Performance of Missing Transverse Momentum Reconstruction in ATLAS studied in Proton-Proton Collisions recorded in 2012 at 8 TeV

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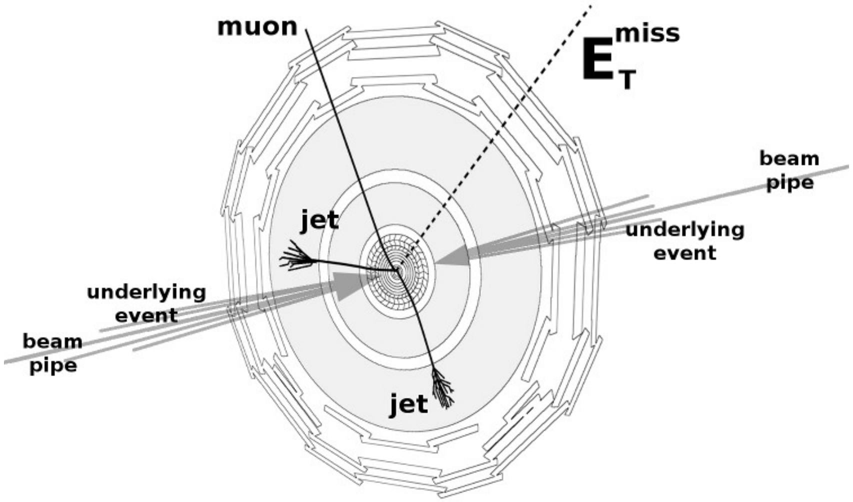
Introduction

- In a hadron collider event the missing transverse momentum (E_T^{miss}) is defined as the momemtum imbalance in the plane transverse to the beam axis, where momentum conservation is useful. Such an imbalance may signal the presence of undetected particles, such as neutrinos or new weakly-interacting particles



- An optimized reconstruction and calibration of E_T^{miss} was developed by the ATLAS Collaboration:
  - This measurement is significantly affected by the contribution of additional pp collisions (pile-up)
  - Methods were developed to suppress such contributions
  - The performance of the reconstructed E_T^{miss} after pile-up suppression is shown here

- The event samples used to assess the quality of the E_T^{miss} reconstruction are:
  - W and Z bosons (leptonic decays)
  - Simulated events with large jet multiplicity: $H \rightarrow \tau\tau$, t t-bar and supersymmetric (SUSY) events
  - The E_T^{miss} performance is studied in both data and Monte Carlo (MC) simulation
  - In simulated events, the E_T^{miss} is calculated from all non-interacting particles: True E_T^{miss} ($E_T^{miss,True}$)

Data, event selection and MC samples

- **Data samples:**

  During 2012, proton-proton (pp) collisions at a centre-of-mass energy of 8 TeV were recorded: L ~20 fb^{-1}

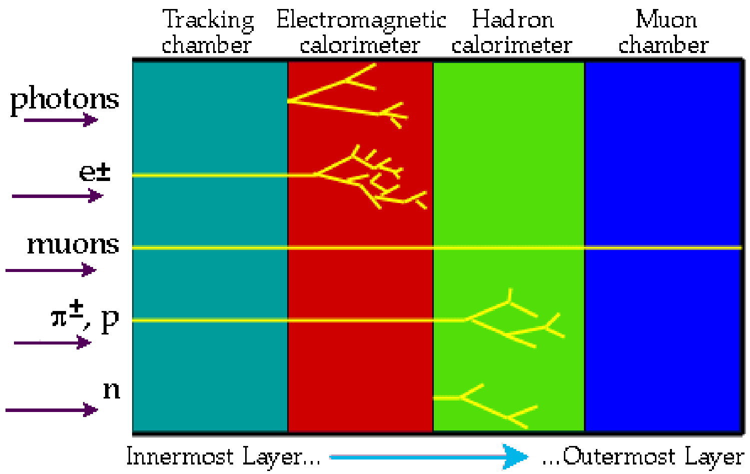
  Only data with fully functioning calorimeter, Inner Detector (ID) and muon spectrometer are analyzed

- **Event selection:**
  - **$Z \rightarrow ll$ event selection: 2 leptons with opposite charge and m_{ll} consistent with Z mass ($66<m_{ll}<116$ GeV)**
    - **$Z \rightarrow \mu\mu$: 2 muons reconstructed in the muon spectrometer with a matched track in ID**
      - **$p_T > 25$ GeV, $|\eta|<2.5$, z displacement of muon track from primary vertex < 10 mm and isolation**
    - **$Z \rightarrow ee$: 2 e with $|\eta|<2.47$ (except $1.37<|\eta|<1.52$), *medium* identification criteria and $p_T>25$ GeV**
  - **$W \rightarrow l\nu$ event selection: 1 lepton (e or μ), isolation, $E_T^{miss} > 25$ GeV and $m_T > 50$ GeV**
    - **Reconstructed mass of transverse momentum of the lepton: m_T**

- **MC simulation samples:**
  - **$Z \rightarrow ll$ and $W \rightarrow l\nu$ are generated with NLO POWHEG model, parton shower by PYTHIA8 and CT10 PDF**
  - **t t-bar events with MC@NLO, $Z \rightarrow \tau\tau$ and $H \rightarrow \tau\tau$ (mH = 125 GeV) with POWHEG, SUSY with HERWIG++**
  - **Additional inelastic pp collisions (pile-up interactions) are generated using PYTHIA8 + MSTW08 PDF**
  - **The same event selection criteria for $Z \rightarrow ll$ and $W \rightarrow l\nu$ data are also applied to MC events**
    - **t t-bar events: 1 e or μ with $p_T>25$ GeV**
    - **$Z \rightarrow \tau\tau$ and $H \rightarrow \tau\tau$ (lepton-hadron): 1 e or μ + 1 τ-jet both with $p_T>20$ GeV**

