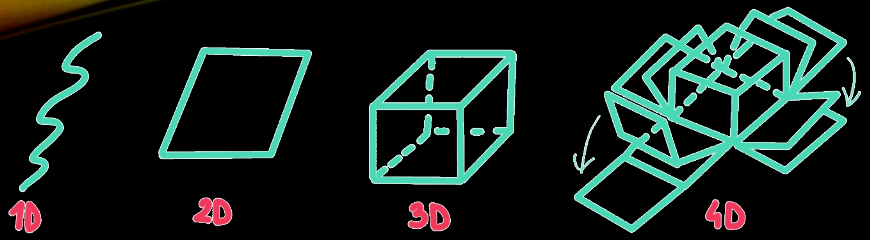


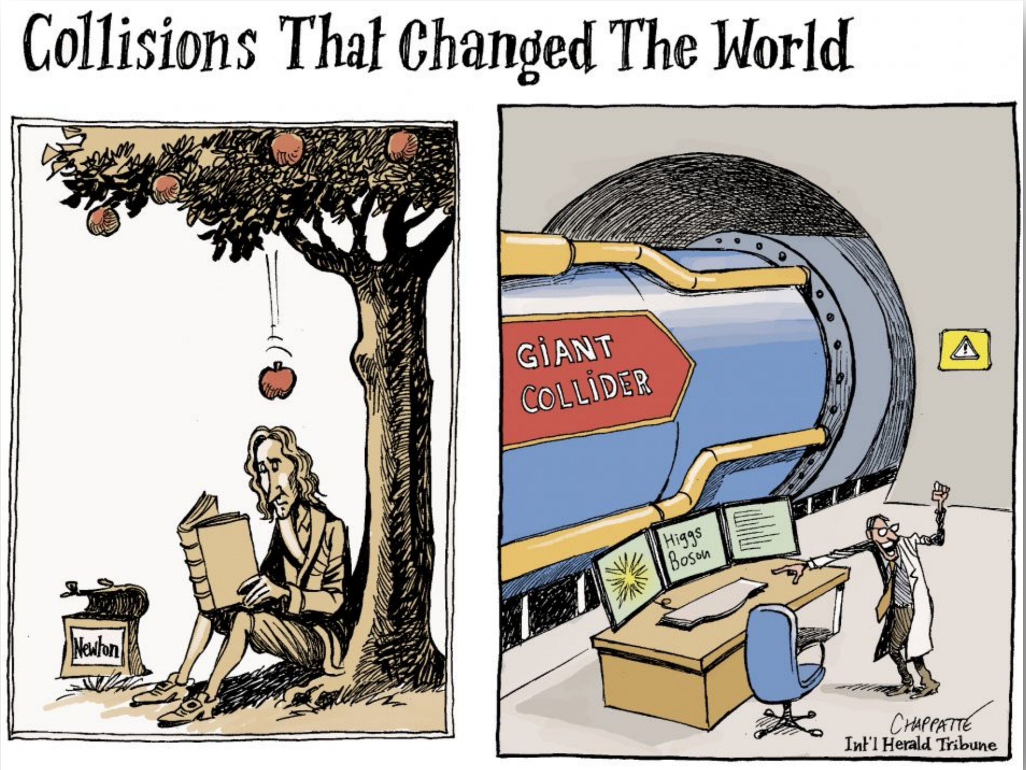
The pile-up challenge and how to address it with 4D Tracking

FCC-hh Studies for the next European Strategy: kickoff meeting

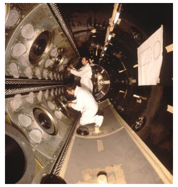
September 3rd, 2024

Valentina M.M. Cairo, Ariel Schwartzman, P. Butti, P. Gessinger,
A. Salzburger, L. Santi, A. Stefl, N. Calace, S. Merianos, N. Hartman,
H. Yang, X. Ai, Y. Wang, et al.

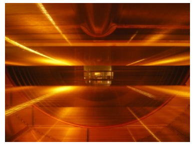
AT THE *HEART* OF COLLIDER PHYSICS: CHALLENGES AND BREAKTHROUGHS



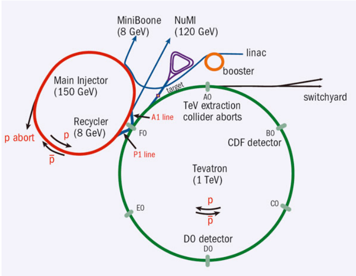
The weak neutral currents and the *bubble chamber* era

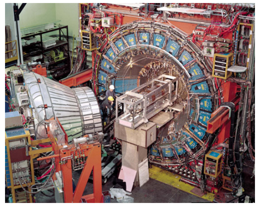


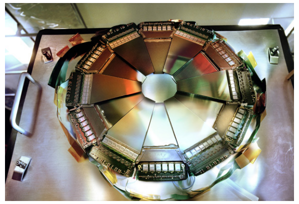
The W,Z bosons and the *drift chamber* era



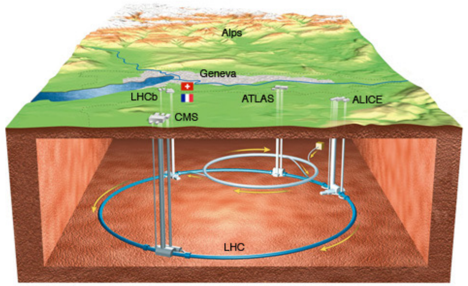
The top quark and the *silicon strip* era

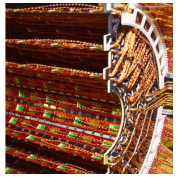


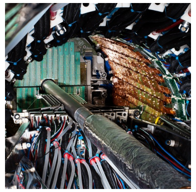




The Higgs boson (and more!) and the *silicon pixel* era

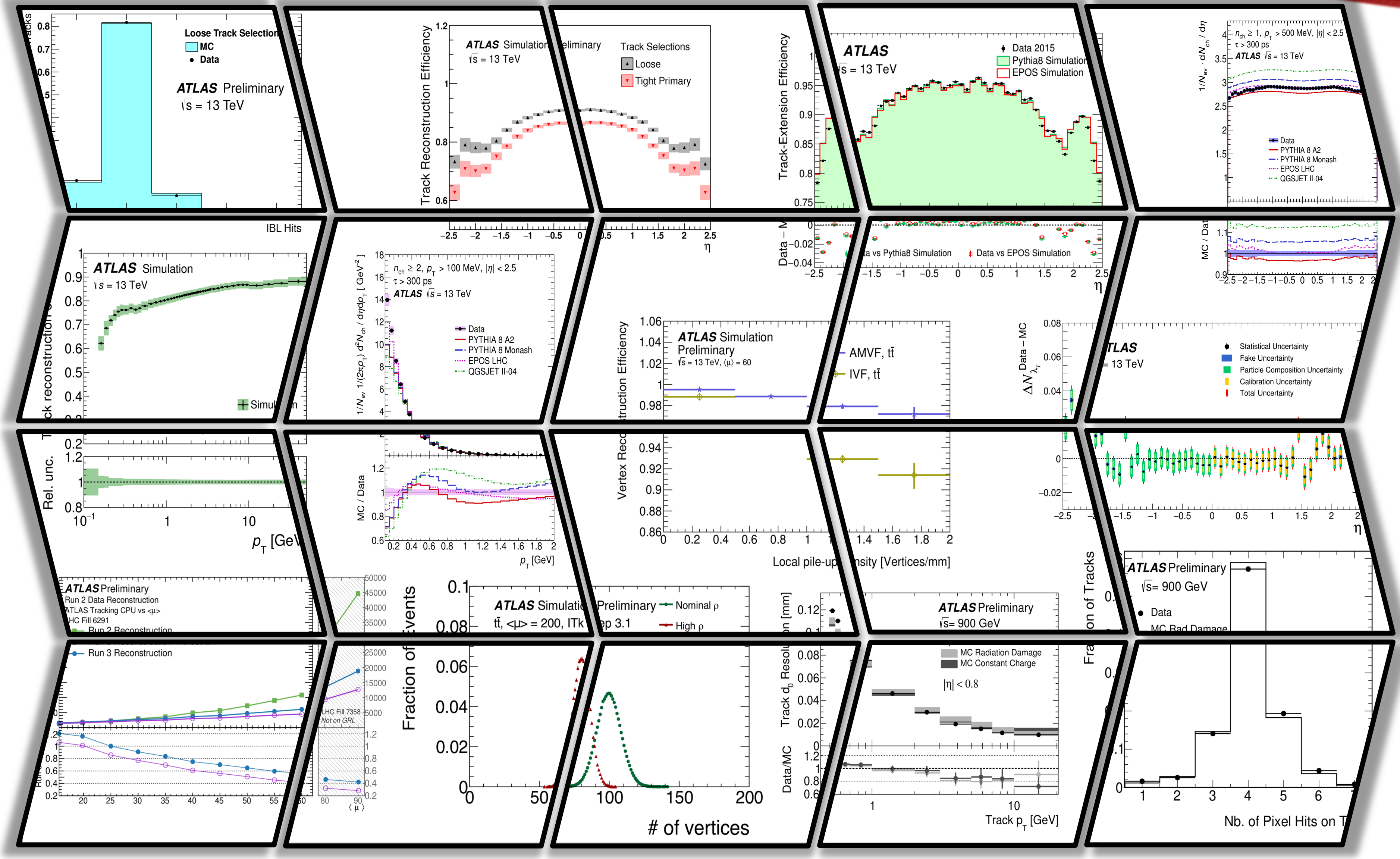




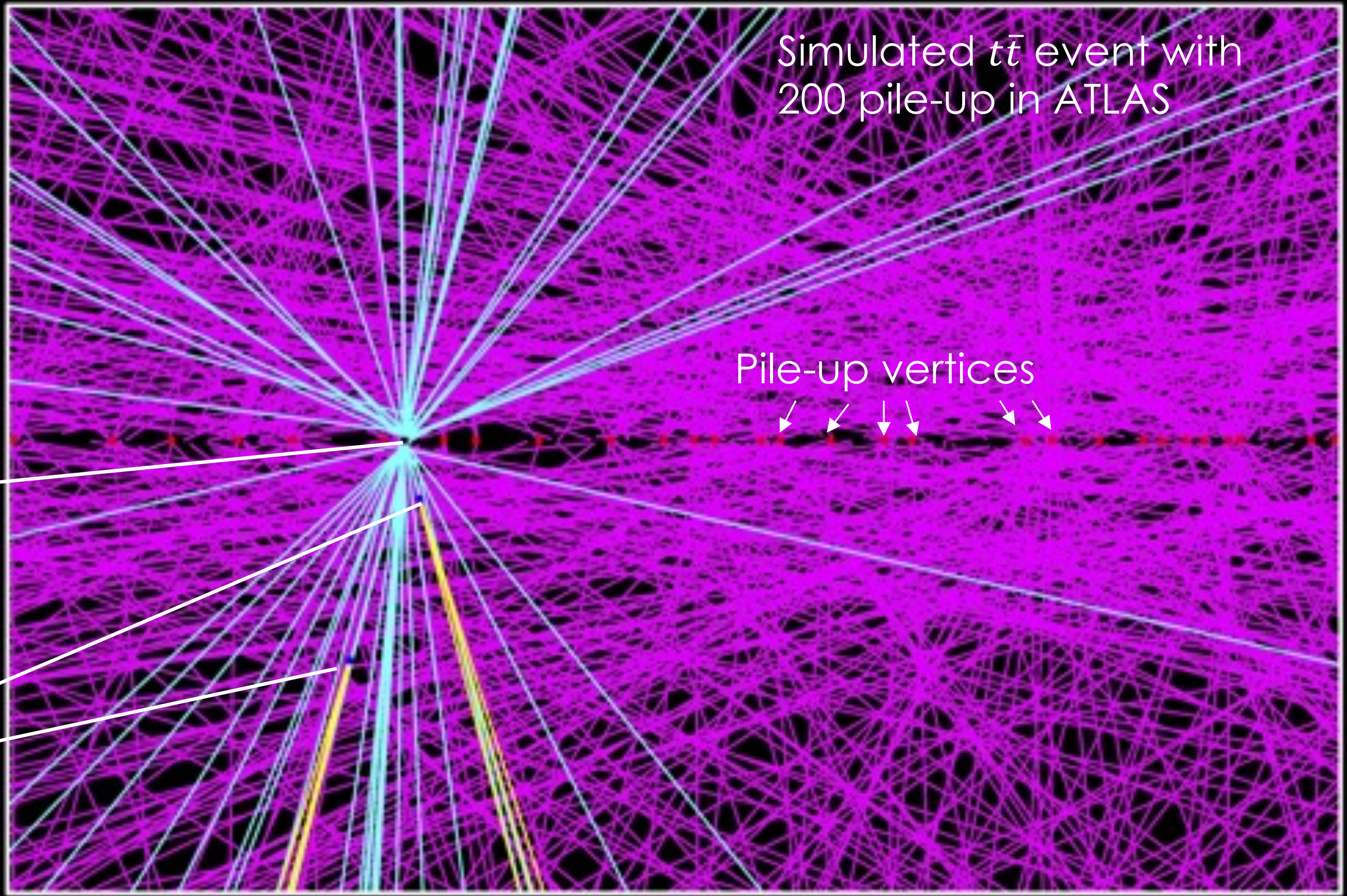


TRACKS AND VERTICES

The building blocks of physics events at colliders



THE PILE-UP CHALLENGE @ HADRON COLLIDERS



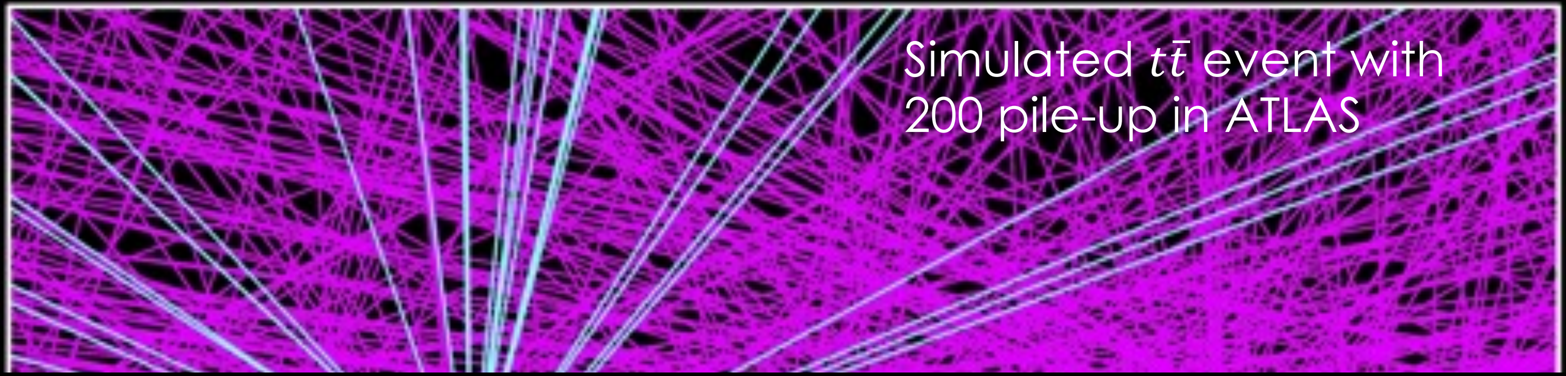
Signal candidate vertex ("hard scatter")

Secondary vertices

2.5 mm

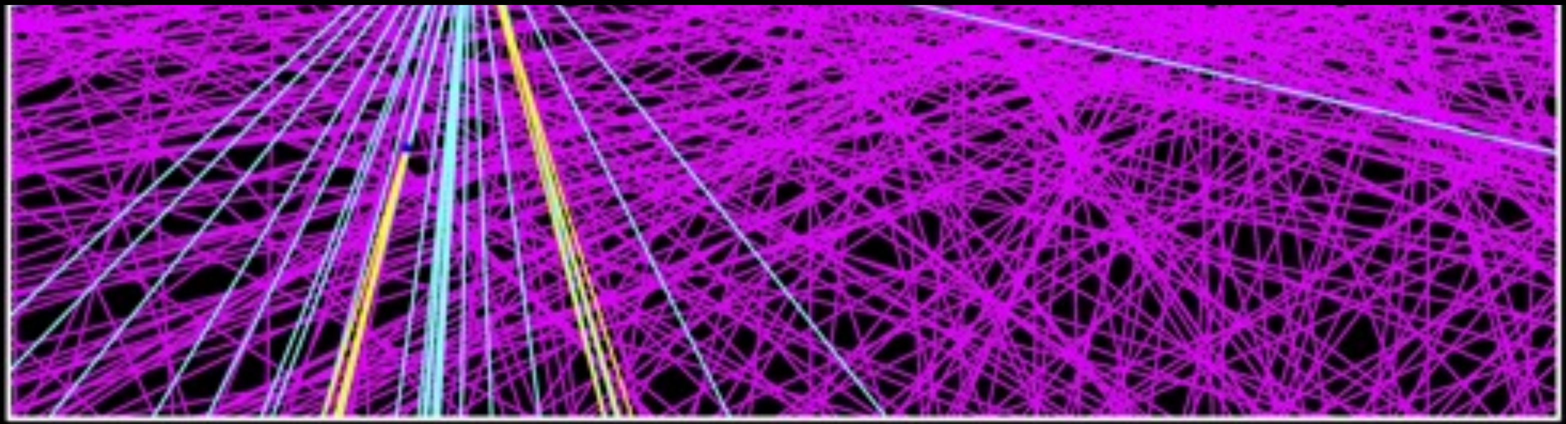
12 cm

THE PILE-UP CHALLENGE @ HADRON COLLIDERS



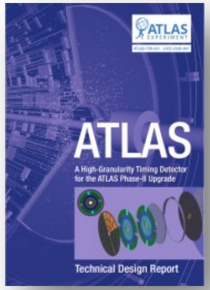
Simulated $t\bar{t}$ event with 200 pile-up in ATLAS

Misassociations of pile-up tracks to the hard-scatter vertex is likely.
If we could **determine** not only the position but also **the time** at which the hard-scatter occurred, pile-up contamination would be strongly reduced…



UNFOLDING A NEW DIMENSION

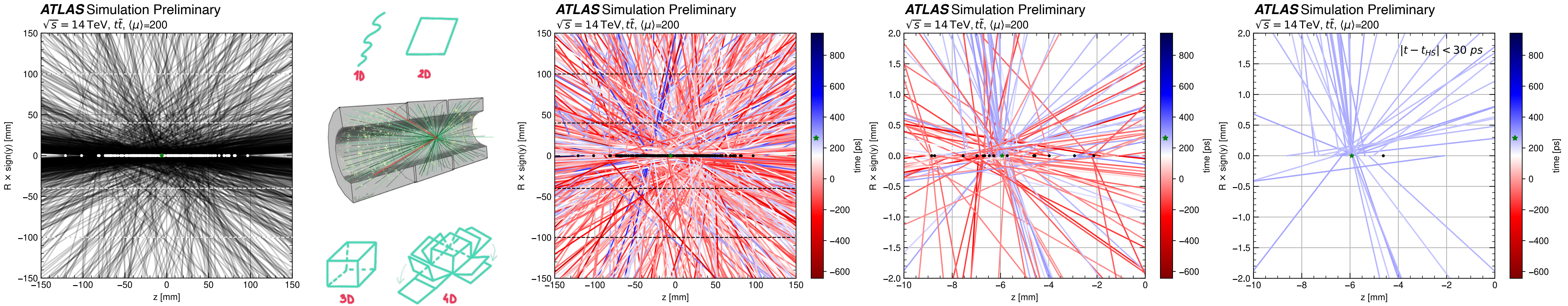
- Addition of timing layers to HEP detectors growing area of interest




FLAVOUR PHYSICS | FEATURE
LHCb looks forward to the 2030s
1 March 2023

- **Next step in advancing technologies are real 4-dimensional silicon trackers** (resolution of O($10\ \mu m$) & O($10\ ps$))

- **Excellent opportunity during HL-LHC and, in particular, for future energy frontier trackers**
  - First exploratory studies in ATLAS



ATL-PHYS-PUB-2023-023

IMPACT ON EXPERIMENTAL PERFORMANCE

- Improve track and vertex reconstruction
  - Performance — Efficiency, purity, IP resolution, low pT tracking?
  - Computing resources — Speed?
- Measure vertex t_0
  - Pile-up suppression
  - Forward jets and leptons
  - Flavour Tagging
  - Long Lived Particles

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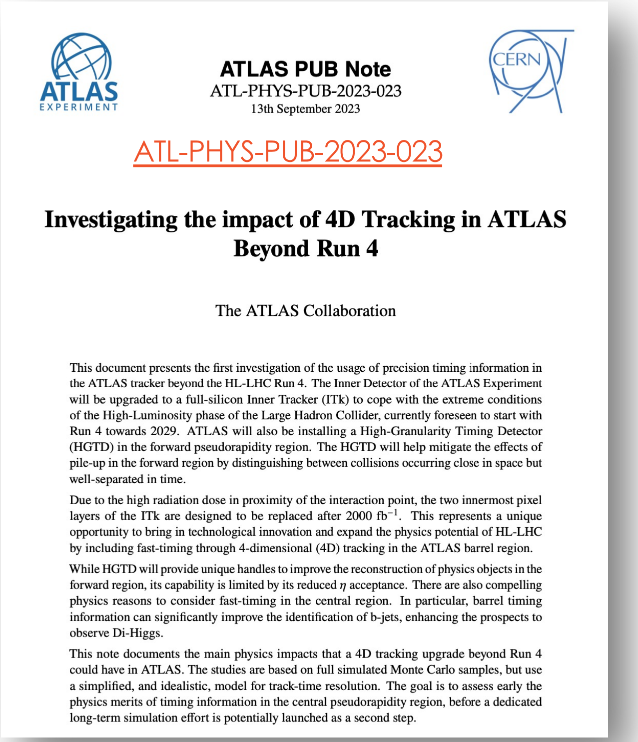


ATLAS PUB Note
ATL-PHYS-PUB-2023-023
13th September 2023

ATL-PHYS-PUB-2023-023

Investigating the impact of 4D Tracking in ATLAS Beyond Run 4

The ATLAS Collaboration

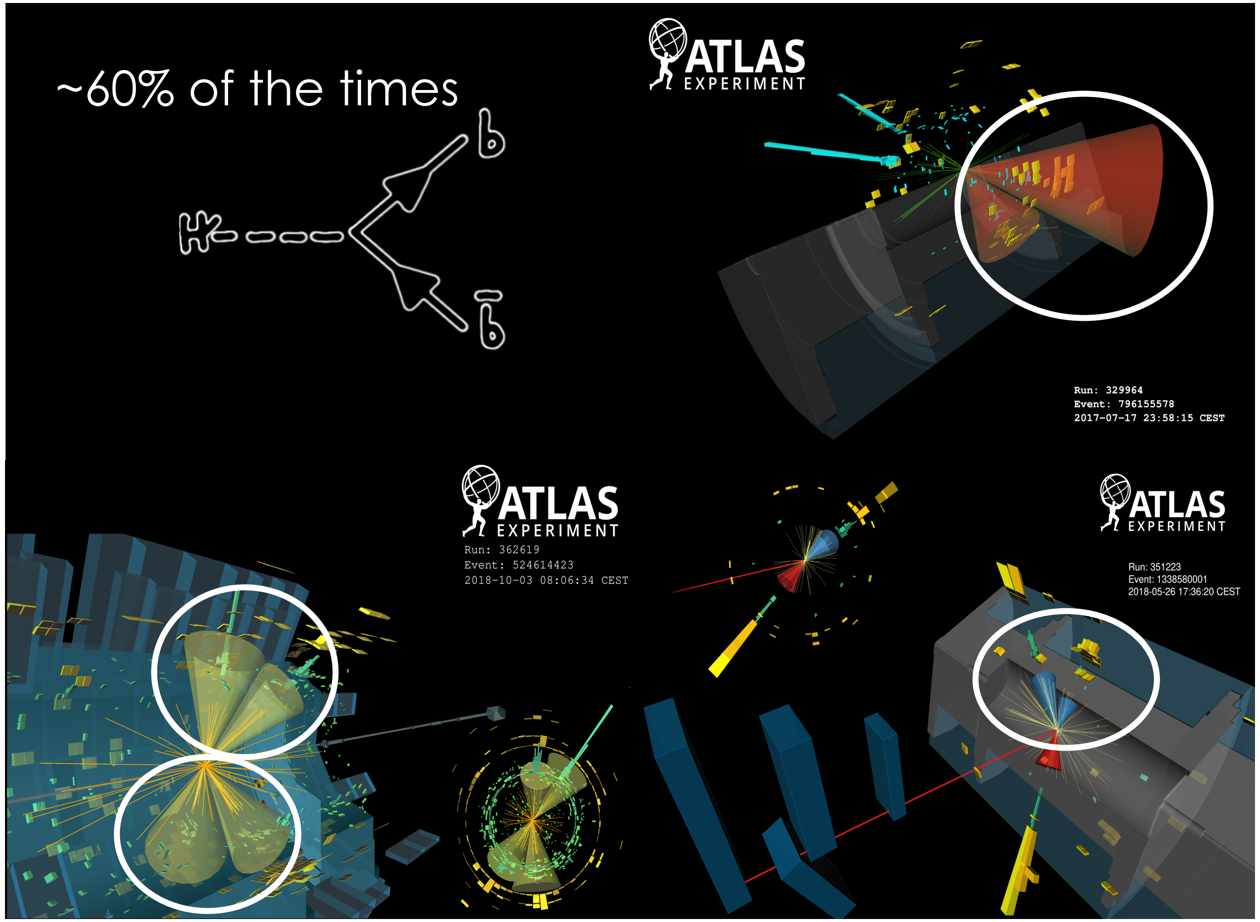
This document presents the first investigation of the usage of precision timing information in the ATLAS tracker beyond the HL-LHC Run 4. The Inner Detector of the ATLAS Experiment will be upgraded to a full-silicon Inner Tracker (ITk) to cope with the extreme conditions of the High-Luminosity phase of the Large Hadron Collider, currently foreseen to start with Run 4 towards 2029. ATLAS will also be installing a High-Granularity Timing Detector (HGTD) in the forward pseudorapidity region. The HGTD will help mitigate the effects of pile-up in the forward region by distinguishing between collisions occurring close in space but well-separated in time.

