ATLAS Run-3 Operations and Highlights

2023 CAP Congress
University of New Brunswick
19 June 2023

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Disclaimer

Far too much material to cover in a single talk!

- Nearly every aspect of ATLAS has been updated in some way:
  - Phase-I detector upgrades
  - Improved TDAQ and new trigger algorithms
  - Improvements to reconstruction
  - New techniques for physics object identification
- In addition, we have already released several measurements with early Run 3 data

I will try to give an overview of all of these activities, but with some personal bias for what I find most exciting

- If you would like to know more about anything in particular, come find me during the breaks!

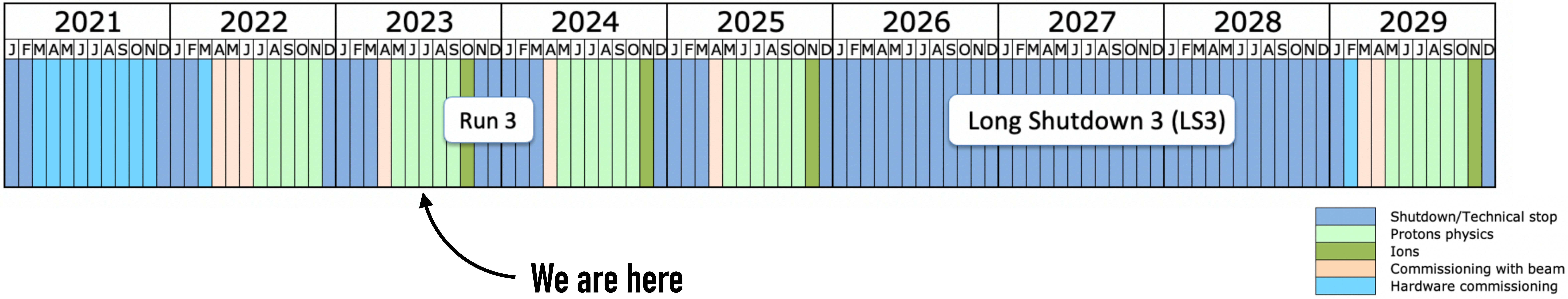
ATLAS Run 3 Operations

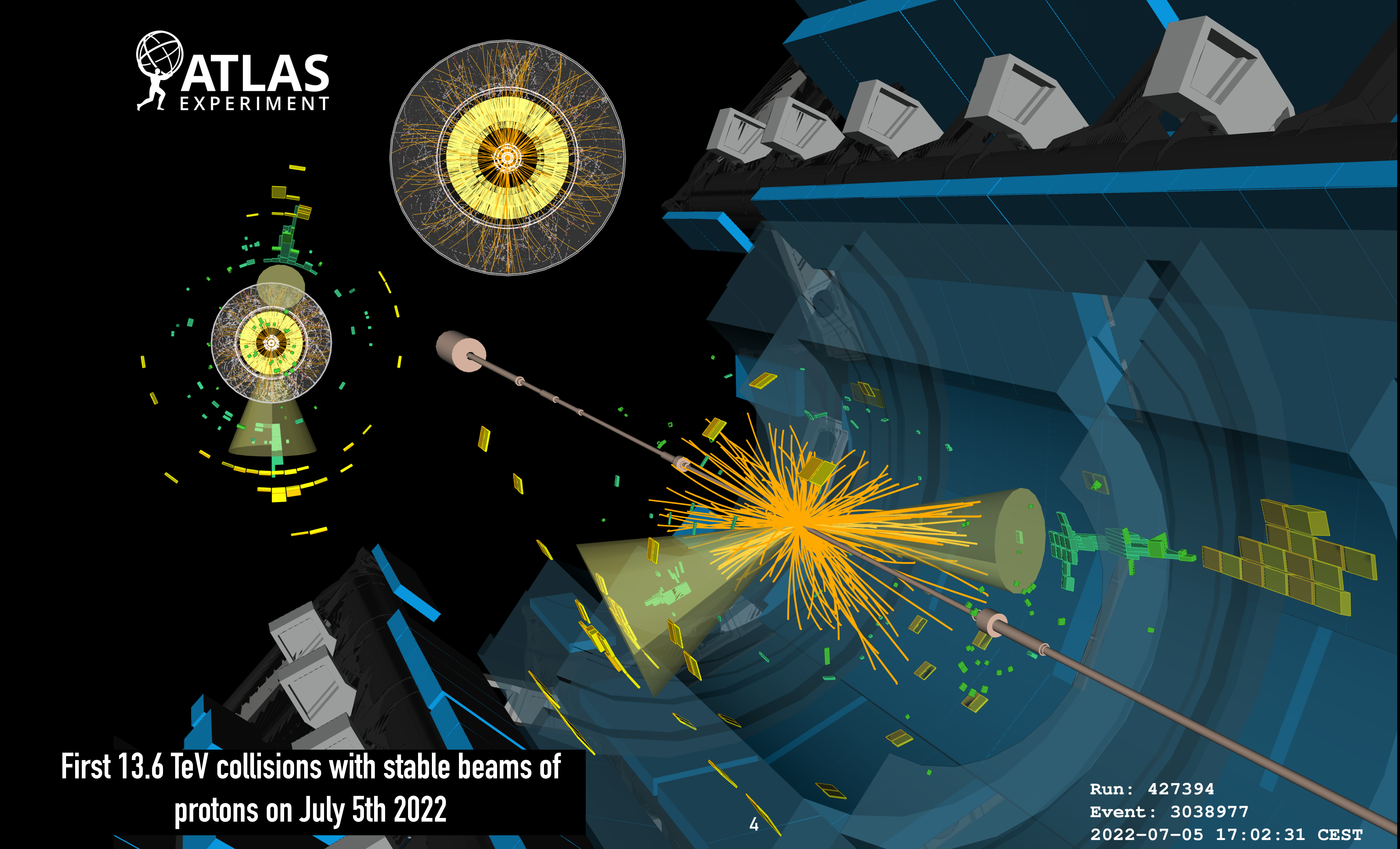
Run 3 of the LHC is under way

- First beam splashes in preparation for Run 3: 22 April 2022
- Stable beams of 6.8 TeV per beam delivered to ATLAS for the first time: 5 July 2022
  - LHC risk analysis found magnet training to 7 TeV infeasible → 6.8 TeV was decided in 2021
- Beam splashes ahead of 2023 data taking: 28 March 2023
- Stable beams resume: 21 April 2023

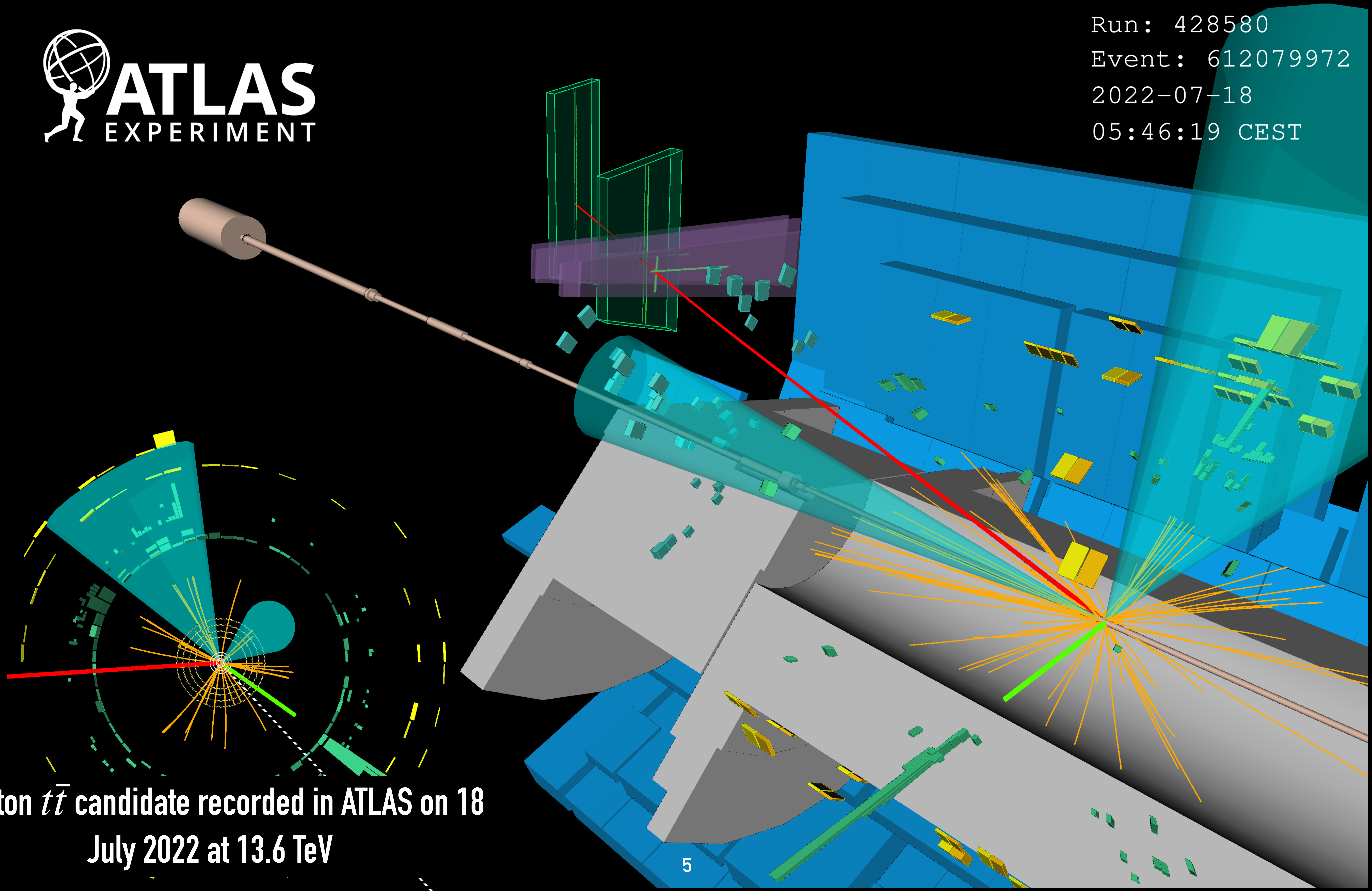
LHC machine schedule as of April 2023

HL-LHC →





First 13.6 TeV collisions with stable beams of protons on July 5th 2022



Dilepton $t\bar{t}$ candidate recorded in ATLAS on 18 July 2022 at 13.6 TeV

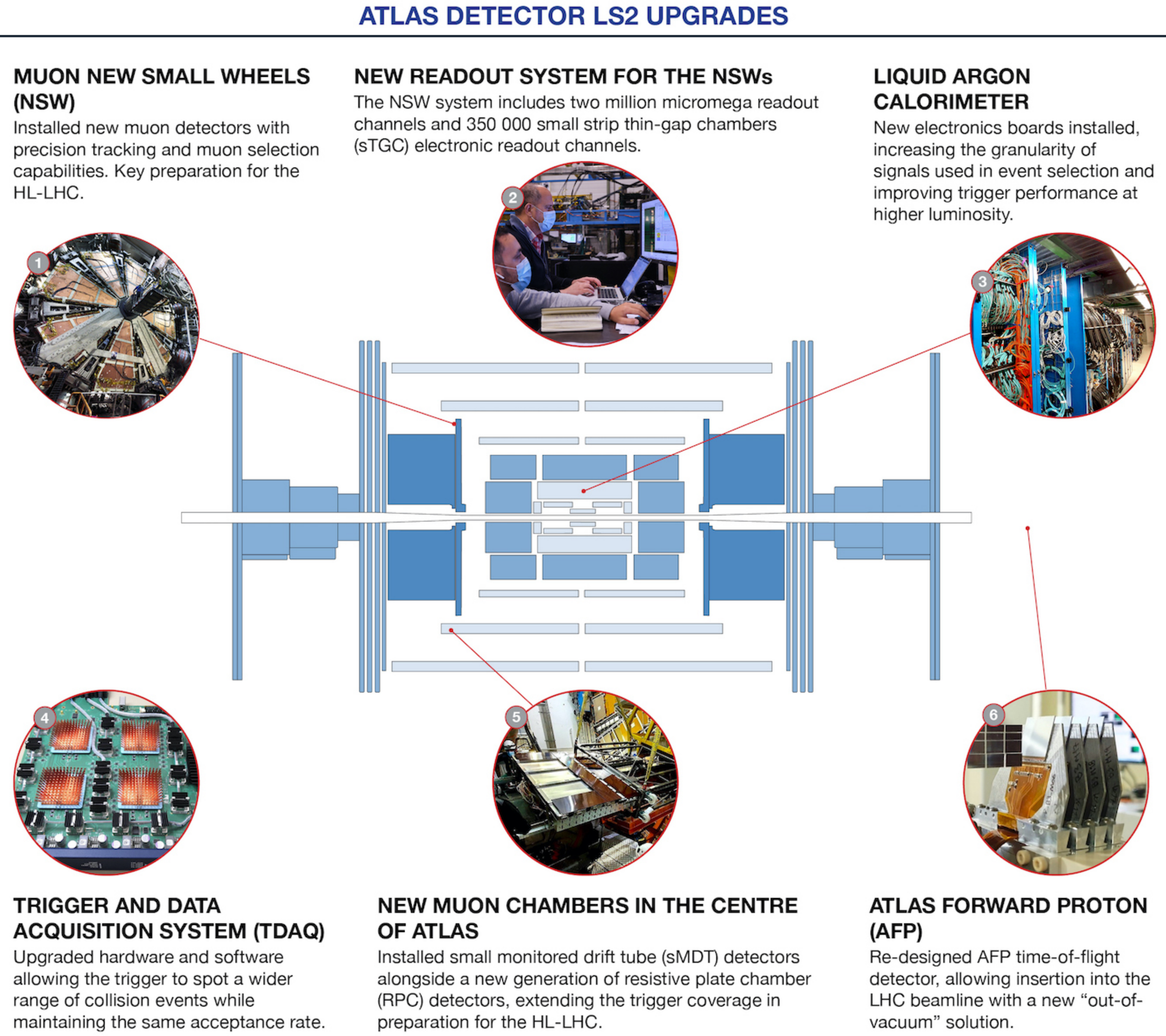
Phase-I upgrade projects

Many upgrades completed to prepare for Run 3 and HL-LHC

Areas where ATLAS Canada made significant contribution:

- Muon New Small Wheels (NSW)
- Liquid Argon Calorimeter (LAr)

For details of Phase-II upgrade, see talk by Luise Poley



Phase-I upgrade projects

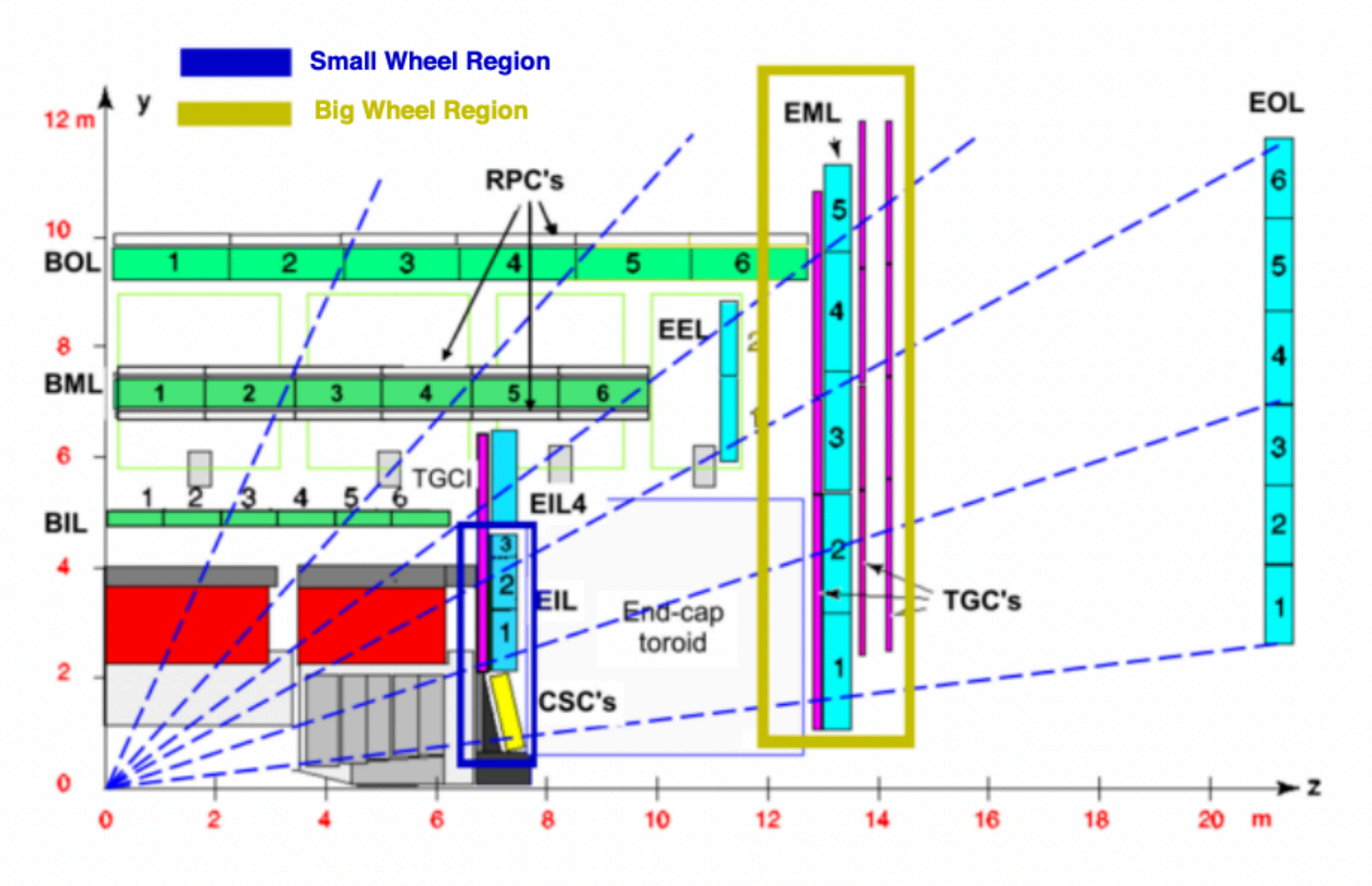
New Small Wheel (NSW) upgrade

The rate of the ATLAS muon trigger increases proportional to the instantaneous luminosity

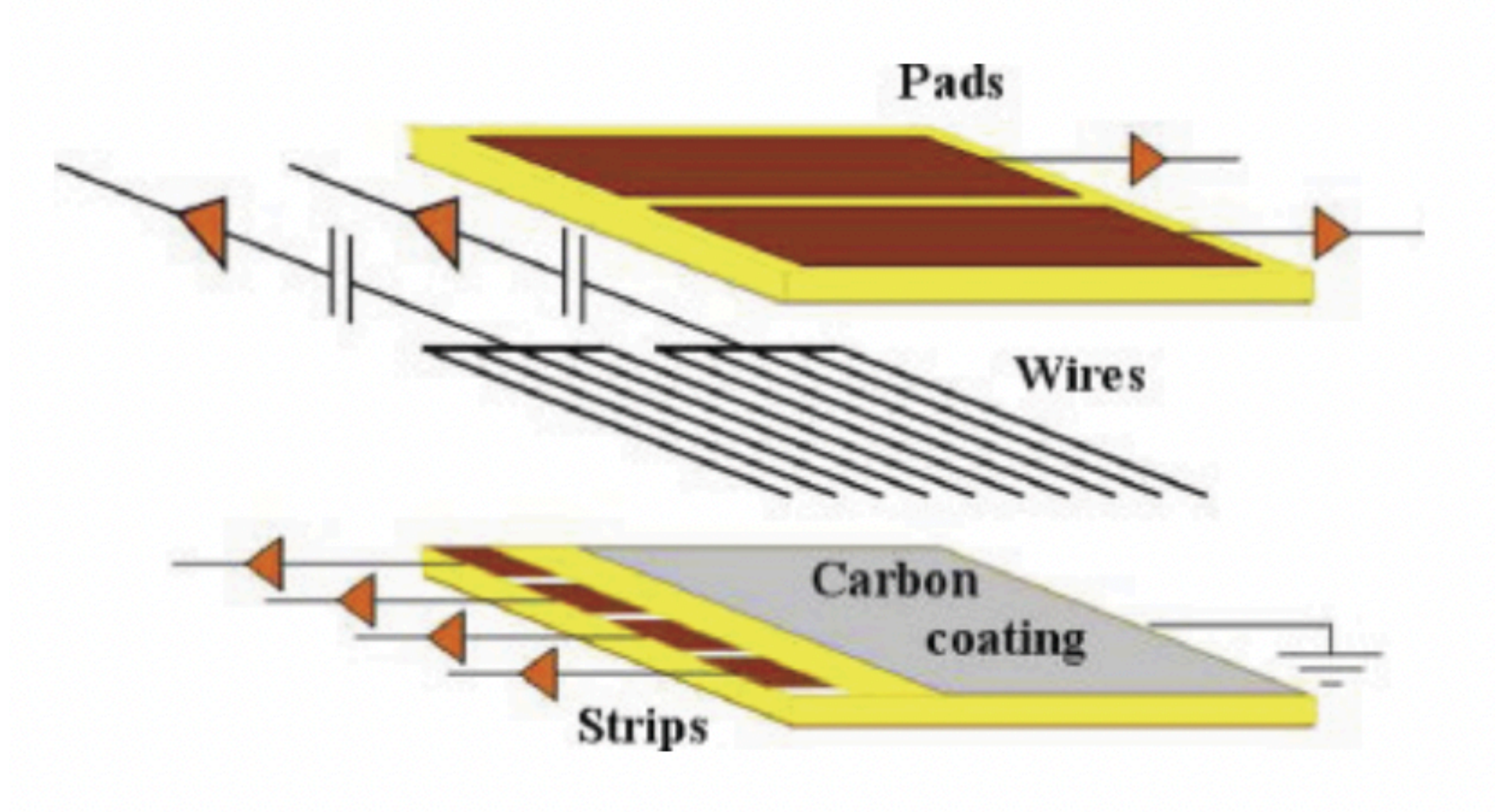
- Run 2 forward muon triggers had a very high fake rate (~90%) due to low energy particles generated in the material between the Small Wheels and the Big Wheels

Muon stations in the forward regions replaced with the so-called New Small Wheels (NSWs)

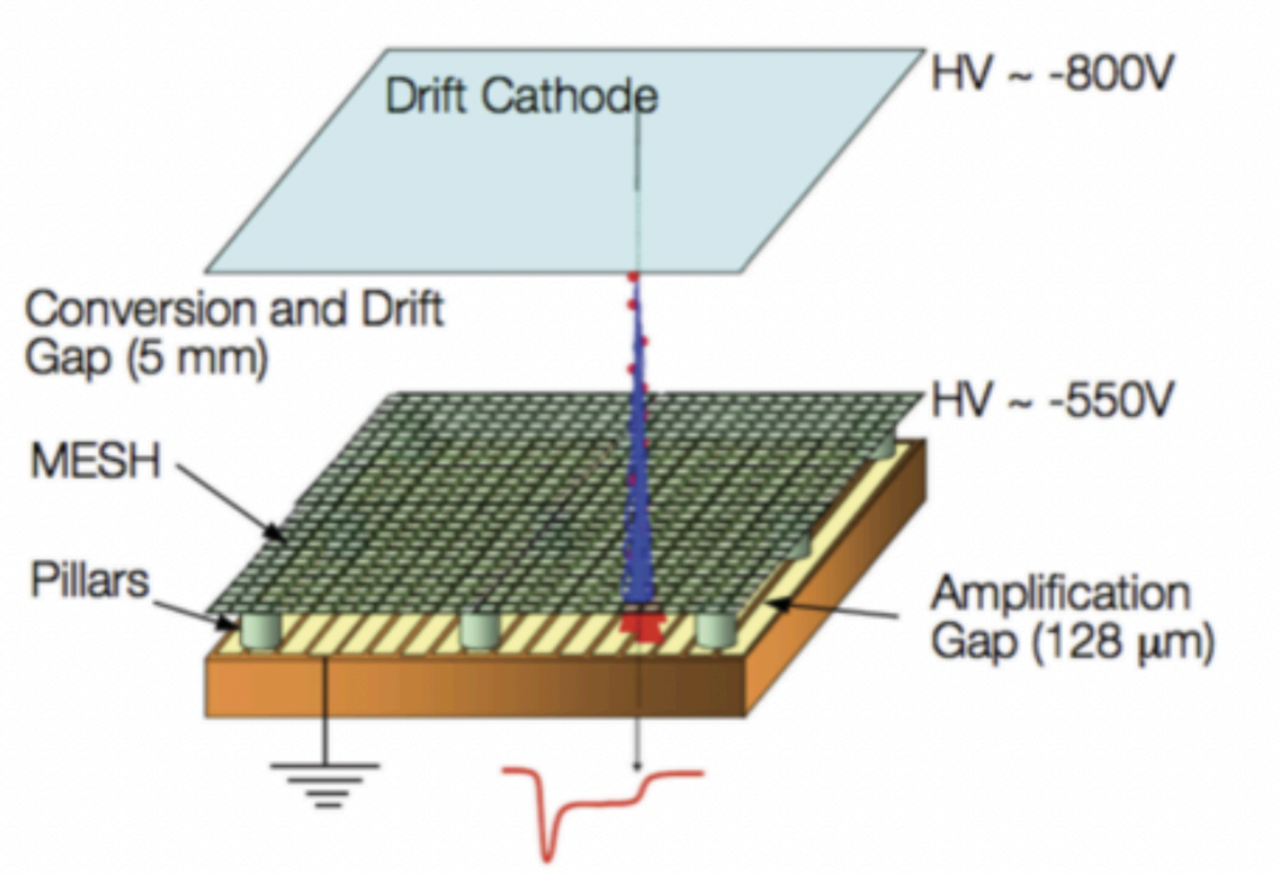
- Provide the muon trigger system with reconstructed track segments of good angular resolution
- Can indicate whether the triggered muons originated from the collision point



The NSWs consist of two technologies both providing trigger and tracking capabilities:



Small Strips Thin Gap Chambers (sTGC)



Micromegas (MM)

