A key variable: Missing Transverse Momentum - reconstruction, pile-up and its significance

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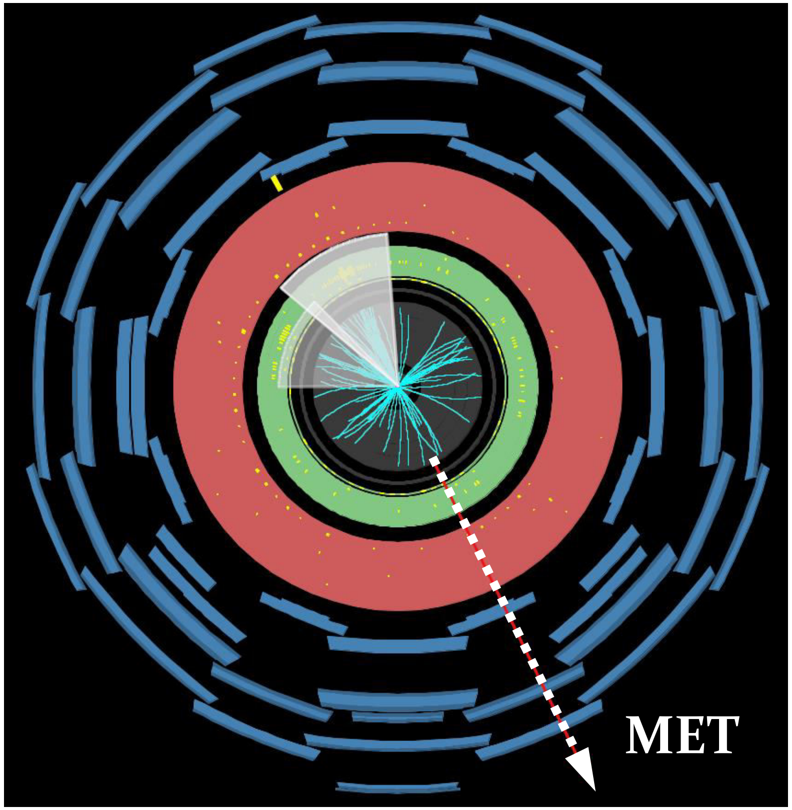
Introduction

What is missing transverse momentum (MET)

- MET - total transverse momentum of the invisible particles

$$E_T^{\text{miss}} \equiv \sum_{\substack{\text{invisible}\\\text{particles}}} \vec{p}_{T,i} = -\sum_{\substack{\text{visible}\\\text{particles}}} \vec{p}_{T,i}$$



- Two sources of MET
  - Real MET:

    weakly interacting particles
  - Fake MET:

    particle out of detector acceptance

    mis-measured objects

    additional interaction (pile-up)

- MET performance is very important for many ATLAS analyses!
  - Improved resolution, better distinction between real and fake MET, etc.

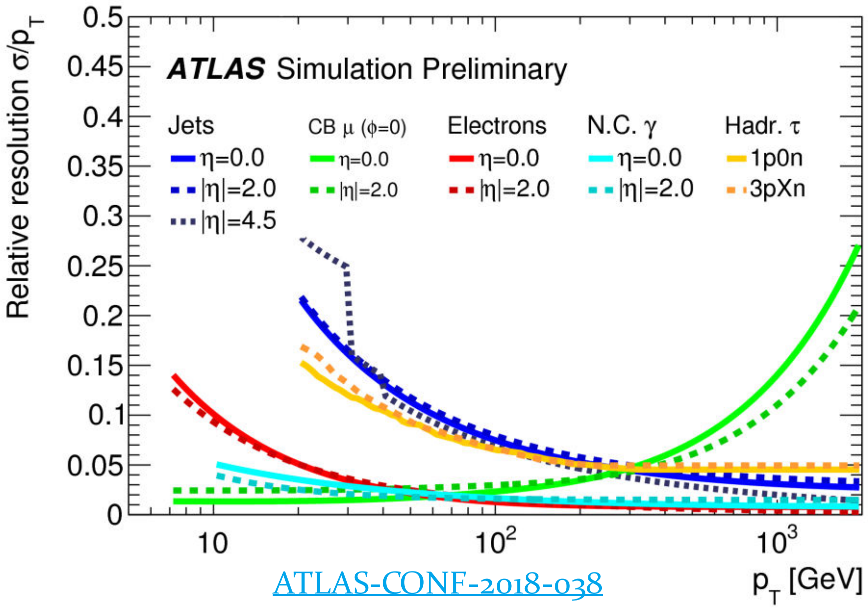
Introduction

Resolution of MET

- Negative vector sum of calibrated objects (hard term) plus soft term

$$E_T^{miss} = -\left(\sum_{i\in muons} p_T{}^i + \sum_{i\in electrons} p_T{}^i + \sum_{i\in photons} p_T{}^i + \sum_{i\in hadronic\ \tau} p_T{}^i + \sum_{i\in jets} p_T{}^i + \sum_{i\in Soft\ Term} p_T{}^i\right)$$

- Resolution of MET
  - RMS extracted from the combined distribution of E_x^{miss} and E_y^{miss}
  - Dependent on the resolution of input objects



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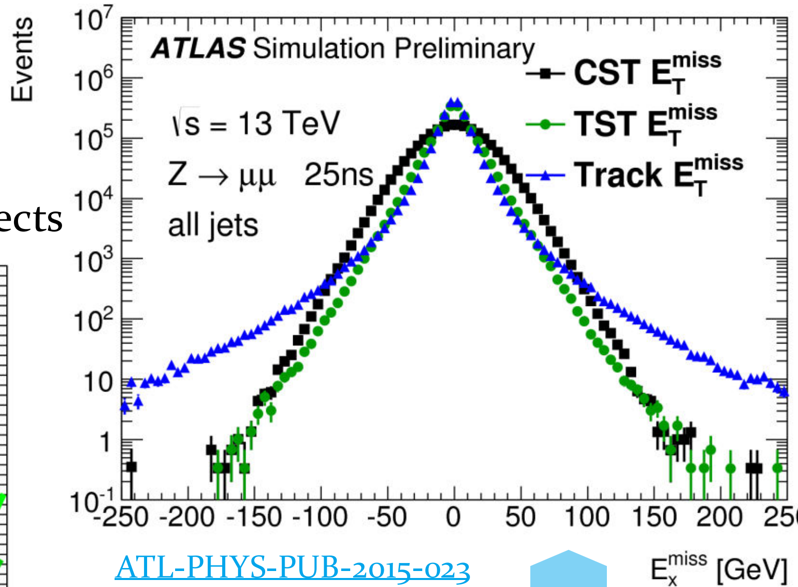


ATL-PHYS-PUB-2015-023

Blue: only uses tracker information
Green: uses tracker-based soft term
Black: uses calorimeter-based soft term

Introduction

MET performance in the ATLAS experiments (2017 - 2018)

Reconstruction input

- Hard term including calorimeter jets
- Tracker-based soft term (TST)

