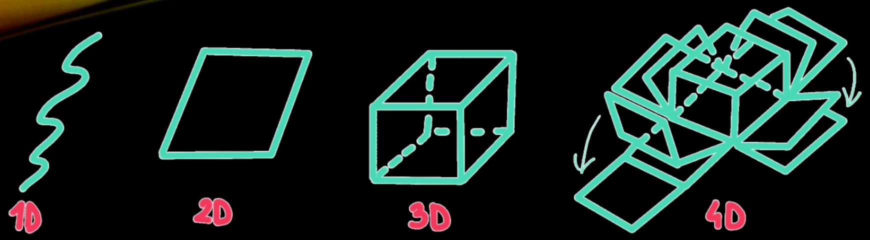


4D Reconstruction needs and challenges

Mini workshop: Trig & Reco Input for European Strategy for Particle Physics 2025

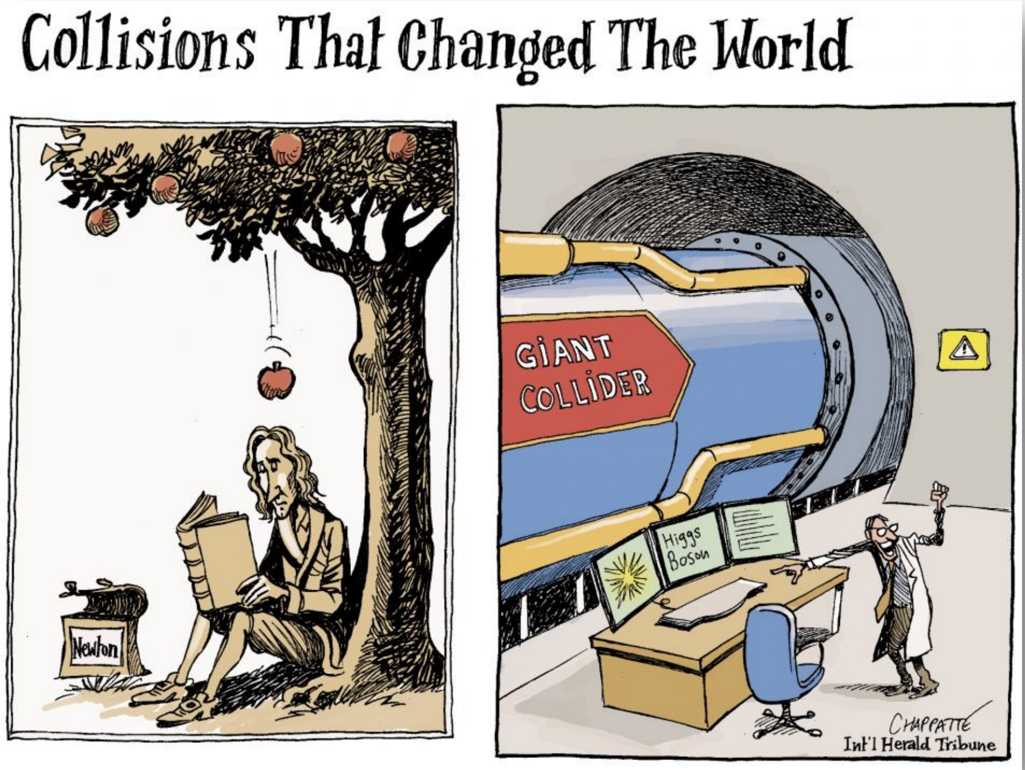
Wednesday 27 Nov 2024, 14:00 → 16:05 Europe/Zurich

ZOOM

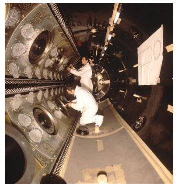
Description Discussion around HEP Software Foundation input to European Strategy for Particle Physics Update 2025 on *common challenges* in HEP for **Software Trigger and Reconstruction**.

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

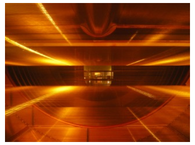
AT THE *HEART* OF COLLIDER PHYSICS: CHALLENGES AND BREAKTHROUGHS



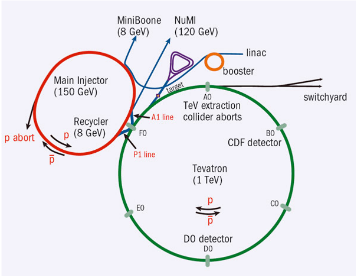
The weak neutral currents and the *bubble chamber* era

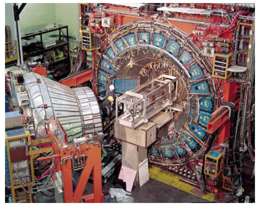


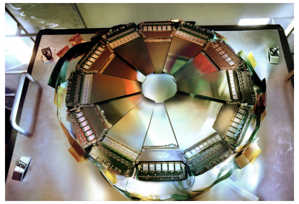
The W,Z bosons and the *drift chamber* era



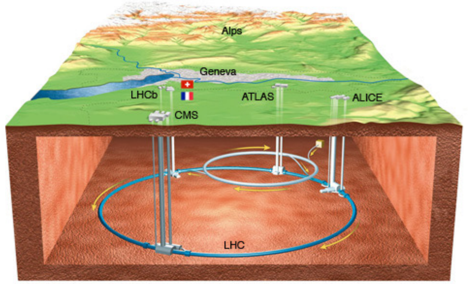
The top quark and the *silicon strip* era

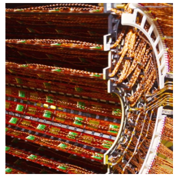


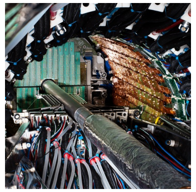




The Higgs boson (and more!) and the *silicon pixel* era

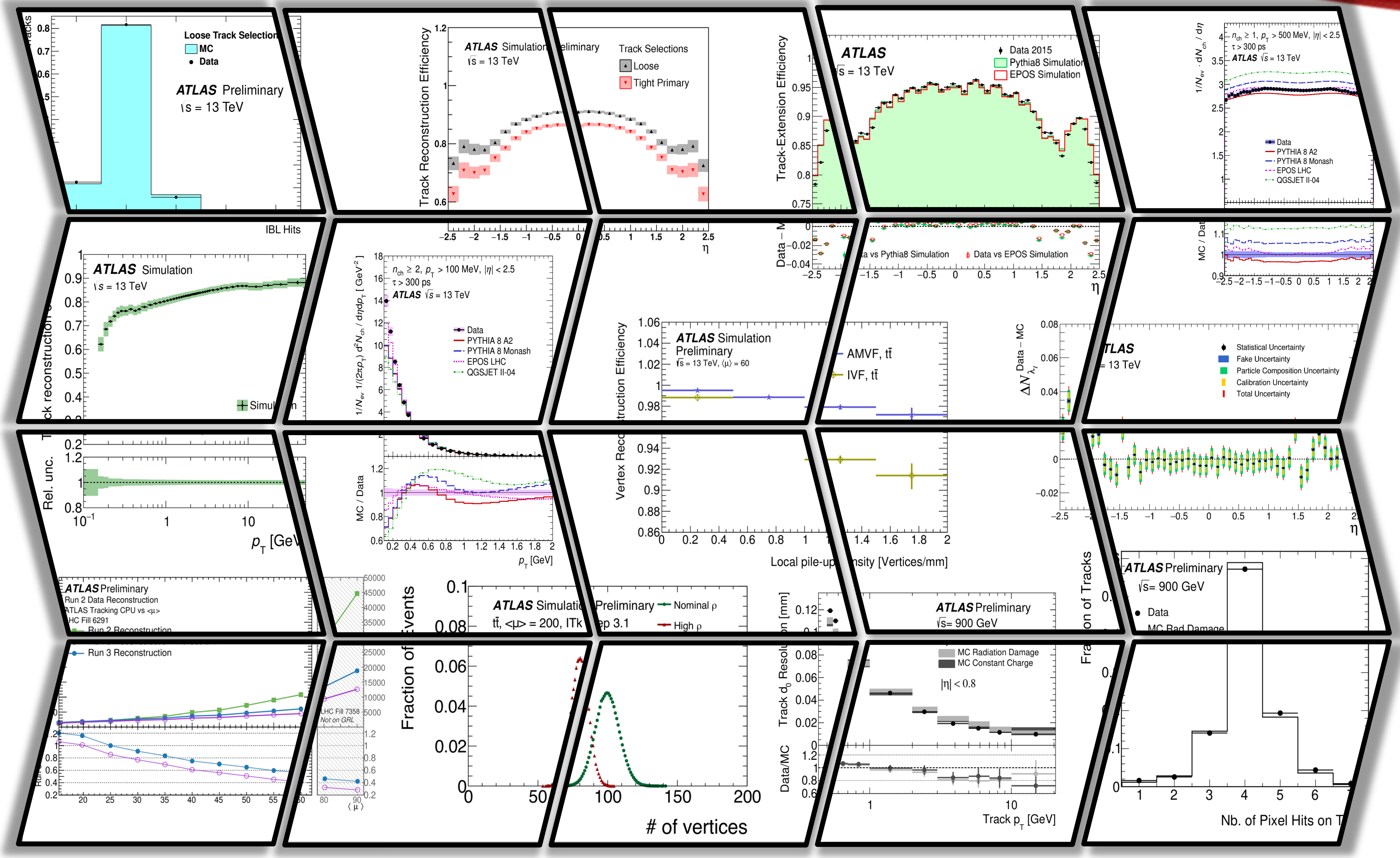






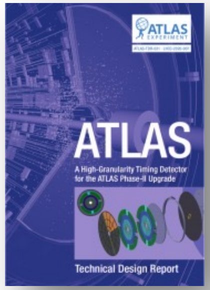
TRACKS AND VERTICES

The building blocks of physics events at colliders



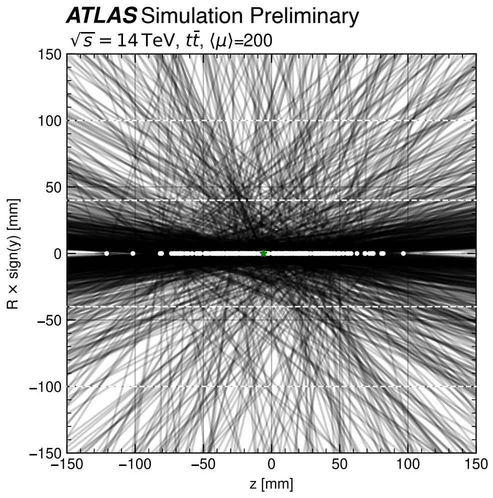
UNFOLDING A NEW DIMENSION

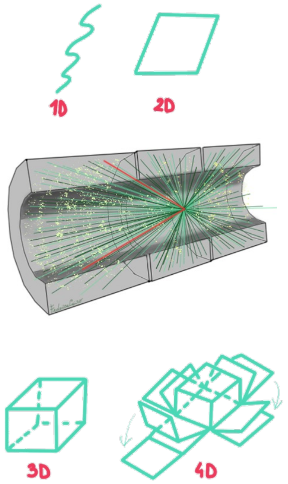
- Addition of timing layers to HEP detectors growing area of interest

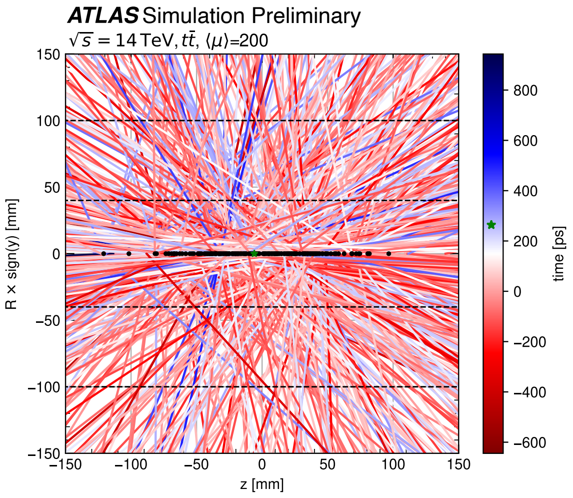


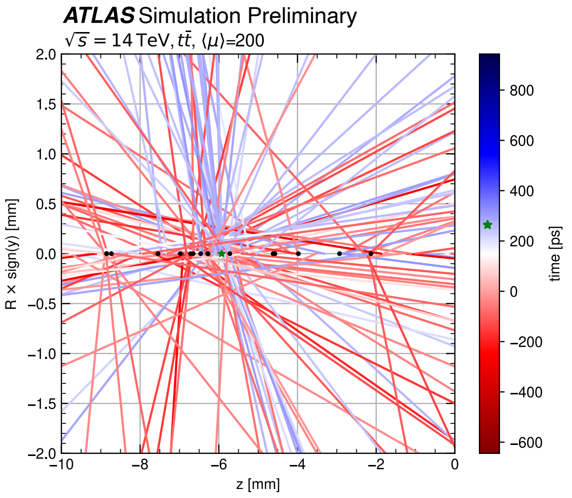
- **Next step in advancing technologies are real 4-dimensional silicon trackers** (resolution of O($10\ \mu m$) & O($10\ ps$))

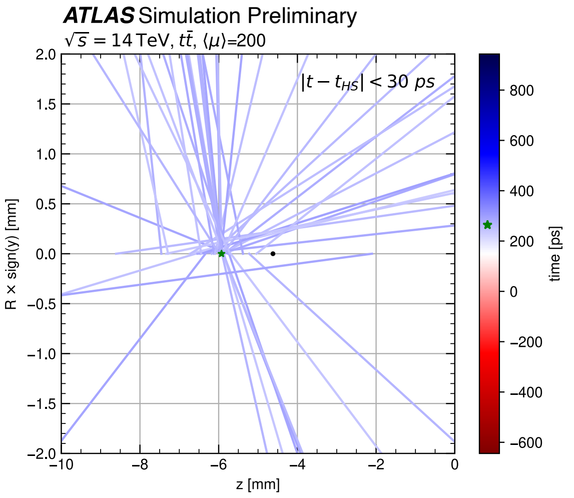
- **Excellent opportunity during HL-LHC and, in particular, for future energy frontier trackers**







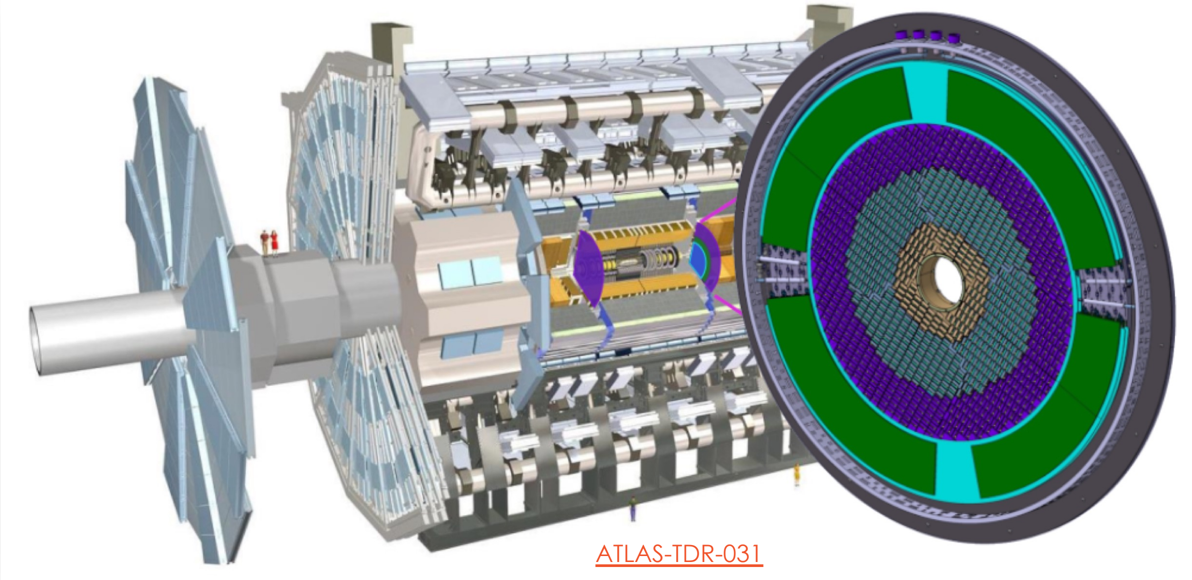




ATL-PHYS-PUB-2023-023

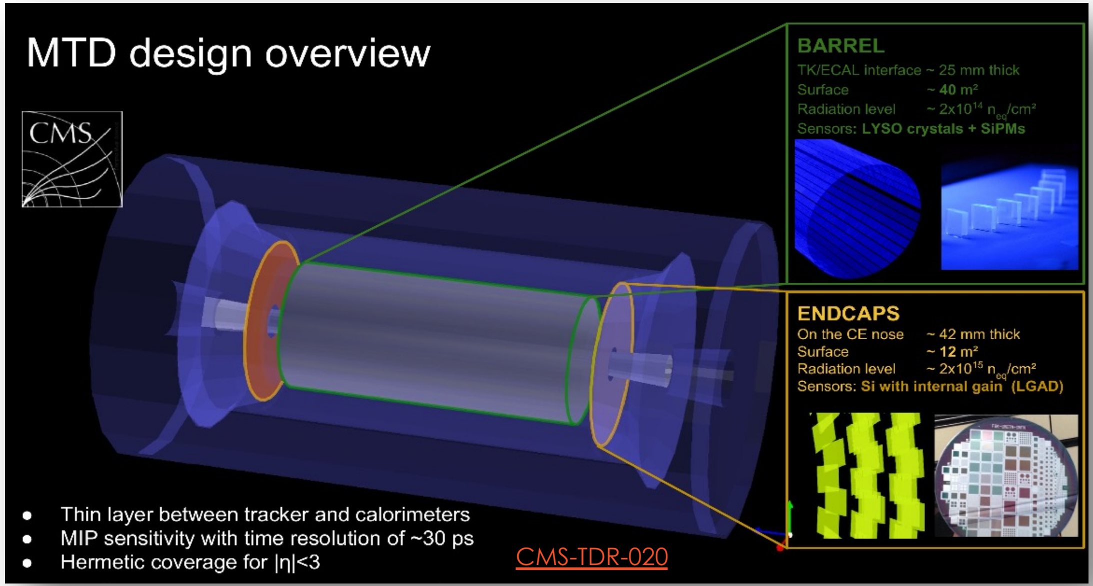
TIMING LAYERS AT HL-LHC

ATLAS High Granularity Timing Detector



ATLAS-TDR-031

CMS MIP Timing Detector



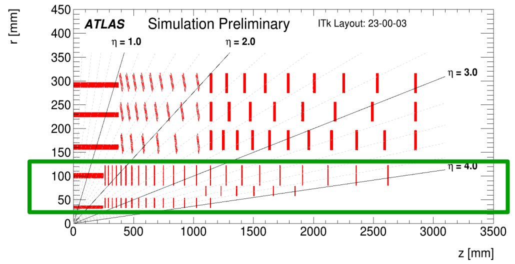
CMS-TDR-020

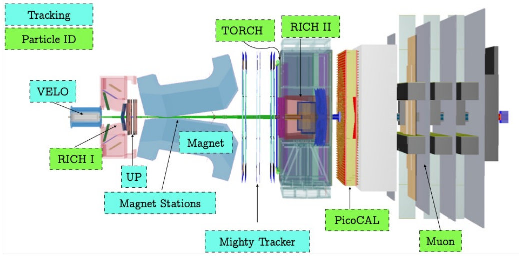
LGADs to cover the
forward pseudorapidity region $2.4 < |\eta| < 4.0$

LGADs and crystals for hermetic coverage
up to $|\eta| < 3.0$

4D TRACKING USE-CASES

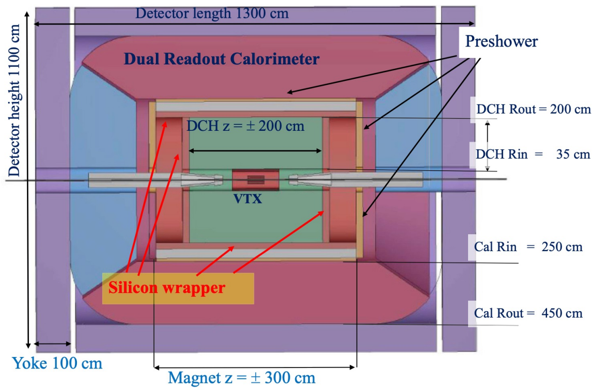
HL-LHC Beyond Run 4





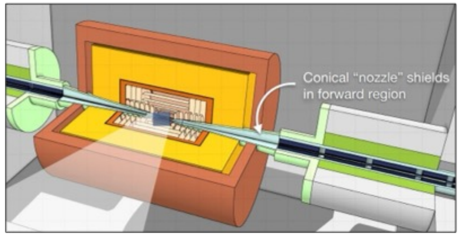
4D tracking for replacements/upgrades?

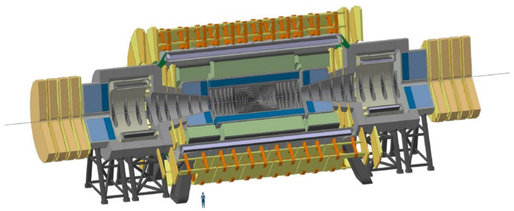
Electron-positron colliders



Timing layers for flavour tagging, particle ID, and LLP searches

Muon collider / hadron colliders





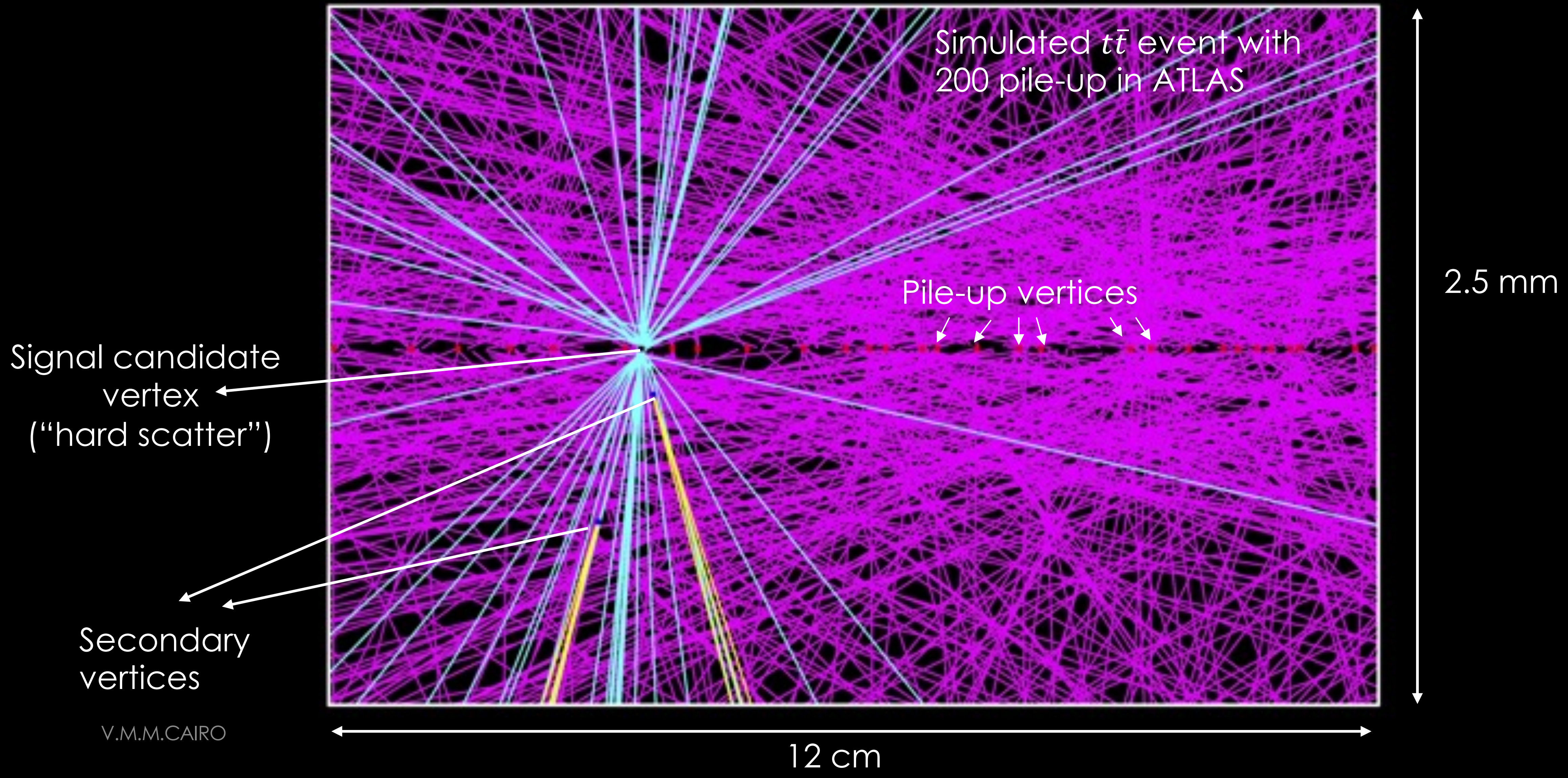
Beam-induced backgrounds (μ) and pile-up suppression (hh)

2035

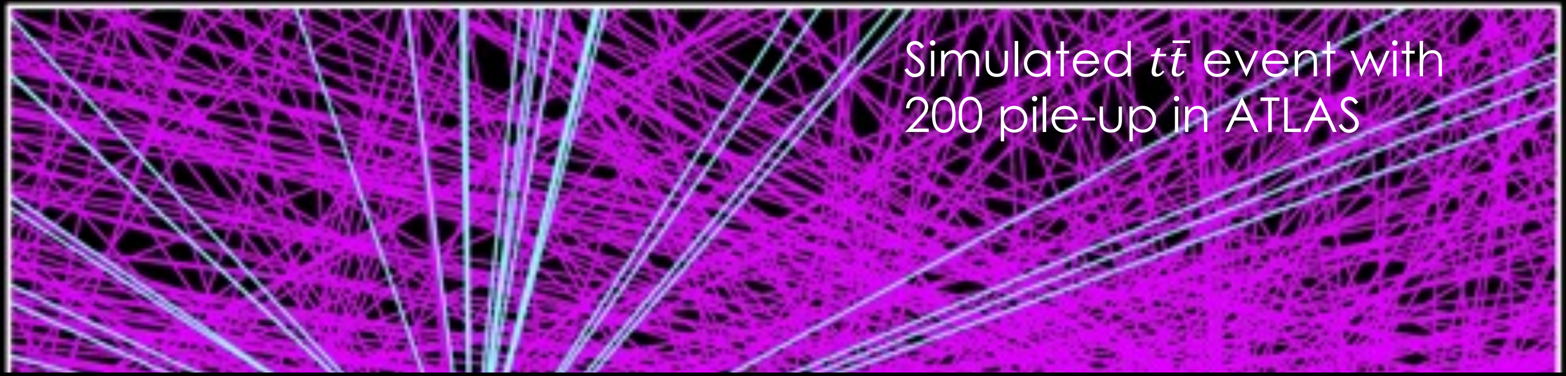
2040s

2050s and beyond

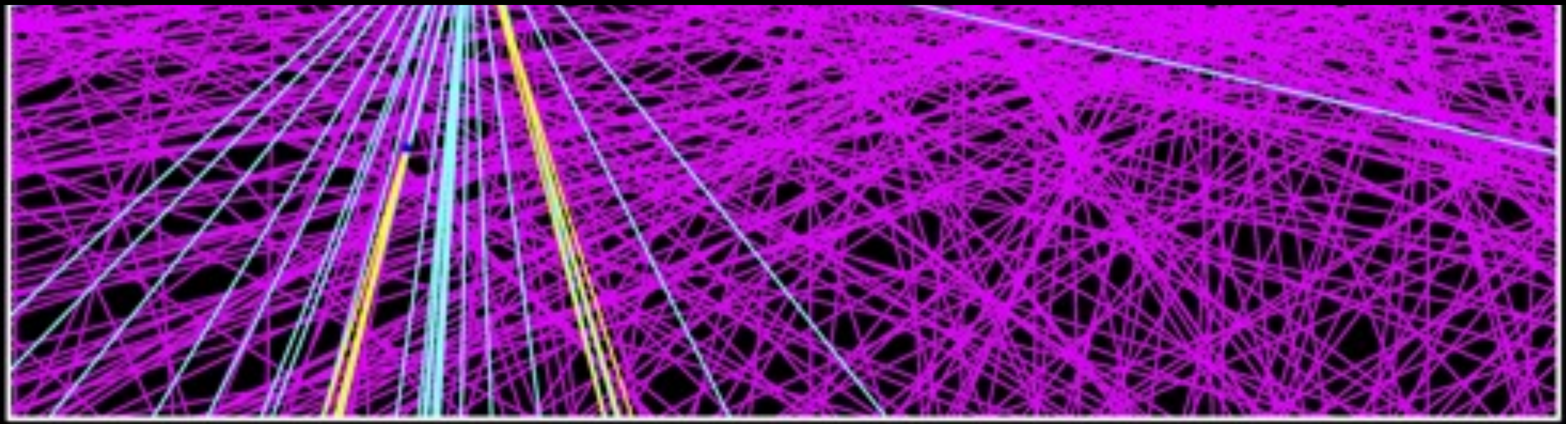
THE PILE-UP CHALLENGE @ HADRON COLLIDERS



THE PILE-UP CHALLENGE @ HADRON COLLIDERS



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…



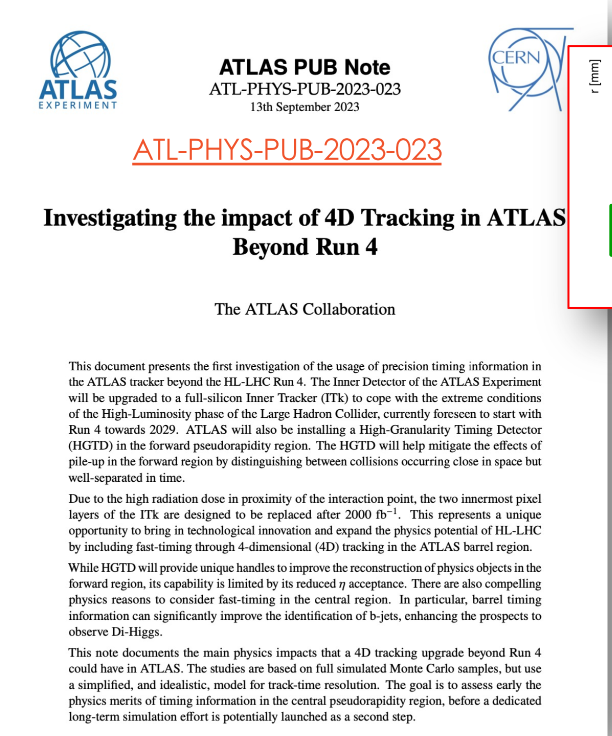
IMPACT ON EXPERIMENTAL PERFORMANCE

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

IMPACT ON EXPERIMENTAL PERFORMANCE

Improve track and vertex reconstruction
- Performance — Efficiency, purity, IP resolution, low pT tracking?
- Computing resources — Speed?

