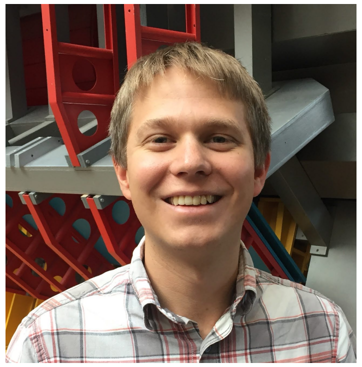
Triggering on hadronic signatures with the ATLAS detector

On behalf of the ATLAS Collaboration

ICHEP
July 29 2020

https://indi.to/5MMHN



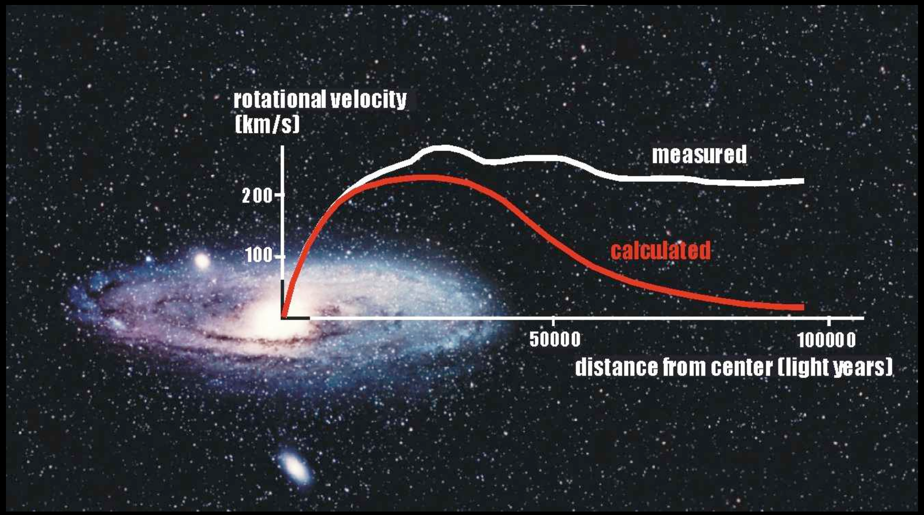
Ben Carlson

https://www.physicsandastronomy.pitt.edu/people/ben-carlson

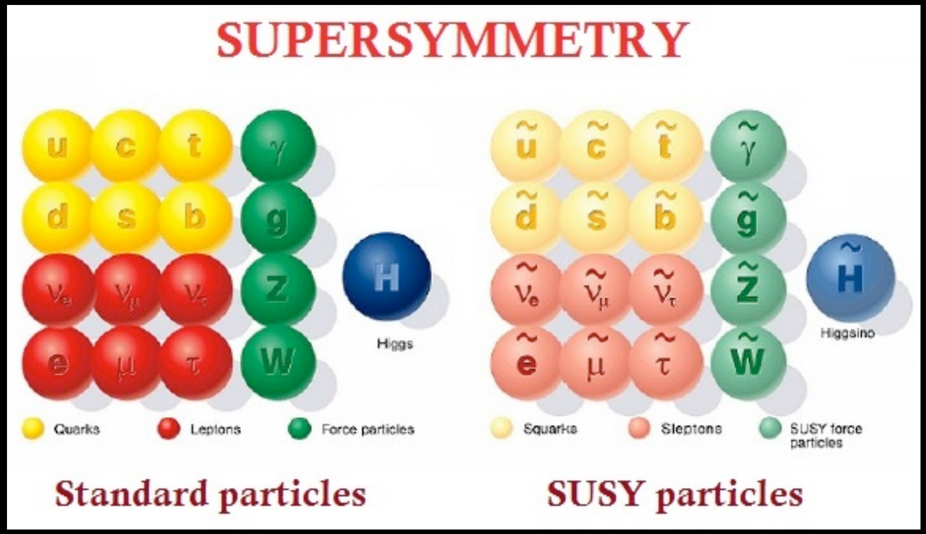
Outline

1. Introduction
    - ATLAS trigger sketch
    - L1 trigger
2. Jets
    - Motivation
    - Single jet
    - Large-R jets
    - Vector boson fusion
3. Missing transverse momentum
    - Motivation
    - Pileup reduction at L1
    - New algorithms
    - Performance

Motivation



Dark matter

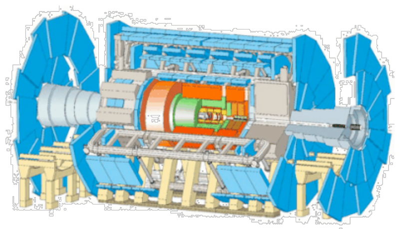


Variety of SUSY models

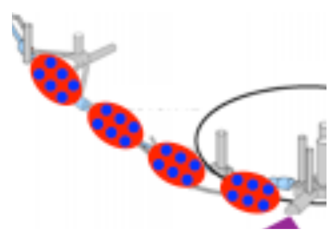
and… Standard Model

Trigger overview

Event size · Event rate = 40 Tb/s



1 Mb*



40 MHz

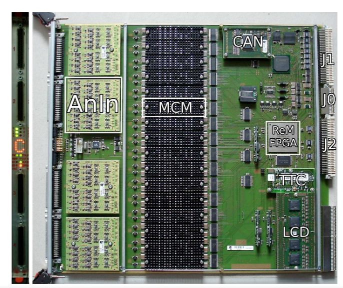
Time

2.2μs

Partial data

Full data buffer

FPGAs



Coarse inputs:
Calo & Muon
reduce rate
100 kHz

100 Gb/s

O(300ms/event)

45k CPUs

Software to
reduce rate
1kHz

Temporary storage

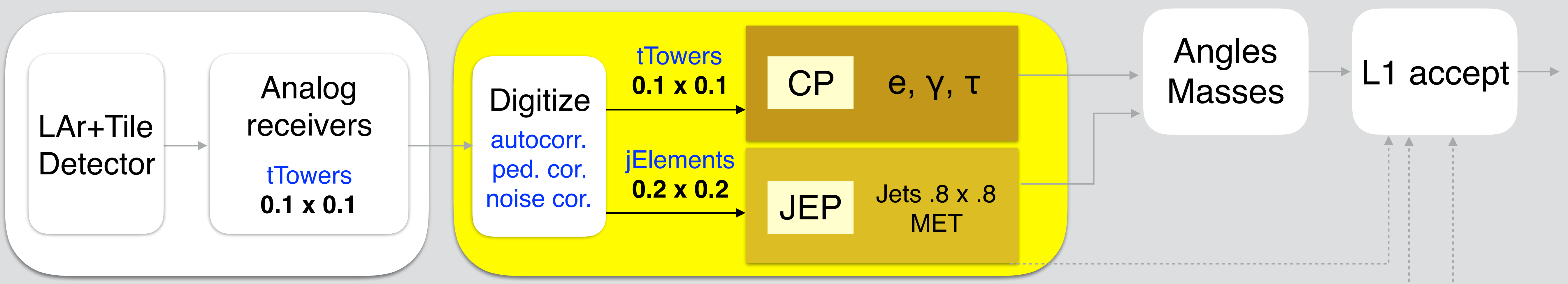
1 Gb/s

Permanent storage

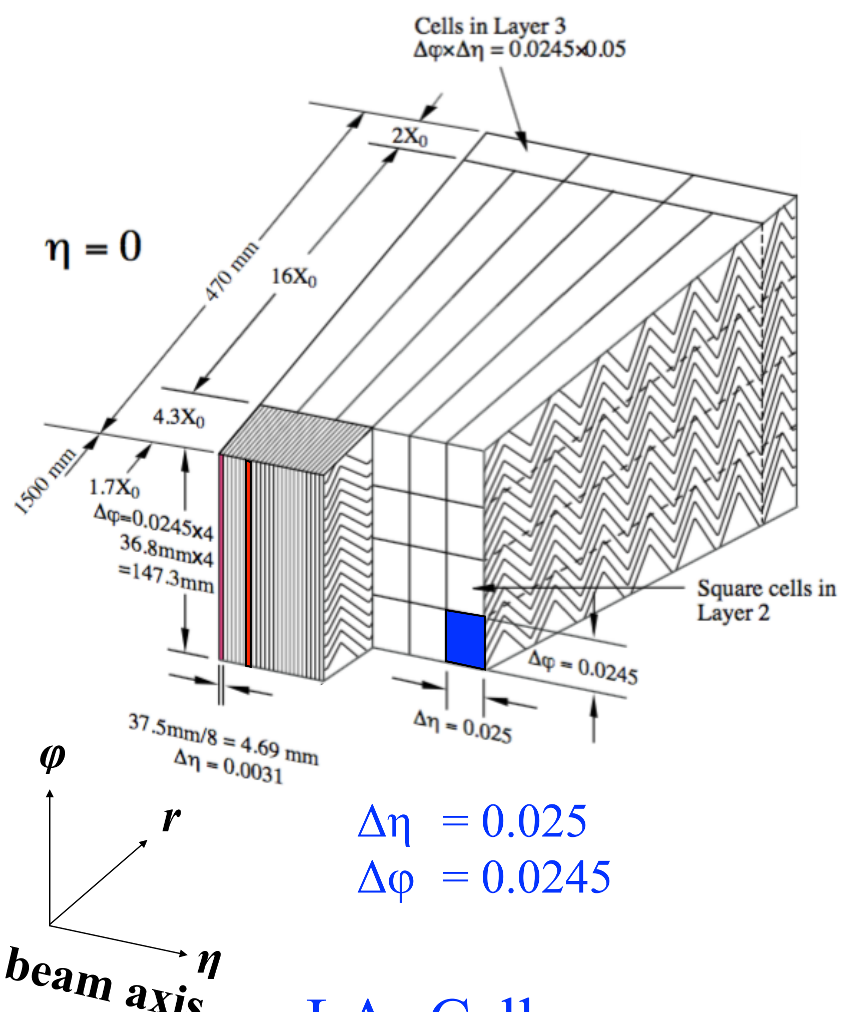
*simplified numbers; actual numbers vary depending on event complexity, and the average event size is 1.5 Mb

Run-1, 2

CP: Cluster Processor
JEP: Jet Energy Processor

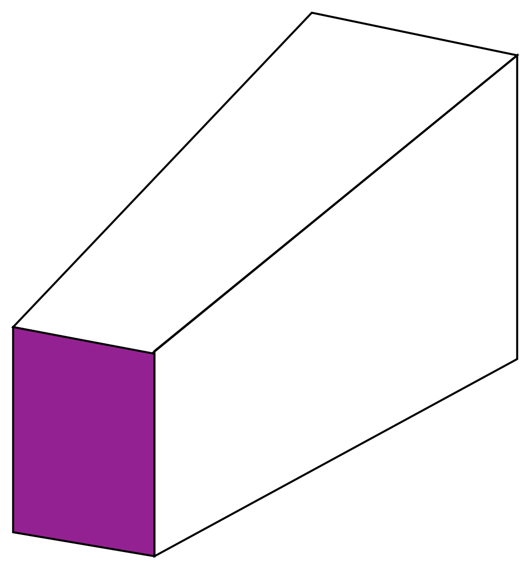


L1Calo in yellow



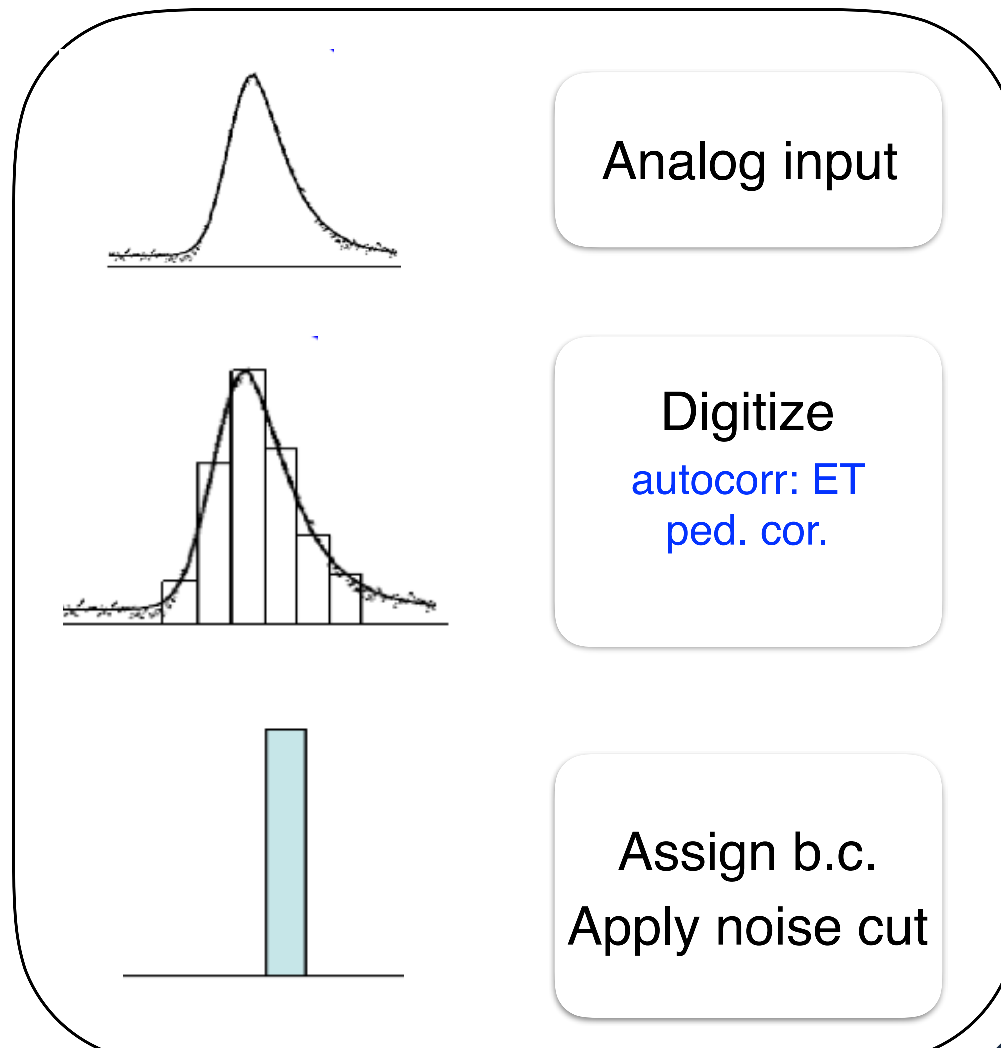
$\Delta\eta = 0.025$
$\Delta\varphi = 0.0245$

LAr Cells



$\Delta\eta = 0.1$
$\Delta\varphi = 0.1$

Trigger Tower
ANALOG INPUT TO L1



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Motivation: dark matter

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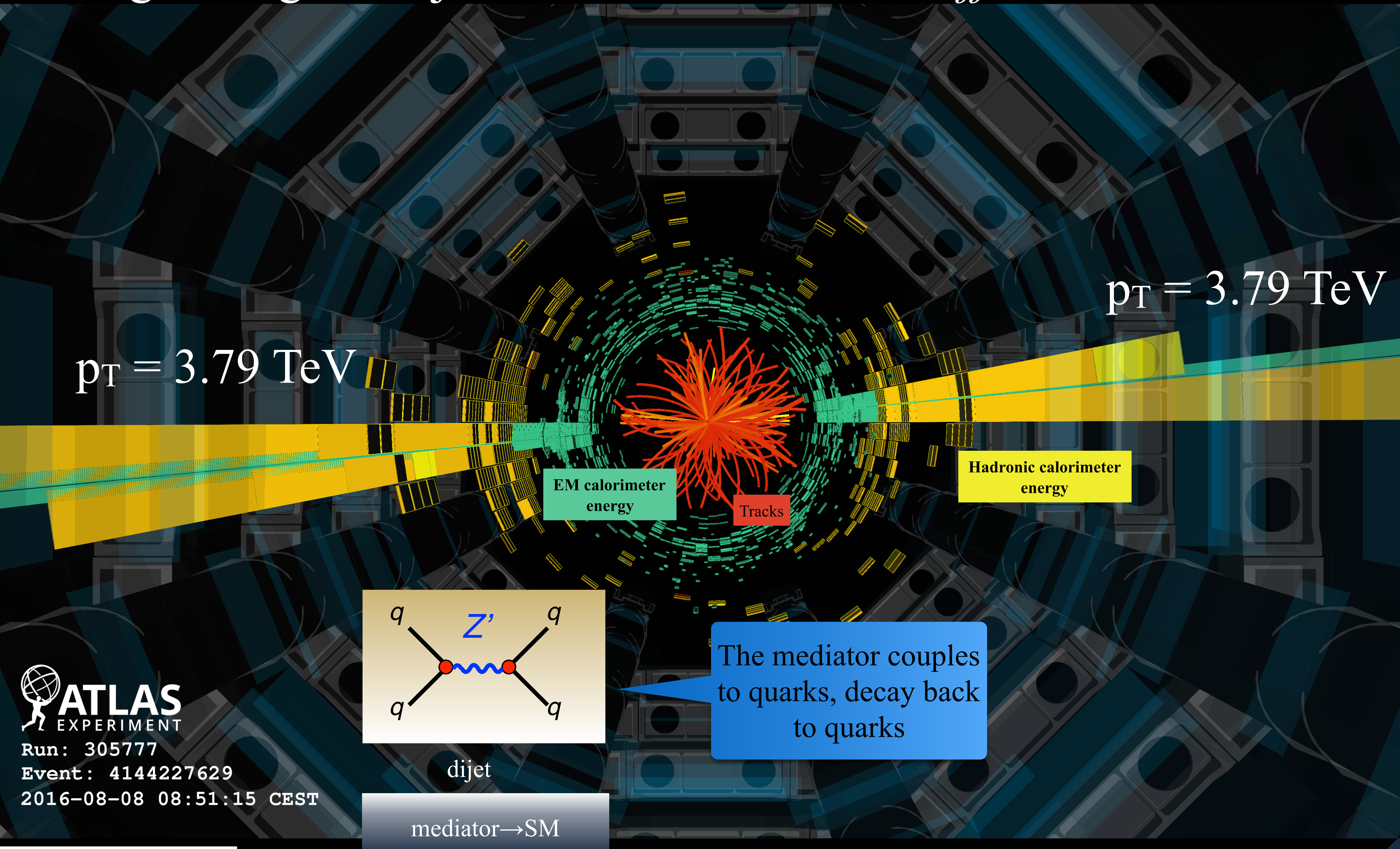
Among the highest dijet mass event recorded: $m_{jj} = 8.12$ TeV

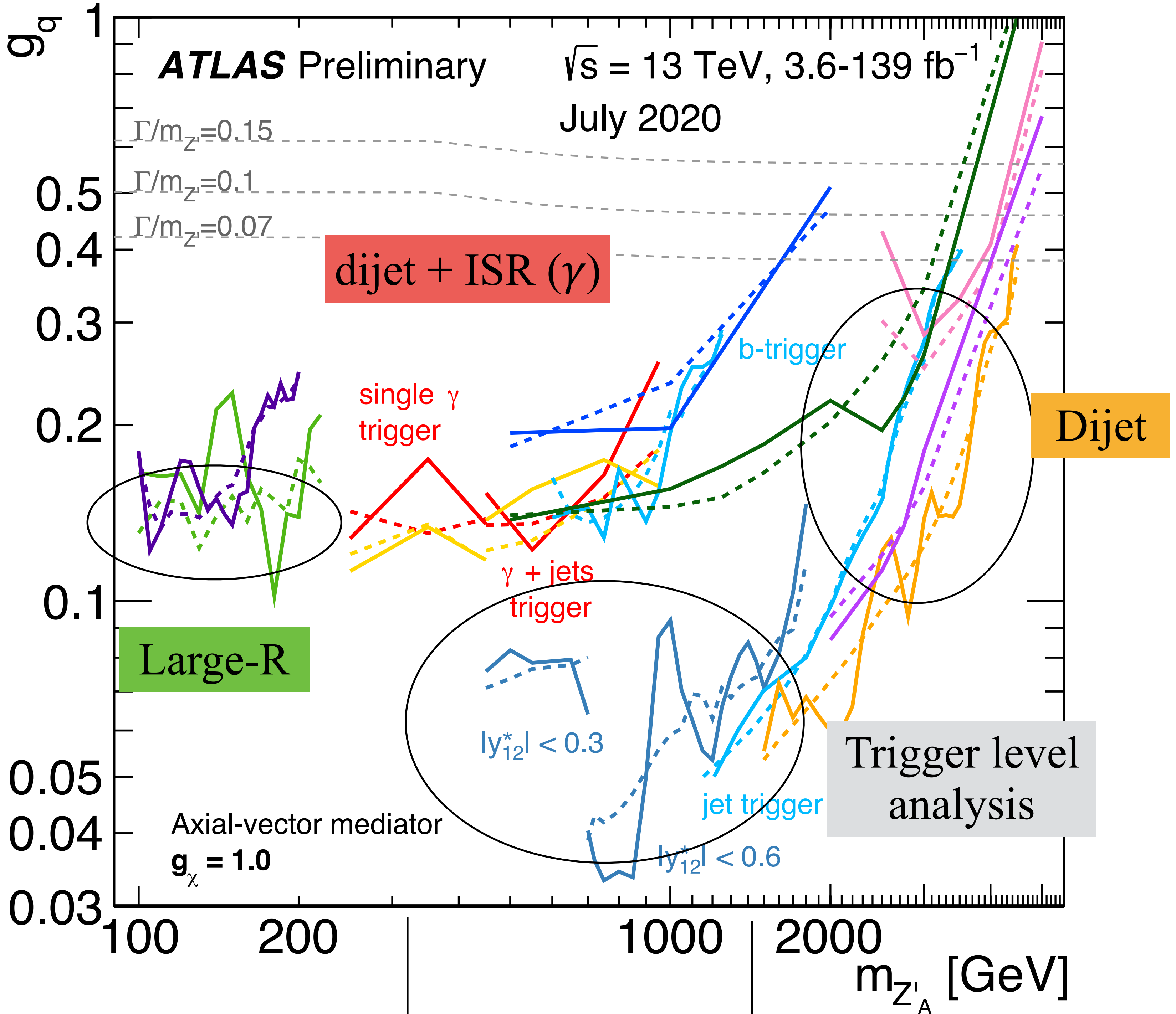


Transverse view

Phys. Rev. D 96, 052004

Z’→qq: a way to think about jet triggers

*dijet + ISR(γ) includes photon trigger



Large-R | TLA | single jet

See my ICHEP talk on DM (link)

Single jets

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetTriggerPublicResults

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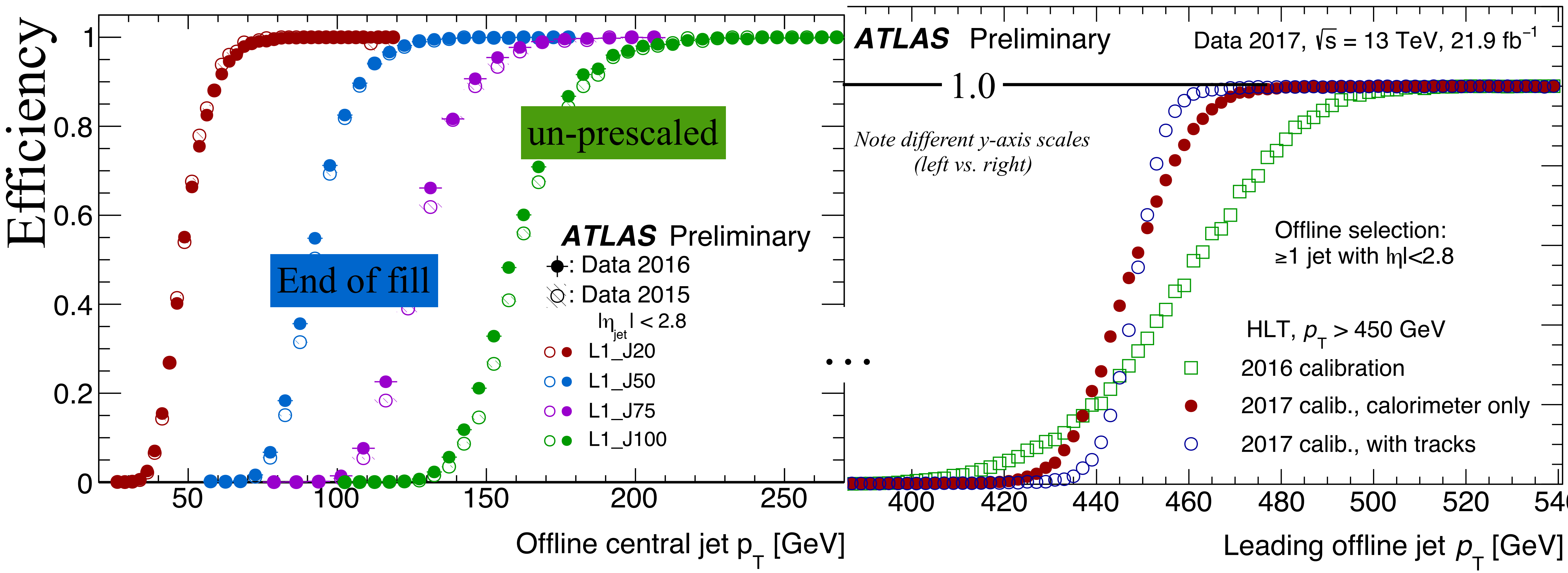
In dark matter context, used for high mass dijet, $m_{jj} > 1.5$ TeV

L1 observations

- J100 fully efficient by 200 GeV

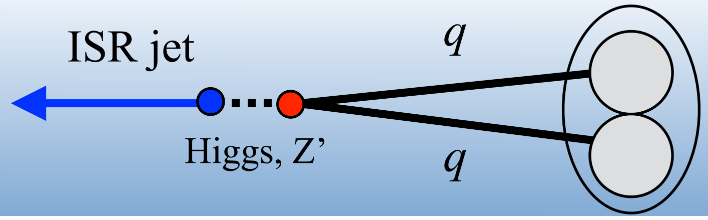
HLT observations

- Lowest unprescaled single jet trigger fully efficient by 460 GeV
- Benefits from improved calibration procedure



Large-R jets

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetTriggerPublicResults



$$\Delta R = \frac{2m_{Z'}}{P_T}$$

Low-mass Z' (200 GeV)

Improvements targeted at large-R jets; both L1 & HLT

- L1: simple cone algorithm uses L1Topo to build large-R jet from smaller jets sent from L1Calo
- L1: Efficiency improves by 20-30 GeV compared to L1Calo (see backup)
- HLT: Apply mass cut in the HLT to lower threshold to 420 GeV for single jet, and 330 GeV for two
- Big picture: we've improved a lot!

