New Results from 13.6 TeV pp Runs

Marco Pieri
University of California San Diego

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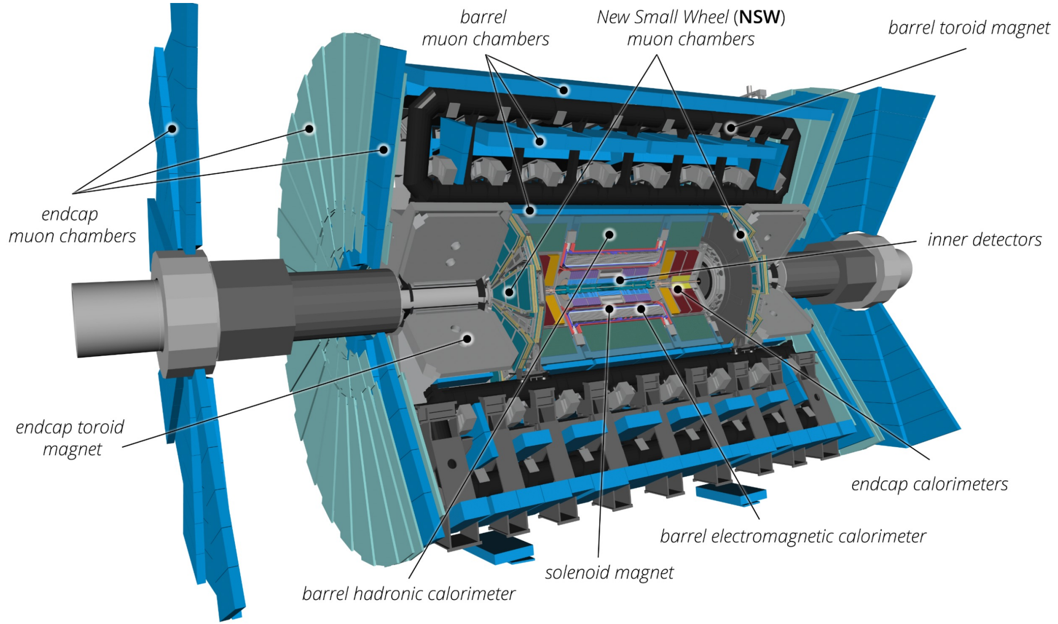
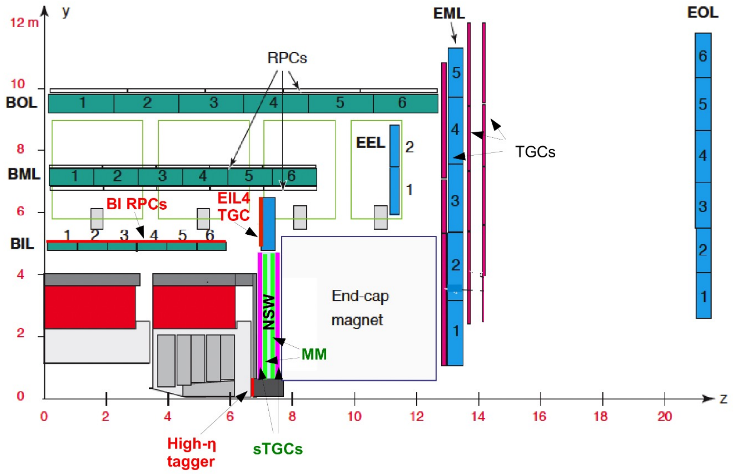
Outline

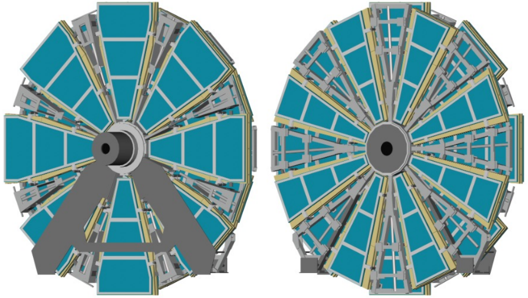
- ATLAS and CMS detectors in Run 3
- Run 3 data
- Detector Performance
- Physics Results
- Summary and Outlook

ATLAS Detector in Run 3



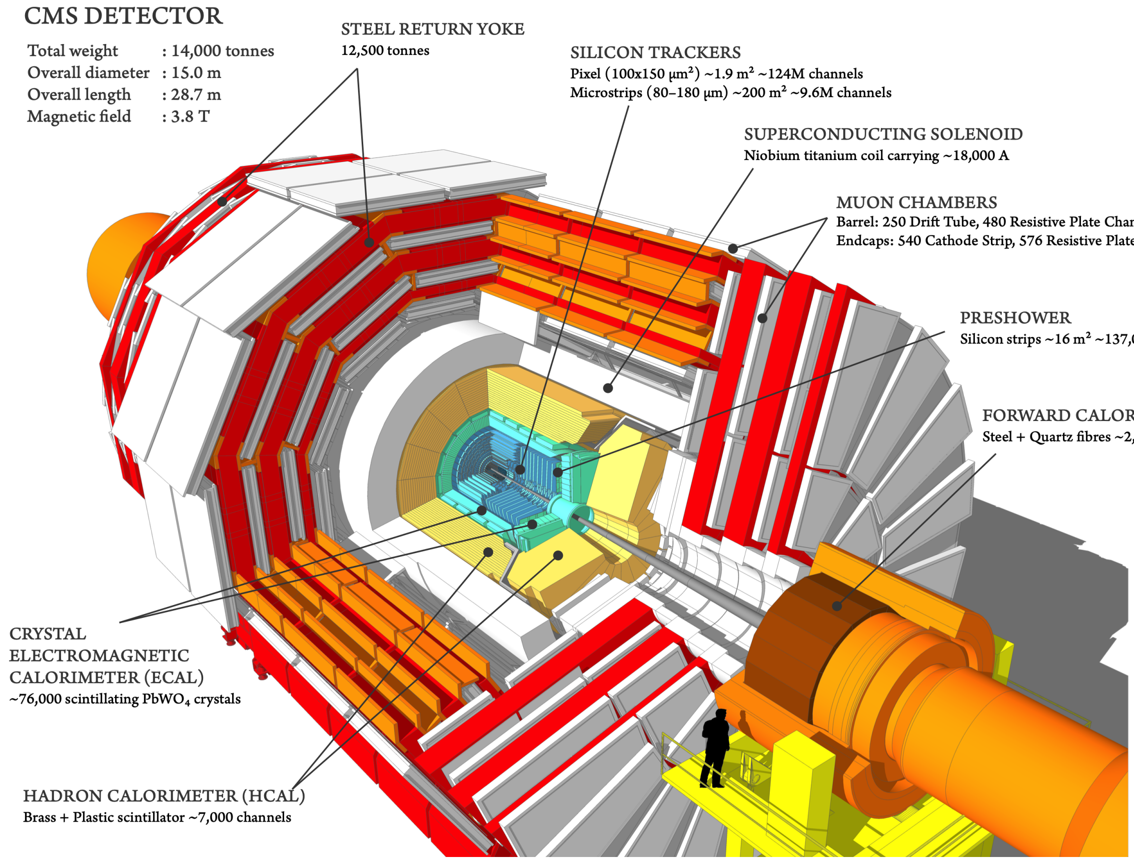
[arXiv:2305.16623](https://arxiv.org/abs/2305.16623)





