ATLAS Monojet Run-II Analysis & MinBias Measurements with the ATLAS Tile Calorimeter

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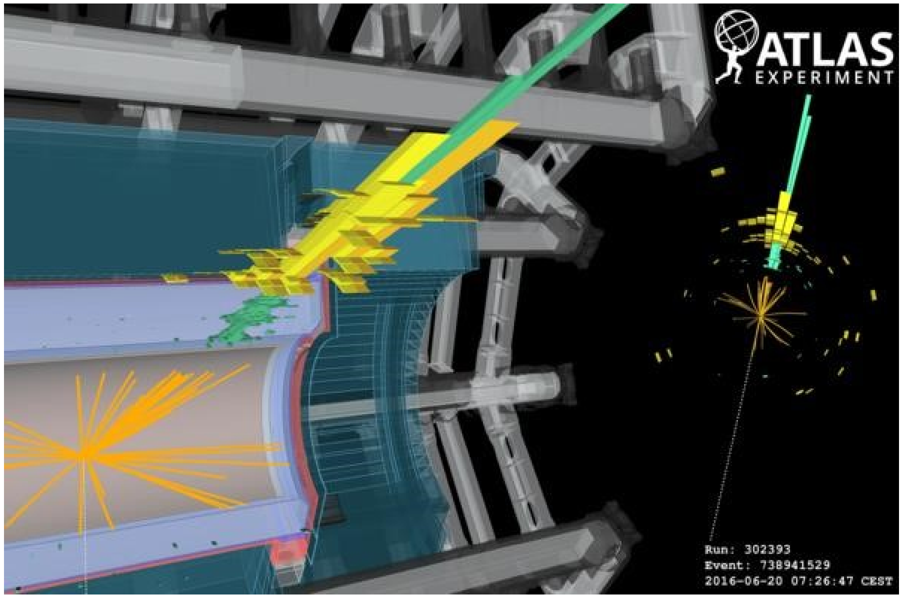
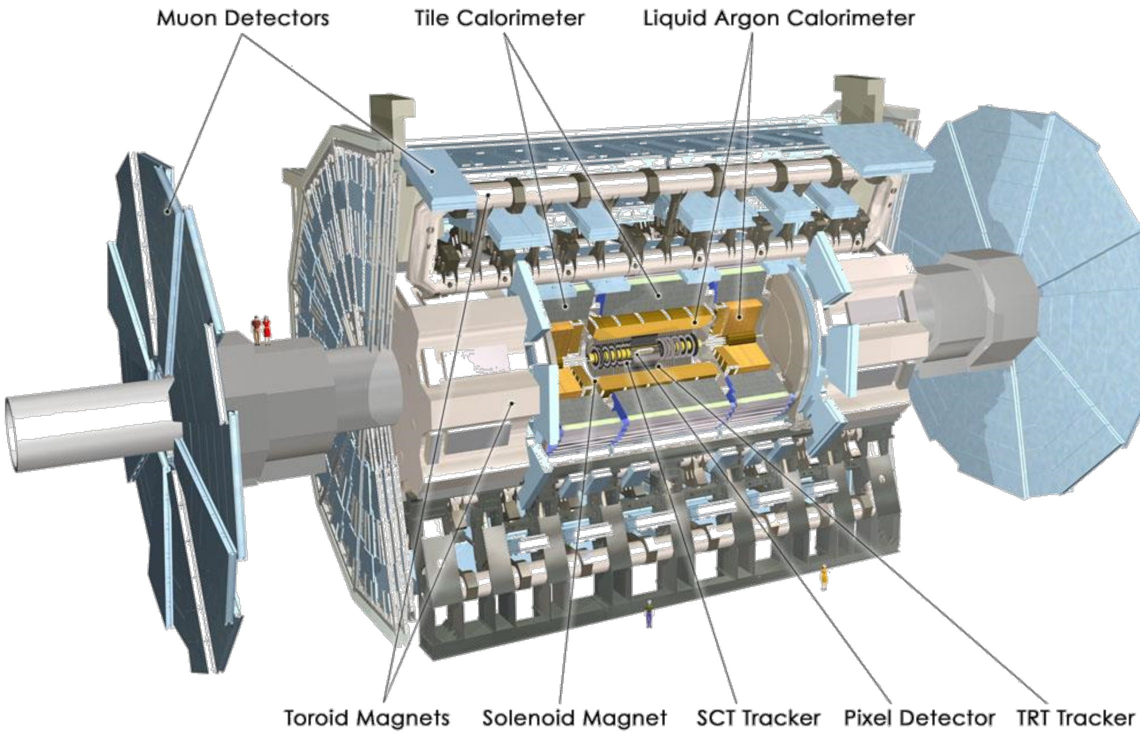
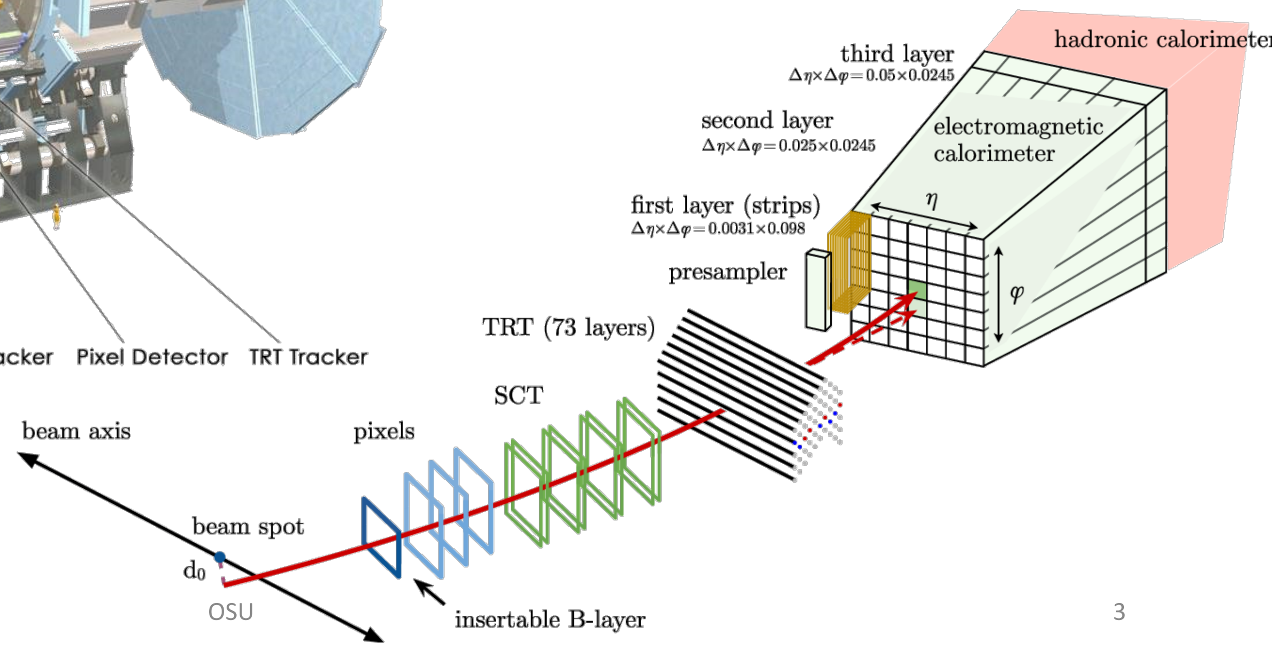
MonoJet Analysis Outline

- ATLAS Detector
- Monojet Signature
- Signal Region
- Backgrounds
  - Non-Collision Background
  - anti-Scale Factors
  - Control Regions
- 2015+2016 Results
- Analysis Improvements



The ATLAS Detector





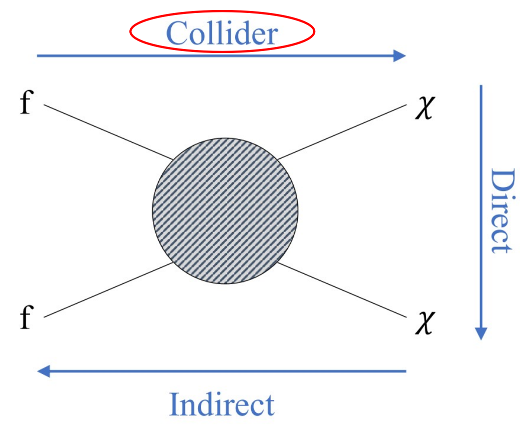
MonoX Signatures

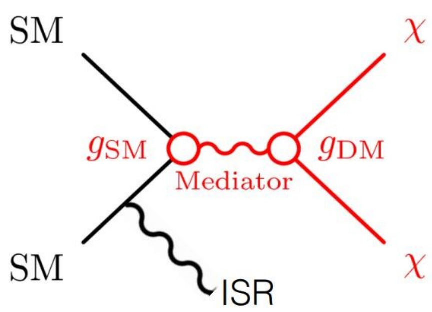
Signature with a **single high energy object X** and large E_T^{miss}

MonoJet, MonoPhoton, MonoV, etc

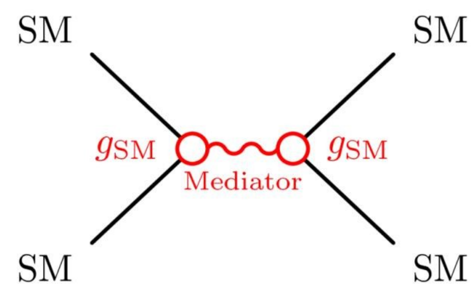
X may be result of initial state radiation (ISR) or associated production

“Traditional” Mono-X dark matter search assumes **pair produced DM particles** with ISR **X** as the **detectable object**





Mono-X
Shape Search



Resonance
Peak Search

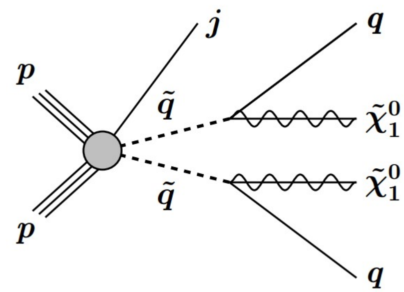
MonoJet Overview

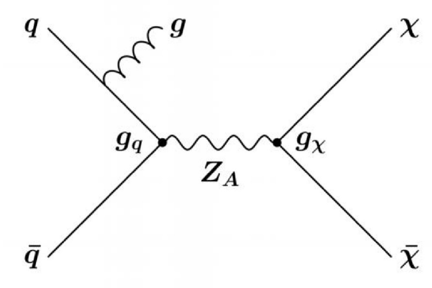
Target models with a **single high energy jet back-to-back** with large E_T^{miss}

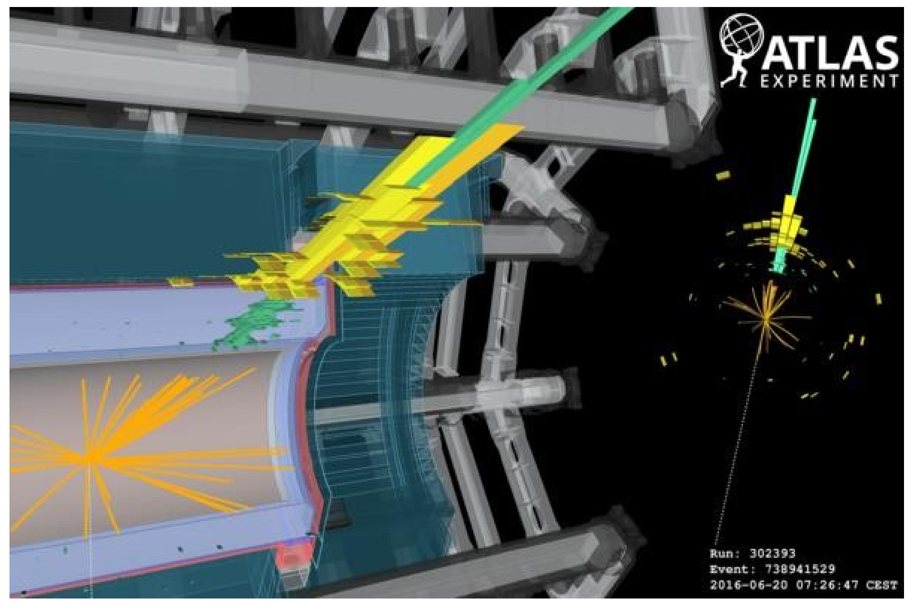
Other *low* E_T jets may be present, but veto on leptons and photons

Can arise from physics associated with many models, such as WIMP DM, Compressed SUSY, ALPs, Dark Energy, etc.

