ATLAS Status

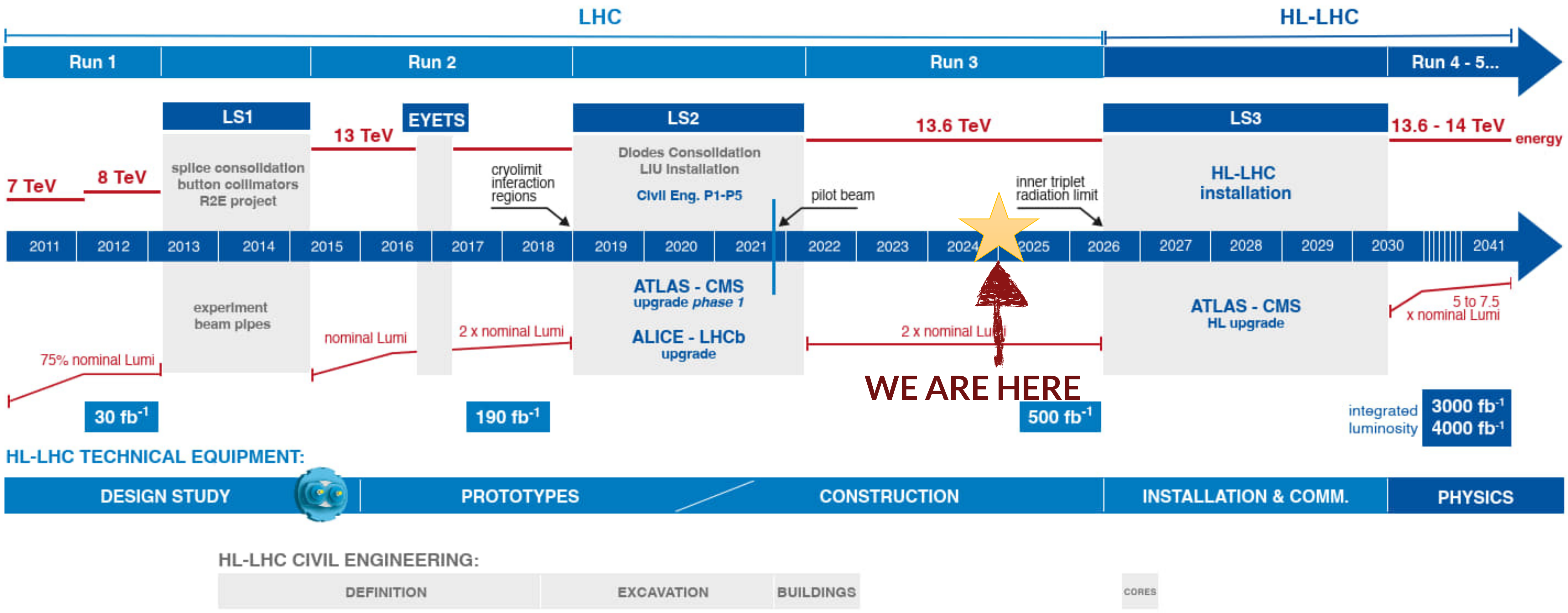
US LHC User Association Meeting

December 17th, 2024

Zhi Zheng, on behalf of ATLAS Collaboration

SLAC National Accelerator Laboratory

LHC / HL-LHC Plan

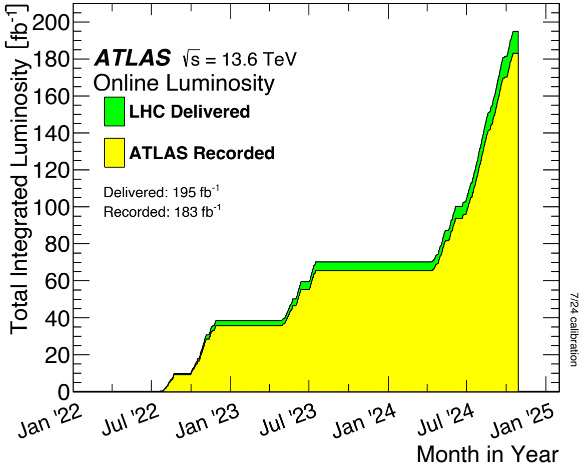


LHC / HL-LHC Plan

HiLumi LARGE HADRON COLLIDER

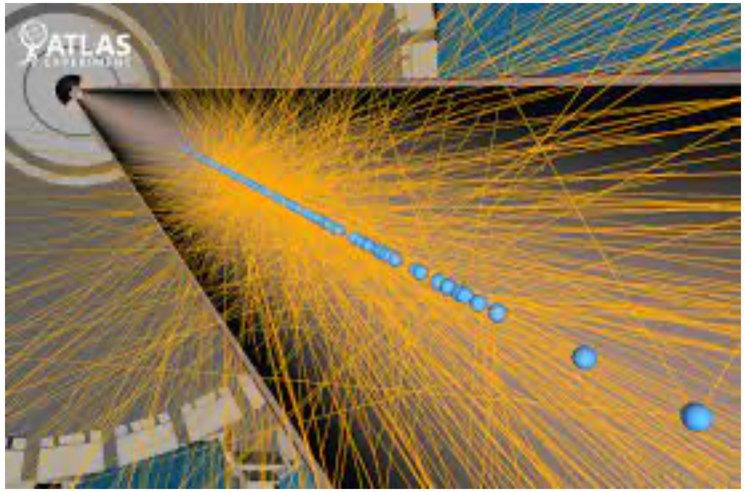
Outline

ATLAS data-taking and operations



New physics results — my pick

HL-LHC upgrades



Run 4 - 5...

.6 - 14 TeV energy

2041

5 to 7.5 nominal Lumi

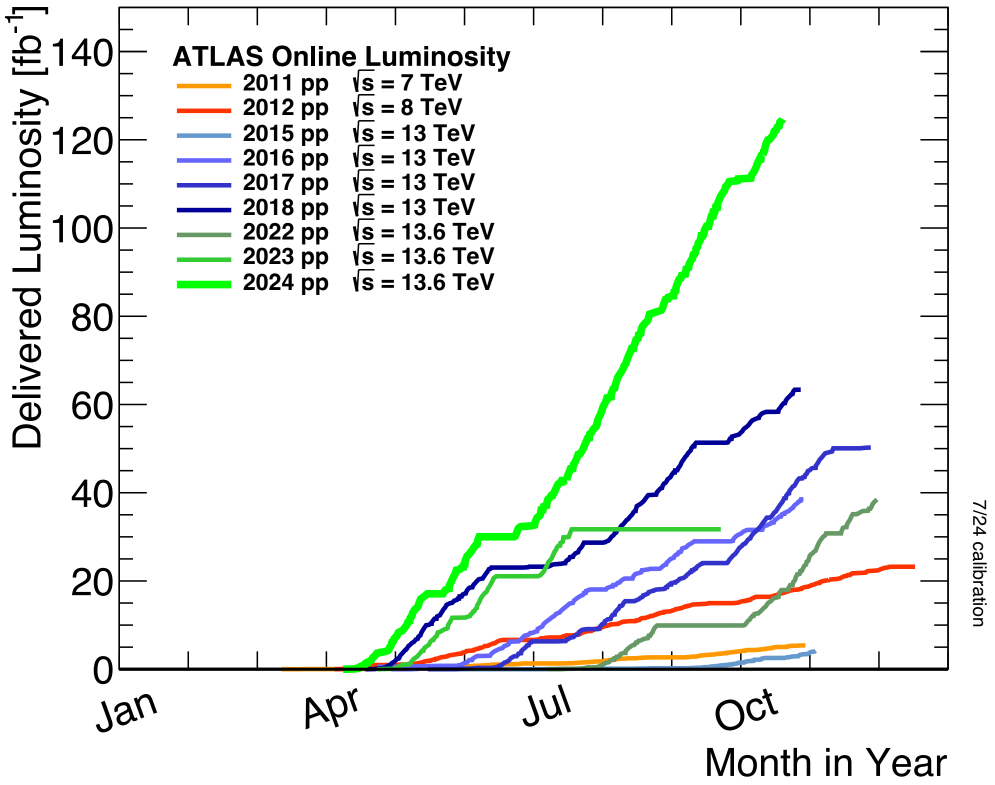
3000 fb^{-1}
4000 fb^{-1}

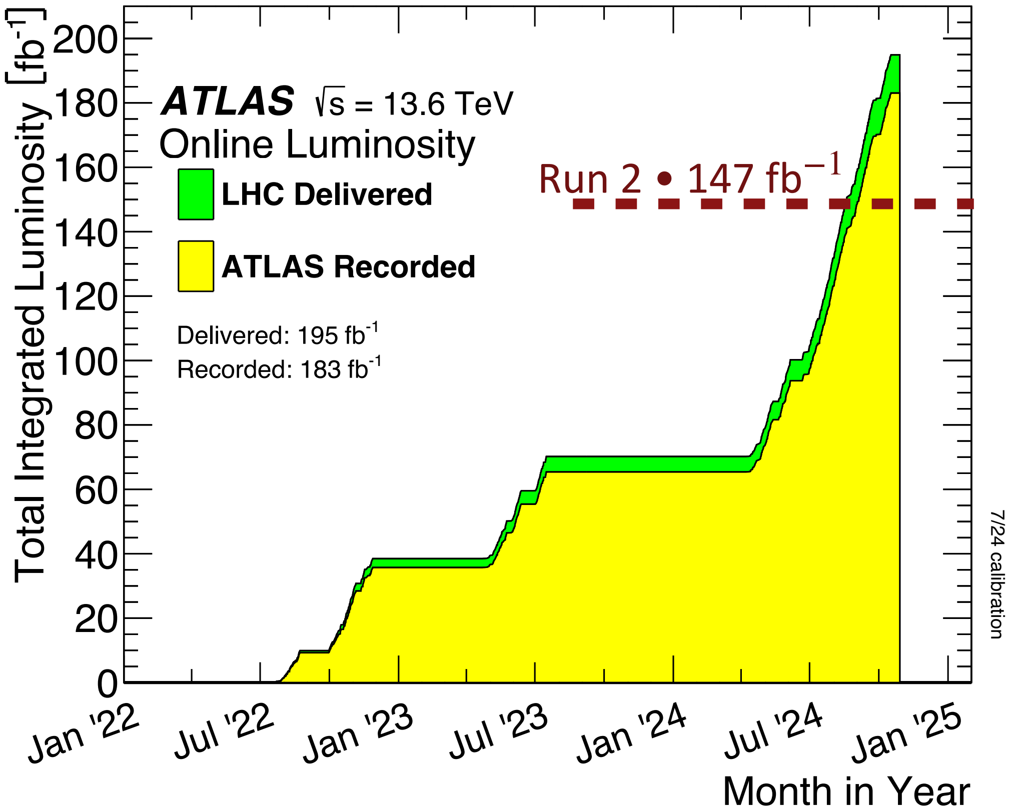
PHYSICS

DEFINITION EXCAVATION BUILDINGS CORES

2024: An extremely impressive year of data -taking

- Exceeded predictions: **Delivered an integrated luminosity of 125 fb^{-1}**
- Surpassed the Run-2 dataset (147 fb^{-1}) in Run 3 (183 fb^{-1})
- PbPb 5.4 TeV 1.82 nb^{-1}

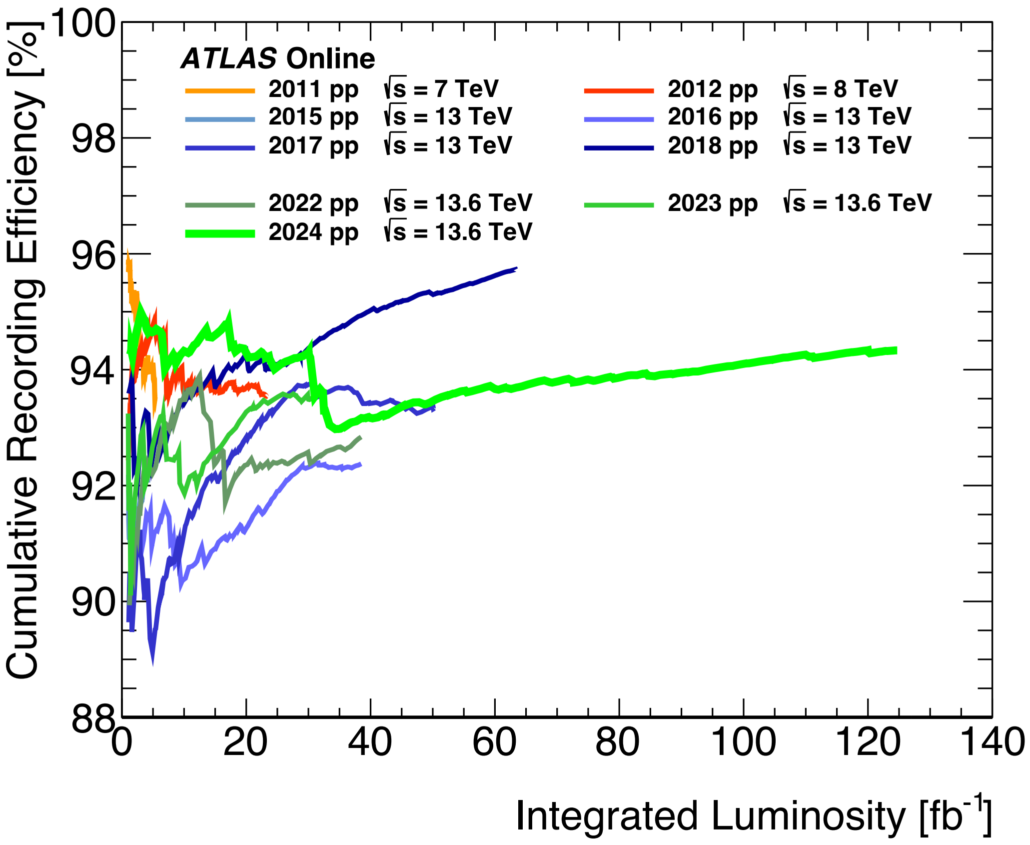


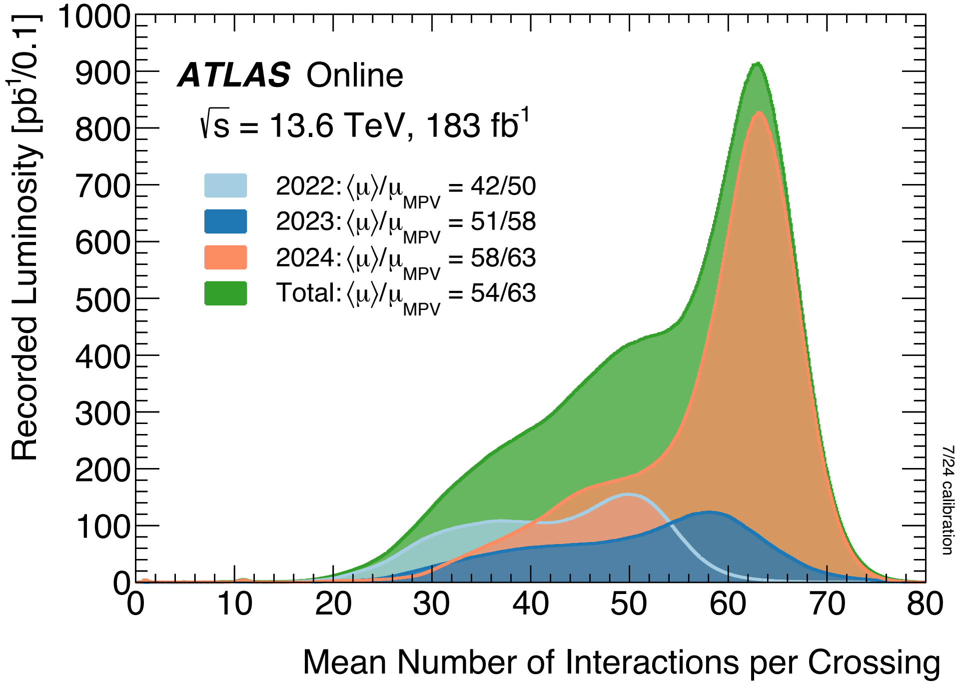


ATLAS Operation Performance in 2024

Data quality efficiency of **94%**, with 110 fb^{-1} good for physics

- On the rise throughout 2024 (and Run 3)
- 2 nd best data - taking year so far (at higher pileup)



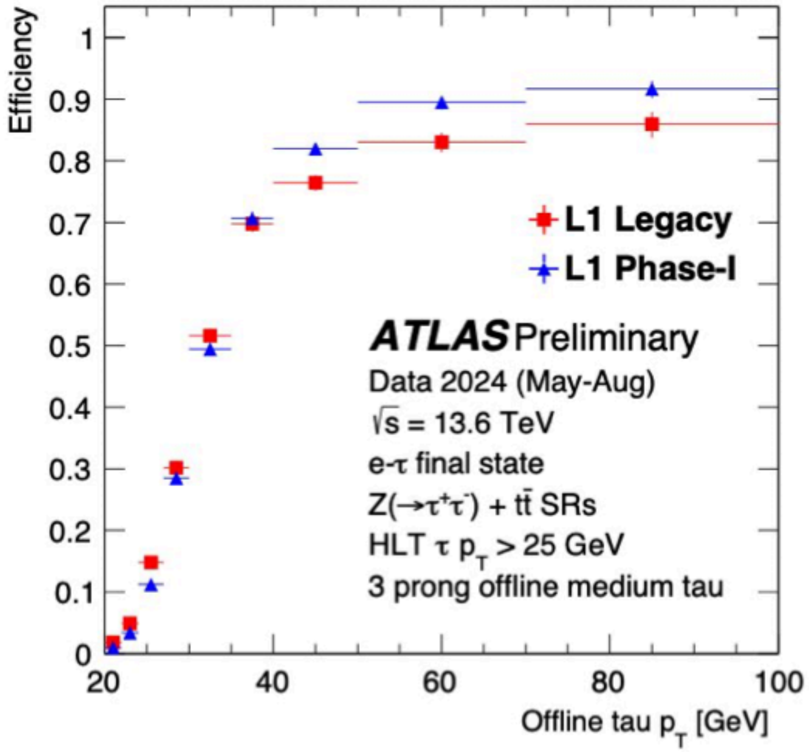


ATLAS Operation Performance in 2024

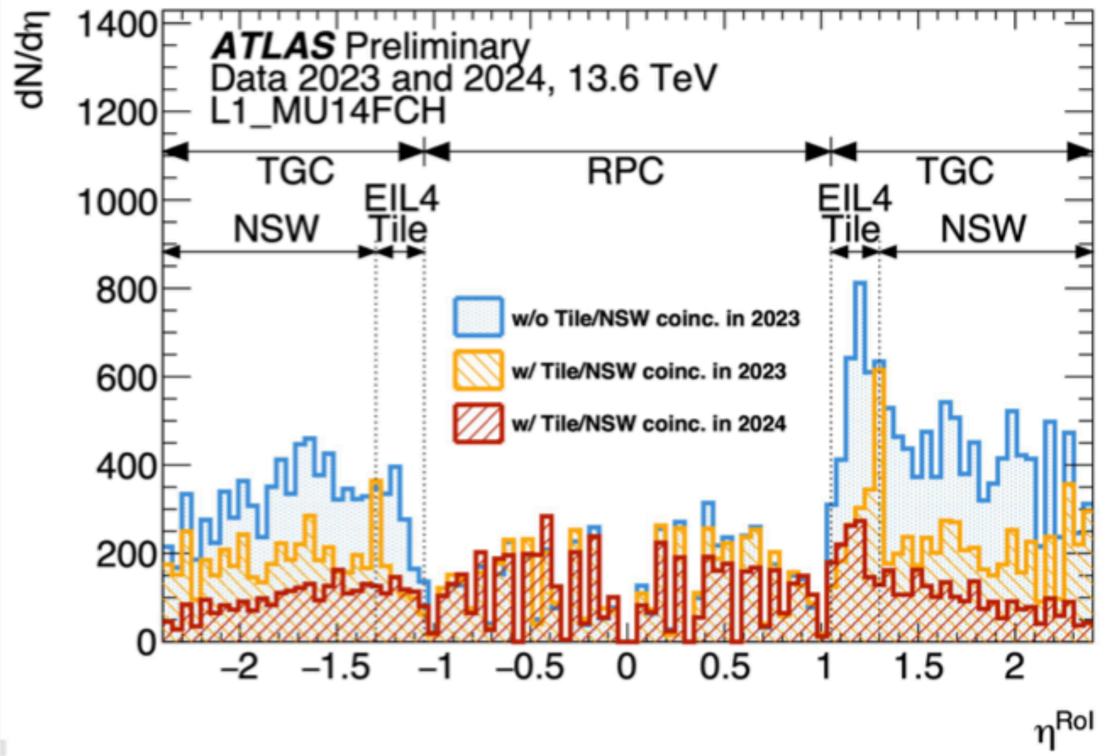
Data quality efficiency of **94%**, with 110 fb^{-1} good for physics

- Improved performance with Phase-I trigger system
- Large inefficiencies due to downtime of magnets

