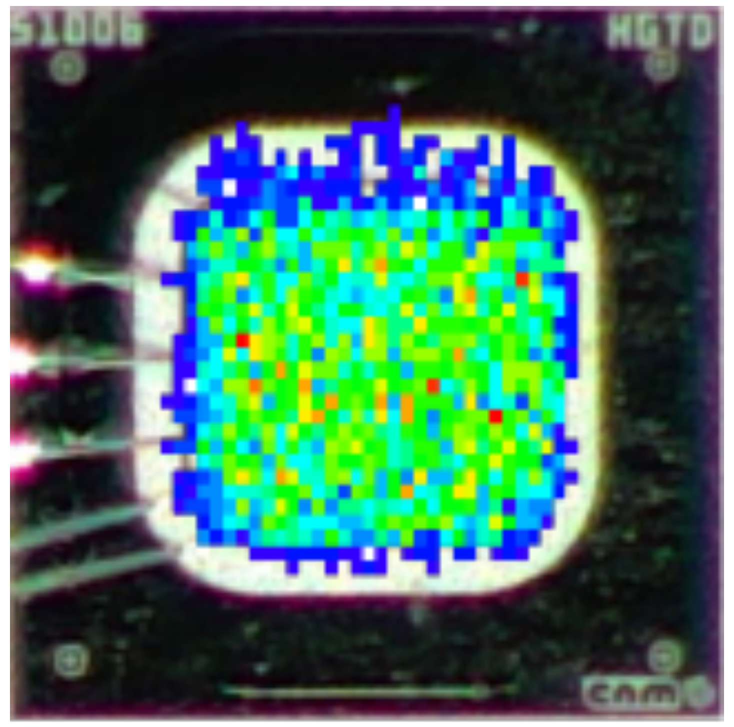
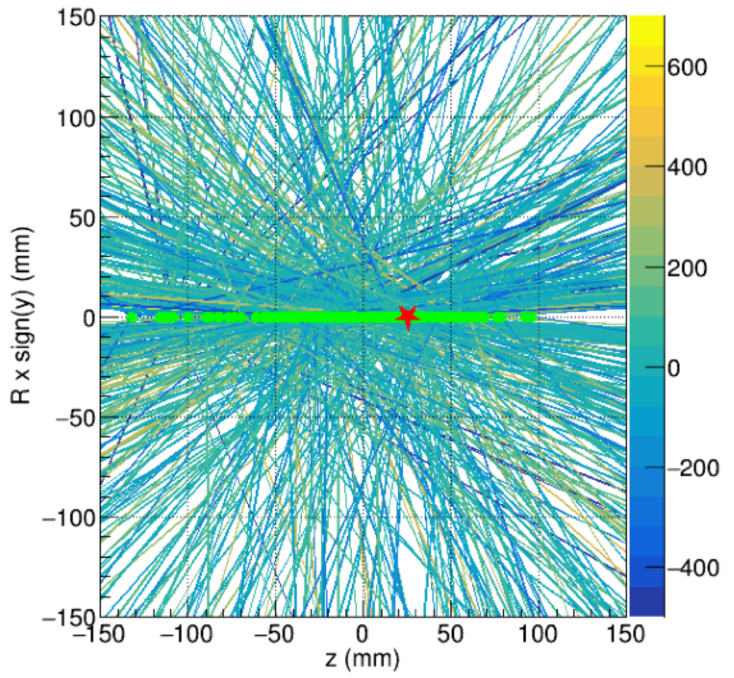
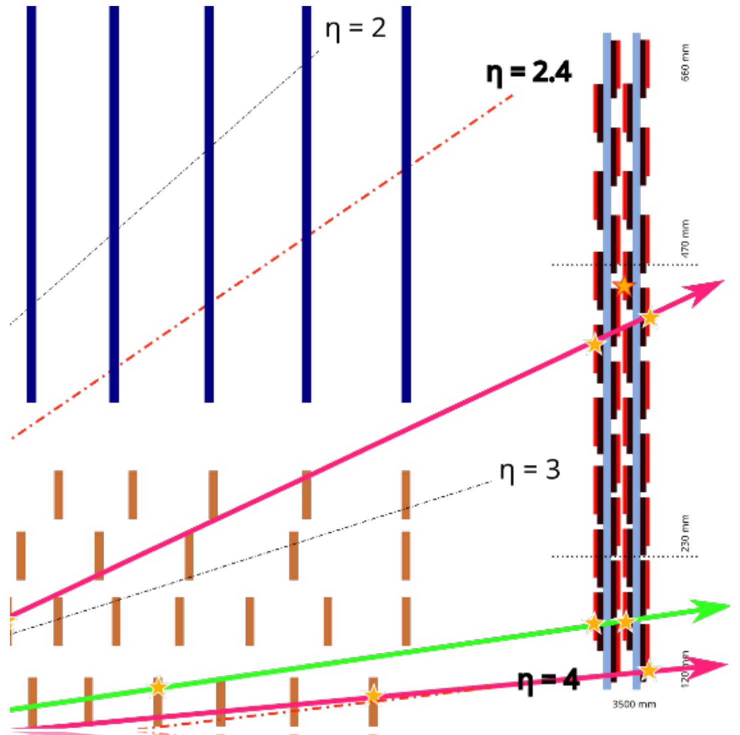
Pileup suppression with timing detectors

Mengqing Wu *(Radboud University & Nikhef)*
On behalf of the ATLAS HGTD group

LHCP 2024, Boston, Oct 3-7 2024







Radboud University
Nikhef
ATLAS EXPERIMENT
LHCP Boston 2024

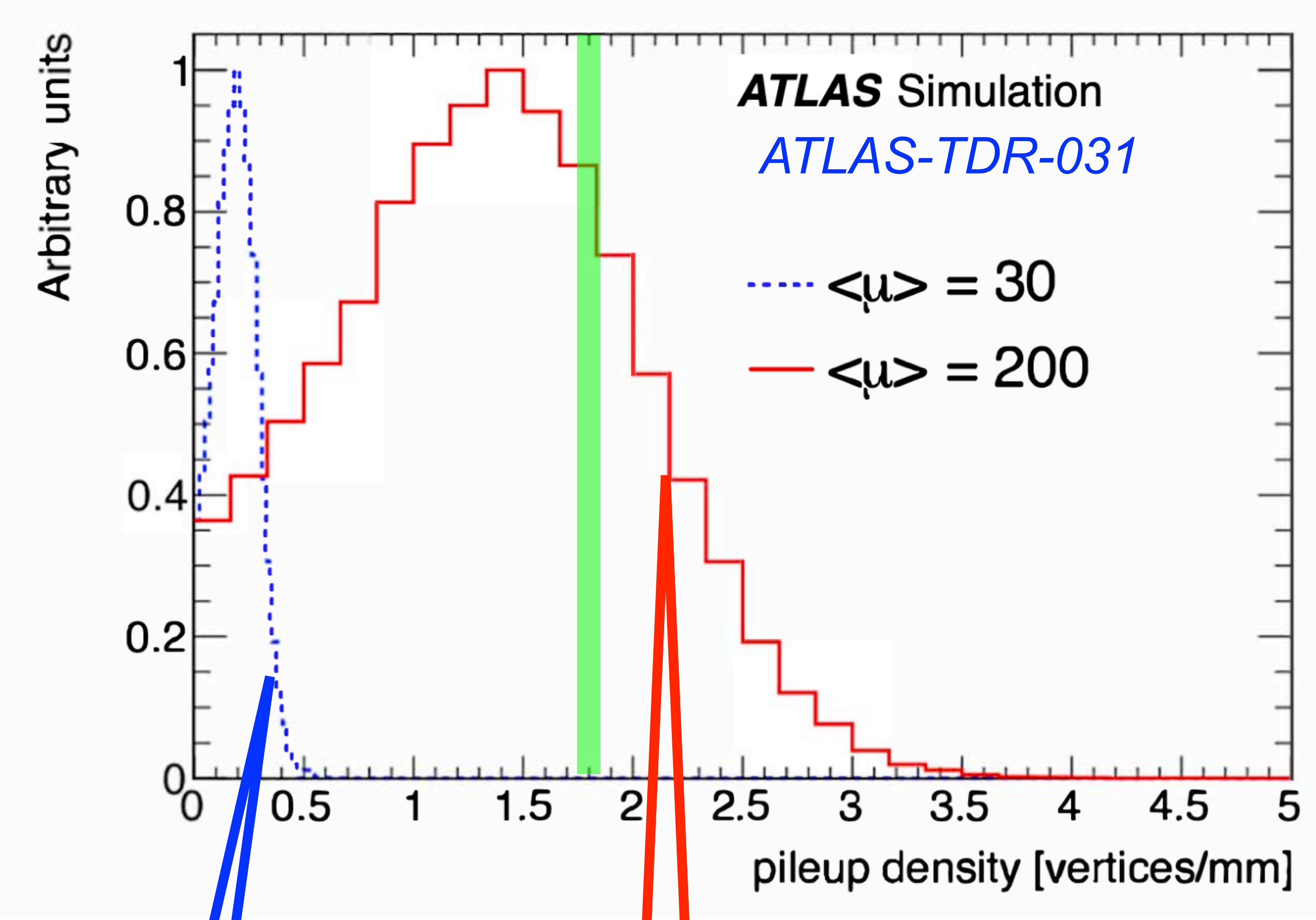
Challenges on Detectors at HL-LHC

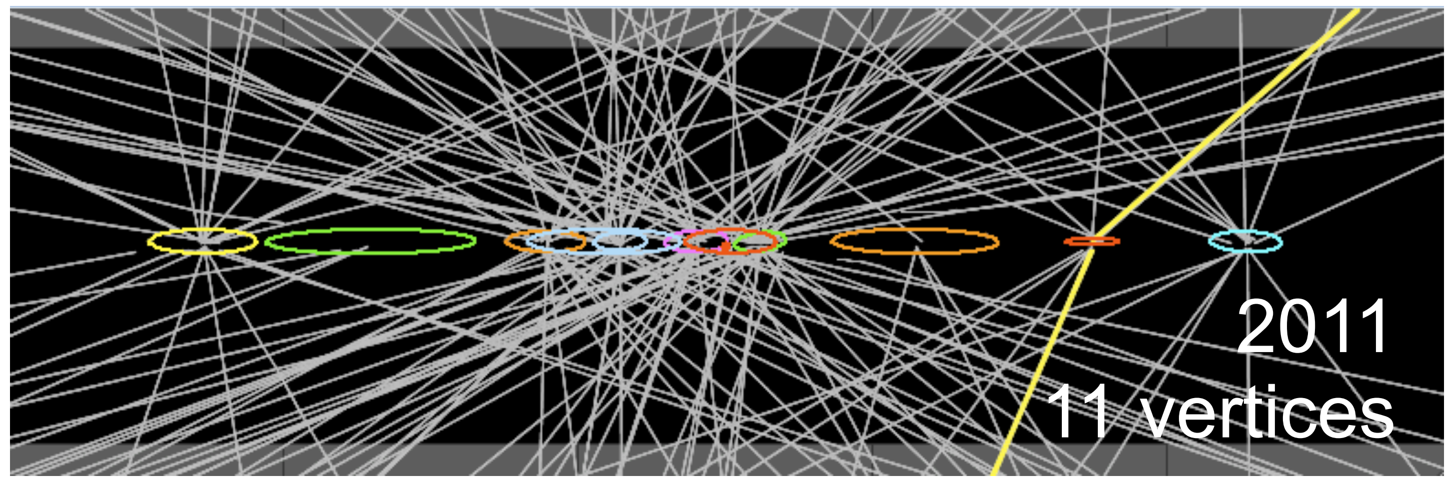
High pileup challenge at HL-LHC, where instantaneous luminosity is **5 times higher**, giving a total integrated luminosity of up to 4 ab^{-1}

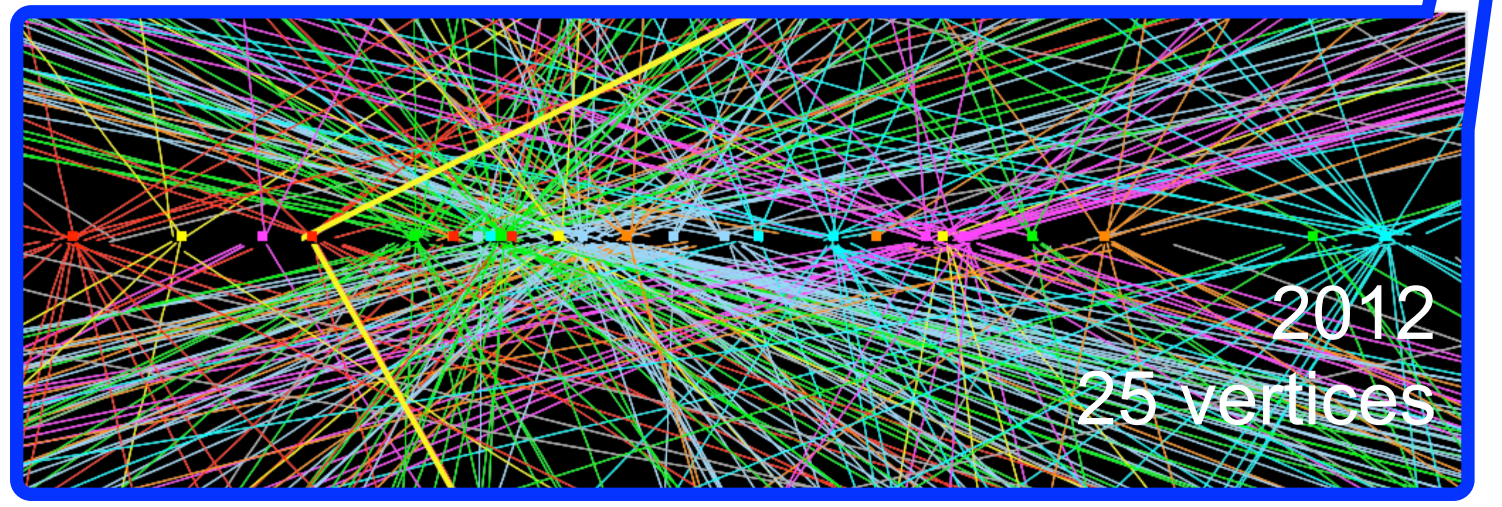
- up to average 200 inelastic pp collisions

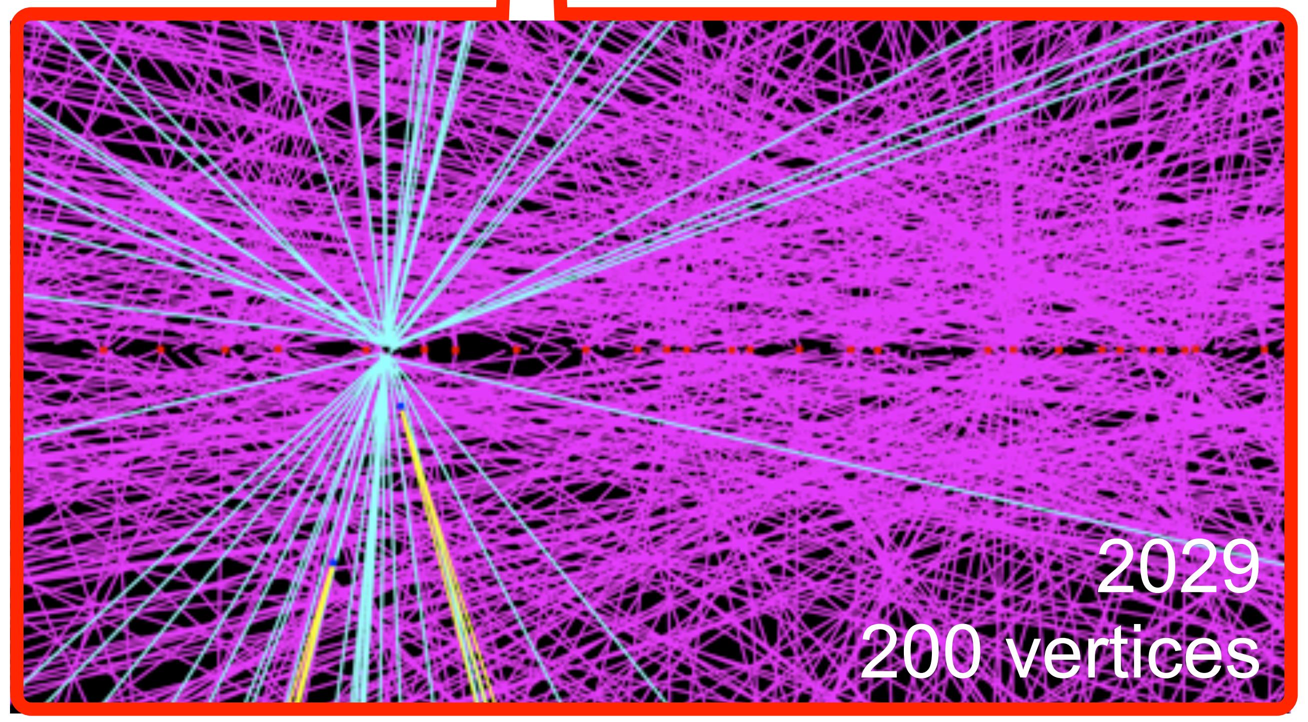
Challenges on the detectors

- to separate the overlapped vertices and objects
  ➔ **motivates** not only finer spatial measurements (ITK) but also **timing measurements** (HGTD)
- performance v.s. accumulated luminosity *(radiation hard)*