Dominate background is $Z \rightarrow \nu\nu$, followed by $\mathrm{W} \rightarrow l\nu$



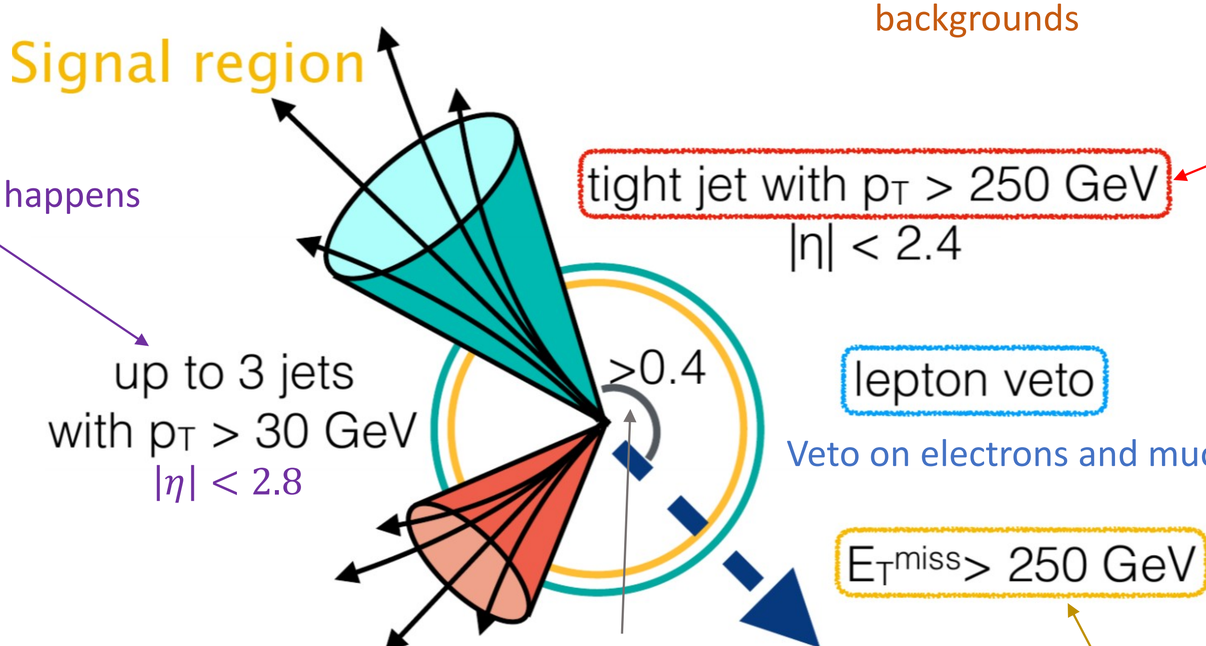




MonoJet Signal Region

- Perform analysis in bins of E_T^{miss}

Many signals have harder E_T^{miss} spectra than SM backgrounds



Identify the monojet as a good jet not from beam-induced background

Multiple ISR happens

$|\eta| < 2.8$

Veto on electrons and muons

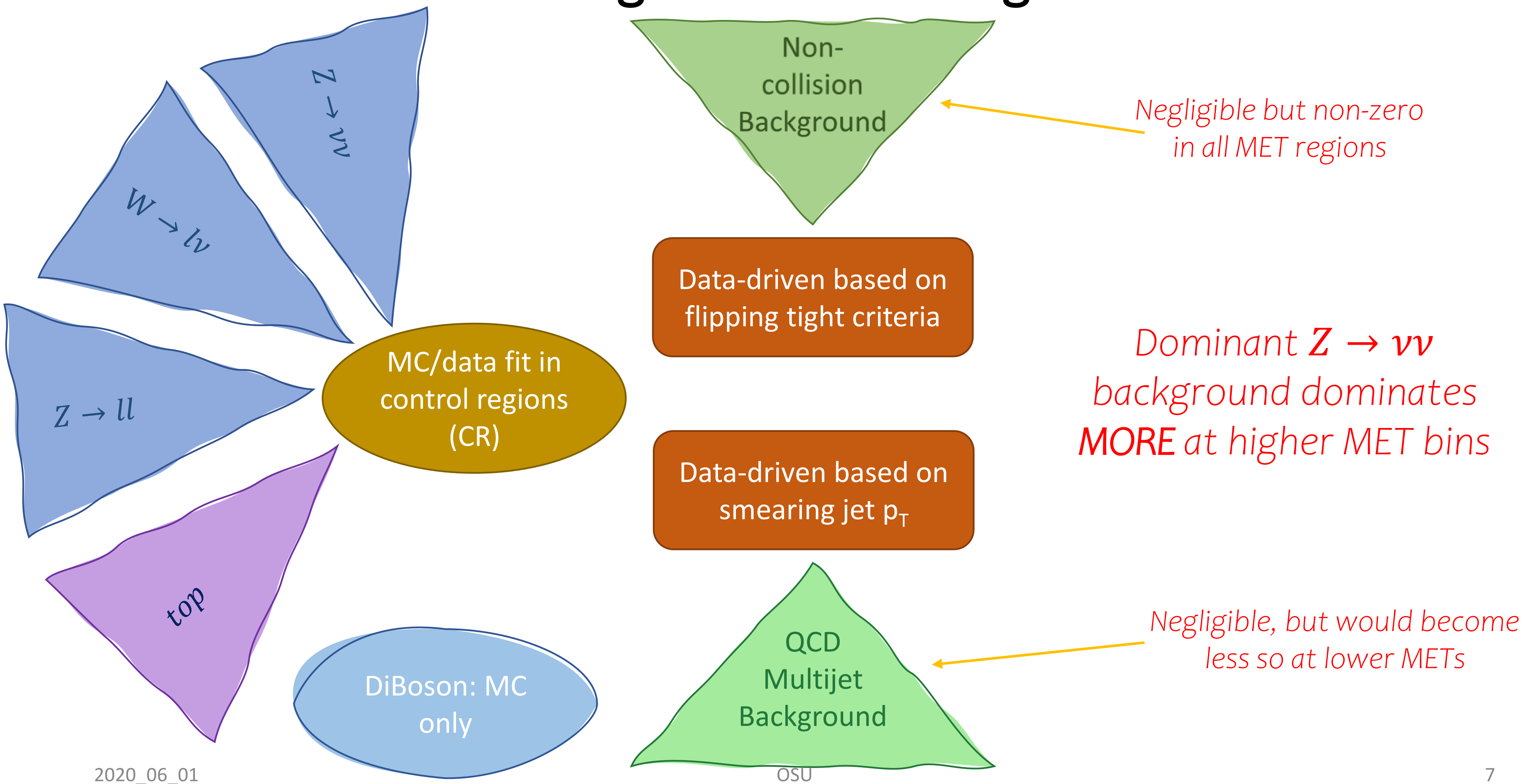
Not an inherent part of interpreted models, present in some backgrounds

$\Delta\phi(jet, \vec{p}_T^{miss}) > 0.4$

Reduce QCD multijet background to negligible levels

Trigger efficiency + high backgrounds at low E_T^{miss}

Estimating MonoJet Backgrounds

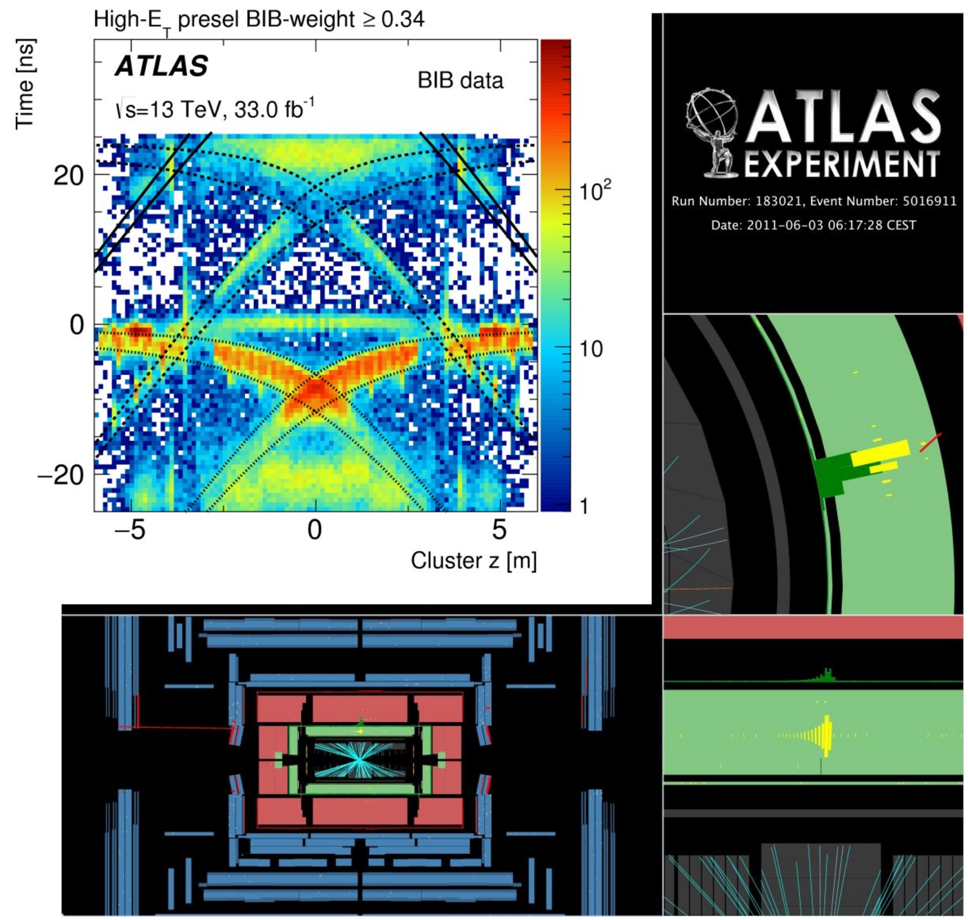


Non-Collision Backgrounds

MET triggers especially sensitive to Beam-Induced Background (**BIB**)

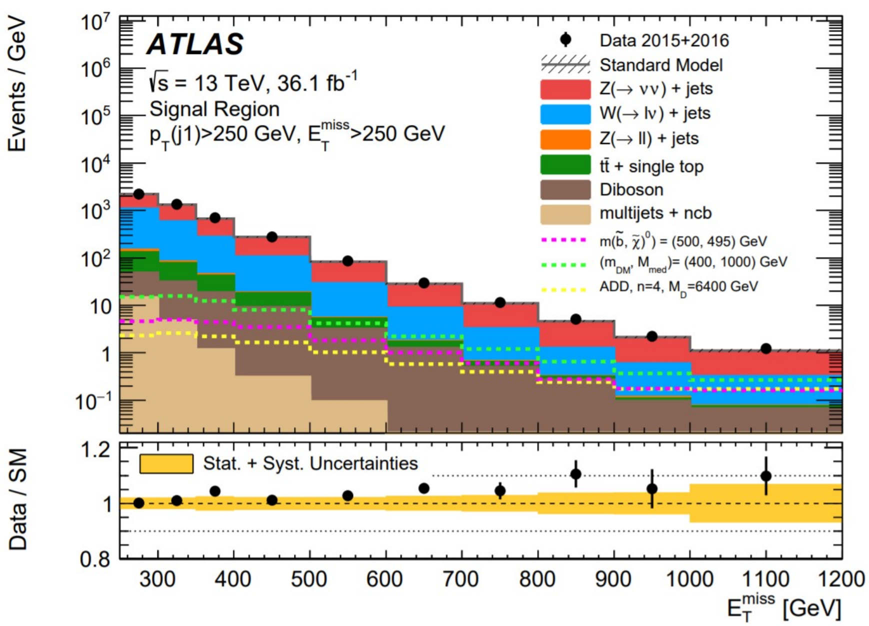
Muon travelling *in-time with proton bunch* and *parallel to the beampipe* emits hard bremsstrahlung radiation, resulting in a fake jet/fake MET

