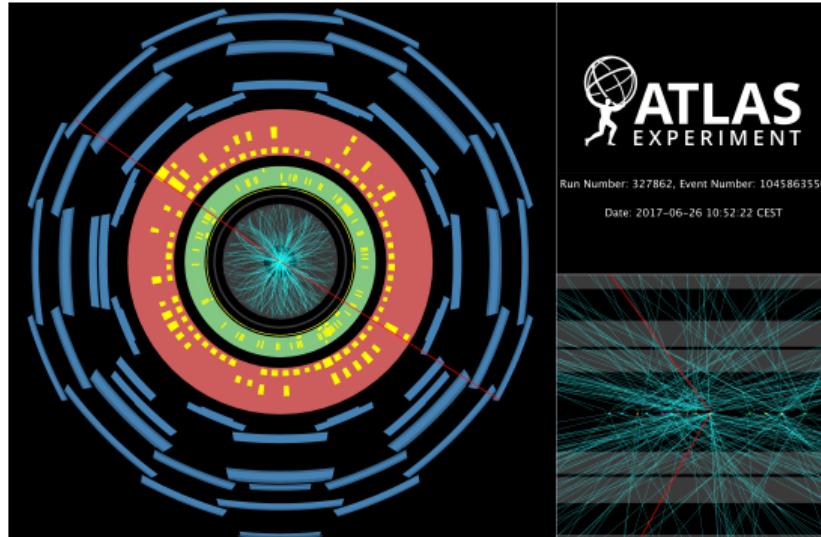


Performance of muon reconstruction and identification in ATLAS at $\sqrt{s} = 13$ TeV



$$m_{\mu\mu} = 2.75 \text{ TeV}, p_T^{\text{leading}} = 1.82 \text{ TeV}$$

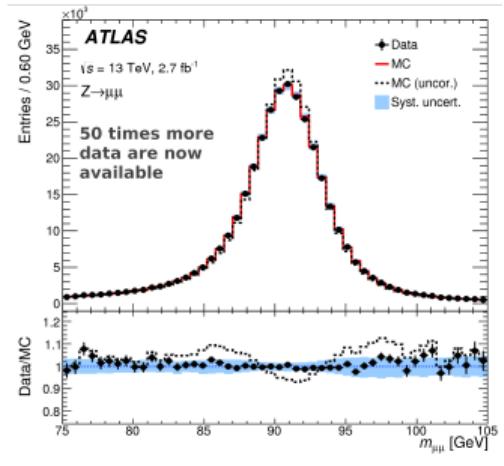
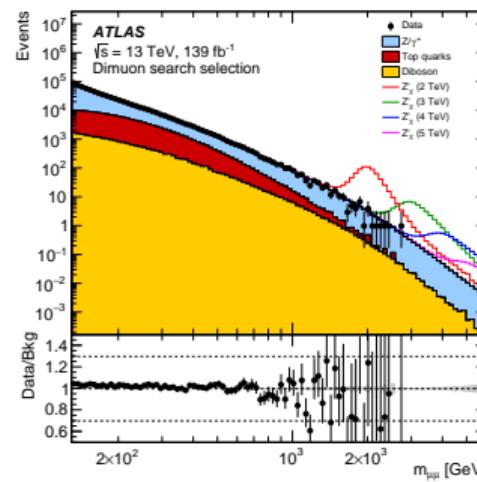
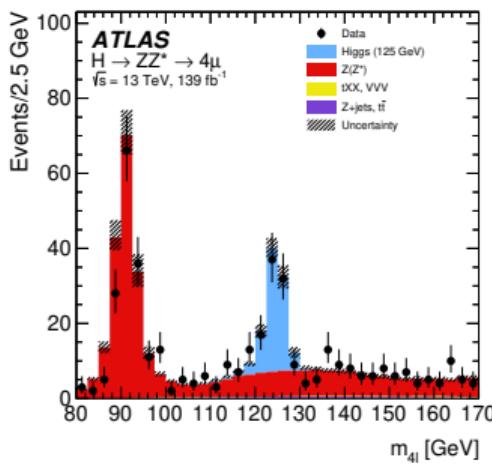
Rustem Ospanov, on behalf of the ATLAS Collaboration

40th International Conference of High Energy Physics

July 31st, 2020

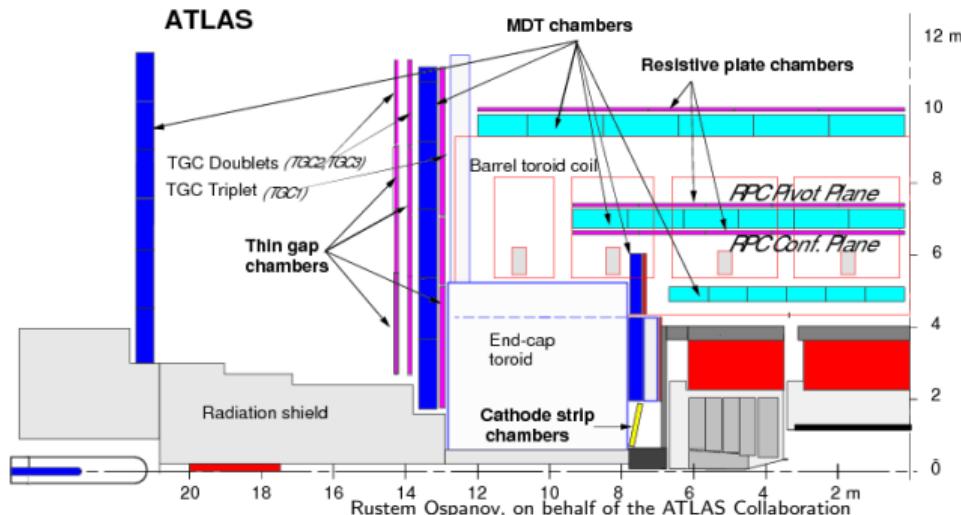
Introduction

- ▶ Muon signatures are used for hundreds of published and upcoming ATLAS results
 - Including Higgs boson measurements, searches for new resonances, and measurements of Standard Model properties
 - **210 million Z and 45 million J/ψ events were used for updated muon calibrations with $\times 5$ smaller uncertainty**
 - Presenting new results released for this conference: [ATLAS-CONF-2020-030](#)
- ▶ ATLAS muon spectrometer (MS) triggers, reconstructs and identifies muon candidates
 - Fast (trigger) detectors for Level 1 hardware trigger operating at 40 MHz with position resolution ~ 1 cm
 - Precision detectors using monitored drift tubes (MDT) and in the forward region cathode-strip chambers (CSC)