Common selections

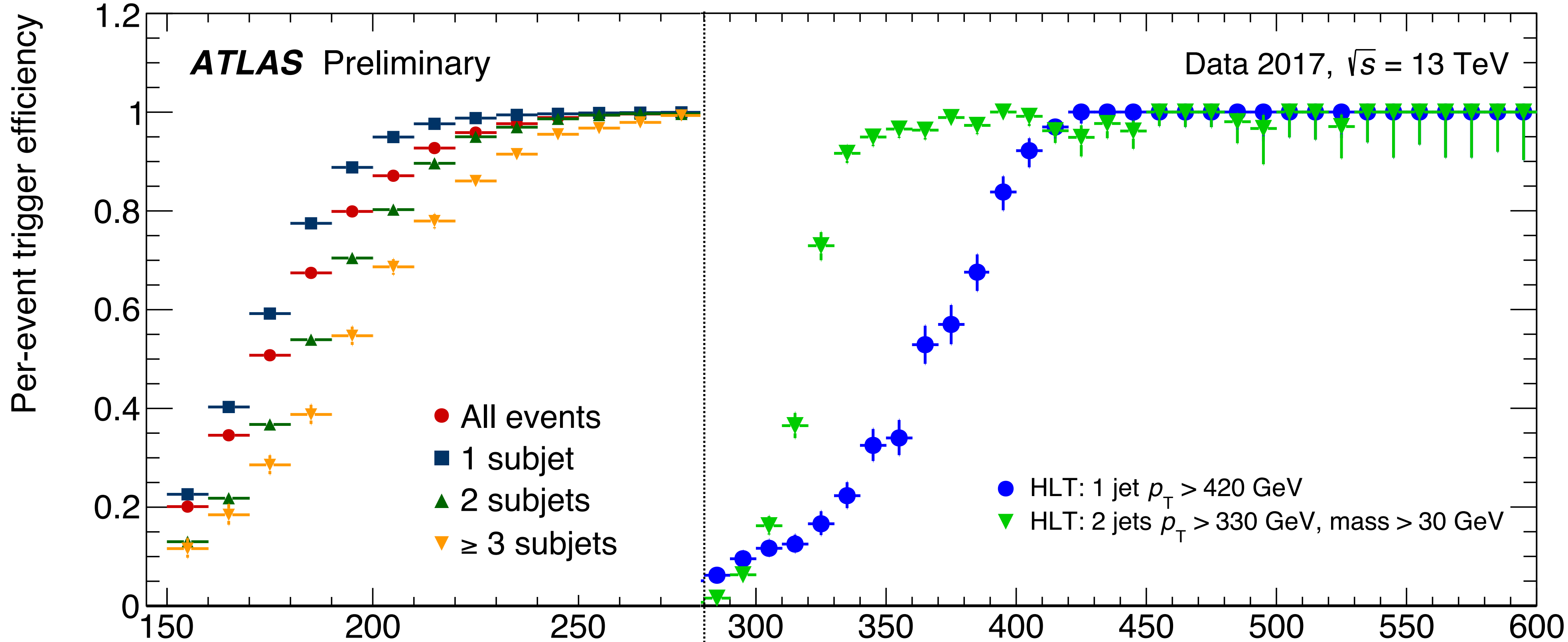
Subjet definition: k_t $R = 0.2$, $p_T > 20$ GeV

Jet definition: trimmed anti-k_t $R = 1.0$ $|\eta| < 2.0$
trimming: $f_{cut} = 0.05$, $R_{sub} = 0.2$

Selections (right only)

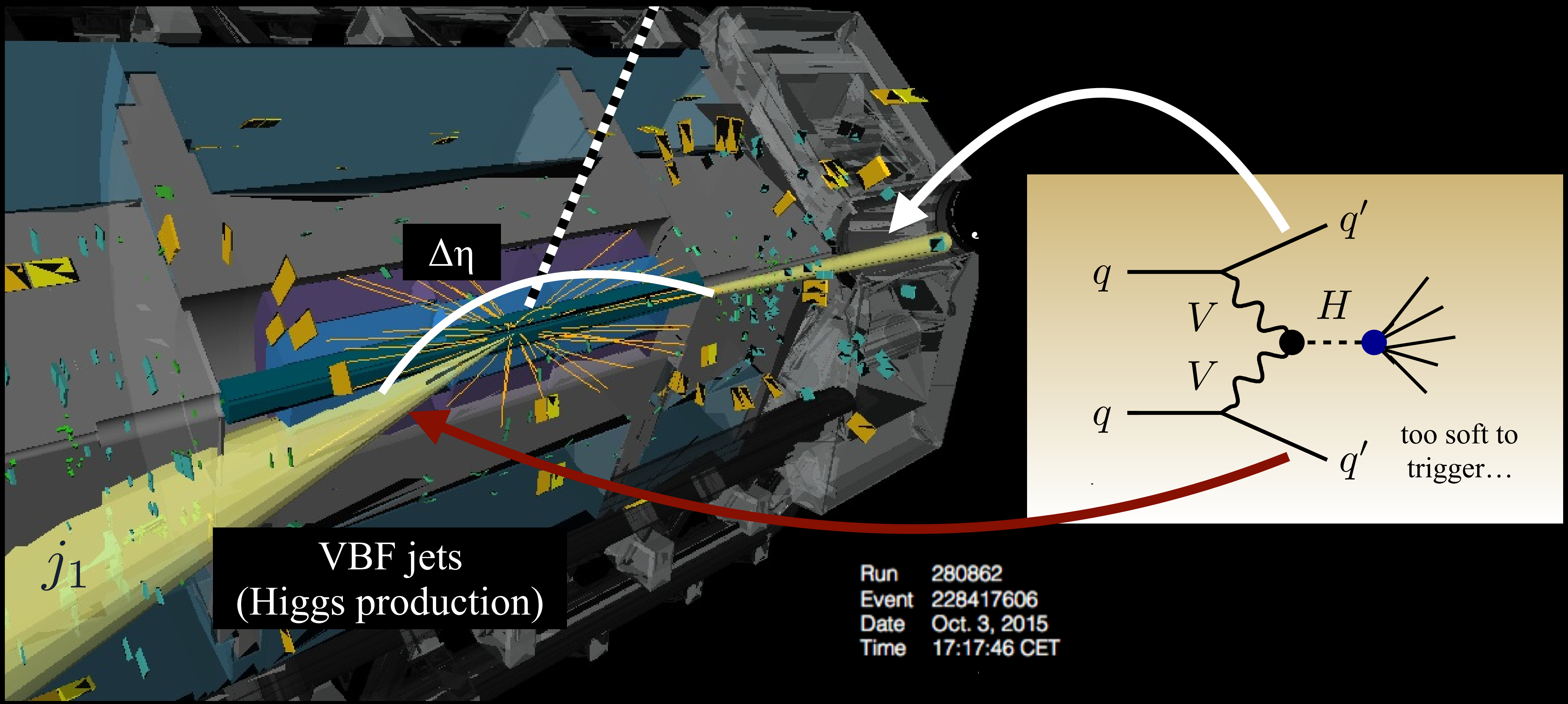
jet mass > 50 GeV

L1 efficiency *HLT efficiency*



R = 1.0 jet p_T (GeV)

Two plots I've stitched together in Keynote; see backup for originals



dijet mass:

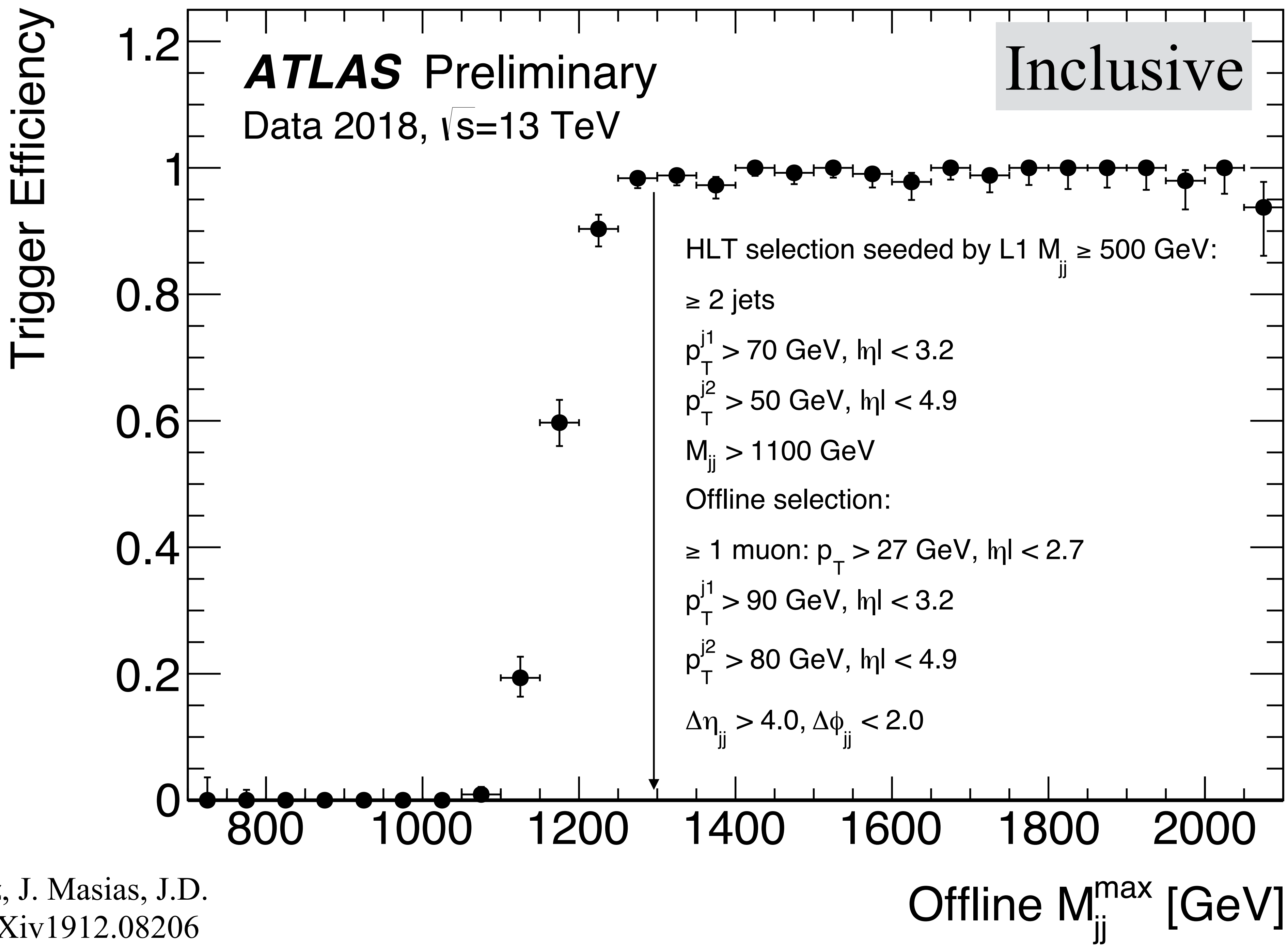
$$m^2(jj) \sim p_T(j_1) \bullet p_T(j_2) \bullet e^{\Delta\eta(jj)}$$

← *Implemented in L1Topo*

VBF trigger

Strategy: single L1 seed for inclusive and exclusive triggers

- L1 rate: 2 kHz
- HLT inclusive: contains $\Delta\phi_{jj} < 2.0$ to reduce QCD rate, **no event requirements other than VBF jets**
- HLT exclusive: **additional** requirements on MET, b-jets, but with lower VBF thresholds



See also: J. Perez, J. Masias, J.D. Ruiz-Alvarez arXiv1912.08206

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Missing transverse momentum

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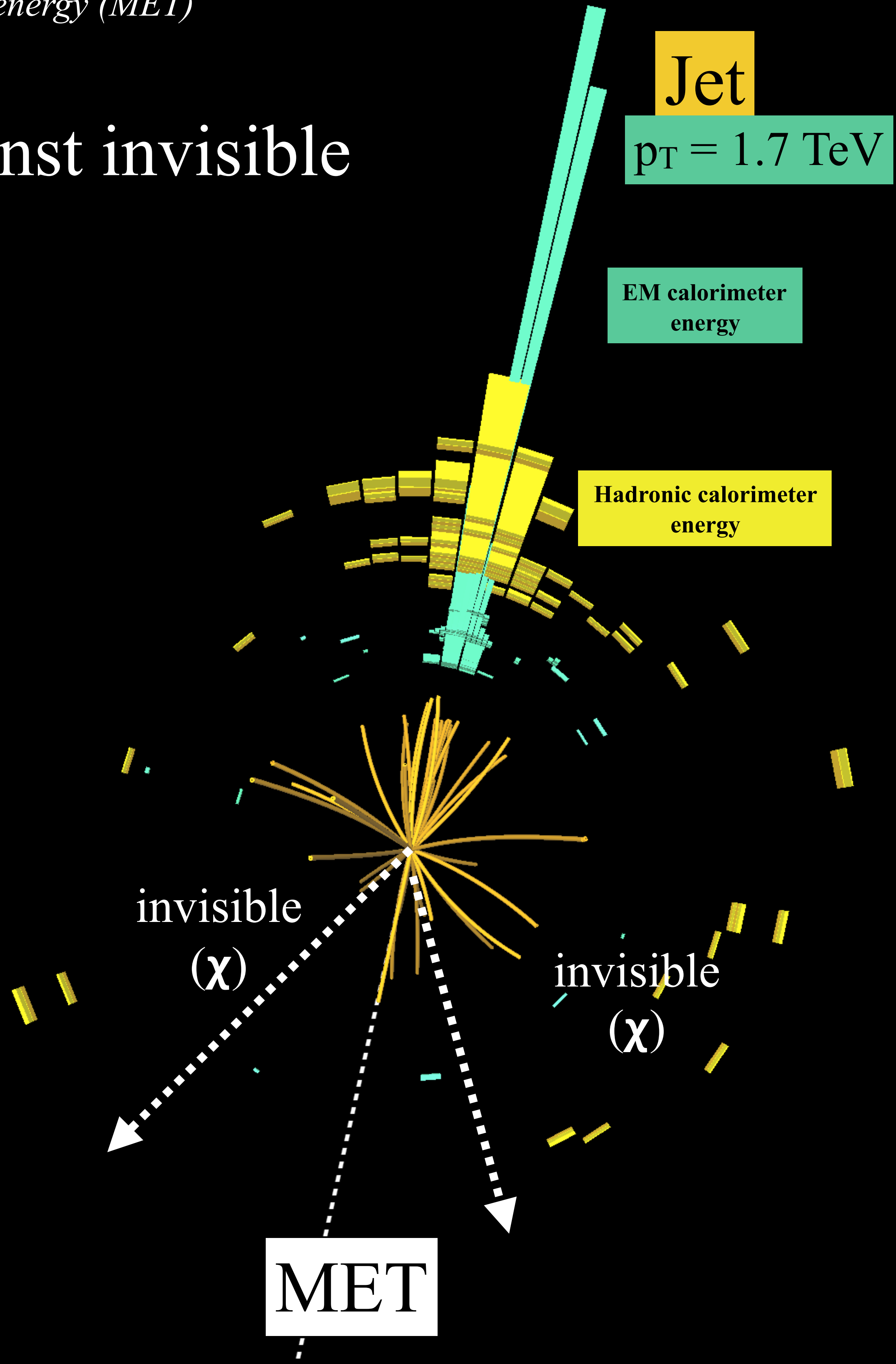
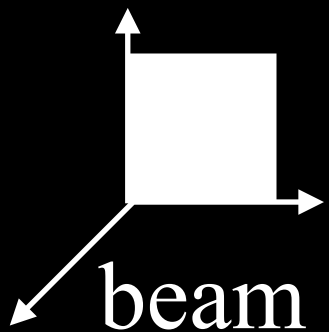
^*Referred to as missing transverse energy (MET)*

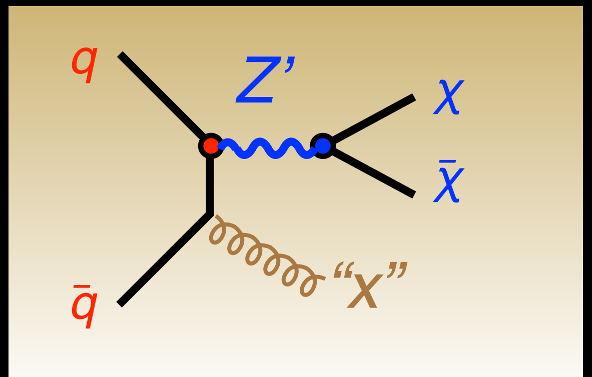
JHEP 01 (2018) 126

Jet recoiling against invisible



Transverse plane

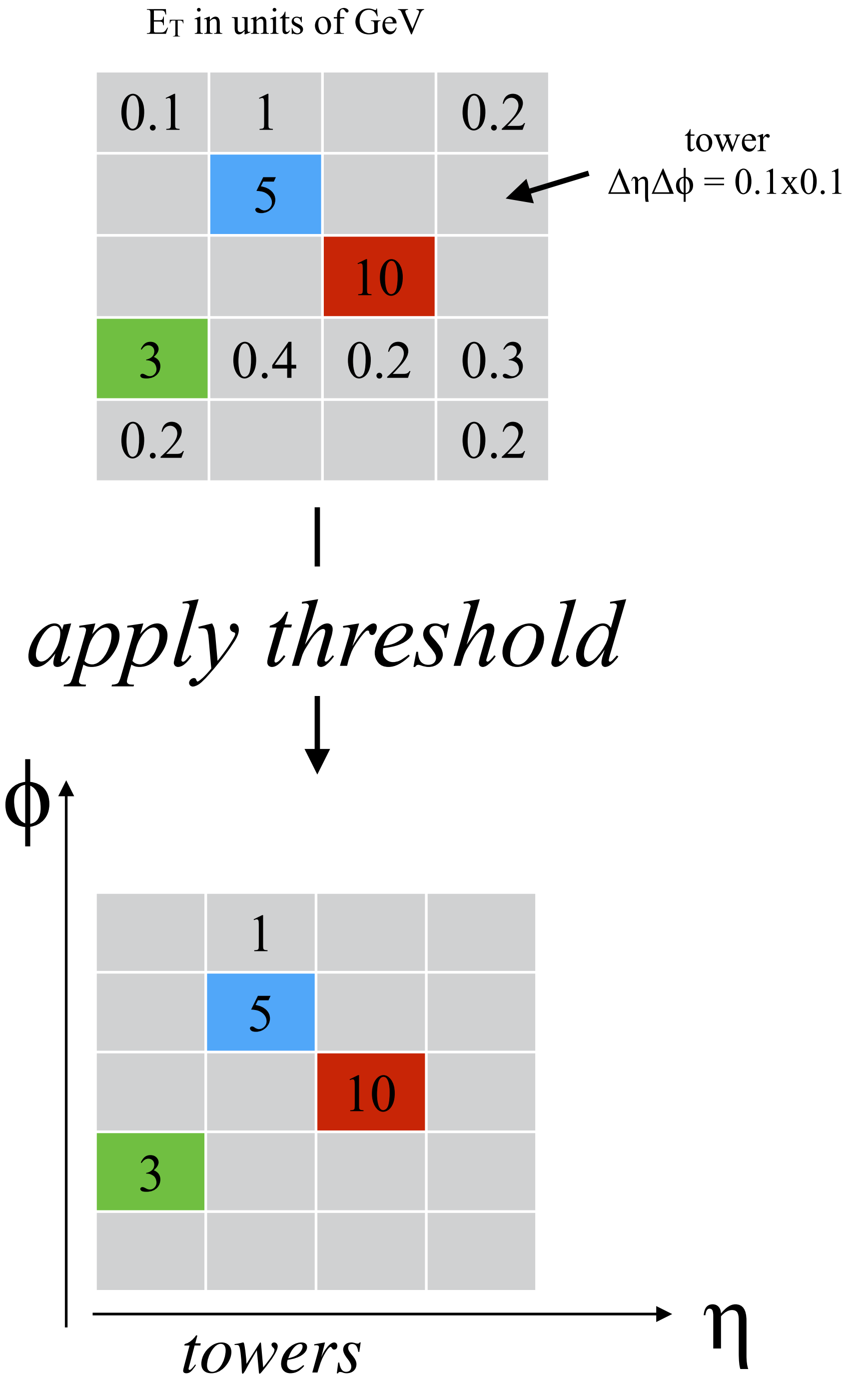




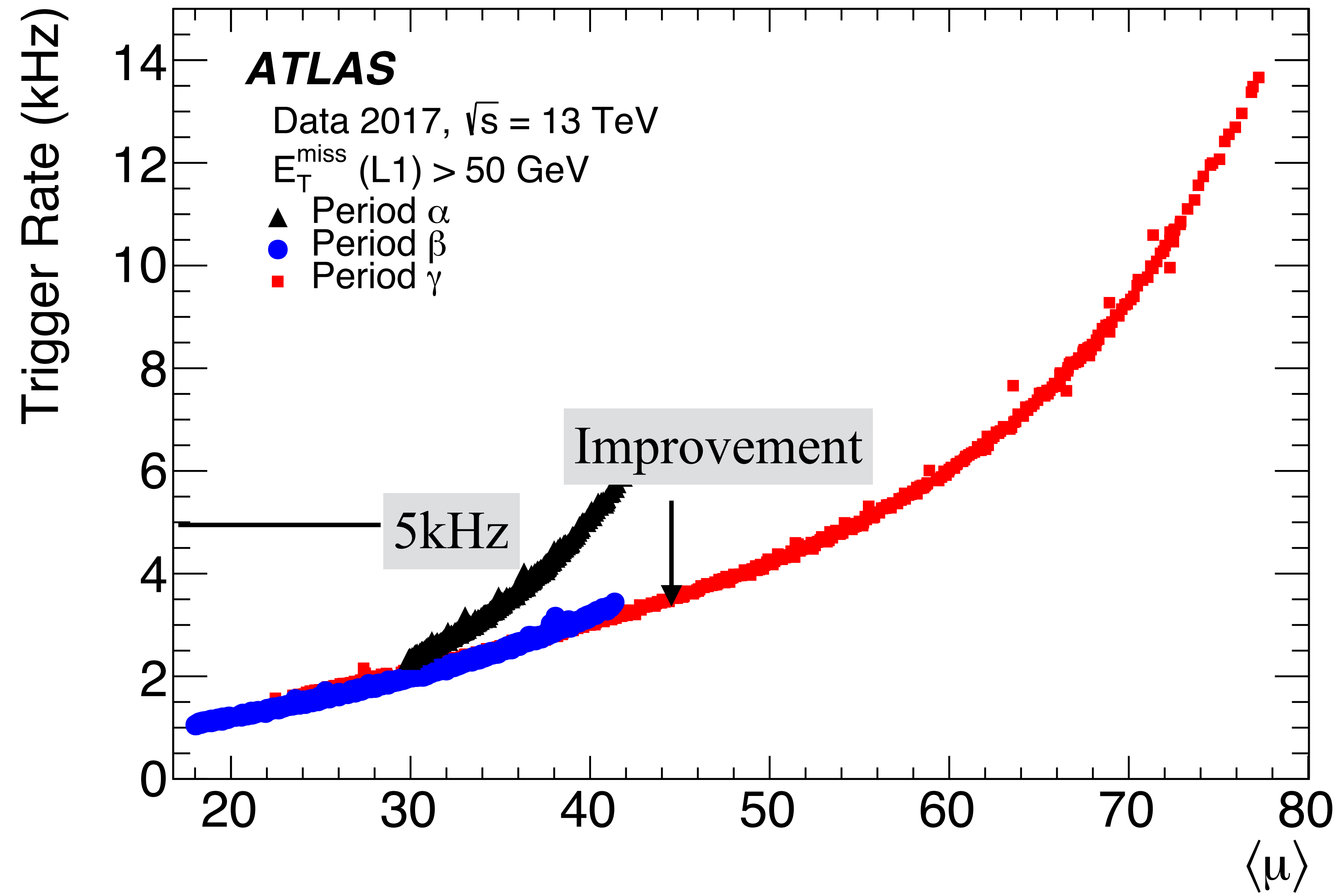
mediator→DM + X

Pileup at L1

- Compute MET from towers above threshold (left)
- Mitigate pileup by raising the E_T threshold per trigger tower (right)