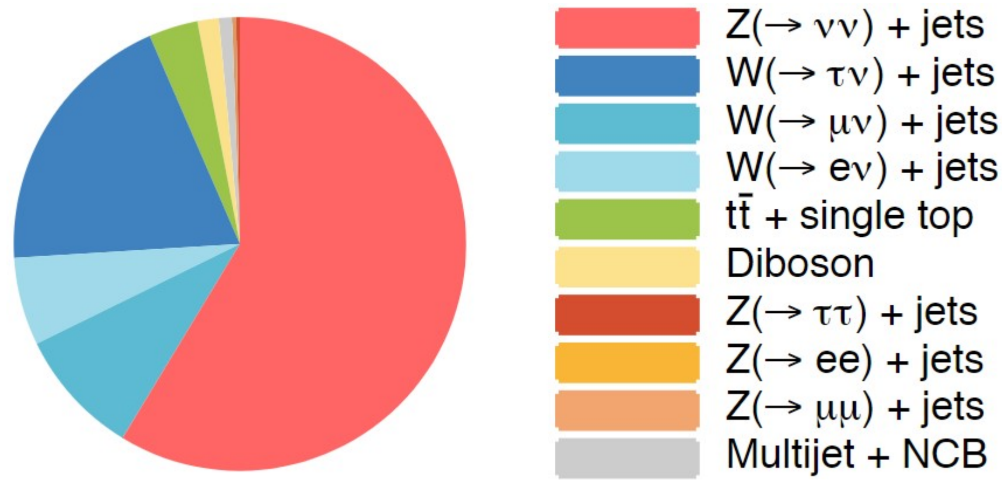
Jets are usually *trackless* and have most of their *energy in a single layer*, properties targeted by the **tight cleaning**

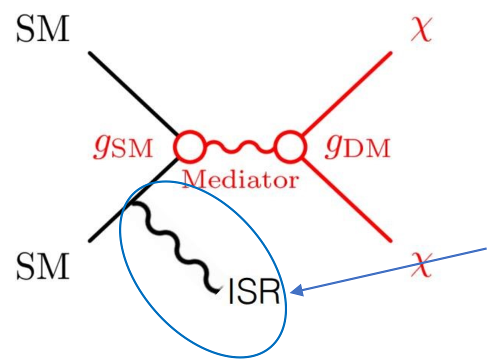


Dominate MonoJet Backgrounds

- $Z \rightarrow \nu\nu$: Dominate and irreducible, ISR boosted just like signal
- $\mathrm{W} \rightarrow l\nu$: ISR boosted + lost lepton

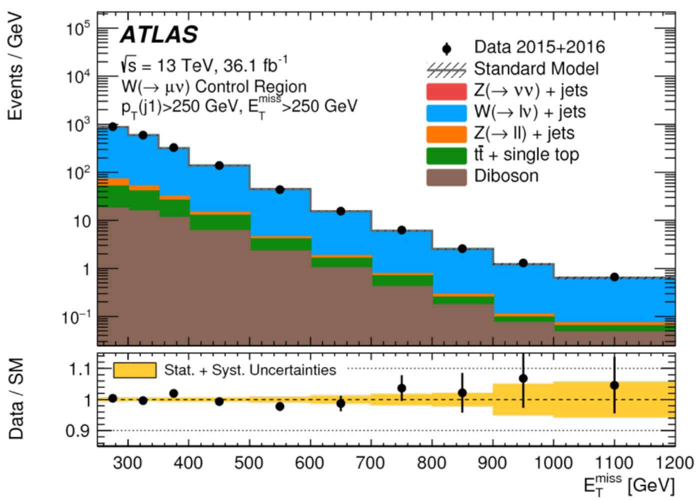


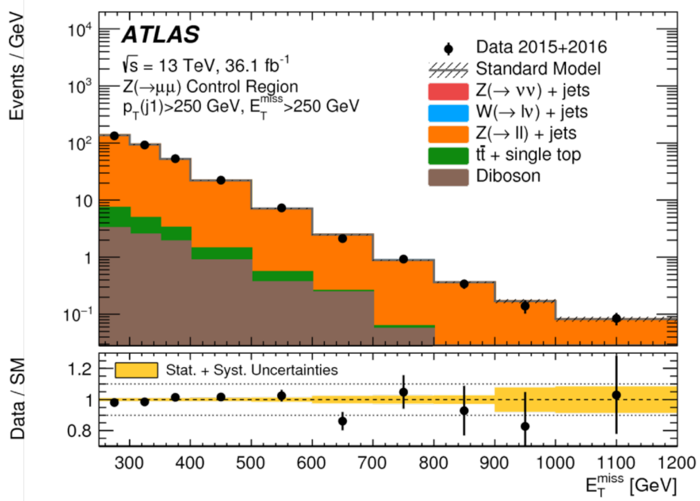


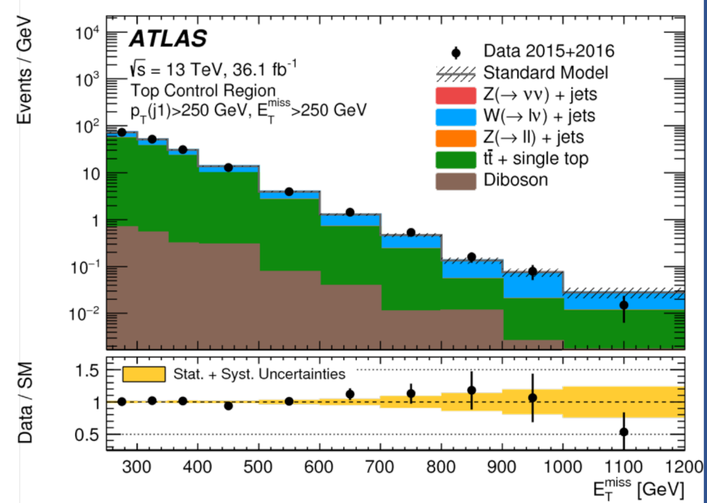


Strong enough for signal, made to boost backgrounds

Control Regions & Simultaneous Fit







- Require a good muon with $p_{\mathrm{T}} > 10$ GeV, but veto b jets
- Add muon to $E_{\mathrm{T}}^{\mathrm{miss}}$
- Require $30 < m_{\mathrm{T}} < 100$ GeV where

$$m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{l}p_{\mathrm{T}}^{\nu}[1-\cos(\phi^{l}-\phi^{\nu})]}$$

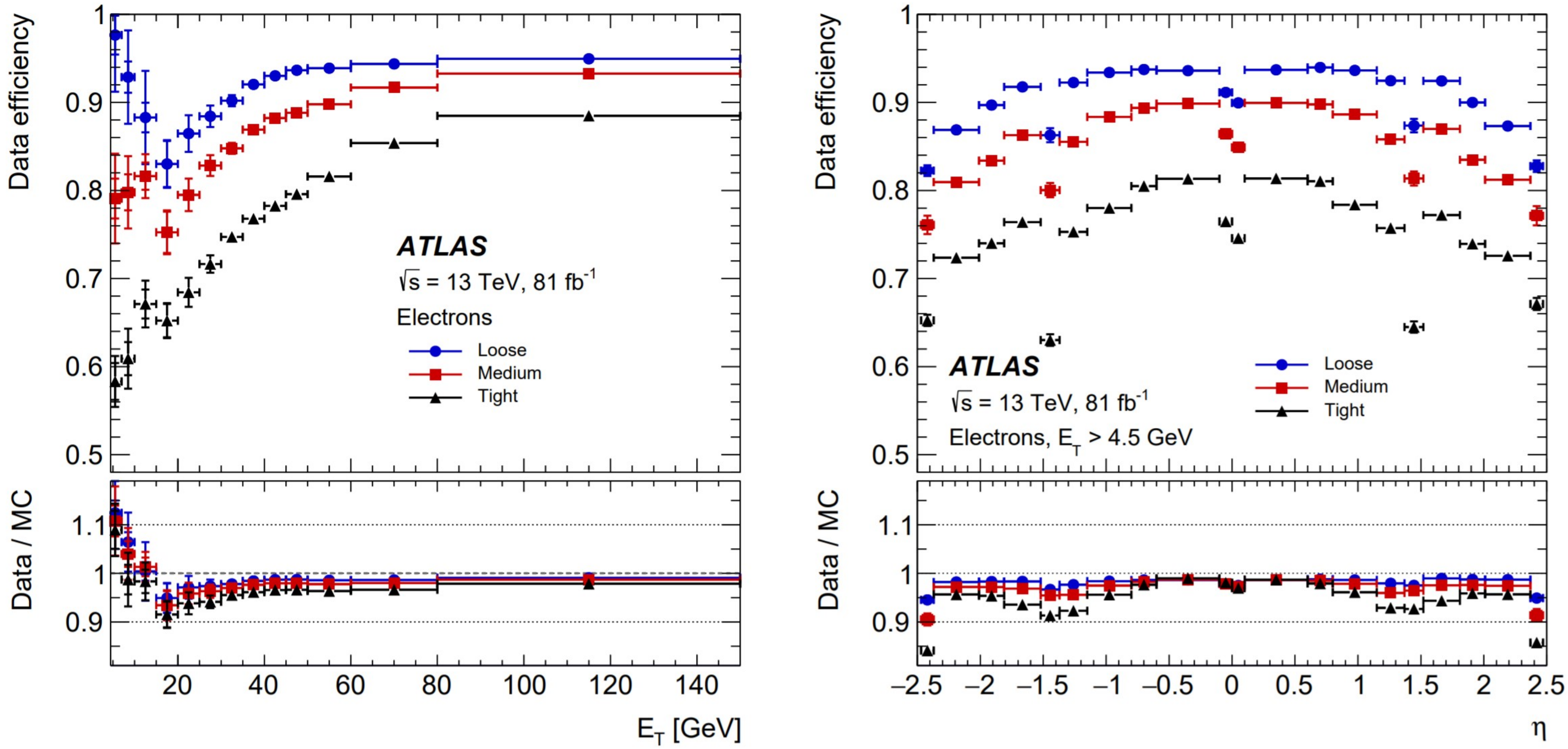
- Require two good muons with $p_{\mathrm{T}} > 10$ GeV, but veto b jets
- Add muons to $E_{\mathrm{T}}^{\mathrm{miss}}$
- Require $66 < m_{\mu\mu} < 116$ GeV

- Require a good muon with $p_{\mathrm{T}} > 10$ GeV
- Require at least one b jets
- Add muon to $E_{\mathrm{T}}^{\mathrm{miss}}$
- Require $30 < m_{\mathrm{T}} < 100$ GeV where

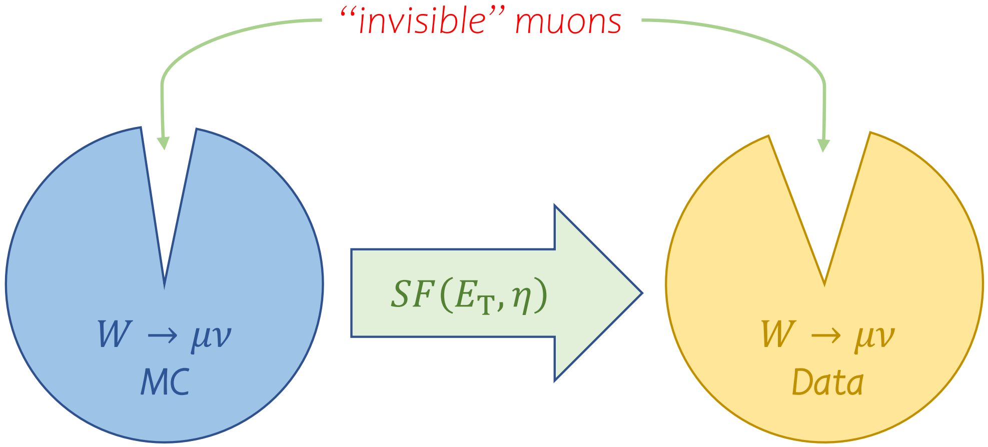
$$m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{l}p_{\mathrm{T}}^{\nu}[1-\cos(\phi^{l}-\phi^{\nu})]}$$

Can use the same $E_{\mathrm{T}}^{\mathrm{miss}}$ as the signal region!

