Search for Dark Matter Produced in Association with a Higgs Boson Decaying to $b\bar{b}$ with ATLAS

Efe Yigitbasi
Boston University

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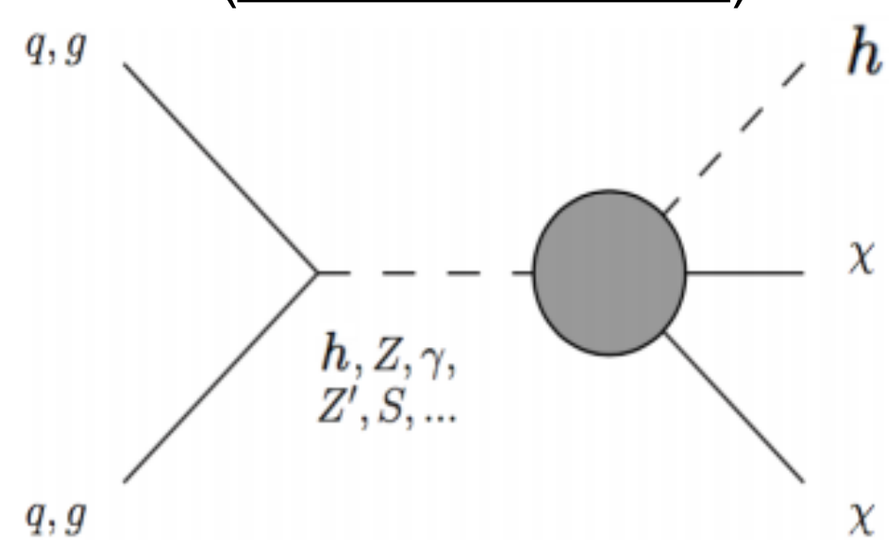
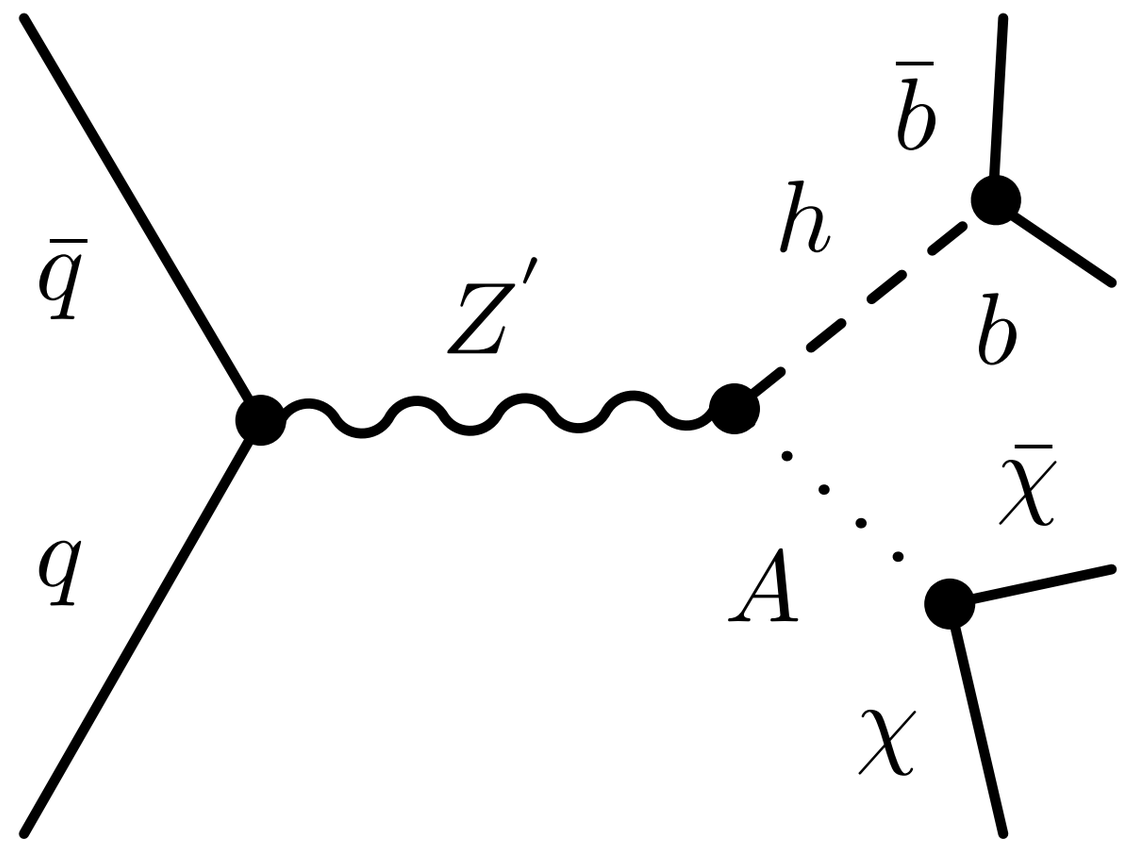
Introduction

- Dark Matter (DM) comprises most of the matter in the universe:
  - A candidate for DM is a stable electrically neutral particle χ whose interactions with standard model (SM) particles are weak.
- DM production at colliders:
  - Missing Transverse Momentum (E_T^{miss}) from DM particles χ recoiling against SM particles: $X+E_T^{miss}$ signature.
  - SM particles are typically radiated from initial state.
    - Mono-Higgs ($h+E_T^{miss}$) directly probes the hard interaction involving DM production.
  - This talk:
    - Mono-h($b\bar{b}$) analysis conducted with 36.1 fb^{-1} of *pp* collisions obtained in 2015+2016 at $\sqrt{s}$ = 13 TeV with the ATLAS detector (arXiv:1707.01302).
      - Mono-h($b\bar{b}$) analysis with only 2015 data (arXiv:1609.04572v2).