L1 trigger rate



$$E_x = \sum_{towers} E_T \cdot cos(\phi)$$

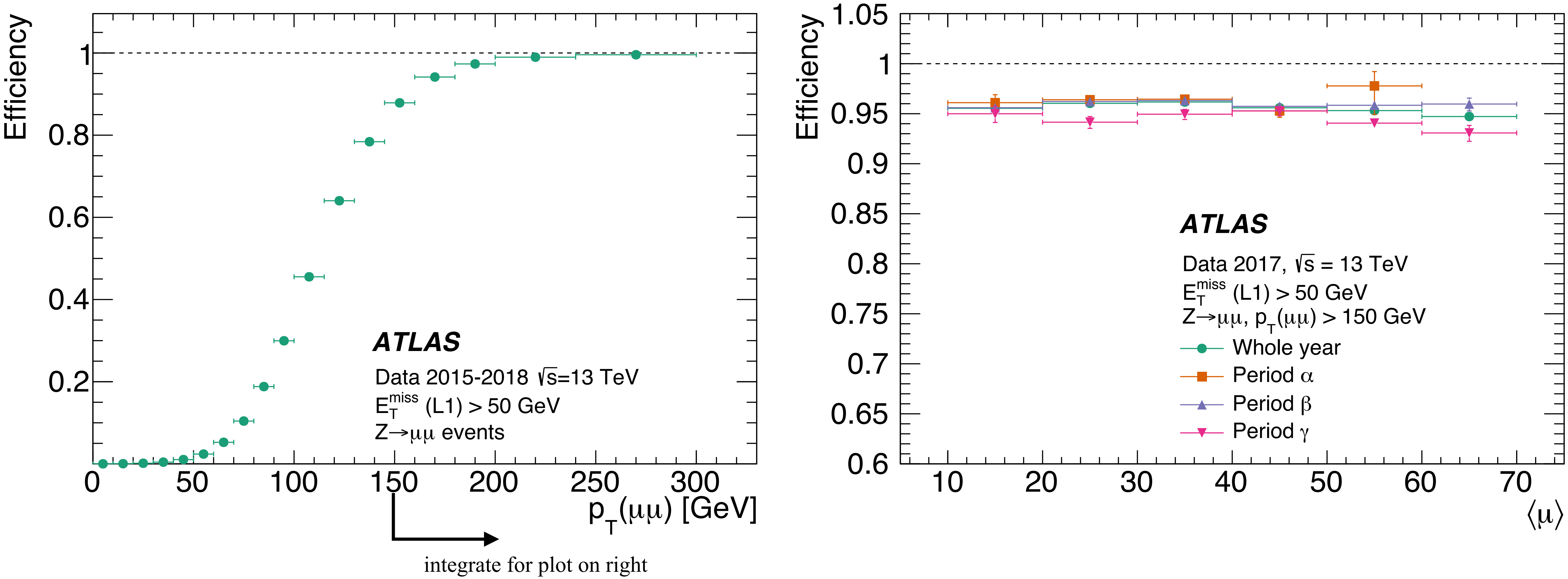
$$E_T^{miss} = \sqrt{E_x^2 + E_y^2}$$

Measure efficiency using Z→μμ events

- $p_T(\mu\mu)$ is a proxy for MET, as the muons are invisible to the calorimeter (see backup)

L1 efficiency is 95% and **stable** for events with $p_T(\mu\mu) > 150$ GeV

- Efficiency as a function of $p_T(\mu\mu)$ (left)
- Efficiency as a function of <μ> (right)
- Efficiency is stable for a range of L1 settings, even as the rate is reduced (previous slide)



Software algorithm definitions

Evaluate in 150ms, and use calorimeter inputs*

Algorithm	Inputs
cell	Calorimeter cells with E_T > threshold
tc_lcw	Calibrated topological clusters
mht	Calibrated calorimeter jets with pileup subtraction
NEW pufit	Dedicated pileup subtraction (algorithm published Appendix of paper)

$$E_x = \sum^{inputs} E_T \cdot cos(\phi) \rightarrow E_T^{miss} = \sqrt{E_x^2 + E_y^2}$$

*tracking is much slower; see backup

Algorithm comparison

Submitted to JHEP, arXiv:2005.09554

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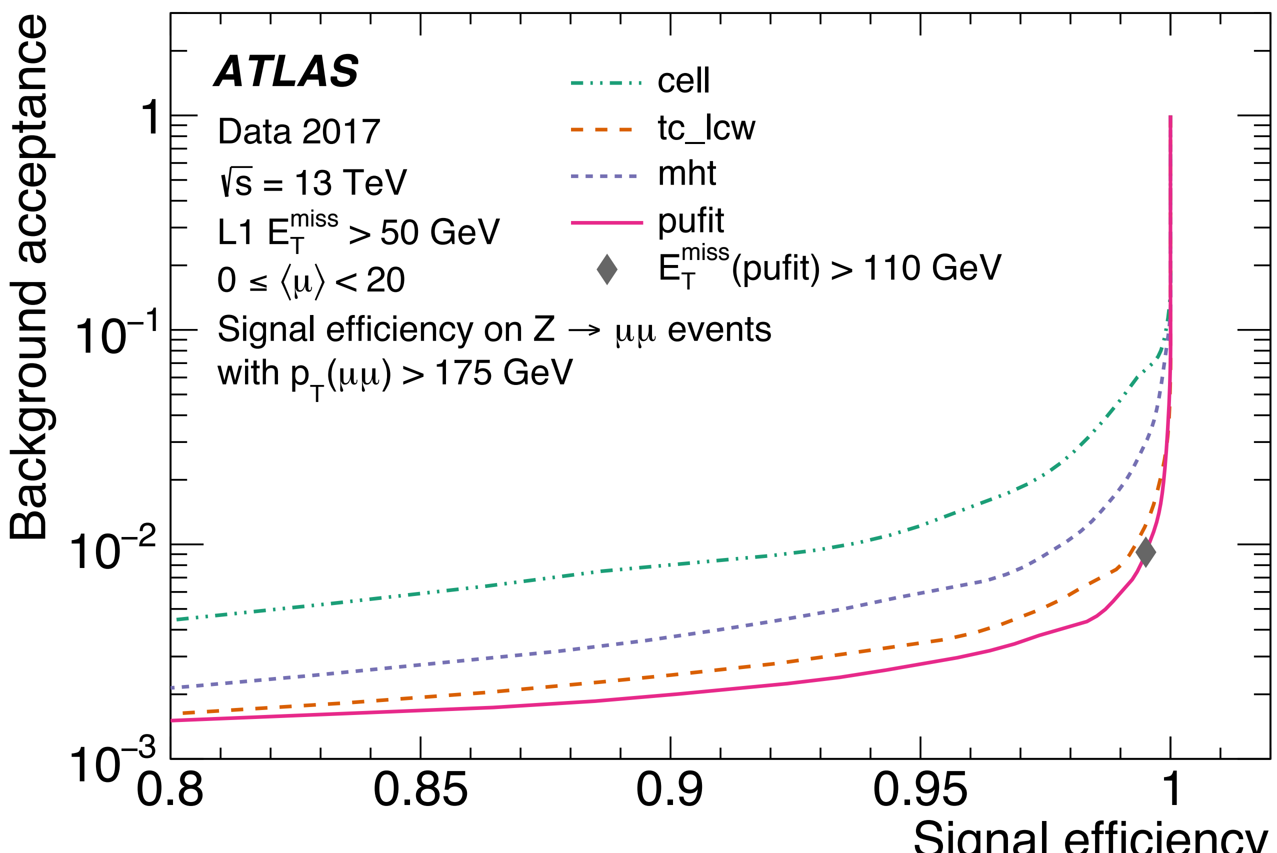
Background acceptance vs. signal efficiency

- Measure background acceptance with respect to L1 for each algorithm
- Efficiency measured for $p_T(\mu\mu) > 175$ GeV

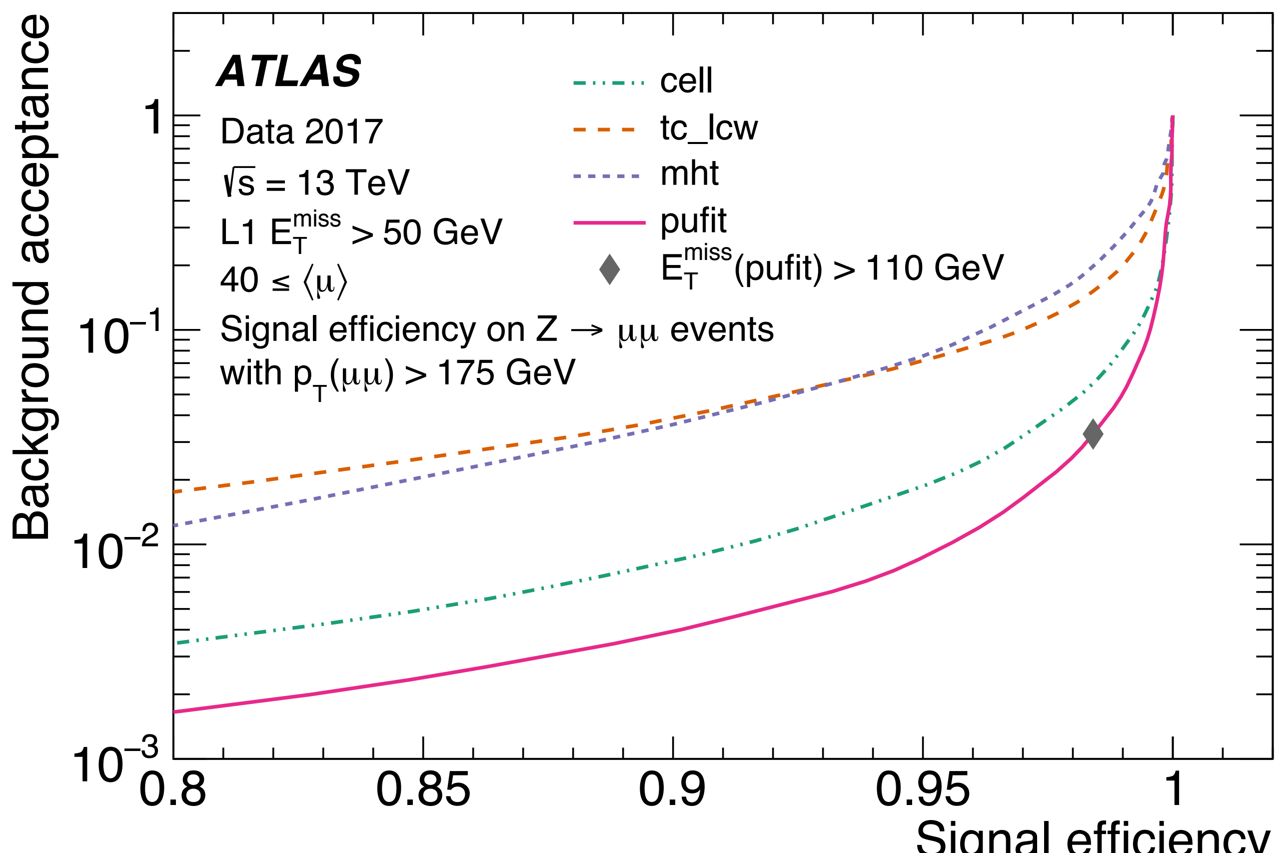
Algorithm performance changes with pileup

- For $\mu < 20$, pufit is only marginally better
- For $\mu > 40$, pufit is significantly better

$\mu < 20$



$\mu > 40$



$\mu < 20$:

1. pufit
2. tc_lcw
3. mht
4. cell

decreasing performance

$\mu > 40$:

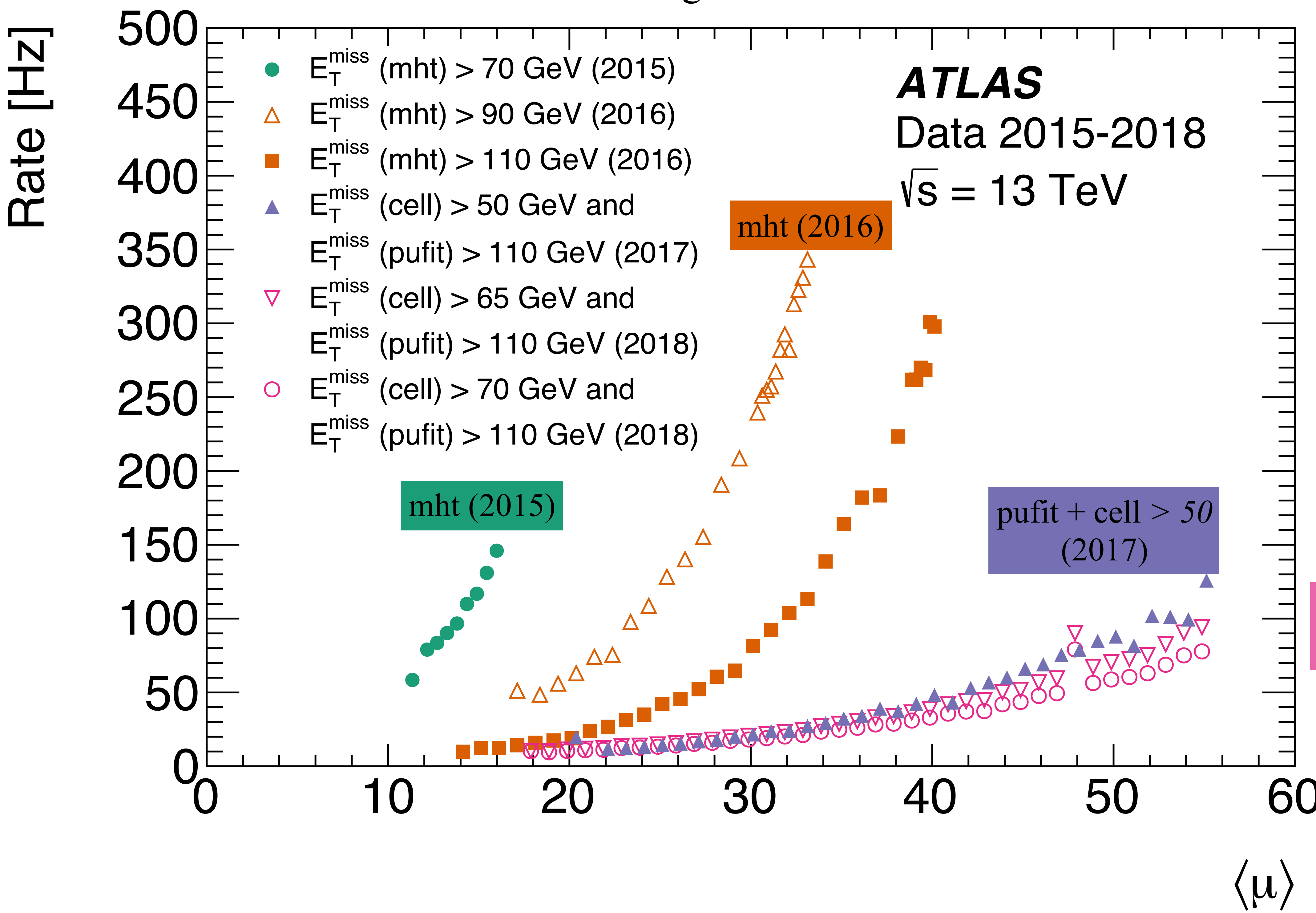
1. pufit
2. cell
3. tc_lcw
4. mht

Algorithm & threshold evolution

Algorithms and thresholds adjusted to control rate

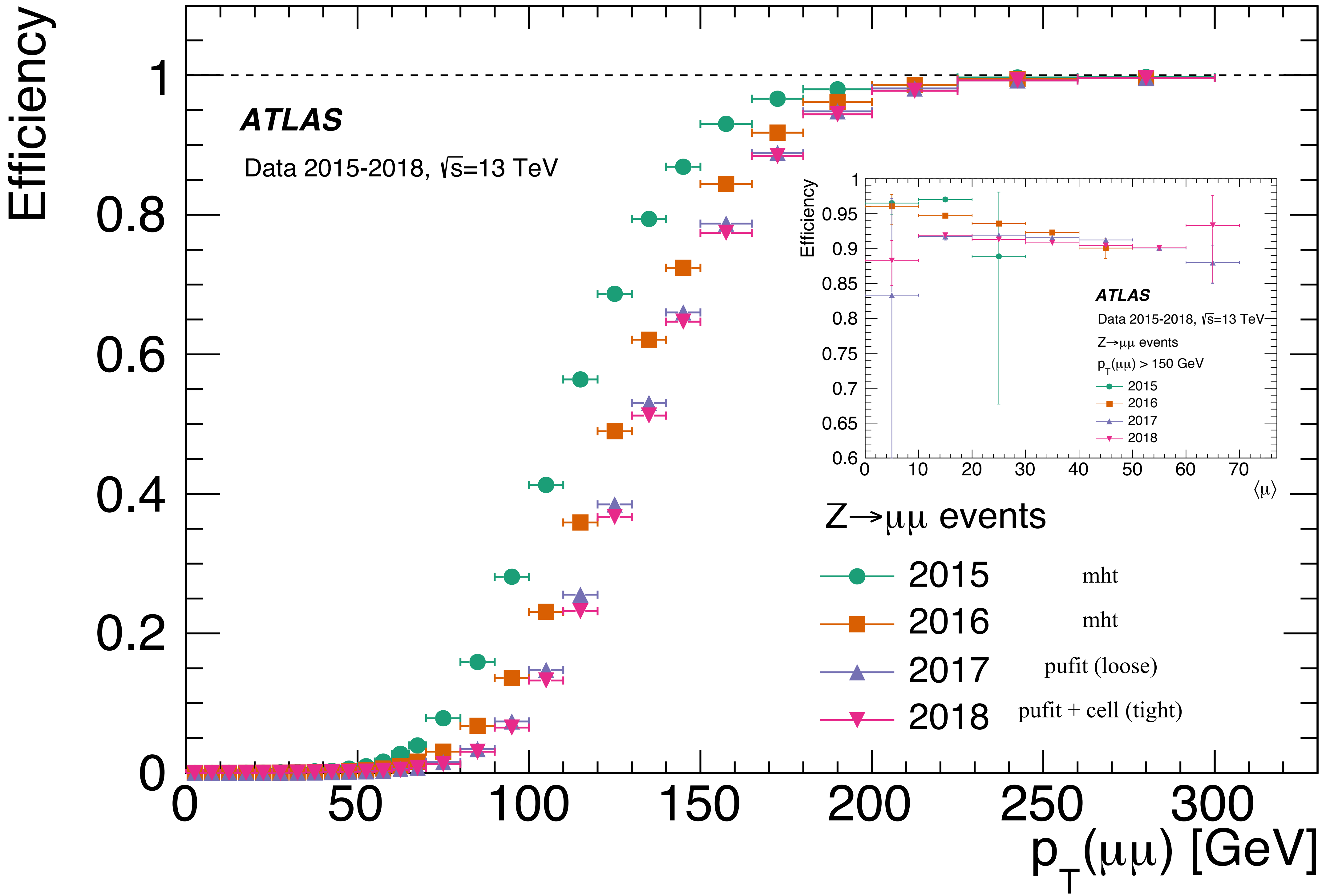
Submitted to JHEP, arXiv:2005.09554

- Average HLT bandwidth ~1 kHz
- Most significant reduction in rate from introducing pufit MET
- Additional rate reduction from combining with cell MET



Efficiency stable over 4 years

- Better performance during first year with lower luminosity



Summary

Feel free to chat on zoom: https://pitt.zoom.us/j/91459719989

1. Introduction
   - Described the trigger system
2. Jets
   - Improvements in the context of dark matter
3. Missing transverse momentum
   - Significant challenge to reduce impact of pileup

Not discussed

- Multijet triggers, b-jet triggers*, combined triggers
- L1 trigger upgrade or the HL-LHC

More information:

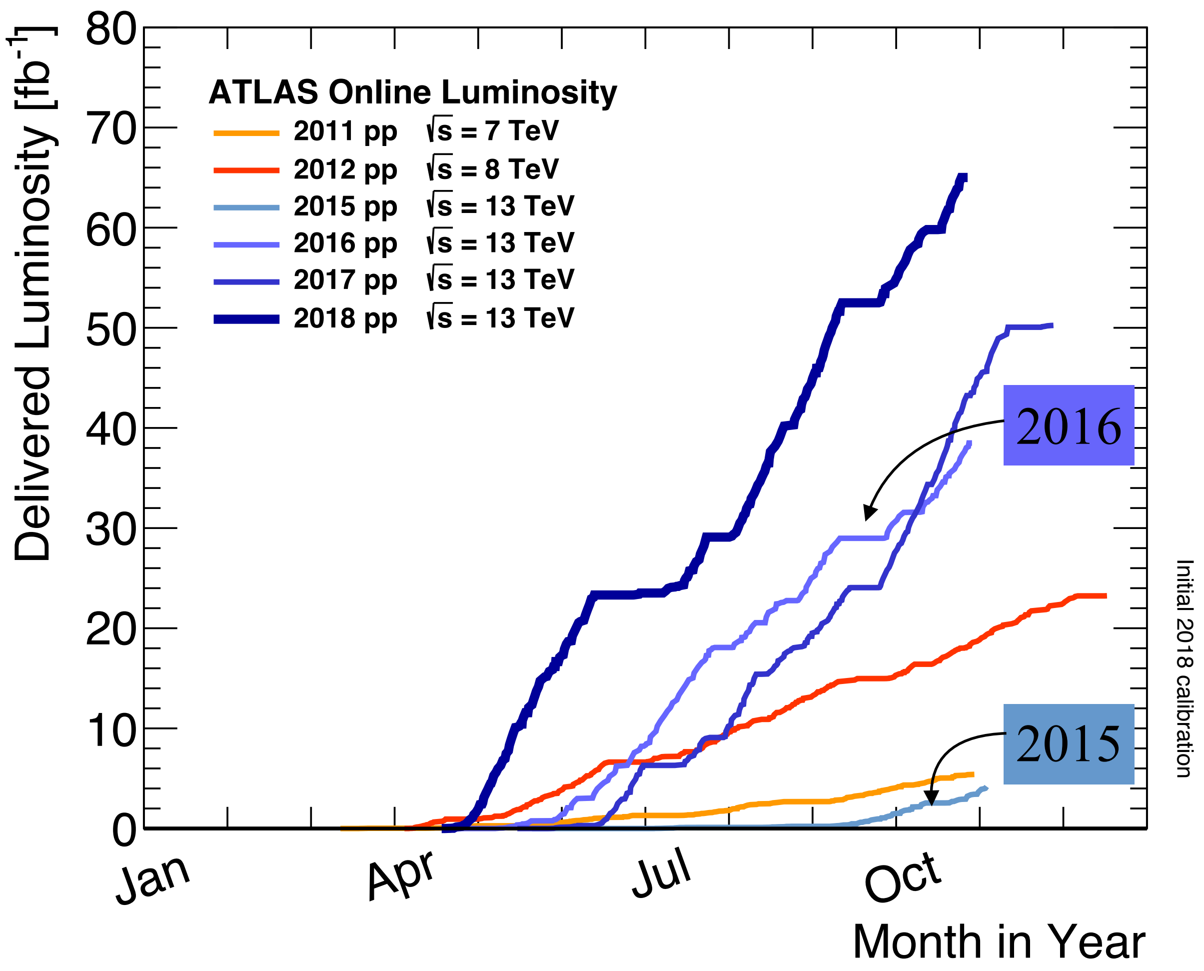
- Performance of the missing transverse momentum triggers for the ATLAS detector during Run-2 data taking. Submitted to JHEP, arXiv:2005.09554
- Performance of the upgraded PreProcessor of the ATLAS Level-1 Calorimeter Trigger. Submitted to JINST, arXiv: 2005.04179
- Twiki pages with preliminary results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TriggerPublicResults

