



University of Minho
uminho.pt

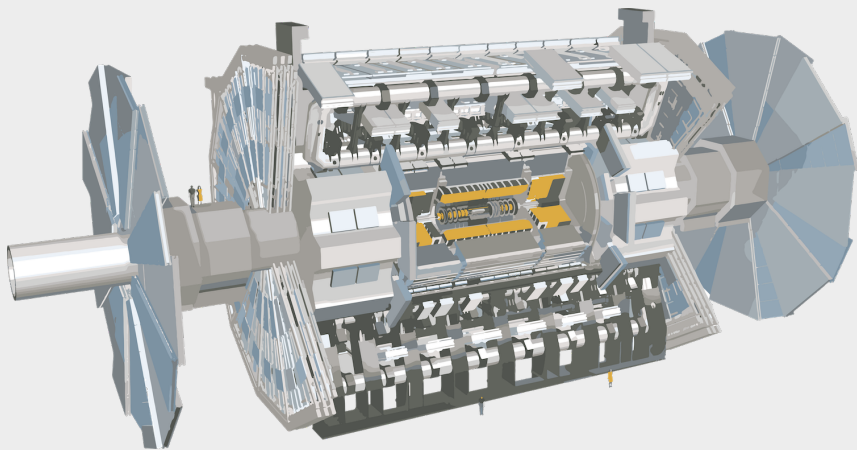


Highlights from ATLAS

Nuno Castro, on behalf of the ATLAS Collaboration

nuno.castro@cern.ch

The ATLAS experiment



New for Run 3 (2022–2026):

- Muon New Small Wheel (reduce trigger fakes)
- energy LAr calorimeter electronics with higher granularity for trigger
- L1 endcap muon and calorimeter triggers

General-purpose detector with excellent reconstruction, identification and energy/momentum resolution for electrons, photons, muons, taus, and jets, as well as excellent flavour-tagging capabilities

- γ energy calibration to 0.2% at 60 GeV, $e^\pm$ energy calibration to 0.05% at 45 GeV
- $\mu^\pm$ momentum calibration to 0.1–0.05%
- jet energy calibration to 1% above 60 GeV
- τ energy calibration to ~1%



Run: 496908

Event: 13885876

2025-05-05 14:14:56 CEST

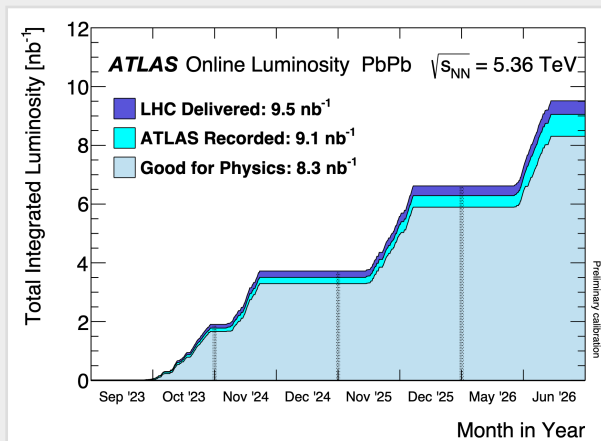
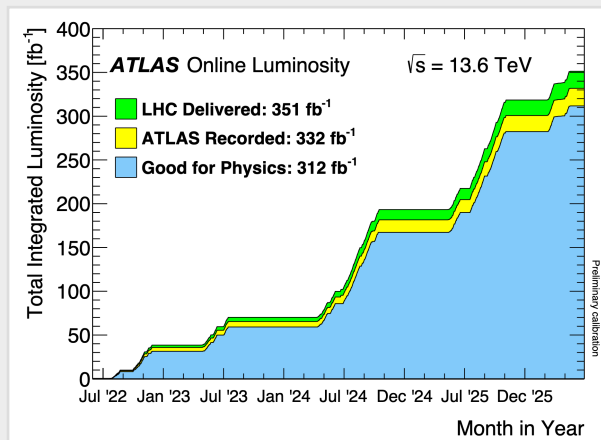
Data taking and performance



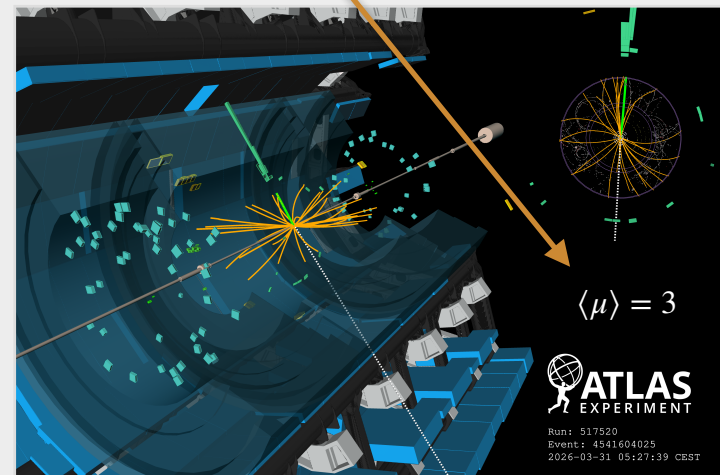
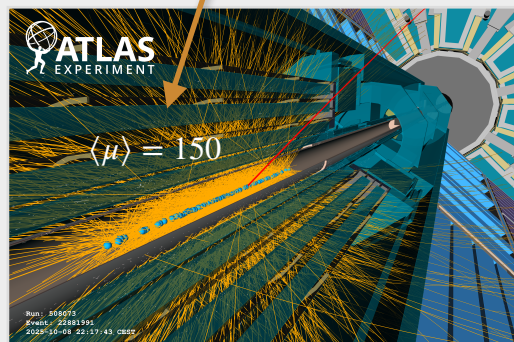
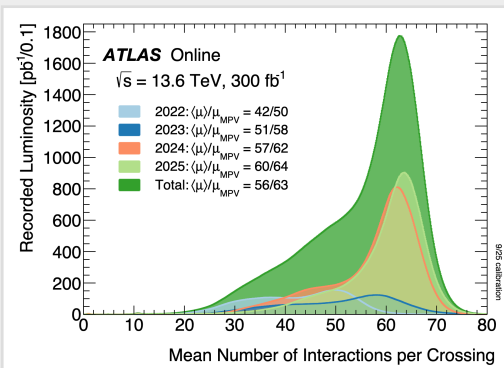
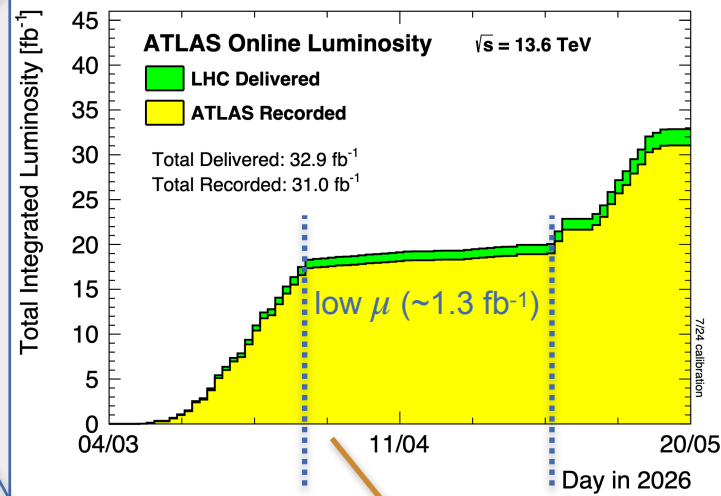
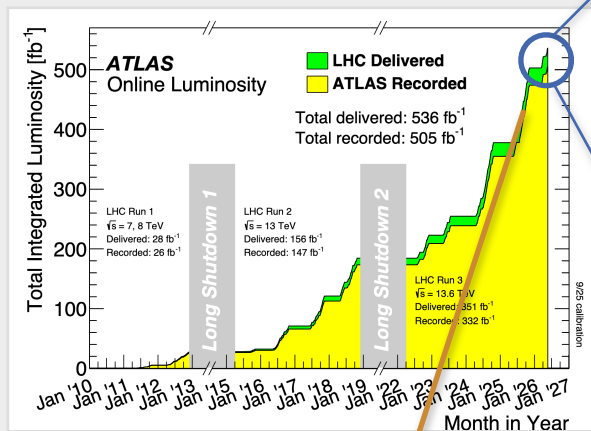
Recorded data in run-3

- **332 fb⁻¹** of pp collision data at **13.6 TeV**
(Compare w/ run 2: 147 fb⁻¹ pp collision data at 13 TeV)
 - High recording (94.6%) and good-for-physics (94%) efficiency
- A diverse set of ion collision data ($\sqrt{s_{NN}} = 5.36$ TeV)
 - 9 nb⁻¹ Pb+Pb (~ 4x Run 2)
 - 465 pb⁻¹ p+p (for reference)
 - 8 nb⁻¹ O+O
 - 1 nb⁻¹ Ne+Ne
 - 11 nb⁻¹ p+O ($\sqrt{s_{NN}} = 9.62$ TeV)

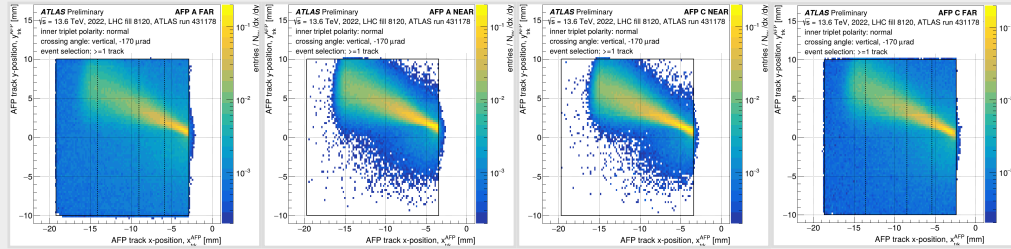
A big thank you to CERN and the LHC!



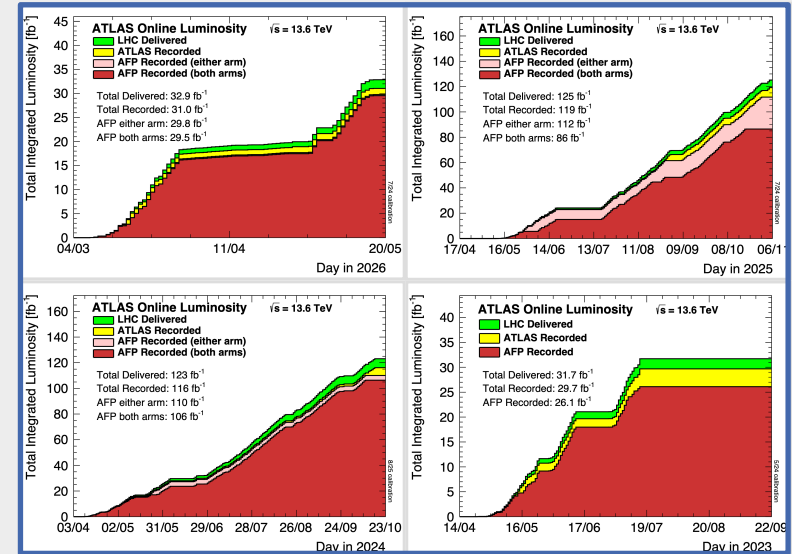
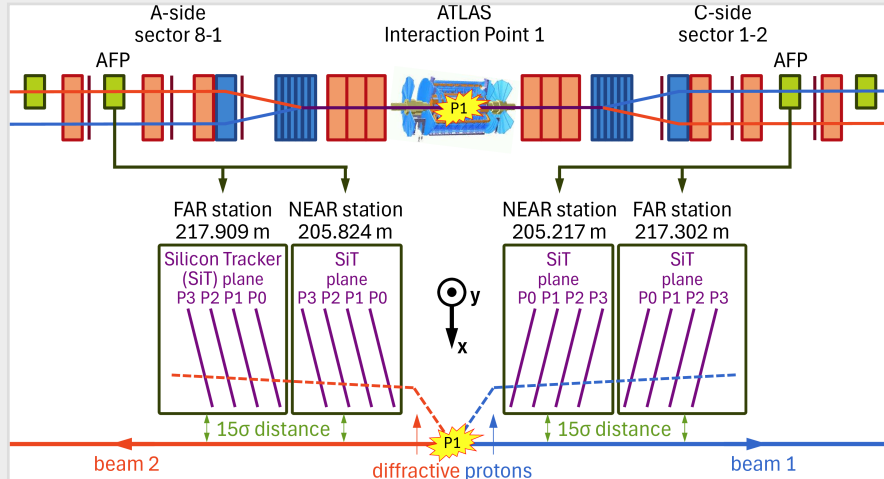
Recorded data in run-3