L1 Calo +LAr shaper turn on and better Efficiency



L1Muon with NSW showed reduced fake rate

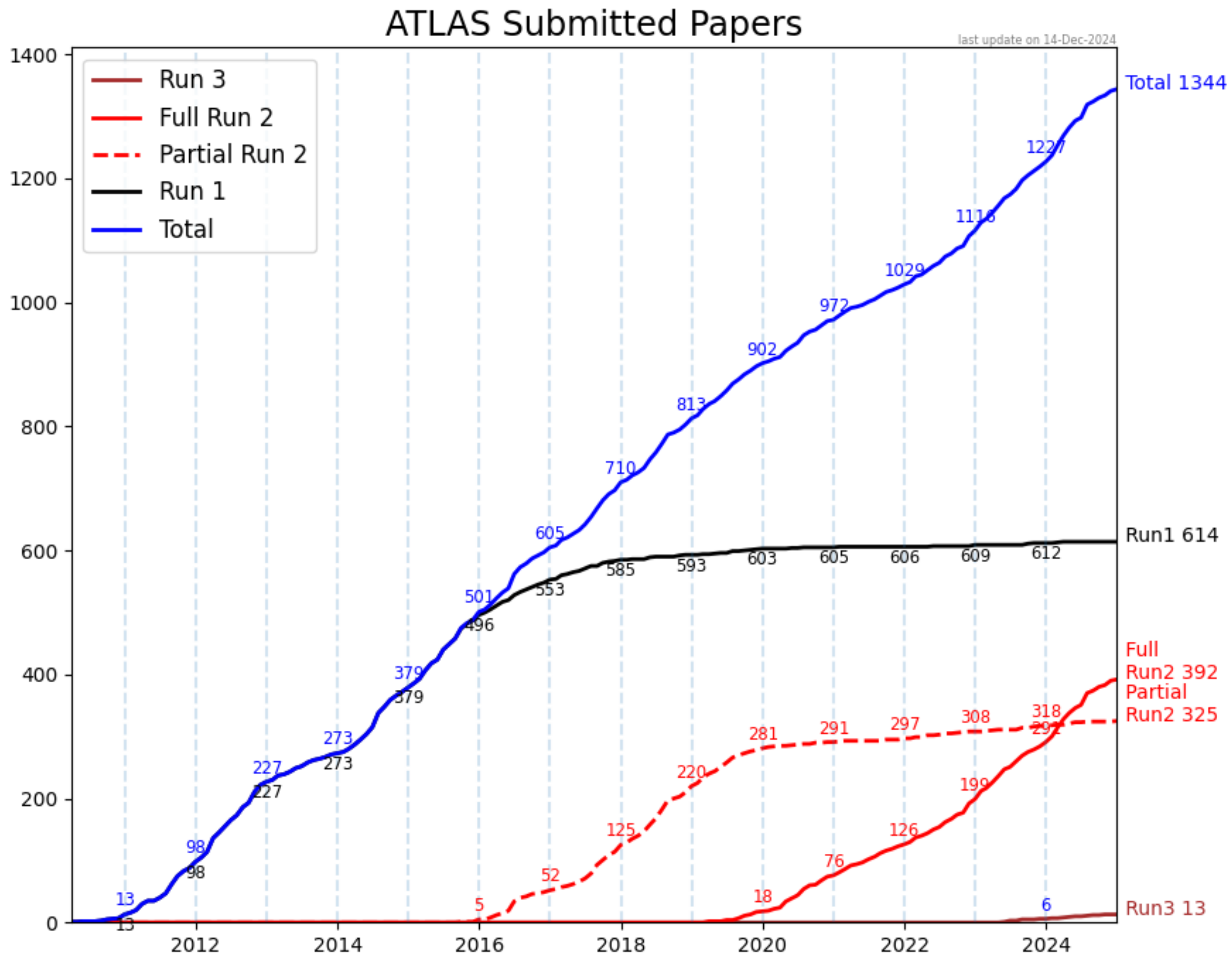


SLAC

A Selection of 2024 public results

Run 2 publication efforts still in full swing

Run 3 publication efforts starts ramping up, more are coming in 2025



A Selection of 2024 public results

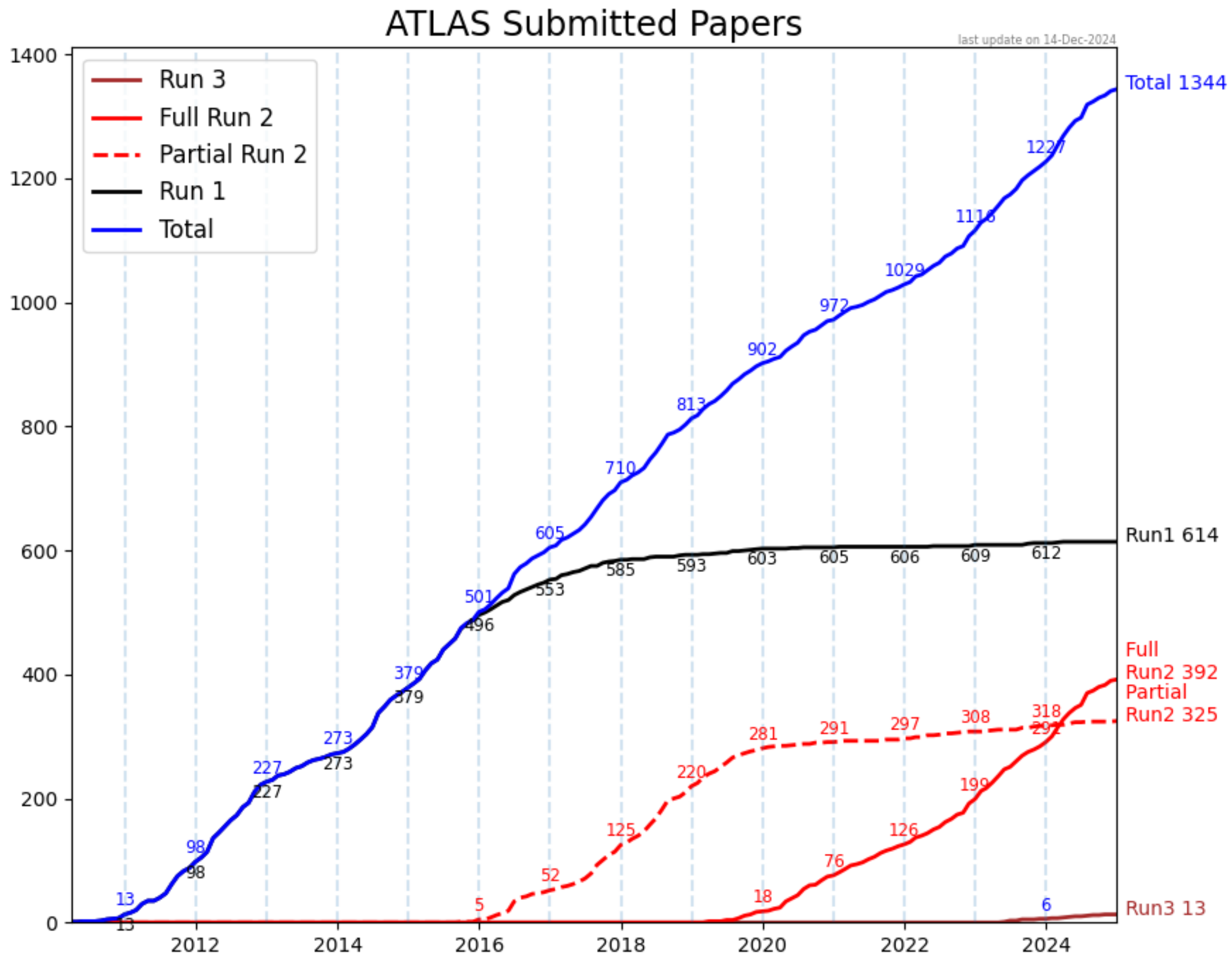
Where we stand now:

- Precision measurements of the Standard Model
- Searches for physics beyond Standard Model

What Lies Ahead:

- New techniques and ML/AI tools improve performance

* A very biased selection, curated by Zhi Zheng!



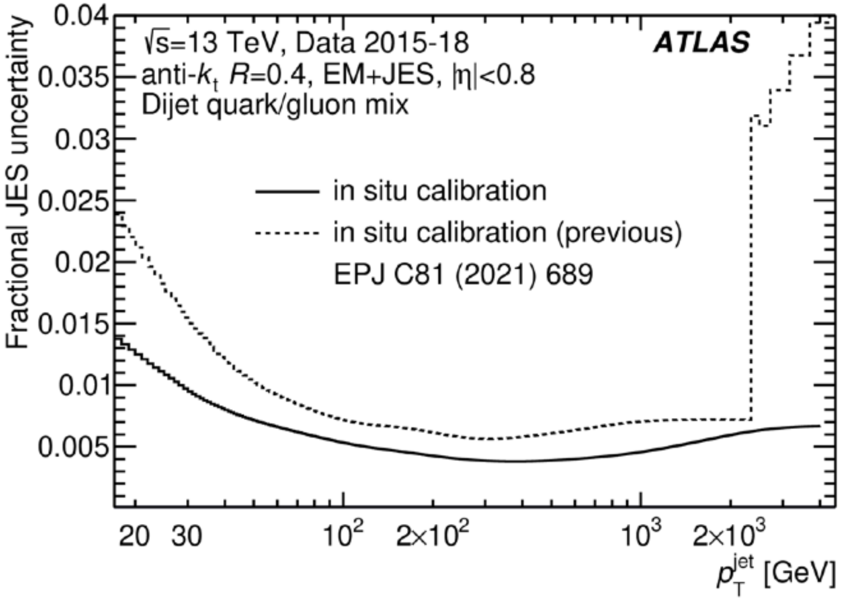
Improvements from Performance

arXiv:2407.15627
arXiv:2412.04370
ATL-PHYS-PUB-2024-015

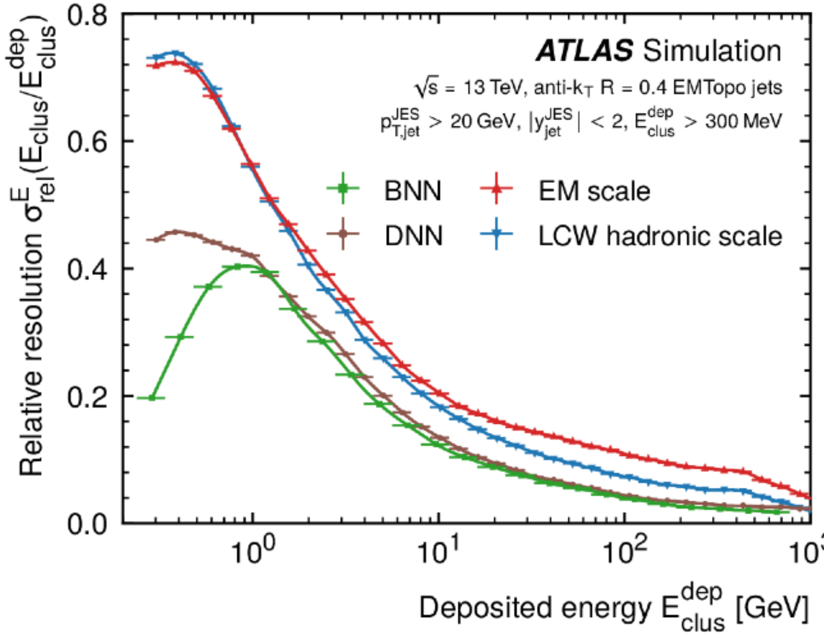
Precision of objection reconstruction much beyond the designed goals

- Advanced ML/AI tools and new method

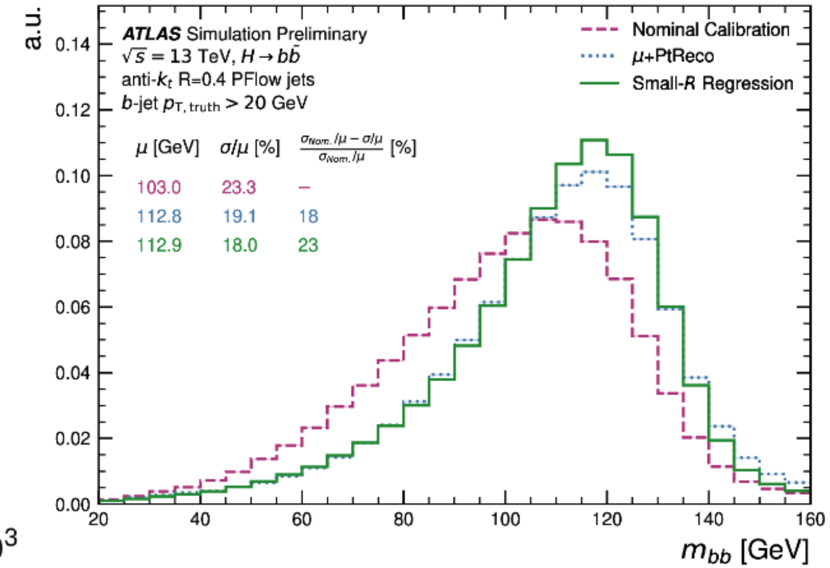
E/p Deconverlution method improve jet energy scale uncertainty < 1%



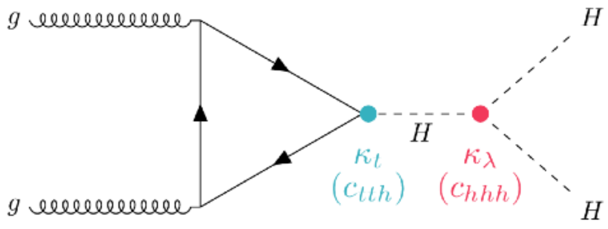
Bayesian neural network (BNN) improves resolution and extend linearity region



Transformer improves resolution for Higgs mass ~ 23%



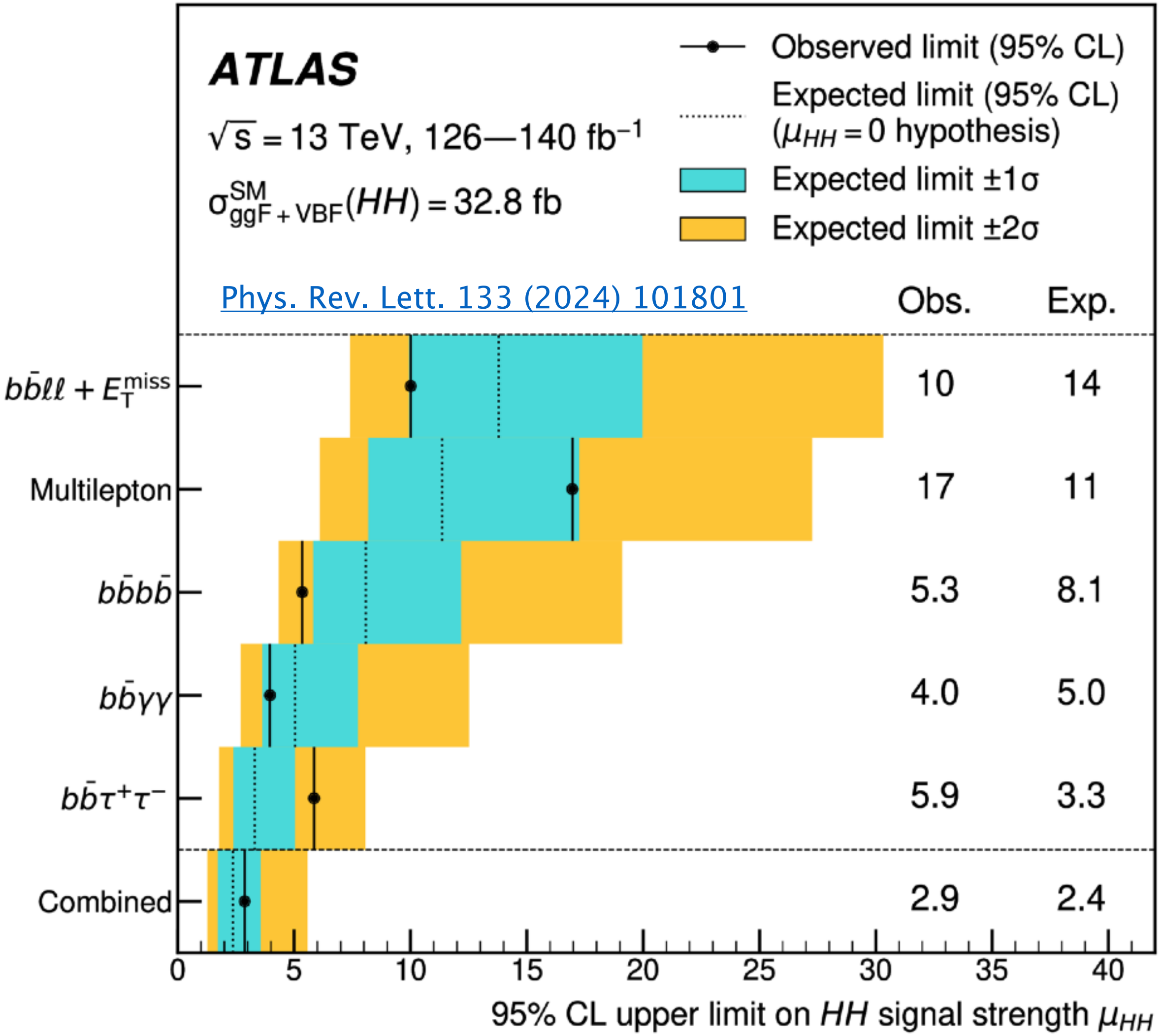
Probing the Higgs Self-Coupling



Continuously exploring new phase space and refining channels for improved results

Best expected sensitivity on HH cross section, self-coupling, κ_λ

$$\mu_{HH} = 0.5^{+0.9}_{-0.8}(\text{Stat.})^{+0.7}_{-0.6}(\text{Syst.})$$



New
JHEP02(2024)037

New
JHEP 08 (2024) 164

New boosted part
Phys. Lett. B 858 (2024) 139007

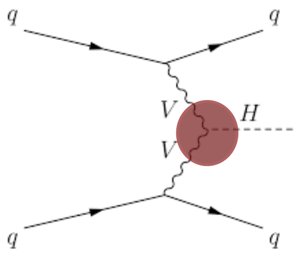
Improved
JHEP 01 (2024) 066

Improved
Phys. Rev. D 110 (2024) 032012

Precision Higgs: Towards Differential Measurements

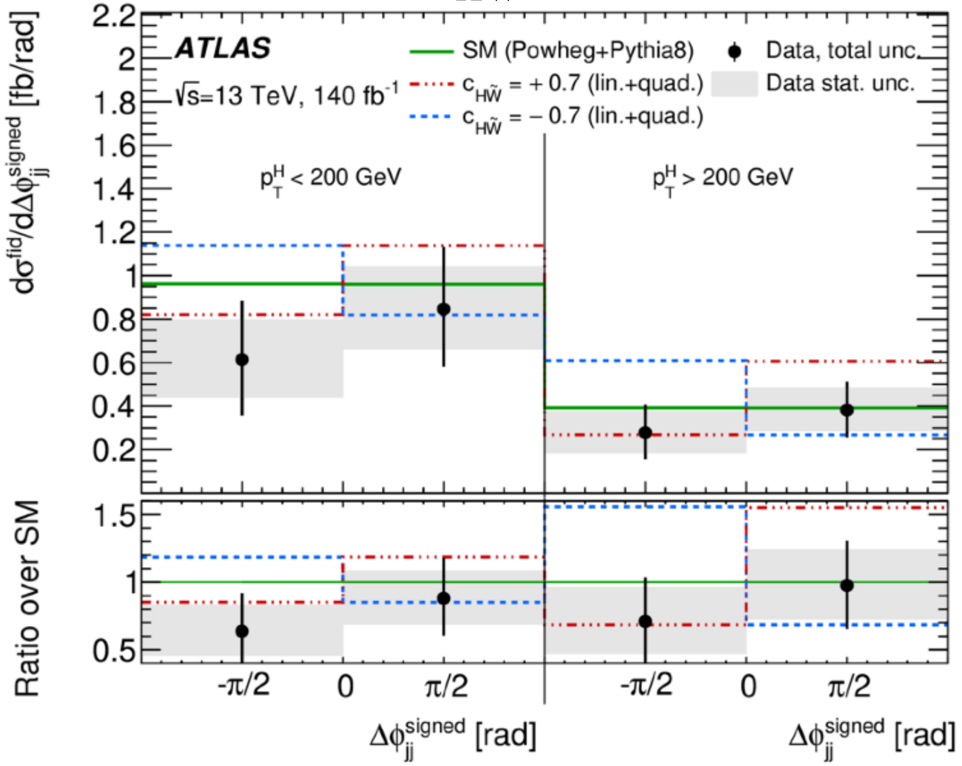
arXiv:2407.16320
arXiv:2407.10904

$H \to \tau\tau$



$\Delta\phi_{jj}^{\text{signed}}$ sensitive to VBF kinematics and BSM effects

Give the **strongest constraints** on CP-odd $C_{H\tilde{W}}$ [-0.31, +0.88]

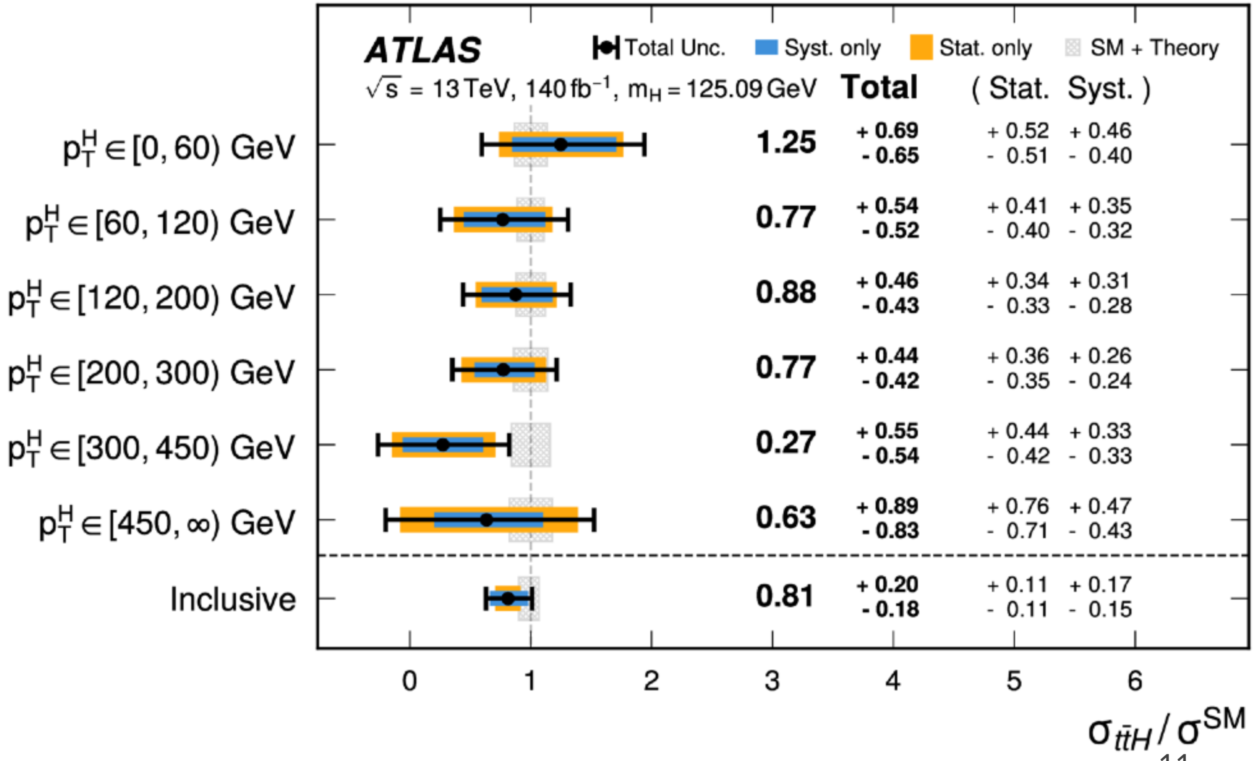


$t\bar{t}H(\to b\bar{b})$

Using Transformer NN for Higgs p_T reconstruction

Total uncertainty reduced by factor of ~2

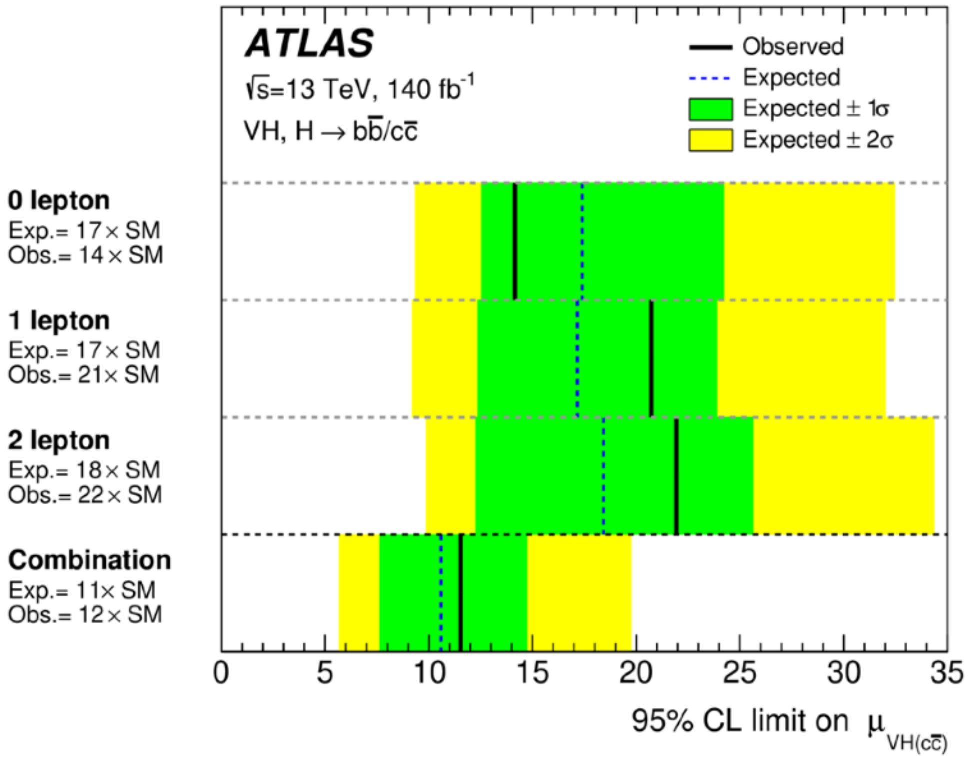
4.6 (5.4)σ observed (expected)



Higgs Rare Processes

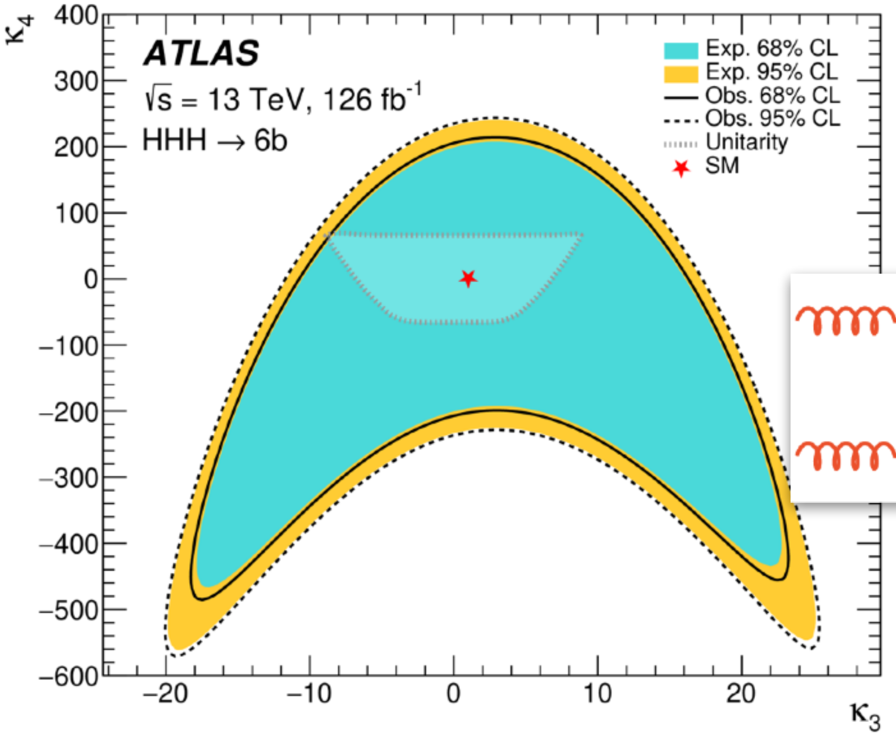
arXiv:2410.19611
arXiv:2411.02040

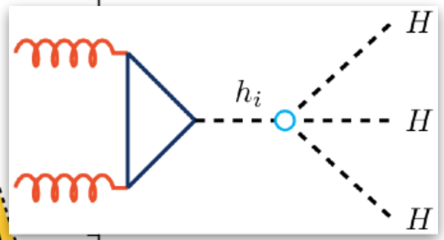
A improvement by a factor of 3 for VHcc
- Current results include only resolved jets
- Further improvements are expected with the addition of the boosted region