Hermetic timing coverage and vertex t_0
- Pile-up suppression
- Forward jets and leptons
- **Flavour Tagging**
- Long Lived Particles



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

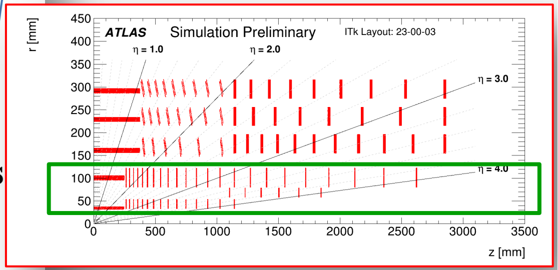
The ATLAS Collaboration

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.

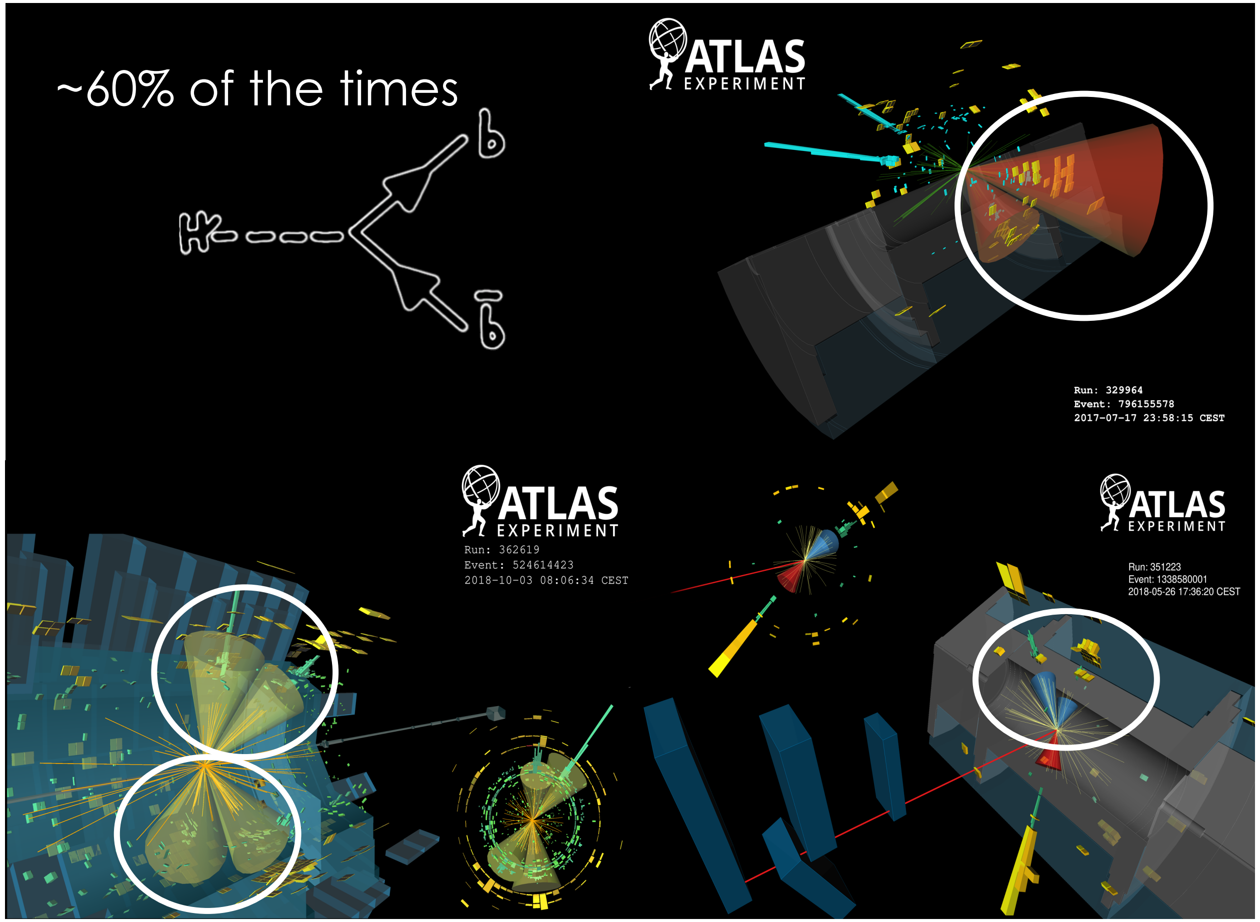
While HGTD will provide unique handles to improve the reconstruction of physics objects in the forward region, its capability is limited by its reduced η acceptance. There are also compelling physics reasons to consider fast-timing in the central region. In particular, barrel timing information can significantly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

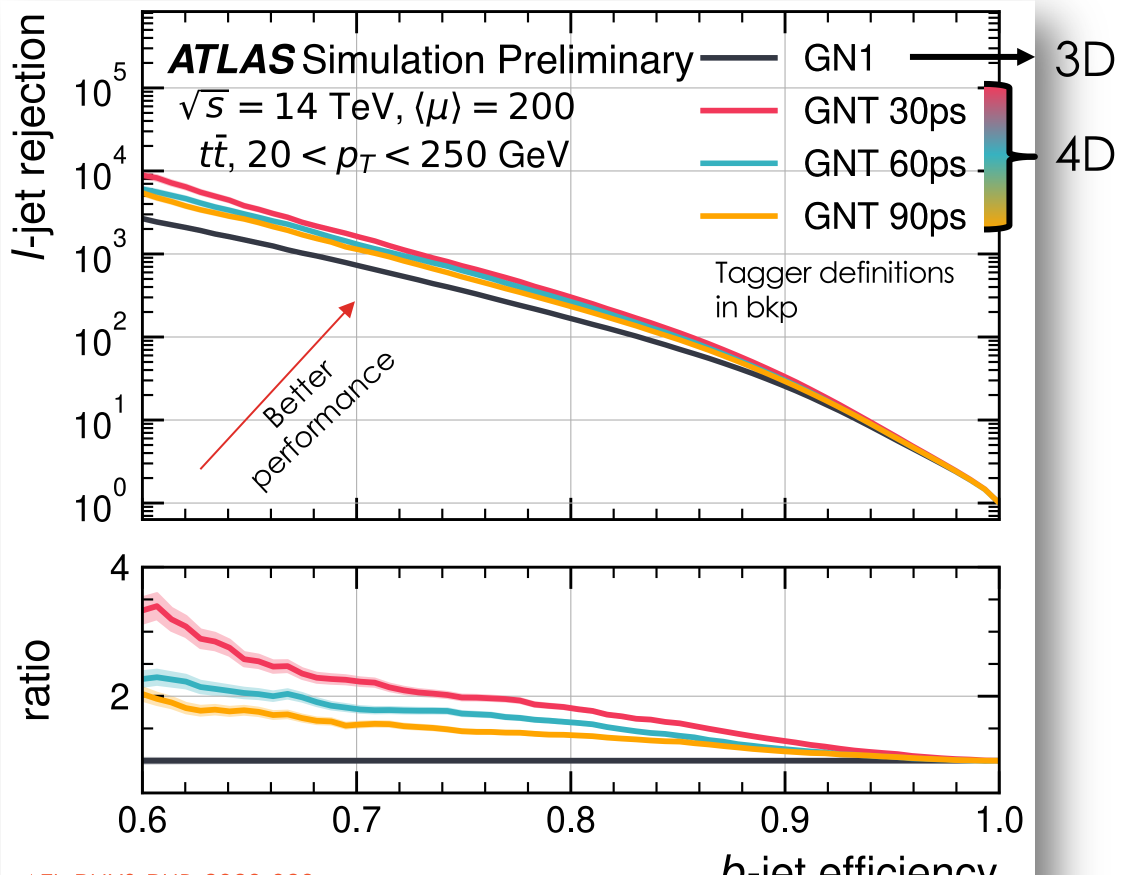
This note documents the main physics impacts that a 4D tracking upgrade beyond Run 4 could have in ATLAS. The studies are based on full simulated Monte Carlo samples, but use a simplified, and idealistic, model for track-time resolution. The goal is to assess early the physics merits of timing information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



In addition, exciting trigger applications via cluster-based btagging being explored in synergy with the **Next Generation Triggers** project (https://indico.cern.ch/event/1421629/)

4-DIMENSIONAL TRACKING & b-TAGGING

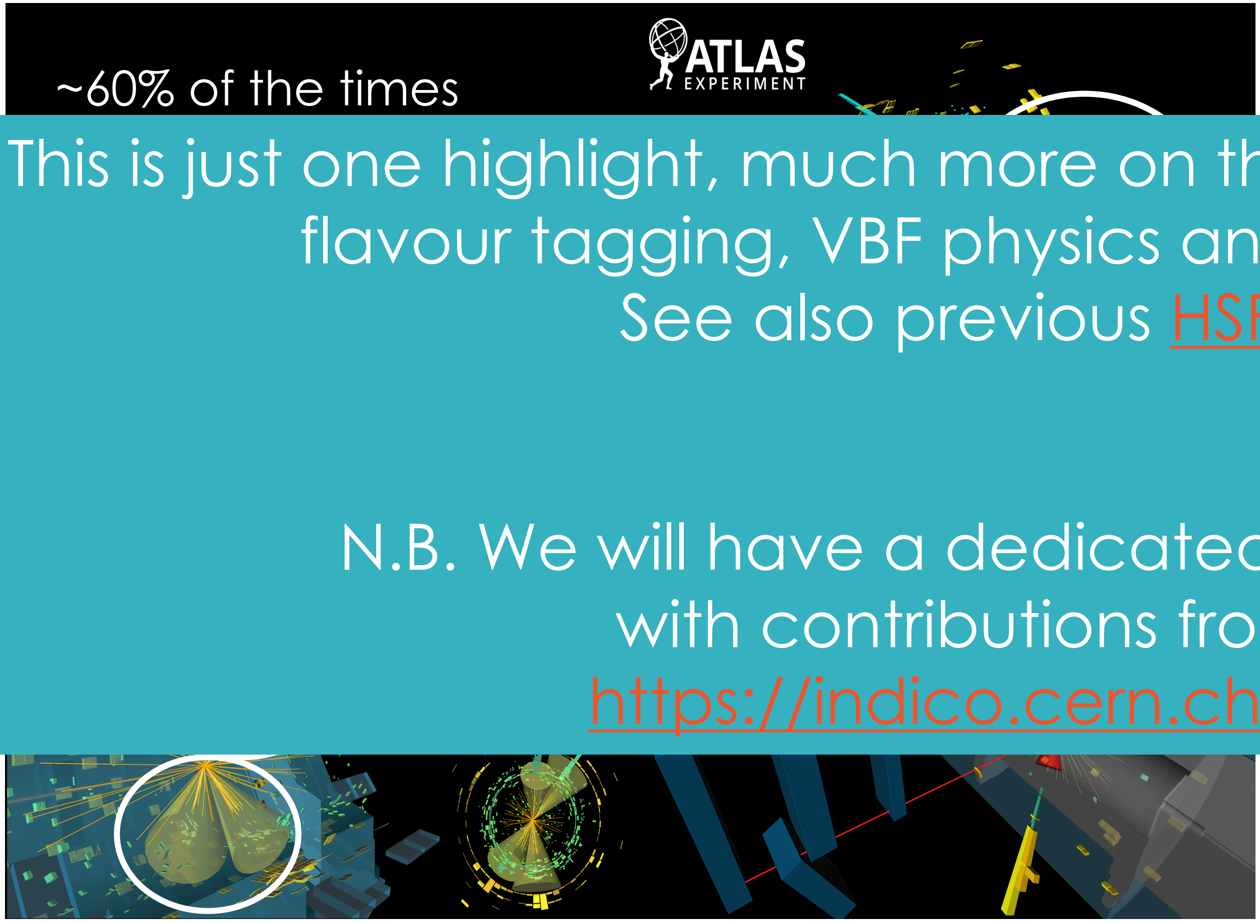


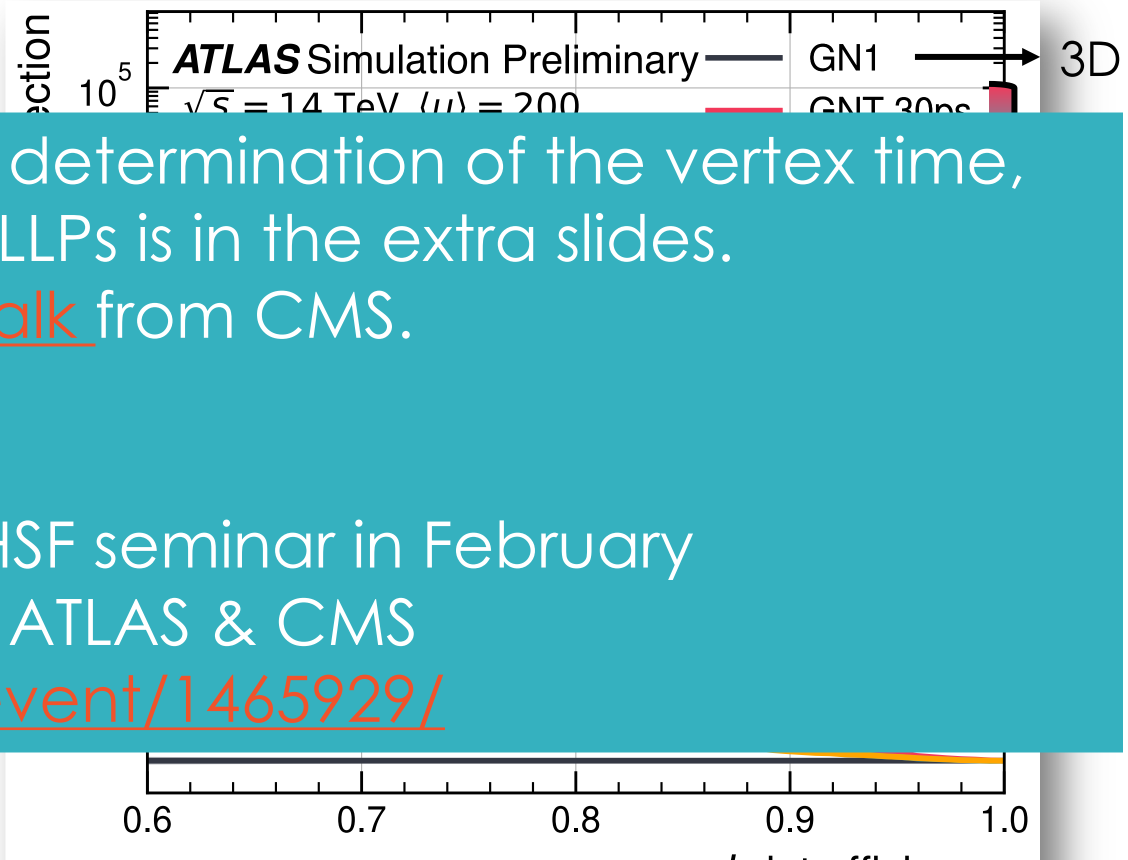


ATL-PHYS-PUB-2023-023

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

4-DIMENSIONAL TRACKING & b-TAGGING





ATL-PHYS-PUB-2023-023

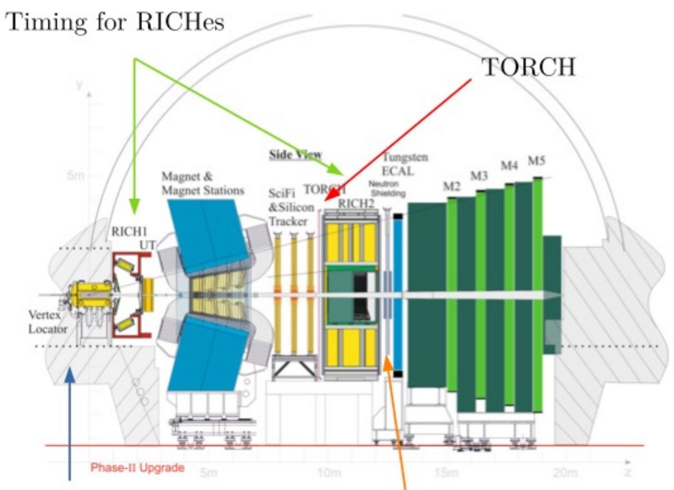
This is just one highlight, much more on the determination of the vertex time, flavour tagging, VBF physics and LLPs is in the extra slides.
See also previous HSF talk from CMS.

N.B. We will have a dedicated HSF seminar in February with contributions from ATLAS & CMS
https://indico.cern.ch/event/1465929/

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

LHCb UPGRADE II

Framework TDR, R. Quagliani's slides, T. Evans' slides



Add $\mathcal{O}(20)$ ps timing →Timing Velo

5D calorimetery →PicoCal

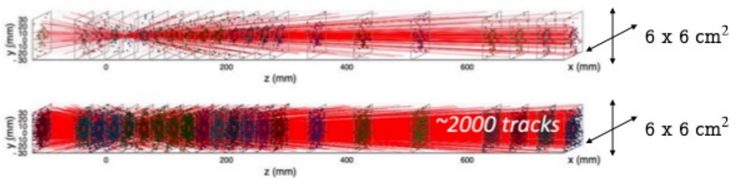
Need to reach a resolution $\mathcal{O}(10)$ ps, while dealing with

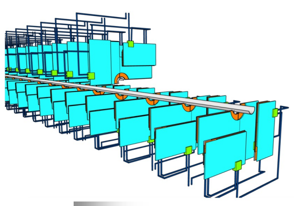
- Huge data rates (> 50Tb/s for whole detector, > 100 kHz for hottest pixels)
- Extreme radiation tolerance ($> 2 \times 10^{16} n_{eq}/\,\text{cm}^2$)

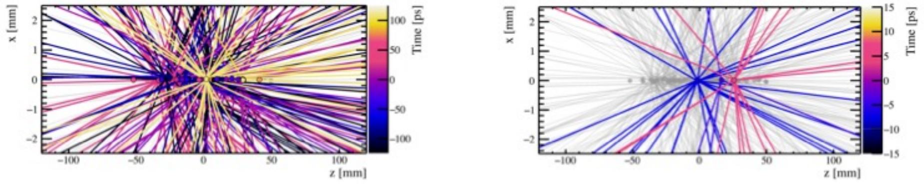
and

- Keeping excellent spatial resolution ($\sim 10\,\mu$m) $\Longrightarrow$ low material budget

- Ensure PV finding/association of tracks/displacement signatures at the core of LHCb physics program
  - Including timing information is mandatory for VELO
- Run 3 (Upgrade I):
  - pile-up ~ 5
- Upgrade II:
  - pile-up ~ 40

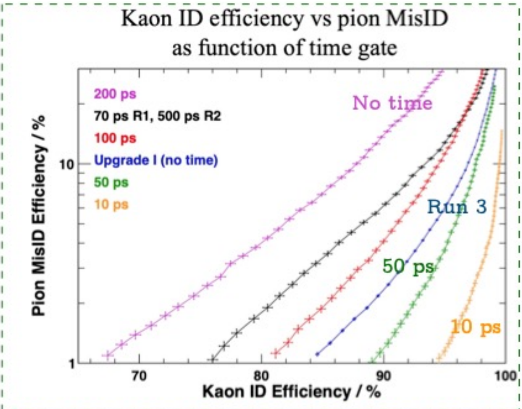


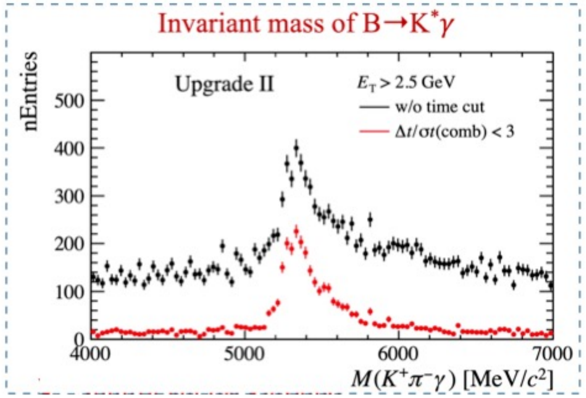




"Problem" complexity with no timing per track "Problem" complexity with 20ps/track resolution

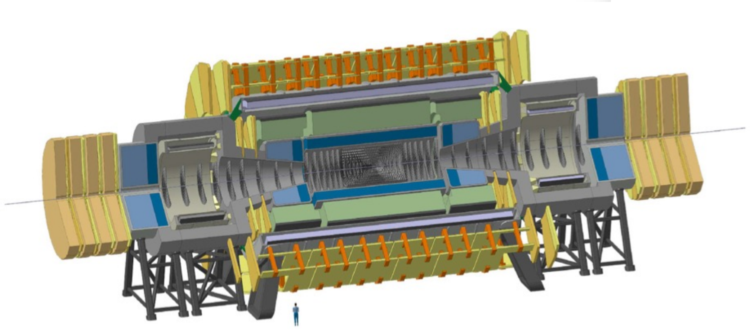
- Ensure charged hadron ID/mis-ID : Include timing information is mandatory also for RICH and PicoCAL (electrons/photons)





FUTURE *hh* COLLIDERS

- The extreme scenario in terms of pile-up challenge is FCC-hh with O(1000) pile-up
- Impact of timing information was studied in the past



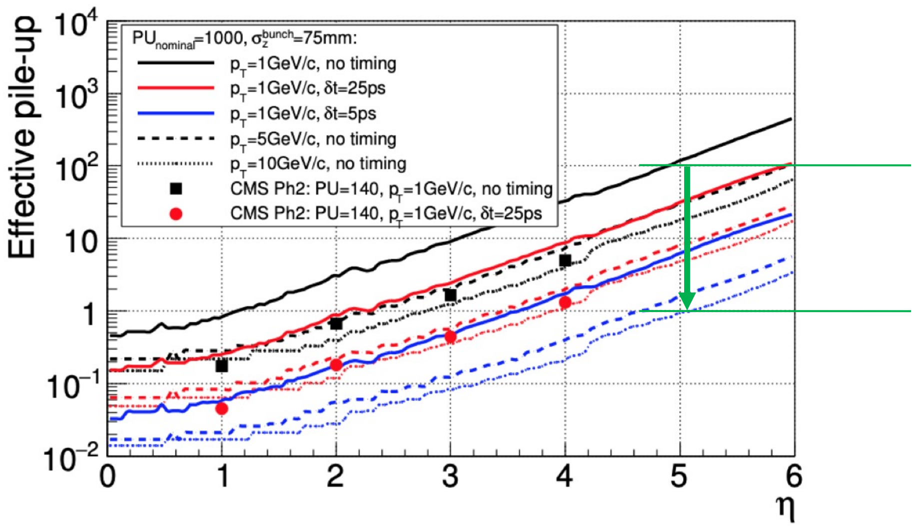


Figure 1: From Ref. [9]. An effective pile-up in the FCC-hh tracker. Several options of timing resolution per track in 3D vertexing are assumed: no timing (black), δ t = 25 ps (red) and δ t = 5 ps (blue). Several p_T values are shown: 1 GeV/c (solid), 5 GeV/c (dashed) and 10 GeV/c (dotted). For reference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

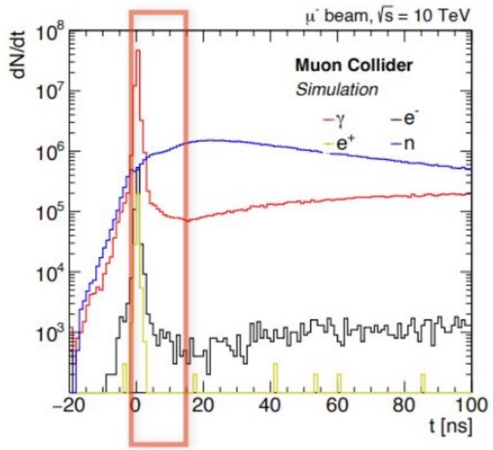
Extreme timing resolution of 5 - 10 ps per track is essential to keep the effective pileup low and prevent the merging of unrelated vertices

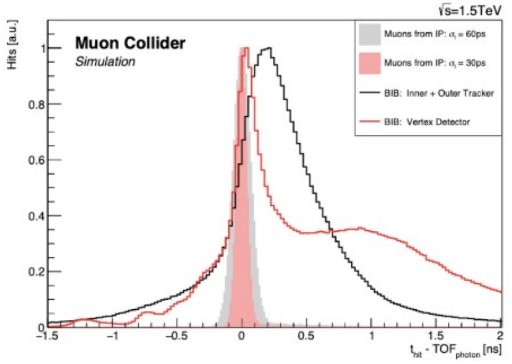
BEYOND HADRON COLLIDERS

FUTURE μ COLLIDERS

See more here

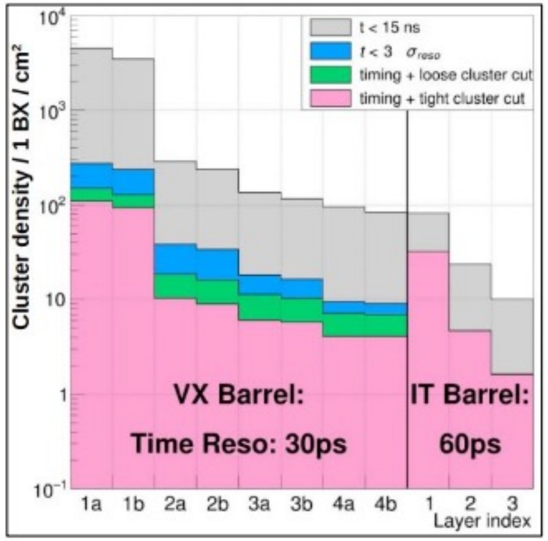
- Large beam-induced background from muon decays and showering of electrons on shielding
  - mostly electrons/photons, some neutrons
  - significant out-of-time component
  - coming from “all” directions!
- Full 4D-tracking is a requirement, not an option





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]

2411.02966



FUTURE e^+e^- COLLIDERS

See more here

- Clean environment, but physics measurements targeting very high precision, different applications of timing
- Some of the detector concepts integrate timing envelopes around main tracker
  - Can enable/improve **TOF-based PID**, flavour tagging, & searches for **Long Lived Particles**

TOF @ SiD

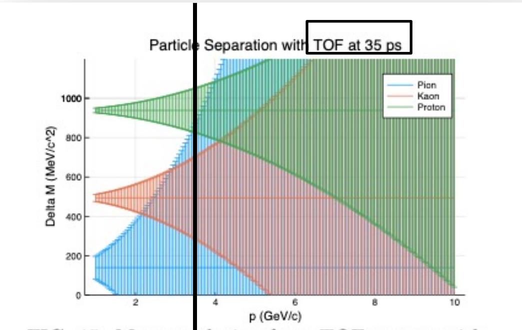


FIG. 15: Mass resolution for a TOF system with HL-LHC level performance of 35 ps time resolution in SiD

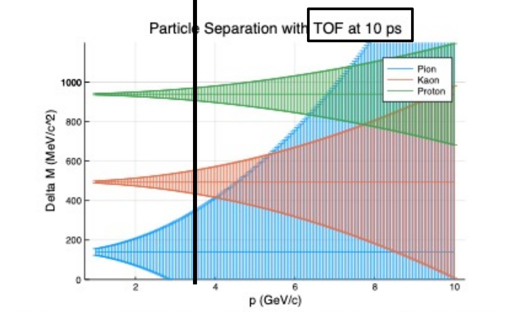
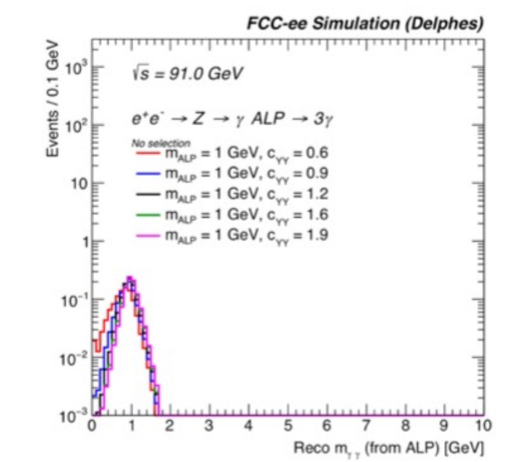


FIG. 16: Mass resolution for a TOF system with a performance of 10 ps in SiD

2110.09965

LLP @ FCC-ee

Heavy neutral leptons, **axion-like particles**, and exotic Higgs boson decays



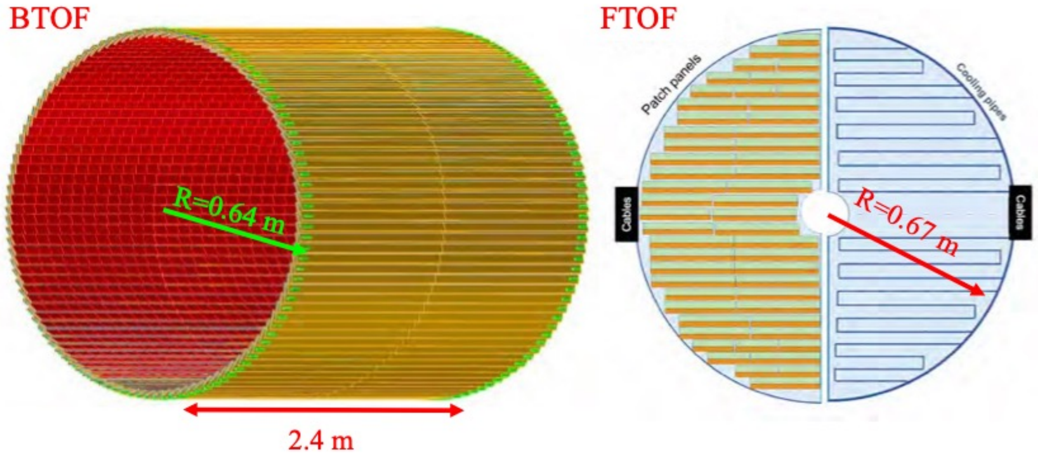
2203.05502

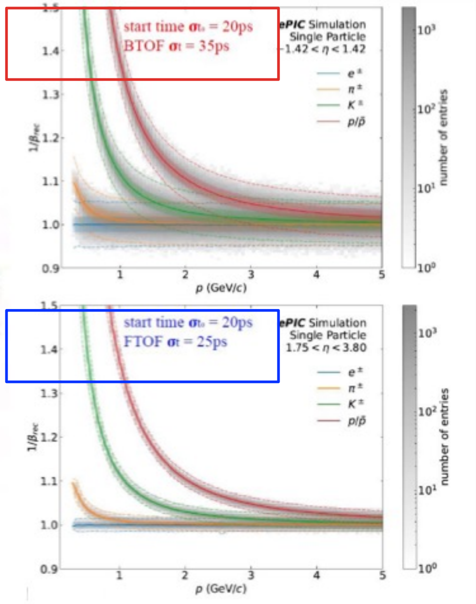
"In addition, calorimeter and precision timing variables will be extremely helpful to include in this study of ALPs that decay to photons."