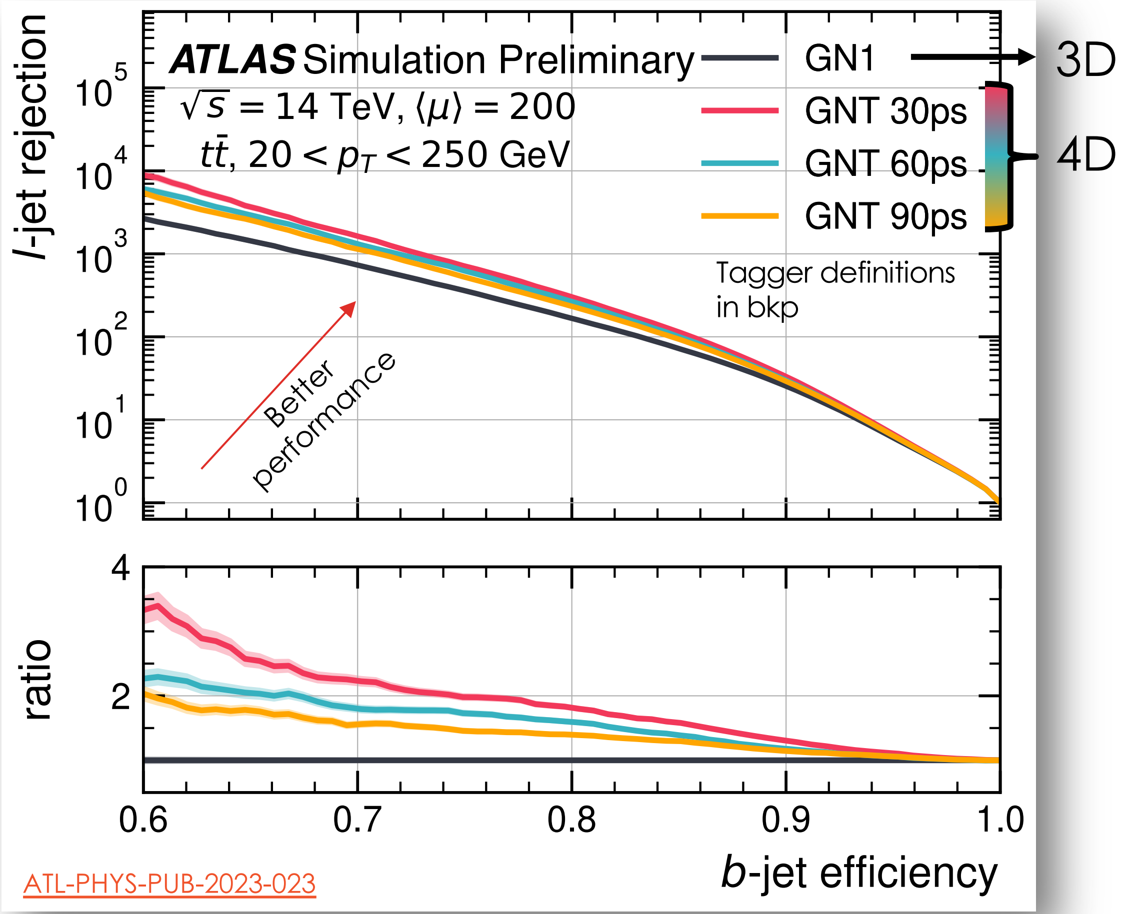
Due to the high radiation dose in proximity of the interaction point, the two innermost pixel layers of the ITk are designed to be replaced after 2000 fb^{-1}. This represents a unique opportunity to bring in technological innovation and expand the physics potential of HL-LHC by including fast-timing through 4-dimensional (4D) tracking in the ATLAS barrel region.

While HGTD will provide unique handles to improve the reconstruction of physics objects in the forward region, its capability is limited by its reduced η acceptance. There are also compelling physics reasons to consider fast-timing in the central region. In particular, barrel timing information can significantly improve the identification of b-jets, enhancing the prospects to observe Di-Higgs.

This note documents the main physics impacts that a 4D tracking upgrade beyond Run 4 could have in ATLAS. The studies are based on full simulated Monte Carlo samples, but use a simplified, and idealistic, model for track-time resolution. The goal is to assess early the physics merits of timing information in the central pseudorapidity region, before a dedicated long-term simulation effort is potentially launched as a second step.

4-DIMENSIONAL TRACKING & b-TAGGING





Interesting potential HH sensitivity increase!
Could boost the reach of rarer HH production modes, e.g. $ttHH$

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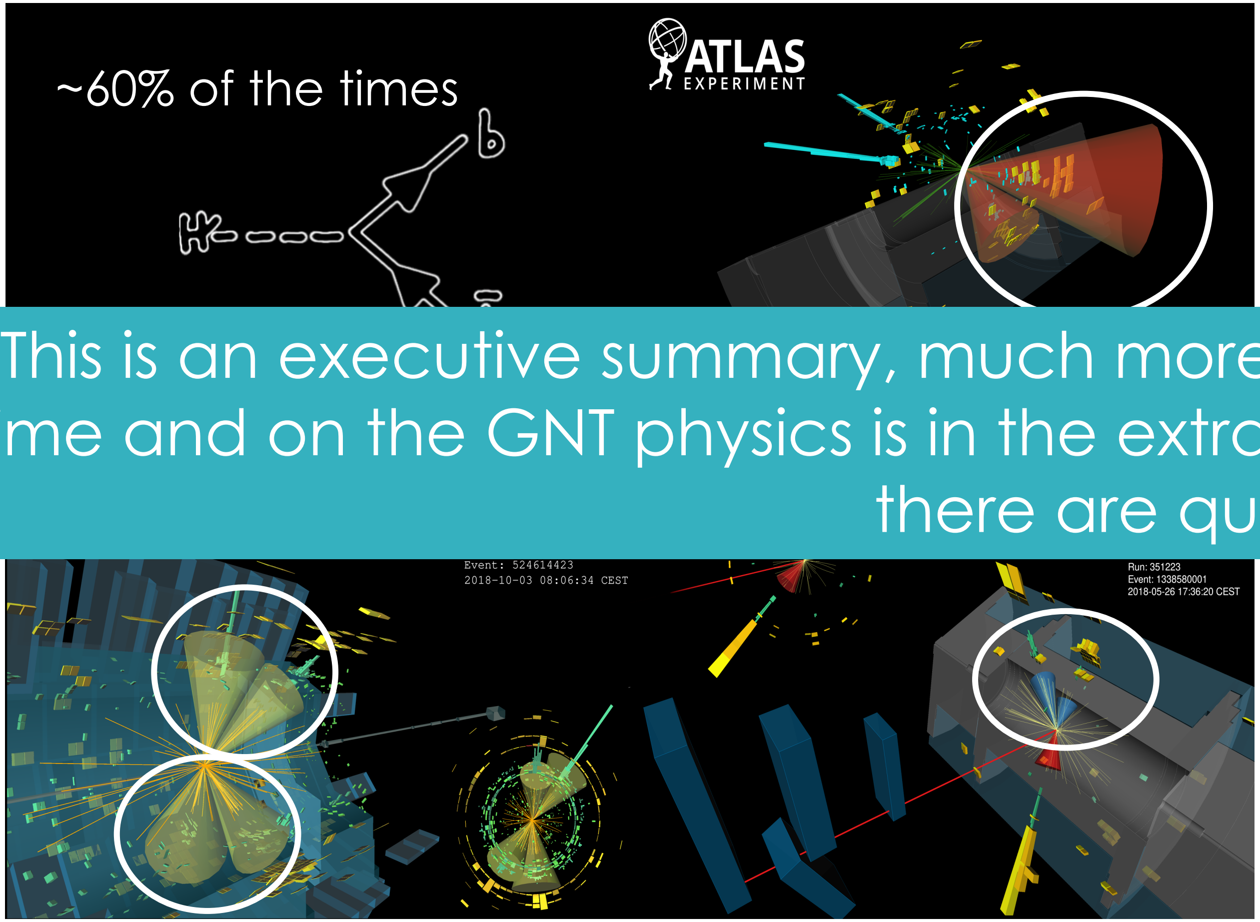

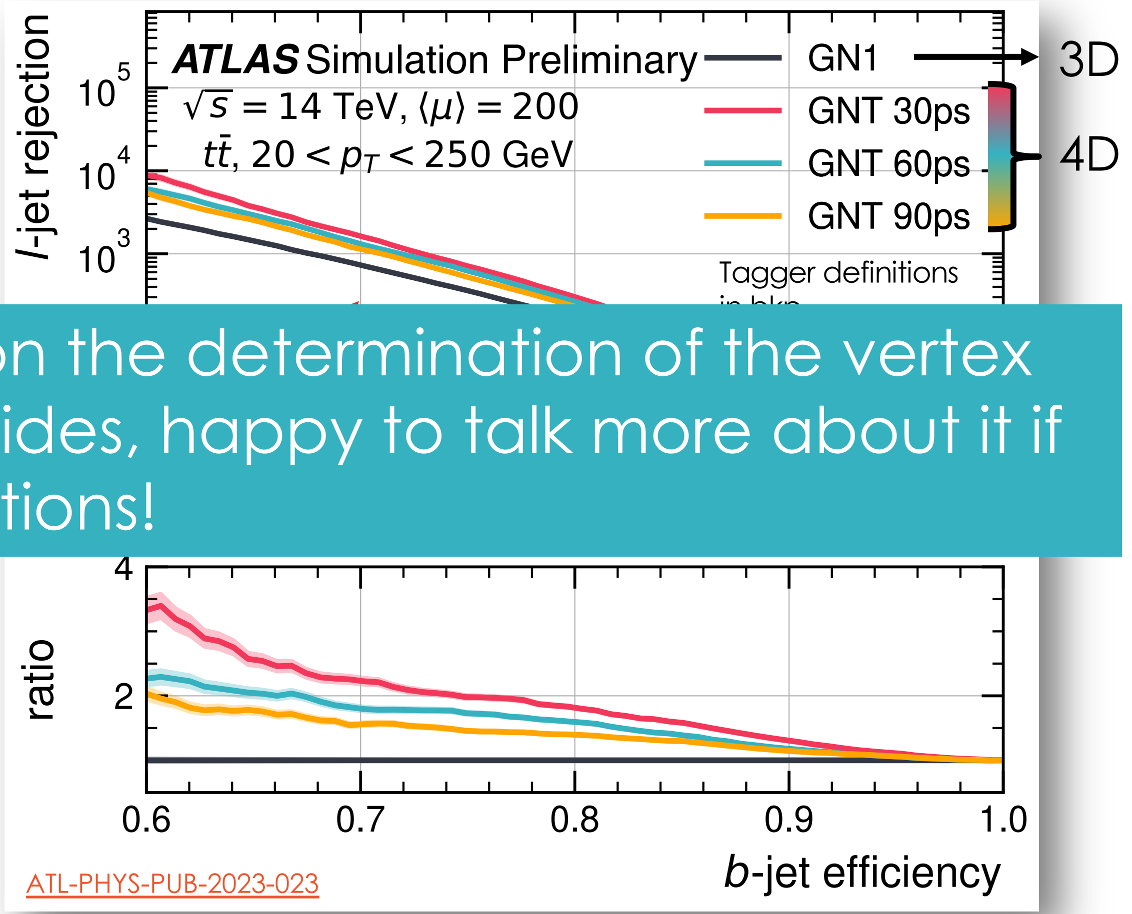

ATL-PHYS-PUB-2023-023

This is an executive summary, much more on the determination of the vertex time and on the GNT physics is in the extra slides, happy to talk more about it if there are questions!

Interesting potential HH sensitivity increase!
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BEYOND ATLAS

4D Tracking has applications in all **Future Collider experiments** (review paper here written during the Snowmass 2021 exercise)

- FCC-hh (1000 pile-up) was also previously studied and mentioned in there

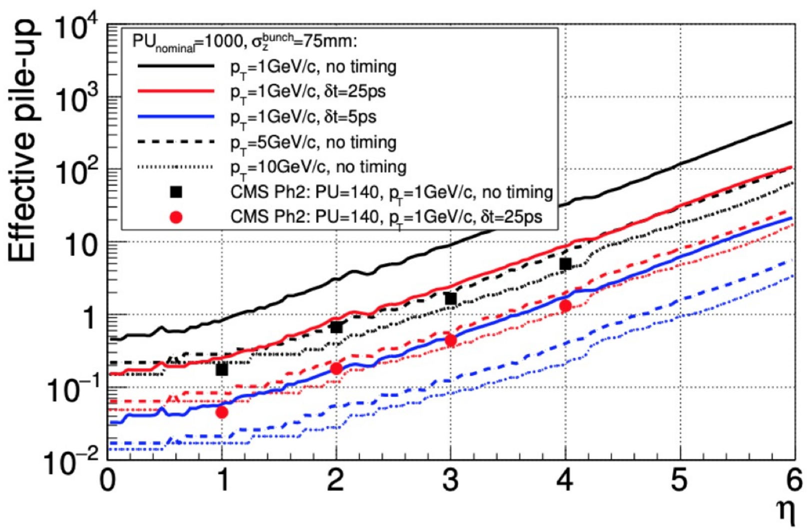

Figure 1: From Ref. [9]. An effective pile-up in the FCC-hh tracker. Several options of timing resolution per track in 3D vertexing are assumed: no timing (black), δ t = 25 ps (red) and δ t = 5 ps (blue). Several p_T values are shown: 1 GeV/c (solid), 5 GeV/c (dashed) and 10 GeV/c (dotted). For reference the effective pile-up for CMS Phase 2 layout, p_T = 1 GeV/c and nominal pile-up=140 is added.

Extreme timing resolution of 5 - 10 ps per track is essential to keep the effective pileup low and prevent the merging of unrelated vertices

ACTS-BASED STUDIES

A Common Tracking Software (ACTS): very useful library to perform time-assisted track reconstruction, will be adopted by ATLAS during HL-LHC, already adopted in Run 3 for ATLAS vertexing and employed by several other experiments (running and/or future):

- Embedded time measurement as one of the 6 track parameters
- We can perform detailed hit-to-track and track-to-vertex association studies
- Offer a generic ***Open Data Detector* (ODD)** layout for a silicon tracker

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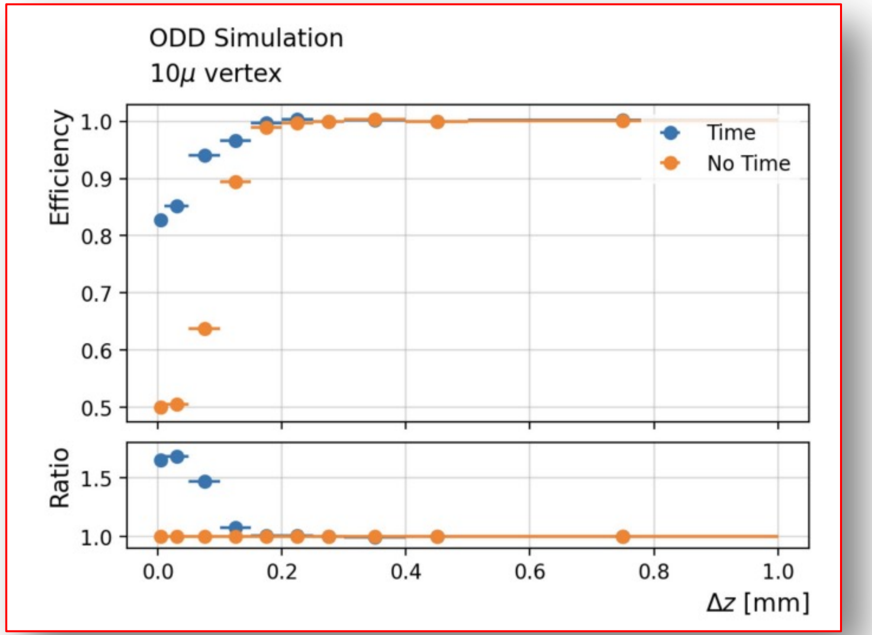
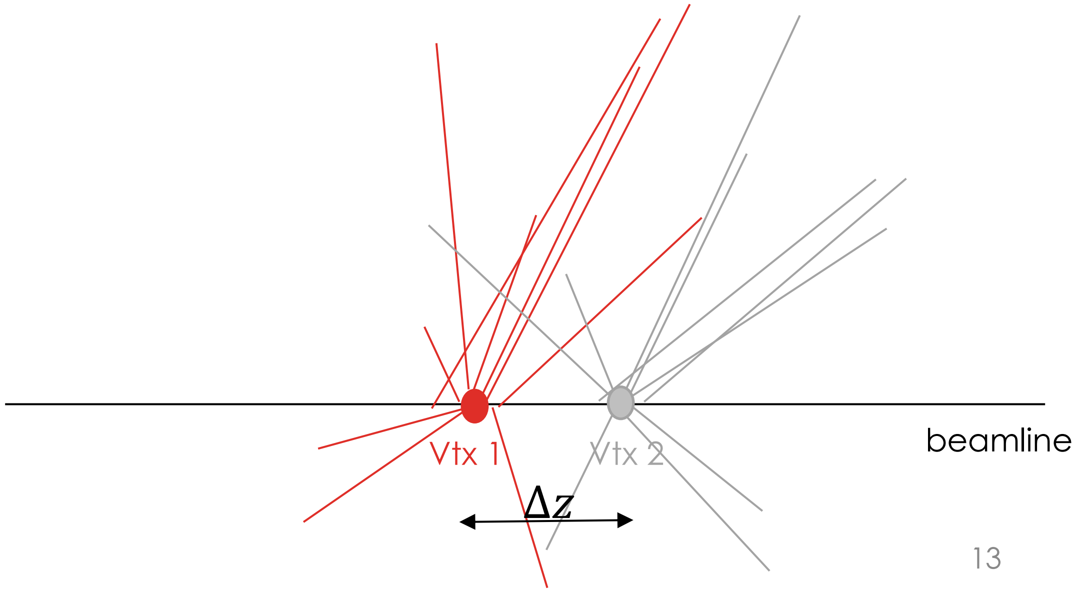
  - 4D vertex finding and fitting implemented, more on tracking here





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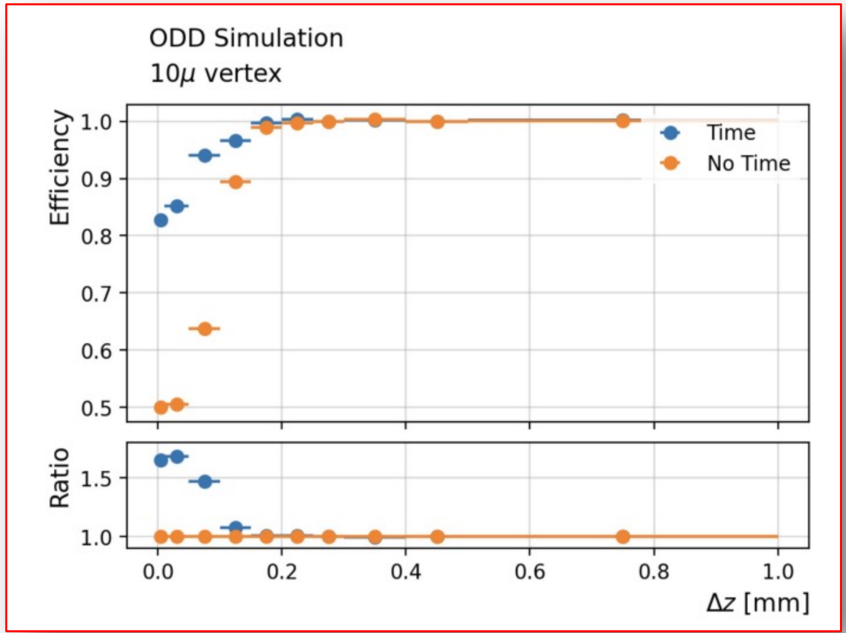
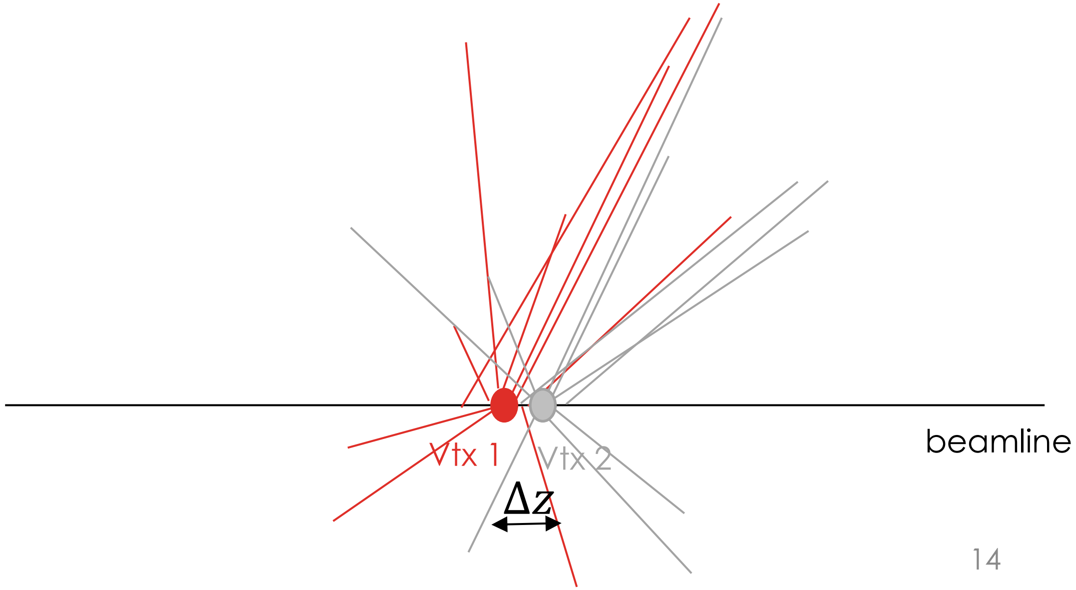
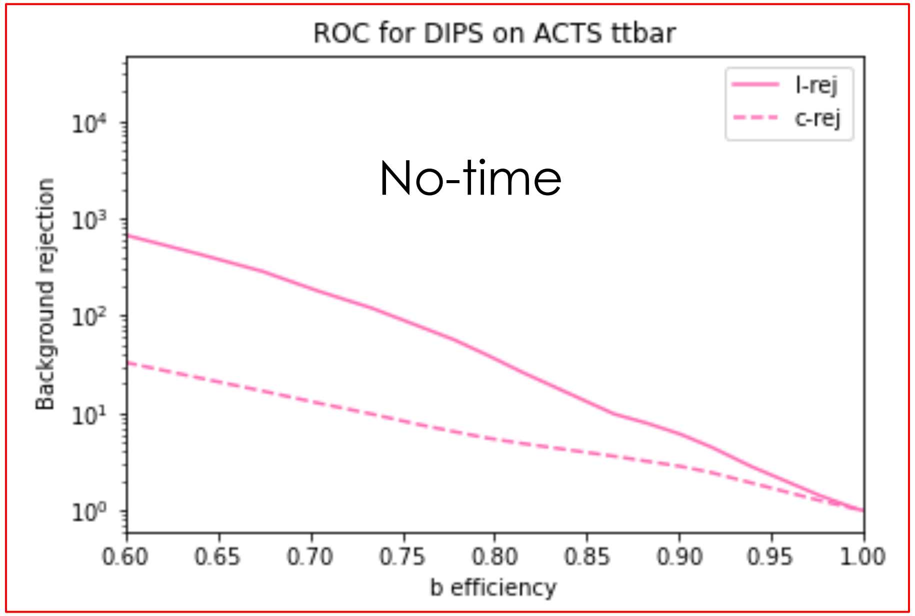




ACTS-BASED STUDIES

- Furthermore, jet reconstruction algorithms (e.g. Fast Jet) **can and have been** interfaced with ACTS to build particle level jets, which can in turn be used for jet and flavour tagging studies



Incoming student to complete the studies with timing information

THE CURRENT TEAM (ALGO)

Me & Lorenzo Santi (CERN)
Ariel Schwartzman (SLAC)

ATLAS PUB Note
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Four-dimensional Vertexing: algorithm and performance

Pierfrancesco Butti[a,b], Valentina M. M. Cairo[b], Paul Gessinger-Befurt[b], Andreas Salzburger[b], Lorenzo Santi[b,c], Ariel Schwartzman[a], Andreas Stefl[b], and Felix Russo[b]

[a] *SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025-7015, USA*
[b] *Experimental Physics Department, CERN, Geneva, Switzerland*
[c] *INFN and Sapienza University of Rome*

September 3, 2024

Time assisted flavour-tagging with a generic detector layout

Pierfrancesco Butti[a,b], Valentina M. M. Cairo[b], Nicole Hartman[c], Camille Mauceri[d], Lorenzo Santi[b], Ariel Schwartzman[a], Andraz Tomsic[e], and Madison VanWyngarden[d]

[a] *SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025-7015, USA*
[b] *Experimental Physics Department, CERN, Geneva, Switzerland*
[b] *Technical University of Munich, Arcisstraße 21, Munich, Bavaria, 80333, Germany*
[d] *Boston University, Commonwealth Ave, Boston, MA 02215, USA*
[e] *Jozef Stefan Institute, Jamova cesta 39, 1000 Ljubljana, Slovenija*

Layout studies and Material Budget studies: Me, P. Butti, A. Schwartzman, N. Calace, S. Merianos, etc

Other tracking experts in the CERN team also involved: M. Elsing, etc

Recently-initiated collaboration with USTC and Zhengzhou University on low-level tracking

A WORD ON TECHNOLOGY

- Several groups working on **developing 4D tracking technologies that could meet the HL-LHC specifications should such replacements take place**, but intensive **R&D is still required and several options are being looked at:**
  - Hybrid Low Gain (DC, AC-coupled), monolithic Low Gain, hybrid No Gain (Planar, 3D), monolithic No Gain (CMOS), and many more!

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  - Hybrid Low Gain (DC, AC-coupled), monolithic Low Gain, hybrid No Gain (Planar, 3D), monolithic No Gain (CMOS), and many more!

- **Radiation Hardness is a key challenge!**
  - At the HL-LHC the innermost layers are placed at O(30) mm from the IP and will receive doses of O(10) MGy after 2 ab-1 of data
  - At FCC-hh, radius of O(20) mm, radiation levels 0.4 GGy expected after 30 ab^{-1} and a fluence of 6×10^{17} per cm^2 1 MeV neq.
  - These are approximately **30 times (600 times) more intense than the environment at the HL-LHC (LHC)**.
  - Dedicated R&D efforts for **extreme timing resolutions and radiation hardness** is needed. These will also be correlated with the spatial resolution and the changes in the material budget, thus analyzing the interplay among them is of key interest

SUMMARY & NEXT STEPS

- Very first investigation of **4D Tracking** impact as a replacement of the ATLAS innermost ITk layers:
  - **Vertex t_0 resolution** and impact on **b-tagging** has been demonstrated
    - Both aspects are **being extended to the ACTS realm**
- **More in-depth Tracking & Vertexing studies started with ODD**
  - Complete 4D vertexing implemented in ACTS
  - Preliminary seeding CPU gain explored (extra slides)
  - Started to look at layout studies to estimate impact of material budget changes, potential pitch changes etc

SUMMARY & NEXT STEPS

- **Some of the conclusions from these studies could be included in the EU Strategy report either as they are or adapted to FCC if time allows**
  - Tracking and b-tagging performance
  - FCC-hh layout and time requirements (how many layers, what time resolution, etc.)
  - Explore trigger capabilities

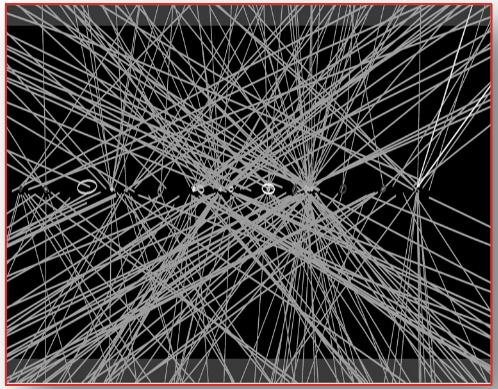
- J. Nierman (EP R&D fellow) and A. Salzburger will translate the FCC-hh (Tracker) into ACTS, in particular to detray/traccc to play with the mu-1000 scenario

- New collaborators are very welcome to join and we could consider more FCC-dedicated studies

CONCLUSIONS

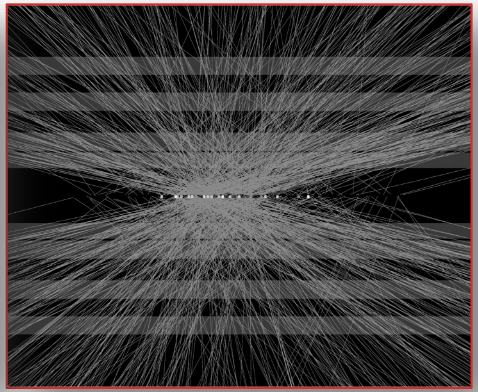
- Our team is broadly investigating 4D tracking in various contexts: HL-LHC, FCC-ee ToF, muC, and FCC-hh, with extensive usage of ACTS ODD
- 4D Tracking is a unique handle for pile-up rejection at hadron colliders
- Both algorithms and technologies are being developed and offer interesting opportunities for HL-LHC and, even more so, FCC-hh!

