

Università di Genova

via
superiore delle castagne

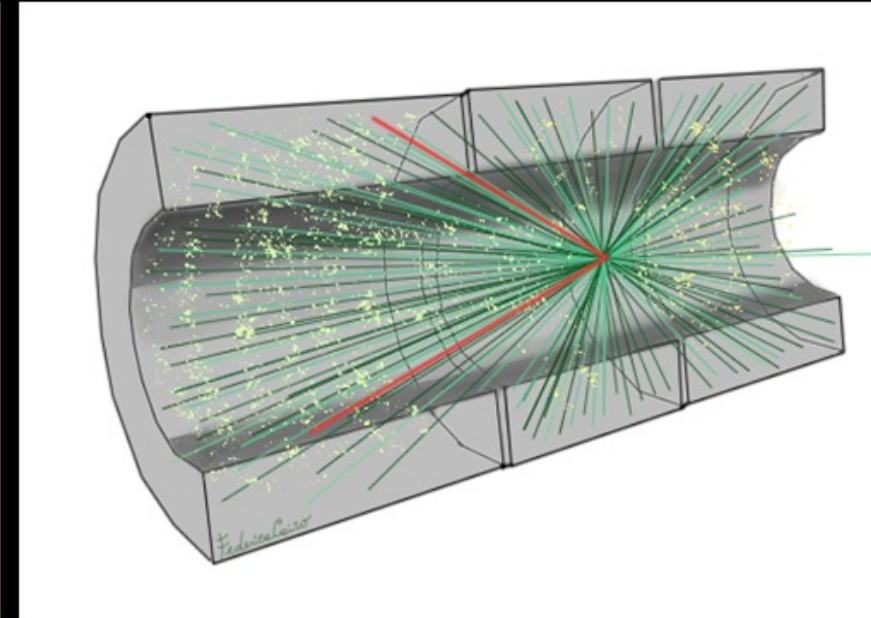
Università degli Studi di Genova
December 4th 2024

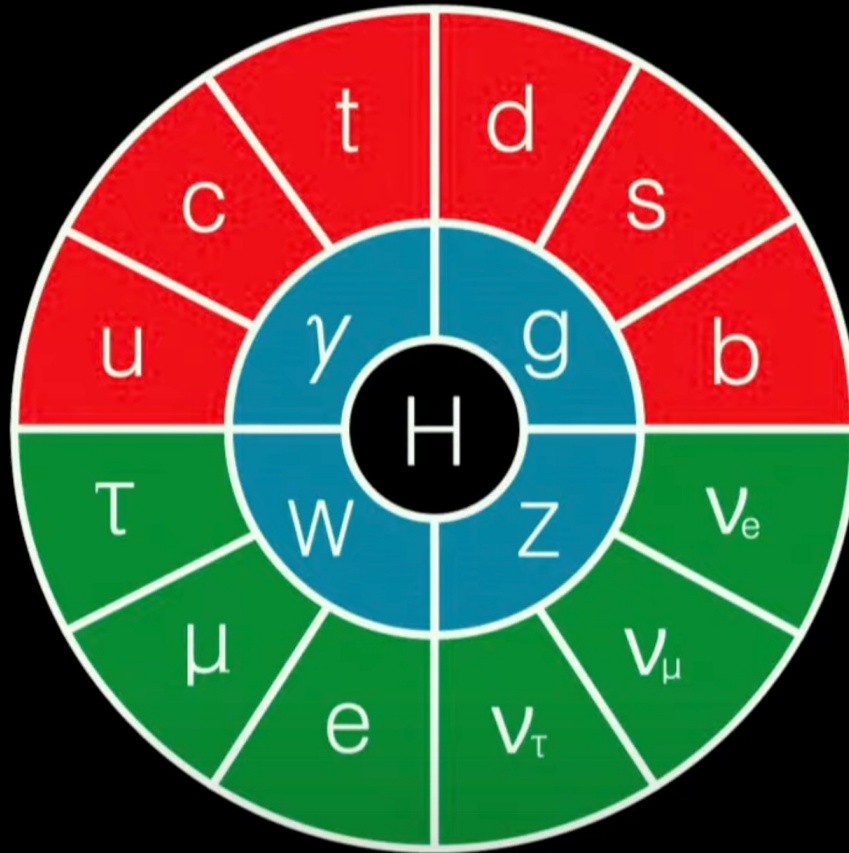
TRACKING DOWN THE HIGGS BOSON PROPERTIES

Valentina Maria Martina Cairo

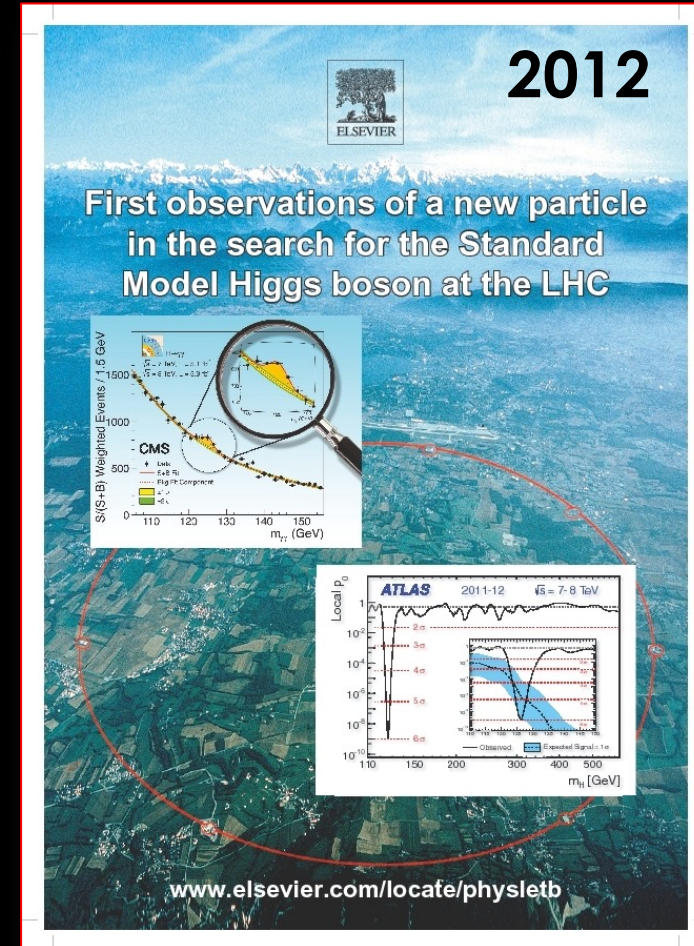


Illustrations:
Federica Cairo





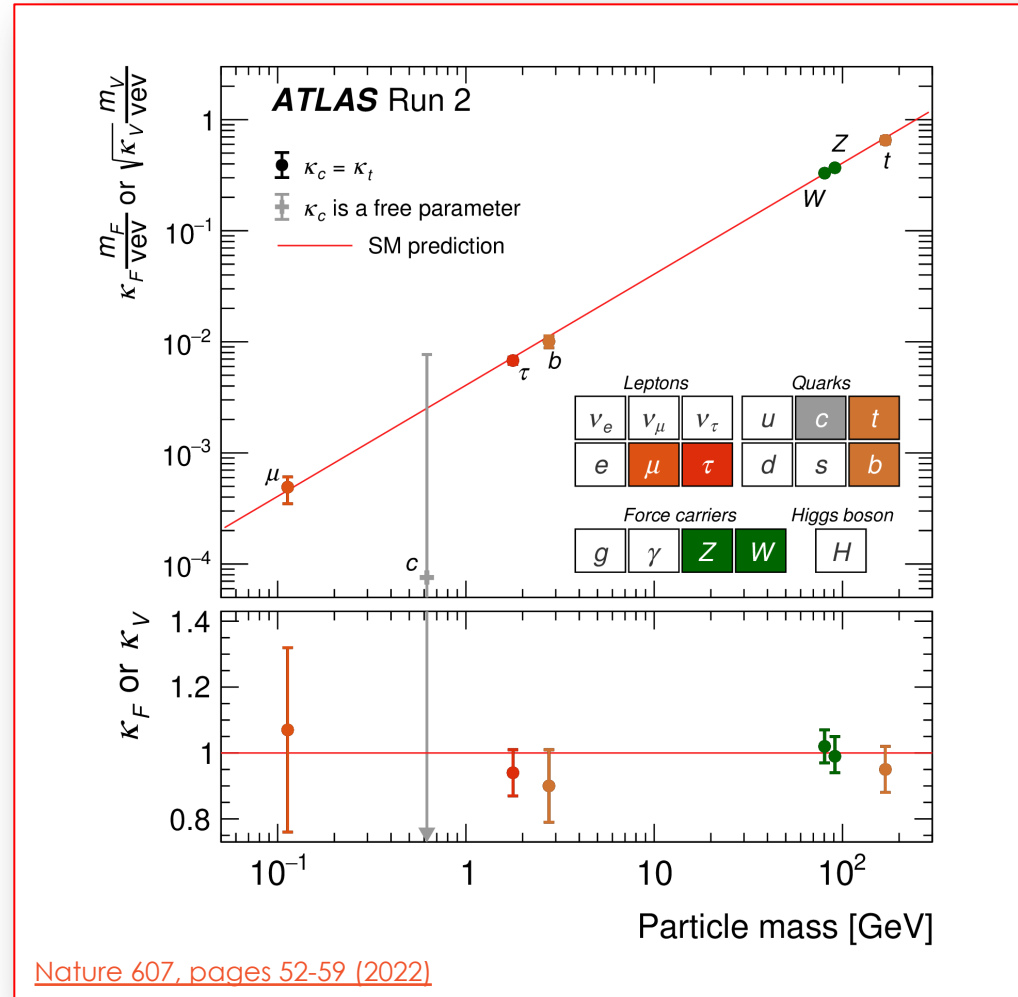
From the movie *Particle Fever*



Profound open questions about the Universe connected to Higgs physics

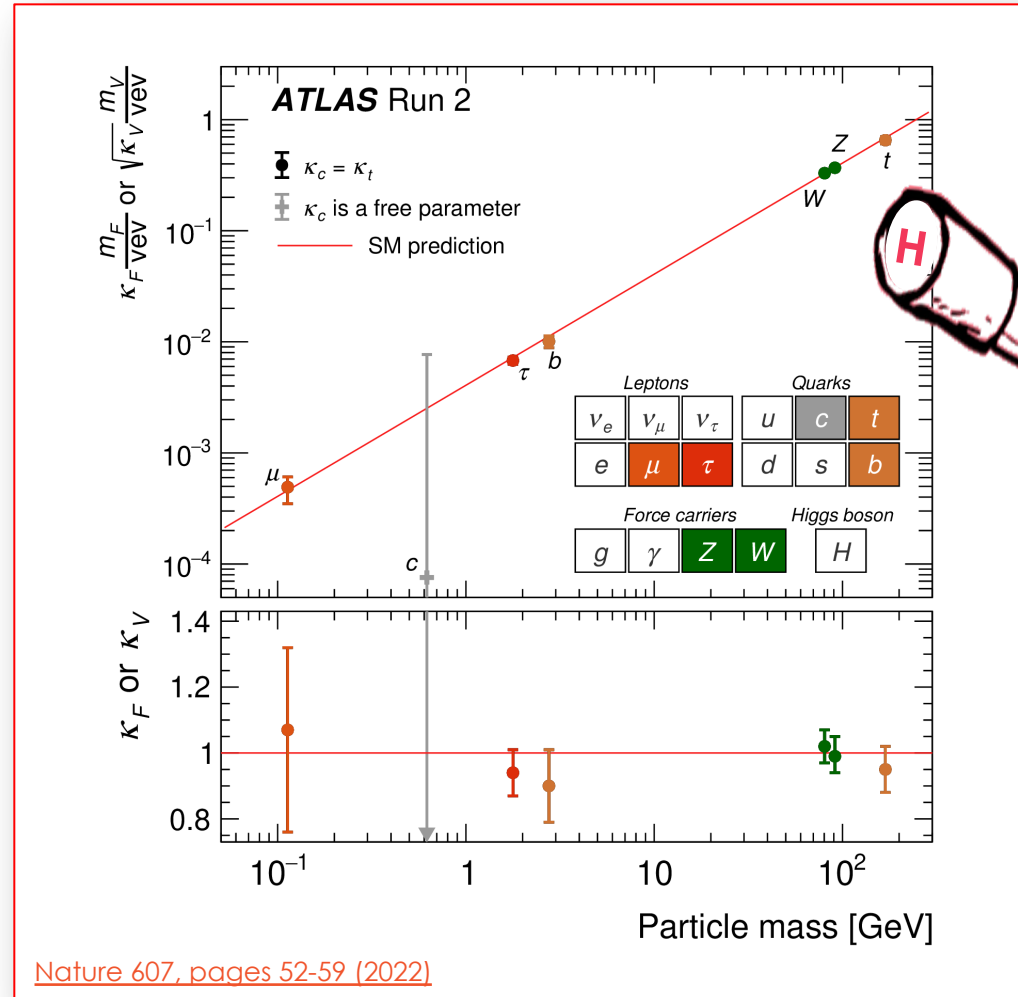
THE POST-HIGGS BOSON ERA

Key to addressing these mysteries is the measurement of the *Higgs boson* couplings



THE POST-HIGGS BOSON ERA

Key to addressing these mysteries is the measurement of the *Higgs boson* couplings



THE THEORY



F. Cairo, From Conn(II)ecting the dots

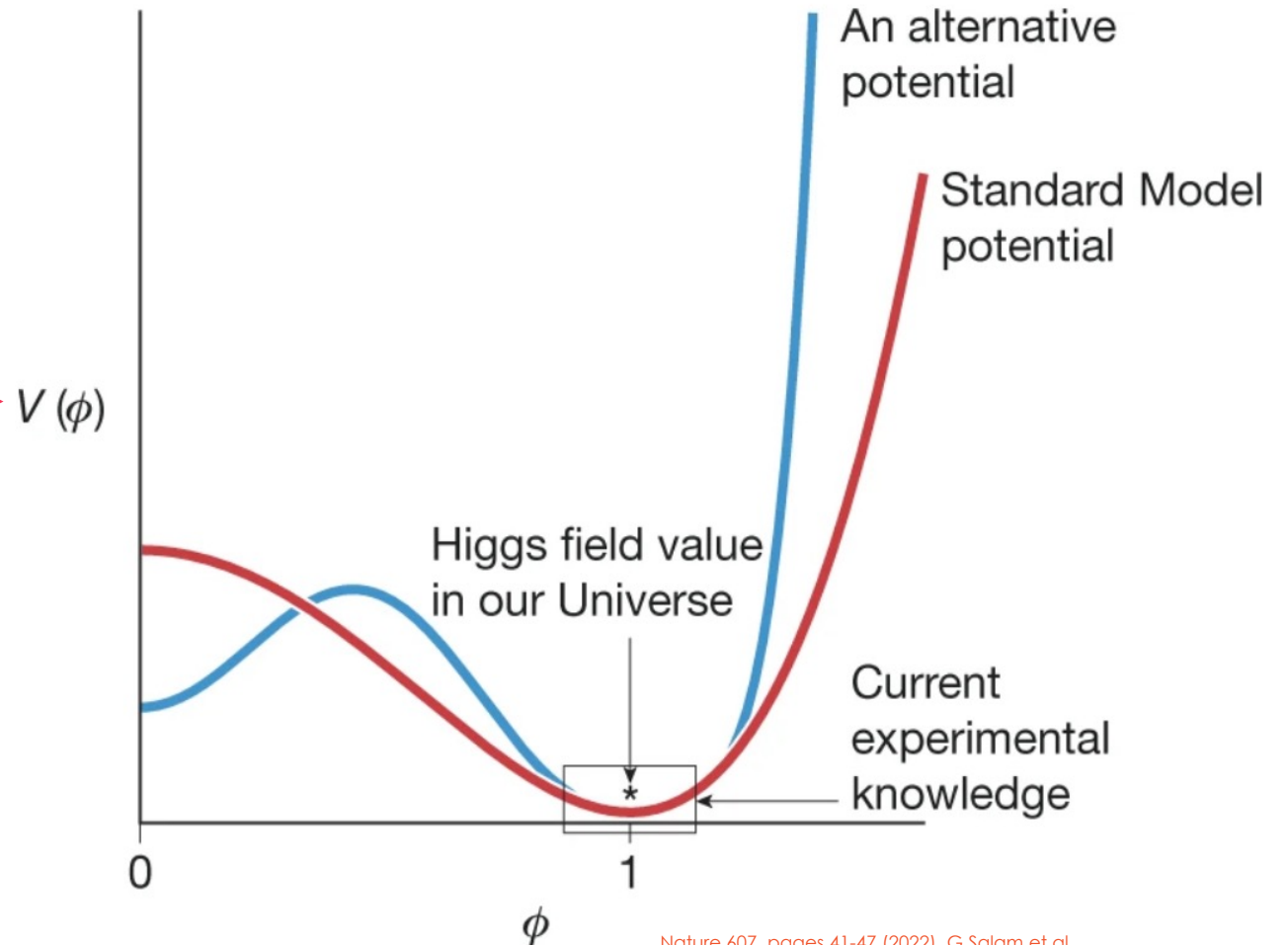


THE HIGGS POTENTIAL AND SELF-COUPLING

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \sum_i y_{ij} \bar{\psi}_i \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

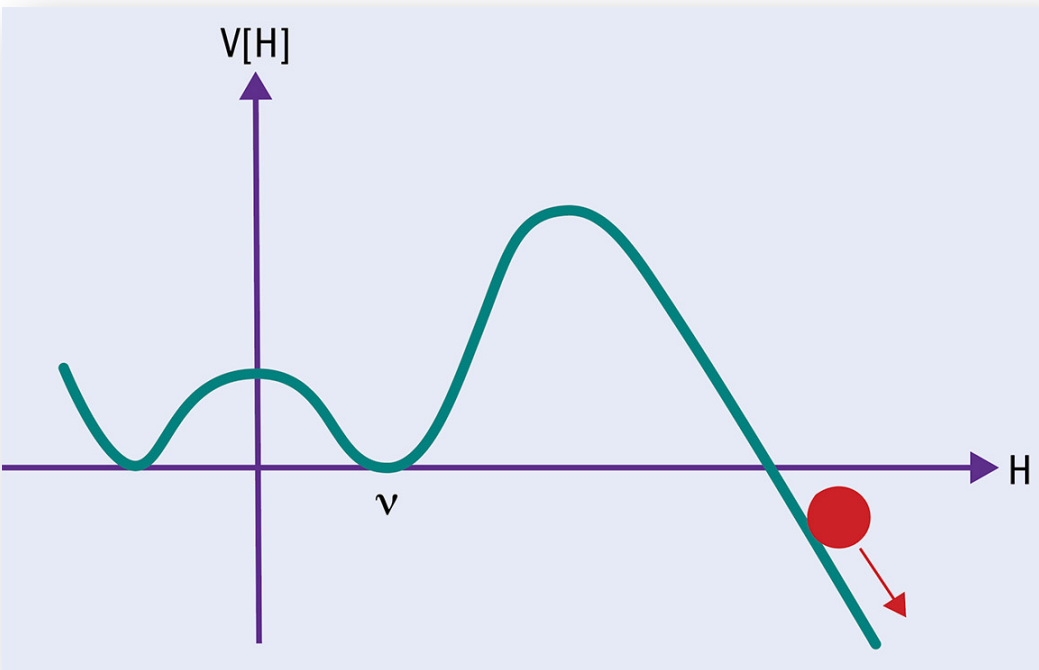
$$V(\phi^\dagger \phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

Higgs
self-coupling
strength

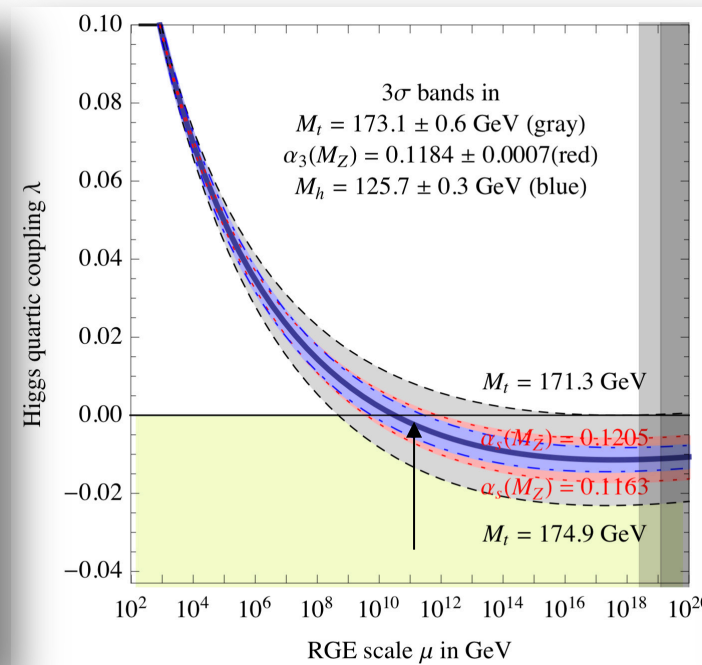


[Nature 607, pages 41-47 \(2022\), G.Salam et al.](#)

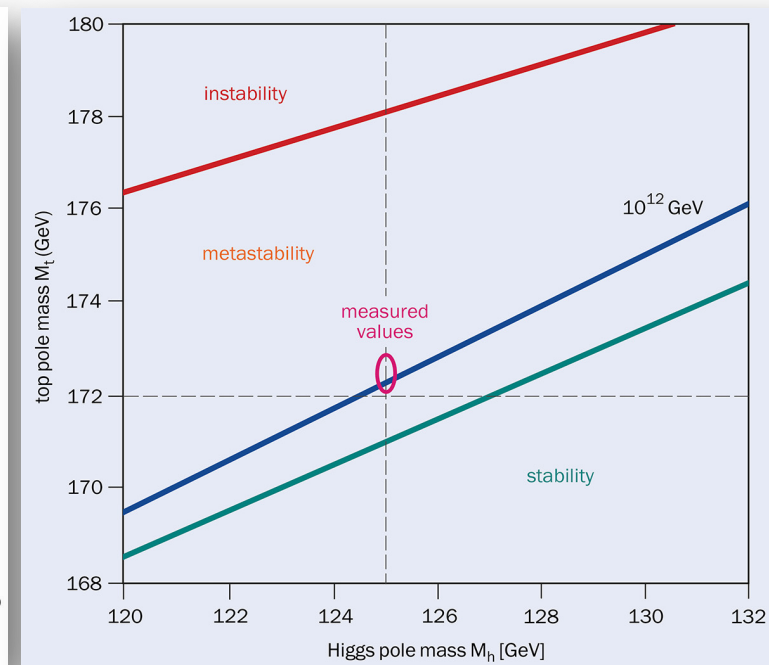
MATTER OF STABILITY



[J. Ellis, The Higgs and the fate of the universe](#)



[JHEP08\(2012\)098](#)



[J. Ellis, The Higgs and the fate of the universe](#)

PROBING THE HIGGS SELF-COUPLING

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \chi_i y_{ij} \chi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

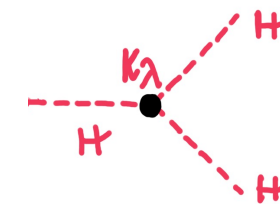
$$V(\phi^\dagger \phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

$$\supset \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4$$

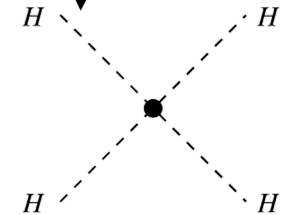
$$m_H = \sqrt{2\lambda v^2}$$

$$v \simeq 246 \text{ GeV}$$

$$\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$$



Direct access
to λ in HH pair
production



Very
challenging
even for HL-LHC

Known m_H (~ 125 GeV), SM predicts λ (~ 0.13)

PROBING THE HIGGS SELF-COUPLING

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \chi_i y_{ij} \chi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

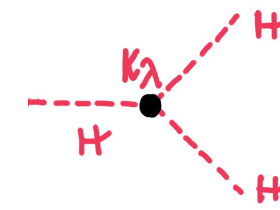
$$V(\phi^\dagger \phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

$$\supset \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4$$

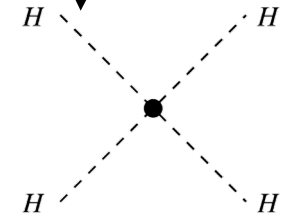
$$m_H = \sqrt{2\lambda v^2}$$

$$v \simeq 246 \text{ GeV}$$

$$\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$$



Direct access
to λ in HH pair
production



Very
challenging
even for HL-LHC

Known m_H (~ 125 GeV), SM predicts λ (~ 0.13)

New physics can alter these numbers $\rightarrow$ Implications on the origin, evolution and stability of the Universe $\rightarrow$ Probing the Higgs-self coupling is a key goal for LHC and HL-LHC!

THE TOOLS

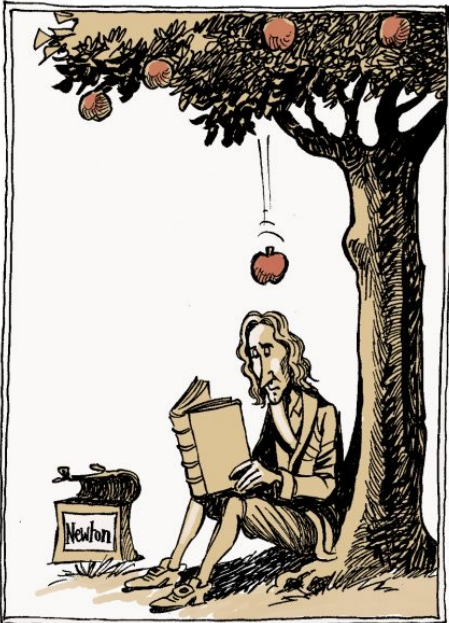


F. Cairo, From Conn(II)ecting the dots

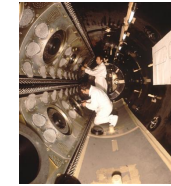
AT THE *HEART* OF COLLIDER PHYSICS: CHALLENGES AND BREAKTHROUGHS

Collisions That Changed The World

N.B. The only exception to my sister's drawings



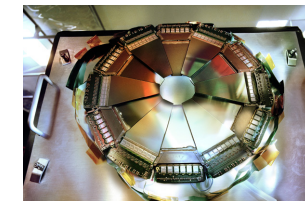
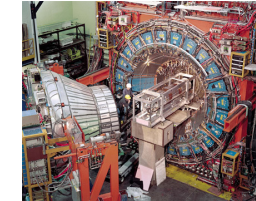
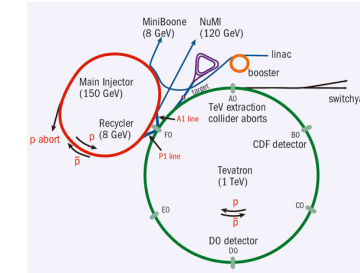
The weak
neutral currents
and the *bubble
chamber era*



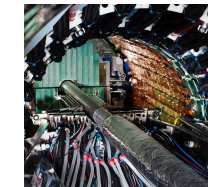
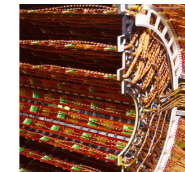
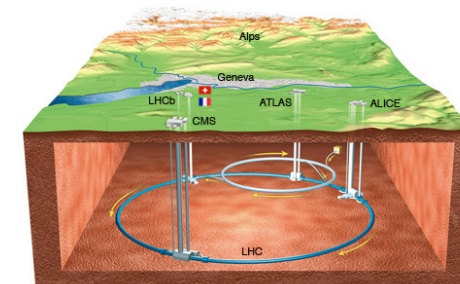
The W,Z
bosons and
the *drift
chamber era*



The top quark and the *silicon strip era*

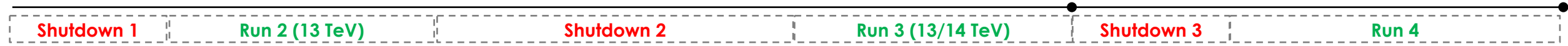


The Higgs boson (and more!) and the *silicon pixel era*



ENABLING HH DISCOVERIES THROUGH TRACKING INNOVATIONS IN ATLAS

04.12.24



HH in Run 1 data

PHYSICAL REVIEW D 92, 092004 (2015)
Searches for Higgs boson pair production in the $hh \rightarrow b\bar{b}\nu\bar{\nu}, \gamma\gamma WW^*, \gamma\gamma b\bar{b}, b\bar{b}b\bar{b}$ channels with the ATLAS detector
G. Aad *et al.*^{*}
(ATLAS Collaboration)
(Received 16 September 2015; published 5 November 2015)

Searches for both resonant and nonresonant Higgs boson pair production are performed in the $hh \rightarrow b\bar{b}\nu\bar{\nu}, \gamma\gamma WW^*$ final states using 20.3 fb⁻¹ of pp collision data at a center-of-mass energy of 8 TeV recorded with the ATLAS detector at the Large Hadron Collider. No evidence of their production is observed and 95% confidence-level upper limits on the production cross sections are set. These results are then combined with the published results of the $hh \rightarrow \gamma\gamma b\bar{b}, b\bar{b}b\bar{b}$ analyses. An upper limit of 0.69 (0.47) pb on the nonresonant hh production is observed (expected), corresponding to 70 (48) times the SM $gg \rightarrow hh$ cross section. For production via narrow resonances, cross-section limits of hh production from a heavy Higgs boson decay are set as a function of the heavy Higgs boson mass. The observed (expected) limits range from 2.1 (1.1) pb at 260 GeV to 0.011 (0.018) pb at 1000 GeV. These results are interpreted in the context of two simplified scenarios of the Minimal Supersymmetric Standard Model.

HH in early Run 2 data

Physics Letters B 800 (2020) 135103
Contents lists available at ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

Combination of searches for Higgs boson pairs in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector
The ATLAS Collaboration^{*}

HH in full Run 2 data

PHYSICAL REVIEW LETTERS 133, 101801 (2024)
Combination of Searches for Higgs Boson Pair Production in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector
G. Aad *et al.*^{*}
(ATLAS Collaboration)
(Received 17 June 2024; accepted 29 July 2024; published 4 September 2024)

This Letter presents results from a combination of searches for Higgs boson pair production using 126–140 fb⁻¹ of proton-proton collision data at $\sqrt{s} = 13$ TeV recorded with the ATLAS detector. At 95% confidence level (CL), the upper limit on the production rate is 2.9 times the standard model (SM) prediction, with an expected limit of 2.4 assuming no Higgs boson pair production. Constraints on the Higgs boson self-coupling modifier $\kappa_h = \lambda_{HHH}/\lambda_{HHH}^{SM}$ and the quartic $HHVV$ coupling modifier $\kappa_{2V} = g_{HHVV}/g_{HHVV}^{SM}$ are derived individually, fixing the other parameter to its SM value. The observed 95% CL intervals are $-1.2 < \kappa_h < 7.2$ and $0.6 < \kappa_{2V} < 1.5$, respectively, while the expected intervals are $-1.6 < \kappa_h < 7.2$ and $0.4 < \kappa_{2V} < 1.6$ in the SM case. Constraints obtained for several interaction parameters within Higgs effective field theory are the strongest to date, offering insights into potential deviations from SM predictions.

HH Extrapolations

ATLAS PUB Note
ATL-PHYS-PUB-2022-053
November 8, 2022

HL-LHC prospects for the measurement of Higgs boson pair production in the $b\bar{b}b\bar{b}$ final state and combination with the $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ final states at the ATLAS experiment
The ATLAS Collaboration



Insertable B-Layer

Preparation for Run 3

Run 3 data taking

new Inner Tracker

?

THE WORK

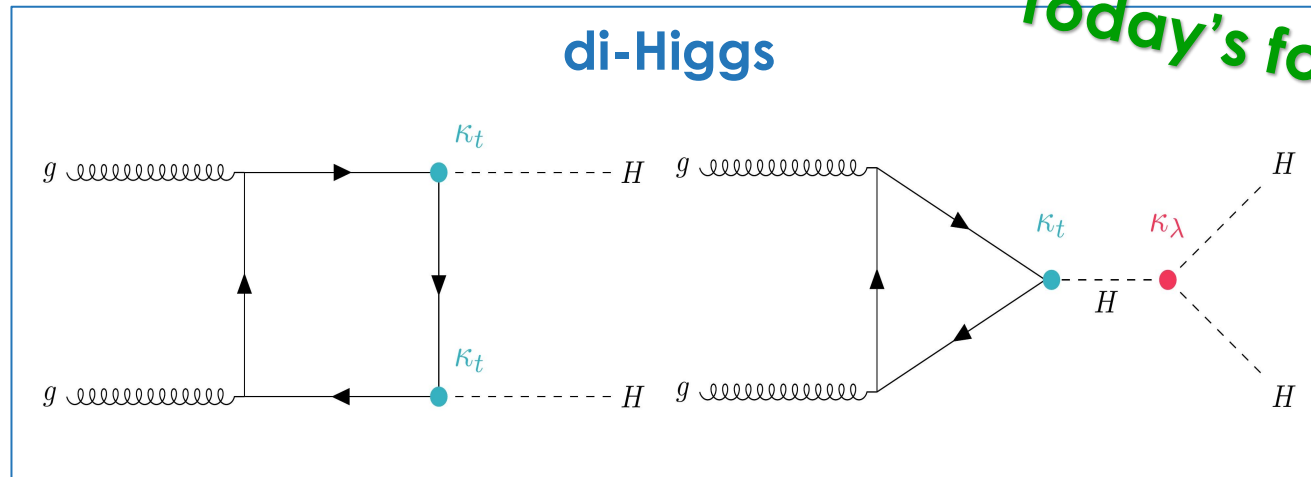


THE HIGGS SELF-COUPLING

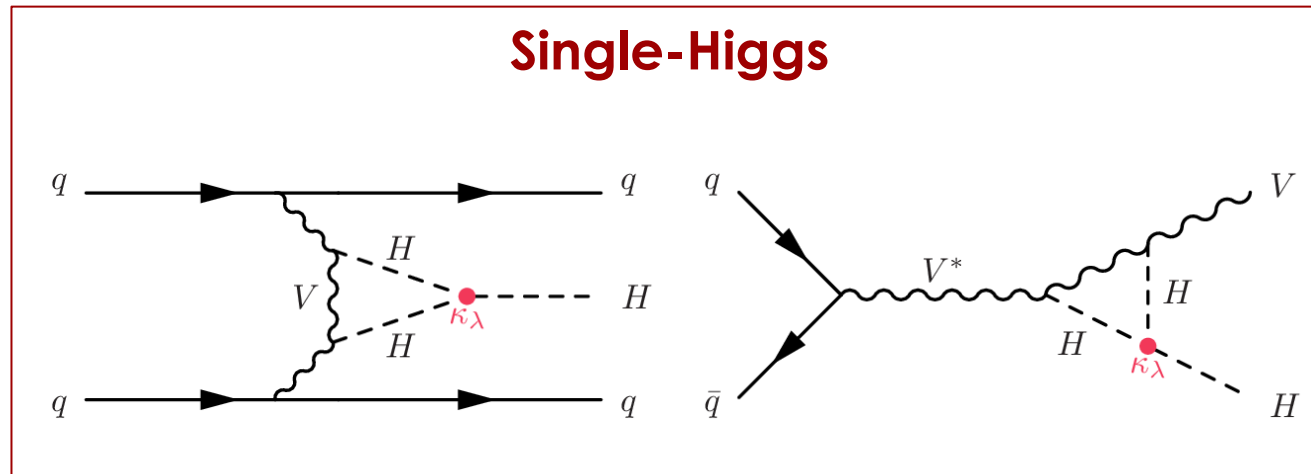
λ_{HHH} can be measured in two complementary ways

Today's focus

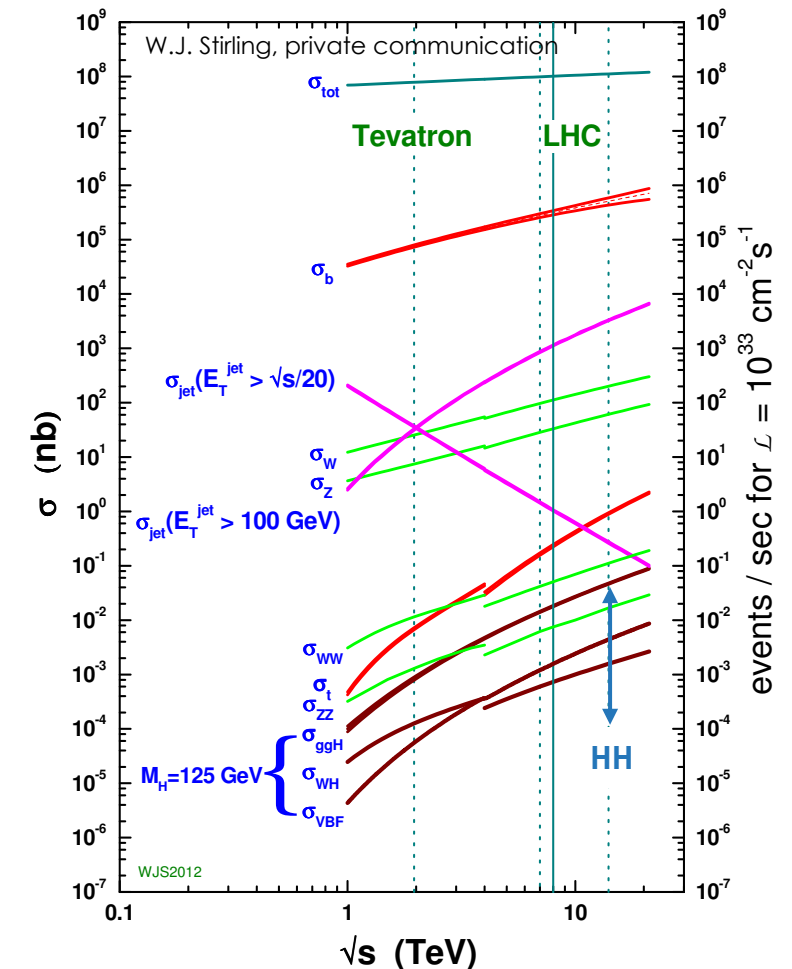
di-Higgs



Single-Higgs

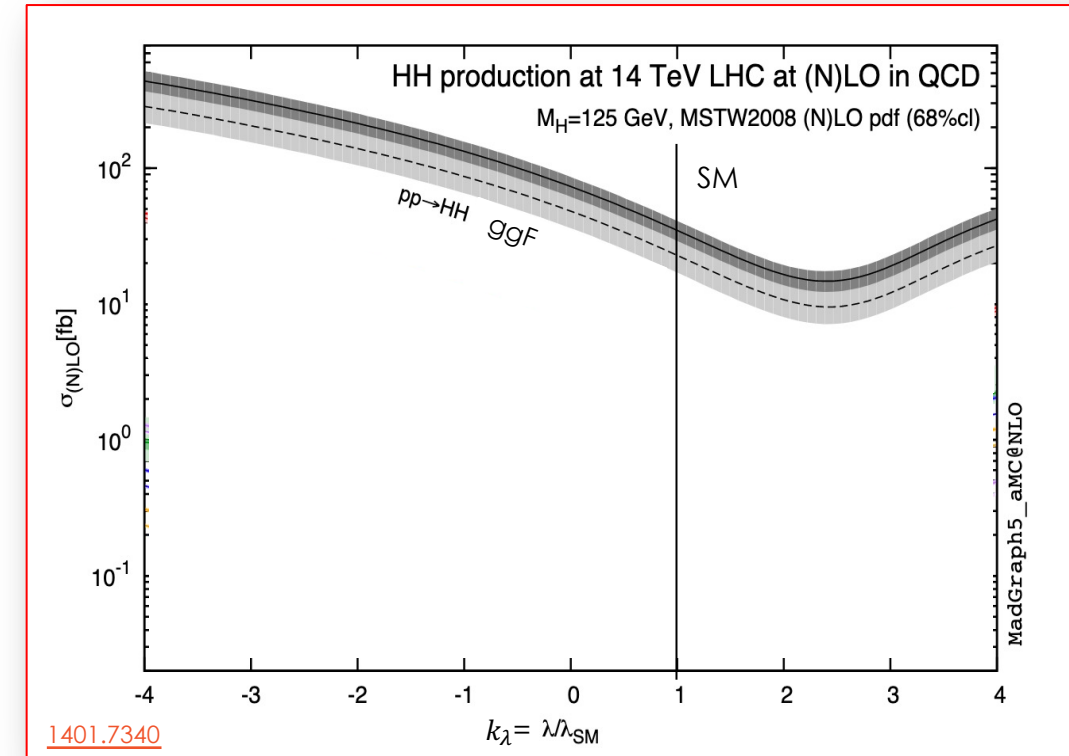
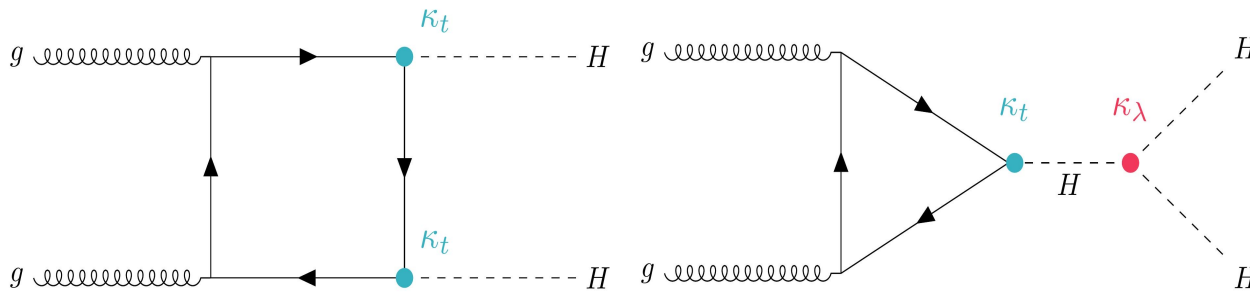


proton - (anti)proton cross sections



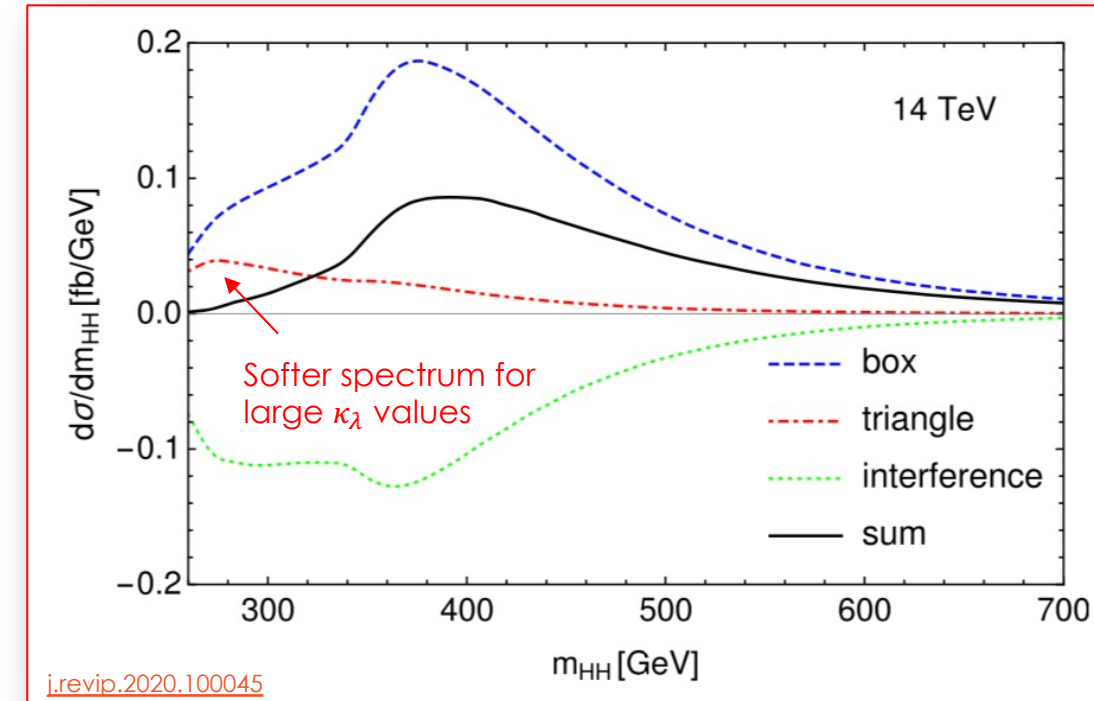
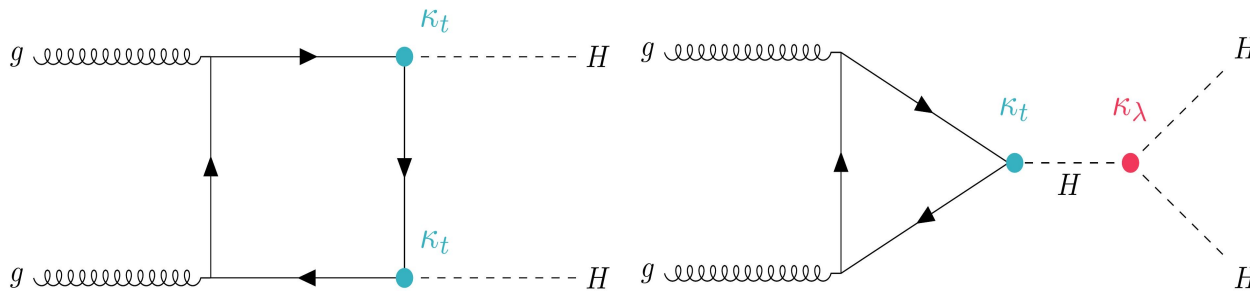
HH PRODUCTION AT THE LHC

Non-resonant $\sigma_{HH}^{ggF} = 31.05 \text{ fb}$ at 13 TeV for $m_H = 125.00 \text{ GeV}$

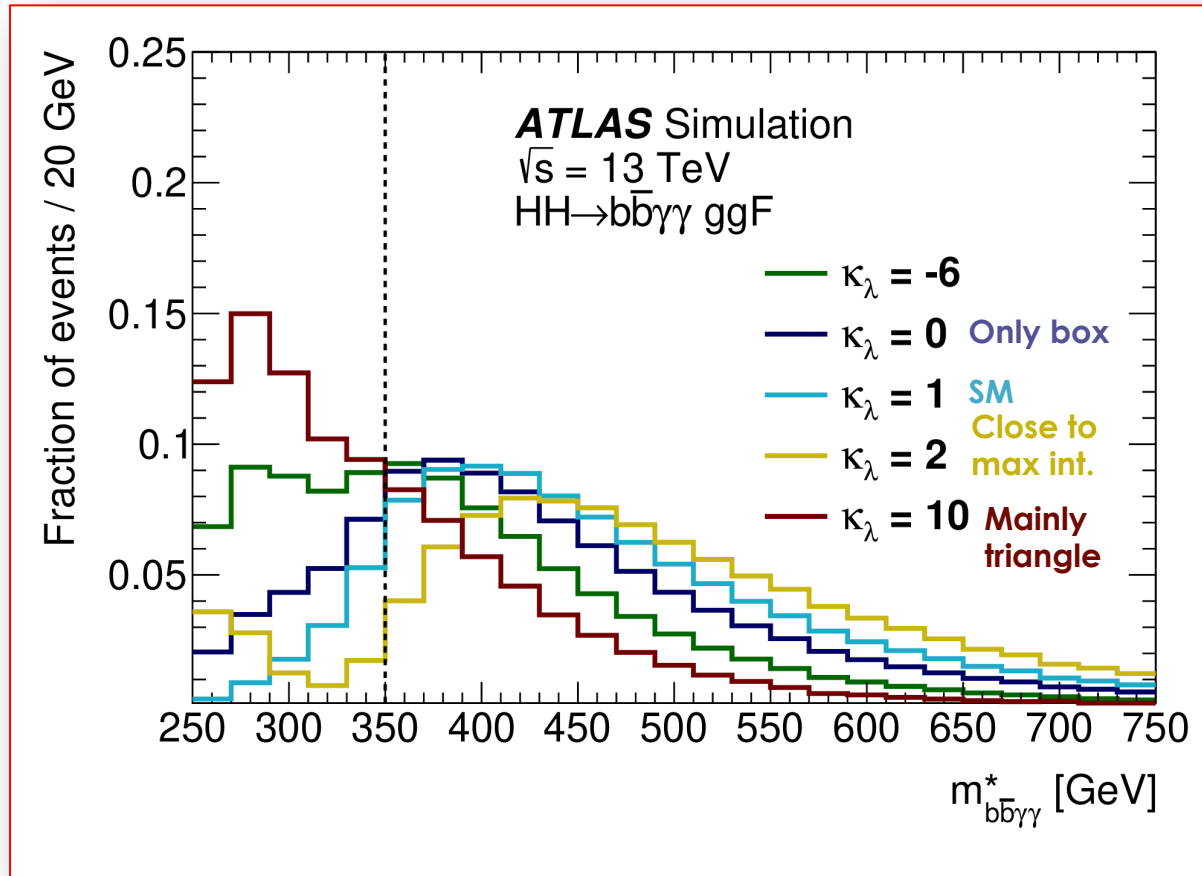


HH PRODUCTION AT THE LHC

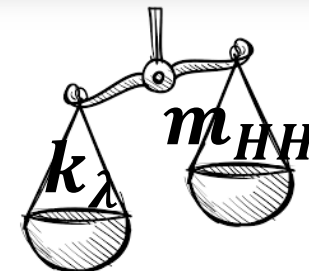
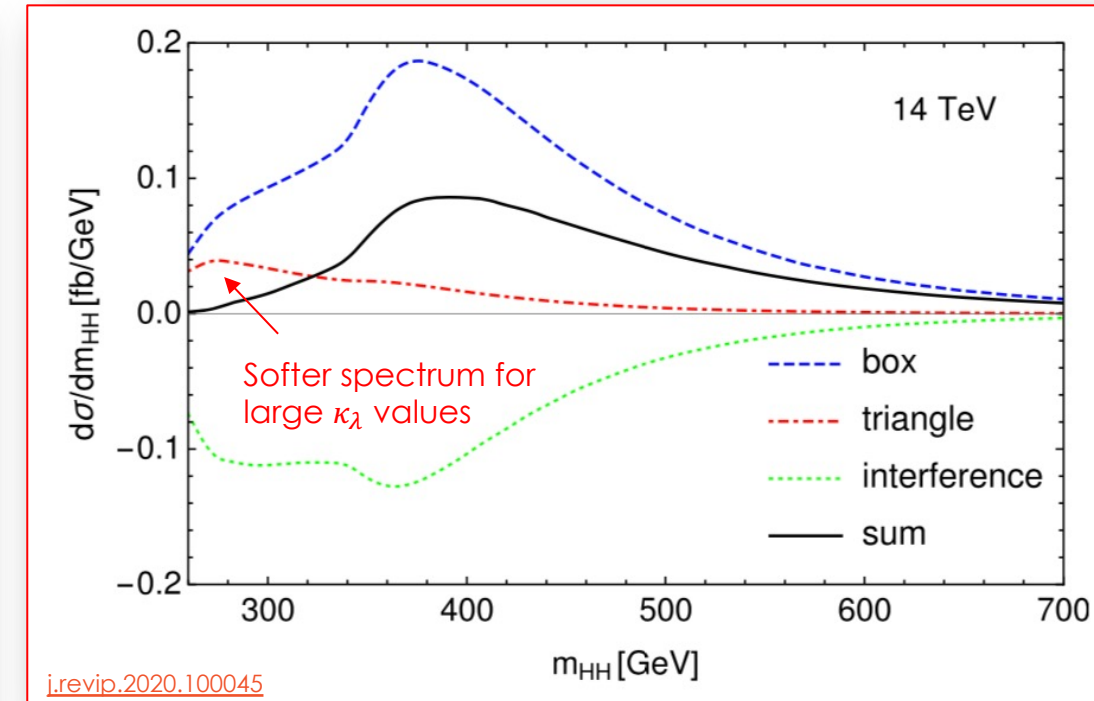
Non-resonant $\sigma_{HH}^{ggF} = 31.05 \text{ fb}$ at 13 TeV for $m_H = 125.00 \text{ GeV}$



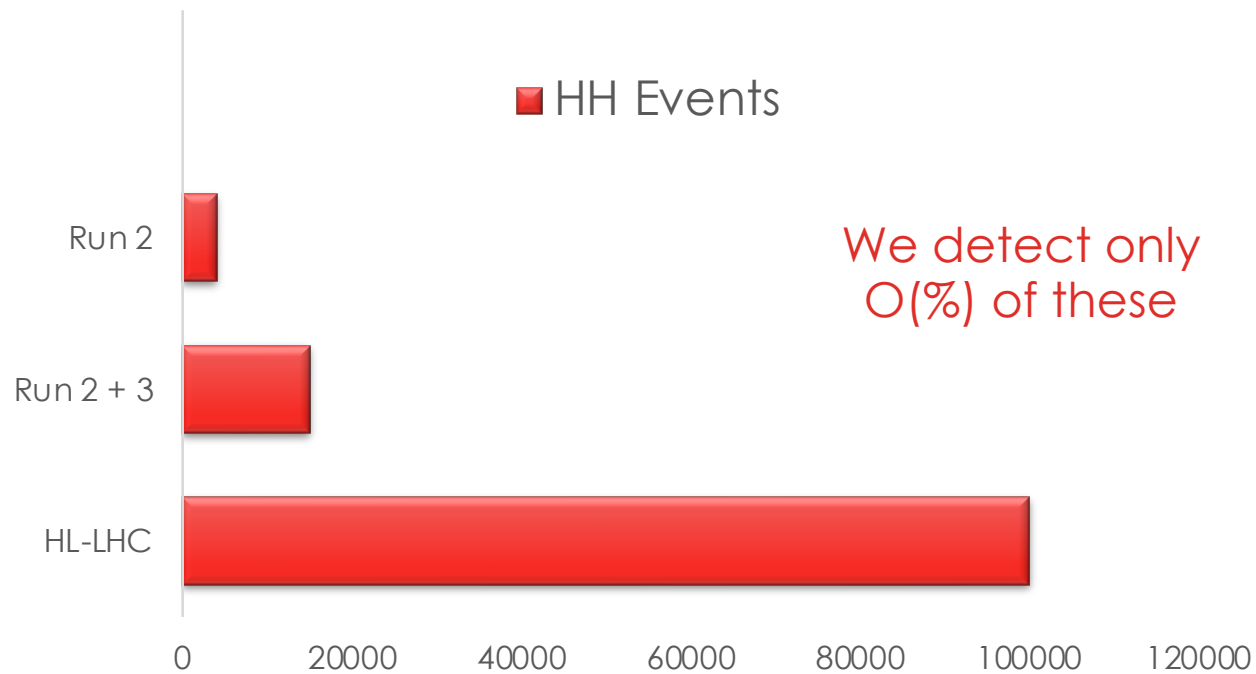
HH PRODUCTION AT THE LHC



Key experimental handle



TWICE THE HIGGS, TWICE THE CHALLENGE

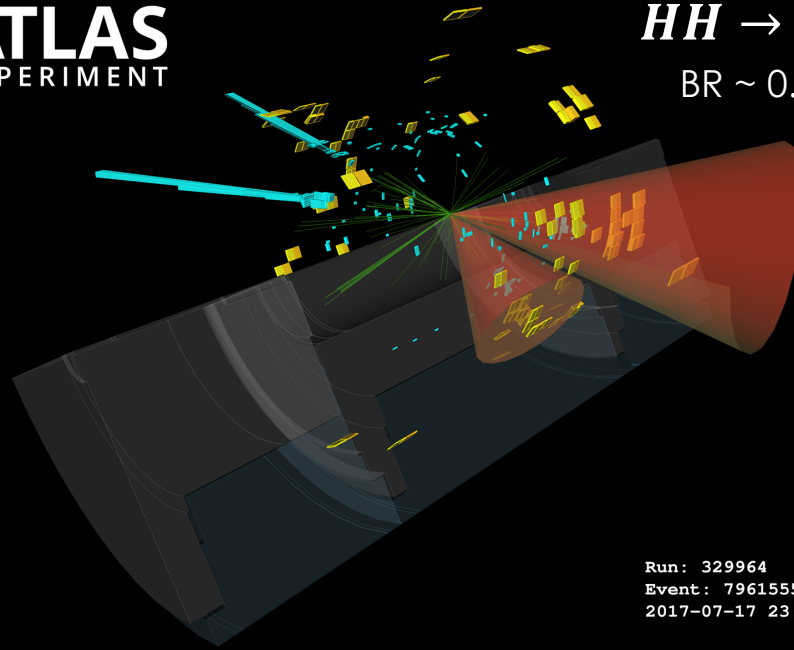


Need to combine
multiple signatures
of Higgs boson decays
to increase sensitivity

$HH \rightarrow b\bar{b}\gamma\gamma$
BR $\sim 0.26\%$

04.12.24

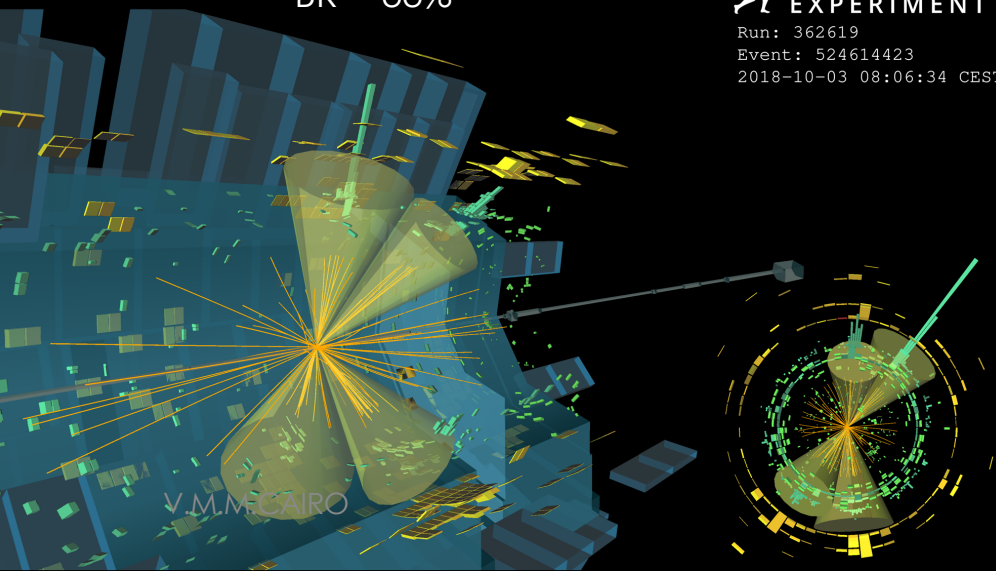
Complementary
strengths and challenges



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

$HH \rightarrow b\bar{b}b\bar{b}$
BR $\sim 33\%$

 **ATLAS**
EXPERIMENT
Run: 362619
Event: 524614423
2018-10-03 08:06:34 CEST

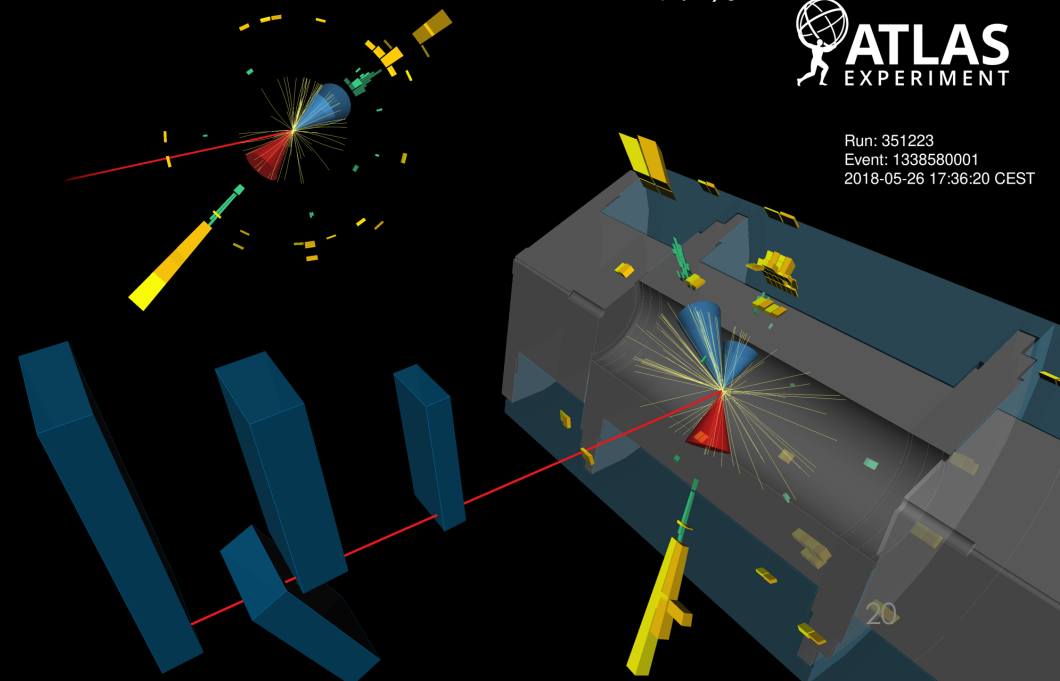


V.M. CAIRO

$HH \rightarrow b\bar{b}\tau\tau$
BR $\sim 7.4\%$

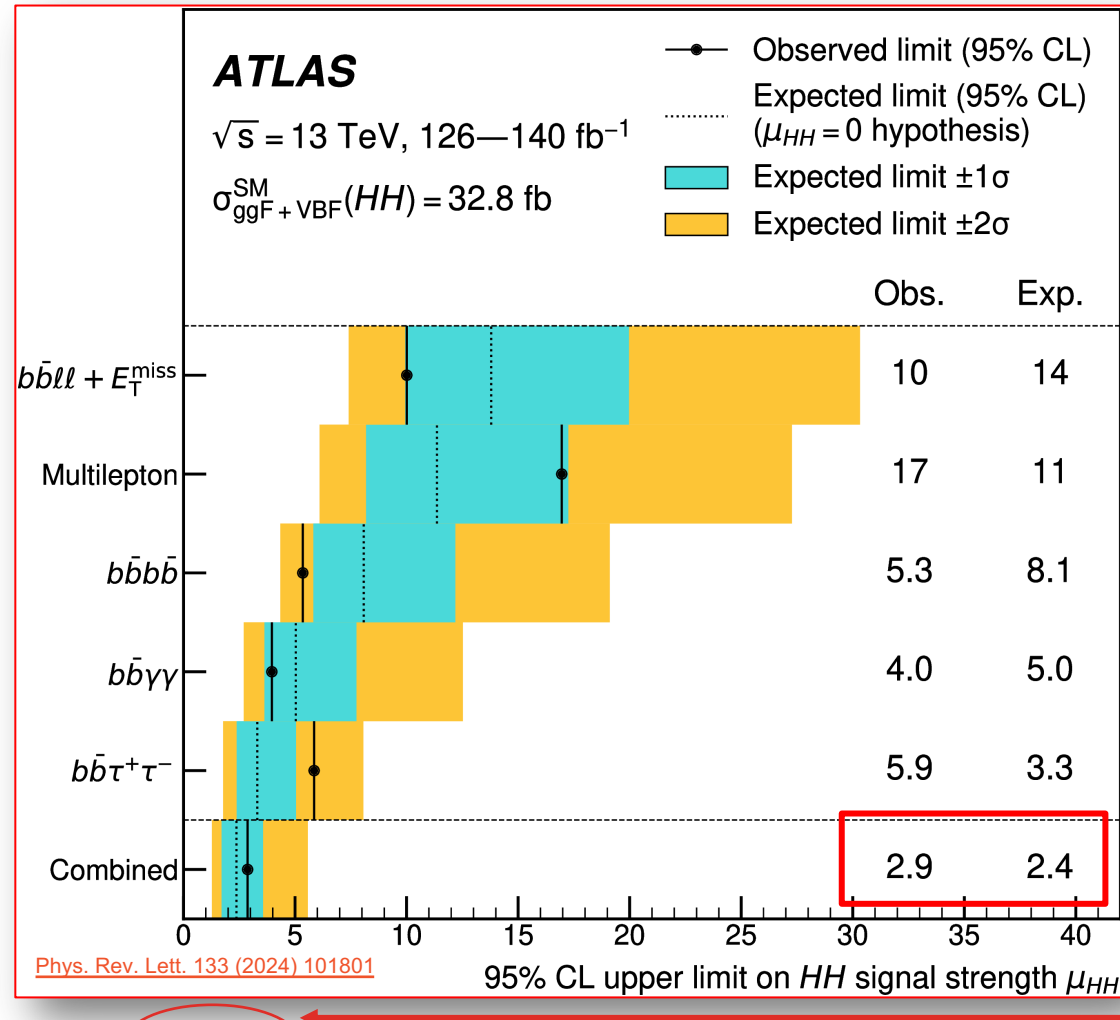
 **ATLAS**
EXPERIMENT

Run: 351223
Event: 1338580001
2018-05-26 17:36:20 CEST



20

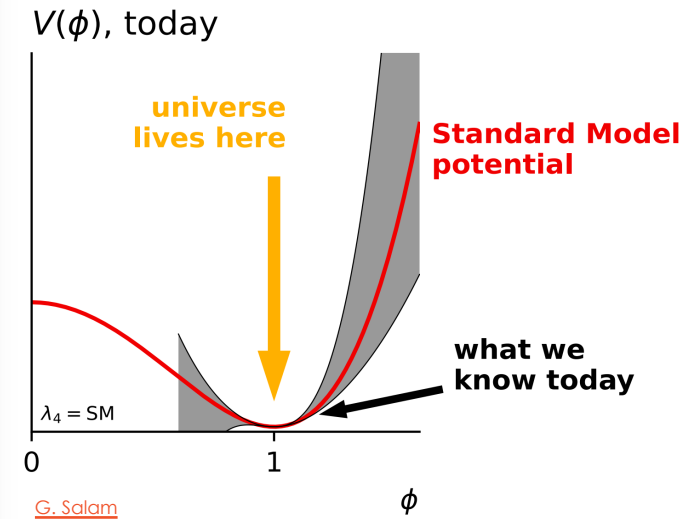
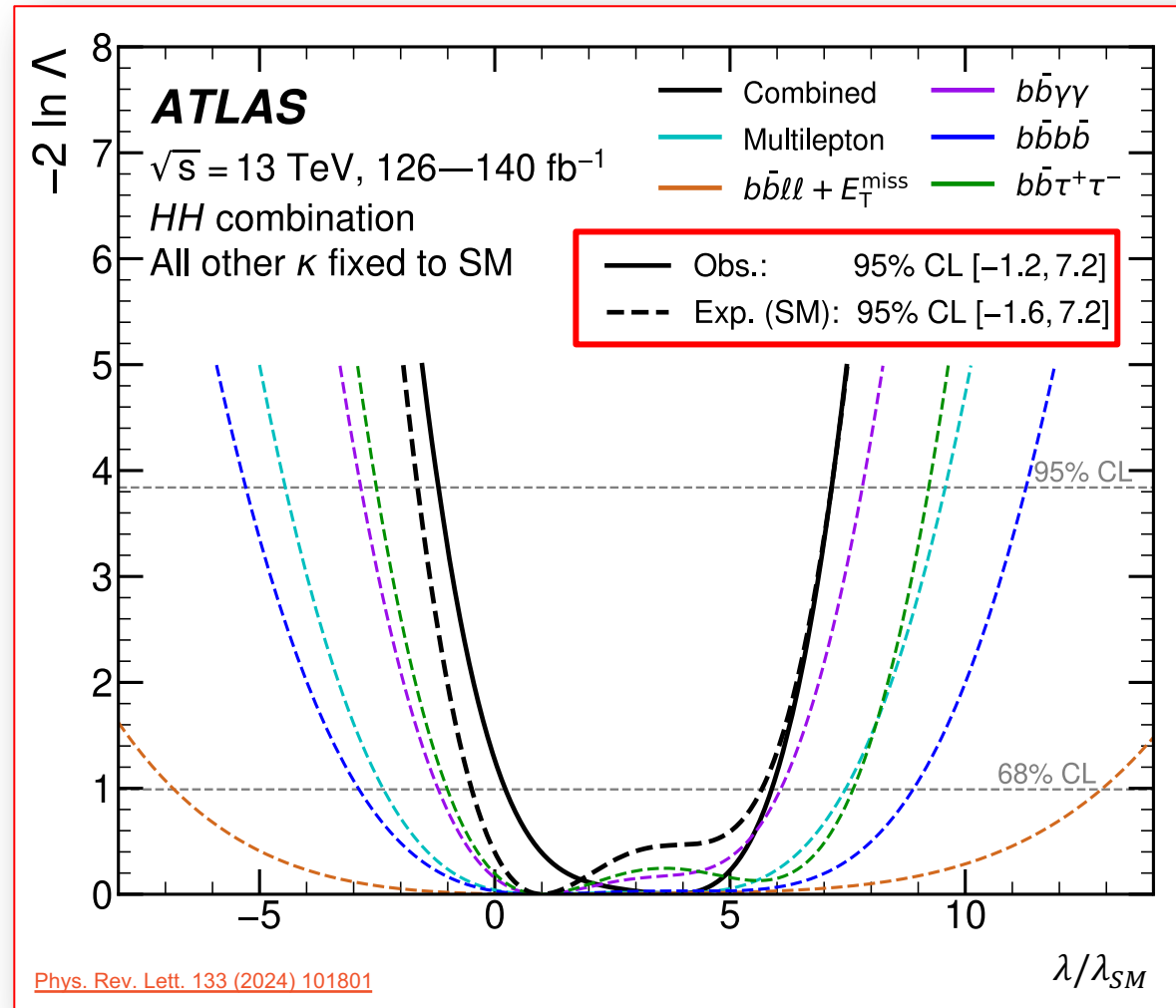
THE POWER OF COMBINATION



1
 ★
 SM prediction

Increasing sensitivity to SM

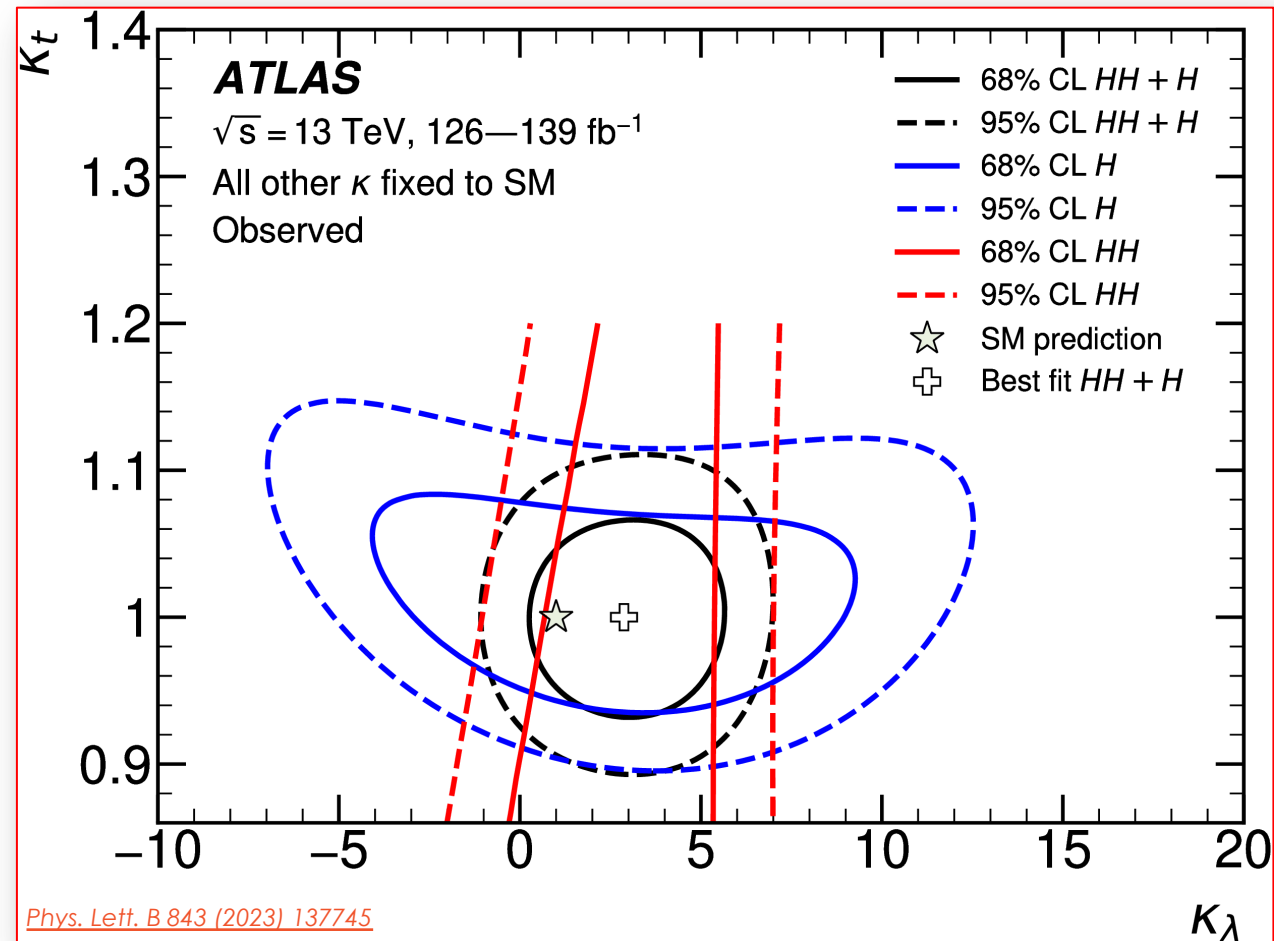
THE POWER OF COMBINATION



From HH cross-section to Higgs self-coupling constraints
 Complementary sensitivity across decay modes

THE POWER OF COMBINATION

$$H + HH$$

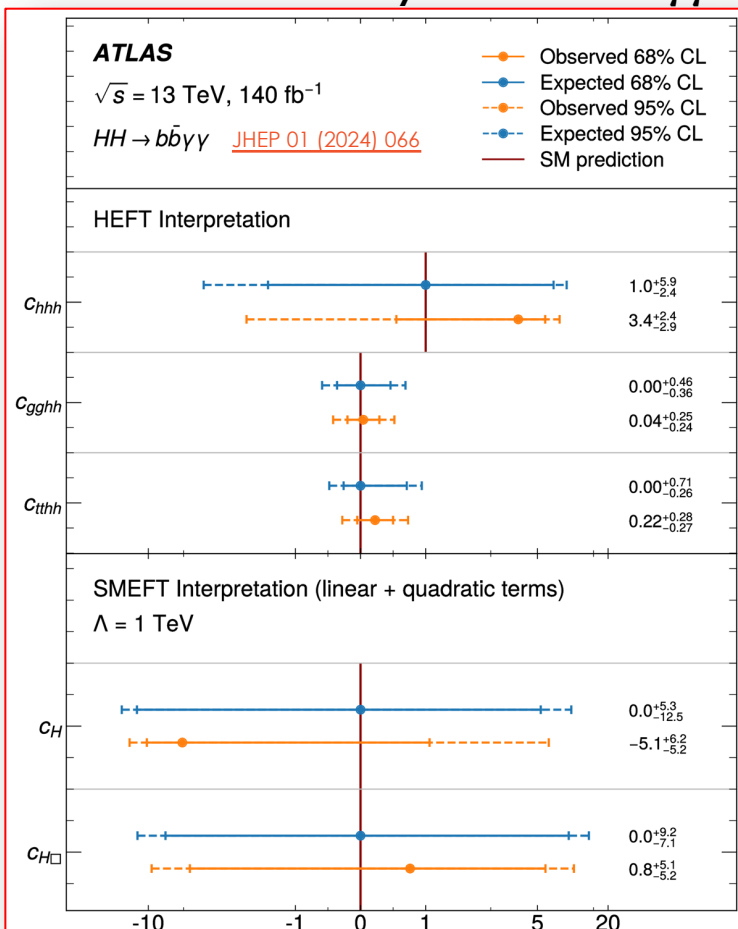


A BROAD AND EXCITING PROGRAMME

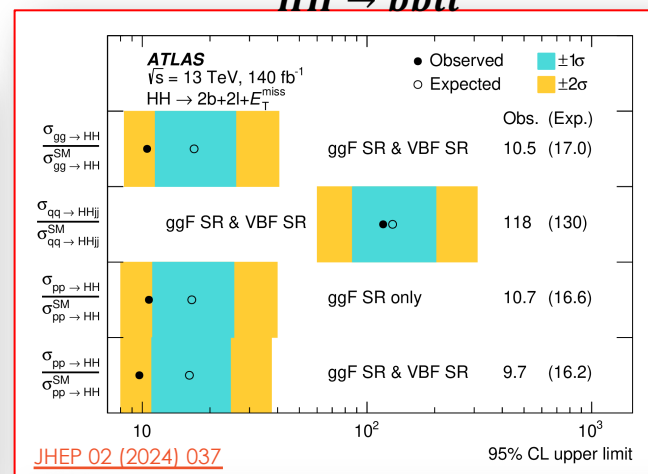
04.12.24

Further improvements to leading channels and new areas to characterise the Higgs sector with HH

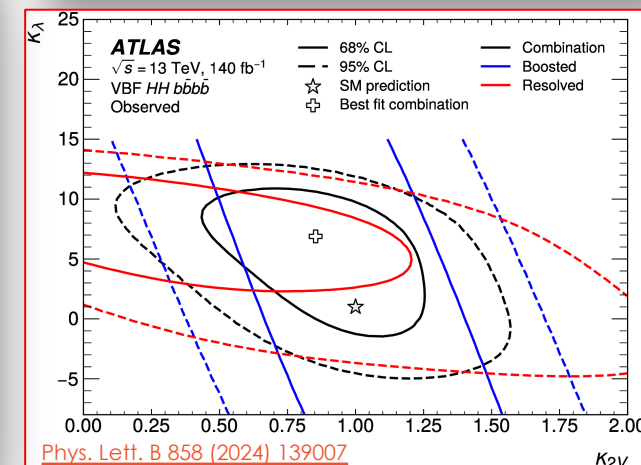
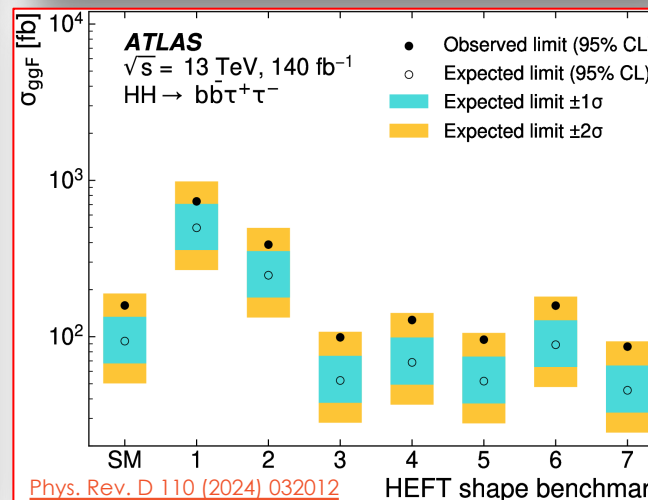
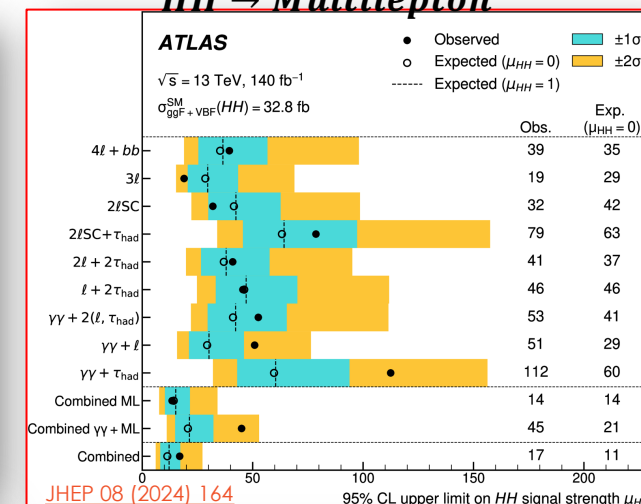
Effective Field Theory with $HH \rightarrow b\bar{b}\gamma\gamma$



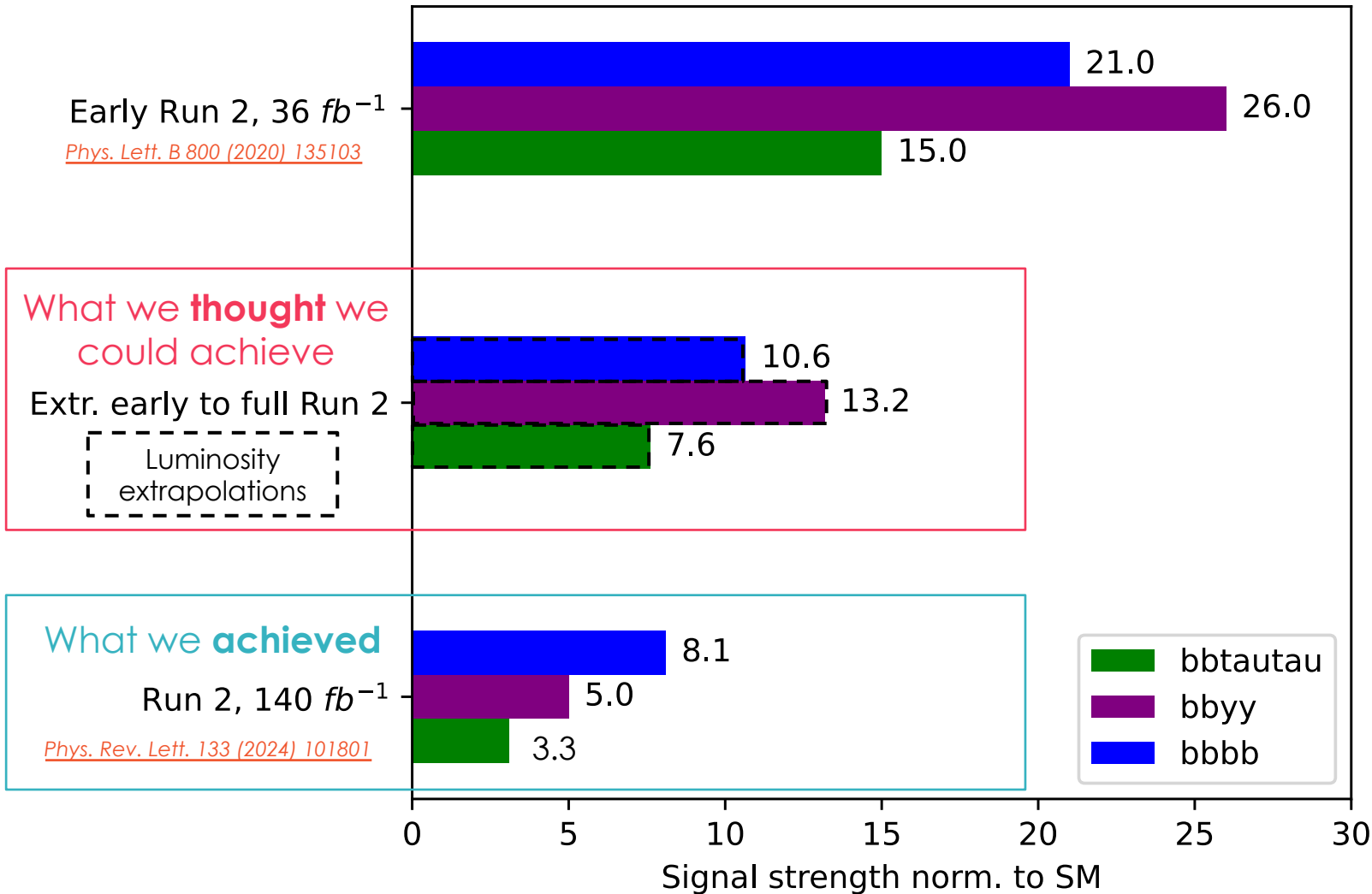
$HH \rightarrow b\bar{b}l\bar{l}$



$HH \rightarrow \text{Multilepton}$



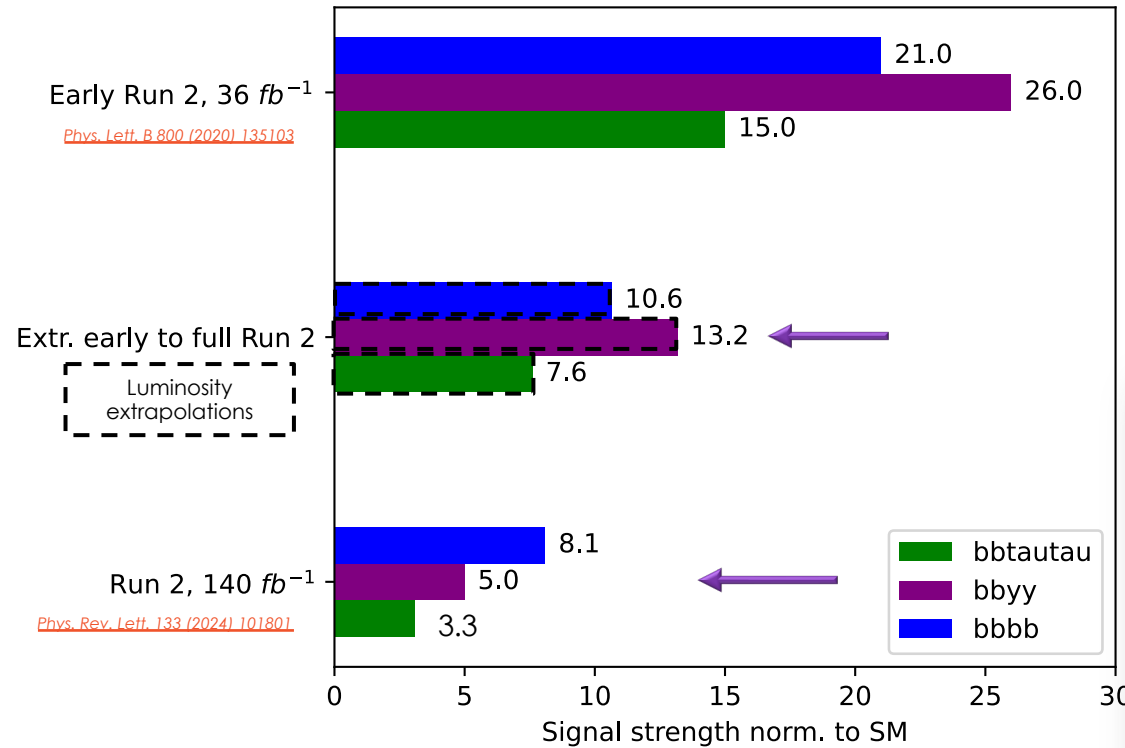
AN IMPRESSIVE SUCCESS



~x2 improvement
on top of luminosity
increase!