Lepton Scale Factors



anti-Scale Factors – An Explanation



MC – fraction of IDed and reconstructed muons in e.g. $W \to \mu\nu$

Data – fraction of IDed and reconstructed muons in e.g. $W \to \mu\nu$

$$SF = \frac{\epsilon_{data}}{\epsilon_{MC}}$$

*Apply **scale factors** (SF) to the leptons in an analysis if **selecting** leptons*

*Apply **???** in an analysis if you **vetoing on** leptons*

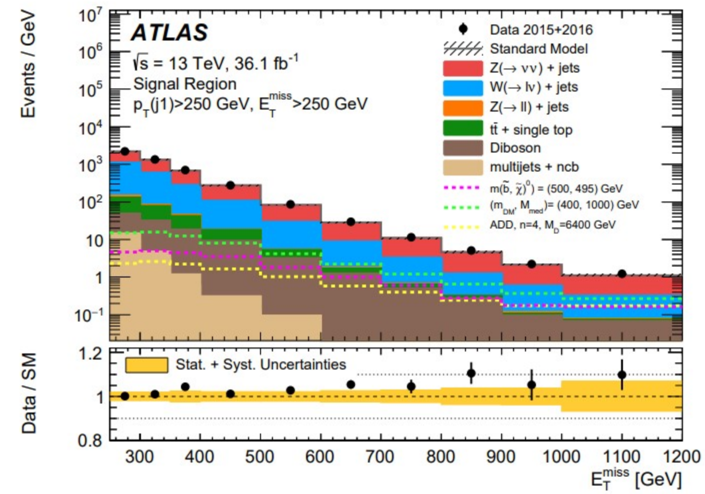
For us, the "???" are what we call "**anti-SF**", and are applied **per-region** to the **full sample** based on the mean SF of the vetoed leptons

For $W \to \mu\nu$ in the SR:
$antiSF \approx 1.05$

JHEP 1801 (2018) 126: 36.1 fb−1 (2015 + 2016 pp collision data)

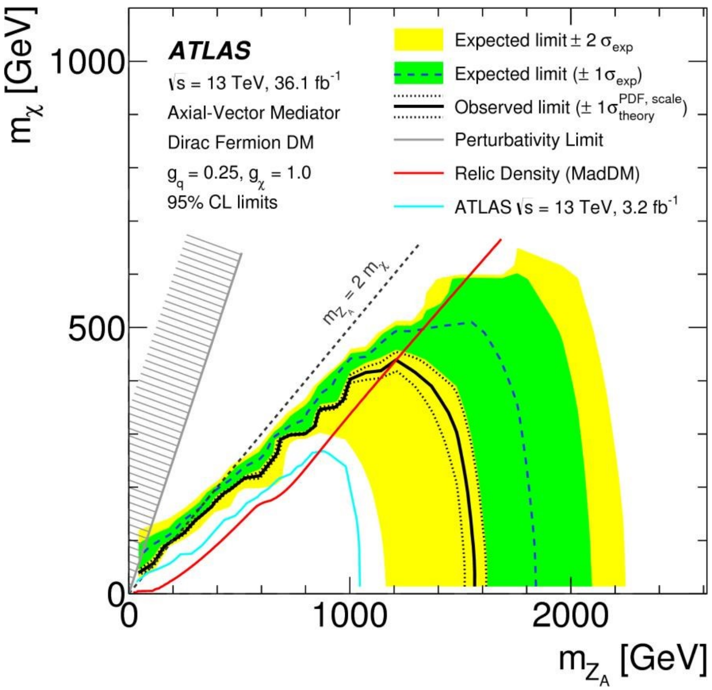
2015+2016 Results

- $\kappa_t = 1.31$
- $\kappa_V = 1.27$
- Set most stringent model-independent limits yet on benchmark DM model
- Additional interpretations were large extra spatial dimensions and SUSY
- Dominate systematics are:
  - Pre-fit: PDF, JES, and theoretical uncertainty on top-quark production
  - Post-fit: Muon, electron ID efficiencies, pileup reweighting
- Projections suggest more to gain by improving analysis (reducing systematics, increasing signal to background) than by gathering more data



Exclusive Signal Region	EM2	EM8	EM9
Observed events (36.1 fb^{-1})	67475	512	223
SM prediction	67100 ± 1400	463 ± 19	213 ± 9
$W(\to e\nu)$	5510 ± 140	18 ± 1	8 ± 1
$W(\to \mu\nu)$	6120 ± 200	21 ± 5	11 ± 1
$W(\to \tau\nu)$	13680 ± 310	55 ± 5	29 ± 2
$Z/\gamma^*(\to e^+e^-)$	0.03 ± 0	–	–
$Z/\gamma^*(\to \mu^+\mu^-)$	167 ± 8	0.4 ± 0.1	0.5 ± 0.1
$Z/\gamma^*(\to \tau^+\tau^-)$	185 ± 6	0.3 ± 0.1	0.31 ± 0.04
$Z(\to \nu\bar{\nu})$	37600 ± 970	337 ± 12	153 ± 7
$t\bar{t}$, single top	2230 ± 200	4 ± 1	1.3 ± 0.4
Diboson	1327 ± 90	26 ± 5	10 ± 2
Multijet background	170 ± 160	1 ± 1	0.1 ± 0.1
Non-collision background	71 ± 71	–	–

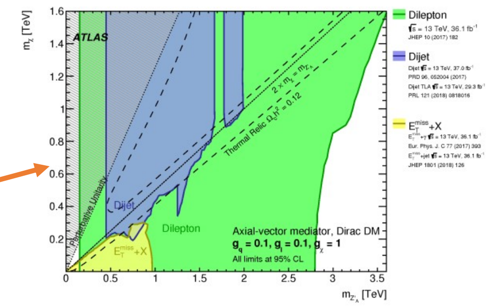
MonoJet Interpretations: Benchmark DM

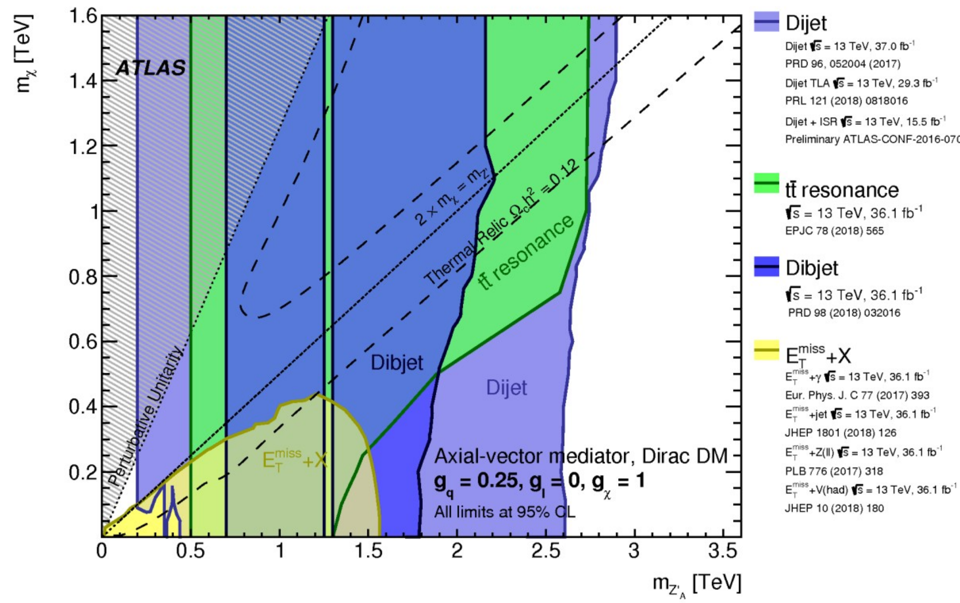


ATLAS/CMS Dark Matter Forum:
1507.00966

ATLAS Mediator DM Summary Paper:
1903.01400

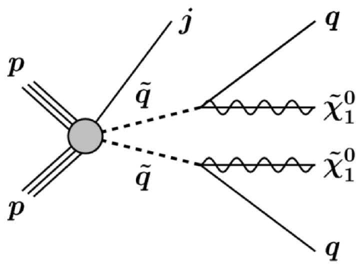
- At higher g_q, resonance searches dominate
- Search complementarity especially clear in leptophilic model

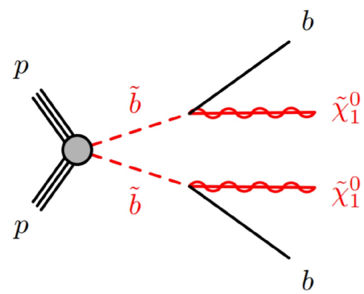


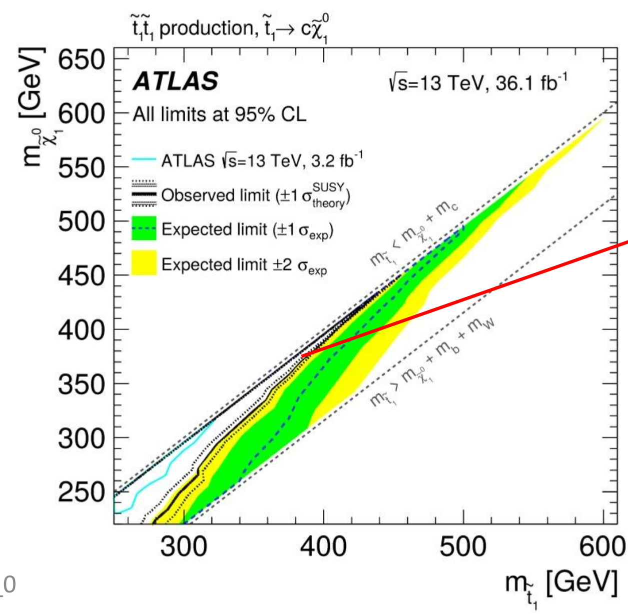


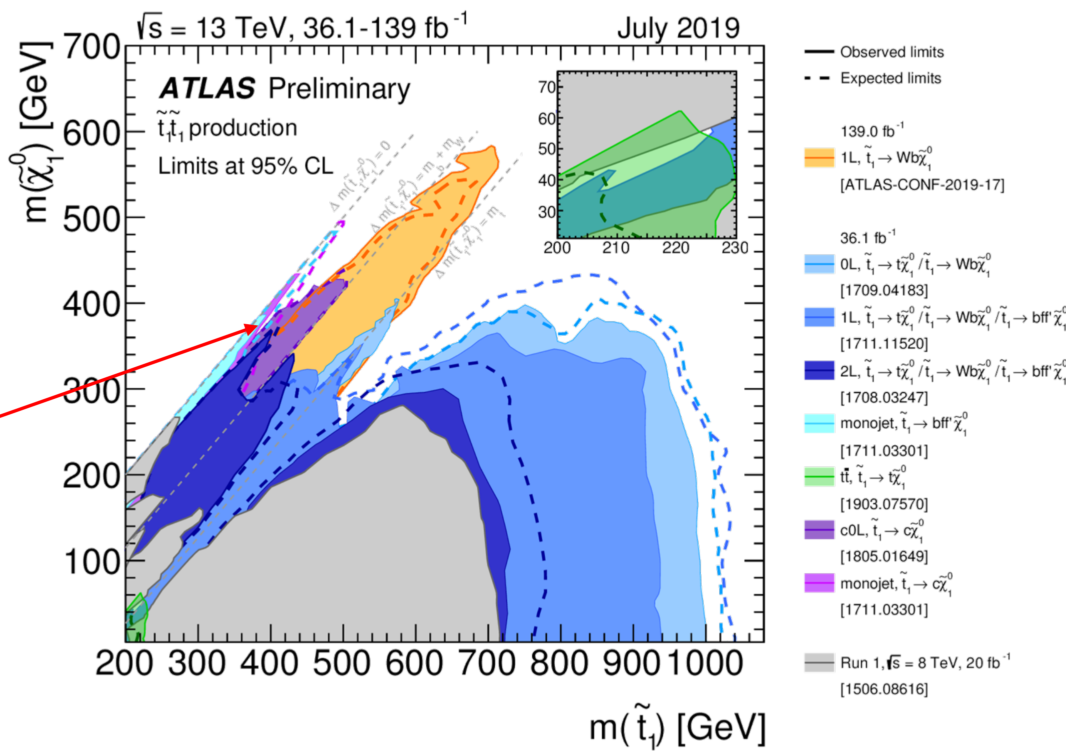
$\Delta m_{\tilde{q}\tilde{\chi}_1^0} \sim \text{small}$