2009



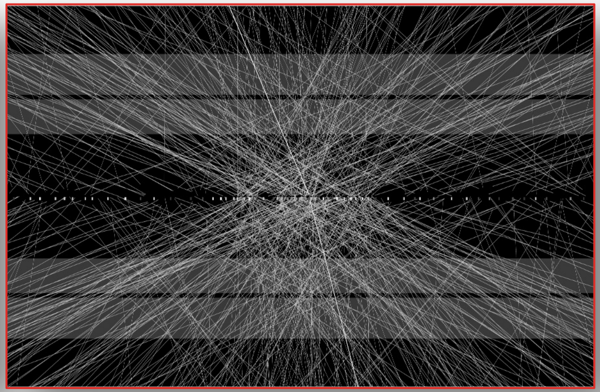
$< pile - up > \sim 20$

2015



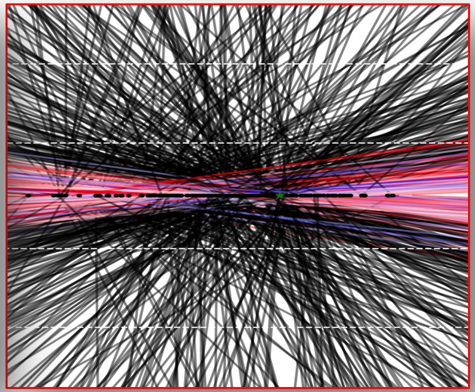
$< pile - up > \sim 30$

2022



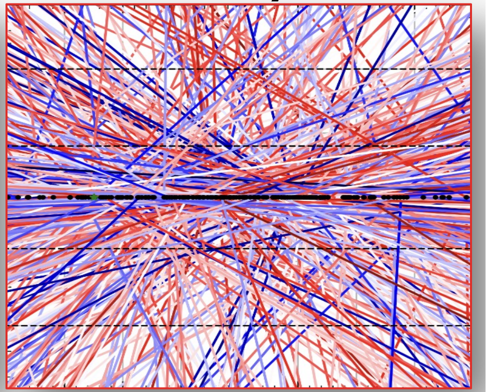
$< pile - up > \sim 60$

2029



$< pile - up > \sim 140$

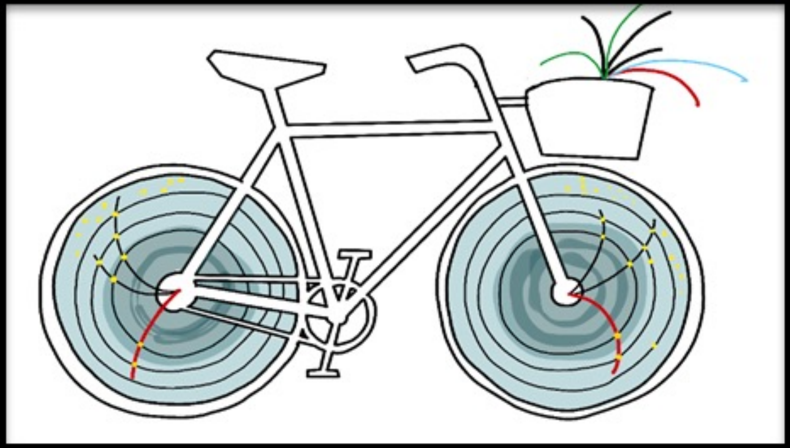
…and beyond?



$< pile - up > \sim 200$

THANK YOU!

E.T. Exploring Tracking-lands, by F. Cairo



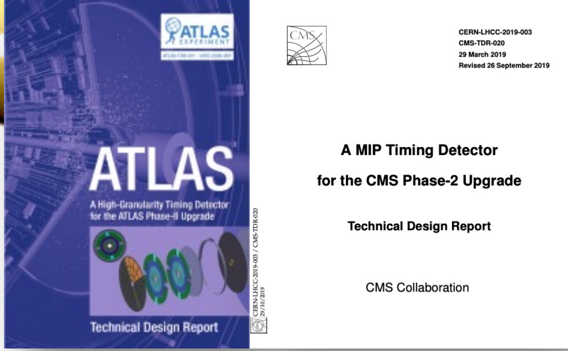
Valentina Maria Martina Cairo

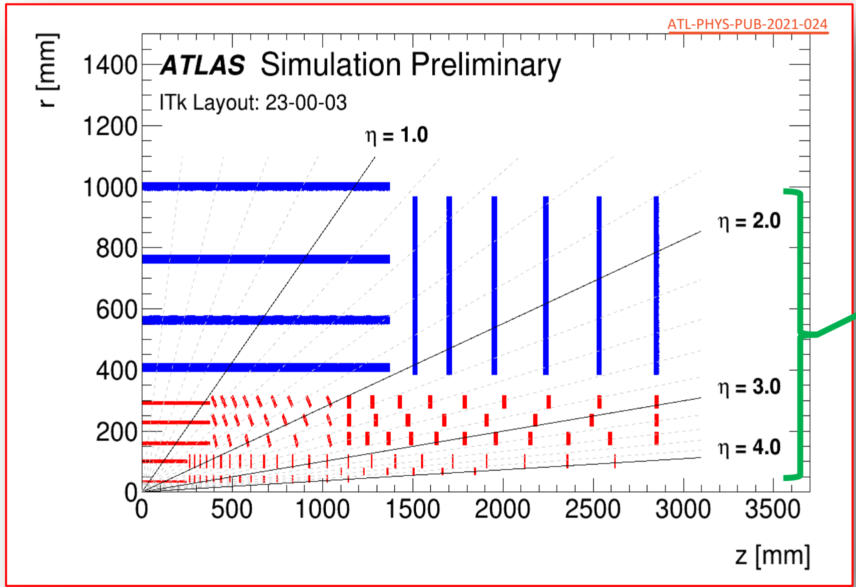
EXTRA SLIDES

F. Cairo, From *Conn(ll)ecting the dots*

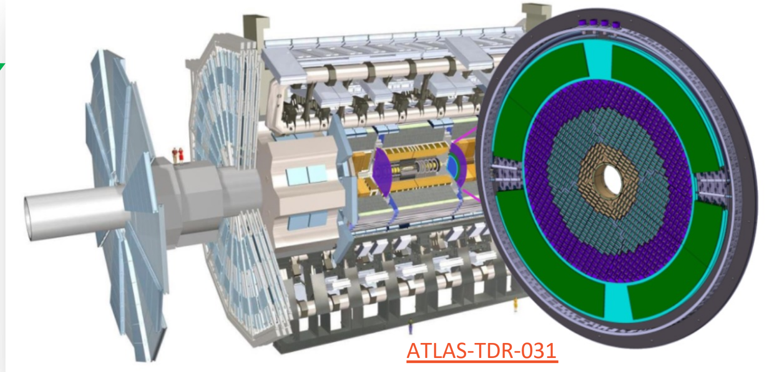
UNFOLDING
A NEW DIMENSION

Addition of timing layers to HEP detectors growing area of interest



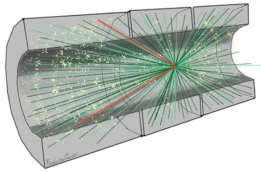


High Granularity Timing Detector



New handles to improve event reconstruction in the forward region, but limited by its reduced η acceptance…

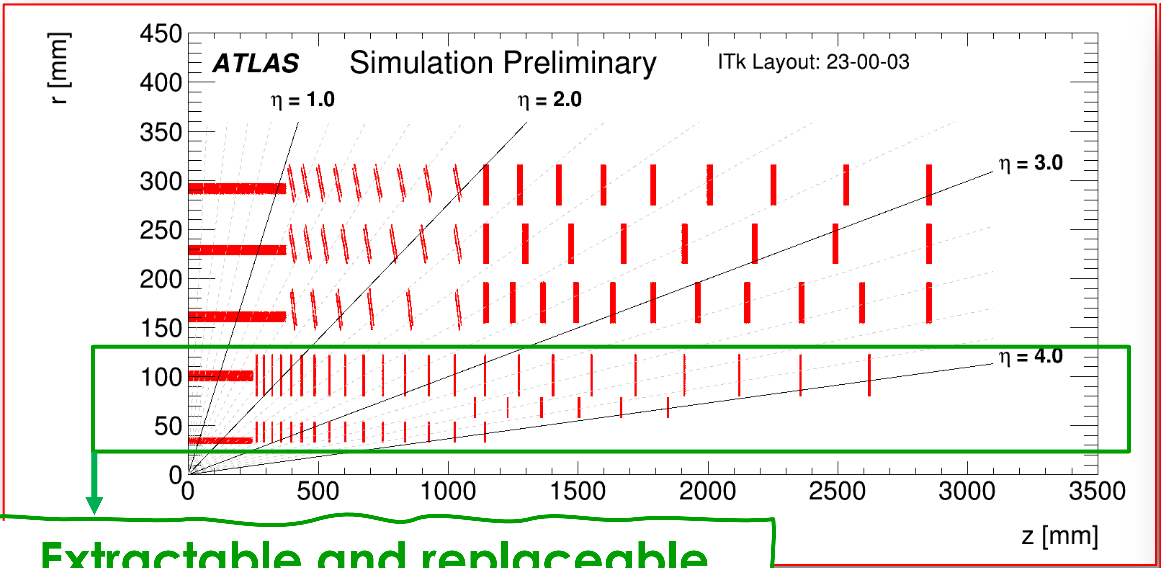
Can we maximize the ATLAS physics potential beyond Run 4 by extending the timing coverage to the full η acceptance?



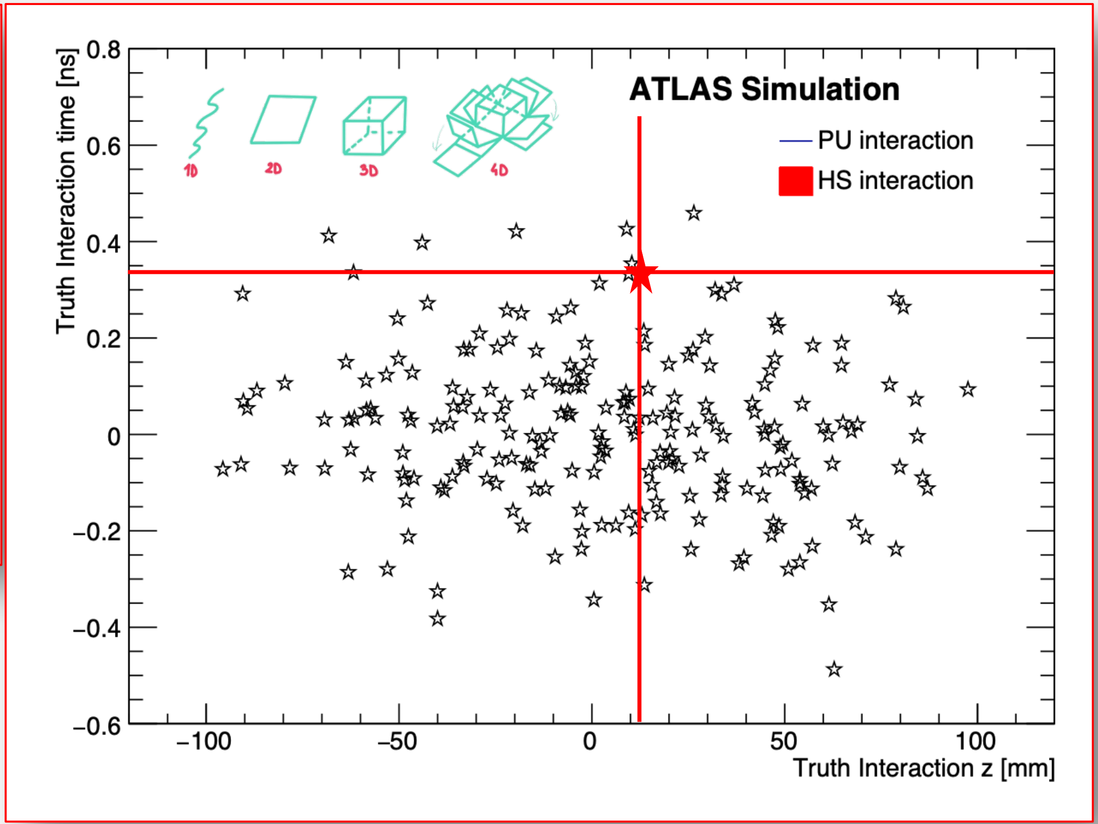
UNFOLDING
A NEW DIMENSION

Next step in advancing technologies are real 4-dimensional silicon trackers (resolution of O($10\ \mu m$) & O($10\ ps$))

- **Excellent opportunity during HL-LHC and, in particular, for future energy frontier trackers**
- **First exploratory studies in ATLAS**
  - Also looked at in LHCb



Extractable and replaceable half-way through HL-LHC (rad-hard up to 10-15 MGy)



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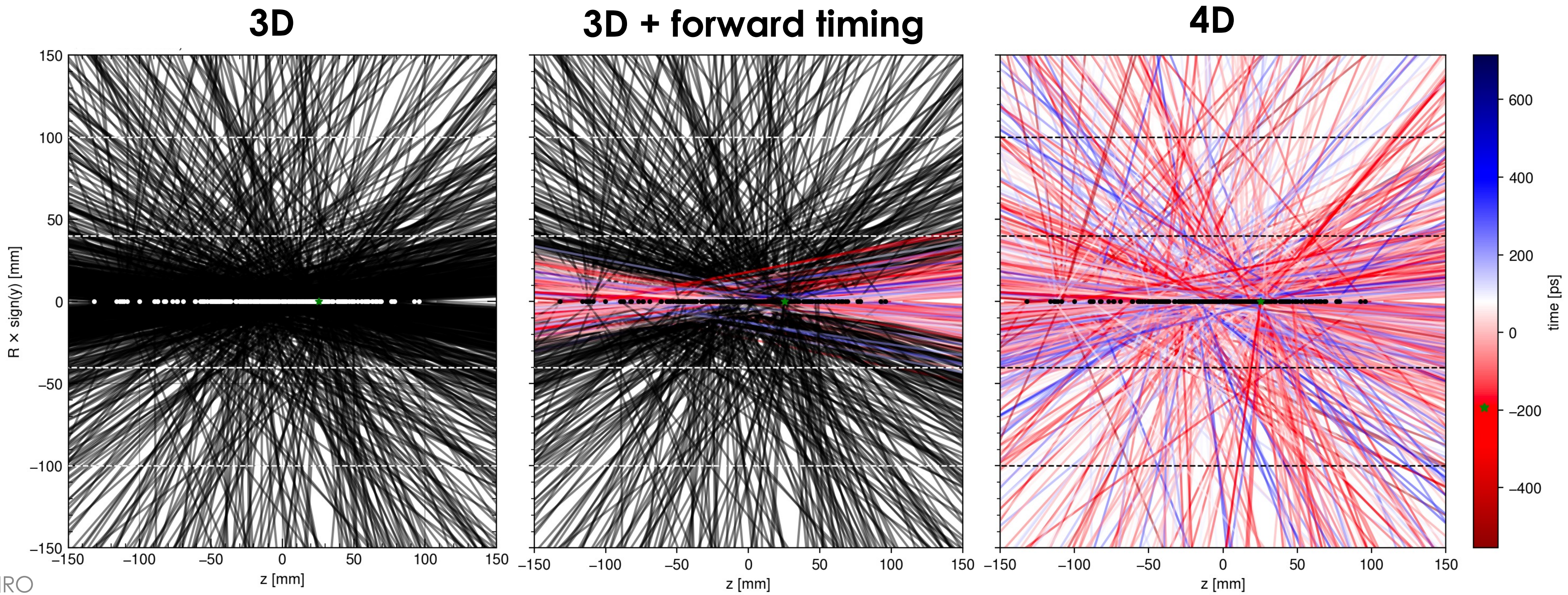
- **First exploratory studies in ATLAS**
  - Also looked at in LHCb



THE RECONSTRUCTION CHAIN

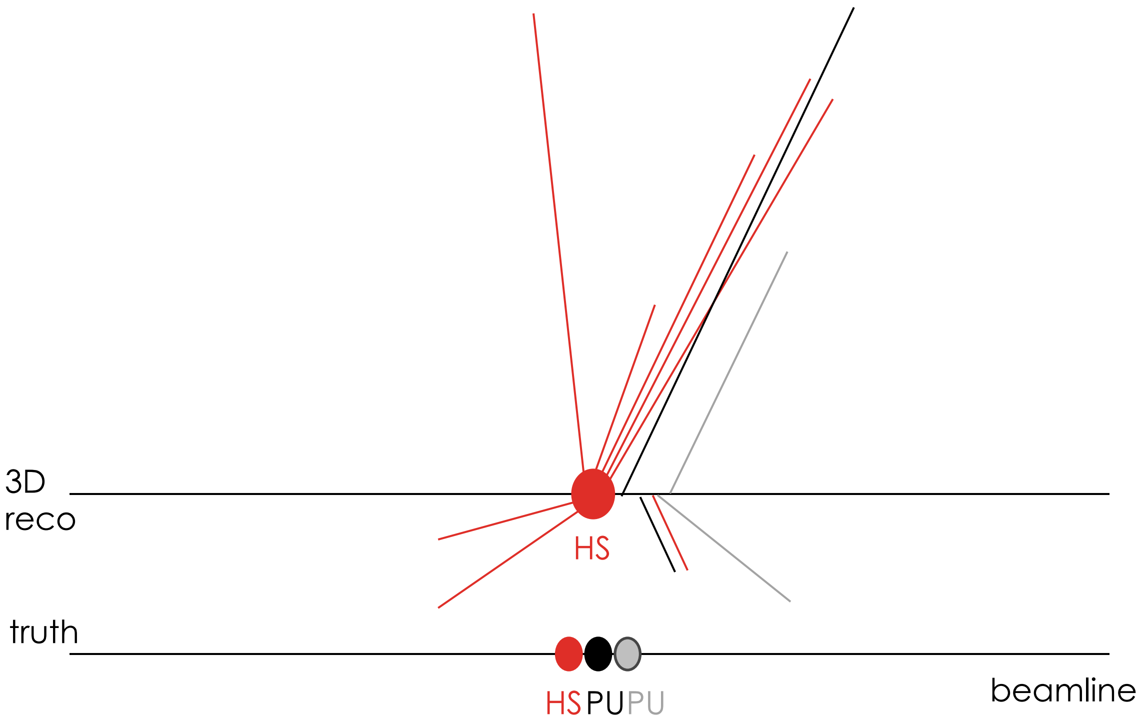
THE RECONSTRUCTION CHAIN

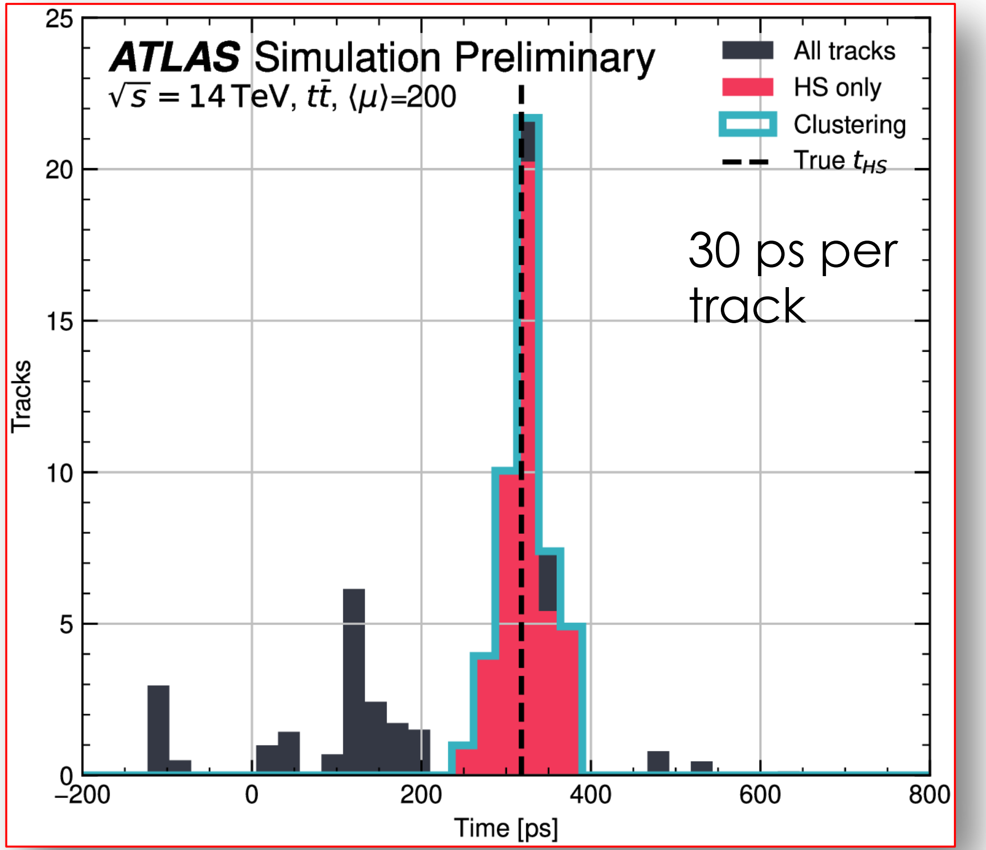
In this first study, track-time
was added here,
based on truth information
and smeared by 30, 60, 90 ps

N.B. track-time, not hit-time

DETERMINING THE VERTEX TIME

- With 4D tracking, **each** charged particle would have a timestamp
- Determining **vertex time crucial for reconstruction/identification of other objects**, e.g. b-jets





Time clustering a posteriori on 3D vertex
→ spurious tracks removed effectively!

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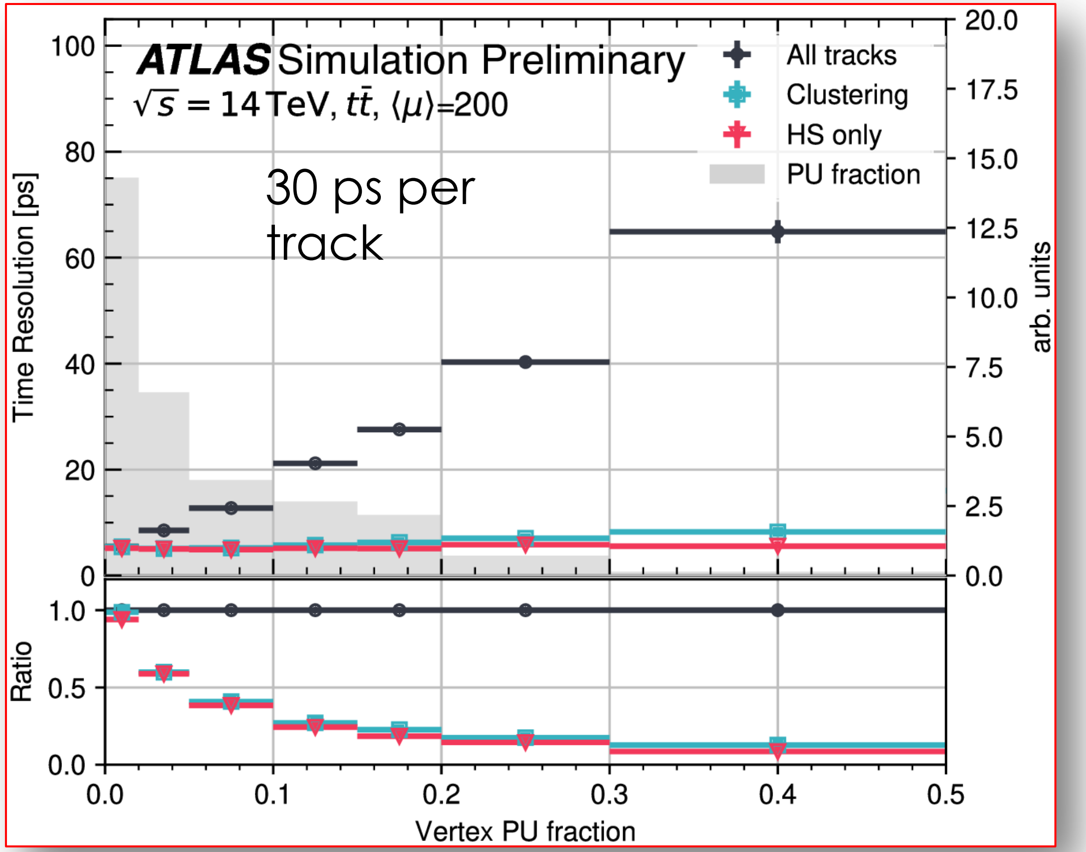
DETERMINING THE VERTEX TIME

- With 4D tracking, **each** charged particle would have a timestamp
- Determining **vertex time crucial for reconstruction/identification of other objects**, e.g. b-jets



Excellent vertex time resolution can be achieved

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DETERMINING THE VERTEX TIME

- With 4D tracking, **each** charged particle would have a timestamp
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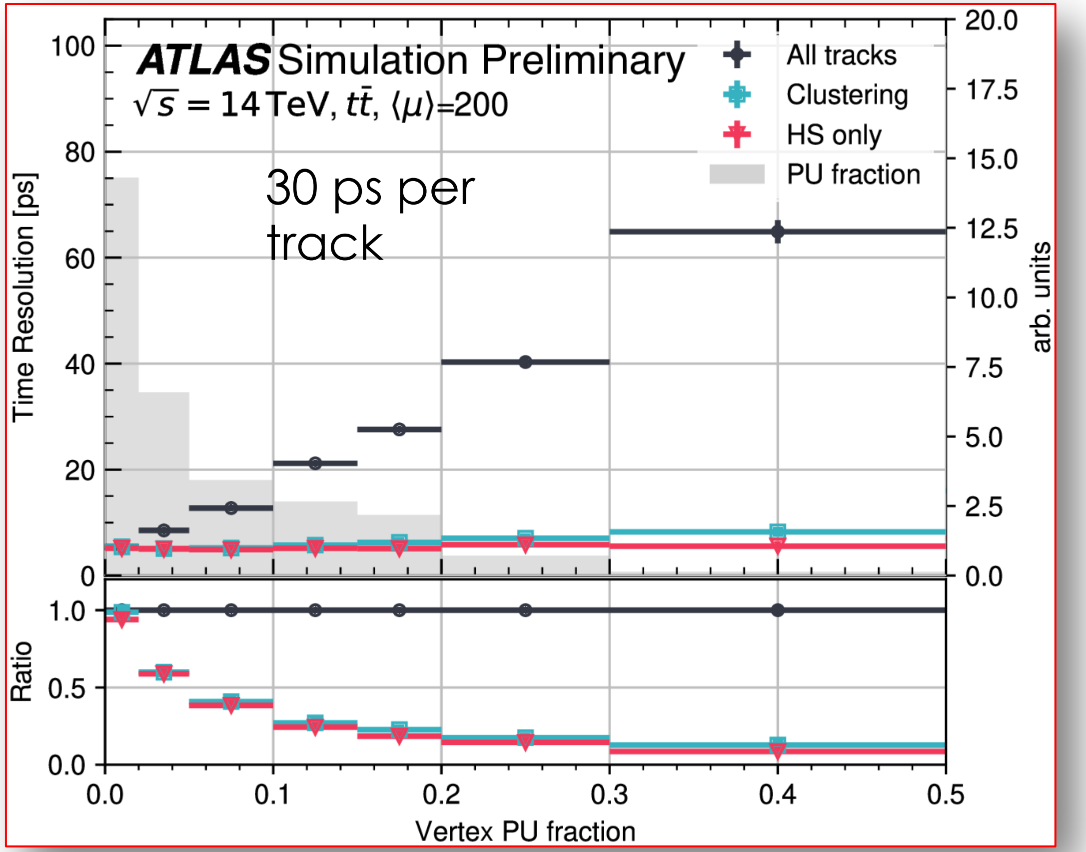