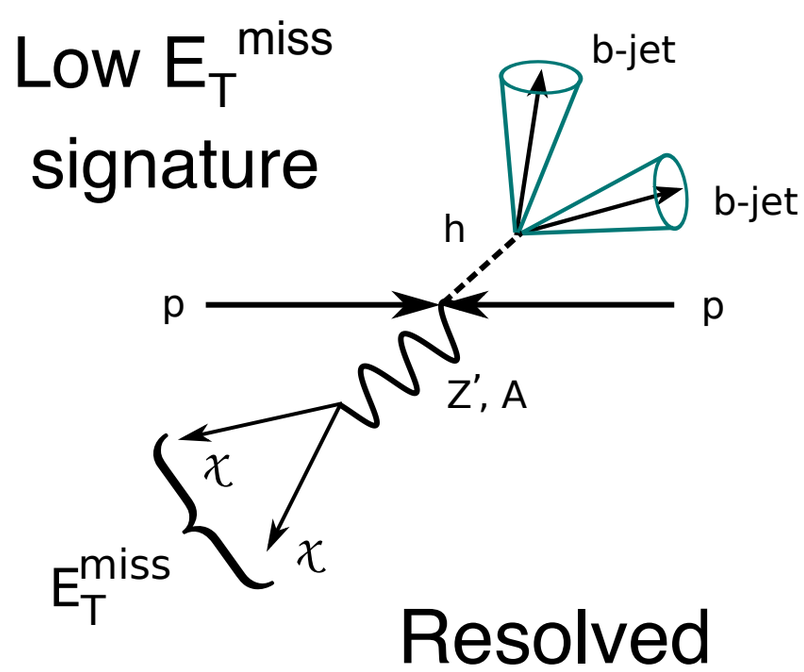
Dark Matter Signal Model

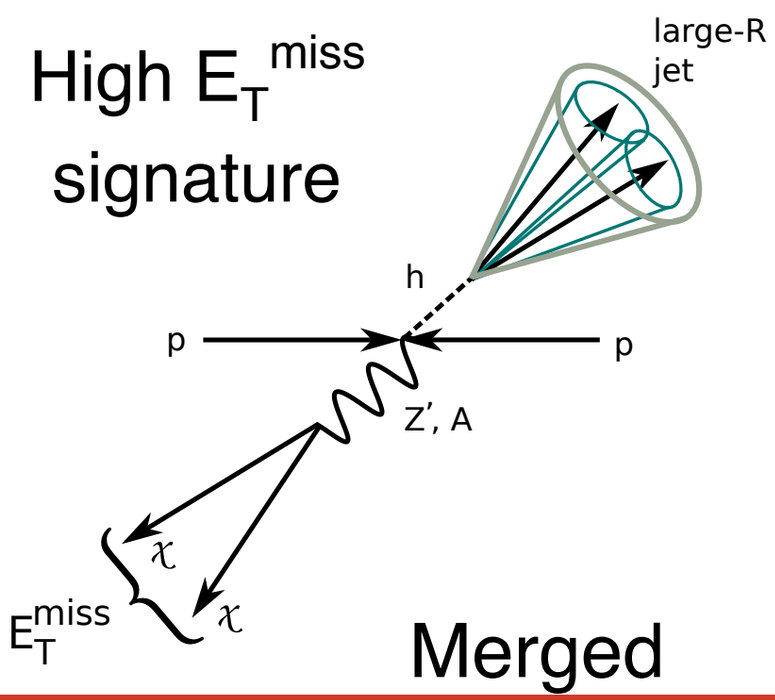
- Two possible approaches for interpretation of data:
  - Using a simplified signal model
  - Interpretation without extra model assumptions
- Simplified signal model:
  - A Z'-2HDM (Type-II) (JHEP06(2014)078):
    - New heavy U(1) gauge boson *Z'*, and a new Higgs doublet
    - After electroweak symmetry breaking:
      - 5 particles: a SM-like Higgs *h,* a pseudo-scalar *A*, a heavy scalar *H*, and two charged scalars $H^{+/-}$.
    - Five free parameters: tanβ, $g_{Z'}$, $m_{Z'}$, m_A, m_χ.
    - BR($A \to \chi\bar{\chi}$) is considered to be large.



Analysis Strategy

- Look for final state: $E_T^{miss} + h(b\bar{b})$ where $E_T^{miss} > 150$ GeV.
- Trigger on large E_T^{miss}: E_T^{miss} trigger threshold is at 110 GeV.
- Using 2 analysis regimes split by E_T^{miss}:
  - Resolved analysis ($E_T^{miss} < 500$ GeV): Decay products of *h* can be resolved into two separate anti-k_t $R = 0.4$ jets (small-*R* jets).
  - Merged analysis ($E_T^{miss} > 500$ GeV): Decay products of *h* are collimated to form a single anti-k_t $R = 1.0$ jet (large-*R* jet).
- Require at least 1 *b*-tagged small-*R* jet (track-jet matched to large-*R* jet) in resolved (merged) analysis.
- Use Higgs candidate mass ($m_{jj/J}$) as the final discriminant:
  - $m_{jj/J}$ is defined as the invariant mass of the dijet system in resolved analysis or the mass of the large-*R* jet in the merged analysis.





