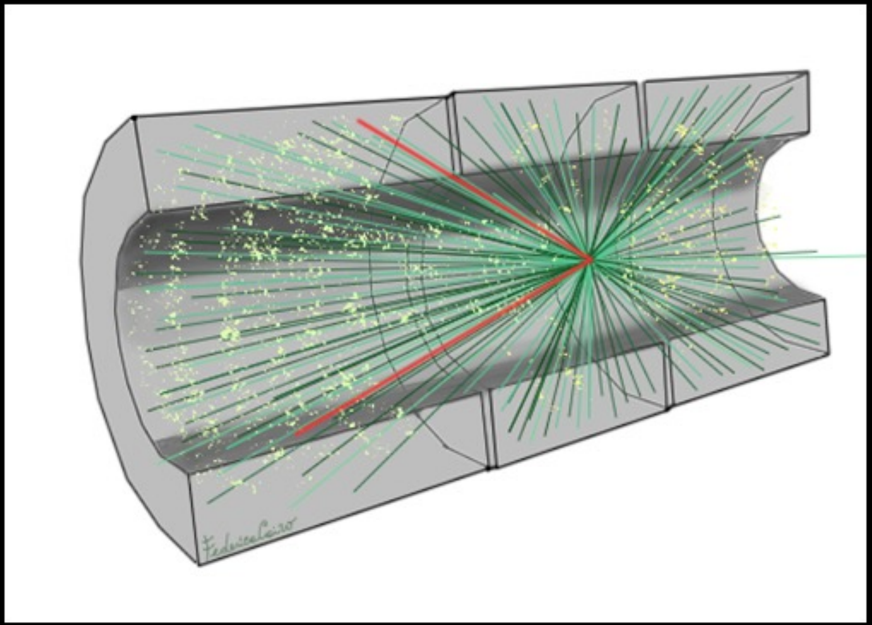
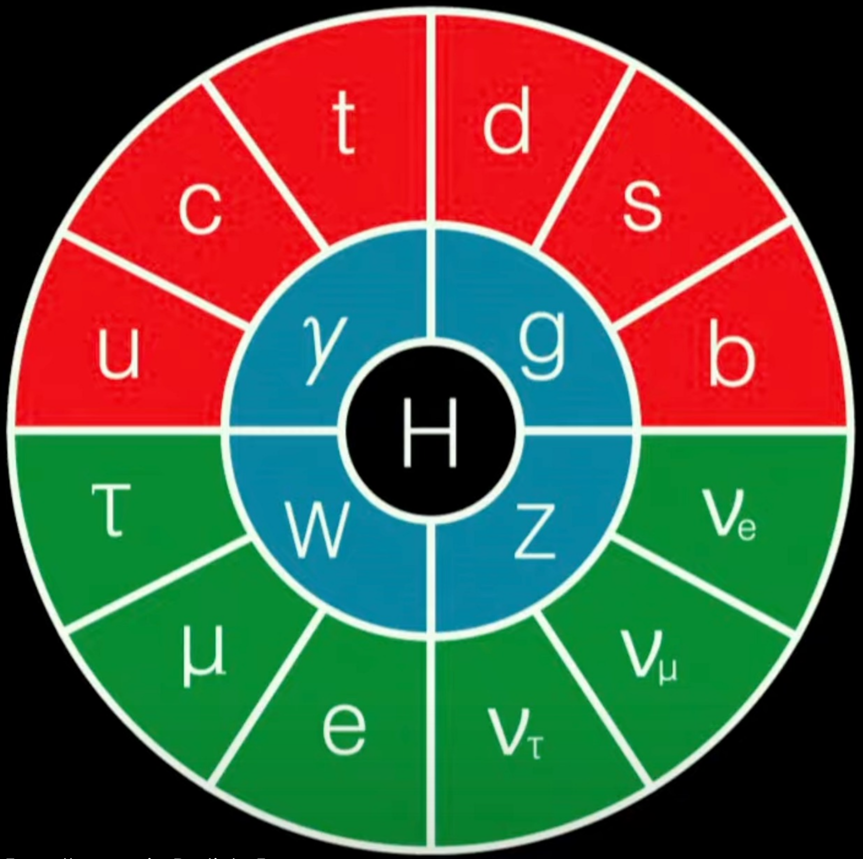
Stockholms Universitet - May 24th 2024

TRACKING DOWN THE HIGGS BOSON PROPERTIES

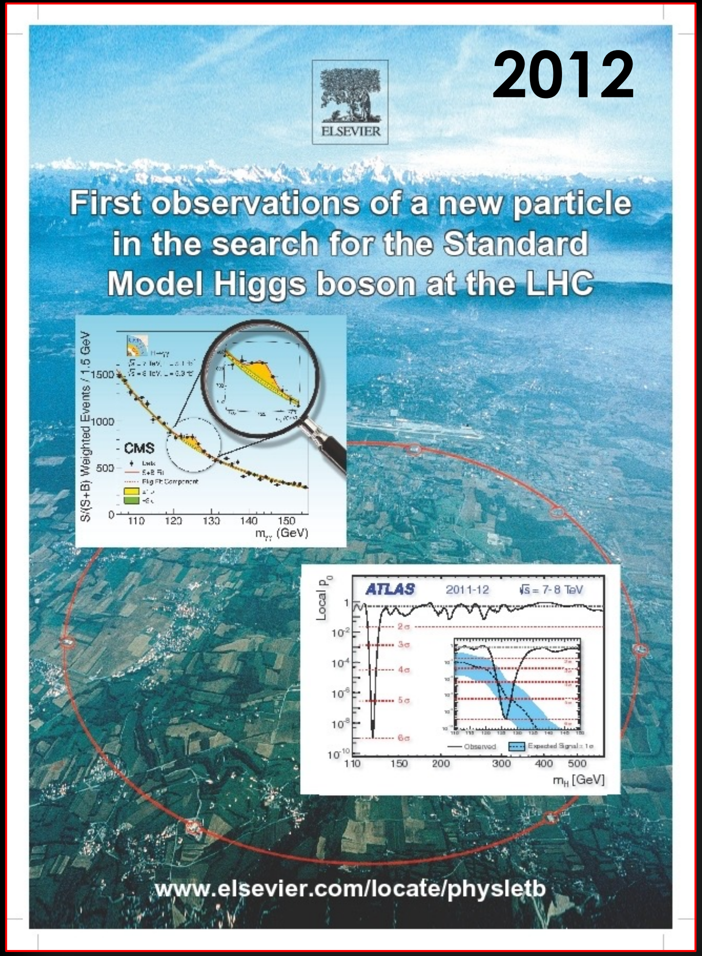
Valentina Maria Martina Cairo

CERN





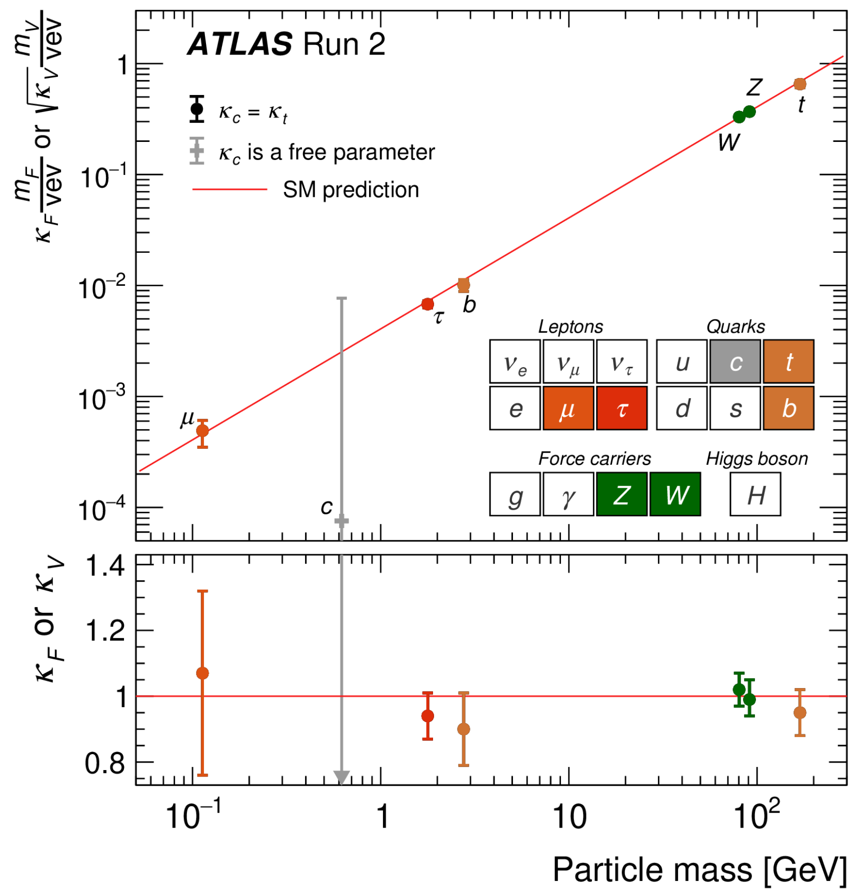
From the movie *Particle Fever*



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*



[Nature 607, pages 52-59 (2022)]

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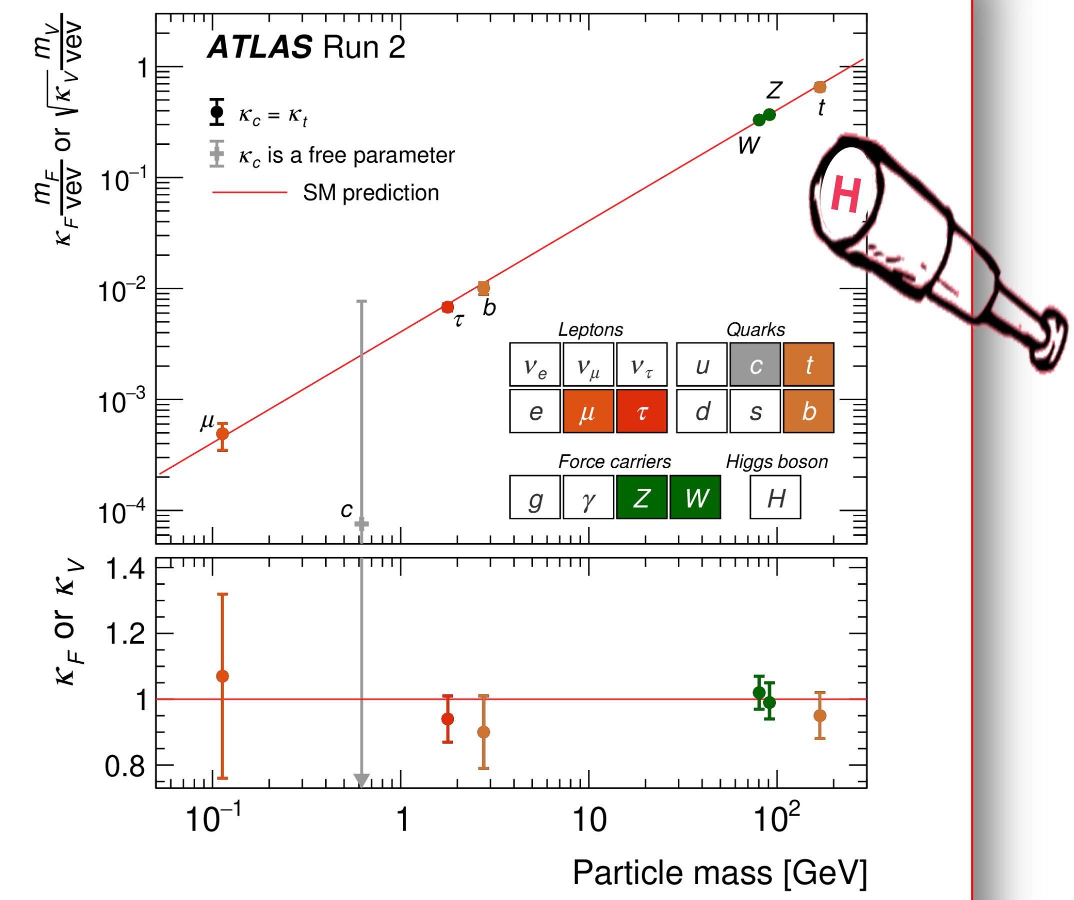


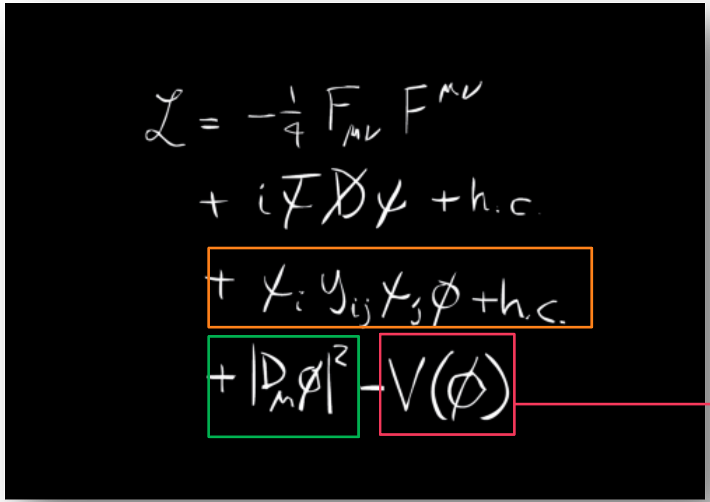
Nature 607, pages 52-59 (2022)

How does the Higgs boson couple to itself?

THE THEORY

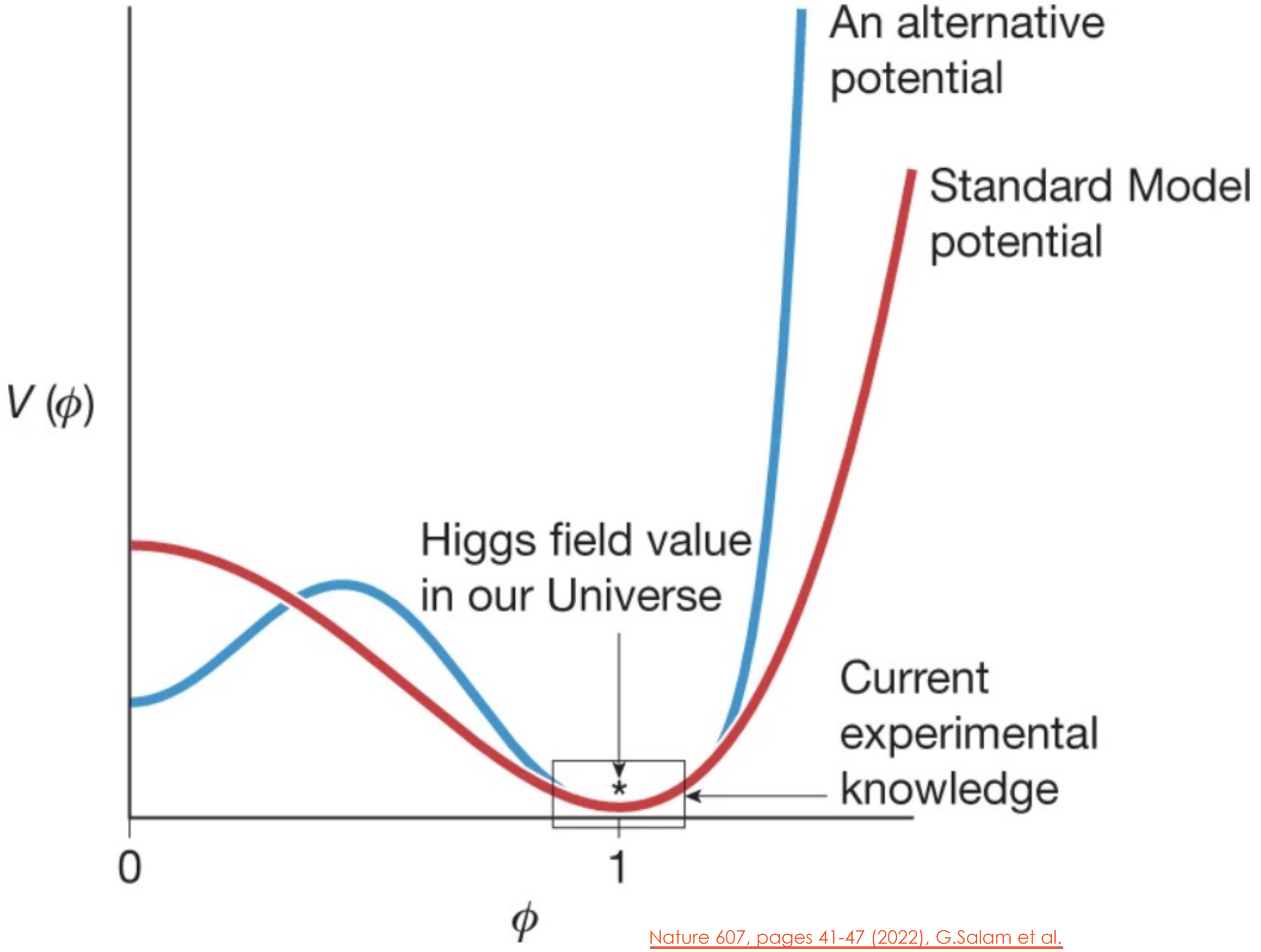
F. Cairo, From *Conn(ll)ecting the dots*

THE HIGGS POTENTIAL AND SELF-COUPLING



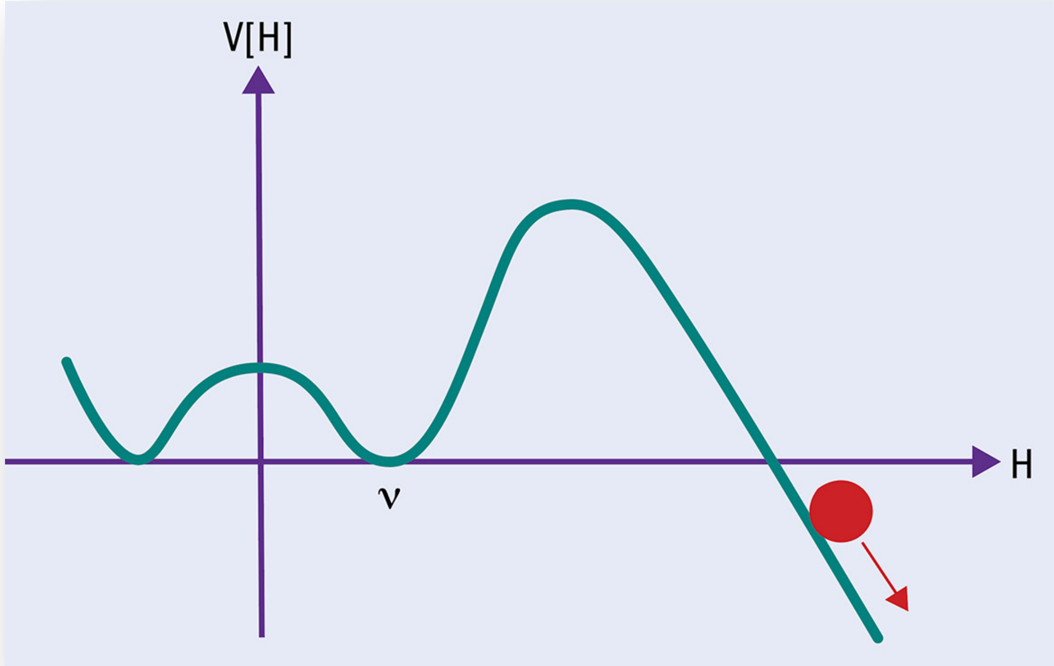
$$V(\phi^\dagger \phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

Higgs self-coupling strength

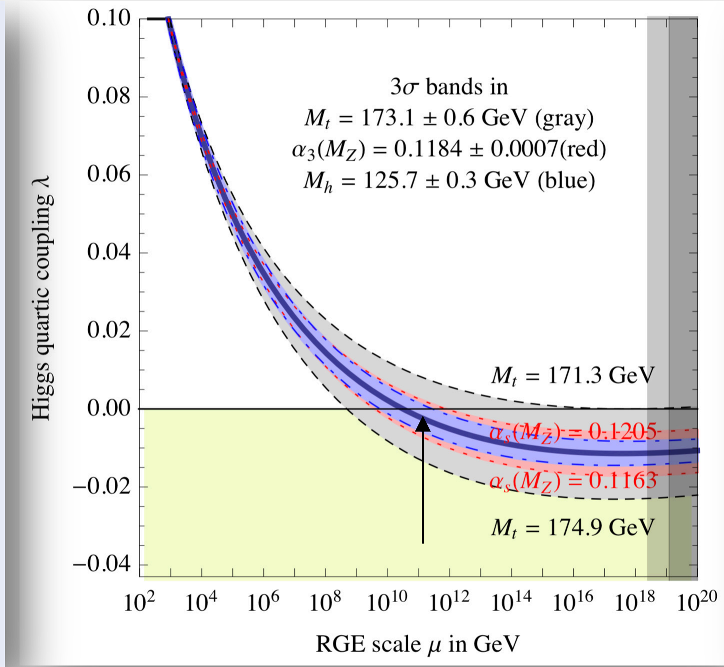


Nature 607, pages 41-47 (2022), G.Salam et al.

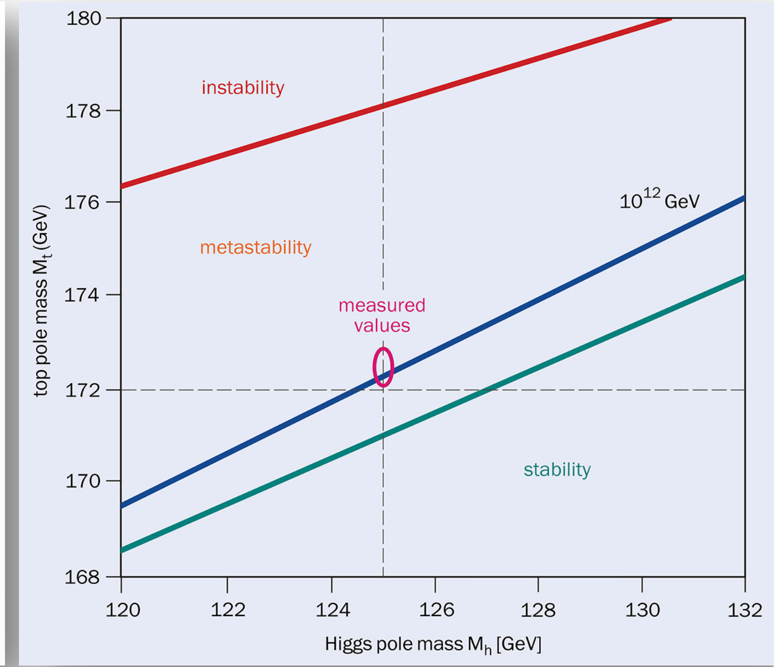
MATTER OF STABILITY



J. Ellis, The Higgs and the fate of the universe

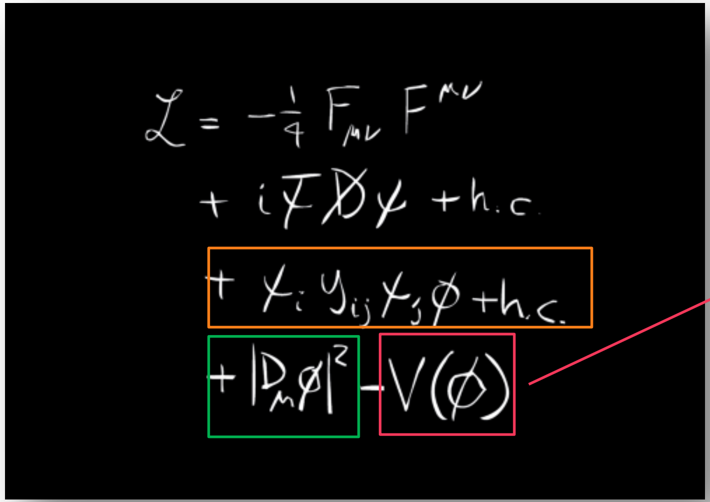


JHEP08(2012)098



J. Ellis, The Higgs and the fate of the universe

PROBING THE HIGGS SELF-COUPLING

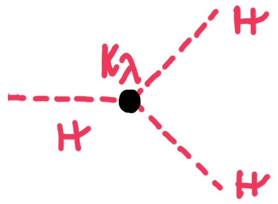


$$V(\phi^\dagger\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$
$$\supset \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4$$

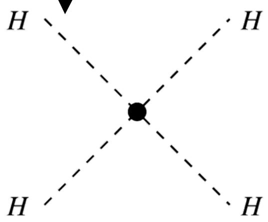
$m_H = \sqrt{2\lambda v^2}$

$v \simeq 246$ GeV.

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



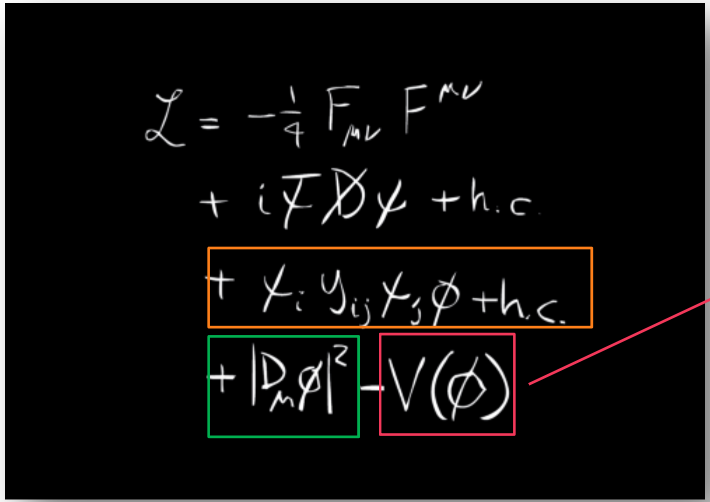
Direct access to λ in HH pair production



Very challenging even for HL-LHC

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

PROBING THE HIGGS SELF-COUPLING



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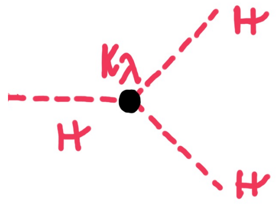

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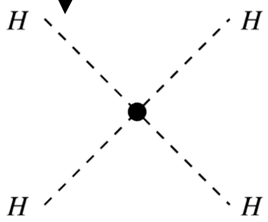
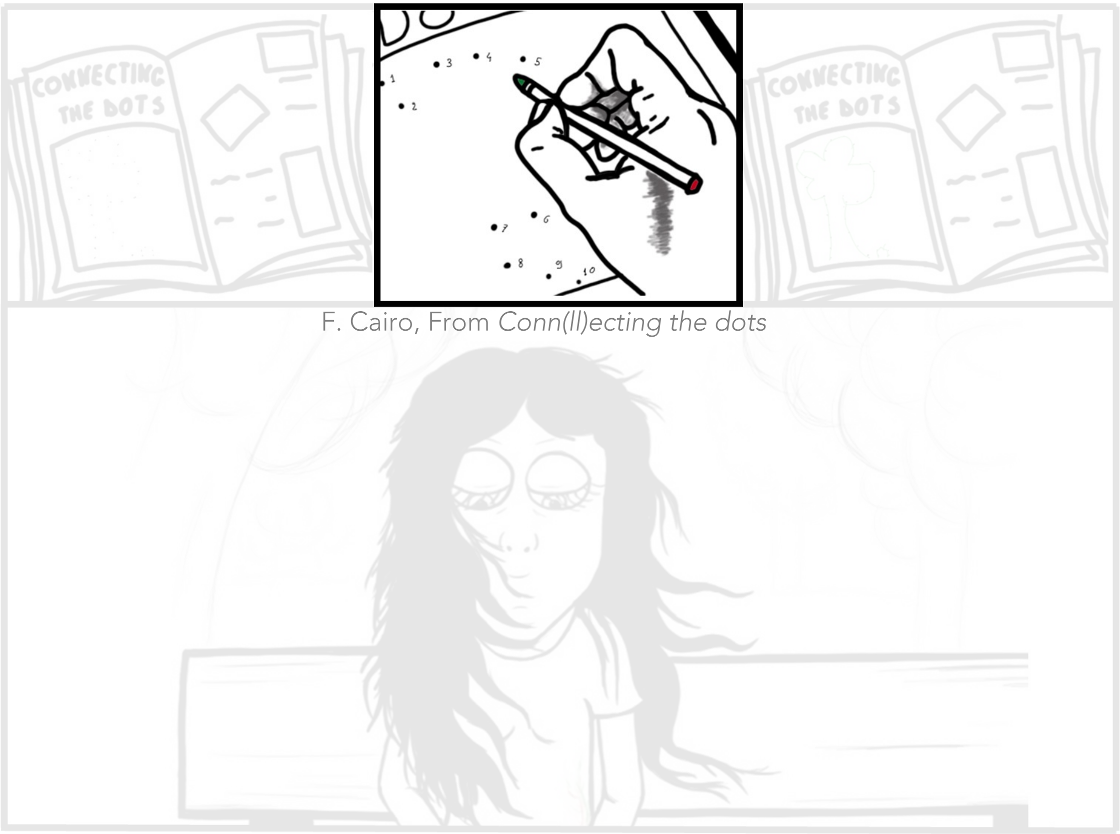


Very challenging even for HL-LHC

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

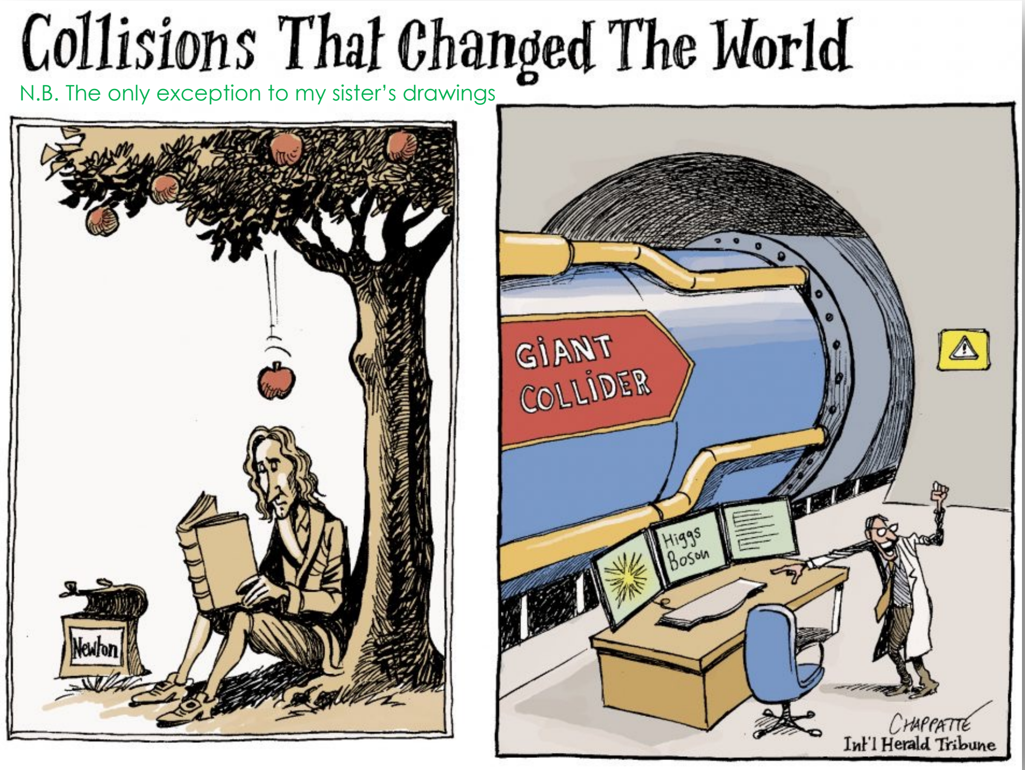
New physics can alter these numbers → Implications on the origin, evolution and stability of the Universe → Probing the Higgs-self coupling is a key goal for LHC and HL-LHC!

THE TOOLS



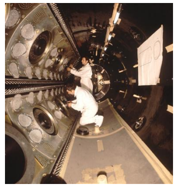
F. Cairo, From *Conn(ll)ecting the dots*

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

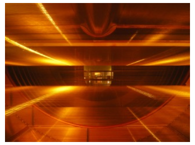


N.B. The only exception to my sister's drawings

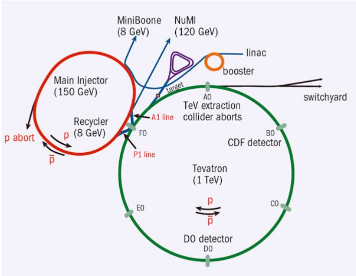
The weak neutral currents and the *bubble chamber* era

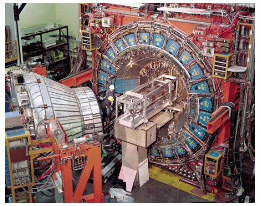


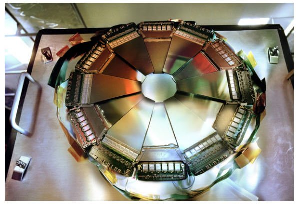
The W,Z bosons and the *drift chamber* era



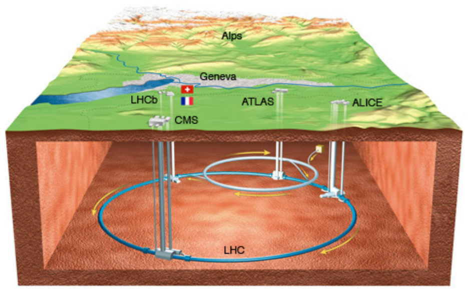
The top quark and the *silicon strip* era

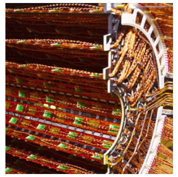


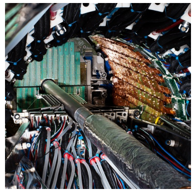




The Higgs boson (and more!) and the *silicon pixel* era



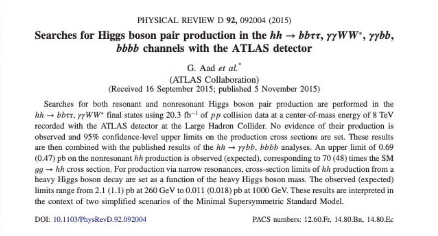




ENABLING HH DISCOVERIES THROUGH TRACKING INNOVATIONS IN ATLAS

Shutdown 1	Run 2 (13 TeV)	Shutdown 2	Run 3 (13/14 TeV)	Shutdown 3	Run 4

HH in Run 1 data


PHYSICAL REVIEW D **92,** 092004 (2015)

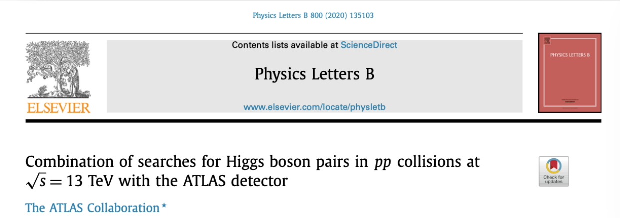
Searches for Higgs boson pair production in the $hh \to bb\tau\tau, \gamma\gamma WW^*, \gamma\gamma bb, bbbb$ channels with the ATLAS detector

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 $hh \to bb\tau\tau, \gamma\gamma WW^*$ 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 $hh \to \gamma\gamma bb, bbbb$ 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 $gg \to hh$ 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.

DOI: 10.1103/PhysRevD.92.092004 PACS numbers: 12.60.Fr, 14.80.Bn, 14.80.Ec

HH in early Run 2 data


Physics Letters B 800 (2020) 135103

Contents lists available at ScienceDirect

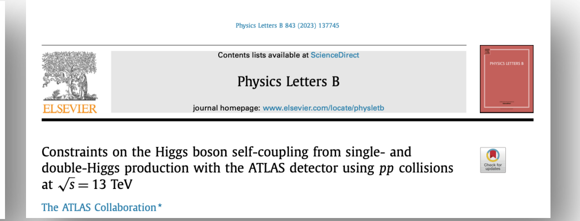
Physics Letters B

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&H in full Run 2 data


Physics Letters B 843 (2023) 137745

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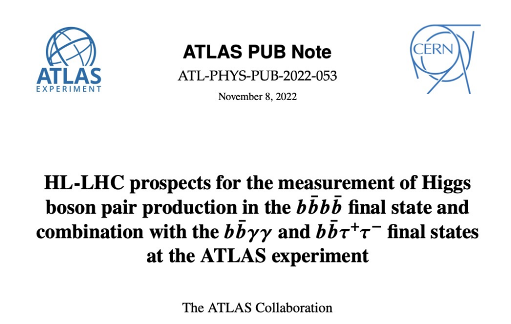
Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

Constraints on the Higgs boson self-coupling from single- and double-Higgs production with the ATLAS detector using pp collisions at $\sqrt{s} = 13$ TeV

The ATLAS Collaboration*

HH Extrapolations

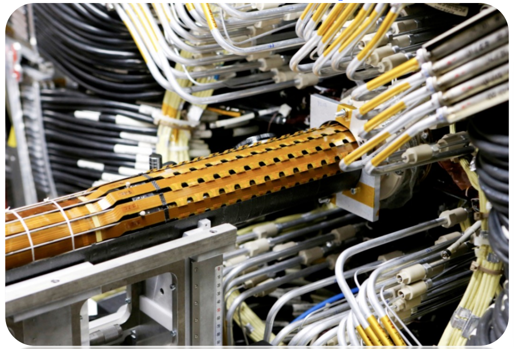

ATLAS PUB Note
ATL-PHYS-PUB-2022-053
November 8, 2022

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

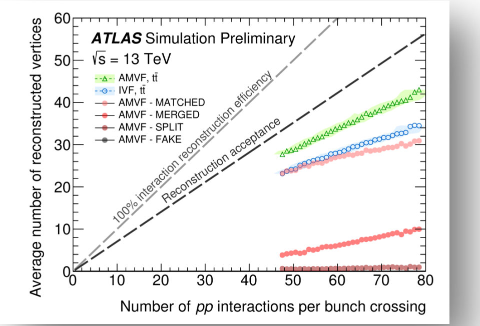
The ATLAS Collaboration

2014 → 2016 → 2018 → 2020 → 2022 → 2024 → 2026 → … → 2036…

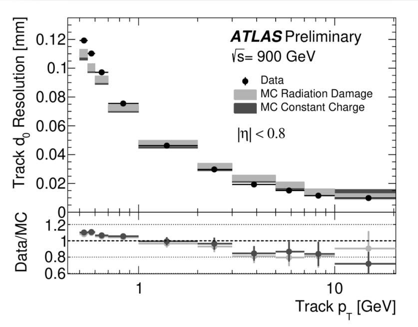
Insertable B-Layer



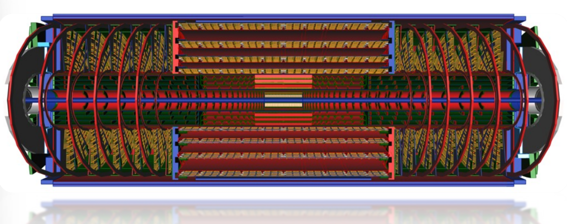
Preparation for Run 3



Run 3 data taking



new Inner Tracker



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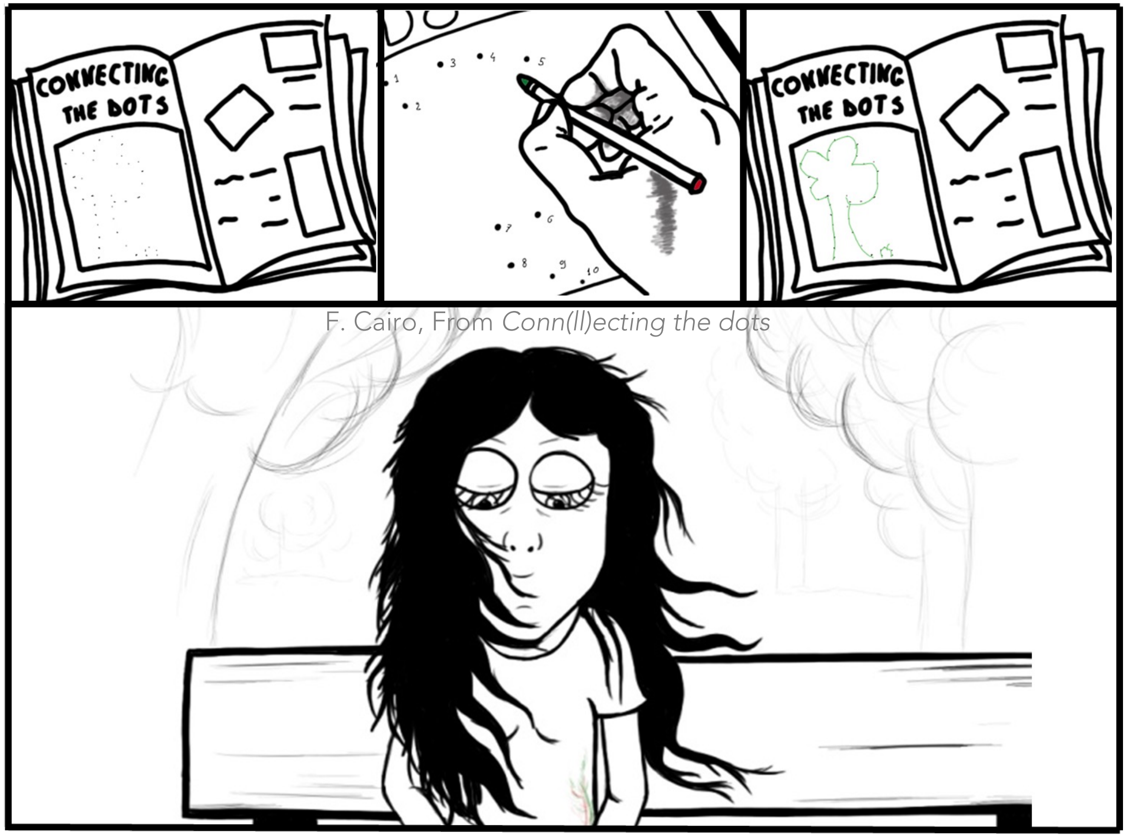
THE WORK



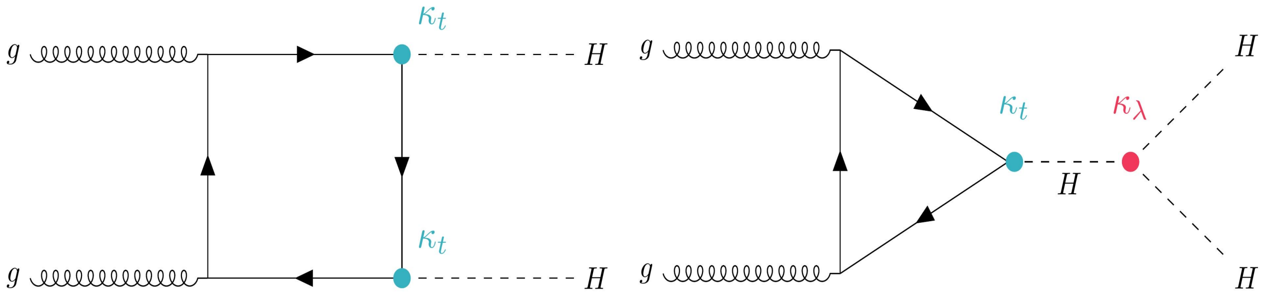
F. Cairo, From *Conn(ll)ecting the dots*

THE HIGGS SELF-COUPLING

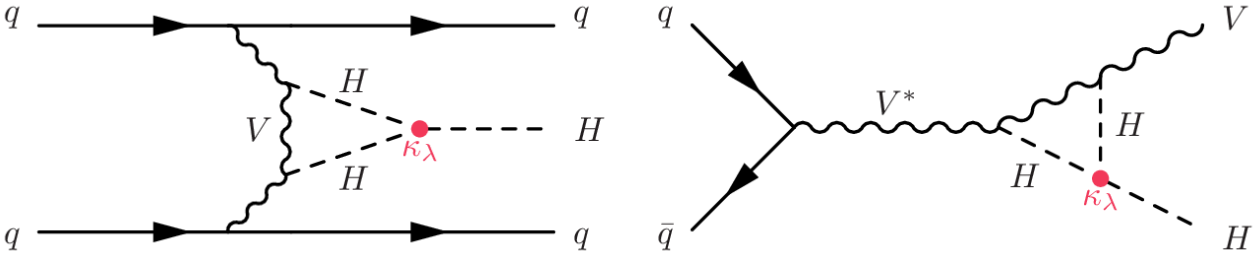
λ_{HHH} can be measured in two complementary ways

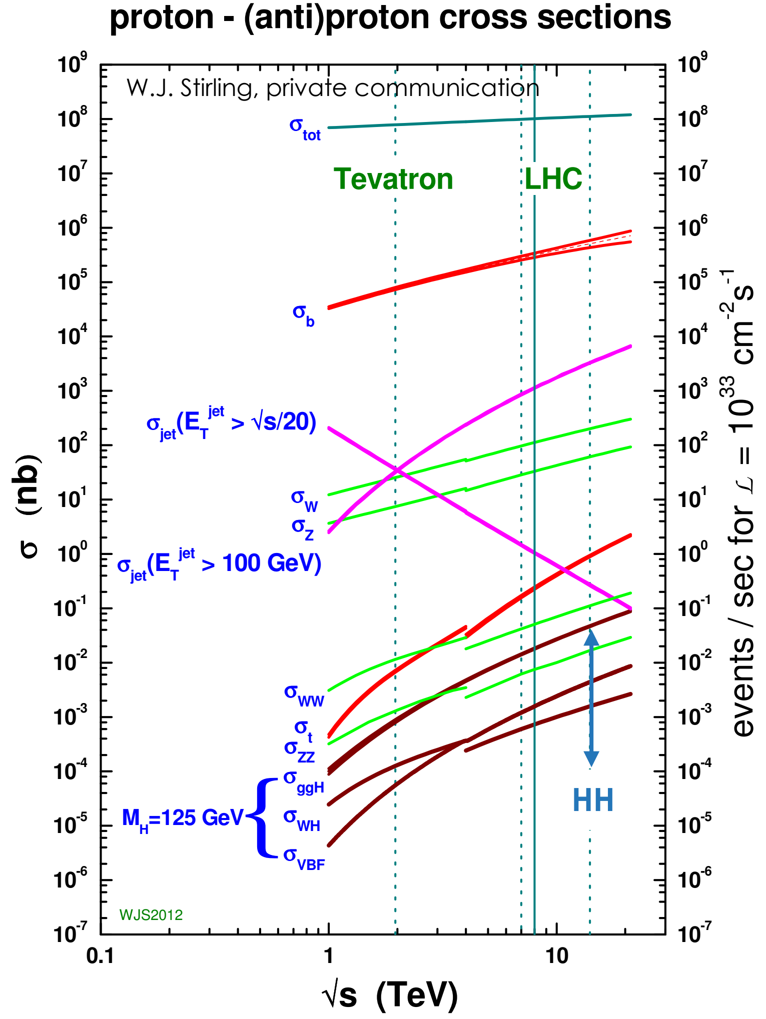
Today's focus

di-Higgs



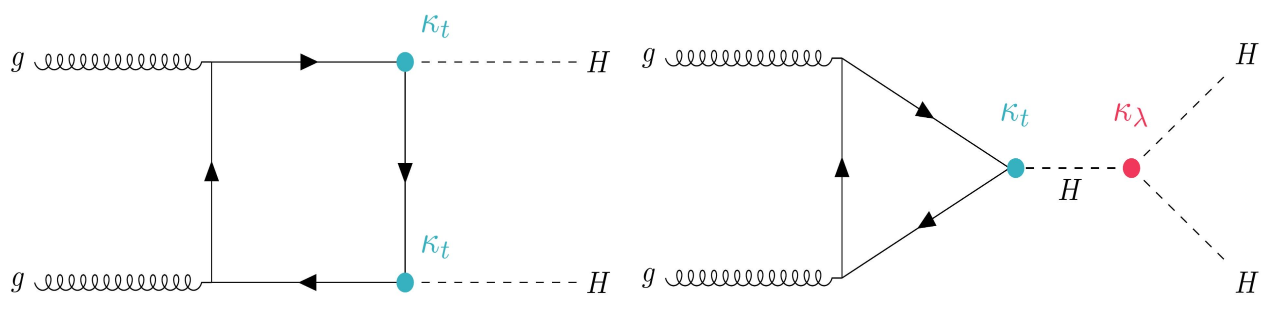
Single-Higgs

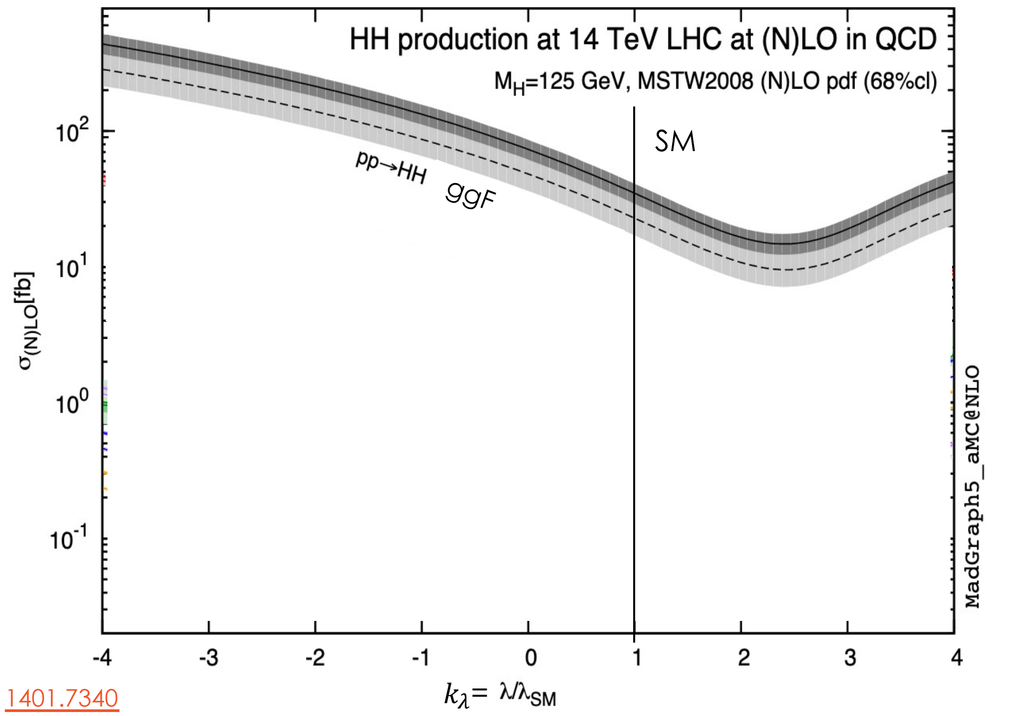




HH PRODUCTION AT THE LHC

Non-resonant σ_{HH}^{ggF} = 31.05 fb at 13 TeV for m_H = 125.00 GeV





1401.7340

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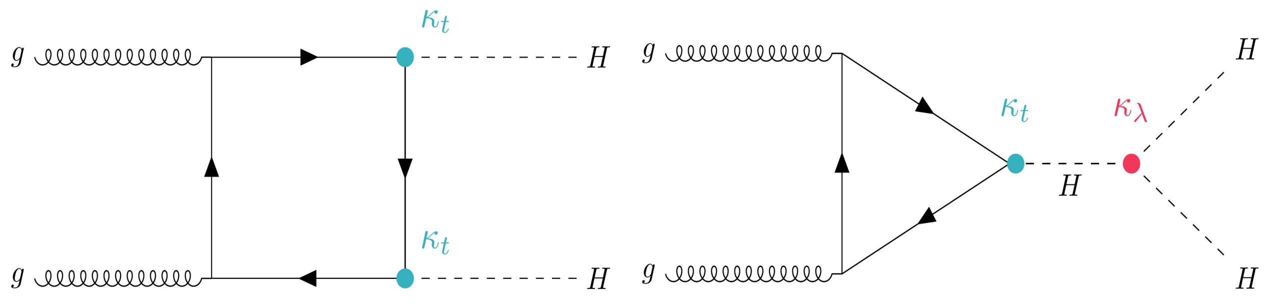
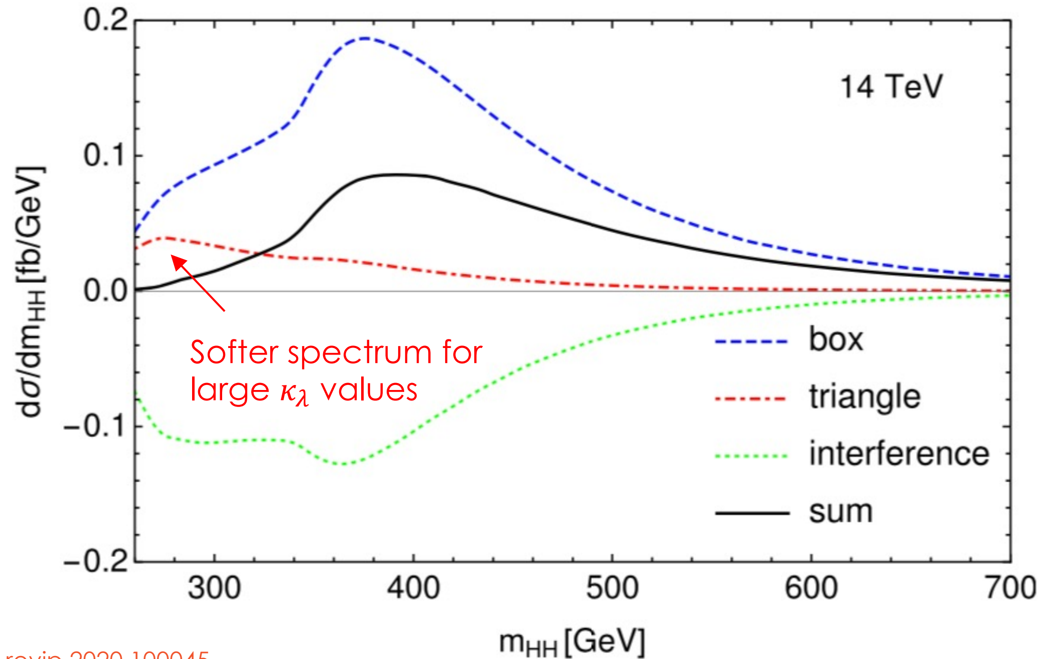
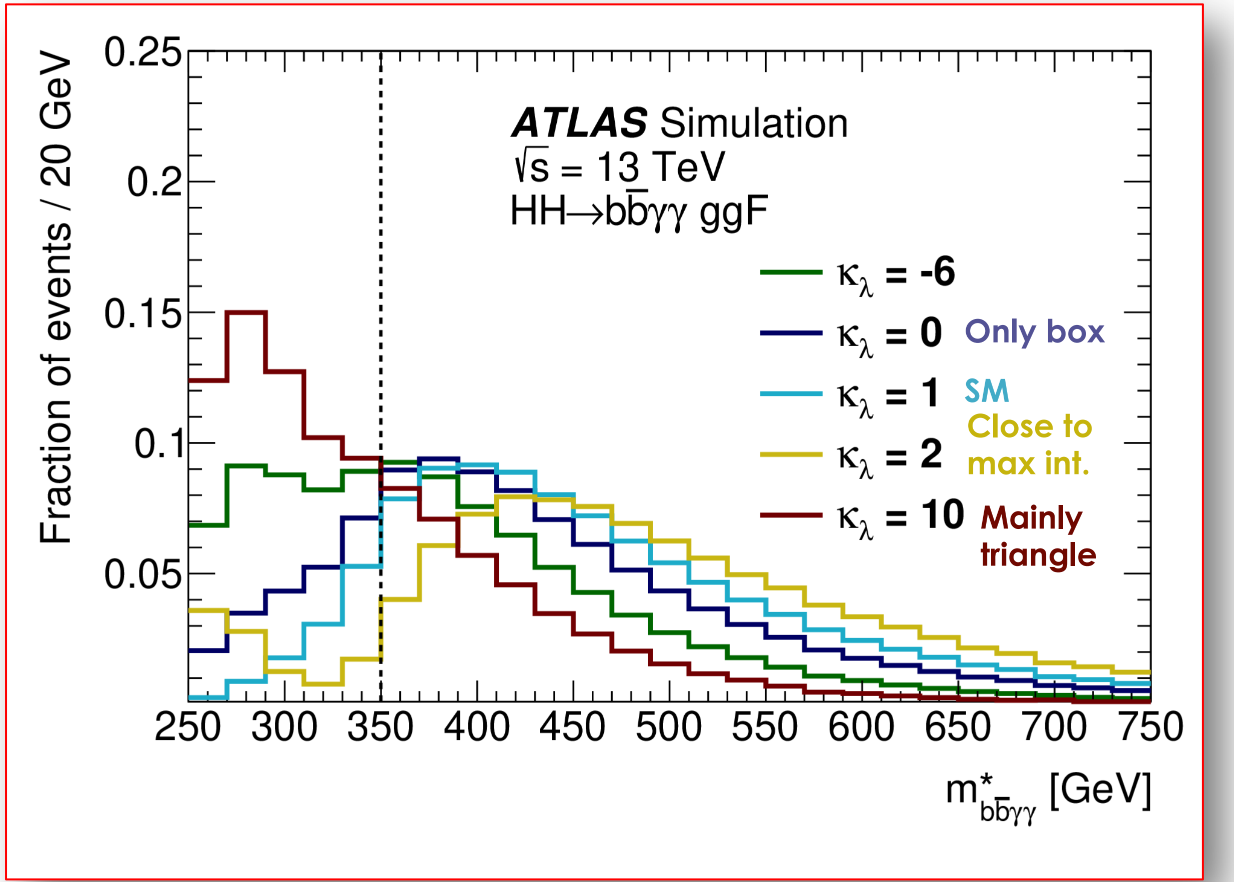


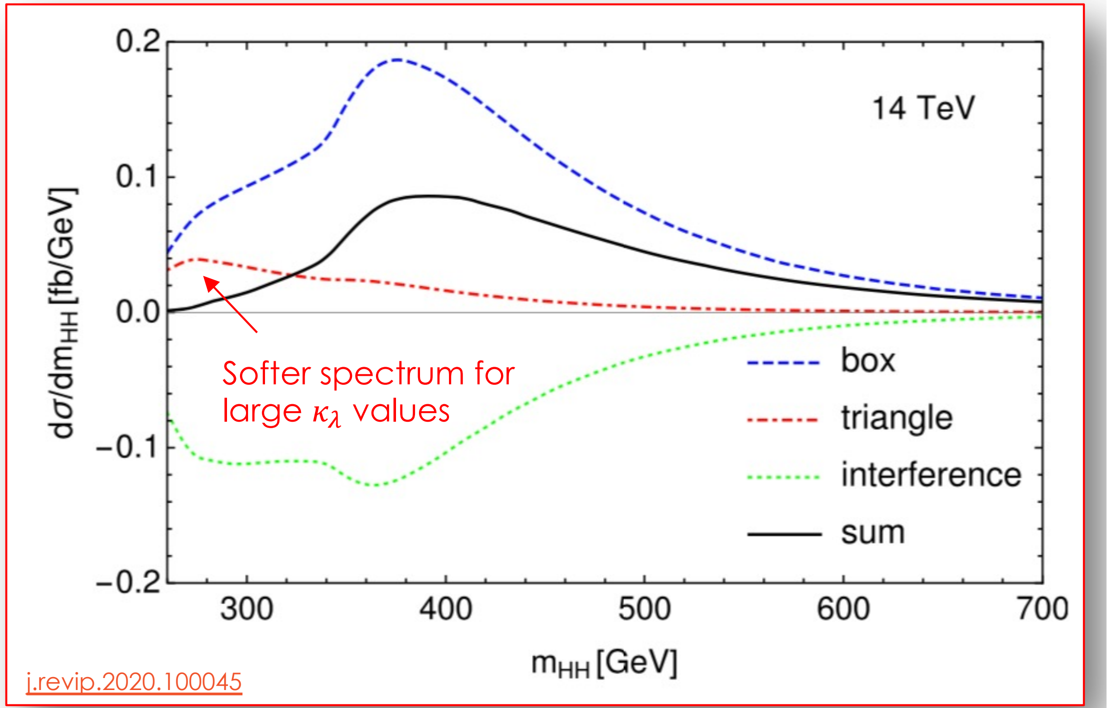


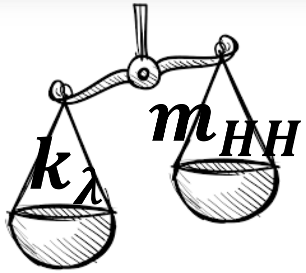
j.revip.2020.100045

HH PRODUCTION AT THE LHC

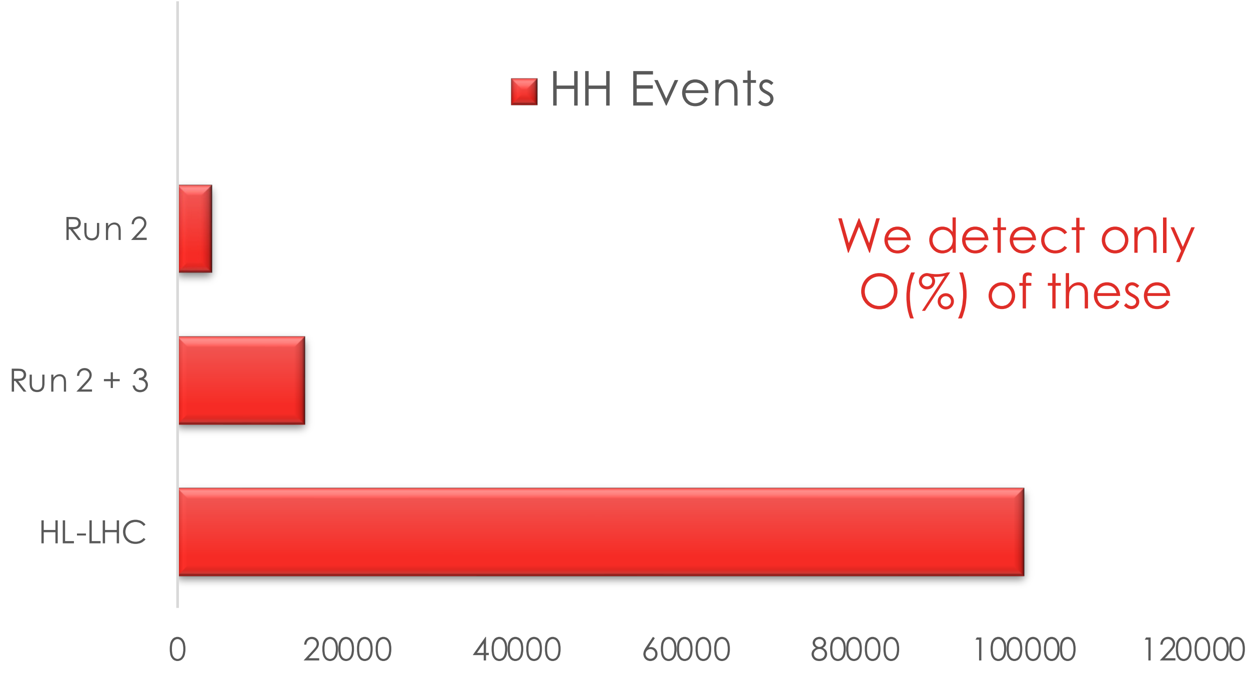


Key experimental handle





TWICE THE HIGGS, TWICE THE CHALLENGE

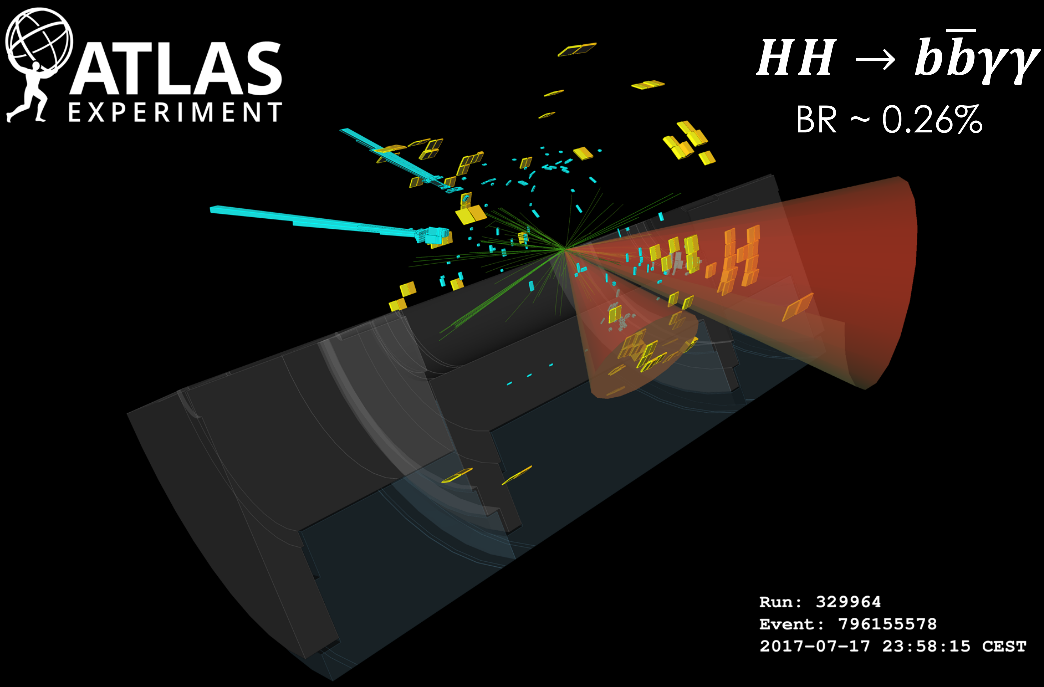


Need to combine multiple signatures of Higgs boson decays to increase sensitivity