How?

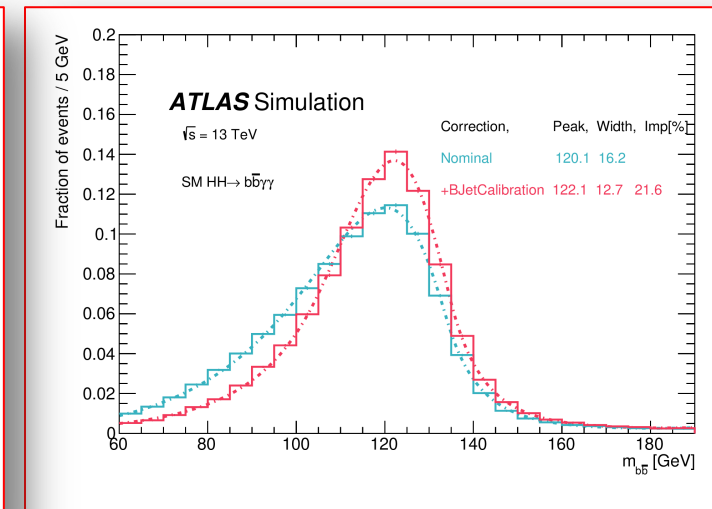
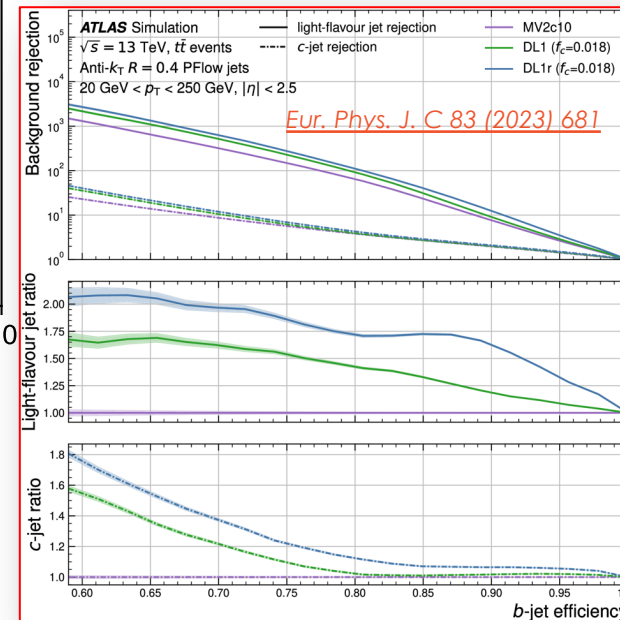
THE $HH \rightarrow b\bar{b}\gamma\gamma$ EXAMPLE



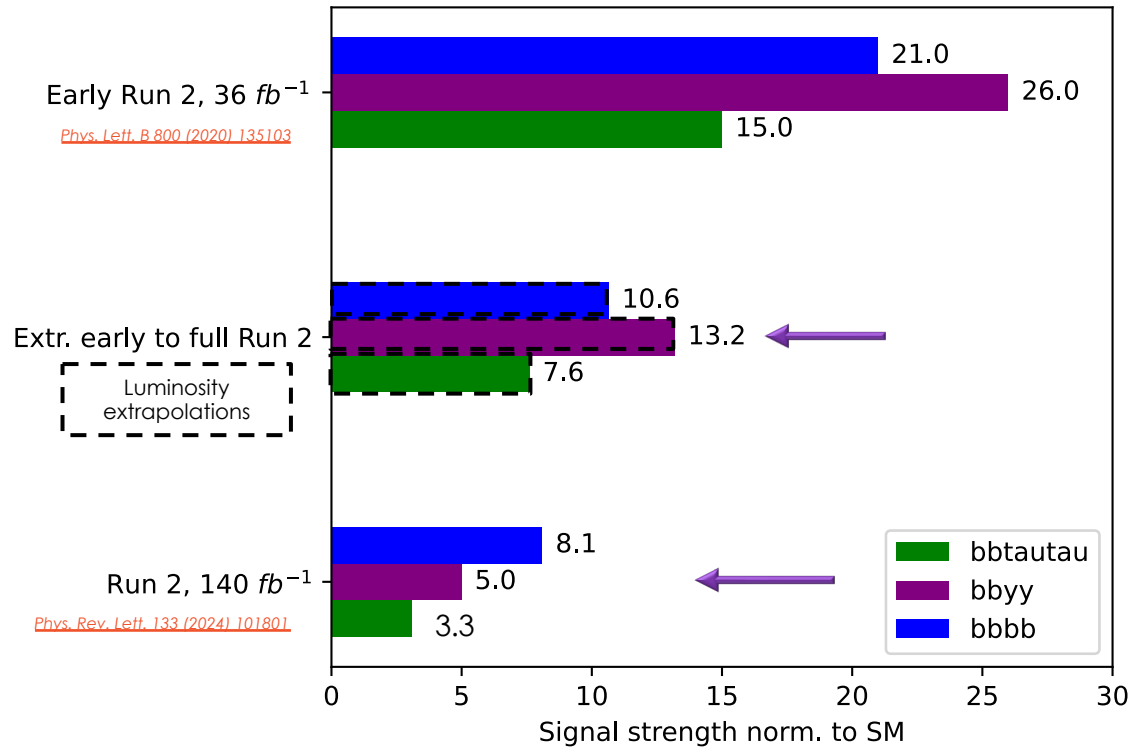
Run 2 $HH \rightarrow b\bar{b}\gamma\gamma$, a fully re-designed analysis with gains from: **Algorithms**

More b-jets, more HH

Dedicated b-jet energy corrections

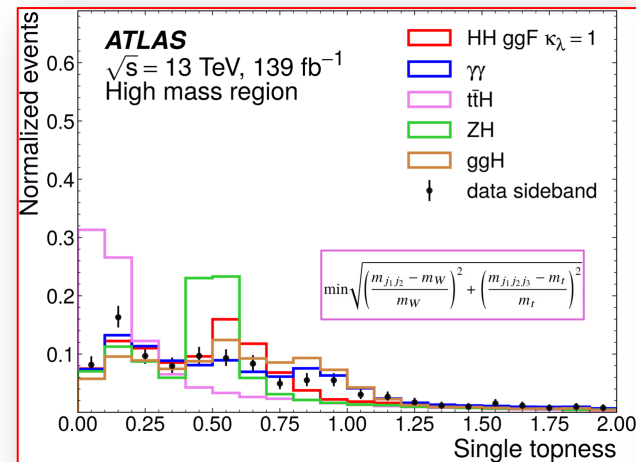


THE $HH \rightarrow b\bar{b}\gamma\gamma$ EXAMPLE

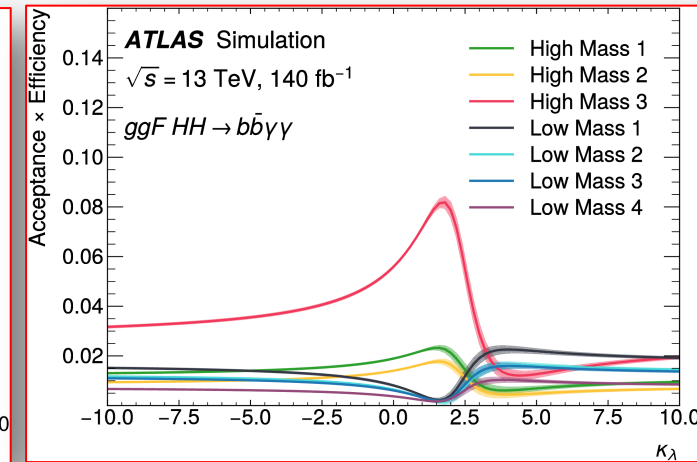


Run 2 $HH \rightarrow b\bar{b}\gamma\gamma$, a fully re-designed analysis with gains from: **Analysis techniques**

Discriminant kinematic variables

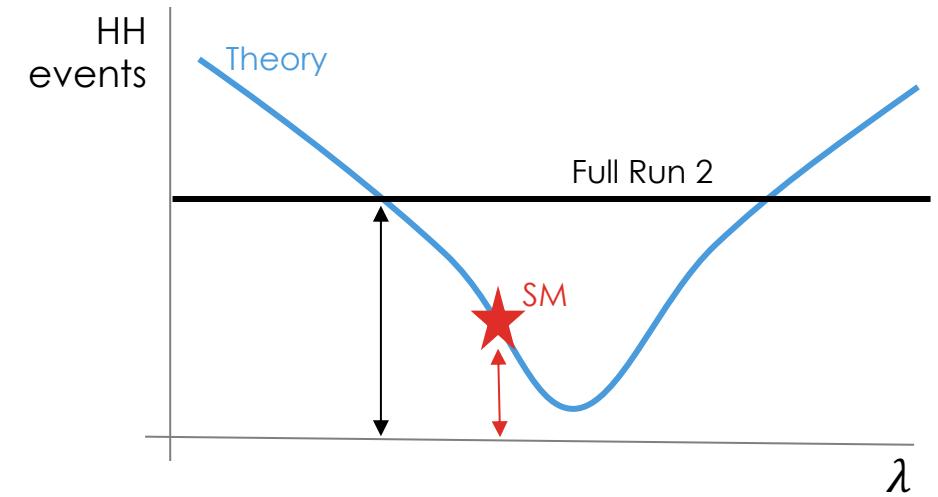
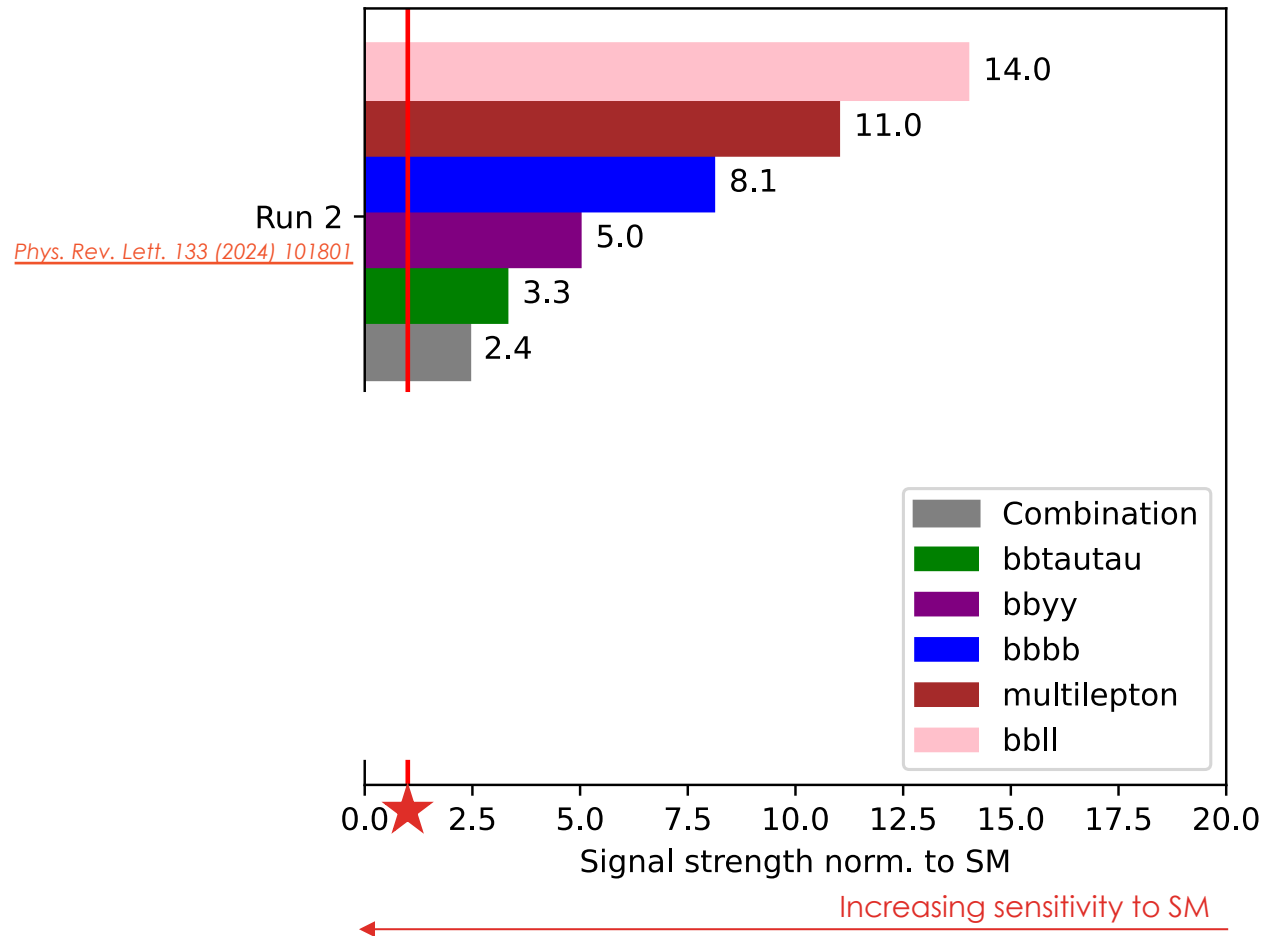


m_{HH} categorization and MVAs



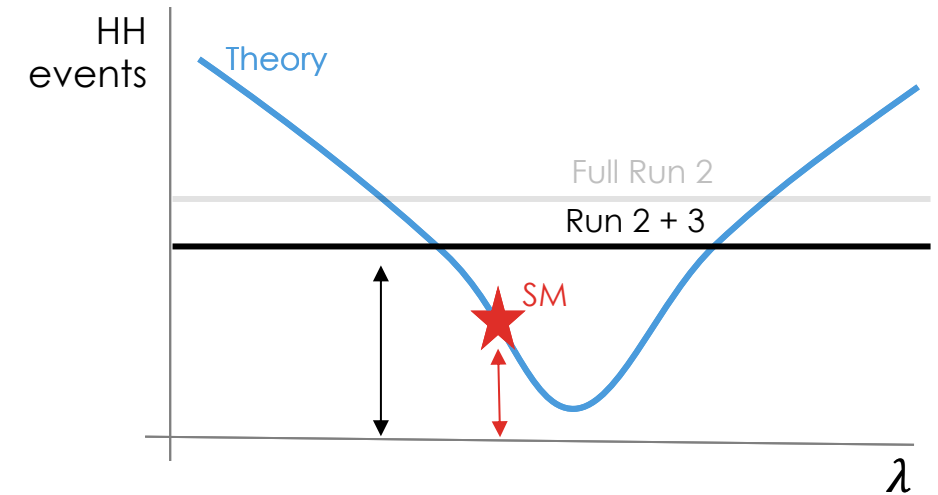
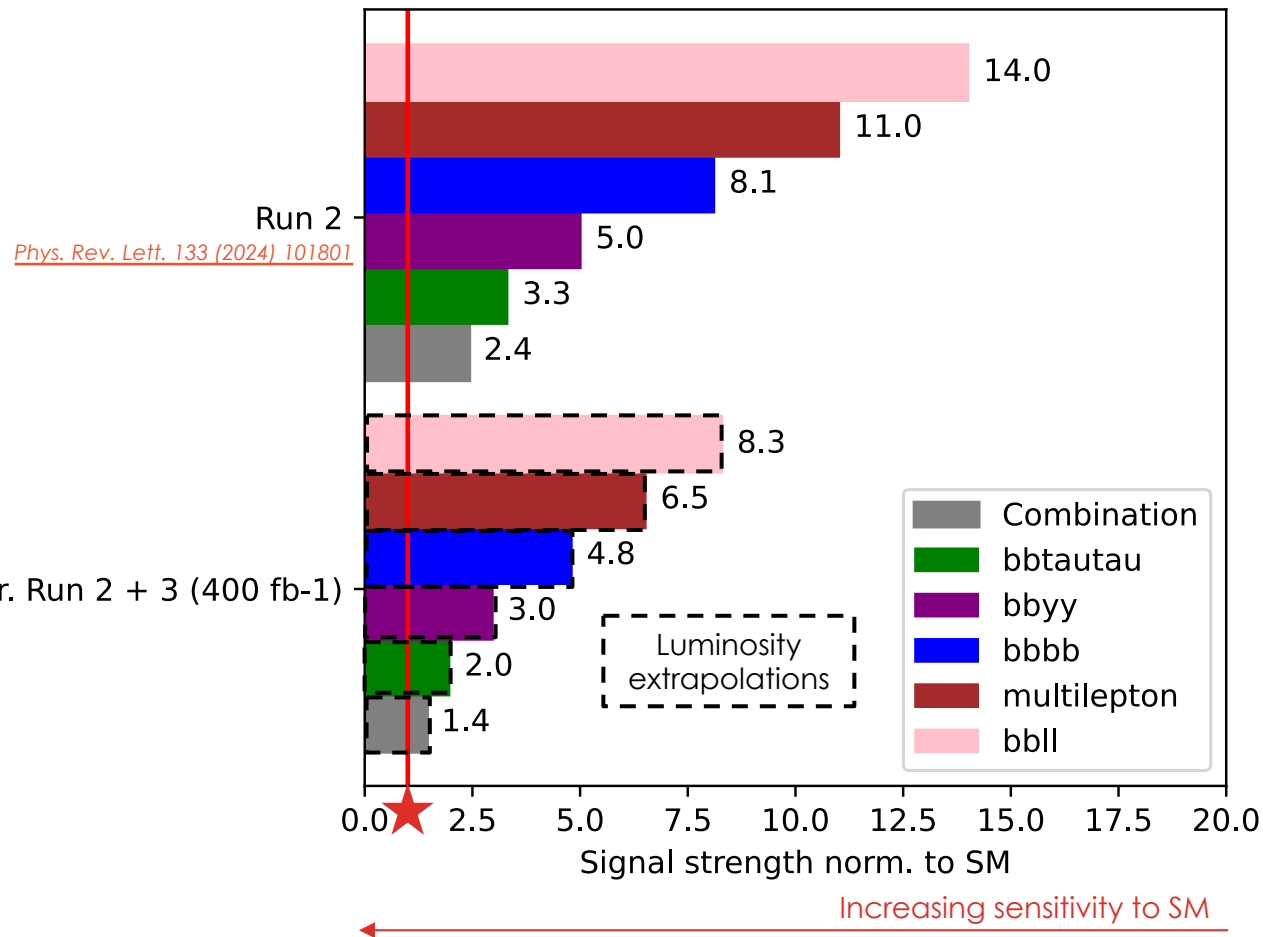
AN EXCITING TIME AHEAD!

04.12.24



AN EXCITING TIME AHEAD!

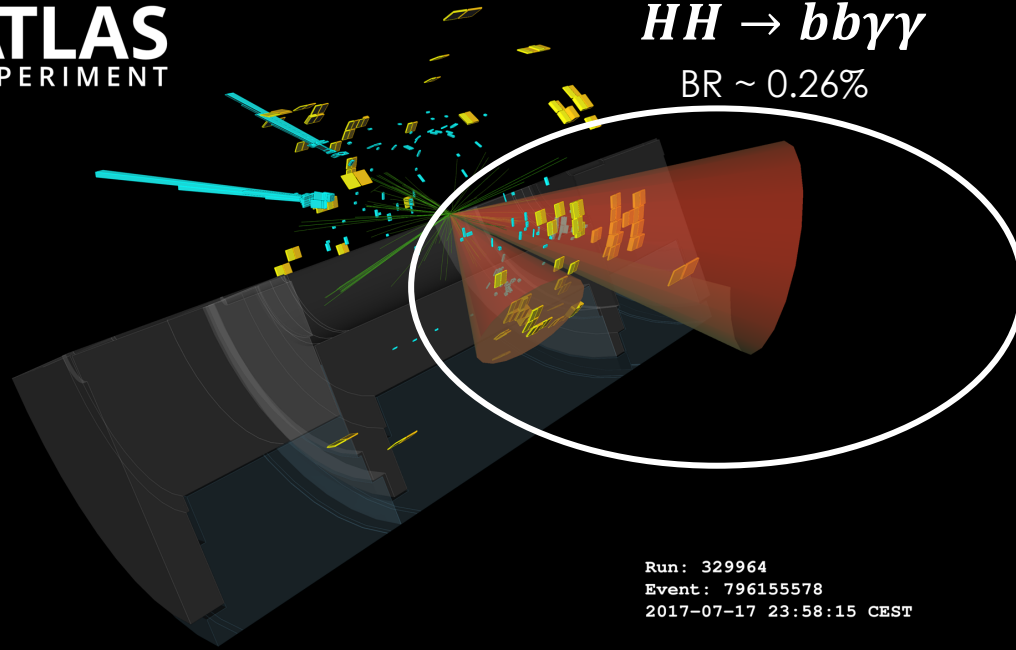
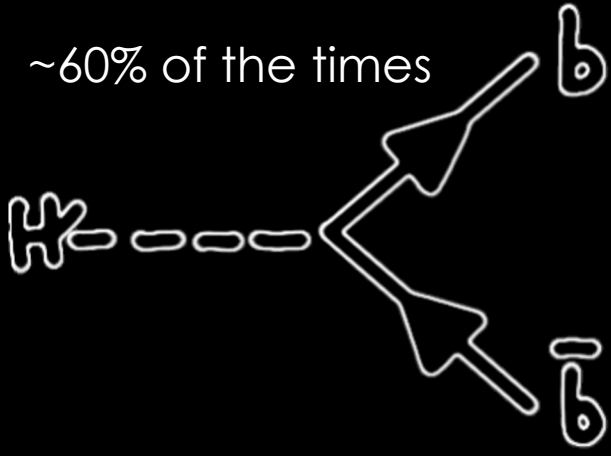
04.12.24



**Will we confirm the SM
or find new physics?**

Run 3 data will take us very close to “seeing” HH if as predicted by the SM, but need to improve analyses’ strategies to get to a statistically significant evidence of HH (in combination with CMS)...

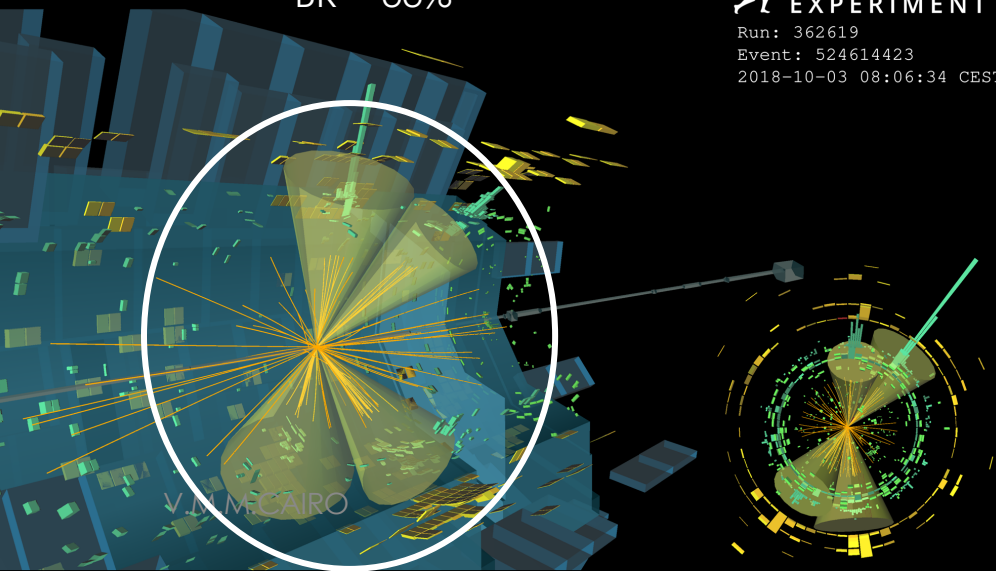
~60% of the times



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

$HH \rightarrow b\bar{b}b\bar{b}$
BR ~ 33%

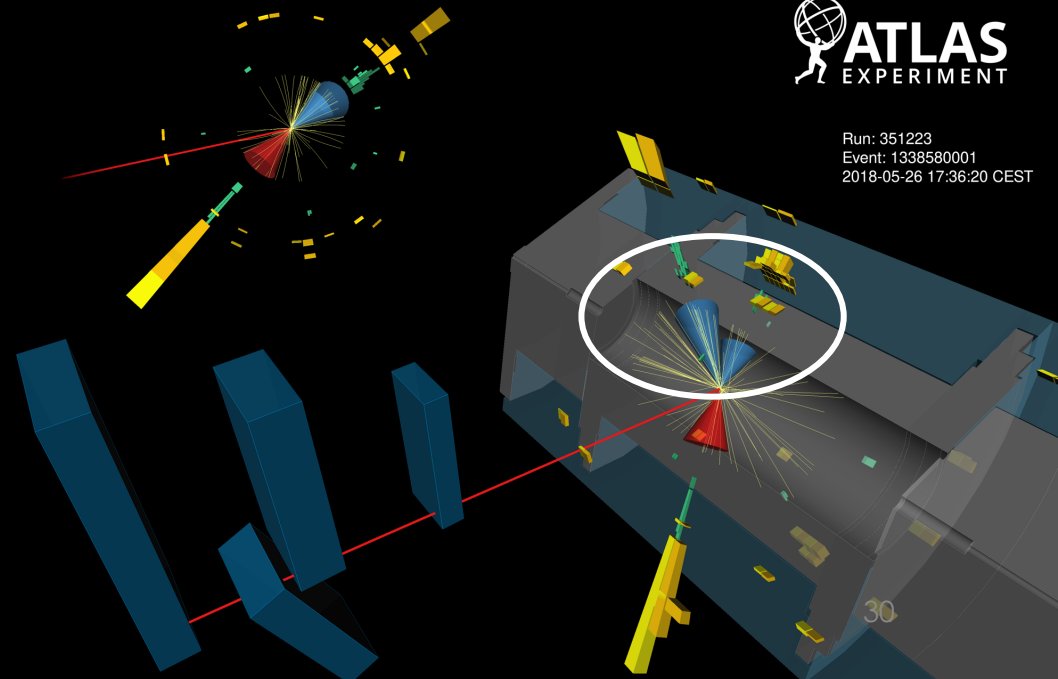
ATLAS
EXPERIMENT
Run: 362619
Event: 524614423
2018-10-03 08:06:34 CEST

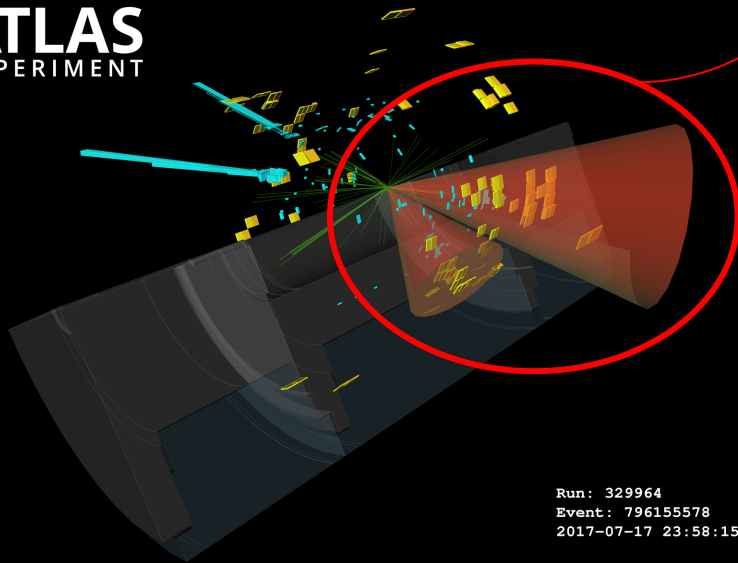


$HH \rightarrow b\bar{b}\tau\tau$
BR ~ 7.4%

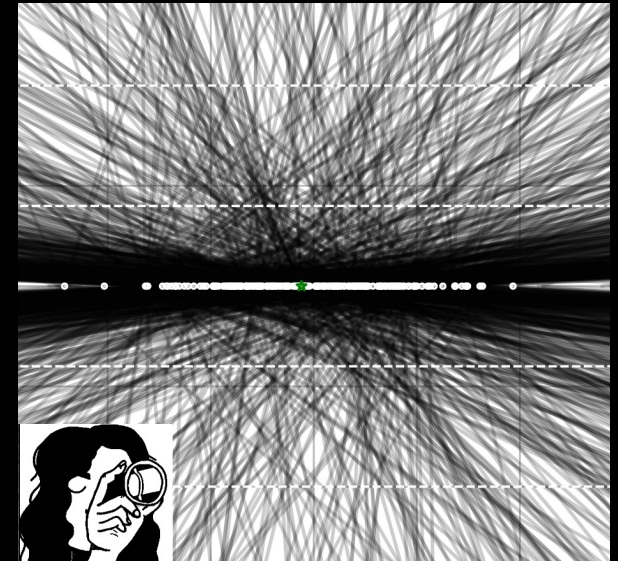
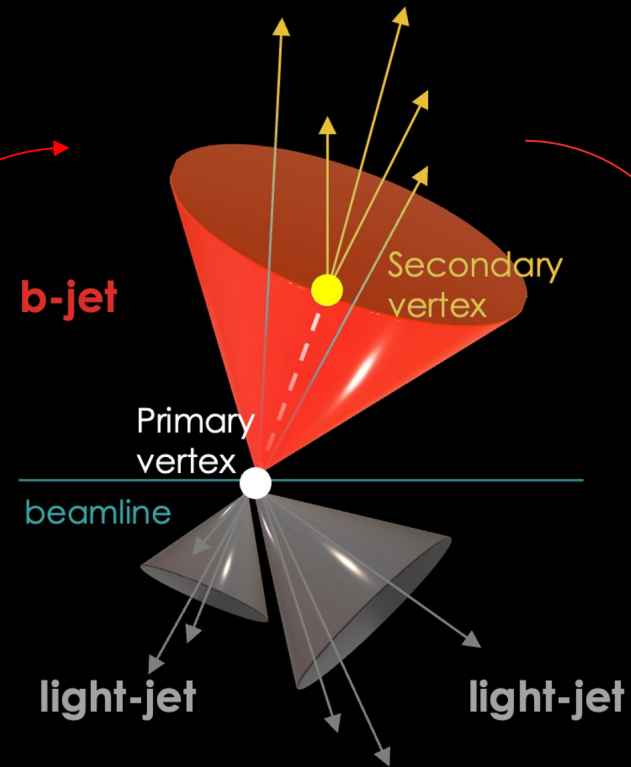
ATLAS
EXPERIMENT

Run: 351223
Event: 1338580001
2018-05-26 17:36:20 CEST



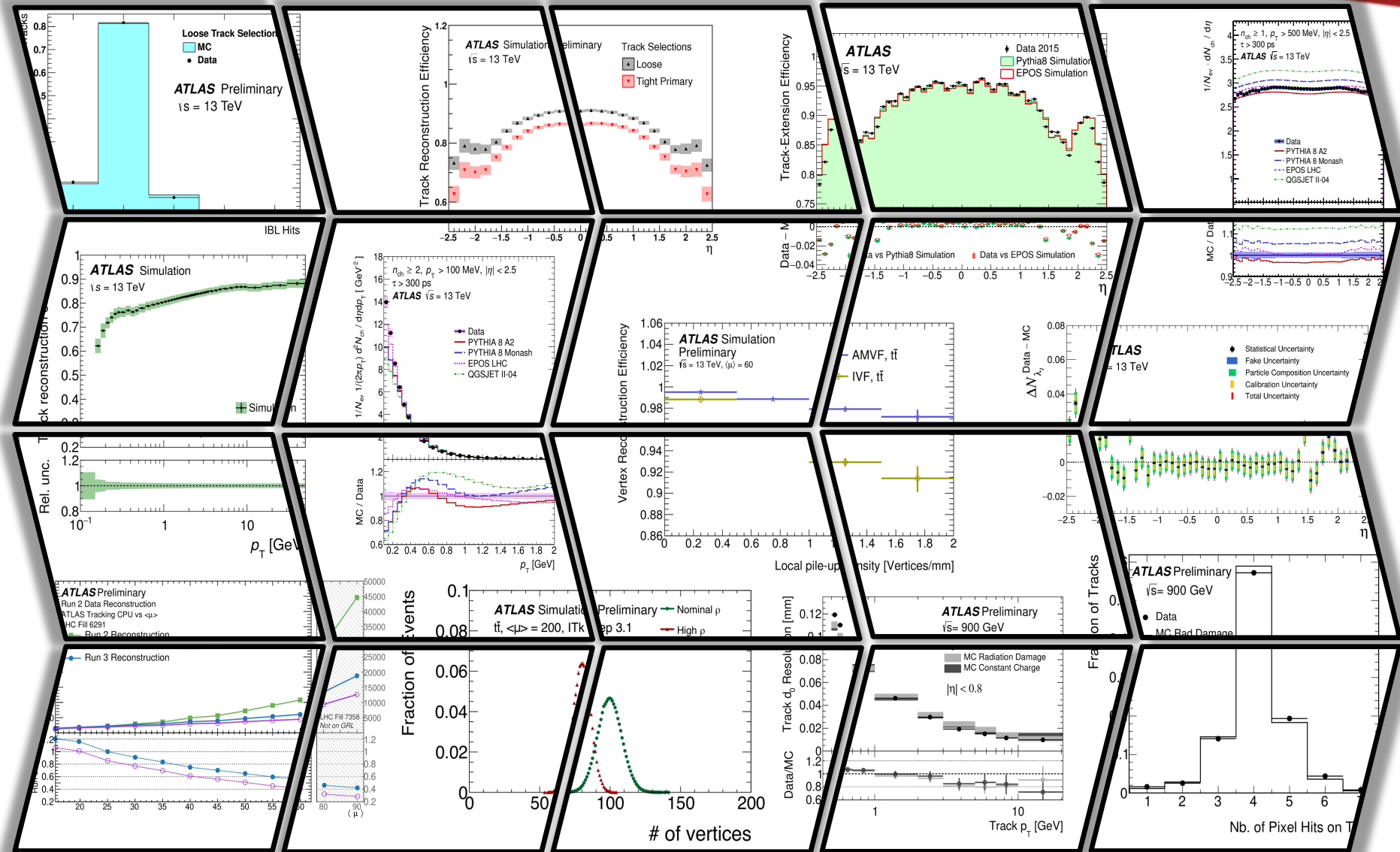


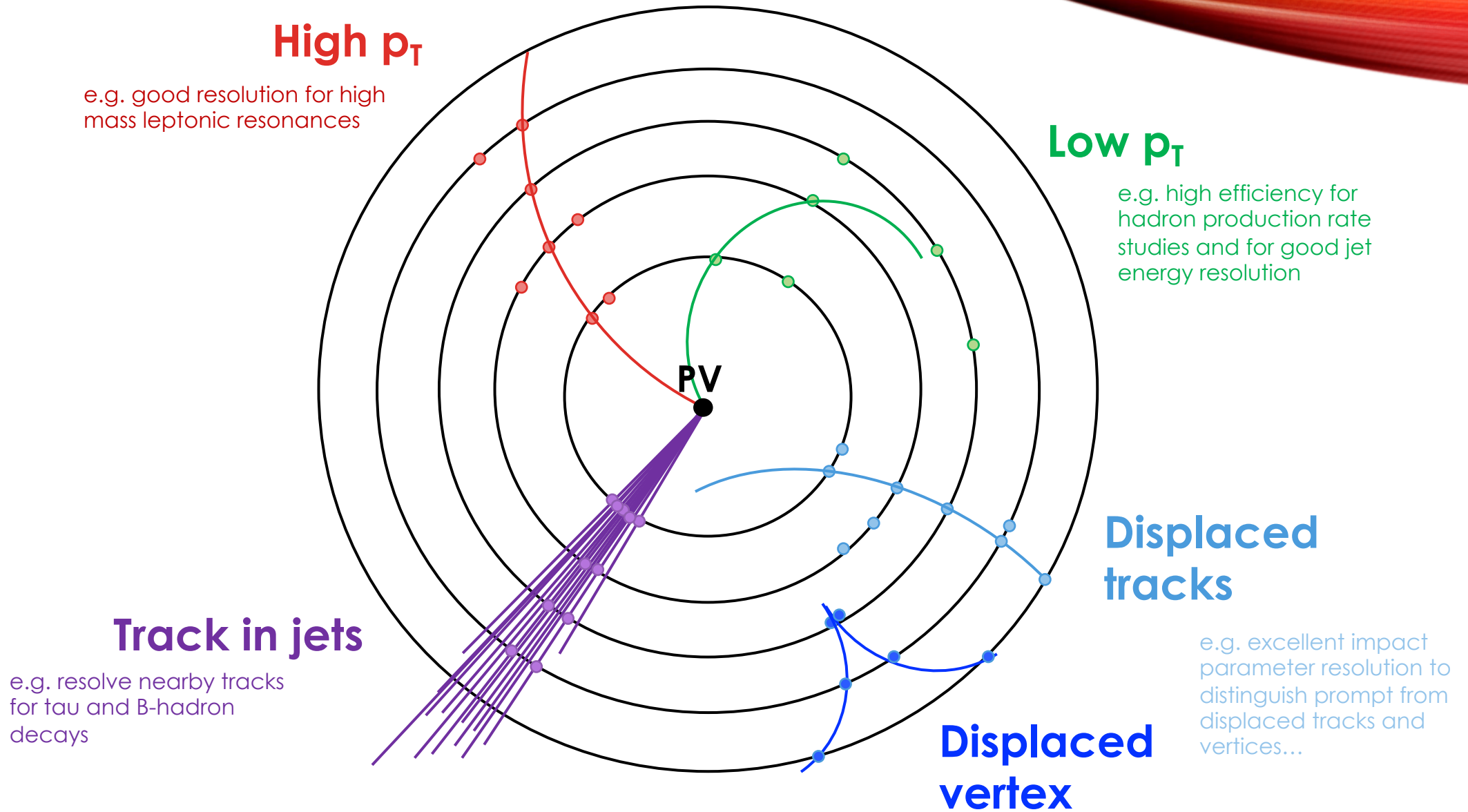
Run: 329964
Event: 796155578
2017-07-17 23:58:15 CEST

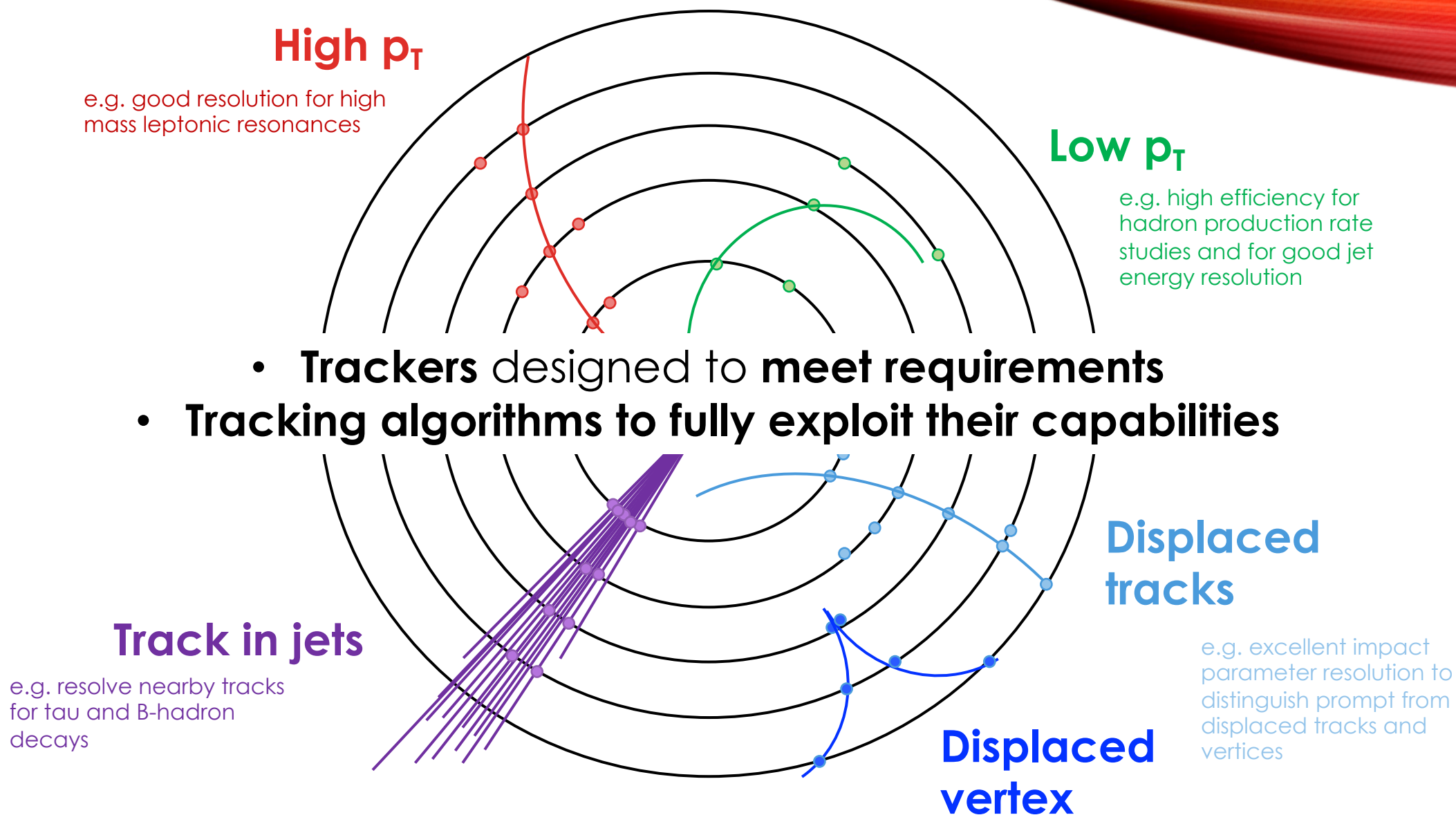


TRACKS AND VERTICES

The
building
blocks
of the
LHC
events







Where the collision happens: primary vertex, a key element of data analysis

04.12.24

Track in jets

High p_T

Displaced vertex

Displaced tracks

Associate tracks to vertices to reconstruct the full kinematic properties of the event

Low p_T

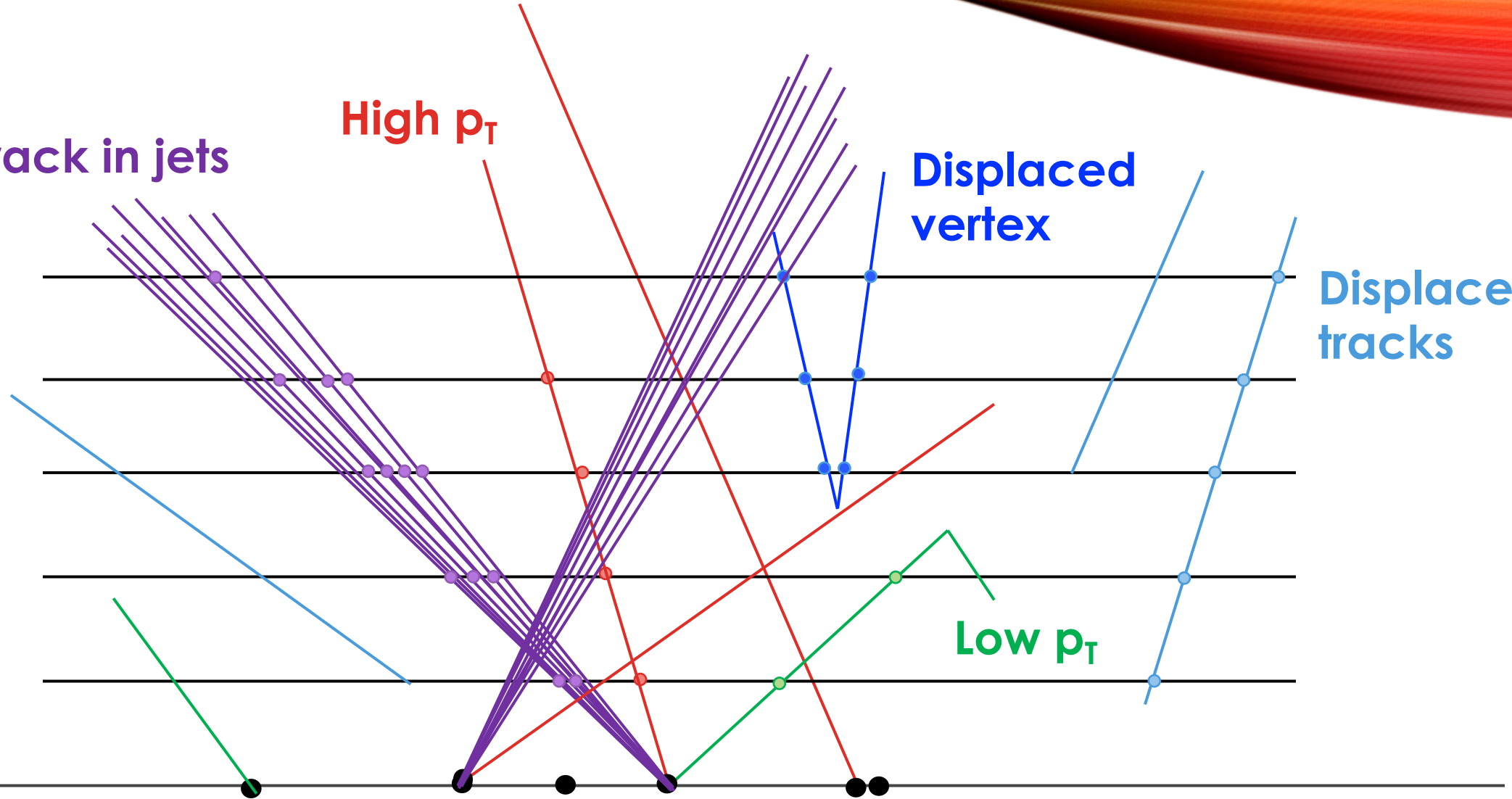
beamline

PV2

PV1

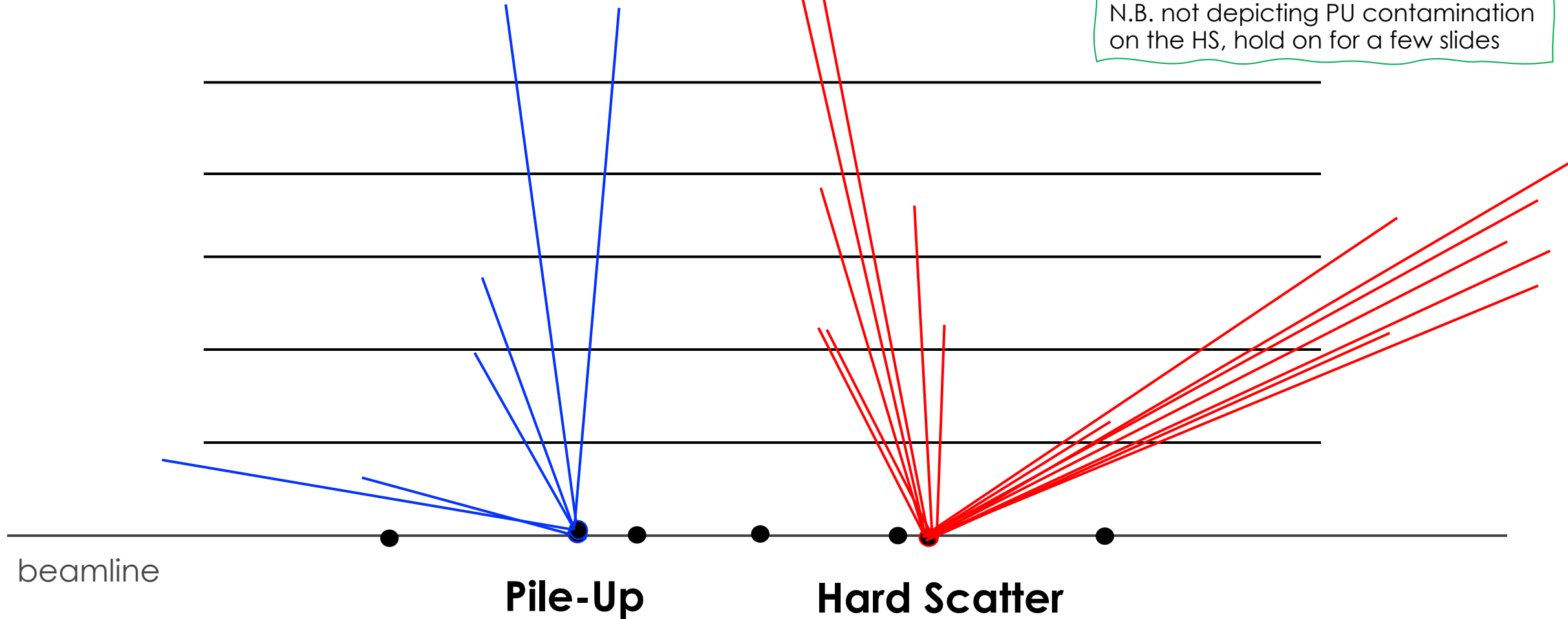
PV3

Determine the **beam spot** and compute **decay length** for b-hadron identification



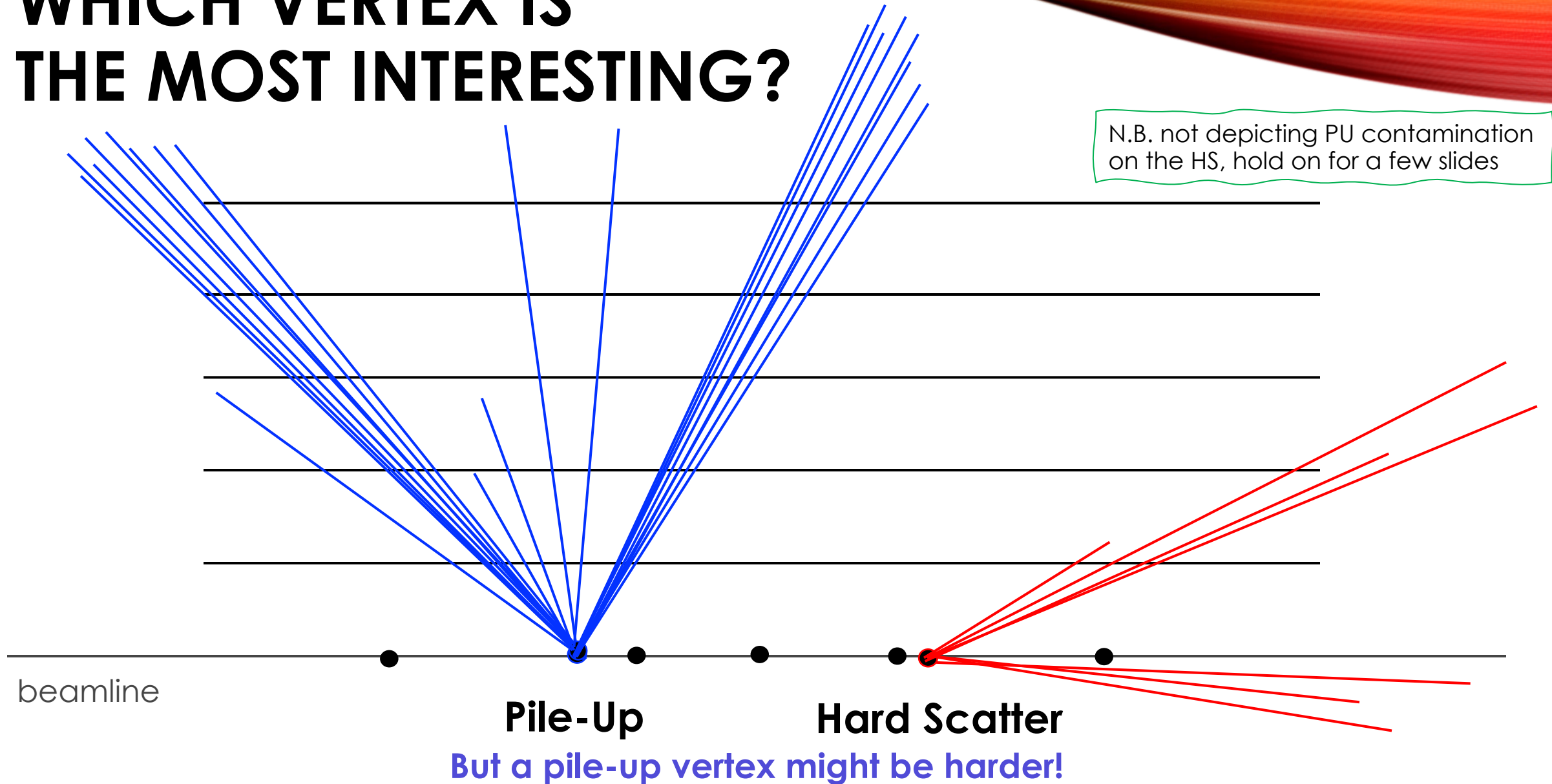
WHICH VERTEX IS THE MOST INTERESTING?

N.B. not depicting PU contamination on the HS, hold on for a few slides



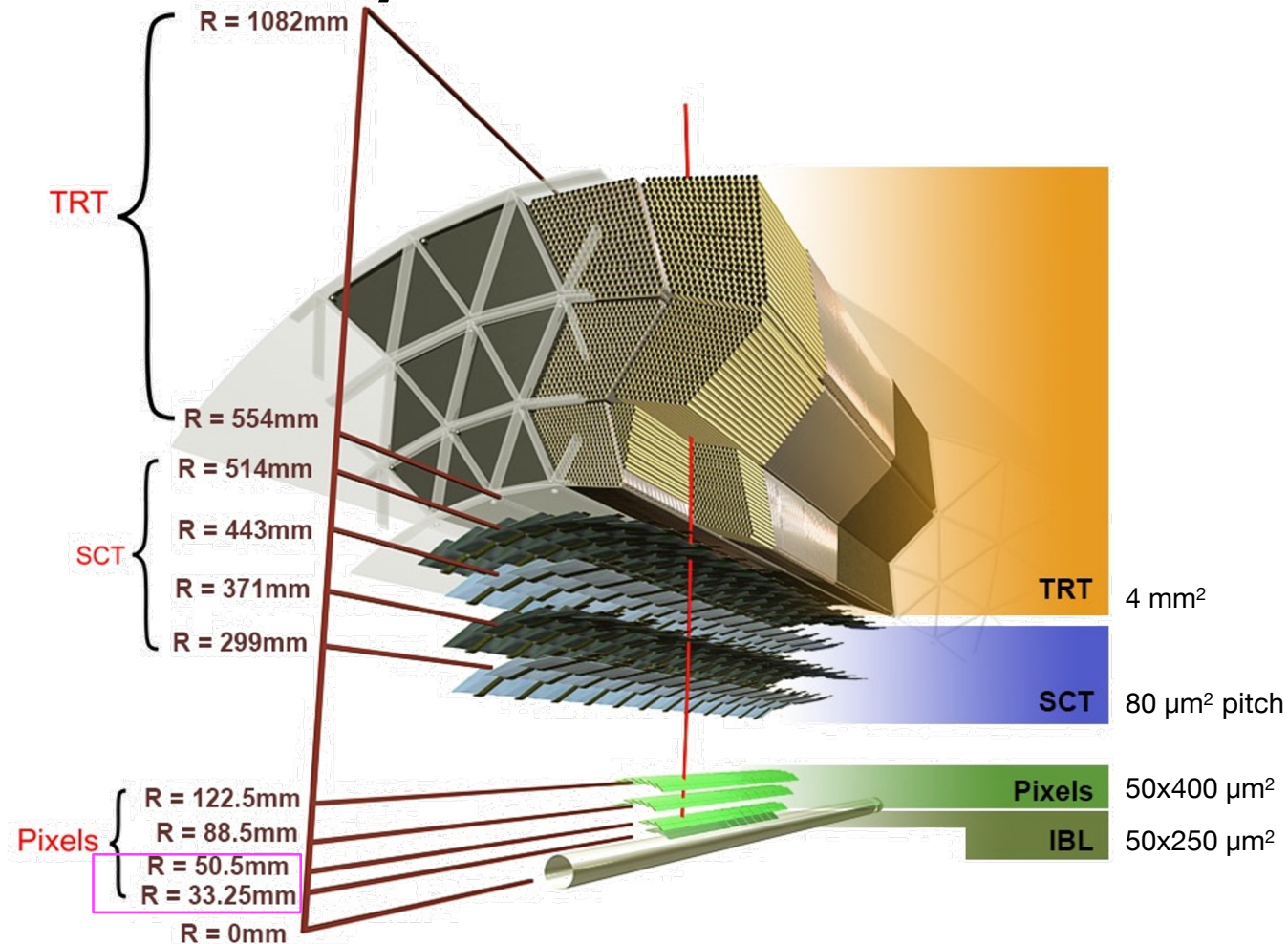
Hard-scatter often identified by the max $\sum track p_T^2$

WHICH VERTEX IS THE MOST INTERESTING?



ATLAS INNER DETECTOR IN RUN 2/3

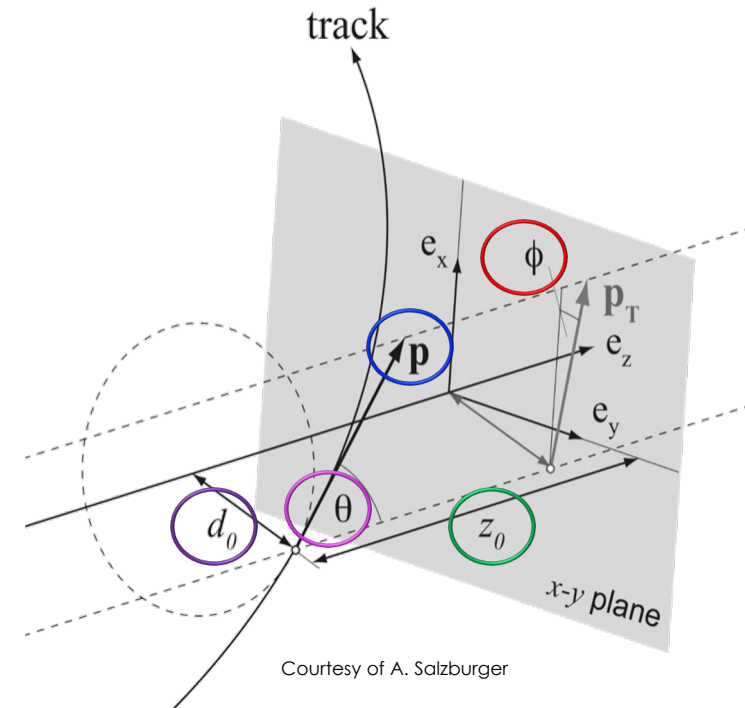
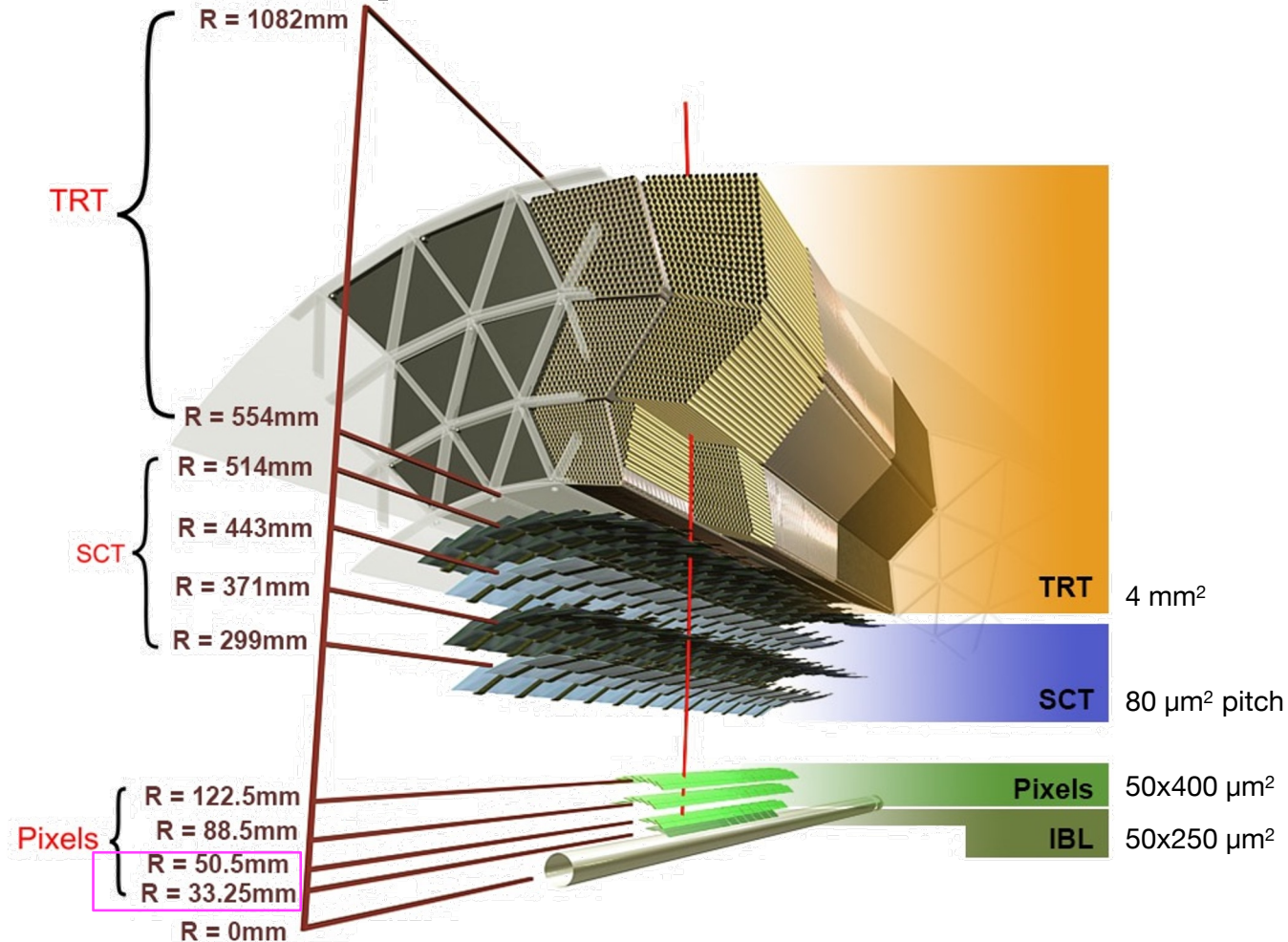
04.12.24



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

ATLAS INNER DETECTOR IN RUN 2/3

04.12.24



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

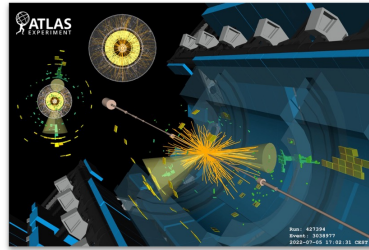
A PERSONAL FAVOURITE: THE START OF RUN 3

Habemus Data! July 5th 2022

16:20 CEST



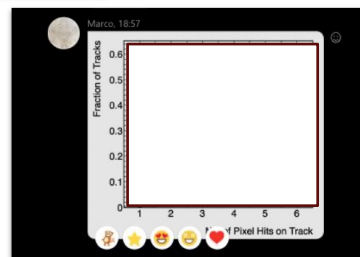
17:02 CEST



16:49 CEST



18:57 CEST



New public plots on 13.6 TeV data



- Shown in ATLAS Highlight talk at ICHEP by G. Unal on Monday July 11th 2:50 pm
 - <https://agenda.infn.it/event/28874/contributions/171901/>

Performance of ATLAS Pixel Detector and Track Reconstruction at the start of Run 3 in LHC Collisions at $\sqrt{s} = 13.6$ TeV

10 July 2022

Content

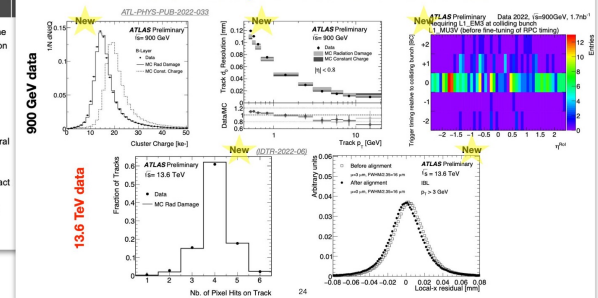
Pixel and tracking performance have been studied on the first 13.6 TeV proton-proton collisions recorded by the ATLAS detectors at the LHC in the first two fills of Run 3 (July 5-6, 2022). These results highlight the main changes implemented in the pixel detector simulation and track reconstruction [ATL-PHYS-PUB-2021-012] for Run 3:

- Radiation damage effects in the barrel pixel sensors [INST-14 (2019) P06012],
- Mixture Density Network (MDN) to determine the pixel hit positions [JHEP-2019-009],
- Adaptive Multi-vertex finder (AMVF) to reconstruct primary vertices [ATL-PHYS-PUB-2019-015, JHEP-2021-002],
- Updated Inner Detector Alignment [ATL-PHYS-PUB-2022-028].

Simulation samples have been generated for minimum-bias and multi-jet events at $\sqrt{s} = 13.6$ TeV. During track reconstruction, pixel clusters compatible with being due to charge depositions of more than one charged particle are identified and split by a dedicated neural network. The analysis follows the same procedures applied in the performance study on the 900 GeV collision data taken during the Run 3 commissioning [ATL-PHYS-PUB-2022-033]. Charged particle tracks are selected applying the following quality cuts: track pseudo-rapidity $|\eta| < 2.1$, the sum of the number of hits in the pixels and SCT NSI ≥ 8 , at least one hit in the pixel detector, track impact parameters $|d_0| < 2$ mm and $|z_0 \sin(\theta)| < 3$ mm and transverse momentum, $p_T > 0.5$ GeV, unless differently specified. Track reconstruction is characterised by studying the number of hits in the Pixel and SCT detectors associated to particle tracks, pixel cluster charge and spatial resolution, the extrapolation resolution of tracks in jets and the rate of split pixel hits, comparing data to simulation predictions, and the scaling of the number of reconstructed primary vertices with pile up.



First look at detector performance with 2022 collision data

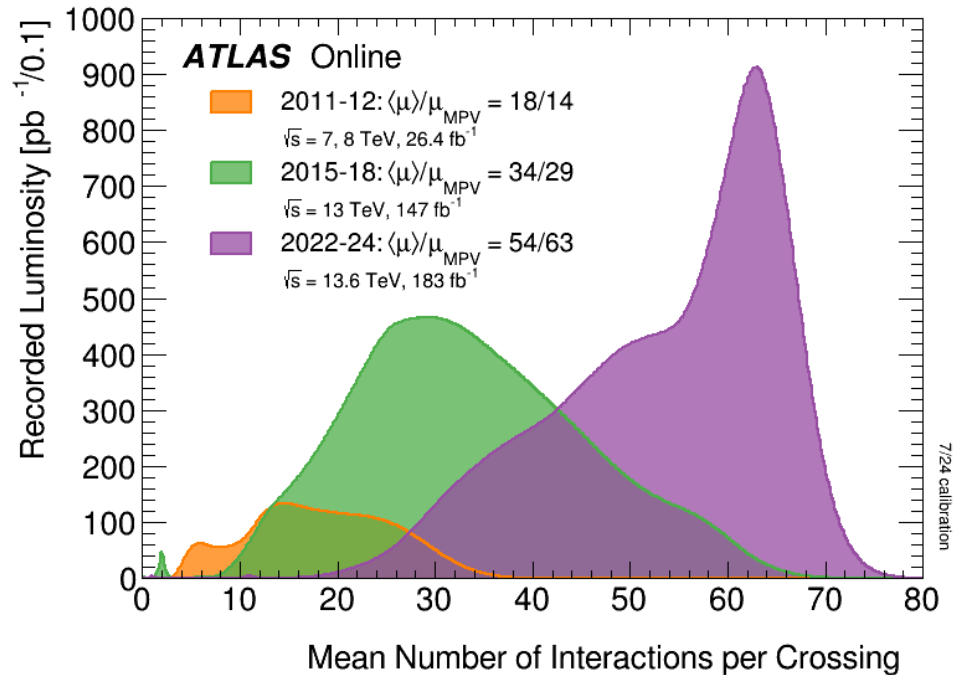


2

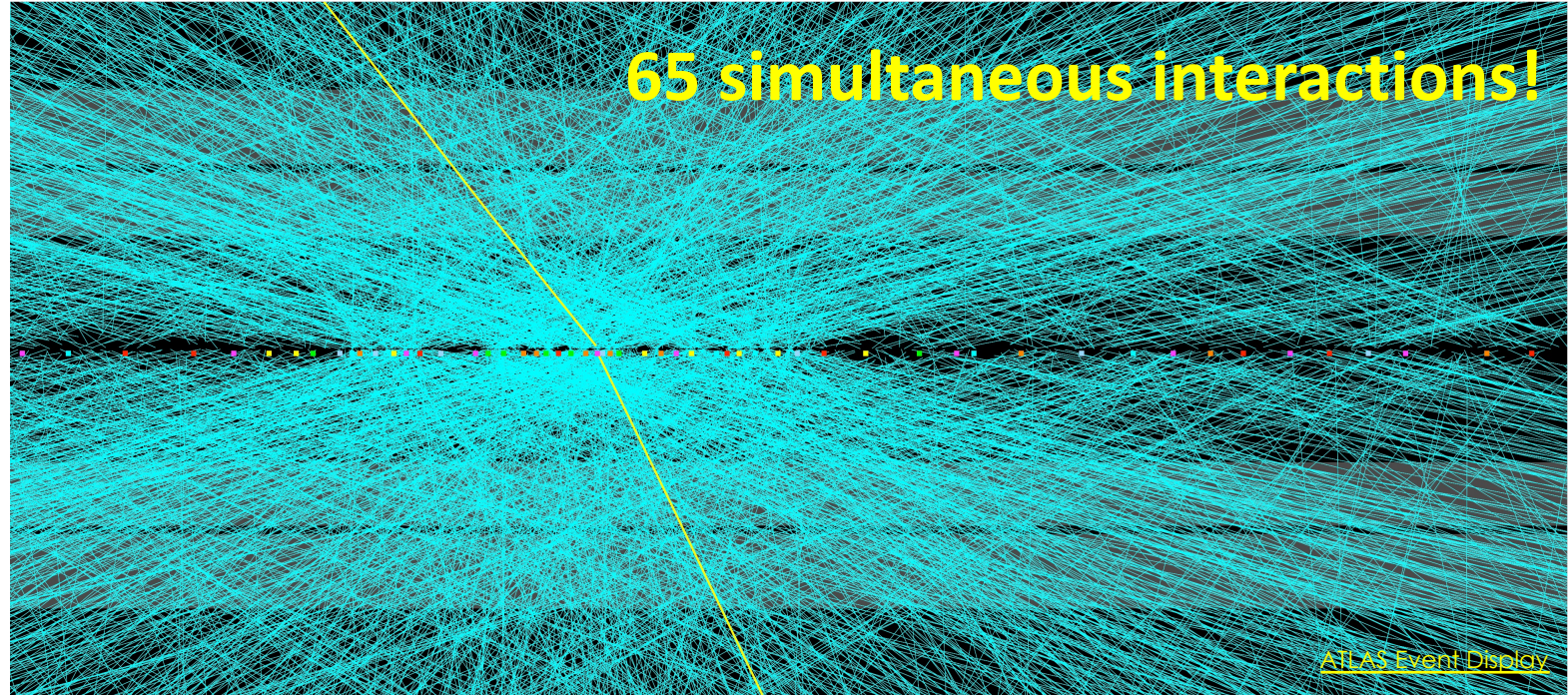
Run 3 give me a break!!!

WHAT'S NEW IN RUN 3?

