CMS (ECAL) precision timing

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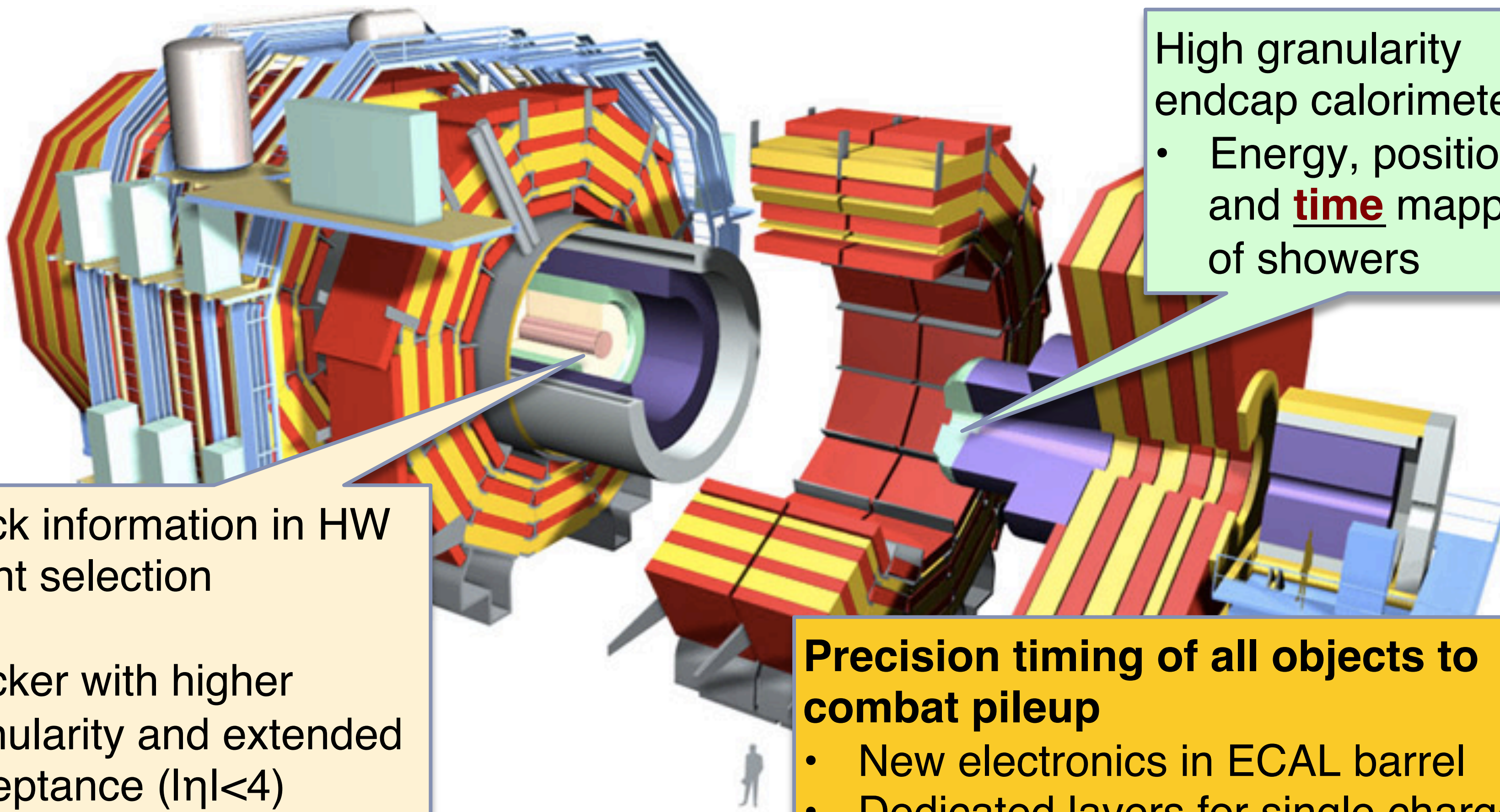
- **Recent studies and technical choices are not all public**
- **Not the latest snapshot in these slides**

Bold aspects of the CMS upgrade for HL-LHC



High granularity endcap calorimeters

- Energy, position and <u>**time**</u> mapping of showers

Track information in HW event selection

Tracker with higher granularity and extended acceptance (|η|<4)

Precision timing of all objects to combat pileup

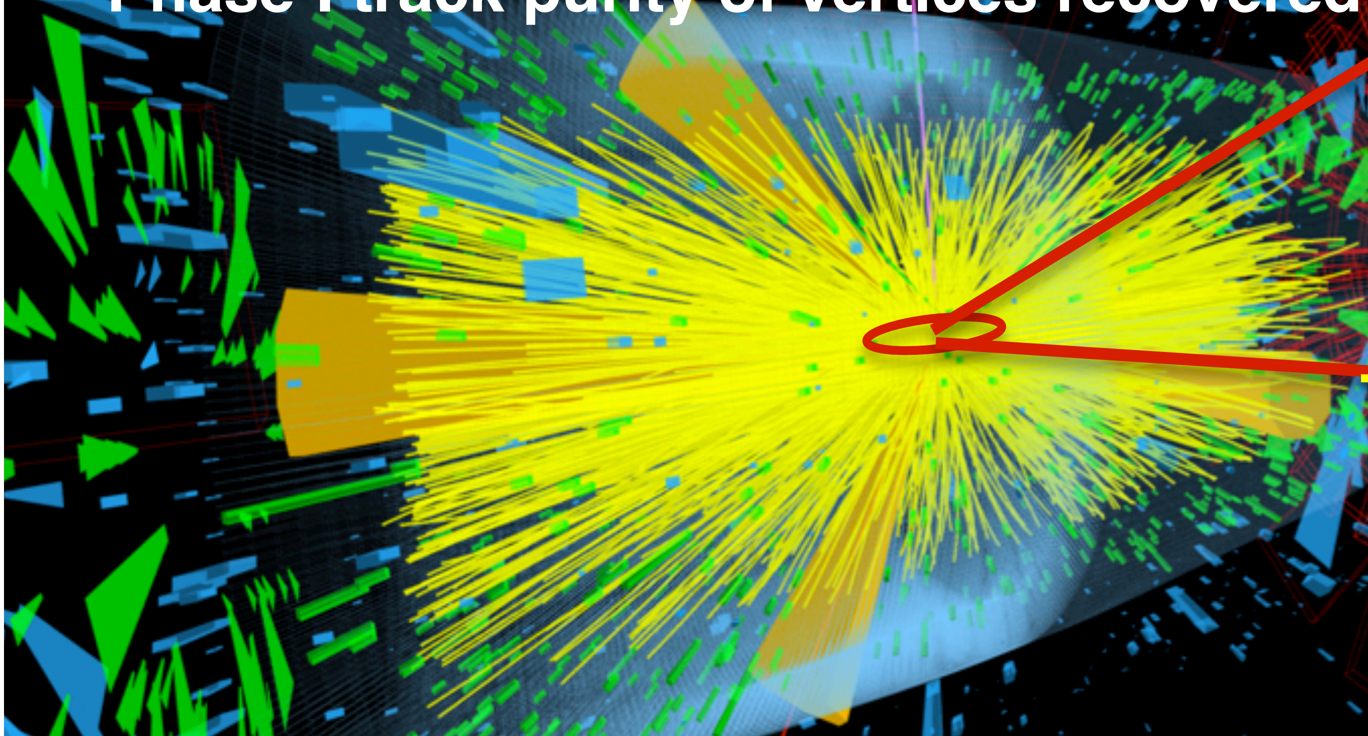
- New electronics in ECAL barrel
- Dedicated layers for single charged track timing just outside the Tracker

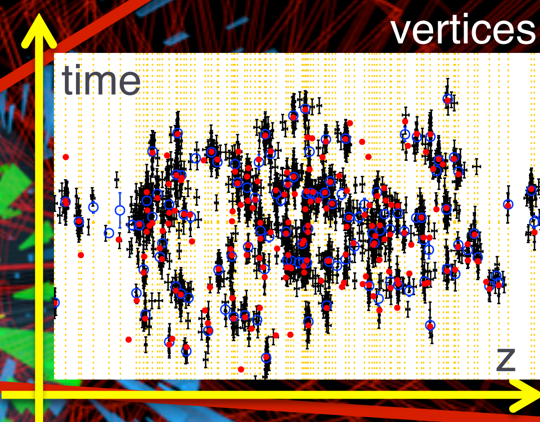
- **Goal: be as efficient, and with low background/fake rate, at 200 pileup as we are today and with an extended acceptance**

Time-aware reconstruction

If beam-spot *sliced* in successive **O(30) ps** time exposures, *effective pileup* reduced by a factor 4-5:

- **~15% merged vertices reduced to 2%**
- **Phase-I track purity of vertices recovered**



