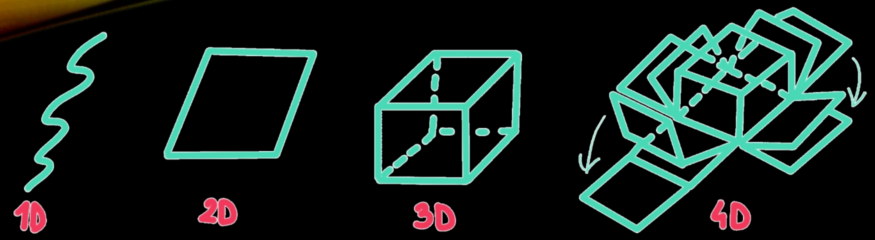


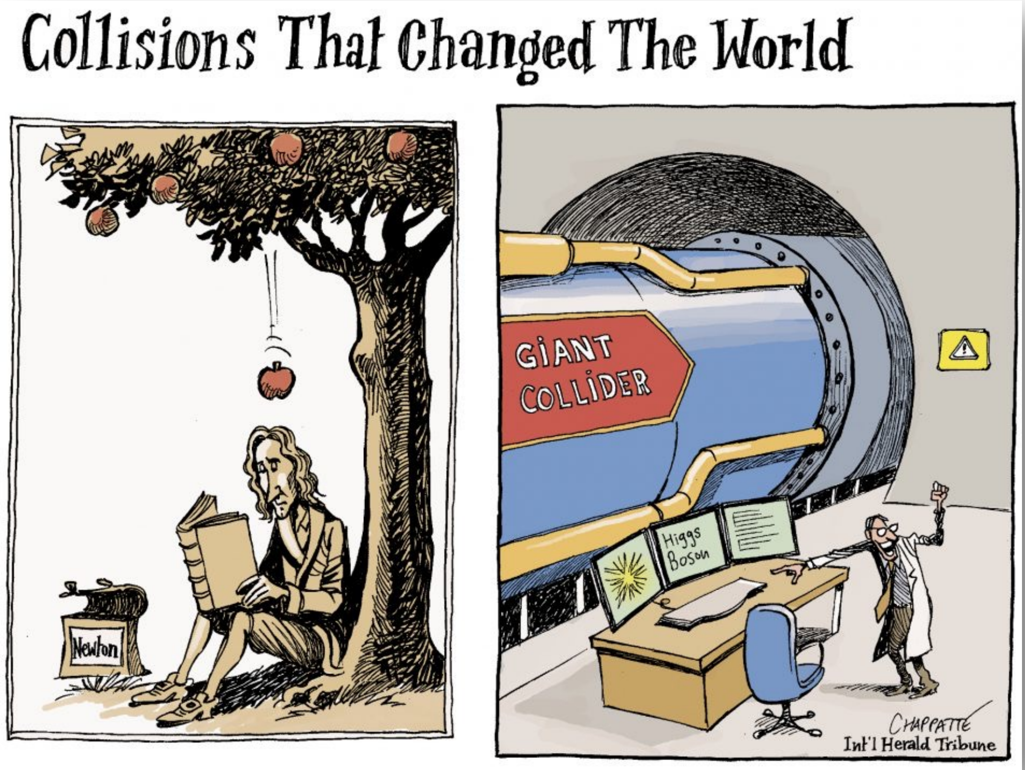
ATLAS 4D b-Tagging: status and prospects

第二届粒子物理实验径迹重建研讨会 2nd workshop on Tracking in Particle Physics Experiments

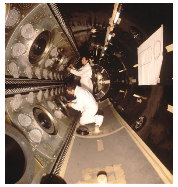
July 22nd, 2025

Valentina M.M. Cairo

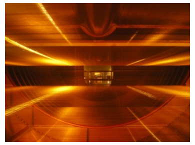
AT THE *HEART* OF COLLIDER PHYSICS: CHALLENGES AND BREAKTHROUGHS



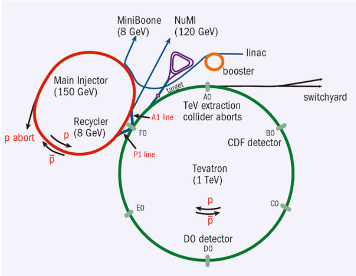
The weak neutral currents and the *bubble chamber* era

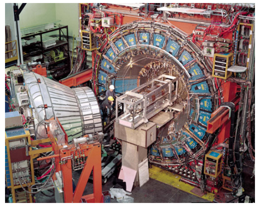


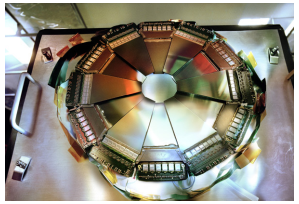
The W,Z bosons and the *drift chamber* era



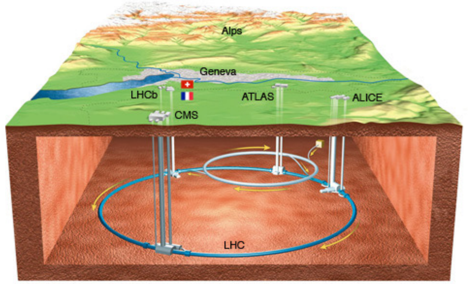
The top quark and the *silicon strip* era

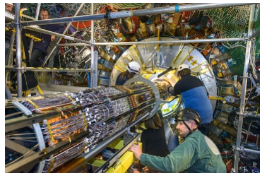


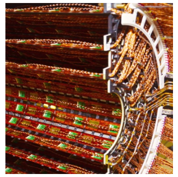


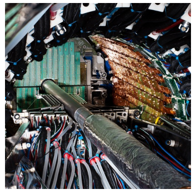


The Higgs boson (and more!) and the *silicon pixel* era



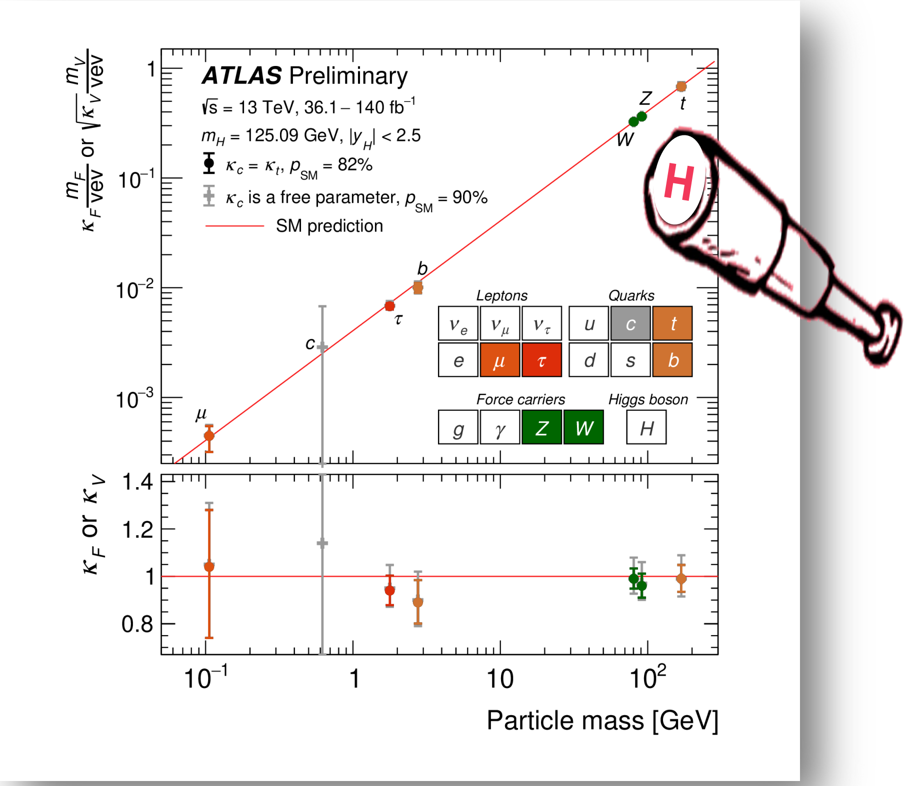






THE POST-HIGGS BOSON ERA

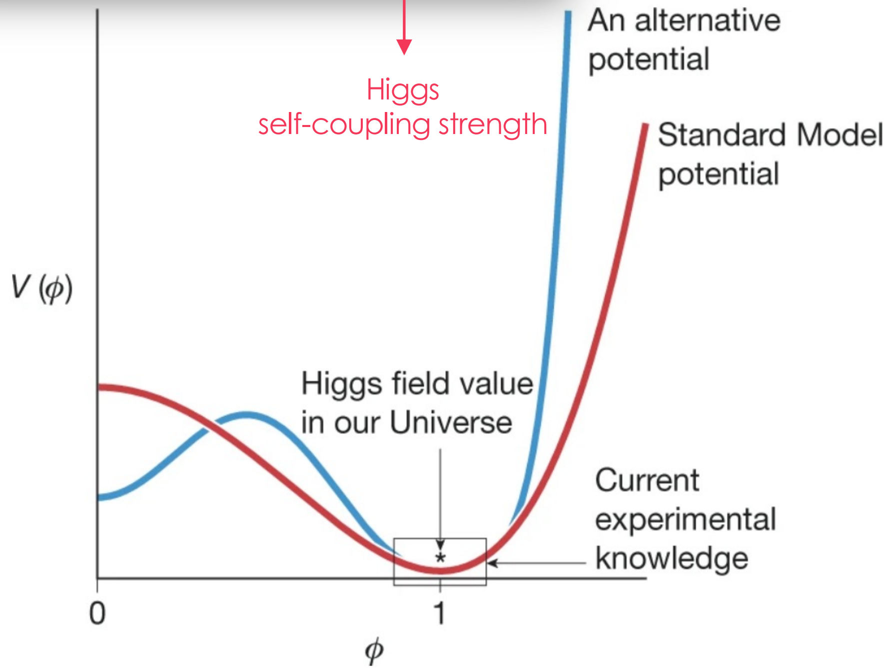
Key to addressing some of the most profound mysteries of the Universe is the measurement of the *Higgs boson couplings*



ATLAS-CONF-2025-006

$$V(\phi^\dagger\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

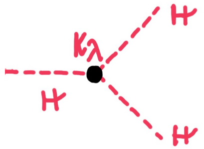
Higgs self-coupling strength



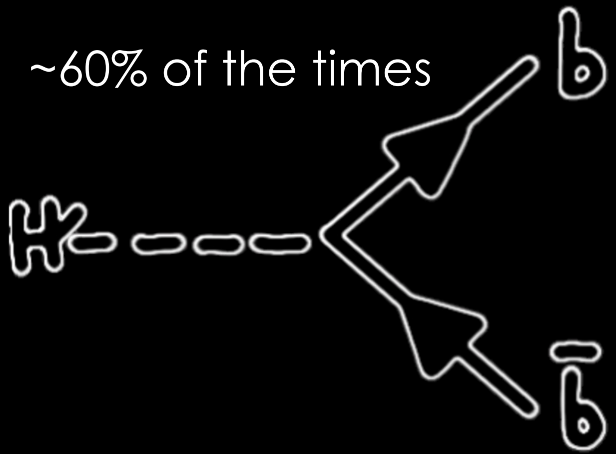
Nature 607, pages 41-47 (2022), G.Salam et al.

How does the Higgs boson couple to itself?