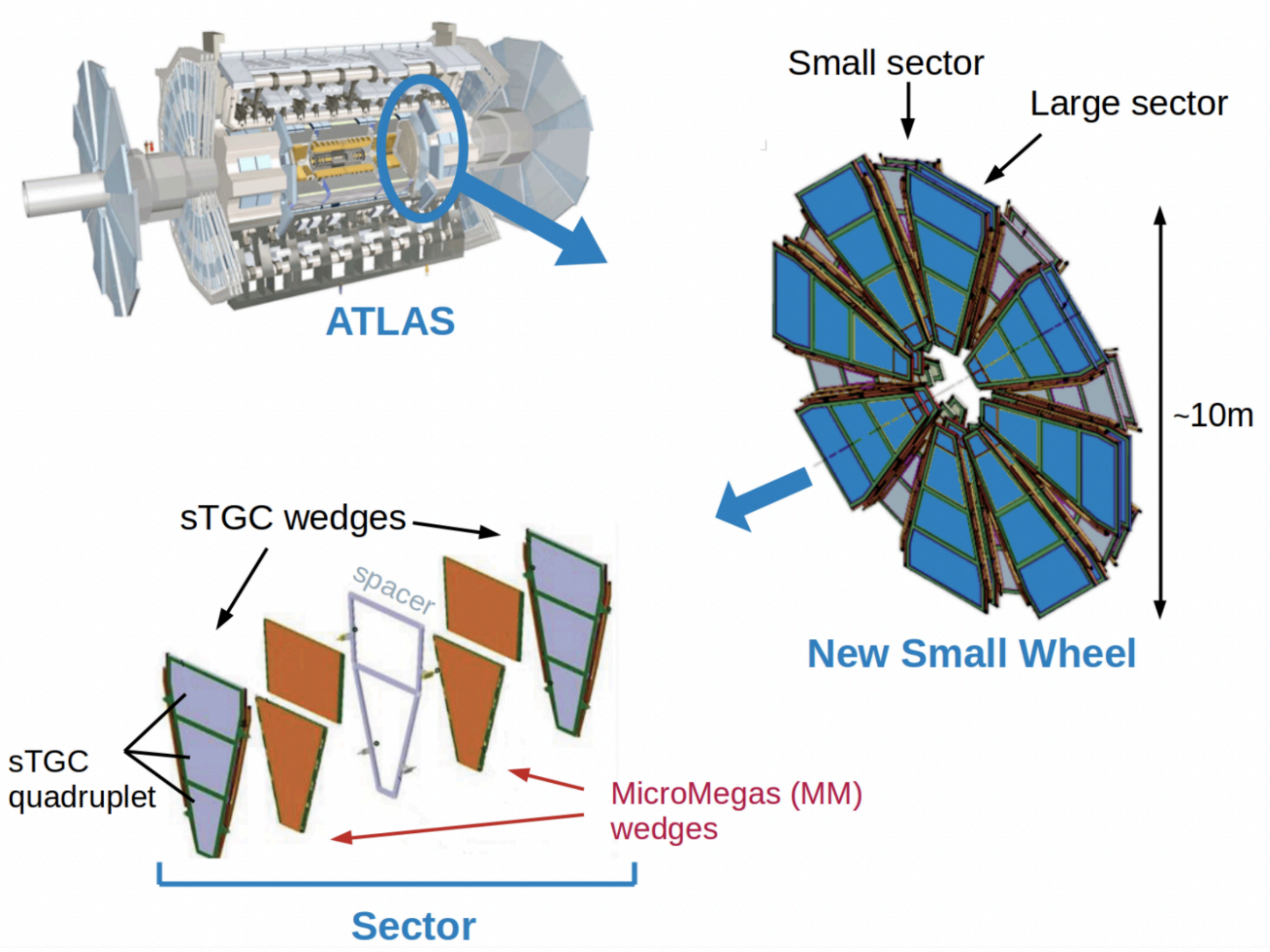
Phase-I upgrade projects

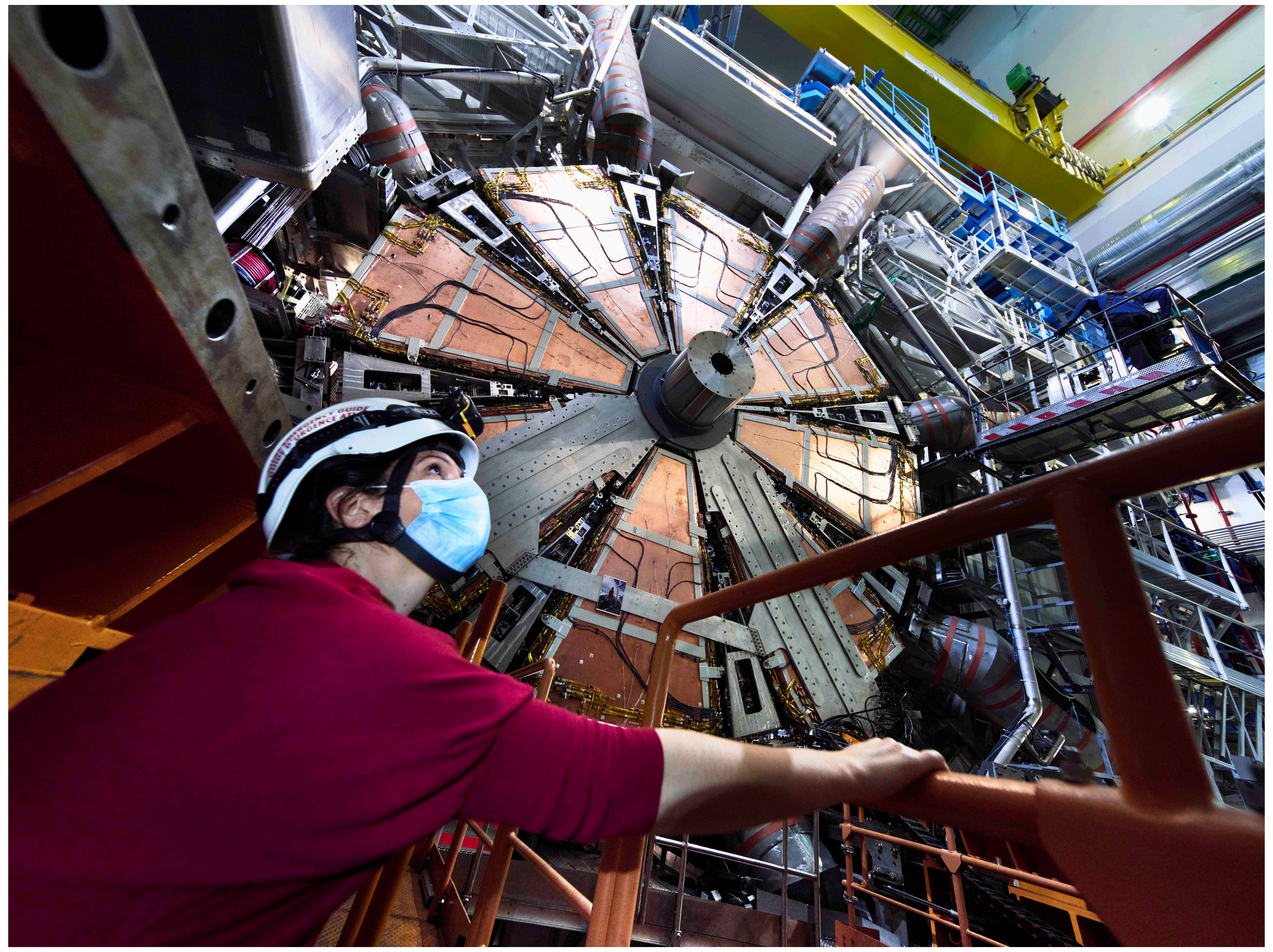
New Small Wheel (NSW) upgrade

Both NSWs successfully installed in ATLAS during LS2

- Largest Phase-I upgrade of the ATLAS detector
- Built in ATLAS institutes around the world and mounted on the wheels at CERN over the course of several years

sTGC-ATLAS PROJECT — TRIUMF, SFU Simon Fraser University, Carleton University, University of Victoria, McGill University





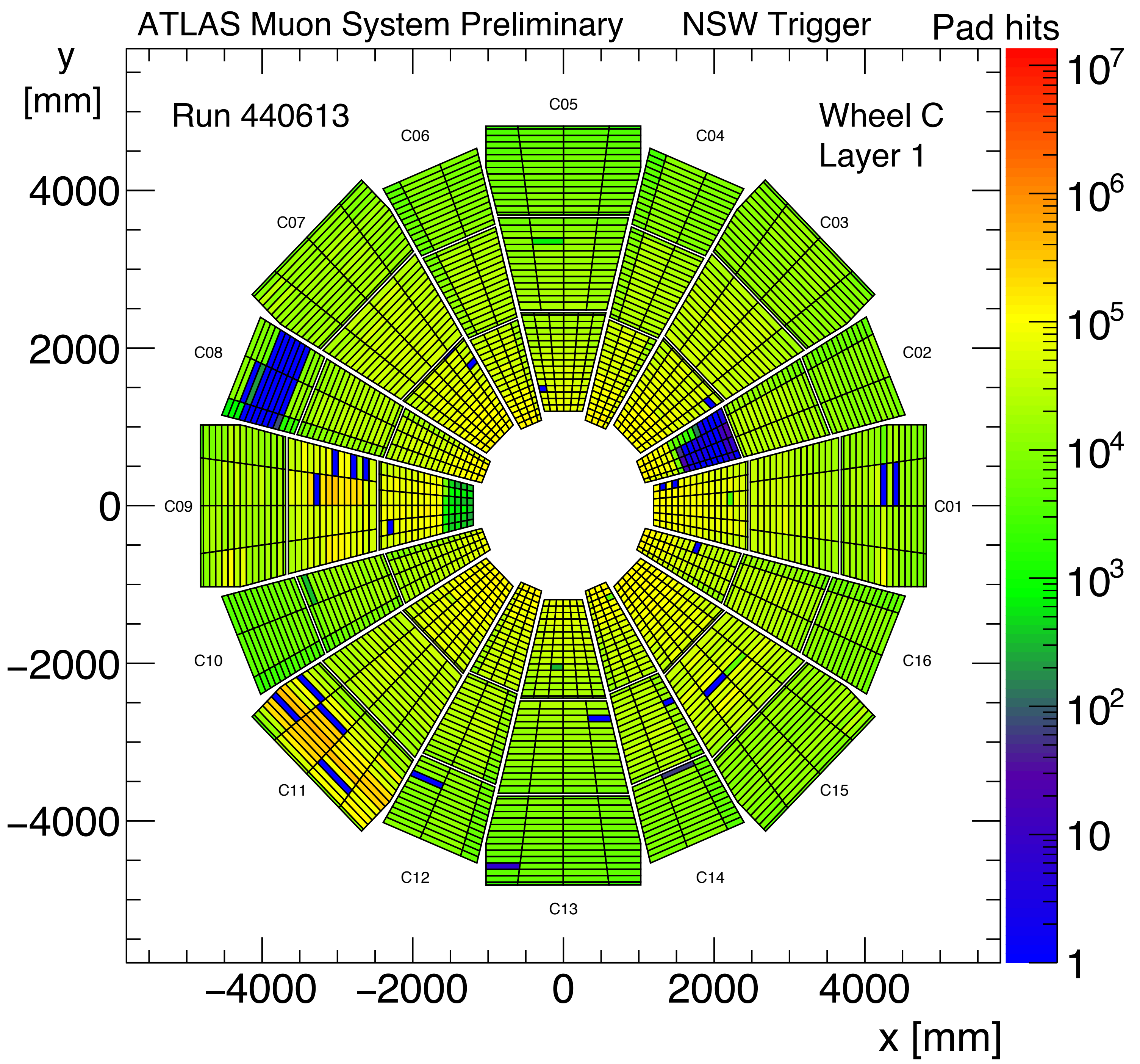
Phase-I upgrade projects

New Small Wheel (NSW) performance

Both NSWs are performing well in Run 3 data taking

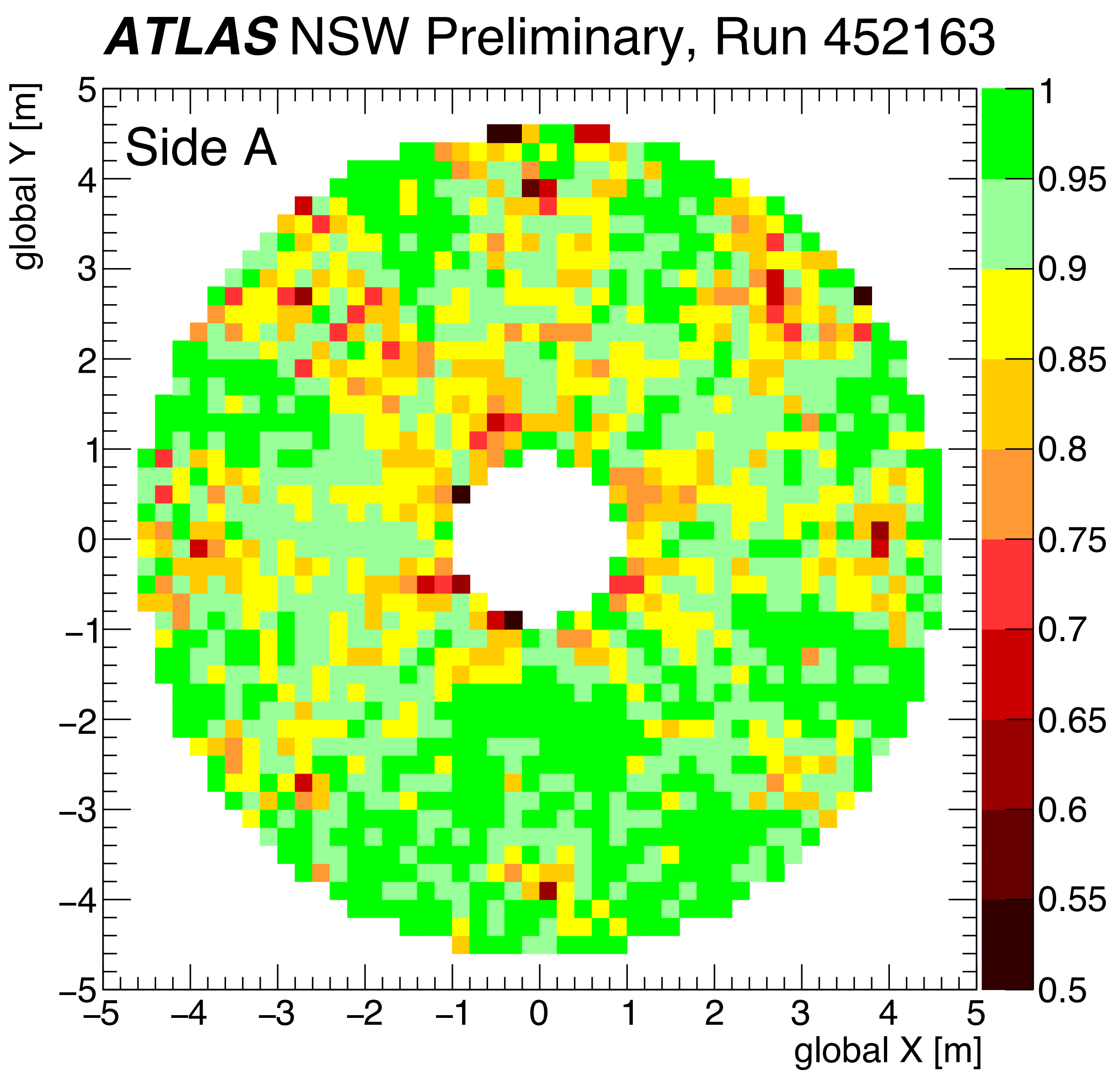
- DAQ stability and in-run recovery procedure significantly improved during 2022 YETS

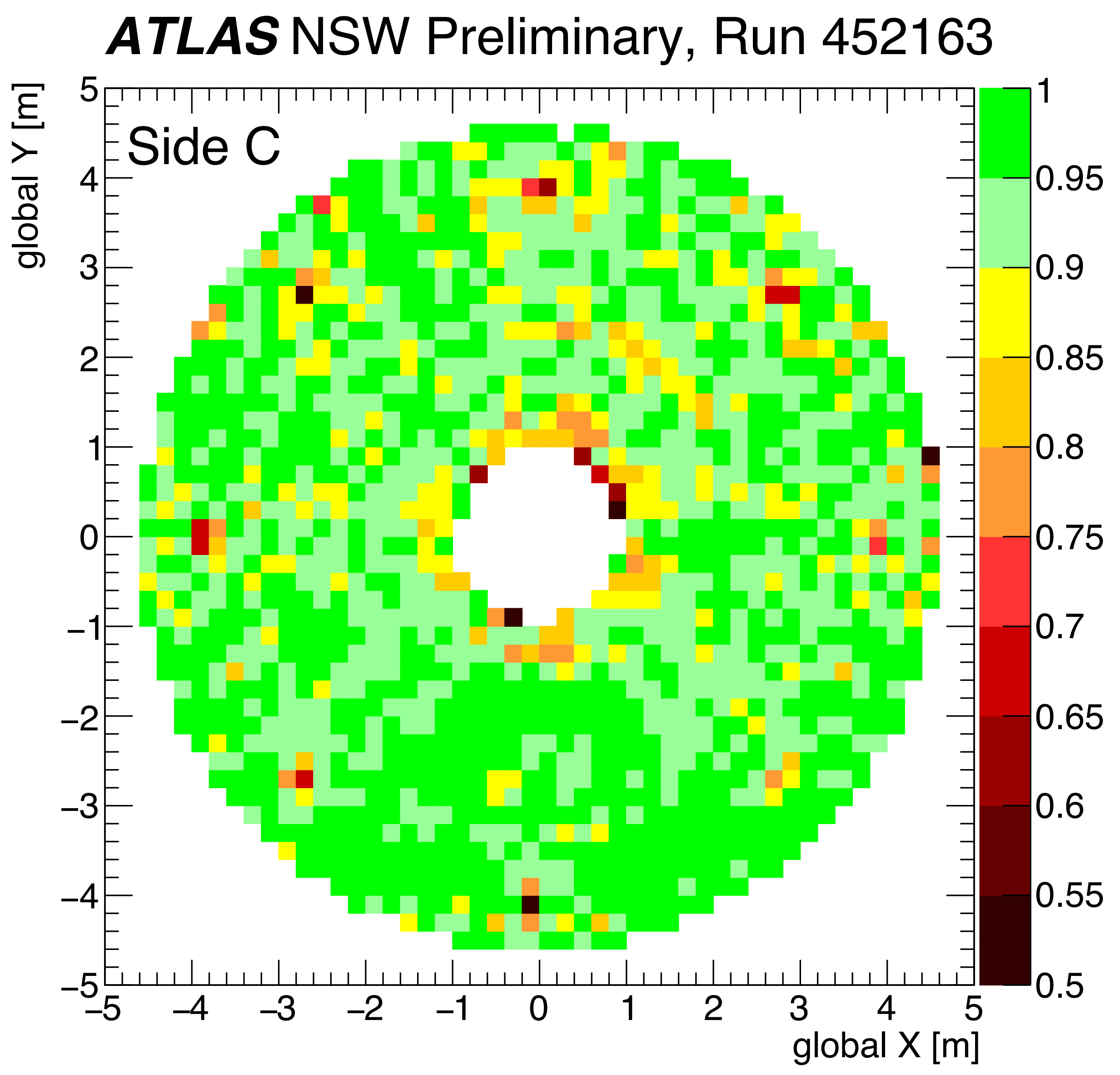
Trigger hits in NSW C



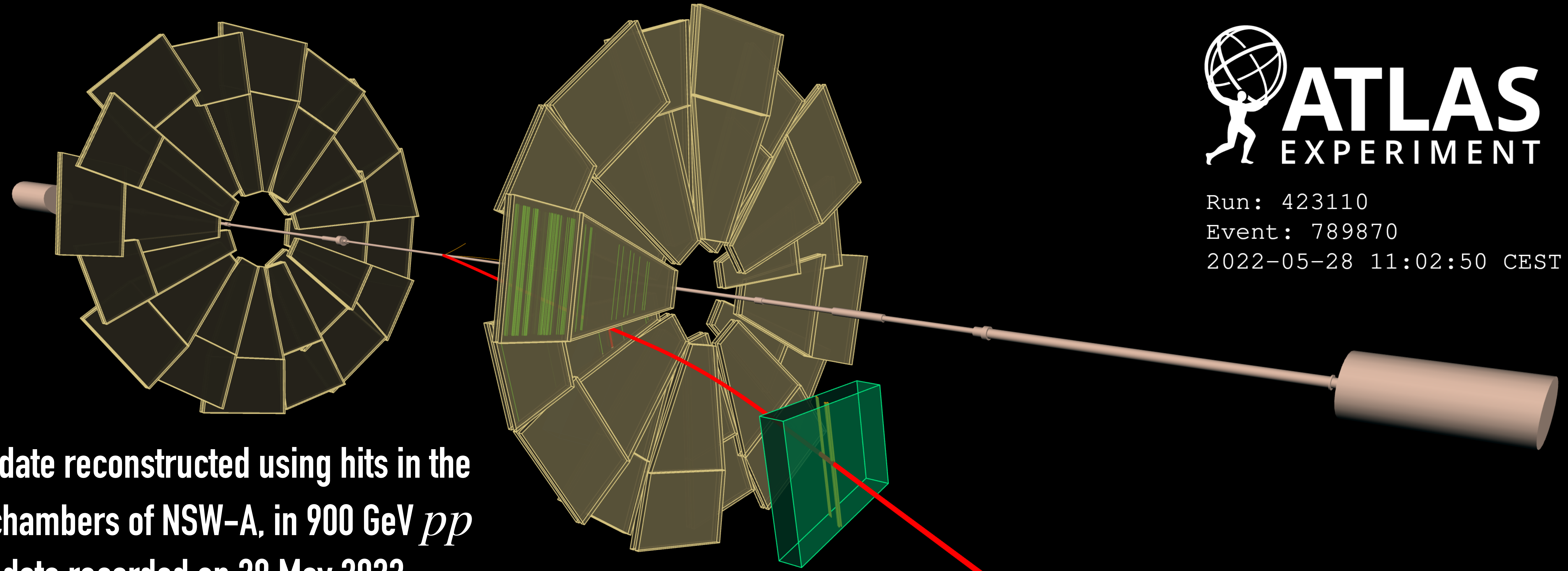
Efficiency for having at least 4/8 layers of either MMs or sTGC strip associated to a muon track

- Quantifies the efficiency with which the NSW is contributing to ATLAS muon track reco

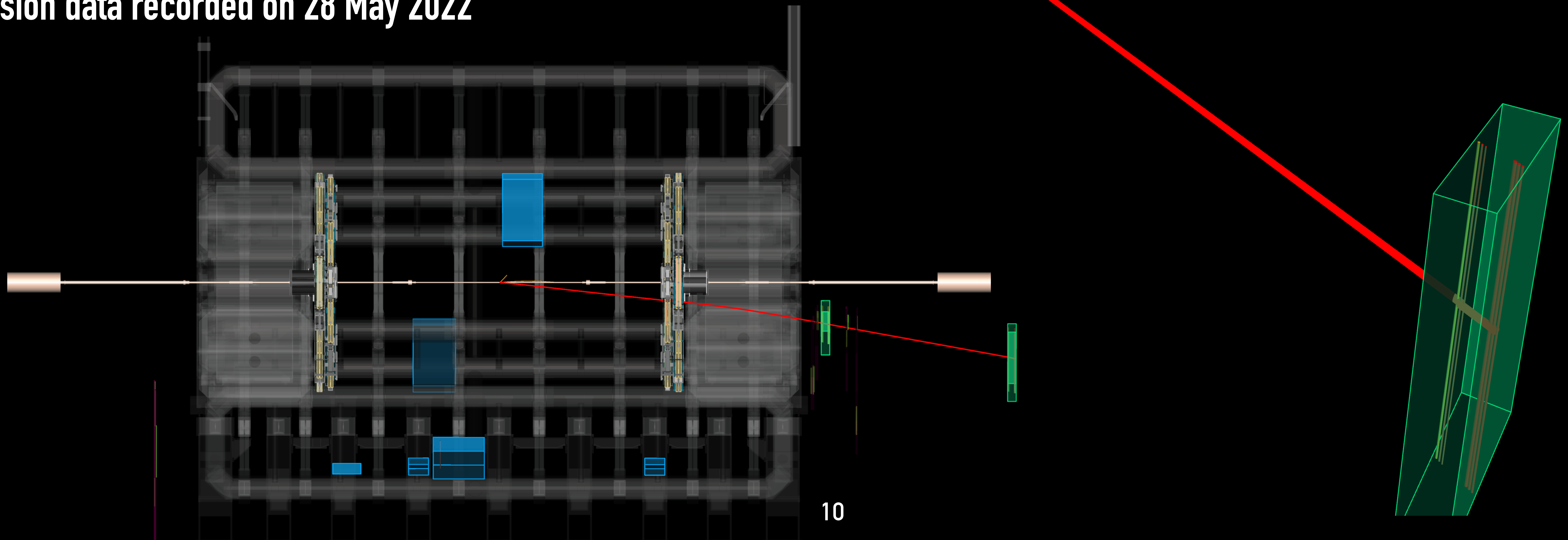




Additional figures available here



A muon candidate reconstructed using hits in the Micromegas chambers of NSW-A, in 900 GeV pp collision data recorded on 28 May 2022



Phase-I upgrade projects

Liquid Argon Calorimeter (LAr) trigger

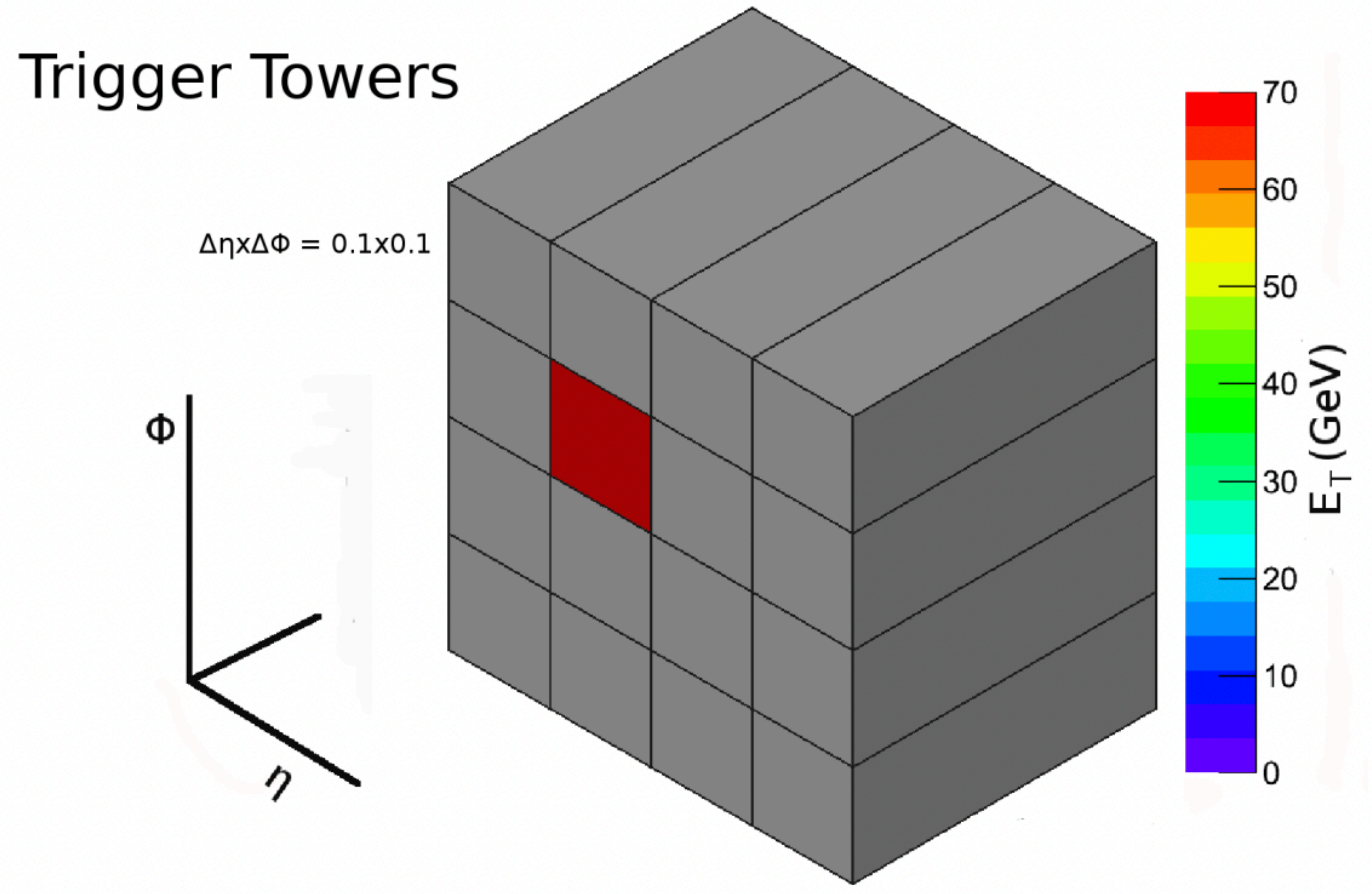
Phase-I digital trigger readout upgrade to maintain L1 trigger thresholds at similar rates to Runs 1-2 in higher μ conditions

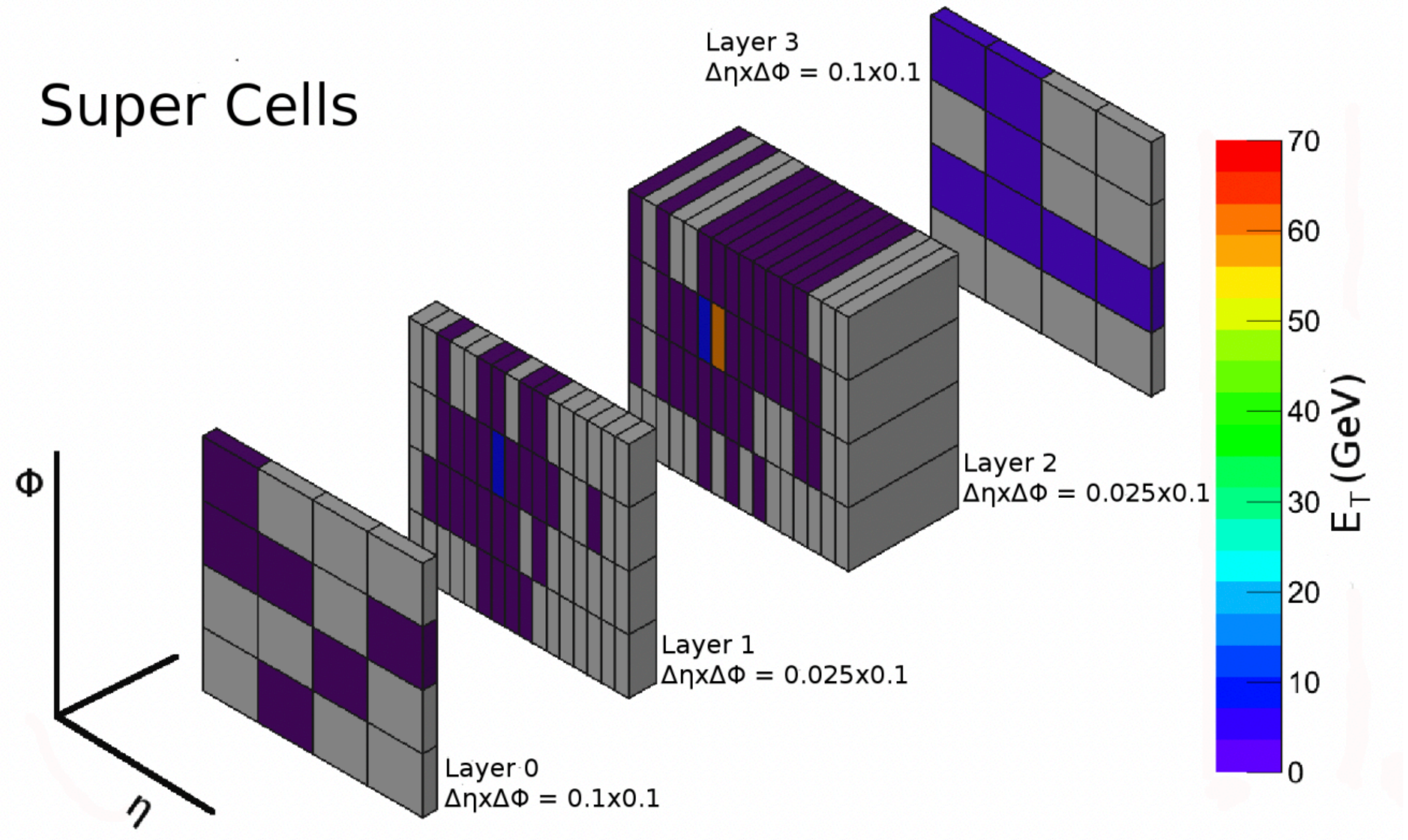
The legacy system sums calorimeter cells in different sampling layers to form "trigger towers"