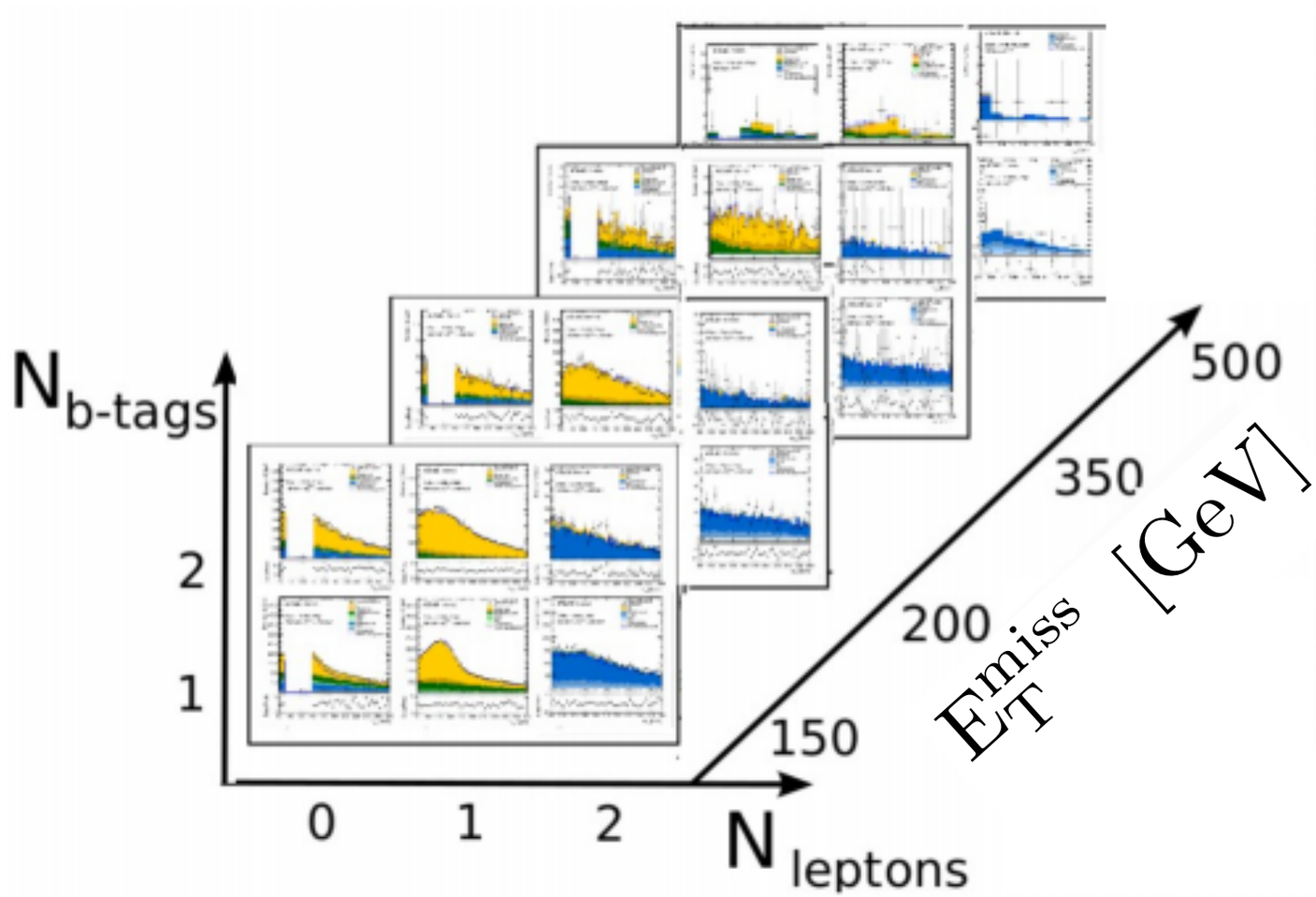
Analysis Strategy

- Normalisations for dominant backgrounds; $Z(\nu\nu)$+jets, W+jets, $t\bar{t}$, are constrained by data in control regions (CR).
- Normalisations for subdominant backgrounds; diboson, Vh, single top-quark, are obtained from Monte Carlo simulations.
- The multijet background was evaluated using a data driven approach.

0 lepton SR	1 muon CR	2 lepton CR
Signal	**Constrain $t\bar{t}$ and W+jets**	**Constrain $Z(\nu\nu)$+jets using $Z(ll)$+jets**