First Direct constraints on κ_4:
- 95% CL upper limit on SM HHH production cross section: 59 fb

The results are mainly limited by statistics



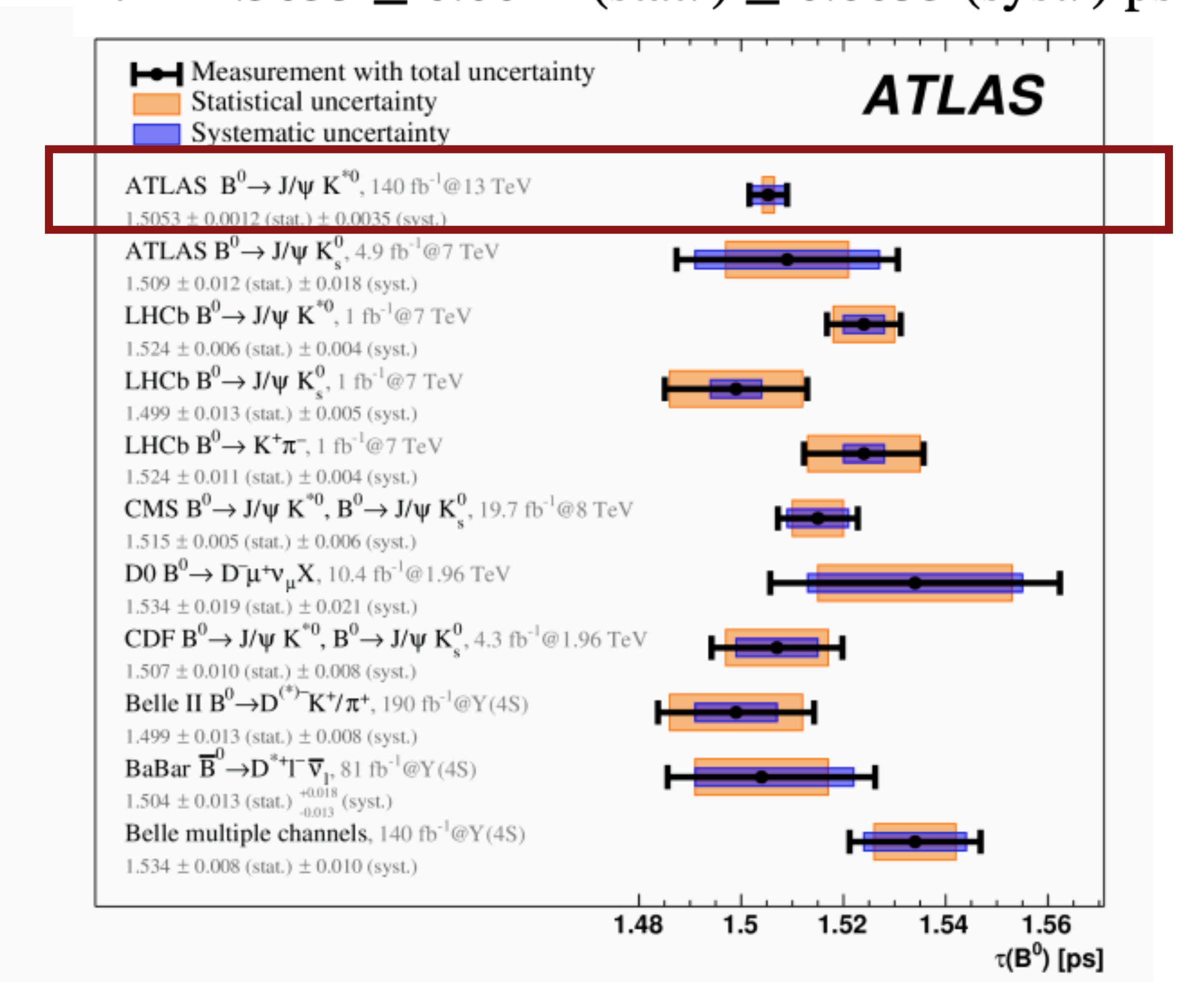


Standard Model Measurements

arXiv:2411.09962
arXiv:2407.13473

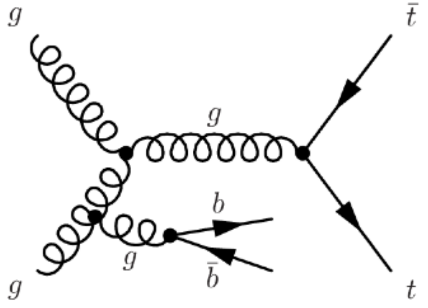
The **most precise** result for B life time

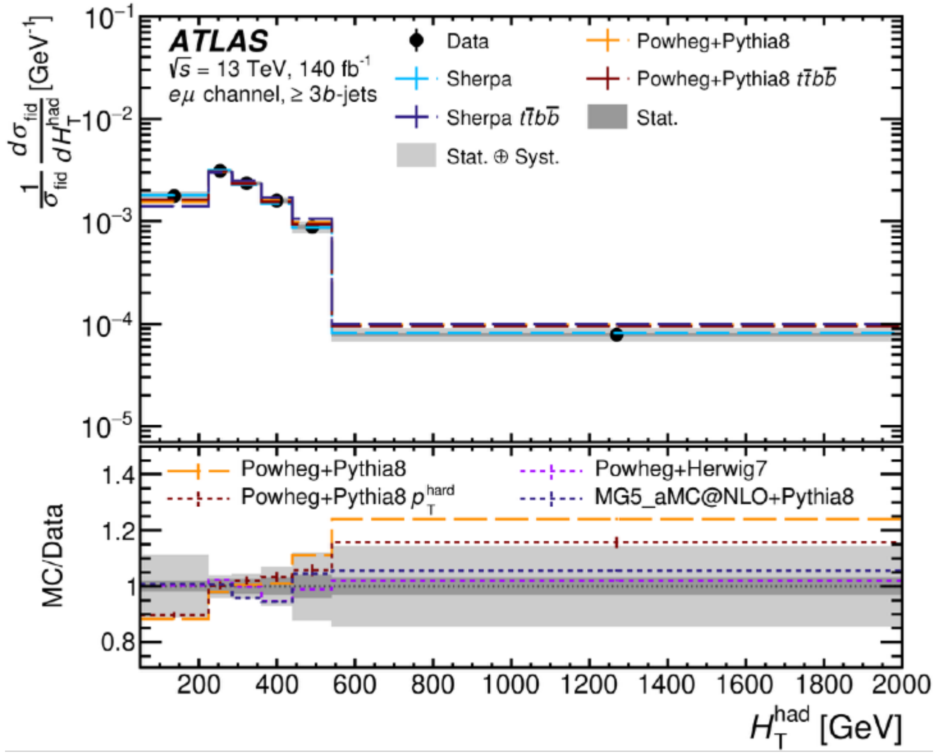
$$\tau = 1.5053 \pm 0.0012\,(\text{stat.}) \pm 0.0035\,(\text{syst.})\ \text{ps.}$$



Measurement of $t\bar{t}$ + heavy flavor

- Extensive measurement for improved theory modeling

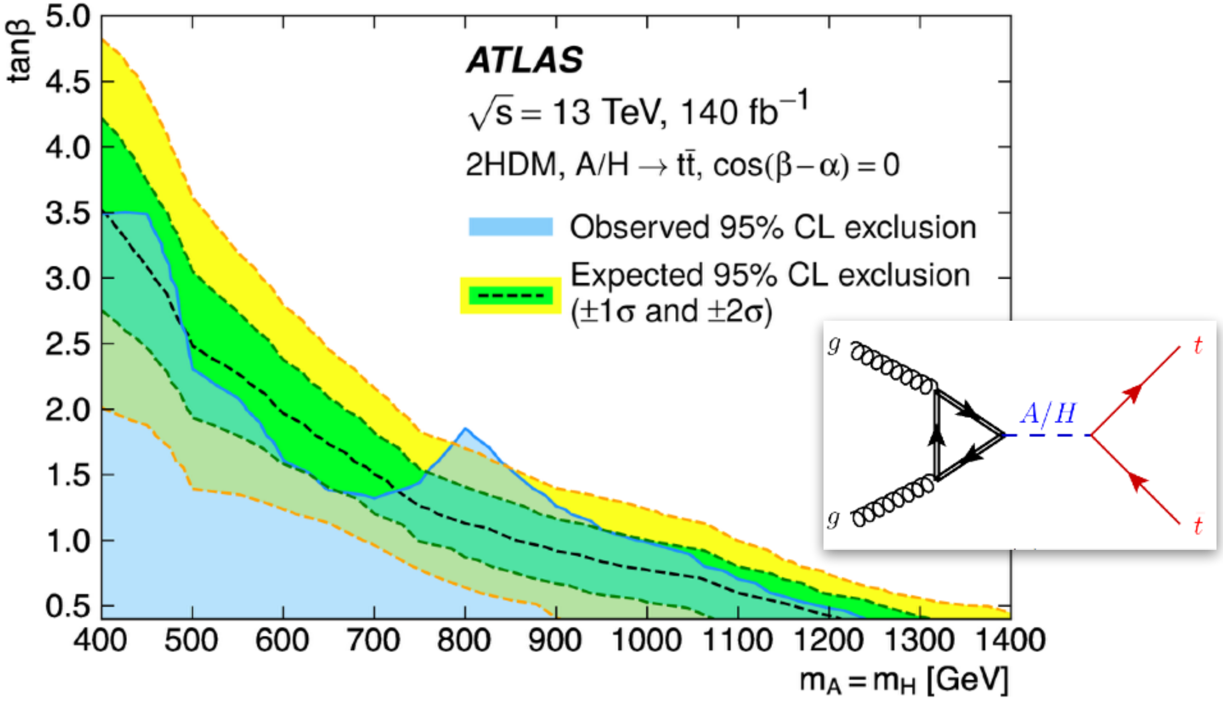




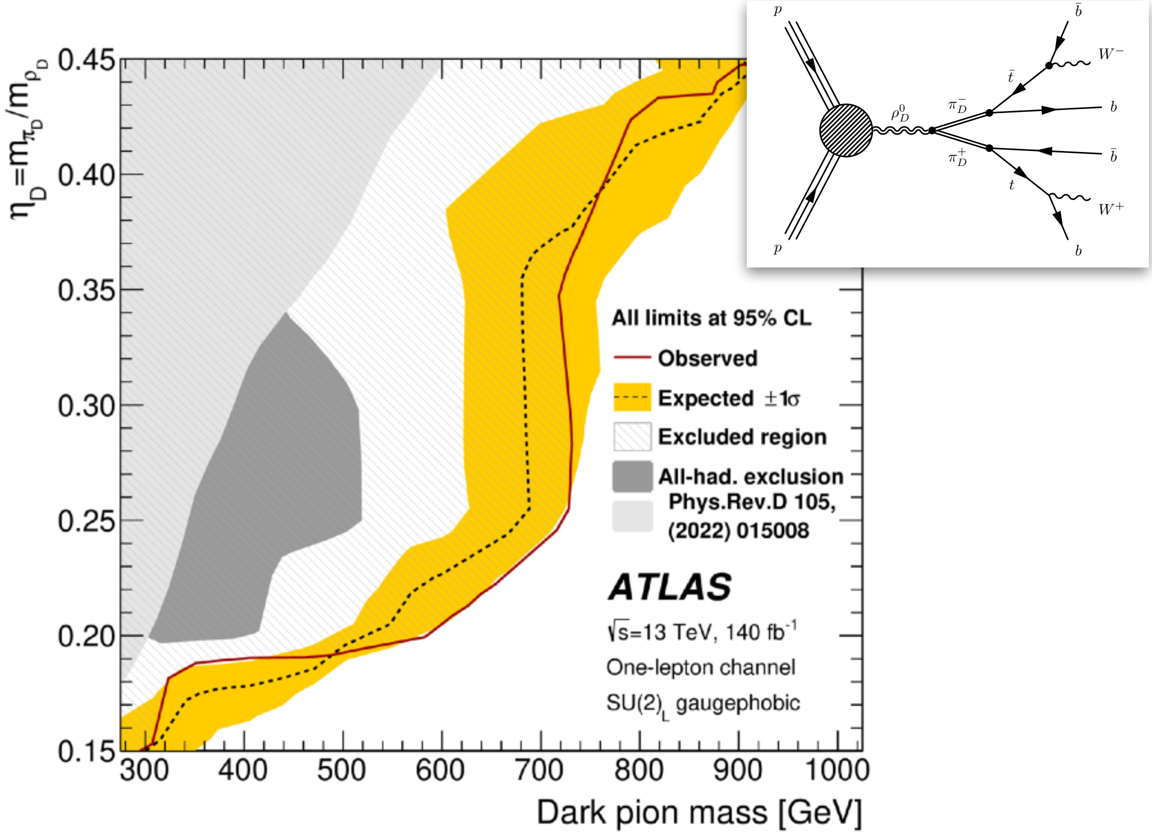
Searches for Physics Beyond Standard Model

[JHEP 08 (2024) 013](#)
[JHEP 09 (2024) 005](#)

Search for additional Higgs Boson with interference in $t\bar{t}$ decays



First LHC search for dark mesons decaying to top and bottom quarks

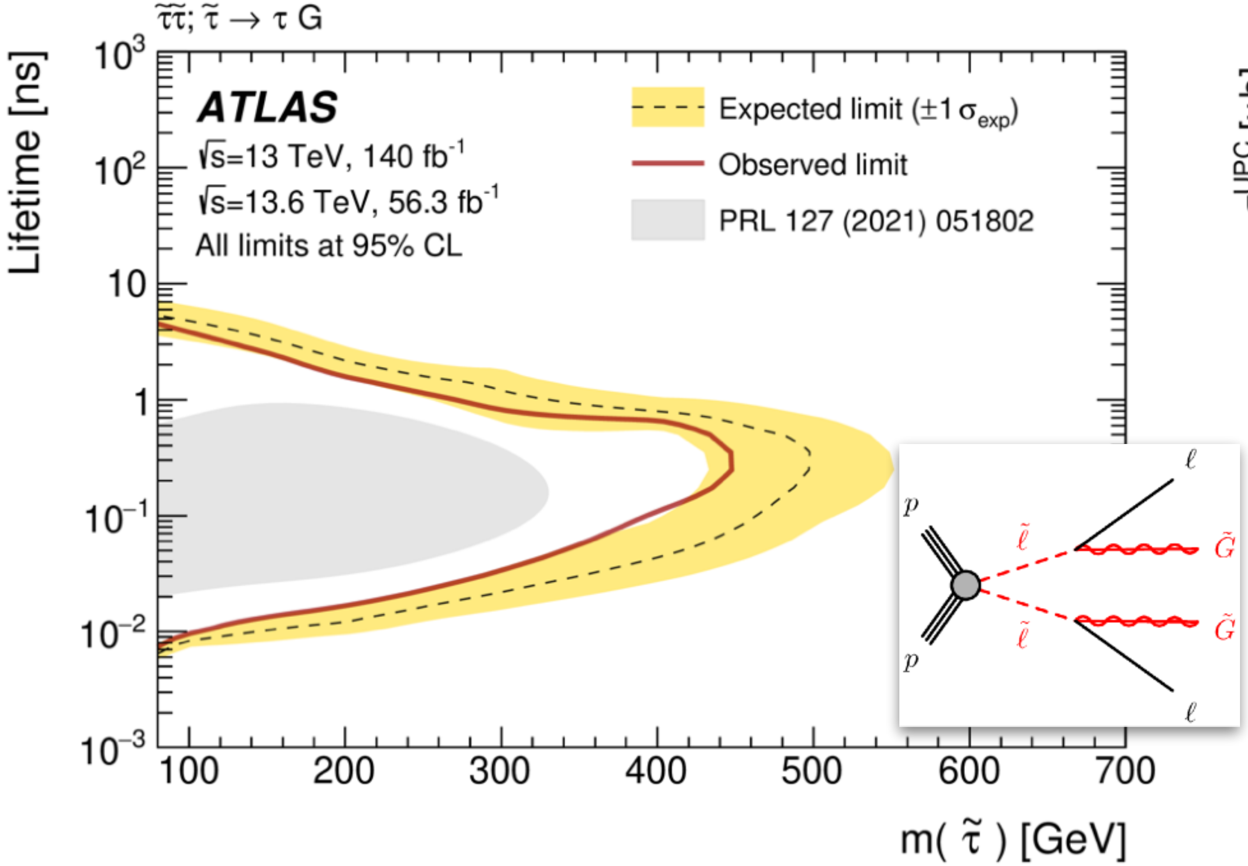


Searches in Run 3

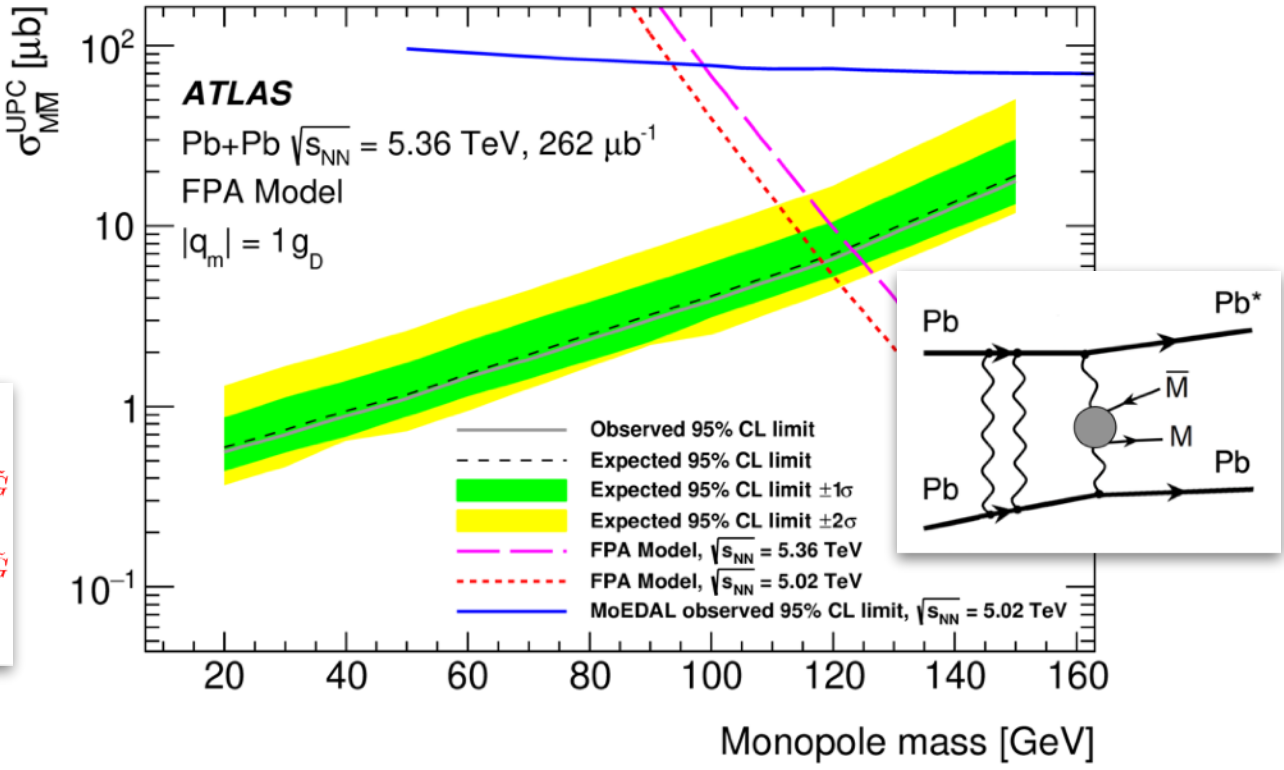
arXiv:2410.16835
arXiv:2408.11035

New data, New triggers and New methodology

New Trigger in Run3: Triggering with large impact parameters tracks

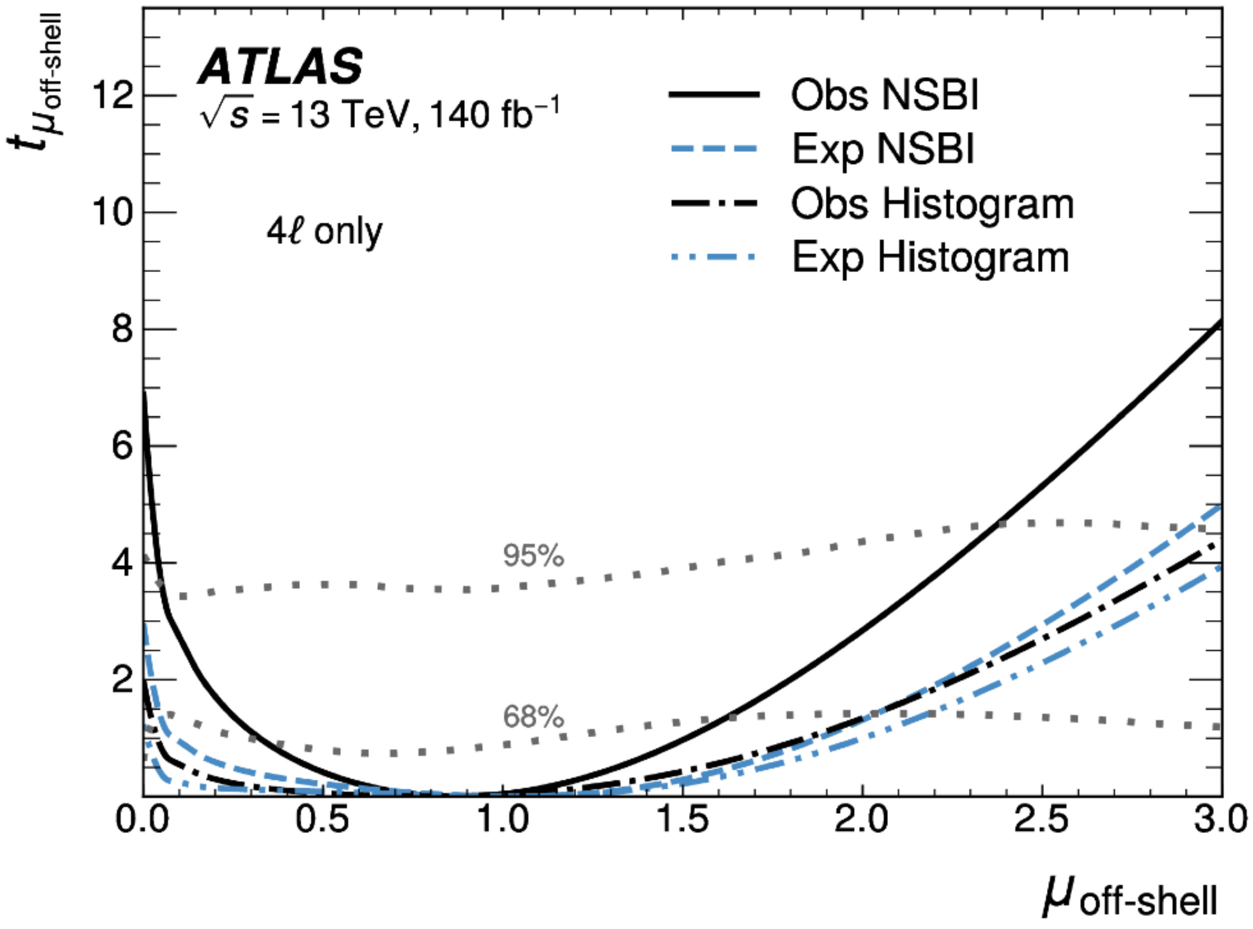


New method to search monopoles in Pb+Pb collision



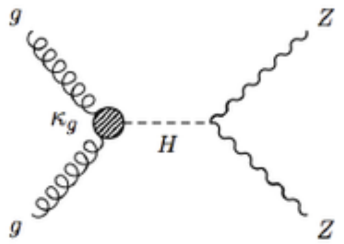
New Methods for Statistical Inference

arXiv:2412.01548



Neural simulation-based inference benefit physics analyses:

Off-shell Higgs production in $H^* \to ZZ$



$$\frac{\mu^{pp\to H^*\to ZZ}_{off-shell} \propto \kappa_{Hgg}\kappa_{HZZ}}{\mu^{pp\to H^*\to ZZ}_{on-shell} \propto \frac{\kappa_{Hgg}\kappa_{HZZ}}{\Gamma_H/\Gamma_H^{SM}}} \propto \frac{\Gamma_H}{\Gamma_H^{SM}}$$

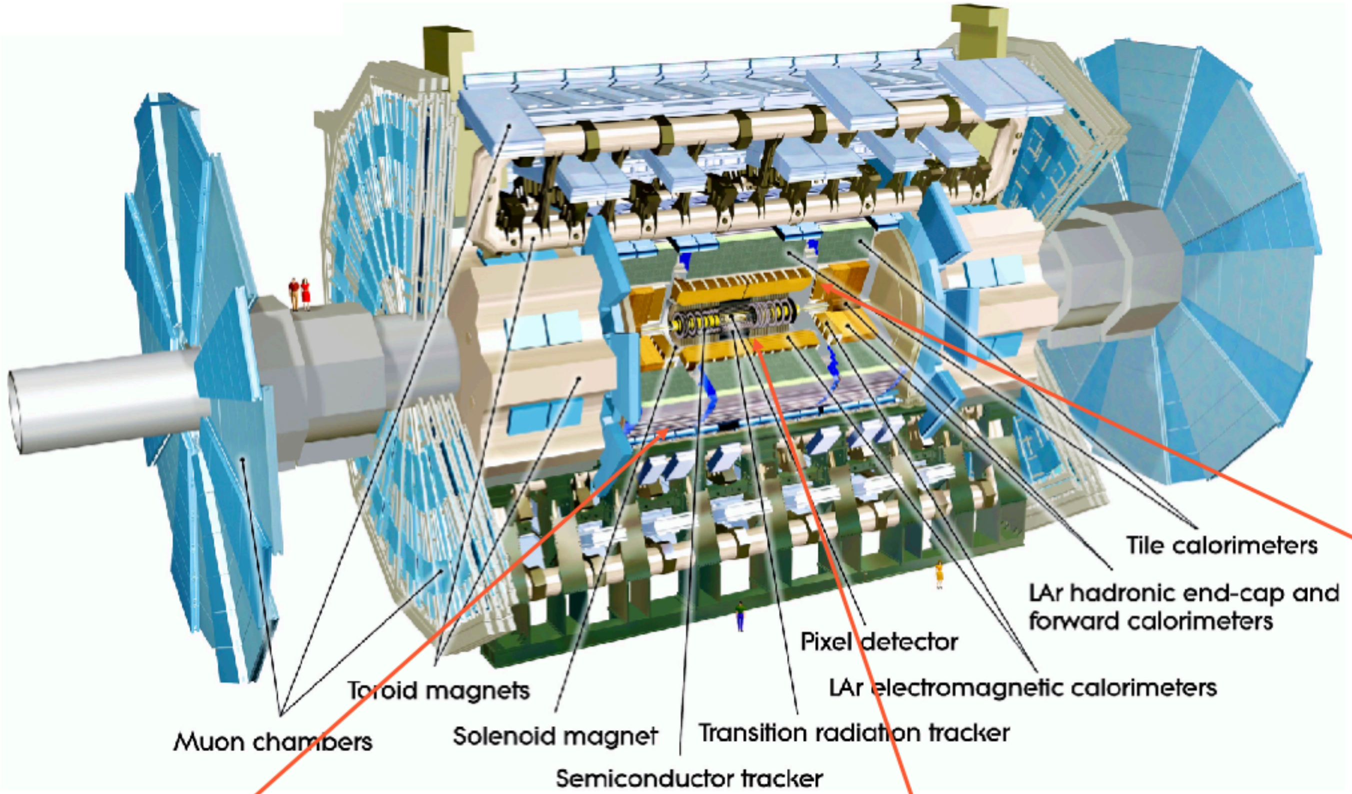
$\Gamma_H = 4.4^{+2.7}_{-1.9}$ MeV

Old Results Based on Histograms

$\Gamma_H = 4.3^{+3.1}_{-2.3}$ MeV Phys. Lett. B 846 (2023) 138223

Improve sensitivity ~ 10%

ATLAS Phase-II upgrade



Upgraded Trigger and Data Acquisition system

Level-0 Trigger at 1 MHz

Improved High-Level Trigger

(150 kHz full-scan tracking)

Electronics Upgrades

LAr Calorimeter

Tile Calorimeter

Muon system

High Granularity Timing Detector (HGTD)

Forward region (2.4 < $|\eta|$ < 4.0)

Low-Gain Avalanche Detectors (LGAD)

30 ps track resolution

New Muon Chambers

Inner barrel region with new RPC and sMDT detectors

New Inner Tracking Detector (ITk)

All silicon, up to $|\eta| = 4$

High-granularity Pixel and Strip systems

Additional upgrades

Luminosity detectors (1% precision goal)

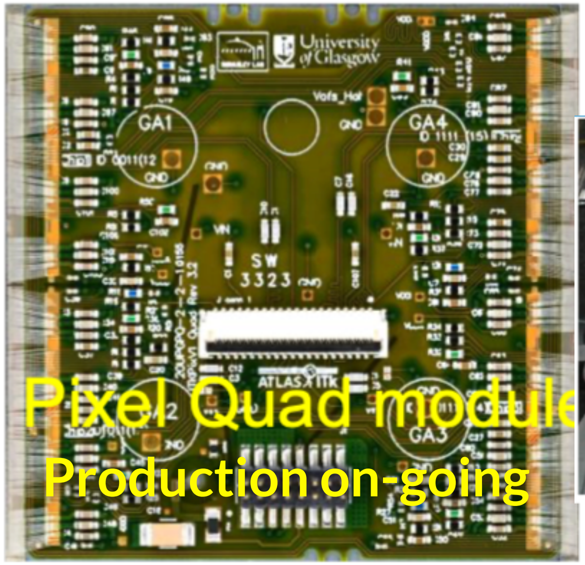
HL-ZDC

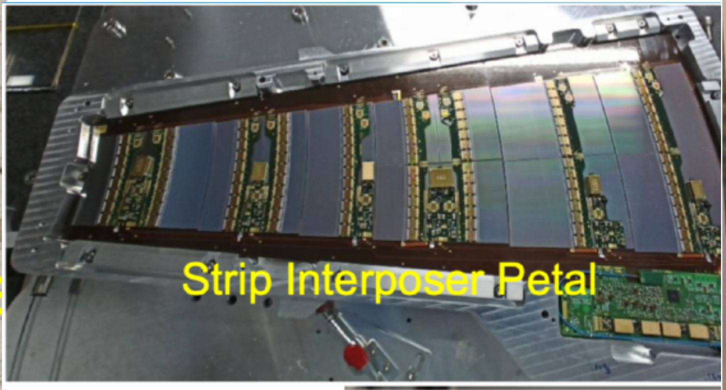
Offline software and computing

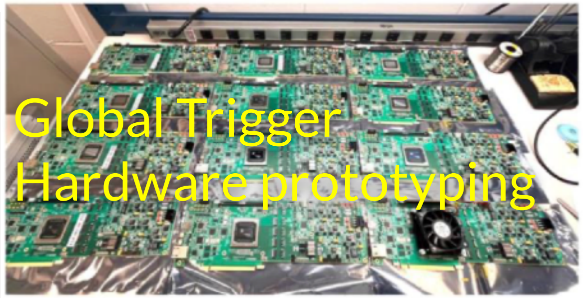
Highlights

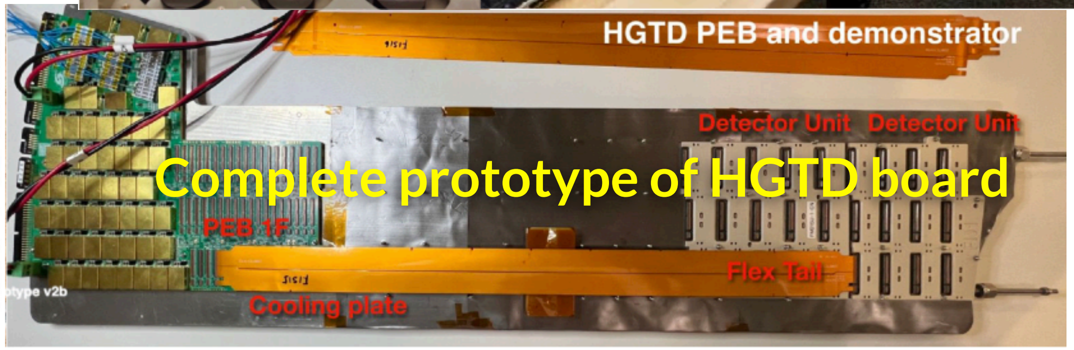
Phase-II upgrade projects have advanced towards production

Many Areas are close to critical path









Summary

Well into Run-3 with a fantastic year of data-taking, excellent performance and good progress with Phase-II upgrades

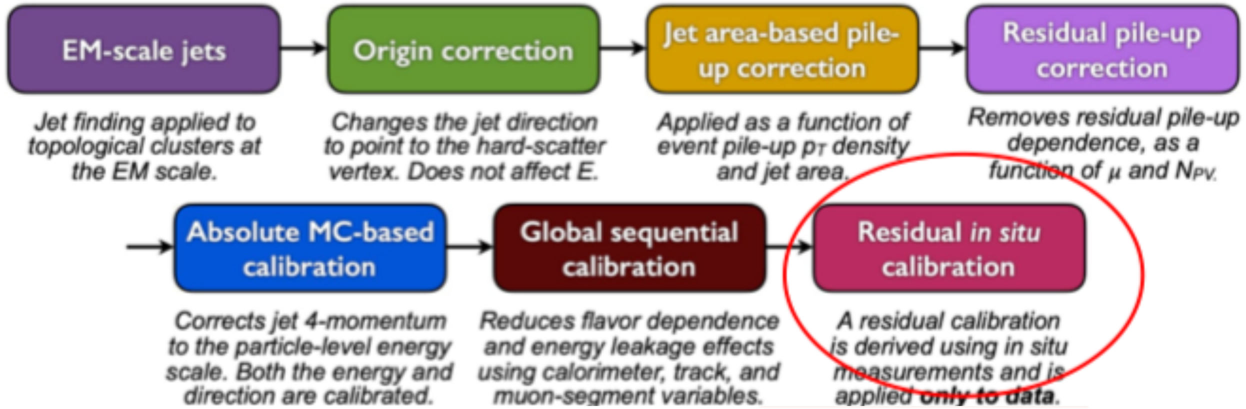
- Continue to search for physics beyond the SM
- Working on high-precision SM measurements
- Exploiting new AI/ML tools and methodology that help us pushing boundaries

With new data, new method and new detector ahead, road ahead is filled with exciting physics

Bonus Content

Jet Energy Scale

[arXiv:2407.15627](https://arxiv.org/abs/2407.15627)

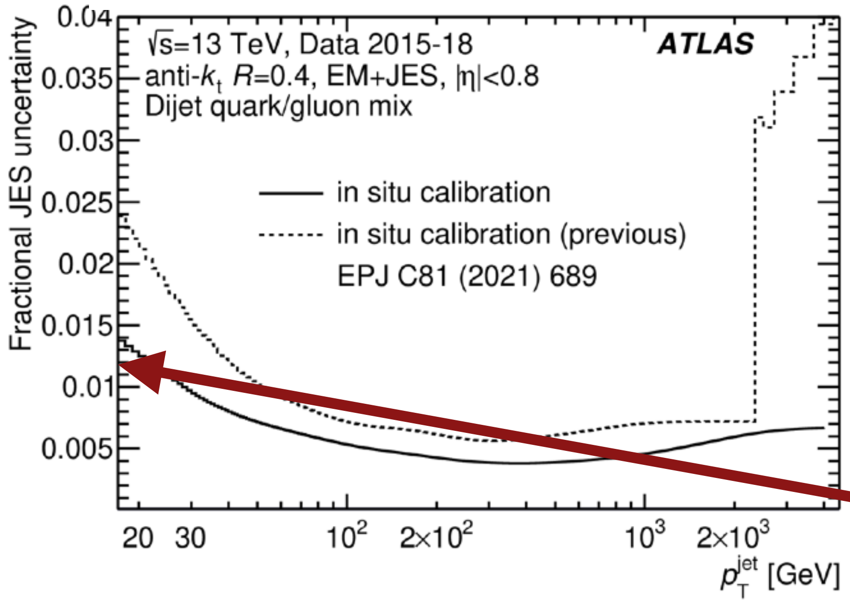


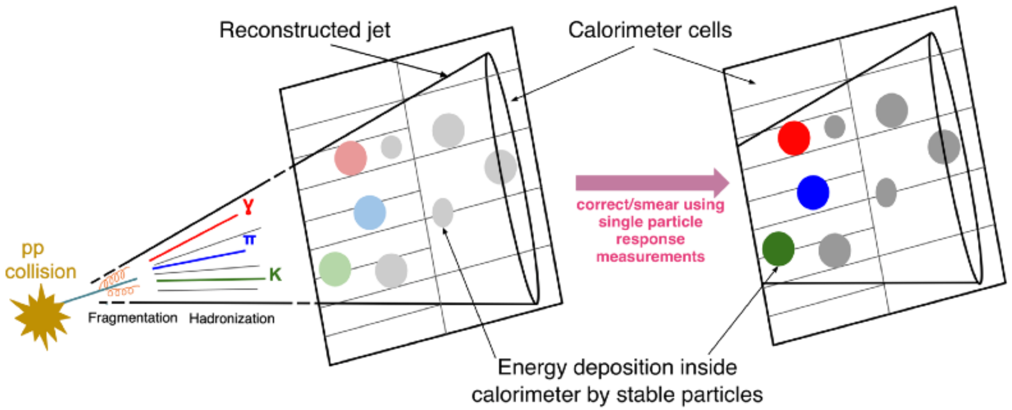
Old Method: In situ calibration with Z+jets pT balanced method

- Limited kinematic reach

New Method: Deconvolution method rely on single particle E/p measurement

Response correction = R_{data} / R_{MC} = Σ(shifted or smeared hit energies) / Σ(nominal hit energy)





E/p for single hadrons were driven:

- Minimum bias events (0.6 < p < 20 GeV)
- $W \rightarrow \tau\nu$ decays (10 < p < 300 GeV)

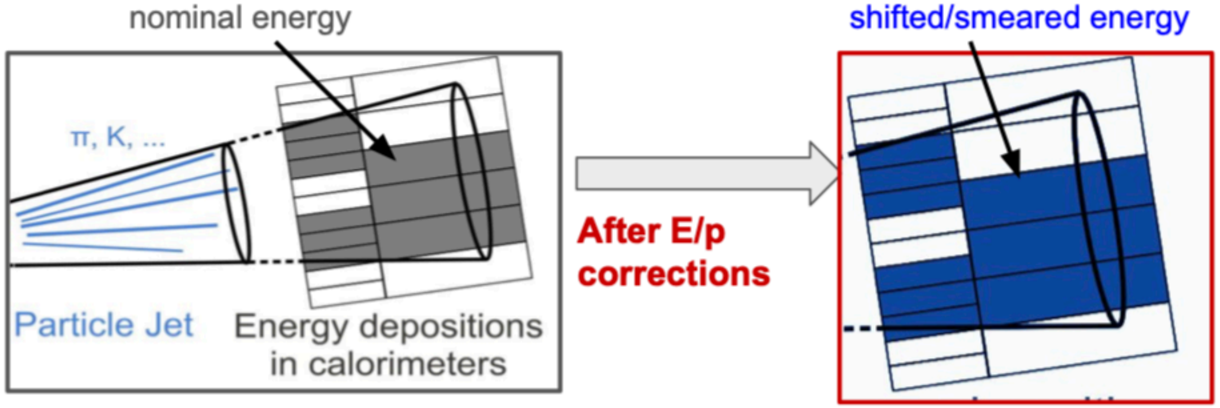
Deconverlution

Truth matched EMTopo jets → EMTopo jets associated cluster of cells → True energy deposition (Hits) inside cells → Pick-up corrections from E/p inputs according to truth particle type and p_T

↓

correct/smear deposited energy corresponds to truth particle

$$f(p_T) = \text{Poisson}(\, f_{Data/MC}(p_T),\ \Delta f_{Data/MC}(p_T)\,)$$



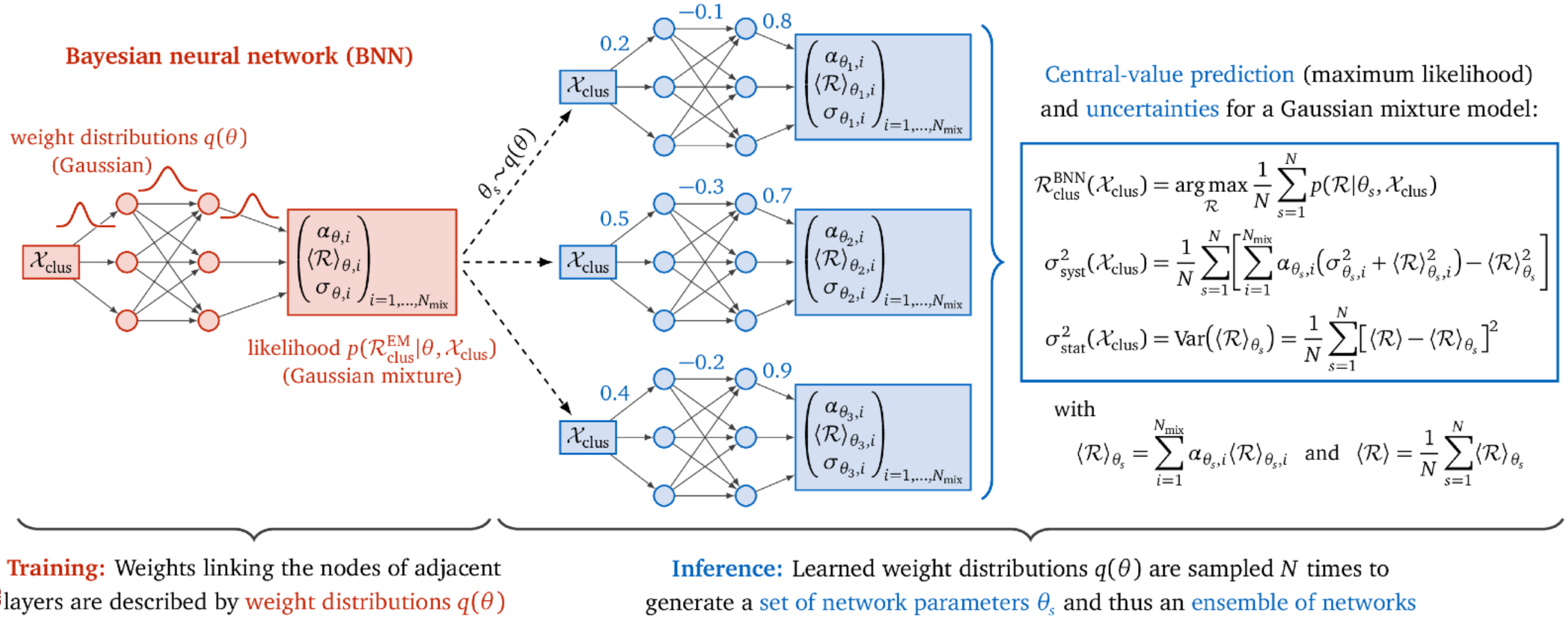
Response correction = R_{data}/ R_{MC} = Σ(shifted or smeared hit energies) / Σ(nominal hit energy)

Precision calibration of calorimeter signals

arXiv:2412.04370

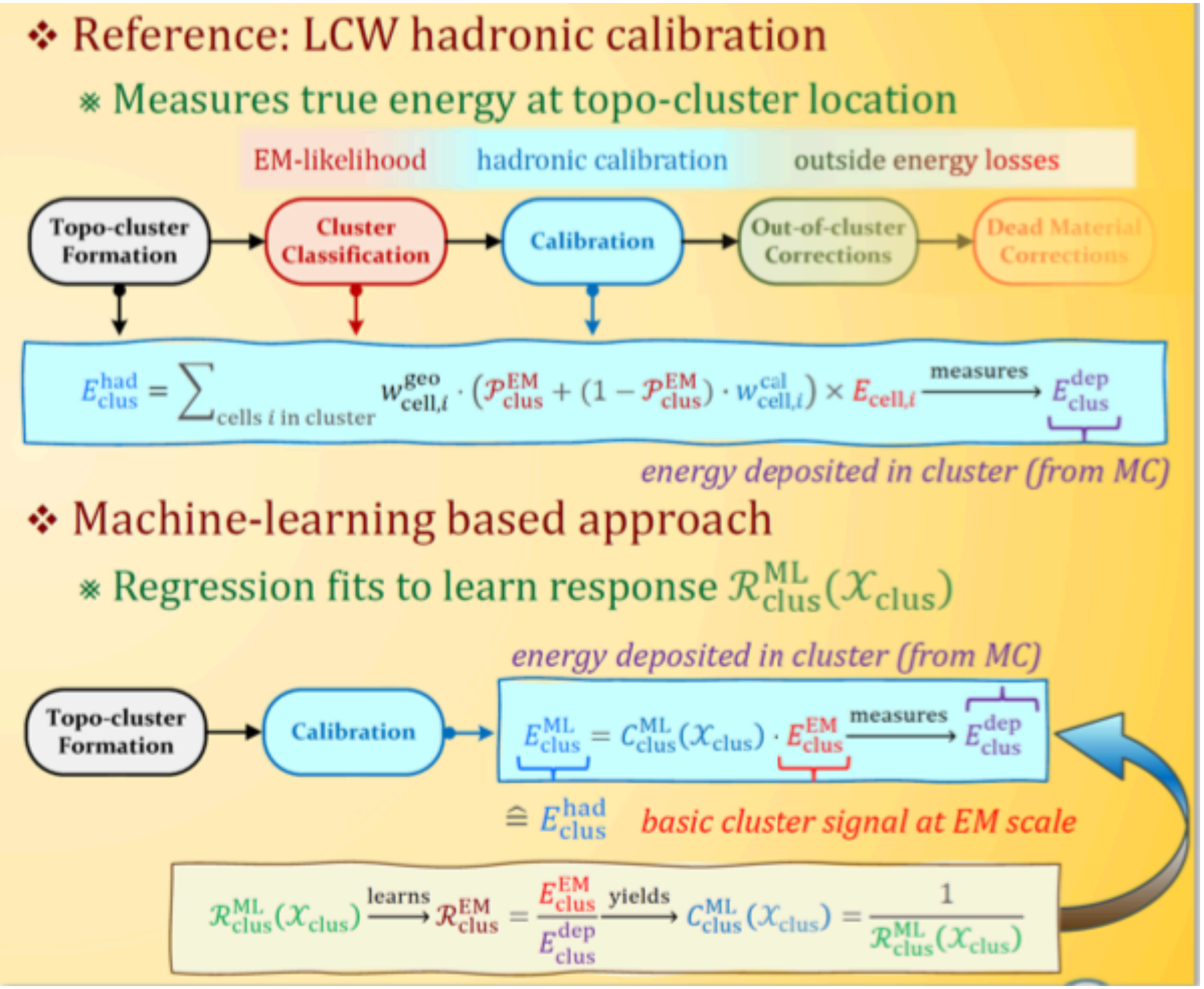
BNN: Local topo-cluster calibration using Machine Learning

