Scale Factors for the ATLAS Muon Triggers

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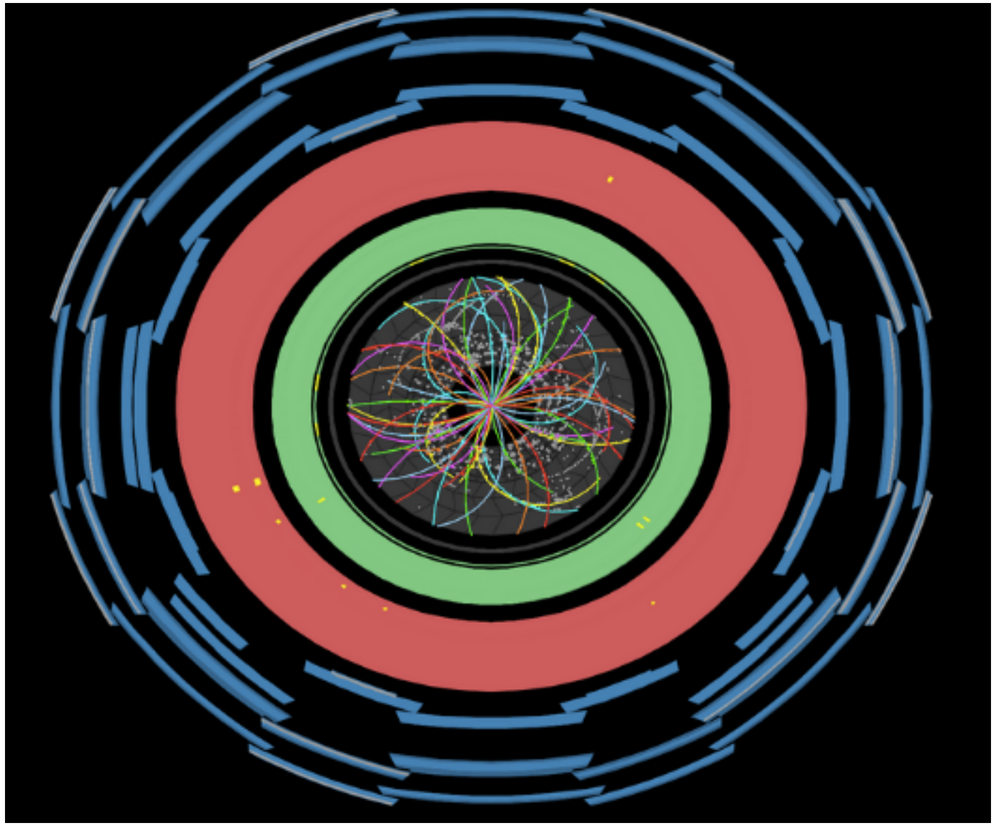
Data-Taking at the ATLAS Detector

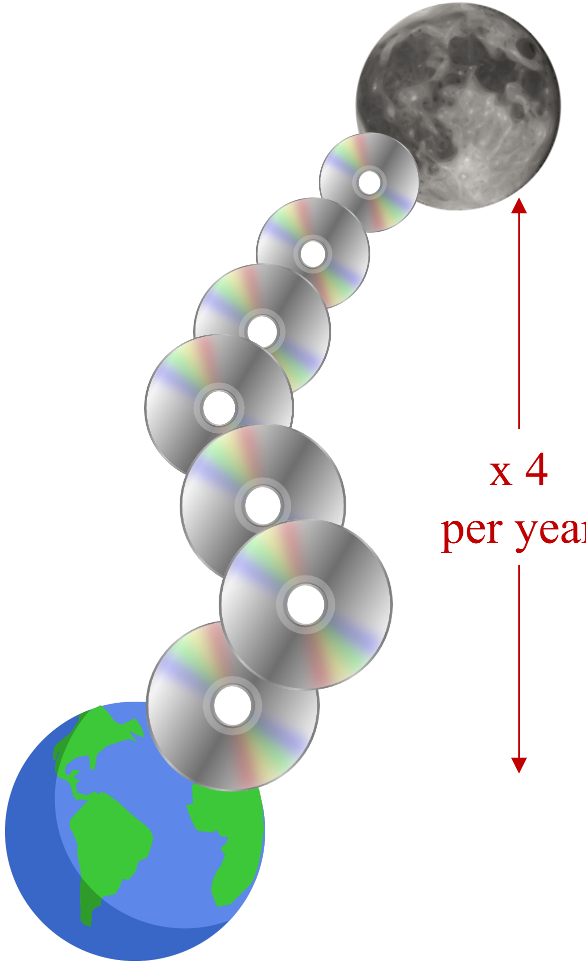
- ATLAS: detector at the **Large Hadron Collider** (LHC)
- Extremely high **collision rate.**

40 MHz bunch crossing x 20-50 interactions per crossing = ~10^9 interactions / second



~10^6 bytes / interaction

Data generation rate: 1 PB / second



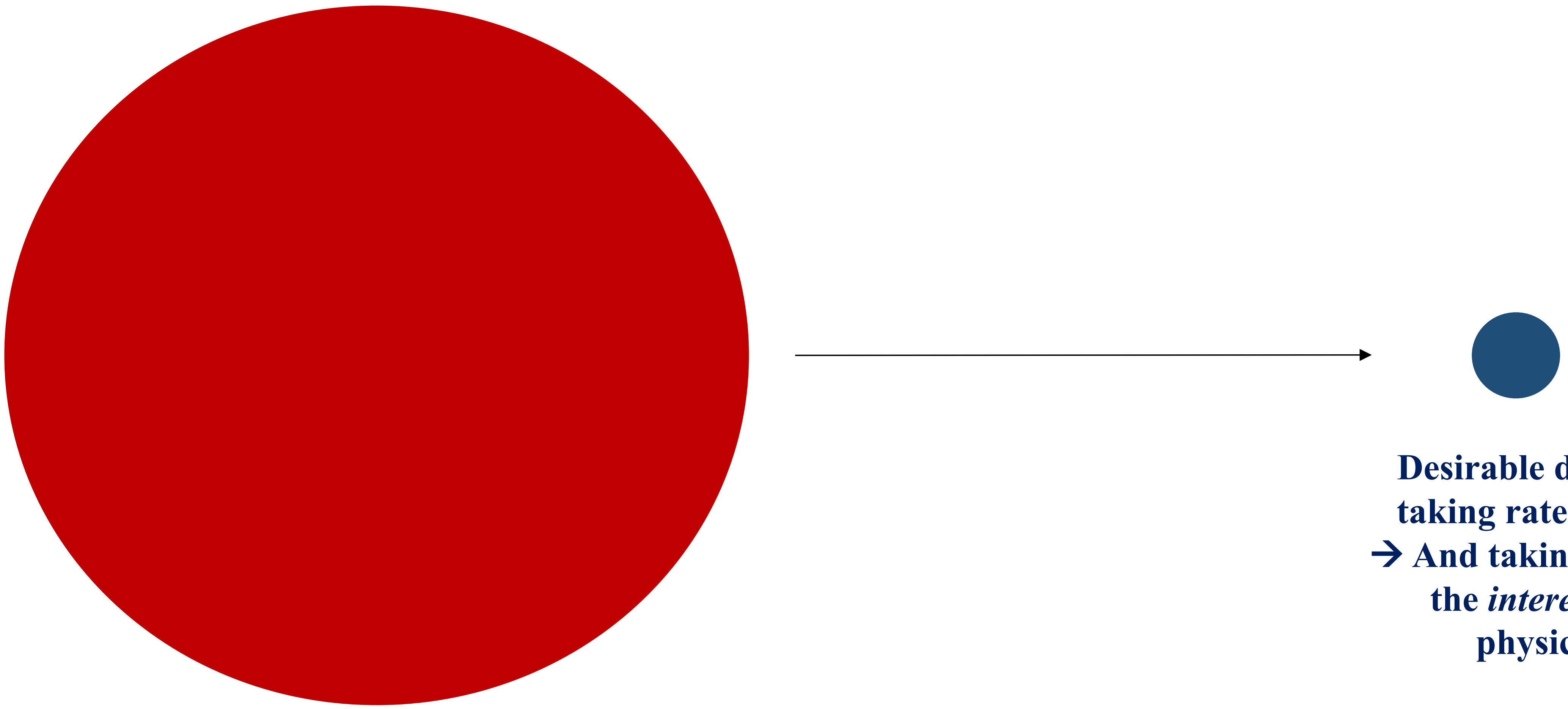
x 4 per year

Keep it all?
→ No way!

Data-Taking at the ATLAS Detector

What we have:

What we want:



Highly not-to-scale: 99.9975% reduction!

Bunch-crossing rate: 40 MHz

Desirable data-taking rate: 1 kHz
→ And taking only the *interesting* physics!

Data-Taking at the ATLAS Detector

What we have:

Bunch-crossing rate: 40 MHz

Triggers!

- Flag events of interest.
- Customized for different physics goals.
- This talk: muon triggers.

What we want:

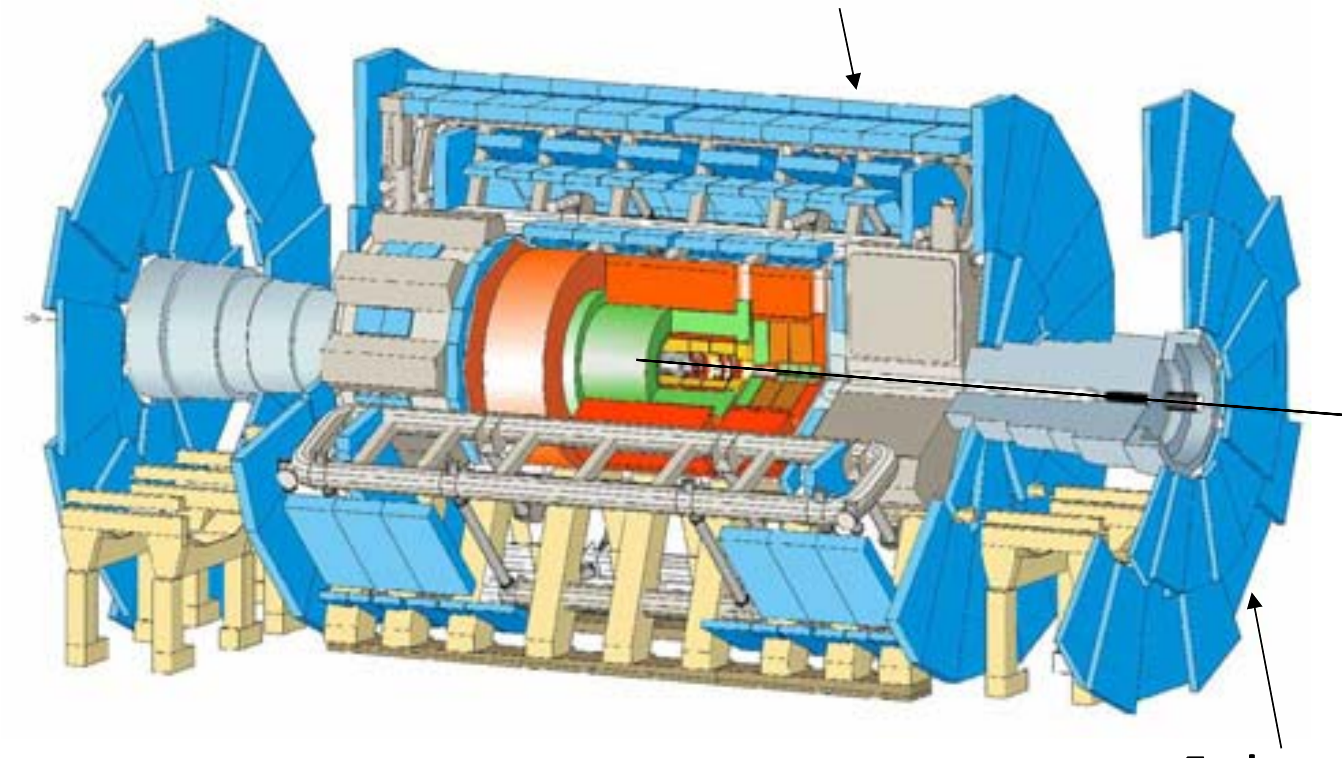
Highly not-to-scale: 99.9975% reduction!

Desirable data-taking rate: 1 kHz → And taking only the *interesting* physics!