Monojet Interpterion: Compressed SUSY









Possible Upcoming Improvements

Lower minimum MET cut & analyze the trigger turn on

Add new control regions, such as $Z \rightarrow ee$

Consider new interpretations, such as axion-line particles and invisible Higgs

Add a tau veto

Try splitting top control region

Veto on softer leptons

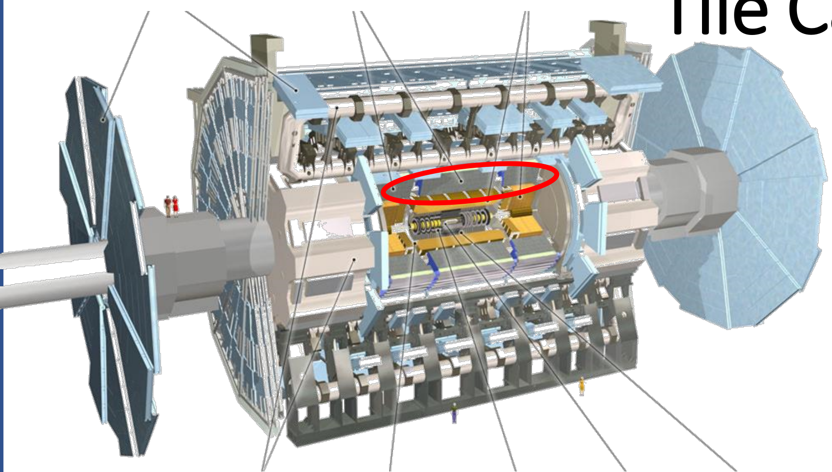
Part 1 Conclusions: ATLAS MonoJet Search

- Monojet analysis looks for enhancement or distortion of missing energy spectrum resulting from new invisible particles recoiling off of an energetic jet
- Both larger backgrounds and trigger limitations drive the lower cut on missing energy
- Analysis utilizes control regions for dominate backgrounds
- Other backgrounds reduced by cleaning criteria
- Largest gain in limits in the future likely to come from analysis evolution more than extra data

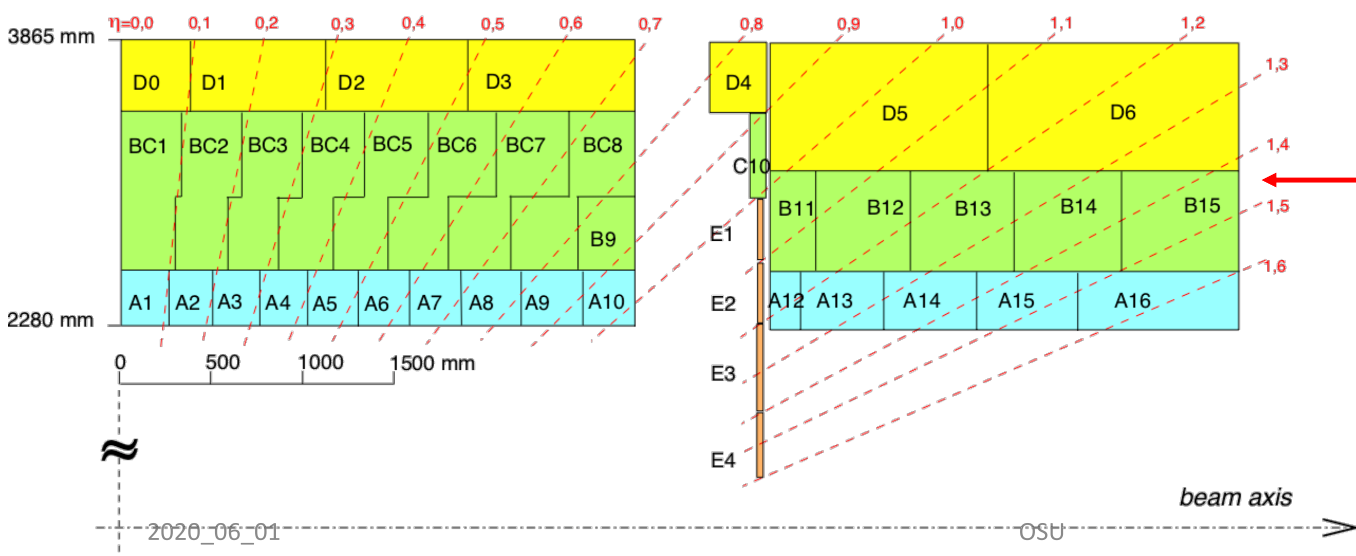
Tile MinBias Outline

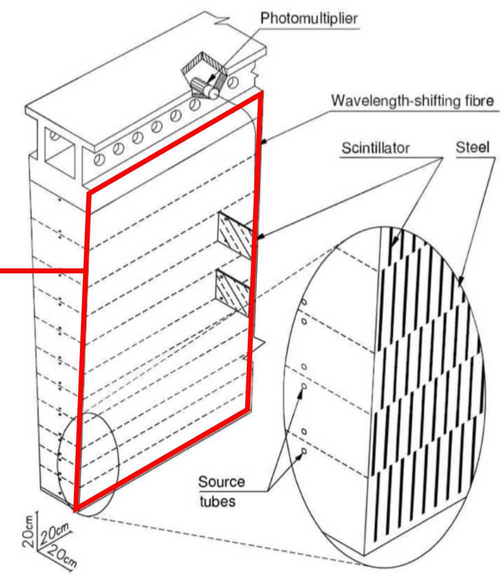
- Tile Calorimeter
- Energy and Aging
- Tile Minbias Measurements
- Luminosity
  - Why it matters
  - What systems can measure it
- Lucid Calibration
- Long Term Stability
- Possible Tile Advancements

Tile Calorimeter Revisited



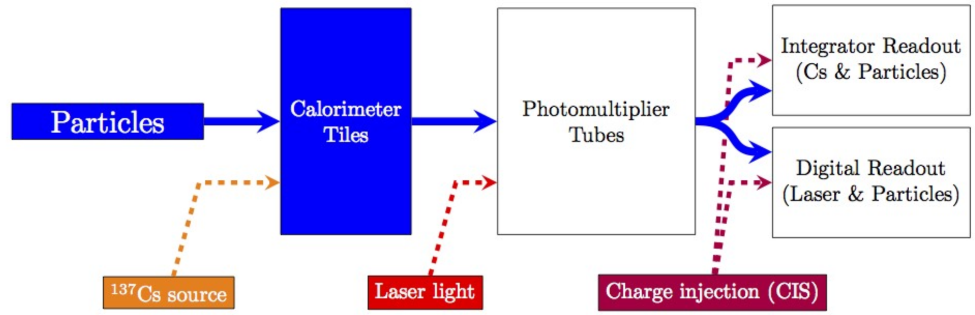
- Tile is a sampling calorimeter composed of alternating steel absorbers and scintillator tiles
- Calorimeter consists of four partitions each with 64 wedge shaped modules
- Modules made up of cells
- Cells defined by bundles of fibers from scintillators fed into the same PMT

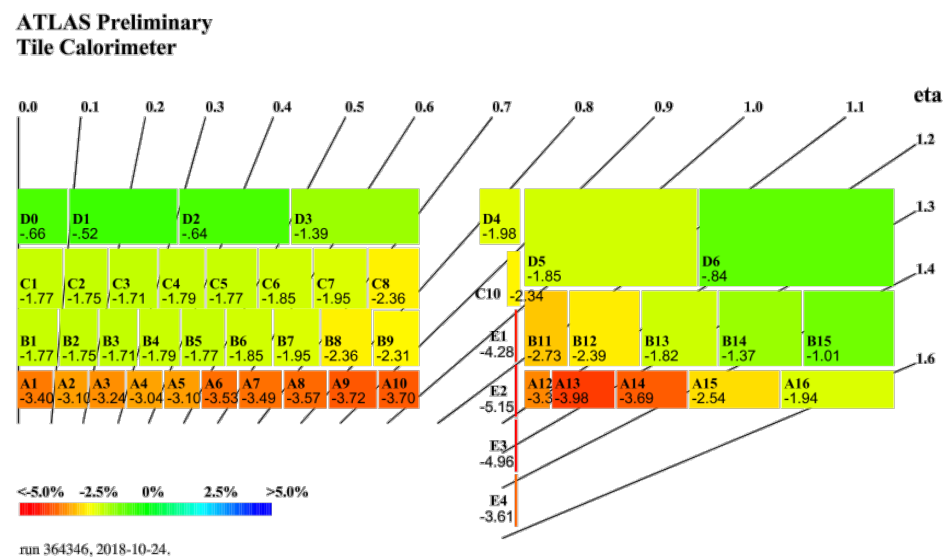




Tile Energy Measurements and Aging

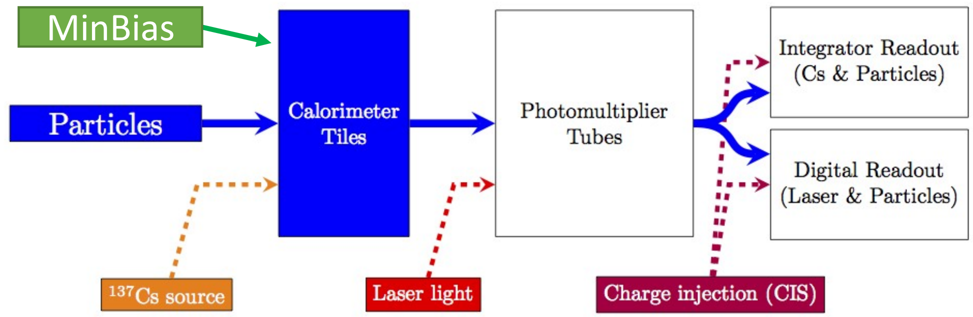
- Particles passes through scintillators, which absorb some of the energy and emit light
- Light collected by the wavelength shifting fibers, which pass it to the PMTs
- PMTs pass a current to the electronics, which yield a recorded signal
- Ideally, the relationship between energy and current is independent of time
- In reality, aging is a major issue and frequent calibration is necessary

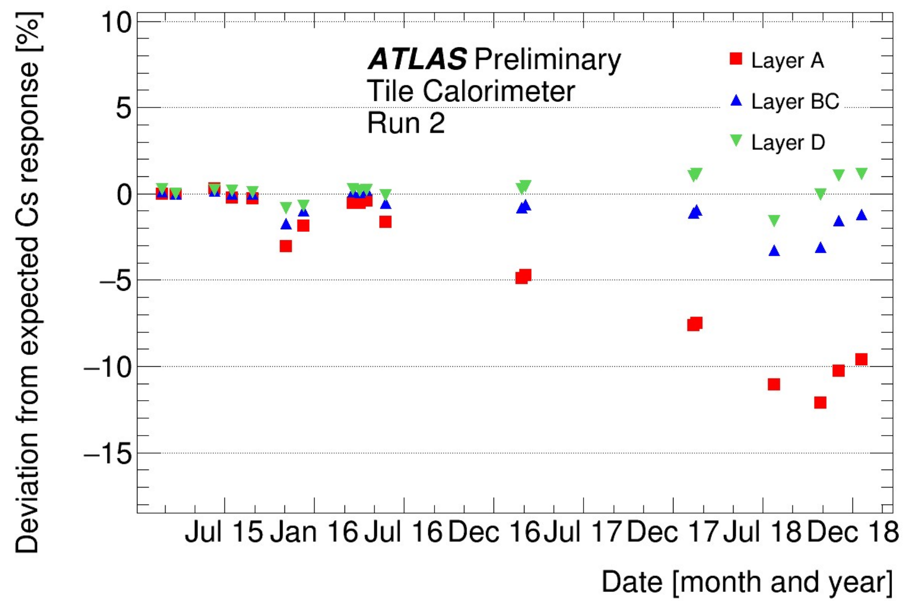




MinBias Measurements

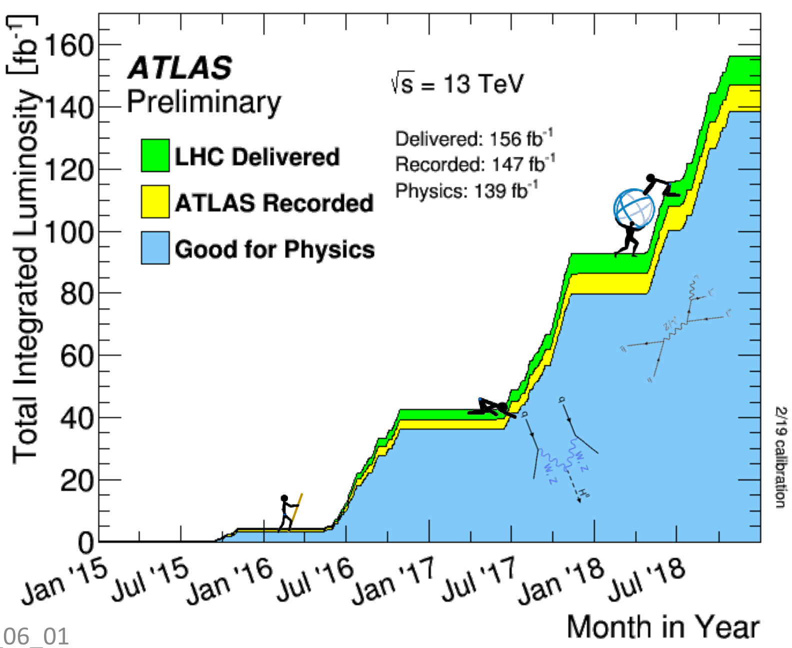
- Tile readout electronics include **low-current integrators** that average current from each PMT over **O(10 ms)**
- Originally intended to measure **low currents from CS** during calibration, but readout from physics runs as well
- Can supplement (or replace) Cs measurements in physics runs!
- Even sensitive in very low current special runs, **good for luminosity**!