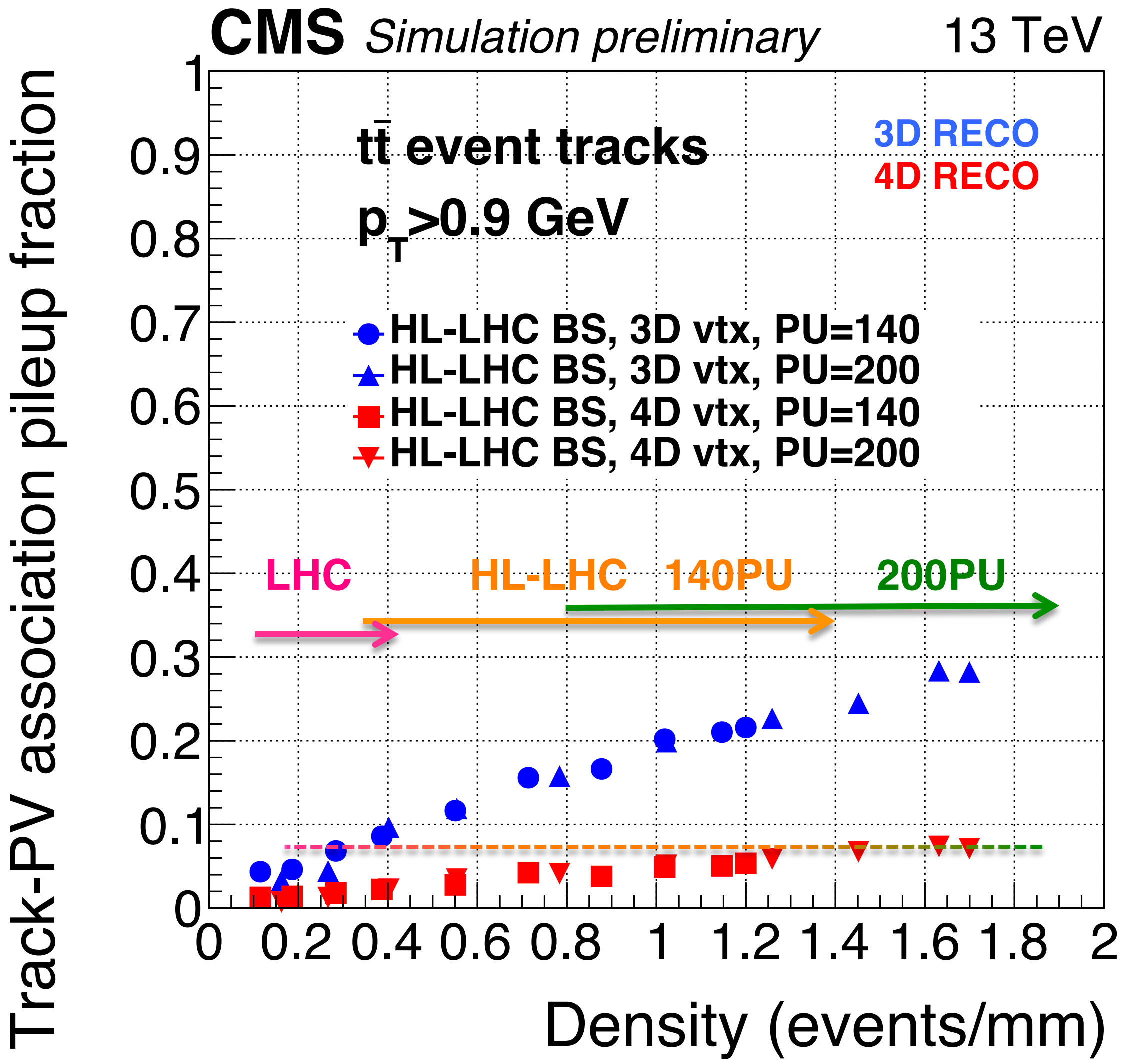


Luminous region

- $t_{RMS} \sim 180$ ps
- $z_{RMS} \sim 4.6$ cm

VBF H→ττ in 200 pp collisions

Track-vertex association – with track timing

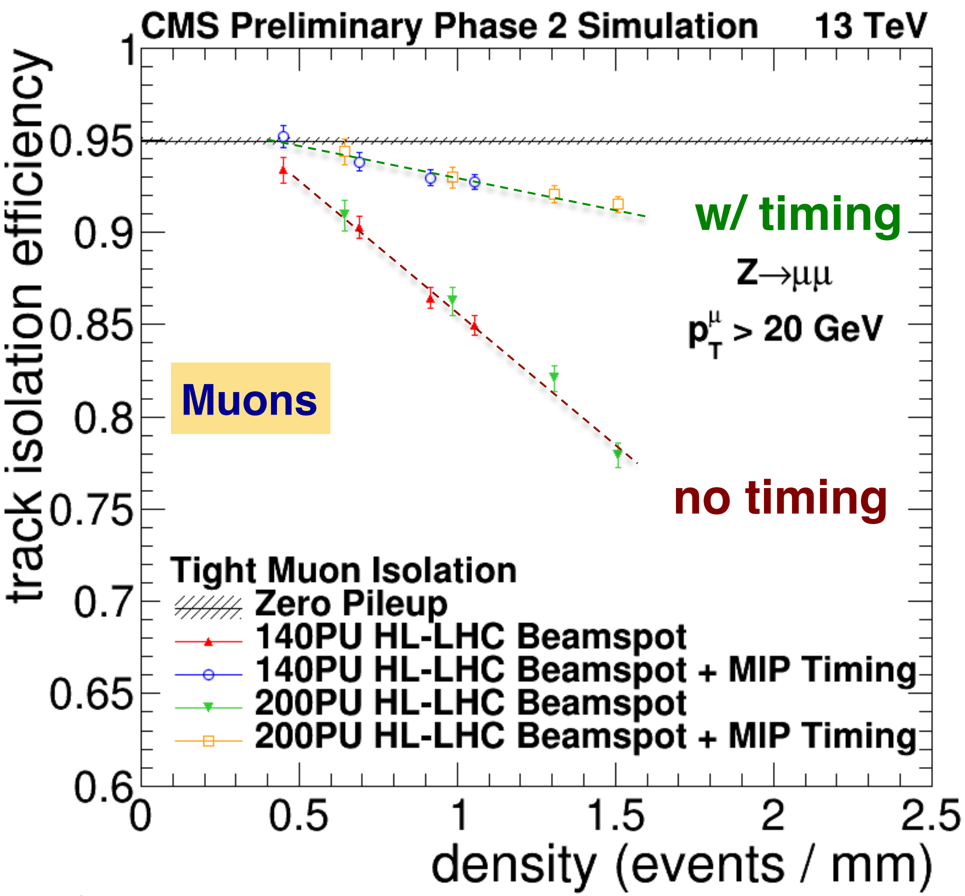


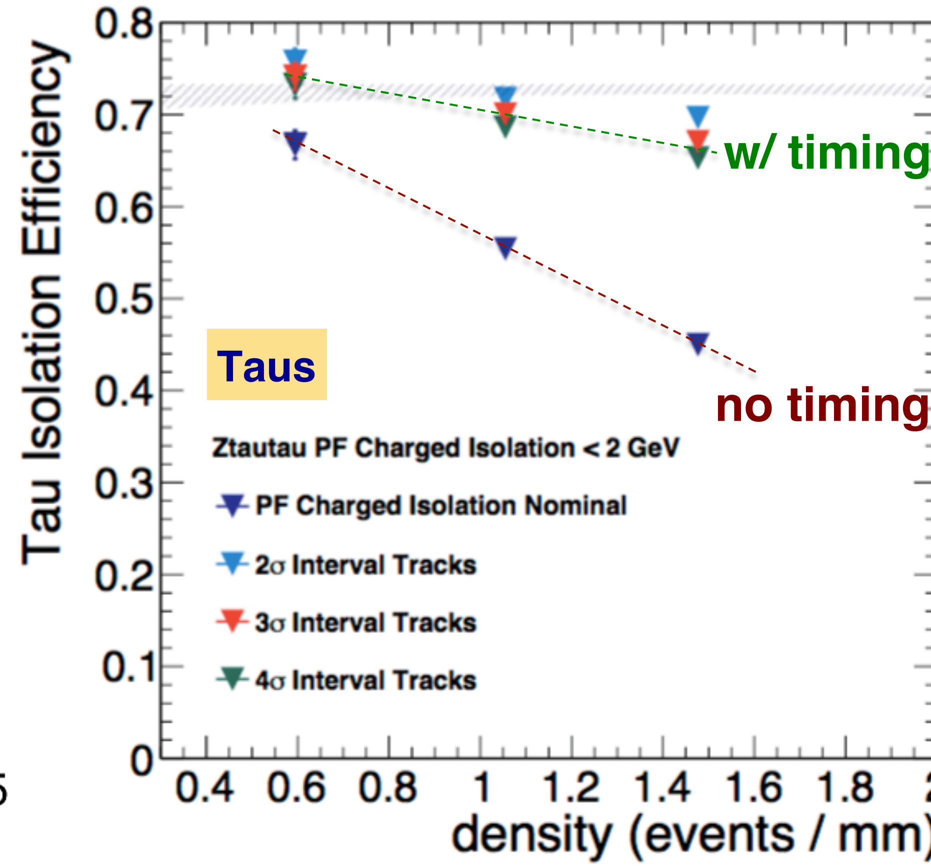
- **With timing, 'effective vertex density' down to LHC level !**

1. Extend performance at 200 PU
2. Strengthen reconstruction at 140 PU
3. Provide robustness against adjustment of luminosity scenarios

- **Recovery from performance degradation in several observables**

Example: track isolation efficiencies

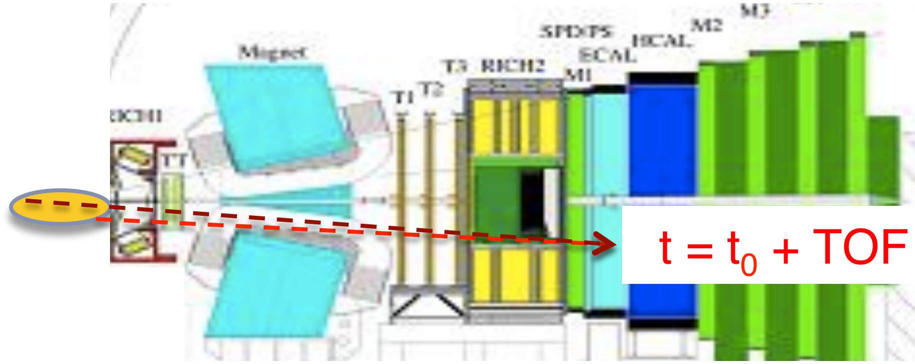




- **Acceptance gain in searches and precision measurements**
  - *[Curves are for constant background reject power]*
- ***Performance benefits also in, missing E_T resolution, pileup jet rejection, …***

