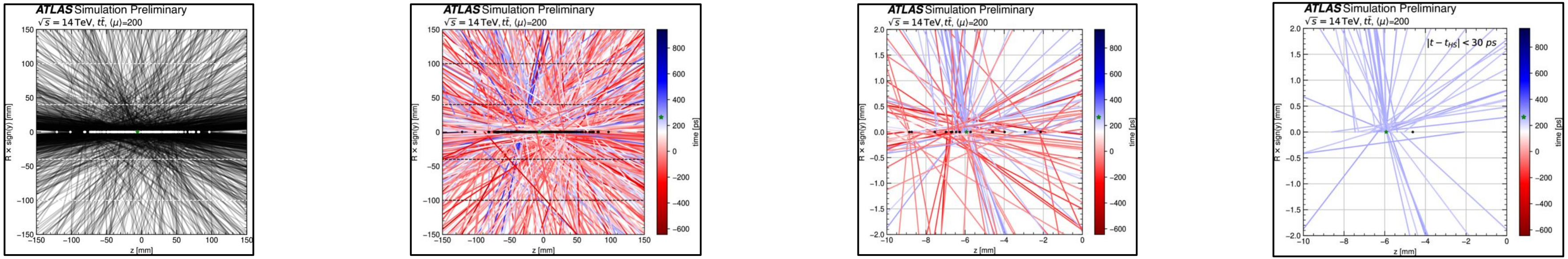

Motivation, Environment and Challenges of 4D Tracking at Future Colliders

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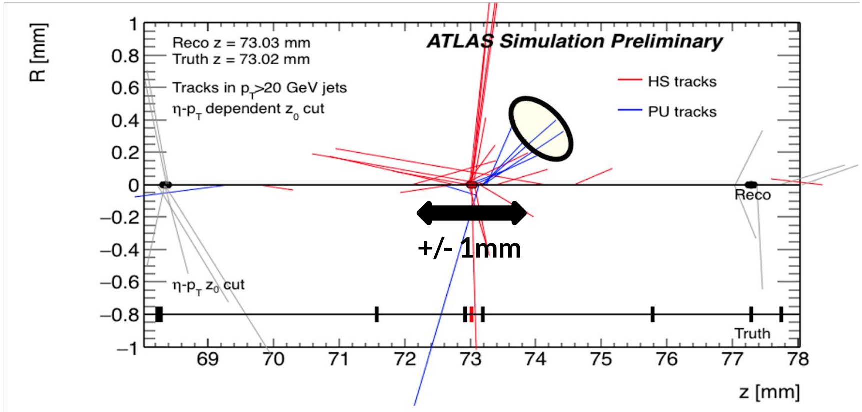
Introduction

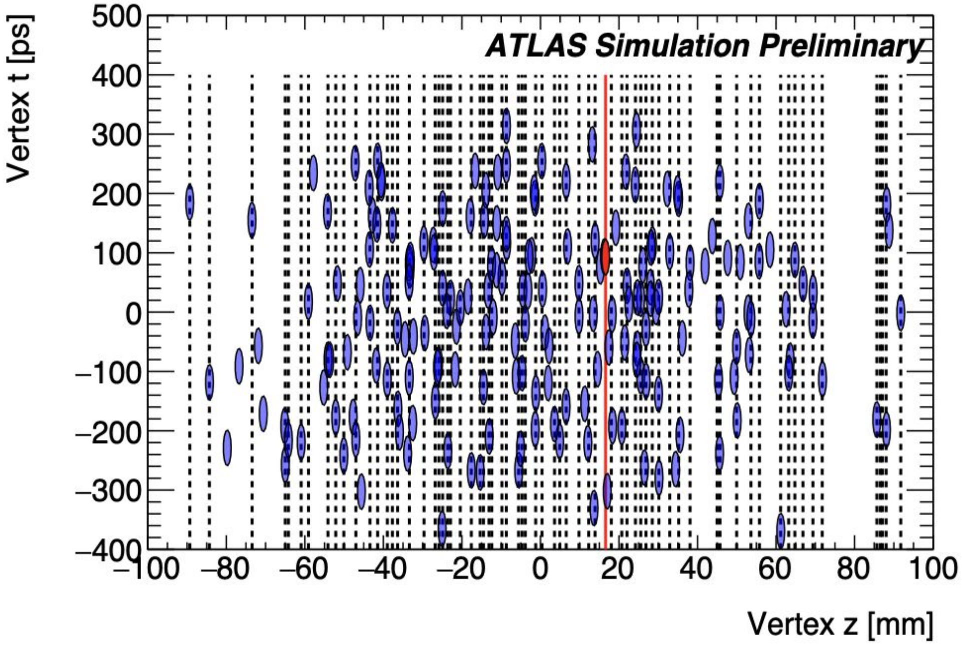
- **While the use of timing in collider detectors has a long history, <u>precision timing at the level of 10-30ps</u> is a new capability for the next generation of particle physics detectors at all future colliders**
  - Address the increasing complexity of events at hadron colliders
    - 4D trackers to resolve vertices at very high pileup densities
  - Identify long-lived particles (LLPs) and expand the reach for new phenomena
  - Enable particle ID capabilities at low momentum
  - Suppress out-of-time beam Induced backgrounds at muon collider
- **R&D to investigate the full potential of fast timing detectors in future Higgs Factories is an exciting opportunity for the particle physics community**

Goals

- What are the main physics cases and experimental challenges for 4D trackers?
- What are the key quantities driving requirements?
- What simulation studies are required to determine detector requirements and address key experimental challenges?
- What questions we would like to answer?
    - Example: what are the key requirements and challenges for a silicon wrapper timing layer at FCC-ee?
- Establish goals for next year and for the next 5 years

Fast Timing at the HL-LHC





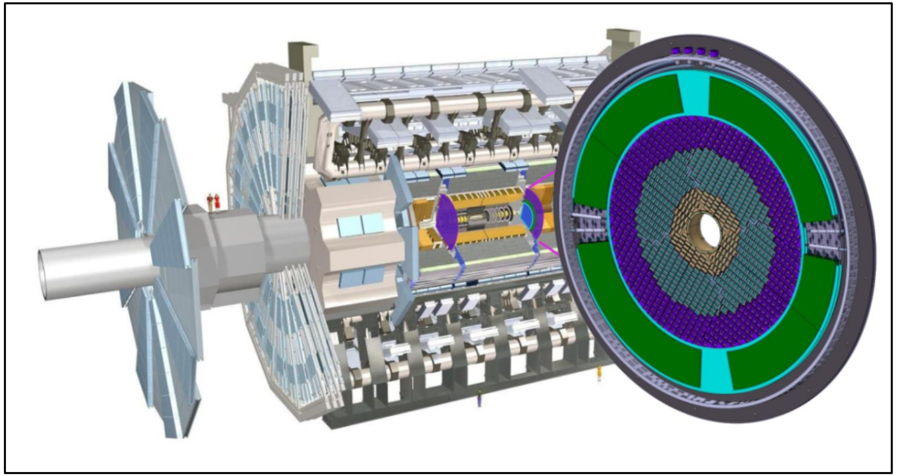
At the HL-LHC, the typical separation between vertices can be comparable to the track longitudinal impact parameter resolution: **<u>the association o tracks to vertices becomes ambiguous</u>**!

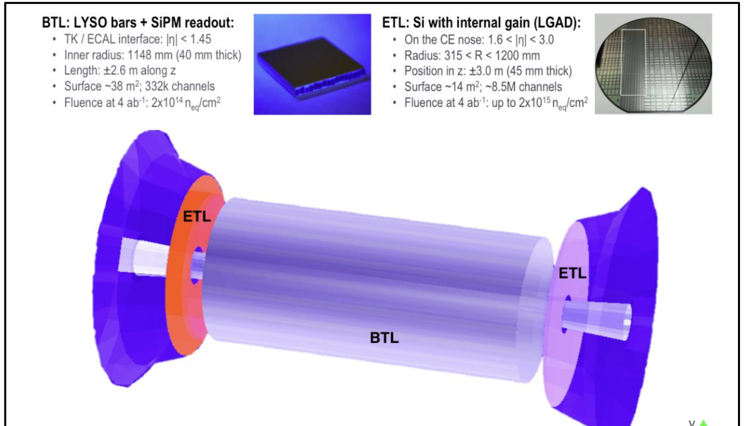
Exploit the time spread of collisions to reduce pileup contamination

Nominal HL-LHC Luminous region σ_t = 180ps
(30ps detector) → 30/180 = **6x pile-up rejection**

ATLAS and CMS

ATLAS HGTD

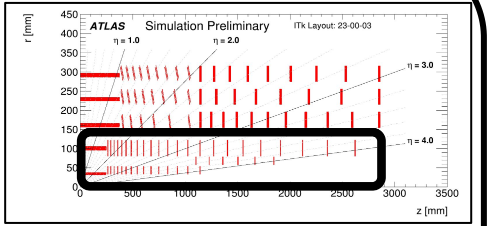


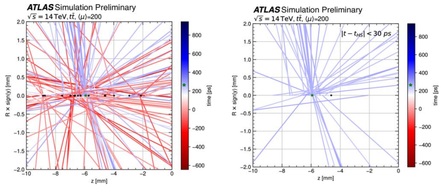


CMS MTD

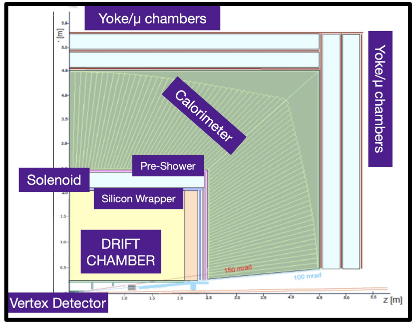
- LGAD sensors in the endcap/forward regions (1.3 x 1.3 mm^2)
- Crystals and SiPM readout in the barrel central region
- ~30ps time resolution per track
- **ATLAS improves forward VBF final states (pileup suppression, lepton isolation)**
- **CMS hermetic coverage improves b-tagging, LLP, and provides PID capabilities**
- **Precursors to future timing layers and 4D trackers in collider experiments**