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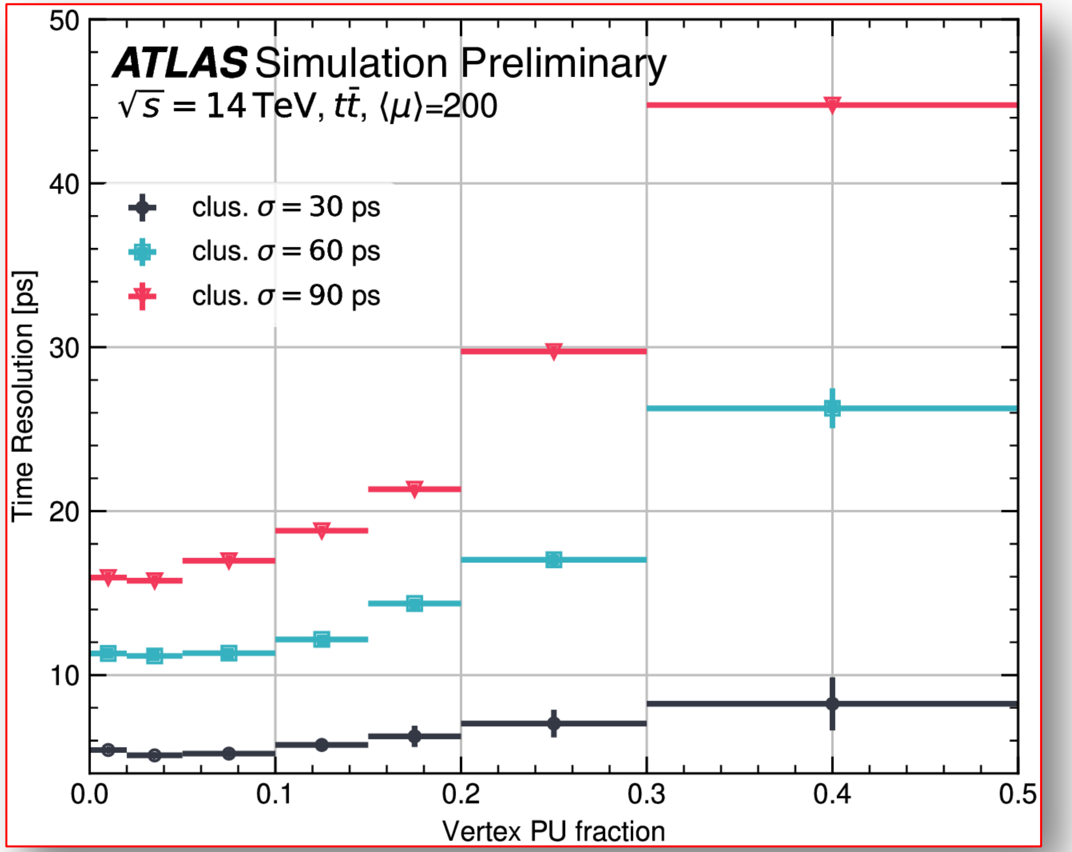

The better the track-time resolution, the more PU-robust the vertex time resolution

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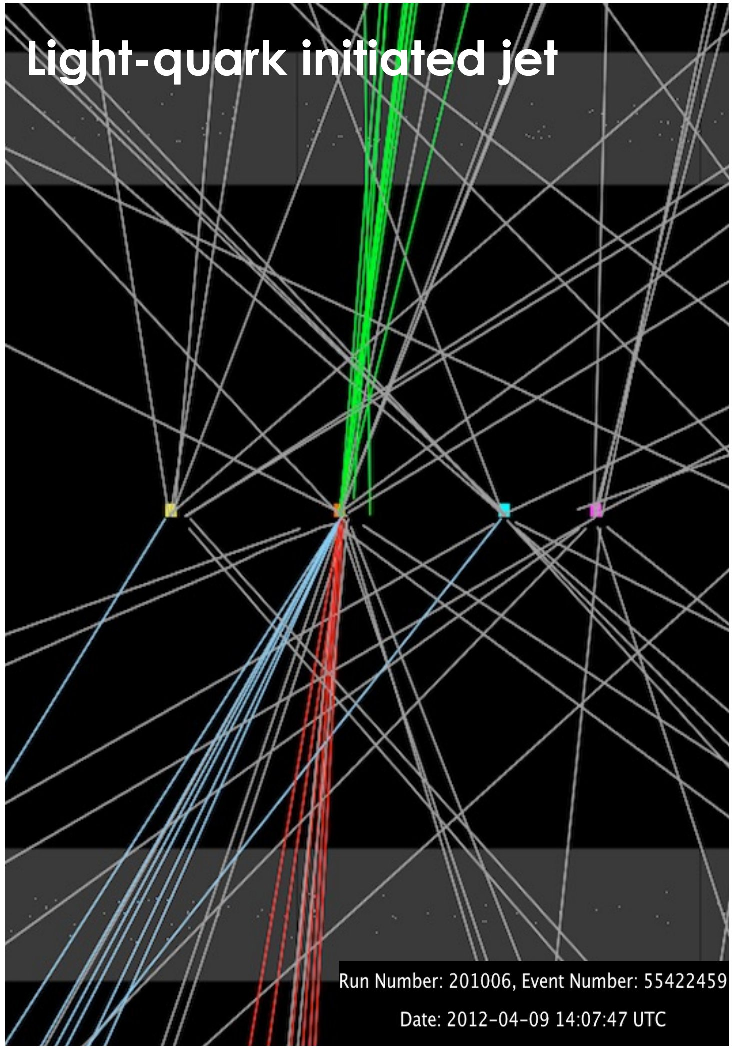
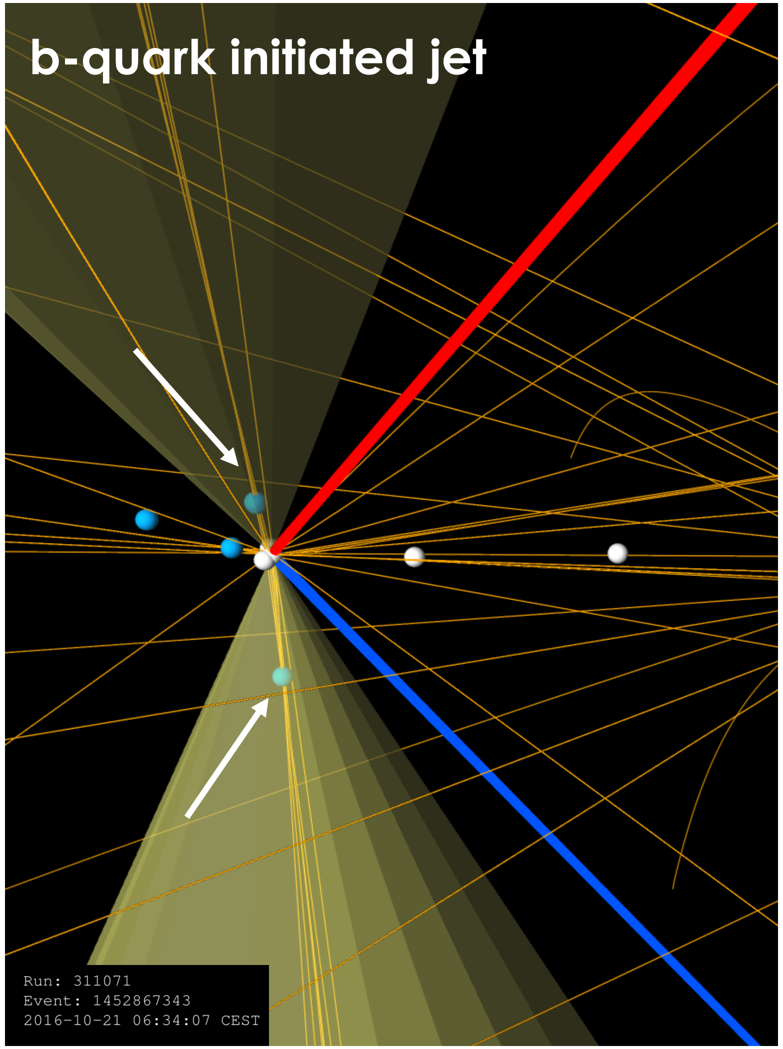
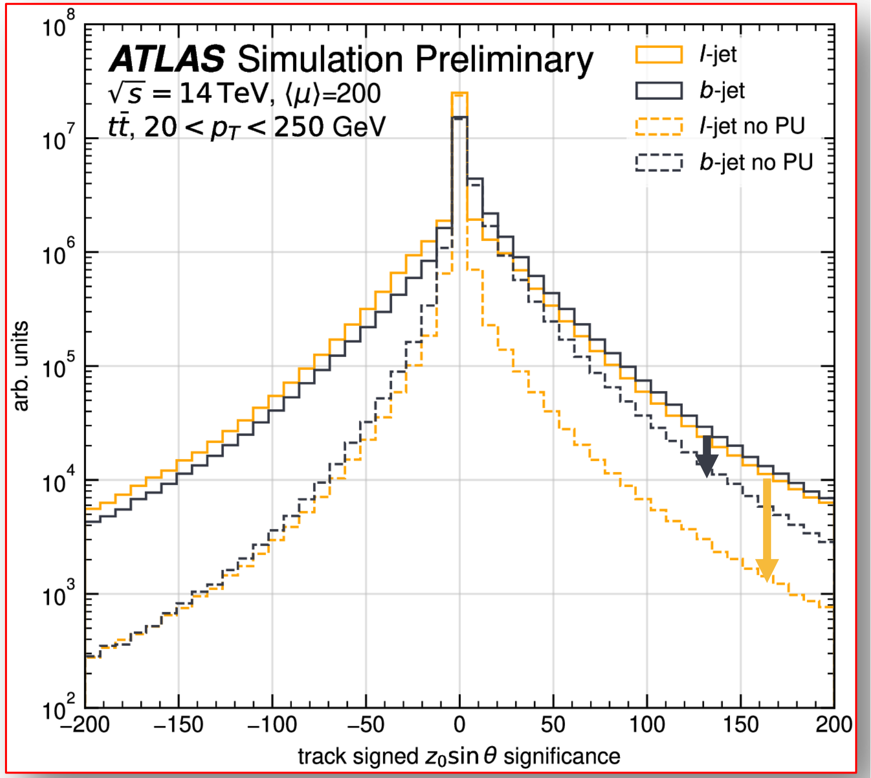
THE KEY FEATURES FOR b-TAGGING

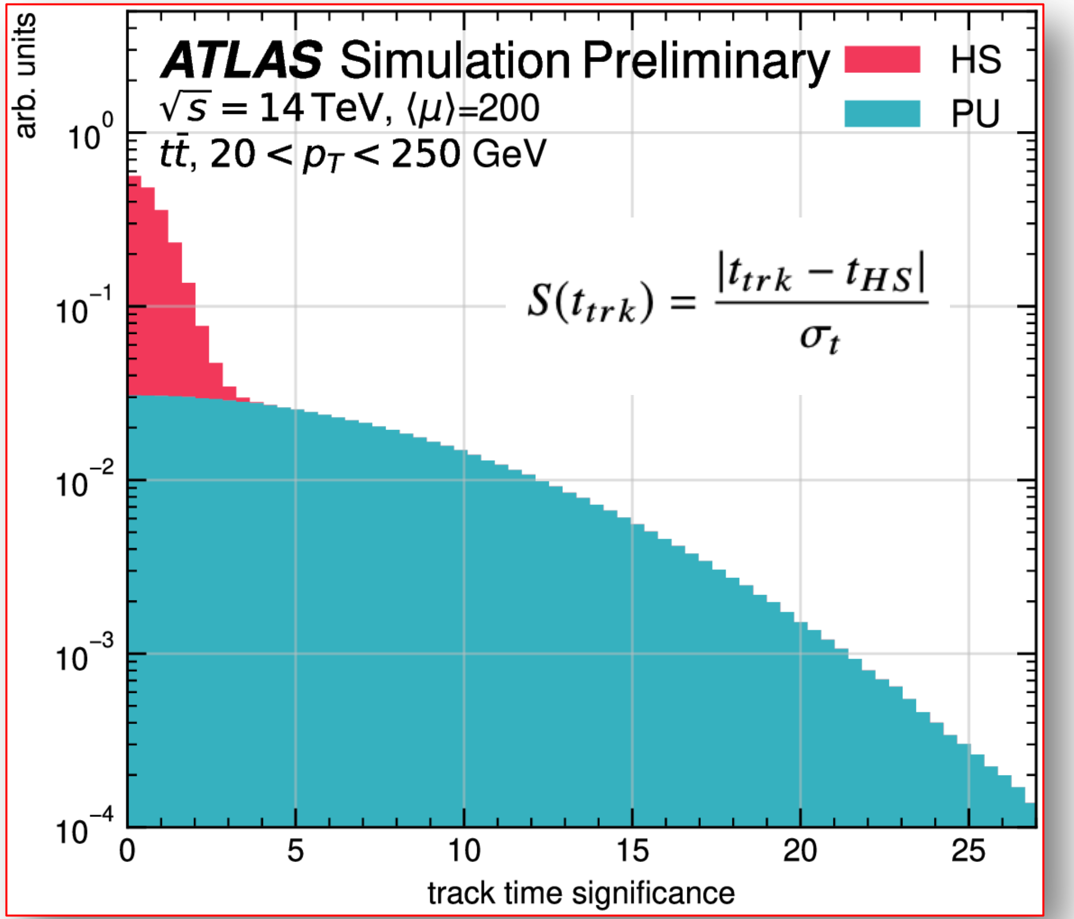






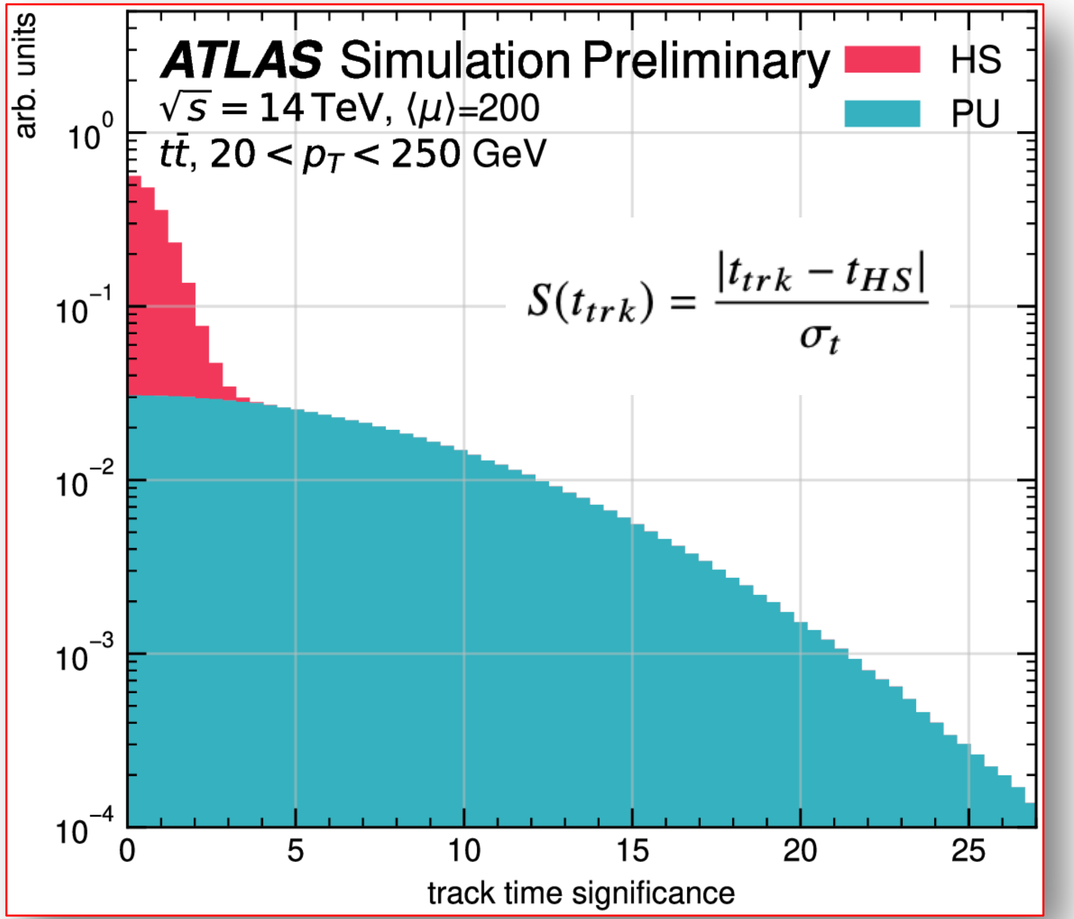
Long lifetime of B-hadrons requires selecting tracks with large IPs →large selection windows around the longitudinal IP → more pile-up contamination that can lead to fake secondary vertices

GNT – 4D b-TAGGING

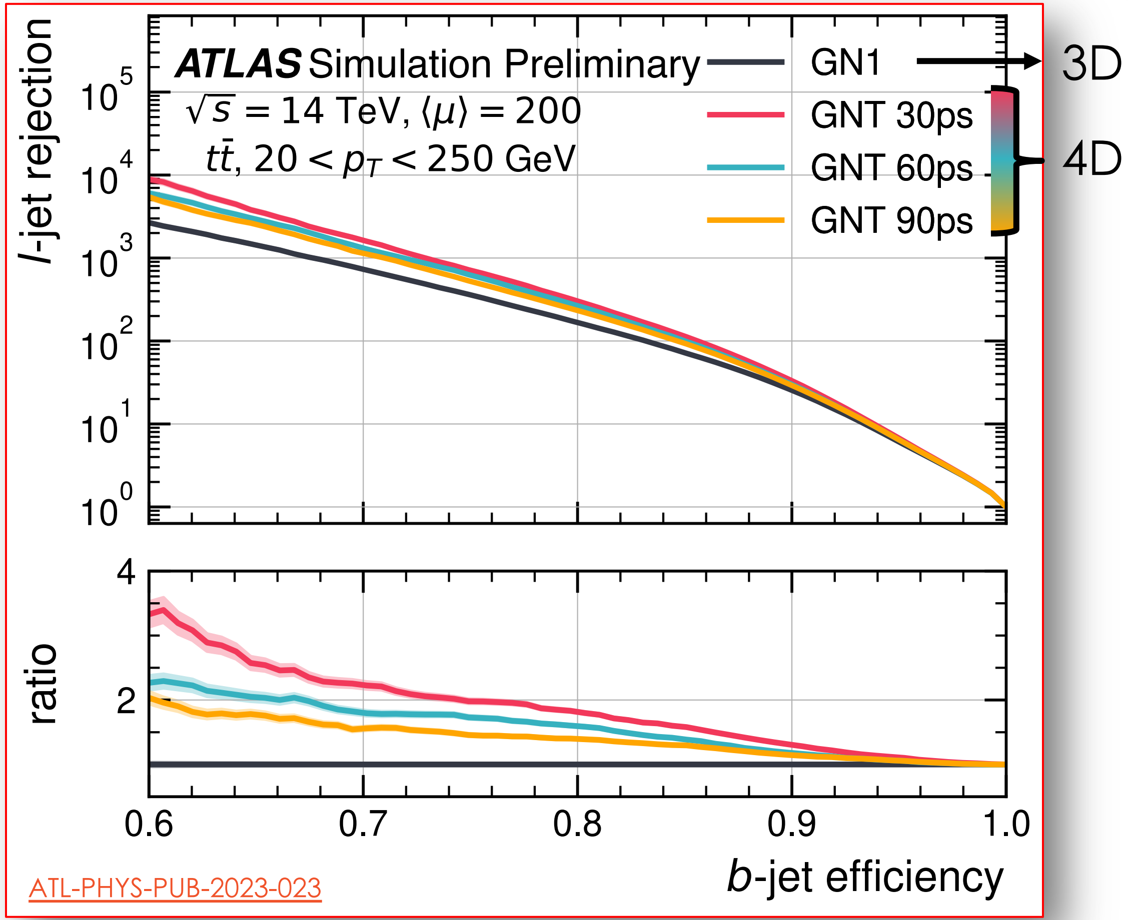


Known track and vertex time, a track time significance is built

GNT – 4D b-TAGGING

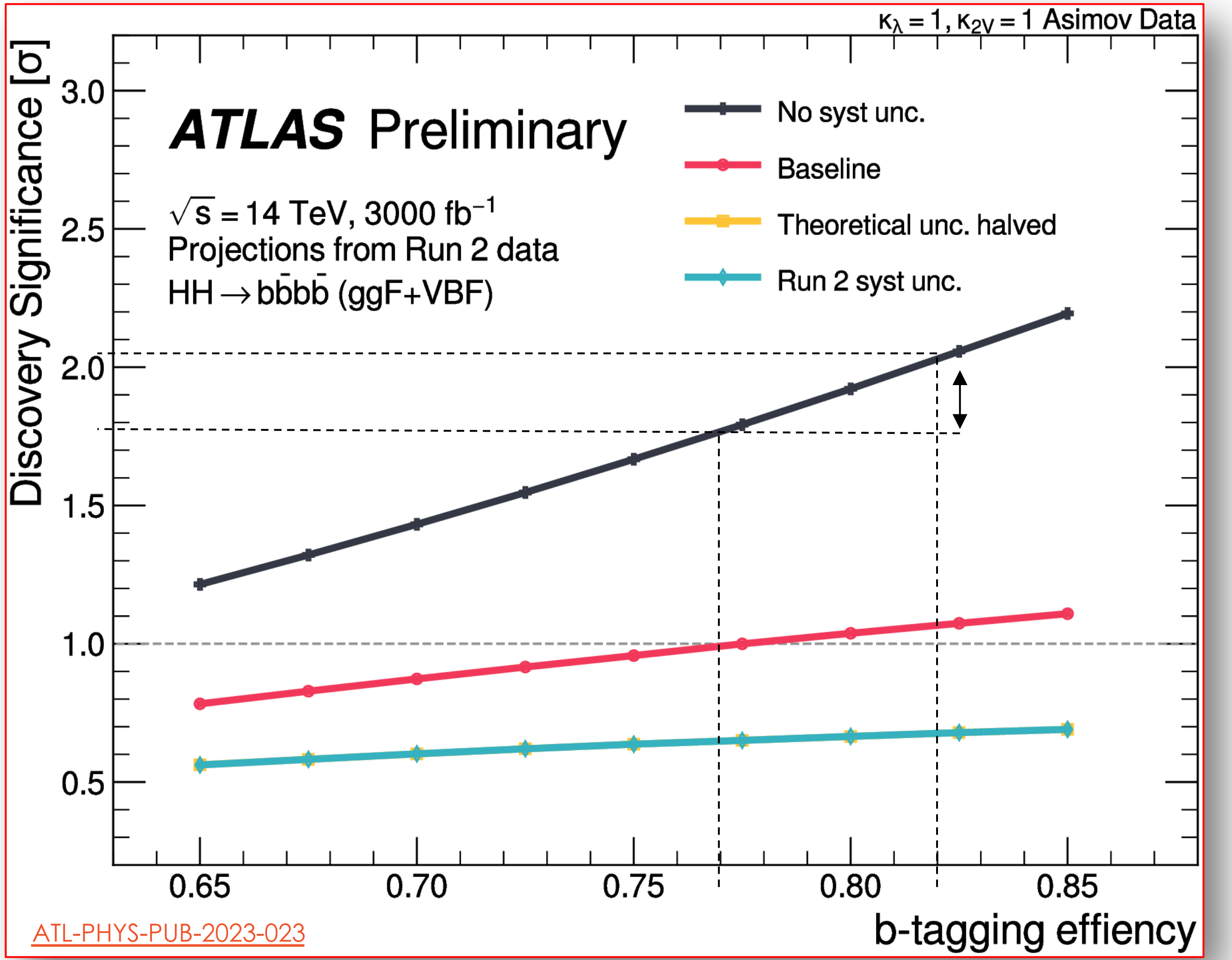


Known track and vertex time, a track time significance is built



Interesting potential sensitivity increase for Higgs physics, in particular **HH**, whose observation is a high-priority goal for HL-LHC

HH PROSPECTS



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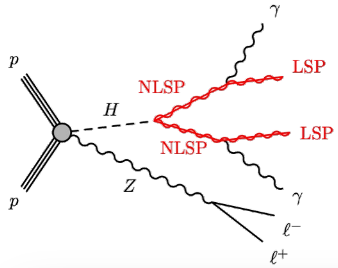
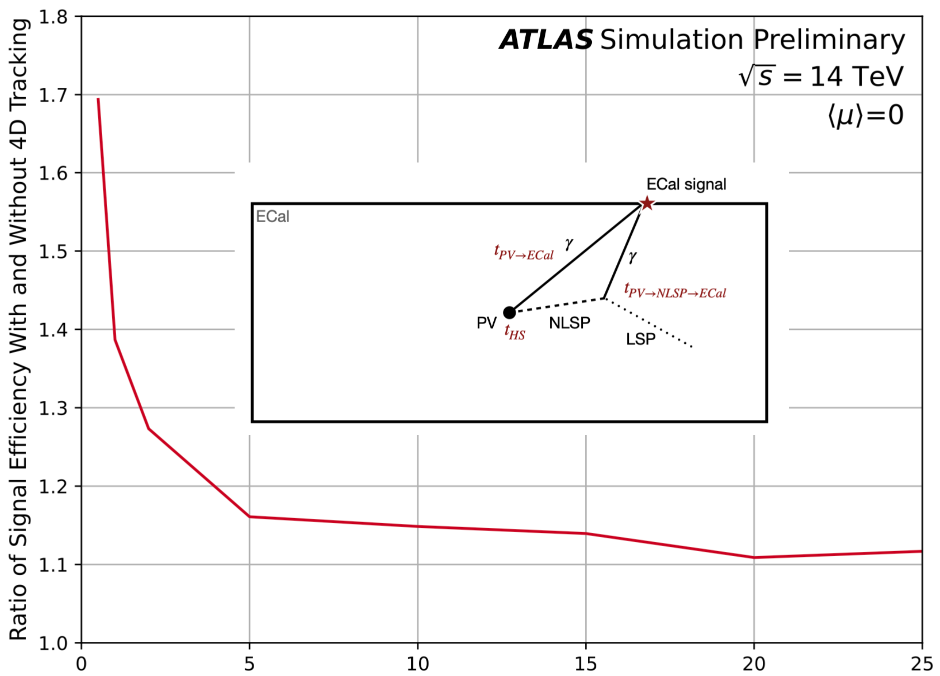
e.g. 77% to 82% → $\sim 0.3\sigma$ improvement (more than 500 fb-1 of data!)