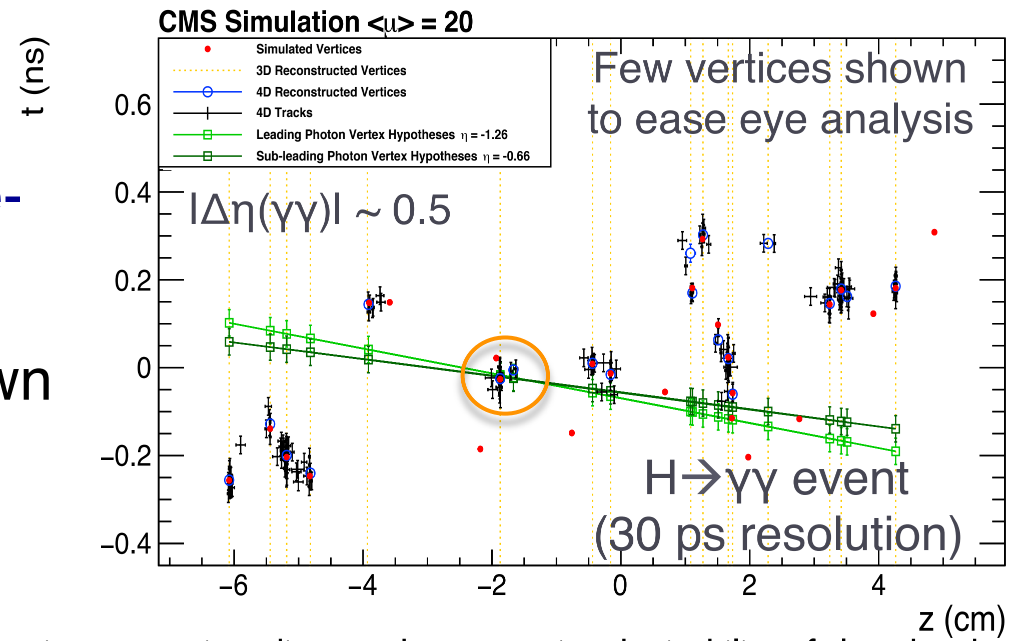
Photon timing and association with vertices

- **Association with vertex requires t_0 information**
  [i.e. charged track timing]

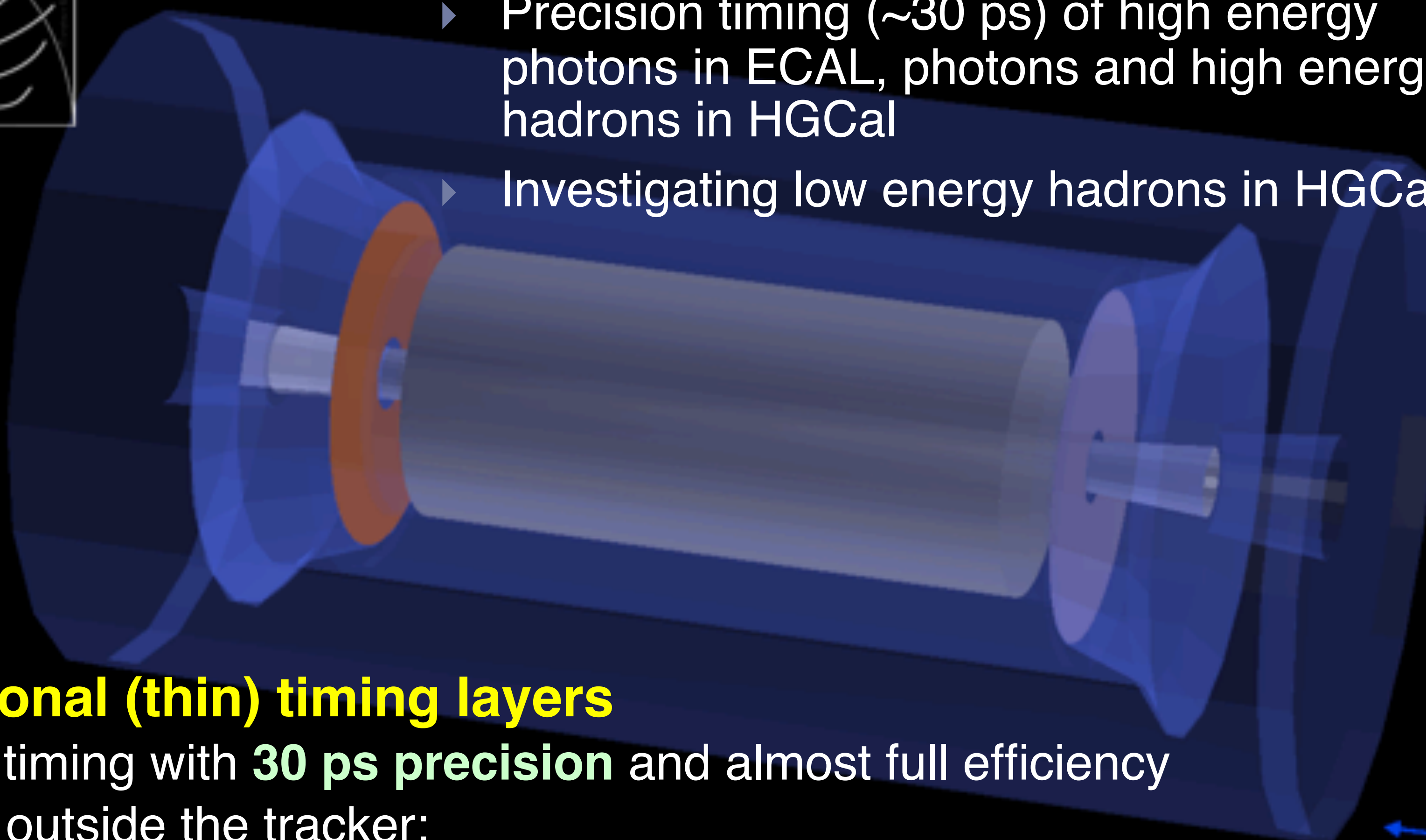


- **Single photon:**
  - early collision + long TOF = late collision + short TOF

- **Two-photons**
  - triangulation: vertex space-time from photon timing
    - For small rapidity gap triangulation breaks down
    - Vertex t_0 to resolve ambiguities



Elements of the timing upgrade of CMS

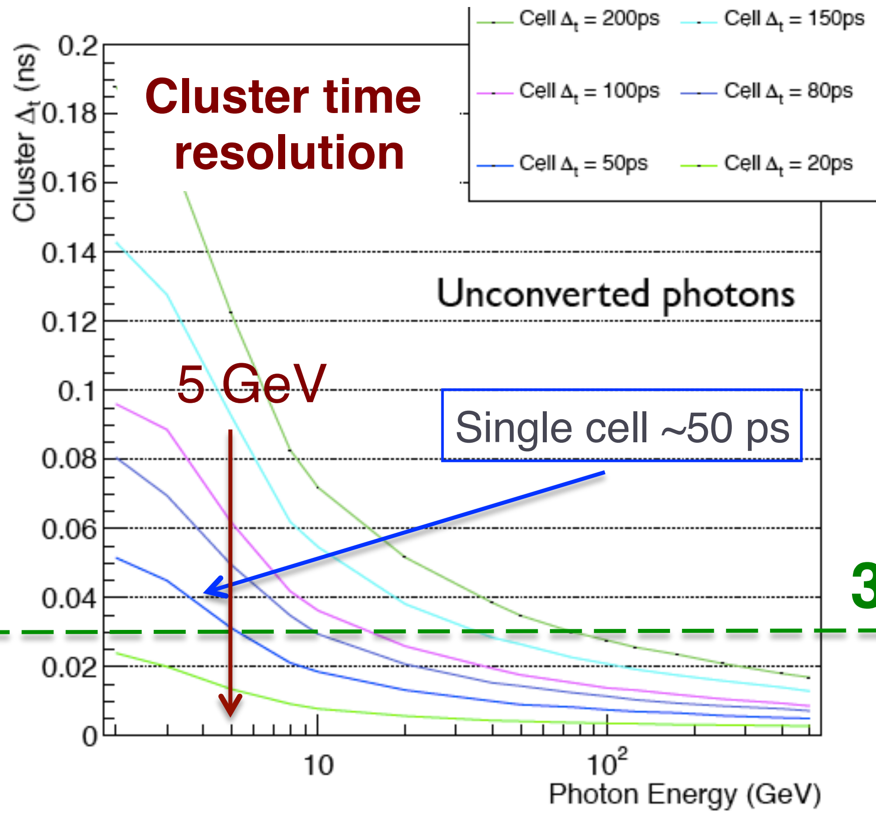


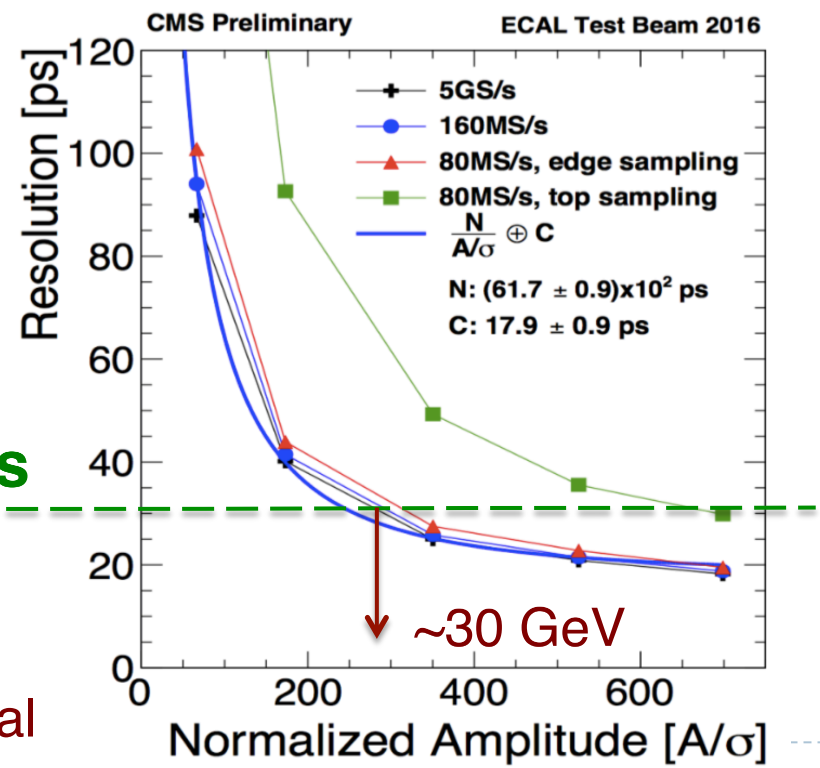
- **Calorimeter upgrades:**
  - Precision timing (~30 ps) of high energy photons in ECAL, photons and high energy hadrons in HGCal
  - Investigating low energy hadrons in HGCal

- **Additional (thin) timing layers**
  - MIP timing with **30 ps precision** and almost full efficiency
  - Just outside the tracker:
    - **Acceptance: IηI<3.0 and p_T>0.7 GeV**

Timing in the CMS upgraded calorimeters

- **HGCal (left):** Si + Cu/W or Pb/Steel: 28 layers – 0.5 and 1 cm^2 cell size
  50 ps / cell [at least for >20 MIPs signals]
- **ECAL (right):** $PbWO_4$ + APDs
  New electronics + 160 MHz sampling