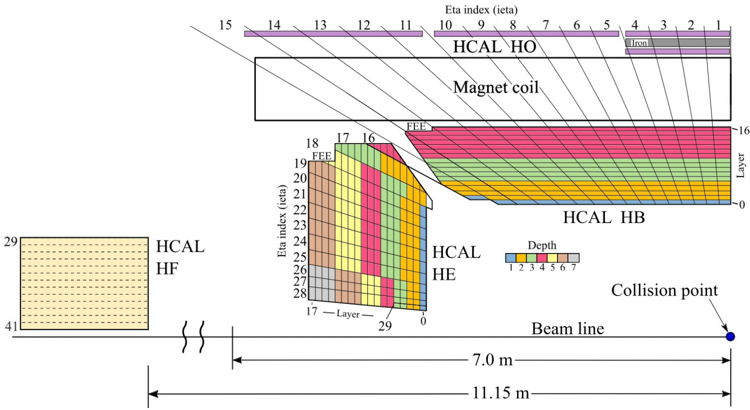
- New Small Weels were installed replacing the innermost forward Muon Stations
  - Improve muon L1 trigger and tracking in forward region in view of HL-LHC
- Other trigger improvements for LAr calorimeter
  - Increased granularity of the readout

CMS Detector in Run 3



- Replaced the pixel detector barrel inner layer
- Increased the longitundinal readout granularity of HCAL

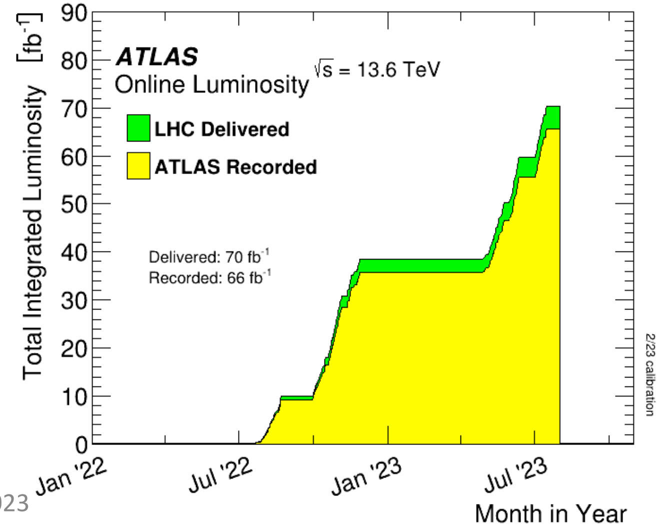
[arXiv:2309.05466]

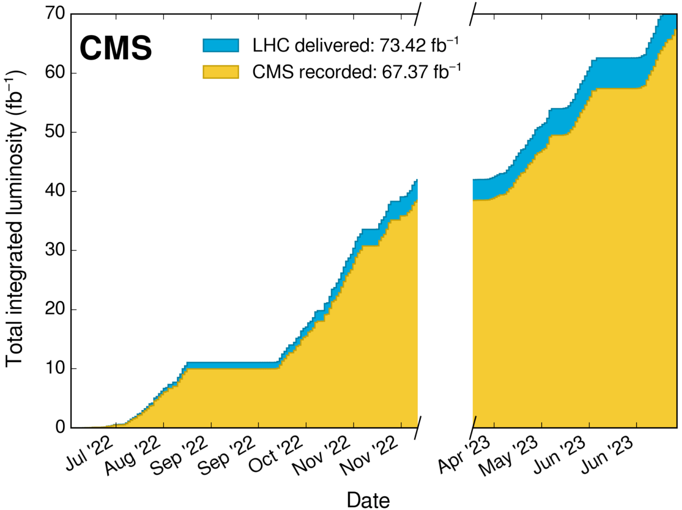


Integrated Luminosity in Run 3

- LHC and the detectors are performing well in Run 3, started in 2022
  - The LHC increased the pp CM energy from 13 to 13.6 TeV in Run 3
- On July 17th, 2023 there was an electrical glitch affecting the LHC and the consequence was a vacuum leak in a bellows
- The recovery went well but about 7 weeks of pp running were lost corresponding to an integrated luminosity of 30-40 fb^{-1}
- First Heavy Ion run in Run 3 ongoing

Total integrated luminosity in Run 3 ~65 fb^{-1} per experiment





Luminosity Measurement

- ATLAS luminosity uncertainty for the full 2022 data is at the 2.2% level
- CMS uncertainty is at a similar level

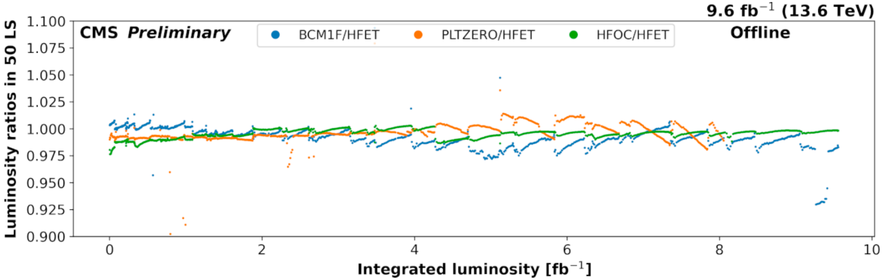
ATL-DAPR-PUB-2023-001

CMS-DP-2022-038

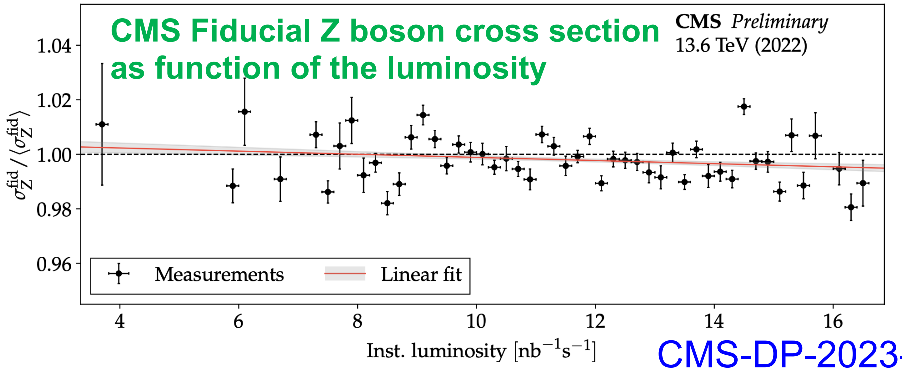
ATLAS contributions to the total uncertainty

Data sample	2022
Uncertainty contributions [%]:	
Statistical uncertainty	0.01
Fit model	0.24
Background subtraction	0.06
FBCT bunch-by-bunch fractions	0.01
Ghost-charge and satellite bunches	0.17
DCCT calibration	0.20
Orbit-drift correction	0.06
Beam position jitter	<0.01
Non-factorisation effects	1.07
Beam–beam effects	0.35
Emittance damping correction	0.21
Length scale calibration	0.03
Inner detector length scale	0.24
Magnetic non-linearity	0.32
Bunch-by-bunch σ_{vis} consistency	0.50
Scan-to-scan reproducibility	0.27
Reference specific luminosity	0.43
Subtotal vdM calibration	1.45
Calibration transfer	1.50
Calibration anchoring	0.53
Long-term stability	0.41
Total uncertainty [%]	2.19