Jet selection

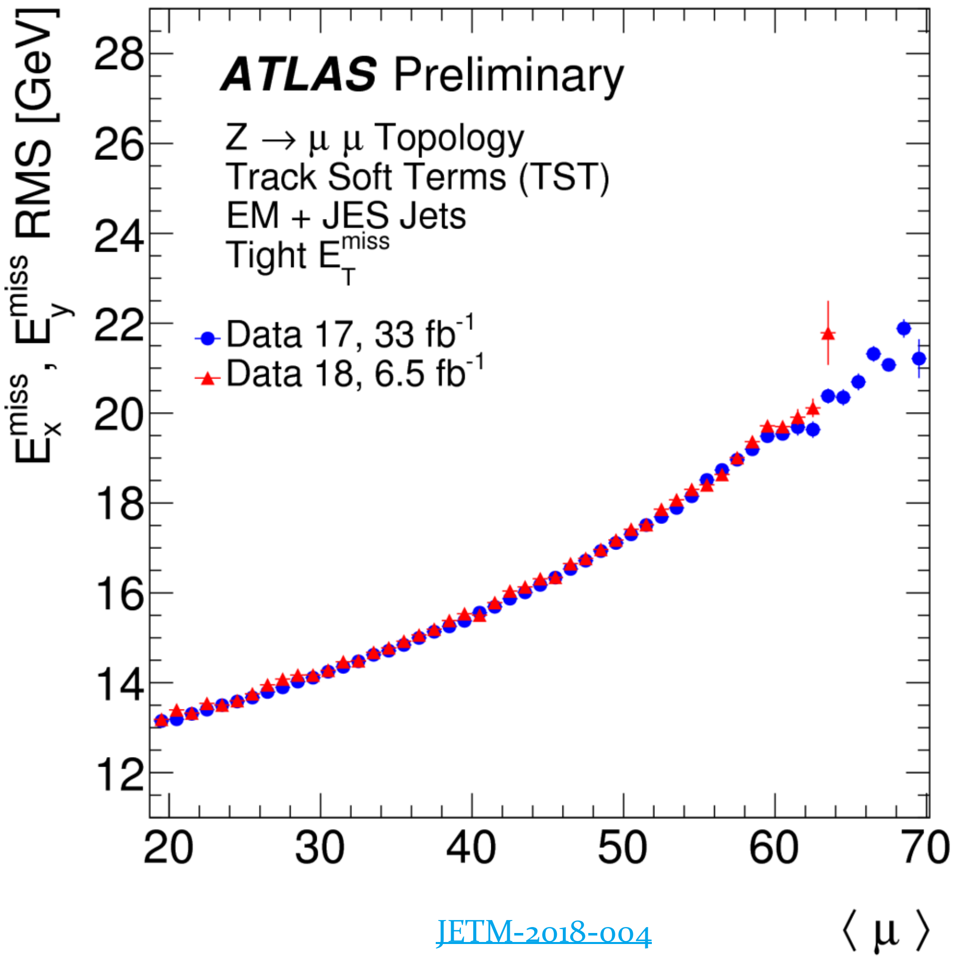
- Central jets ($|\eta| < 2.4$):
  - pass **Jet Vertex Tagger** requirement
  - transverse momentum (p_T) > 20 GeV
- Forward jets ($|\eta| > 2.4$):
  - transverse momentum (p_T) > 30 GeV

<μ> - average number of interaction

- Higher <μ> indicates higher pile-up

Jet Vertex Tagger (JVT)

- A multivariate approach to reject pile-up objects via jet-vertex association



JETM-2018-004

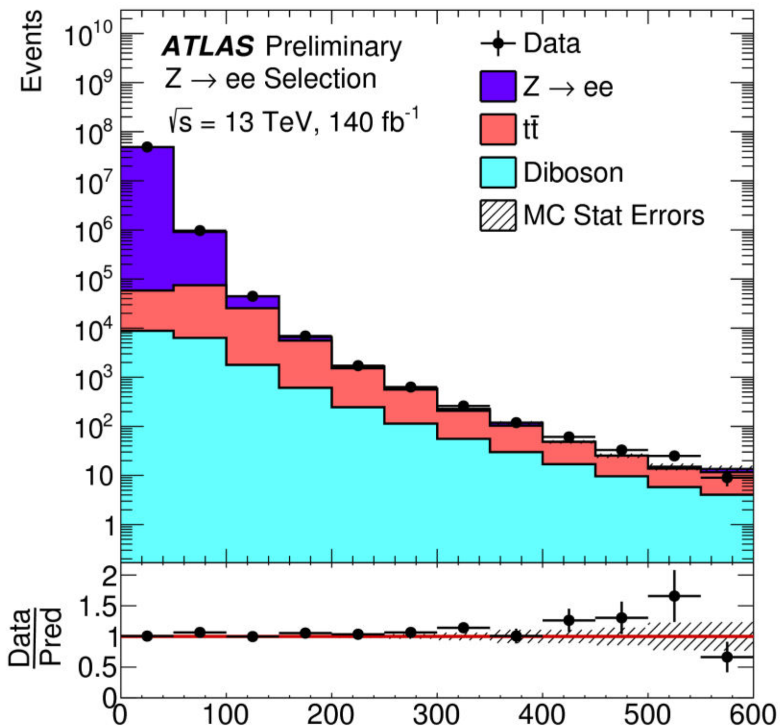
Towards higher precision

Particle Flow (PFlow) reconstruction

- Particle Flow (PFlow) MET
  - Combine the optimal resolution of tracker and calorimeter information

    higher accuracy of the charged-hadron measurement

    retaining the calorimeter measurements of neutral-particle energies



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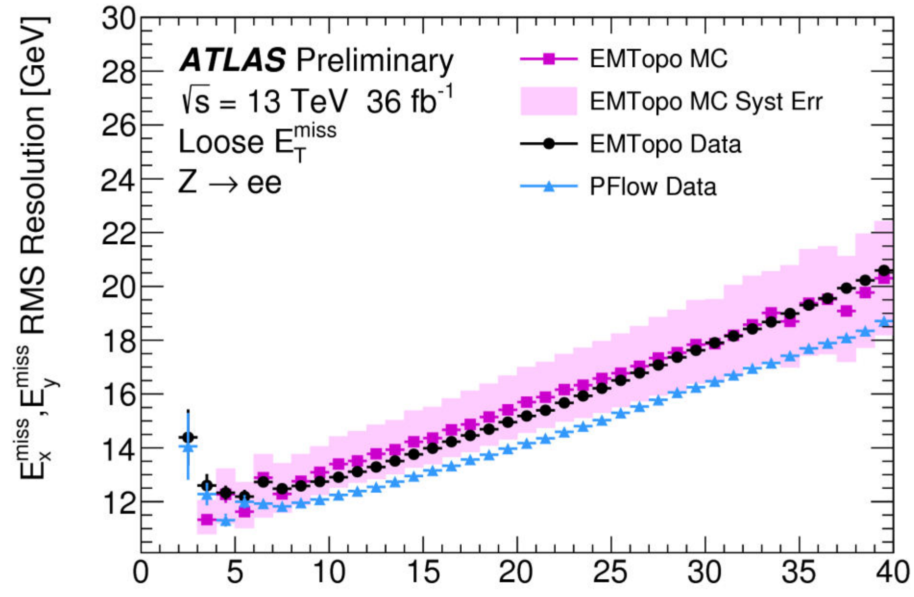

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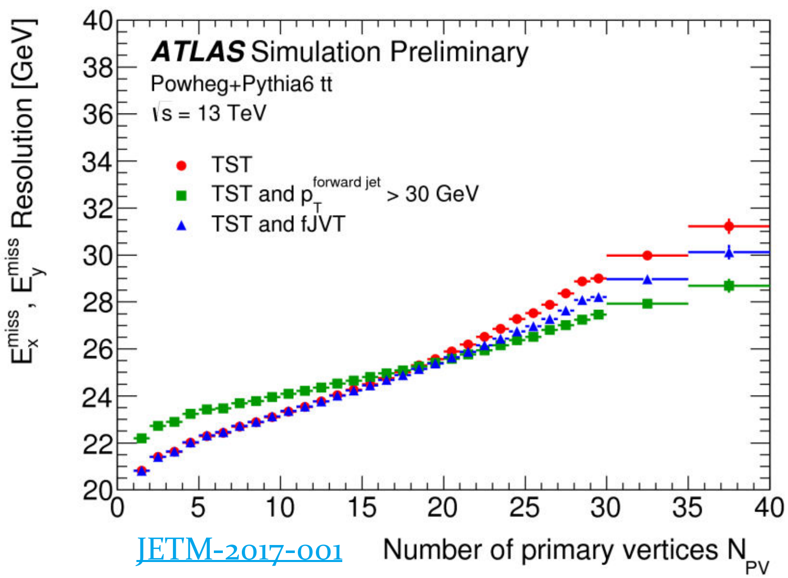
Towards higher precision