Complementary strengths and challenges

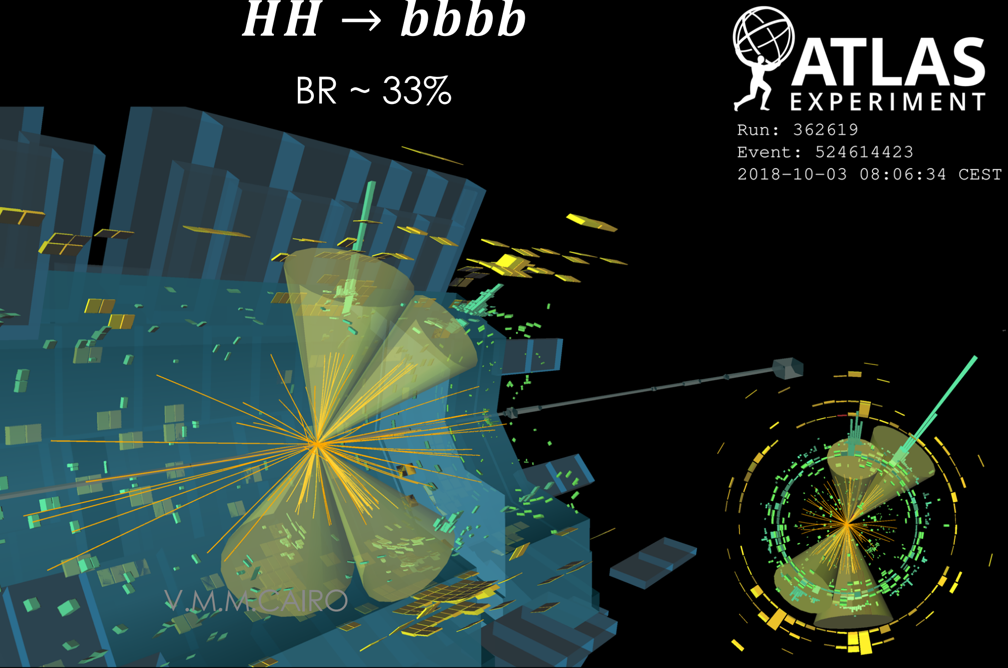
$HH \to b\bar{b}\gamma\gamma$

BR ~ 0.26%



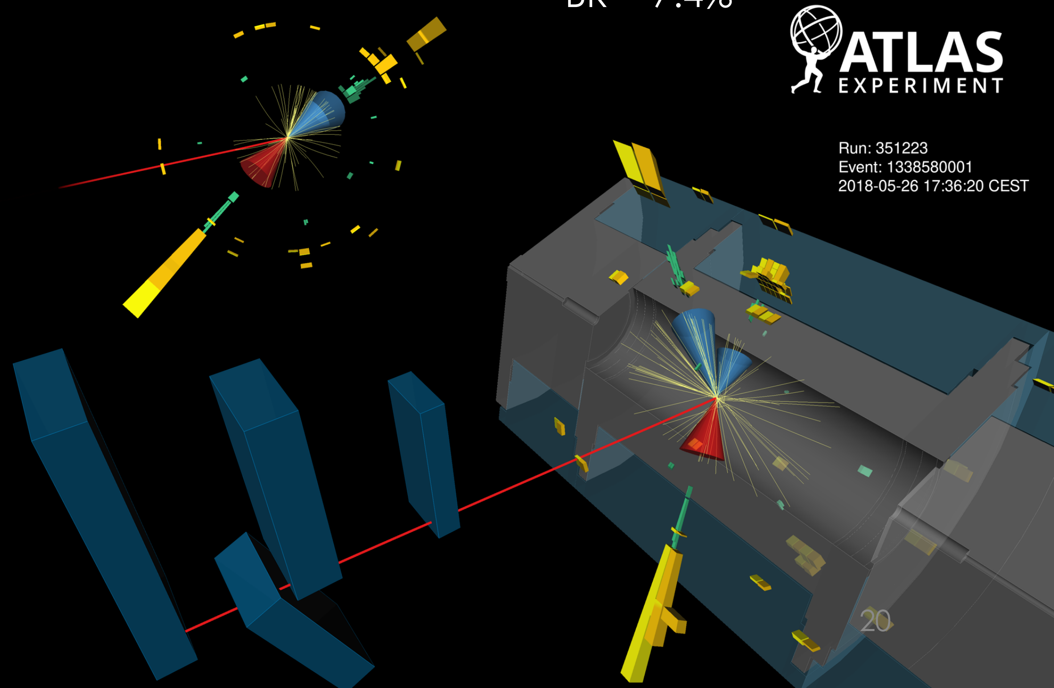
$HH \to b\bar{b}b\bar{b}$

BR ~ 33%



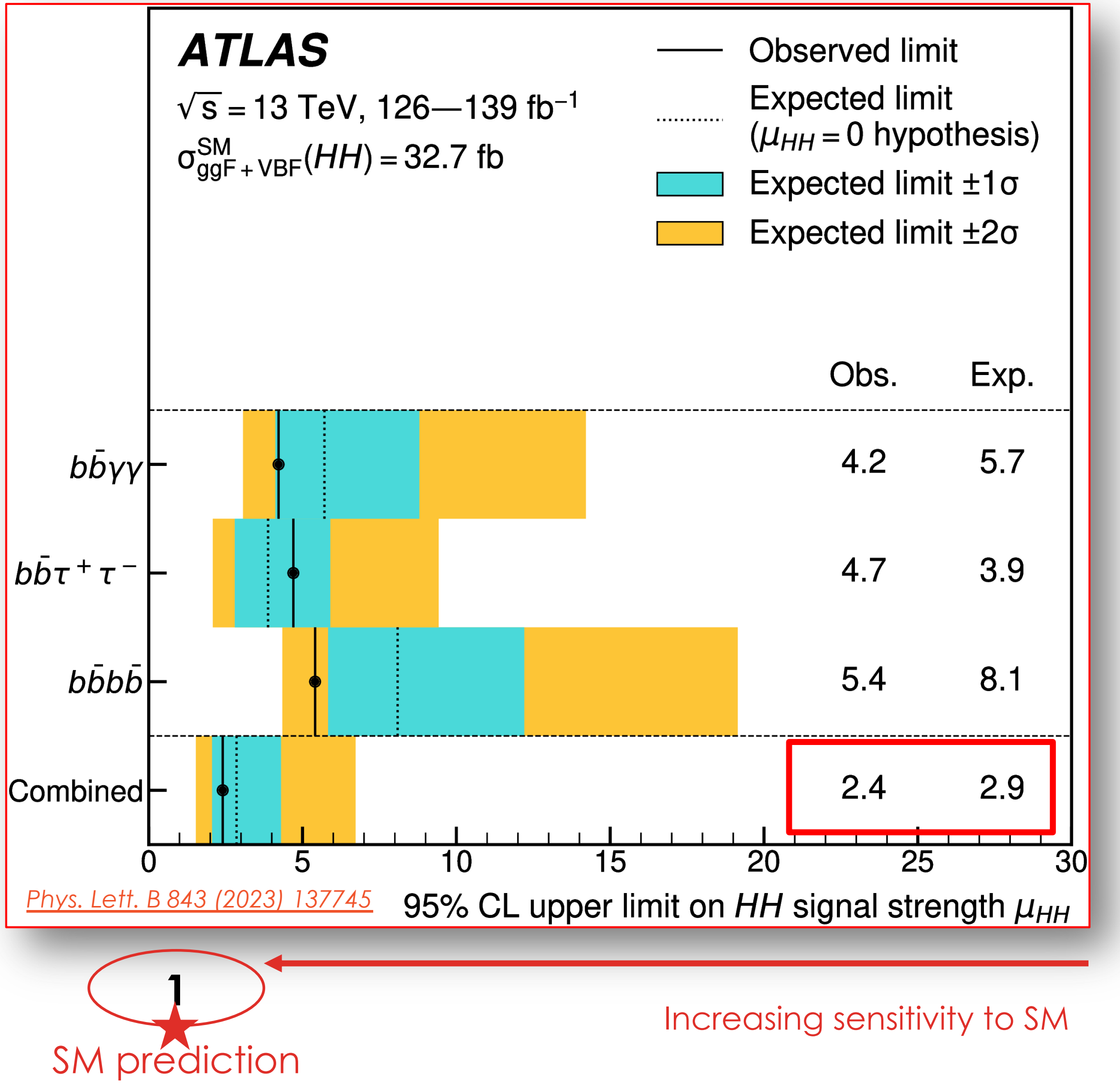
$HH \to b\bar{b}\tau\tau$

BR ~ 7.4%



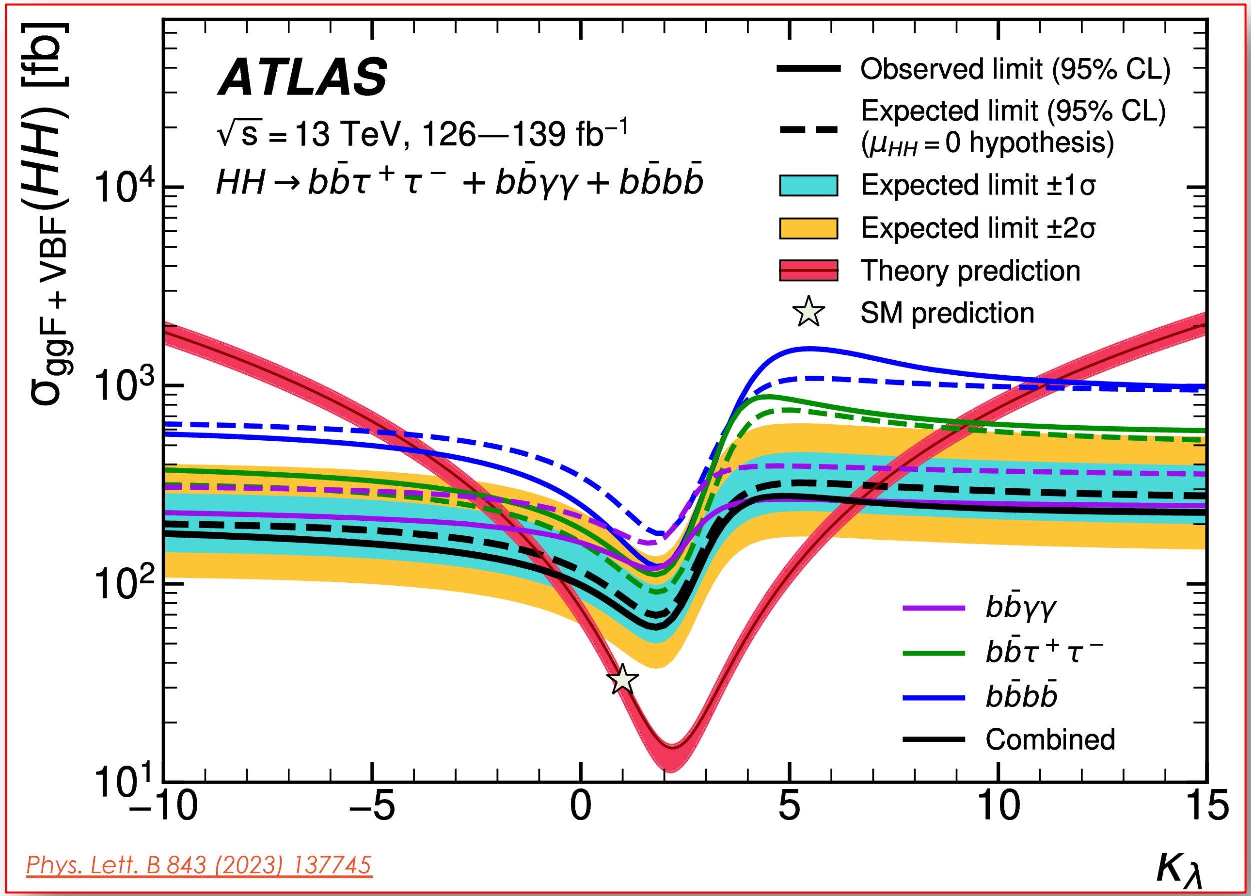
THE POWER OF COMBINATION

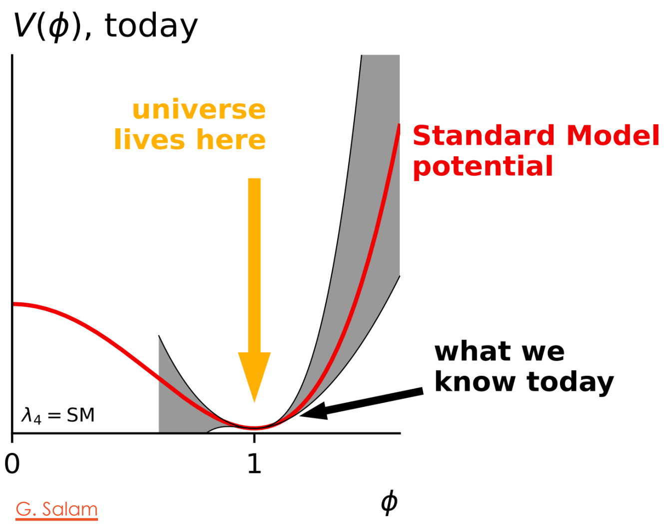
$$HH \to b\bar{b}\tau\tau + b\bar{b}\gamma\gamma + b\bar{b}\,b\bar{b}$$



THE POWER OF COMBINATION

$HH \rightarrow b\bar{b}\tau\tau + b\bar{b}\gamma\gamma + b\bar{b}\,b\bar{b}$



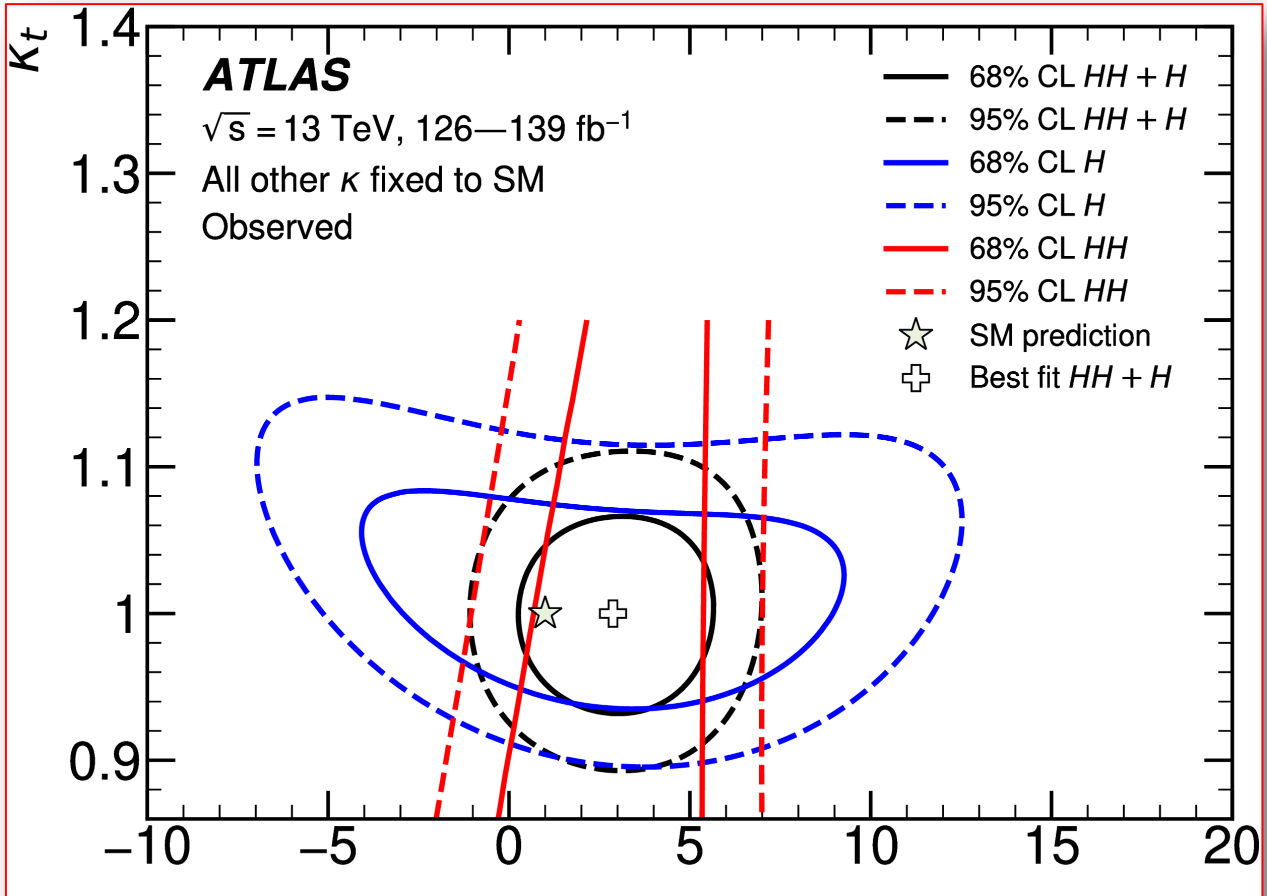


World's best constraints to date on Higgs boson's self coupling from HH searches

Observed(expected): $-0.6< k_{\lambda}<6.6$ ($-2.1< k_{\lambda}< 7.8$)

THE POWER OF COMBINATION

$H + HH$



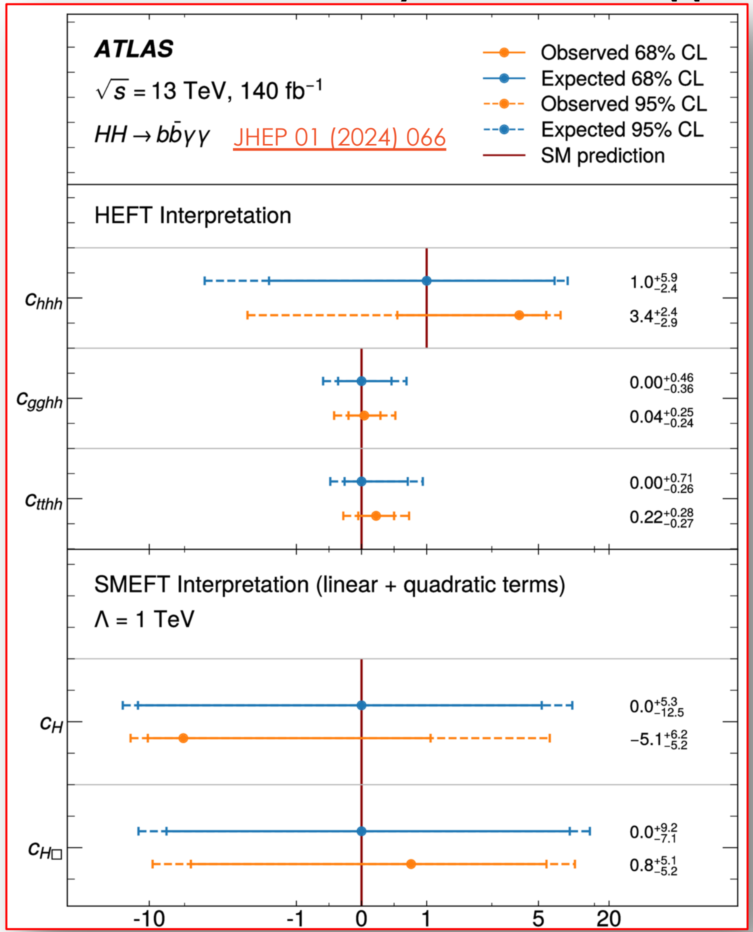
Phys. Lett. B 843 (2023) 137745

A BROAD AND EXCITING PROGRAMME

24.05.24

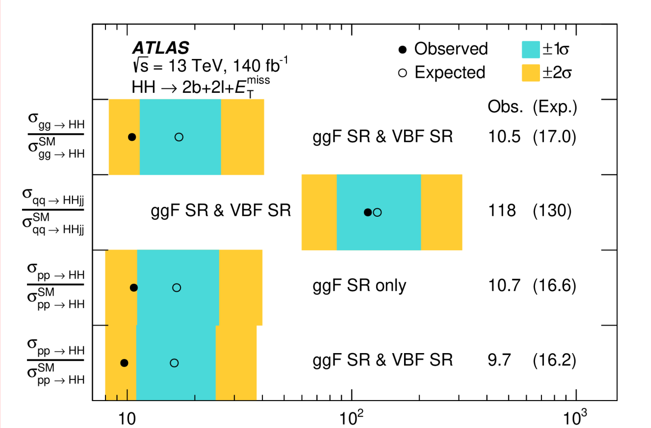
Further improvements to leading channels and new areas to characterise the Higgs sector with HH

Effective Field Theory with $HH \rightarrow bb\gamma\gamma$



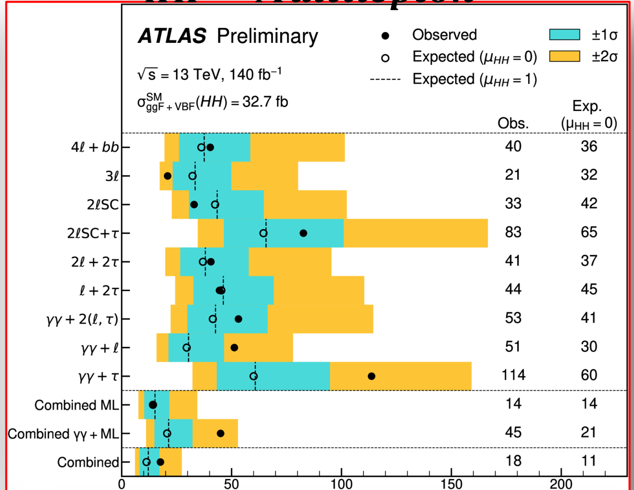
JHEP 01 (2024) 066

$HH \rightarrow bbll$

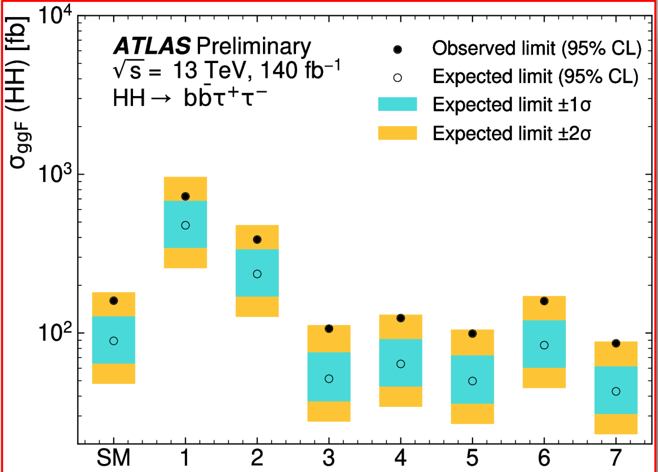


JHEP 02 (2024) 037

$HH \rightarrow Multilepton$

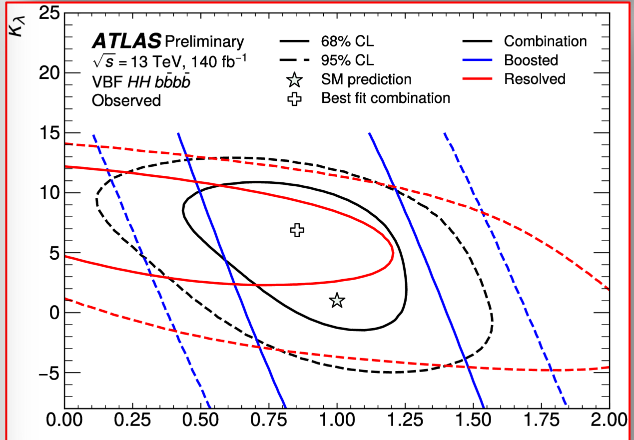


ATLAS-CONF-2024-005



ATLAS-CONF-2023-071

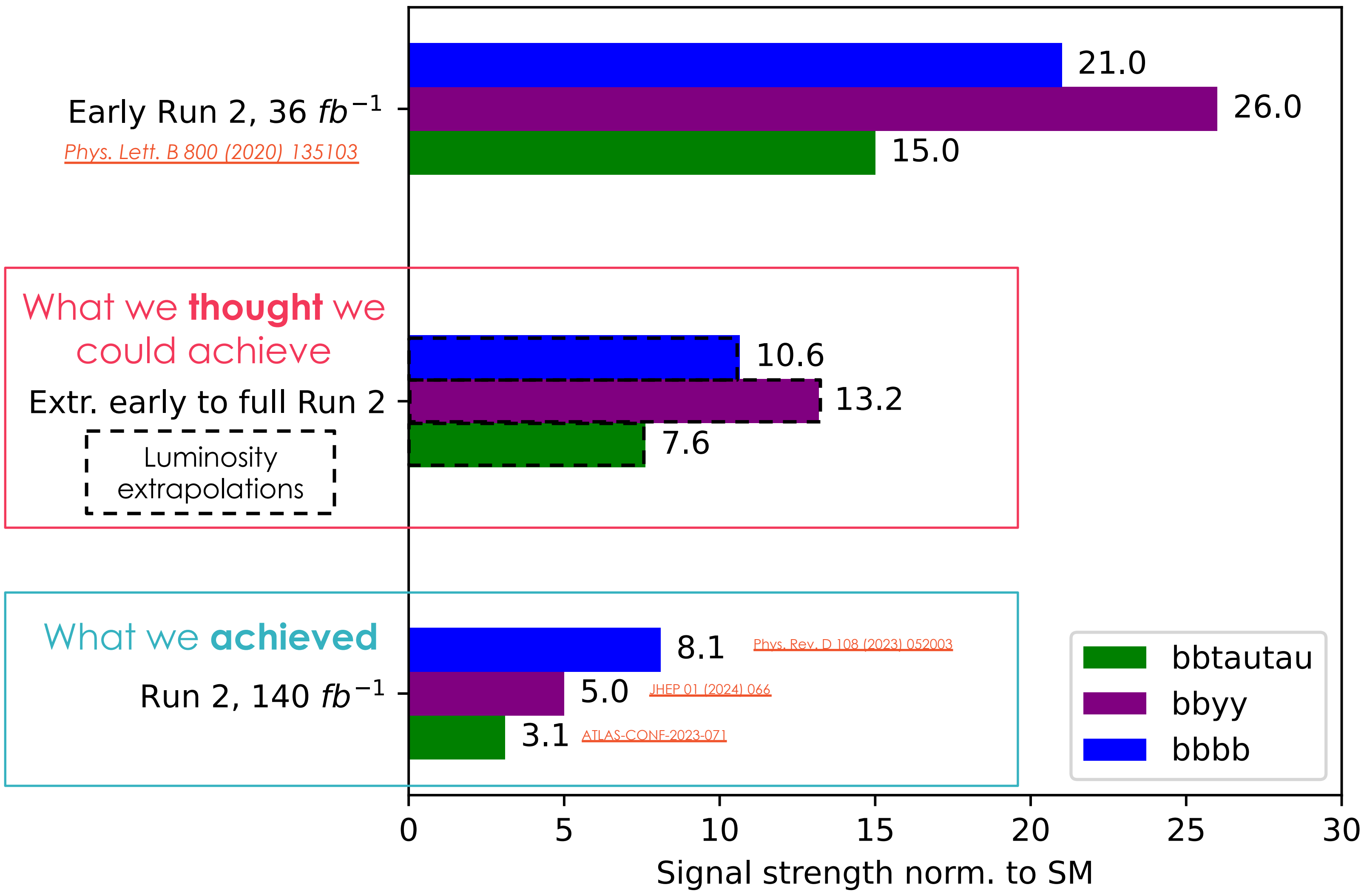
Effective Field Theory with $HH \rightarrow bb\tau\tau$



ATLAS-CONF-2024-003

Boosted $HH \rightarrow bbbb$

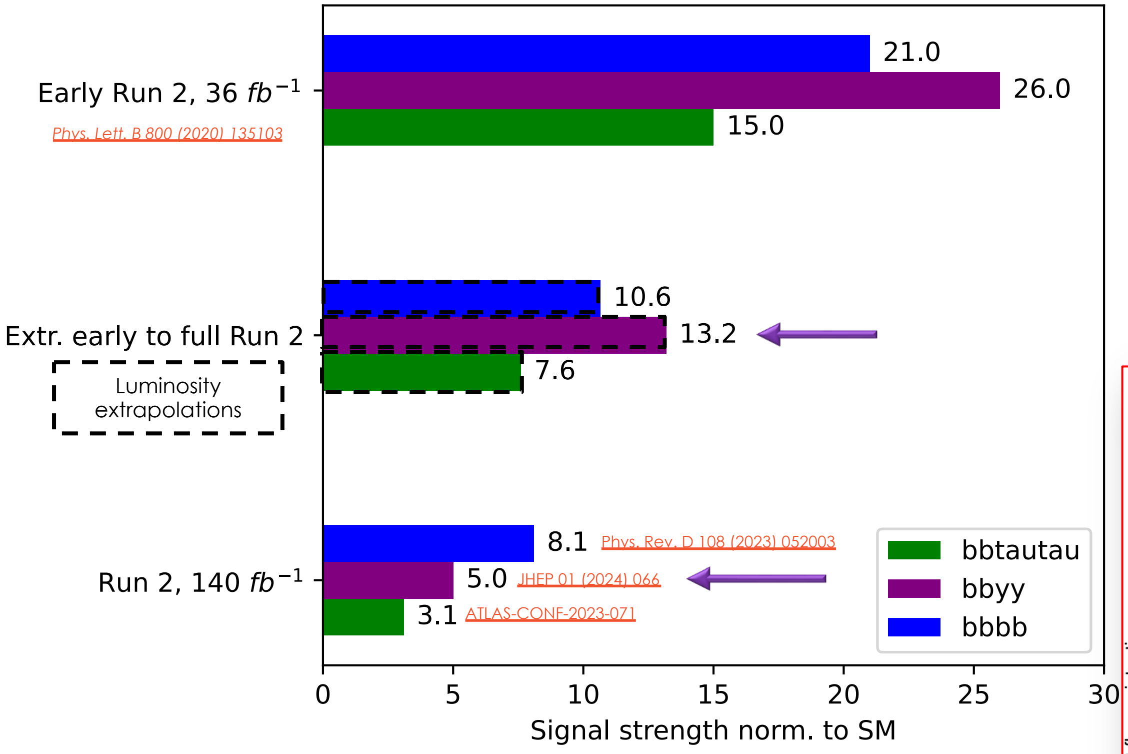
AN IMPRESSIVE SUCCESS



~x2 improvement on top of luminosity increase!

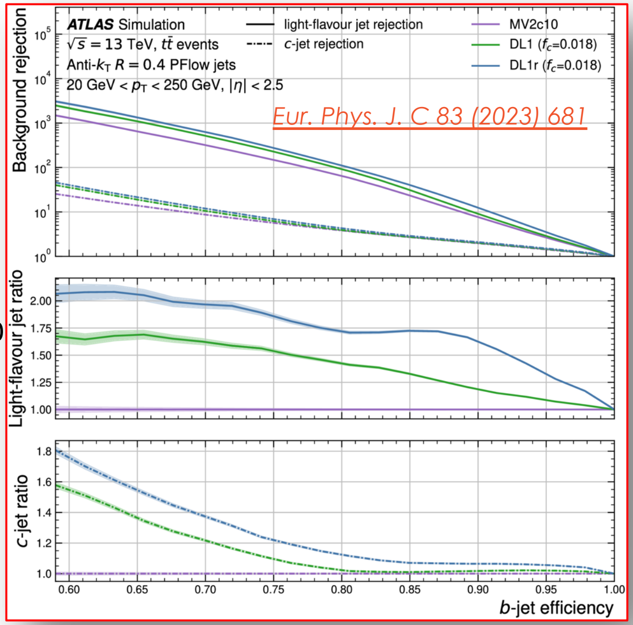
How?

THE $HH \rightarrow bb\gamma\gamma$ EXAMPLE

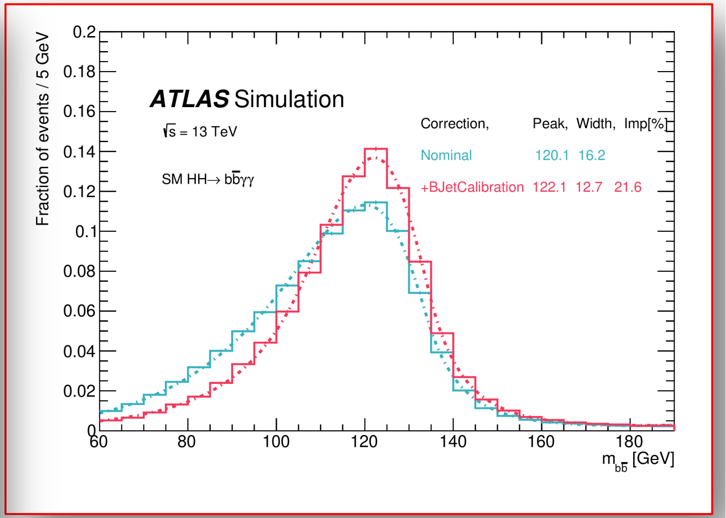


Run 2 $HH \rightarrow bb\gamma\gamma$, a fully re-designed analysis with gains from: **Algorithms**

More b-jets, more HH

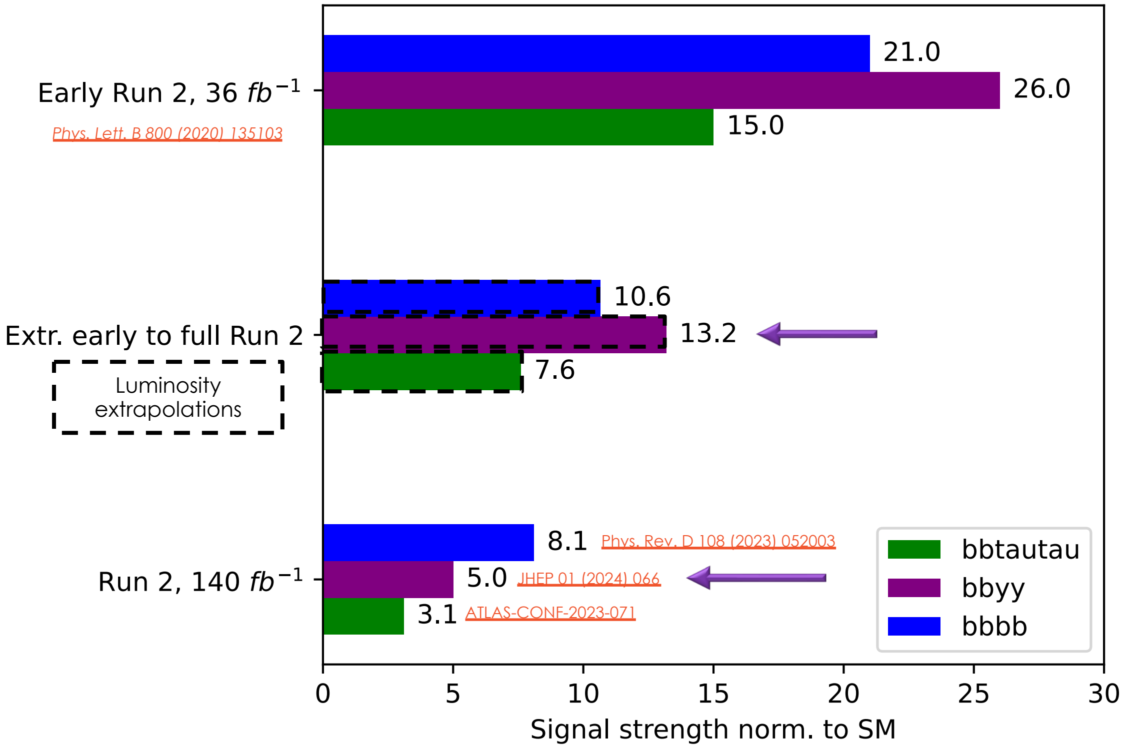


Dedicated b-jet energy corrections



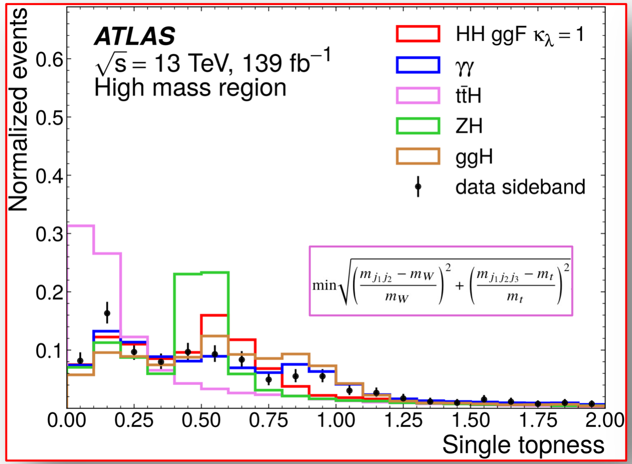
Full Run 2 paper: Phys. Rev. D 106 (2022) 052001
Legacy Run 2 Paper: JHEP 01 (2024) 066

THE $HH \rightarrow bb\gamma\gamma$ EXAMPLE

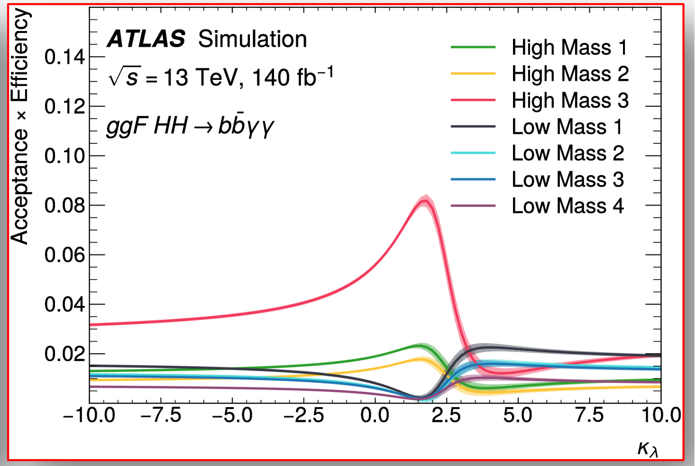


Run 2 $HH \rightarrow bb\gamma\gamma$, a fully re-designed analysis with gains from: **Analysis techniques**

Discriminant kinematic variables

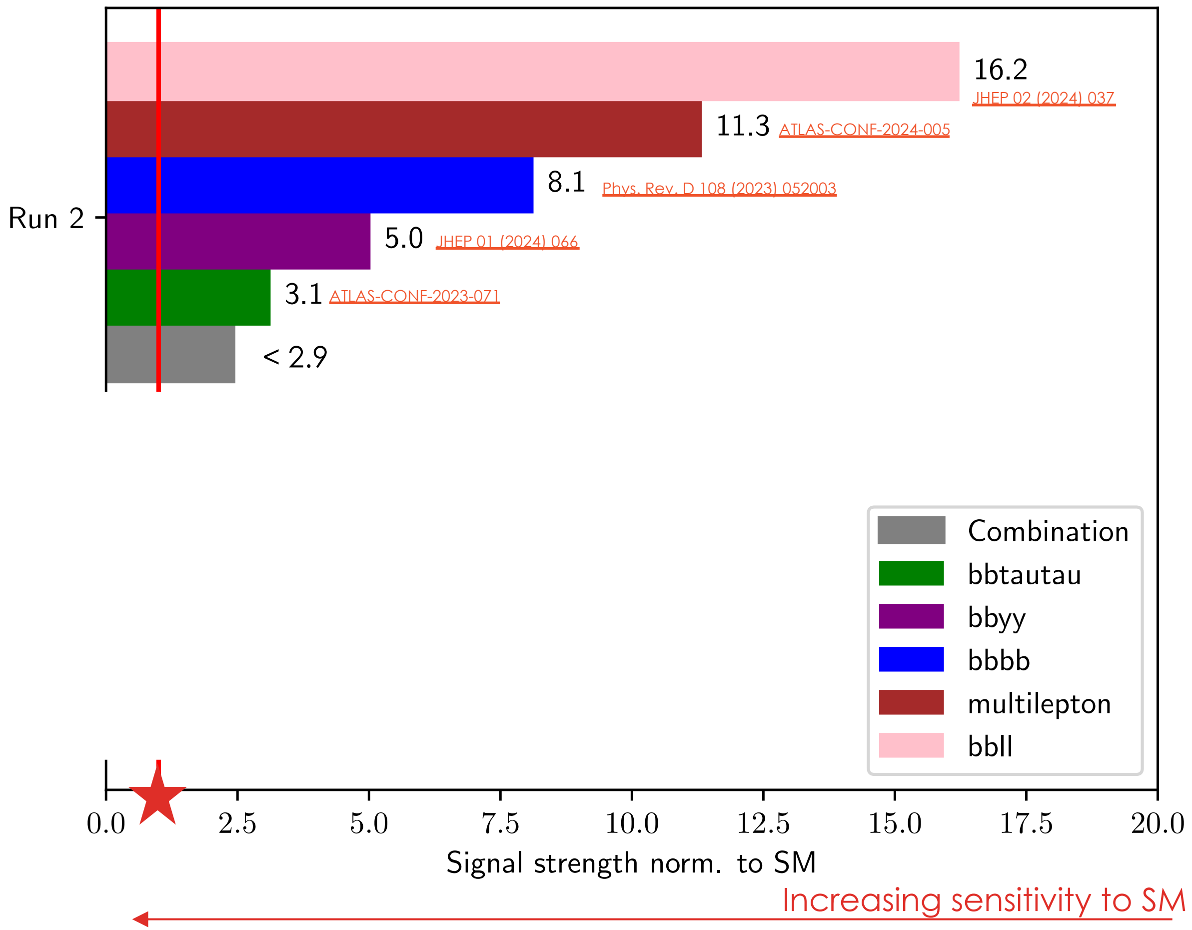


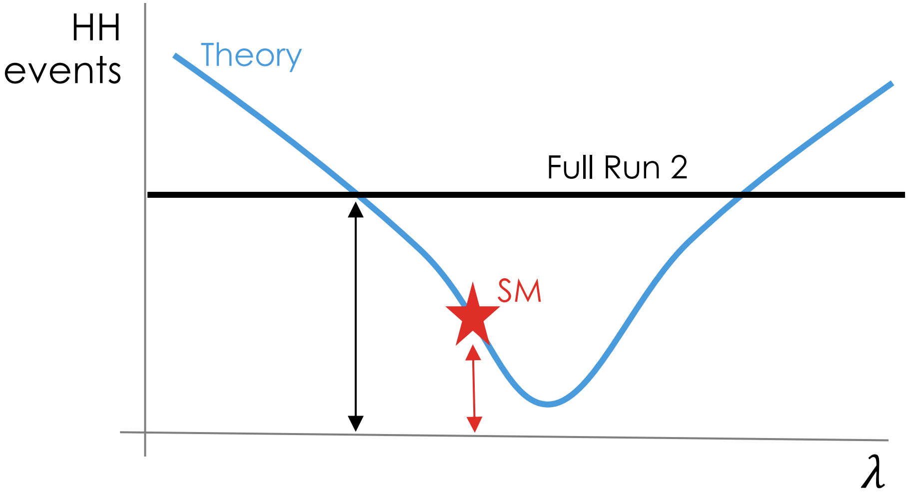
m_{HH} categorization and MVAs



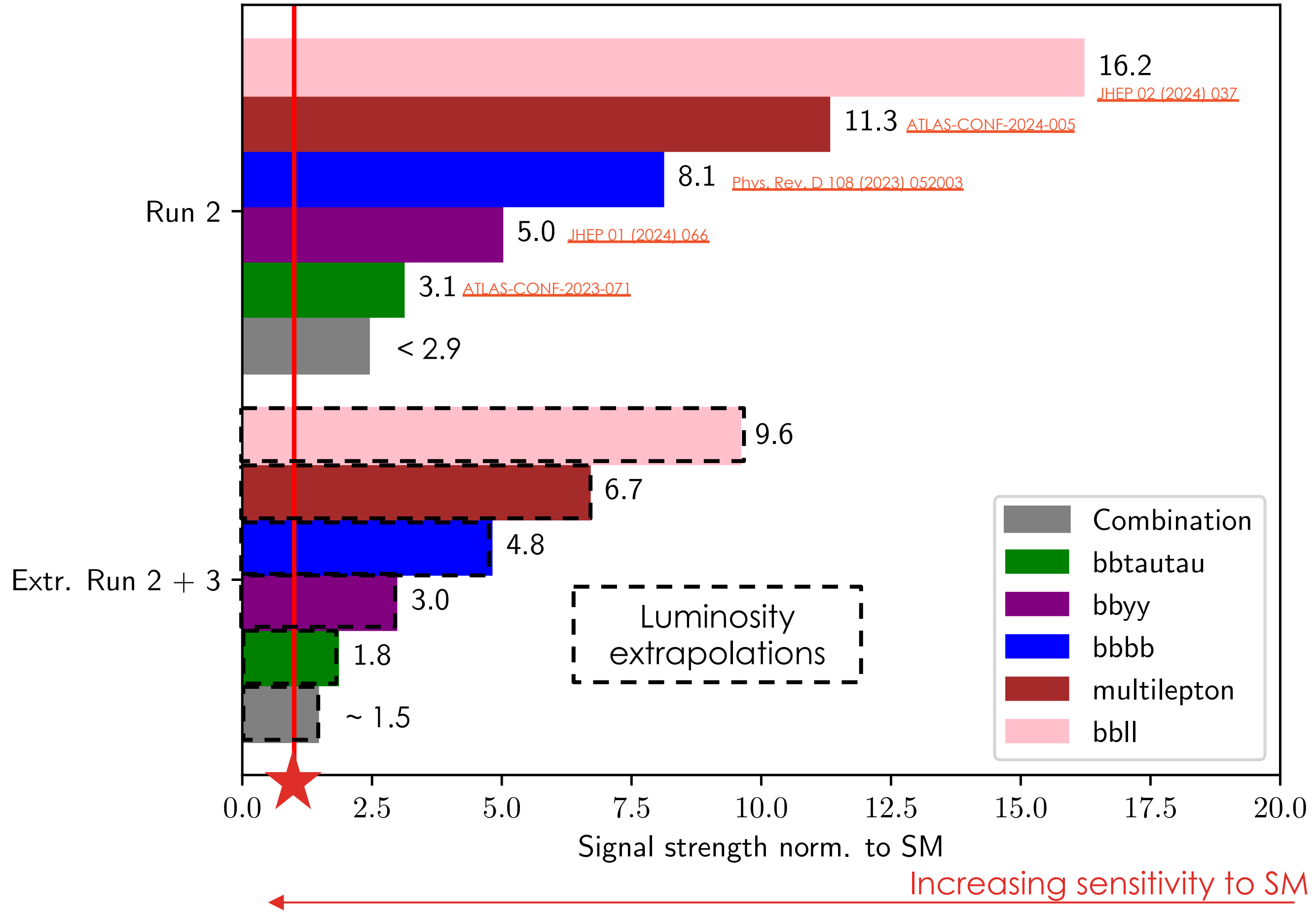
Full Run 2 paper: Phys. Rev. D 106 (2022) 052001
Legacy Run 2 Paper: JHEP 01 (2024) 066

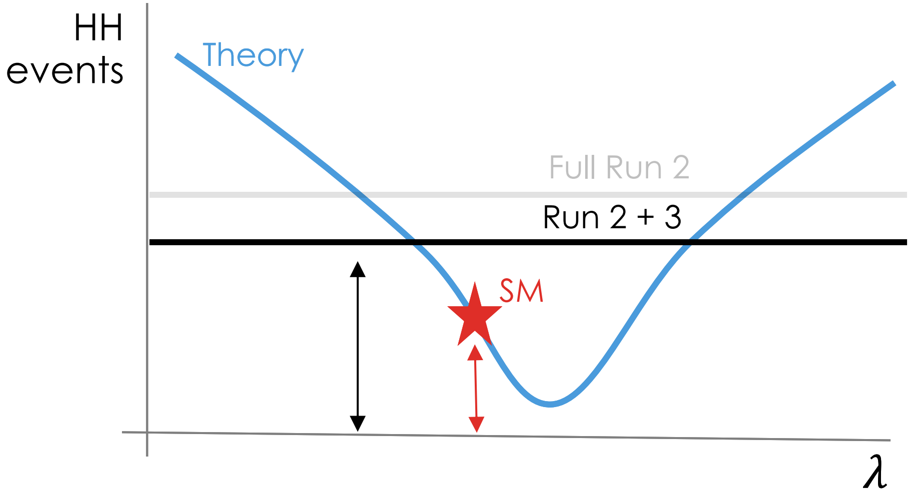
AN EXCITING TIME AHEAD!





AN EXCITING TIME AHEAD!

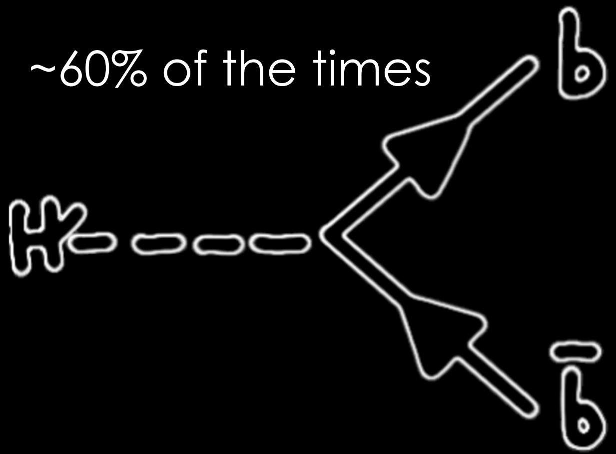




Will we confirm the SM or find new physics?

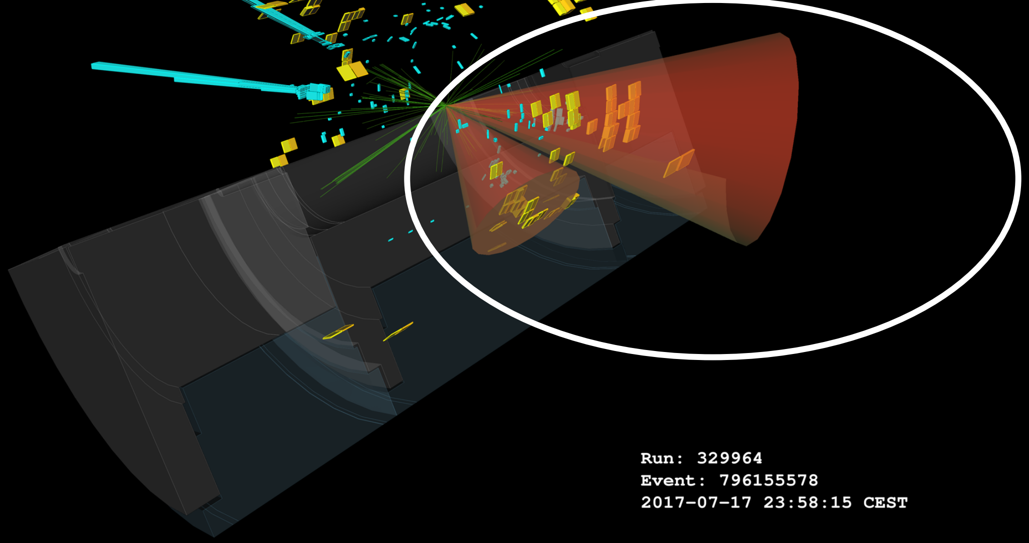
Run 3 data will take us very close to “seeing” HH if as predicted by the SM, but need to improve analyses’ strategies to get to a statistically significant evidence of HH (in combination with CMS)…

~60% of the times



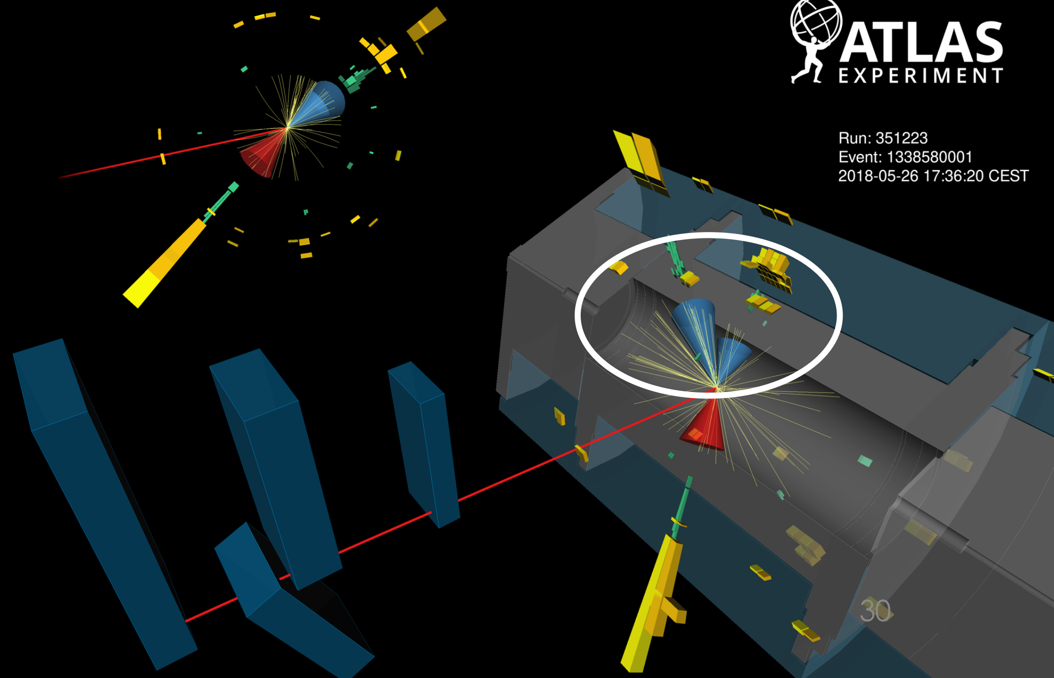
$HH \to b\bar{b}\gamma\gamma$

BR ~ 0.26%



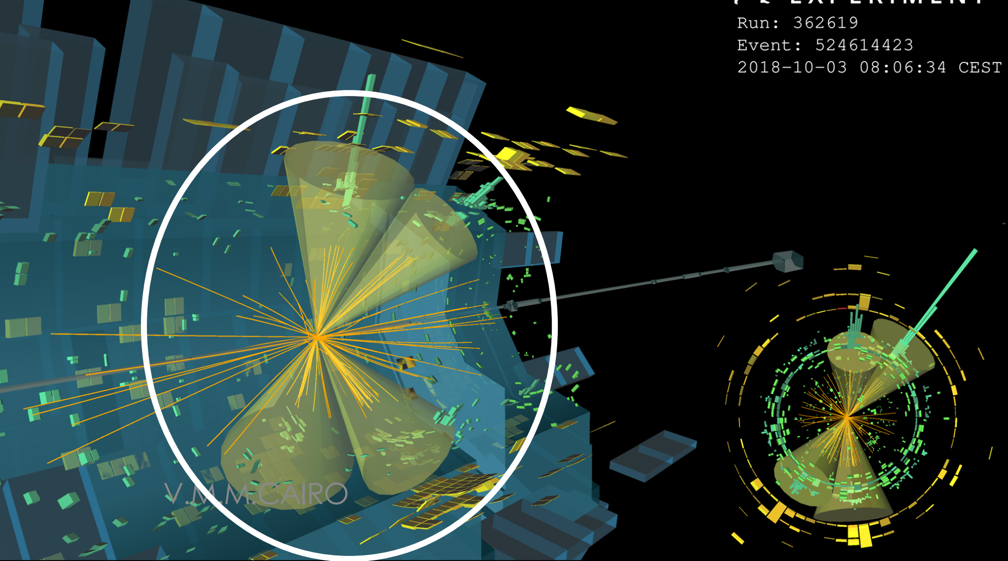
$HH \to b\bar{b}\tau\tau$

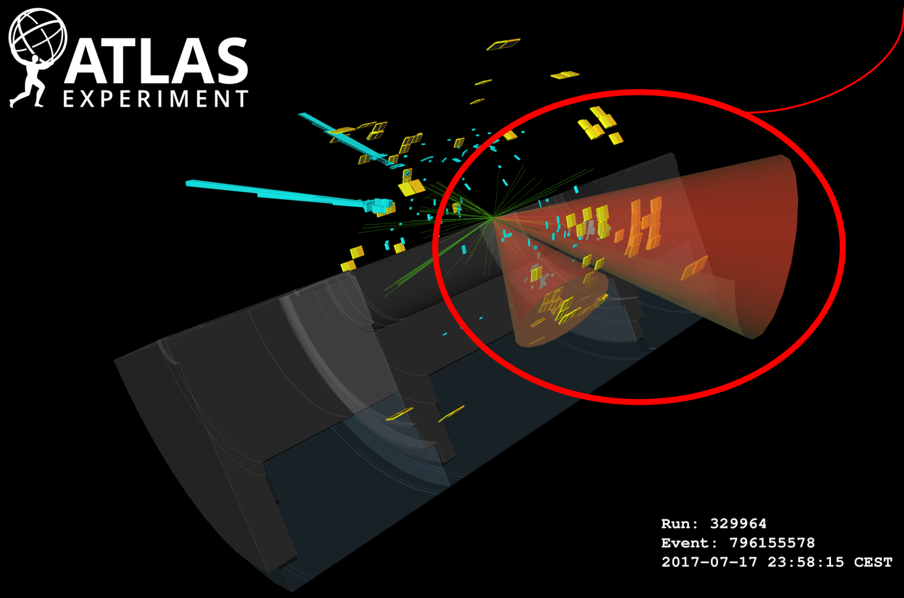
BR ~ 7.4%

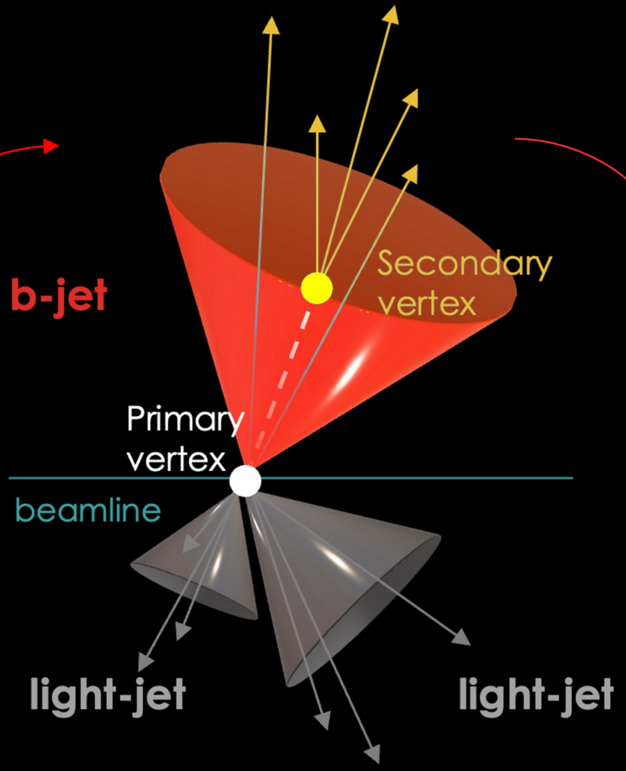


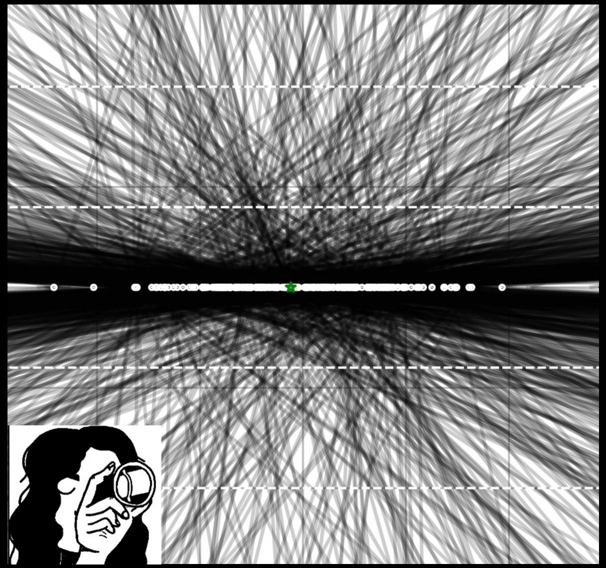
$HH \to b\bar{b}b\bar{b}$

BR ~ 33%



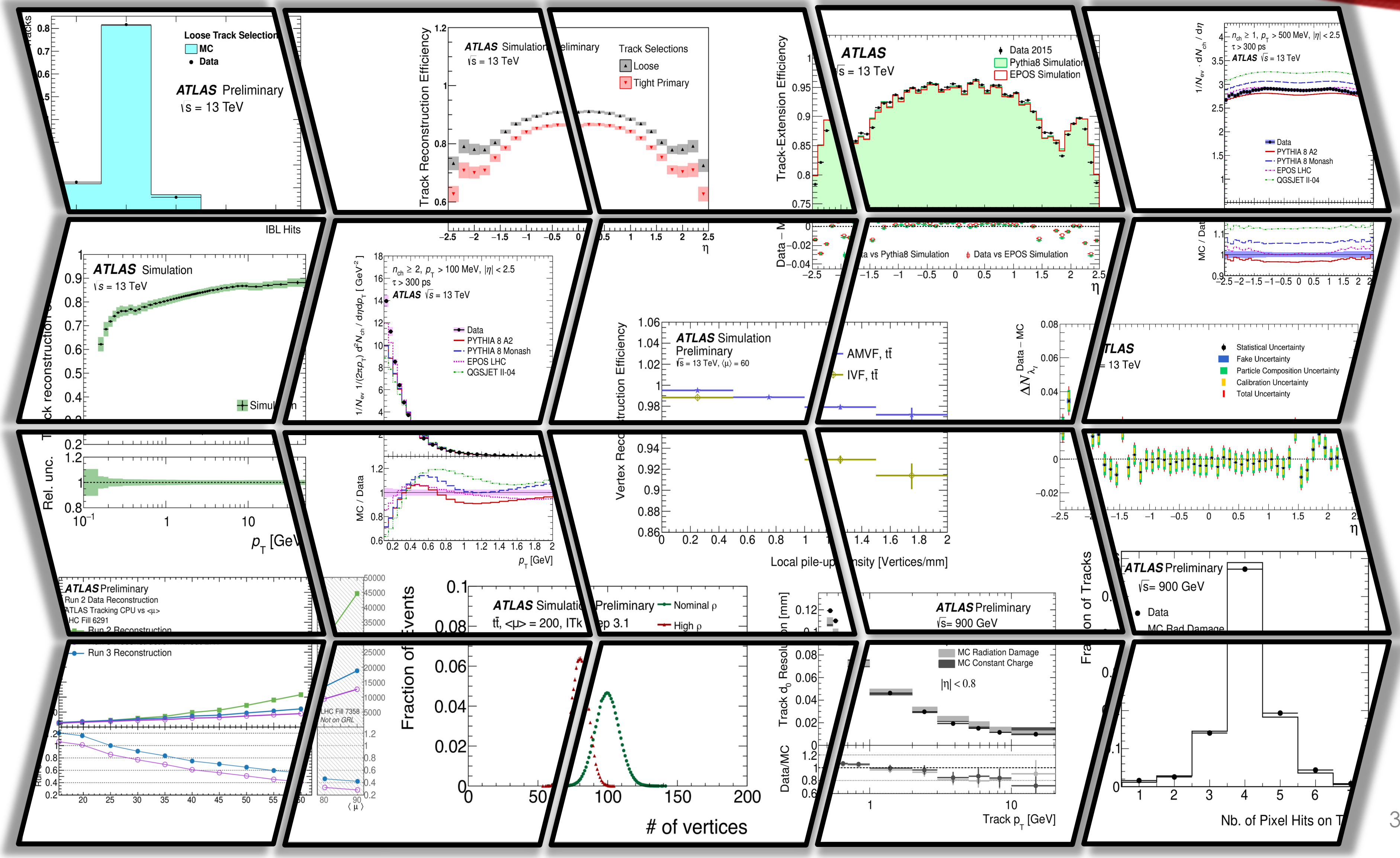

ATLAS
EXPERIMENT
Run: 329964
Event: 796155578
2017-07-17 23:58:15 CEST


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

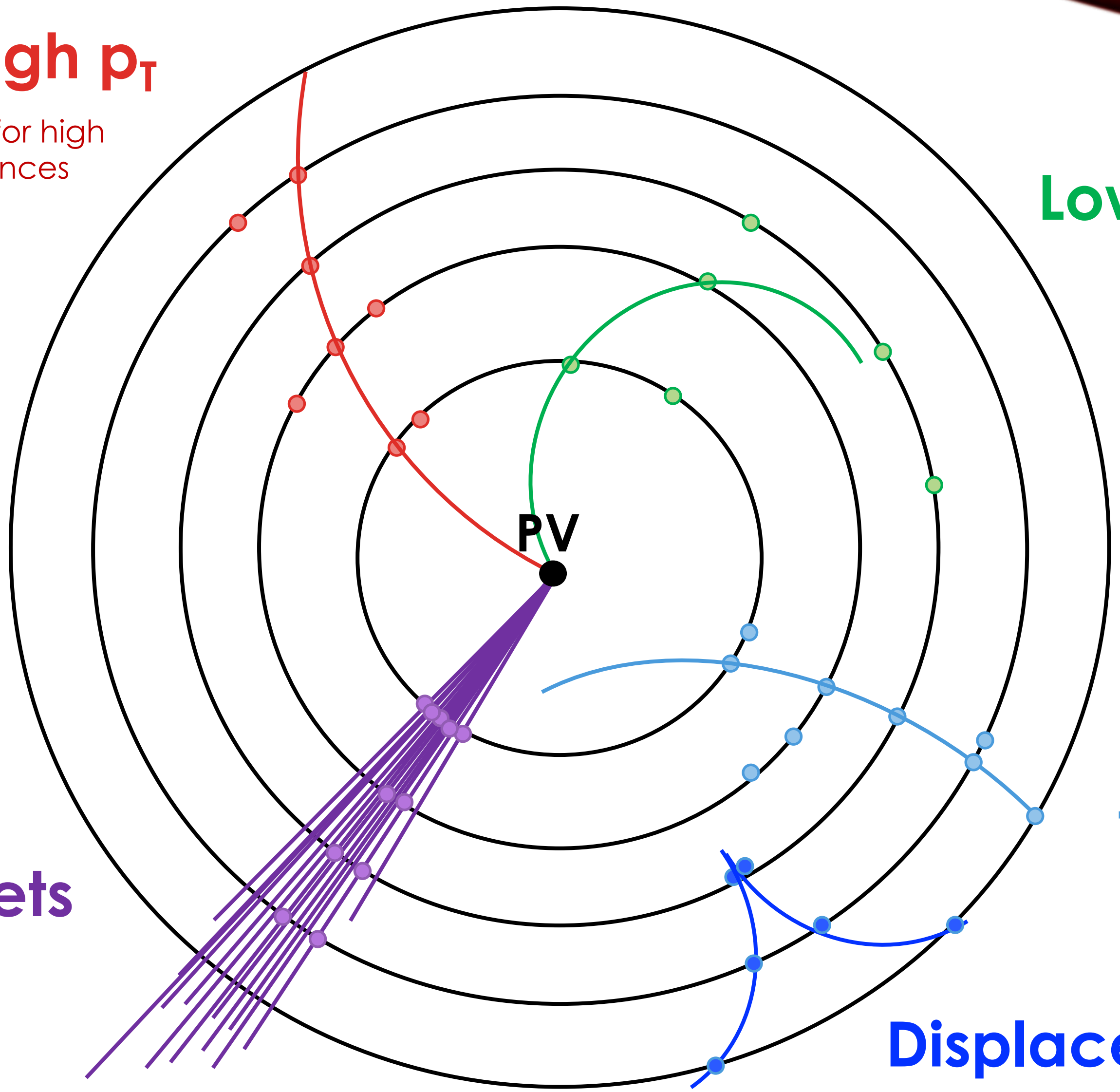


TRACKS AND VERTICES

The building blocks of the LHC events



Demanding requirements on tracking systems from physics benchmarks



High p_T

e.g. good resolution for high mass leptonic resonances

Low p_T

e.g. high efficiency for hadron production rate studies and for good jet energy resolution

Displaced tracks

Displaced vertex

e.g. excellent impact parameter resolution to distinguish prompt from displaced tracks and vertices…

Track in jets

e.g. resolve nearby tracks for tau and B-hadron decays

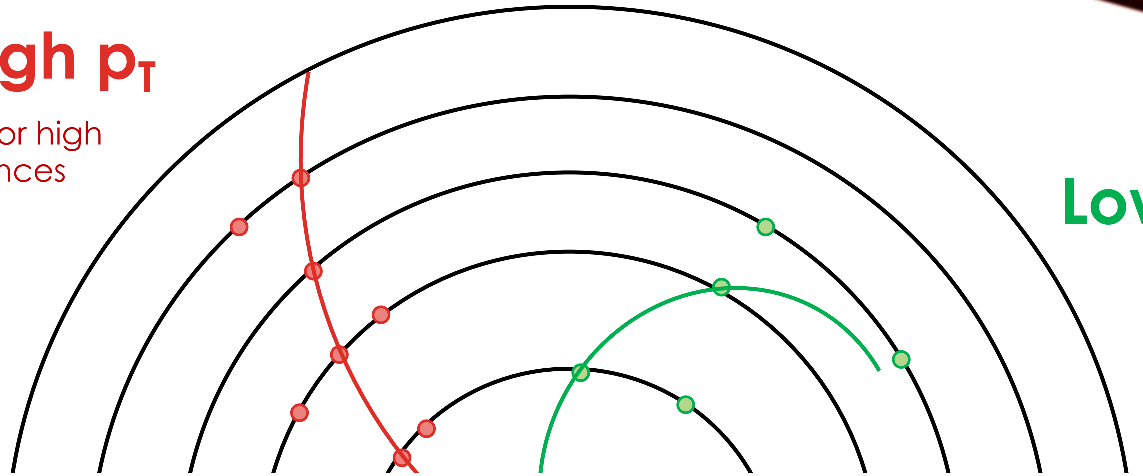
Demanding requirements on tracking systems from physics benchmarks

High p_T

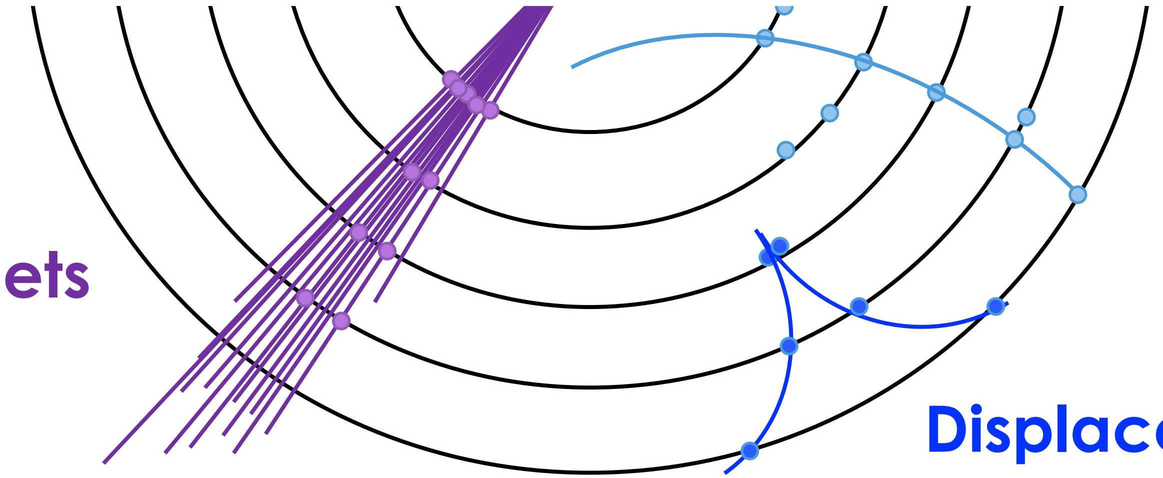
e.g. good resolution for high mass leptonic resonances

Low p_T

e.g. high efficiency for hadron production rate studies and for good jet energy resolution



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



Track in jets

e.g. resolve nearby tracks for tau and B-hadron decays

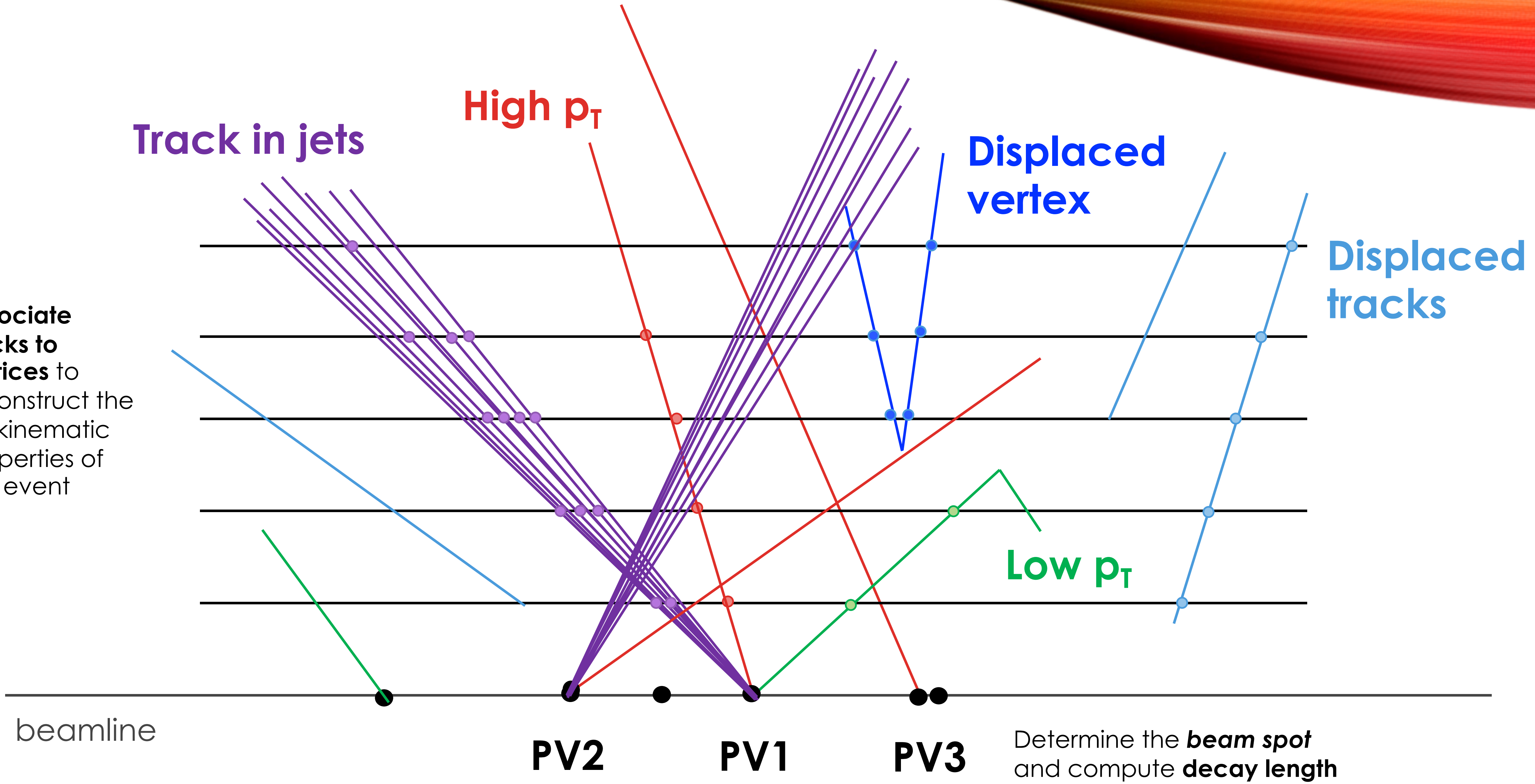
Displaced tracks

e.g. excellent impact parameter resolution to distinguish prompt from displaced tracks and vertices

Displaced vertex

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

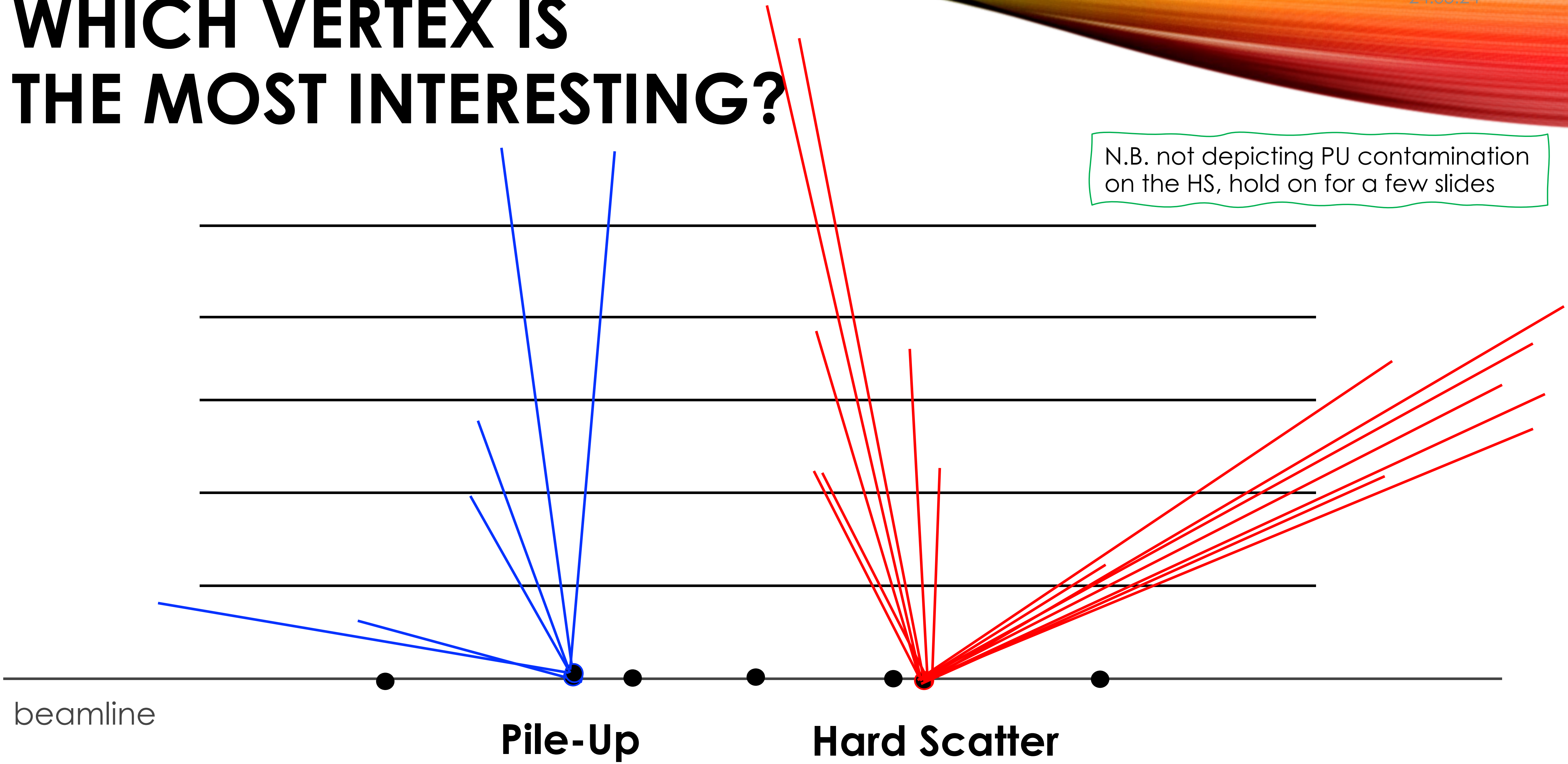
Associate tracks to vertices to reconstruct the full kinematic properties of the event



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

WHICH VERTEX IS THE MOST INTERESTING?