CMS Ratio of luminosity measurements in different luminometers



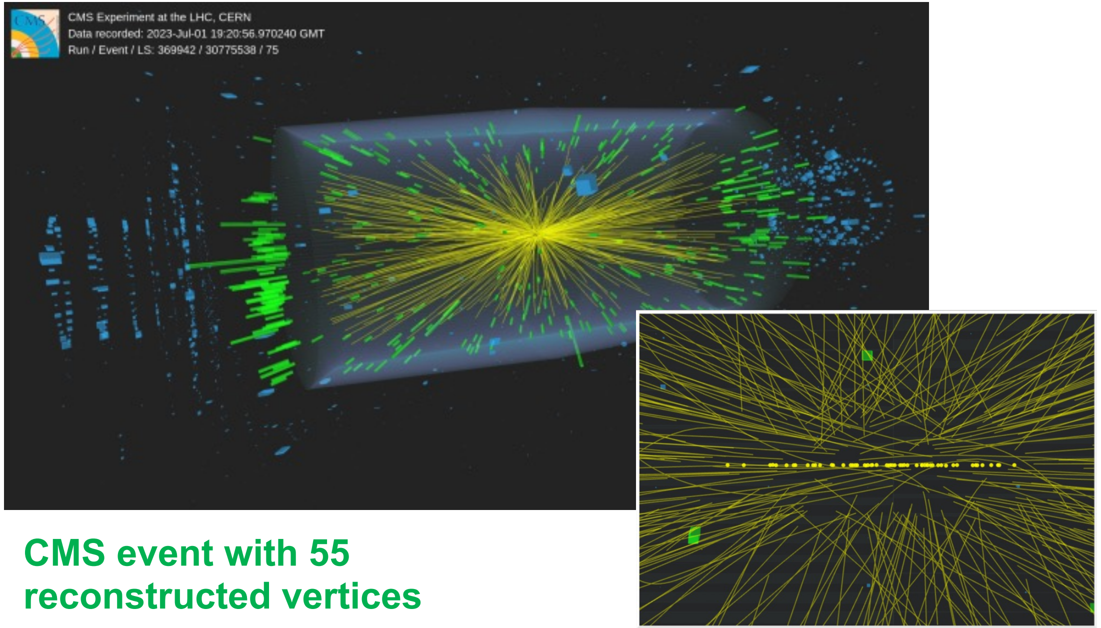
CMS Fiducial Z boson cross section as function of the luminosity



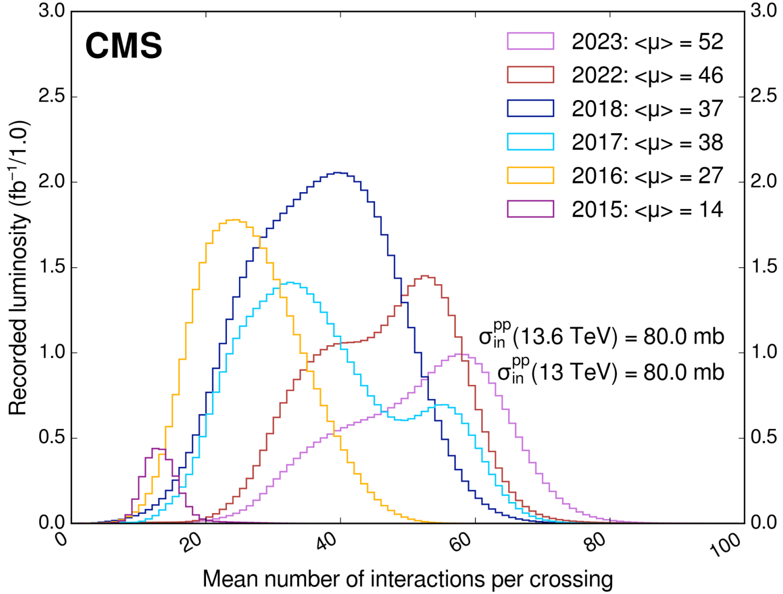
CMS-DP-2023-003

LHC Operations in Run 3

- In Run 3 luminosity and pileup are higher than the LHC design
- The LHC is able to reach a maximum luminosity and pileup of 2.4×10^{34} $cm^{-2}s^{-1}$ and 70
- Levelling time and average pileup are still increasing during Run 3



CMS event with 55 reconstructed vertices



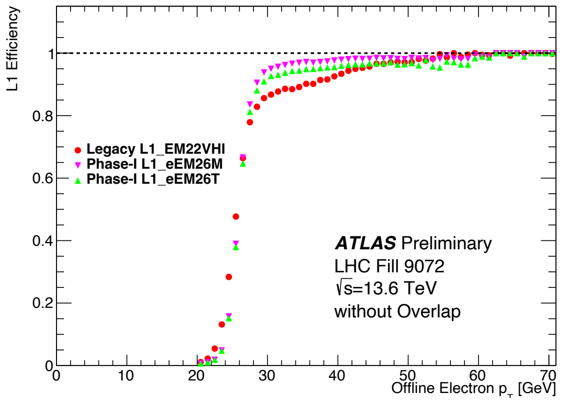
Trigger in ATLAS in Run 3

ATLAS improved several triggers to cope with the higher trigger rate during LHC luminosity levelling

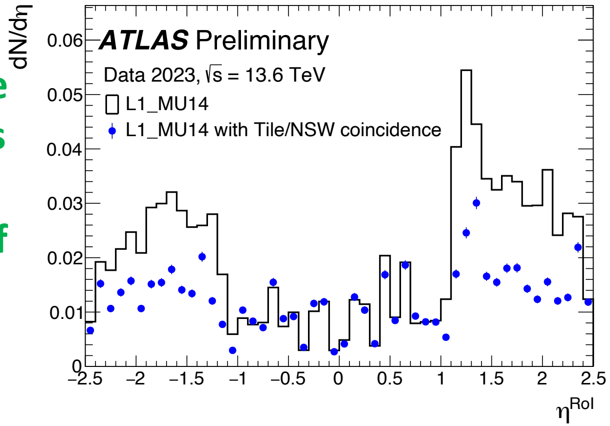
arXiv:2305.16623

arXiv:2306.09738

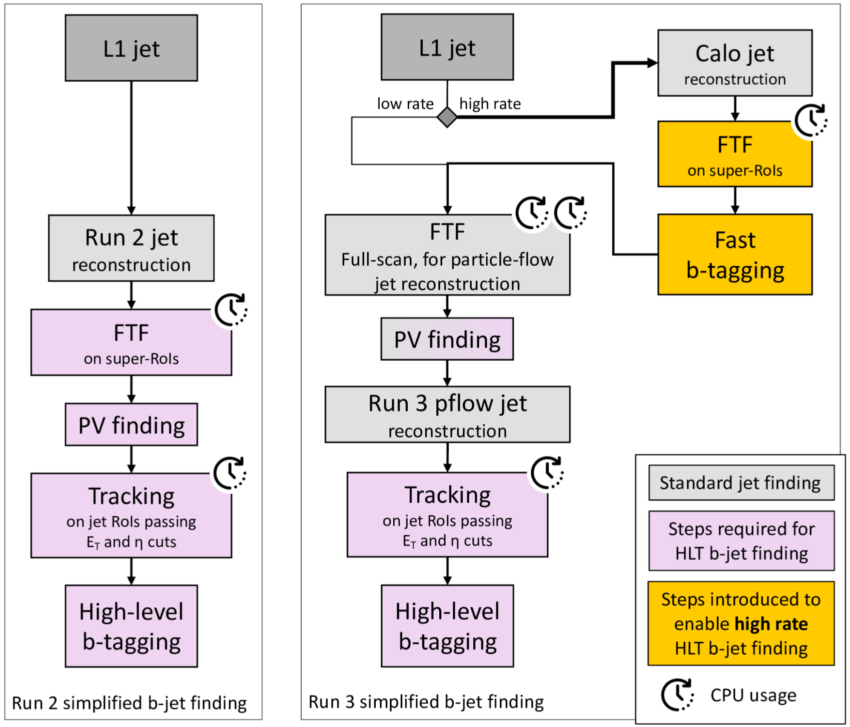
Level 1 calorimeter single electron trigger



NSW coincidence largely decreases the background with small loss of efficiency



Modifications have also been made to the HLT to cope the higher luminosity and pileup



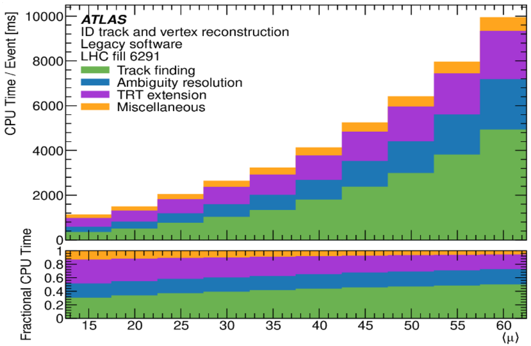
Reconstruction Improvements in ATLAS

- ATLAS also carried out several improvements in the track reconstruction
  - Considerably speeded up the HLT

