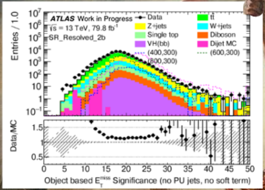


Search for Dark Matter + $H(b\bar{b})$

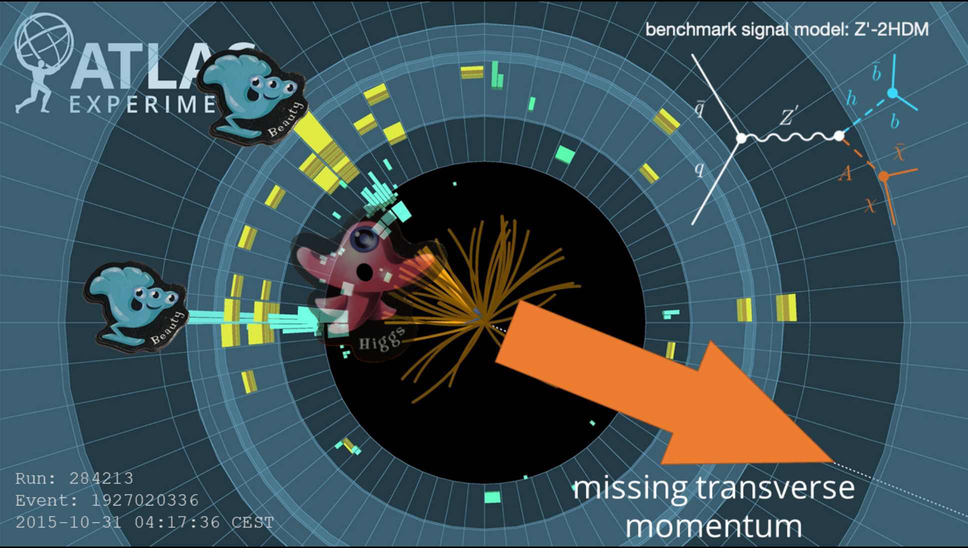
How to get rid of the multijet background using the object-based E_T^{miss} significance

Philipp Gadow | Max-Planck-Institut für Physik, München

DPG Frühjahrstagung Aachen - 28.03.2019

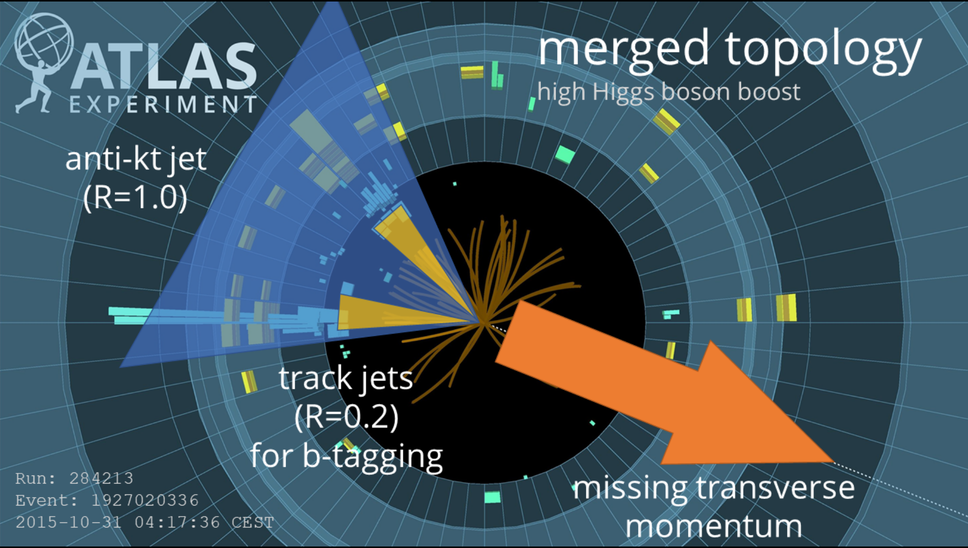
FSP 103 ATLAS

ATLAS EXPERIMENT



ATLAS EXPERIMENT
Beauty
Beauty
Higgs
benchmark signal model: Z'-2HDM
$\bar{q}$
q
Z'
h
$\bar{b}$
b
A
$\bar{\chi}$
χ
missing transverse momentum
Run: 284213
Event: 1927020336
2015-10-31 04:17:36 CEST

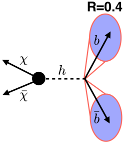

ATLAS
EXPERIMENT
resolved topology
low Higgs boson boost
two anti-kt jets
(R=0.4)
Run: 284213
Event: 1927020336
2015-10-31 04:17:36 CEST
missing transverse
momentum


ATLAS
EXPERIMENT
merged topology
high Higgs boson boost
anti-kt jet
(R=1.0)
track jets
(R=0.2)
for b-tagging
missing transverse
momentum
Run: 284213
Event: 1927020336
2015-10-31 04:17:36 CEST

Signature and event selection

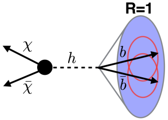
Signature: missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$ with $H \to b\bar{b}$ reconstructed as

- (resolved) two small-R b-jets ($R = 0.4$)



$150\,\mathrm{GeV} < E_{\mathrm{T}}^{\mathrm{miss}} < 500\,\mathrm{GeV}$

- (merged) one large-R jet ($R = 1.0$) with 2 associated b-tagged track jets



$E_{\mathrm{T}}^{\mathrm{miss}} > 500\,\mathrm{GeV}$

Base event selection:

- $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger (70 GeV to 110 GeV)
- lepton veto, τ veto, additional b-jet veto
- anti-QCD: $\min \Delta\varphi(E_{\mathrm{T}}^{\mathrm{miss}}, jets) > 20^\circ$, $\Delta\varphi(E_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}^{\mathrm{miss}}) < 90^\circ$
- additional cuts on jet p_{T} and event topology

Signal and background

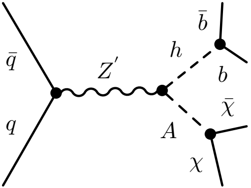
Benchmark signal

$Z' + \text{2HDM model (Type II)}$

Fixed parameters:

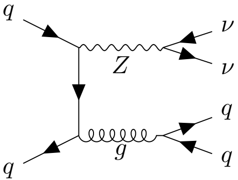
$m_\chi = 100$ GeV, $\tan\beta = 1.0$ $g_{Z'} = 0.8$,

$m_H = m_{H^\pm} = 300$ GeV, BR$(A \to \chi\bar{\chi}) = 100\%$

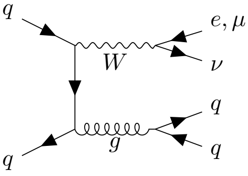


Dominant background processes

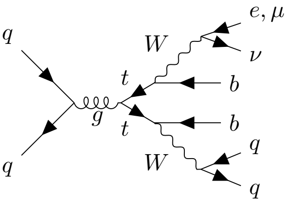
$Z \to \nu\bar{\nu}$ + jets



W + jets

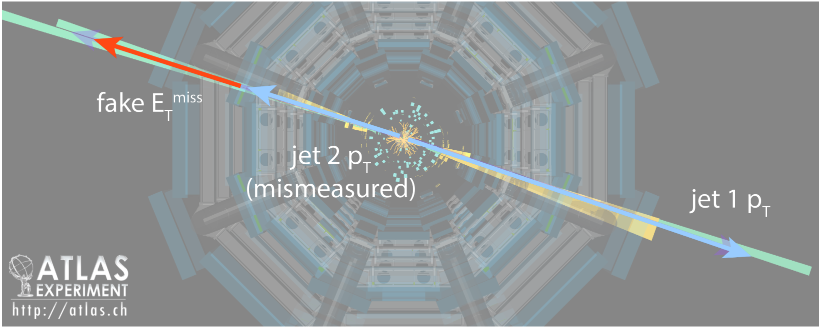


$t\bar{t}$



Other background processes: single top quark, diboson, *VHbb*

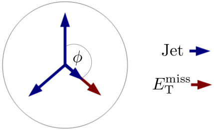
Multijet background



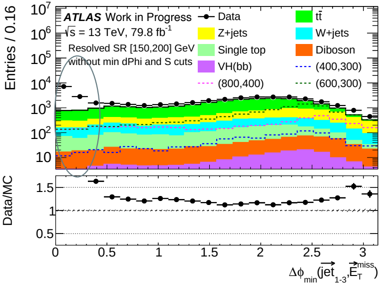
- Mismeasured jet p_T can create fake E_T^{miss} in multijet processes, allowing them to enter event selection
- Multijet background difficult to simulate, often requires data-driven methods for estimation (templates, jet smearing)

Established anti-QCD cuts

$\min \Delta\varphi(\textbf{jets}, E_T^{miss})$ cut



fake E_T^{miss} being often parallel to jet p_T allows to define strong cut



Event-based E_T^{miss} significance

$$\frac{E_T^{miss}}{\sqrt{\sum E_T^{miss}}} \quad \text{or} \quad \frac{E_T^{miss}}{\sqrt{H_T^{miss}}}$$

with $\vec{H}_T^{miss} := \sum_{e,\mu,\gamma,\tau,\text{jets}} \vec{p}_T$

- denominator serves as event-based approximation to E_T^{miss} resolution
- high value indicates observed E_T^{miss} cannot be explained from momentum resolution effects alone

Object-based $E_{\mathrm{T}}^{\mathrm{miss}}$ significance

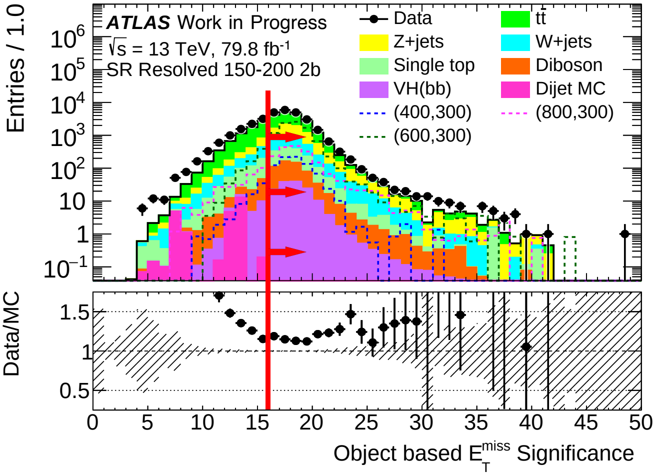
Objective: Improve multijet suppression provided by cuts such as $\min \Delta\varphi(\text{jets}, E_{\mathrm{T}}^{\mathrm{miss}})$ in event selection by introducing an additional cut on $E_{\mathrm{T}}^{\mathrm{miss}}$ significance.

Object-based $E_{\mathrm{T}}^{\mathrm{miss}}$ significance is a variable that

- takes into account the full event composition of **all objects entering the $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction** and their respective resolution and the correlations among them
- distinguishes between processes with real and fake $E_{\mathrm{T}}^{\mathrm{miss}}$

Rather new development in ATLAS: ATLAS-CONF-2018-038

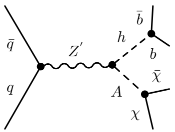
Introducing an object-based E_T^{miss} significance requirement



New object-based E_T^{miss} significance $\mathcal{S} > 16$ requirement in resolved topology event selection to suppress multijet background.

$E_{\mathrm{T}}^{\mathrm{miss}}$ significance performance in Mono-$H(b\bar{b})$

Signal: Z'-2HDM model

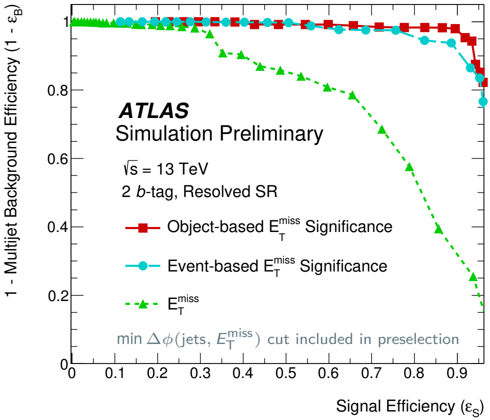


$(m_{Z'} = 400$ GeV, $m_A = 300$ GeV$)$

Background: dijet MC

$\mathcal{S} > 16$ working point:

- Signal efficiency $\geq 90\%$
- Dijet rejection $> 95\%$



- With cut: only 51 multijet events, background can be neglected
- 95% reduction w.r.t. PRL 119 181804

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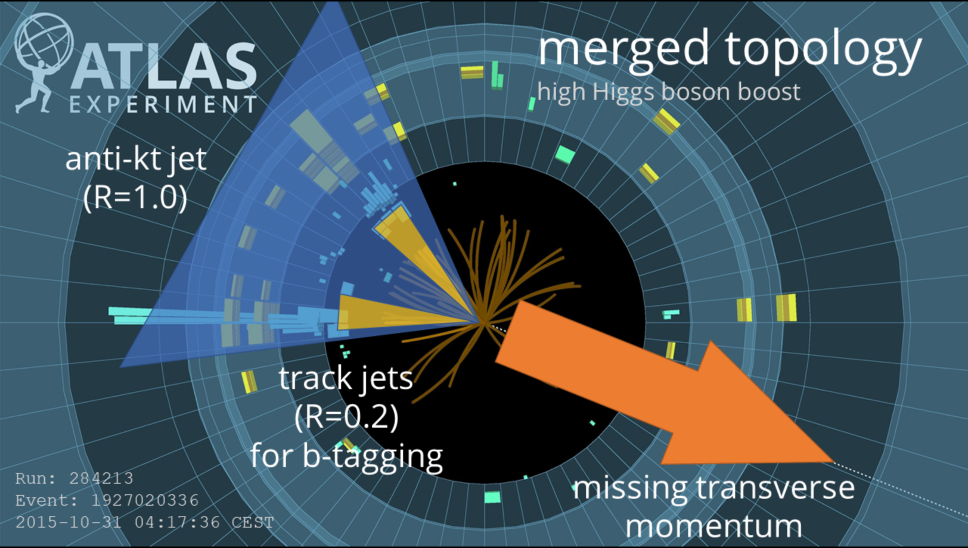
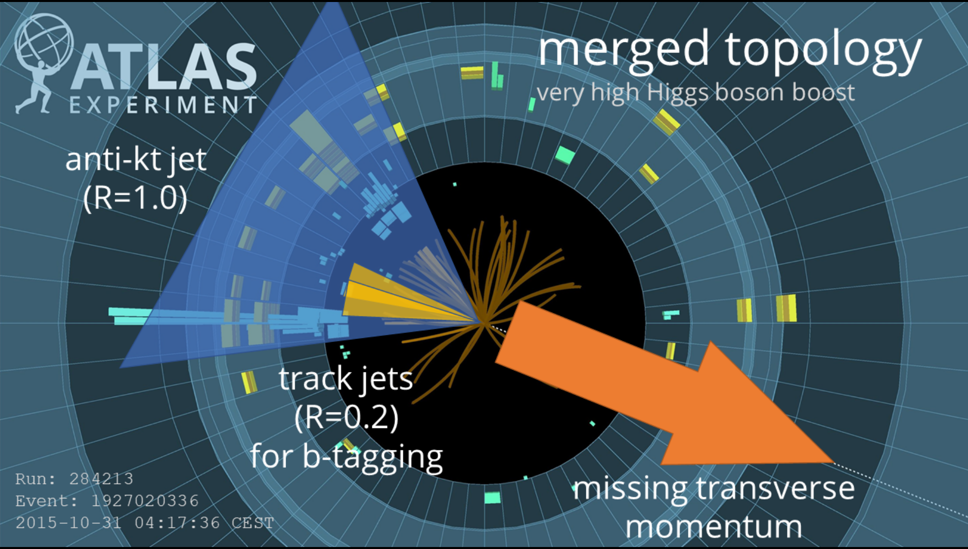

ATLAS EXPERIMENT
merged topology
high Higgs boson boost
anti-kt jet
(R=1.0)
track jets
(R=0.2)
for b-tagging
missing transverse
momentum
Run: 284213
Event: 1927020336
2015-10-31 04:17:36 CEST


ATLAS
EXPERIMENT
merged topology
very high Higgs boson boost
anti-kt jet
(R=1.0)
track jets
(R=0.2)
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missing transverse
momentum
Run: 284213
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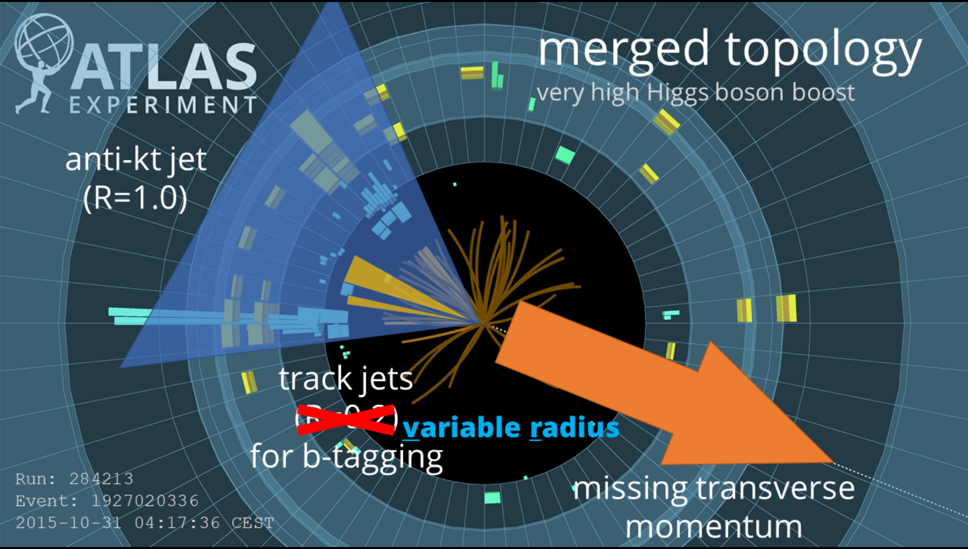
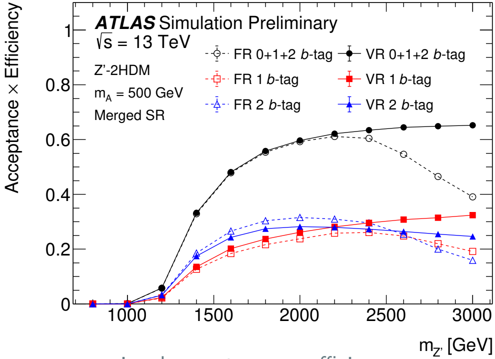