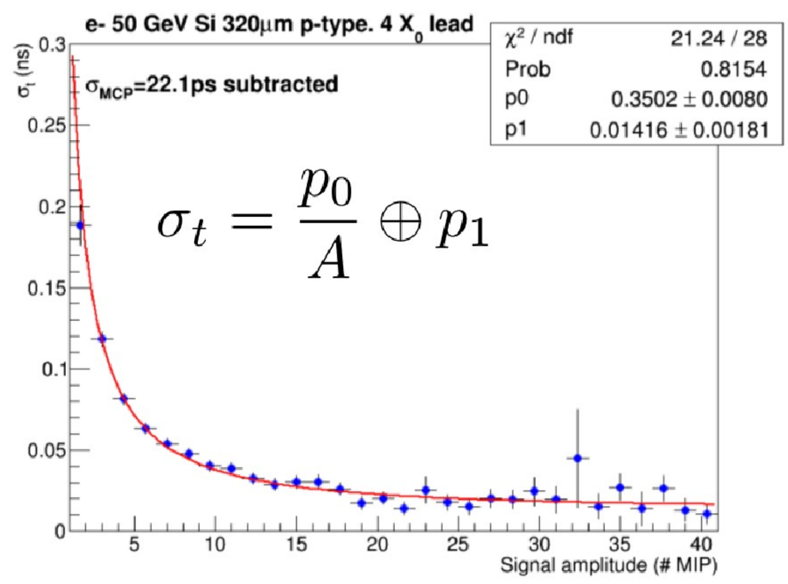




- Investigating low energy hadrons in HGCal

Timing tests of the HGCal Si sensors

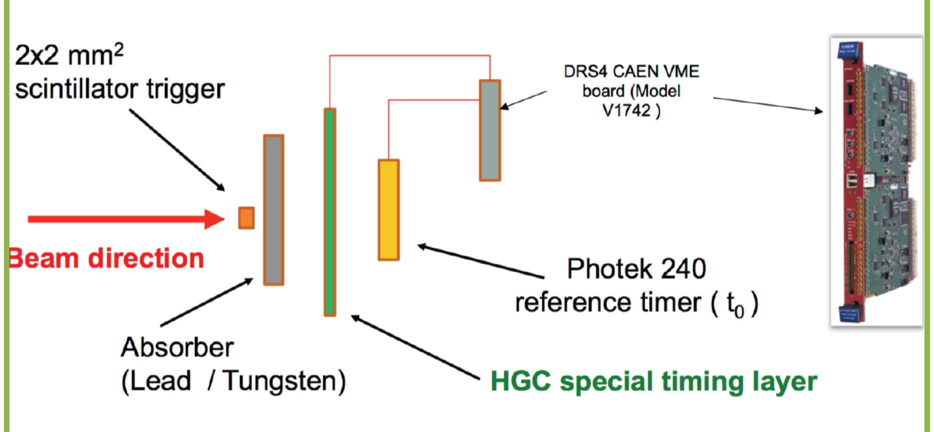
Timing resolution vs amplitude



Time resolution improves with S/N

Constant term: 14 ps, for S > 20 mips

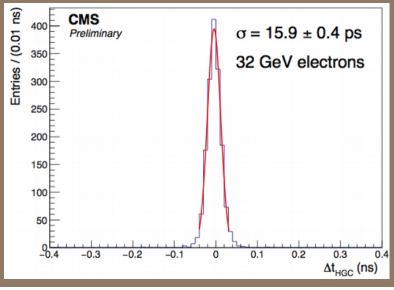
Timing test with special fast readout



Timing test with 300 μm layer

Fast readout

16 ps for 32 GeV electrons



CERN beam tests in November 2016

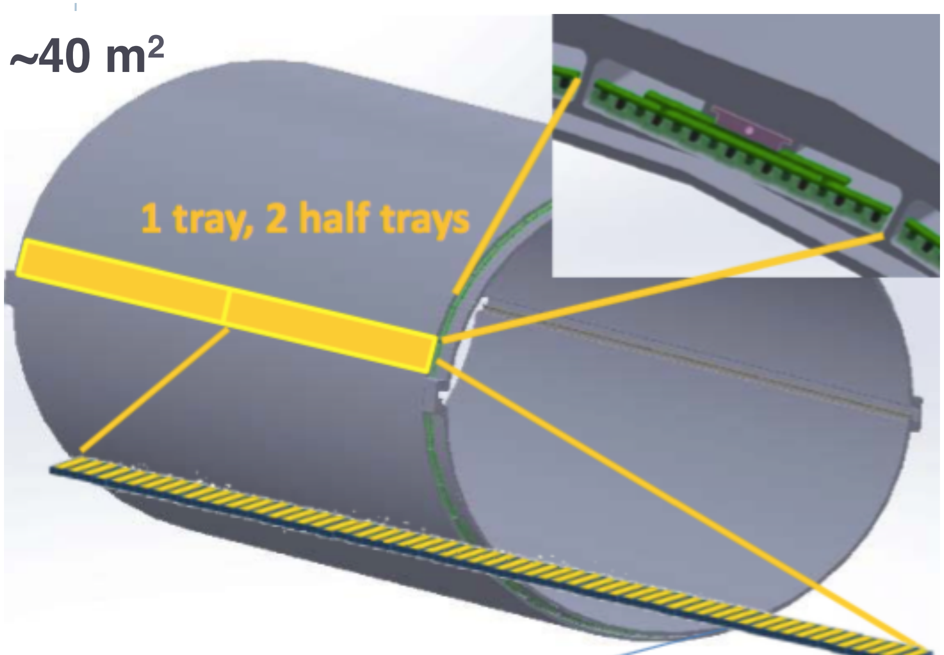
Up to 250 GeV electrons

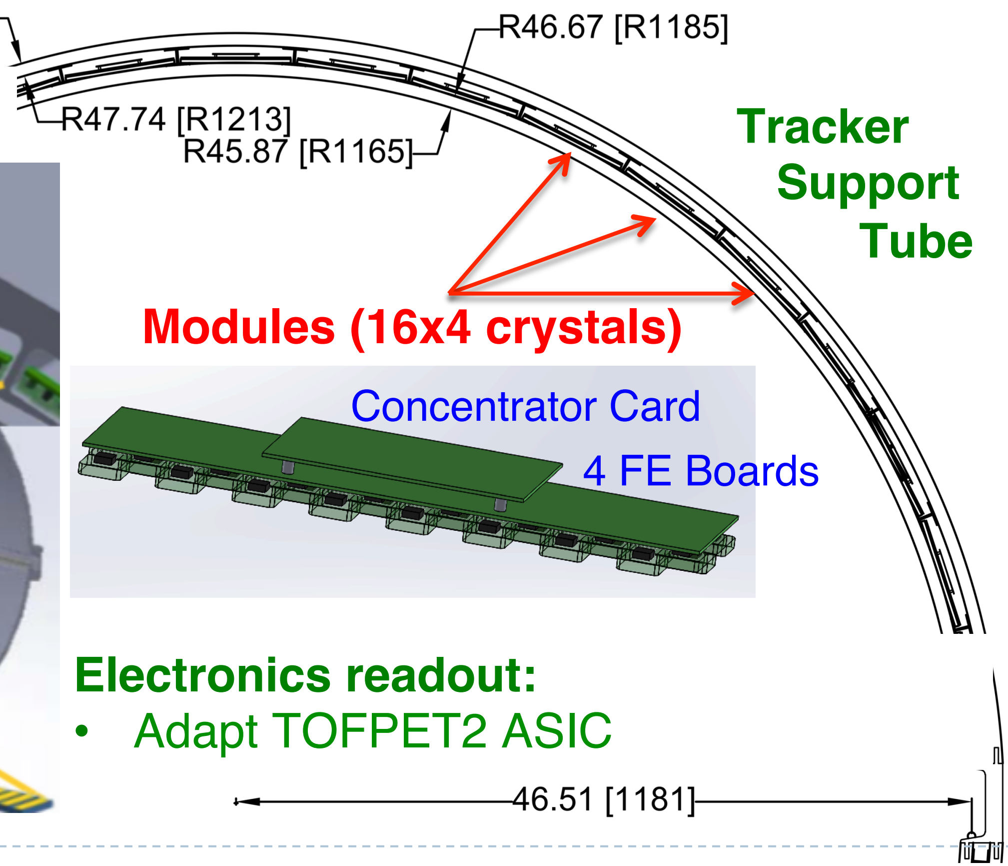
Analysis ongoing

Barrel MIP timing detector

- **LYSO crystals + SiPM embedded in the Tracker tube**
  - Ready before TK integration
  - Maintain performance at radiation levels of **$2\times10^{14}\ n_{eq}/cm^2$**

~40 m²

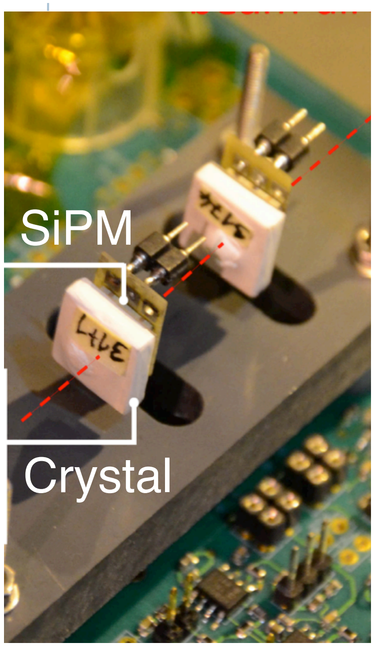




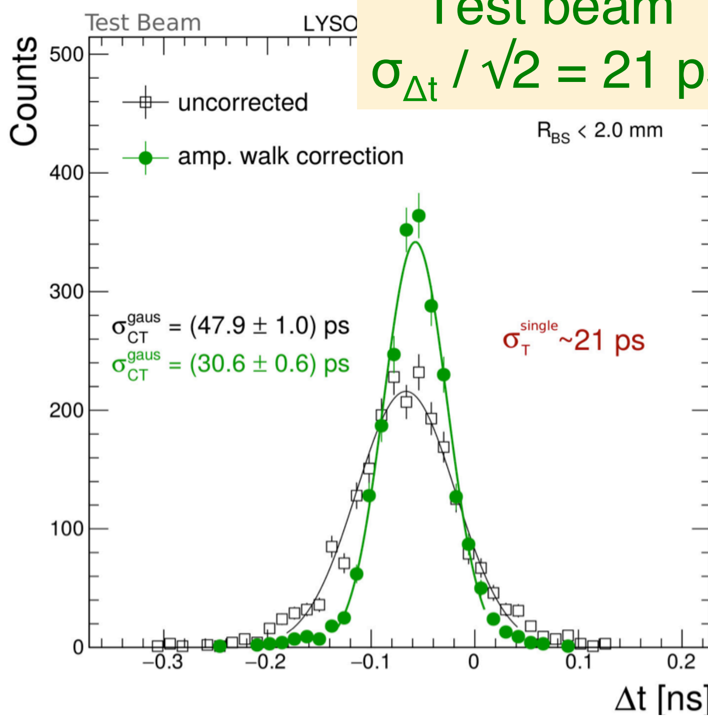
Electronics readout:
- Adapt TOFPET2 ASIC