4D Tracking at Future Colliders

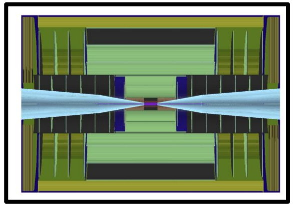


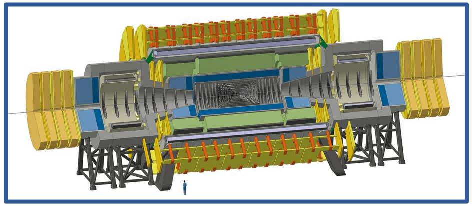


HL-LHC: (*2035*)
4D tracker inner system replacement



FCCee/ILC: (*2040*)
Timing layers for flavor tagging, particle ID, and LLP searches





10 TeV muon and hadron colliders (*2050+*)
Full 4D tracker for BIB rejection (muC) and pileup suppression (FCC-hh) at extremely high radiation environments

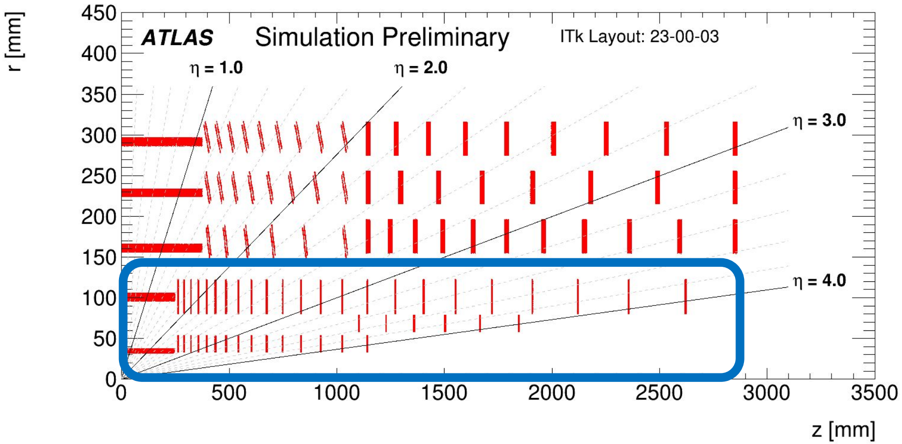
Motivations for 4D Tracking at the HL-LHC beyond Run 4

- The inner pixel replacement presents an opportunity to <u>investigate the physics case of 4D tracking beyond Run 4</u>

Precise determination of vertex t_0:
forward jets and leptons, and large $c\tau$ LLPs

Improve physics objects in the central region:
<u>b-tagging</u>, small $c\tau$ LLPs

Improve track and vertex reconstruction:
CPU time, efficiency, purity, resolution, lower the minimum track p_T threshold

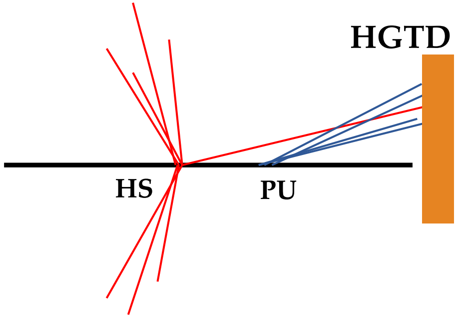


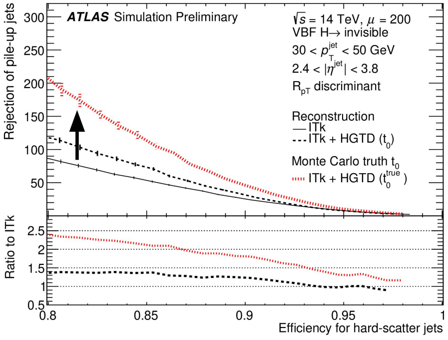
ATLAS Inner Pixel is designed to to be replaced mid-way through HL-LHC

4D tracking physics motivation studies

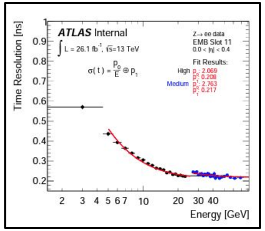
ATL-PHYS-PUB-2023-023

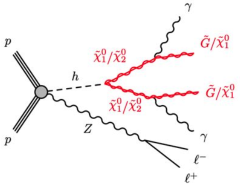
Improved vertex t_0: forward pileup jet rejection



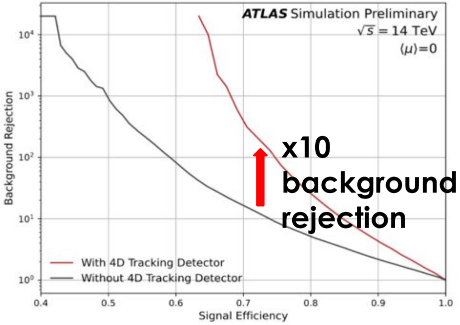


Improved vertex t_0: Long lived particles



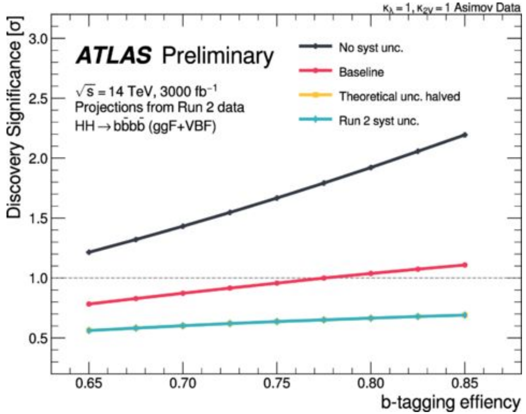


LAr Time resolution dominated by lack of knowledge of vertex t_0



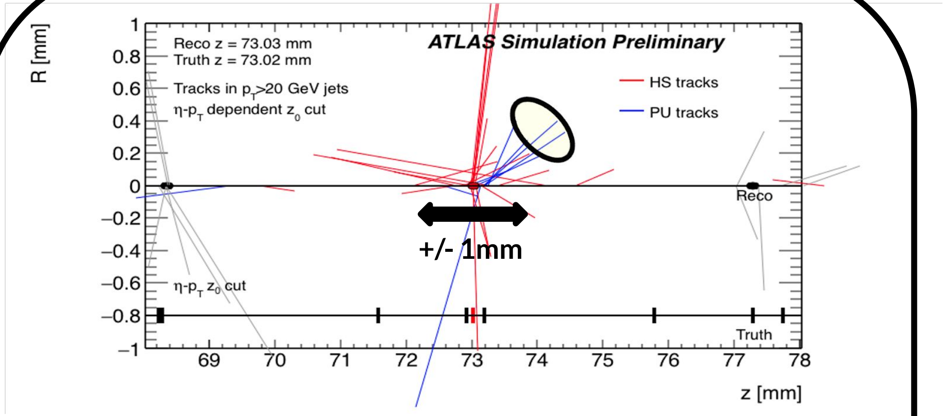
x10 background rejection

Improved b-tagging

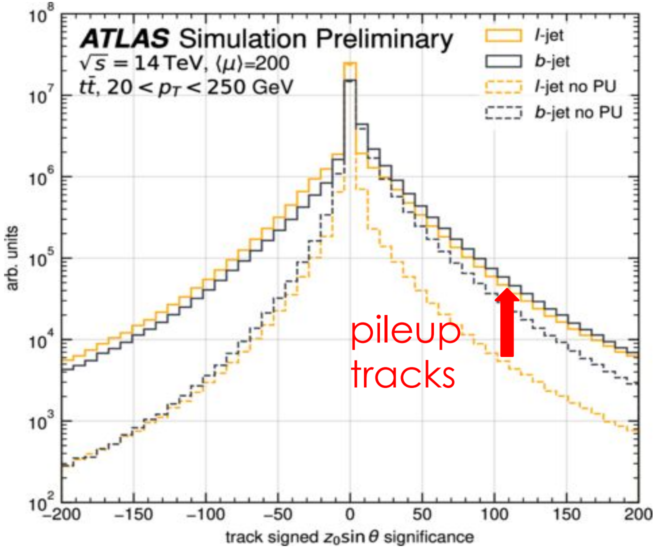


5% b-tagging efficiency improvement ⇒ 0.3σ gain in discovery significance for HH → 4b