Recorded data in run-3: ATLAS Forward Proton (AFP) detector



ATL-COM-FWD-2025-018

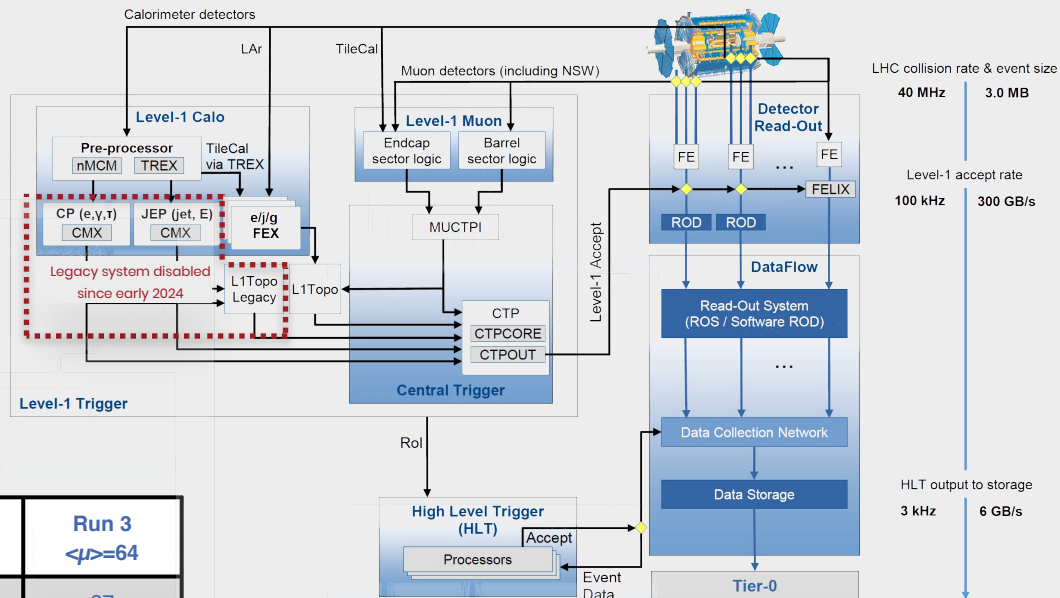


Trigger performance

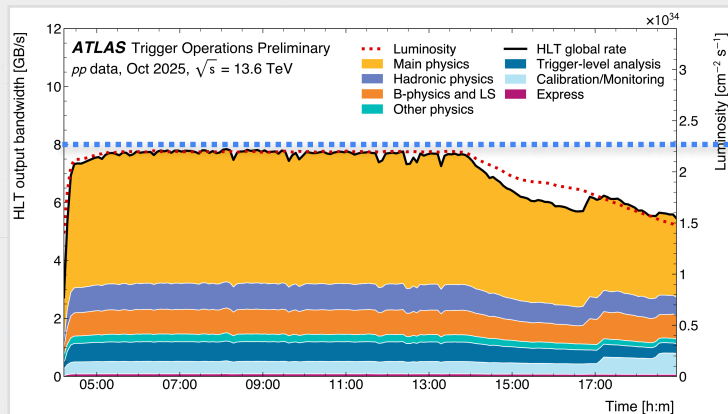
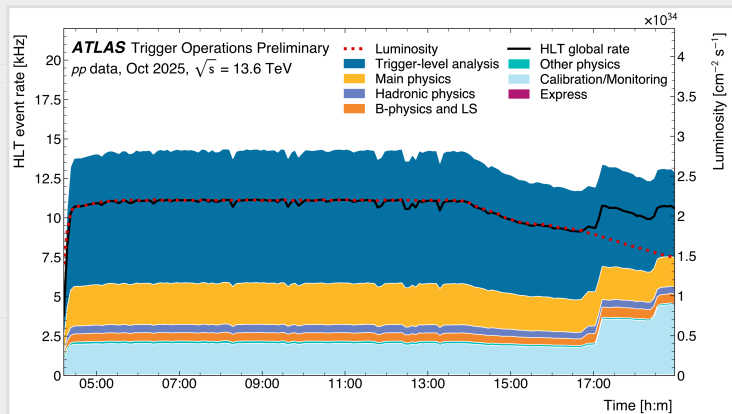
Run 3 trigger improvements driven by:

- Phase-I upgrade over LS2 (TDAQ + NSW)
- Smarter configurations
- Offline-like HLT algorithms
- Inclusion of ML at all levels

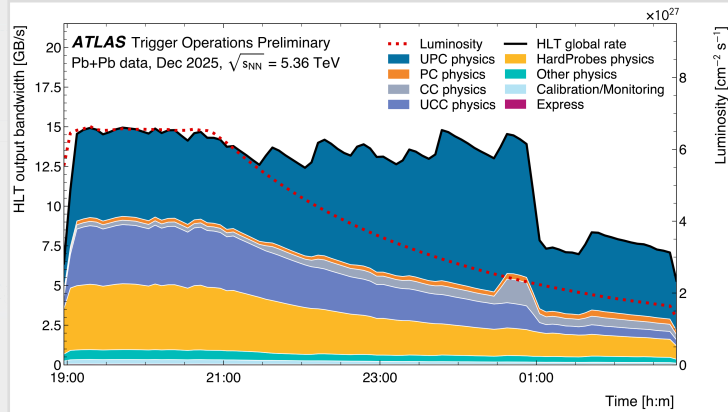
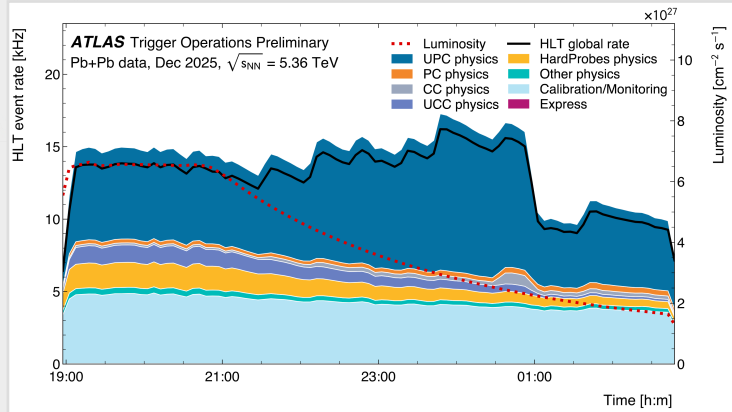
Trigger Selection offline threshold (GeV)	Run 1 $\langle\mu\rangle=14$	Run 2 $\langle\mu\rangle=29$	Run 3 $\langle\mu\rangle=64$
isolated single e	25	27	27
Isolated single μ	25	27	25
di- γ	25,25	20,20	20,20
di- τ	40,30	40,30	35,25
four-jet w/ b-jets	4x45	4x45	4x45 + asymmetric
HT	700	700	700
MET	150	200	200



Trigger performance



8 GB/s standard data taking limit



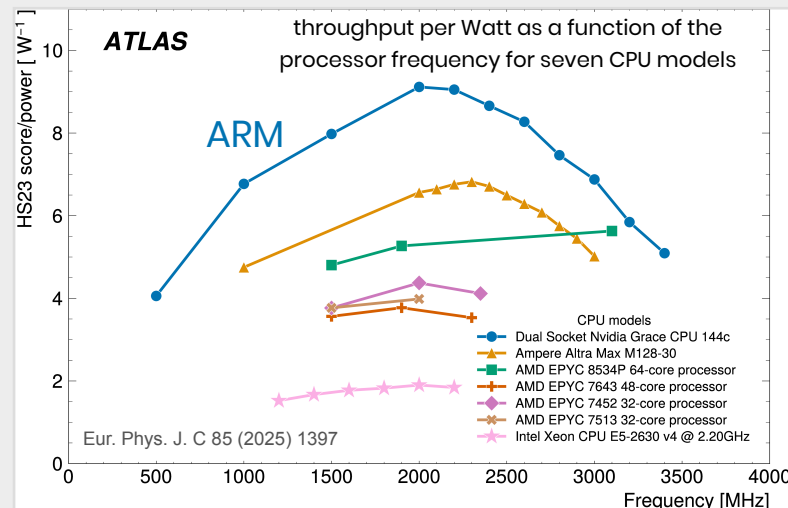
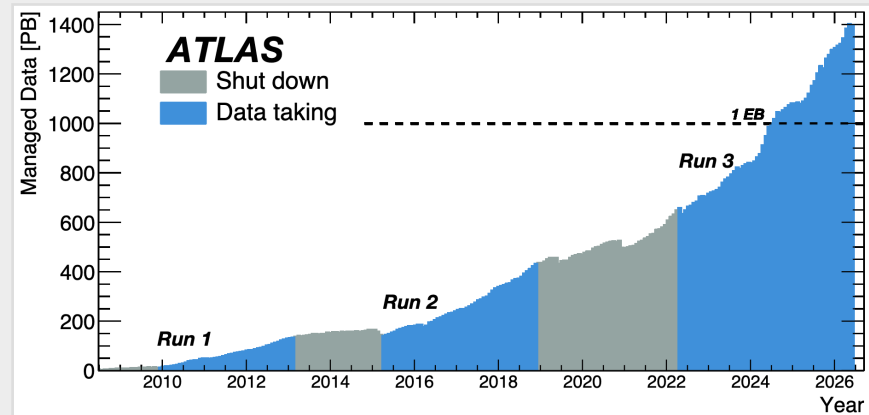
ATLAS computing in Run 3

- ATLAS uses global distributed computing
- > 1 EB of managed data with efficient data placement
- Simulation dominates CPU usage: emphasis on fast simulation (AtI Fast3 – factor 3 improvement)
- Exploring heterogeneous computing
 - ARM CPUs now pledged and deployed at multiple sites
 - GPU workflows under development to exploit opportunistic resources