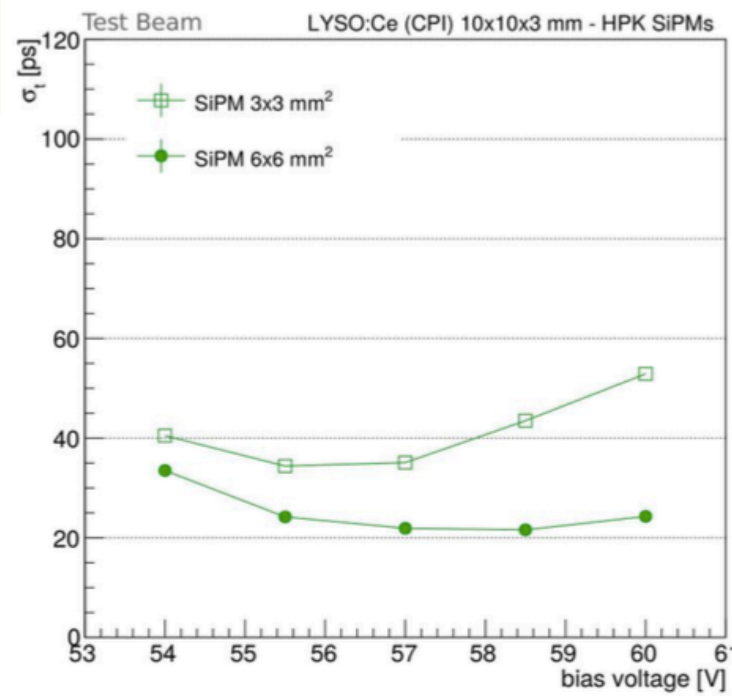
Barrel sensors (LYSO + SiPMs)

- **Nominal geometry: 12 x12 mm^2 (~ 3 mm thick) + 4x4 mm^2 SiPMs**
- **Production-like geometry qualified in test beams**
- **Good radiation hardness of production-ready SiPMs**
  - Operate SiPMs at ~ –35 ^{0}C (limit self-heating and dark rate)



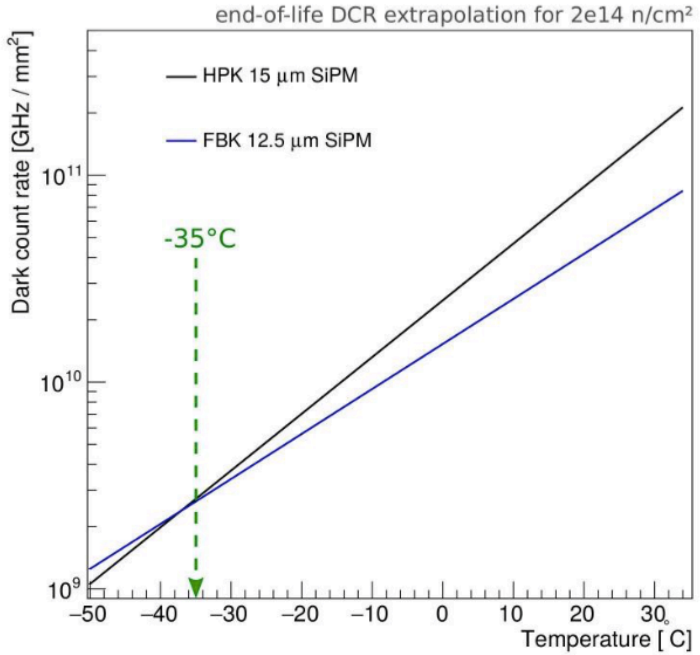
Test beam
$\sigma_{\Delta t} / \sqrt{2}$ = 21 ps

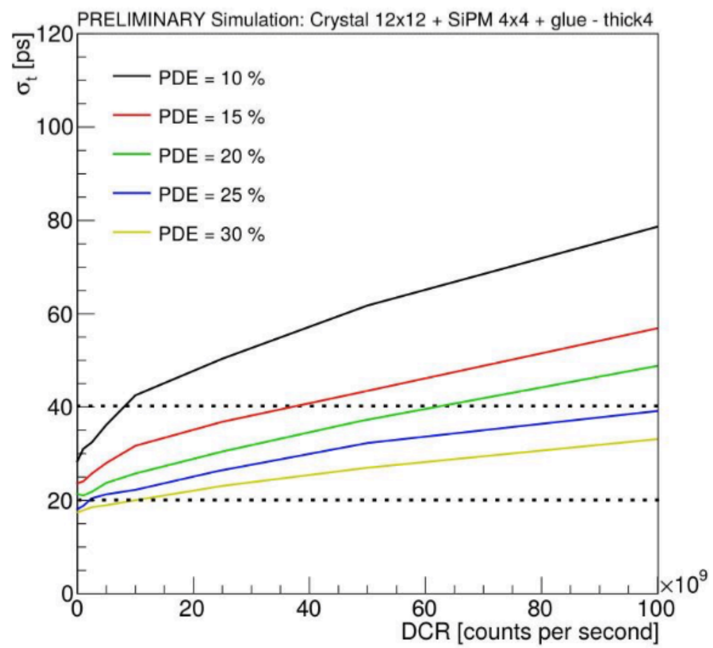




Radiation hardness: SiPMs

- **Radiation fluence is a fierce foe**
  - SiPMs self-heating ~ 30 mW/channel
  - Dark count rate (DCR) a few 1 GHz/mm at -35 ^{0}C
- LYSO scintillation to boost signal above dark counts noise
- Optimal SiPMs require balance between photon detection efficiecy (PDE) and DCR to maintain 30 ps at the end of life



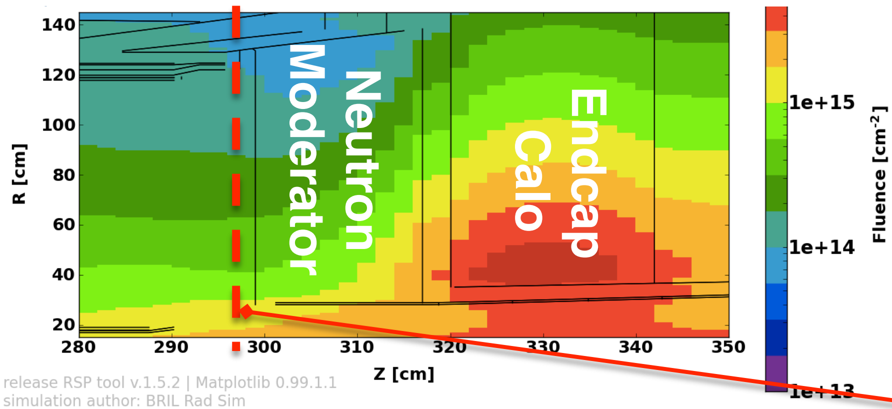


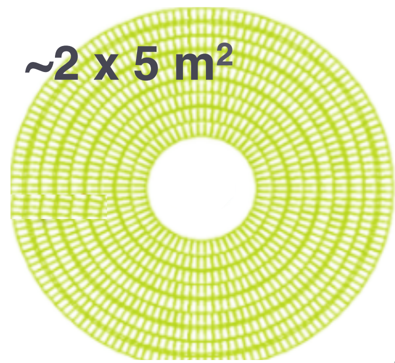
LYSO:Ce tile, 4 mm effective thickness

LYSO is radiation hard at the required level

Endcap MIP timing detector

- **Single layer of low gain silicon detectors just outside TK**
  - Ready at the end of TK or HGCal integration
  - Maintain performance at radiation level **$2x10^{15}$ n_{eq}/cm^2**



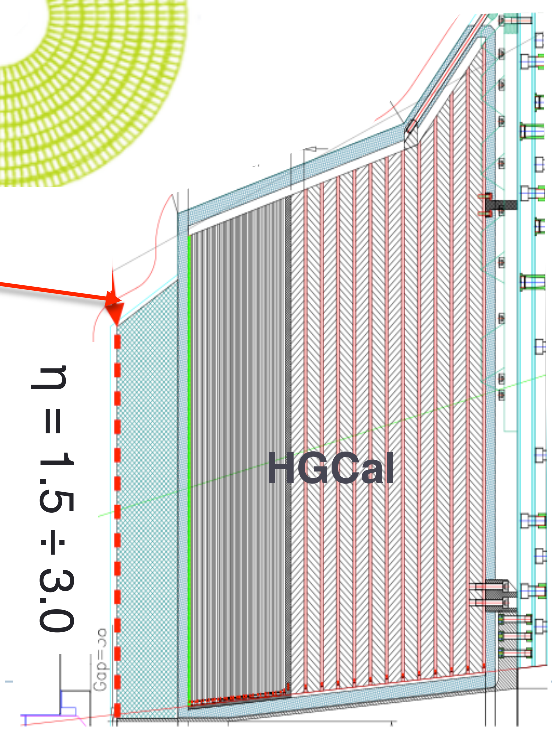


η	TK / HGCal nose
1.6	1.1×10^{14}
2.0	2.1×10^{14}
2.5	4.8×10^{14}
3.0	10.0×10^{14}