Two main physics cases

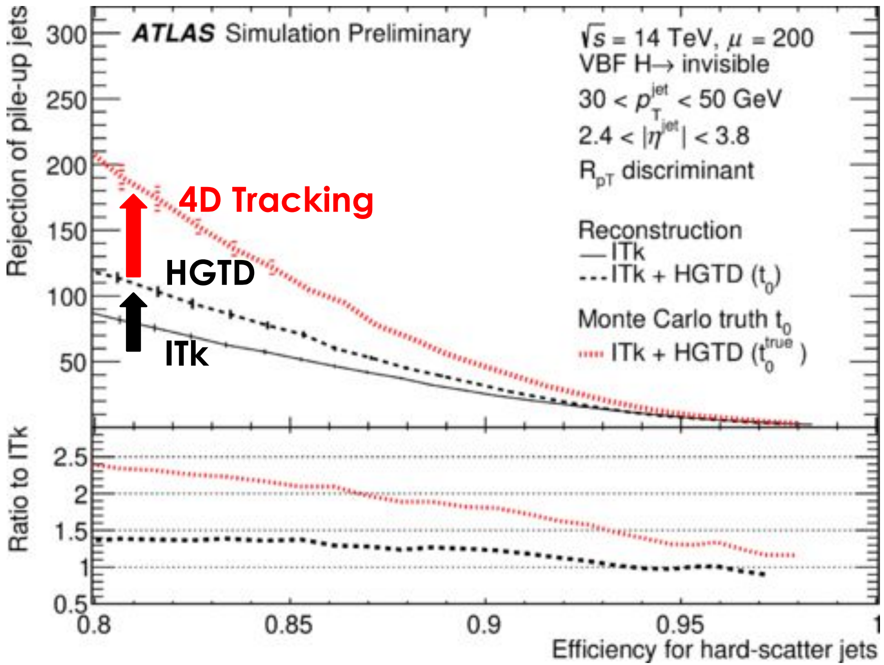


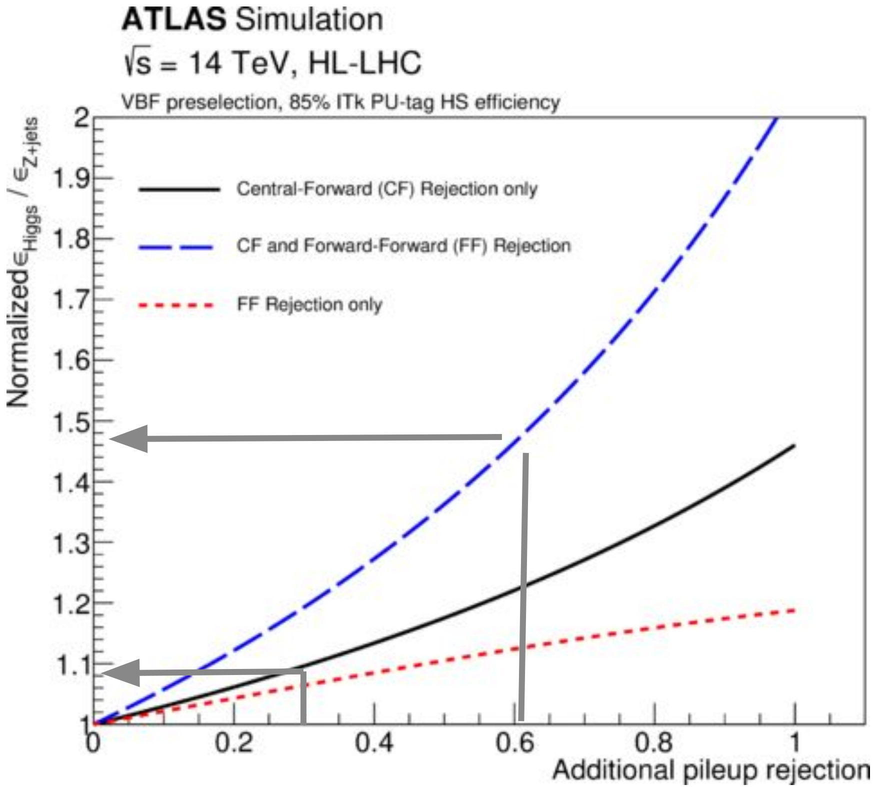
Detector resolution:
Distance between primary vertices < z impact parameter resolution



Physics:
z impact parameter from B hadrons >> distance between primary vertices

VBF pileup jet suppression

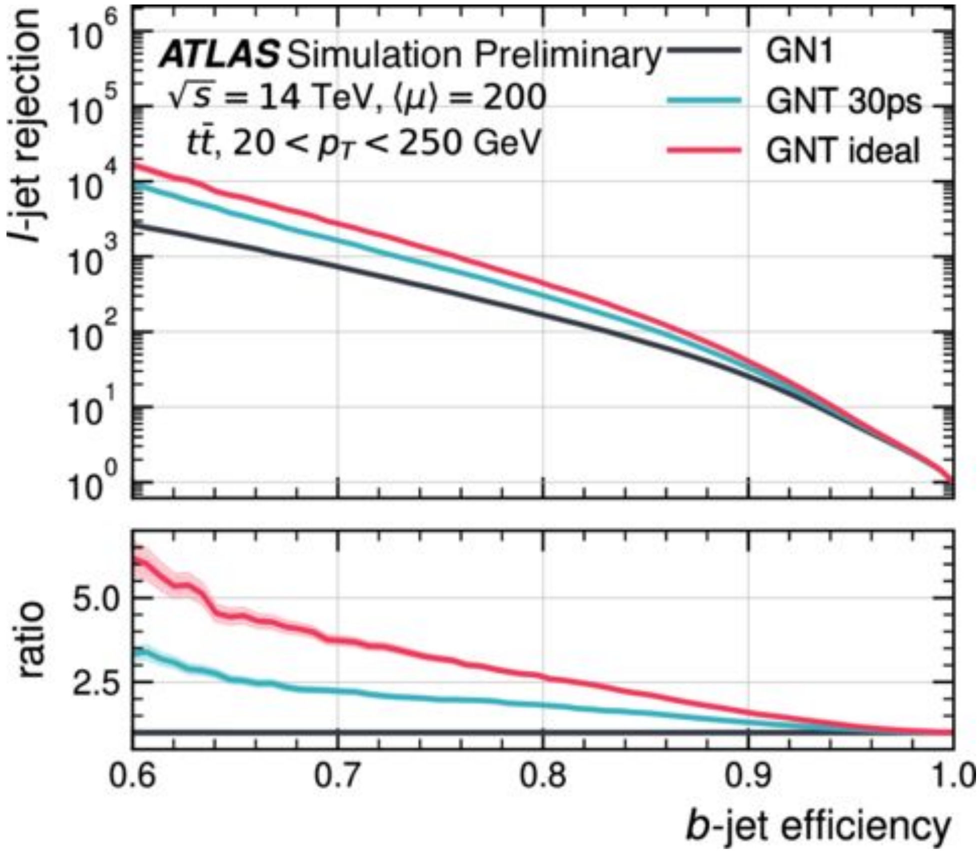




50% Improvement in VBF H→invisible

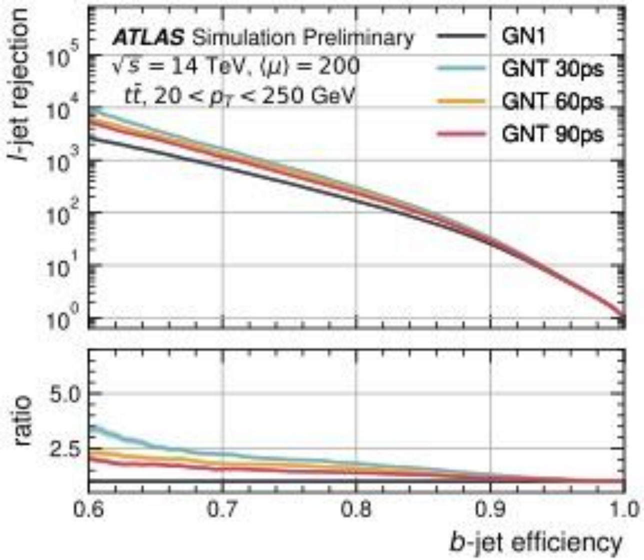
- improved PU jet suppression
- access to the full acceptance of central-forward jets

b-tagging



Graph NN (GN1) b-tagging using track timing information

2x improvement in rejection at 70% efficiency and 30ps track time resolution

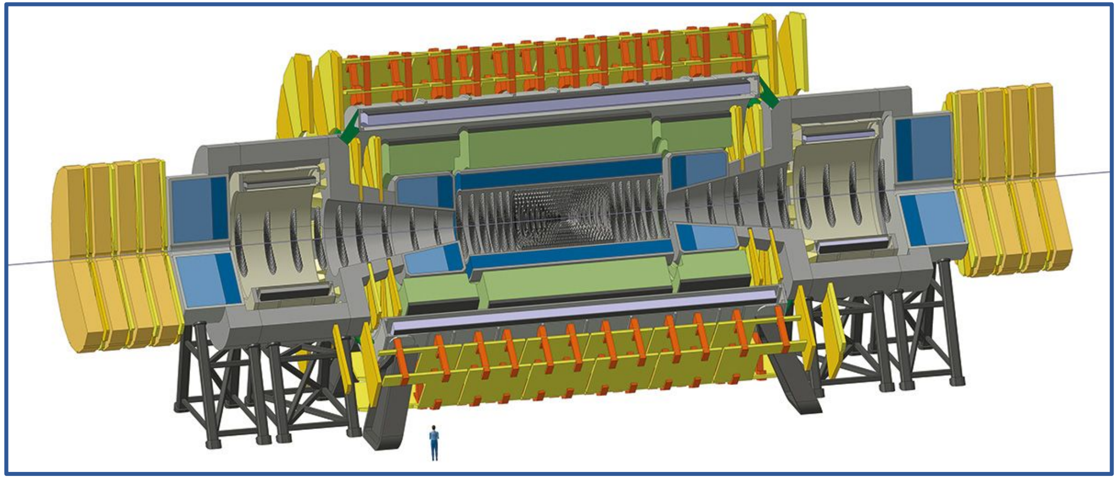


Phase-3 HL-LHC Challenges

- Sensors and electronics capable of reaching 30-50ps time resolution per track under a high radiation environment (10^{16} n_{eq}/cm^2) and ~10 MGy
- Small pitch: ~$50\mu m^2$, high occupancy
- Low power to minimize additional material
- Data transmission for ToA and ToT and bandwidth requirements
  - TDC range → power
  - on-chip data reduction schemes?
    - provide single time for clusters
    - 4D clustering
    - …

FCC-hh

- 100 TeV → SM process are low mass and boosted in the forward region → **|eta|<6 acceptance**
- Jet substructure for boosted topologies require high granularity and resolution



- **Unprecedented O(1000) pileup conditions**!
- Detector R&D required to archive a **radiation hardness** for an intensity ~30 times larger than HL-LHC ($8.10^{17} n_{eq}/cm^2$ at 2.5cm radius) and 300 MGy
  - HL-LHC radiation levels for outer tracker (R > 40cm)
- 3 times more readout channels than HL-LHC trackers