ATLAS Muon Triggers

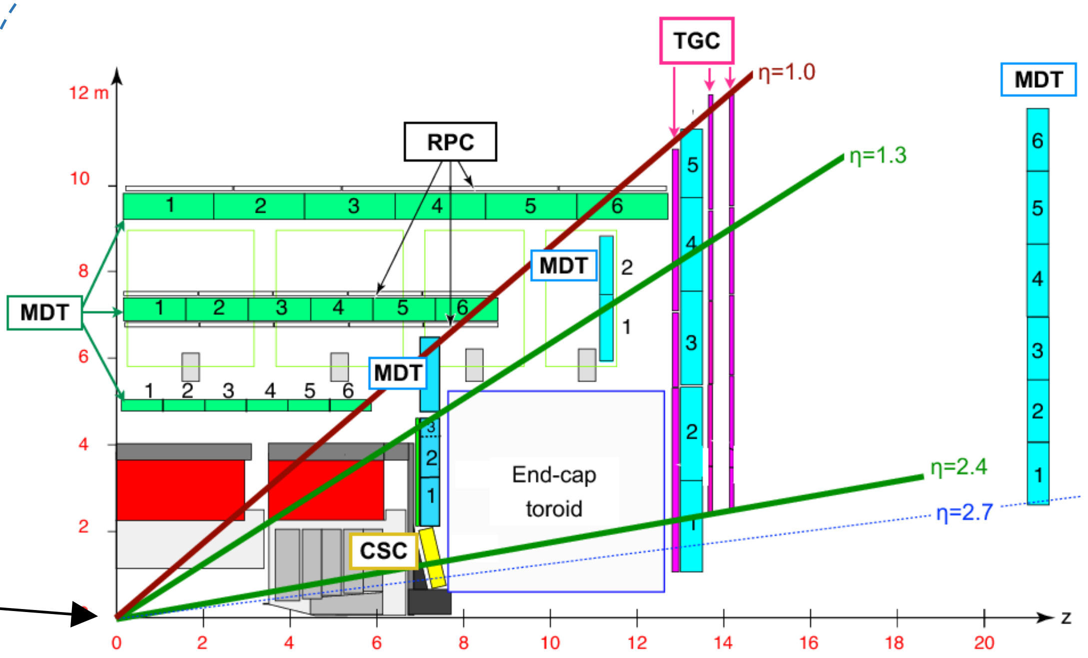
- **Muon triggers** specifically identify events containing muon candidates
- These rely on info from the **muon spectrometer** (MS): outermost part of the detector designed for muon measurements.

Barrel



Endcap

Take a slice of the detector along the beam axis:



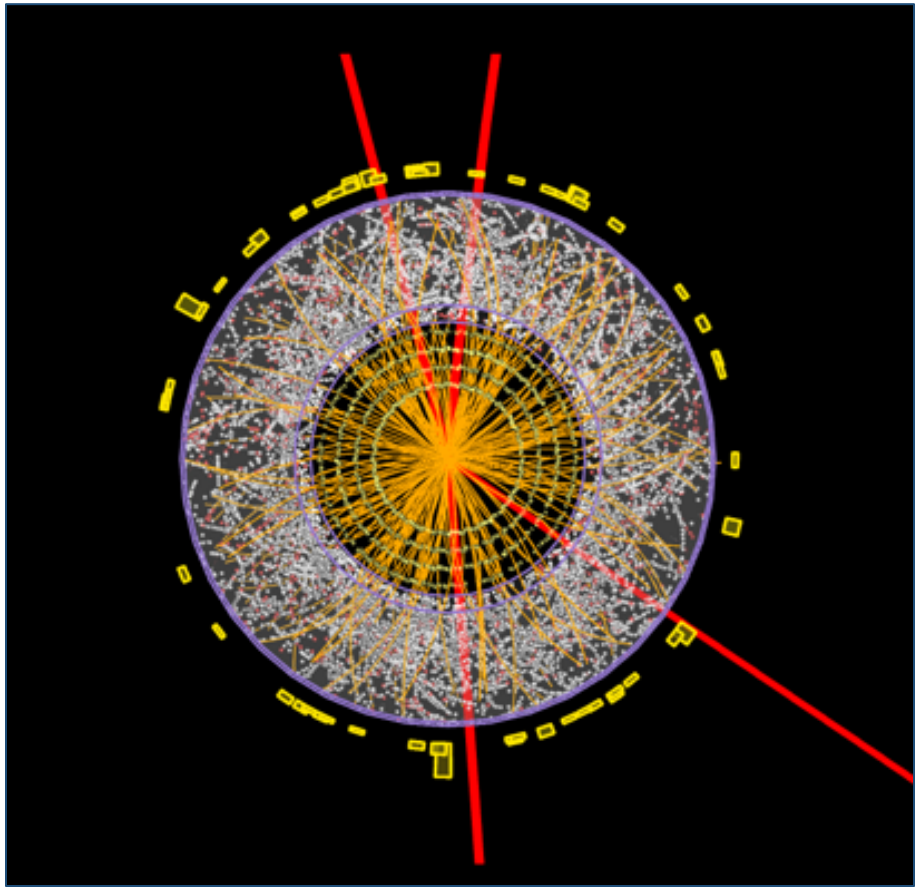
1. L1 trigger: **Resistive plate chambers** and **thin gap chambers** of the MS.

2. High-level trigger: combine info from MS and inner detector.

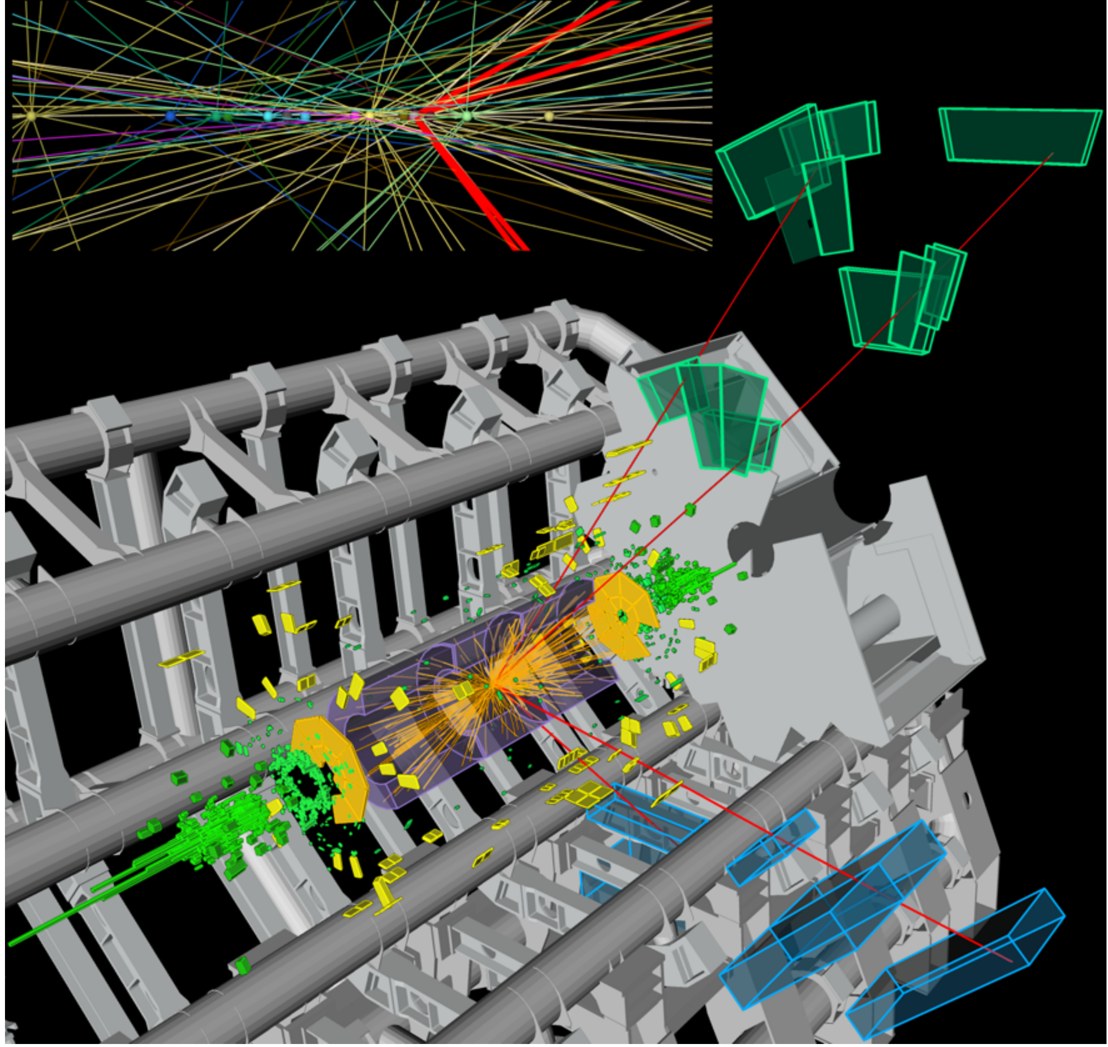
1. Performance of the ATLAS muon trigger in pp collisions at √s=8 TeV. ATLAS Collaboration (Aad, Georges *et* al.) Eur.Phys.J. C75 (2015) 120 arXiv:1408.3179 [hep-ex]. DOI: 10.1140/epjc/s10052-015-3325-9

Muon Triggers in Action

- A large selection of muon triggers exists: low, medium and high-p_T, single and di-muon, and muon triggers in combination with other triggers (electrons, jets, missing E_T).



H → 4μ candidate event. Muon tracks are in red.



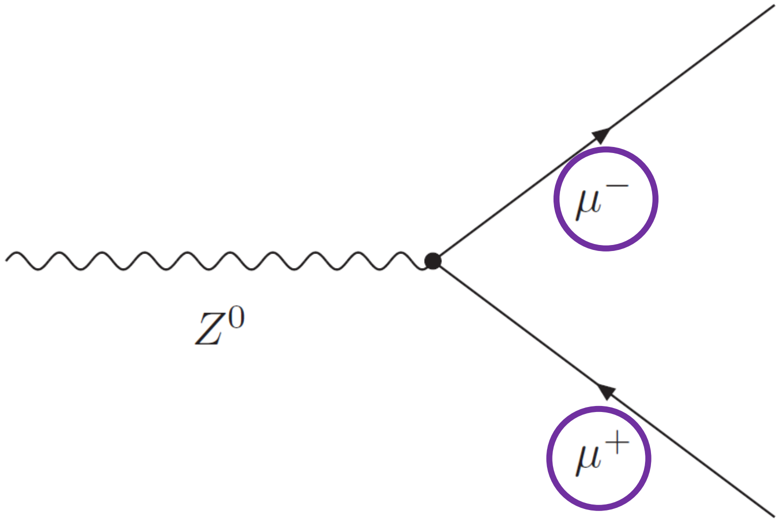
In green and blue: muon chambers that registered hits in this event.

- These are crucial in identification of important physics, eg. Higgs boson decaying to muons

Trigger Performance: Efficiency

- The **efficiency** of a trigger is a measure of its performance
  → What fraction of events of interest does a trigger catch?

- One way to measure efficiency: the **tag-and-probe** method applied to Z→ $\mu^+\mu^-$
  - Creates a pool of muons that can be used to measure trigger efficiency in an unbiased way.



Event Selection:

Tag:
- $|\eta| < 2.8$
- $p_T > 10$ GeV
- Caused a low p_T-threshold trigger to fire.

Probe:
- $|\eta| < 2.5$
- $p_T >$ (trigger threshold*1.05 GeV)
- Desired quality

Also: same interaction vertex, in Z mass window, opposite charge

The probe muon is considered to have fired the trigger of interest if it lies within ΔR<0.1 of a trigger object.

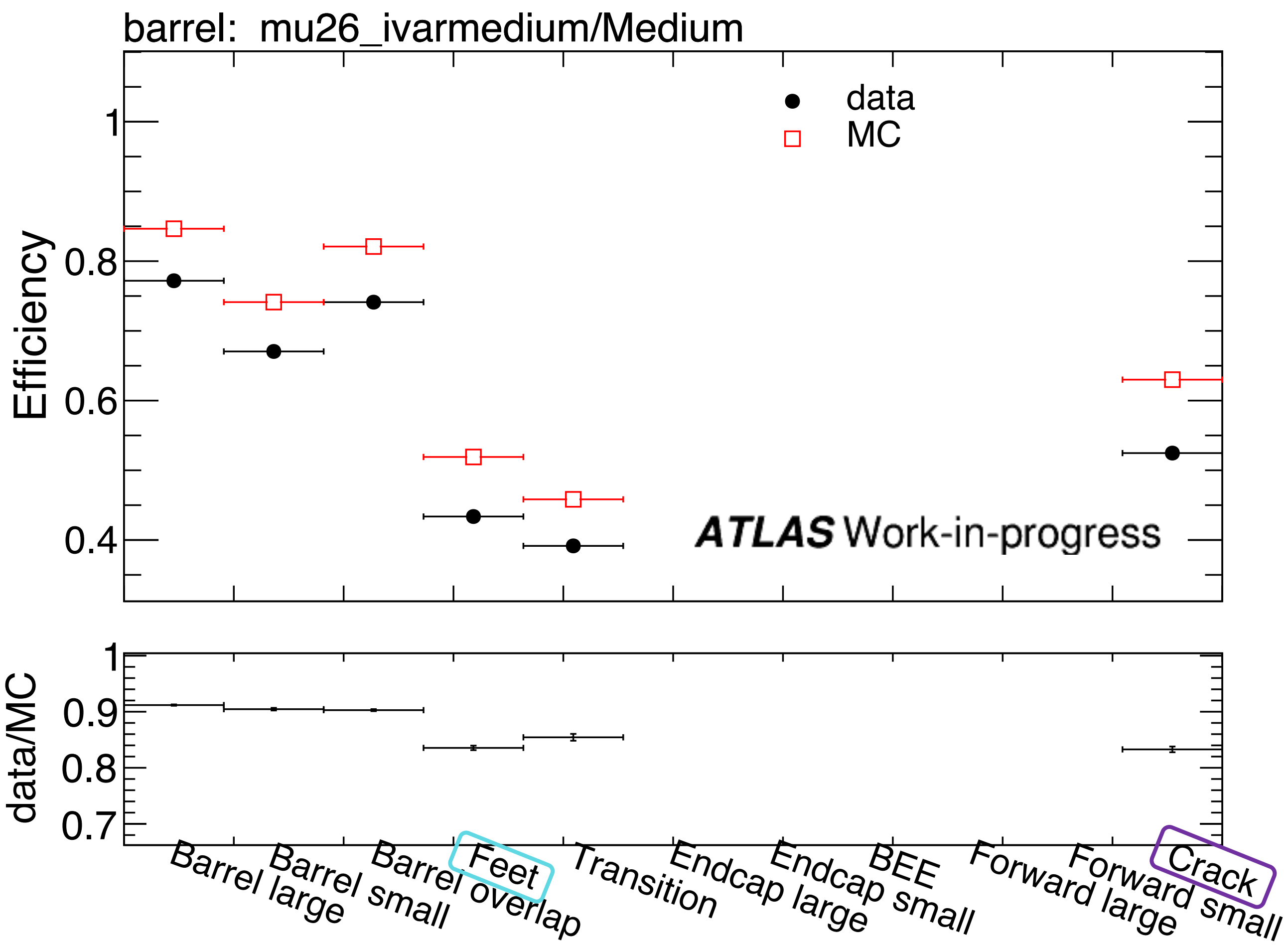
⇒

$$\textbf{Efficiency} = \frac{\textbf{\# Triggered probe muons}}{\textbf{Total \# probe muons}}$$

Matching Efficiencies: Scale Factors

- Analyses use **data** and **Monte Carlo (MC) simulations**.
  - Triggers are present in both.
  - But trigger performances (efficiencies) are not necessarily identical.

