• Recent studies and technical choices are not all public
• Not the latest snapshot in these slides
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 $O(30) \text{ ps}$ time exposures, *effective pileup* reduced by a factor 4-5:

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

VBF $H \rightarrow \tau \tau$ in 200 pp collisions

Luminous region

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

---

**H → γγ event (30 ps resolution)**
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: $|\eta|<3.0$ 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 cm² cell size
  - **50 ps / cell** [at least for >20 MIPs signals]

- **ECAL (right):** PbWO₄ + APDs
  - New electronics + 160 MHz sampling

Investigating low energy hadrons in HGCal
Timing tests of the HGCal Si sensors

Timing resolution vs amplitude

\[ \sigma_t = \frac{p_0}{A} \oplus p_1 \]

- Time resolution improves with S/N
- Constant term: 14 ps, for S > 20 mips

Timing test with special fast readout

- 2x2 mm^2 scintillator trigger
- Beam direction
- Absorber (Lead / Tungsten)
- HGC special timing layer

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 $2 \times 10^{14} \text{n}_{\text{eq}}/\text{cm}^2$

~40 m$^2$

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 ~ $-35 \, ^{0}\text{C}$ (limit self-heating and dark rate)

Test beam

$\sigma_{\Delta t} / \sqrt{2} = 21 \, \text{ps}$
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 °C
  - LYSO scintillation to boost signal above dark counts noise
  - Optimal SiPMs require balance between photon detection efficiency (PDE) and DCR to maintain 30 ps at the end of life

- 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 $2 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$

<table>
<thead>
<tr>
<th>$\eta$</th>
<th>TK / HGCal nose</th>
<th>Fluence [$\text{n}_{\text{eq}}/\text{cm}^2$] at 3000 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td>1.1 x $10^{14}$</td>
<td>Single layer OK here</td>
</tr>
<tr>
<td>2.0</td>
<td>2.1 x $10^{14}$</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>4.8 x $10^{14}$</td>
<td>Requires further R&amp;D (or multiple layers)</td>
</tr>
<tr>
<td>3.0</td>
<td>10.0 x $10^{14}$</td>
<td></td>
</tr>
</tbody>
</table>

Fluence [$\text{n}_{\text{eq}}/\text{cm}^2$] at 3000 fb$^{-1}$
Silicon detectors with gain

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

  - **Deep Depleted APDs**
    - Gain $O(500)$ - one supplier (RMD)
    - **15 ps on 1 cm$^2$ pads**
    - Not yet fully qualified at CMS radiation levels

  - **Low Gain Avalanche Diodes (LGADs)**
    - Gain $O(10)$ - Three suppliers (FBK, CNM, HPK)
    - Additional doping layer to achieve gain

  - **Ultra Fast Si Detectors** – Drift region $\sim 50 \mu m$
    - to limit Landau fluctuations
    - Small pads to limit capacitance

Details on the technology in M.Obertino’s talk
Endcap sensors (ultra-fast Si detectors)

- **Nominal geometry:** 4.8 x 9.6 cm² modules with 1x3 mm² pads
  - 16 ASICs bump-bonded to sensors (ASIC being developed)
  - 3:1 ganging in the TDC at small $\eta$ (3x3 mm² 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)

Inner rings

- 4 channels
- ROC for small pixels
- 24 channels

Outer rings

- 4 channels
- ROC for large pixels
- 8 channels

1 channel is 3x3 mm²

**Irradiated, Medium Dose**

J. Lange, JINST, P05003 (2012)

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

Glass+ALD 5x5 cm²

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
- **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
- **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!
Luminous region
Examples (w/o timing information): the anti-luminosity effect

- VBF $H \rightarrow \tau\tau$ requires >40% more luminosity at 200 than 140 PU
- Jet fake rate and $E_T^{\text{miss}}$ resolution
- Searches with $E_T^{\text{miss}}$ 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
Above gain ~20 resolution is determined by charge non-uniformity (Landau fluctuations)