- As a result, information about the development of shower shapes is lost, and cannot be used as a discriminating variable in the trigger decision

Digital trigger groups cells into "super cells" which provide information from up to four layers

- Readout has 10x finer granularity with respect to existing legacy system and longitudinal information to better exploit EM shower shapes





An electron (with 70 GeV of transverse energy) as seen by the legacy and upgraded Level-1 Calorimeter trigger electronics

Phase-I upgrade projects

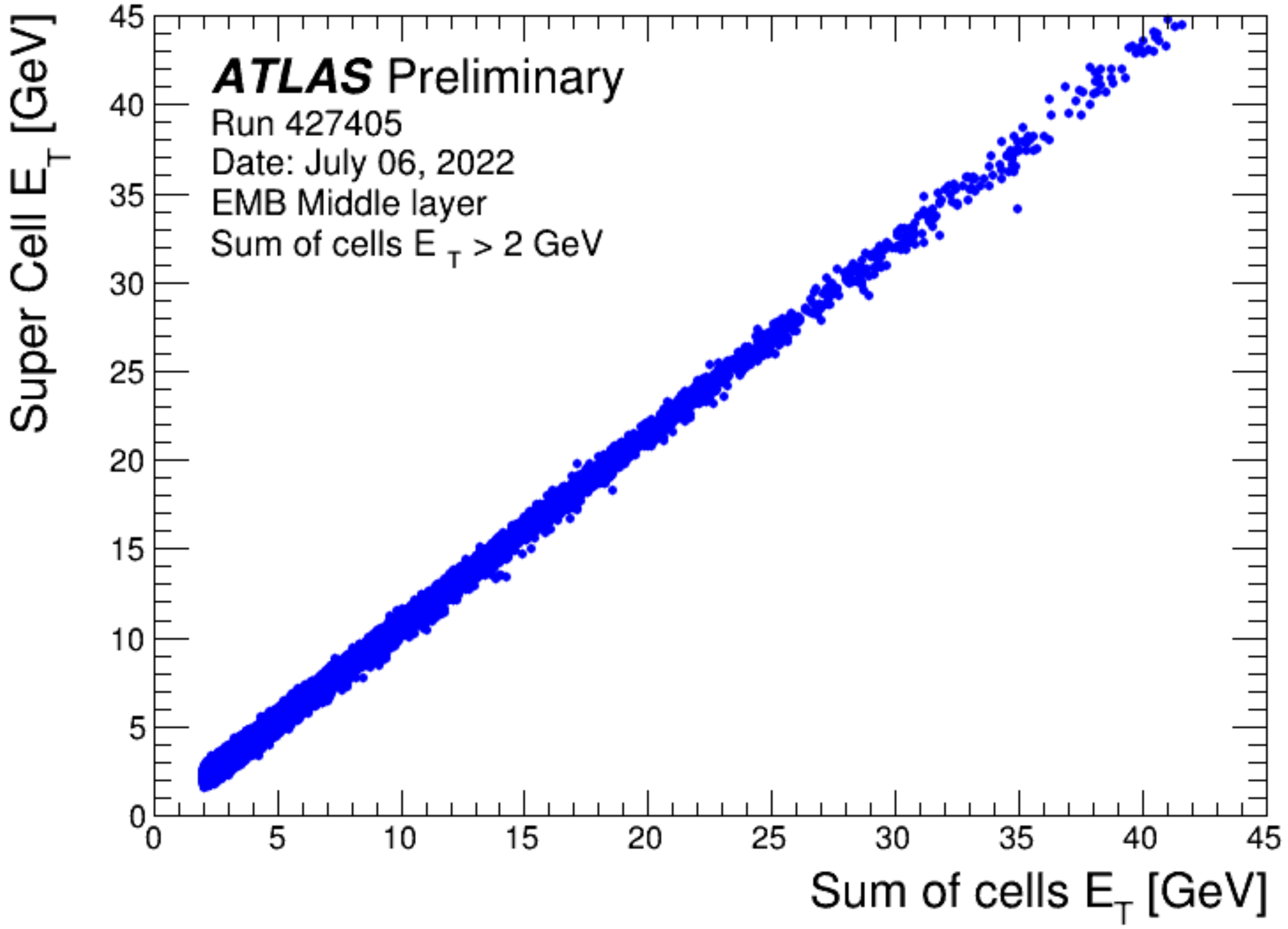
Liquid Argon Calorimeter (LAr) trigger

All hardware has been fully installed and operational since the beginning of 2022

- Both the legacy and digital trigger LAr systems included in all physics runs during 2022 data-taking
- Good agreement is observed between the two readouts systems

During 2022 data taking, legacy system kept as default trigger while commissioning the digital trigger system

- Mid-November 2022: Successfully ran with HLT seeded by the digital trigger
- Digital trigger system successfully run at high rate



Additional figures here

Detector commissioning — alive channels

Subdetector	Number of channels	Operational fraction [%] (May 2023)	Operational fraction [%] (March 2019)
Pixels	92 M	**95.3%**	95.7%
SCT Silicon Strips	6.3 M	**98.4%**	98.6%
TRT Transition Radiation Tracker	350 k	**94.9%**	97.2%
LAr EM Calorimeter	170 k	**100%**	100%
Tile Calorimeter	5200	**99.4%**	99.5%
Hadronic End-Cap LAr	5600	**99.9%**	99.7%
Forward LAr Calorimeter	3500	**99.8%**	99.8%
LVL1 Calo Trigger Legacy	7160	**99.9%**	99.9%
LVL1 Muon RPC Trigger	383 k	**99.8%**	100%
LVL1 Muon TGC Trigger	312 k	**100%**	99.9%
MDT Muon Drift Tubes	344 k	**99.7%**	99.7%
CSC Cathode Strip Chambers	31 k	**—**	93.0%
MicroMegas NSW	2.1 M	**98.0%**	—
STGC NSW	358 k	**95.0%**	—
RPC Barrel Muon Chambers	383 k	**90.1%**	93.3%
TGC End-Cap Muon Chambers	312 k	**99.3%**	98.9%
ALFA	10 k	**100%**	99.9%
AFP	430 k	**98.1%**	97.0%
LUCID	2x(12+8)	**100%**	Not given
ZDC	2x(4+16)	**100%**	Not given

All detector subsystems are healthy and operational

- Similar operational fraction as end of Run 2
- New small wheel (NSW) operating fraction 98% for MicroMegas, 95% for STGC

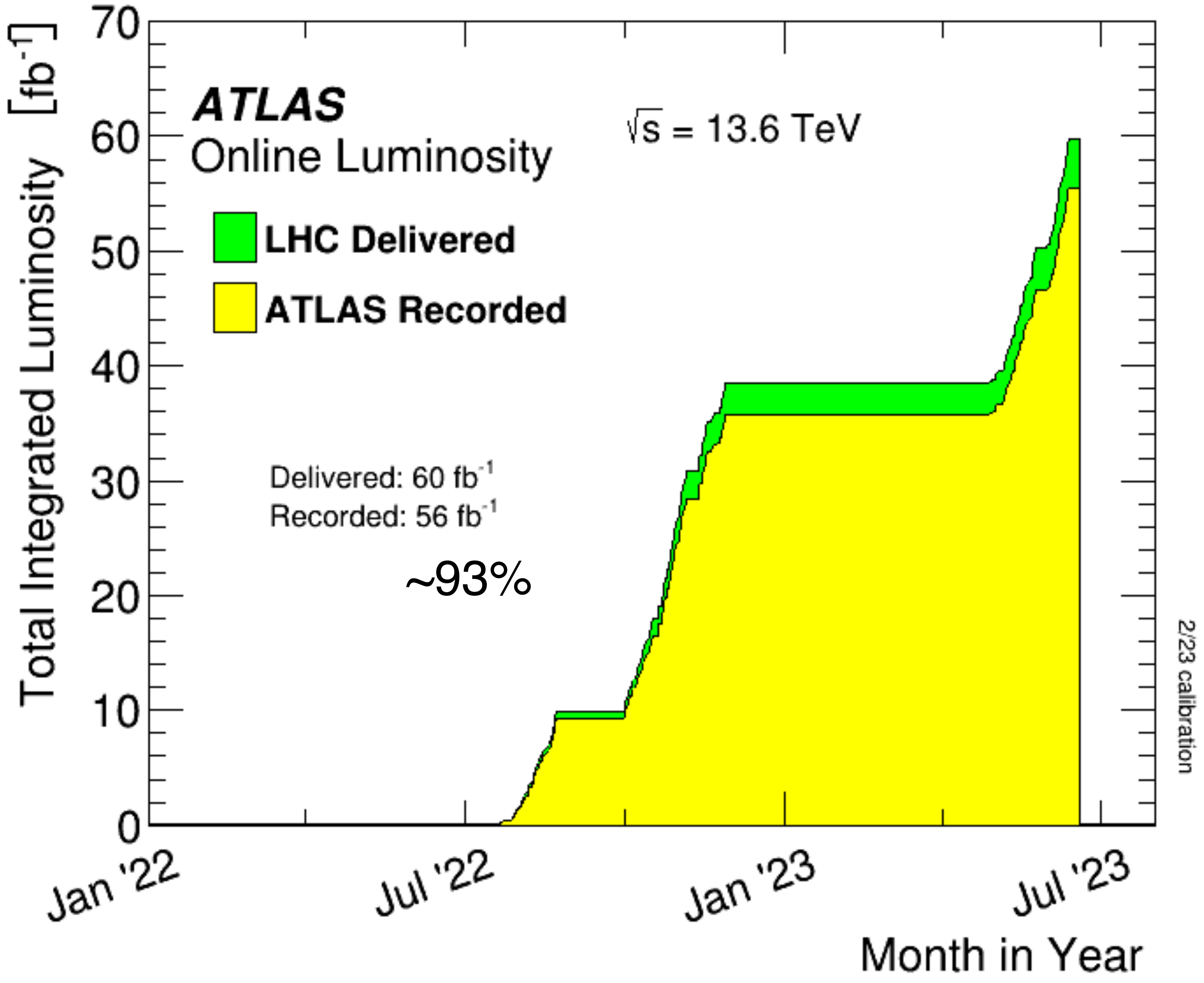
More tables and information here

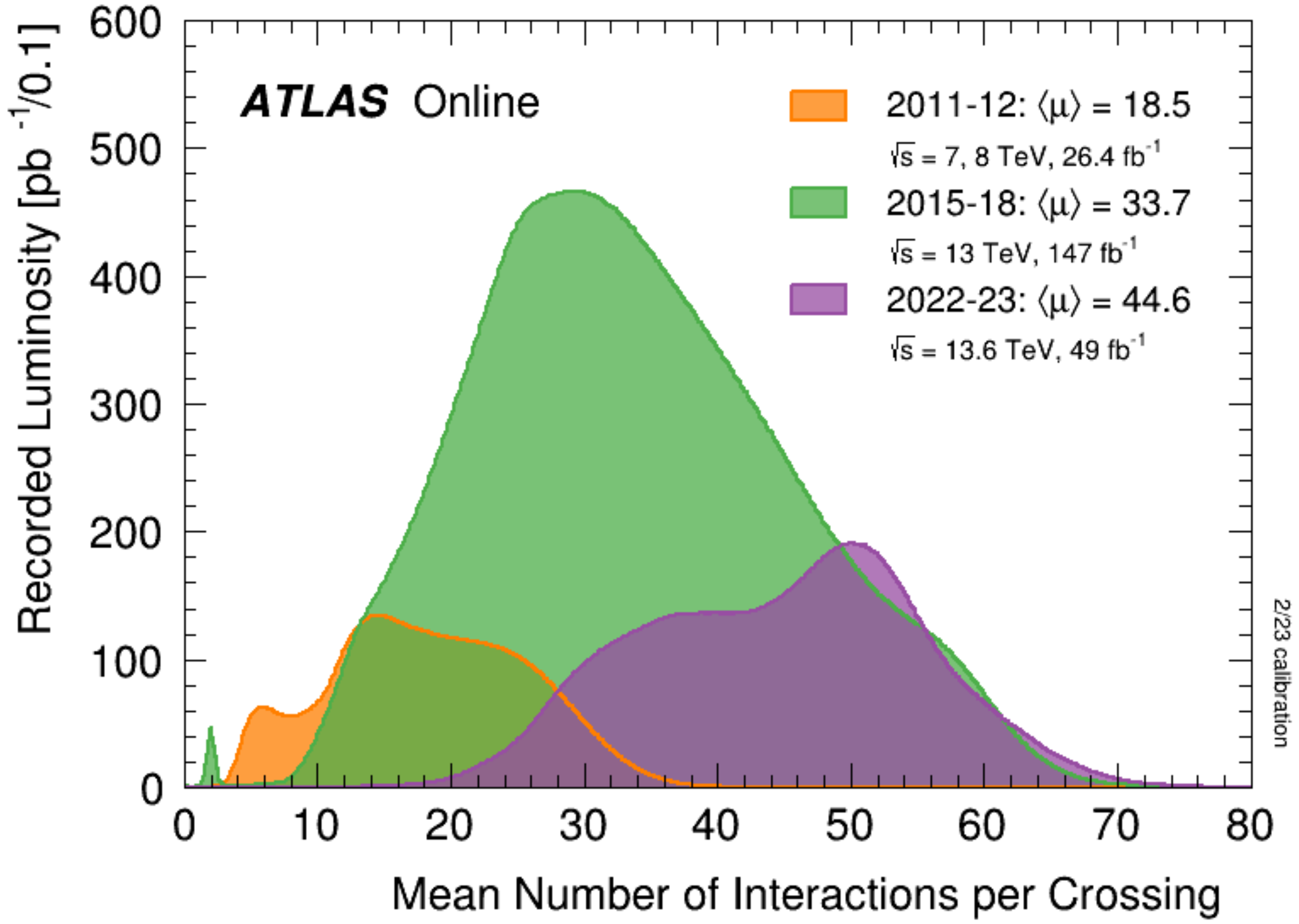
ATLAS Operations — luminosity

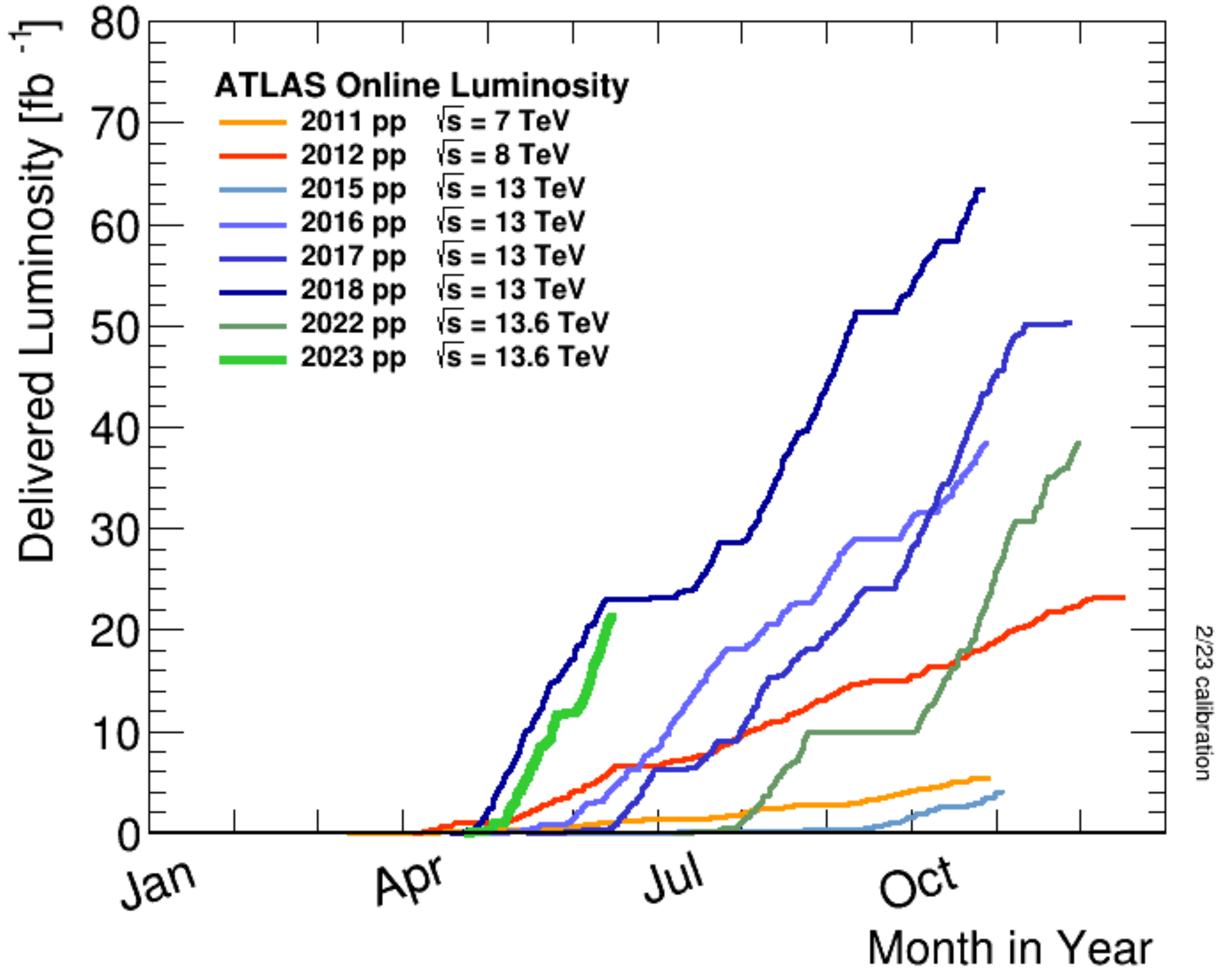
ATLAS recording data with good data taking efficiency

$56\ \mathrm{fb}^{-1}$ of data collected thus far in Run 3

- Average data taking efficiency of 93%
- Mean pileup (interactions per bunch crossing) of $\langle \mu \rangle = 44.6$







Additional figures available here

What's in store for Run 3?

Slightly higher CM energy, double the luminosity of Run 2

Higher CM energy provides non-negligible increases in cross section for many interesting physics processes

- Improves discovery potential significantly for high-mass searches for e.g. Z' and quantum black holes (QBH)

Larger dataset will increase precision for measurements of rare processes which are dominated by statistical uncertainties

Channel	13.6 / 13 TeV
H (ggF)	**7%**
HH	**11%**
tt	**11%**
ttH	**13%**
tttt	**19%**
SUSY stop (1.2–1.5 TeV)	**20–30%**
Z' (5–6 TeV)	**50–70%**
QBH (9.5 TeV)	**250%**

Major improvements to reconstruction and trigger

Better track reconstruction, improved flavour tagging, (and more) to improve sensitivity and precision

- Significant improvements for long-lived particle (LLP) searches

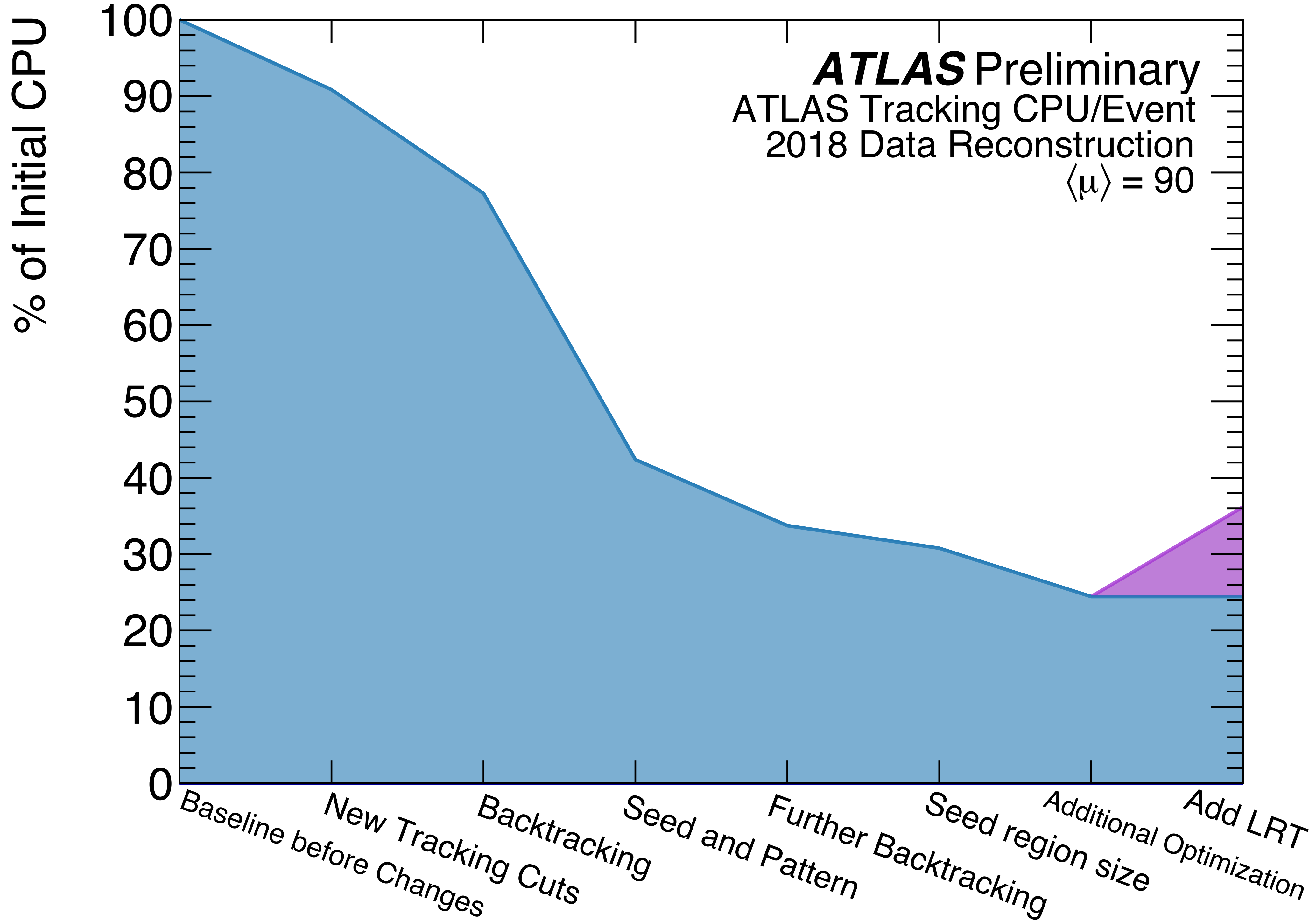
New triggering strategies for challenging signatures

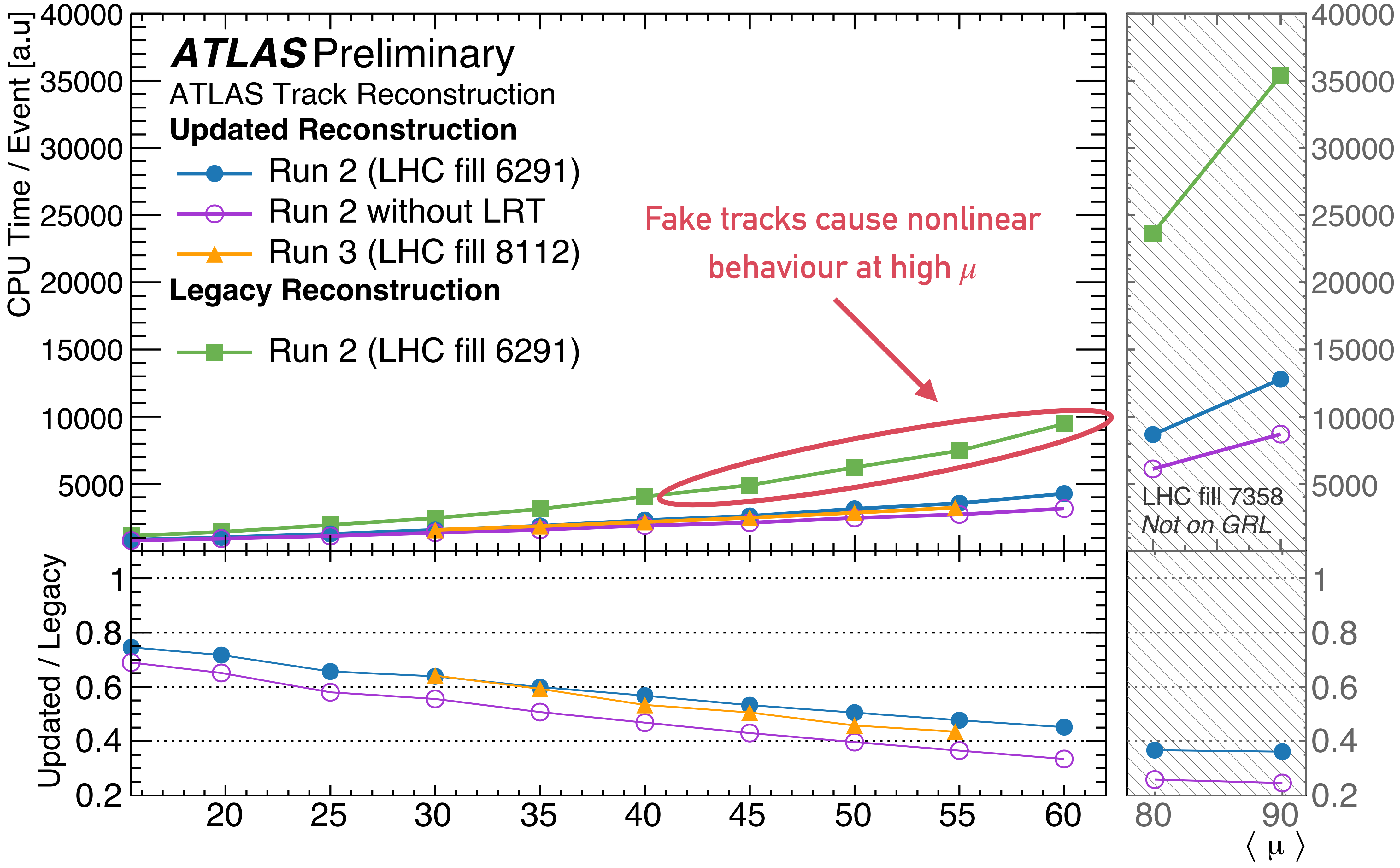
Improved track reconstruction

Significant improvements made to ATLAS track reconstruction

In preparation for higher values of $\langle\mu\rangle$, track reconstruction software overhauled