[LuminosityPublicResultsRun3](#)



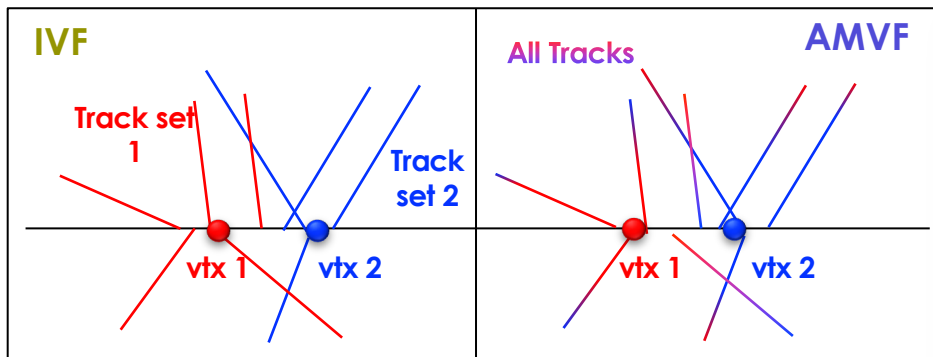
↑
algorithms previously
optimized for $\langle\mu\rangle \cong 20$



[Ref] By the end of Run 3, #particles hitting the innermost pixel layers comparable to what it would receive if placed only a few km from the Sun during a solar flare → Radiation damage

VERTEXING IN RUN 3

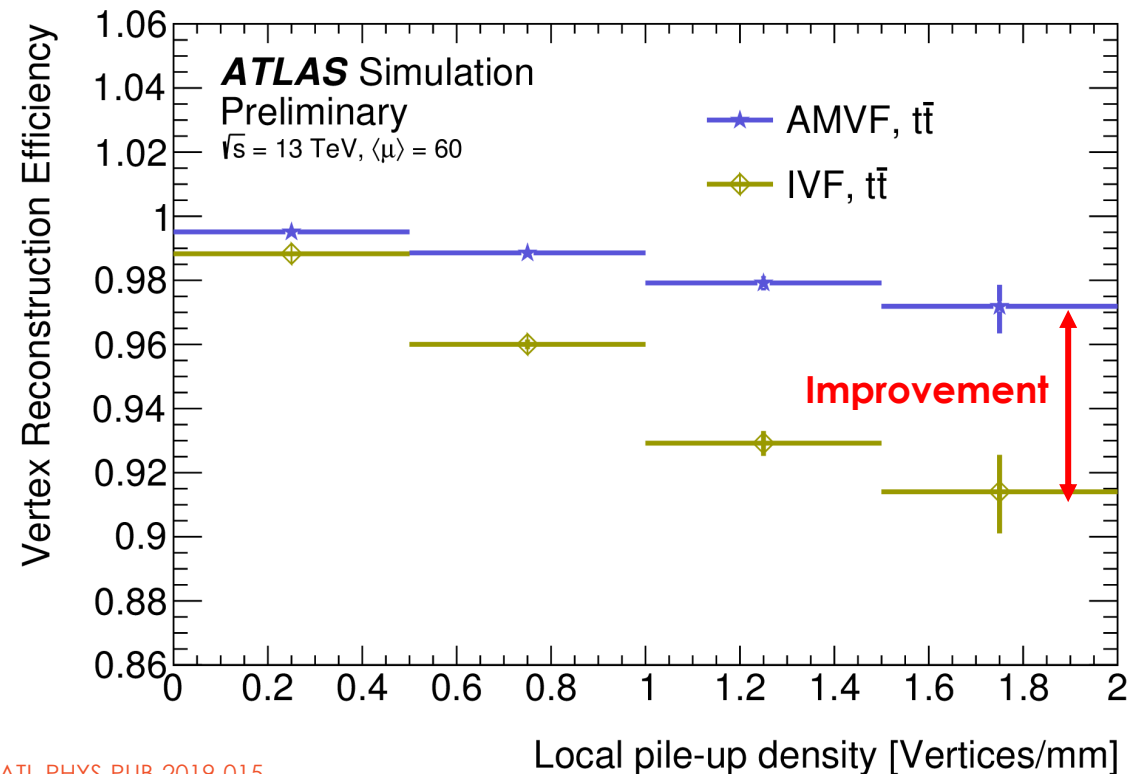
- **Run 2** → **Run 3** : more **challenging pile-up** conditions and **aging** detector
- **All physics objects must be reconstructed wrt the correct primary vertex**
- Innovation: adaptive **multi-vertex** fitting procedure (**AMVF**)



Significant performance improvements:

- ~10% better vertex selection efficiency
- ~20% better longitudinal resolution
- ~30% inclusive efficiency recovery

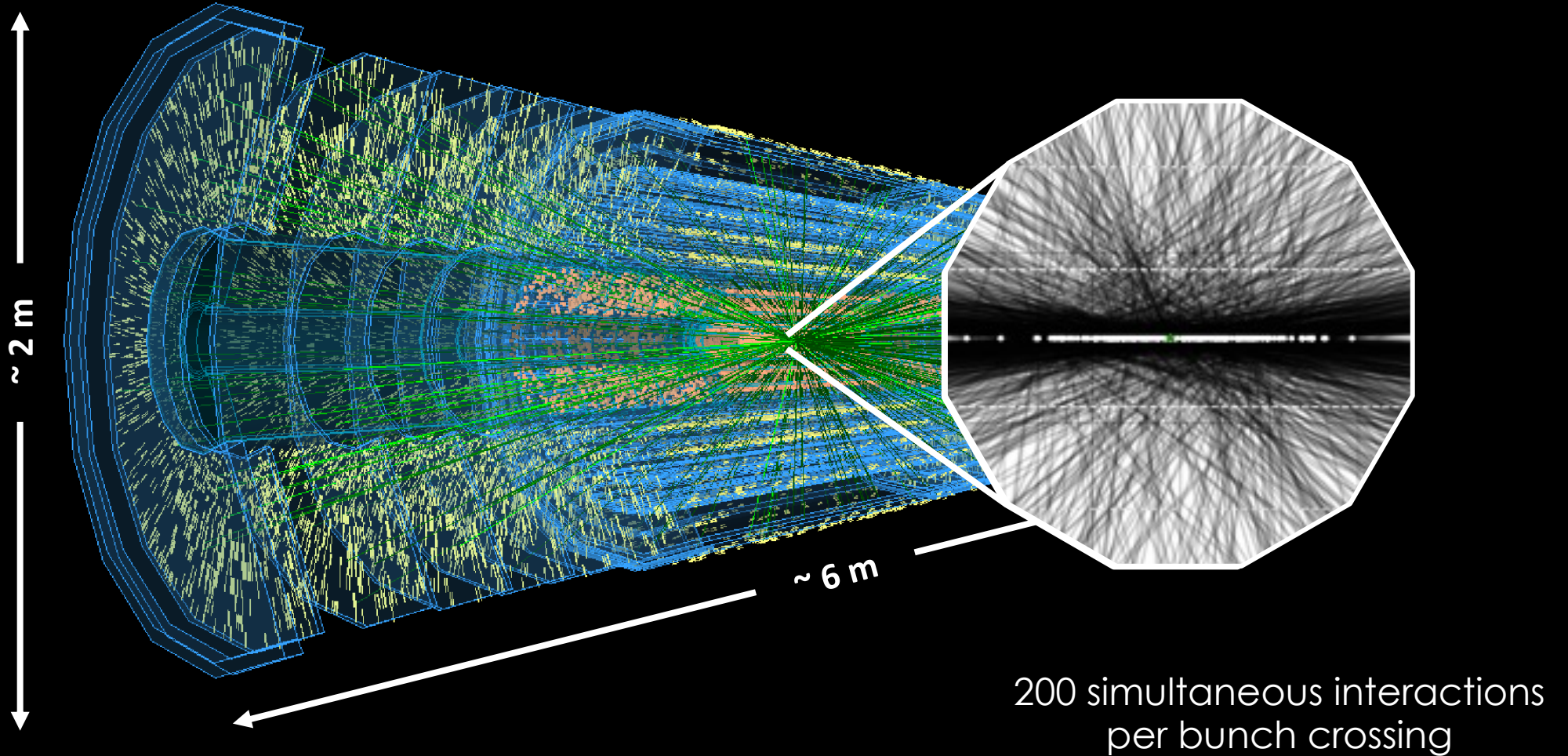
All relevant for
the HL-LHC ATLAS silicon Inner Tracker



ATL-PHYS-PUB-2019-015

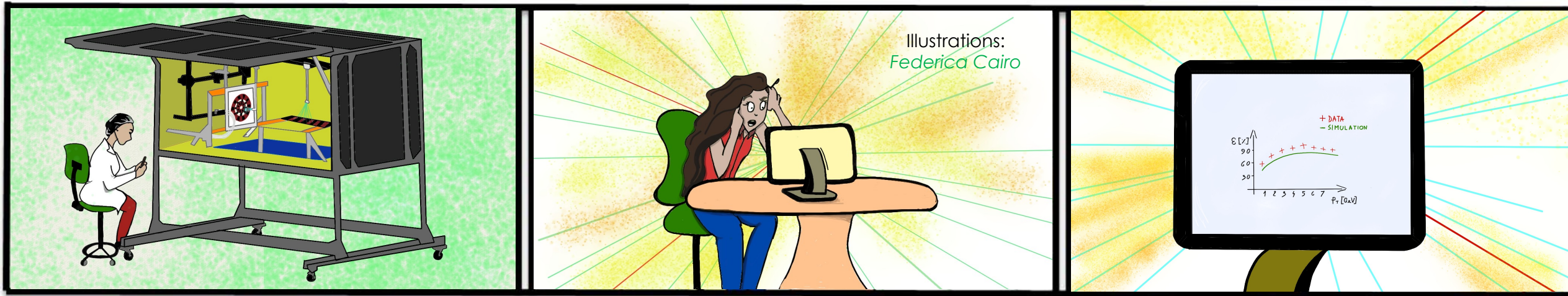
HL-LHC: USING GIGANTIC CAMERAS FOR RARE & COMPLEX EVENTS!

ATLAS Inner
Tracker
(ITk) in
preparation
for
HL-LHC
(2030)

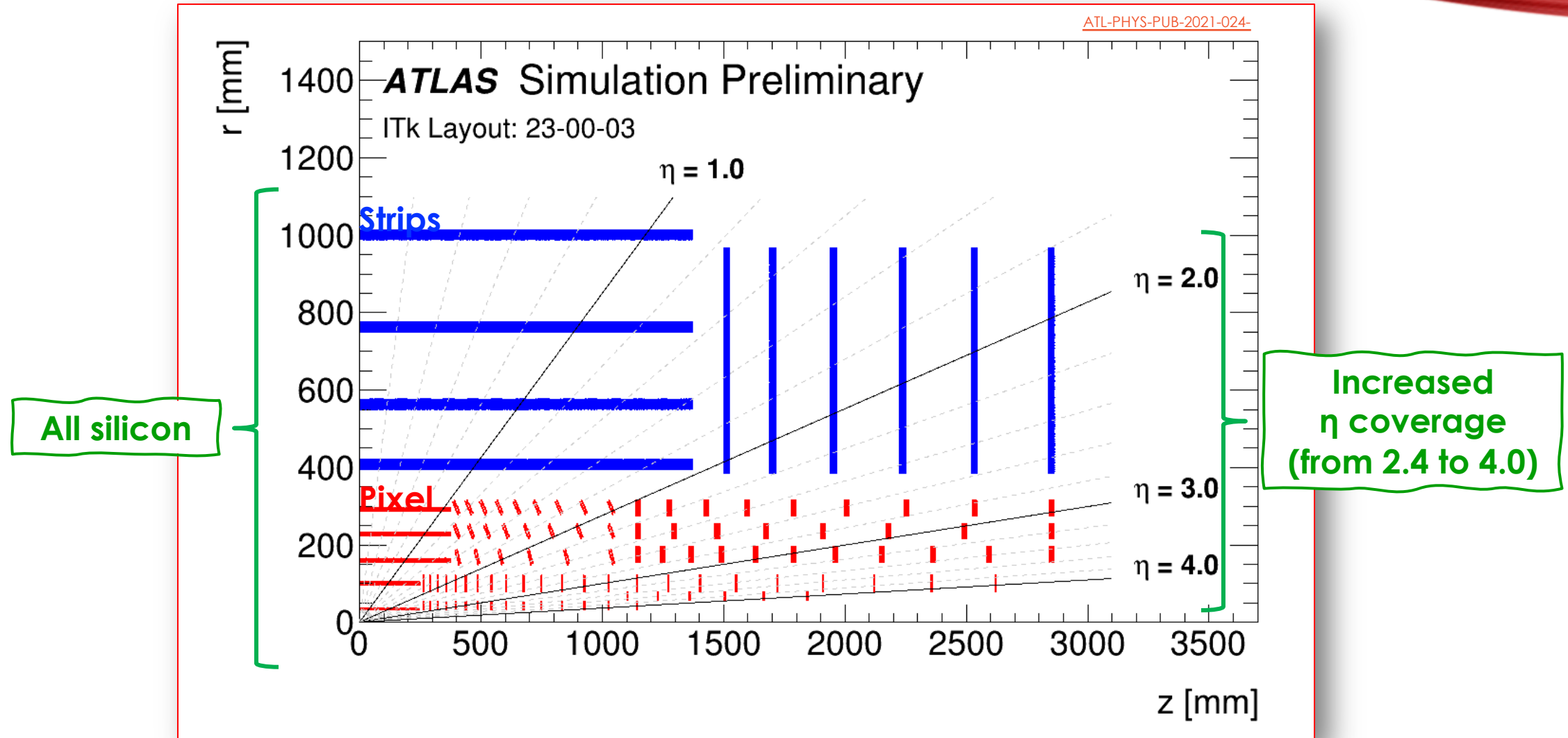


A CONSTRUCTION, COMPUTATIONAL AND PERFORMANCE CHALLENGE

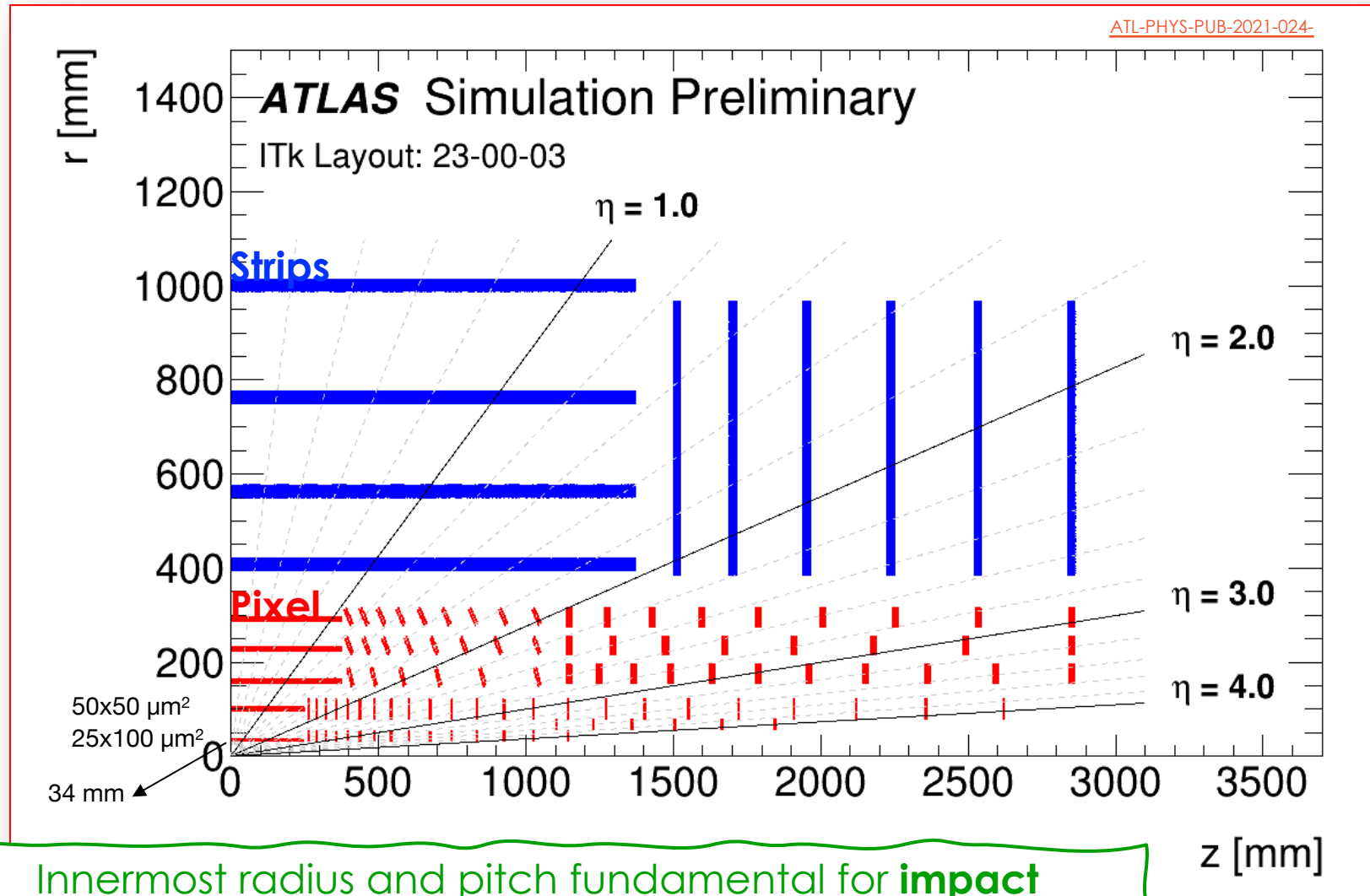
04.12.24



THE ATLAS ITK

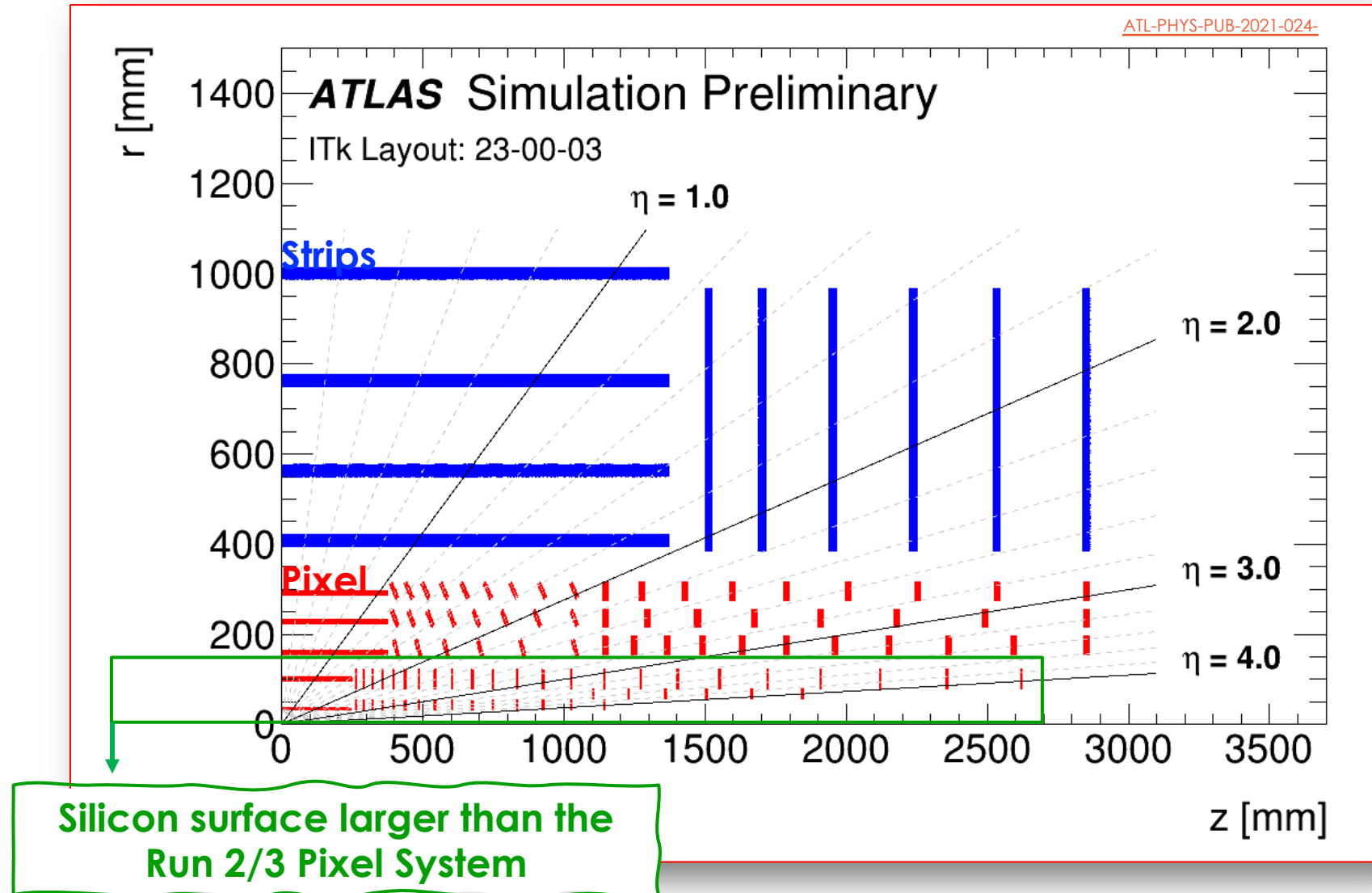


THE ATLAS ITK



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

THE ATLAS ITK

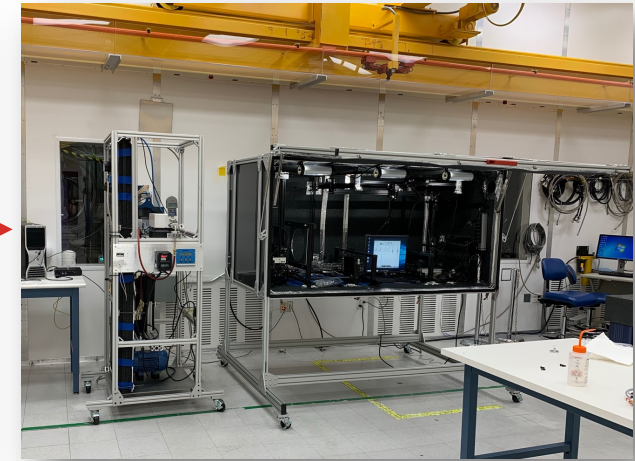
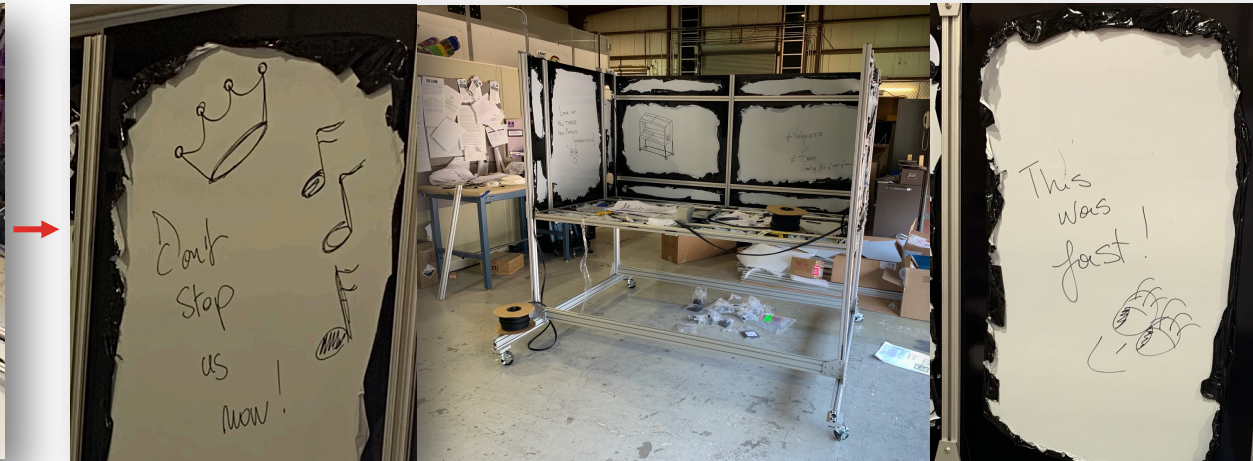


BUILDING THE ATLAS ITK

One of several challenges: Radiation hardness up to 10-15 MGy, operate cold, prevent leakage current & thermal runaway

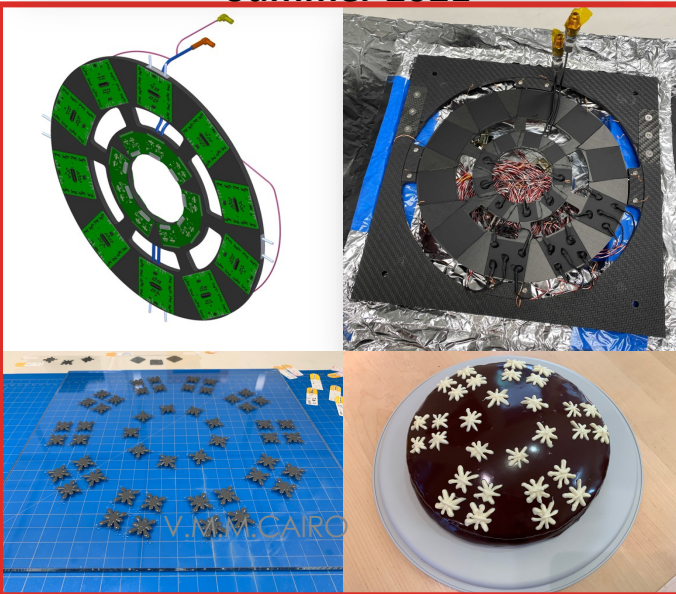
Fall 2019

Early 2020

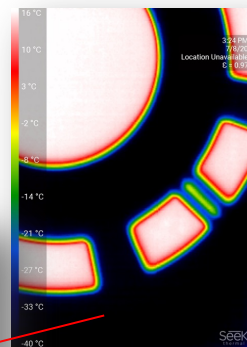
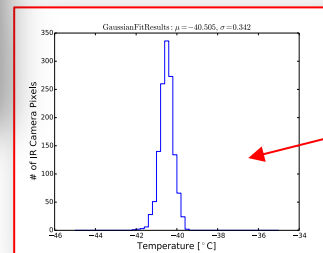


Summer 2021

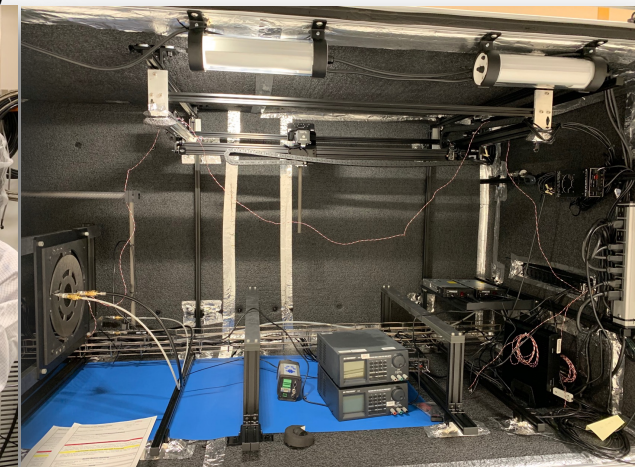
Early 2021



Bare local support meets specifications

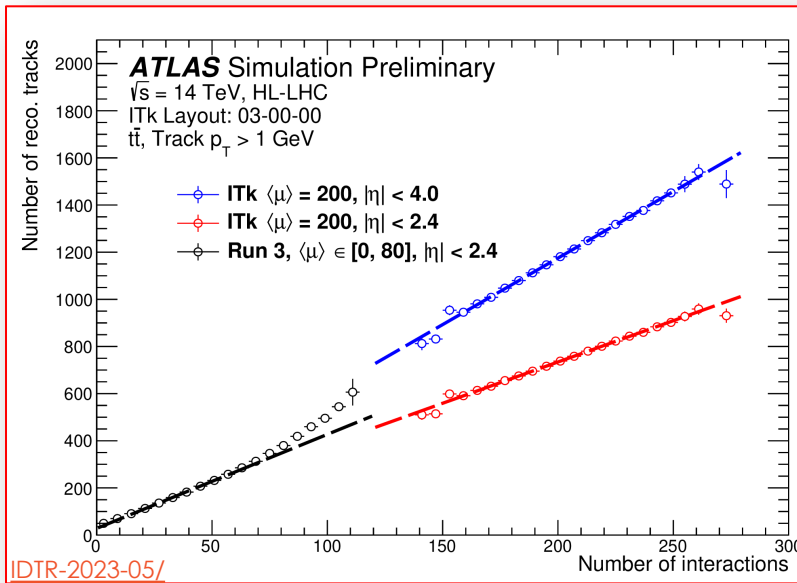


$$T = -40.5 \pm 0.3^{\circ}\text{C}$$

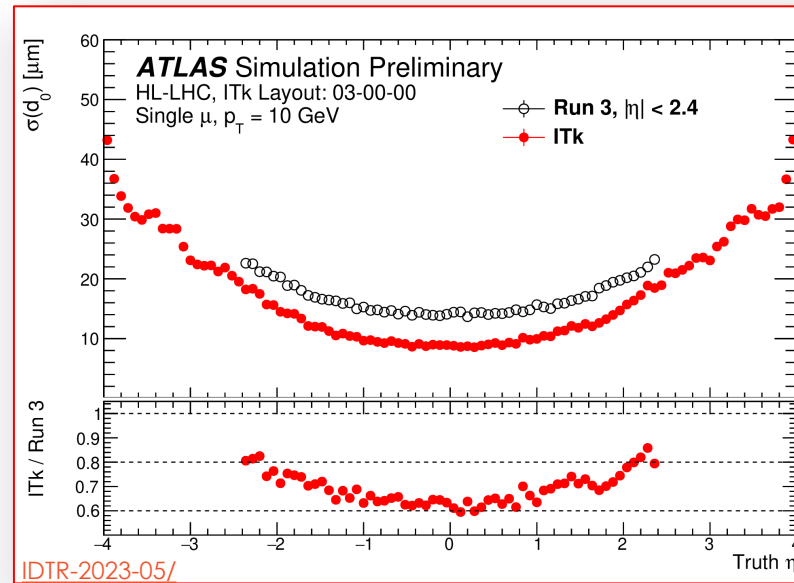


HL-LHC TRACKING

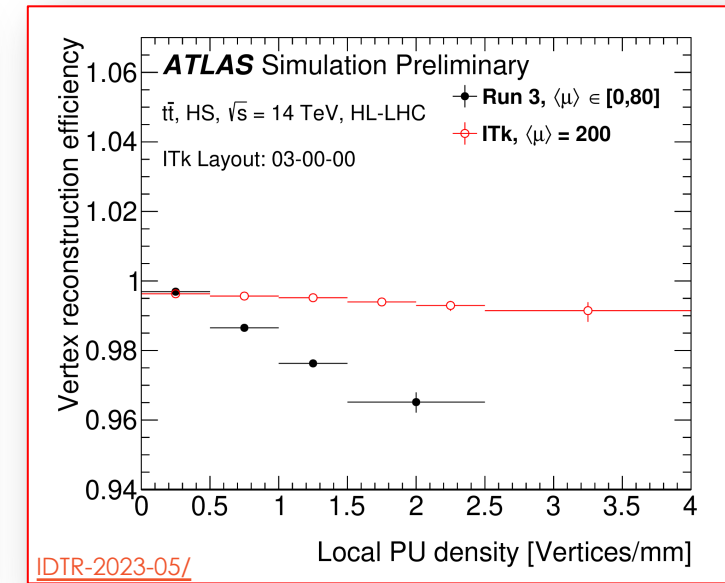
A detector designed to be pile-up robust, and algorithms designed to leverage such features



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



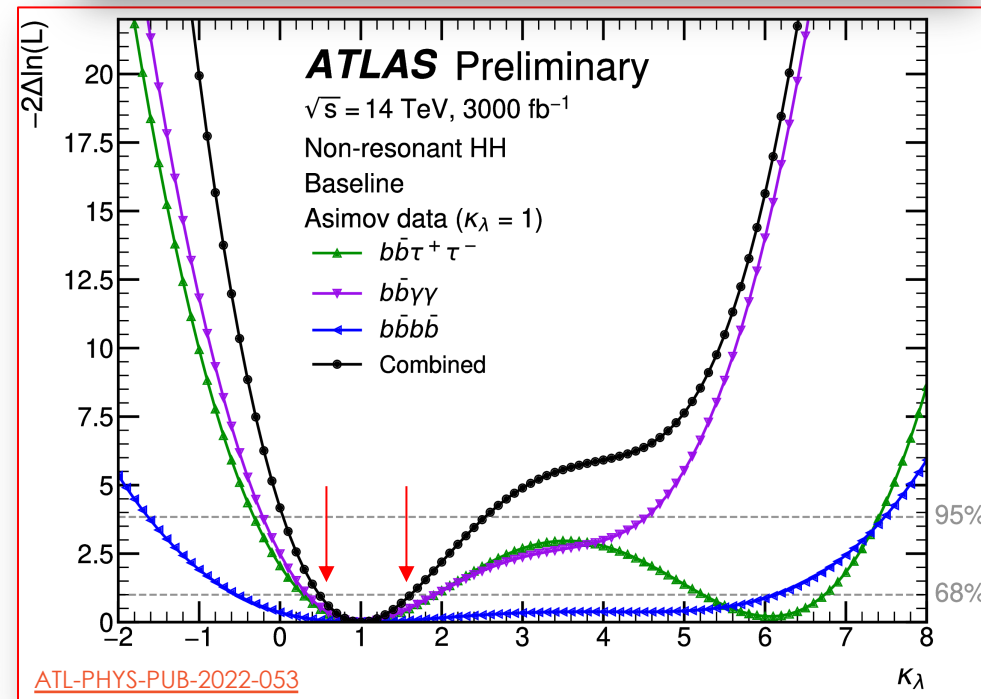
Improved IP resolution



More PU-robust vertexing

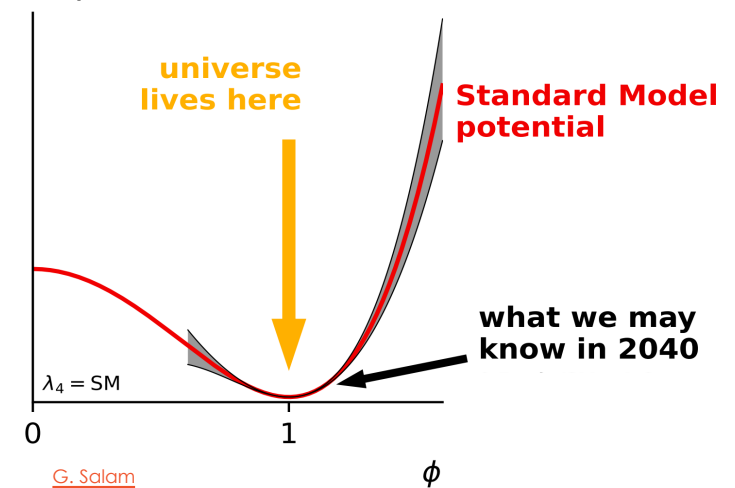
HOW DOES HH LOOK IN HL-LHC?

Uncertainty scenario	Significance [σ]			
	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$	Combination
No syst. unc.	2.3	4.0	1.8	4.9
Baseline	2.2	2.8	0.99	3.4



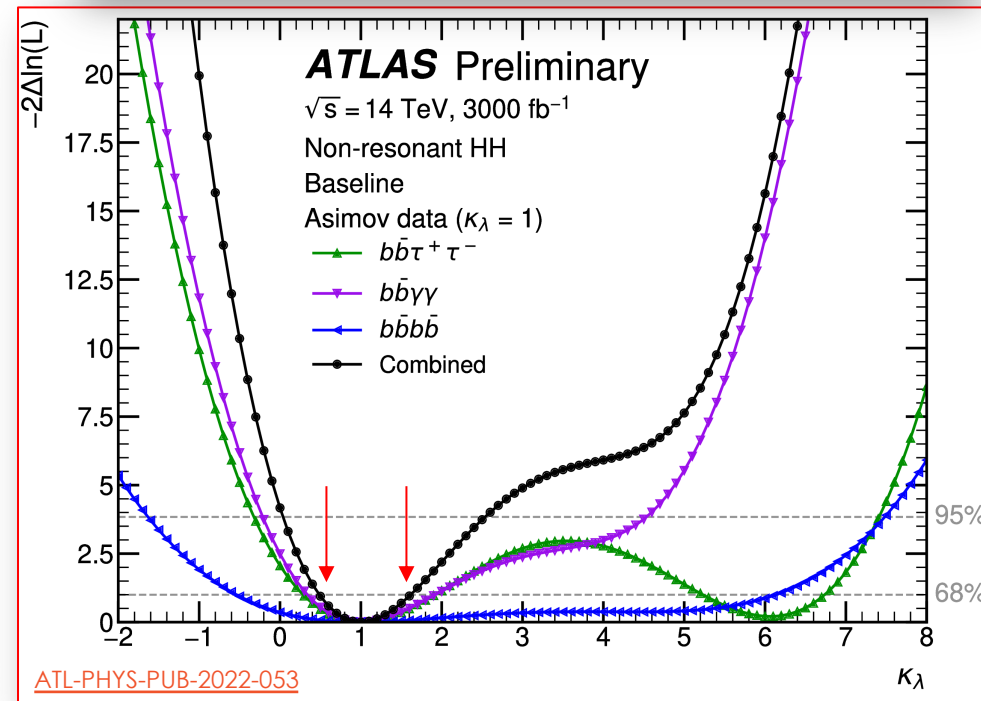
$$0.5 \lesssim \kappa_\lambda \lesssim 1.6 \text{ at } 1\sigma$$

$V(\phi)$, 2040 (HL-LHC)



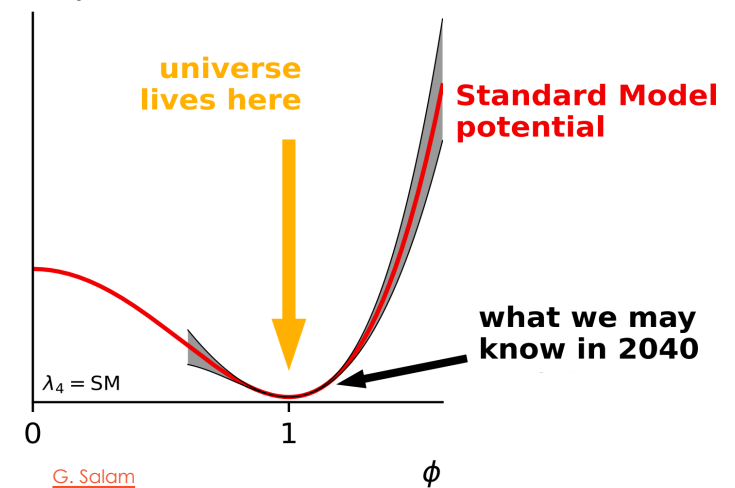
HOW DOES HH LOOK IN HL-LHC?

Uncertainty scenario	Significance [σ]			
	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$	Combination
No syst. unc.	2.3	4.0 4.6	1.8	4.9
Baseline	2.2	2.8 3.5	0.99	3.4

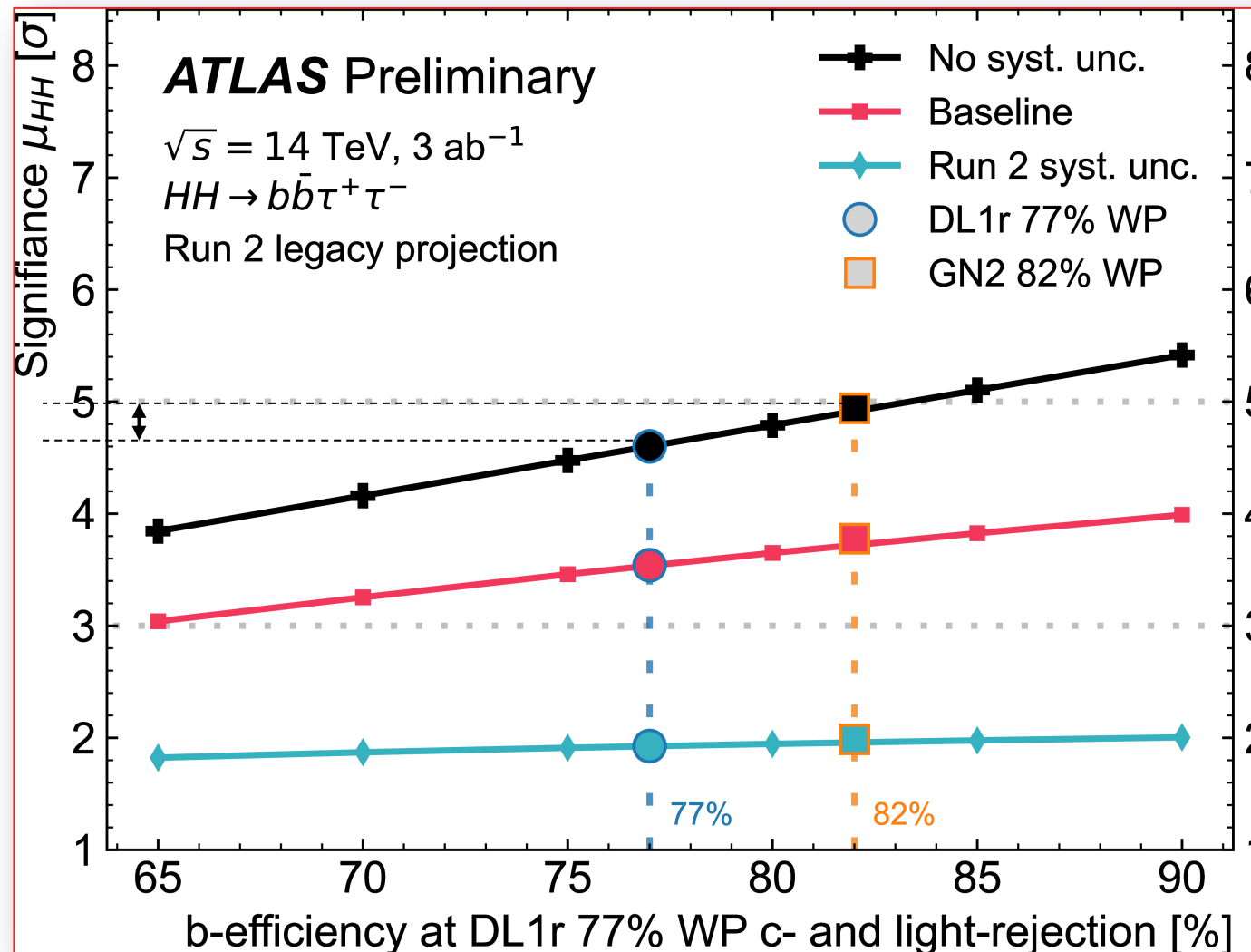


$0.5 \lesssim \kappa_\lambda \lesssim 1.6$ at 1σ

$V(\phi)$, 2040 (HL-LHC)



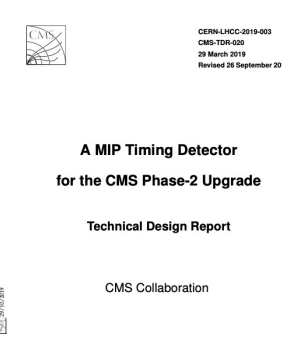
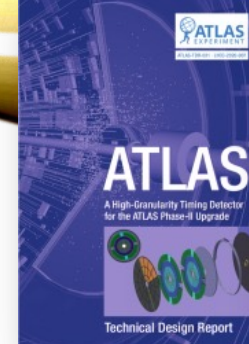
HOW BETTER CAN WE DO?



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

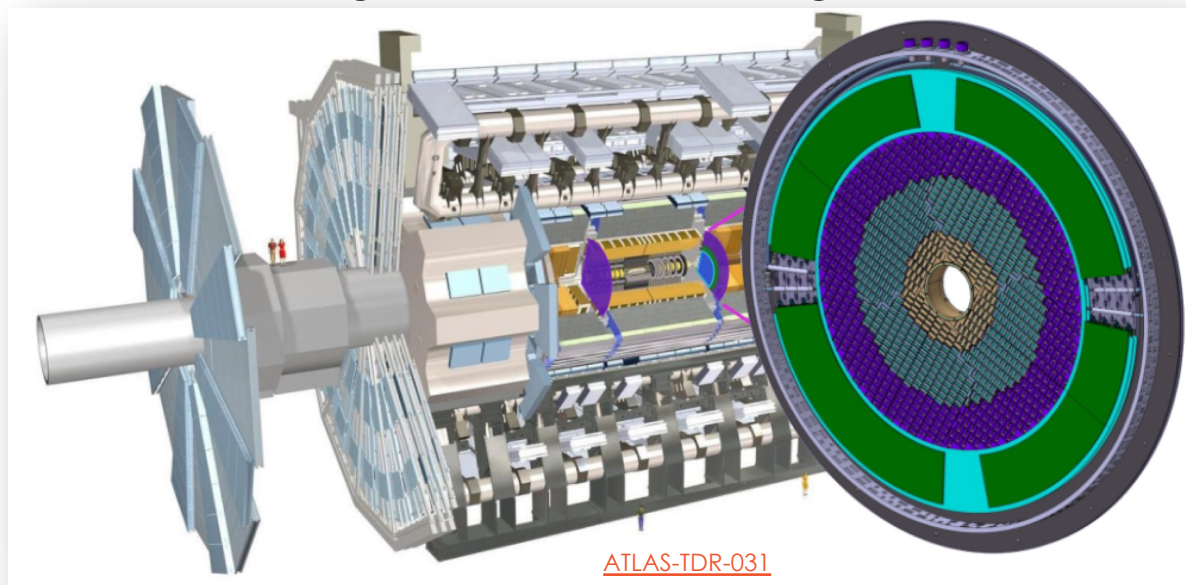
UNFOLDING A NEW DIMENSION

Addition of timing layers to HEP detectors growing area of interest



04.12.24

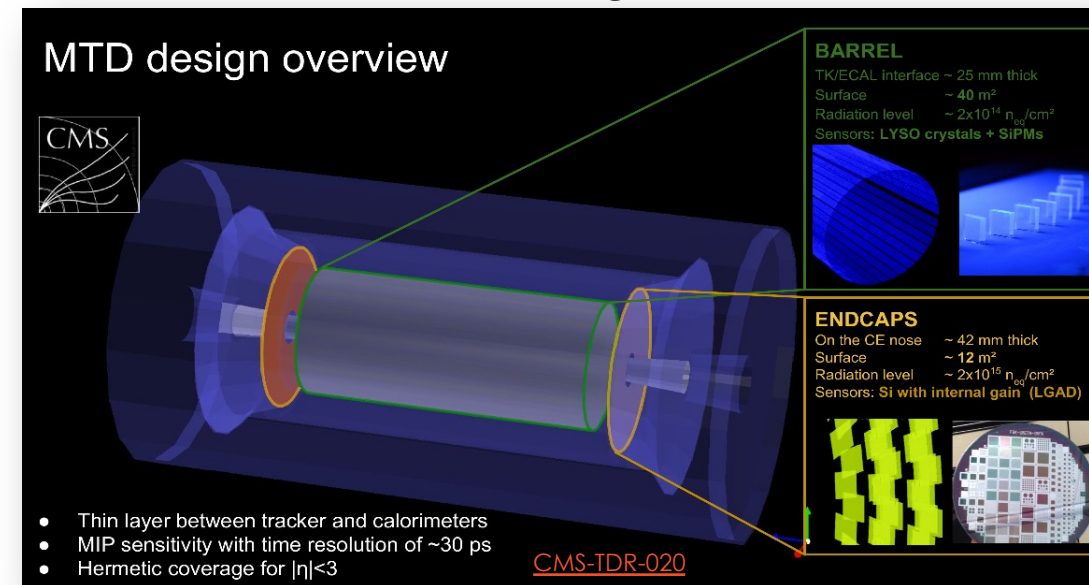
ATLAS High Granularity Timing Detector



[ATLAS-TDR-031](#)

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

CMS MIP Timing Detector



- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of ~ 30 ps
- Hermetic coverage for $|\eta| < 3$

[CMS-TDR-020](#)

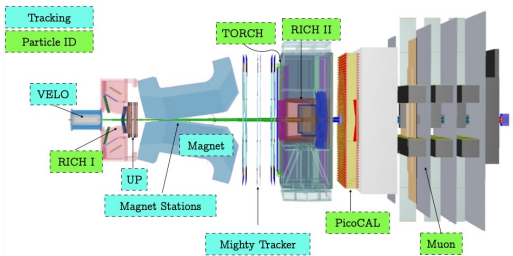
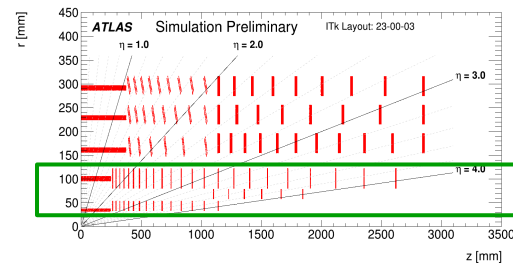
LGADs and crystals for hermetic coverage up to $|\eta| < 3.0$

4D TRACKING

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

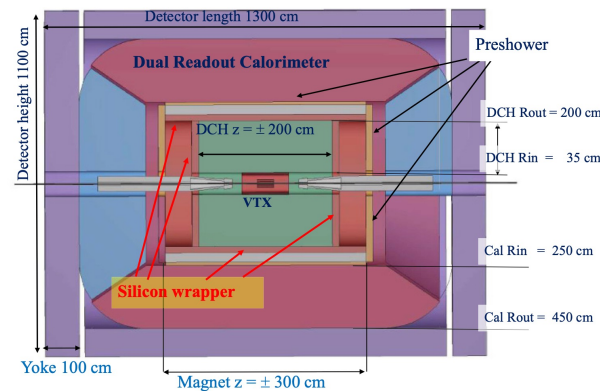
- Interesting opportunities during HL-LHC and, in particular, for future energy frontier trackers

HL-LHC Beyond Run 4



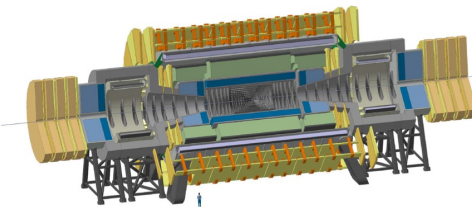
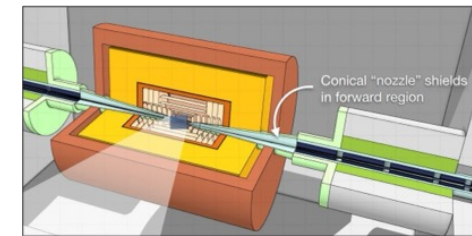
4D tracking for
replacements/upgrades?

Electron-positron colliders



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

Muon collider / hadron colliders

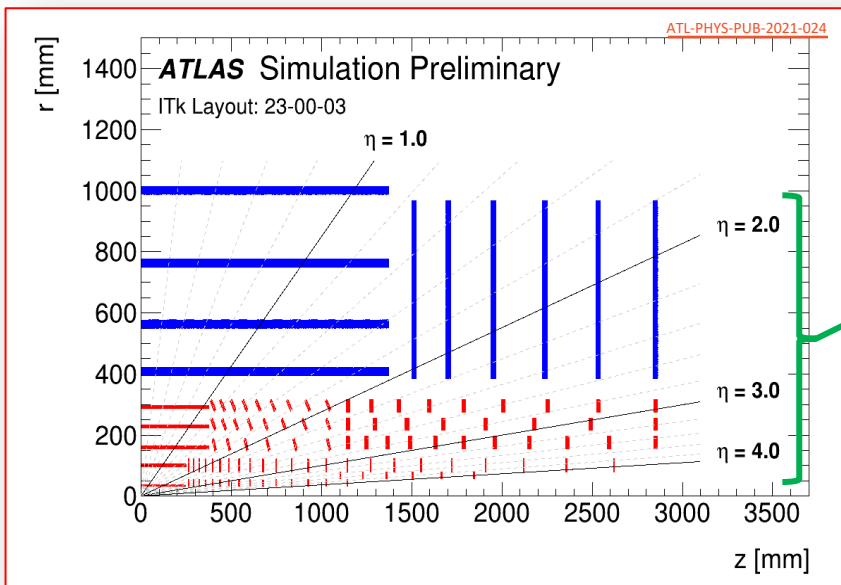


Beam-induced
backgrounds (μ) and pile-
up suppression (hh)

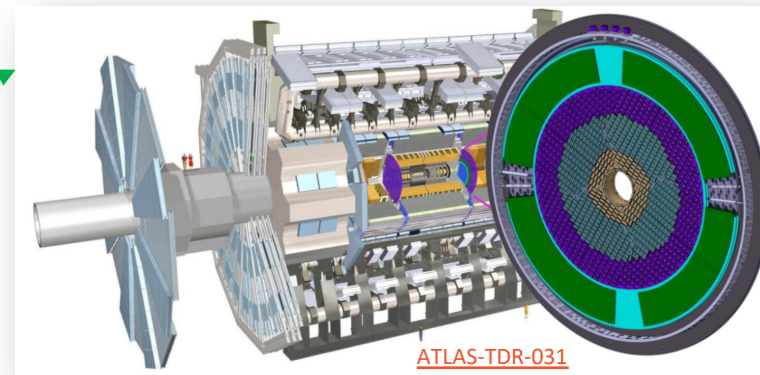
4D TRACKING

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

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

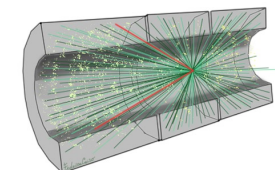


High Granularity Timing Detector



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

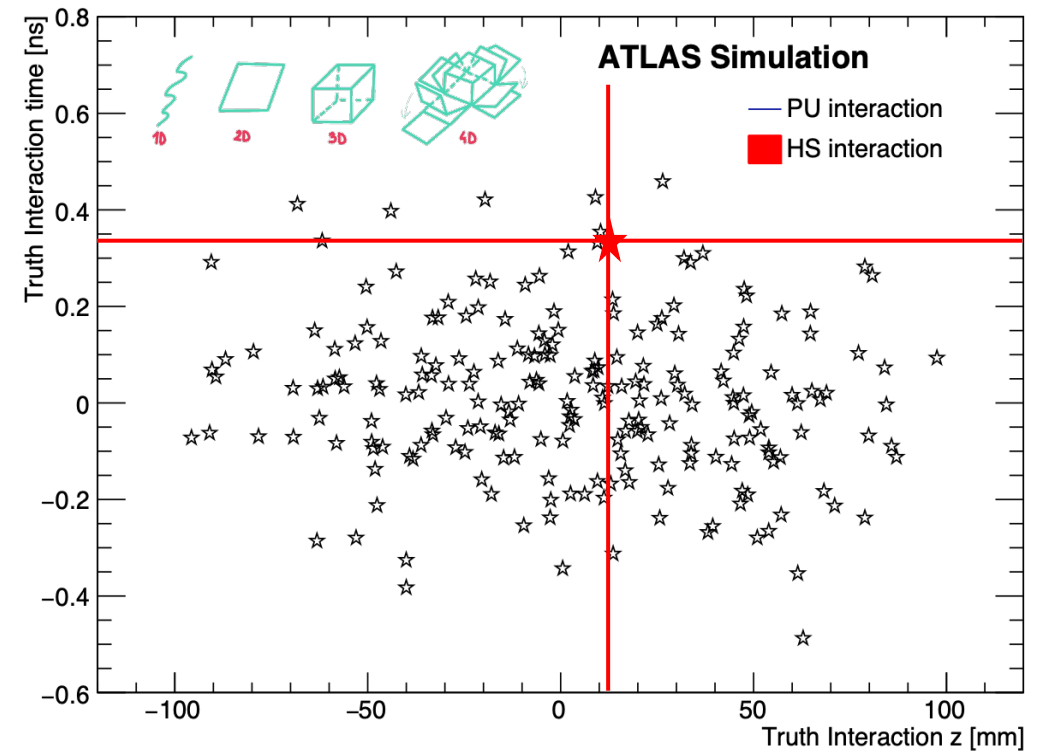
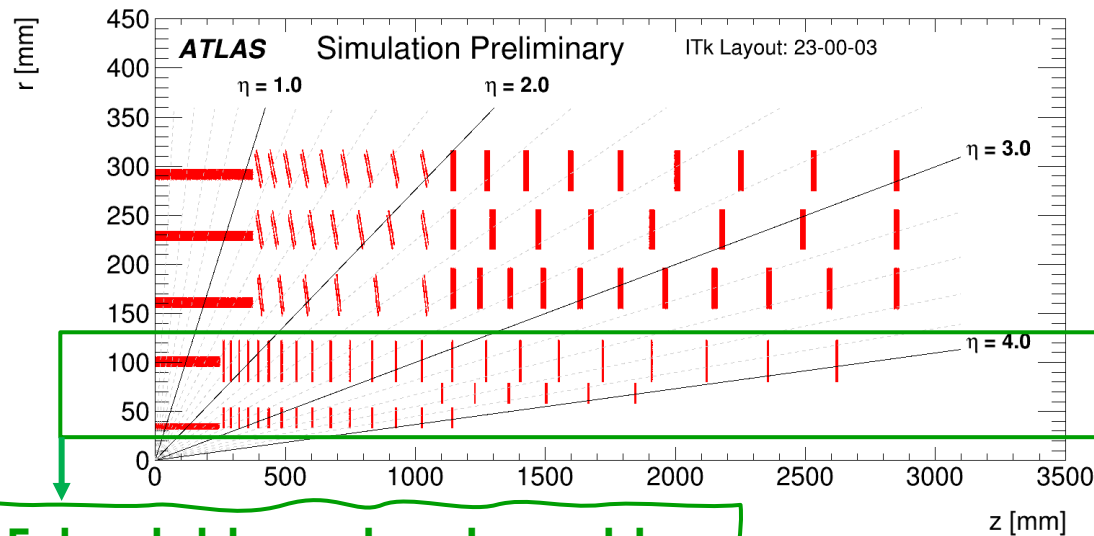
Can we maximize the ATLAS physics potential beyond Run 4 by extending the timing coverage to the full η acceptance?



4D TRACKING

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

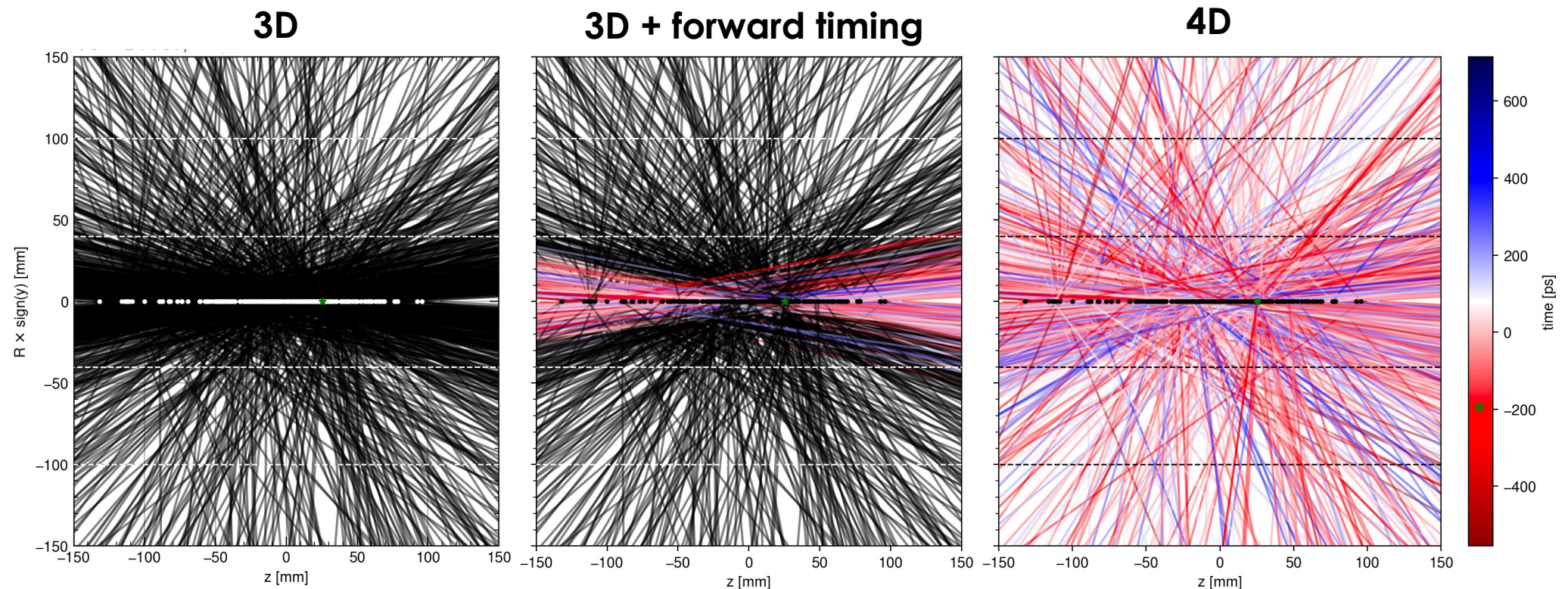
- Interesting opportunities during HL-LHC and, in particular, for future energy frontier trackers
- First exploratory studies in ATLAS



4D TRACKING

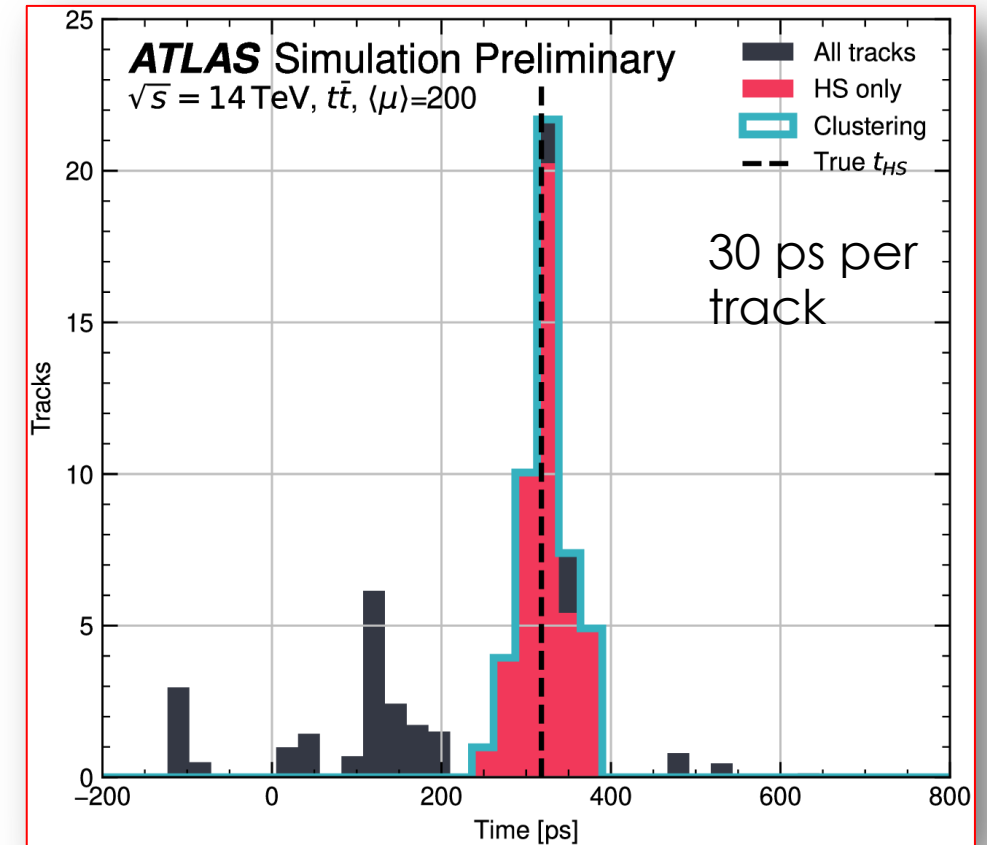
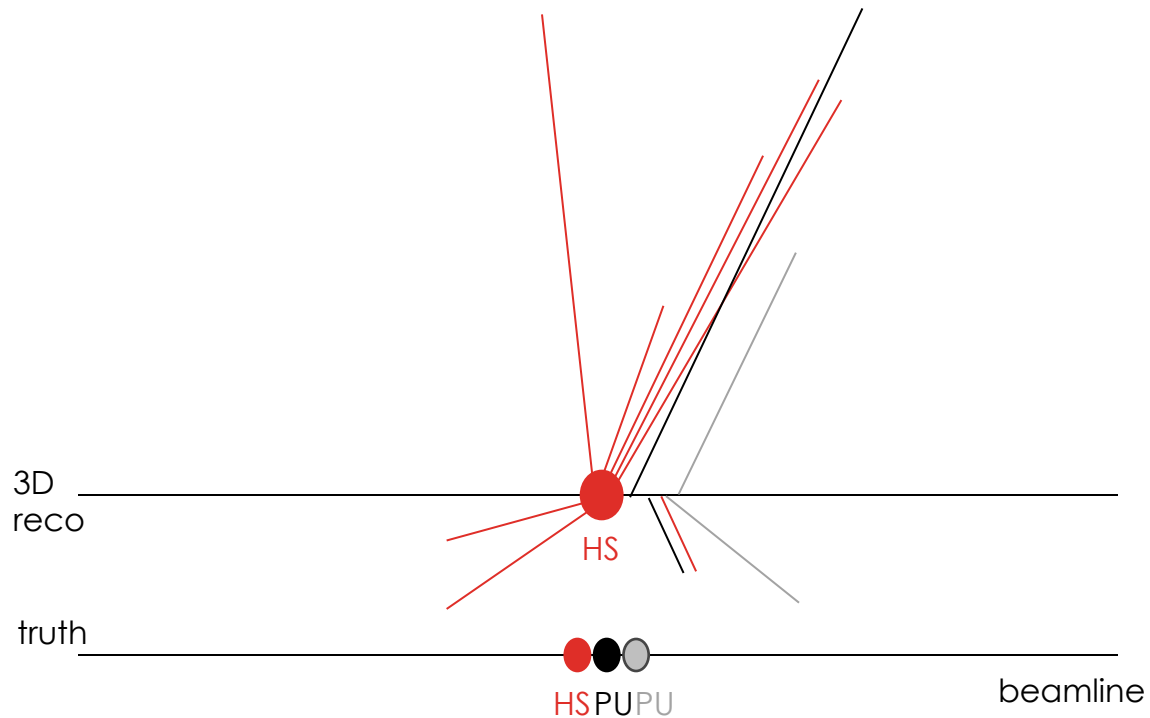
Next step in advancing technologies are real 4-dimensional silicon trackers
with resolution of $\mathcal{O}(10\ \mu\text{m})$ & $\mathcal{O}(10\ \text{ps})$

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



DETERMINING THE VERTEX TIME

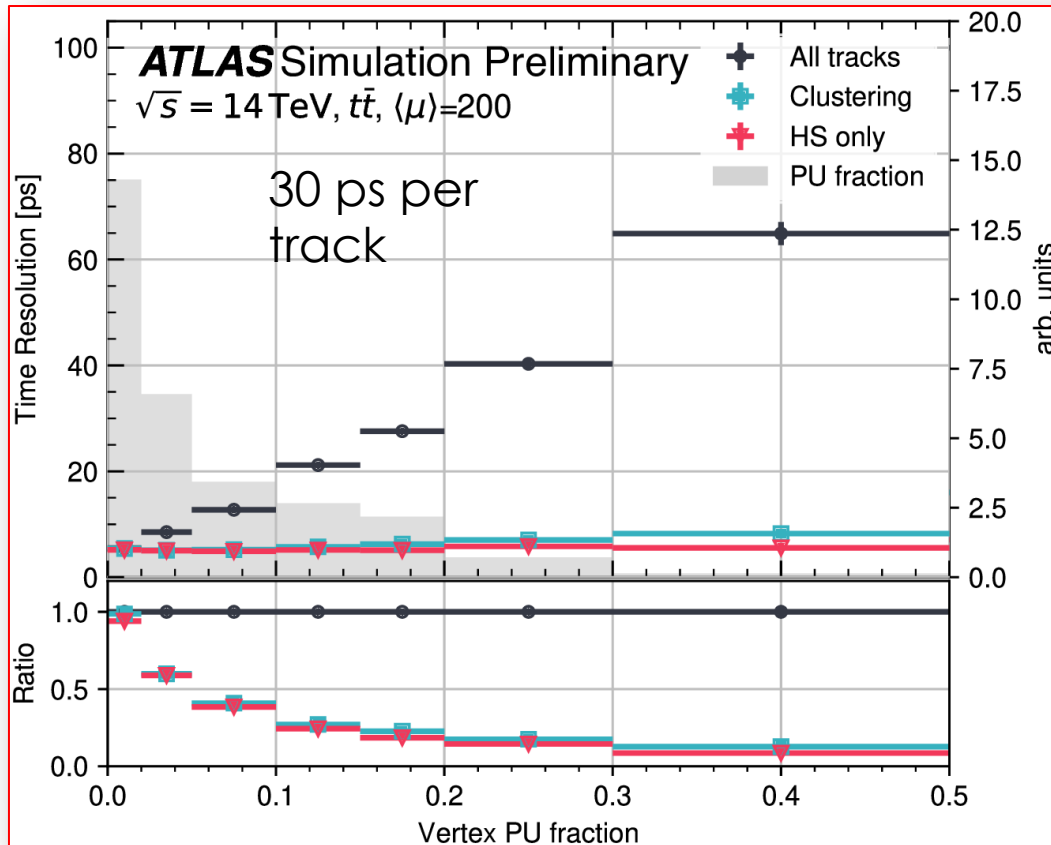
- With 4D tracking, **each** charged particle would have a timestamp
- Determining **vertex time** crucial for reconstruction/identification of other objects, e.g. b-jets



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

DETERMINING THE VERTEX TIME

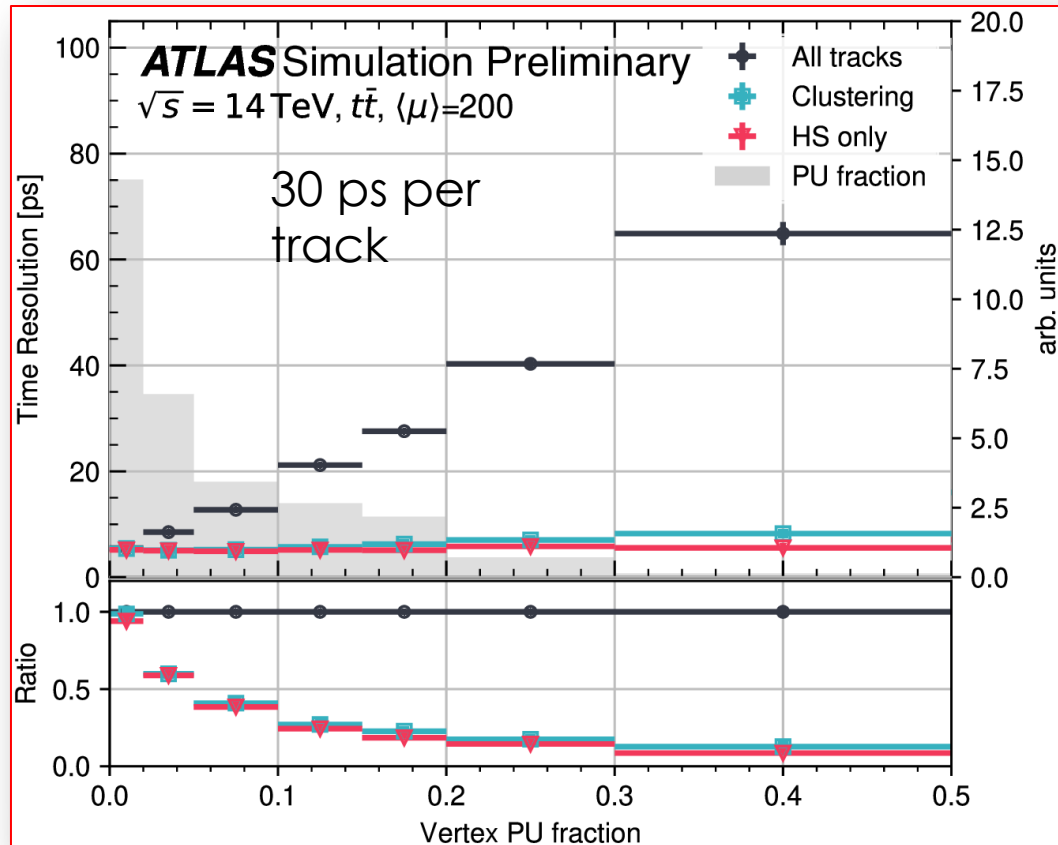
- With 4D tracking, **each** charged particle would have a timestamp
- Determining **vertex time crucial for reconstruction/identification of other objects**, e.g. b-jets



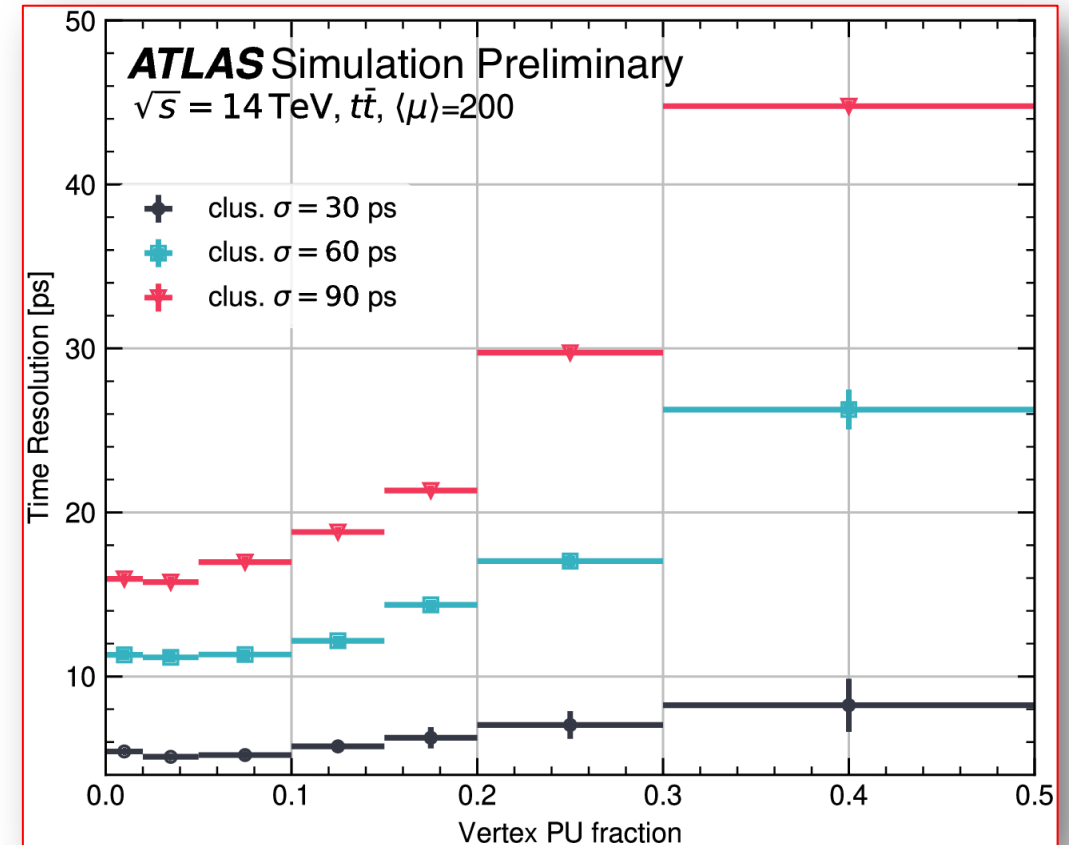
Excellent vertex time resolution can be achieved

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

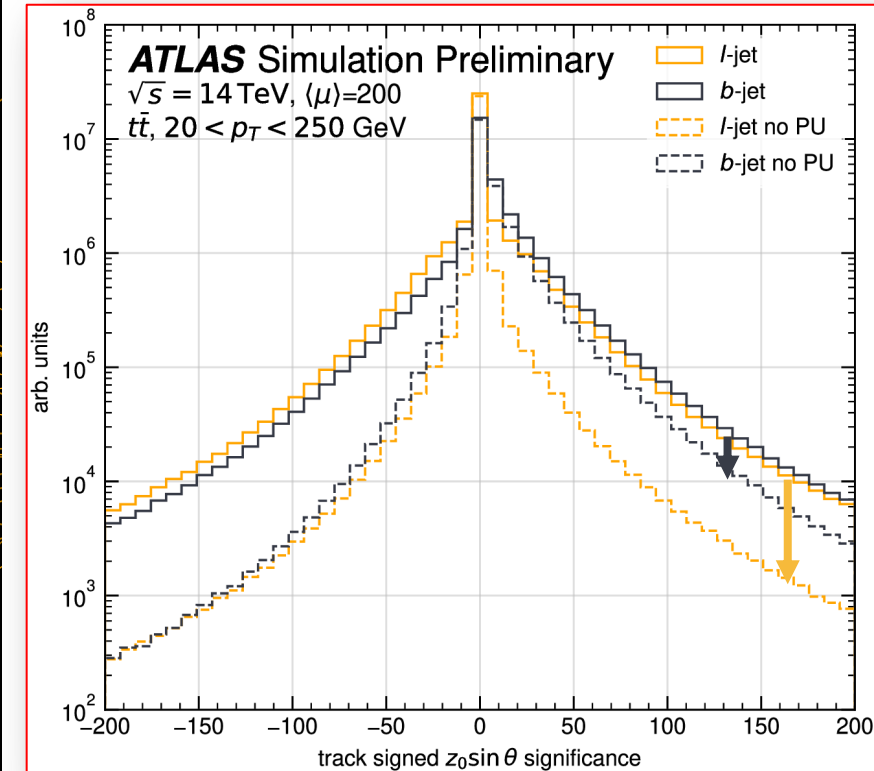
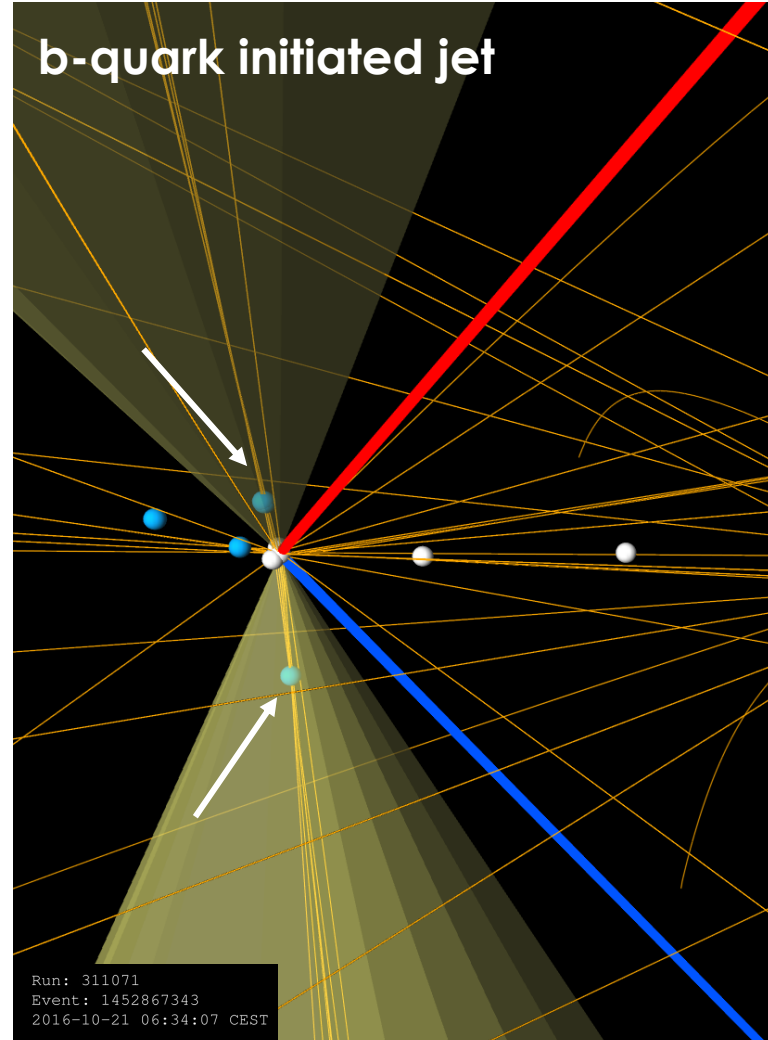
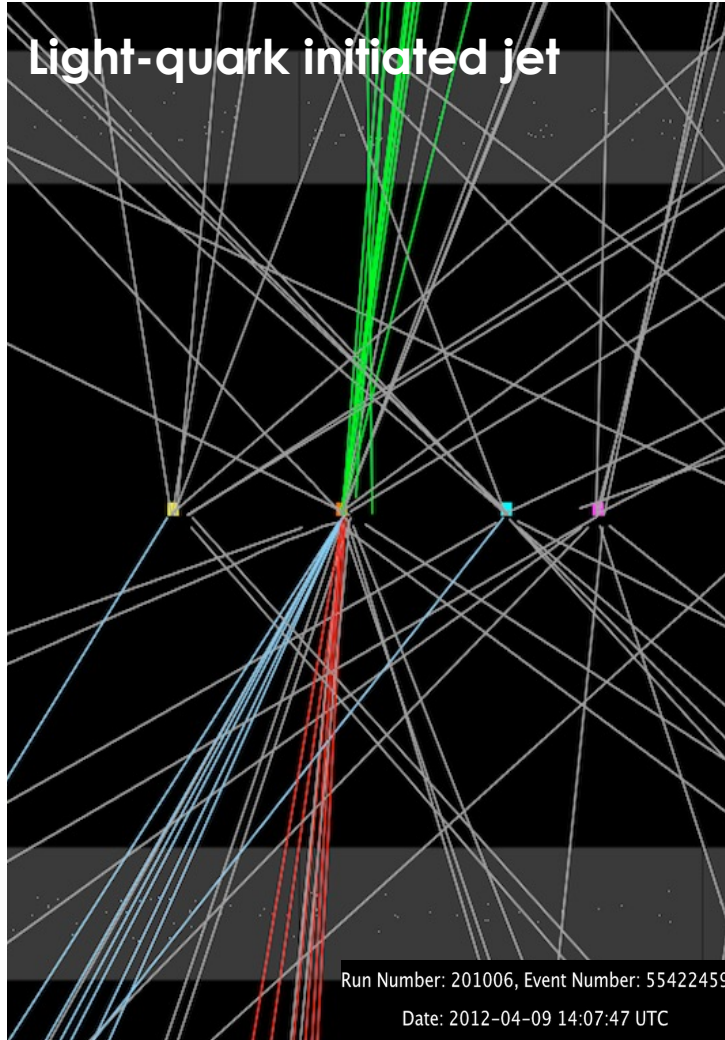