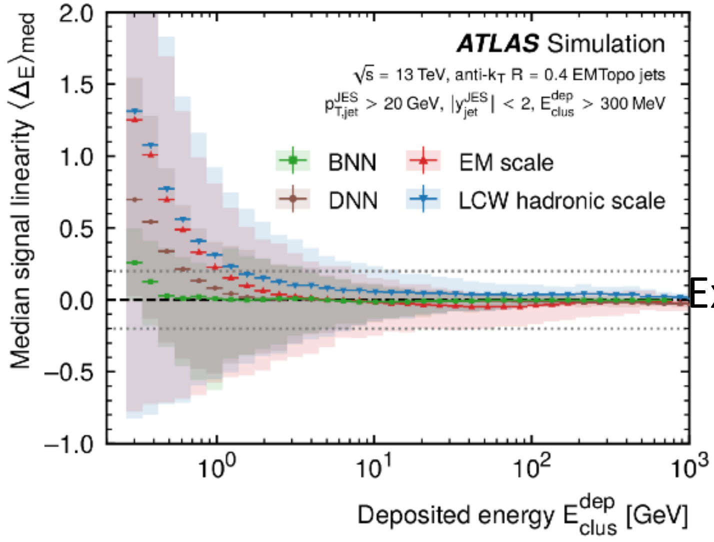
- Improved response measurements in jets, hadronic recoil and event shape
- Assess per-cluster systematic uncertainties for bottom-up approaches, add handle for cluster selection based on signal quality



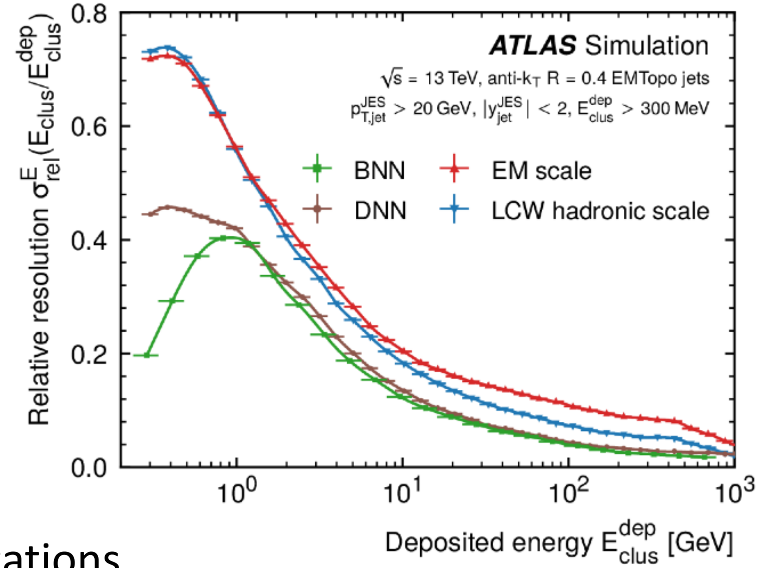
Precision calibration of calorimeter signals

arXiv:2412.04370





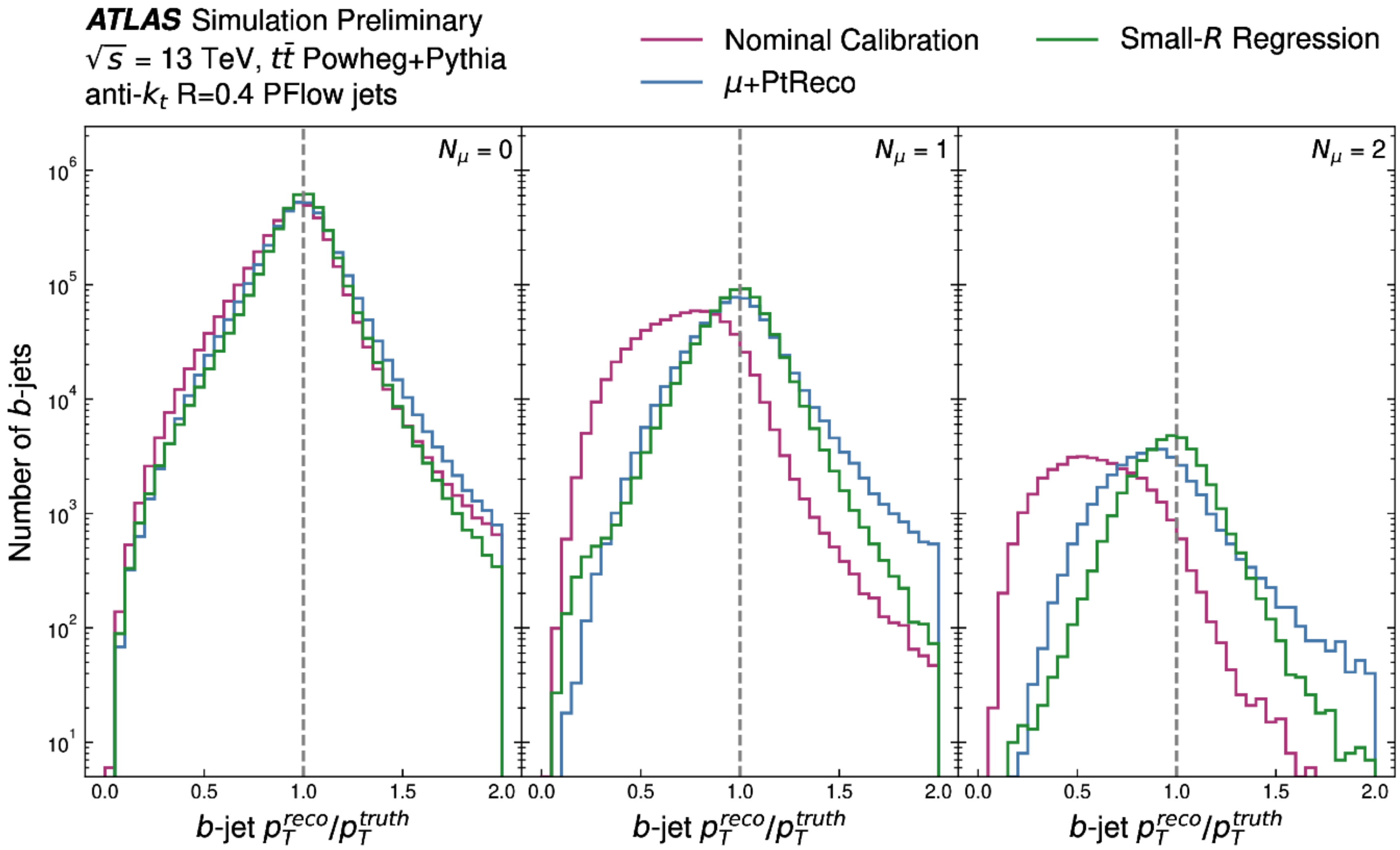
Extend linearity



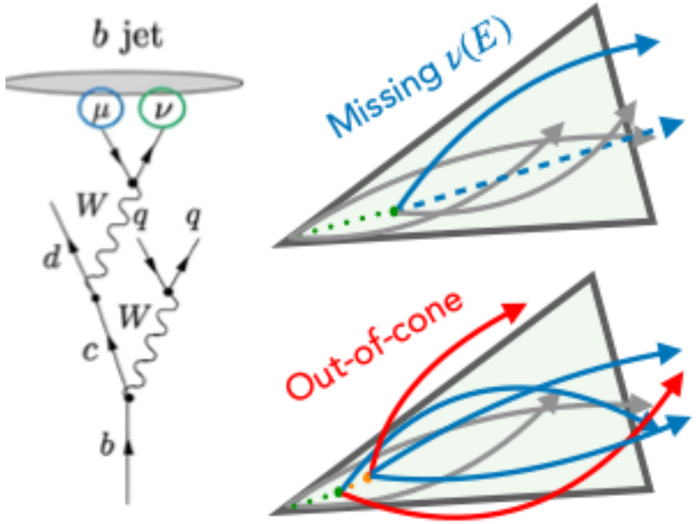
Ionizations (Landau) ← Hadronic shower fluctuation

B-jet calibration with Transformer

ATL-PHYS-PUB-2024-015



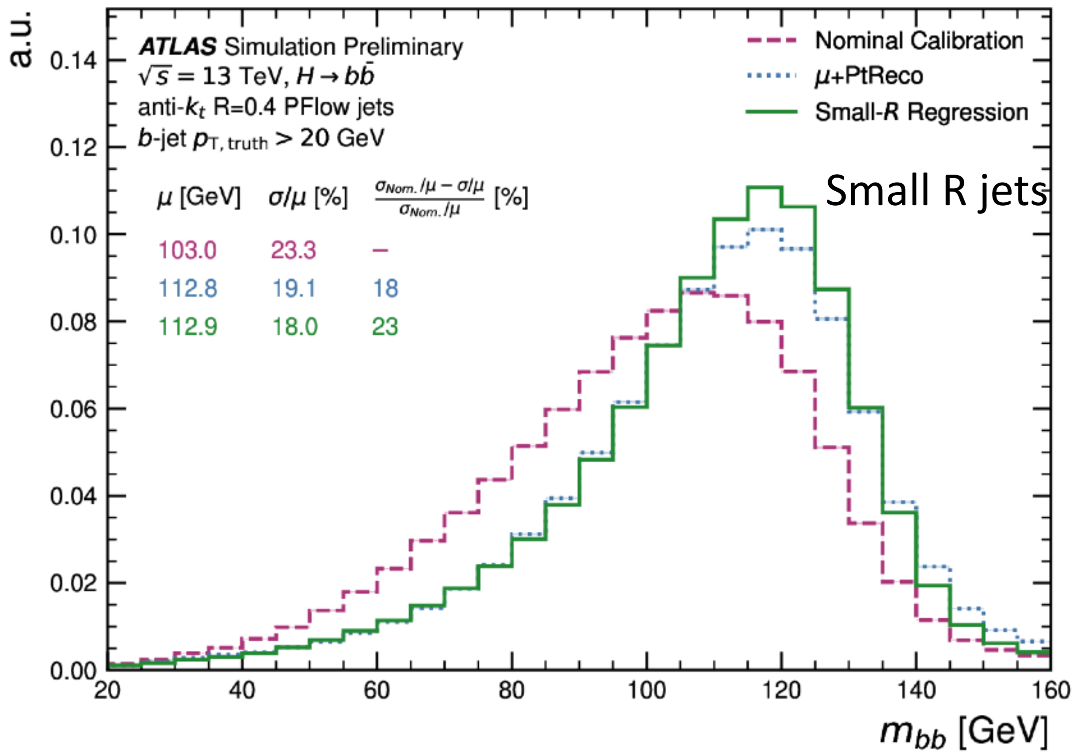
Improvements are even more pronounced in the semileptonic channel

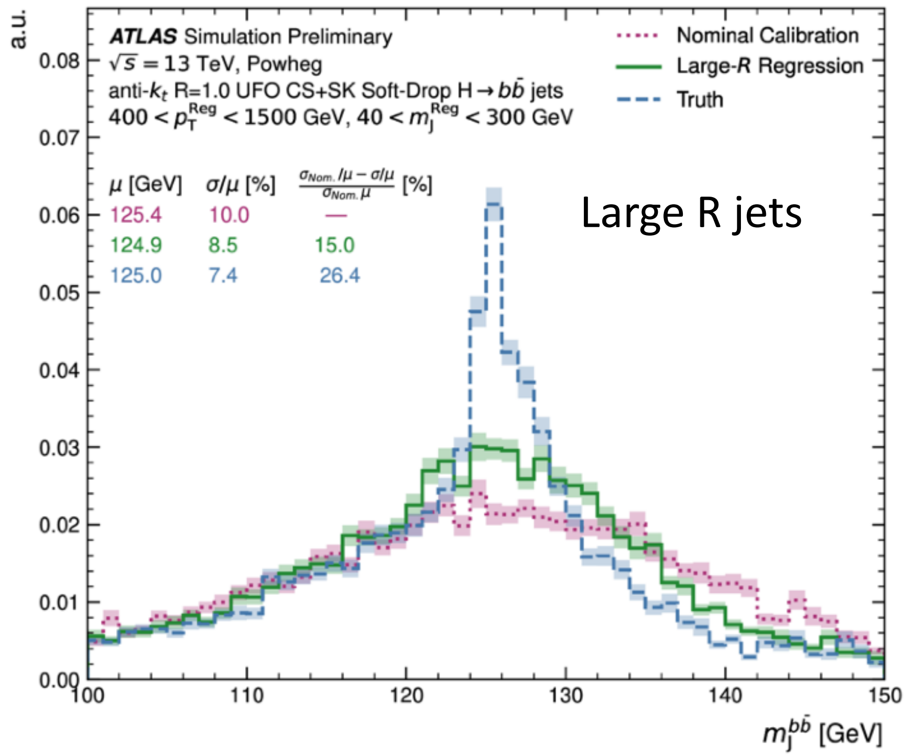


From Brendon & Prajita

B-jet calibration with Transformer

ATL-PHYS-PUB-2024-015





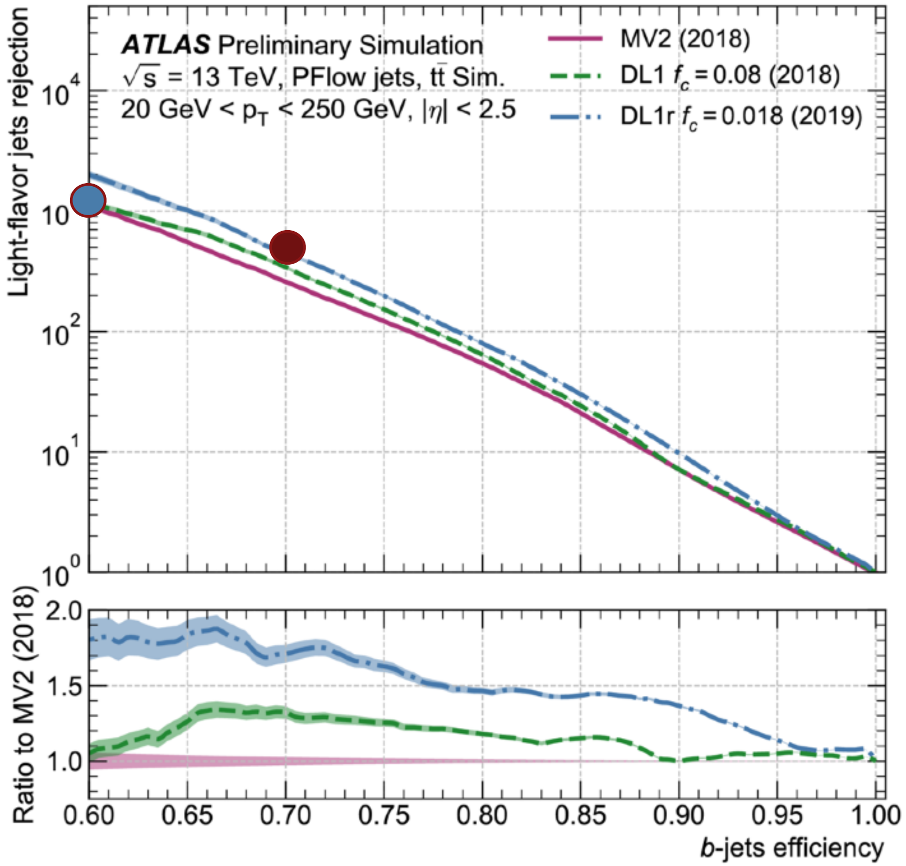
ttH bb analysis

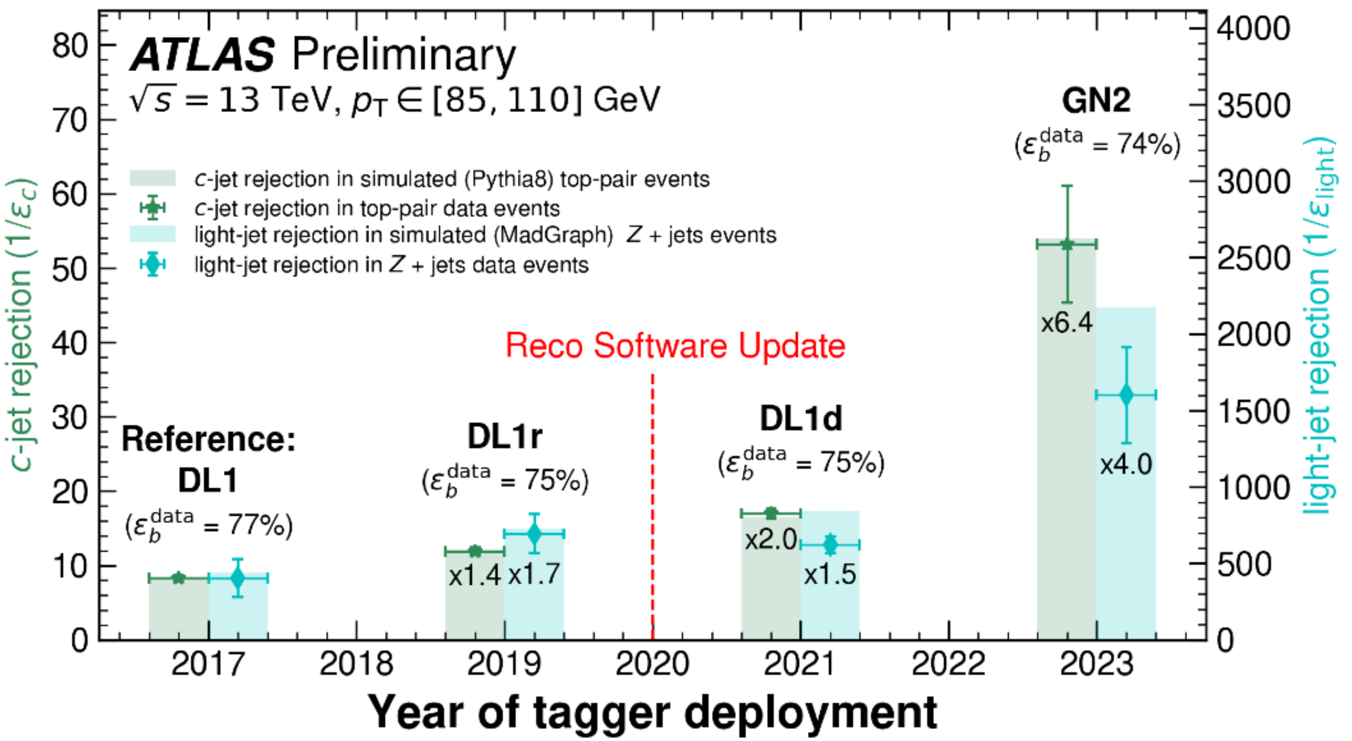
[arXiv:2407.10904](https://arxiv.org/abs/2407.10904)

Improvements comes from b-tagging: MV2c10 60% WPs → DL1r 70%

- More improvements is expected to come with new GN2 tagger * bjets regression

New $t\bar{t}$ Monte Carlo and tt+b-jet modeling: more improvements will come from the latest results of $t\bar{t}$+HF



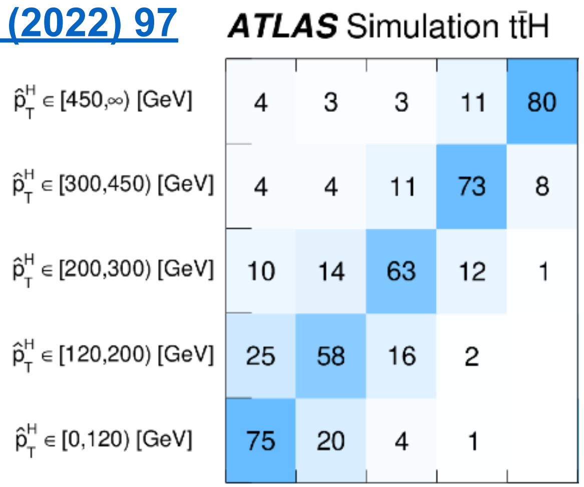


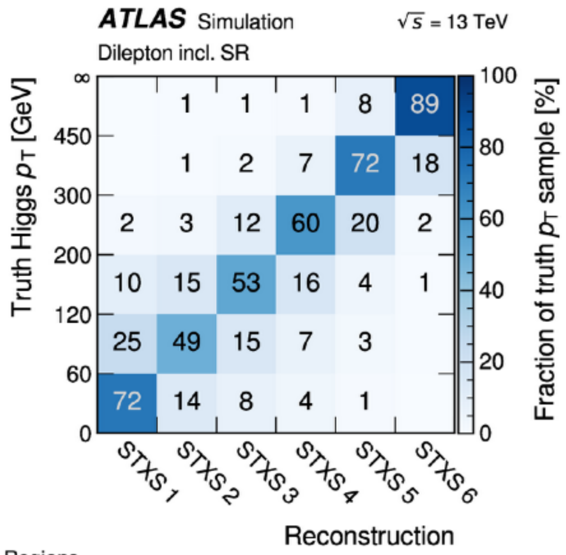
ttH bb analysis

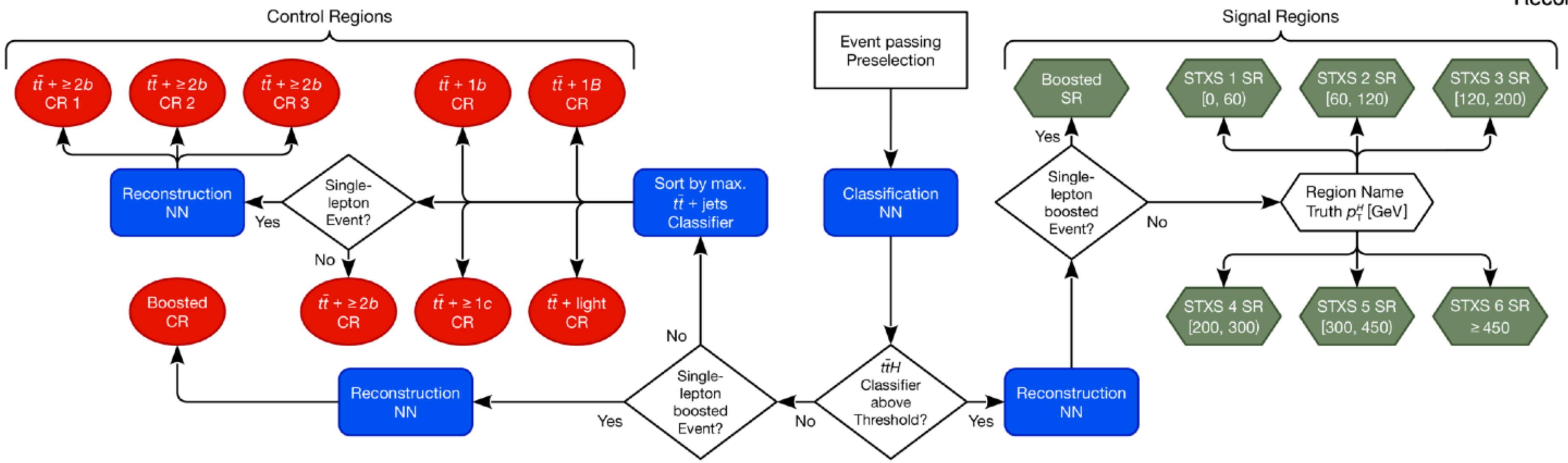
[arXiv:2407.10904](https://arxiv.org/abs/2407.10904)

Improved signal and background categorization and reconstruction on multi class NN with transform

[JHEP 06 (2022) 97]()