N.B. this plot was made by scaling to the full HL-LHC luminosity

OTHER PHYSICS CASES

- **VBF H → inv** extensively studied at the time of the HGTD TDR, results still valid
- Long Lived Particles studied in the PubNote, in particular ***delayed photons***
- Other applications to be further explored, e.g. **c-tagging** (similar considerations as for b-tagging), **tau reconstruction and identification**, etc





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A COMPARISON WITH CMS' MIP TIMING DETECTOR

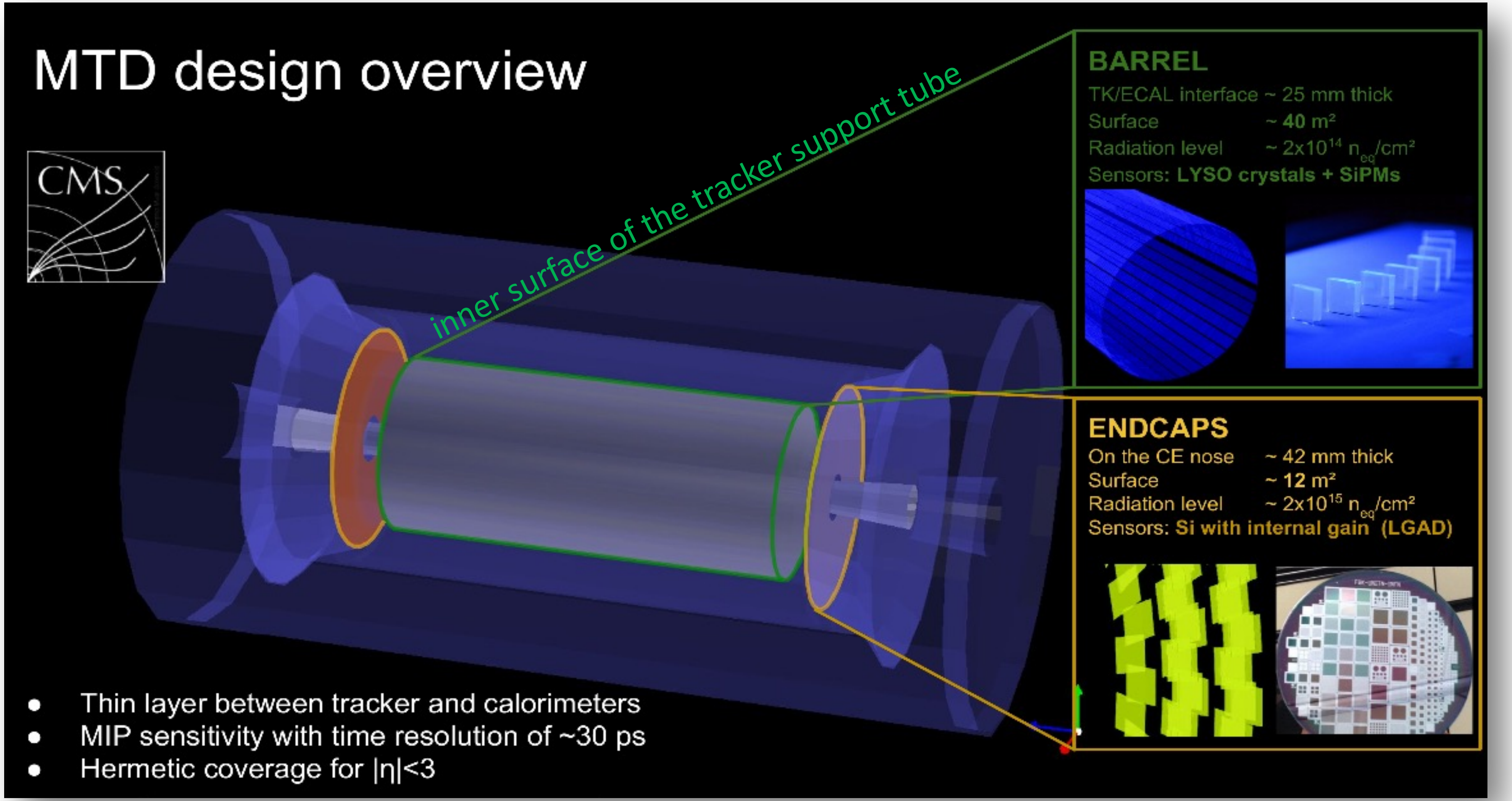
From CMS MTD TDR: *"The MTD will give timing information for MIPs with 30–40 ps resolution at the beginning of HL-LHC operation in 2026, degrading slowly as a result of radiation damage to 50–60 ps by the end of HL-LHC operations."*

Table 1.1: Expected scientific impact of the MIP Timing Detector, taken from Ref. [8].

Signal	Physics measurement	MTD impact
$H \to \gamma\gamma$ and $H \to 4$ leptons	+15–25% (statistical) precision on the cross section $\to$ Improve coupling measurements	Isolation and Vertex identification
VBF$\to$H$\to \tau\tau$	+30% (statistical) precision on cross section $\to$ Improve coupling measurements	Isolation VBF tagging, p_T^{miss}
HH	+20% gain in signal yield $\to$ Consolidate searches	Isolation b-tagging
EWK SUSY	+40% background reduction $\to$ 150 GeV increase in mass reach	MET b-tagging
Long-lived particles (LLP)	Peaking mass reconstruction $\to$ Unique discovery potential	β_{LLP} from timing of displaced vertices

about 200. The integrated luminosity $\times$ efficiency is increased and this gain is equivalent to collecting data for three additional years beyond the ten year run planned for the HL-LHC.

CMS' MIP TIMING DETECTOR



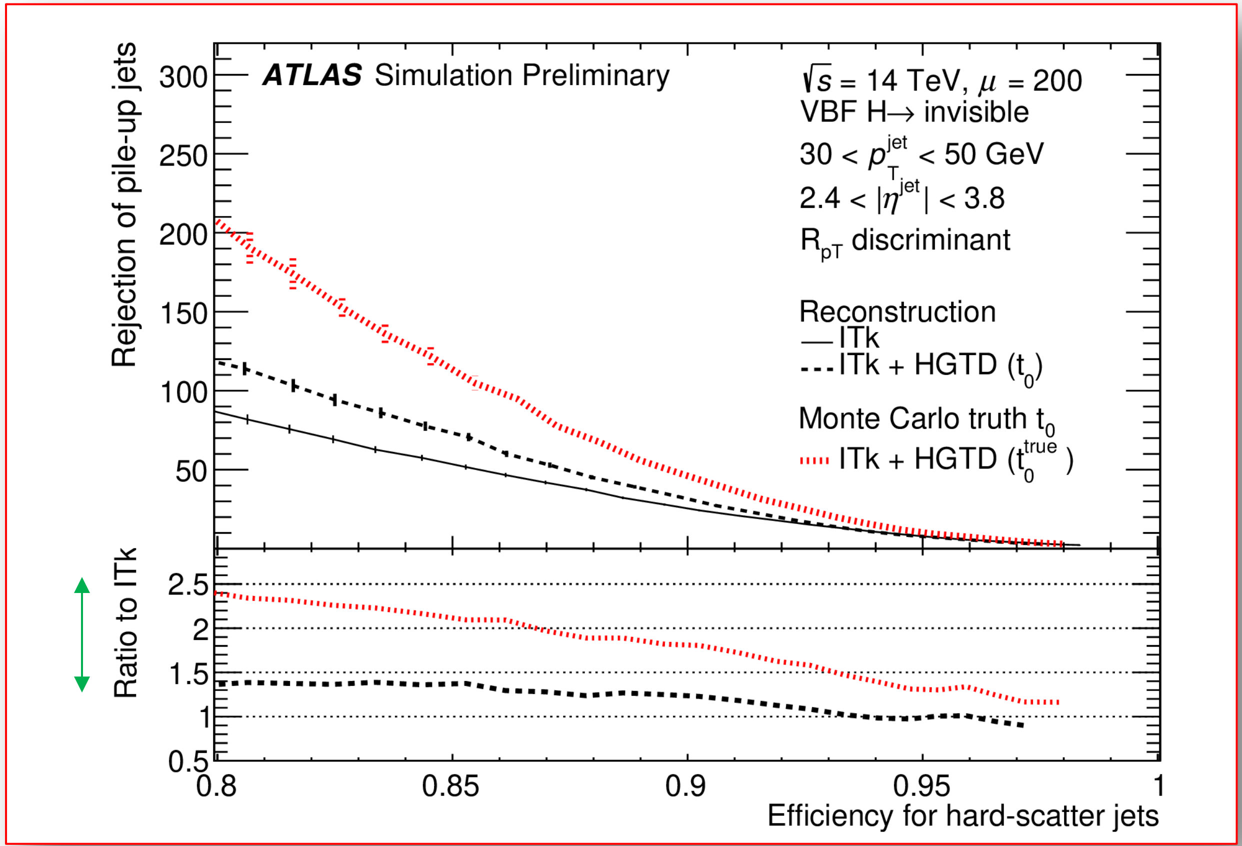
|eta|<1.5

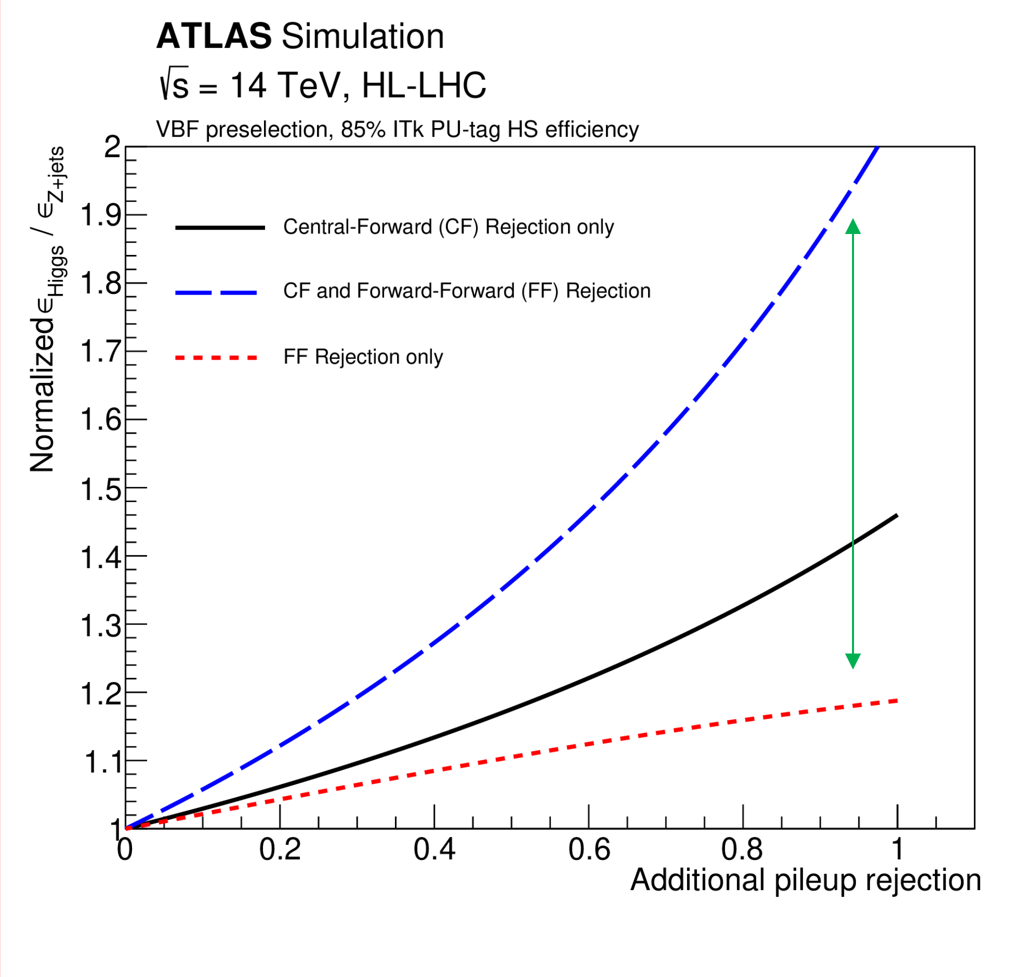
1.5 <|eta|<3.0

Beyond Run 4, CMS is also considering to add timing layers in the innermost part of the tracker.

OTHER PHYSICS CASES

$VBF\ H \rightarrow inv$





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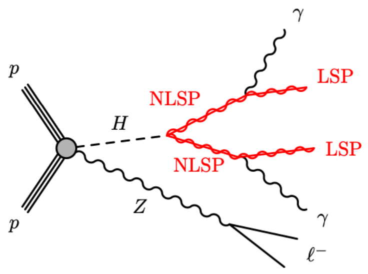
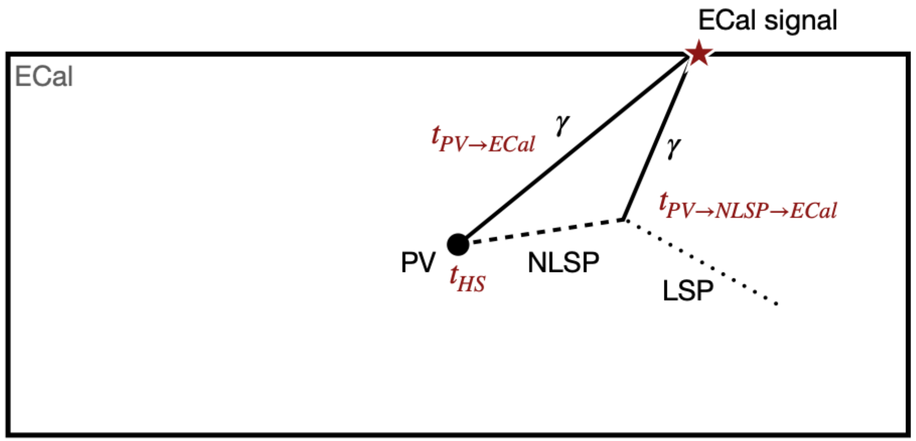
OTHER PHYSICS CASES

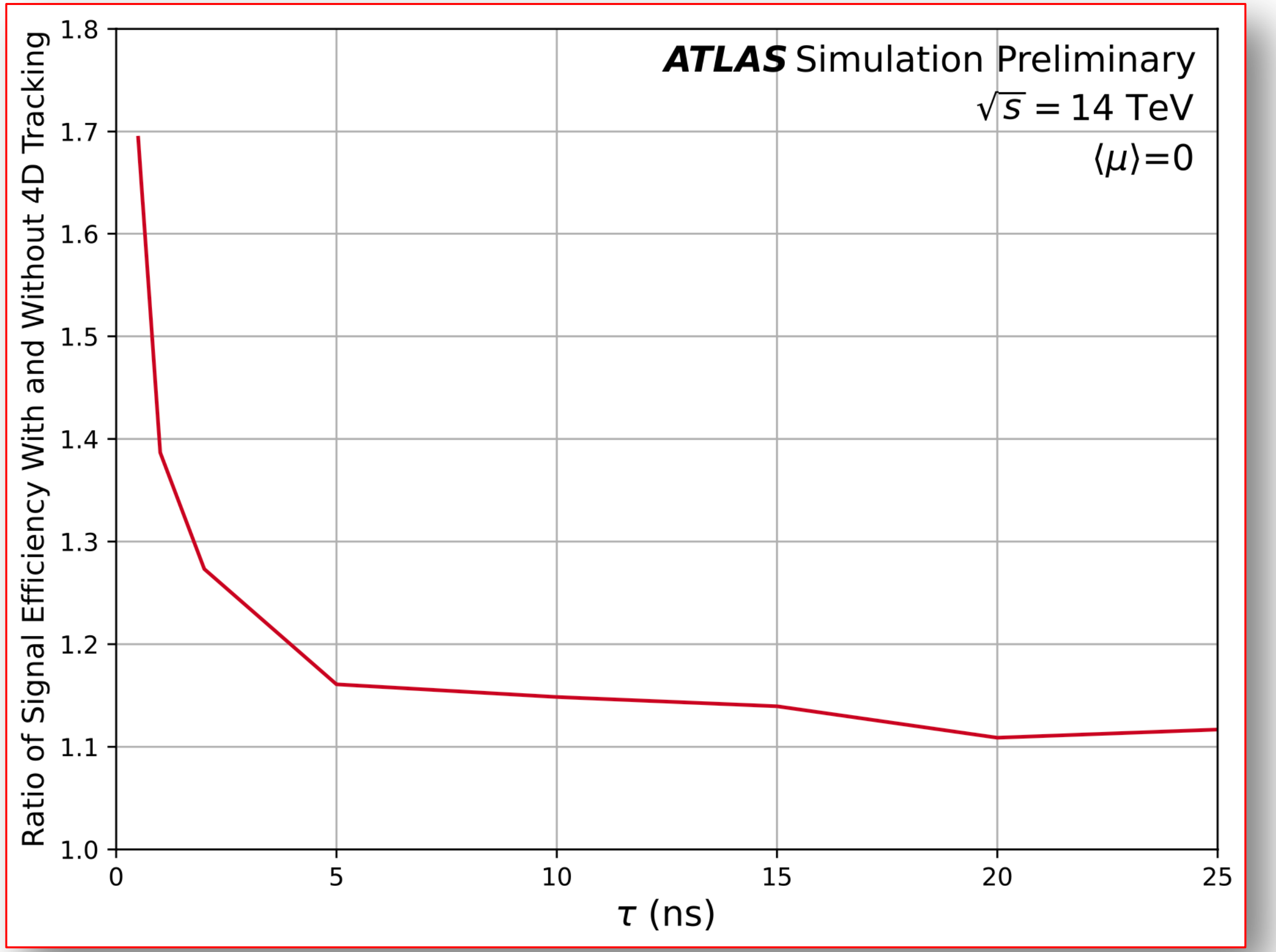
Delayed photons





$$t_{\mathrm{ECal}}^{\mathrm{Measured}} = t_0 + t_{\mathrm{IP}\to\mathrm{ECal}}$$

$$\Delta t^{\mathrm{Reconstructed}} = t_{\mathrm{ECal}}^{\mathrm{Measured}} - t_{\mathrm{IP}\to\mathrm{ECal}}^{\mathrm{Reconstructed}} - t_0^{\mathrm{Reconstructed}}$$



VBF HIGGS→ INVISIBLE

$VBF\ H \rightarrow inv$ extensively studied at the time of the HGTD TDR, results still valid!

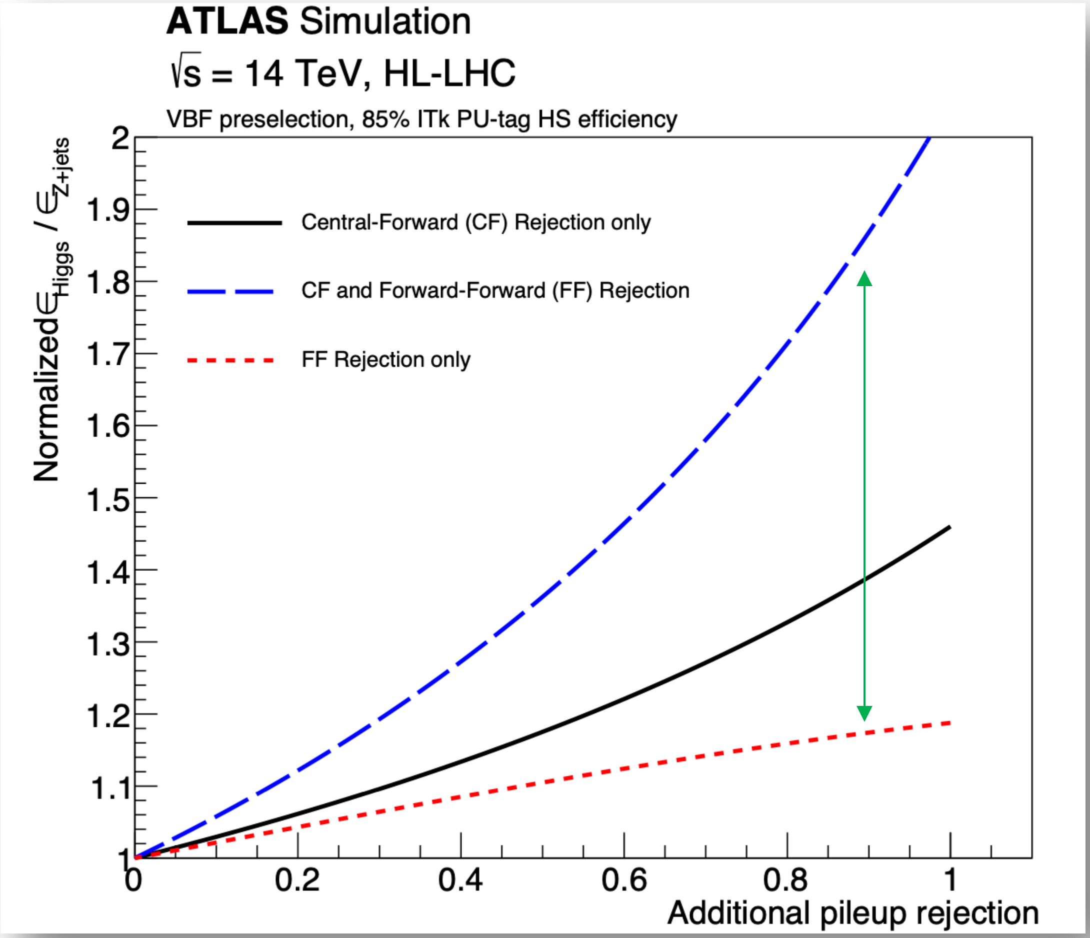


Fig. 3.25
Normalized signal over background gain relative to ITk-only pileup jet suppression performance, as a function of the additional pileup jet rejection from HGTD. The solid black (dotted red) line represents the HGTD improvement from the CF (FF) event topologies separately. The dotted blue line shows the total improvement when the combined HGTD+ITk pileup suppression algorithm is applied to all jets in the event.

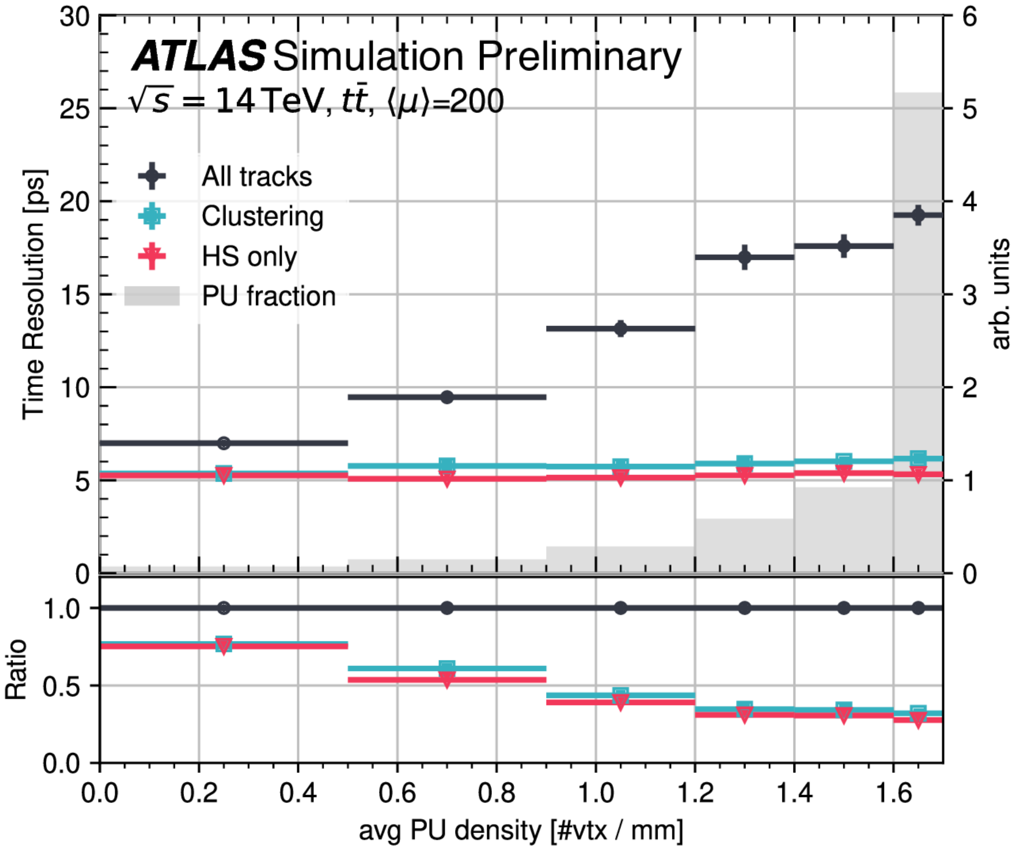
VERTEX T0

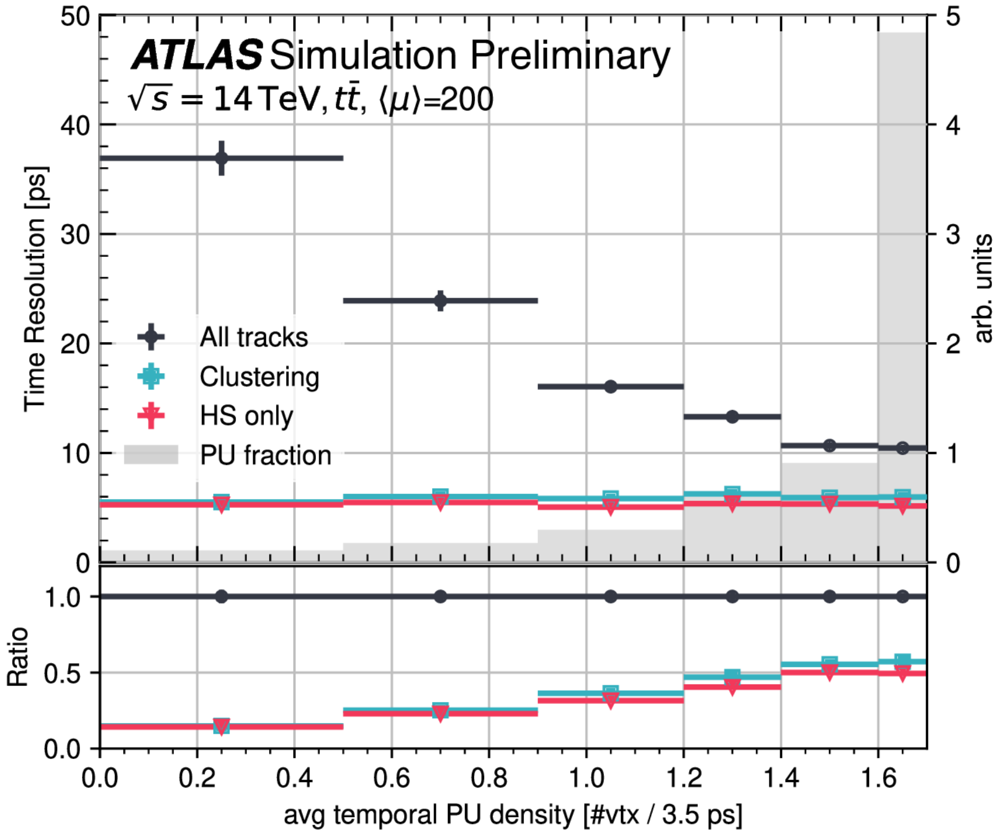
The average spatial pile-up density is defined as:

$$\langle\rho\rangle(z_{HS}) = \frac{\langle\mu\rangle}{\sqrt{2\pi}\sigma_z}\exp\left(-\frac{z_{\mathrm{HS}}^2}{2\sigma_z^2}\right)$$

The average temporal pile-up density is defined as:

$$\langle\rho\rangle(t_{HS}) = \frac{\langle\mu\rangle}{\sqrt{2\pi}\sigma_t}\exp\left(-\frac{t_{\mathrm{HS}}^2}{2\sigma_t^2}\right)$$