Higgs boson pairs give direct access to λ

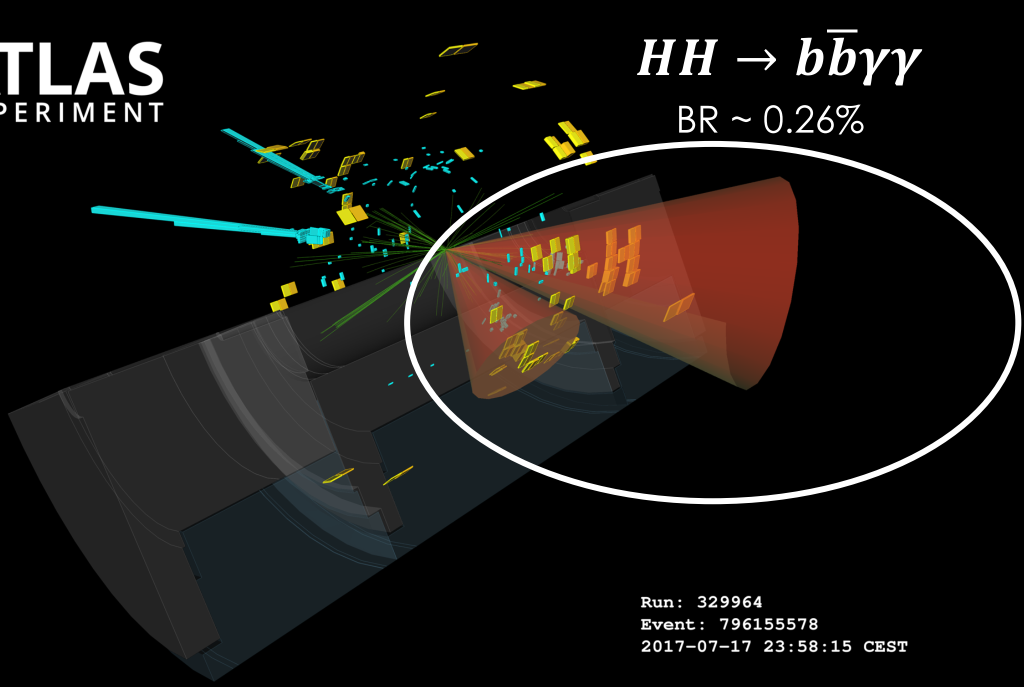


~60% of the times



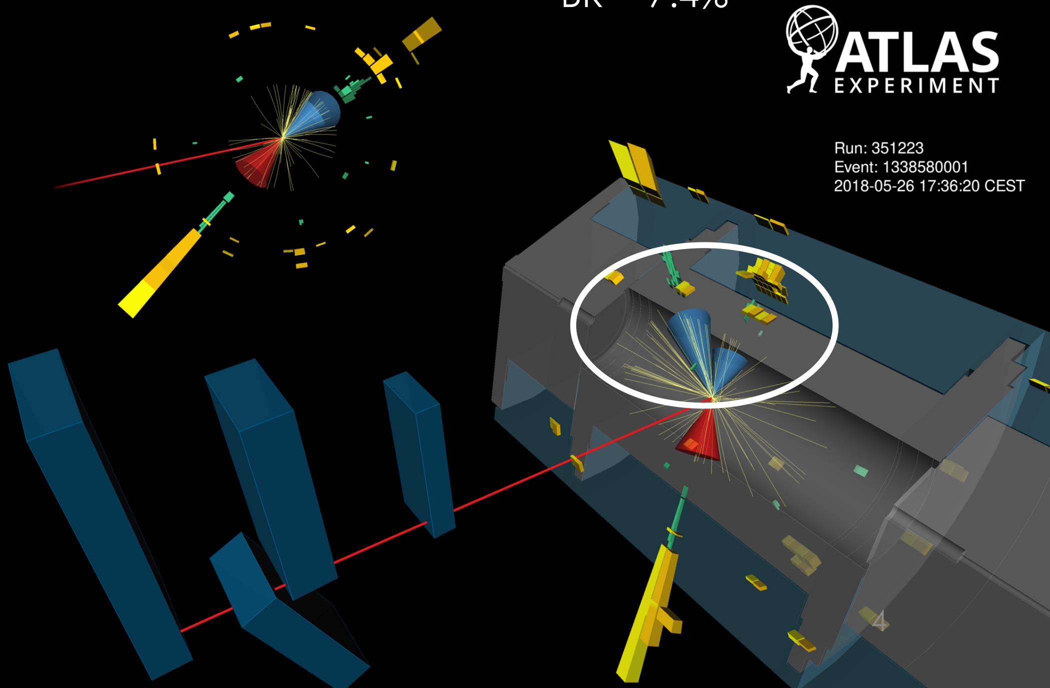
$HH \to b\bar{b}\gamma\gamma$

BR ~ 0.26%



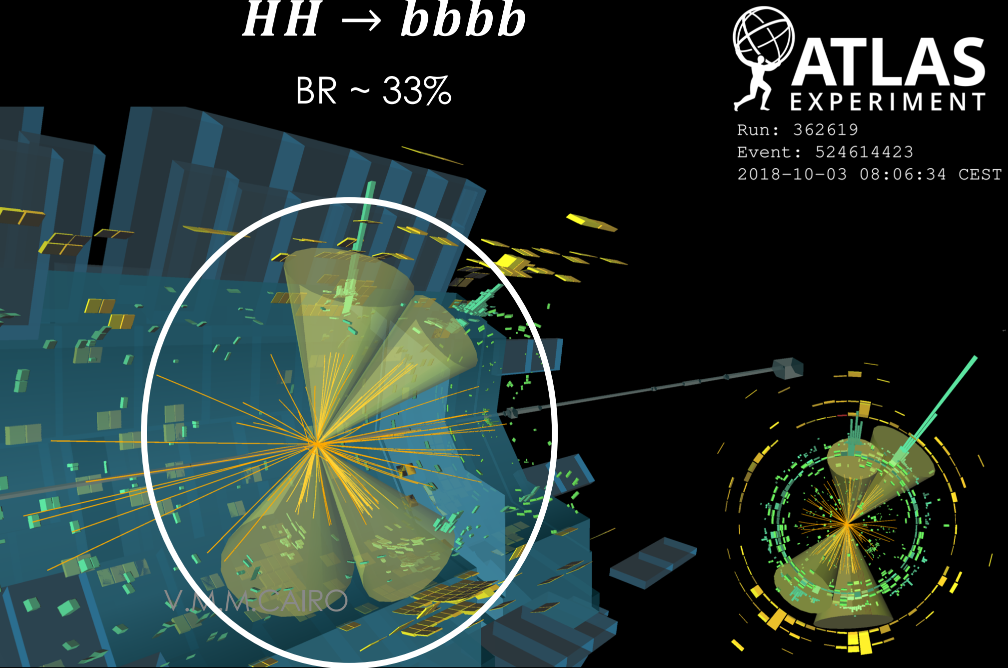
$HH \to b\bar{b}\tau\tau$

BR ~ 7.4%



$HH \to b\bar{b}b\bar{b}$

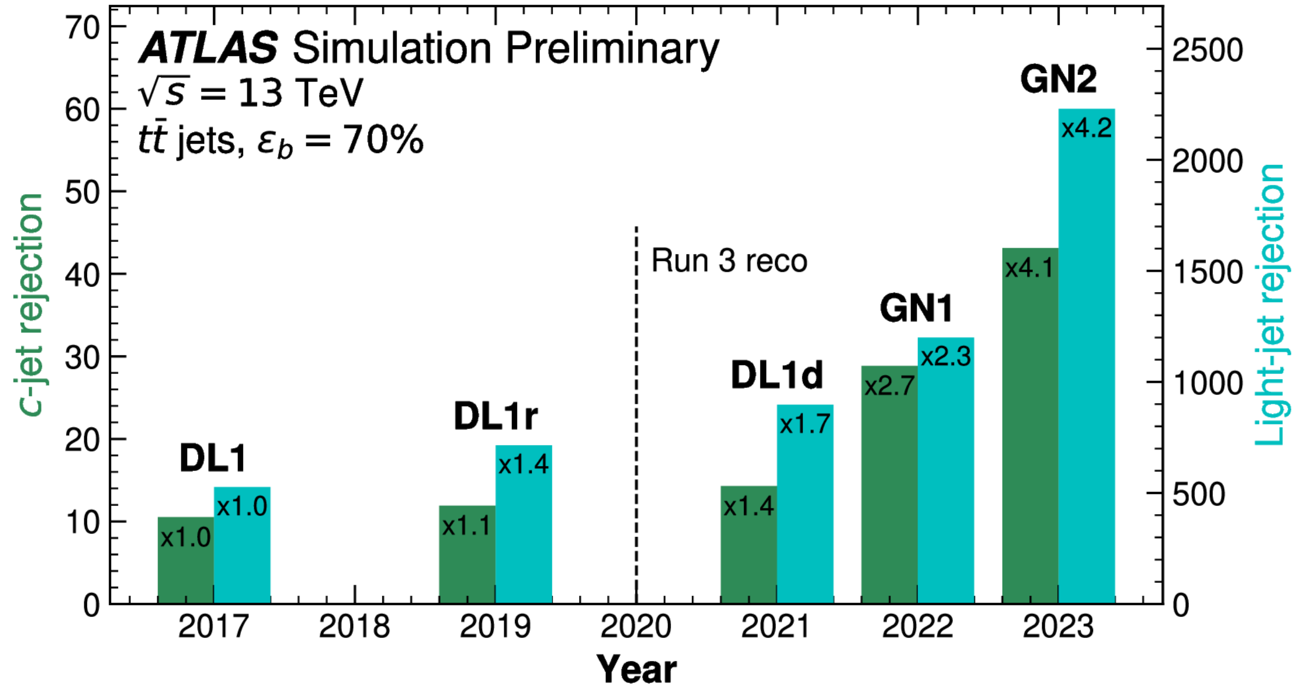
BR ~ 33%



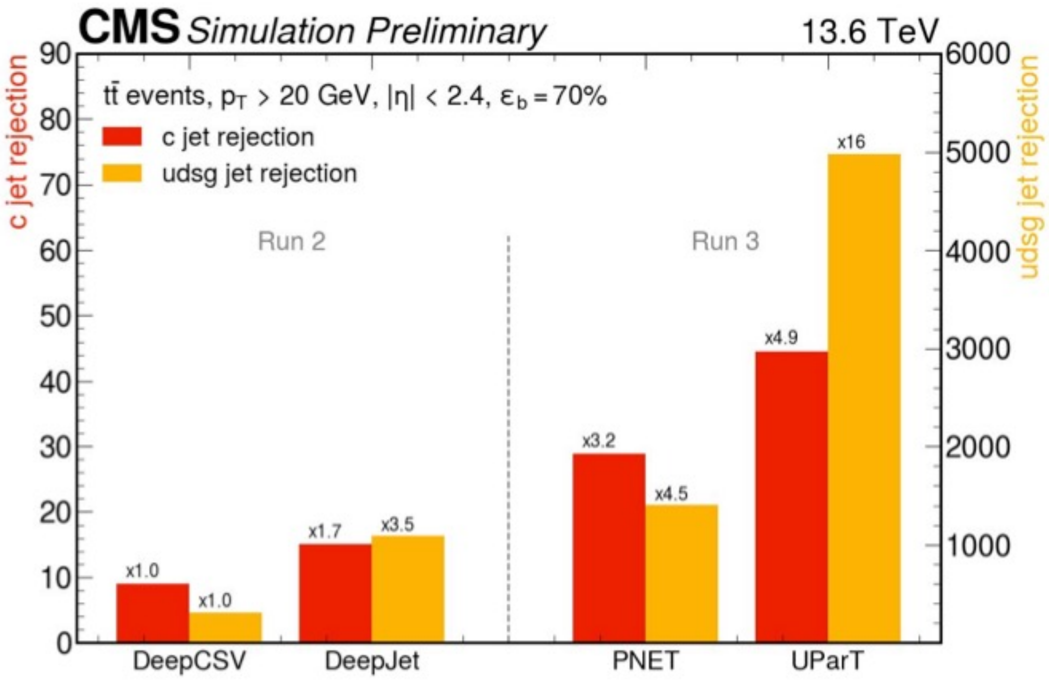
THE HEAVY FLAVOUR CHALLENGE

- Requires both advanced detectors and algorithms!
- Detector developments and AI applications hand-in-hand