Excellent vertex time resolution can be achieved

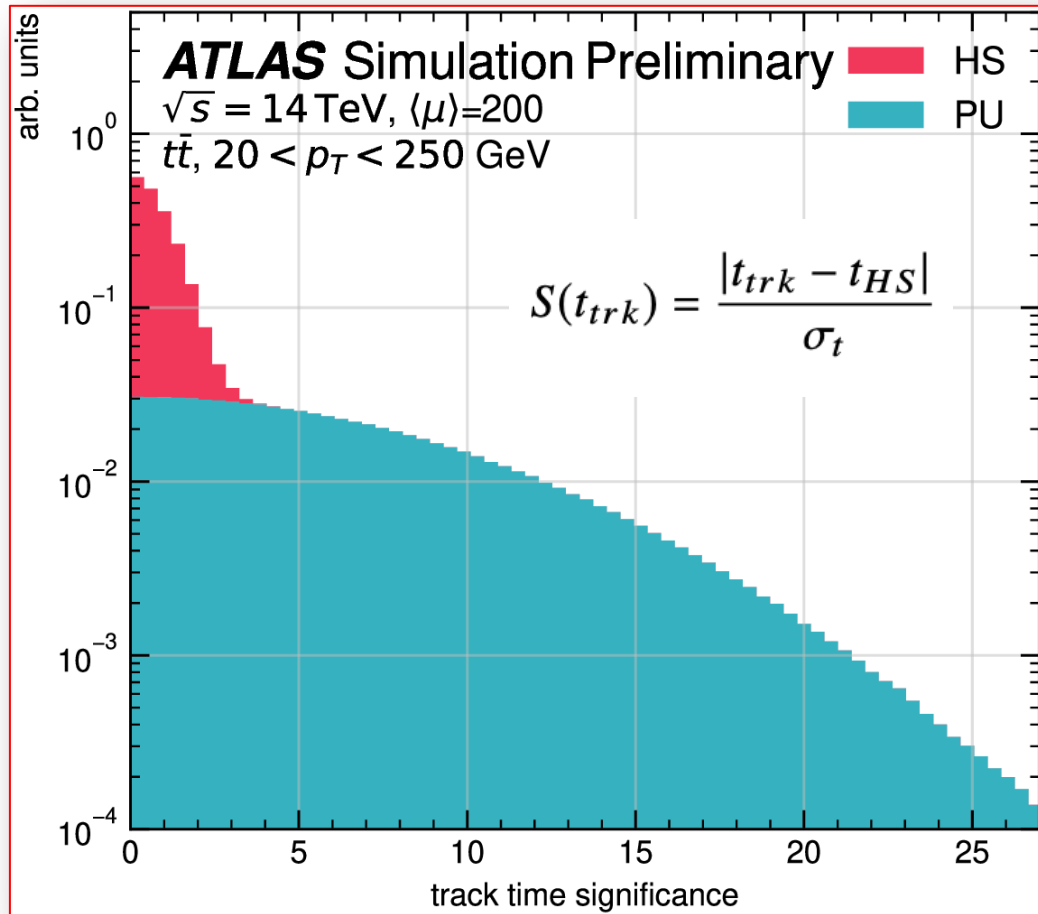


The better the track-time resolution, the more PU-robust the vertex time resolution

THE KEY FEATURES FOR b -TAGGING

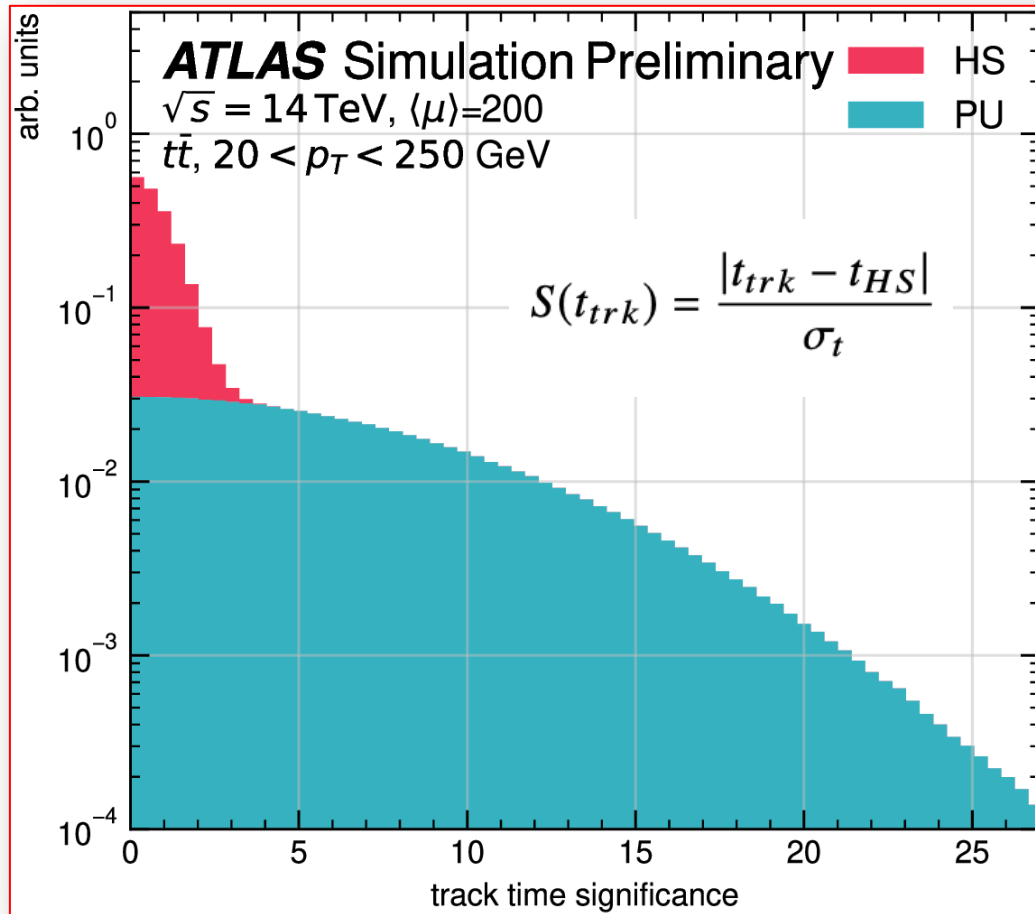


GNT – 4D b -TAGGING

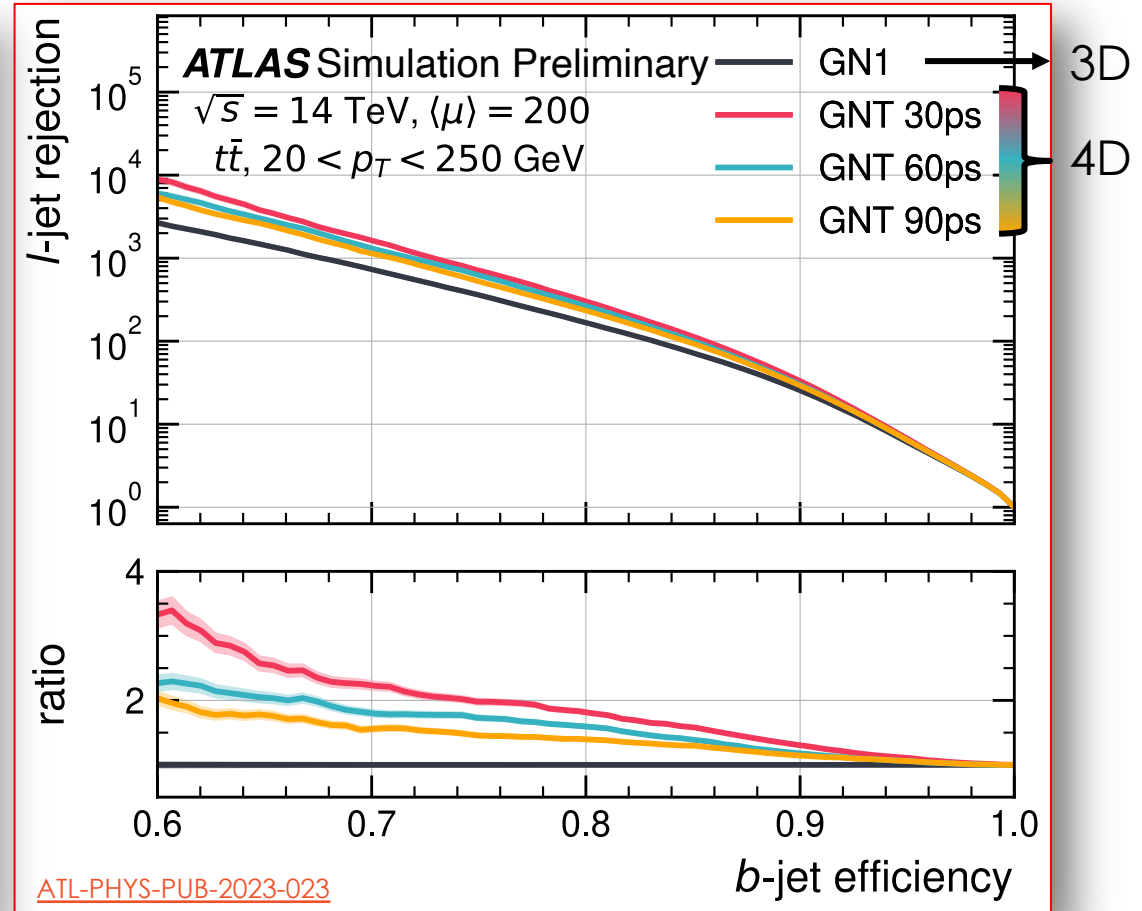


Known track and vertex time, a track time significance is built

GNT – 4D b -TAGGING

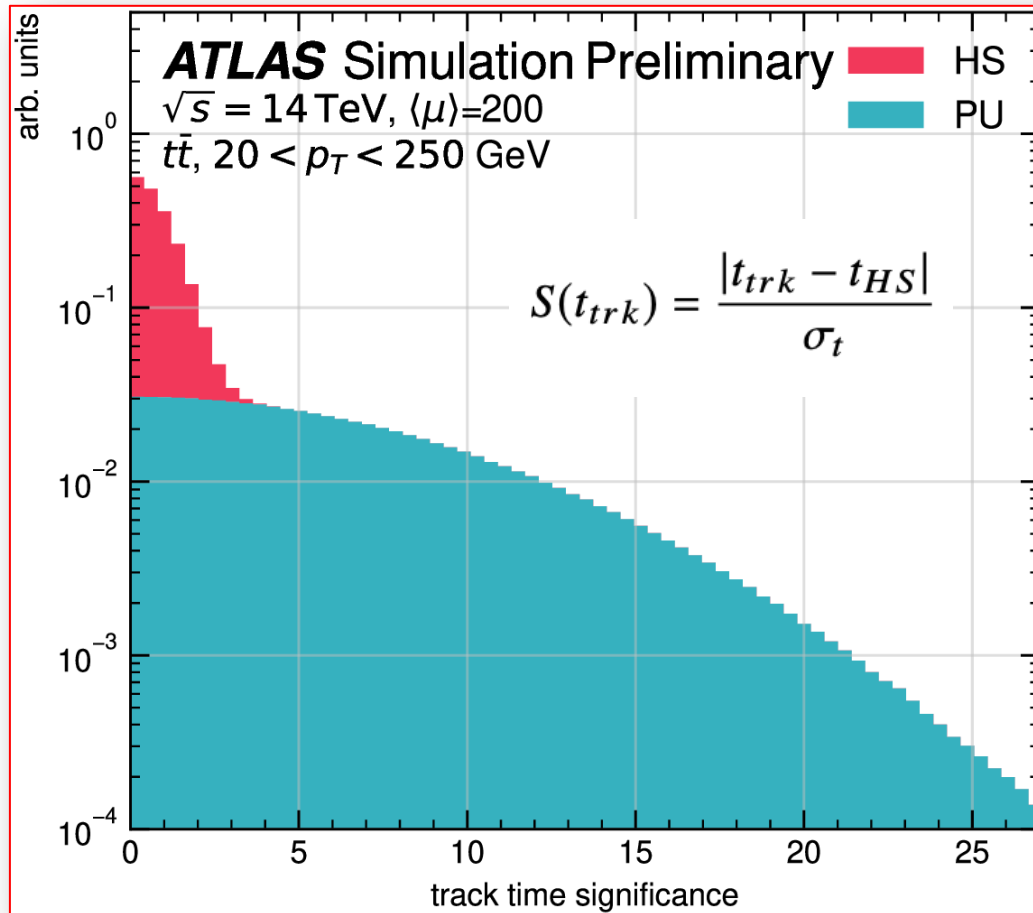


Known track and vertex time, a track time significance is built



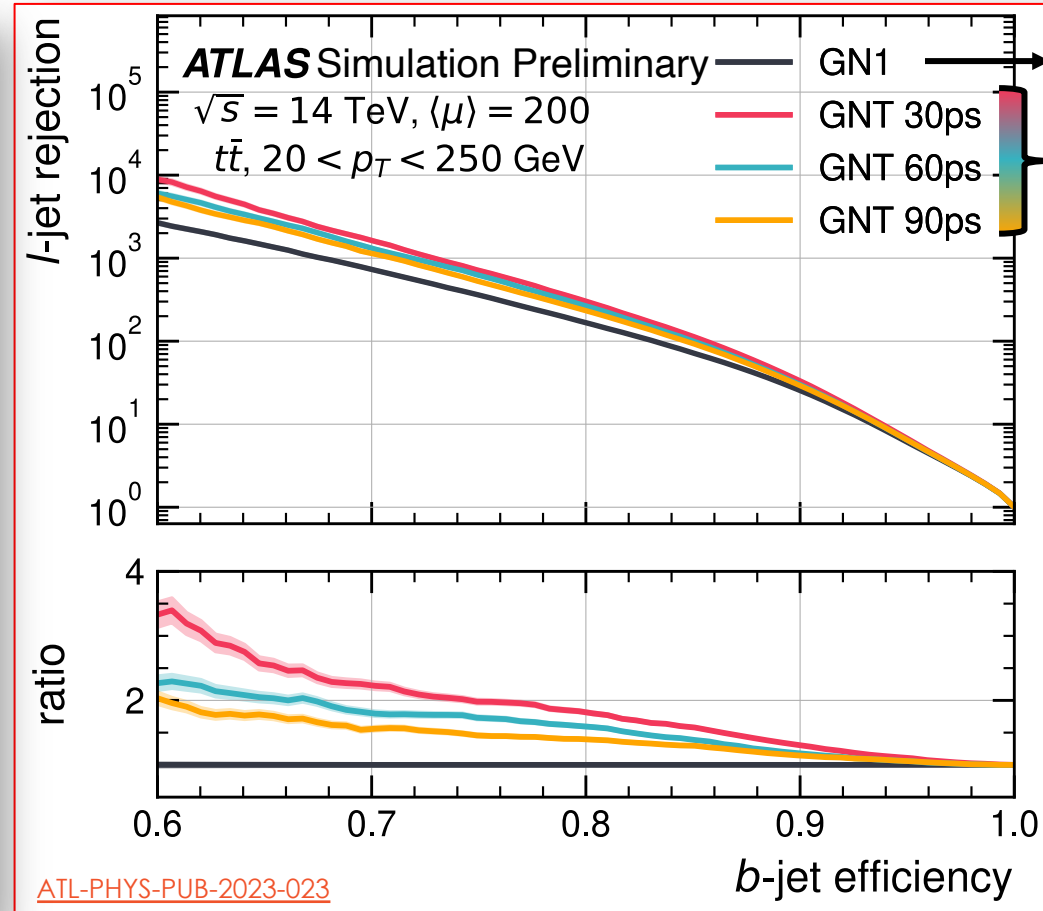
Interesting potential HH sensitivity increase!

GNT – 4D b -TAGGING



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

V.M.M.CAIRO



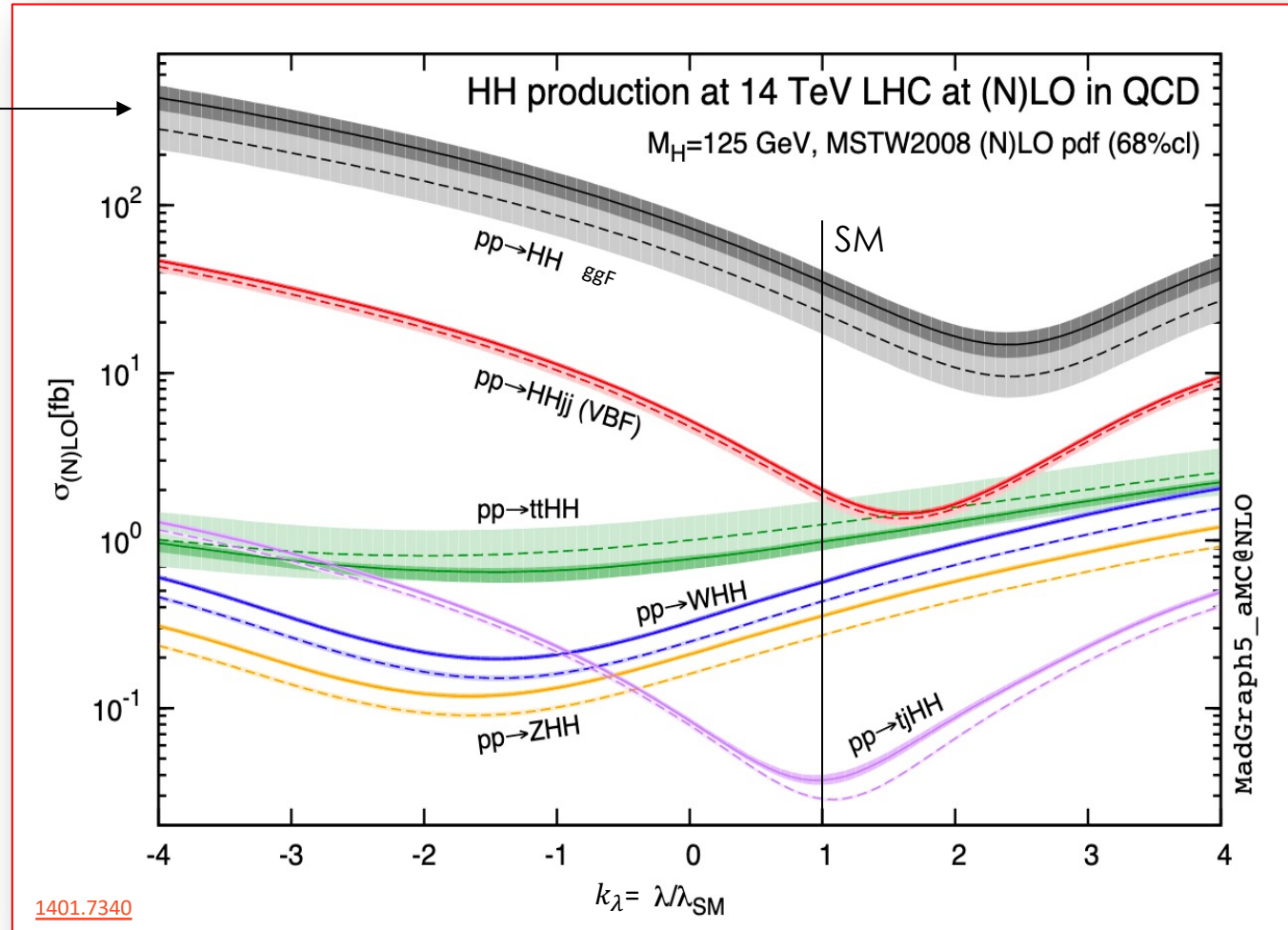
[ATL-PHYS-PUB-2023-023](#)

Interesting potential HH sensitivity increase!

In addition, exciting detector-agnostic developments with the **ACTS library**, and trigger applications via cluster-based b -tagging being explored in synergy with the **Next Generation Triggers project**

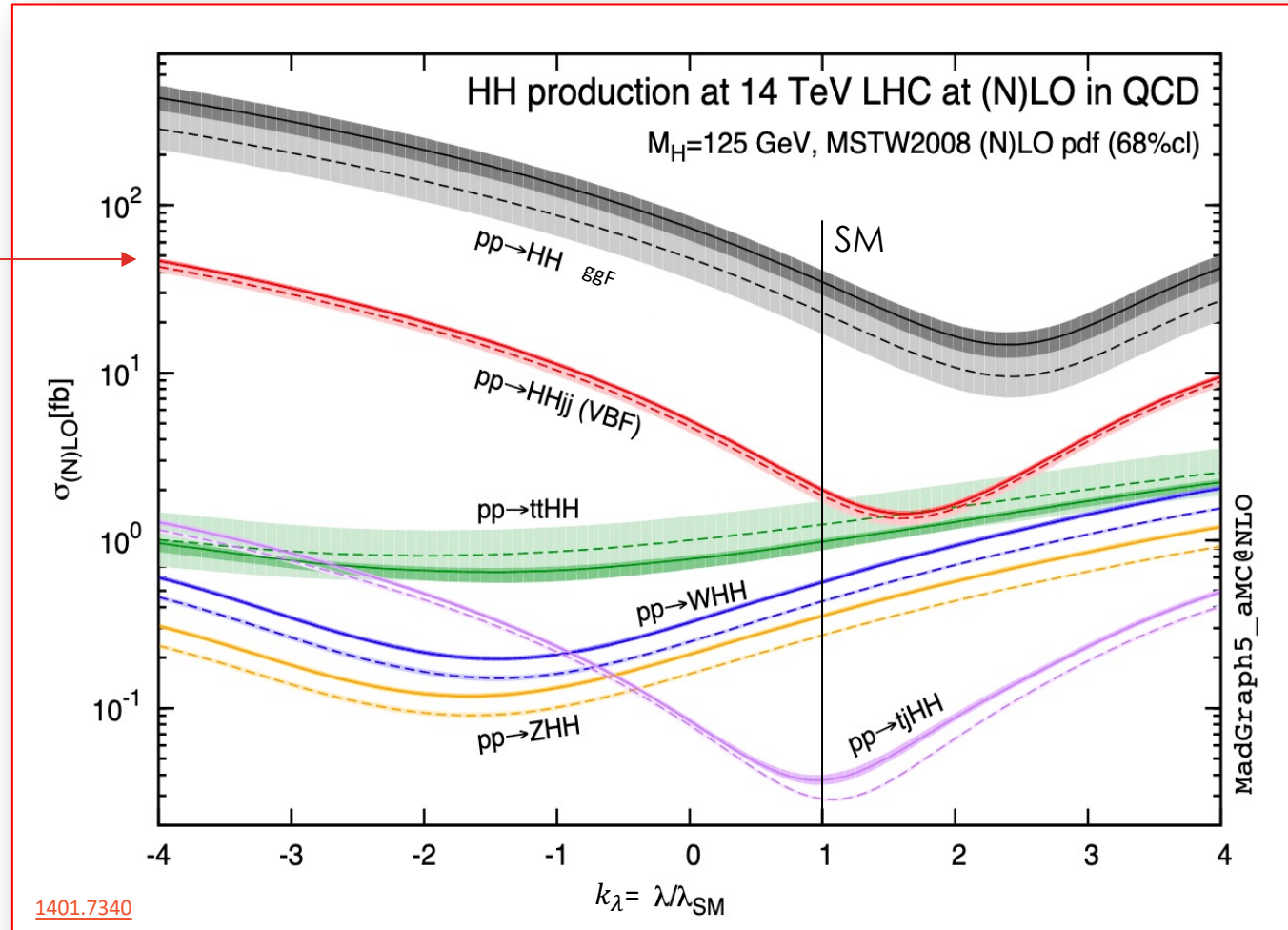
4D TRACKING: BEYOND THE CURRENT HH PROGRAMME

Our
current
focus



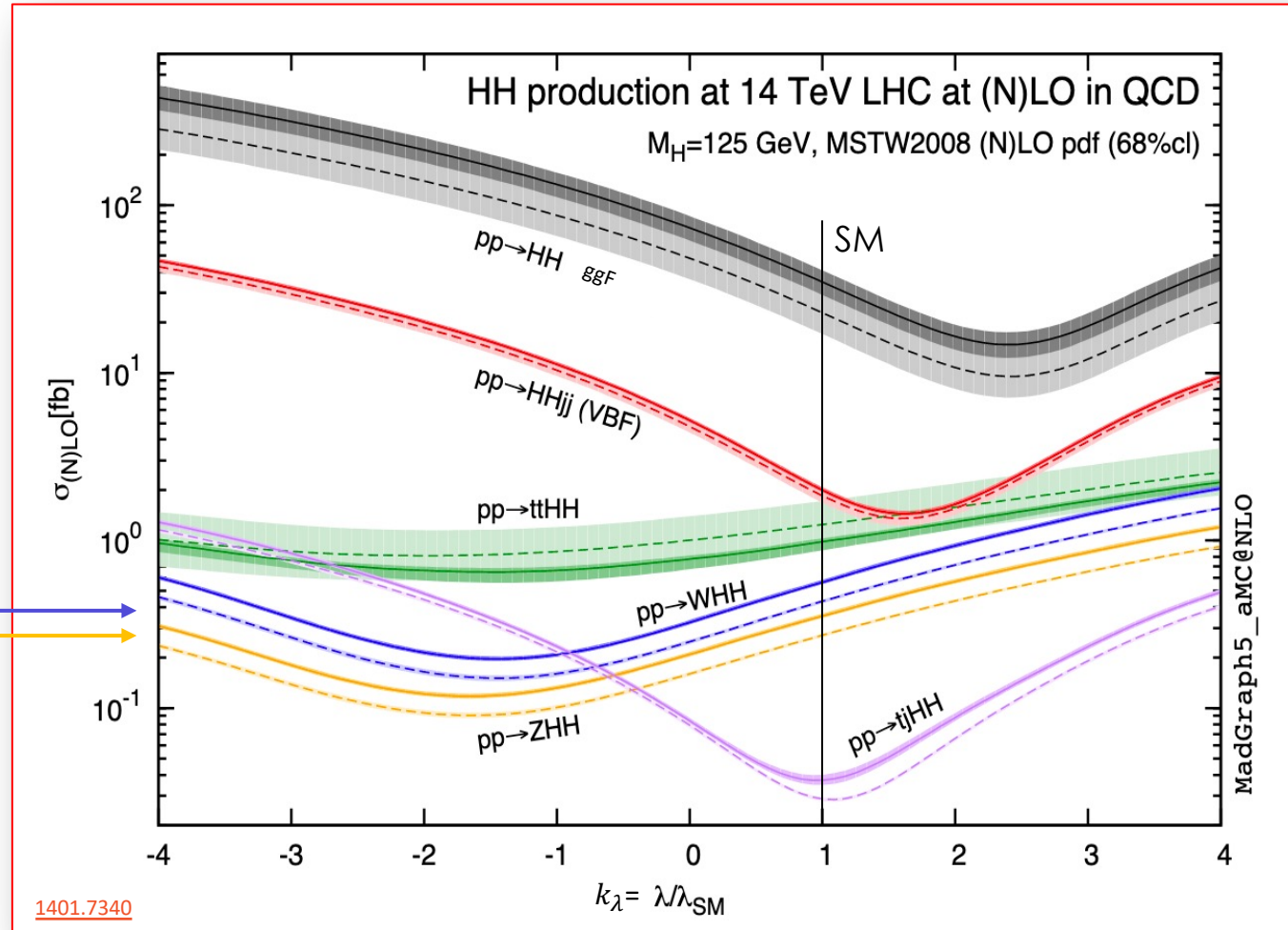
4D TRACKING: BEYOND THE CURRENT HH PROGRAMME

Already being
searched for,
Enhanced by
ITk forward
capabilities



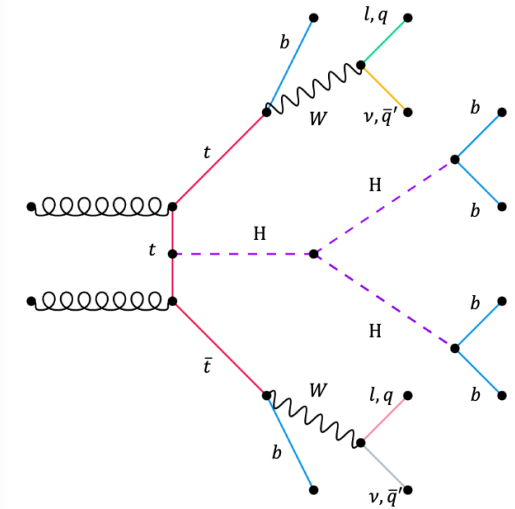
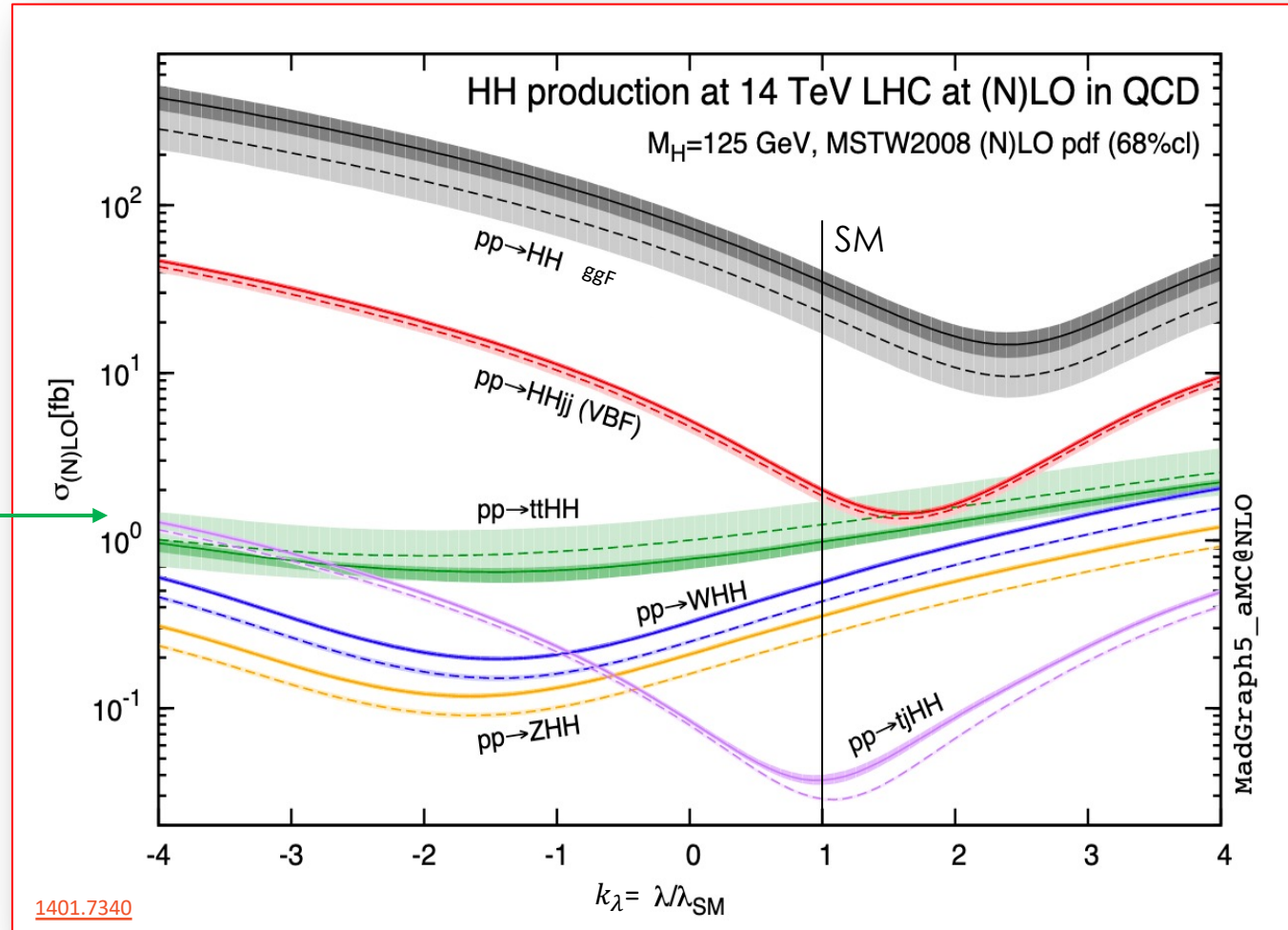
4D TRACKING: BEYOND THE CURRENT HH PROGRAMME

VHH already
being
searched for
([epjc/s10052-023-11559-y](https://arxiv.org/abs/1401.7340))



4D TRACKING: BEYOND THE CURRENT HH PROGRAMME

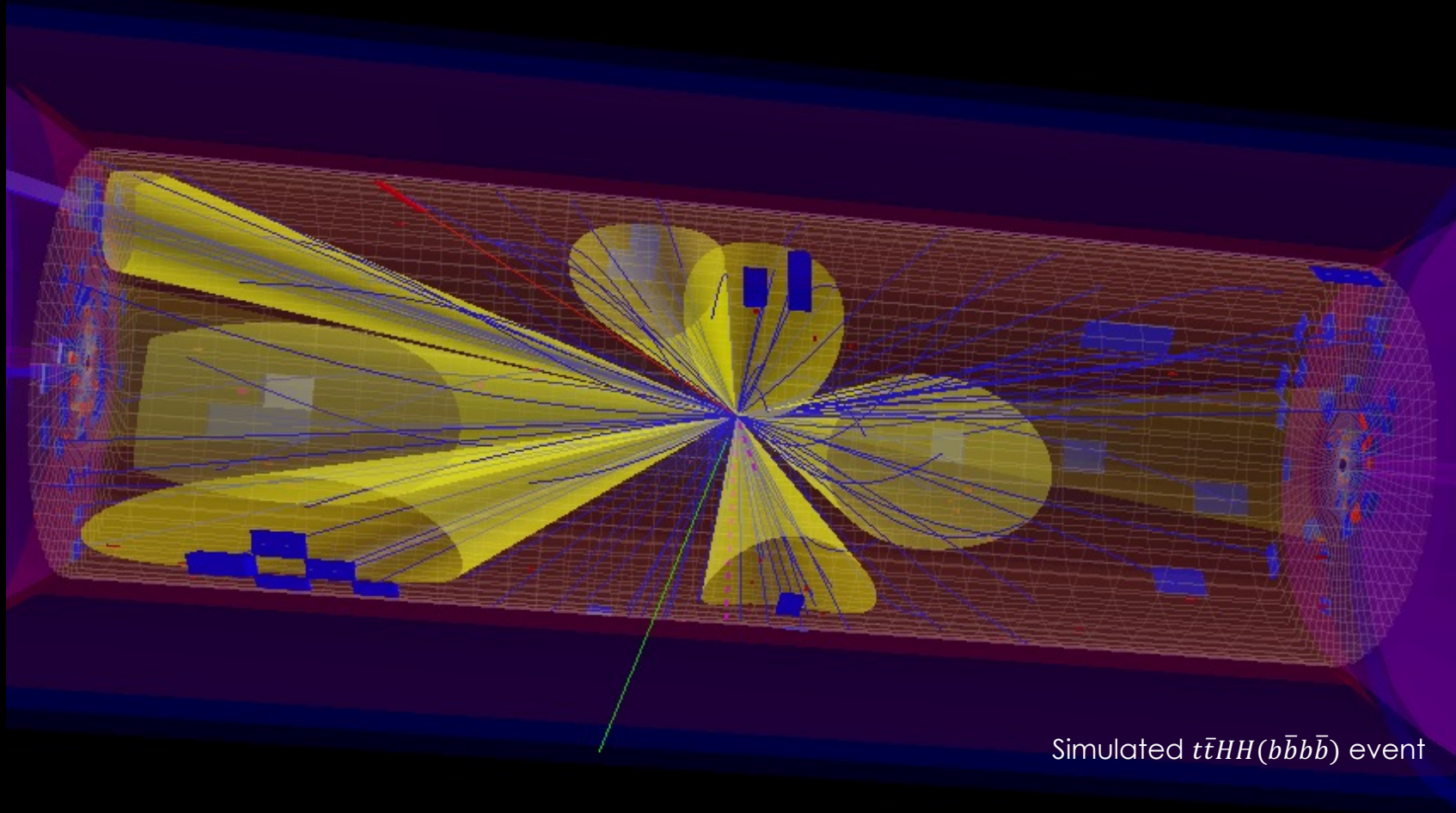
A new
frontier to
explore
the Higgs
and Top
sectors...



AT THE EDGE OF OUR CAPABILITIES:

$t\bar{t}HH$

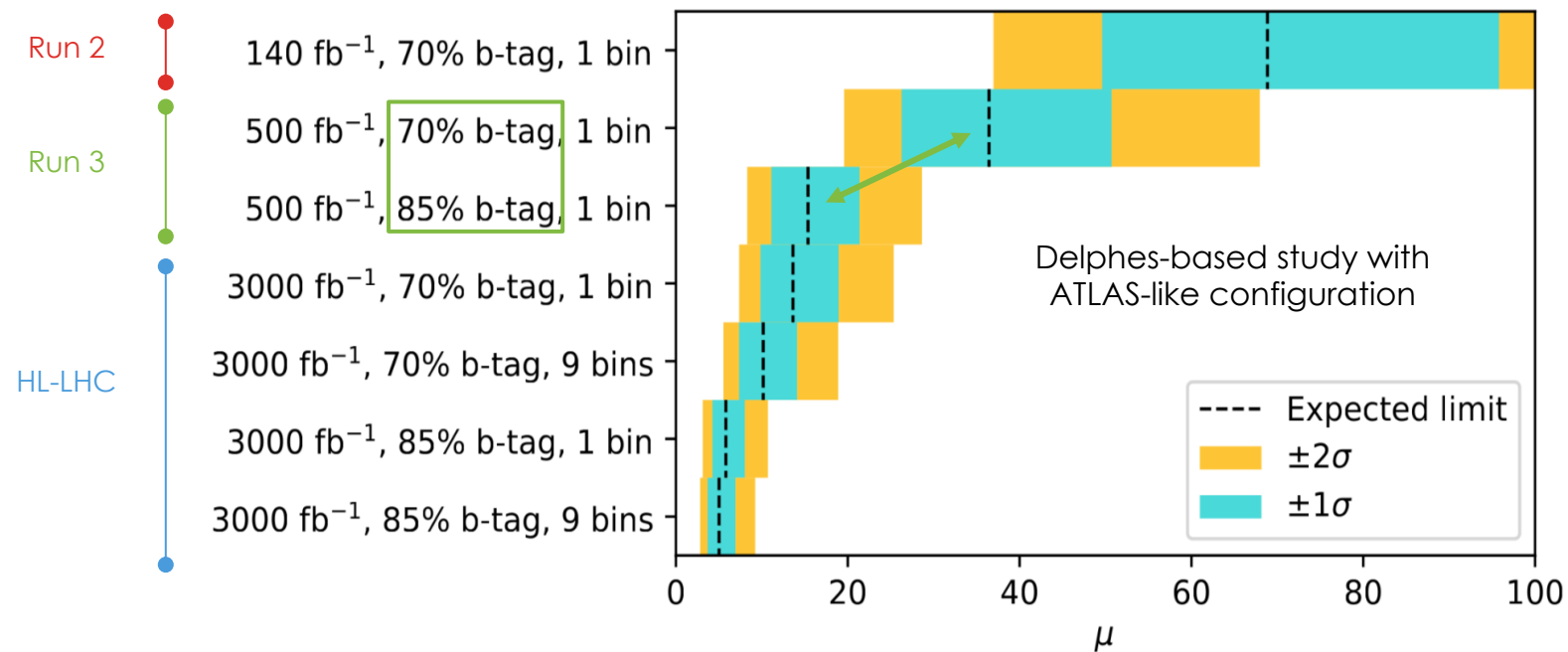
- Largely uncharted at the LHC, very rare and experimentally complex channel
- Many b-jets in the detector



Simulated $t\bar{t}HH(b\bar{b}b\bar{b})$ event

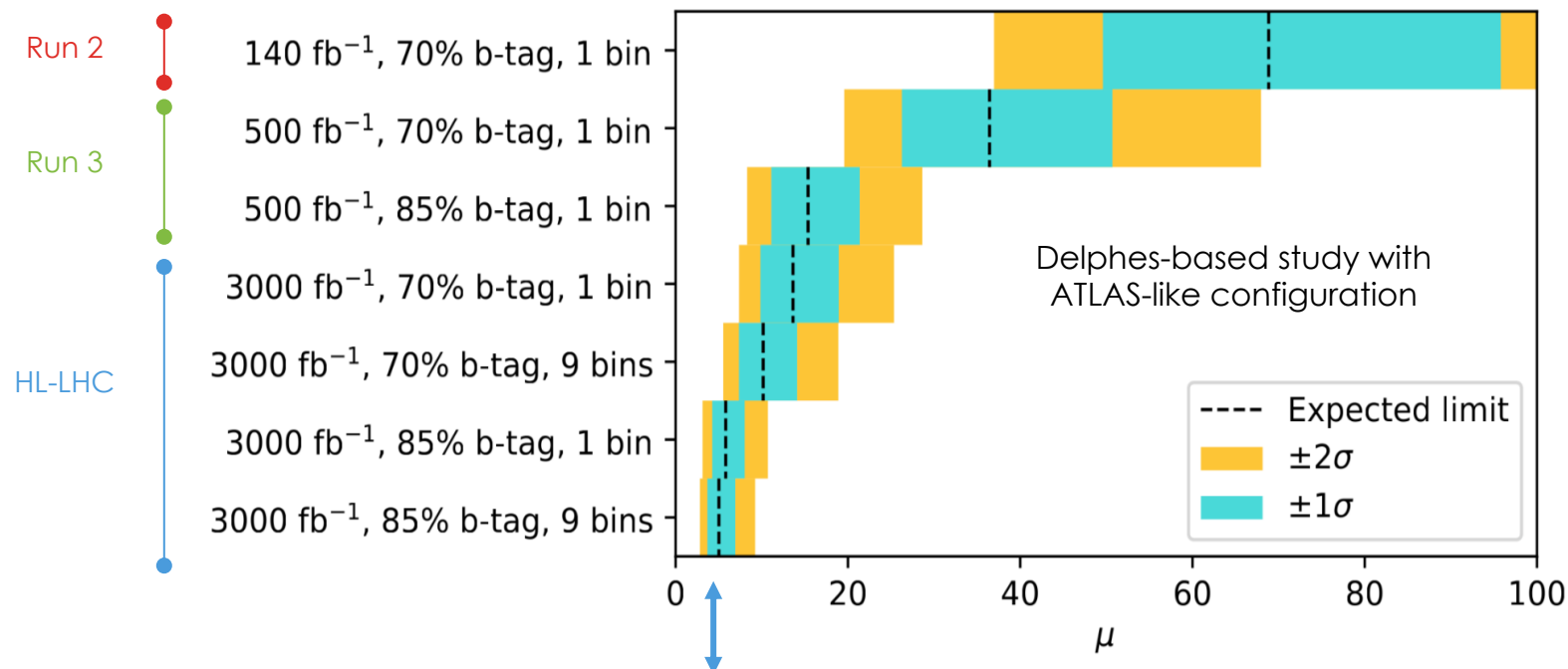
PUSHING THE BOUNDARIES OF $ttHH$ WITH 4D TRACKING

- Unique access to $ttHH$ quartic interaction predicted by Physics Beyond the Standard Model (BSM)
- Proof-of-concept demonstrates analysis feasibility under SM assumptions and identifies several areas for improving the sensitivity → tracking (b-tagging!) is crucial



PUSHING THE BOUNDARIES OF $ttHH$ WITH 4D TRACKING

- Unique access to $ttHH$ quartic interaction predicted by Physics Beyond the Standard Model (BSM)
- Proof-of-concept demonstrates analysis feasibility under SM assumptions and identifies several areas for improving the sensitivity → tracking (b-tagging!) is crucial



WHAT'S NEXT?



FUTURE COLLIDERS



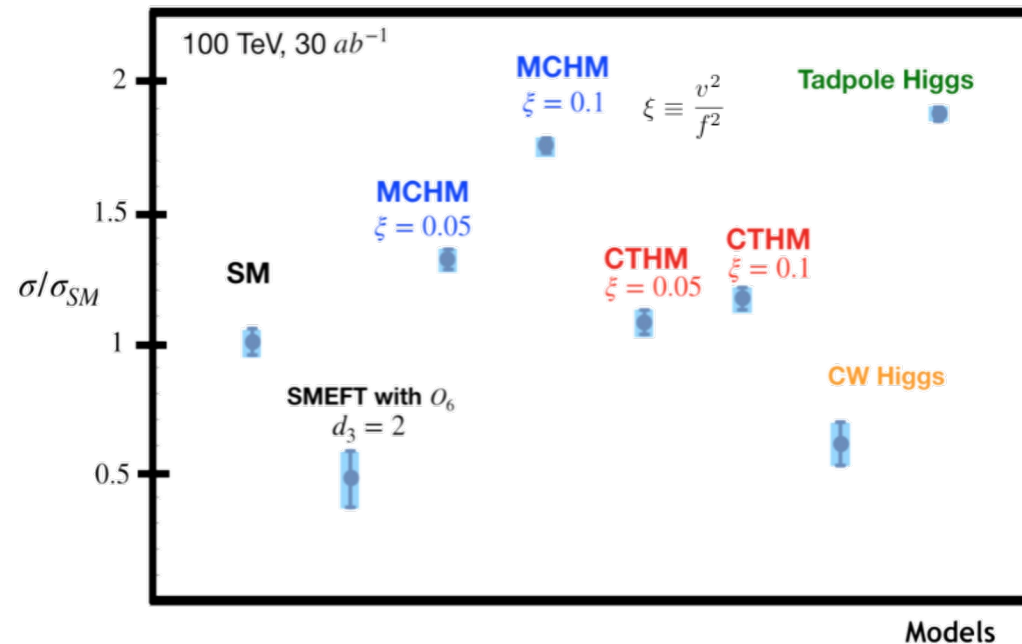
Symmetry

Illustration by Sandbox Studio, Chicago

IMPLICATIONS ON THE HIGGS POTENTIAL

04.12.24

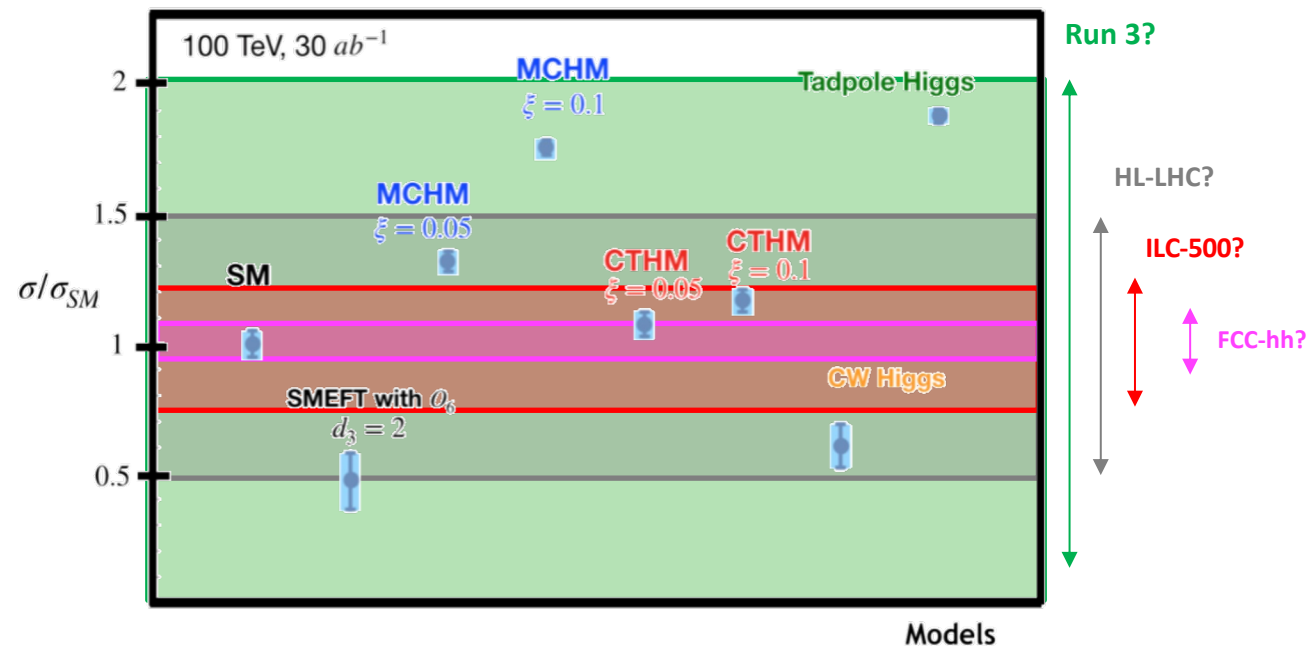
As an example: [arXiv:1907.02078v2](https://arxiv.org/abs/1907.02078v2)



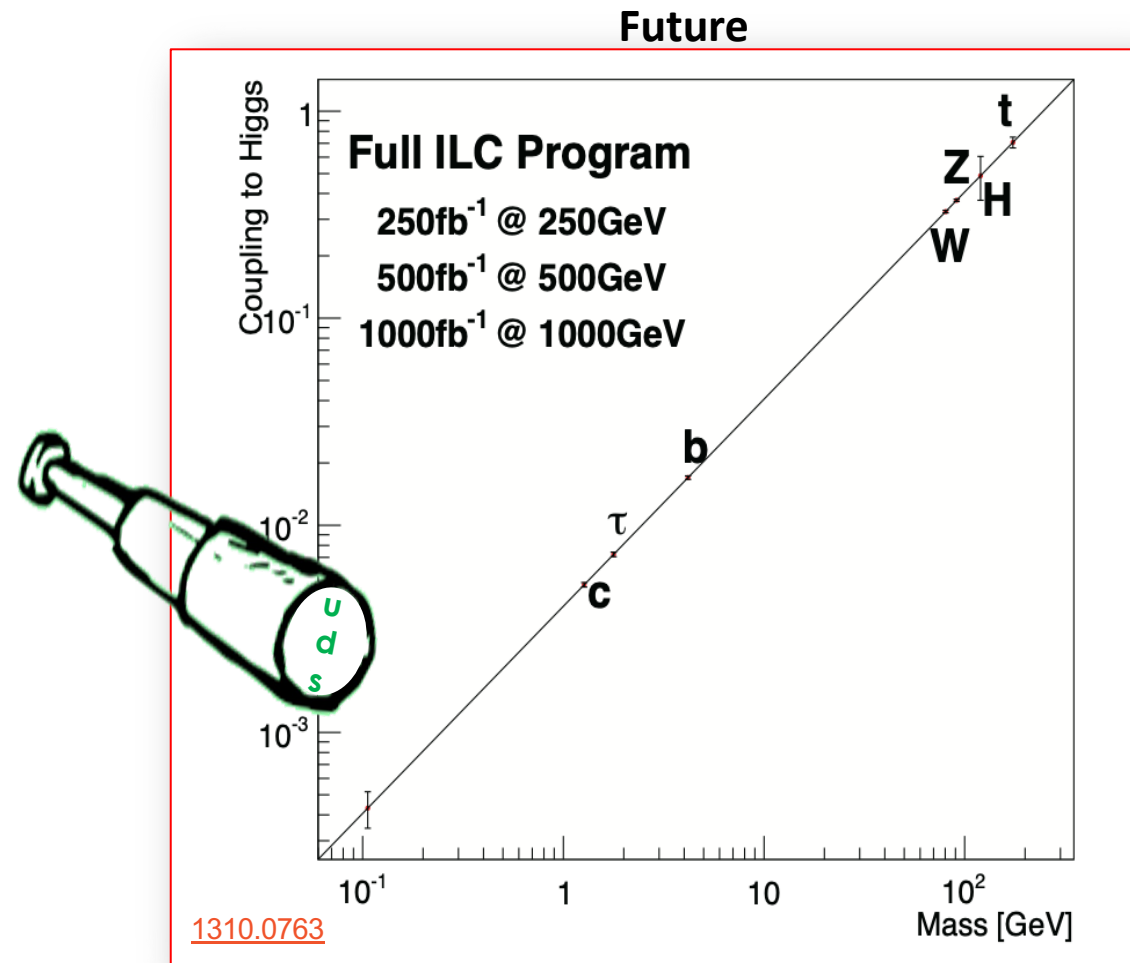
IMPLICATIONS ON THE HIGGS POTENTIAL

04.12.24

As an example: [arXiv:1907.02078v2](https://arxiv.org/abs/1907.02078v2)



NATURE IS *LIGHT*...



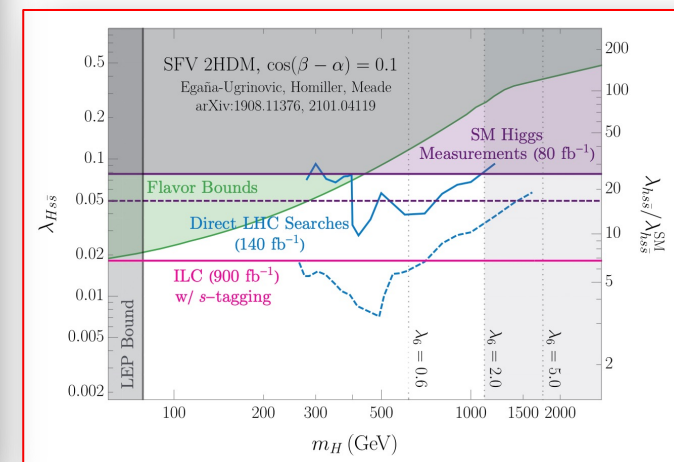
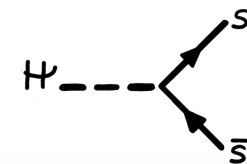
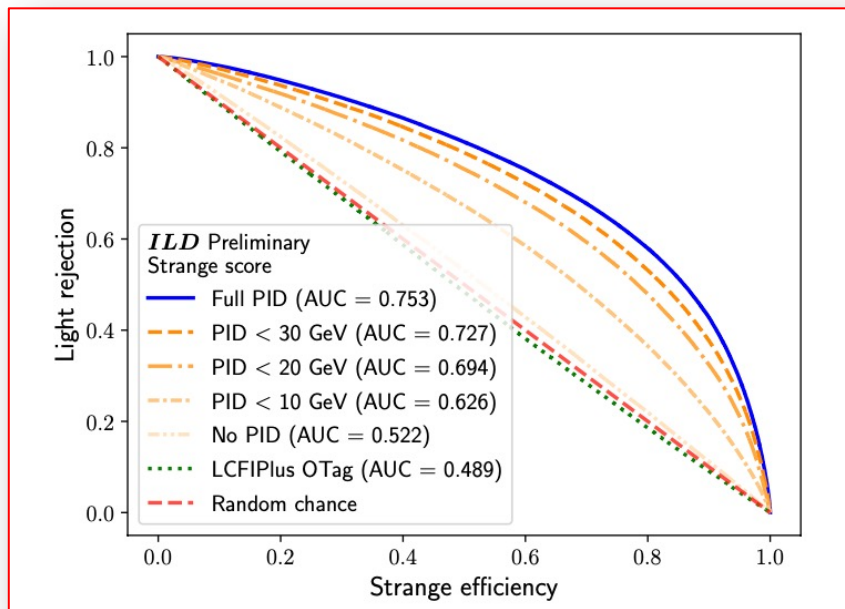
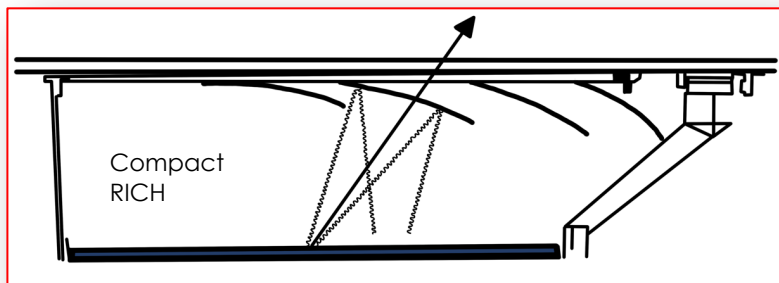
Do light and heavy fermions acquire mass in the same way?
 Are the Higgs Yukawa couplings *really* universal?

A *strange* AND EXCITING RESEARCH LINE

[2203.07535](#)

04.12.24

Next step in detector technologies, algorithms and analysis!



Cutting edge detectors for high momentum PID

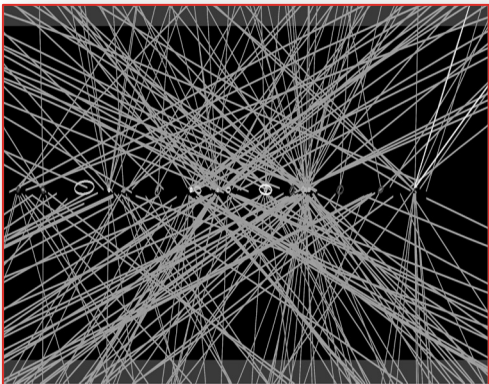
Complex and extensive jet flavour identification, including specific light flavours

Probing rare Higgs decays to **strange quarks**... SM or BSM?

CONCLUSIONS

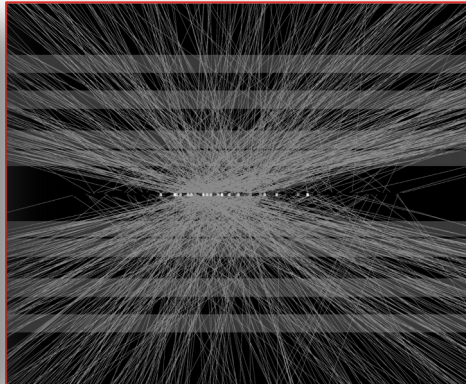
- **Exciting science ahead** to track down the Higgs boson properties and solve some of the yet-to-be answered questions about the Universe
- Interplay between **detector design, performance and analysis techniques** is of paramount importance for Particle Physics

2009



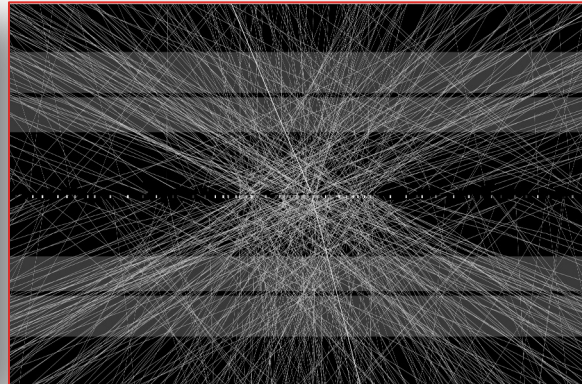
$\langle \text{pile-up} \rangle \sim 20$

2015



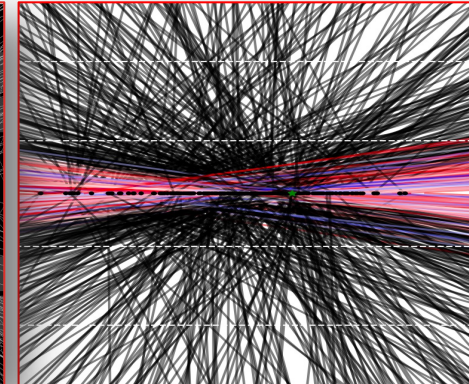
$\langle \text{pile-up} \rangle \sim 30$

2022



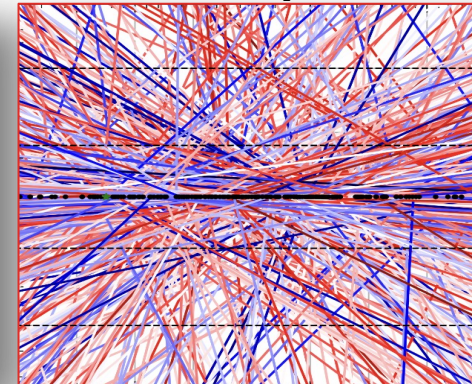
$\langle \text{pile-up} \rangle \sim 60$

2029



$\langle \text{pile-up} \rangle \sim 140$

...and beyond?

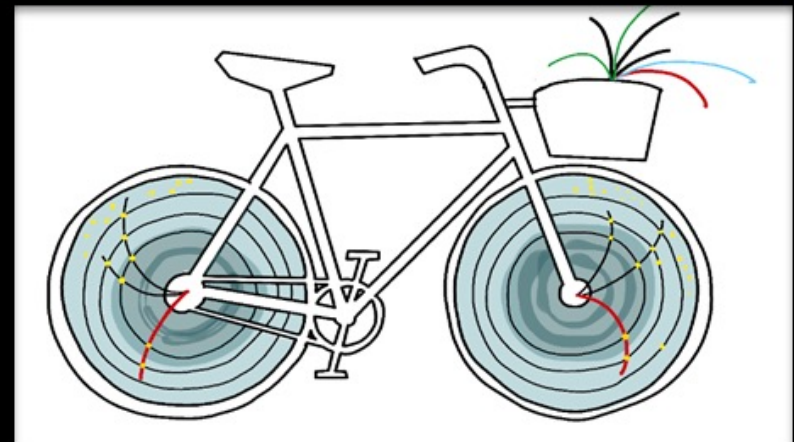


$\langle \text{pile-up} \rangle \sim 200$

THANK YOU!



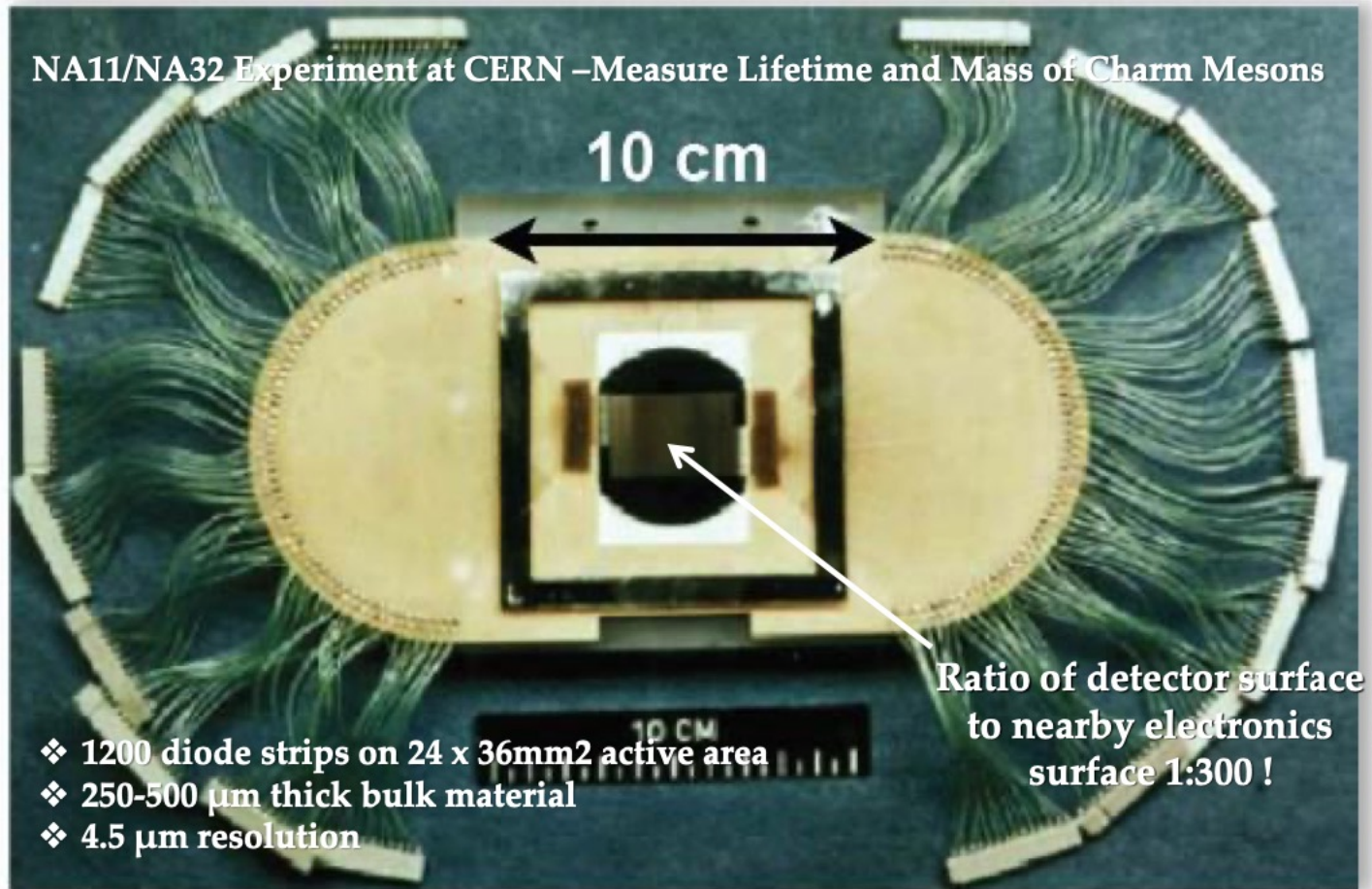
E.T. Exploring Tracking-lands, by F. Cairo



EXTRA SLIDES



1983: First Silicon Strip Detector in HEP

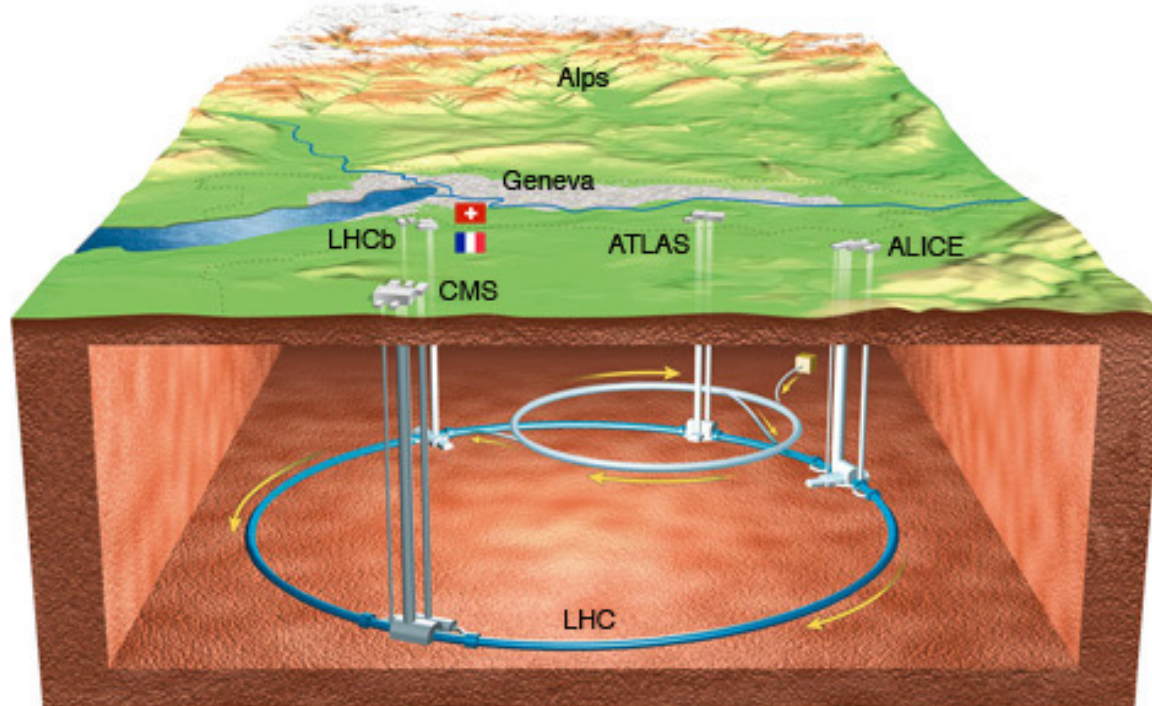


https://indico.cern.ch/event/572952/contributions/3368805/attachments/1828183/2992794/MTitov_10042019_3_F.pdf

THE LARGE HADRON COLLIDER

Need **high energy** to produce a **Higgs boson pair** & **high luminosity** to produce many

- ~ **1 in 1 billion** proton-proton collisions @LHC produces a **Higgs boson**
- ~ **1 in 1 trillion** proton-proton collisions @LHC produces a **Higgs boson pair**



Outperformed specifications during **Run 2**:

- **Peak Luminosity**: x2 ($2.14 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$)
- **Integrated Luminosity**: 140 fb^{-1}
- **Avg interaction per crossing** $\langle \mu \rangle$: x2 (~ 40)

Ongoing:

- **Run 3**: 13.6 TeV, $\langle \mu \rangle \sim 60$

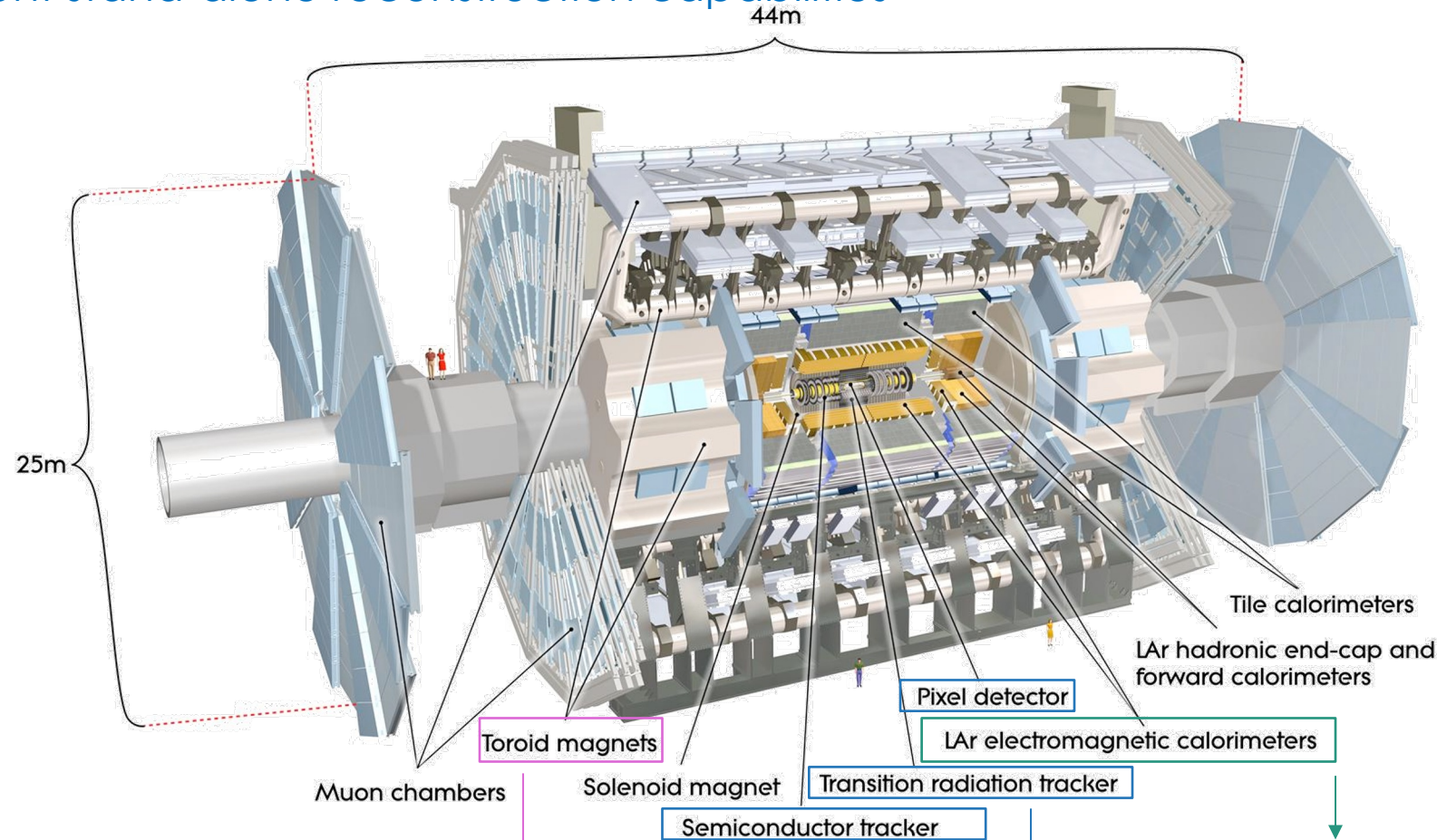
To go:

- **Run 4**: 14 TeV, $\langle \mu \rangle \sim 200$

THE ATLAS DETECTOR

Physics benchmarks drove the design of the detector

- Excellent stand-alone reconstruction capabilities

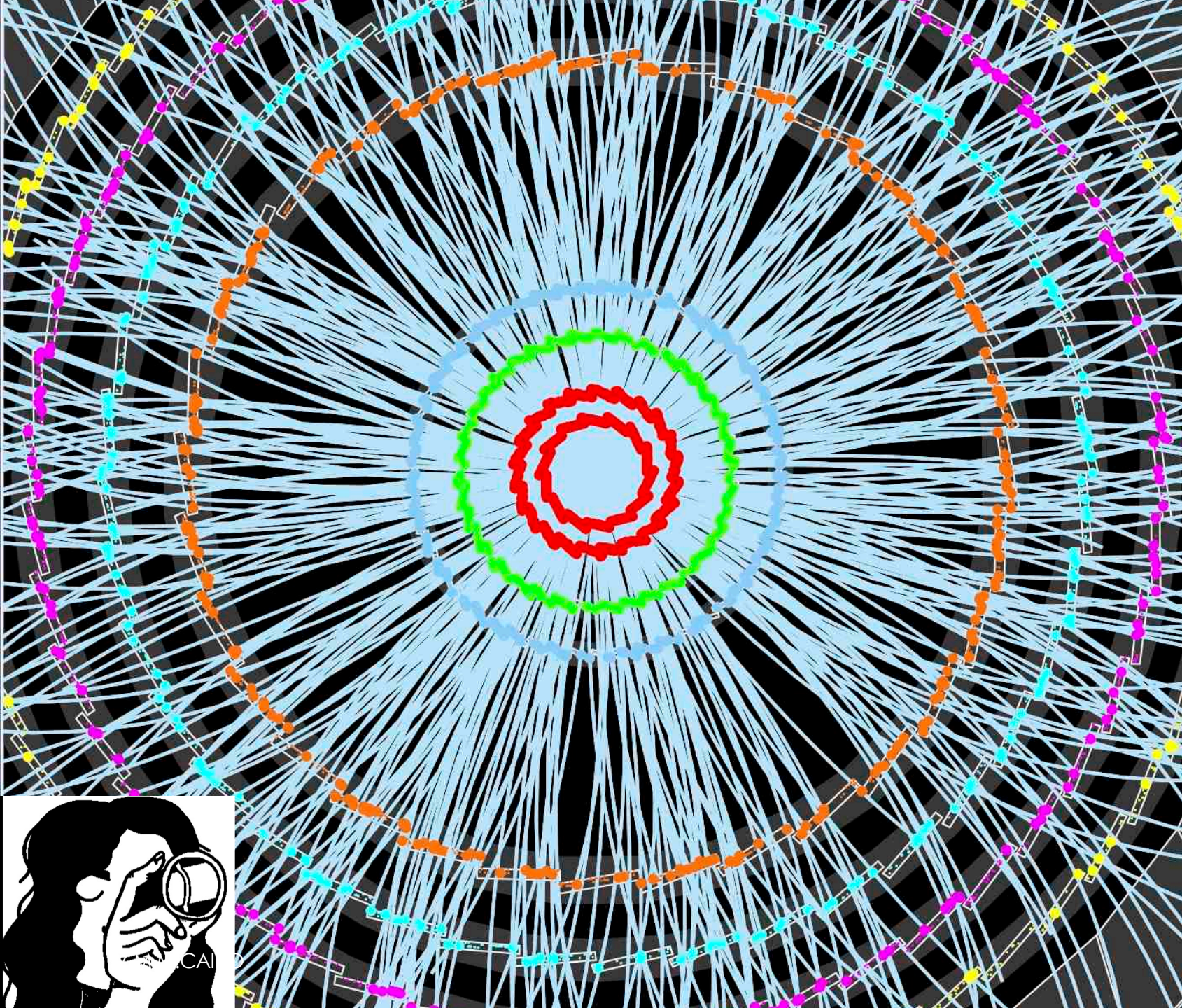


Determines the ATLAS geometry

V.M.M.CAIRO

Combined technologies

maximize $H \rightarrow \gamma\gamma$ sensitivity



ATLAS

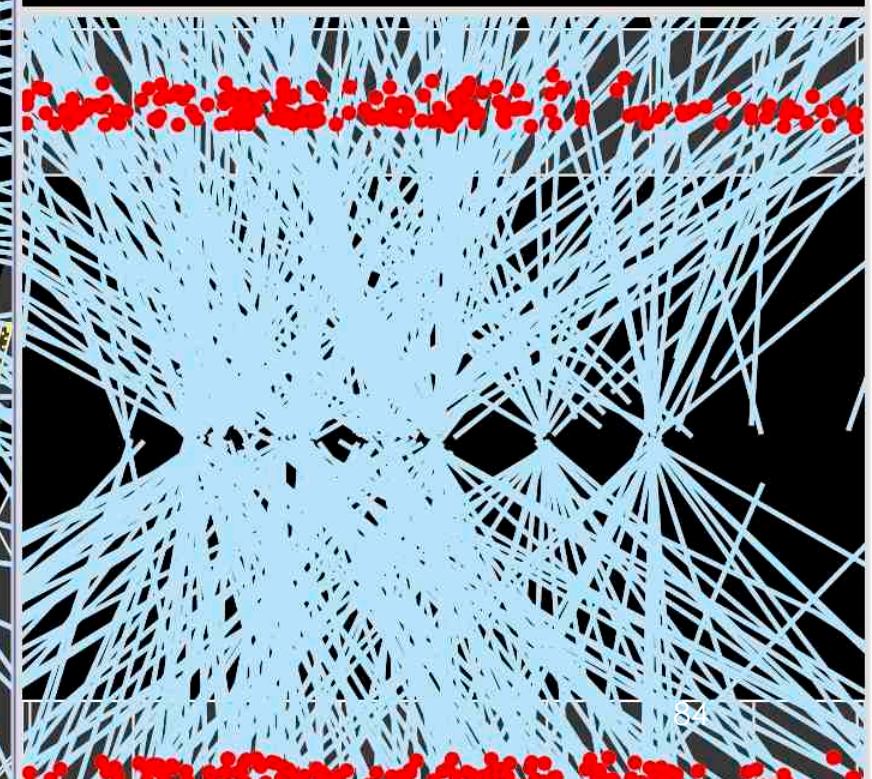
EXPERIMENT

0.2.2

Run Number: 266904, Event Number: 25884805

Date: 2015-06-03 13:41:54 CEST

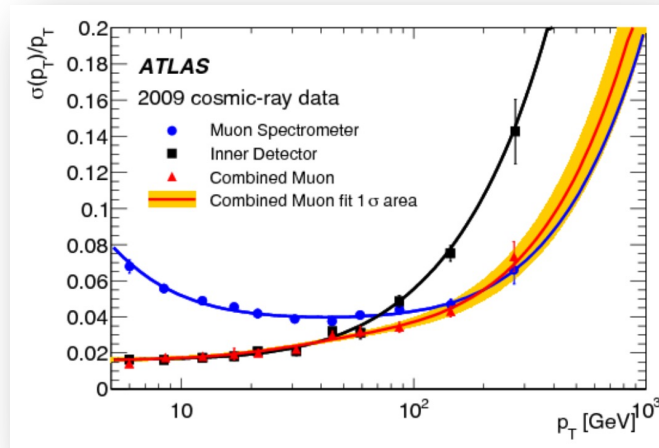
O(15) charged-particles per p-p interaction
X # simultaneous p-p interaction