Efficiencies reflect detector configuration: physical features like the **detector feet** and **cracks** are not well-modelled.

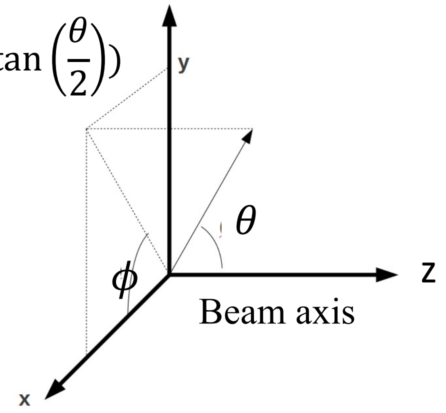


- Scale factors (SFs) are provided to account for mismatch between data and MC trigger efficiencies

$$\text{Scale Factor} = \frac{\text{Data efficiency}}{\text{MC efficiency}}$$

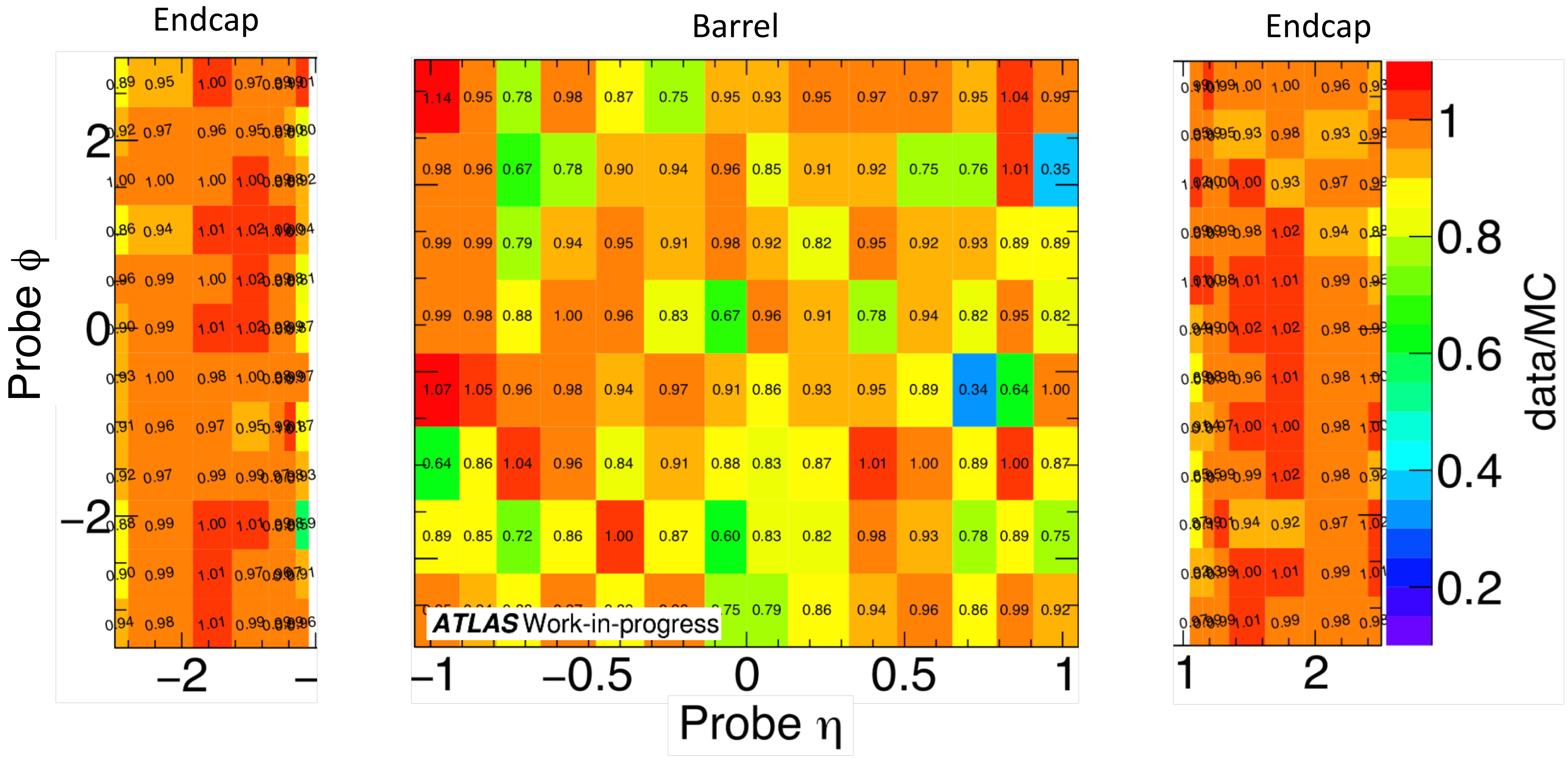
Matching Efficiencies: Scale Factors

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$



End Result:

1. Scale factor maps in two detector dimensions for the barrel and endcap regions of MS, produced for each trigger, in each data-taking period.



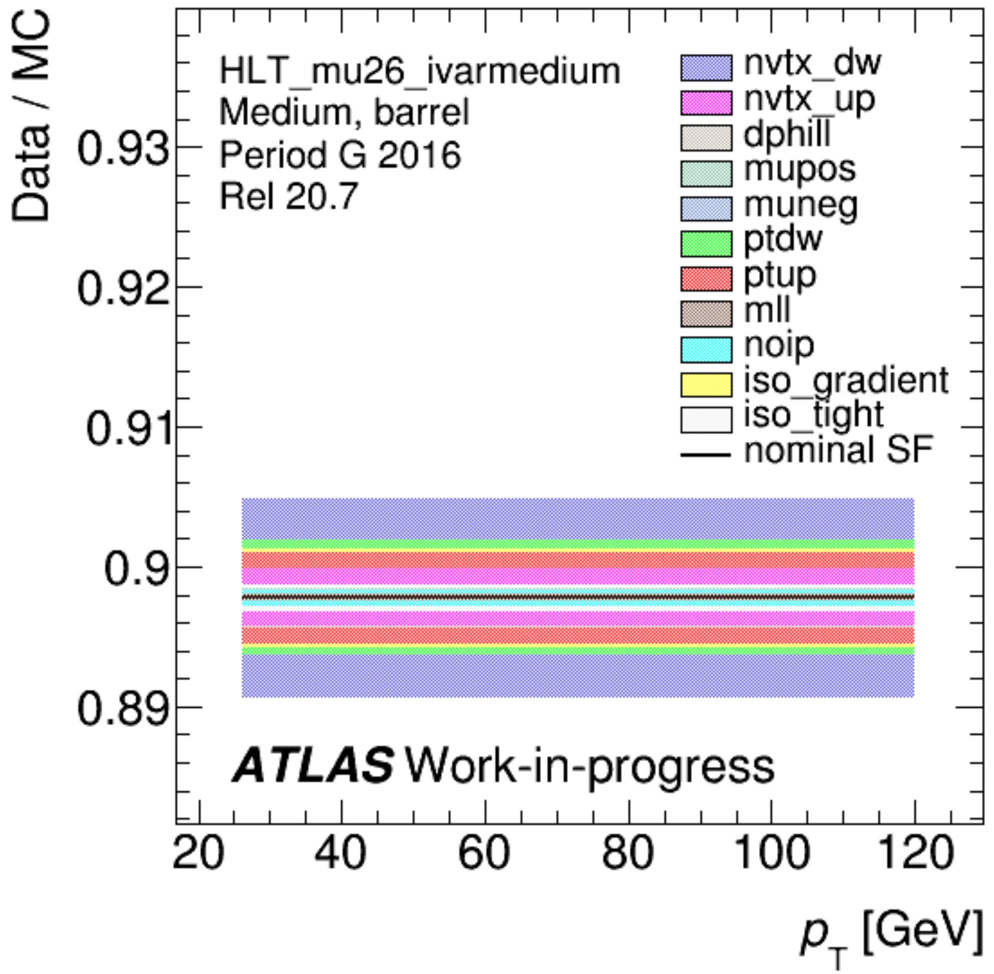
Matching Efficiencies: Scale Factors

End Result:

2. A breakdown of systematic uncertainties for the relevant trigger, region and data-taking period.

- Many sources of systematic uncertainty are taken into account:
    - Pile-up dependence ("nvtx up", "nvtx dw")
    - Probe isolation ("iso_tight", "iso_gradient")
    - Z mass window definition ("mll")
    - Probe p_T dependence ("ptup", "ptdw")
    - Probe muon charge ("mupos", "muneg")
    - Interaction parameter ("noip")
    - Detectory symmetry ("dphill").

- Yield a total systematic uncertainty on the scale factors of usually ~1-2%.

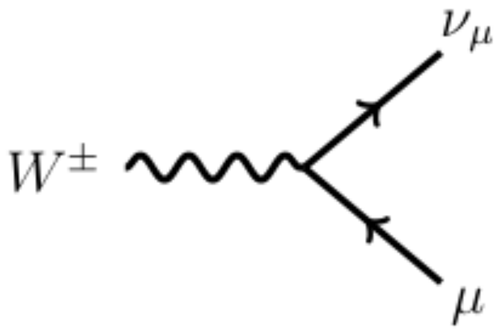


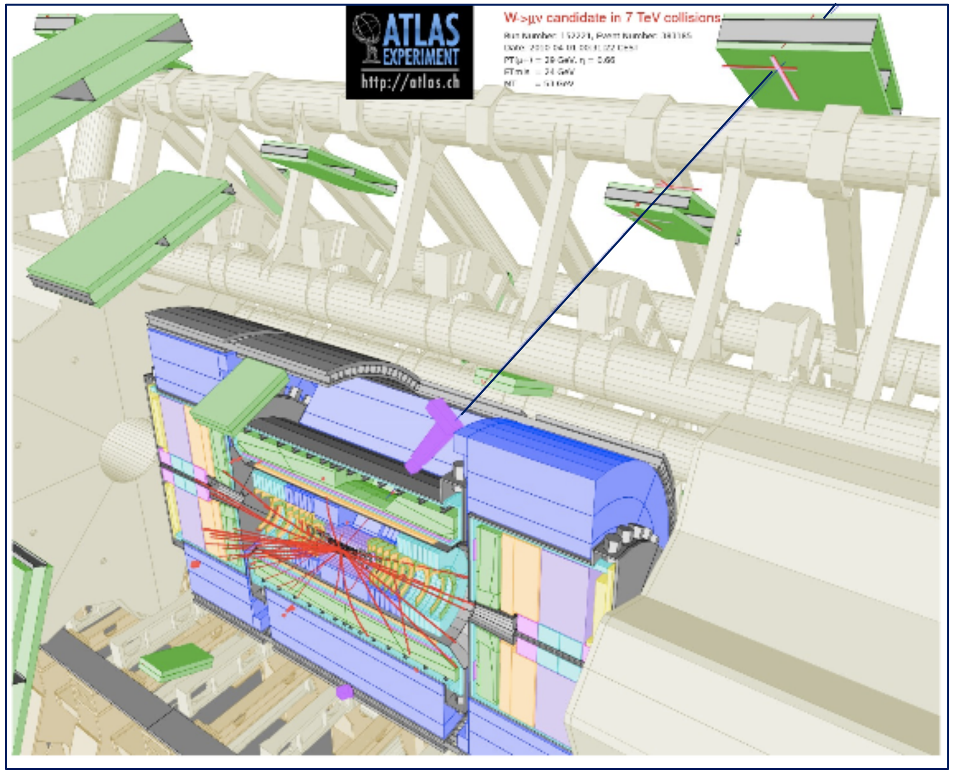
→ Systematic bands shown overlapped (not added)

Why Do We Care About Scale Factors?

- Many analyses rely on the **muon trigger** in data and simulations, so they also rely on the muon trigger **scale factors**.
  - Need scale factors that are **a) available,** and **b) precise.**

- Just one example: **W boson mass measurement**.
  - Muon triggers used →
  - High-precision
  - Trigger efficiency was the **second-largest source** of systematic uncertainty in the 2017 measurement[2].