GNN

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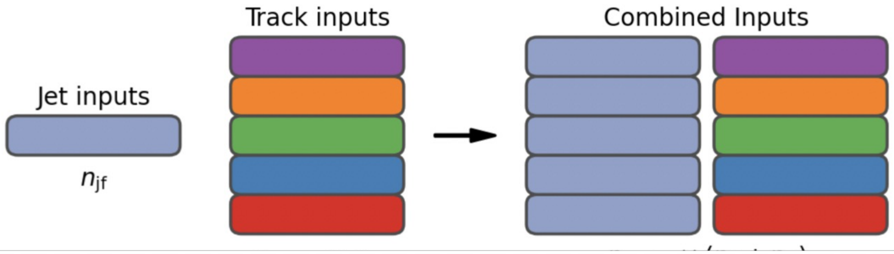
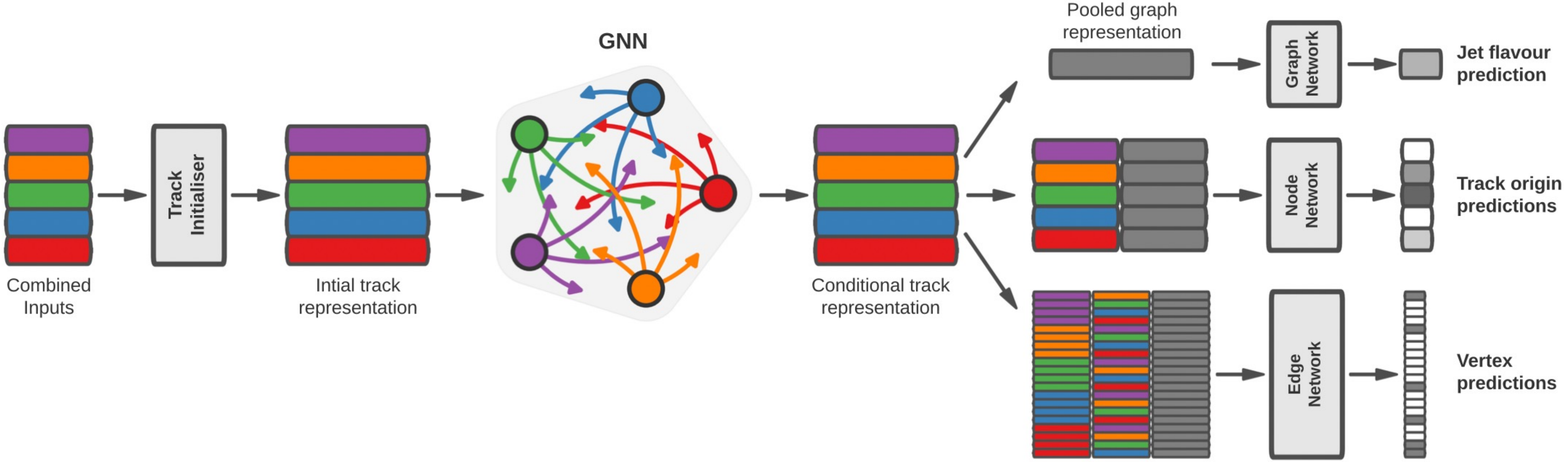


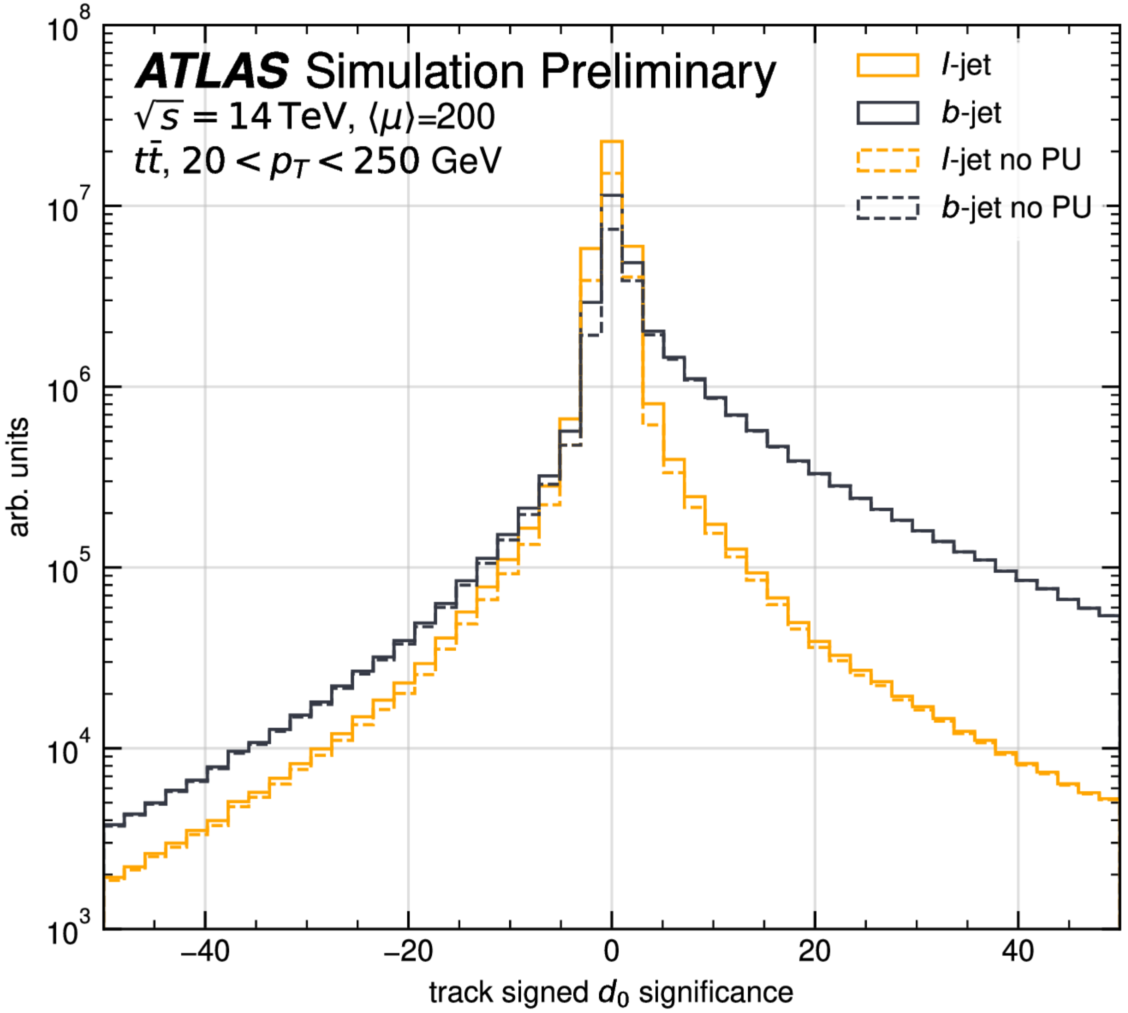


GNN

Track Variables	GN1 ITk	GN1 ITk time
d0	x	x
z0SinTheta	x	x
σ(Theta)	x	x
qOverP	x	x
σ(qOverP)	x	x
φ	x	x
σ(φ)	x	x
signed d0 significance	x	x
signed z0 significance	x	x
Δη(trk, jet)	x	x
Δφ(trk, jet)	x	x
n pix hits	x	x
n pix hits (11 variables)	x	x
dt		x

nPixHits	Number of pixel hits
nStripHits	Number of strip hits
nInnermostPixHits	Number of hits from the innermost pixel layer
nNextToInnermostPixHits	Number of hits from the next-to-innermost pixel layer
nInnermostPixShared	Number of shared hits from the innermost pixel layer
nInnermostPixSplit	Number of split hits from the innermost pixel layer
nPixShared	Number of shared pixel hits
nPixSplit	Number of split pixel hits
nStripShared	Number of shared strip hits
nPixHoles	Number of pixel holes
nStripHoles	Number of strip holes

4D TRACKING



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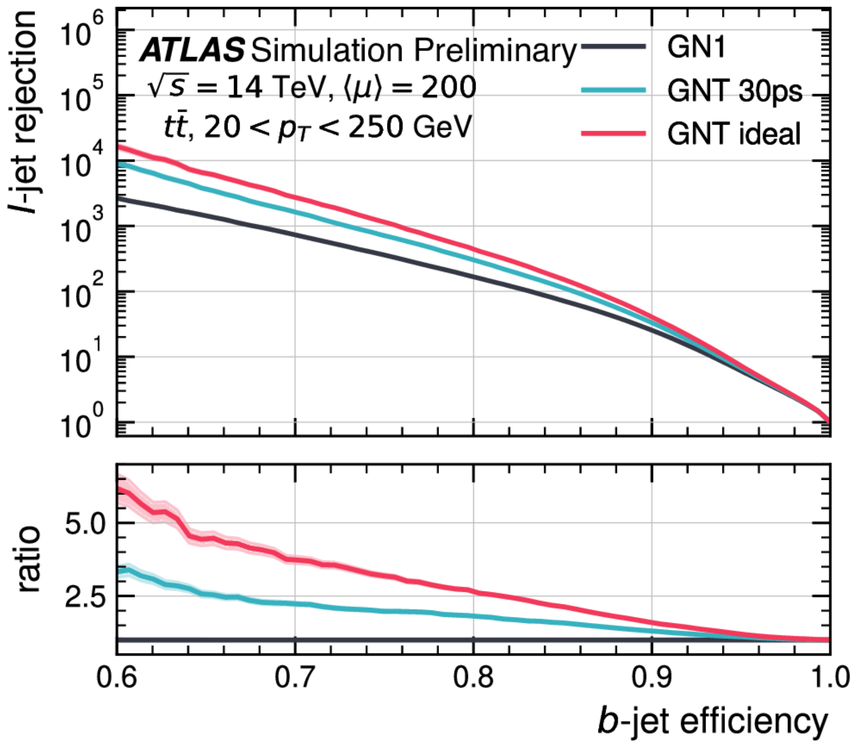
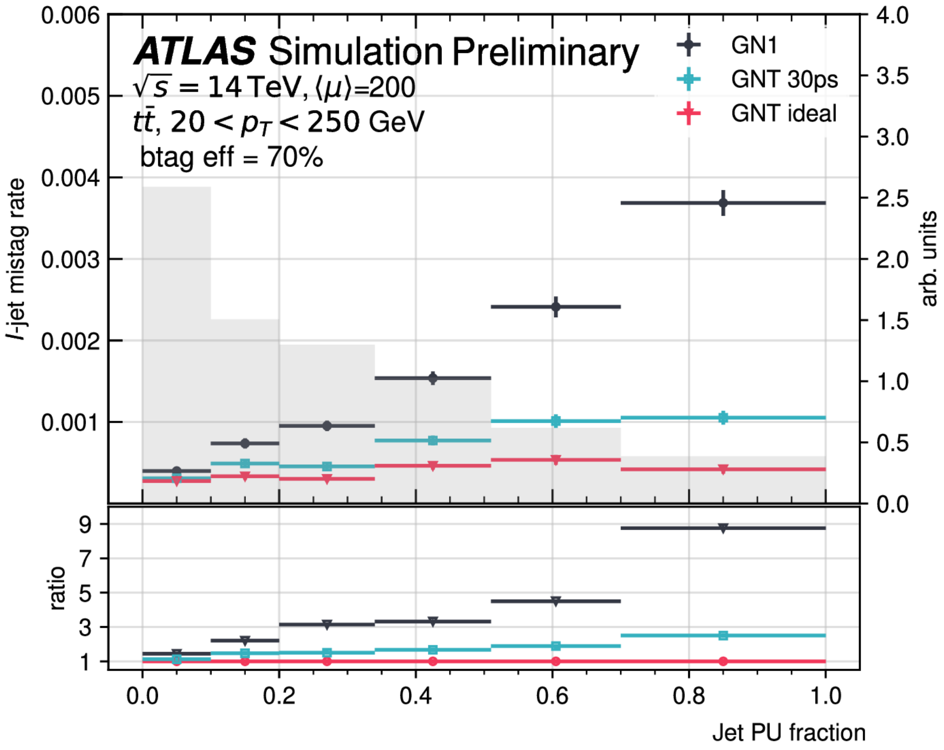
4D FTAG





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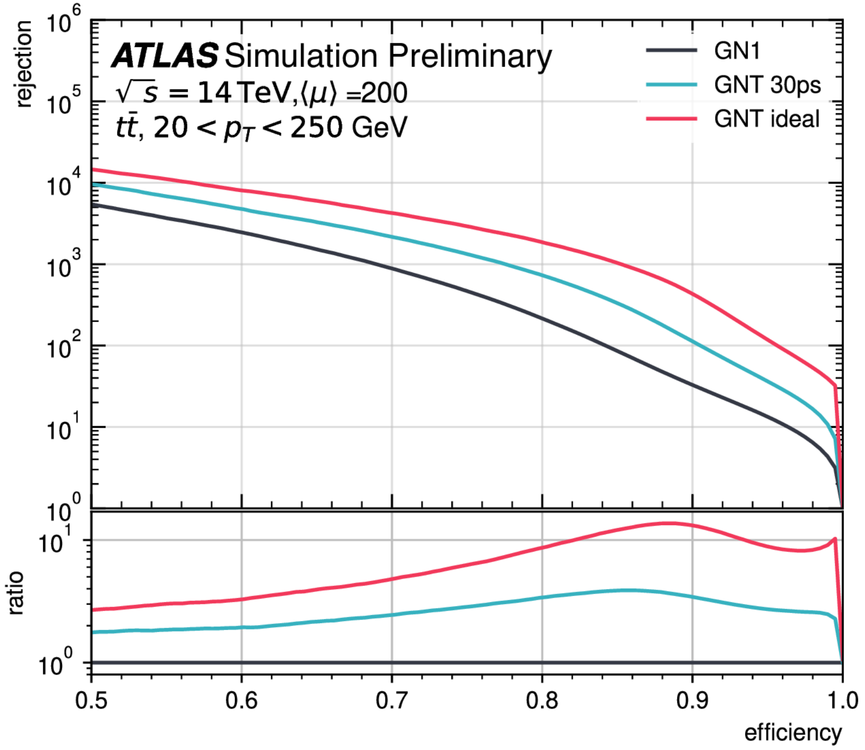
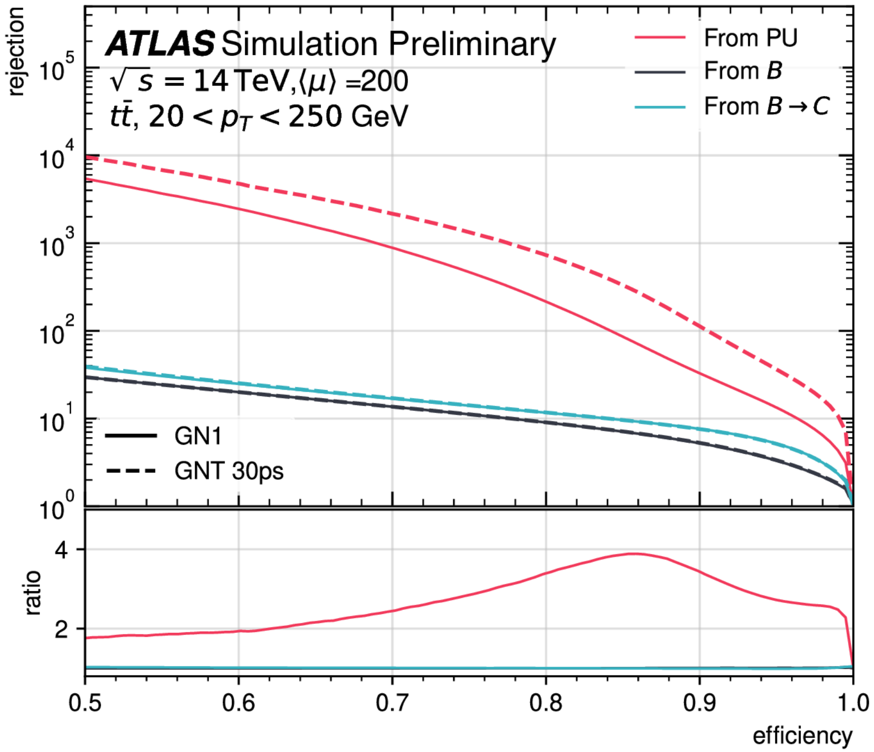
4D FTAG





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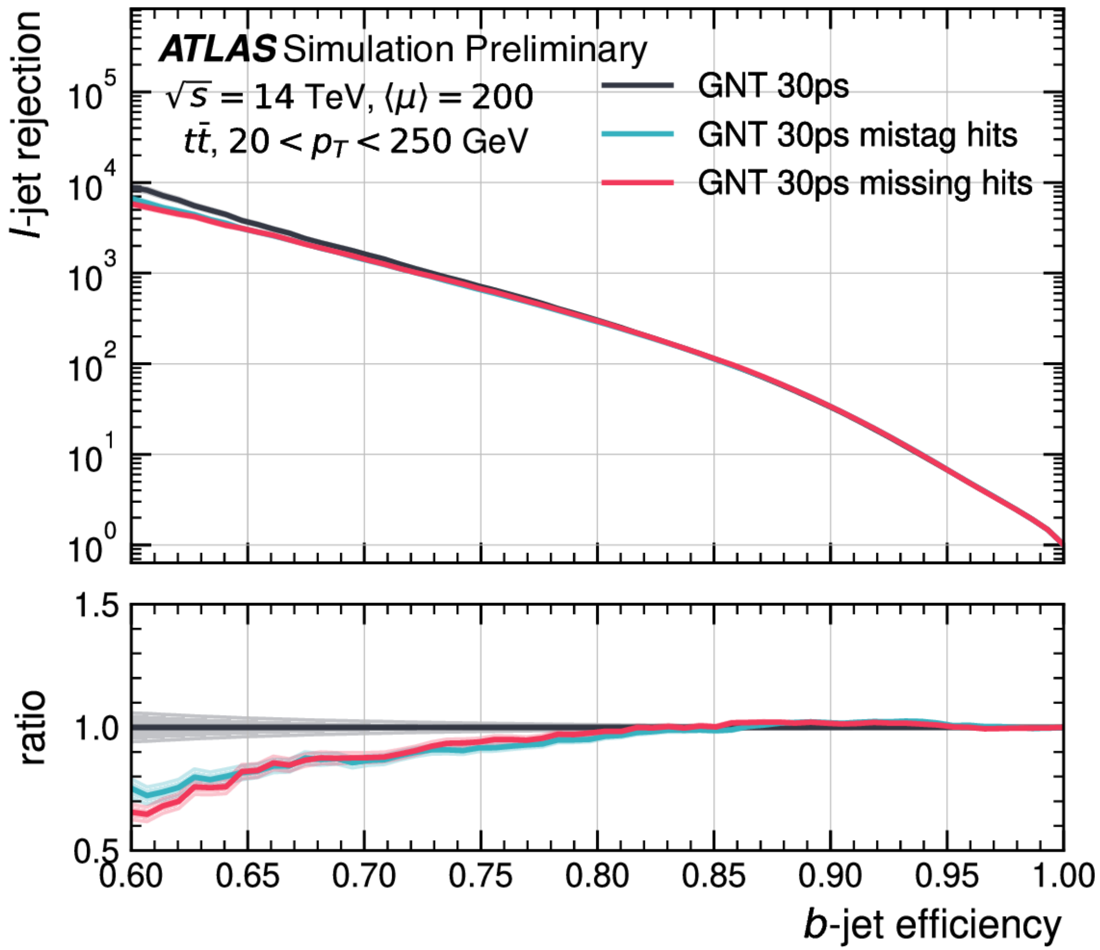
4D FTAG

A complete simulation is needed for an accurate study

We investigated independently the impact of missing hits and mistag hits showing that the performances get degraded mostly at low b-jet efficiencies

missing hit: assuming time only in 2nd layer; if a track has no hit the significance of the track is randomly emulated as HS

mistag hit: for tracks with Truth Match Probability < 80% the significance is randomly emulated as PU



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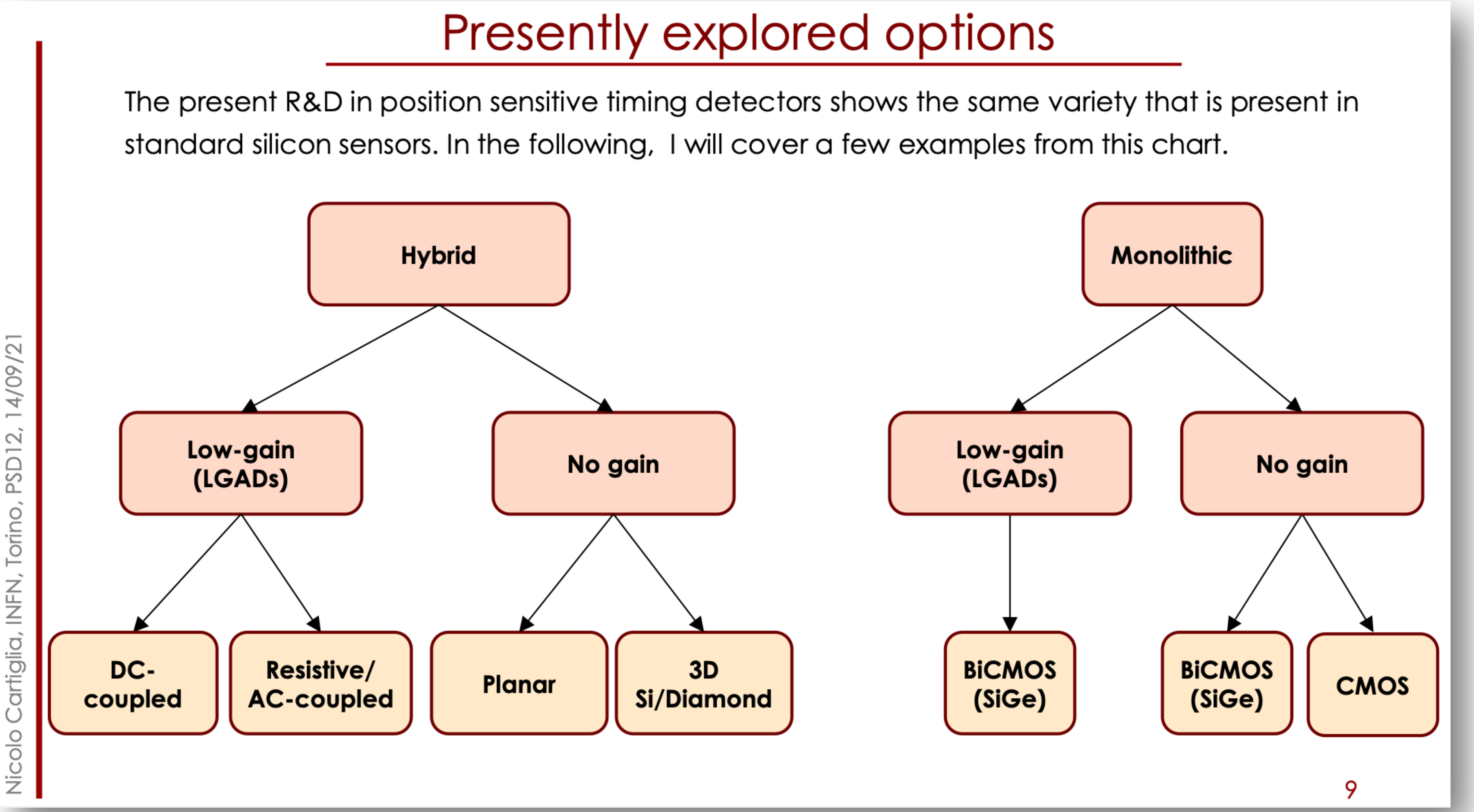
Technologies



https://indico.cern.ch/event/797047/contributions/3638198/attachments/2308674/3928223/Position_sensitive_timing.pdf

Technologies

- AC-LGADs
  - **Characterization of BNL and HPK AC-LGAD sensors with a 120 GeV proton beam (R. Heller et al.)**
    - https://arxiv.org/abs/2201.07772
    - *"We present a world's first demonstration of silicon sensors in a test beam that simultaneously achieve better than **5–10 µm position** and **30 ps time resolution**."*

Name Unit	Pitch µm	Primary signal amp. mV	Position res. µm	Time res. ps
BNL 2020	100	101 ± 10	≤6	29 ± 1
BNL 2021 Narrow	100	104 ± 10	≤9	32 ± 1
BNL 2021 Medium	150	136 ± 13	≤11	30 ± 1
BNL 2021 Wide	200	144 ± 14	≤9	33 ± 1
HPK C–2	500	128 ± 12	22 ± 1	30 ± 1
HPK B–2	500	95 ± 10	24 ± 1	27 ± 1

Technologies

- Monolithics (https://arxiv.org/pdf/2404.12885)

Prepared for submission to JINST

Testbeam results of irradiated SiGe BiCMOS monolithic silicon pixel detector without internal gain layer

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[b] *CERN, CH-1211 Geneva 23, Switzerland*
[c] *IHP — Leibniz-Institut für innovative Mikroelektronik, Im Technologiepark 25, Frankfurt (Oder), Germany*
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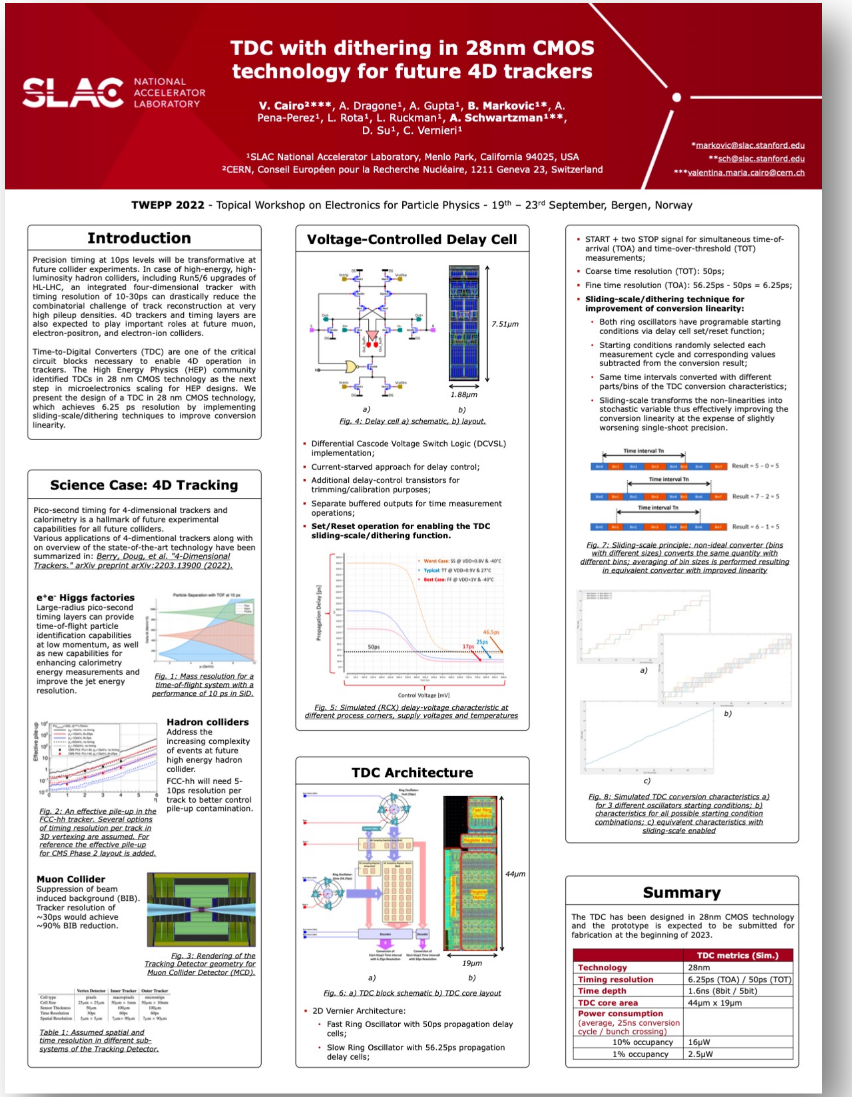
Abstract: Samples of the monolithic silicon pixel ASIC prototype produced in 2022 within the framework of the Horizon 2020 MONOLITH ERC Advanced project were irradiated with 70 MeV protons up to a fluence of 1×10^{16} n_{eq}/cm^2, and then tested using a beam of 120 GeV/c pions. The ASIC contains a matrix of 100 μm pitch hexagonal pixels, read out by low noise and very fast frontend electronics produced in a 130 nm SiGe BiCMOS technology process. The dependence on the proton fluence of the efficiency and the time resolution of this prototype was measured with the frontend electronics operated at a power density between 0.13 and 0.9 W/cm^2. The testbeam data show that the detection efficiency of 99.96% measured at sensor bias voltage of 200 V before irradiation becomes 96.2% after a fluence of 1×10^{16} n_{eq}/cm^2. An increase of the sensor bias voltage to 300 V provides an efficiency to 99.7% at that proton fluence. The timing resolution of 20 ps measured before irradiation rises for a proton fluence of 1×10^{16} n_{eq}/cm^2 to 53 and 45 ps at HV = 200 and 300 V, respectively.