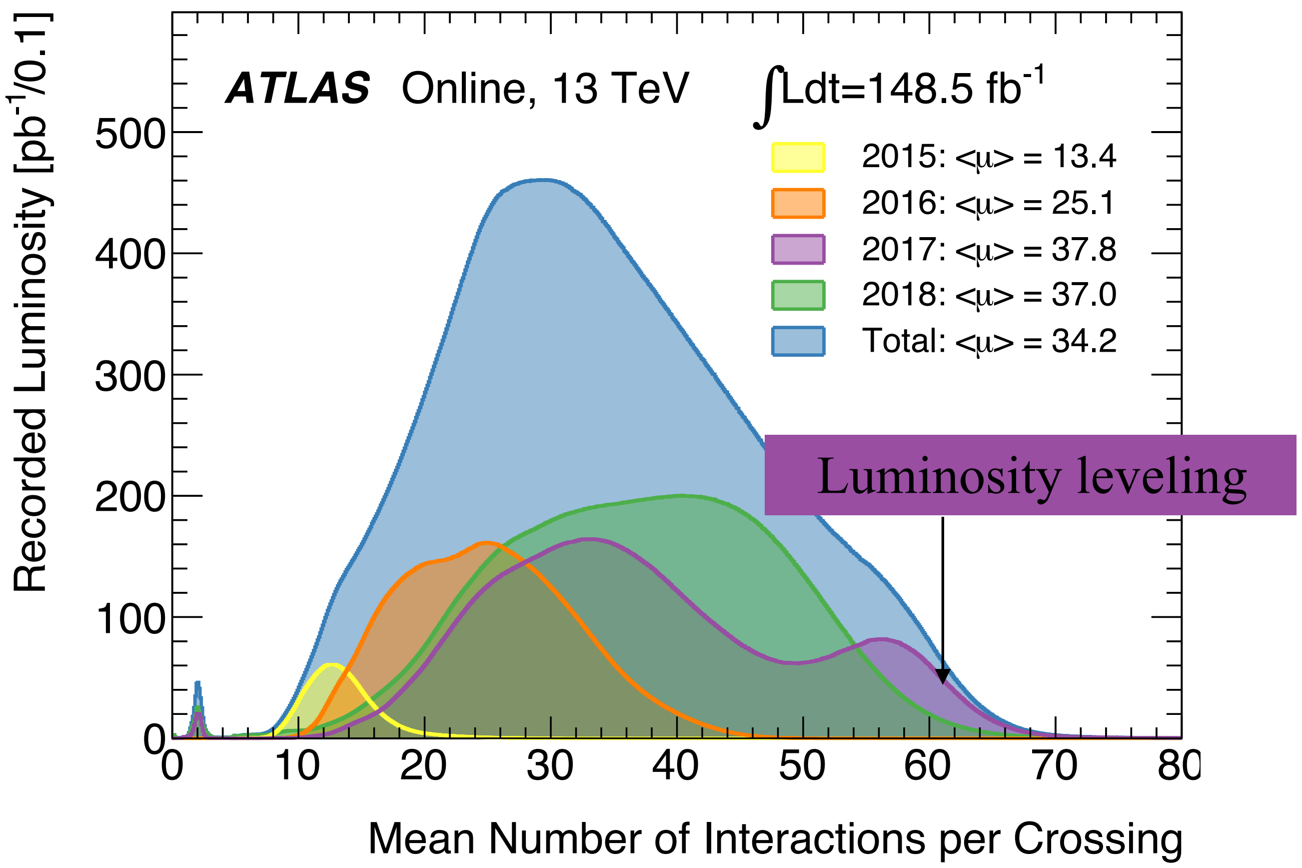
General

The slope dramatically increased over the seven years plotted

At the cost of increasing pileup

multiple interactions per bunch crossing





Maintaining a high efficiency MET trigger for high μ was a challenge

Jet Trigger

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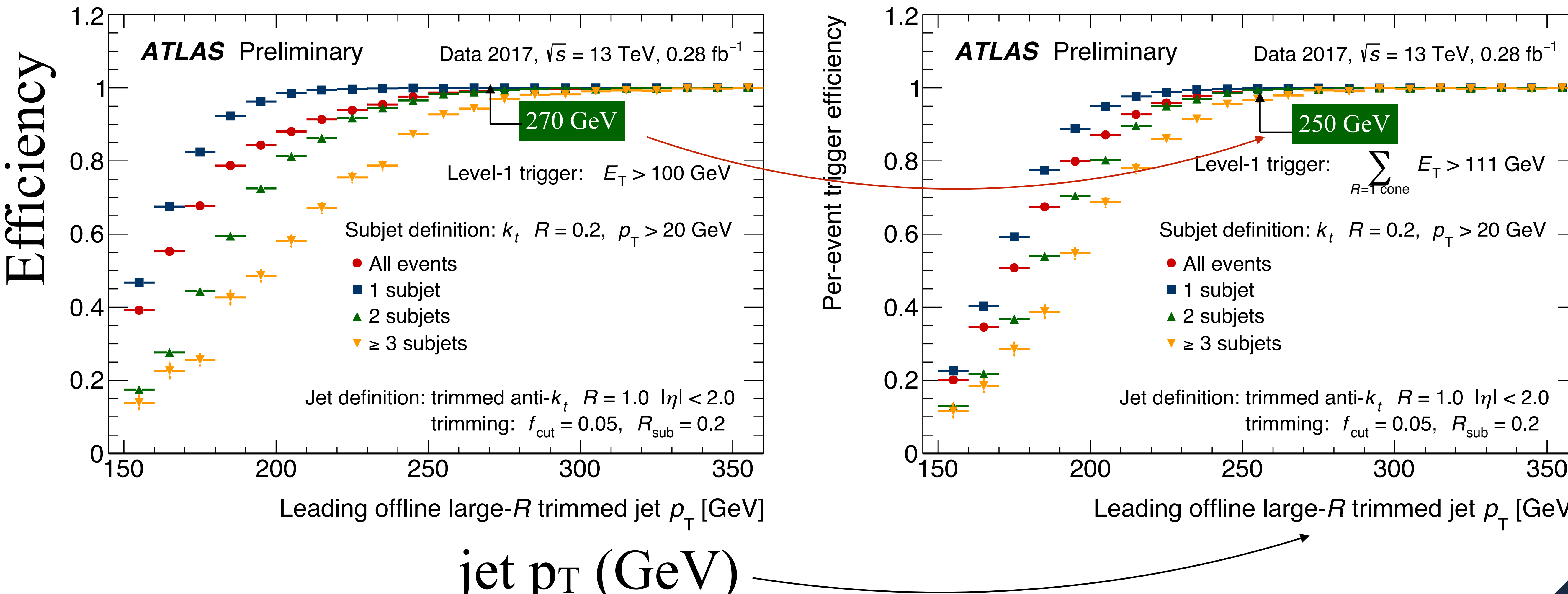
New L1Topo algorithm for improved large-R jet efficiency

- L1Calo jets: square jet (0.8x0.8) efficiency drops for multiple sub-jets as energy is not included in the jet definition (left)
- Simple cone L1Topo: sum all jets with $p_T > 15$ GeV in a cone with R = 1.0, includes more of the energy with multiple sub-jets (right)
- Threshold where Simple Cone is fully efficient for a large-R jet with two sub-jets is approximately 20 GeV lower than J100 for the same rate

Efficiency for J100 (L1Calo) *Efficiency for SC111 (L1Topo)*



Motivation: HH

JHEP 01 (2019) 030

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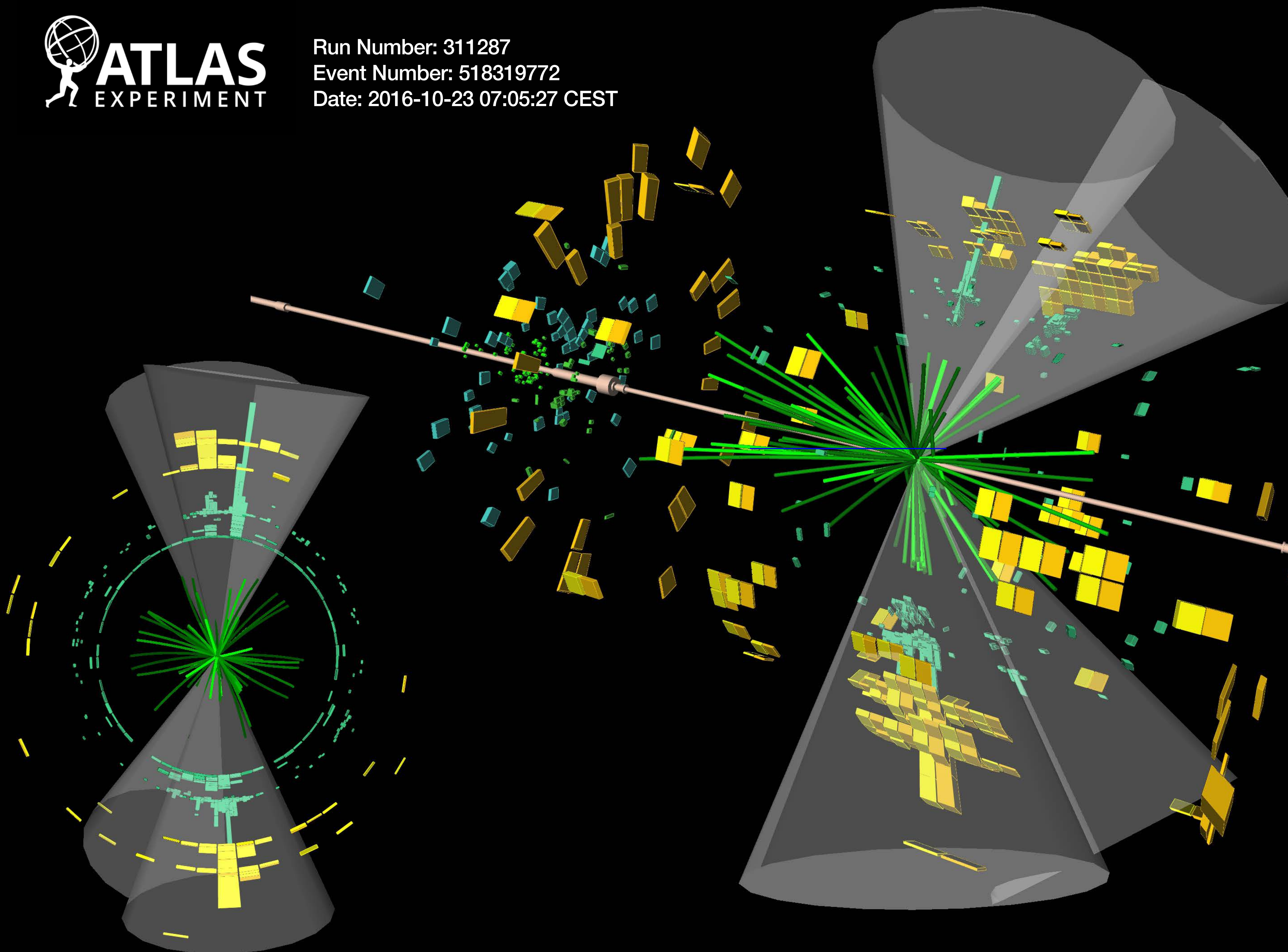

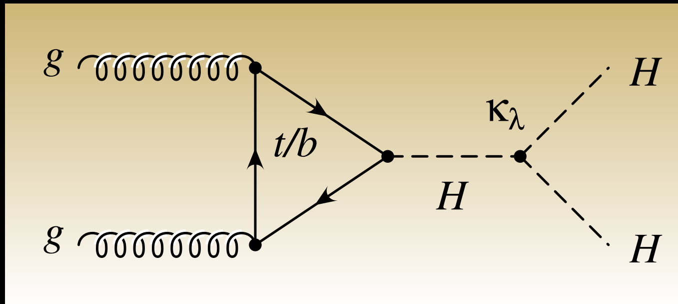

Triggers for measuring the Higgs self-coupling

HH→4b trigger

Jet trigger public (link)
HH4b projection (link)

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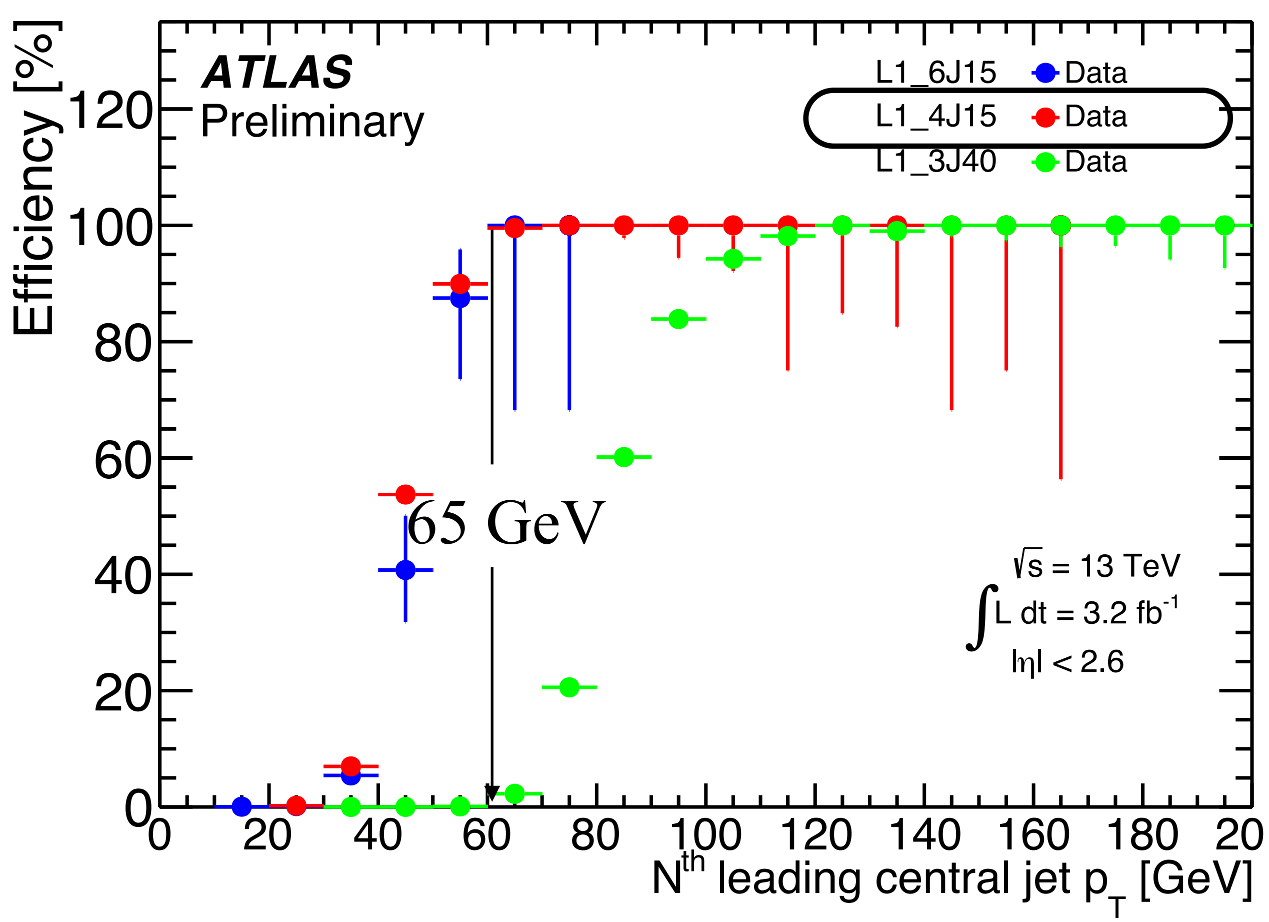
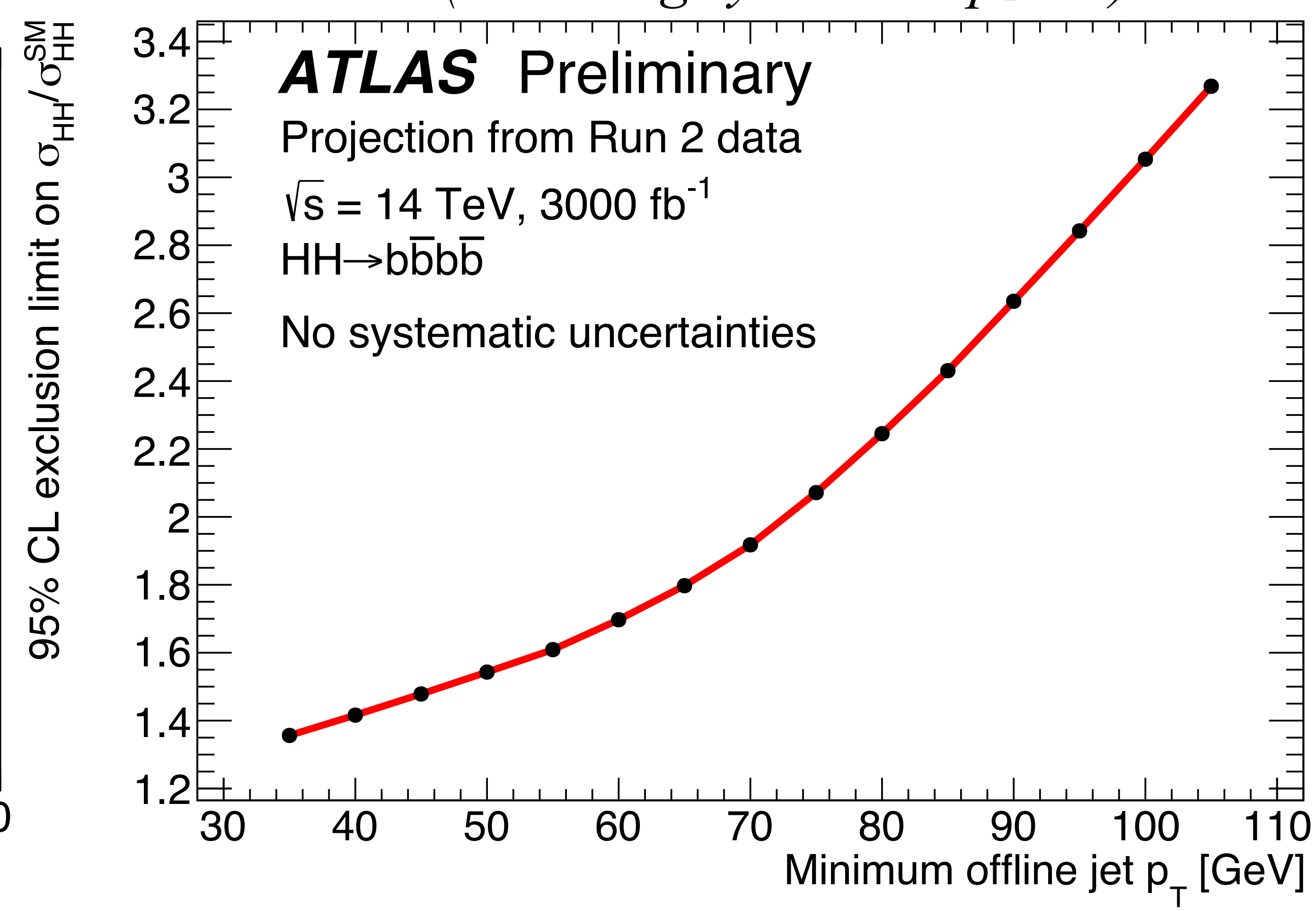
Reminder of limitation from using 4 jets at L1



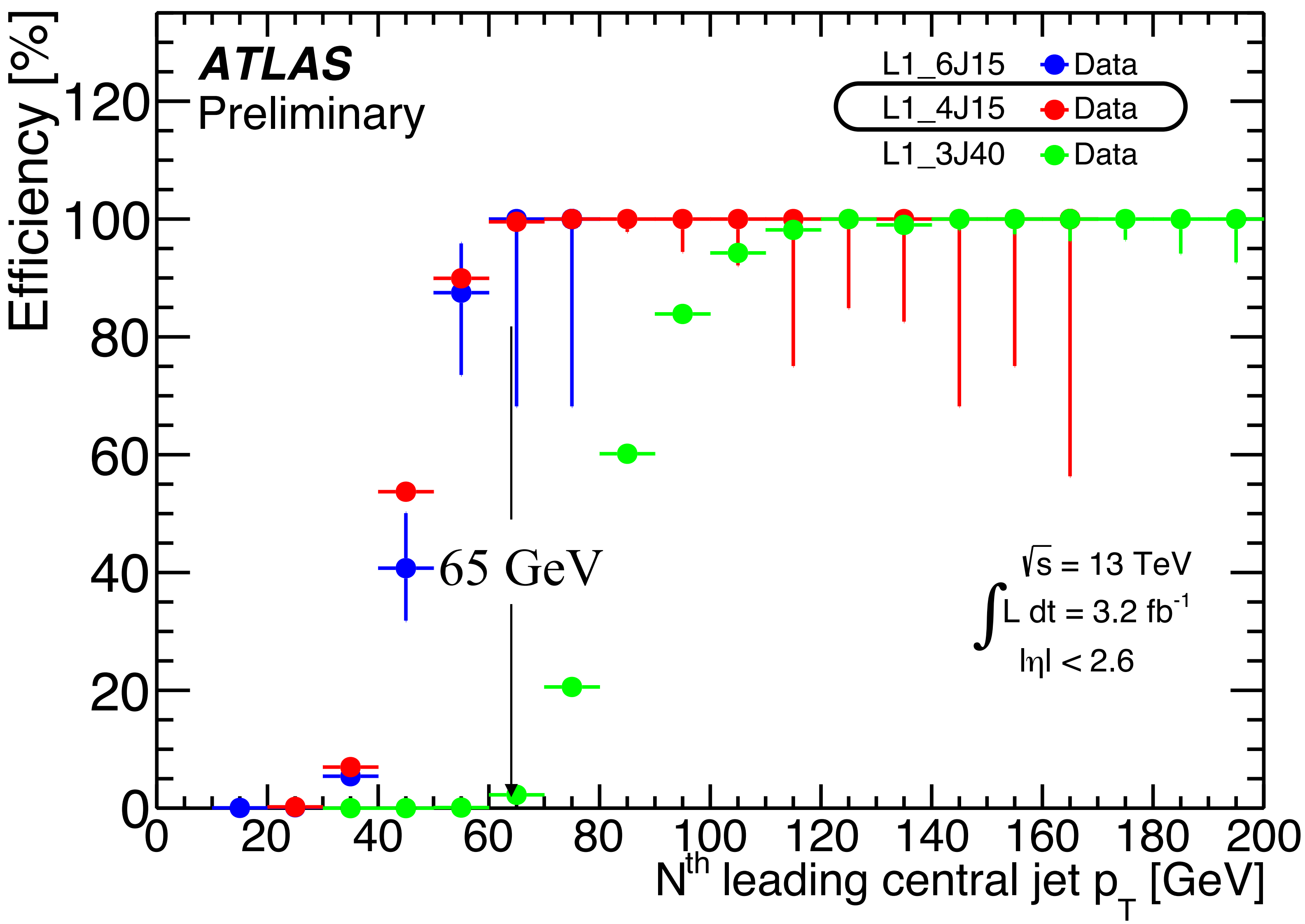
Run 2: use 2 b-jets + 2 jets with $p_T > 35$ GeV in the HLT

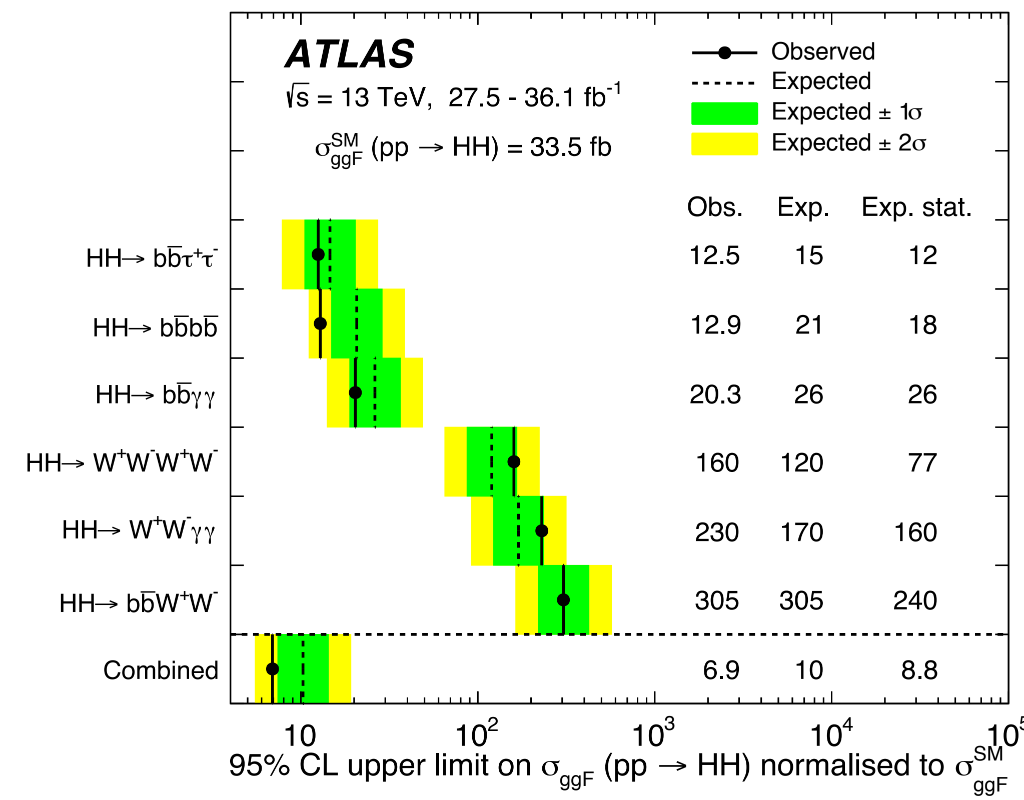
Projected sensitivity vs. minimum jet p_T (assuming symmetric p_T cut)