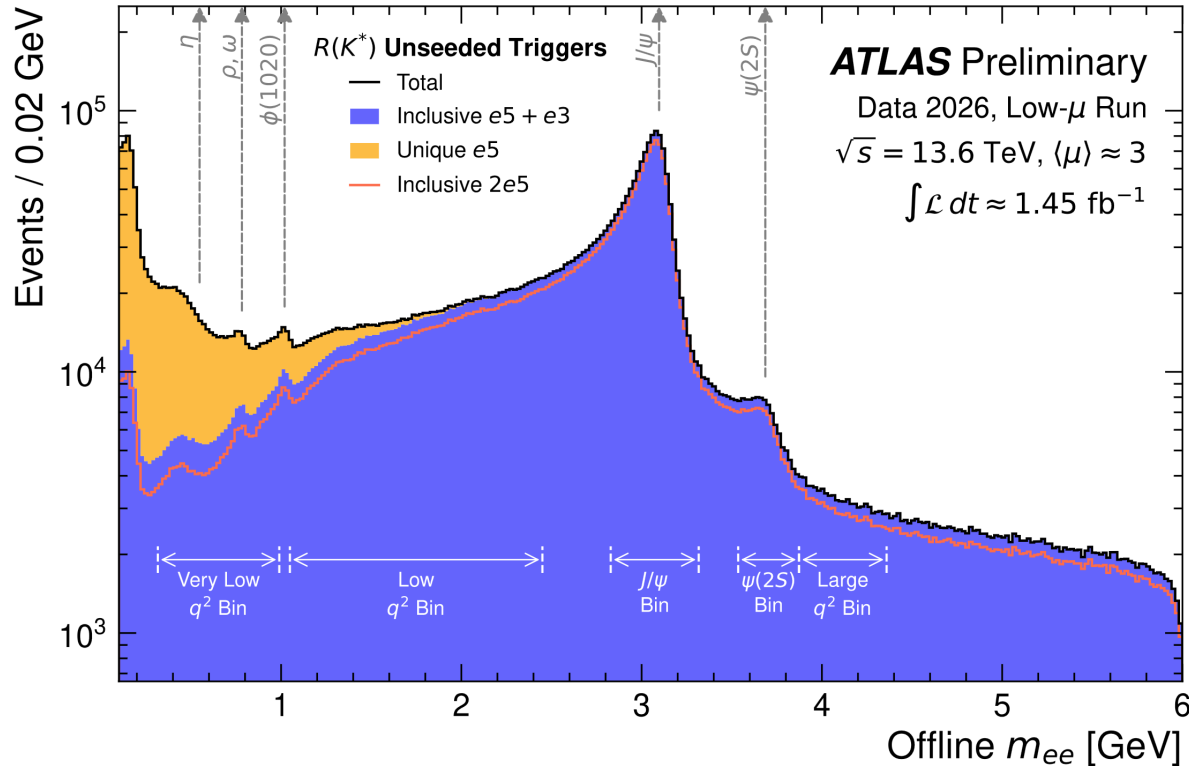
Status of GPU-accelerated workflows in ATLAS

Evgen	Mature for key generators
Full Simulation	Success with GEANT4 + Celeritas/ Adept, moderate speed-up (x1.4) for EM sim
Reconstruction	Calorimeter: significant acceleration Tracking: well-developed
Validation	Good progress

Eur. Phys. J. C 85 (2025) 234



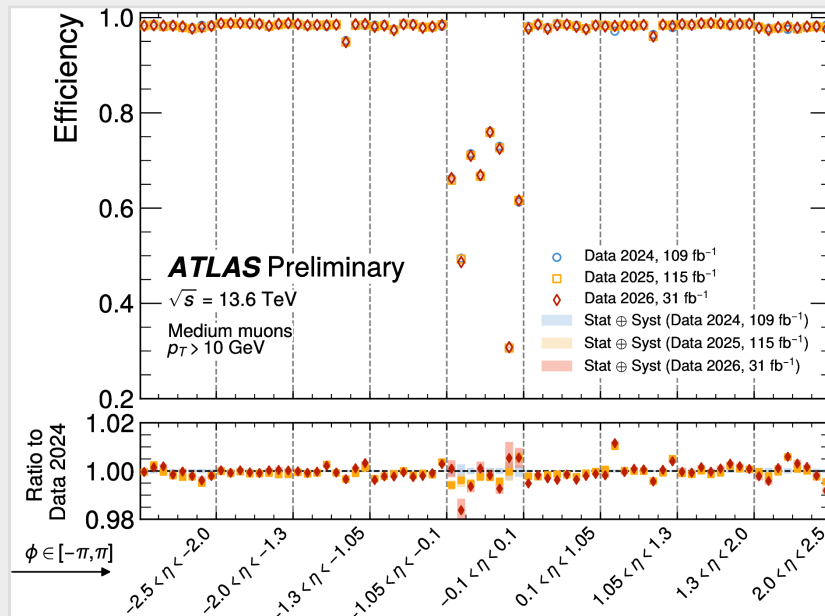
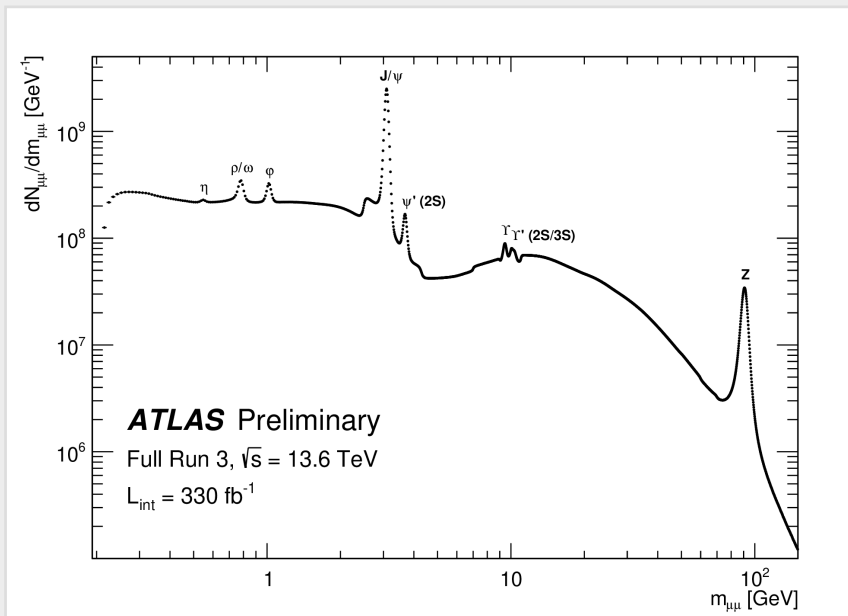
Improvement of the B -physics trigger performance



Invariant mass distribution for oppositely charged electron pair candidates that pass the “unseeded” dielectron triggers introduced for the $R(K^*)$ analysis, using the low- $\langle\mu\rangle$ data collected during 2026

An example of the reconstruction performance: muons

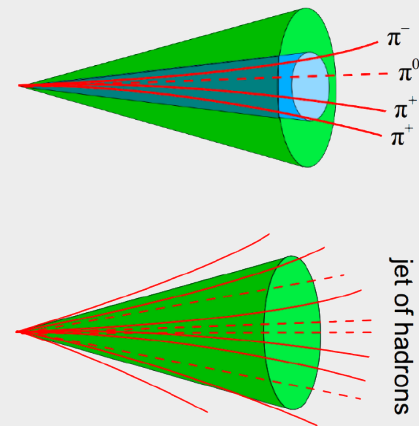
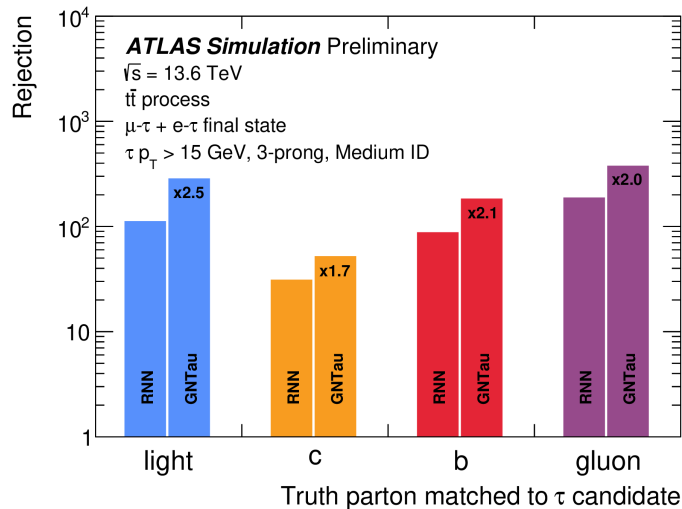
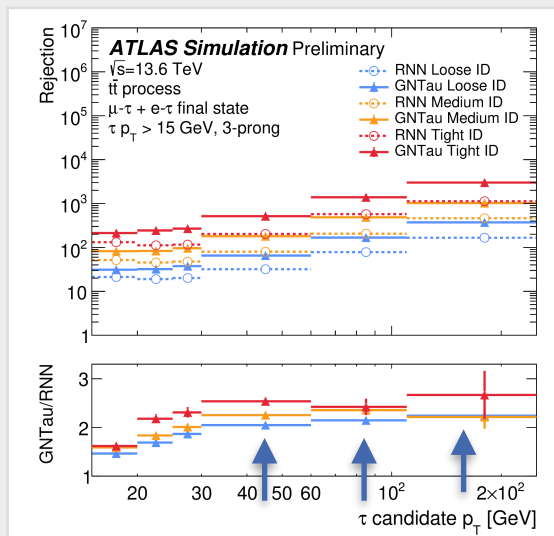
Reconstruction and identification efficiencies for μ
measured up to 2026 data with $Z \rightarrow \mu\mu$



Transformers: a powerful ML tool for reconstruction and analysis

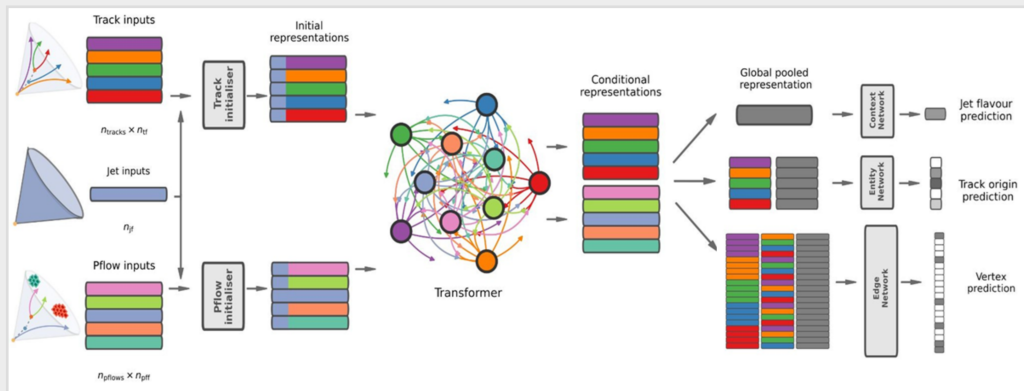
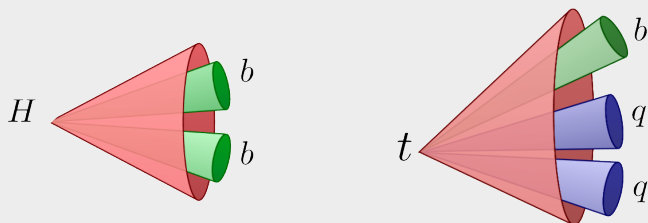
Transformer-based machine learning algorithms in combination with high-statistics training samples promise **significant improvements**, especially for complex hadronic signatures

GNTau: Hadronic τ -lepton decays

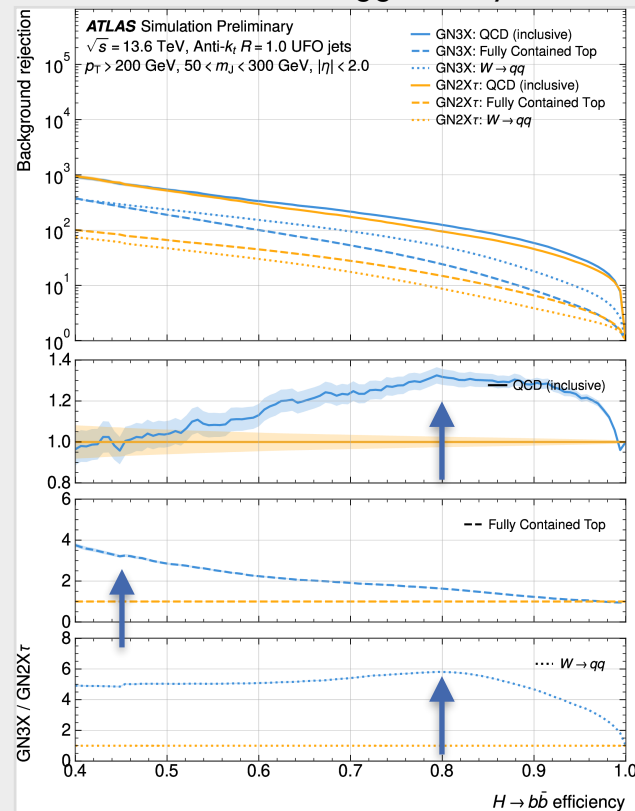


Transformers: a powerful ML tool for reconstruction and analysis

Transformer-based machine learning algorithms in combination with high-statistics training samples promise **significant improvements**, especially for complex hadronic signatures