Forward jet selection

- PFlow MET is nice, but what about the forward region?
  - Inclusion of forwards jets is crucial to MET reconstruction

    more precise MET computation under low pile-up condition

    more pronounced pile-up dependence



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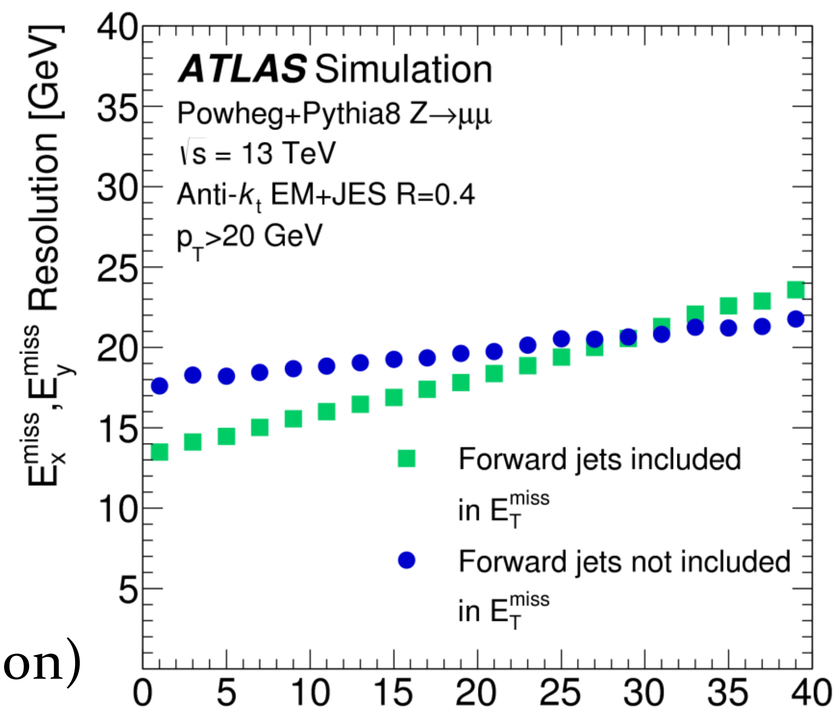


Eur. Phys. J. C 77 (2017) 580 ⟨μ⟩

- Forward jet selection (pile-up rejection)
  - Simple p_T cut: p_T > 30 GeV
  - **Forward Jet Vertex Tagger (fJVT)**

MET significance

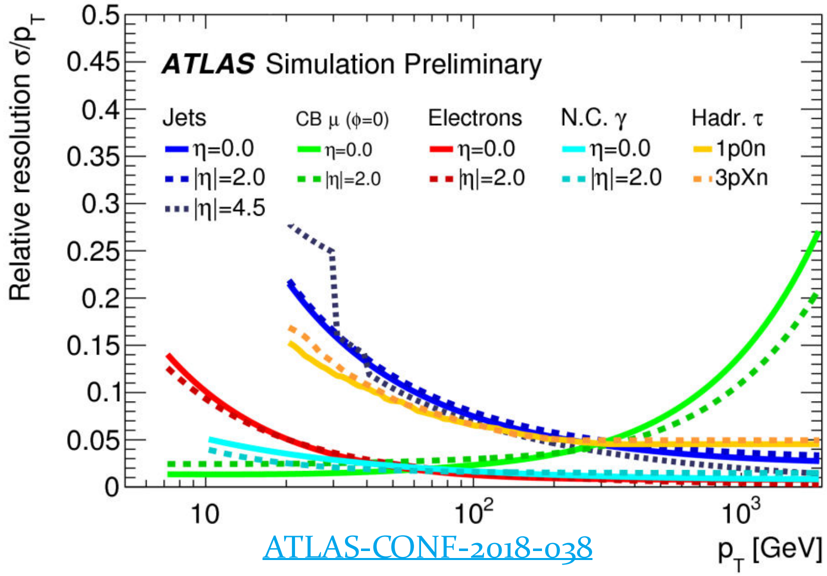
Object-based MET significance

- Evaluation of MET significance
  - Is the reconstructed MET consistent with the zero MET hypothesis, when taking the resolution of all input objects into account?
  - High MET significance means:
    MET cannot be explained from momentum resolution effects
    indicate the presence of **true invisible particle**

$$\mathcal{S} = \frac{E_T^{\text{miss}}}{\sigma(E_T^{\text{miss}})}$$

Object-based MET significance

- Compared to the traditional event-based MET significance, object-based MET significance considers the **expected resolutions for all objects** entering MET computation and their **angular correlation**
- Momentum resolution on p_T scale and direction, pile-up mitigation and soft term…



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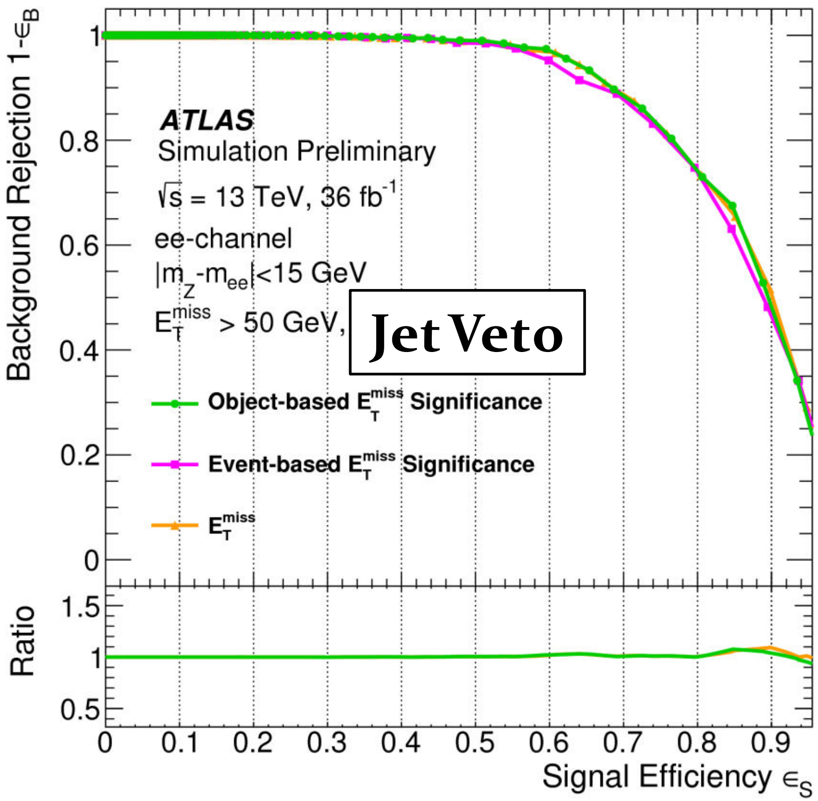
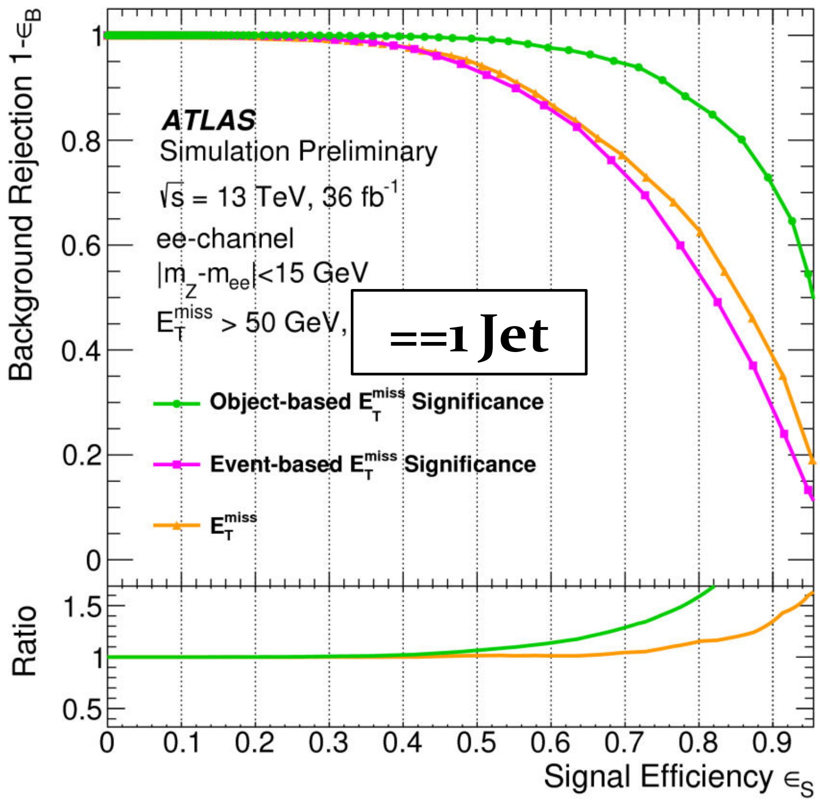
MET significance

