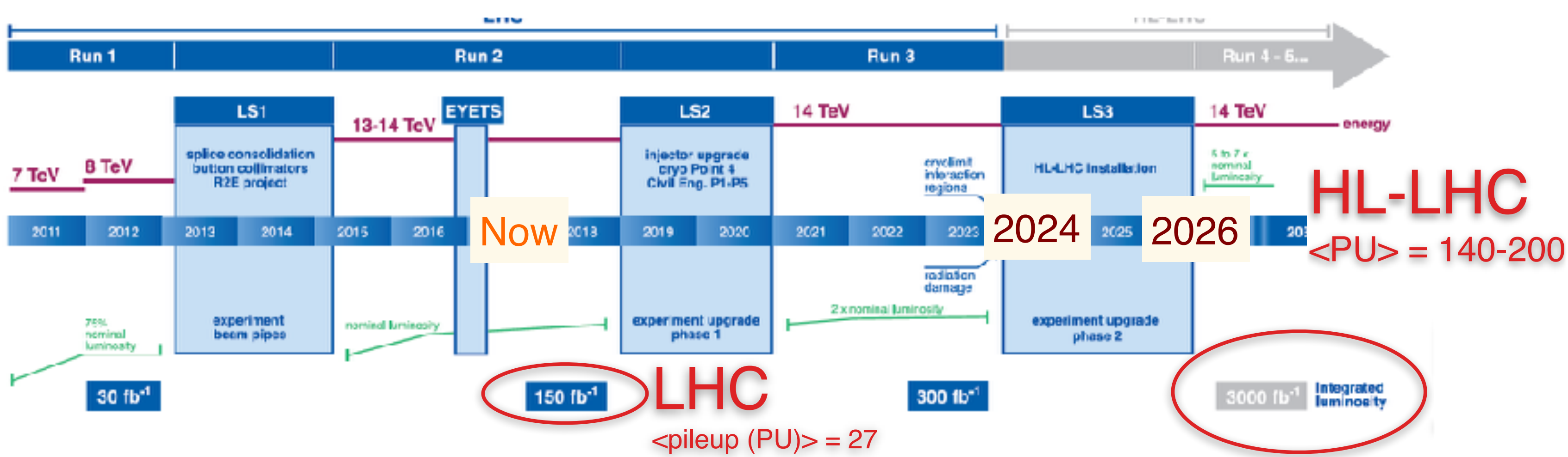
Studies of precision time-tagging with scintillating crystals for the Phase-II upgrade of CMS

Tommaso Tabarelli-de-Fatis – on behalf of CMS
Università and INFN di Milano Bicocca (Italy)

Scint 2017 – Chamonix – Sep 18

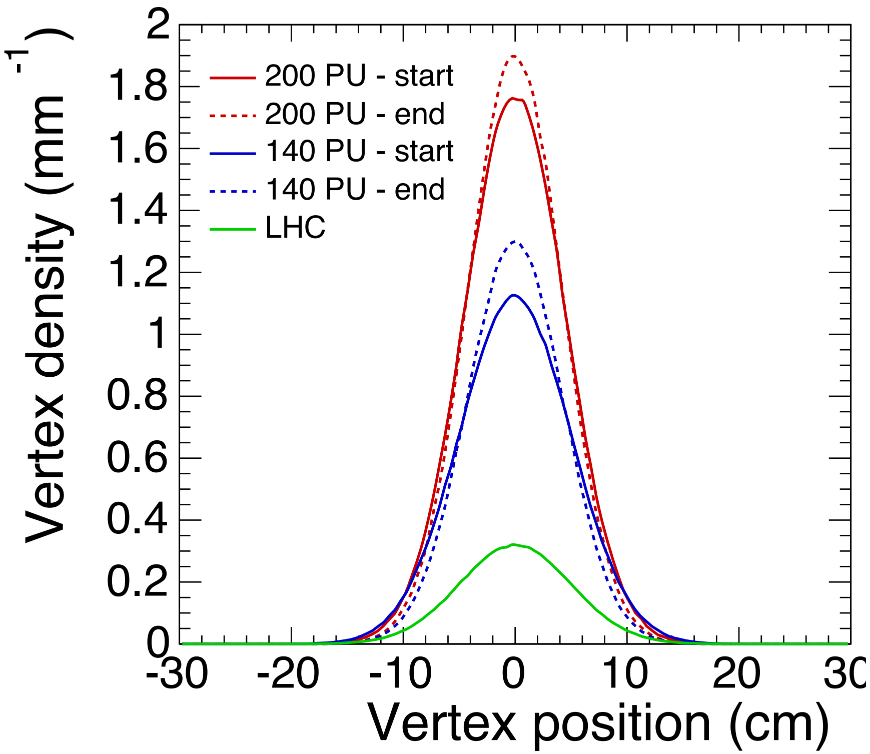
High Luminosity – LHC (Phase-II)

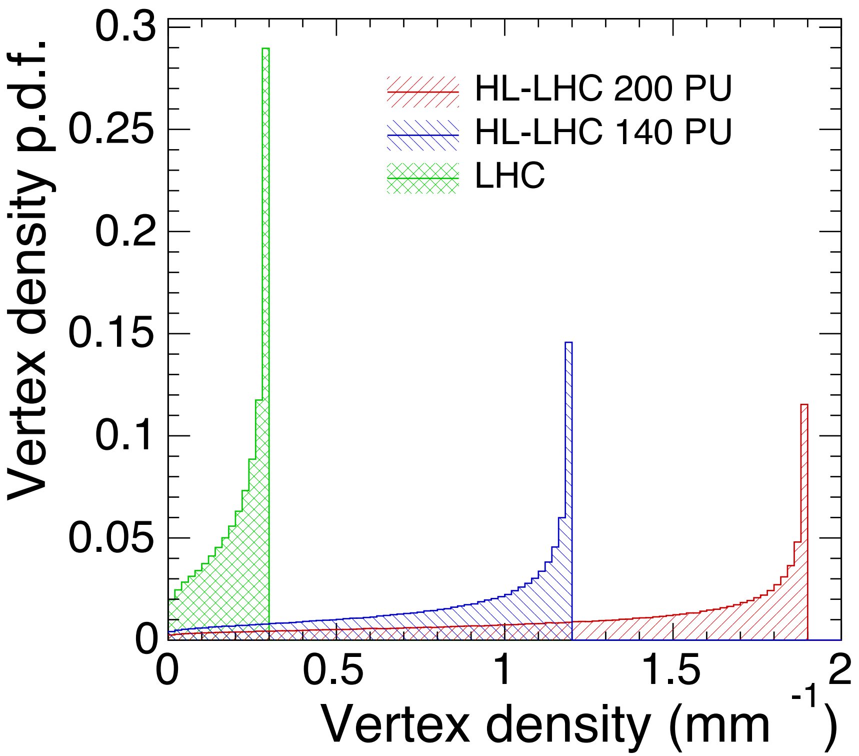


- **HL-LHC:** Upgrade of LHC and injectors to increase beam intensity
  - $L_{inst} > 5 \times 10^{34}$ cm^{-1} s^{-1}, up to 140-200 pileup
  - Ultimate integrated luminosity target of 3000 fb^{-1} (10x LHC) - baseline

- **Experiments:** ATLAS and CMS upgrades for HL-LHC conditions
  - Radiation hardness
  - Mitigate physics impact of high pileup (more than 5x LHC)