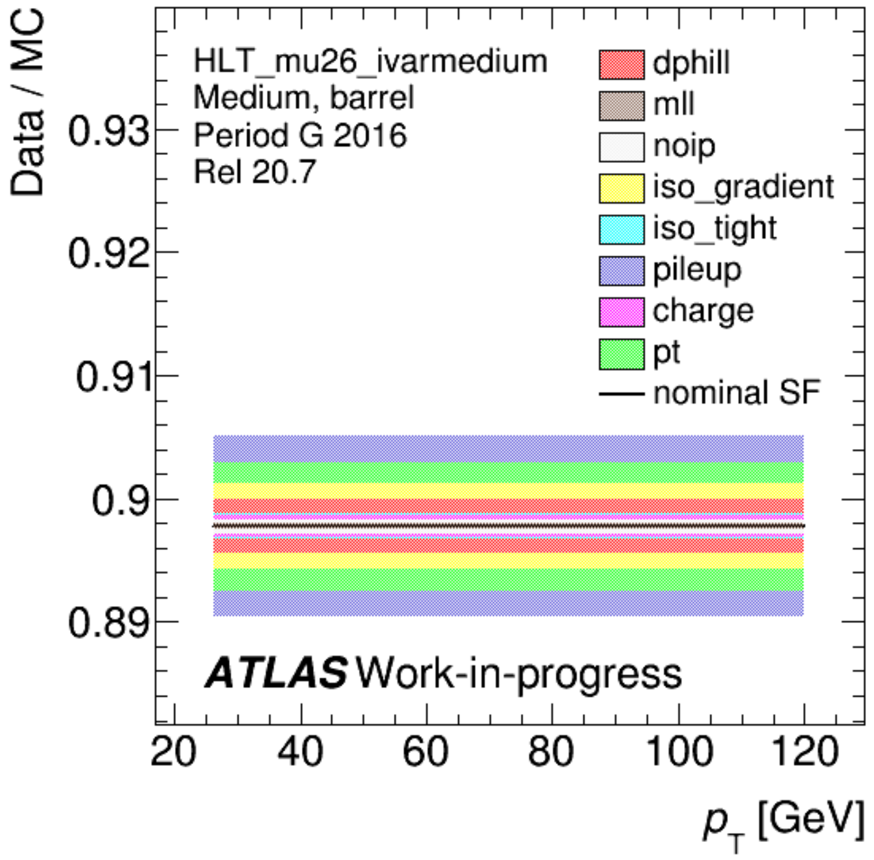


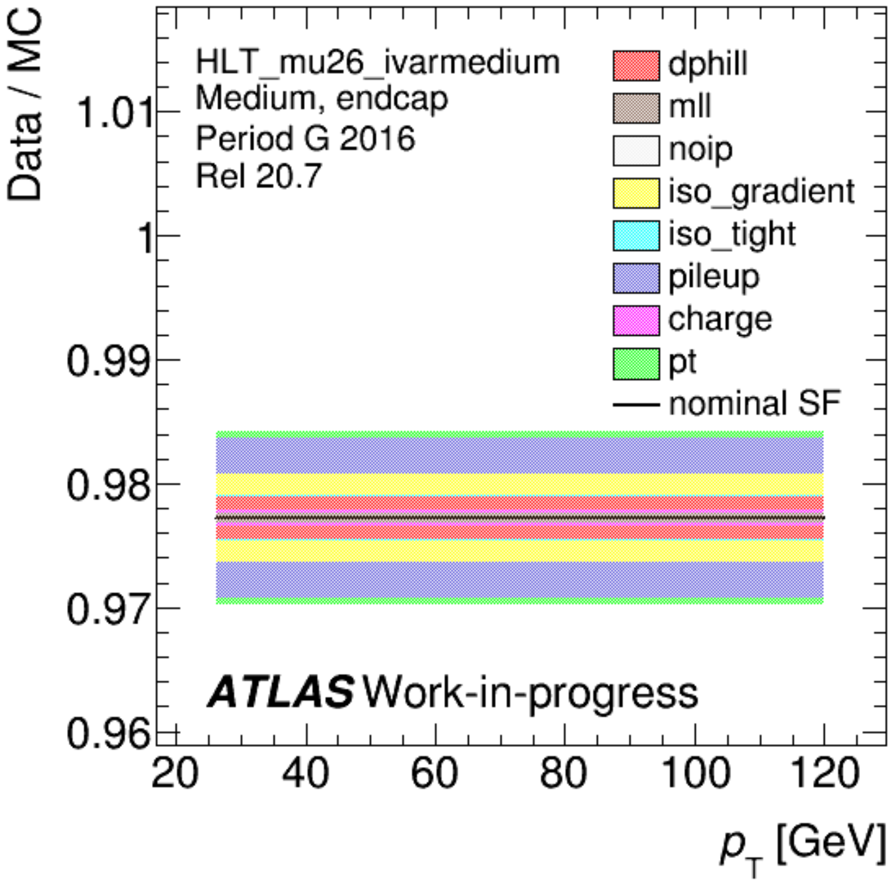
Large uncertainty on the scale factors = large uncertainty in the analysis → **What can we do about this?**

2. Measurement of the W boson mass in pp collisions at √s=7 TeV. ATLAS Collaboration (Aad, Georges *et* al.). Jan 25 2017. CERN-EP-2016-305 arXiv:1701.07240

A Closer Look at Scale Factor Systematic Uncertainties

→ Compare systematic sizes: p_T dependence is the second-largest systematic in the barrel and dominates in the endcap.





- Suggests a starting point for a study of SF systematics: p_T dependence.
  - **Goals:** 1) Determine whether current p_T systematic covers p_T dependence of SFs
    2) Test feasibility of producing separate SF maps for each p_T range

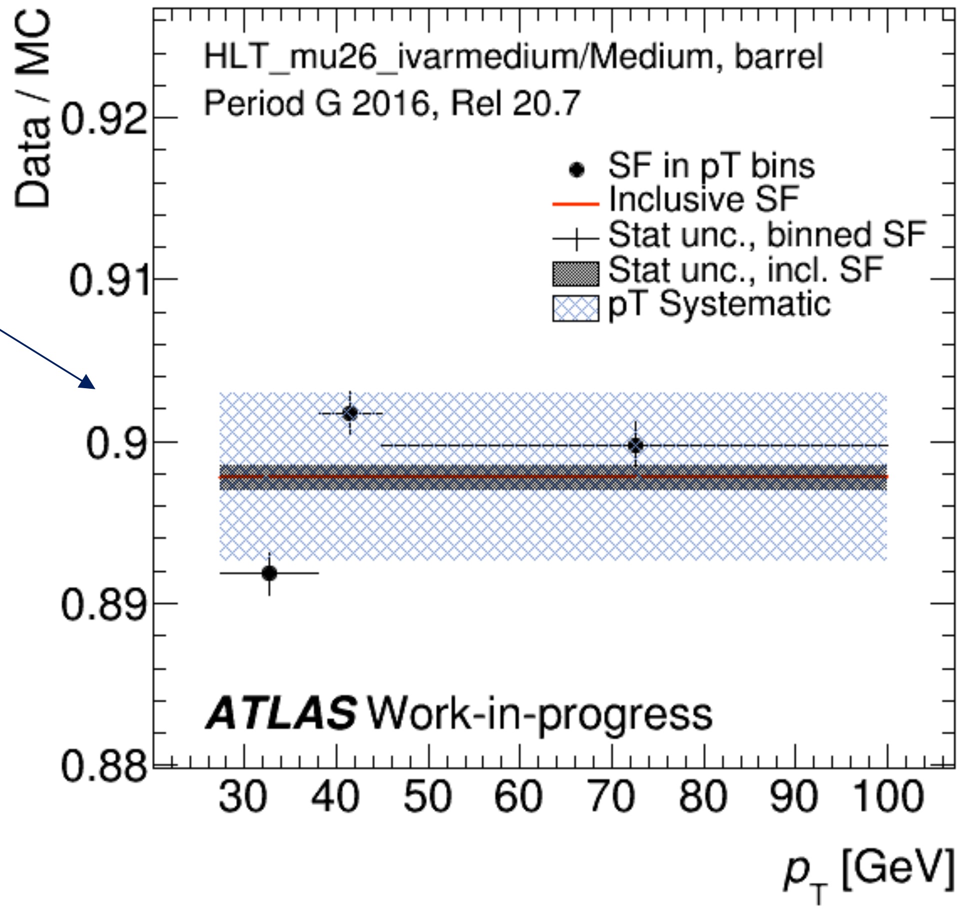
1. p_T Dependence of Scale Factors

- **Methodology:** selection on probe p_T changed to break up the p_T range into four bins: 26*1.05 - 38 GeV, 38 – 45 GeV, 45-100 GeV, >100 GeV.
  → Achieved roughly equal statistics in the first three p_T bin
  - Focused on a single trigger (HLT_mu26_ivarmedium) used in 2016

- **Output:** a scale factor for each p_T bin.
  - Plot these against p_T
  - Showing only the first 3 p_T bins because of poor stats in the highest p_T region

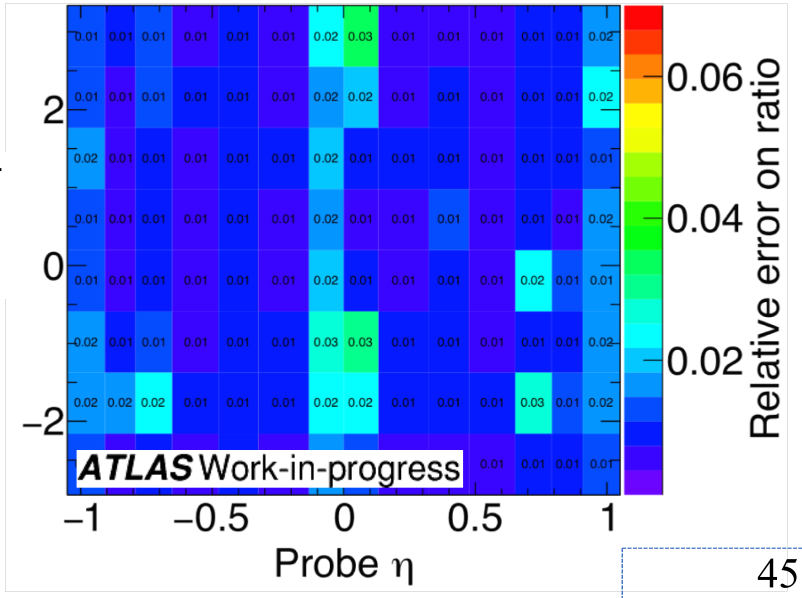
- **Look for:**
  - **Trends in SF p_T dependence** that are reproduced across data-taking periods.
  - Does the **current p_T systematic** on the **inclusive nominal SF** cover the variation in SFs among p_T **bins**?

Sample plot of scale factors vs. p_T



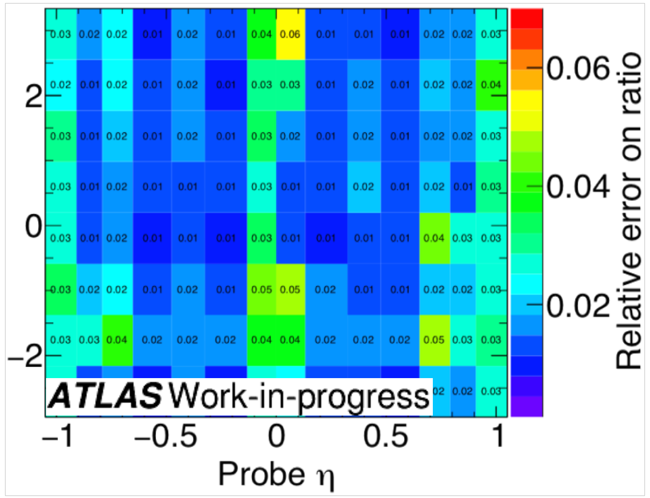
2. Producing Scale Factor Maps in p_T Bins

Current error on the scale factors:

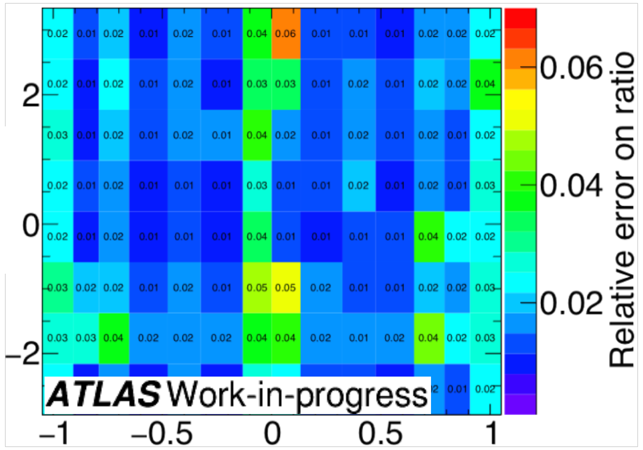


Error on SF maps derived in bins of p_T:

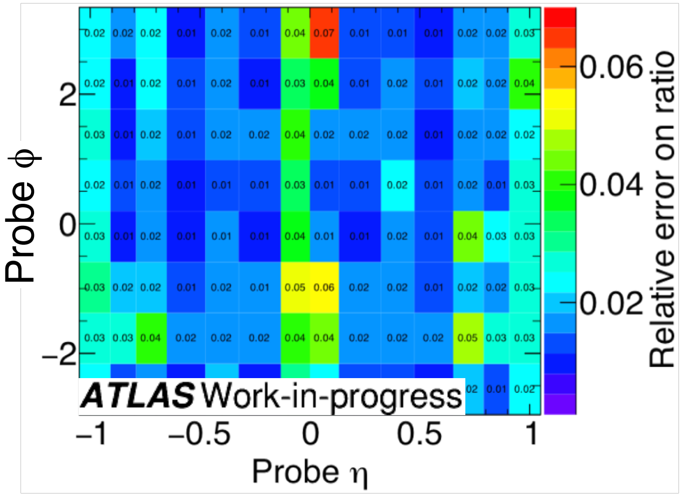
26*1.01 GeV < p_T < 38 GeV



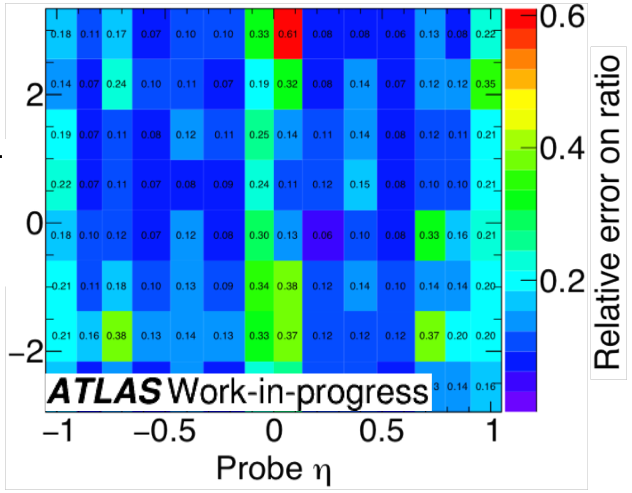
38 GeV < p_T < 45 GeV



45 GeV < p_T < 100 GeV



p_T > 100 GeV



Note the changed scale! Error is ~10x larger in this p_T bin.