FUTURE *EIC* Z. Ye's slides

- The Electron-Ion Collider (2031+) is among the highest priority of US Nuclear Physics
- Electron-Proton and -Ion Collider detector (ePIC) concept includes PID capabilities via AC-LGAD layers (also vertex identification for far-forward hadrons)

AC-LGAD Detectors for ePIC



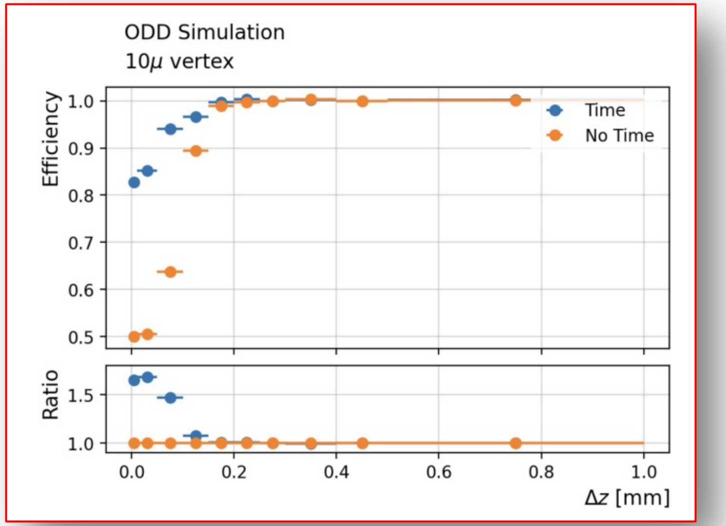


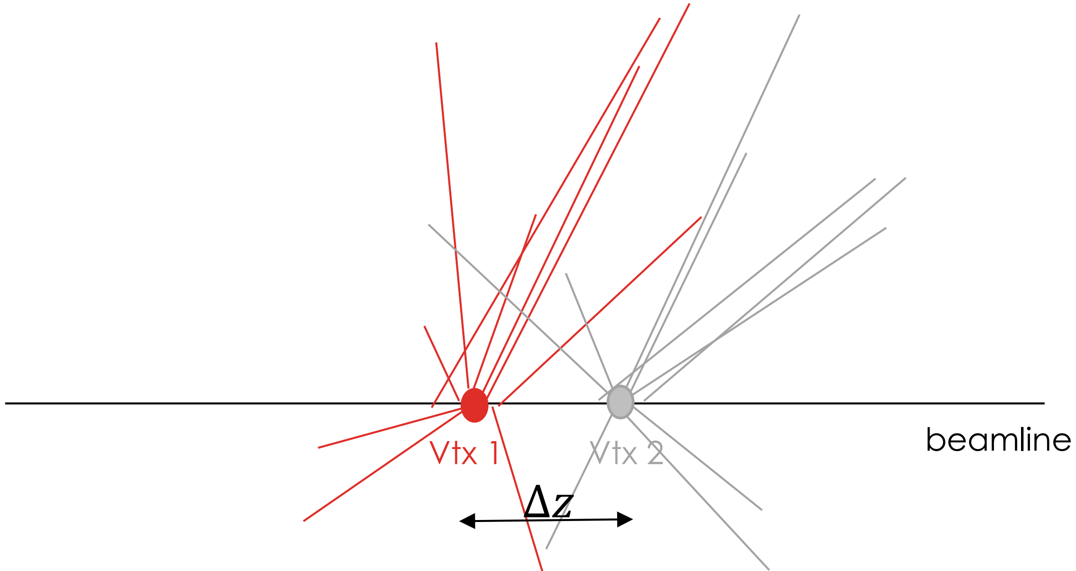
	Area (m²)	Channel size (mm²)	# of Channels	Timing Resolution	Spatial resolution	Material budget
Barrel TOF	10	0.5*10	2.4M	35 ps	30 μm in $r \cdot \varphi$	0.01 X_0
Forward TOF	1.4	0.5*0.5	5.6M	25 ps	30 μm in x and y	0.05 X_0
B0 tracker	0.07	0.5*0.5	0.28M	30 ps	20 μm in x and y	0.05 X_0
RPs/OMD	0.14/0.08	0.5*0.5	0.56M/0.32M	30 ps	140 μm in x and y	no strict req.

ACTS-BASED RECONSTRUCTION

A Common Tracking Software (ACTS): 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
- Ongoing work to translate the FCC-hh tracker into ACTS, in particular to detray/traccc
- 4D vertex finding and fitting implemented, more on tracking here
- 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





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!

- **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

IN VIEW OF THE ESPP UPDATE

- For Snowmass, we released a document (2203.13900) that "*reviews the impact of integrating 4D tracking capabilities on several physics benchmarks both in potential upgrades of the HL-LHC experiments and in several detectors at future colliders, and summarizes the currently available sensor technologies as well as electronics, along with their limitations and directions for R&D.*"

- Substantial work has been performed since then, with **promising advancements in reconstruction**
  - See proof-of-concepts from ATLAS, LHCb, etc
  - Reconstruction for detectors at Muon Colliders
  - Generic 4D tracking in ACTS, crucial for fast turnarounds

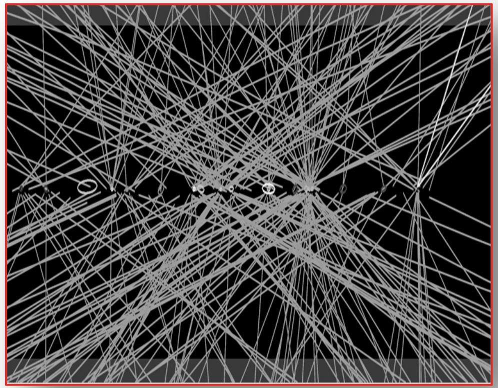
- **Technologies have also advanced**

- Input to the **ESPP could focus on these aspects**, i.e. what's new since Snowmass

CONCLUSIONS

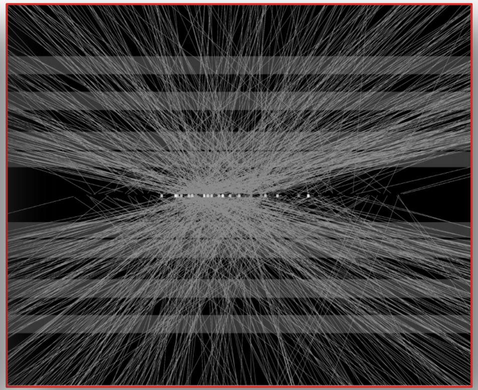
- We are broadly investigating **4D tracking in various contexts**: HL-LHC, FCC-ee ToF, muC, and FCC-hh, with extensive usage of ACTS ODD
  - **Challenges change with the collider environment**:
    - e^+e^- clean environment, but high precision requirements, timing for e.g. TOF
    - HL-LHC upgrades, MuC, FCC-hh, etc: increasingly busy environments, critical to identify hard scatter
  - Differences in backgrounds and collider can imply different strategies but synergies exist
- **4D Tracking is a unique feature to boost the experimental physics reach**, and can be combined with advancements in track reconstruction algorithms
- Both algorithms and technologies are being developed and offer interesting opportunities for HL-LHC and, even more so, future colliders!

2009



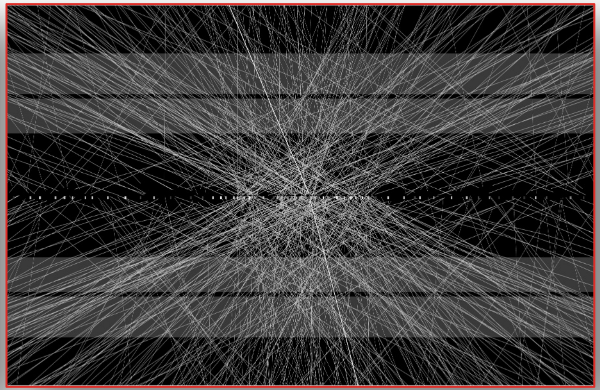
$< pile - up > \sim 20$

2015



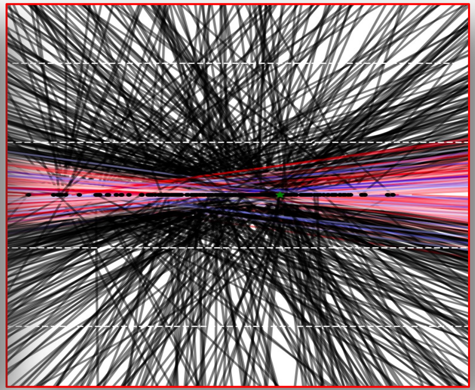
$< pile - up > \sim 30$

2022



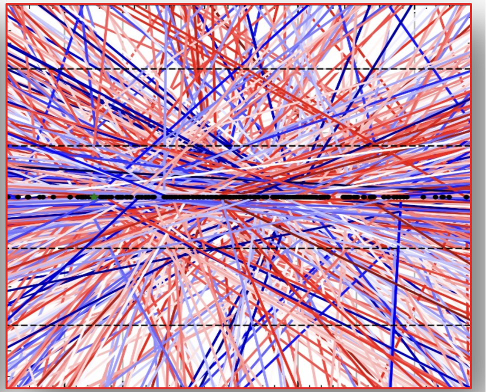
$< pile - up > \sim 60$

2030



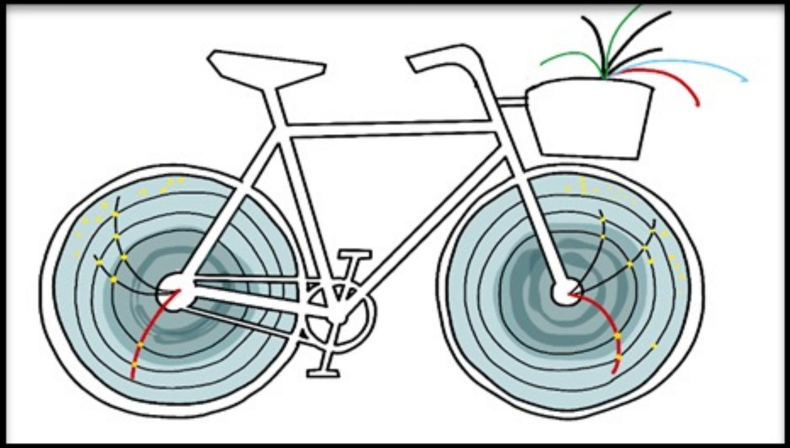
$< pile - up > \sim 140$

...and beyond?



$< pile - up > \sim 200$

THANK YOU!



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

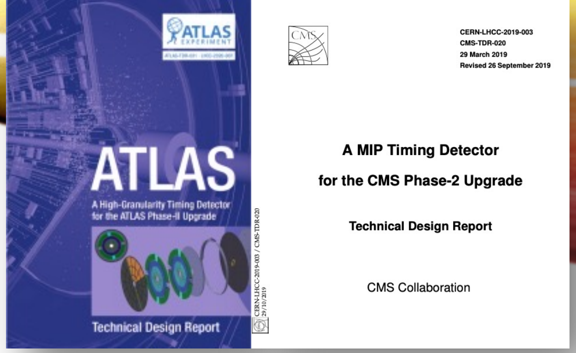
Valentina Maria Martina Cairo

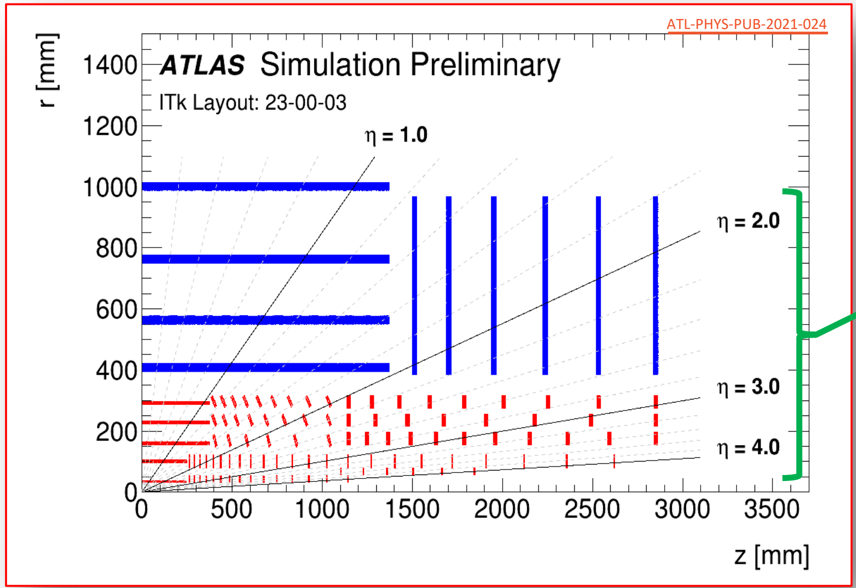
EXTRA SLIDES

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

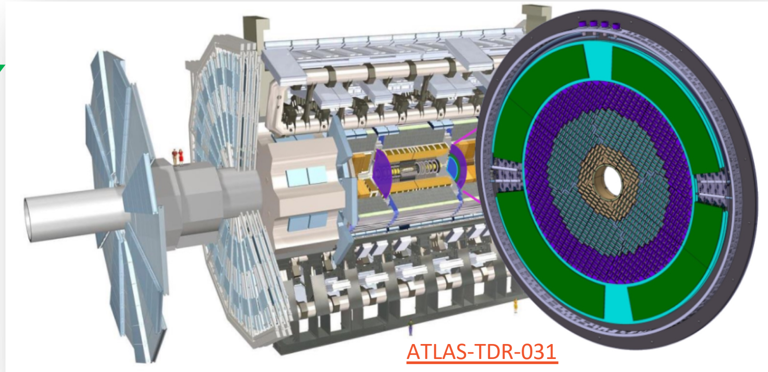
UNFOLDING
A NEW DIMENSION

Addition of timing layers to HEP detectors growing area of interest



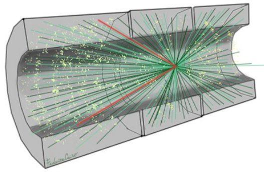


High Granularity Timing Detector



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 <u>extending the timing coverage to the full η acceptance?</u>



A COMPARISON WITH CMS' MIP TIMING DETECTOR

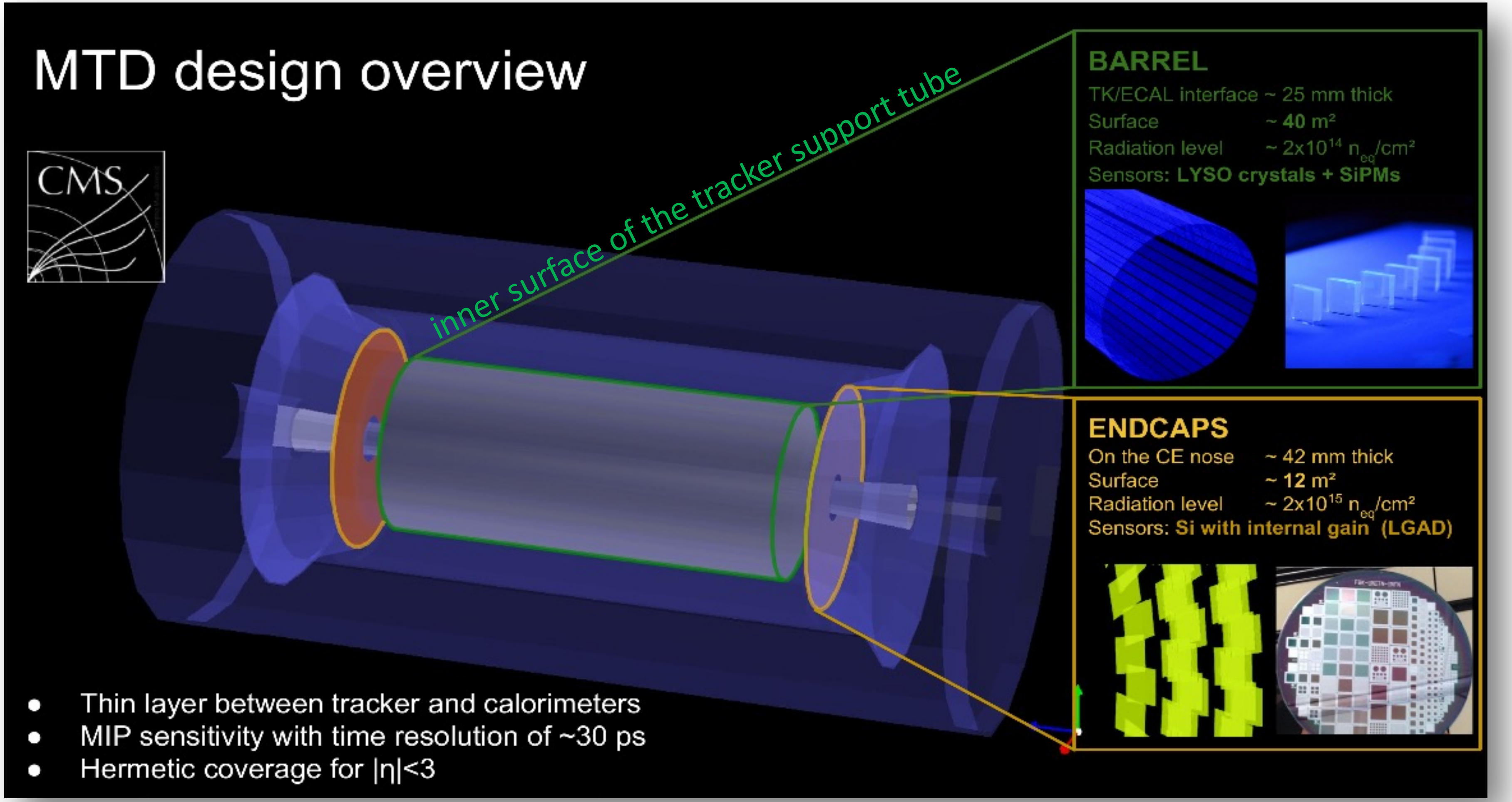
From CMS MTD TDR: *"The MTD will give timing information for MIPs with 30–40 ps resolution at the beginning of HL-LHC operation in 2026, degrading slowly as a result of radiation damage to 50–60 ps by the end of HL-LHC operations."*

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

about 200. The integrated luminosity × 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

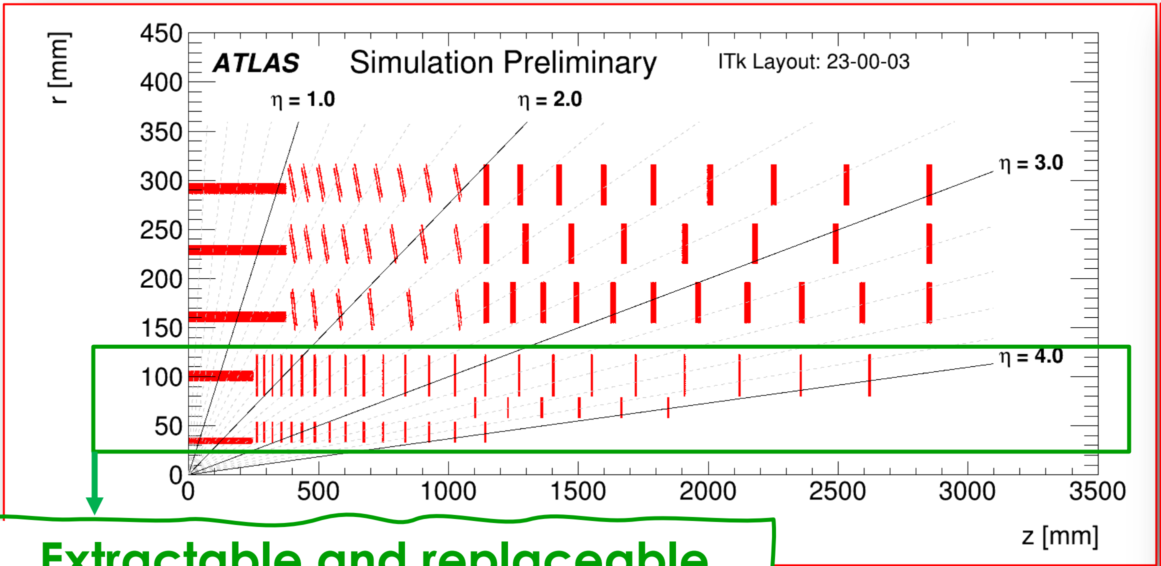
1.5 <|eta|<3.0

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

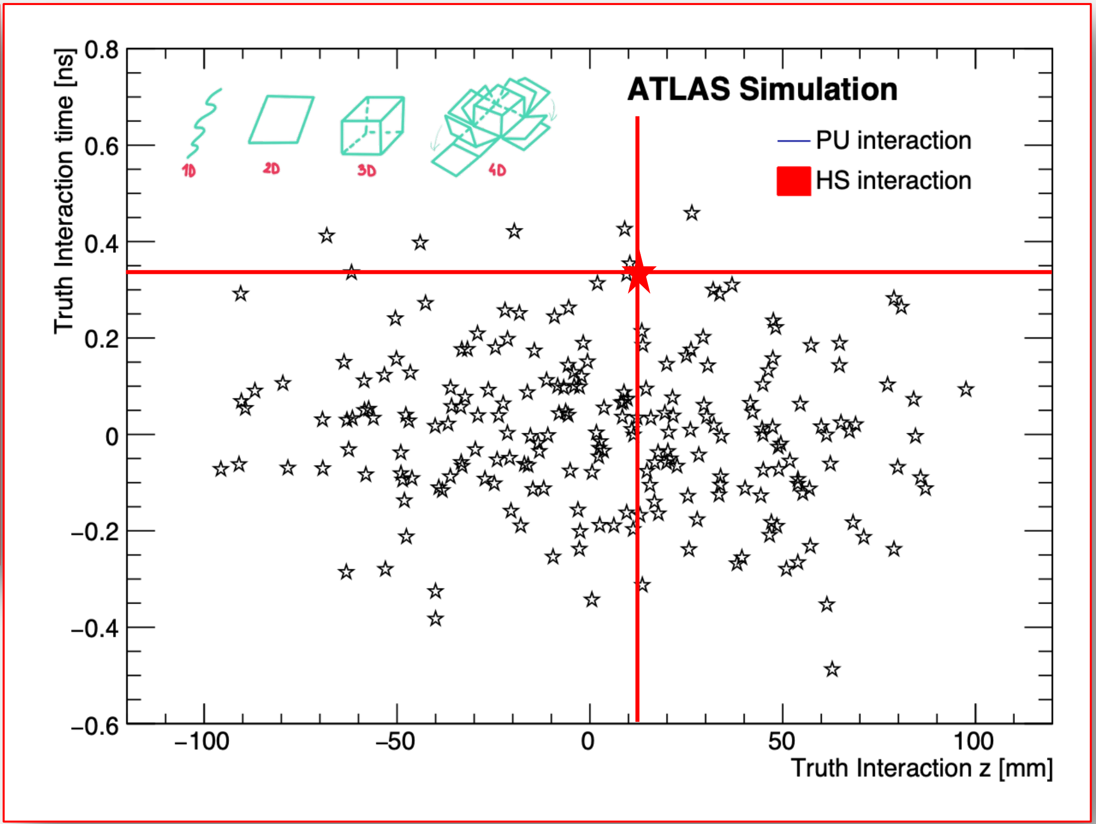
UNFOLDING
A NEW DIMENSION

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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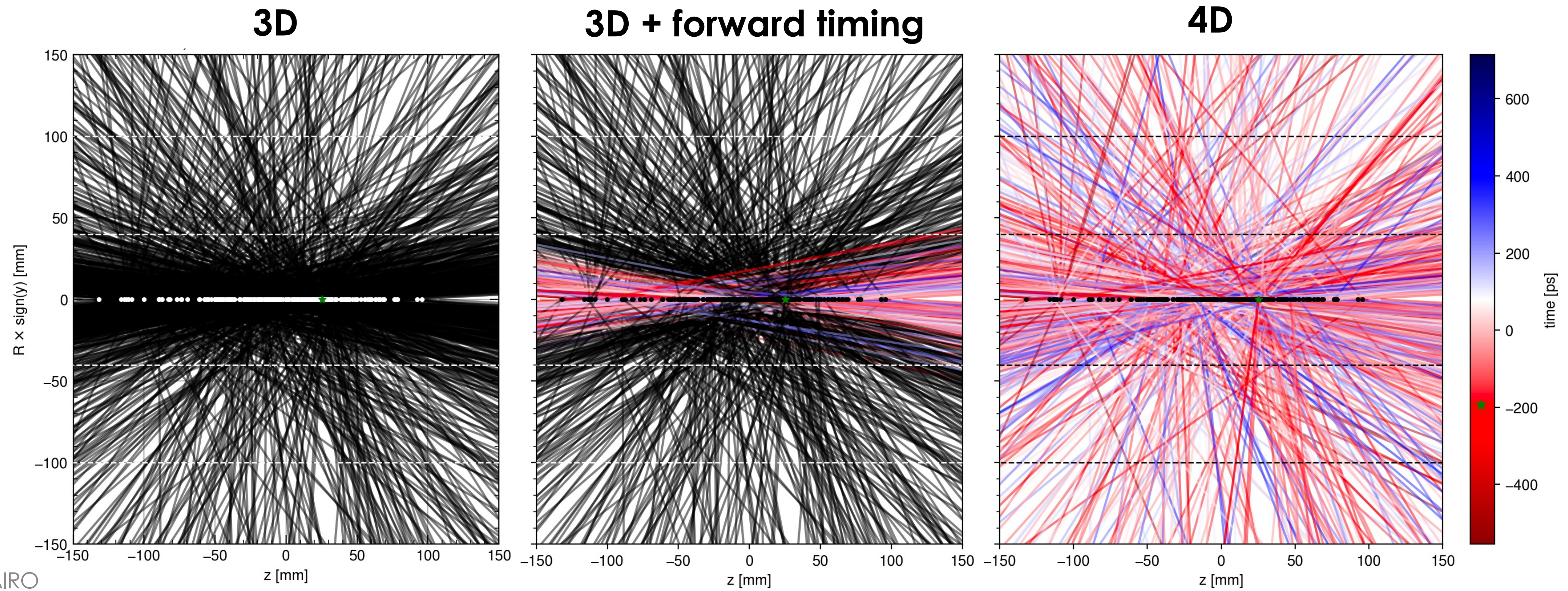
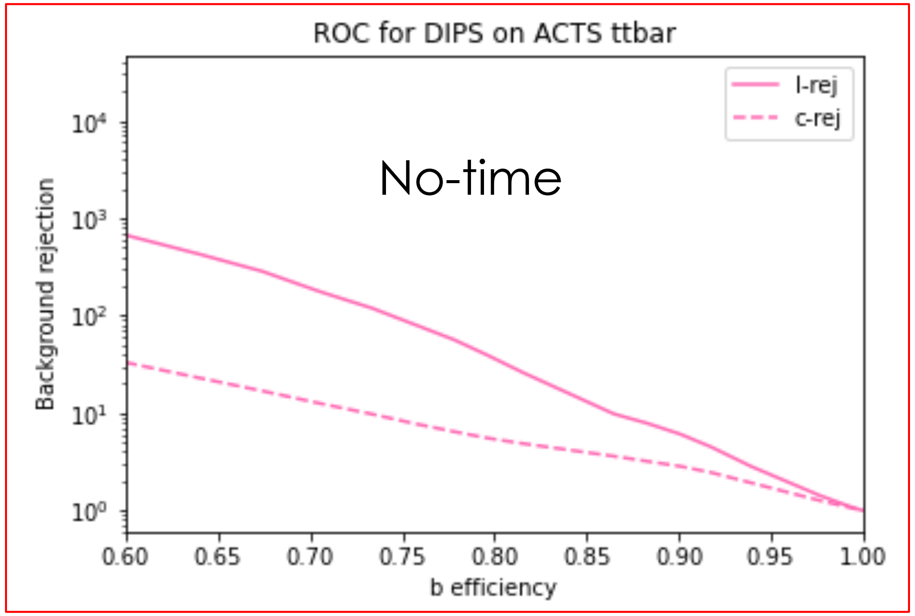