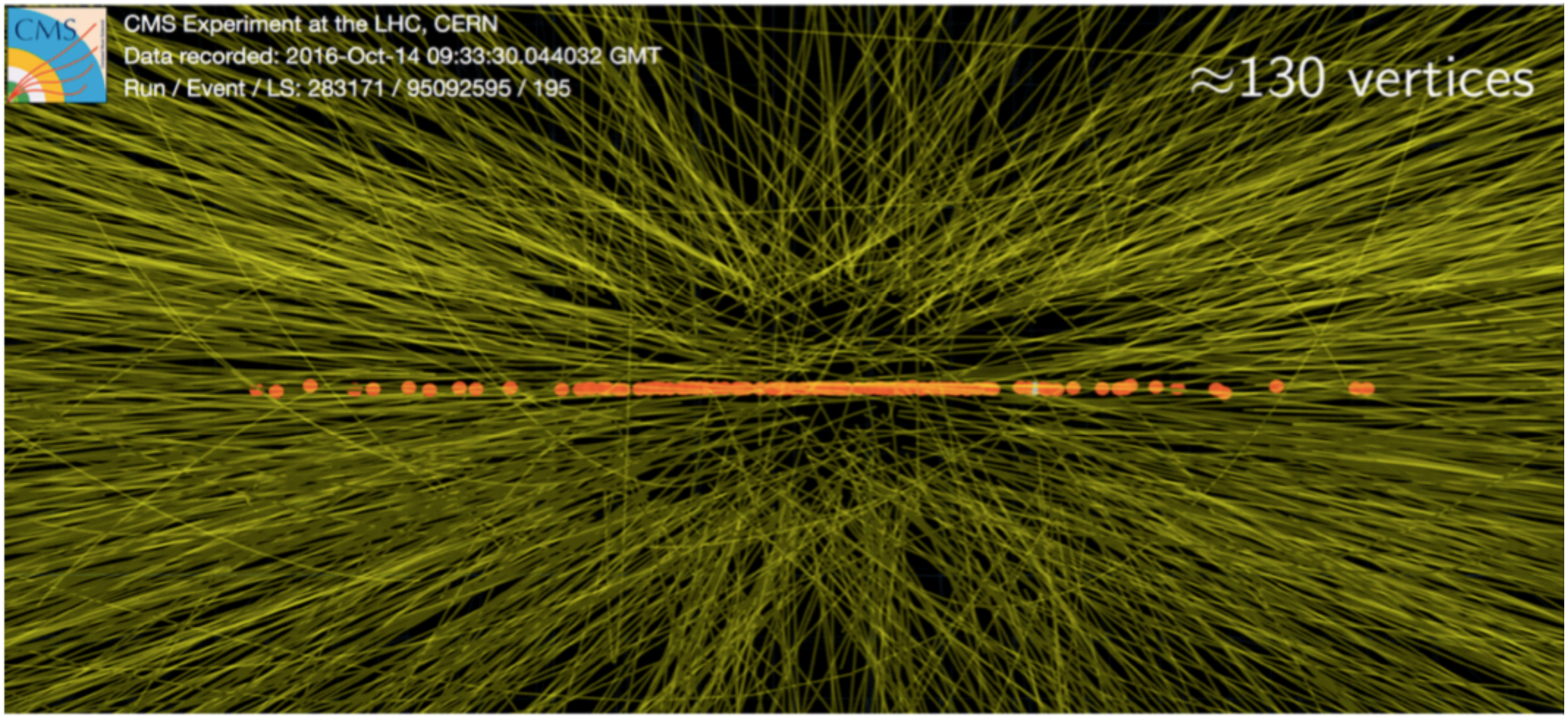
Luminous region





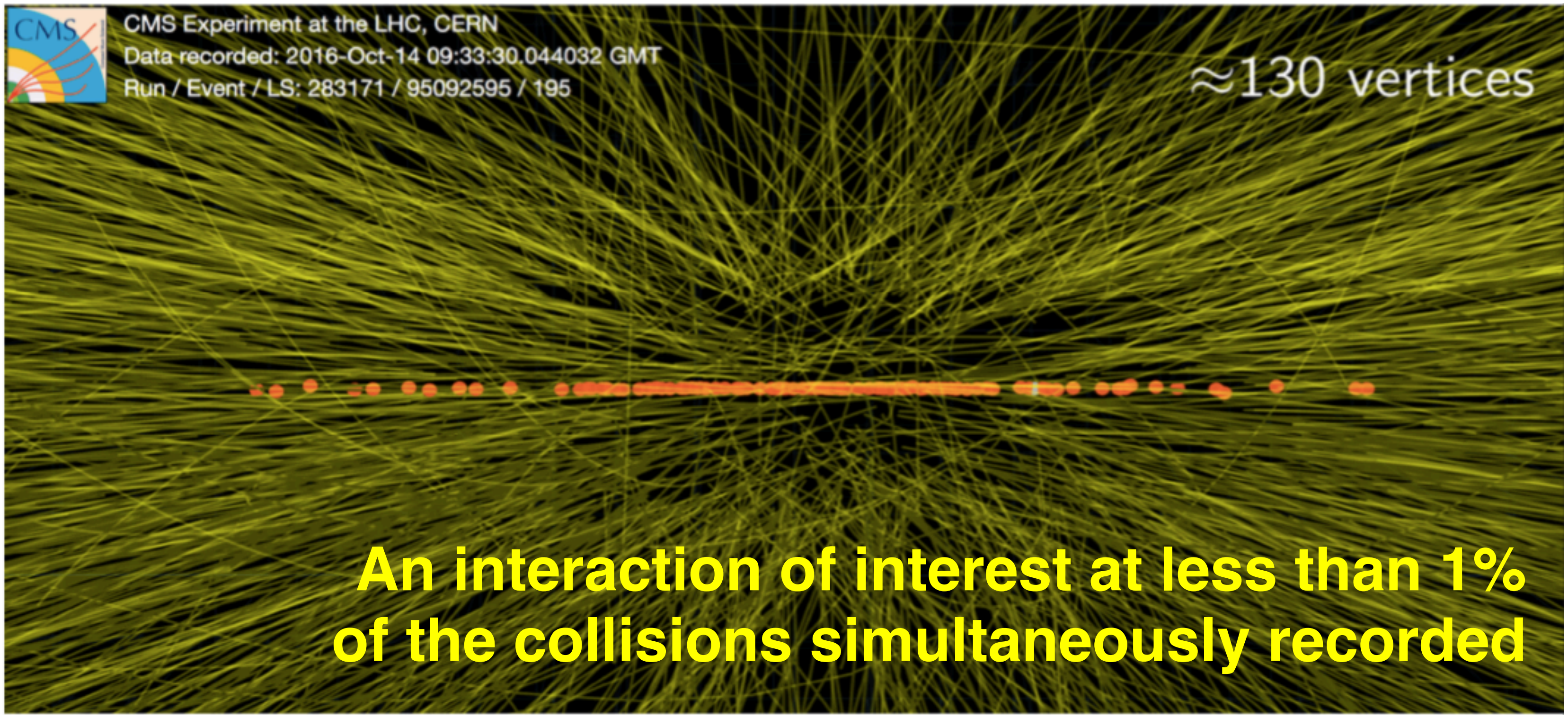
- **Luminosity leveled to "what the experiments can stand"**
  - Adjust the beam transverse size at the interaction point (β* function)
- L_{inst} = 5.3×10^{34} cm^{-2} s^{-1} → 140 pileup
- L_{inst} = 7.6×10^{34} cm^{-2} s^{-1} → 200 pileup

Proof of concept



- **Real life event with HL-LHC-like pileup from special run in 2016 with individual high intensity bunches**
  - One such collision every 25 ns at HL-LHC

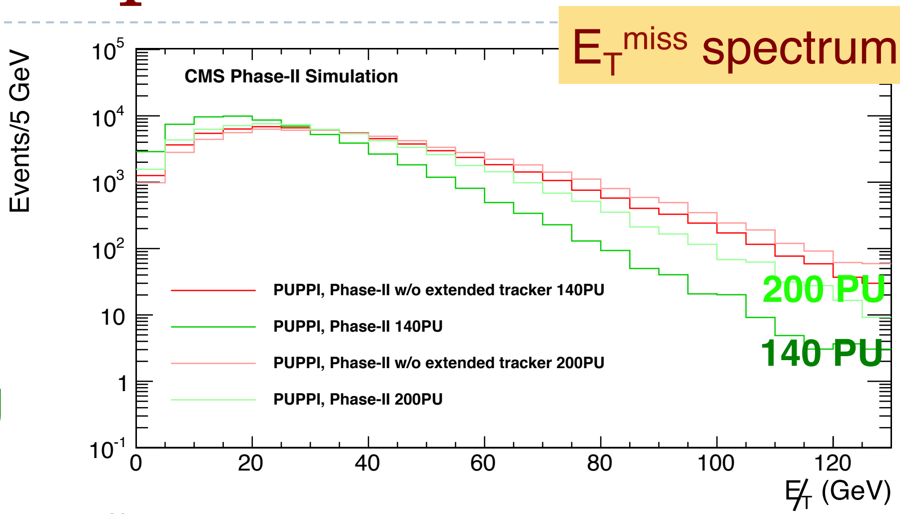
Proof of challenge !