Object-based MET significance

- Performance of MET significance dependent on event topology
  - ZZ → eeνν vs. Z → ee, pre-selected with MET > 50 GeV and $|m_Z - m_{ee}| < 15$ GeV





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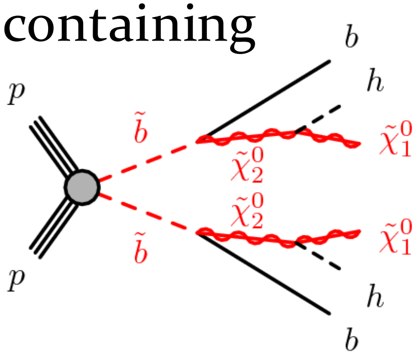
MET significance

Application of object-based MET significance in SUSY: sbottom multi-b

- Search for bottom-squark pair production in final states containing Higgs bosons, b-jets and missing transverse momentum
  - Multiple b-jets + no lepton + MET (from neutralinos)
  - Three kinematic topologies - SRA, SRB and **SRC**



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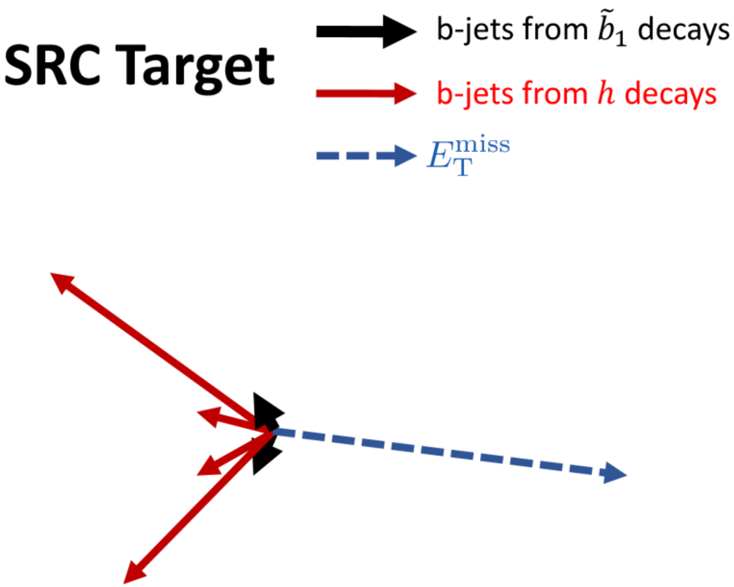

- In SRC the ΔR-based Higgs reconstruction is ineffective due to low b-jet multiplicity
- Object-based MET significance becomes the best discriminating variable in SRC

Small mass splitting between $\tilde{b}_0$ and $\tilde{\chi}_2^0$, $m(\tilde{\chi}_1^0)$ = 60 GeV

Soft b-jets from $\tilde{b}_0$ and Higgs, lower b-jet multiplicity required in the final state

Discriminating variable: ***object-based MET significance***

MET significance

Application of object-based MET significance in SUSY: sbottom multi-b

Integrated expected significance for scalar signal, $m(\tilde{b}_0, \tilde{\chi}_2^0, \tilde{\chi}_1^0) = (1100, 1095, 60)$ GeV
All standard model backgrounds and total uncertainty taken into consideration

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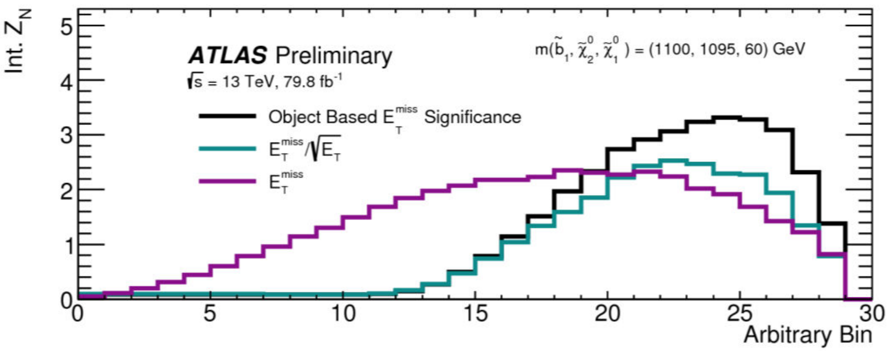

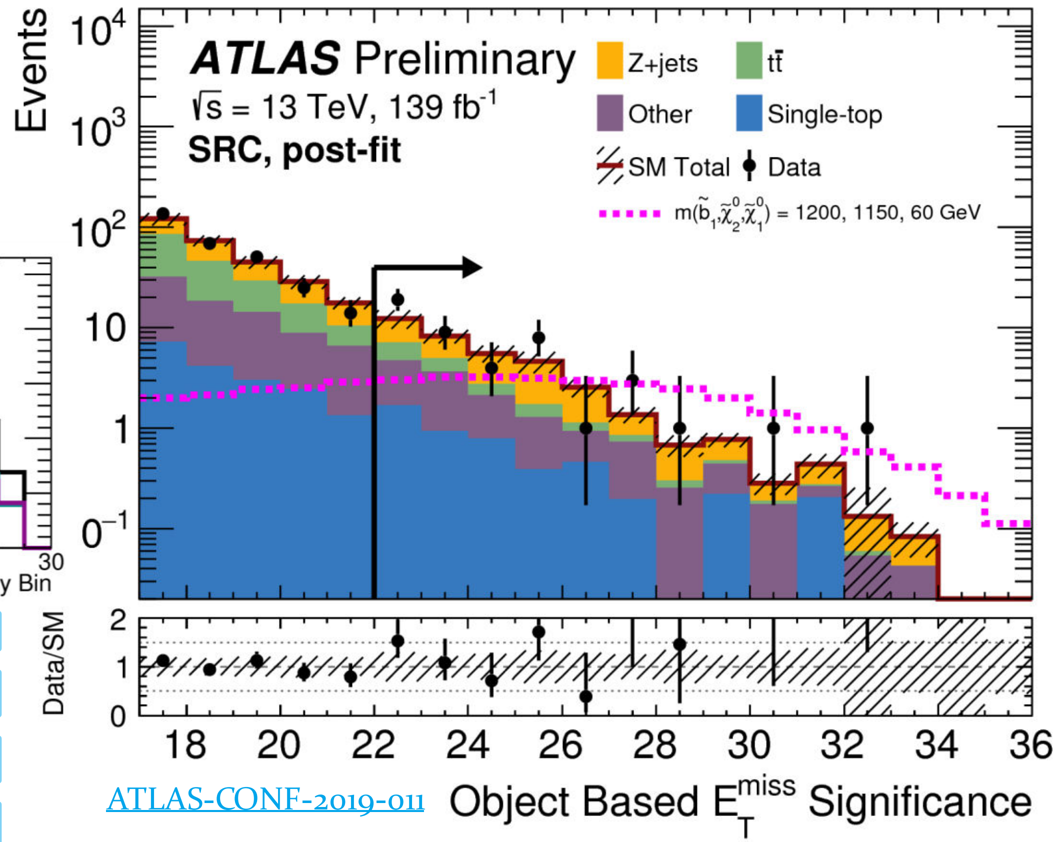

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Aside from sbottom multi-b, another recent SUSY search also uses object-based MET significance as one of the discriminating variables: **EW 2L0J**

Search for electroweak production of charginos and sleptons decaying in final states with two leptons and missing transverse momentum

Summary

- Missing transverse momentum (MET)
  - Used in many ATLAS analyses
  - **Distinguish between real and fake MET**
- Efforts are made to improve MET performance
  - Usage of **Particle Flow jets**
  - **Forward jet selections**
- Object-based MET significance
  - Considers **the resolution of all objects**
  - Better discriminating power wrt. the traditional approach
  - Used in several SUSY searches, e.g. **sbottom multi-b**

Thanks for your attention!