Analysis Strategy

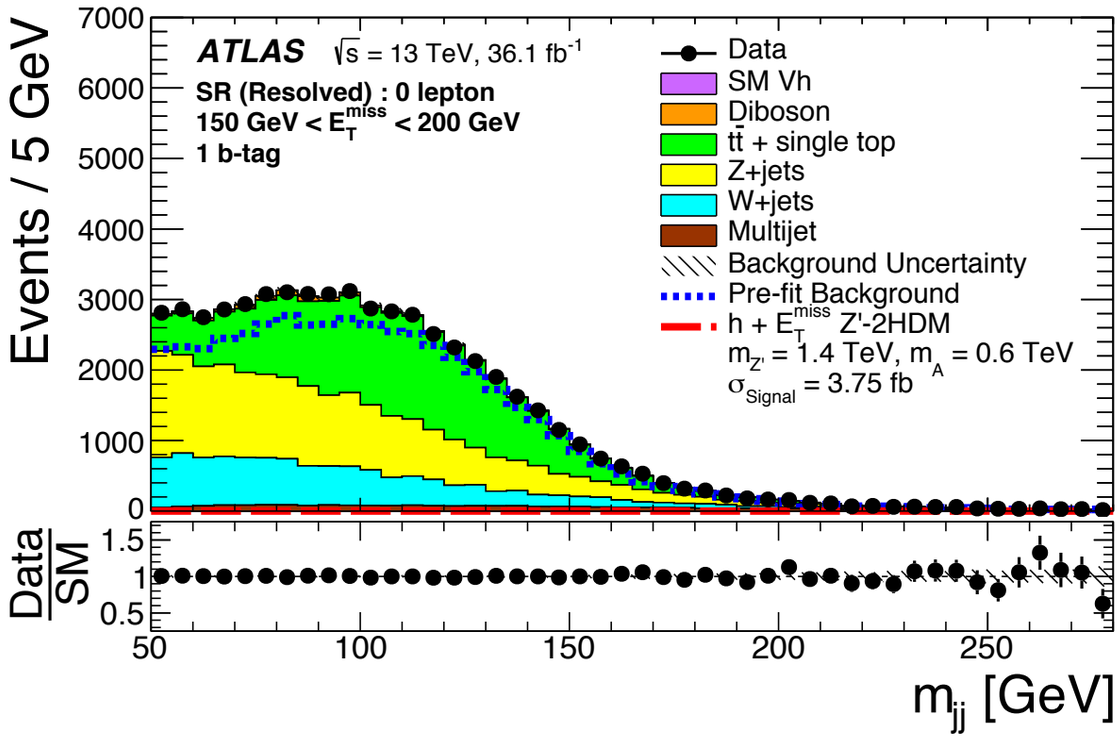
- The resolved analysis is further split into 3 E_T^{miss} regions, and a profile likelihood fit to $m_{jj/J}$ is applied to all analysis regions simultaneously.
  - [150,200) GeV, [200,350) GeV, [350,500) GeV, [500,∞) GeV
- Modelling and systematic uncertainties were considered as nuisance parameters for the fit.
  - The dominant sources of uncertainties are given in the table below for three representative points in ($m_{Z'}$, m_A) phase space.
    - (a): (0.6 TeV, 0.3 TeV), (b): (1.4 TeV, 0.6 TeV), (c): (2.6 TeV, 0.3 TeV)