GN3X: Boosted hadronic Higgs decays ($bb, cc, \tau\tau$)





Physics highlights: testing the SM



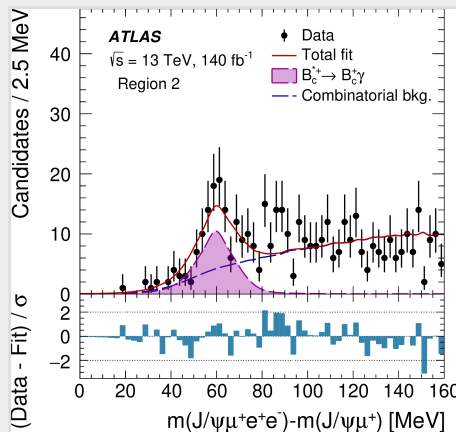
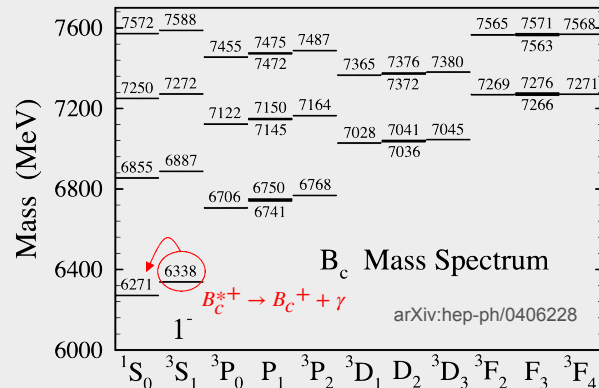
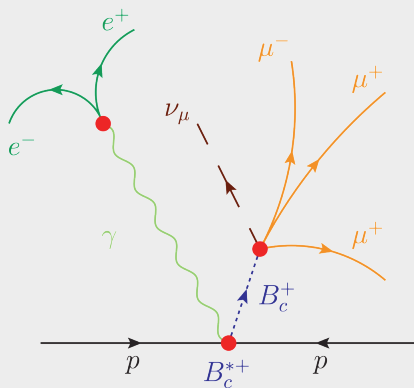
Run: 517520
Event: 4541637302
2026-03-31 05:27:40 CEST

Observation of B_c^{*+}

- The lightest B_c^+ excitation, B_c^{*+} (3S_1 state) is abundant but challenging experimentally
 $\Delta m(B_c^{*+} - B_c^+) \sim 70 \text{ MeV}$
 very soft photon from $B_c^{*+} \rightarrow B_c^+ + \gamma$
- Semileptonic channel for B_c^+ reconstruction
- Soft converted photons reconstructed from tracks down to 100 MeV on preselected set of events
- New state observed with $> 8\sigma$ significance

$$\Delta m(B_c^{*+} - B_c^+) = 64.5 \pm 1.4 \text{ (stat.)}^{+1.0}_{-1.4} \text{ (syst.) MeV}$$

- In agreement with theory predictions based on QCD potential models
- Larger than recent lattice QCD calculations



Source	Uncertainty [MeV]
Material modelling and photon momentum scale & resolution	+0.44 -1.13
B_c^+ production modelling	± 0.19
$B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu X$ decay modelling	± 0.05
$N_{B_c^{*+}}^{R1} / N_{B_c^{*+}}^{R2}$ ratio	± 0.12
Muon reconstruction and trigger	± 0.16
Background shape modelling	± 0.79
Total	+0.95 -1.41

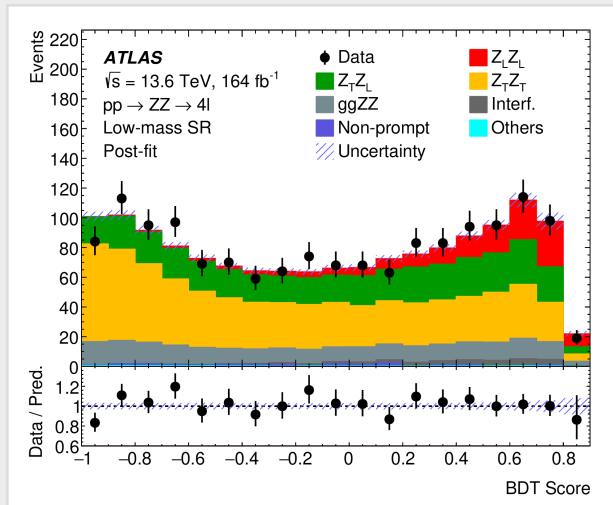
arXiv:2605.16228

Polarised bosons: a window into the Higgs mechanism

- Longitudinally polarised gauge bosons are intrinsically linked to electroweak symmetry breaking

first observation of $Z_L Z_L$ production

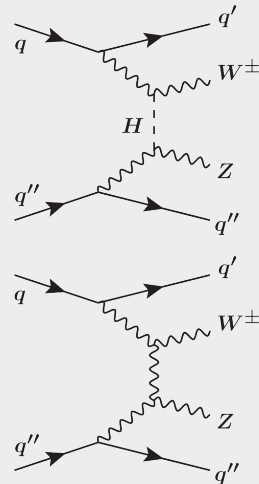
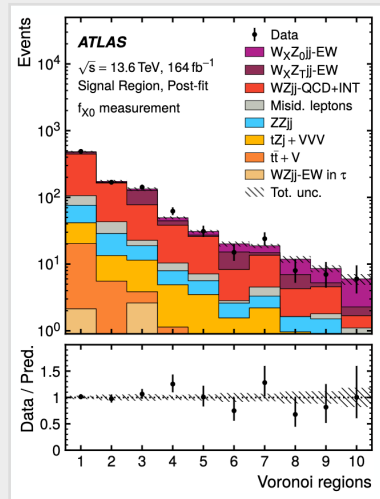
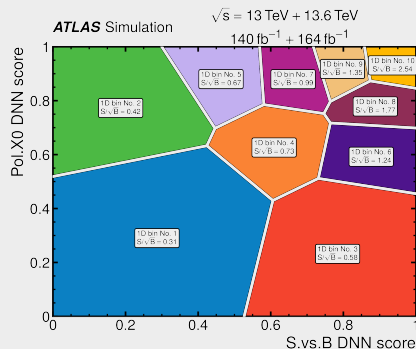
after evidence of $W^\pm W^\pm_L jj$ in 2025 [arXiv:2503.11317] now first evidence of $W Z_L jj$ production



using 2022–2024 data and combining with Run 2

$$Z_{\text{obs}} = 6.5\sigma \text{ (} 5.6\sigma \text{ expected)}$$

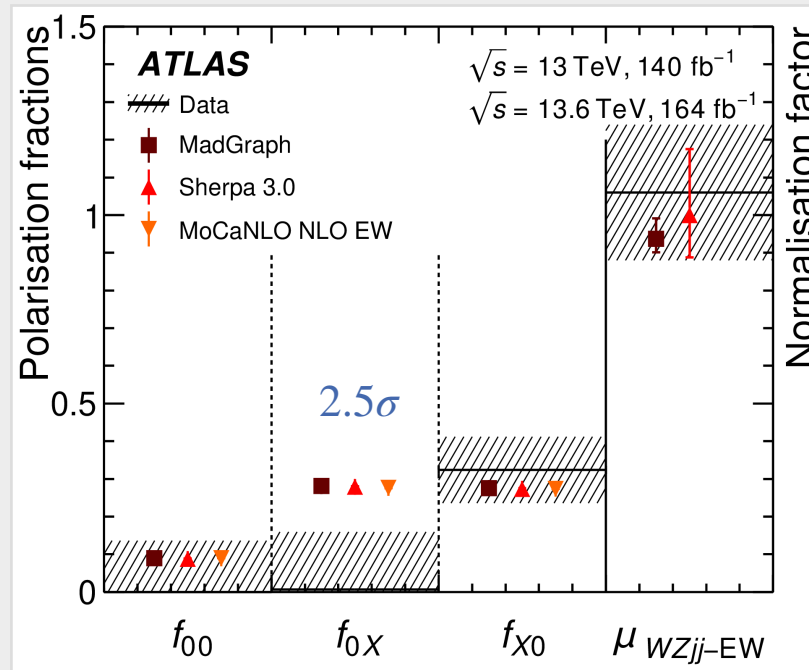
$$f_{LL}^{\text{low-}m4l} = 0.108 \pm 0.028 \quad f_{LL}^{\text{high-}m4l} = 0.011 \pm 0.017$$



using Run 2 + 2022–2024 data

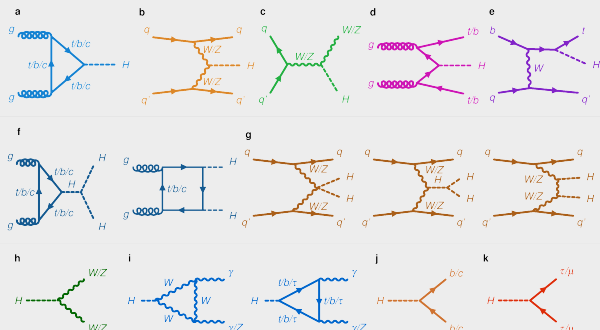
$$Z_{\text{obs}} = 4.0\sigma \text{ (} 2.9\sigma \text{ expected)}$$

Polarised bosons: a window into the Higgs mechanism



The polarisation of one of the bosons can also be measured regardless of the state of the other, determining the individual polarisation fractions $f_{0X}(f_{X0})$ and $f_{TX}(f_{XT})$ for W (Z) bosons (x indicates either of the two 0 or T polarisation states)

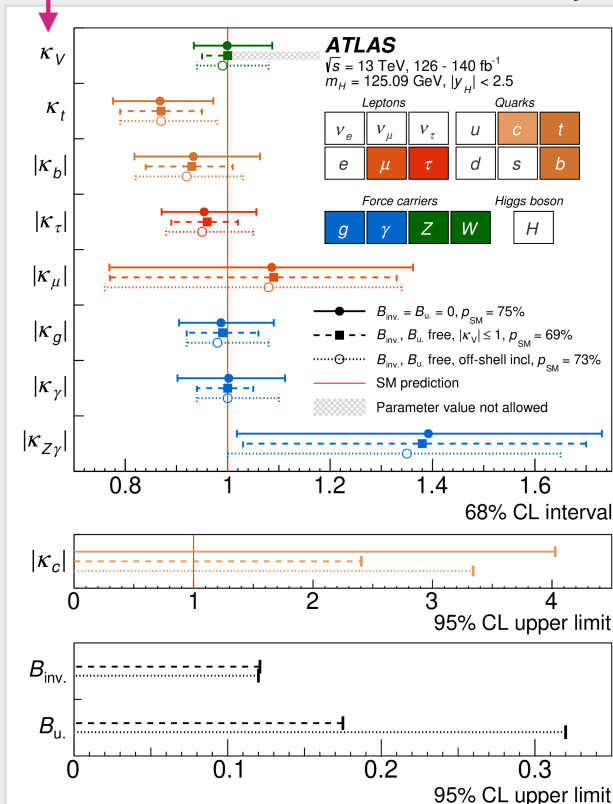
Characterising the Higgs boson



- Combination of 26 individual analyses using the Run 2 data set to yield the most complete and detailed profile of Higgs boson production and decay rates, couplings and (pseudo-)differential cross-sections (STXS)

- Couplings to W, Z, t, b, τ measured with 5-12 % precision
- Charm Yukawa coupling constrained to $|\kappa_c| < 4.1$ (95% CL)
- Inv branching ratio constrained to $B_{\text{inv}} < 12\%$ (95% CL)
- Higgs boson width: $\Gamma_H = 3.6^{+2.1}_{-1.6}$ MeV (combination of off-shell and on-shell analyses)
- STXS cross-section measured in 44 exclusive kinematic regions

coupling modifiers $\kappa_i = \frac{g_i}{g_i^{\text{SM}}}$



Searching for $HH \rightarrow bb\tau\tau$

- Rate and kinematics of HH production offer direct access to the Higgs boson self-coupling λ
→ important test of the Higgs potential shape