HH search: relies on hadronic triggers

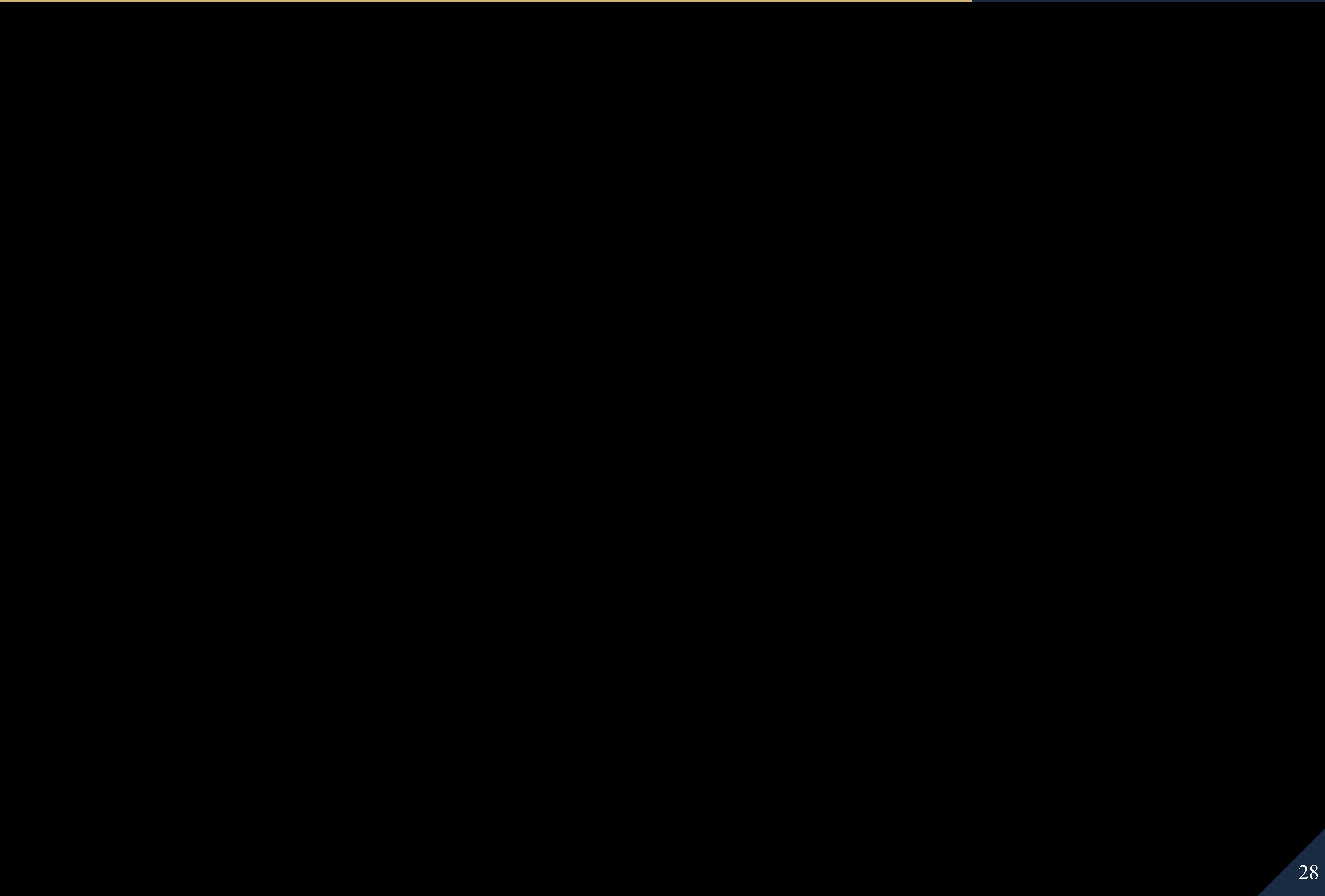
- Key channels: 4b and bb$\tau\tau$ are the most sensitive channels, and an interesting trigger challenge
- 4b channel uses 4J15 at L1 (left), with two b-tags in the HLT
- Note that 15 GeV at L1 corresponds to ~65 GeV offline, one of the main limitations
- Same L1 seed used for a variety of other triggers, e.g., multi-jets





4b & bb$\tau\tau$: 40% of HH events

Trigger



ZH sensitivity

CERN-LHCC-2017-020

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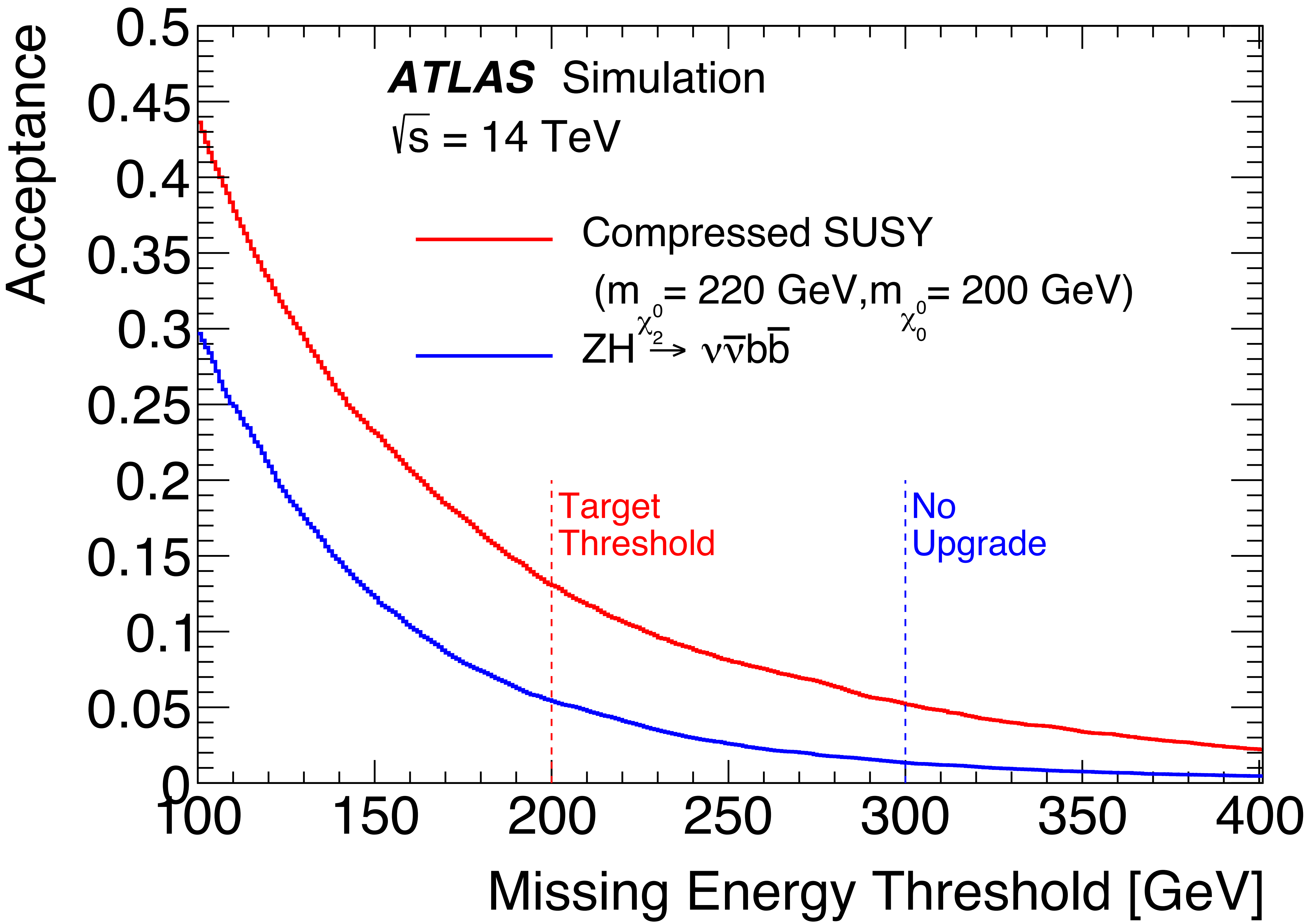

HLT: Reject early

Eur. Phys. J. C 77 (2017) 317

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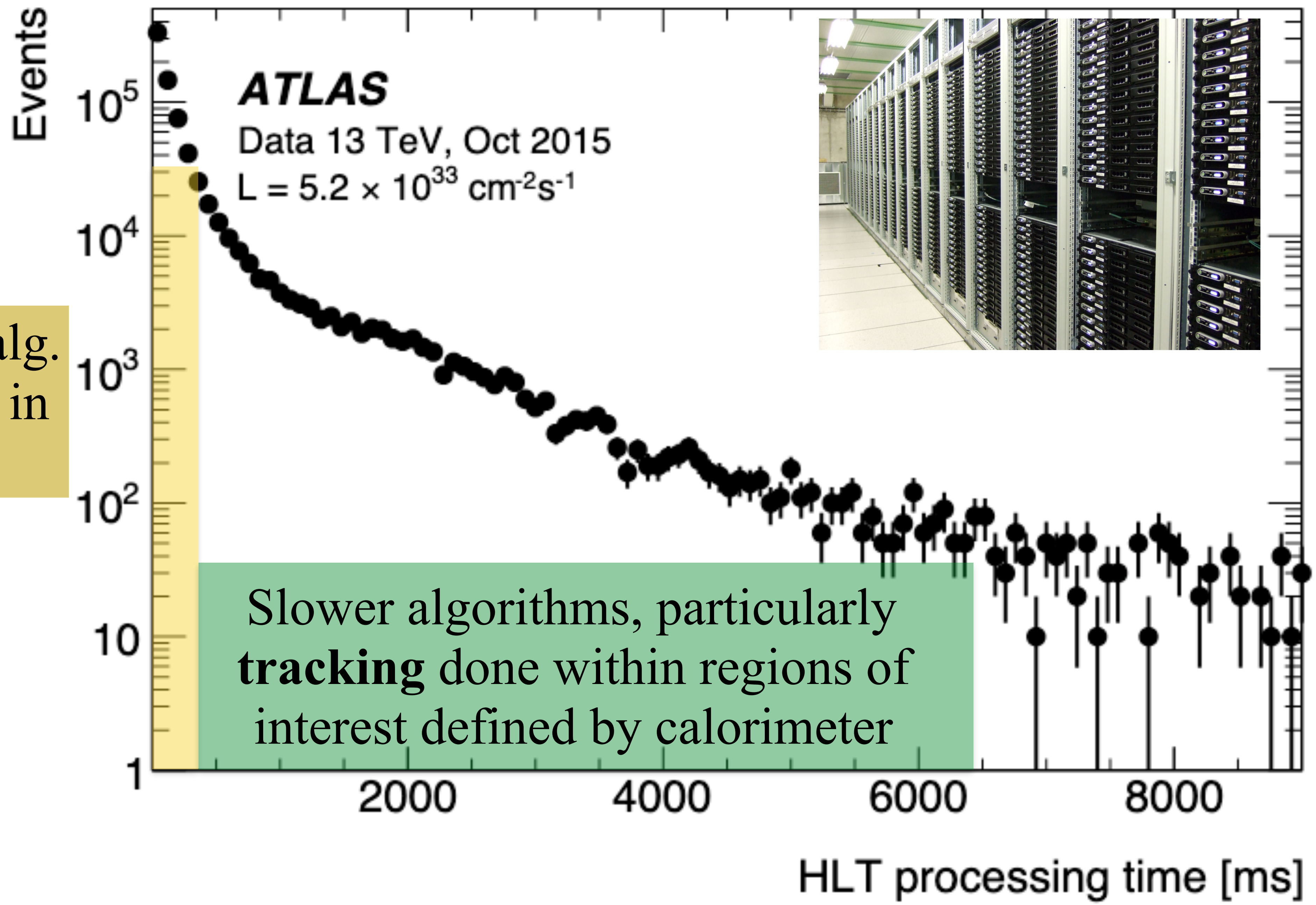
The HLT has ~50k cores (at the end of Run 2)

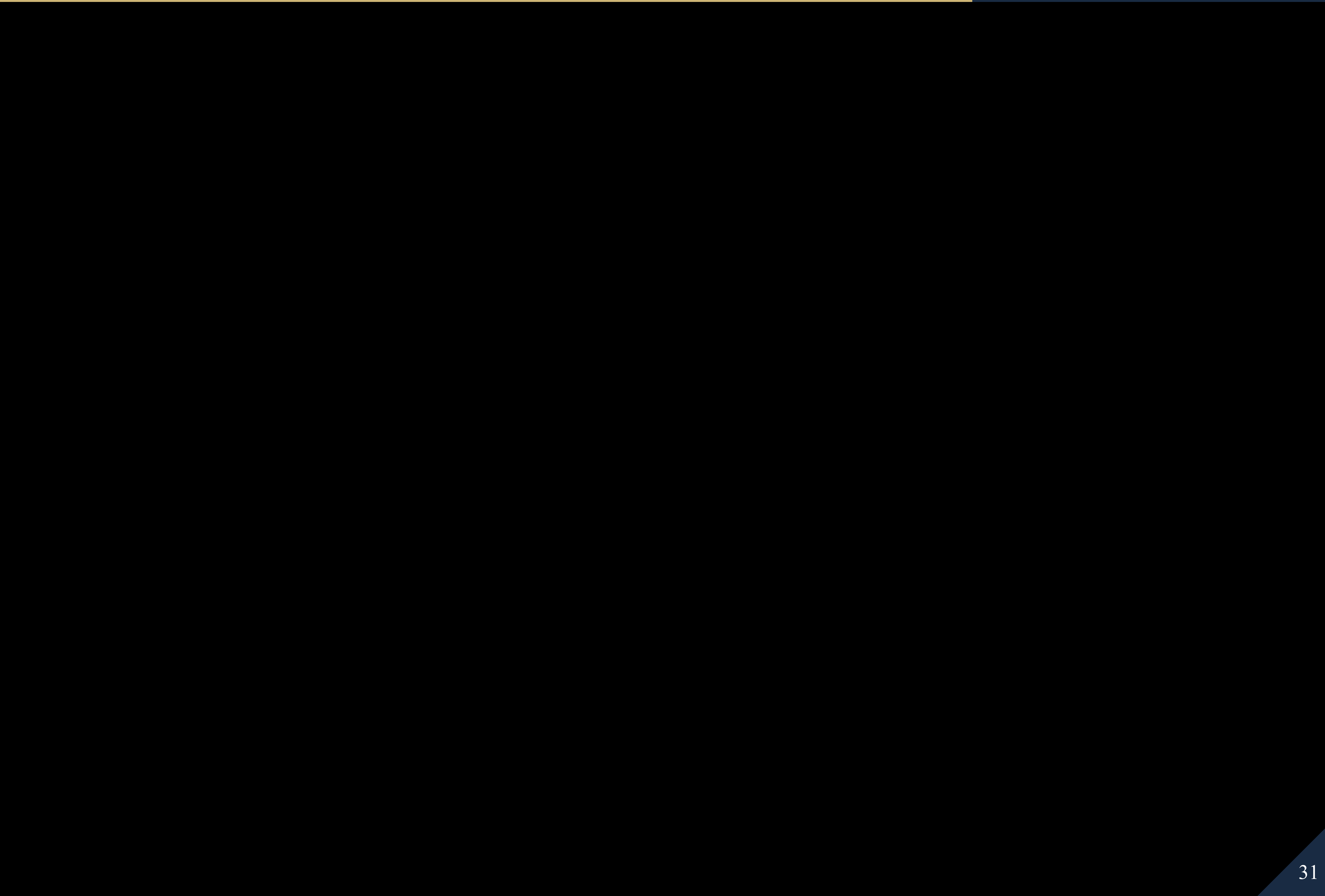
- On average we have 500ms / event to make a decision [100kHz x 500ms/event = 50k cores]

Reject using *fast* calculations first

- For MET, use the calorimeter, which is 5x faster than tracking
- We cannot run tracking for all the events we might want to

Calorimeter alg. reject events in ~200ms

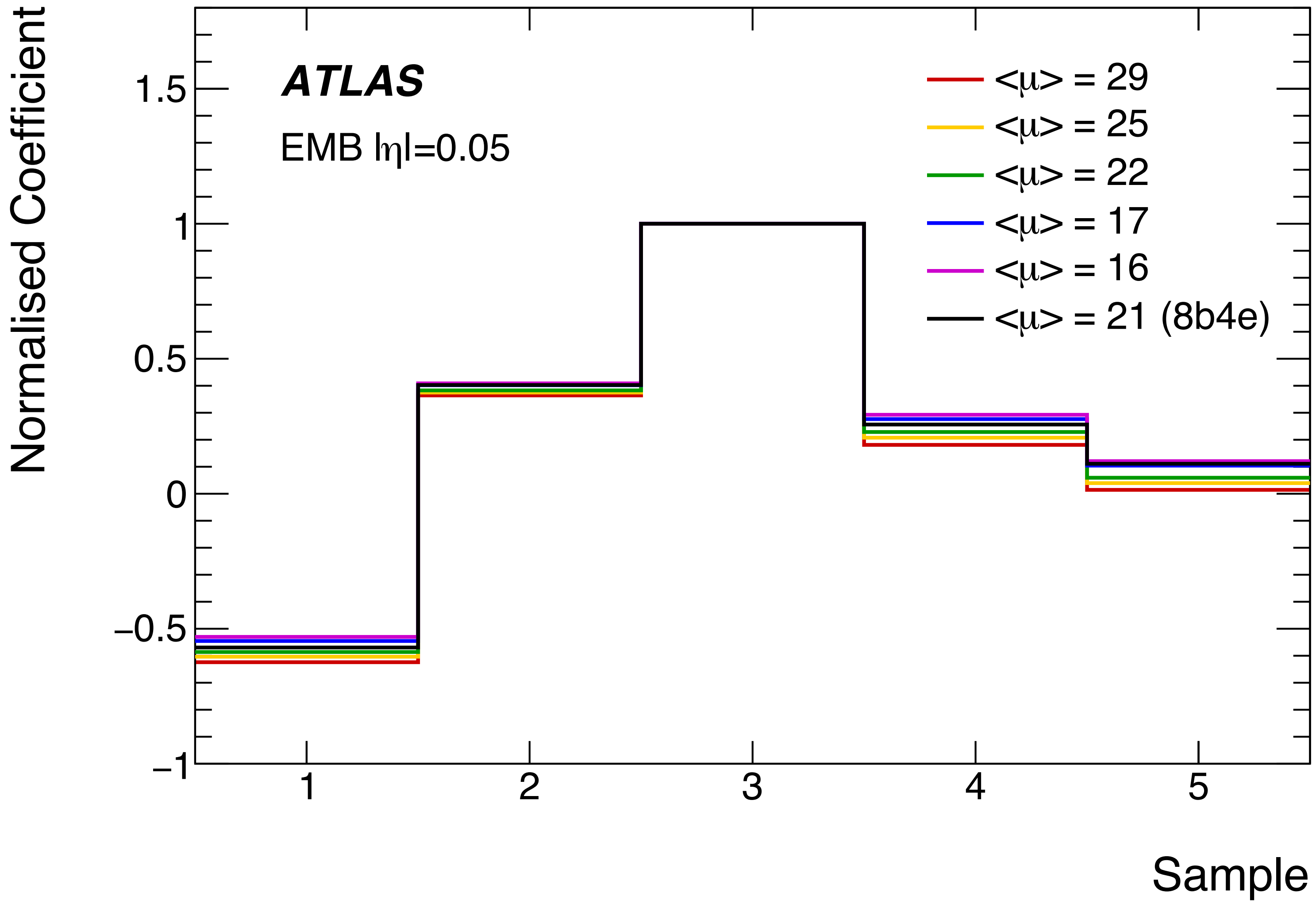




Apply several techniques to mitigate pileup

- *Pedestal correction* Removes bunch train dependence
- ***Autocorrelation filter*** Removes sensitivity to previous bunches

Filter coefficients

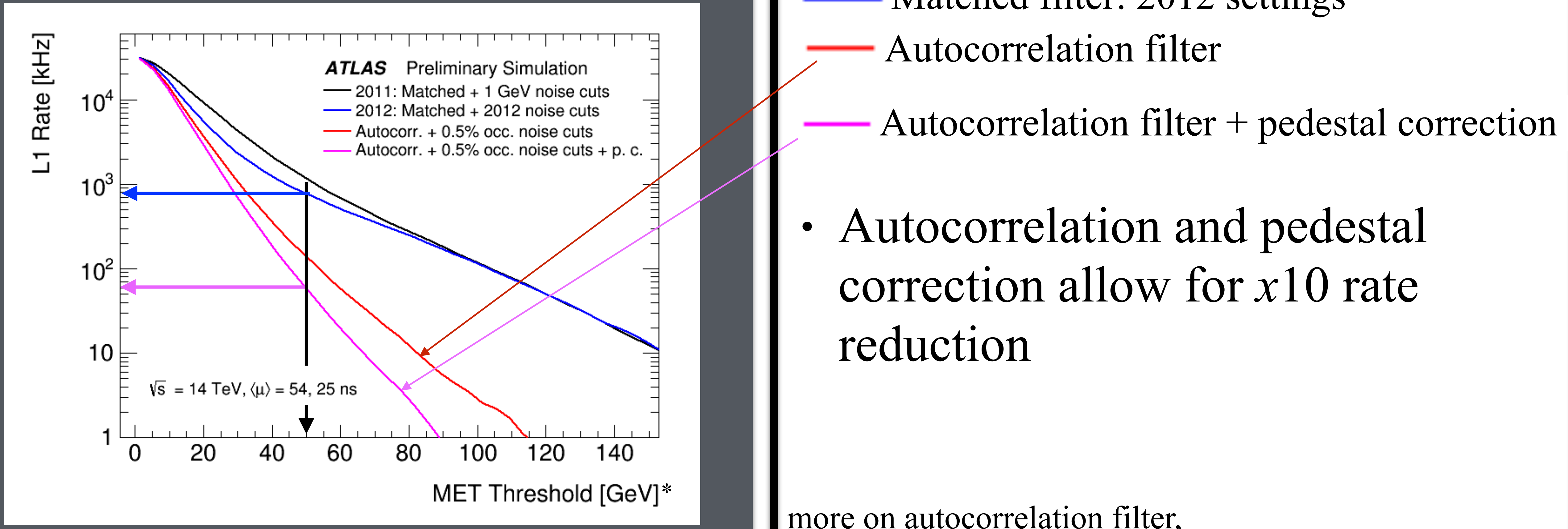


Apply several techniques to mitigate pileup

- *Pedestal correction* Removes bunch train dependence
- ***Autocorrelation filter*** Removes sensitivity to previous bunches