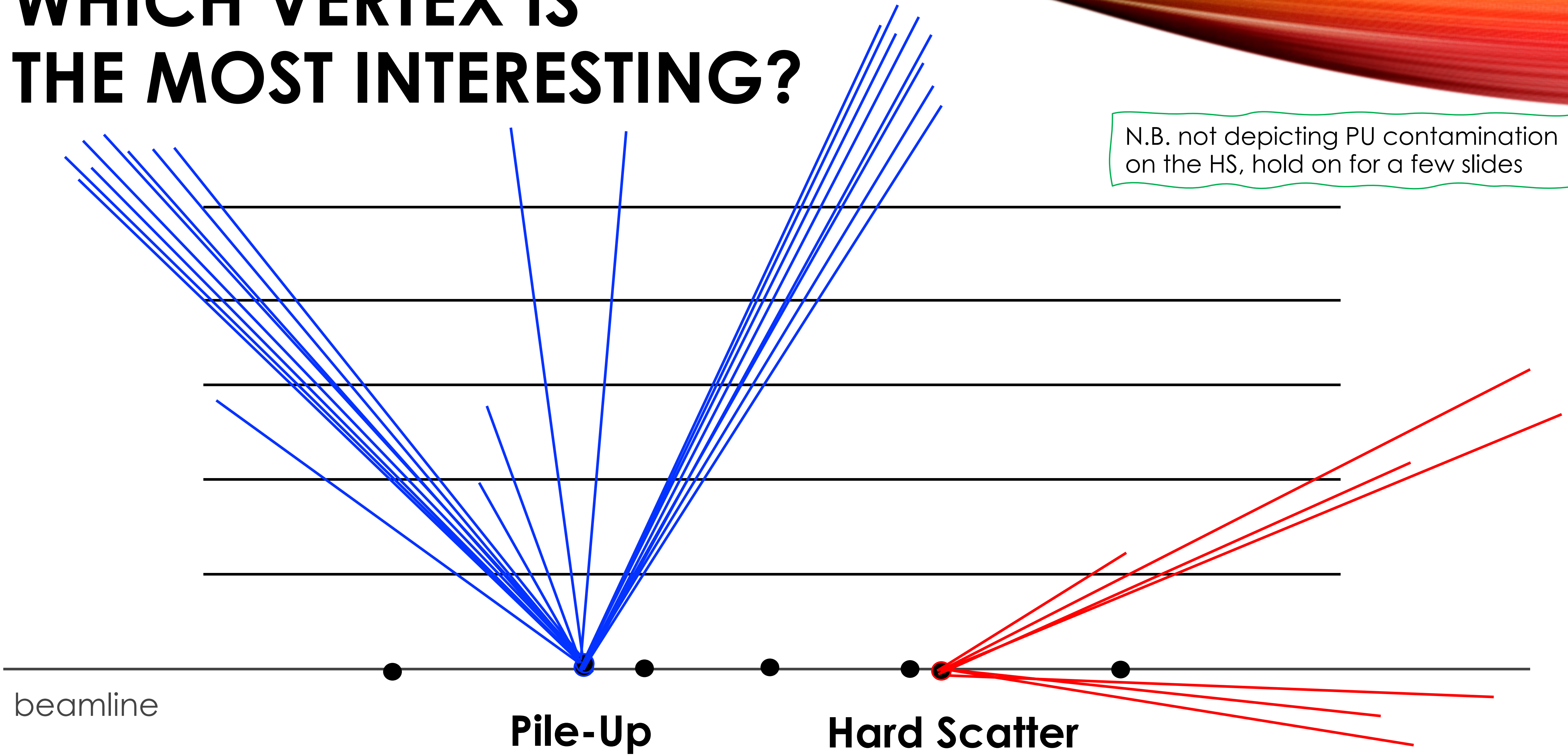
N.B. not depicting PU contamination on the HS, hold on for a few slides



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

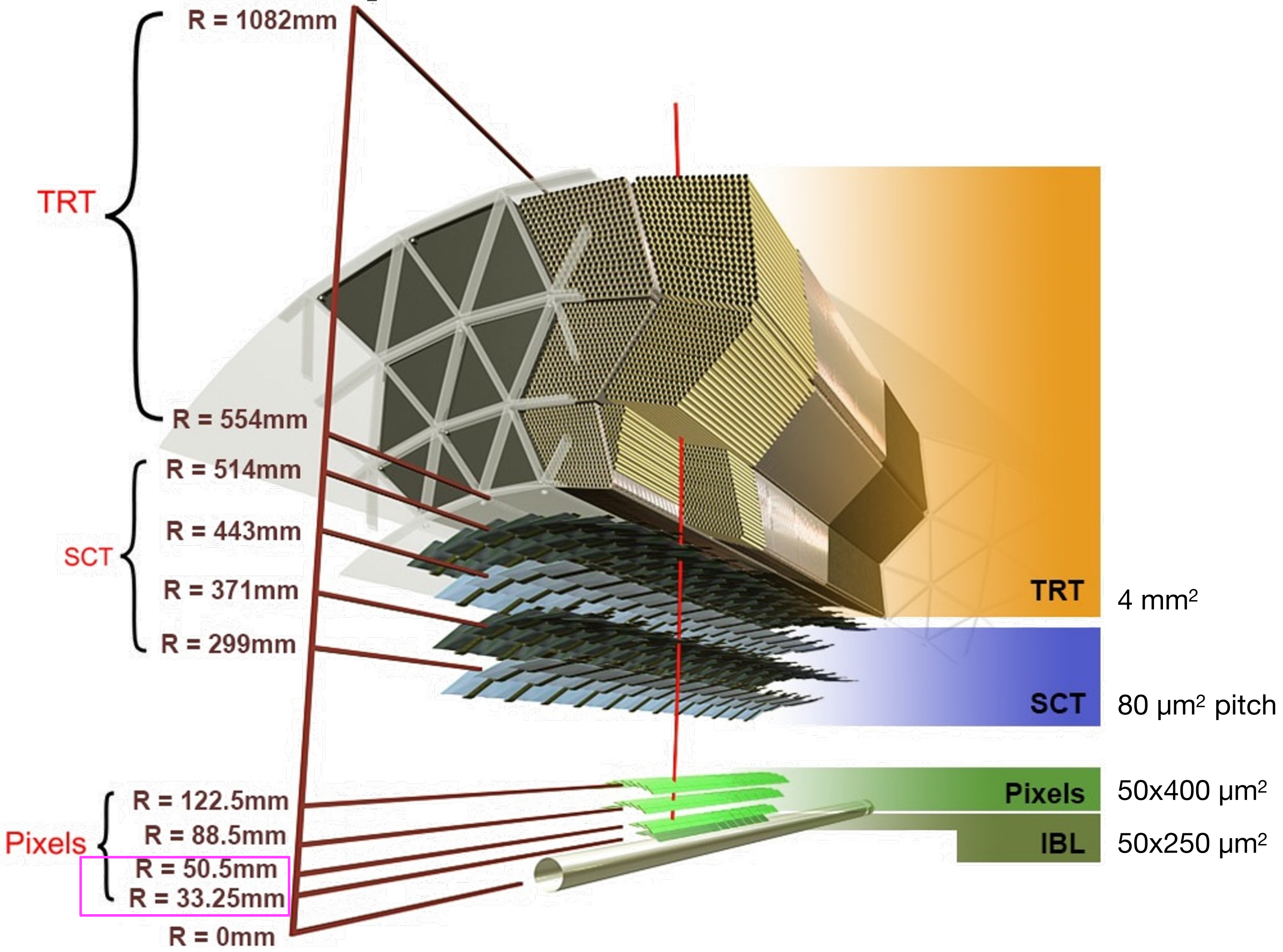
WHICH VERTEX IS THE MOST INTERESTING?

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



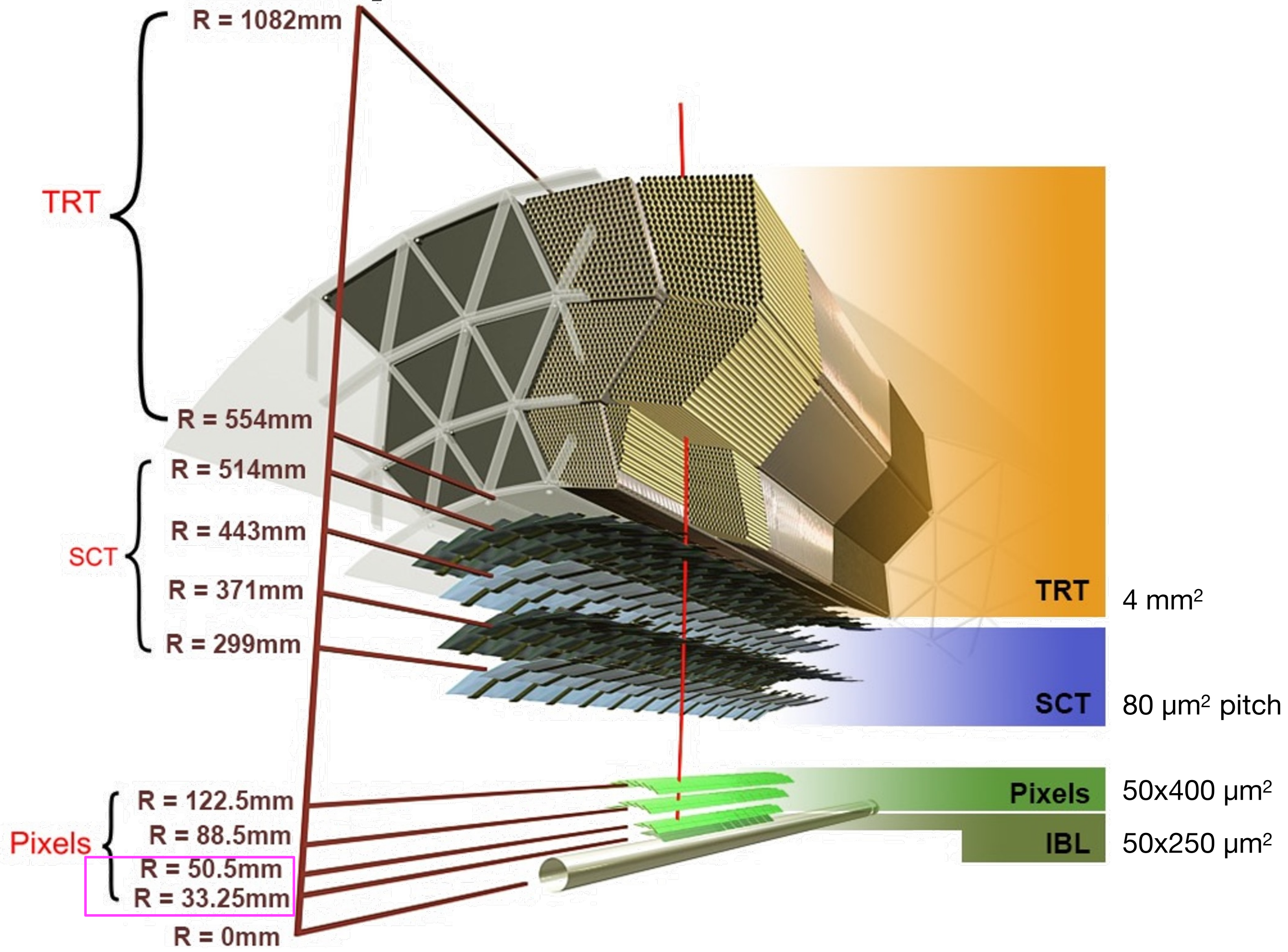
But a pile-up vertex might be harder!

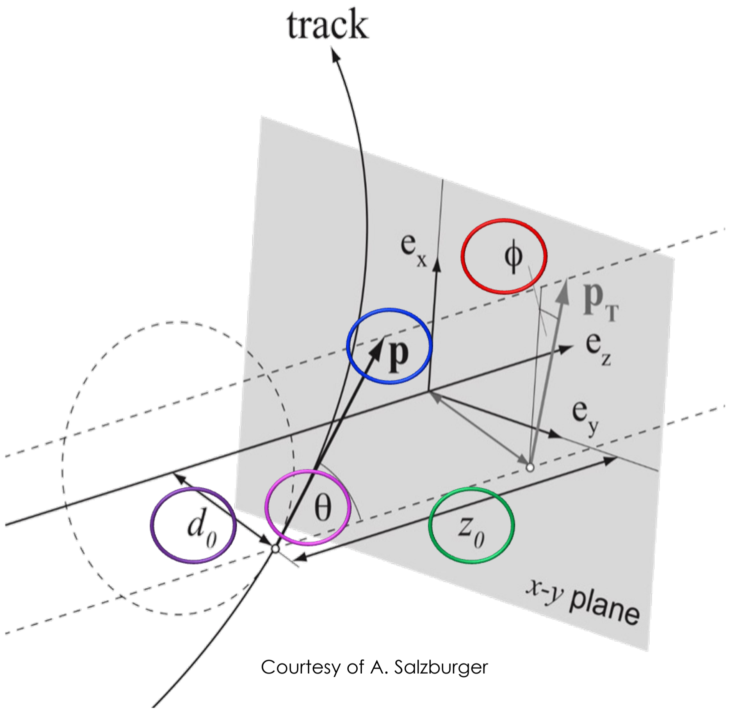
ATLAS INNER DETECTOR IN RUN 2/3



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

ATLAS INNER DETECTOR IN RUN 2/3

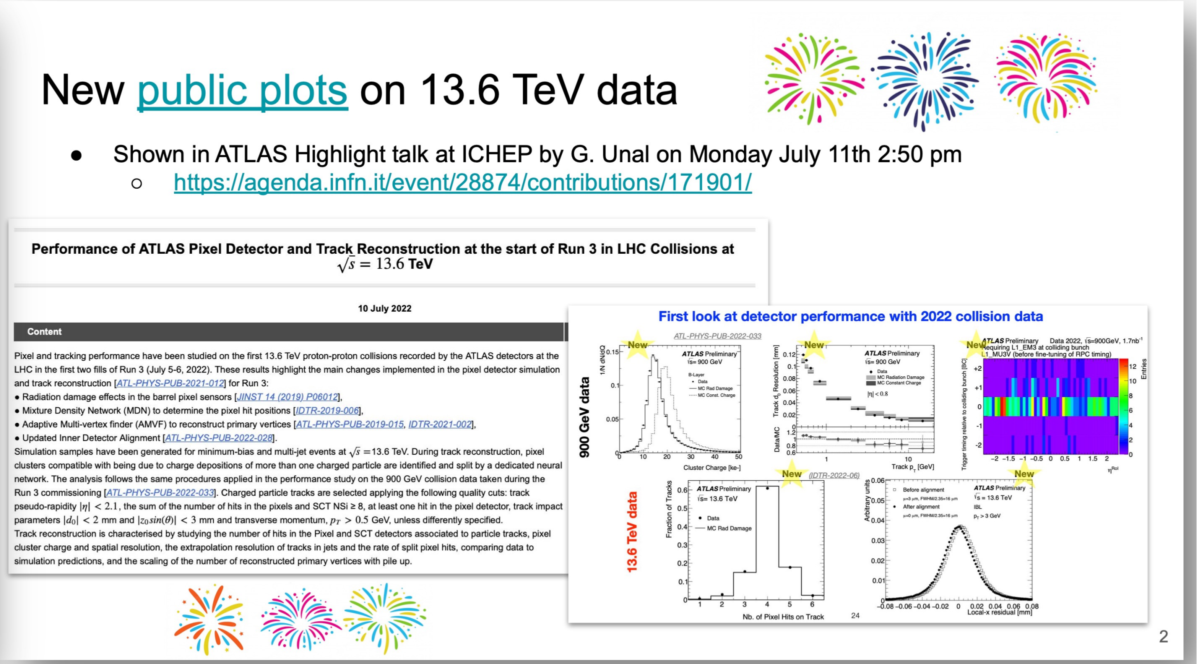




Courtesy of A. Salzburger

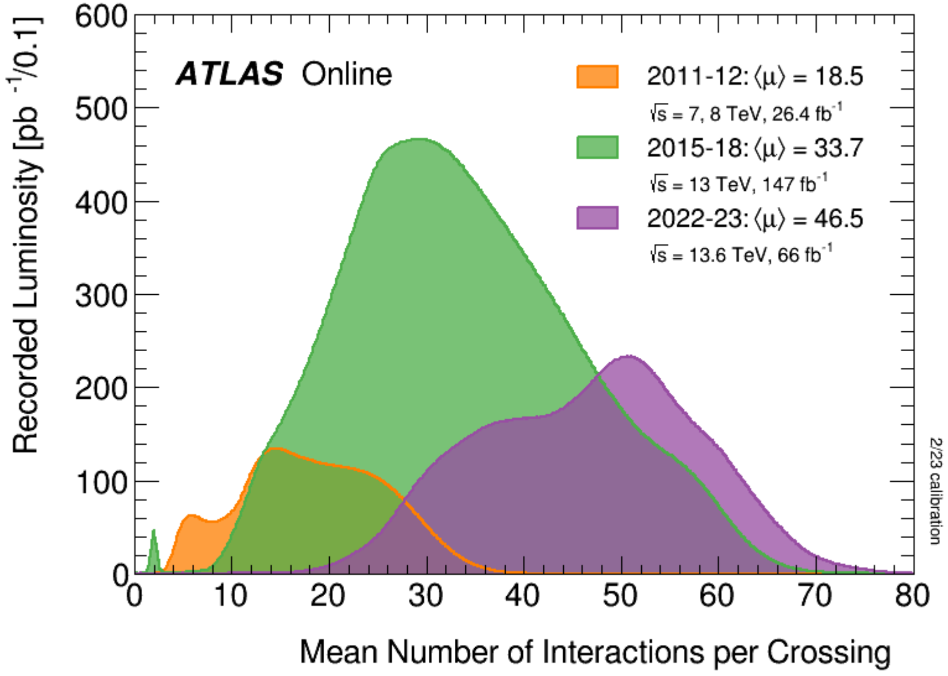
Innermost radius and pitch fundamental for **impact parameter** determination and thus **b-tagging performance**!

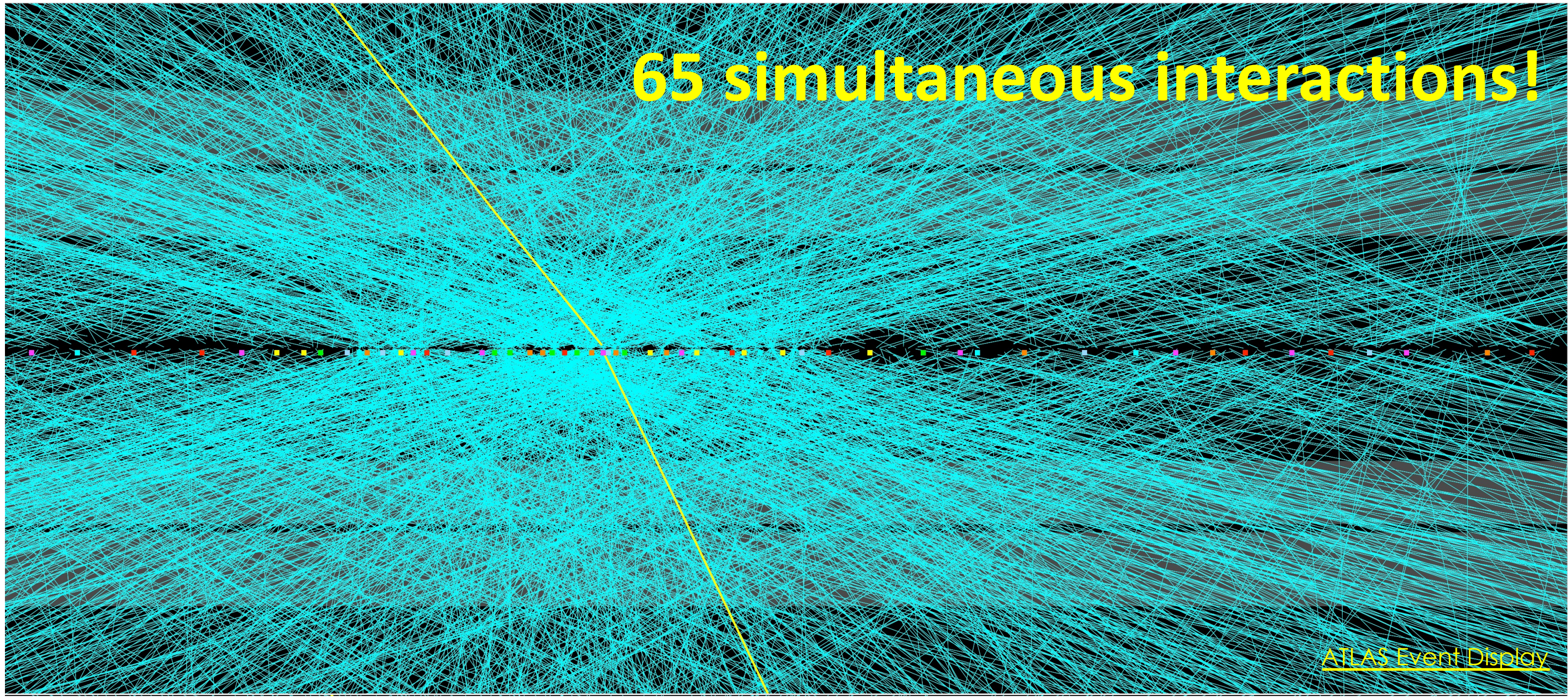
A PERSONAL FAVOURITE: THE START OF RUN 3



WHAT'S NEW IN RUN 3?

LuminosityPublicResultsRun3



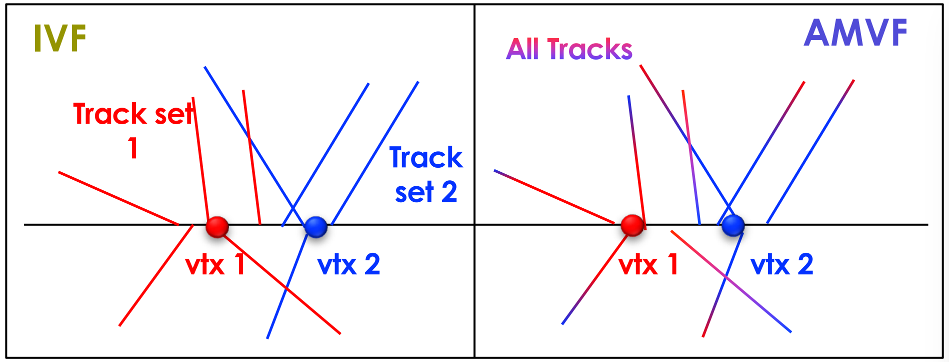


algorithms previously optimized for $<\mu> \cong 20$

[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:

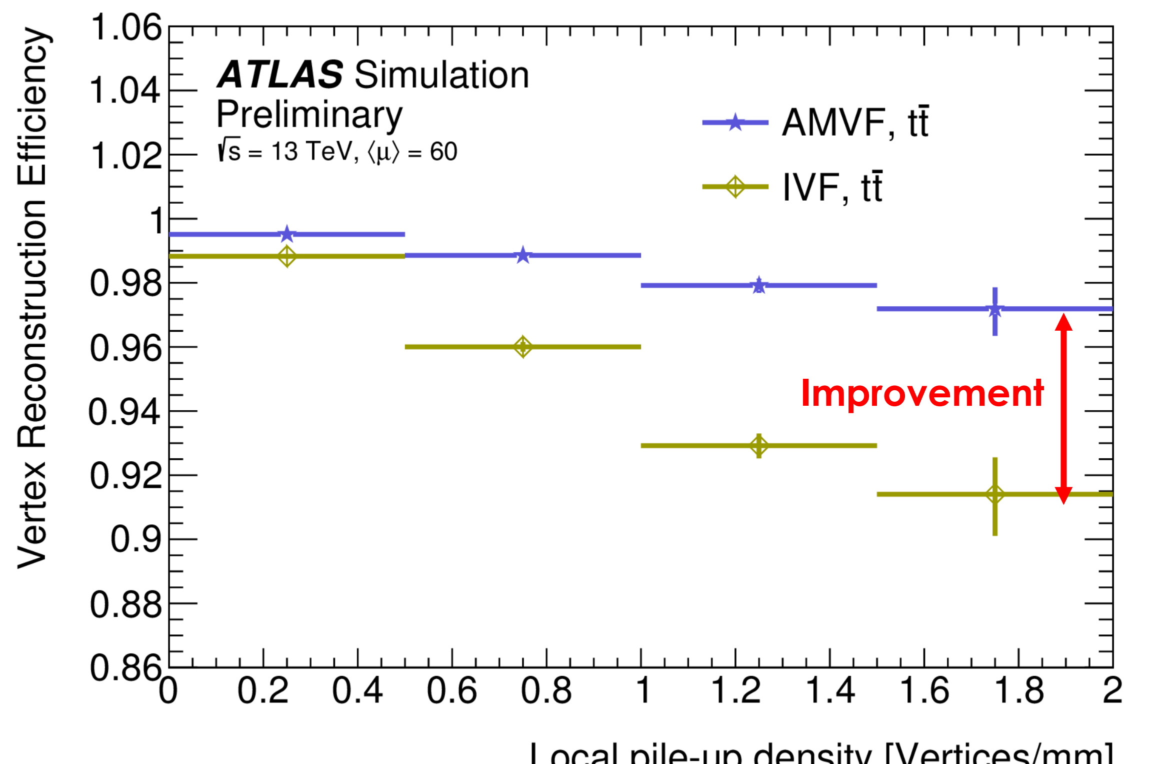
~**10%** better vertex selection efficiency

~**20%** better longitudinal resolution

~**30%** inclusive efficiency recovery

All relevant for

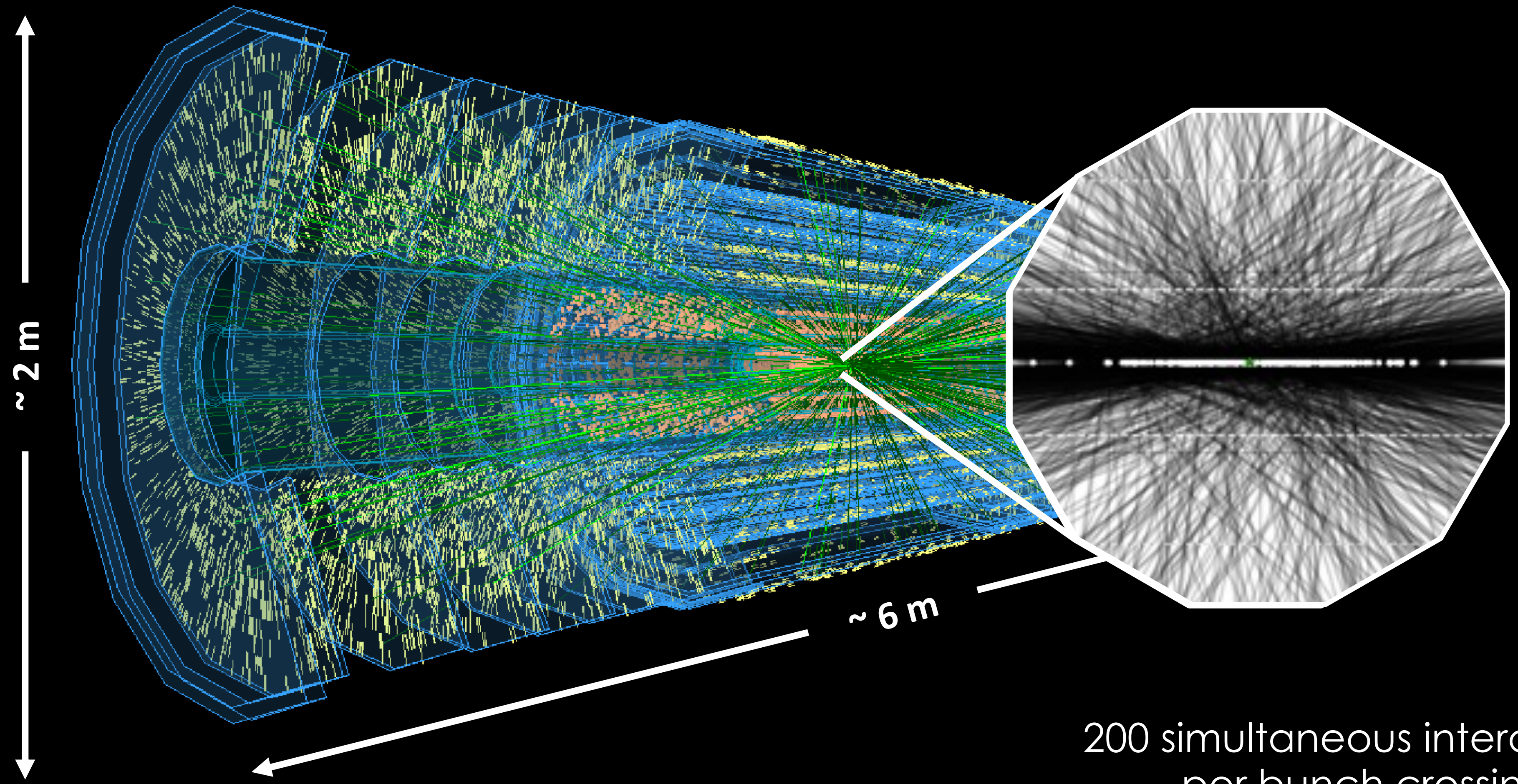
the HL-LHC ATLAS silicon Inner Tracker



ATL-PHYS-PUB-2019-015

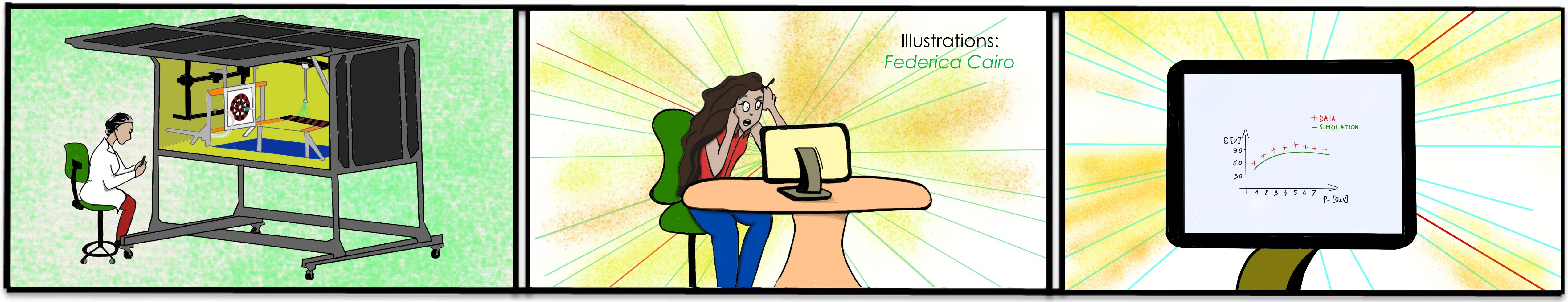
HL-LHC: USING GIGANTIC CAMERAS FOR RARE & COMPLEX EVENTS!

ATLAS Inner Tracker (ITk) in preparation for HL-LHC (2029)

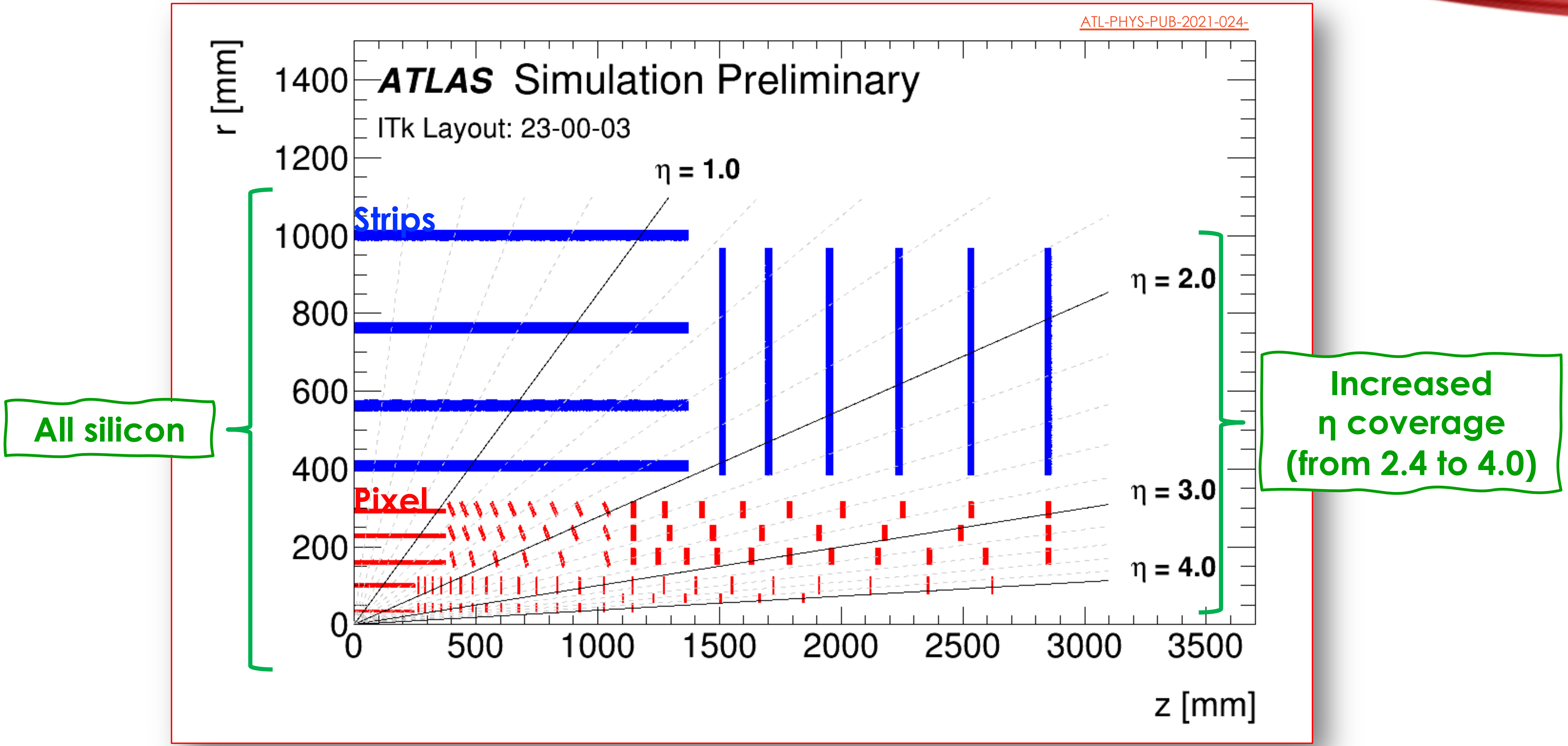


200 simultaneous interactions per bunch crossing

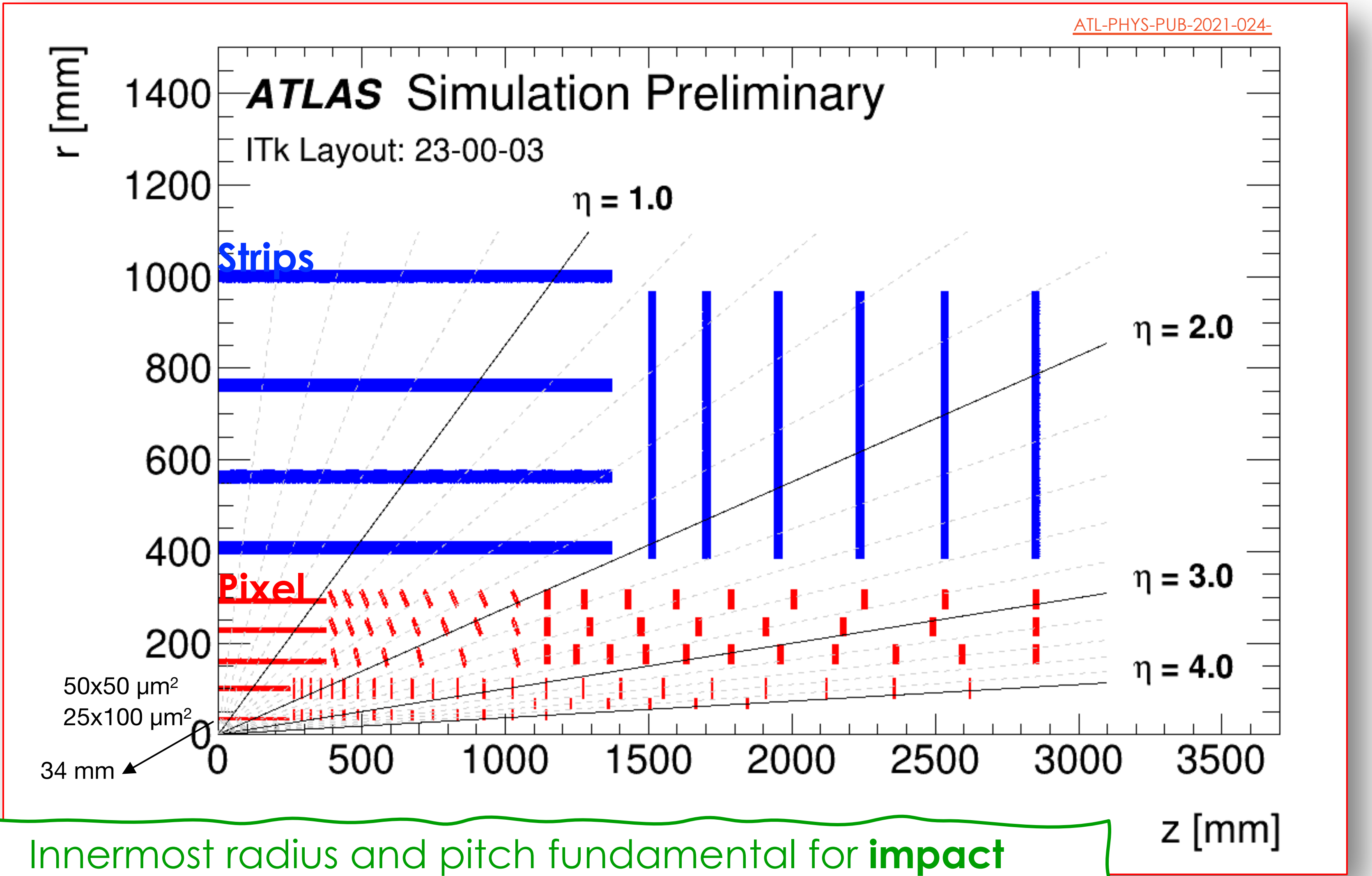
A CONSTRUCTION, COMPUTATIONAL AND PERFORMANCE CHALLENGE



THE ATLAS ITK



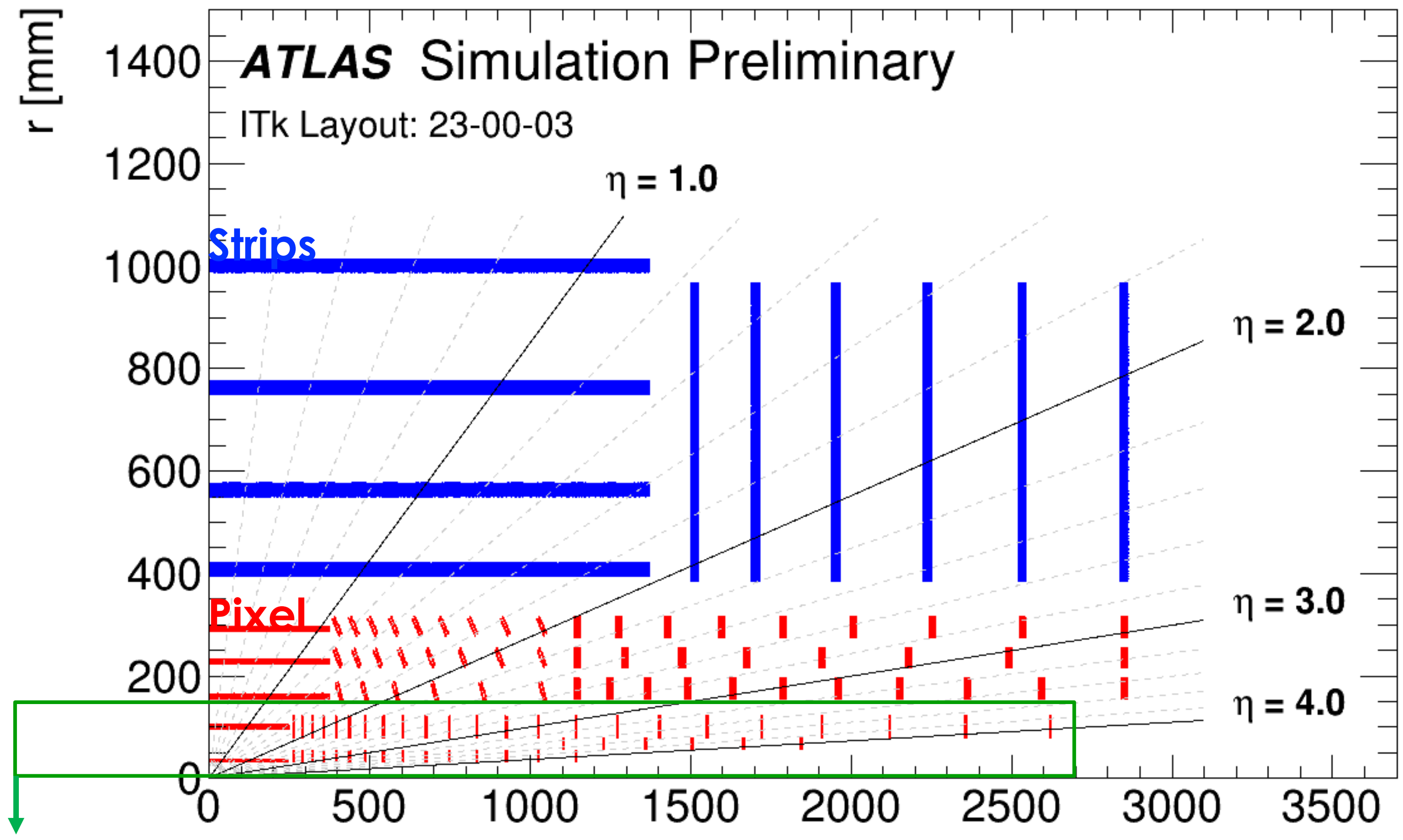
THE ATLAS ITK



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

THE ATLAS ITK

ATL-PHYS-PUB-2021-024-

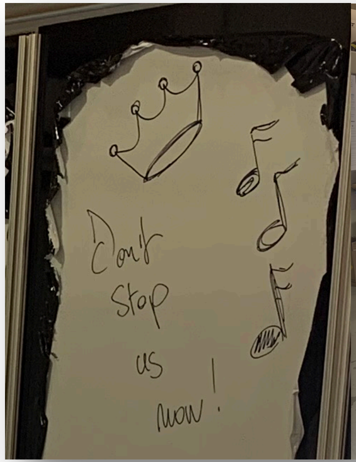


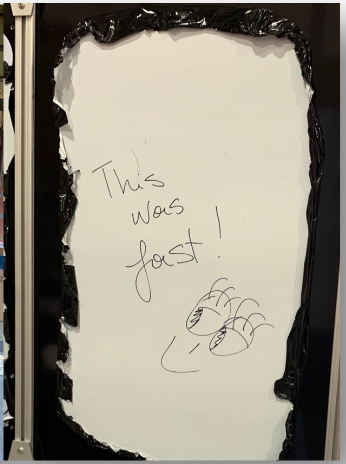
Silicon surface larger than the Run 2/3 Pixel System

BUILDING THE ATLAS ITK

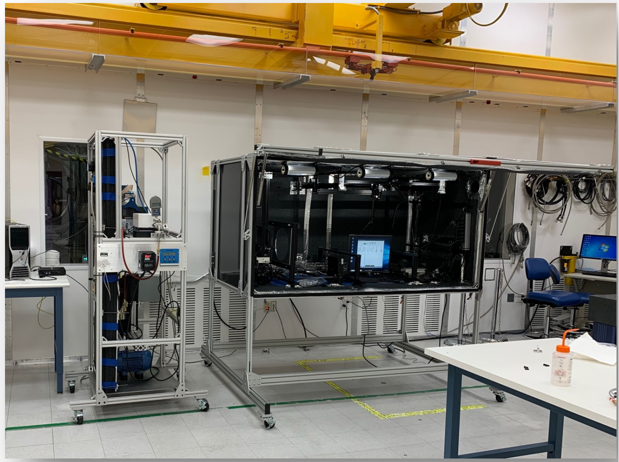
One of several challenges: Radiation hardness up to 10-15 MGy, **operate cold**, prevent leakage current & thermal runaway

Fall 2019

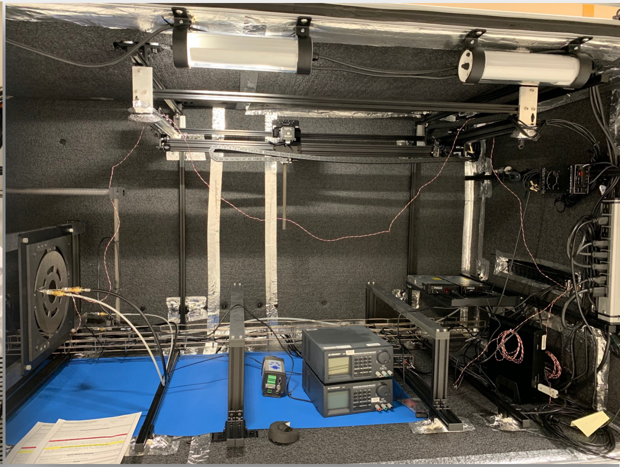




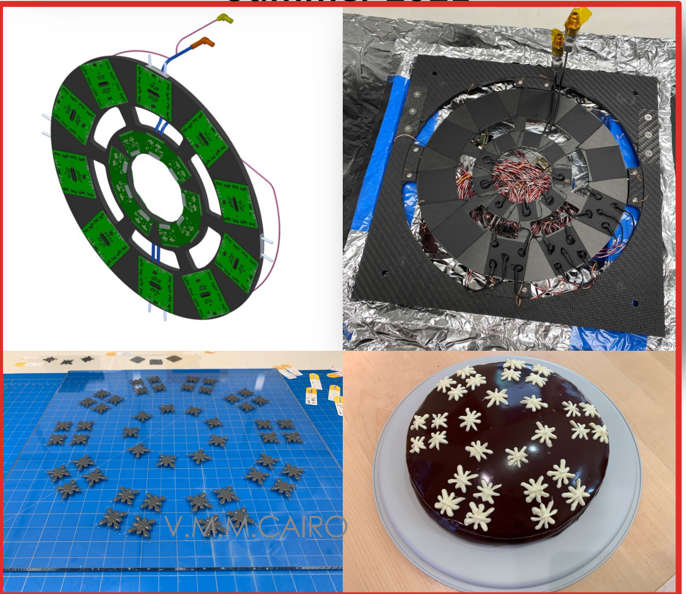
Early 2020



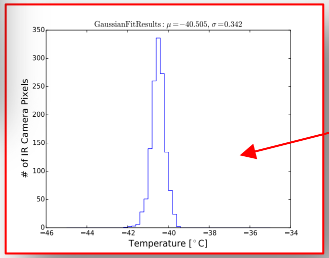
Early 2021

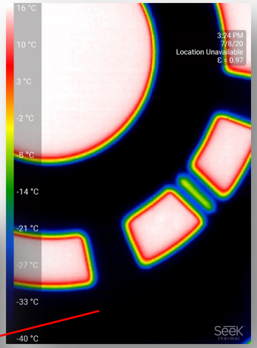


Summer 2021



Bare local support meets specifications

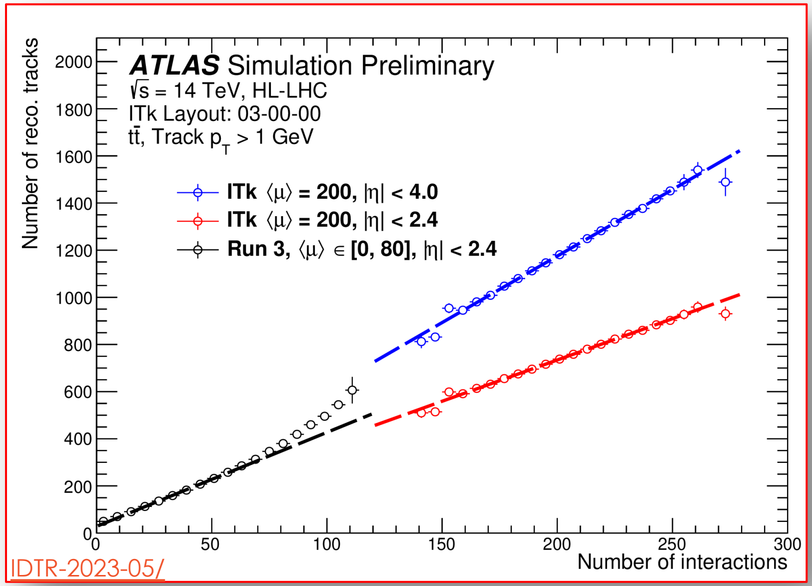




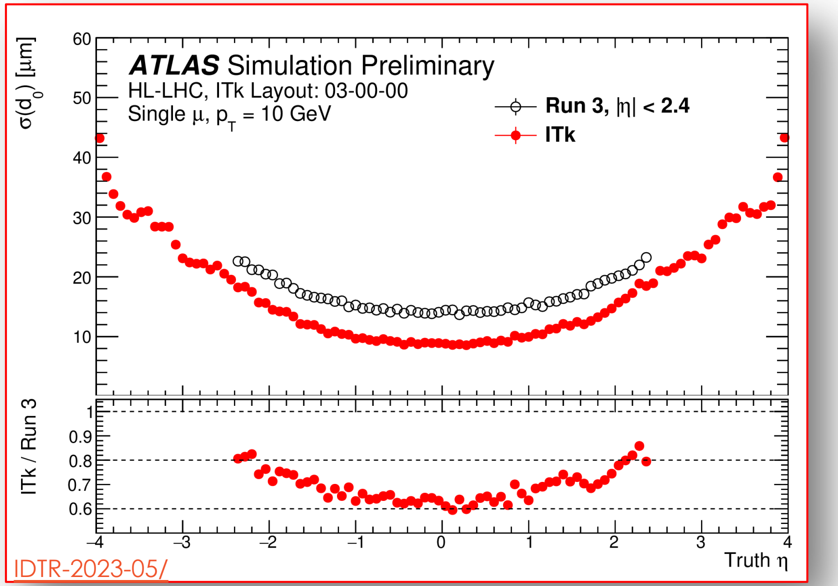
$T = -40.5 \pm 0.3$℃

HL-LHC TRACKING

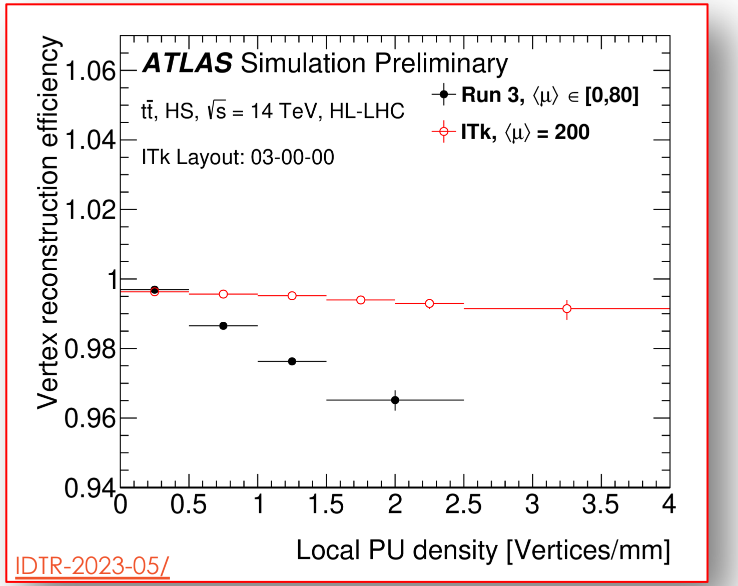
A detector designed to be pile-up robust, and algorthms designed to leverage such features



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



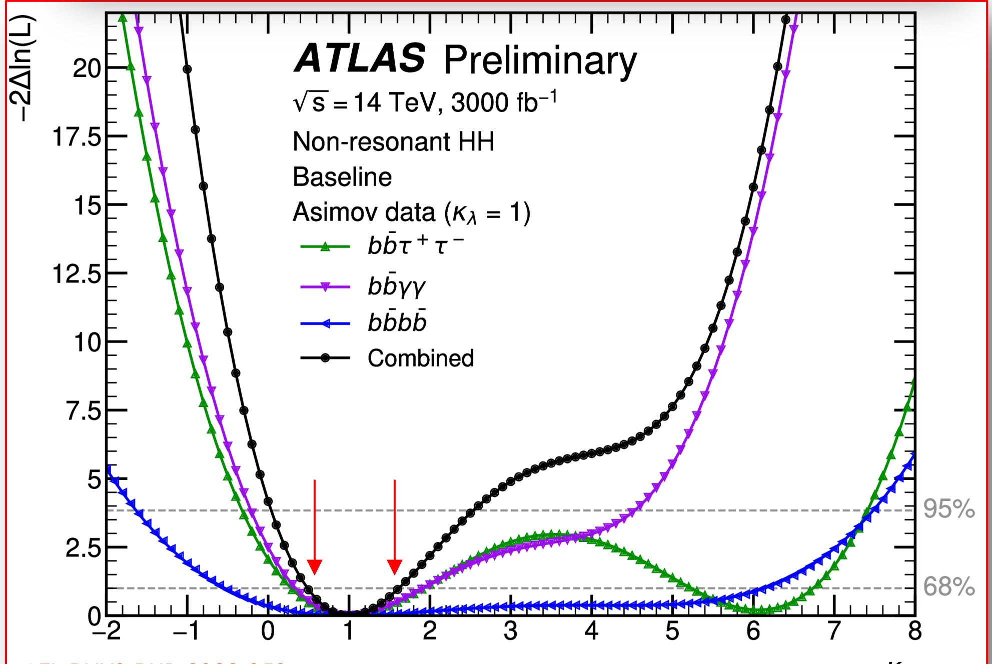
Improved IP resolution



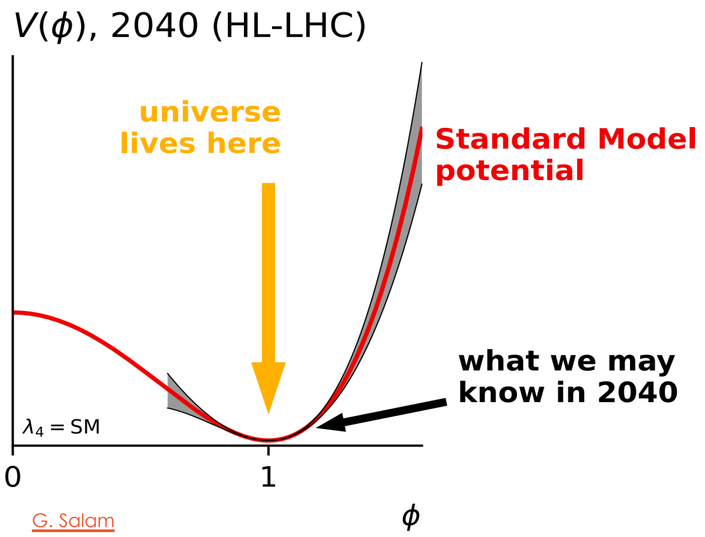
More PU-robust vertexing

HOW DOES HH LOOK IN HL-LHC?

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



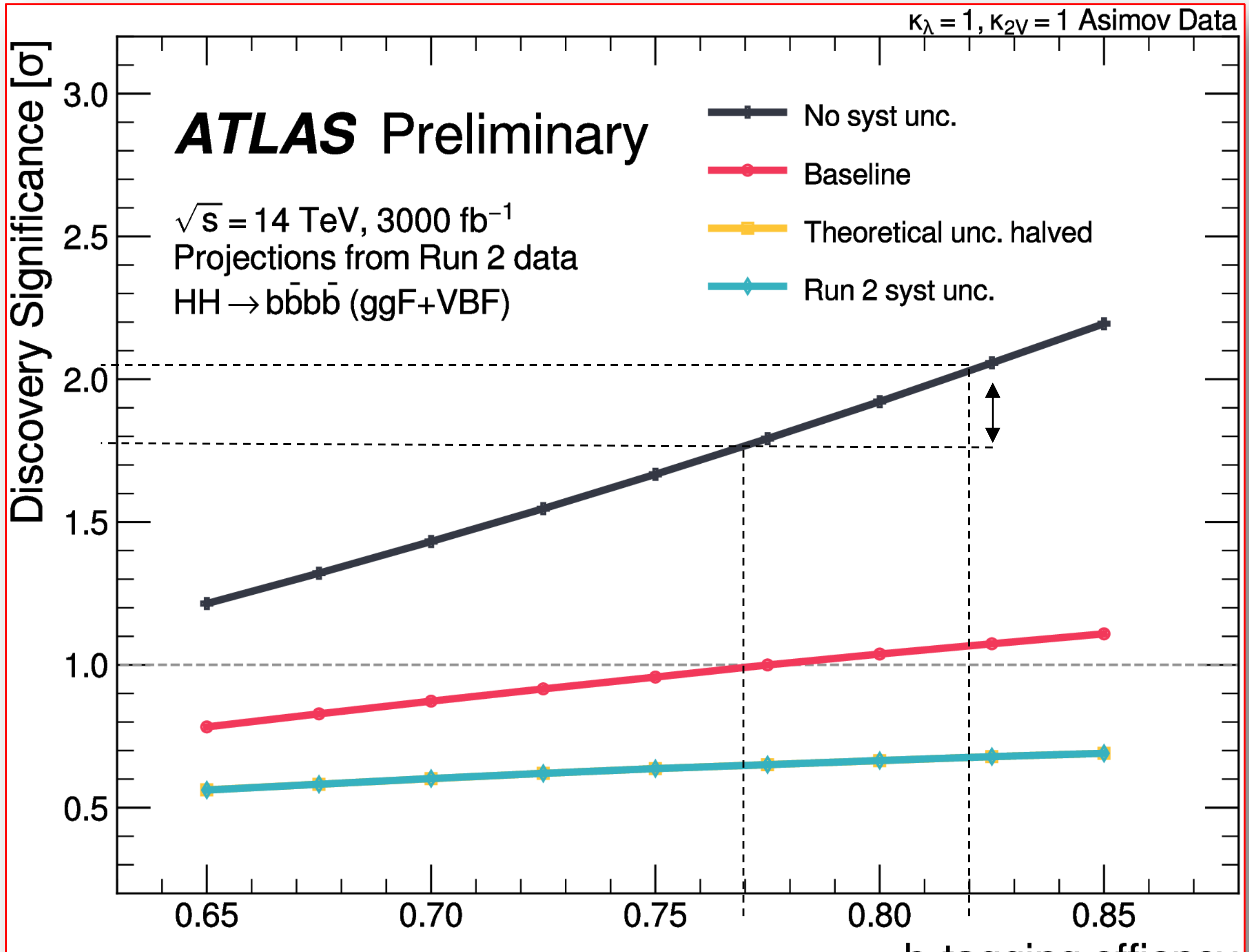
ATL-PHYS-PUB-2022-053



G. Salam

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

HOW BETTER CAN WE DO?

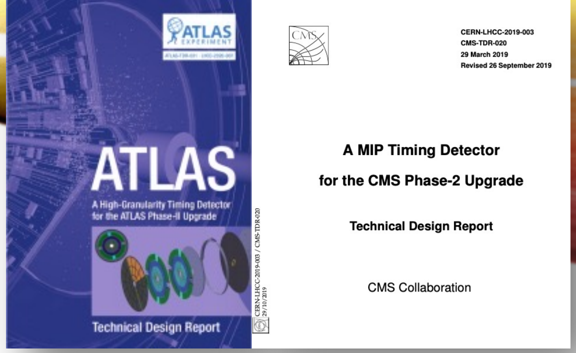


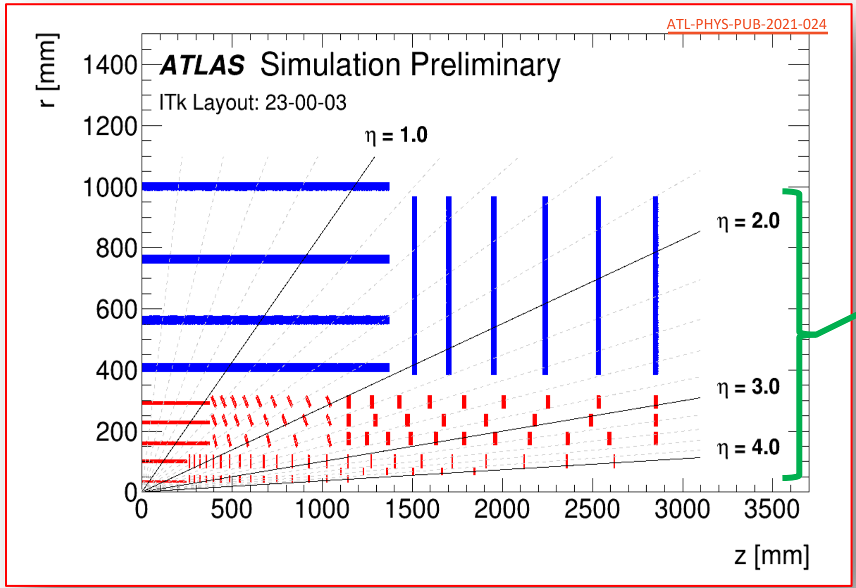
ATL-PHYS-PUB-2023-023

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

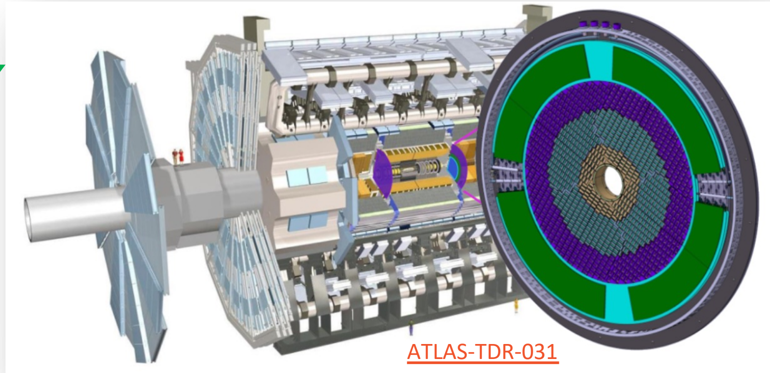
UNFOLDING A NEW DIMENSION

Addition of timing layers to HEP detectors growing area of interest





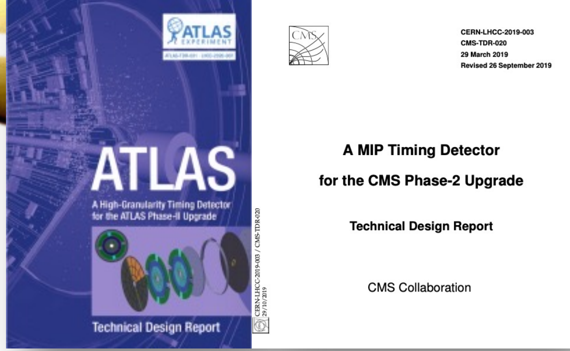
High Granularity Timing Detector

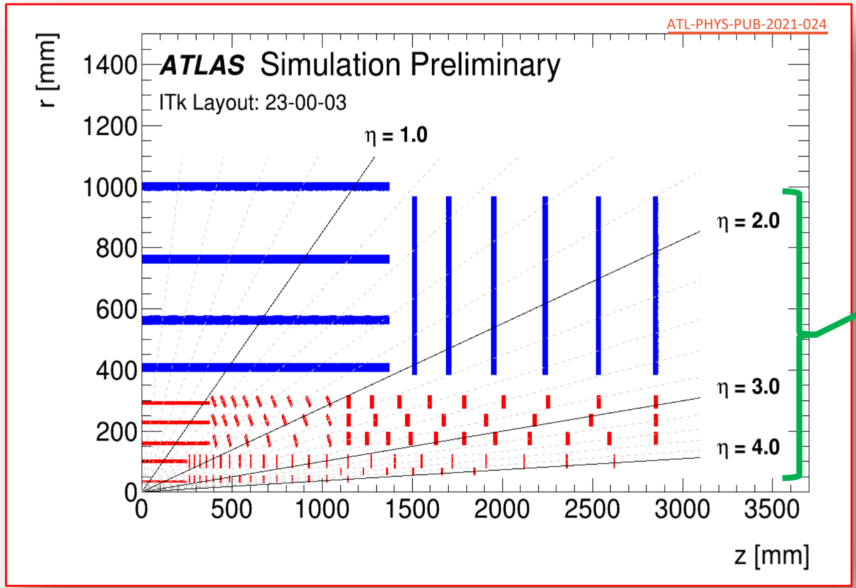


New handles to improve event reconstruction in the forward region, but limited by its reduced η acceptance…

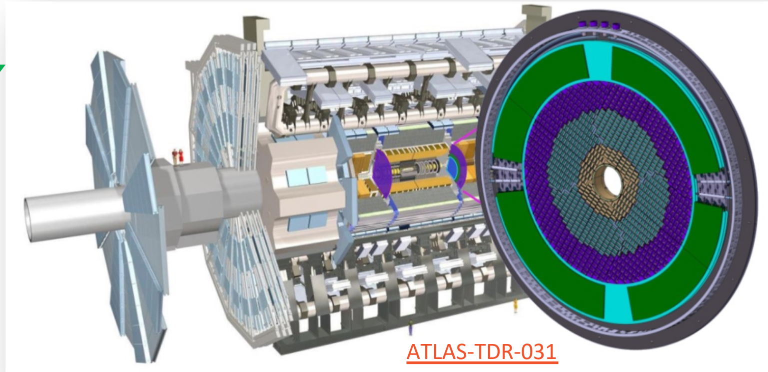
UNFOLDING
A NEW DIMENSION

Addition of timing layers to HEP detectors growing area of interest



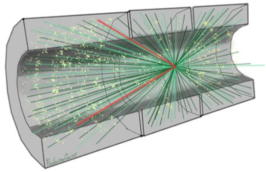


High Granularity Timing Detector



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

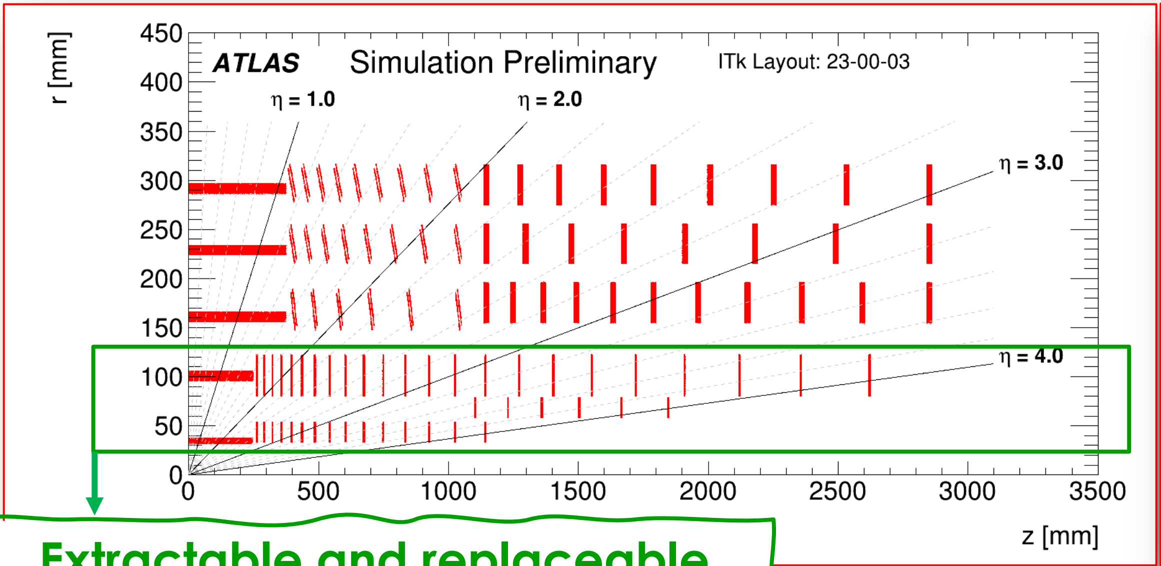
Can we maximize the ATLAS physics potential beyond Run 4 by extending the timing coverage to the full η acceptance?