- Analysis of Run 2 + 2022+2023 pp data:

$$\mu_{HH} = 2.6^{+1.4}_{-1.0} = 2.6^{+1.0}_{-0.9} (\text{stat.})^{+1.0}_{-0.5} (\text{syst.})$$

- observed significance: $Z_{\text{obs}} = 2.6\sigma$ (1.2σ expected)
- limit: $\mu_{HH} < 5.3$ at 95% CL ($\mu_{HH} < 2.4$ expected)

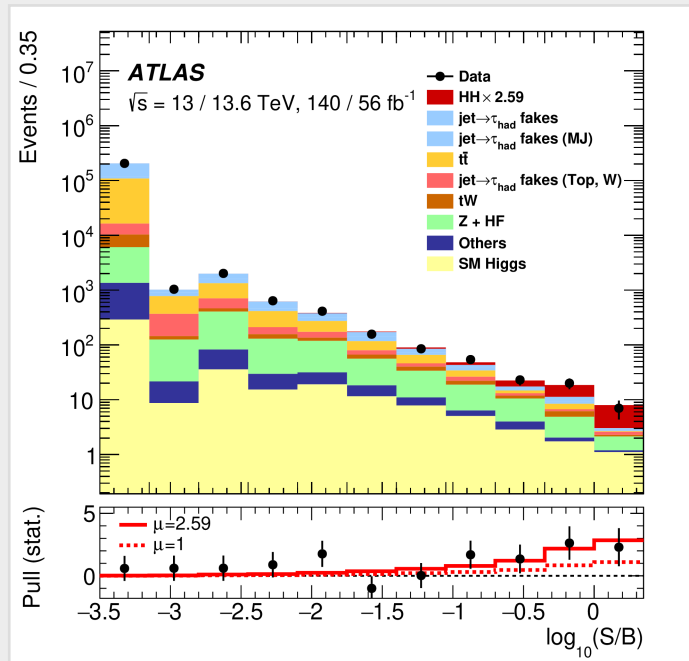
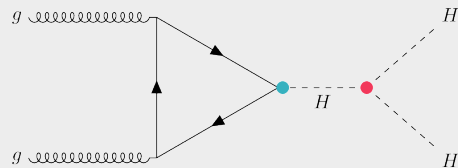
Validation of analysis strategy using
 $ZZ \rightarrow bb\tau\tau$ and $ZH \rightarrow bb\tau\tau$:

$$\mu_{ZZ} = 0.64^{+0.39}_{-0.36}$$

$$Z_{\text{obs}} = 1.8\sigma$$

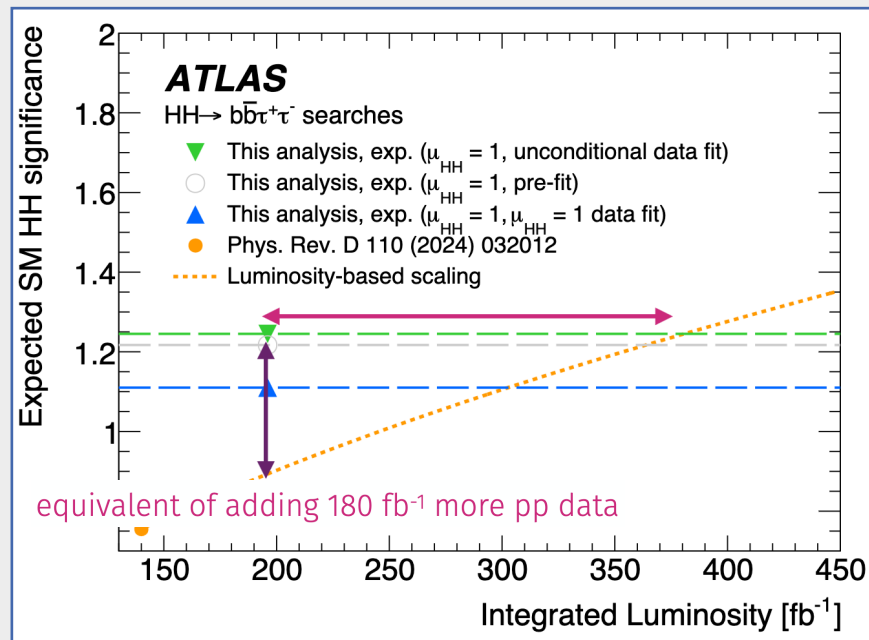
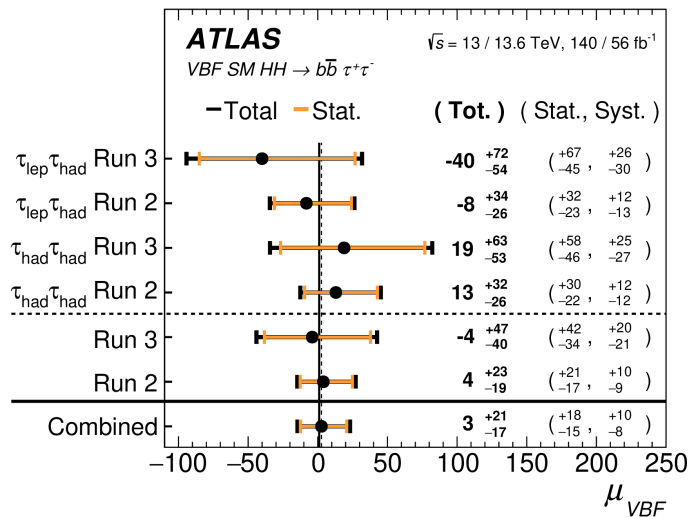
$$\mu_{ZH} = 1.52^{+0.52}_{-0.48}$$

$$Z_{\text{obs}} = 3.5\sigma \rightarrow \text{evidence}$$



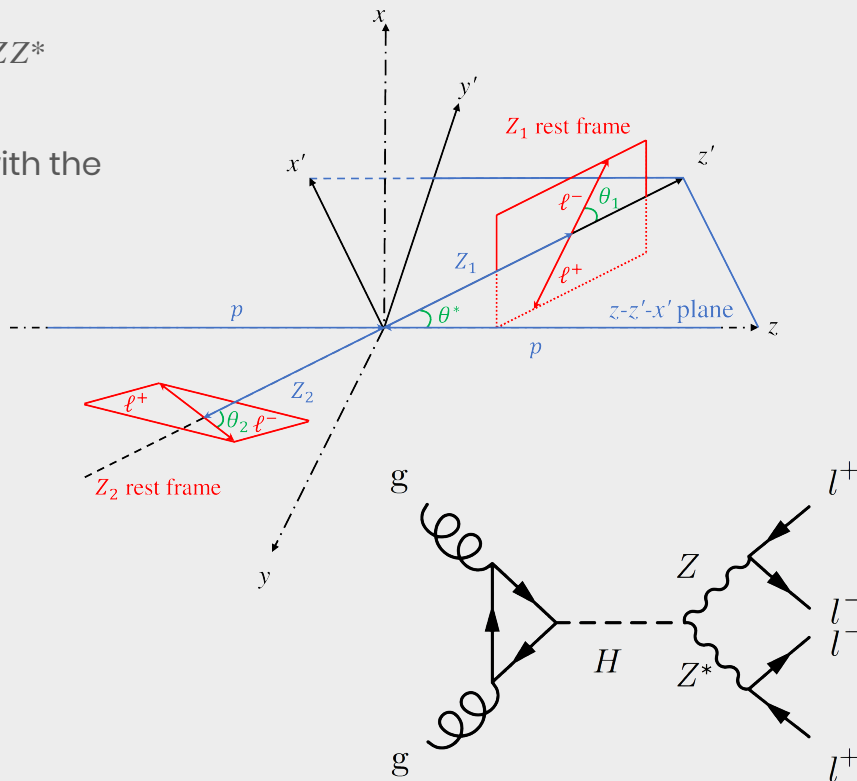
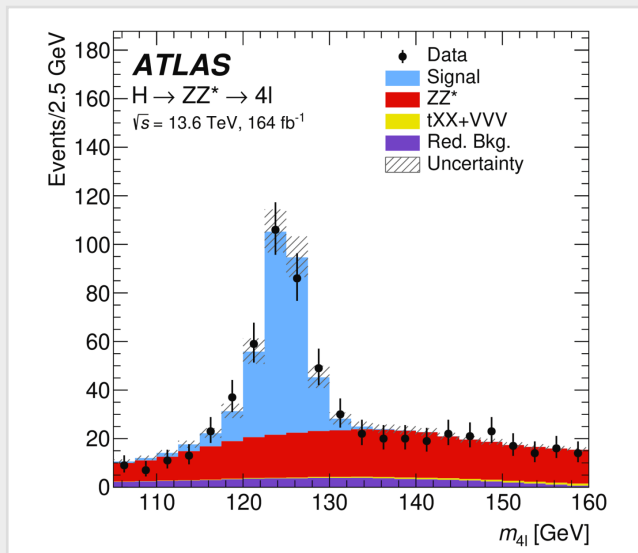
Searching for $HH \rightarrow b\bar{b}\tau\tau$

- Several improvements over the run-2 analysis
 - more data
 - improved b-tagging
 - new ML strategy

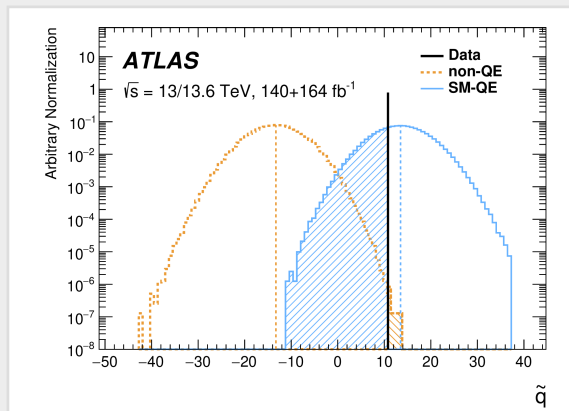
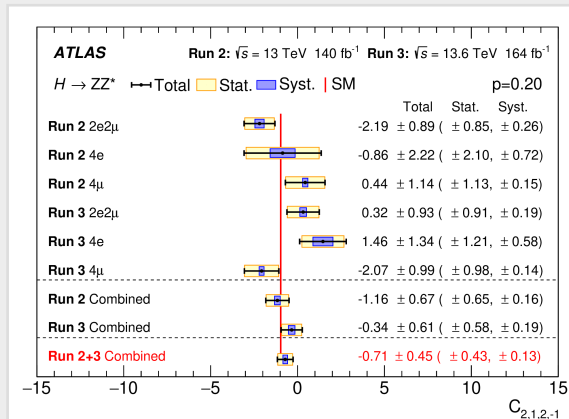
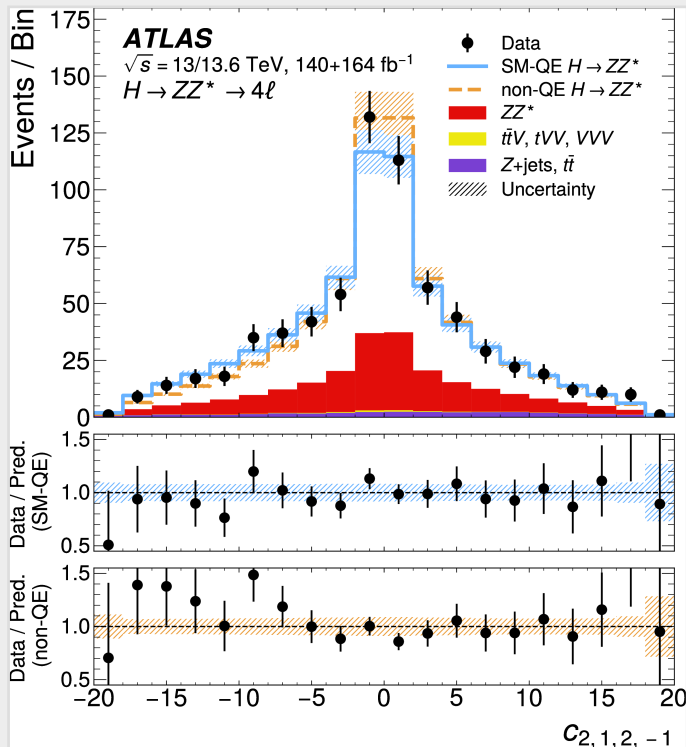