[1] Corresponding author.

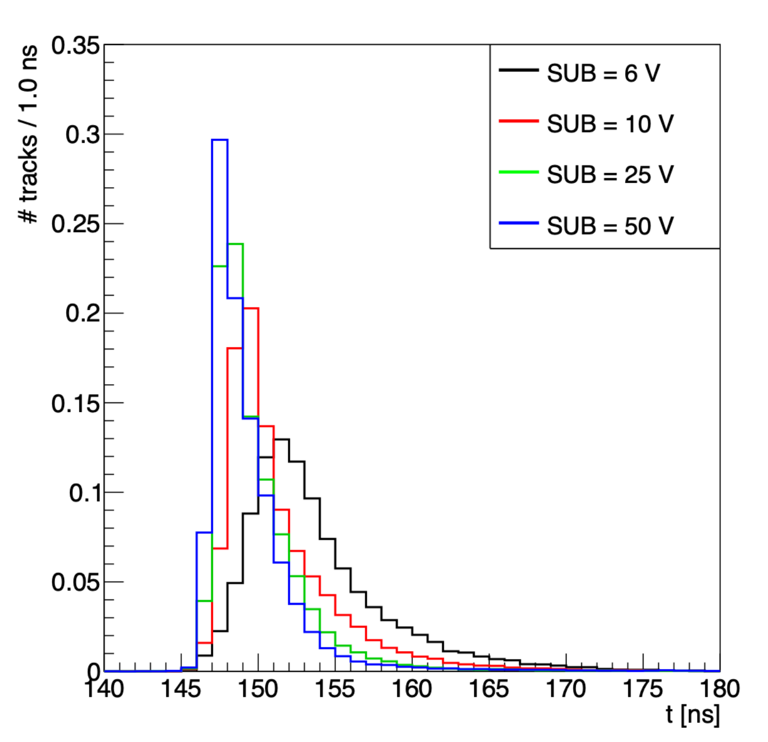
Technologies

- **TDC studies**, see [1, 2]



Technologies

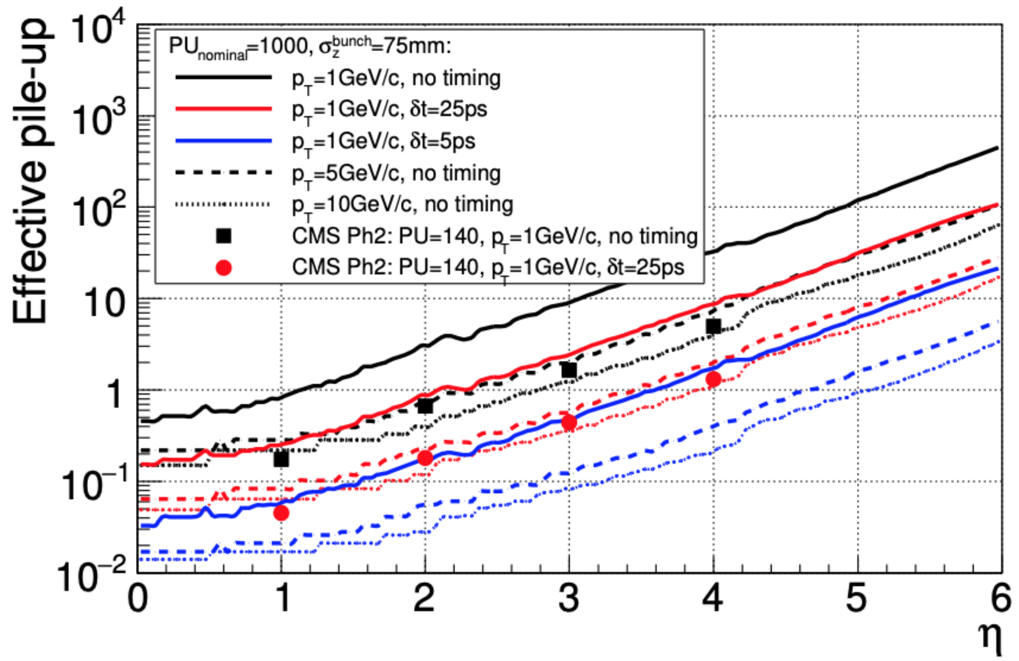
- MALTA
  https://twiki.cern.ch/twiki/bin/viewauth/Atlas/MaltaApprovedPlots#Time_resolution



Difference in time of the fastest hit of the cluster (matched with the track in the DUT) and the time of the hit in the scintillator (σPMT ≈ 1 ns not subtracted) for a MALTA non-irradiated sample Czochralski silicon with no modification (STD) versus substrate bias. Measurements were done with low energy electrons from Sr-90 β-decay

Future Collider Requirements

Effective pile-up is defined as the number of pile-up vertices which effectively lead to a confusing assignment of low p_T tracks to the original primary vertex



- Studies on primary vertexing at the FCC-hh demonstrate that 2D vertexing with an extreme timing resolution of 5 10 ps per track is essential to keep the levels of effective pile-up under control at large pseudorapidities (|η| > 3) which would otherwise reach level of tens or hundreds leading to large merging effects in vertex reconstruction and large confusion in vertex selection.

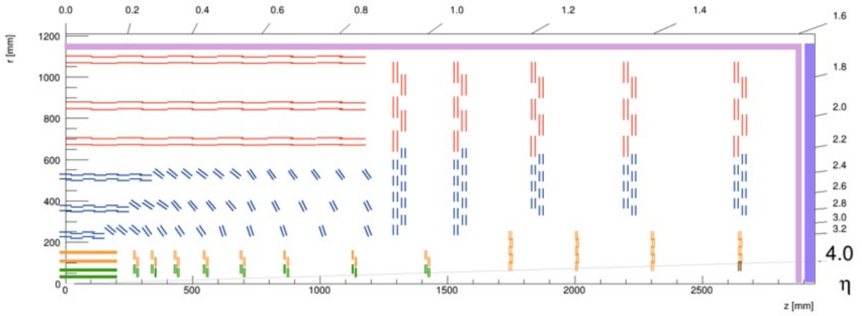
- Also: 30 times (600 times) more radiation compared to HL-LHC (LHC), making none of the existing technologies suitable

Technologies

Timing in tracking detectors

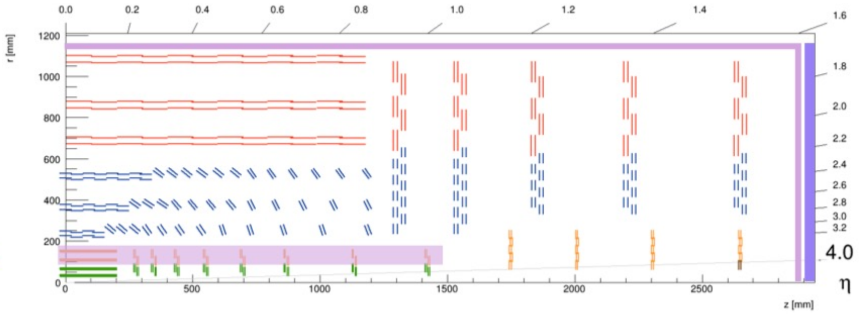
CMS installing the timing layer outside the tracker:

- **σ_t = 30-60ps**
- **approved for the Phase 2 upgrade** (→2027)
- **1 time measurement per track**
  + 1 more forward hit in HGCAL



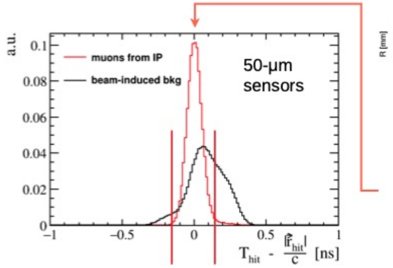
CMS might add 1-2 more timing layers closer to the IP

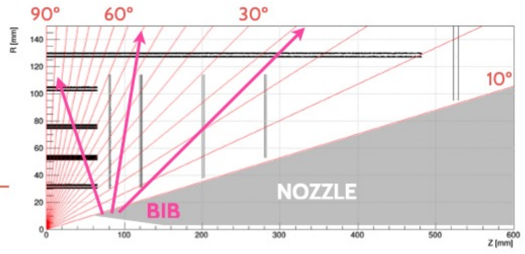
- **σ_t = 30-60ps ?** ← depends on technology progress
  granularity + radiation hardness + material budget constraints
- **conceptually possible for the Phase 3 upgrade** (→2036)
  Inner Tracker will have to be replaced to sustain the radiation damage throughout the HL-LHC program



Full tracker made of fast Si considered for Muon Collider

- **σ_t = 20-50ps** ← planning for the distant future (→2035+)
- **primarily used for TOF-based rejection of BIB hits**
  readout time windows tailored to sensor positions
- **much more is possible with this timing information**





https://indico.cern.ch/event/1048211/contributions/4413728/attachments/2274142/3862895/2021_06_30_bartosik_v0.pdf

AC-Coupled LGADs

AC-Coupled Low Gain Avalance Diodes (AC-LGADs) [1, 2] are a new generation of silicon devices optimized for high-precision 4D tracking and conceived for experiments at future colliders. They are n-in-p sensors based on the LGAD technology with two additional key features (Figure 1): the AC-coupling of the read-out, occurring through a dielectric layer, and a continuous resistive n^+ implant. Given the presence of the resistive n^+ layer, AC-LGADs are called Resistive Silicon Detectors (RSD). RSD devices are provided with one continuous gain layer, and the read-out segmentation is obtained simply by the position of the AC pads; therefore, this design allows to reach 100% fill-factor.

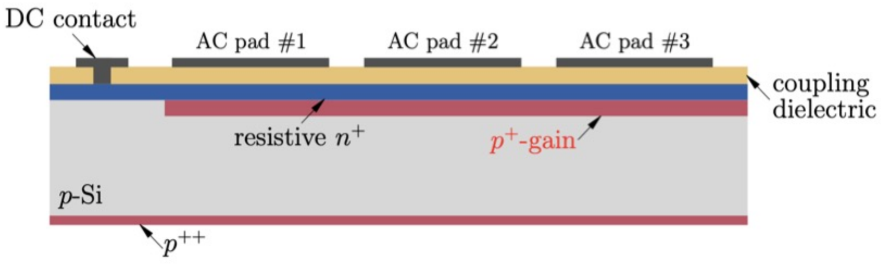


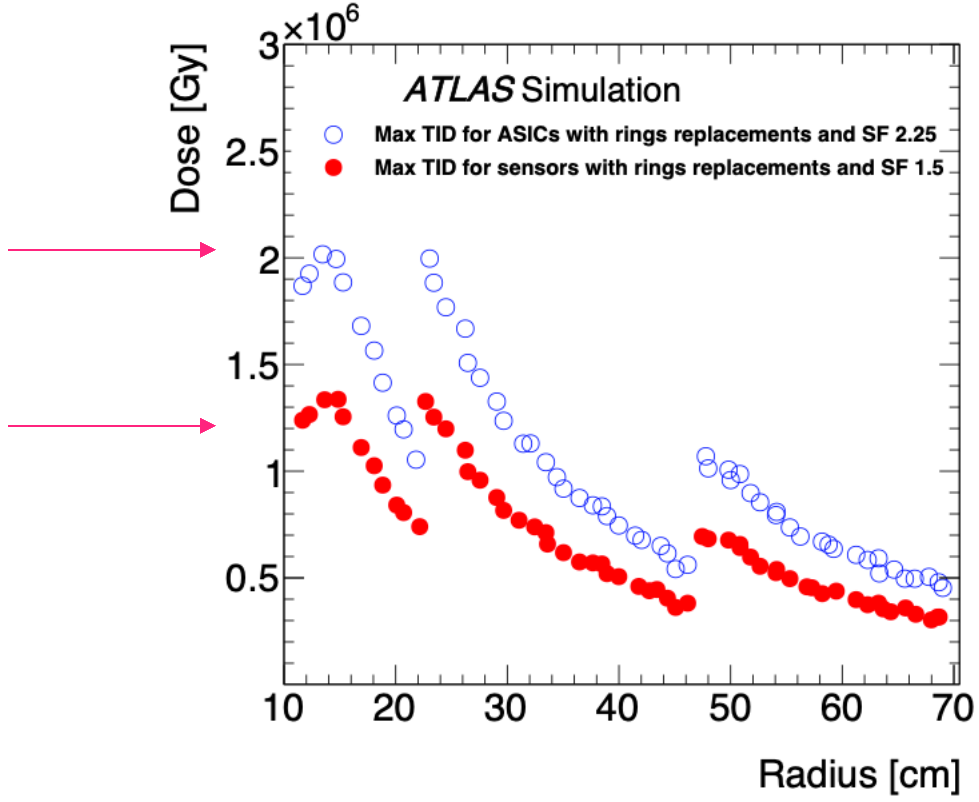
Figure 1: Cross-section of RSDs internal structure: their properties are based on the combination of a resistive n^+ layer and a coupling dielectric oxide, allowing a local AC-coupling.

The remarkable feature of this design is that it leads naturally to signal sharing among pads. Internal signal sharing, in combination with internal gain, opens a new avenue for high precision tracking without relying only

https://arxiv.org/pdf/2007.09528.pdf

HGTD Rad. dose

HGTD TDR, fig. 2.15



This leads to a total safety factor of 1.5 for the sensors that are most sensitive to the particle fluence, and 2.25 for the electronics which are more sensitive to the TID. After applying these, the detector would need to withstand 8.3 × 1015 neq cm−2 and **7.5 MGy** (if the vessel is not replaced)

How to boost analysis sensitivity in HL-LHC?

VBF H->inv extensively studied at the time of the HGTD TDR, results still valid!

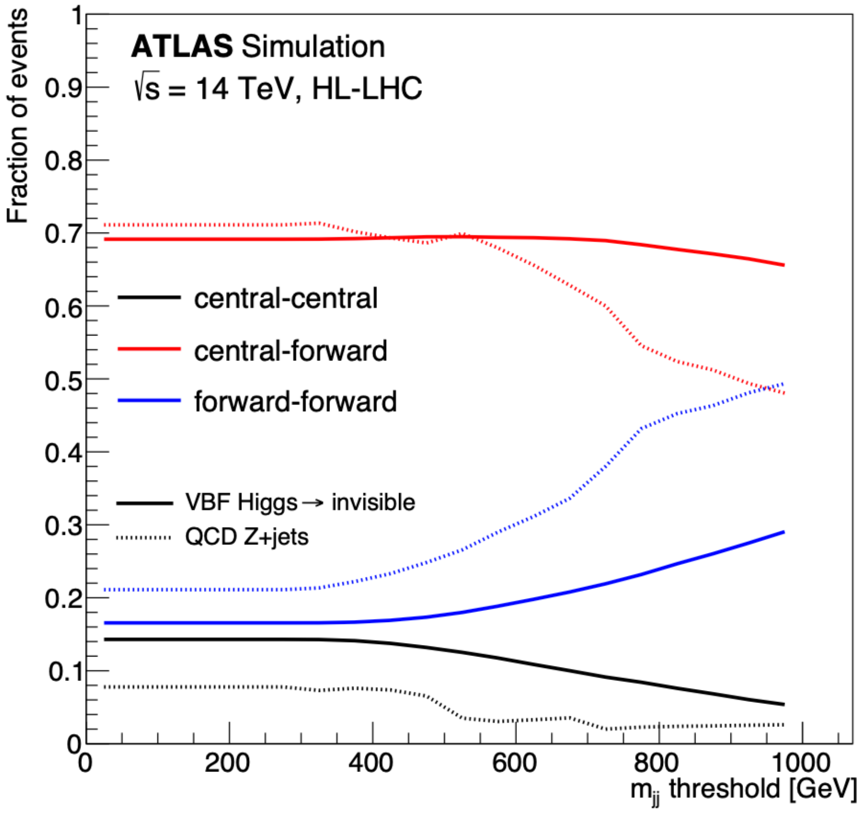
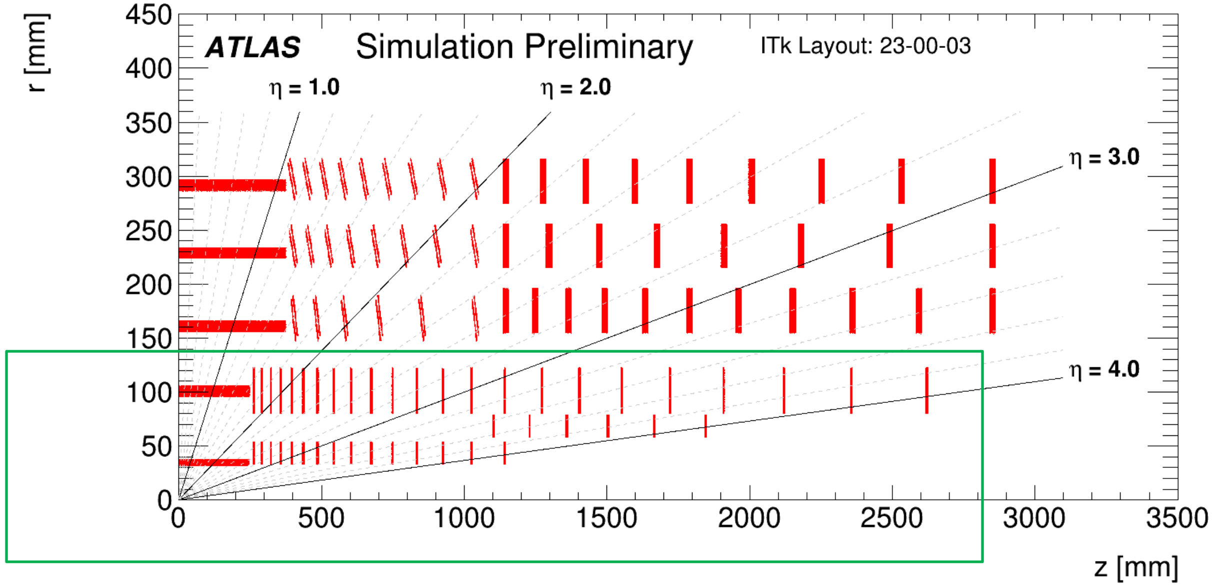
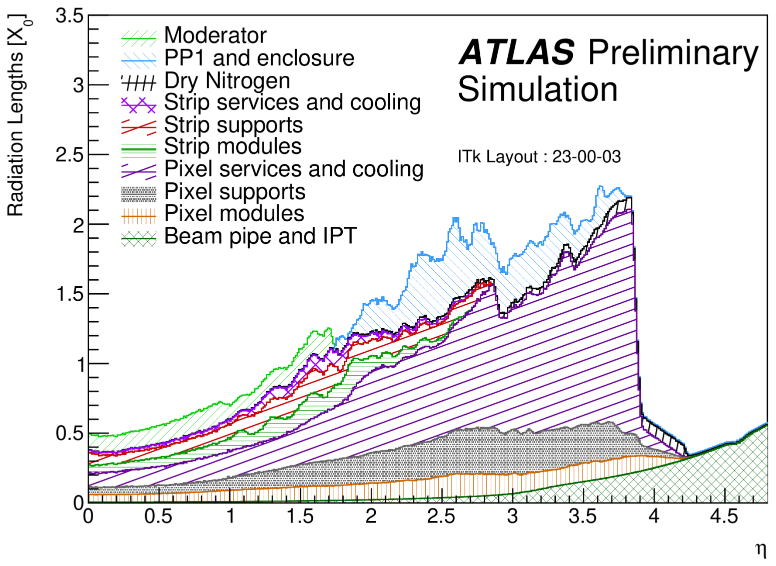


Figure 3.24: The dashed line shows the fraction of signal VBF $H \rightarrow$ invisible and Z+jet background events as a function of a m_{jj} threshold after a loose VBF preselection. Forward jets are those with $|\eta| > 2.4$. Solid (dotted) lines correspond to VBF $H \rightarrow$ invisible (Z+jet) events. The fraction of central-central, central-forward, and forward-forward events are shown in black, red, and blue colors respectively.

DETECTOR LAYOUT STUDIES

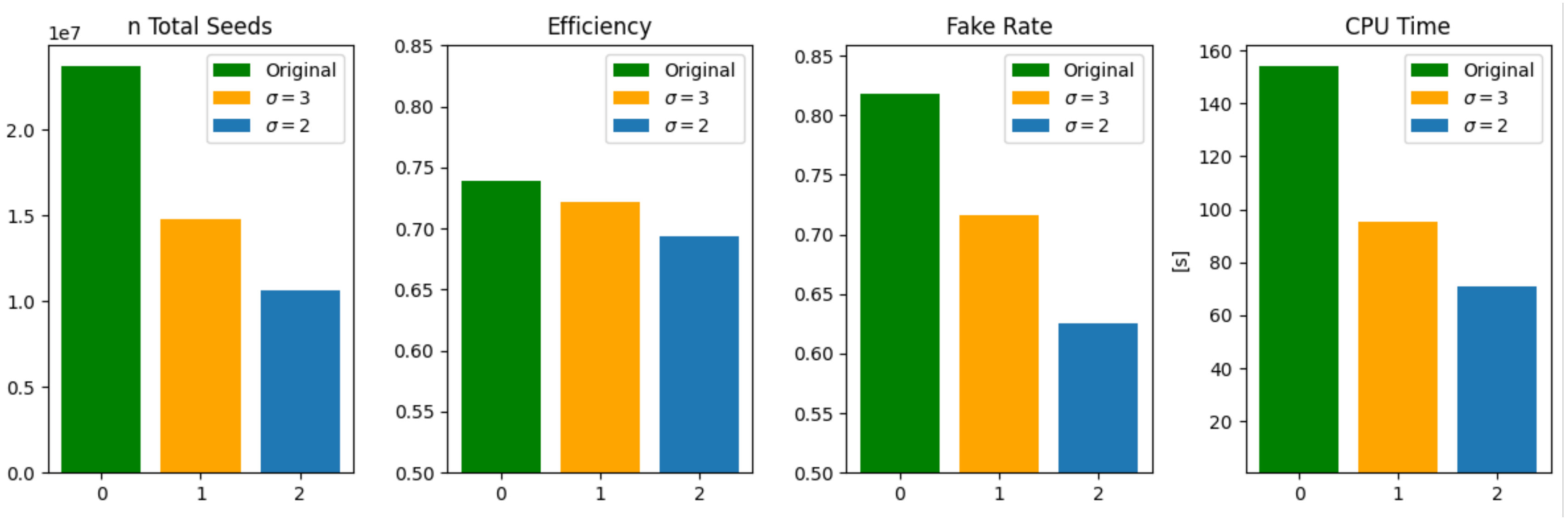
A change in tracking technology would imply changes in material budget due to different power, cooling, data transmission etc and would require a re-evaluation of the optimal detector layout





OTHER ACTIVITIES

CERN has initiated studies on seeding to evaluate **CPU** gains with former student Steven Bos, and plans to continue
https://cds.cern.ch/record/2879352



OTHER ACTIVITIES

DIPS algorithm with timing:
https://cds.cern.ch/record/2908429

Vertex Grid seeder optimization
https://indico.cern.ch/event/1435014/contributions/6038249/attachments/2902452/5090667/Poster2024-Nicollin.pdf

RADIATION

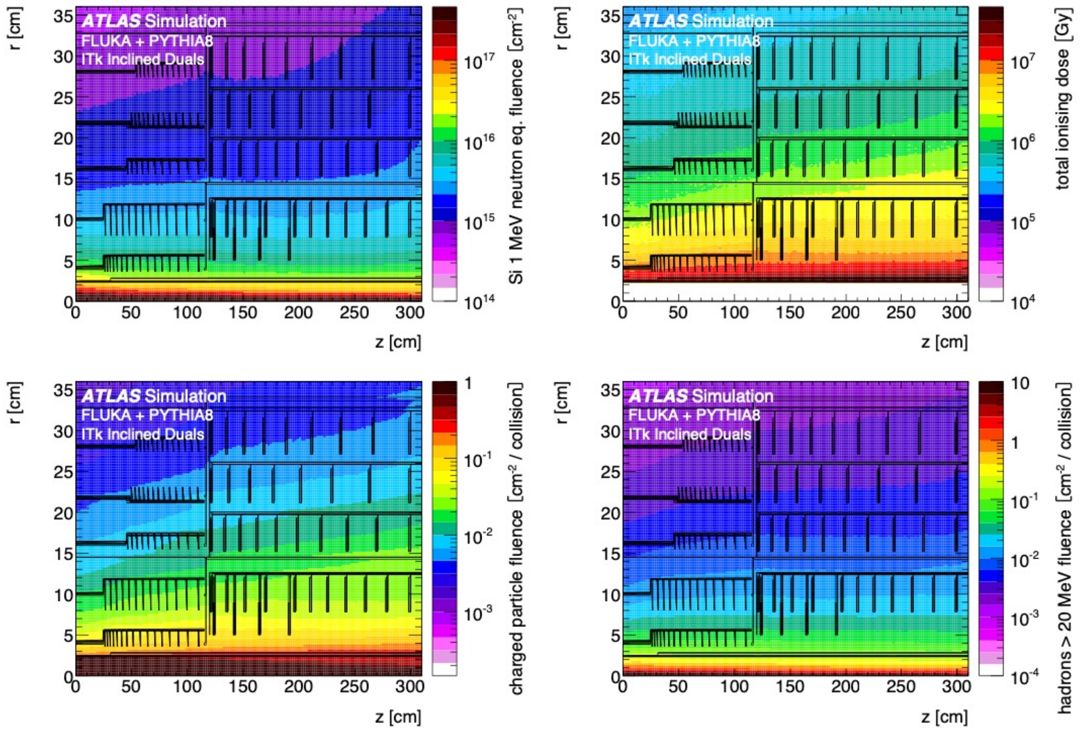
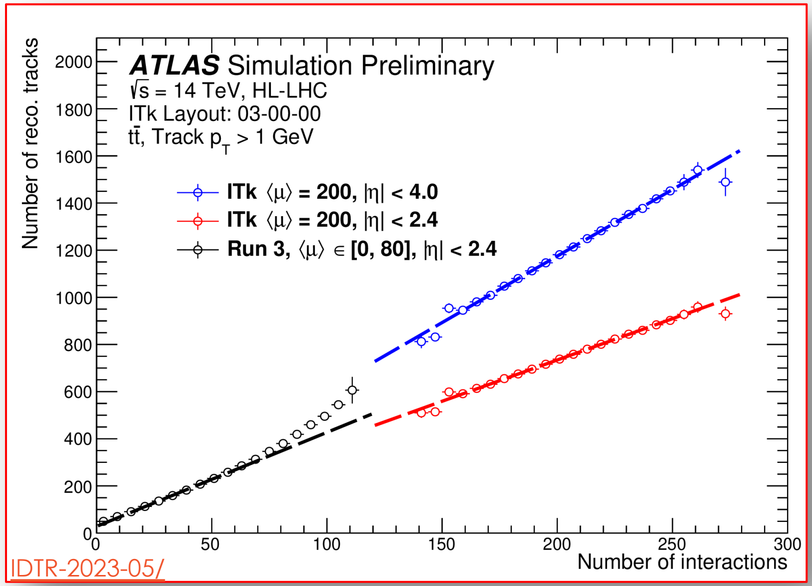


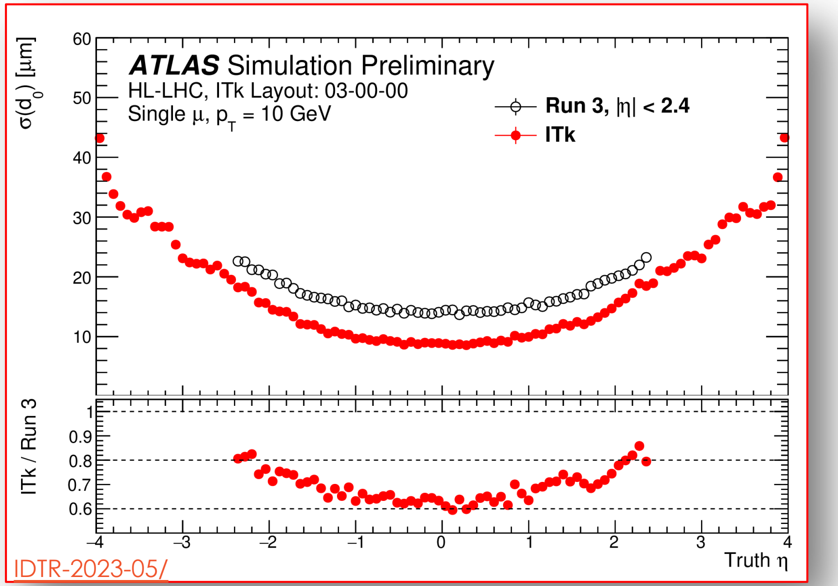
Figure 2.18: The fluence and dose distributions for the Pixel Detector. **Top left**: 1 MeV neutron equivalent fluence. **Top right**: Total ionising dose. **Bottom left**: Charged particle fluence. **Bottom right**: Hadron fluence for energies greater than 20 MeV. The top two lots are normalised to 4000 fb^{-1}. No safety factors are taken into account for this Figure.