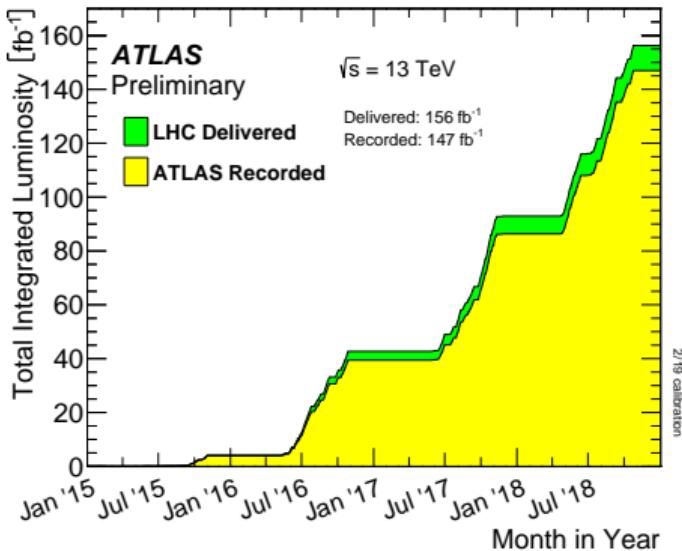


ATLAS muon spectrometer (MS)

- ▶ 2 precision detectors for measuring muon deflections in r - z bending plane
 - Muon Drift Tubes (MDT) for $|\eta| < 2.7$ with single-hit position resolution of $\sim 80 \mu\text{m}$
 - Cathode Strip Chambers (CSC) for $2.0 < |\eta| < 2.7$ in the innermost layer with single-hit resolution of $\sim 60 \mu\text{m}$
 - 3 precision layers provide up to 20 measurements per MS track
- ▶ 3 superconducting air-core toroidal magnets with field integral 2 to 6 T·m for muon tracks
 - Inner detector (ID) reconstructs charged particle tracks in 2 T magnetic field
 - Calorimeters and shielding material stop nearly all energetic hadrons from reaching MS
 - Only minimum-ionising particles (MIPs) with $p_T > 3 \text{ GeV}$ typically reach MS from the interaction point



So far, LHC delivered about a half of originally planned integrated luminosity



Outline:

- Muon reconstruction
- Tag&probe with Z and J/ψ decays to $\mu^+\mu^-$
- Muon identification
- Muon isolation selection
- Muon efficiency results, systematic uncertainty and stability

Muon reconstruction

► Several sources of muons in LHC collisions

- Prompt muons produced in decays of Z and W bosons and τ leptons - μ track in ID and MS
- Non-prompt muons produced in decays of heavy flavour b/c hadrons - μ track in ID and MS
- Non-prompt muons produced in decays of pions and kaons - π/K track in ID and μ track in MS

► Several types of reconstructed muons

- Combined muons (CB) are reconstructed by matching and fitting ID and MS tracks - *majority of muon candidates*
- MS tracks extrapolated to the collision point - *primarily in the forward region without full ID coverage*
- ID tracks matched with calorimeter clusters or MS segments - *primarily in regions with limited MS coverage*

► 5 identification working points (WP) aim to select prompt muons and non-prompt b/c muons

- *Loose, medium and tight* WPs are used by most analyses
- *Low and high p_T* WP s were specially developed for targeted analyses

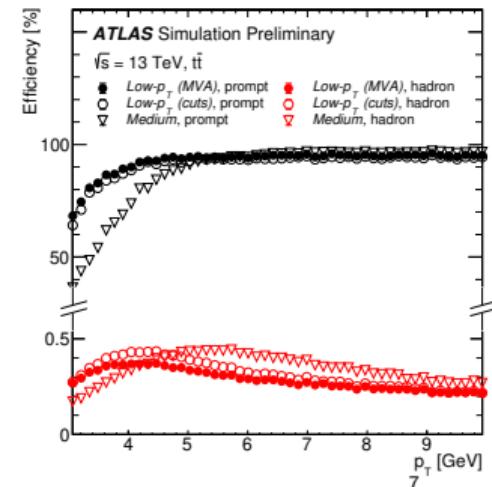
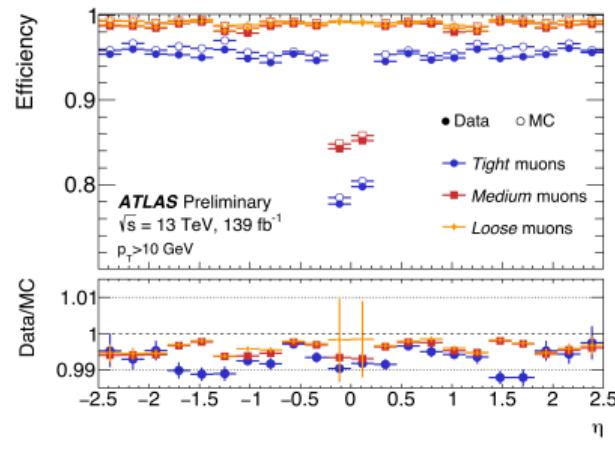
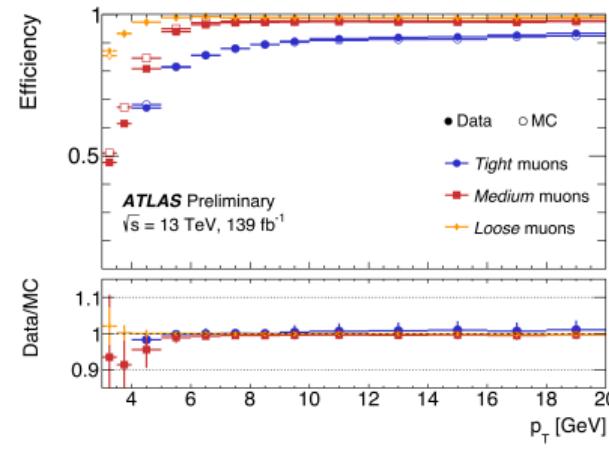
Working point	$3 < p_T < 5 \text{ GeV}$		$5 < p_T < 20 \text{ GeV}$		$20 < p_T < 100 \text{ GeV}$		$p_T > 100 \text{ GeV}$	
	$\epsilon_\mu [\%]$	$\epsilon_{\text{had}} [\%]$	$\epsilon_\mu [\%]$	$\epsilon_{\text{had}} [\%]$	$\epsilon_\mu [\%]$	$\epsilon_{\text{had}} [\%]$	$\epsilon_\mu [\%]$	$\epsilon_{\text{had}} [\%]$
<i>Loose</i>	90	1.17	98	1.06	99	0.25	98	0.12
<i>Medium</i>	70	0.63	97	0.85	97	0.17	97	0.07
<i>Tight</i>	36	0.15	90	0.38	93	0.12	93	0.04
<i>Low-p_T</i> (cut-based)	86	0.82	95	0.71	97	0.17	97	0.07
<i>Low-p_T</i> (multivariate)	88	0.73	96	0.66	97	0.17	97	0.07
<i>High-p_T</i>	45	0.34	79	0.60	80	0.13	80	0.05