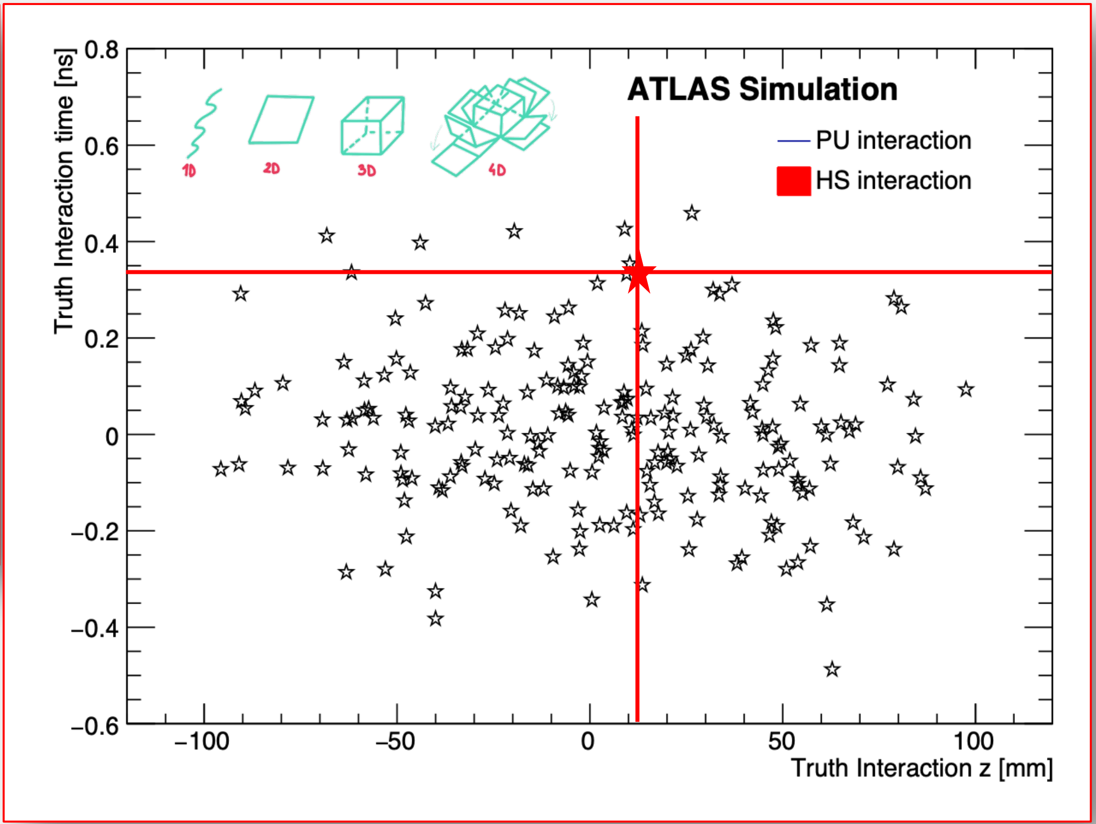
UNFOLDING
A NEW DIMENSION

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

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



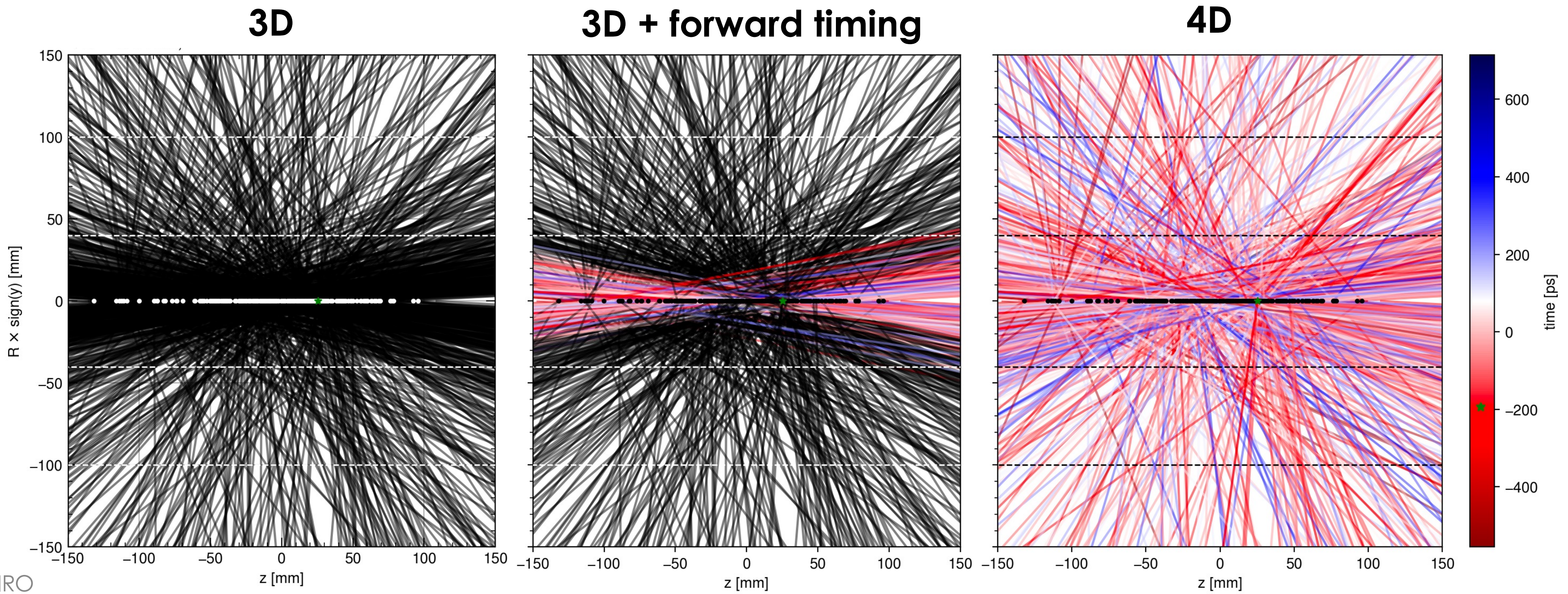
Extractable and replaceable half-way through HL-LHC



UNFOLDING A NEW DIMENSION

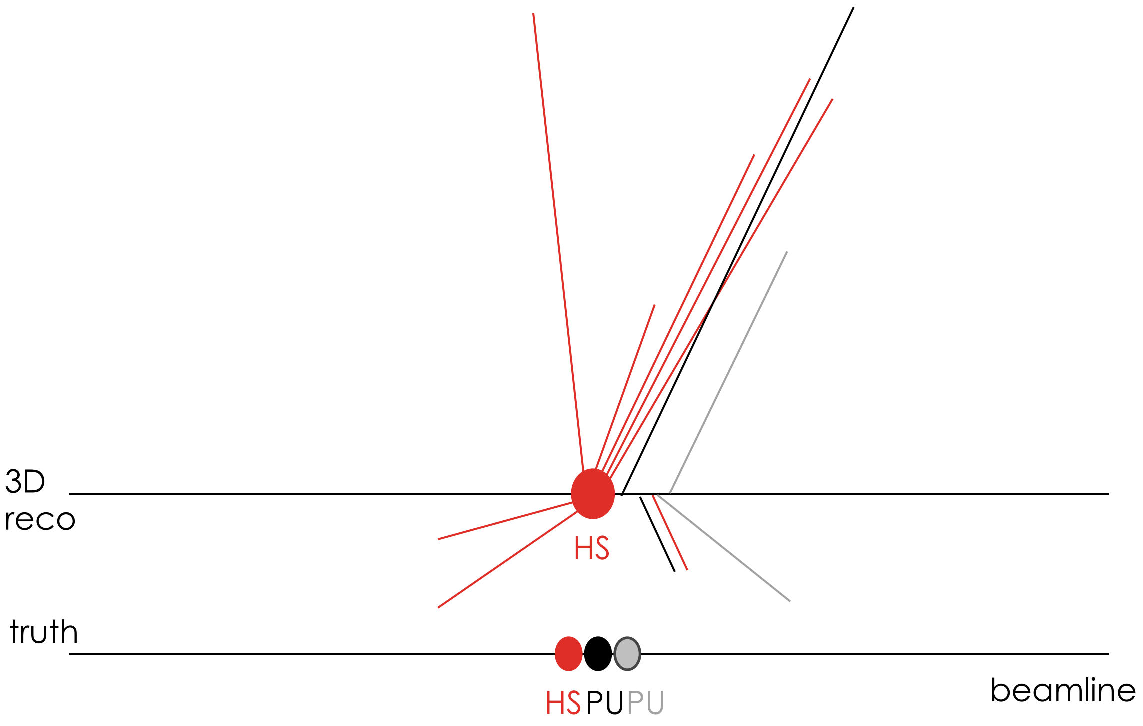
Next step in advancing technologies are real 4-dimensional silicon trackers (resolution of O($10\ \mu m$) & O($10\ ps$))

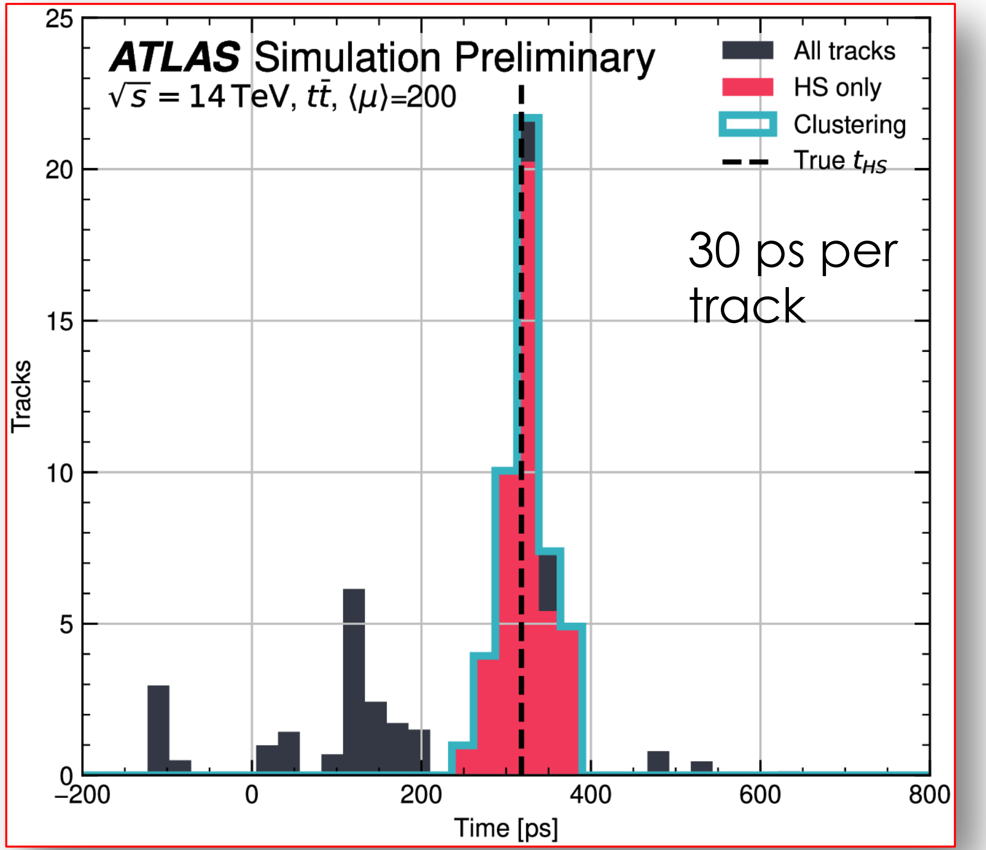
- **Excellent opportunity during HL-LHC and, in particular, for future energy frontier trackers**
- **First exploratory studies in ATLAS**
  - Also looked at in LHCb



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!

ATL-PHYS-PUB-2023-023

DETERMINING THE VERTEX TIME

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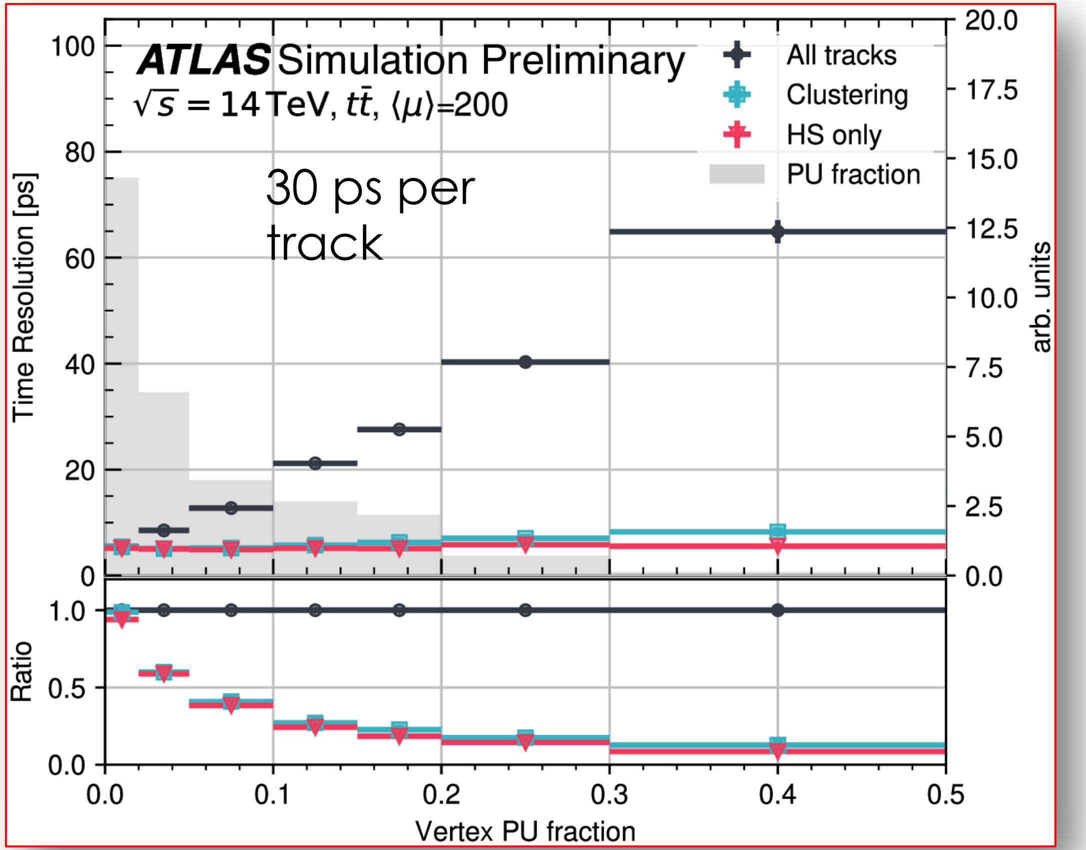

Excellent vertex time resolution can be achieved

ATL-PHYS-PUB-2023-023

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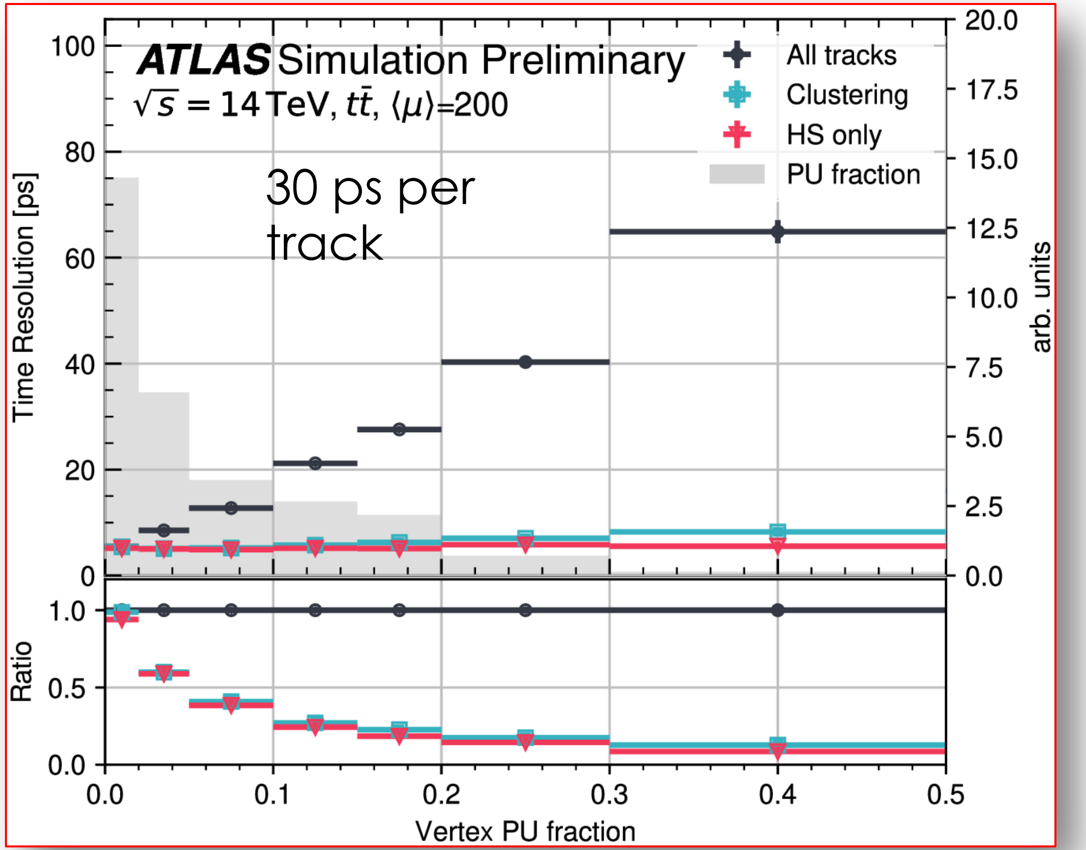

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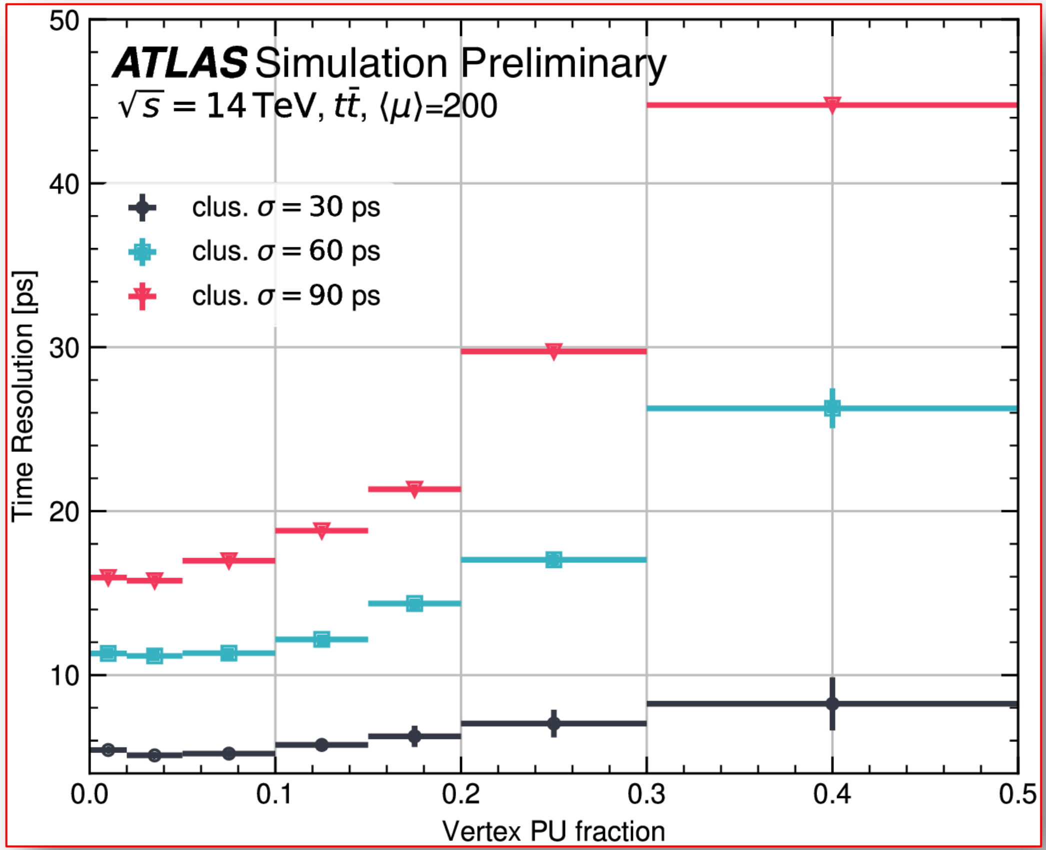
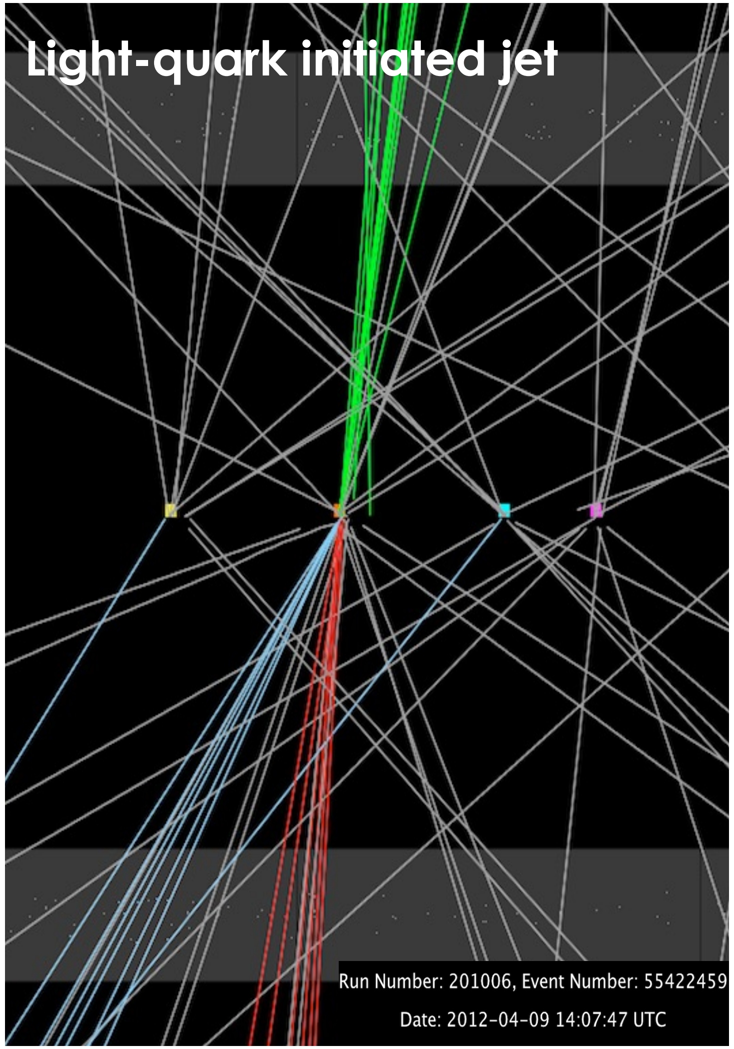
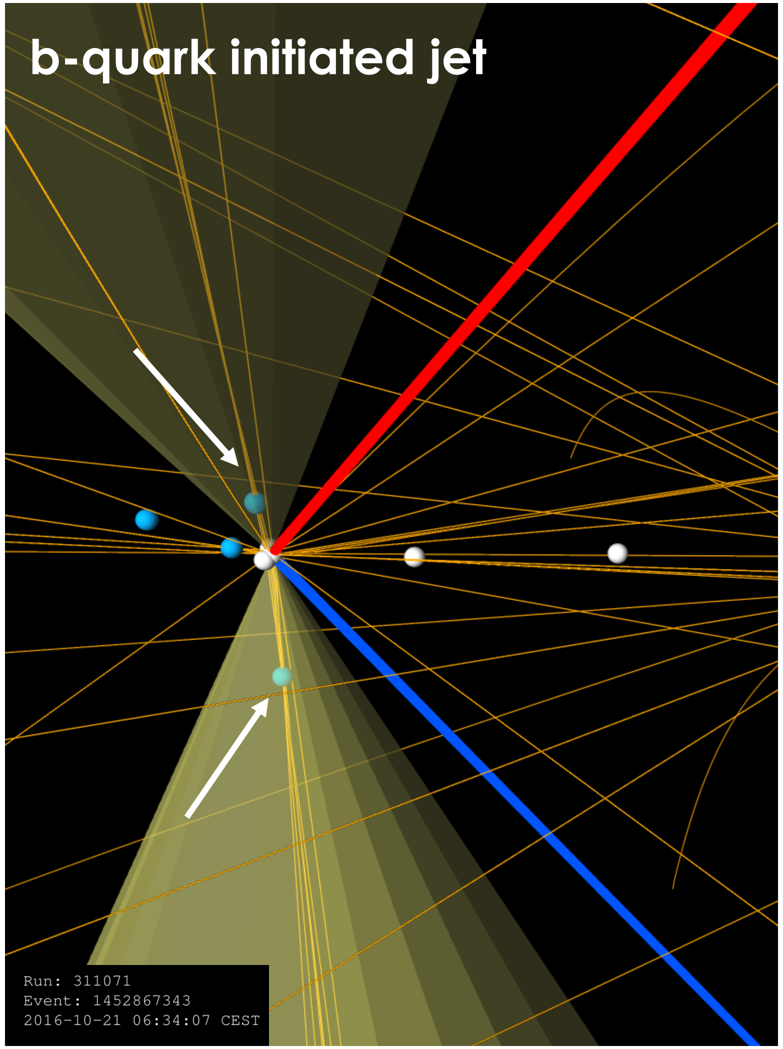


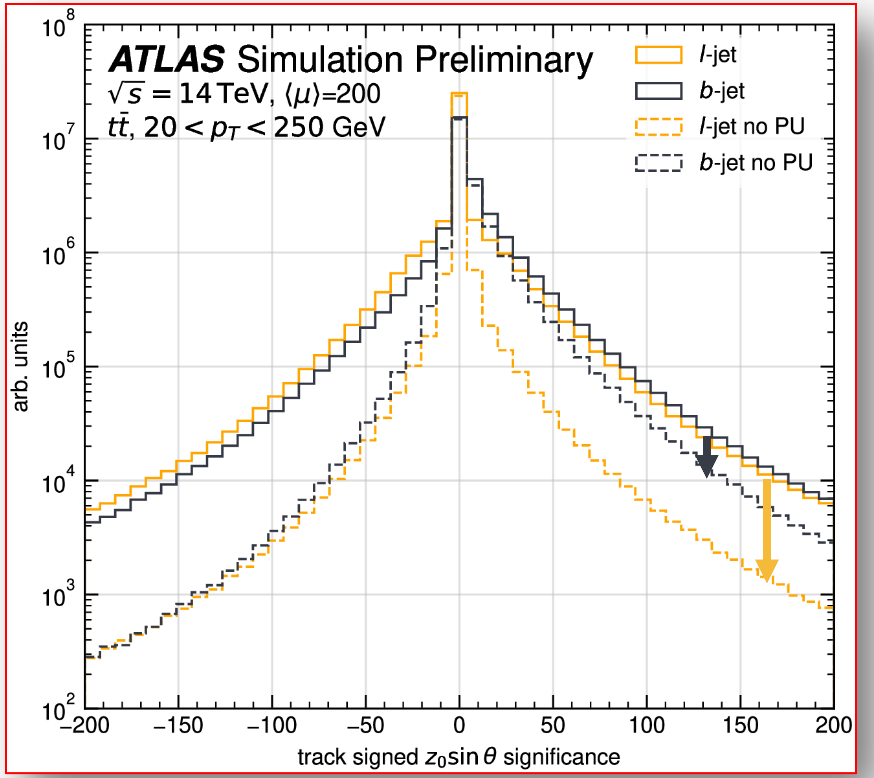
The better the track-time resolution, the more PU-robust the vertex time resolution

ATL-PHYS-PUB-2023-023

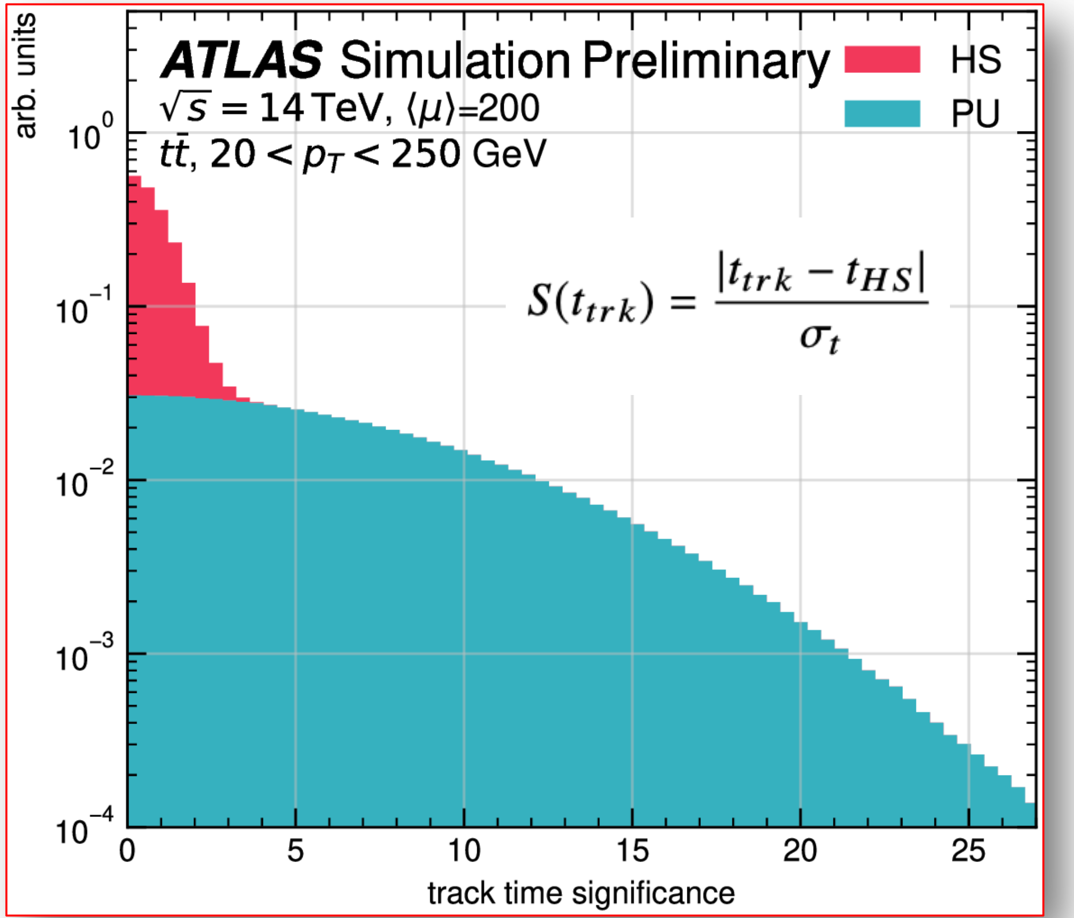
THE KEY FEATURES FOR b-TAGGING





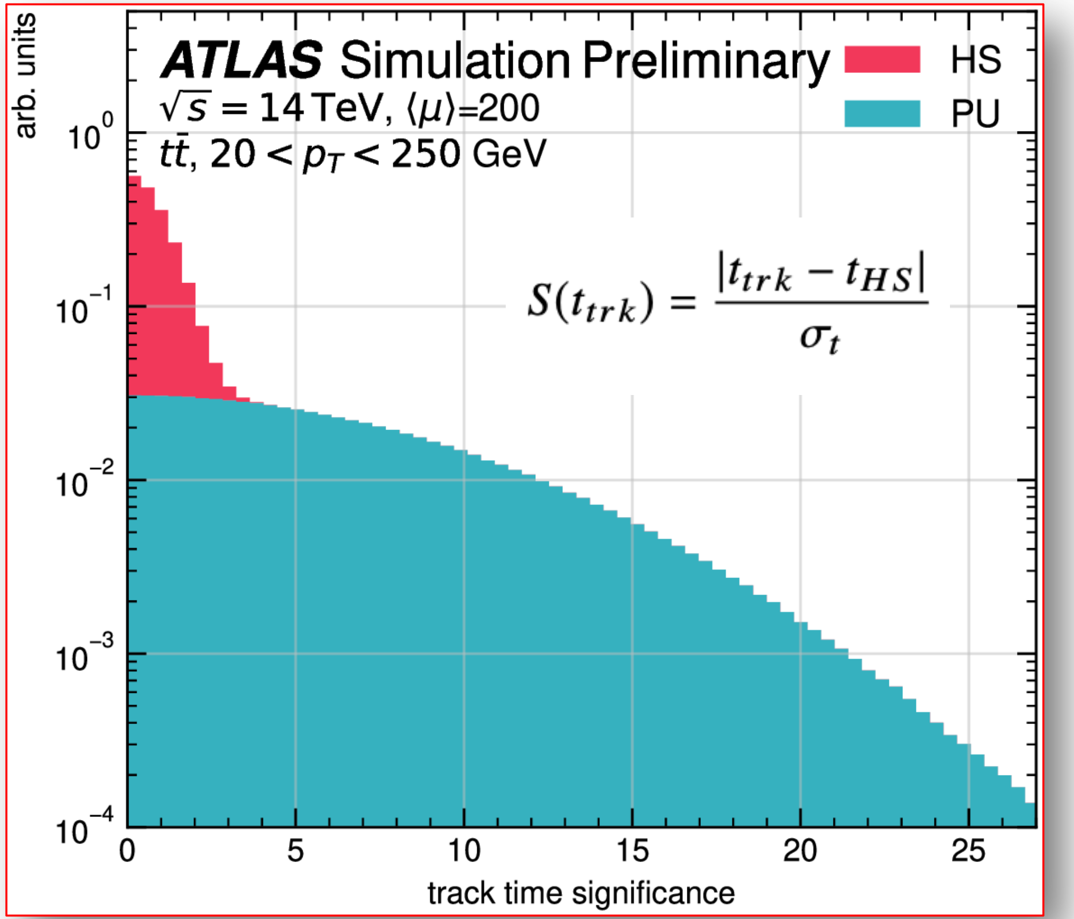


GNT – 4D b-TAGGING



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

GNT – 4D b-TAGGING



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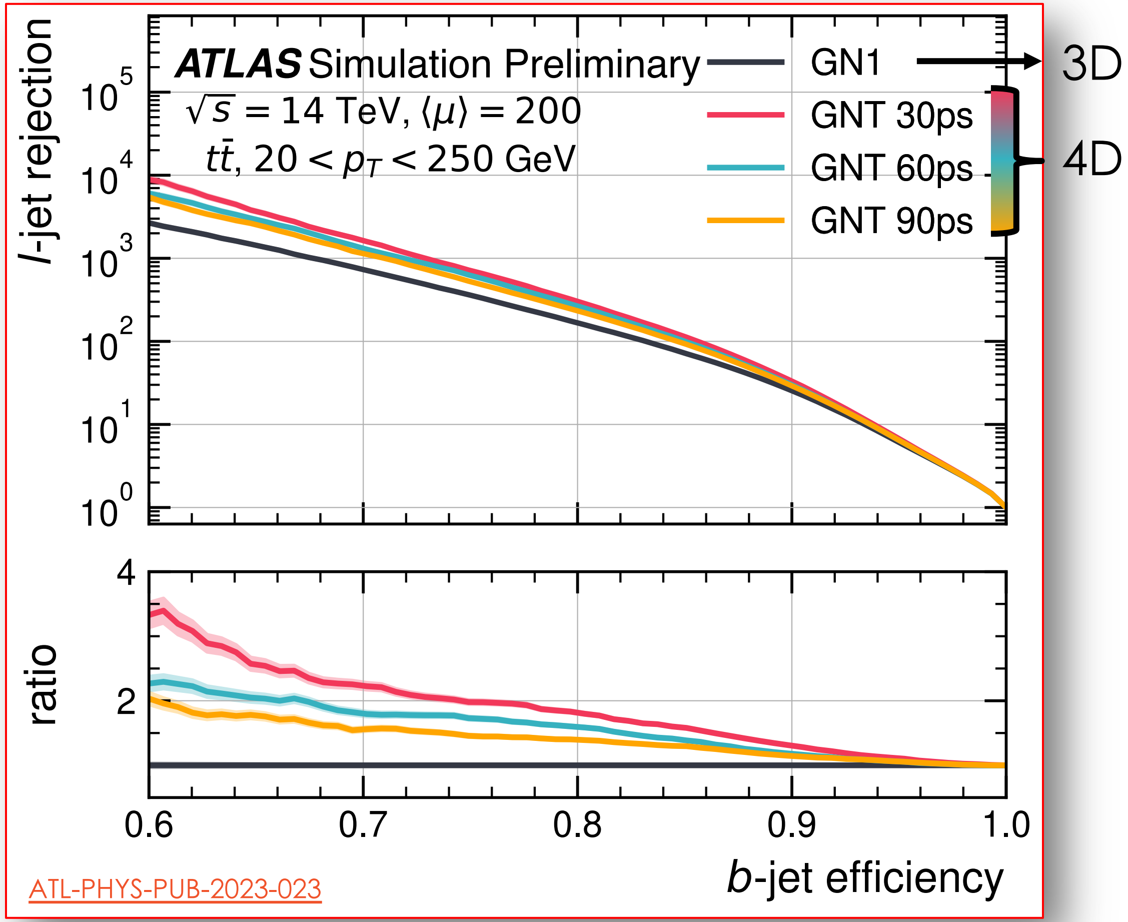
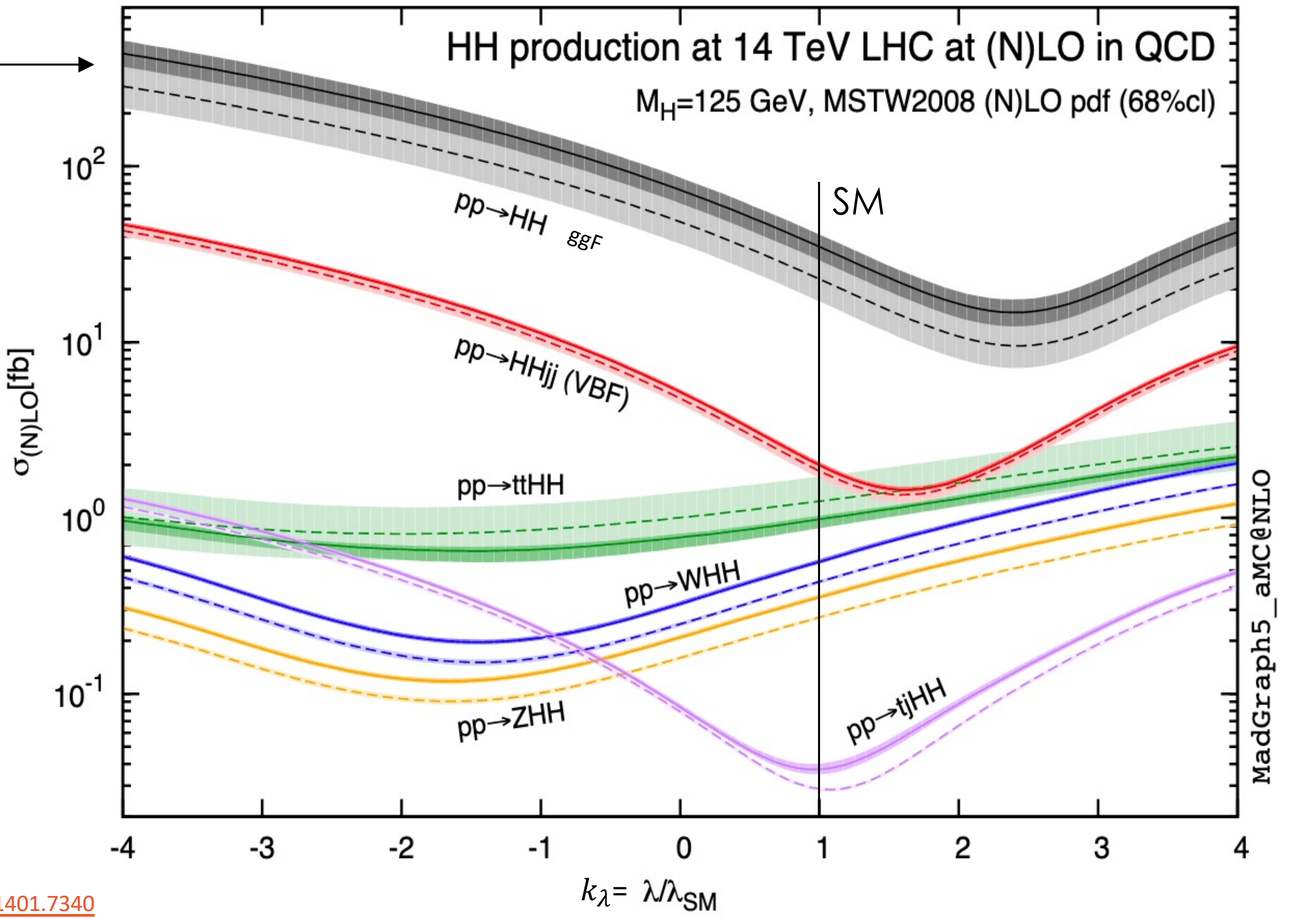


Interesting potential HH sensitivity increase!

4D TRACKING: BEYOND THE CURRENT HH PROGRAMME

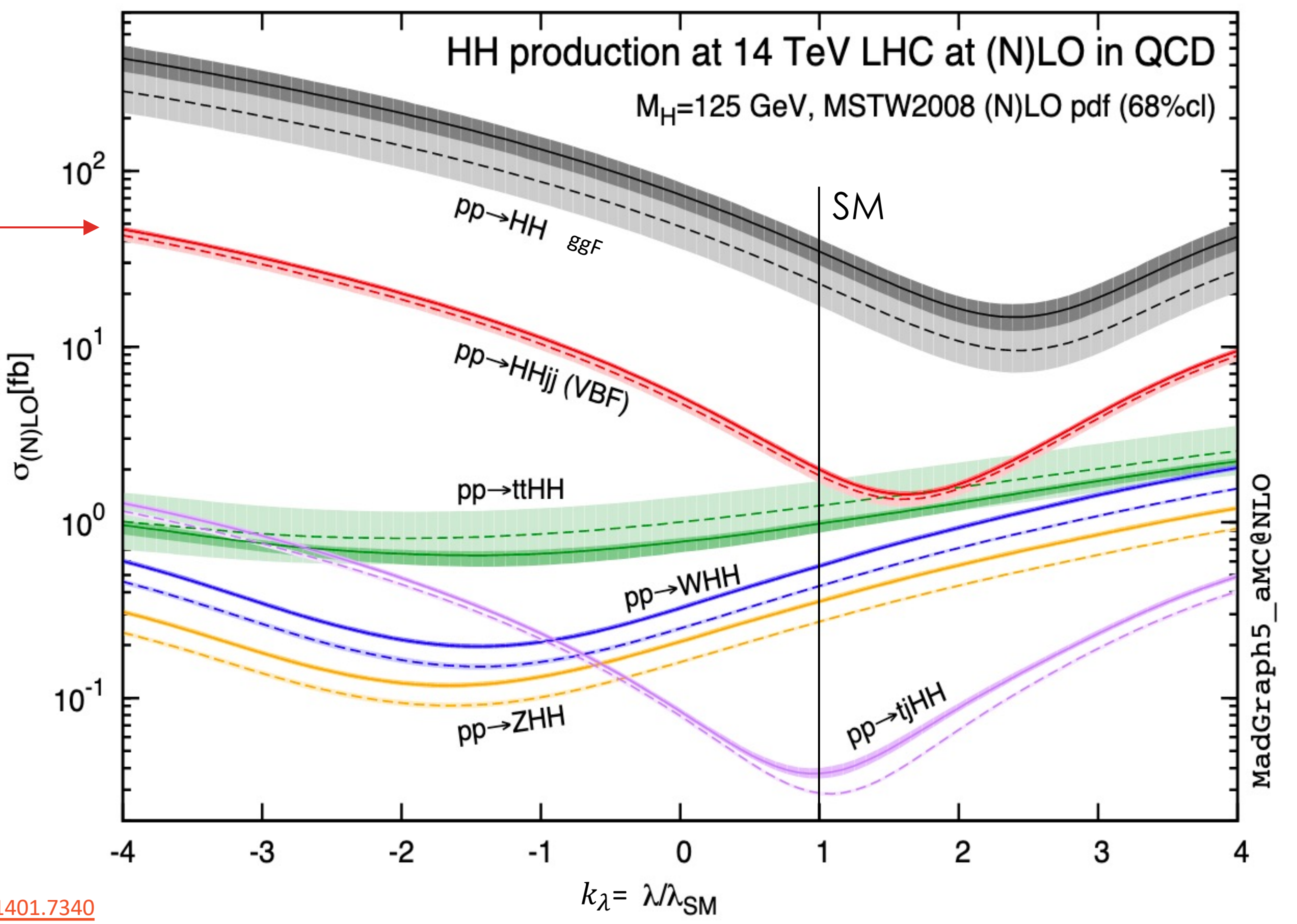
Our current focus



1401.7340

4D TRACKING: BEYOND THE CURRENT HH PROGRAMME

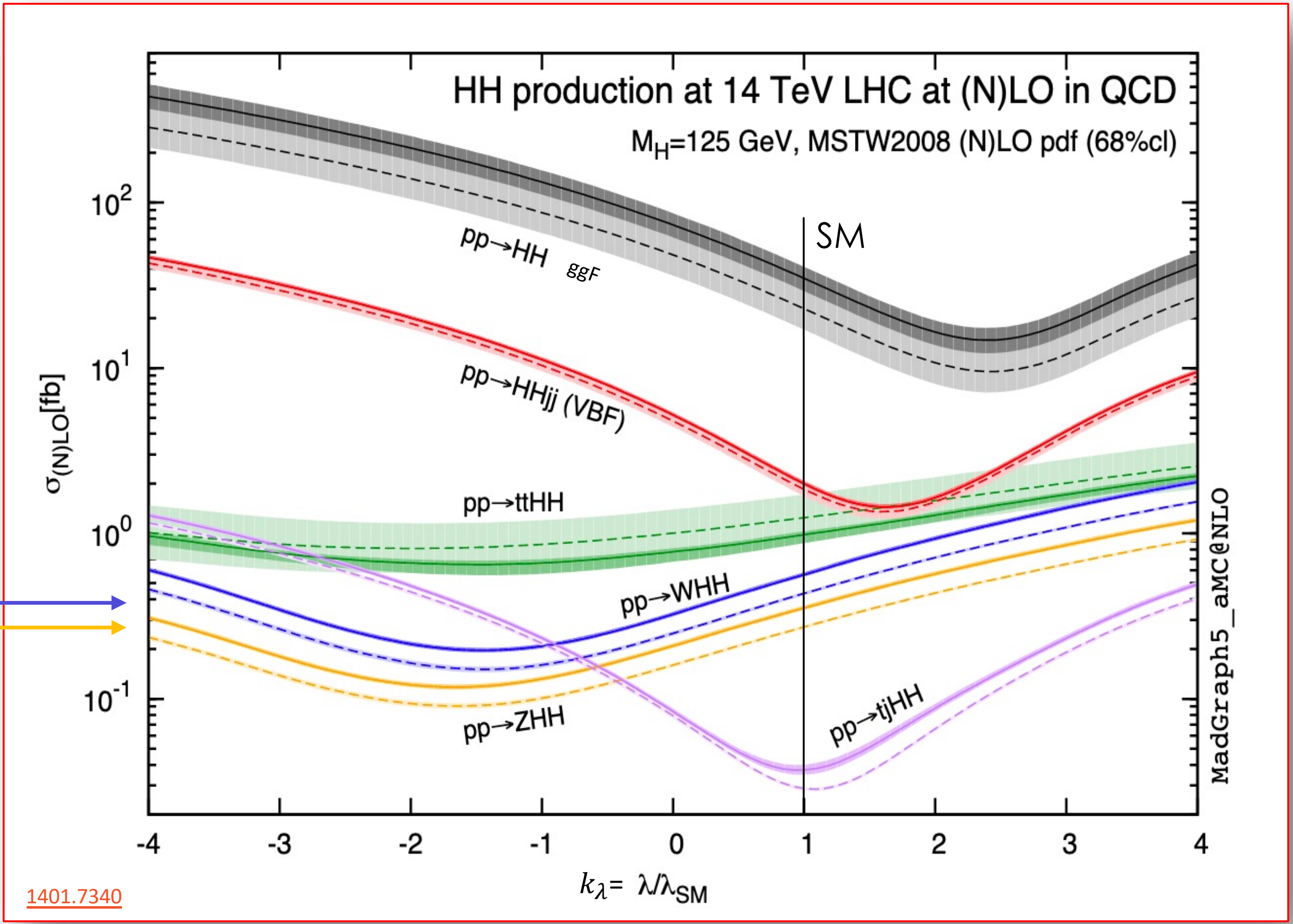
Already being searched for, Enhanced by ITk forward capabilities



1401.7340

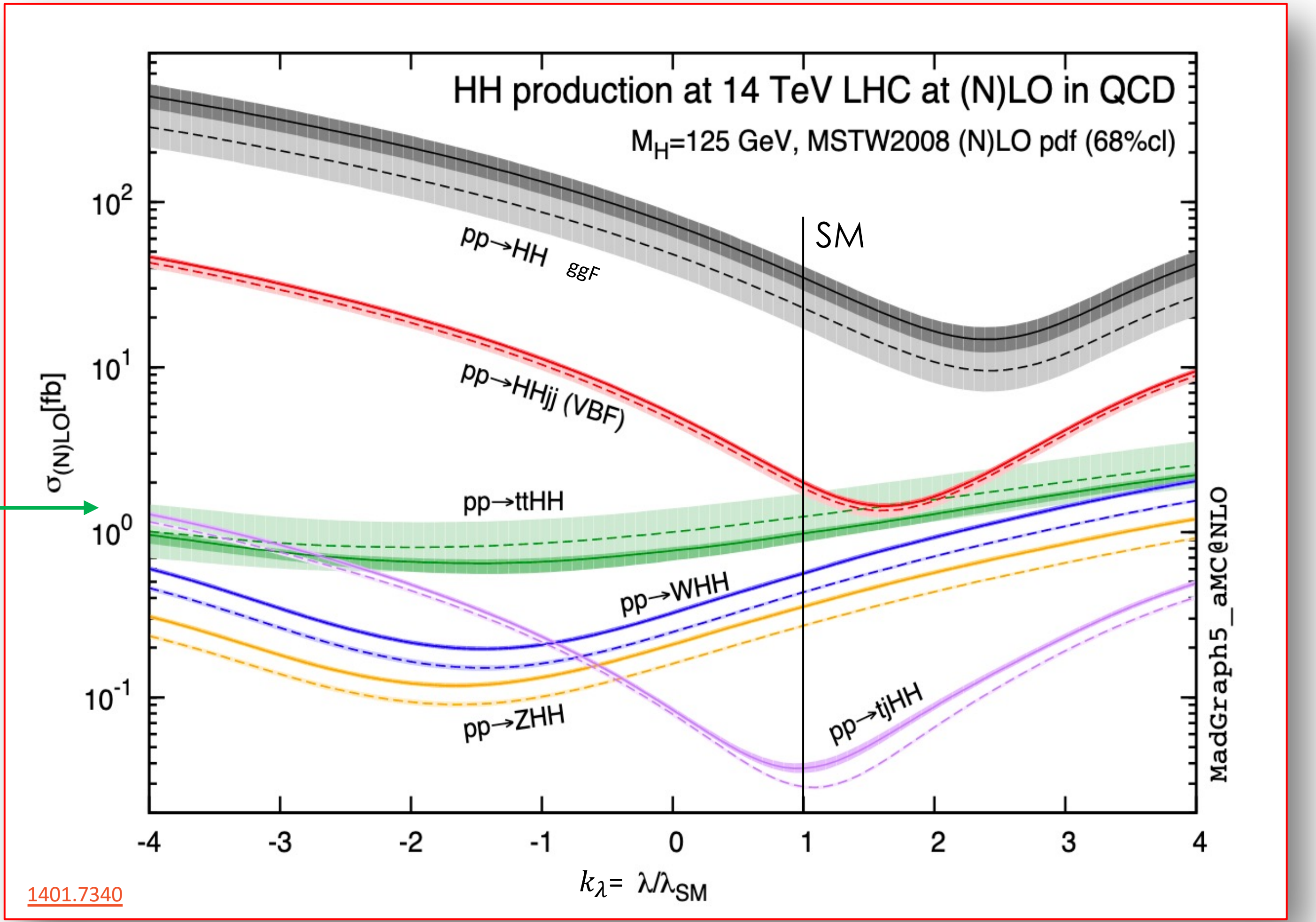
4D TRACKING: BEYOND THE CURRENT HH PROGRAMME

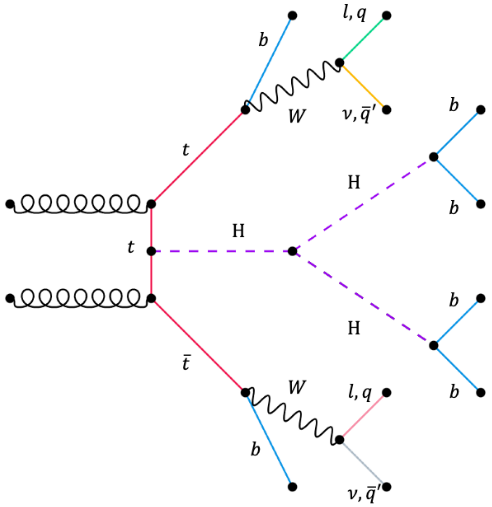
VHH already being searched for (epjc/s10052-023-11559-y)



4D TRACKING: BEYOND THE CURRENT HH PROGRAMME

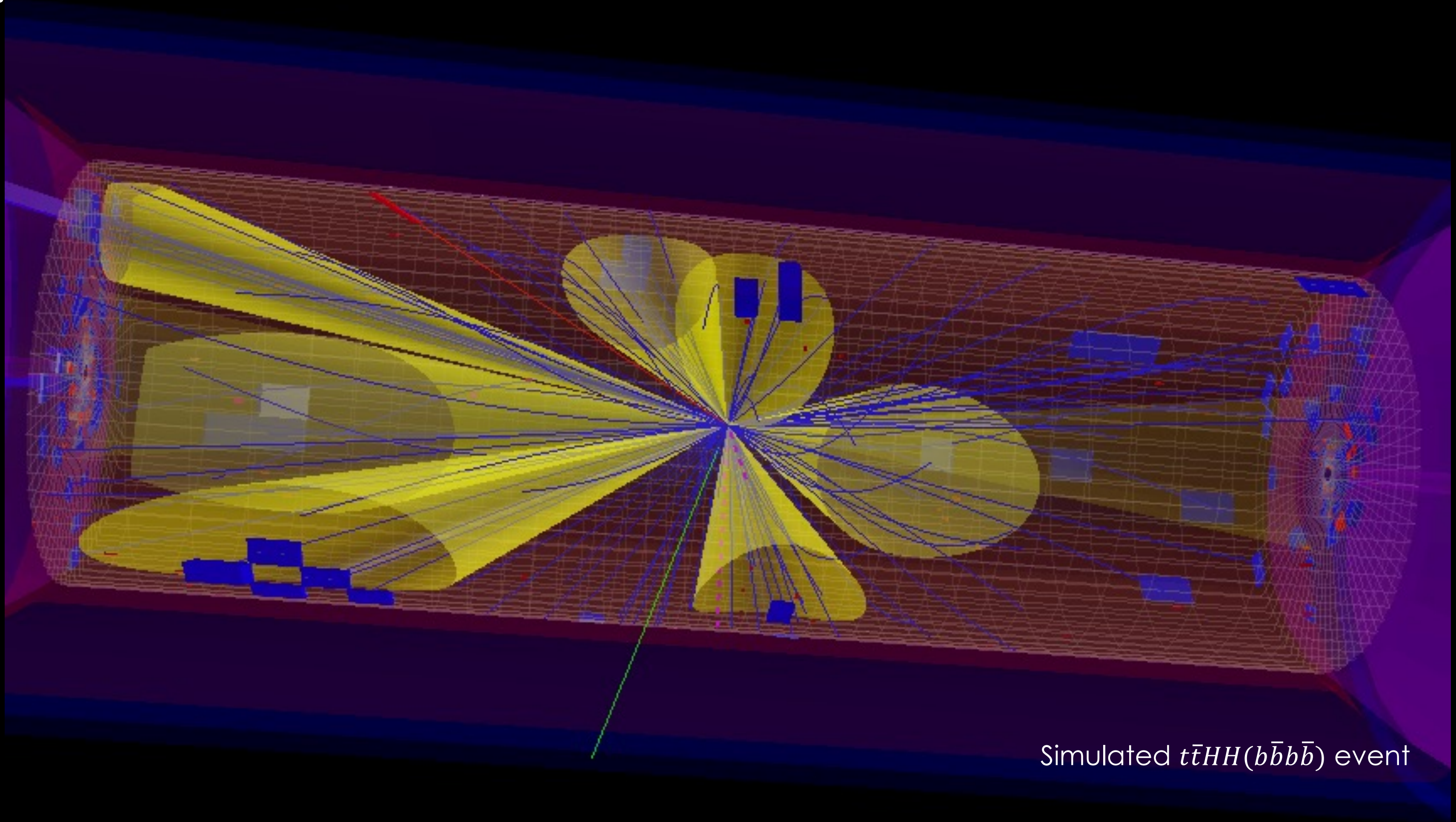
A new frontier to explore the Higgs and Top sectors…





AT THE EDGE OF OUR CAPABILITIES: $ttHH$

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

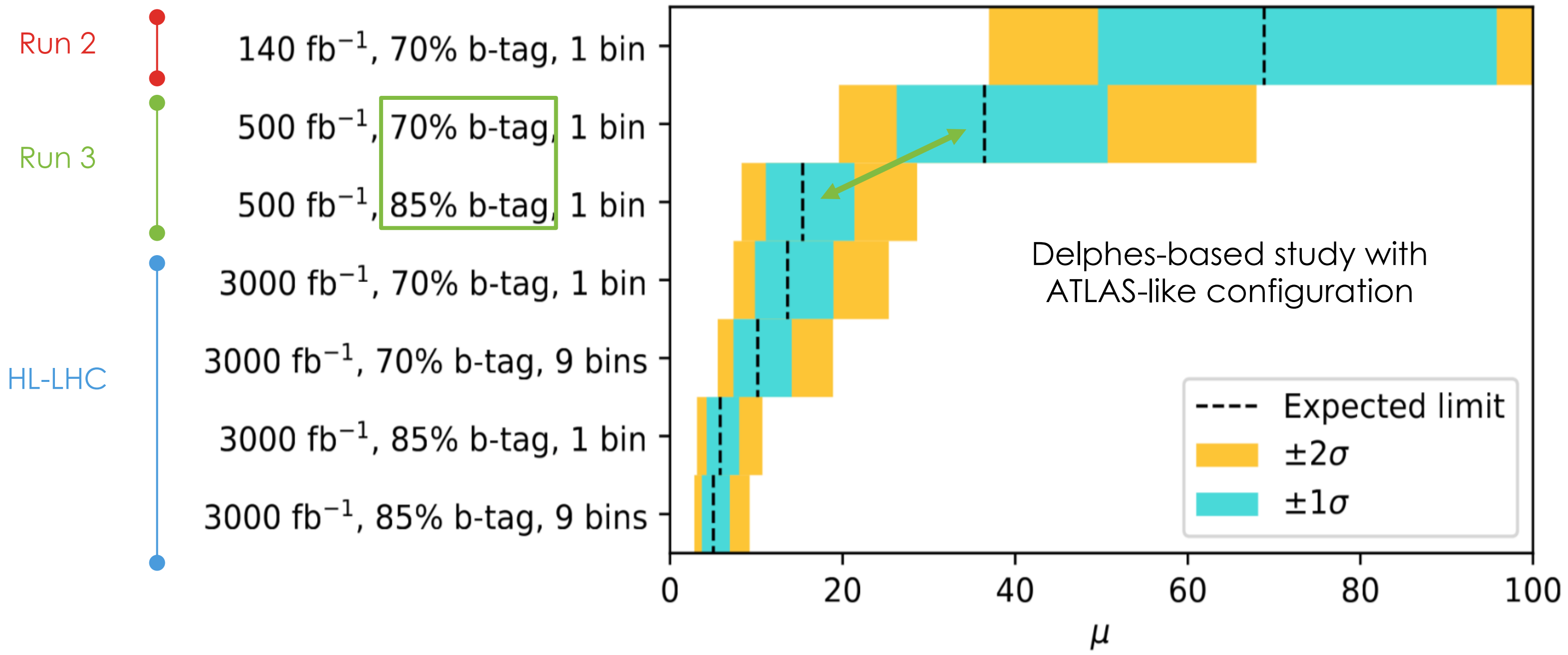


Simulated $t\bar{t}HH(b\bar{b}b\bar{b})$ event

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



See also HL-LHC study by CMS [link]

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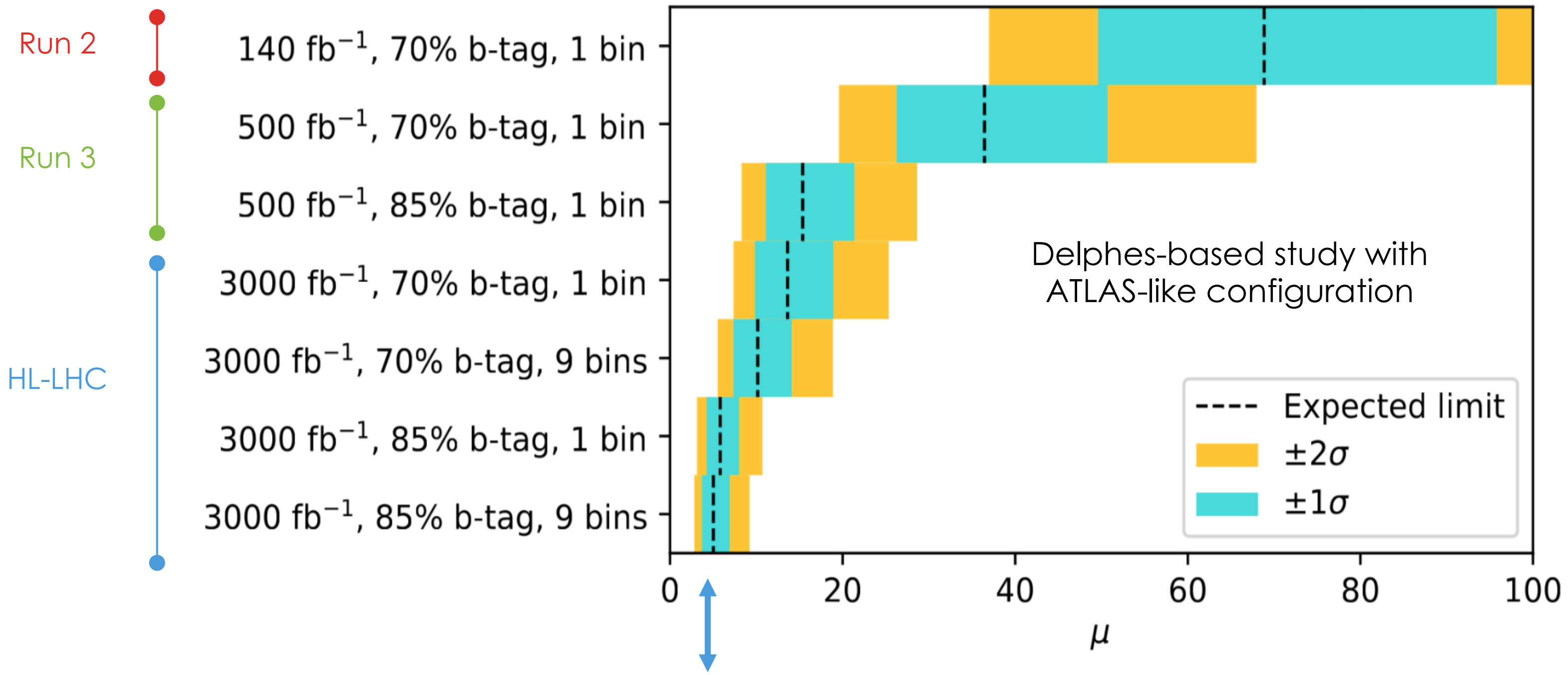


Let's make it reachable during HL-LHC!

See also HL-LHC study by CMS [link]

WHAT'S NEXT?