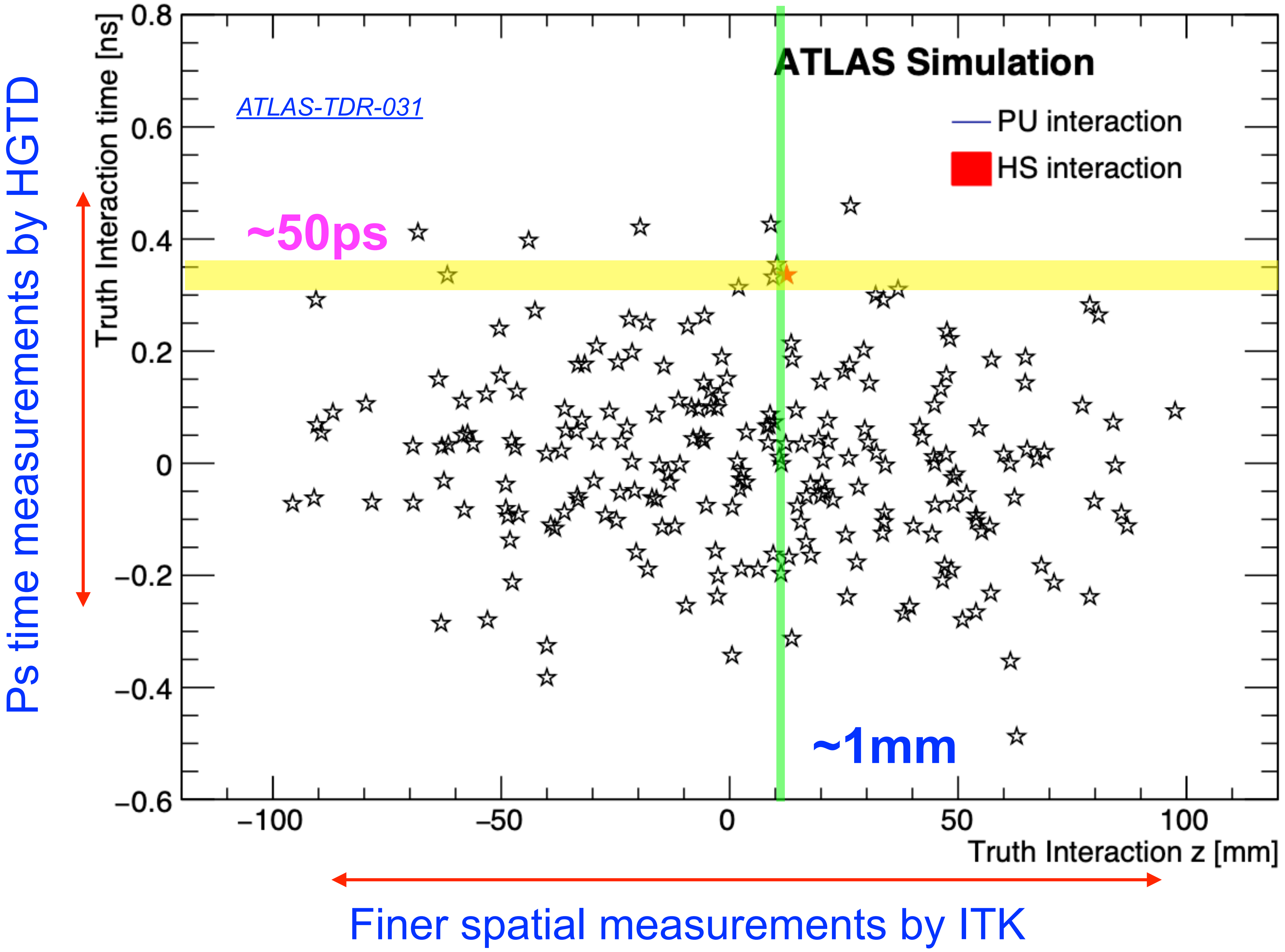




Exploit the 4th Dimension: Time

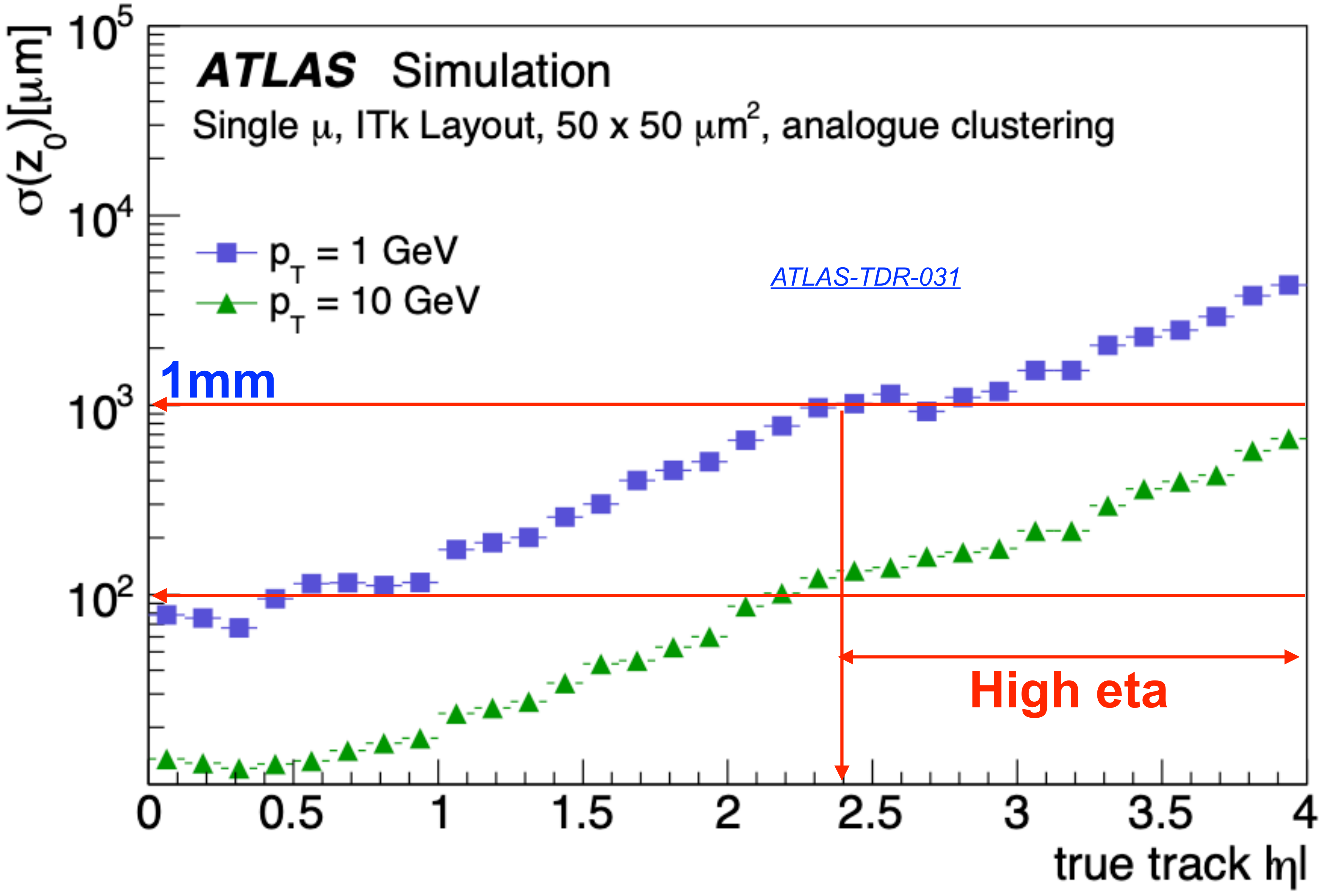
Interactions spread not only along z but also in t (RMS ~ 175 ps), with σ_t **< 50ps**

➔ pile-up suppression by **a factor of ~6**

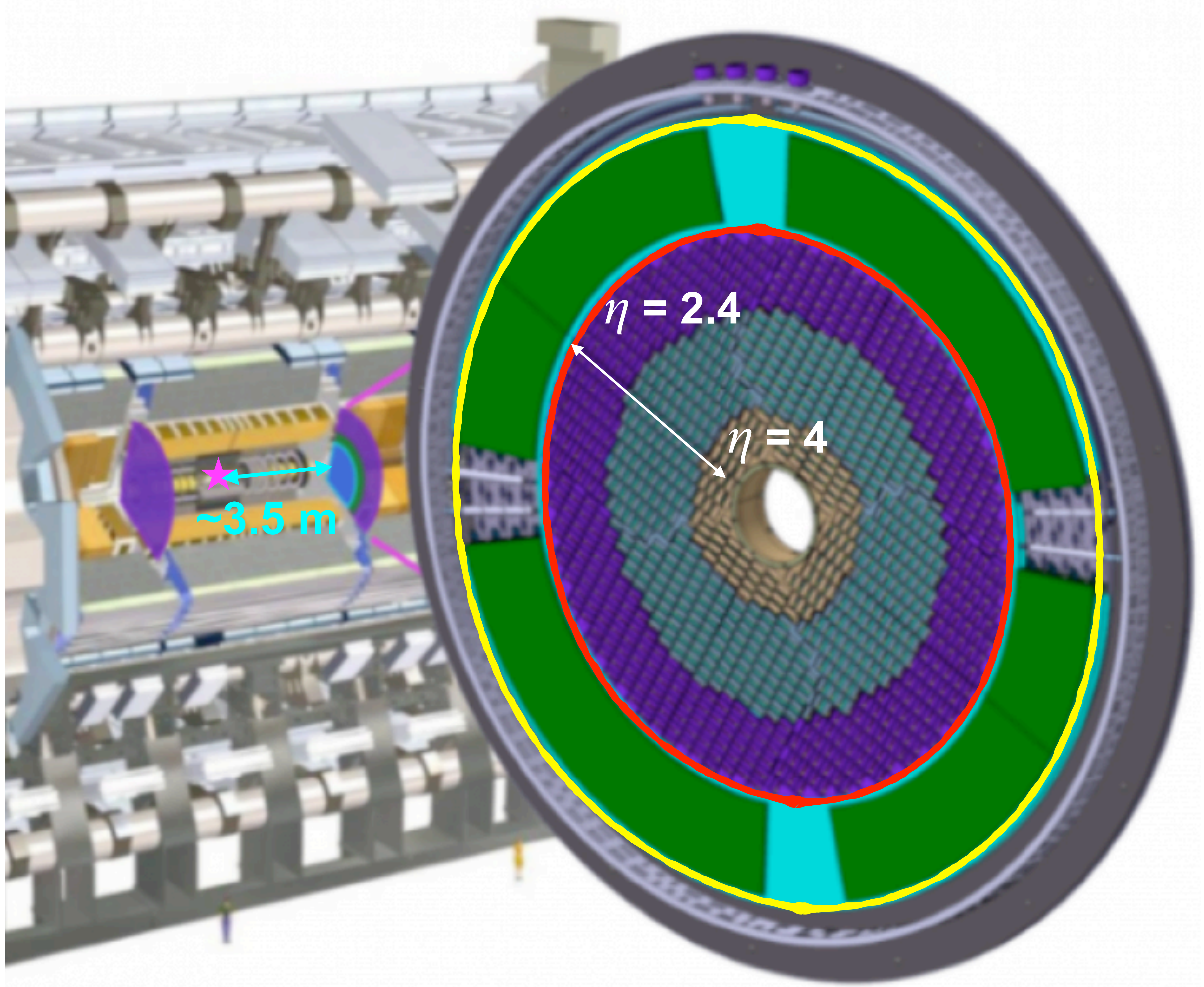


Timing is crutial to the success of the physics programme in **high |η| region**

➔ as impact parameter deteriorates with |η|



High Granularity Timing Detector



Pixelated detector providing **highly precise time** measurements $< 50\,\mathrm{ps}$ in the forward region

- Four layers of sensors (different overlap depending on the radius): **1 - 4 hits per track**
- Precise **luminosity** measurements with 1% luminosity uncertainty (bunch-by-bunch 40MHz readout - very challenging readout design)

More luminosity see Simone's talk on Friday

Detector specs:

- $|z| \sim 3.5\,\mathrm{m}$ from the nominal interaction point (installed in the gap between barrel and end-cap calorimeter)
- Forward region: $2.4 < |\eta| < 4.0$
- Radiation hard up to:

  2.5 x 10^{15} n_{eq}/cm^2 (w/ Safety Factor=1.5) for sensor;
  2 MGy (w/ Safety Factor=2.25) for electronics.

Low Gain Avalanche Diode

Low Gain Avalanche Diodes (LGAD) - a **novel silicon sensor** technology

- Key feature - **the gain layer**, providing a modest gain of 10 - 50 comparing to APD and SiPM *(radiation deteriorates the gain)*
- Picosecond fast timing features *(intrinsic sensor timing constant)*: high drifting velocity (fast, gain), thin active layer (fast), meanwhile large signal (gain, σ_t).

HGTD LGAD geometry

- Thin: 50 µm thick
  - Compromise between Landau fluctuations contributing to the time resolution, charge/bias property etc.
- Pad size: 1.3 x 1.3 mm^2
  - Compromise between rise time, capacitance, occupancy, fill factor…
- Strong signals: 10 fC (w/ 20 gain) unirradiated and 4 fC (w/ 8 gain) end-of-life

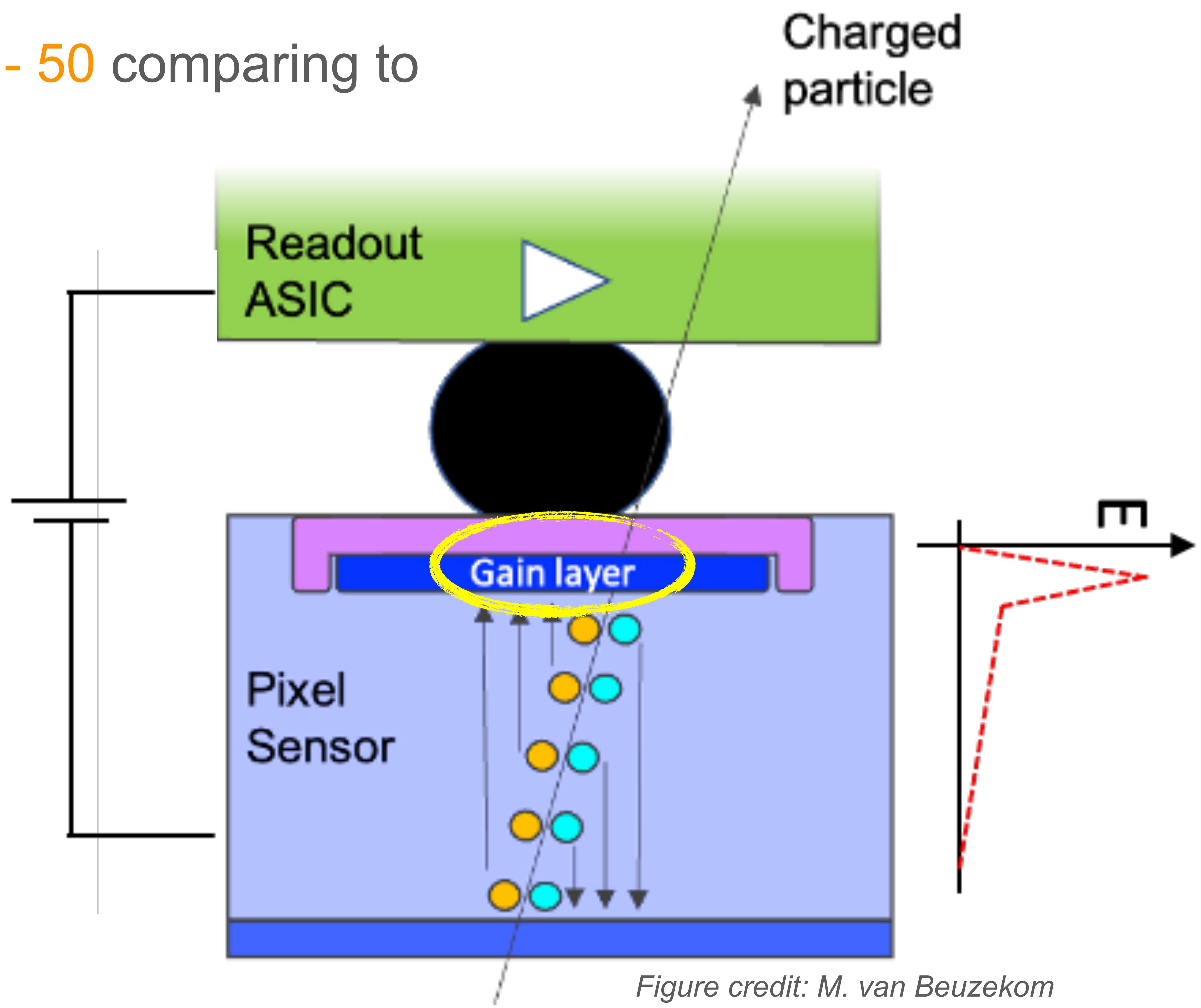


Figure credit: M. van Beuzekom

Single Hit Time Measurement - Readout Electronics

Time Resolution is dominant by three components*

$$\sigma_t^2 = \sigma_{\text{TimeWalk}}^2 + \sigma_{\text{jitter}}^2 + \sigma_{\text{TDC}}^2$$