More in Bing's talk

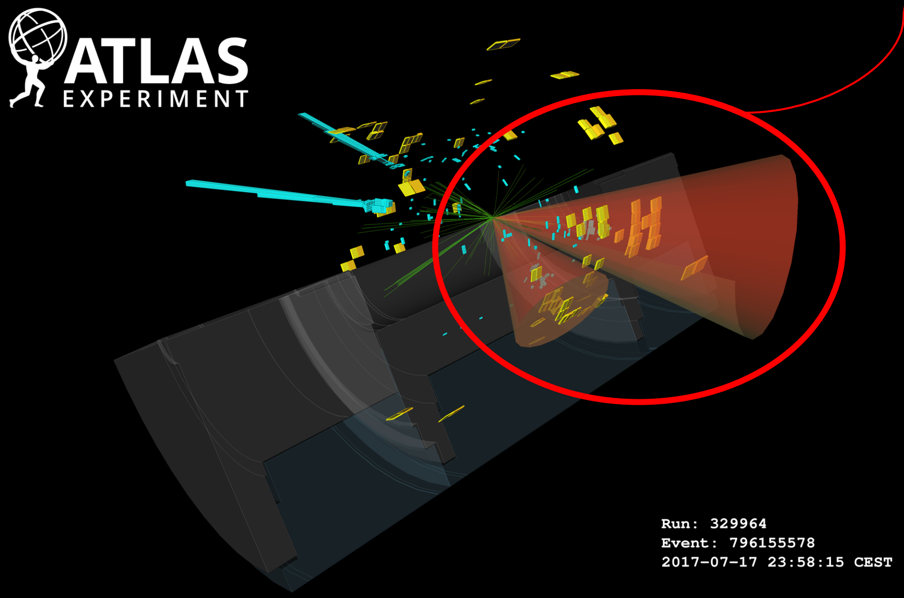


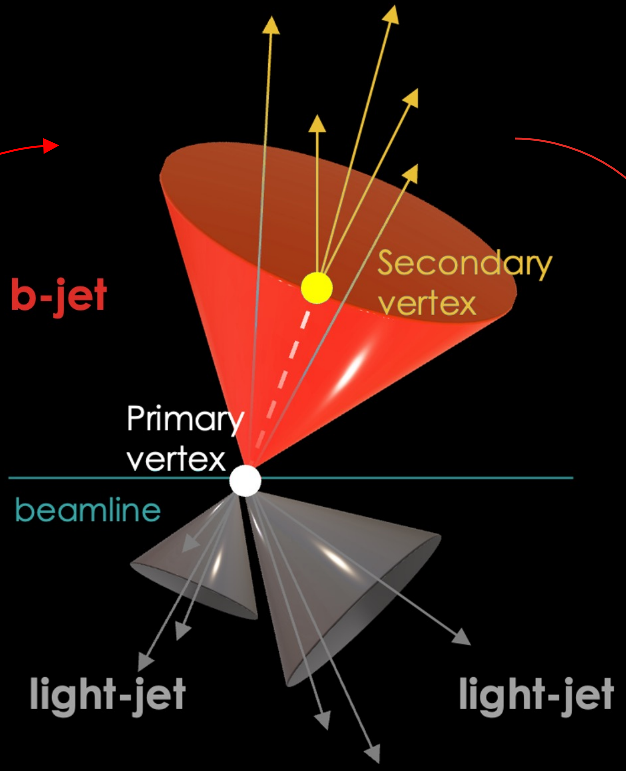
FTAG-2023-01/

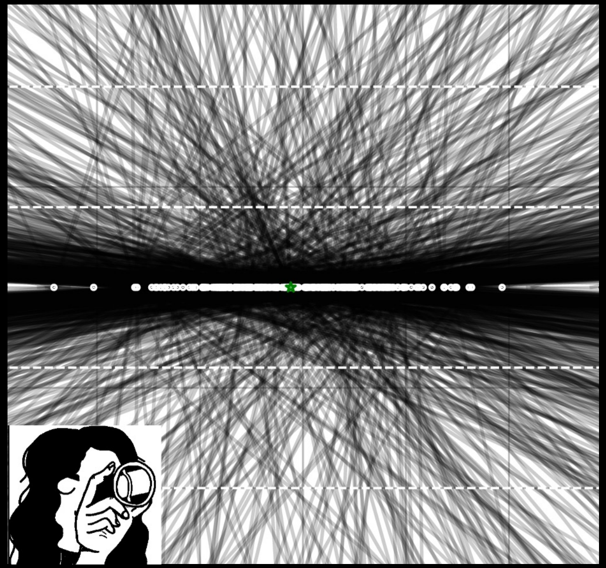


https://cds.cern.ch/record/2904702

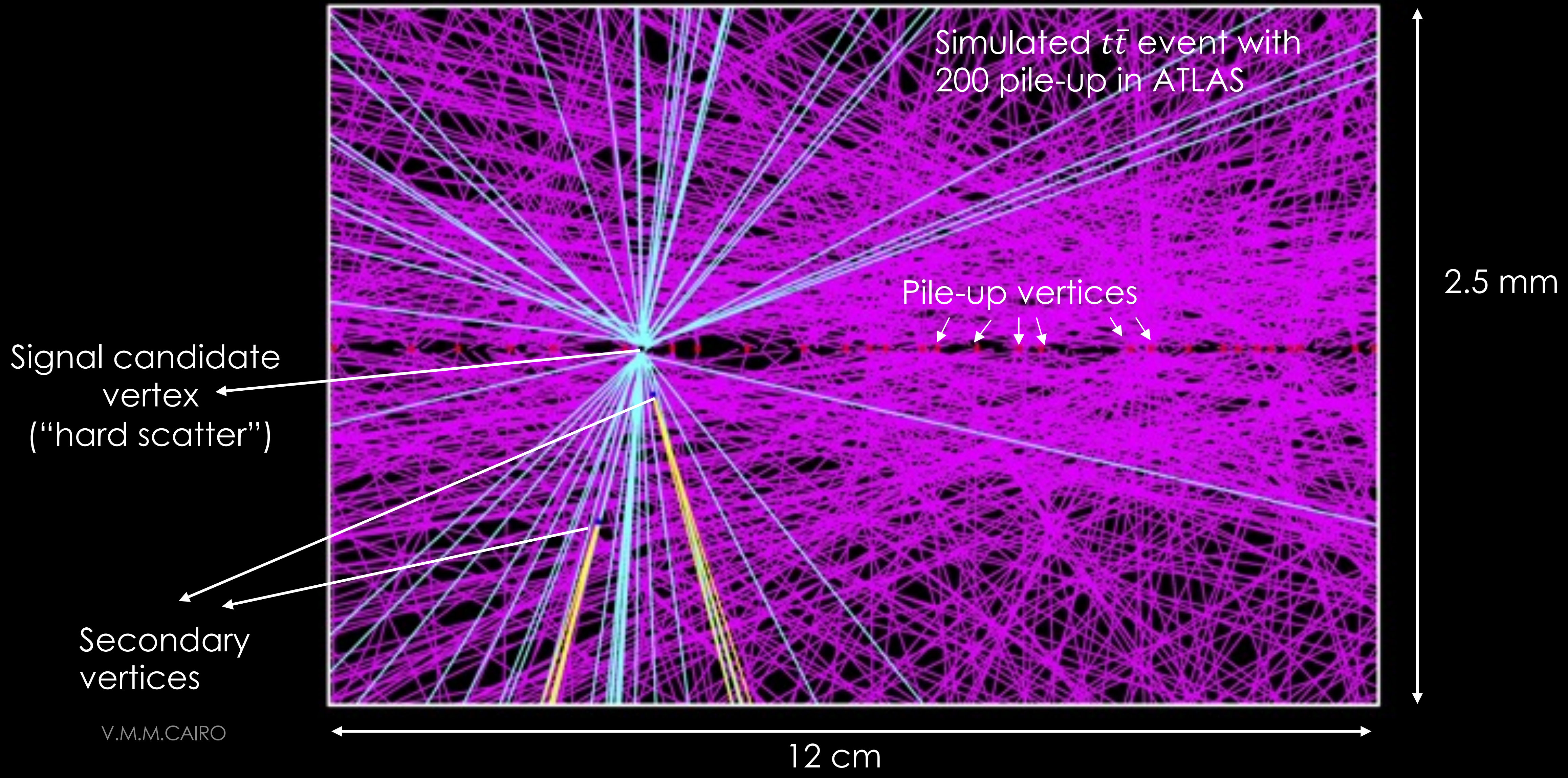
Fake rate improved by ~2 orders of magnitude since the Tevatron! Ref 1, 2


ATLAS
EXPERIMENT
Run: 329964
Event: 796155578
2017-07-17 23:58:15 CEST

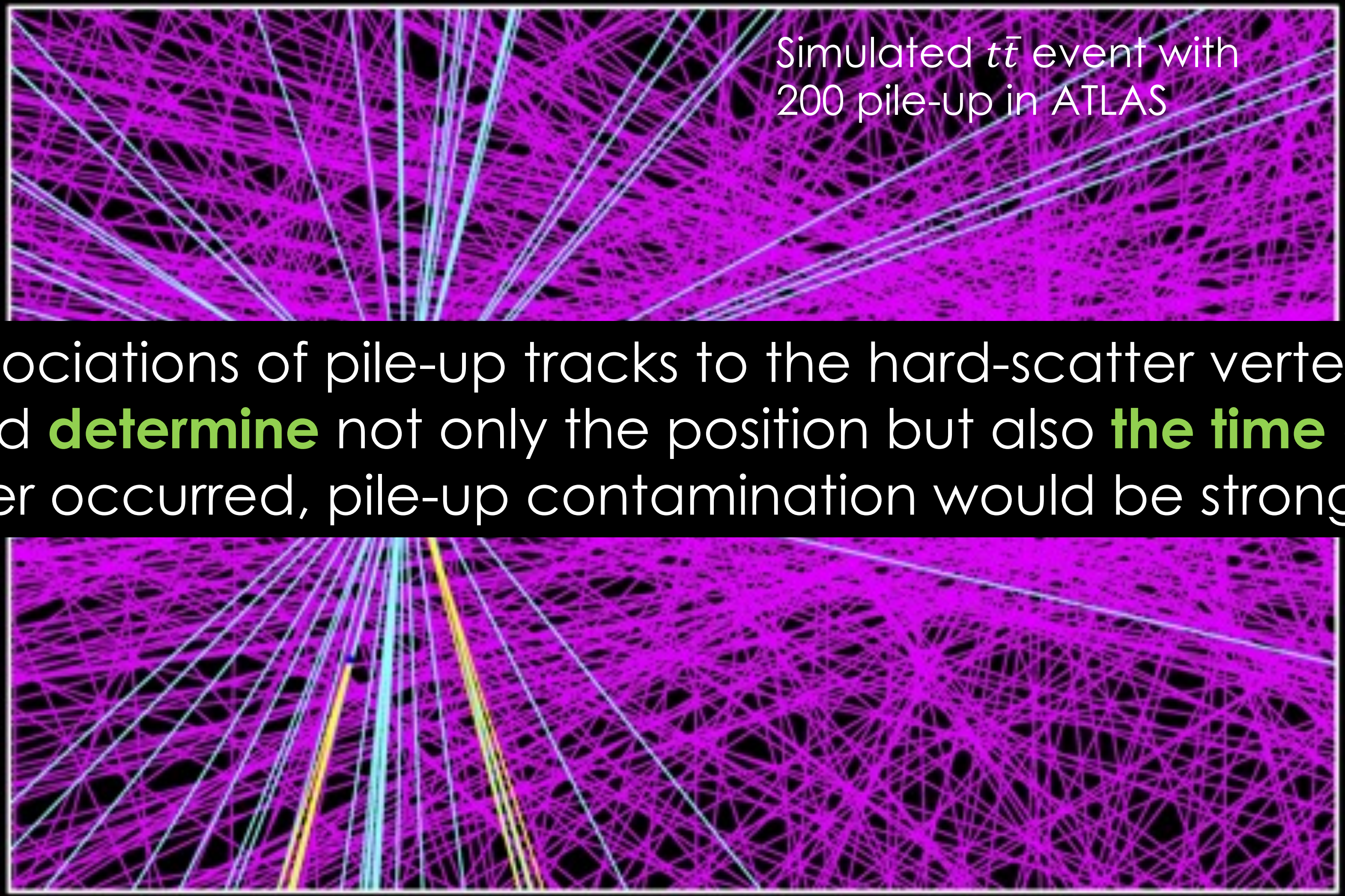

b-jet
Secondary
vertex
Primary
vertex
beamline
light-jet
light-jet



THE PILE-UP CHALLENGE @ HL-LHC

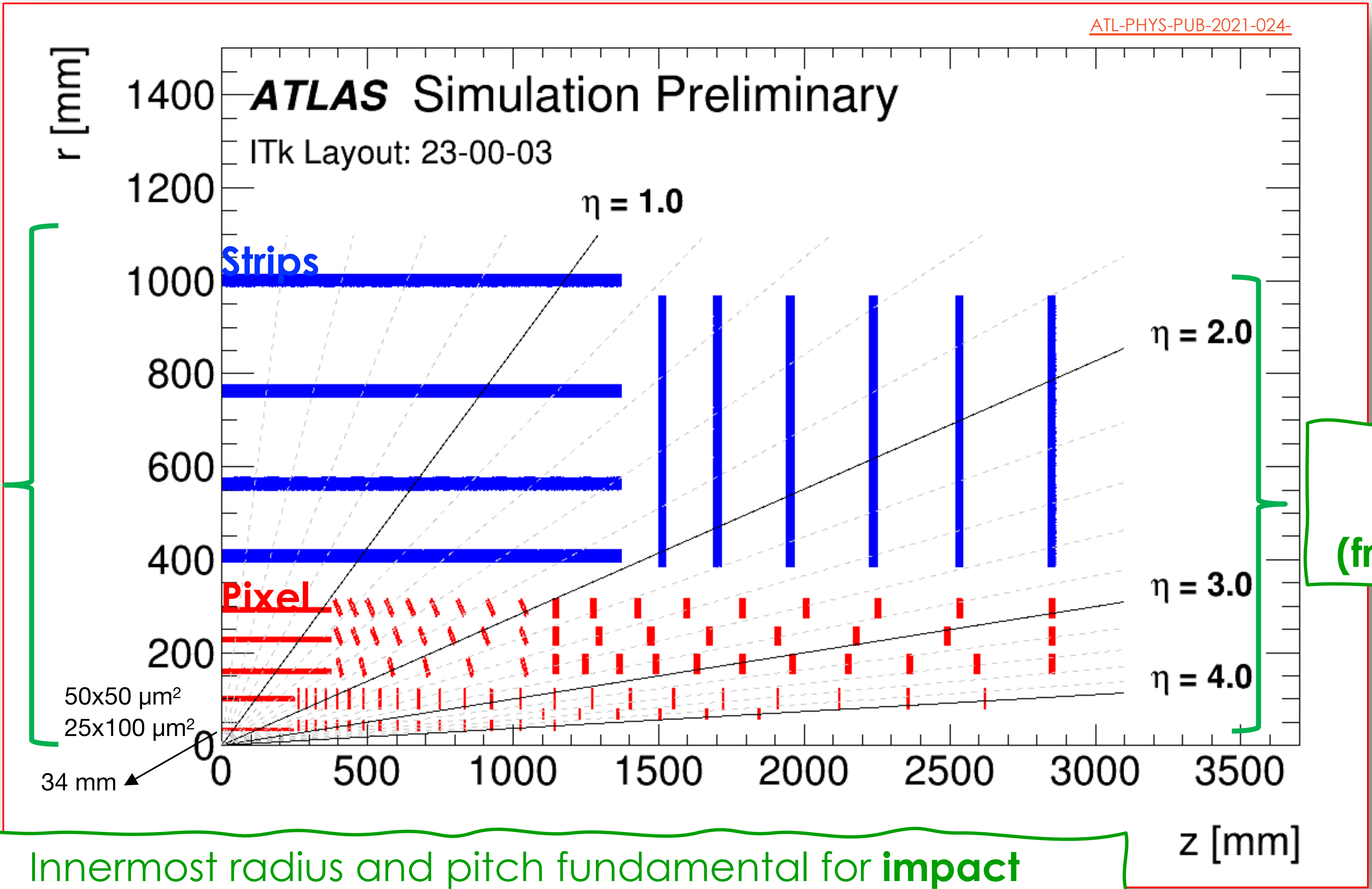


THE PILE-UP CHALLENGE @ HL-LHC



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…

THE ATLAS ITK

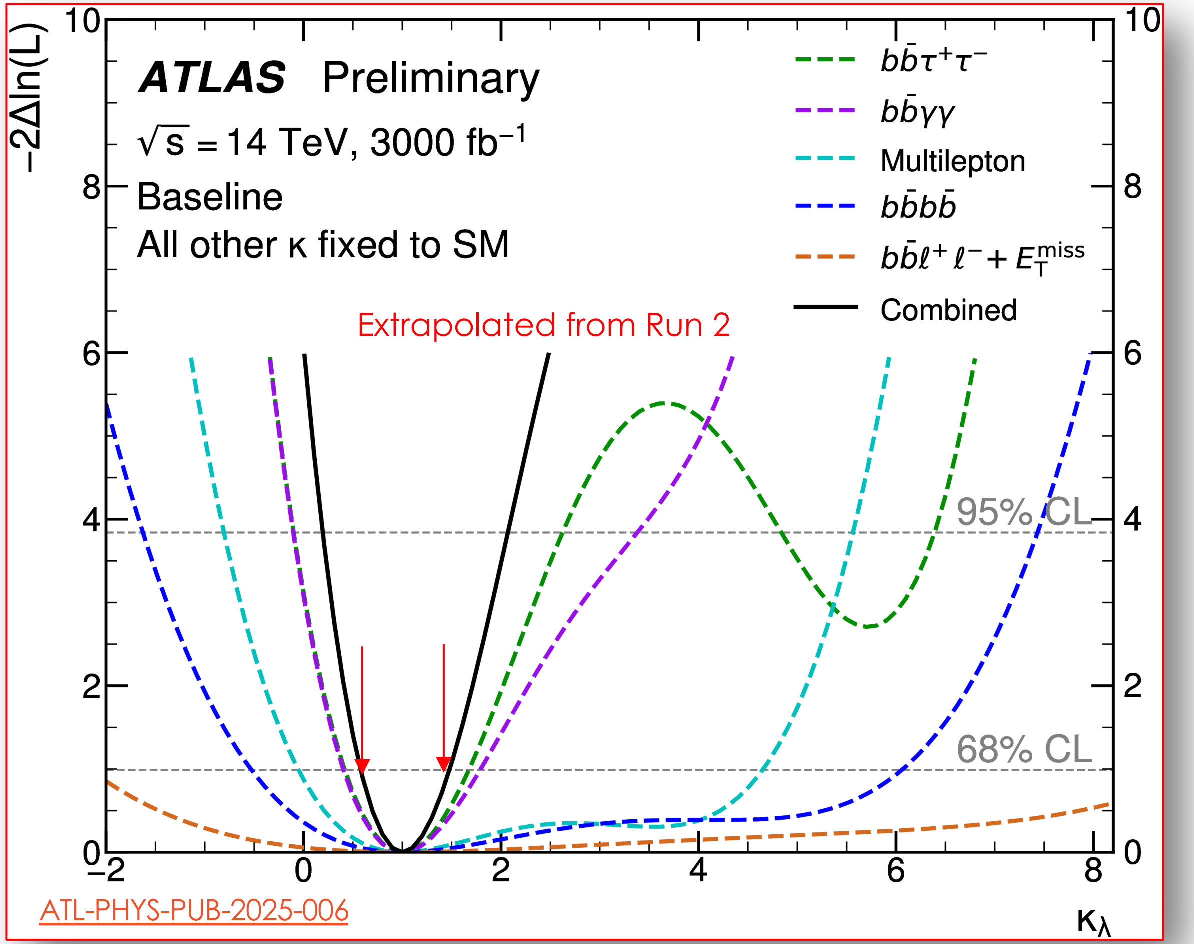


All silicon

Increased η coverage (from 2.4 to 4.0)

Innermost radius and pitch fundamental for **impact parameter** determination and thus **b-tagging performance**!