separate signal from pileup noise by deweighting previous bunches

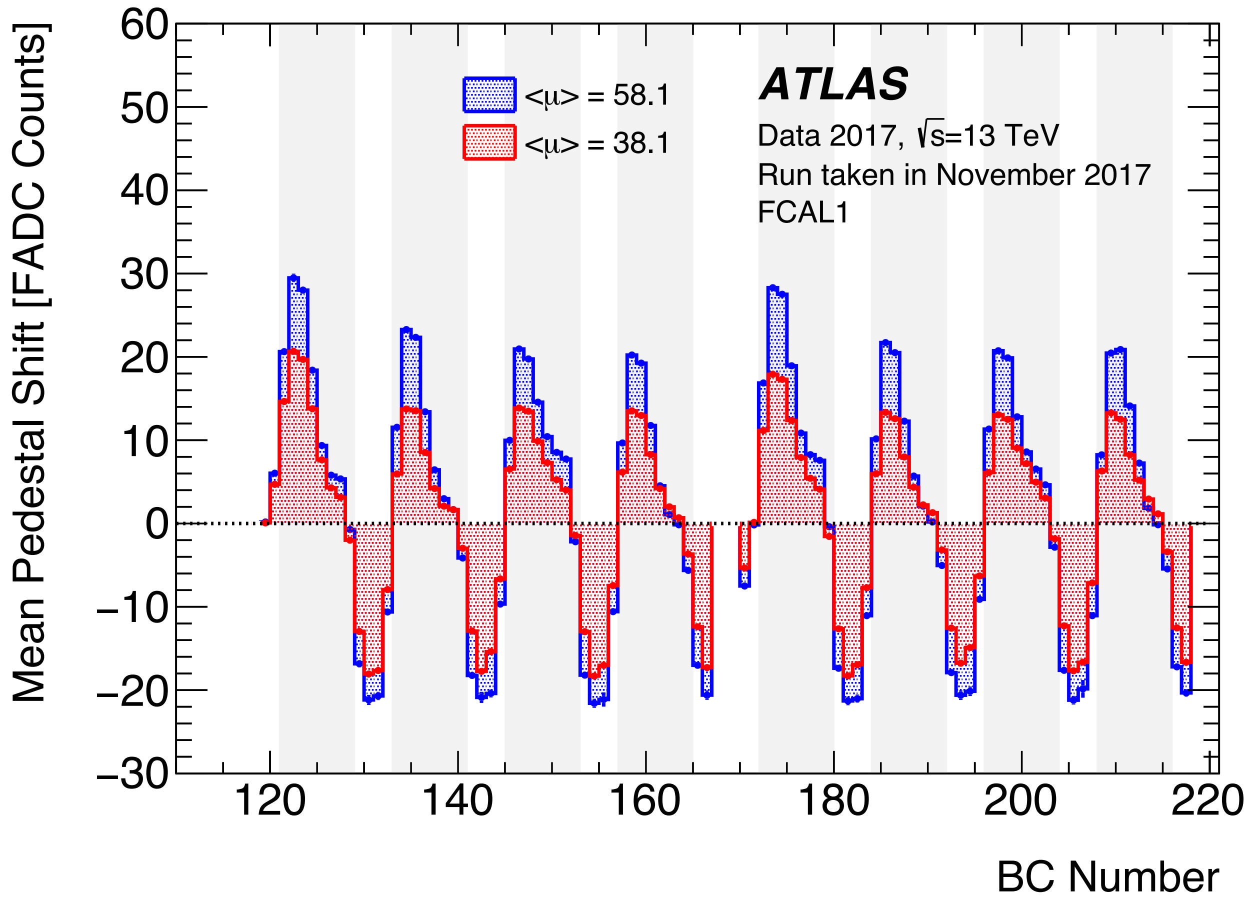
L1 rate vs. E_T^{miss} threshold

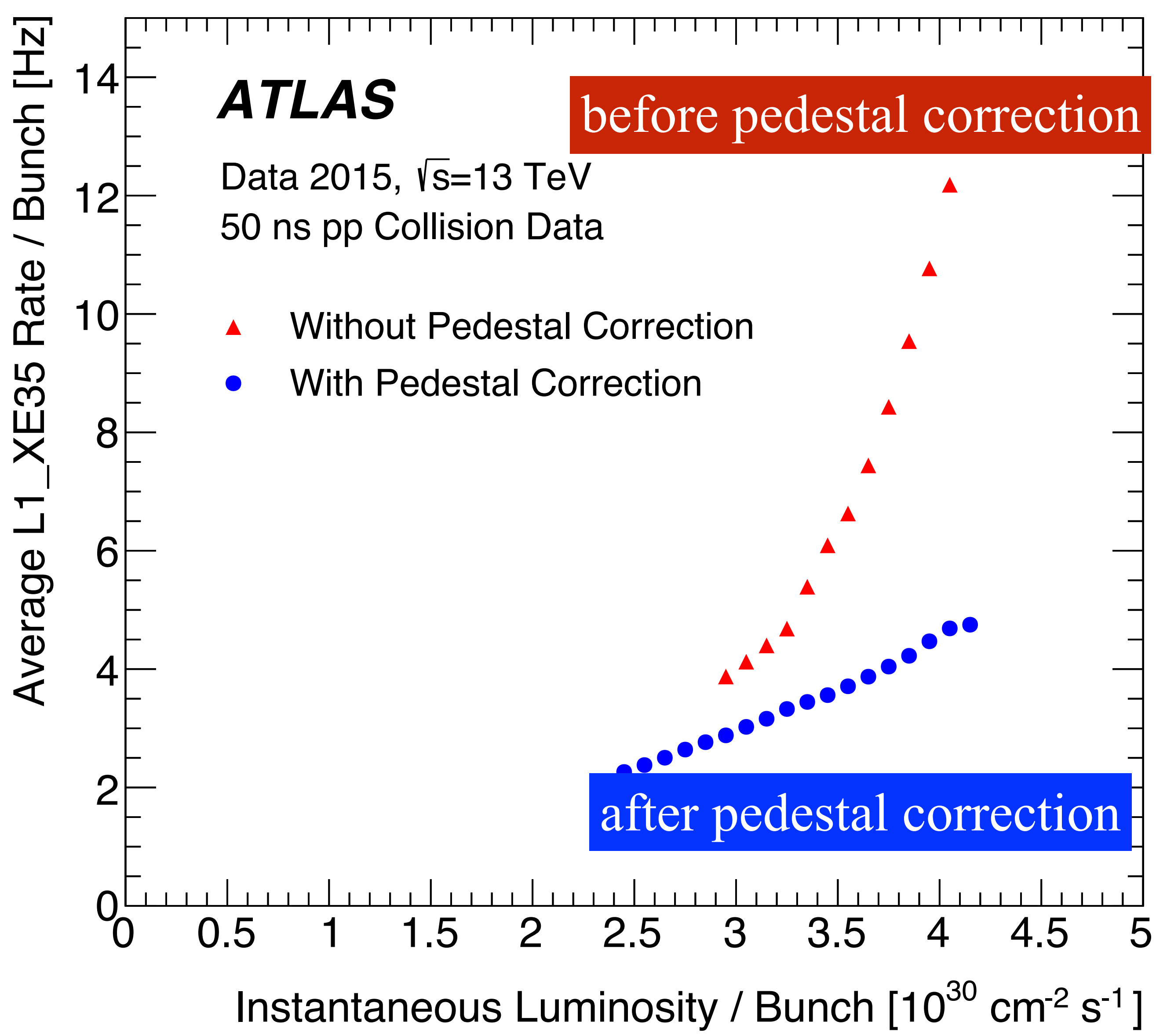


*Threshold at L1 not equivalent to offline E_T^{miss}

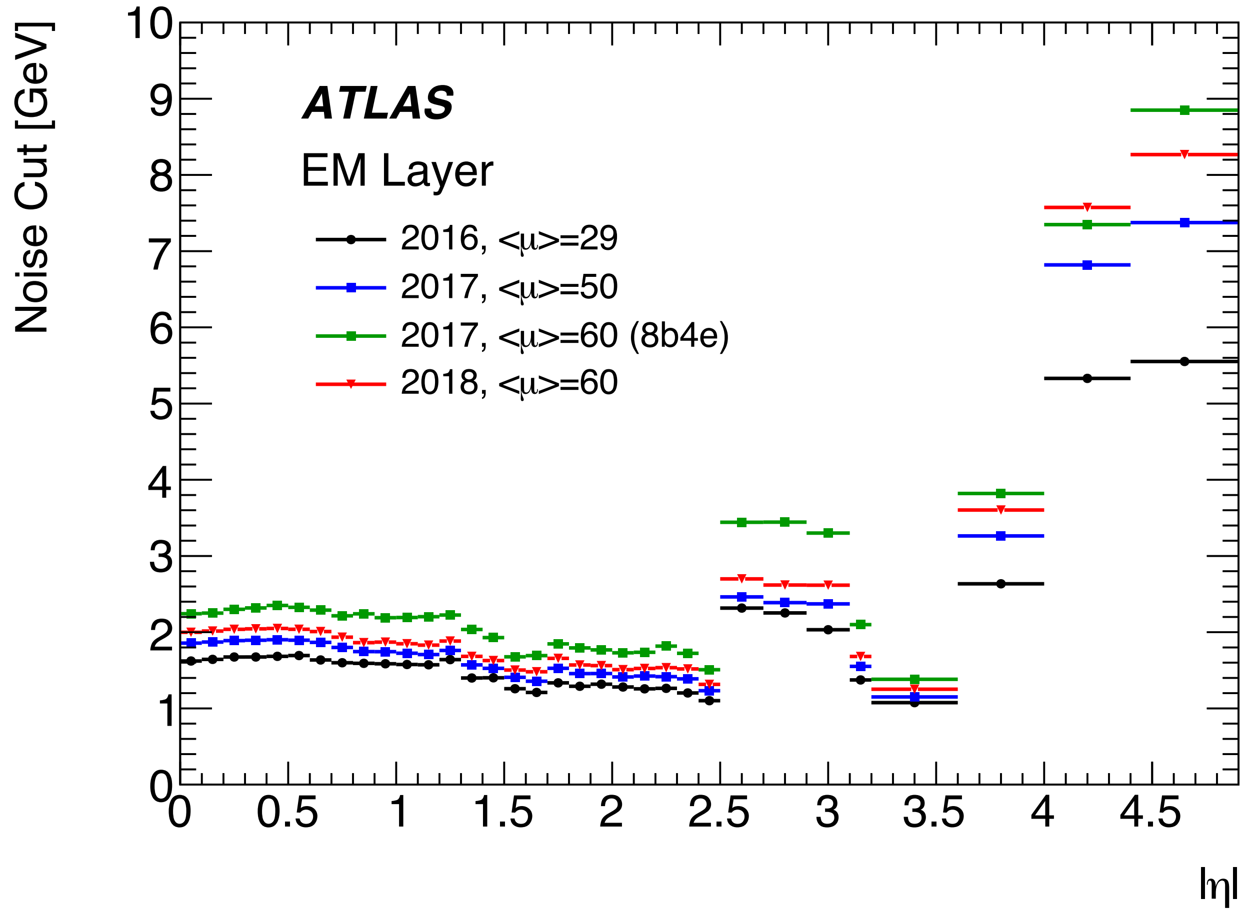
- Autocorrelation and pedestal correction allow for *x*10 rate reduction

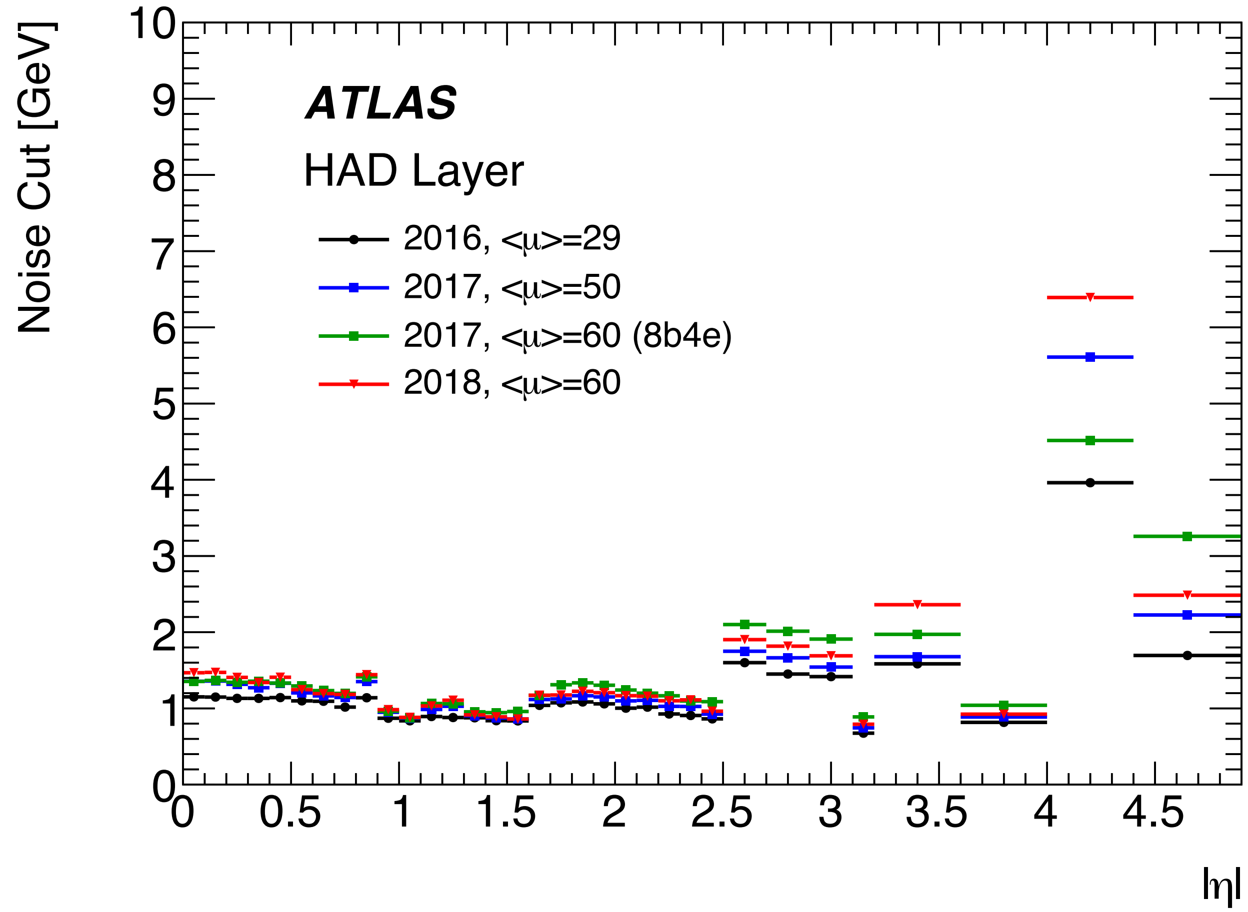
more on autocorrelation filter, see Wikipedia!


ATLAS
Data 2017, √s=13 TeV
Run taken in November 2017
FCAL1
<μ> = 58.1
<μ> = 38.1
Mean Pedestal Shift [FADC Counts]
BC Number


ATLAS
Data 2015, √s=13 TeV
50 ns pp Collision Data
Without Pedestal Correction
With Pedestal Correction
before pedestal correction
after pedestal correction
Average L1_XE35 Rate / Bunch [Hz]
Instantaneous Luminosity / Bunch [10^30 cm^-2 s^-1]

Variable thresholds at L1 lead to reduction in rate at high pileup



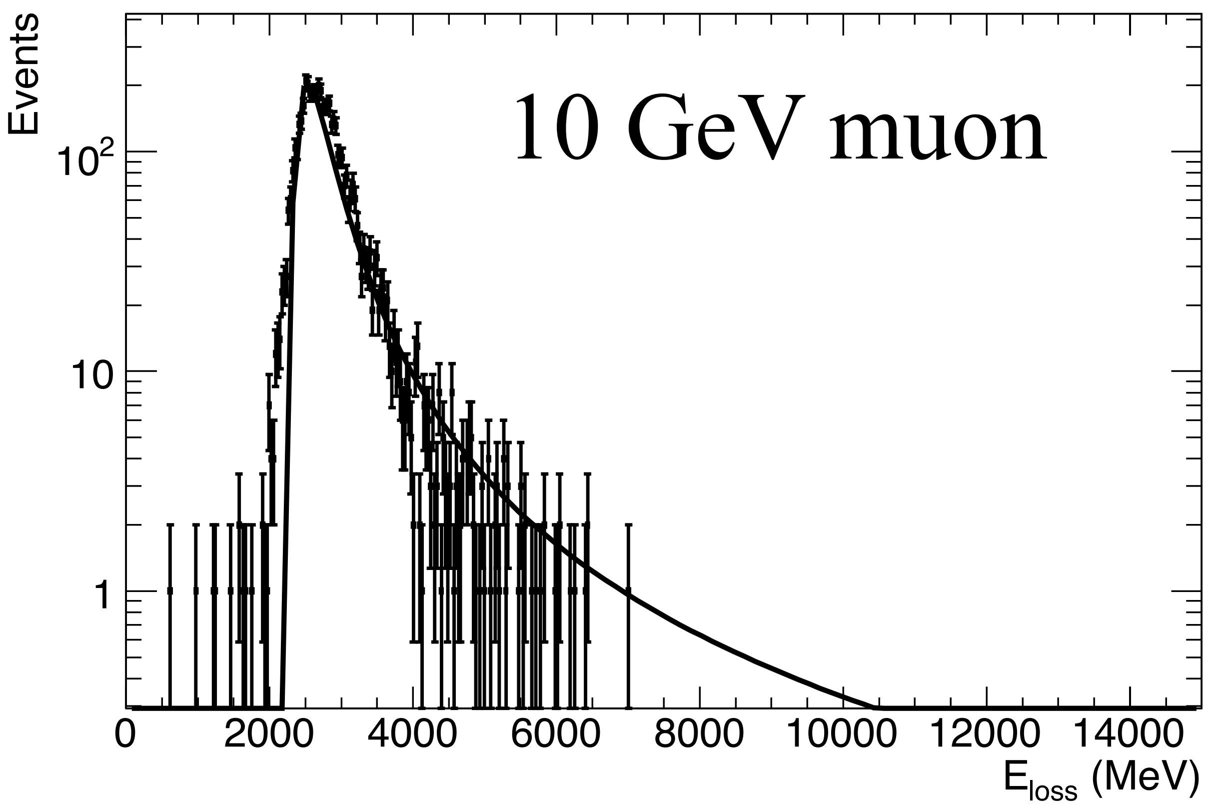


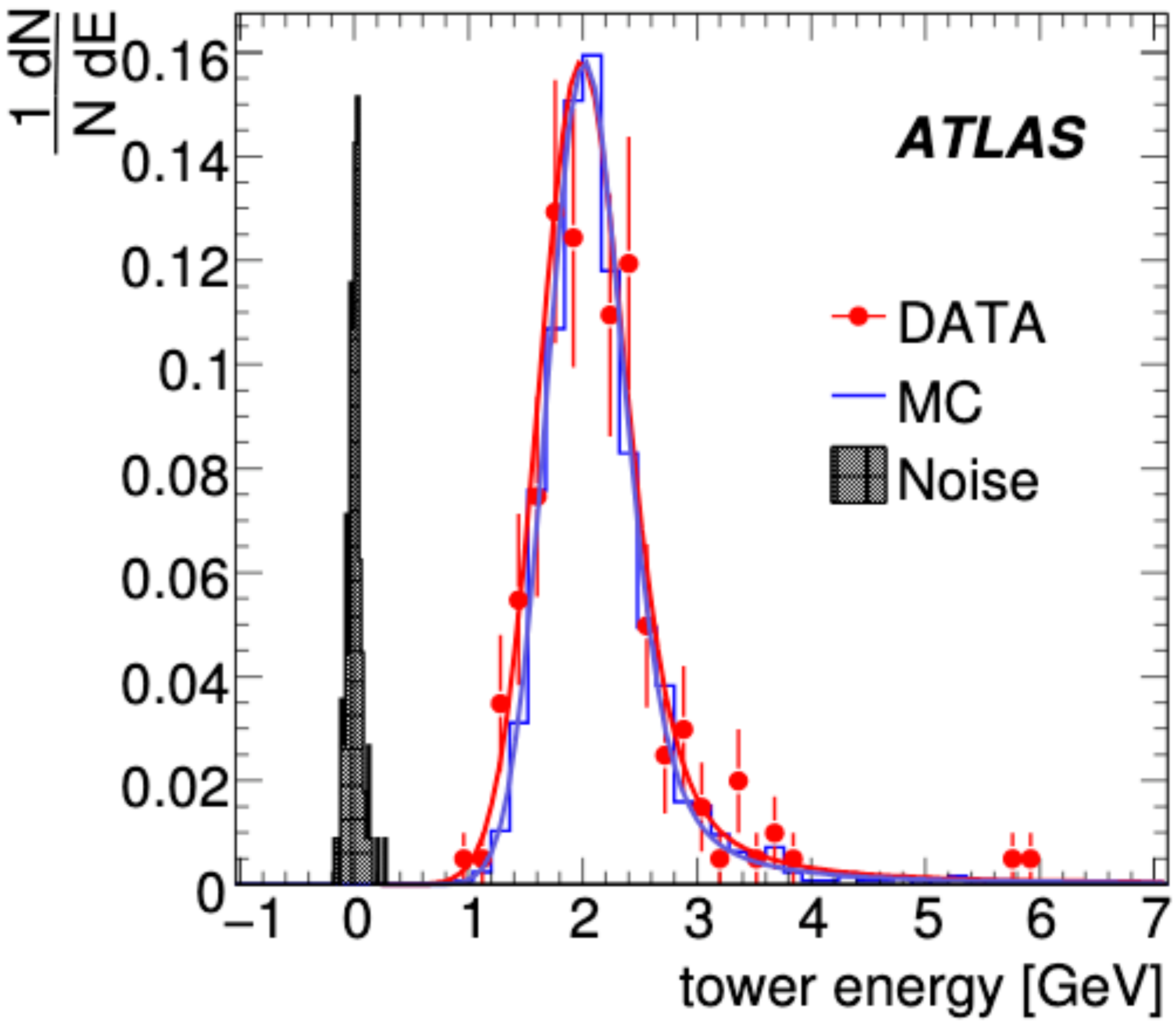
Muon in calo

Eur. Phys. J. C (2010) 70: 1193–1236
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/MuonPerformancePublicPlotsSimulation

Muons typically deposit 3-4 GeV the calorimeter, mostly tile

10-30 GeV cosmic ray muons in tile calorimeter

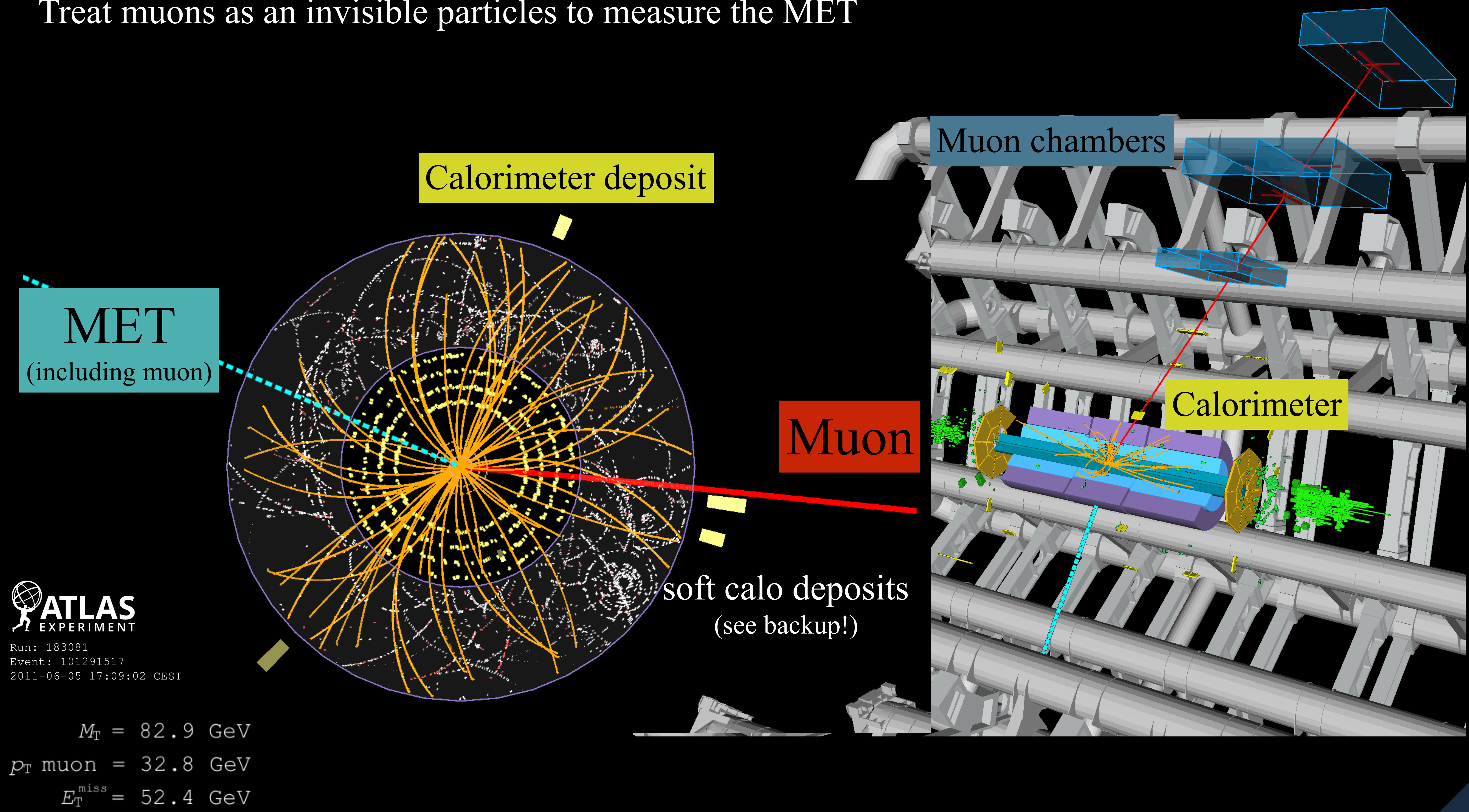




*for more information about using calorimeter information in muons, checkout the thesis of Gustavo Ordonez Sanz http://cdsweb.cern.ch/record/1196071