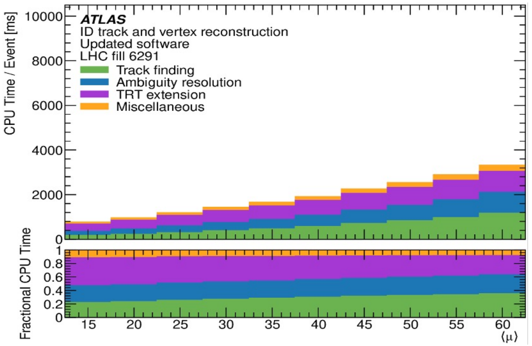
arXiv:2304.12867

arXiv:2308.09471

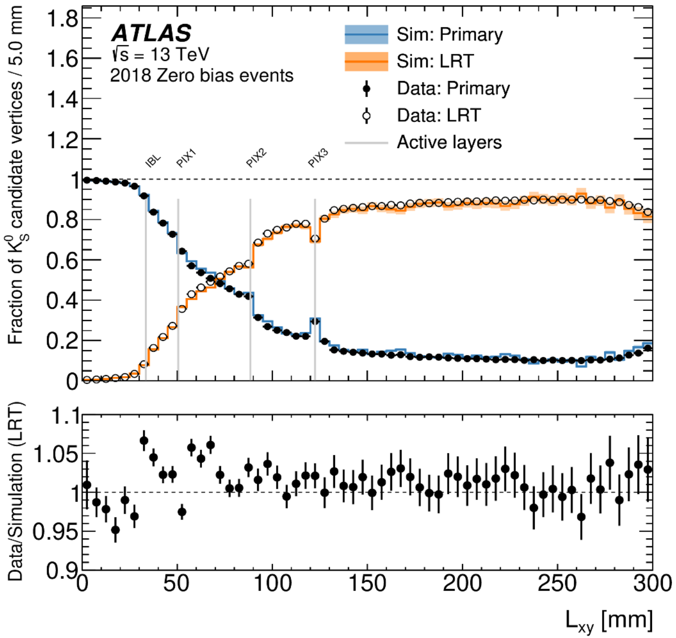
Legacy reconstruction



Updated reconstruction



Also deployed an improved Large Radius Tracking for long-lived particles

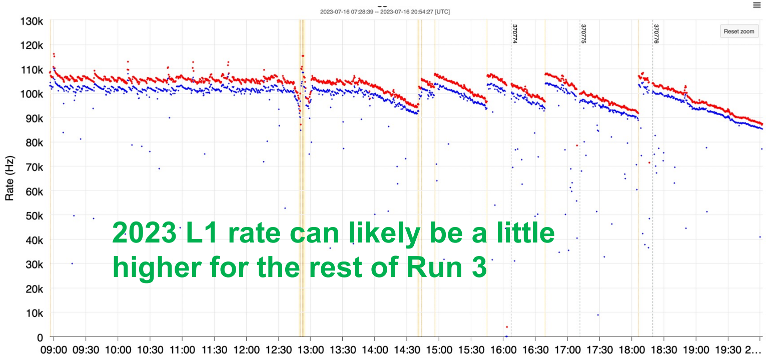


Large improvement in tracking performance at high PU: 2-3 times faster, less fakes with very similar reconstruction efficiency

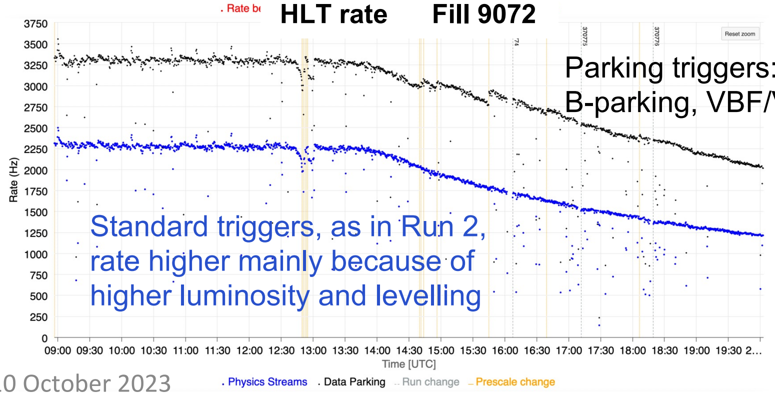
Trigger in CMS in Run 3

Trigger capabilities for Run 3 have been expanded and the performance has been improved for several triggers

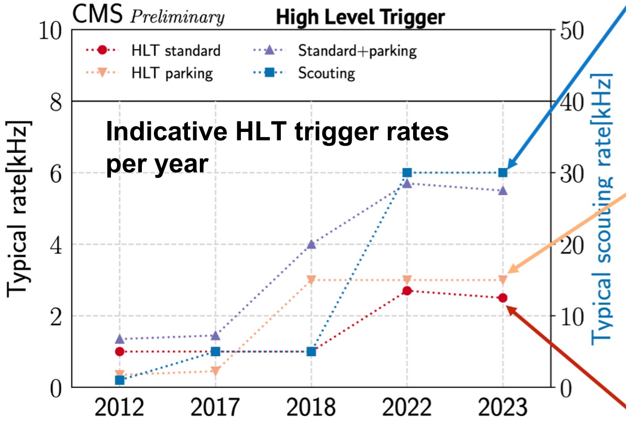
L1 trigger rate Fill 9072



HLT rate Fill 9072



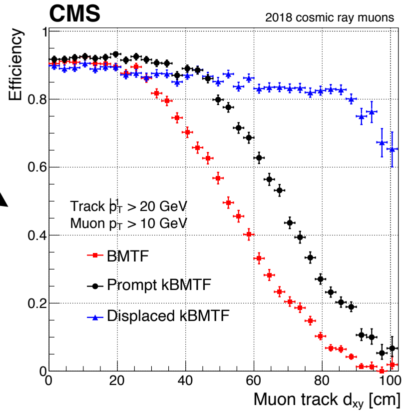
Parking triggers: long lived particles, B-parking, VBF/VBS, 4b



HLT reconstructed data at 30 kHz (scouting)

Parked triggers above 3 kHz: B-parking, long lived, 4b and VBF

Standard triggers about 2.5 kHz

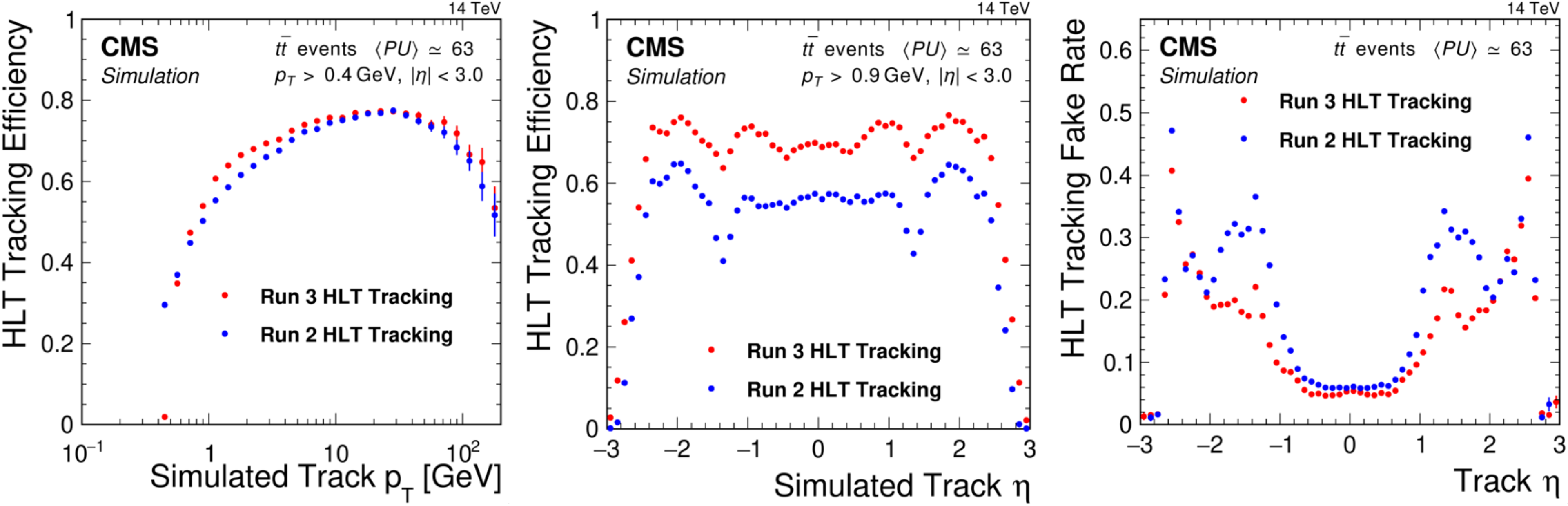


Kalman filter muon L1 trigger largely improves trigger efficiency for displaced muons