Muon efficiency measurements with *tag&probe* method

- ▶ Using decays of Z and J/ψ to $\mu^+\mu^-$ where one muon is *tag* and another is *probe*
- ▶ *Tag muon:*
 - Fires single muon trigger to record event and passes stringent quality criteria
- ▶ *Probe muon:*
 - Loosely reconstructed muon candidate: ID track, MS track or ID track tagged with calorimeter MIP cluster
 - Dimuon *tag&probe* invariant mass is consistent with m_Z or $m_{J/\psi}$
- ▶ Backgrounds are measured from data fit:
 - Same sign dimuon events for Z analysis and sidebands fit for J/ψ analysis
- ▶ Efficiency measurements as a function of several (binned) variables:
$$\epsilon = \frac{N_X^{\text{probe}}}{N_{\text{All}}^{\text{probe}}}, \text{ where X is the target working point: } \textit{Loose}, \textit{Medium}, \text{etc}$$
 - ▶ $\times 5$ smaller systematic uncertainty, ranging from 0.1% to 0.7% for $|\eta| > 0.1$ - new
 - ▶ Muon efficiency measurements down to $p_T > 3$ GeV using J/ψ events - new

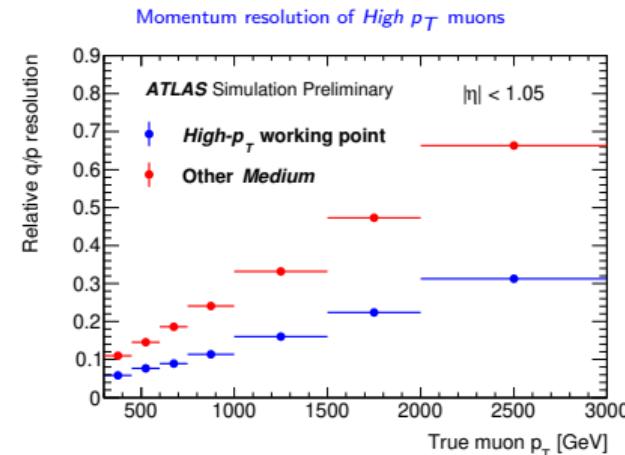
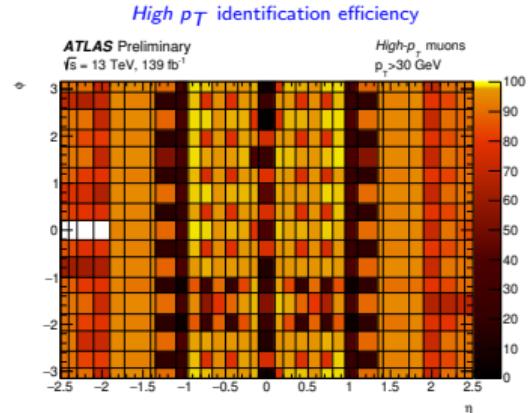
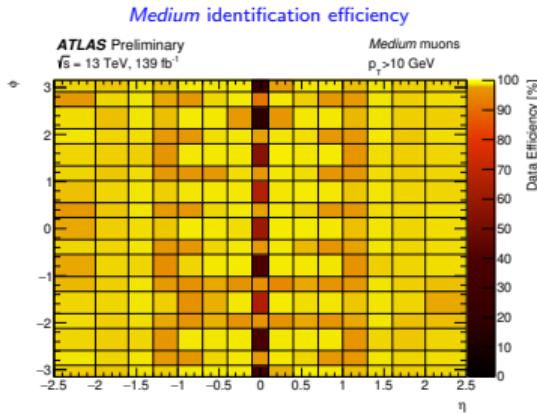
Loose, medium, tight and low p_T muon identification

- ▶ Medium WP selects combined (ID and MS) muons, as well as MS-only tracks for $2.5 < |\eta| < 2.7$ region without full ID coverage
- ▶ Loose muons add ID tracks tagged by calorimeter or matching MS segments for $|\eta| < 0.1$
- ▶ Tight muons require hits at least two precision MDT or CSC layers, and stricter fit quality criteria
- ▶ Low p_T selection was optimised for muon $p_T < 18\text{ GeV}$ - new
 - Two algorithms: “cut-based” and multi-variate algorithms use muon candidate quality parameters
 - Tuned for improved efficiency and better overall rejection of muons produced in π/K decays



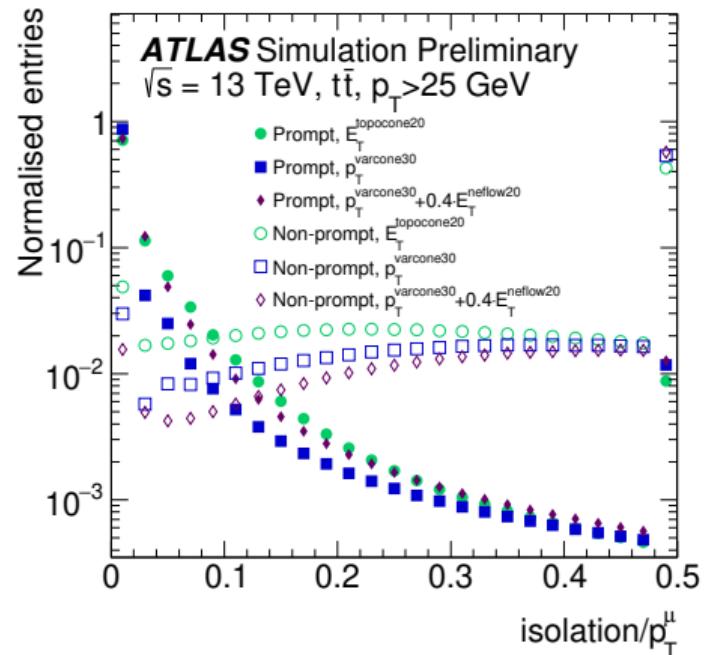
High p_T muon identification

- ▶ MS provides precise momentum measurement due to its long lever arm and low material density
- ▶ High p_T identification was **re-optimised** for measuring more precisely muon $p_T \gtrsim 100$ GeV
- ▶ Require MS tracks with 3 precision layers or best-quality tracks with 2 precision layers for $|\eta| < 1.3$
- ▶ Exclude regions with insufficient precision of detector alignment constants
- ▶ Almost a factor of two improvement in muon momentum resolution