E_T^{miss} reconstruction

- The E_T^{miss} reconstruction uses energy deposits in the calorimeters and muon spectrometer



- The E_T^{miss} calculation uses reconstructed and calibrated physics objects
  - Calorimeter energy deposits are associated with a reconstructed and identified high-p_T parent object
  - The E_T^{miss} is calculated as follows: $E_T^{miss} = \mathrm{sqrt}((E_x^{miss})^2 + (E_y^{miss})^2)$

$$E_{x(y)}^{miss} = E_{x(y)}^{miss,e} + E_{x(y)}^{miss,\gamma} + E_{x(y)}^{miss,\tau} + E_{x(y)}^{miss,jets} + E_{x(y)}^{miss,SoftTerm} + E_{x(y)}^{miss,\mu}$$

  where $E_x^{miss,e} = -\sum p_T^e \cos\phi^e$, ...

    - Only jets with calibrated p_T>20 GeV are used to calculate the jet term
    - The soft term is calculated from calorimeter cells and tracks not associated to high-p_T objects

- The total transverse energy in the calorimeters
  - It is defined as the scalar sum: $\sum E_T = \sum E_T^e + \sum E_T^\gamma + \sum E_T^\tau + \sum E_T^{jets} + \sum E_T^{SoftTerm}$

    (scalar sum of the transverse energy of reconstructed and calibrated objects and of the soft term)
  - The total transverse energy in the event: $\sum E_T(\mathrm{event}) = \sum E_T + \sum p_T^\mu$

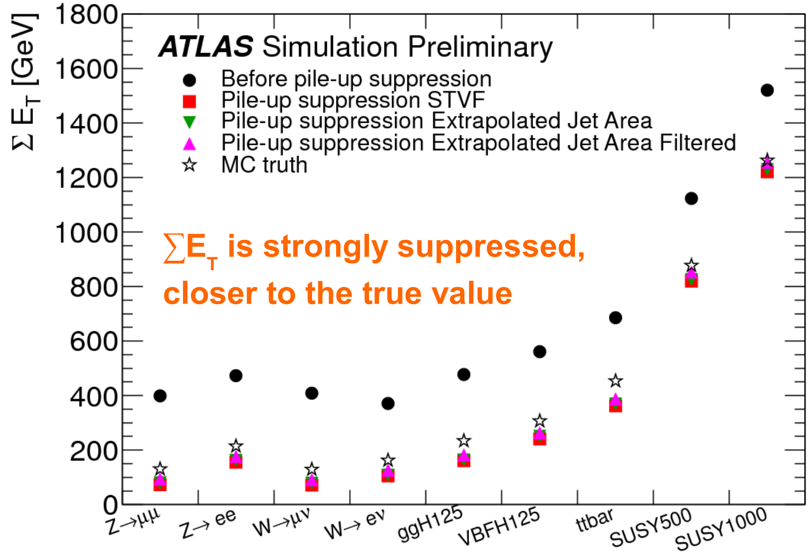
Methods for pile-up suppression in E_T^{miss}

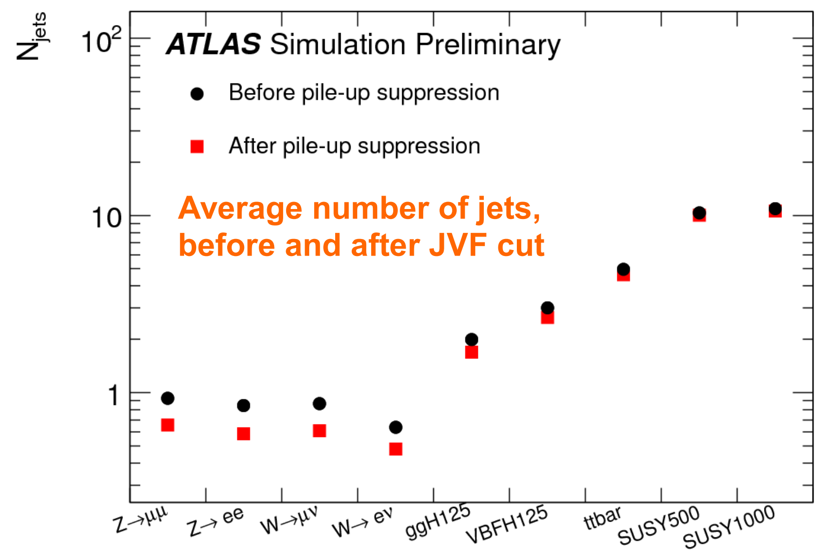
- **A clear deterioration of the E_T^{miss} performance is observed when the average number of pile-up interactions per event increases**
  - **All E_T^{miss} terms are affected, but the terms which are most affected are the jets and soft terms**