Measurements of Z-boson pair entanglement in decays of Higgs boson

- Measurements of angular observables sensitive to ZZ^* spin-density-matrix elements in $H \rightarrow ZZ^* \rightarrow 4\ell$
- Combined data from LHC Run 2 at 13 TeV together with the three years of 13.6 TeV

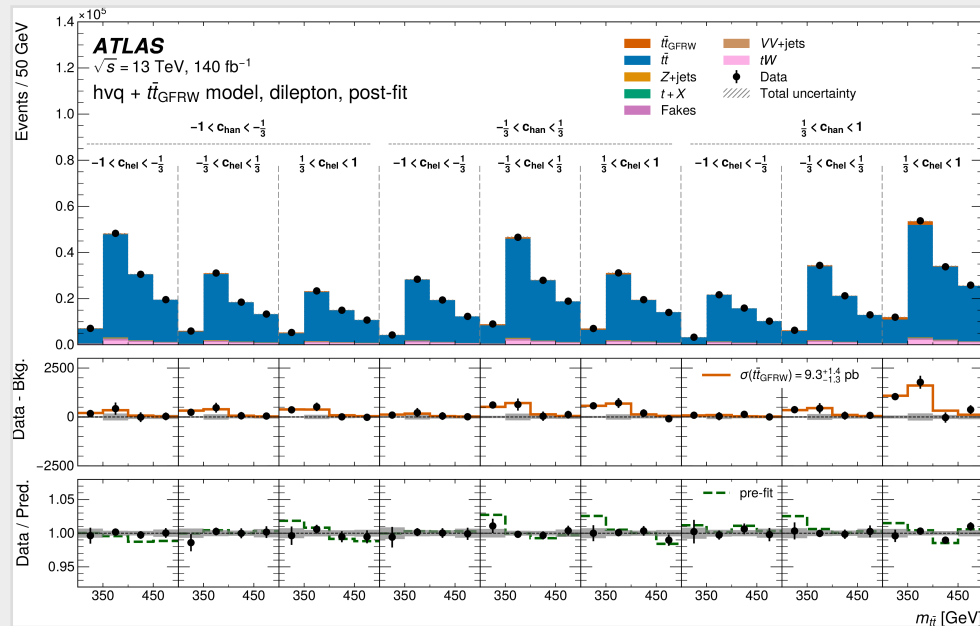
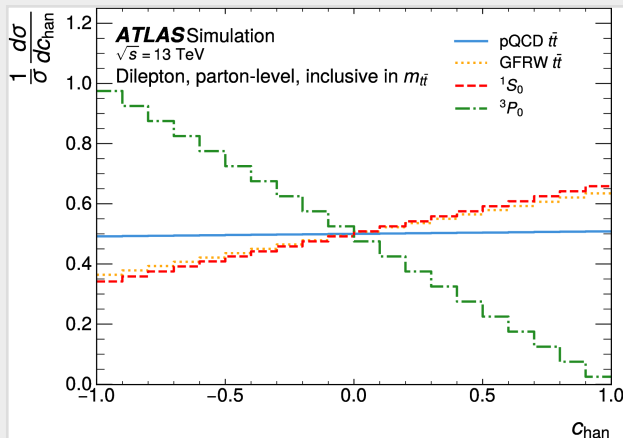


Measurements of Z-boson pair entanglement in decays of Higgs boson



Observation of a cross-section enhancement near the $t\bar{t}$ production threshold

- Using angular observables sensitive to spin-correlations in the $t\bar{t}$ system
- Dilepton selection



Observation of a cross-section enhancement near the $t\bar{t}$ production threshold

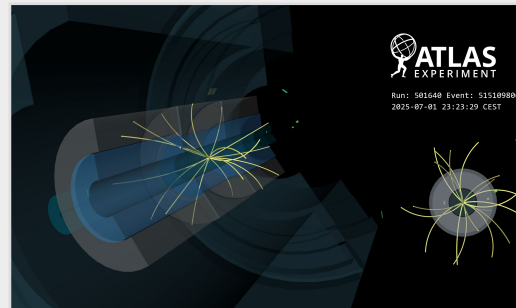
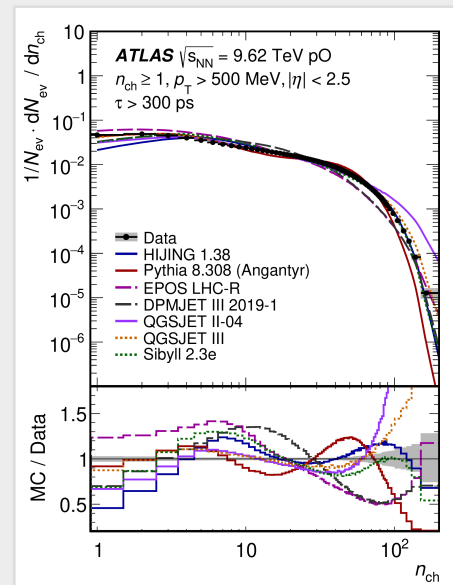
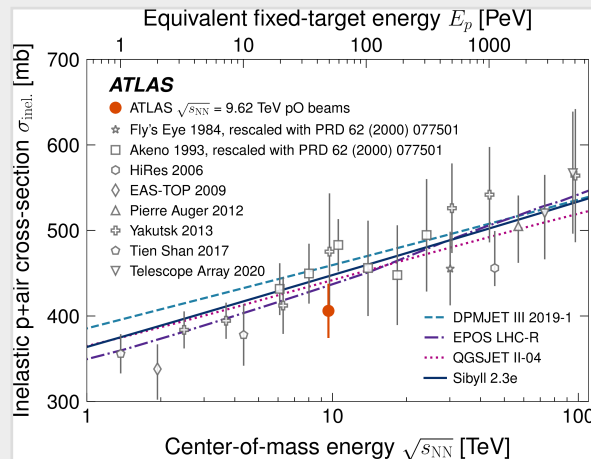
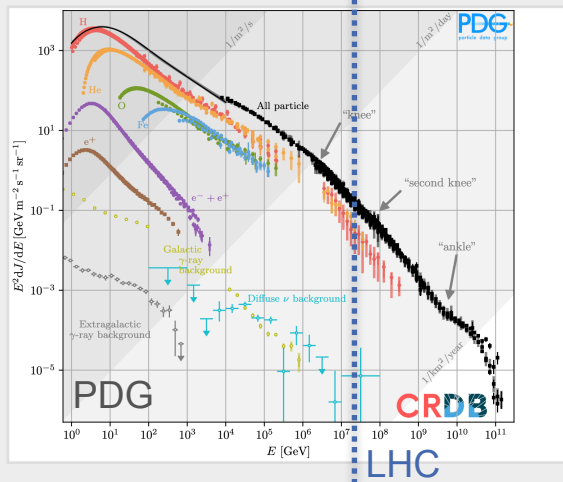
- Excess is observed over the baseline perturbative QCD prediction (8σ)
 - consistent with the formation of colour-singlet and spin-singlet S-wave quasi-bound $t\bar{t}$ states

$$\sigma(t\bar{t}_{\text{GFRW}}) = 9.3_{-1.3}^{+1.4} \text{ pb} = 9.3_{-1.0}^{+1.1} (\text{stat.}) \pm 0.8 (\text{syst.}) \text{ pb}$$

Category	Impact
$t\bar{t}_{\text{GFRW}}$ modelling	6.9%
pQCD $t\bar{t}$ modelling	4.7%
JES pile-up	1.5%
b -tagging	1.3%
Instrumental (other)	0.9%
JES η inter-calibration	0.9%
Jet energy scale (JES)	0.6%
Background normalisations	0.6%
Leptons	0.6%
JES flavour	0.6%
tW modelling	0.5%
Limited MC statistics	0.3%
Jet energy resolution (JER)	0.2%
Total syst. uncertainties	8.8%
Total stat. uncertainties	11%

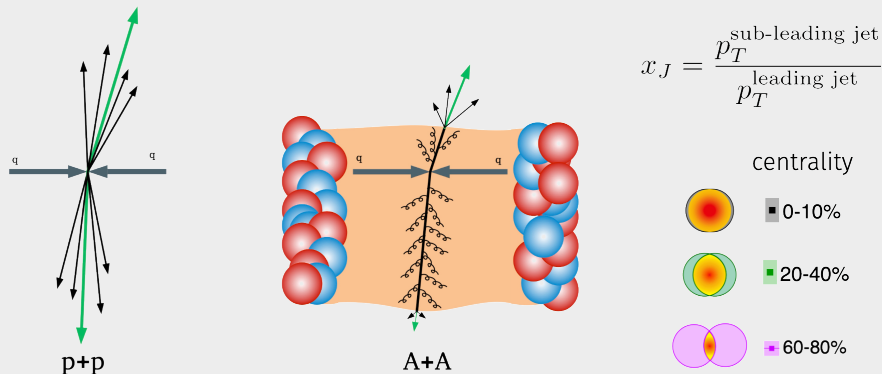
ATLAS as a cosmic-ray laboratory with proton-oxygen collisions

- First collider measurement mimicking cosmic-ray atmospheric interactions at 49 PeV equivalent energy
- Fiducial proton-oxygen cross section consistent with MC generators (EPOS-LHCR and HIJING)
- Measurement precision is an order of magnitude better than the spread among the models
 - About 40% disagreements at low multiplicity

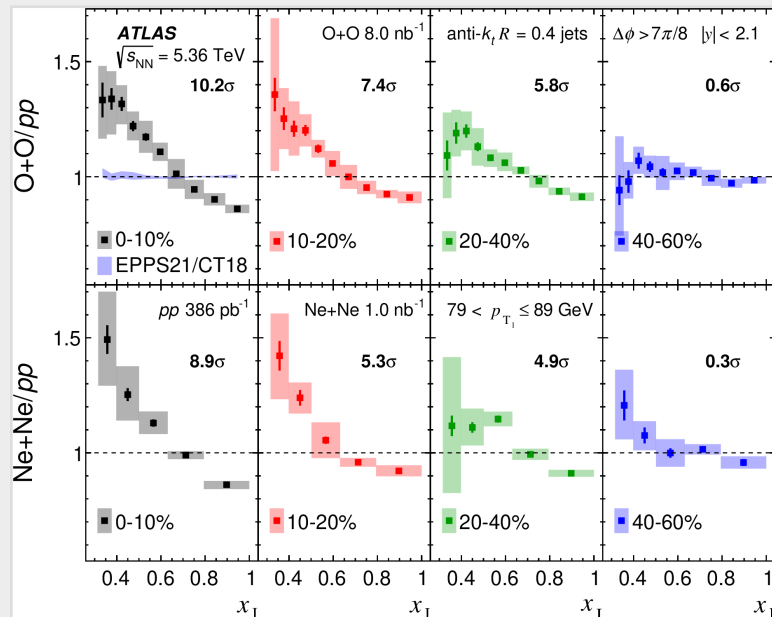


Jet quenching in OO and NeNe collisions

- Jet energy loss when high energy quarks and gluons traverse the dense medium of QGP
 - leads to imbalance in jet transverse momentum in di-jet events



first observation of jet quenching in OO and NeNe collisions,
the smallest systems so far that show this phenomenon
→ helps to pinpoint the system size at which a QGP is formed