Relative view point, by F. Cairo

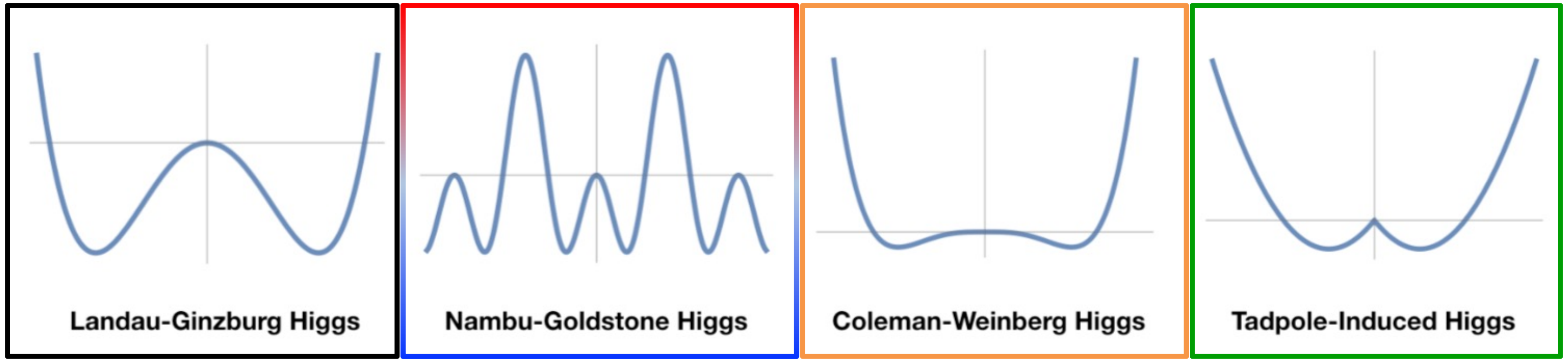
FUTURE COLLIDERS

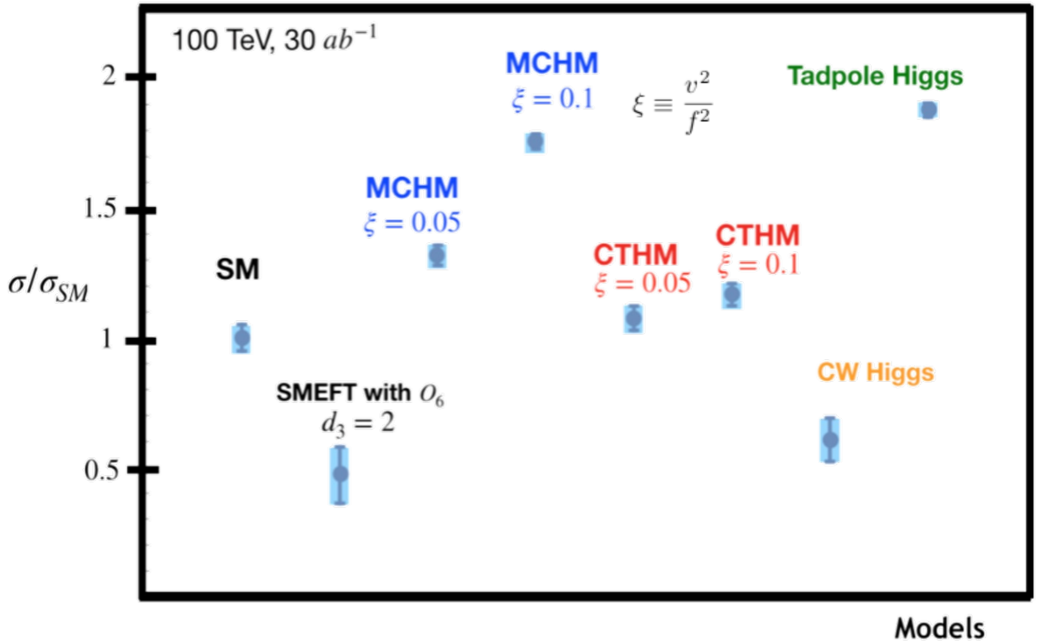
Symmetry

Illustration by Sandbox Studio, Chicago

IMPLICATIONS ON THE HIGGS POTENTIAL

As an example: arXiv:1907.02078v2





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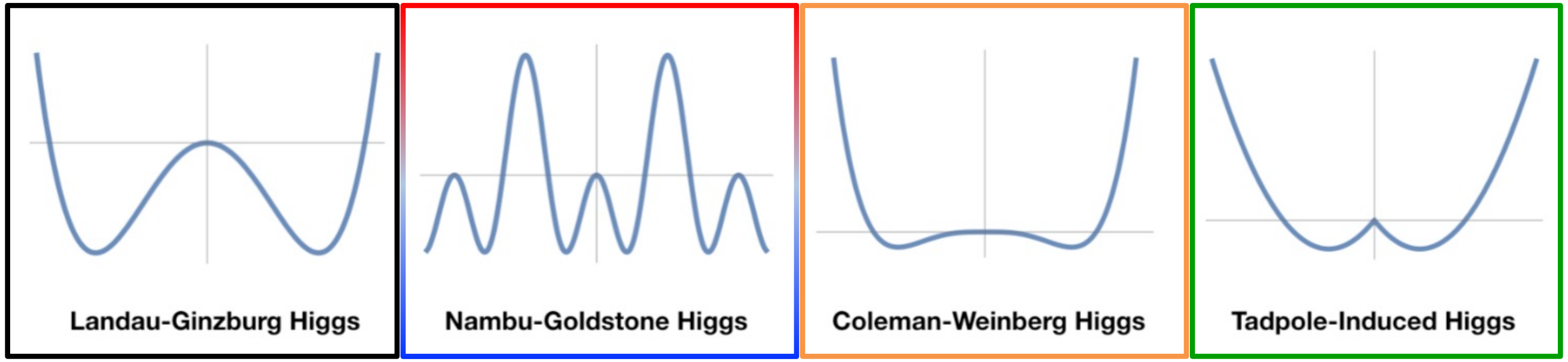
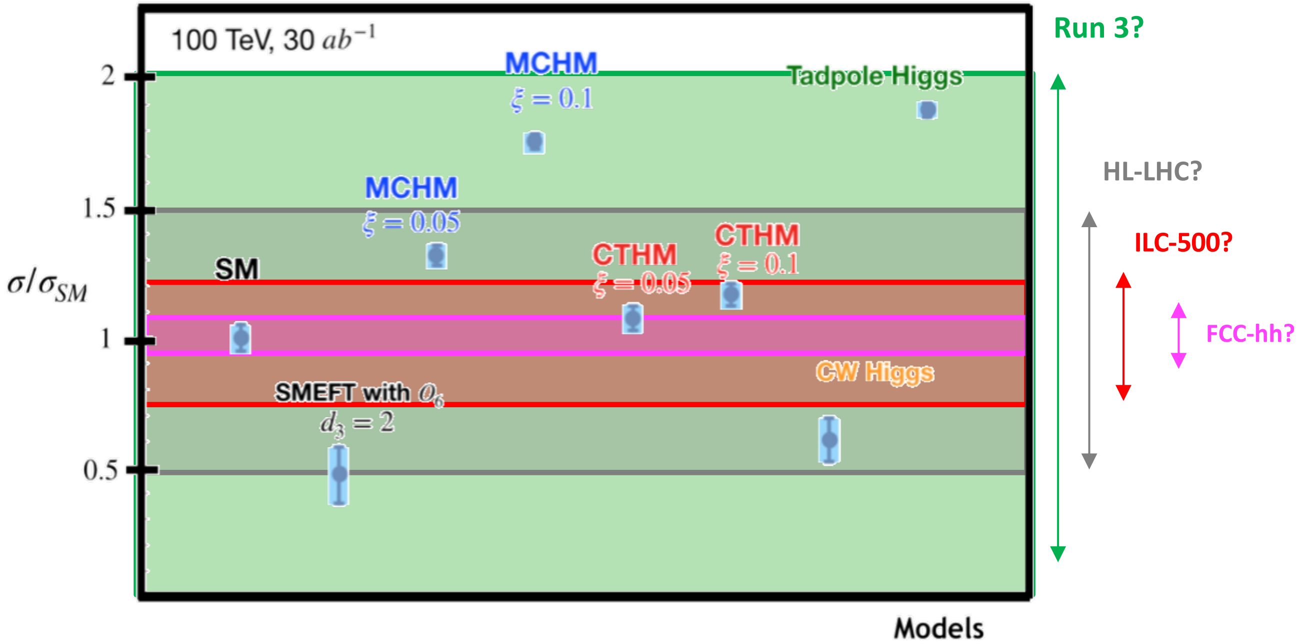
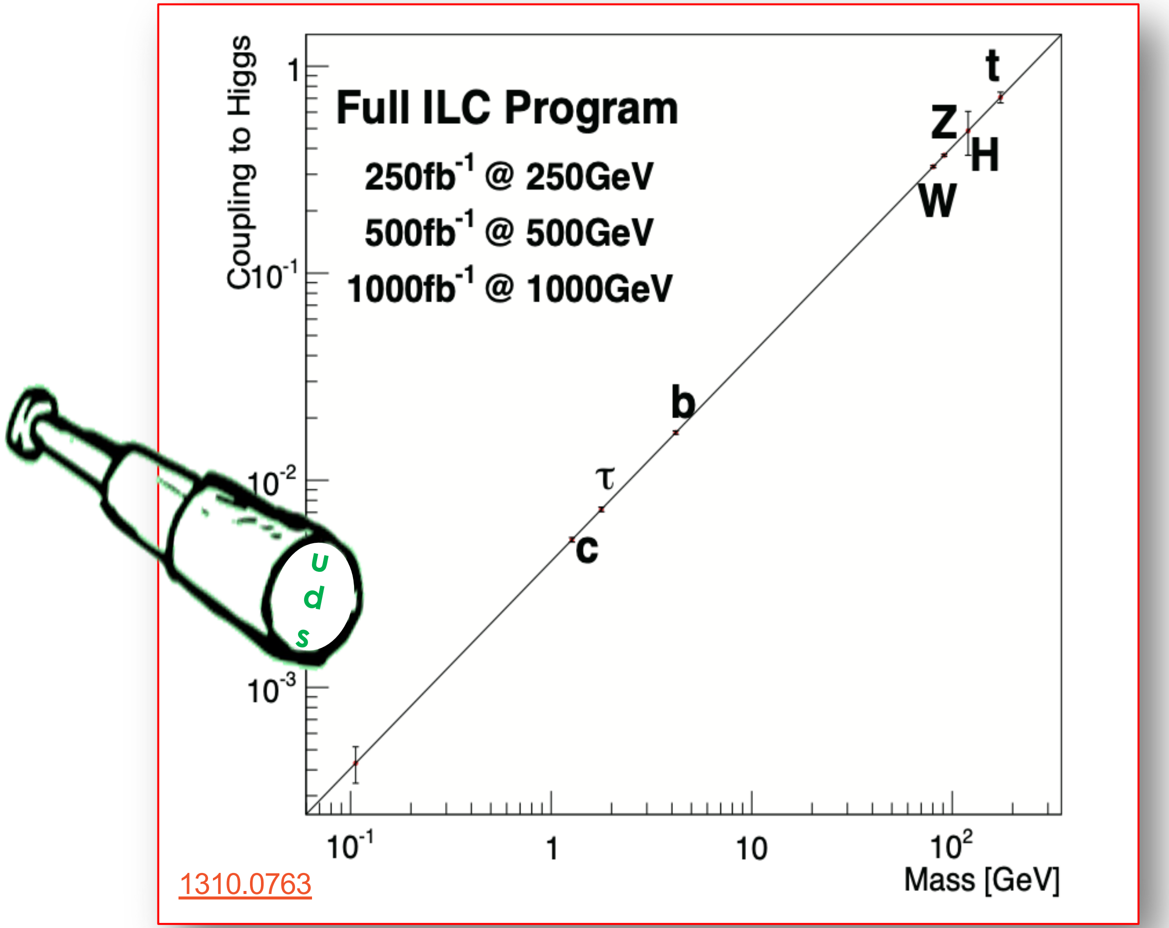




NATURE IS *LIGHT*…

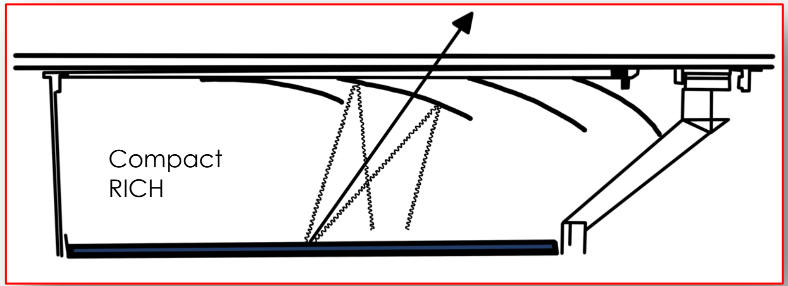
Future

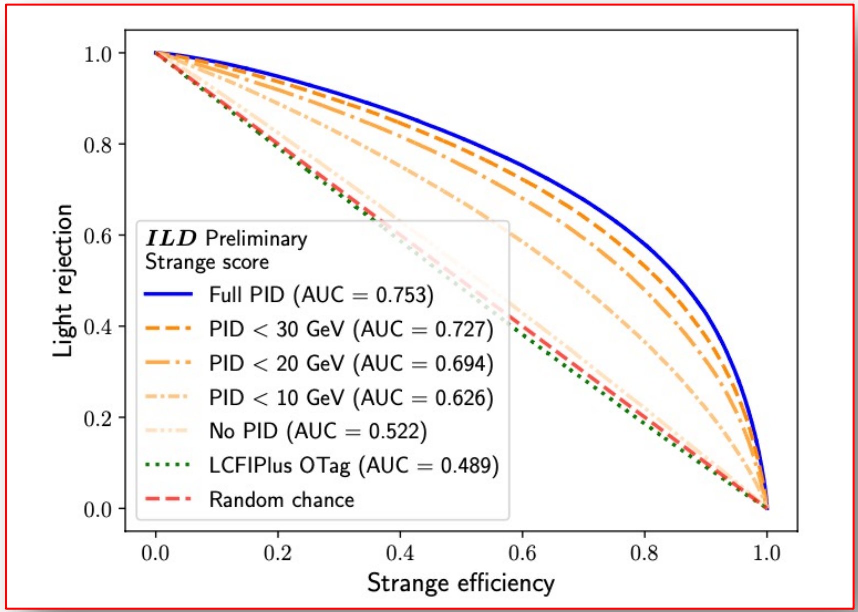


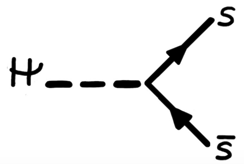
Do light and heavy fermions acquire mass in the same way?
Are the Higgs Yukawa couplings *really* universal?

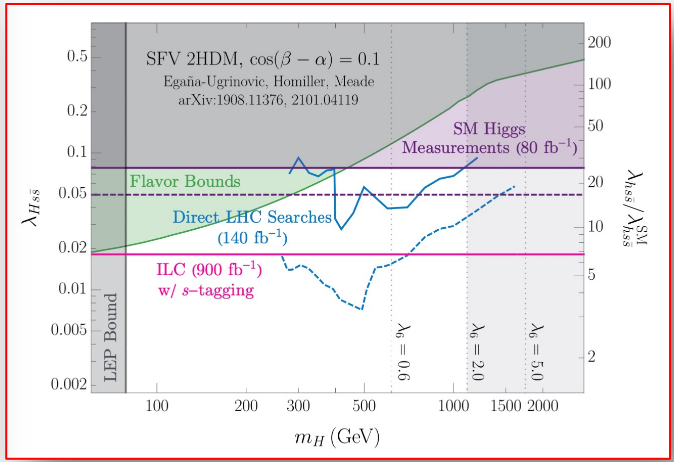
A *strange* AND EXCITING RESEARCH LINE 2203.07535

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

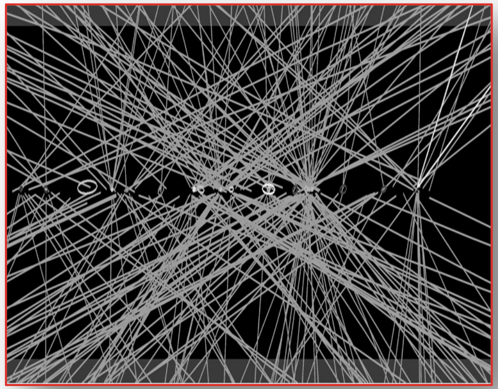
Probing rare Higgs decays to **strange quarks**… SM or BSM?

CONCLUSIONS

- **Exciting science ahead** to track down the Higgs boson properties and solve some of the yet-to-be answered questions about the Universe

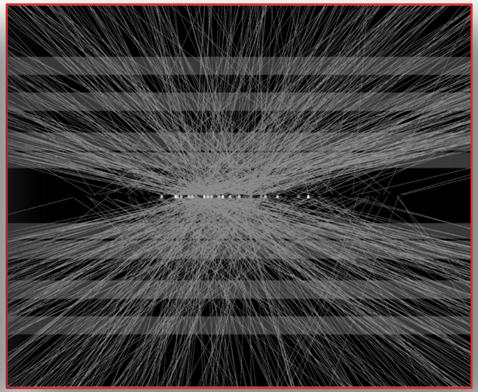
- Interplay between **detector design**, **performance**, **measurements and searches** is of paramount importance for Particle Physics

2009



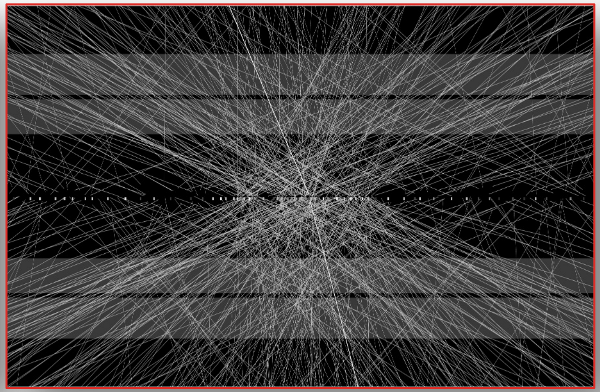
$< pile - up > \sim 20$

2015



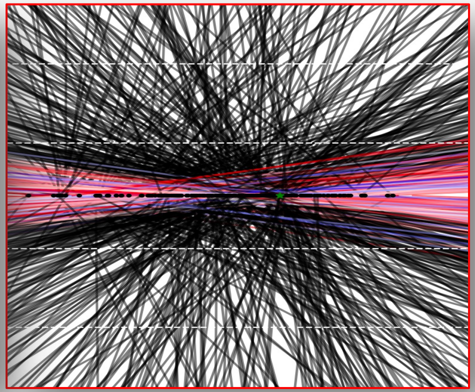
$< pile - up > \sim 30$

2022



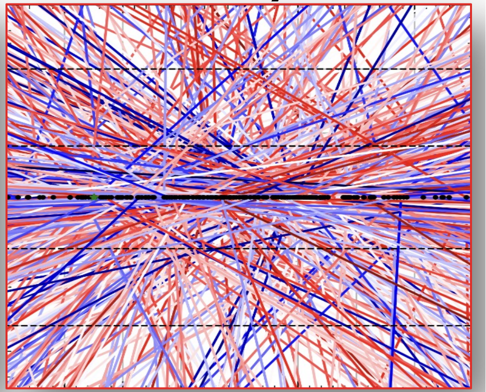
$< pile - up > \sim 60$

2029



$< pile - up > \sim 140$

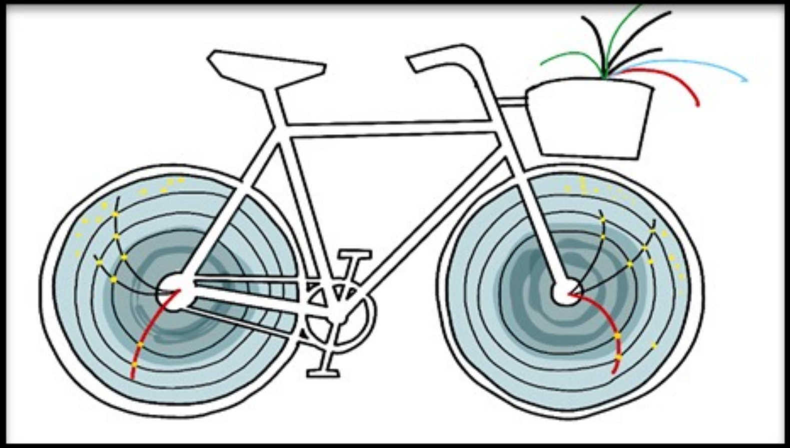
…and beyond?



$< pile - up > \sim 200$

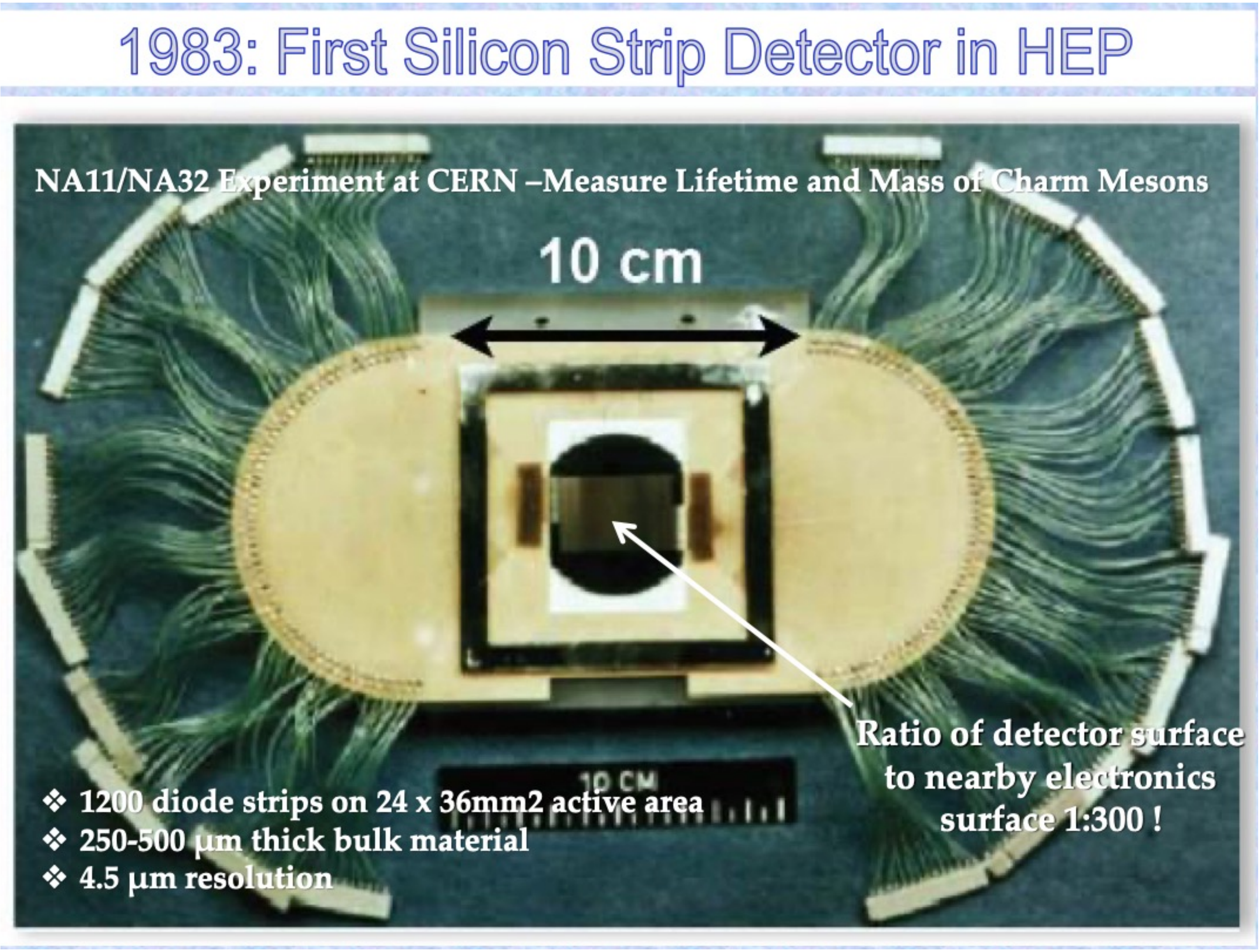
THANK YOU!

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



EXTRA SLIDES

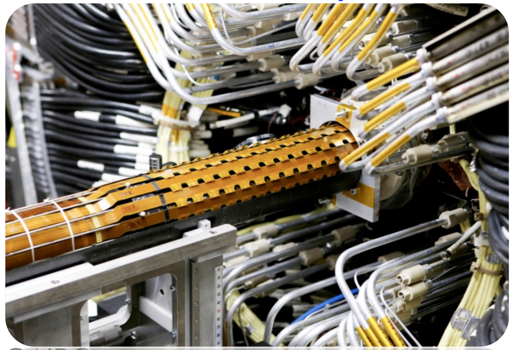
F. Cairo, From *Conn(ll)ecting the dots*



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

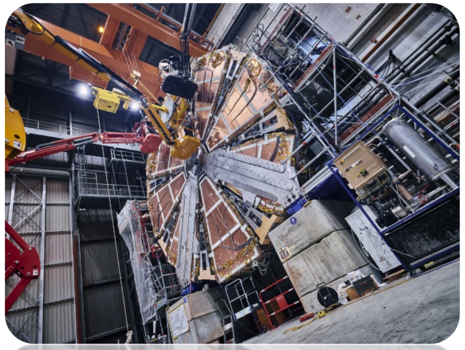
THE ATLAS TIMELINE

Insertable B-Layer



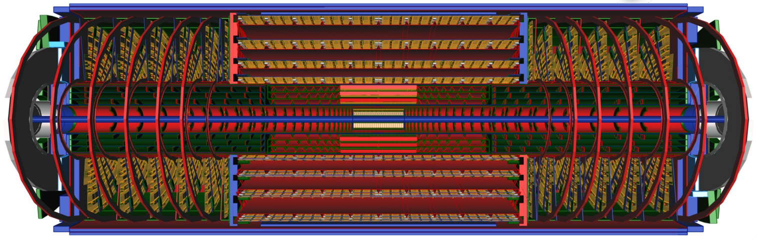
source

New Small Wheels



source

Inner Tracker

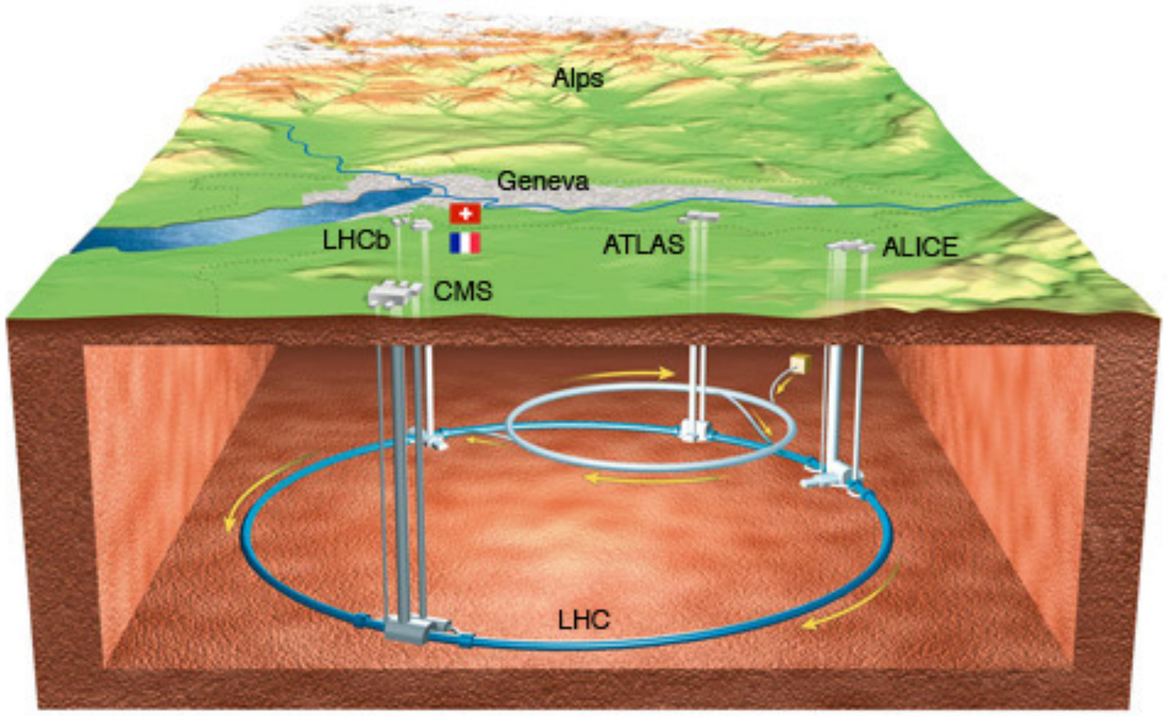


source

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 x 10^{34} $cm^{-2}s^{-1}$)
- **Integrated Luminosity**: 140 fb^{-1}
- **Avg interaction per crossing** $<\mu>$: x2 (~40)

Ongoing:

- **Run 3**: 13.6 TeV, $<\mu>$ ~60

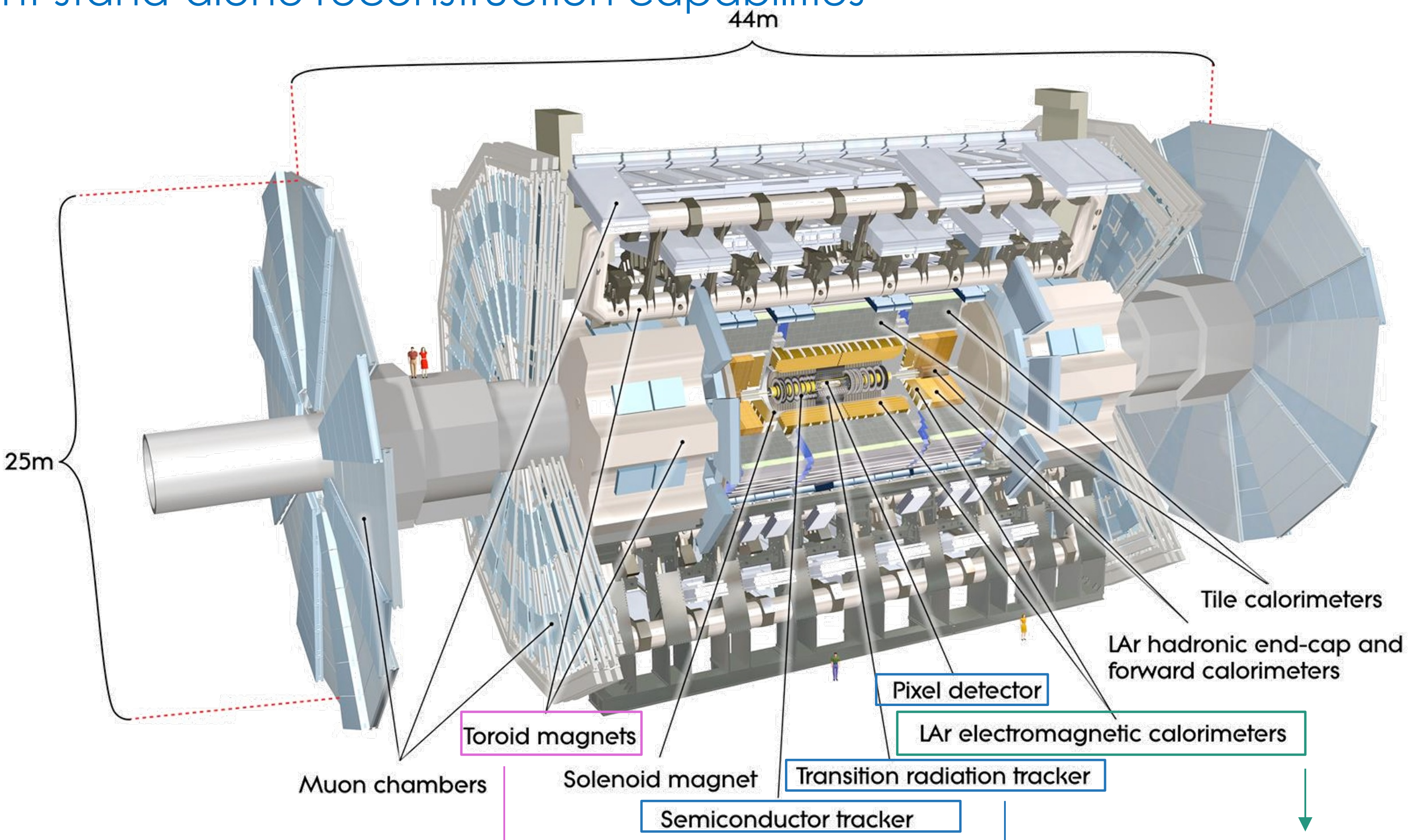
To go:

- **Run 4**: 14 TeV, $<\mu>$ ~200

THE ATLAS DETECTOR

Physics benchmarks drove the design of the detector

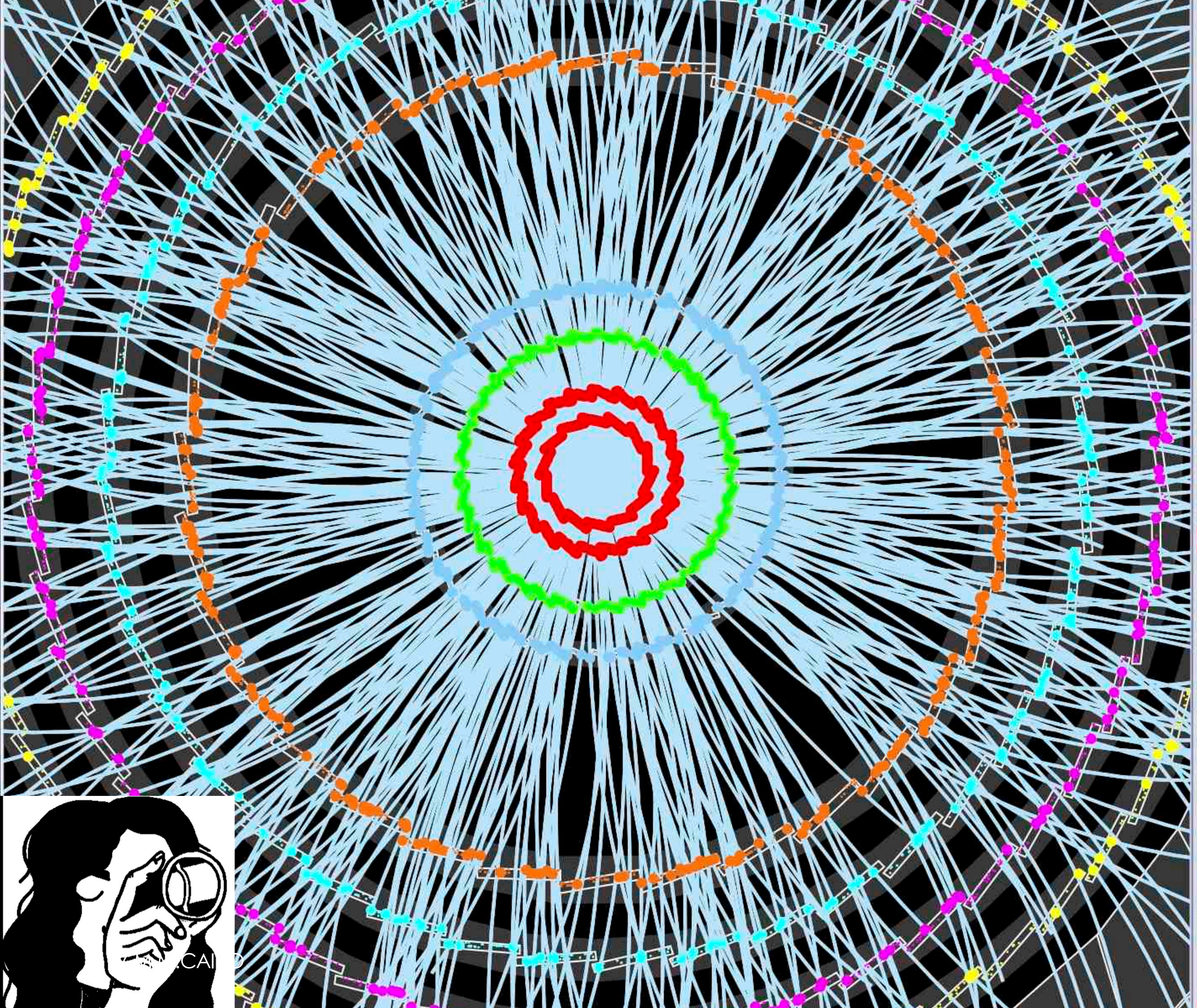
- Excellent stand-alone reconstruction capabilities



Determines the ATLAS geometry

maximize $H \rightarrow \gamma\gamma$ sensitivity

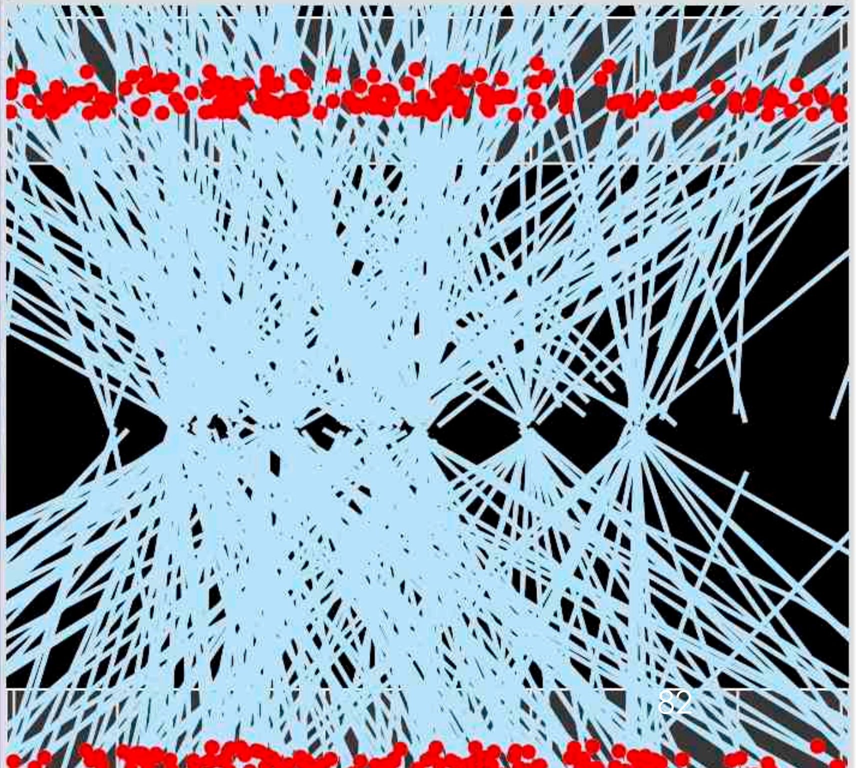
Combined technologies



Run Number: 266904, Event Number: 25884805

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

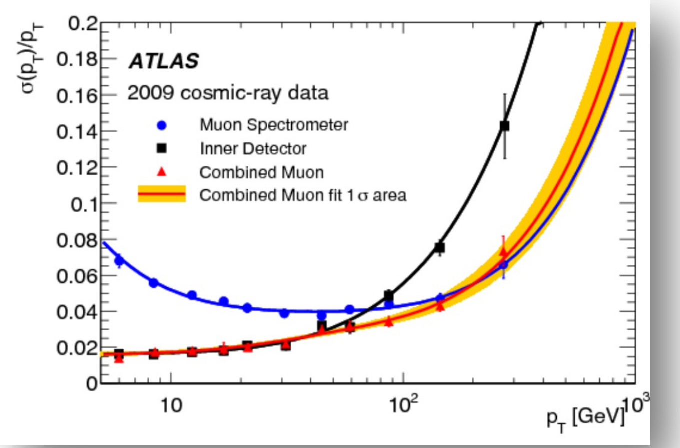
O(15) charged-particles per p-p interaction
X # simultaneous p-p interaction



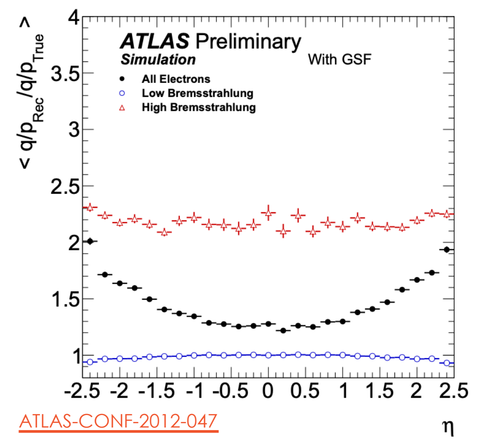
FROM CHARGED PARTICLES TO EVENT RECONSTRUCTION

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

Muons

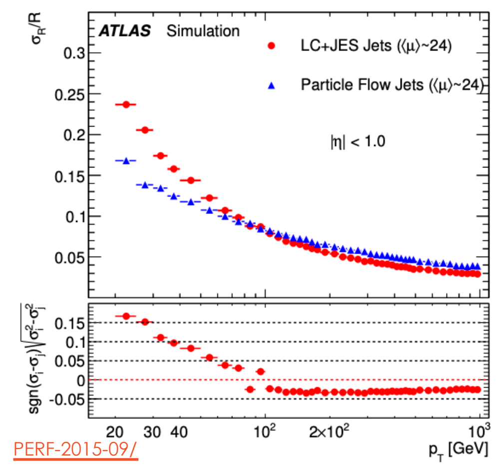


Electrons



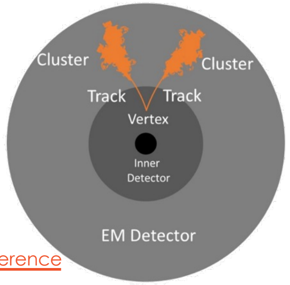
ATLAS-CONF-2012-047

Particle FlowJets



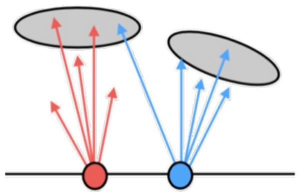
PERF-2015-09/

Photon conversions

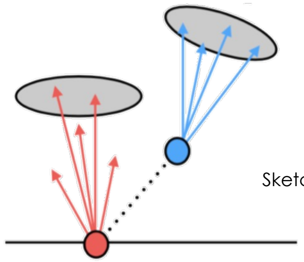


Reference

Pile-up removal

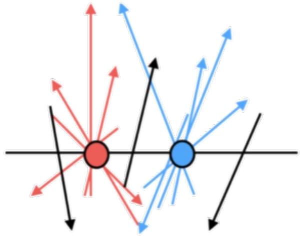


Jet-flavour tagging



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

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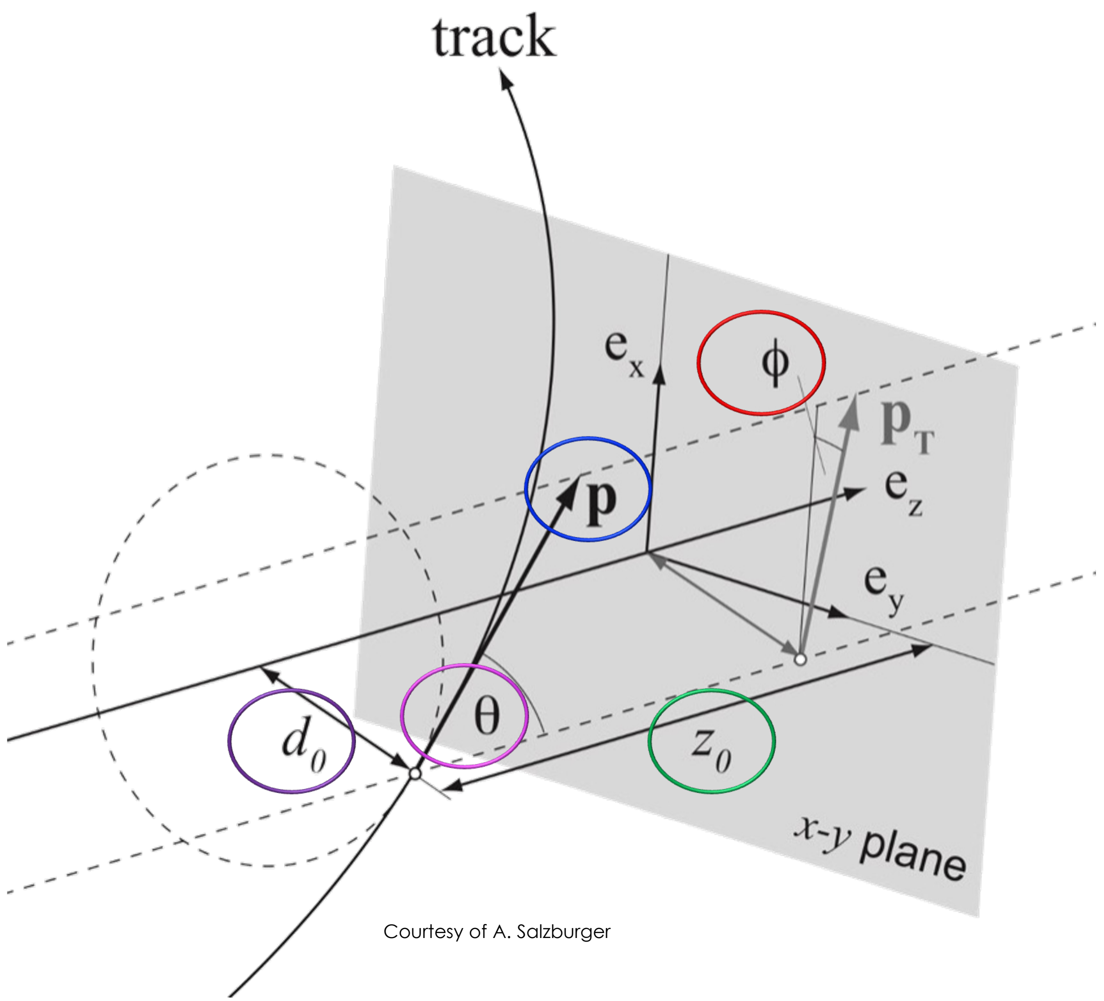
- **Trackers** designed to **meet requirements**
- **Tracking algorithms to fully exploit their capabilities**

HOW TO PARAMETERIZE A TRACK

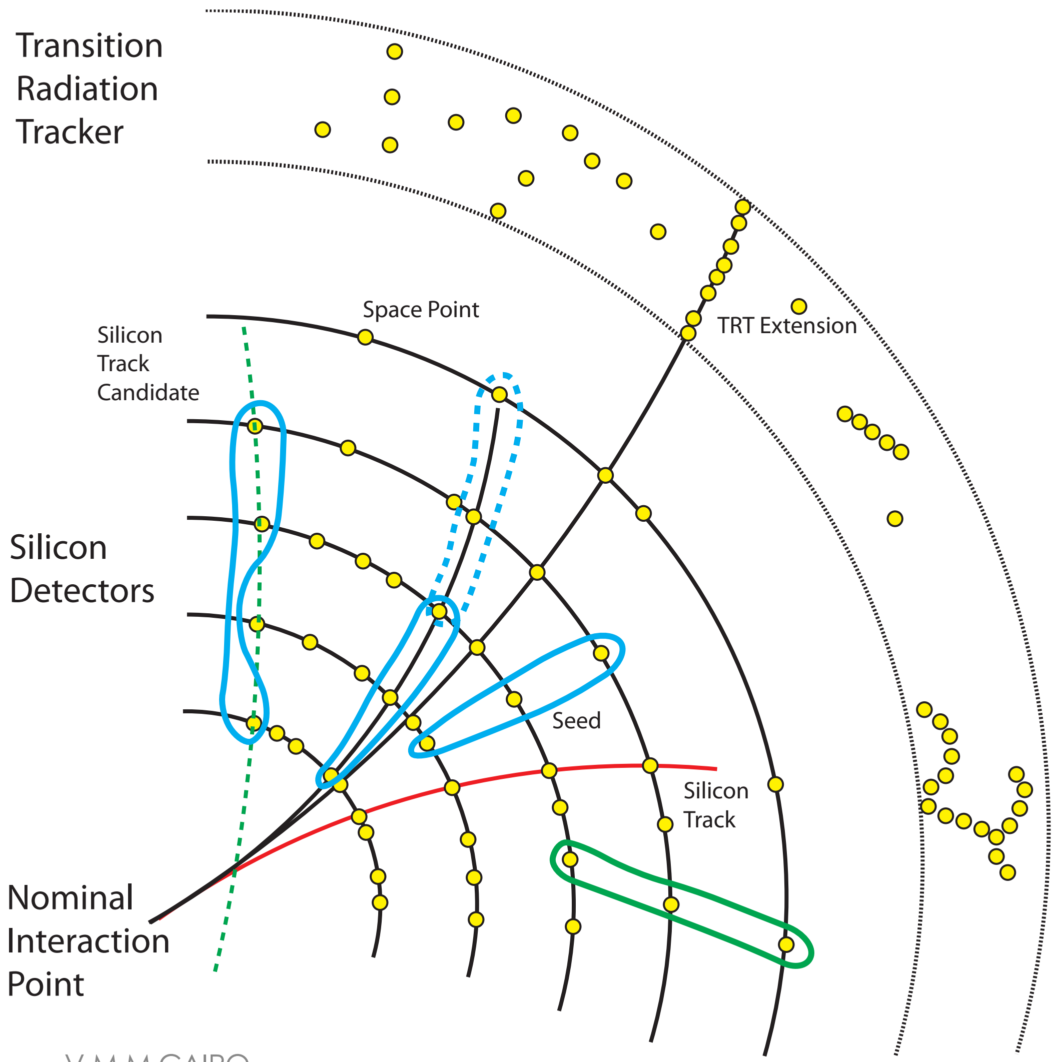
5 parameters describe the helical path of a charged particle in a solenoidal magnetic field:

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



Courtesy of A. Salzburger

THE (CURRENT)ATLAS TRACKING CHAIN



Inside-out

- Space Points
- Seed finding
- Track Candidates (Combinatorial Kalman Filter)
- Ambiguity solving
- TRT Extension

By default, enabled only in ROIs

Outside-in

- Seed finding
- Track Candidates (Combinatorial Kalman Filter)
- Ambiguity solving

VERTEXING

Primary vertex: point in space where interactions have occurred

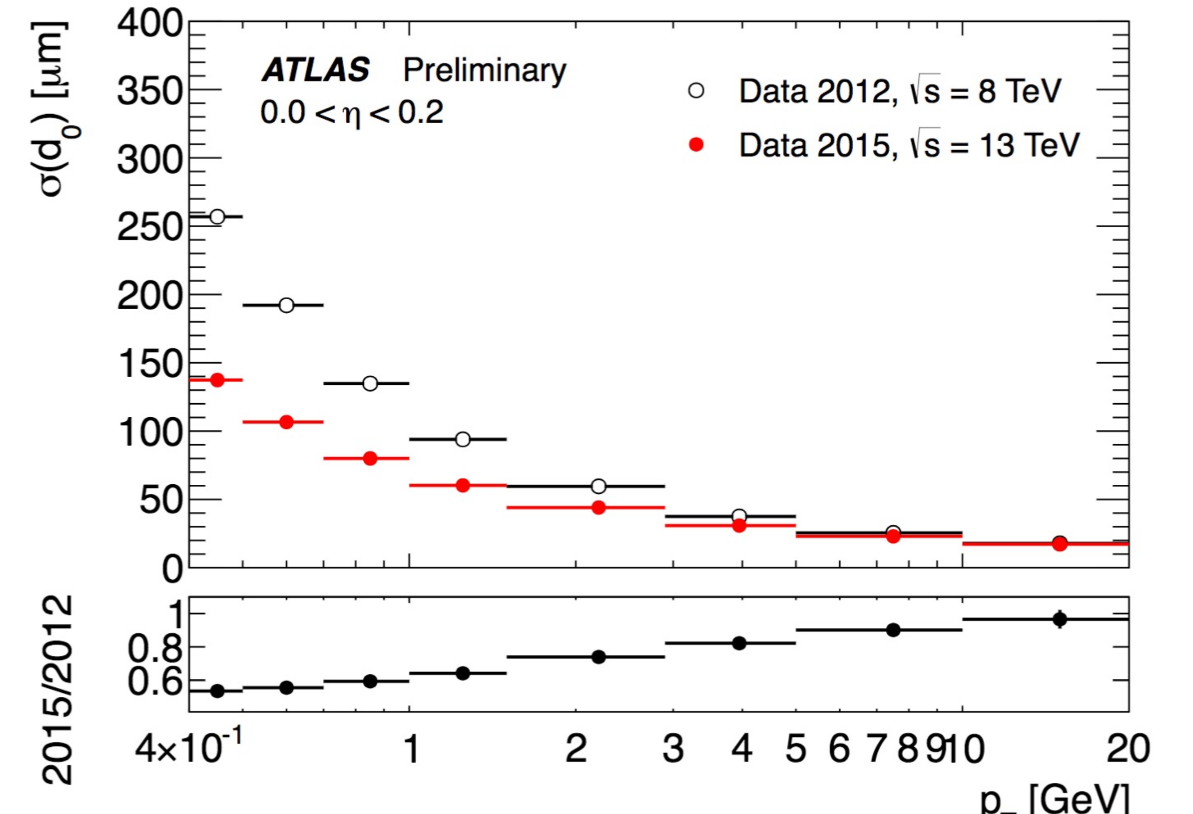
- Fundamental element of **data analysis**
- **Track-to-vertex association** essential in reconstructing the full kinematic properties of the event
- Important for the **determination of the luminous region**, or beam spot, where collisions take place and to **compute decay length for b-tagging**

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

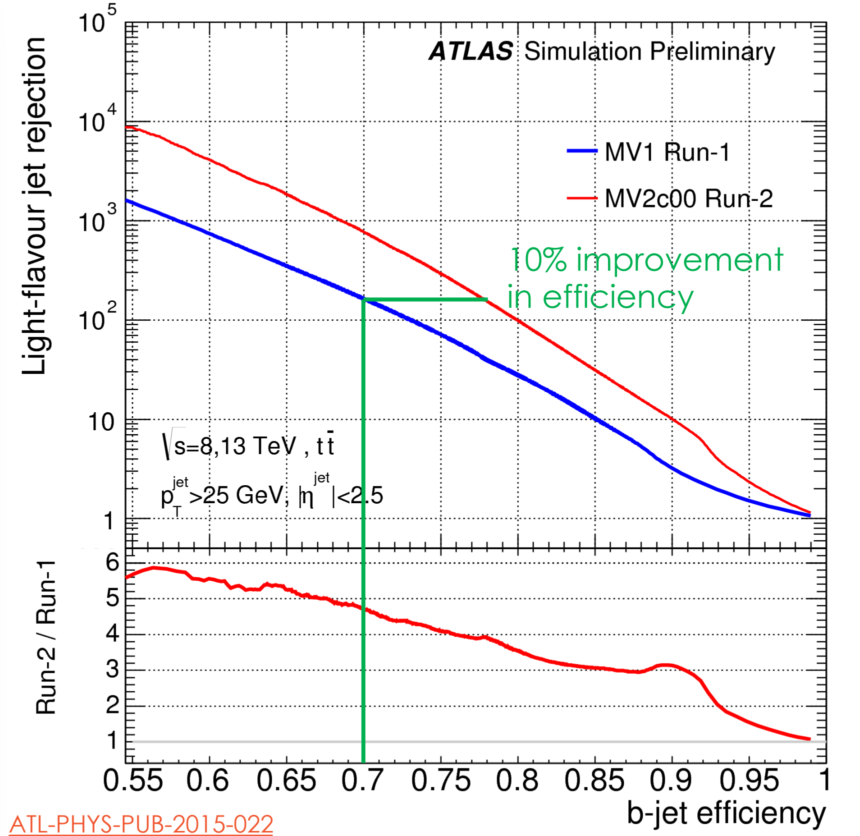
- **Often identified by the highest squared sum of track transverse momentum p_T** ($\sum p_T^2$)
- It is crucial that the **HS** be **distinguished from** the surrounding **pile-up** interactions

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



IDTR-2015-007



ATL-PHYS-PUB-2015-022

THE (CURRENT)ATLAS APPROACH

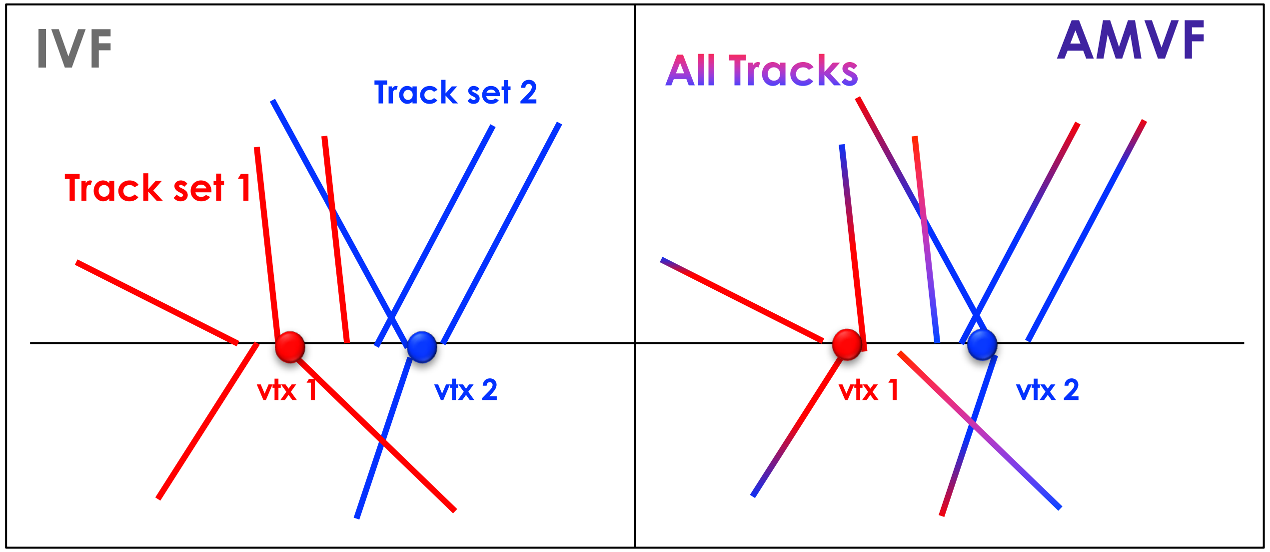
Seed-finding

Track-to-seed assignment

Fitting

Acceptance/Rejection

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



TIMING AND THE COMPUTATIONAL CHALLENGE

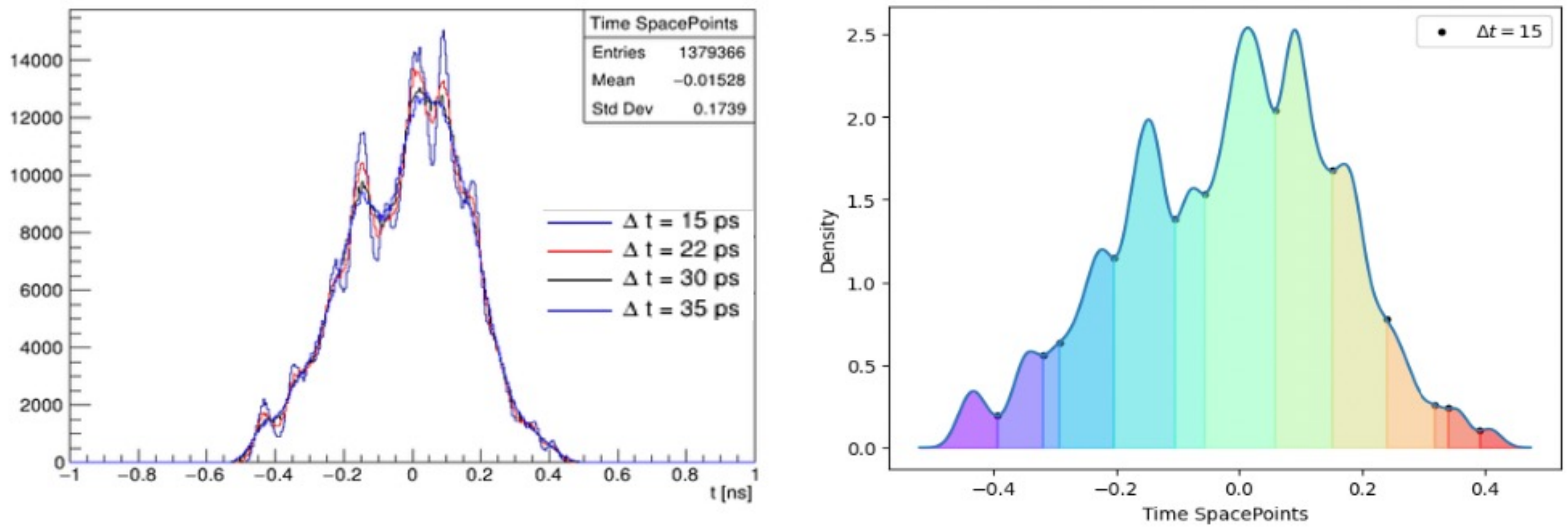
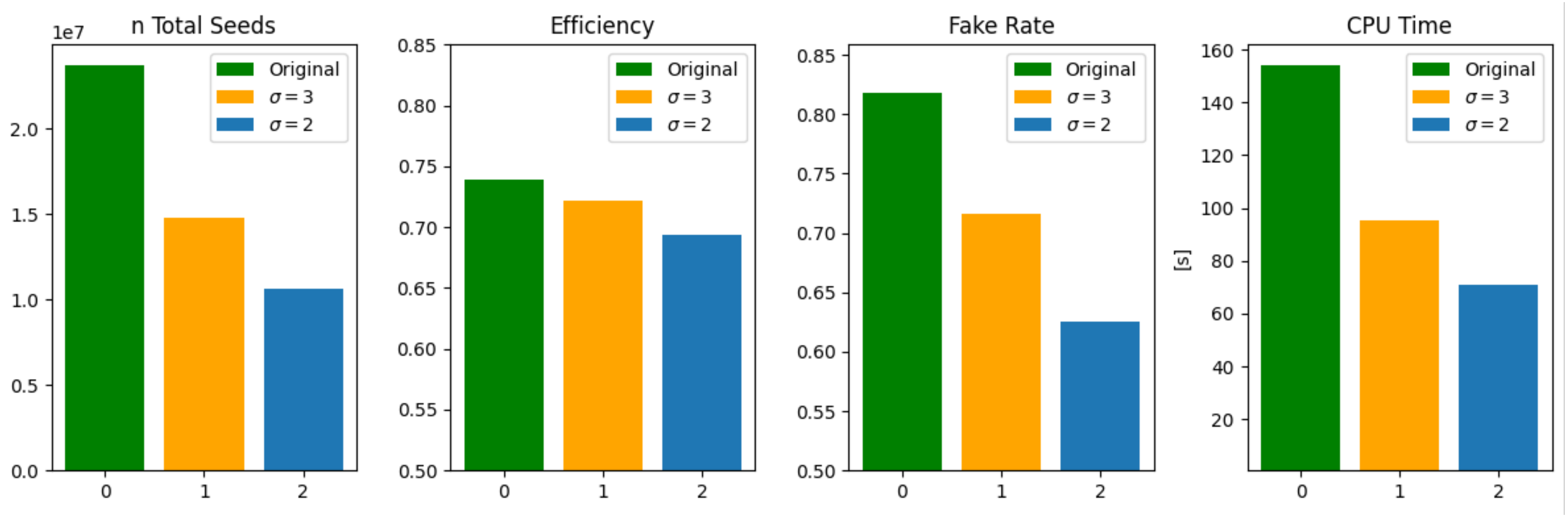


Figure 17 (Left) Simulation of the SP times in the 2nd ITk layer for a $t\bar{t}$ event with a pile-up of 200. Different values of time resolution are shown. (Right) Clustering of SP times in the 2nd ITk layer of ITk with 15 ps. The SPs are clustered by calculating the minima of the Gaussian Kernel-Density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

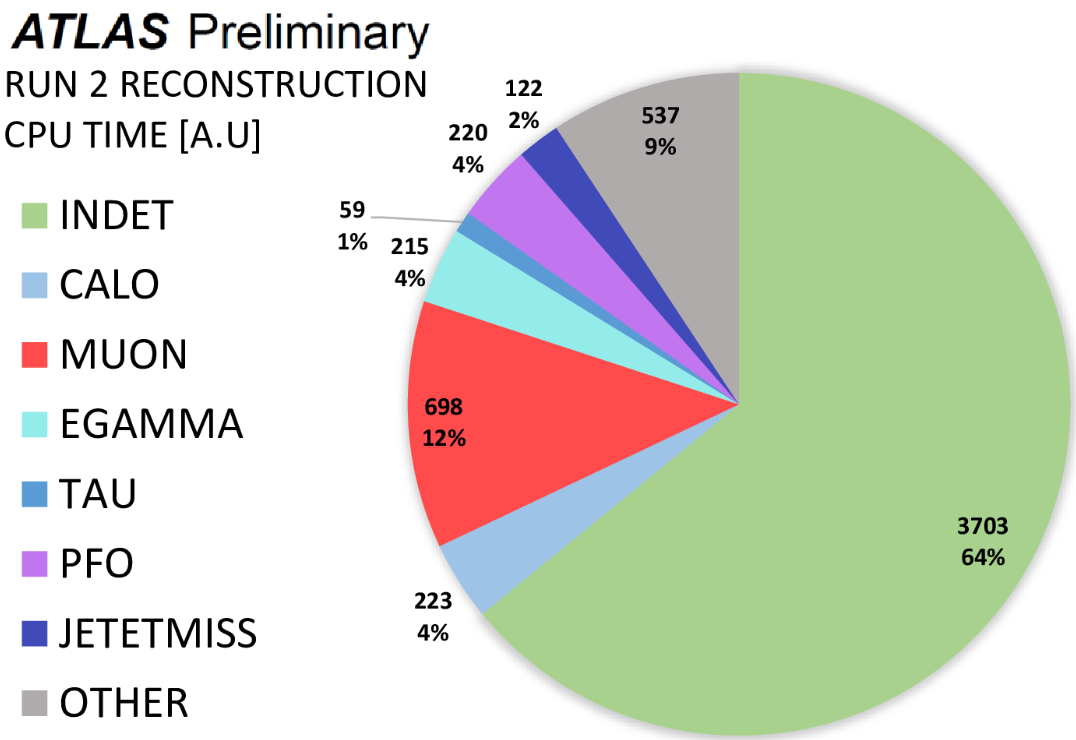
https://cds.cern.ch/record/2879352

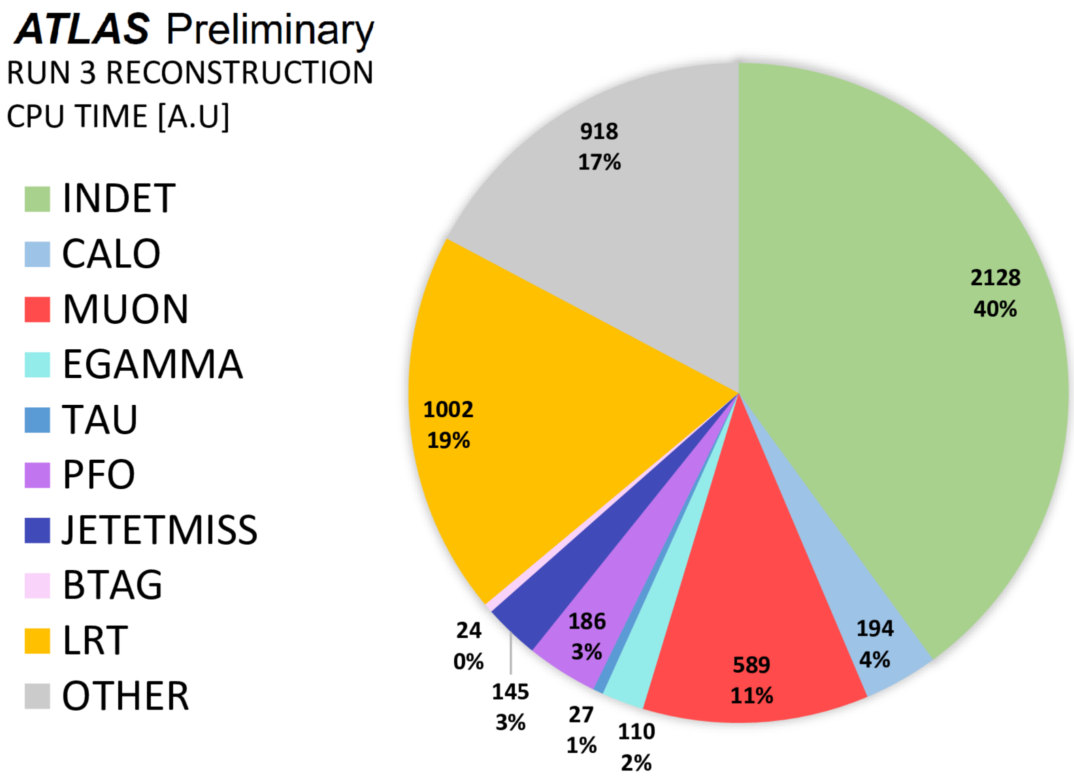
TIMING AND THE COMPUTATIONAL CHALLENGE



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

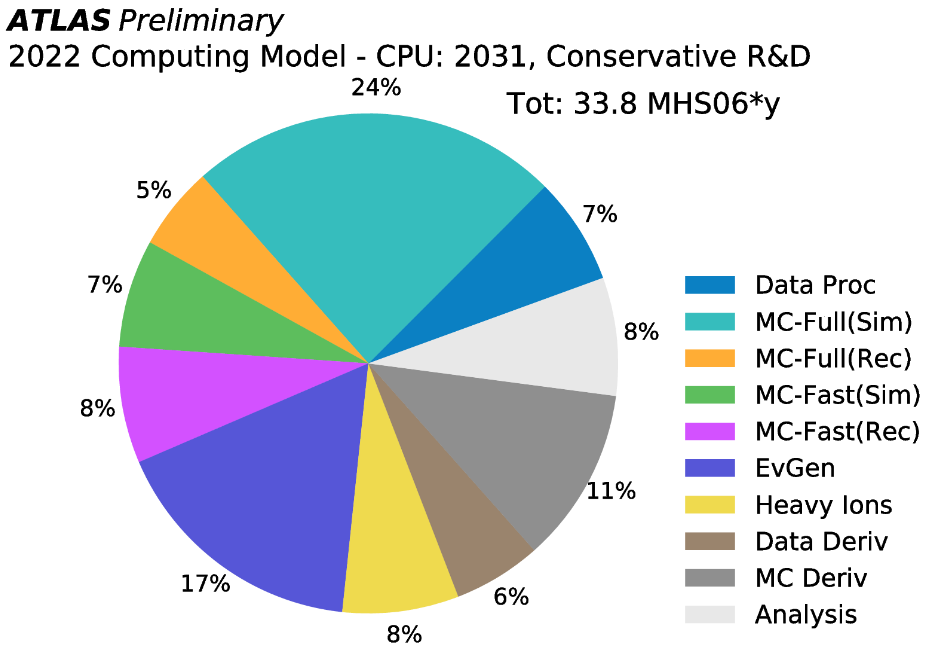
S&C:
STATE OF THE ART

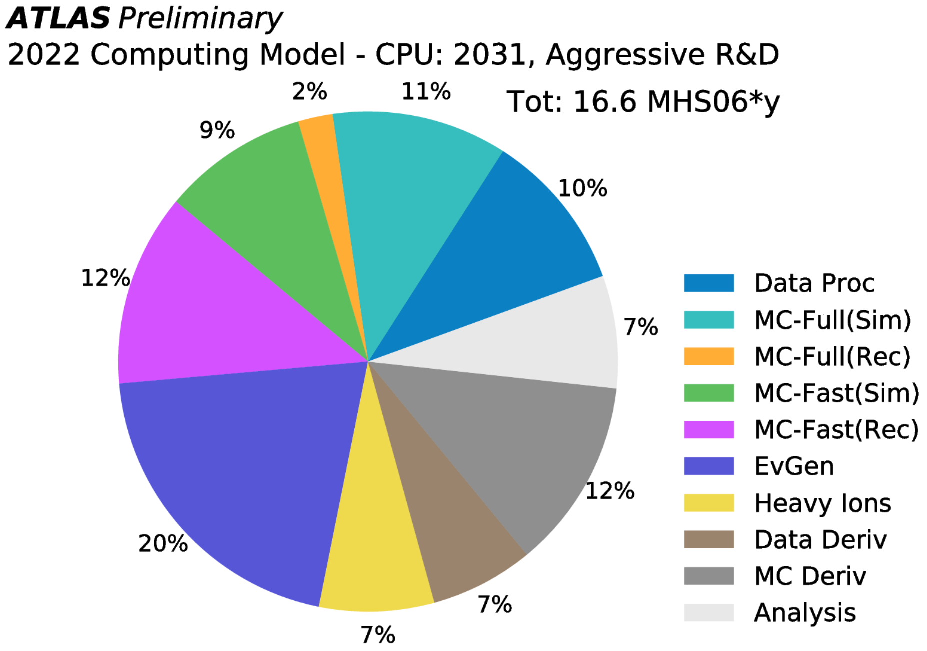




ATLAS S&C HL-LHC roadmap

S&C:
STATE OF THE ART

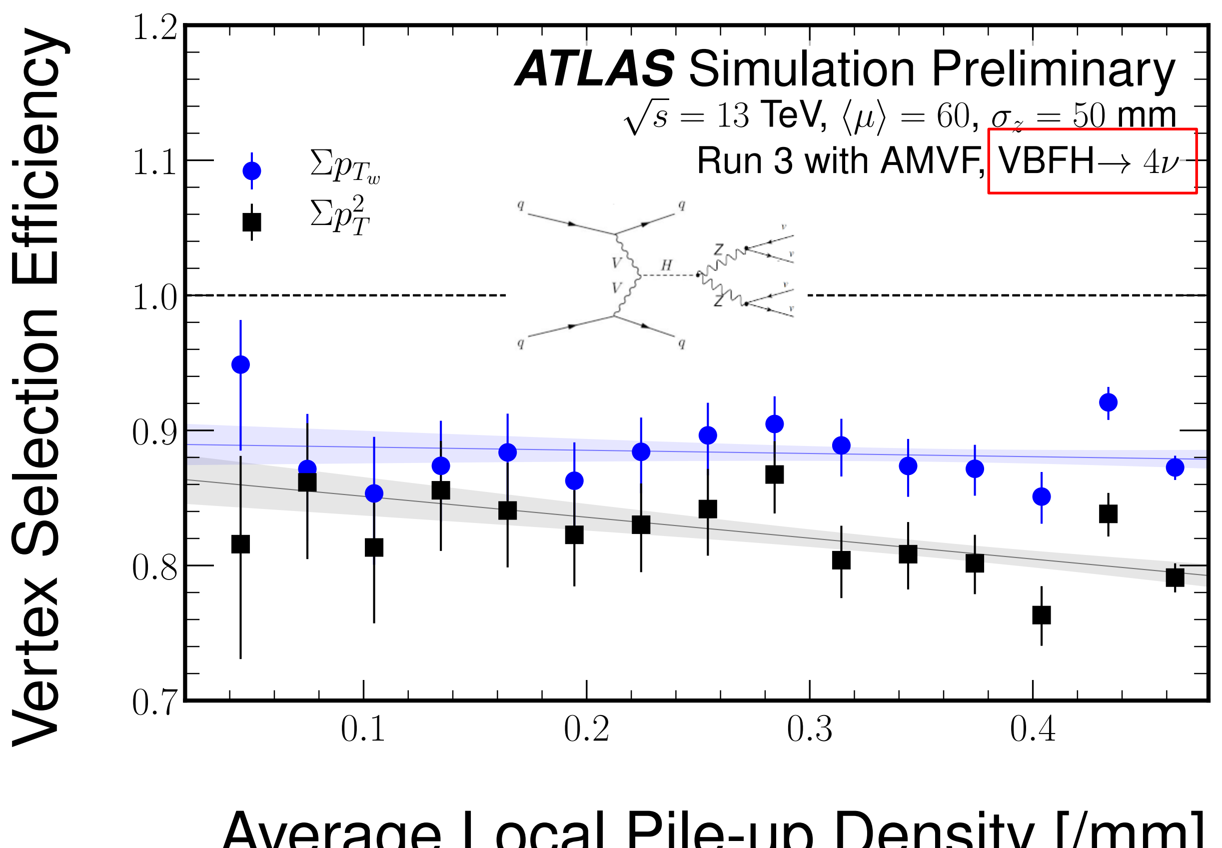




ATLAS S&C HL-LHC roadmap

THE HOTSPOT: VERTEXING

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



IDTR-2020-002

Benefits even more from the forward ITk acceptance…

PERFORMANCE FIGURES

Track Reconstruction efficiency:

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

Fake Rate:

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

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

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

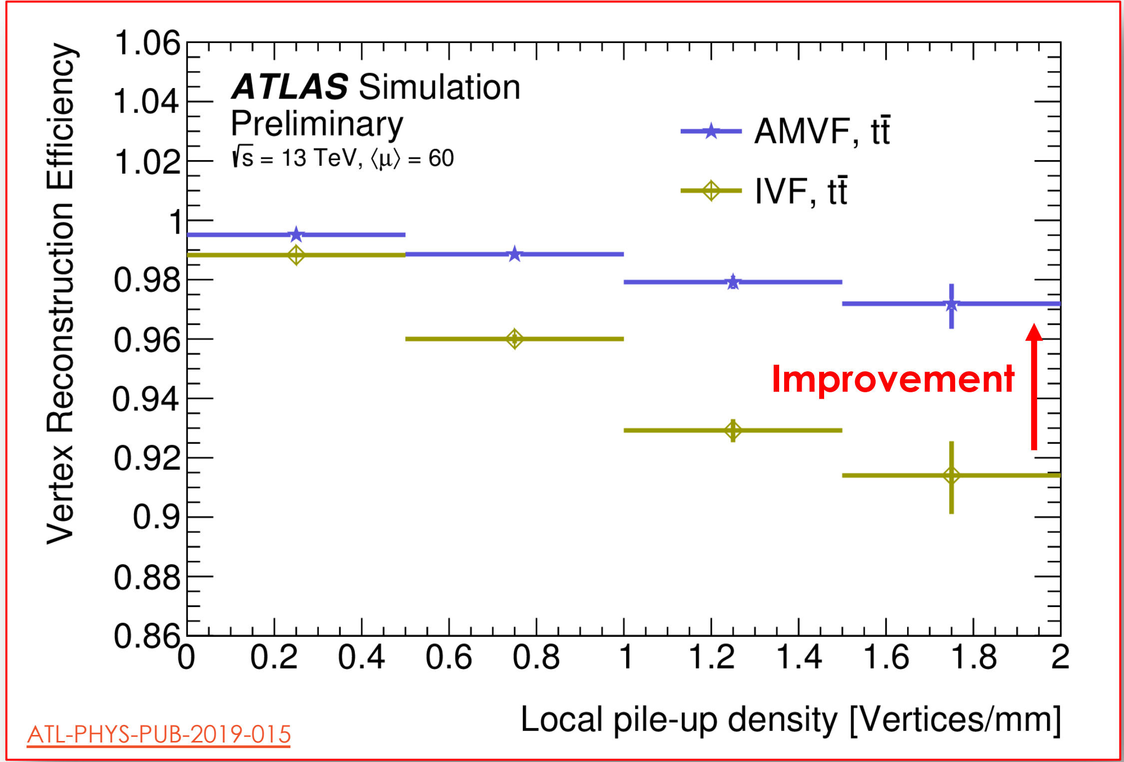
Matching criterion:

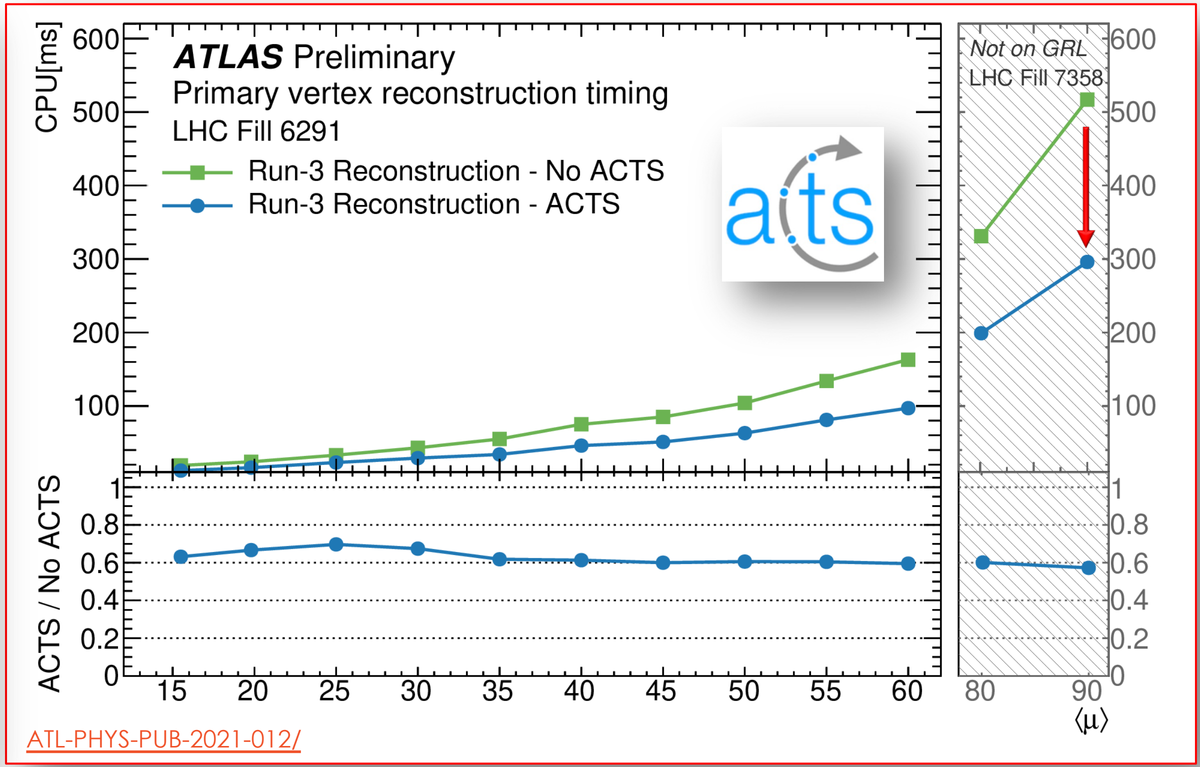
ATLAS: weighted hit-based track-to-truth particle association

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

Technical/Algorithmic Efficiency: Ngen -> Ngen_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

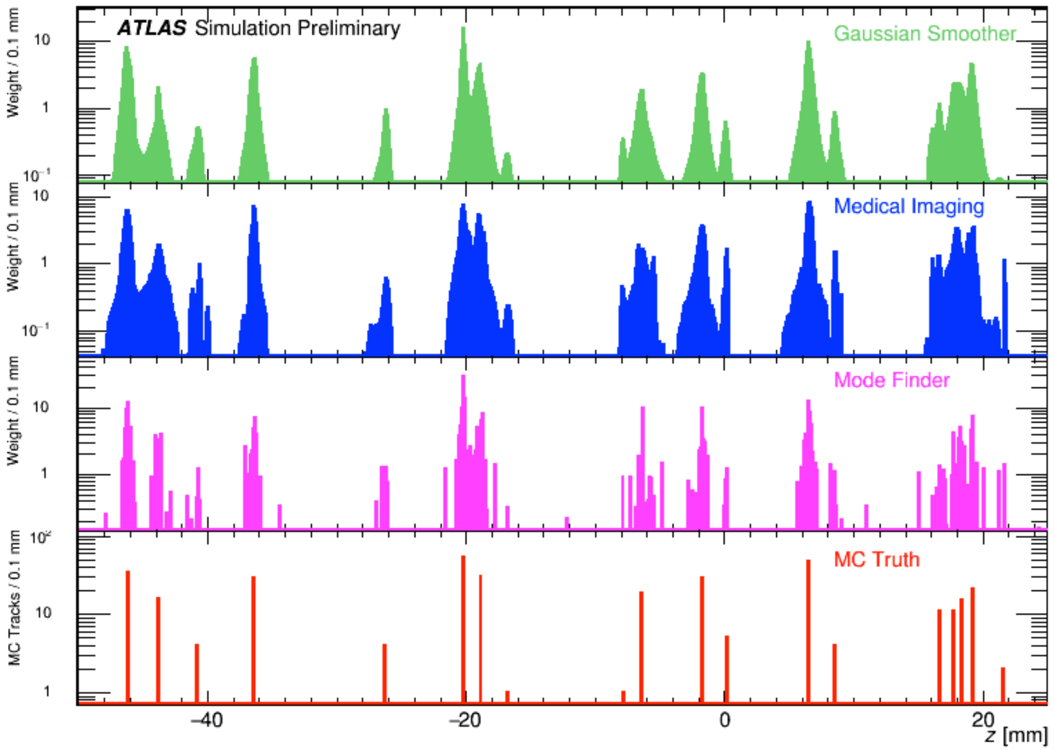
Implemented within the ACTS framework

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

All relevant for **the HL-LHC ATLAS silicon Inner Tracker (ITk)**

GAUSSIAN TRACK DENSITY SEED FINDER

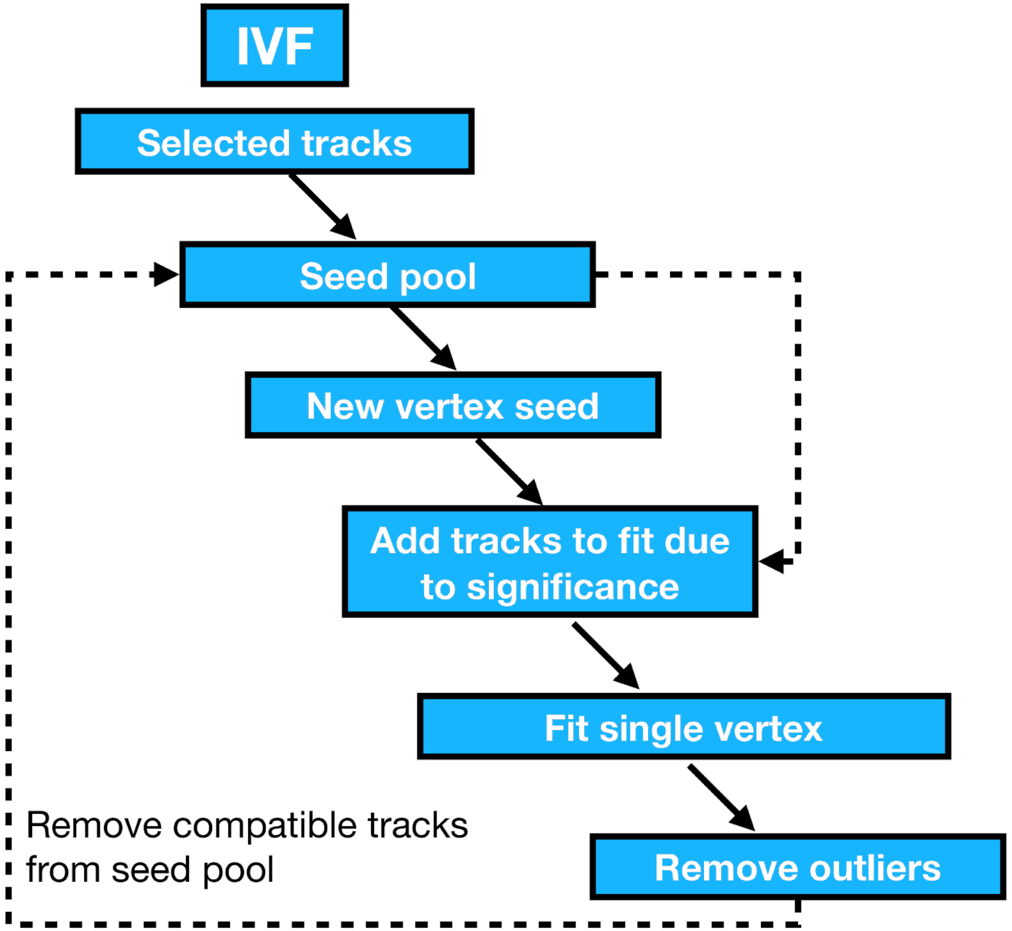
- Use a seeder that is **analytic** and **accounts for** the **track uncertainties**
  - Allows to exploit the **seed width (σ_z) to constrain the vertex fit**



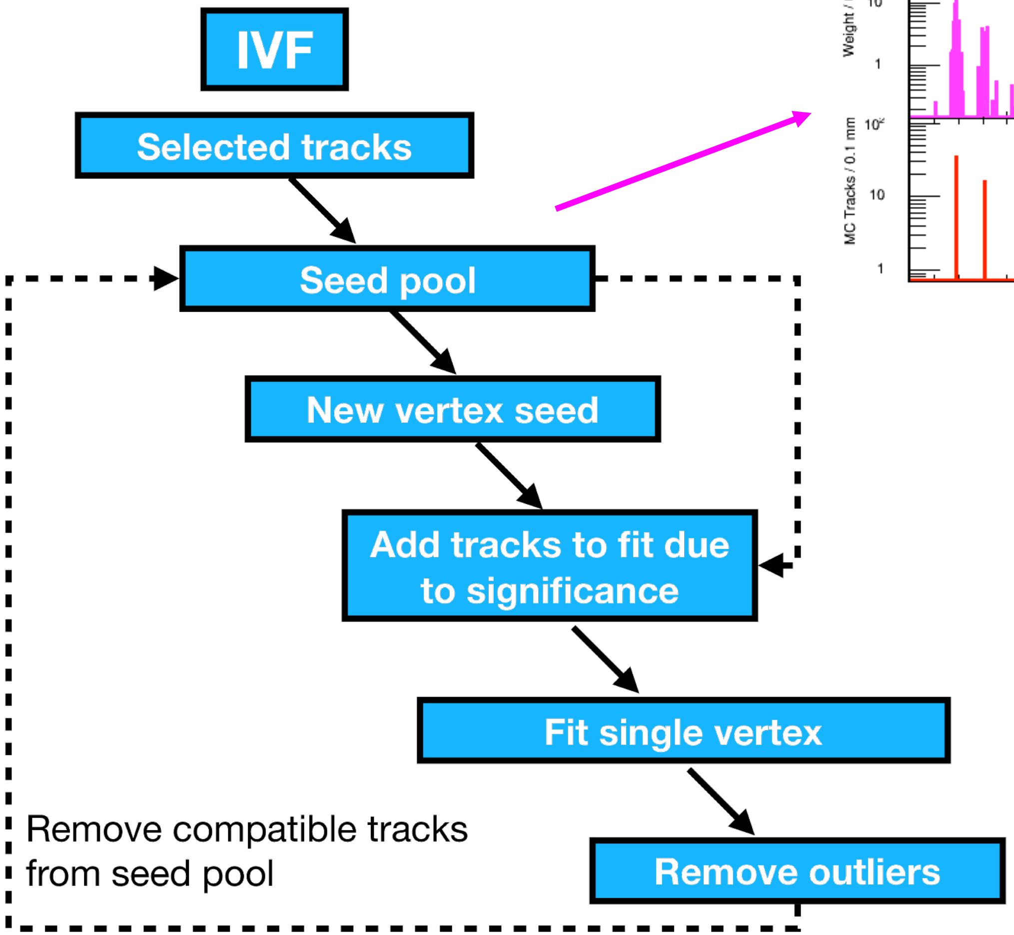
Seed finding weights calculated using a **longitudinal Gaussian** function with a **transverse Gaussian** function acting as an independent quality control

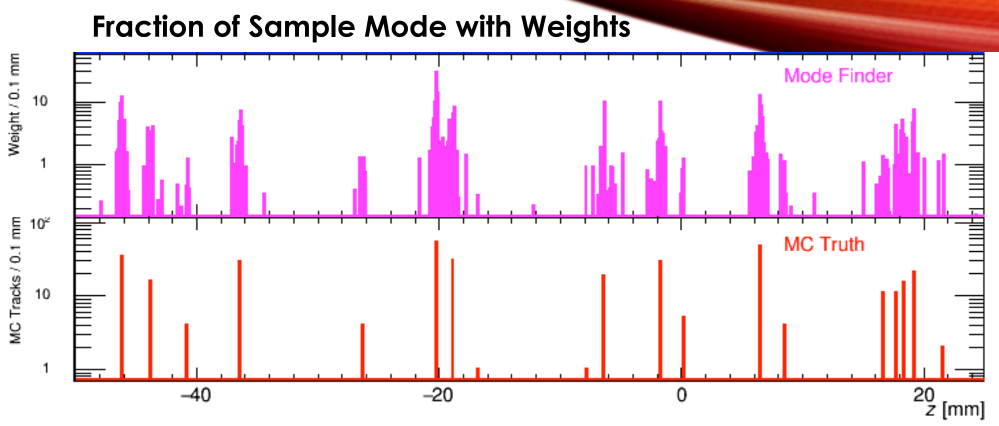
$$\lim_{\sigma(d_0,z_0)\to 0} \rho(z) = \left(\frac{1}{\sqrt{2\pi}\sigma(d_0)} e^{-\frac{1}{2}d_0^2/\sigma^2(d_0)}\right)\left(\frac{1}{\sqrt{2\pi}\sigma(z_0)} e^{-\frac{1}{2}(z-z_0)^2/\sigma^2(z_0)}\right).$$

ATLAS IN RUN1/2: ITERATIVE VERTEX FINDER



ATLAS IN RUN1/2: ITERATIVE VERTEX FINDER

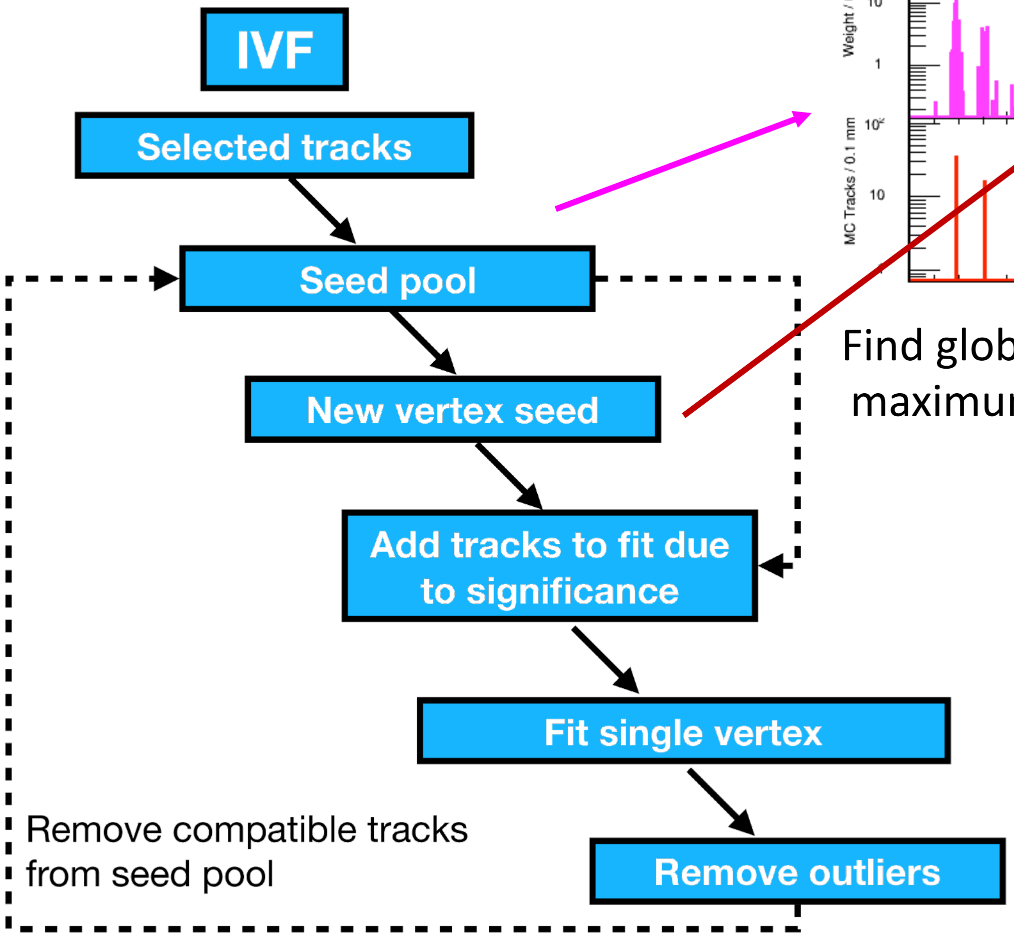


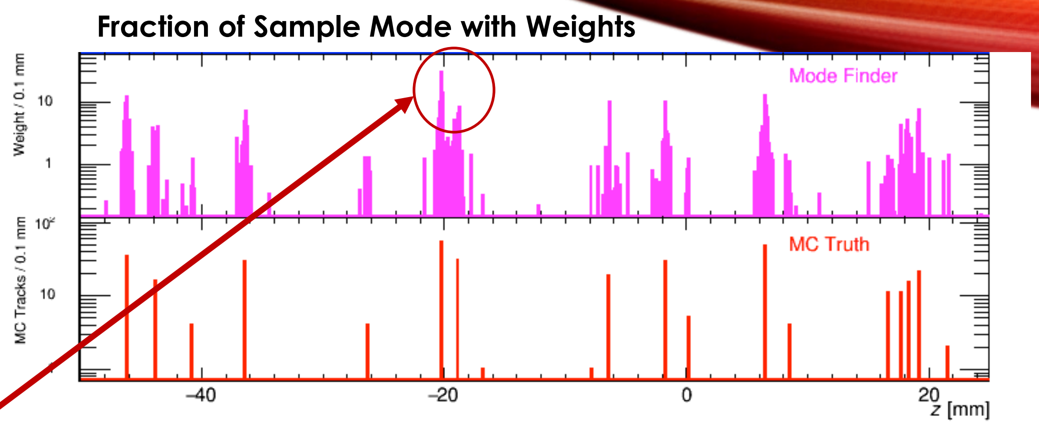


Goal: use tracks to find approximate vertex location

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

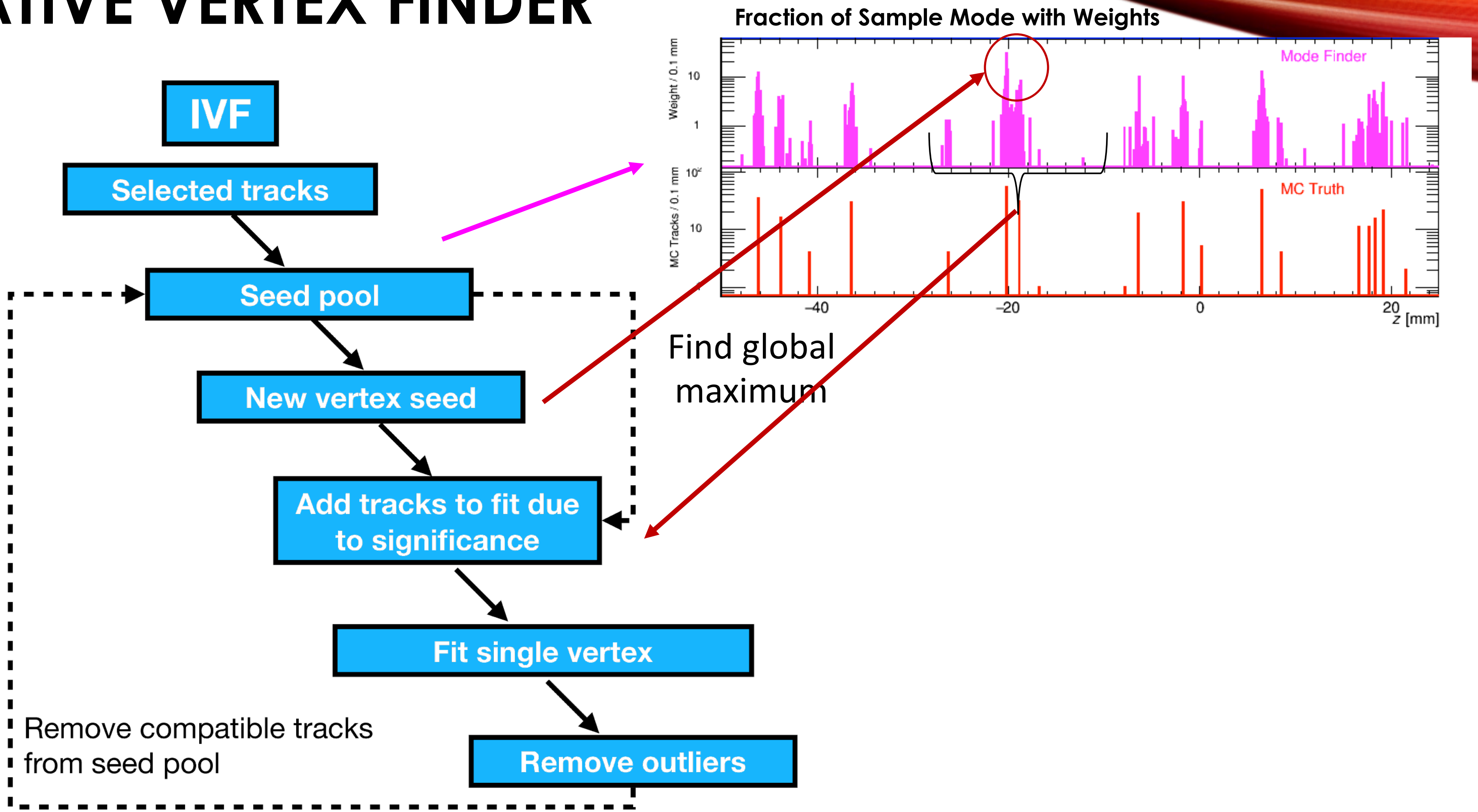
ATLAS IN RUN1/2: ITERATIVE VERTEX FINDER



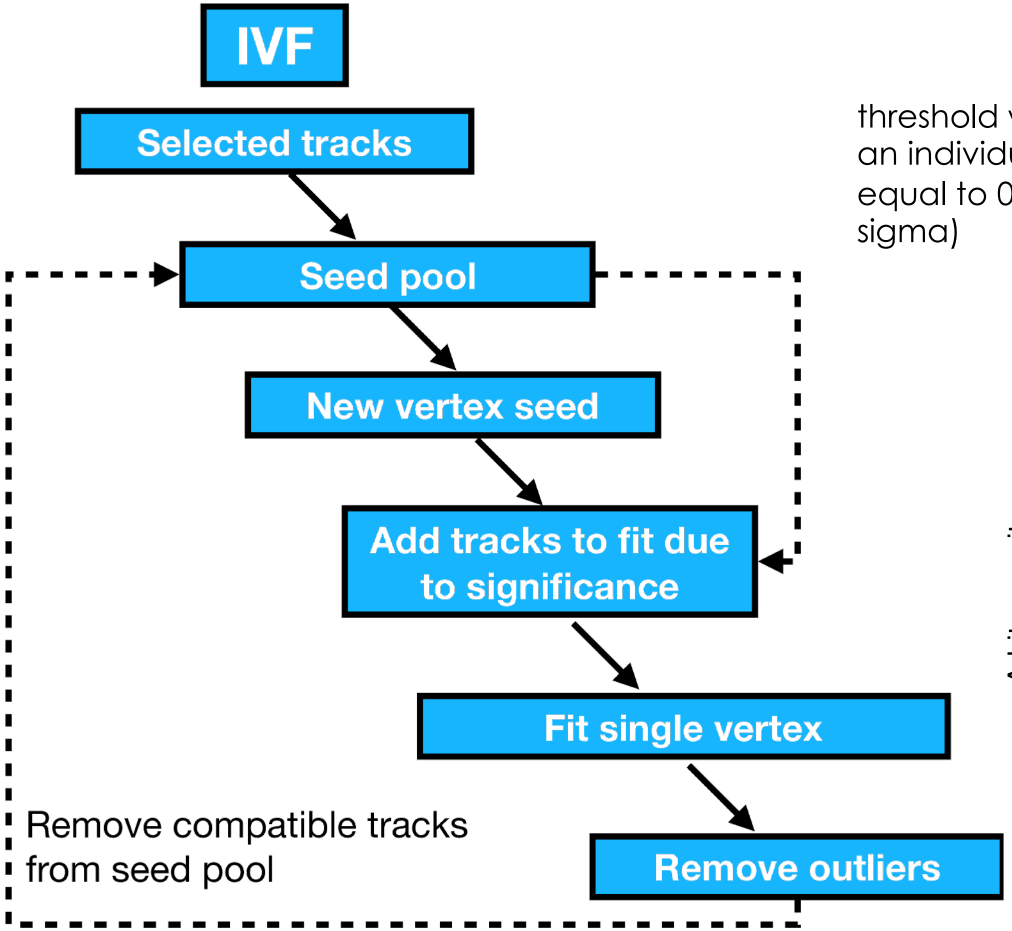


Find global maximum

ATLAS IN RUN1/2: ITERATIVE VERTEX FINDER



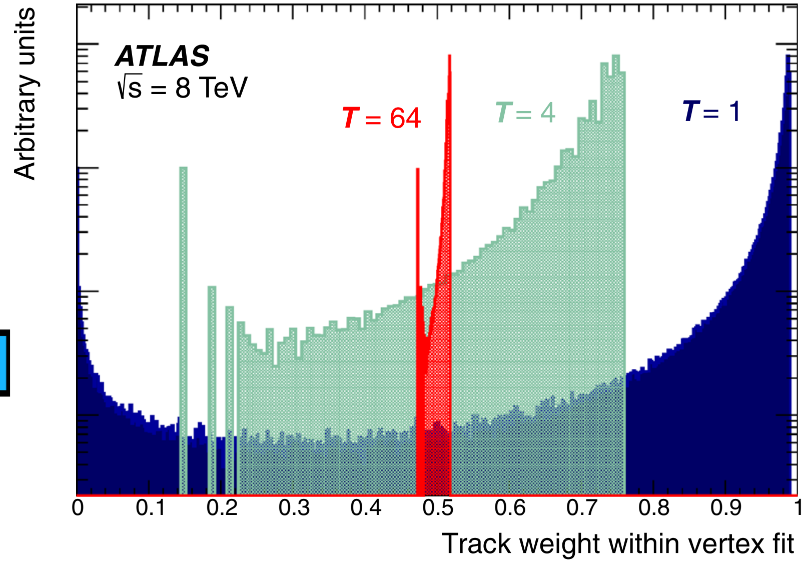
ATLAS IN RUN1/2: ITERATIVE VERTEX FINDER



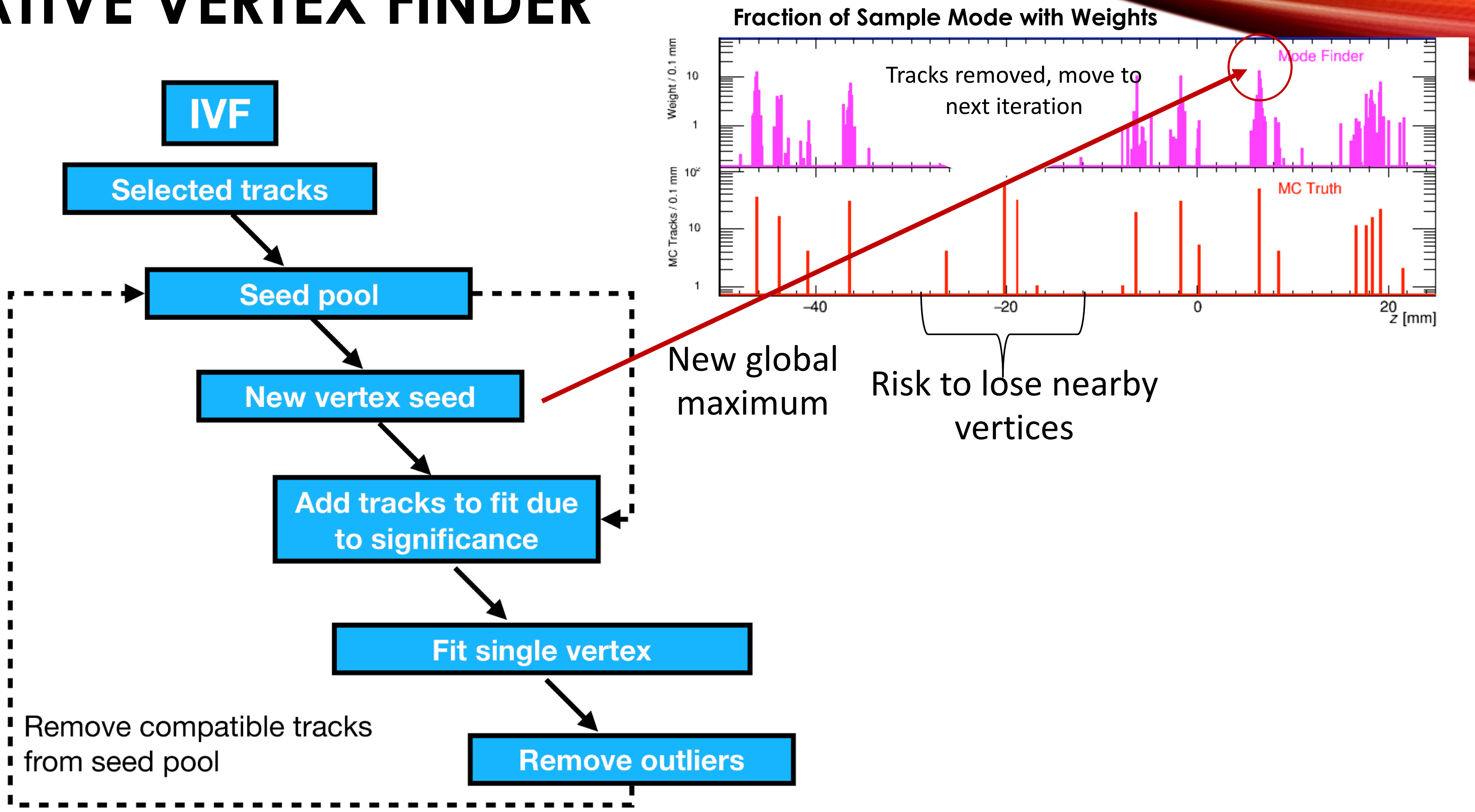
$$\omega(\chi^2, T) = \frac{1}{1 + e^{-\frac{1}{2}(\chi^2_{\text{cut}} - \chi^2)/T}}$$

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 $T = 1$.

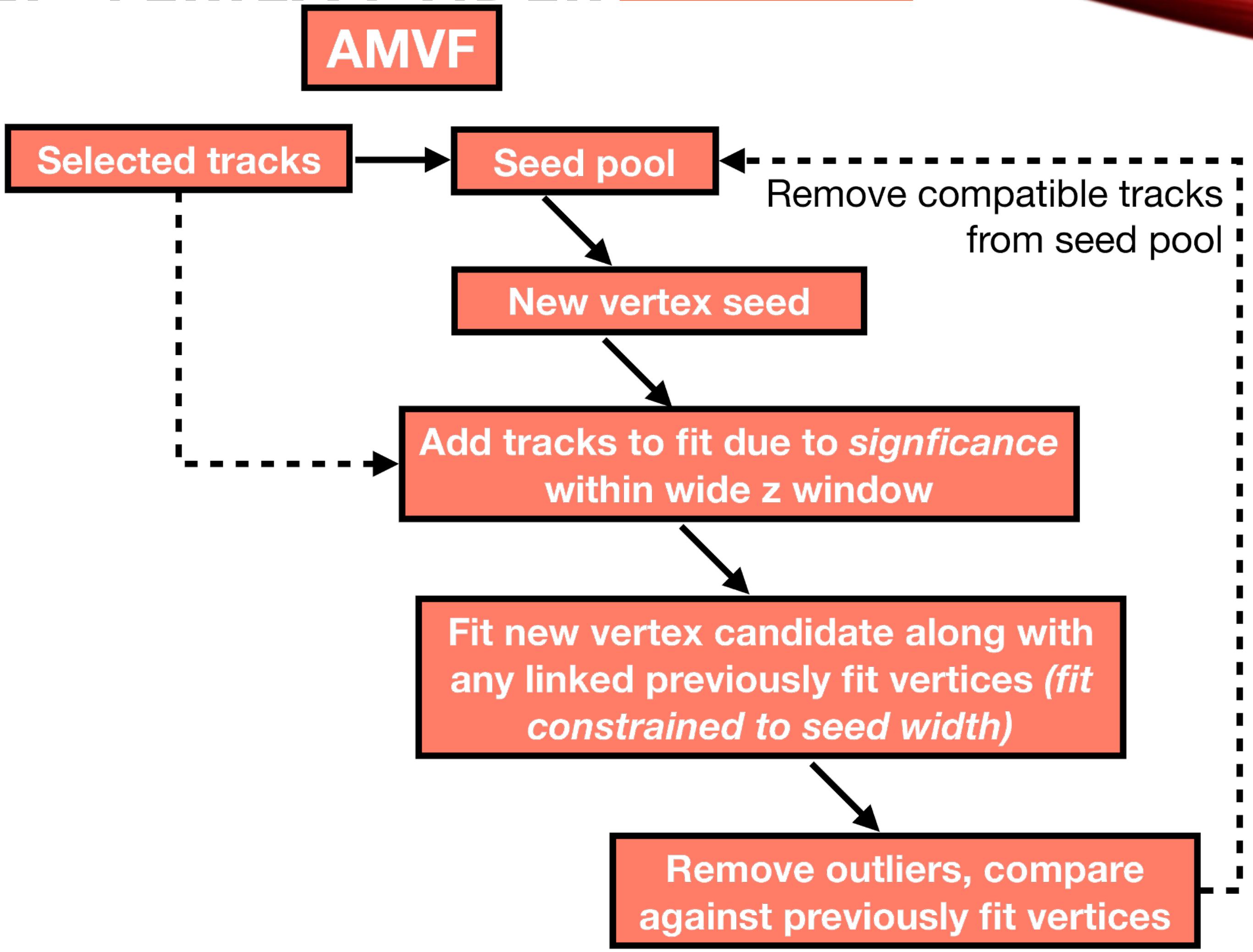


ATLAS IN RUN1/2: ITERATIVE VERTEX FINDER



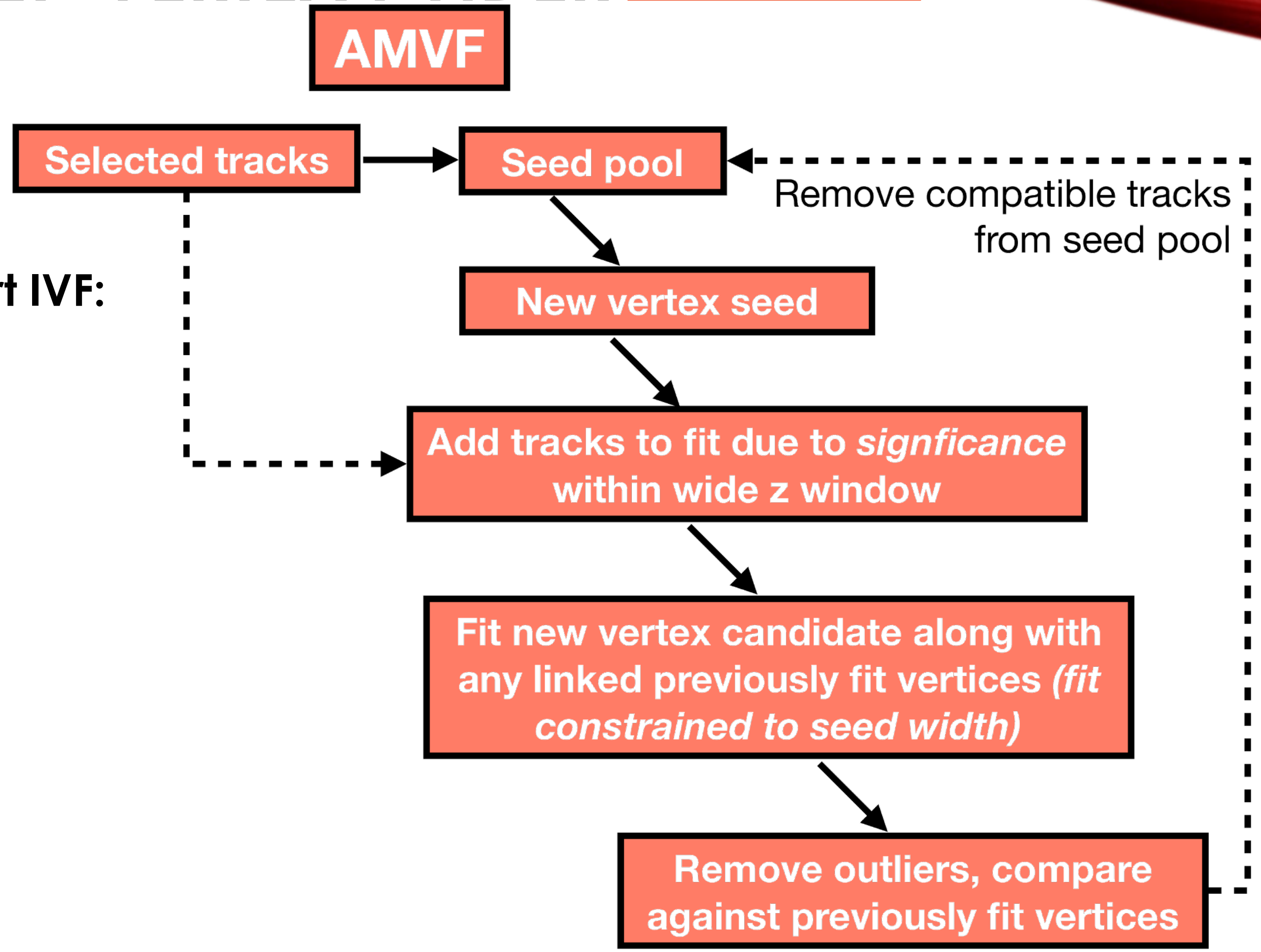
ATLAS IN RUN3: ADAPTIVE MULTI VERTEX FINDER

ATL-PHYS-PUB-2019-015



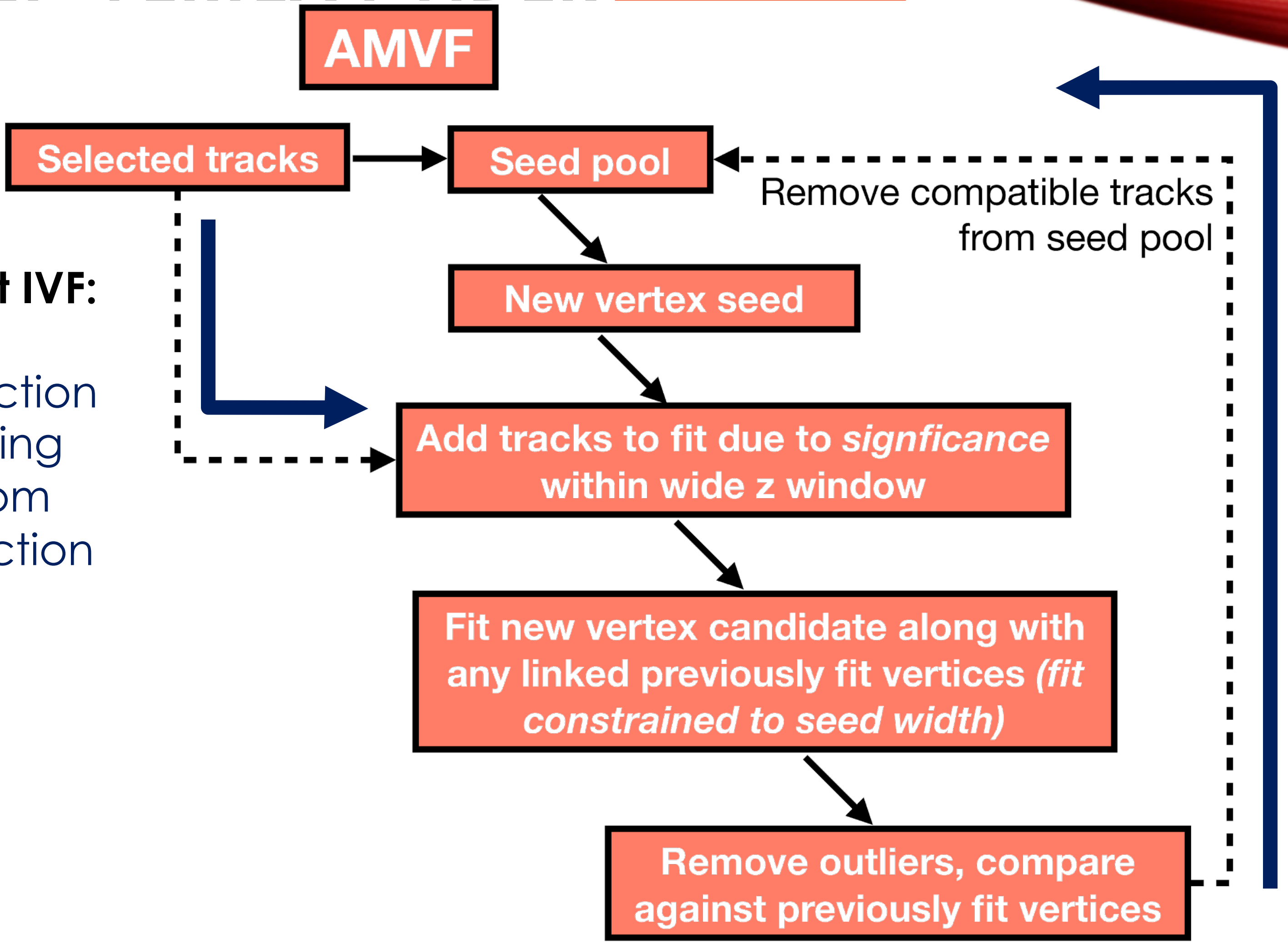
ATLAS IN RUN3:
ADAPTIVE MULTI VERTEX FINDER [ATL-PHYS-PUB-2019-015]

Differences wrt IVF:



ATLAS IN RUN3: ADAPTIVE MULTI VERTEX FINDER

ATL-PHYS-PUB-2019-015



Differences wrt IVF:

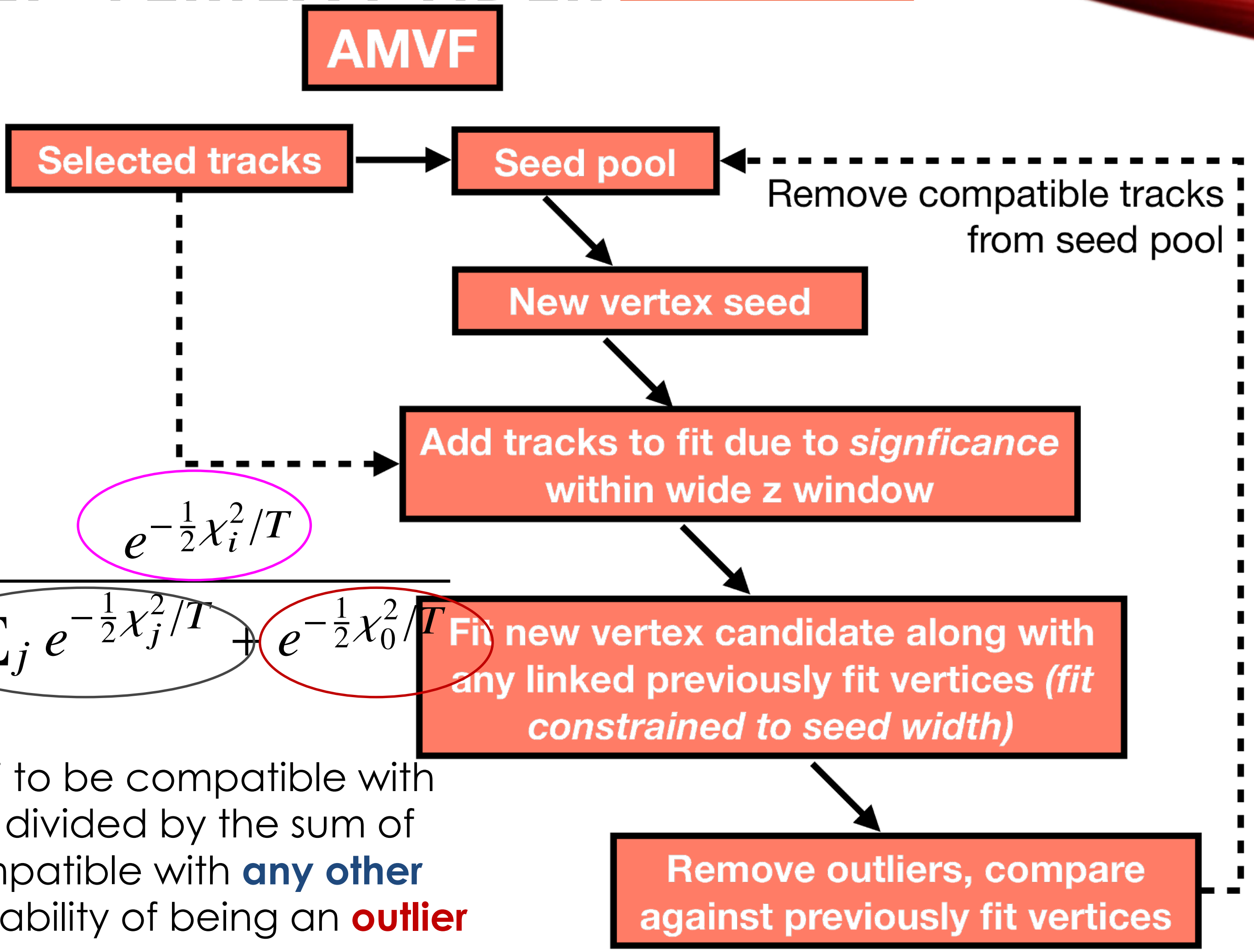
1. Track collection used for fitting different from track collection used in the seeding

ATLAS IN RUN3: ADAPTIVE MULTI VERTEX FINDER

ATL-PHYS-PUB-2019-015

Differences wrt IVF:

2. Tracks compete for vertices

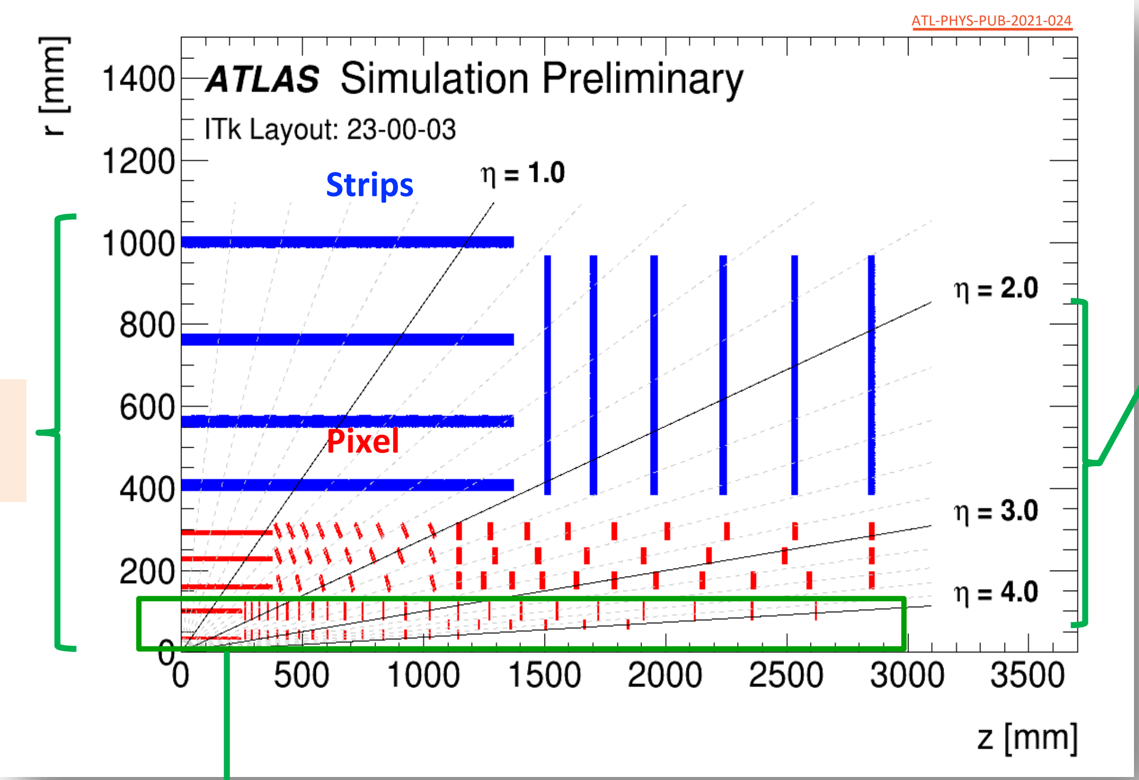


$$\omega_i(\chi_i^2, T) = \frac{e^{-\frac{1}{2}\chi_i^2/T}}{\sum_j e^{-\frac{1}{2}\chi_j^2/T} + e^{-\frac{1}{2}\chi_0^2/T}}$$

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

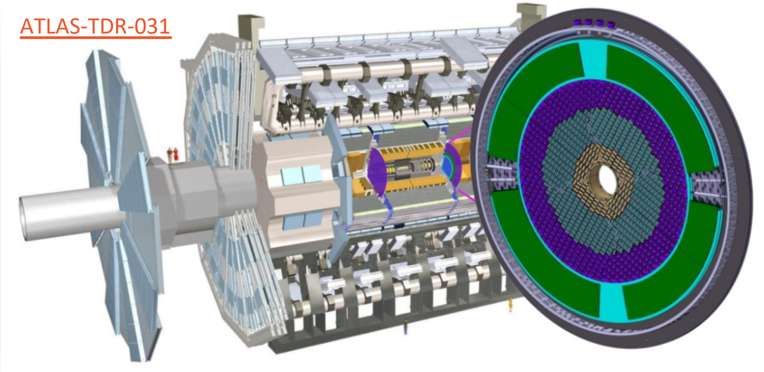
ITk



All Si

Increased η coverage (from 2.4 to 4.0)

HGTD



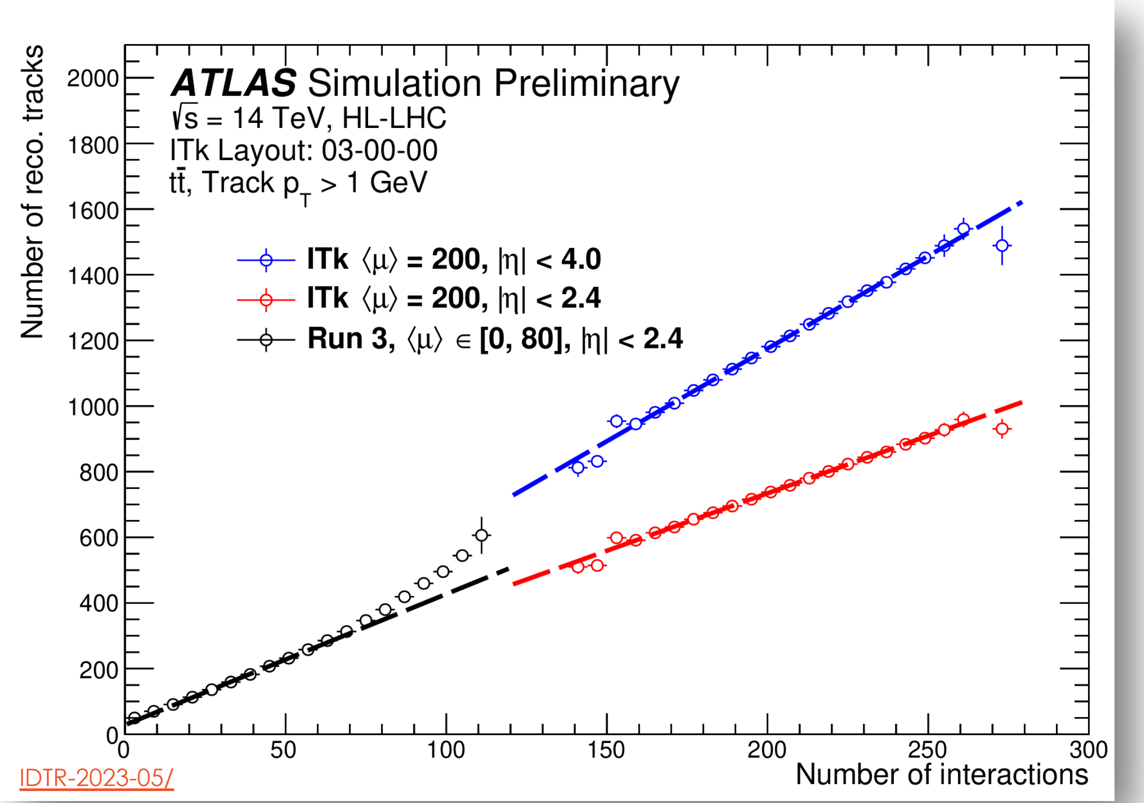
Extractable & Replaceable
(Radiation hardness up to ~10-15 MGy)

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

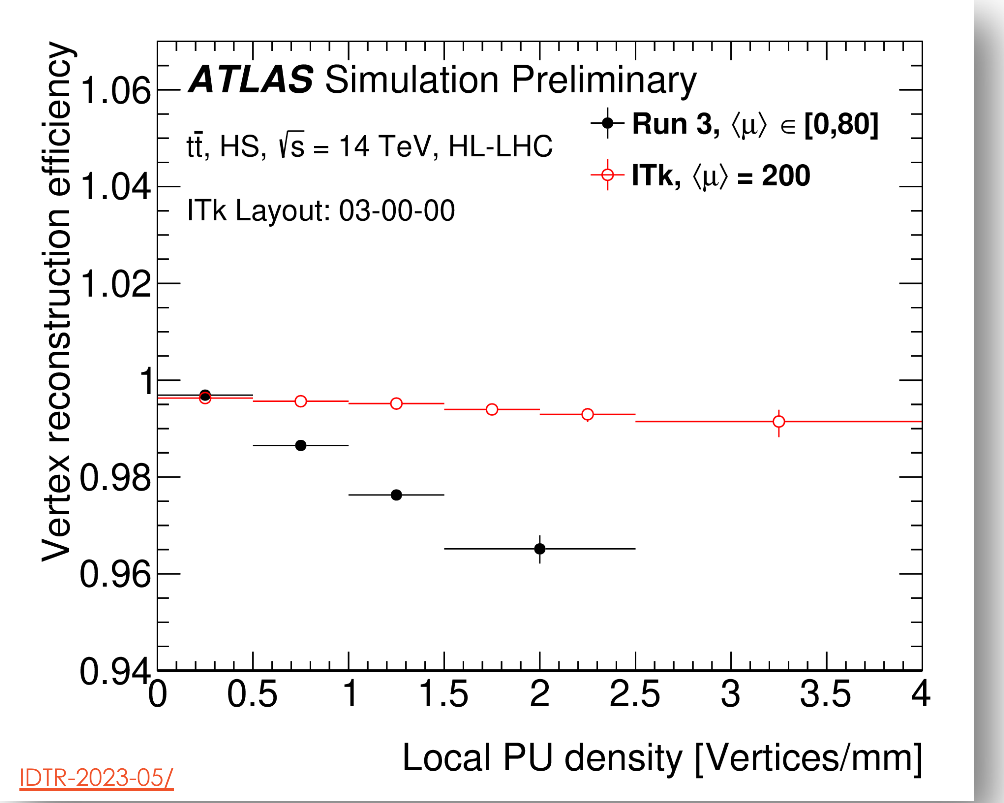
Average time resolution per hit (start and end of operational lifetime) $2.4 < \|\eta\| < 4.0$	≈ 35 ps (start), ≈ 70 ps (end)
Average time resolution per track (start and end of operational lifetime)	≈ 30 ps (start), ≈ 50 ps (end)

HL-LHC TRACKING

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



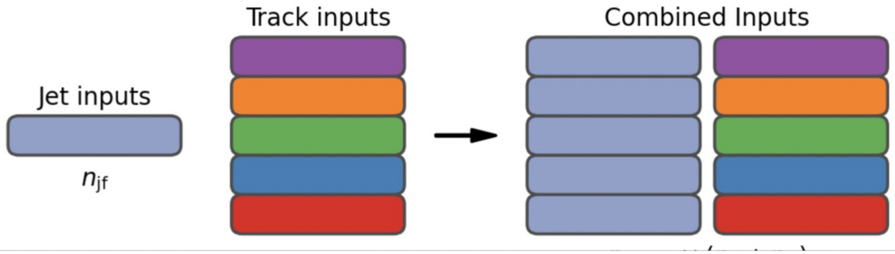
The lower the fake rate, the better the CPU and storage usage

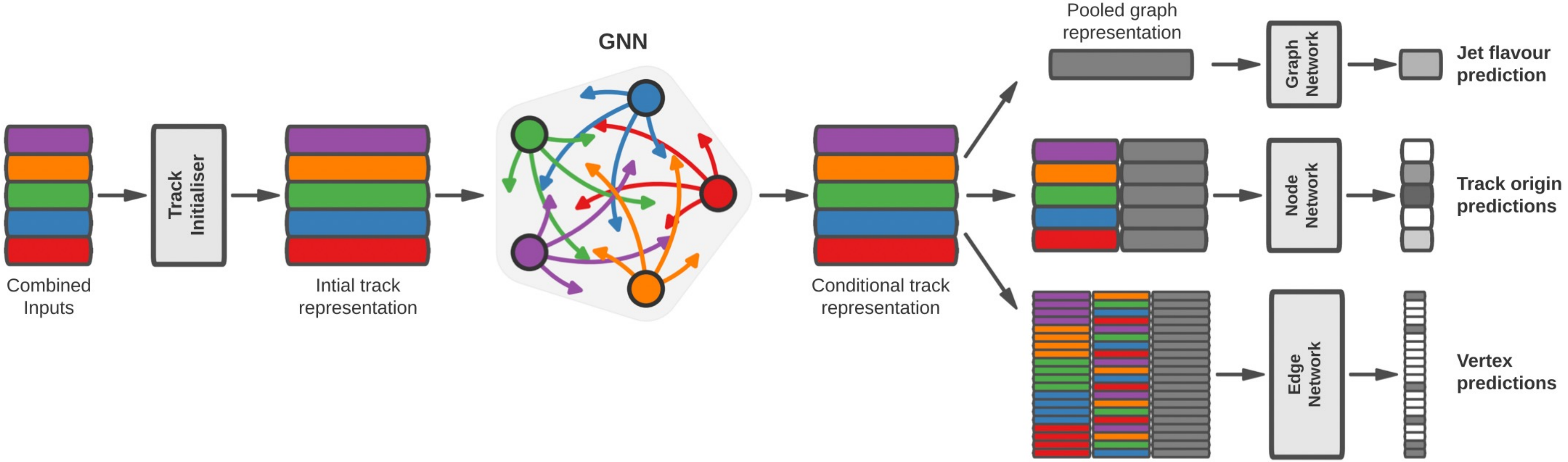


More PU-robust vertexing

GNN

ATL-PHYS-PUB-2022-027.pdf



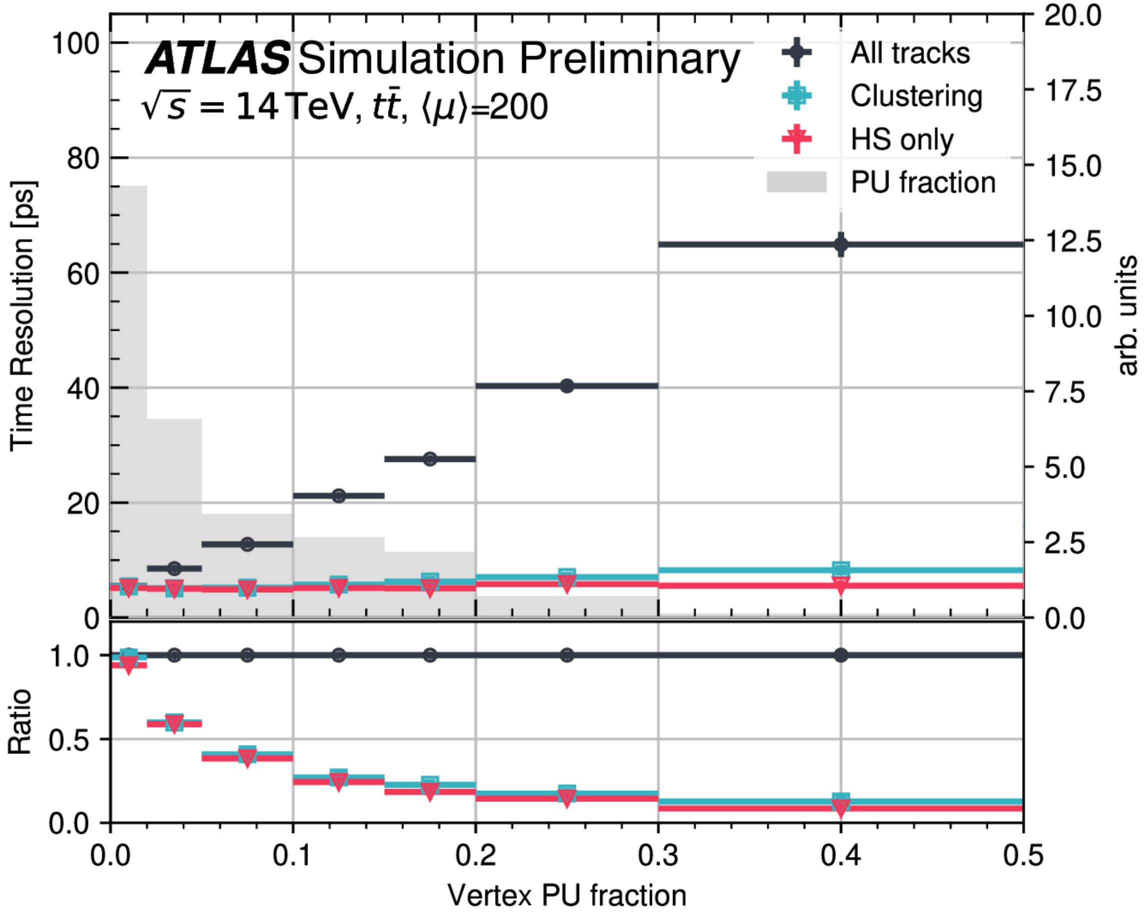


GNN

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

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

4D TRACKING



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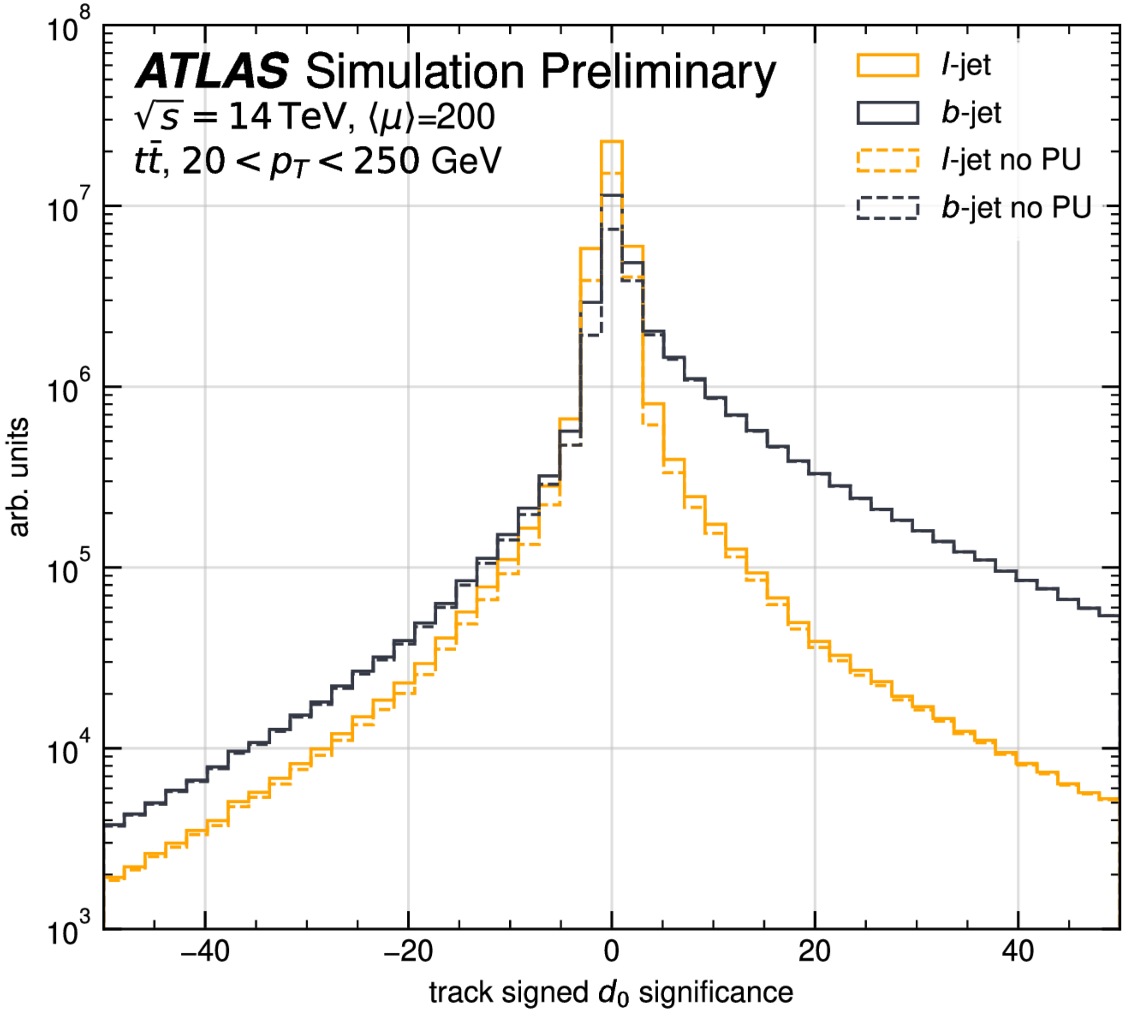
4D TRACKING



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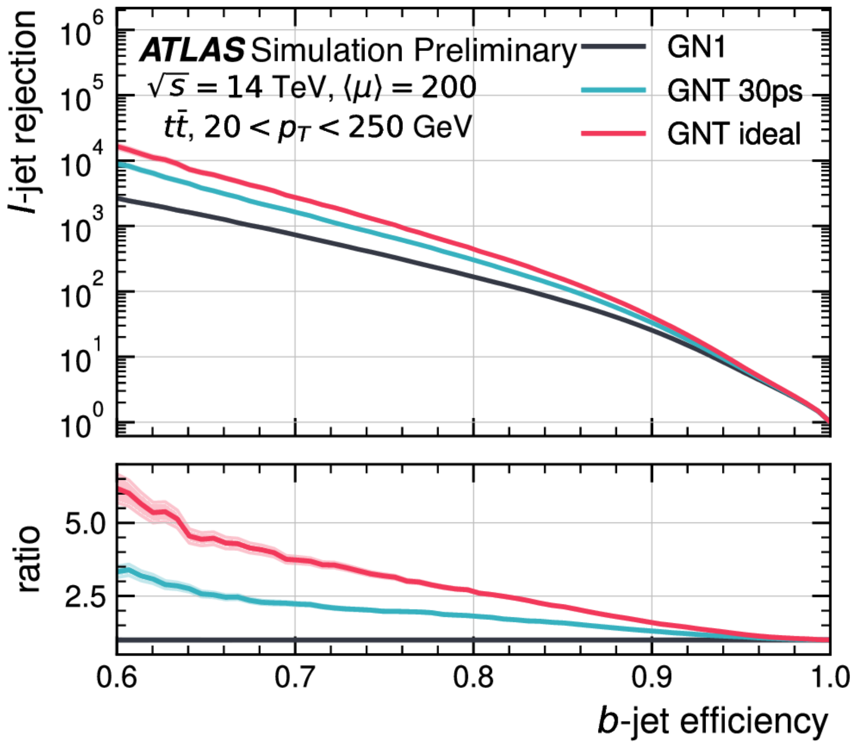
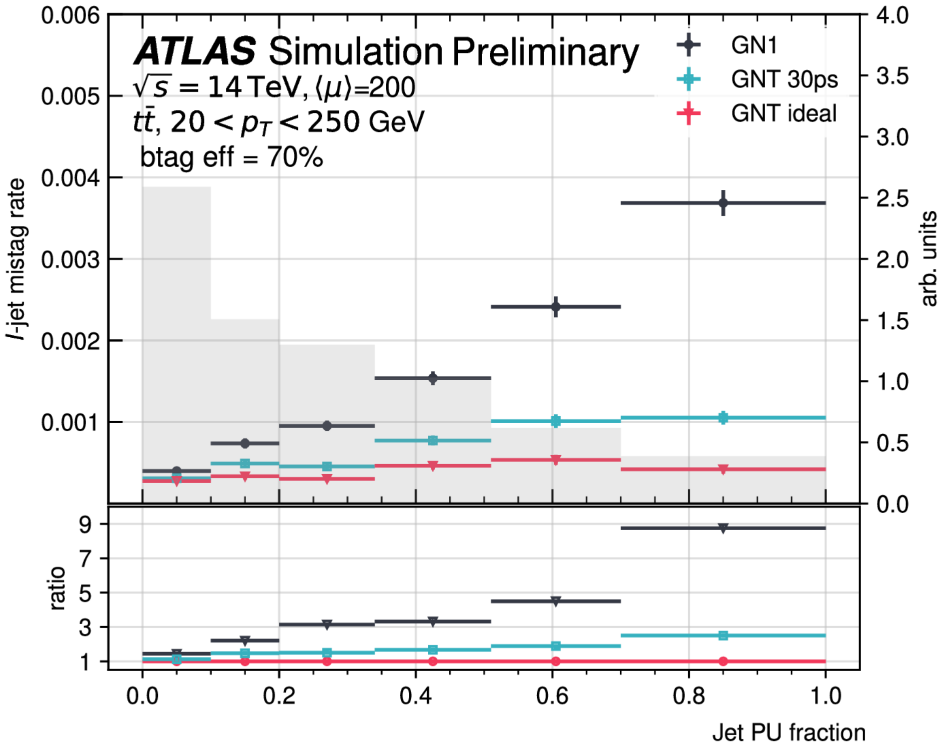
4D FTAG