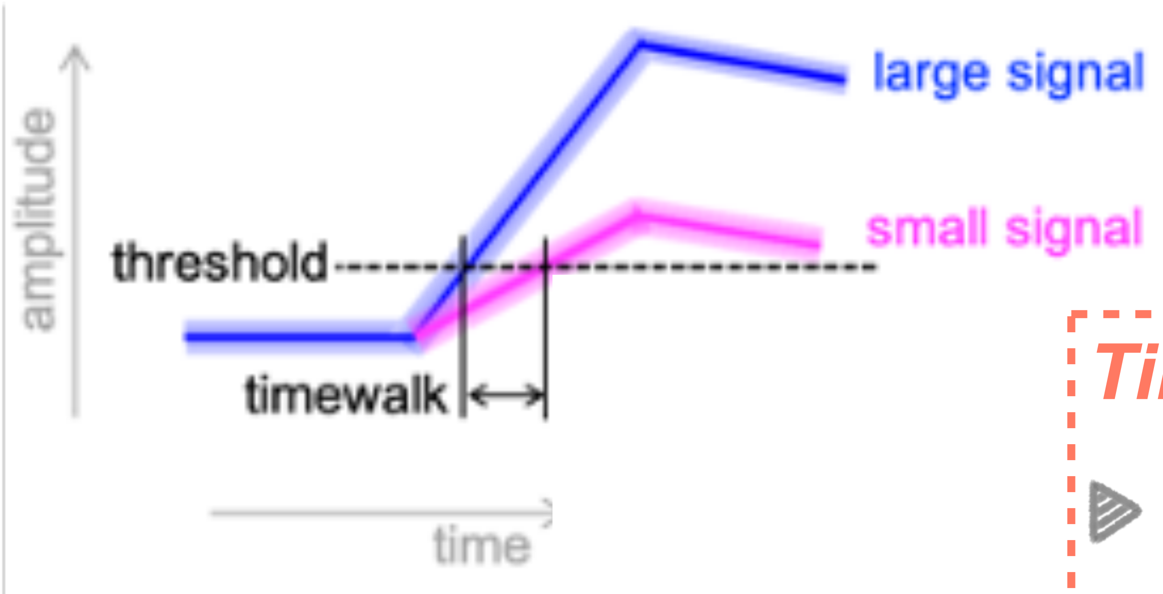


Figure credit: M. van Beuzekom

Requires:
- Low threshold
- Large signal S
- Short rise time t_r

Time walk

- Time-of-Arrival (ToA) relates to the time when signal cross the threshold - thus depending on signal magnitude (energy loss Landau fluctuations) and signal shape (hit position)
- Compensation can be done by introducing **Time-over-Threshold (ToT)** measurement or using **Constant-Fraction-Discriminator (CFD)**
  - ToT is a common solution, while CFD is hard to be implemented at ASIC level

* This equation has other variations, depending on how one categories the resource; the format here is commonly used in detector R&D community

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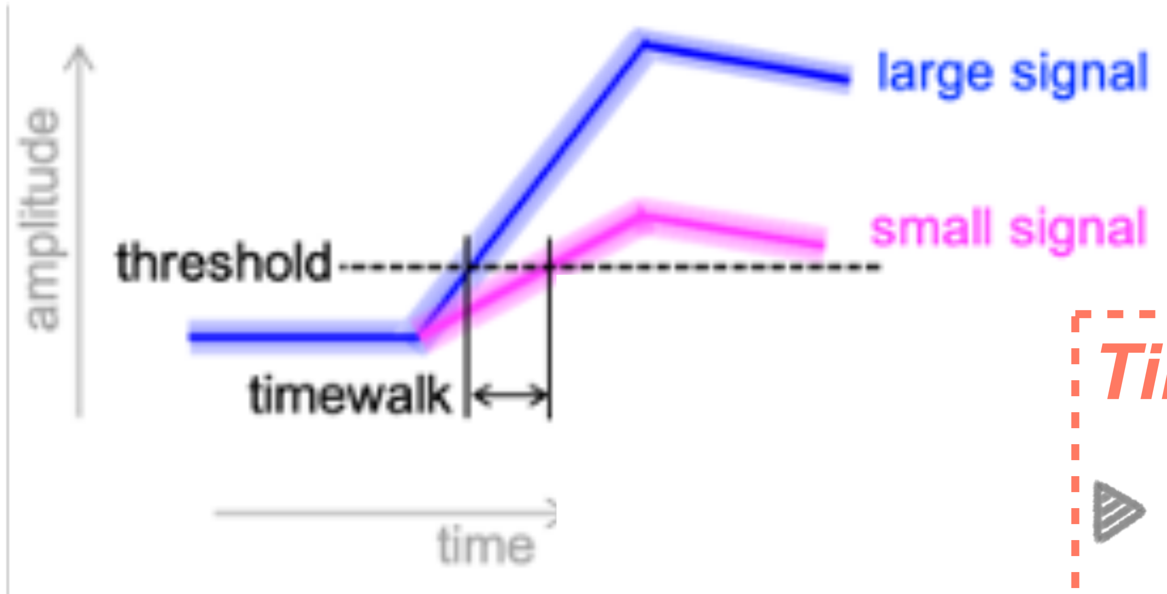

Figure credit: M. van Beuzekom

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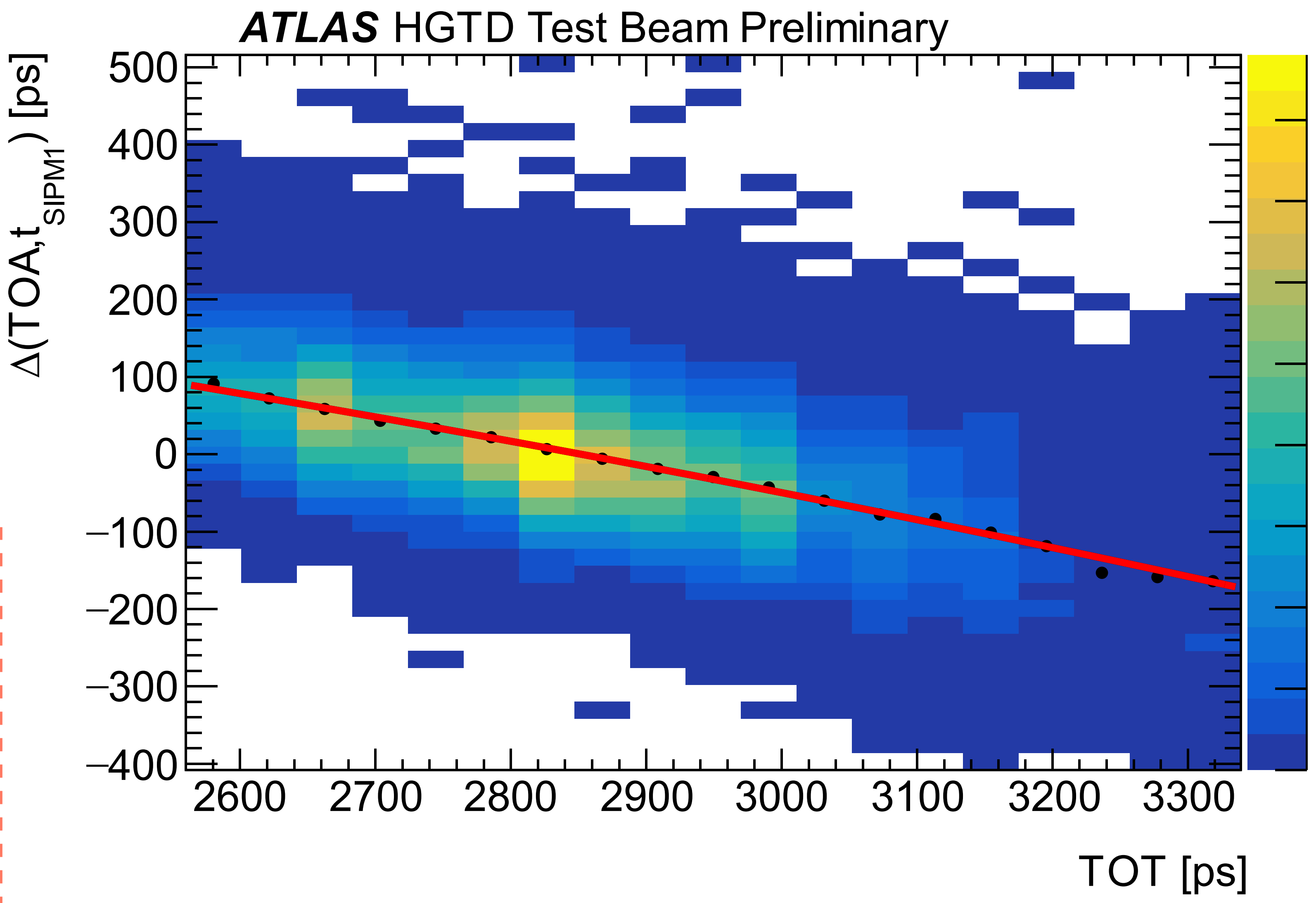
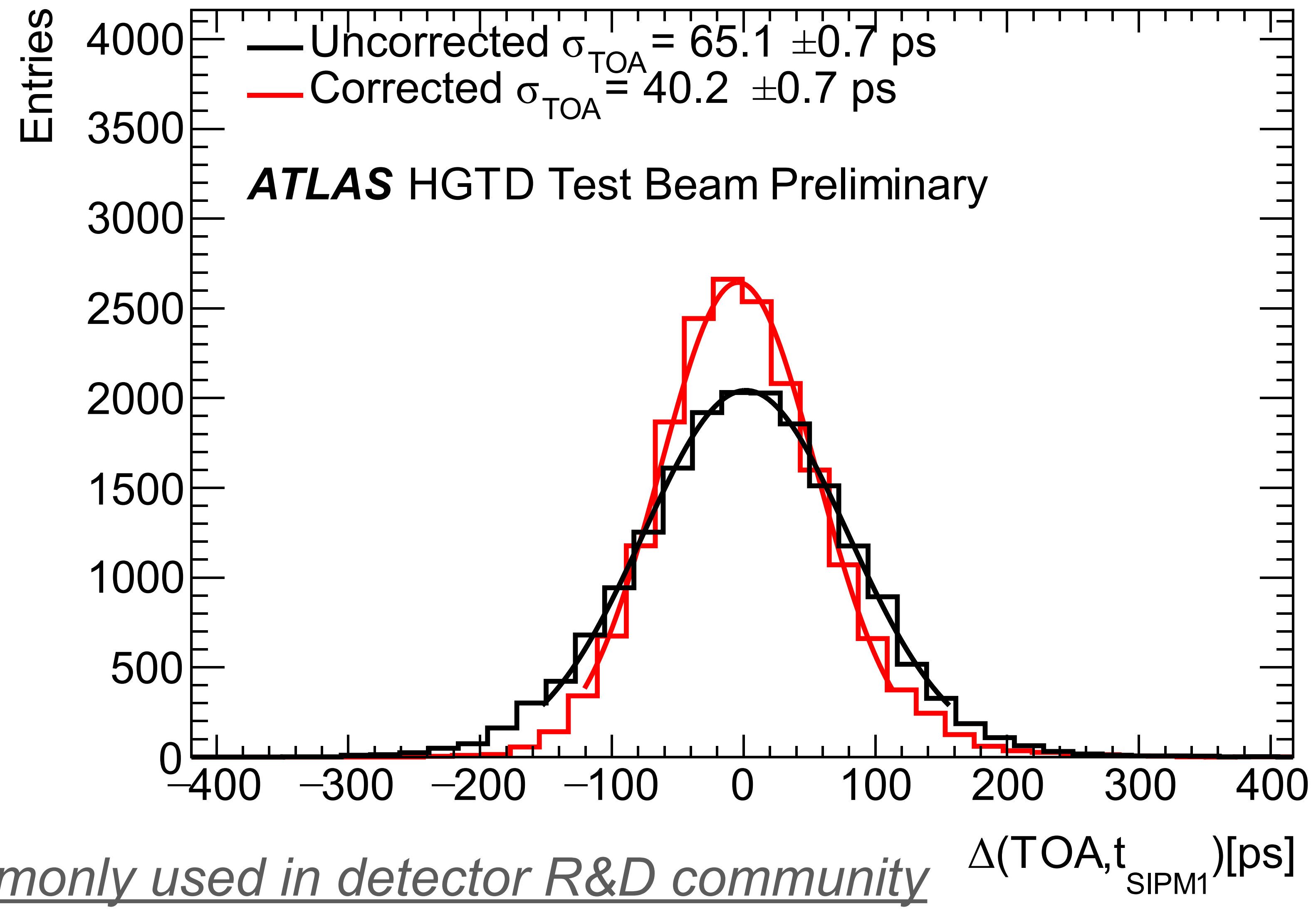
  - ToT is a common solution, while CFD is hard to be implemented at ASIC level
- HGTD TB results show: after Time-walk correction, unirradiated modules meet requirement of $\sigma_t < 50\,\mathrm{ps}$





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Single Hit Time Measurement - Readout Electronics

Time Resolution is dominant by three components*

Challenging to build such a readout system to fulfil the time requirement

$$\sigma_t^2 = \sigma_{\text{TimeWalk}}^2 + \sigma_{\text{jitter}}^2 + \sigma_{\text{TDC}}^2$$

Requires:
- ❏ Low threshold
- ❏ Large signal S
- ❏ Short rise time t_r

Can be corrected/ compensated

Requires:
- ❏ High Signal-to-Noise
- ❏ Short rise time t_r

Largest component
Depending on detector geometry and system electronic noise

TDC Granularity (bin size) & reference clock stability, requiring
- ❏ Trade-off: fine TDC binning ≡ power hunger
- ❏ High clock performance: stability and jitter

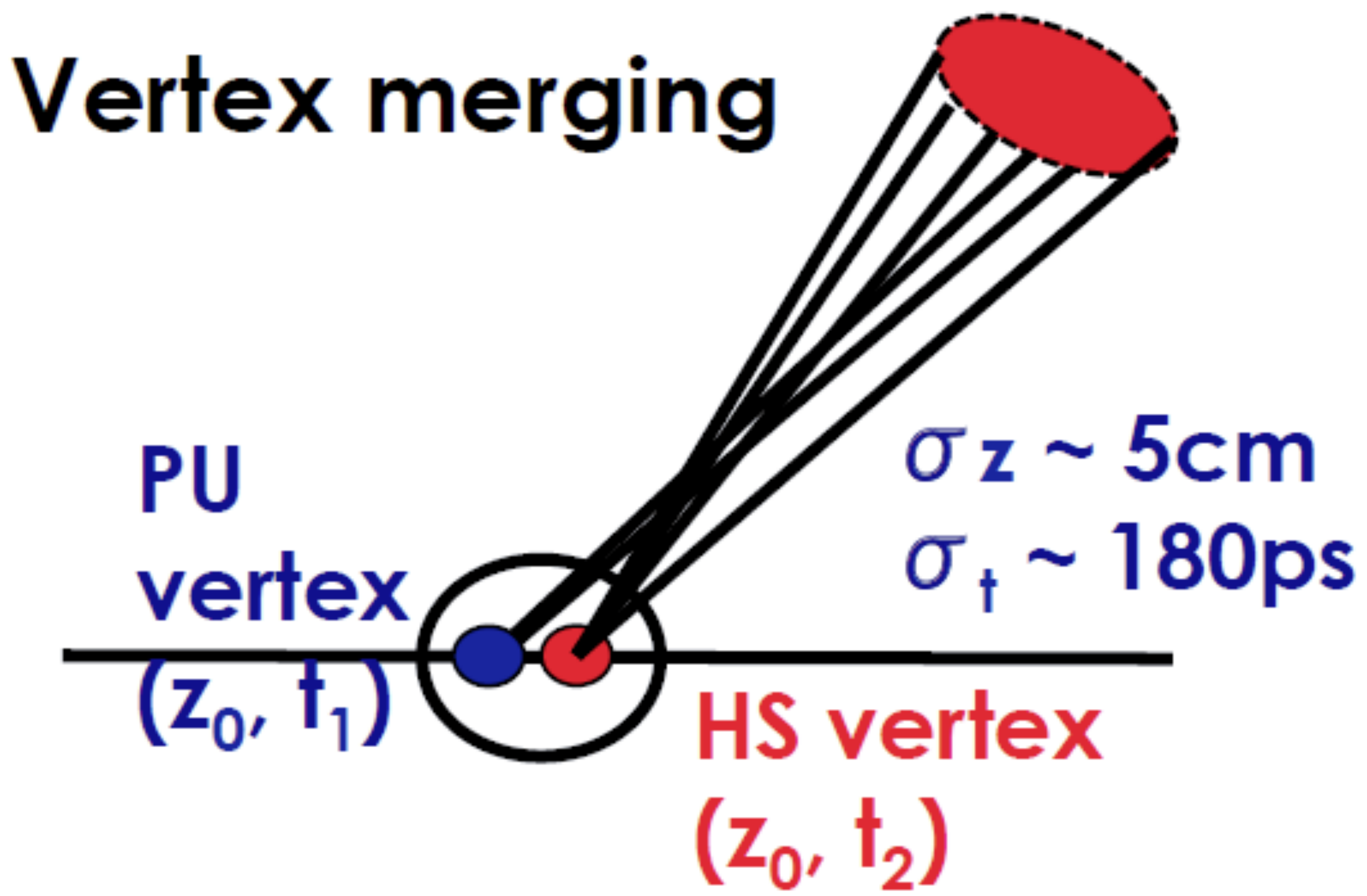
Overall clock distribution needs to be $< 15\ \text{ps}$

It is important to notice that, **intrinsic sensor contribution** (geometry, technology driven) is **NOT** discussed here, **partial sensor contribution** is considered under the *TimeWalk* term in this function.