Reconstruction Improvements in CMS

- Hetherogeneous HLT reconstruction for Run 3 in CMS
- All online filter farm machines are equipped with two Nvidia T4 GPUs
- 40-50% of the HLT reconstruction is offloaded to the GPU
- Achieved large improvements in performance of the track reconstruction

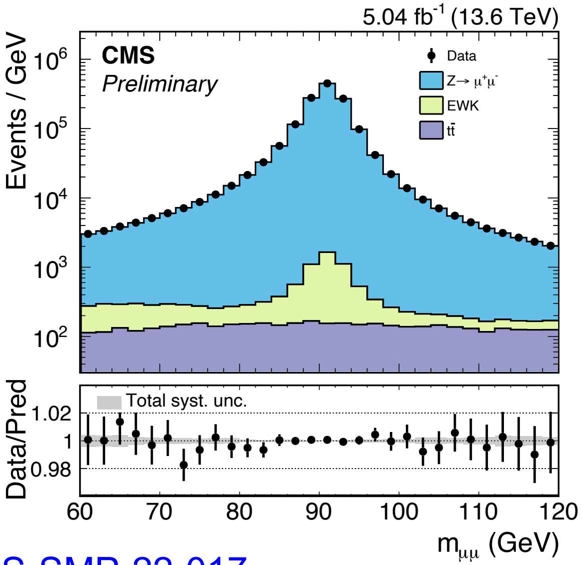
arXiv:2309.05466



Physics Results

Z Production Cross Section

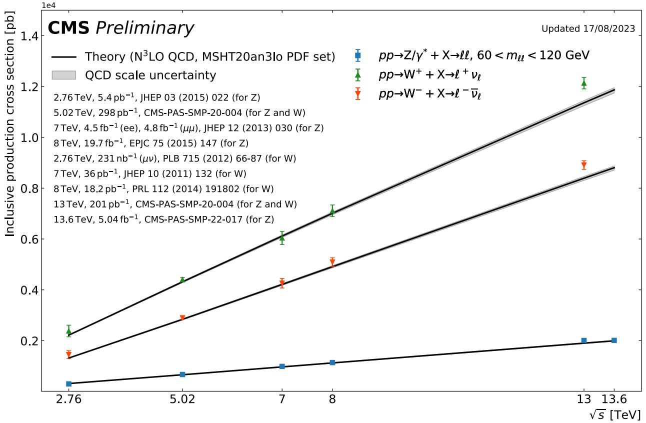
- CMS measured the Z production fiducial and total cross section at 13.6 TeV CM energy using dimuon events with 5 fb^{-1}



CMS-PAS-SMP-22-017

Process	Pre–fit yield	Post–fit yield
Z	3 060 990	2 984 730 ± 27 520
$t\bar{t}$	9 350	8 390 ± 810
EWK	14 650	14 090 ± 1 400
Data	3 006 429	

$$(\sigma_{\text{tot}}\mathcal{B})_{\text{measured}} = (2.010 \pm 0.001(\text{stat}) \pm 0.018(\text{syst}) \pm 0.046(\text{lumi}) \pm 0.007(\text{theo}))\,\text{nb},$$
$$(\sigma_{\text{tot}}\mathcal{B})_{\text{predicted}} = (2.018 \pm 0.012(\text{PDF})^{+0.018}_{-0.023}(\text{scale}))\,\text{nb},$$ **NNLO QCD + qT resumm.**



arXiv:2308.09529

- ATLAS measures the fiducial cross section for $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ with 29 fb^{-1} at 13.6 TeV
- The fiducial phase-space is defined by lepton p_T > 27 GeV, lepton $|\eta|$ < 2.5 and an invariant mass 66 < m_{ll} < 116 GeV for l = e, μ

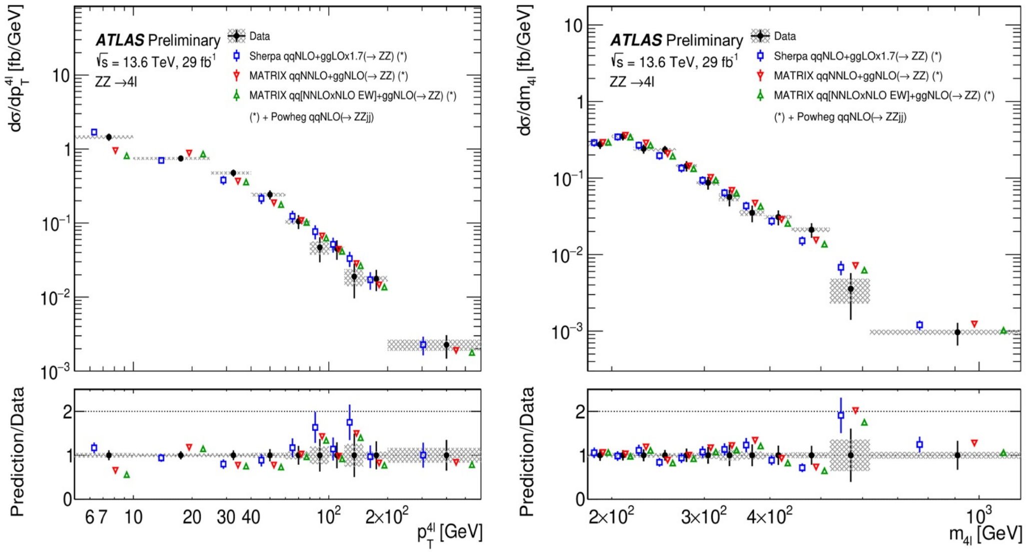
$$\sigma^{\text{fid.}}_{Z\rightarrow\ell\ell} = 744 \pm 11\ (\text{stat.} + \text{syst.}) \pm 16\ (\text{lumi.})\ \text{pb}$$
$$\sigma^{\text{fid.,theory}}_{Z\rightarrow\ell\ell} = 746^{+21}_{-22}\ (\text{scale+PDF+}\alpha_s)\ \text{pb}$$ **NNLO QCD, NLO EW**

ATLAS ZZ cross section

ATLAS measured the ZZ cross section at 13.6 TeV using the 2022 data with $Z \to \ell$ (ℓ=e, μ)

Process	$q\bar{q} \to ZZ$	$gg \to ZZ$	EW $qq \to ZZ + 2j$	$t\bar{t}Z$	VVV	Reducible	Total	Data
Yield	514.8 ± 49.6	73.6 ± 44.3	4.7 ± 1.0	5.5 ± 0.8	2.1 ± 0.2	25.4 ± 8.1	626.1 ± 88.4	625