ATLAS
EXPERIMENT
merged topology
very high Higgs boson boost
anti-kt jet
(R=1.0)
track jets
(R=0.2) variable radius
for b-tagging
missing transverse
momentum
Run: 284213
Event: 1927020336
2015-10-31 04:17:36 CEST

New analysis technique: VR track jets

VR track jets

b-tagging for merged topology: objects supplied by jet algorithm using tracks as input with p_T-dependent radius parameter

$$R \rightarrow R_{\text{eff}} = \frac{30\,\text{GeV}}{p_T} \qquad (0.02 \leq R_{\text{eff}} \leq 0.4)$$



signal acceptance × efficiency

Use of variable-radius track jets improves acceptance × efficiency in the highly boosted regime for the benchmark Z'+2HDM model

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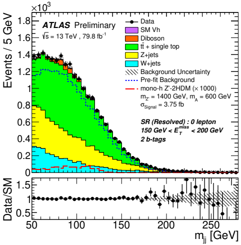
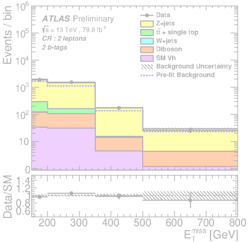
Statistical analysis

"Fit the model to data": profile likelihood fit

$$\mathcal{L}(\mu, \theta) = \prod_{\text{SR bins: } i} \text{Pois}(n_i | \mu S_i(\theta) + B_i(\theta)) \prod_{\text{CR bins: } j} \text{Pois}(n_j | B_j(\theta)) \prod_{\text{Nuisance parameters: } k} \text{Gaus}(0 | x = \theta_k, \sigma =$$

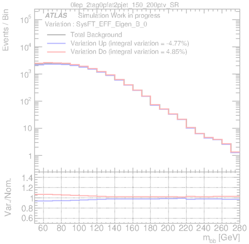


0 lepton signal region



1 lepton control region

2 lepton control region



systematic uncertainties

- Major backgrounds unconstrained, minor backgrounds constrained by theory.
- Control regions improve (dominant) background estimation in signal region.

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Statistical analysis

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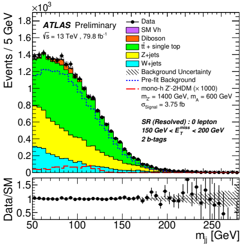
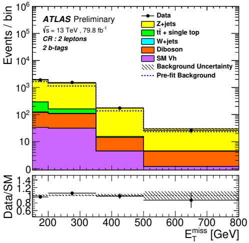
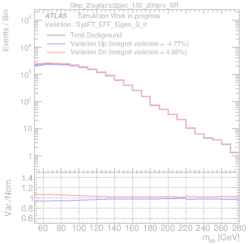


0 lepton signal region



1 lepton control region

2 lepton control region



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ATLAS-CONF-2018-039

Statistical analysis

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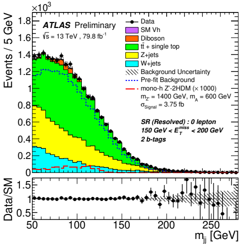
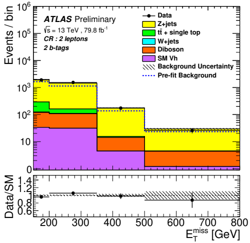
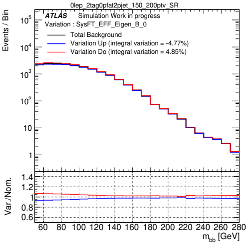


0 lepton signal region



1 lepton control region

2 lepton control region



systematic uncertainties

- Major backgrounds unconstrained, minor backgrounds constrained by theory.
- Control regions improve (dominant) background estimation in signal region.

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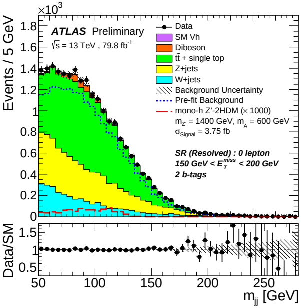
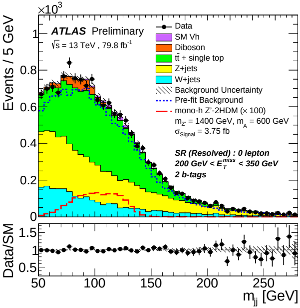
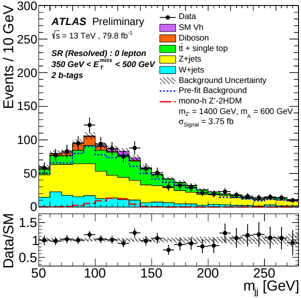
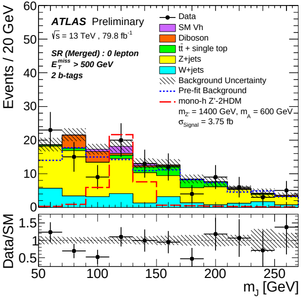
Signal region m_{jj}/m_J distributions after fit to data ($\mu = 0$)









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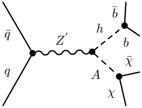
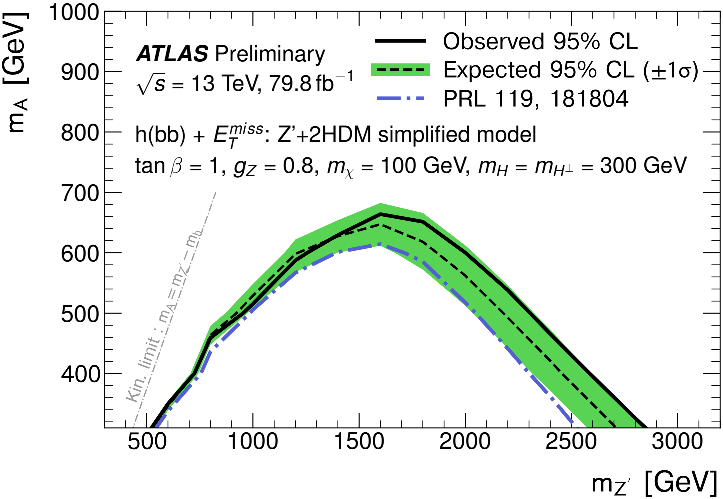
Exclusion limits for Z'+2HDM model





Model parameters excluded at 95%CL$_S$: $m_{Z'} \leq 2850$ GeV and $m_A \leq 650$ GeV.