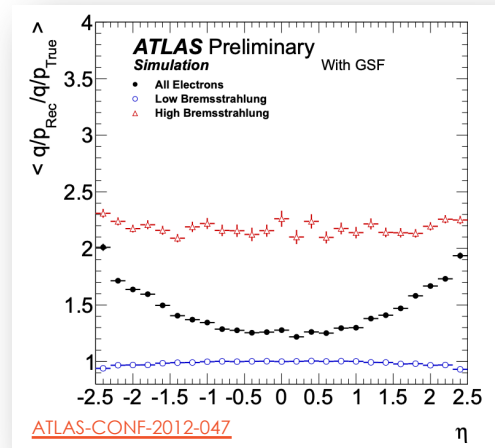
FROM CHARGED PARTICLES TO EVENT RECONSTRUCTION

Tracks used in the reconstruction of ~ all physics objects at the Large Hadron Collider

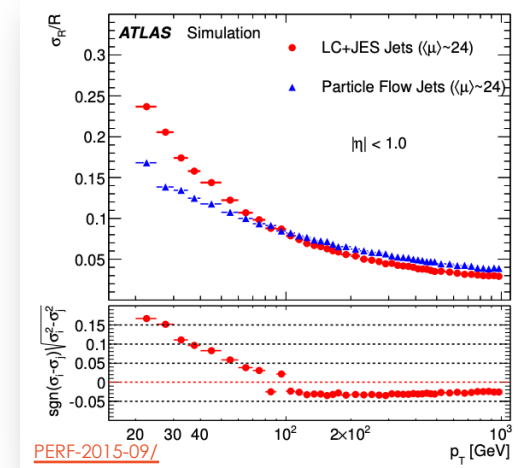
Muons



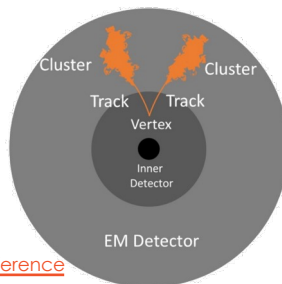
Electrons



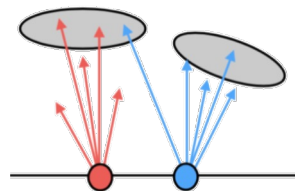
Particle FlowJets



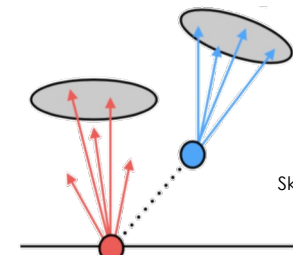
Photon conversions



Pile-up removal

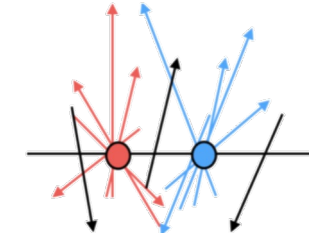


Jet-flavour tagging



Sketch courtesy of H. Gray

Vertices



KEY REQUIREMENTS FOR TRACKING

Physics benchmarks @LHC experiments place demanding requirements on the tracking system performance

Searches for high-mass di-lepton resonances require **good momentum resolution for high momentum tracks**

For hadron production rate studies and for good jet energy resolution in particle flow jet, instead, **highly efficient low momentum reconstruction is needed**

Resolving nearby tracks is essential, for instance in boosted 3-prong tau or B-hadron decays

Excellent impact parameter resolution is crucial for measuring the position of primary vertices and for identifying b-quark jets

KEY REQUIREMENTS FOR TRACKING

Physics benchmarks @LHC experiments place demanding requirements on the tracking system performance

Searches for high-mass di-lepton resonances require **good momentum resolution for high momentum tracks**

For hadron production rate studies and for good jet energy resolution in particle flow jet, instead, **highly efficient low momentum reconstruction is needed**

Resolving nearby tracks is essential, for instance in boosted 3-prong tau or B-hadron decays

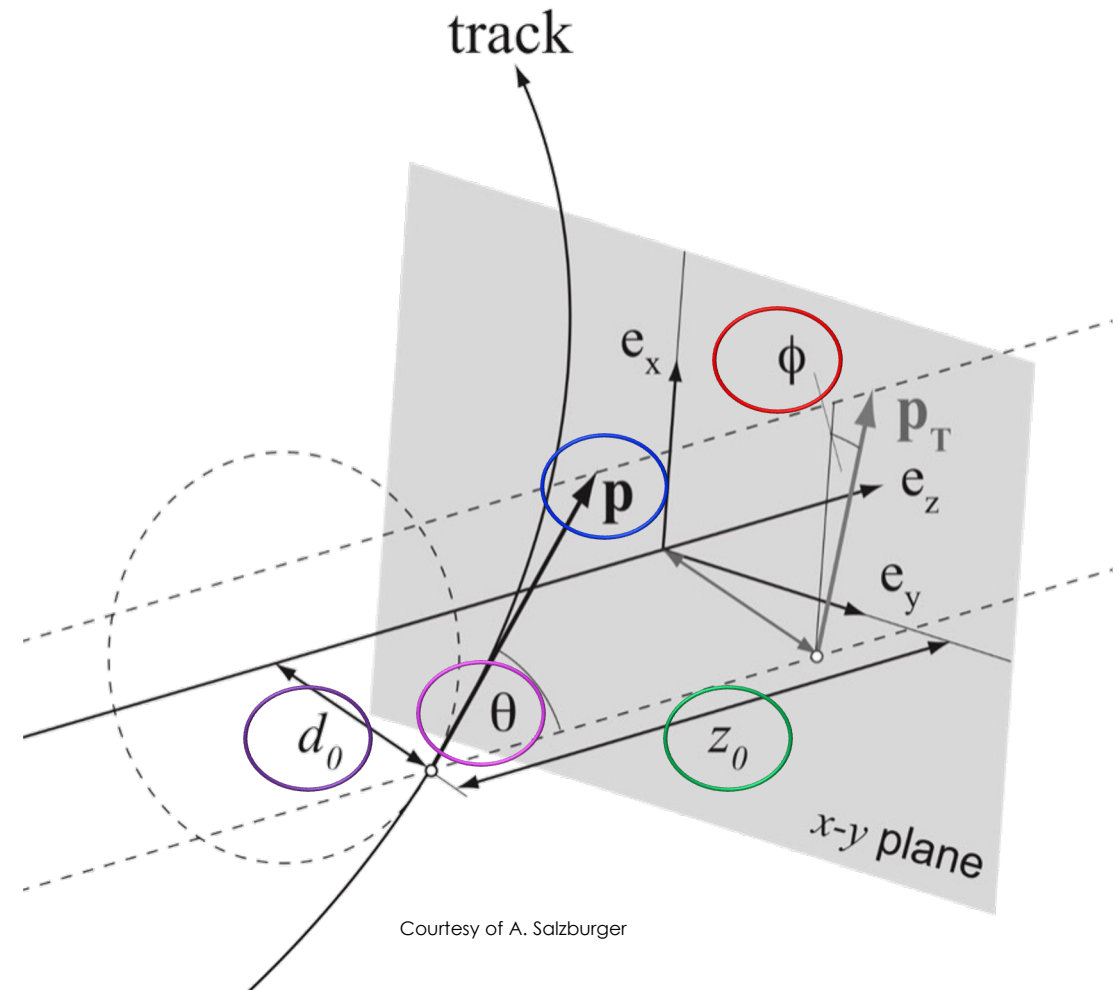
Excellent impact parameter resolution is crucial for measuring the position of primary vertices and for identifying b-quark jets

- **Trackers designed to meet requirements**
- **Tracking algorithms to fully exploit their capabilities**

HOW TO PARAMETERIZE A TRACK

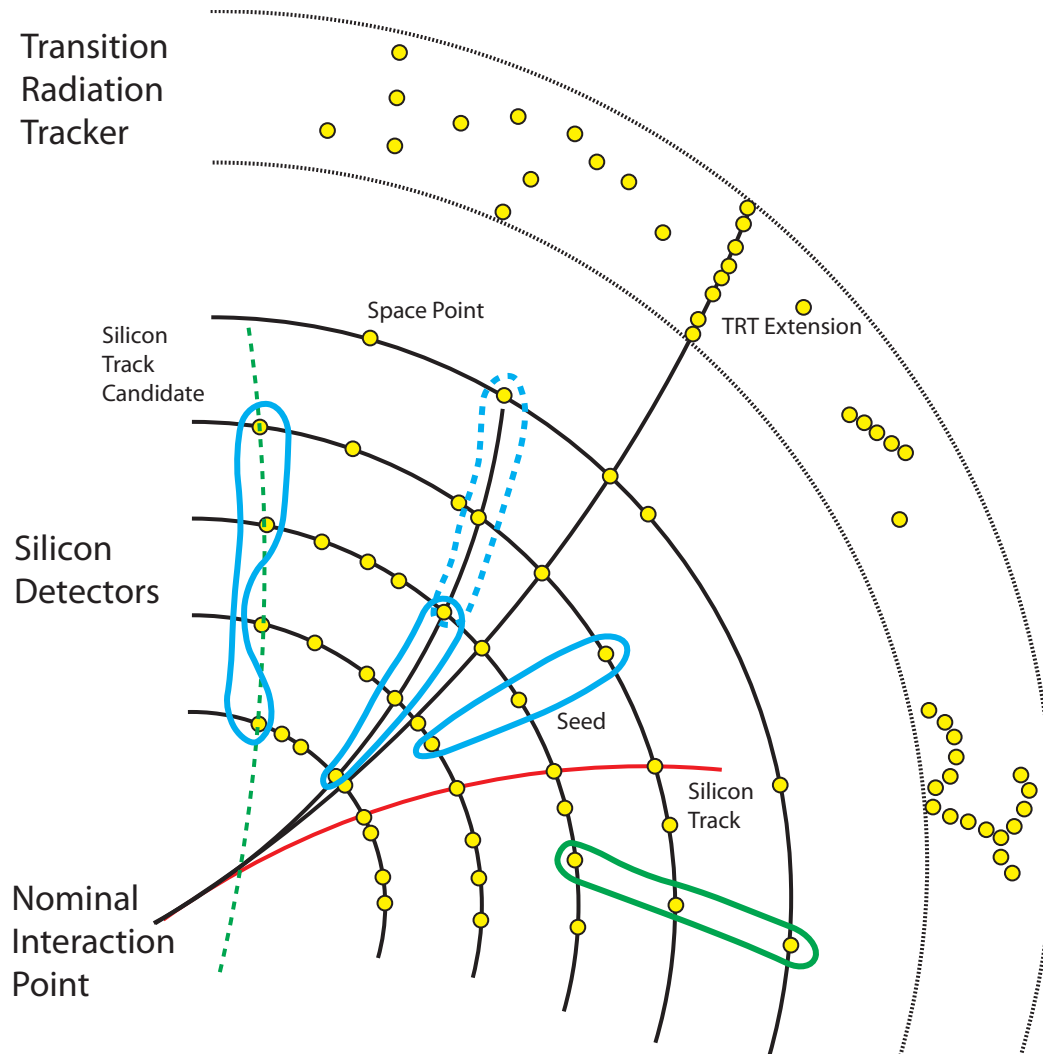
5 parameters describe the helical path of a charged particle in a solenoidal magnetic field:

- **Transverse** d_0 and **longitudinal** z_0 impact parameters (points of closest approach wrt perigee),
- **Azimuthal** ϕ (measured in the transverse plane $[-\pi, \pi]$) and **polar** θ (measured from the z axis $[0, \pi]$), **pseudorapidity** $\eta = -\ln(\tan\theta/2)$
- **Charge/momentum** q/p defining orientation and curvature

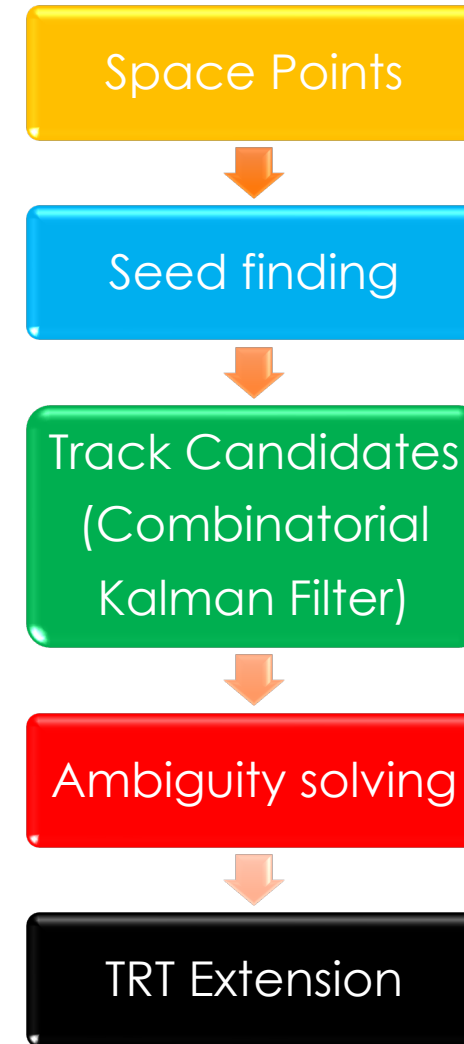


Courtesy of A. Salzburger

THE (CURRENT) ATLAS TRACKING CHAIN

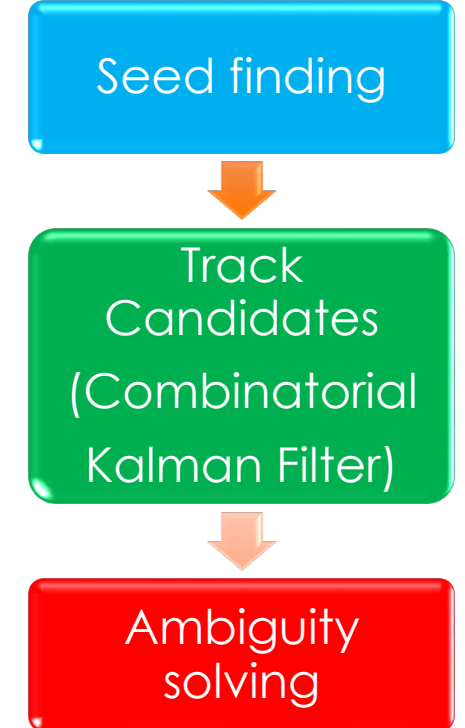


Inside-out



By default,
enabled
only in ROIs

Outside-in



VERTEXING

Primary vertex: point in space where interactions have occurred

Fundamental element of **data analysis**

Track-to-vertex association essential in reconstructing the full kinematic properties of the event

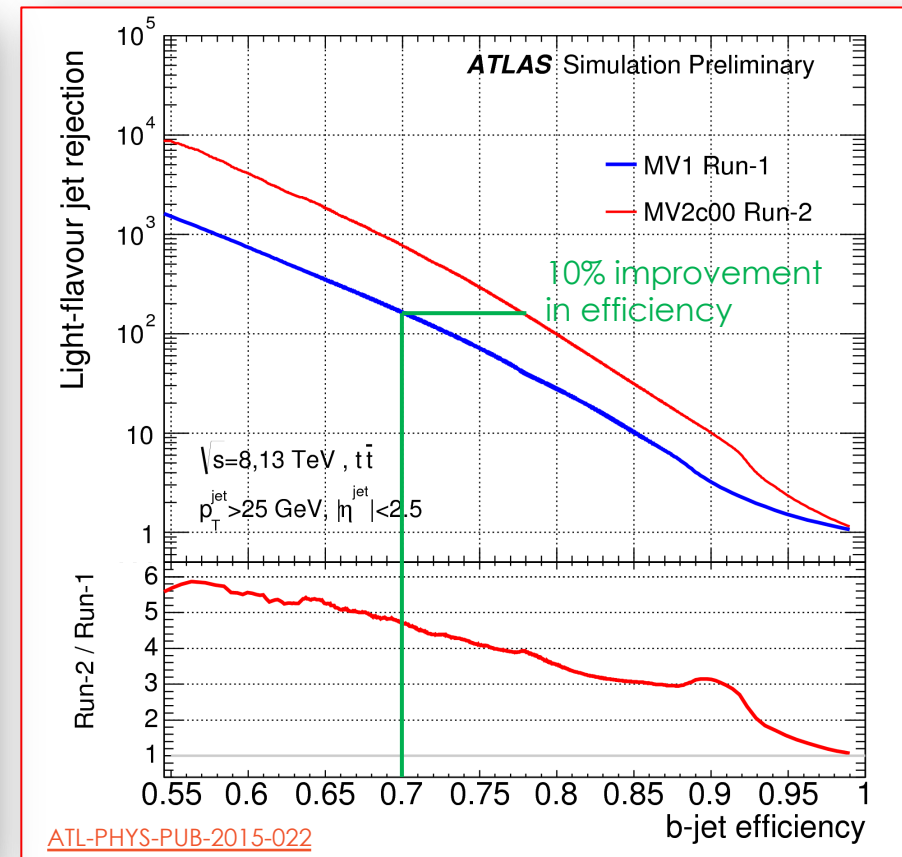
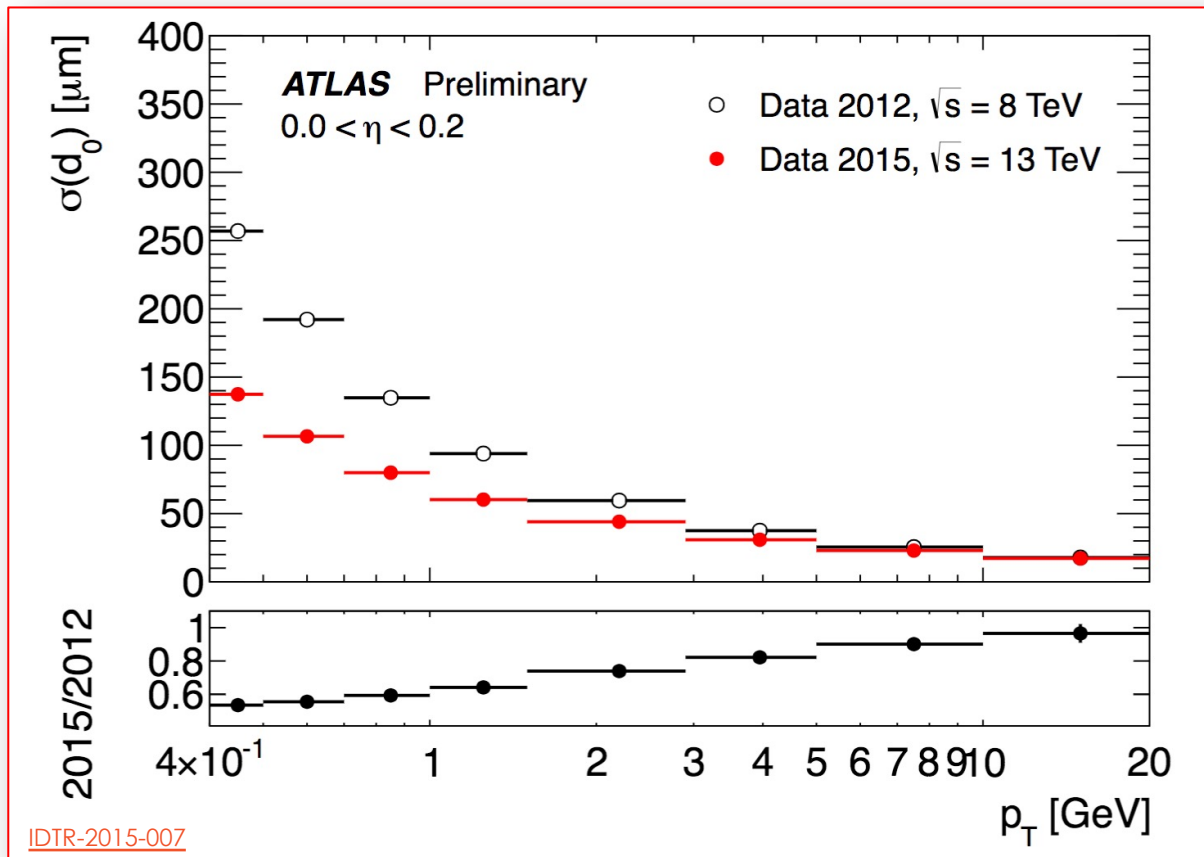
Important for the **determination of the luminous region**, or beam spot, where collisions take place and to **compute decay length for b-tagging**

Typically, only **one *pp* interaction** in a given beam crossing, the **Hard-Scatter (HS)** interaction, **is interesting for physics analyses**

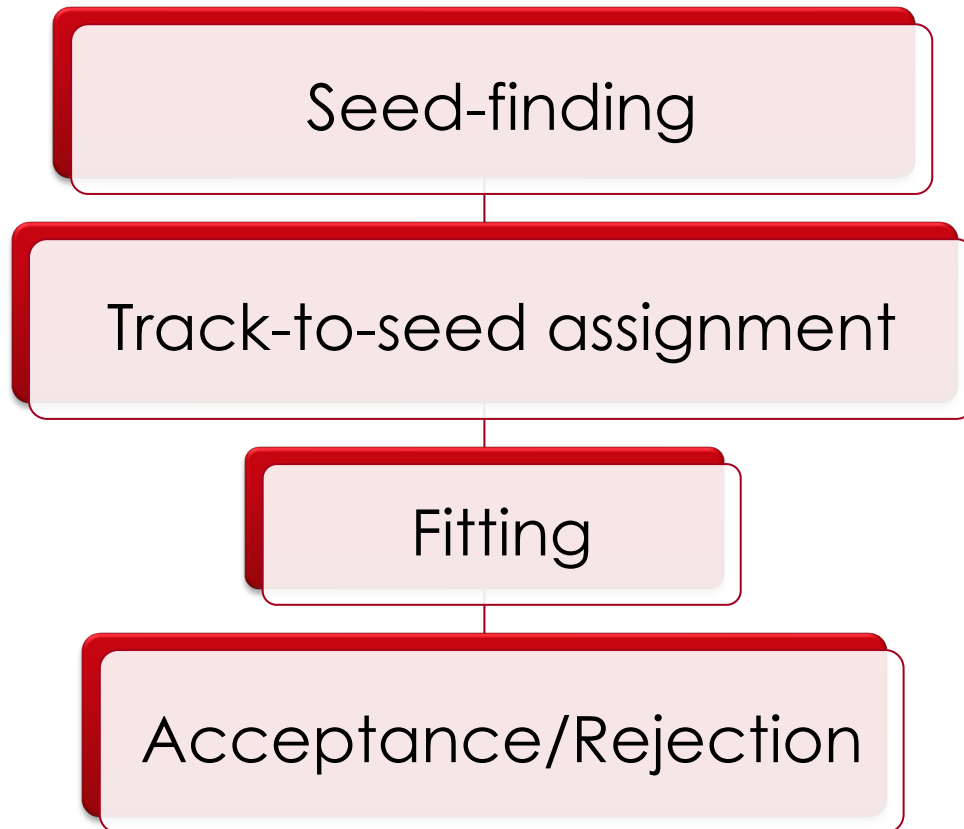
- **Often identified by the highest squared sum of track transverse momentum p_T ($\sum p_T^2$)**
- It is crucial that the **HS** be **distinguished from** the surrounding **pile-up** interactions

RUN 2 PERFORMANCE HIGHLIGHTS

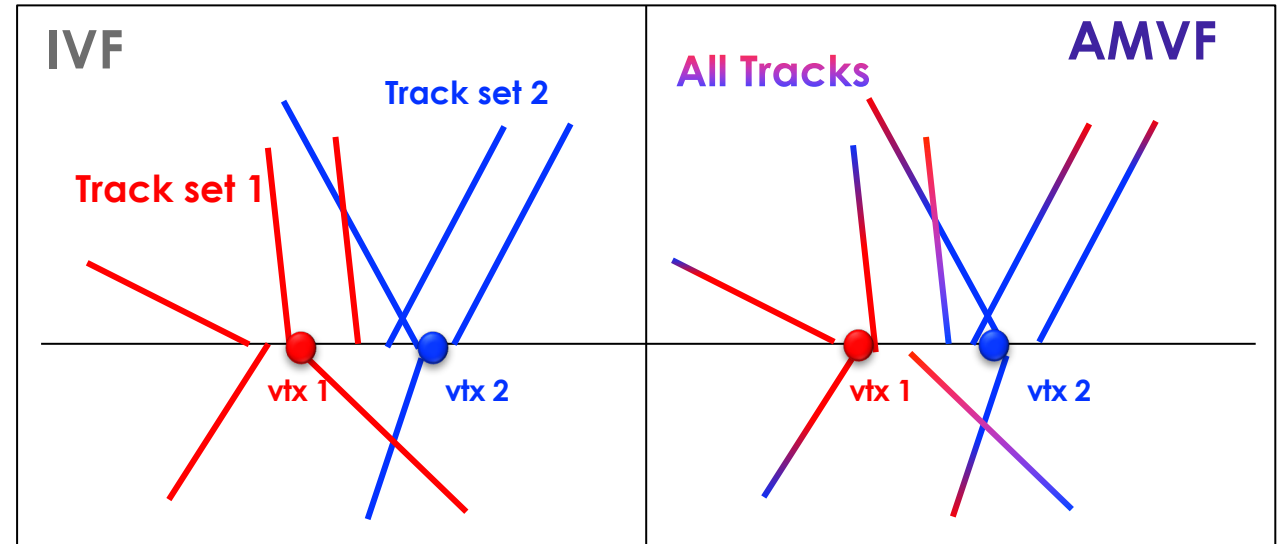
- **Run 1** → **Run 2**: upgraded detector with **Insertable B-layer** (IBL) at $R = 33$ mm
 - 2x better IP resolution, 4-5x better light-jet rejection in b-tagging



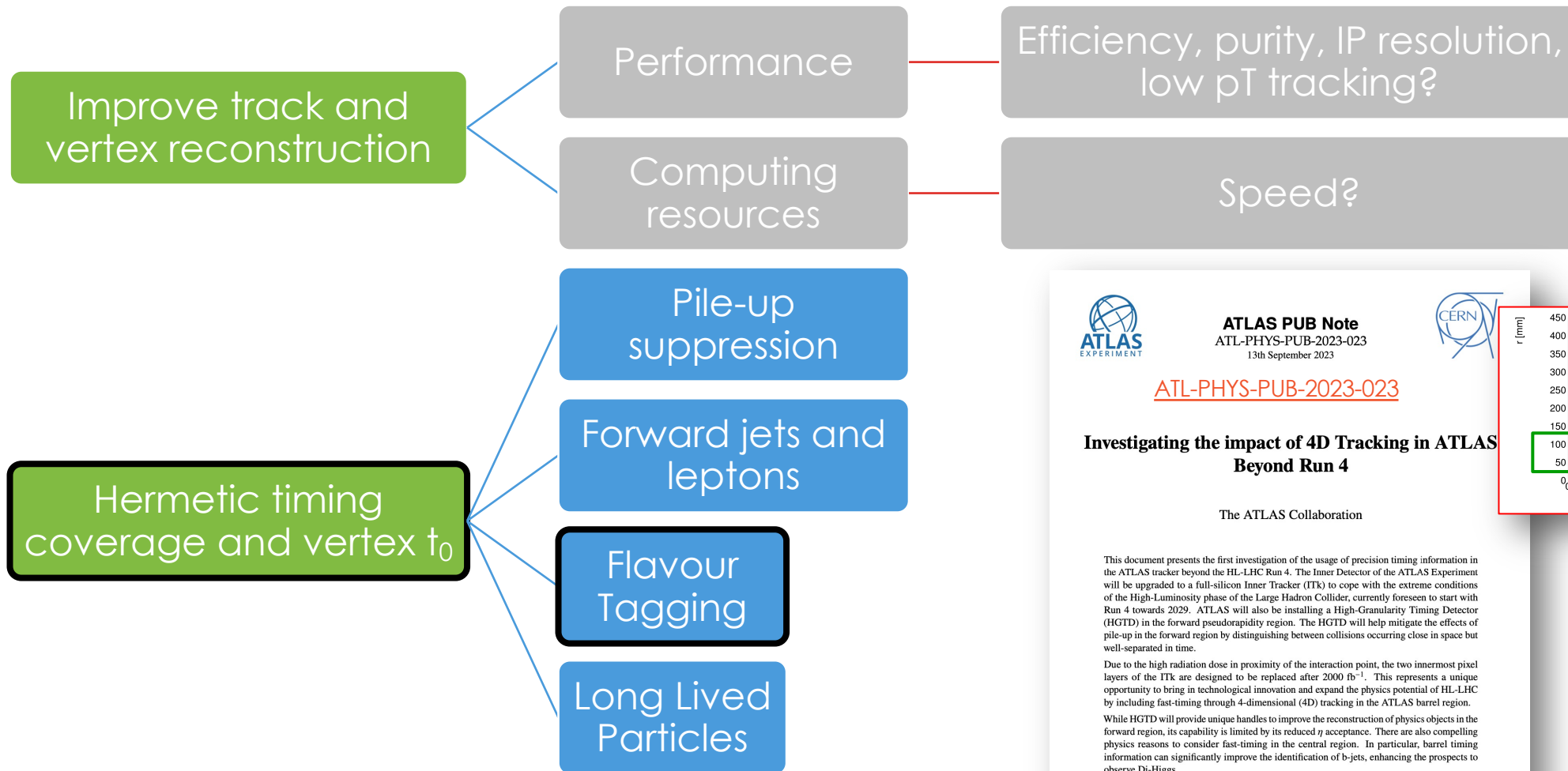
THE (CURRENT) ATLAS APPROACH



Run 1/2 → Run 3/4/... : main innovation is an adaptive **multi-vertex** fitting procedure (**AMVF**) as opposed to an **iterative vertexing (IVF)** procedure



IMPACT ON EXPERIMENTAL PERFORMANCE



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

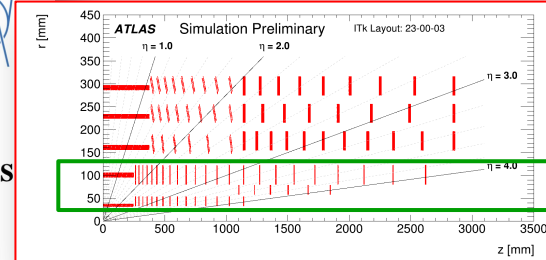
The ATLAS Collaboration

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.



TIMING AND THE COMPUTATIONAL CHALLENGE

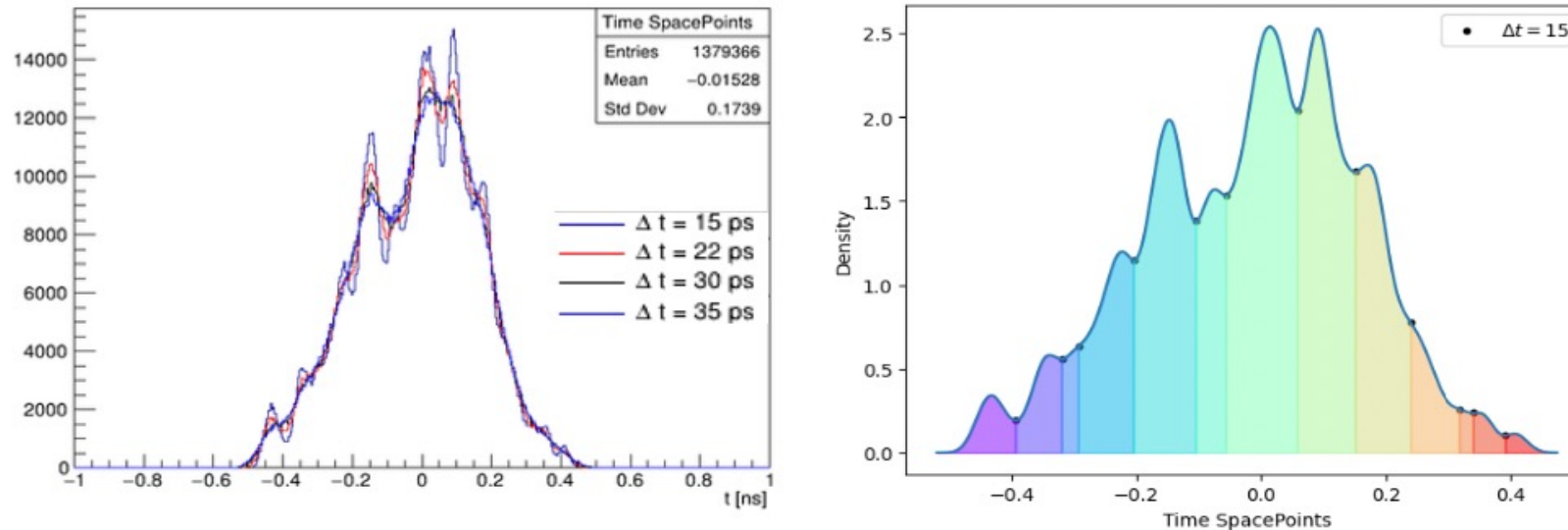
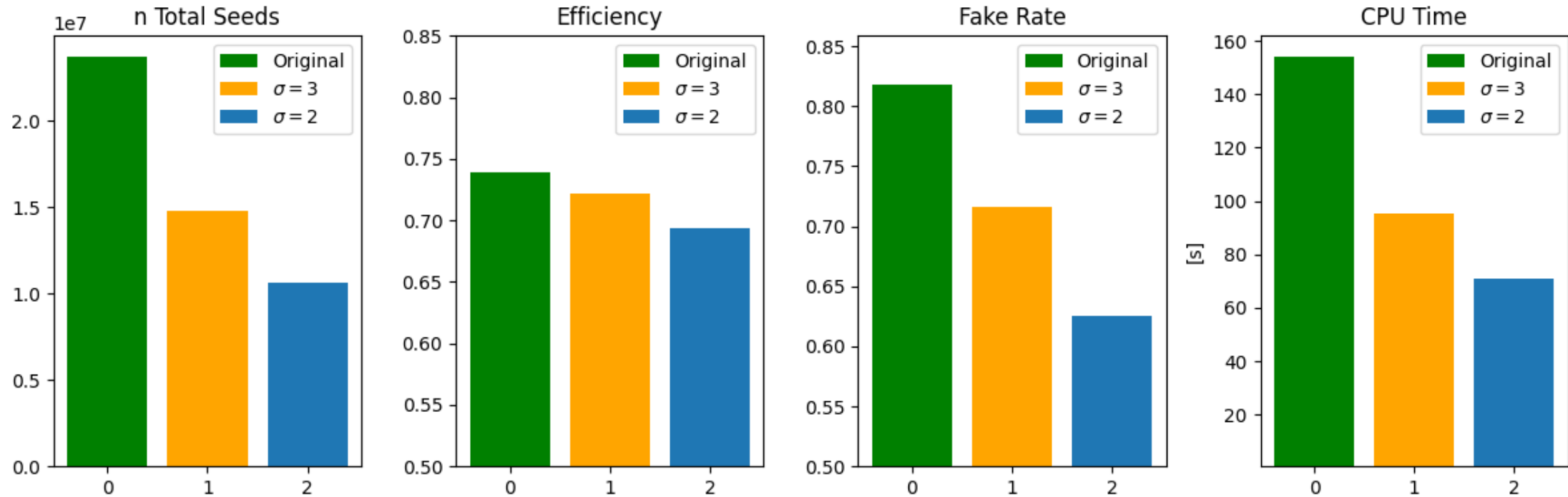


Figure 17 (Left) Simulation of the SP times in the 2nd ITk layer for a $t\bar{t}$ event with a pile-up of 200. Different values of time resolution are shown. (Right) Clustering of SP times in the 2nd ITk layer of ITk with 15 ps. The SPs are clustered by calculating the minima of the Gaussian Kernel-Density Estimate of the time information. A local minimum indicates the edge of the time cluster. From Ref. [zz].

<https://cds.cern.ch/record/2879352>

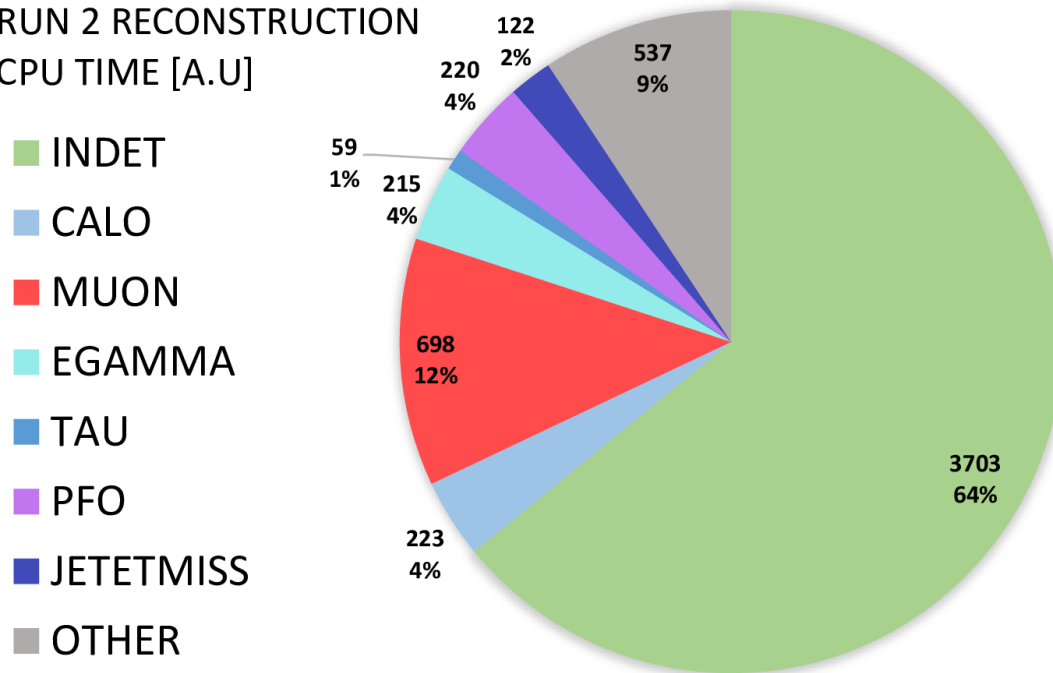
TIMING AND THE COMPUTATIONAL CHALLENGE



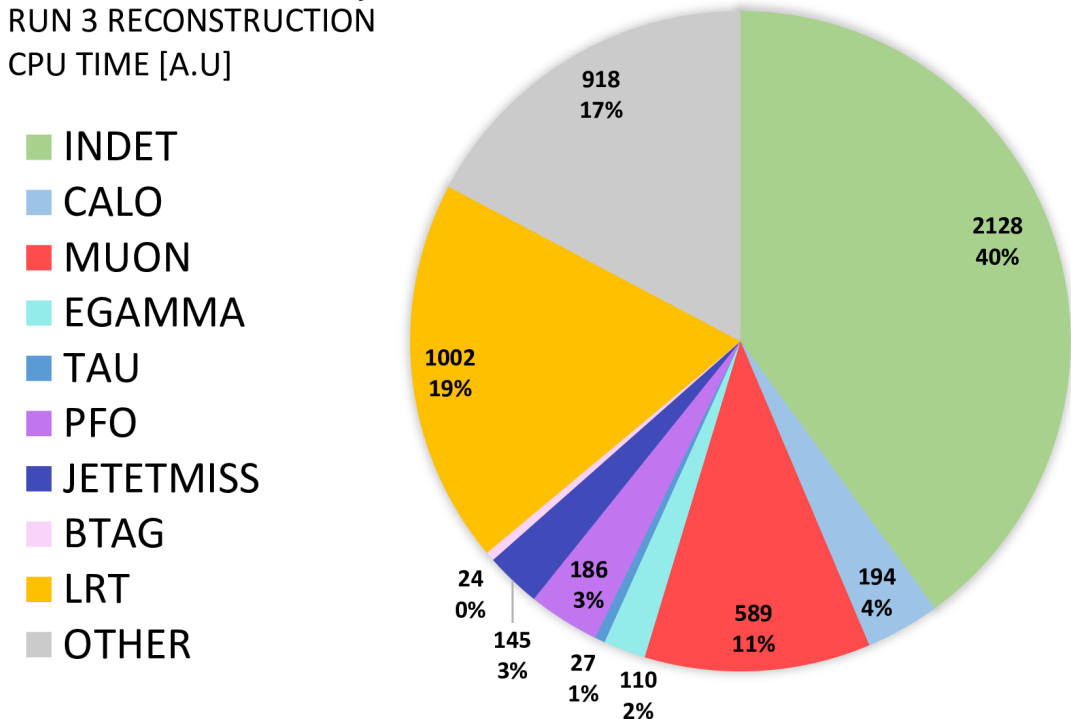
<https://cds.cern.ch/record/2879352>

S&C: STATE OF THE ART

ATLAS Preliminary
RUN 2 RECONSTRUCTION
CPU TIME [A.U]



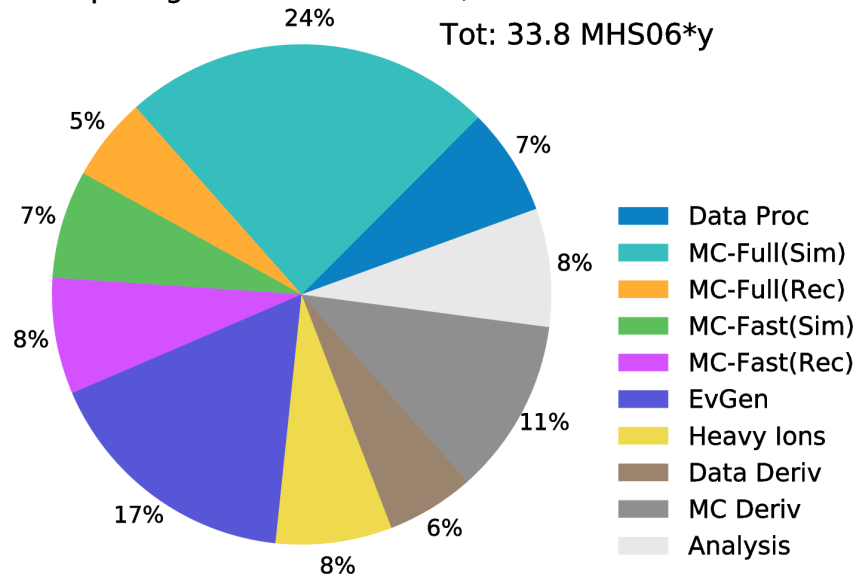
ATLAS Preliminary
RUN 3 RECONSTRUCTION
CPU TIME [A.U]



S&C: STATE OF THE ART

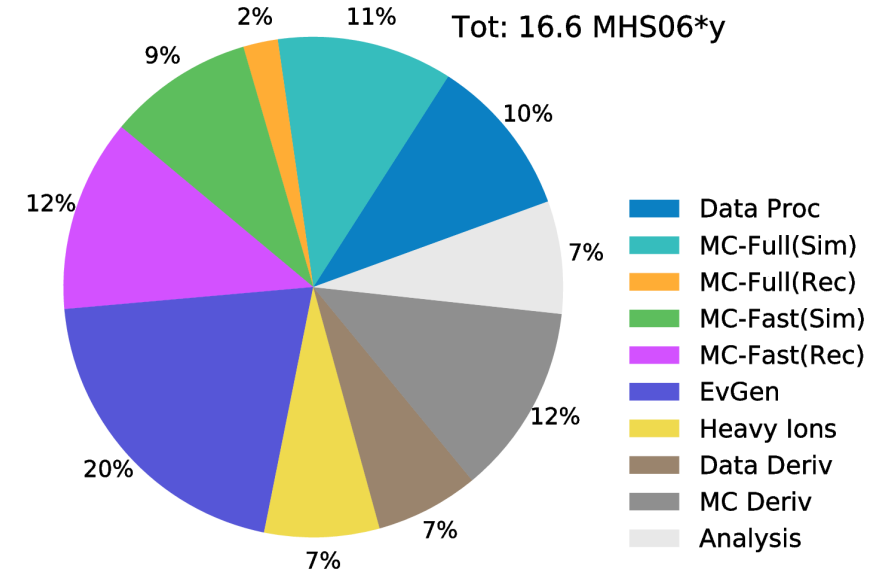
ATLAS Preliminary

2022 Computing Model - CPU: 2031, Conservative R&D
Tot: 33.8 MHS06*y



ATLAS Preliminary

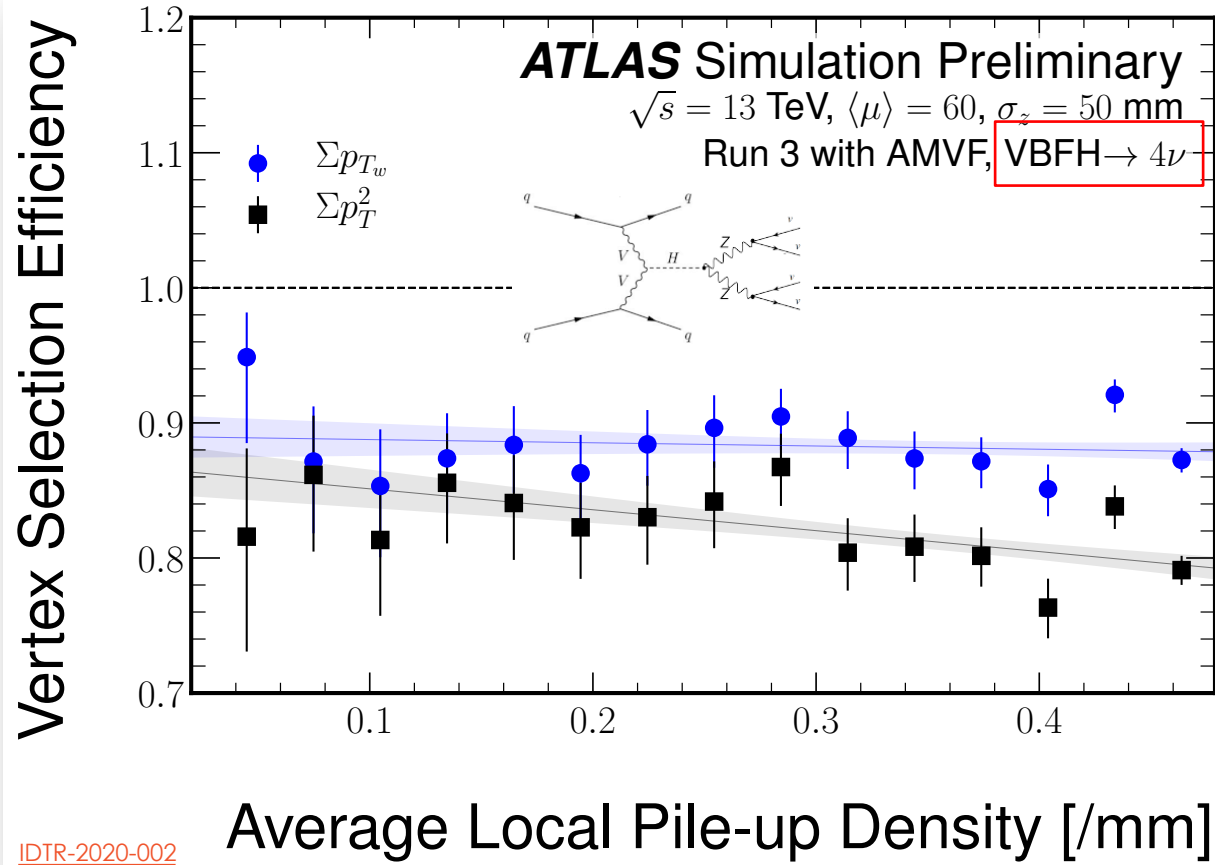
2022 Computing Model - CPU: 2031, Aggressive R&D
Tot: 16.6 MHS06*y



ATLAS S&C HL-LHC [roadmap](#)

THE HOTSPOT: VERTEXING

$$\text{sumPT} = \sum_{\text{tracks}} p_T^2 \quad \longrightarrow \quad \text{sumPTw} = \sum_{\text{tracks}} p_{T_w} = \sum_{\text{tracks}} p_{T(\text{track})}^2 p_{T(\text{closest jet})}^2 \frac{1}{\Delta R} 1(\Delta R < 0.4) 1(p_{T(\text{jet})} > p_{T(\text{threshold})})$$



PERFORMANCE FIGURES

Track Reconstruction efficiency:

$$\epsilon_{\text{trk}}(p_T, \eta) = \frac{N_{\text{rec}}^{\text{matched}}(p_T, \eta)}{N_{\text{gen}}(p_T, \eta)}$$

Fake Rate:

$$r_{\text{fake}}(p_T, \eta) = \frac{N_{\text{rec}}^{\text{unmatched}}(p_T, \eta)}{N_{\text{rec}}^{\square}(p_T, \eta)}$$

ID

$$P_{\text{match}} = \frac{10 \cdot N_{\text{Pixel}}^{\text{common}} + 5 \cdot N_{\text{SCT}}^{\text{common}} + 1 \cdot N_{\text{TRT}}^{\text{common}}}{10 \cdot N_{\text{Pixel}}^{\text{track}} + 5 \cdot N_{\text{SCT}}^{\text{track}} + 1 \cdot N_{\text{TRT}}^{\text{track}}}$$

ITk

$$P_{\text{match}} = \frac{2N_{\text{common}}^{\text{pix}} + N_{\text{common}}^{\text{strip}}}{2N_{\text{track}}^{\text{pix}} + N_{\text{track}}^{\text{strip}}}$$

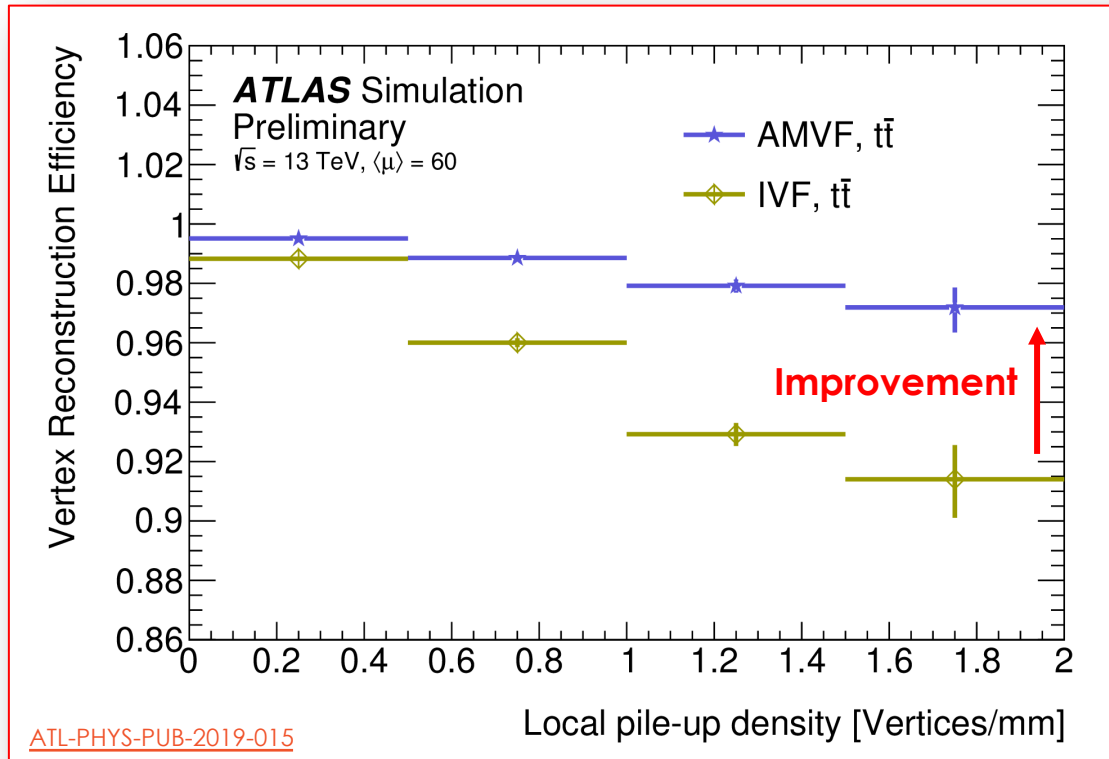
Matching criterion:

ATLAS: weighted hit-based track-to-truth particle association

A reconstructed track is matched to a generated particle if $P_{\text{match}} > 0.5$

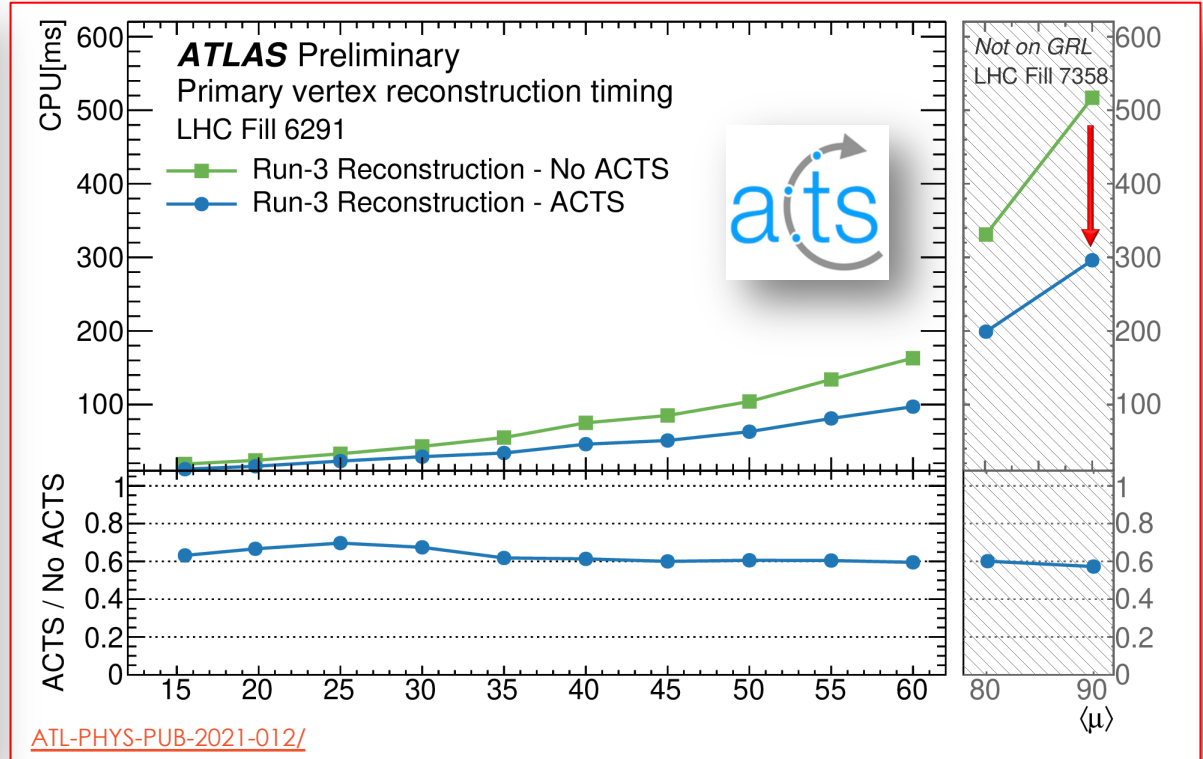
Technical/Algorithmic Efficiency: $N_{\text{gen}} \rightarrow N_{\text{gen_reconstructable}}$ (e.g enough hits in the detector)

RUN 3 PERFORMANCE HIGHLIGHTS



Significant performance improvements:

- ~**10%** better vertex selection efficiency
- ~**20%** better longitudinal resolution
- ~**30%** inclusive efficiency recovery



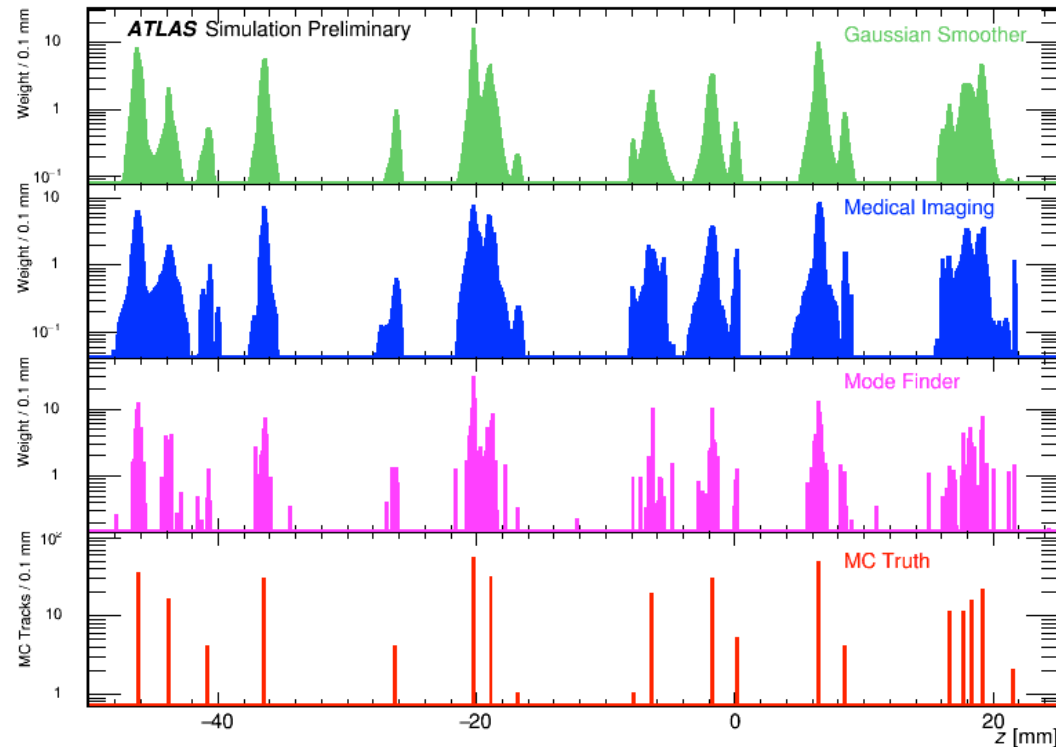
Implemented within the ACTS framework

- First ACTS production use in an LHC experiment
 - Factor of ~ **2 speed up**

GAUSSIAN TRACK DENSITY SEED FINDER

04.12.24

- Use a seeder that is **analytic** and **accounts for the track uncertainties**
 - Allows to exploit the **seed width (σ_z) to constrain the vertex fit**

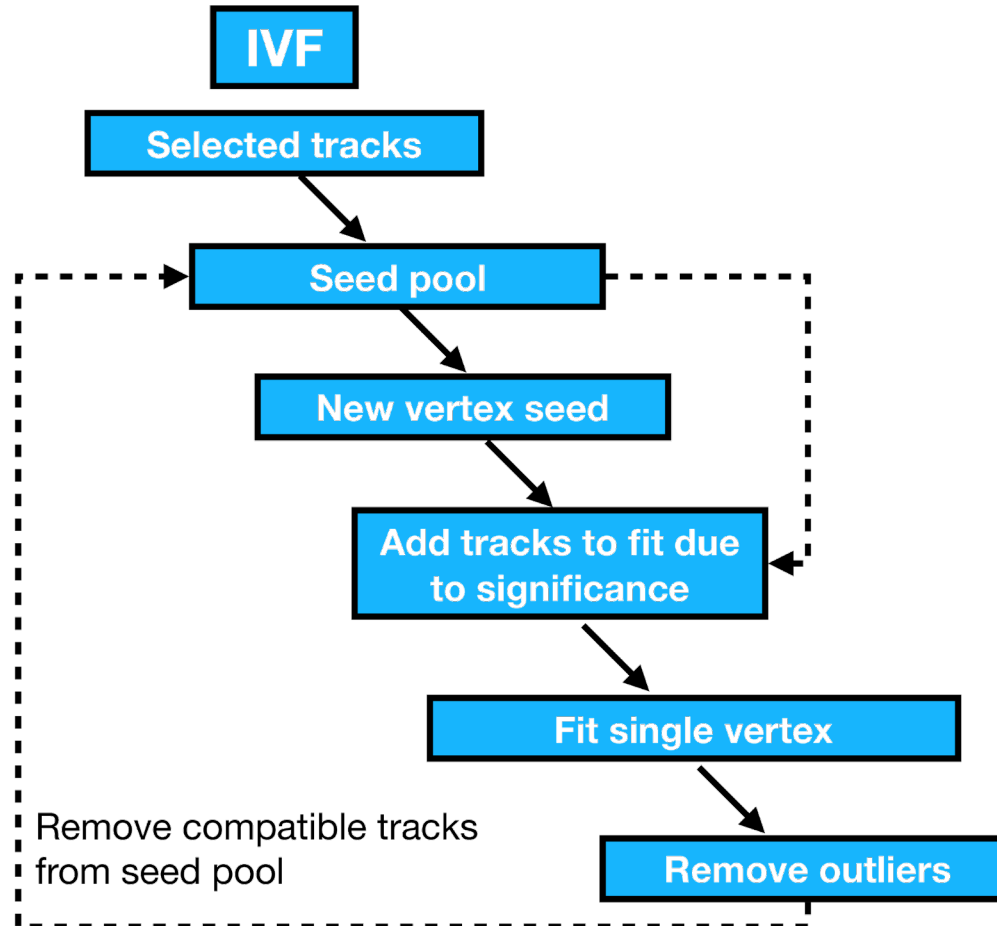


Seed finding weights calculated using a **longitudinal Gaussian** function with a **transverse Gaussian** function acting as an independent quality control

$$\lim_{\sigma(d_0, z_0) \rightarrow 0} \rho(z) = \left(\frac{1}{\sqrt{2\pi}\sigma(d_0)} e^{-\frac{1}{2}d_0^2/\sigma^2(d_0)} \right) \left(\frac{1}{\sqrt{2\pi}\sigma(z_0)} e^{-\frac{1}{2}(z-z_0)^2/\sigma^2(z_0)} \right).$$

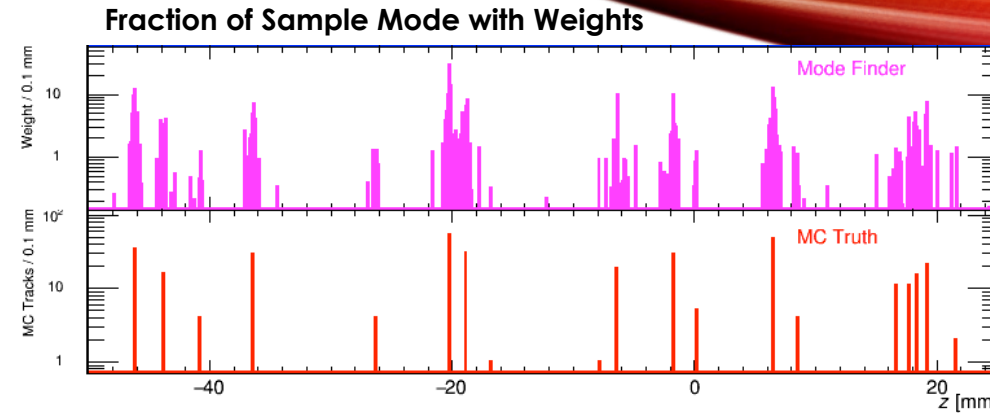
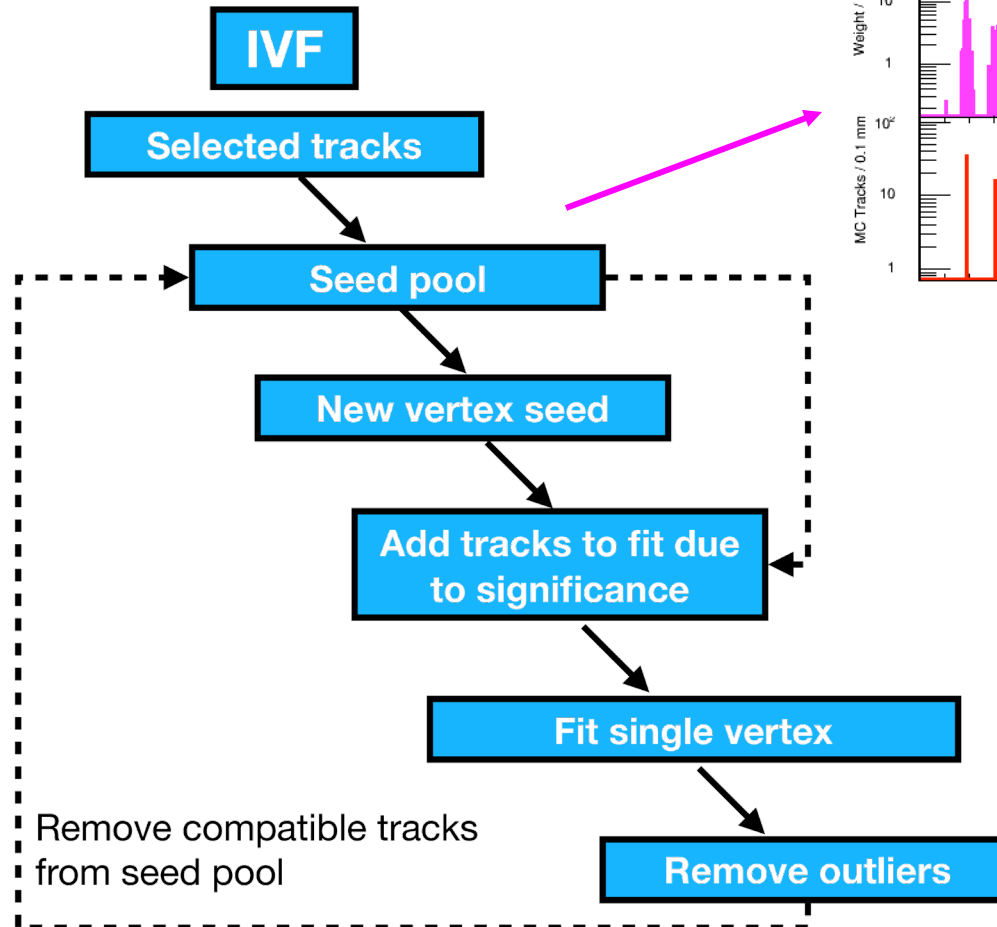
ATLAS IN RUN1/2: ITERATIVE VERTEX FINDER

04.12.24



ATLAS IN RUN1/2: ITERATIVE VERTEX FINDER

04.12.24

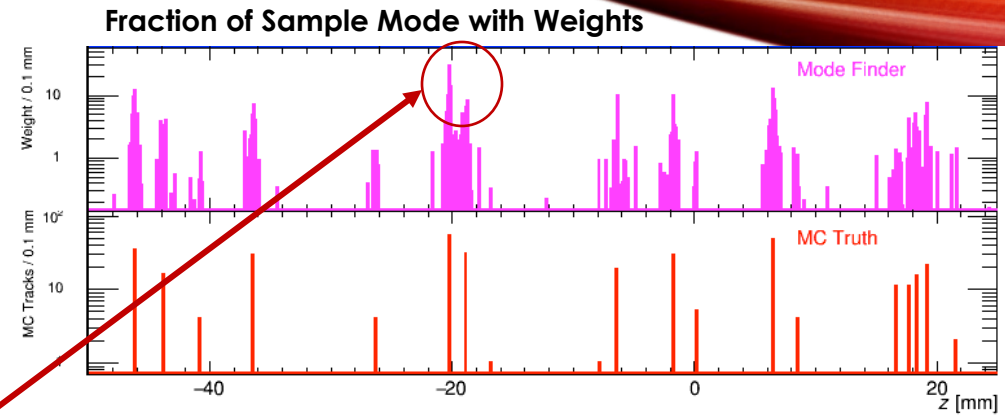
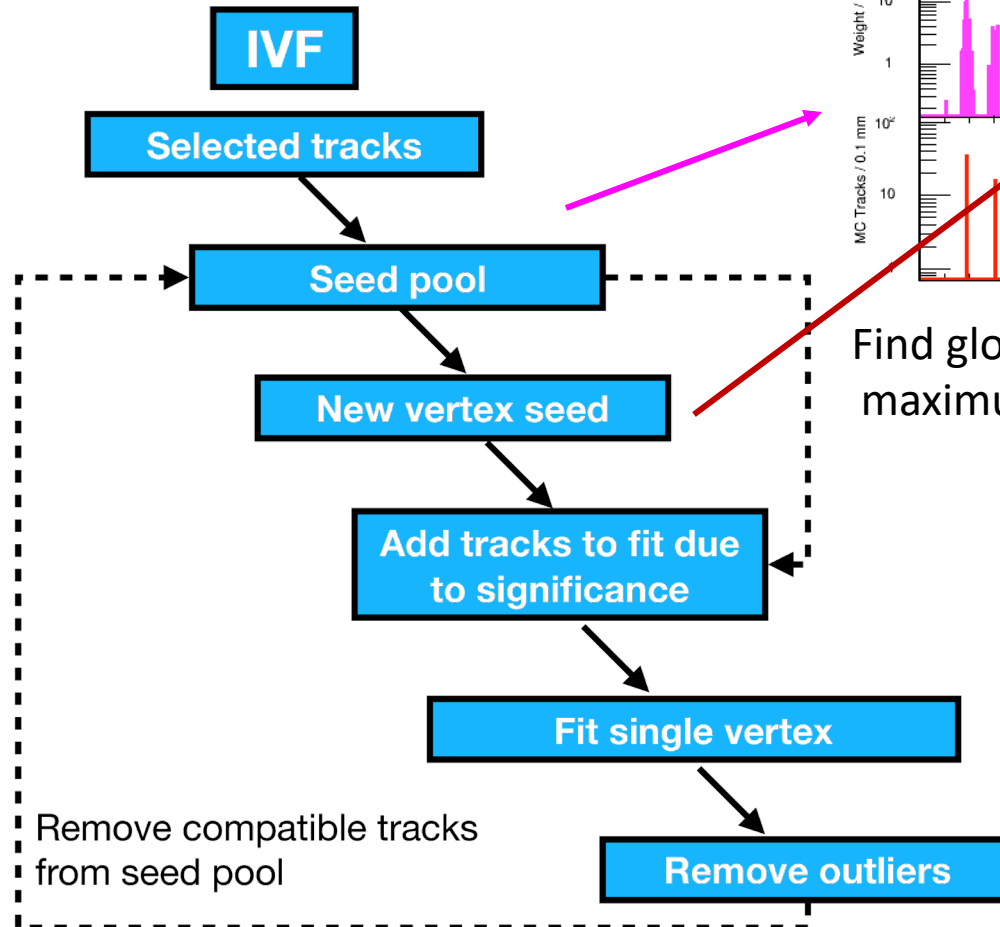


**Goal: use tracks to find
approximate vertex location**

**When beam-spot is known, all
strategies use longitudinal track
density along beam axis**

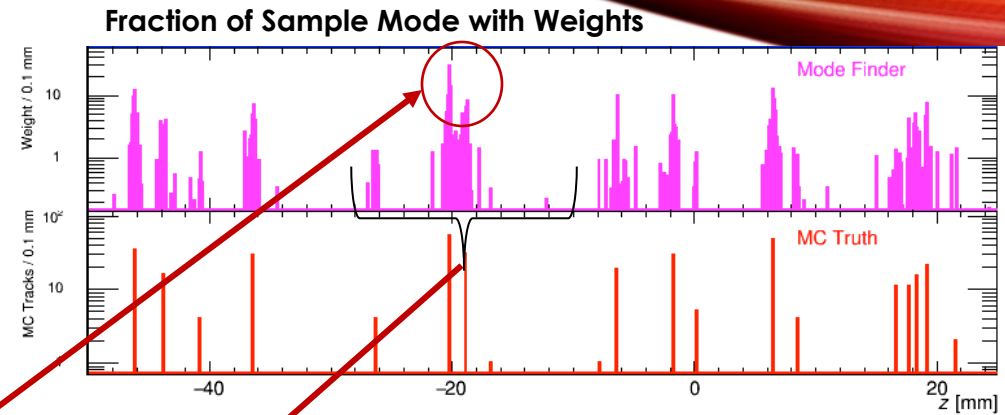
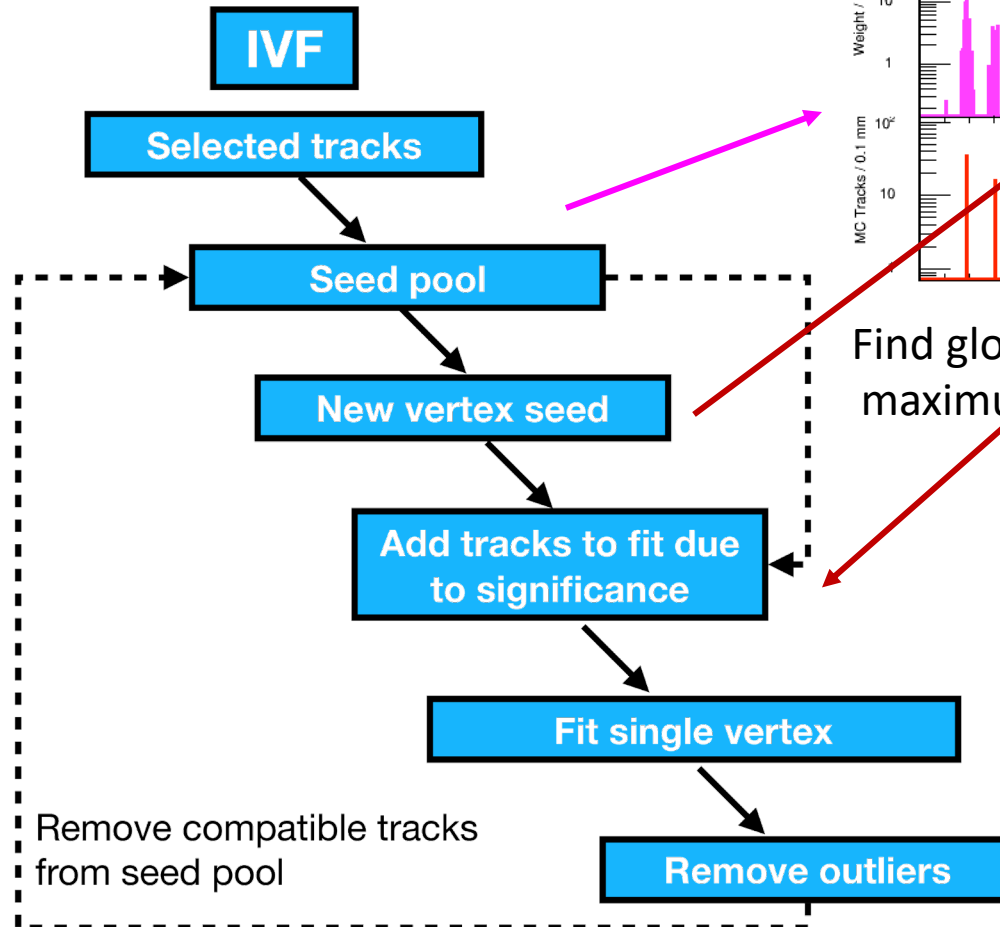
ATLAS IN RUN1/2: ITERATIVE VERTEX FINDER

04.12.24

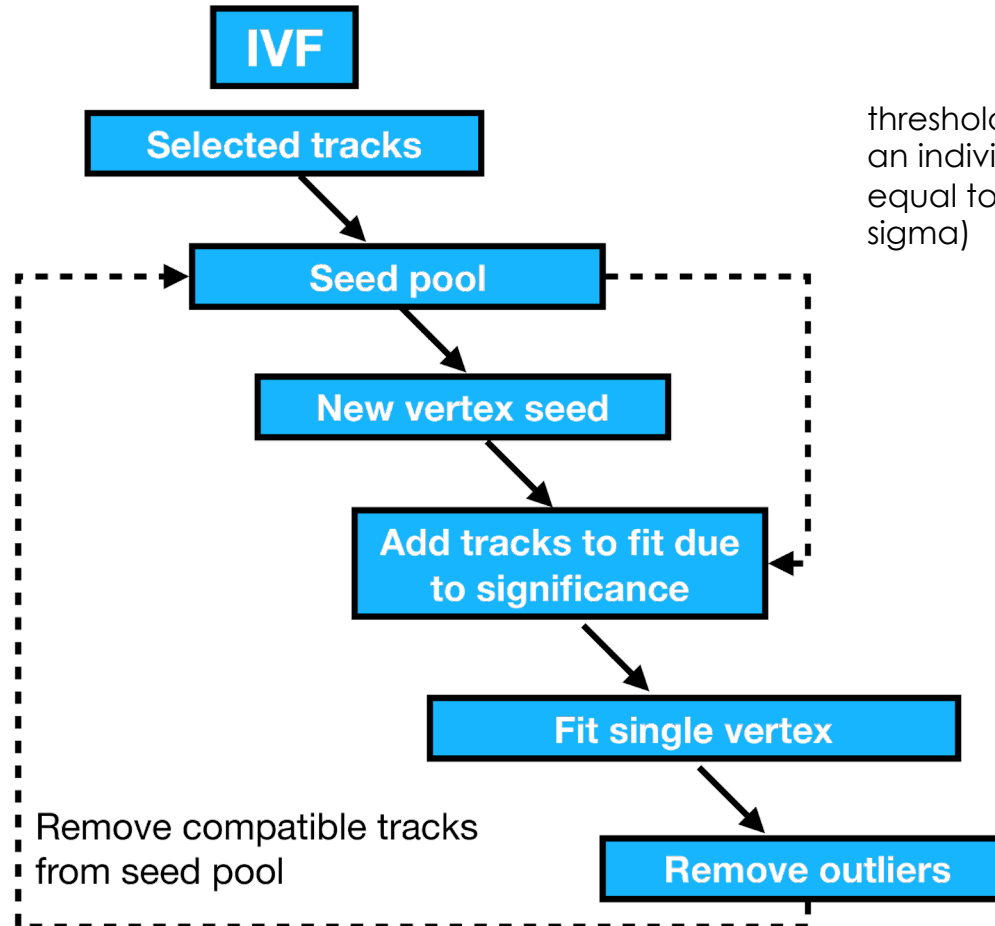


ATLAS IN RUN1/2: ITERATIVE VERTEX FINDER

04.12.24



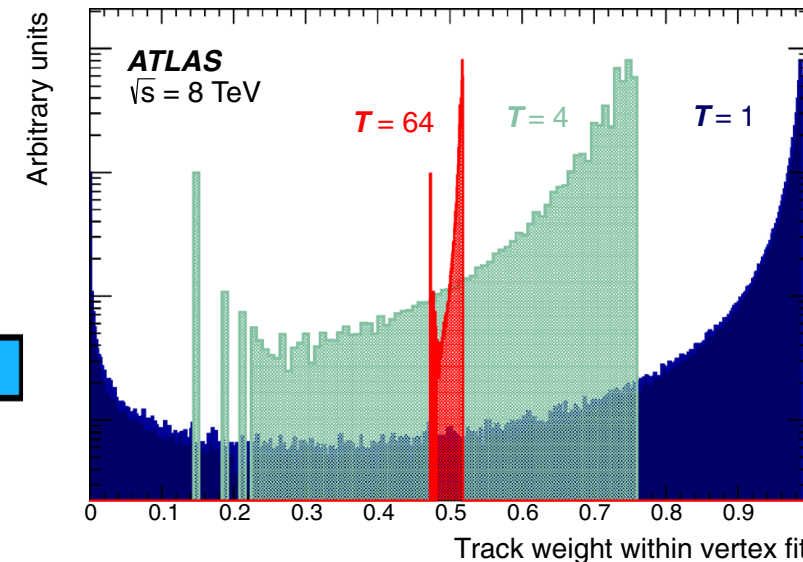
ATLAS IN RUN1/2: ITERATIVE VERTEX FINDER



$$\omega(\chi^2, T) = \frac{1}{1 + e^{-\frac{1}{2}(\chi_{\text{cut}}^2 - \chi^2)/T}}$$

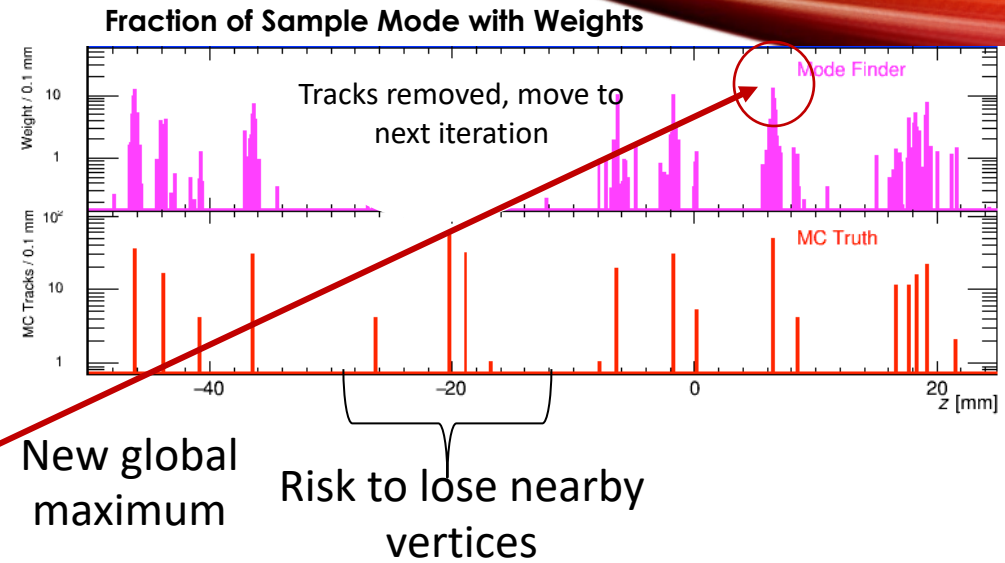
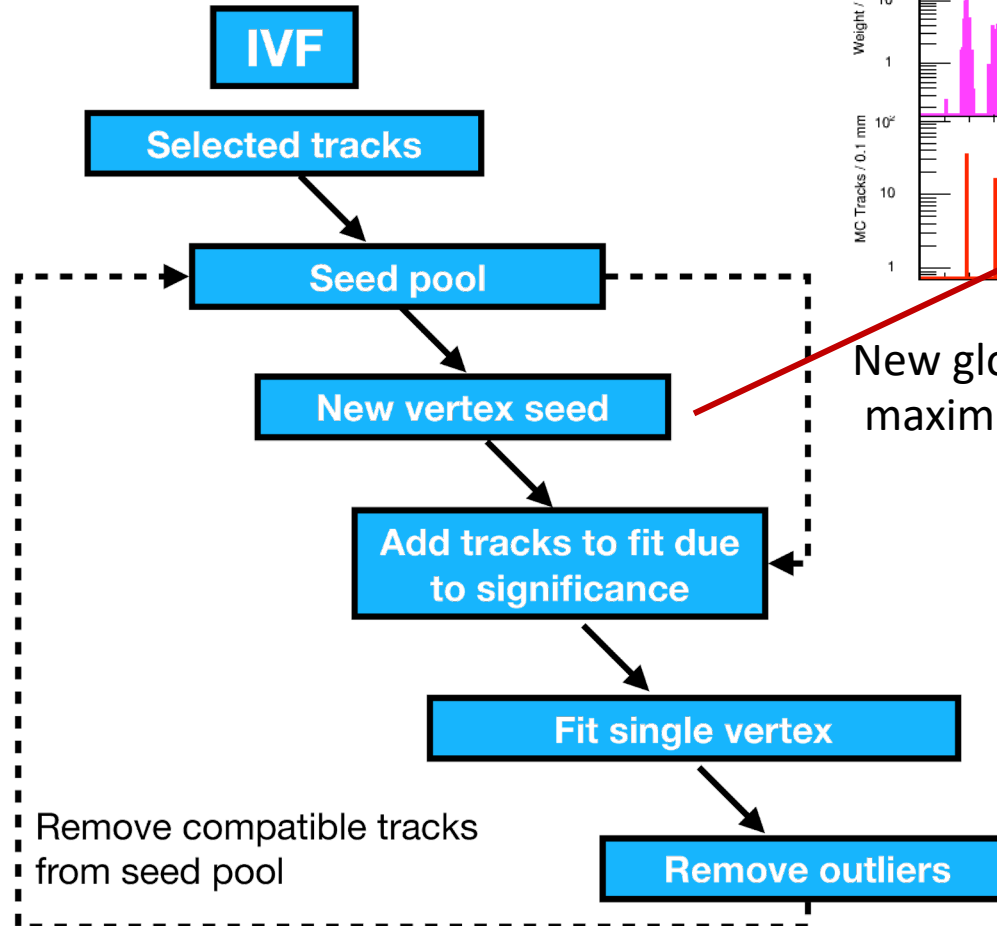
threshold where the weight of an individual track becomes equal to 0.5 (set to 9, about 3 sigma)

controls smoothness of weighting procedure, lowered from some high starting value in a **pre-defined (deterministic) sequence of steps** that converges at $T = 1$.