HL-LHC TRACKING

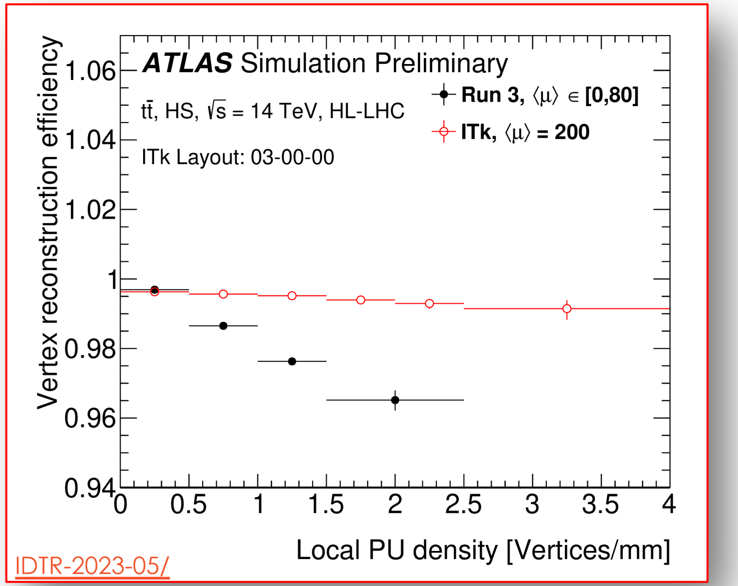
A detector designed to be pile-up robust, and algorthms designed to leverage such features



The lower the fake rate, the better the CPU and storage usage



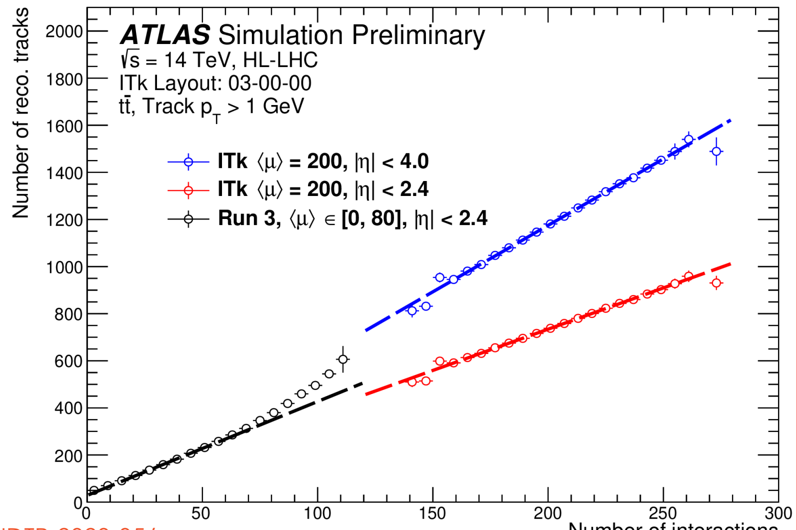
Improved IP resolution



More PU-robust vertexing

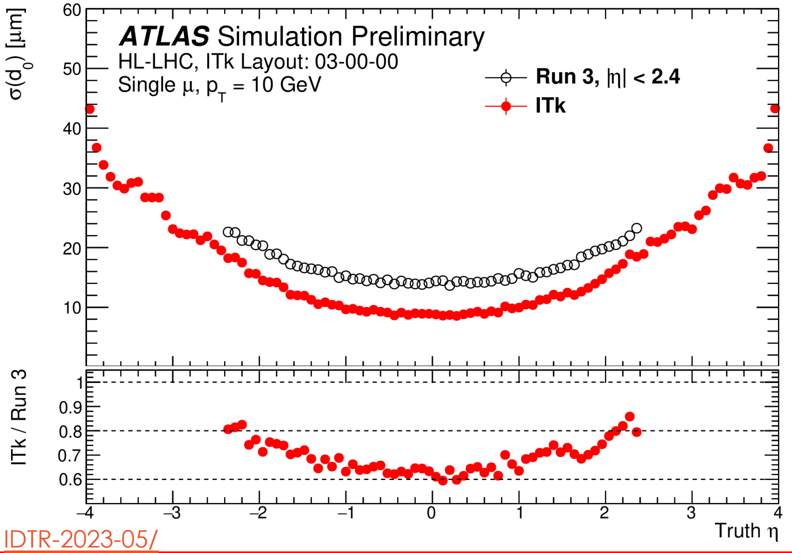
HL-LHC TRACKING

A detector designed to be pile-up robust, and algorthms designed to leverage such features



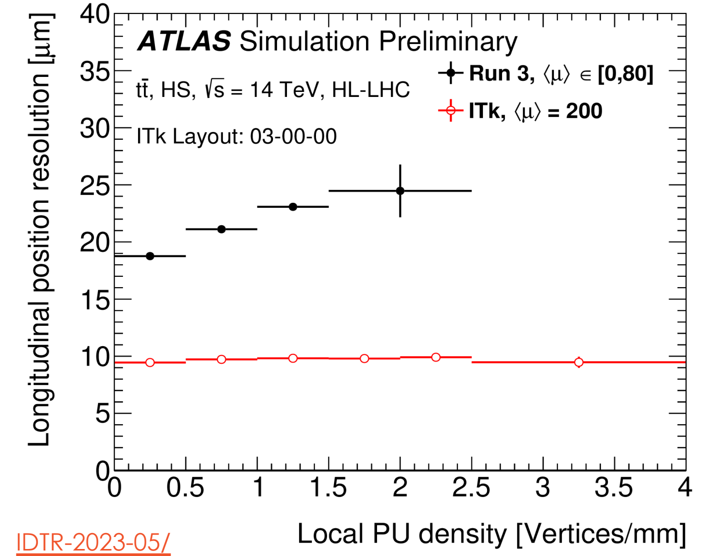
IDTR-2023-05/

The lower the fake rate, the better the CPU and storage usage



IDTR-2023-05/

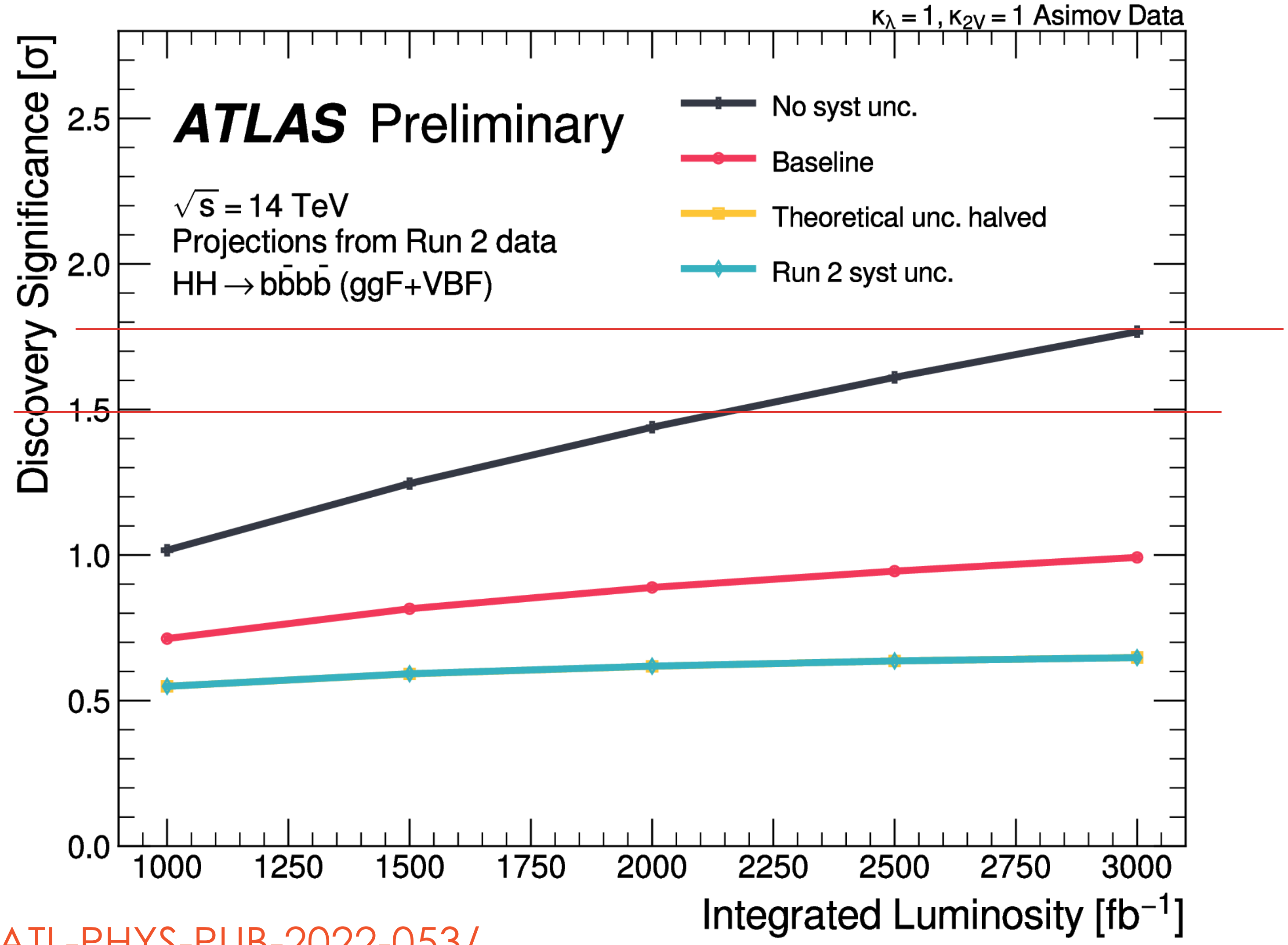
Improved IP resolution



IDTR-2023-05/

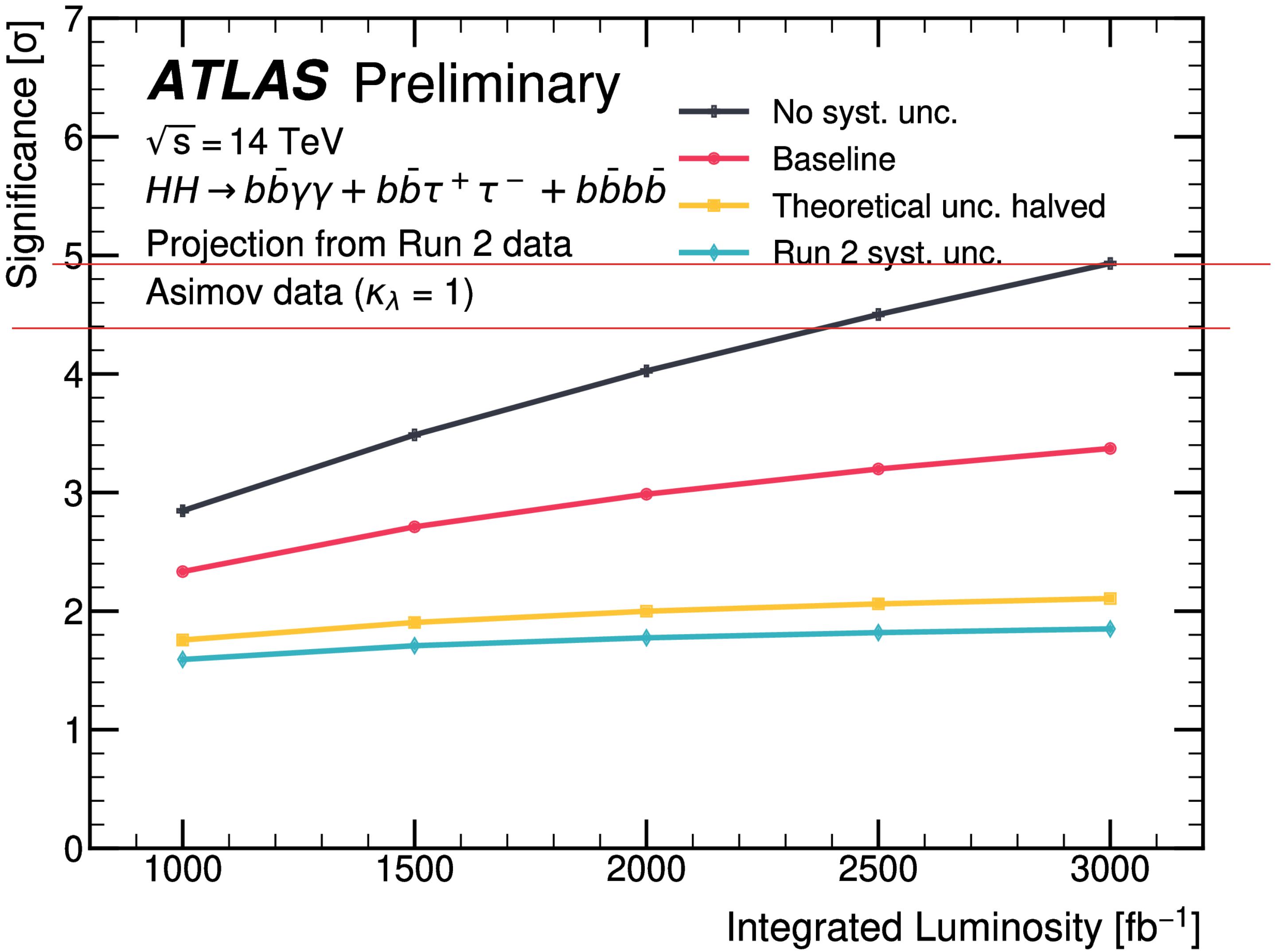
More PU-robust vertexing

HOW DOES HH LOOK IN HL-LHC?



ATL-PHYS-PUB-2022-053/

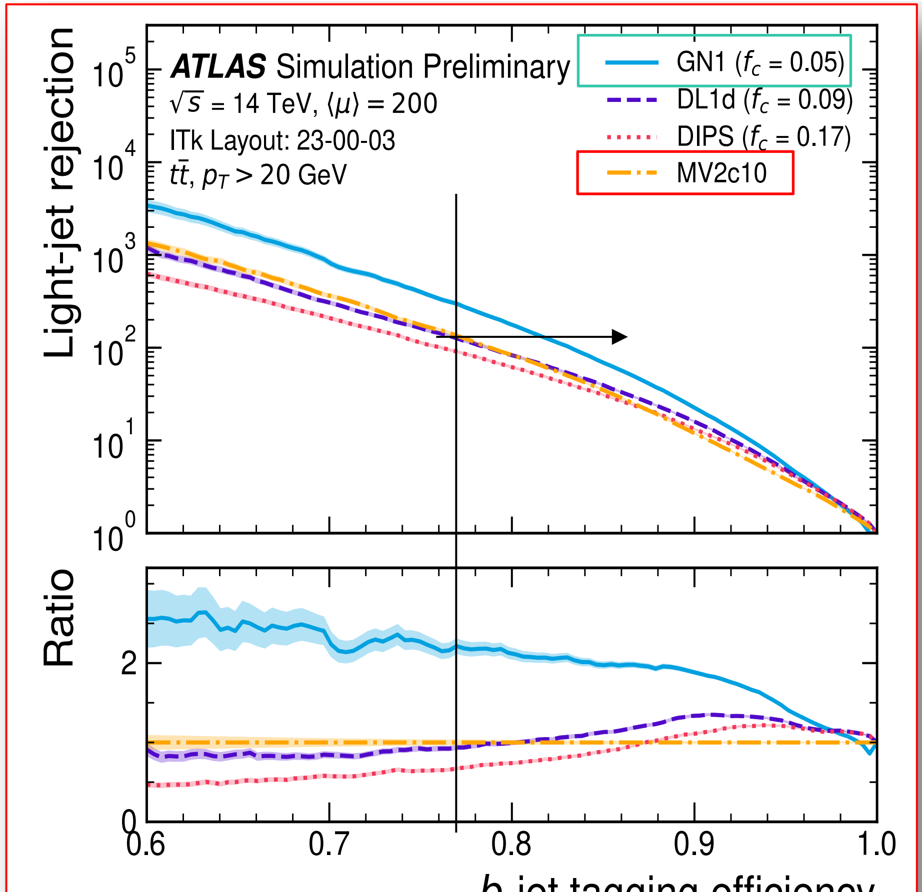
HOW DOES HH LOOK IN HL-LHC?



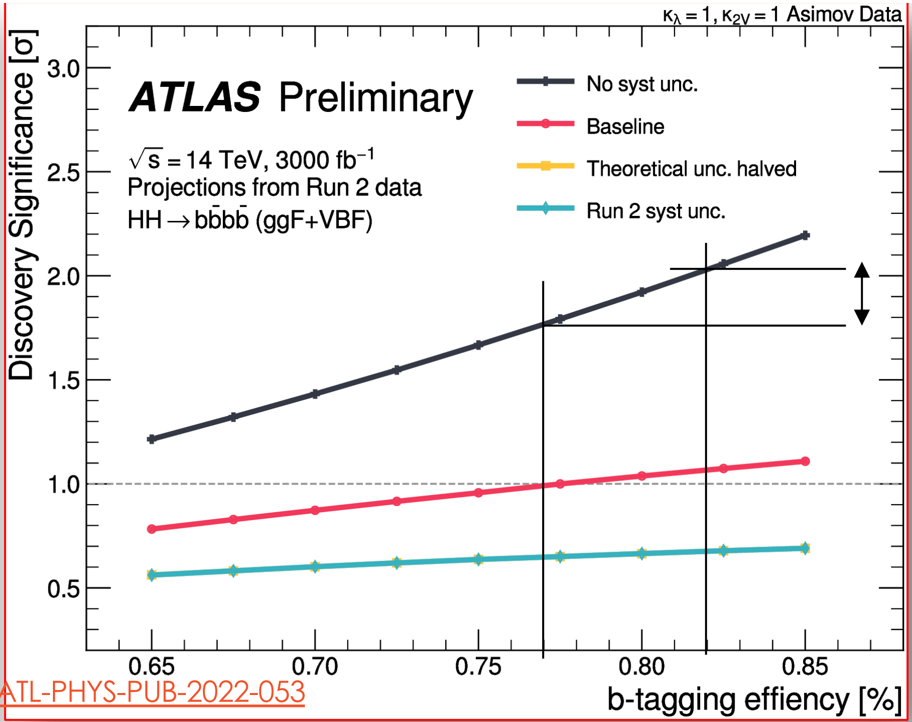
ATL-PHYS-PUB-2022-053/

HOW DOES HH LOOK IN HL-LHC?

Modern flavor tagging algorithms based on **Graph Neural Networks** fully exploit the potential of the ITk → large sensitivity gains for HH!



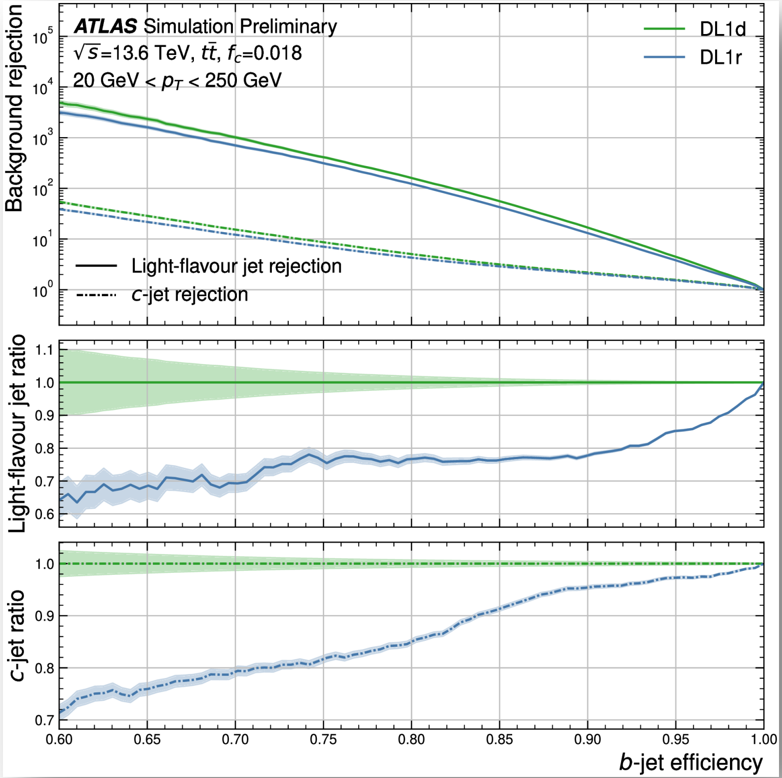
ATL-PHYS-PUB-2022-047/



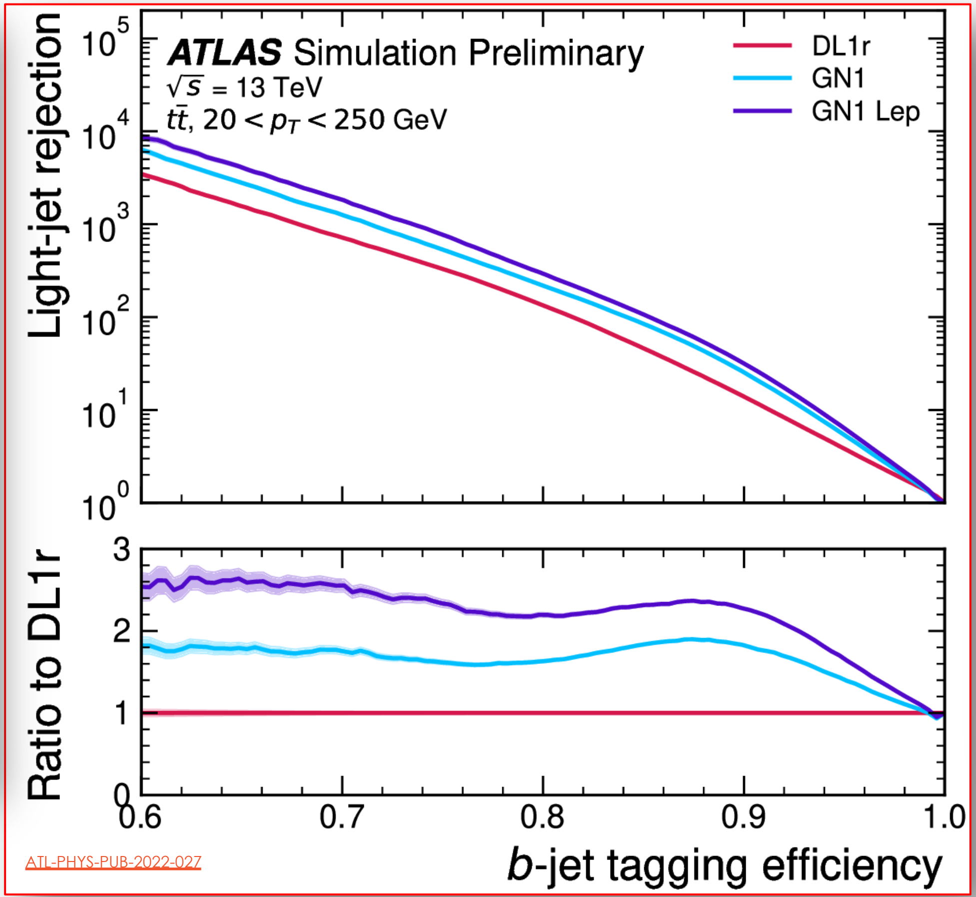
ATL-PHYS-PUB-2022-053

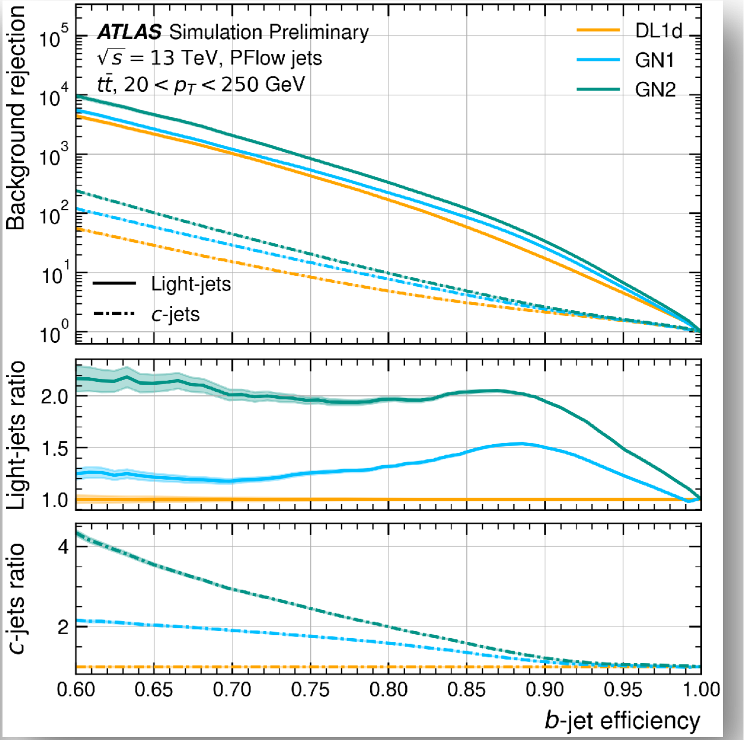
+ 5% efficiency for the same mistag rate → + 0.3 σ sensitivity gain for $HH \to b\bar{b}b\bar{b}$

RUN 3 b-TAGGING



FTAG-2022-004/





FTAG-2023-01/