- Significant track reconstruction speed-up and reduction in fake tracks





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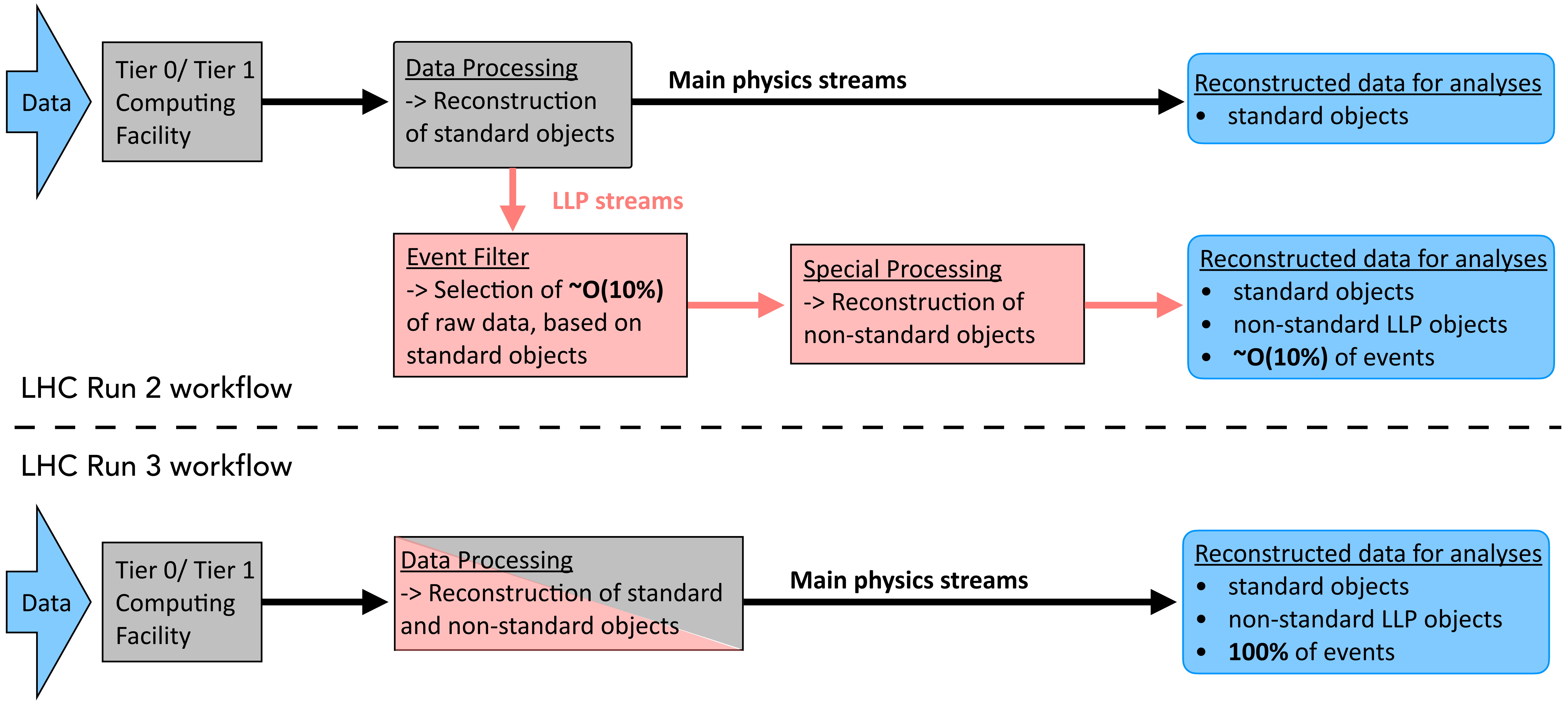
Improved track reconstruction

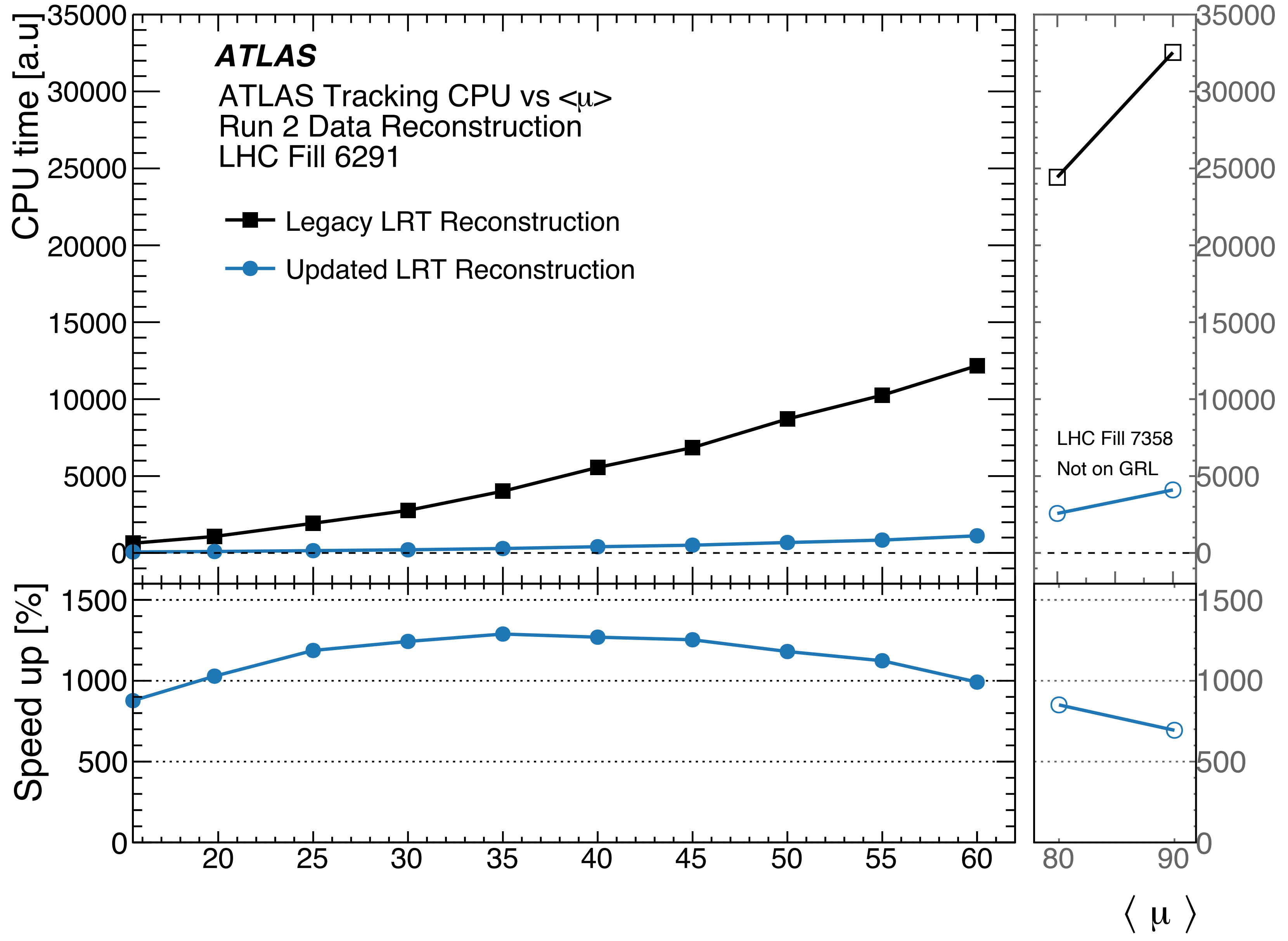
Dedicated track reconstruction for long-lived particles

ATLAS employs a dedicated “large radius track” (LRT) reconstruction pass for tracks with large transverse impact parameter ($|d_0| > 5\,\mathrm{mm}$)

- Run II LRT implementation optimized for high reconstruction efficiency but with a high rate of fake tracks
  - Very high rate prohibited LRT being run in standard reconstruction → special data stream needed
- Run III implementation re-optimized for fake reduction and CPU time
  - Factor of >1000% speed up enabled this reconstruction to be integrated into standard reconstruction and run for all events

IDTR-2021-03

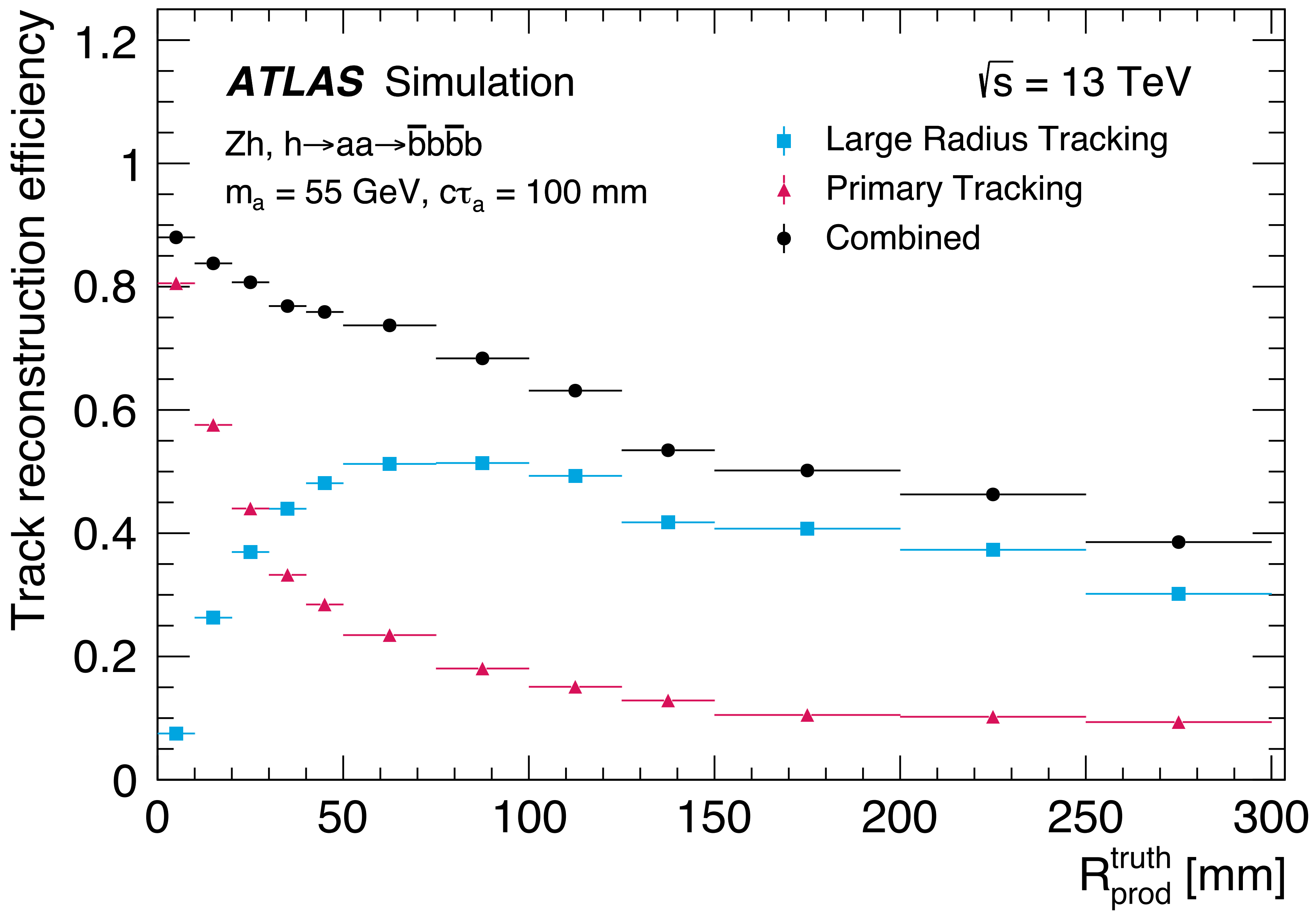


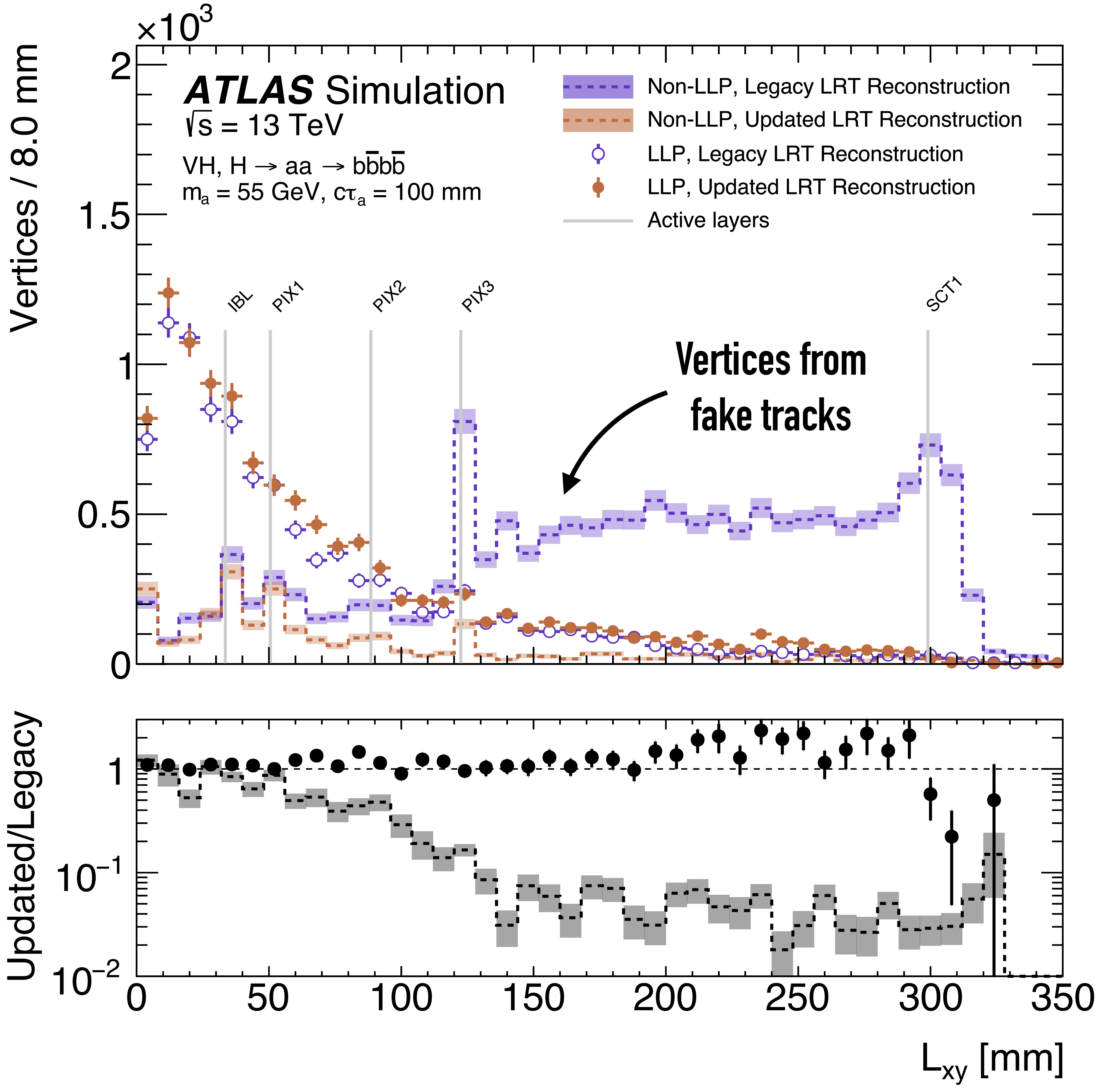


Improved track reconstruction

Dedicated track reconstruction for long-lived particles

- Track reconstruction efficiencies minimally affected by updated configuration
- Run 3 LRT configuration gives rise to ~10x fewer fake secondary vertices
  - Despite tighter LRT cuts, vertex reconstruction efficiency improves due to cleaner vertexing environment
- Large gains in analysis sensitivity expected





IDTR-2021-03

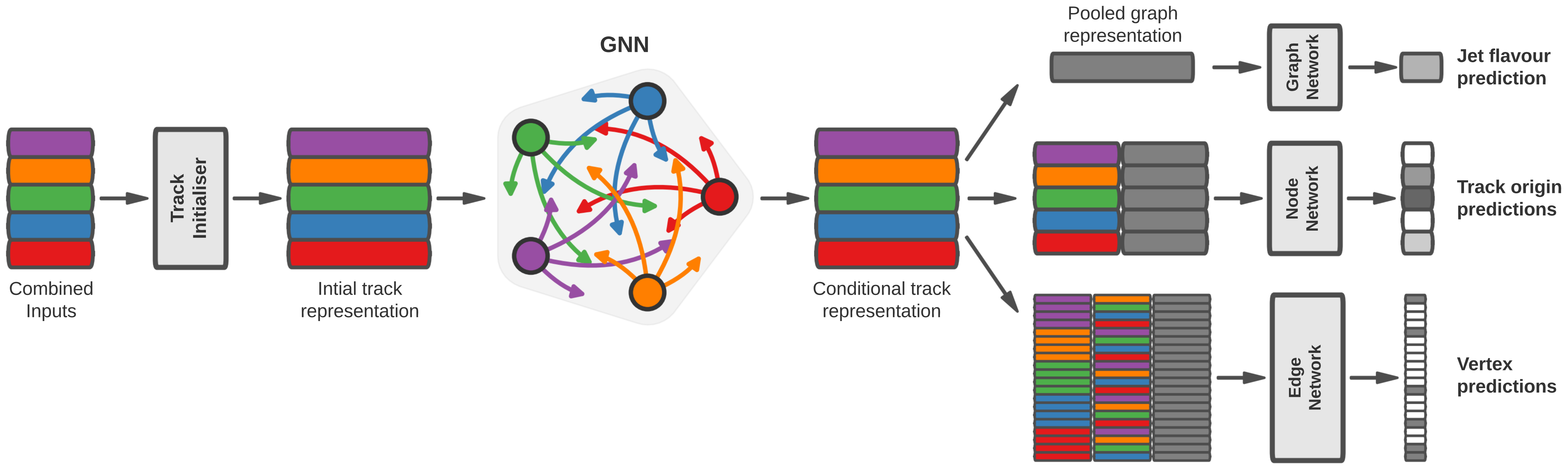
Improved flavour tagging

New graph neural network (GNN) taggers deployed

Fully track-based, eliminates need for hand-tuned low-level algorithms

Significant performance gains achieved

- 4x improvement in light-jet and charm-jet rejection from legacy DL1 tagger



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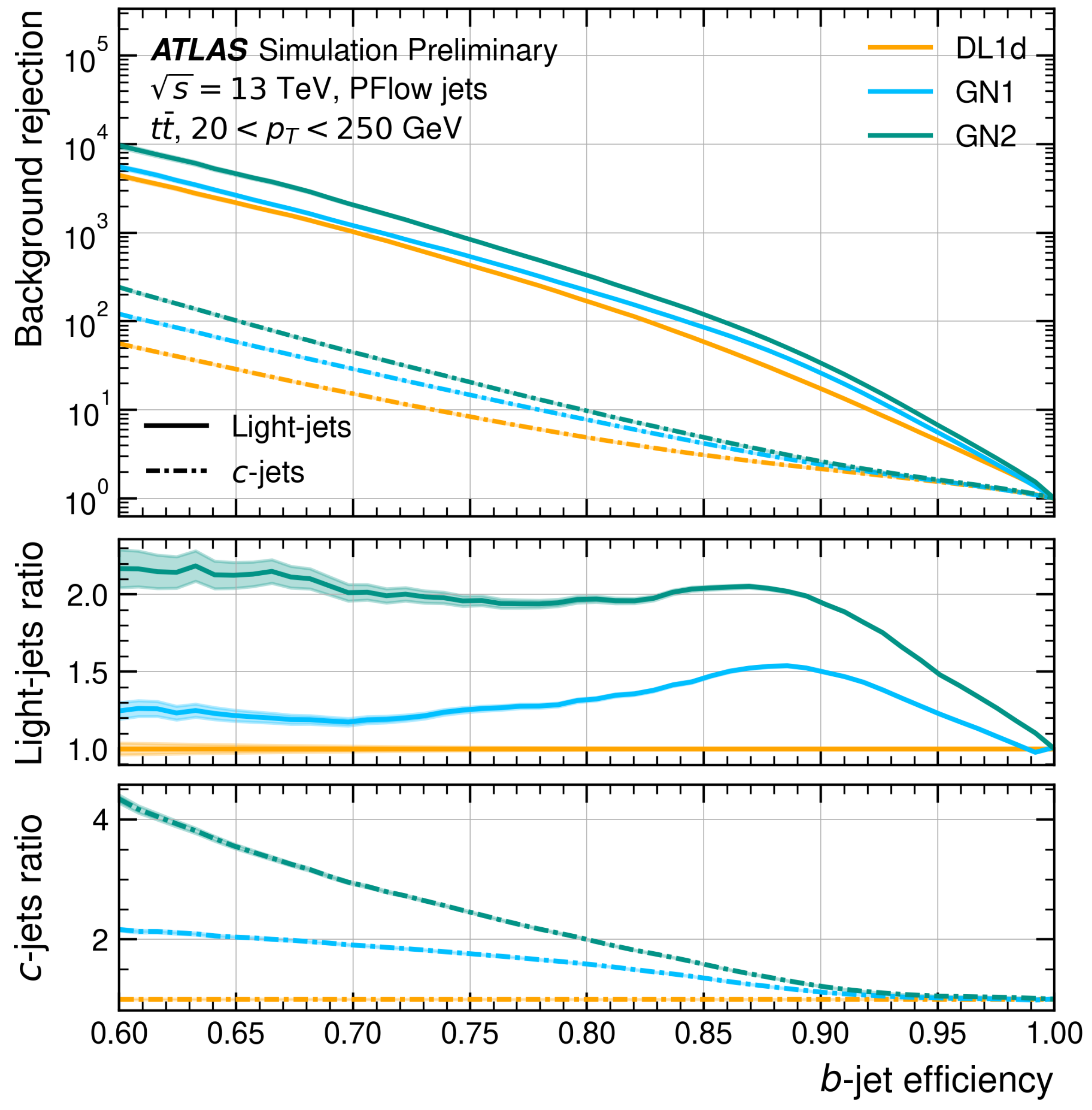
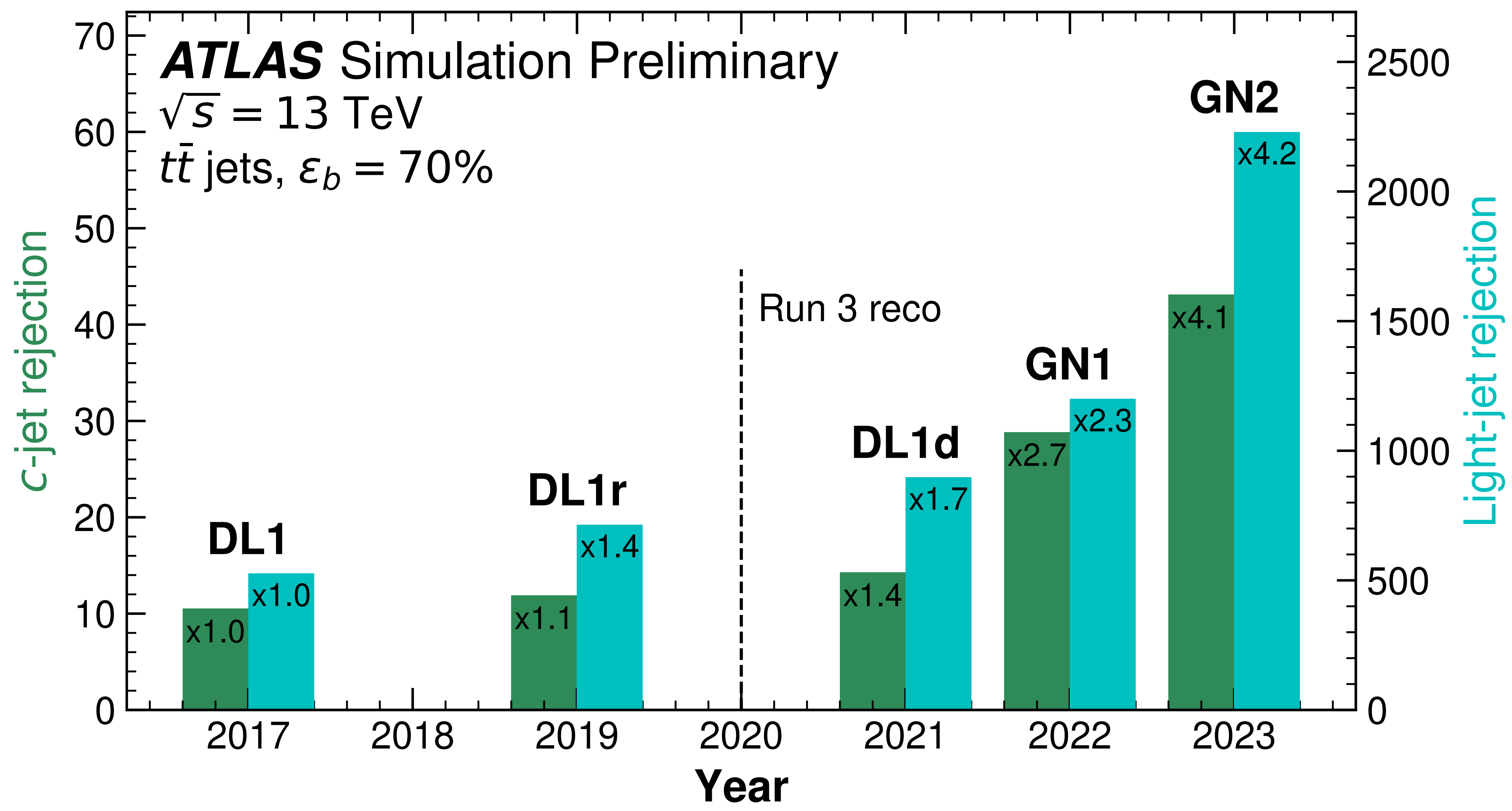