HOW DOES HH LOOK IN HL-LHC FROM ATLAS?



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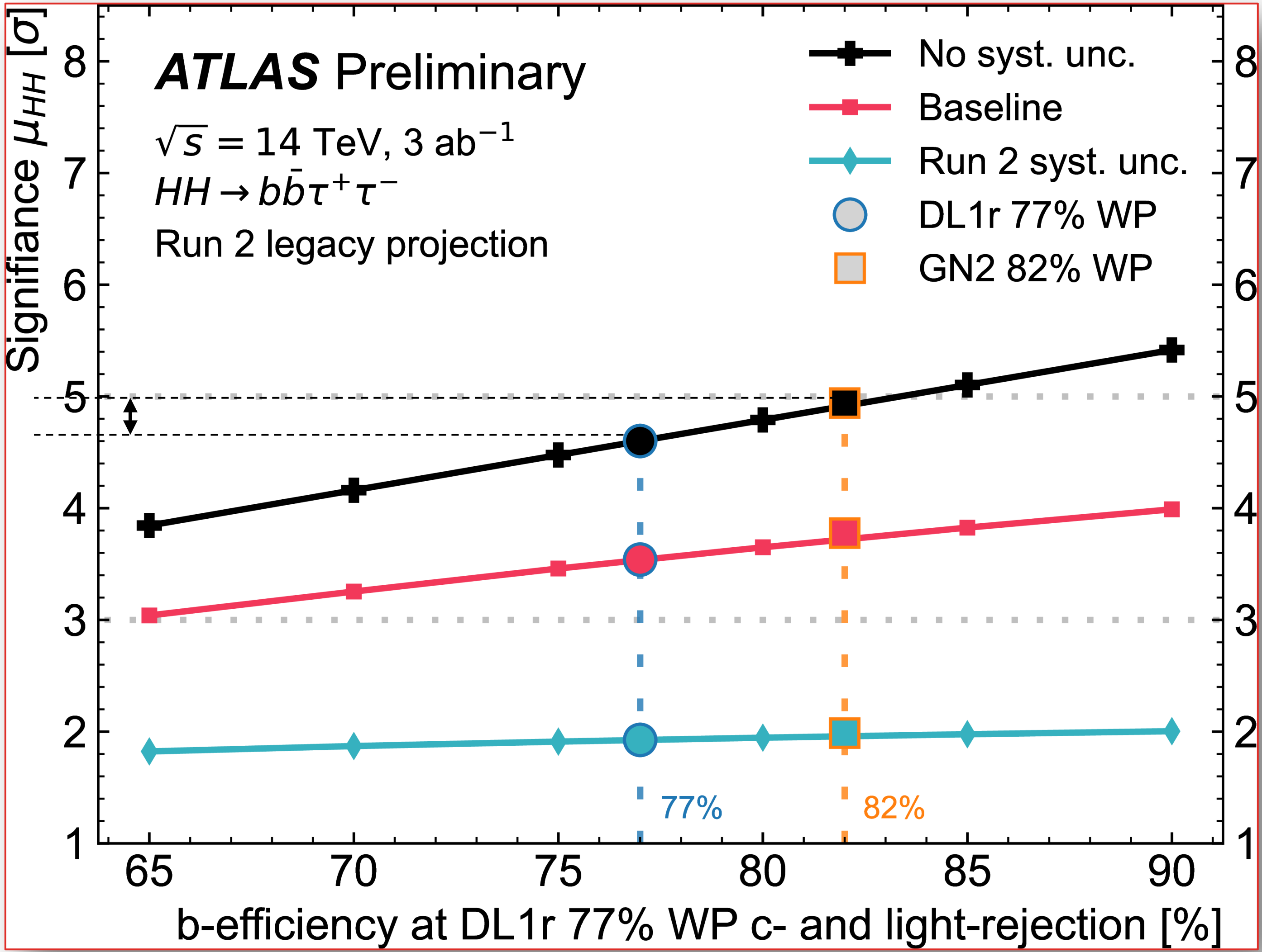
Much more here

$\sim 4.3\sigma$ HH discovery significance & k_λ expected to be measured as $1^{+48\%}_{-42\%}$

Better than previous extrapolation for combined ATLAS+CMS

HOW BETTER CAN WE DO?



e.g. 77% to 82% → $\sim 0.3\sigma$ improvement (about 500 fb^{-1} of data!)

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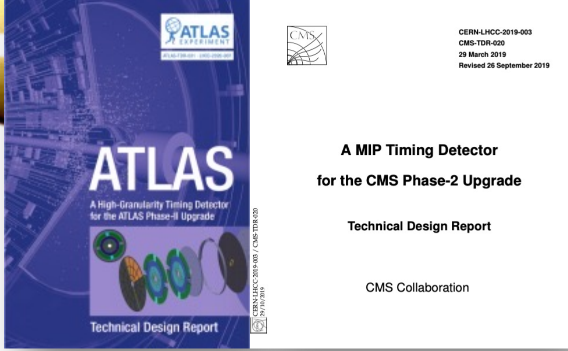
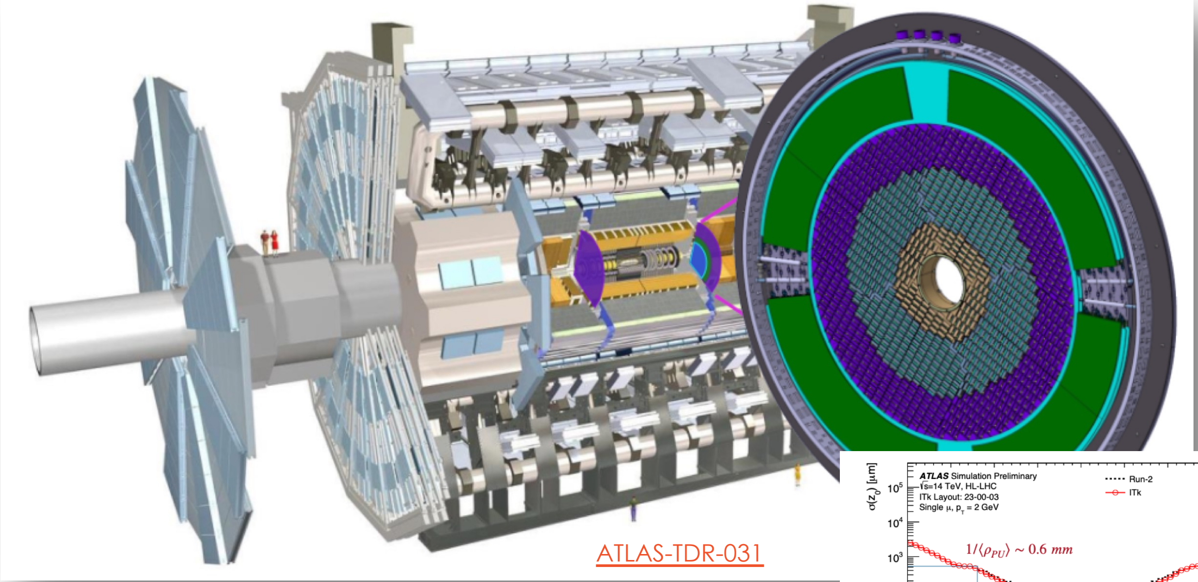
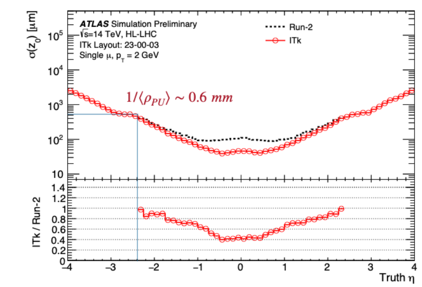
UNFOLDING A NEW DIMENSION