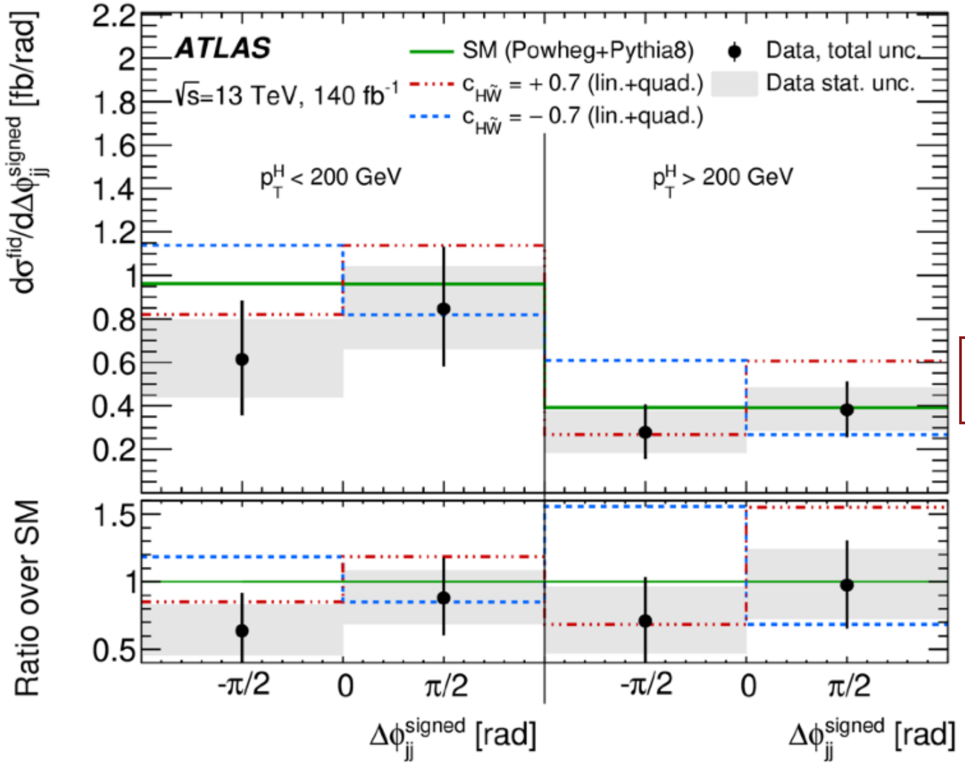


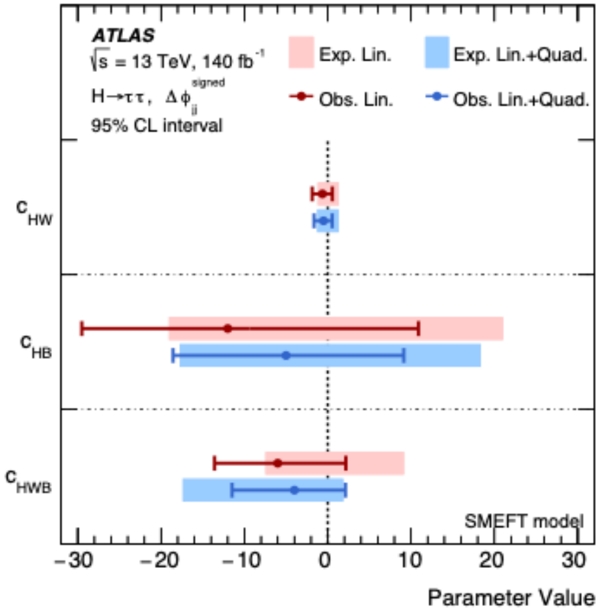


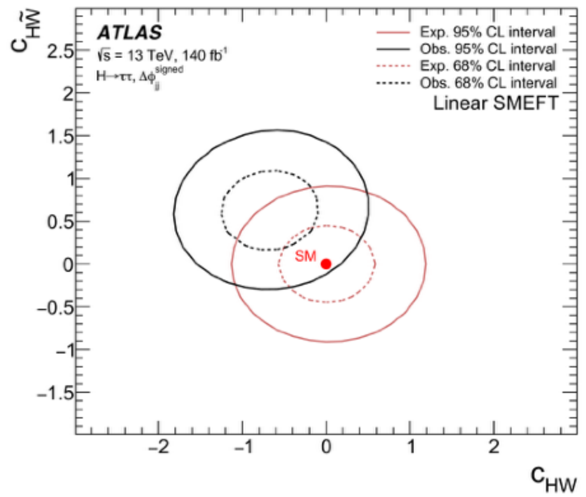
H→ ττ

[arXiv:2407.10904]

Give the strongest constraints on the CP-odd $C_{H\tilde{W}}$ [-0.31, +0.88]







B meson Lifetime

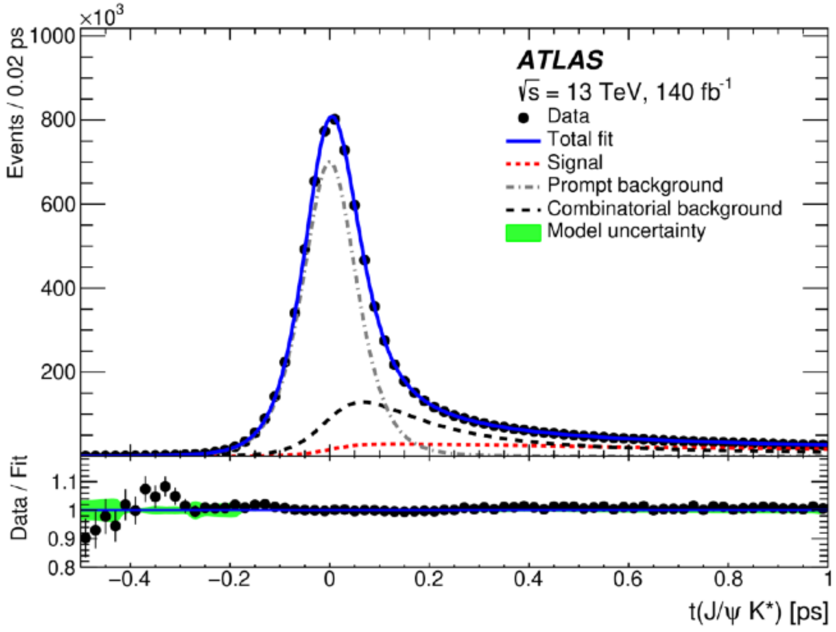
arXiv:2411.09962

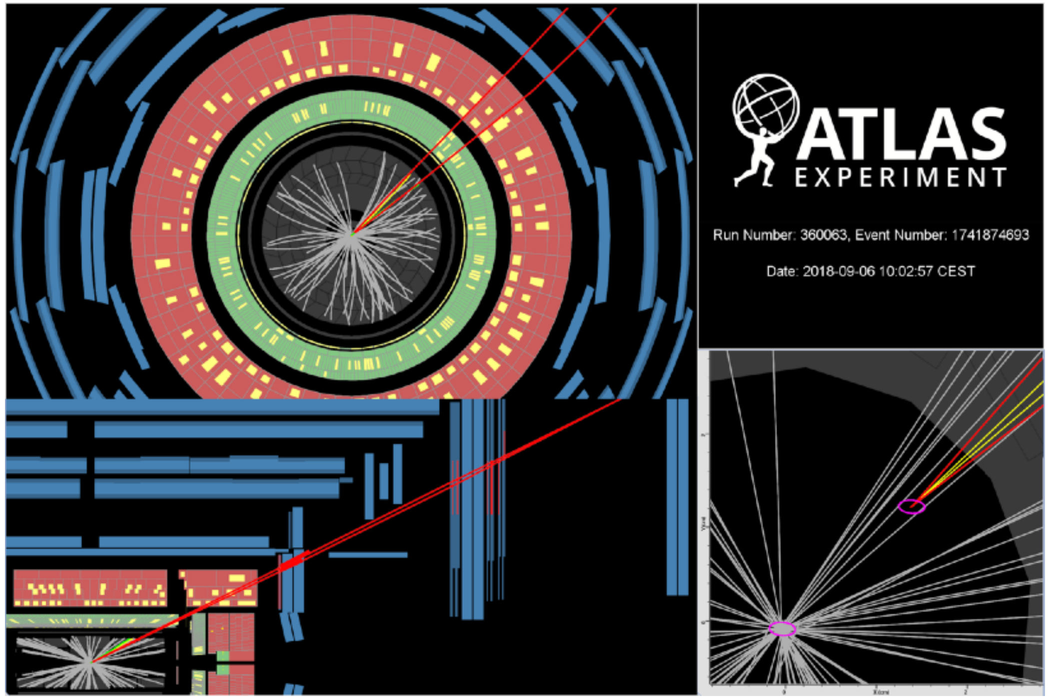
$J/\psi(\mu^+\mu^-)$

- $\mu^+\mu^-$ refitted to a common vertex
- χ^2/ndof<10
- divided into 3 pseudorapidity bins [EE, BE, BB]

$K^{*0}(K^\pm\pi^\mp)$

- $p_T(K^\pm)$ >1 GeV
- $p_T(\pi^\mp)$ >0.5 GeV
- $m(K^\pm\pi^\mp) \in$ (846, 946) MeV
- $p_T(K^*)$ >3.5 GeV





B meson Lifetime

arXiv:2411.09962

Systematic uncertainty reduced by a factor of 4.7, improvements comes from :

- insertable B-layer
- better ID alignment
- More statistics

$$\tau_{B^0} = 1.5053 \pm 0.0012(\text{stat.}) \pm 0.0025(\text{sys.})\ \text{ps}$$

$$\Gamma_d = (0.63^{+0.11}_{-0.07})\ \text{ps}^{-1}$$

$$\Gamma_d/\Gamma_s = (0.9905 \pm 0.0022(stat.) \pm 0.0032(sys.) \pm 0.0057(ext.))$$

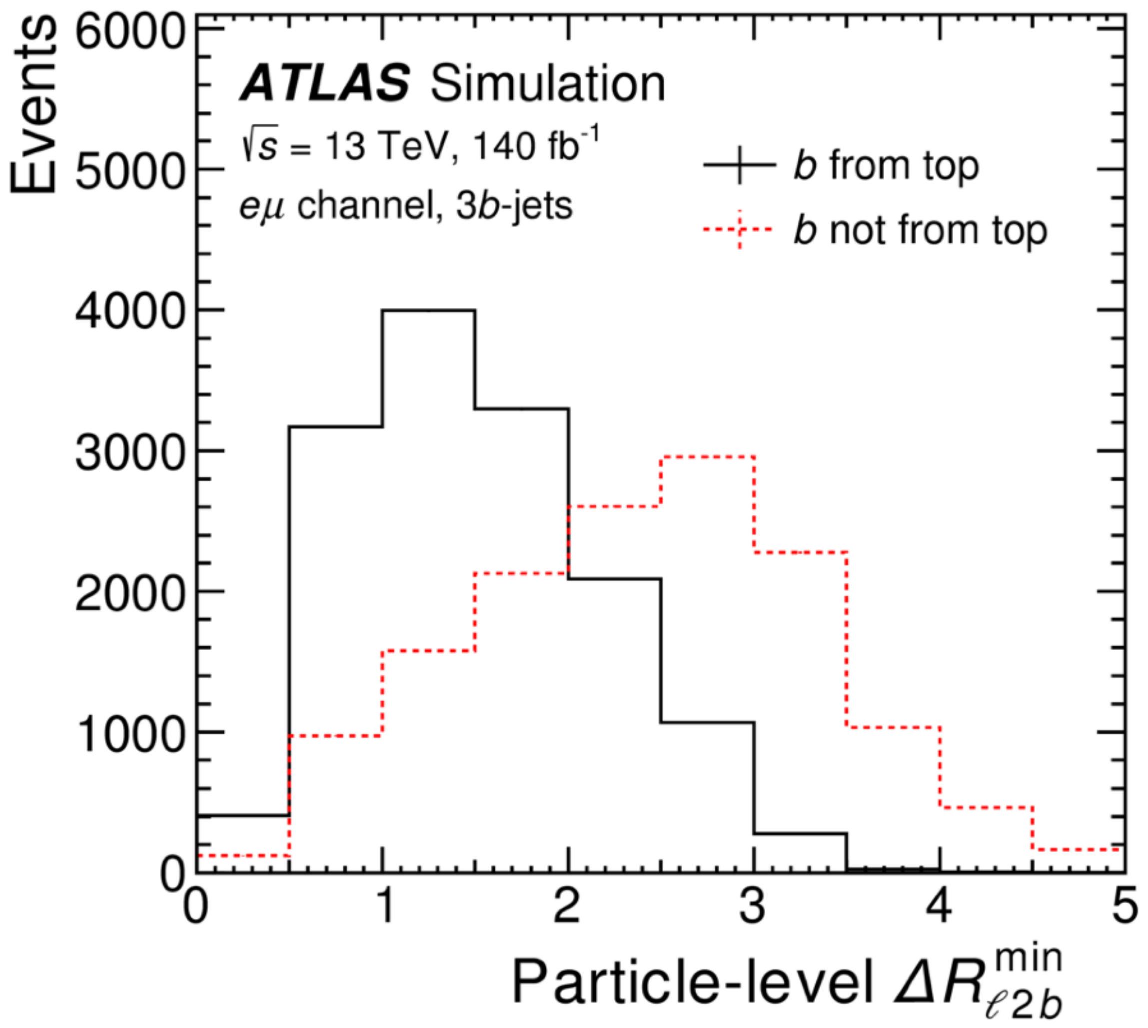
Phys. Rev. D 87, 032002 (2013)

Source of uncertainty	Systematic uncertainty [ps]
ID alignment	0.00108
Choice of mass window	0.00104
Time efficiency	0.00130
Best-candidate selection	0.00041
Mass fit model	0.00152
Mass-time correlation	0.00229
Proper decay time fit model	0.00010
Conditional probability model	0.00070
Fit model test with pseudo-experiments	0.00002
Total	0.0035

Systematic uncertainty	$\sigma_\tau^{\text{syst}}$ (fs)	σ_m^{syst} (MeV)
Selection/reco. bias	12	0.9
Background fit models	9	0.2
B_d^0 contamination	7	0.2
Residual misalignment	1	...
Extra material	3	0.2
Tracking p_{T} scale	...	0.5
Total systematic error	17	1.1

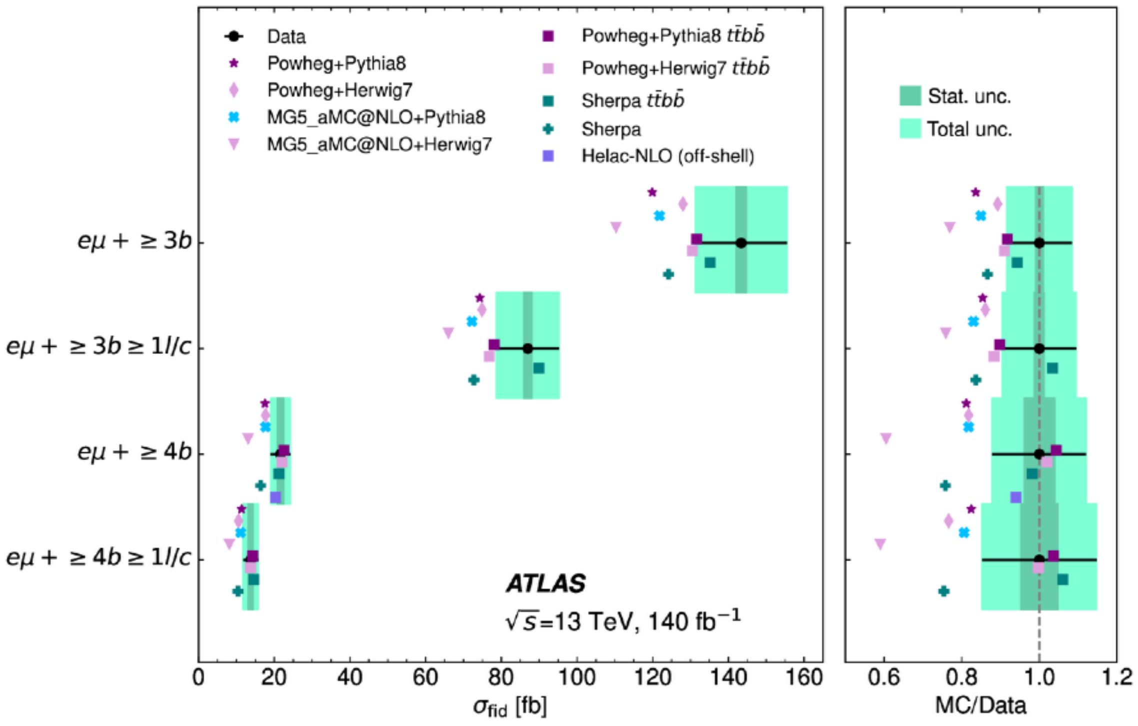
ttbar+HF

arXiv:2407.13473



B-jets calcification:assignment to top

Sherpa ttbb agrees better with data

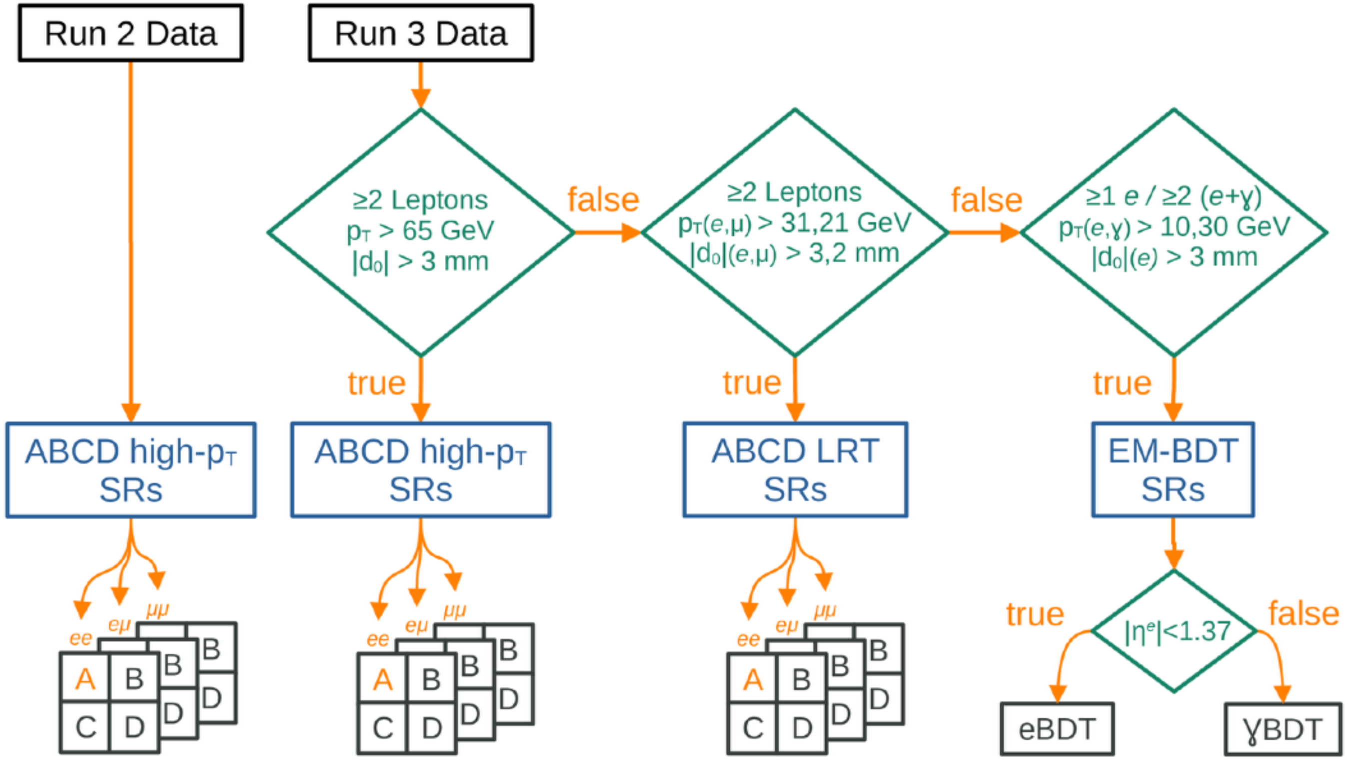


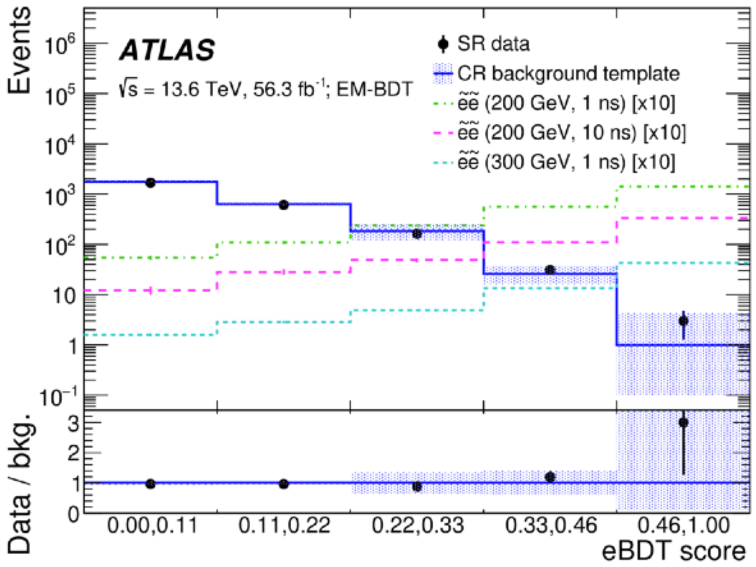
LLP

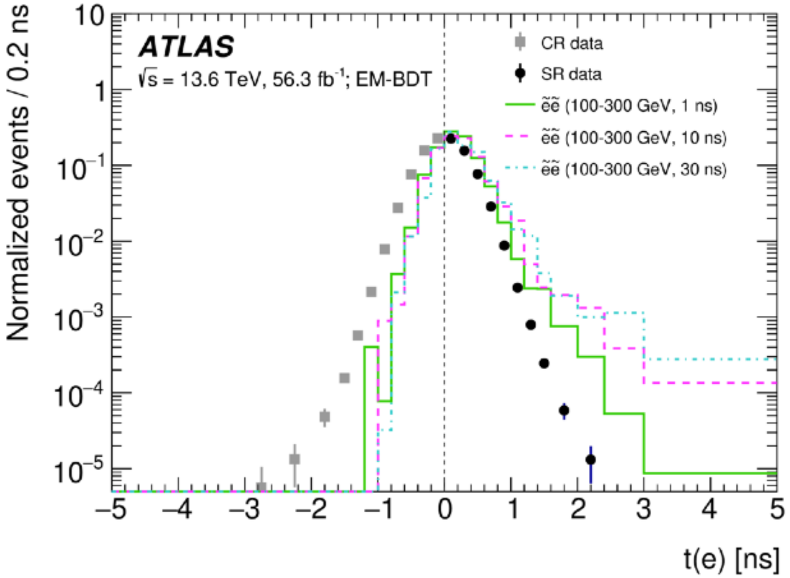
arXiv:2410.16835

New data, New trigger and New method

Adding new EM-BDT channel to probe electron/tau partners with long lifetimes







Calo time as input

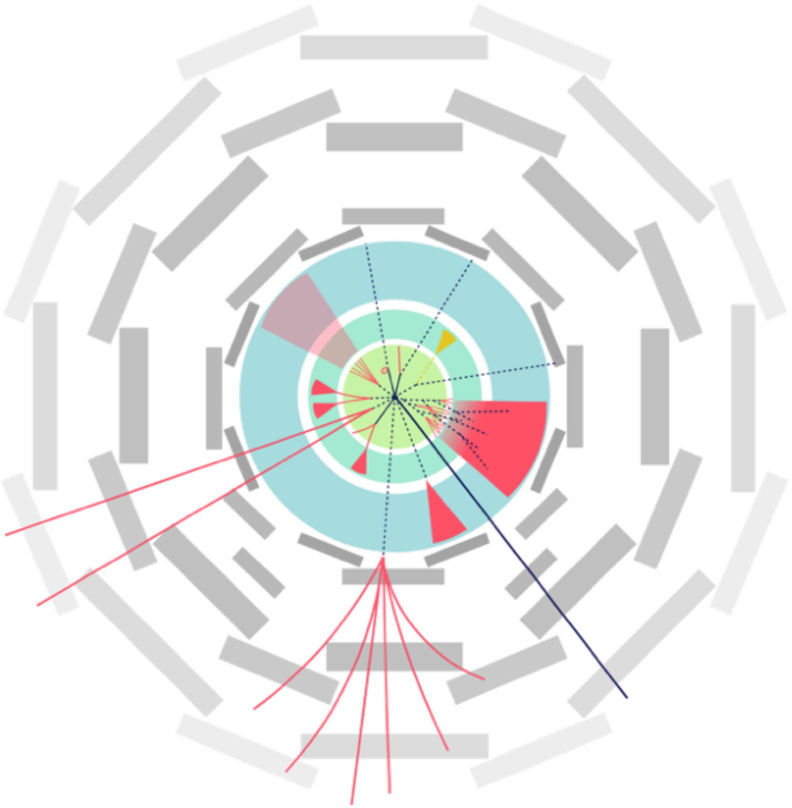
LLP

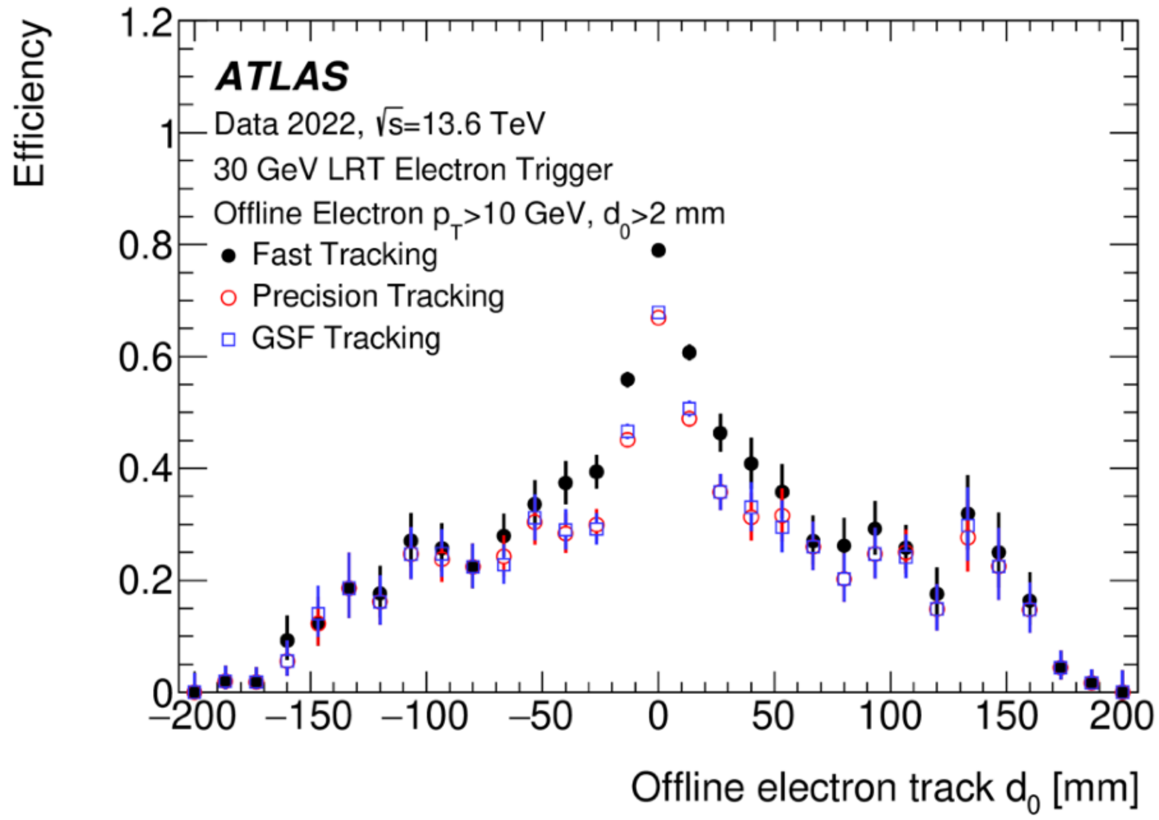
arXiv:2410.16835

New data, New trigger and New method

Using new trigger for LRT in run3

Large Radius Tracking (LRT) introduced in the HLT for Run 3[JINST 19 (2024) P06029]

