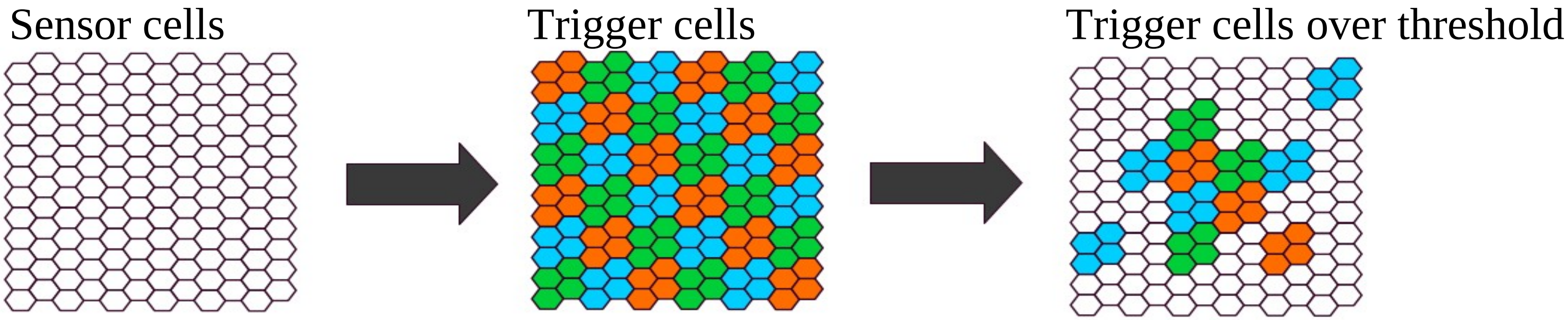
LpGBT links: ~16k links for 25k modules:
8k links for:

- Trigger
- Full resolution data (DAQ)

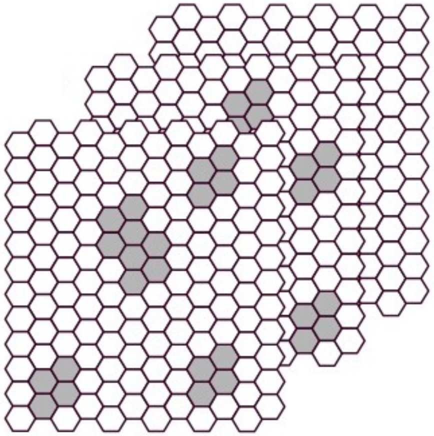
HGCAL: data transmission & algorithm

First online data reduction:

- HGCAL cells grouped together 4:1, re-linearized across ADC & TOT readouts
- Summed "trigger" cells sorted. Only the most energetic cells sent for BE processing

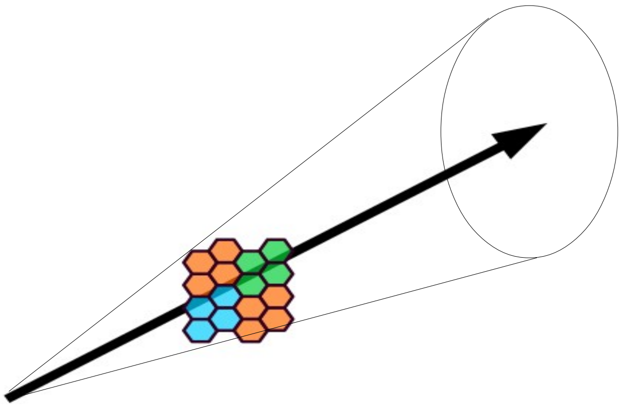


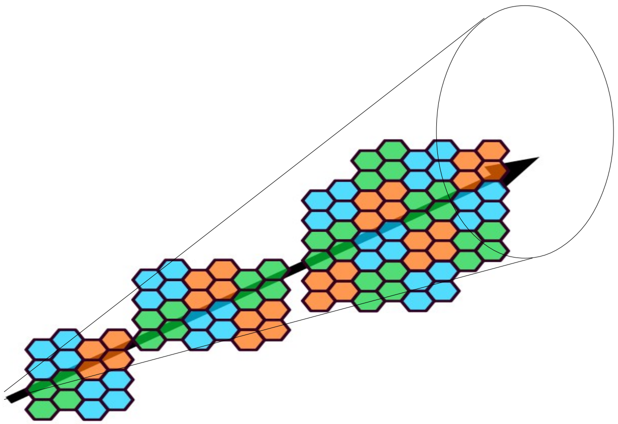
- First "shot" to mitigate PU:
  - Simplest way: count N(cells) above a threshold
  - Longitudinal segmentation allows for an efficient estimate using only the first layers, dominated by PU
- Get Clustering & Isolation thresholds, Energy corrections



HGCAL: cluster algorithm

- Seeding & direction finding
- Clustering around a direction across longitudinal planes
  - Smoothing of hits / detector plane
  - Maximum finding (different approaches)
  - Cone algorithm: associate all (hit) maximums within a cone whose size can be tuned. Association can be based on:
    - Distance between hits
    - Energy of hits