Scale factor maps are limited by statistics in the highest p_T bin
→ Could be addressed by combining Z → $\mu\mu$ with higher-p_T W+jets and ttbar samples

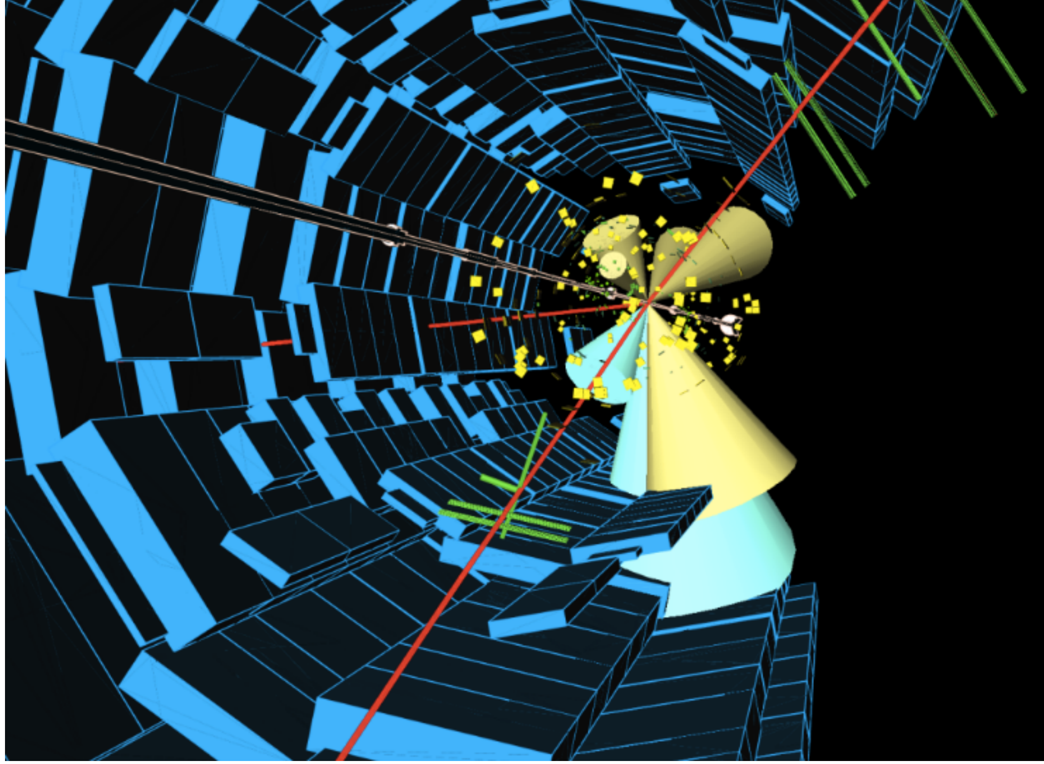
Conclusions and Next Steps

- **Triggers** are crucial for data-taking at ATLAS.
  - Muon triggers are instrumental in recording interesting physics, eg. Higgs and new physics searches.

- Using triggers also requires using **scale factors.**
  - Have to be reproduced to keep up with changes to the detector, new data, new processing of data or Monte Carlo simulations …

- Many analyses rely on **accurate and precise** muon trigger scale factors.
  - eg. W boson mass measurement

  → Worth investigating the most significant sources of systematic uncertainty.



Candidate event in the search for ttH in multilepton final states, 2016.
Muon tracks in red.

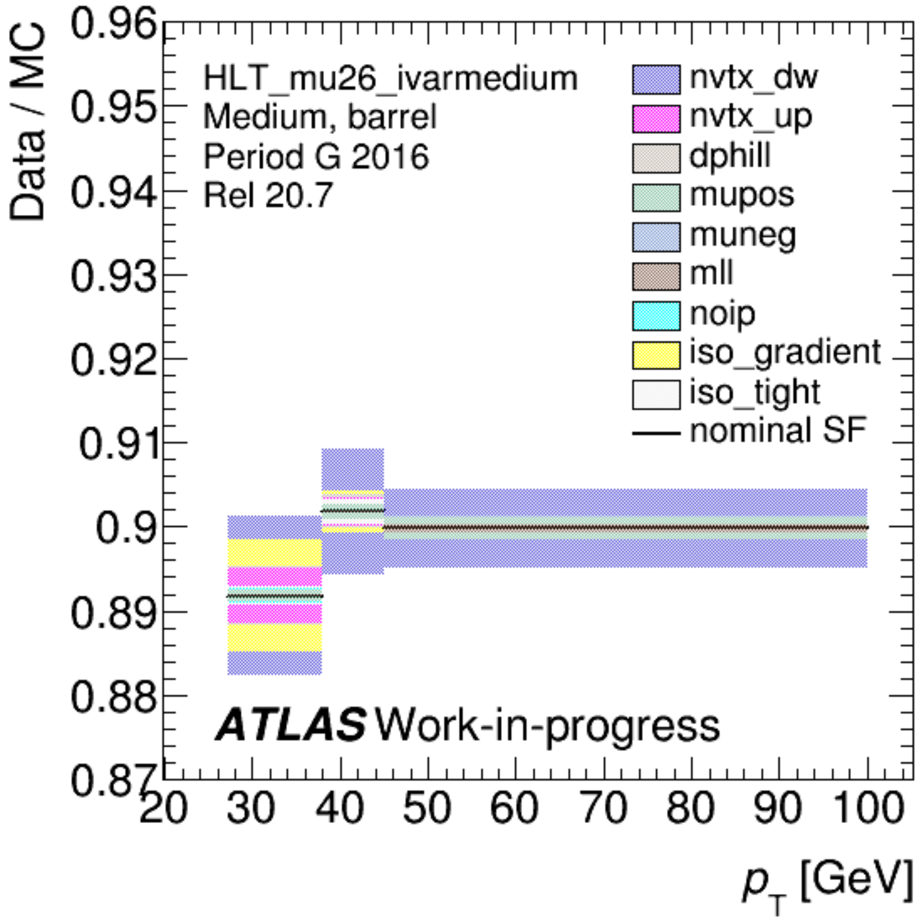
Next steps:

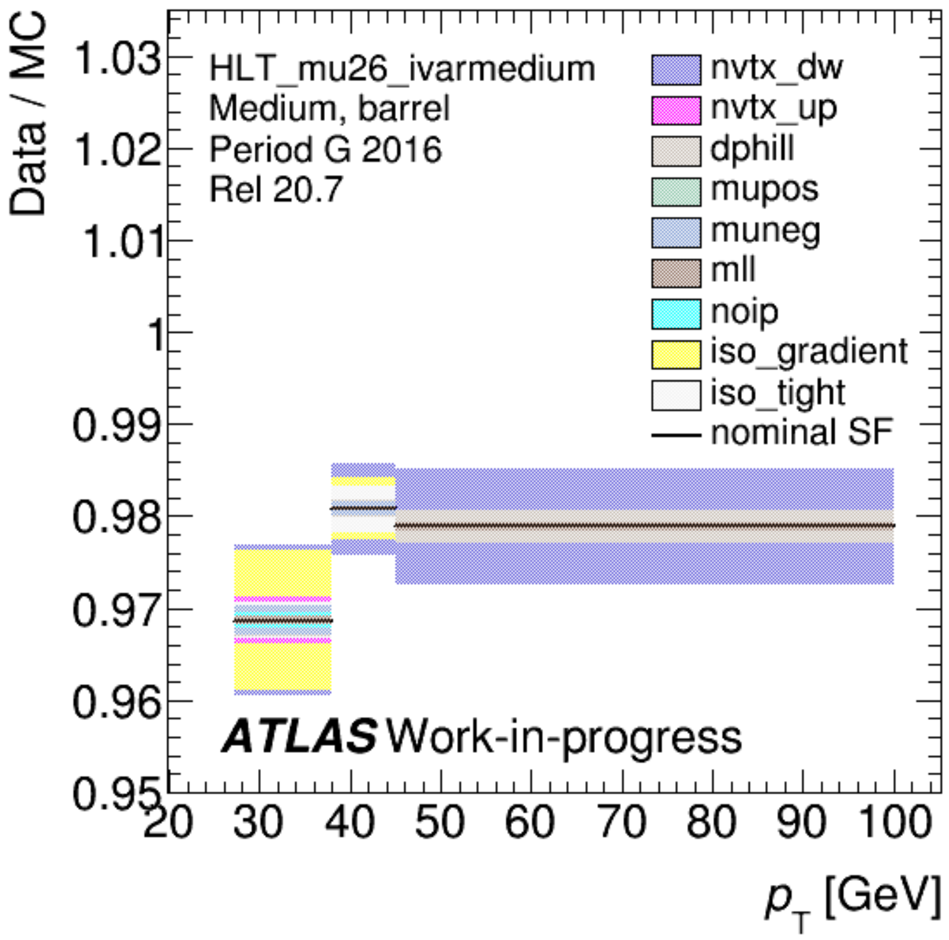
- New scale factors to be produced regularly!
- Look into methods that improve stats in highest p_T bin, so that separate SF maps can be delivered for each p_T range.
- Continue work on understanding largest sources of systematic uncertainty.

Back-up slides

3. Onto the Remaining Systematics

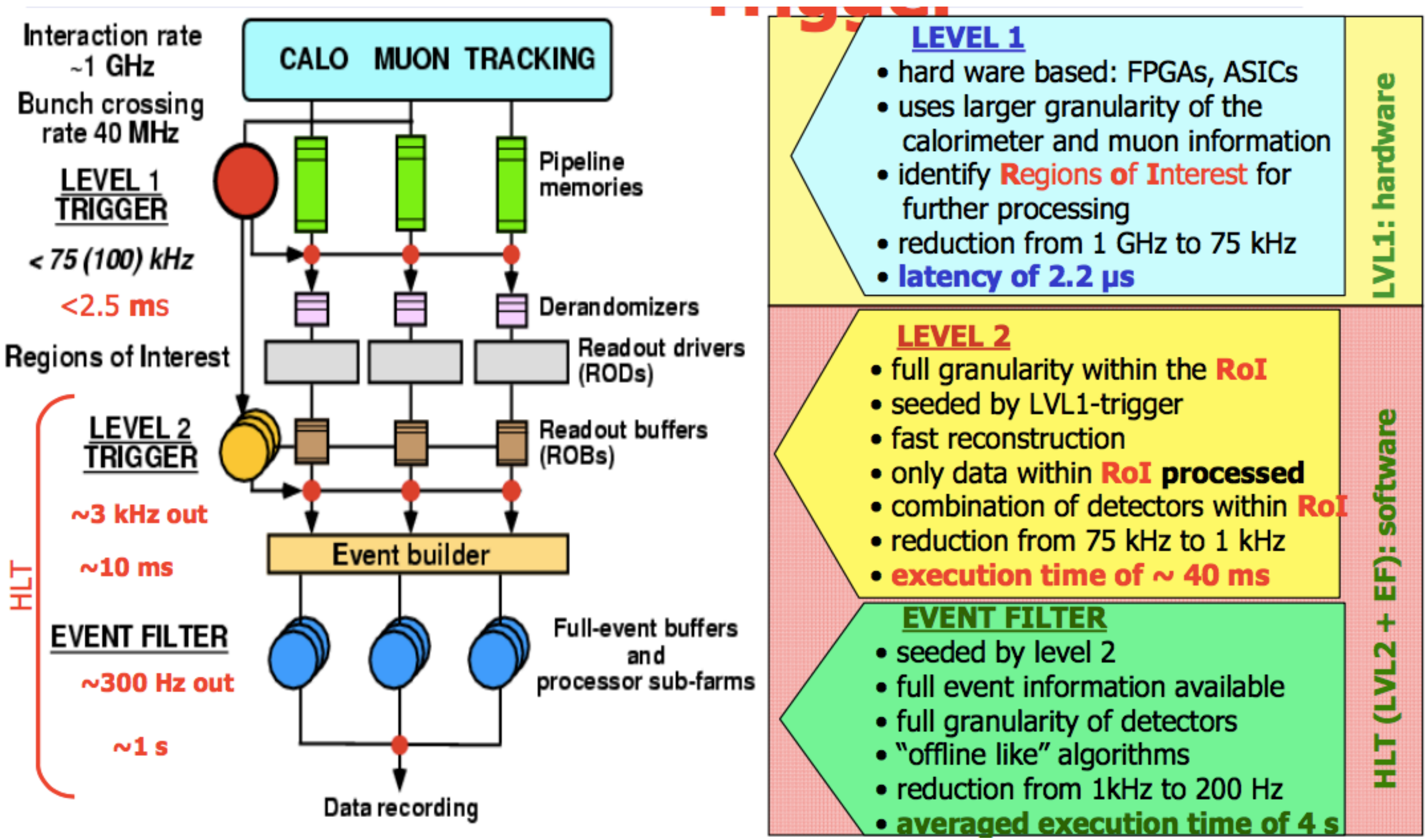
- With p_T dependence gone, what important systematic dependences remain?