Fluence [n_{eq}/cm^2] at 3000 fb^{-1}

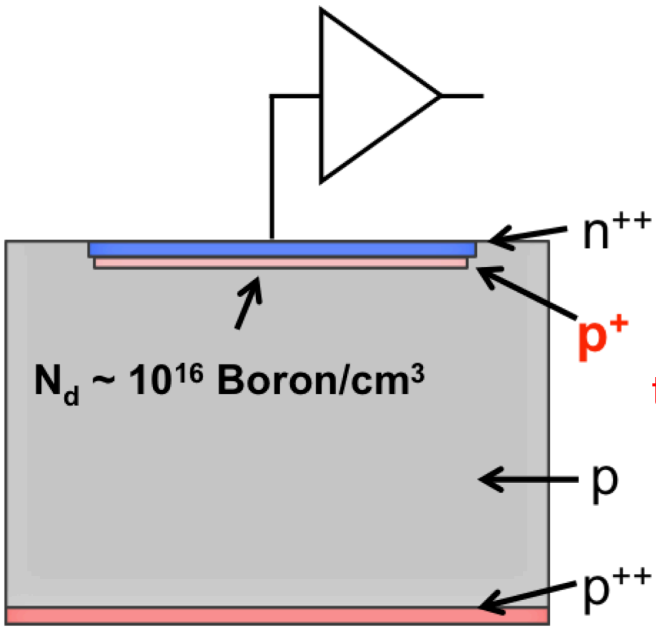
Single layer OK here

Requires further R&D (or multiple layers)



Silicon detectors with gain

Different gain / E-field geometries under study (RD50)



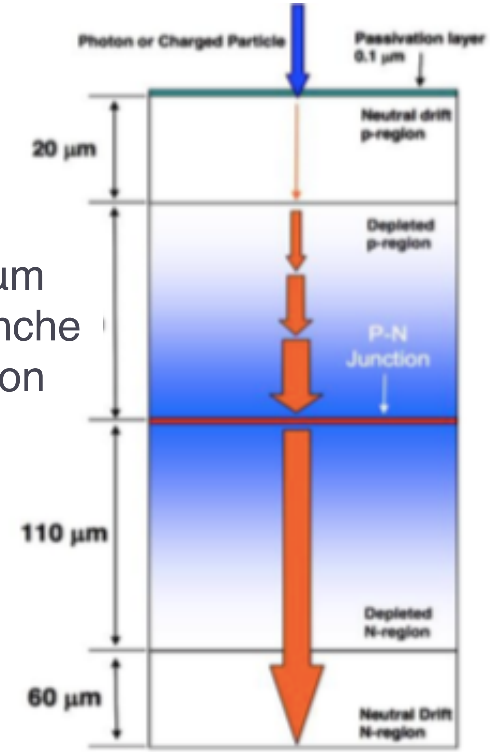
Additional doping layer to achieve gain

Low Gain Avalanche Diodes (LGADs)
Gain O(10) - Three suppliers (FBK, CNM, HPK)

Ultra Fast Si Detectors – Drift region ~ 50 µm to limit Landau fluctuations
Small pads to limit capacitance

Details on the technology in M.Obertino's talk

40 µm avalanche region



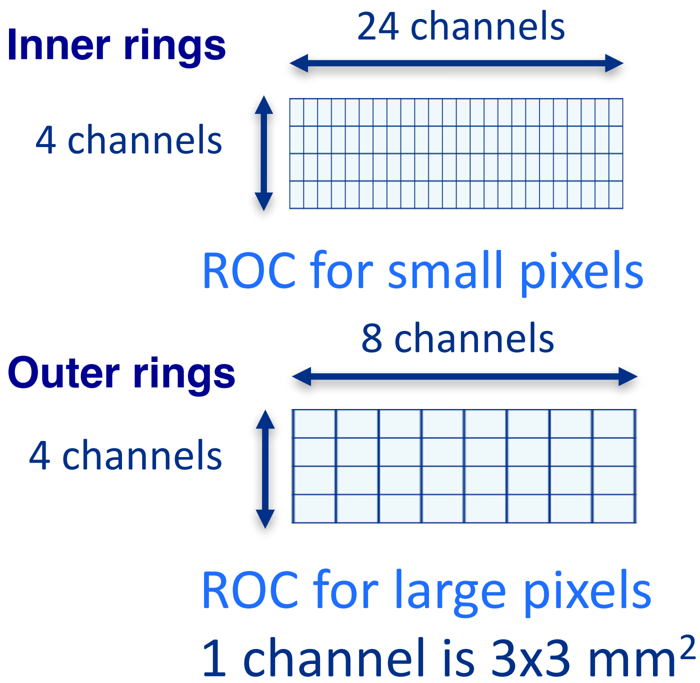
Deep Depleted APDs
Gain O(500) - one supplier (RMD)

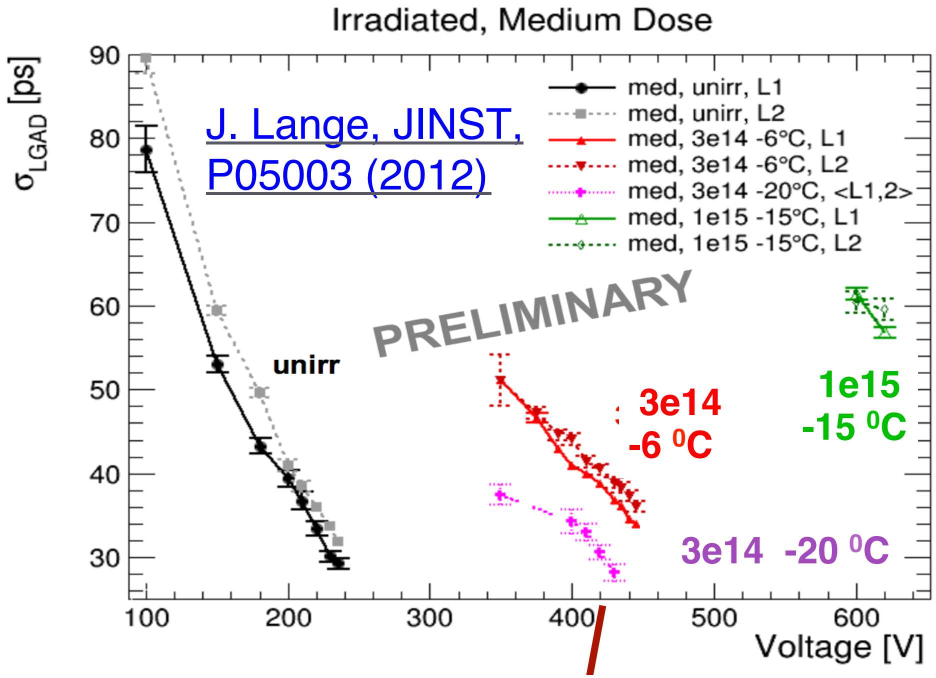
- **15 ps on 1 cm^2 pads**
- Not yet fully qualified at CMS radiation levels

[S.White, at Frontier Detectors etc., Elba, (Italy) 2015]

Endcap sensors (ultra-fast Si detectors)

- **Nominal geometry: 4.8 x 9.6 cm^2 modules with 1x3 mm^2 pads**
  - 16 ASICs bump-bonded to sensors (ASIC being developed)
  - 3:1 ganging in the TDC at small η (3x3 mm^2 granularity)
- **Single pads shown to have $\sigma_t \leq 50$ ps up to 10^{15} n_{eq}/cm^2**
  - Compensate gain loss with bulk gain (higher external bias)

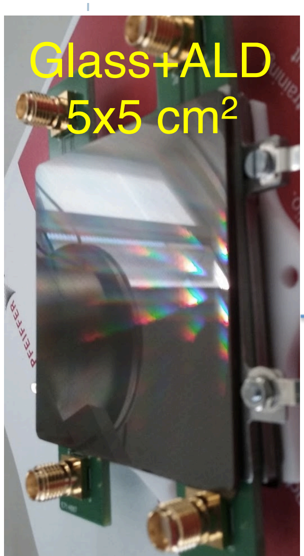


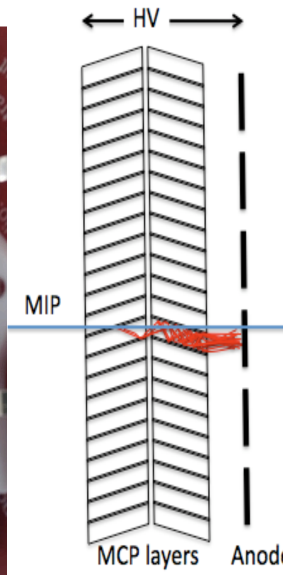


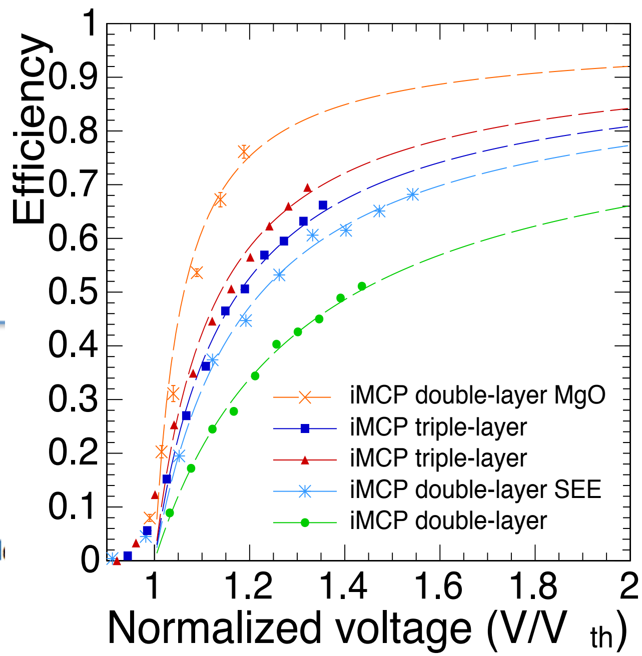
Details on the technology and R&D prospects in M.Obertino's talk