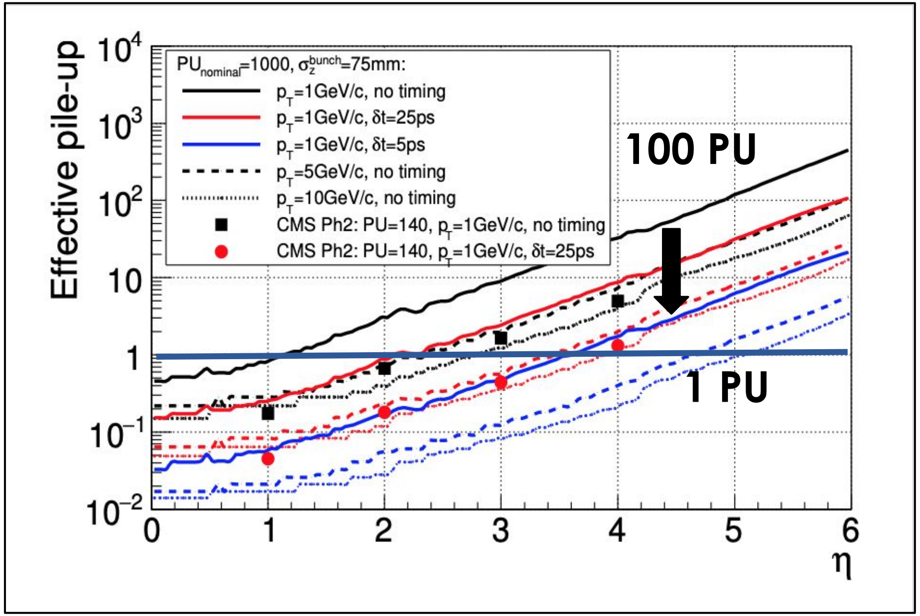
FCC-hh

Full 4D tracking becomes essential to address the pileup challenge for the association of hits, tracks, and vertices consistent in time

Need O(5ps) resolution per track to achieve a similar environment as HL-LHC

Significant detector R&D required to archive sensors capable of operating at 30 times the radiation hardness of HL-LHC trackers

Need detailed simulation studies to understand the 4D tracking layout and its timing requirements for various physics benchmarks

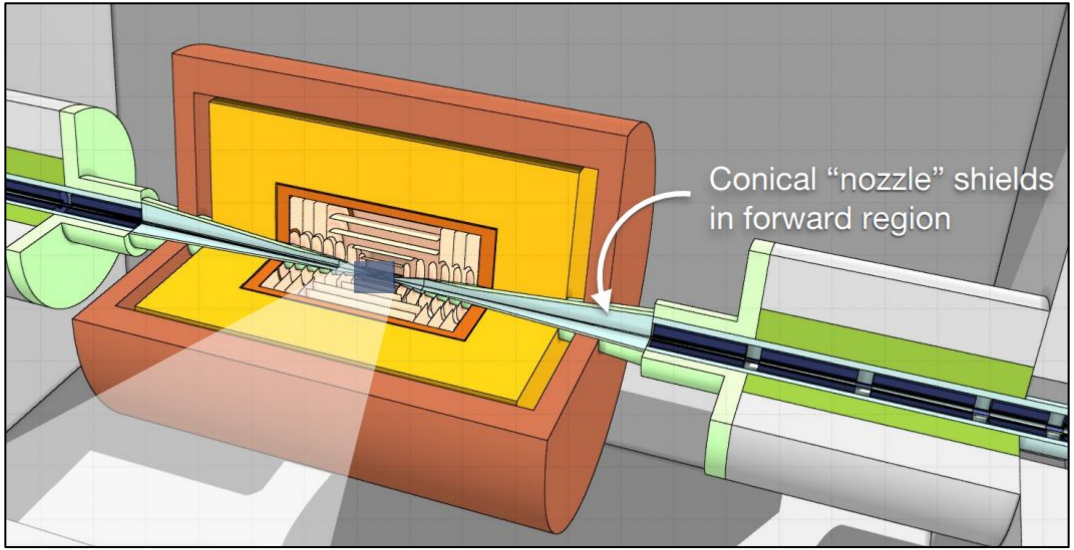


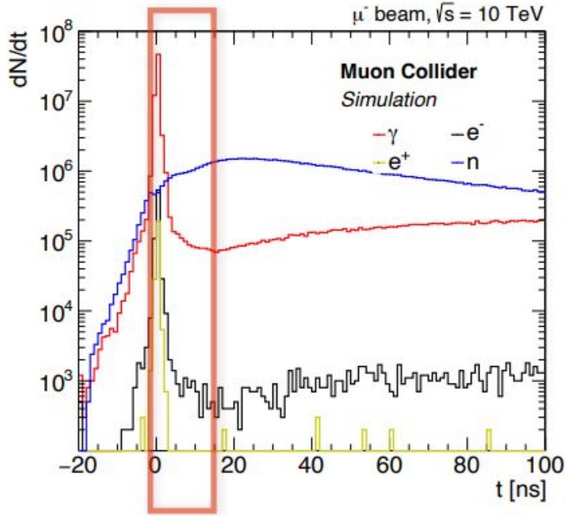
Muon Collider

- **Very different environment than we're used to → challenges & opportunities**
- Large beam-induced background from muon decays and showering of electrons on shielding
  - mostly electrons/photons, some neutrons
  - significant out-of-time component
  - coming from "all" directions!

Accelerator & Detector Parameters: 2411.02966

Time between bunch x-ing	**~30μs**
Bunch length (space/time)	1.5mm / 0.005ns
Max tracker dose / fluence [@3cm]	1MGy (100 Mrad) / $1\cdot10^{15}$ 1-MeV-neq/cm^2

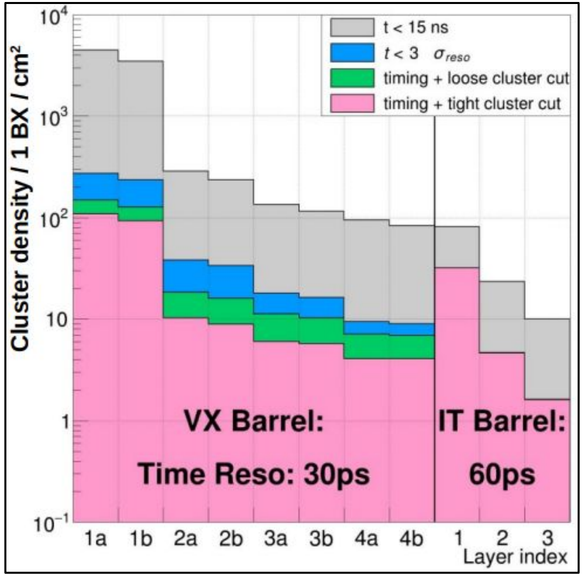




Muon Collider

- **Tracking detector design requires high-granularity and precision timing**
  - Full **4D-tracking** is a **requirement**, not an option.
  - However, timing resolution is not as strict as e.g. FCC-hh

Sub-Detector MAIA/MUSIC	Technology	# Layers /Rings	"Cell" Size	Sensor Thickness	Hit Time Resolution	Signal Time Window
Units			μm^2	μm	ps	ns
Vertex Barrel	Pixels	4*/5	25 x 25	50	30	[-0.18, 15.0]
Vertex Endcap	Pixels	4	25 x 25	50	30	[-0.18, 15.0]
Inner Barrel	Macro-Pixels	3	50 x 1000	100	60	[-0.36, 15.0]
Inner Endcap	Macro-Pixels	7	50 x 1000	100	60	[-0.36, 15.0]
Outer Barrel	Macro-Pixels	3	50 x 10000	100	60	[-0.36, 15.0]
Outer Endcap	Macro-Pixels	4	50 x 10000	100	60	[-0.36, 15.0]

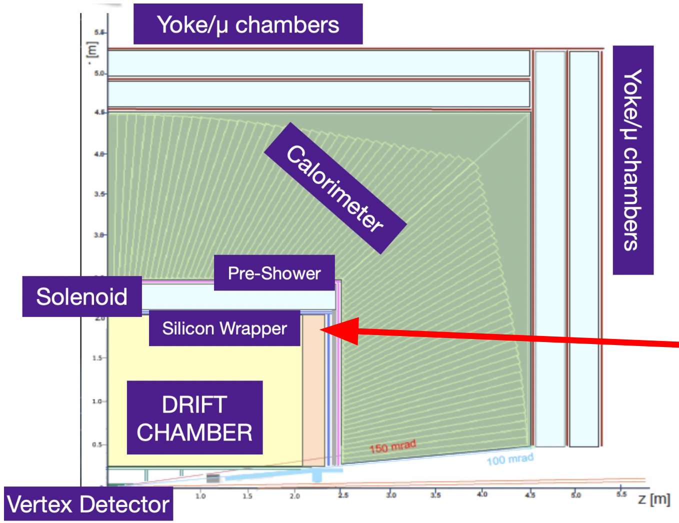


- Reduction of complexity through filtering
  - time-based
  - cluster-shape
- Together with a streamlining-like readout, implies advanced on-chip processing capabilities extremely useful!

Synergies: precision timing also critical for calorimeter, PID, Muons, …
Forward-muon tracker (inside shielding! see backup) has enormous physics potential and very different and new challenges!