Backup

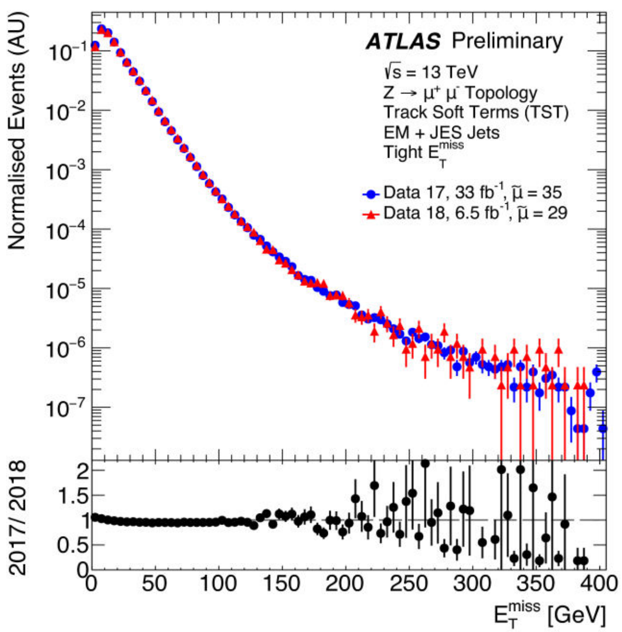
Introduction

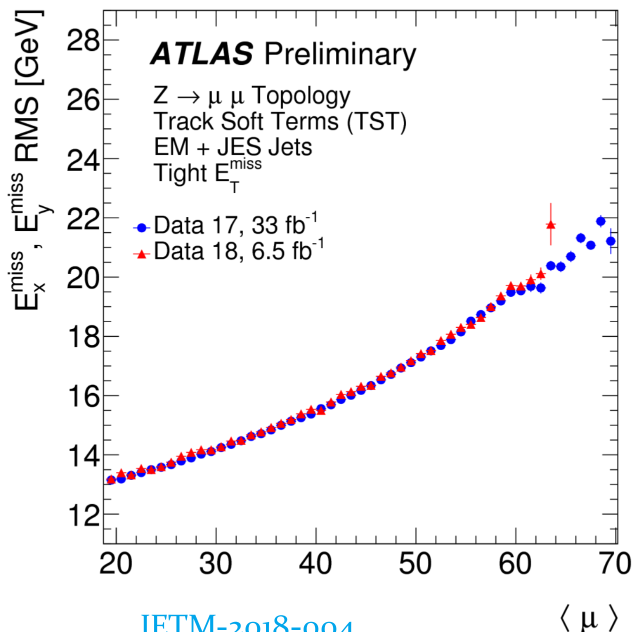
MET performance in the ATLAS experiments (2017 - 2018)

- Reconstruction performance of MET is evaluated using data collected by the ATLAS detector in 2017 and 2018
  - Hard term including calorimeter jets + tracker-based soft term
  - Pile-up (PU) suppression

    central jets ($|\eta| < 2.4$): pass Jet Vertex Tagger, $p_T > 20$ GeV

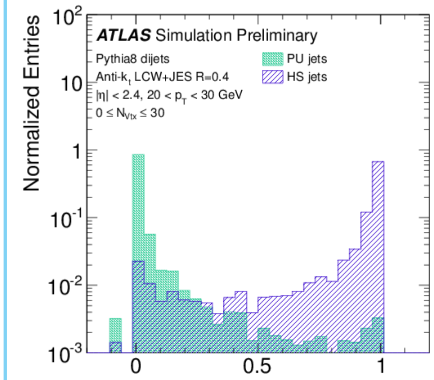
    forward jets ($|\eta| > 2.4$): $p_T > 30$ GeV



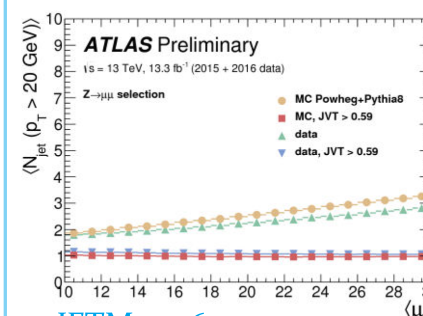


[JETM-2018-004]

Jet Vertex Tagger (JVT)



[ATLAS-CONF-2014-018]



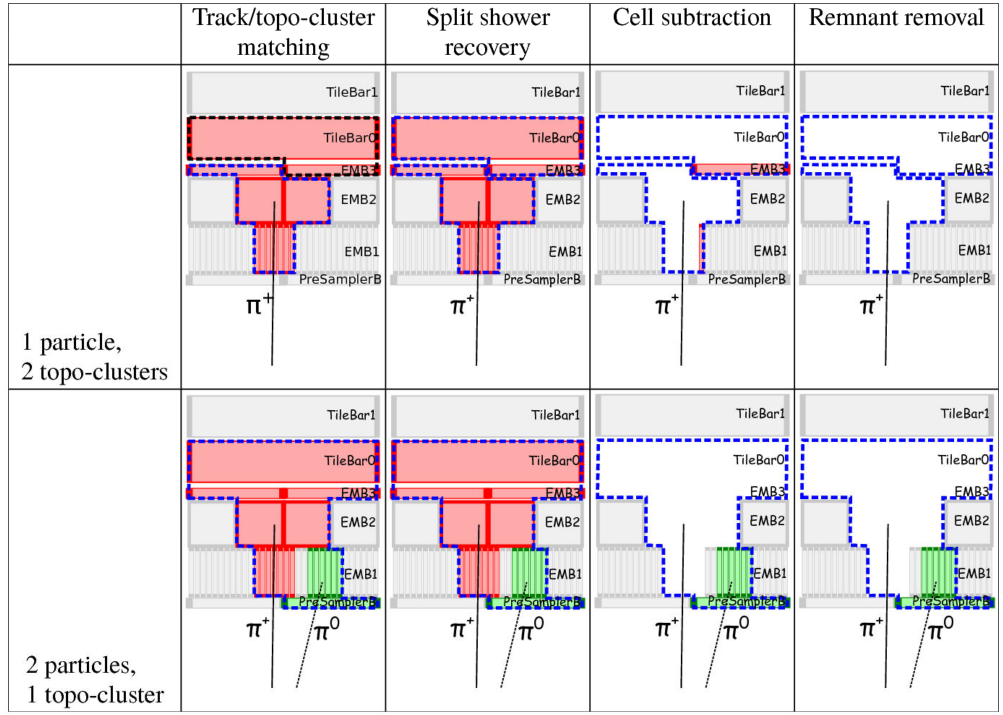
[JETM-2016-011]

Towards higher precision

Particle Flow (PFlow) reconstruction

4 steps of the PFlow algorithm

1. Match each track to one topo-cluster
2. Add neighbouring topo-clusters if higher energy deposit is expected in the calorimeter (calculation based on tracker information)
3. Subtract the expected energy cell-by-cell from the matched topo-cluster until the expected energy is reached
4. Clean the remnants if it's fluctuation