** This equation has other variations, depending on how one categories the resource; the format here is commonly used in detector R&D community*

Challenges of Event Reconstruction

Challenges in **track-to-vertex association** and **track-to-object association**:



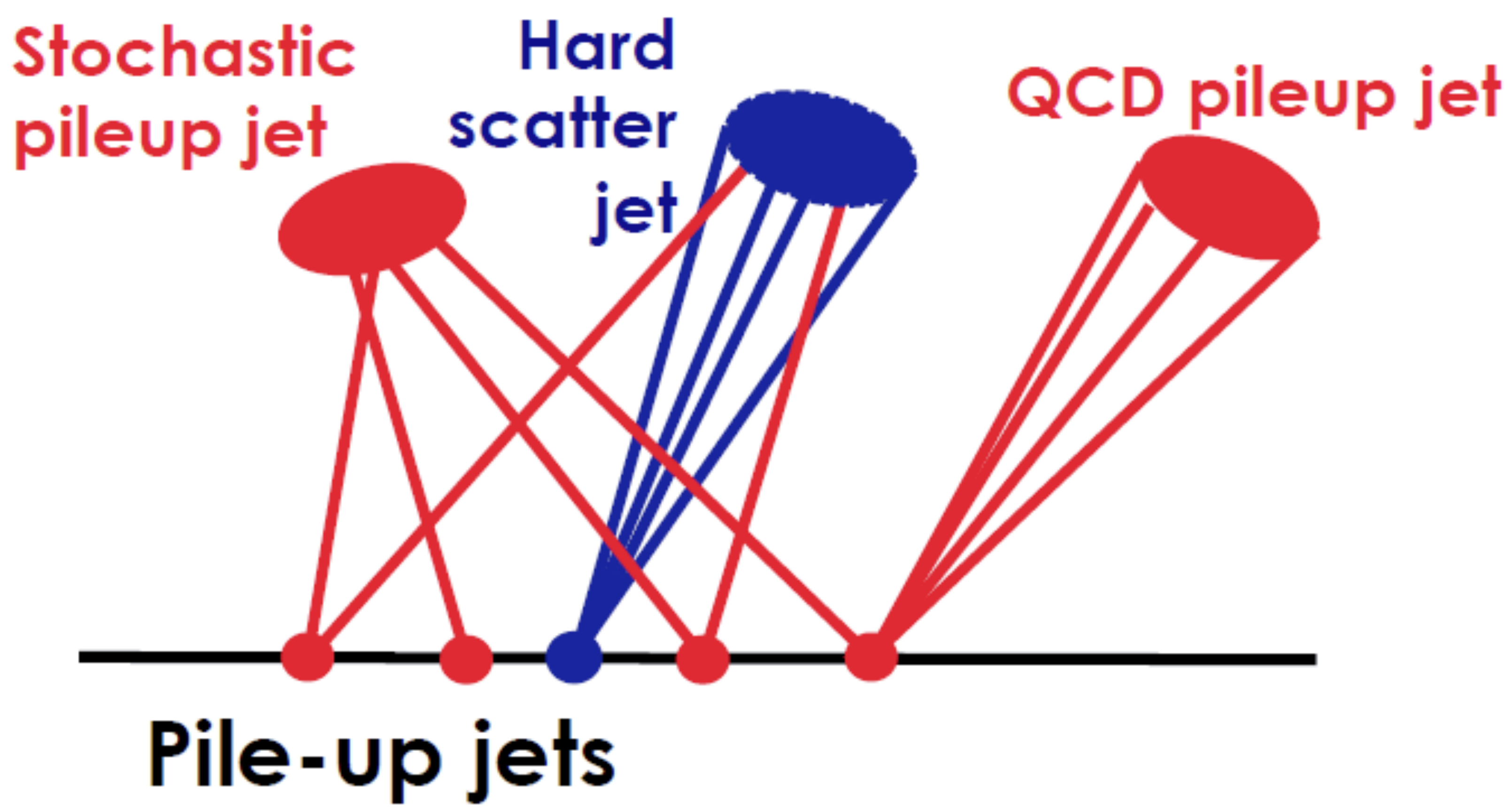


Figure credit: G. Kramberger

Adding time to track-to-vertex association

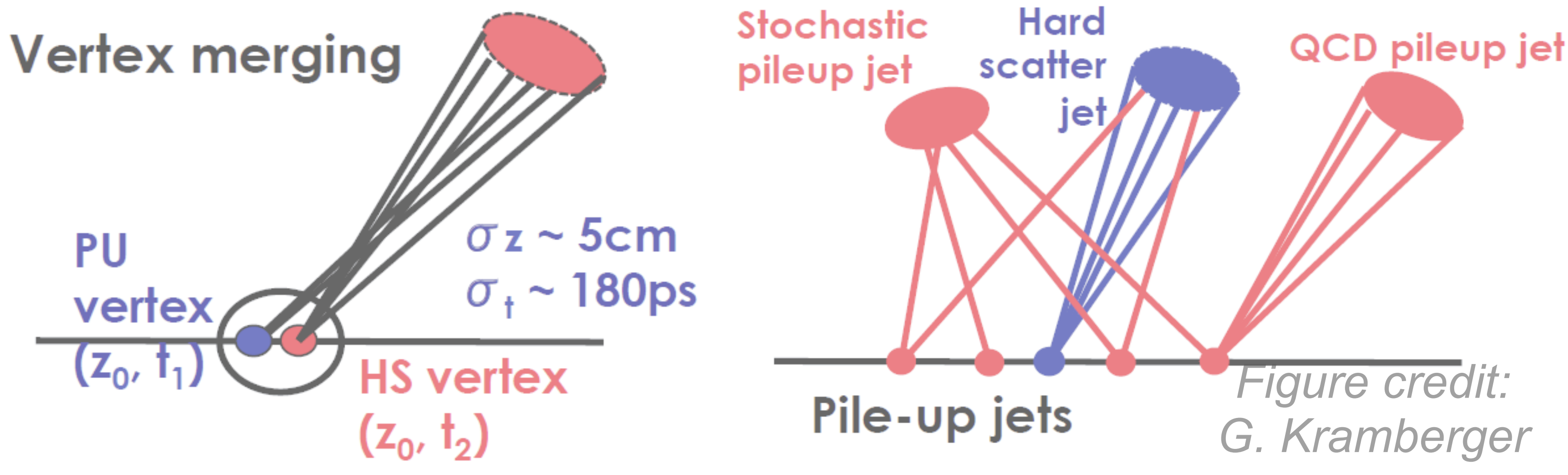
- **Spatial-based association:** track z_0 geometrically compatible in z-axis with respect to the vertex position

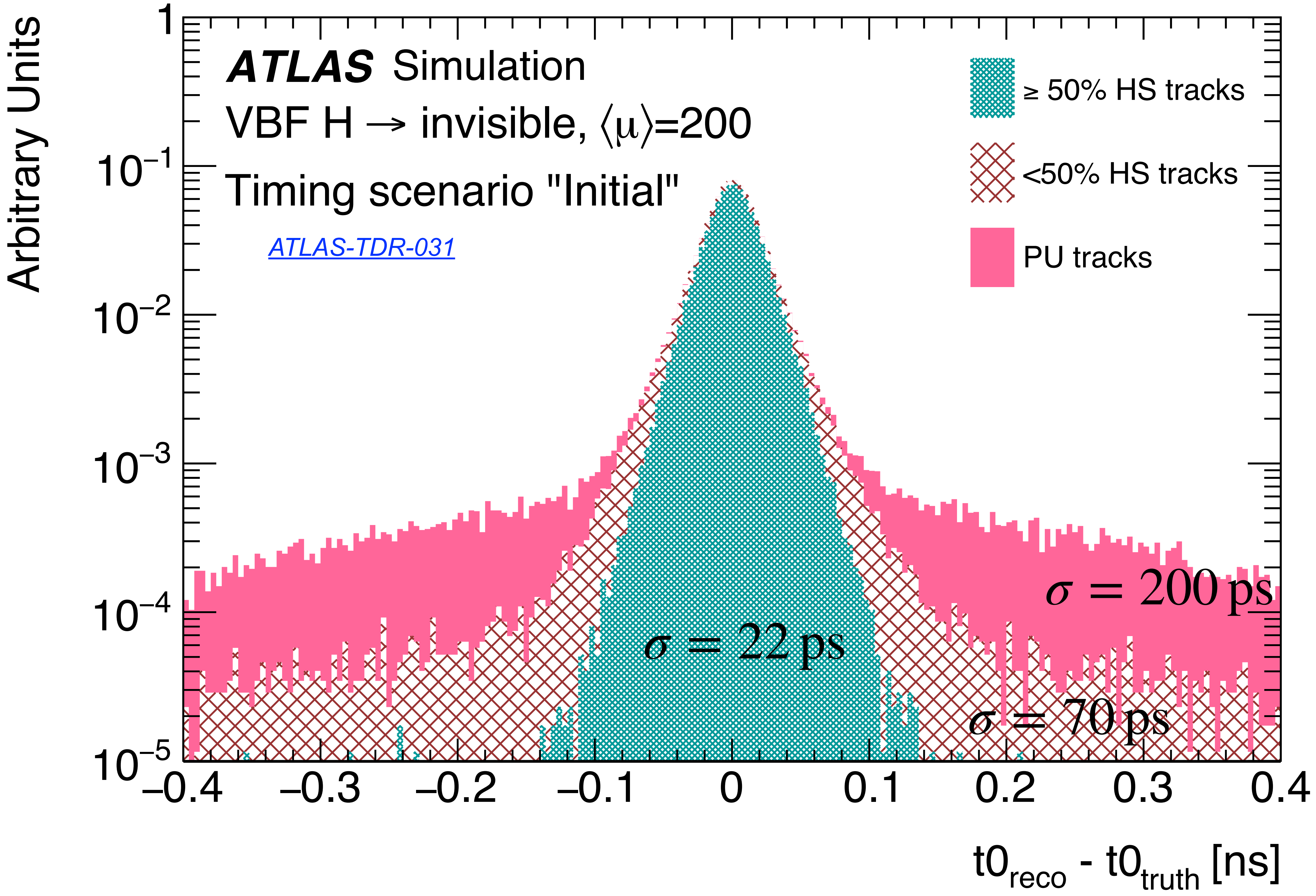
$$\frac{|z_0 - z_{\mathrm{vertex}}|}{\sigma_{z_0}} < s = 2.5\,(3)$$

- Additional **time-based association:**
  - If knowing the hard scatter (HS) vertex time t_0

$$\frac{|t_{\mathrm{trk}} - t_0|}{\sigma_t} < s = 2\,(3)$$

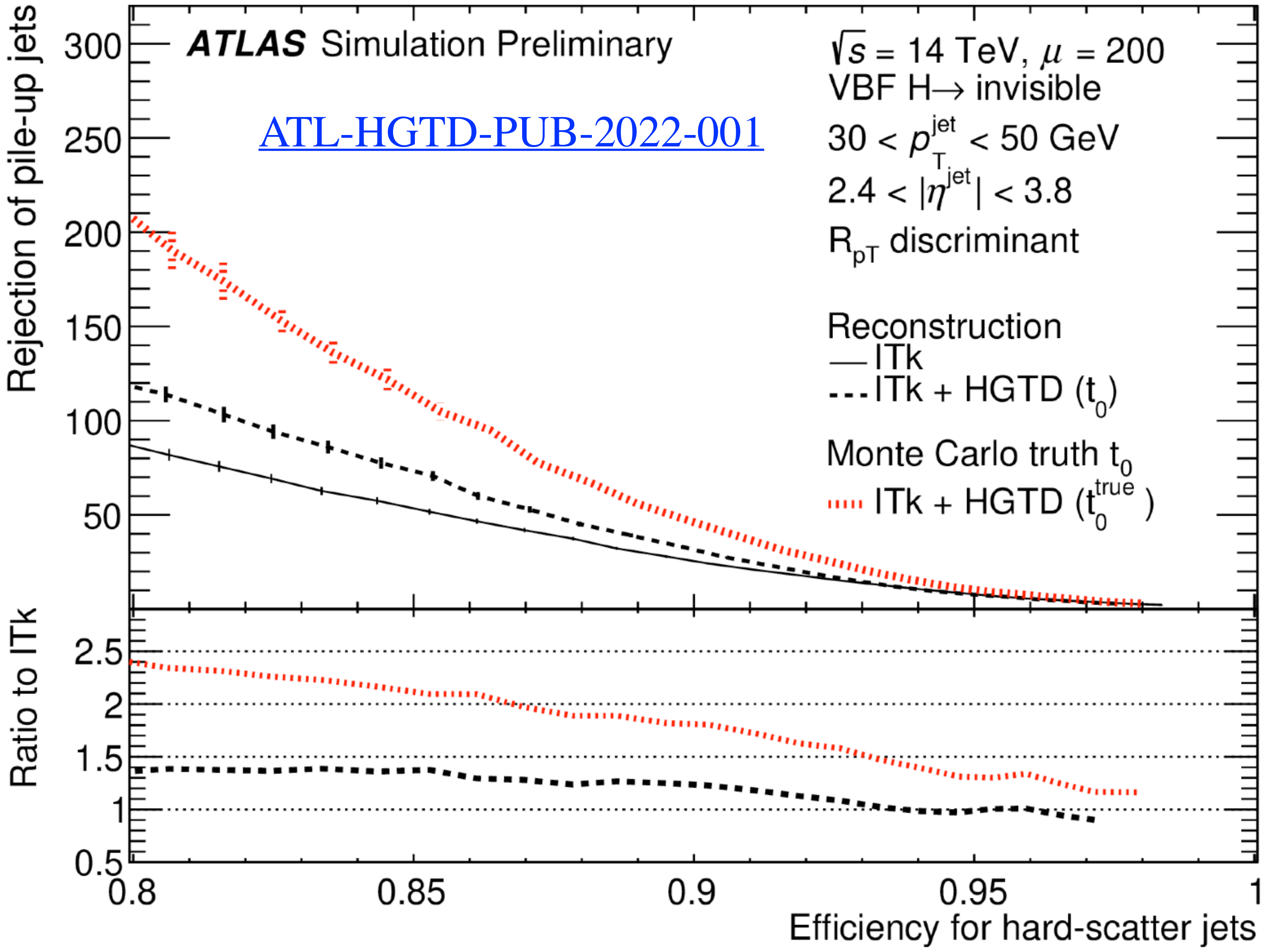
    - **Challenging t_0 determination:** (1) limited $|\eta|$ coverage; (2) HS vertex t_0 measurement built upon the prior track-to-vertex association
  - *If t_0 unknown:* so-called *self-tagging* approach - for given reconstructed object, check time consistency to clean/remove time incompatible components





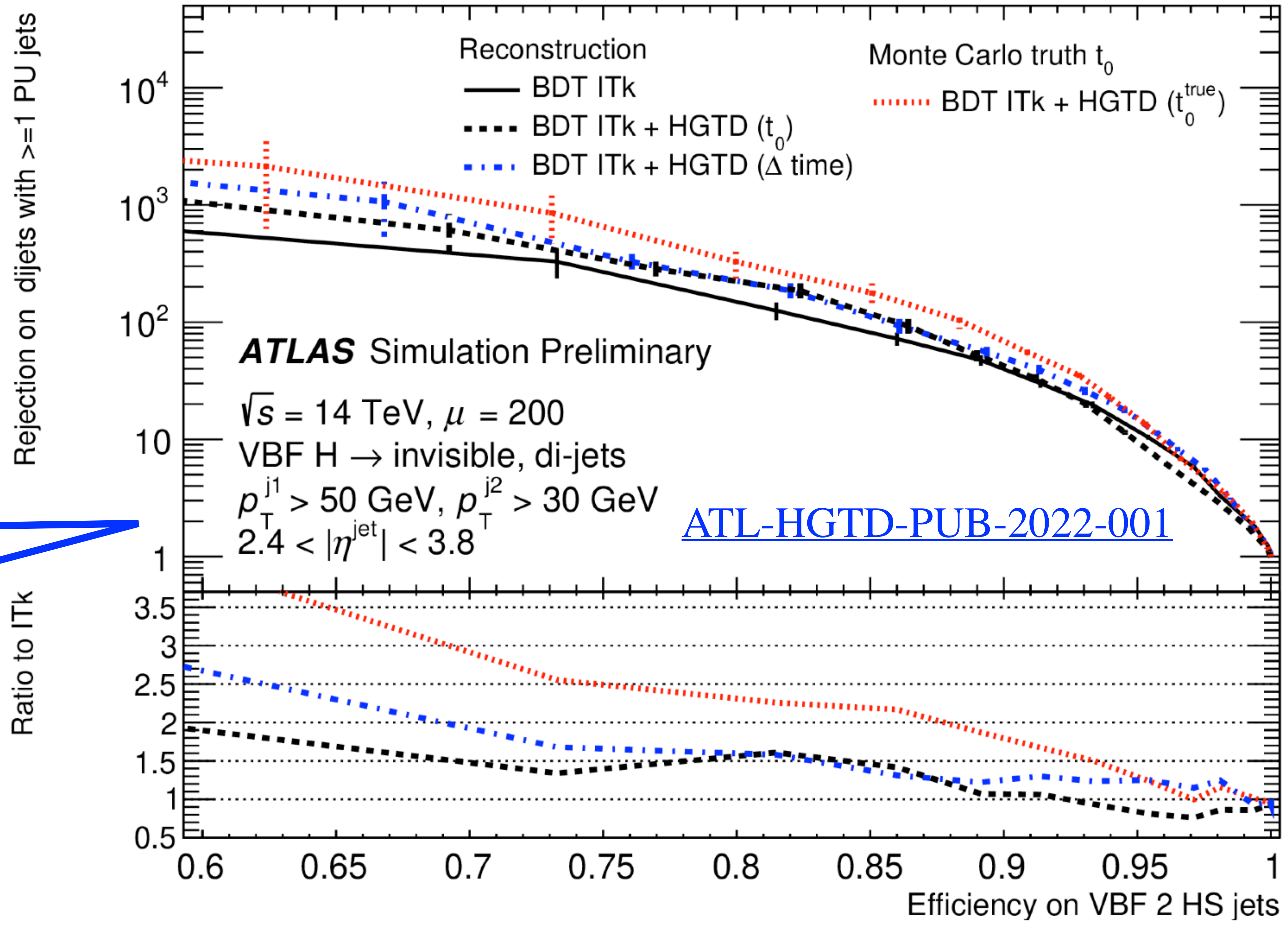
Adding time to suppress pile-up jets

Use the *self-tagging* approach to reduce pile-up track contamination thus improving discriminant variables such as R_{P_T} (JHEP 04 (2008) 063) and JVF (ATLAS-CONF-2014-018) for the jet-vertex tagging