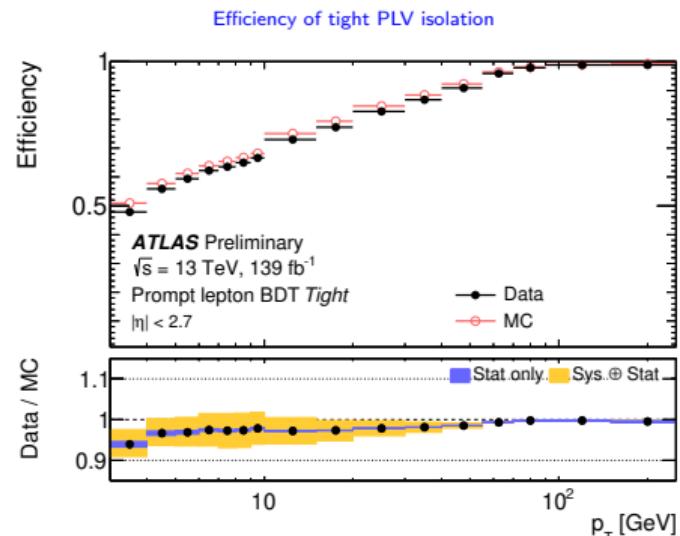
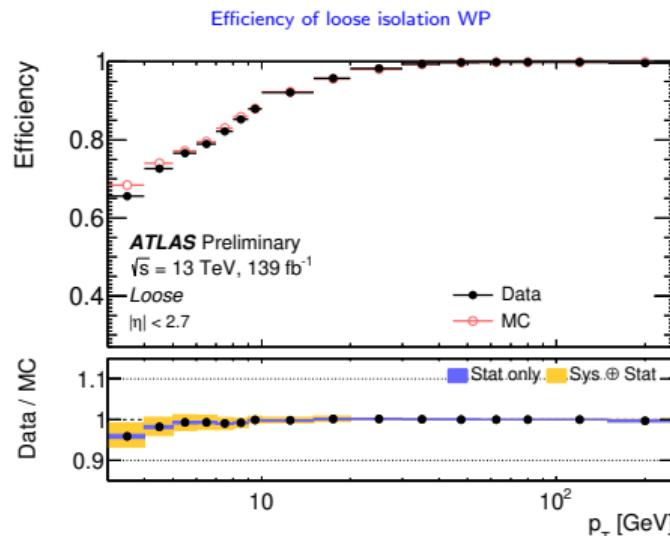
Muon isolation working points (WPs)

- ▶ Select prompt muons from $W/Z/\tau$ decays and reject non-prompt muons produced in hadronic processes
 - Muon produced in decays of b/c hadrons and π/K are typically embedded in a jet of hadrons
 - Decays of π/K contribute at low p_T
- ▶ Require muons to be isolated:
 - Track-based isolation is scalar sum of p_T of ID tracks within $\Delta R < 0.2\text{-}0.3$ around the muon
 - Calorimeter-based isolation is sum of E_T of topological clusters within $\Delta R < 0.2$ around the muon
 - Particle-flow isolation matches ID tracks with calorimeter clusters to remove contributions from other collisions
- ▶ 6 “cut-based” isolation WPs
 - Simple selection criteria defined using ratios of track-based isolation and calorimeter isolation over muon p_T
- ▶ 2 multi-variate isolation WPs - “PromptLepton BDT”
 - Isolation and impact parameter measurements are combined using Boosted Decision Tree algorithm (BDT)



6 “cut-based” and 2 “PromptLepton BDT” working points for selecting isolated muons

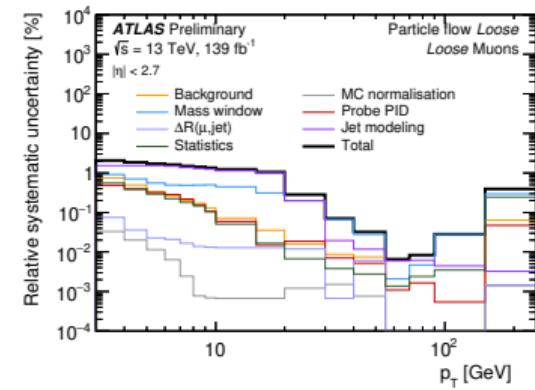
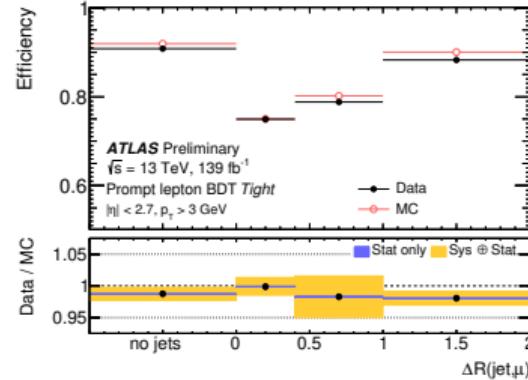
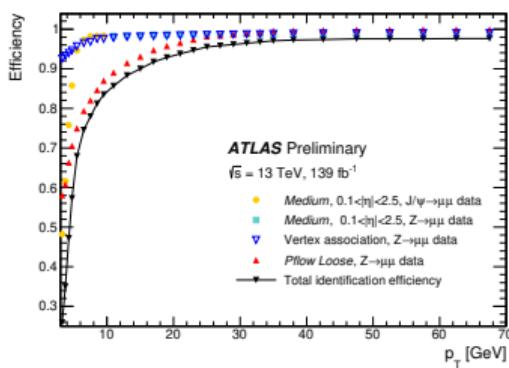
	$3 < p_T < 5 \text{ GeV}$	$5 < p_T < 20 \text{ GeV}$	$20 < p_T < 100 \text{ GeV}$	$p_T > 100 \text{ GeV}$
Working point	$\epsilon_\mu [\%]$	$\epsilon_{\text{HF}} [\%]$	$\epsilon_\mu [\%]$	$\epsilon_{\text{HF}} [\%]$
<i>Loose</i>	63	14.3	86	7.2
<i>Tight</i>	53	11.9	70	4.2
<i>PflowLoose</i>	62	12.9	86	6.8
<i>PflowTight</i>	45	8.5	63	3.1
<i>HighPtTrackOnly</i>	92	35.9	92	17.2
<i>TightTrackOnly</i>	80	19.9	81	7.0
<i>PLBDTLoose</i>	81	17.4	83	5.1
<i>PLBDTTight</i>	57	9.6	69	2.7



Muon efficiency results, systematic uncertainty and stability

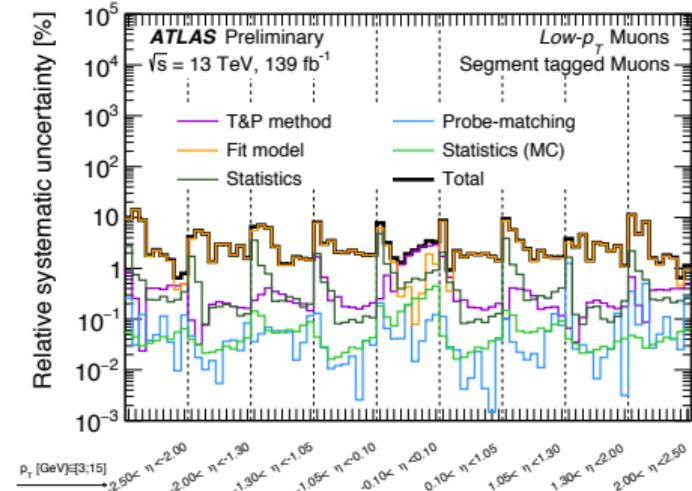
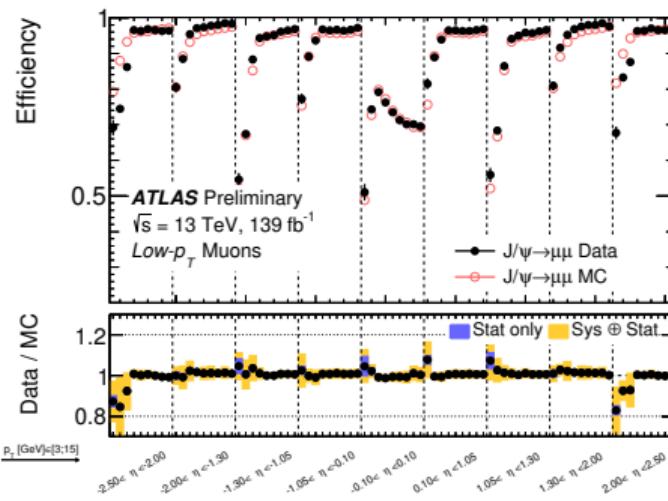
Muon efficiency measurements and systematic uncertainty