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Towards higher precision

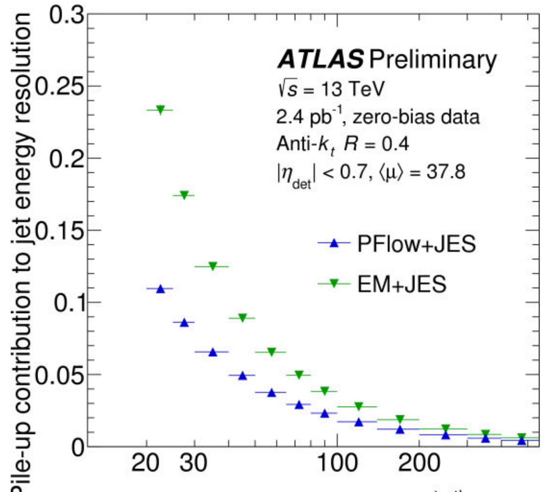
Particle Flow (PFlow) reconstruction

Performance of PFlow jet

- Better energy resolution at low p_T region due to track matching
- Fake jet ratio significantly lowered at central region - *forward region outside of tracker acceptance*
- PU energy removed from the topo-cluster if matched with a PU track - **effective PU suppression**

Performance of PFlow MET

- Better resolution of MET due to track matching
- Great PU mitigation at central region - *no JVT available for EMTopo jets with p_T > 60 GeV*
- MET tail mainly due to muon mis-measurement and mis-identified jets



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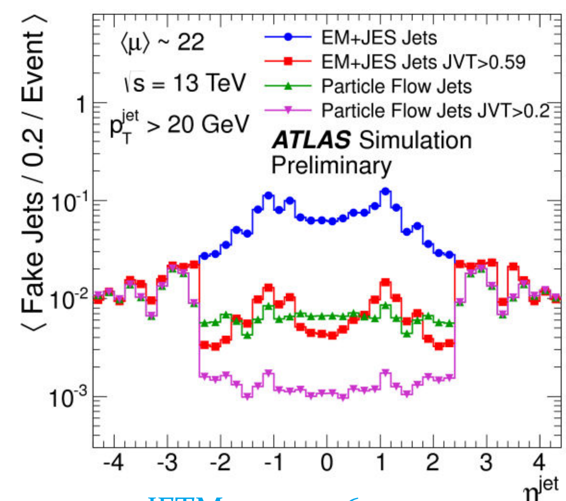

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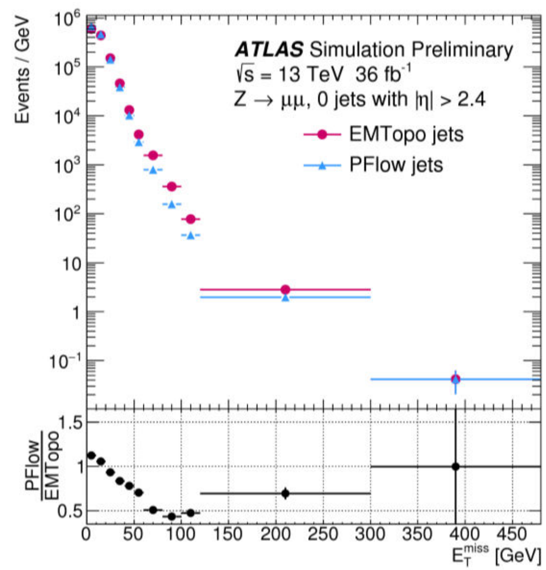

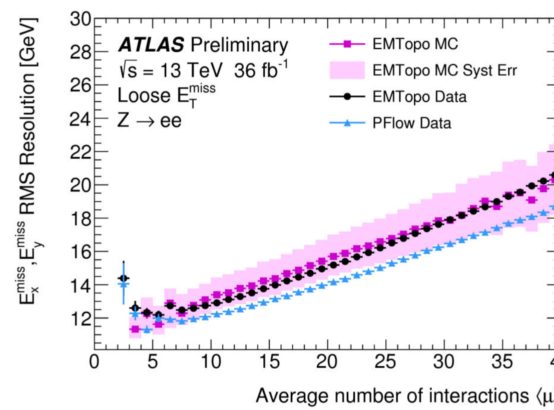

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Towards higher precision

Forward jet selection

Forward Jet Vertex Tagger

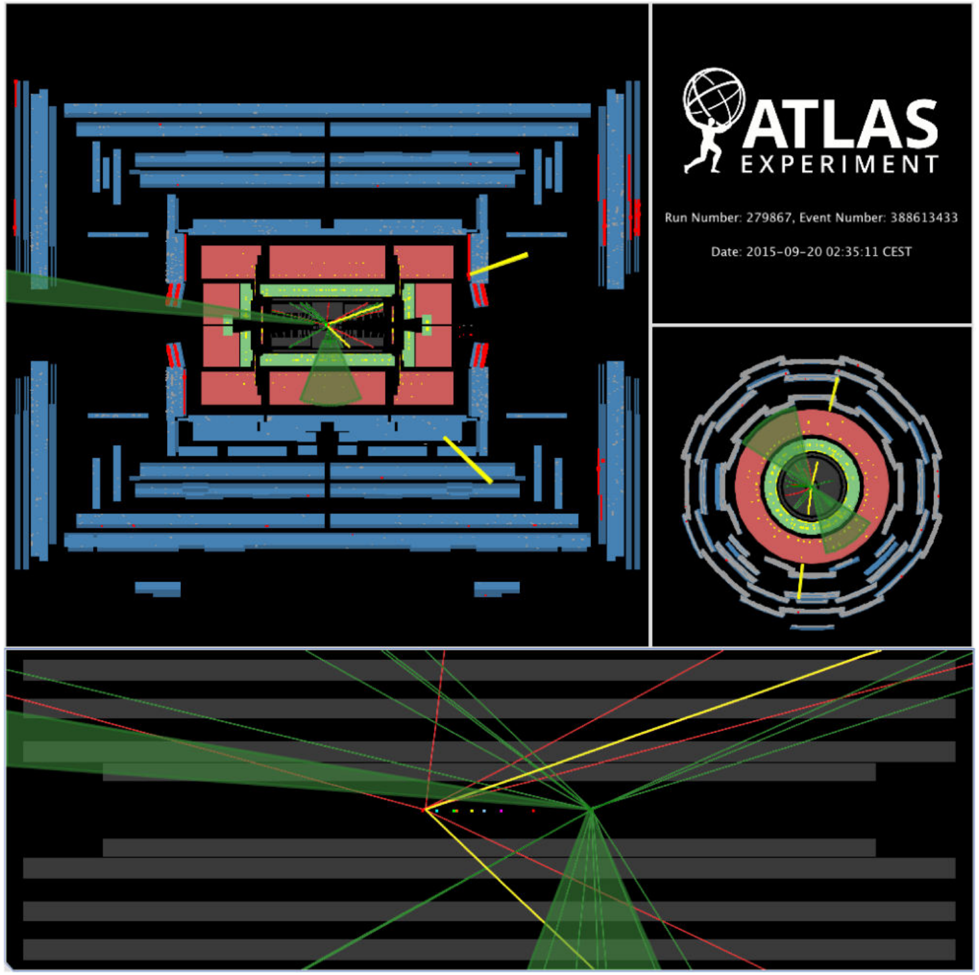
1. For each vertex i, compute $p_T^{miss,\, i}$ with QCD pile-up tracks;
2. Check if there is a forward jet balancing the $p_T^{miss,\, i}$;
3. If so, remove this forward jet.