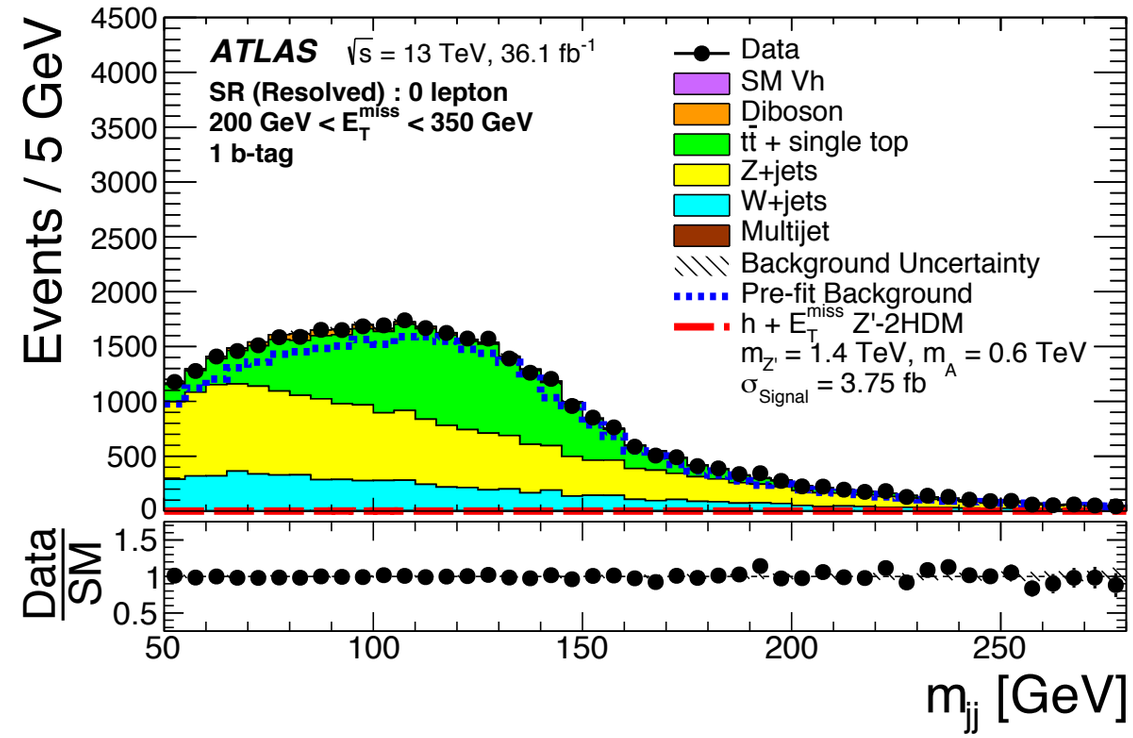


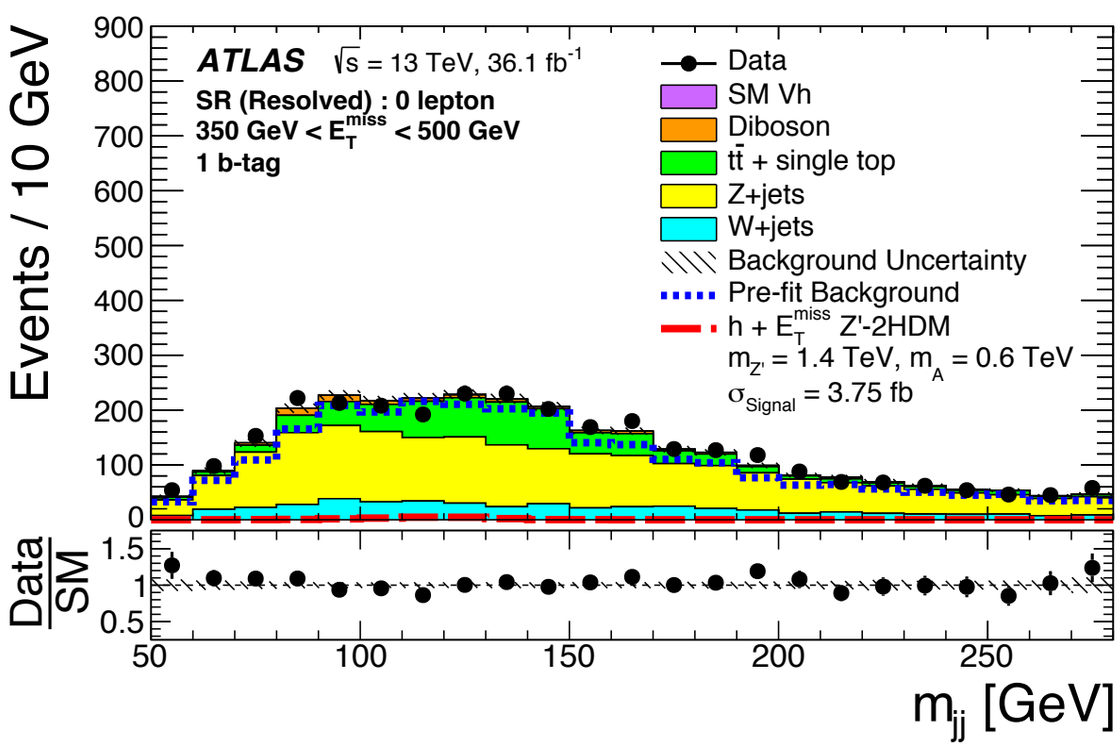
Source of uncert.	Impact [%] (a)	(b)	(c)
V+jets modeling	5.0	5.7	8.2
$t\bar{t}$, single-t modeling	3.2	3.0	3.9
SM $Vh(b\bar{b})$ norm.	2.2	6.9	6.9
Signal modeling	3.9	2.9	2.1
MC statistics	4.9	11	22
Luminosity	3.2	4.5	5.4
b-tagging, track-jets	1.4	11	17
b-tagging, calo jets	5.0	3.4	4.7
Jets with $R = 0.4$	1.7	3.8	2.1
Jets with $R = 1.0$	<0.1	1.2	4.7
Total syst. uncert.	10	21	36
Statistical uncert.	6	38	62
Total uncert.	12	43	71