ACTS-BASED STUDIES

- 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 RECONSTRUCTION CHAIN

Inputs to higher level objects

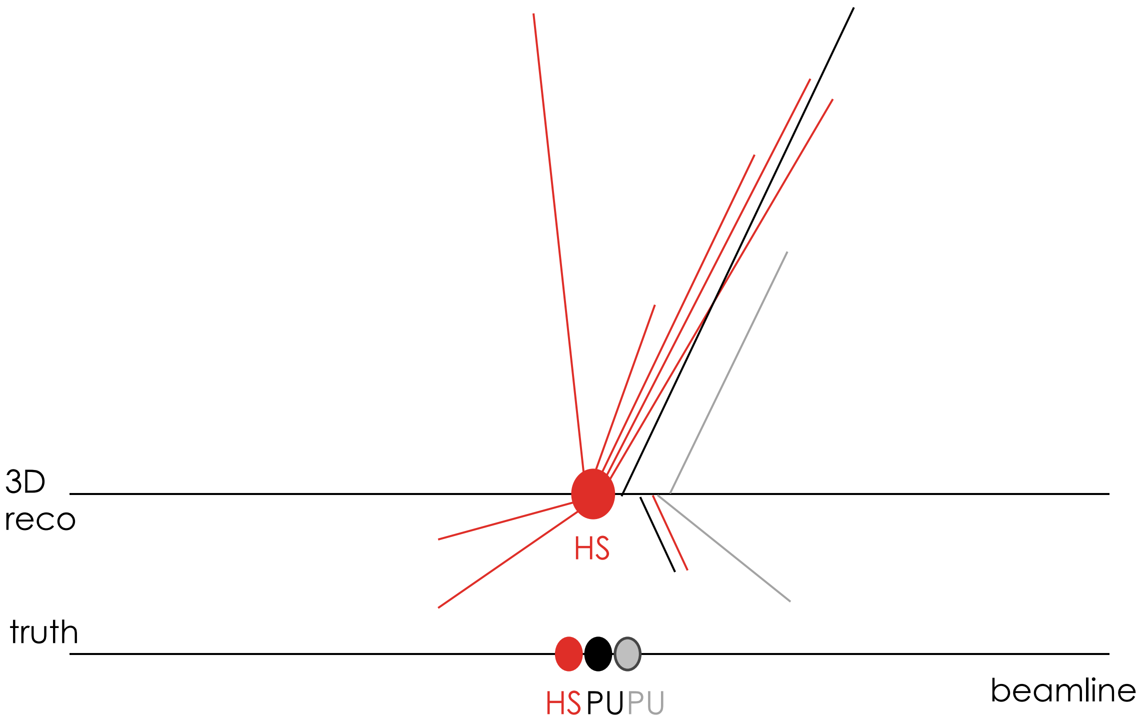
THE RECONSTRUCTION CHAIN

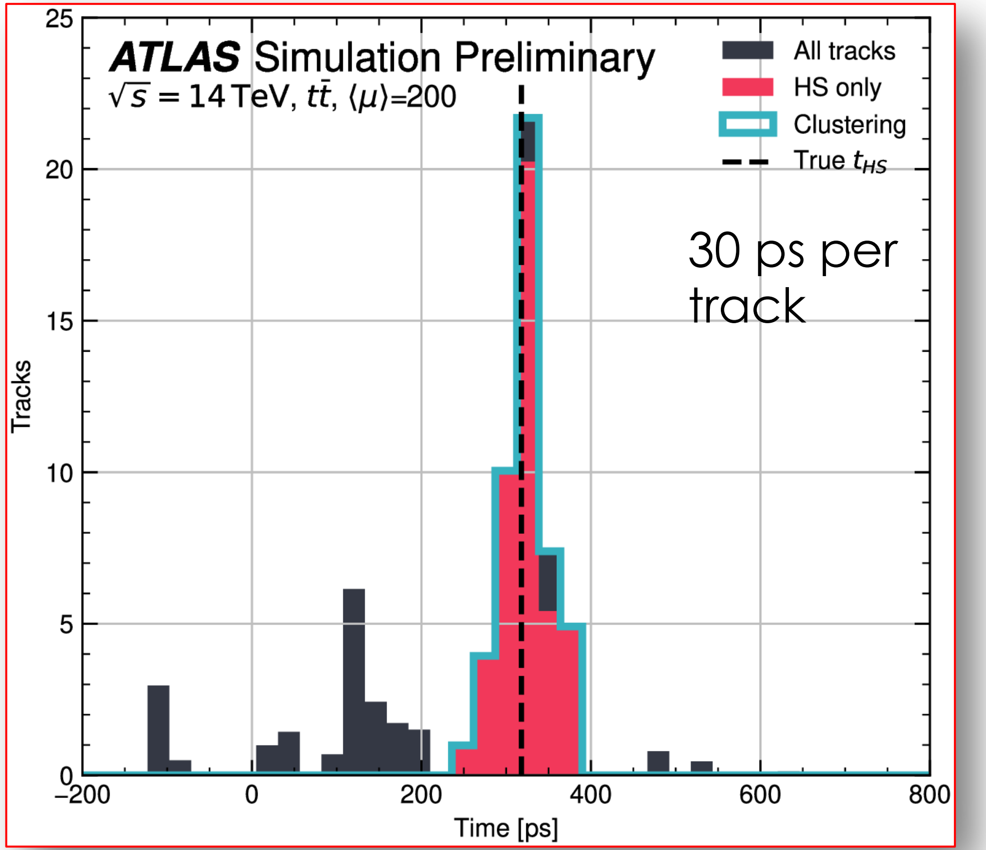
In this first study, track-time
was added here,
based on truth information
and smeared by 30, 60, 90 ps

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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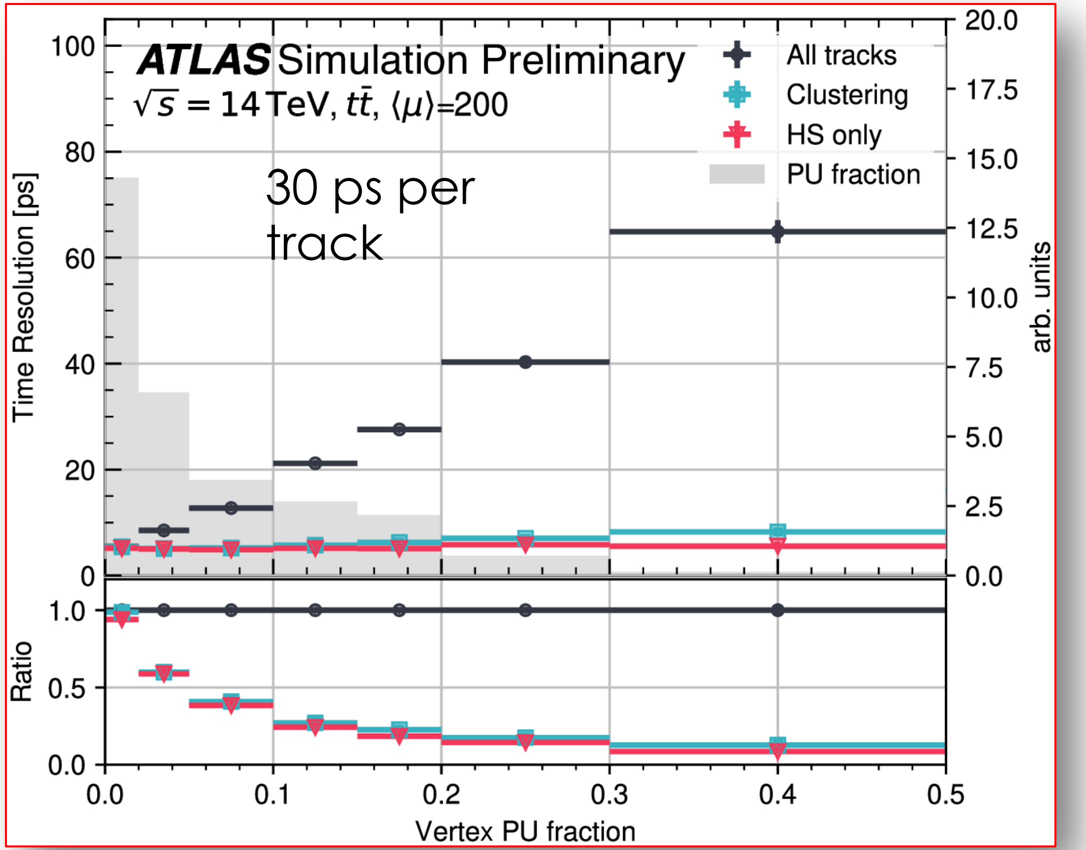
DETERMINING THE VERTEX TIME

- 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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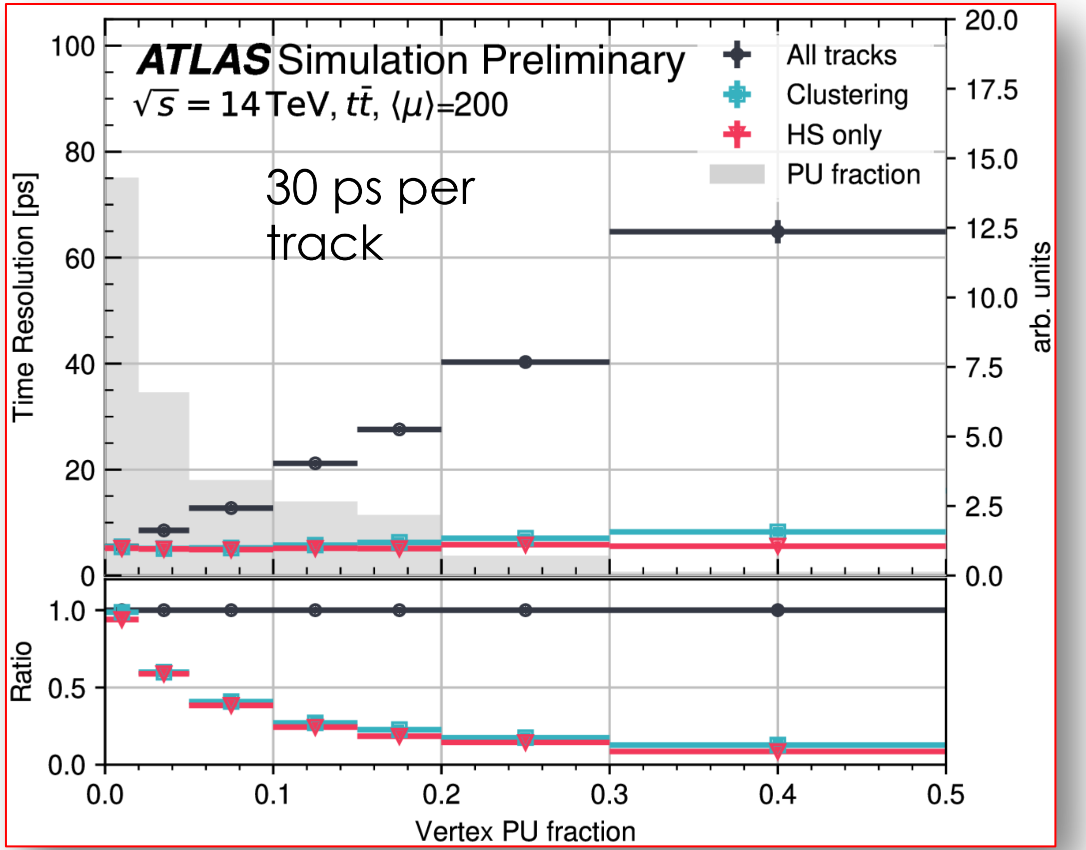

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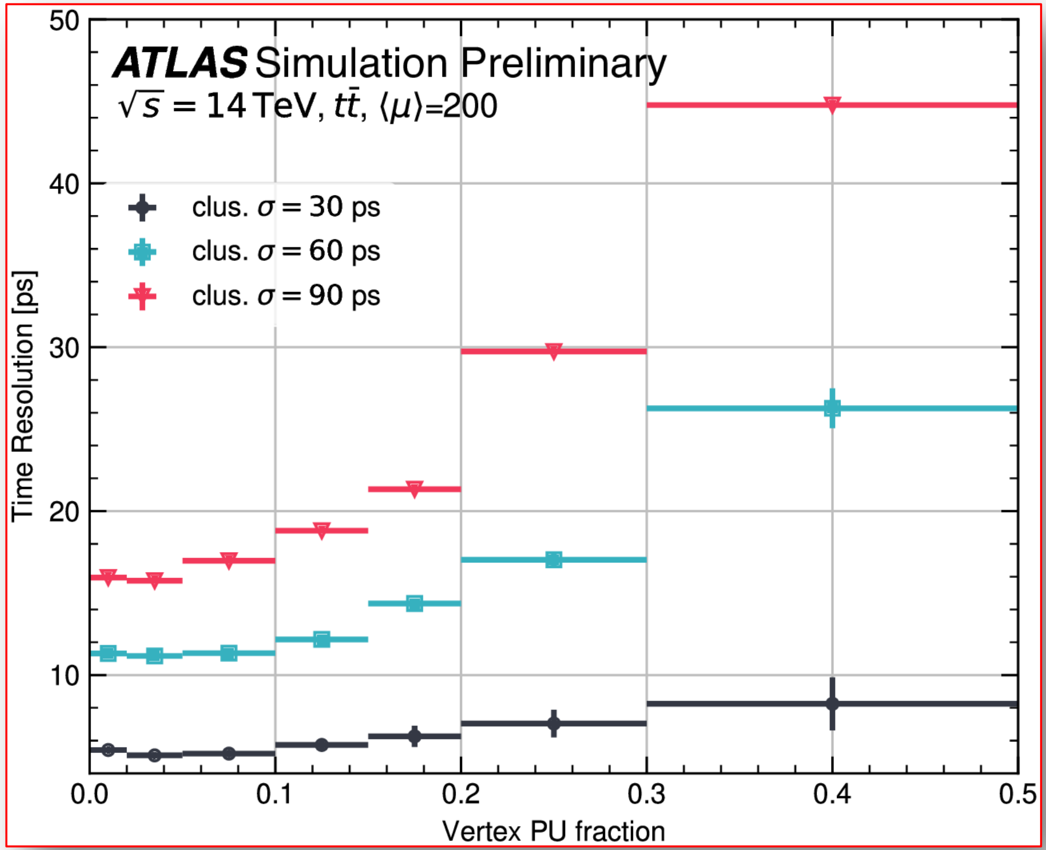

The better the track-time resolution, the more PU-robust the vertex time resolution

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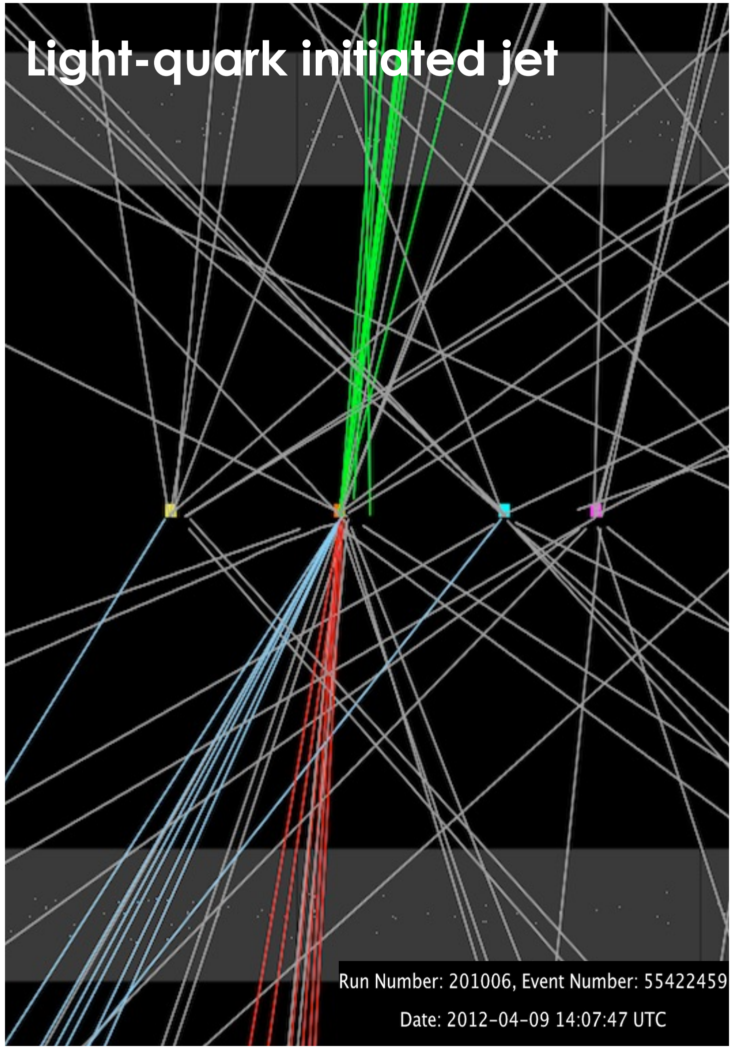
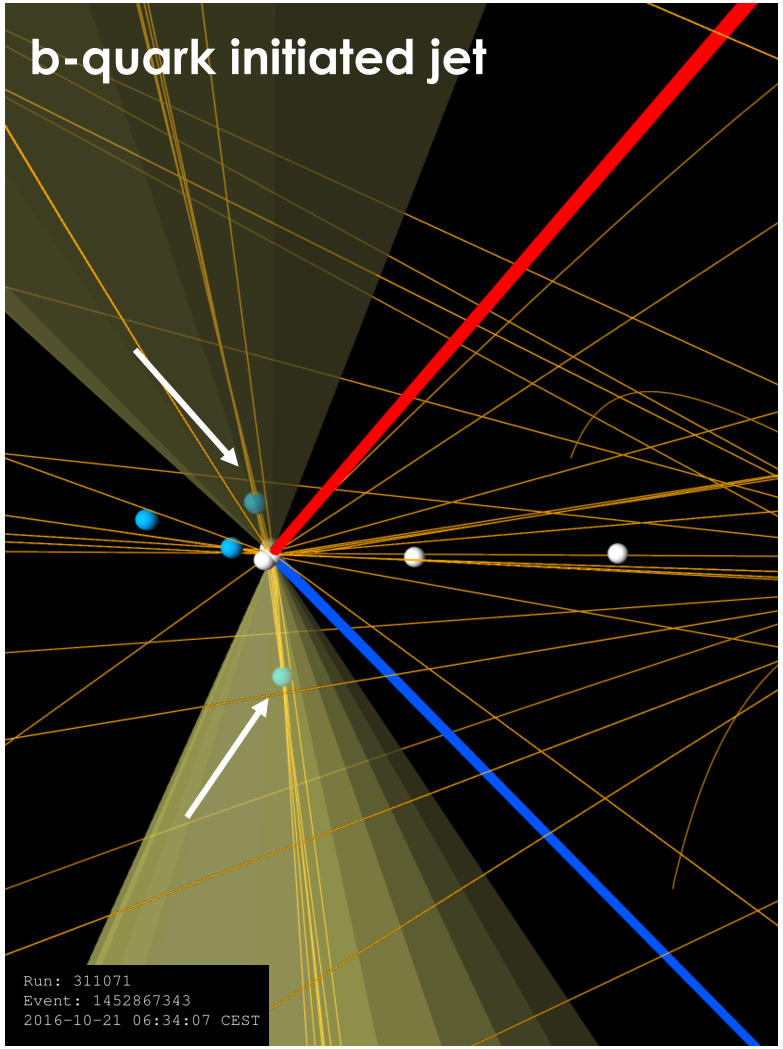
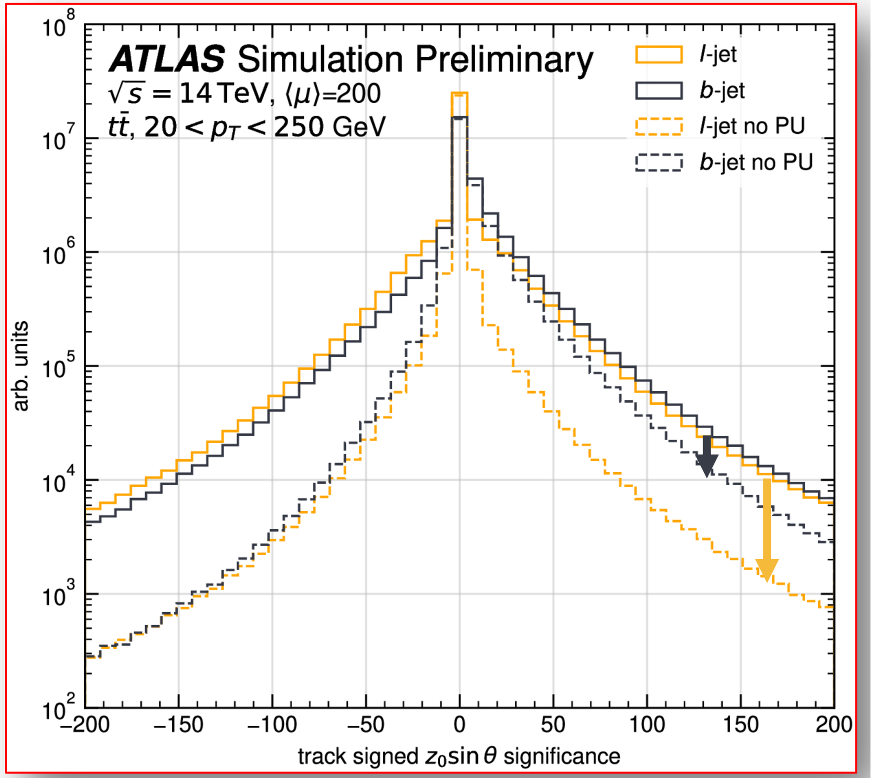
THE KEY FEATURES FOR b-TAGGING

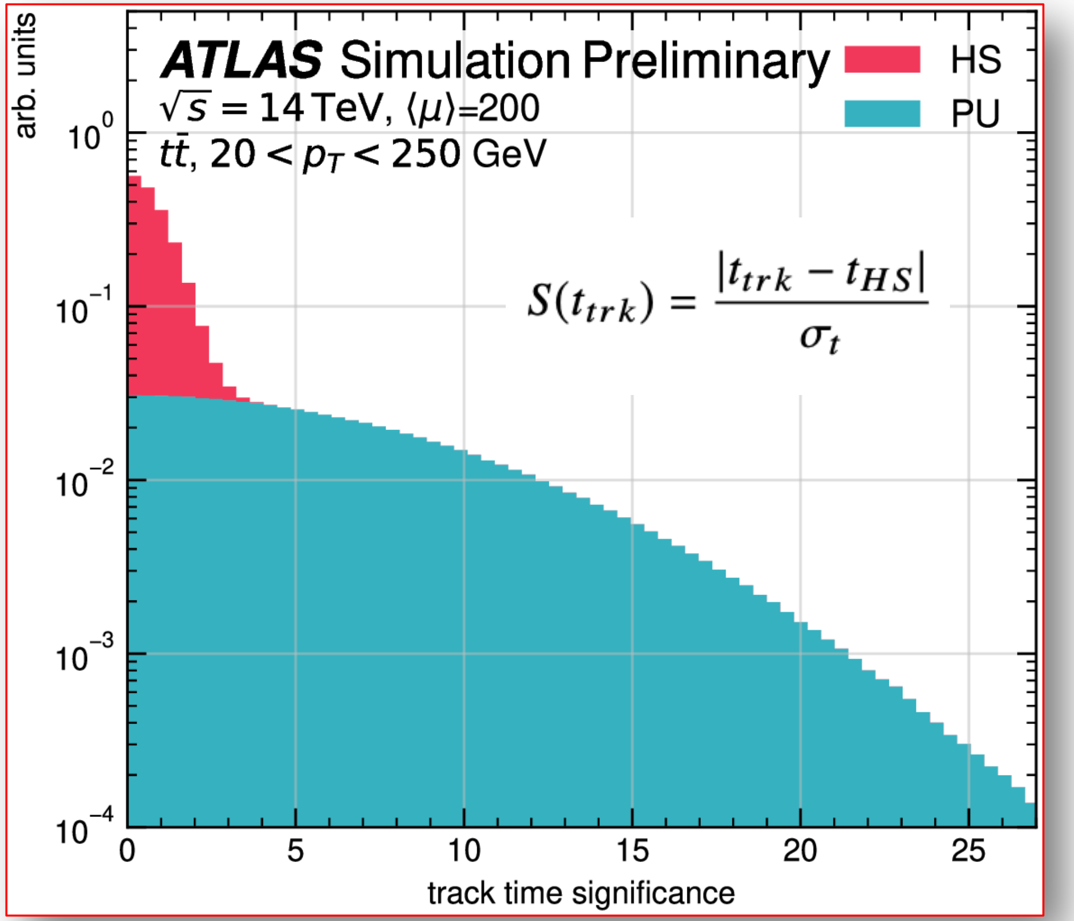






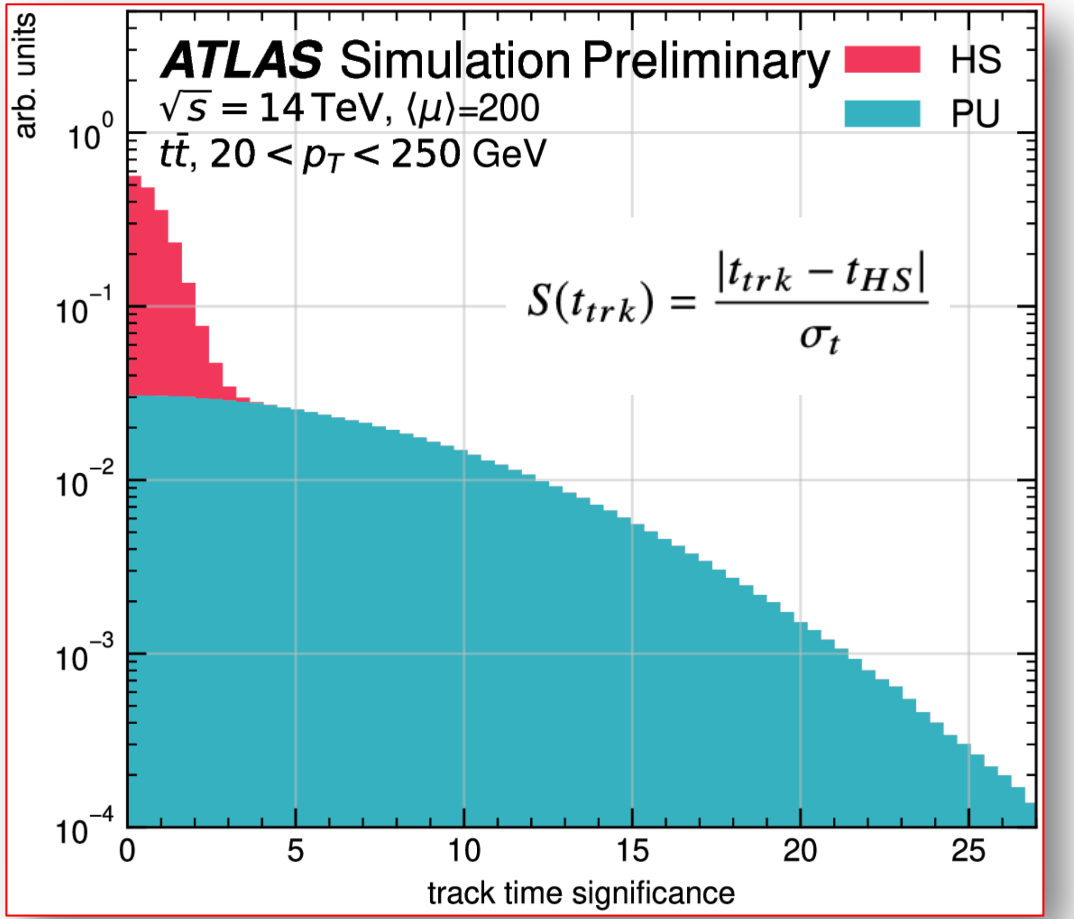
Long lifetime of B-hadrons requires selecting tracks with large IPs →large selection windows around the longitudinal IP → more pile-up contamination that can lead to fake secondary vertices