Why Luminosity Matters

- 139 fb^{-1} *pp* data for Run-II
- Preliminary uncertainty for Run-II dataset at 1.7%
- Luminosity uncertainty is the dominant uncertainty for many precision measurements



Measurement of the $Z(\rightarrow \ell^+\ell^-)\gamma$ production cross-section in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector
(1911.04813)

Source	Uncertainty [%] $e^+e^-\gamma$	Uncertainty [%] $\mu^+\mu^-\gamma$	Correlation
Trigger efficiency	–	0.2	no
Photon identification efficiency	1.0		yes
Photon isolation efficiency	0.9		yes
Electron identification efficiency	1.4	–	no
Electron reconstruction efficiency	0.3	–	no
Electron–photon energy scale	0.9	0.6	partial
Muon isolation efficiency	–	0.4	no
Muon identification efficiency	–	0.7	no
Z + jets background	1.3		yes
Pile-up background	0.6		yes
Other backgrounds	0.8	0.7	partial
Monte Carlo event statistics	0.4	0.4	no
Integrated luminosity	1.7		yes
Systematic uncertainty	3.2	2.9	
Statistical uncertainty	0.6	0.5	
Total uncertainty	3.2	3.0	

A Matter of Uncertainty

Data sample	2015+16	2017	2018	Comb.
Integrated luminosity (fb^{-1})	36.2	44.3	58.5	139.0
Total uncertainty (fb^{-1})	0.8	1.0	1.2	2.4
Uncertainty contributions (%):				
DCCT calibration†	0.2	0.2	0.2	0.1
FBCT bunch-by-bunch fractions	0.1	0.1	0.1	0.1
Ghost-charge correction*	0.0	0.0	0.0	0.0
Satellite correction†	0.0	0.0	0.0	0.0
Scan curve fit model†	0.5	0.4	0.5	0.4
Background subtraction	0.2	0.2	0.2	0.1
Orbit-drift correction	0.1	0.2	0.1	0.1
Beam position jitter†	0.3	0.3	0.2	0.2
Beam-beam effects*	0.3	0.3	0.2	0.3
Emittance growth correction*	0.2	0.2	0.2	0.2
Non-factorization effects*	0.4	0.2	0.5	0.4
Length-scale calibration	0.3	0.3	0.4	0.2
ID length scale*	0.1	0.1	0.1	0.1
Bunch-by-bunch σ_{vis} consistency	0.2	0.2	0.4	0.2
Scan-to-scan reproducibility	0.5	1.2	0.6	0.5
Reference specific luminosity	0.2	0.2	0.4	0.2
Subtotal for absolute vdM calibration	1.1	1.5	1.2	-
Calibration transfer†	1.6	1.3	1.3	1.3
Afterglow and beam-halo subtraction*	0.1	0.1	0.1	0.1
Long-term stability	0.7	1.3	0.8	0.6
Tracking efficiency time-dependence	0.6	0.0	0.0	0.2
Total uncertainty (%)	2.1	2.4	2.0	1.7

Systematic is *partially* correlated between years

Systematic is *fully* correlated between years

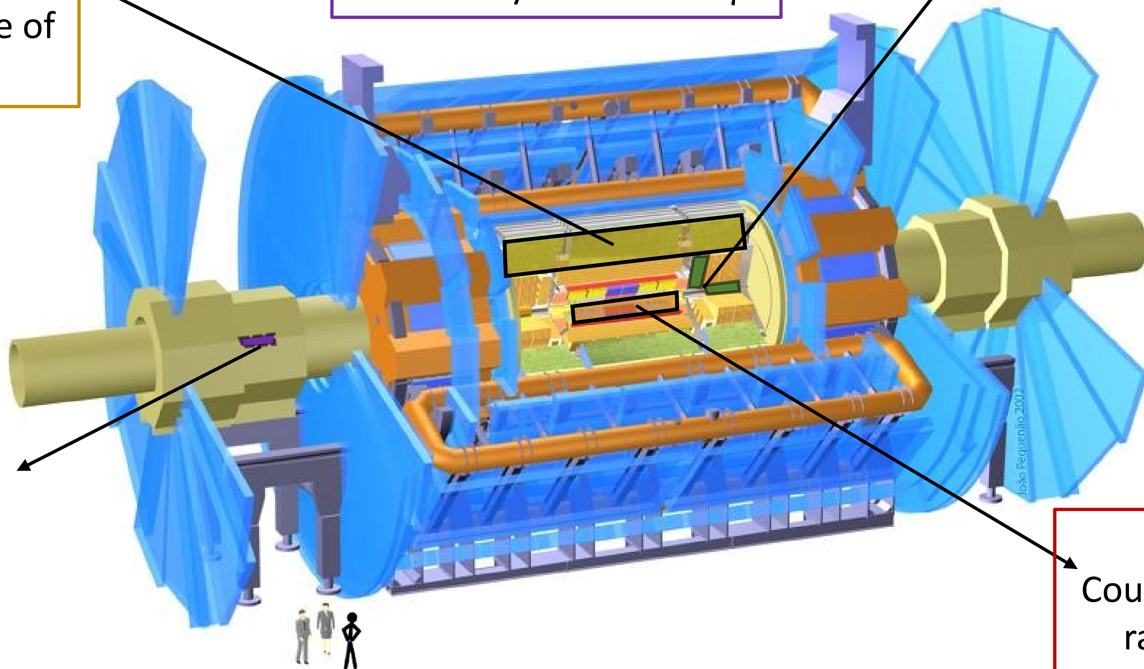
Correlations in uncertainty between years results in a reduced combined uncertainty

Luminosity Detectors & Algorithms

Tile
Diverts ~1% of PMT current and integrates over O(10) ms
Sensitive over wide range of luminosities

Z-counting
Cross-check of baseline luminosity vs time and μ

FCal & EMEC
Read out LAr gap HV currents over O(1) s integration times
Use of HV current bypasses trigger limitations



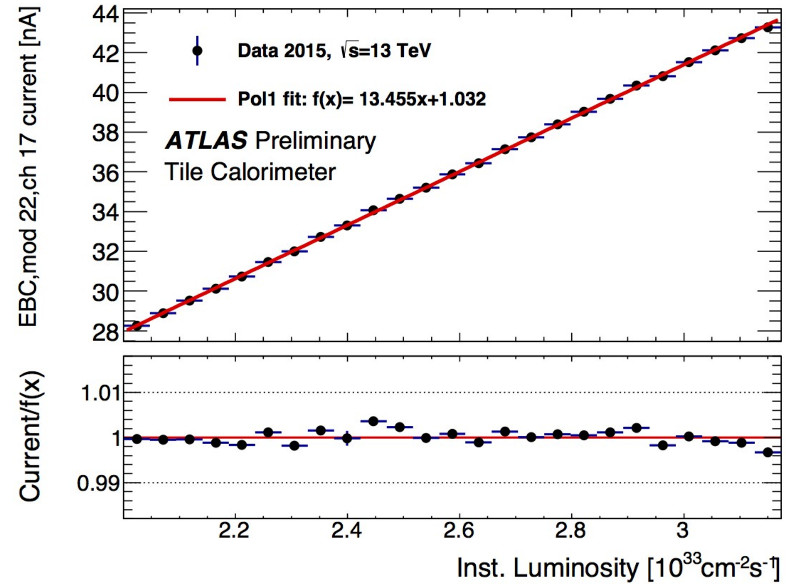
BCM and TPX
BCM only for low (μ) and HI runs
TPX for monitoring radiation

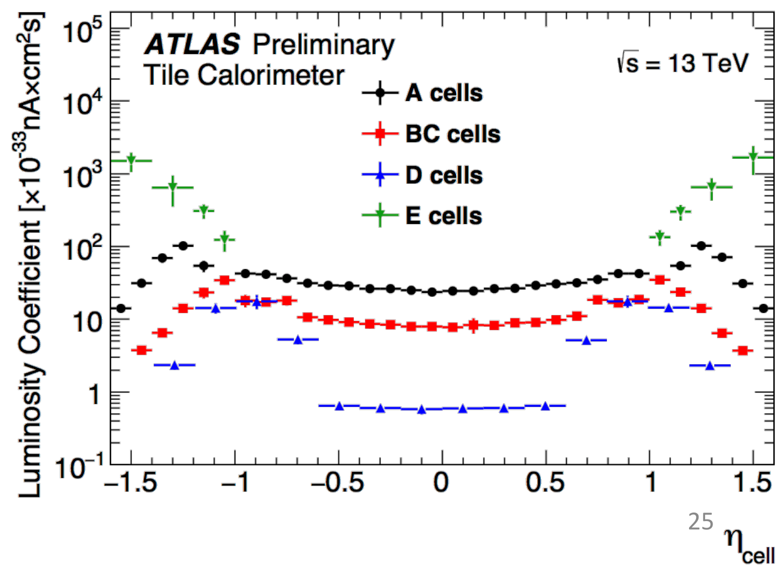
LUCID-2
The ATLAS reference luminometer, uses a hit counting algorithm
Provides real-time measurement of luminosity at any number of interactions per LHC bunch crossing (μ)

Tracks
Count reconstructed Si tracks in randomly triggered events
Sensitive over wide luminosity range

Luminosity Measurements with Tile

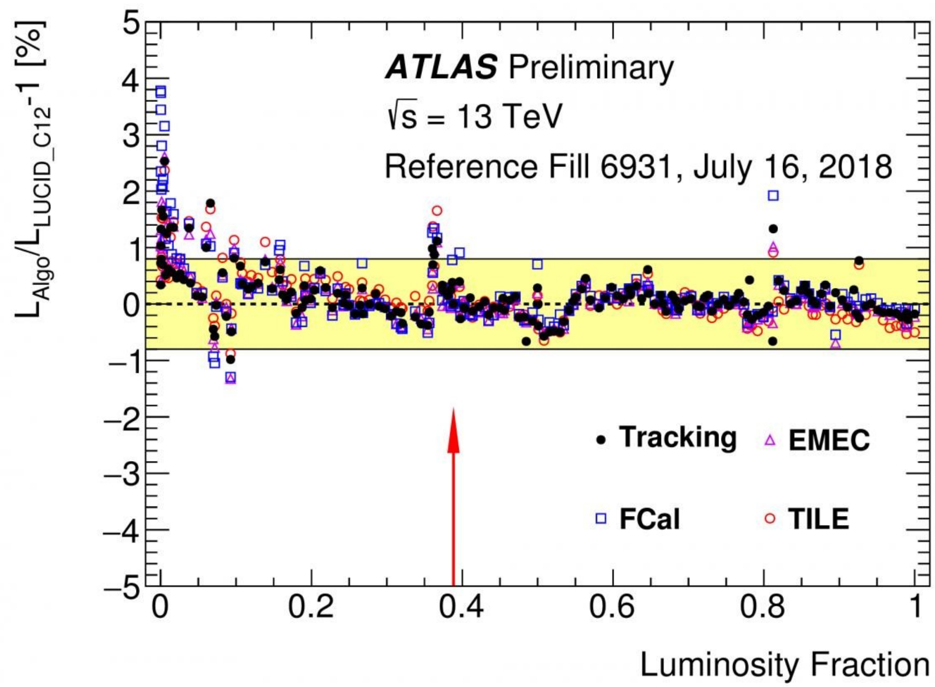
- The minbias current measured by Tile is **directly proportional to the luminosity**, to low order
- The slope of the relationship is the luminosity coefficient
- **Luminosity coefficients ideally constant**, but aging necessitates corrections to the luminosity, especially for the aging and recovery of PMTs
- Tile provides the only luminosity measurement in addition to Track Counting that is **robust against pileup**