- **Pile-up suppression in the E_T^{miss} jet term based on tracks**
  - **A cut is applied based on the Jet Vertex Fraction (JVF): JVF = $\sum_{tracks\_jet,PV} p_T / \sum_{tracks\_jet} p_T$**
  - **Any jet with p_T < 50 GeV, |η|<2.4 and which does not satisfy |JVF|>0 is discarded for $E_T^{miss,jets}$ term**
- **Pile-up suppression in the E_T^{miss} soft term based on tracks**
  - **It is calculated as: Soft Term Vertex Fraction (STVF) = $\sum_{tracks\_SoftTerm,PV} p_T / \sum_{tracks\_SoftTerm} p_T$**
  - **The $E_T^{miss,SoftTerm}$ is multiplied by the STVF factor (this E_T^{miss} is called STVF)**
- **Pile-up suppression in the E_T^{miss} soft term using the jet area method**
  - **The contribution due to pile-up in the jet area is subtracted from each Jet: $p_T^{jetcorr} = p_T^{jet} - \rho \times A^{jet}$**
  - **The are 2 methods which differ only in their calculation of ρ (level of diffuse noise):**
    - **Extrapolated Jet Area Filtered: ρ as the median of p_T^{jet}/A^{jet} from jets (R=0.4) and |η|<1.8**
    - **Jet Are Filtered: ρ as the median of p_T^{jet}/A^{jet} from jets (R=0.8) and |η|<5**

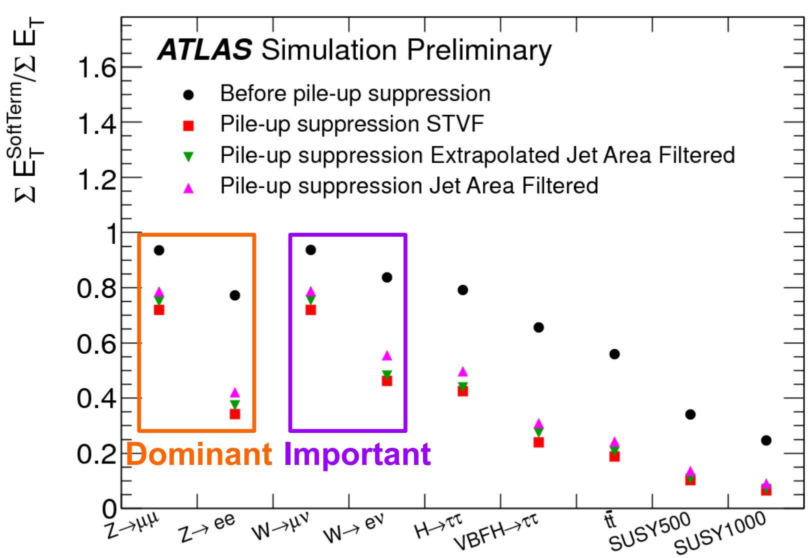
Characterization of samples for E_T^{miss} performance

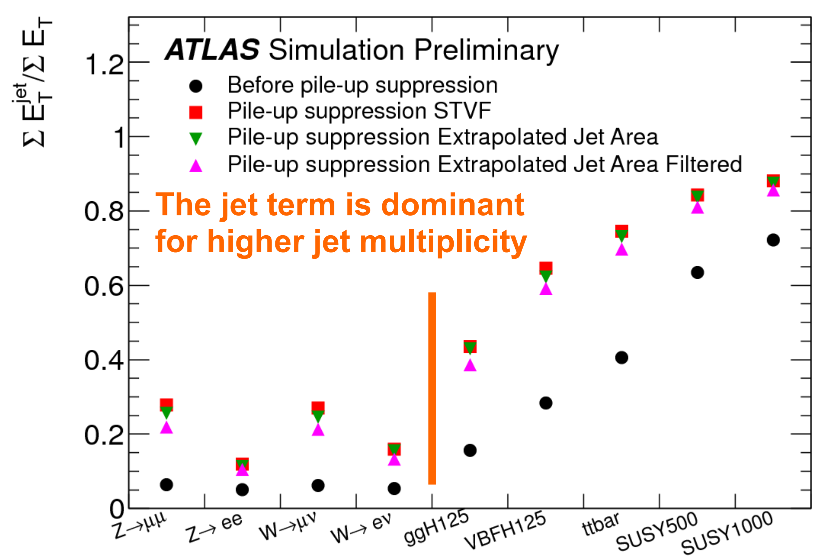
The E_T^{miss} performance depends on the event topology: Presence of leptons, jet activity, etc.





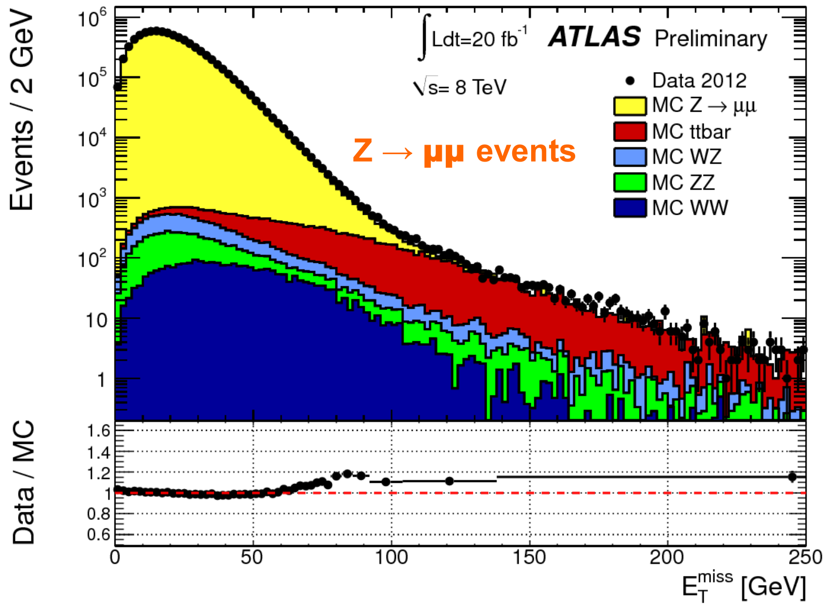
The importance of the soft and jet terms is shown here:

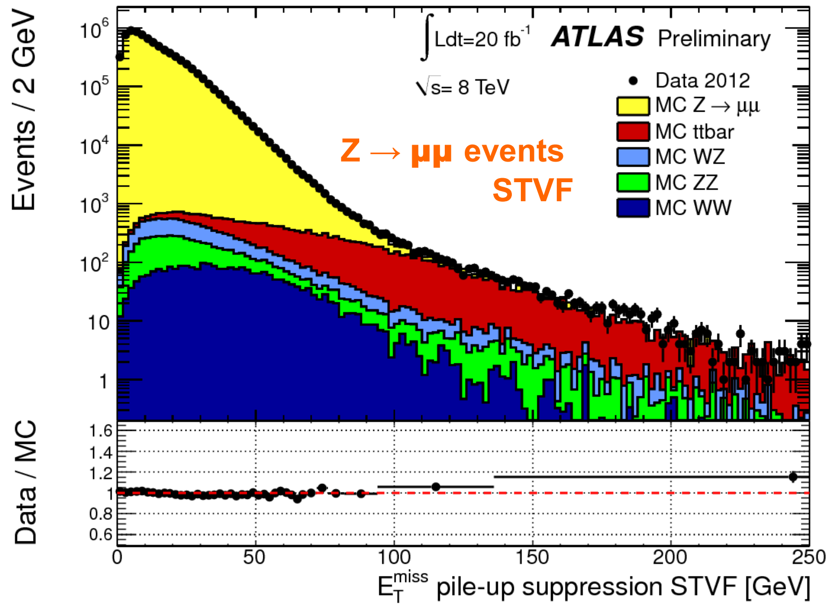




E_T^{miss} distribution in Z → μμ events: Data/MC

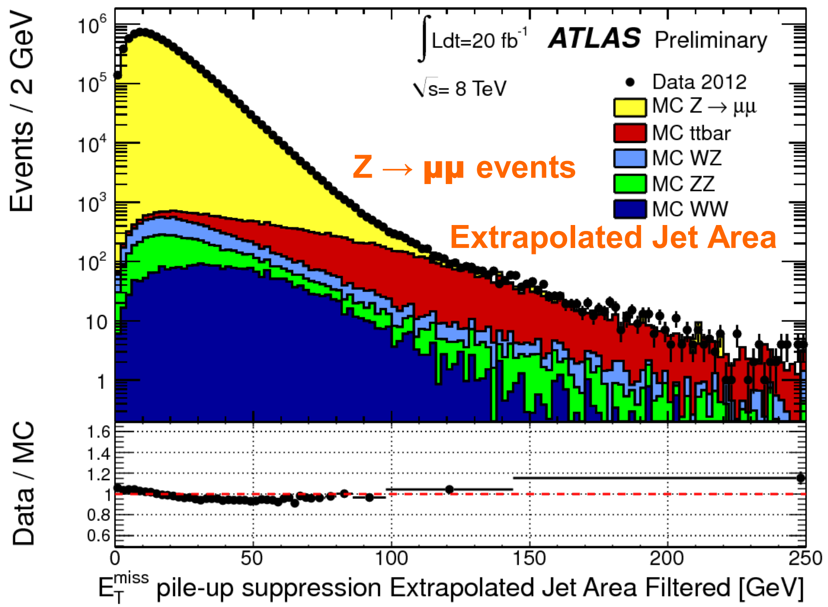
The Z → ll channel is well-suited to the study of E_T^{miss} performance: clean event signature

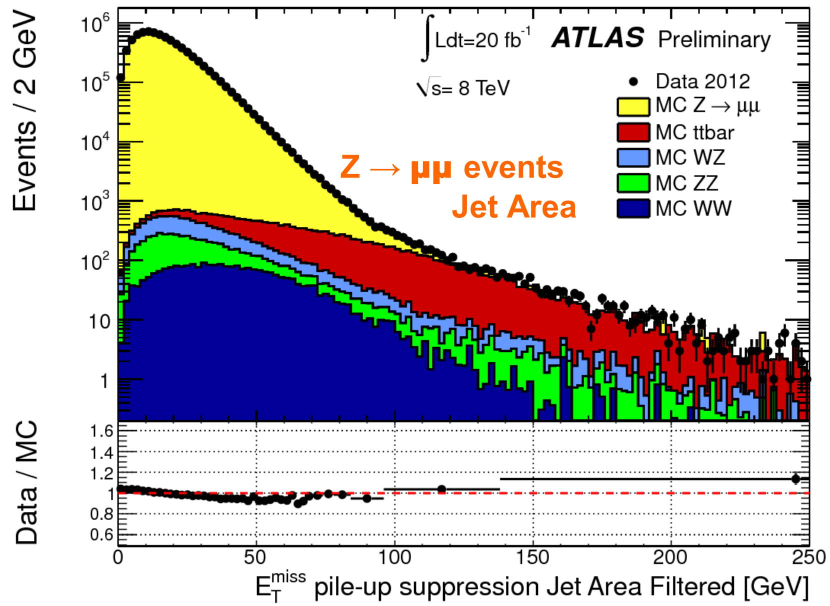




The MC simulation, from Z → μμ events and from dominant backgrounds, are superimposed

A good agreement between data and MC simulation is observed, both before and after pile-up suppression