Addition of timing layers to HEP detectors growing area of interest



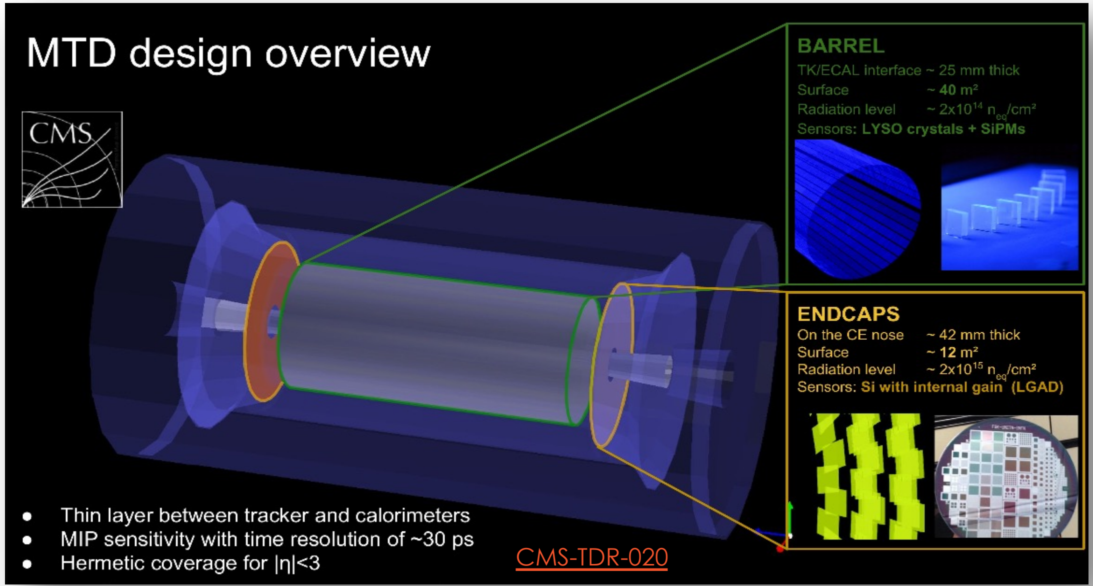
ATLAS High Granularity Timing Detector





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

CMS MIP Timing Detector

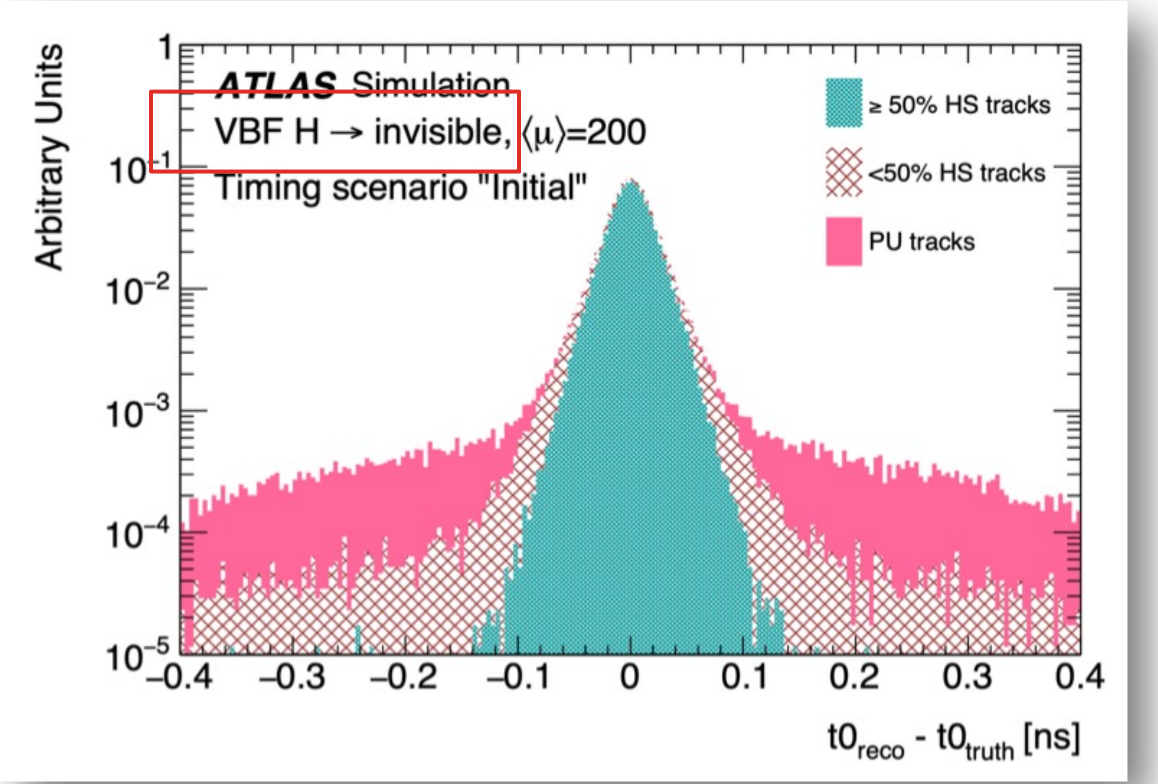


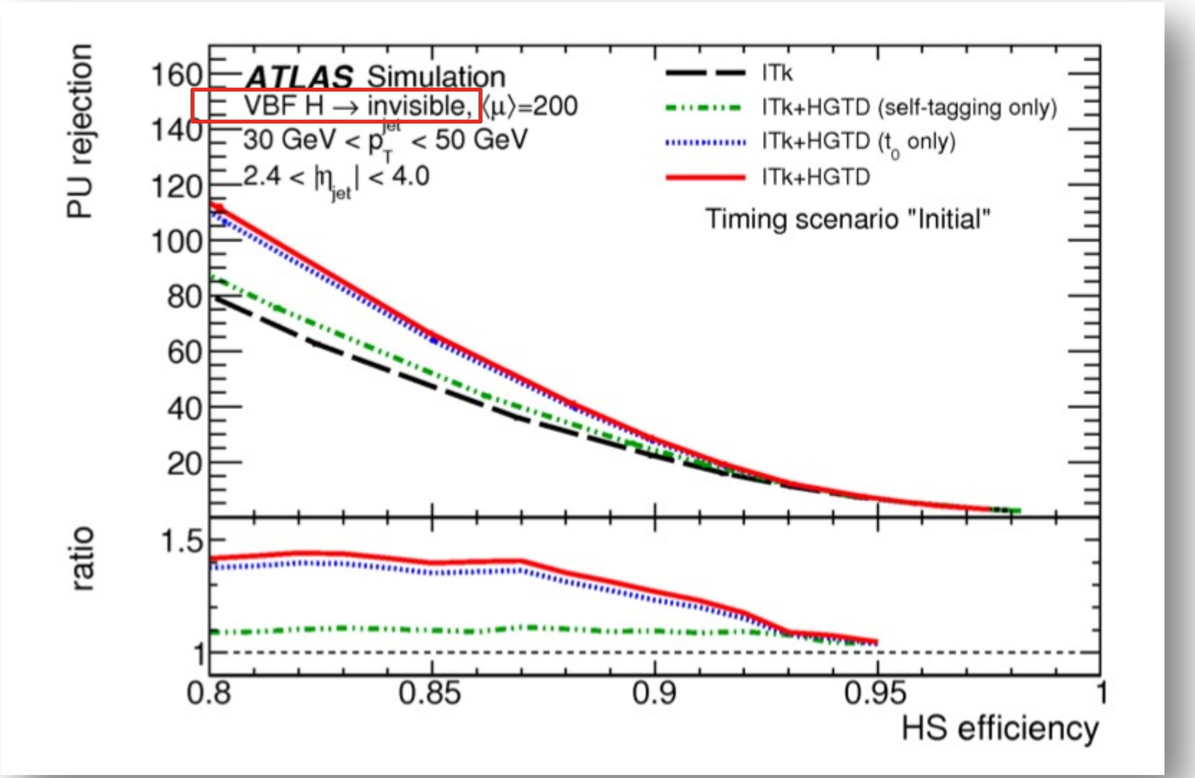
LGADs and crystals for hermetic coverage up to $|\eta| < 3.0$

More in the CMS talk!

ATLAS HGTD

- Based on Low Gain Avalanche Detectors (LGAD)
- Track time resolution: from 30ps (initial) to 50ps (final)





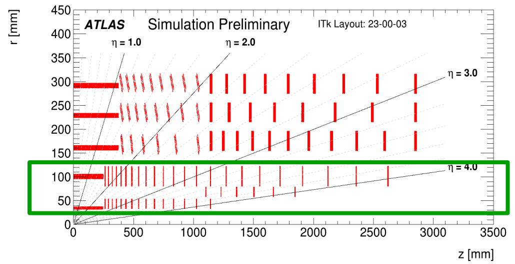
New handles to improve event reconstruction in the forward region, but limited by its reduced η acceptance…

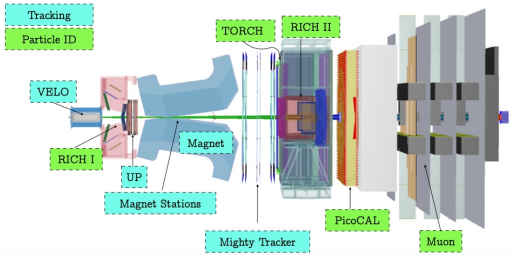
4D TRACKING

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

- **Interesting opportunities during HL-LHC and, in particular, for future energy frontier trackers**

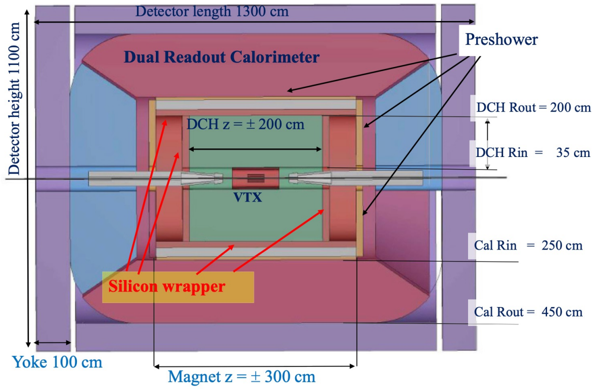
HL-LHC Beyond Run 4





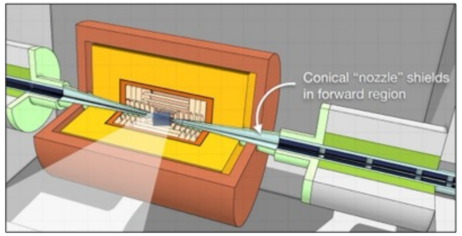
4D tracking for replacements/upgrades?

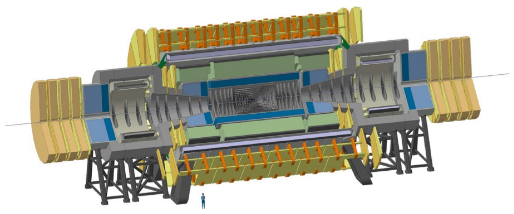
Electron-positron colliders



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

Muon collider / hadron colliders





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

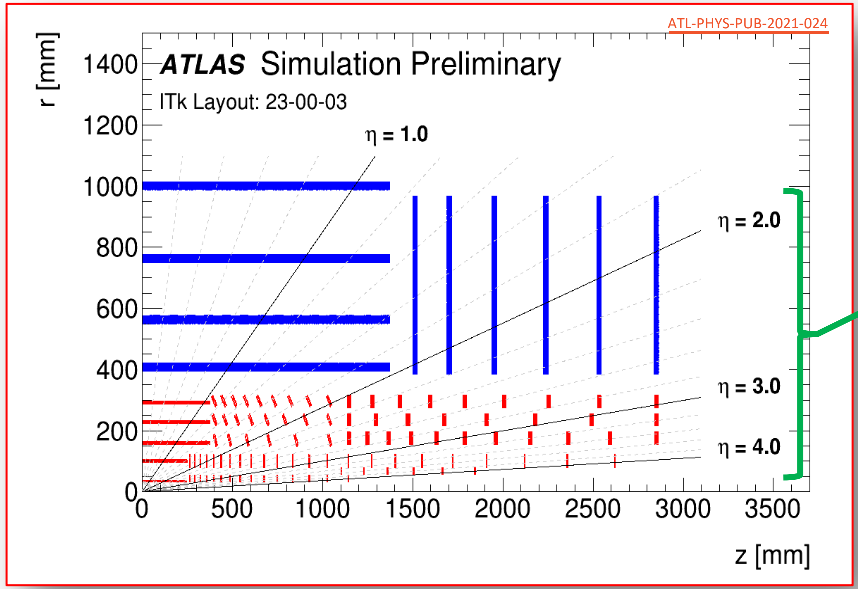
2035 2040s 2050s and beyond

2203.13900

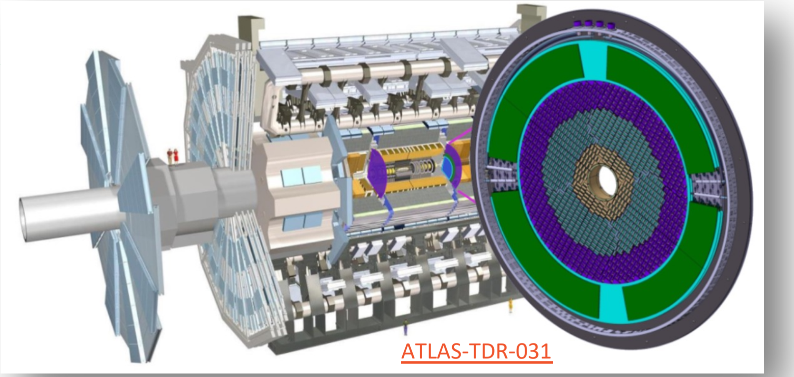
4D TRACKING

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

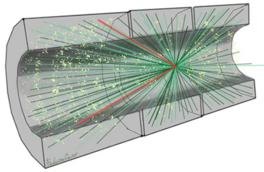
- **Interesting opportunities during HL-LHC and, in particular, for future energy frontier trackers**
- **First exploratory studies in ATLAS**



High Granularity Timing Detector



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



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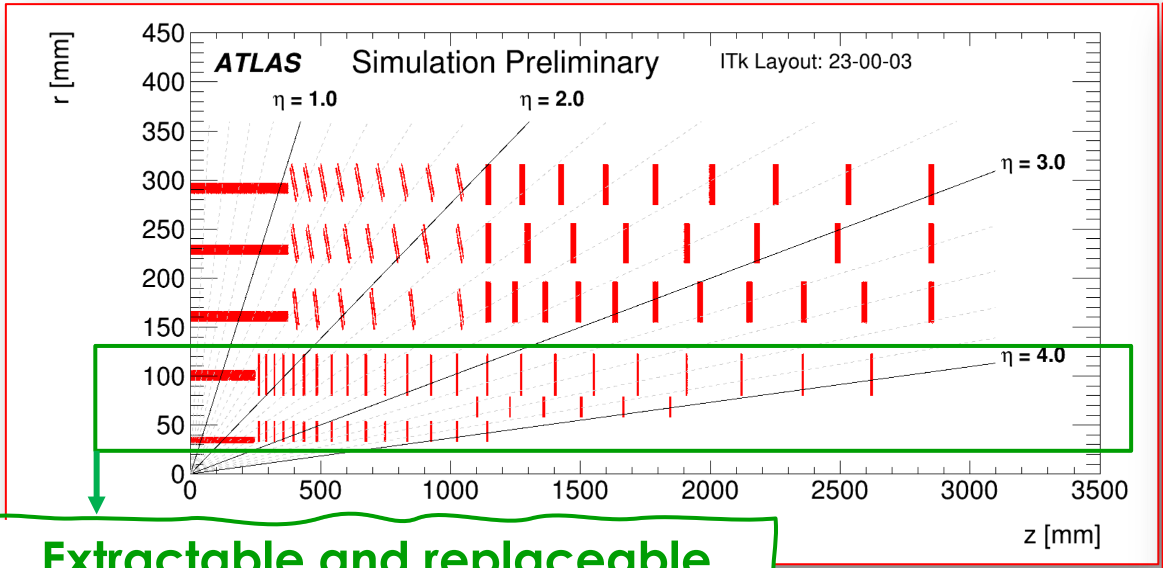
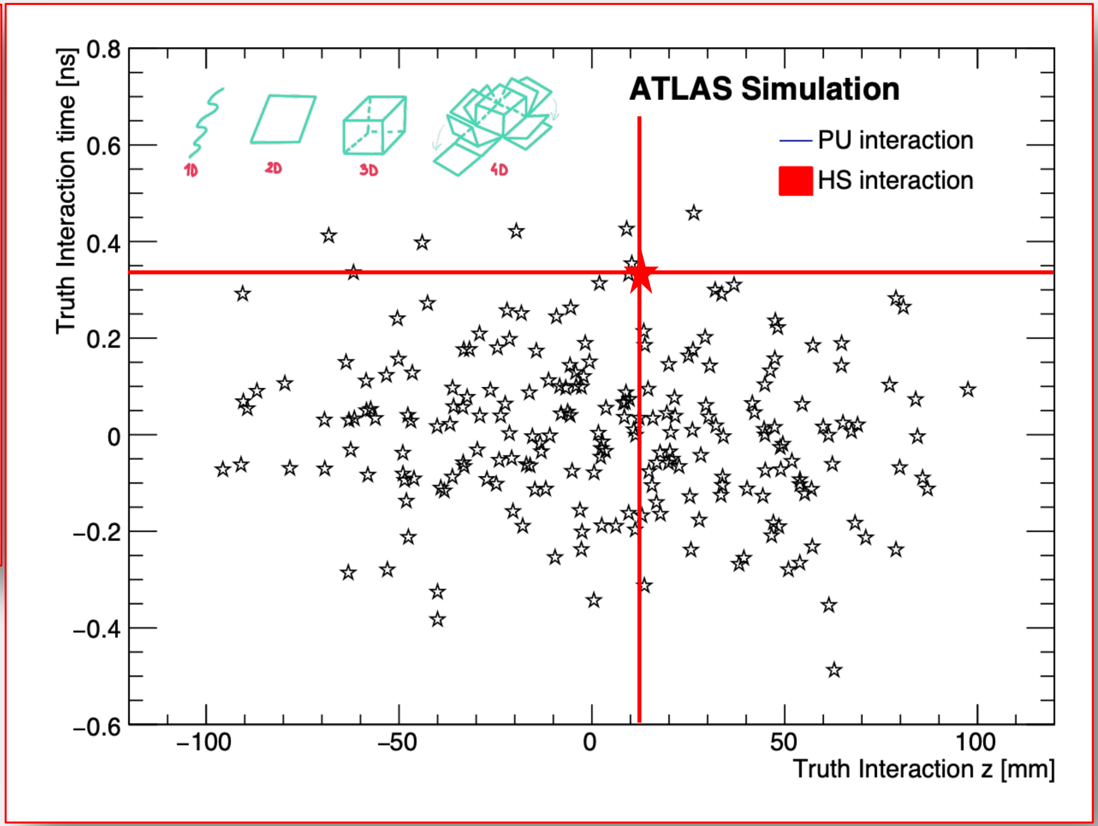