FCC-ee Timing layers

FCC-ee IDEA



Silicon Wrapper

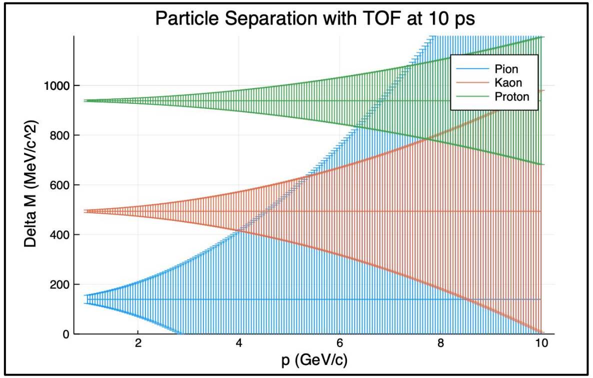
FCC-ee ALLEGRO

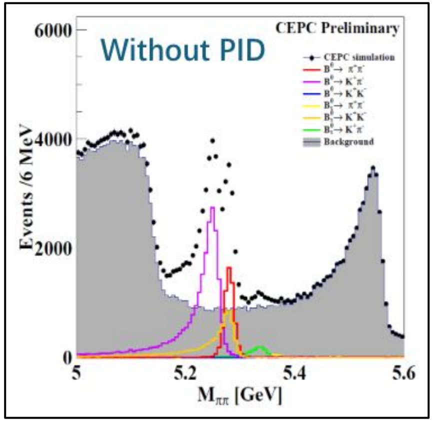
- **Silicon Wrapper detectors in FCC-ee detector concepts**
  - ToF PID at low momentum: Flavor tagging
  - Long lived particle searches
- **Need physics studies to fully establish physics case and understand detector requirements and impacts in overall physics performance**
  - (material, power consumption, readout, **calorimeter timing**, …)

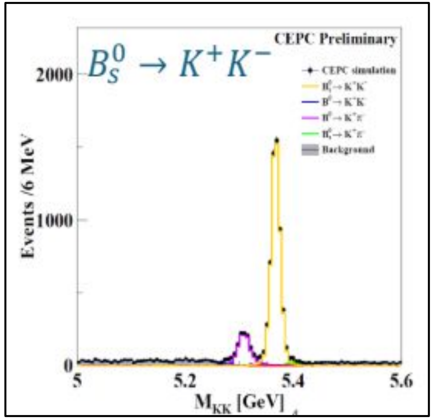
ToF: Particle ID

- Large-radius timing layers in front of the calorimeter can provide **Time-of-Flight (ToF) for PID**
  - Flavour physics
- Need 10ps resolution for K/pi separation at low momentum (up to ~3-4 GeV)
- **Complements other PID sub-detectors in the low momentum region**

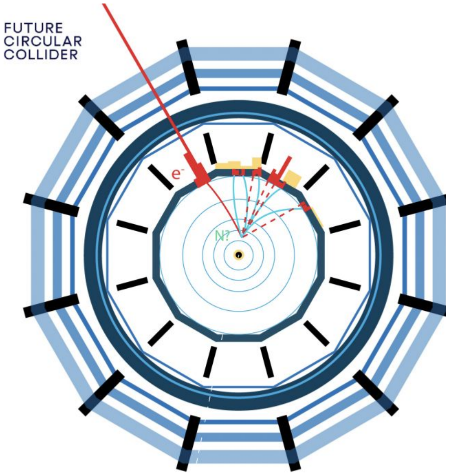
Updating the SiD Detector concept [Breidenbach, et. al.]

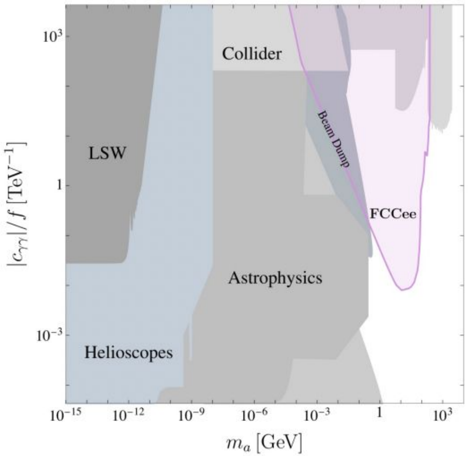






ToF: Long Lived Particles



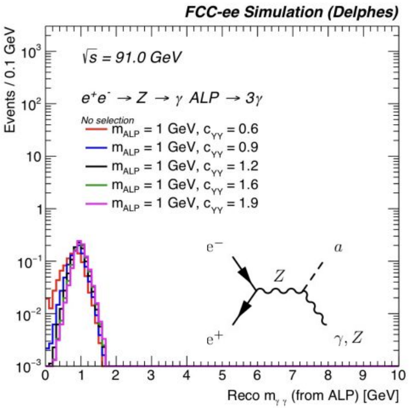


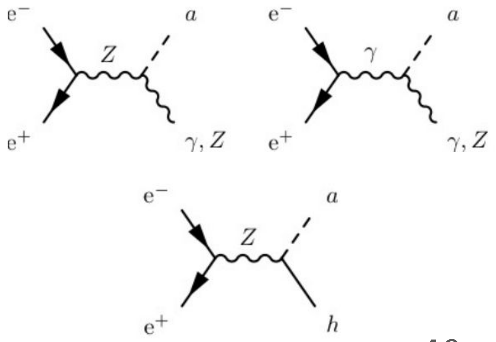
Exploit high luminosity Z run of FCC-ee to search for LLP:

- Heavy Neutral Leptons
- Axion-like particles
- Exotic Higgs decays

Timing information:

- Simultaneous determination of mass and proper decay time combining decay path and ToF
- Combine with displaced vertex reconstruction for enhanced performance

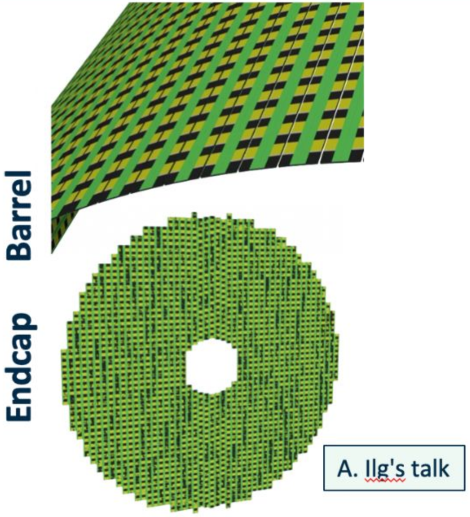


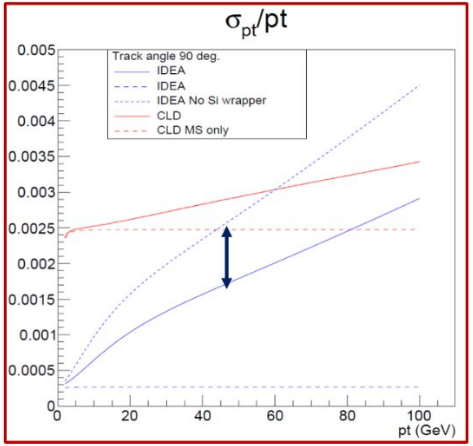


[Searches for Long-Lived Particles at the Future FCC-ee](#)

The IDEA Concept: Si Wrapper

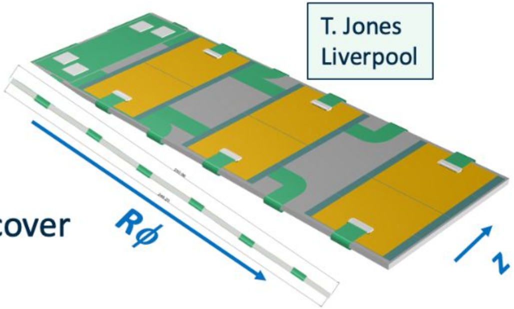
- **Precision silicon layer around the central tracker**
  - **improve momentum resolution**
  - **extend tracking coverage in the forward/backward region** by providing an additional point to particles with few measurements in the drift chamber
  - precise and stable ruler for acceptance definition
  - *it may provide TOF measurement*





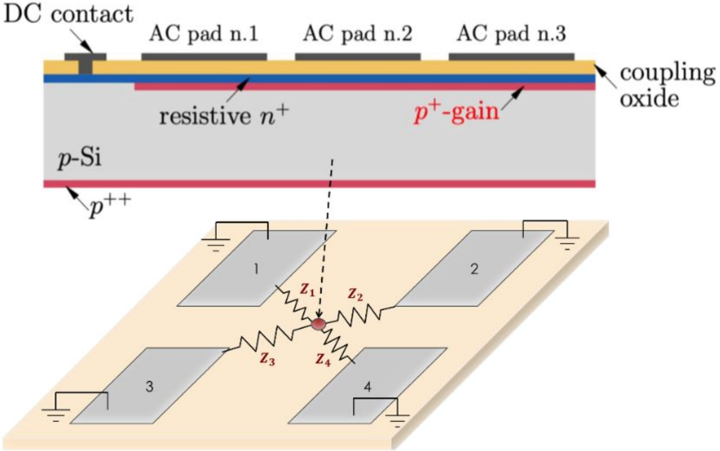
- Covered area ~100 m²
  - important impact on services
  - technology suitable for large size production

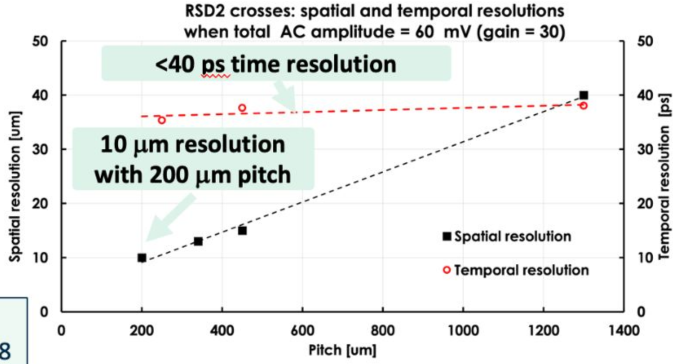
- Re-use the ATLASPIX3 quad-module concept
- **No detailed layout of the mechanical structure yet**
- Using multi-module tiles to cover the whole acceptance area