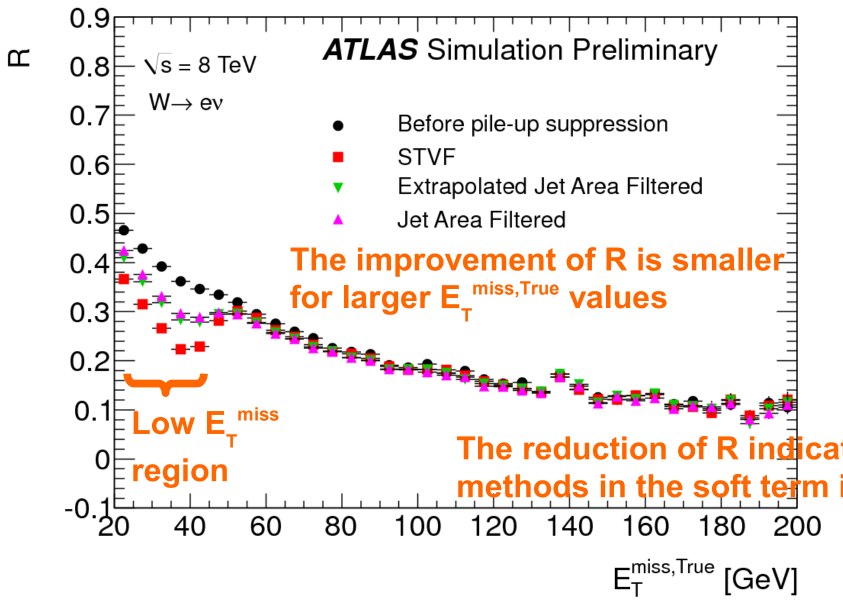


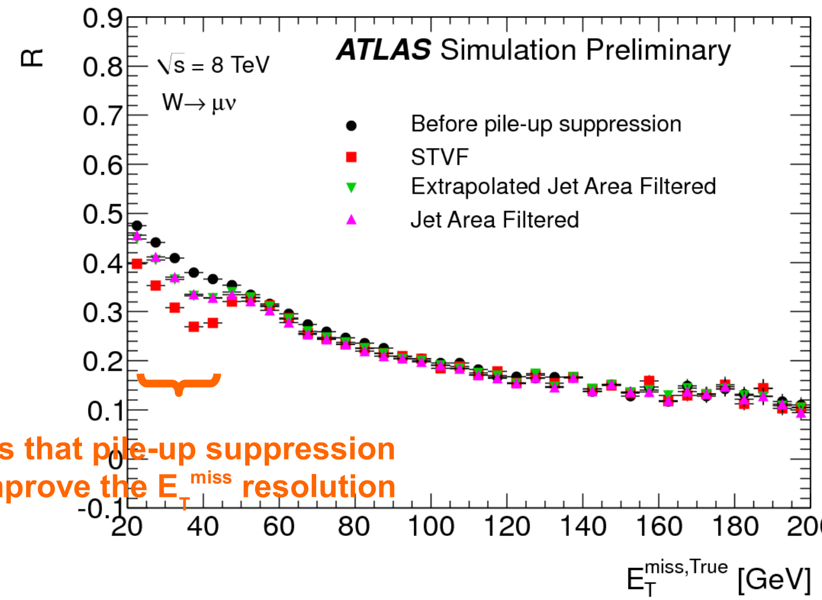


Study of E_T^{miss} resolution

The study of the E_T^{miss} resolution is performed using: $R = RMS(E_T^{miss}/E_T^{miss,True})/\langle E_T^{miss}/E_T^{miss,True}\rangle$

The low $E_T^{miss,True}$ region ($E_T^{miss,True}$ < 40 GeV) is mostly populated by events without jets