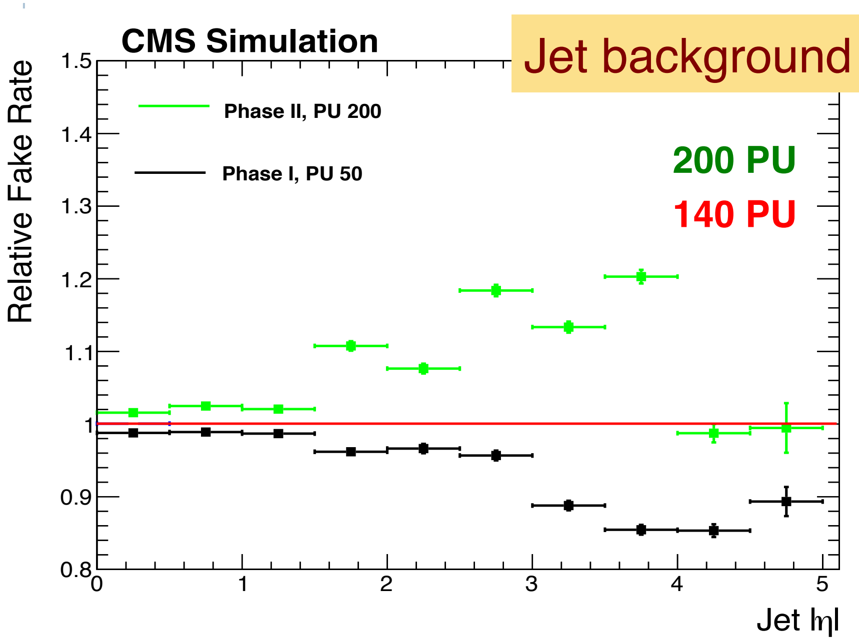


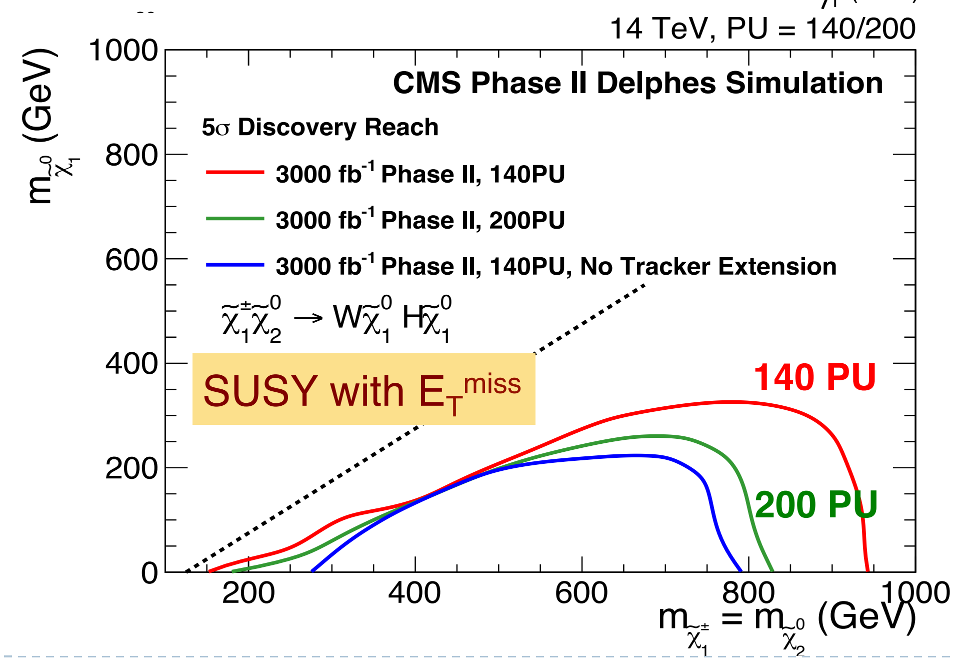
- **Vertex merged in ~15% of the cases at 200 PU**
  - Hardest reconstructed collision not necessarily the most interesting
- **Incorrect association of tracks (and neutrals) with vertices**
  - Degradation in local and global event observables
  - Incorrect reconstruction of the event kinematics

Physics impact by example

- **VBF H→ττ requires >40% more luminosity at 200 than 140 PU**
  - Jet fake rate and E_T^{miss} resolution and tau isolation
- **Searches with E_t^{miss} less sensitive at 200 PU than 140 PU**





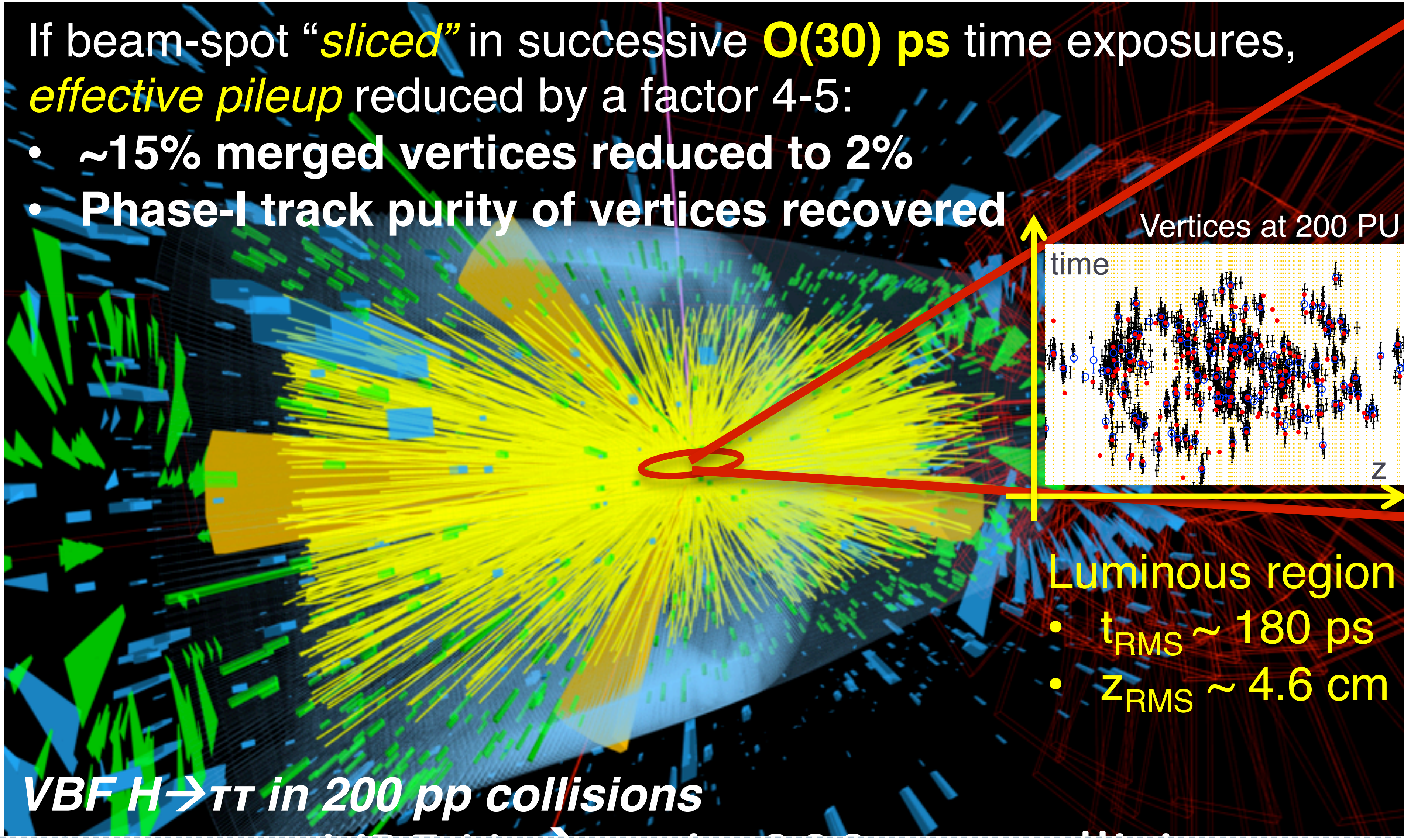


Reference: CMS Upgrade Scope document: [CERN-LHCC-2015-19, LHCC-G-165]