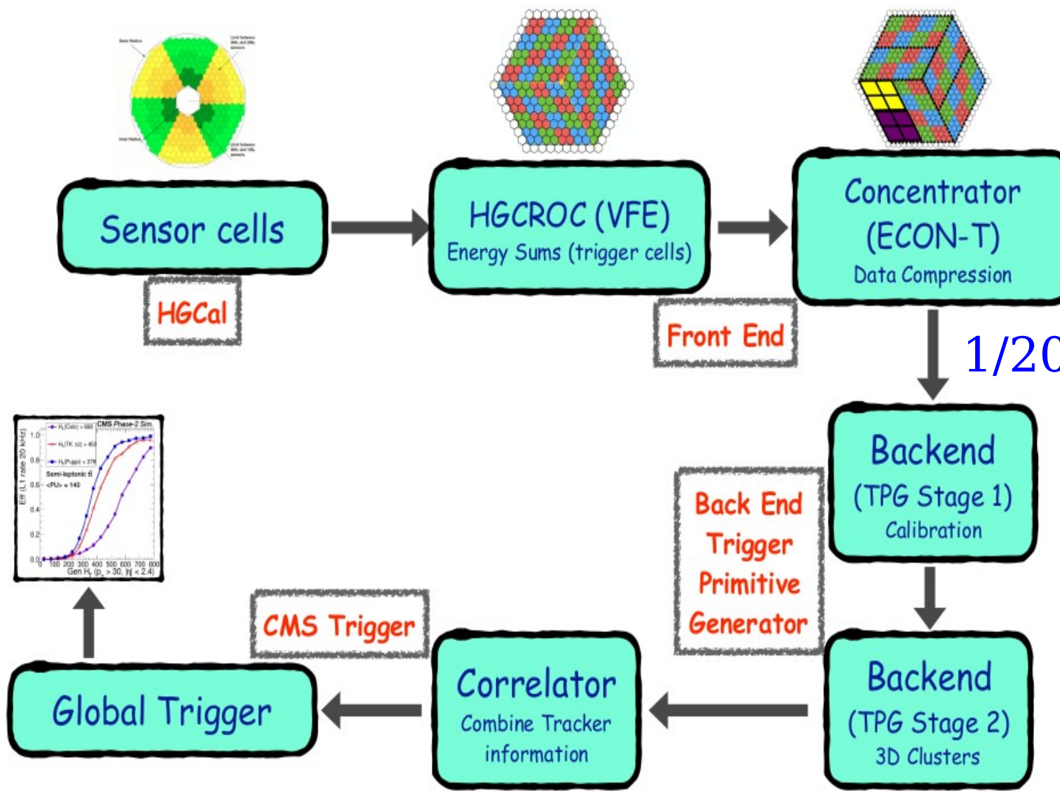




- With 3D information:
  - EM / HAD clusters
  - Isolation

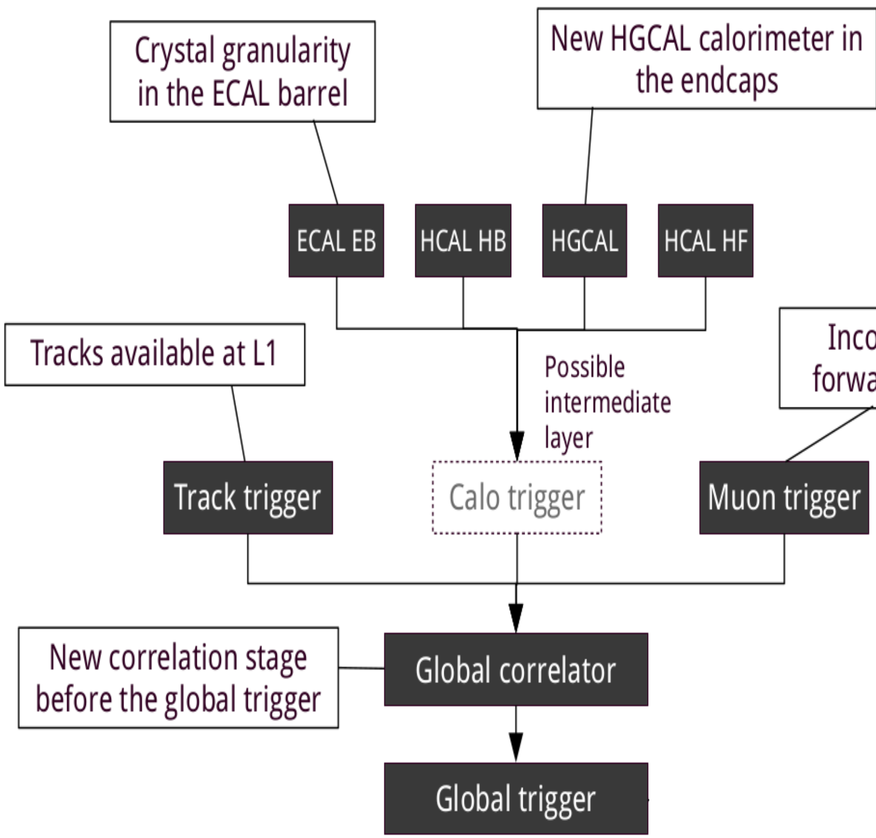
Trigger: processing done both on- & off-detector

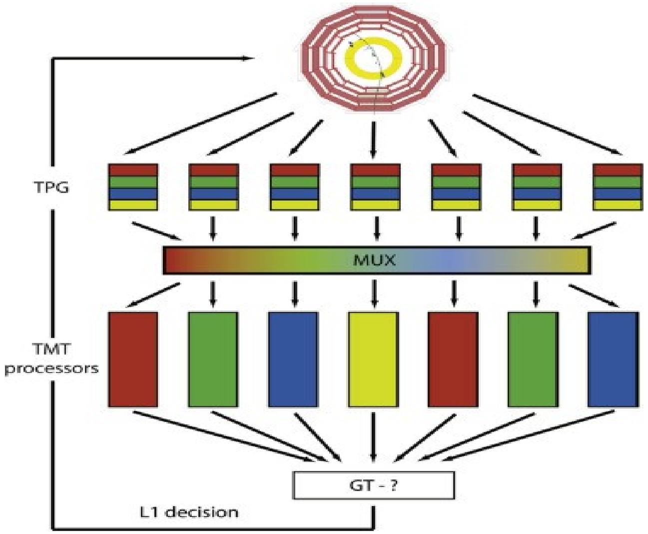
- On detector: Data needs to:
  - Be reduced to 40 MHz to be sent off-detector
  - Kept simple for reducing power consumption & maximizing flexibility
- Off detector in FPGAs:
  - Clustering, PU estimation, ...
  - Can be done in several processing layers
  - Time multiplexing in trigger architecture
- Trigger primitives sent to L1:
  - 3D clusters (position, energy, topological variables)
  - projective energy map to evaluate unclustered energy



Trigger: picture @ HL-LHC

- **Maximum L1 rate: O(100kHz) → O(1MHz)**
- Fixed latency: 4 μs → 12.5 μs
- {Time-multiplexing} & {Track info} & {latest FPGA} & {fast optical links} → PF possible @ L1





Classical data-flow: each FPGA collects data from all bunch-crossings
MUX: each FPGA collects data from the same bunch crossing & an entire region of the detector (120° sector)
→ Reduces the intra-FPGA data sharing hence bandwidth. Concentrates data

Timing

Silicon sensors: intrinsically fast response time + Design of the FE (ToA)
→ Each cell with enough energy can give a precise time stamp

Threshold (ToA)=12 fC

$$\sigma_t = \sigma_{\text{jitter}} \oplus \sigma_{\text{floor}}$$

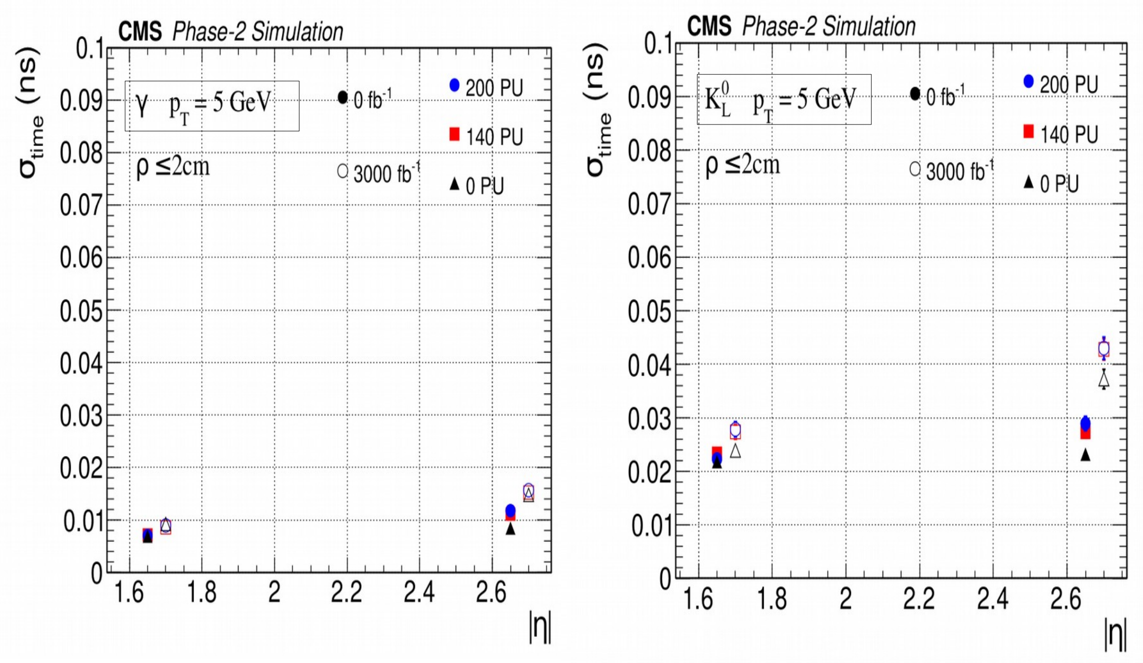
$$\sigma_{\text{jitter}} = \frac{A}{(S/N)}$$