But is this due to the increased dataset or due to the use of VR track jets?

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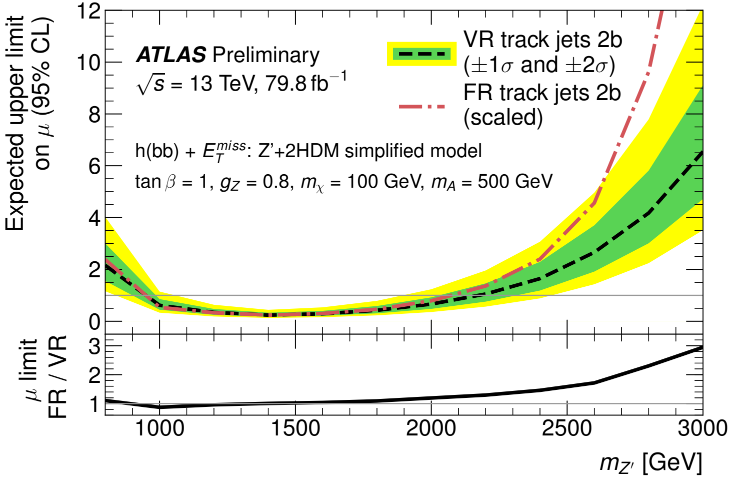
Expected μ limit comparision using VR/FR track jets

VR track jets



Expected limit on signal strength μ for $m_A = 500\,\text{GeV}$ slice

comparision shows: improvement due to new analysis techniques!

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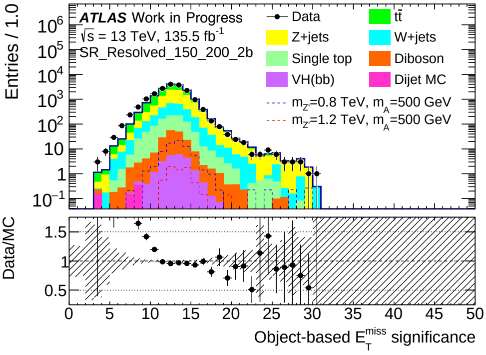
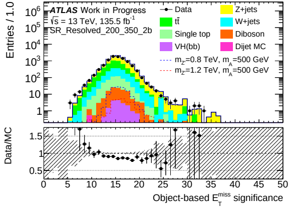
Outlook: E_T^{miss} significance in full Run-2 dataset

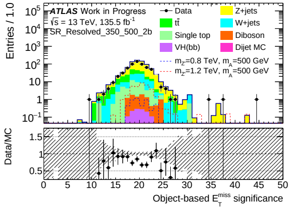
blinded in Higgs mass window (not included: $70\ \text{GeV} < m_{jj} < 140\ \text{GeV}$)



($150\ \text{GeV} < E_T^{miss} < 200\ \text{GeV}$)



($200\ \text{GeV} < E_T^{miss} < 350\ \text{GeV}$)



($350\ \text{GeV} < E_T^{miss} < 500\ \text{GeV}$)

Full Run-2 analysis: re-optimise cut value of object-based E_T^{miss} significance requirement because of updated object calibrations.

Summary

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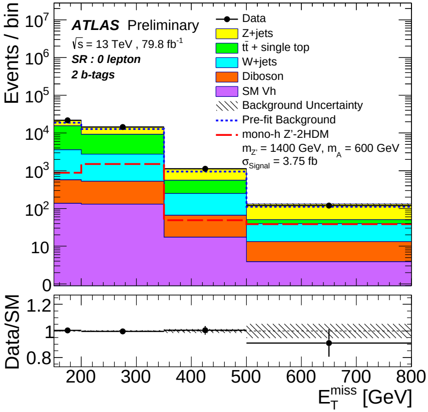
- Search for Dark Matter with Higgs boson ($\to b\bar{b}$)
- Improved sensitivity due to

- First time use of VR trackjets in ATLAS: helps to maintain double b-tagging efficiency also in highly boosted topologies
- The object-based $E_{\mathrm{T}}^{\mathrm{miss}}$ significance allows to suppress the multijet background to the extent that it does not need to be accounted for in the background model of the statistical interpretation.

Backup

Background estimation



Simulated background estimates:

- Z + jets: Sherpa 2.2.1
- W + jets: Sherpa 2.2.1
- $t\bar{t}$: Powheg v2 + Pythia 8
- single t: Powheg v2 + Pythia 8
- $WW/WZ/ZZ$: Sherpa 2.2.1
- $VHbb$: Powheg v2 (MINLO) + Pythia 8

Data-driven background estimate:

- Multijet: negligible (ABCD-method)

Reduce untertainties on background estimation by using control regions:

- 0 lepton signal region + 1 lepton / 2 lepton control regions

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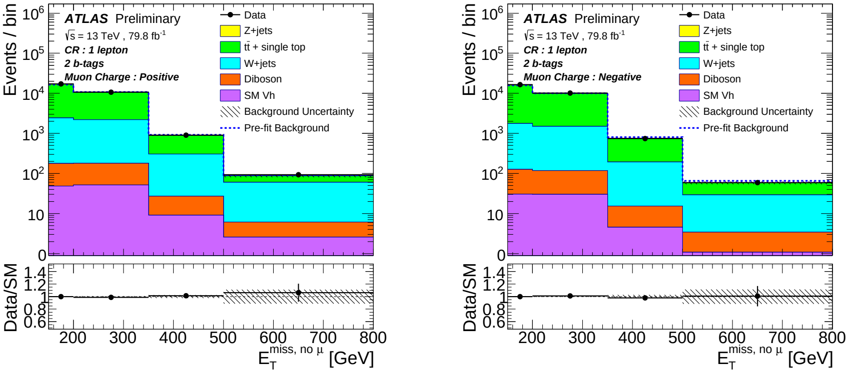
Event selection