A candidate $Z \rightarrow \mu\mu$ event containing two QCD pile-up jets

Red: tracks from the primary vertex

Yellow: tracks from the muons

Green: tracks from the pile-up vertex with highest $\sum p_T^2$



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Towards higher precision

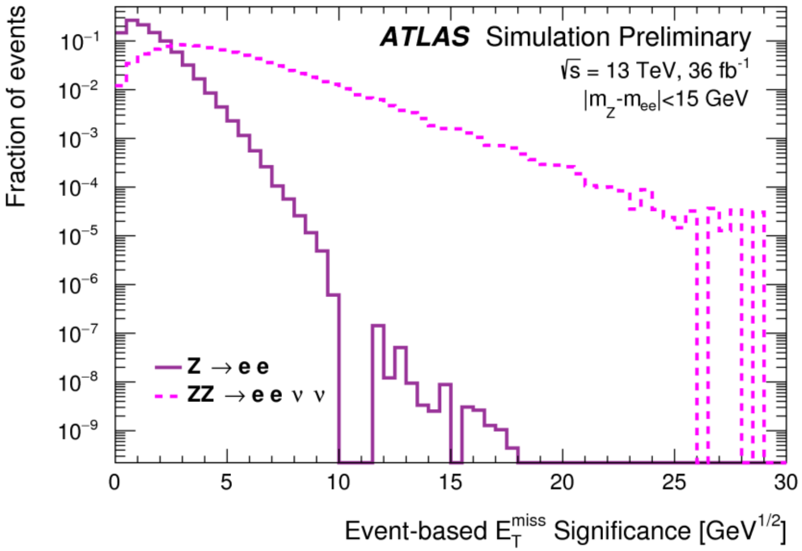
Different MET working points

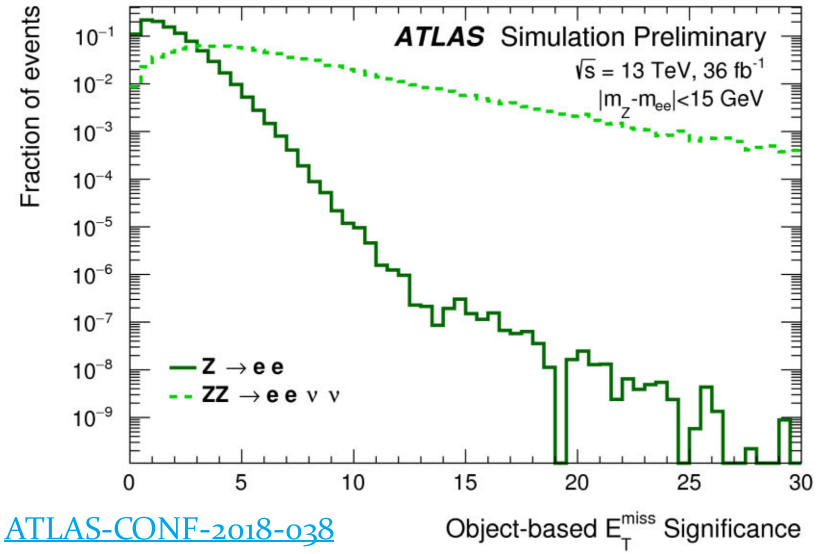
- MET working points based on different forward jet selections
  - Loose working point
    retaining hard-scatter jets in the forward region, good resolution at low PU
  - Tight working point
    much better resolution at high PU wrt. loose working point, worse at low PU
  - fJVT working point
    improved resolution at high PU wrt. loose working point
    optimal for analyses where hard-scatter forward jets are expected, e.g. VBF process

Working Point	Central jets ($\|\eta\| < 2.5$)	Forward jets ($\|\eta\| > 2.5$)
Loose	$p_T > 20$ GeV pass JVT when $p_T < 60$ GeV	$p_T > 20$ GeV
Tight	$p_T > 20$ GeV pass JVT when $p_T < 60$ GeV	$p_T > 30$ GeV
fJVT	$p_T > 20$ GeV pass JVT when $p_T < 60$ GeV	$p_T > 20$ GeV pass fJVT when $p_T < 50$ GeV

MET significance

Event-based and object-based MET significance





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Event-based MET significance

- Event-based quantity, neglecting the physics nature of different objects
- Only consider the scale of p_T, no angular correlation taken into account

$$\mathcal{S} = \frac{E_T^{miss}}{\sqrt{\sum E_T}}$$

Object-based MET significance

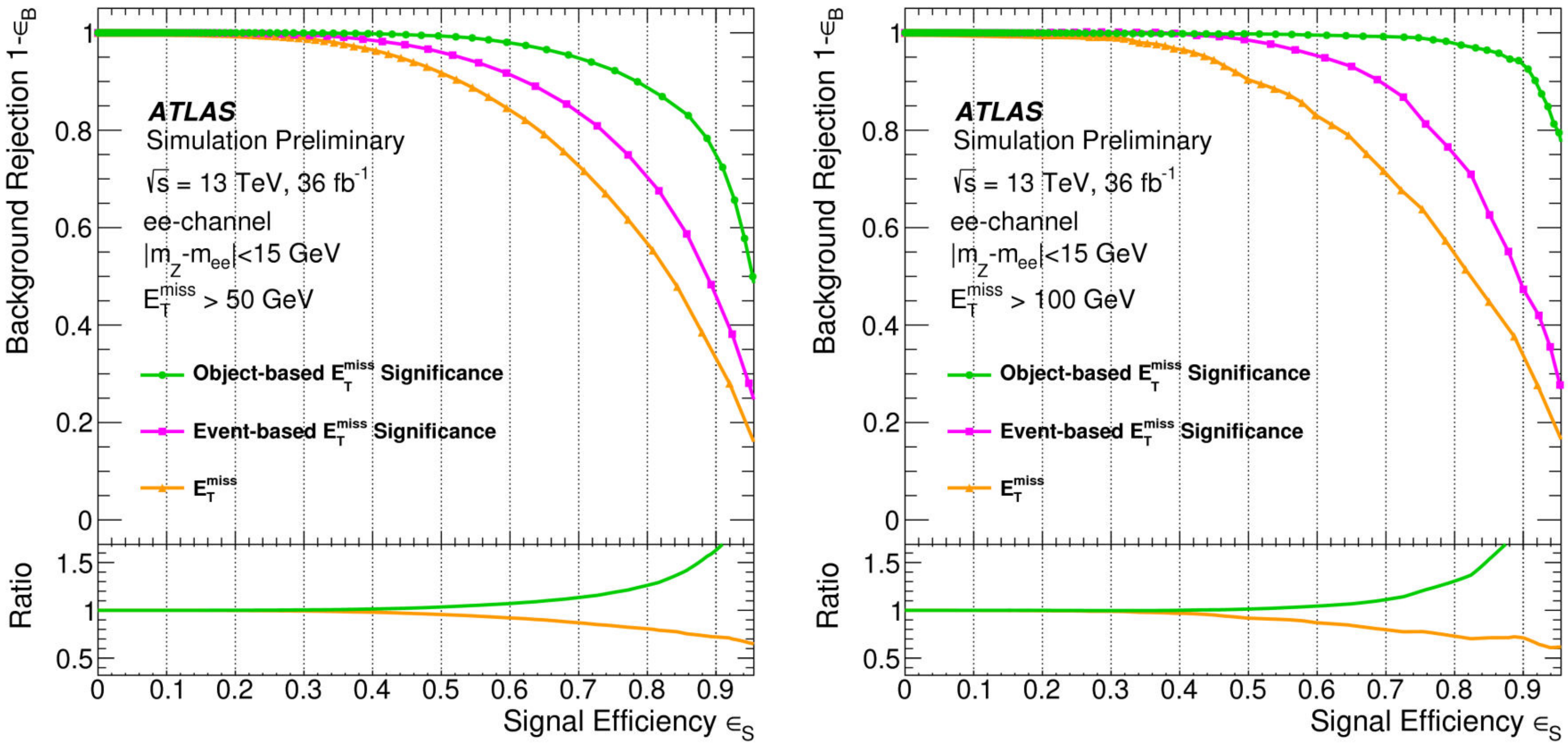
- Based on the expected resolutions for all objects entering MET computation
- Momentum resolution on p_T scale and direction, PU mitigation and soft term

$$\mathcal{S} = \frac{\left|E_T^{miss}\right|}{\sqrt{\sigma_L^2\left(1-\rho_{LT}^2\right)}}$$

MET significance

Object-based MET significance

- Performance of MET significance dependent on event topology
  - ZZ → eeνν vs. Z → ee, pre-selected with $|m_Z - m_{ee}| < 15$ GeV



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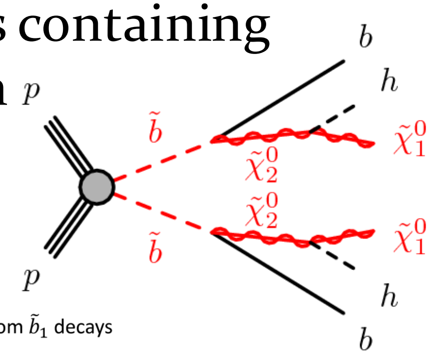
MET significance