Si-Wrapper: alternative RSD option

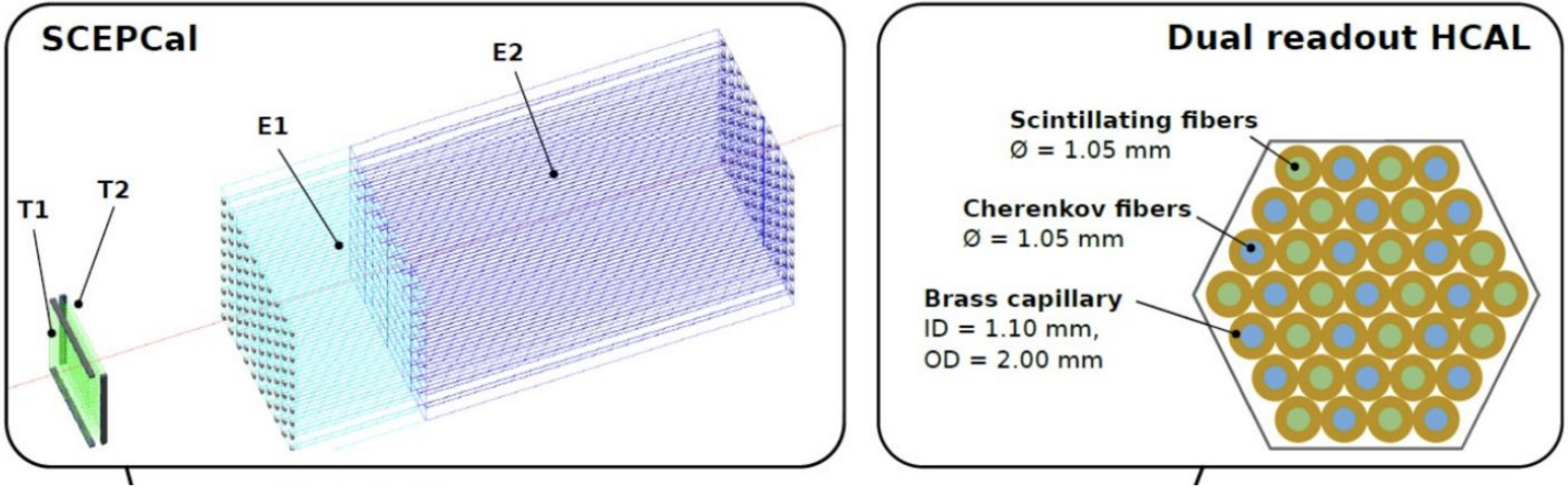
- LGAD detector with **continuous gain layer**
- Charge collection through **resistive n-layer**
- Readout by induction on **AC coupled pads**
- Fully active detector
  - avoids inefficient regions due to the insulation between pixels needed in LGAD sensors
- Charge sharing defined by the relative impedance of the path between the charge deposition and readout electrodes
  - Sharing is deterministic (in low pitch pixel detectors sharing is dominated by Landau fluctutations)
  - Timing resolution approximatively independent from pixel pitch
  - Position resolution ~5% of the readout pitch: more space in readout pixel cell to implement precision TDC





N. Cartiglia et al.
arXiv:2301.02968

Calorimeter timing layers



- Calorimeters concepts incorporate timing layers (for example crystals+SIPMs in CalVision dual readout EM section)
  - inorganic scintillator square fibers, $3x3mm^2$, 20ps resolution
- Excellent time with coarser spatial resolution
- **Need to study interplay between silicon wrapper and calorimeter timing**

ePIC @ EIC: TOF detector

Tracking and Vertexing:
- MAPS
- MPGD

PID:
- AC-LGAD TOF (also for tracking)
- hpDIRC
- pfRICH
- dRICH

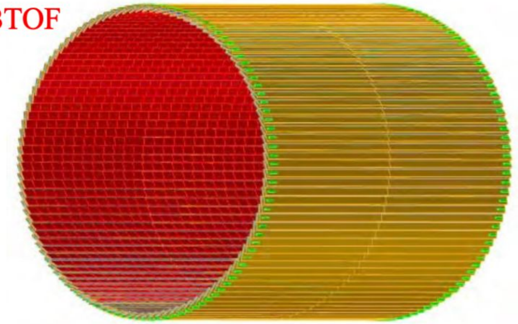
EMCal:
- PbWO EEMCal
- Pb/SciFi Barrel EMCal with Imaging
- W/SciFi FEMC

Hadronic Calorimeter
- Fe/Sc Backward HCAL
- Barrel HCal (sPHENIX re-use)
- Fe/Sc&W/Sc LFHCAL

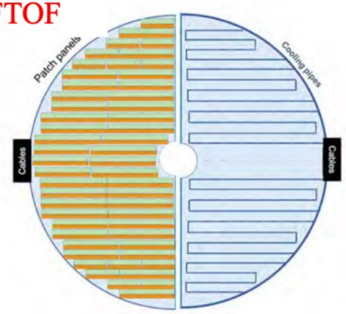
https://indico.cern.ch/event/1298458/contributions/5991545/

AC-LGAD Detectors for ePIC

BTOF



FTOF



Roman Pots

	Area (m^2)	Channel size (mm^2)	# of Channels	Timing Resolution	Spatial resolution	Material budget
Barrel TOF	10	0.5*10	2.4M	35 ps	30 μm in $r \cdot \varphi$	0.01 X_0
Forward TOF	1.4	0.5*0.5	5.6M	25 ps	30 μm in x and y	0.05 X_0
B0 tracker	0.07	0.5*0.5	0.28M	30 ps	20 μm in x and y	0.05 X_0
RPs/OMD	0.14/0.08	0.5*0.5	0.56M/0.32M	30 ps	140 μm in x and y	no strict req.

Requirements on timing and spatial resolutions and material budget are still being evaluated and are subject to change as the design matures, and we will continue to explore common designs for these detectors where possible to reduce cost and risk.

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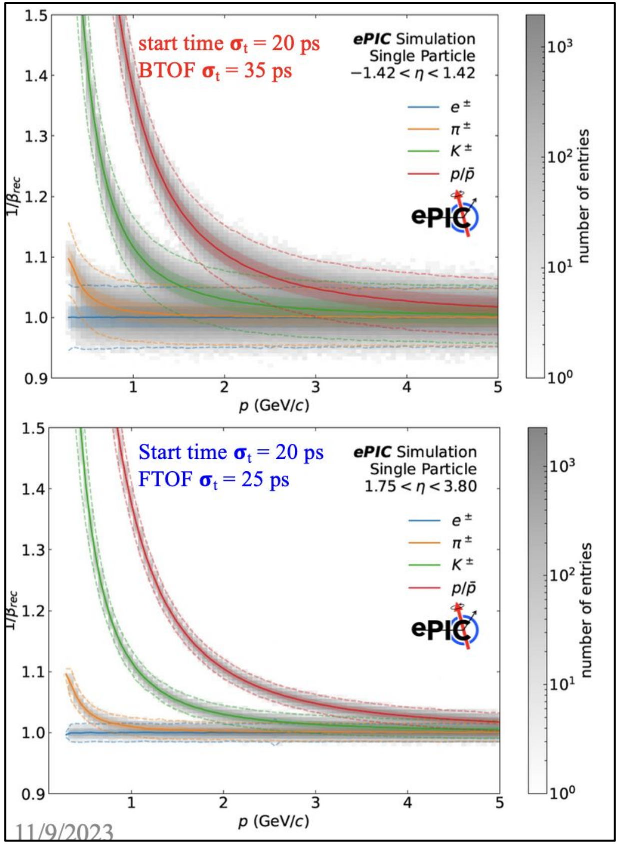
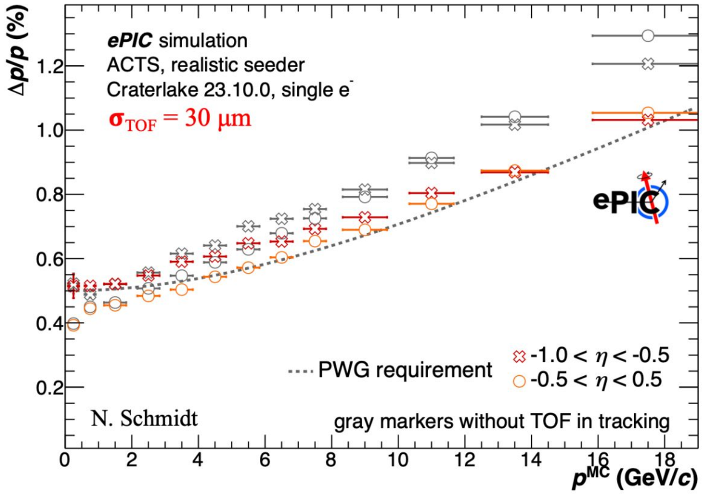
ePIC @ EIC: TOF detector



AC-LGAD Detectors for Tracking



- BTOF with a spatial resolution of 30 μm improves momentum resolution at high p
- TOF helps track reconstruction by rejecting beam background and pileup hits in Si-MAPSs

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35ps (25ps) timing resolution provides 3σ π/K separation up to ~1.3 (~2.4) GeV/c in the barrel (forward) region

Challenges, questions, next steps

Addressing the various challenges and open questions of future 4D trackers requires detailed simulation studies to inform detector requirements and evaluate physics performance

HL-LHC / Muon Collider / FCC-hh

- Tracking layout studies, including impact of additional material from cooling and data transmission
- Data transmission and bandwidth requirements
- Detailed digitization and ACTS 4D tracking/vertexing
- Study the impact of timing information in track seeding and how it can speed up and improve track reconstruction
- Study the trade-offs of various detector layout concepts and their impact in performance
- Study the impact of 4D tracking in physics benchmarks: HH (b-tagging), VBF (pileup jet suppression), LLP, …