- ▶ Efficiency is measured independently for each step of selecting a muon candidate:
 - Identification selection, vertex association, and isolation selection - most left plot
- ▶ Simulation is corrected to match data using scale factors = $\epsilon_{\text{data}} / \epsilon_{\text{simulation}}$
 - Measured as a function of muon p_T , η , ϕ and distance to the closest hadronic jet ($\Delta R(\text{jet}, \mu)$ - middle plot)
 - Applied as a function of 2 most relevant variables for each step, eg p_T and $\Delta R(\text{jet}, \mu)$ for isolation
- ▶ Systematic uncertainty is a dominant source of uncertainty for efficiency measurements
 - Intrinsic bias of *tag&probe* method measured using simulated events - dominant source for identification selections
 - Modelling of nearby jets estimated with simulation - dominant source for isolation selections (most right plot)



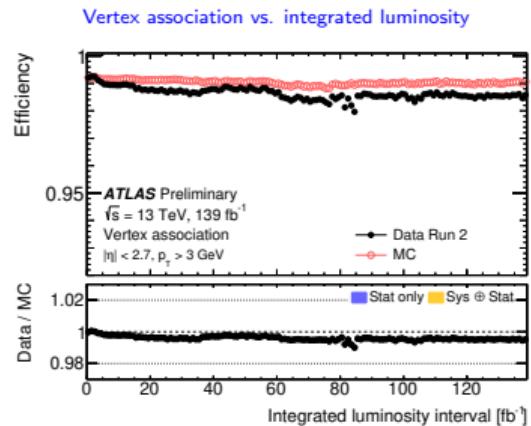
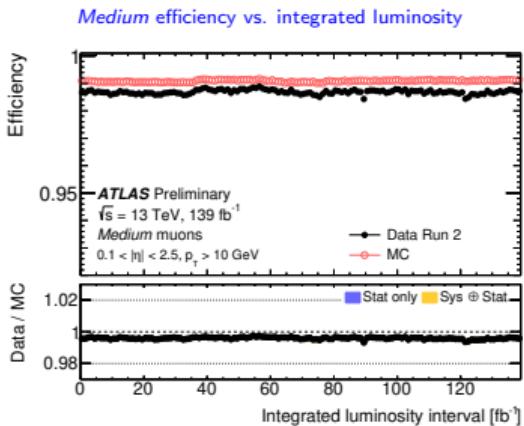
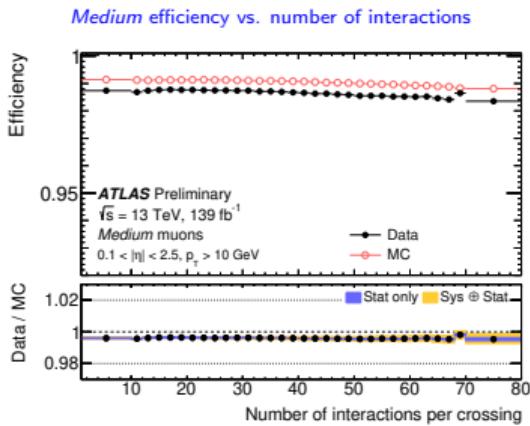
Muon efficiency measurements and systematic uncertainty with J/ψ

- ▶ J/ψ events are used for muons with $3 \text{ GeV} < p_T < 10 \text{ GeV}$
 - Excellent agreement between Z and J/ψ in the overlap region
- ▶ Background are measured from the sideband fit with a polynomial function
- ▶ Systematic uncertainty is a dominant source of uncertainty for efficiency measurements
 - Background modelling uncertainty and statistical uncertainty
 - Intrinsic bias of *tag&probe* method measured using simulated events



Stability of muon efficiency

- ▶ Muon efficiency was also measured as a function of the number of interactions per event and integrated luminosity
 - On average, 13 and 36 collisions per event in 2015 and 2018, respectively
- ▶ Muon efficiency is generally very stable except for the vertex association (most right plot)
 - Small mismodelling for events with a high number of proton-proton interactions in one event
 - Differences in mean number of interactions per event in different years



Summary

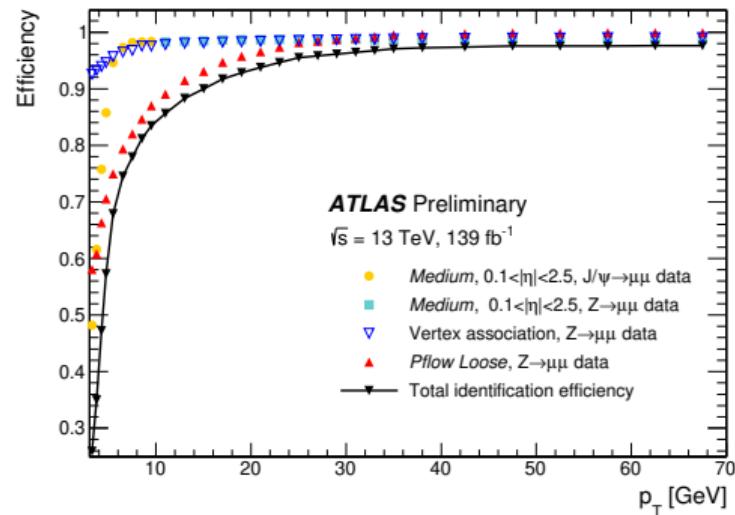
- ▶ ATLAS detector was completed in 2008 and will operate until ~ 2040 after upgrades
- ▶ Excellent performance of the ATLAS muon spectrometer since 2008
- ▶ About 147 fb^{-1} of ATLAS data was recorded in 2015-2018 at $\sqrt{s} = 13 \text{ TeV}$
- ▶ ATLAS collaboration developed several muon working points that serve all analyses using muons
 - New *low p_T* working point and re-optimised *high p_T* working point
 - New isolation selection working points using multi-variate and particle flow algorithms
 - Utilised for hundreds of already published and upcoming ATLAS results
- ▶ Presented new precise measurements of muon reconstruction and identification efficiencies
 - Used 210 million Z and 45 million J/ψ events recorded in 2015-2018 data - [ATLAS-CONF-2020-030](#)
 - Improved procedures for measuring muon reconstruction and selection efficiency
 - New procedures result in $\times 5$ smaller systematic uncertainty
 - Achieved 0.1% level precision for calibrating muon reconstruction and identification efficiencies

Thank you!