R_{P_T}: scalar P_T sum of all tracks that are inside the jet cone and originate from the HS vertex, divided by the fully calibrated jet pT

JVF: scalar p_T sum of tracks that associate to jet and originate from the HS vertex, divided by the scalar p_T sum of all associated tracks



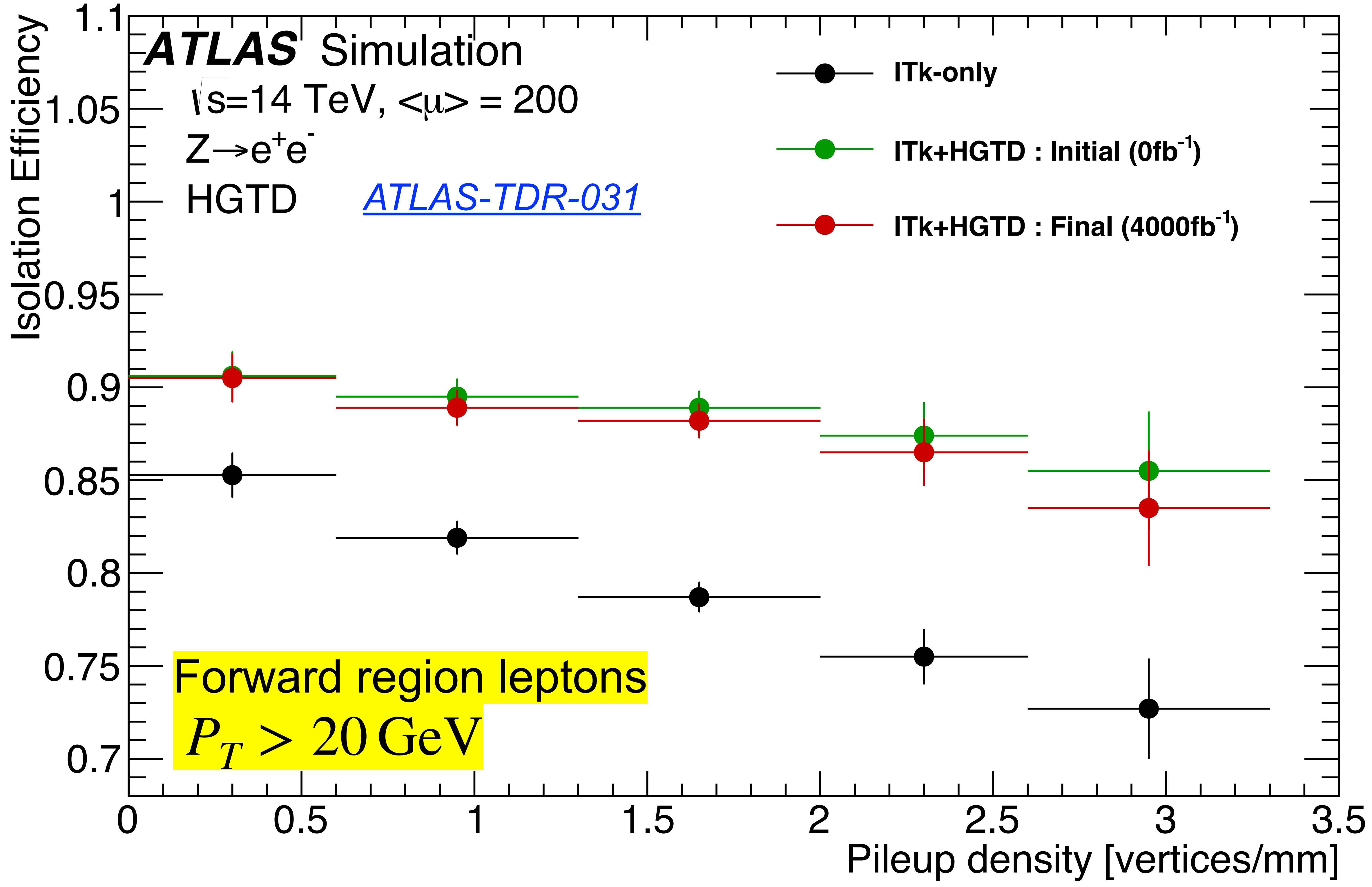
Taking ITK only scenario as benchmark to see how HGTD time measurement adds.

Pile-up jet tagging improves by up to 40% for low P_T forward jets.

Double pile-up jet tagging is up to 1.9-2.7 times better
➔ Good potential for a VBF/VBS HLT using HGTD.

Adding time to improve electron isolation efficiency

- The efficiency of *track-based lepton isolation* $\epsilon(P_T^{\text{iso}})$ is defined as the **probability** that no additional track with $P_T > 1\,\text{GeV}$ is within a cone of $\Delta R = 0.2$ from the electron track
- This variable is sensitive to pile-up density
  - can be recovered by applying a time consistency criterion to reduce the pile-up track contamination in the isolation cone
- With time: this efficiency is improved by about 10% for local pile-up density at 1.6 vertices/mm *(mean value at HL-LHC)*
- Further confirms the impact of pile-up suppression with time at physics object level



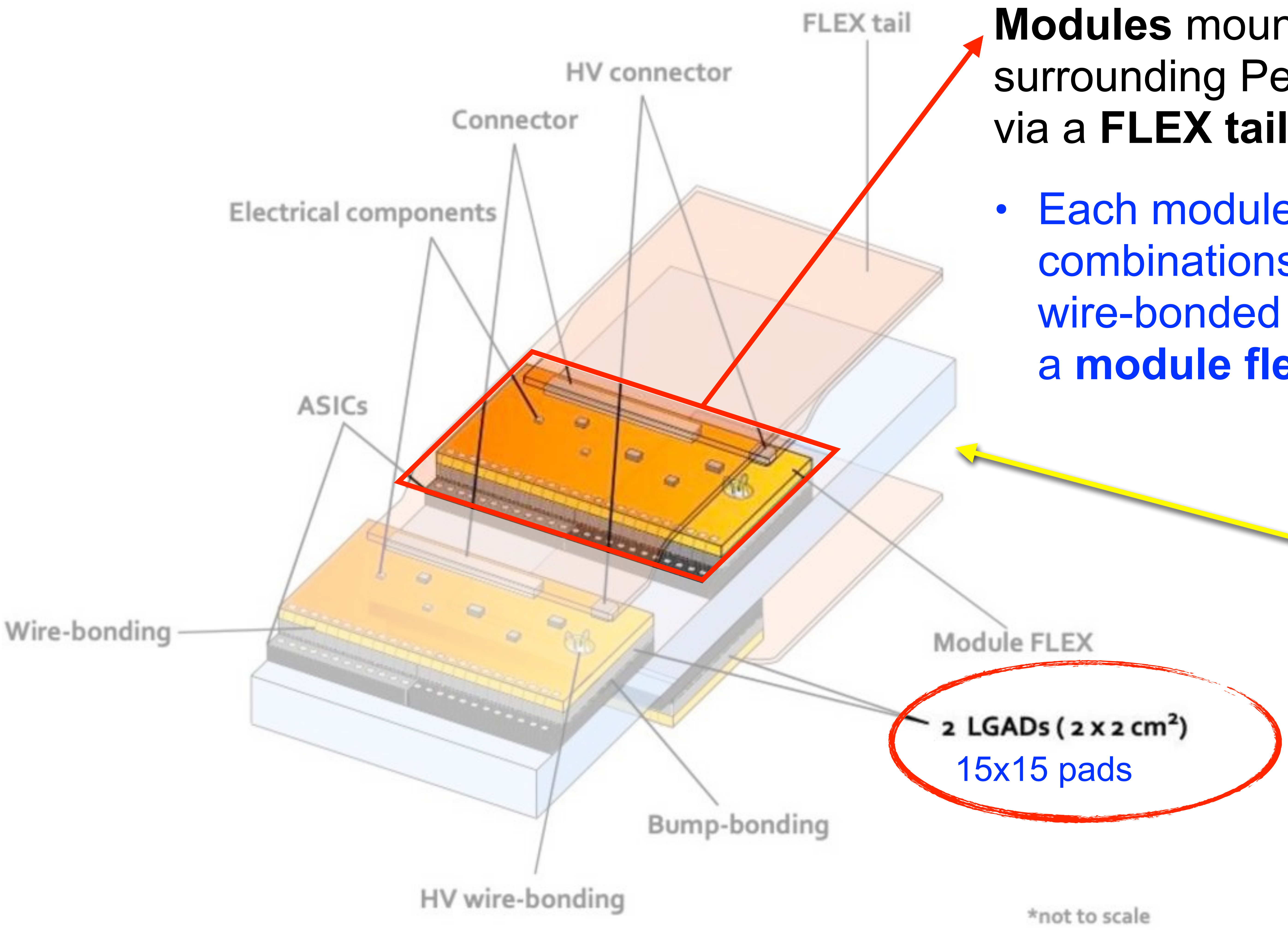
Conclusion and outlook

- The significantly increased instantaneous luminosity impose **a great challenge on distinguishing the overlapped vertices and physics objects**
  - additional precise timing measurement helps, especially in the forward region where impact parameter measurements deteriorate.
  - HGTD based on LGAD technology is under construction to provide a track time measurement with a resolution better than 50 ps in the forward region $2.4 < |\eta| < 4$ and a precise luminosity measurement (which can be vital as HL-LHC physics goals is dominant by precision measurements)
- **Challenges on building such a detector** to achieve a better than 50ps time resolution
  - The LGAD sensor needs to meet the radiation hardness requirement while providing an intrinsic time resolution better than 50ps
  - Besides, the entire readout electronic chain needs to fulfil time requirement - various development challenges to tackle to mitigate effects of time walk, noise jitter and TDC.

Backup

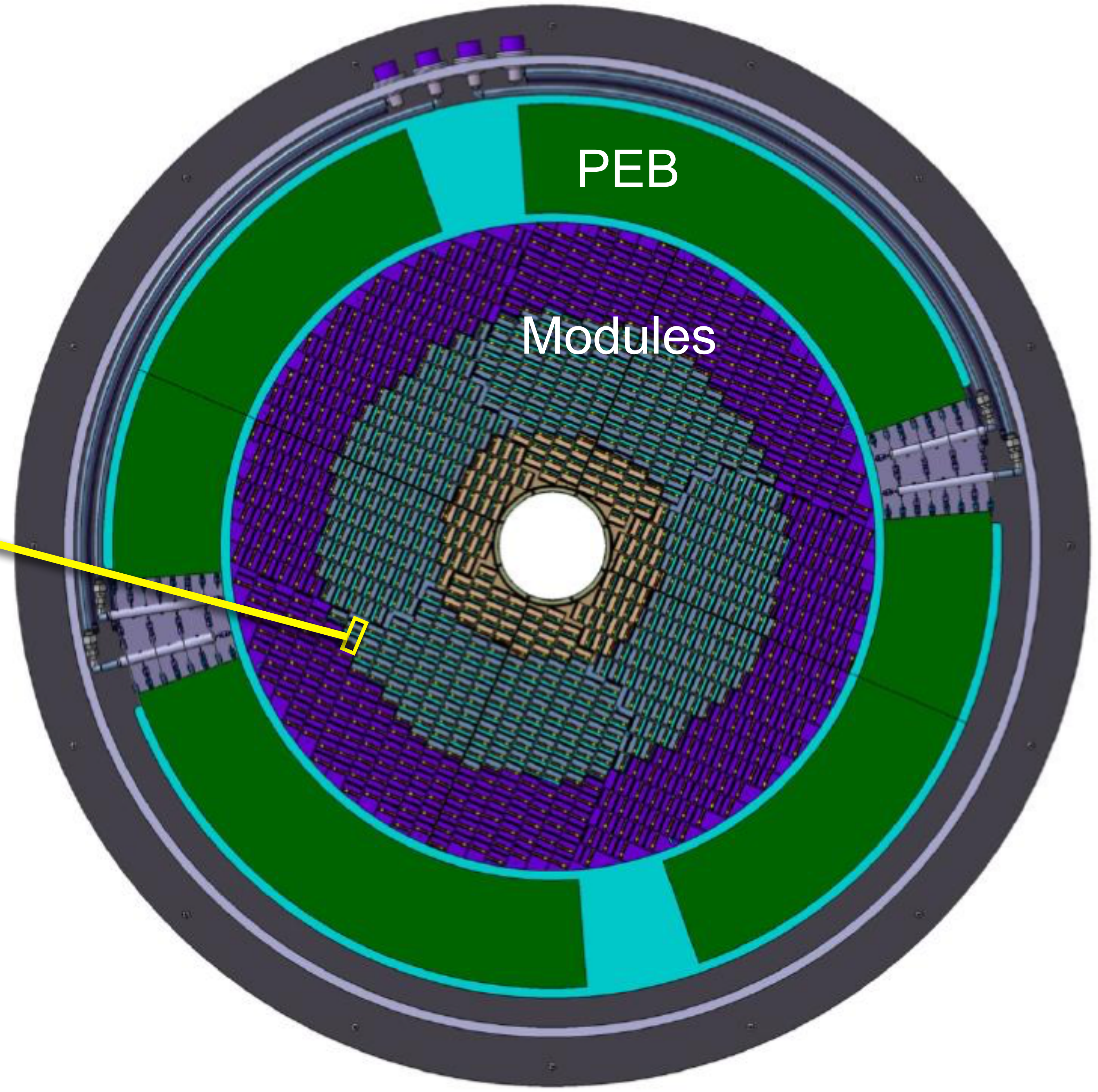
You’ve got one

HGTD Zoom-in: Detector Module



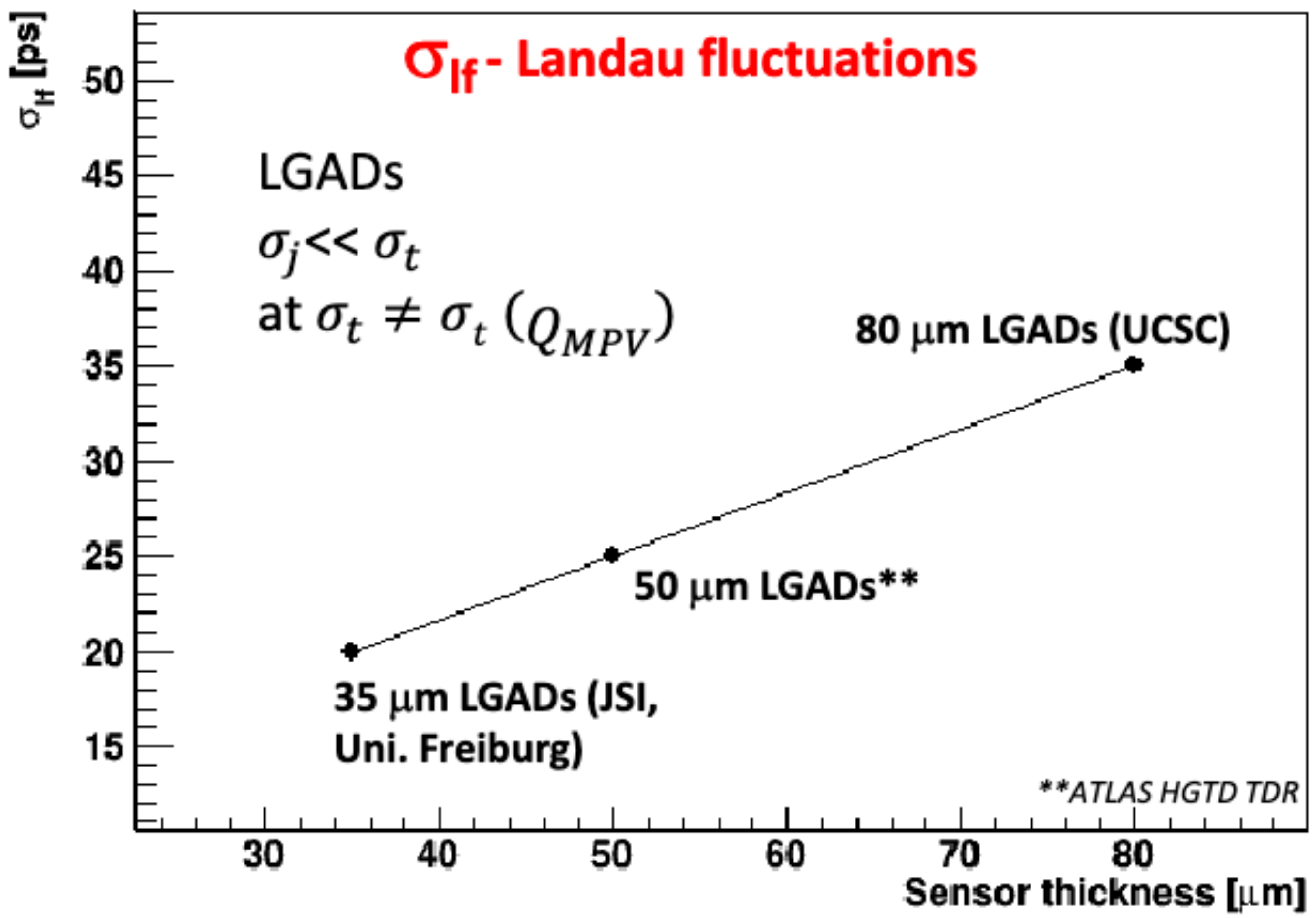
Modules mounted on cooling plate, connected to the surrounding Peripheral Electronics Boards (**PEB**s) via a **FLEX tail** cable