FCC-ee/ILC Silicon Wrapper

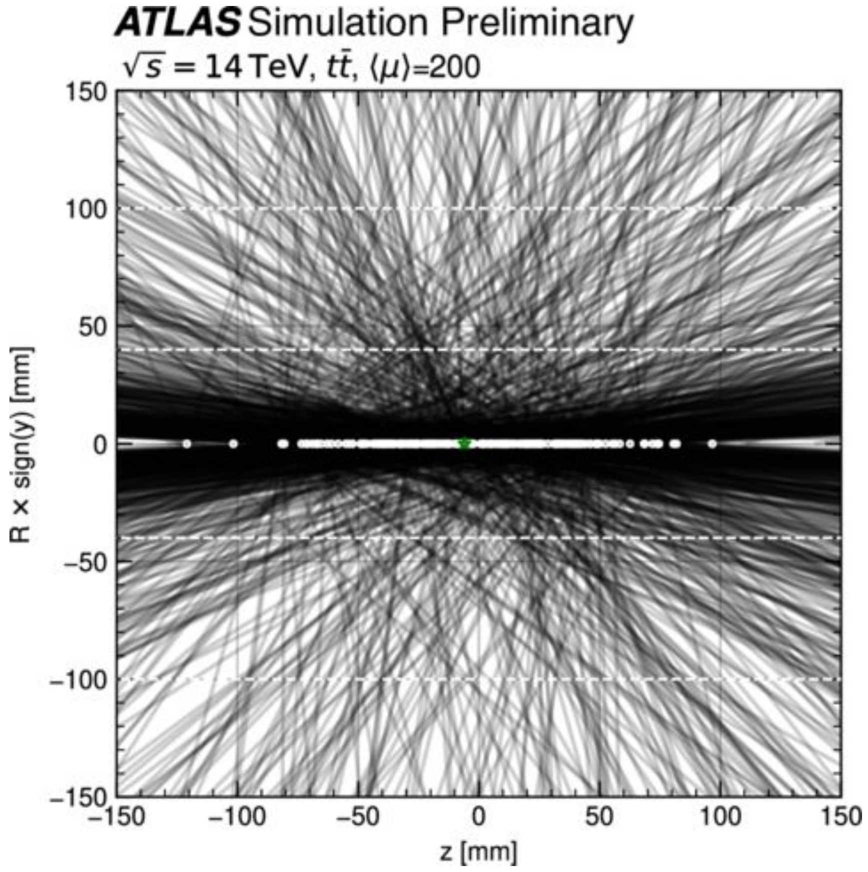
- Detector requirements (spatial and time resolution) for different PID benchmarks
- Impact of material and data transmission on physics performance
- readout and on-chip data processing
- Vertex t_0 and interplay with calorimeter timing layers
- Timing layer and beam background suppression - connection to MAPS vertex detector
- Sharpen physics case: flavor tagging, PID, long lived particles, track reconstruction

Summary

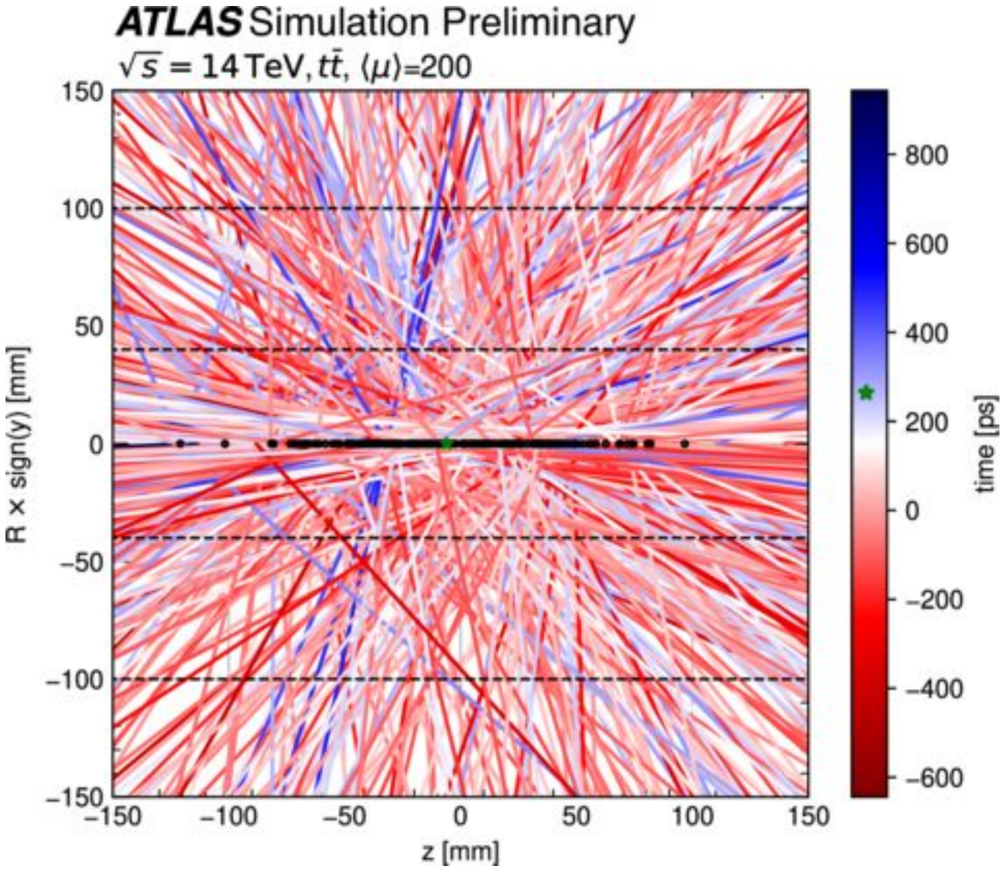
- 4D trackers with a resolution at the level of 10μm and 10ps is a transformative new capability for the next generation of detectors at future colliders
- While potentially a game changer, pushing the frontier of fast-timing detectors requires significant R&D
- Different applications present unique challenges that we should investigate using simulations
- Detailed simulations studies, and a common framework to perform then, will be critical over the next years to answer how to best utilize fast-timing information at future colliders and inform a detector demonstration proposal
    - Topic of next talk!