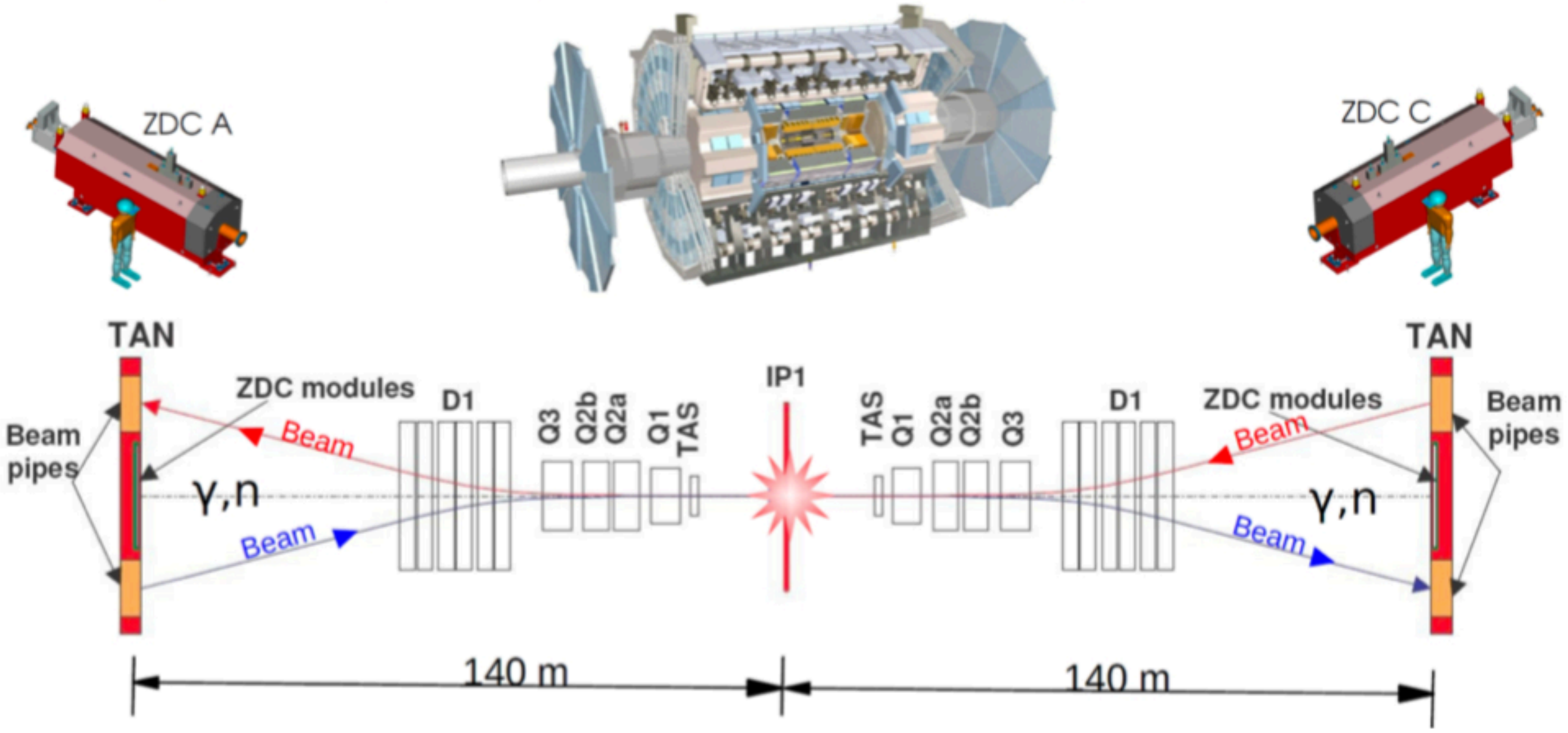


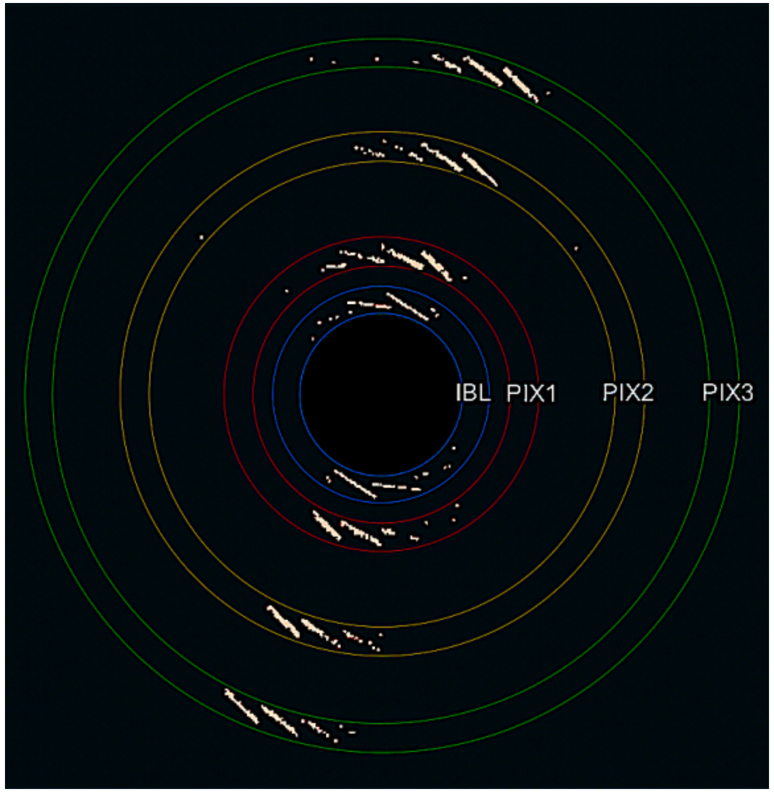


Magnetic monopole search

arXiv:2408.11035

Mainly use Pixel detector and Zero Degree Calorimeters (ZDC)





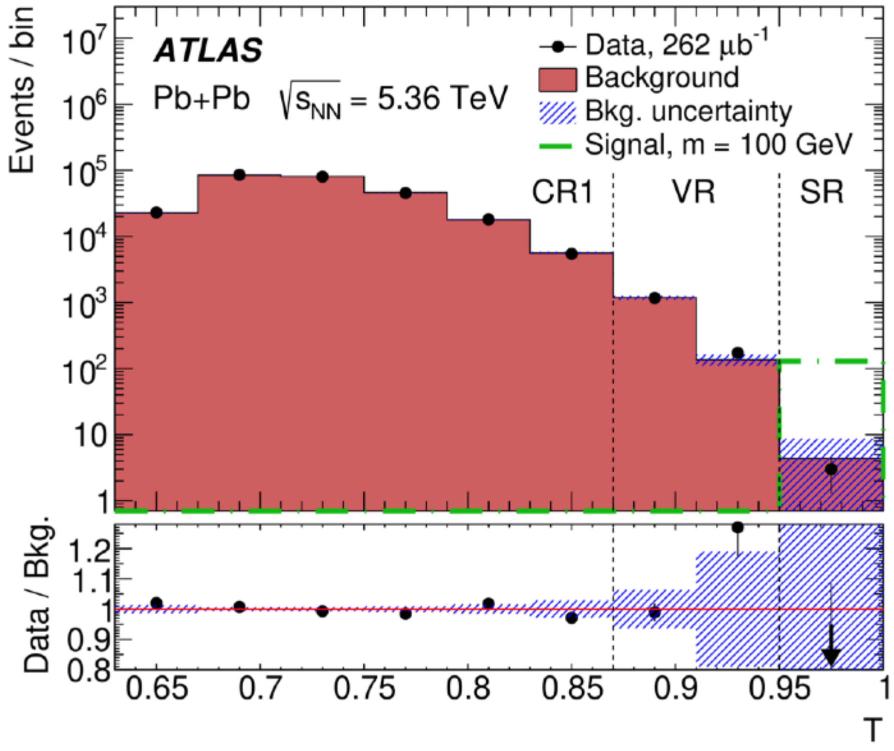
Magnetic monopole search

arXiv:2408.11035

Analysis improvements:

$$T = 1/n_{Pix} \sum_{i=1}^{Pix} \hat{r}_i \hat{n}_i$$

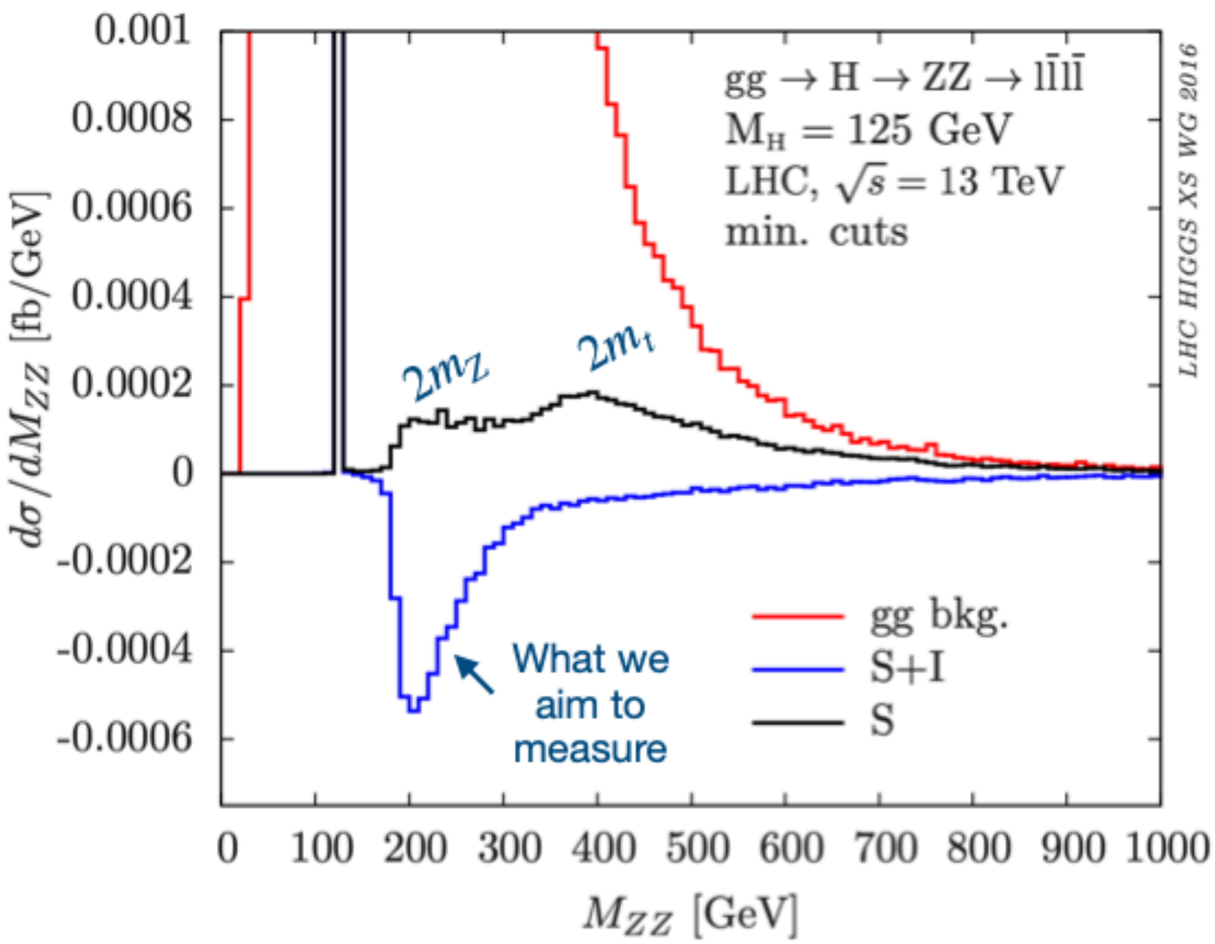
- The use of dedicated trigger, improves data statistics by a factor of approximately 1600
- Introduced of validation region, very close to signal region, ensuring background estimation
- Tighter requirements for pixel clusters and IBL hits- better suppress background
- Dedicated selection to suppress the impact from noisy Pixel modules (modules masking, geometrical cuts)
- Track selection

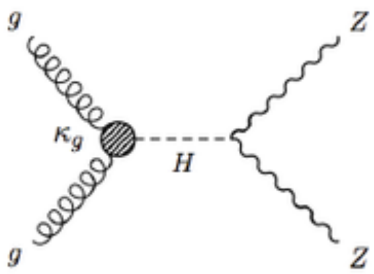


New Methods for Statistical Inference

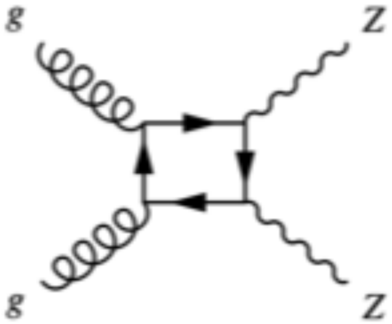
arXiv:2412.01548

Neural simulation-based inference (SBI) benefit physics analyses:





Signal

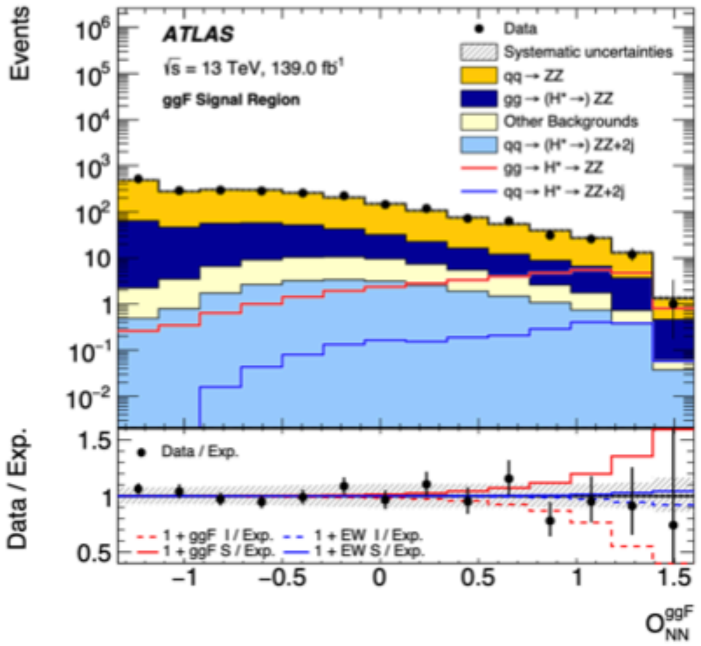


Interfering background

New Methods for Statistical Inference

arXiv:2412.01548

Neural simulation-based inference (SBI) benefit physics analyses:



$$O_{NN} = \frac{p_S}{p_B + 0.1 \cdot p_{NI}}$$

Standard Signal vs Background classification

$$\frac{P(x|S)}{P(x|B)} \sim \mu \cdot \frac{P(x|S)}{P(x|B)}$$

Traditional way of building MVA for Signal vs Background would work

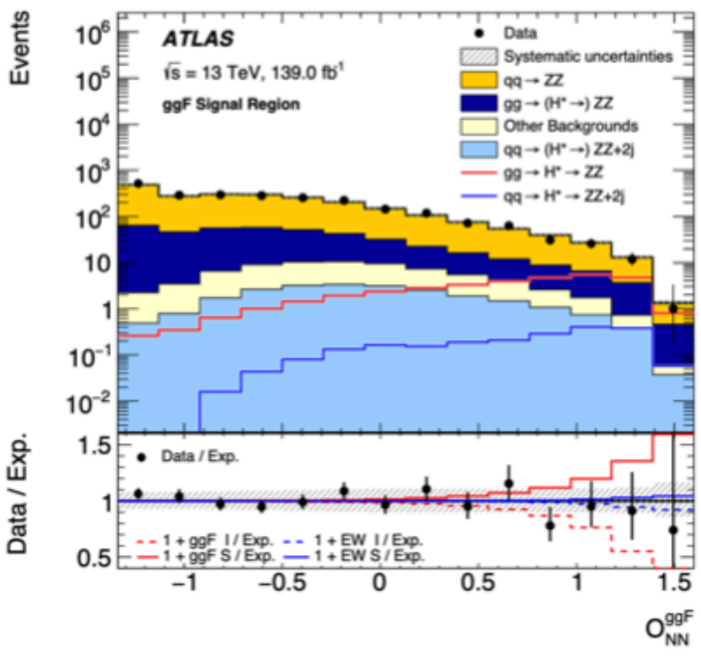
$$\frac{P(x|S)}{P(x|B)} \sim \mu \cdot \frac{P(x|S)}{P(x|B)} + \sqrt{\mu} \cdot \frac{p_I(x)}{p_B(x)}$$

This interference term is not properly treated in the classification

New Methods for Statistical Inference

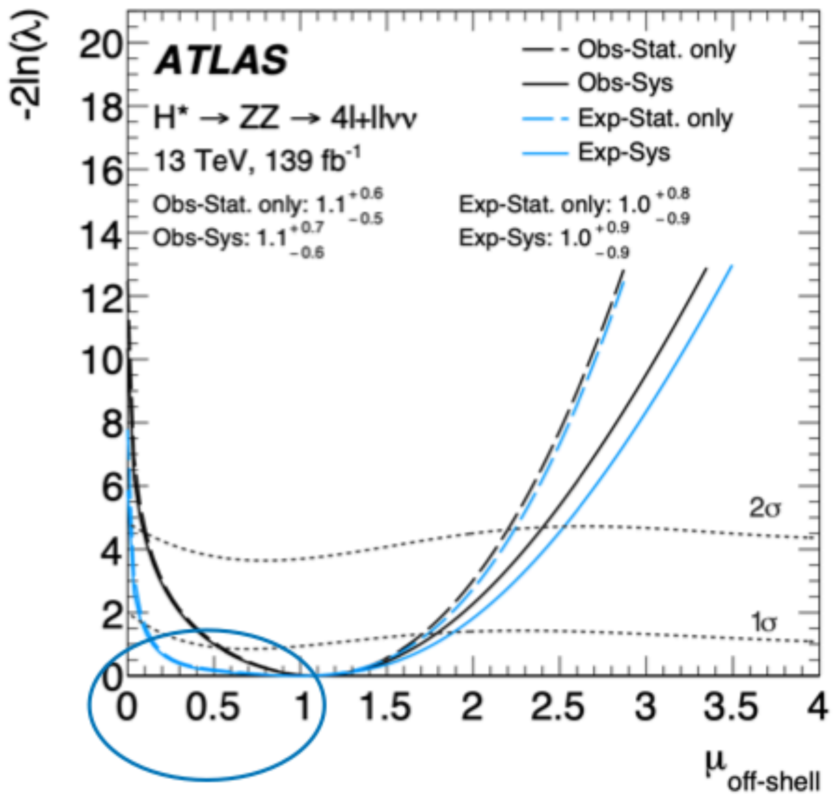
arXiv:2412.01548

Neural simulation-based inference (SBI) benefit physics analyses:



$$O_{NN} = \frac{p_S}{p_B + 0.1 \cdot p_{NI}}$$

Standard Signal vs Background classification

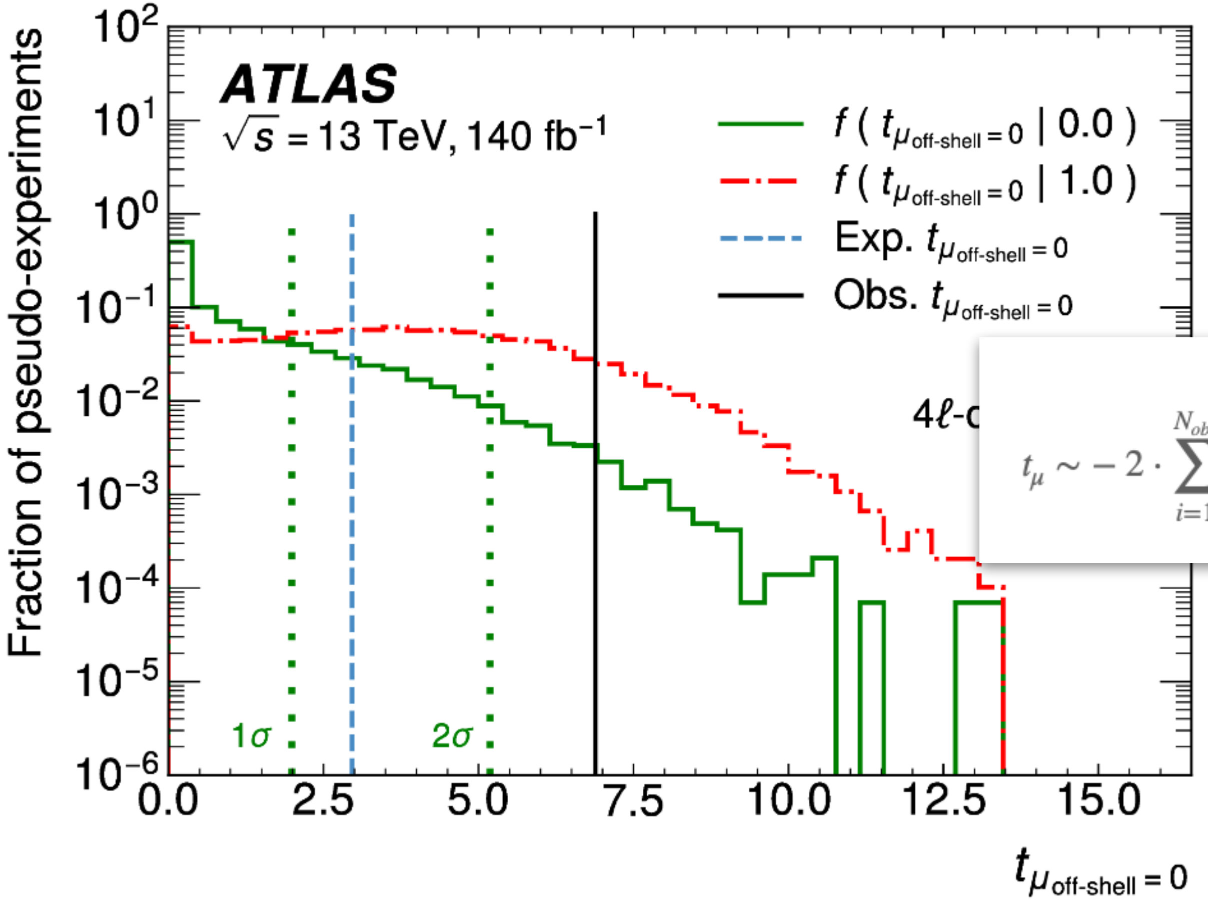


Flat NLL region implies sub-optimality in regions with $\sqrt{\mu} \cdot p_I \gg \mu \cdot p_S$