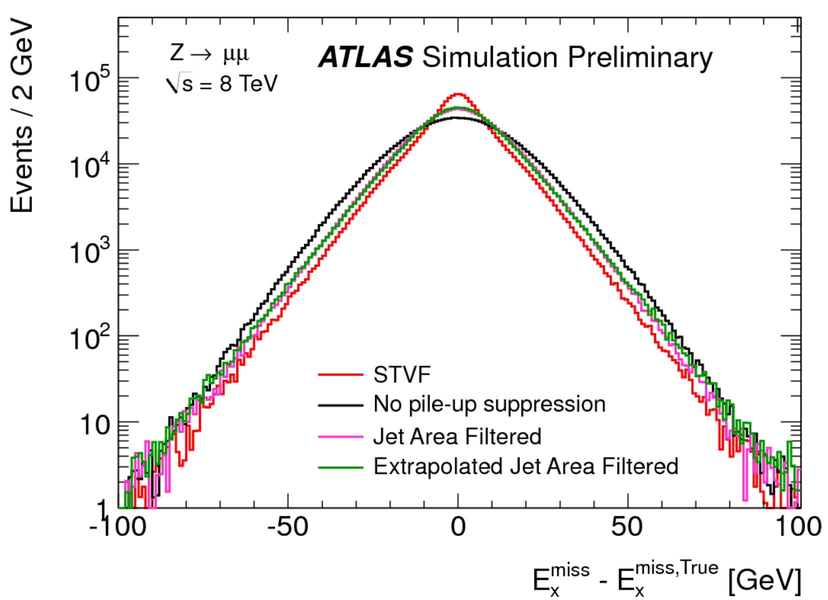


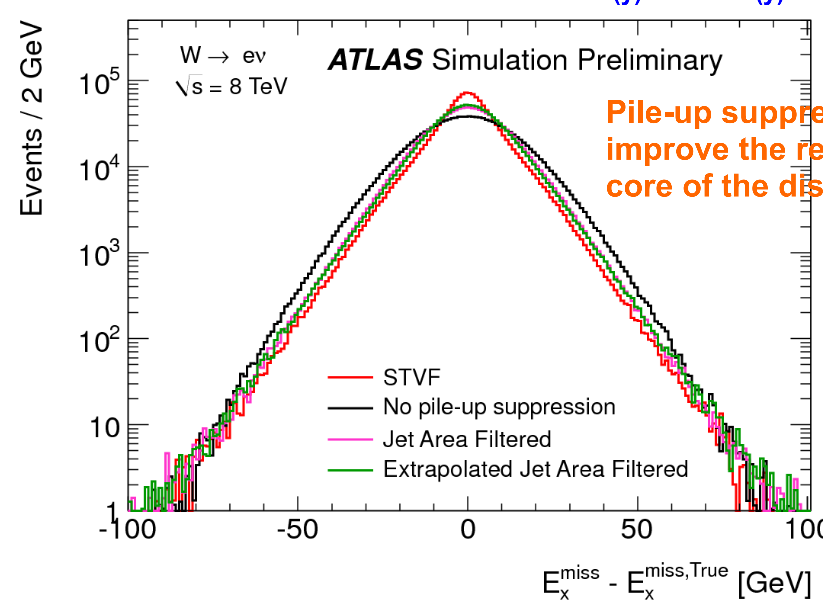
The improvement of R is smaller for larger $E_T^{miss,True}$ values

Low E_T^{miss} region

The reduction of R indicates that pile-up suppression methods in the soft term improve the E_T^{miss} resolution

The resolution of the two E_T^{miss} components is studied from the width of: $E_{x(y)}^{miss}-E_{x(y)}^{miss,True}$



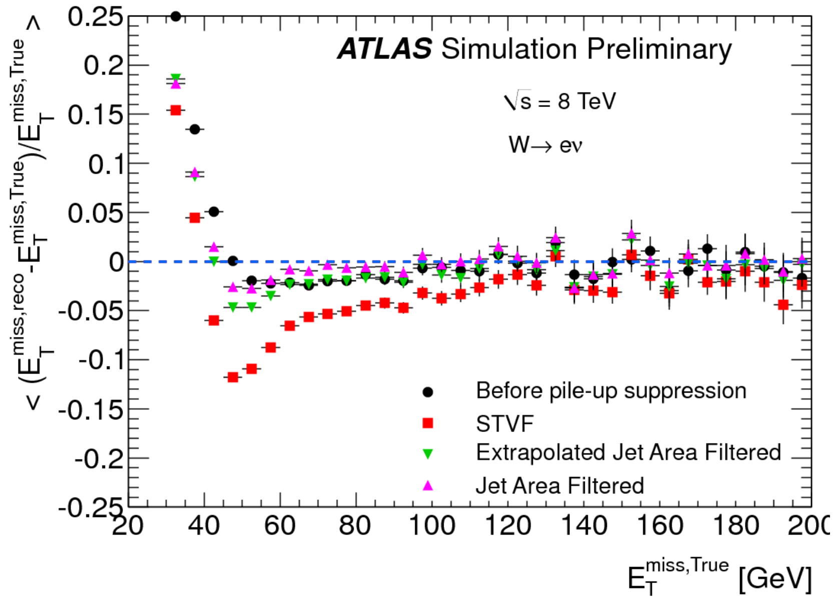


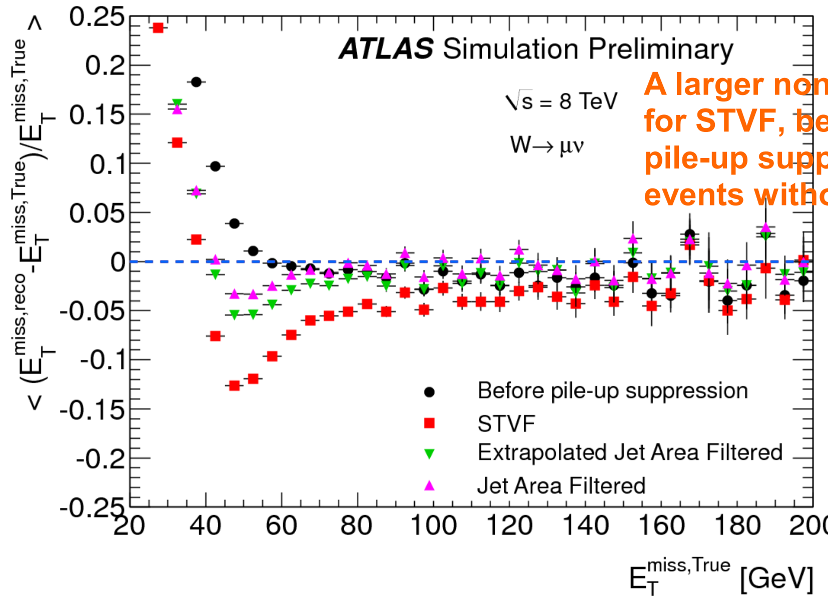
Pile-up suppression methods improve the resolution of the core of the distributions