σ_t(single cell) ∈ [20,150] ps ↔ O(100 ps) of single bunch-crossing

Multiple cells measurement lowers σ_t

Time measurement: require ≥ 3 cells within radius ρ of shower axis, each with an energy deposit of > 12 fC

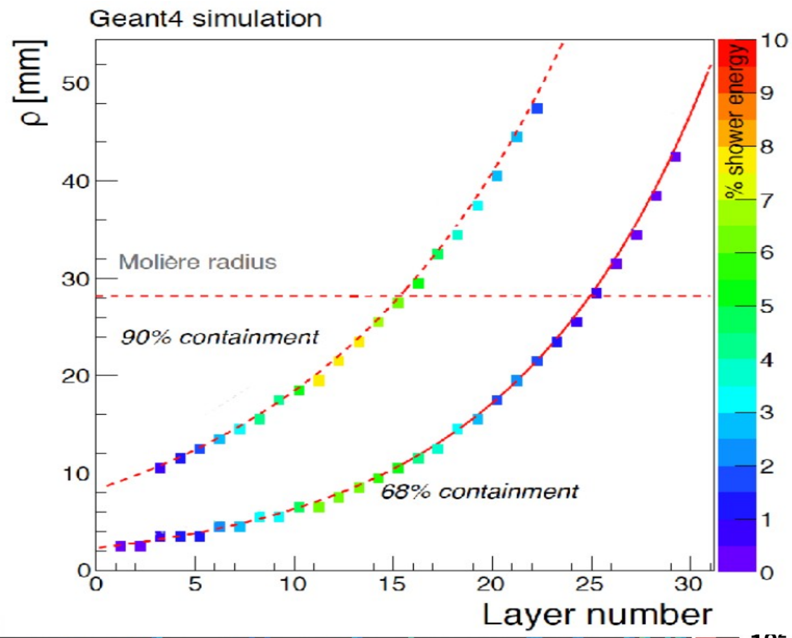
Achievable resolution on the ToA expected from the specification of the sensors, FE, & the clock distribution: A=5 ns σ_{floor}=20 ps



Timing & granularity: PU rejection

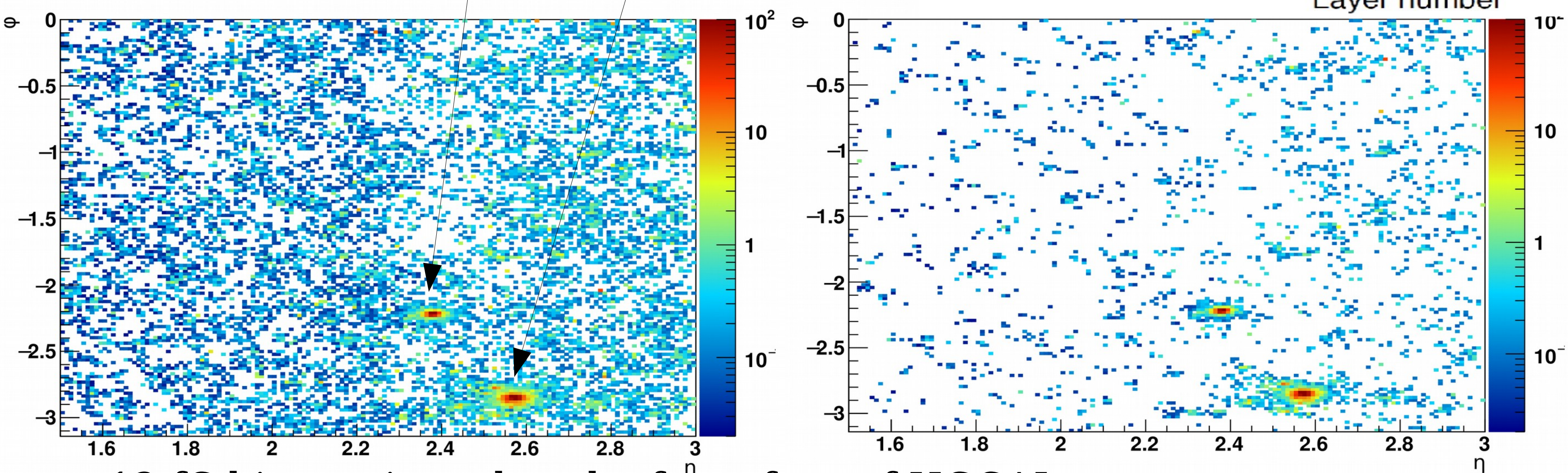
Cell size [0.5,1.] cm^2 imposed by:

- Physics performance
  (lateral spread of EM showers)
- Keeping cell capacitance manageable (<65 pF)



Timing + Granularity : 5D detector

VBF H → γγ event: γ / VBF jet

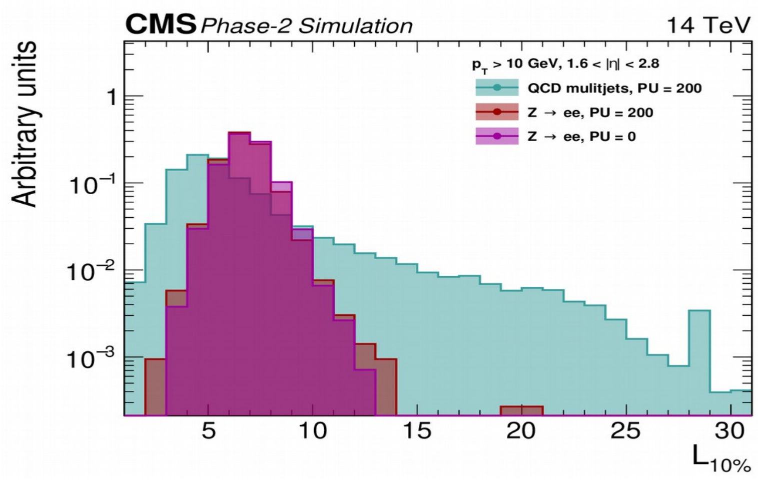


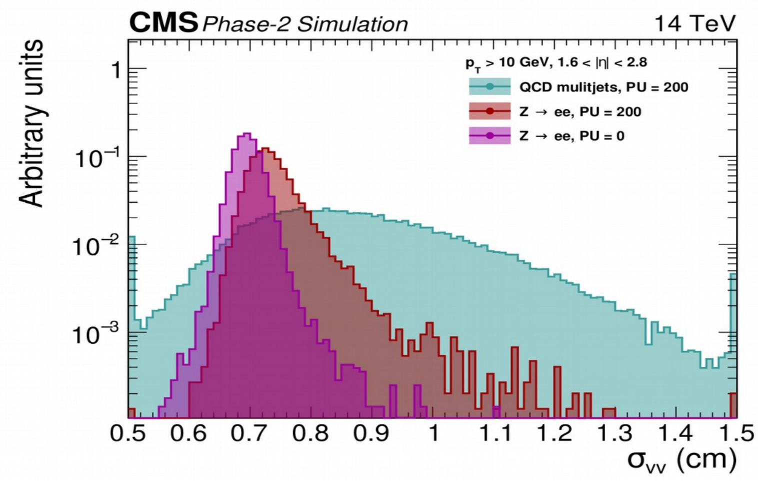
<u>> 12 fC hits</u> projected to the front face of HGCAL:

No time requirement |Δt| > 90 ps

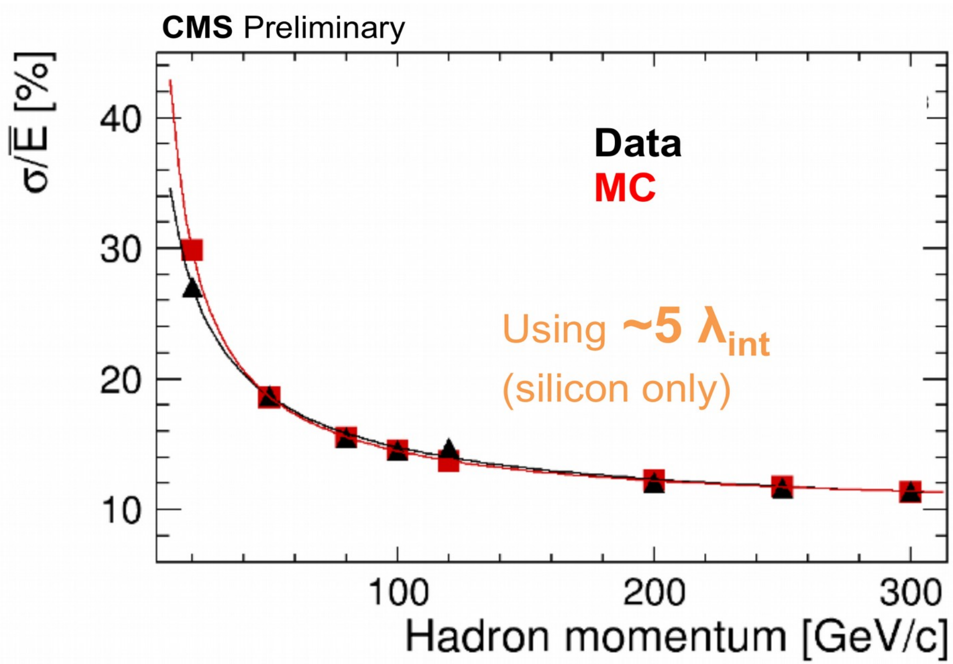
Physics: Object reconstruction

Shower shape variables to disentangle hadronic & electromagnetic jets

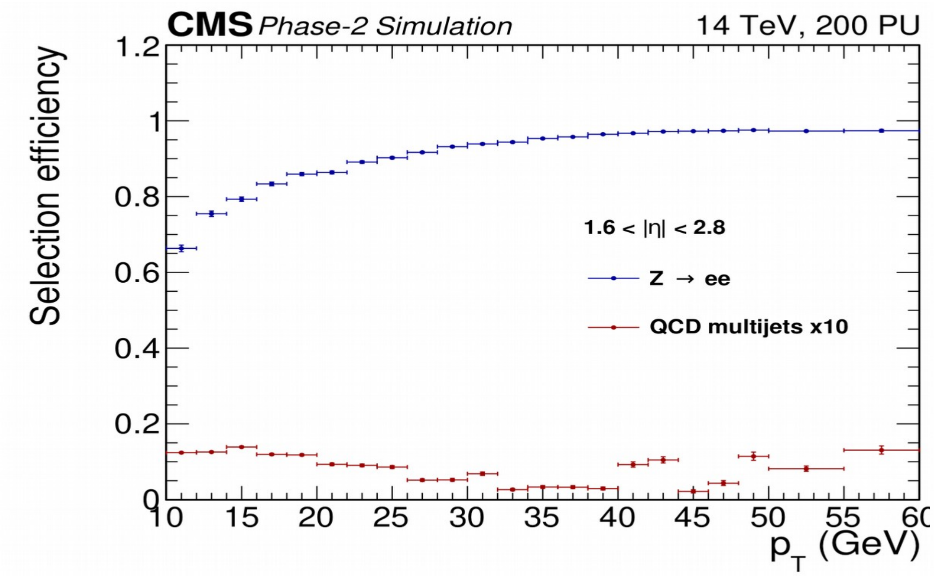


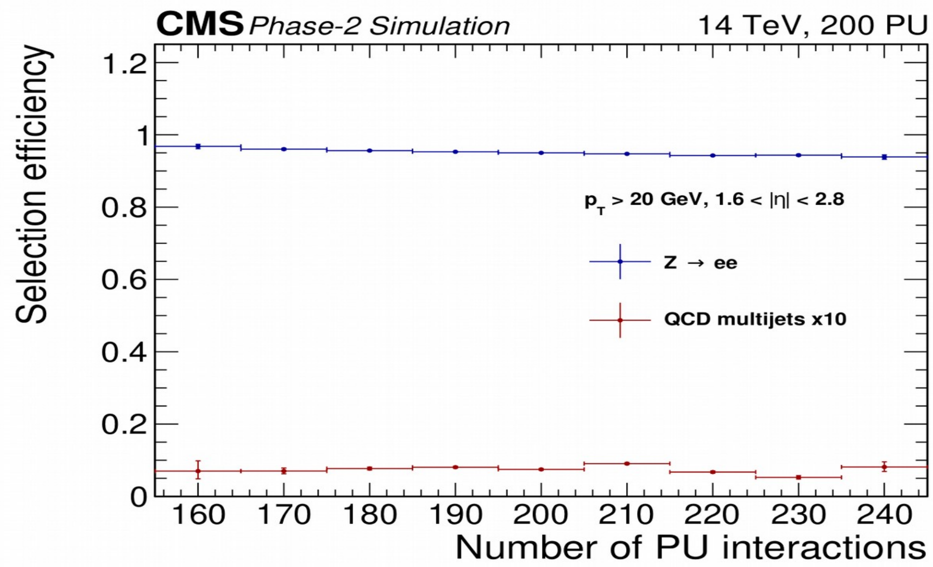


Energy resolution: Jets

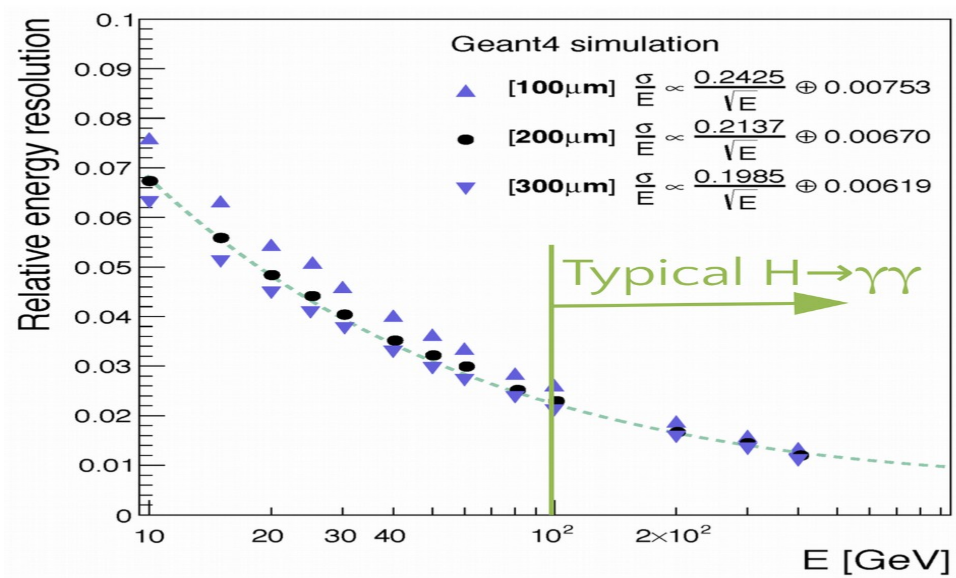


Physics: Object reconstruction





Energy resolution: Photon

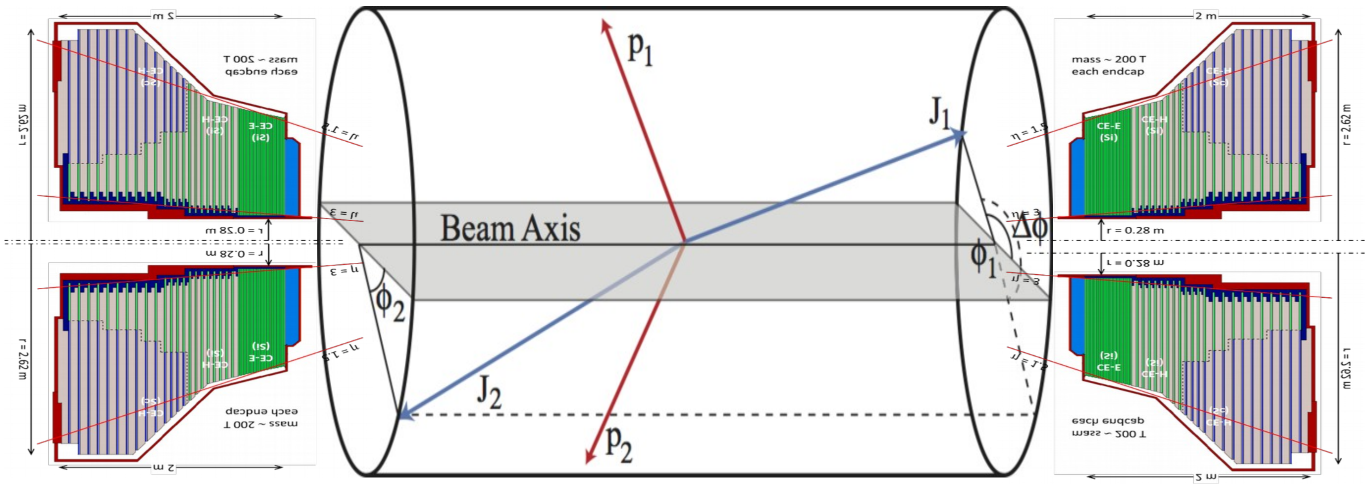