GNT – 4D b-TAGGING

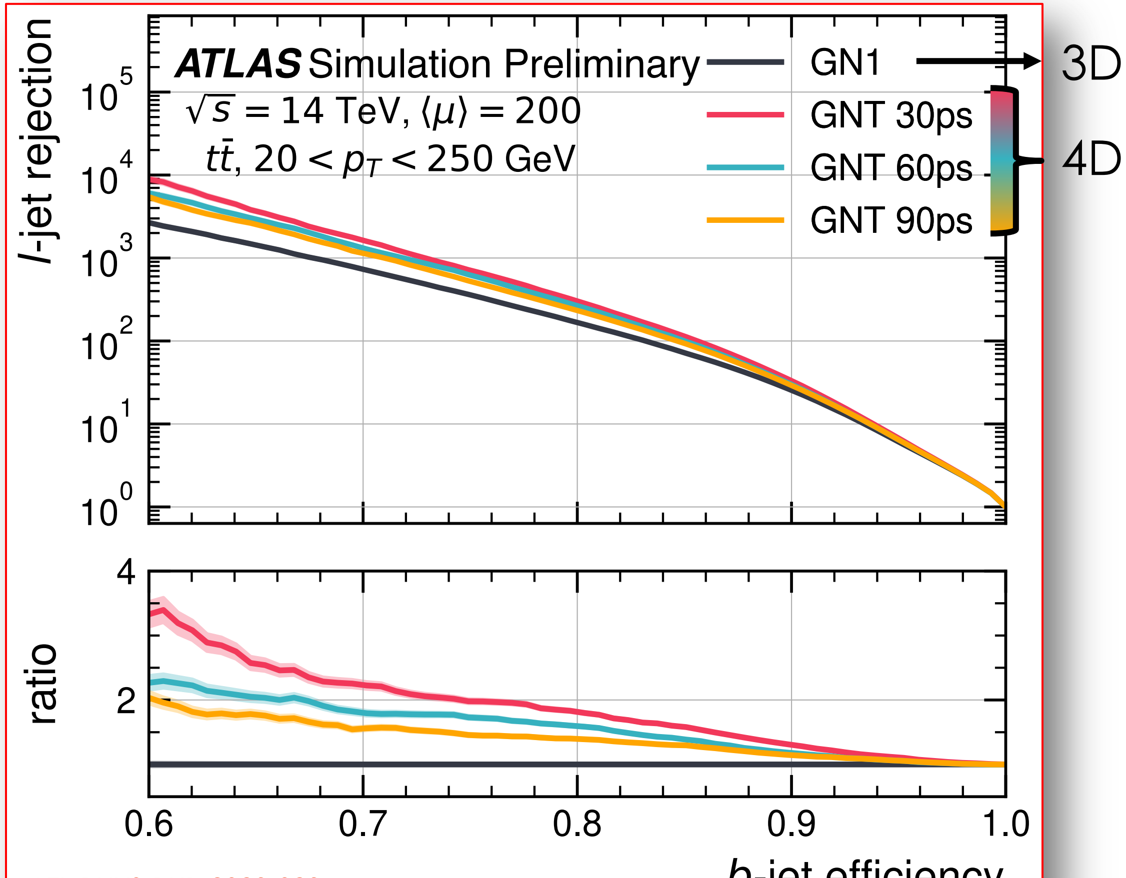


Known track and vertex time, a track time significance is built

GNT – 4D b-TAGGING



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



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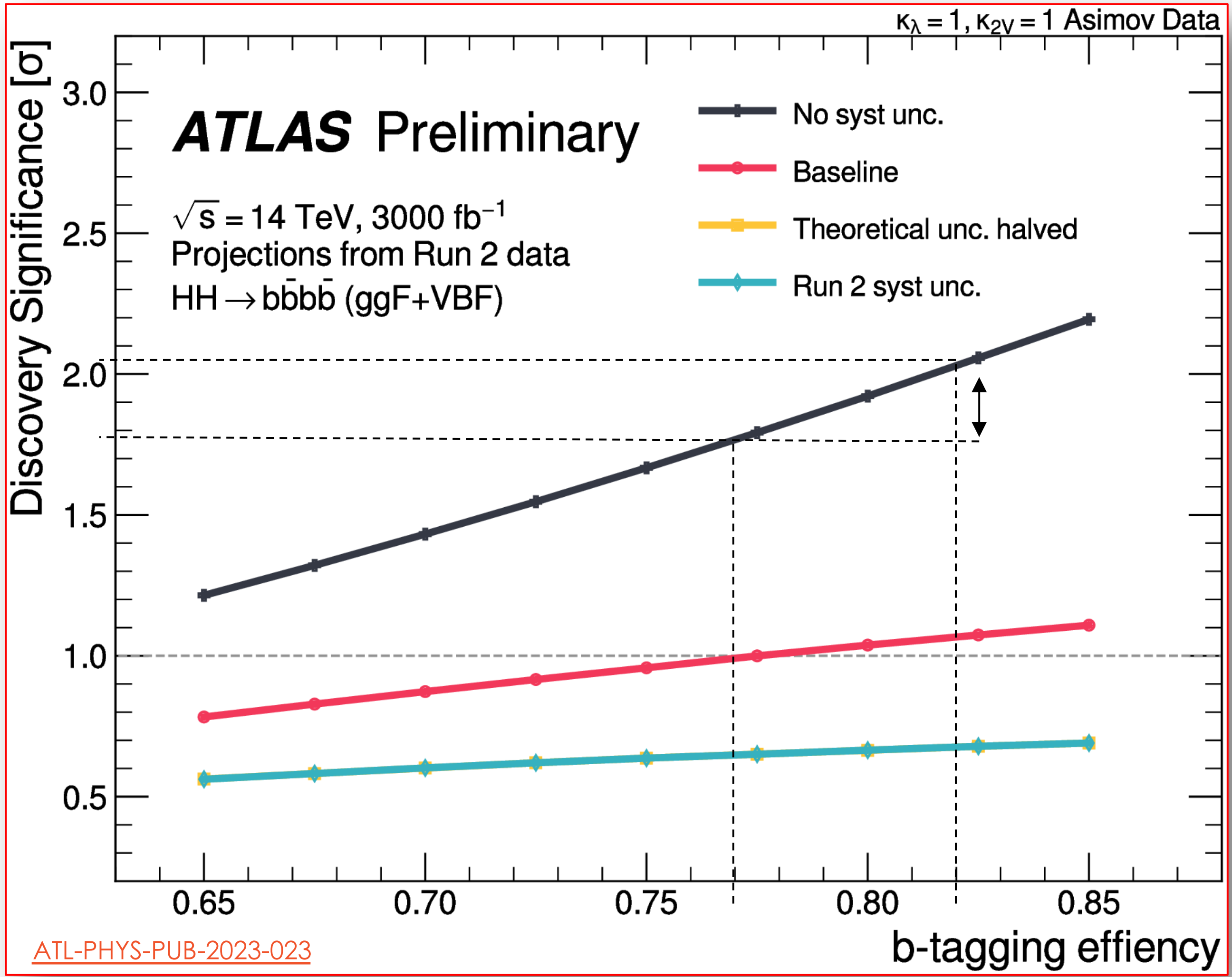
Interesting potential sensitivity increase for Higgs physics, in particular **HH**, whose observation is a high-priority goal for HL-LHC

HH PROSPECTS



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

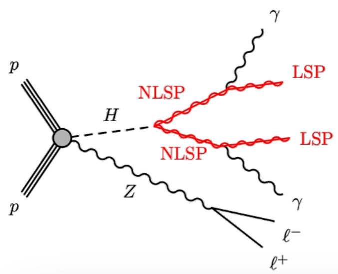
N.B. this plot was made by scaling to the full HL-LHC luminosity

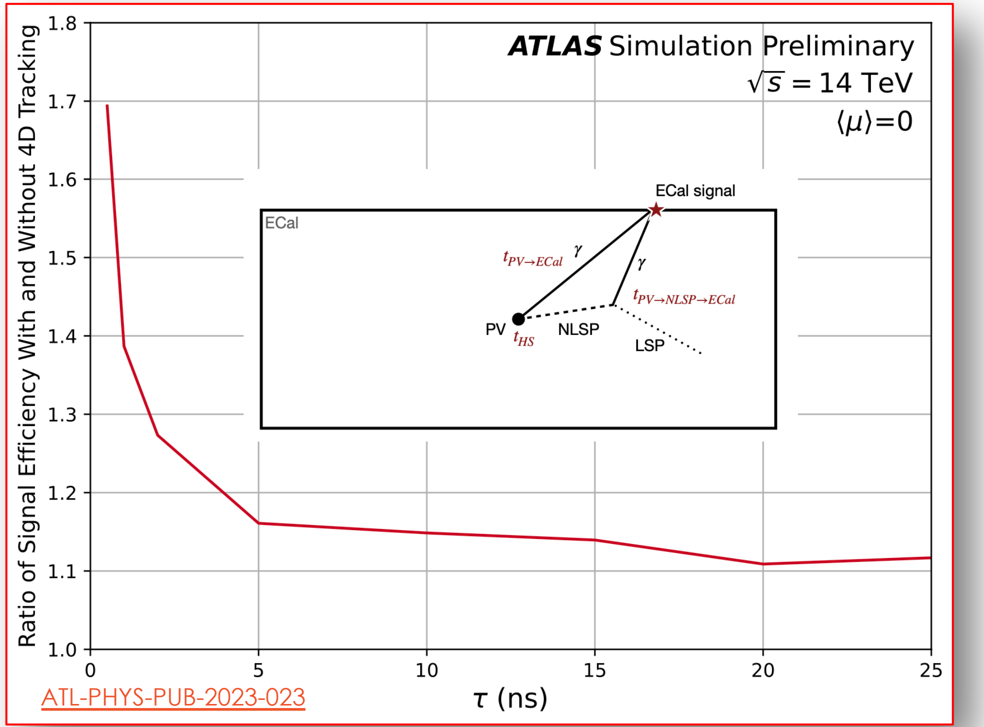
OTHER PHYSICS CASES

- **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***

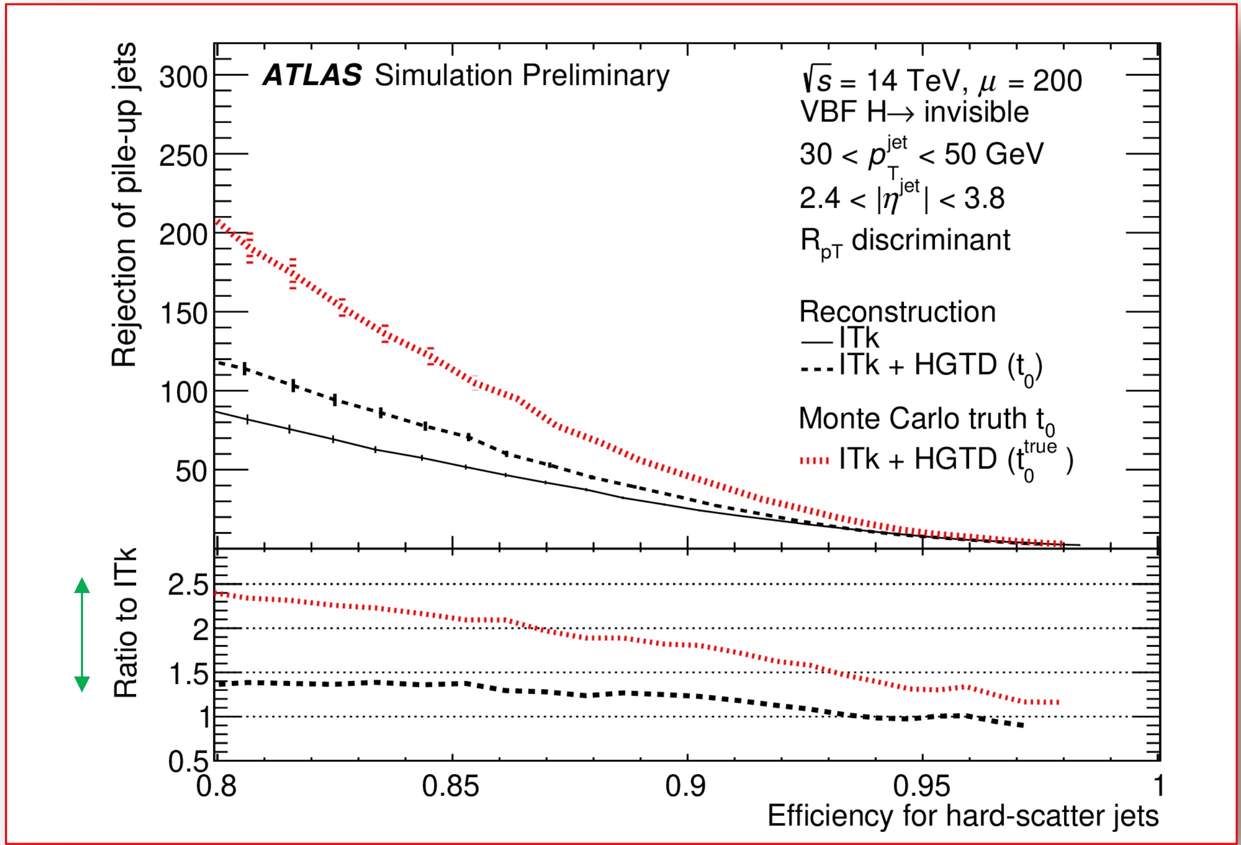
- Other applications to be further explored, e.g. **c-tagging** (similar considerations as for b-tagging), **tau reconstruction and identification**, etc

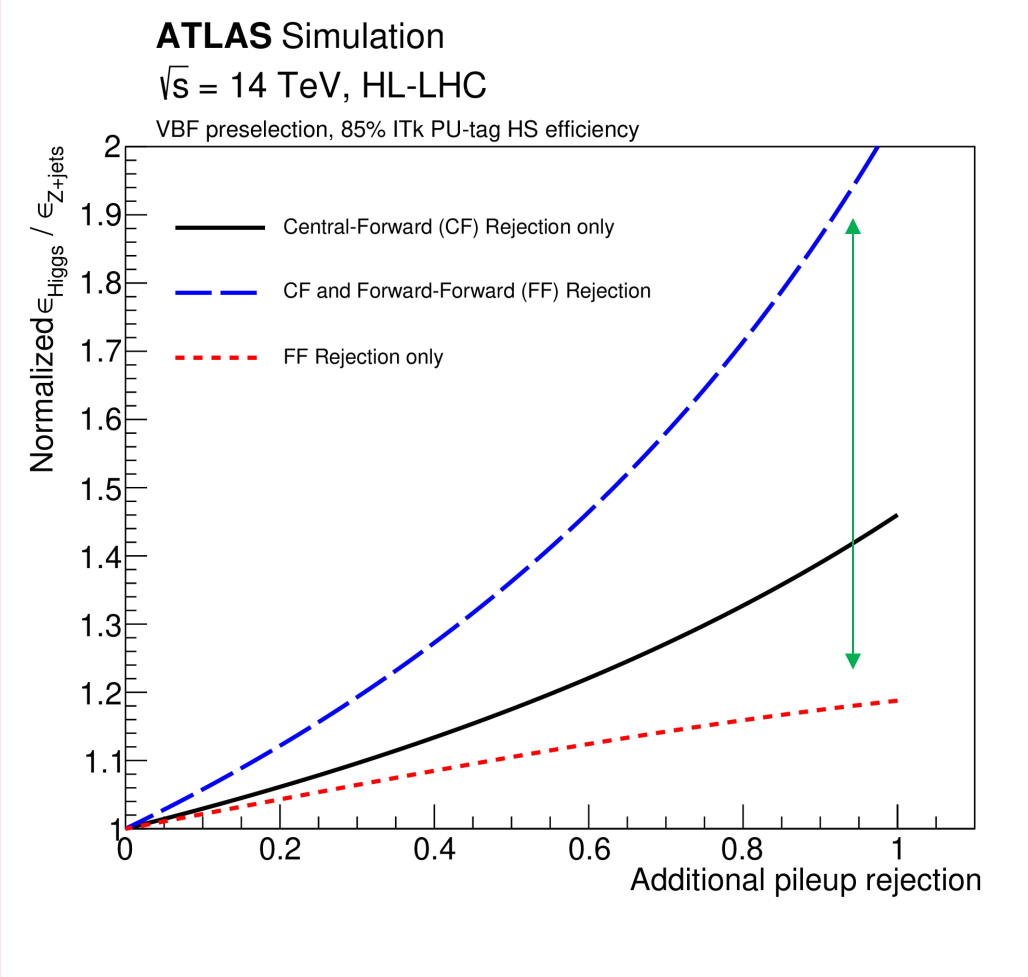




OTHER PHYSICS CASES

$VBF\ H \rightarrow inv$





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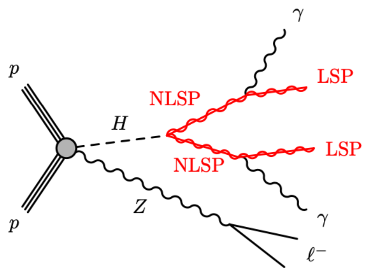
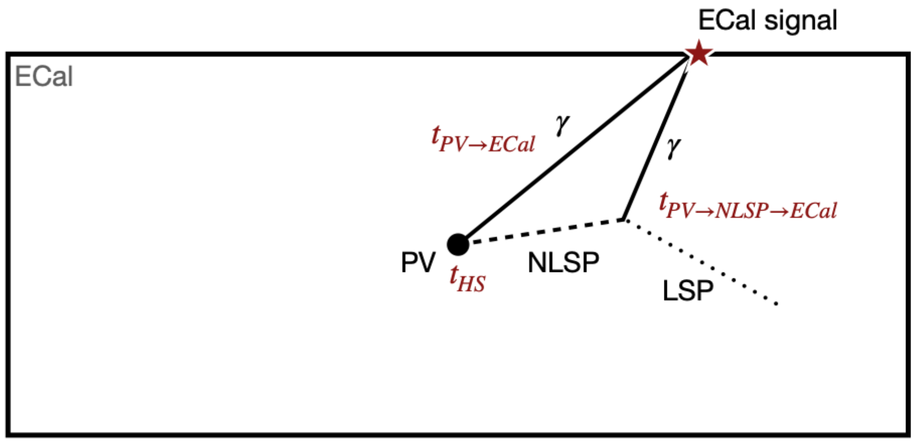
OTHER PHYSICS CASES

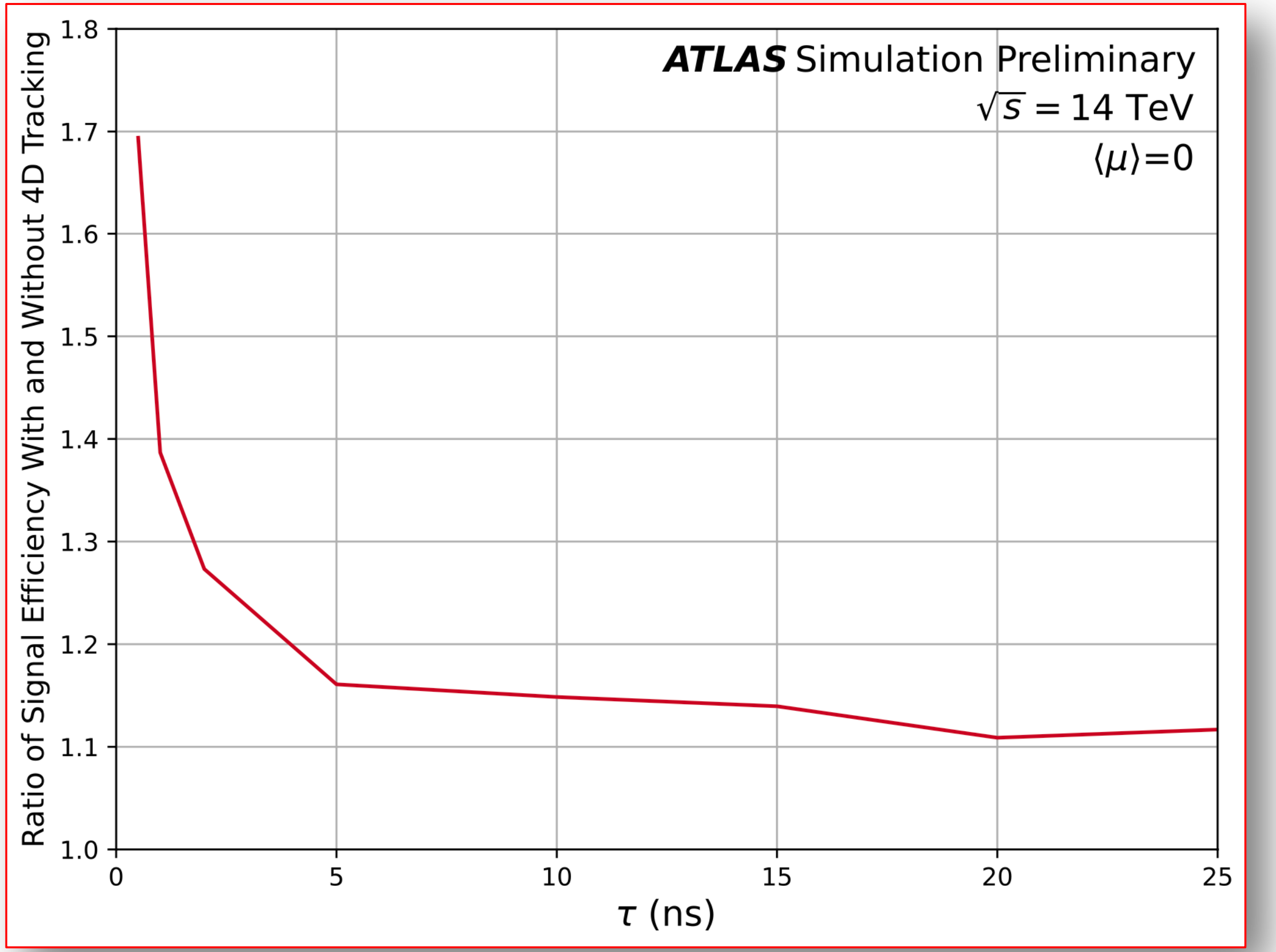
Delayed photons





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

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



VBF HIGGS→ INVISIBLE

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

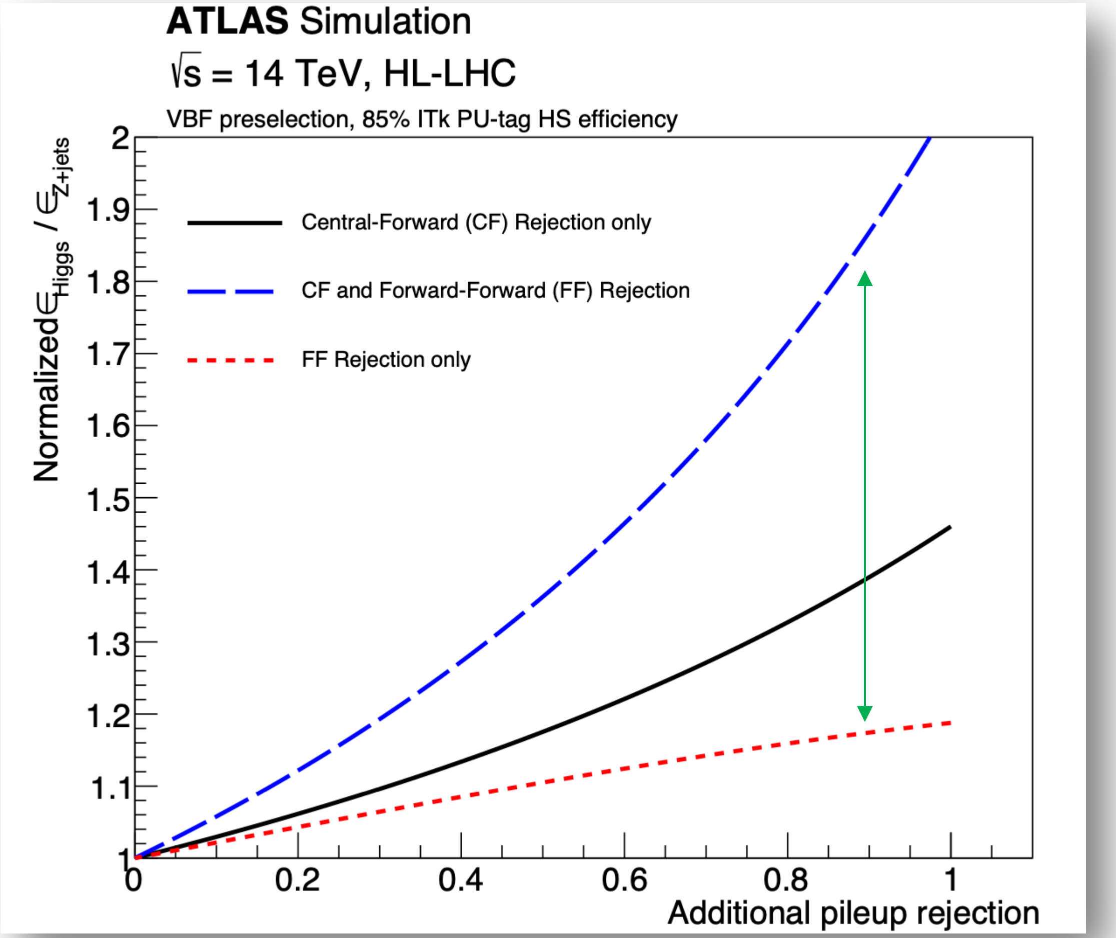


Fig. 3.25
Normalized signal over background gain relative to ITk-only pileup jet suppression performance, as a function of the additional pileup jet rejection from HGTD. The solid black (dotted red) line represents the HGTD improvement from the CF (FF) event topologies separately. The dotted blue line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

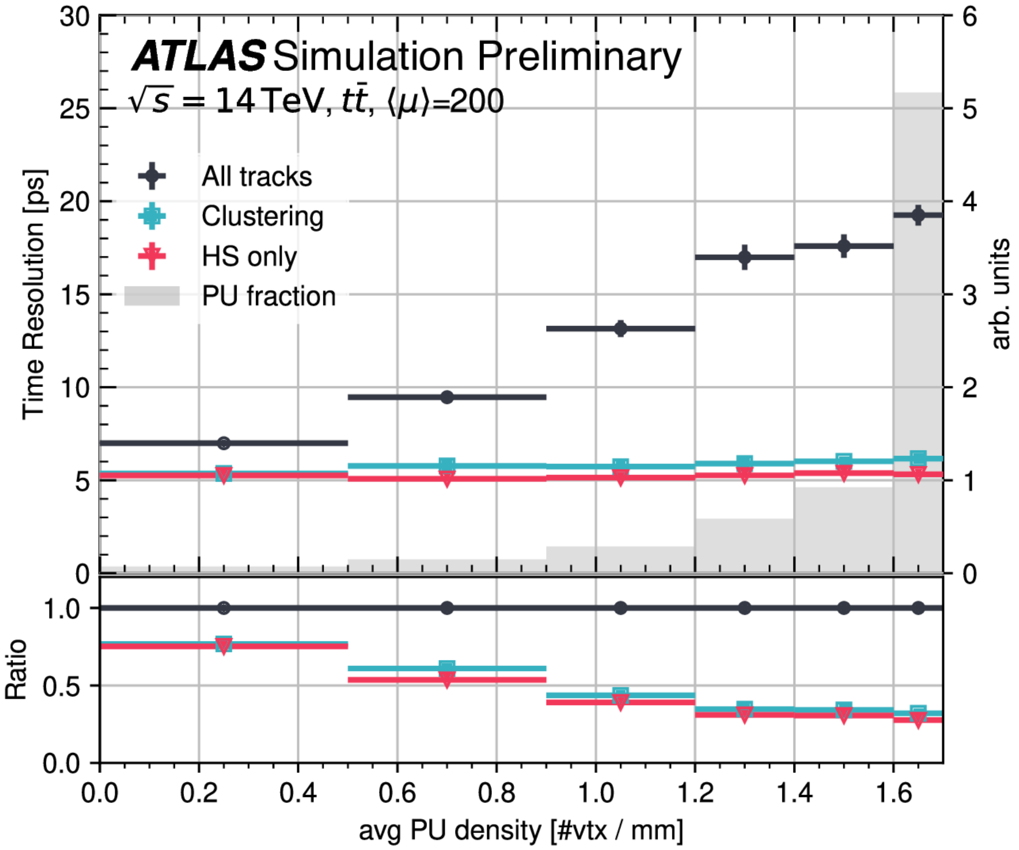
VERTEX T0

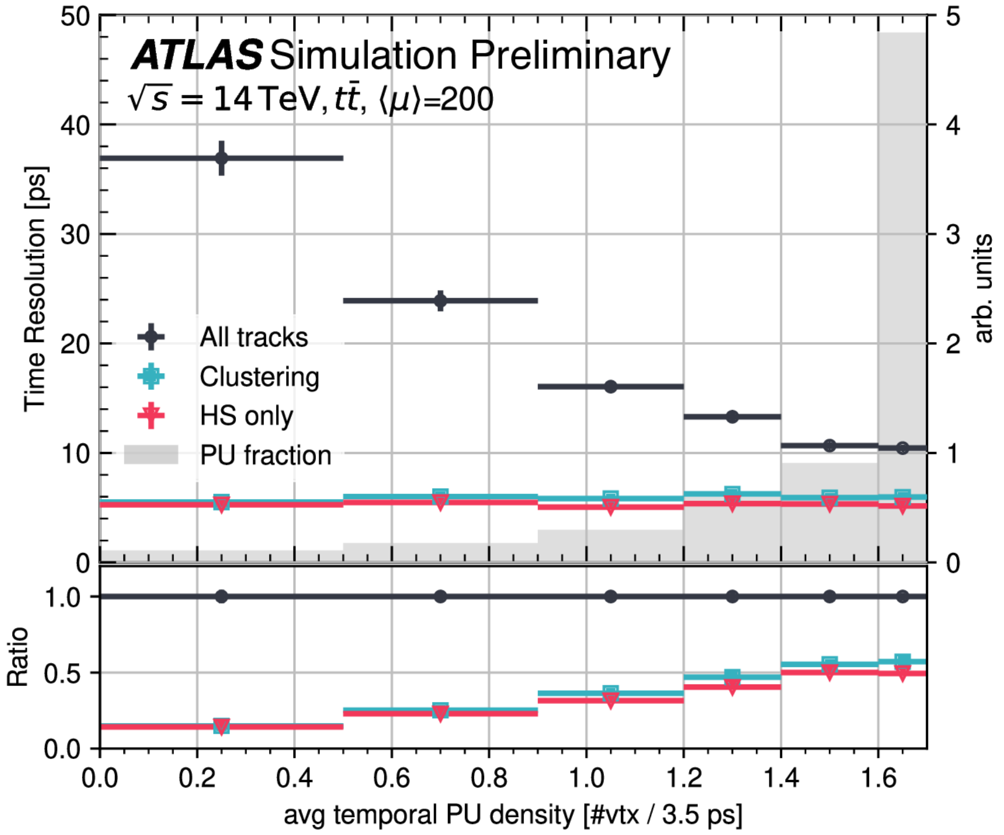
The average spatial pile-up density is defined as:

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

The average temporal pile-up density is defined as:

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





GNN

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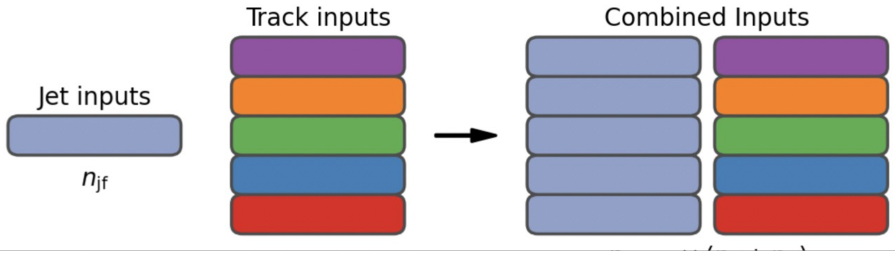
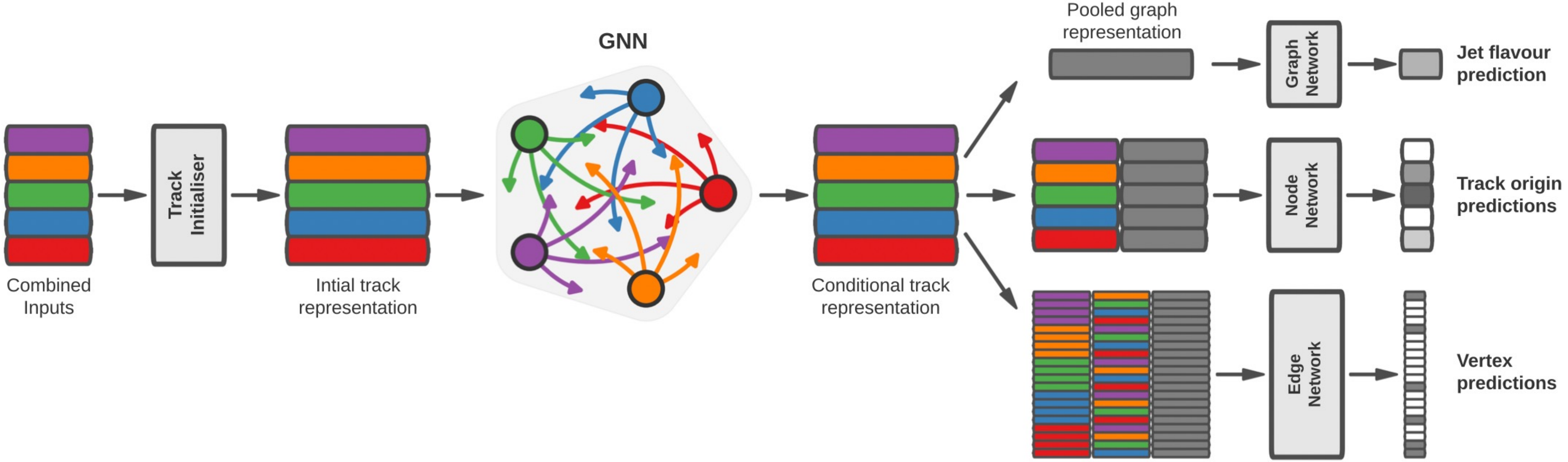


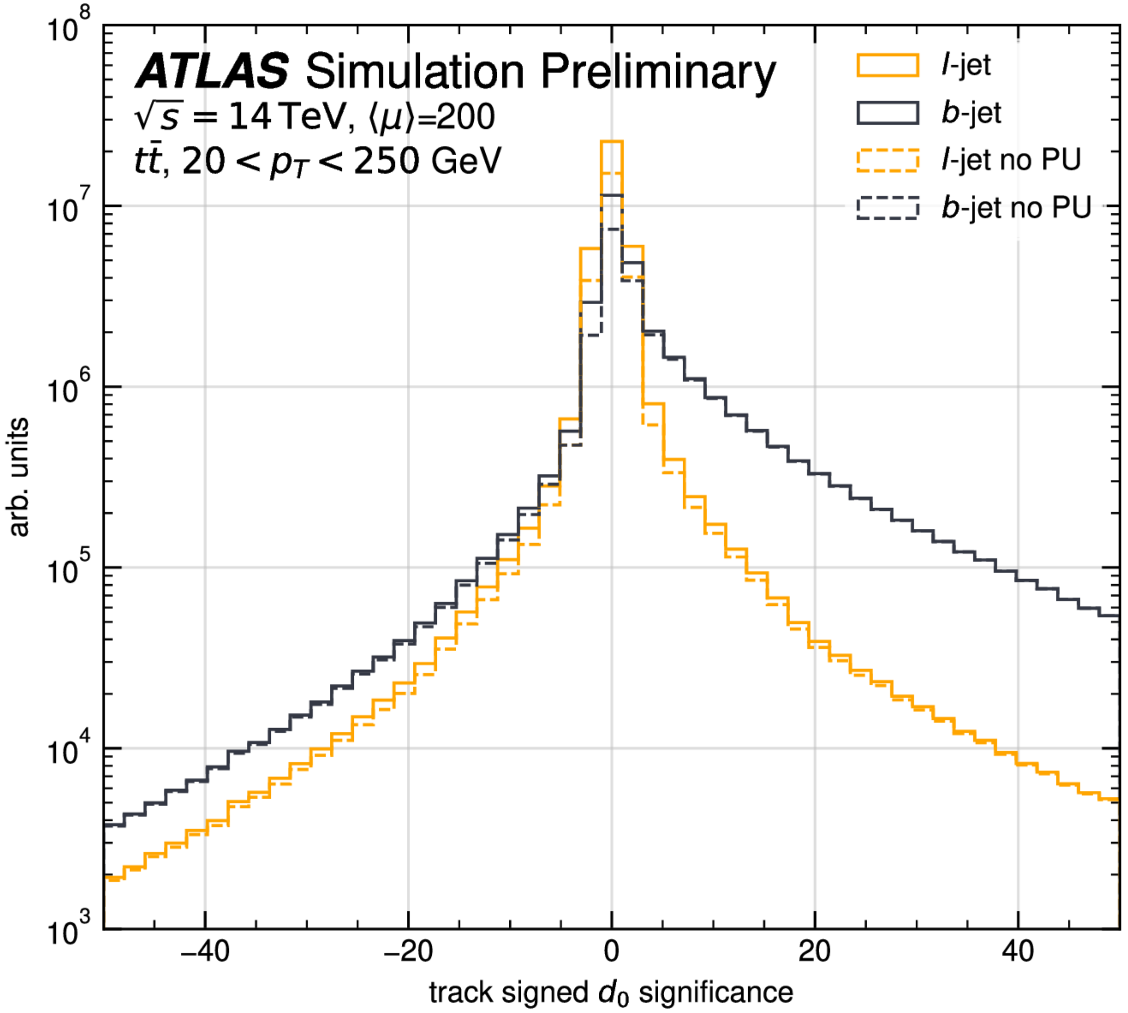


GNN

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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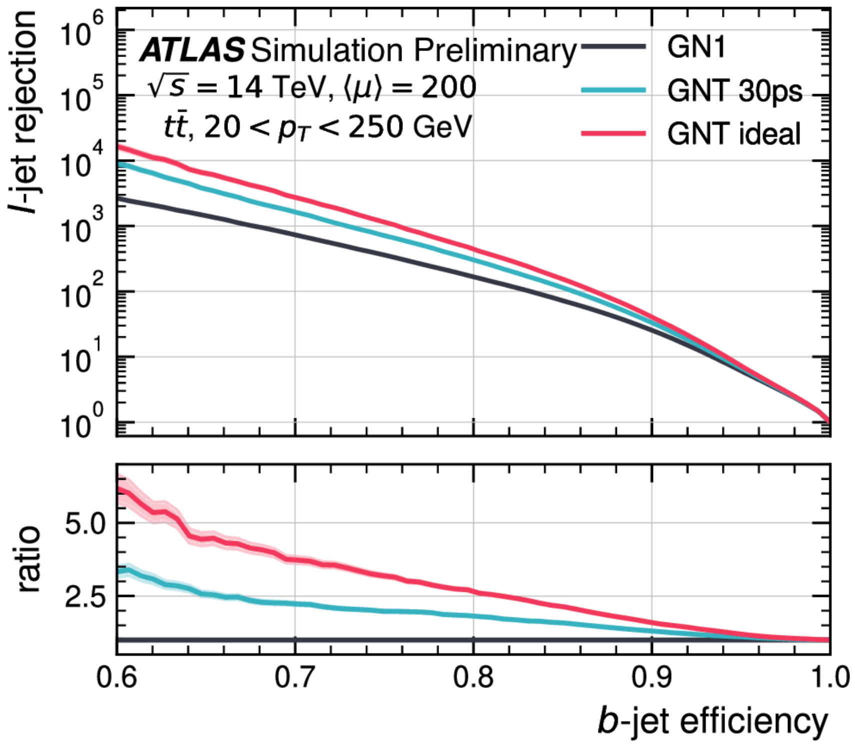
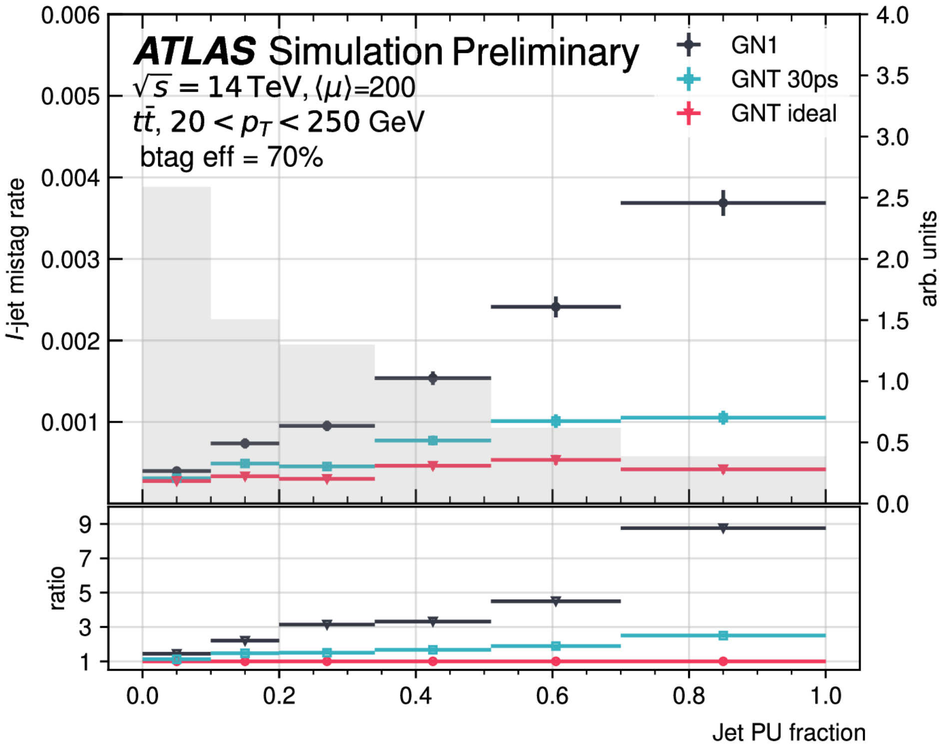
4D FTAG





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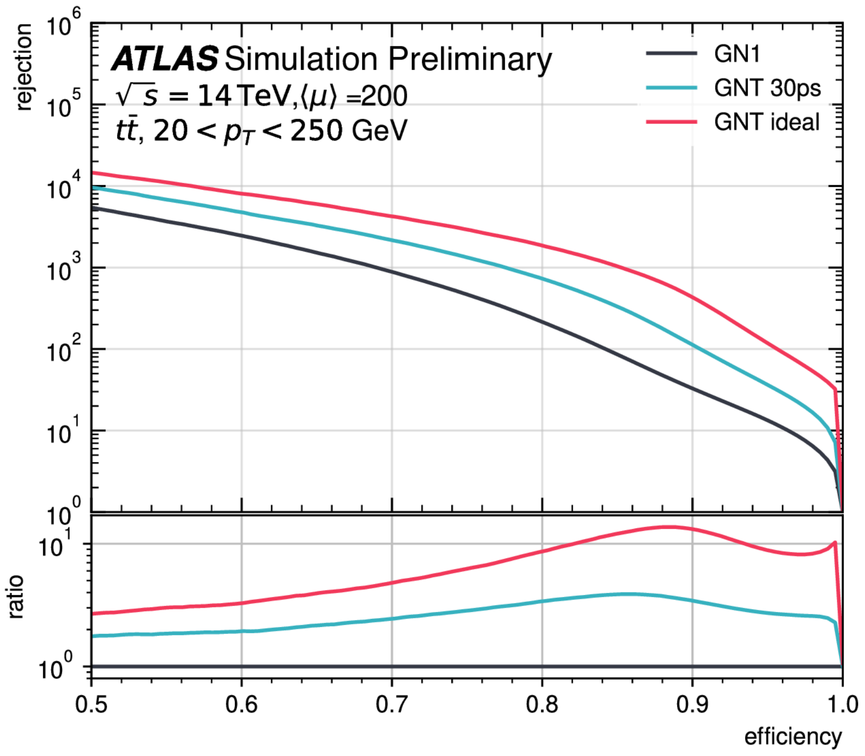
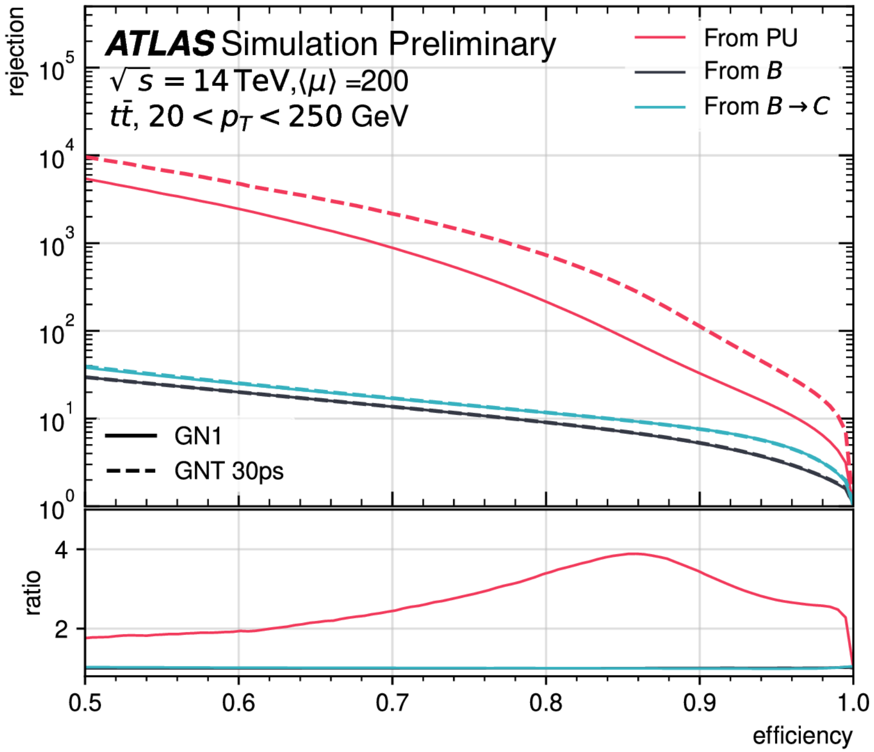
4D FTAG





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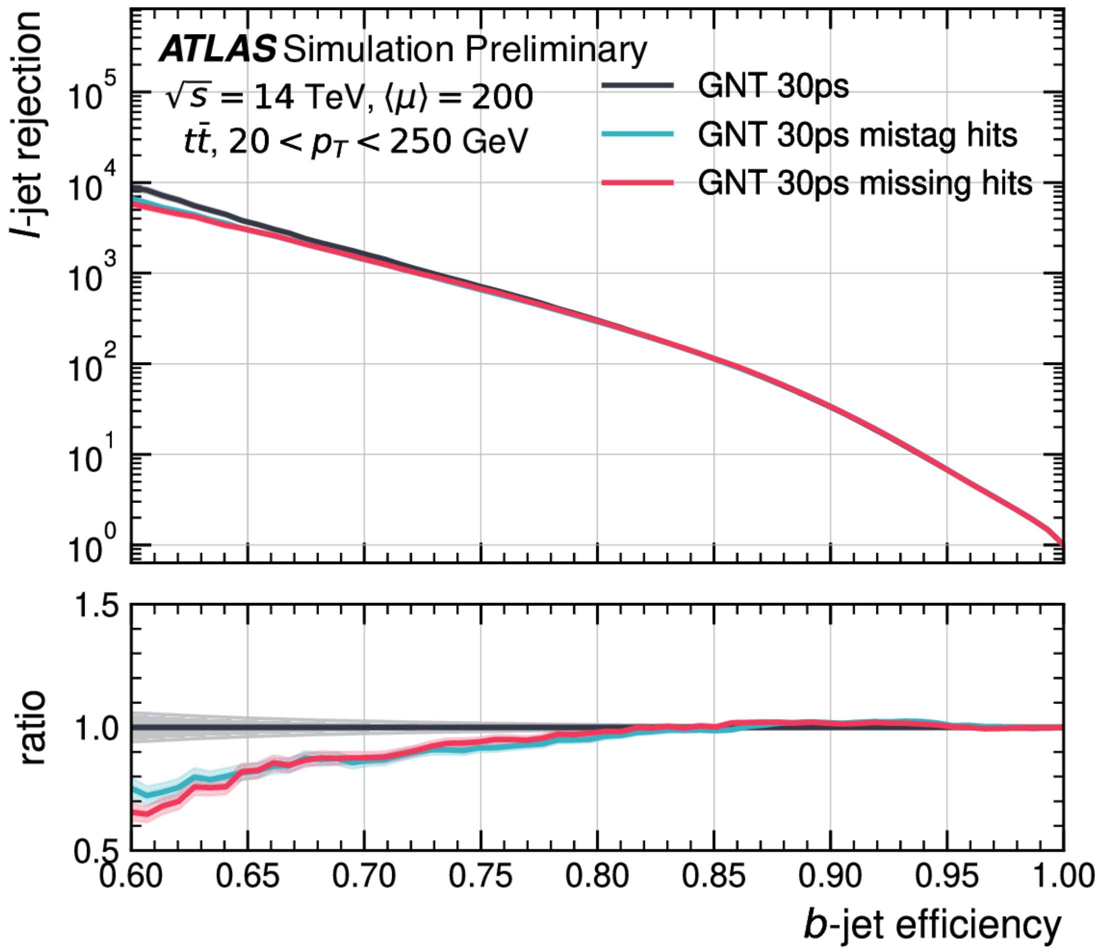
4D FTAG

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

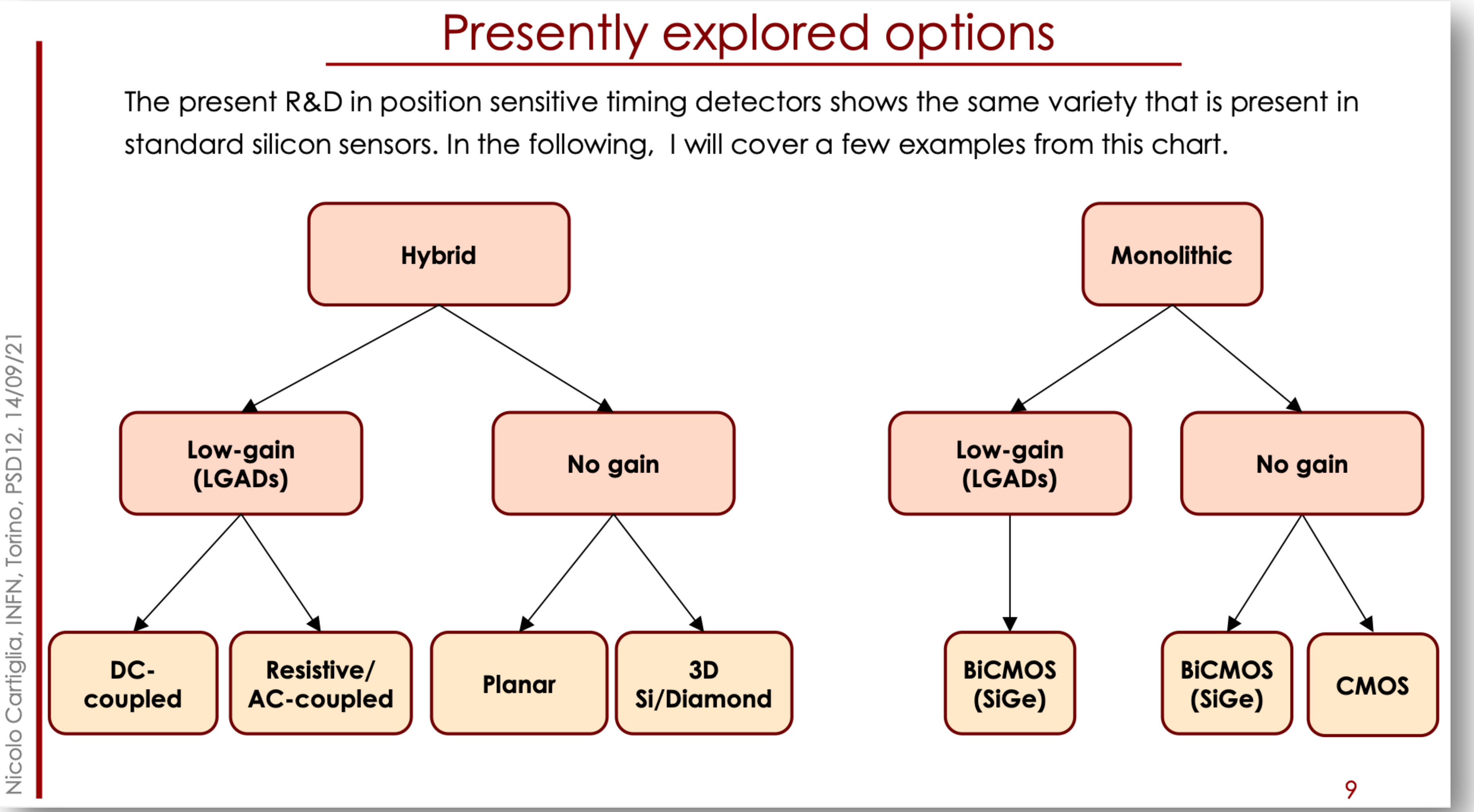
missing hit: assuming time only in 2nd layer; if a track has no hit the significance of the track is randomly emulated as HS

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



ATL-PHYS-PUB-2023-023

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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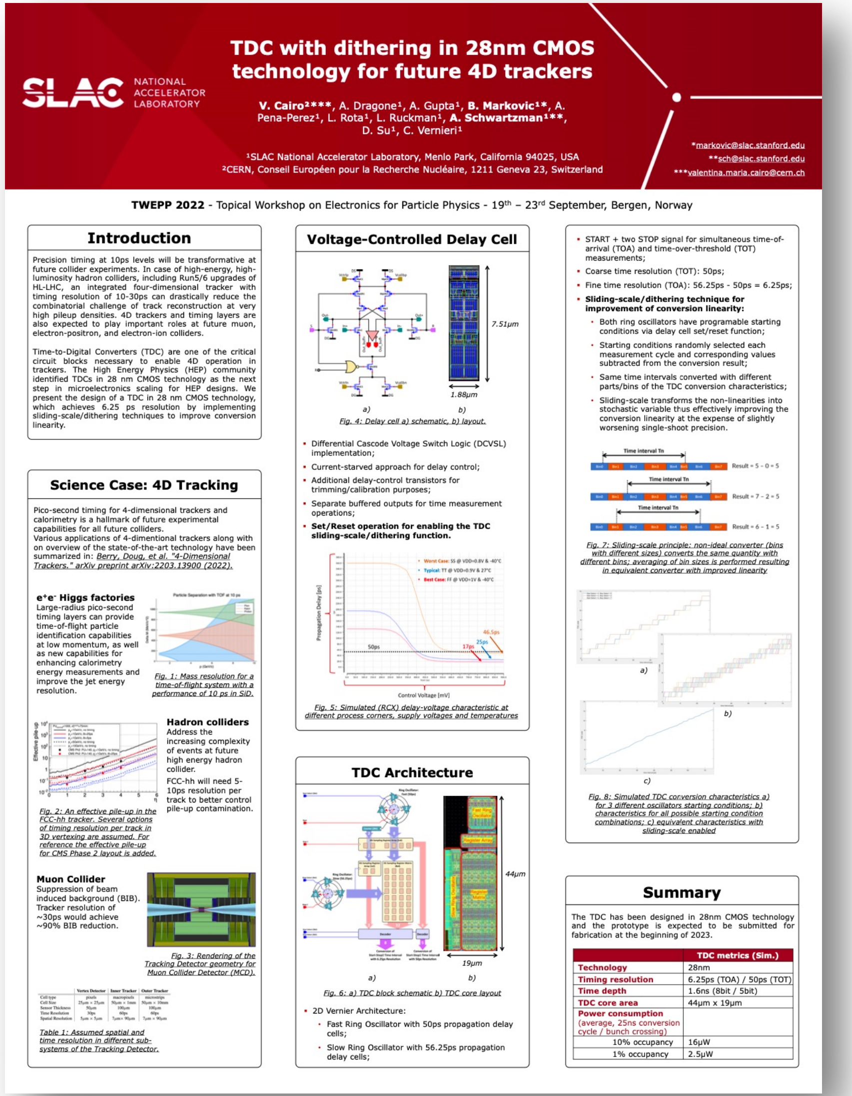
Abstract: Samples of the monolithic silicon pixel ASIC prototype produced in 2022 within the framework of the Horizon 2020 MONOLITH ERC Advanced project were irradiated with 70 MeV protons up to a fluence of 1×10^{16} n_{eq}/cm^2, and then tested using a beam of 120 GeV/c pions. The ASIC contains a matrix 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]



TDC with dithering in 28nm CMOS technology for future 4D trackers

SLAC NATIONAL ACCELERATOR LABORATORY

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TWEPP 2022 - Topical Workshop on Electronics for Particle Physics - 19th – 23rd September, Bergen, Norway

Introduction

Precision timing at 10ps levels will be transformative at future collider experiments. In case of high-energy, high-luminosity hadron colliders, including Run5/6 upgrades of HL-LHC, an integrated four-dimensional tracker with timing resolution of 10-30ps can drastically reduce the combinatorial challenge of track reconstruction at very high pileup densities. 4D trackers and timing layers are also expected to play important roles at future muon, electron-positron, and electron-ion colliders.

Time-to-Digital Converters (TDC) are one of the critical circuit blocks necessary to enable 4D operation in trackers. The High Energy Physics (HEP) community identified TDCs in 28 nm CMOS technology as the next step in microelectronics scaling for HEP designs. We present the design of a TDC in 28 nm CMOS technology, which achieves 6.25 ps resolution by implementing sliding-scale/dithering techniques to improve conversion linearity.

Science Case: 4D Tracking

Pico-second timing for 4-dimensional trackers and calorimetry is a hallmark of future experimental capabilities for all future colliders.
Various applications of 4-dimentional trackers along with on overview of the state-of-the-art technology have been summarized in: *Berry, Doug, et al. "4-Dimensional Trackers." arXiv preprint arXiv:2203.13900 (2022).*

e^+e^- Higgs factories
Large-radius pico-second timing layers can provide time-of-flight particle identification capabilities at low momentum, as well as new capabilities for enhancing calorimetry energy measurements and improve the jet energy resolution.

Fig. 1: Mass resolution for a time-of-flight system with a performance of 10 ps in SiD.