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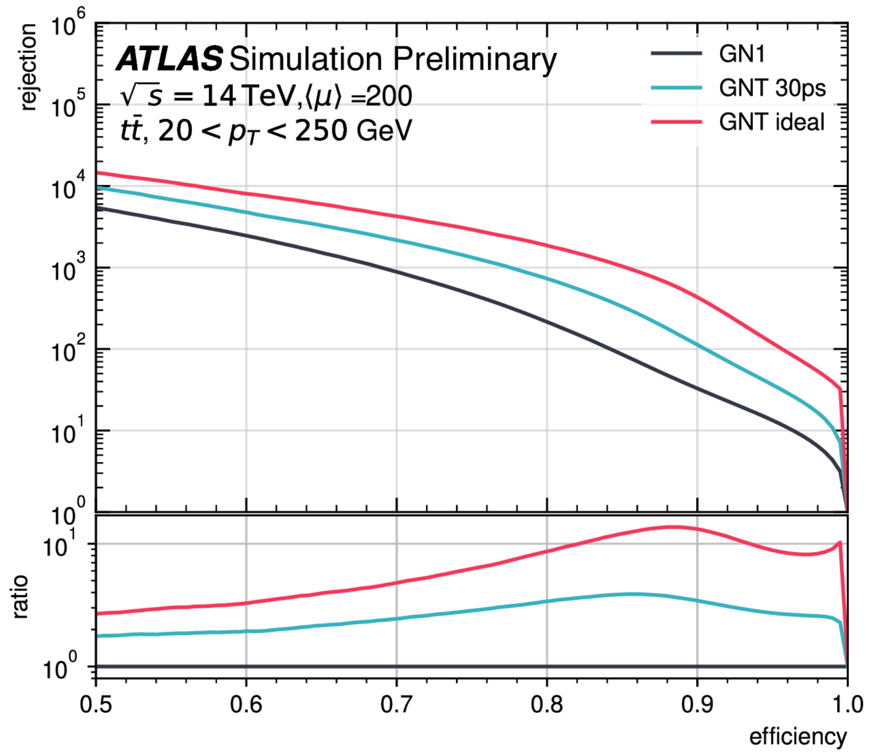
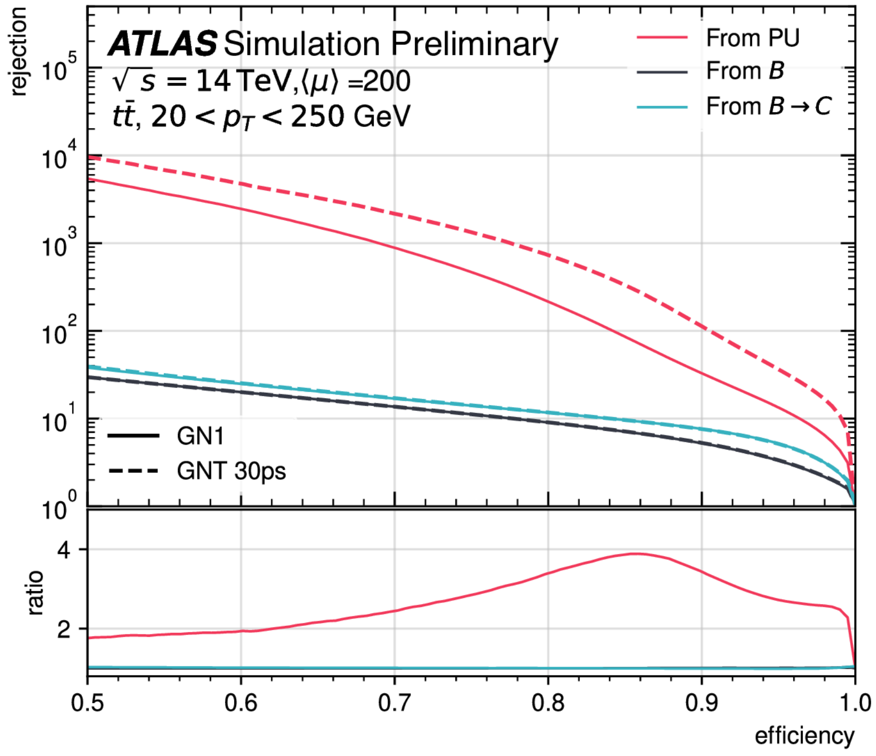
4D FTAG



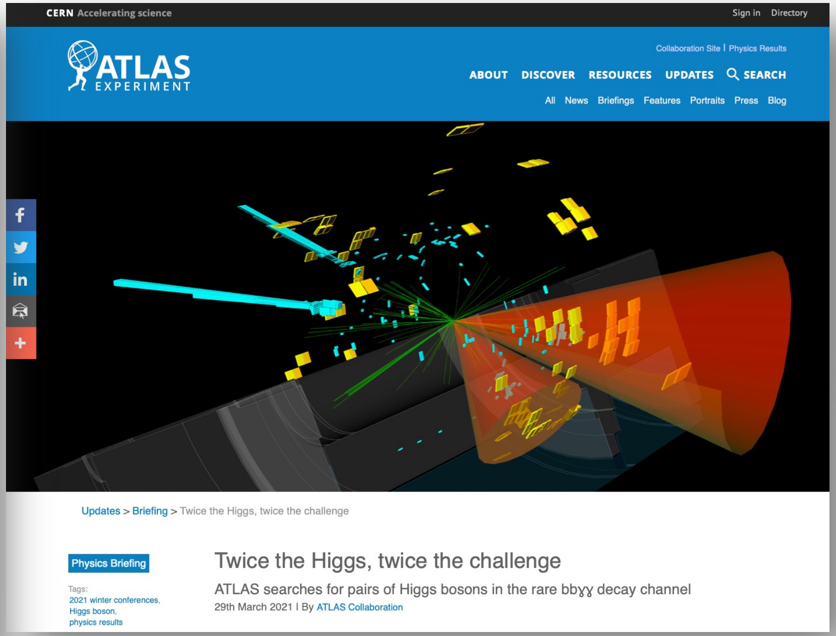


ATL-PHYS-PUB-2023-023

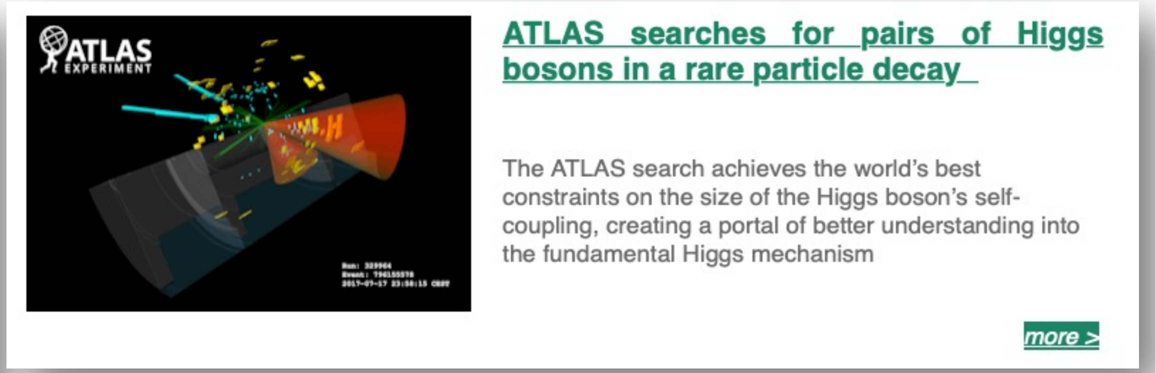
A VERY POPULAR RESEARCH TOPIC

Video

Twice-higgs-twice-challenge



CERN Bulletin (April 2021)



A VERY POPULAR RESEARCH TOPIC

Video

Twice-higgs-twice-challenge

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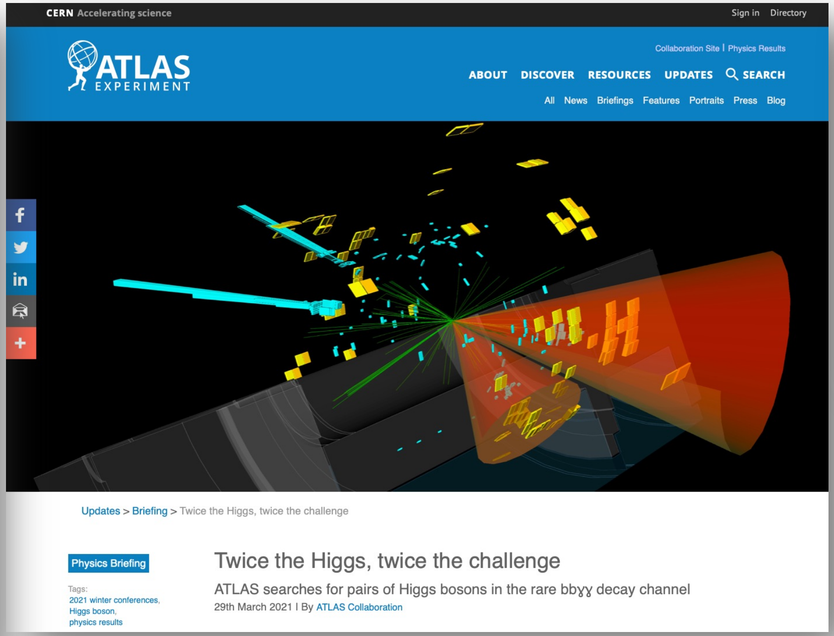
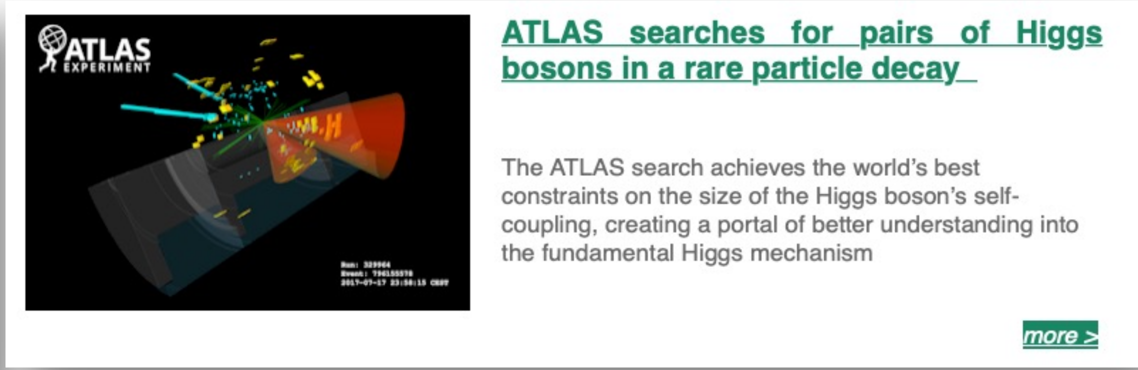
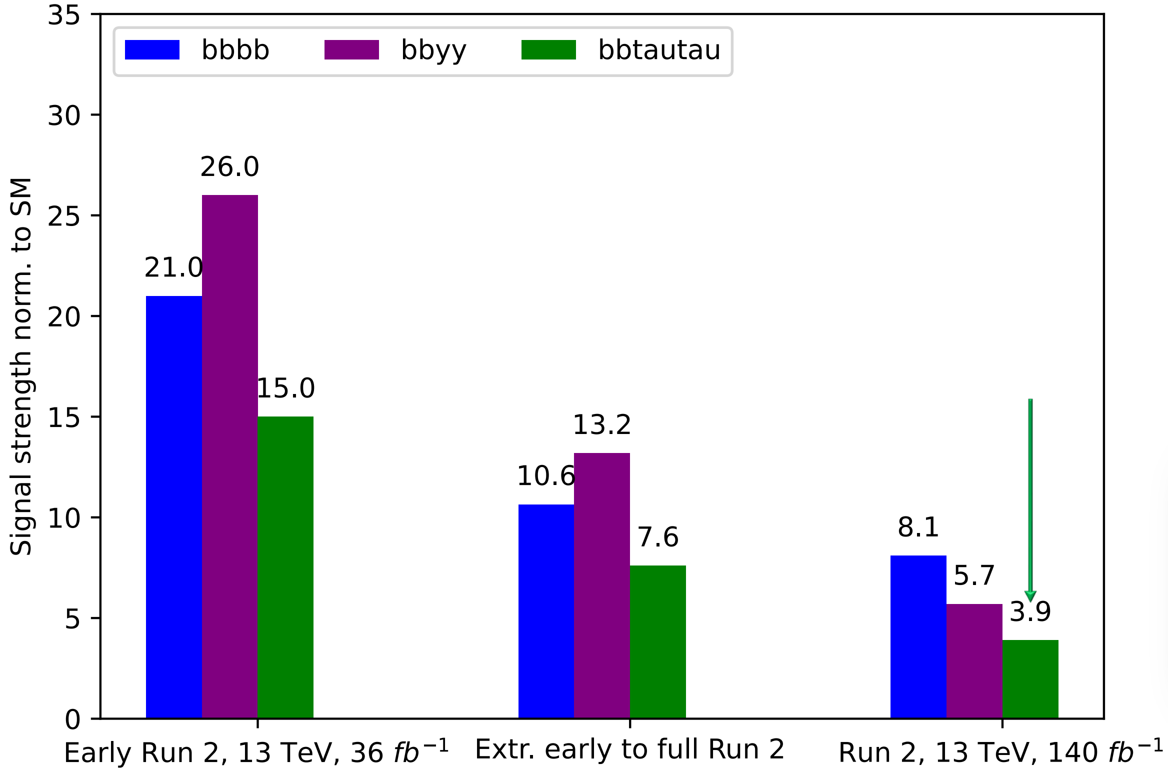




Why so exciting?

ANOTHER EXAMPLE



Phys. Lett. B 800 (2020) 135103

Phys. Lett. B 843 (2023) 137745

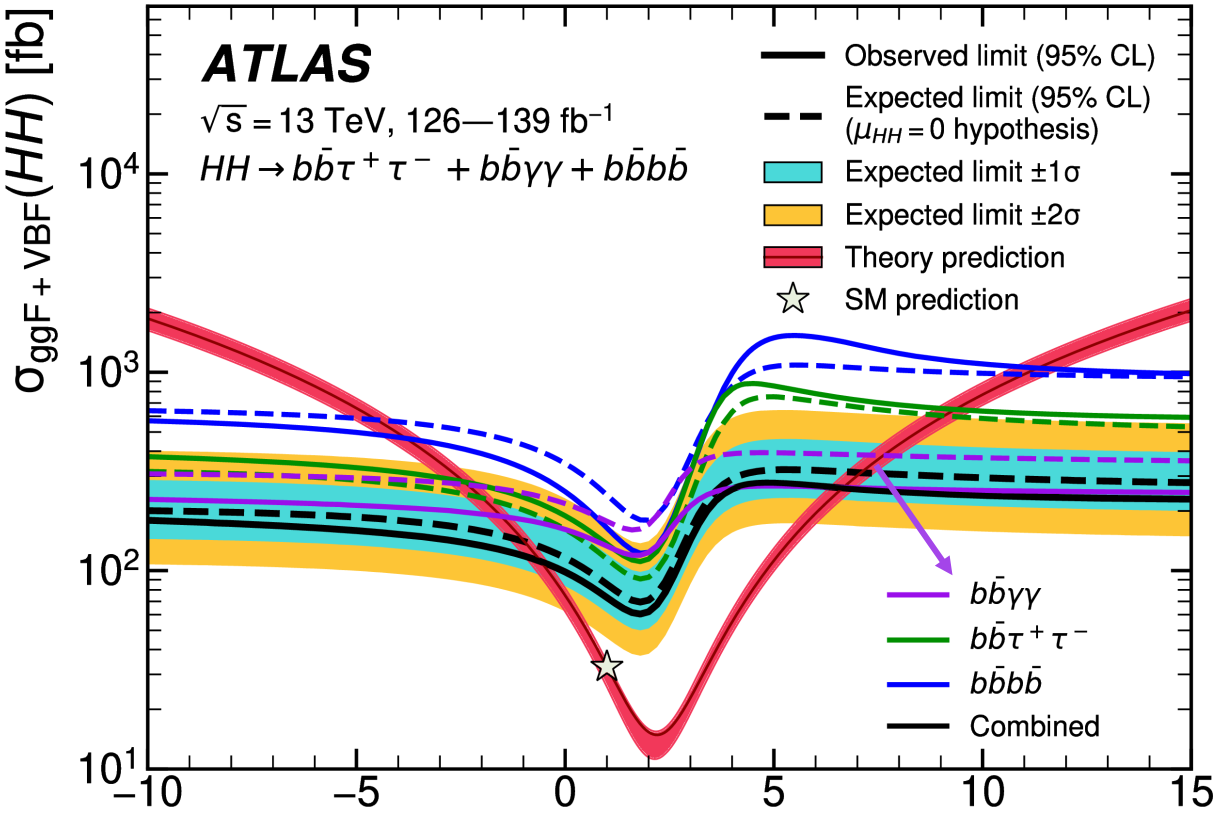
From 2015 **HL-LHC** study of $HH \rightarrow bb\tau\tau$

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

$HH \rightarrow b\bar{b}\tau\tau + b\bar{b}\gamma\gamma + b\bar{b}\, b\bar{b}$



Phys. Lett. B 843 (2023) 137745

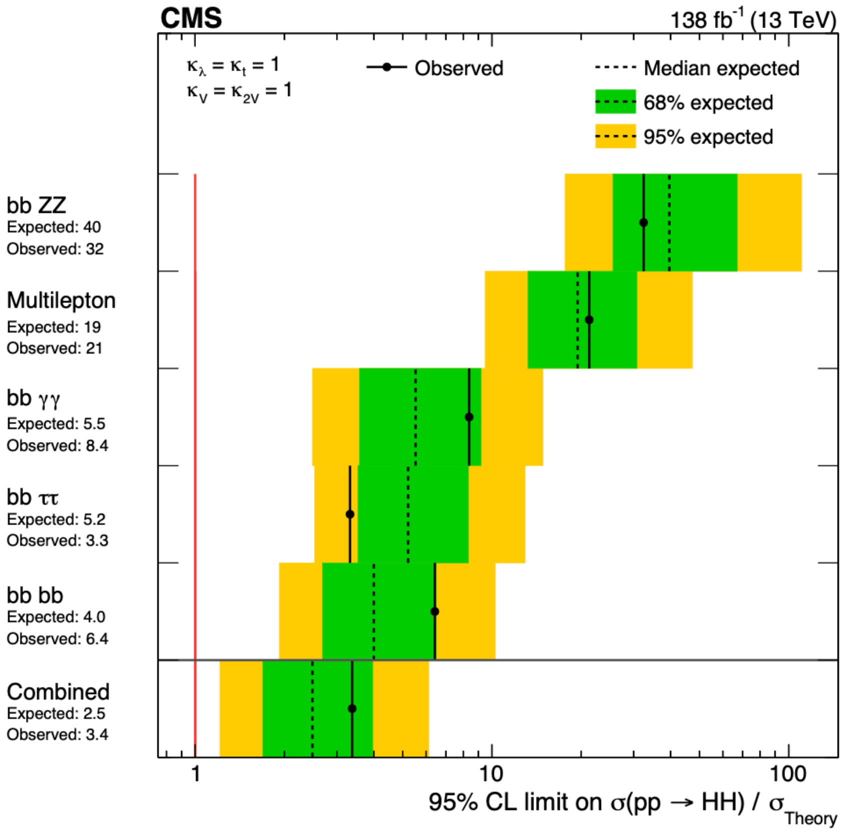
World's best constraints to date on Higgs boson's self coupling from HH searches

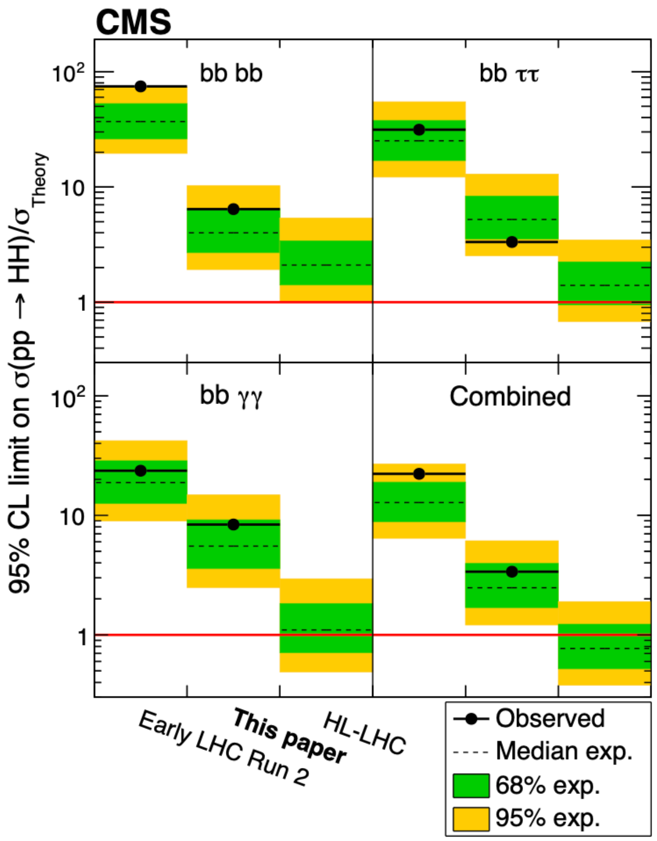
Observed(expected): -0.6< k_λ<6.6 (-2.1< k_λ< 7.8)

$HH \rightarrow b\bar{b}\gamma\gamma$ drives the sensitivity at large k_λ!

PUTTING EVERYTHING TOGETHER

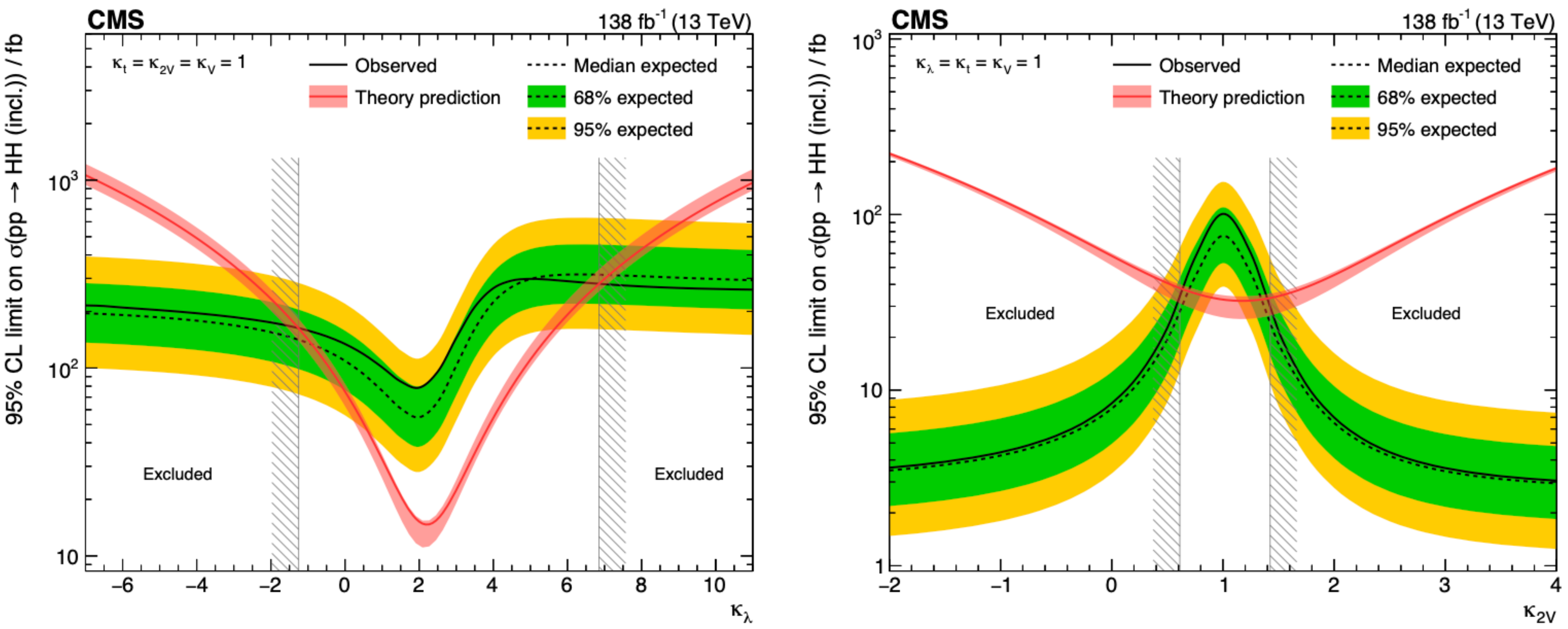
https://arxiv.org/pdf/2207.00043.pdf





PUTTING EVERYTHING TOGETHER

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



VBF HH PRODUCTION VS KL AND K2V

Reviews in Physics 5 (2020) 100045

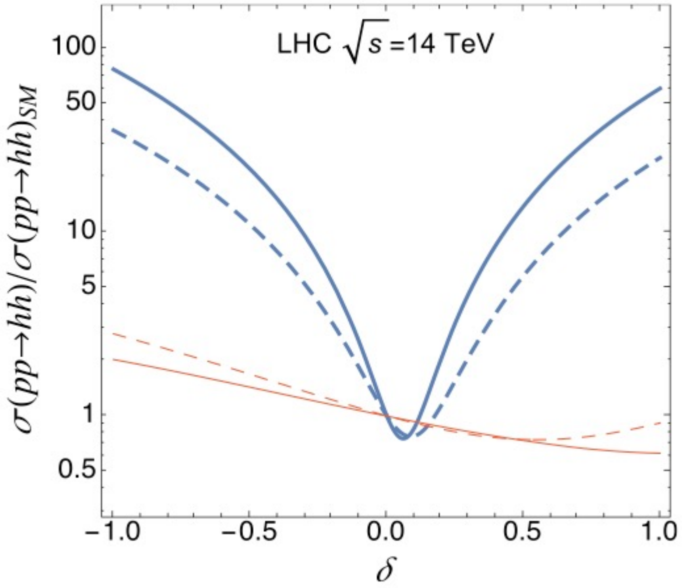
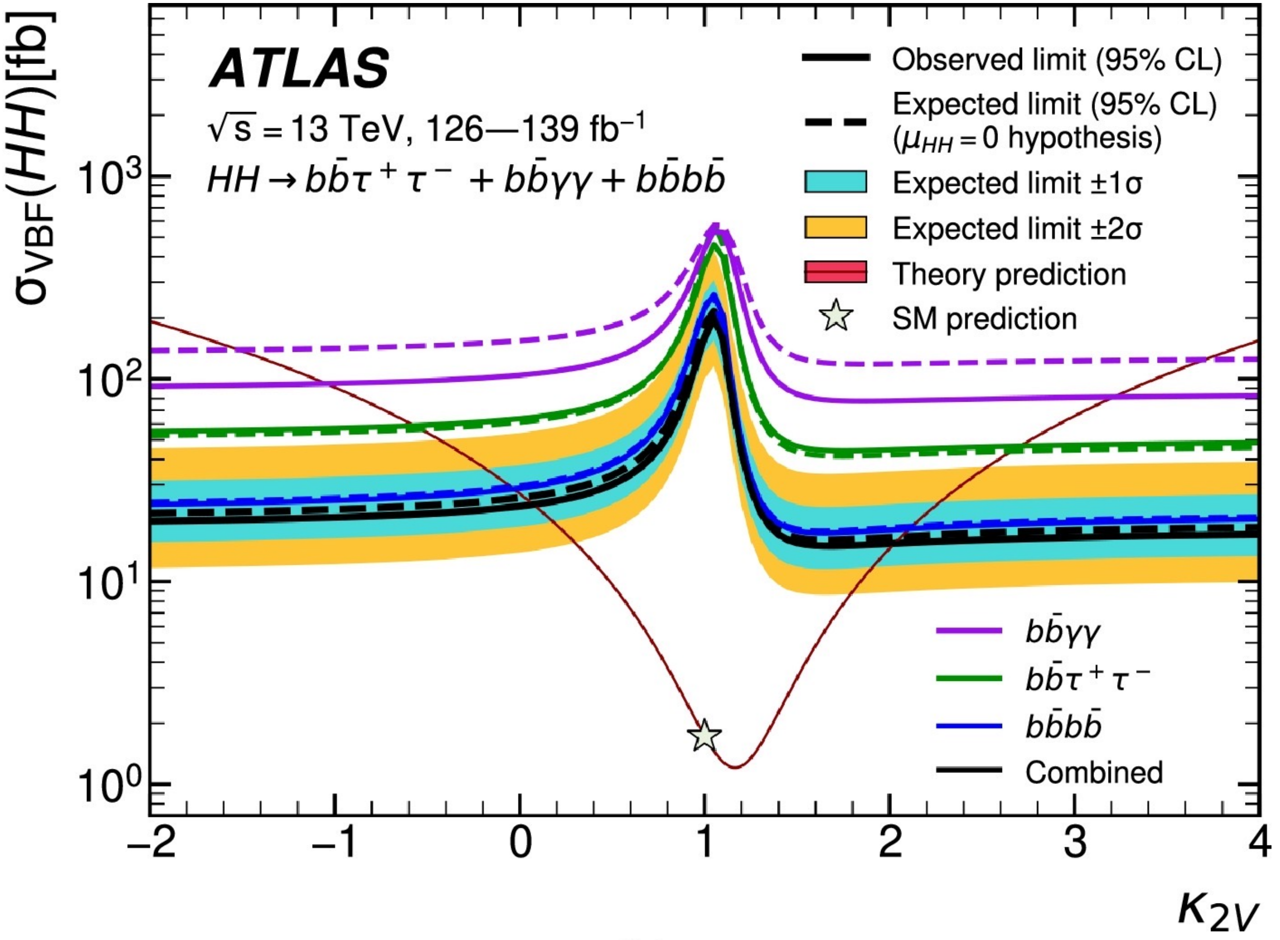


Fig. 82. VBF *HH* production cross section as a function of the coupling deviation from the SM value for the *HHVV* (*HHH*) vertex in blue (red). The solid line is after acceptance cuts, the dashed line is after analysis cuts applied on the rapidity difference and M_{jj} [455]. (For interpretation of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

K2V

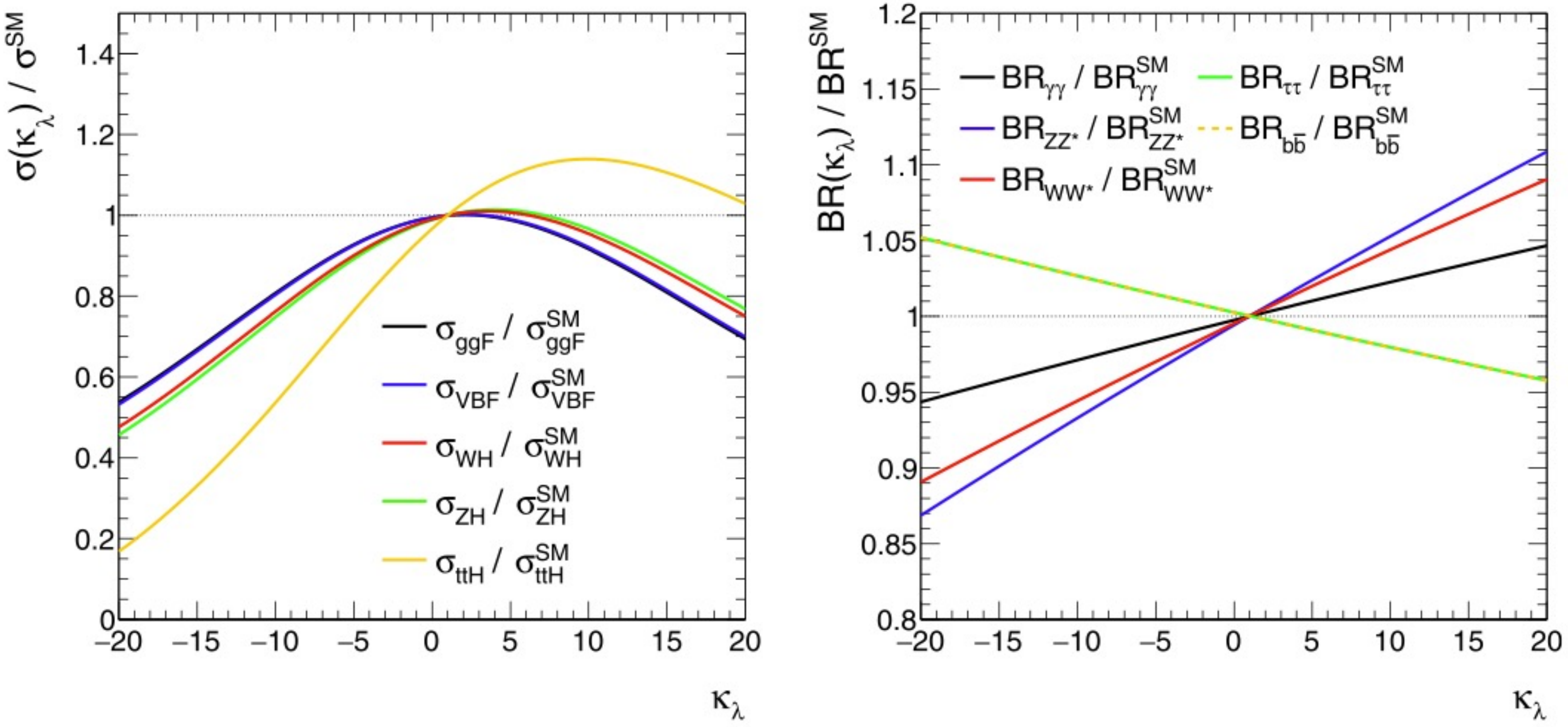
https://doi.org/10.1016/j.physletb.2023.137745



(b)

SINGLE HIGGS

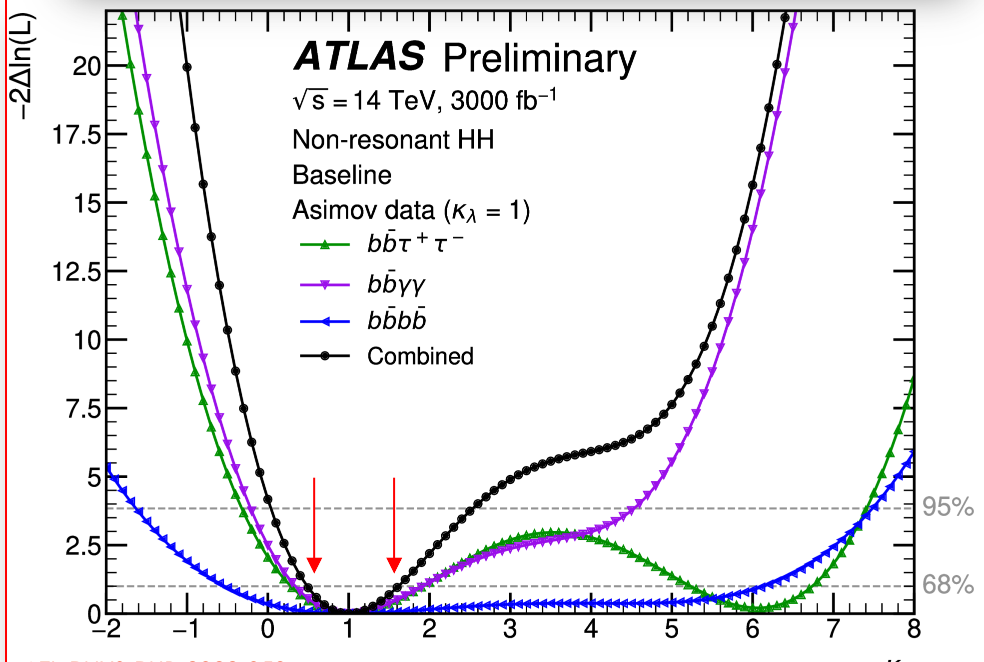
https://doi.org/10.1016/j.revip.2020.100045



HOW DOES HH LOOK IN HL-LHC?

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

was 3.3!



ATL-PHYS-PUB-2022-053

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

ATLAS alone comparable to previous expectation from ATLAS + CMS

FUTURE COLLIDERS

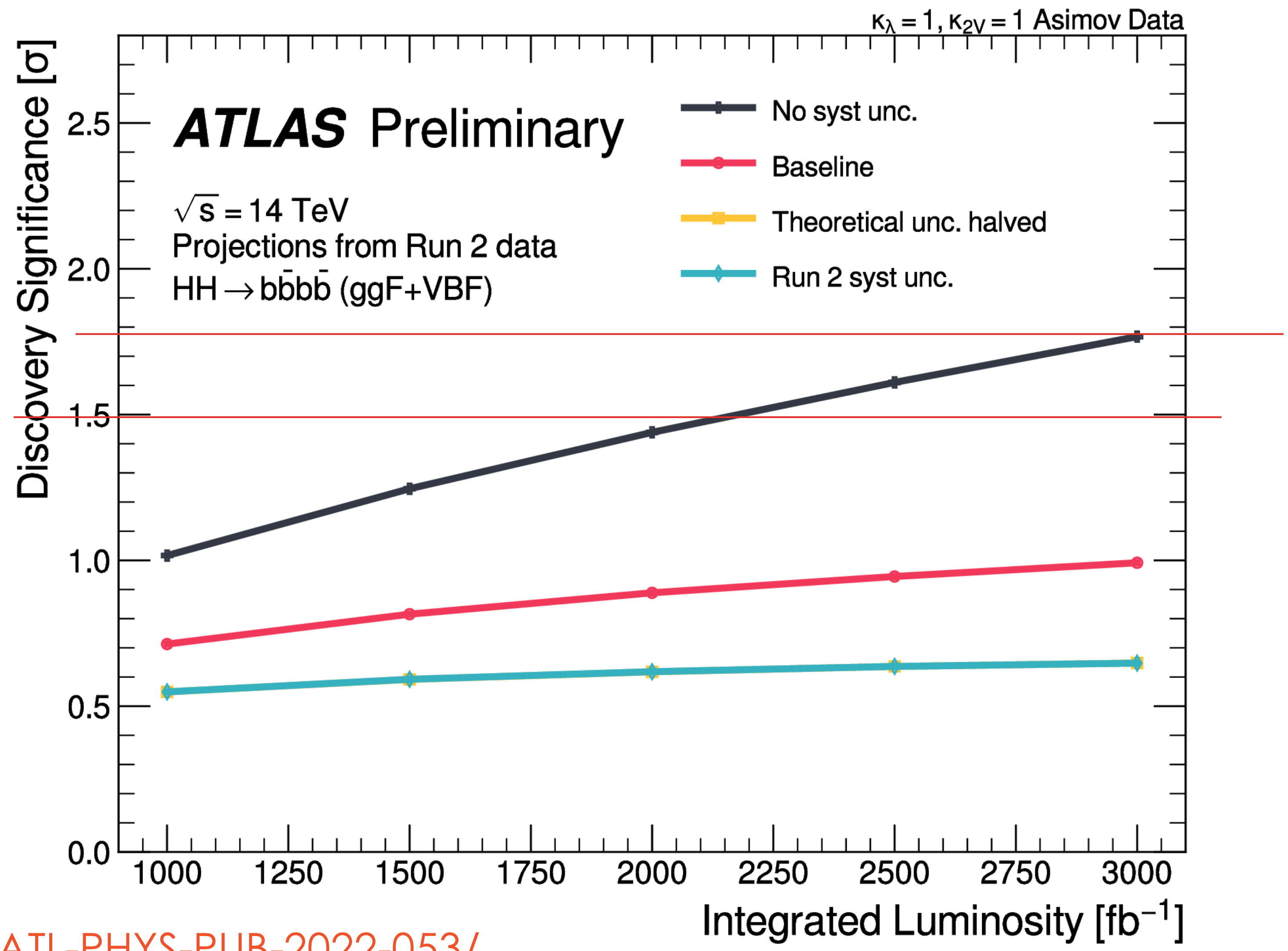
arXiv:1907.02078v2

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

	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	$\simeq 0$	$\simeq 0$

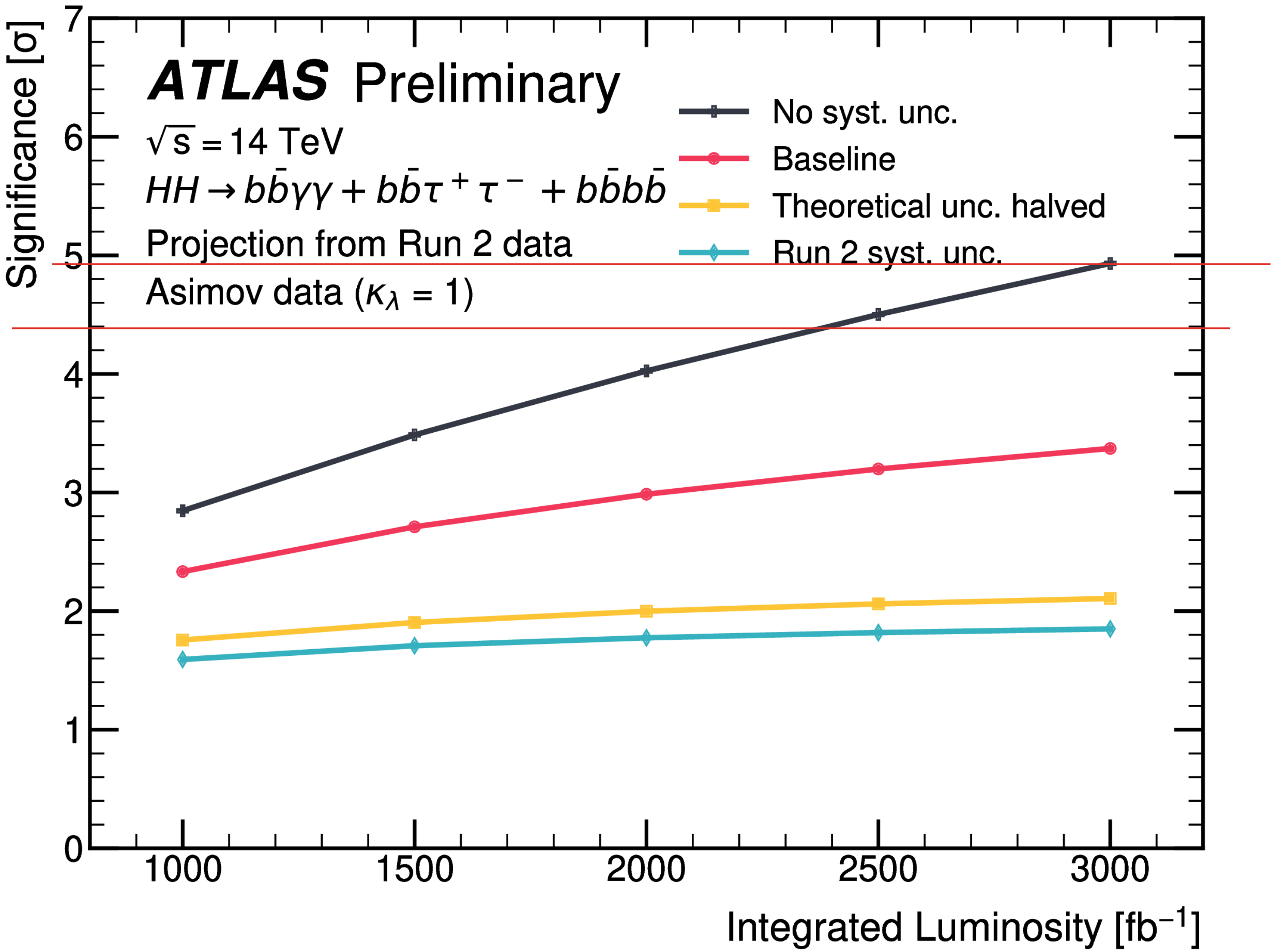
Table 1: Higgs couplings, defined in Eqs. (2.1) and (2.3), for the SM and various NP scenarios. For the Coleman-Weinberg (CW) Higgs scenario, we also present in the parenthesis the Higgs self-couplings up to the two-loop order, predicted in the two of the simplest conformal extensions of the scalar sector: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

HOW DOES HH LOOK IN HL-LHC?



ATL-PHYS-PUB-2022-053/

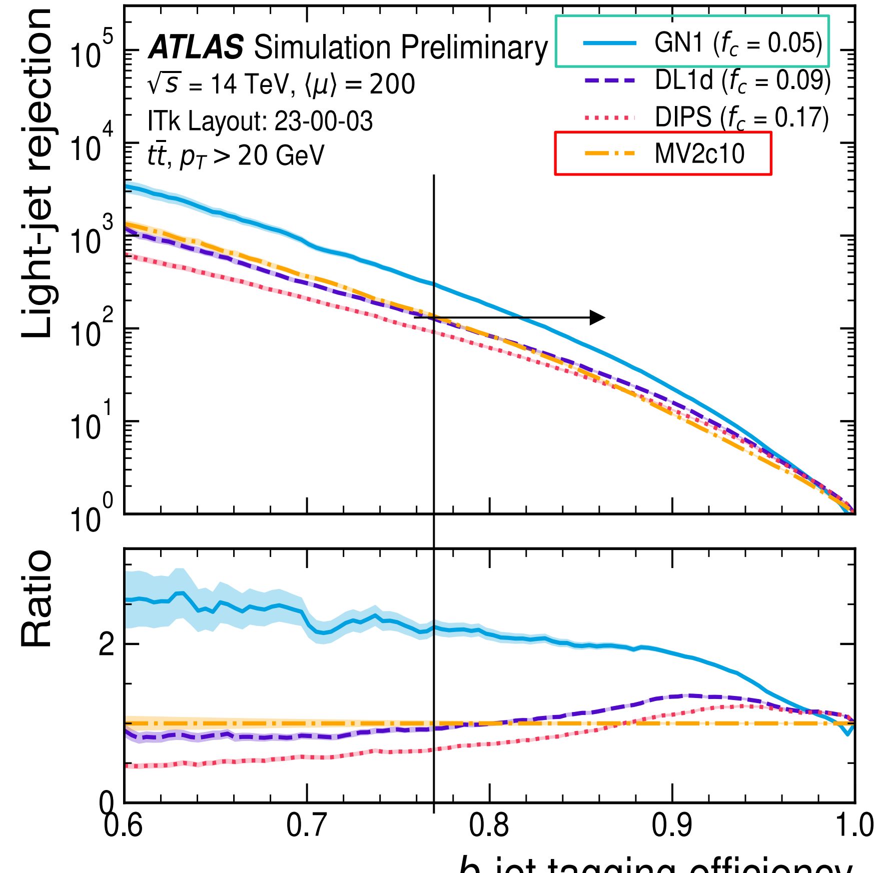
HOW DOES HH LOOK IN HL-LHC?



ATL-PHYS-PUB-2022-053/

HOW DOES HH LOOK IN HL-LHC?

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



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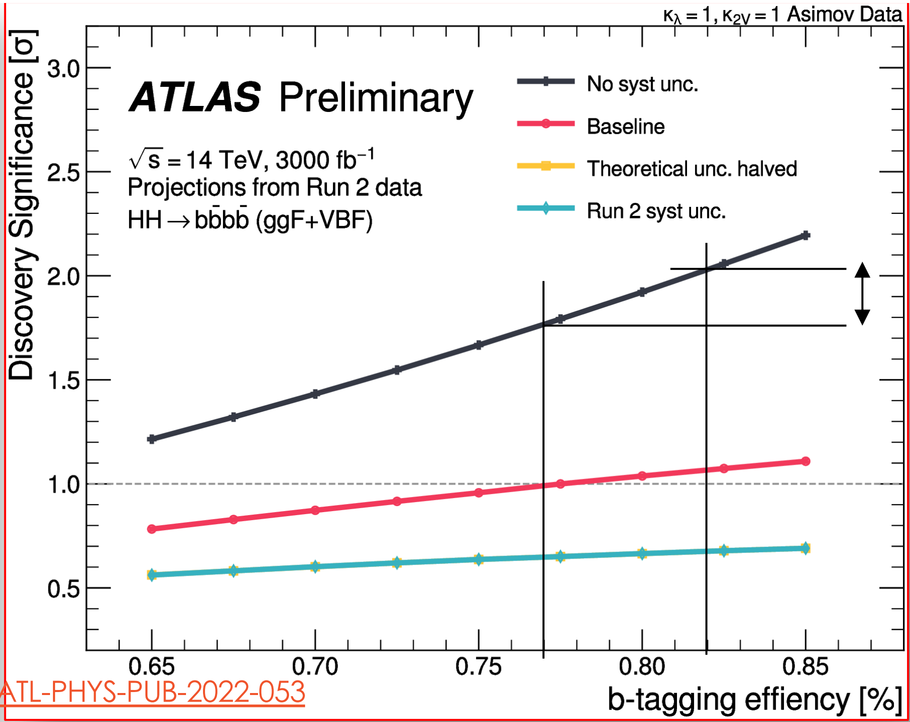
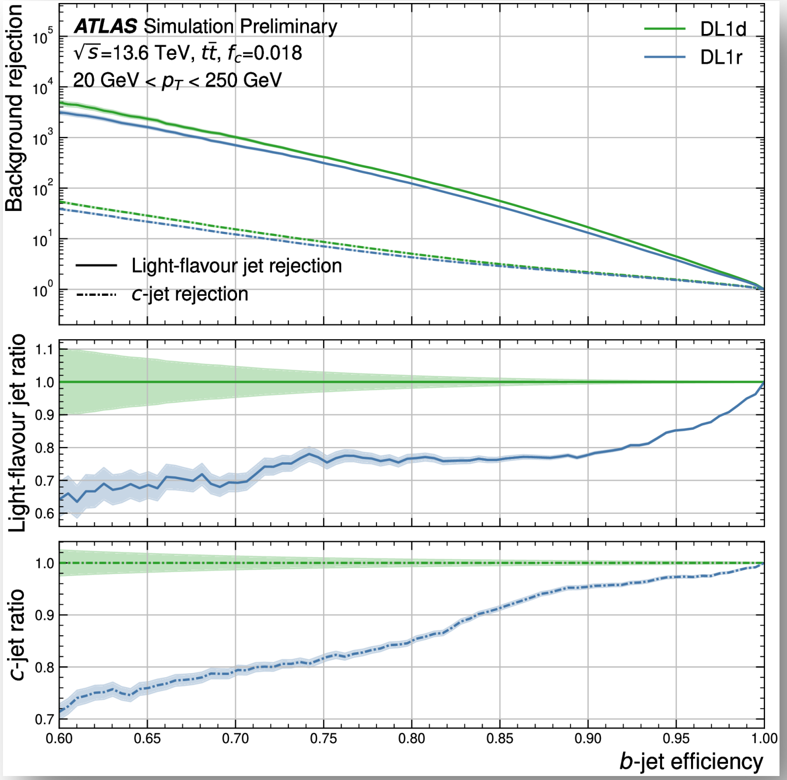


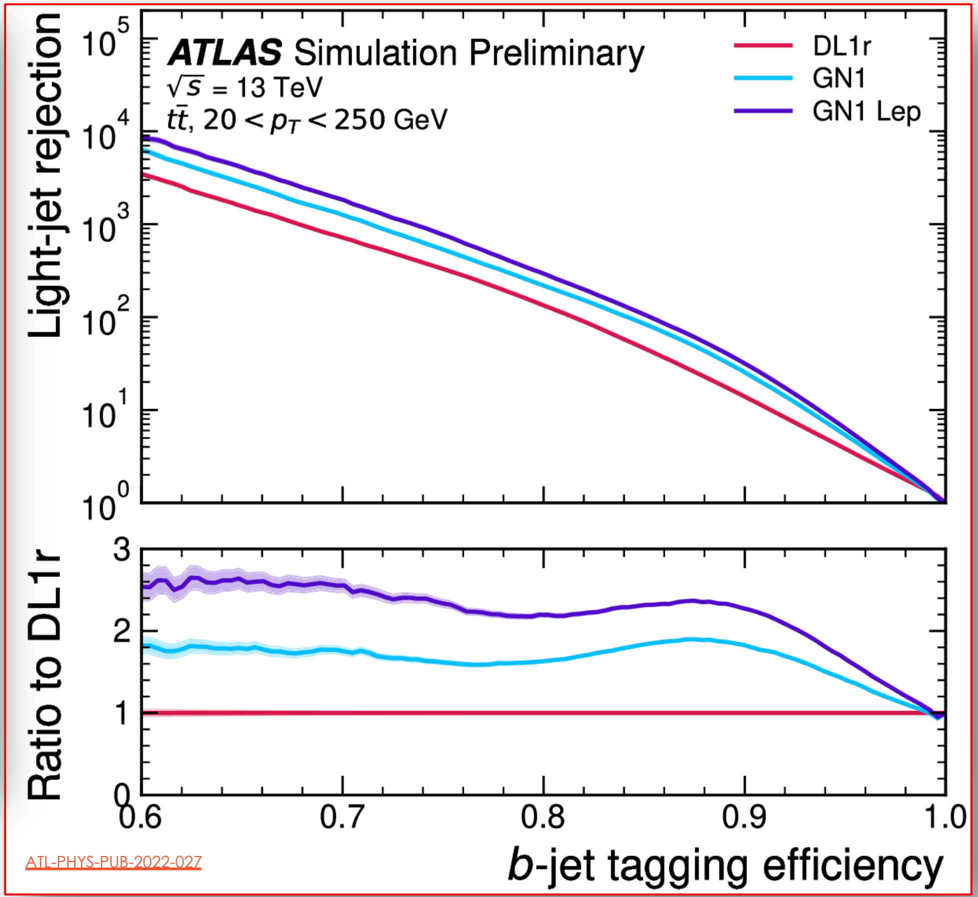
ATL-PHYS-PUB-2022-053

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

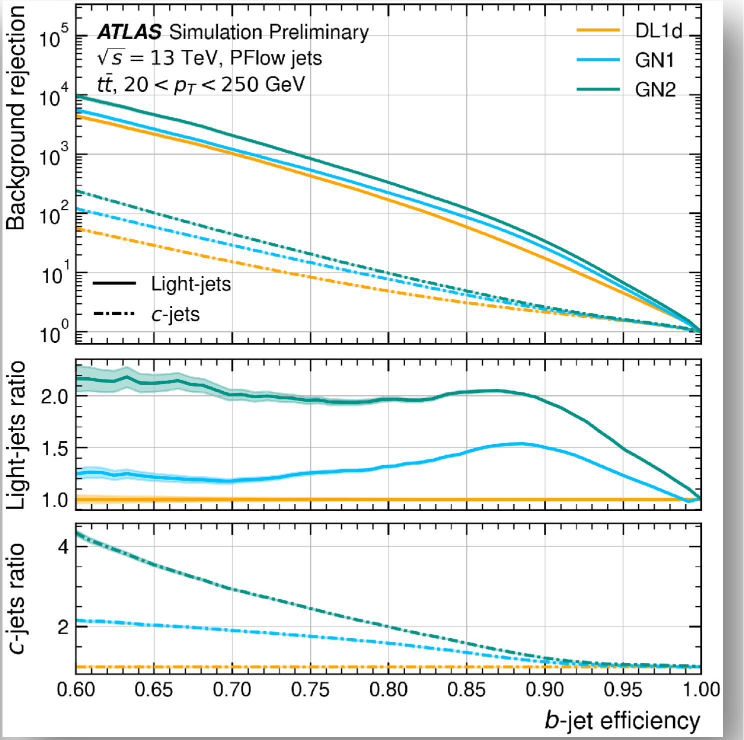
RUN 3 b-TAGGING



FTAG-2022-004/



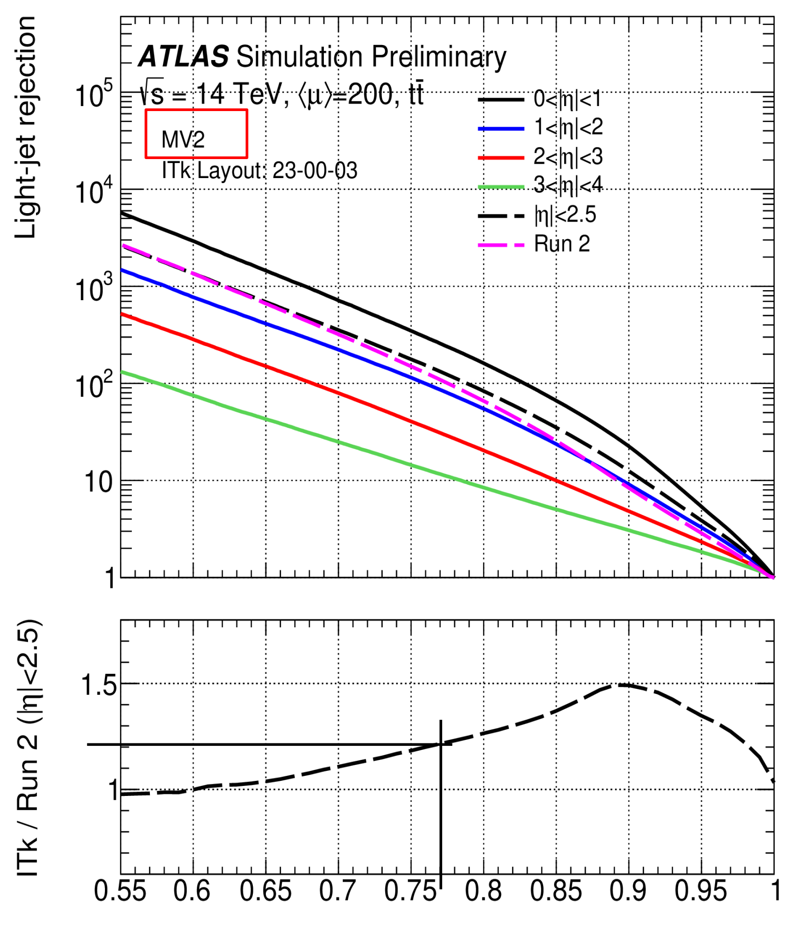
ATL-PHYS-PUB-2022-027



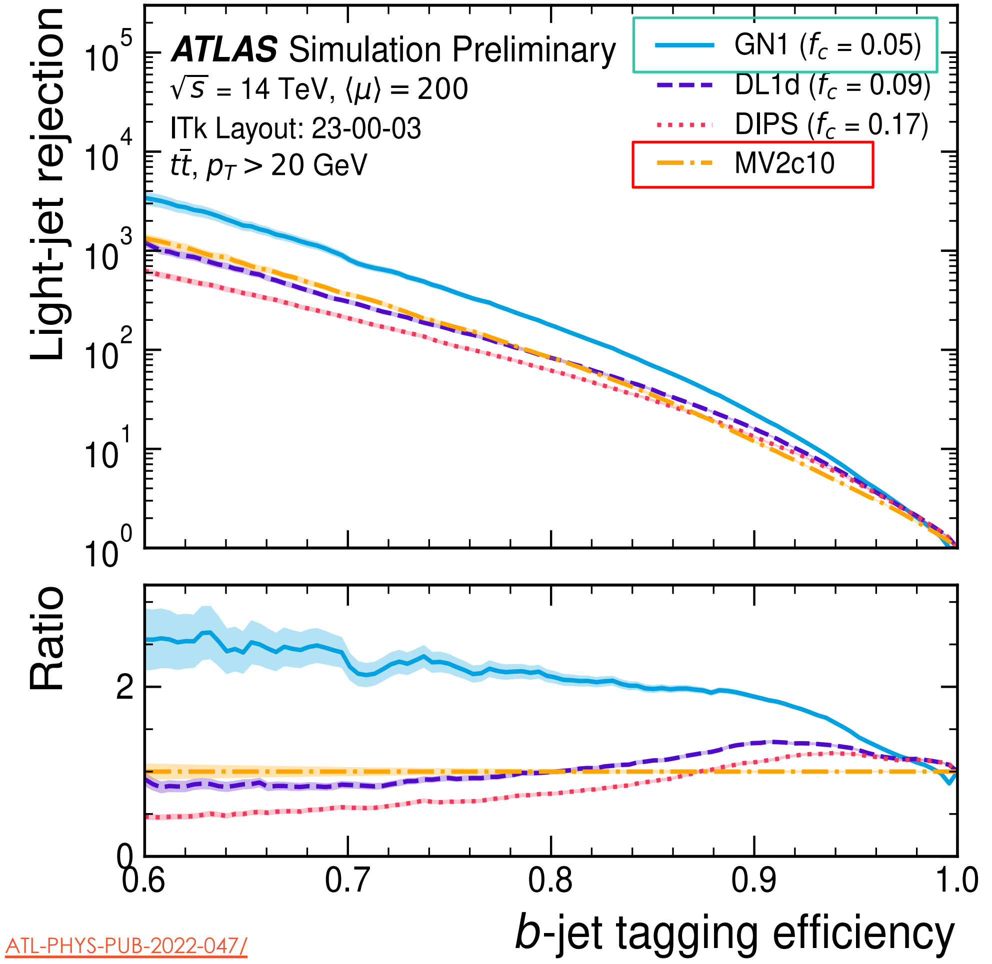
FTAG-2023-01/

ITK BTAGGING

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



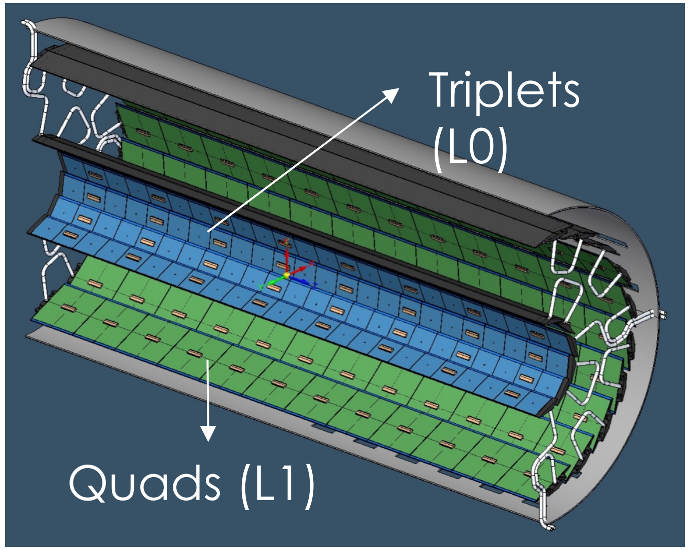
ATL-PHYS-PUB-2021-024-

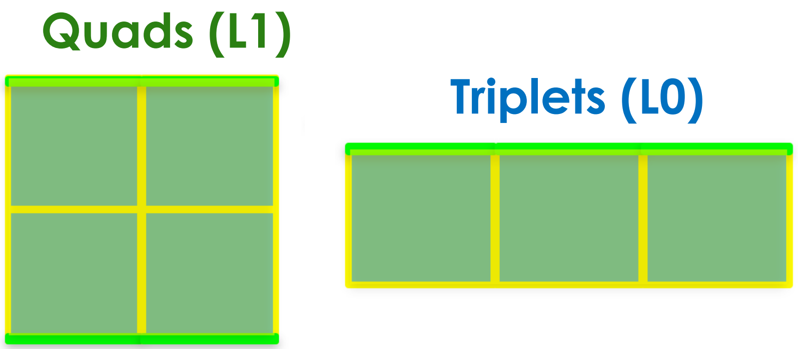


ATL-PHYS-PUB-2022-047/

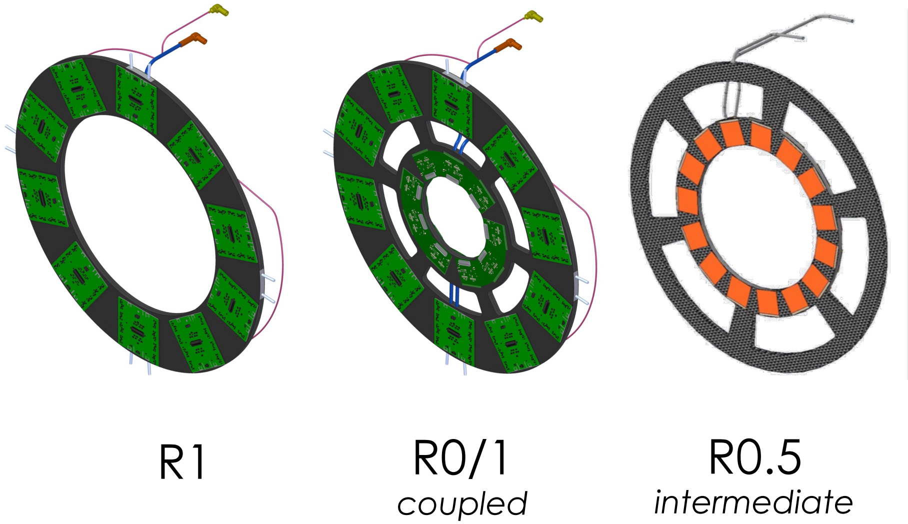
ITK

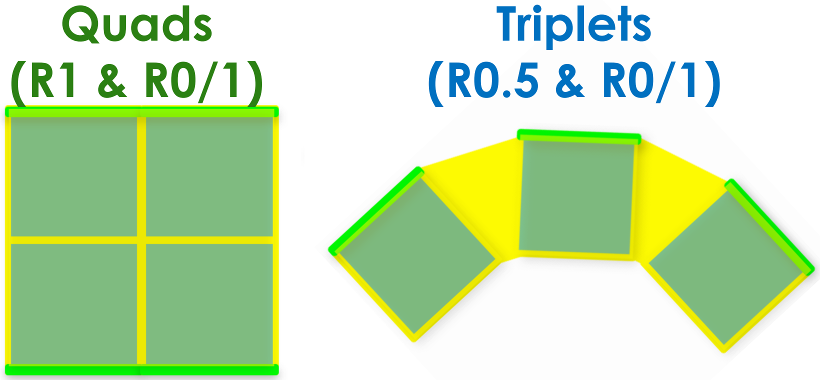
Barrel Staves





Endcap Rings





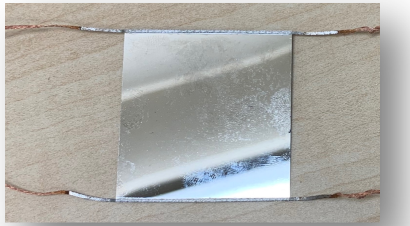
ITK

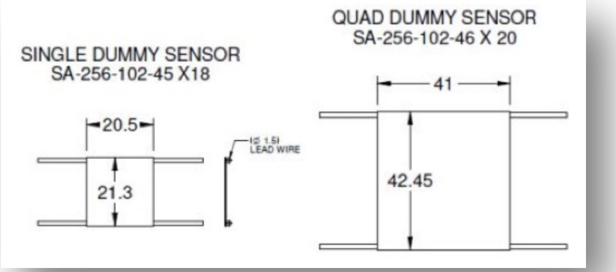
Validate Local Support design and loading procedure

Thermo-mechanical prototype

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

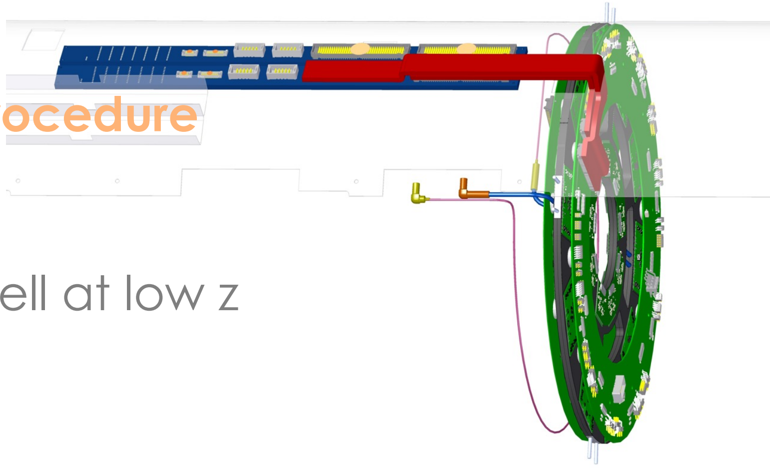
Heaters





Electrical prototype

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



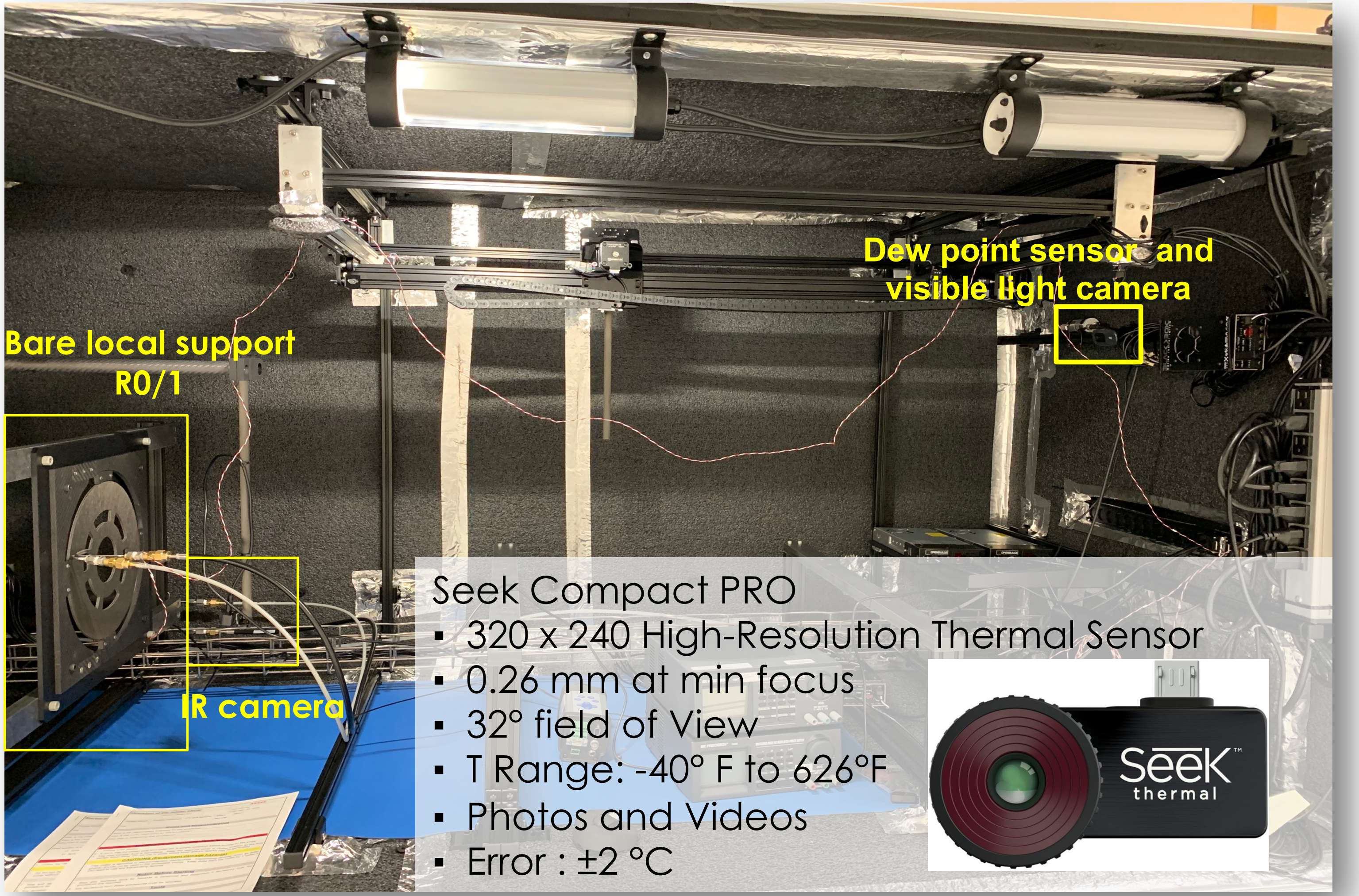
Validate Local Support design and loading procedure