→ One systematic is noticeably larger in the lowest p_T bin than in the rest: probe isolation.

Trigger Architecture (rates slightly outdated)

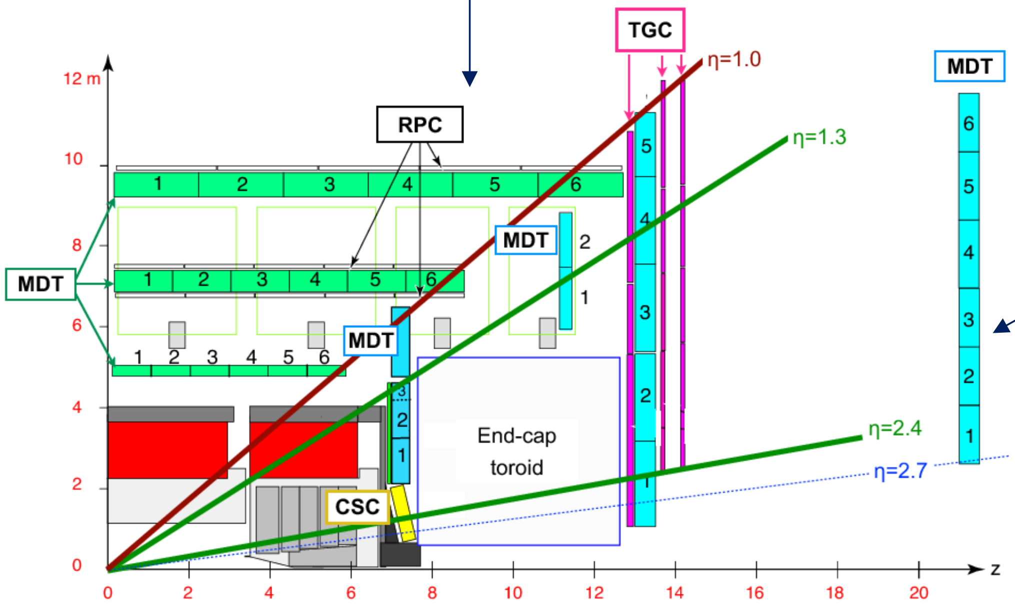


Triggers & the Muon Spectrometer

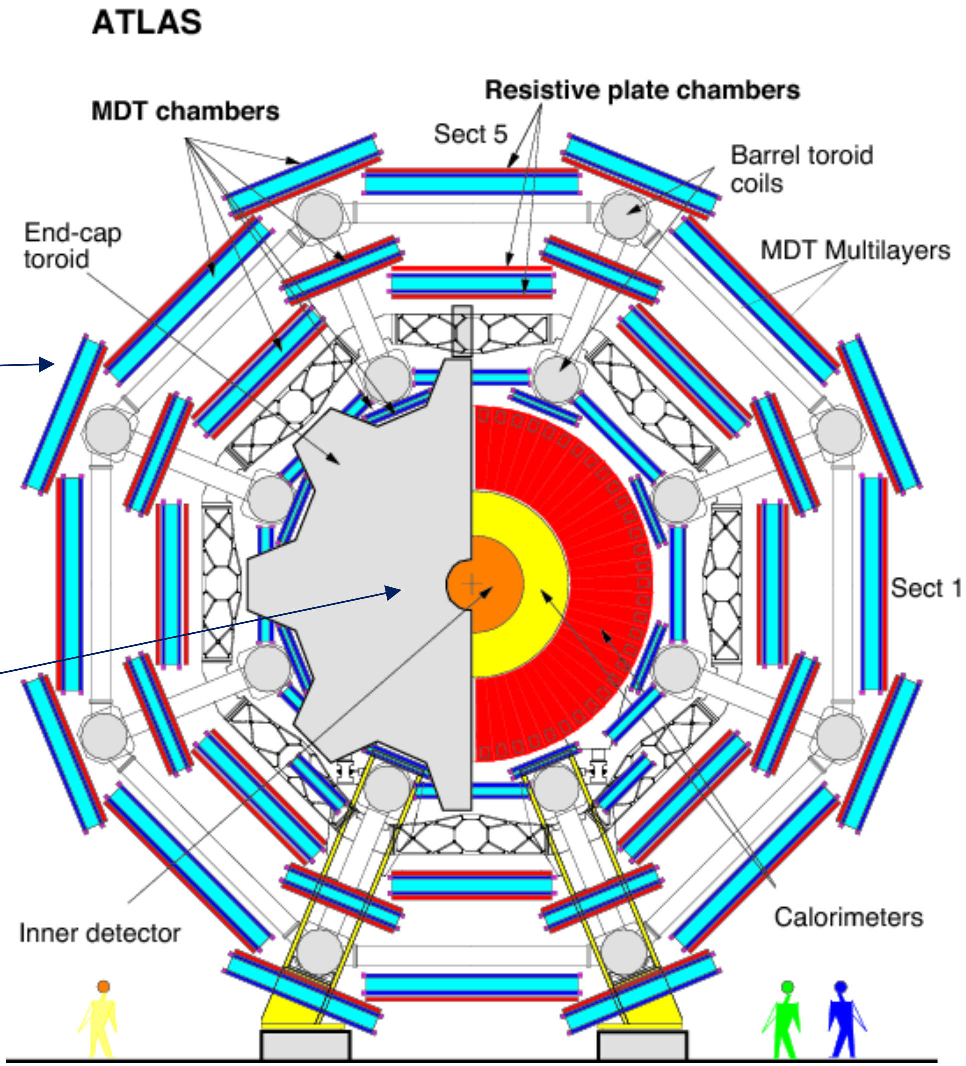
- **Resistive plate chambers** (RPC) and **thin gap chambers** (TGC) of the MS house L1 triggers.
- Also in MS: cathode strip chambers, monitored drift tube chambers.

Barrel region

Endcap region



Muon system with beam axis in-plane[1].



Cross-section of the muon system[2].

1. Performance of the ATLAS muon trigger in pp collisions at √s=8 TeV. ATLAS Collaboration (Aad, Georges *et* al.) Eur.Phys.J. C75 (2015) 120 arXiv:1408.3179 [hep-ex]. DOI: 10.1140/epjc/s10052-015-3325-9
2. Commissioning of the ATLAS muon spectrometer with cosmic rays. ATALS Collaboration (Aad, Georges *et al.*) Eur.Phys.J. C70 (2010) 875-916 arXiv:1006.4384 [physics.ins-det] 10.1140/epjc/s10052-010-1415-2

Systematic Uncertainties in Scale Factors

- Many **sources of systematic uncertainty** are taken into account:

Pile-up dependence (“nvtx up”, “nvtx dw”): Effect of raising and lowering # reconstructed vertices on efficiencies.

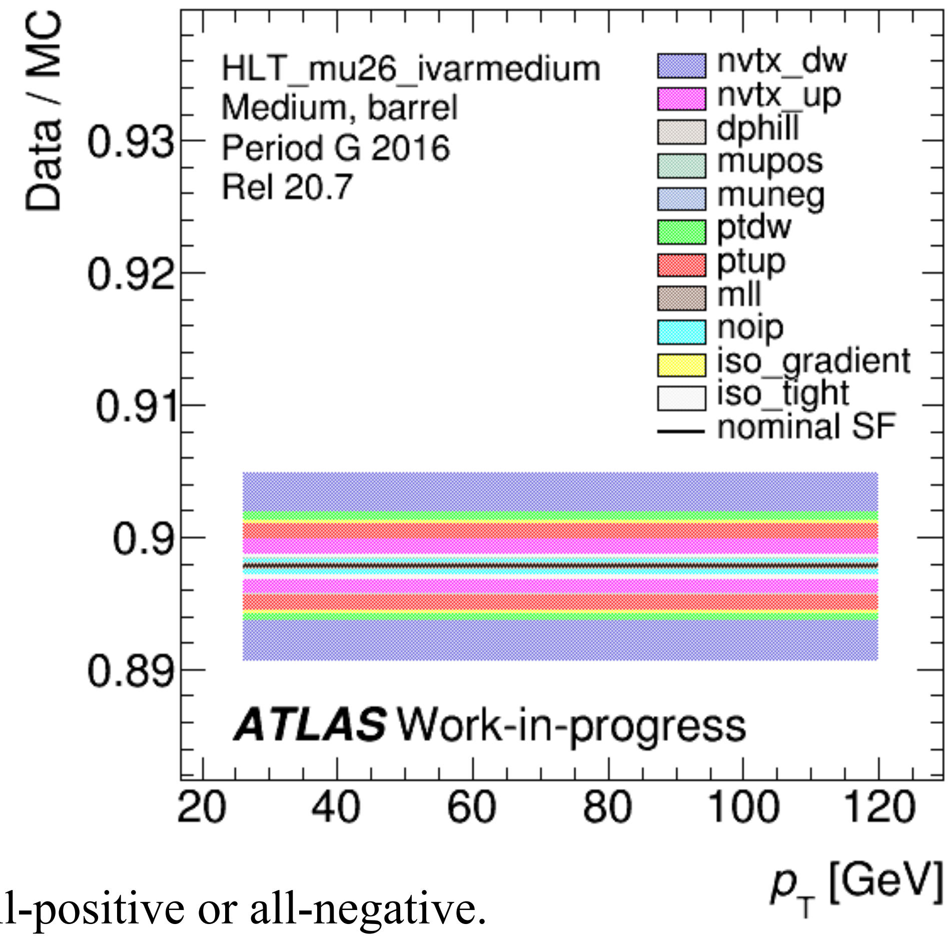
Probe isolation (“iso_tight”, “iso_gradient”): Effect of isolation requirement on probe.

Z mass window definition (“mll”): Effect of changing the tag + probe invariant mass requirement.

Probe p_T dependence (“ptup”, “ptdw”): Effect of raising and lowering probe p_T cutoff.

Sample systematics breakdown:

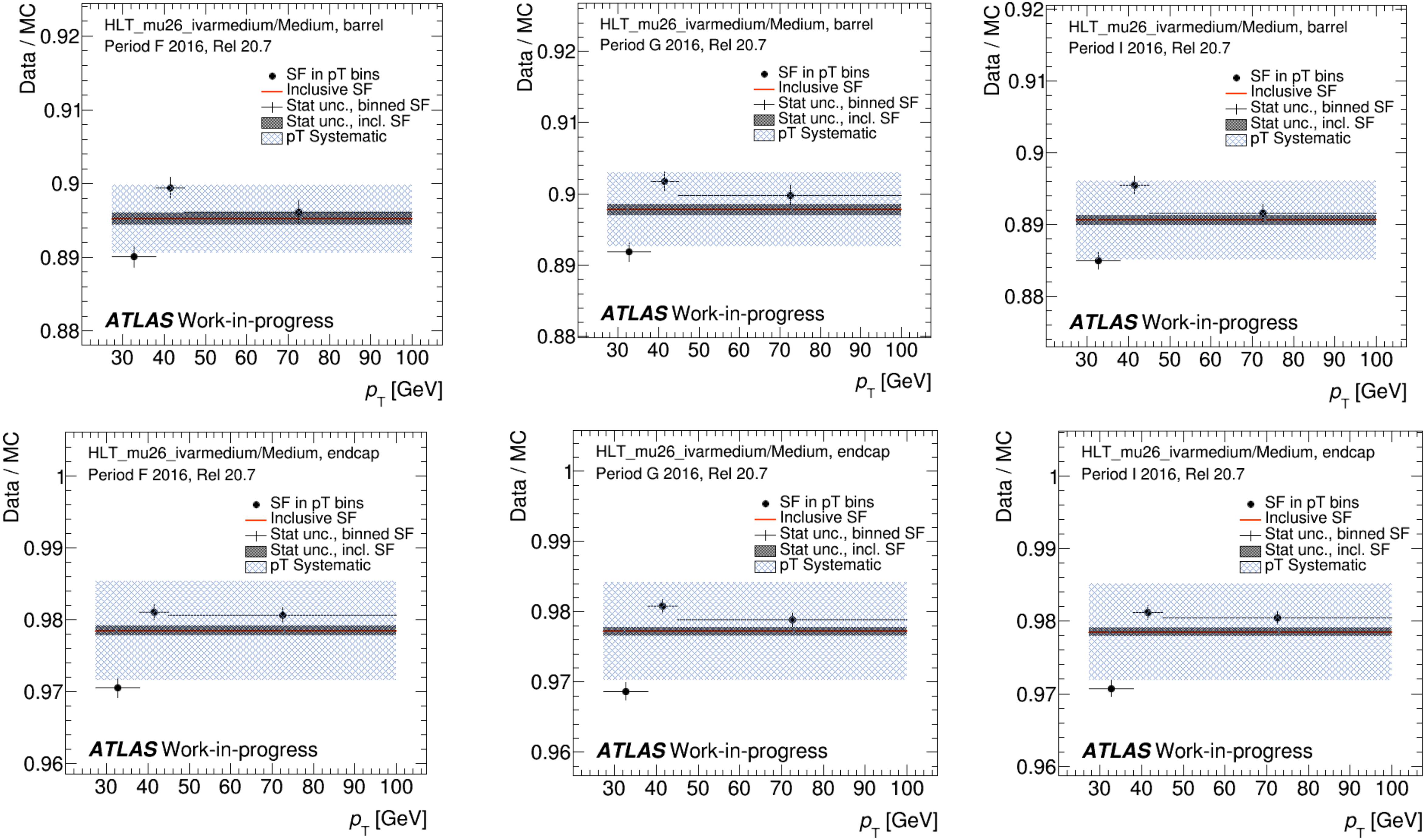
→ Systematic bands shown overlapped (not added)