Extractable and replaceable half-way through HL-LHC



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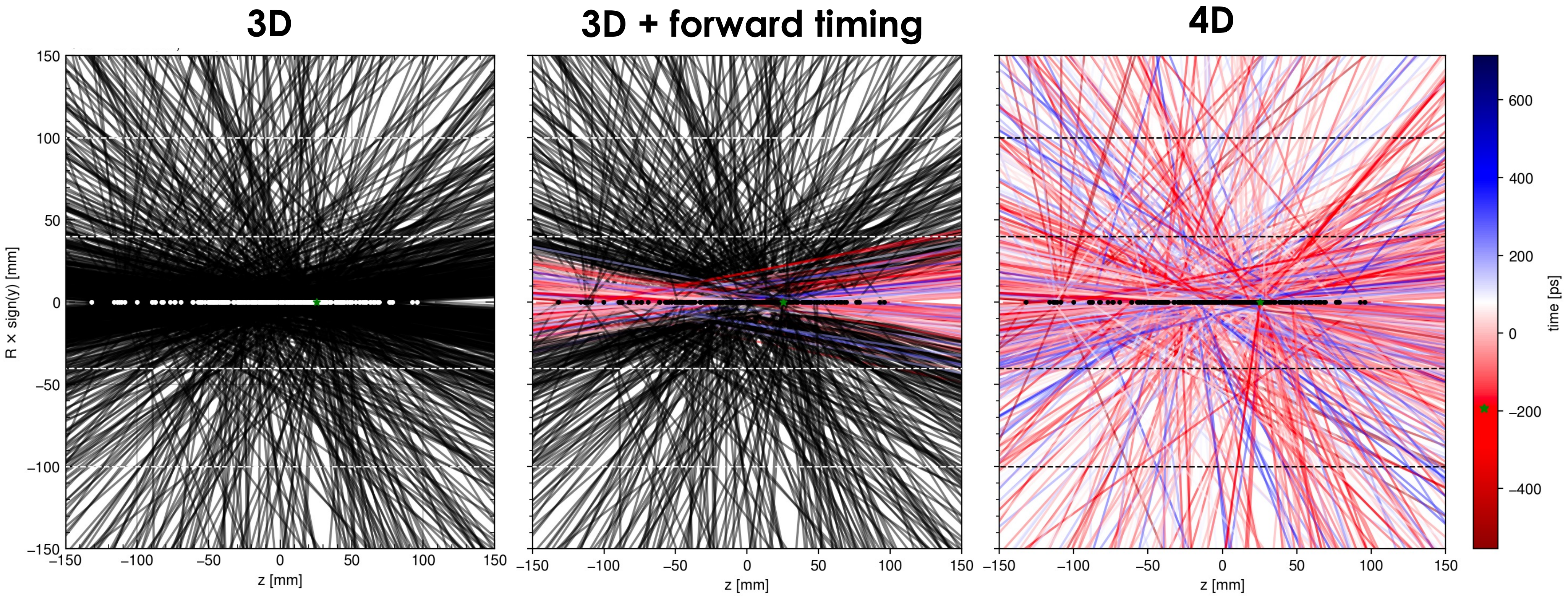
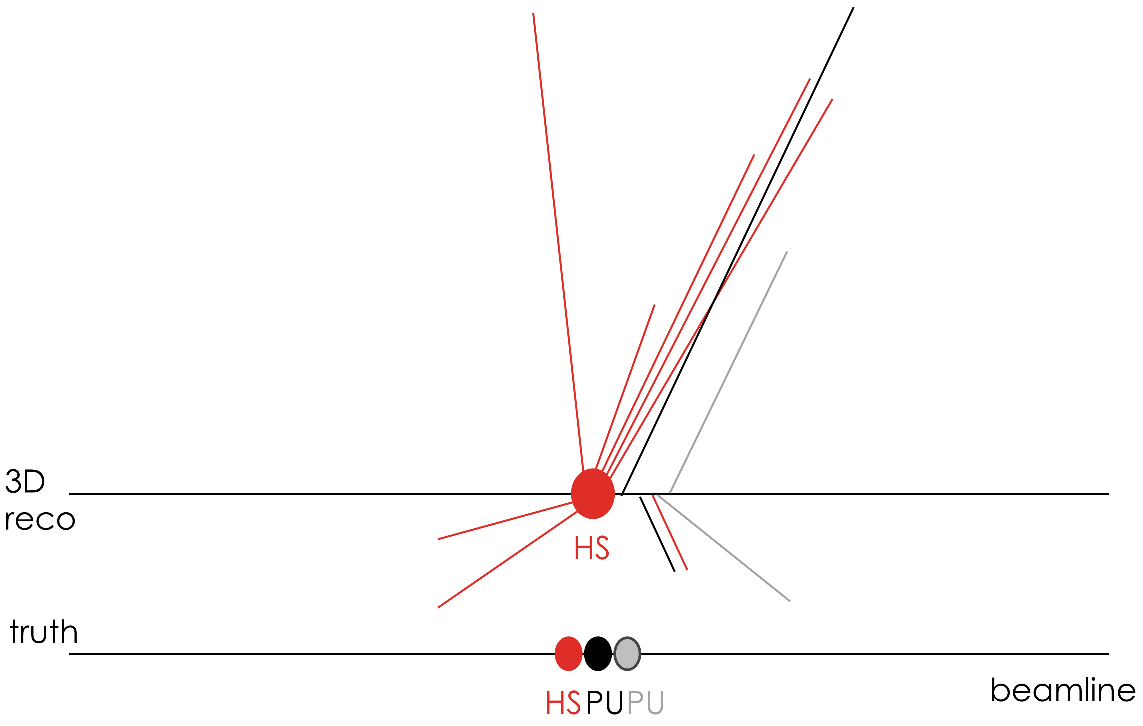
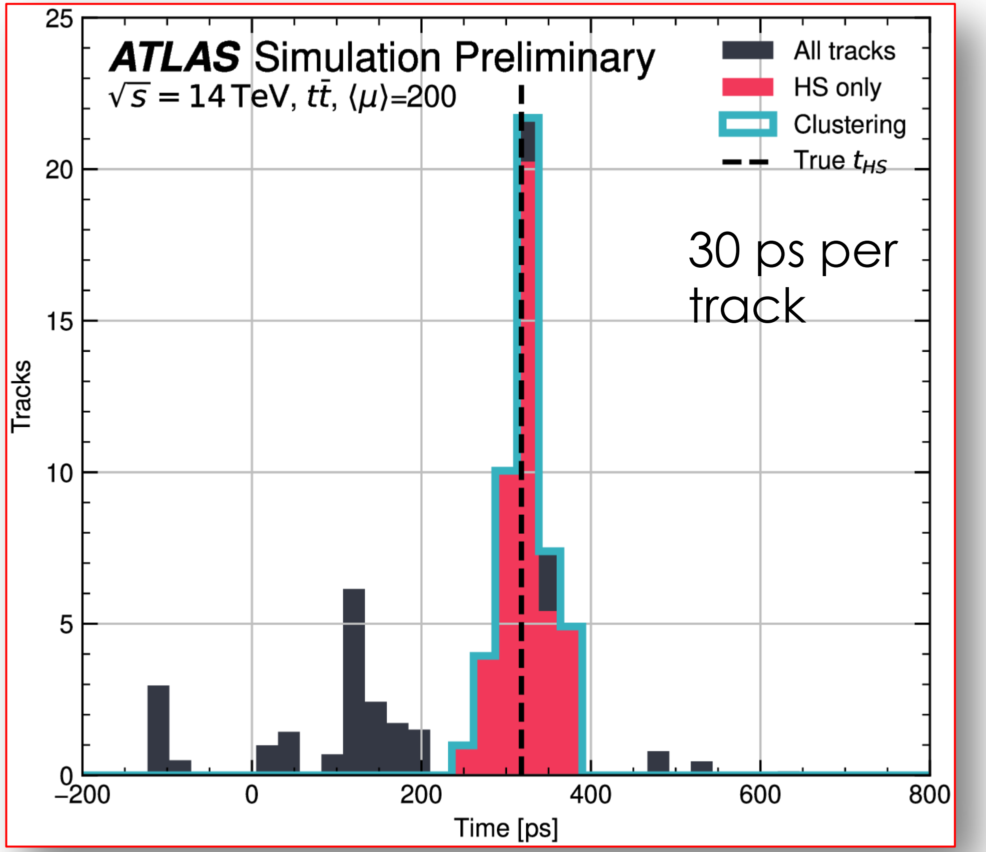


DETERMINING THE VERTEX TIME

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





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

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DETERMINING THE VERTEX TIME

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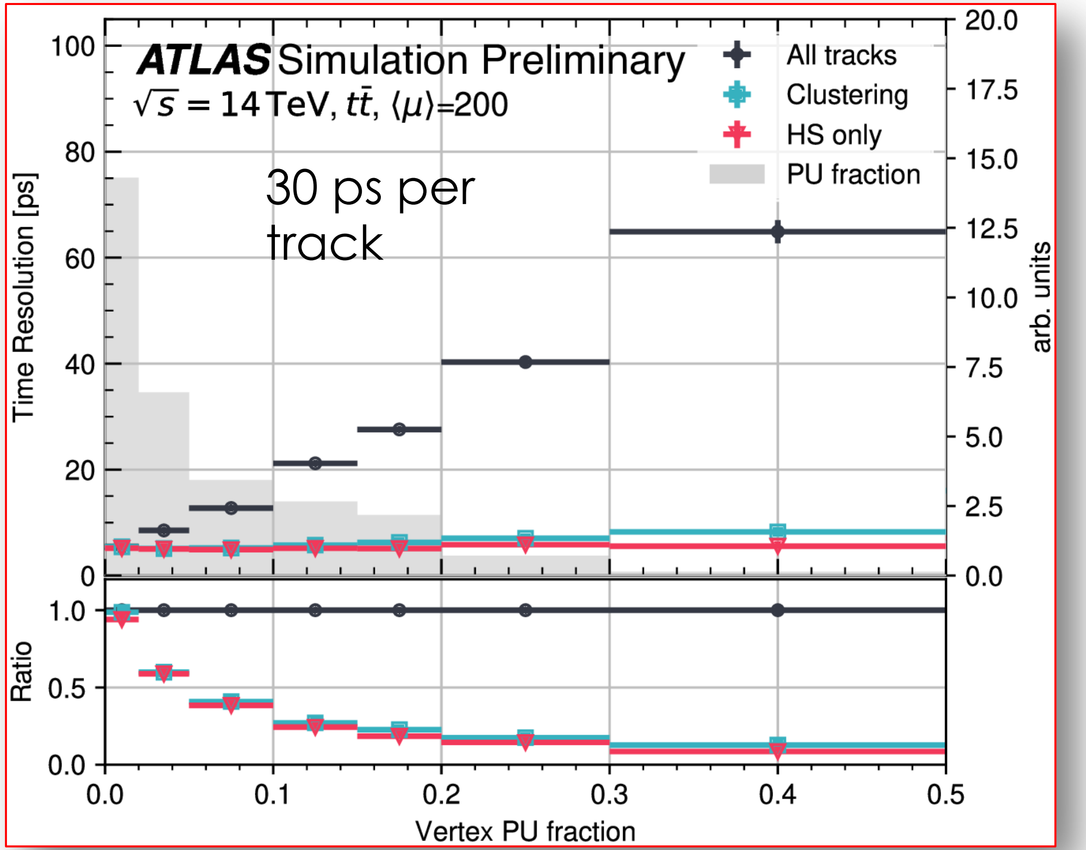

Excellent vertex time resolution can be achieved

ATL-PHYS-PUB-2023-023

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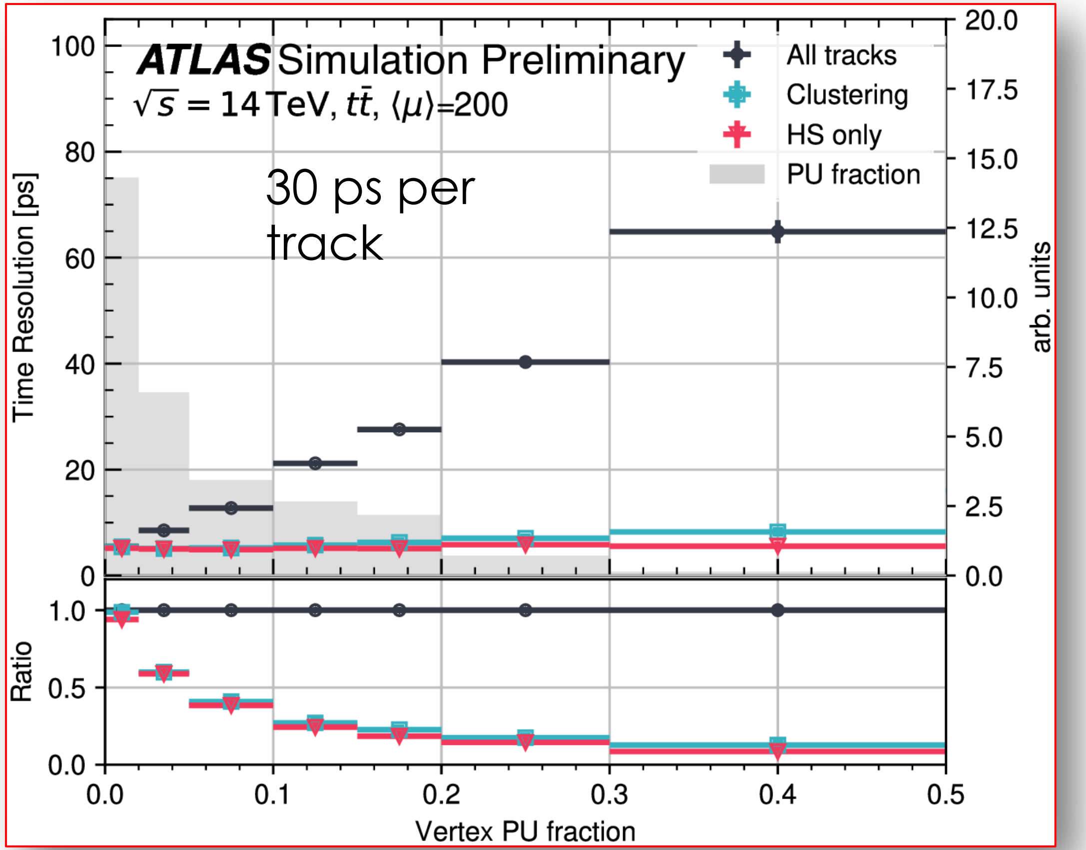