Integration prototypes

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

ITK

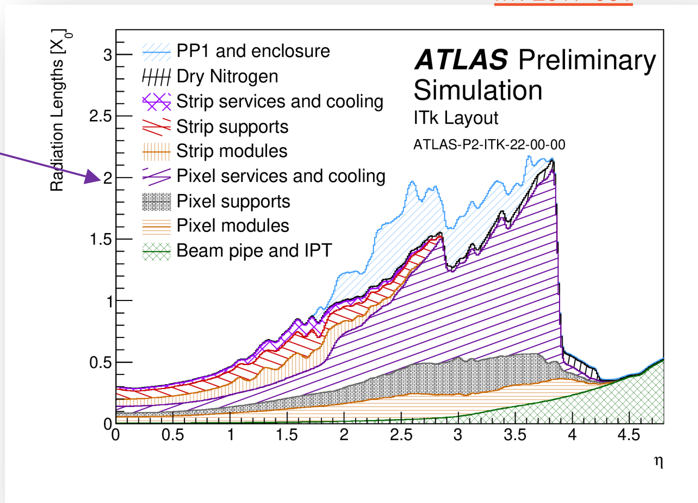
- **Test box details**



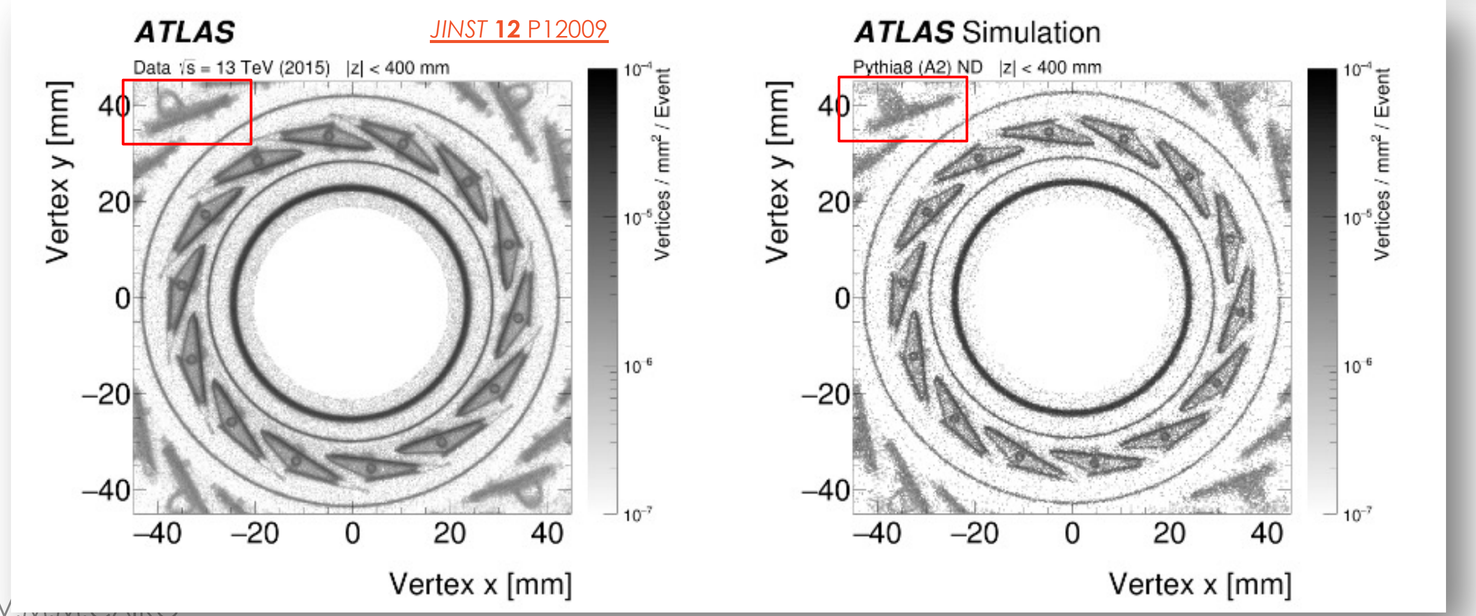
LESSONS FROM THE PAST

- 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

ITK-2019-001



JINST 12 P12009

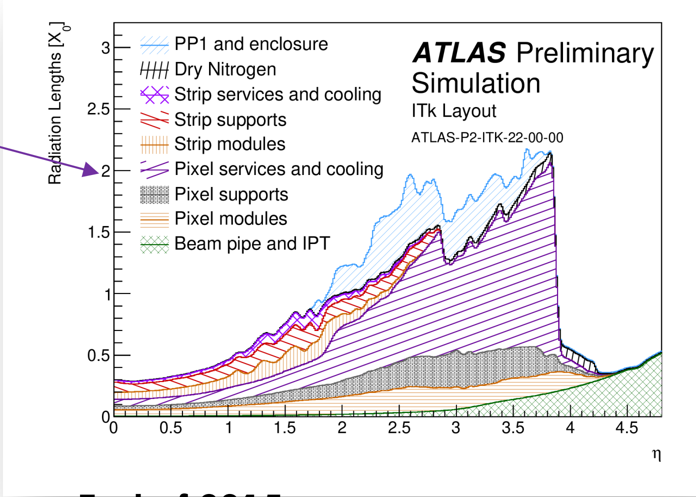


Cooling fluid incorrectly modelled in simulation

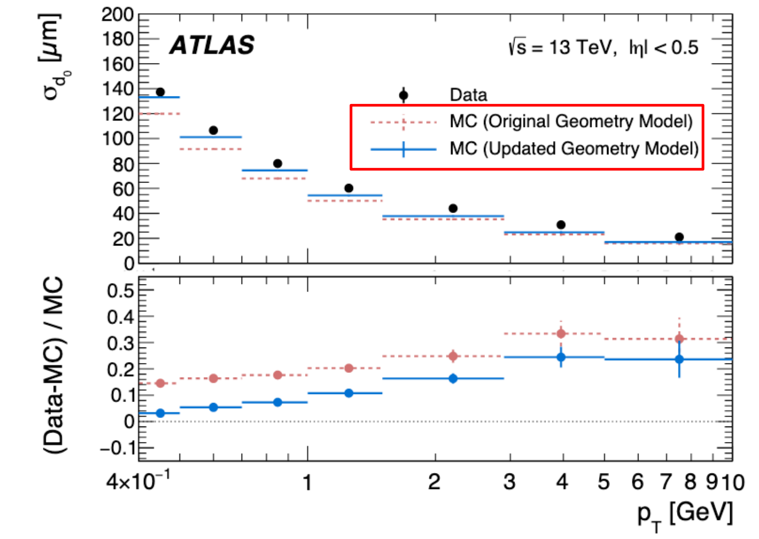
LESSONS FROM THE PAST

- 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

ITK-2019-001



JINST **12** P12009



End of 2015

Track Reconstruction Efficiencies and Systematic Uncertainties

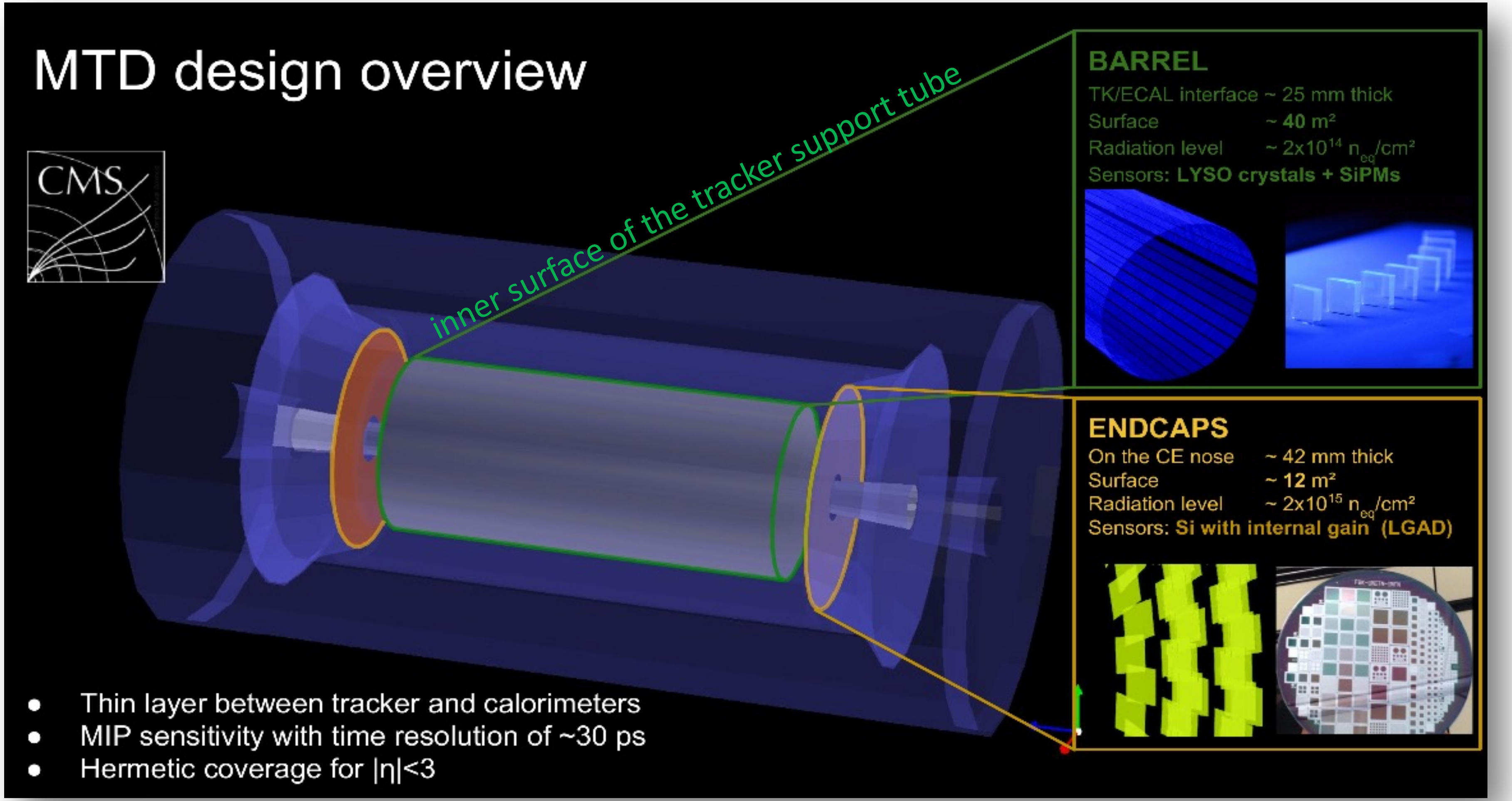
Track Quality Selection	Loose		Tight Primary	
η Range	$\lvert\eta\rvert \leq 0.1$	$2.3 \leq \lvert\eta\rvert \leq 2.5$	$\lvert\eta\rvert \leq 0.1$	$2.3 \leq \lvert\eta\rvert \leq 2.5$
Track Reconstruction Efficiency	91%	73%	86%	63%
$\mathrm{Sys}_{+5\% Extra}$	0.4%	0.9%	0.5%	1.1%
$\mathrm{Sys}_{PixServExtra}$	—	2.0%	—	2.3%
$\mathrm{Sys}_{+30\% IBLExtra}$	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	$\lvert\eta\rvert \leq 0.1$	$2.3 \leq \lvert\eta\rvert \leq 2.5$	$\lvert\eta\rvert \leq 0.1$	$2.3 \leq \lvert\eta\rvert \leq 2.5$
Track Reconstruction Efficiency	90%	71%	85%	61%
$\mathrm{Sys}_{+5\% Extra}$	0.3%	1.0%	0.4%	1.2%
$\mathrm{Sys}_{PixServExtra}$	—	1.1%	—	1.4%
$\mathrm{Sys}_{IBLExtra}$	0.1%	0.2%	0.1%	0.1%
$\mathrm{Sys}_{PhysModel}$	0.2%	0.1%	0.1%	0.1%
Total Systematic Uncertainty	0.4%	1.5%	0.5%	1.8%

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.

A COMPARISON WITH CMS' MIP TIMING DETECTOR

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

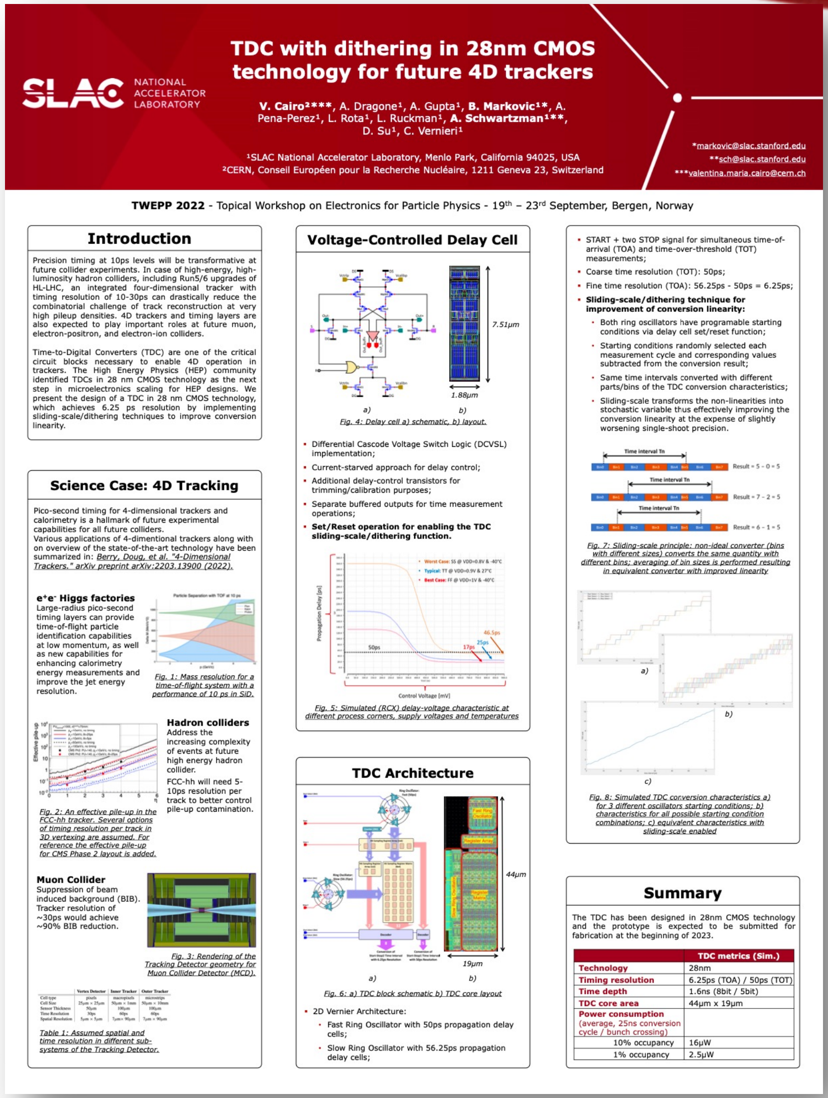
Table 1.1: Expected scientific impact of the MIP Timing Detector, taken from Ref. [8].

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

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

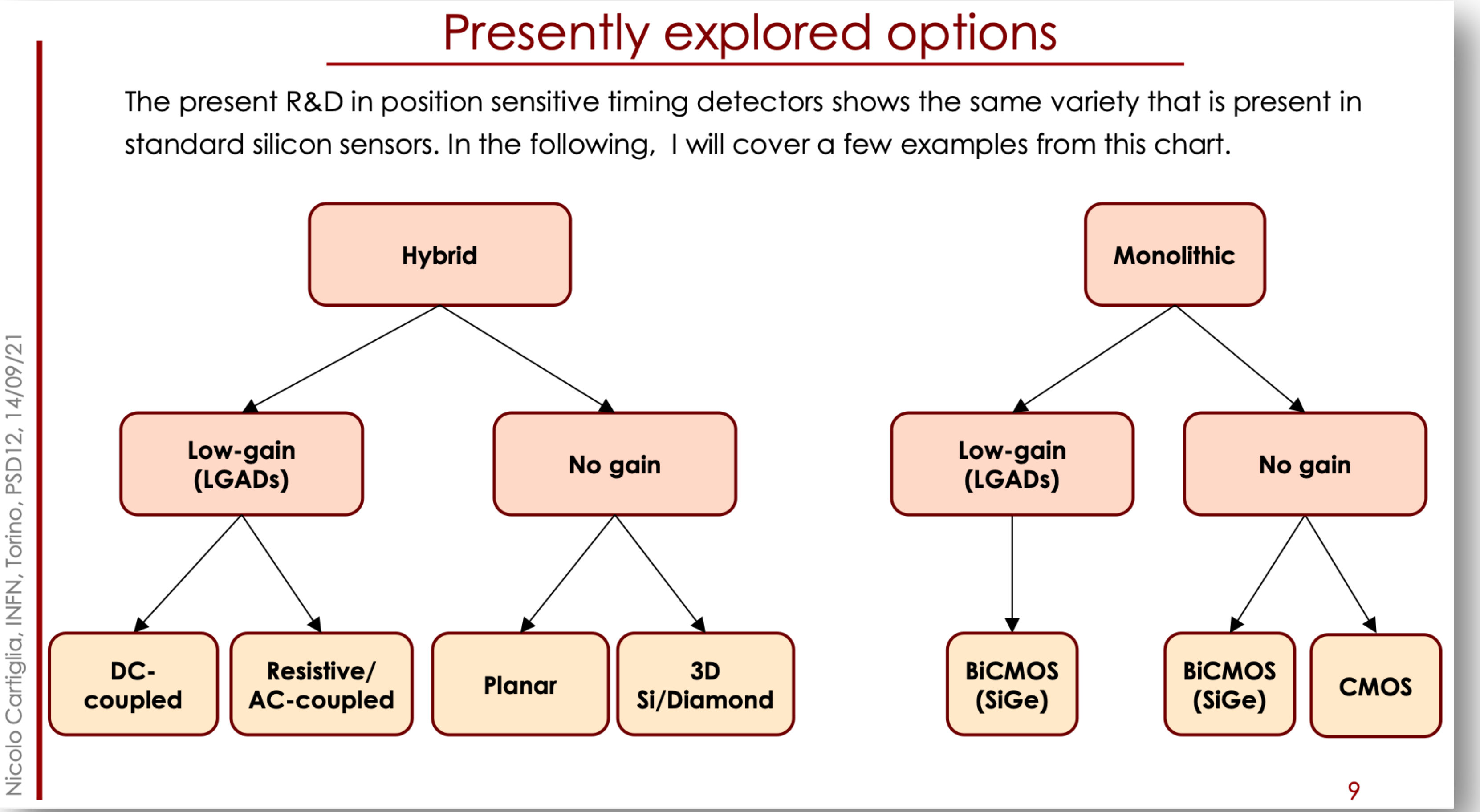
A WORD ON TECHNOLOGY

- 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



Just submitted for fabrication

A WORD ON TECHNOLOGY

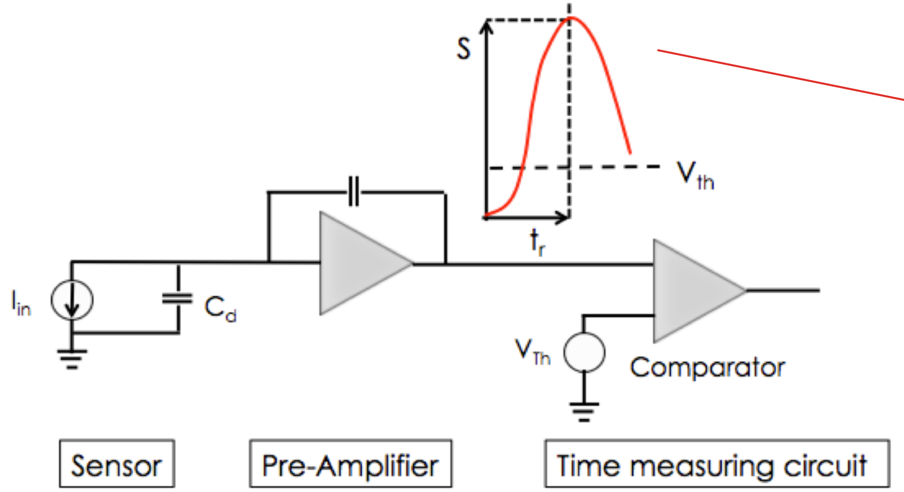


https://indico.cern.ch/event/797047/contributions/3638198/attachments/2308674/3928223/Position_sensitive_timing.pdf

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}.

Generate extra heat compared to a space only tracker

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.

Strong interplay between sensor and electronics

N. Cartiglia, INFN, Torino - EPS Venice 07/07/17

8

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	19.5×19.5 mm^2	5 mW/chan	2 MGy
ETROC	65 nm	1.3 mm	20.8×20.8 mm^2	3 mW/chan	1 MGy
RD53A/HL-LHC pixels	65 nm	50 µm	20×11.6 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:

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

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:

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

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

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

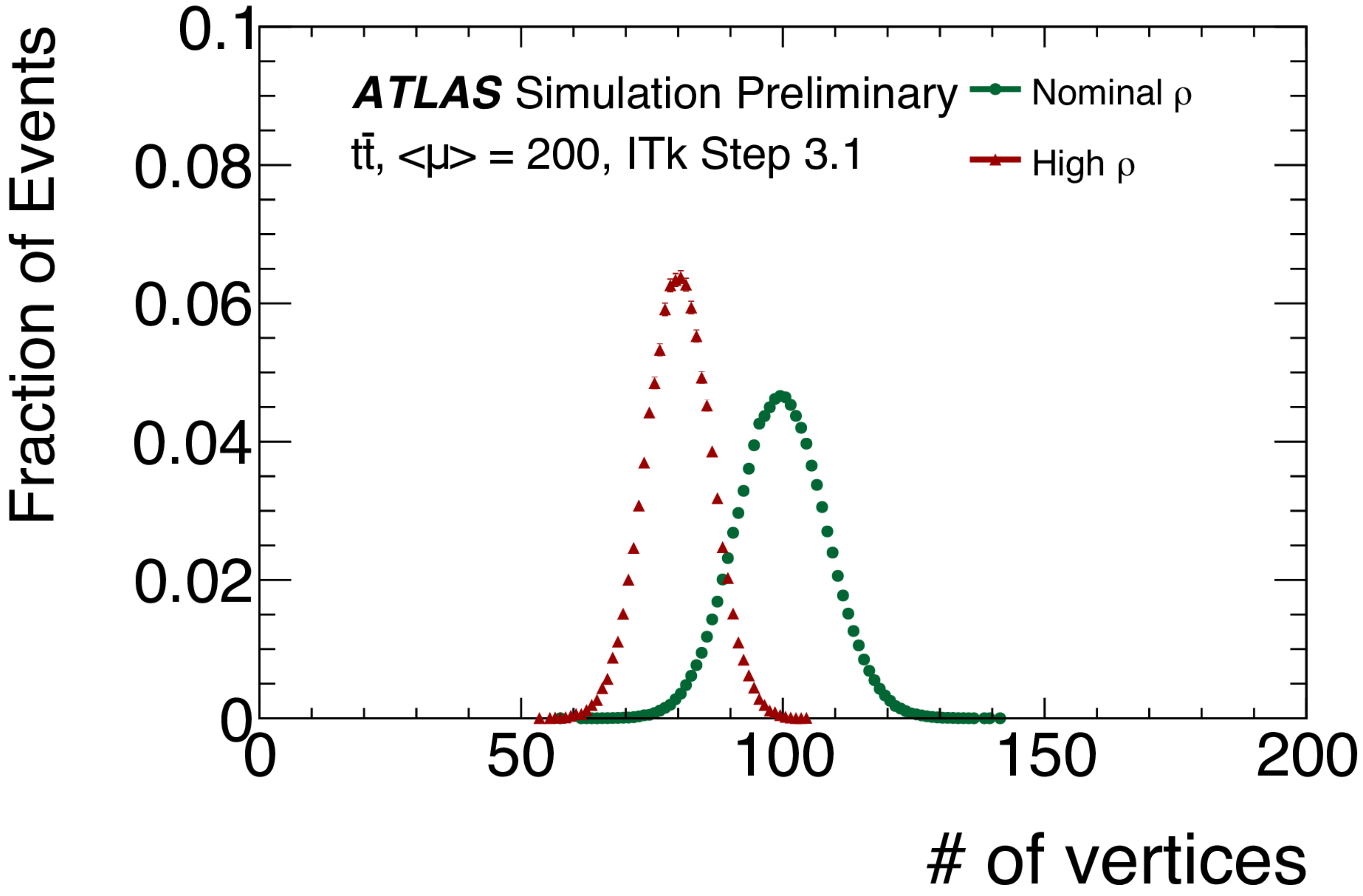
Therefore σ^2_{Jitter} is proportional to the rise time and inversely proportional to the S/N ratio. Since the rise time is proportional to the drift time of charge carriers in the sensor, again a sensor with short drift time and high signal to noise ratio is advantageous.

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^2_{TDC} is given by the bin size divided by $\sqrt{12}$ which is about 5ps.

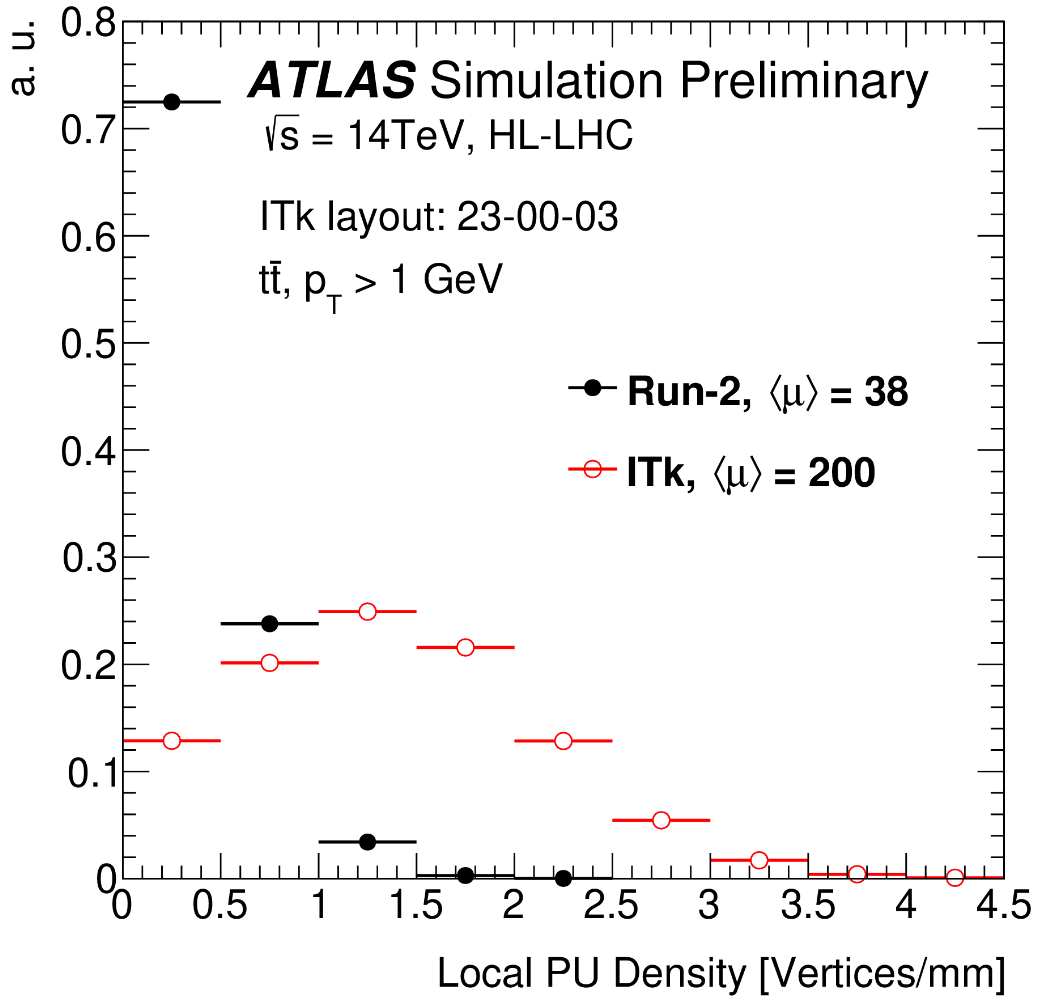
To summarize, a candidate timing device would need to have the following characteristics: short drift time (reduces rise time), high signal to noise (reduces jitter component), limited thickness in the path of a MIP (reduces Landau component), and small TDC bin size (reduces TDC component). These properties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



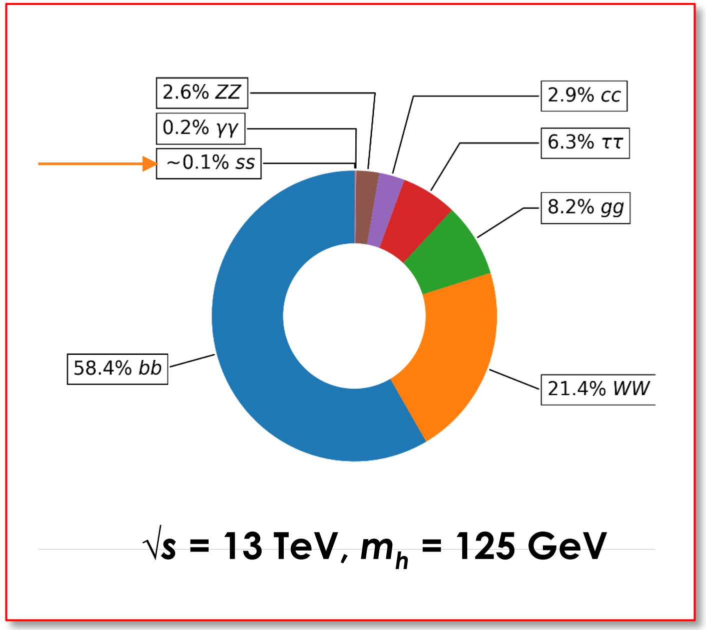
VERTEXING STUDIES



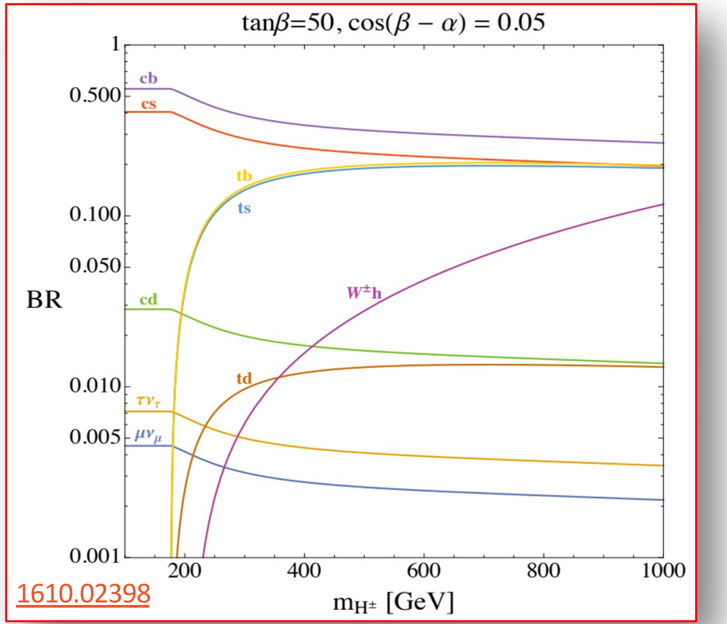
THE STRANGE QUARK AS A PROBE FOR NEW PHYSICS

2203.07535

SM Higgs



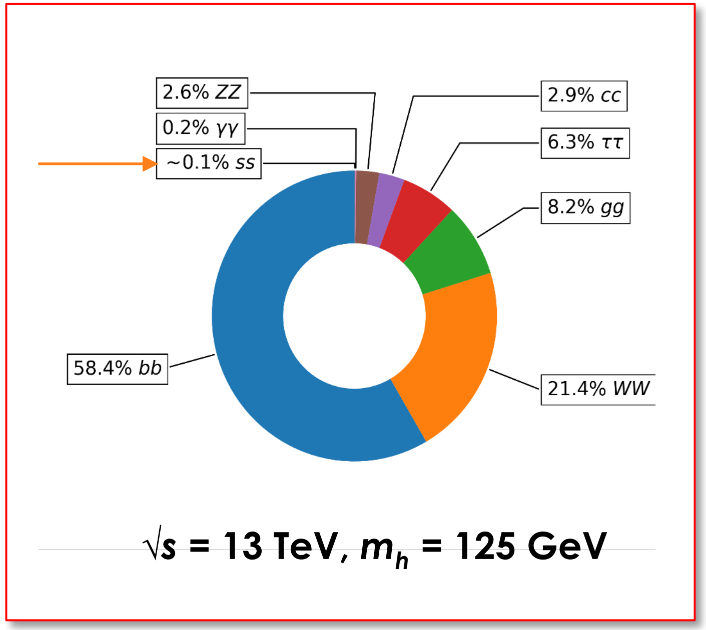
BSM Charged Higgs



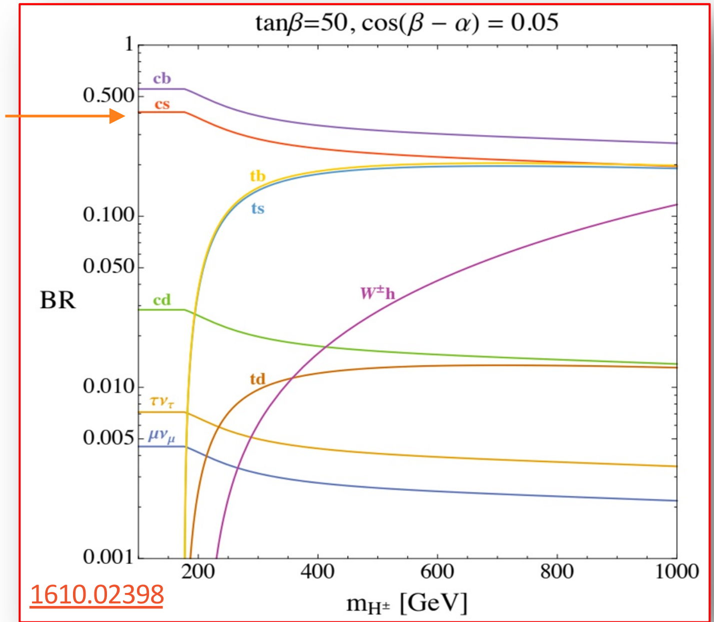
THE STRANGE QUARK AS A PROBE FOR NEW PHYSICS

2203.07535

SM Higgs



BSM Charged Higgs

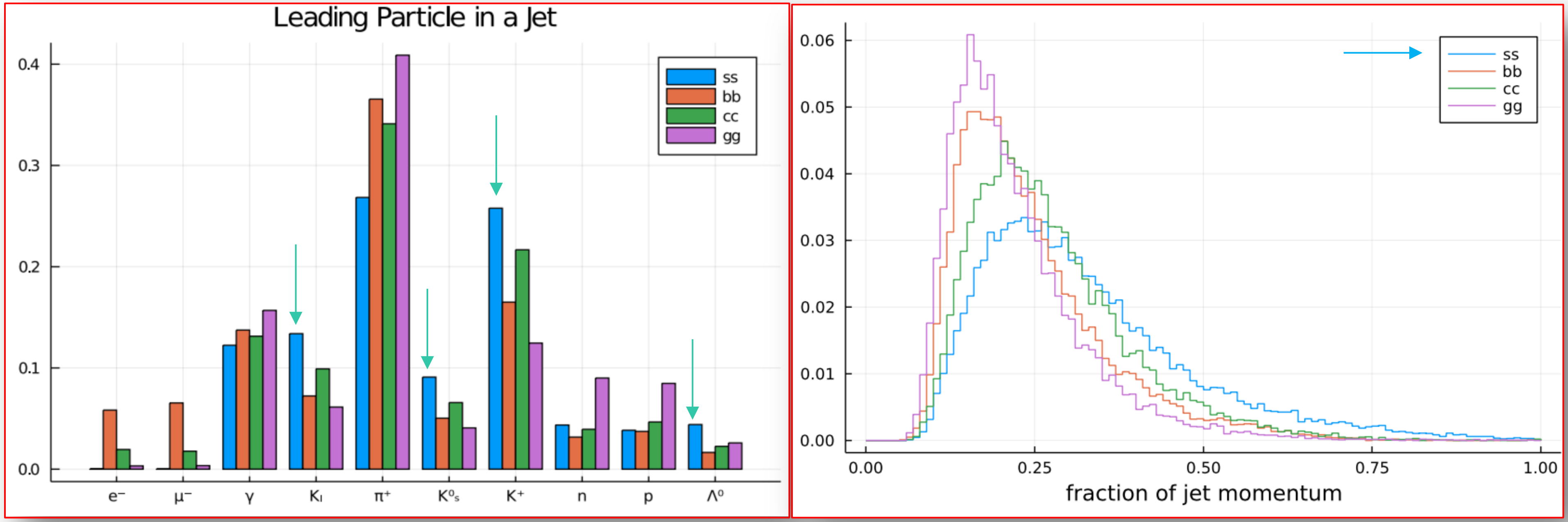


Assess the sensitivity of Higgs to strange couplings(*) at future Higgs Factories and study detector design enabling strange jet tagging

(*)many more SM analyses would benefit from strange tagging, e.g. $ee \to ss$, $Z \to ss, W \to cs$, etc!

THE *STRANGE* FEATURES

2203.07535



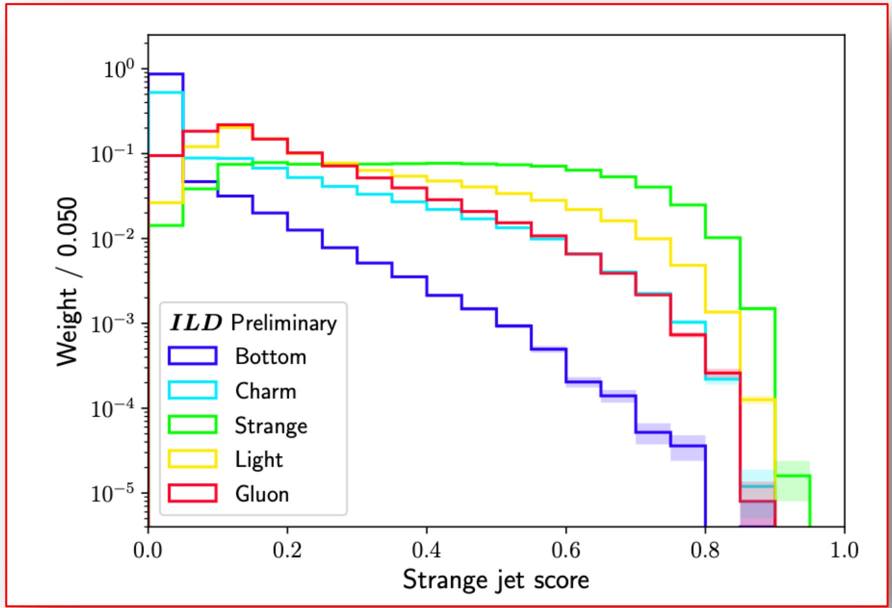
Particle Identification is crucial!

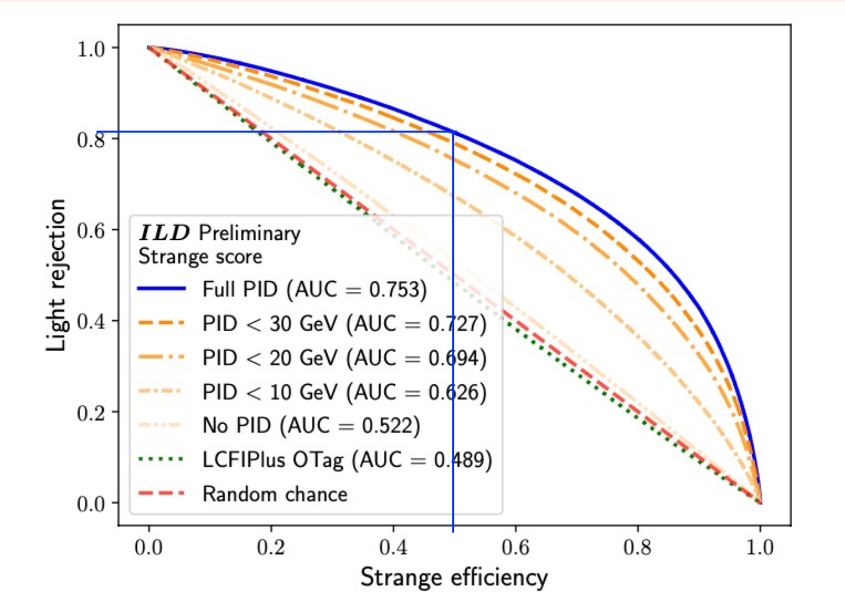
Need **p/K discrimination** over a momentum range of approximately (0.2-0.7) x 0.5 x 125 ≅ **12 to 50 GeV**

IMPACT OF PID ON STRANGE TAGGING

2203.07535

- Use a Recurrent Neural Net tagger for classifying jet-flavour, train on **full ILD(*) simulation** $(Z \to inv)(H \to qq/gg)$ 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

(*) **ILD** = multi-purpose **International Large Detector** concept @ the International Linear Collider

IMPACT OF PID ON STRANGE TAGGING

2203.07535

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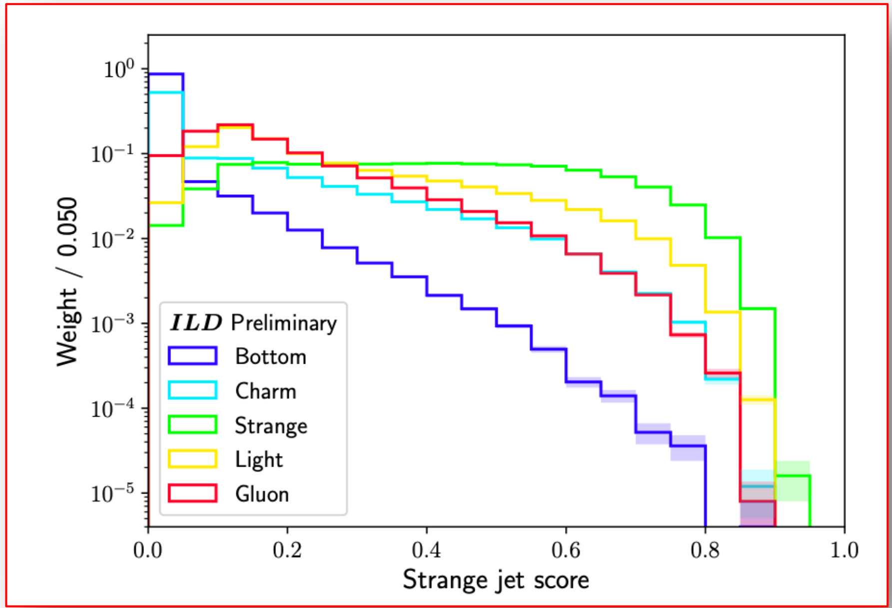

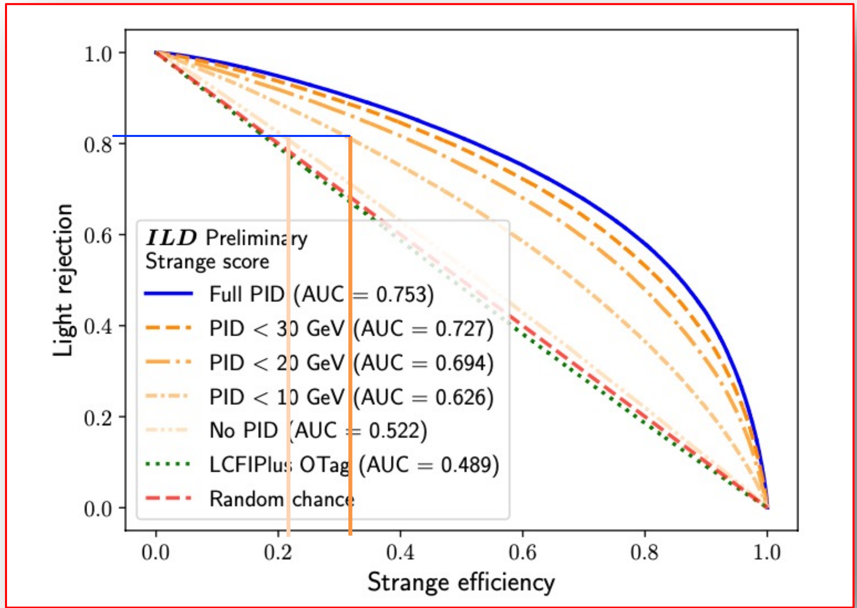

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At fixed light rejection:
No PID to PID < 10 GeV: ~1.5x efficiency

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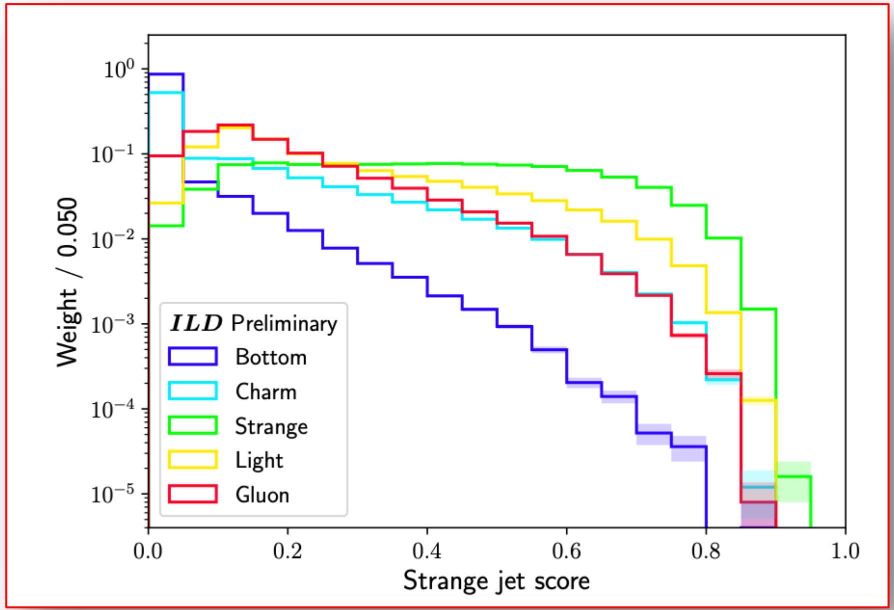

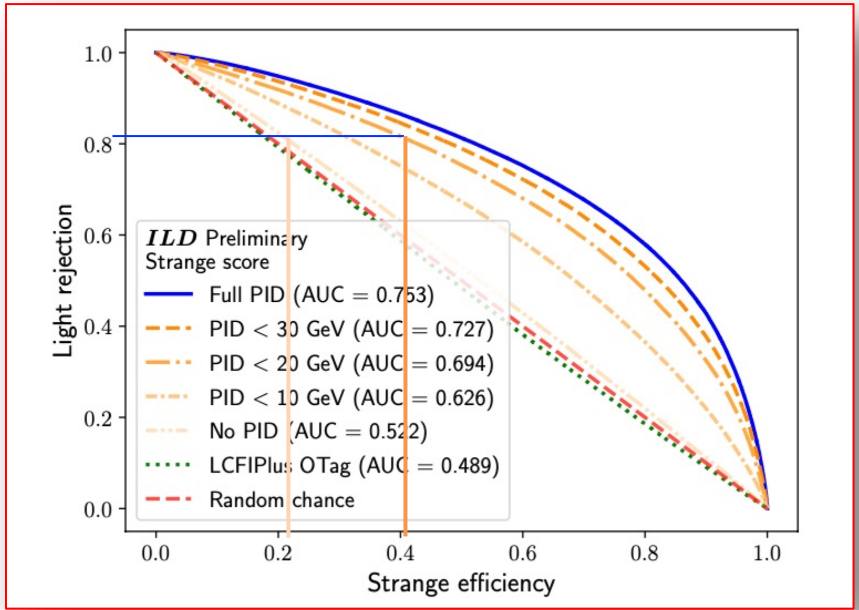

Good discrimination of s-jets from u/d- and g-jets

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

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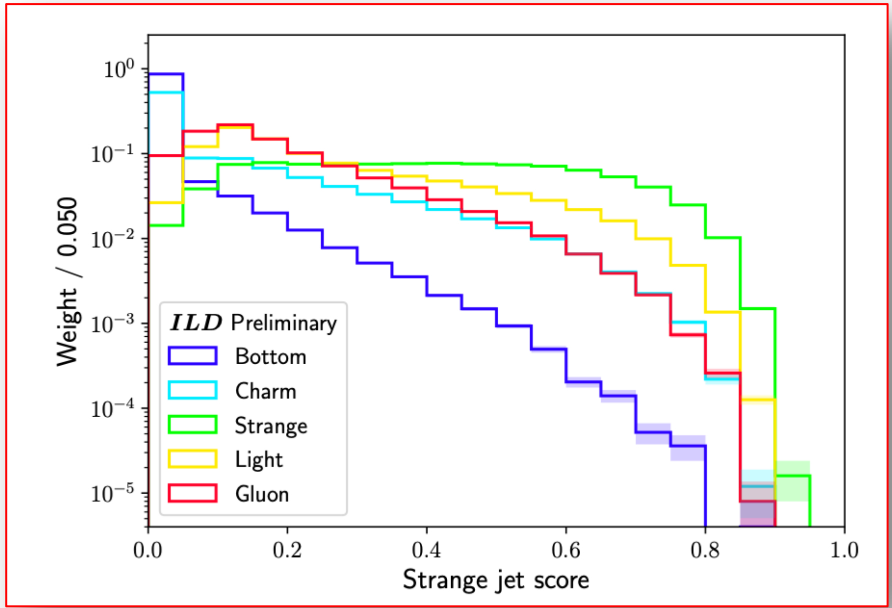

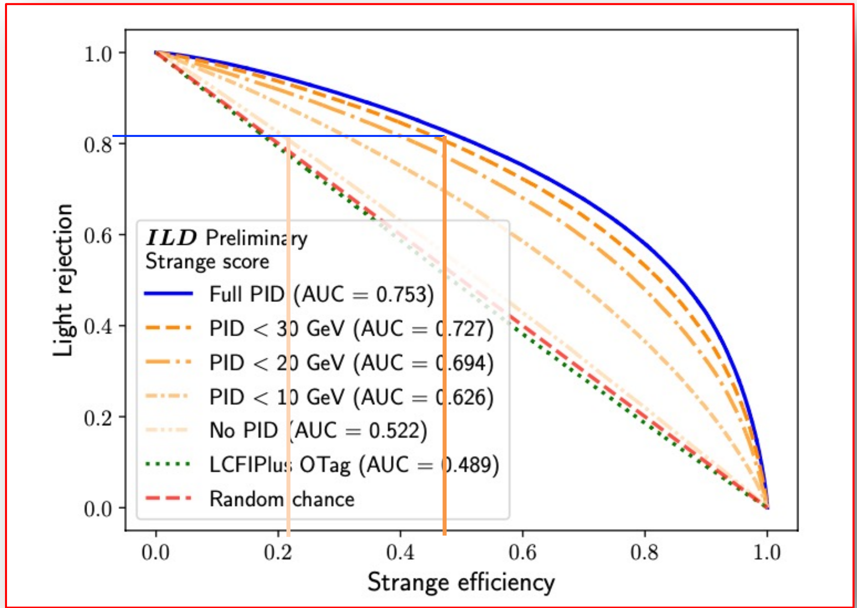

Good discrimination of s-jets from u/d- and g-jets

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: $h \to ss$ ANALYSIS @ THE INTERNATIONAL LINEAR COLLIDER

2203.07535

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

σ_H @ $\sqrt{s} = 250$ GeV ~ 200 fb (dominated by ZH production)

2000 fb^{-1} collected in 10y by ILC

→ ~ 400k Higgs → ~ 80 $h \to ss$

But of course, new physics boosts these numbers!

$h \to ss$ ANALYSIS IN A NUTSHELL

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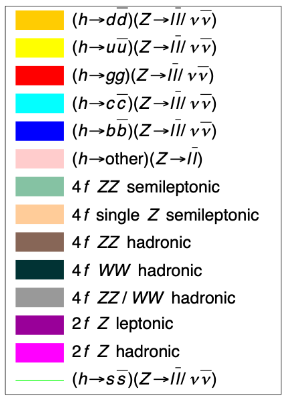
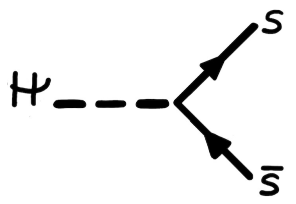
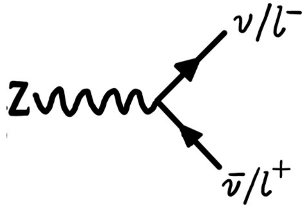




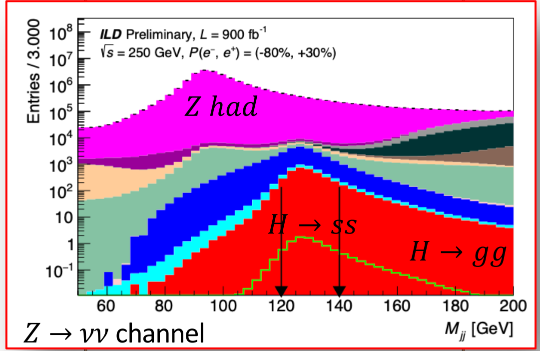
2 jets



0 or 2 SFOS leptons

Object definition

Event selection



Cut-based approach, reject $ZH(!\,ss), V, VV$

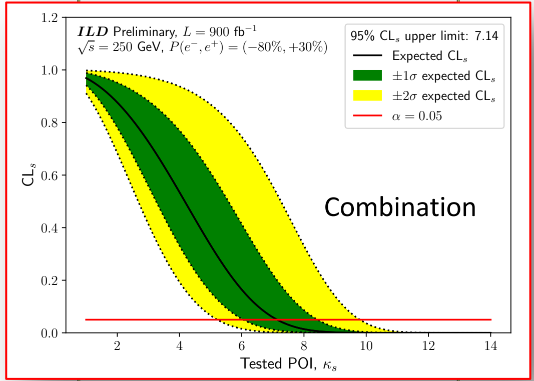
Sum of

$jet_0 + jet_1$

strange tagging scores

Signal discriminant

s-Yukawa constraints



$k_s \lesssim 7$ x SM

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

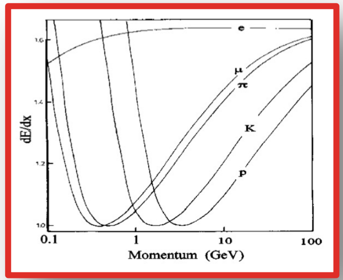
- This triggered recent studies of what may be possible with a system that pioneered particle ID:
the **Ring Imaging Cherenkov detector**

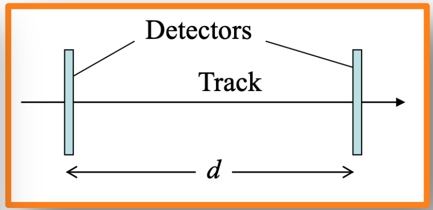
PARTICLE IDENTIFICATION TECHNIQUES

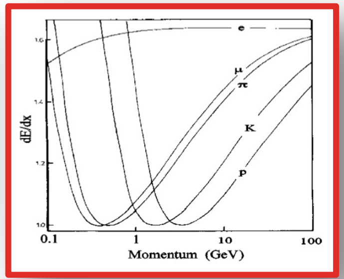
- Various technologies allow to identify hadrons in different momentum ranges

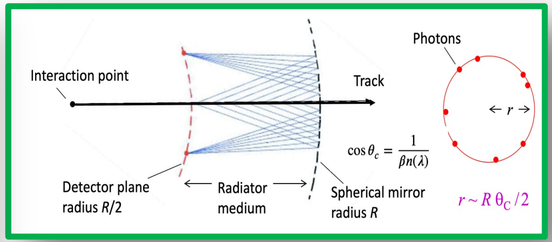
3σ *separation for* π/K			
dE/dx in silicon	**Time-of-flight** via Fast Timing in silicon envelopes or calorimetry	**dE/dx** in Time Projection or Drift Chambers	**Ring Imaging Cherenkov Detectors**
$\lesssim$ 5 GeV	$\lesssim$ 5 GeV	$\lesssim$ 30 GeV (scales with volume)	O(tens of GeV)

Momentum



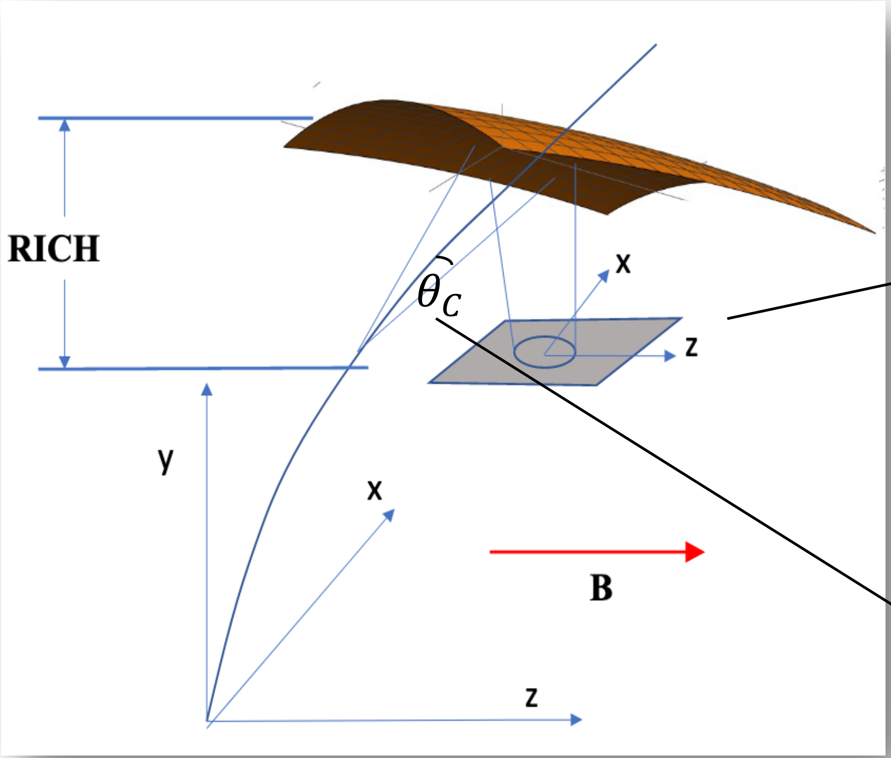




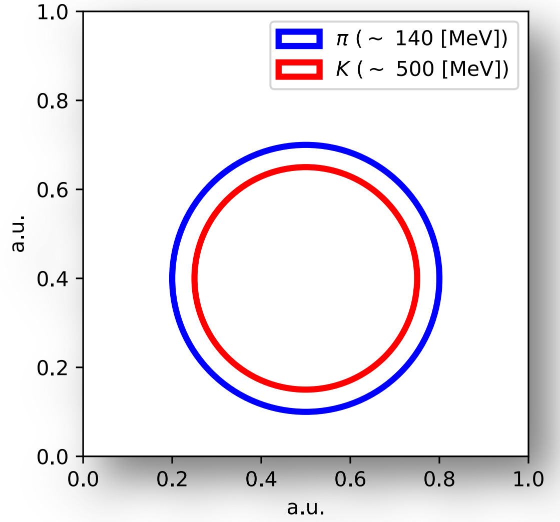


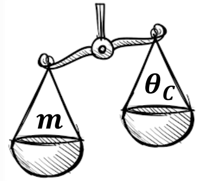
RING IMAGING CHERENKOV DETECTORS

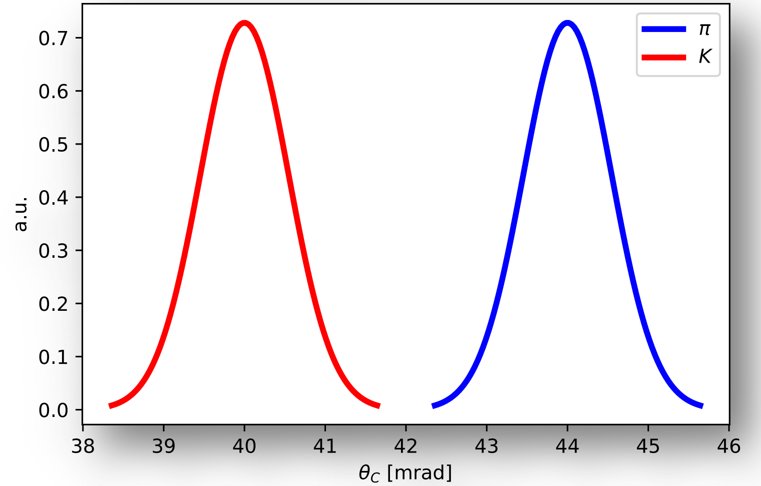
- RICH detectors use the angle of emitted Cherenkov radiation (as photons) which, coupled with momenta measurements, yield particle masses



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







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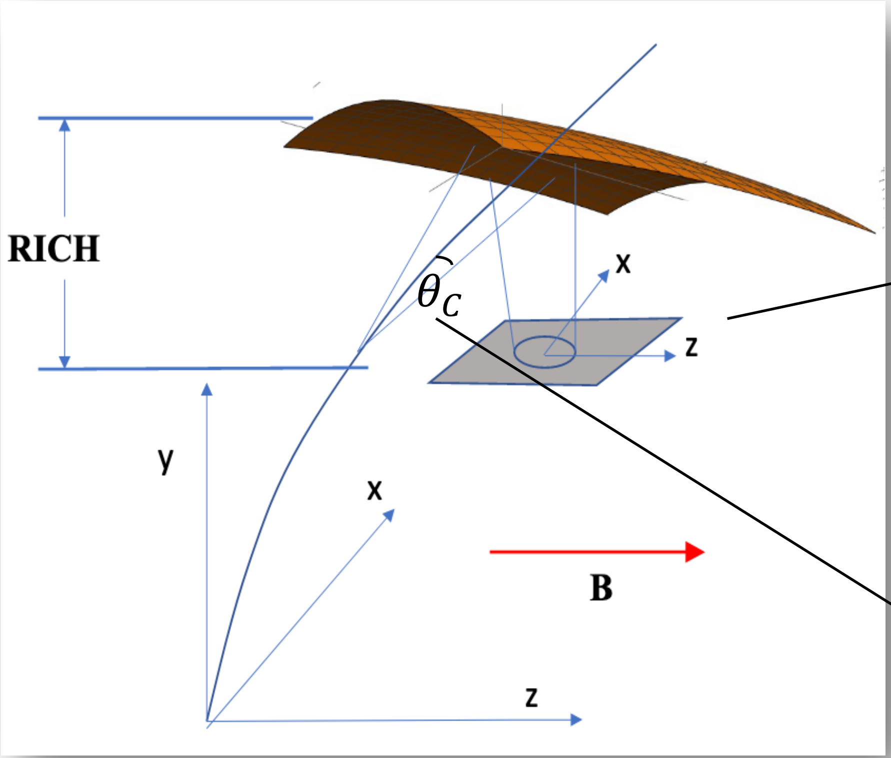

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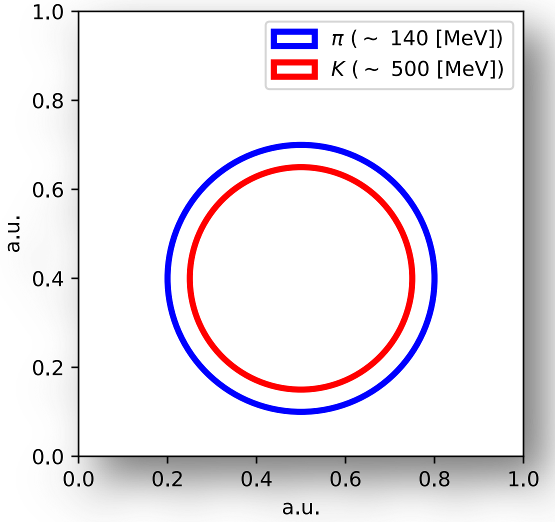
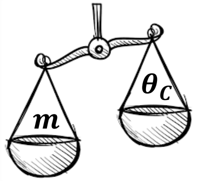
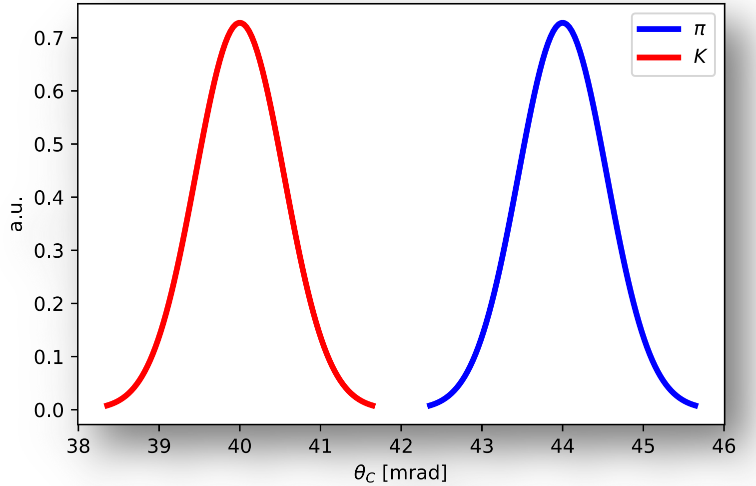
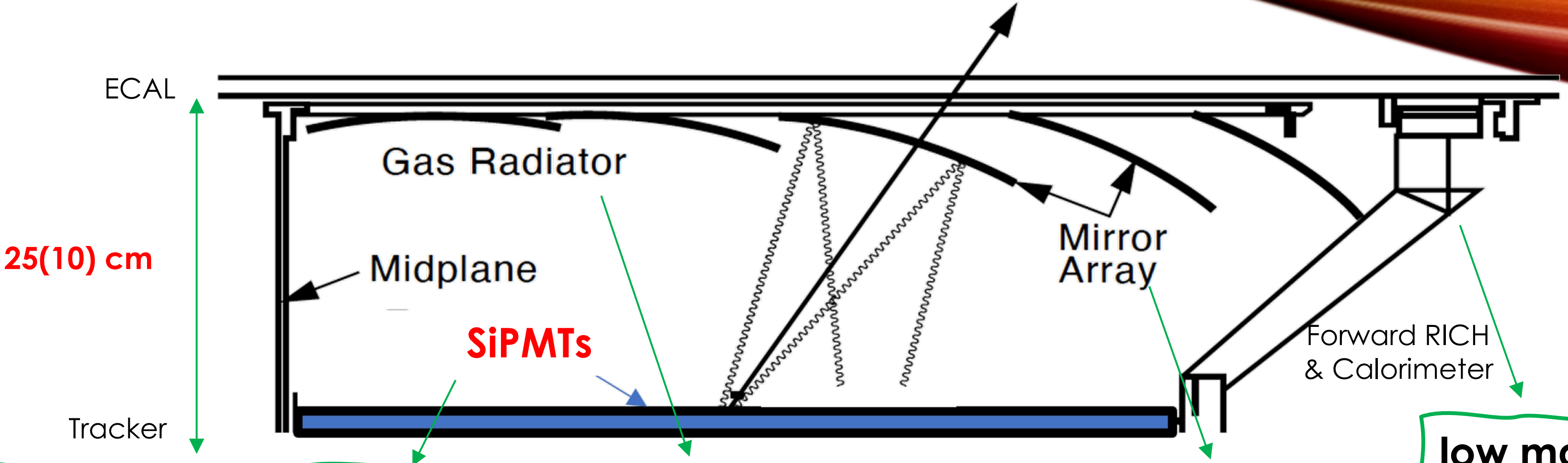






Will it be possible to accommodate a compact RICH system while preserving performance in tracking and calorimetry?

COMPACT GASEOUS RICH WITH SIPMTS

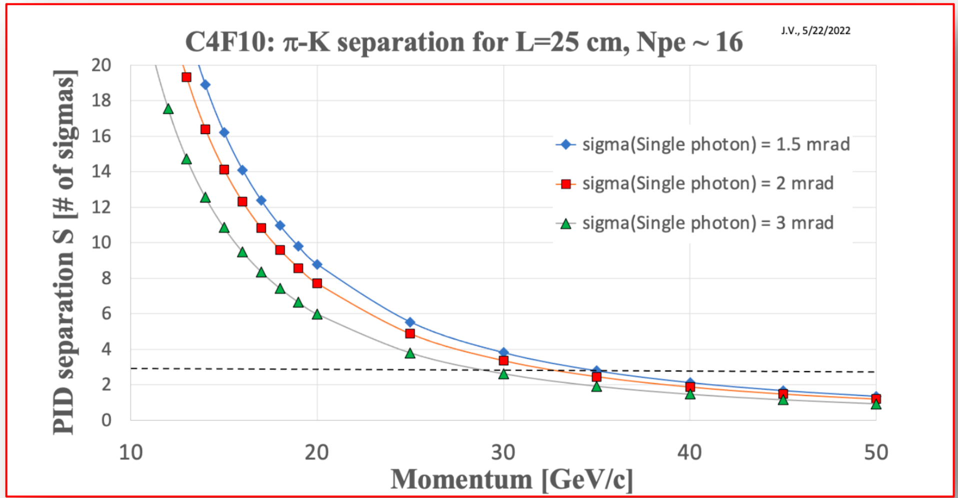


Fast timing device (<100 ps) to provide ToF covering the lower p range and complementing the RICH

Pure $\mathbf{C_4F_{10}}$ at 1 bar (boiling point -1.9 C at 1 bar, good refraction index)

Beryllium with reflective coating

low mass carbon-composite material for the structure



Can reach $3\sigma\ \pi/K$ separation up to 30 GeV with state-of-the-art technology!

2203.07535

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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 $k_s \lesssim 7\ x\ SM$ (we probed also u/d)