Backup

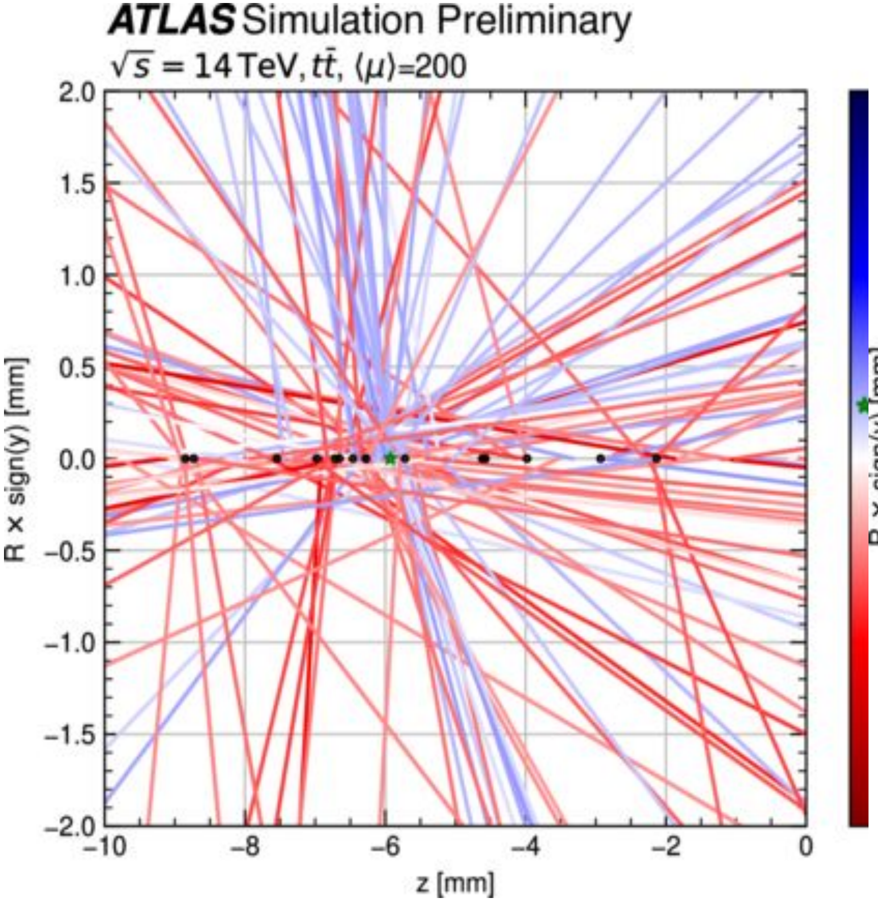
ITk



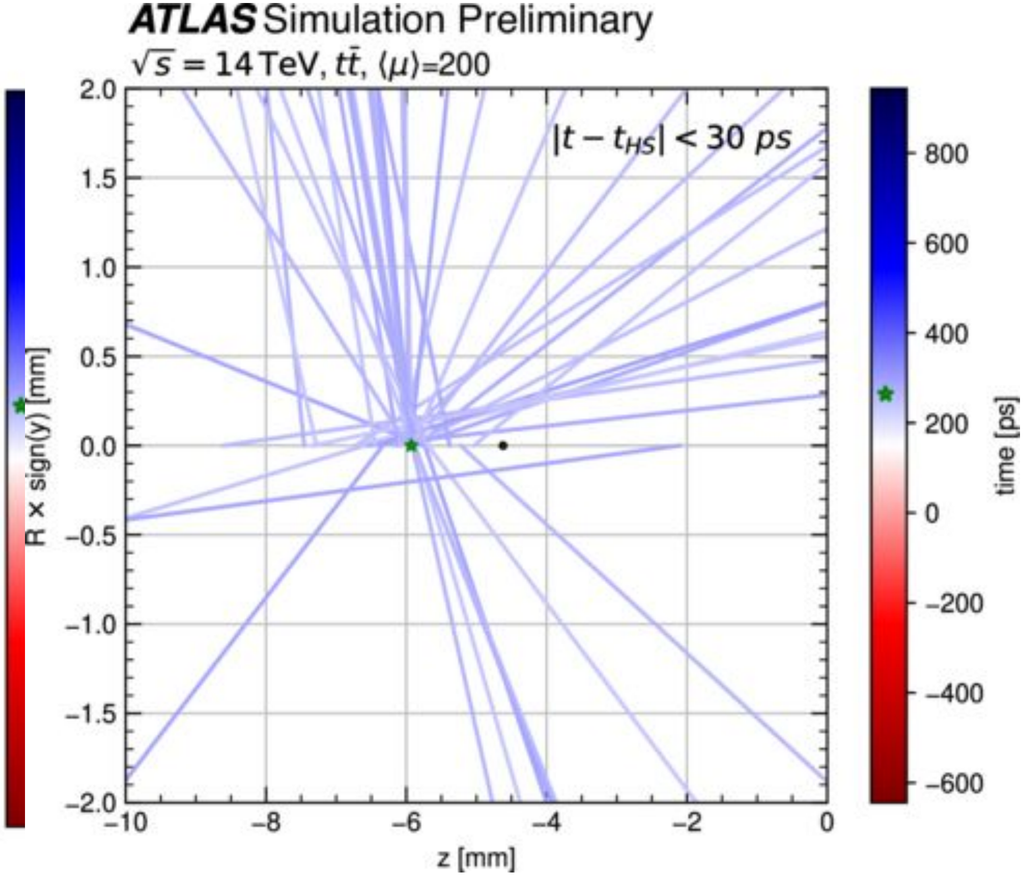
4D Tracker



zoom

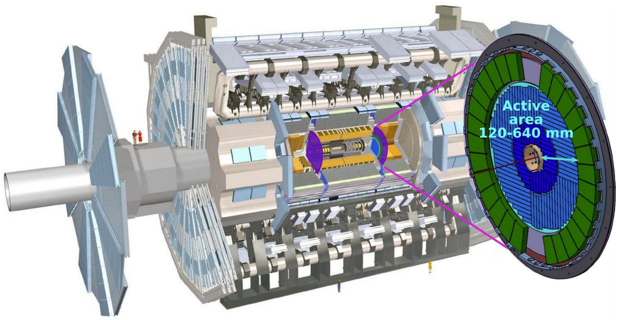


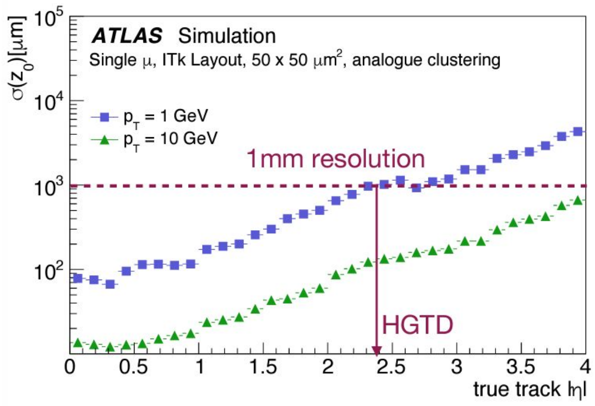
pixel timing cut

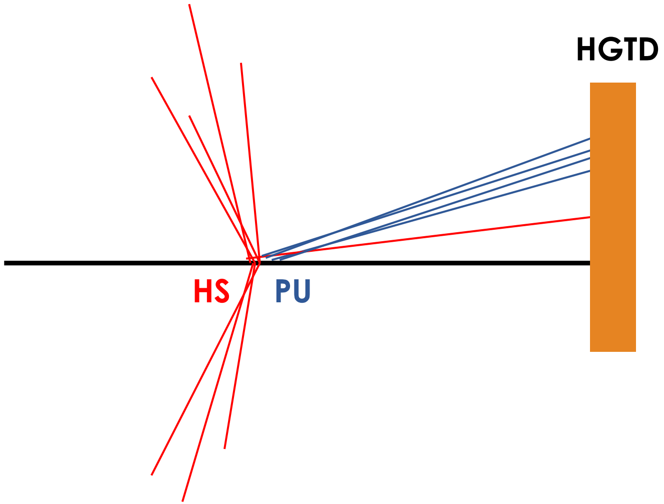


Impact of HGTD Eta Coverage

HGTD: silicon pixel detector with coarse spatial resolution and picosecond timing







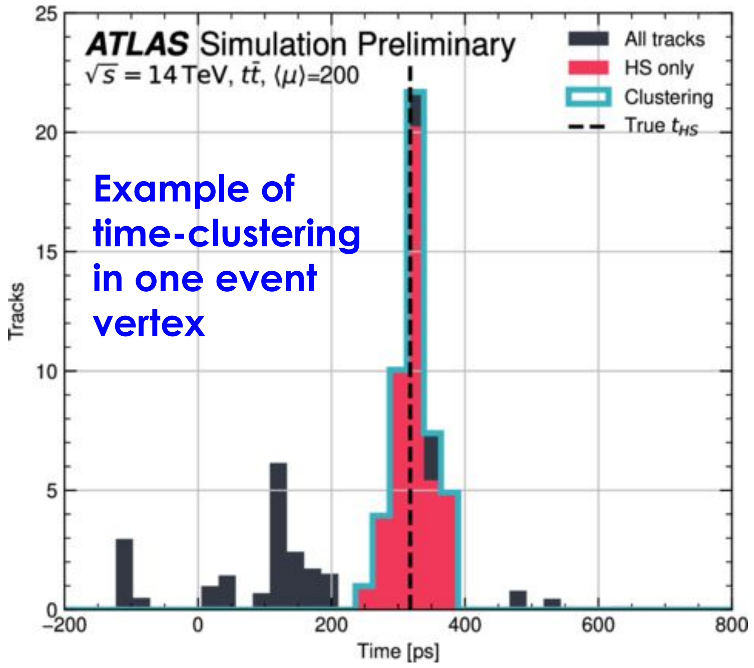
While the large ITk z0 resolution is mainly forward, HGTD requires a precise knowledge of the **vertex time** (t_0) to be able to relate a track time to a reference vertex time

The reconstruction of t_0 becomes challenging when only forward tracks are available

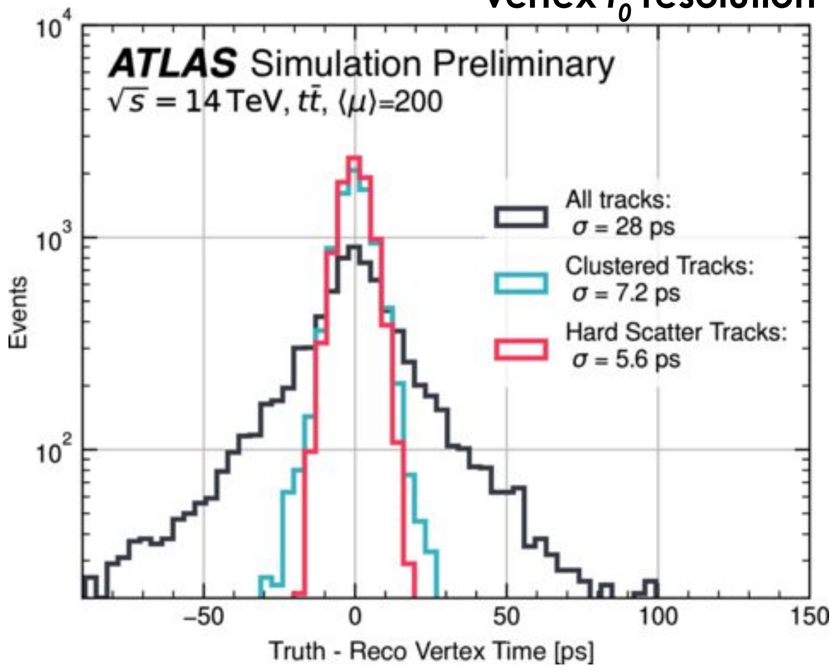
Vertex t_0 reconstruction

DBSCAN clustering + average of track times

Assumed time resolution: 30ps/track



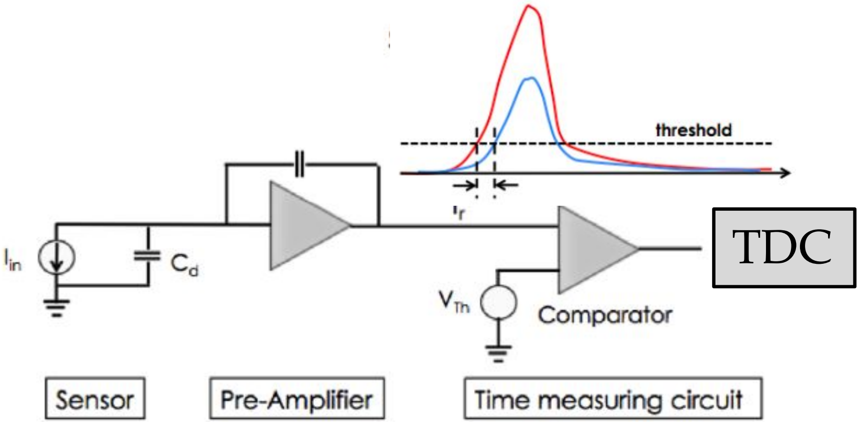
vertex t_0 resolution



Excellent (<<30ps) vertex t_0 resolution for **all events**!

Time resolution

$$\sigma_t^2 = \sigma_{Landau}^2 + \sigma_{timewalk}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2 + \sigma_{clock}^2$$



- Time walk
  - Variable threshold (CFD)
  - Correction based on TOT

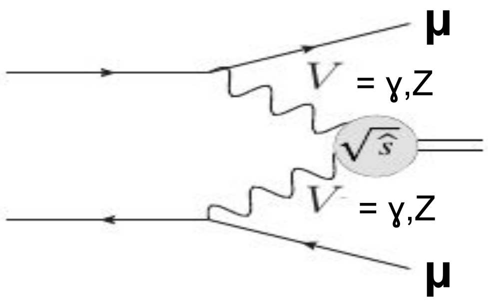
$$\sigma_{jitter} = \frac{N}{\frac{dV}{dt}} \propto \frac{t_{rise}}{S/N}$$

- TDC quantization error (bin size)
  - ATLAS/CMS 20-30ps ToA
  - ATLAS/CMS 40-100ps TOT
  - $\sigma_{TDC} = {}^{binsize}/_{\sqrt{12}} \sim 7ps$

Key to precision timing: Large signal with short rise time and low noise (reduce jitter), limited thickness (reduce Landau), and small TDC bin size (reduce TDC component)

(Very) Forward Muons in a Muon Collider

Due to the predominance of VBF processes
- when neutral current, muons in final state
- unfortunately some get “captured” since very close to beam trajectory



Forward muons ($\eta > 5$)	–	tag	$\sigma_p/p \sim 10\%$

Forward Muon Tagging
- already incredibly useful to tag neutral-current interactions
- angular information

Forward Muon Momentum
- ideally some momentum resolution can increase our physics reach, e.g. H->inv
- Very non trivial, a few studies point to ~10% as a great target
- Several ideas to instrument the nozzle already being developed.