Run: 496908

Event: 17131827

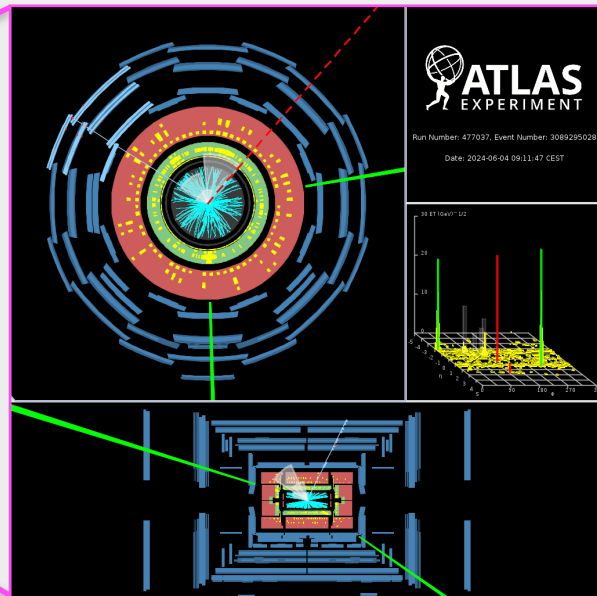
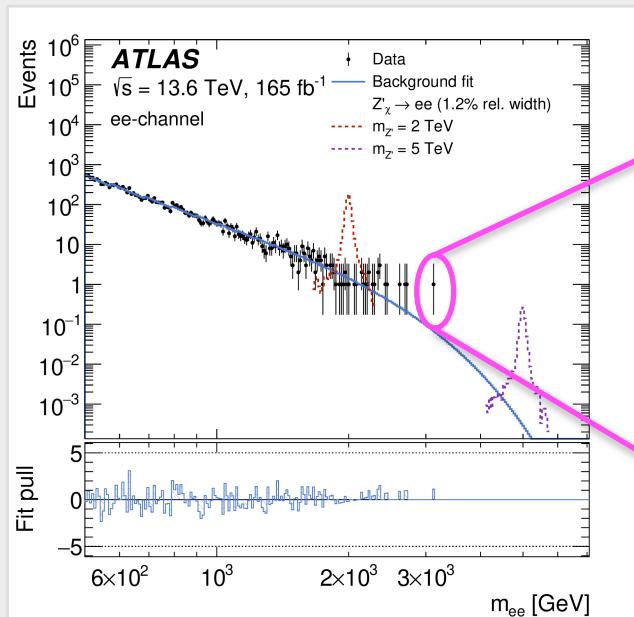
2025-05-05 14:22:14 CEST

Physics highlights: searches for phenomena beyond the SM



Search for high-mass di-lepton resonances

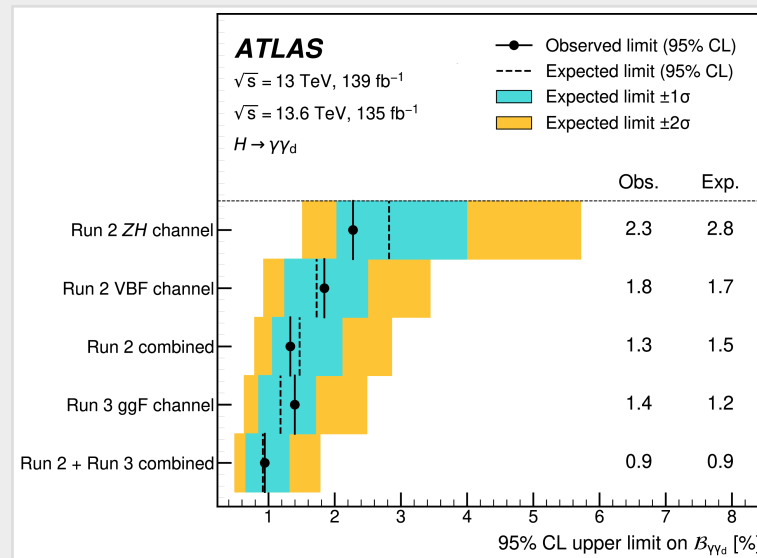
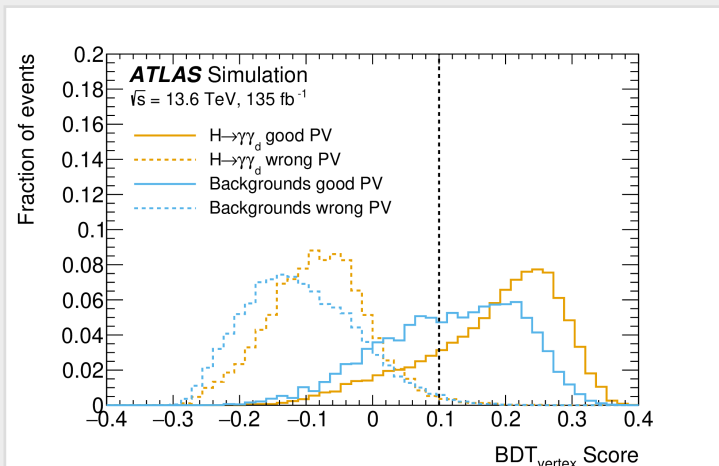
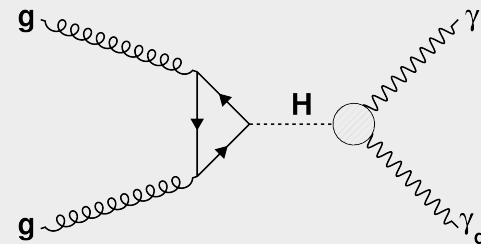
- Search for high-mass vector bosons decaying into electron or muon pairs using 2022–2024 data



- No significant deviation from the background-only hypothesis found
 - Upper limits on SM extensions, e.g. Z'_{SSM} masses $< 5.5 \text{ TeV}$ ruled out at 95% CL

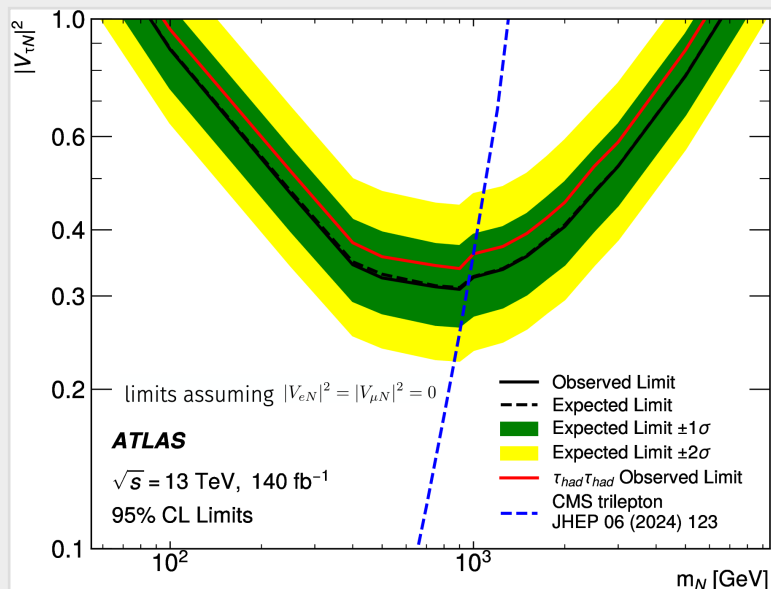
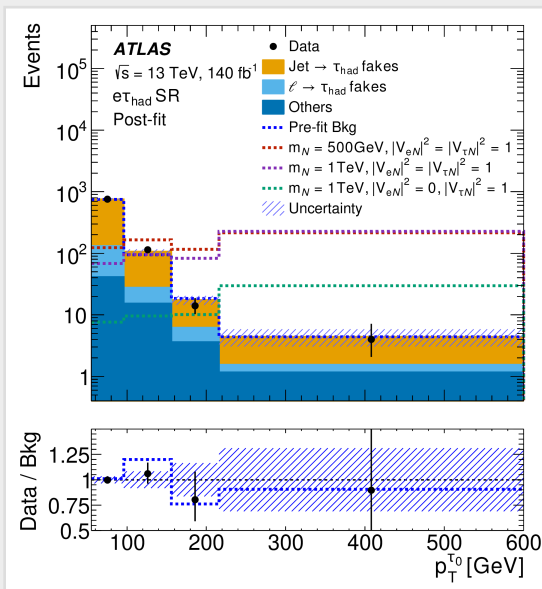
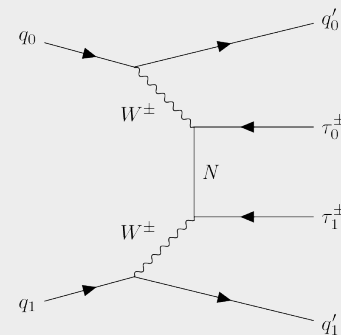
Search for dark photons in Higgs decays

- Predicted as the gauge boson of dark U(1) group in hidden sector
- Targeting $H(125 \text{ GeV})$ in ggF production
- Dedicated new trigger improves acceptance by factor two – Run 3 (2023+2024) data
- BDT used to reject events where the vertex is misidentified



Search for heavy Majorana N in τ final states

- First search for heavy Majorana neutrinos in vector boson scattering (t-channel) using τ -lepton final states at the LHC
 - complementarity to s-channel searches for high m_N

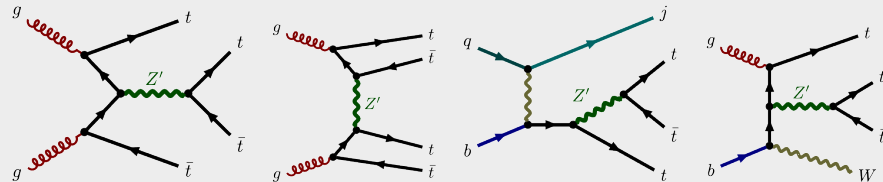


Search for a top-philic heavy resonance in association with top quarks

- 2ℓ SS or $\geq 3\ell + \text{b-jets}$:

Region	N_b	N_ℓ
SR 2b2 ℓ	= 2	= 2
SR 2b3 ℓ	= 2	≥ 3
SR 3b2 ℓ	= 3	= 2
SR 3b3 ℓ	= 3	≥ 3
SR 4b	≥ 4	≥ 2

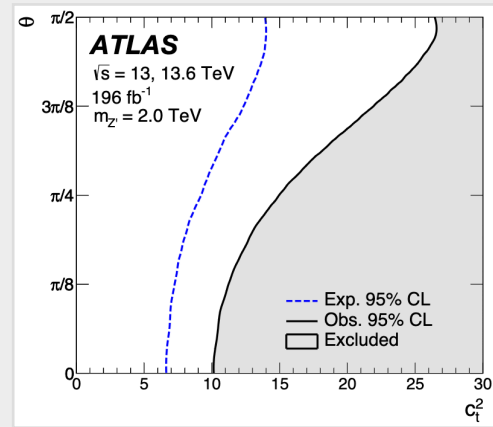
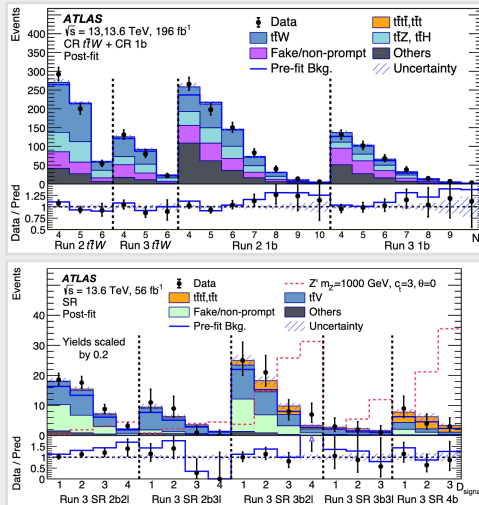
- 13 TeV (2015-18) + 13.6 TeV (2022-23) data