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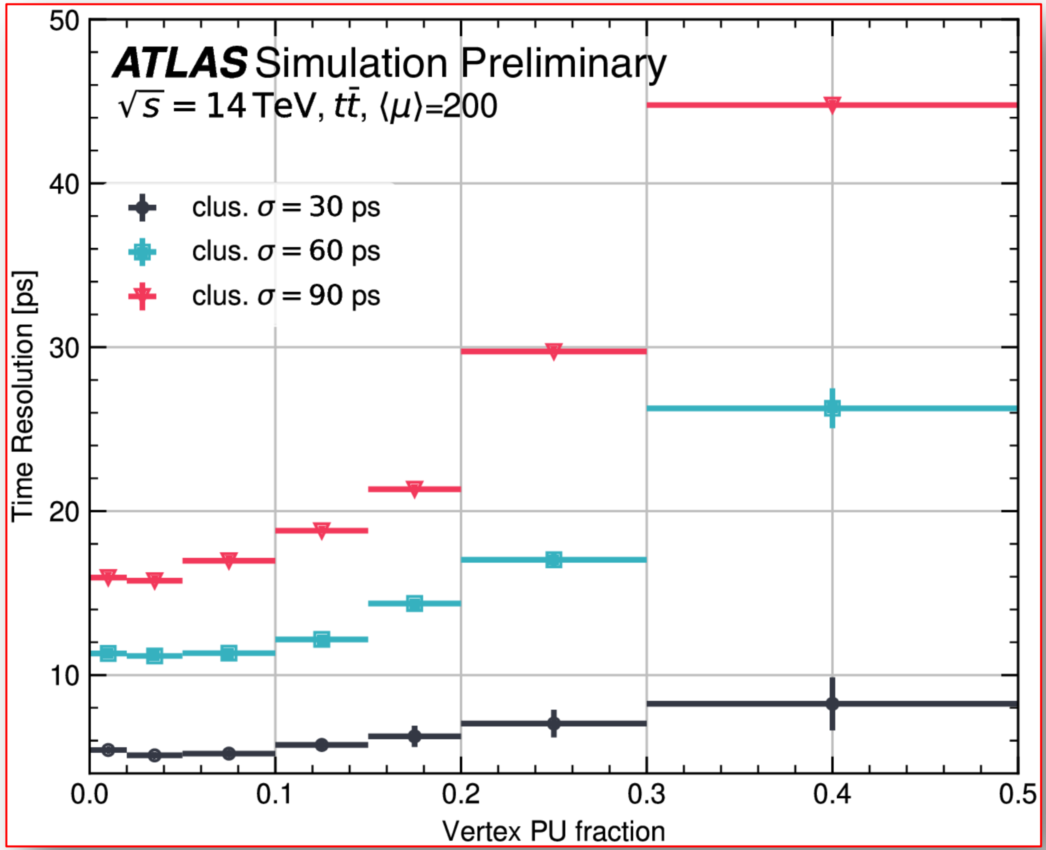

The better the track-time resolution, the more PU-robust the vertex time resolution

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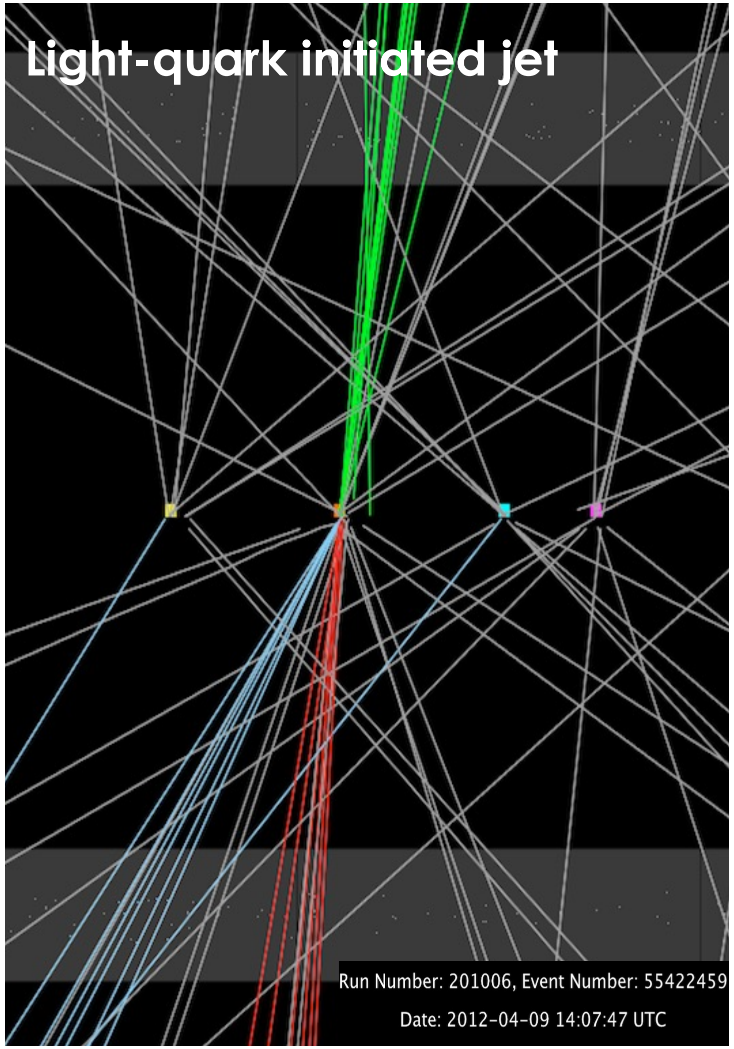
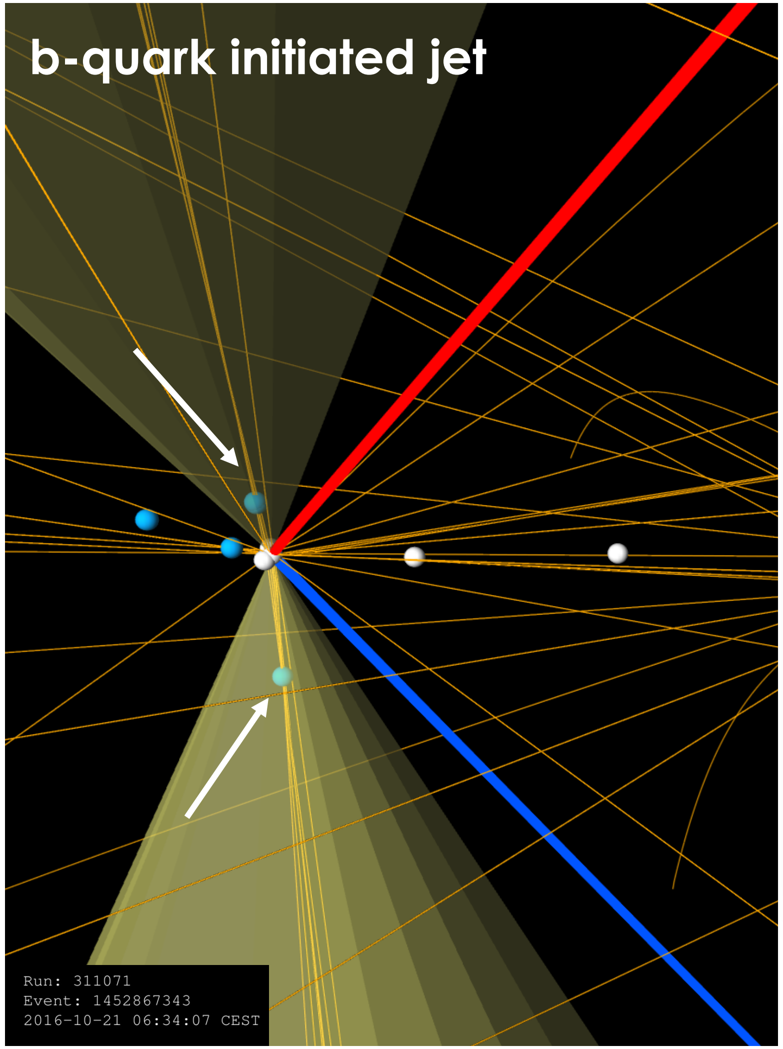
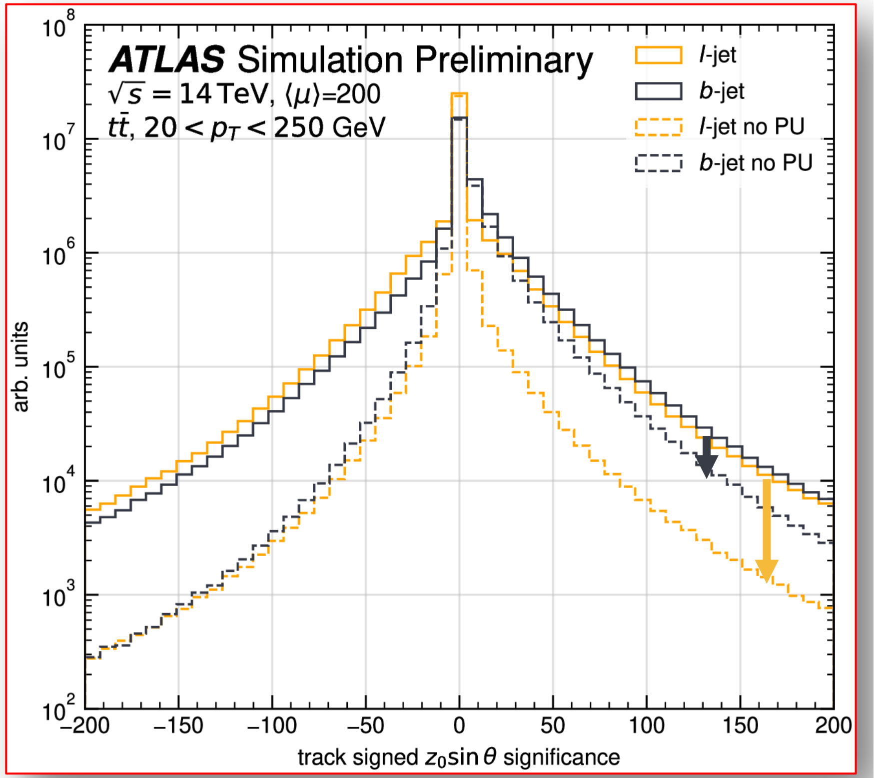
THE KEY FEATURES FOR b-TAGGING