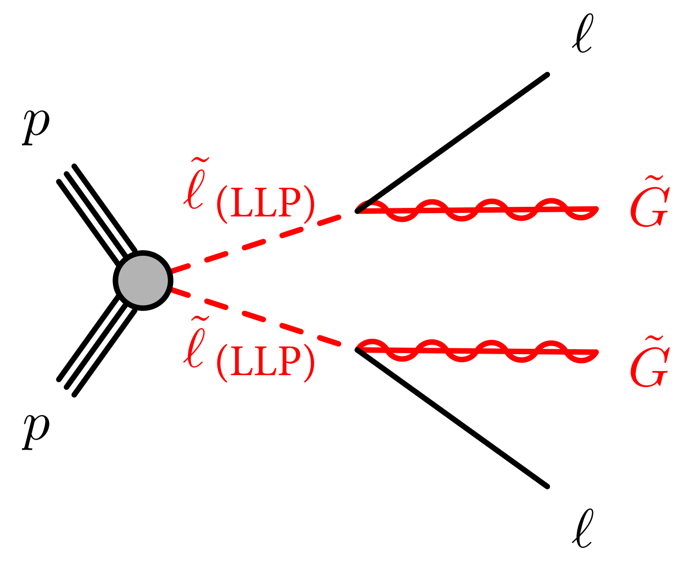
FTAG-2023-01

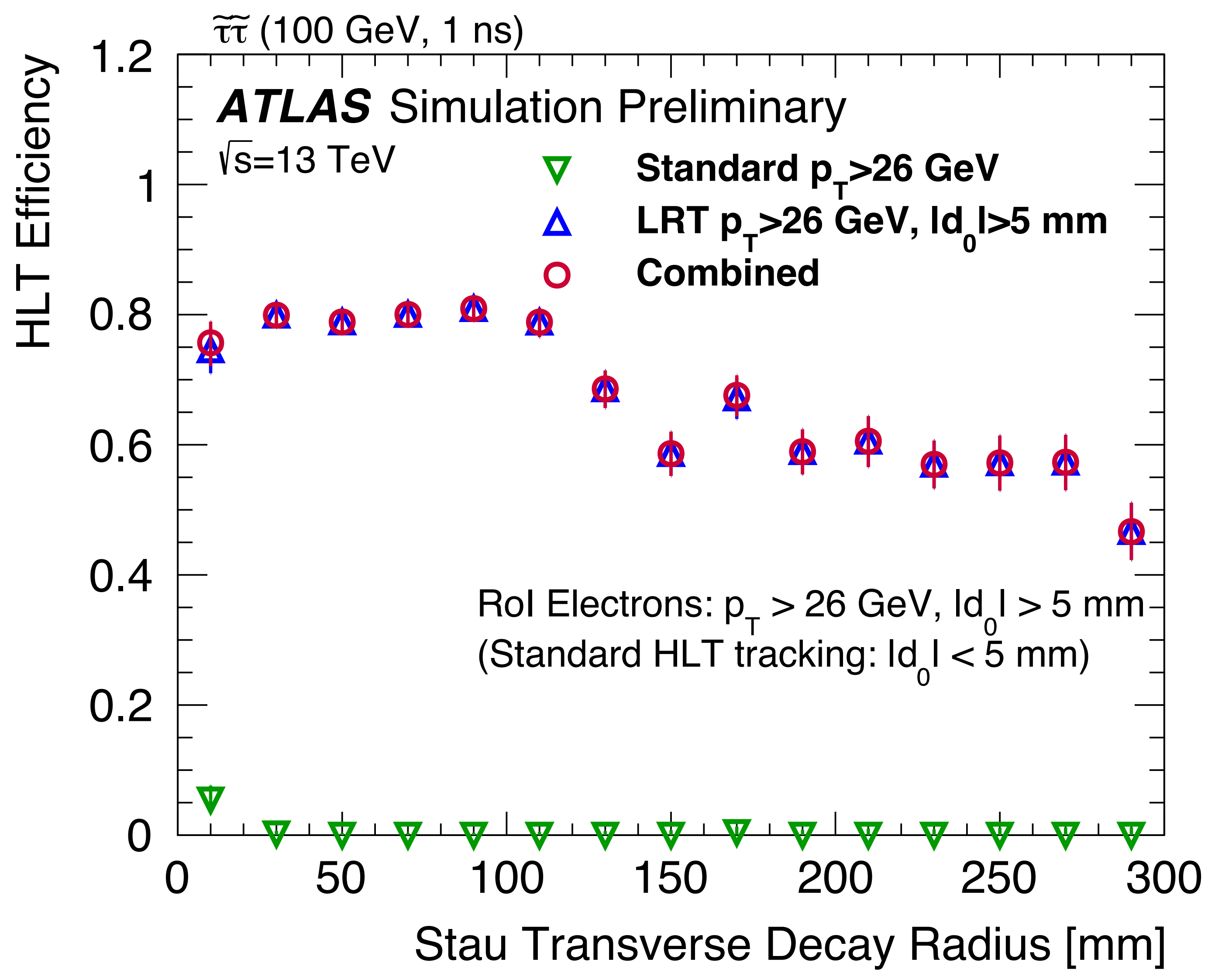
New Triggers for Run-3

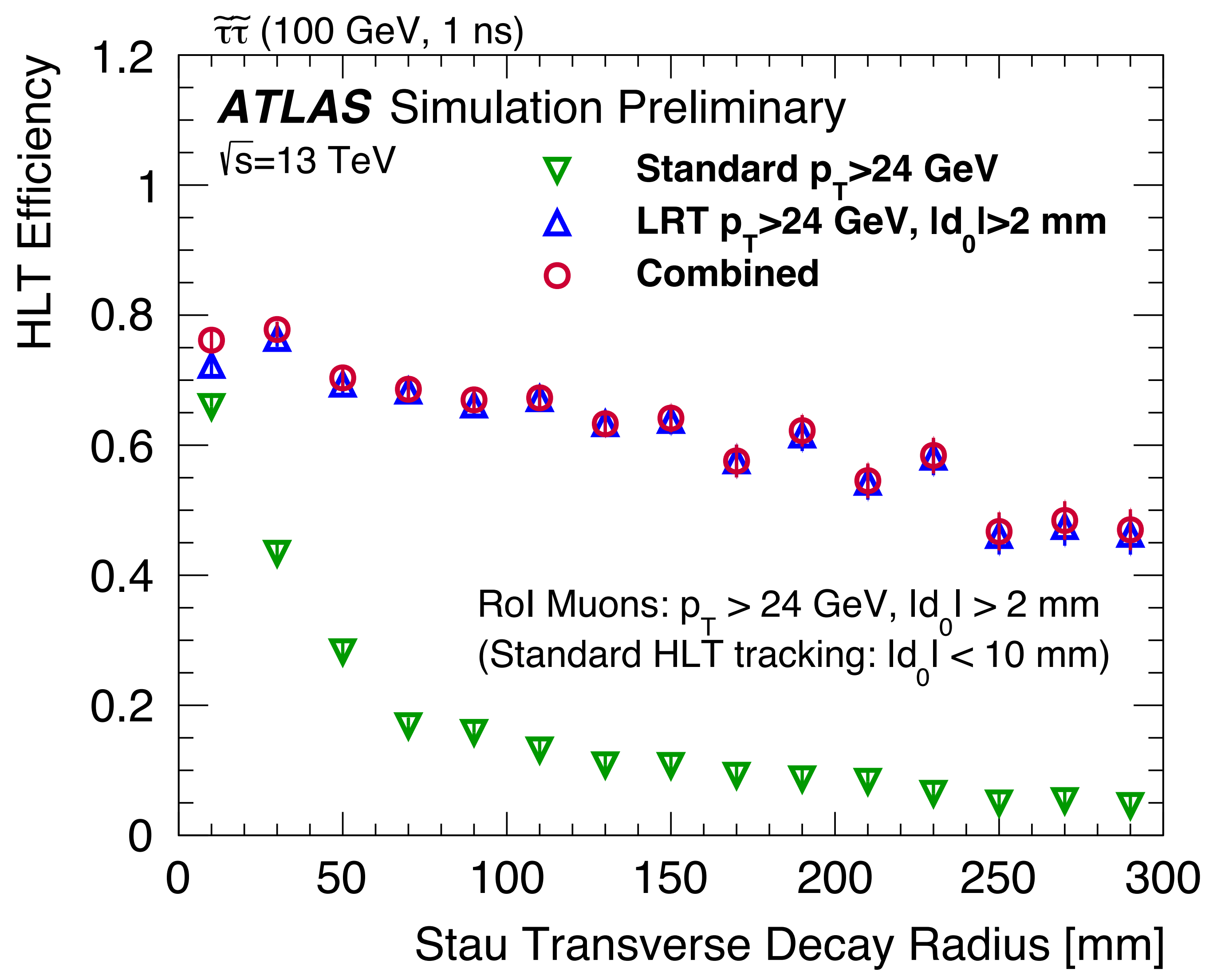
Many new triggers commissioned for Run-3 data taking for probing challenging and displaced signatures

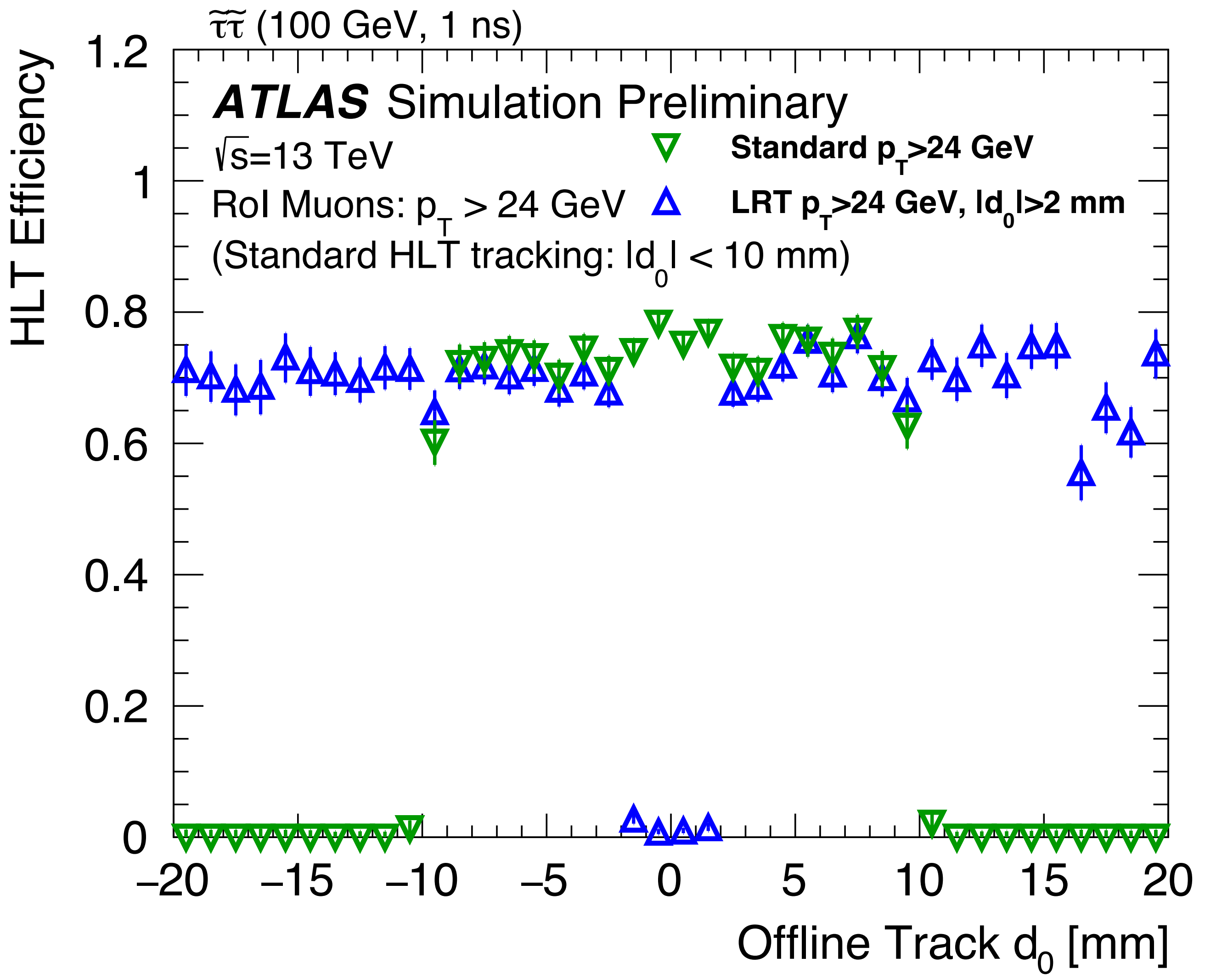
New displaced lepton triggers targeting ex. long-lived slepton decays

- Exploits improved offline large-radius track reconstruction configuration in the trigger









- Massive gain in HLT efficiency with respect to standard chains
- Lower thresholds compared to Run 2 trigger strategy

- Complements coverage in d_0 from standard chains

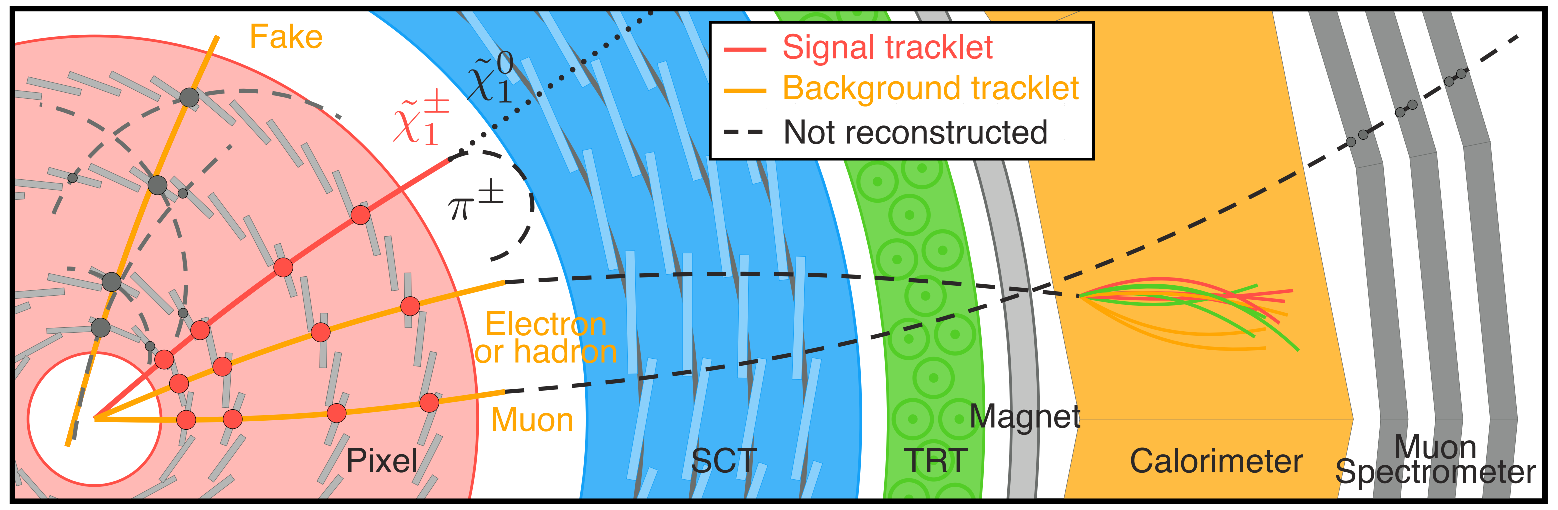
ATL-COM-DAQ-2022-023

New Triggers for Run-3

Many new triggers commissioned for Run-3 data taking for probing challenging and displaced signatures

New “disappearing track” trigger targeting long-lived chargino decays

- Characteristic of models with small mass splitting between $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$
- Dedicated “tracklet” reconstruction seeded by L1 MET triggers
- BDT used to select signal-like tracklets



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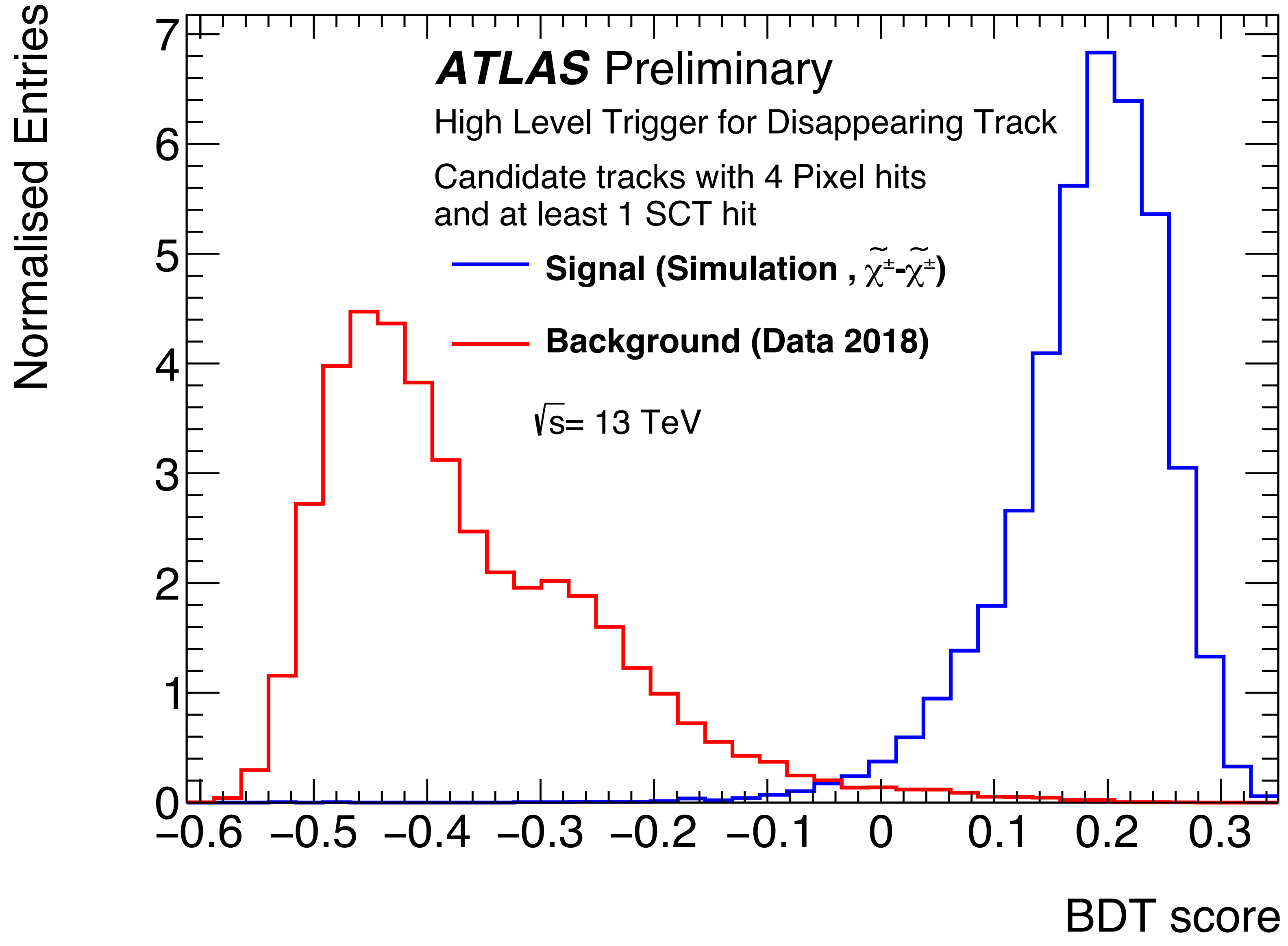
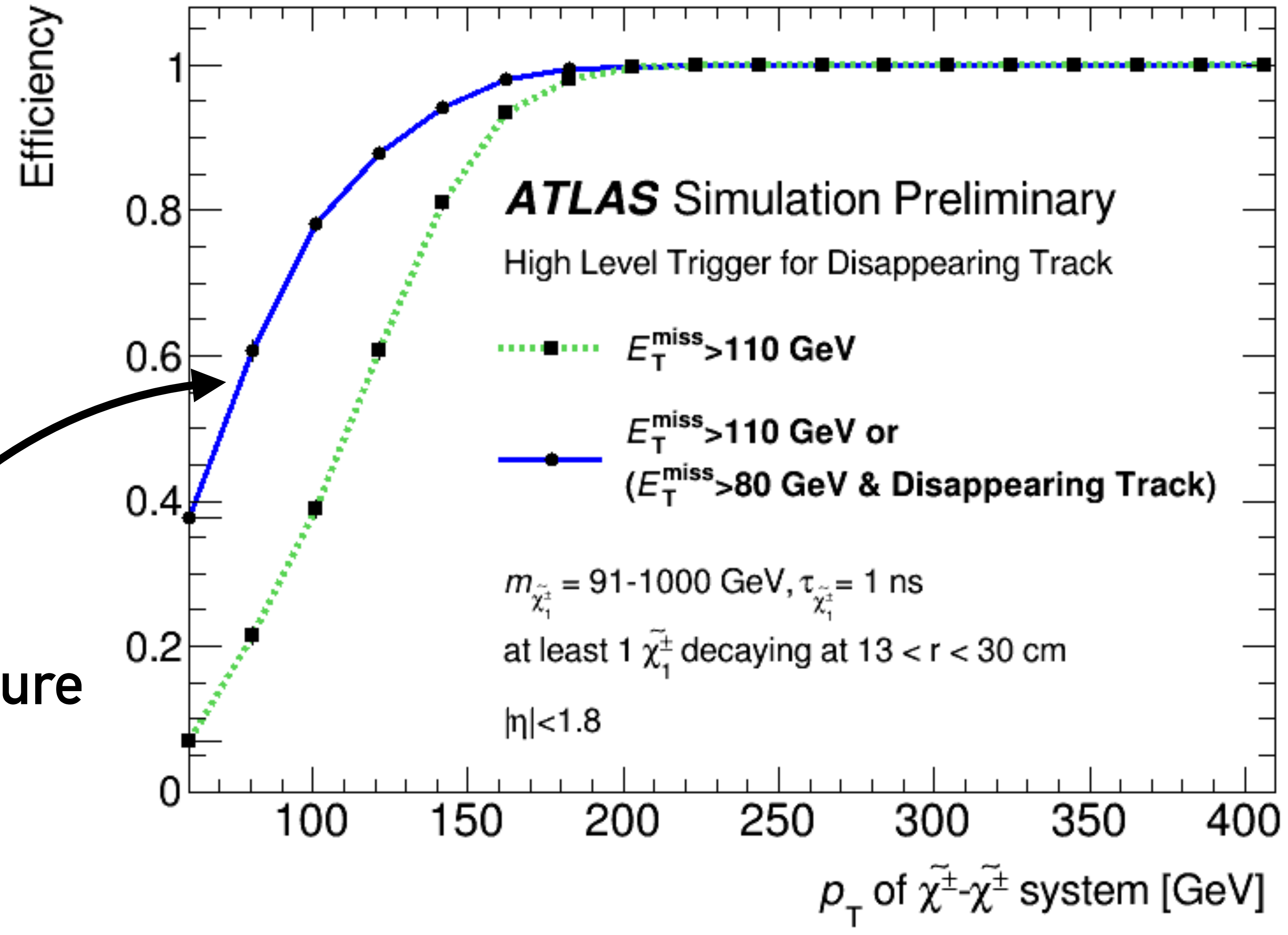


Improves acceptance over pure MET trigger for lower momentum models



Early Run 3 Physics results

Measurement of $t\bar{t}$ and Z-boson cross sections

Measurements performed with $11.3\,\mathrm{fb}^{-1}$

- Inclusive $t\bar{t}$ cross-section in dilepton ($e\mu$ channel only)
- Fiducial Z-boson cross section ($ee/\mu\mu$ channels)
- $t\bar{t}/Z$ cross section ratio
  - reduction of uncertainties
  - sensitive to gluon/quark PDFs

Important test of MC, detector + software validation

- Measurements strongly affected by the luminosity uncertainty (2.2%)

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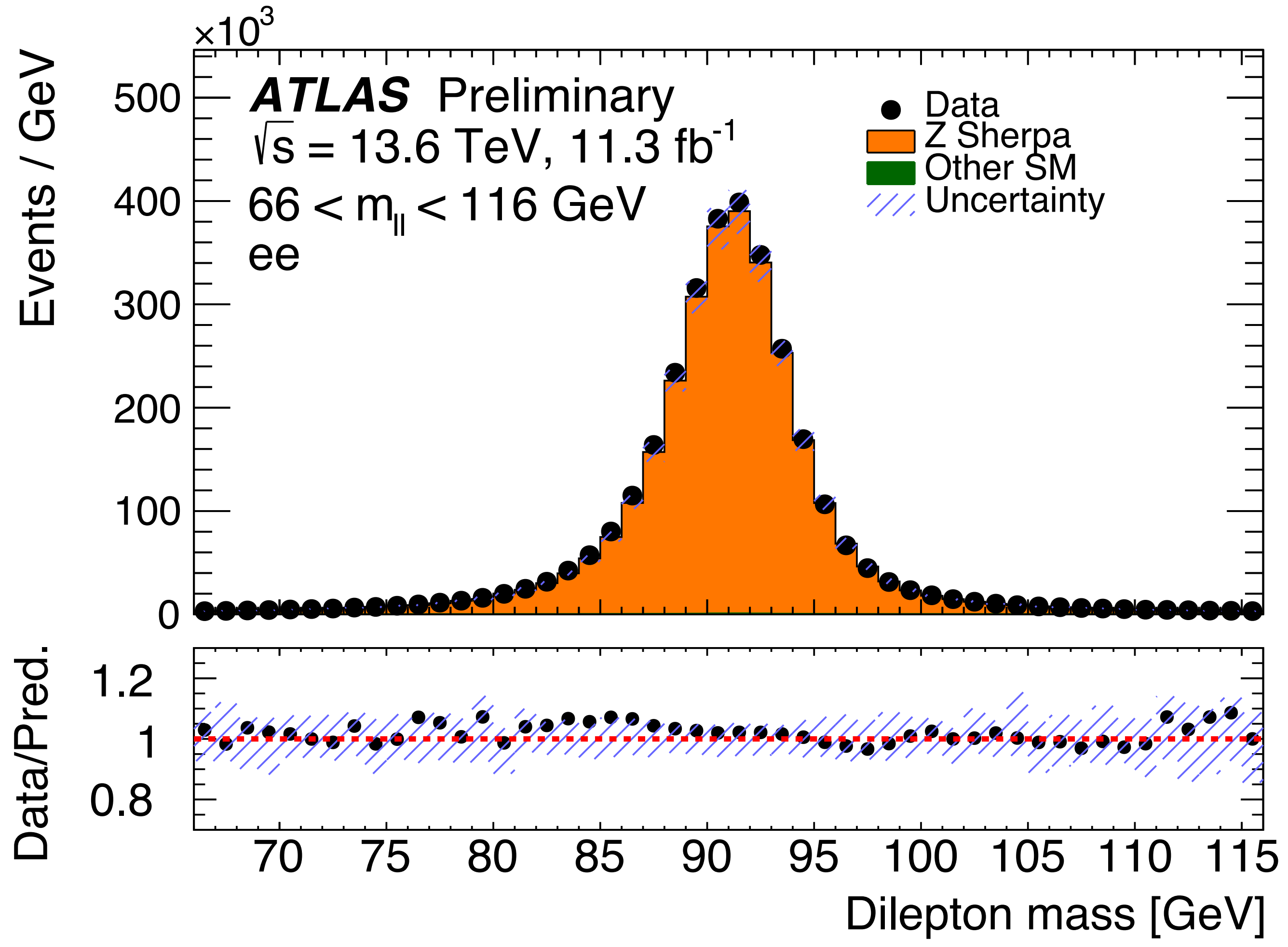
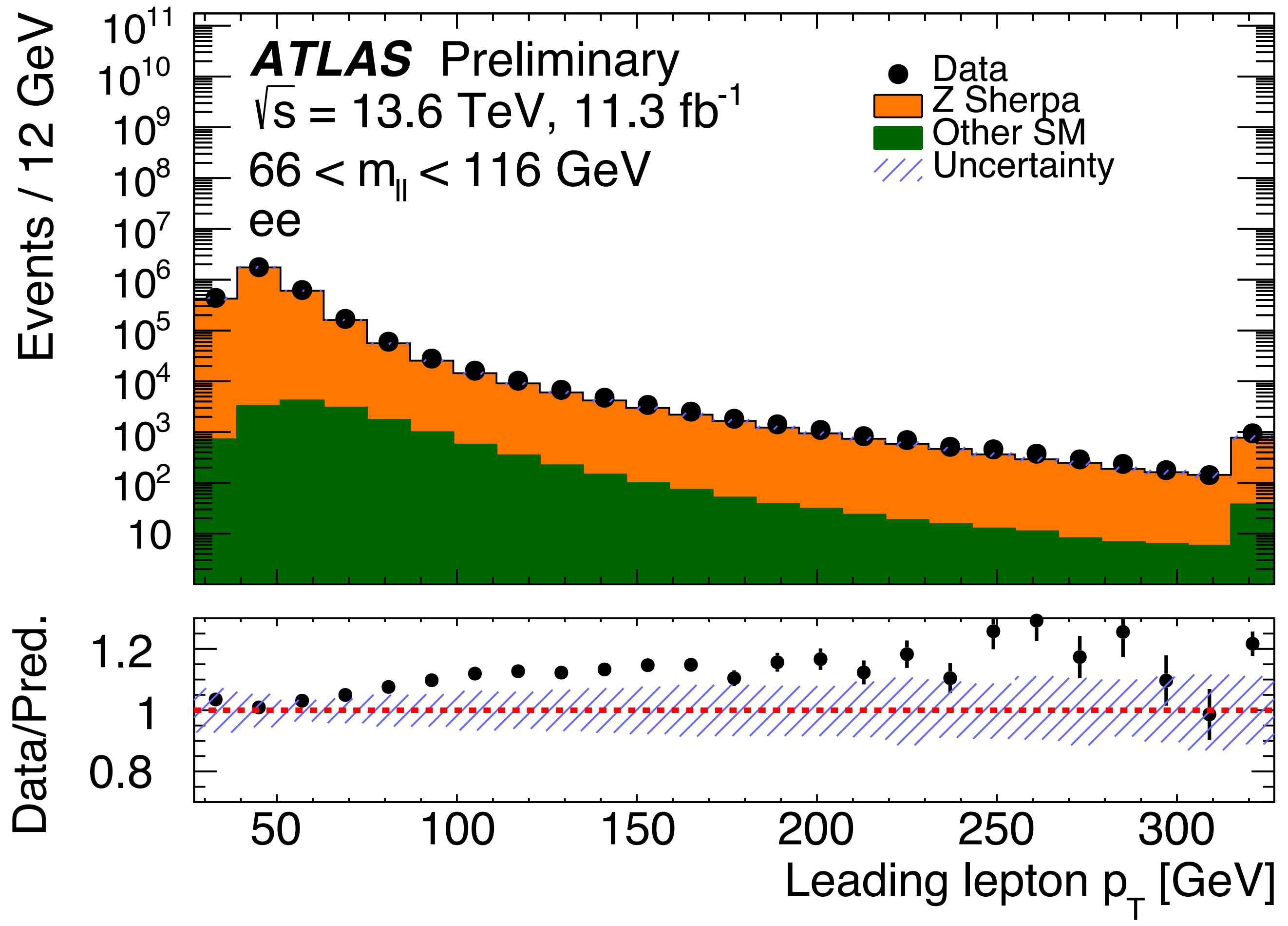
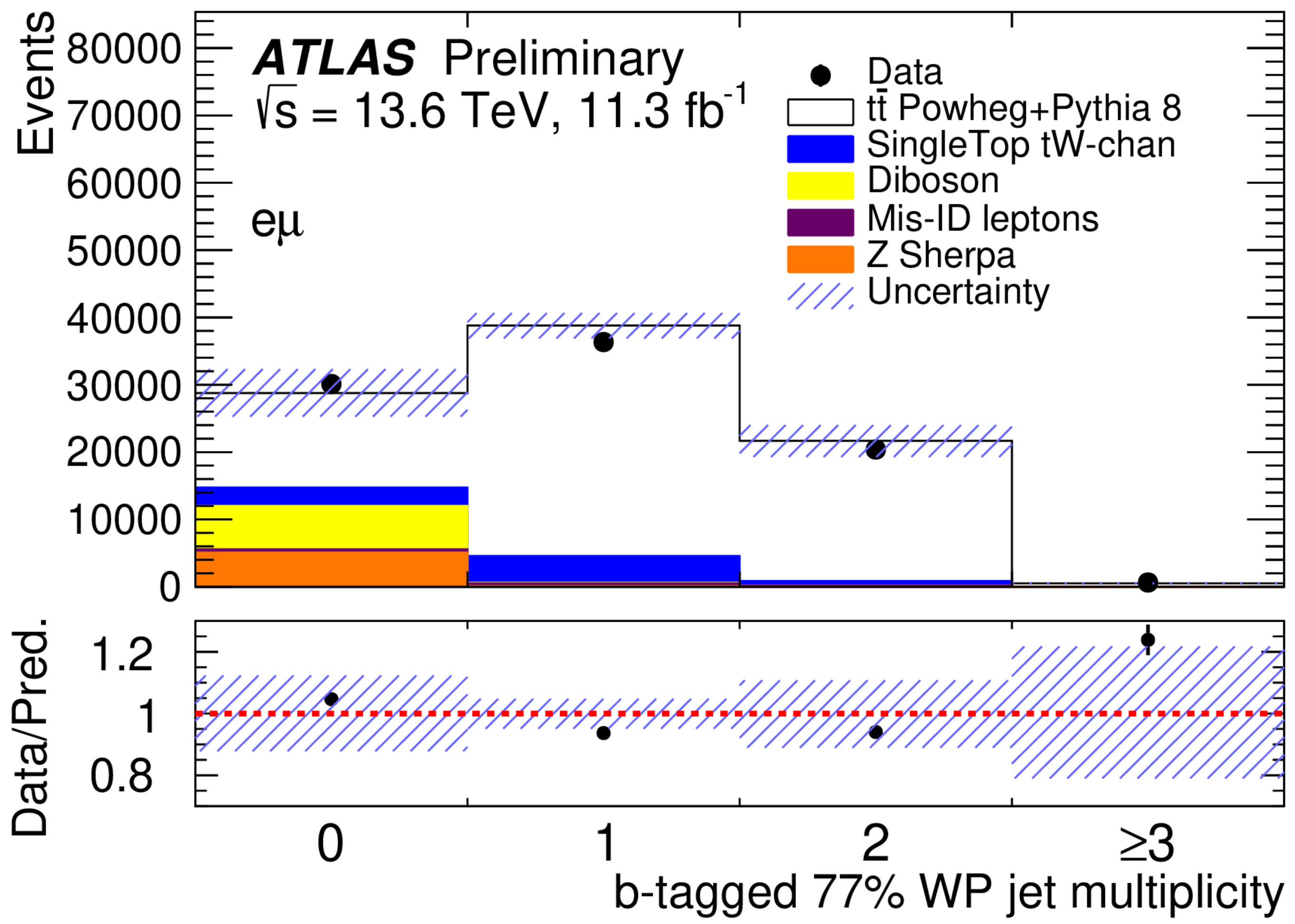
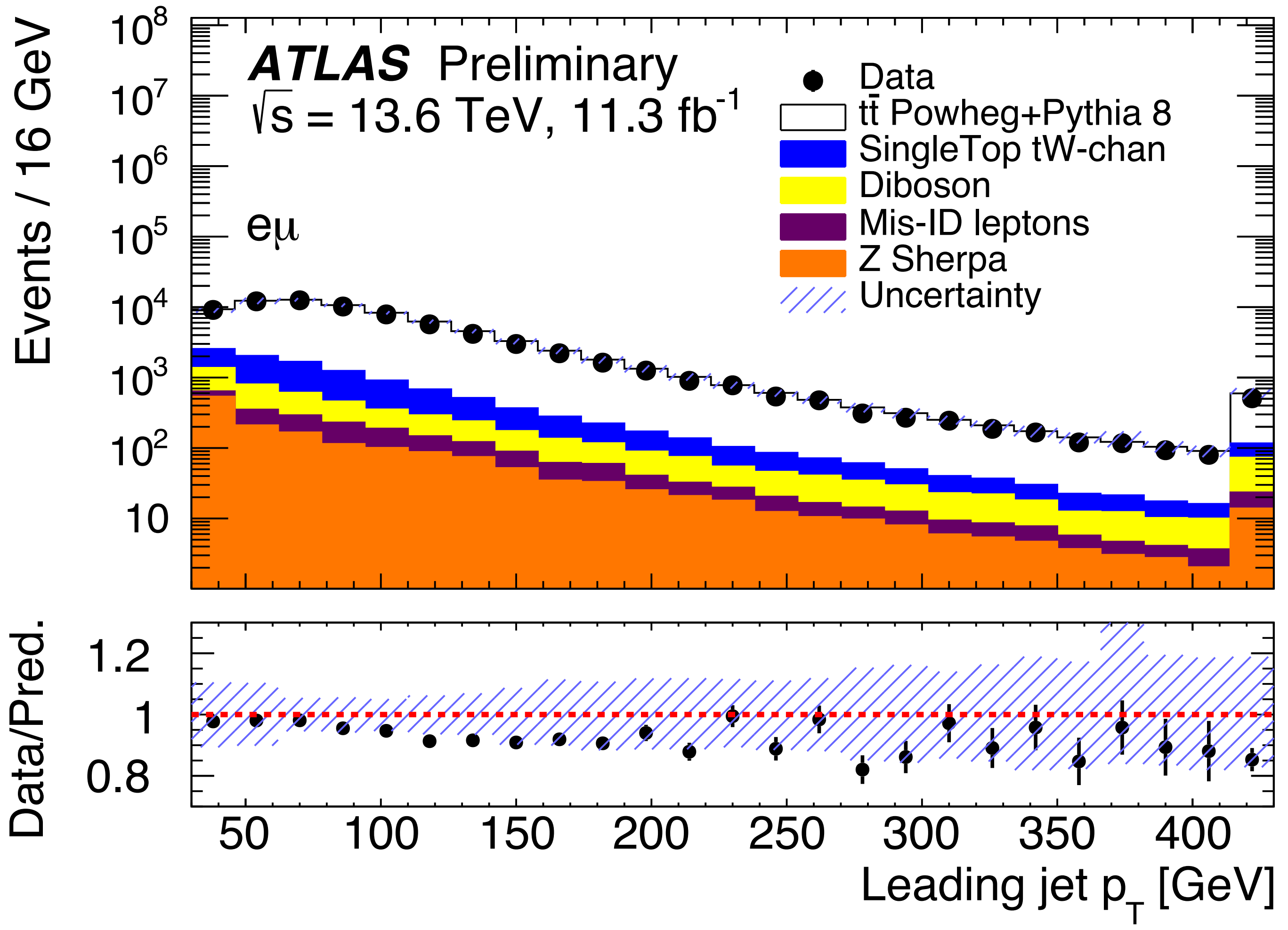
$\ell\ell$