Hadron colliders
Address the increasing complexity of events at future high energy hadron collider.
FCC-hh will need 5-10ps resolution per track to better control pile-up contamination.

Fig. 2: An effective pile-up in the FCC-hh tracker. Several options of timing resolution per track in 3D vertexing are assumed. For reference the effective pile-up for CMS Phase 2 layout is added.

Muon Collider
Suppression of beam induced background (BIB). Tracker resolution of ~30ps would achieve ~90% BIB reduction.

Fig. 3: Rendering of the Tracking Detector geometry for Muon Collider Detector (MCD).

	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	25μm × 25μm	50μm × 1mm	50μm × 10mm
Sensor Thickness	50μm	100μm	100μm
Time Resolution	30ps	60ps	60ps
Spatial Resolution	5μm × 5μm	7μm × 90μm	7μm × 90μm

Table 1: Assumed spatial and time resolution in different sub-systems of the Tracking Detector.

Voltage-Controlled Delay Cell

7.51μm
1.88μm
a) b)

Fig. 4: Delay cell a) schematic, b) layout.

- Differential Cascode Voltage Switch Logic (DCVSL) implementation;
- Current-starved approach for delay control;
- Additional delay-control transistors for trimming/calibration purposes;
- Separate buffered outputs for time measurement operations;
- **Set/Reset operation for enabling the TDC sliding-scale/dithering function.**

Worst Case: SS @ VDD=0.8V & -40°C
Typical: TT @ VDD=0.9V & 27°C
Best Case: FF @ VDD=1V & -40°C
Propagation Delay [ps]
50ps
17ps
25ps
46.5ps
Control Voltage [mV]

Fig. 5: Simulated (RCX) delay-voltage characteristic at different process corners, supply voltages and temperatures

TDC Architecture

44μm
19μm
a) b)

Fig. 6: a) TDC block schematic b) TDC core layout

- 2D Vernier Architecture:
  - Fast Ring Oscillator with 50ps propagation delay cells;
  - Slow Ring Oscillator with 56.25ps propagation delay cells;
- START + two STOP signal for simultaneous time-of-arrival (TOA) and time-over-threshold (TOT) measurements;
- Coarse time resolution (TOT): 50ps;
- Fine time resolution (TOA): 56.25ps - 50ps = 6.25ps;
- **Sliding-scale/dithering technique for improvement of conversion linearity:**
  - Both ring oscillators have programable starting conditions via delay cell set/reset function;
  - Starting conditions randomly selected each measurement cycle and corresponding values subtracted from the conversion result;
  - Same time intervals converted with different parts/bins of the TDC conversion characteristics;
  - Sliding-scale transforms the non-linearities into stochastic variable thus effectively improving the conversion linearity at the expense of slightly worsening single-shoot precision.

Time interval Tn — Result = 5 - 0 = 5
Time interval Tn — Result = 7 - 2 = 5
Time interval Tn — Result = 6 - 1 = 5

Fig. 7: Sliding-scale principle: non-ideal converter (bins with different sizes) converts the same quantity with different bins; averaging of bin sizes is performed resulting in equivalent converter with improved linearity

a) b) c)

Fig. 8: Simulated TDC conversion characteristics a) for 3 different oscillators starting conditions; b) characteristics for all possible starting condition combinations; c) equivalent characteristics with sliding-scale enabled

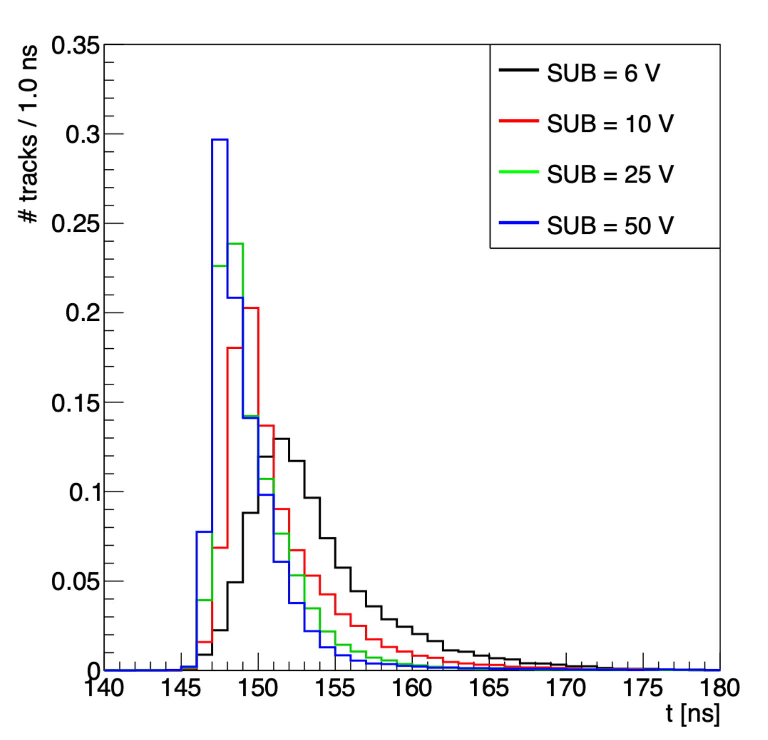
Summary

The TDC has been designed in 28nm CMOS technology and the prototype is expected to be submitted for fabrication at the beginning of 2023.

	TDC metrics (Sim.)
Technology	28nm
Timing resolution	6.25ps (TOA) / 50ps (TOT)
Time depth	1.6ns (8bit / 5bit)
TDC core area	44μm x 19μm
Power consumption (average, 25ns conversion cycle / bunch crossing)	
10% occupancy	16μW
1% occupancy	2.5μW

Technologies

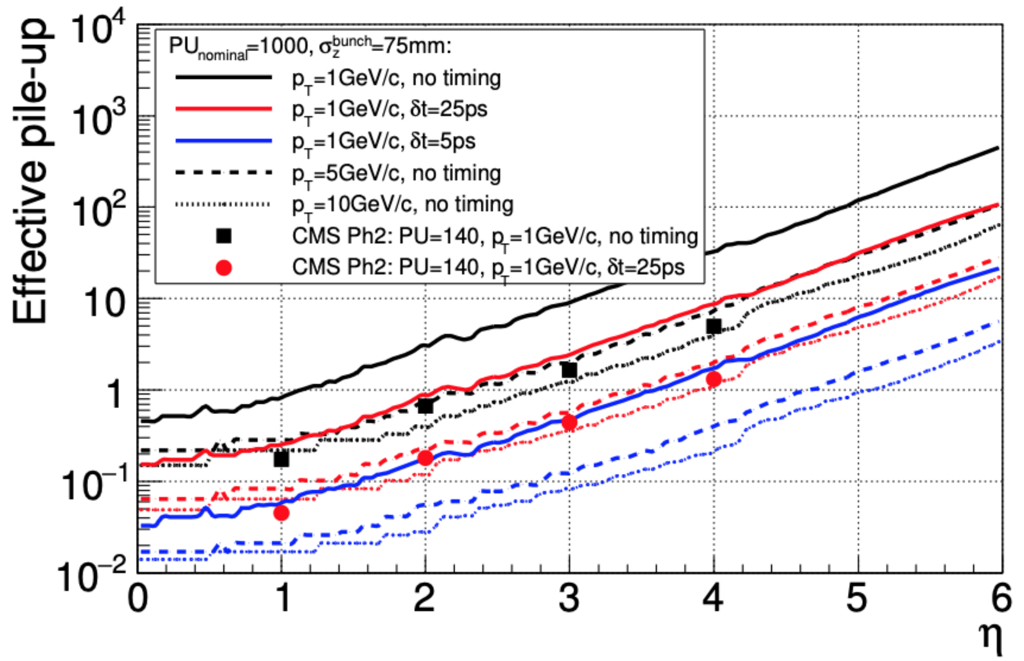
- MALTA
  https://twiki.cern.ch/twiki/bin/viewauth/Atlas/MaltaApprovedPlots#Time_resolution



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



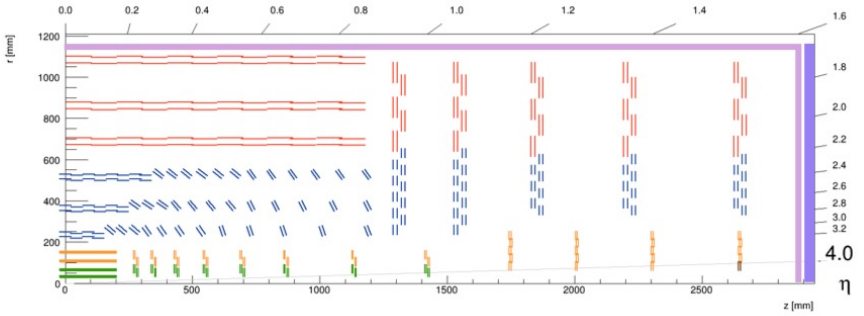
- Studies on primary vertexing at the FCC-hh demonstrate that 2D vertexing with an extreme timing resolution of 5 10 ps per track is essential to keep the levels of effective pile-up under control at large pseudorapidities (|η| > 3) which would otherwise reach level of tens or hundreds leading to large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

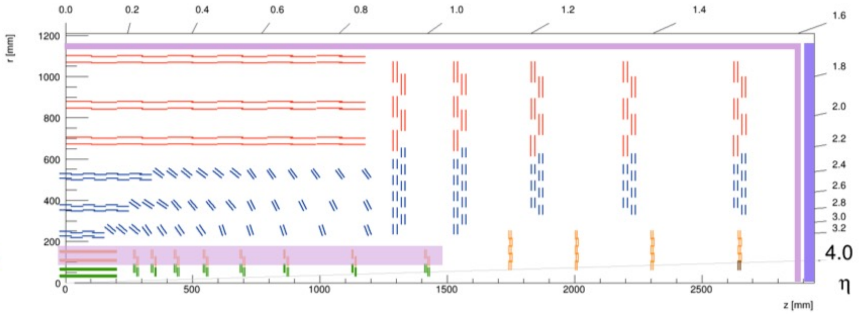
CMS installing the timing layer outside the tracker:

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



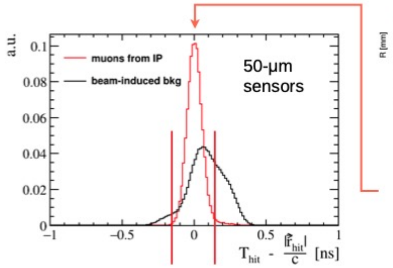
CMS might add 1-2 more timing layers closer to the IP

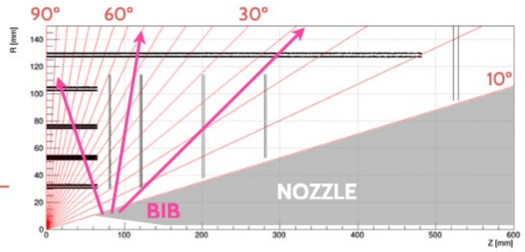
- **σ_t = 30-60ps ?** ← depends on technology progress
  granularity + radiation hardness + material budget constraints
- **conceptually possible for the Phase 3 upgrade** (→2036)
  Inner Tracker will have to be replaced to sustain the radiation damage throughout the HL-LHC program



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.

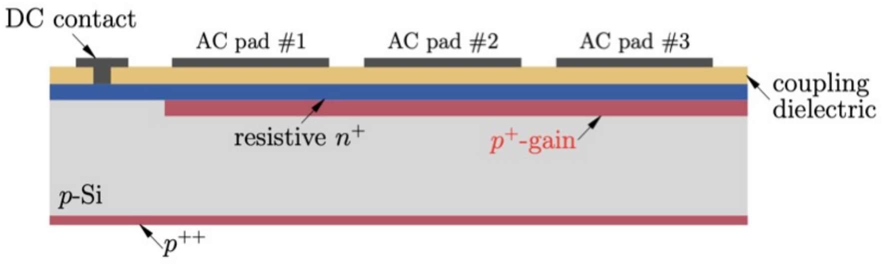


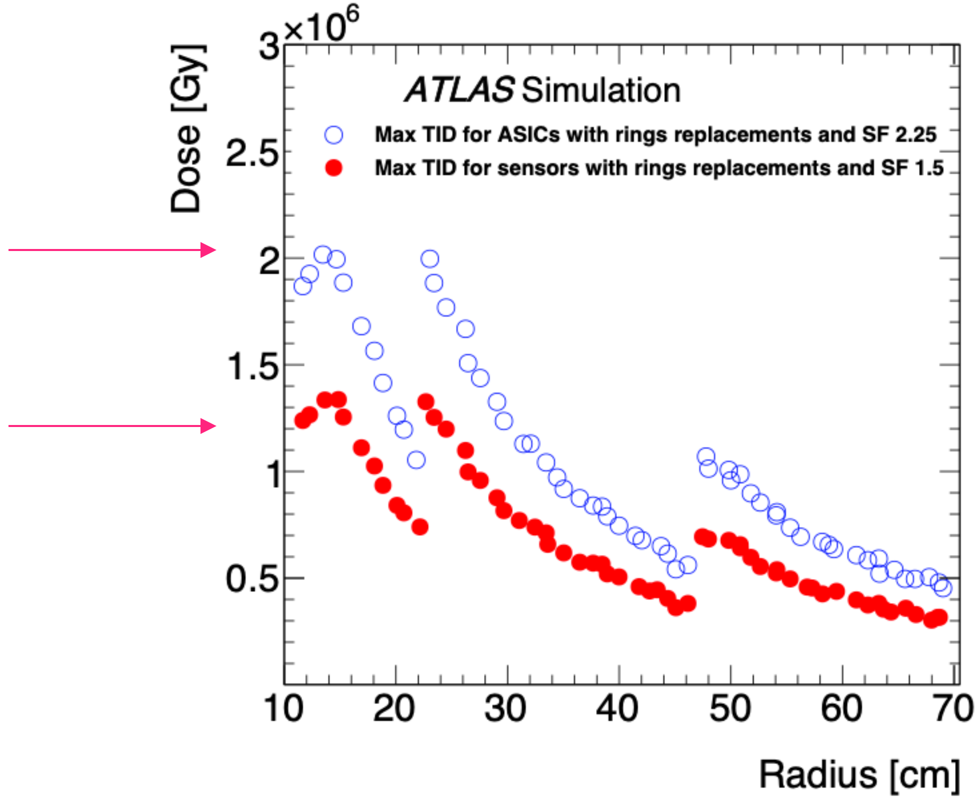
Figure 1: Cross-section of RSDs internal structure: their properties are based on the combination of a resistive n^+ layer and a coupling dielectric oxide, allowing a local AC-coupling.

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!

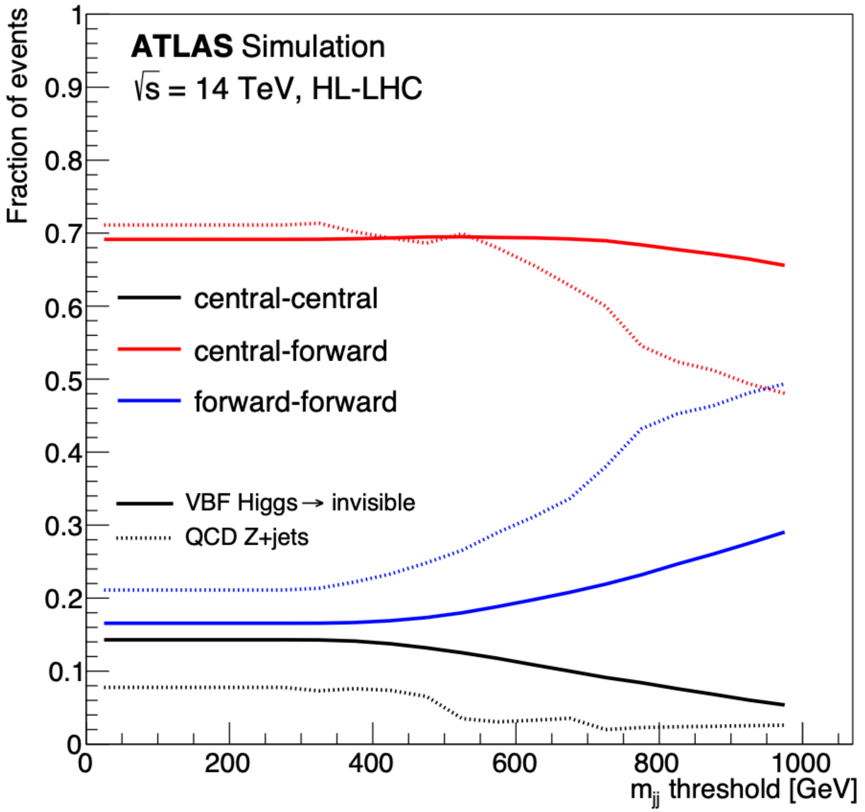
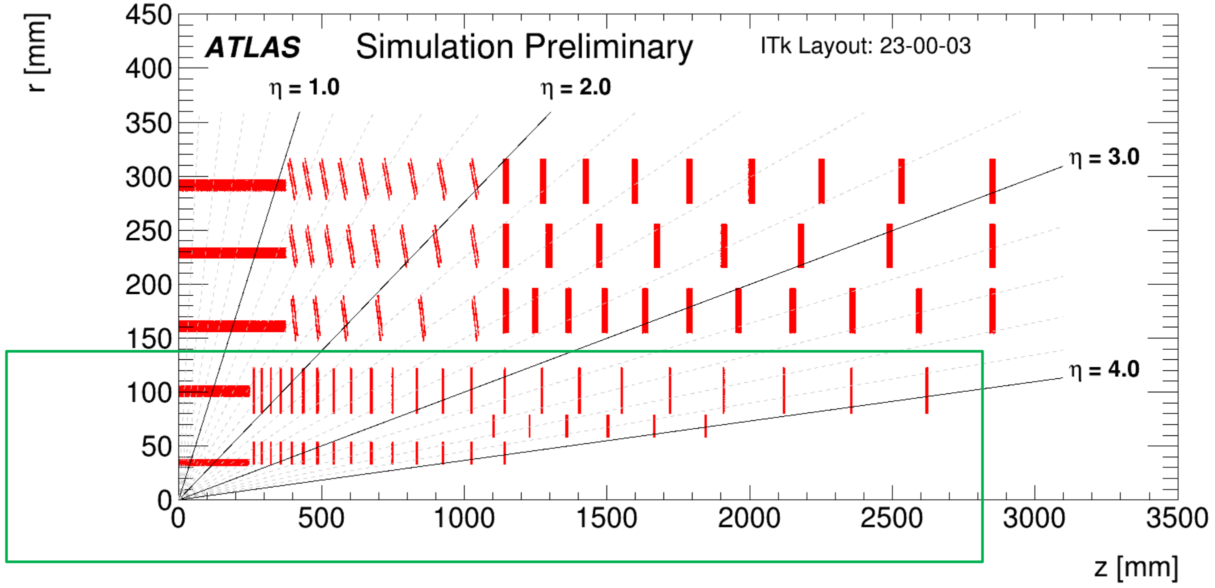
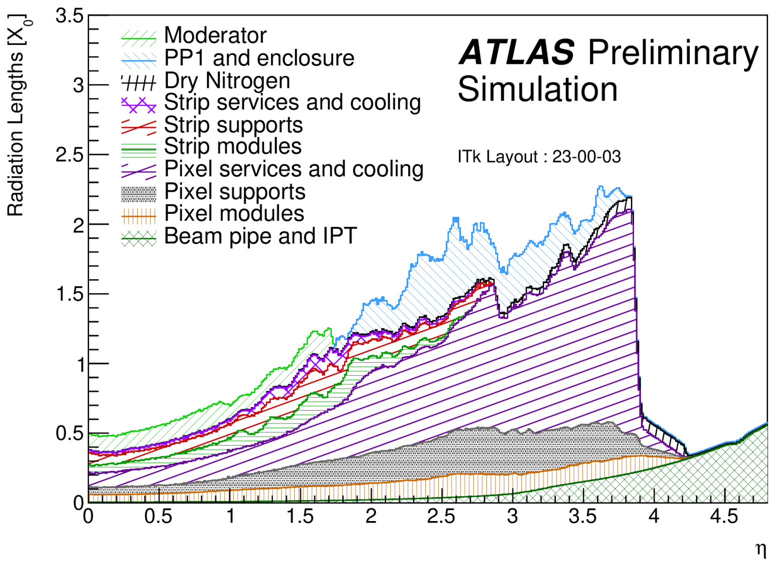


Figure 3.24: The dashed line shows the fraction of signal VBF $H \to$ invisible and Z+jet background events as a function of a m_{jj} threshold after a loose VBF preselection. Forward jets are those with $|\eta| > 2.4$. Solid (dotted) lines correspond to VBF $H \to$ invisible (Z+jet) events. The fraction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

DETECTOR LAYOUT STUDIES

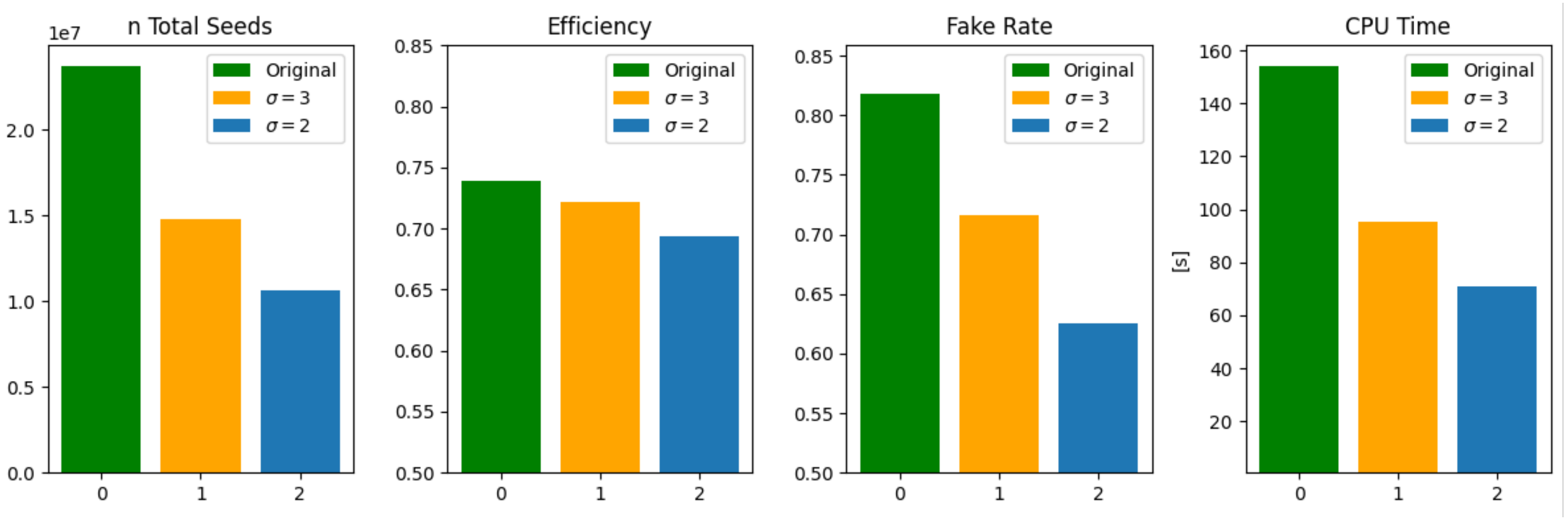
A change in tracking technology would imply changes in material budget due to different power, cooling, data transmission etc and would require a re-evaluation of the optimal detector layout





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

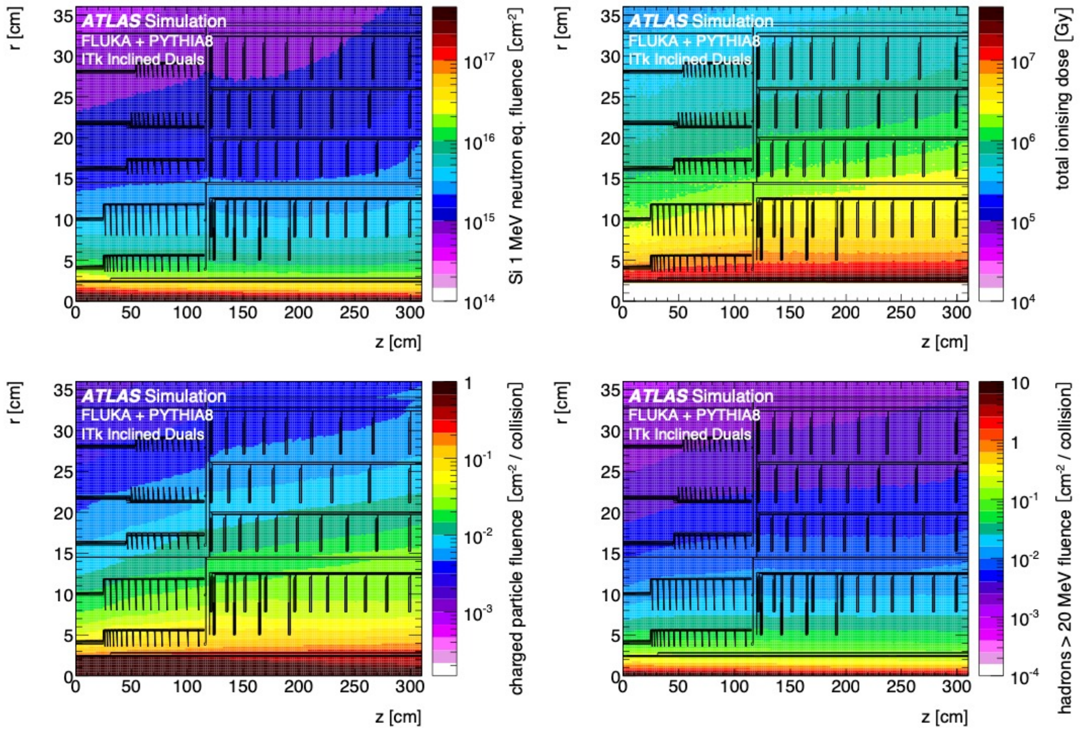
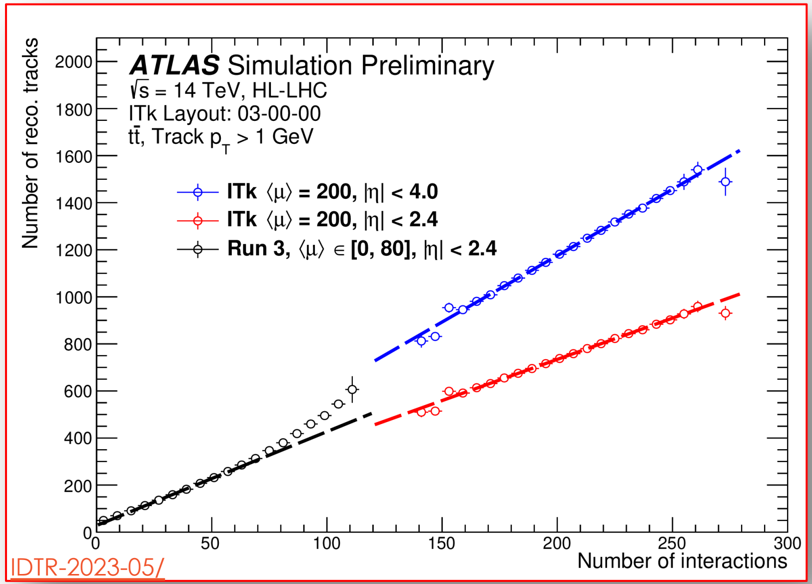


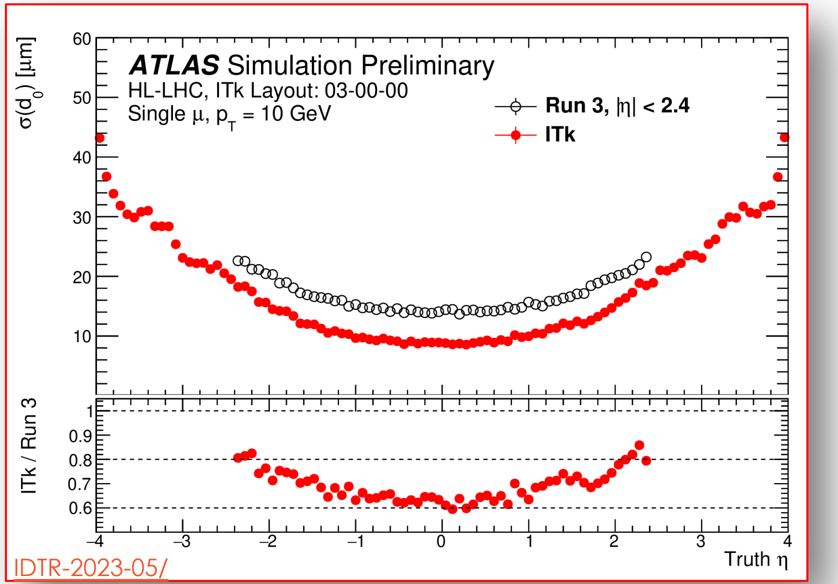
Figure 2.18: The fluence and dose distributions for the Pixel Detector. **Top left**: 1 MeV neutron equivalent fluence. **Top right**: Total ionising dose. **Bottom left**: Charged particle fluence. **Bottom right**: Hadron fluence for energies greater than 20 MeV. The top two lots are normalised to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