ATLAS IN RUN1/2: ITERATIVE VERTEX FINDER

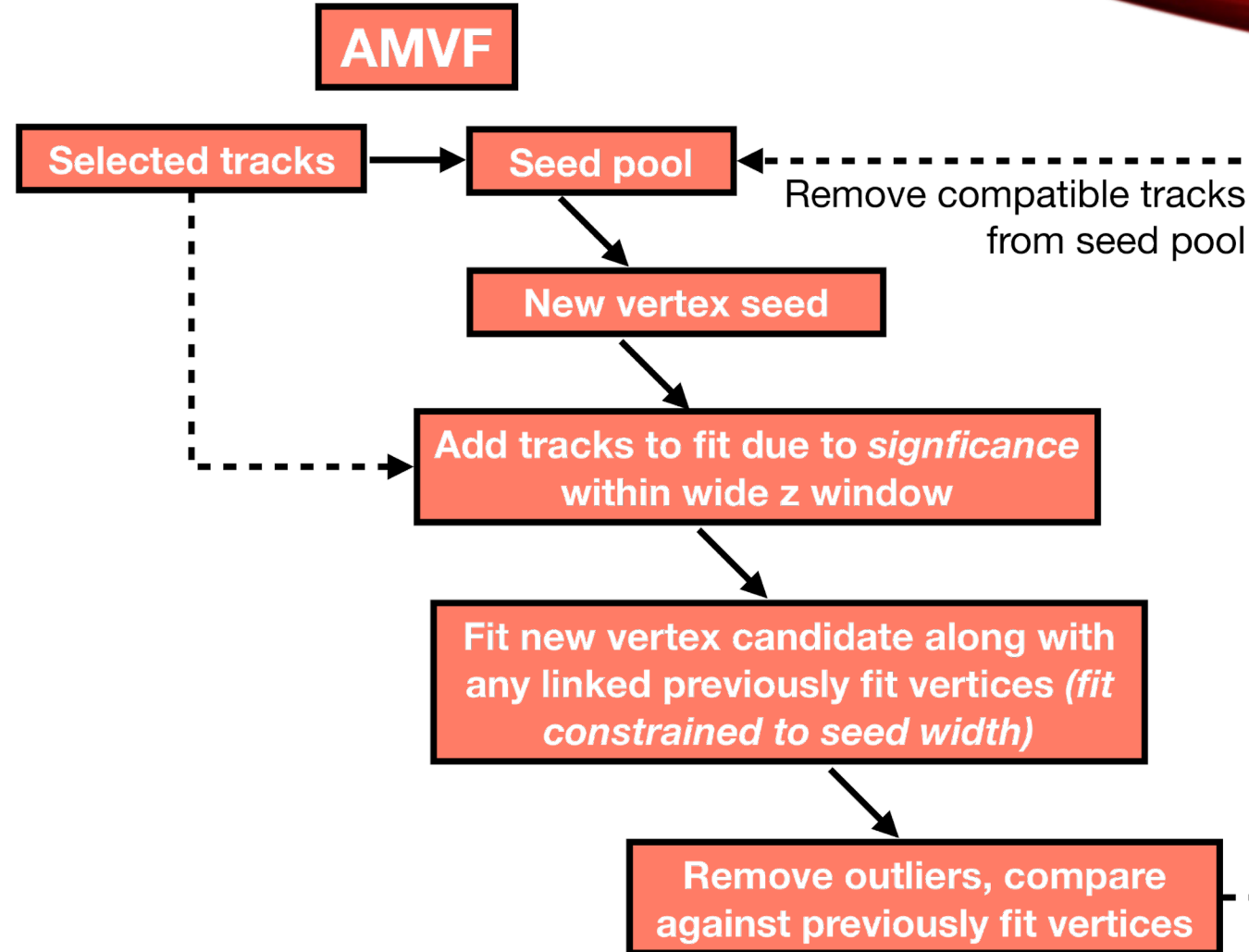
04.12.24



ATLAS IN RUN3: ADAPTIVE MULTI VERTEX FINDER

04.12.24

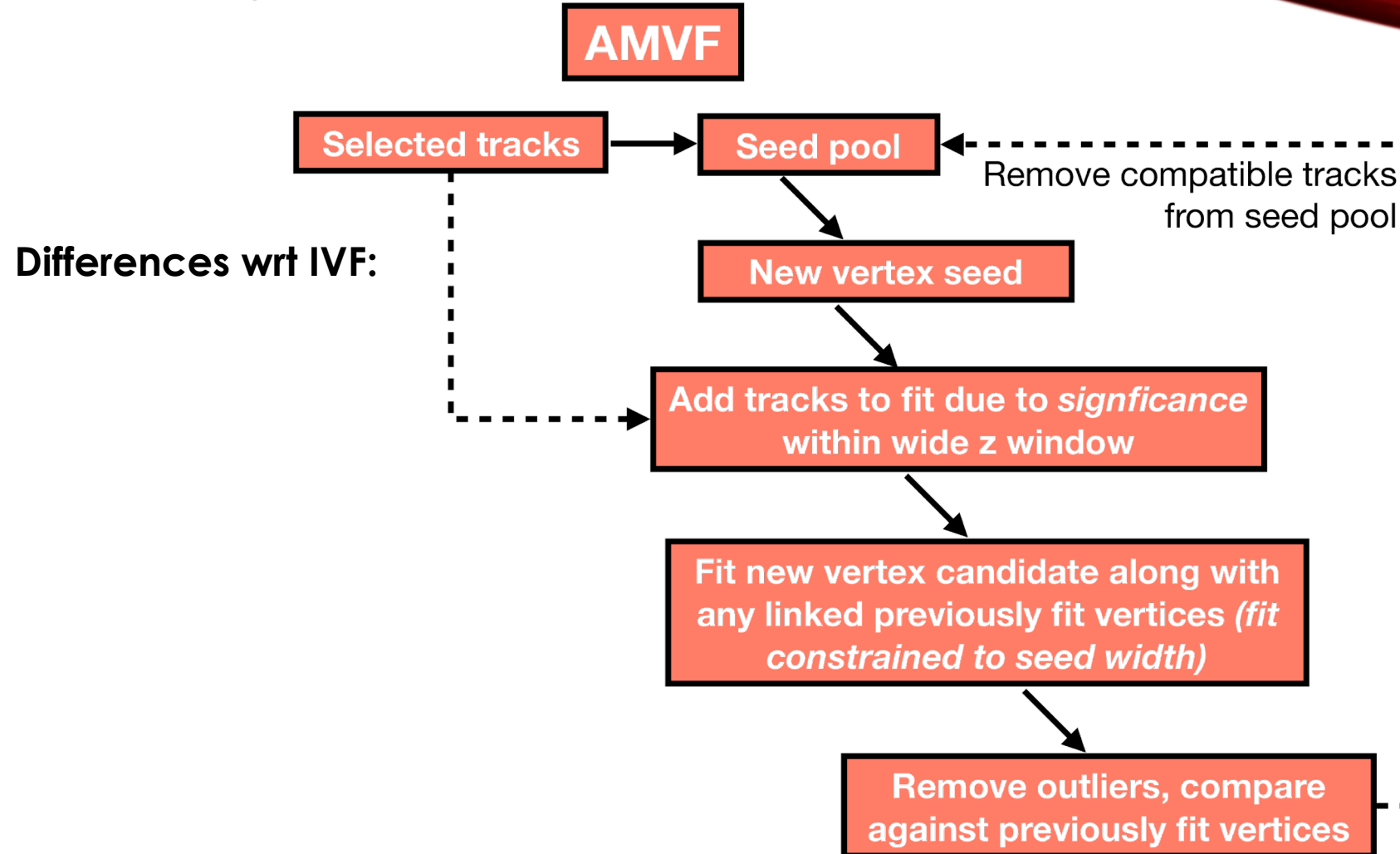
[ATL-PHYS-PUB-2019-015](#)



ATLAS IN RUN3: ADAPTIVE MULTI VERTEX FINDER

04.12.24

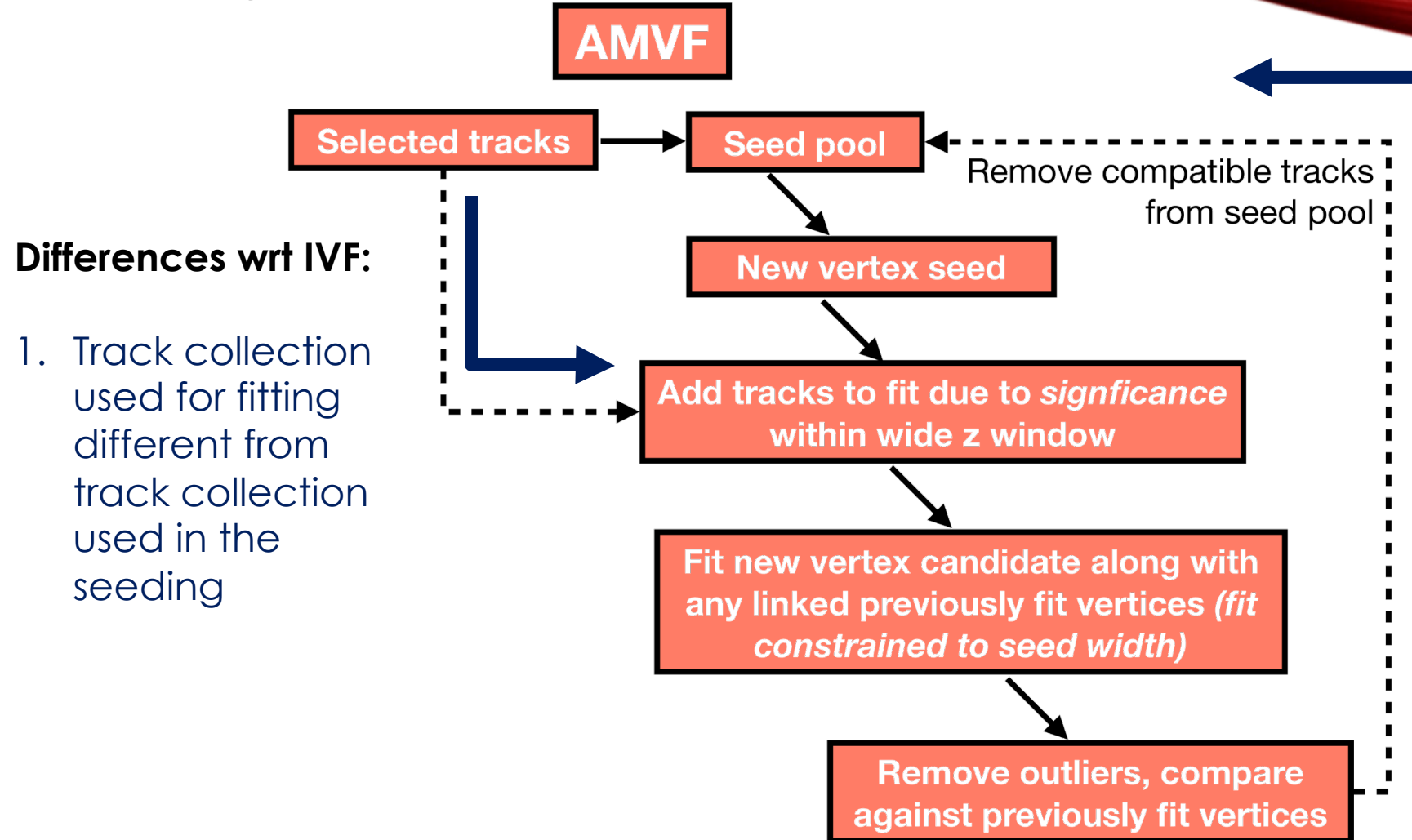
[ATL-PHYS-PUB-2019-015](#)



ATLAS IN RUN3: ADAPTIVE MULTI VERTEX FINDER

[ATL-PHYS-PUB-2019-015](#)

04.12.24



ATLAS IN RUN3: ADAPTIVE MULTI VERTEX FINDER

04.12.24

ATL-PHYS-PUB-2019-015

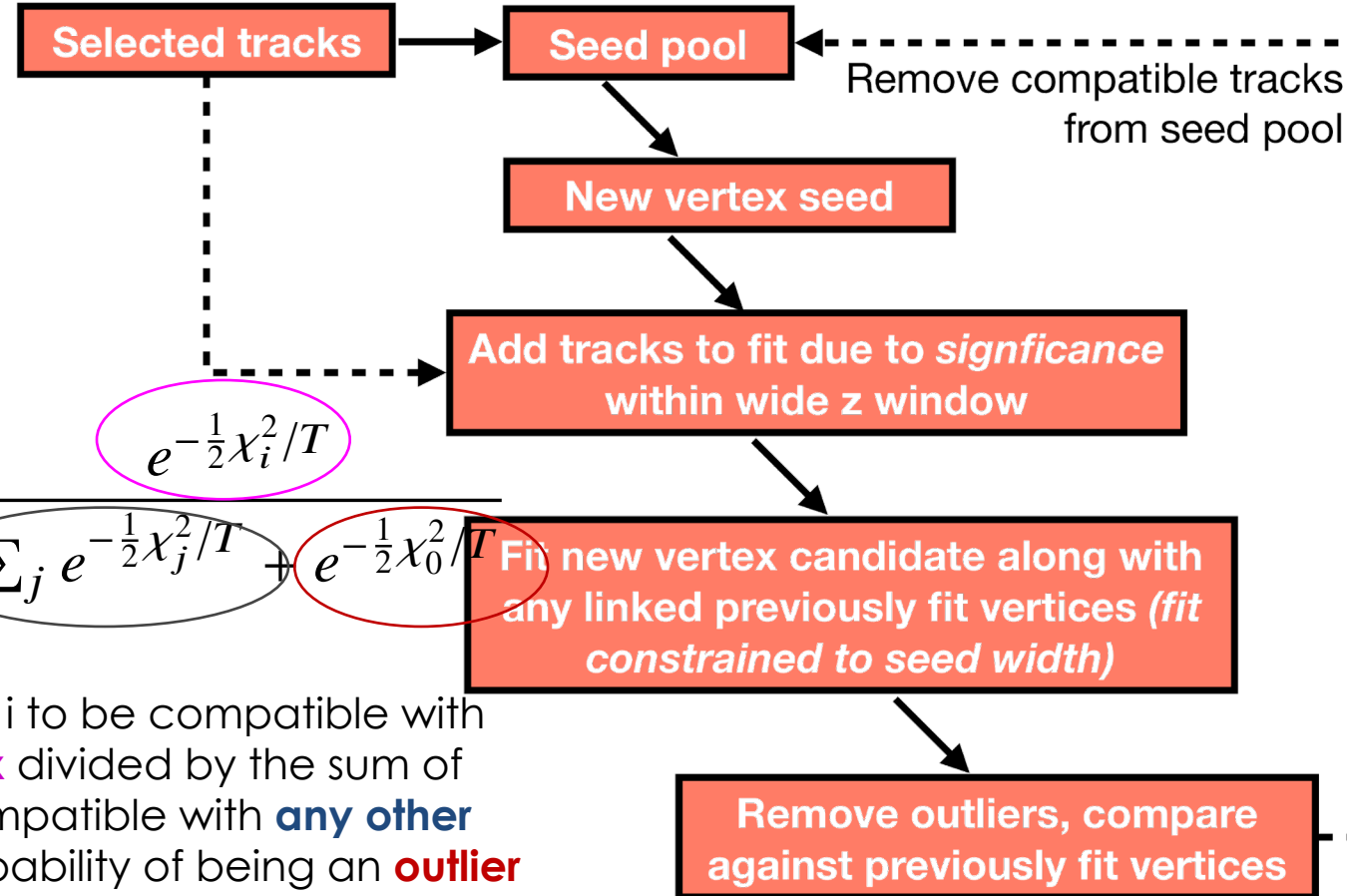
AMVF

Differences wrt IVF:

2. Tracks compete for vertices

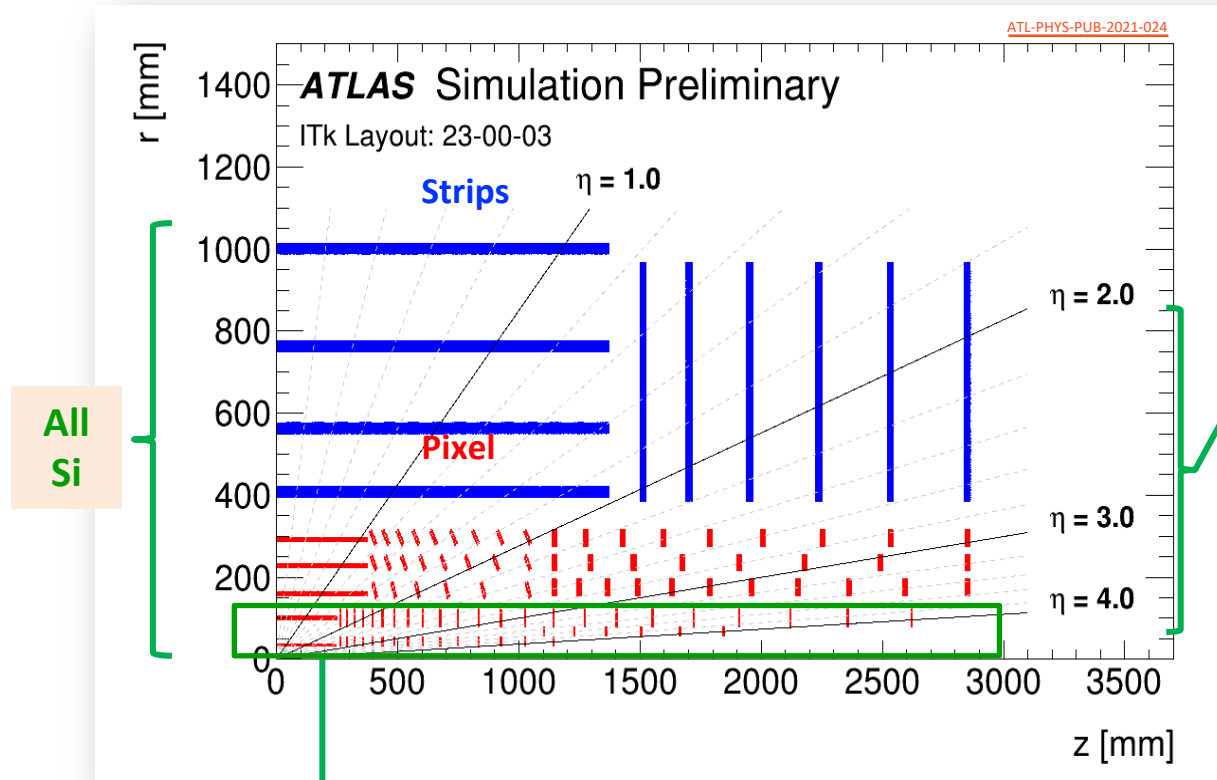
$$\omega_i(\chi_i^2, T) = \frac{e^{-\frac{1}{2}\chi_i^2/T}}{\sum_j e^{-\frac{1}{2}\chi_j^2/T} + e^{-\frac{1}{2}\chi_0^2/T}}$$

Probability of the track i to be compatible with the **considered vertex** divided by the sum of probabilities to be compatible with **any other vertex plus** the prior probability of being an **outlier**



THE ATLAS DETECTOR IN RUN 4

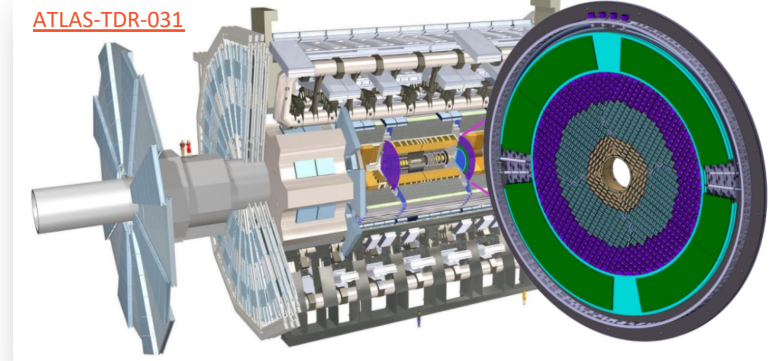
ITk



Extractable & Replaceable
(Radiation hardness up to **~10-15 MGy**)

Increased η coverage
(from 2.4 to 4.0)

HGTD

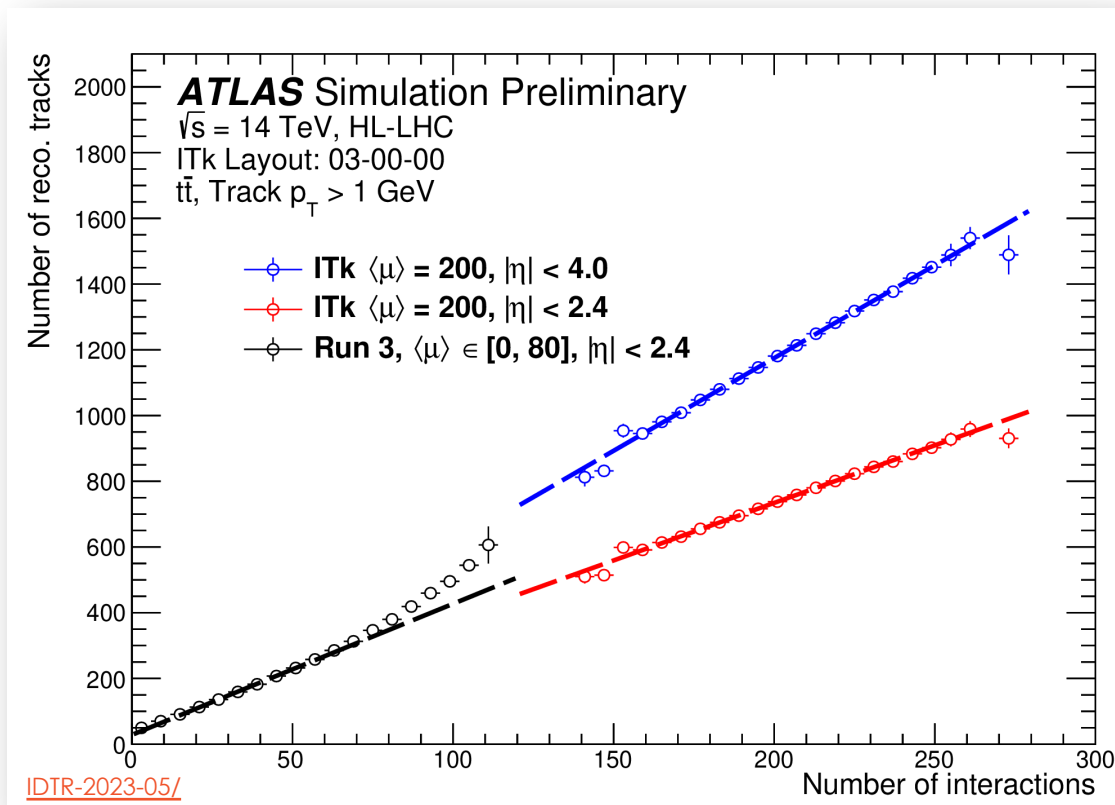


Extractable & Replaceable
(Radiation hardness up to **~2 MGy**)

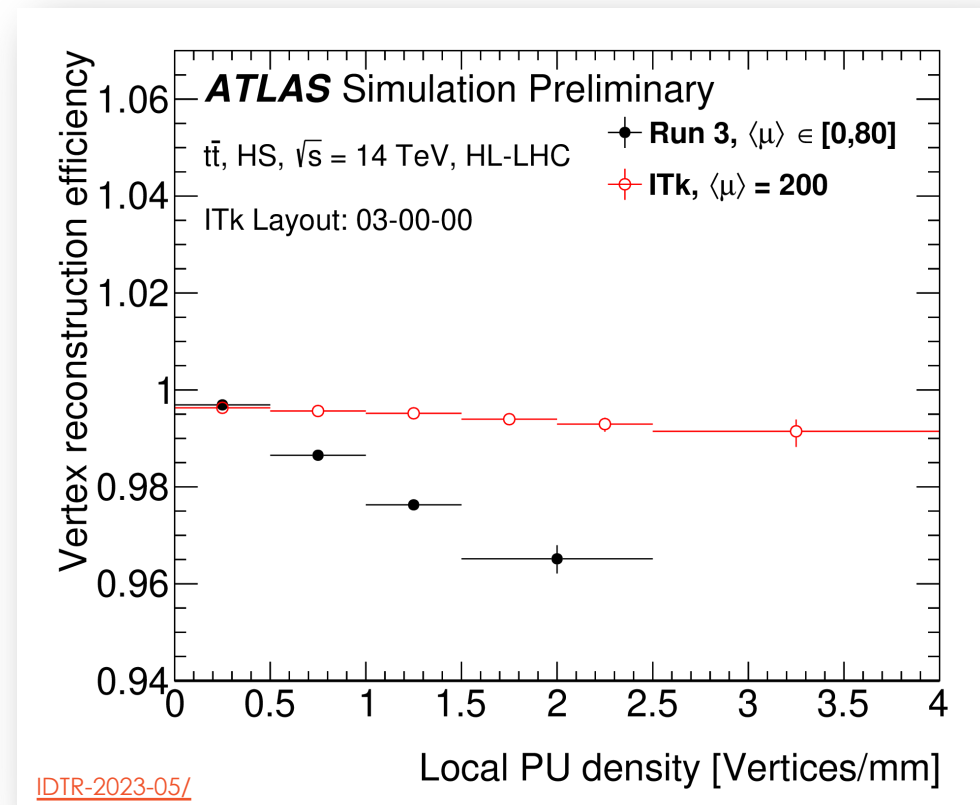
Average time resolution per hit (start and end of operational lifetime)	
$2.4 < \eta < 4.0$	≈ 35 ps (start), ≈ 70 ps (end)
Average time resolution per track (start and end of operational lifetime)	≈ 30 ps (start), ≈ 50 ps (end)

HL-LHC TRACKING

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



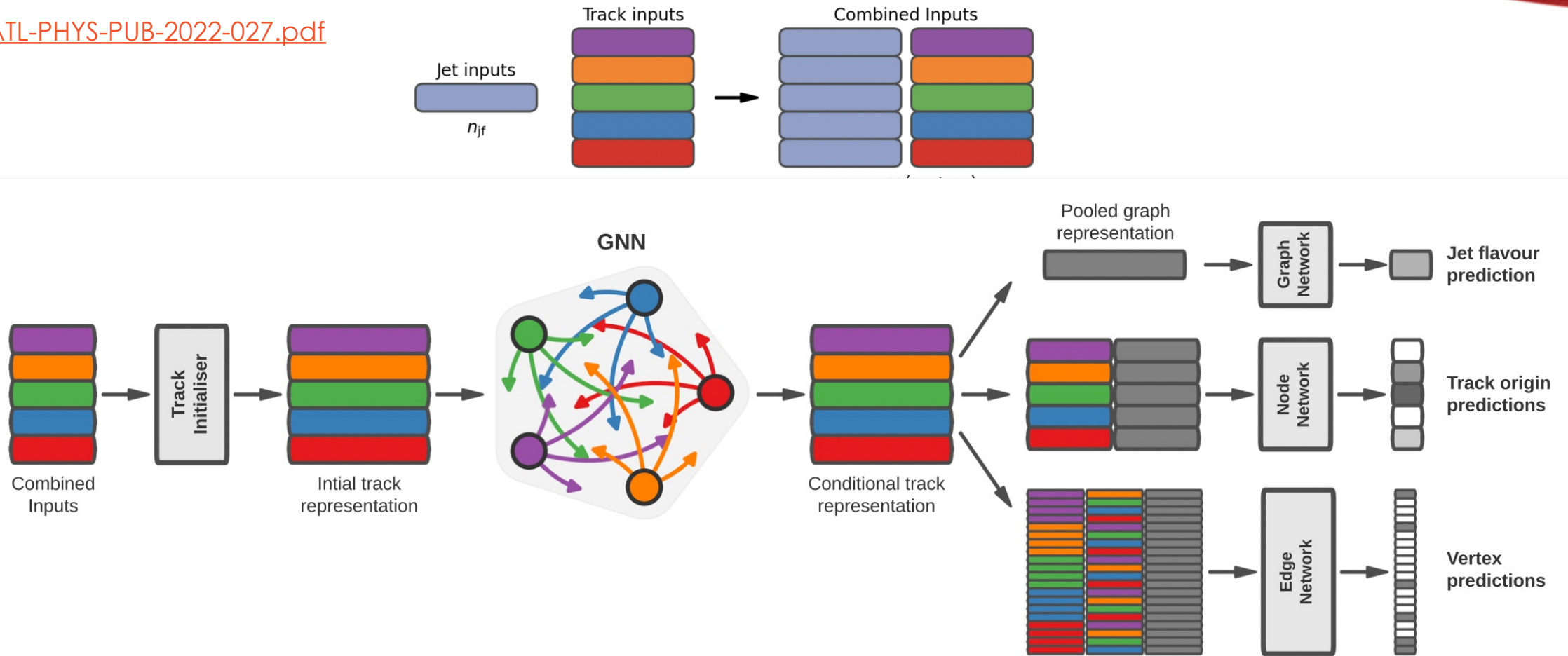
The lower the fake rate, the better the CPU and storage usage



More PU-robust vertexing

GNN

[ATL-PHYS-PUB-2022-027.pdf](#)



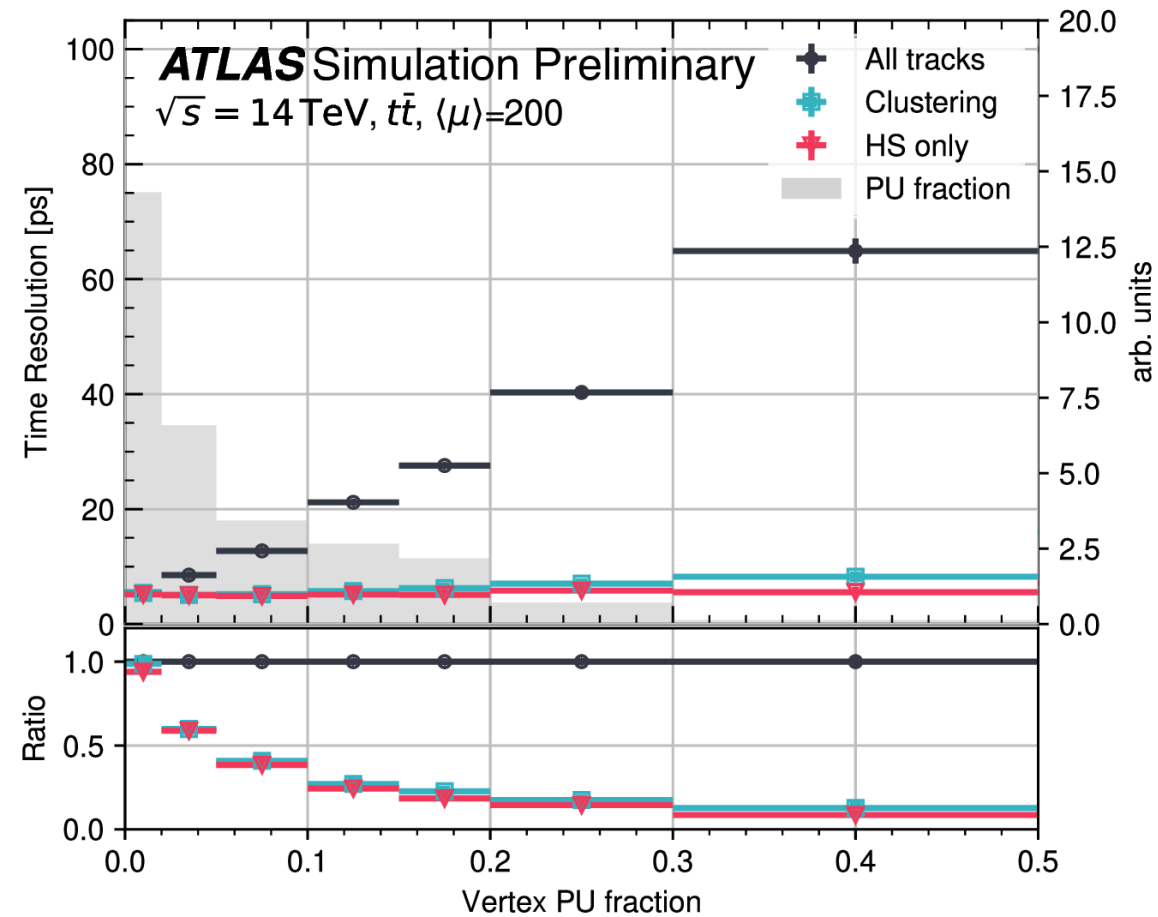
GNN

Track Variables	GN1 ITk	GN1 ITk time
d0	x	x
z0SinTheta	x	x
$\sigma(\text{Theta})$	x	x
qOverP	x	x
$\sigma(\text{qOverP})$	x	x
φ	x	x
$\sigma(\varphi)$	x	x
signed d0 significance	x	x
signed z0 significance	x	x
$\Delta\eta(\text{trk, jet})$	x	x
$\Delta\varphi(\text{trk, jet})$	x	x
n pix hits	x	x
n pix hits (11 variables)	x	x
dt		x

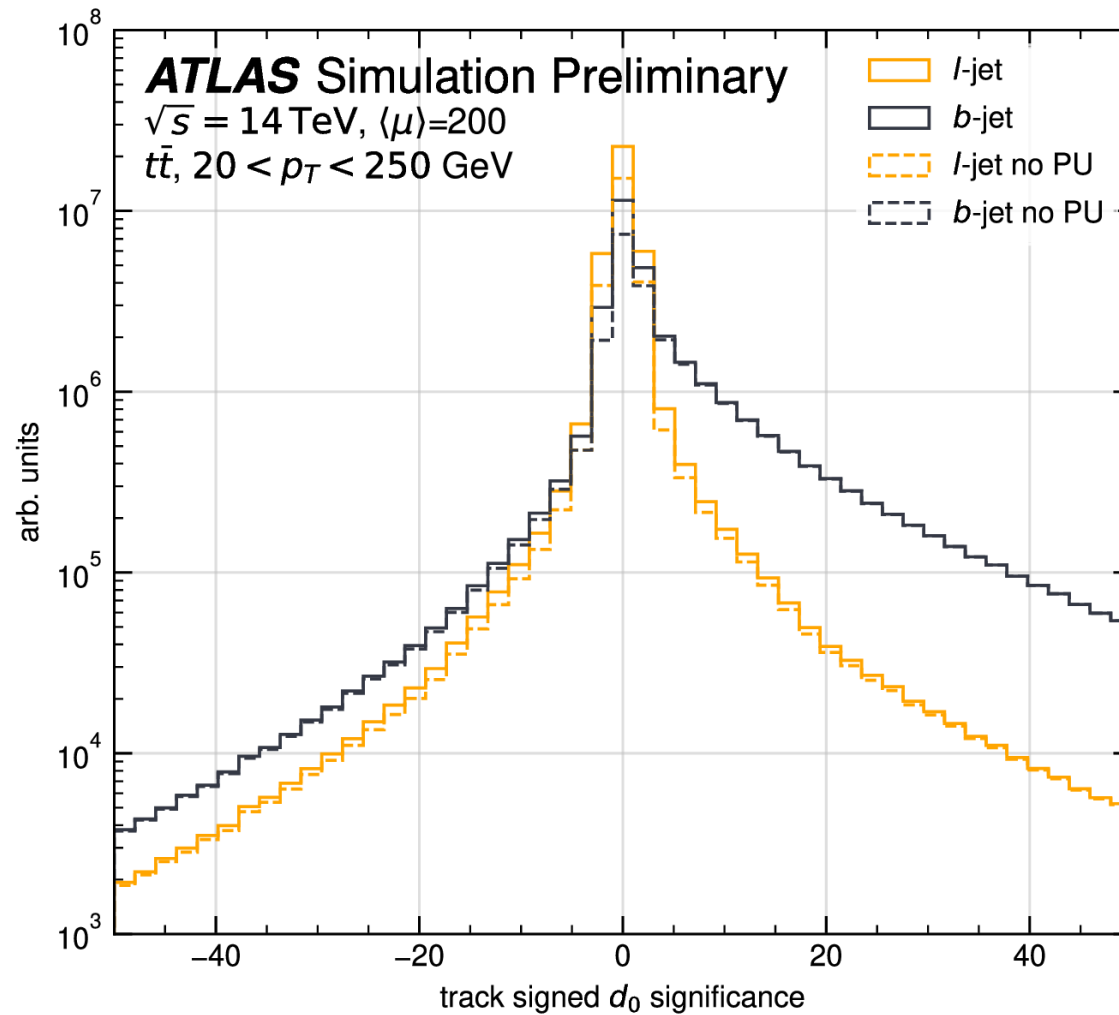
nPixHits
 nStripHits
 nInnermostPixHits
 nNextToInnermostPixHits
 nInnermostPixShared
 nInnermostPixSplit
 nPixShared
 nPixSplit
 nStripShared
 nPixHoles
 nStripHoles

Number of pixel hits
 Number of strip hits
 Number of hits from the innermost pixel layer
 Number of hits from the next-to-innermost pixel layer
 Number of shared hits from the innermost pixel layer
 Number of split hits from the innermost pixel layer
 Number of shared pixel hits
 Number of split pixel hits
 Number of shared strip hits
 Number of pixel holes
 Number of strip holes

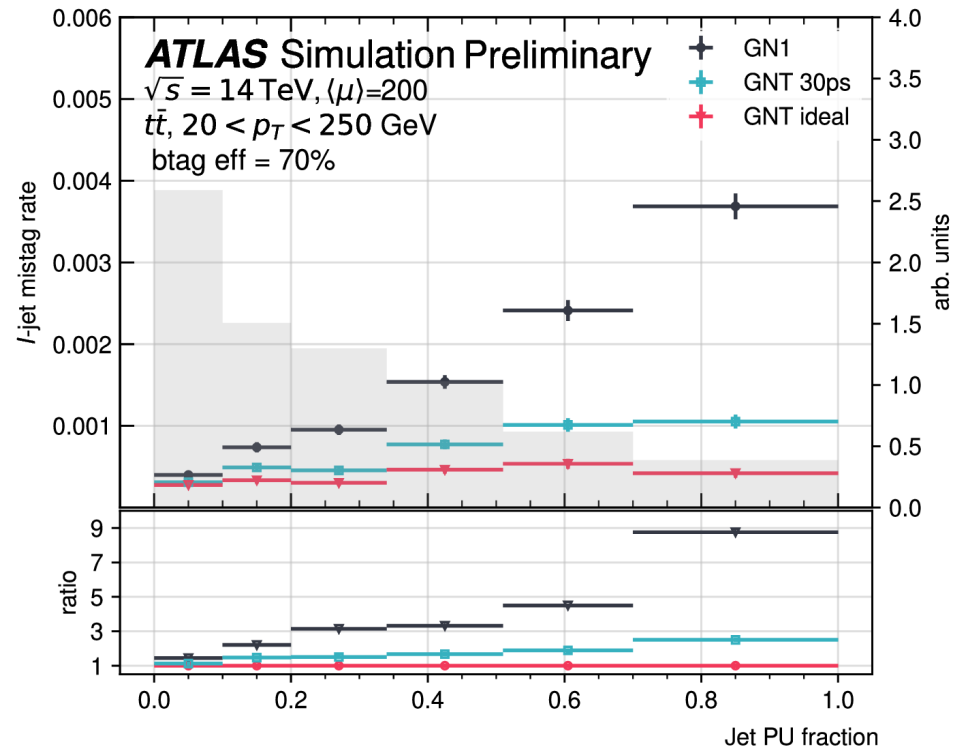
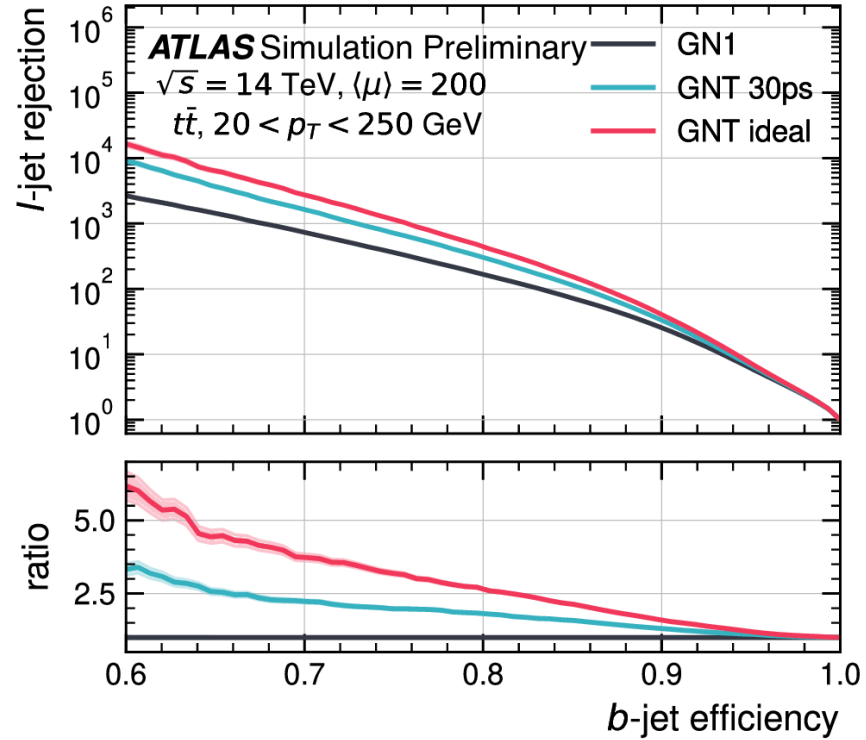
4D TRACKING



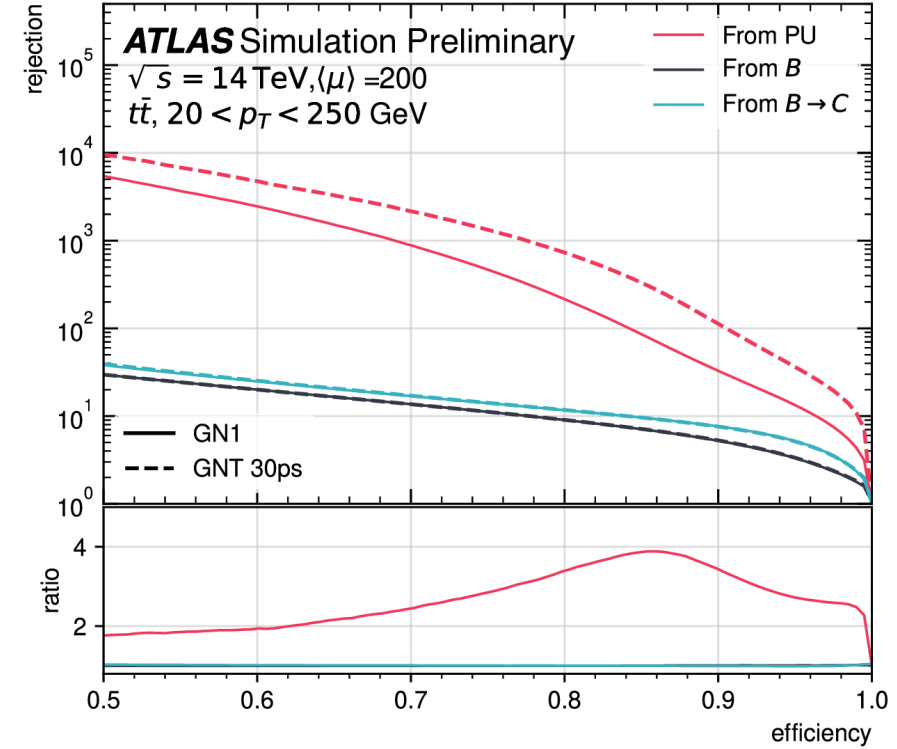
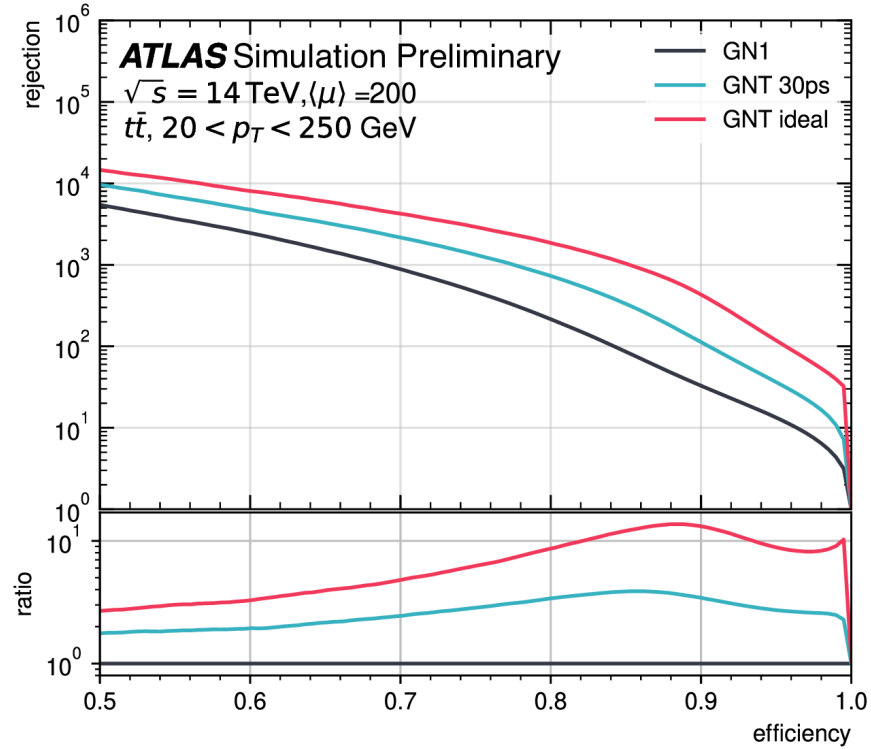
4D TRACKING



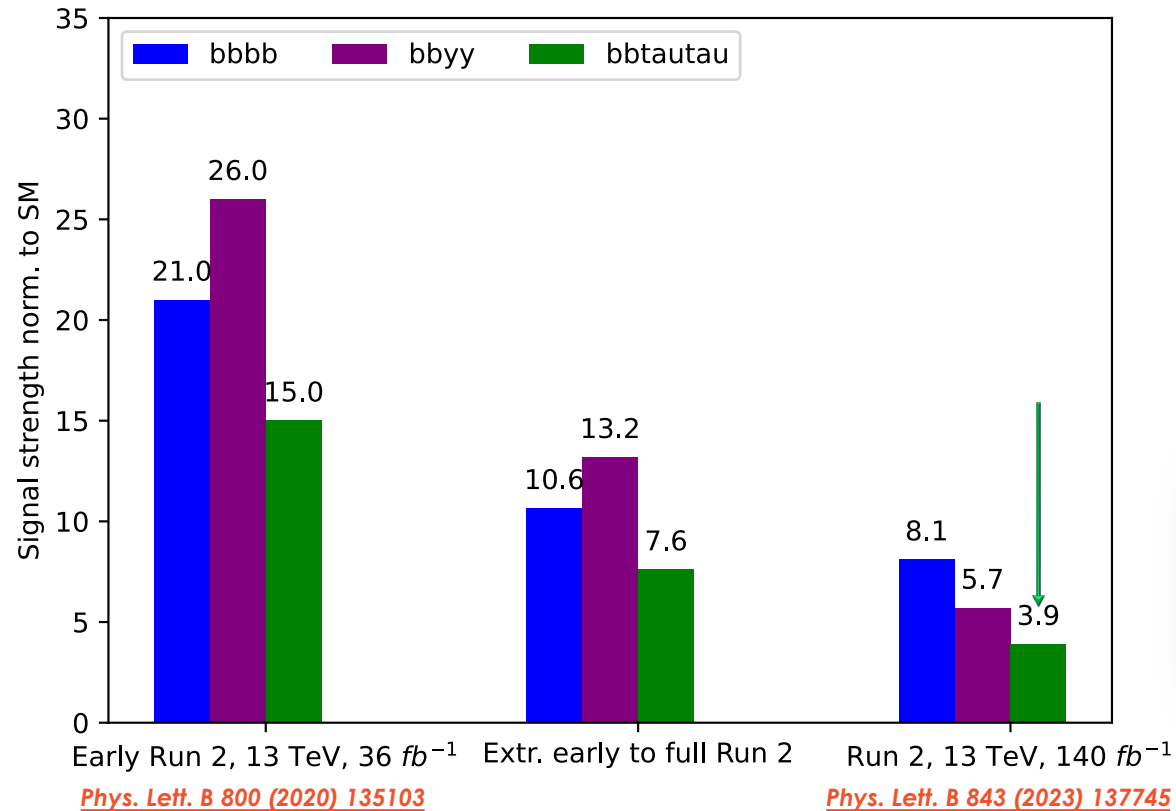
4D FTAG



4D FTAG



ANOTHER EXAMPLE

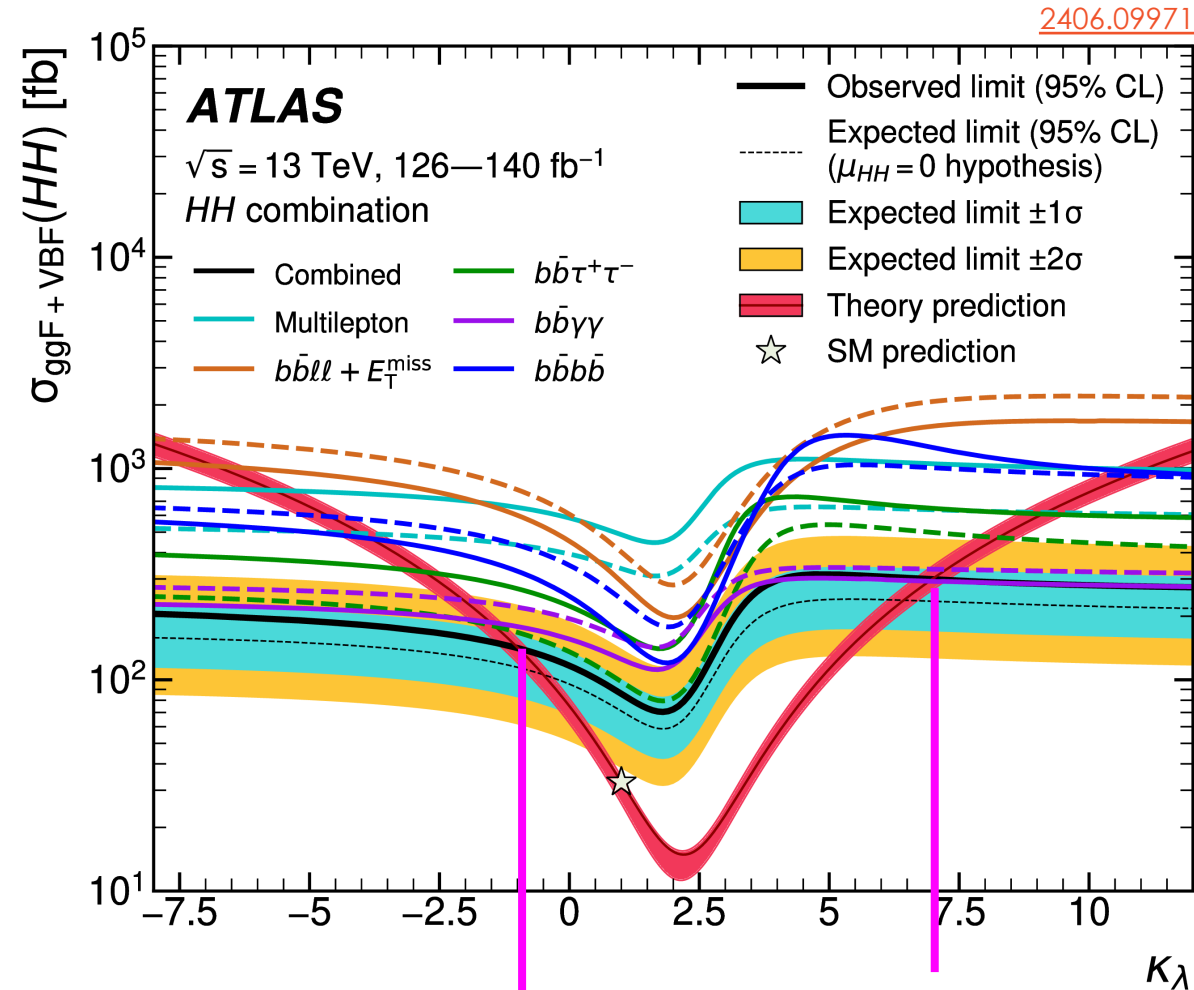


From 2015 **HL-LHC** study of $HH \rightarrow b\bar{b}\tau\tau$

[ATL-PHYS-PUB-2015-046](#)

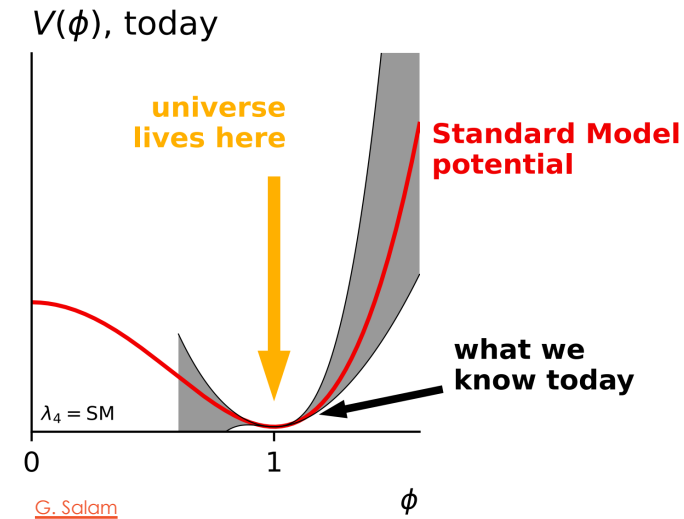
performed under different assumptions for the Higgs trilinear self-coupling values. Assuming SM background and SM signal, we expect to set an upper limit of the cross section for the di-Higgs production of $4.3 \times \sigma(HH \rightarrow b\bar{b}\tau^+\tau^-)$ at 95% Confidence Level. Using an effective Lagrangian for the Higgs potential, and allowing its trilinear self-coupling to vary, we can project an exclusion of $\lambda_{HHH}/\lambda_{SM} \leq -4$ and $\lambda_{HHH}/\lambda_{SM} \geq 12$.

PUTTING EVERYTHING TOGETHER



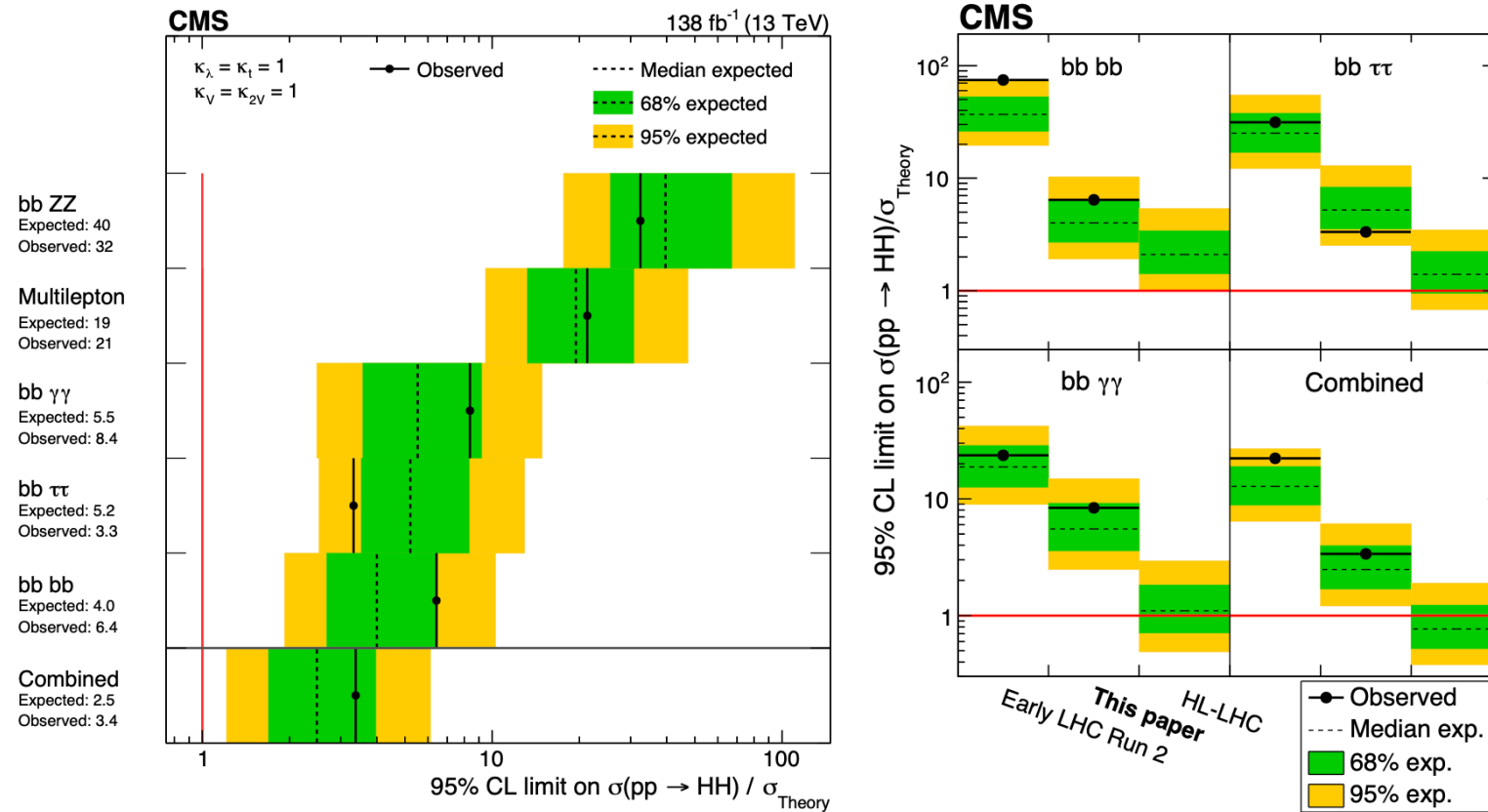
From HH cross-section to Higgs self-coupling constraints

Observed(expected): $-1.2 < k_\lambda < 7.2$ ($-1.6 < k_\lambda < 7.2$)



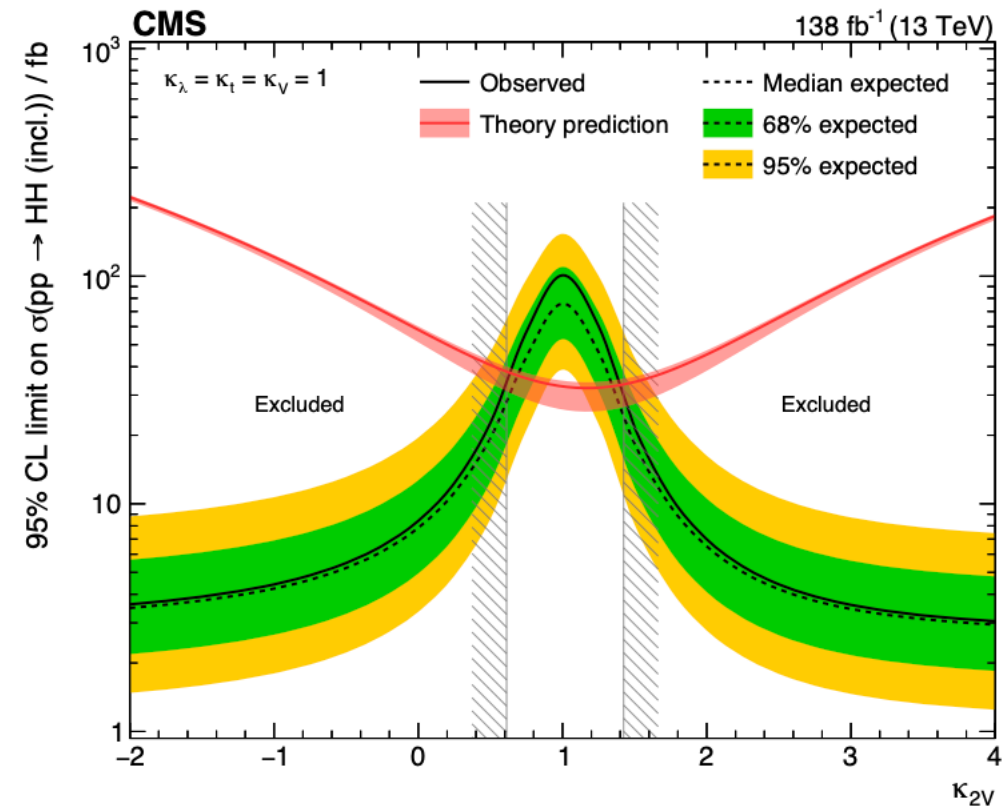
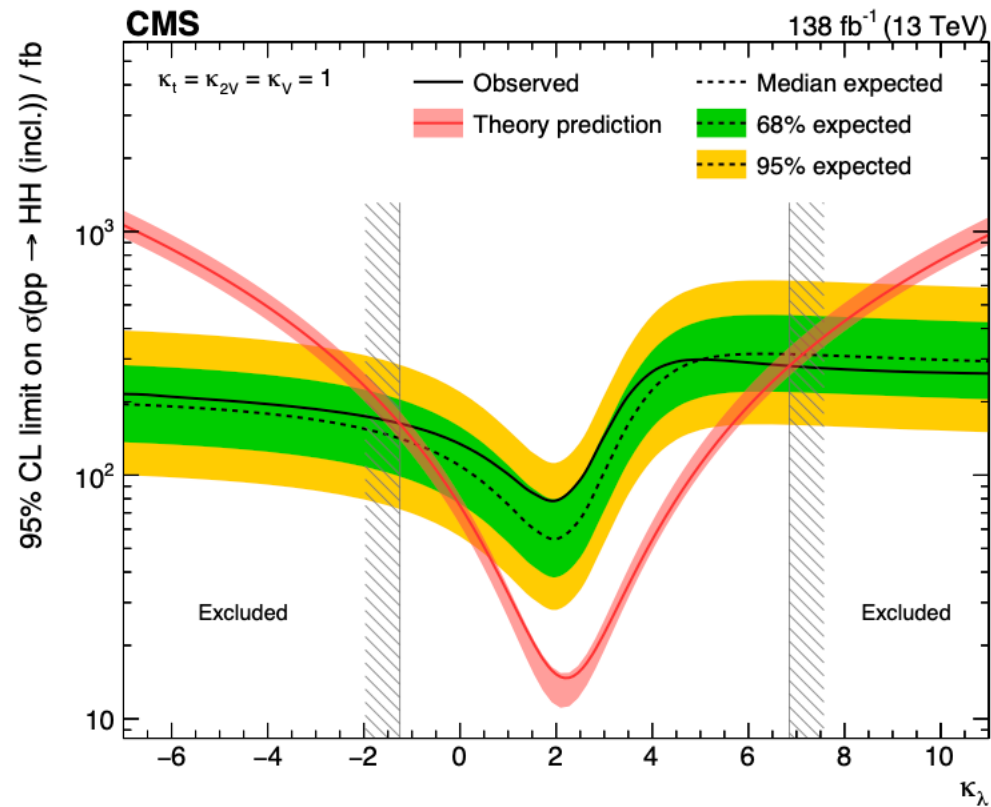
PUTTING EVERYTHING TOGETHER

<https://arxiv.org/pdf/2207.00043.pdf>



PUTTING EVERYTHING TOGETHER

<https://arxiv.org/pdf/2207.00043.pdf>



VBF HH PRODUCTION VS KL AND K2V

Reviews in Physics 5 (2020) 100045

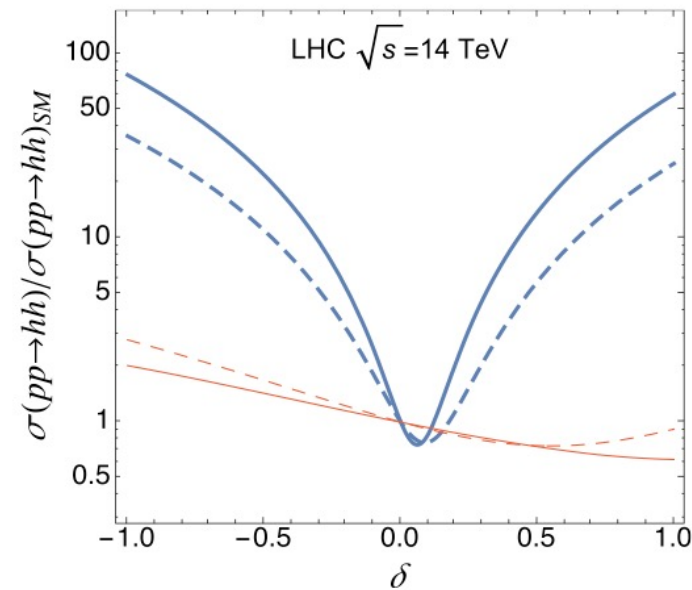
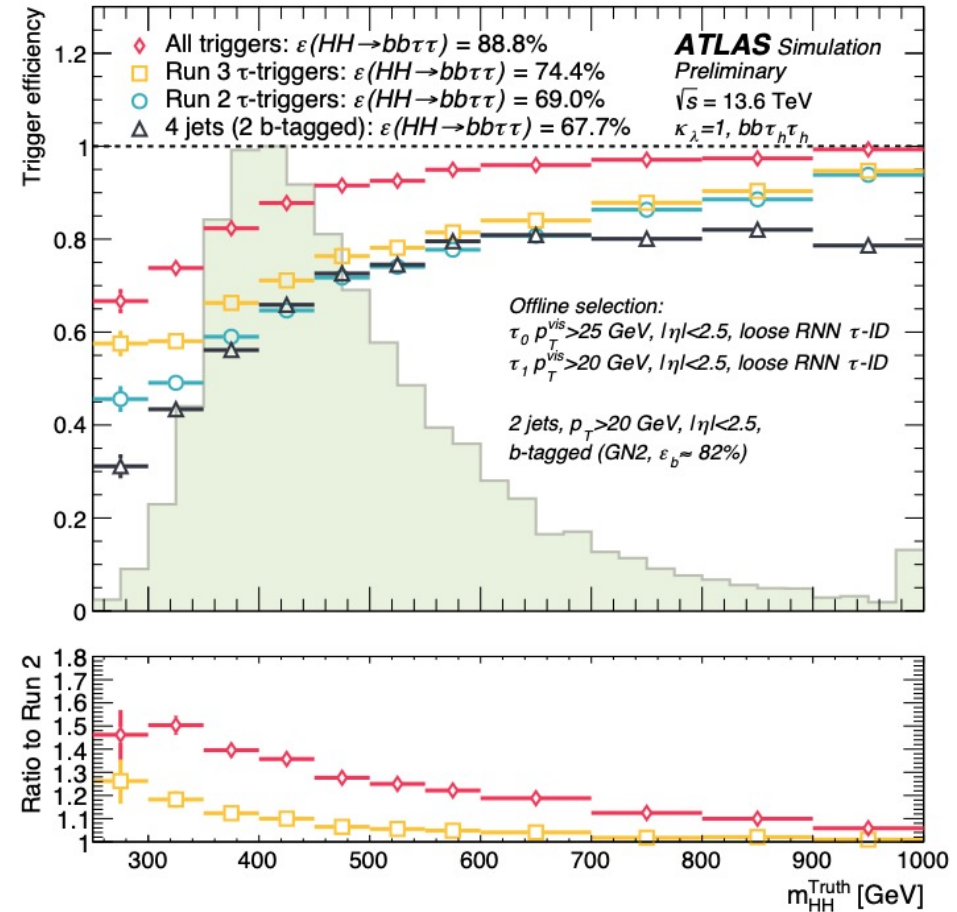
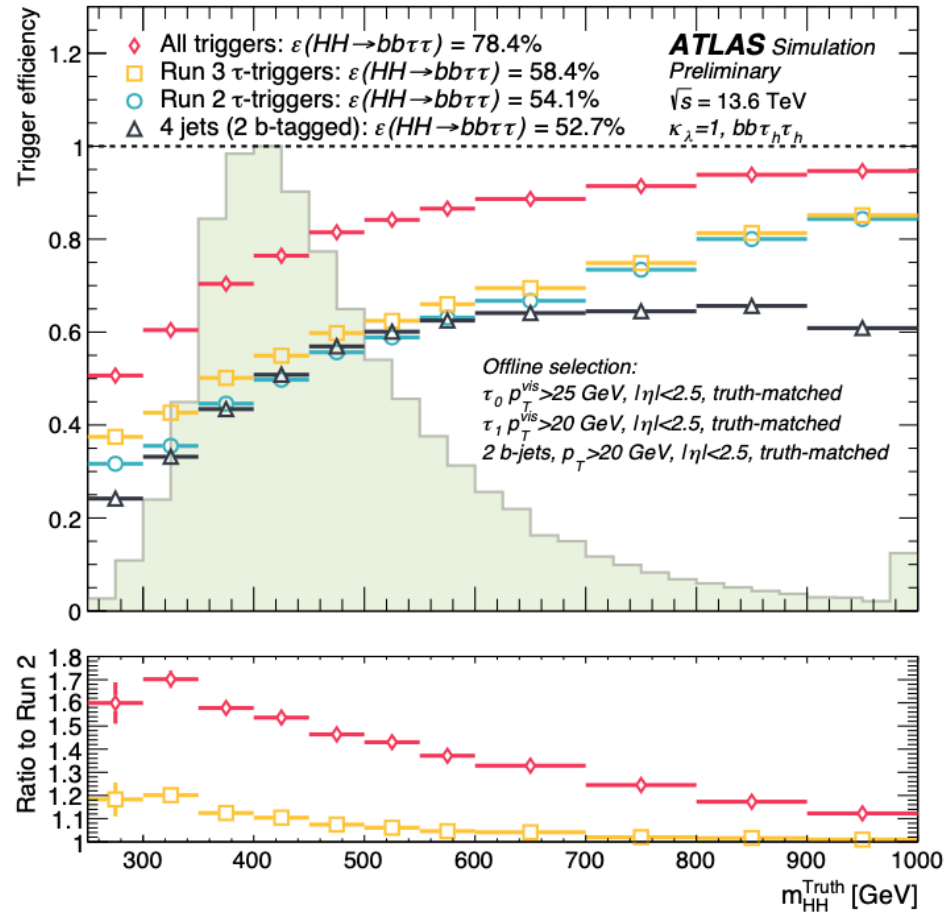
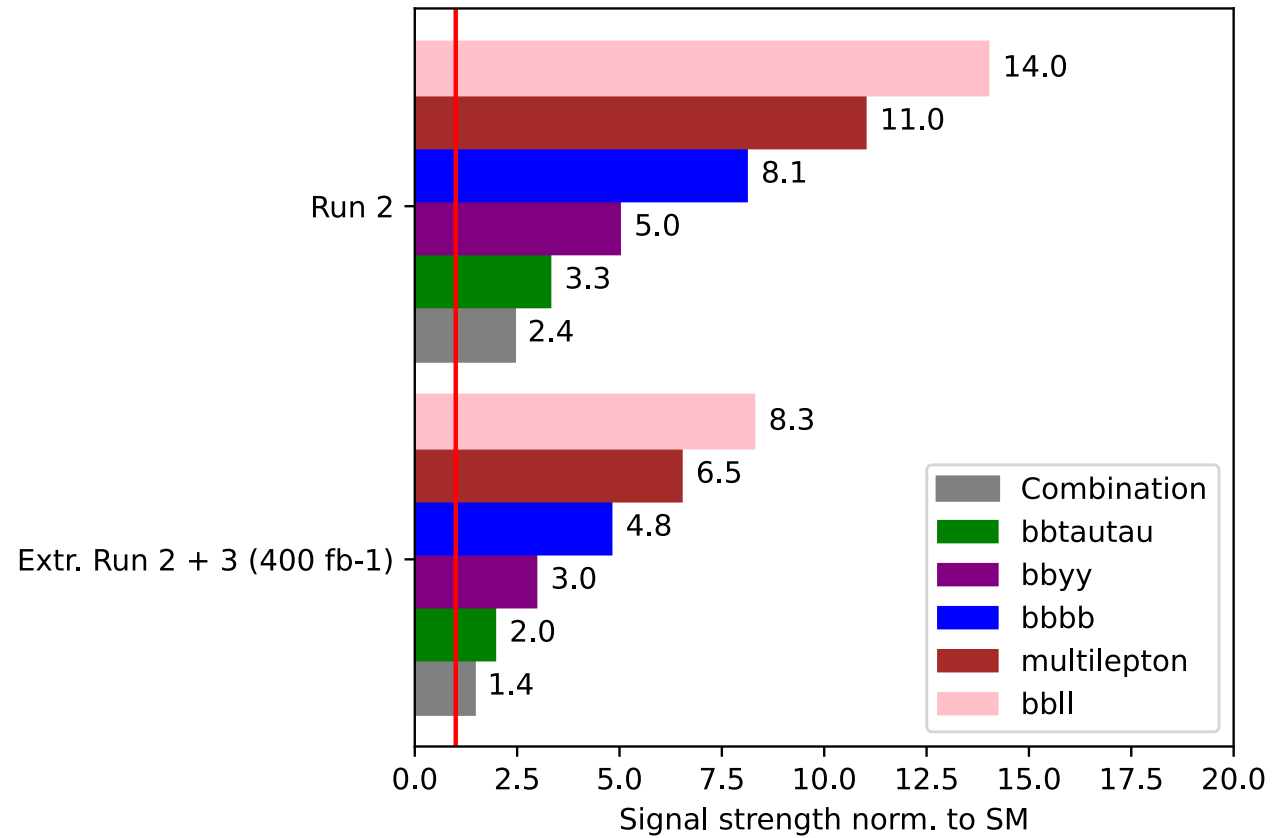


Fig. 82. VBF HH production cross section as a function of the coupling deviation from the SM value for the $HHVV$ (HHH) vertex in blue (red). The solid line is after acceptance cuts, the dashed line is after analysis cuts applied on the rapidity difference and M_{jj} [455]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