- Each module consists of two bump-bonded **sensor** + **ASIC** combinations, glued and wire-bonded to a **module flex**



Choice of detector geometry

Slide from G. Kramberger



$$\sigma_t^2 = \sigma_j^2 + \sigma_{tw}^2 + \sigma_{TDC}^2$$

time res. (σ_t), noise jitter (σ_j), time walk (σ_{tw}), TDC (σ_{TDC})

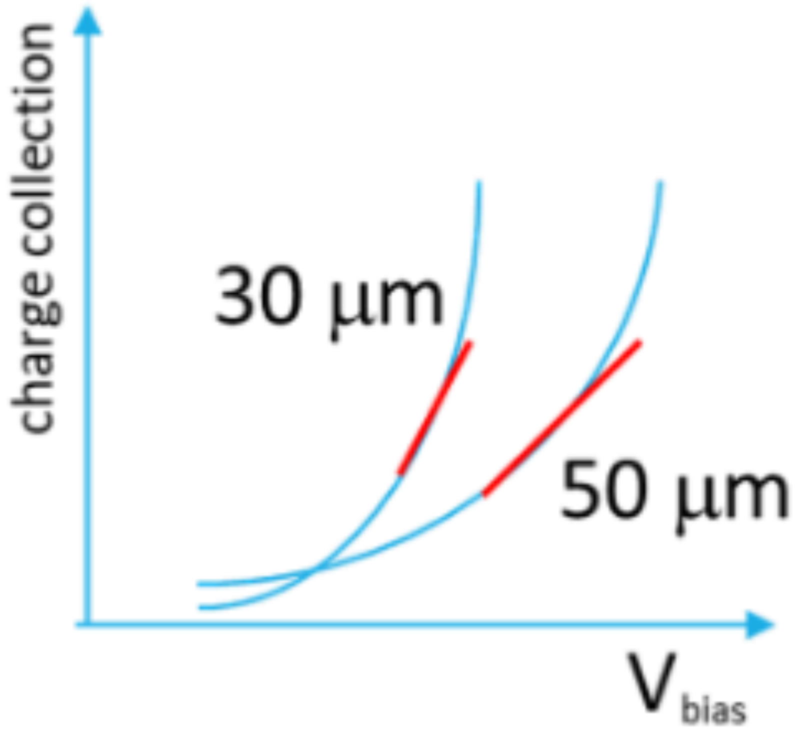
$$\sigma_j = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} \approx \frac{\sigma_n}{\left|\frac{S}{\tau_p}\right|} = \frac{\tau_p}{S/N}$$

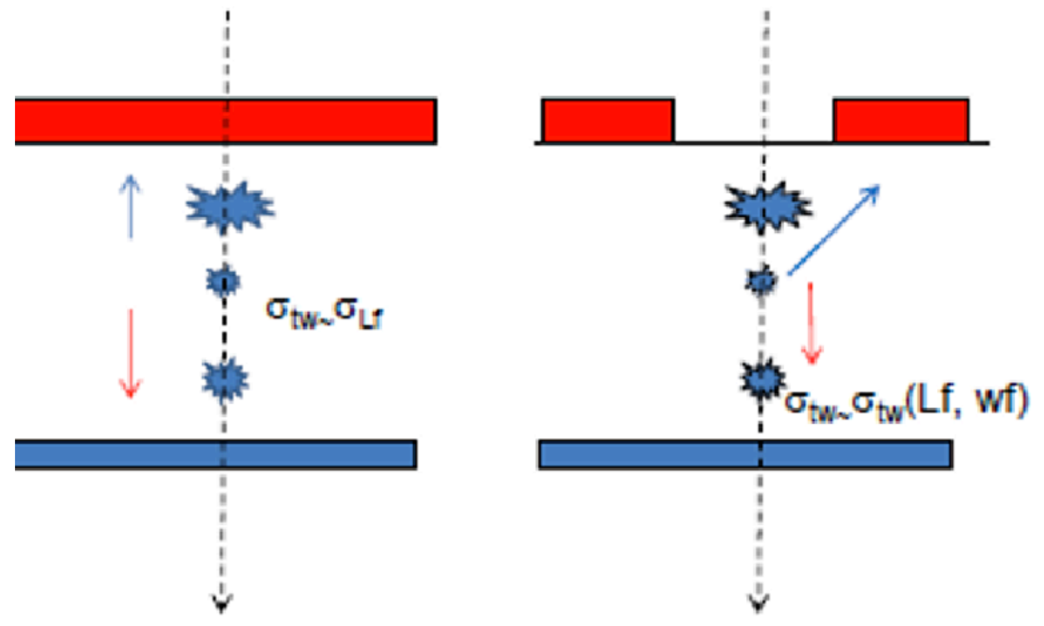
Active thickness ~50 (+/-5) μm

- large capacitance (noise) can be offset by gain -> good S/N
- In order to reach the desired time resolution the thickness is limited to <80 μm (Landau fluctuations)
- thinner sensors have steeper Q-V (difficult to control the bias voltage over a single module)

Cell size 1.3x1.3 mm² determines:

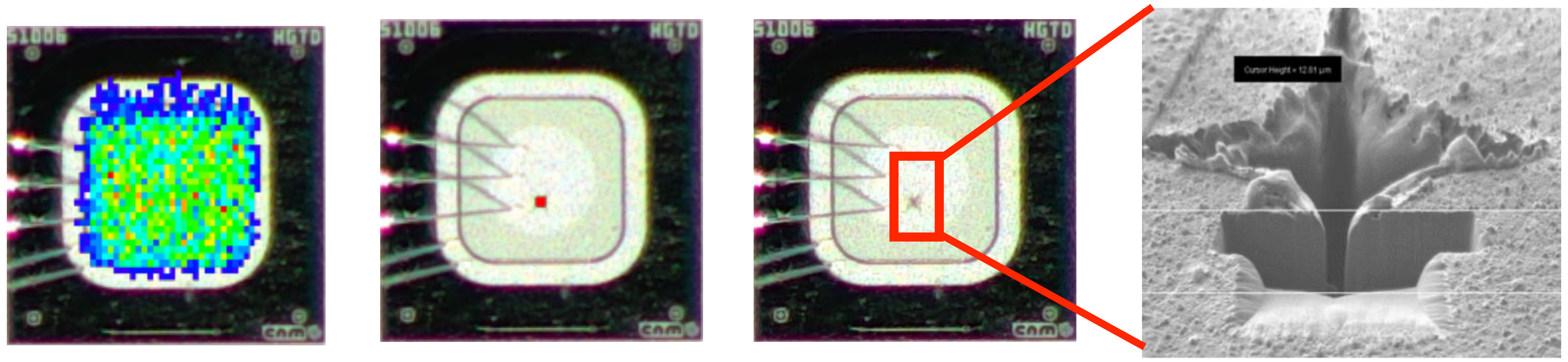
- capacitance (dominated by capacitance to the back, inter-pixel capacitance ~0.5 pF – measured and shown at PDR)
- assures that weighting field is 1/thickness and that the role in contribution to the time walk is negligible – dominated by the σ_{lf}
- pixel hit occupancy and fill factor (indirectly)

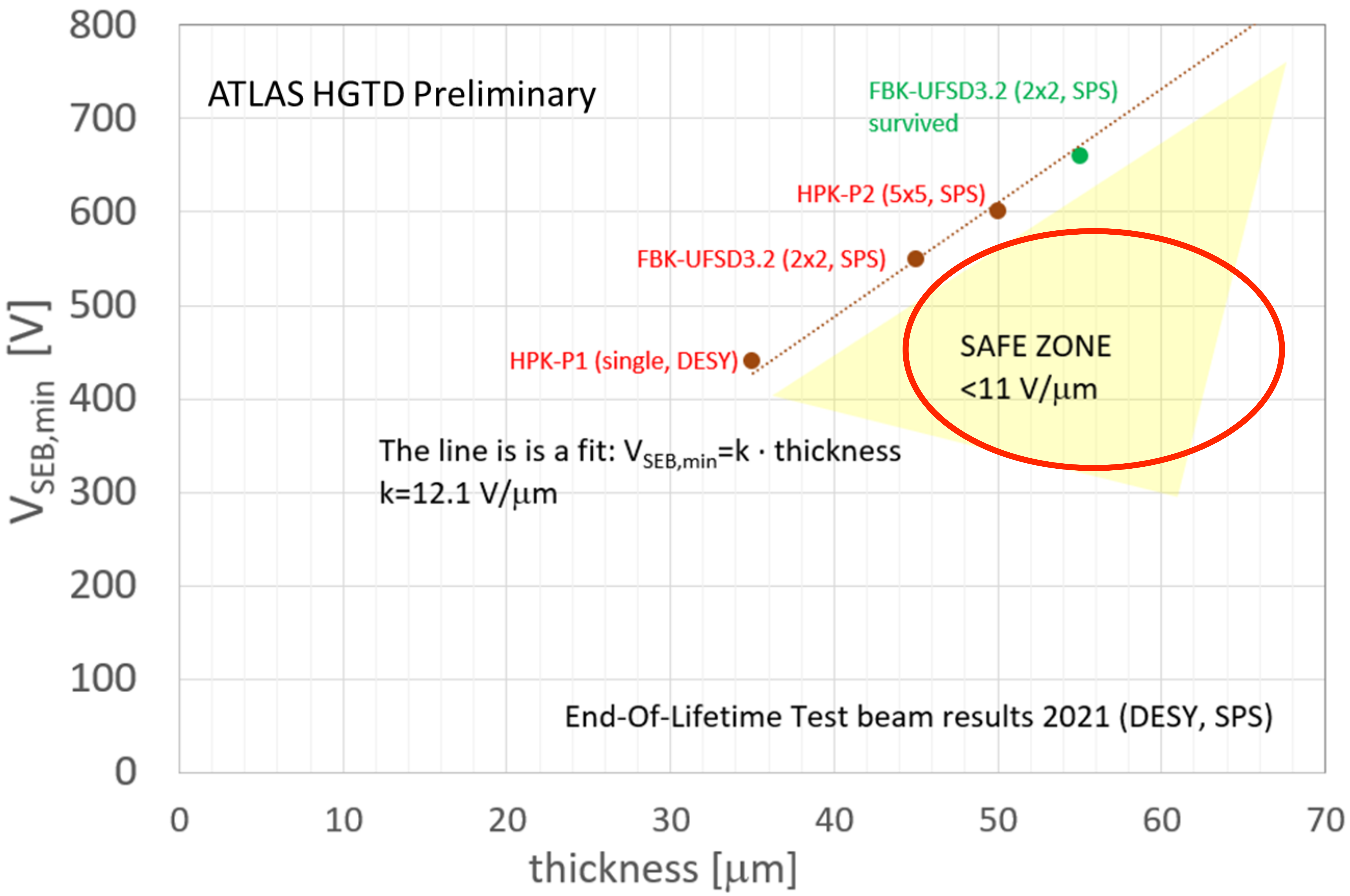




Single Event Burnout

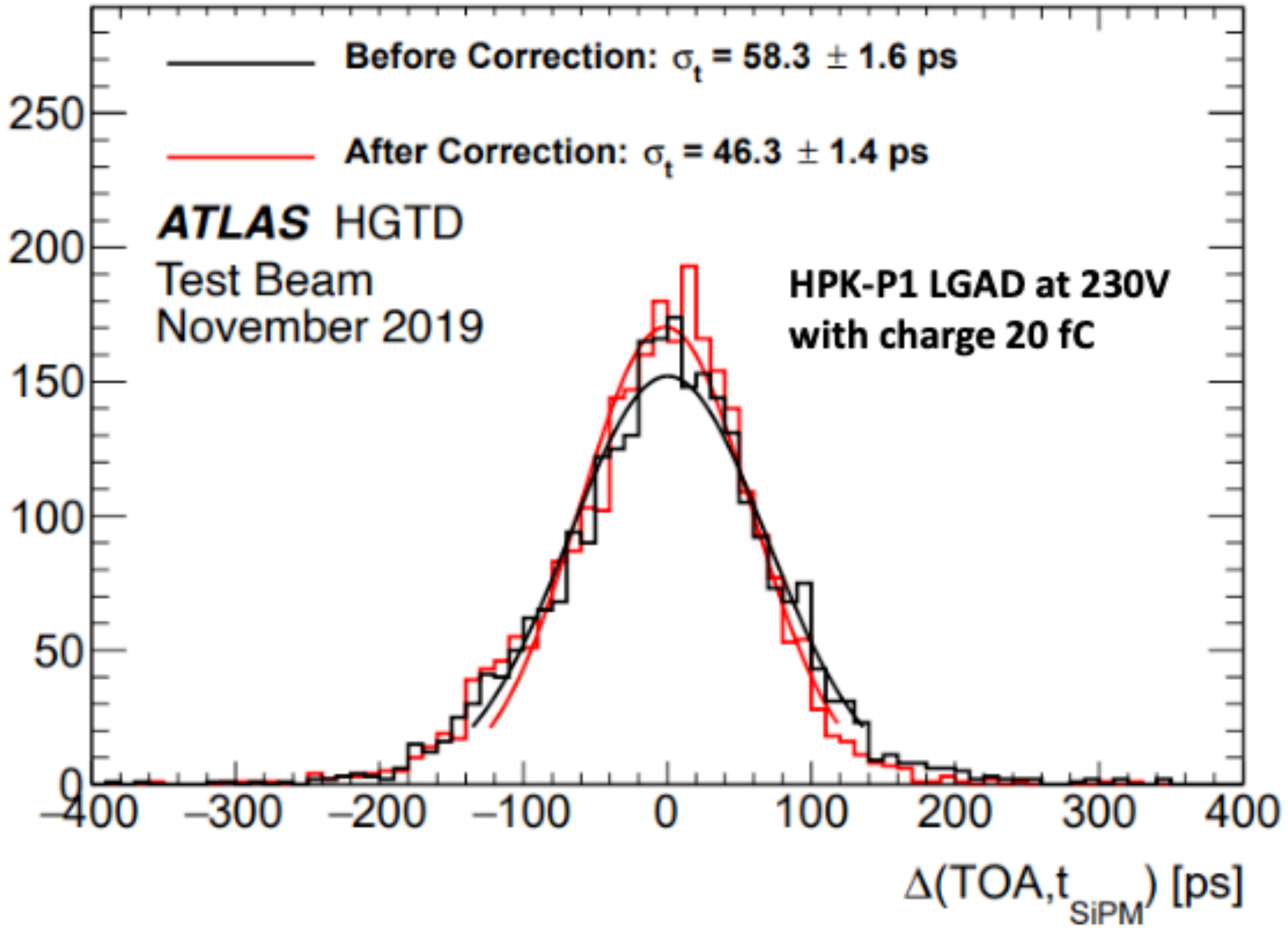
- Single Event Burnout (SEB) - when heavily irradiated sensors (~end-of-life 2.5e15 n_{eq}*cm^{-2}) operated with high bias voltage
  - Not a problem if operated with lower voltage!
  - A single particle which deposits enough energy (~tens MeV) causes: conductive path leading to destructive breakdown
    - Confirmed & cross checked with R&D at CMS and RD50
  - Bias voltage safe from SEB: **< 11V/µm (i.e. <~550V for 50µm)**