HL-LHC TRACKING

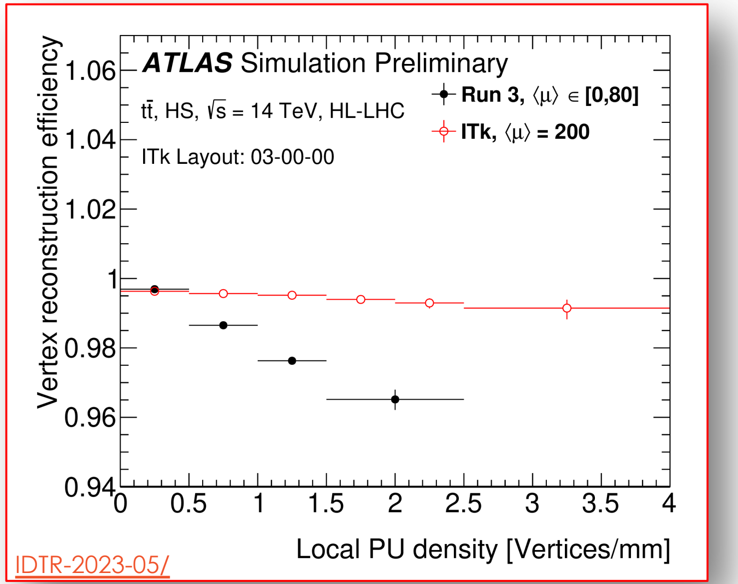
A detector designed to be pile-up robust, and algorthms designed to leverage such features



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



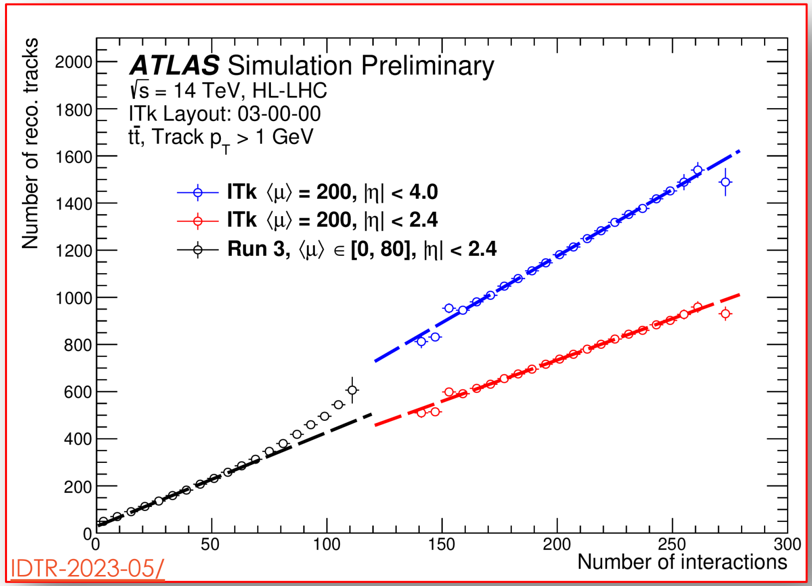
Improved IP resolution



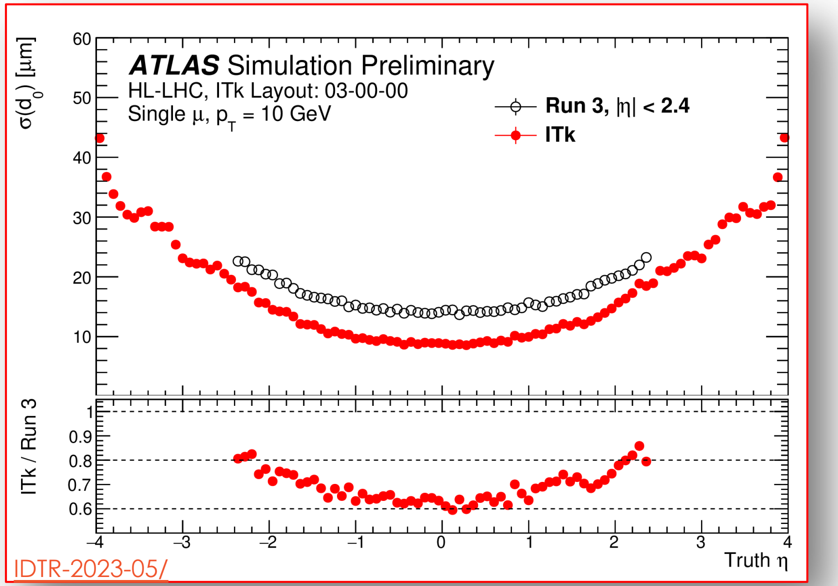
More PU-robust vertexing

HL-LHC TRACKING

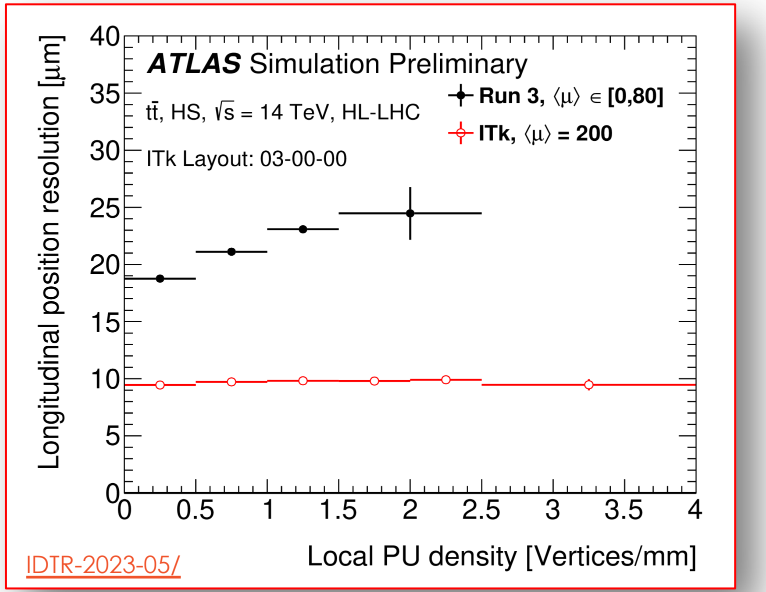
A detector designed to be pile-up robust, and algorthms designed to leverage such features



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

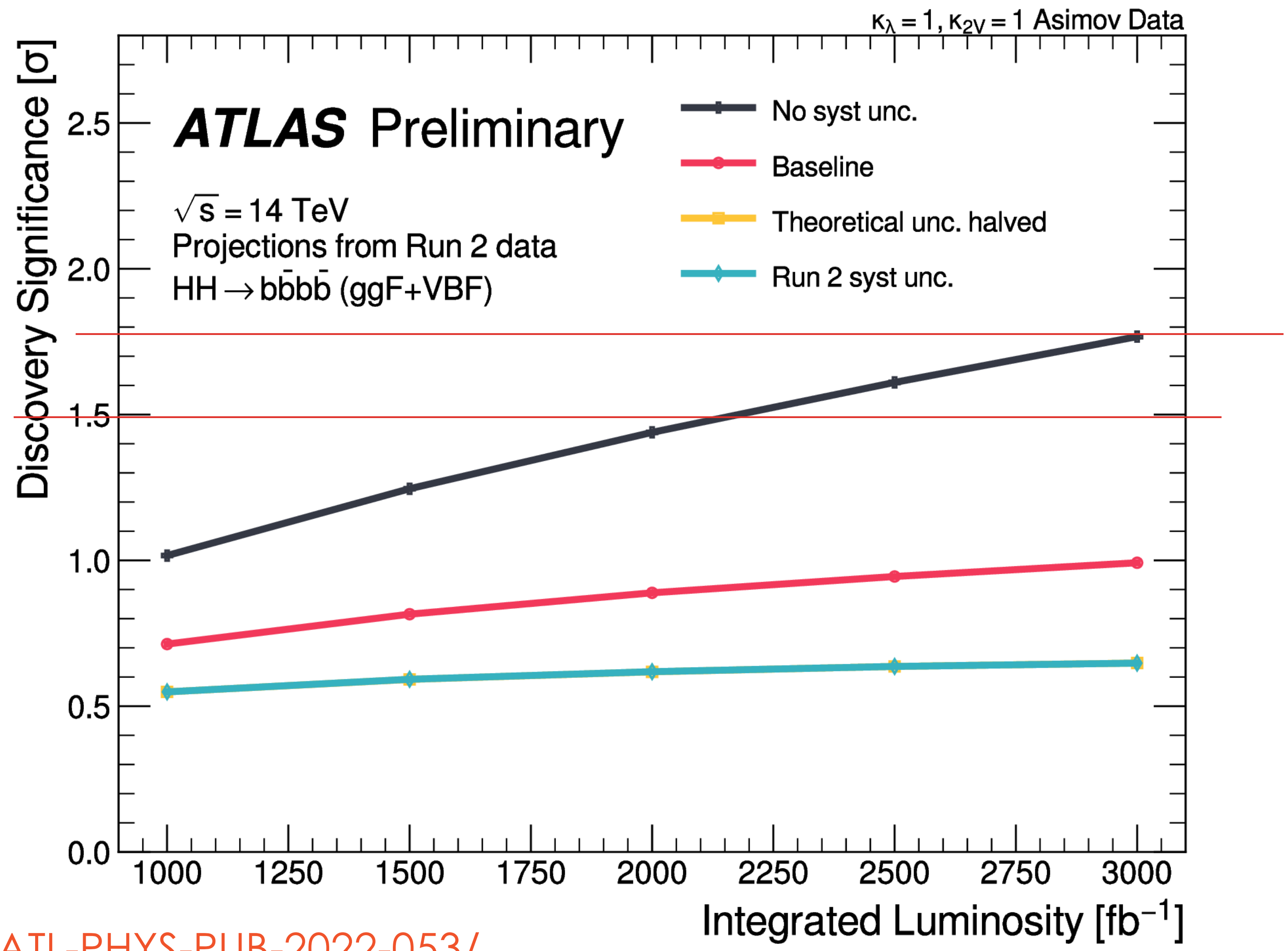


Improved IP resolution



More PU-robust vertexing

HOW DOES HH LOOK IN HL-LHC?



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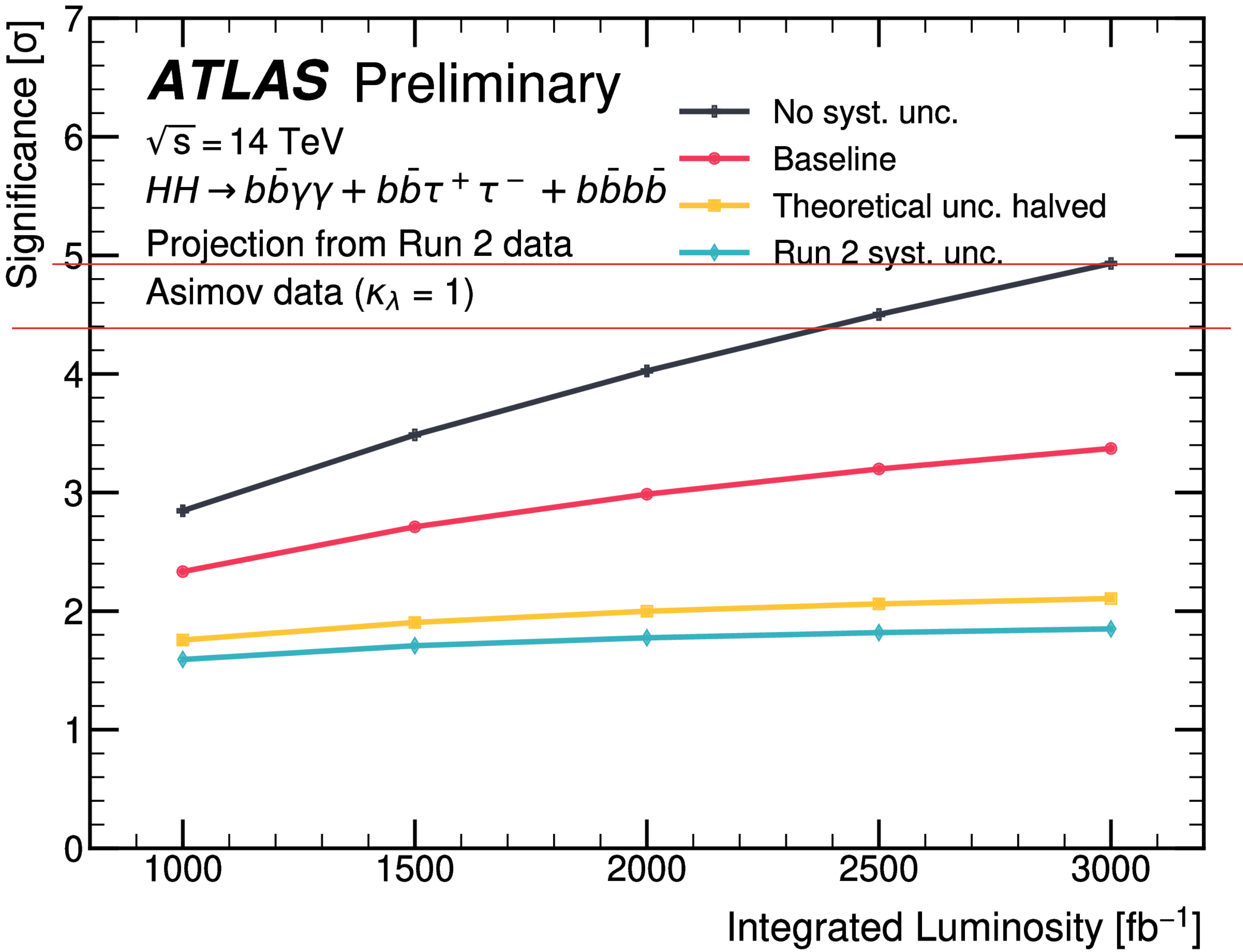
HOW DOES HH LOOK IN HL-LHC?



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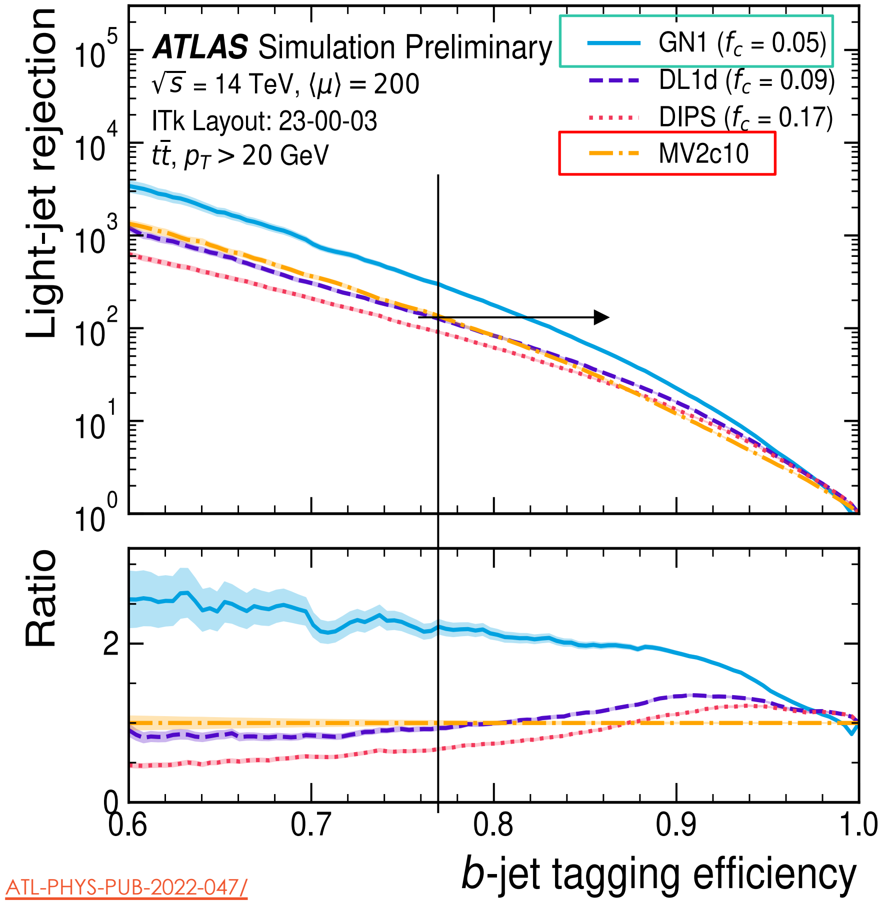
HOW DOES HH LOOK IN HL-LHC?

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



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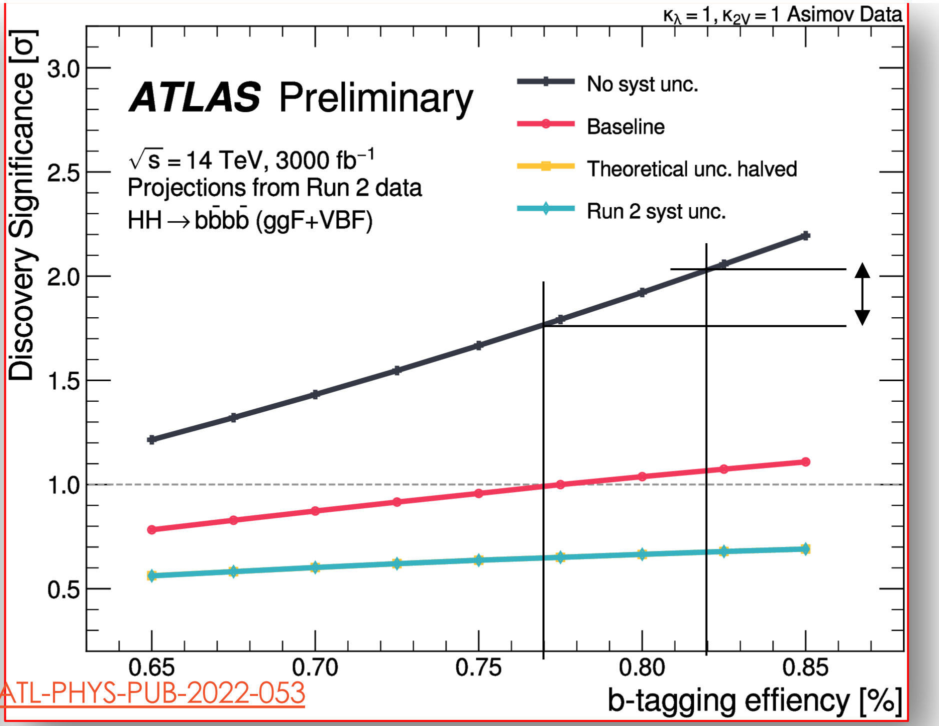
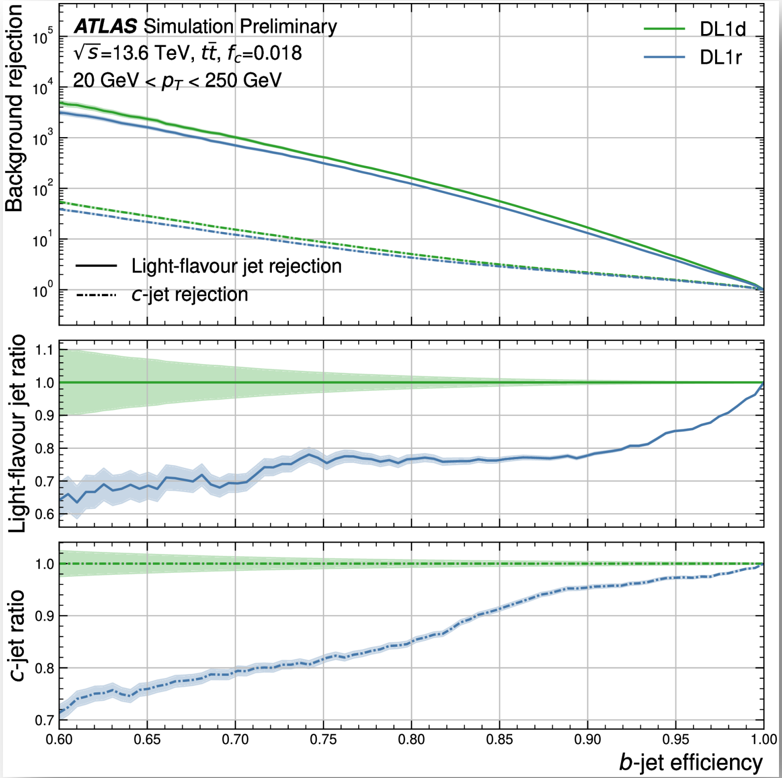


ATL-PHYS-PUB-2022-053

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

RUN 3 b-TAGGING



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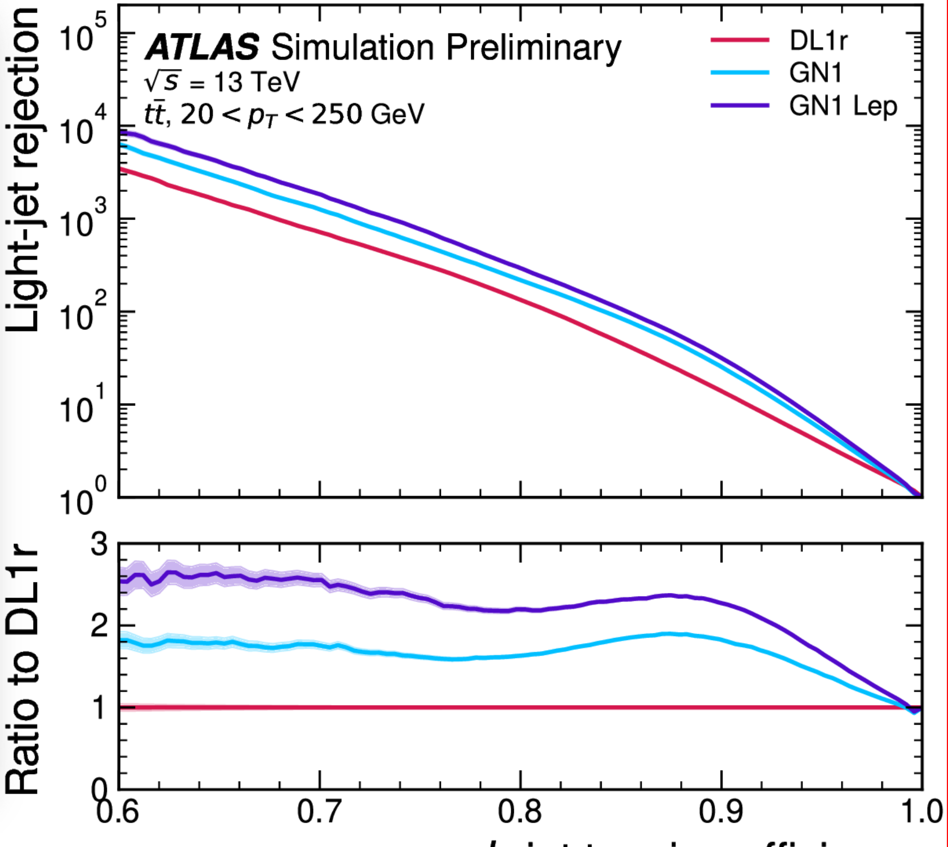

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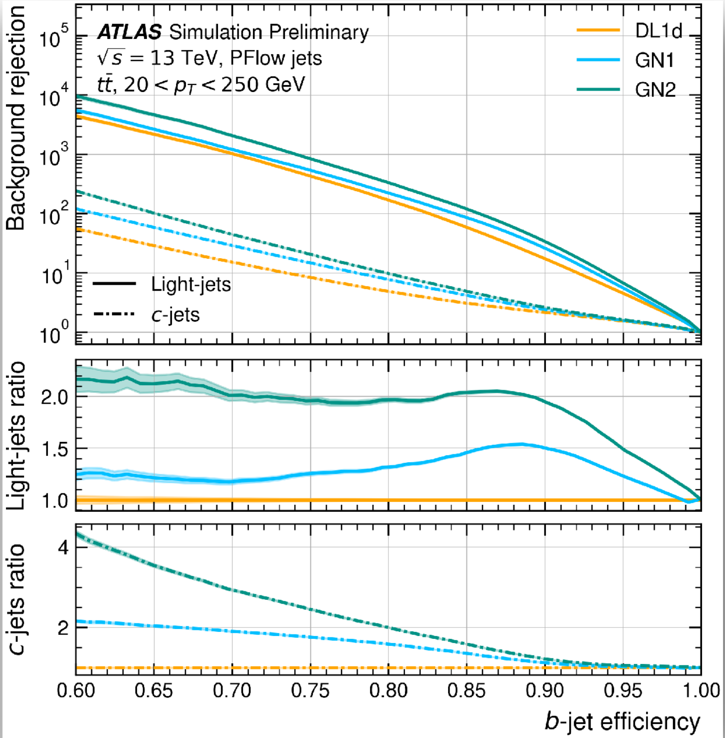


FTAG-2023-01/

ILD TPC & TOF

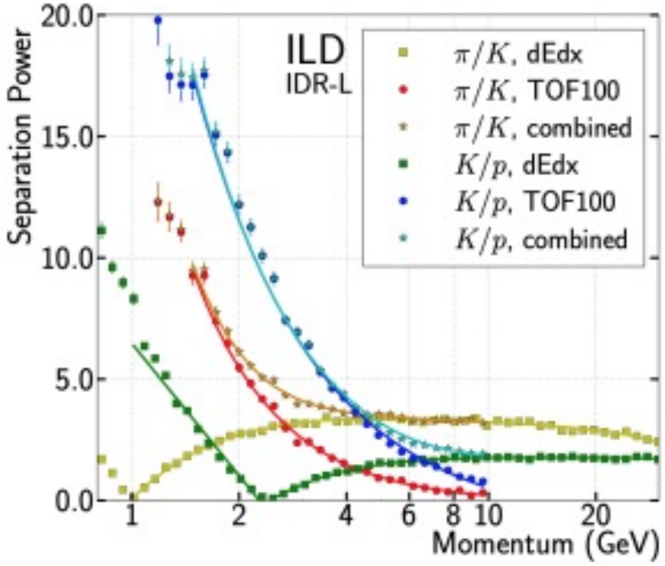
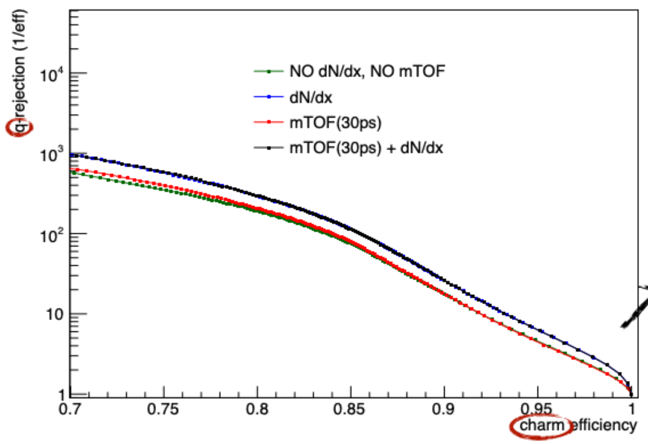


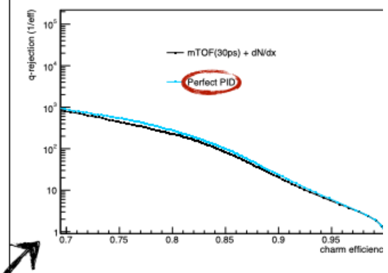
Figure 3: From Ref. [19]. Particle separation power for π/k and K/p based on the dE/dx measurement in the TPC and on a time-of-flight estimator from the first ten ECAL layers. The separation power obtained when the information from the two systems is combined is also shown.

FCC

https://indico.in2p3.fr/event/32629/contributions/142638/attachments/87407/131939/Sciandra_ECFA2024_10_09_24.pdf

Charm Tagging & Light Rejection



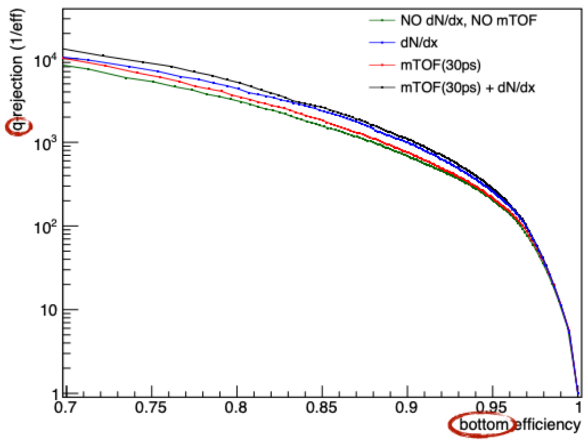


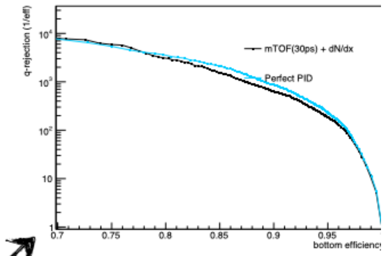
"Enhancement" due to ideal PID, significant but smaller than relative gain from dN/dx itself

- **dN/dx dominates** again, as expected from kinematic regime of *ZH* events
- **Visible** contribution from **TOF, in absence of dN/dx**

[A. Sciandra | Tagging & Detector Requirements @FCC-ee | ECFA | Oct 9, 2024] 13

Bottom Tagging & Light Rejection





As compared to charm, larger "gain" from ideal PID

- Most of PID gain from dN/dx, but…
- **Significant contribution from TOF, with and without dN/dx!**
  - Benchmark: 80% efficiency -> light rejection 4400 (dN/dx) vs. 5100 (dN/dx+mTOF)

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