Resolved	Merged	Cut motivation
trigger		
lepton veto (SR) or selection (CRs)		
(modified) $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV		trigger efficiency
min $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jets}) > 20^{\circ}$		anti-QCD
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}^{\mathrm{miss}}) < 90^{\circ}$		anti-QCD
$\mathcal{S} > 16$ (SR only)	—	anti-QCD
$E_{\mathrm{T}}^{\mathrm{miss}} < 500$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 500$ GeV	signal topology
N(central small-R jets) ≥ 2	N(central large-R jets) ≥ 1	signal topology
$p_{\mathrm{T}}^{\mathrm{jet}_1} > 45$ GeV || $p_{\mathrm{T}}^{\mathrm{jet}_2} > 45$ GeV	—	signal topology
$\sum_{i=1}^{2(3)} p_{\mathrm{T}}^{\mathrm{jet}_i} > 120$ GeV (150 GeV)	—	signal topology
$\Delta\phi(\mathrm{jet}_1, \mathrm{jet}_2) < 140^{\circ}$	—	anti-QCD
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, h) > 120^{\circ}$	—	anti-QCD
τ-veto		$Z(\tau\tau)$+jets reduction
additional b-jet veto		$t\bar{t}$ reduction
H_T ratio		$t\bar{t}$ reduction
$\Delta R(\mathrm{jet}_1, \mathrm{jet}_2) < 1.8$	—	anti-QCD
—	$\frac{\Delta R(\mathrm{VR}_1, \mathrm{VR}_2)}{R_{\mathrm{min}}} > 1$	VR track jet calibration
b-tag requirement on small-R jets	VR track-jets	

1 lepton control region



- Fit variables: $E_T$miss distribution in 4 bins and muon charge in 2 bins
- Muon charge asymmetry allows to disentangle W+jets and $t\bar{t}$ contributions

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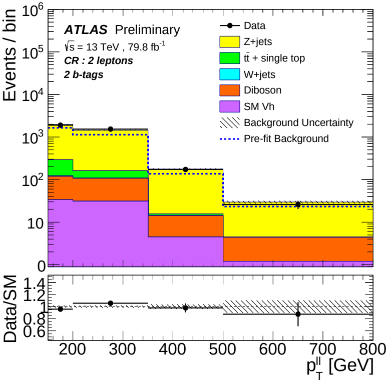
2 lepton control region



- Fit variable: $E_T$miss distribution in 4 bins

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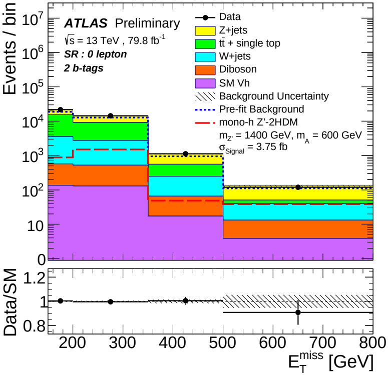
E_T^{miss} distribution in signal region



- Fit variables: $m_{b\bar{b}}$ distribution in 46/46/23/11 bins, $E_T$miss distribution in 4 bins
- Shown here: integral of m_{bb} distributions in each $E_T$miss bin

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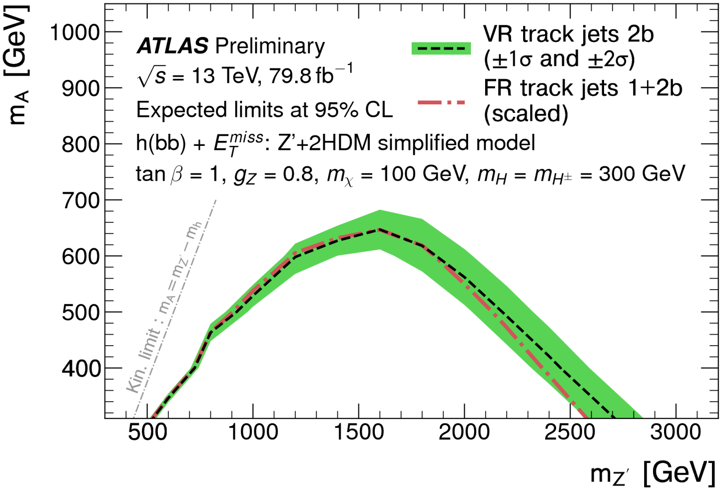
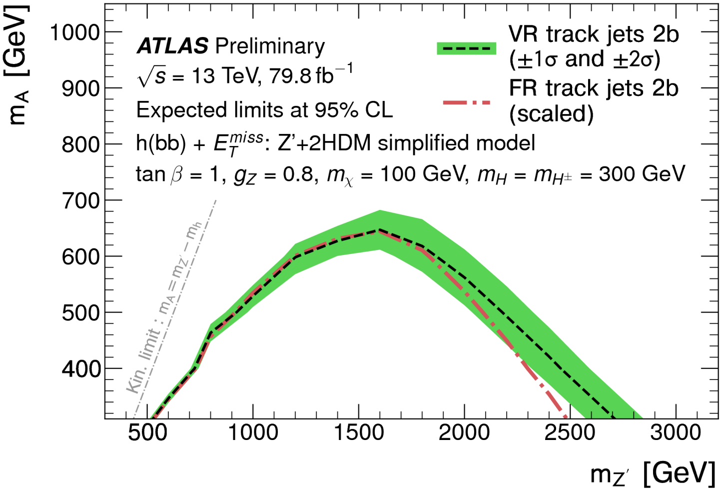
Exclusion limit comparison for Z'+2HDM model (1)



ATLAS-CONF-2018-039

Exclusion limit comparison for Z'+2HDM model (2)