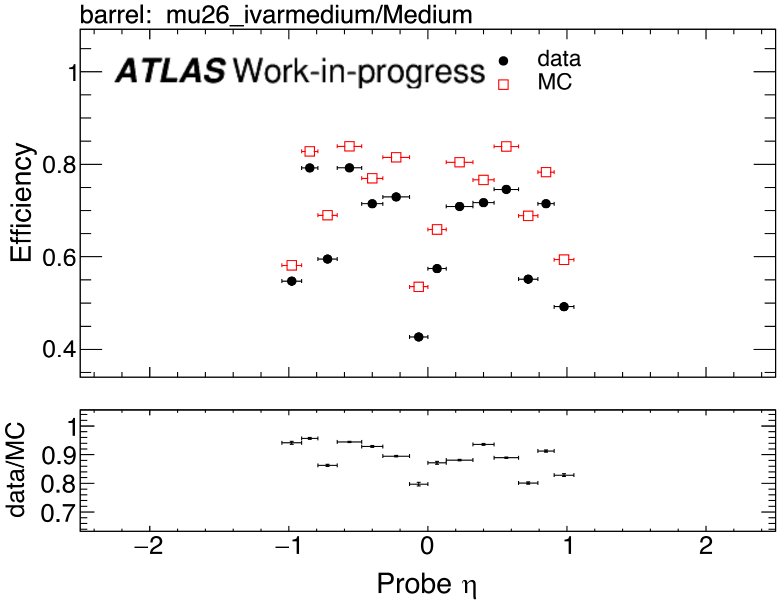
Probe muon charge (“mupos”, “muneg”): Effect of forcing probes to be all-positive or all-negative.

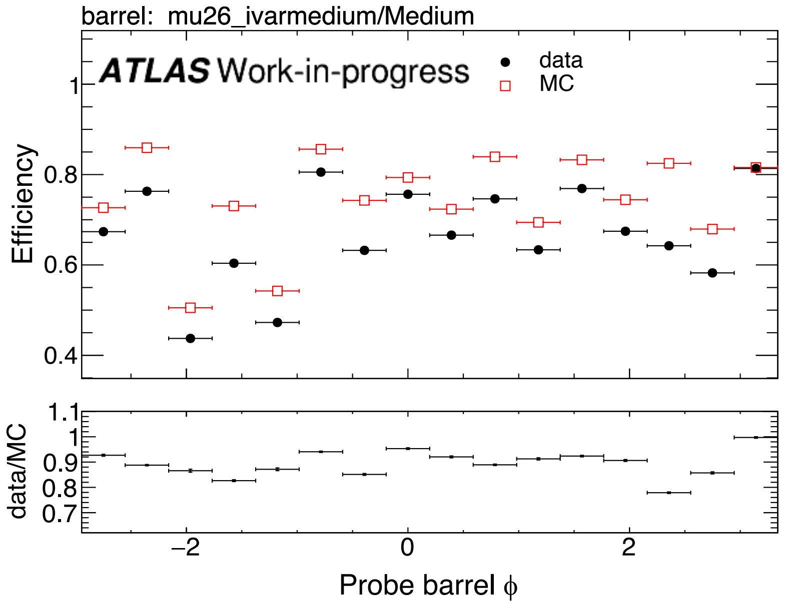
Interaction parameter (“noip”): Removes the requirement that probe and tag come from same interaction vertex

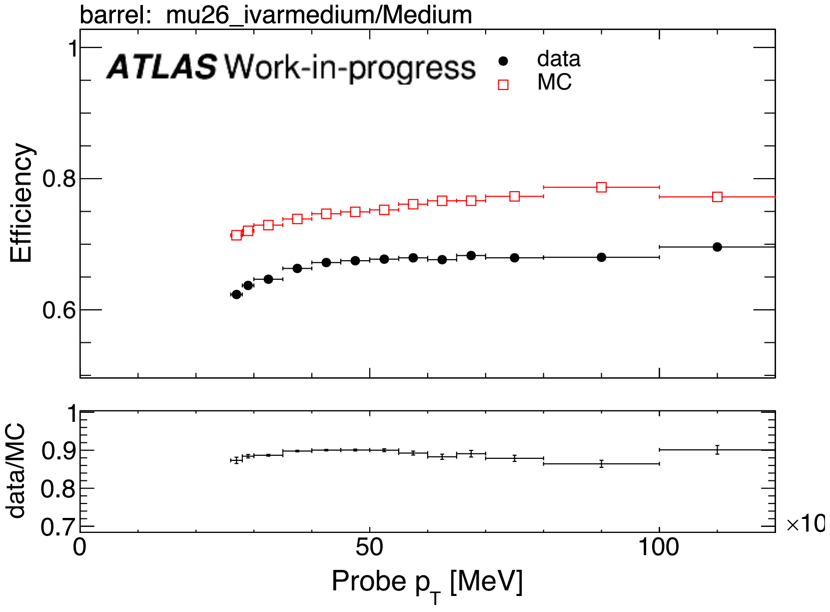
Detector symmetry (“dphill”): Effect of back-to-back muons on efficiency, given 12- and 16-fold ϕ detector symmetry

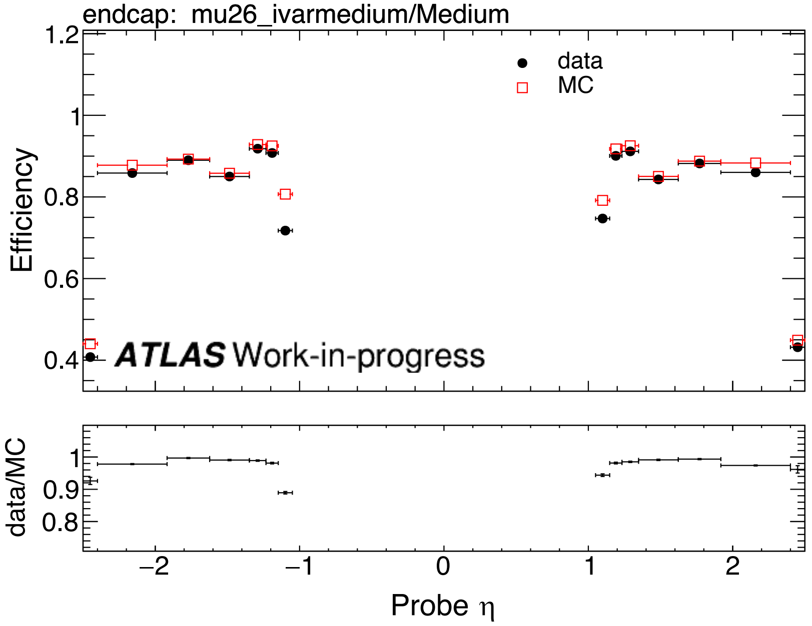

HLT_mu26_ivarmedium/Medium, barrel
Period F 2016, Rel 20.7
SF in pT bins
Inclusive SF
Stat unc., binned SF
Stat unc., incl. SF
pT Systematic
ATLAS Work-in-progress
Data / MC
p_T [GeV]
HLT_mu26_ivarmedium/Medium, barrel
Period G 2016, Rel 20.7
HLT_mu26_ivarmedium/Medium, barrel
Period I 2016, Rel 20.7
HLT_mu26_ivarmedium/Medium, endcap
Period F 2016, Rel 20.7
HLT_mu26_ivarmedium/Medium, endcap
Period G 2016, Rel 20.7
HLT_mu26_ivarmedium/Medium, endcap
Period I 2016, Rel 20.7