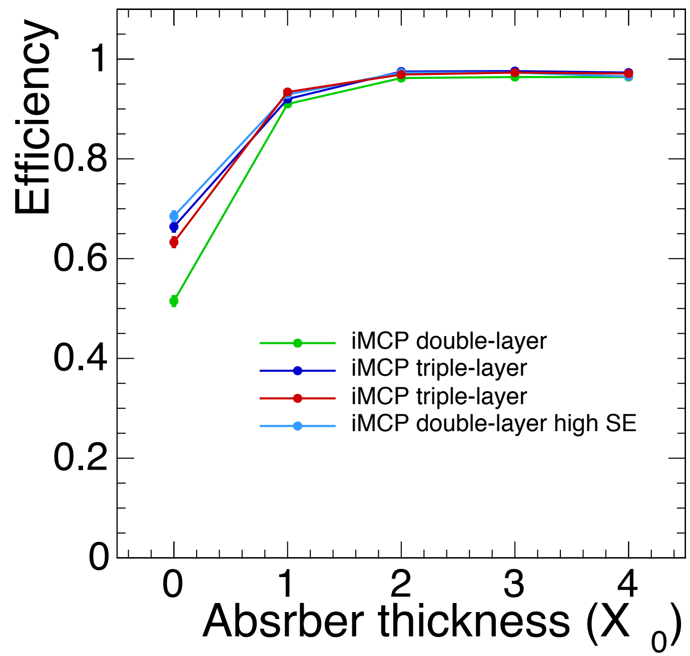
Other R&Ds on timing sensors

- **Micro channel plates:**
  - not immune to B-field, but might be viable for LHCb
- ~20-30 ps as secondary emission and amplification device
- ~70% efficiency to MIPs, full efficiency to (pre)showers









- [A.Ronzhin et al, Nucl. Instrum. Meth. A795 (2015) 52–57]
- [L.Brianza et al. Nucl. Instrum. Meth. A797 (2015) 216–221]

Summary

- **Timing resolutions that are a factor 5-10 smaller than the timing spread of the beam spot open up new capabilities**
- **Possible with both light and charge collection technologies**
  - Dimensions matter a lot! Requires the technological capability to cover square meters of surface with small, thin tiles (1-100 mm^2)

- **Options for calorimeters:**
  - **Correct vertex association requires vertex-t_0 information**

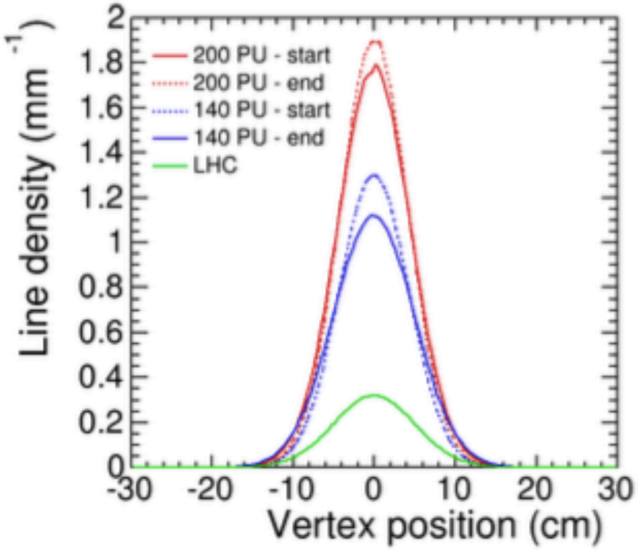
I. **Shower Max** – *dedicated layer(s) embedded in the EM calorimeter or from the full longitudinal EM energy profile*
Additional Timing Layer – *a low-mass accompaniment to a silicon tracking system situated in front of a calorimeter system*

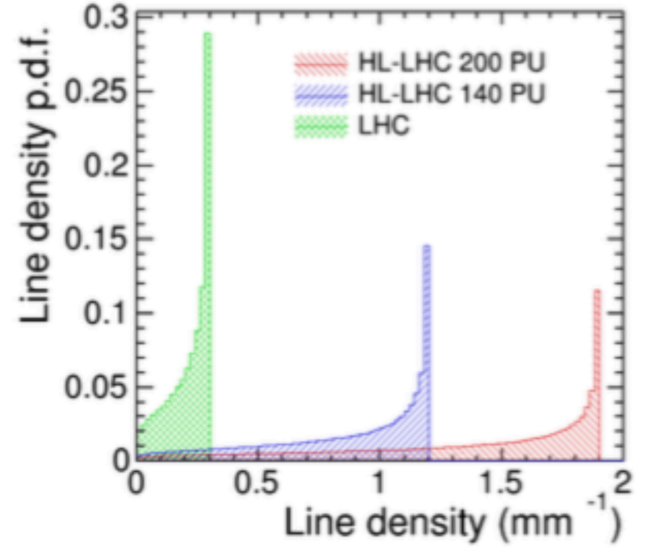
II. **Pre-shower** – *front compartment of the electromagnetic calorimeter - balancing low occupancy MIP identification with EM showering*

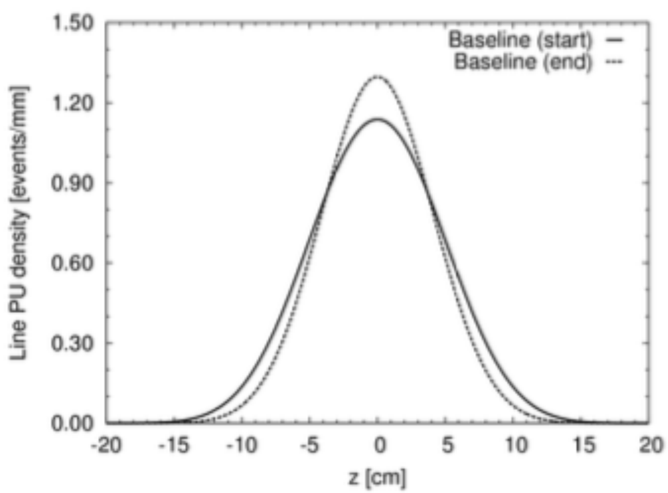
- **Specific choices informed by radiation levels, integration and schedule constraints - make your choice and optimization!**