Muons are approximately invisible to the calorimeter

- 50 GeV muons typically deposit 3-4 GeV, thus approximately invisible to the calorimeter
- Trigger on and reconstruct muons using muon spectrometer
- Treat muons as an invisible particles to measure the MET



PUFIT

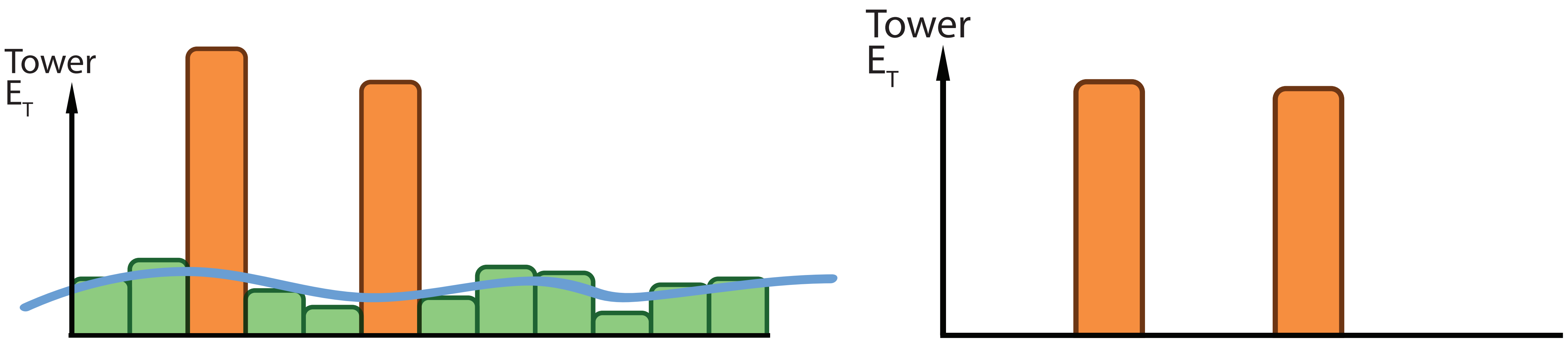


Figure credit: Emanuel Gouveia

- Divide ~0.7×0.7 “patches” into “Hard Scatter” & “Soft”
- Construct a chi-sq. to minimize soft MET under constraint of pileup fluctuation scale
- Subtraction measured pileup density from Hard Scatter
- ∑ corrected HS terms = MET

Description of PUFIT

- Divide ~0.7×0.7 "patches" into "Hard Scatter" & "Soft"
- Construct a chi-sq. to minimize soft MET under constraint of pileup fluctuation scale
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- ∑ corrected HS terms = MET

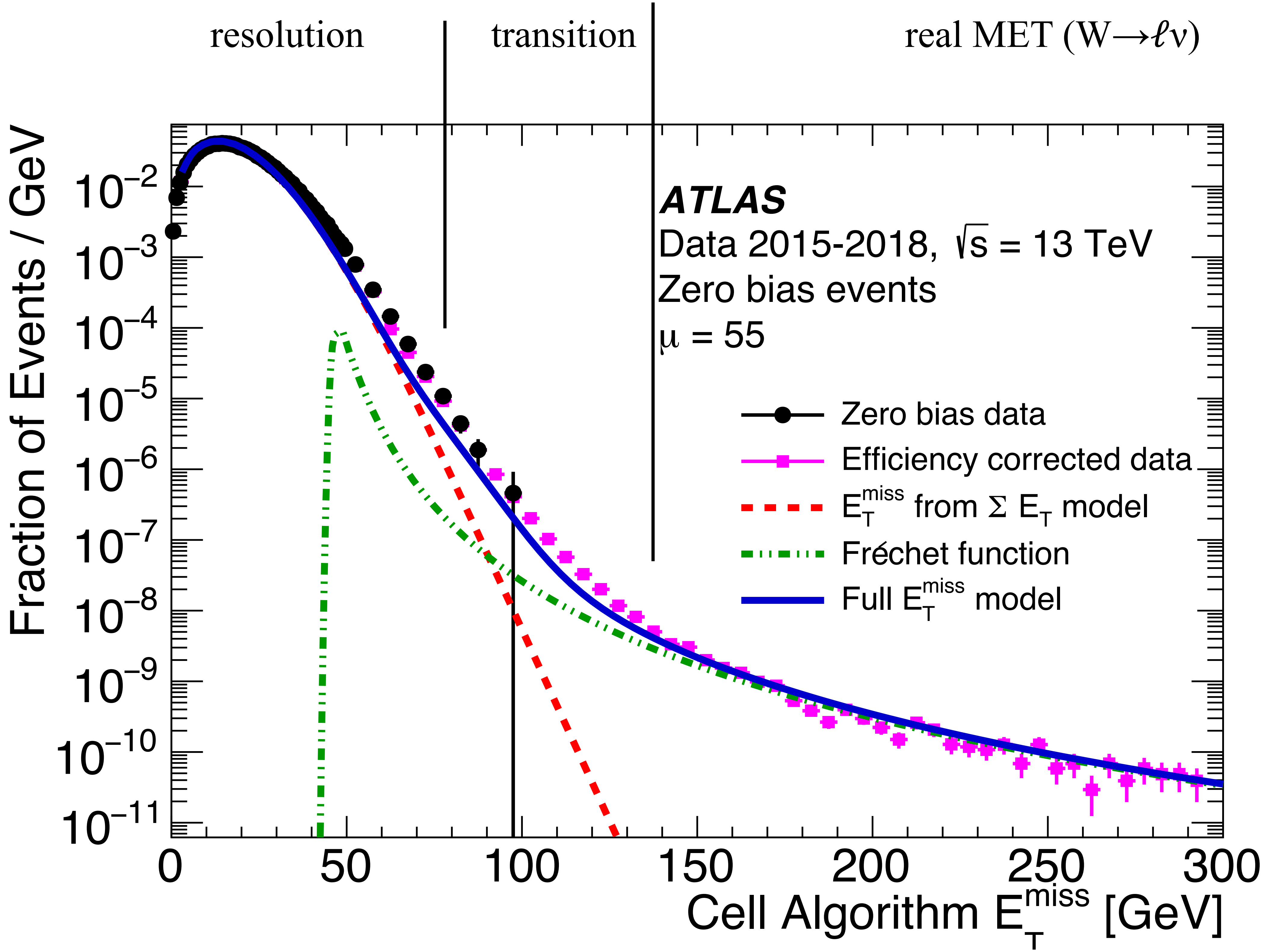
Details in appendix

$$\chi^2(\mathcal{E}_{\mathrm{T}_1}, \ldots, \mathcal{E}_{\mathrm{T}_m}) = \Delta^T V^{-1} \Delta \, .$$

$$\Delta = \begin{pmatrix} \sum_{i=1}^{N_{\mathrm{low}}} E_{x_i} + \sum_{k=1}^{m} \mathcal{E}_{\mathrm{T}_k} \cos\phi_k \\ \sum_{i=1}^{N_{\mathrm{low}}} E_{y_i} + \sum_{k=1}^{m} \mathcal{E}_{\mathrm{T}_k} \sin\phi_k \\ A_1/A_{\mathrm{low}} \times \sum_{i=1}^{N_{\mathrm{low}}} E_{\mathrm{T}_i} - \mathcal{E}_{\mathrm{T}_1} \\ \vdots \\ A_m/A_{\mathrm{low}} \times \sum_{i=1}^{N_{\mathrm{low}}} E_{\mathrm{T}_i} - \mathcal{E}_{\mathrm{T}_m} \end{pmatrix} \qquad V = \begin{pmatrix} V_{11} & V_{12} & 0 & 0 & \ldots & 0 \\ V_{12} & V_{22} & 0 & 0 & \ldots & 0 \\ 0 & 0 & sV_{\mathrm{patch}} & 0 & \ldots & 0 \\ 0 & 0 & 0 & \ddots & \ldots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & \ldots & sV_{\mathrm{patch}} \end{pmatrix}$$

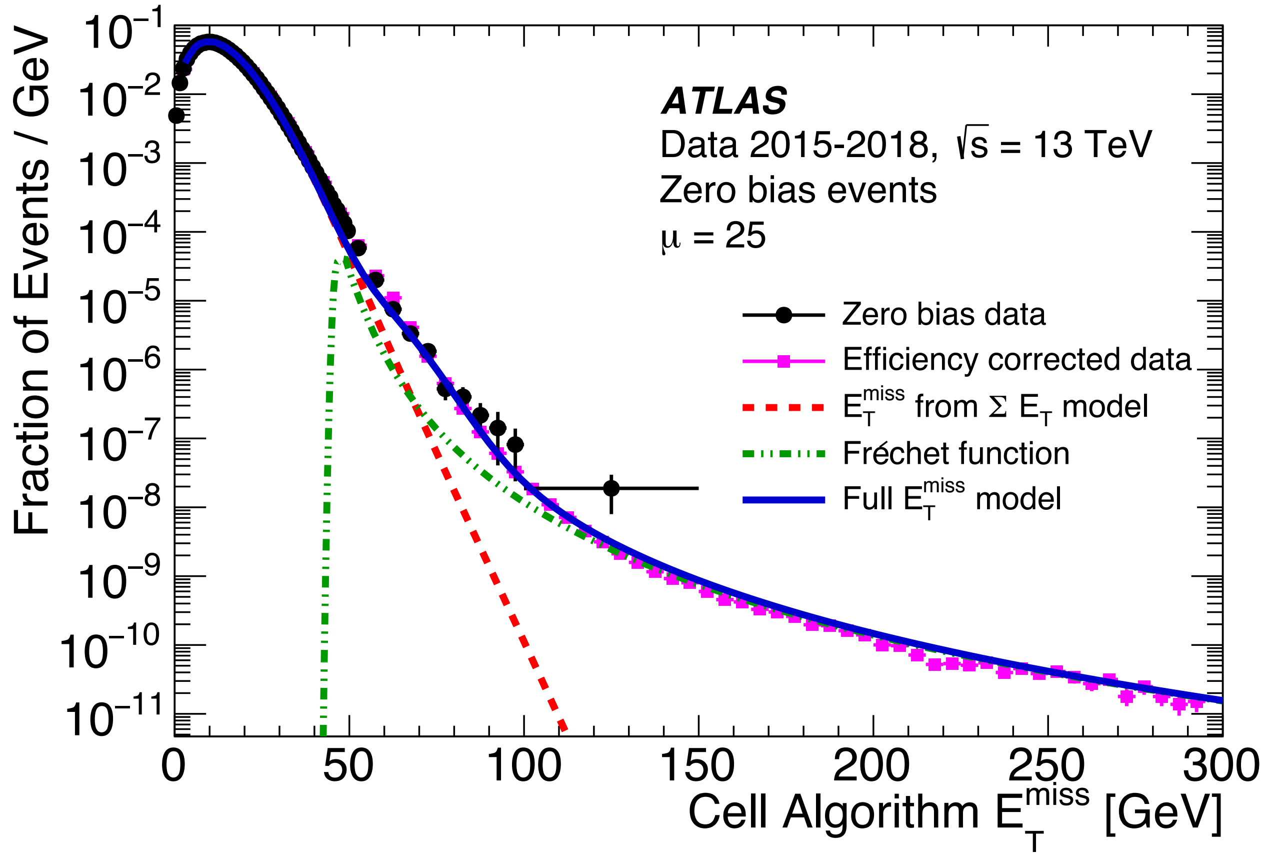
Analytic model

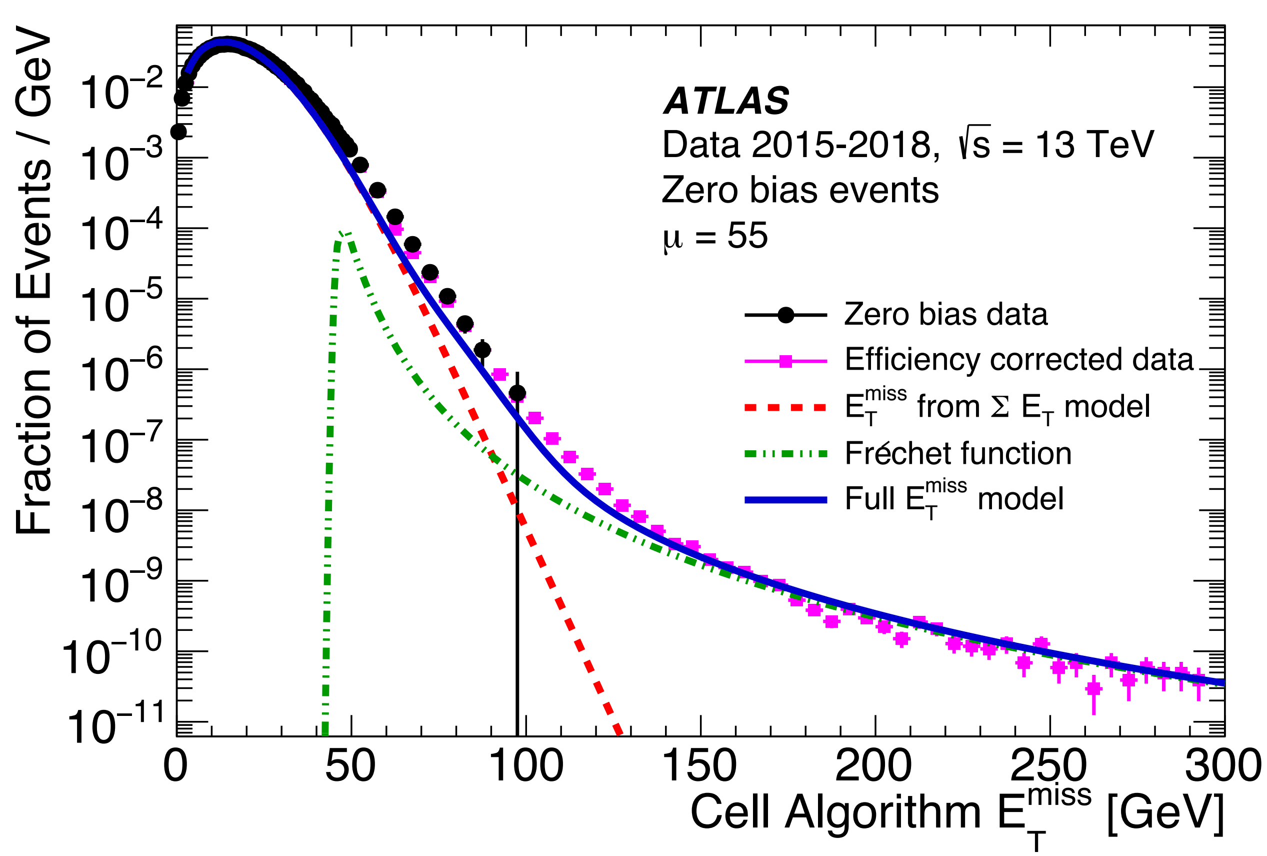
Model based on detector resolution describes spectrum



From μ = 25 to 55

Submitted to JHEP, arXiv:2005.09554





Prediction from data

Submitted to JHEP, arXiv:2005.09554

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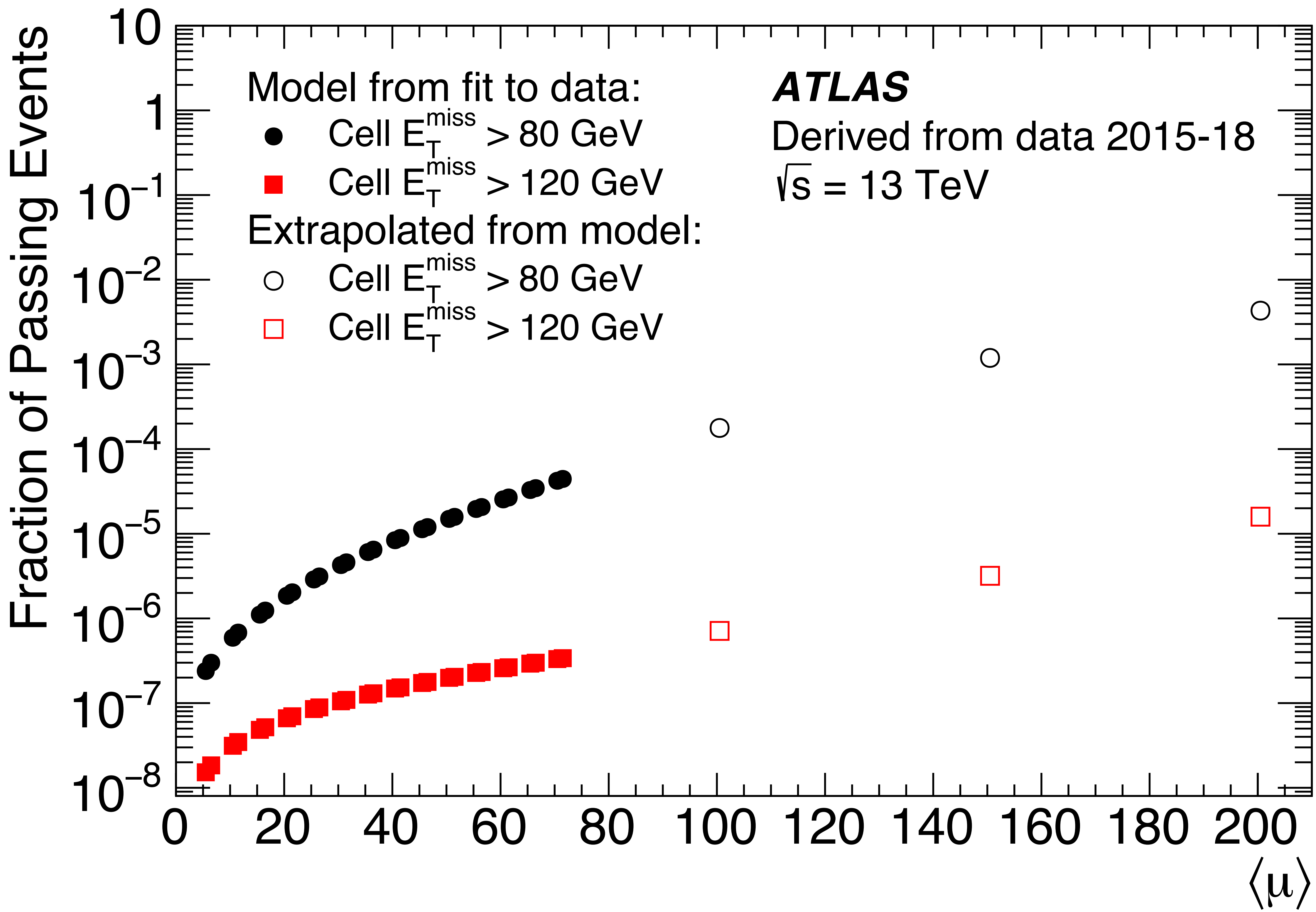
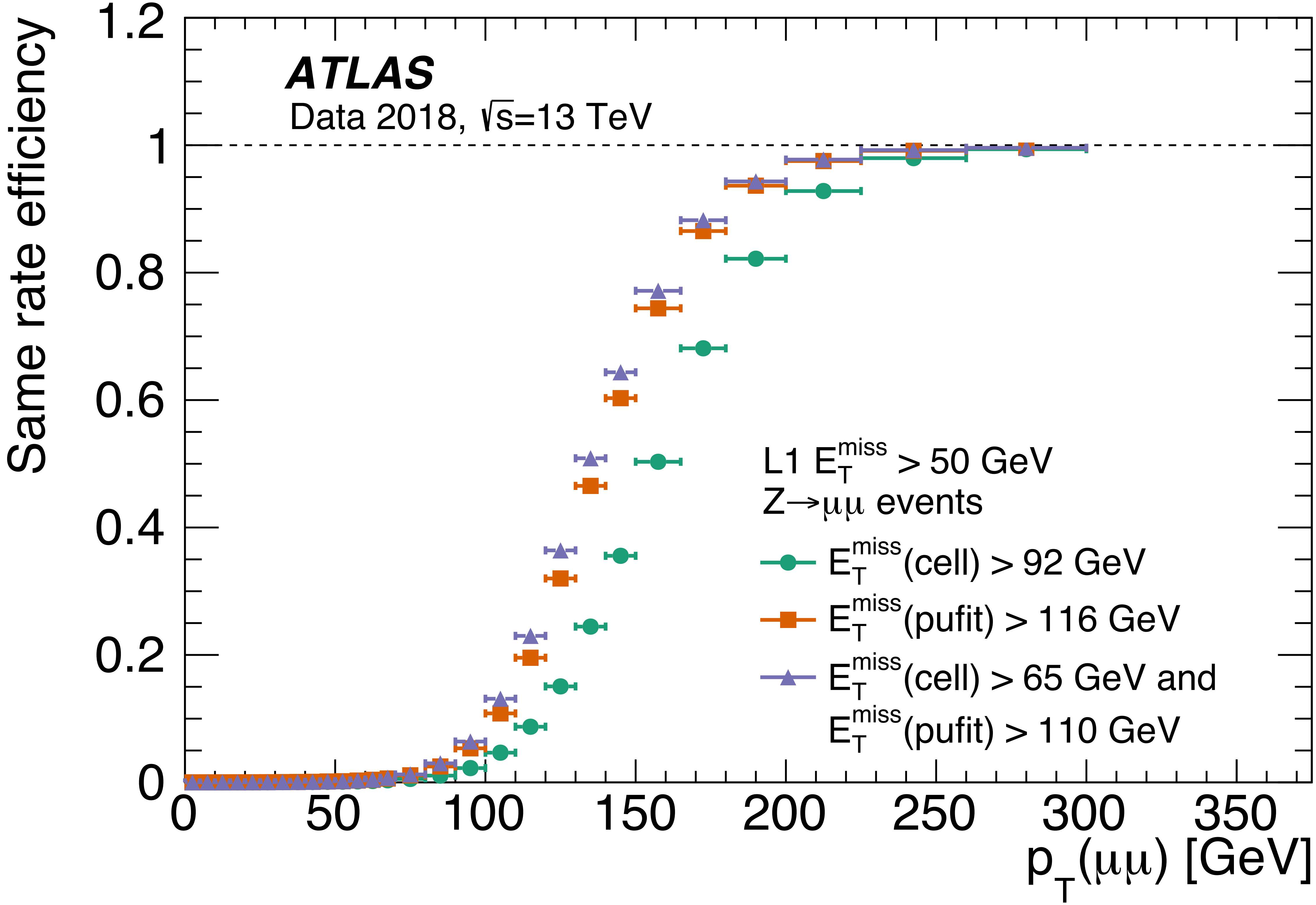