Mitigation of pileup with precision timing

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**

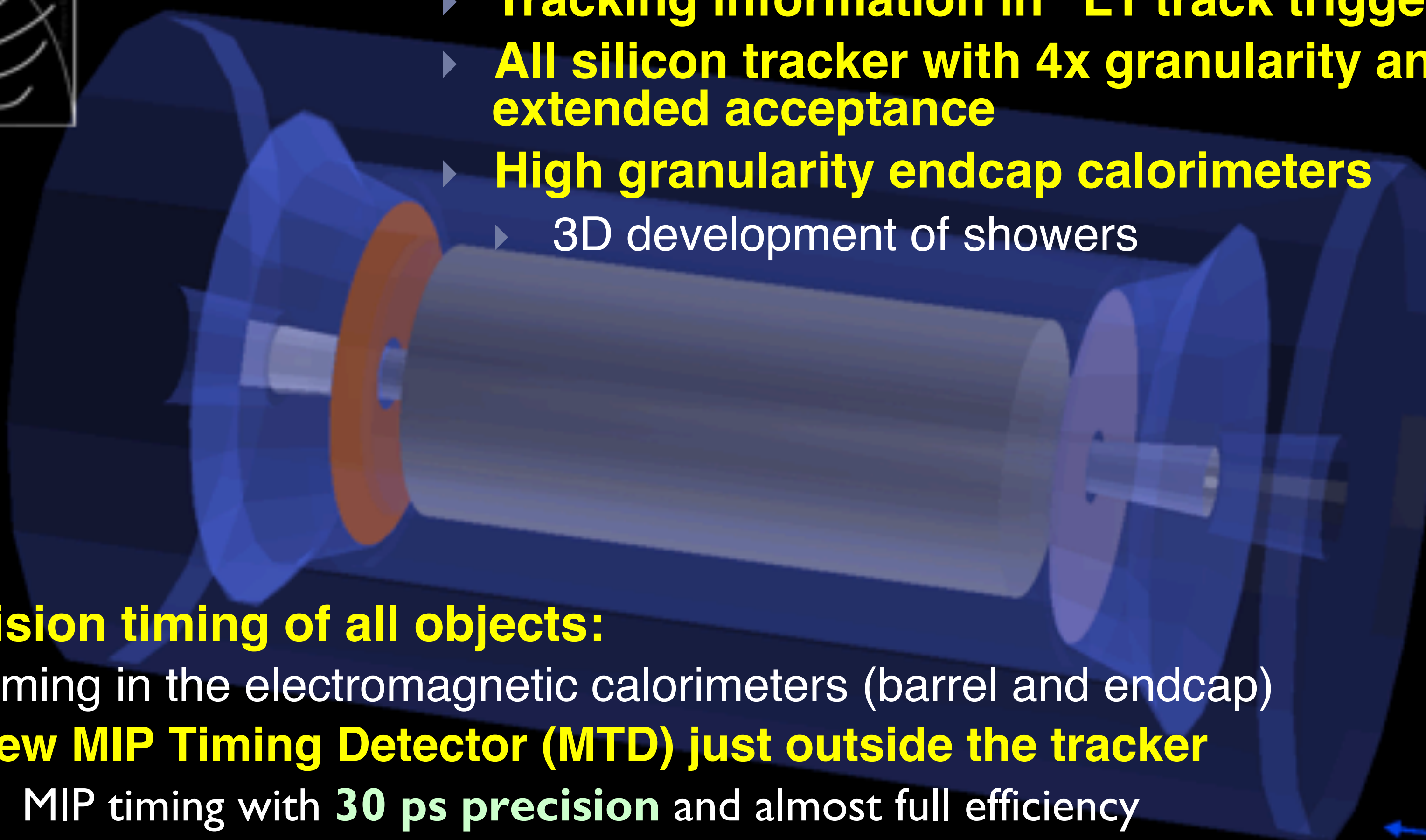


Luminous region

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

VBF H→ττ in 200 pp collisions

Bold aspects of CMS upgrade for Phase-II



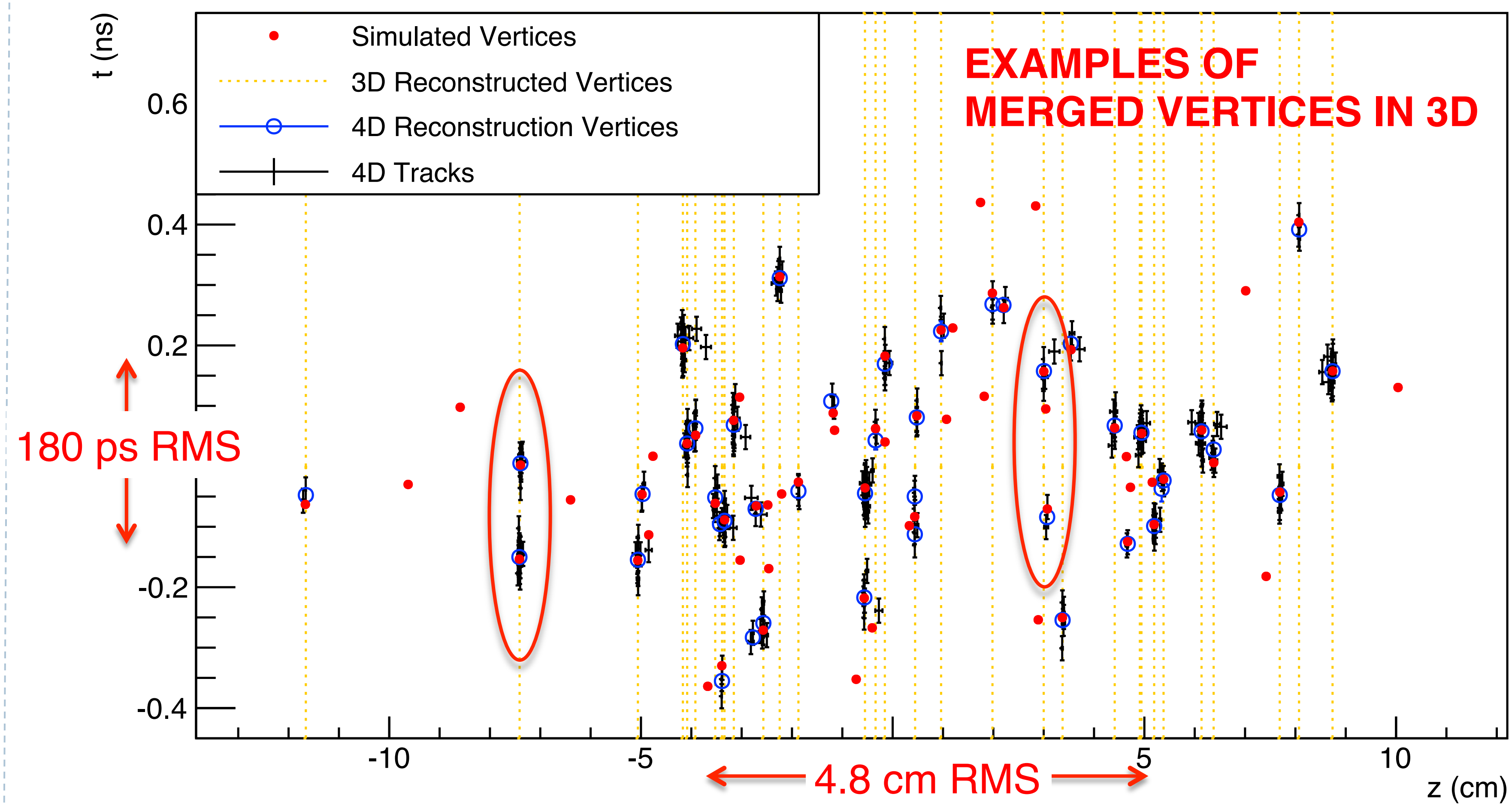
- **Level-1 trigger accept rate 750 kHz**
- **Tracking information in "L1 track trigger"**
- **All silicon tracker with 4x granularity and extended acceptance**
- **High granularity endcap calorimeters**
  - 3D development of showers

+ Precision timing of all objects:

- Timing in the electromagnetic calorimeters (barrel and endcap)
- **New MIP Timing Detector (MTD) just outside the tracker**
  - MIP timing with **30 ps precision** and almost full efficiency
  - **Acceptance: $|\eta|<3.0$ and $p_T>0.7$ GeV**