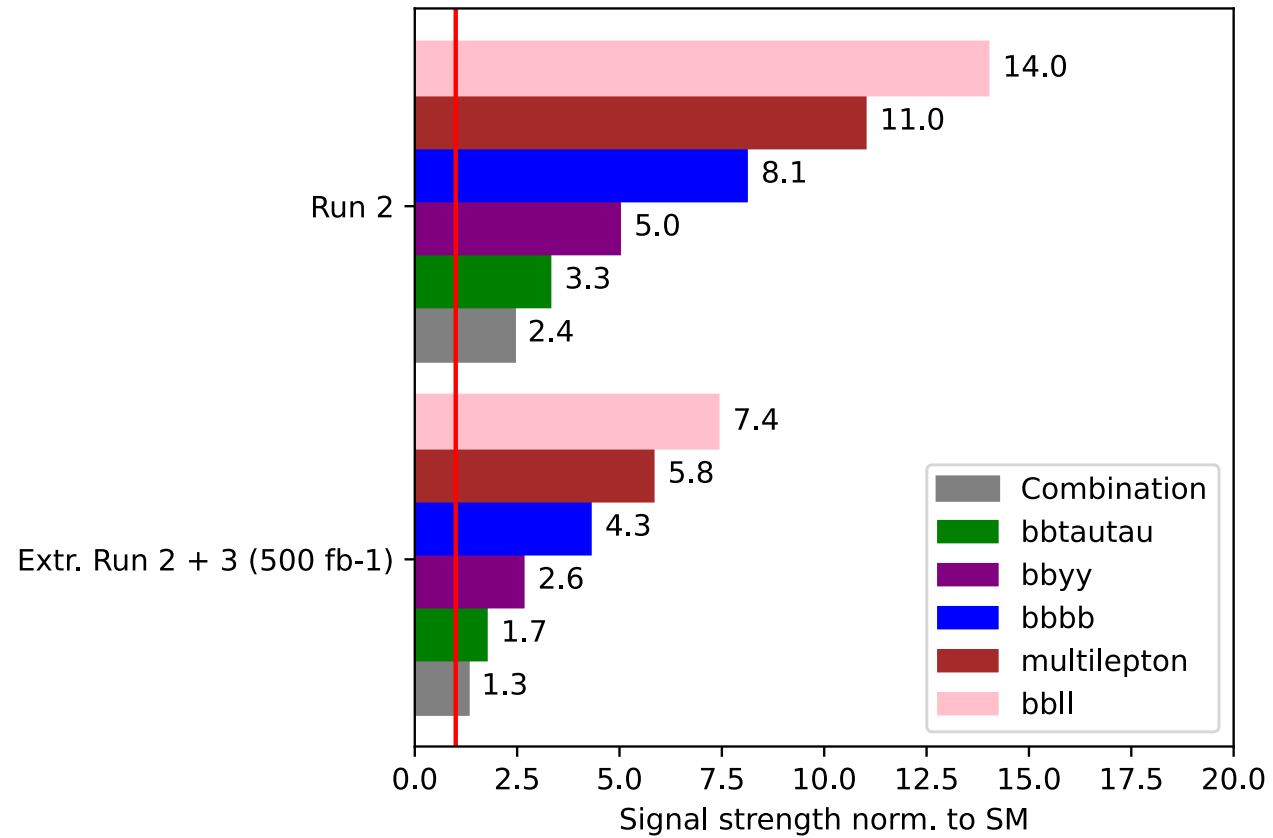
TAU TRIGGERS



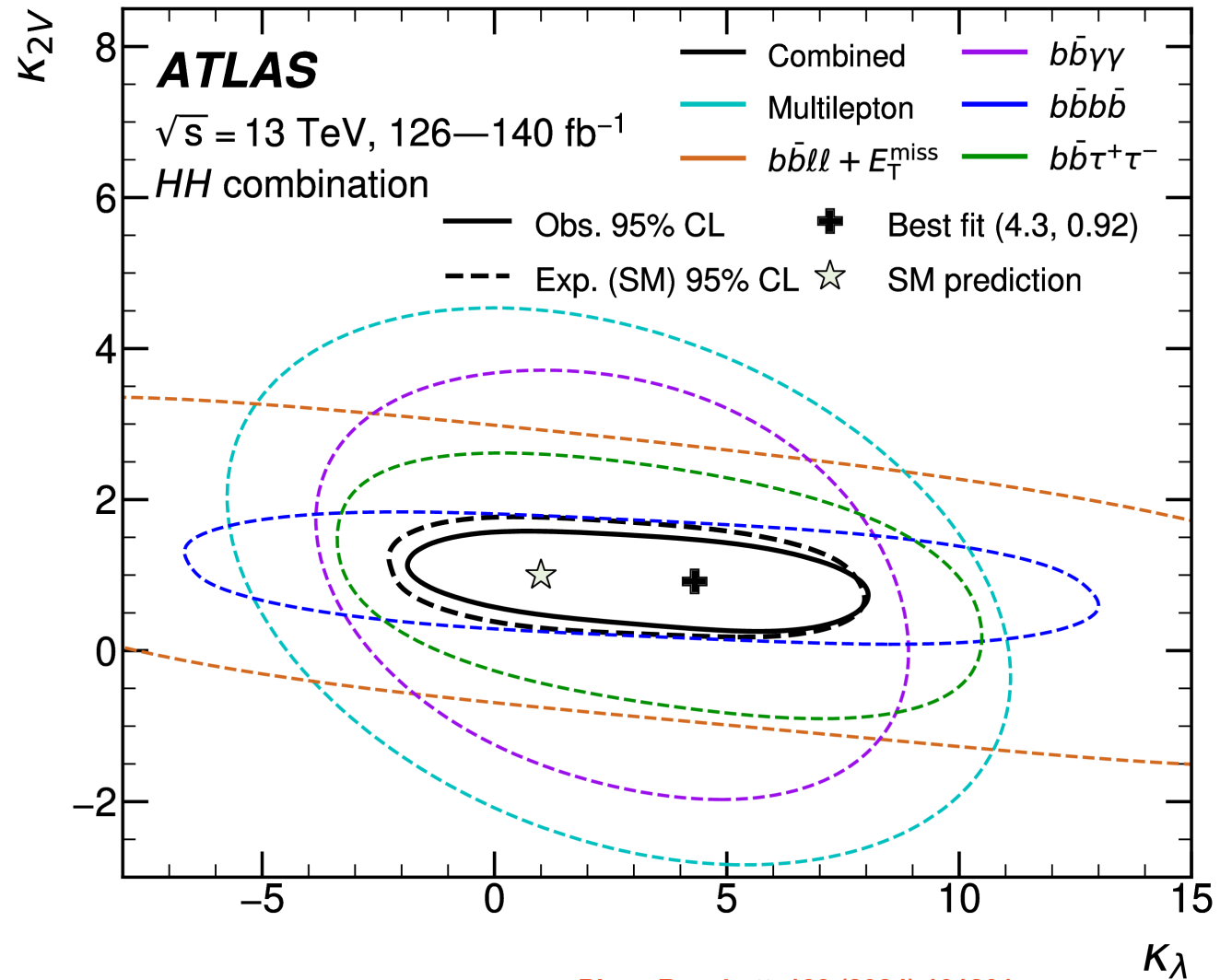
RUN 3 (400 VS 500 FB-1)



RUN 3 (400 VS 500 FB-1)

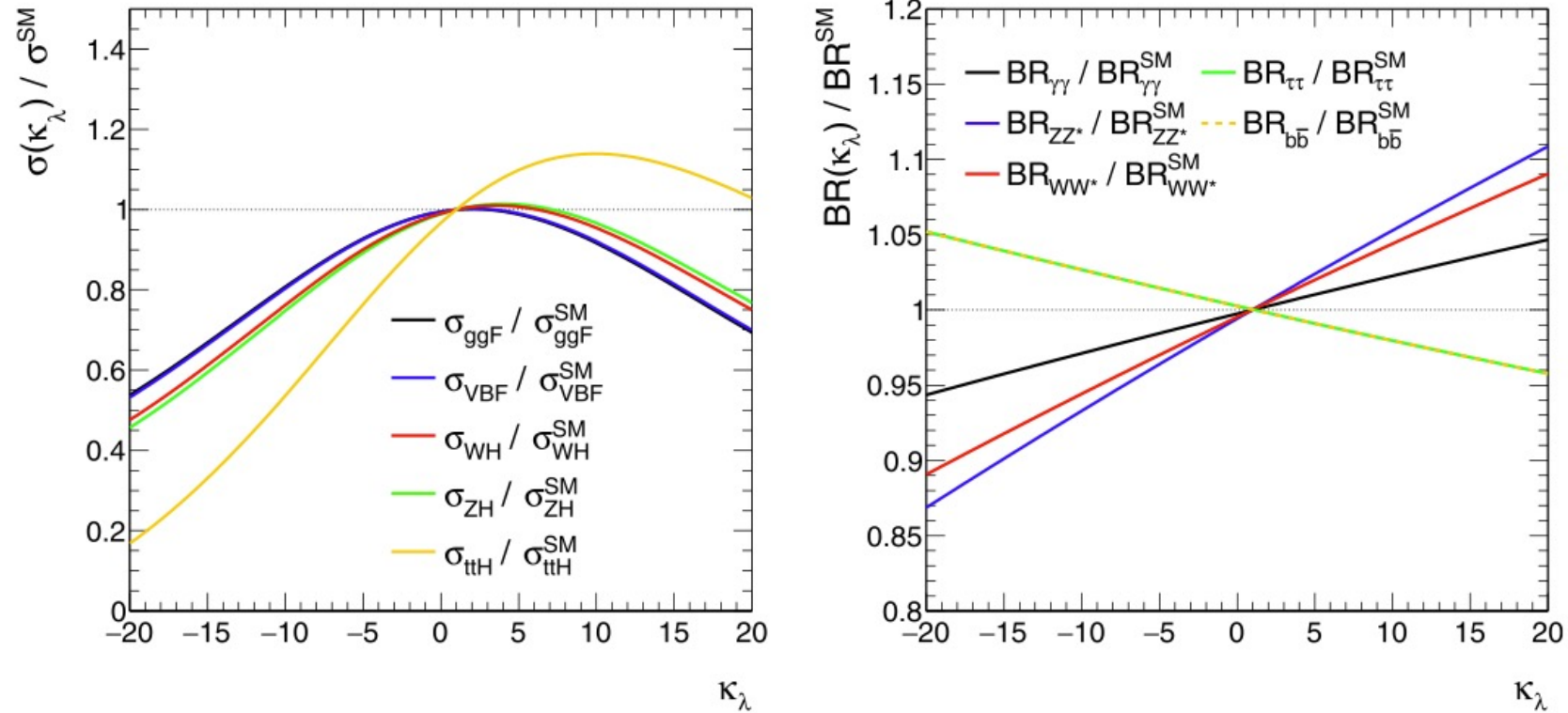


2D COUPLINGS



SINGLE HIGGS

<https://doi.org/10.1016/j.revip.2020.100045>



FUTURE COLLIDERS

arXiv:1907.02078v2

$$V(H) \simeq \begin{cases} -m^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{c_6 \lambda}{\Lambda^2} (H^\dagger H)^3, & \text{Elementary Higgs} \\ -a \sin^2(\sqrt{H^\dagger H}/f) + b \sin^4(\sqrt{H^\dagger H}/f), & \text{Nambu-Goldstone Higgs} \\ \lambda (H^\dagger H)^2 + \epsilon (H^\dagger H)^2 \log \frac{H^\dagger H}{\mu^2}, & \text{Coleman-Weinberg Higgs} \\ -\kappa^3 \sqrt{H^\dagger H} + m^2 H^\dagger H, & \text{Tadpole-induced Higgs} \end{cases}$$

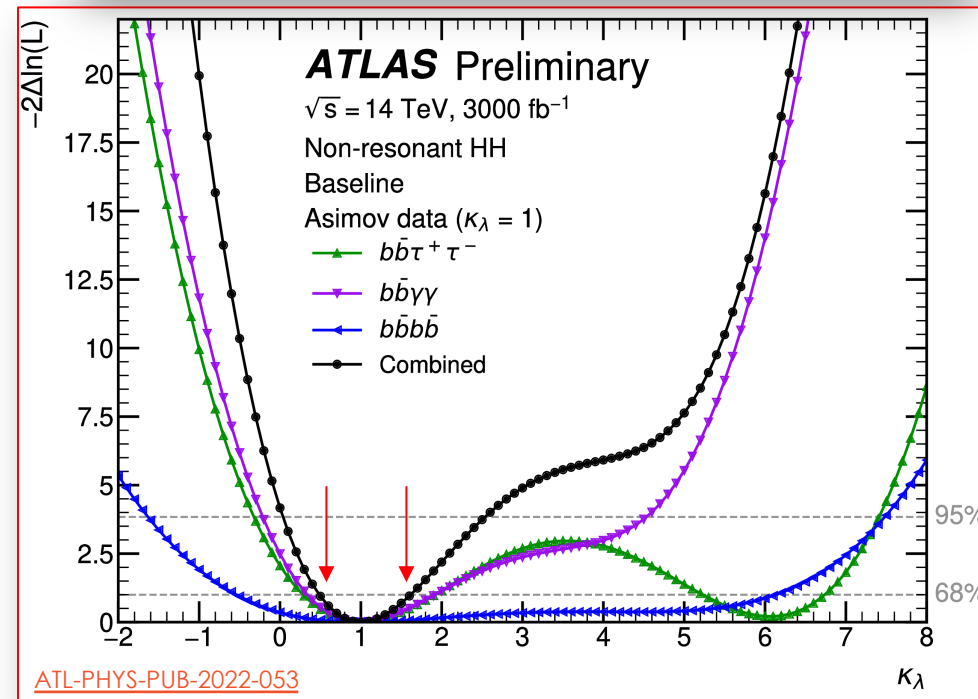
	a	b	c_1	c_2	c_3	d_3	d_4
relevant couplings	hVV	$hhVV$	$h\bar{t}t$	$hh\bar{t}t$	$hhh\bar{t}t$	hhh	$hhhh$
SM	1	1	1	0	0	1	1
SMEFT (with O_6)	1	1	1	0	0	$1 + c_6 \frac{v^2}{\Lambda^2}$	$1 + c_6 \frac{6v^2}{\Lambda^2}$
MCH ₅₊₅	$1 - \frac{\xi}{2}$	$1 - 2\xi$	$1 - \frac{3}{2}\xi$	-2ξ	$-\frac{2}{3}\xi$	$1 - \frac{3}{2}\xi$	$1 - \frac{25}{3}\xi$
CTH ₈₊₁	$1 - \frac{\xi}{2}$	$1 - 2\xi$	$1 - \frac{1}{2}\xi$	$-\frac{1}{2}\xi$	$-\frac{1}{6}\xi$	$1 - \frac{3}{2}\xi$	$1 - \frac{25}{3}\xi$
CW Higgs (doublet)	1	1	1	0	0	$\frac{5}{3}(1.75)$	$\frac{11}{3}(4.43)$
CW Higgs (singlets)	1	1	1	0	0	$\frac{5}{3}(1.91)$	$\frac{11}{3}(4.10)$
Tadpole-induced Higgs	$\simeq 1$	$\simeq 1$	$\simeq 1$	0	0	$\simeq 0$	$\simeq 0$

Table 1: Higgs couplings, defined in Eqs. (2.1) and (2.3), for the SM and various NP scenarios. For the Coleman-Weinberg (CW) Higgs scenario, we also present in the parenthesis the Higgs self-couplings up to the two-loop order, predicted in the two of the simplest conformal extensions of the scalar sector: SM Higgs doublet with another doublet [14], and SM Higgs doublet with two additional singlets [15].

HOW DOES HH LOOK IN HL-LHC?

Uncertainty scenario	Significance [σ]			Combination
	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$	
No syst. unc.	2.3	4.0	1.8	4.9
Baseline	2.2	2.8	0.99	3.4

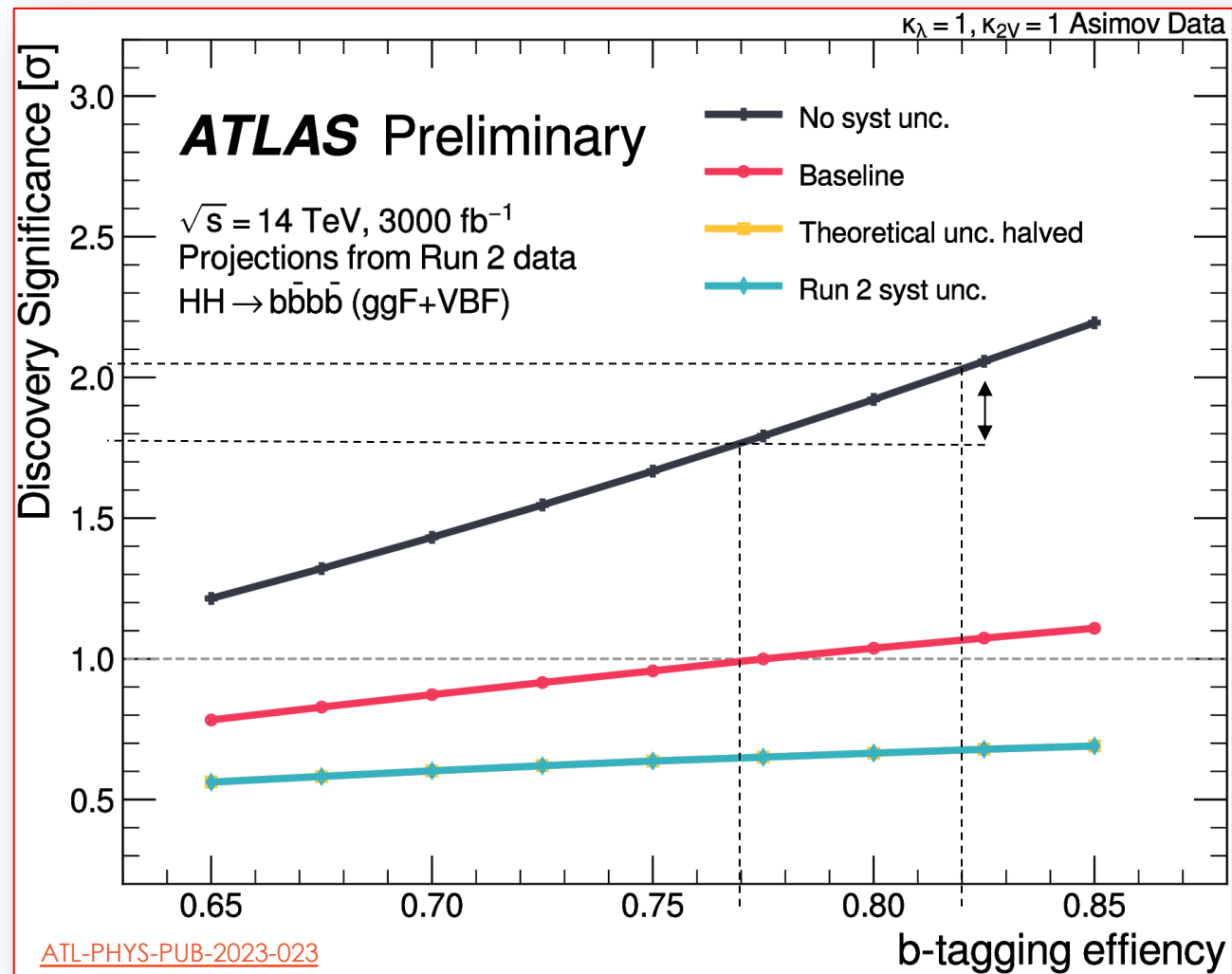
was 3.3!



ATLAS alone
 comparable to
 previous expectation
 from ATLAS + CMS

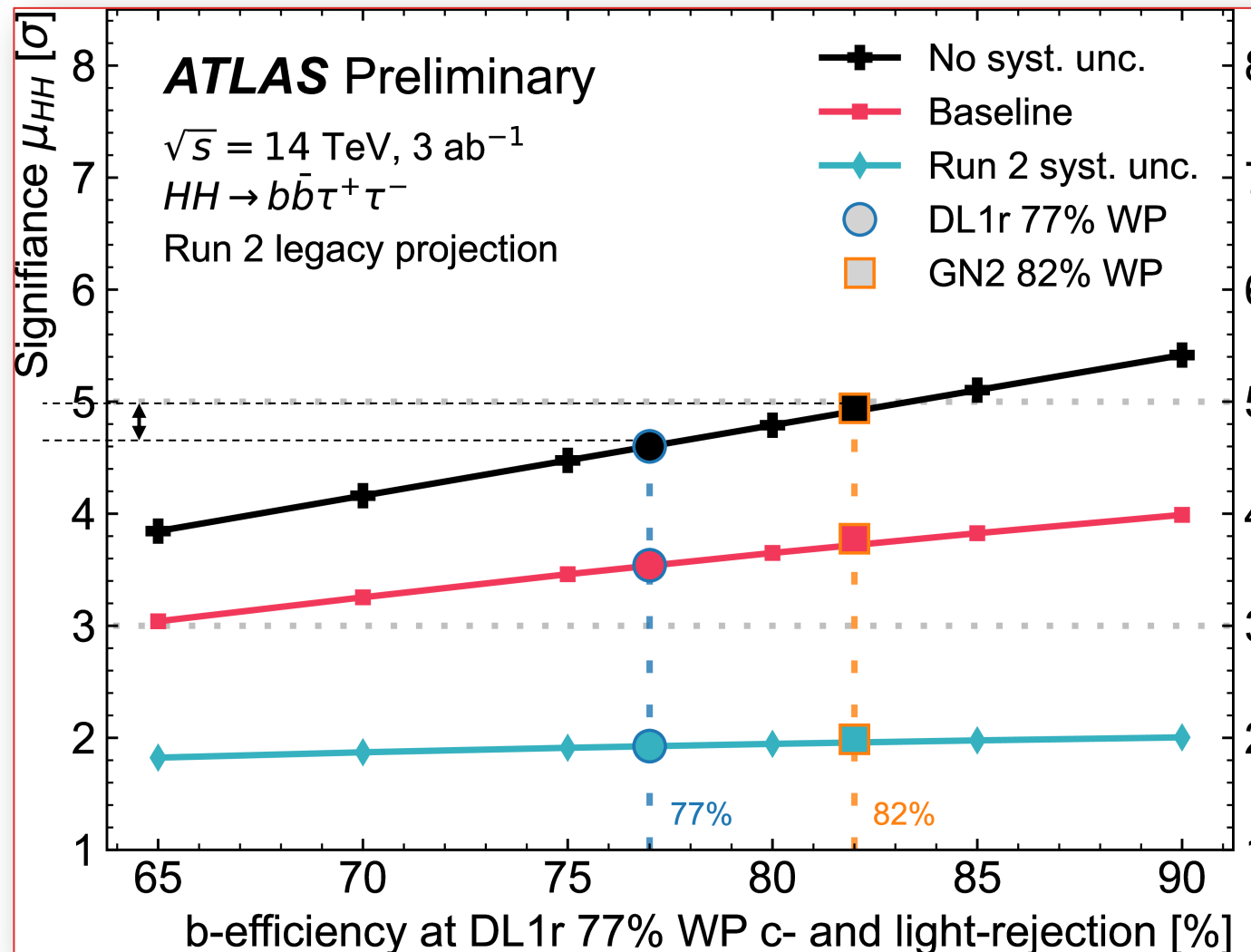
$0.5 \lesssim \kappa_\lambda \lesssim 1.6$ at 1σ

HOW BETTER CAN WE DO?

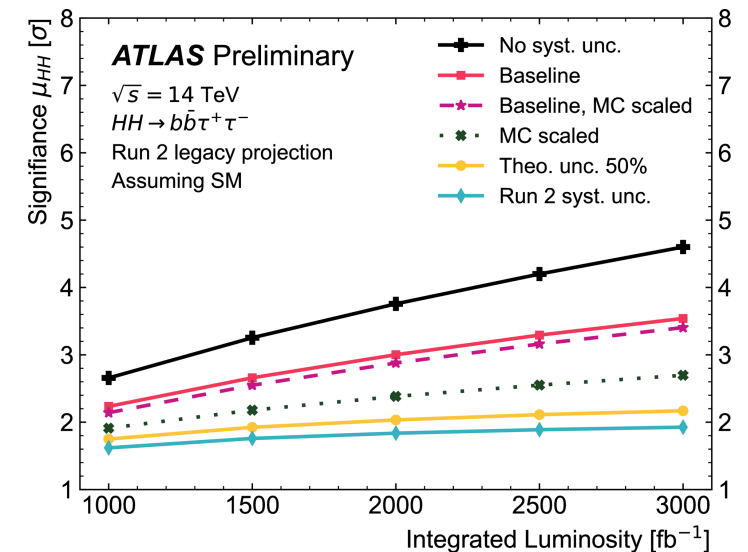


e.g. 77% to 82% $\rightarrow$
 $\sim 0.3\sigma$ improvement
 (more than
 500 fb⁻¹ of data!)

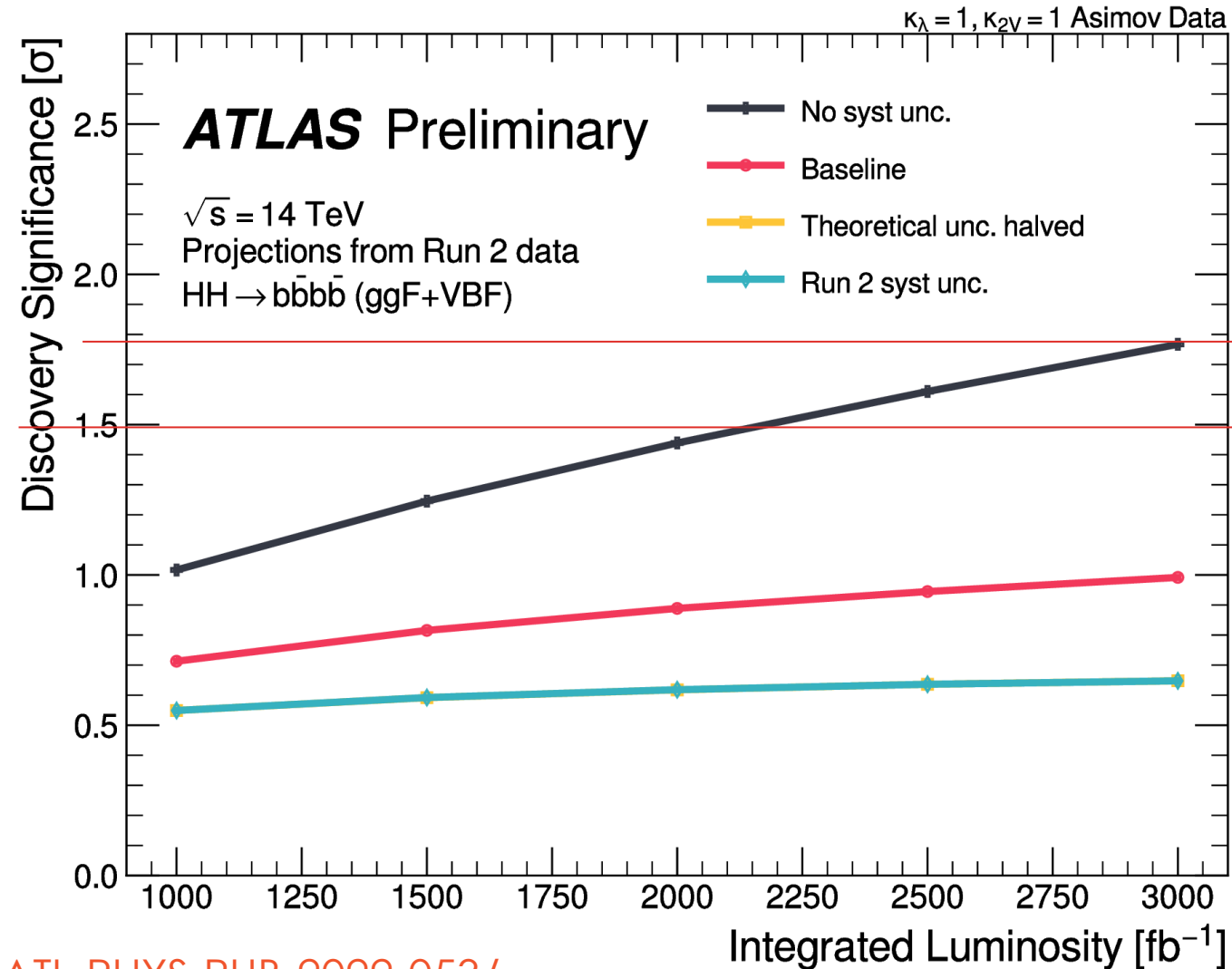
HOW BETTER CAN WE DO?



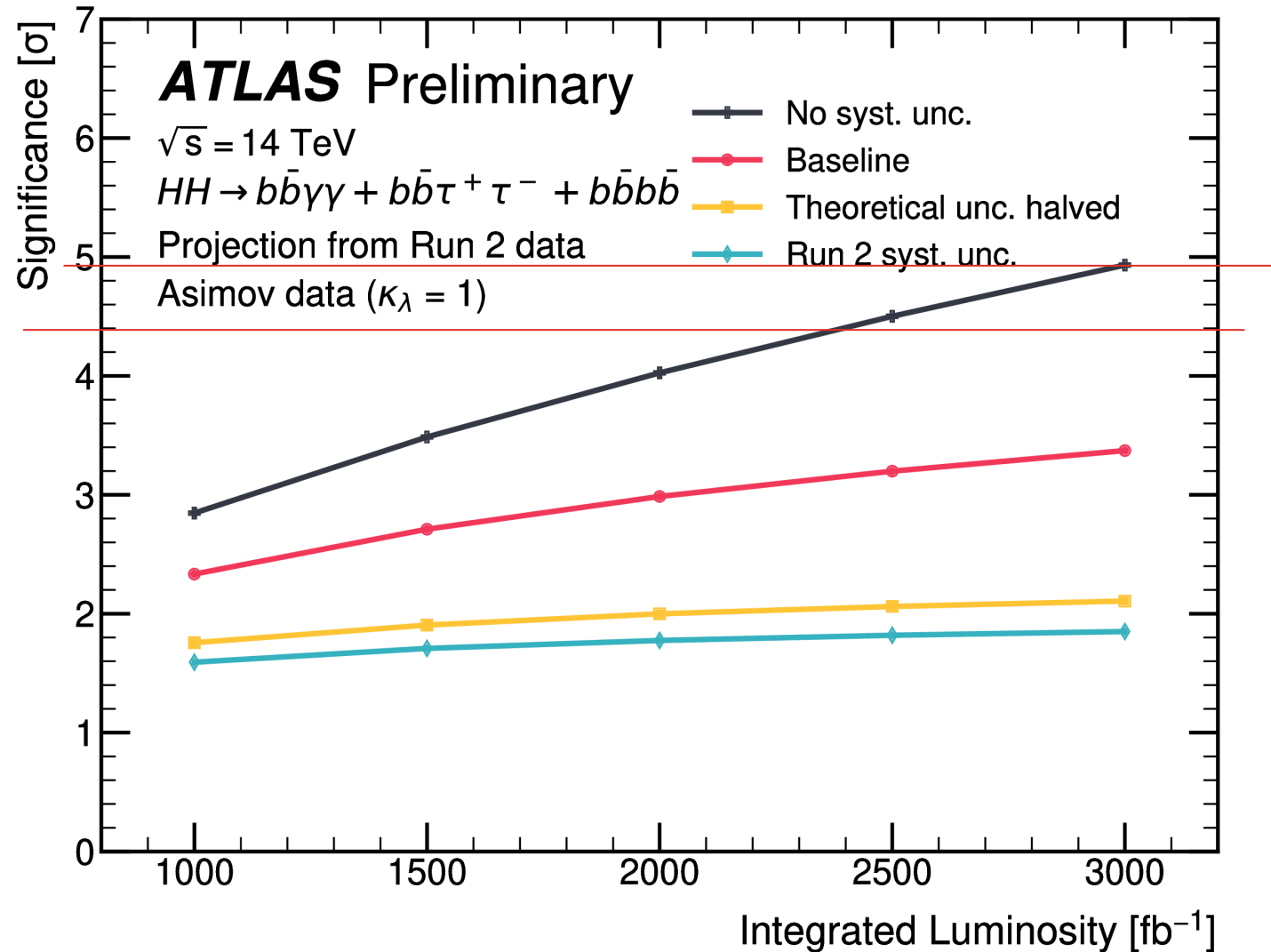
e.g. 77% to 82% $\rightarrow$
 $\sim 0.3\sigma$ improvement
 (about
 500 fb $^{-1}$ of data!)



HOW DOES HH LOOK IN HL-LHC?

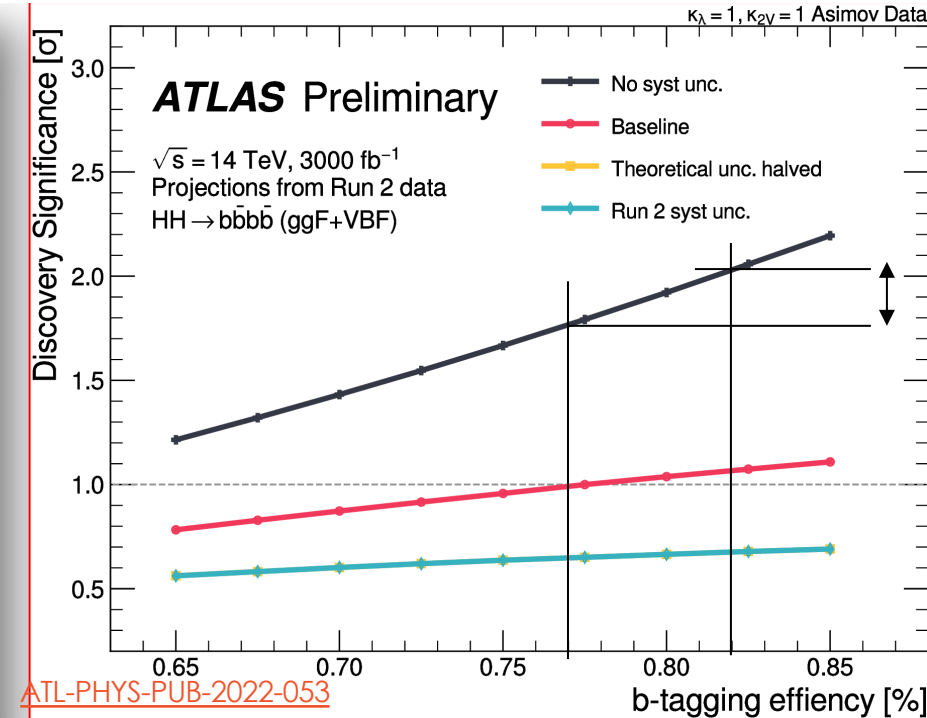
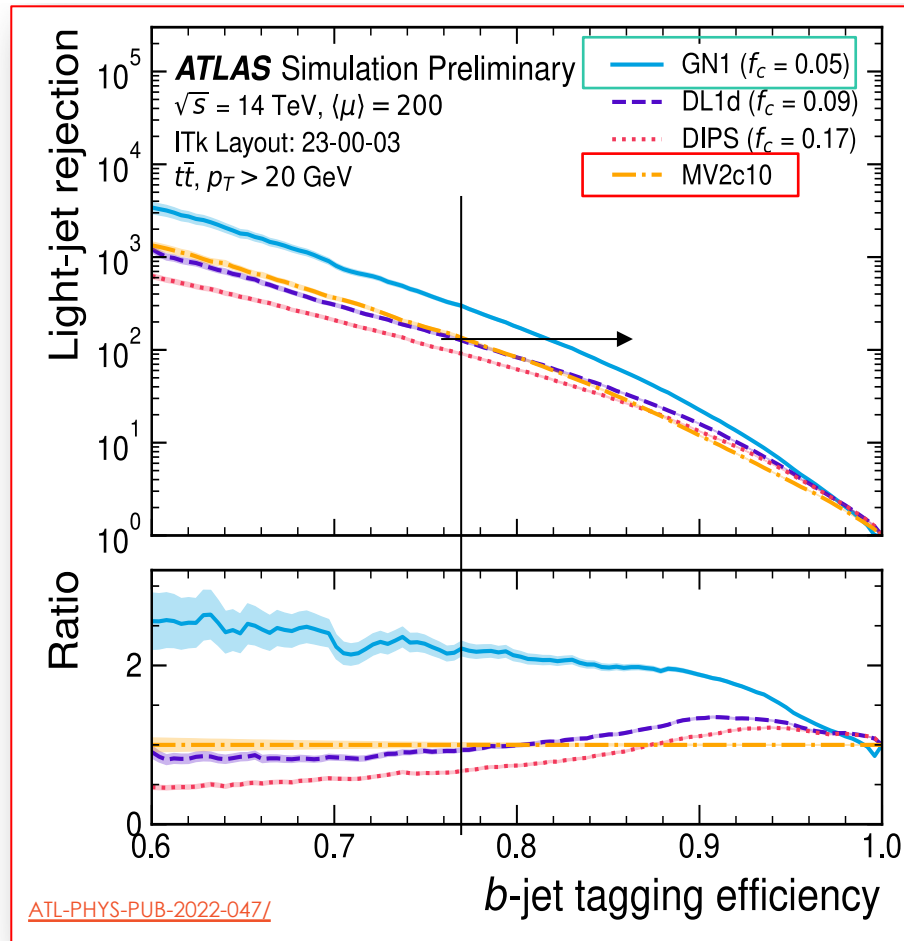


HOW DOES HH LOOK IN HL-LHC?



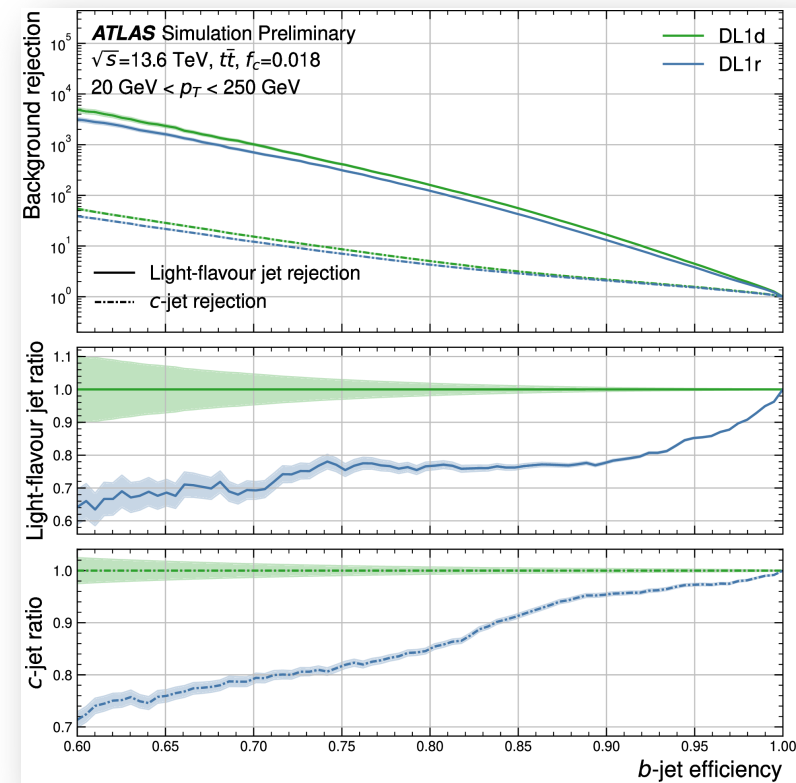
HOW DOES HH LOOK IN HL-LHC?

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

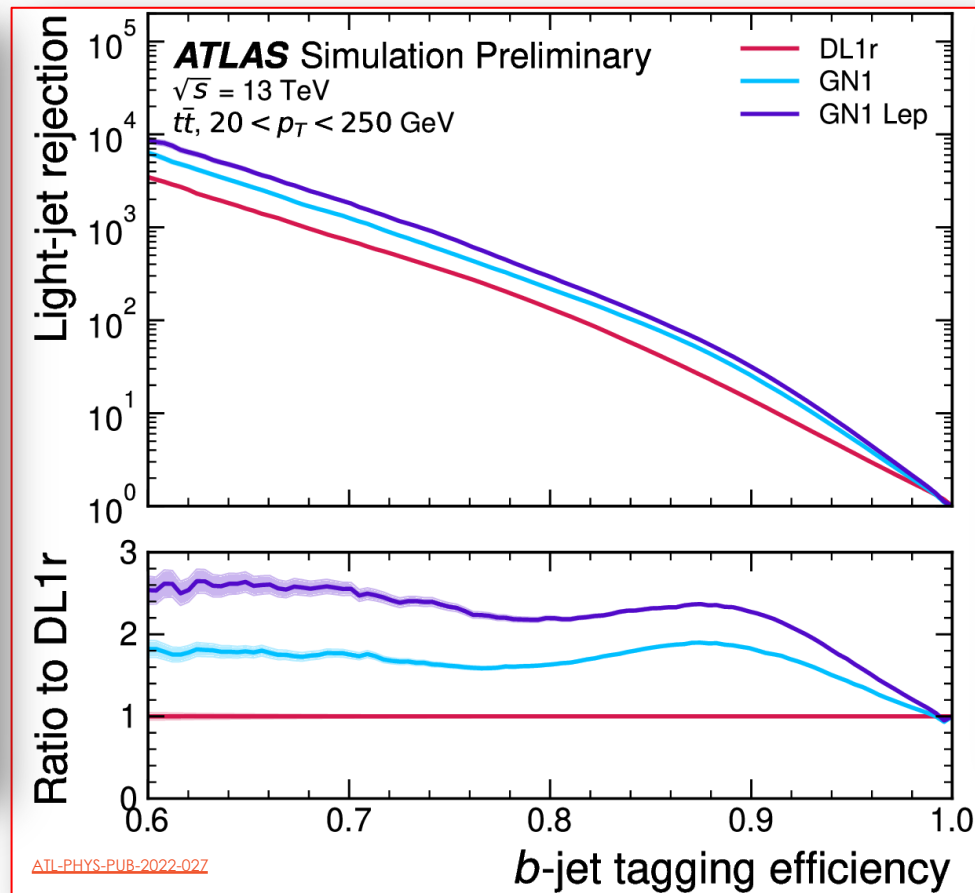


+ 5% efficiency for the same mistag rate → + 0.3 σ sensitivity gain for $HH \rightarrow b\bar{b}b\bar{b}$

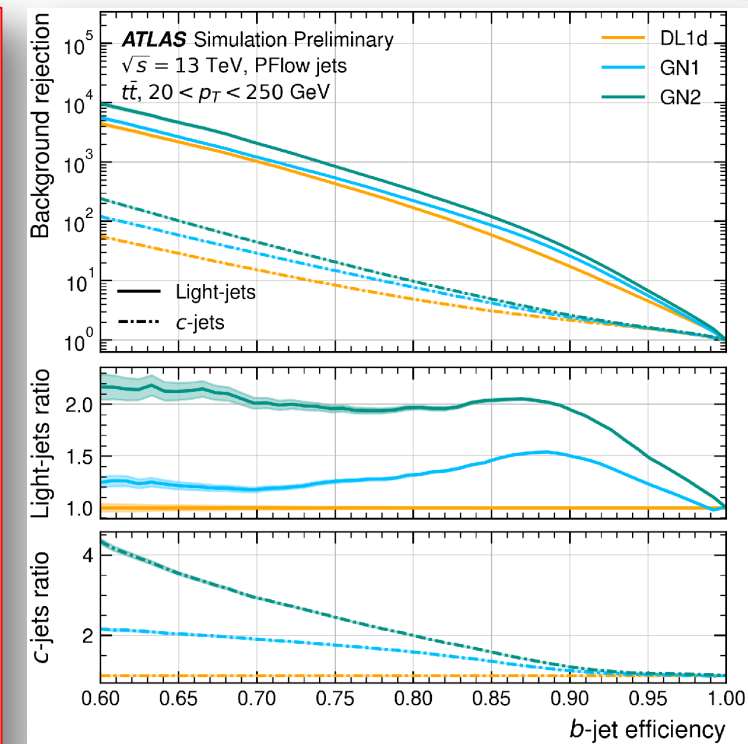
RUN 3 *b*-TAGGING



[FTAG-2022-004/](#)



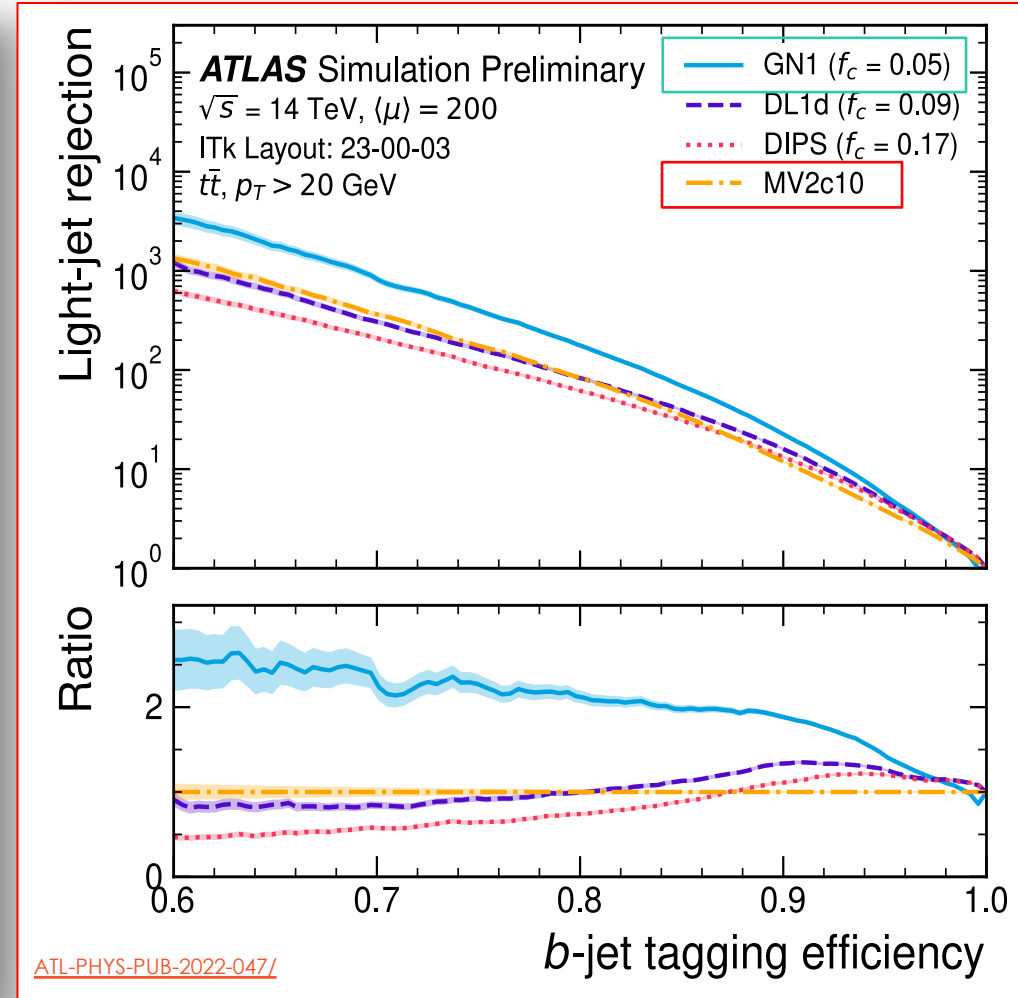
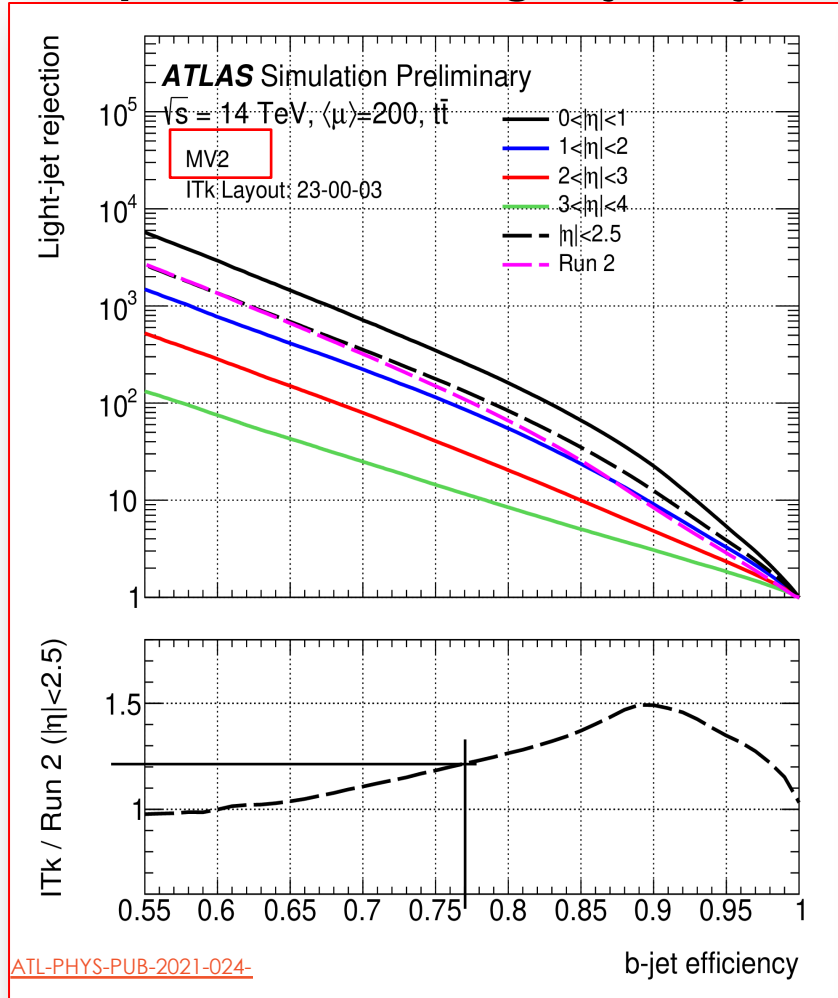
[ATL-PHYS-PUB-2022-027](#)



[FTAG-2023-01/](#)

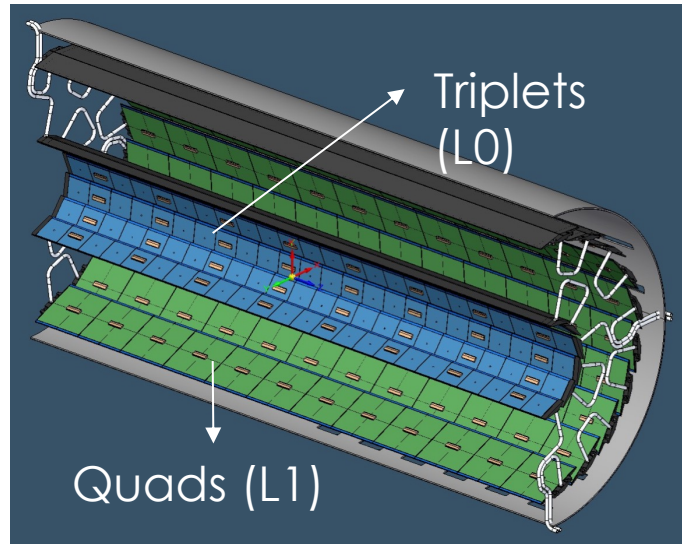
ITK BTAGGING

Moder taggers based on **Graph Neural Networks** further exploit the potential of the ITk: **up to x2 improvement in light-jet rejection!**

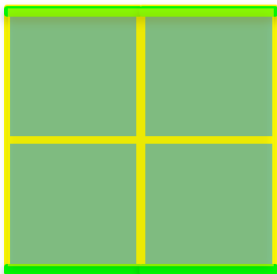


ITK

Barrel Staves



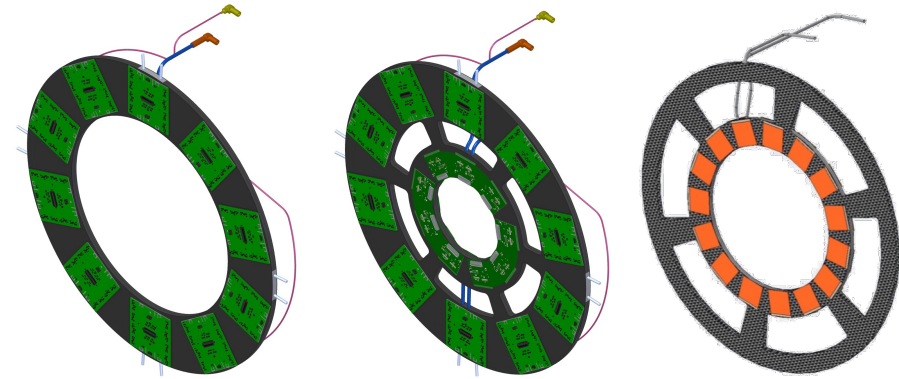
Quads (L1)



Triplets (L0)



Endcap Rings

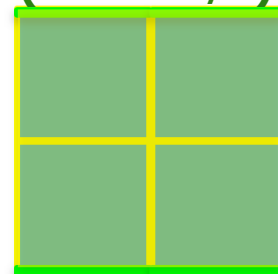


R1

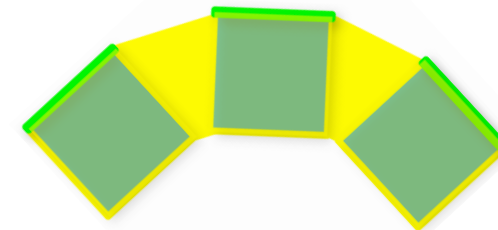
R0/1
coupled

R0.5
intermediate

Quads
(R1 & R0/1)



Triplets
(R0.5 & R0/1)

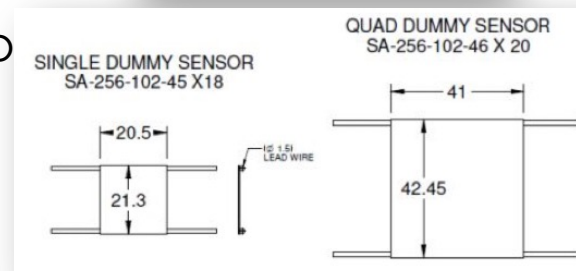
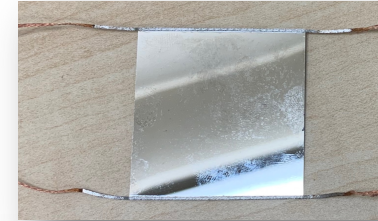


Validate Local Support design and loading procedure

Thermo-mechanical prototype

- Load with dummy modules
 - silicon heaters with platinum coating
 - power to dissipate 0.7 W/cm^2 (chip end-on)
 - measure *Thermal Figure of Merit*
- R0/1 coupled ring and L0 stave

Heaters



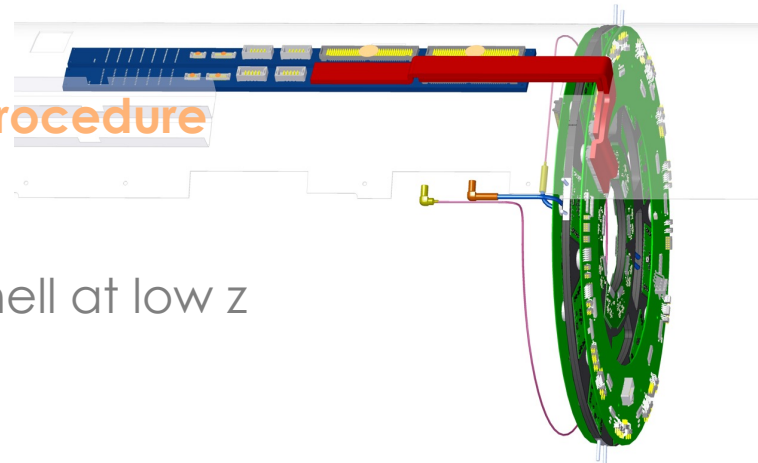
Electrical prototype

- Load with RD53A modules
- R0/1 coupled ring, L0 stave, L1 stave

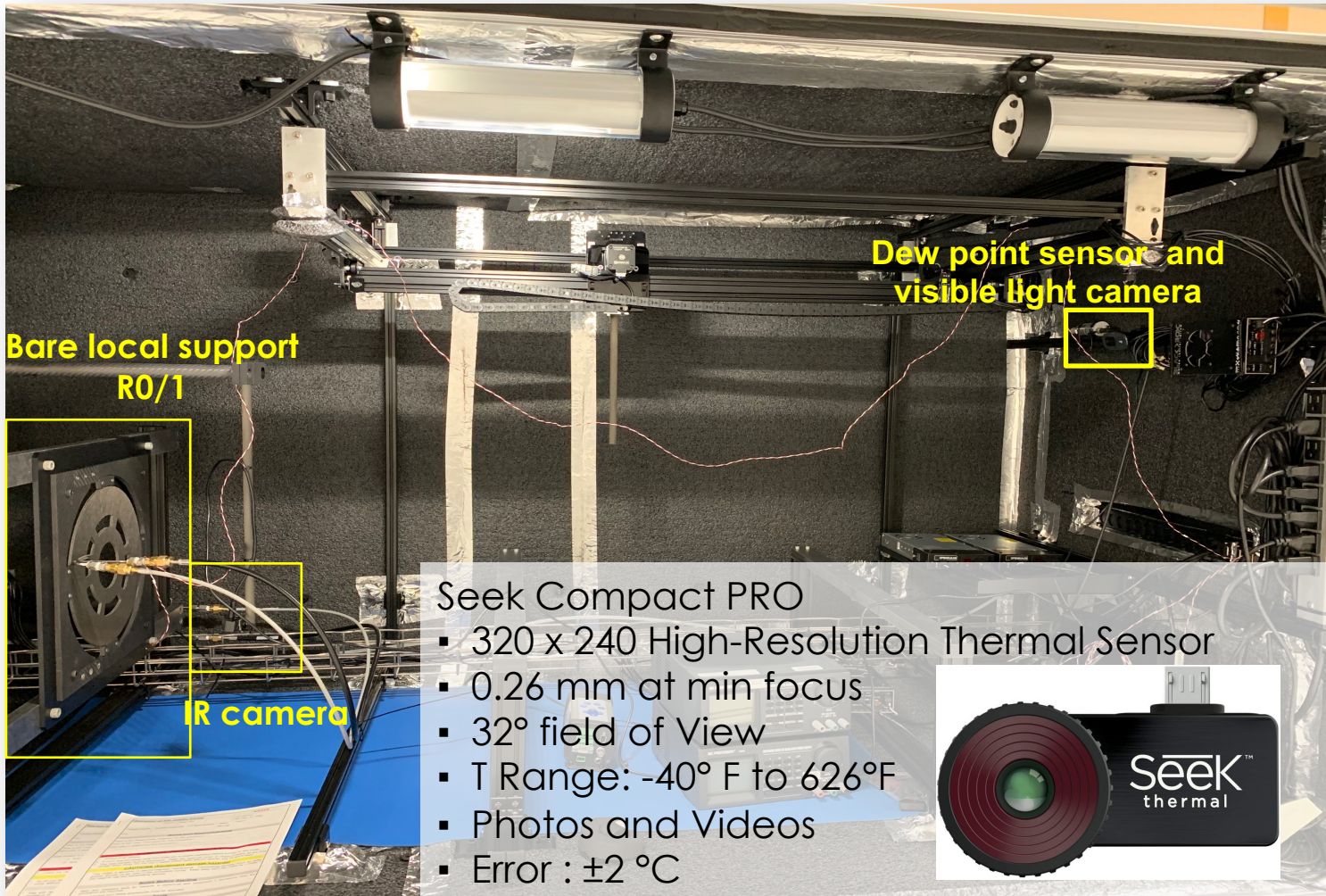
Validate Local Support design and loading procedure

Integration prototypes

- Integrate electrical prototype in quarter shell at low z
- Integrate additional stave/ring flavors



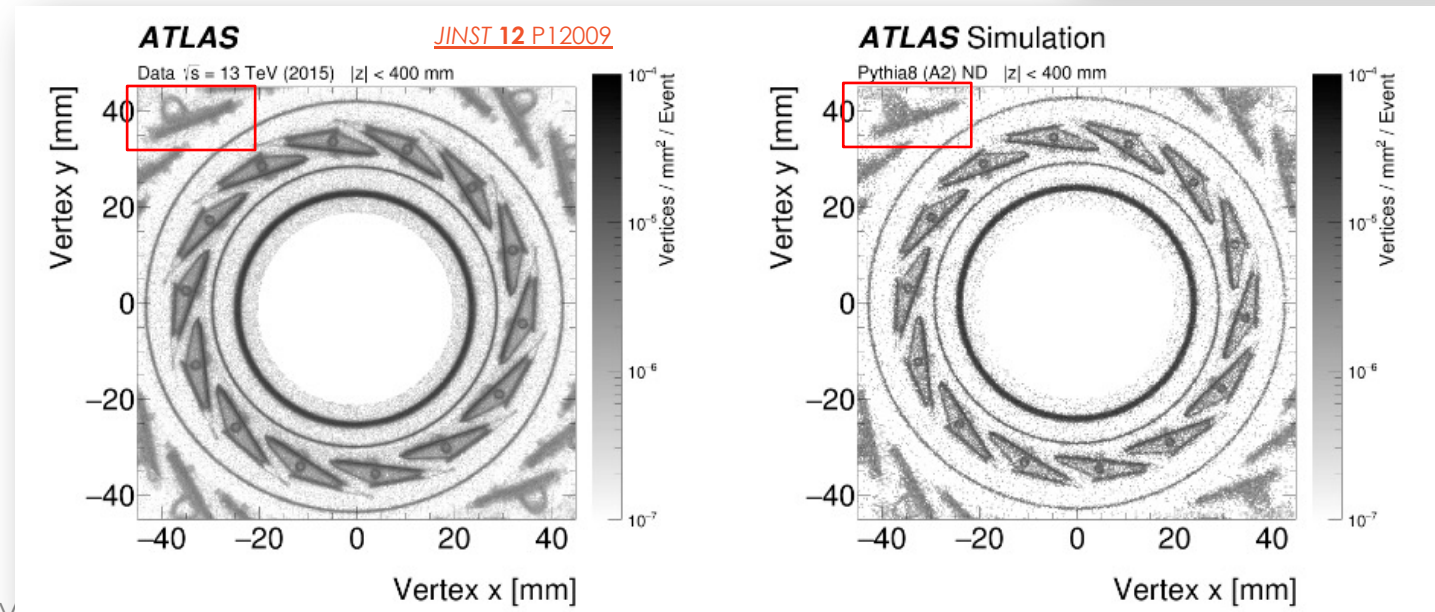
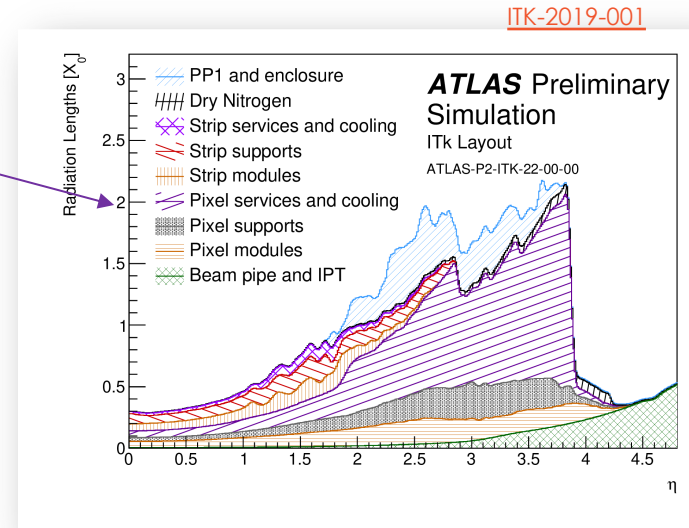
- Test box details



LESSONS FROM THE PAST

04.12.24

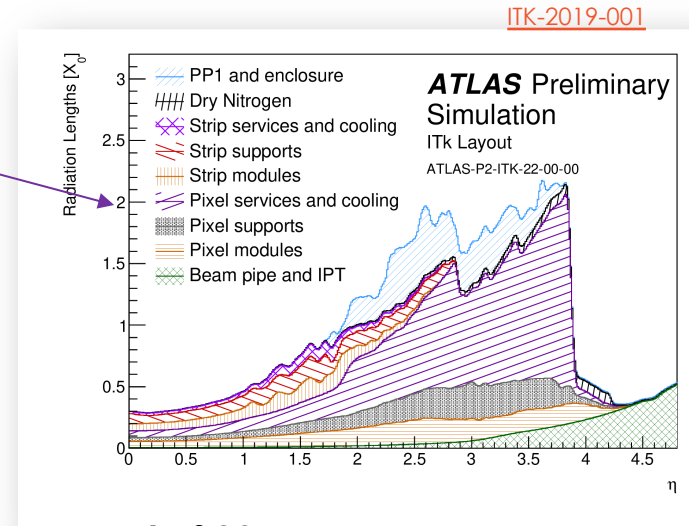
- Every small detail in construction plays a role later on in performance
- **Large amount of material in the tracker from Pixel services and cooling**
- Estimated a priori, but requires data-driven methods during actual operation
- **Many lessons learned after IBL installation**
 - Hadronic interactions & photon conversions
 - Track extension efficiency



Cooling fluid
incorrectly
modelled in
simulation

LESSONS FROM THE PAST

- Every small detail in construction plays a role later on in performance
- **Large amount of material in the tracker from Pixel services and cooling**
- Estimated a priori, but requires data-driven methods during actual operation
- **Many lessons learned after IBL installation**
 - Hadronic interactions & photon conversions
 - Track extension efficiency



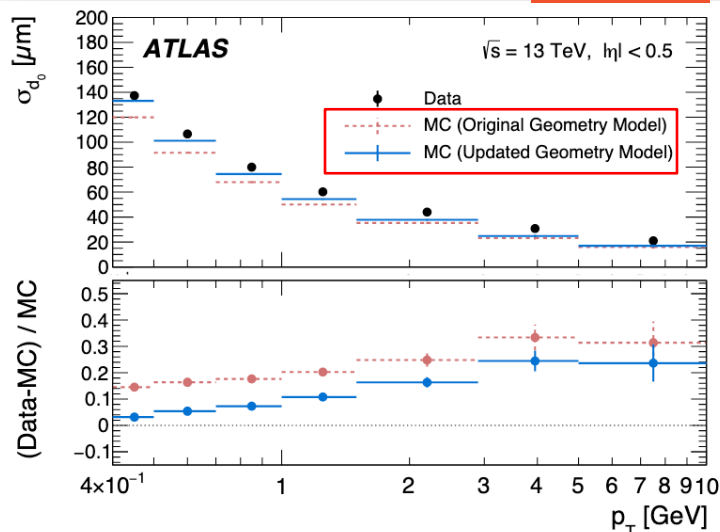
End of 2015

Track Reconstruction Efficiencies and Systematic Uncertainties				
Track Quality Selection	Loose		Tight Primary	
η Range	$ \eta \leq 0.1$	$2.3 \leq \eta \leq 2.5$	$ \eta \leq 0.1$	$2.3 \leq \eta \leq 2.5$
Track Reconstruction Efficiency	91%	73%	86%	63%
$Sys_{+5\%Extra}$	0.4%	0.9%	0.5%	1.1%
$Sys_{PixServExtra}$	—	2.0%	—	2.3%
$Sys_{+30\%IBLExtra}$	0.2%	0.5%	0.2%	0.5%
Total Systematic Uncertainty	0.4%	2.2%	0.5%	2.6%

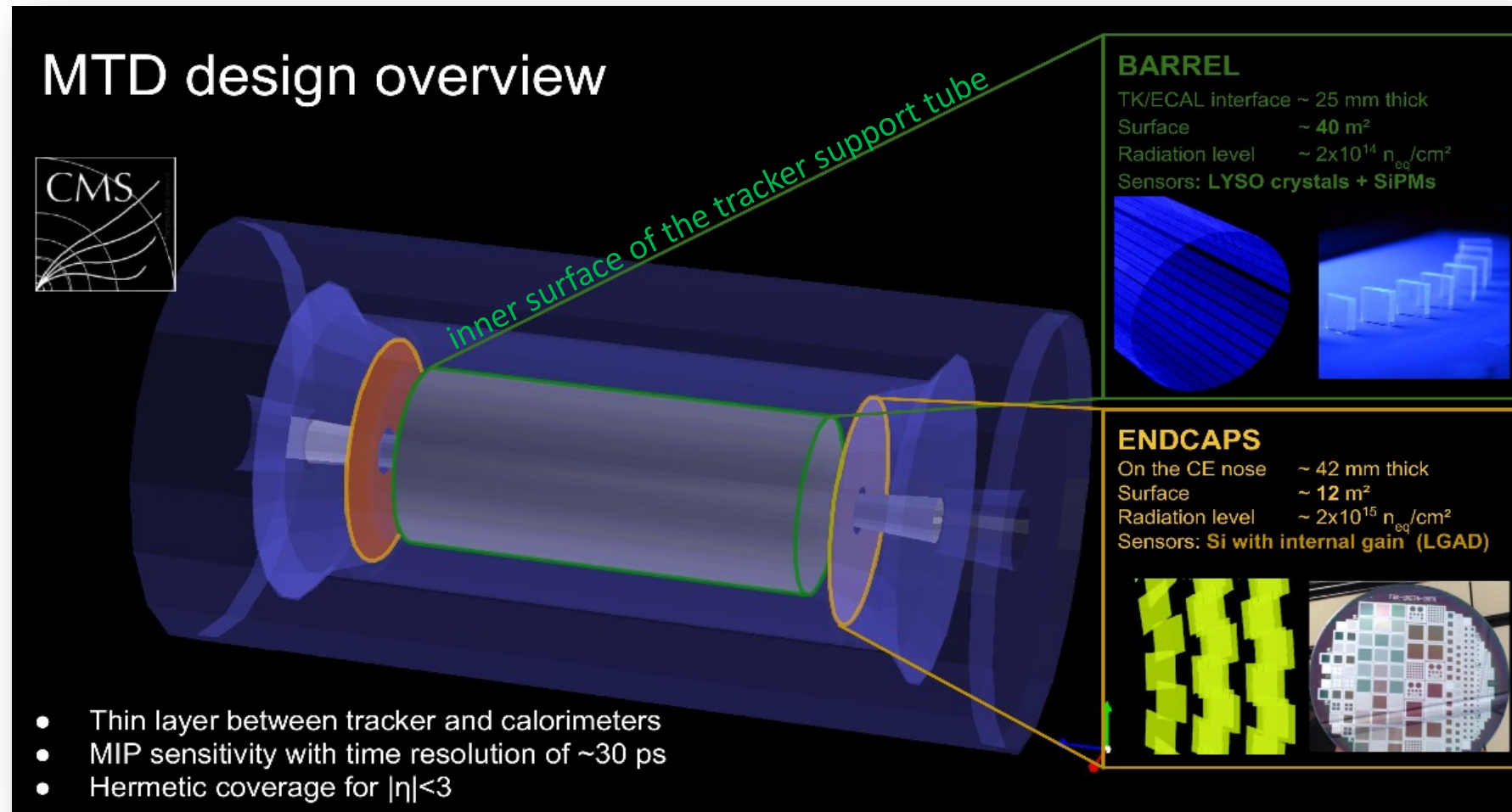
Beginning of 2018

Updated (release 21) Track Reconstruction Efficiencies and Systematic Uncertainties				
Track Quality Selection	Loose		Tight Primary	
η Range	$ \eta \leq 0.1$	$2.3 \leq \eta \leq 2.5$	$ \eta \leq 0.1$	$2.3 \leq \eta \leq 2.5$
Track Reconstruction Efficiency	90%	71%	85%	61%
$Sys_{+5\%Extra}$	0.3%	1.0%	0.4%	1.2%
$Sys_{PixServExtra}$	—	1.1%	—	1.4%
$Sys_{IBLExtra}$	0.1%	0.2%	0.1%	0.1%
$Sys_{PhysModel}$	0.2%	0.1%	0.1%	0.1%
Total Systematic Uncertainty	0.4%	1.5%	0.5%	1.8%

JINST 12 P12009



CMS' MIP TIMING DETECTOR



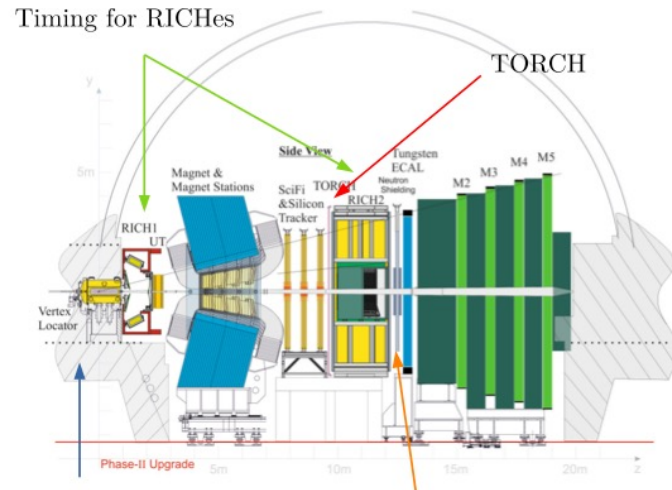
$|\eta| < 1.5$

$1.5 < |\eta| < 3.0$

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

LHCb UPGRADE II

Framework [TDR](#), R. Quagliani's [slides](#), T. Evans' [slides](#)



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

5D calorimetry $\rightarrow$ PicoCal

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

- Huge data rates ($> 50\text{Tb/s}$ for whole detector, $> 100\text{kHz}$ for hottest pixels)
 - Extreme radiation tolerance ($> 2 \times 10^{16} n_{eq}/\text{cm}^2$)
- and
- Keeping excellent spatial resolution ($\sim 10\mu\text{m}$) $\Rightarrow$ low material budget

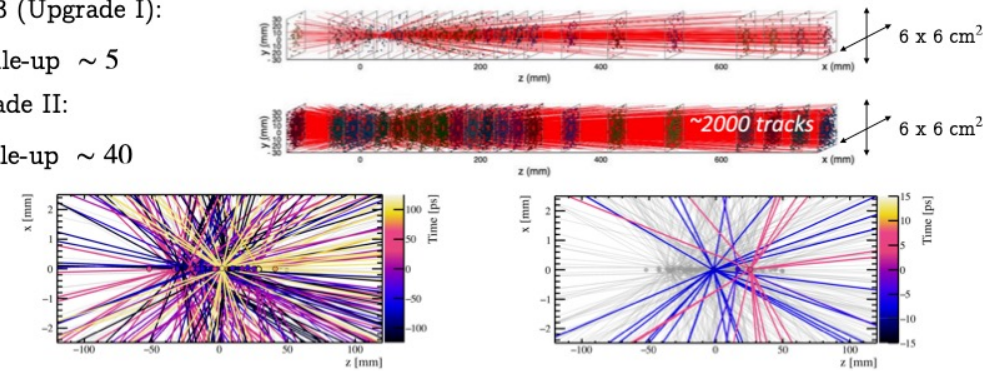
- ▶ [Ensure PV finding/association of tracks/displacement signatures at the core of LHCb physics program](#) ▶ Including timing information is mandatory for **VELO**

- ▶ Run 3 (Upgrade I):

- pile-up ~ 5

- ▶ Upgrade II:

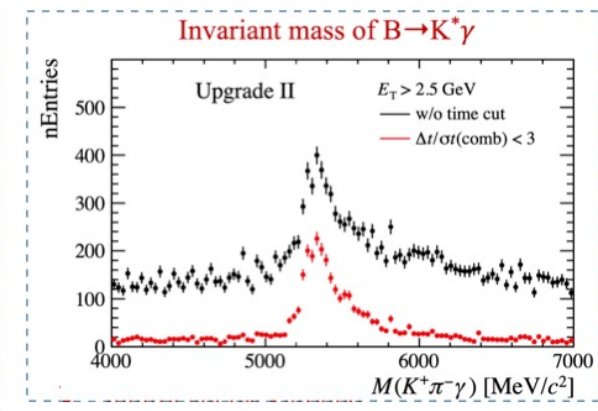
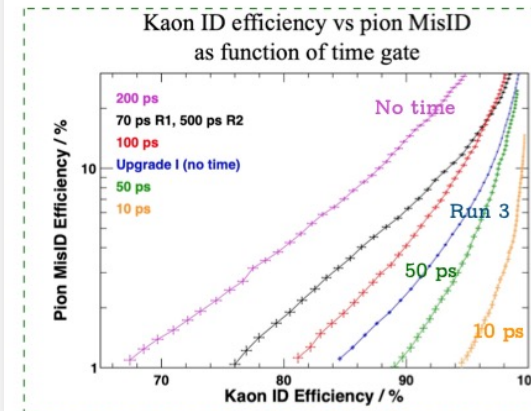
- pile-up ~ 40



“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

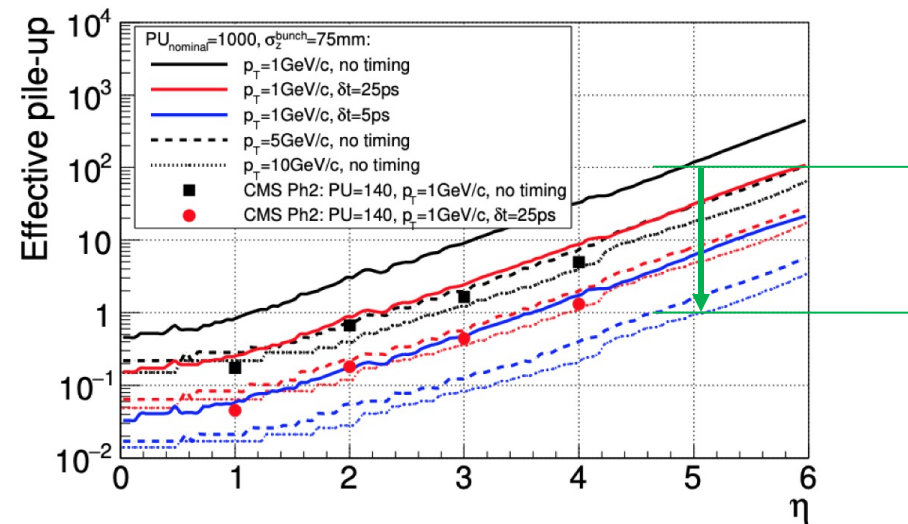
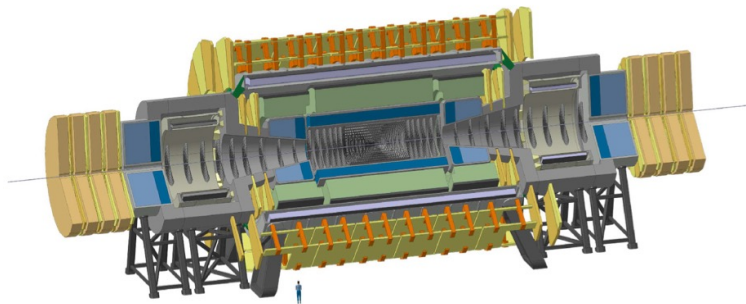


Figure 1: From Ref. [9]. An effective pile-up in the FCC-hh tracker. Several options of timing resolution per track in 3D vertexing are assumed: no timing (black), $\delta t = 25$ ps (red) and $\delta t = 5$ ps (blue). Several p_T values are shown: 1 GeV/c (solid), 5 GeV/c (dashed) and 10 GeV/c (dotted).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

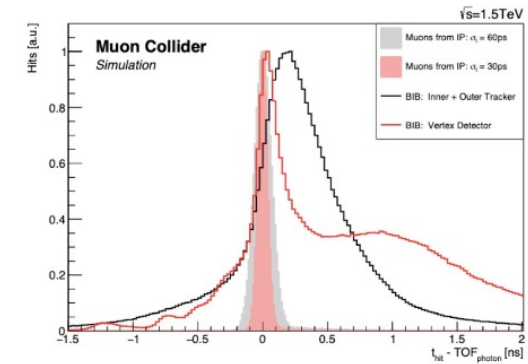
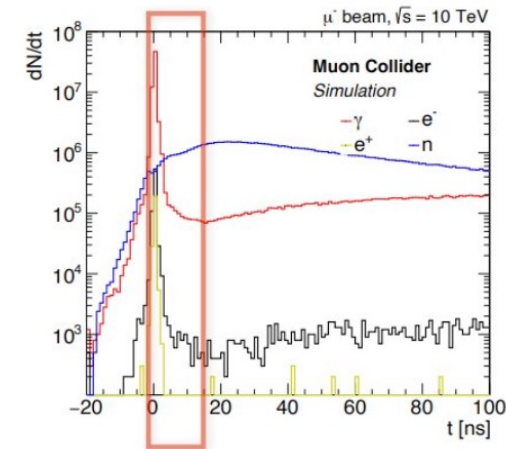
Extreme timing resolution of 5 - 10 ps per track is essential to keep the effective pileup low and prevent the merging of unrelated vertices

BEYOND HADRON COLLIDERS

FUTURE μ COLLIDERS

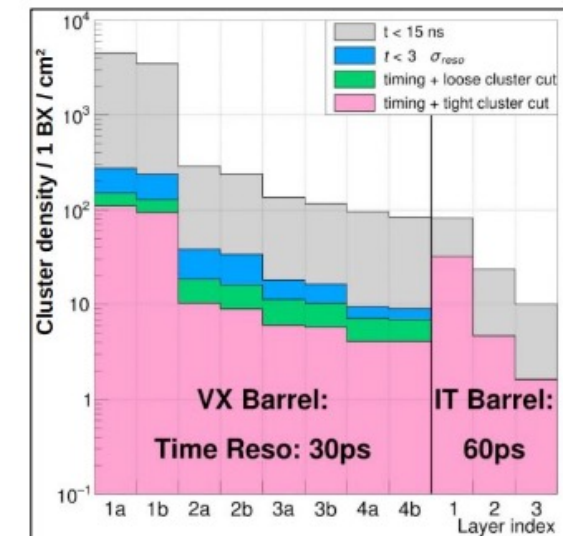
See more [here](#)

- 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 Units	Technology	# Layers /Rings	"Cell" Size μm^2	Sensor Thickness μm	Hit Time Resolution ps	Signal Time Window 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

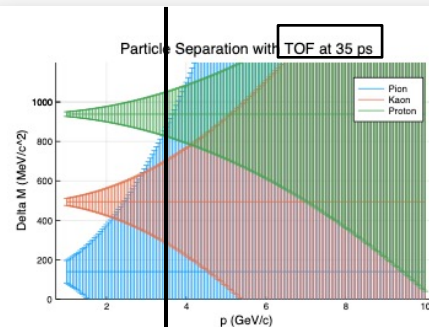


FIG. 15: Mass resolution for a TOF system with HL-LHC level performance of 35 ps time resolution in SiD

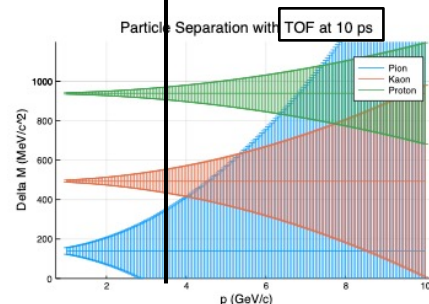
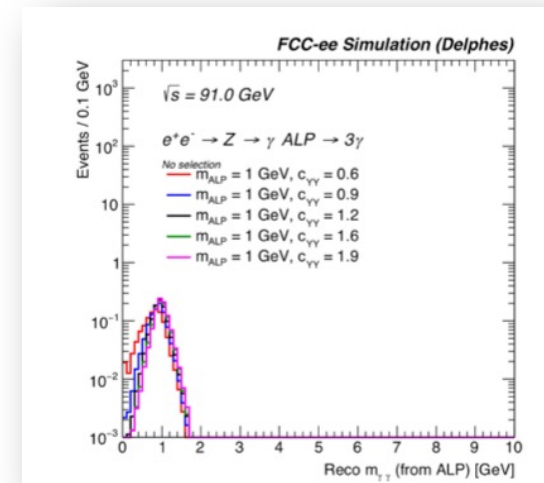


FIG. 16: Mass resolution for a TOF system with a performance of 10 ps in SiD

LLP @ FCC-ee

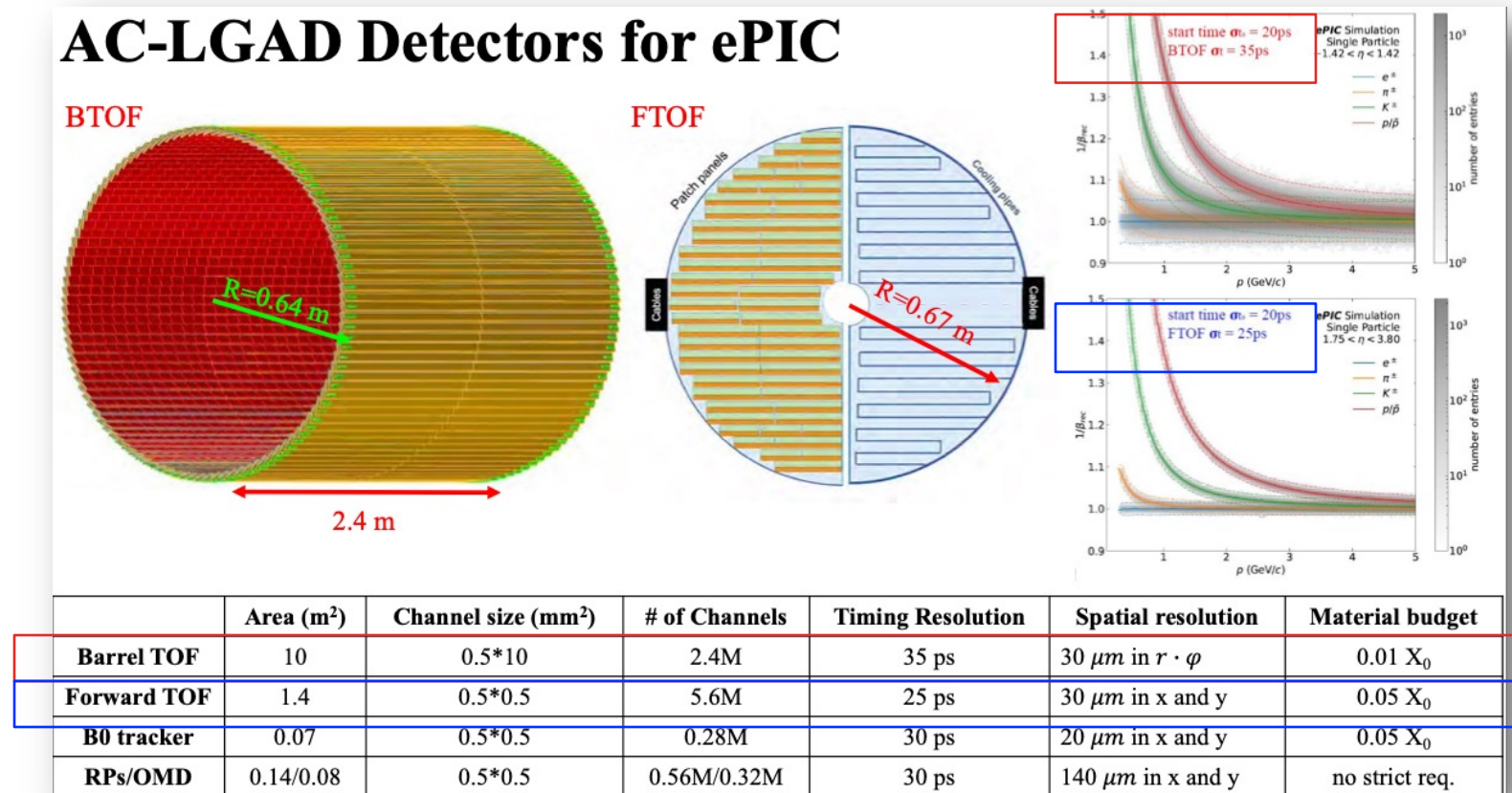
Heavy neutral leptons, **axion-like particles**, and exotic Higgs boson decays



"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](#)

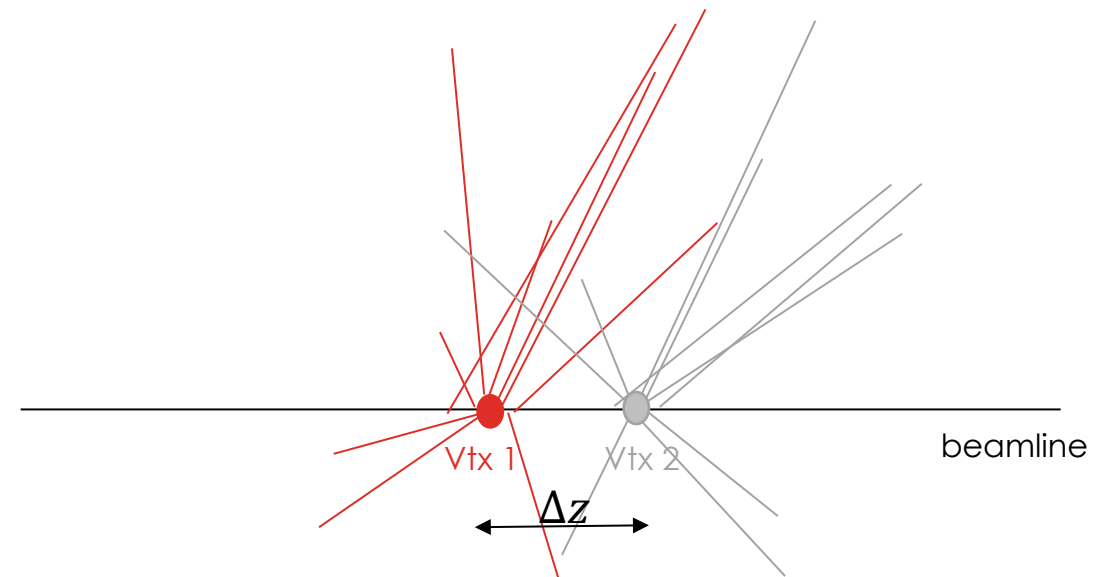
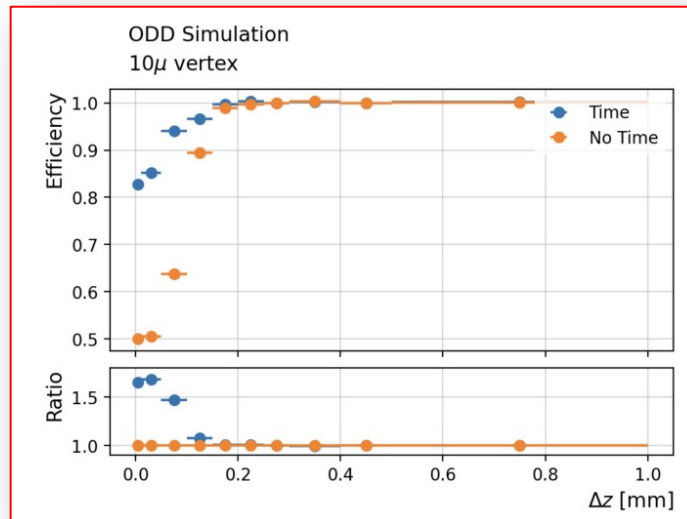
- The Electron-Ion Collider (2031+) is among the highest priority of US Nuclear Physics
- Electron-Proton and -Ion Collider detector (ePIC) concept includes PID capabilities via AC-LGAD layers (also vertex identification for far-forward hadrons)



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 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 $\rightarrow$ $\gamma\gamma$ and H $\rightarrow$ 4 leptons	+15–25% (statistical) precision on the cross section $\rightarrow$ Improve coupling measurements	Isolation and Vertex identification
VBF $\rightarrow$ H $\rightarrow$ $\tau\tau$	+30% (statistical) precision on cross section $\rightarrow$ Improve coupling measurements	Isolation VBF tagging, p_T^{miss}
HH	+20% gain in signal yield $\rightarrow$ Consolidate searches	Isolation b-tagging
EWK SUSY	+40% background reduction $\rightarrow$ 150 GeV increase in mass reach	MET b-tagging
Long-lived particles (LLP)	Peaking mass reconstruction $\rightarrow$ 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.