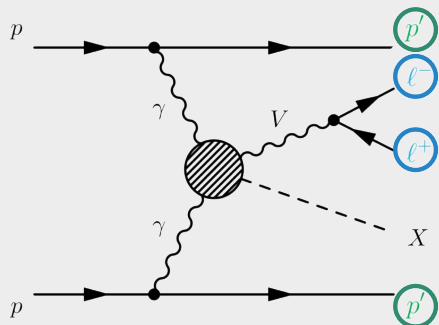
$$\mathcal{L} = \bar{t} \gamma_\mu (c_L P_L + c_R P_R) t Z'^\mu$$

$$= c_t \bar{t} \gamma_\mu (\cos \theta P_L + \sin \theta P_R) t Z'^\mu$$

Region	Channel	N_j	N_b	Other selection	Fitted variable
SR	SS2L,3L	≥ 6	≥ 2	$H_T > 500$ GeV	D_{signal}
CR $t\bar{t}W^{+/-}$	SS $e\mu, \mu\mu$	≥ 4	≥ 2	$p_T^\ell > 25$ GeV, $ \eta(e) < 1.37$ $N_b = 2$: $H_T < 500$ GeV or $N_j < 6$ $N_b \geq 3$: $H_T < 500$ GeV CR $t\bar{t}W^+$: total lepton charge > 0 CR $t\bar{t}W^-$: total lepton charge < 0	N_j
CR 1b(+/-)	SS2L, 3L	≥ 4	= 1	$p_T^\ell > 25$ GeV $H_T > 500$ GeV CR 1b(+): total lepton charge > 0 CR 1b(-): total lepton charge < 0	N_j
CR Low m_{γ^*}	SS $e\mu, e\mu$	$4 \leq N_j < 6$	≥ 1	Only one e from $\gamma^* \rightarrow ee$ No e from $\gamma \rightarrow ee$	Yield
CR Mat. Conv.	SS $e\mu, e\mu$	$4 \leq N_j < 6$	≥ 1	Only one e from $\gamma \rightarrow ee$ No e from $\gamma^* \rightarrow ee$	Yield
CR HF μ	$e\mu\mu, \mu\mu\mu$	≥ 1	= 1	$100 < H_T < 300$ GeV $E_T^{\text{miss}} > 50$ GeV total lepton charge = ± 1	p_T^ℓ
CR HF e	$eee, ee\mu$	≥ 1	= 1	$100 < H_T < 275$ GeV $E_T^{\text{miss}} > 35$ GeV total lepton charge = ± 1	p_T^ℓ



Dilepton + X Missing Mass with AFP

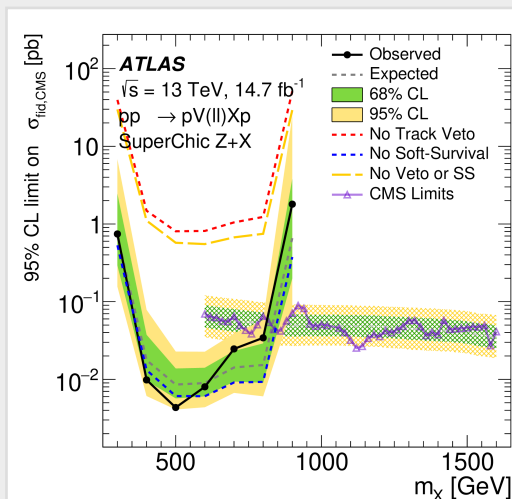
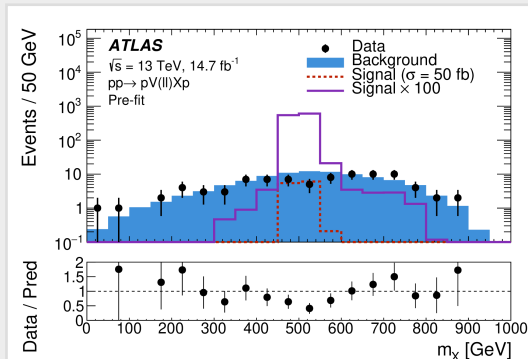
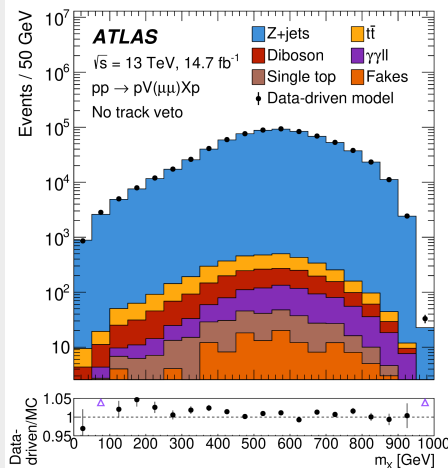


$$m_X^2 = (E_{\gamma\gamma} - E_V)^2 - (\vec{p}_{\gamma\gamma} - \vec{p}_V)^2$$

$$= \left[\begin{pmatrix} \xi_1 E_p + \xi_2 E_p \\ 0 \\ 0 \\ \xi_1 E_p - \xi_2 E_p \end{pmatrix} - \begin{pmatrix} E_V \\ p_x^V \\ p_y^V \\ p_z^V \end{pmatrix} \right]^2$$

AFP ATLAS

- Fully data-driven background
- Modelled by “mixing” central and AFP event components in data



A 3D visualization of a particle accelerator beam pipe. The beam pipe is a long, dark blue cylindrical structure with a series of blue spherical components along its length. A red laser line is visible, extending from the right side of the frame towards the center. The background is filled with a dense, chaotic pattern of yellow and orange lines, representing particle trajectories or data. The overall color scheme is dominated by blue and yellow.

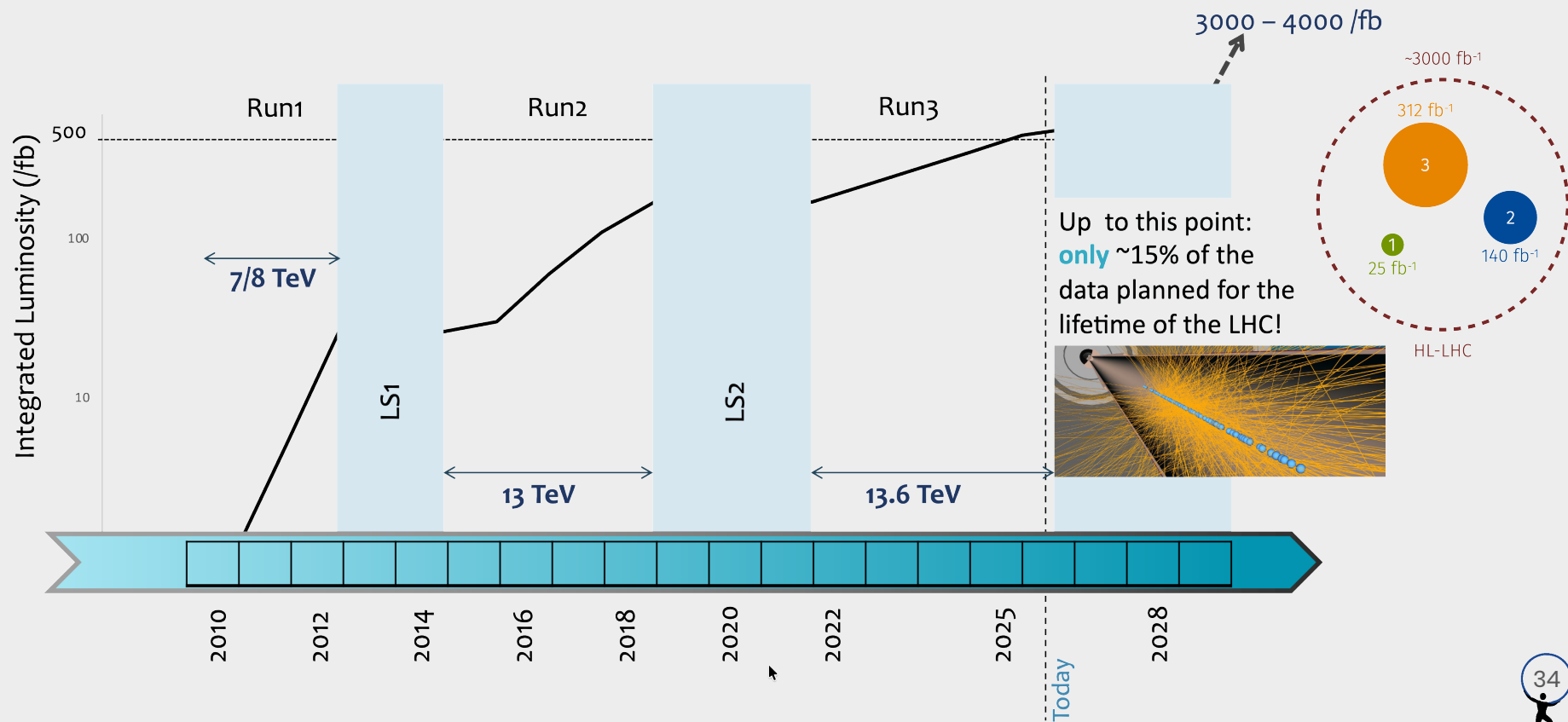
Preparing for the high luminosity phase

Run: 508073

Event: 22881991

2025-10-08 22:17:43 CEST

The HL-LHC



The ATLAS Phase-II Upgrades

New Muon Chambers

Inner barrel region with new RPCs and SMDTs → improved trigger efficiency and reduced fake rate
Improved forward coverage (TGCs)

Upgraded Trigger and Data Acquisition System

First level trigger at 1 MHz (10x higher than today): complete event with full-granularity calorimeter data at hardware trigger level (in addition to high-resolution muon trigger)
Improved High-Level Trigger (150 kHz full-scan tracking)

New and Upgraded Forward and Luminosity Detectors

High Granularity Timing Detector (HGTD)

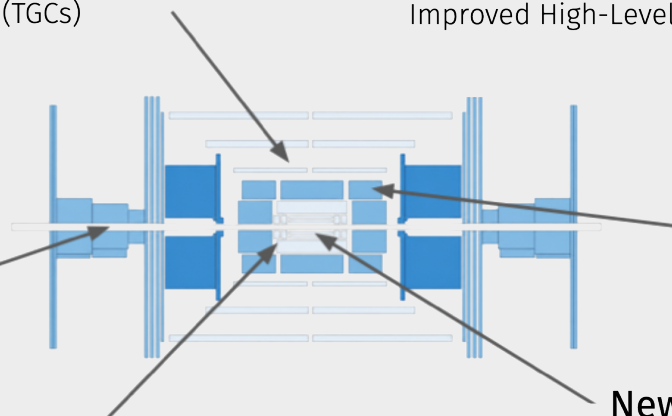
Covering the forward region from $2.4 < |\eta| < 4.0$
Low-Gain Avalanche Detectors (LGADs) aiming at 30-50ps per track time resolution

Electronic Upgrades

LAr Calorimeter
Tile Calorimeter
Muon Spectrometer

New Inner Tracking Detector (ITk)

All silicon, up to $|\eta| = 4.0$
Inner layers pixels, outer layers strips (50x more channels than today)
10 x higher radiation tolerance and higher granularity for pileup rejection



Summary

- **ATLAS enters Long Shutdown 3 on the back of a highly successful Run 3**
- **A wealth of new physics results has followed, including:**
 - the most detailed characterisation of the Higgs boson to date
 - the most sensitive single HH search yet, in the $HH \rightarrow b\bar{b}\tau\tau$ channel
 - first observation of $Z_L Z_L$ production, and first evidence for VBS WZ_L production
 - first observation of jet quenching in O+O and Ne+Ne collisions
 - Probe of quantum mechanics using high energy events
 - Multiple searches for BSM phenomena, probing very challenging regions of the phase space
- **None of this would be possible without continued advances in detector performance**
 - improved detector understanding, novel algorithms, calibration strategies