$e\mu$





Early Run 3 Physics results

Measurement of $t\bar{t}$ and Z-boson cross sections

Results:

- Inclusive $t\bar{t}$ production cross-section

$$\sigma_{t\bar{t}} = 859 \pm 4\,(\text{stat.}) \pm 22\,(\text{syst.}) \pm 19\,(\text{lumi.})\,\text{pb}$$

$$\sigma_{t\bar{t}}^{\text{theory}} = 924^{+32}_{-40}\,(\text{scale} + \text{PDF})\,\text{pb}$$

- Fiducial Z boson production cross-section

$$\sigma_{Z\to\ell\ell}^{\text{fid.}} = 751 \pm 0.3\,(\text{stat.}) \pm 15\,(\text{syst.}) \pm 17\,(\text{lumi.})\,\text{pb}$$

$$\sigma_{Z\to\ell\ell}^{\text{fid.,theory}} = 741 \pm 15\,(\text{scale} + \text{PDF})\,\text{pb}$$

- Ratio of the cross sections:

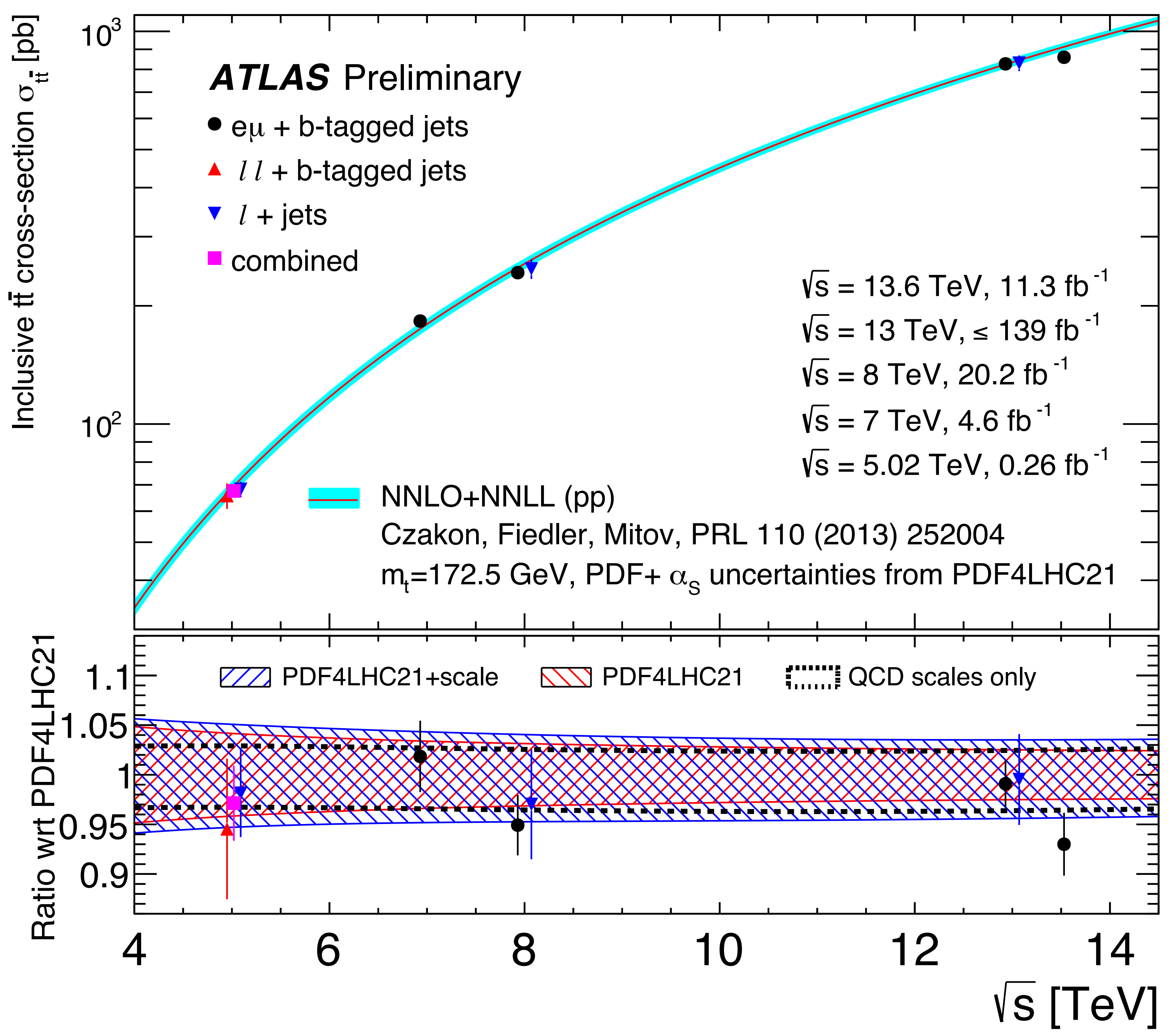
$$R_{t\bar{t}/Z} = 1.144 \pm 0.006\,(\text{stat.}) \pm 0.022\,(\text{syst.}) \pm 0.003\,(\text{lumi.})$$

$$R_{t\bar{t}/Z}^{\text{theory}} = 1.245 \pm 0.076\,(\text{scale} + \text{PDF})$$

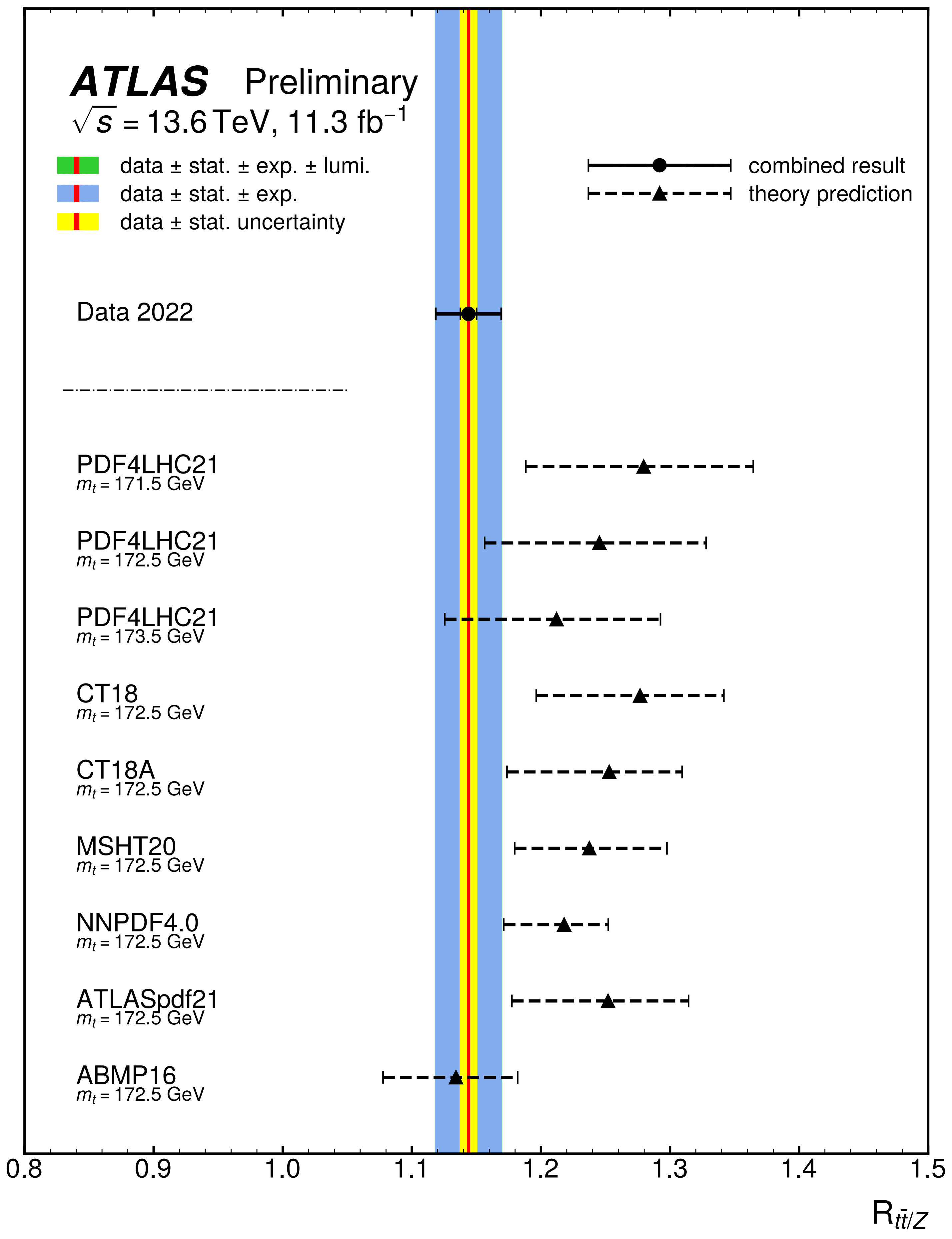
Reduction of uncertainties in ratio

ATLAS-CONF-2023-006

$t\bar{t}$ cross-section



$t\bar{t}/Z$ cross-section ratio

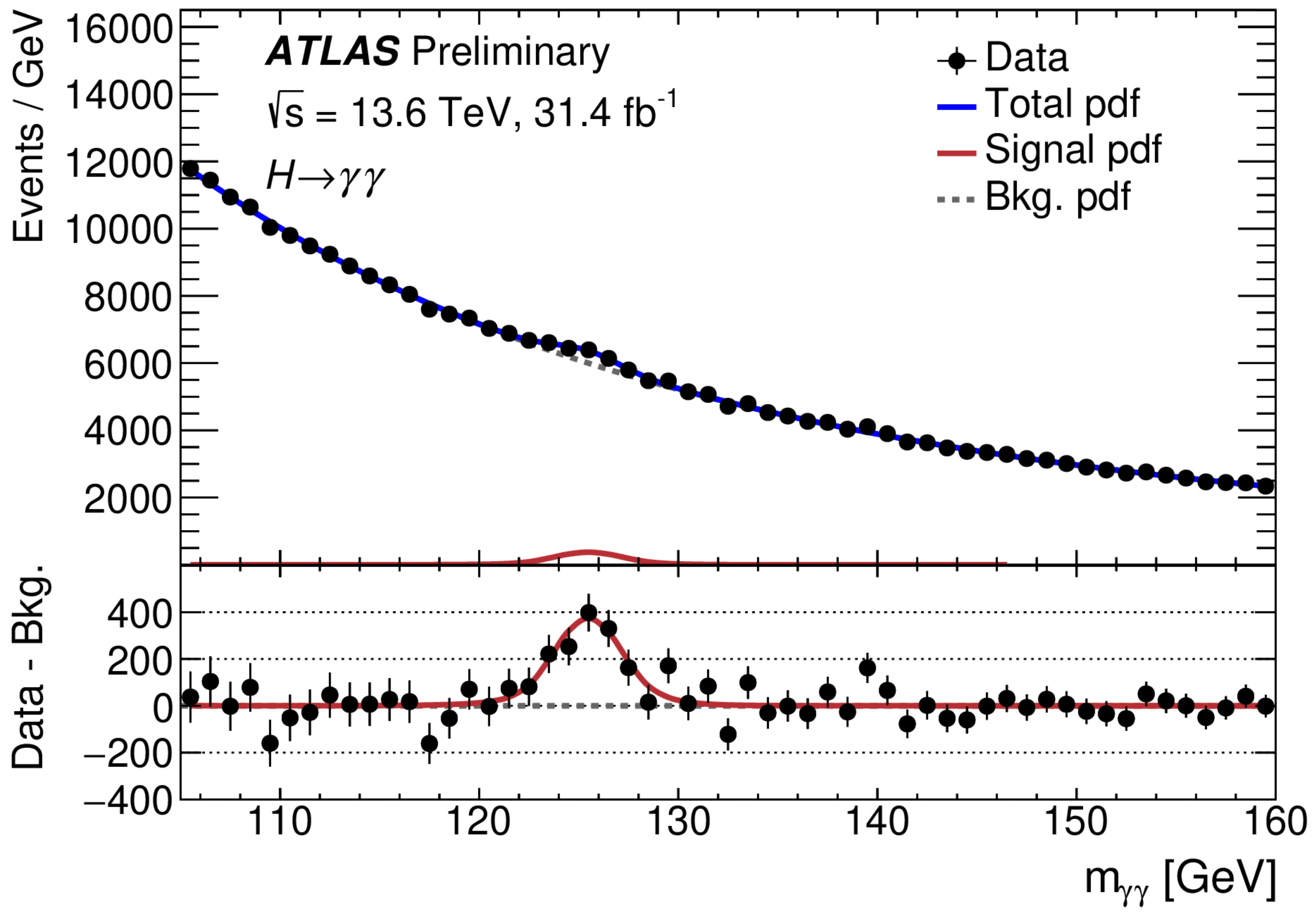


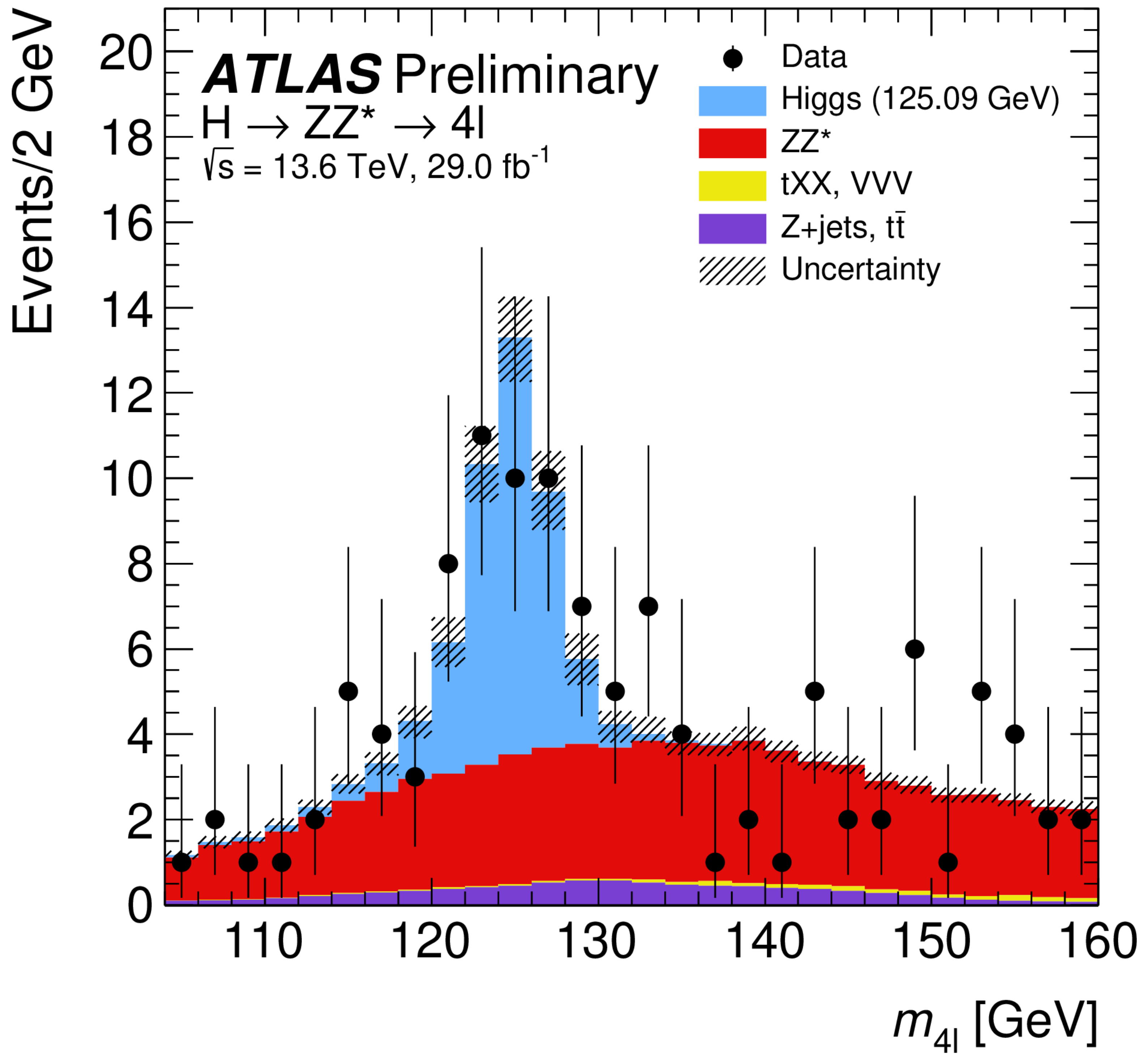
Early Run 3 Physics results

Measurement of the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ cross-sections

Higgs boson cross section at $13.6\,\mathrm{TeV}$ measured in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$ channels

- Measurements performed using $31.4\,\mathrm{fb}^{-1}$ and $29.0\,\mathrm{fb}^{-1}$





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Early Run 3 Physics results

Measurement of the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ cross-sections

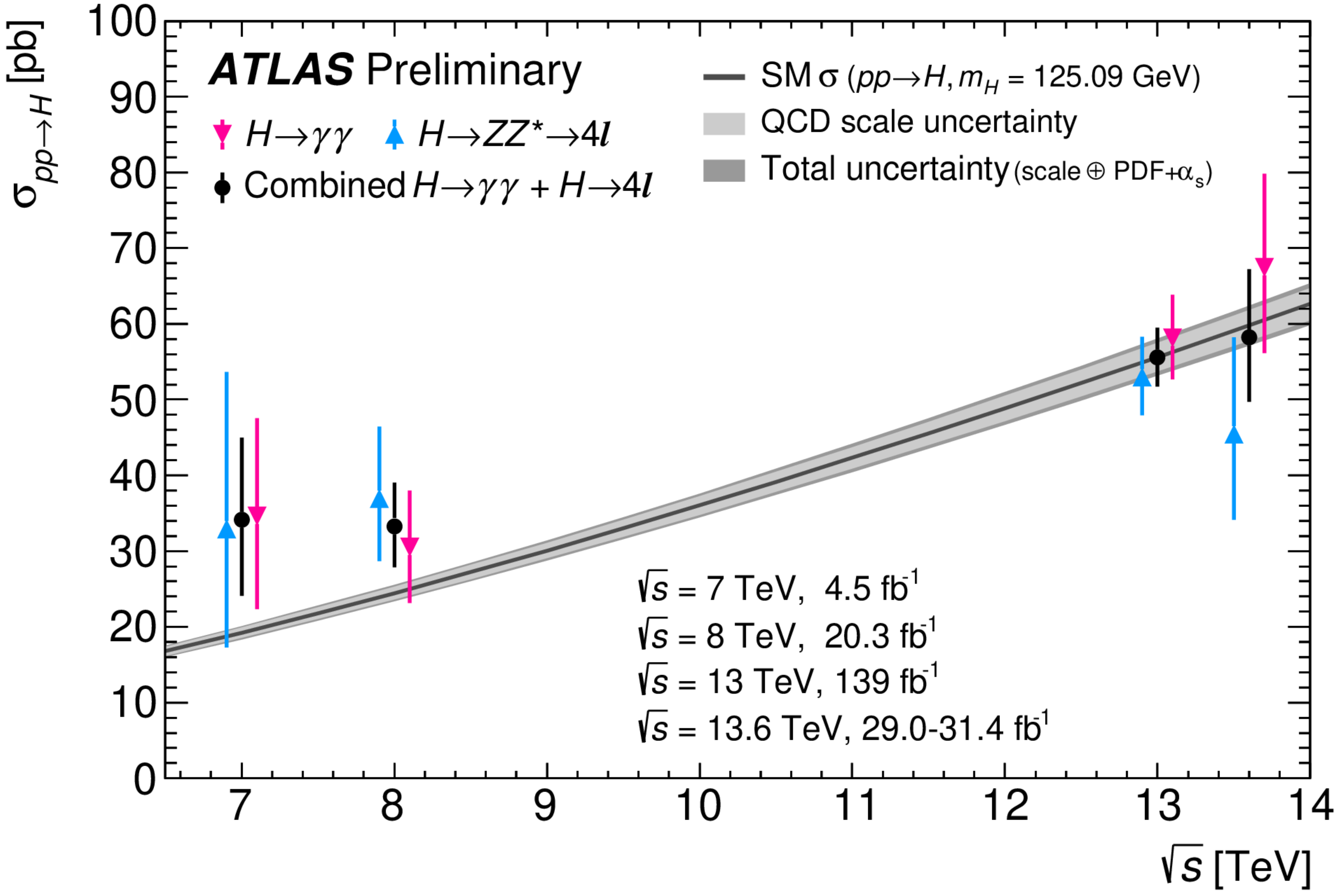
Likelihood combination of the two decay channels is performed

Measured cross sections agree with SM prediction of $\sigma(pp \to H)_{\mathrm{SM}} = 59.2 \pm 2.6\,\mathrm{pb}$

- $H \to \gamma\gamma$: $\sigma(pp \to H) = 67^{+12}_{-11}\,\mathrm{pb}$
- $H \to ZZ$: $\sigma(pp \to H) = 46 \pm 12\,\mathrm{pb}$
- Combined: $58.2 \pm 8.7 = 58.2 \pm 7.5\,(\mathrm{stat.}) \pm 4.5\,(\mathrm{syst.})\,\mathrm{pb}$

Dominated by statistical uncertainty

Important test of Higgs boson production cross section at new centre of mass energy



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Summary

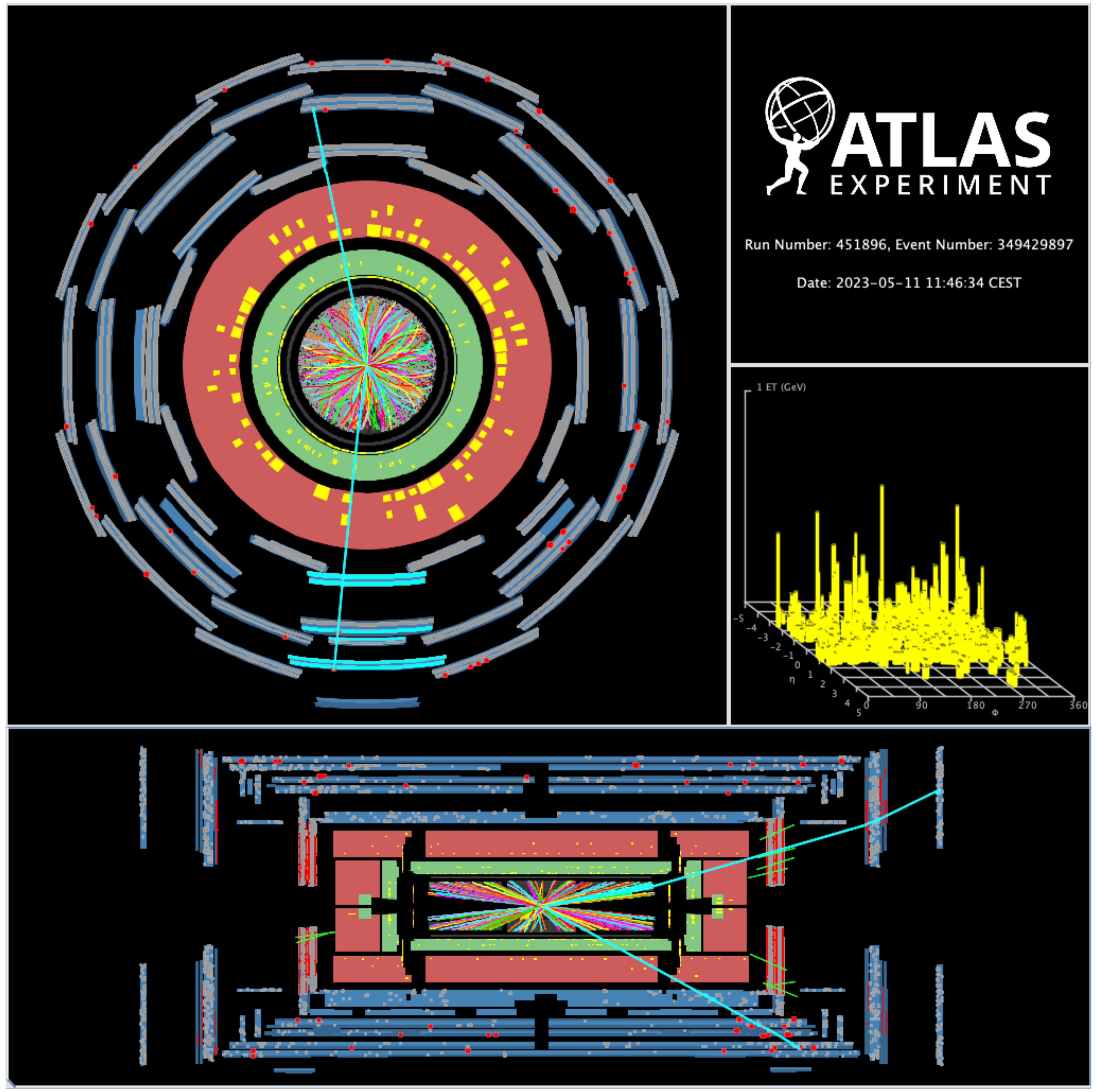
Run 3 of the LHC is under way

Phase-I upgrades of NSW and LAr commissioned and installed

- Both performing well in Run 3 data-taking

ATLAS taking data with high efficiency

- $56\ \mathrm{fb}^{-1}$ of data collected during 2022 and 2023 thus far



Major improvements both online and offline

Improvements expected to bring significant gains in sensitivity and precision for searches and measurements

Early physics results show good agreement with SM predictions

Show that ATLAS is prepared for high-quality physics results using Run 3 data

Many more results coming soon, stay tuned!