Application of object-based MET significance in SUSY: sbottom multi-b

- Search for bottom-squark pair production in final states containing Higgs bosons, b-jets and missing transverse momentum
  - Multiple b-jets + no lepton + MET (from neutralinos)
  - Three kinematic topologies - SRA, SRB and **SRC**



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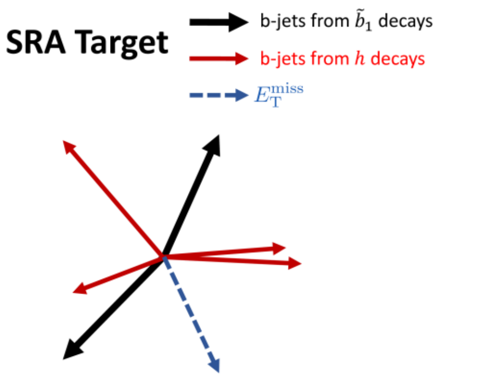

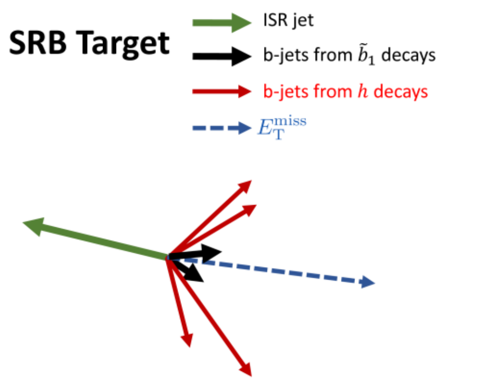

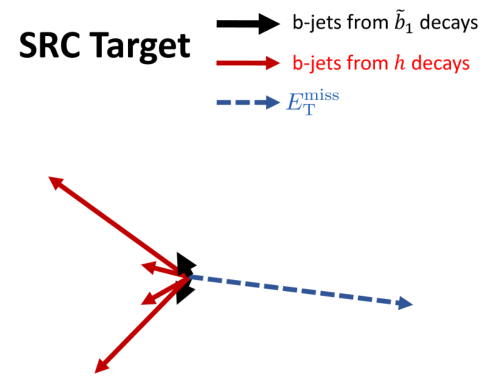

High mass splitting between $\tilde{b}_0$ and $\tilde{\chi}_2^0$

All b-jets have relatively high p_T, Higgs tagging possible

Discriminating variable: *effective mass*

Small mass splitting between $\tilde{b}_0$ and $\tilde{\chi}_2^0$, $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ = 130 GeV

Very soft b-jets from $\tilde{b}_0$ decay, Higgs tagging possible

Discriminating variable: *effective mass*

Small mass splitting between $\tilde{b}_0$ and $\tilde{\chi}_2^0$, $m(\tilde{\chi}_1^0)$ = 60 GeV

Soft b-jets from $\tilde{b}_0$ and Higgs, lower b-jet multiplicity required in the final state

Discriminating variable: ***object-based MET significance***

MET significance

Application of object-based MET significance in SUSY: sbottom multi-b

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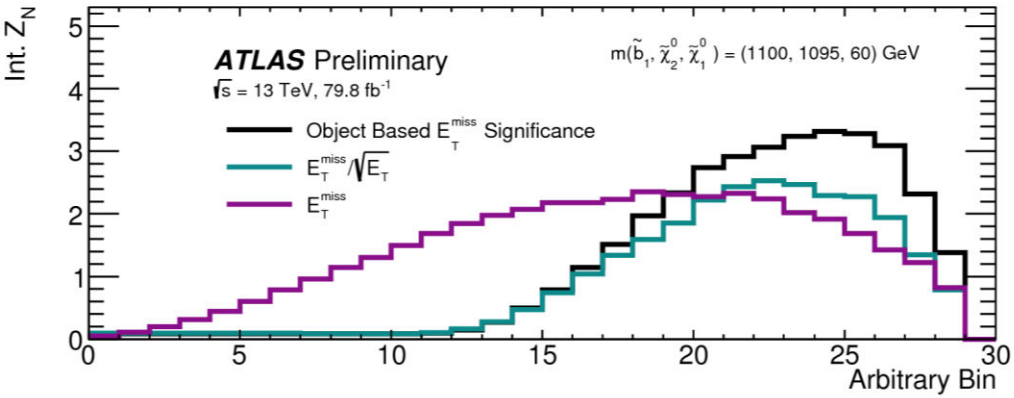

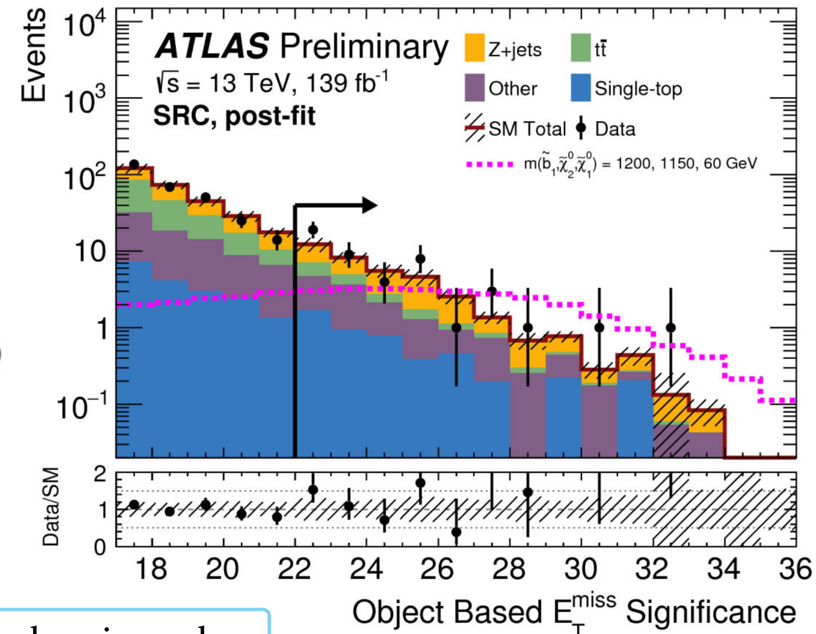

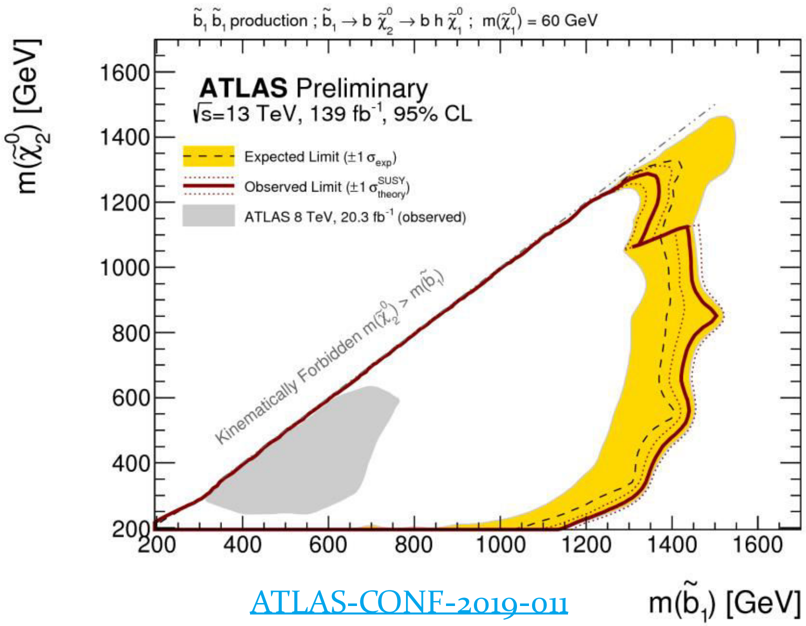

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4 non-overlapping sub-sets of SRC binned in object-based MET sig.

Major bkgs constrained in a bkg-only fit in CRs

Exclusion limit:
~ 1.4 TeV sbottom mass