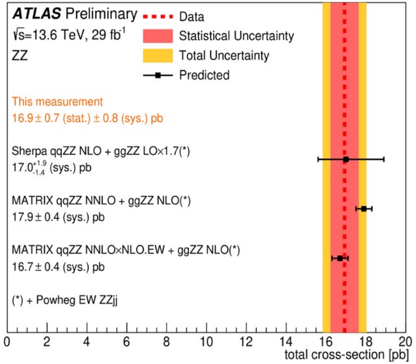
Differential unfolded distributions



	Fiducial phase space	Total lepton phase space
Muon selection	Bare, $p_T > 5$ GeV , $\lvert\eta\rvert < 2.5$	Born
Electron selection	Dressed, $p_T > 7$ GeV , $\lvert\eta\rvert < 2.47$	Born
Four-lepton signature	≥ 2 SFOC pairs	≥ 2 SFOC pairs
Lepton kinematics	$p_T > 27/10$ GeV	
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.05$	
Low-mass $\ell^+\ell^-$ veto	$m_{ij} > 5$ GeV	$m_{ij} > 5$ GeV
Z mass window	$66 < m_{\ell\ell,1}, m_{\ell\ell,2} < 116$ GeV	$66 < m_{\ell\ell,1}, m_{\ell\ell,2} < 116$ GeV
ZZ on-shell	$m_{4l} > 180$ GeV	

$$\sigma_{\text{fid}} = 36.7 \pm 1.6(\text{stat}) \pm 1.5(\text{syst}) \pm 0.8(\text{lumi})\ \text{fb}$$

$$\sigma_{\text{total}} = 16.9 \pm 0.7(\text{stat}) \pm 0.7(\text{syst}) \pm 0.4(\text{lumi})\ \text{pb}$$

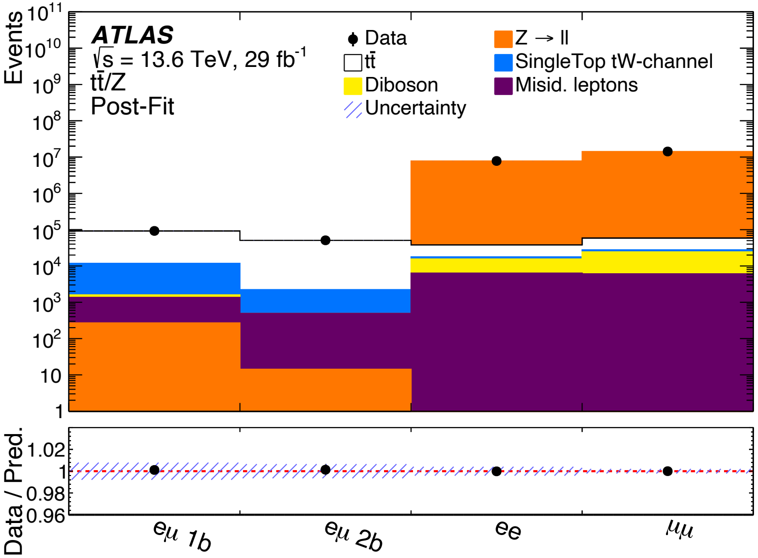


ATLAS-CONF-2023-062

ATLAS $t\bar{t}$ (and Z) Cross Section Measurement

Use dilepton events to simultanously measure tt and Z cross sections

arXiv:2308.09529



$$\sigma_{t\bar{t}} = 850 \pm 3(\text{stat.}) \pm 18(\text{syst.}) \pm 20(\text{lumi.})\ \text{pb},$$
$$R_{t\bar{t}/Z} = 1.145 \pm 0.003(\text{stat.}) \pm 0.021(\text{syst.}) \pm 0.002(\text{lumi.})$$

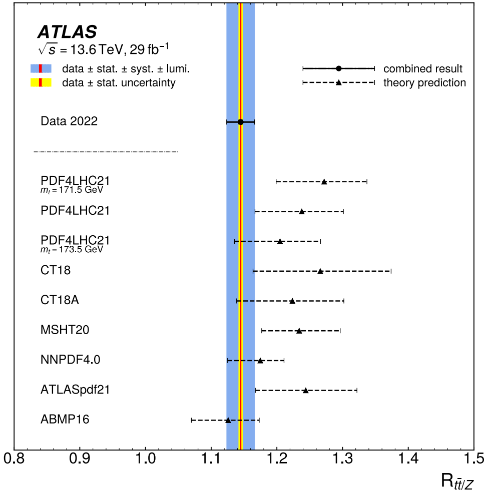
$$\sigma_{t\bar{t}}^{\text{theory}} = 924^{+32}_{-40}\ (\text{scale+PDF+}\alpha_s)\ \text{pb},$$ NNLO+NNLL QCD
$$R_{t\bar{t}/Z}^{\text{theory}} = 1.238^{+0.063}_{-0.071}\ (\text{scale+PDF+}\alpha_s)$$

The measurements agree with theory within 1.5 and 1.3 σ respectively

Systematic uncertainties breakdown

Category		Uncertainty [%]		
		$\sigma_{t\bar{t}}$	$\sigma^{\text{fid.}}_{Z\to\ell\ell}$	$R_{t\bar{t}/Z}$
$t\bar{t}$	$t\bar{t}$ parton shower/hadronisation	0.9	< 0.2	0.9
	$t\bar{t}$ scale variations	0.4	< 0.2	0.4
	$t\bar{t}$ normalisation	-	< 0.2	-
	Top quark p_T reweighting	0.6	< 0.2	0.6
Z	Z scale variations	< 0.2	0.4	0.3
Bkg.	Single top modelling	0.6	< 0.2	0.6
	Diboson modelling	< 0.2	< 0.2	0.2
	$t\bar{t}V$ modelling	< 0.2	< 0.2	< 0.2
	Fake and non-prompt leptons	0.6	< 0.2	0.6
Lept.	Electron reconstruction	1.2	1.0	0.4
	Muon reconstruction	1.4	1.4	0.3
	Lepton trigger	0.4	0.4	0.4
Jets/tagging	Jet reconstruction	0.4	-	0.4
	Flavour tagging	0.4	-	0.3
	PDFs	0.5	< 0.2	0.5
	Pileup	0.7	0.8	< 0.2
	Luminosity	2.3	2.2	0.3
	Systematic uncertainty	3.2	2.8	1.8
	Statistical uncertainty	0.3	0.02	0.3
	Total uncertainty	3.2	2.8	1.9

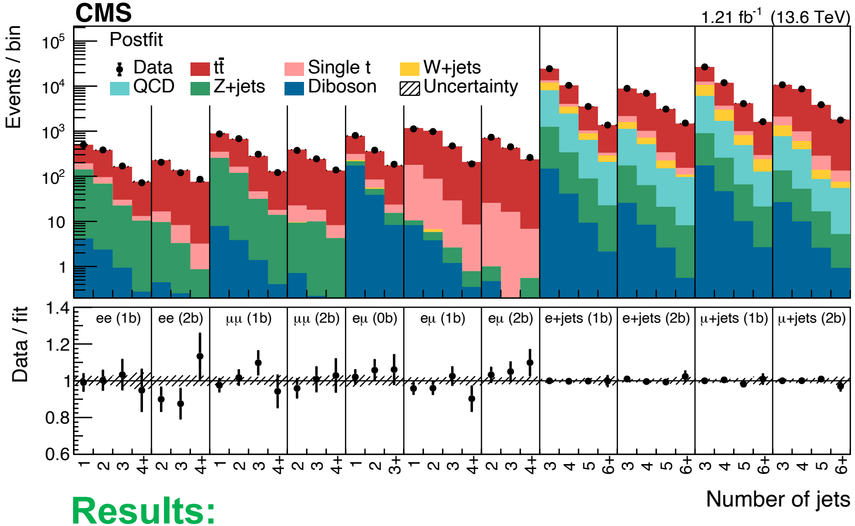
Comparison of $\sigma(tt)/\sigma(Z)$ with theory predictions using different PDF sets