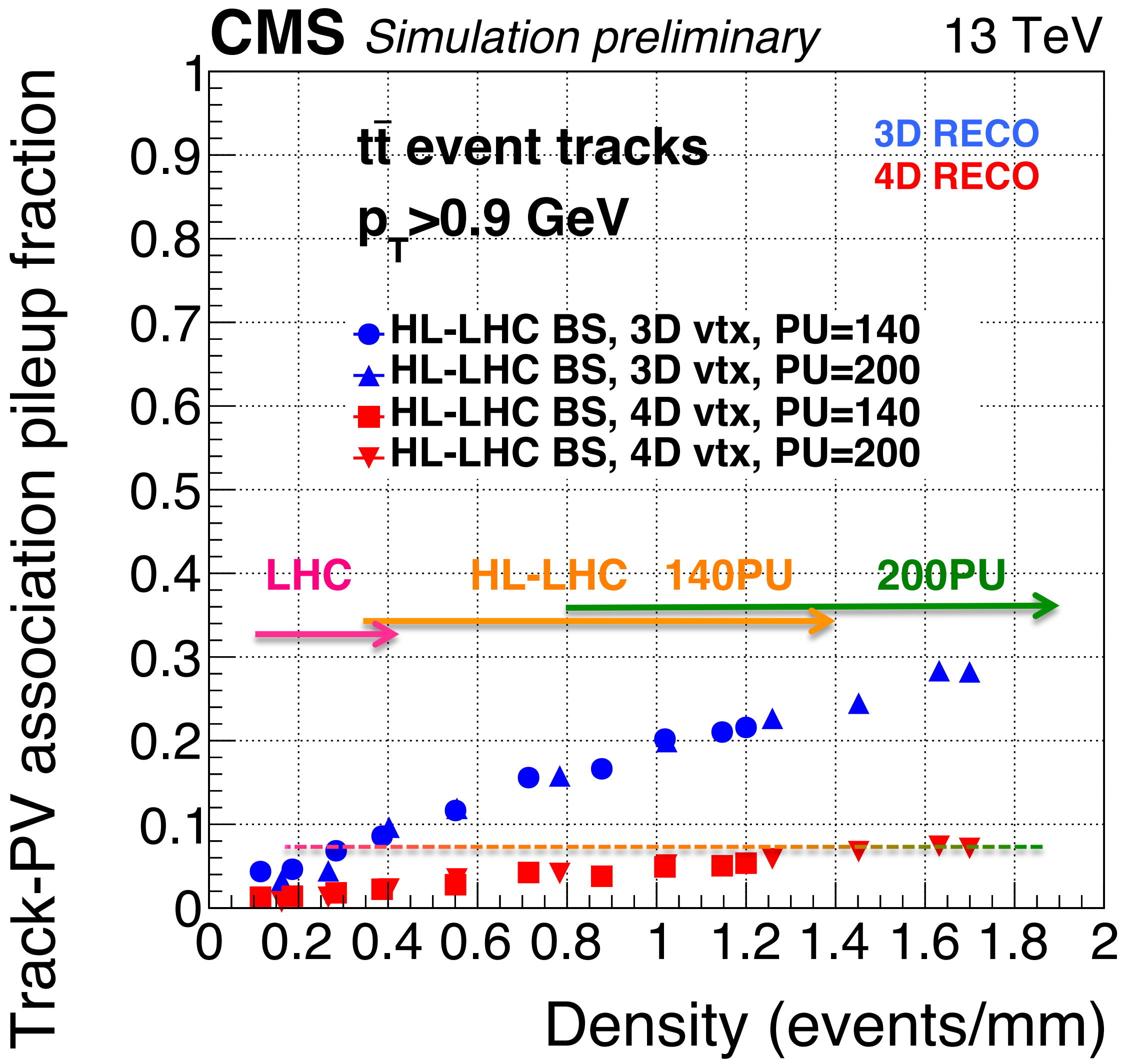
Example of time-aware vertexing

- **Event with 50 pileup collisions to ease eye analysis**



- 4D reconstruction with track time information: σ~25 ps

Track-vertex association – with track timing

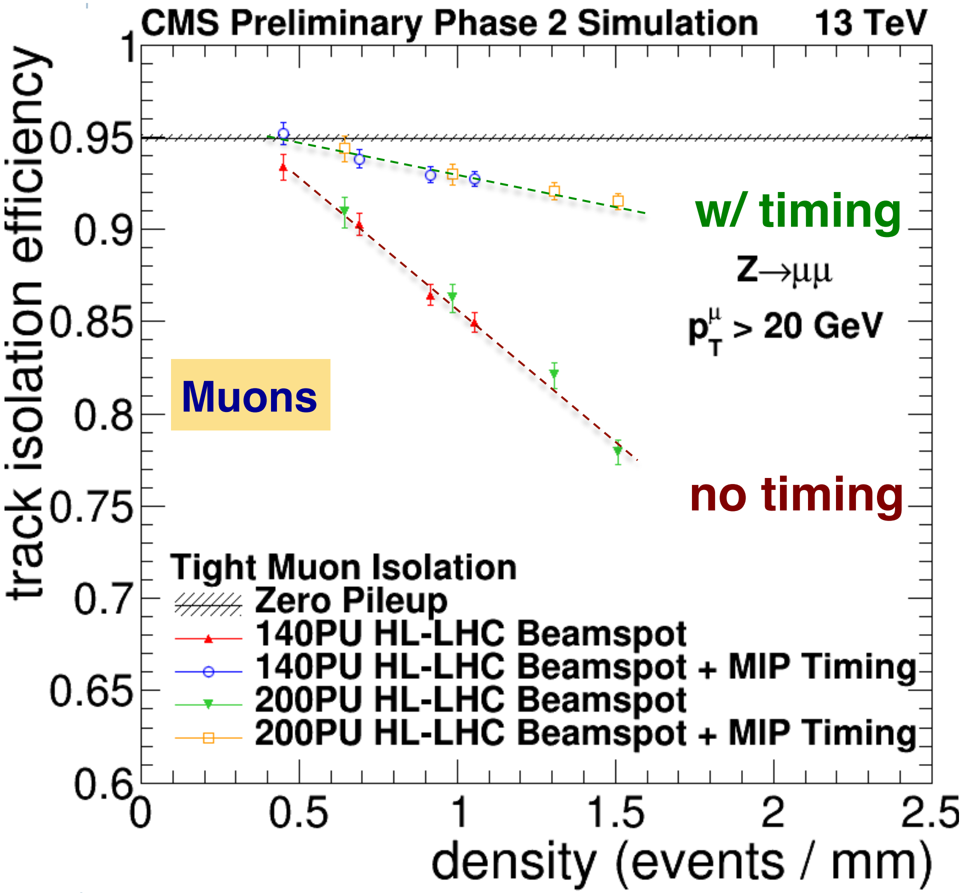


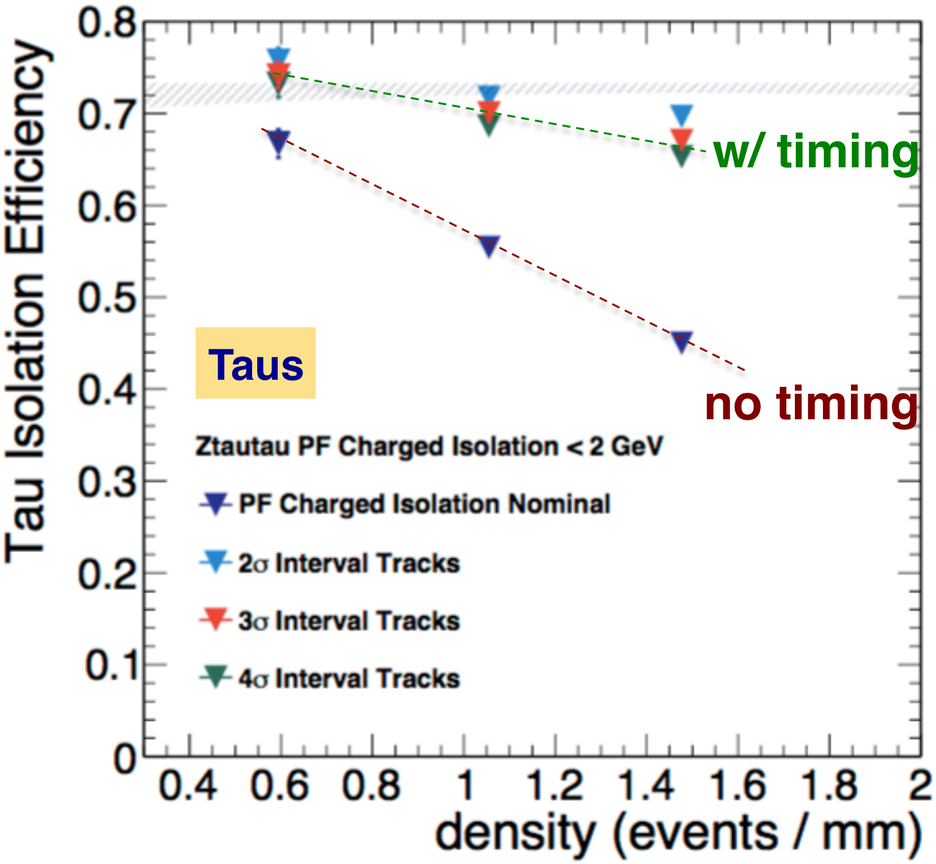
- **With timing, 'effective vertex density' down to LHC level !**

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**

Performance gain: one example





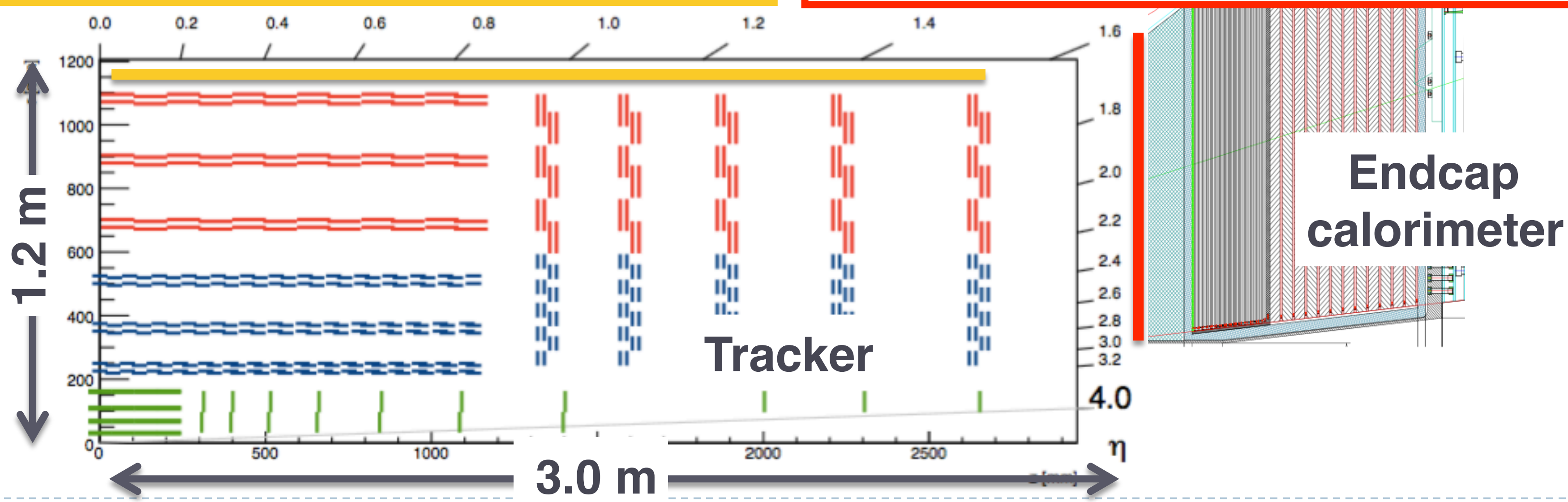
- **Isolation efficiency for constant background rejection power**
  - Performance degradation due to pileup offset by time aware reconstruction
  - [Gain also in pileup jet rejection, missing energy reconstruction, etc.]