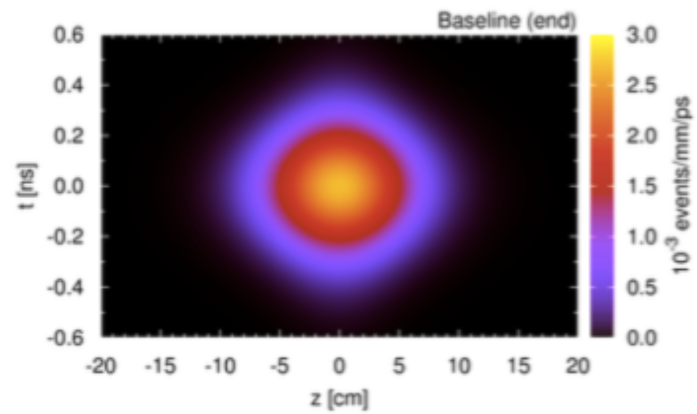
Appendix

Luminous region



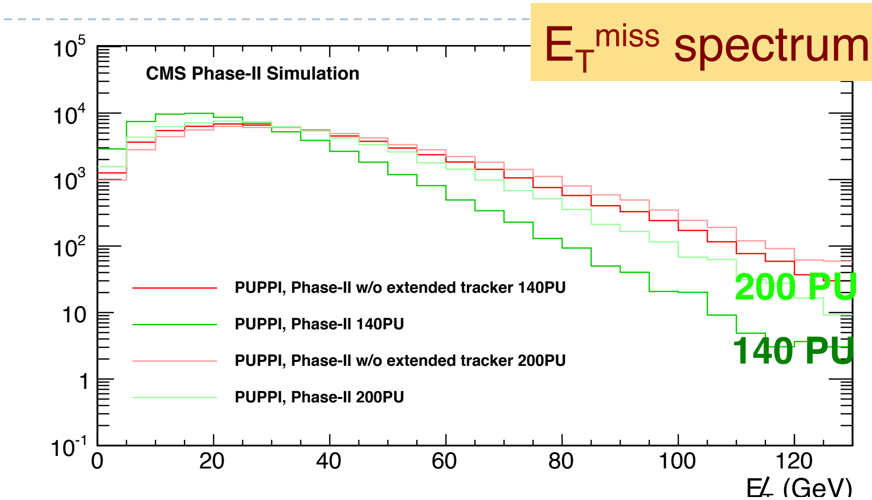


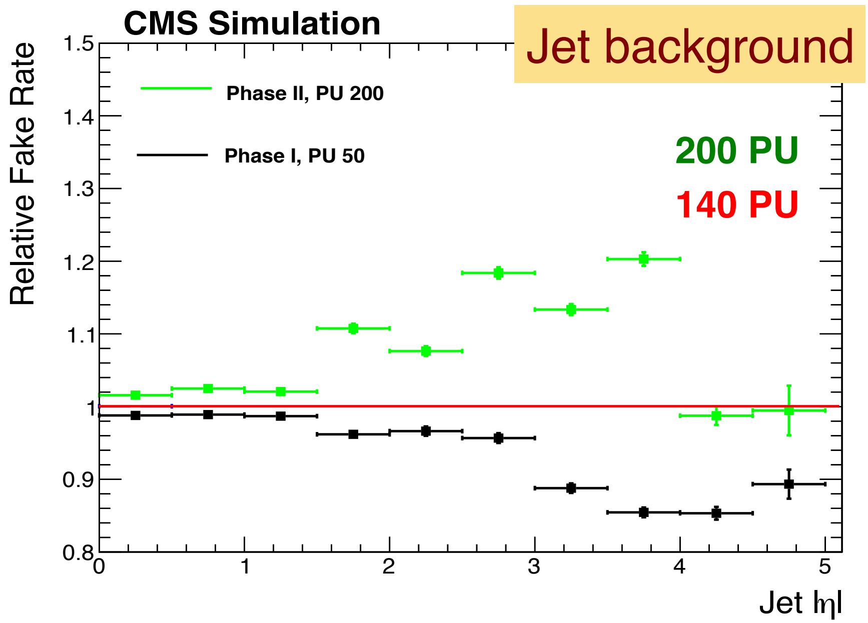


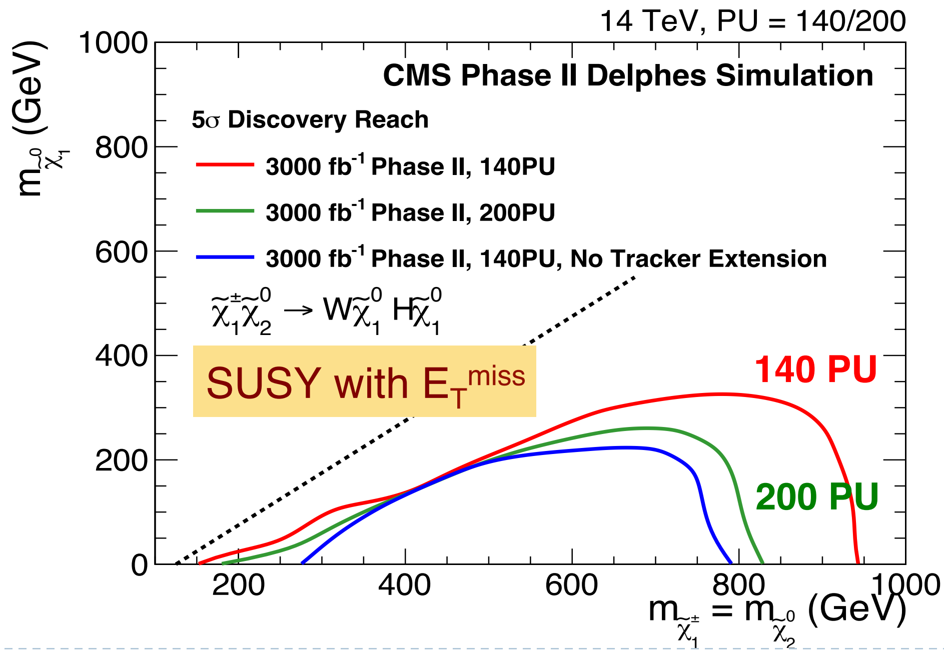


Examples (w/o timing information): the anti-luminosity effect

- CMS Upgrade Scope document:
  - [CERN-LHCC-2015-19, LHCC-G-165]
- **VBF H→ττ requires >40% more luminosity at 200 than 140 PU**
  - Jet fake rate and E_T^{miss} resolution
- **Searches with E_T^{miss} less sensitive at 200 PU than 140 PU**

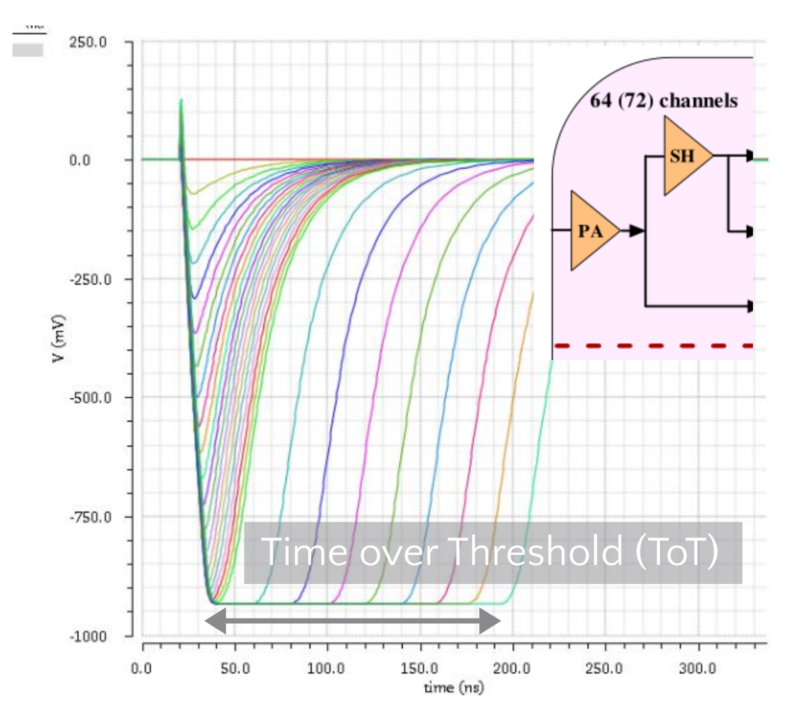




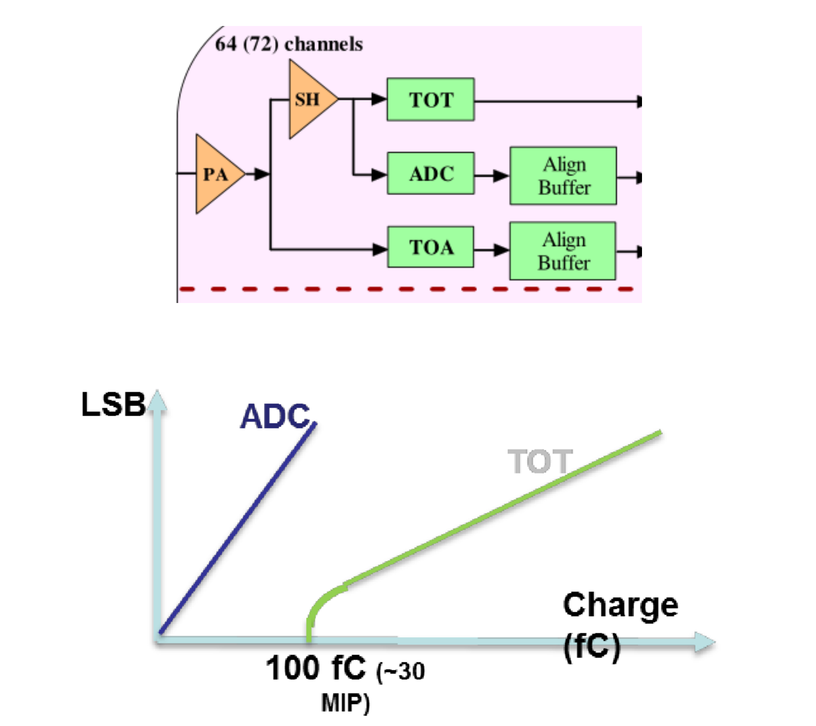


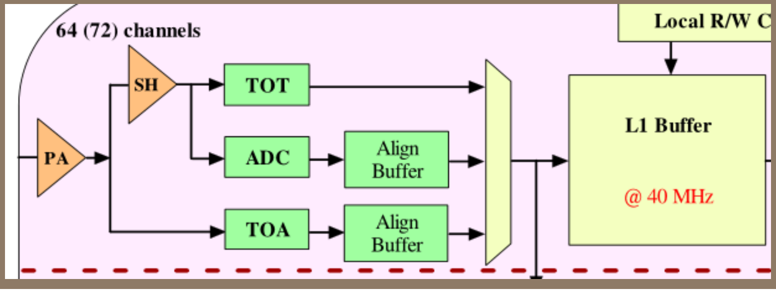
HGCal front end

Signal after shaper



ADC – ToT





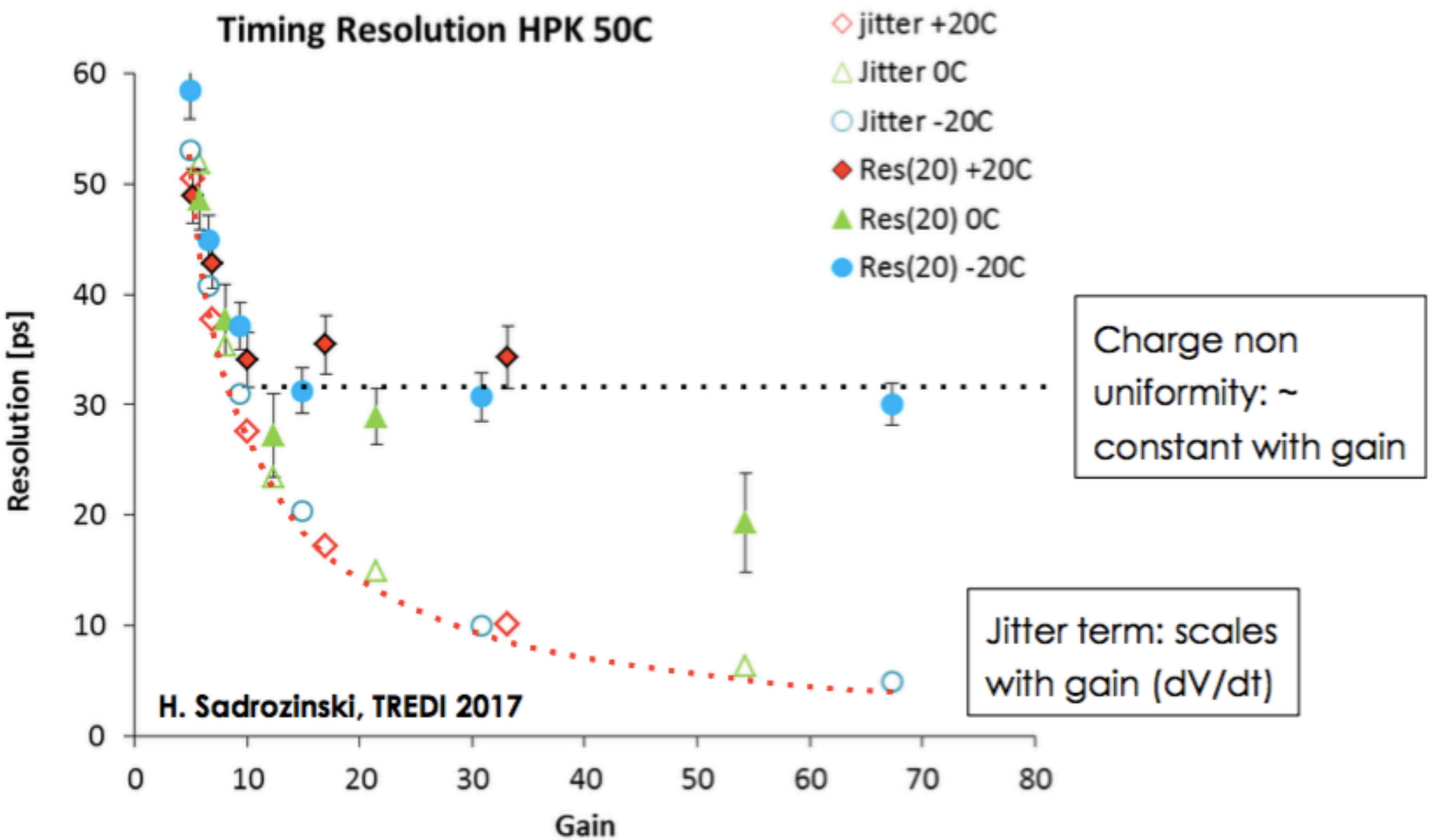
Buffer waiting L1 trigger accept

12.5 μs latency

512 events × 32 bits = 16.4 kb / channel

Power consumption: 2 mW / channel

UFSDs - Sensors



- Above gain ~20 resolution is determined by charge non-uniformity (Landau fluctuations)