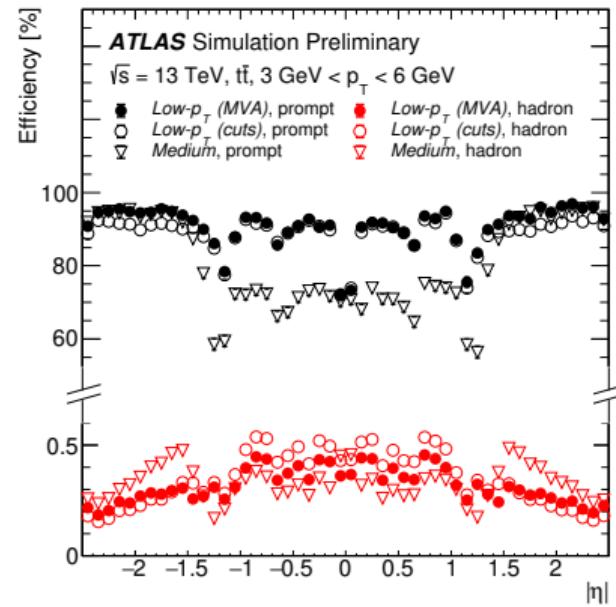
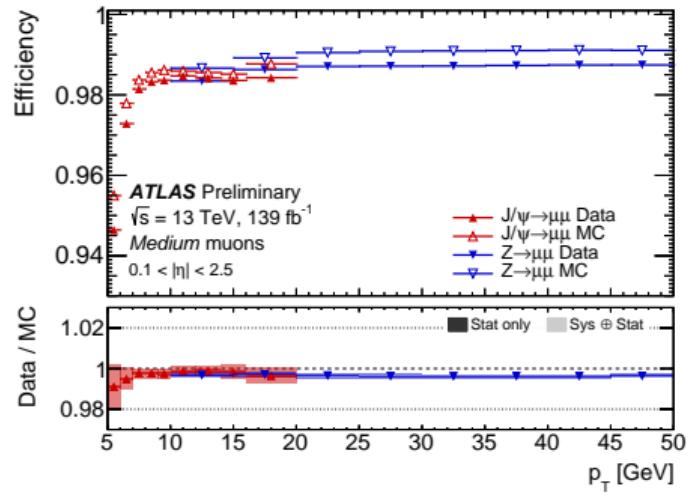
BACKUP

Muon efficiency measurements

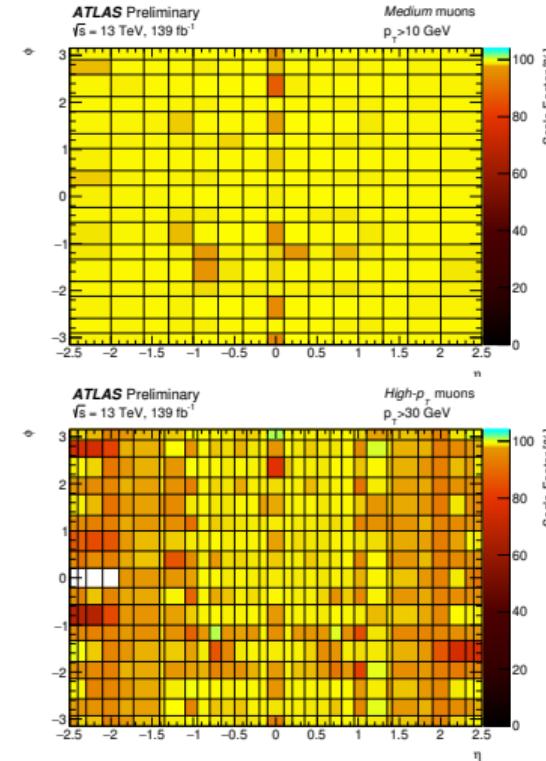
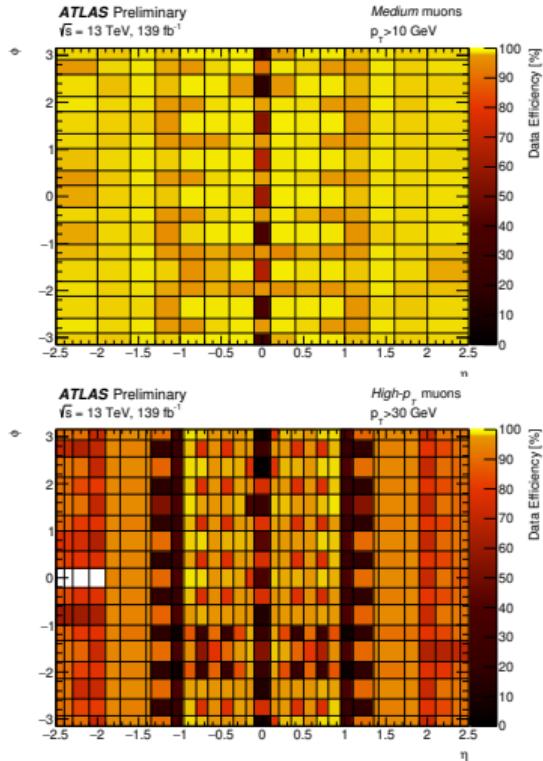
- ▶ Efficiency measured is independently for each selection step:
 - Identification, vertex association and isolation selections
- ▶ Simulation is corrected to match data using scale factors
 $= \epsilon_{\text{data}} / \epsilon_{\text{simulation}}$
 - Measured as a function of muon p_T , η , ϕ and distance to the closest reconstructed hadronic jet