Backup

Large Radius Tracking

Large Radius Tracking (LRT) is an additional ID tracking pass that is run after standard tracking

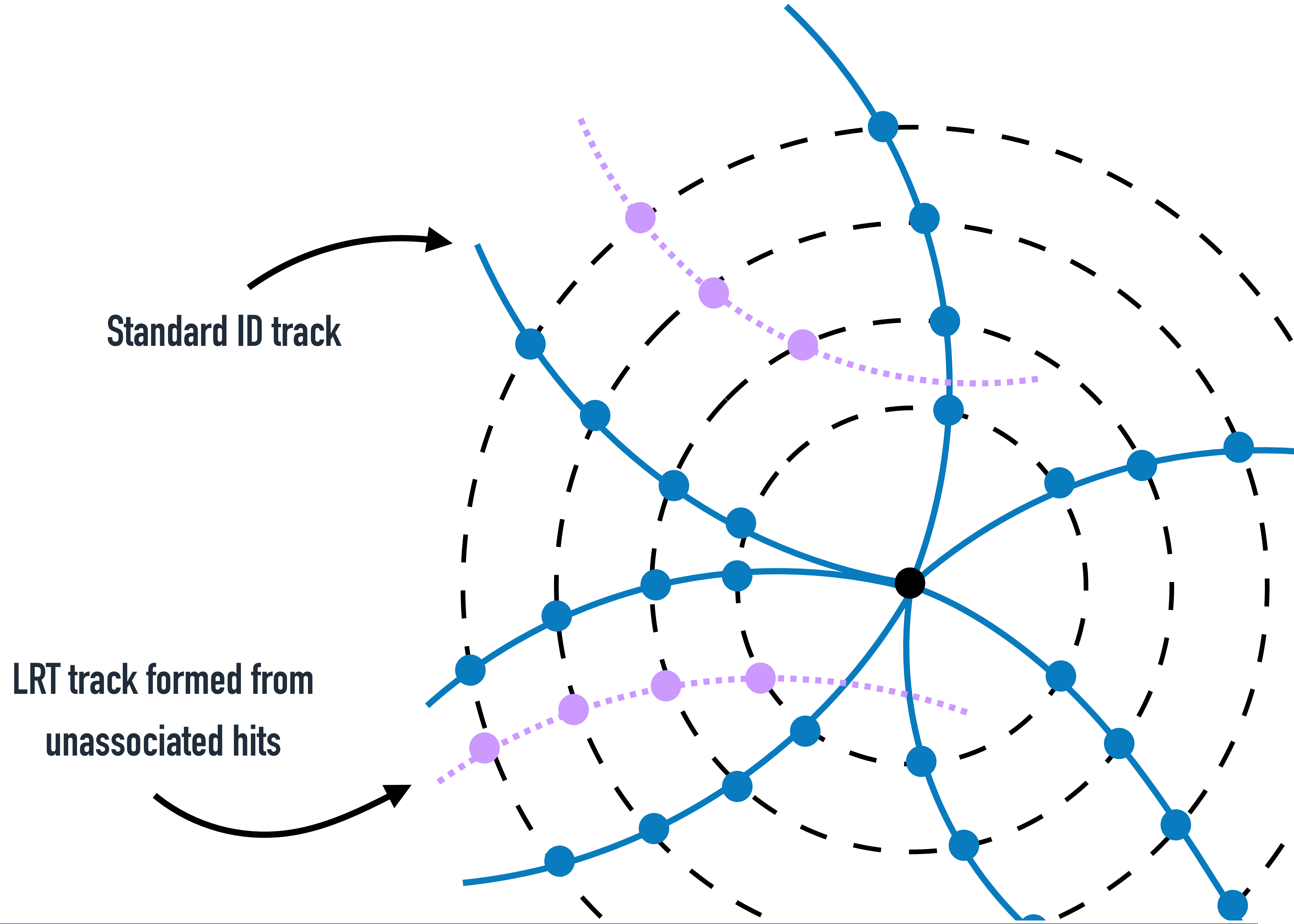
- Run on unused hits with LLP-focused tracking cuts
- Optimized to reconstruct the charged particles originating from LLP decays

Crucial component of many LLP searches

- Increasingly important aspect of ATLAS search program

LRT is based off of the standard ATLAS track reconstruction with several modifications, ex:

- $|d_{0,\max}|$: 5mm → 300mm
- $|z_{0,\max}|$: 200mm → 500mm

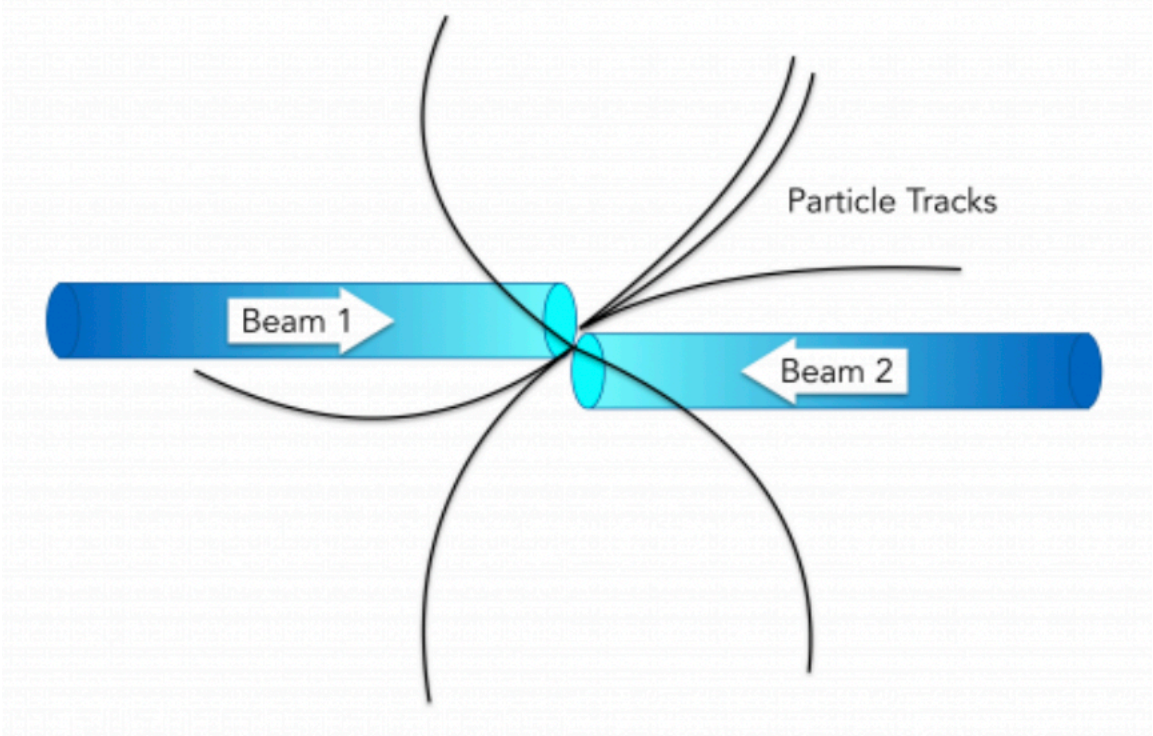


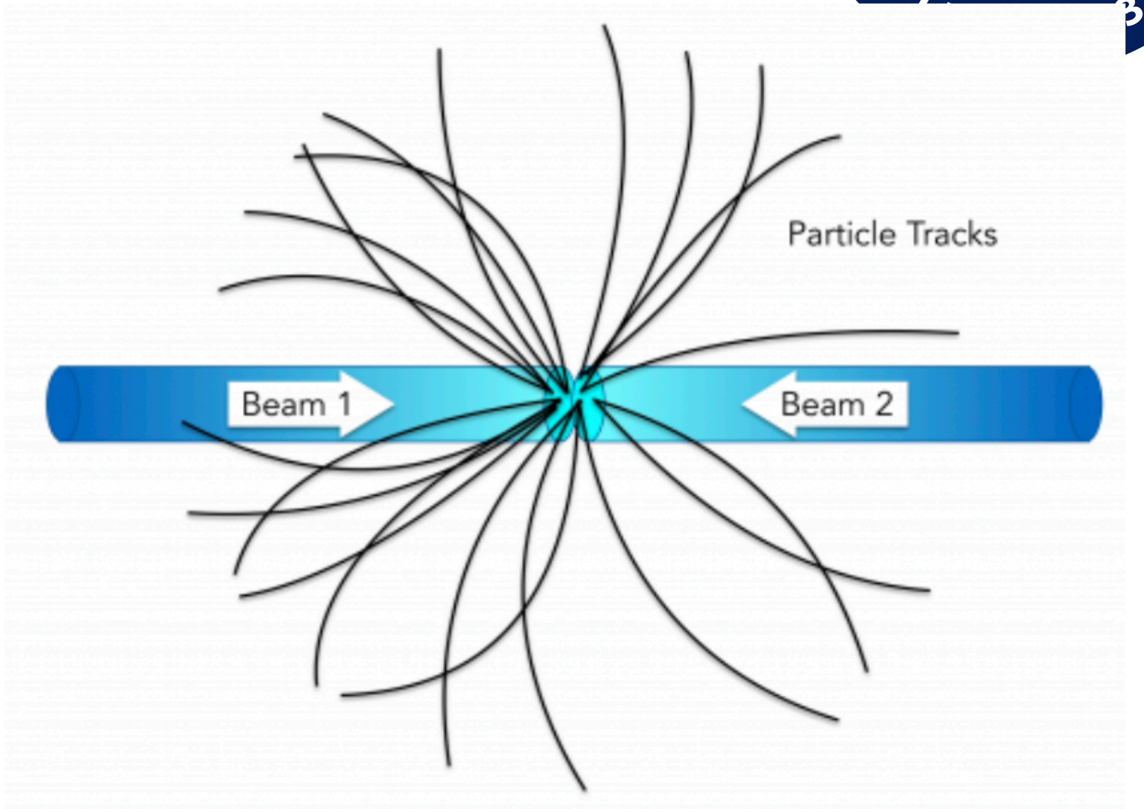
Determination of the luminosity

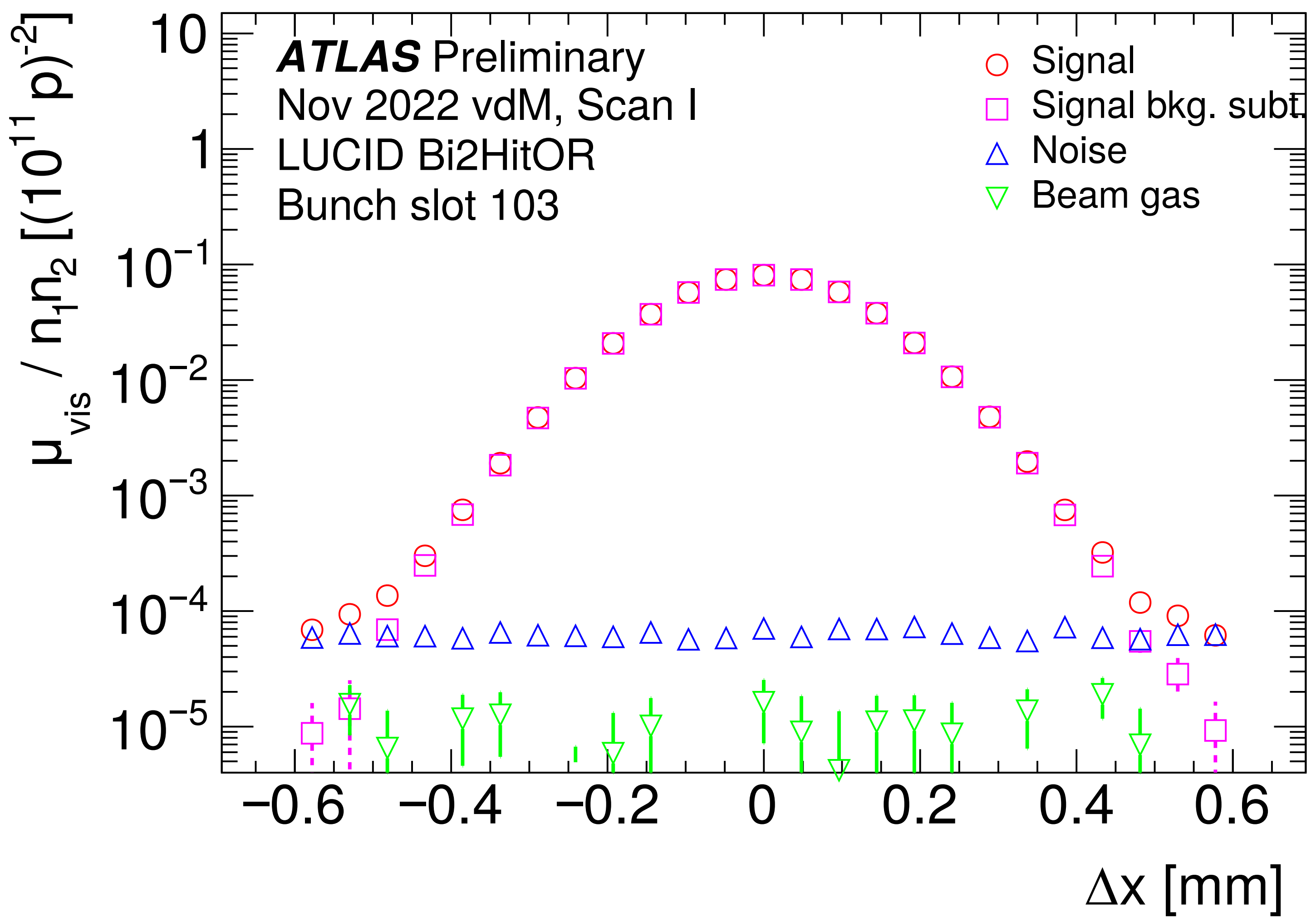
Preliminary luminosity measurements with the LUCID detector

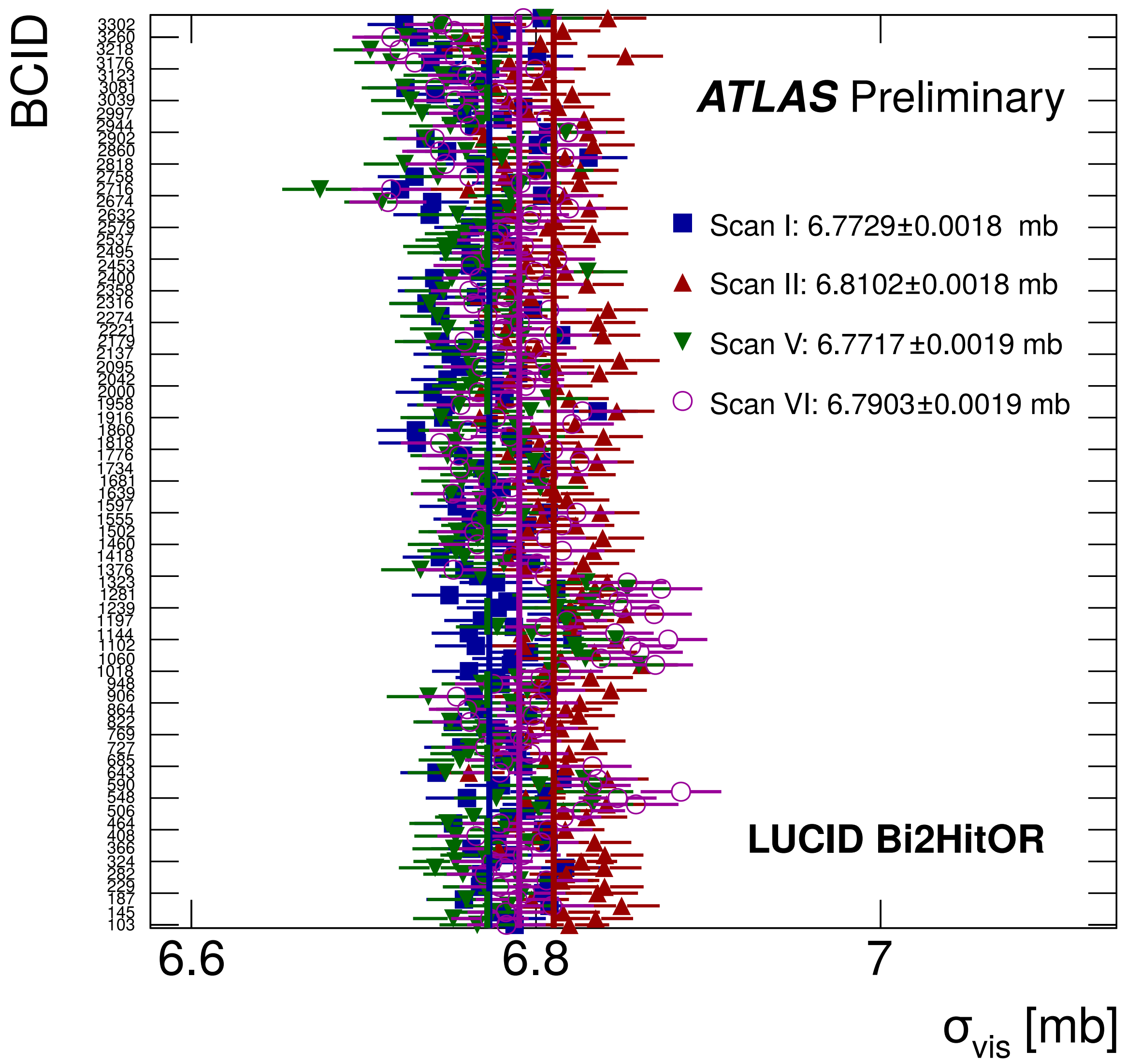
Van der Meer beam separation scan

- First precise measurements of Luminosity
- Uncertainty: ~2.2%









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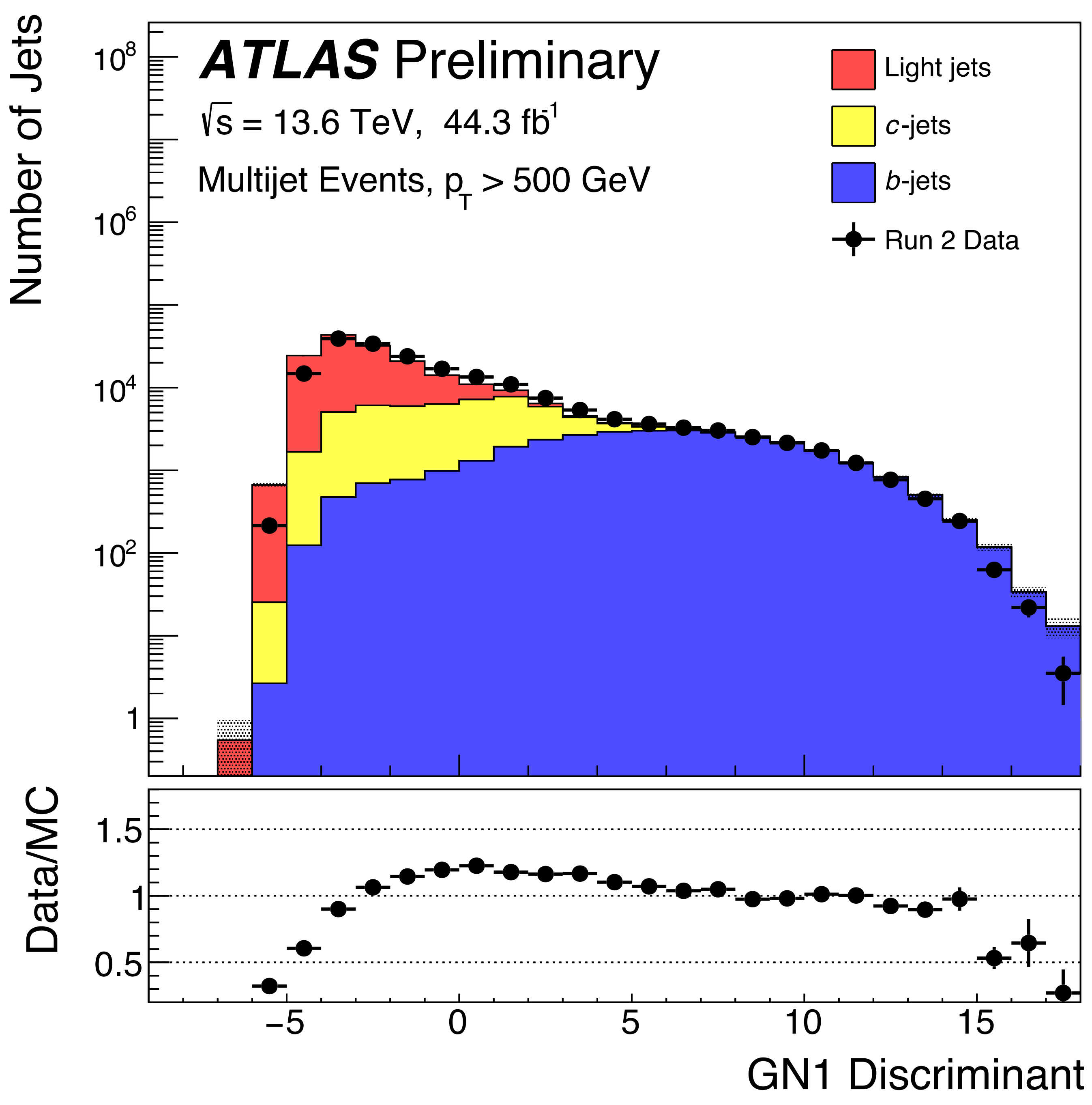
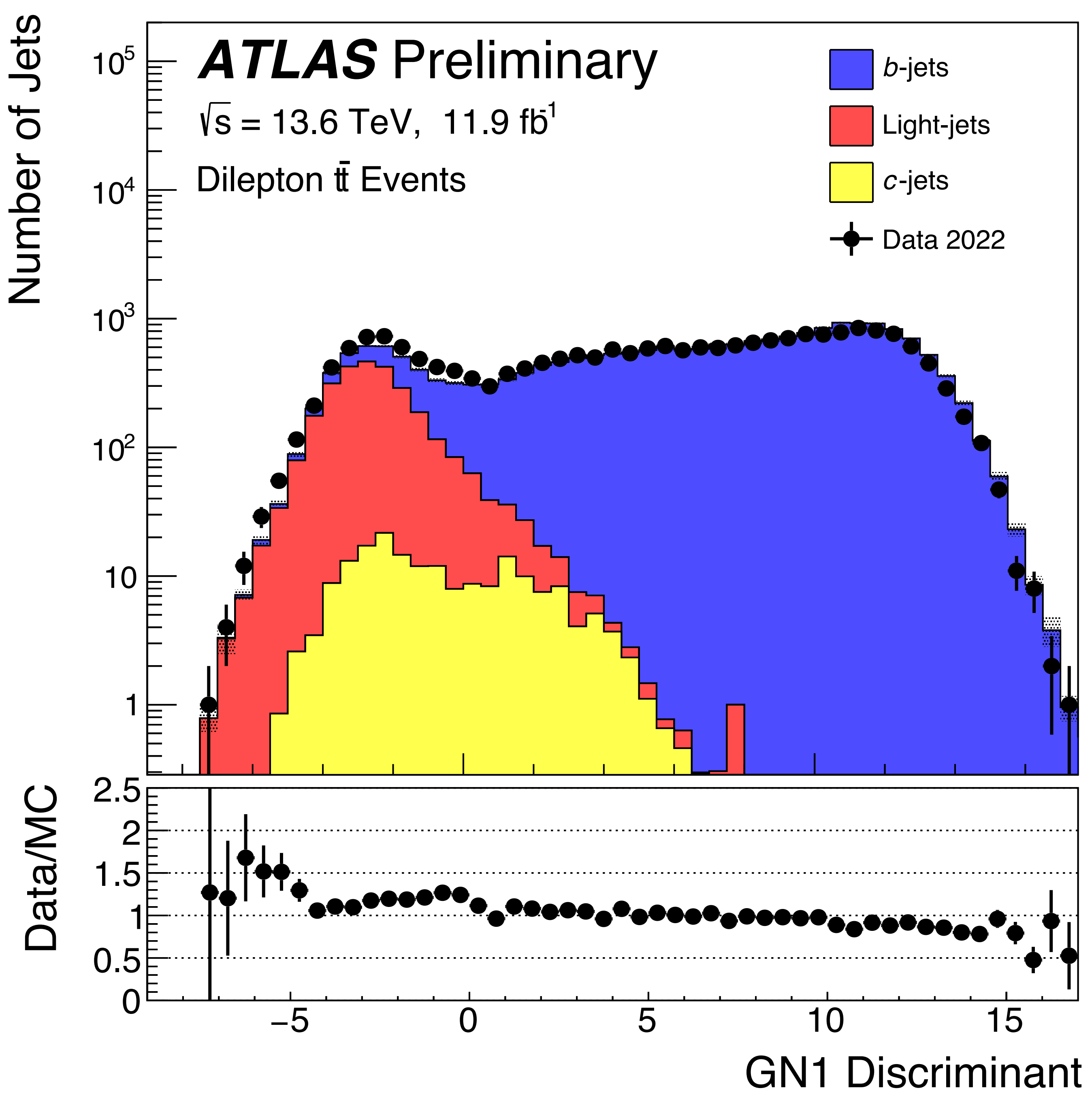
Improved flavour tagging

New graph neural network (GNN) taggers deployed

Calibration of new taggers is in progress

- Very good Data/MC ratio in the bulk of the distribution
- Demonstrates the taggers generalise between LHC runs