Study of E_T^{miss} response

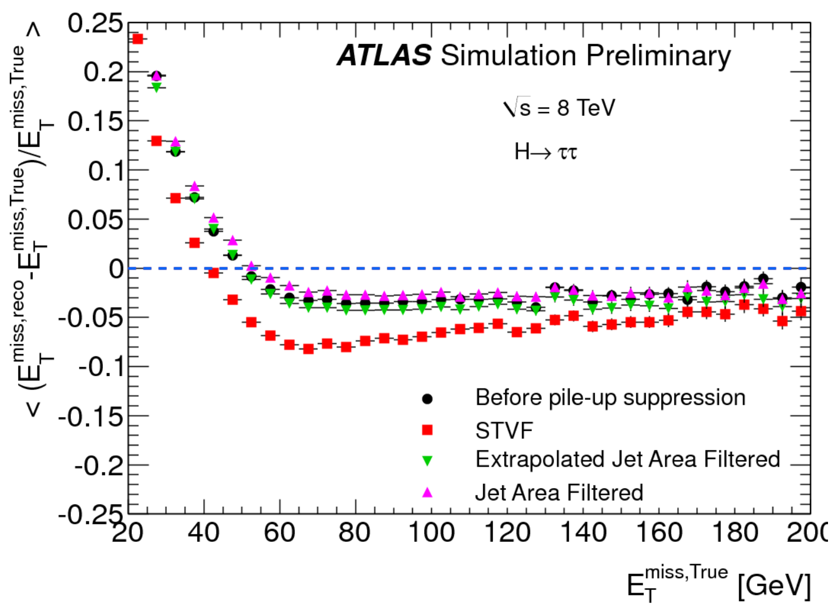
It is important to check that the pile-up suppression methods, introduced to reduce the effect of pile-up on the E_T^{miss} resolution, do not have an adverse effect on the E_T^{miss} response.

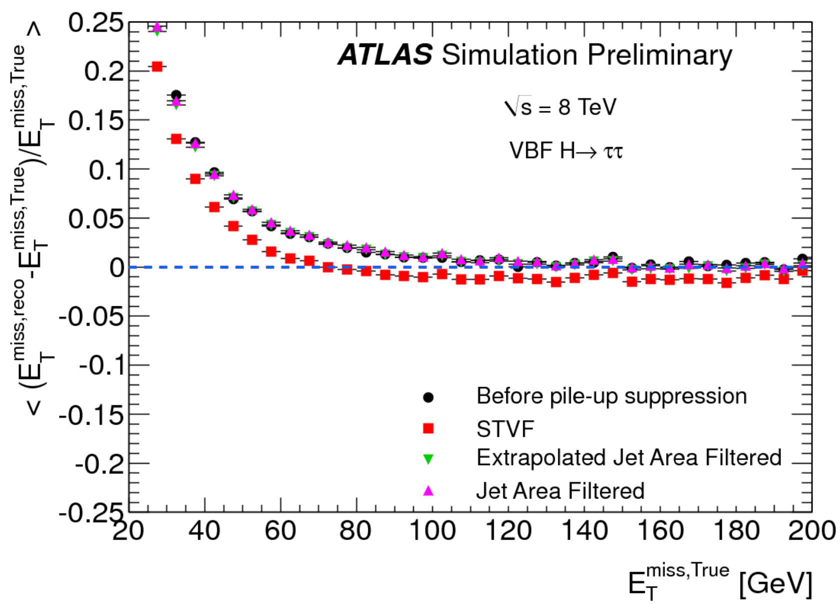
The E_T^{miss} linearity is defined as the mean value of the ratio: $(E_T^{miss}-E_T^{miss,True})/E_T^{miss,True}$





A larger non-linearity is observed for STVF, because of the strong pile-up suppression mainly in events without jets





A positive bias is observed for low $E_T^{miss,True}$ values due to the finite resolution of the E_T^{miss} measurement.

For larger $E_T^{miss,True}$ values, the bias is within 5% for all samples

Evaluation of the systematic uncertainty on E_T^{miss}

Overall systematic uncertainty on the E_T^{miss} measurement → combining uncertainties on each term

These ones are evaluated given the knowledge of the reconstructed objects that are used to build them

In events containing W and Z bosons decaying to leptons:

- **Uncertainties on the scale and resolution of leptons and jets → propagated to estimate E_T^{miss}**
- **Another significant contribution comes from the soft term:**

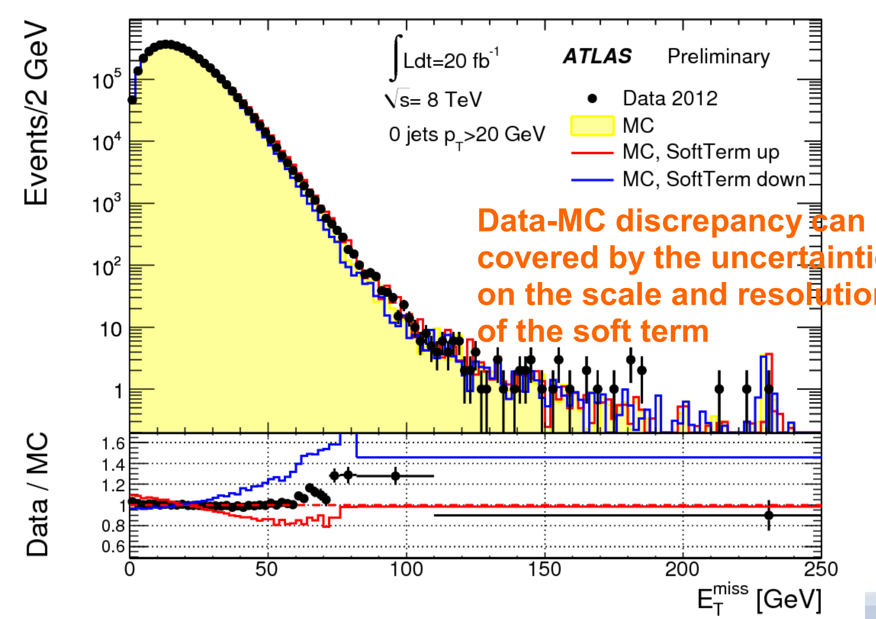
Two methods used with Z→μμ:

- Data/MC ratio in events without jets

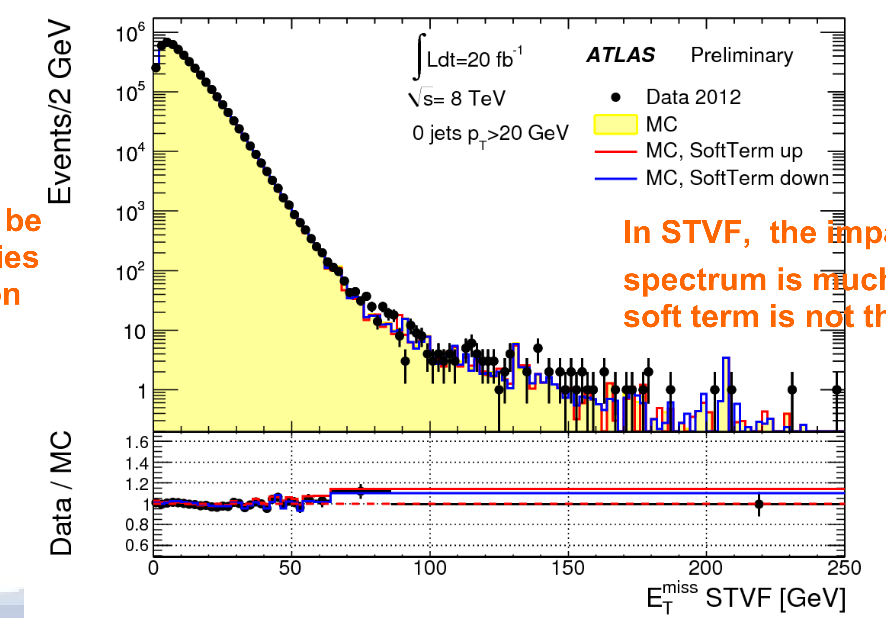
- Balance between soft terms and hard objects

$E_T^{miss,SoftTerm}$ uncertainty	data/MC method		balance method		
	scale	resolution	scale		resolution
	(%)	(%)	([GeV])	(%)	(%)
Default	3.6	2.3	< 1 GeV	<13	2.0
STVF	7.9	4.8	< 1 GeV	<12	4.5
Extrapolated Jet Area Filtered	4.7	2.0	< 1 GeV	< 18	3.0
Jet Area Filtered	5.8	2.5	< 1 GeV	< 16	2.0

Data compared with Z→μμ MC and MC after scaling and smearing the $E_T^{miss,SoftTerm}$ (data/MC ratio method):



Data-MC discrepancy can be covered by the uncertainties on the scale and resolution of the soft term



In STVF, the impact on the E_T^{miss} spectrum is much smaller, since the soft term is not the dominant one

Conclusions

- The missing transverse momentum (E_T^{miss}) performance has been studied in events with different topologies in proton-proton collisions at a centre-of-mass energy of 8 TeV recorded with the ATLAS detector in 2012.
- The value of E_T^{miss} is calculated from calibrated reconstructed objects and from the unmatched topological clusters and tracks ($E_T^{miss,SoftTerm}$). Several methods for pile-up suppression in the soft term are described, based on the use of tracks (STVF method) or on the jet area method.
- The Monte Carlo simulation describes the data in general rather well. Some discrepancy in data-MC comparison is observed after pile-up suppression in the $E_T^{miss,SoftTerm}$ and in the contribution from jets, due to the corrections applied for pile-up suppression.
- The E_T^{miss} resolution improves after pile-up suppression in events where the contribution of the soft term is important and it becomes closer to that observed in the absence of pile-up, mainly with the STVF.
- The linearity of the E_T^{miss} measurement is studied in MC simulation as a function of the true E_T^{miss}. Except for the bias observed at small true E_T^{miss} values (visible up to 40 GeV), due to the finite E_T^{miss} resolution, the linearity is better than 5% in all samples and it is very good in events with a very large number of jets.
- The systematic uncertainty on the scale and the resolution of the $E_T^{miss,SoftTerm}$ is determined comparing data and MC $Z \rightarrow ll$ events with two different methods, and it is found to be of the order of a few percent. The effect of the uncertainty on the $E_T^{miss,SoftTerm}$ has a visible effect on the E_T^{miss} only before pile-up suppression, while it is negligible after the pile-up suppression because of the strong reduction on the $E_T^{miss,SoftTerm}$.

Back-up slides

Medium electron identification selection criteria

Type	Description	Variable name
Loose cuts		
Acceptance of the detector	⋆ $\|\eta\| < 2.47$	
Hadronic leakage	⋆ Ratio of E_T in the first layer of the hadronic calorimeter to E_T of the EM cluster (used over the range $\|\eta\| < 0.8$ and $\|\eta\| > 1.37$) ⋆ Ratio of E_T in the hadronic calorimeter to E_T of the EM cluster (used over the range $\|\eta\| > 0.8$ and $\|\eta\| < 1.37$)	R_{had1} R_{had}
Second layer of EM calorimeter	⋆ Ratio in η of cell energies in 3×7 versus 7×7 cells. ⋆ Lateral width of the shower.	R_{η} $w_{\eta 2}$
Medium cuts (includes Loose)		
First layer of EM calorimeter.	⋆ Total shower width. ⋆ Ratio of the energy difference associated with the largest and second largest energy deposit over the sum of these energies	w_{stot} E_{ratio}
Track quality	⋆ Number of hits in the pixel detector (≥ 1). ⋆ Number of hits in the pixels and SCT (≥ 7). ⋆ Transverse impact parameter (<5 mm).	 d_0
Track matching	⋆ $\Delta\eta$ between the cluster and the track (< 0.01).	$\Delta\eta_1$