MTD: technologies under study

- Immunity to magnetic field (3.8 T)
- Radiation: **$2x10^{14}$ (barrel)** and **up to $2x10^{15}$ n/cm^2 (endcap)**
- Minimal impact on the calorimeters performance
- Schedule, power, service, and space constraints

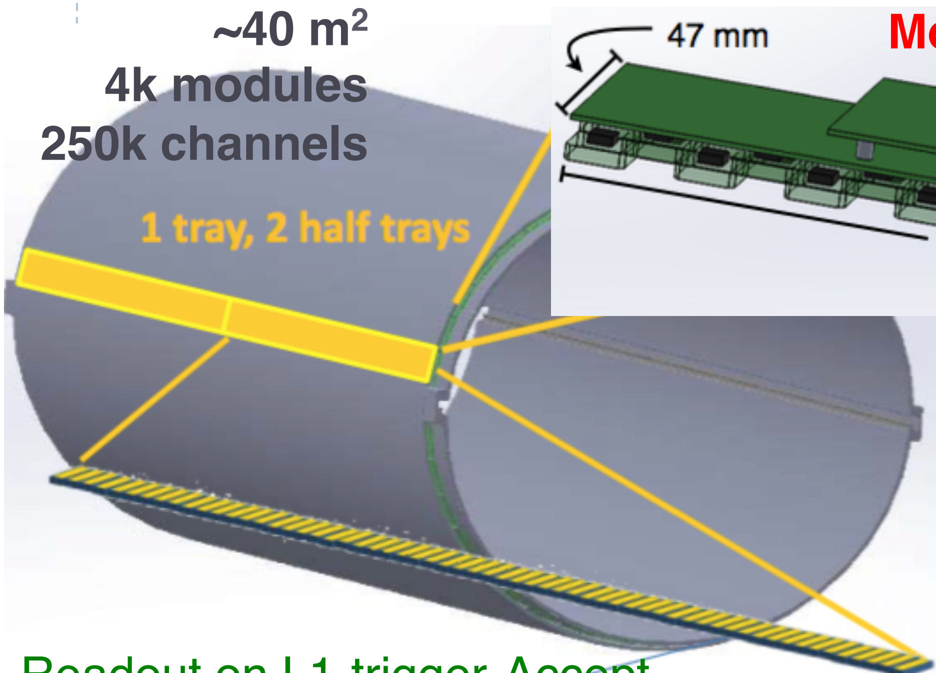
LYSO/LSO tiles with SiPM readout:
- At the end of the tracker
- Surface ~40 m^2
- Installation - 2023

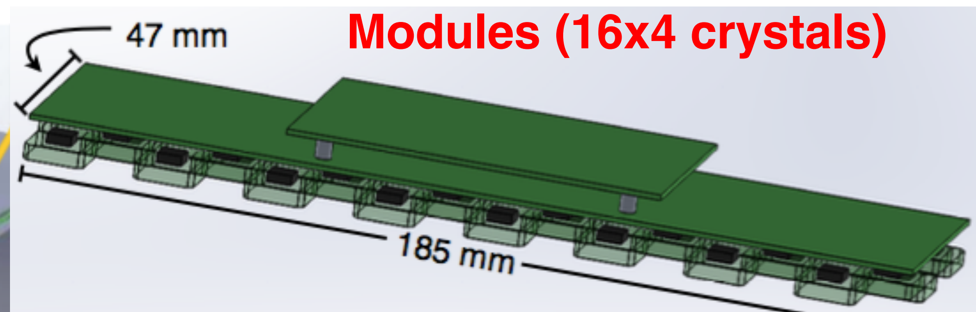
Si with internal gain (LGAD):
- In front of the new endcap ECAL
- Surface ~9 m^2
- Installation - 2025

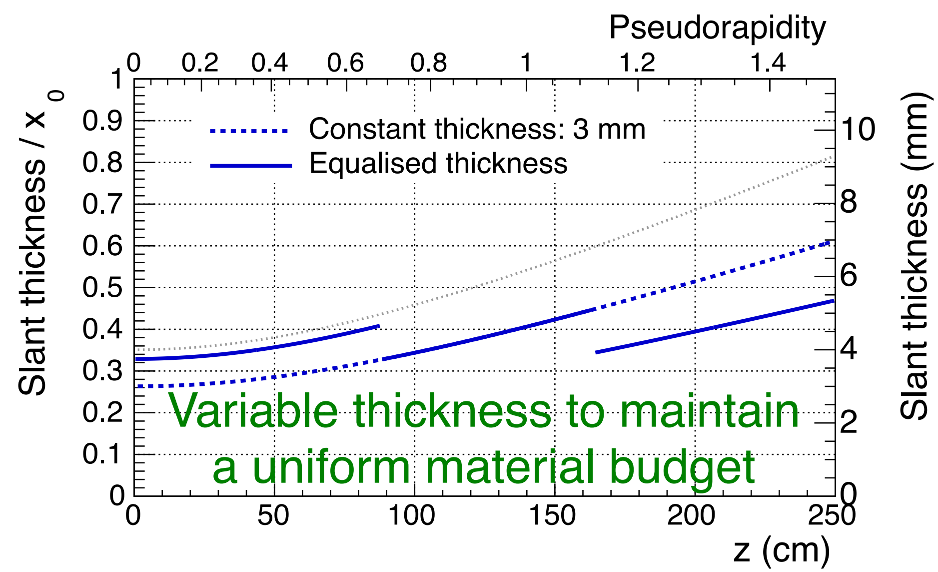


Barrel timing layer (BTL) layout

- **LYSO/LSO:Ce + SiPMs embedded in the tracker support tube**
  - Production-ready and scalable technology
  - CO_2 cooling at ~ –30 ^{0}C (limit SiPMs self-heating and dark rate)





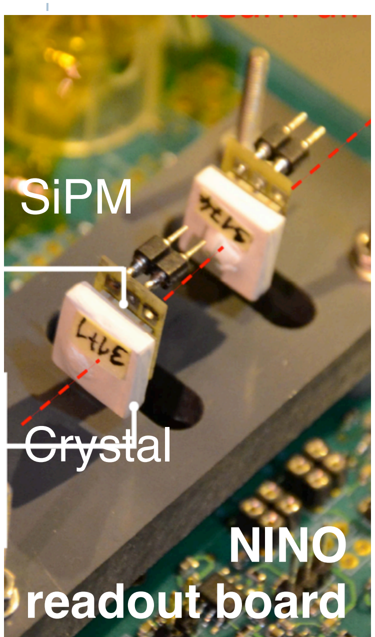


Readout on L1-trigger-Accept

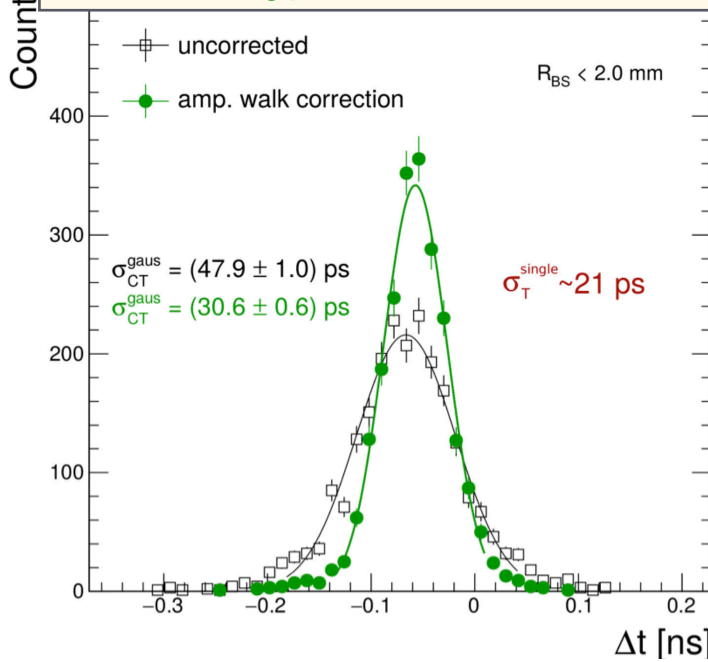
- 3% occupancy (0.5 mip threshold)
- **Adapt TOFPET2 ASIC**
  Leading edge timing + amplitude meas.

BTL tile time resolution

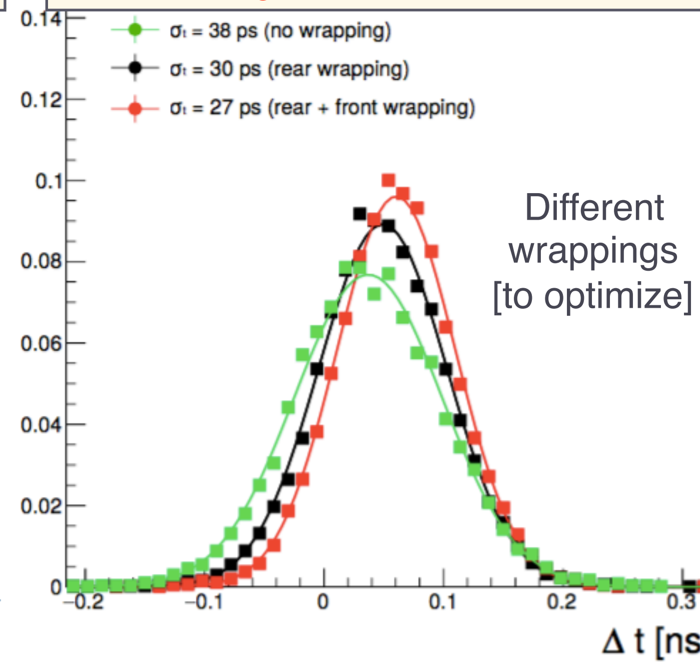
- **Nominal geometry: 11 x11 mm² + 4x4 mm² SiPMs**
  - Slant thickness ~ 4 mm
- **Production-like geometries qualified in test beams**
  - Aligned crystals in a parallel beam or impact point restricted
  - Amplitude-walk correction