- Efficiency(e) > 95% for p_T>30
- Efficiency(e) suffers minor deterioration with PU
- Resolution(γ)<3% for p_T>100

Physics

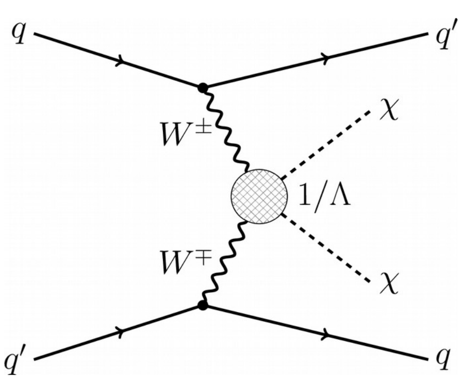
Boosted objects giving narrow (e.g. $\tau \rightarrow$ hadrons) or merged jets (e.g. from hadronic decays of W/Z)

By definition of the detector: Vector Boson Fusion (VBF) is the production process of predilection

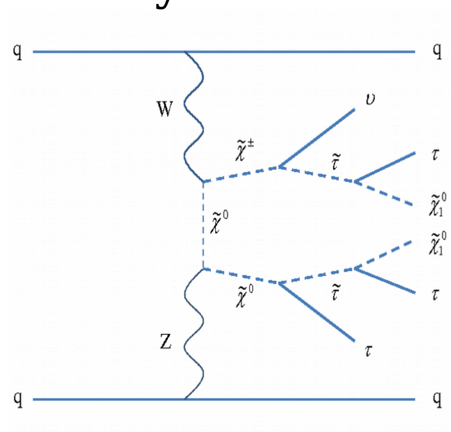


<u>Gateway to many different physics</u>:

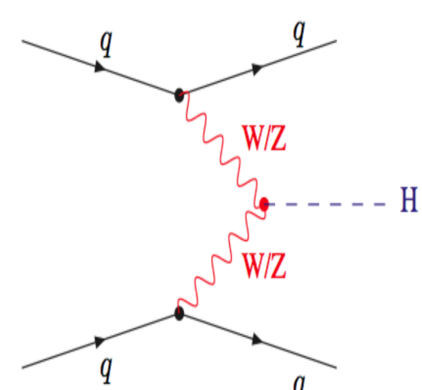
Whatever beyond



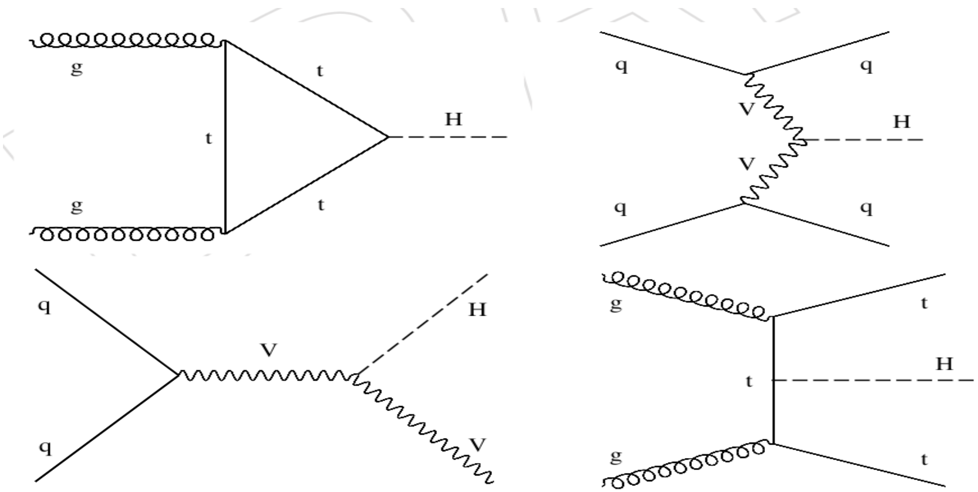
Susy

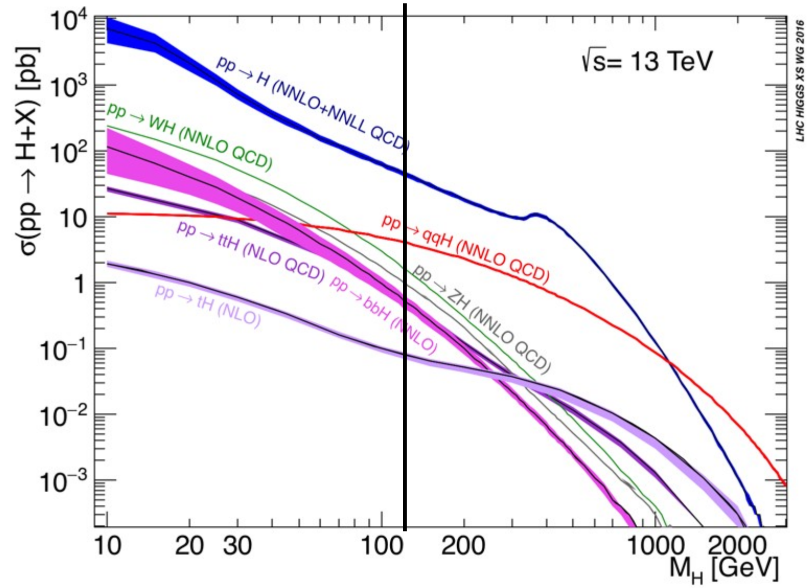


Higgs: VBF



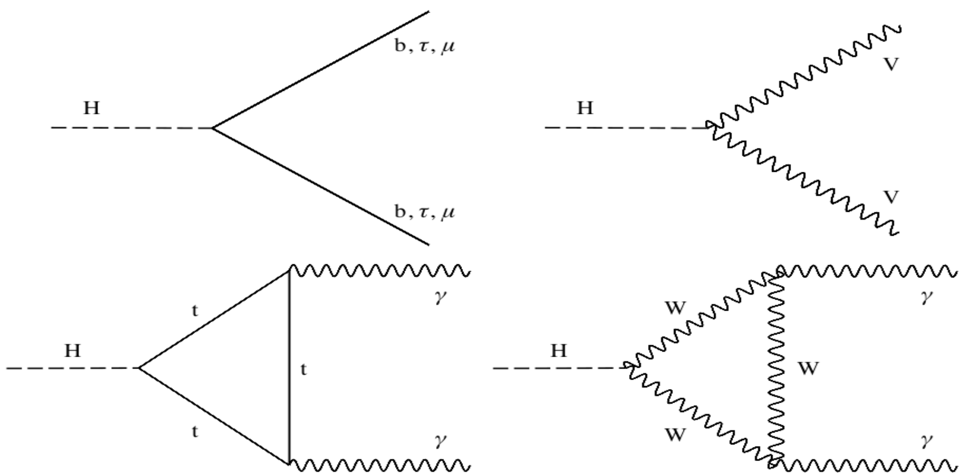
Physics: Higgs - VBF





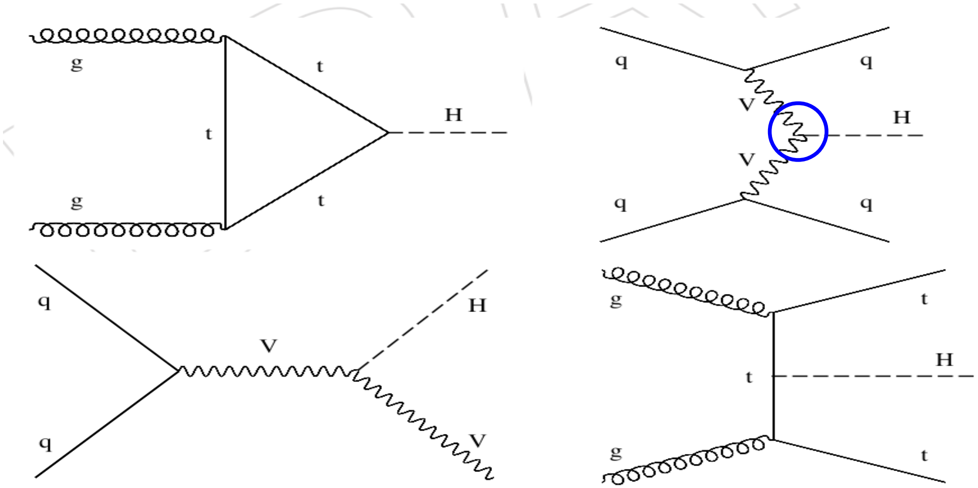
VBF:

- 2^{nd} most profuse source of Higgs production
- While cleaner than ggH: 2 extra jets in forward region (HGCAL)
- → Will be a privileged window to measure Higgs properties @ HL-LHC



- Like any other production mode: gateway to Higgs decays to different fermions & bosons

Physics: Higgs - VBF



Formalism to measure deviations of Higgs from the SM:

$$\kappa_x = \sigma_x(\text{measure}) \;/\; \sigma_x(\text{SM})$$

VBF:
Window to measure Higgs coupling to:

- W and Z boson
- And any fermion (or boson again) in the Higgs decay

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(\text{ggH})$	✓	b − t	κ_g^2	$1.04 \cdot \kappa_t^2 + 0.002 \cdot \kappa_b^2 - 0.038 \cdot \kappa_t\kappa_b$
$\sigma(\text{VBF})$	−	−		$0.73 \cdot \kappa_W^2 + 0.27 \cdot \kappa_Z^2$
$\sigma(\text{WH})$	−	−		κ_W^2
$\sigma(\text{qq/qg} \to \text{ZH})$	−	−		κ_Z^2
$\sigma(\text{gg} \to \text{ZH})$	✓	Z − t		$2.46 \cdot \kappa_Z^2 + 0.47 \cdot \kappa_t^2 - 1.94 \cdot \kappa_Z\kappa_t$
$\sigma(\text{ttH})$	−	−		κ_t^2
$\sigma(\text{gb} \to \text{WtH})$	−	W − t		$2.91 \cdot \kappa_t^2 + 2.40 \cdot \kappa_W^2 - 4.22 \cdot \kappa_t\kappa_W$
$\sigma(\text{qb} \to \text{tHq})$	−	W − t		$2.63 \cdot \kappa_t^2 + 3.58 \cdot \kappa_W^2 - 5.21 \cdot \kappa_t\kappa_W$
$\sigma(\text{bbH})$	−	−		κ_b^2
Partial decay width				
Γ^{ZZ}	−	−		κ_Z^2
Γ^{WW}	−	−		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	W − t	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.67 \cdot \kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	−	−		κ_τ^2
Γ^{bb}	−	−		κ_b^2
$\Gamma^{\mu\mu}$	−	−		κ_μ^2
Total width for $\text{BR}_{\text{BSM}} = 0$				
Γ_H	✓	−	κ_H^2	$0.58 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.08 \cdot \kappa_g^2 +$ $+ 0.06 \cdot \kappa_\tau^2 + 0.026 \cdot \kappa_Z^2 + 0.029 \cdot \kappa_c^2 +$ $+ 0.0023 \cdot \kappa_\gamma^2 + 0.0015 \cdot \kappa_{Z\gamma}^2 +$ $+ 0.00025 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