A WORD ON TECHNOLOGY

- Technology that could potentially match the requirements **starts to arise**, but still **requires a lot of R&D**
- Radiation Hardness is a key challenge!**
- 4D Tracking White Paper for Snowmass reviews state of the art and R&D for use-cases and technologies at e+e- and hadronic colliders**
 - <https://arxiv.org/abs/2203.13900>
- CERN-SLAC collaboration on electronics**, also in connection with CERN 28 nm forum



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

V. Cairo^{1,***}, A. Dragone¹, A. Gupta¹, B. Markovic^{1,*}, A. Pena-Perez¹, L. Rota¹, L. Ruckman¹, A. Schwartzman^{1,***}, D. Su¹, C. Vernieri¹

¹SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA
²CERN, Conseil Européen pour la Recherche Nucléaire, 1211 Geneva 23, Switzerland

*markovic@slac.stanford.edu
**sch@slac.stanford.edu
***valentina.maria.cairo@cern.ch

Introduction

Precision timing at 10ps levels will be transformative at future collider experiments. In case of high-energy, high-luminosity hadron colliders, including Run/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.

Voltage-Controlled Delay Cell

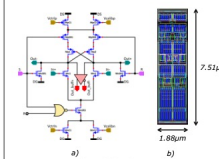


Fig. 4: Delay cell a) schematic, b) layout.

- 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.

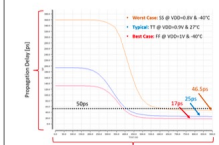


Fig. 5: Simulated (DCV) delay-voltage characteristic at different process corners, supply voltages and temperatures

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-dimensional trackers along with an 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

Larger-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.

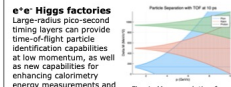


Fig. 1: Timing resolution for a time-of-flight system with a performance of 10 ps in SiO₂.

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.

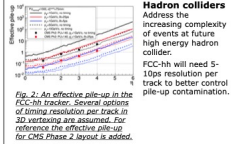


Fig. 2: An effective pile-up in the FCC-hh tracker. Several additions of timing resolution per track in 2D vertexing are assumed. For reference, the effective pile-up for CMS Phase 2 layout is added.

Muon Collider

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

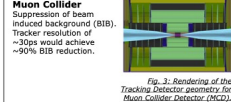


Fig. 3: Rendering of the Tracking Detector geometry for Muon Collider Detector (MCD).

TDC Architecture

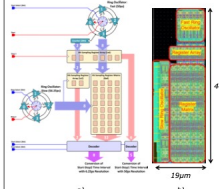


Fig. 6: a) TDC block schematic b) TDC core layout

- 2D Vernier Architecture;
- Fast Ring Oscillator with 50ps propagation delay cells;
- Slow Ring Oscillator with 56.25ps propagation delay cells;

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.

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

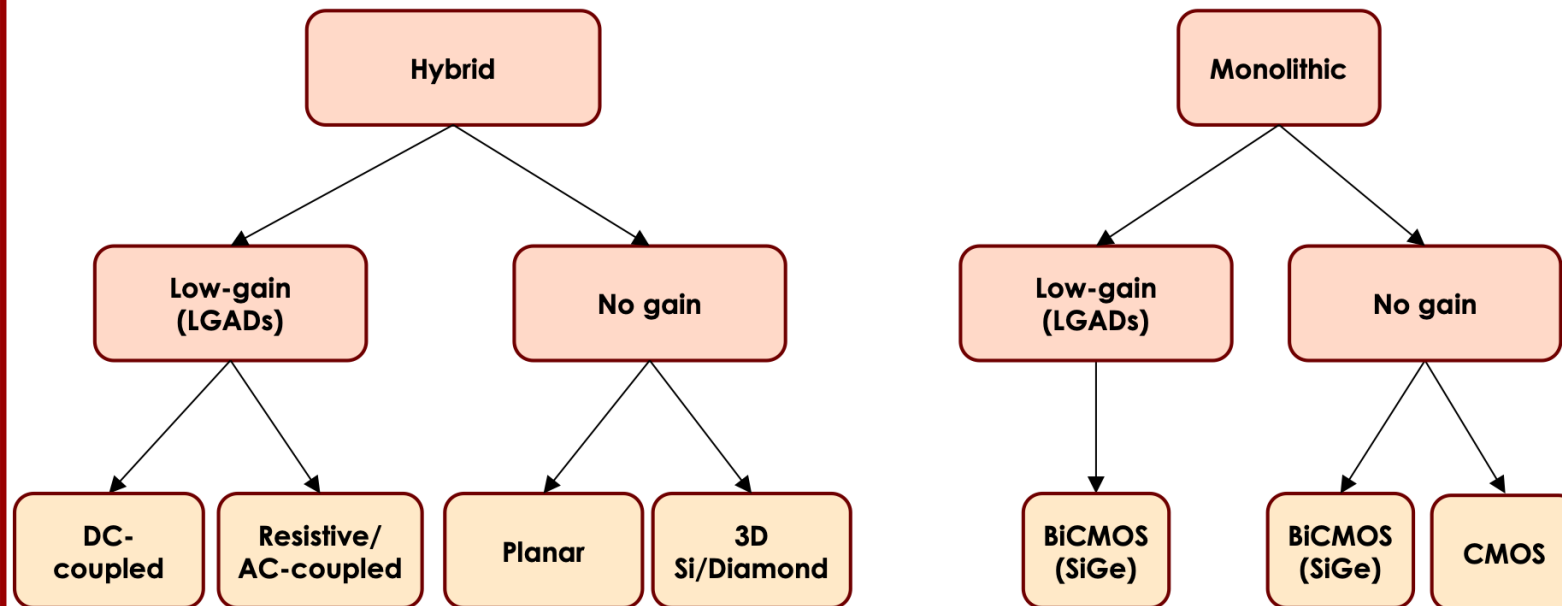
A WORD ON TECHNOLOGY

- 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 $\mathcal{O}(30)$ mm from the IP and will receive doses of $\mathcal{O}(10)$ MGy after 2 ab^{-1} of data
 - At FCC-hh, radius of $\mathcal{O}(20)$ 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

A WORD ON TECHNOLOGY

Presently explored options

The present R&D in position sensitive timing detectors shows the same variety that is present in standard silicon sensors. In the following, I will cover a few examples from this chart.



9

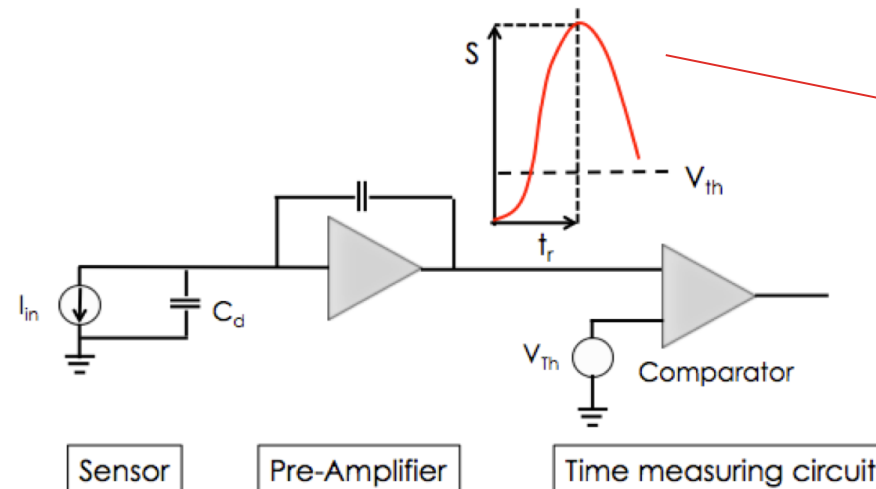
https://indico.cern.ch/event/797047/contributions/3638198/attachments/2308674/3928223/Position_sensitive_timing.pdf

TIMING DETECTORS



Silicon time-tagging detector

(a simplified view)



the time of a hit is set when the signal reaches a certain value V_{th} .

Time is set when the signal crosses the comparator threshold

The timing capabilities are determined by the characteristics of the signal at the output of the pre-Amplifier and by the TDC binning.

Generate extra heat compared to a space only tracker

Strong interplay between sensor and electronics

TIMING DETECTORS

Nuclear Inst. and Methods in Physics Research, A 1040 (2022) 167228

Table 1

Compilation of front-end ASICs and monolithic systems. The first 5 systems use an hybrid design, the bottom 4 are monolithic. The first 4 systems are very advanced or completed, while the bottom 5 are in their R&D phase, so performances might change rapidly.

Name	Sensor	Node [nm]	Pixel size [μm^2]	Temporal precision [ps]	Power [W/cm ²]
ETROC	LGAD	65	1300 × 1300	~ 40	0.3
ALTIROC	LGAD	130	1300 × 1300	~ 40	0.4
TDCpix	PIN	130	300 × 300	~ 120	0.32 matrix + 4.8 periphery
TIMEPIX4	PIN, 3D	65	55 × 55	~ 200	0.4 analog + 0.3 digital
TimeSpot1	3D	28	55 × 55	~ 30 ps	3–5
FASTPIX	MAPS	180	20 × 20	~ 130	5–10
miniCACTUS	MAPS	150	500 × 1000	~ 90	0.15–0.3
MonPicoAD	MAPS	130 SiGe	100 × 100	~ 36	1.8
Monolith	Multi Junct. MAPS	130 SiGe	100 × 100	~ 25	0.9

TIMING DETECTORS

<https://arxiv.org/abs/2203.13900>

Table 1: Requirements for state-of-the-art readout chips designed for timing (ALTIROC [1] and ETROC [2]) and for pixel detectors (RD53A / CMS Phase II tracker [28, 67].)

ASIC	Technology	Pitch	Total size	Power consumption	TID tolerance
ALTIROC	130 nm	1.3 mm	$19.5 \times 19.5 \text{ mm}^2$	5 mW/chan	2 MGy
ETROC	65 nm	1.3 mm	$20.8 \times 20.8 \text{ mm}^2$	3 mW/chan	1 MGy
RD53A/HL-LHC pixels	65 nm	50 μm	$20 \times 11.6 \text{ mm}^2$	< 10 μW /chan	5–15 MGy

TIME RESOLUTION

<https://arxiv.org/abs/2203.13900>

Time resolution is the crucial new ingredient to achieve 4D tracking. In this section a brief introduction to its separate components is discussed. The time resolution of a detector can be expressed as follows:

$$\sigma_{\text{timing}}^2 = \sigma_{\text{timewalk}}^2 + \sigma_{\text{Landau}}^2 + \sigma_{\text{Jitter}}^2 + \sigma_{\text{TDC}}^2 \quad (1)$$

The time walk and Landau resolution components, intrinsic to the sensor, can be reduced respectively with short drift time and limited thickness in the path of a MIP.

The time errors arising from the jitter and the TDC, which are instead related to the readout chip's electronics, benefit respectively from high signal to noise ratio and small TDC bin size.

TIME RESOLUTION

Time resolution is the crucial new ingredient to achieve 4D tracking. In this section a brief introduction to its separate components is discussed. The time resolution of a detector can be expressed as follows:

$$\sigma_{\text{timing}}^2 = \sigma_{\text{timewalk}}^2 + \sigma_{\text{Landau}}^2 + \sigma_{\text{Jitter}}^2 + \sigma_{\text{TDC}}^2 \quad (1)$$

The first two components, time walk and Landau, are intrinsic to the sensor. Time walk refers to the variation of the deposited charge event-by-event, shifting the threshold crossing earlier for larger charges and later for smaller charges. This component can be minimized by either using a variable threshold or a corrected constant threshold. A variable threshold is, for example, the Constant Fraction Discriminator (CFD) where the 20-50% of the pulse maximum is used as the time of arrival. A more common method in integrated electronic chips is to correct the time walk on the time of arrival (TOA) with a calibration based on the time over threshold (TOT), which serves as a proxy for the charge. Beyond variation in the total ionization, the Landau term represents the spatial variation of the deposited charge along the path of a minimum ionizing particle (MIP), as charges from different depths are collected at different times. Since a MIP usually traverses the entire sensor perpendicularly, this component is smaller for thinner devices or sensors with short drift times. In devices where the S/N is high and time walk can be adequately corrected, the irreducible Landau component is usually the limit of the achievable time resolution.

TIME RESOLUTION

The second two components are related to the readout chip's electronics. The jitter is described as

$$\sigma_{Jitter}^2 = \frac{Noise}{dV/dt} \approx \frac{T_{rise}}{S/N} \quad (2)$$

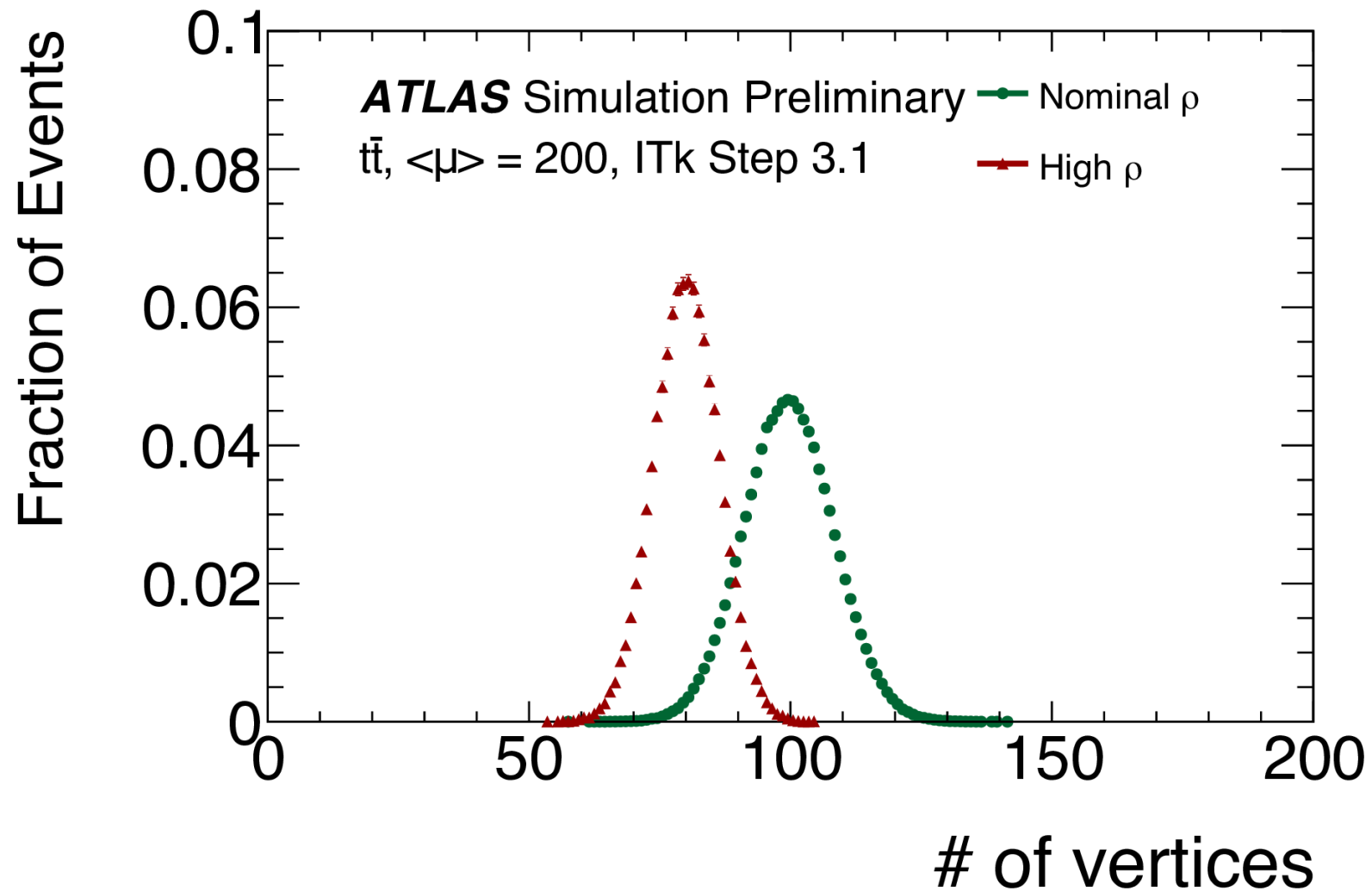
Therefore σ_{Jitter}^2 is proportional to the rise time and inversely proportional to the S/N ratio. Since the rise time is proportional to the drift time of charge carriers in the sensor, again a sensor with short drift time and high signal to noise ratio is advantageous.

The time to digital conversion (TDC) component is related to the readout chip's TDC precision to measure TOA and TOT, given by the quantization bin size. In the case of the planned timing detectors at the HL-LHC, they range between 20ps (ATLAS) and 30ps (CMS) for the TOA TDC, and 40ps (ATLAS) and 100ps (CMS) for the TOT used for the time walk correction. Given that quantization errors are described by an uniform probability density, σ_{TDC}^2 is given by the bin size divided by $\sqrt{12}$ which is about 5ps.

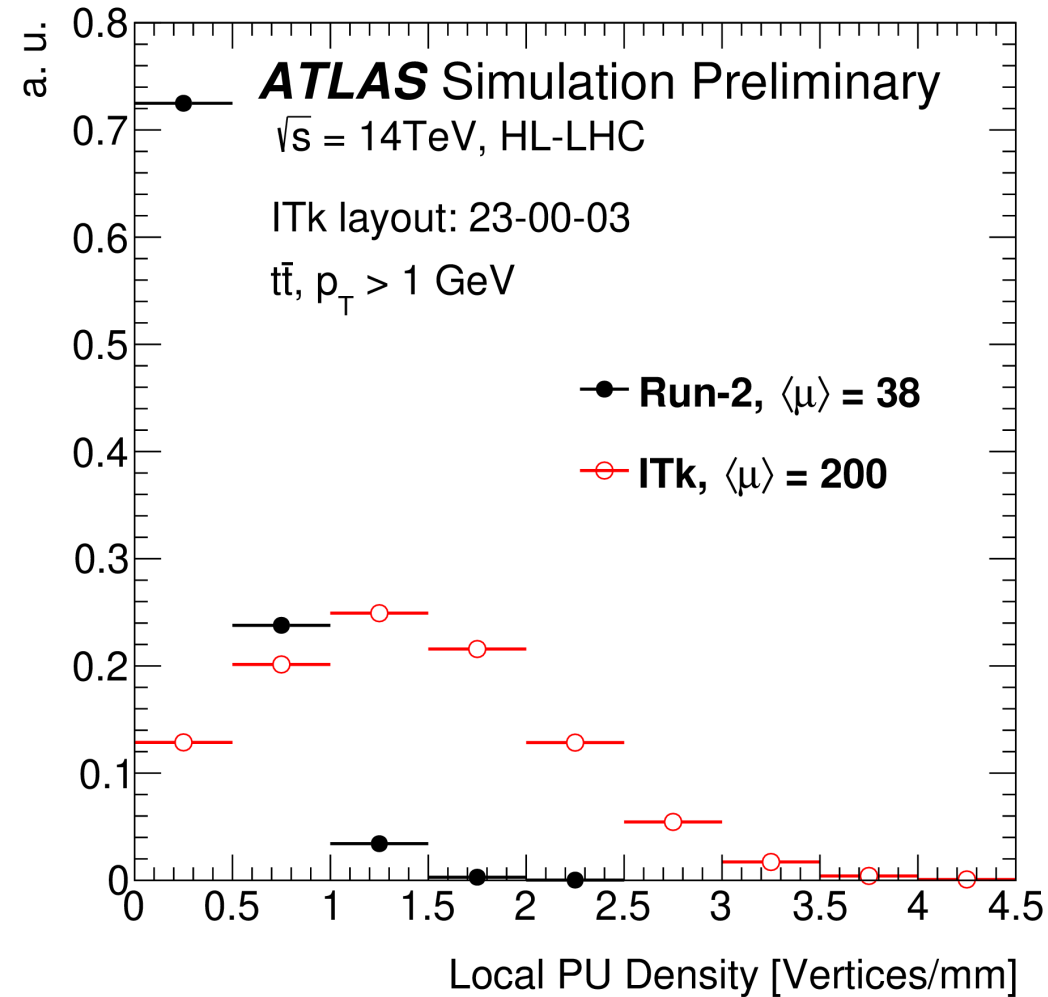
To summarize, a candidate timing device would need to have the following characteristics: short drift time (reduces rise time), high signal to noise (reduces jitter component), limited thickness in the path of a MIP (reduces Landau component), and small TDC bin size (reduces TDC component). These properties can be achieved by exploiting several technologies introduced in the following section.

VERTEXING STUDIES

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-023/>



VERTEXING STUDIES

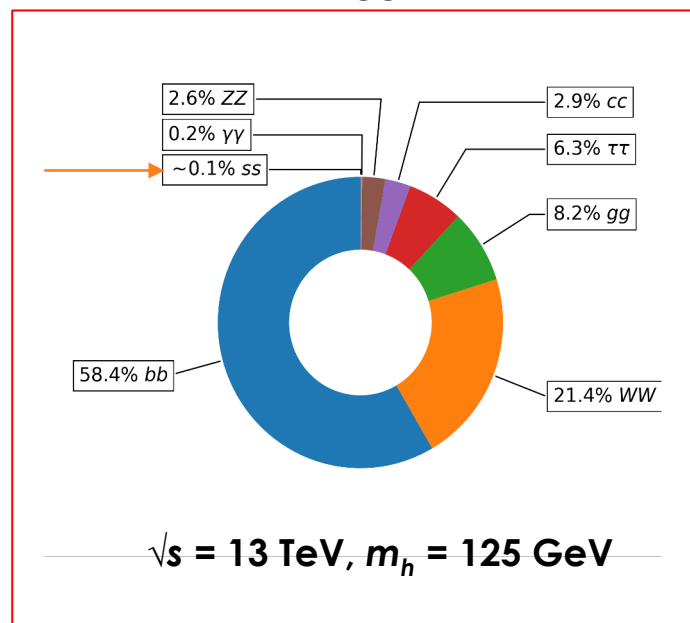


THE STRANGE QUARK AS A PROBE FOR NEW PHYSICS

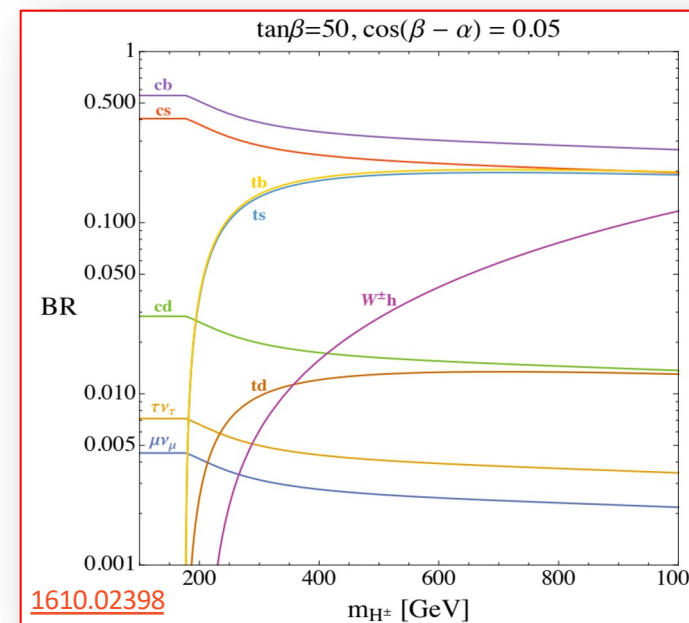
04.12.24

[2203.07535](#)

SM Higgs



BSM Charged Higgs

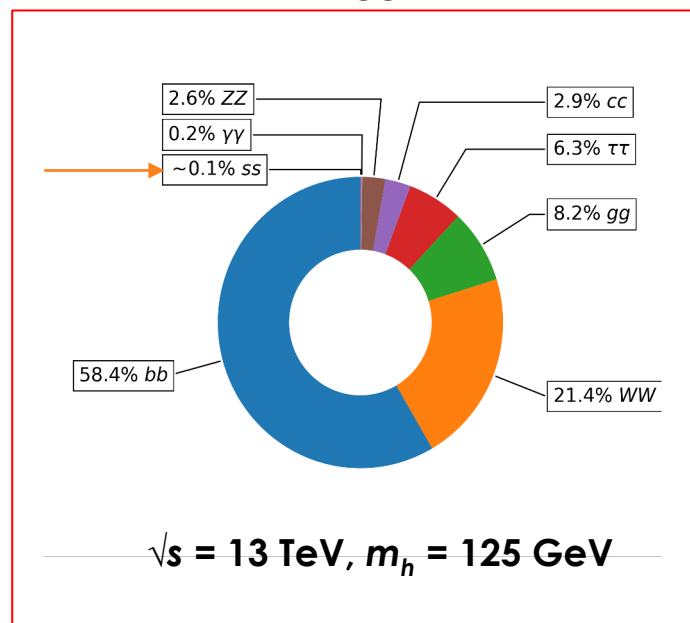


THE STRANGE QUARK AS A PROBE FOR NEW PHYSICS

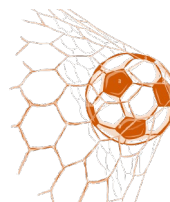
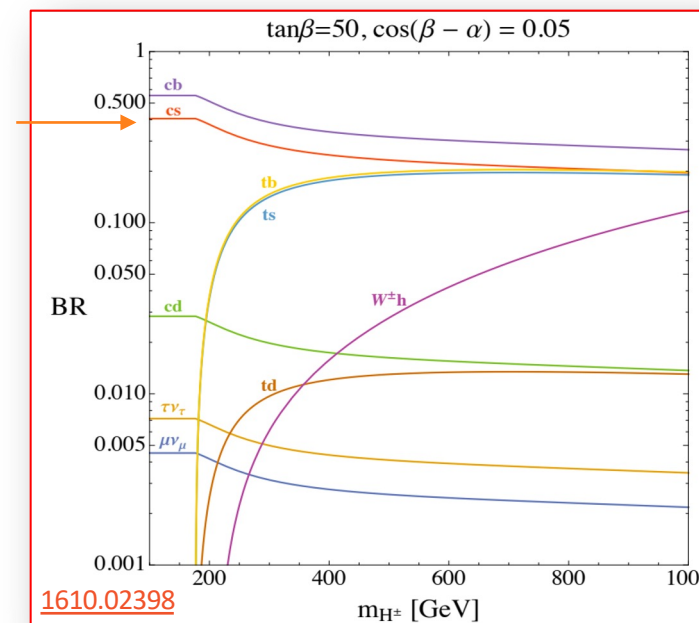
04.12.24

2203.07535

SM Higgs



BSM Charged Higgs

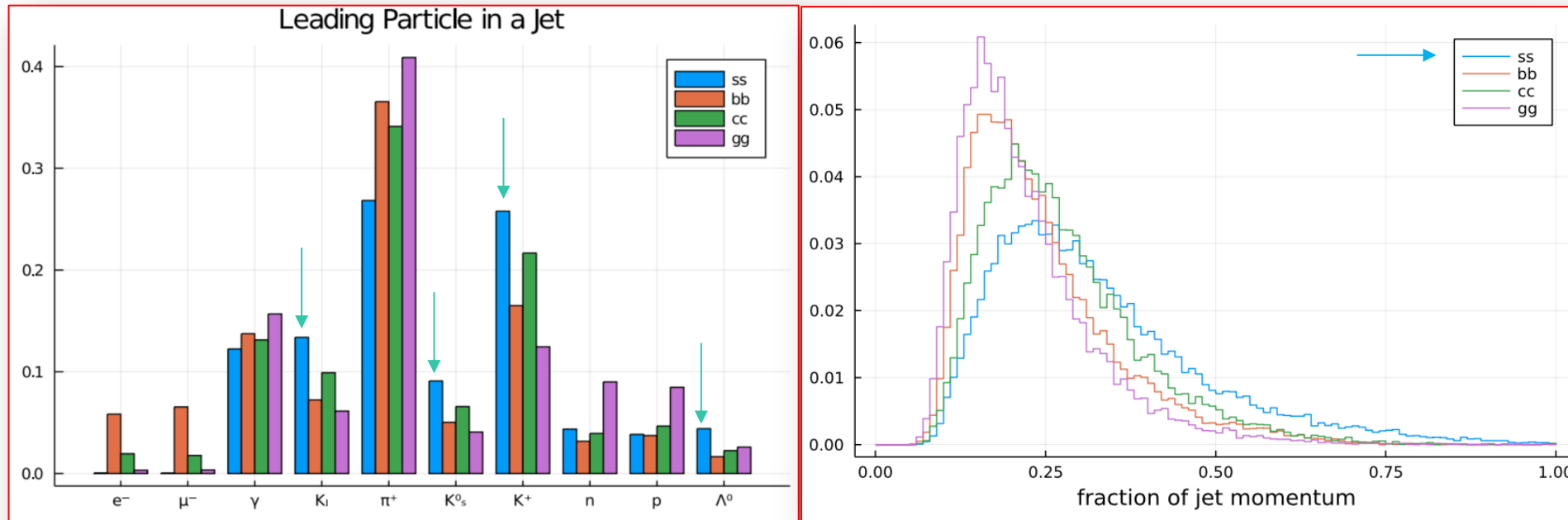


Assess the sensitivity of Higgs to strange couplings^(*) at future Higgs Factories and study detector design enabling strange jet tagging

THE *STRANGE* FEATURES

04.12.24

2203.07535



Particle Identification is crucial!

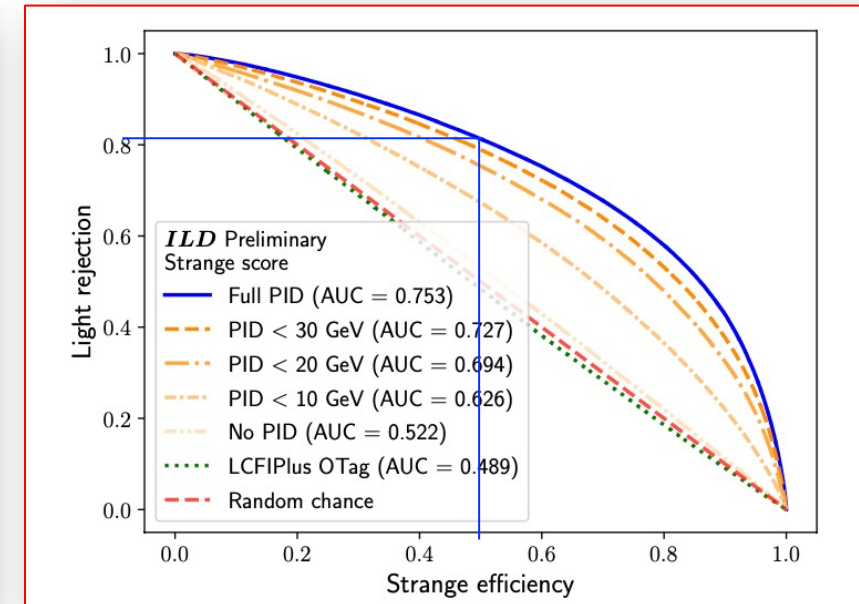
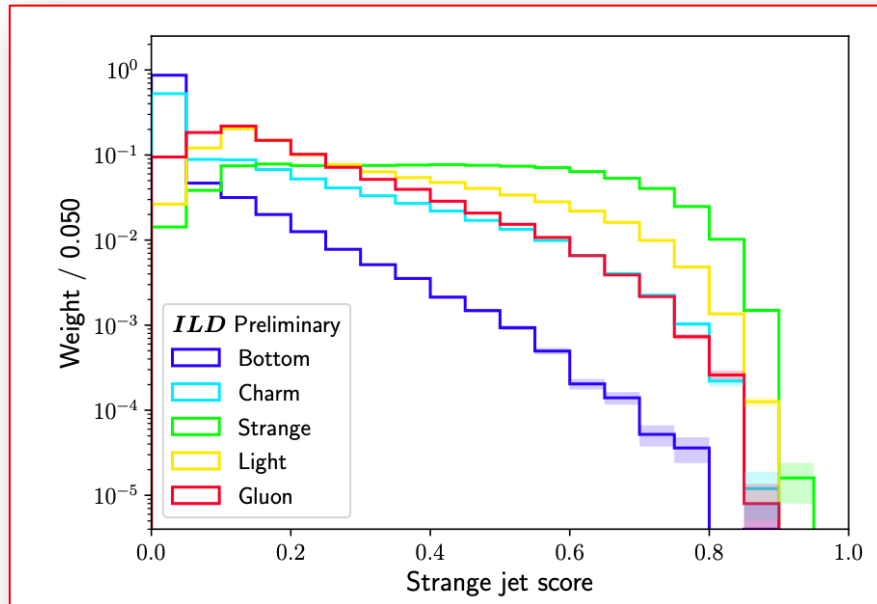
Need **p/K discrimination** over a momentum range of approximately
 $(0.2-0.7) \times 0.5 \times 125 \cong$ **12 to 50 GeV**

IMPACT OF PID ON STRANGE TAGGING

04.12.24

[2203.07535](#)

- Use a Recurrent Neural Net tagger for classifying jet-flavour, train on **full ILD(*) simulation** ($Z \rightarrow inv$)($H \rightarrow qq/gg$) samples and include **per-jet level inputs & variables** on the **10 leading particles** in each jet, **including PDG-based PID** → general validity for various future collider scenarios!
 - [See a similar tagger for FCC-ee](#)



Good discrimination of **s-jets**
from **u/d-** and **g-jets**

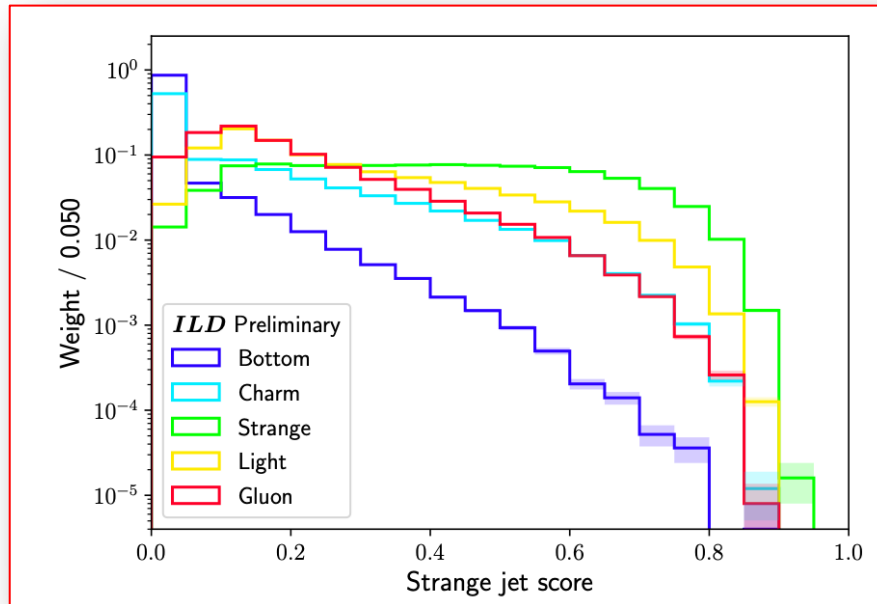
@50% **s-jet** tagging efficiency,
>80% **u/d-jet** rejection with Full PID

IMPACT OF PID ON STRANGE TAGGING

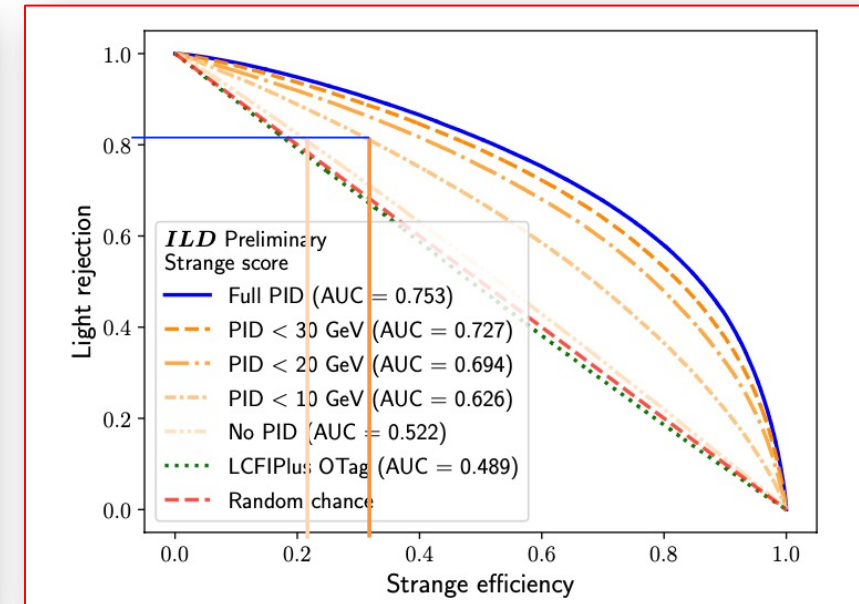
04.12.24

[2203.07535](#)

- Use a Recurrent Neural Net tagger for classifying jet-flavour, train on **full ILD(*) simulation** ($Z \rightarrow inv)(H \rightarrow qq/gg)$ samples and include **per-jet level inputs & variables** on the **10 leading particles** in each jet, **including PDG-based PID** → general validity for various future collider scenarios!
 - [See a similar tagger for FCC-ee](#)



**Good discrimination of s-jets
from u/d- and g-jets**



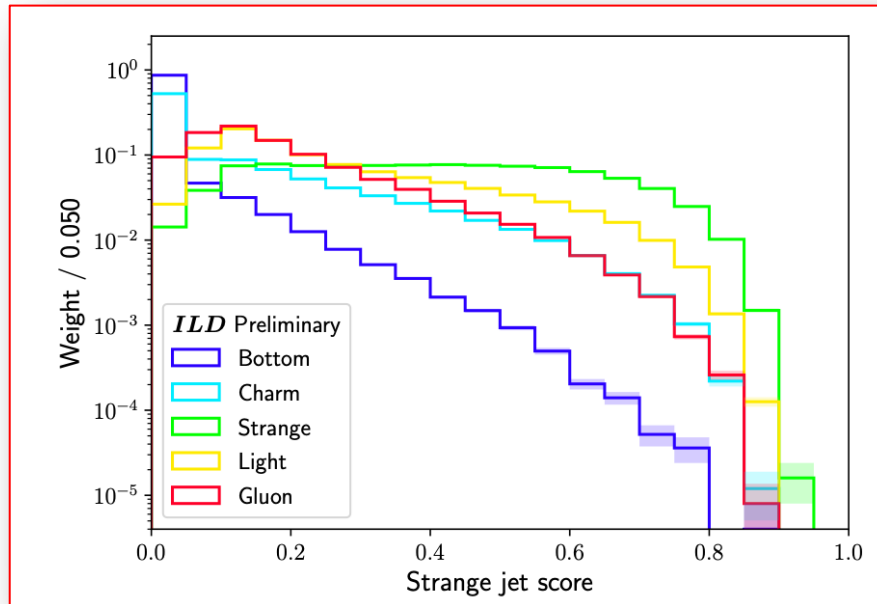
At fixed light rejection:
No PID to PID < 10 GeV: ~1.5x efficiency

IMPACT OF PID ON STRANGE TAGGING

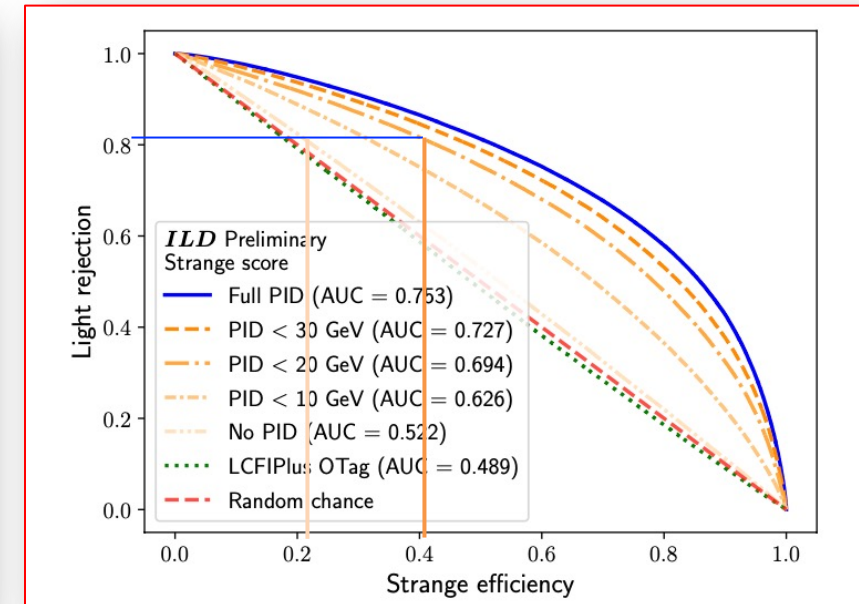
04.12.24

[2203.07535](#)

- Use a Recurrent Neural Net tagger for classifying jet-flavour, train on **full ILD(*) simulation** ($Z \rightarrow inv)(H \rightarrow qq/gg)$ samples and include **per-jet level inputs & variables** on the **10 leading particles** in each jet, **including PDG-based PID** → general validity for various future collider scenarios!
 - [See a similar tagger for FCC-ee](#)



**Good discrimination of s-jets
from u/d- and g-jets**



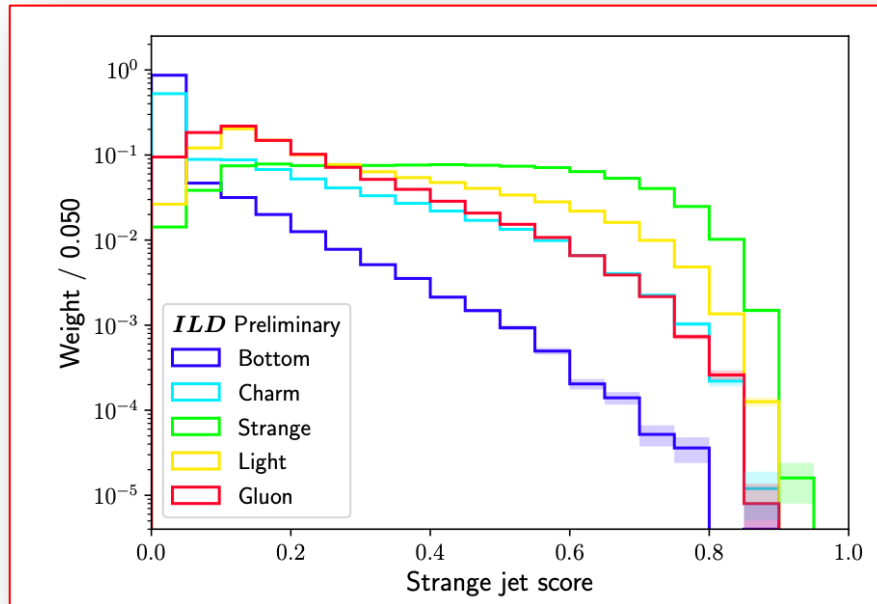
At fixed light rejection:
No PID to PID < 10 GeV: ~1.5x efficiency
No PID to PID < 20 GeV: ~2.0x efficiency

IMPACT OF PID ON STRANGE TAGGING

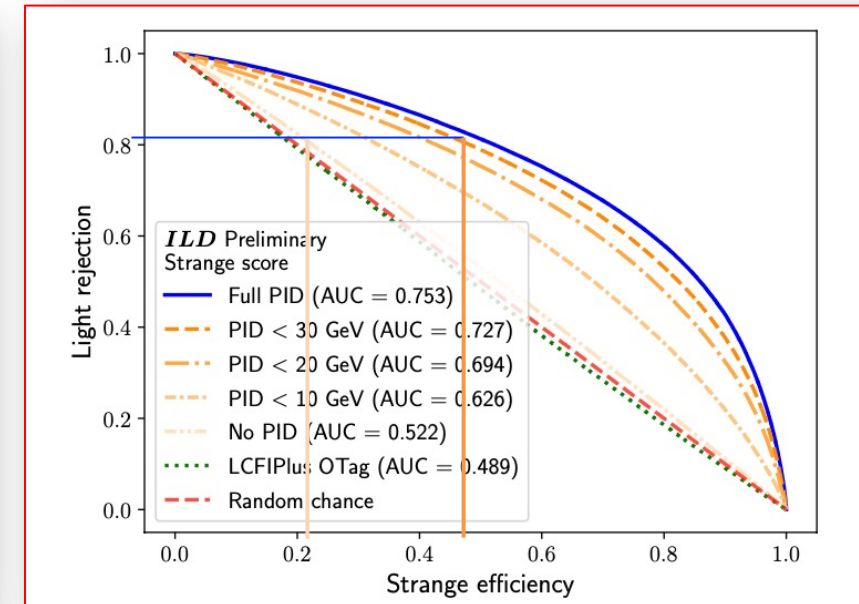
04.12.24

[2203.07535](#)

- Use a Recurrent Neural Net tagger for classifying jet-flavour, train on **full ILD(*) simulation** ($Z \rightarrow inv$)($H \rightarrow qq/gg$) samples and include **per-jet level inputs & variables** on the **10 leading particles** in each jet, **including PDG-based PID** → general validity for various future collider scenarios!
 - [See a similar tagger for FCC-ee](#)



**Good discrimination of s-jets
from u/d- and g-jets**



At fixed light rejection:
No PID to PID < 10 GeV: ~1.5x efficiency
No PID to PID < 20 GeV: ~2.0x efficiency
No PID to PID < 30 GeV: ~2.5x efficiency

A PHYSICS BENCHMARK: $h \rightarrow ss$ ANALYSIS @ THE INTERNATIONAL LINEAR COLLIDER

[2203.07535](#)

Foreseen to run at several $\sqrt{s}$, dedicated **250** GeV run for Higgs couplings studies

$\sigma_H @ \sqrt{s} = 250 \text{ GeV} \sim 200 \text{ fb}$ (dominated by ZH production)

2000 fb⁻¹ collected in 10y by ILC

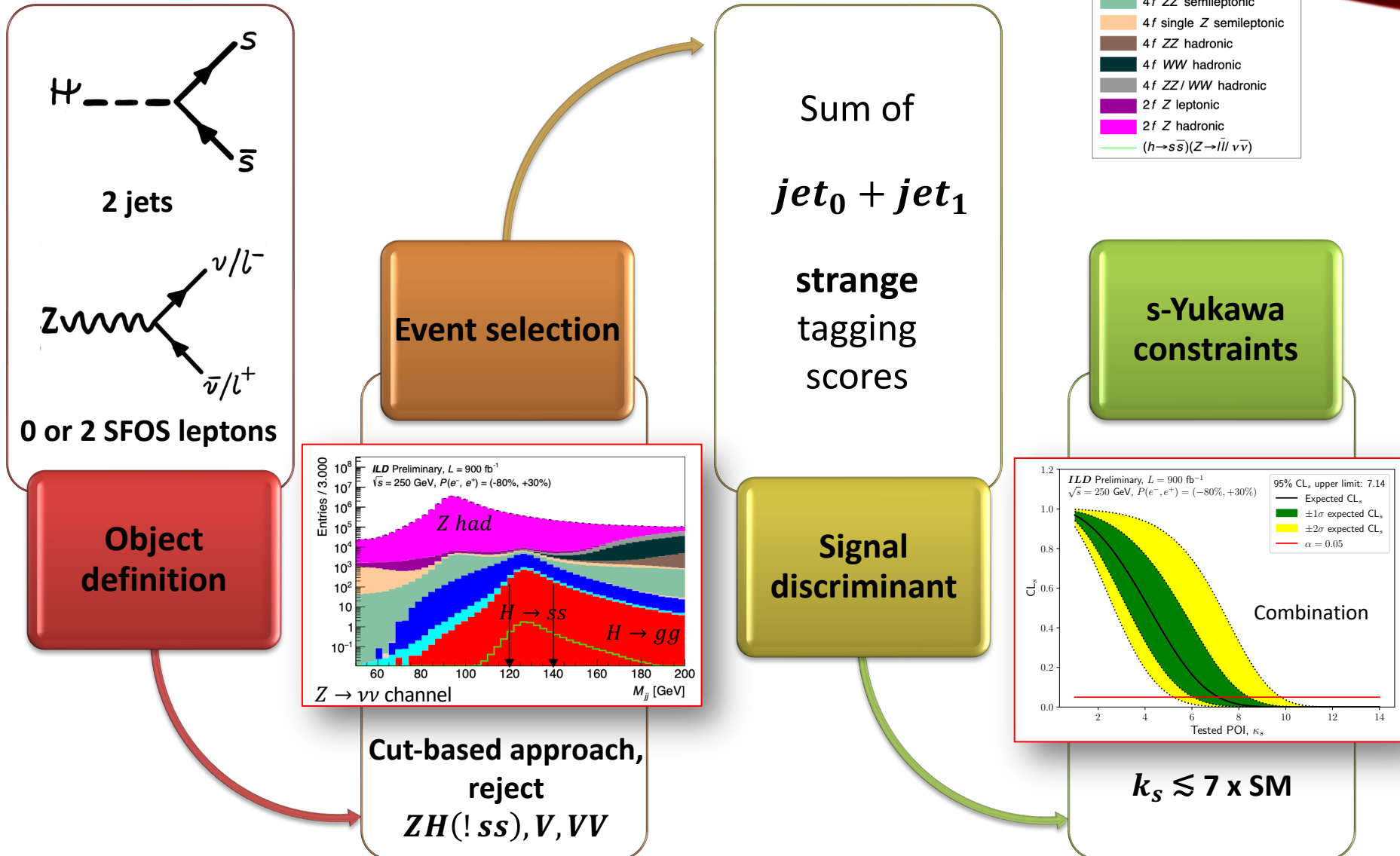
$\rightarrow \sim 400\text{k Higgs} \rightarrow \sim 80 h \rightarrow ss$

But of course, new physics boosts these numbers!

$h \rightarrow ss$ ANALYSIS IN A NUTSHELL

04.12.24

2203.07535





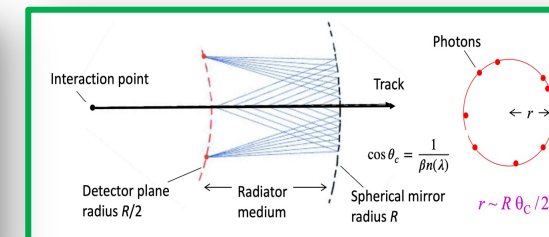
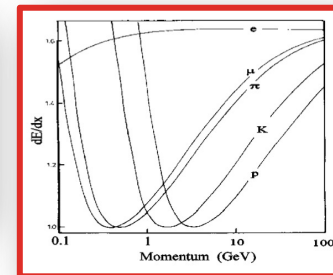
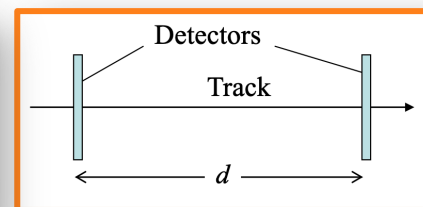
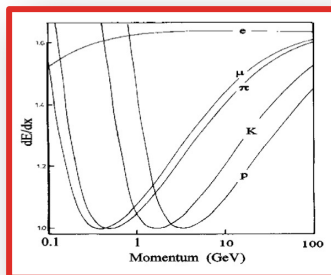
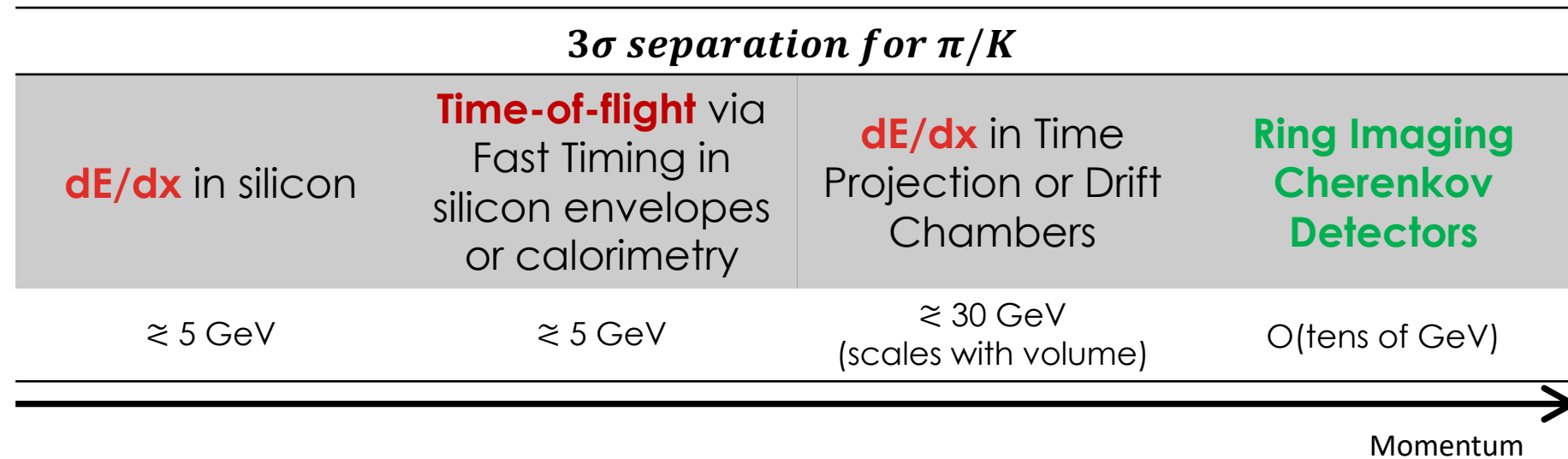
- If we can tag strange jets, we can probe the **Higgs strange Yukawa** coupling...
But **we need π/K discrimination at high momenta!**



- This triggered recent studies of what may be possible with a system that pioneered particle ID: the **Ring Imaging Cherenkov detector**

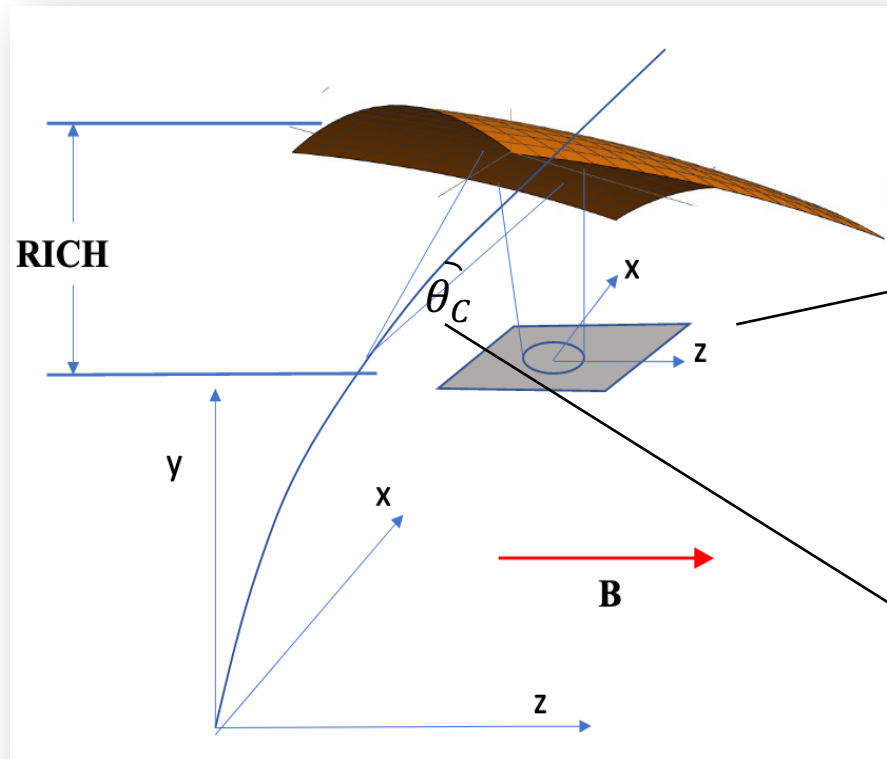
PARTICLE IDENTIFICATION TECHNIQUES

- Various technologies allow to identify hadrons in different momentum ranges

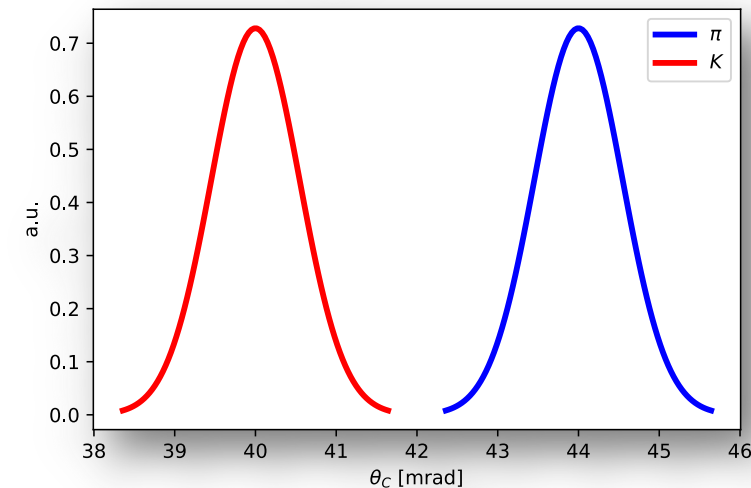
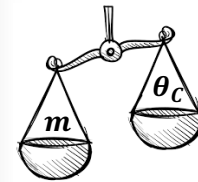
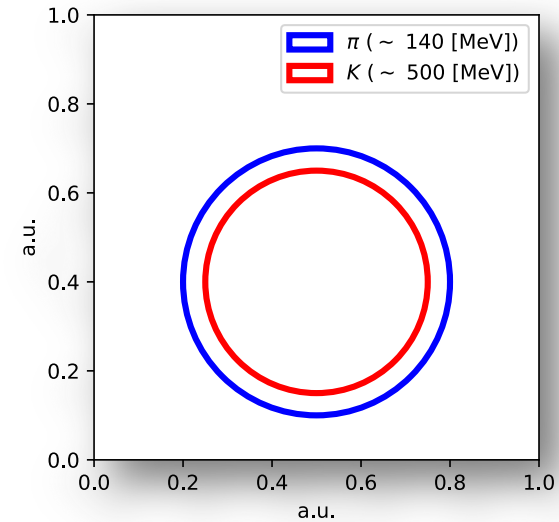


RING IMAGING CHERENKOV DETECTORS

- RICH detectors use the angle of emitted Cherenkov radiation (as photons) which, coupled with momenta measurements, yield particle masses

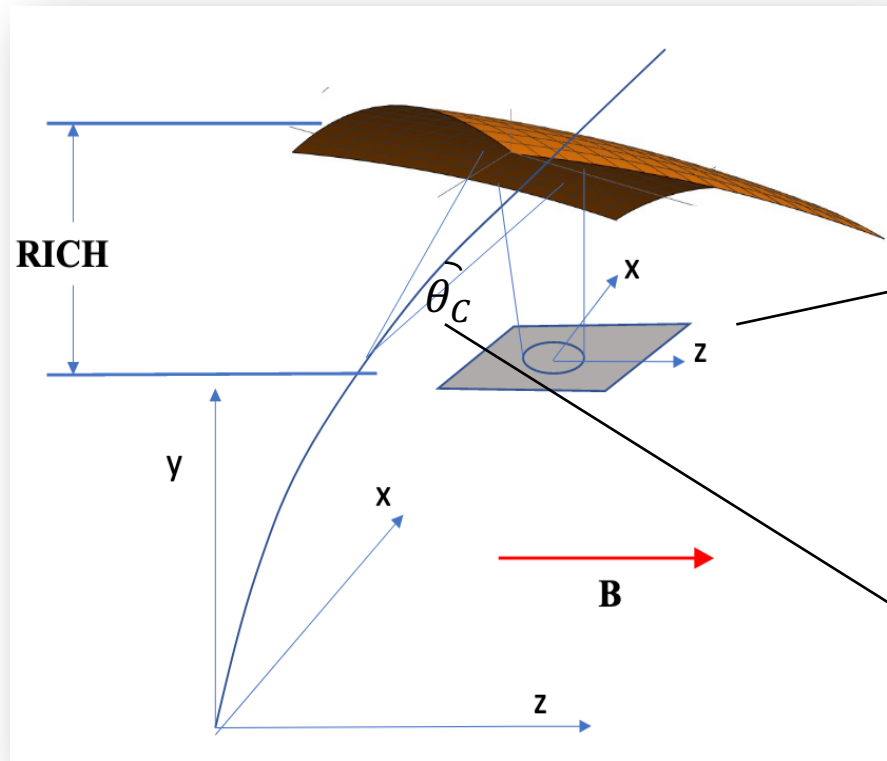


<https://doi.org/10.1016/j.nima.2023.168992>



RING IMAGING CHERENKOV DETECTORS

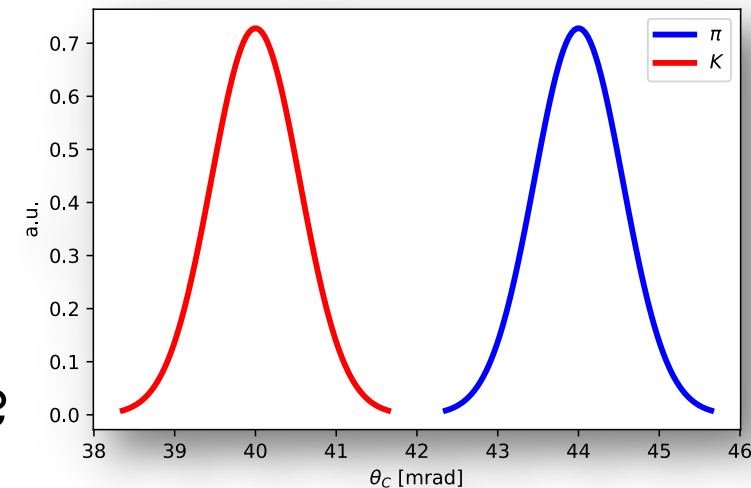
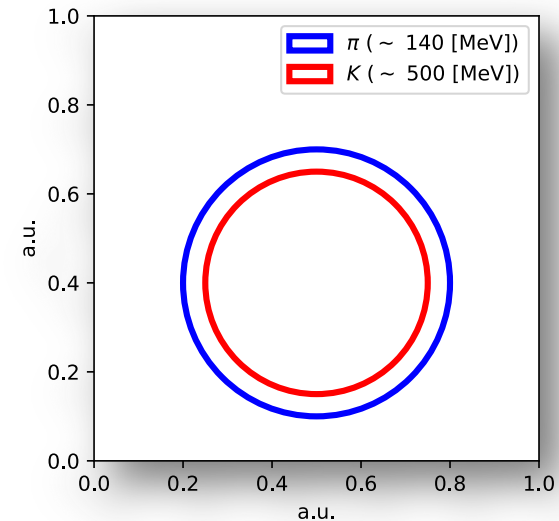
- RICH detectors use the angle of emitted Cherenkov radiation (as photons) which, coupled with momenta measurements, yield particle masses



<https://doi.org/10.1016/j.nima.2023.168992>

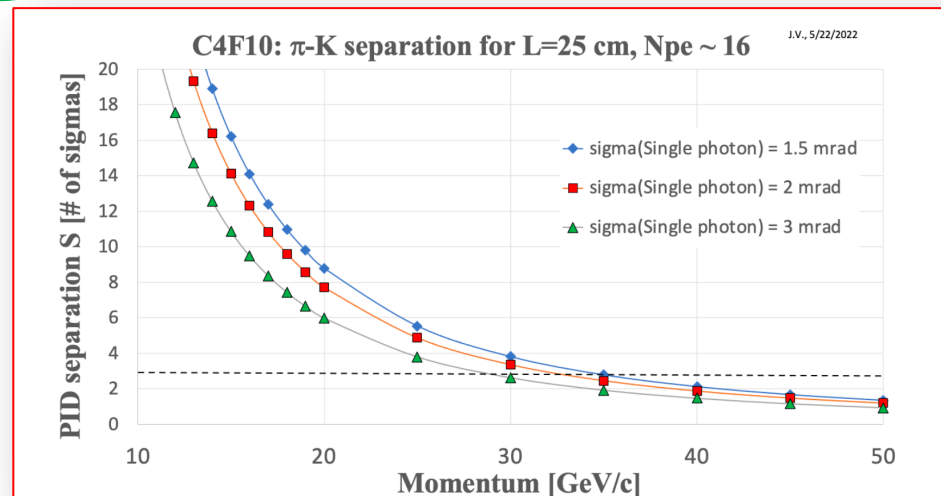
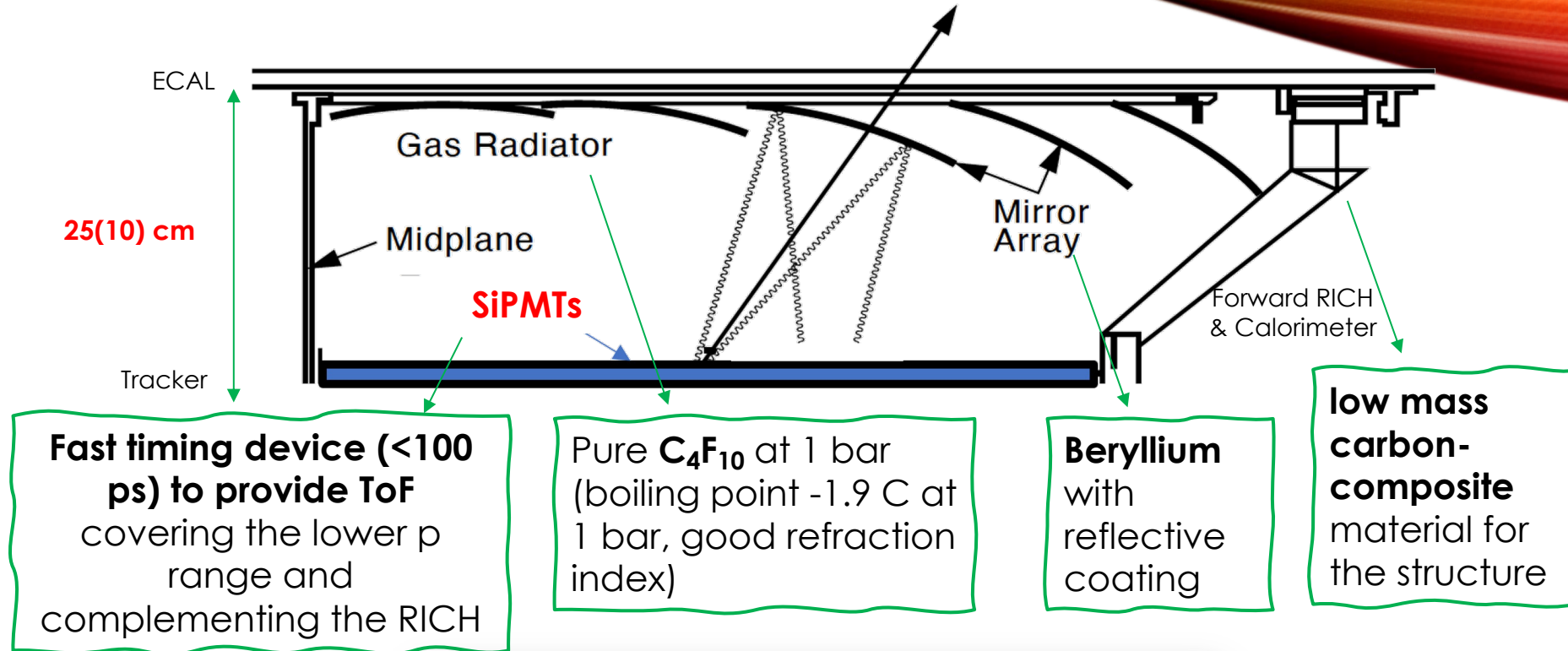
Will it be possible to accommodate a compact RICH system while preserving performance in tracking and calorimetry?

V.M.M.CAIRO



COMPACT GASEOUS RICH WITH SIPMTs

04.12.24



**Can reach
 3σ π/K
 separation
 up to 30 GeV
 with state-of-
 the-art
 technology!**

[2203.07535](https://doi.org/10.1016/j.nima.2023.168992)

<https://doi.org/10.1016/j.nima.2023.168992>

THE IMPORTANCE OF *STRANGE* SCIENCE [2203.07535](#)

- Many unexplored physics benchmarks rely on **strange tagging**, in turn enabled by π/K PID at high momenta
 - Higgs & friends Factories: **Z, W, top, flavor physics in general...**
- Ordinary matter composed by electron and light quarks
 - none of the Higgs boson couplings to such particles has been verified yet!**
- Testing Yukawa universality is a **key benchmark** for future Higgs factories
- Best constraints on **strange Yukawa** derived via a direct SM $h \rightarrow ss$ search: phase space for new physics reduced to $k_s \lesssim 7 \times SM$ (we probed also u/d)