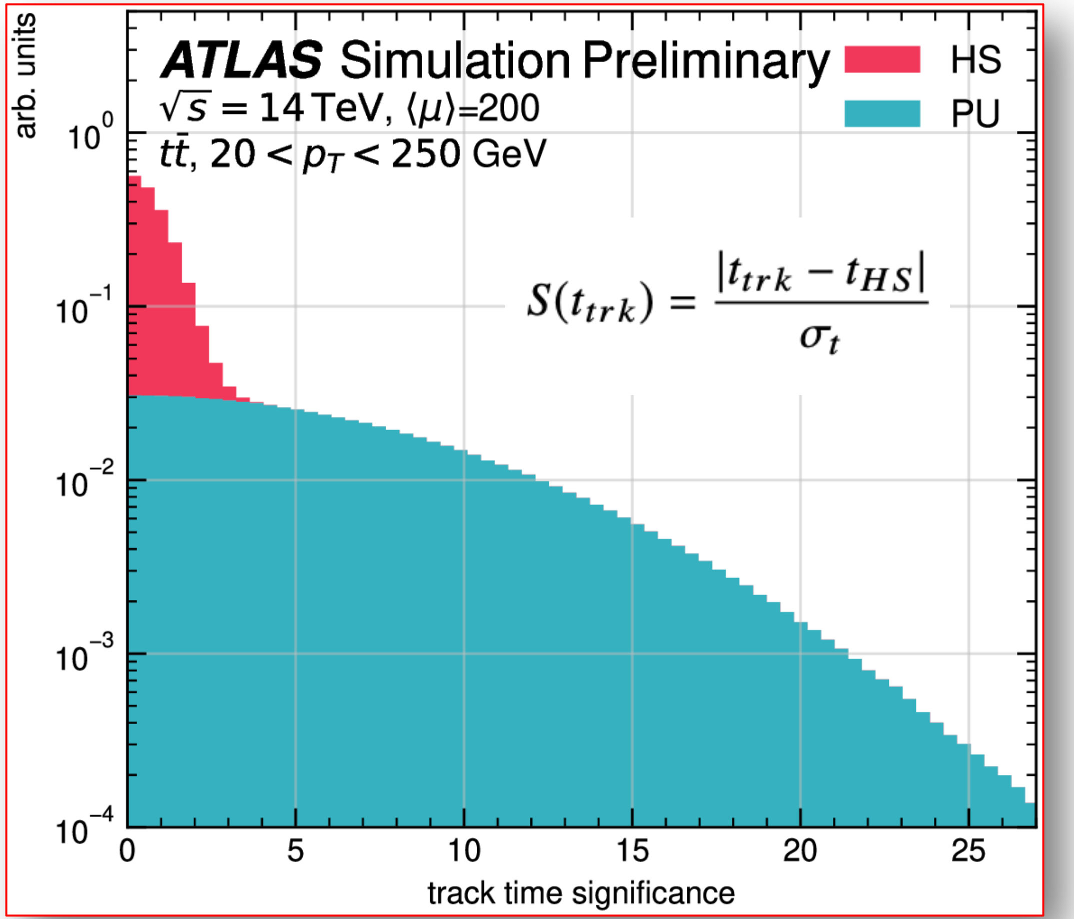






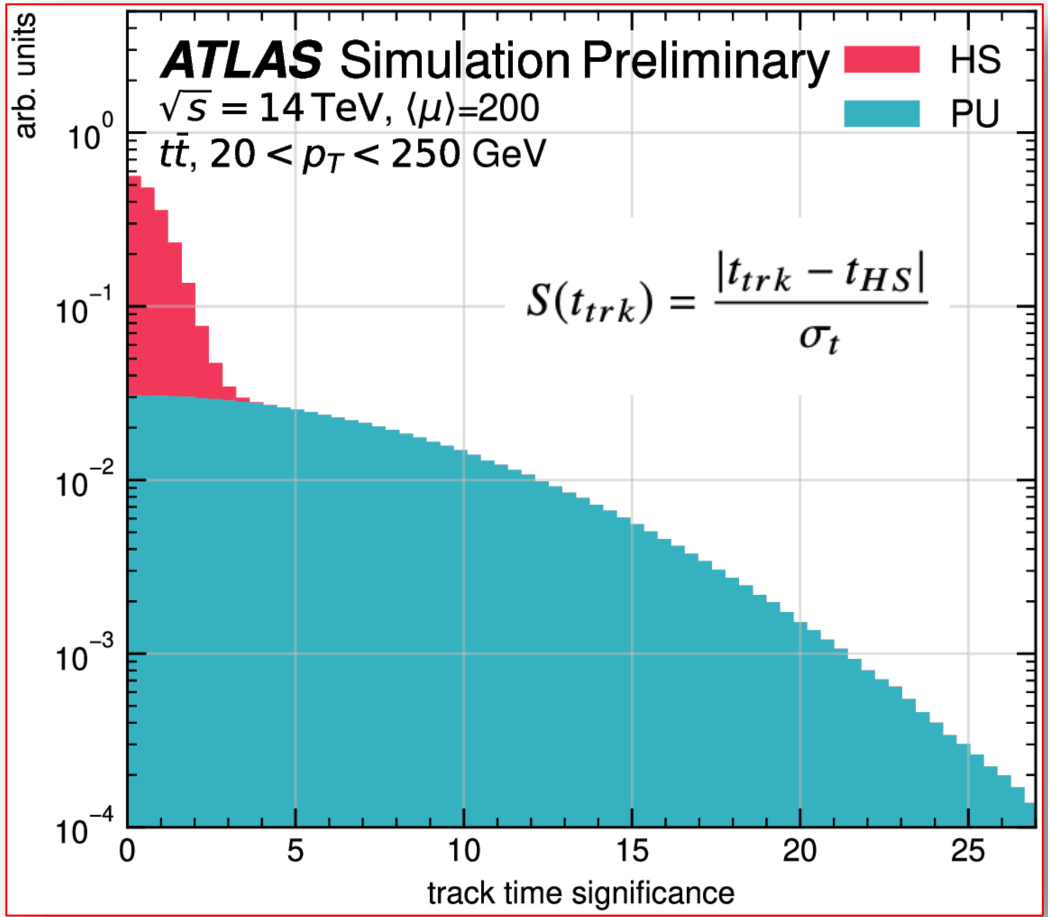
Long lifetime of B-hadrons requires selecting tracks with large IPs →large selection windows around the longitudinal IP → more pile-up contamination that can lead to fake secondary vertices

GNT – 4D b-TAGGING



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

GNT – 4D b-TAGGING



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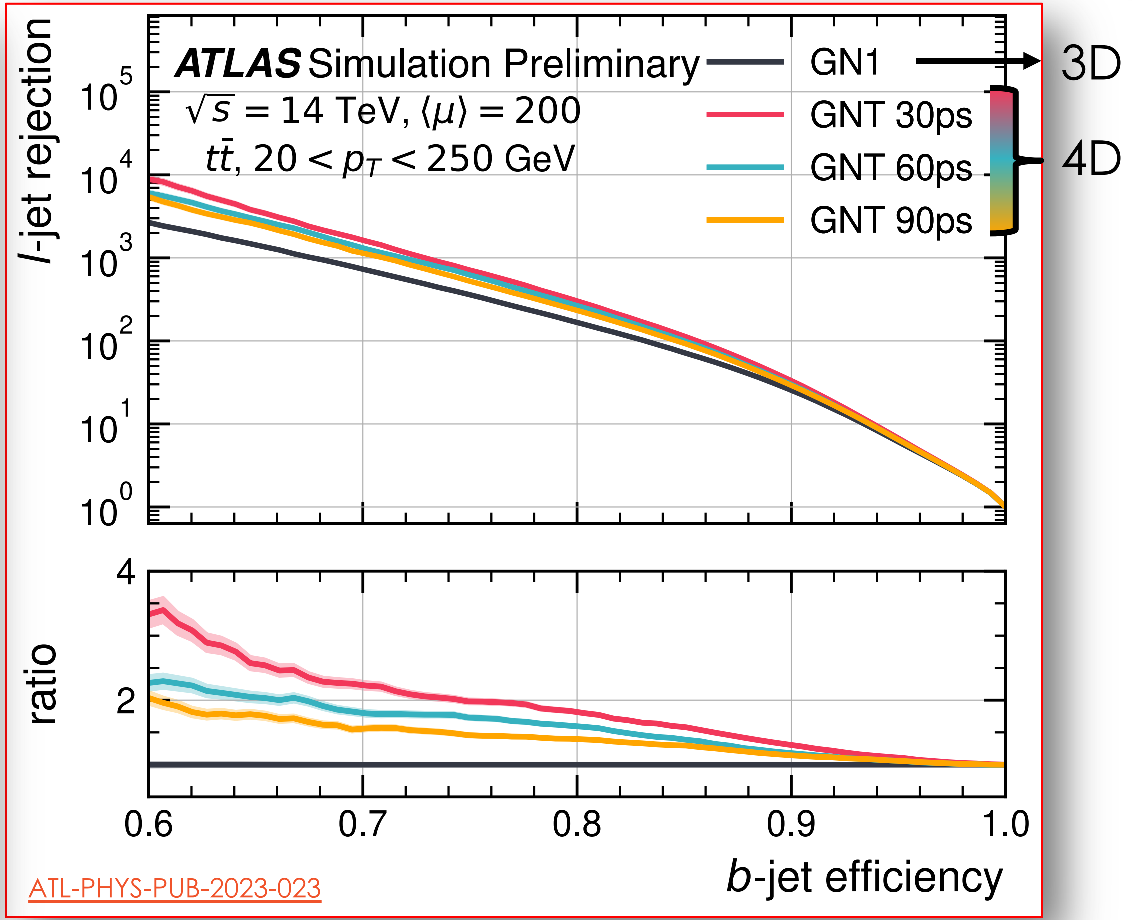


Interesting potential HH sensitivity increase!

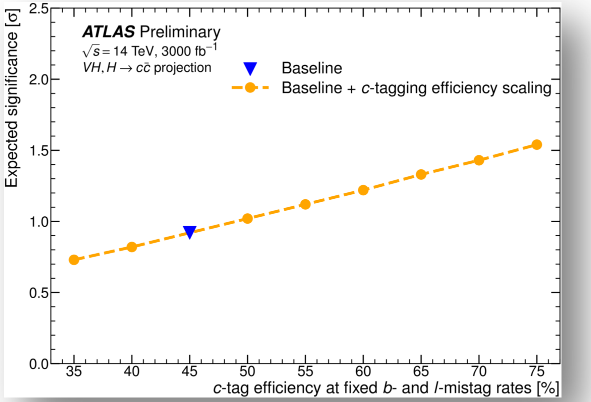
NEXT STEPS

- Exciting detector-agnostic developments also with the **ACTS library to generalise applicability**
  - Tracking and vertexing studies well advanced (see next talk)
  - Already performed b-tagging studies with DIPS algorithm, next step is to move to transformer-based b-tagging

- Trigger applications via cluster-based btagging being explored in synergy with the **Next Generation Triggers** project

- Investigate other flavours
  - c-jets, taus, etc

- Expand physics applications of 4D tracking
  - See delayed photons studies, VBF, etc



ATL-PHYS-PUB-2025-012

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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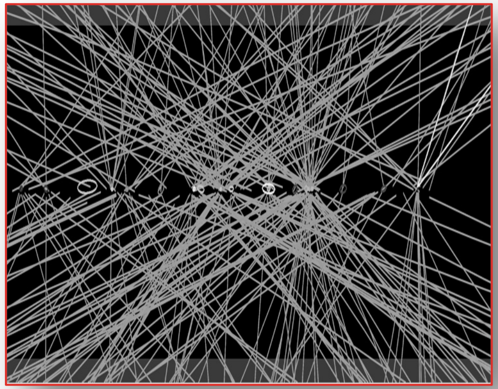
- **Radiation Hardness is a key challenge!**
  - At the HL-LHC the innermost layers are placed at O(30) mm from the IP and will receive doses of O(10) MGy after 2 ab-1 of data
  - At FCC-hh, radius of O(20) mm, radiation levels 0.4 GGy expected after 30 ab^{-1} and a fluence of 6×10^{17} per cm^2 1 MeV 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

- **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 future colliders

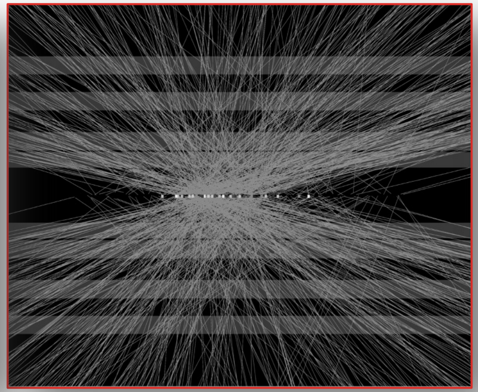
- Very first investigation of **4D Tracking** impact as a replacement of the ATLAS innermost ITk layers:
  - **Vertex t_0 resolution** and impact on **b-tagging** has been shown
    - Both aspects are **being extended to the ACTS realm**
    - **In-depth Tracking/Vertexing/b-tagging studies with ACTS in the Open Data Detector**
  - More in Yanqi's talk

2009



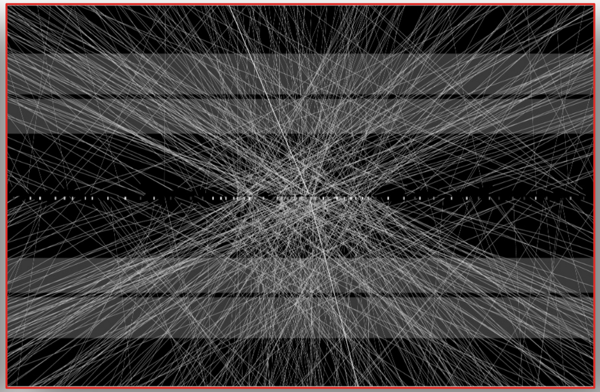
$< pile - up > \sim 20$

2015



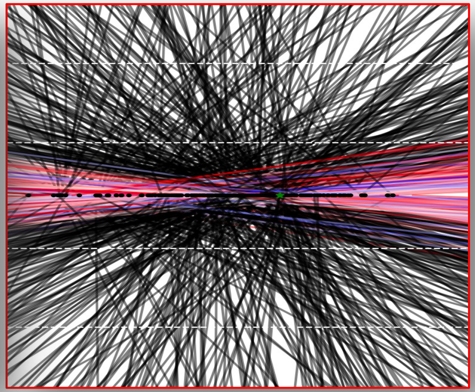
$< pile - up > \sim 30$

2022



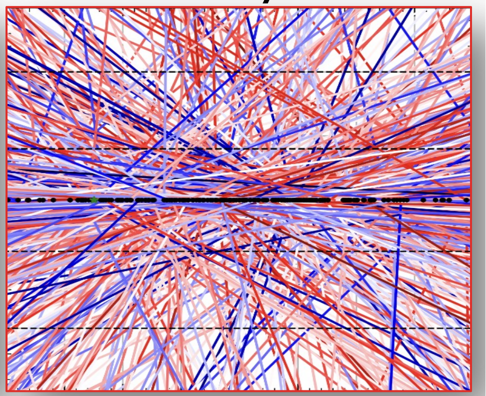
$< pile - up > \sim 60$

2029



$< pile - up > \sim 140$

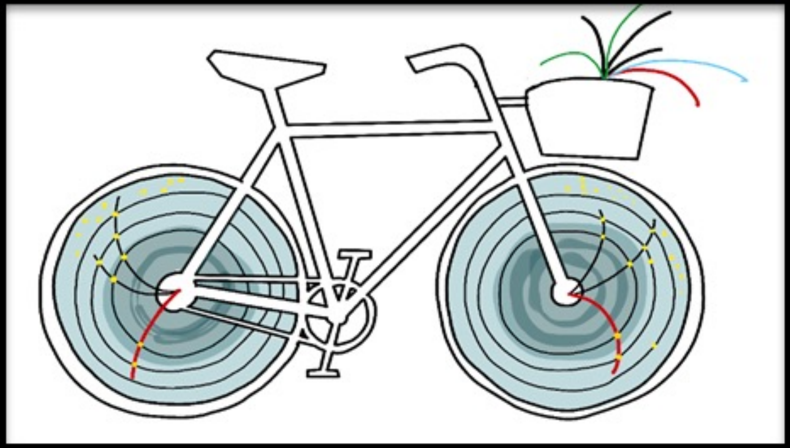
…and beyond?



$< pile - up > \sim 200$

THANK YOU!

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



Valentina Maria Martina Cairo

EXTRA SLIDES