Conclusions

High Granularity CALorimeter for HL-LHC:

- Radiation-hardness: Meets exigencies – Si-based
- Timing: Projected resolution better than 50 ps for large variety of particles
- Timing + High Granularity: Will help to mitigate the PU
- Will naturally be part of the new L1 trigger stage
- Physics: Will be great for Higgs coupling measurement with very high precision: 3000 fb^{-1} with HL-LHC

Directions of work: Many !
Here are some in the Trigger Primitive Group:

- 3D clustering algorithm
  - ML approaches ?
- Jet / Electron / Gamma / Tau identification
  - Electron is based on BDT
- VBF jets ↔ PU jet separation (BDT)

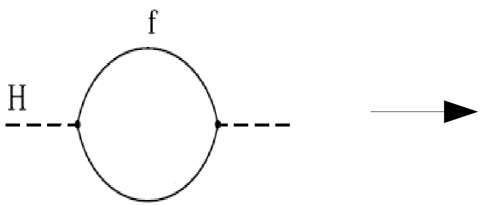
Backup

SUperSYmmetry: Natural cure of Hierarchy problem

- **Greatest discovery in HEP in last decades:**

  Higgs boson: m_H = 125 GeV/c^2

- **Consider Higgs mass correction from fermionic loop:**



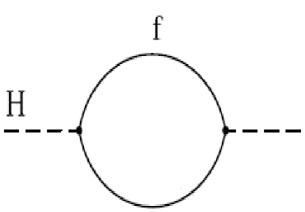
$$\Delta m_H^2 = \frac{\lambda_f^2}{16\pi^2}\cdot\left[-2\Lambda_{UV}^2 + ...\right]$$

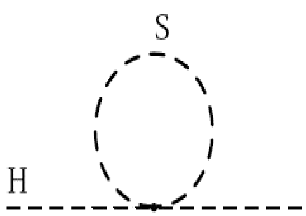
Λ_{UV}: Energy-scale at which new physics alters the Standard-Model (momentum cut-off regulating the loop-integral)

If Λ_{UV} ~ M_P → Δm^2_H ~ $O(10^{30})$ larger than m_H !!!

And all Standard-Model masses indirectly sensitive to Λ_{UV} !!!

$$\Delta m_H^2 = \frac{\lambda_f^2}{16\pi^2}\cdot\left[-2\Lambda_{UV}^2 + ...\right]$$





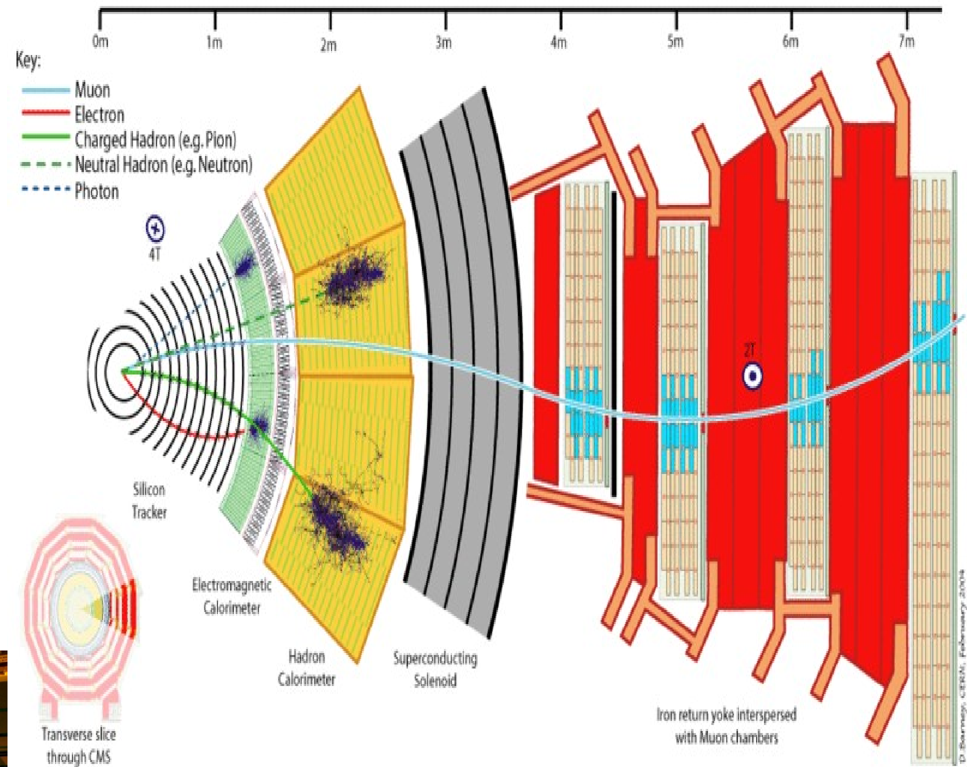
$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\cdot\left[\Lambda_{UV}^2 - ...\right]$$

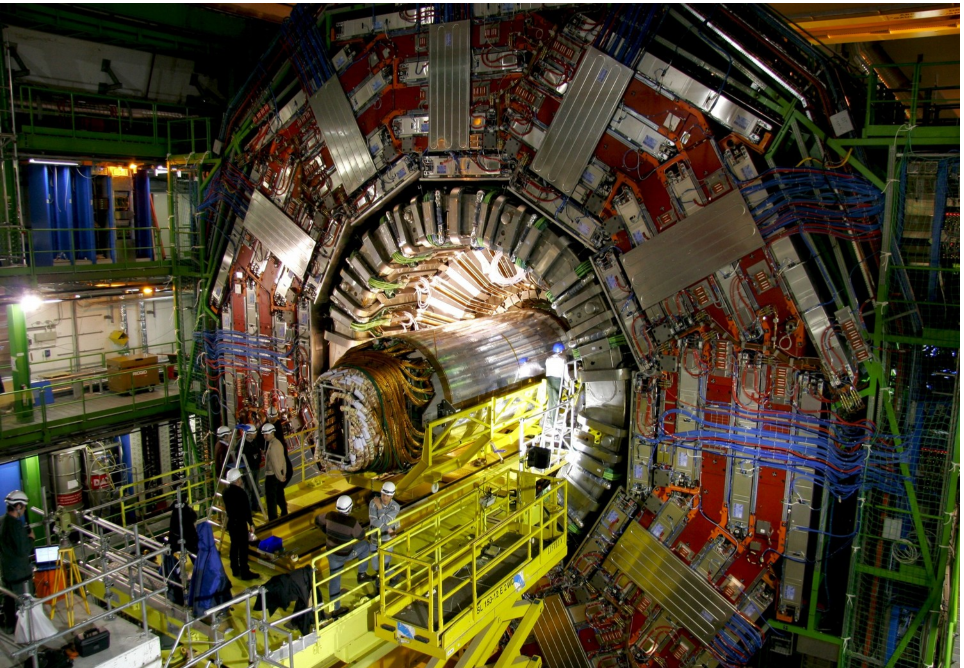
Δm^2_H quadratic divergence canceled :

Hierarchy problem naturally solved !