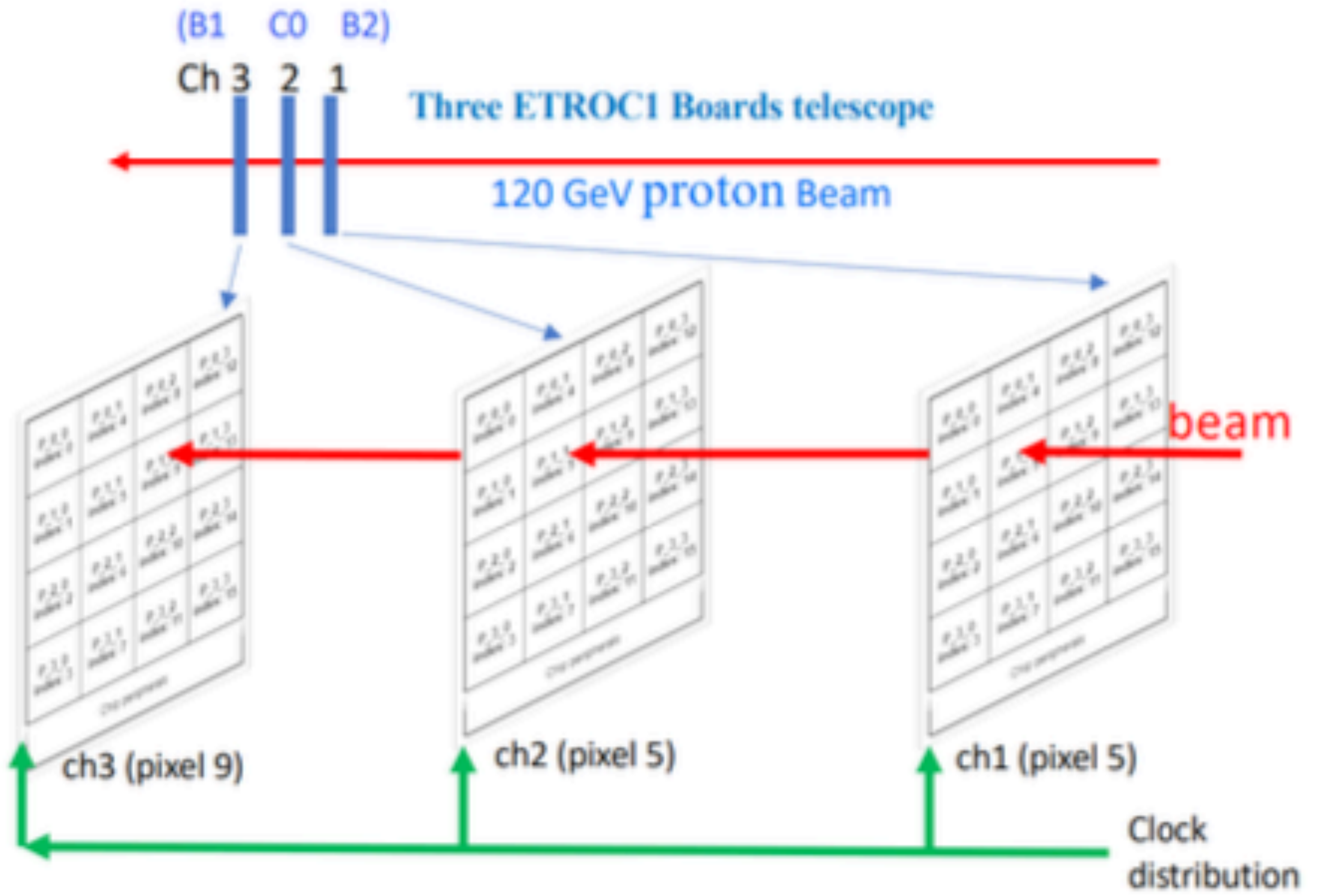
ALTIROC1+LGAD TB performance

Slide from G. Kramberger



LGAD Landau	25 ps	the reason for part of the high jitter found **26 (known reasons)**
Jitter+system/internal clock+time walk residual	37 ps	
TDC clock	7 ps	Total resolution: 36 ps (likely achievable for 20 fC)/ 70 ps for (4 fC)
Per hit total	46 ps	

LGAD+ETROC1 – Preliminary Test Beam Results **(HPK-P1/P2 LGAD at 230V with charge 20 fC)**



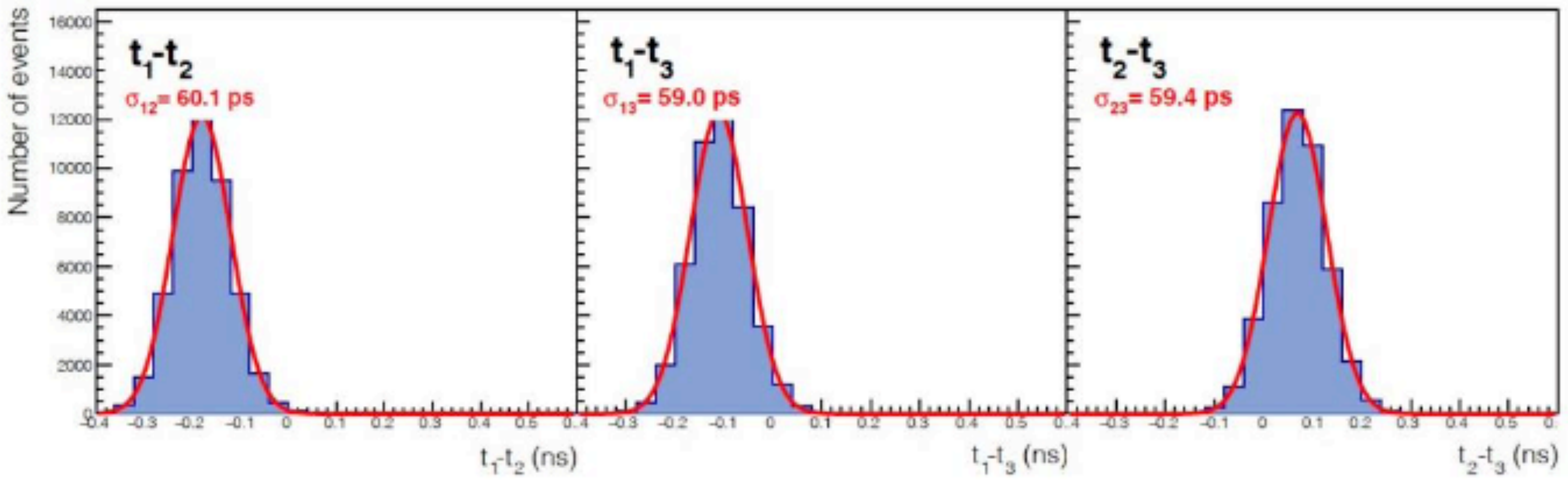
ETL Time resolution

Simulation /expectation

LGAD+ preamp/discriminator + TDC bin	35 ps
Time-walk correction residual	< 10 ps
Internal clock distribution	< 10 ps
System clock distribution	< 15 ps
Per hit total time resolution	41 ps

courtesy of Ted Liu (FNAL)

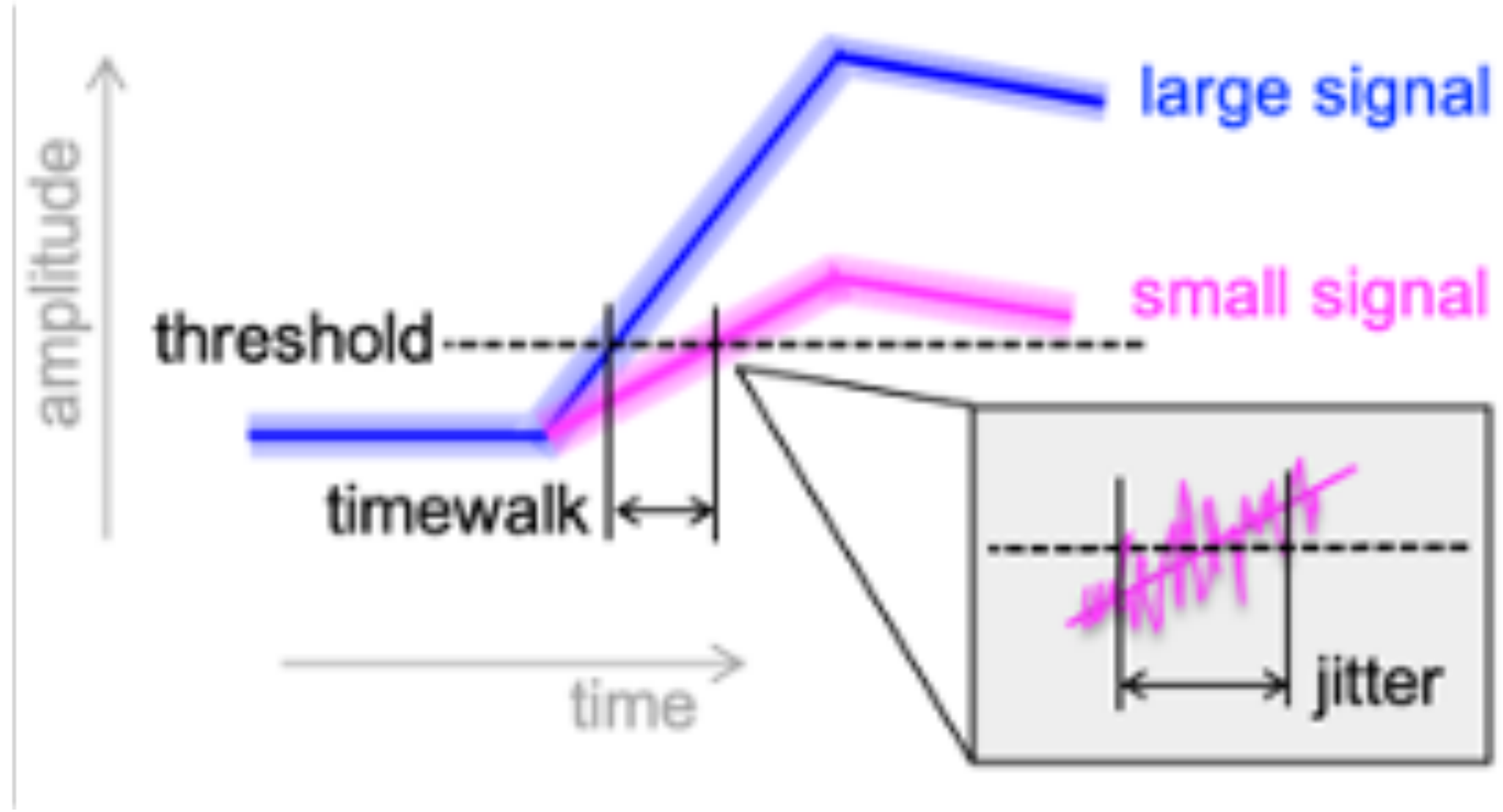
Ted



Time Resolution: Jitter

Time Resolution is dominant by three components*

$$\sigma_t^2 = \sigma_{\mathrm{TimeWalk}}^2 + \sigma_{\mathrm{jitter}}^2 + \sigma_{\mathrm{TDC}}^2$$



Jitter

- Amplitude fluctuations affect the exact threshold crossing time
- Fluctuations come from:
  - Thermal noise of the pre-amplifier
    - Large signal and/or high gain (power) mitigates this effect
  - Local fluctuations in the ionisation density

Clock and Time Measurement

Time Resolution is dominant by three components*

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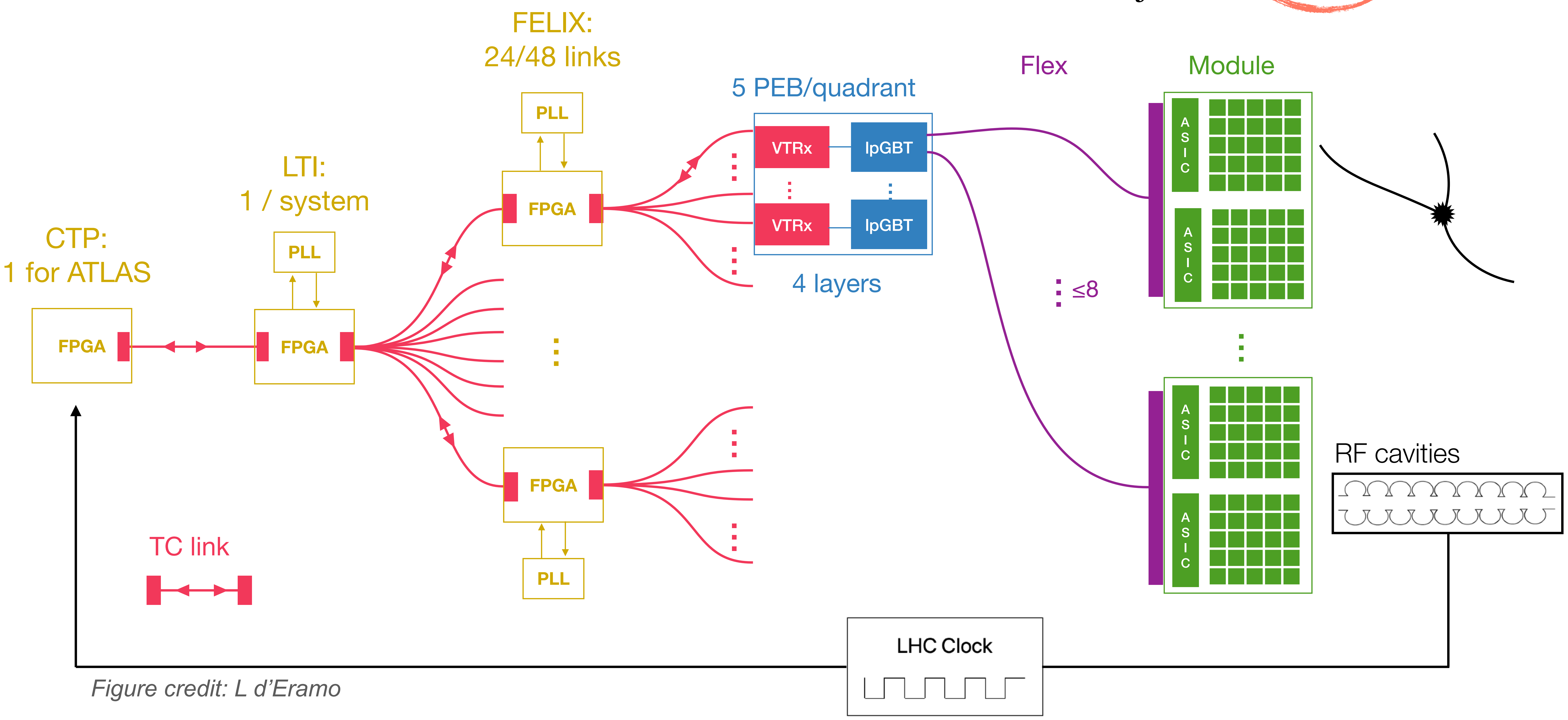


Figure credit: L d'Eramo

Clock

All time measurements are done w.r.t. a reference clock

Every hop introduce noise over the clock

Long cable can introduce time drift/wander (slow component) and jitter (fast component)

Actions:

- Compensation on hardware to ensure a precise clock distribution - TCLink
- Calibration of time offsets - challenging, *stay tuned* for our results!