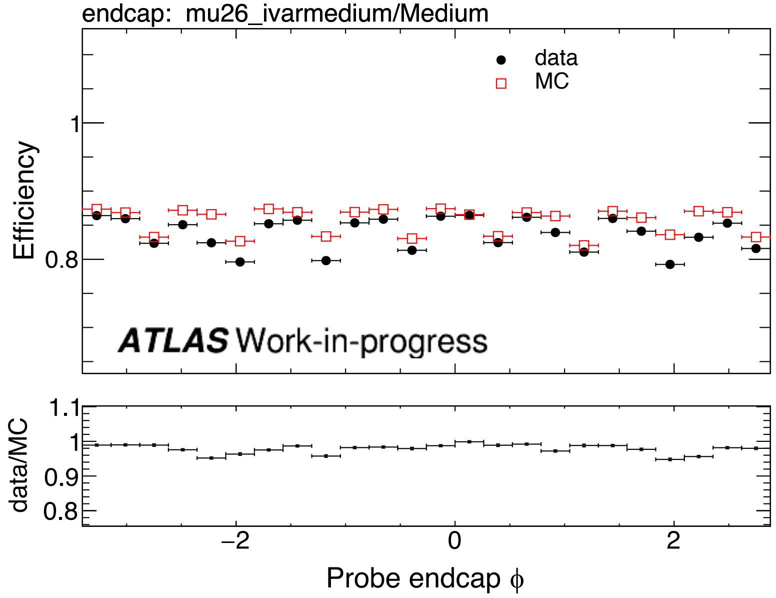
Period F 2016

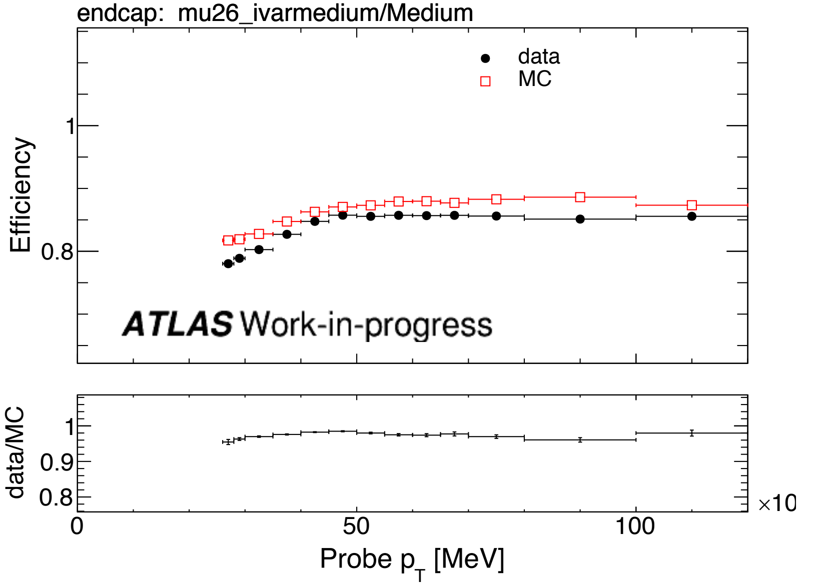




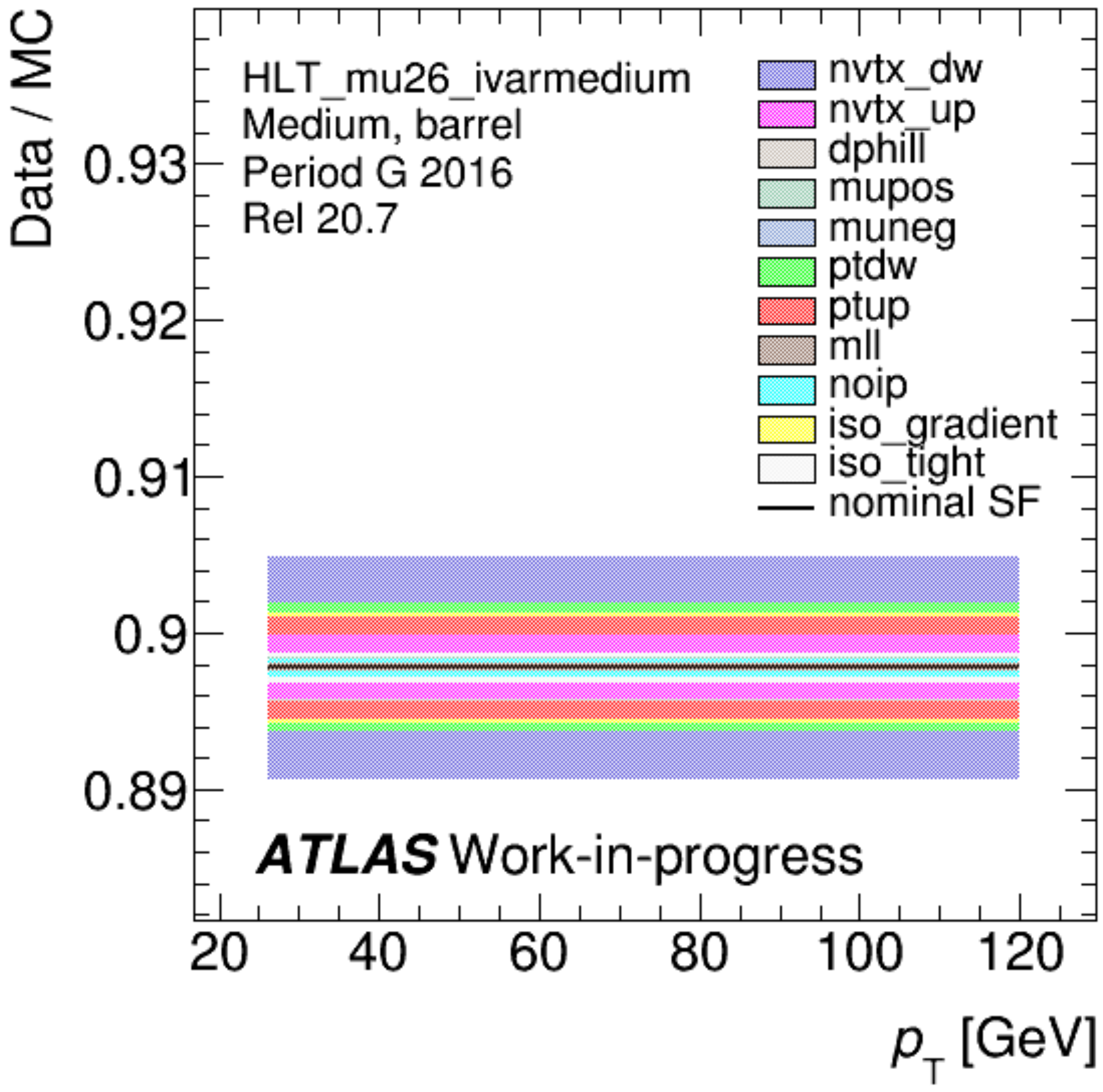


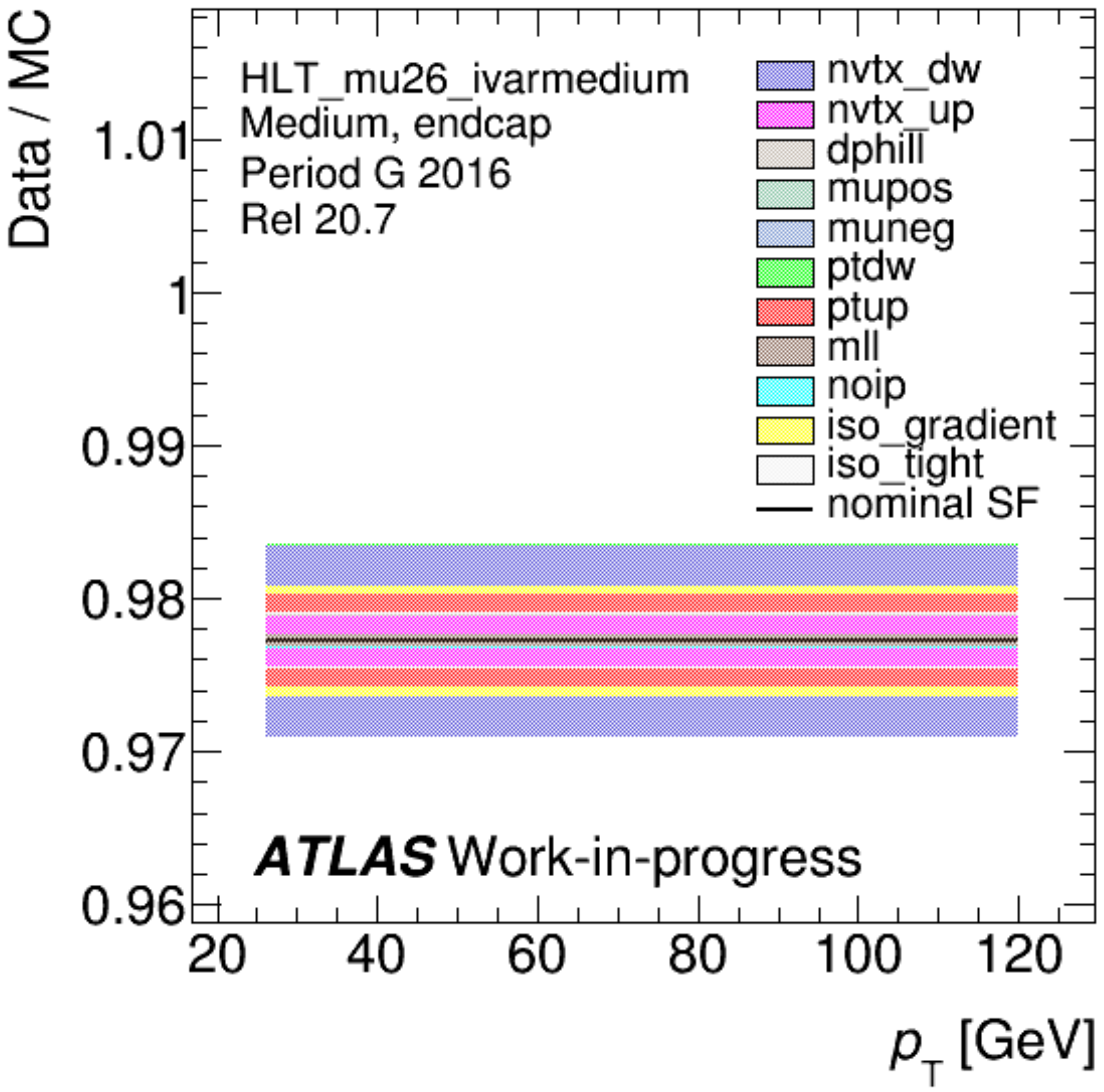




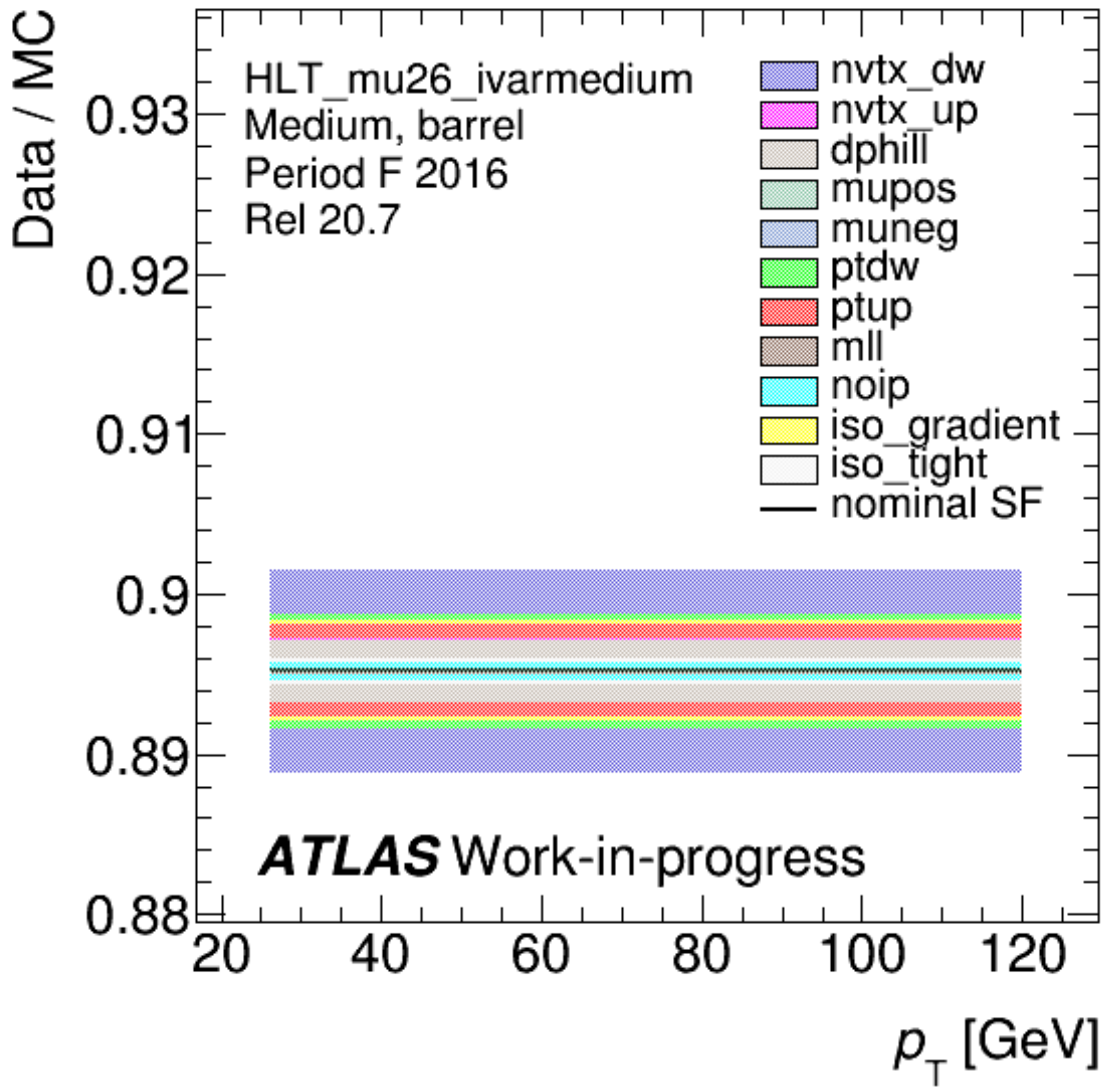


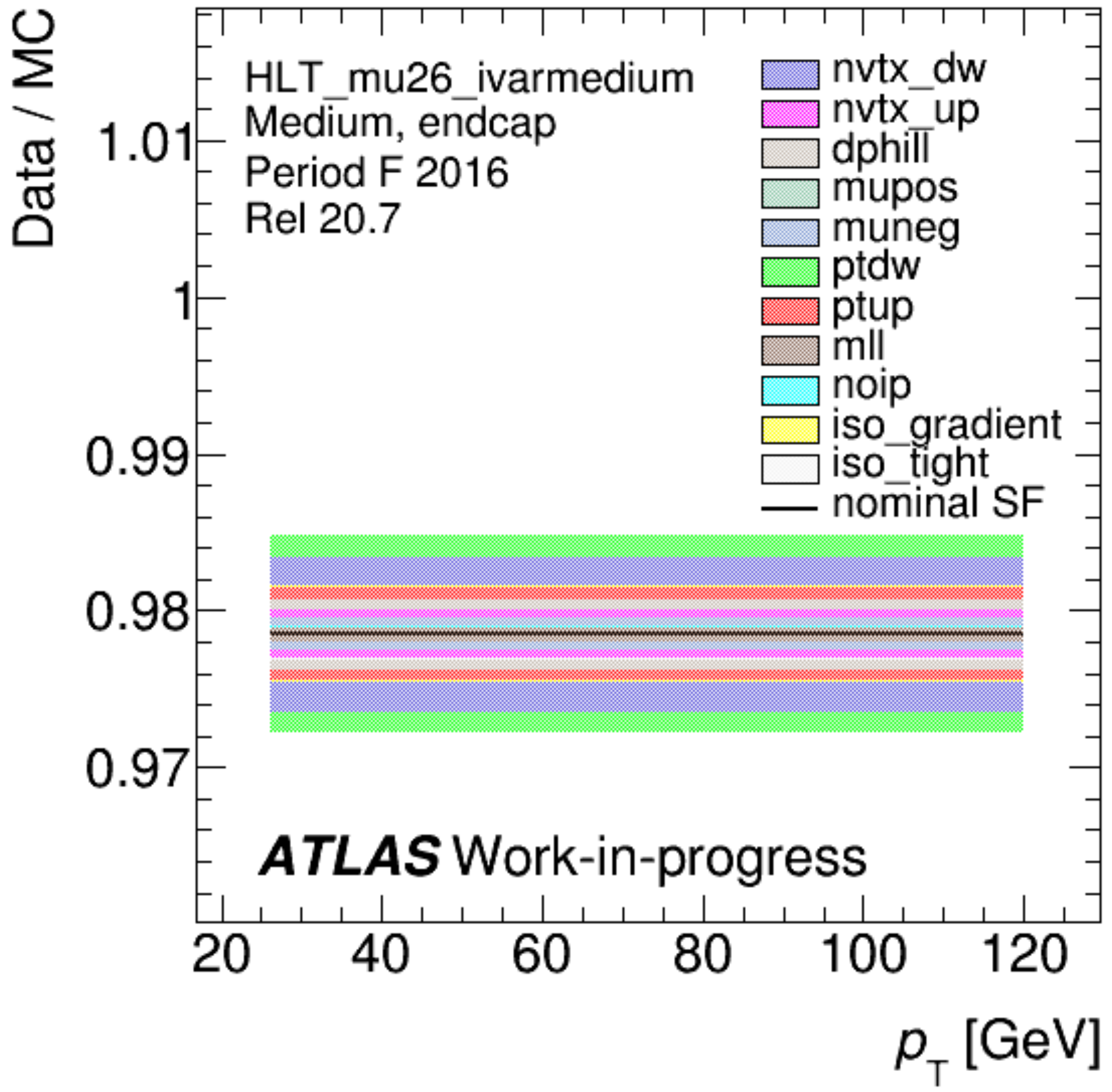
Period G 2016





Period F 2016





Period F 2016