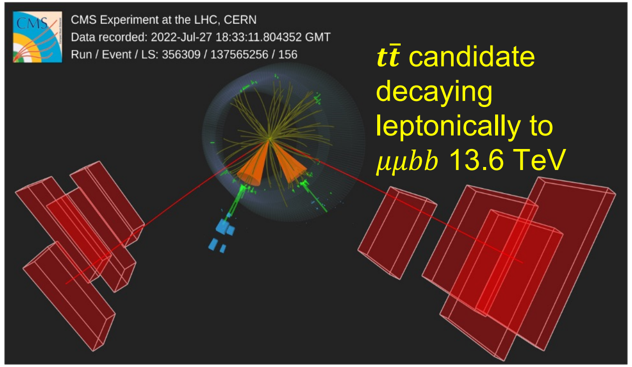


CMS $t\bar{t}$ Cross Section Measurement

[arXiv:2303.10680]

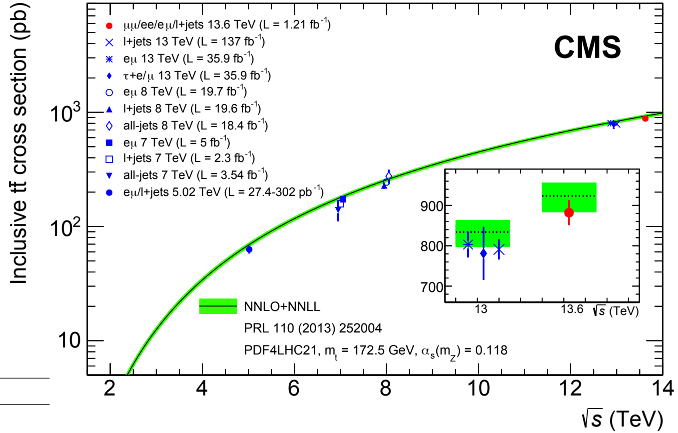
- CMS measurement of the tt cross section
  - Use all leptonic and semileptonic decays with e and μ
  - Z-veto for same flavour events





Systematic uncertainties

Source	Uncertainty (%)
Lepton ID efficiencies	1.6
Trigger efficiency	0.3
JES	0.6
b tagging efficiency	1.1
Pileup reweighting	0.5
ME scale, $t\bar{t}$	0.5
ME scale, backgrounds	0.2
ME/PS matching	0.1
PS scales	0.3
PDF and α_S	0.3
Top quark p_T	0.5
tW background	0.7
t-channel single-t background	0.4
Z+jets background	0.3
W+jets background	<0.1
Diboson background	0.6
QCD multijet background	0.3
Statistical uncertainty	0.5
Combined uncertainty	2.5
Integrated luminosity	2.3



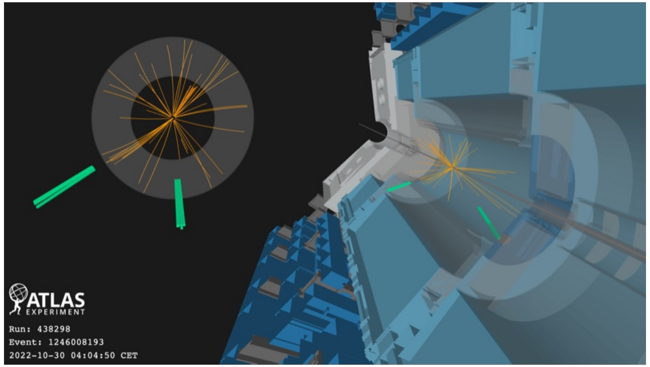
Results:

$$\sigma(tt) = 881 \pm 23\,(\text{stat + syst}) \pm 20\,(\text{lumi})\ \text{pb}$$

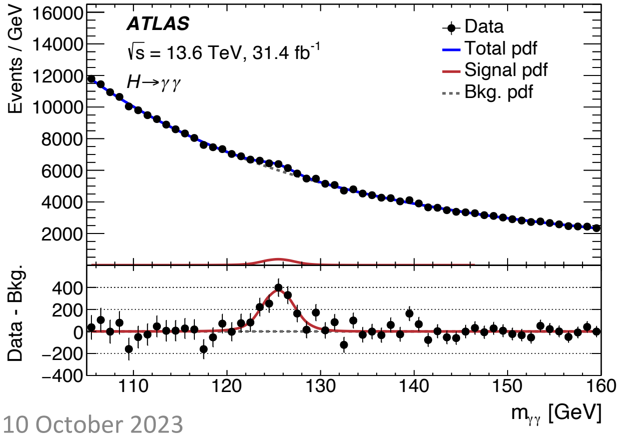
$$\sigma_{tt}^{theory} = 924^{+32}_{-40}$$ **NNLO+NNLL QCD**

Higgs cross section (ATLAS) - $H \to \gamma\gamma$

- Fiducial cross section in the two cleanest Higgs boson decay channels: $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell, \ell = e, \mu$
- $H \to \gamma\gamma$ arXiv:2306.11379
  - excellent mass resolution
  - small branching fraction, $B(H \to \gamma\gamma) = 2\times10^{-3}$
  - rather large BG from diphoton and photon plus jet
- Analysis is similar to the Run 2 analysis
  - Fit to the mass spectrum using a background model derived from simulation and data
  - Improved method compared to Run 1 to derive BG composition



$\gamma\gamma$ invariant mass



Results:
$\sigma_{fid}(H \to \gamma\gamma) = 76^{+14}_{-13}$ fb
in agreement with the SM prediction

The cross section is extrapolated to the full $(pp \to H)$ cross section

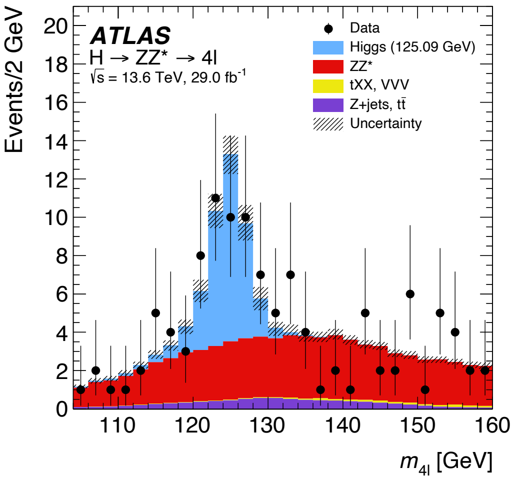
Breakdown of the systematic uncertainties

Source	Uncertainty [%]
Statistical uncertainty	14.0
Systematic uncertainty	10.3
Background modelling (spurious signal)	6.0
Photon trigger and selection efficiency	5.8
Photon energy scale & resolution	5.5
Luminosity	2.2
Pile-up modelling	1.2
Higgs boson mass	0.1
Theoretical (signal) modelling	<0.1
Total	17.4

Higgs cross section (ATLAS) - $H \to ZZ \to 4\ell$

- Fiducial cross section in the two cleanest Higgs boson decay channels: $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell, \ell = e, \mu$
- $H \to ZZ \to 4\ell, \ell = e, \mu$ arXiv:2306.11379
  - excellent mass resolution
  - small background, mostly from ZZ* production
  - tiny branching fraction, $B(H \to ZZ \to 4\ell, \ell = e, \mu) = 1\times10^{-4}$

4ℓ invariant mass



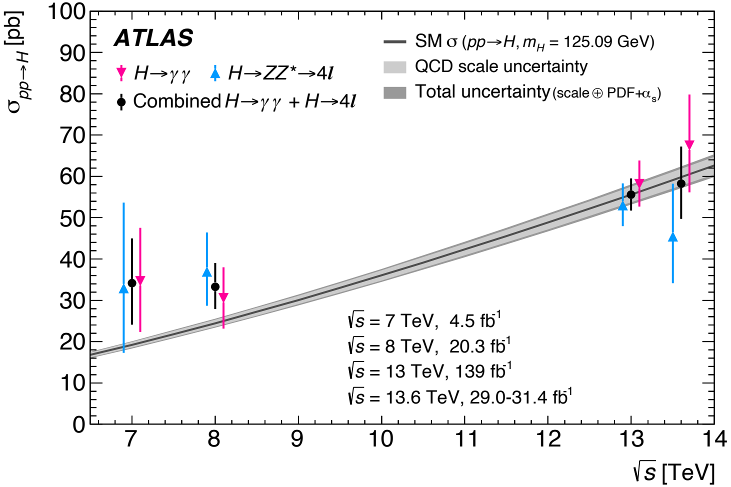
Fiducial region

Leptons	
Leptons	$p_T > 5$ GeV, $\|\eta\| < 2.7$
Lepton selection and pairing	
Lepton kinematics	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Subleading pair (m_{34})	remaining SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Event selection (at most one quadruplet per event)	
Mass requirements	50 GeV $< m_{12} <$ 106 GeV and 12 GeV $< m_{34} <$ 115 GeV
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs
Mass window	105 GeV $< m_{4\ell} <$ 160 GeV
If extra lepton with $p_T > 12$ GeV	quadruplet with largest matrix element value