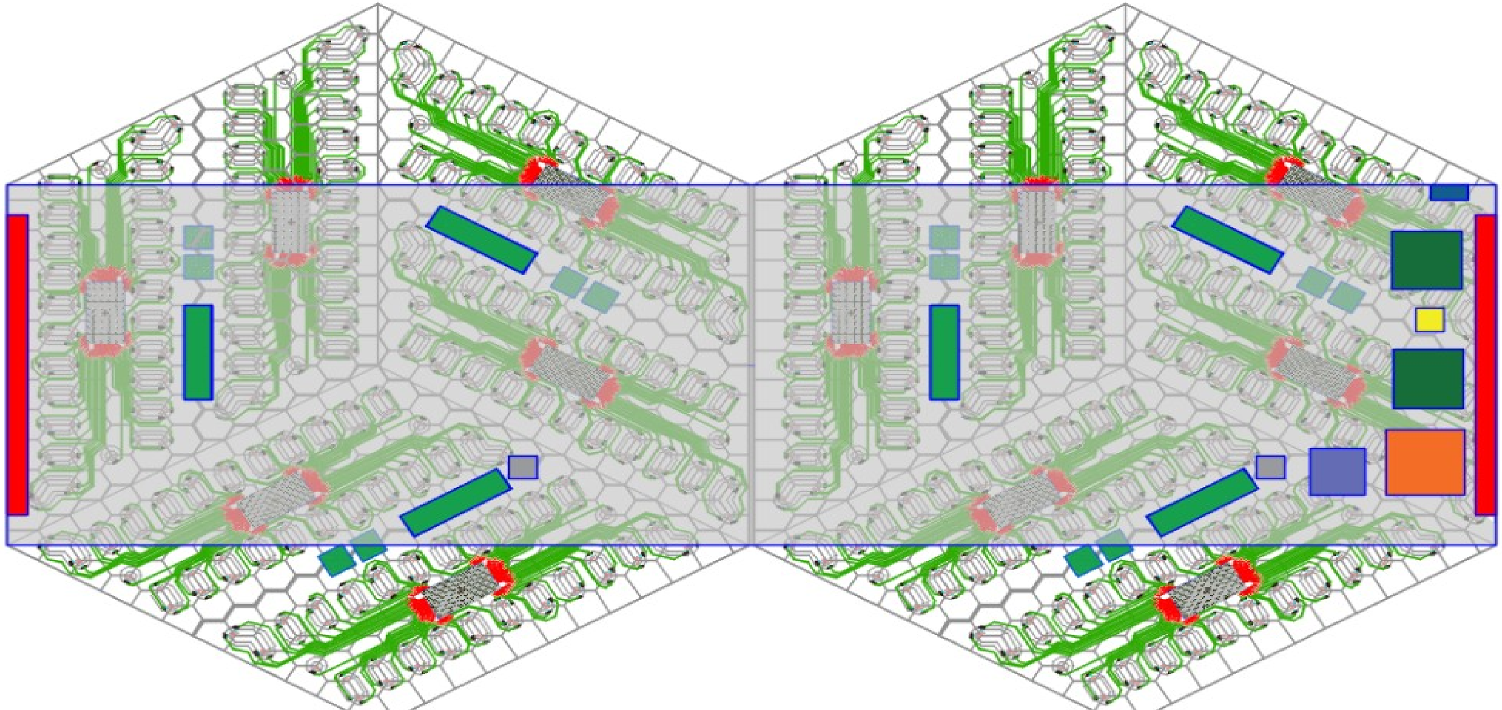
CMS detector

- **Tracker:**
  - 13/14 silicon layers in Barrel (B) / End-Cap (EC)
- **EM calorimeter:**
  - $PbWO_4$ crystals, extremely dense & optically clear material
- **HAD calorimeter**:
  - Layers of dense material (brass or steel) interleaved with tiles of plastic scintillators

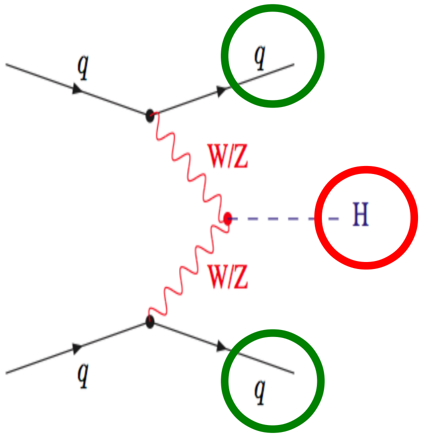


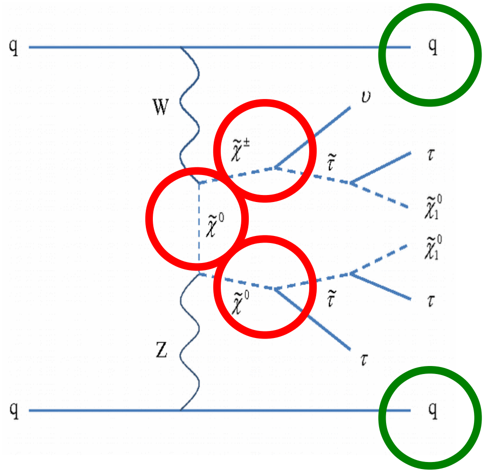


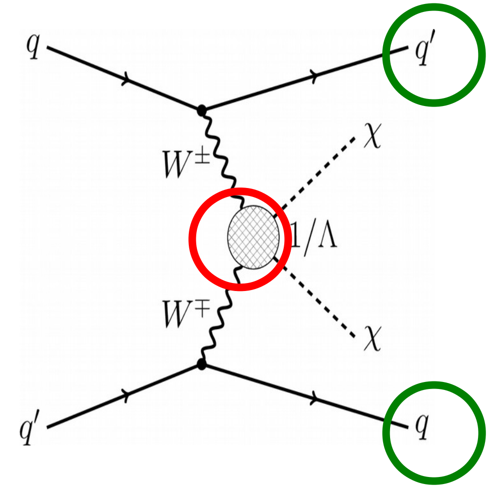
- **Magnet:** 3.8 T / Return yoke after...
- **Muon system:**
  - Drift-Tube (B): Measure
  - Cathod-Strip-Chamber (EC): Measure & Trigger
  - Resistive-Plate-Chamber: Trigger



Motivation & strategy







VBF signatures cover a wide variety of searches @ LHC, while main background, to all of them = Pile-Up

→ If we want to preserve good efficiency for <u>any</u> VBF signature, we should base decision on VBF quarks, not on produced object and/or decay products

→ Allow us claim a bit more bandwidth @ TSG, justified by (wide) range of VBF-based searches, i.e. 1 – O(10 kHz)

1/ Know which variables are worth being transmitted to L1

2/ Trigger: Provide a tool for separating PU from VBF events:

→ based only on jet properties

→ “simple” enough for it to be (hopefully) implemented in trigger