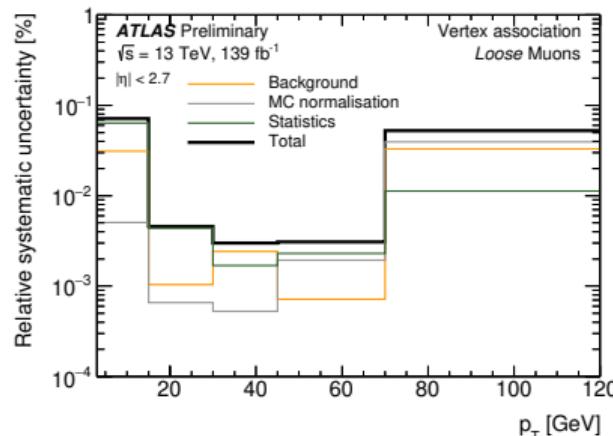
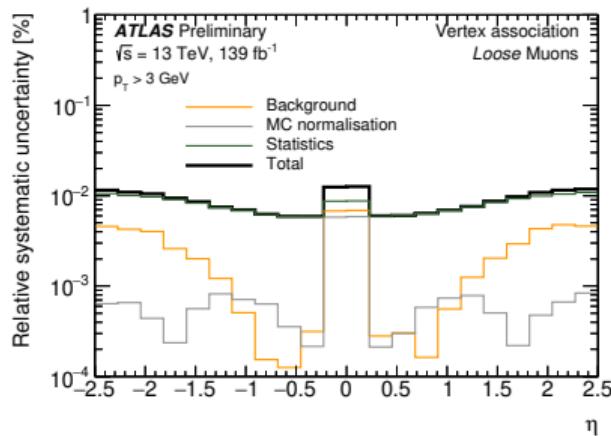
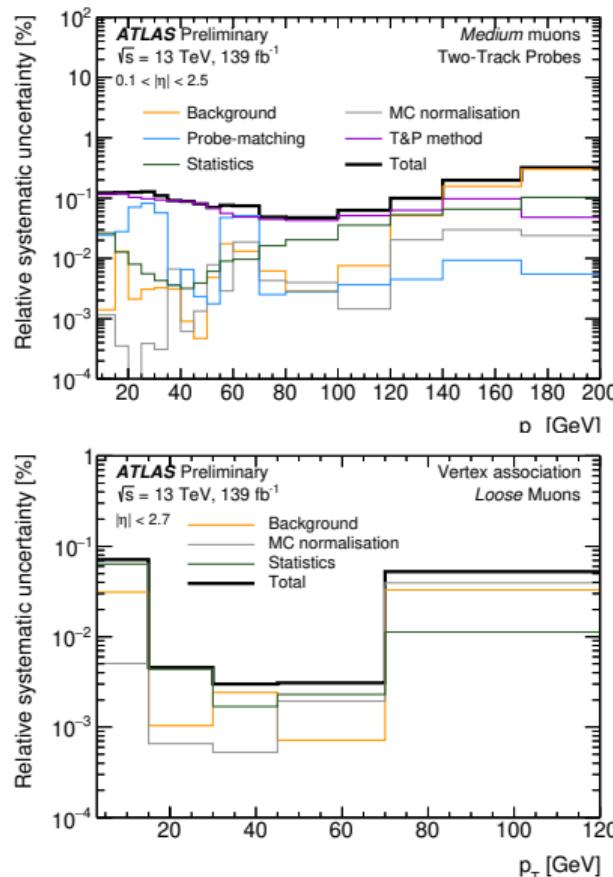
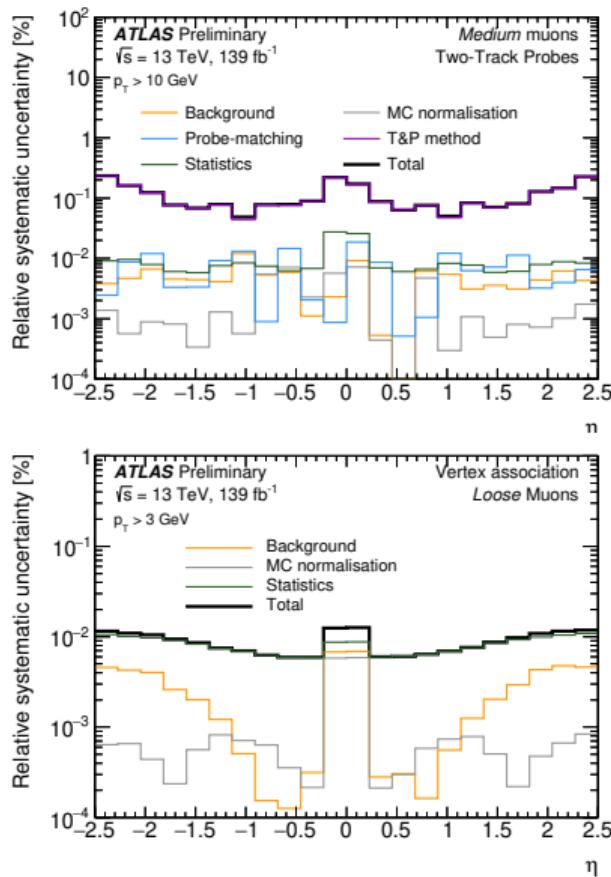
Efficiency



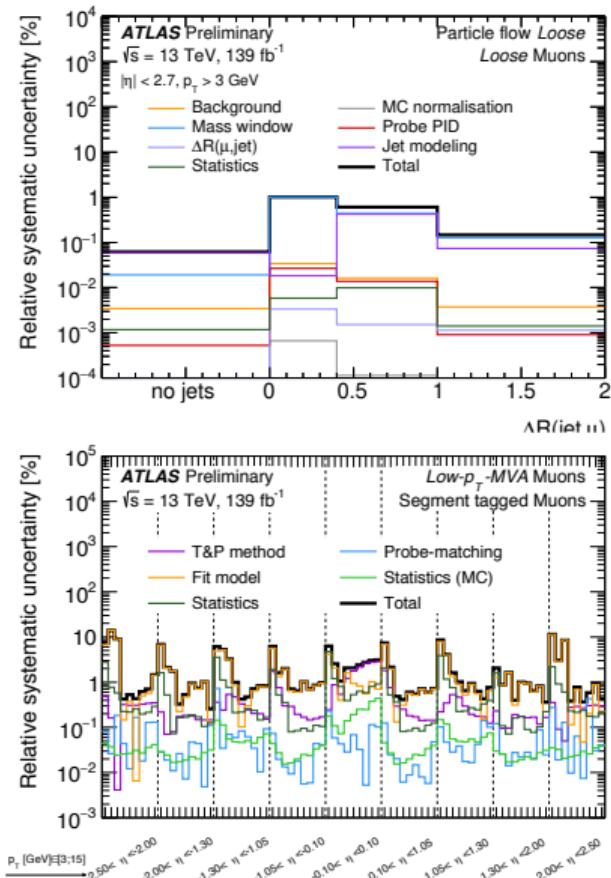
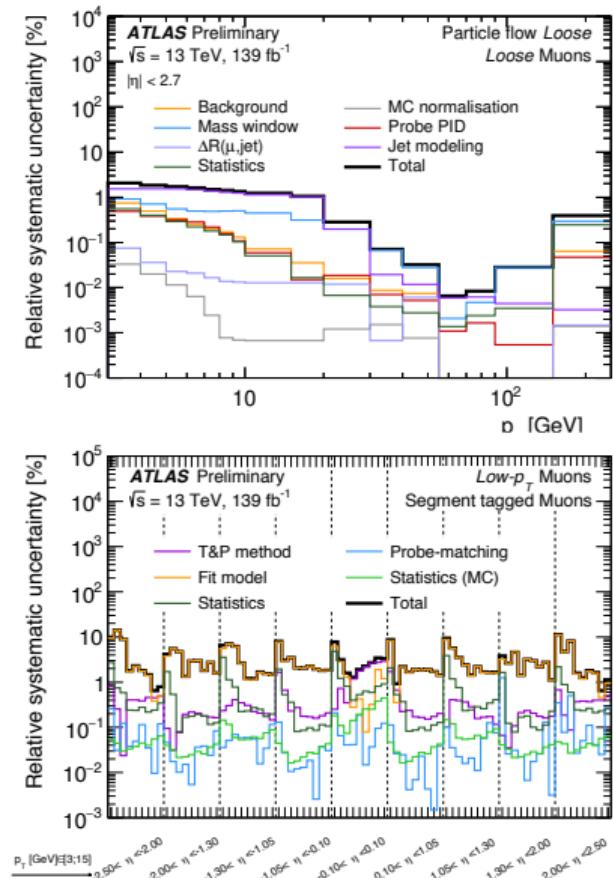
Efficiency and scale factors