** This equation has other variations, depending on how one categories the resource; the format here is commonly used in detector R&D community*

4D Tracking: A Glimpse into the Future

To realise a **'real' 4D tracking**

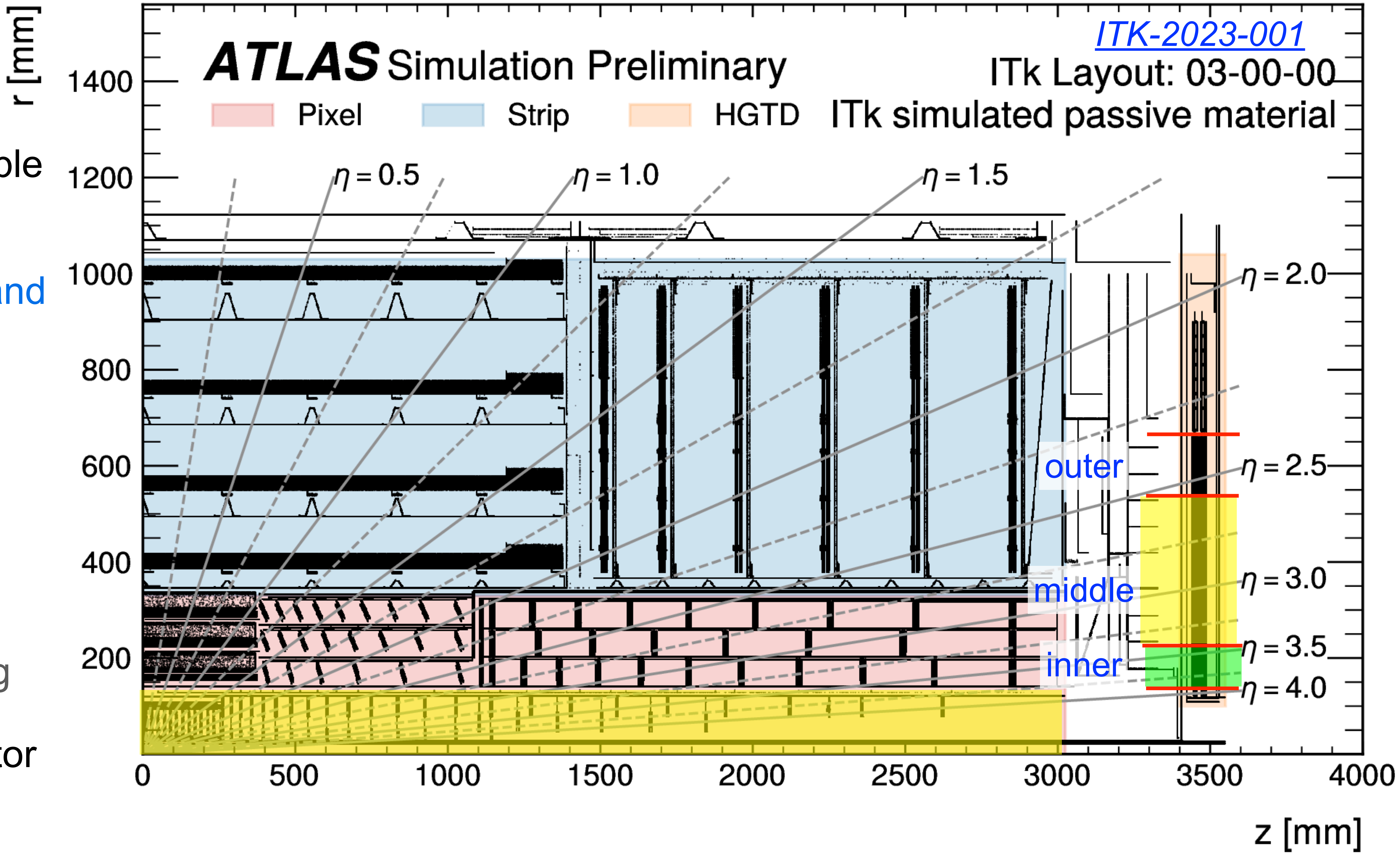
- To obtain temporal measurement on every track - with full 4π coverage

Replacement plan provides a chance to enable 4D tracking at HL-LHC:

- Every 2 ab^{-1}: *innermost ITK pixel layers* and *HGTD middle ring* to be replaced
- Every 1 ab^{-1}: HGTD inner ring to be replaced

Challenges:

- *Novel 4D tracking algorithms to built*: use time information in track finding and fitting
- Unknown impact of 4D tracking on detector geometry choice



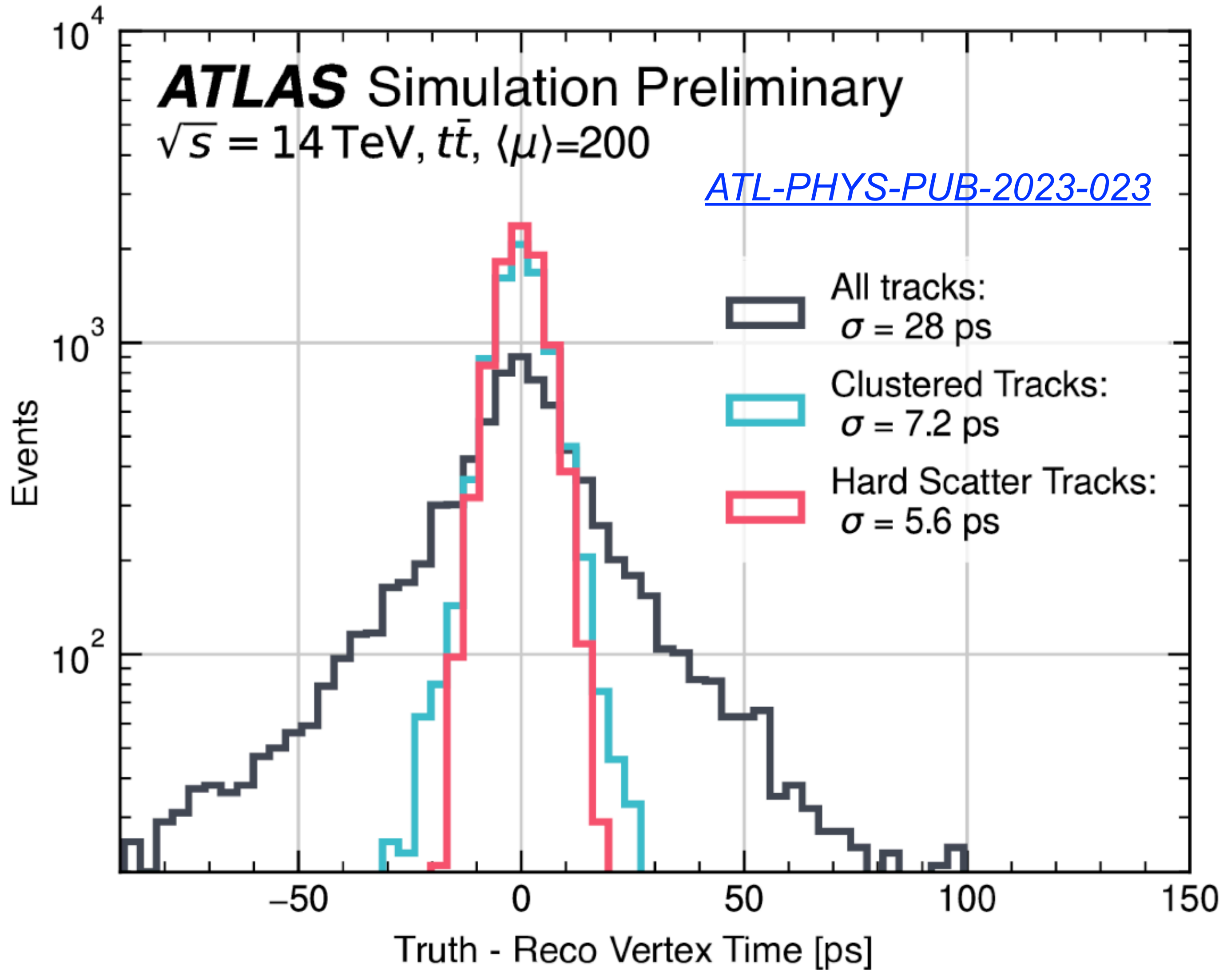
4D Tracking: A Glimpse into the Future

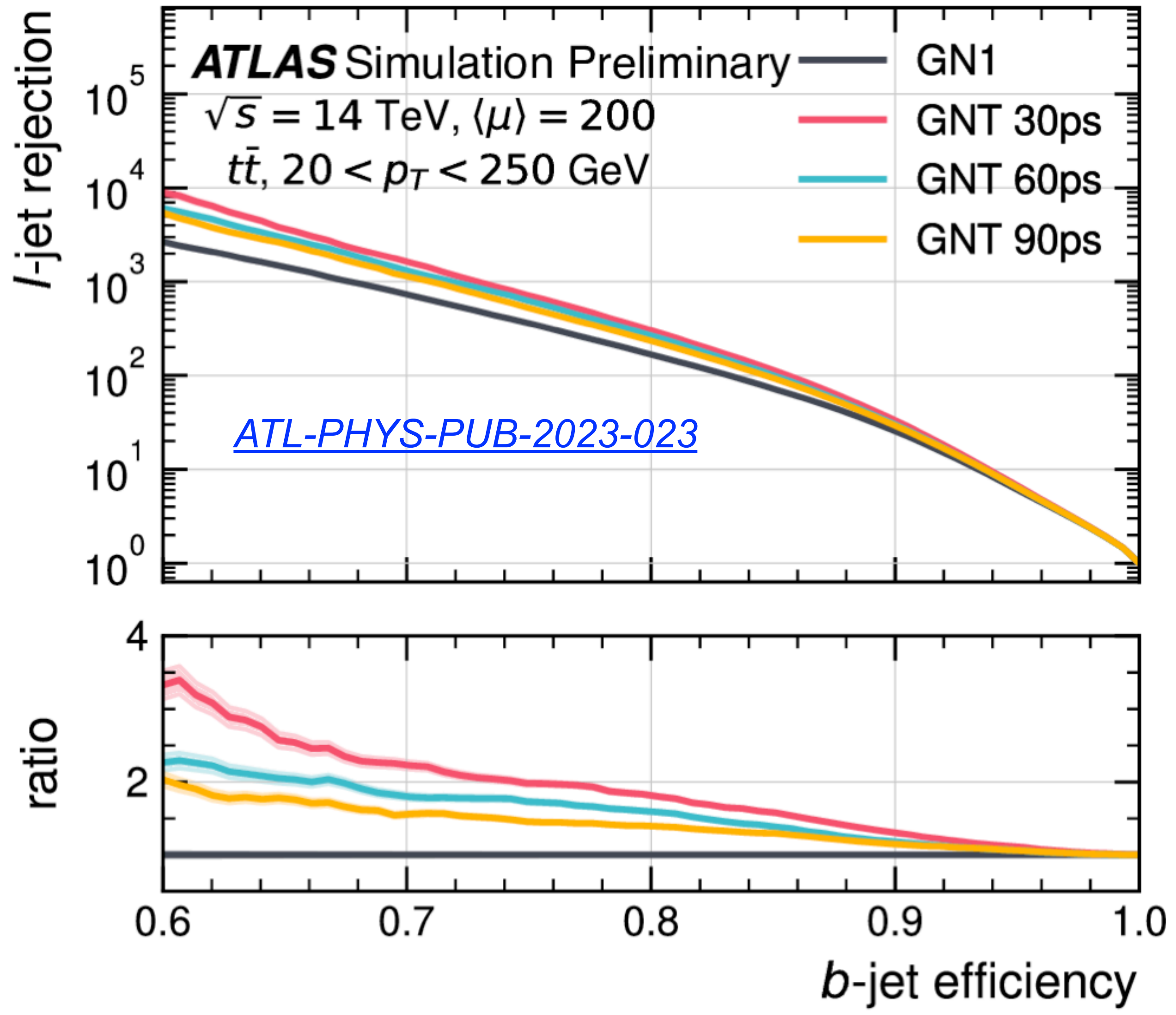
Pioneer simulation studies have been made using simulations

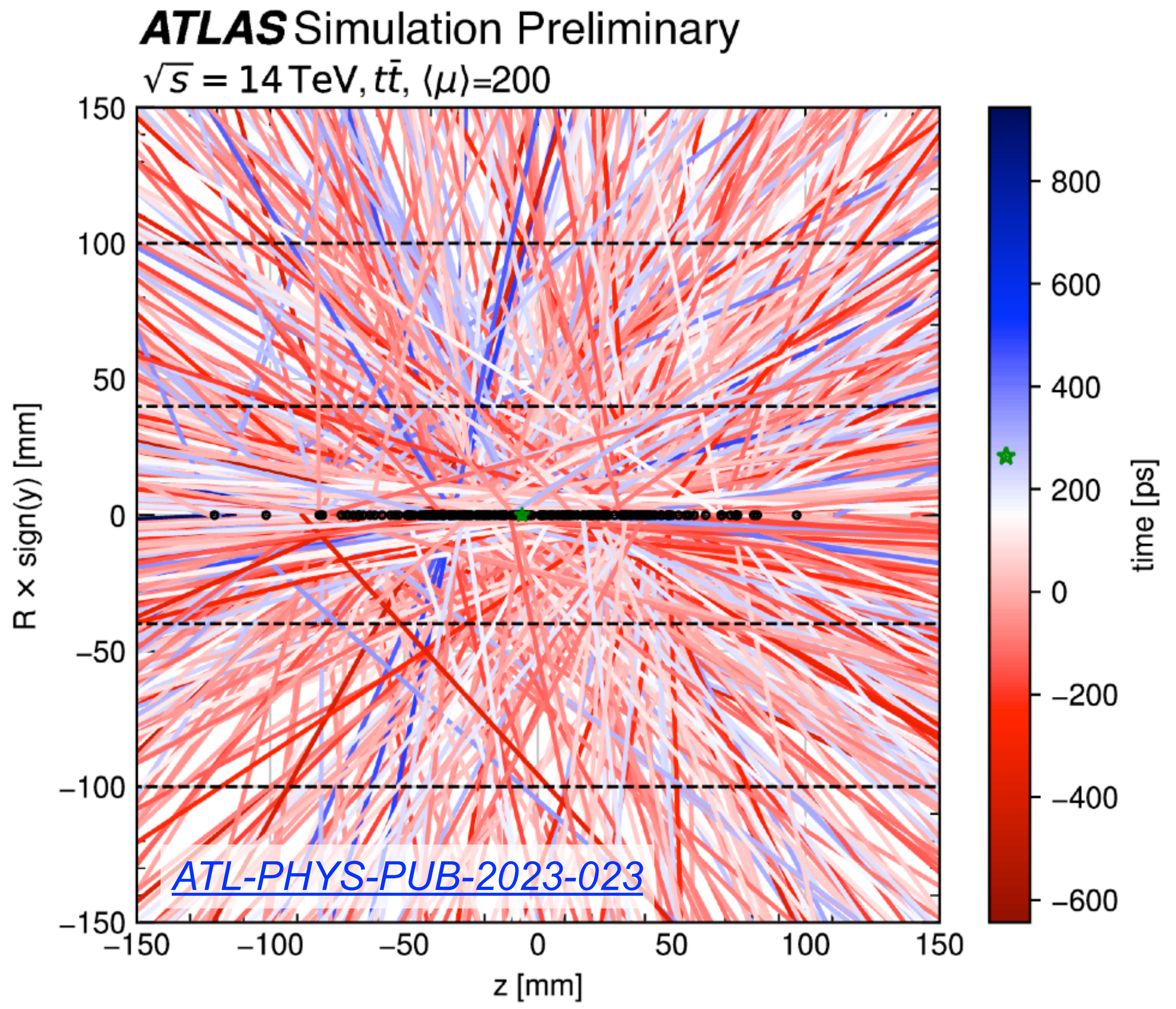
- Time of every vertex (incl. central vertices) can be reconstructed

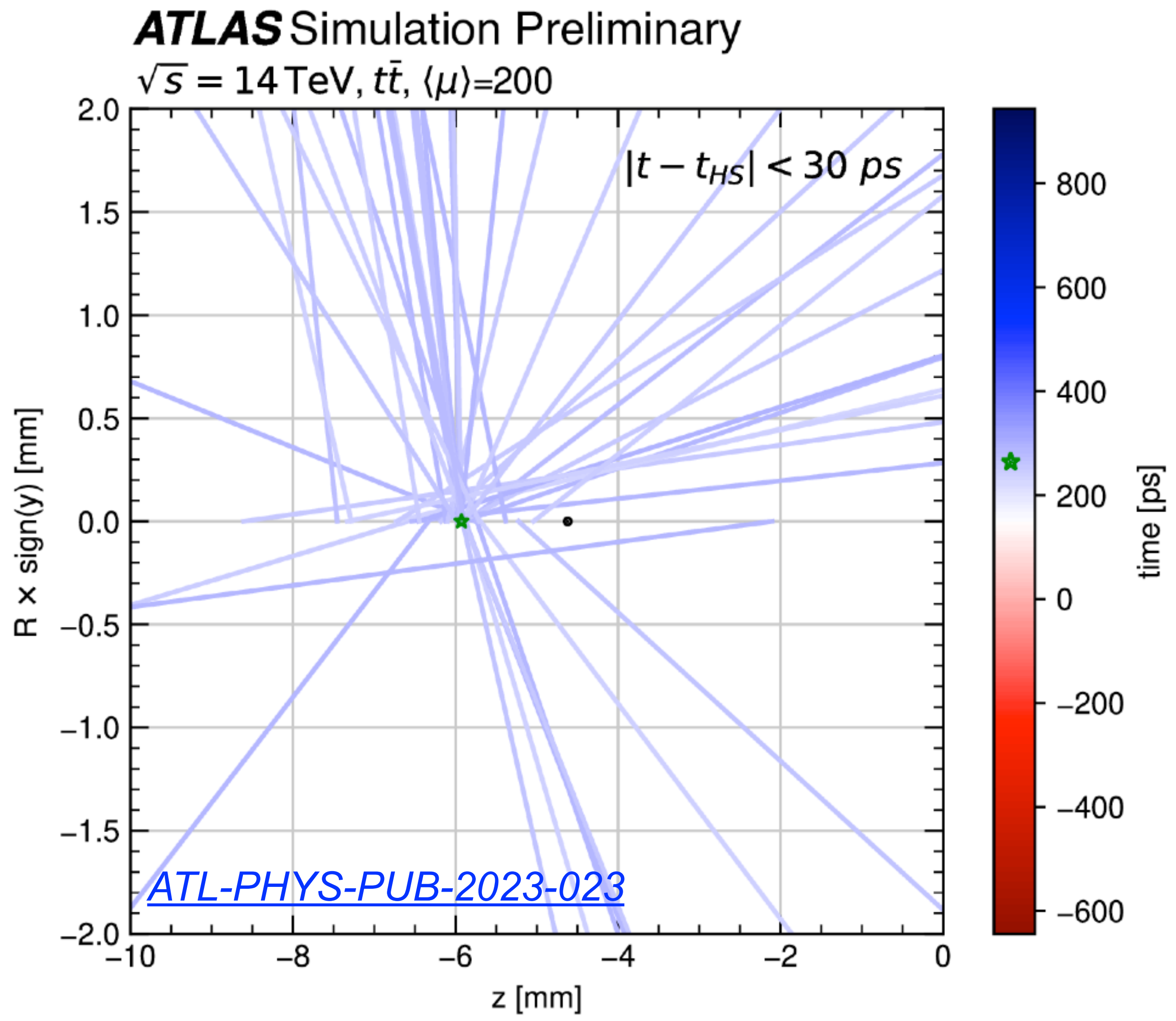
Performance potentials:

- Strong pileup suppression
- Full η coverage for a better HS vertex t_0 determination









Pioneer simulation studies have been made using simulations

- B-tagging improved up to a factor 3.5 using timing information also in the central region