Results:
$\sigma_{fid}(H \to ZZ \to 4\ell) = 2.80 \pm 0.74$ fb
in agreement with the SM prediction

The cross section is extrapolated to the full $(pp \to H)$ cross section

Higgs production cross section

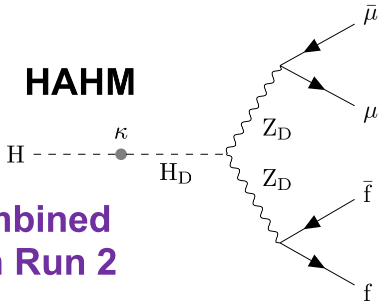


First search for BSM Physics at Run 3

- Search for long lived particles decaying to two opposite charge muons — CMS-PAS-EXO-23-014
- Dimuon masses larger than 10 GeV are selected
- Mostly model independent and sensitive to a wide range of lifetimes and masses
- Results interpreted in two different models giving rise to long lived particles

Hidden Abelian Model: A Dark Higgs mixing with the SM Higgs photon and decaying into two long lived dark photons ($m_{Z_D} < m_H/2$)

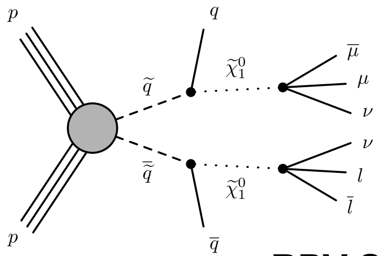
HAHM



Combined with Run 2

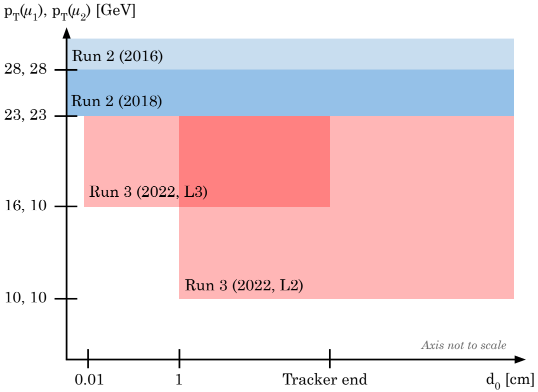
R-parity violating SUSY model: a pair o squarks decay into a quark and a long lived neutralino

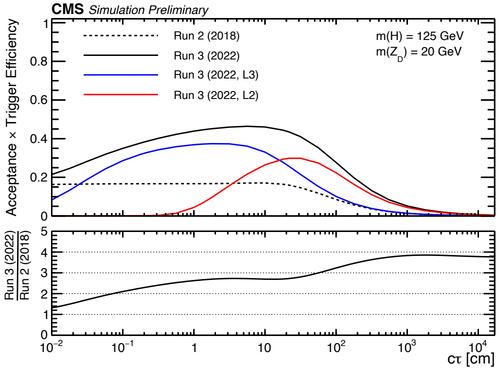
New interpretation in Run 3



RPV SUSY

Improved trigger in Run 3 removing beam spot constraint at L1 and accepting lower p_T muons



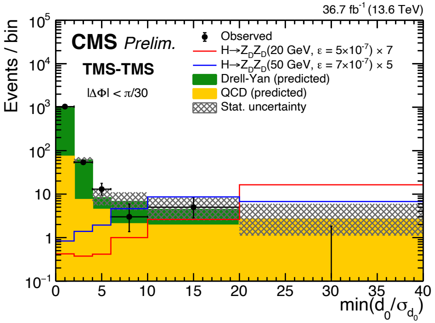


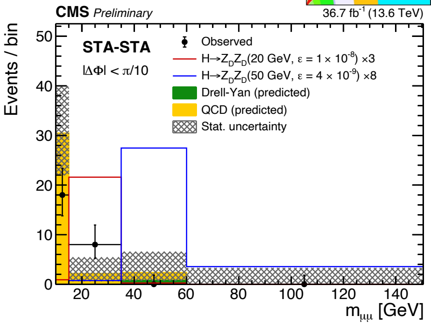
Large improvement in acceptance x trigger efficiency at large $c\tau$ compared to Run 2, factor 2-4 for $c\tau > 0.1$ cm

Results

- Events passing the final selection for the two models considered
- Use tracks reconstructed in the tracker but also in the muon system only, also efficient for large displacements
- Require $\Delta\Phi <$ threshold where $\Delta\Phi$ is the angle in the transverse plane between the p_T of the dimuons and the displacement of the vertex
- At large $c\tau$ the results based on the 2022 data have higher sensitivity than the full Run 2 ones
- The combined limits in the HAHM model are the best to date for masses larger than 20 GeV and less than $m_H/2$

HAHM





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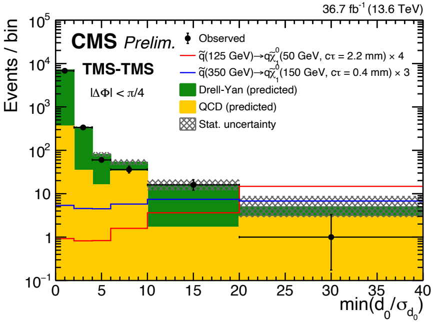
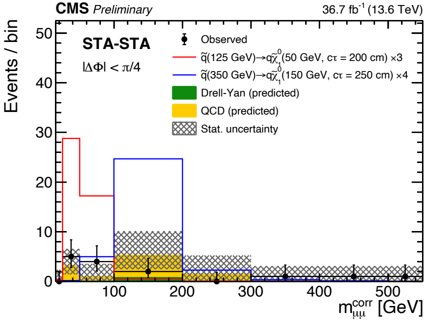
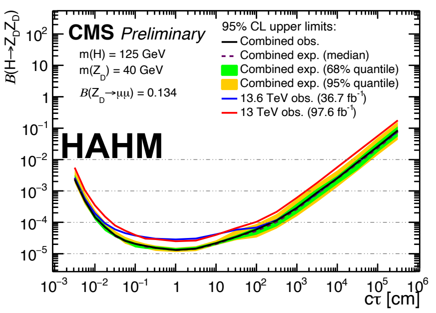
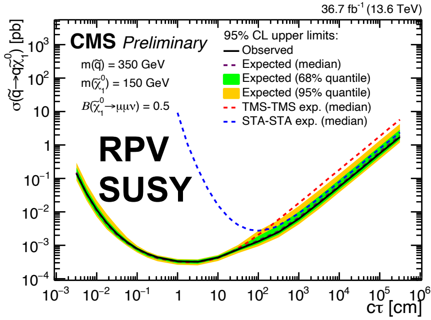




No signal observed, 95% CL exclusion limits derived





Summary and Outlook

- ATLAS and CMS made several improvements in trigger, reconstruction and object identification for Run 3
  - Run 3 does not simply add integrated luminosity but also new triggers and lower thresholds which enable new physics directions
- ATLAS and CMS collected approximately 65 fb^{-1} of integrated luminosity each in Run 3
- The first analyses have been made public or published:
  - Measurements of cross sections at 13.6 TeV
  - Searches based on triggers that are more efficient than in Run 2
    - Prominent examples are long lived particle searches
- Many more analyses in the pipeline but in many cases may wait for the full Run 3 integrated luminosity