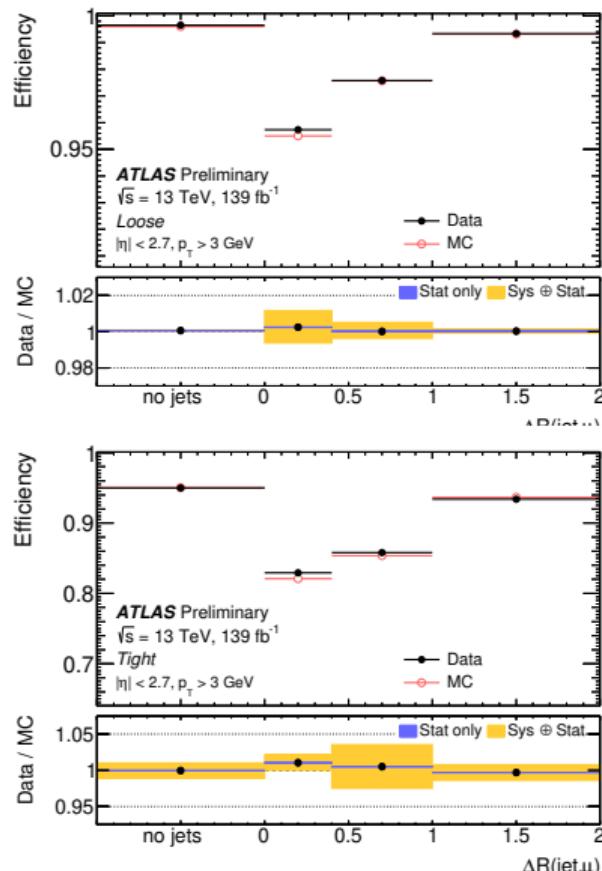
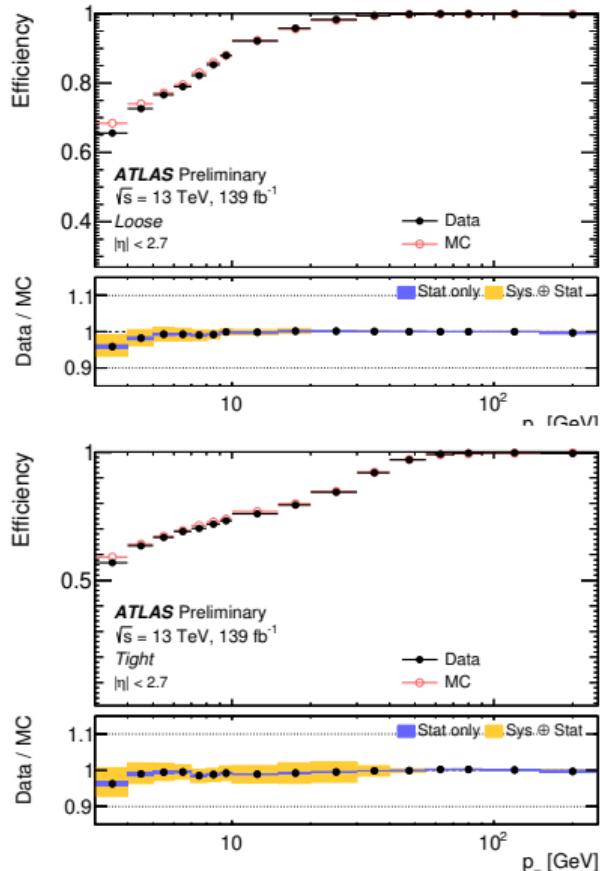
Systematic uncertainty



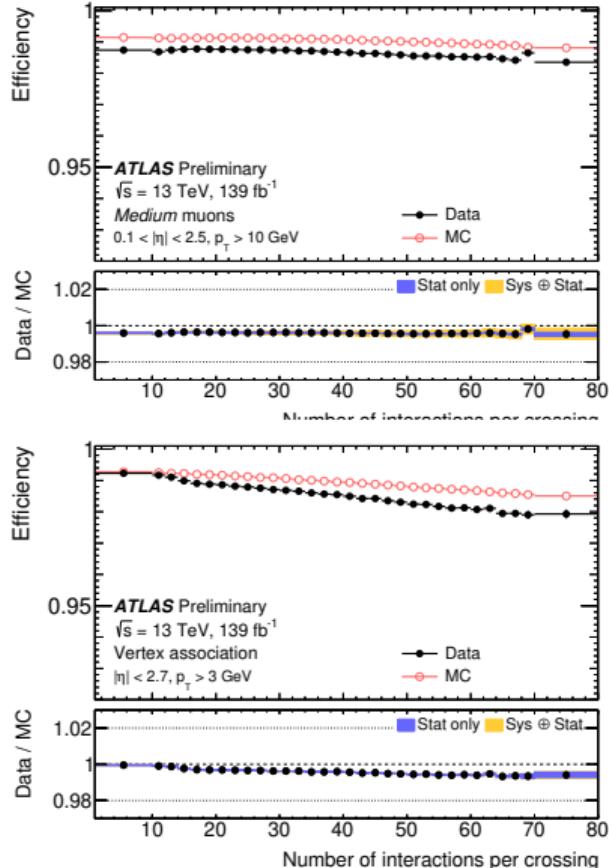
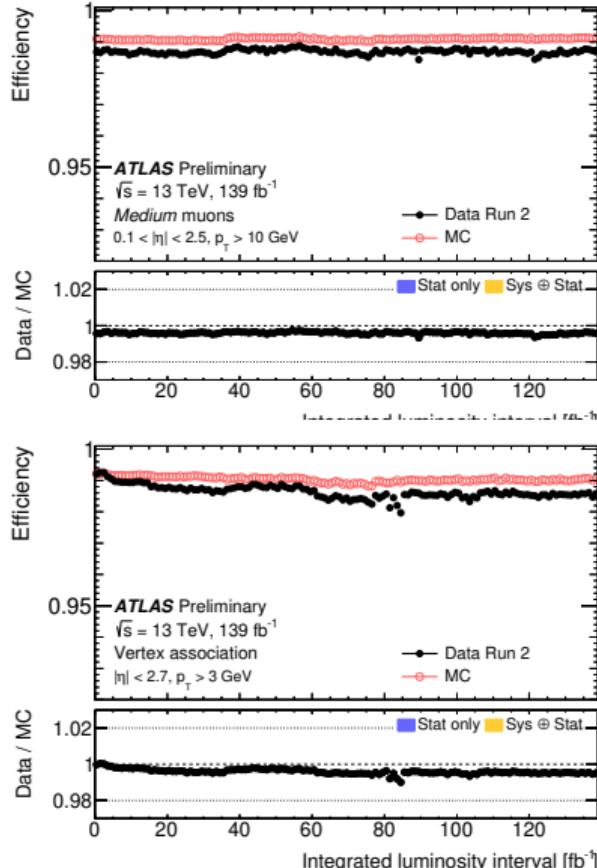
Systematic uncertainty



Isolation selection efficiency



Stability



Stability