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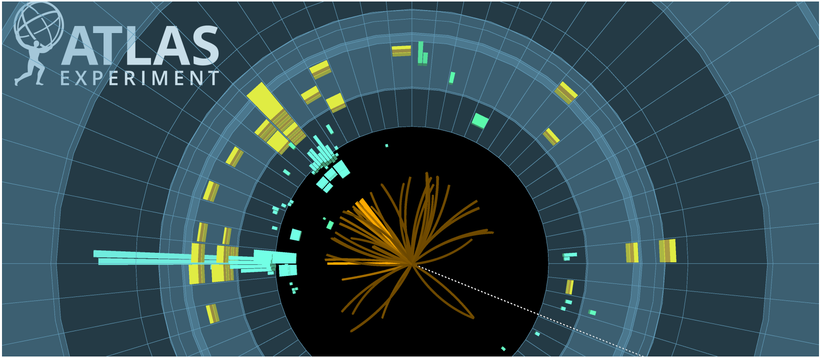
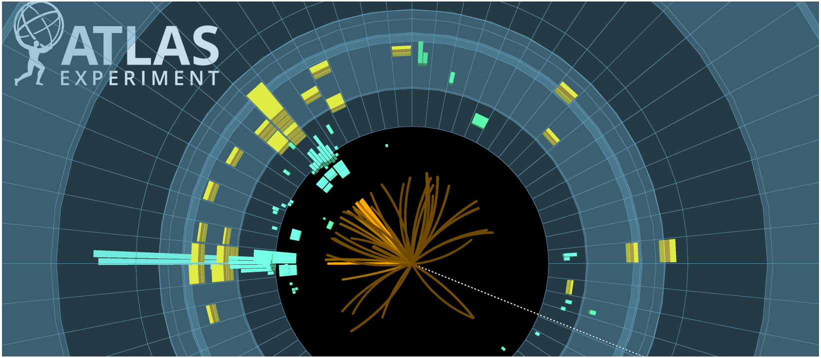
Missing transverse momentum E_T^{miss}



$$\vec{E}_T^{miss} = -\left(\sum_{e,\mu,\gamma,\tau,\text{jets}} \vec{p}_T + \sum_{\text{soft term}} \vec{p}_T \right)$$

Probe for weakly interacting, stable particles in final state, such as: neutrinos, BSM physics (SUSY, dark matter, ...) particles

Missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$



$$\vec{E}_{\mathrm{T}}^{\mathrm{miss}} = -\left(\sum_{e,\mu,\gamma,\tau,\mathrm{jets}} \vec{p}_{\mathrm{T}} + \sum_{\mathrm{soft\ term}} \vec{p}_{\mathrm{T}} \right)$$

Probe for weakly interacting, stable particles in final state, such as: neutrinos, BSM physics (SUSY, dark matter, ...) particles

Object-based $E_{\mathrm{T}}^{\mathrm{miss}}$ significance (I)

Define as likelihood ratio $\mathcal{S}^2$ to test hypothesis that the observed $E_{\mathrm{T}}^{\mathrm{miss}}$ is due to momentum $p_{\mathrm{T}}^{\mathrm{inv}}$ associated to invisible particles:

$$\mathcal{S}^2 = 2\ln\left(\frac{\max_{p_{\mathrm{T}}^{\mathrm{inv}}\neq 0} \mathcal{L}(E_{\mathrm{T}}^{\mathrm{miss}}|p_{\mathrm{T}}^{\mathrm{inv}})}{\max_{p_{\mathrm{T}}^{\mathrm{inv}}=0} \mathcal{L}(E_{\mathrm{T}}^{\mathrm{miss}}|p_{\mathrm{T}}^{\mathrm{inv}})}\right)$$

Corresponds to χ^2 variable assuming Gaussian resolutions with $\mathcal{L}(E_{\mathrm{T}}^{\mathrm{miss}}|p_{\mathrm{T}}^{\mathrm{inv}}) \propto \exp[-1/2\,(E_{\mathrm{T}}^{\mathrm{miss}} - p_{\mathrm{T}}^{\mathrm{inv}})^T (\sum_i V_i)^{-1} (E_{\mathrm{T}}^{\mathrm{miss}} - p_{\mathrm{T}}^{\mathrm{inv}})]$:

$$\mathcal{S}^2 = 2\ln\left(\frac{\mathcal{L}(E_{\mathrm{T}}^{\mathrm{miss}}|E_{\mathrm{T}}^{\mathrm{miss}})}{\mathcal{L}(E_{\mathrm{T}}^{\mathrm{miss}}|0)}\right) = (\vec{E}_{\mathrm{T}}^{\mathrm{miss}})^T \left(\sum_i V_i\right)^{-1} (\vec{E}_{\mathrm{T}}^{\mathrm{miss}})$$

with covariance matrix V_i for each object in $E_{\mathrm{T}}^{\mathrm{miss}}$ calculation.

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with covariance matrix V_i for each object in $E_{\mathrm{T}}^{\mathrm{miss}}$ calculation.

Object-based $E_{\mathrm{T}}^{\mathrm{miss}}$ significance (II)

In coordinate system with parallel (L) and perpendicular (T) axis defined with respect to $\vec{E}_{\mathrm{T}}^{\mathrm{miss}} = (E_{\mathrm{T}}^{\mathrm{miss}}, 0)$:

$$\mathcal{S}^2 = \frac{(E_{\mathrm{T}}^{\mathrm{miss}})^2}{\sigma_L^2(1-\rho_{LT}^2)}$$

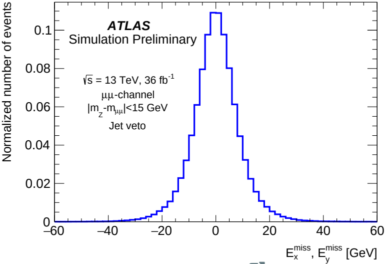
- correlation factor $\rho_{LT} = \frac{\sigma_{LT}^2}{\sqrt{\sigma_L^2\sigma_T^2}}$
- total longitudinal variance $\sigma_L^2 = (\sigma_L^{\mathrm{hard}})^2 + (\sigma_L^{\mathrm{soft}})^2$

hard term resolution:

for $i \in e, \mu, \tau, \gamma$, jets in L-T basis

$$V_i = \begin{pmatrix} \sigma_L & \rho_{LT}\sigma_L\sigma_T \\ \rho_{LT}\sigma_L\sigma_T & \sigma_T \end{pmatrix}$$

soft term resolution: 10 GeV (RMS of $E_{\mathrm{T}}^{\mathrm{miss}}$ components)