New Methods for Statistical Inference

arXiv:2412.01548

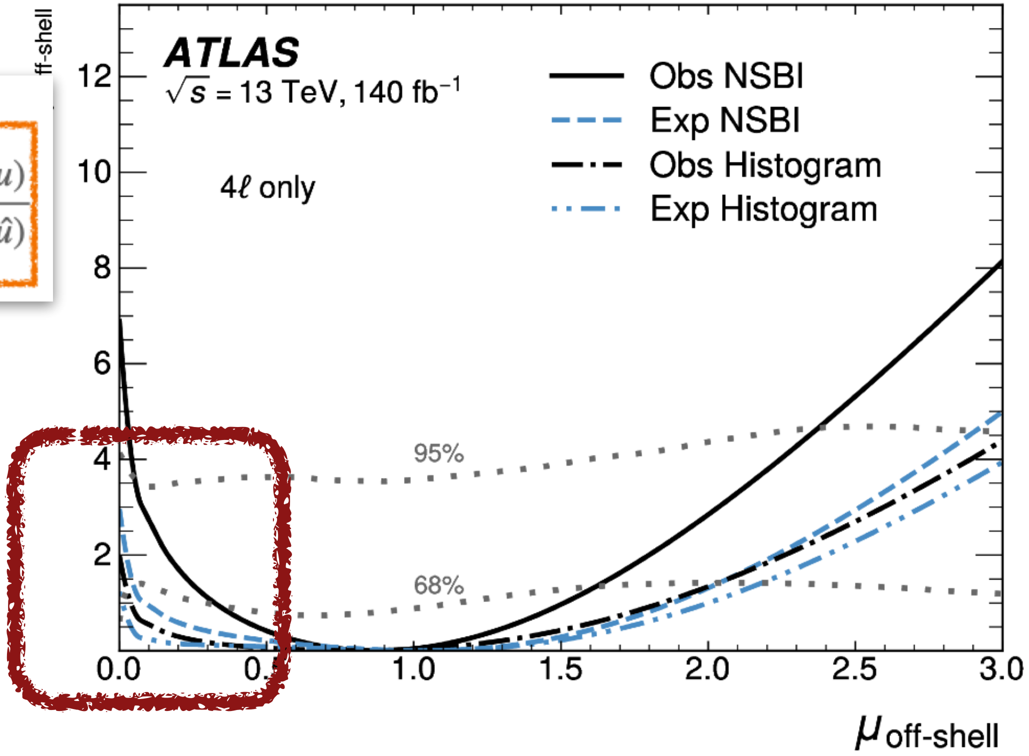
Neural simulation-based inference (SBI) benefit physics analyses:



$$t_\mu \sim -2 \cdot \sum_{i=1}^{N_{obs}} \log \frac{p(x_i|\mu)}{p(x_i|\hat{\mu})}$$

$$\frac{P(x|S)}{P(x|B)} \sim \mu \cdot \frac{P(x|S)}{P(x|B)} + \sqrt{\mu} \cdot \frac{p_I(x)}{p_B(x)}$$

Large interference from Background can be treated by SBI



ITK Highlights

ITk Pixel

- Pixel production progresses well with sensors and FE ASIC; hybridisation has started with 2 (of 4) vendors (hope to qualify 3rd soon), some bare local supports & services in production
- Many areas close to critical path, tightly following up

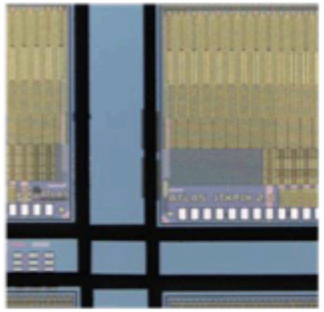
ITk Strip

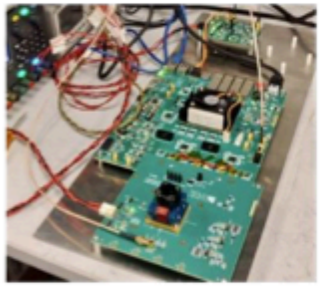
- Many areas (sensors, ASICs, EOS, bus-tapes, cores, etc.) in production; sites ready for production
- Module site qualification well advanced (94% completed)
- **Strip sensor fracturing of cold mounted modules under intense follow up**
    - Solution with 50 µm kapton interposer developed and successfully tested for the barrel down to –70 °C
    - Initial test on an endcap ½ petal shows no evidence of cracks down to –65 °C
    - Final reviews this year, module production start Jan 2025

Production of ITk common items and structures proceeds well

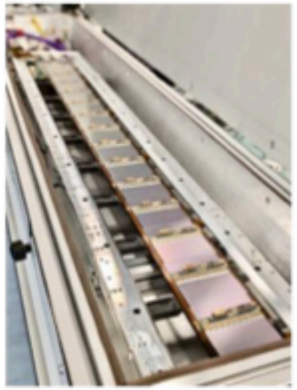
ITk Pixel quad modules

ITkPixV2 wafer





FEB2 mass testing board



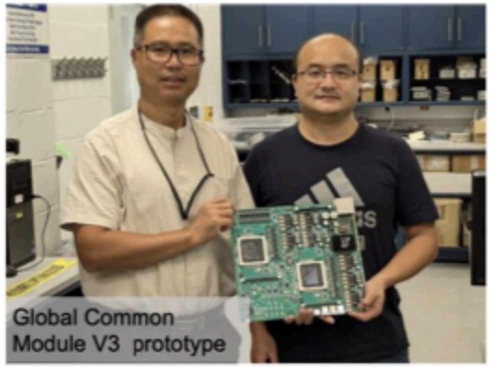
Strip Half-stave in climate chamber at RAL

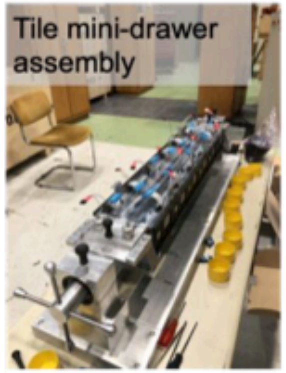
From C. Bernius

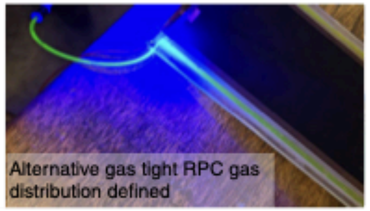
Other components Highlights

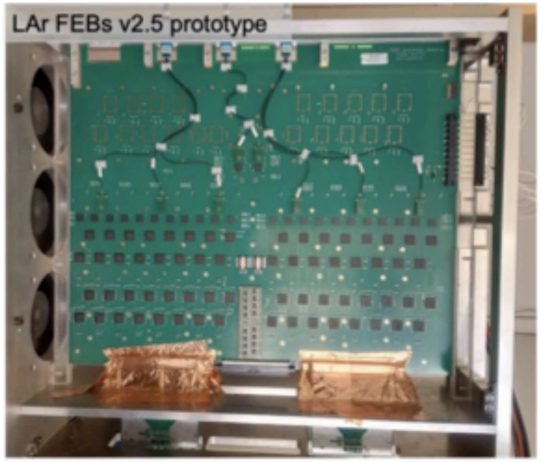
Other systems progressing well, no critical issues

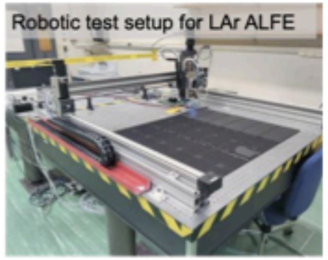
- **LAr**: ASICs in production with excellent test results, completing design of electronics boards (FEB2, LASP)
- **Tile**: good overall progress, comfortable contingency
- **HGTD**: pre-production LGAD and ALTIROC hybrids under test; Demonstrator with 54 modules being tested in clean room with CO2 cooling
- **Muon**: good progress on sMDT, finalise RPC readout electronics, started RPC readout chain tests with prototypes/emulators, fixing gas-gap leaks
- **TDAQ**: good progress in many areas (online software, dataflow, EF Tracking technology choice, …), more effort identified for delayed NSW trigger processor

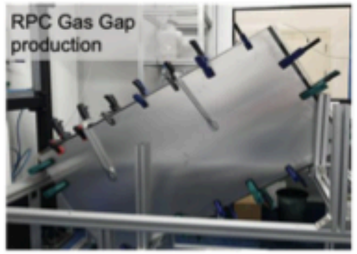






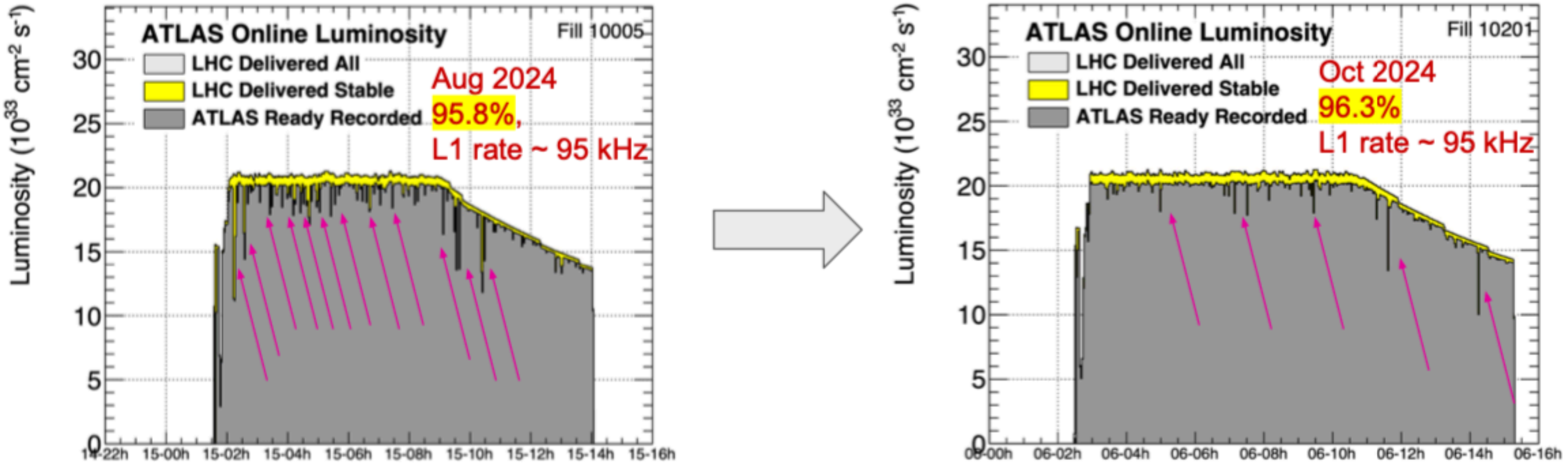






From C. Bernius

Detector system improvements in 2024



Across the ATLAS detector subsystems:

Improvements of operational robustness and reduction of inefficiencies during data-taking

⇒ visible in the reduction of the small dips that indicate a brief interruption of data-taking

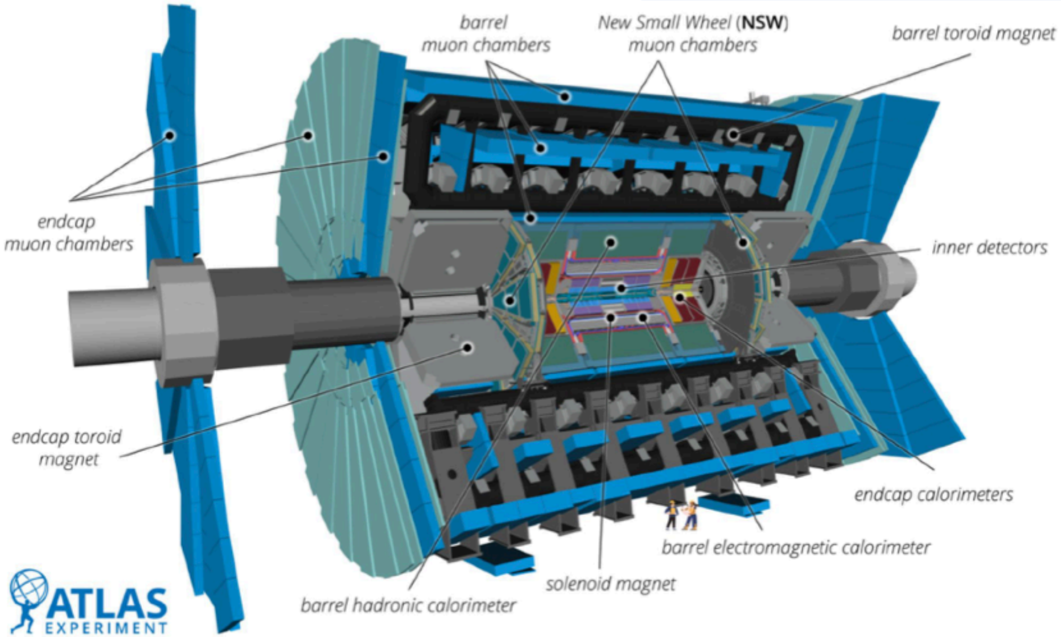
Detector status 2024

Inner Detector (Pixel, SCT, TRT):
Good status
No limitation to operating ATLAS in 2026; updated projections to ~ 550 fb^{-1} indicate that radiation damage effects can be mitigated

Forward: AFP suffers from backgrounds / increased radiation, ToF had to be removed from the tunnel; LUCID good; ZDC installed in TS2 for HI programme

TDAQ: No limitations with DAQ system; Trigger: Phase-I L1 systems in operation, better efficiency with reduced background trigger rates; L1 & HLT deal well with higher lumi and pileup; HLT CPU sufficient

Calorimeters:
LAr: Good status
Tile: FE electronics cooling leaks at limit but stable so far; 3.5 modules switched off (1.4%)

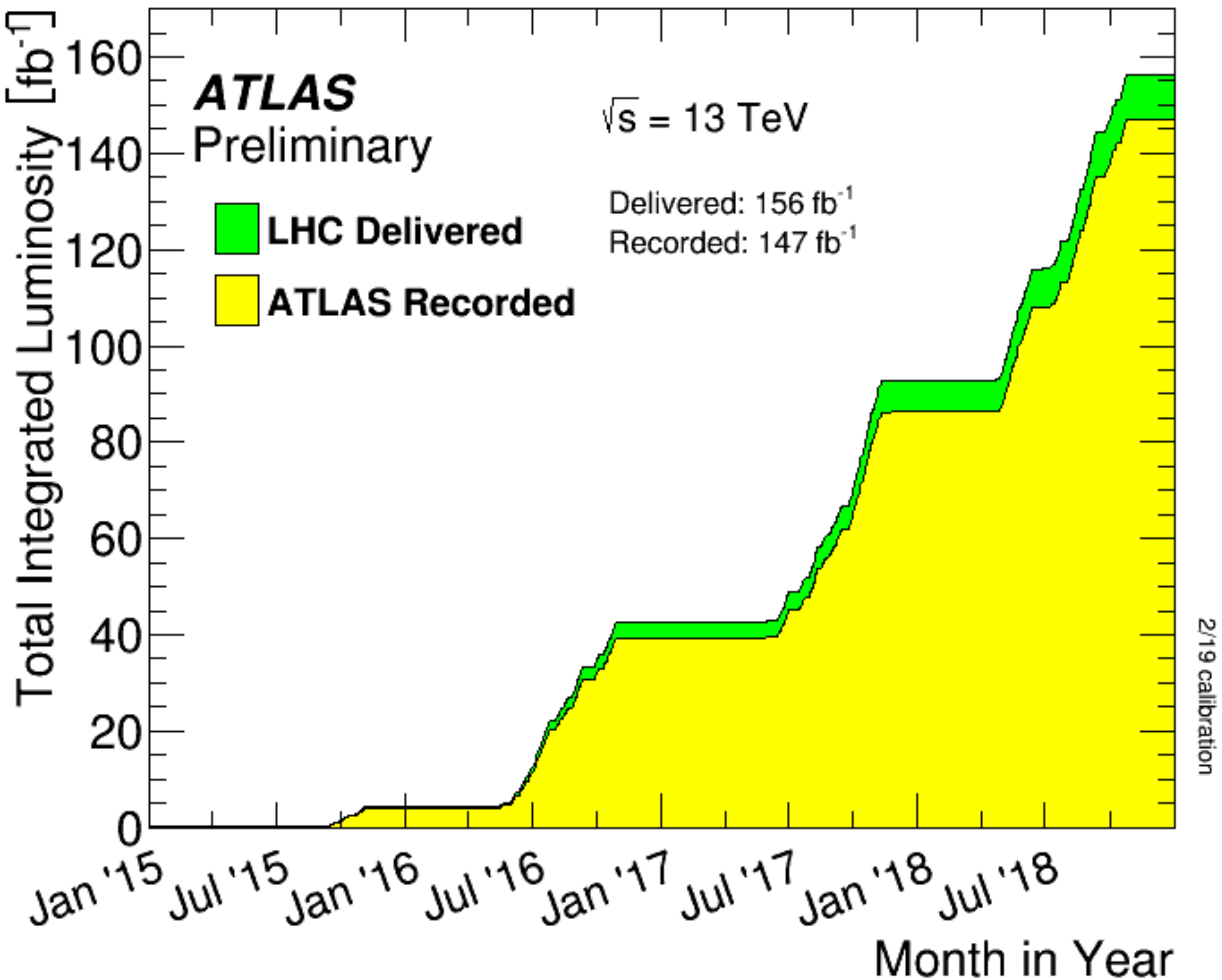


Muons:
MDT, TGC: Good status
RPC: Inlet repairs and resin application during last EYETS did not reduce leak rate significantly; increase effort to consolidate during upcoming YETS (145 person-weeks)
NSW: DAQ stable; sTGC pad & MM triggers operating, sTGC strips under work; Rising number of sTGC HV failures at inner radius (105/256 (41%), in total 180/1024 (18%))

Mitigations: lowering HV reduces failure rate; tests with spare sectors underway (irradiation, HV stress)

Magnets: 7 solenoid and 8 toroid slow dumps; Efforts to enhance magnet operational resilience ongoing (water cooling, electrical perturbation, cryo system)

Offline computing:
Tier0 reconstruction operating smoothly (~8 GB/s)


ATLAS
Preliminary
√s = 13 TeV
Delivered: 156 fb⁻¹
Recorded: 147 fb⁻¹
LHC Delivered
ATLAS Recorded
Total Integrated Luminosity [fb⁻¹]
0
20
40
60
80
100
120
140
160
Jan '15
Jul '15
Jan '16
Jul '16
Jan '17
Jul '17
Jan '18
Jul '18
Month in Year
2/19 calibration

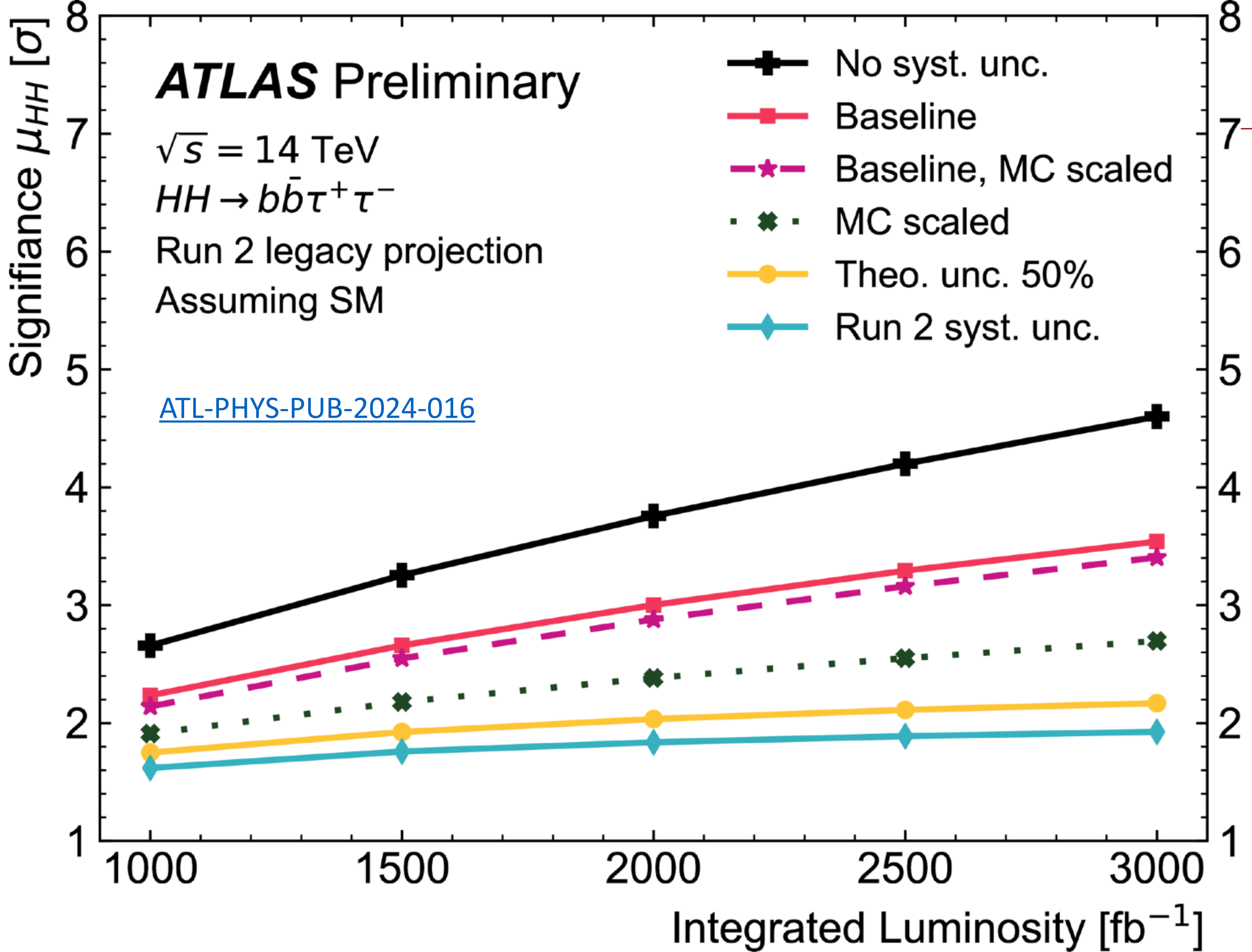
Data quality

ATLAS pp Run-3: 2024														
Trigger	Inner Tracker			Calorimeters		Muon Spectrometer					Magnets		Global	
L1+HLT	Pixel	SCT	TRT	LAr	Tile	MDT	RPC	TGC	MM	sTGC	Solenoid	Toroid	Lumi. calib.	Other
99.7	99.7	99.8	99.9	99.8	99.3	100	99.8	99.8	100	100	98.3	96.6	99.6	99.9
Good for physics: 93.8% (110 fb^{-1})														

Luminosity weighted good data quality efficiencies (in %) in 2024 during stable beam operations of *pp* physics runs at $\sqrt{s} = 13.6$ TeV, corresponding to an integrated luminosity of 110 fb^{-1}, for 118 fb^{-1} *pp* data recorded. Technical runs such as luminosity calibration scans totalling 0.6 fb^{-1} recorded are not accounted for in the efficiencies.

When the stable beam flag is raised, the tracking detectors initiate a "warm start", which involves ramping up the high-voltage and activating the pre-amplifiers for the Pixel and SCT systems. The inefficiency due to this, as well as the DAQ inefficiency, are not included in the table above, but accounted for in the ATLAS recording efficiency.

The good-for-physics luminosity is 110 fb^{-1} for all analyses, except those relying on *b*-jet triggers, where the data quality efficiency is slightly lower (93.5%) due to the brief time needed to measure the online beamspot at the start of a run.


ATLAS Preliminary
$\sqrt{s} = 14$ TeV
$HH \rightarrow b\bar{b}\tau^+\tau^-$
Run 2 legacy projection
Assuming SM
ATL-PHYS-PUB-2024-016
No syst. unc.
Baseline
Baseline, MC scaled
MC scaled
Theo. unc. 50%
Run 2 syst. unc.
Significance μ_{HH} [σ]
Integrated Luminosity [fb^{-1}]
1
2
3
4
5
6
7
8
1000
1500
2000
2500
3000