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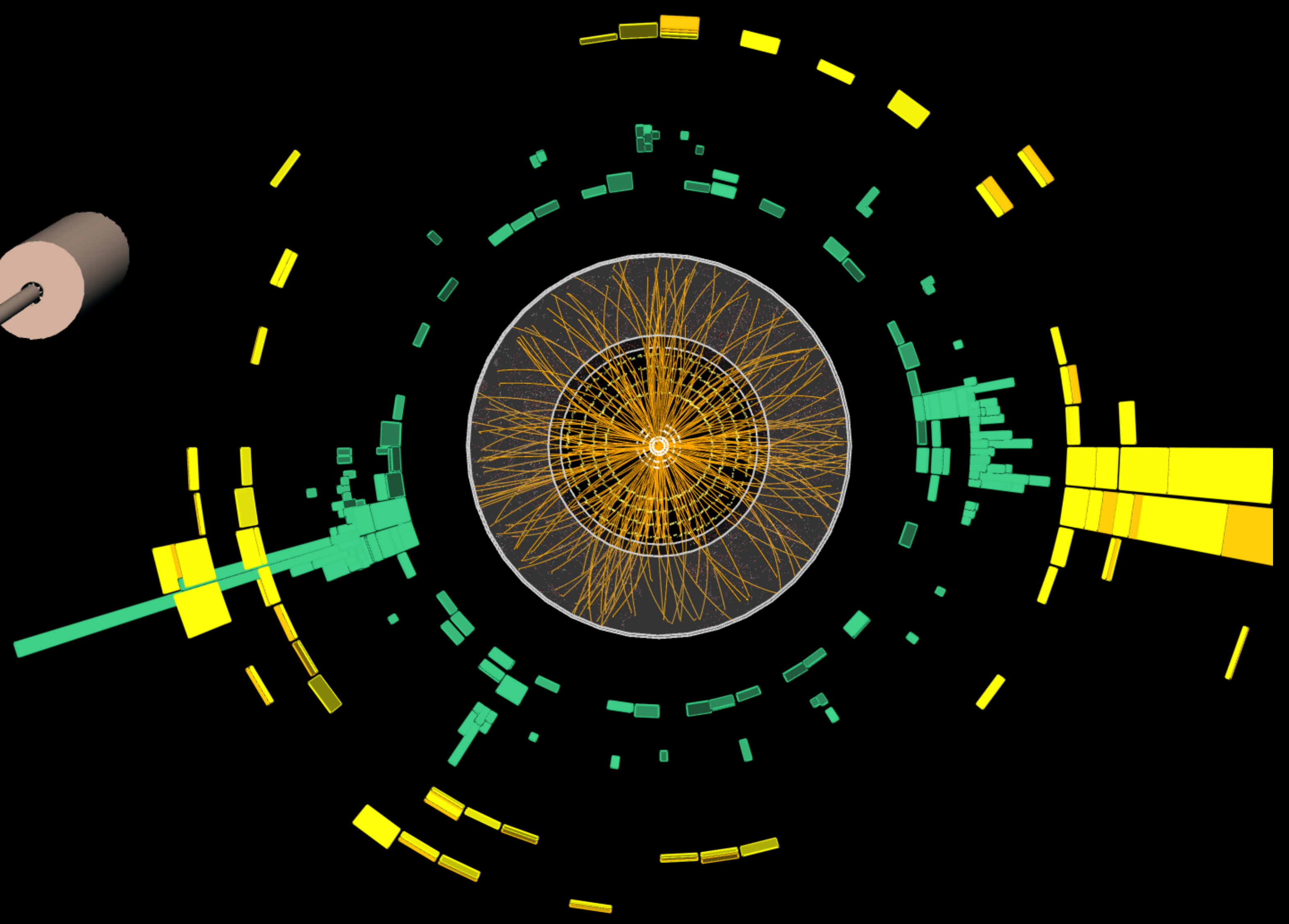
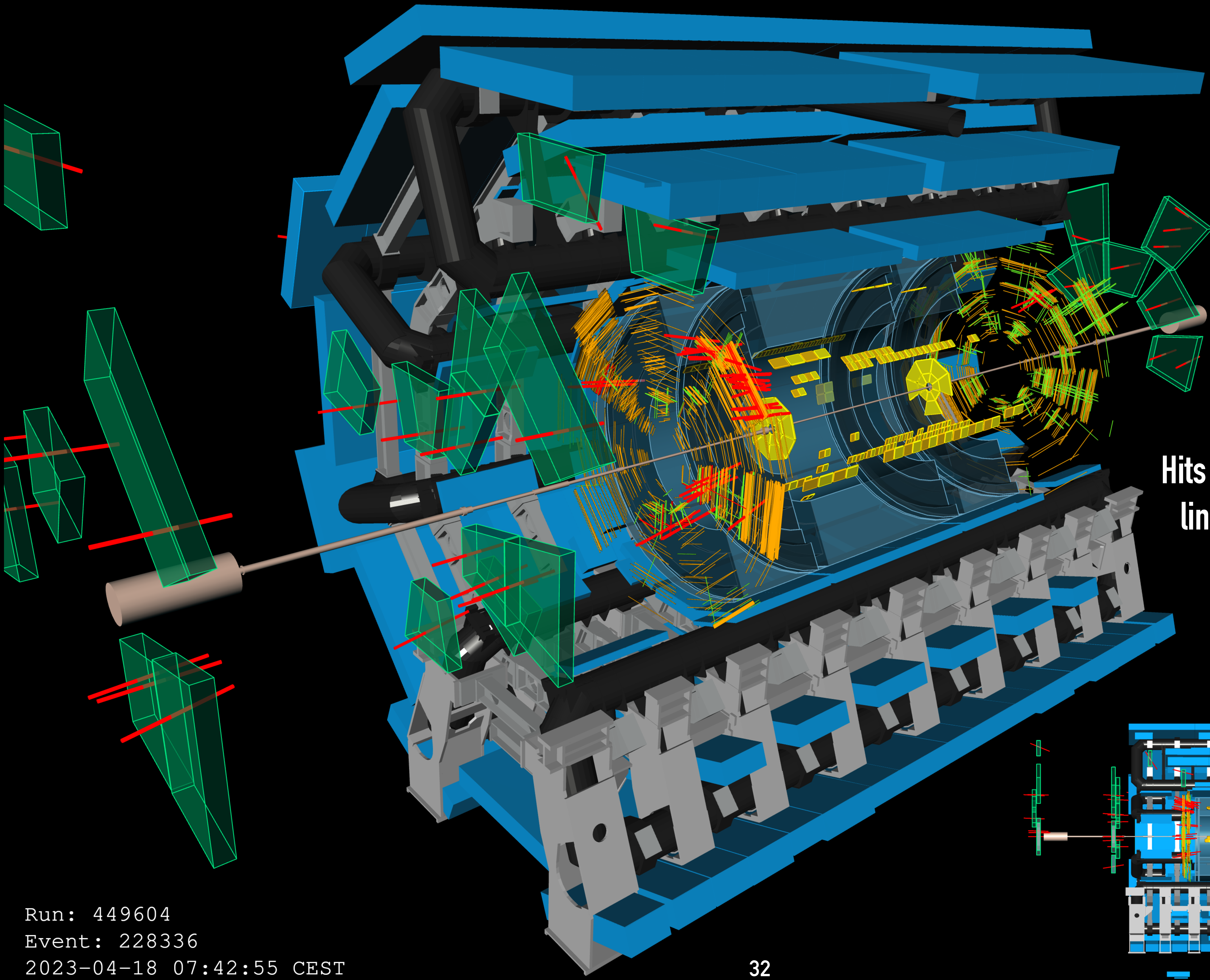


Stable beams resume 21 April 2023

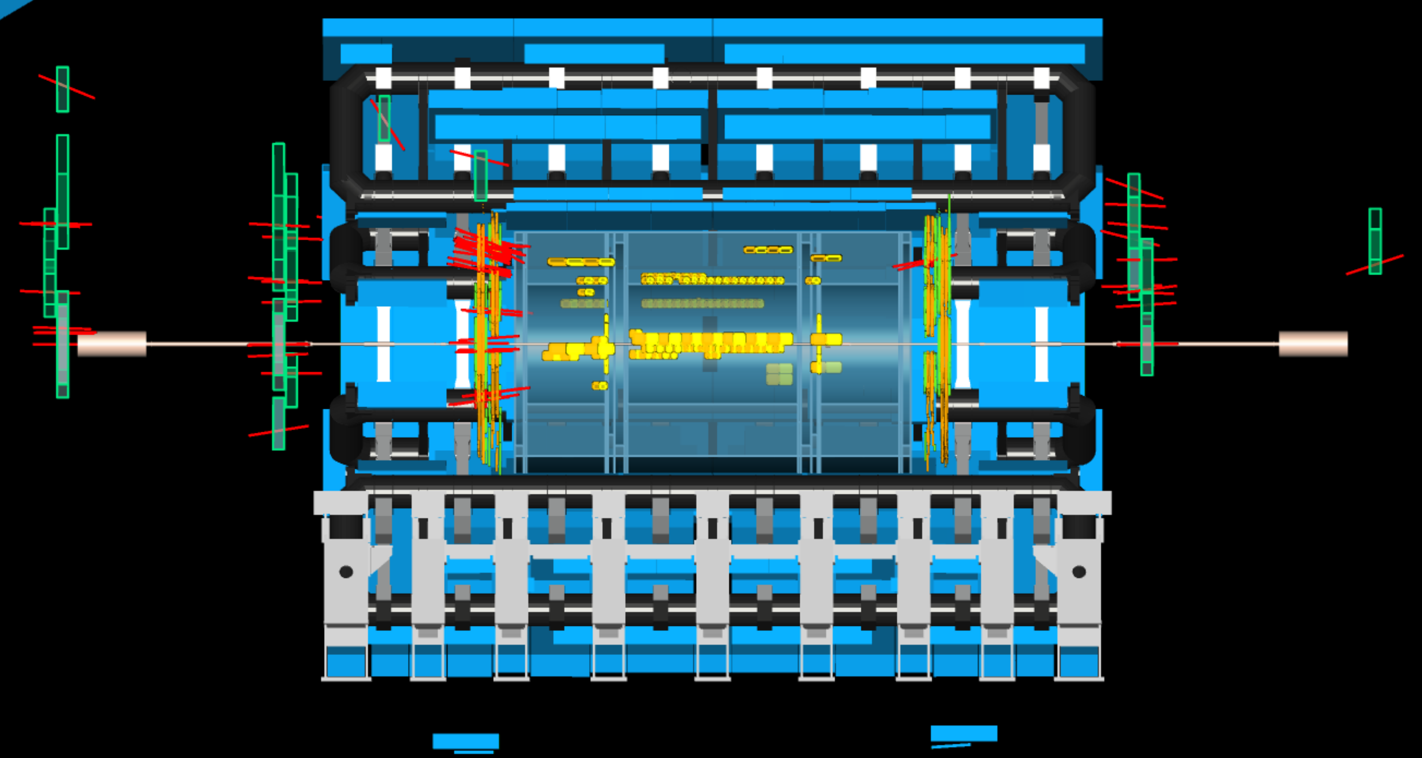
ATLAS
EXPERIMENT

Run: 450227
Event: 6327489
2023-04-21 19:24:16 CEST

ATLAS EXPERIMENT

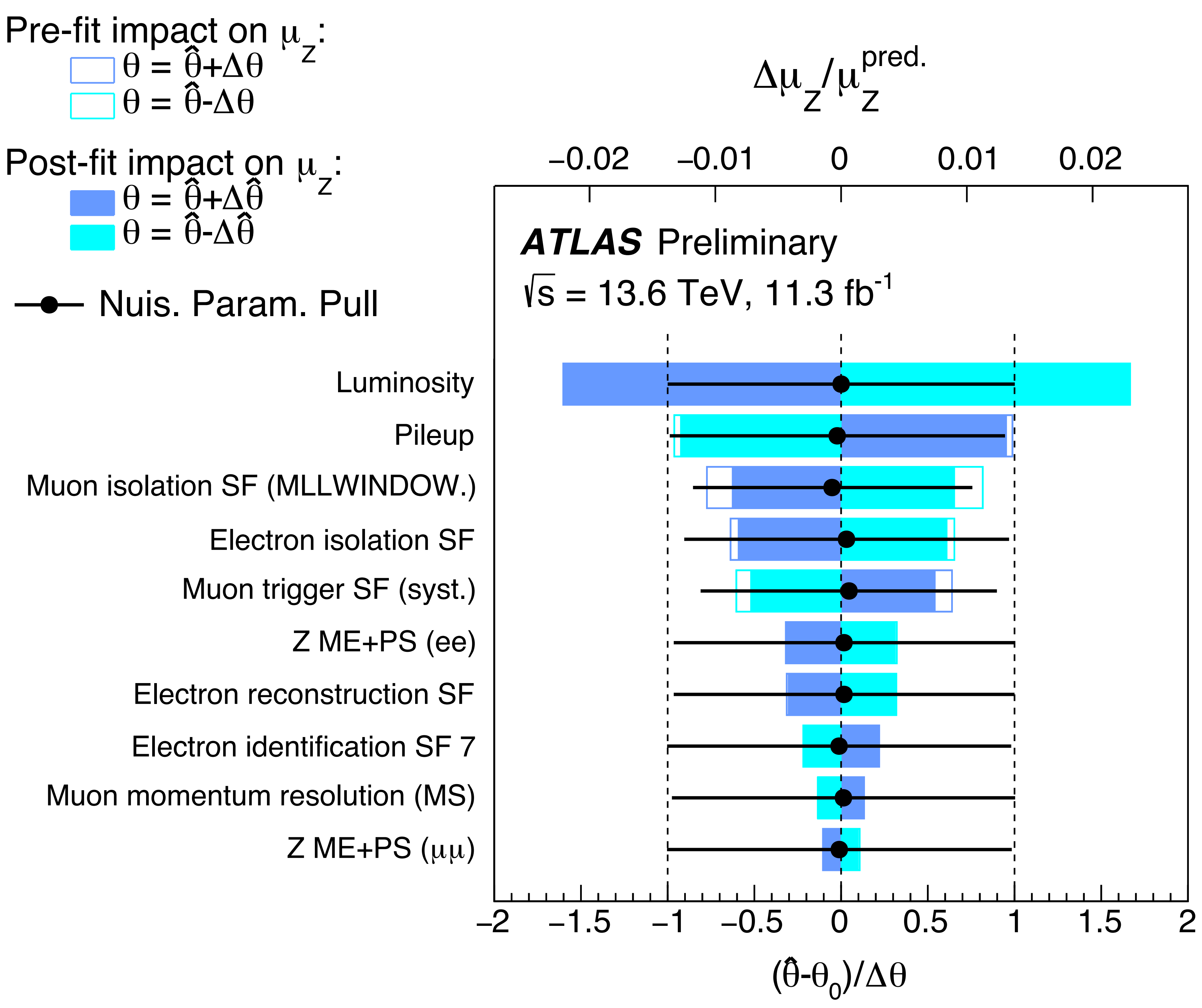


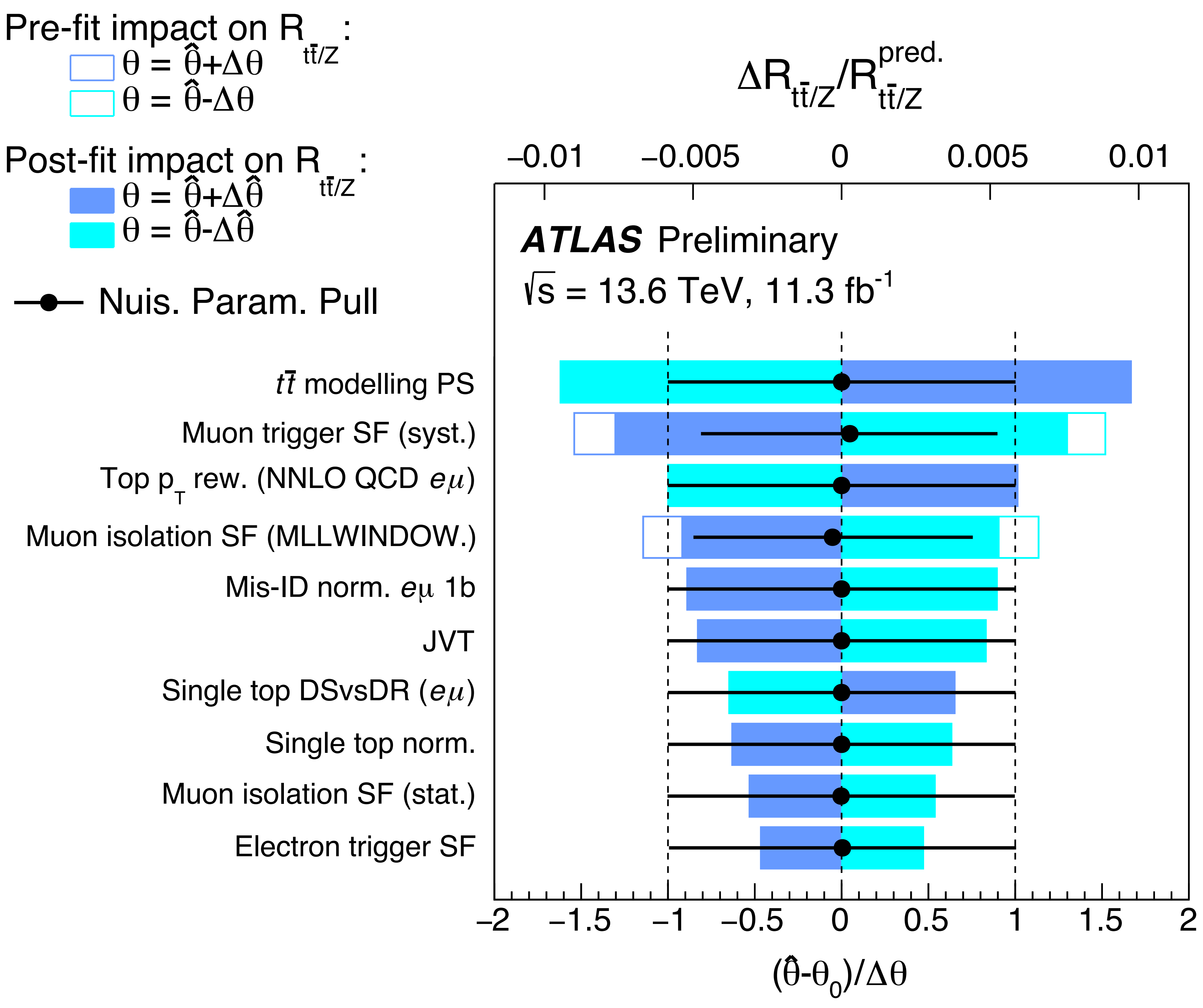
Hits in the NSW detector (orange/green lines) during special calibration run



Early Run 3 Physics results

Measurement of $t\bar{t}$ and Z-boson cross sections





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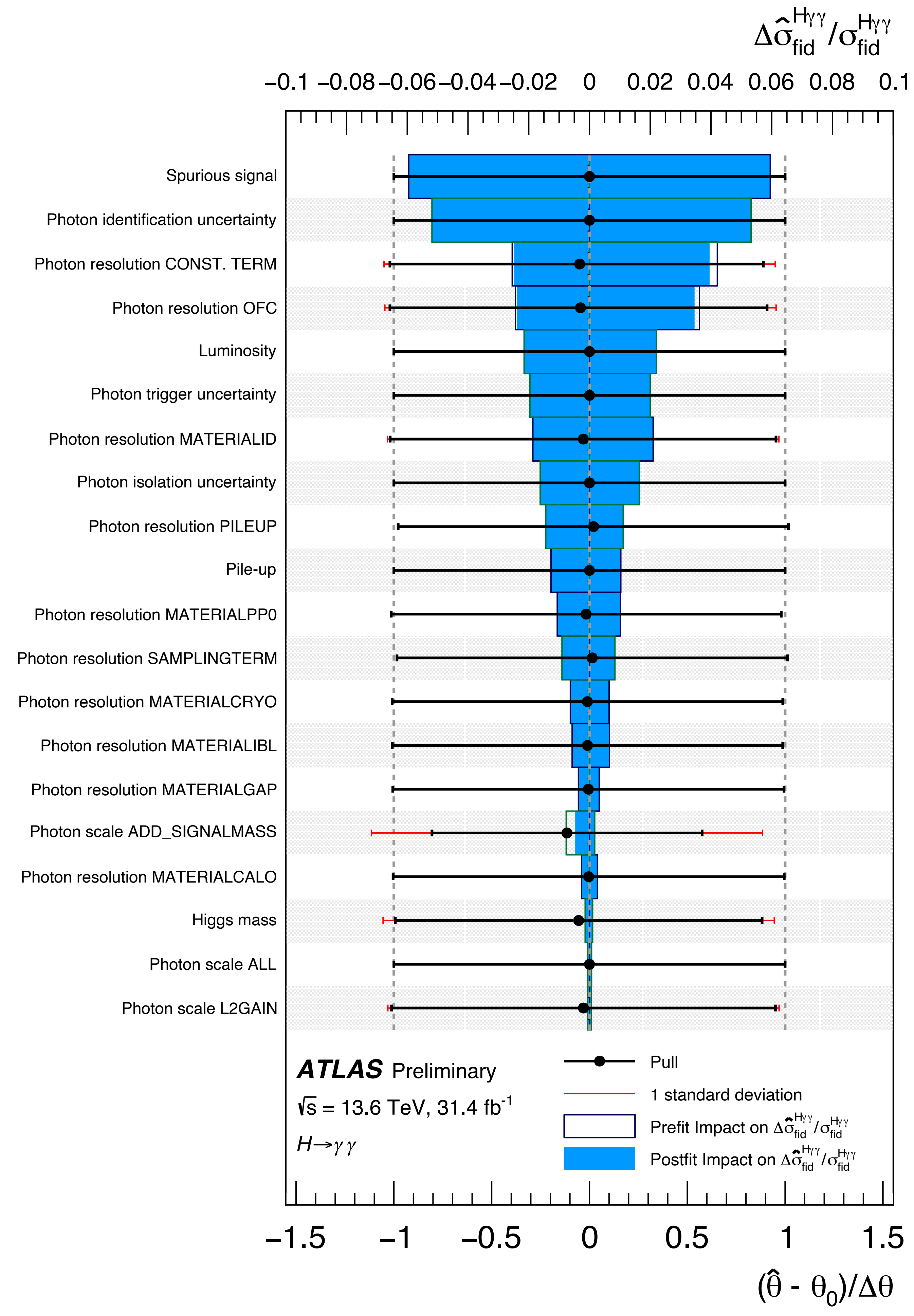
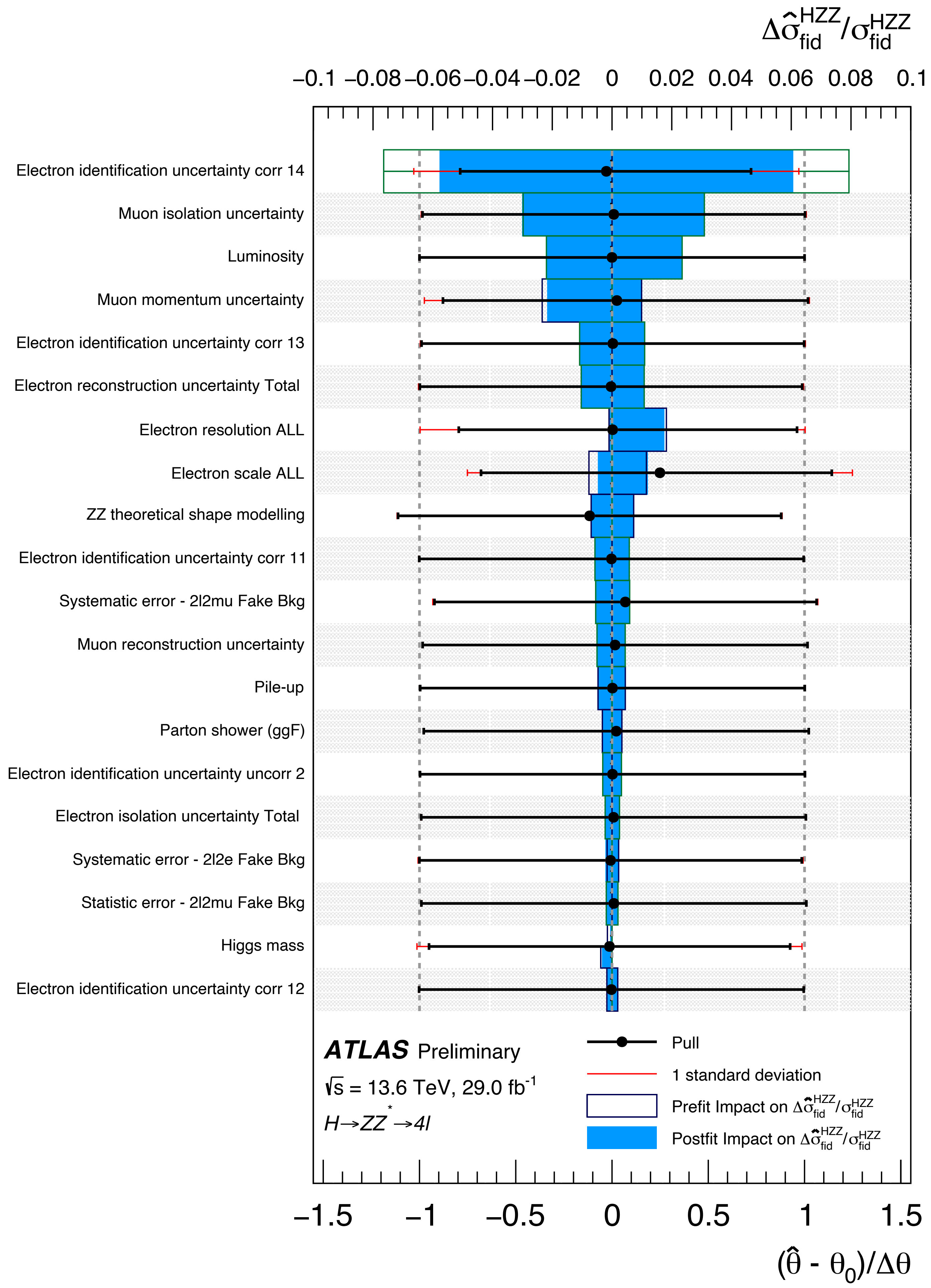
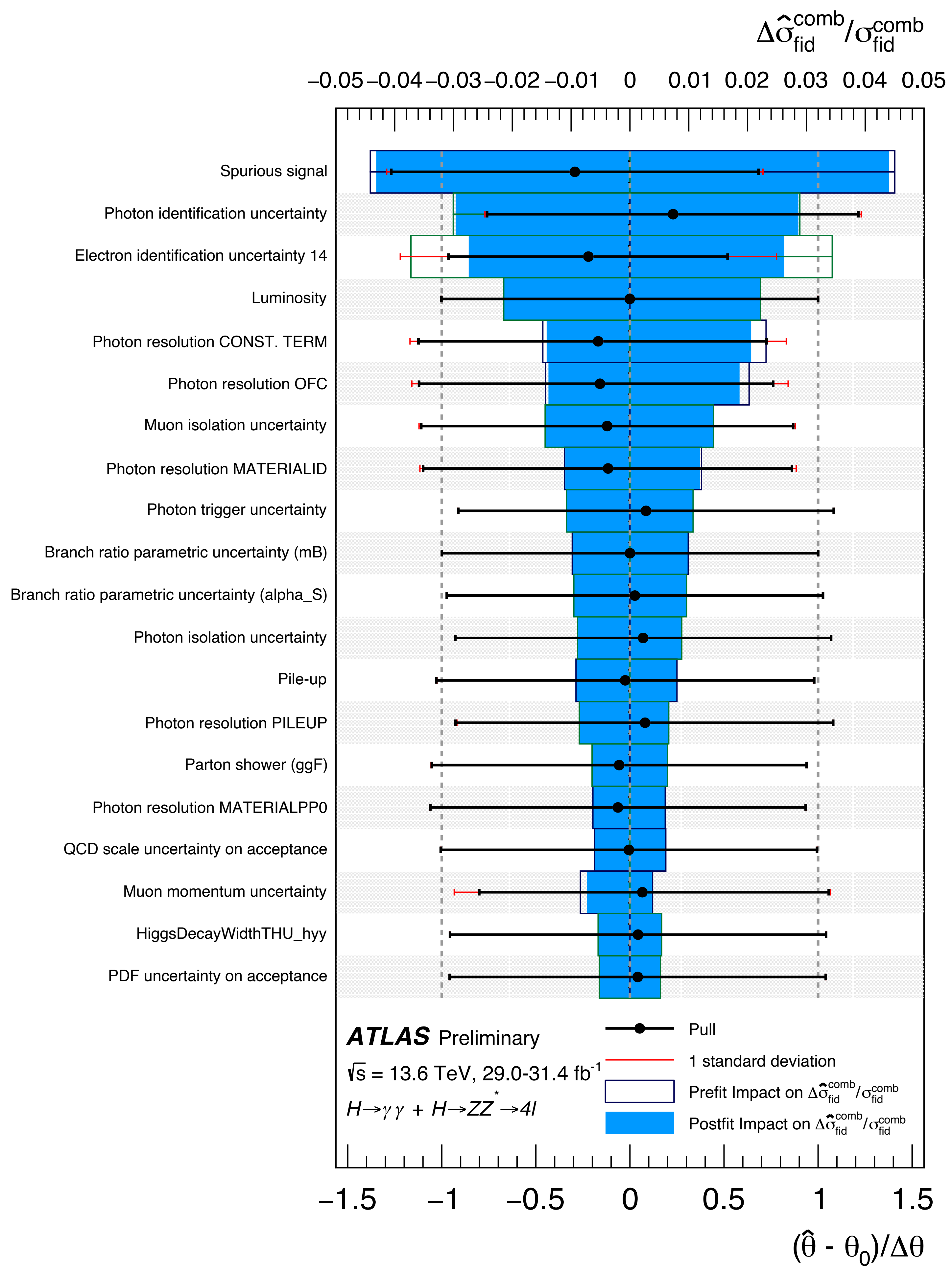
Early Run 3 Physics results

Measurement of the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ cross-sections







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