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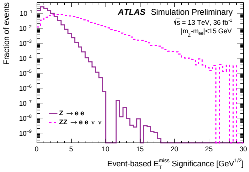
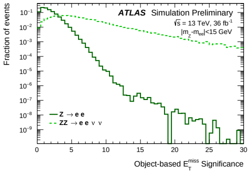
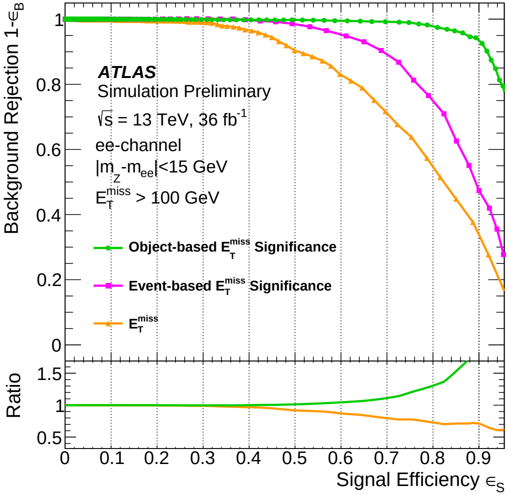
Object-based E_T^{miss} significance performance

Signal: $ZZ \rightarrow e\bar{e}\,\nu\bar{\nu}$
Background: $Z \rightarrow e\bar{e}$







Strong fake E_T^{miss} rejection while maintaining high signal efficiency

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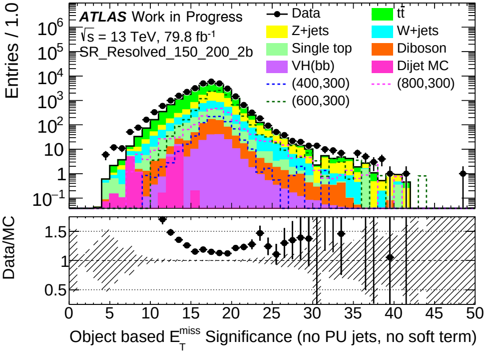
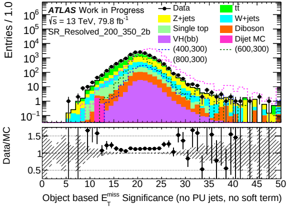
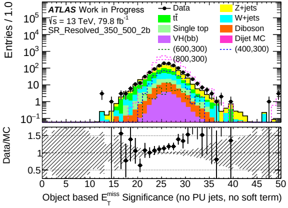
Object-based E_T^{miss} significance distributions



$(150\ \mathrm{GeV} < E_T^{miss} < 200\ \mathrm{GeV})$



$(200\ \mathrm{GeV} < E_T^{miss} < 350\ \mathrm{GeV})$



$(350\ \mathrm{GeV} < E_T^{miss} < 500\ \mathrm{GeV})$

Study of different object-based E_T^{miss} significance cut values

Objective: find cut value with no significance degredation

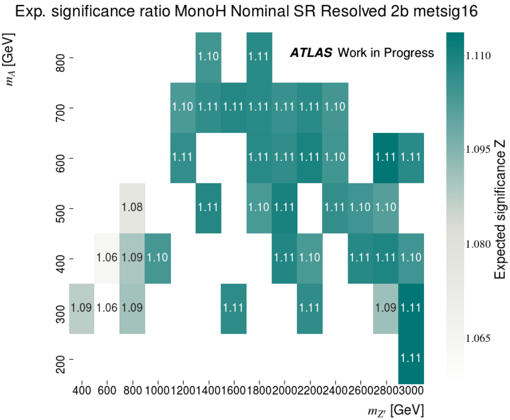
Study expected significance

$$Z = \sqrt{2\left((s+b)\ln\left(1+\frac{s}{b}\right)-s\right)}$$

and compare ratio

$$\frac{Z(\text{cut applied})}{Z(\text{no cut})}$$

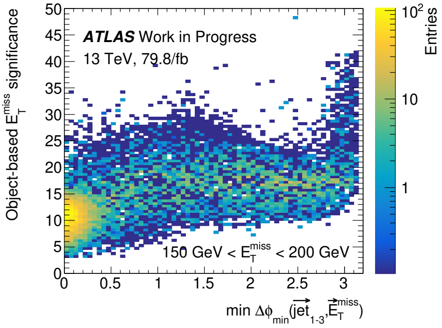
to find optimal cut.



Choice of cut: object-based E_T^{miss} significance $\mathcal{S} > 16$

Multijet estimate

Estimate residual multijet event yield after object-based E_T^{miss} significance and other anti-QCD cuts with ABCD method:



- Define regions A,B,C by cut values on min $\Delta\phi(j_{1,2,3}, E_T^{\text{miss}})$ and $\mathcal{S}$
- Multijet yield prediction for signal region (SR):

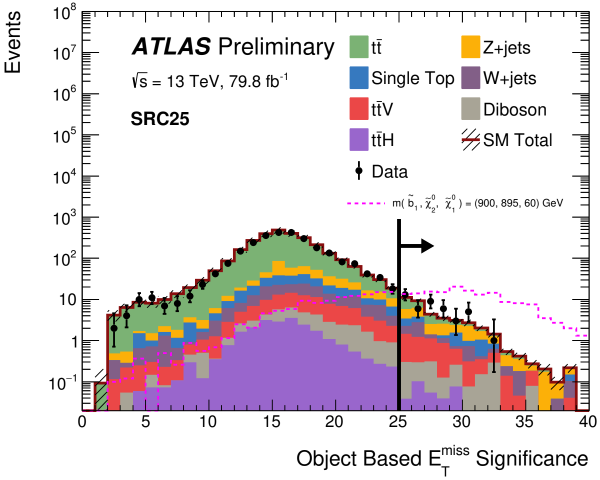
$$N_{SR} = \frac{N_B \cdot N_C}{N_A}$$

Predicted numbers of multijet background events in each region:

Region	150 GeV $< E_T^{\text{miss}} <$ 200 GeV	200 GeV $< E_T^{\text{miss}} <$ 350 GeV	350 GeV $< E_T^{\text{miss}} <$ 500 GeV
Multijet yield	38 ± 17	14 ± 22	0.1 ± 81

$\Rightarrow$ negligible since smaller than data statistical uncertainty

E_T^{miss} significance in sbottom multi-b jet search



Object-based E_T^{miss} requirement $\mathcal{S} > 25$ in signal region event selection to reject Standard Model background,

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