10x10 x 3 mm³ – HPK 6x6 mm²
$\sigma_{CT} / \sqrt{2}$ = 21 ps



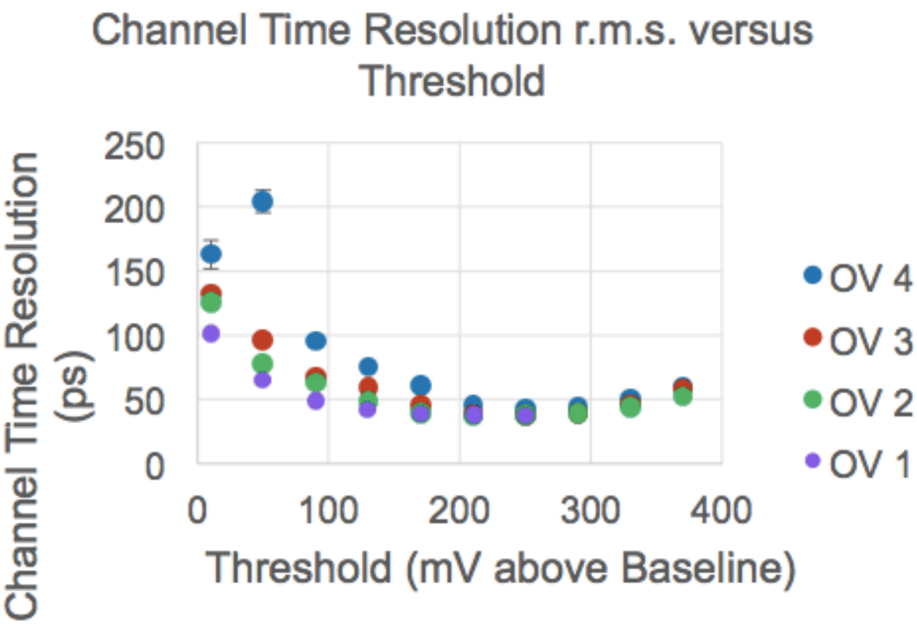
11x11 x 3 mm³ – FBK 5x5 mm²
$\sigma_{CT} / \sqrt{2}$ = 27 ps



BTL ASIC tests

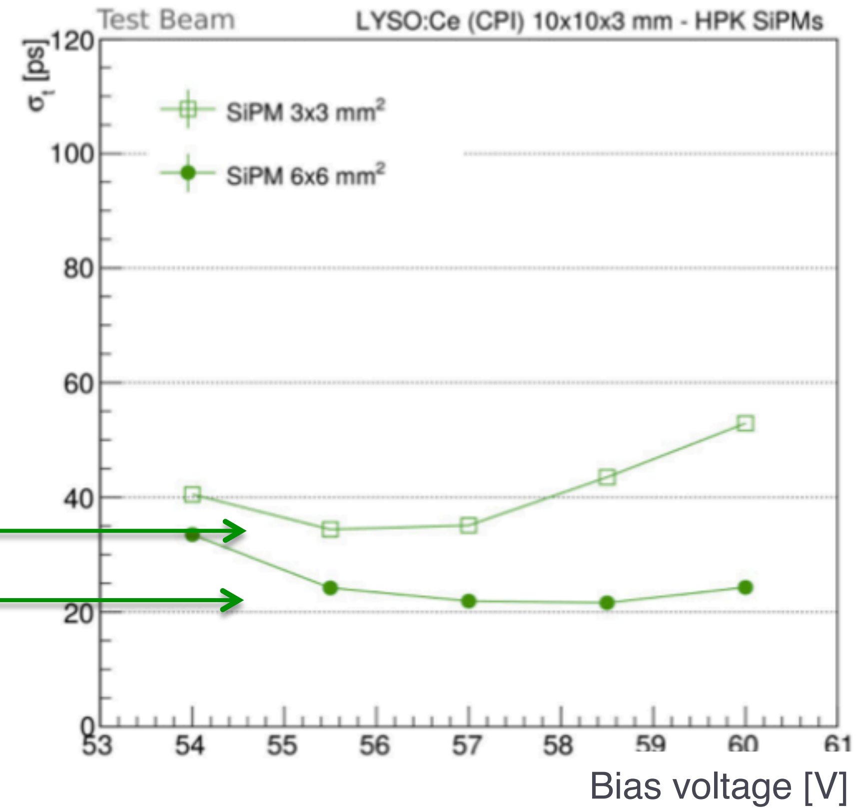
J.Varela et al.

- **TOFPET2 resolution close to NINO + waveform digitizer**
  - **Time resolution RMS: 37 ps** [25 ps with NINO, same setup]
- **Reasons for the difference understood**
  - Pulse slew rate (amplifier configuration) and TDC contribution
  - Will be corrected in BTL tailored ASIC (TOFHiR)
  - Radiation hard design in parallel



SiPMs+Crystal optimization

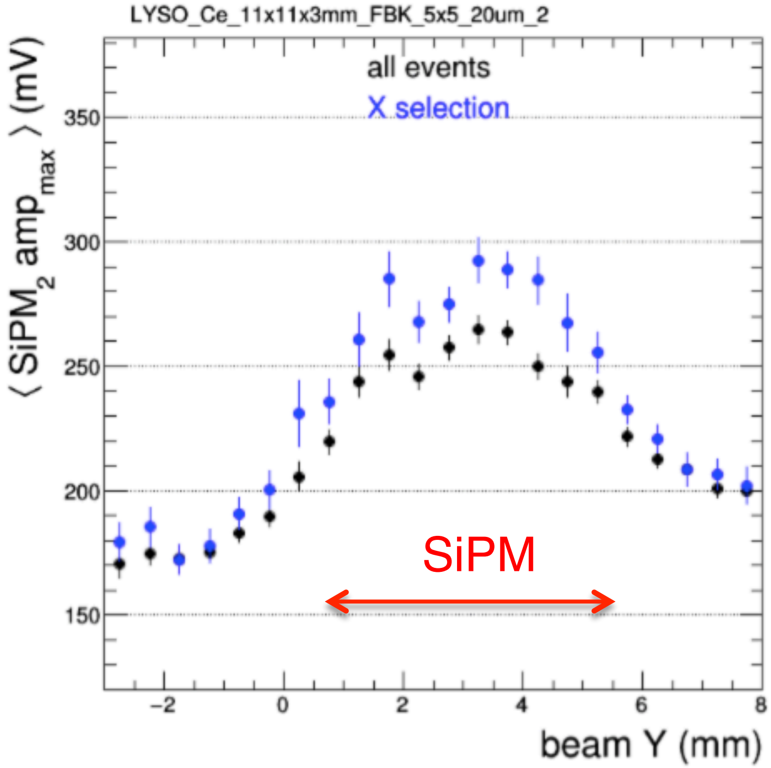
- **Small area SiPMs preferable (mandatory)**
  - Dark Count Rate (DCR) and power consumption with radiation
  - Capacitance
- **Large area SiPMs provide better resolution:**
  - CTR/√2 of two 10x10 mm² crystals in a parallel beam
  - Time-walk correction applied
  - 3x3 mm² SiPMs : 35 ps
  - 6x6 mm² SiPMs : 21 ps



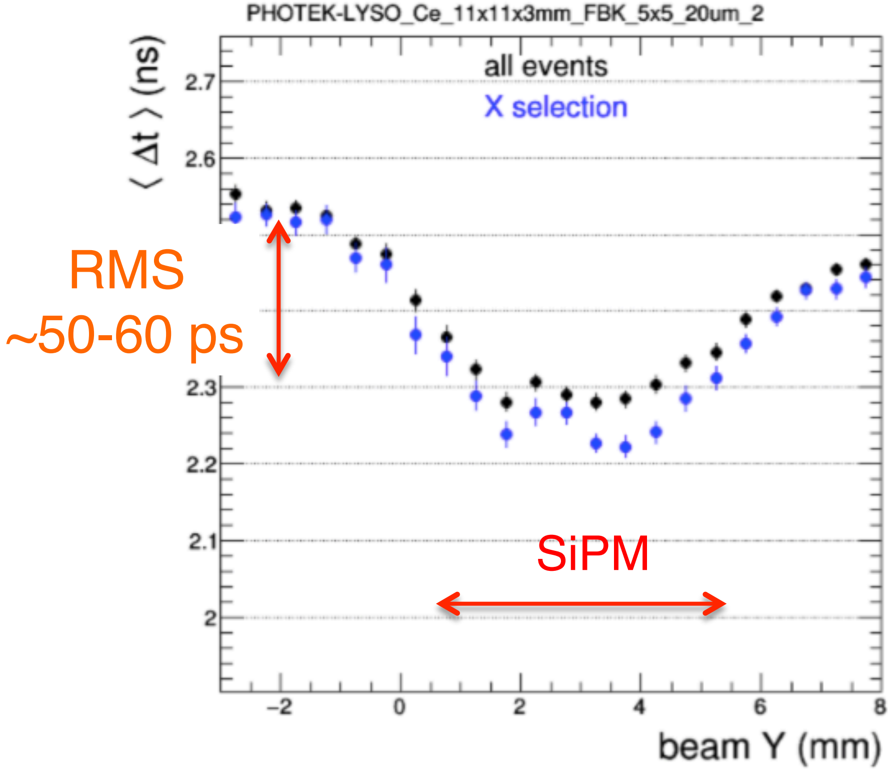
- **Not only a photon detector efficiency (PDE) effect…**