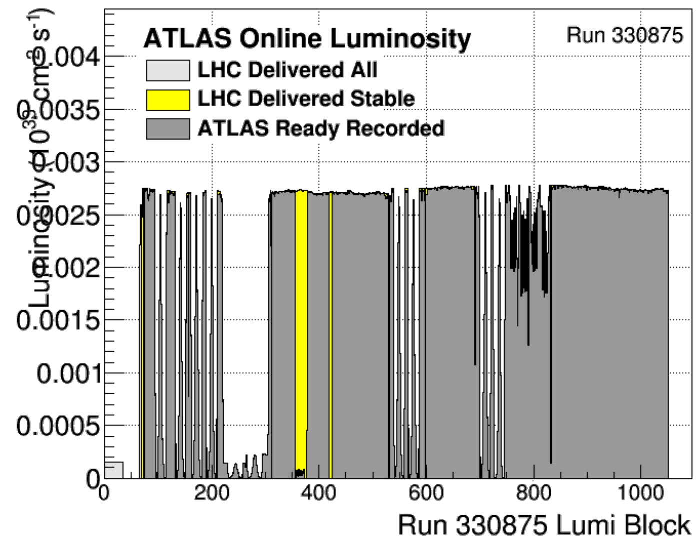
Long Term Stability

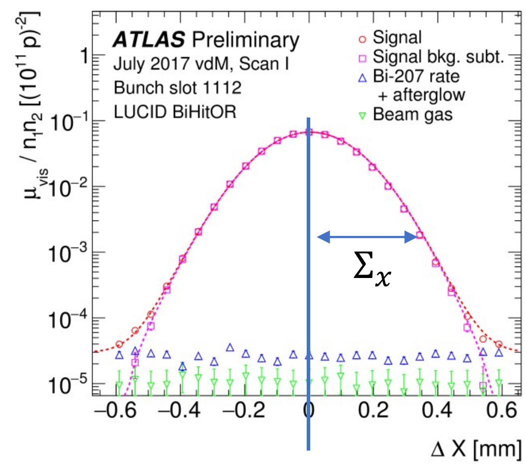
- Long-term stability uncertainty comes from a comparison of the luminosity measured by other luminometers to LUCID-2
- Reference run chosen for which all systems' luminosities are normalized to LUCID (red arrow)
- Contributing data from physics data runs, with calibration for LUCID coming from special calibration runs



LUCID Calibration

- vdM scans carried out with very low luminosity and isolated bunches
    - Multiple scans allow for evaluation of scan-to-scan reproducibility
    - Off-axis scans allow for evaluation of non-factorization
- Reference luminosity for calibrating LUCID comes from beam parameters
- O(10^{-4}) corrections account for Bi-207 and beam-gas interactions



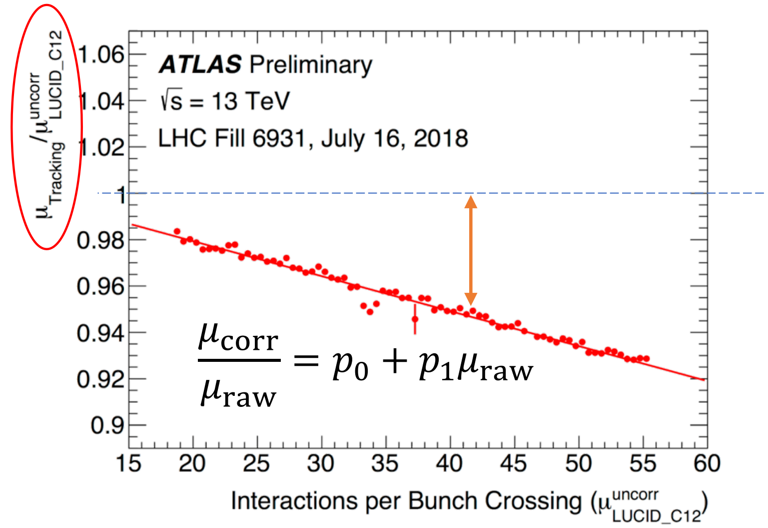


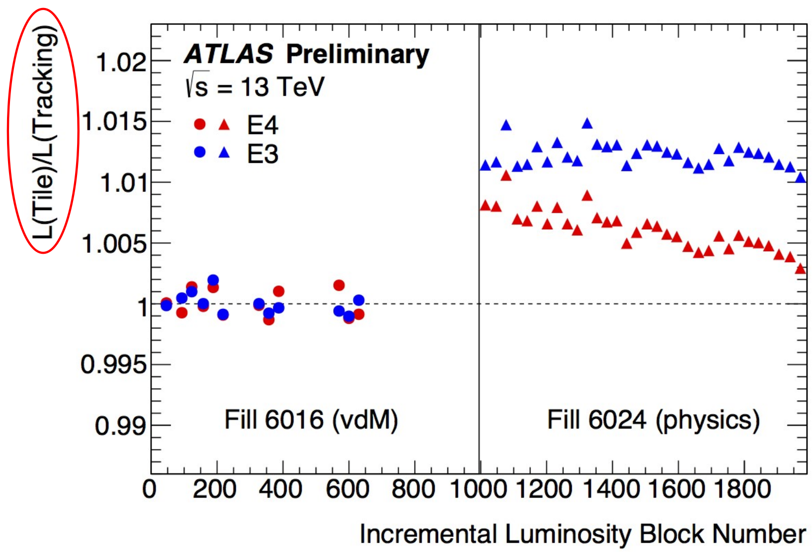
$$\mathcal{L} = f_{\text{LHC}} \frac{n_1 n_2}{2\pi \Sigma_x \Sigma_y}$$

$$\sigma_{vis} = f_{\text{LHC}} \frac{\mu_{vis}}{\mathcal{L}}$$

Calibration Transfer

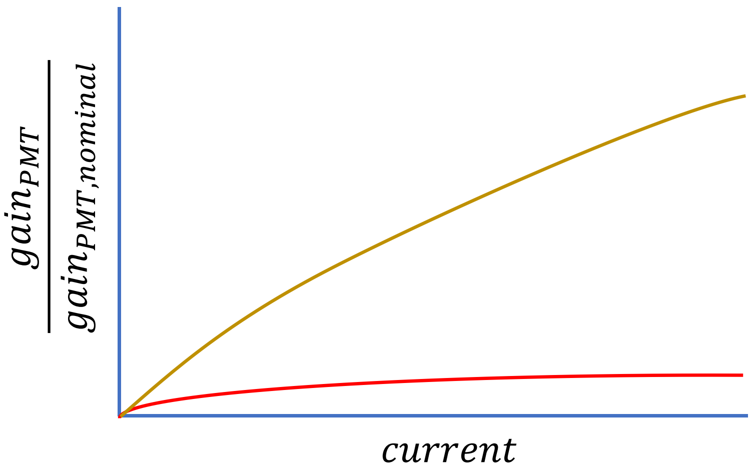
- LUCID measurements sensitive to pileup and bunch train running → calibration from VdM run results in an **overestimate** of luminosity in physics running conditions
- **Correction** needed for μ_{vis} at high luminosities from track counting
- **Uncertainty** on calibration transfer from comparison of track counting and Tile luminosity measurements in same pairs of runs

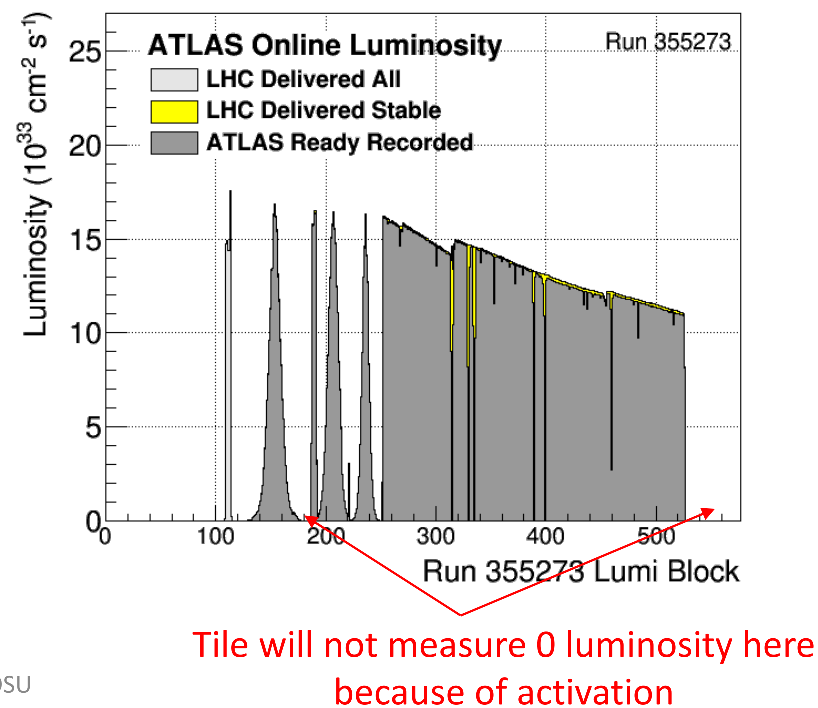




Advancing Tile Measurements

- Tile measurements affected by:
  - Aging – Currently accounted for in calibration transfer
  - Non-linearity of PMTs – PMT gain depends on anode current, higher at high luminosity
  - Activation of material – Radiation produced by activated materials in ATLAS induces a bias in Tile Luminosity measurements



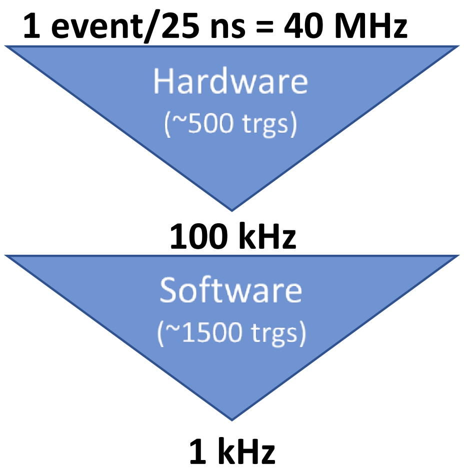


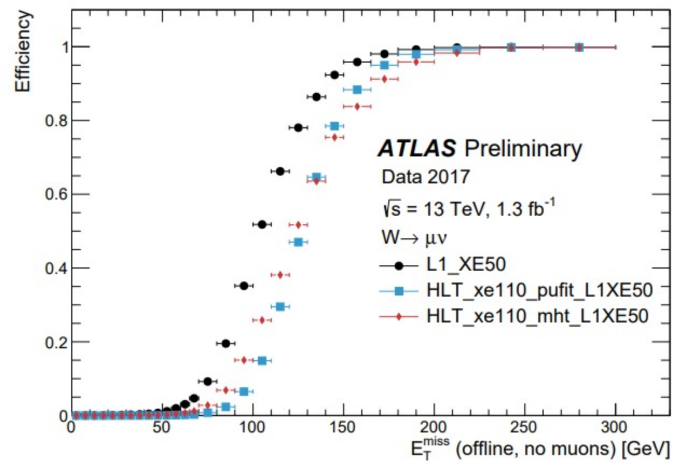
Part 2 Conclusions: Tile Calorimeter MinBias

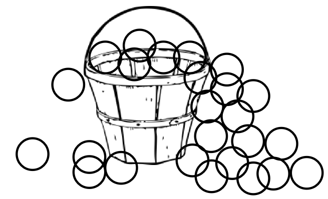
- Tile Minimum Bias measurements average current over long (on LHC timescales) periods of time
- This can help fill in “missing” data from lack of Cs calibrations to monitor the scintillator aging
- Tile also play an important role in luminosity measurements, especially for the calibration transfer from van der Meer runs to physics running conditions
- Current work in Tile is dedicated to improving the measurement of minbias via measurements of activation and PMT response non-linearities