Equal rate comparison

Submitted to JHEP, arXiv:2005.09554



More complicated final states

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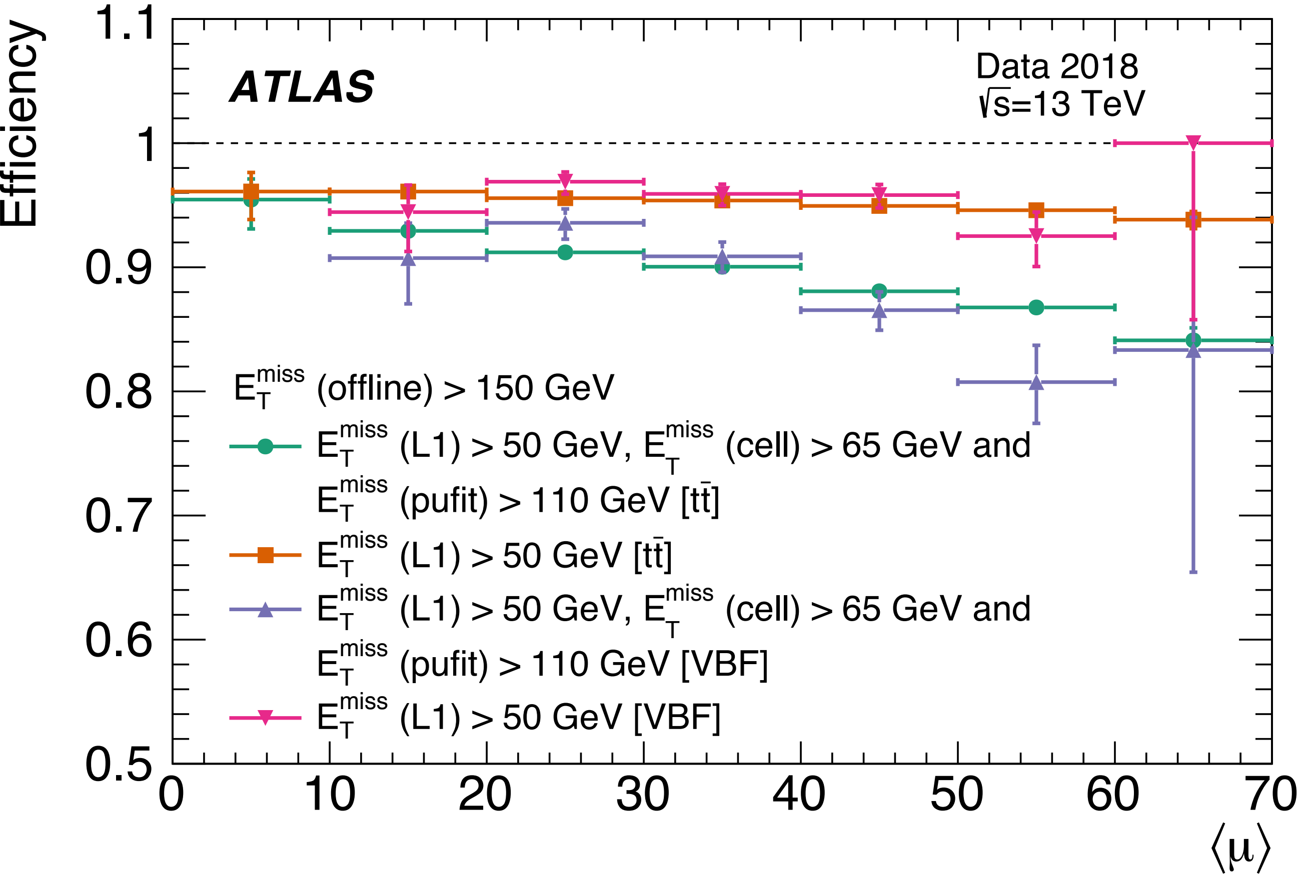
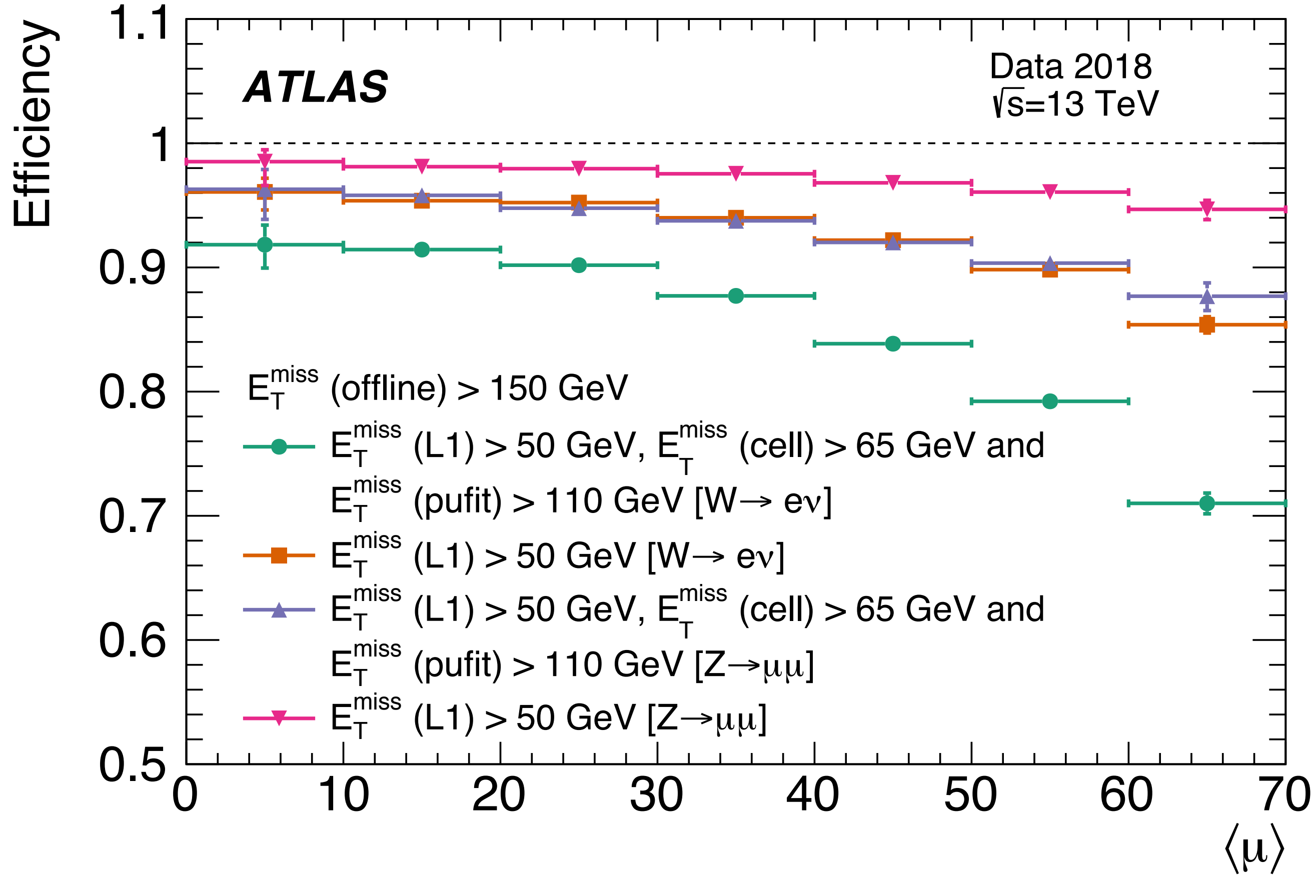
Submitted to JHEP, arXiv:2005.09554

VBF, TTbar

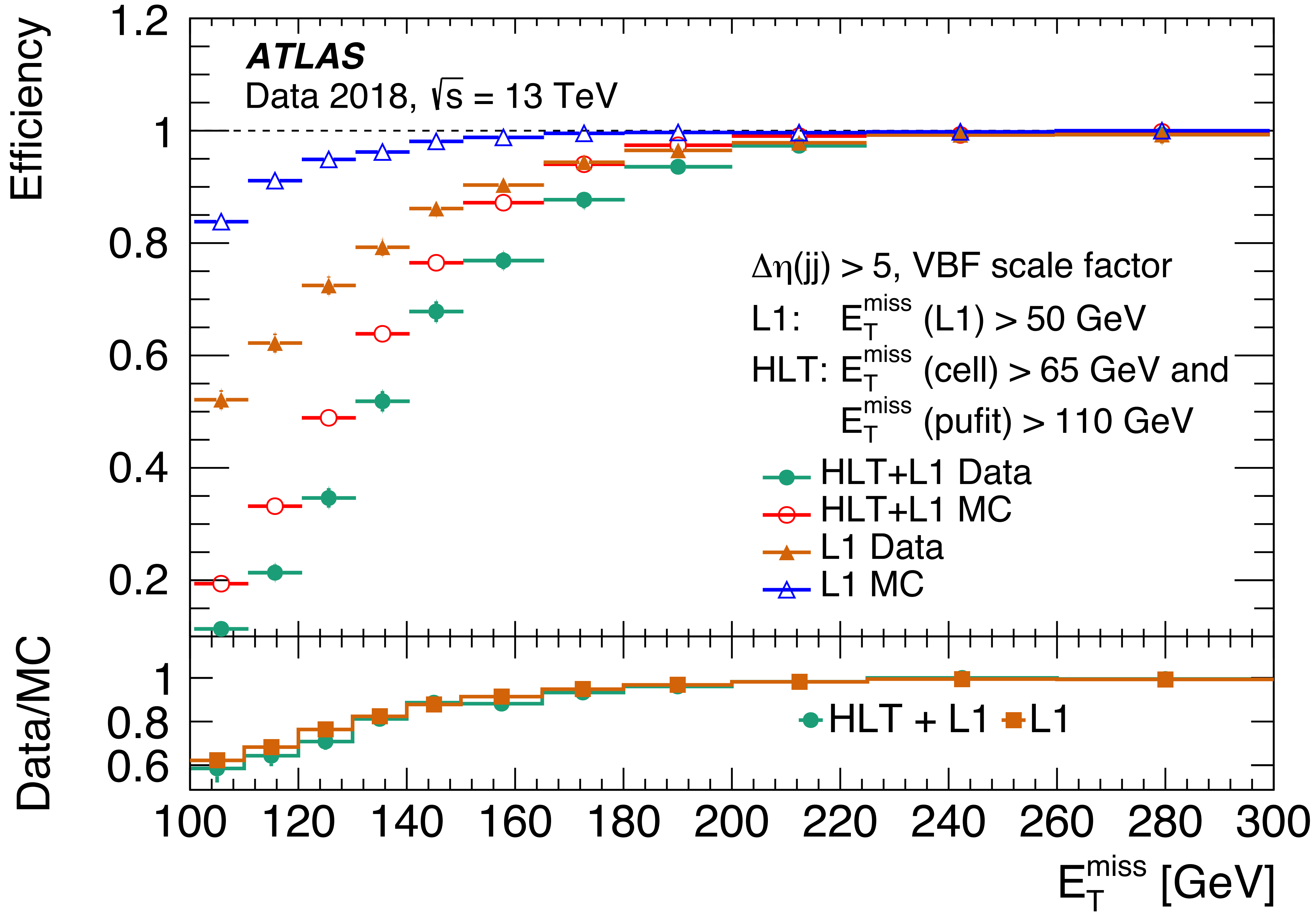
W/Z



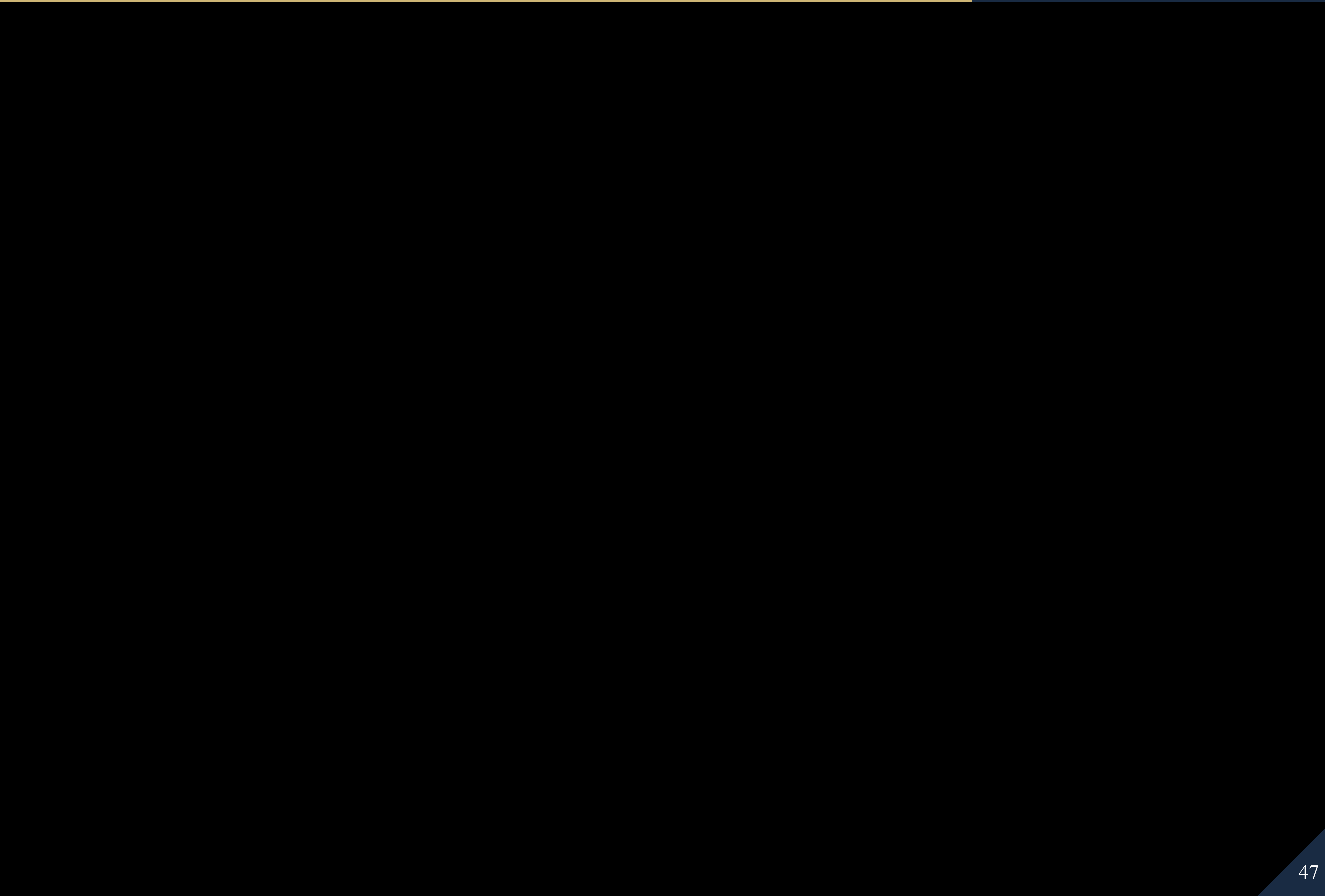


Improve acceptance by using region with < 100% efficiency

- Derive and apply data/MC corrections
- Example demonstrate the size of the corrections, dominated by L1

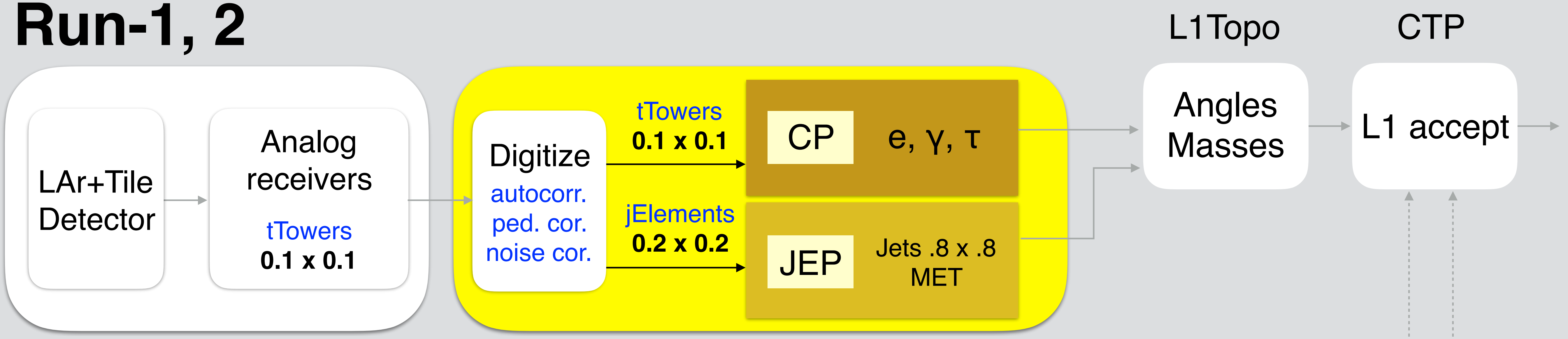


Run 3



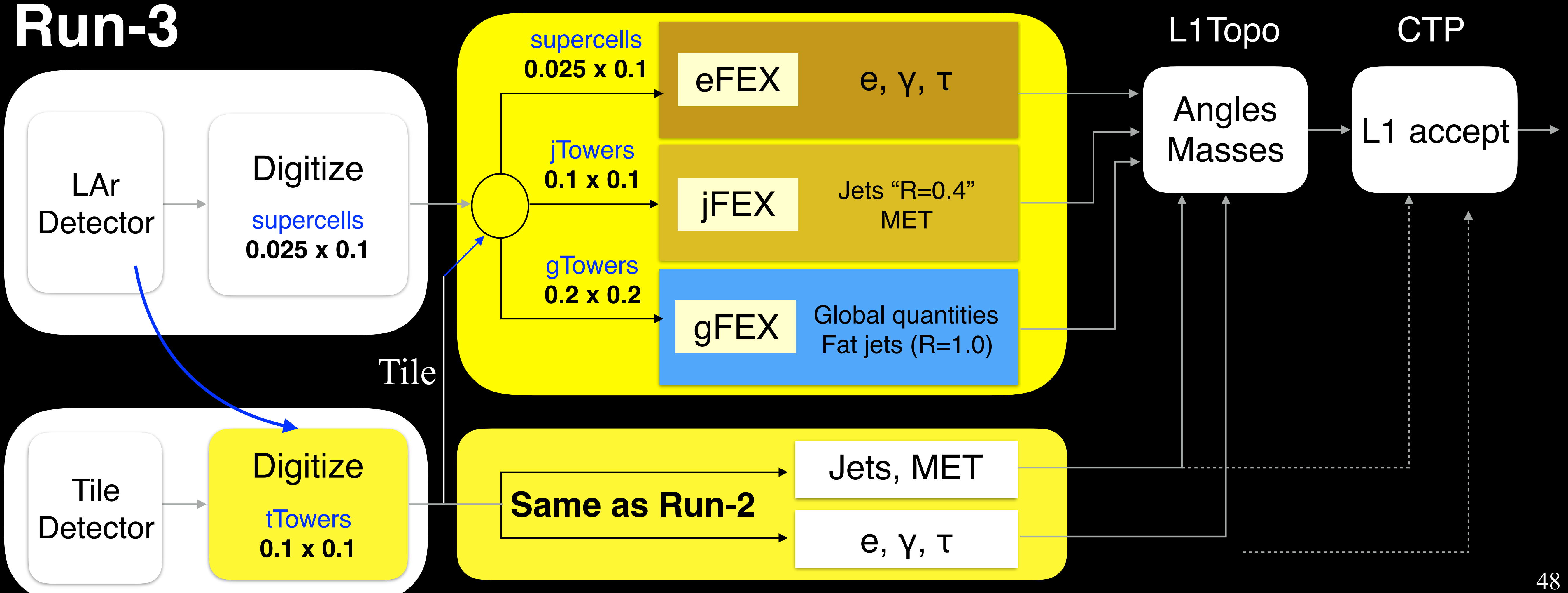
Upgrade (starting now!)

Run-1, 2



L1Calo in yellow

Run-3



Impact: jets and MET

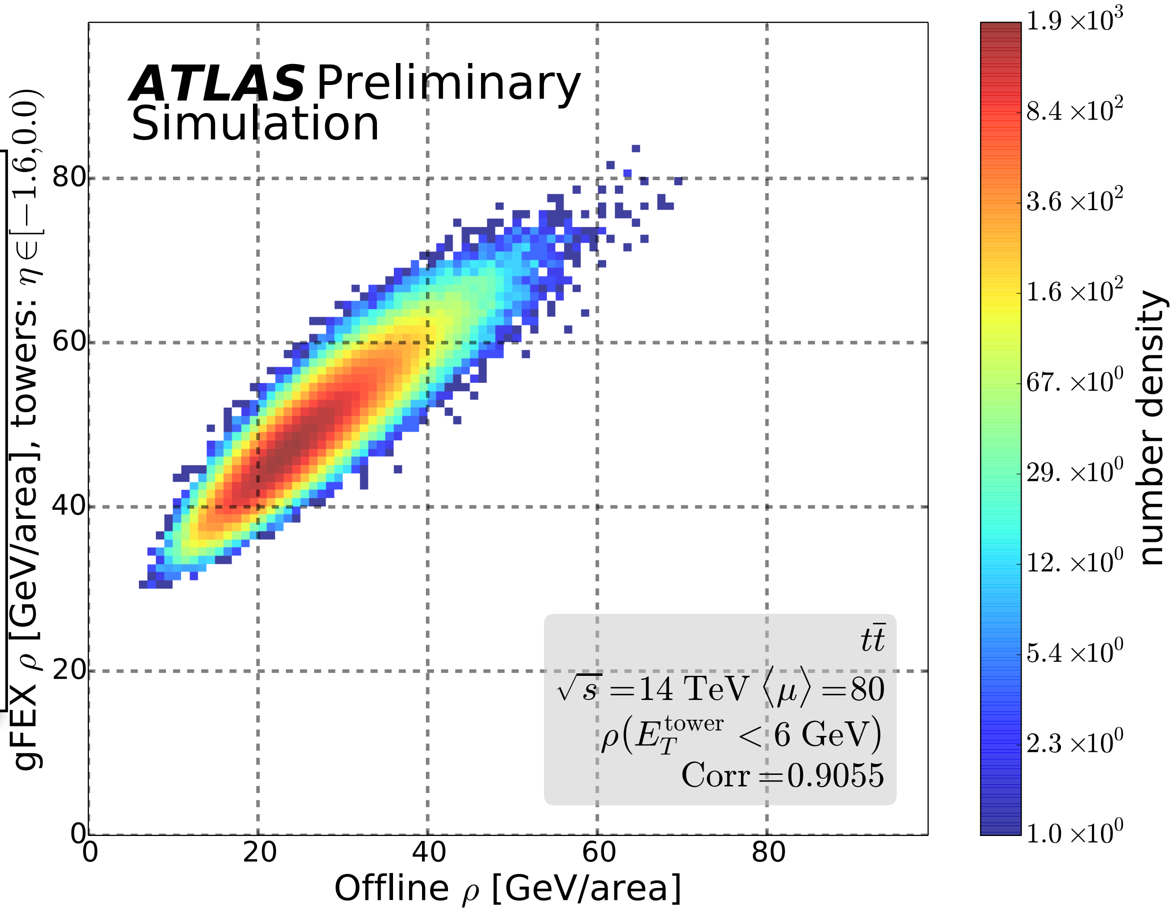
Jet trigger public (August 2014)
L1Calo public (July 2018)

Ben Carlson

Improving MET

MET is sensitive to pileup
Working on pileup subtraction for L1

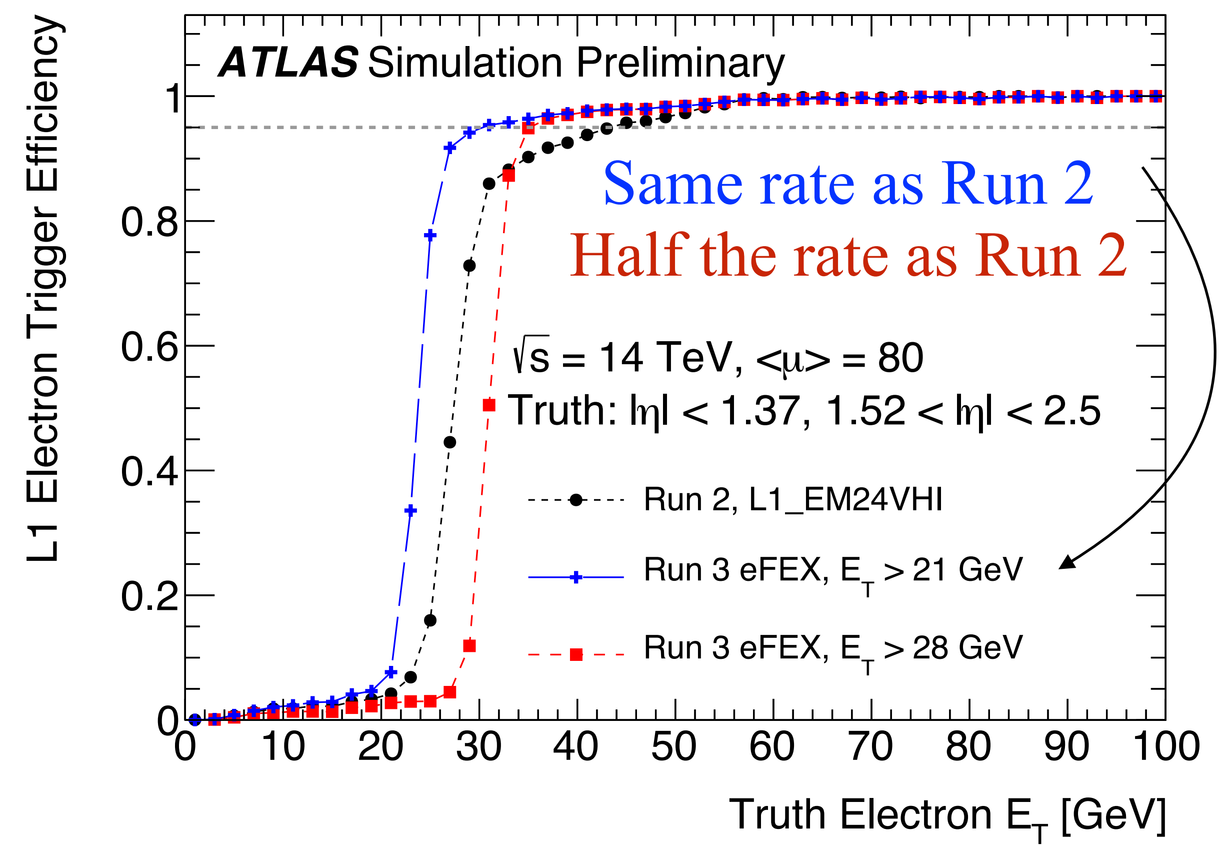
Online ρ



Offline ρ

Dramatic improvement

(Uses additional granularity to target electrons)



Lots of rate saved, use it for DM triggers?