Dependence on the impact point

Amplitude variation
[light collection efficiency]



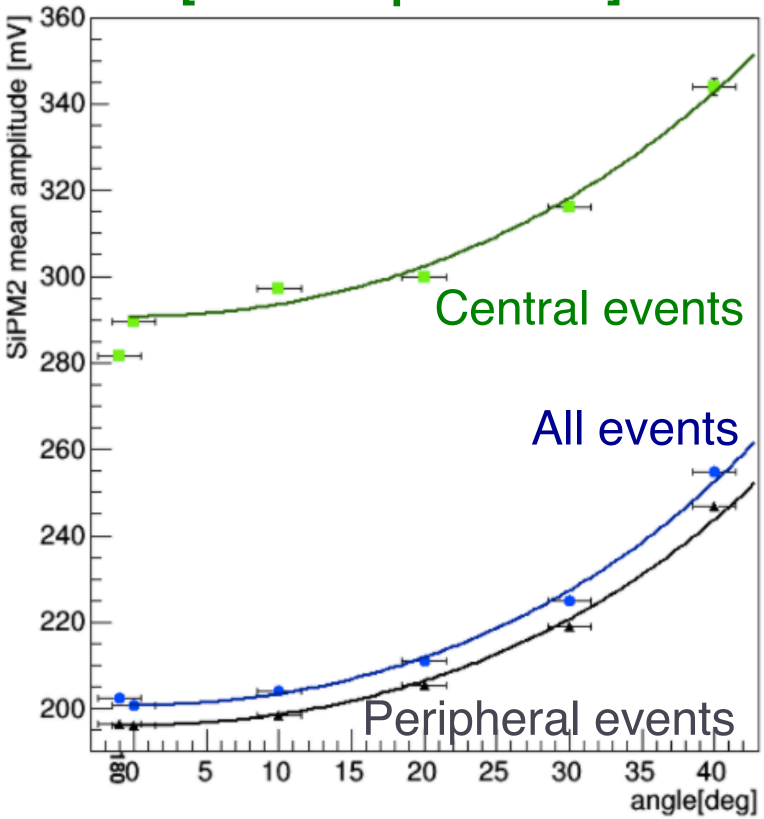
Δt relative to a reference MCP
[light path/components variation]



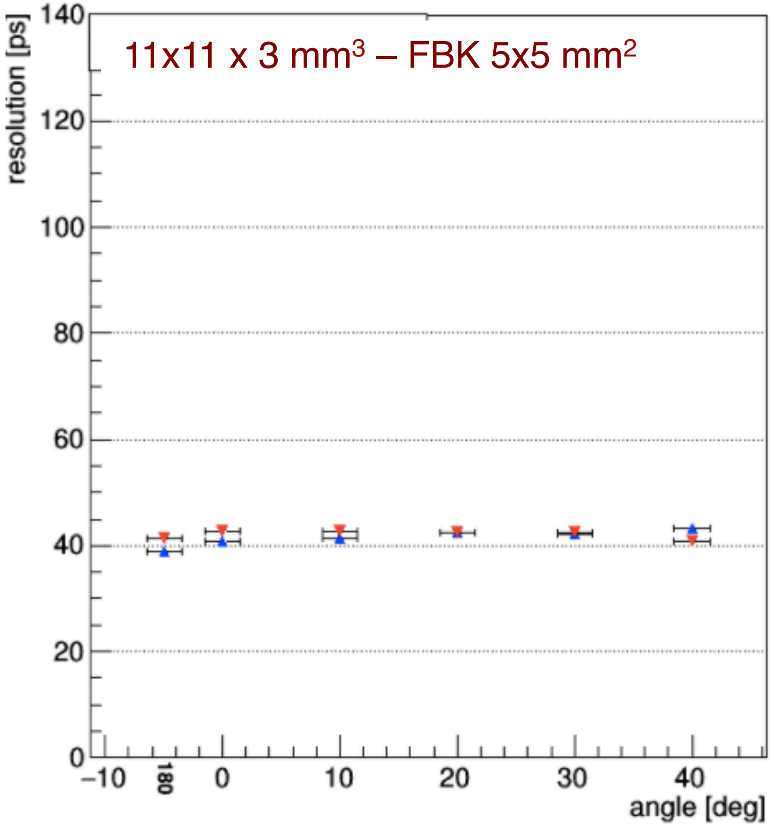
- Requires position dependent correction with ~2 mm precision
- Or more uniform surface coverage (at constant active area)

Dependence on the angle of incidence

Amplitude variation
[slant depth effect]



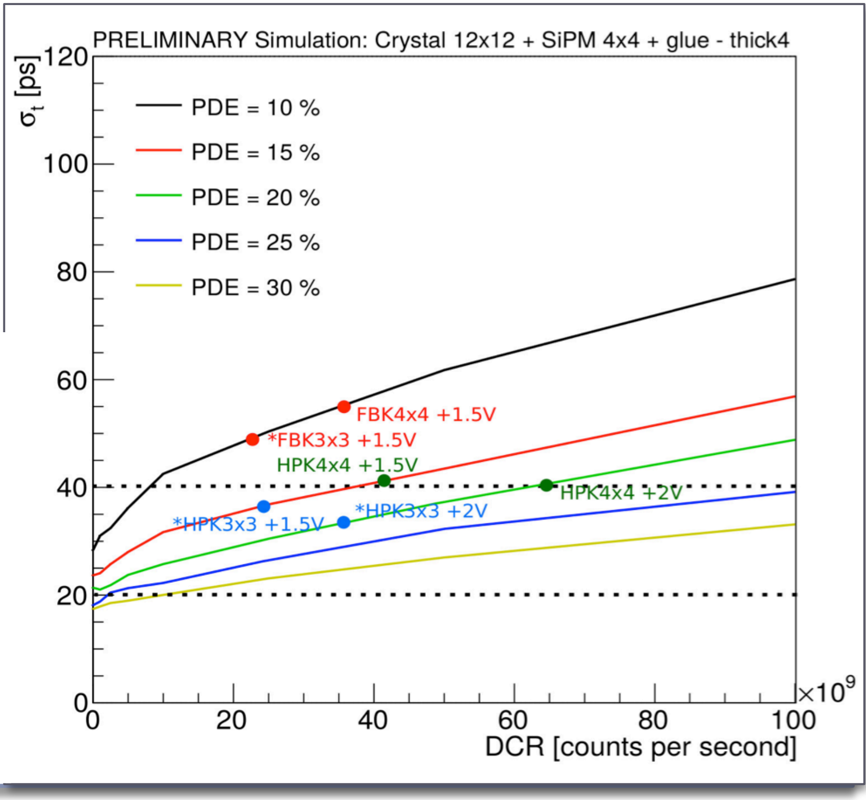
Time resolution



- **Time resolution independent of the angle**
  - After amplitude walk and position correction (universal)

BTL tile radiation hardness

- **Radiation fields at the end of HL-LHC**
  - Fluence: 1.3-1.6 × 10^{14} n_{eq}/cm^2
  - Dose: 20 kGy
- **LYSO tiles:**
  - Negligible induced radio-luminicence and light loss [RIAC = 3 m^{-1} at $1x10^{15}$ cm^2 and 100 kGy]
- **SiPMs: Time resolution degradation from increased DCR: 20 ps → 40 ps**
  - **Lines**: resolution from simulation with different PDE and DCR
  - **Points**: extrapolation to $2x10^{14}$ n_{eq}/cm^2 of SiPMs irradiation studies
    - A.Heering et al. NIMA 824 (2016) 111



- **Room for optimization: reflective wrappings, SiPMs size / layout, thicker tiles, …**

Why LYSO/LSO?

- **Well characterized for PET scanners and EM calorimeters**
  - Available, radiation hard, relatively fast and bright
  - Matches the target performance for this application
- **Yet, not necessarily the best choice for MIP timing with leading edge time discrimination**
  - **Photons beyond ~100 ps not exploited**
  - **High Z unnecessary (unwanted)**
    - Radiation length grows with Z (in front of a calorimeter)
    - Scintillation yield scales with the mass thickness (**ρd**)
    - Cherenkov yield scales with the thickness (**d**)
  - **Cost is relatively high compared to other crystals**

	n	X_0 [cm]	d [mm]	d [(X_0)]	C Yield	Scint. Yield [first 40 ps]
LSO/LYSO	1.8	1.1	3	0.27	80 / eV	~90

- **In want of a fast crystal with d_{max} <6 mm and <0.3 X_0**

Summary

- **The exploitation of the HL-LHC physics potential requires significant upgrades to CMS**

- **30 ps MIP timing provides crucial discriminating information for resolving 140-200 PU vertices**
  - *Phase-I track purity of vertices recovered at 200 PU*

- **Technology is within reach:**
  - Room for significant optimization: crystal choice, SiPM selection and optimization and SiPM+Crystal matching