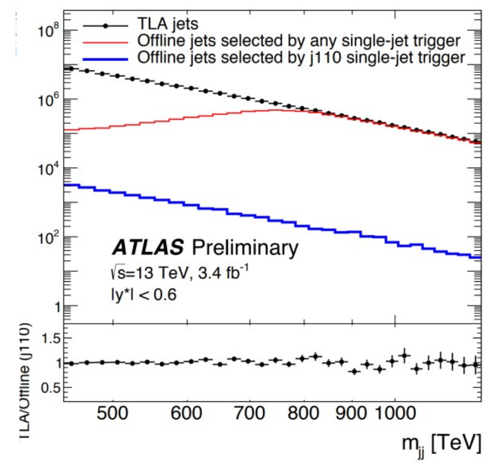
Backup

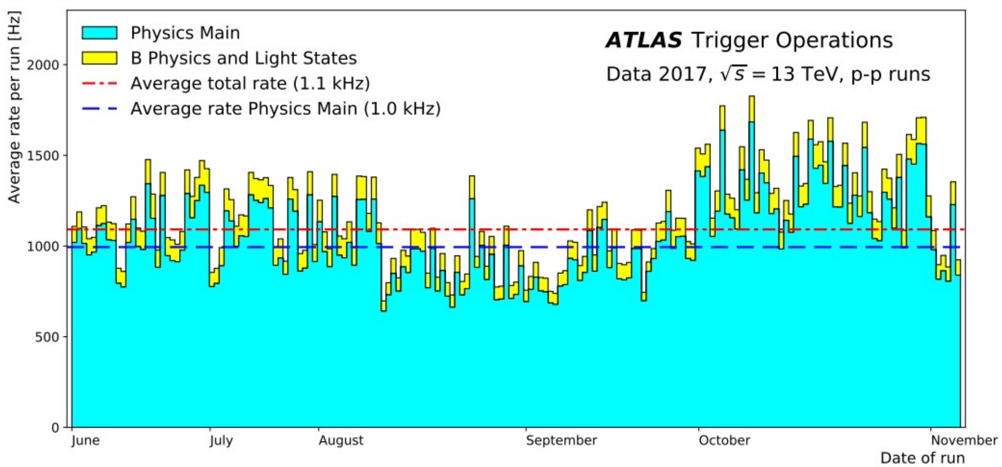
Building an Analysis – Trigger

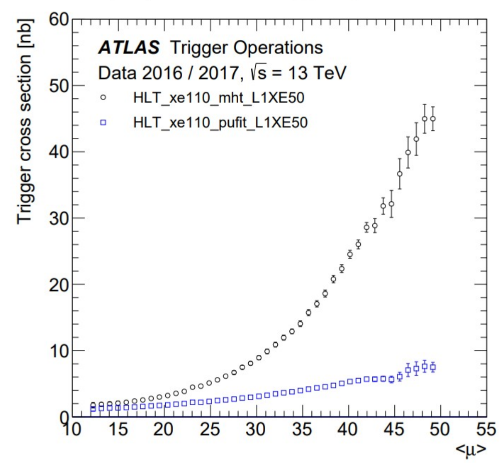




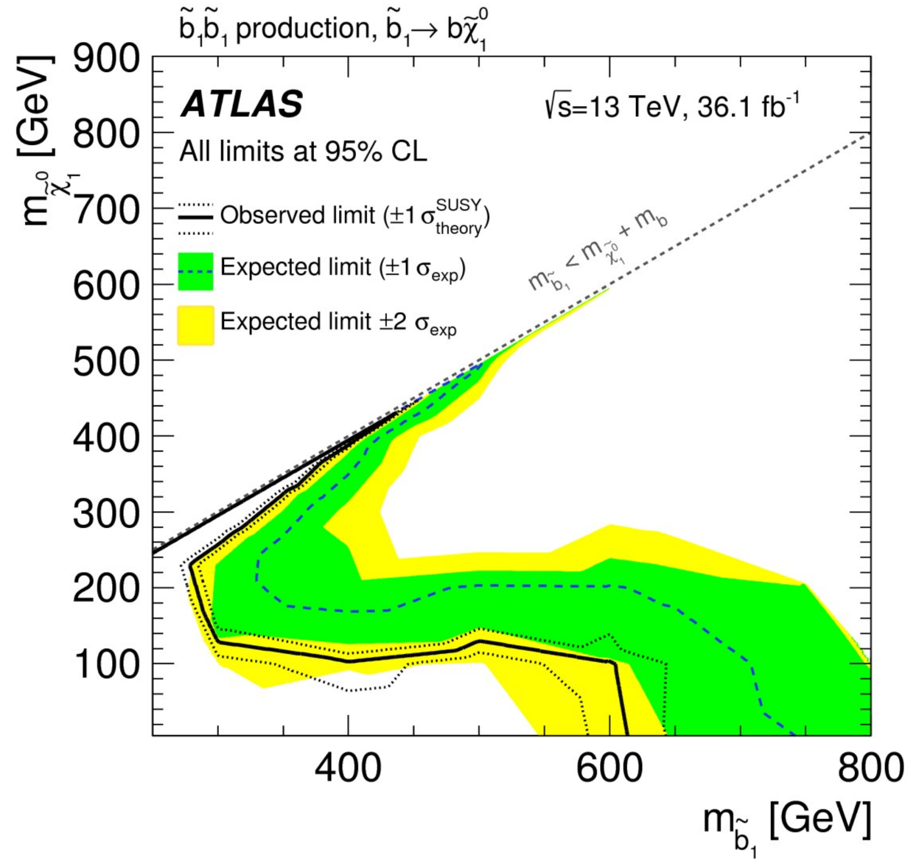






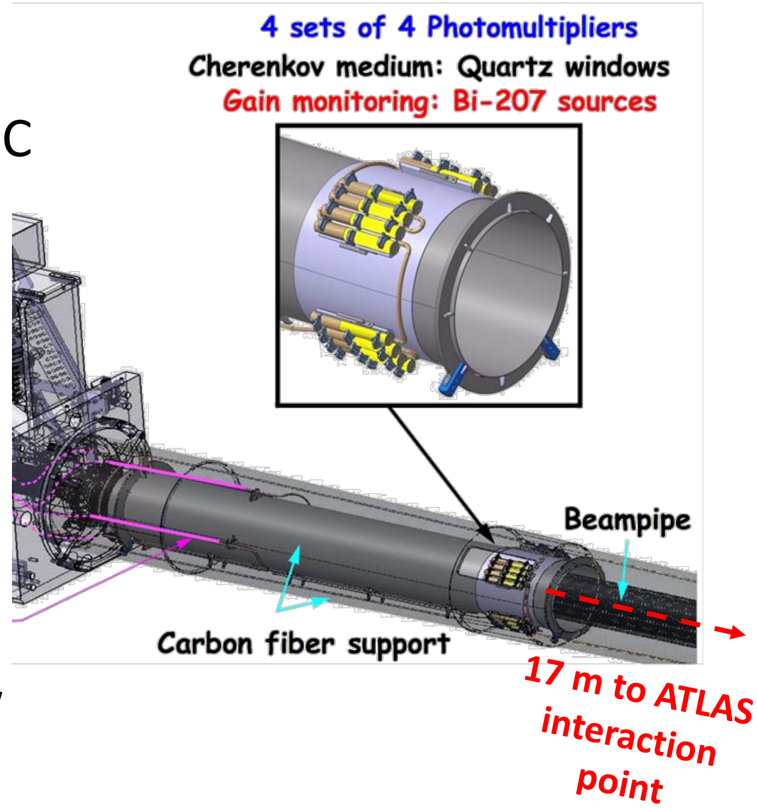


MonoJet Interpretations: Compressed SUSY



LUCID-2

- LUCID (LUminosity Cherenkov Integrating Detector): Provides real-time measurement of luminosity at any number of interactions per LHC bunch crossing (μ)
  - Primary luminosity detector in ATLAS from 2015+
- 2*4*4 IP-pointing PMTs with small acceptance (Cherenkov radiation from quartz window sufficient) to cope with high occupancy
- Fast read-out electronics to cope with 25 ns bunch spacing
- Radioactive Bi-207 deposited on quartz window allows for continuous monitoring of PMT gains



Luminosity Calibration Procedure: Overview

Use low luminosity van-der-Meer (VdM) scans to determine absolute luminosity of each colliding bunch as related to bunch intensity ($n_1 n_2$) by measuring beam overlap integral ($\Sigma_x \Sigma_y$)

$$\mathcal{L}_{bunch} = f_{\mathrm{LHC}} \frac{n_1 n_2}{2\pi \Sigma_x \Sigma_y}$$

LUCID-2 measurements relate visible interactions per bunch crossing (μ_{vis}) and cross section (σ_{vis})
PMT gain stability monitored by Bi-207 calibration

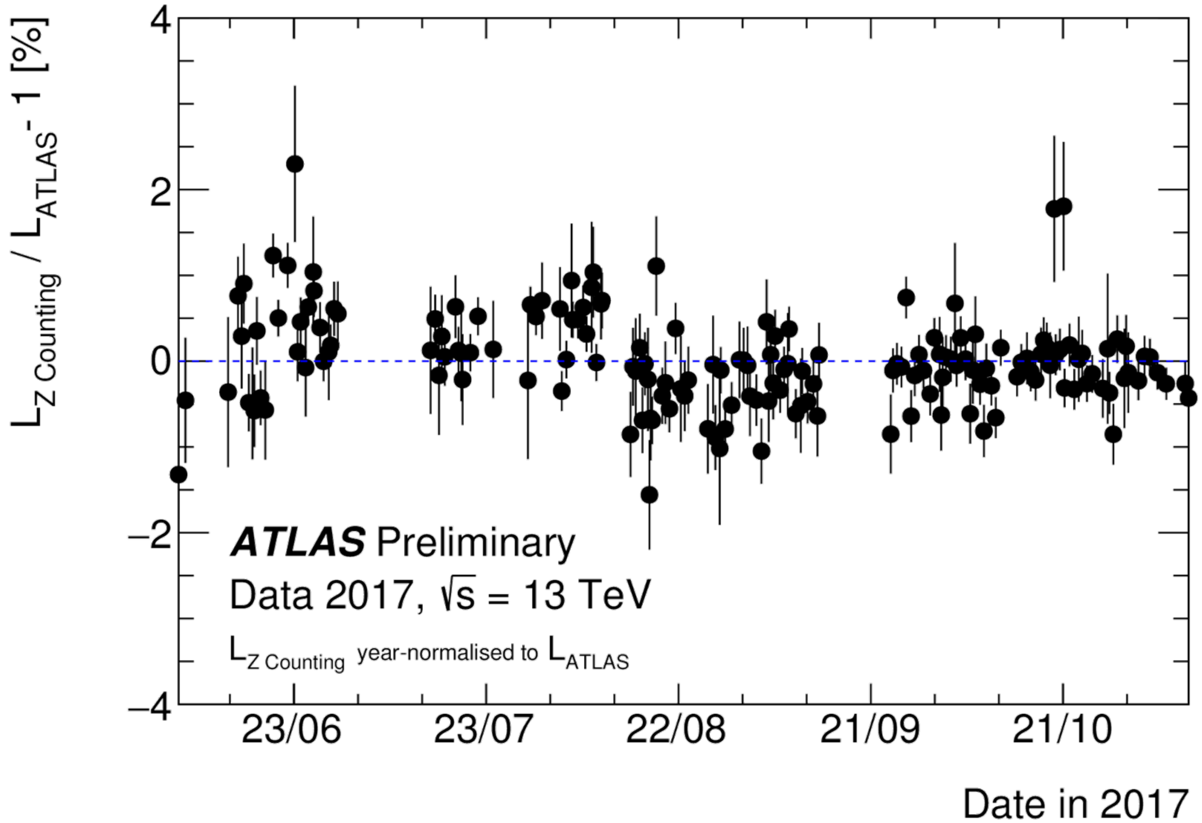
$$\mu_{\mathrm{vis}} = -(1 - P_{\mathrm{HIT}})$$

$$\mathcal{L} = f_{\mathrm{LHC}} \frac{\mu_{vis}}{\sigma_{vis}}$$

Use linearity of track counting luminosity measurement to extrapolate VdM calibration to “normal” LHC running conditions, i.e. the calibration transfer
$\mu{\sim}0.5 \rightarrow \mu{\sim}50$

Long-Term Stability

- Long-term stability uncertainty comes from a comparison of the luminosity measured by other luminometers to LUCID-2
- Reference run chosen for which all systems' luminosities are normalized to LUCID (red arrow)



Tile Laser-in-Gap Measurements

- Fire laser pulse in LHC abort gap
- Observe resulting signal in Tile PMTs
- Readout amplitude affected by any change in PMT gain