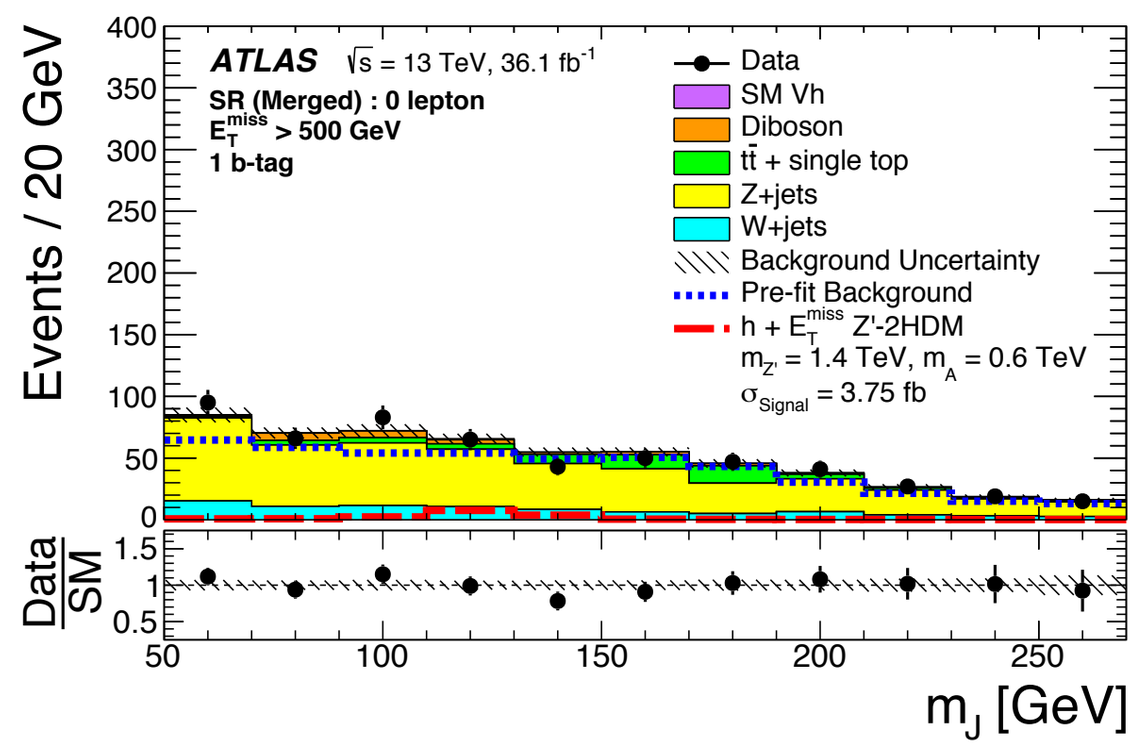
Results

- $m_{jj/J}$ distributions for 0 Lepton SR with 1 *b*-tag:





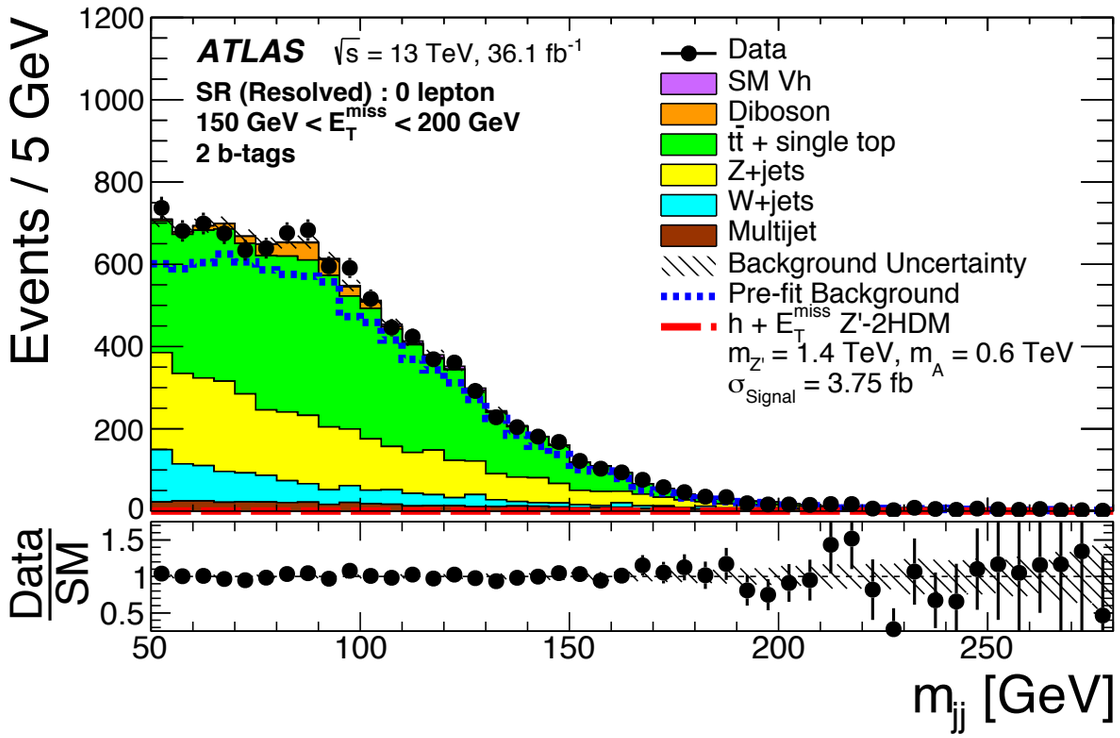


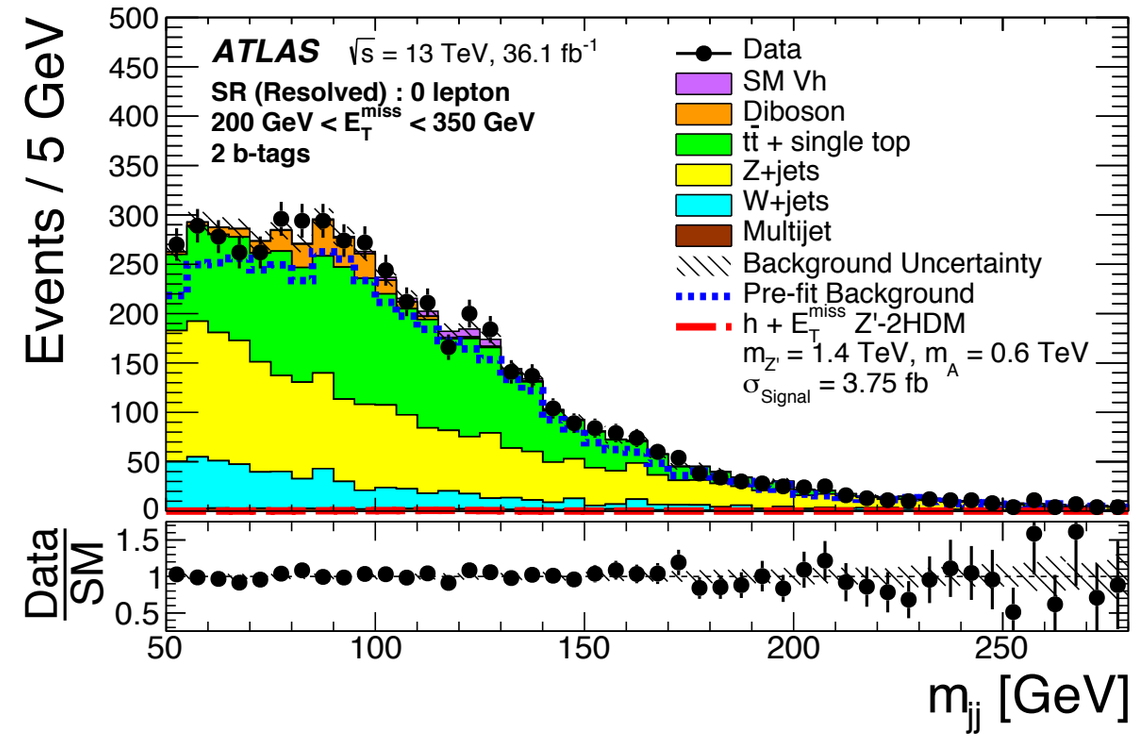


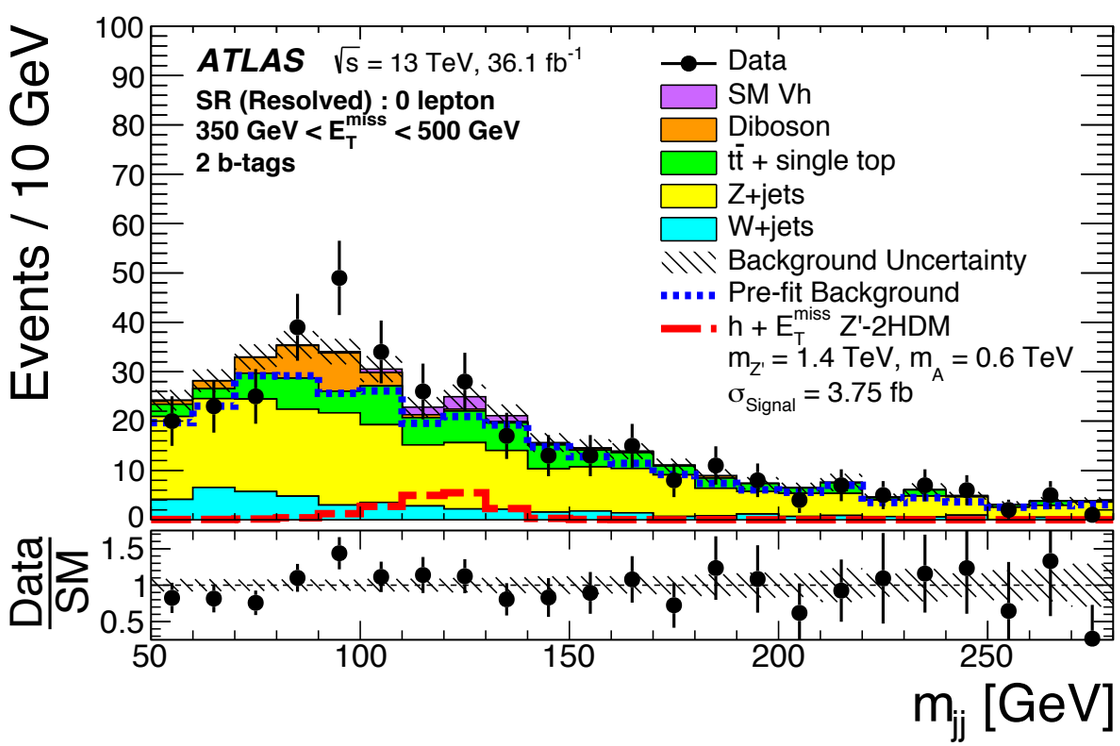
arXiv:1707.01302

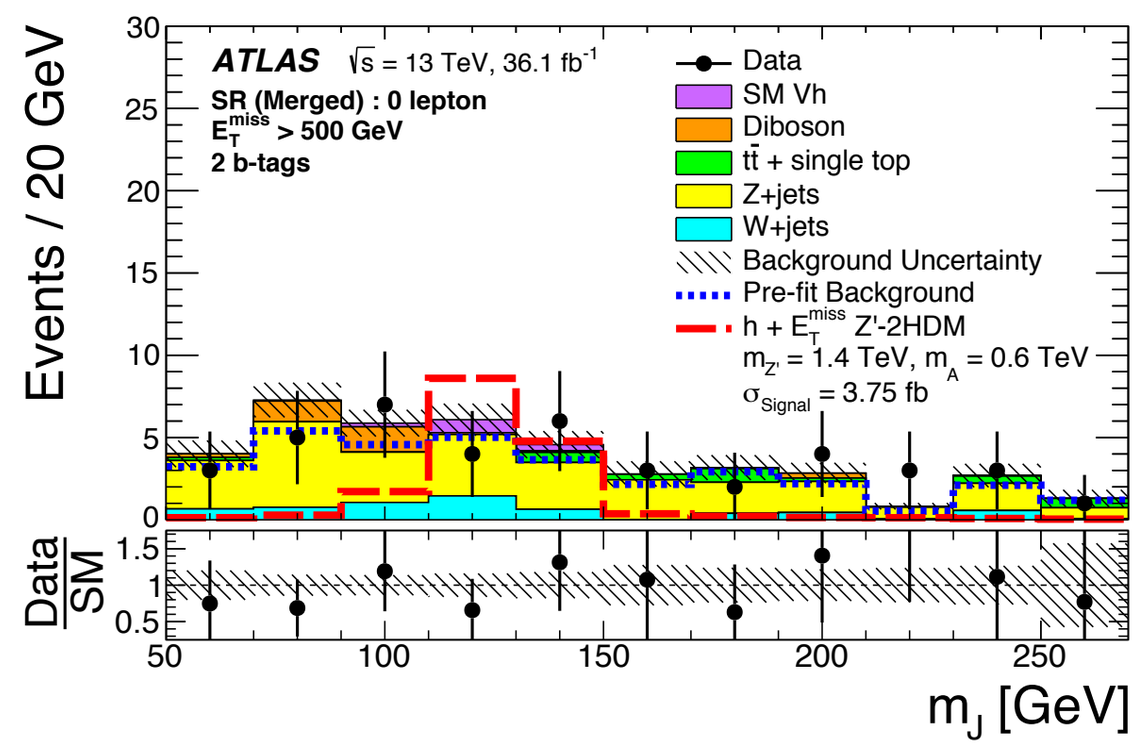
Results

- $m_{jj/J}$ distributions for 0 Lepton SR with 2 *b*-tags:





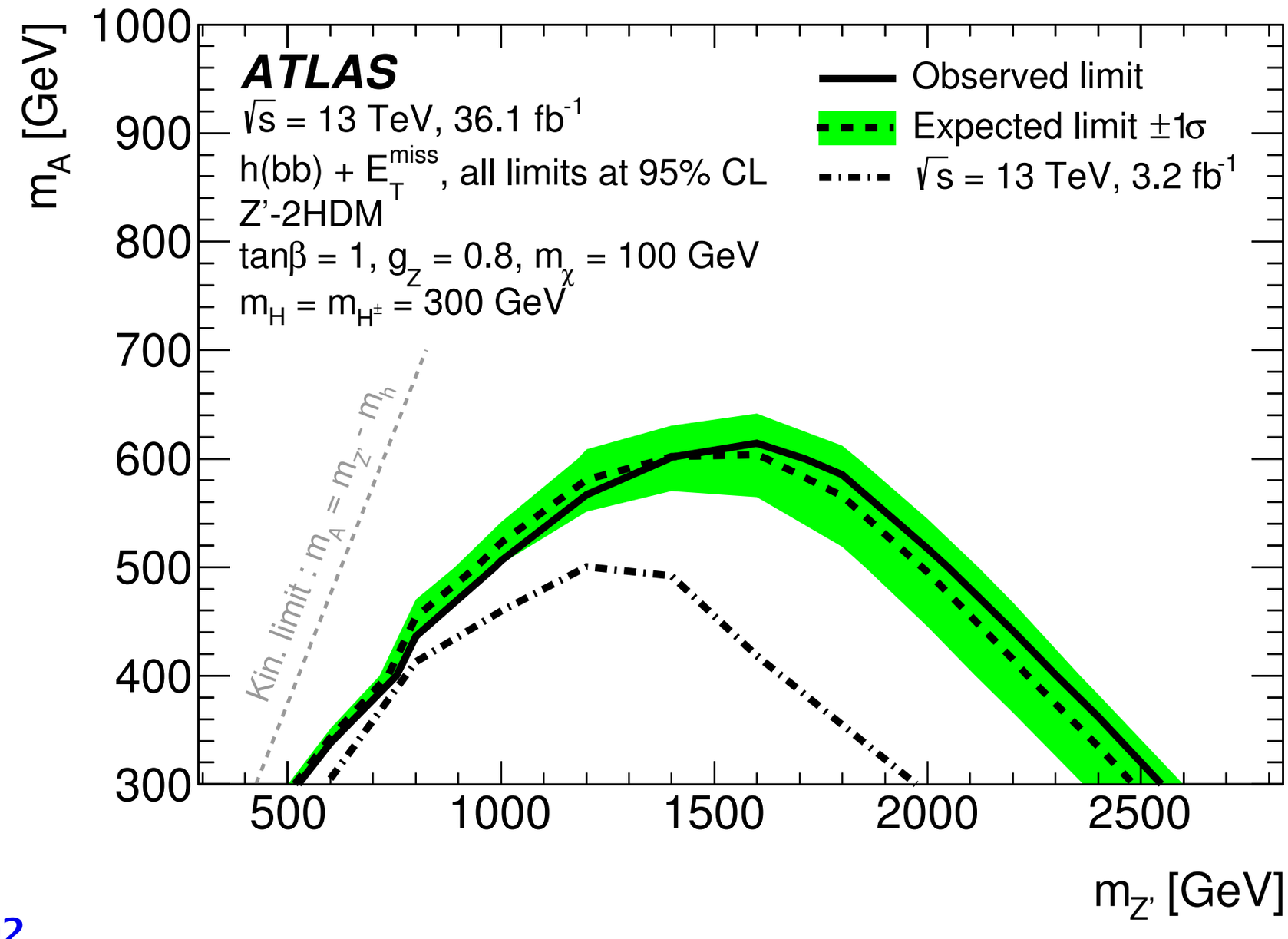




arXiv:1707.01302

Results

- Limits for *Z'*-2HDM signal model with tanβ = 1, $g_{Z'}$ = 0.8, m_χ = 100 GeV as suggested by LHC Dark Matter Forum (arXiv:1507.00966).
  - The masses for other scalar particles *H*, $H^{+/-}$ were fixed at 300 GeV.



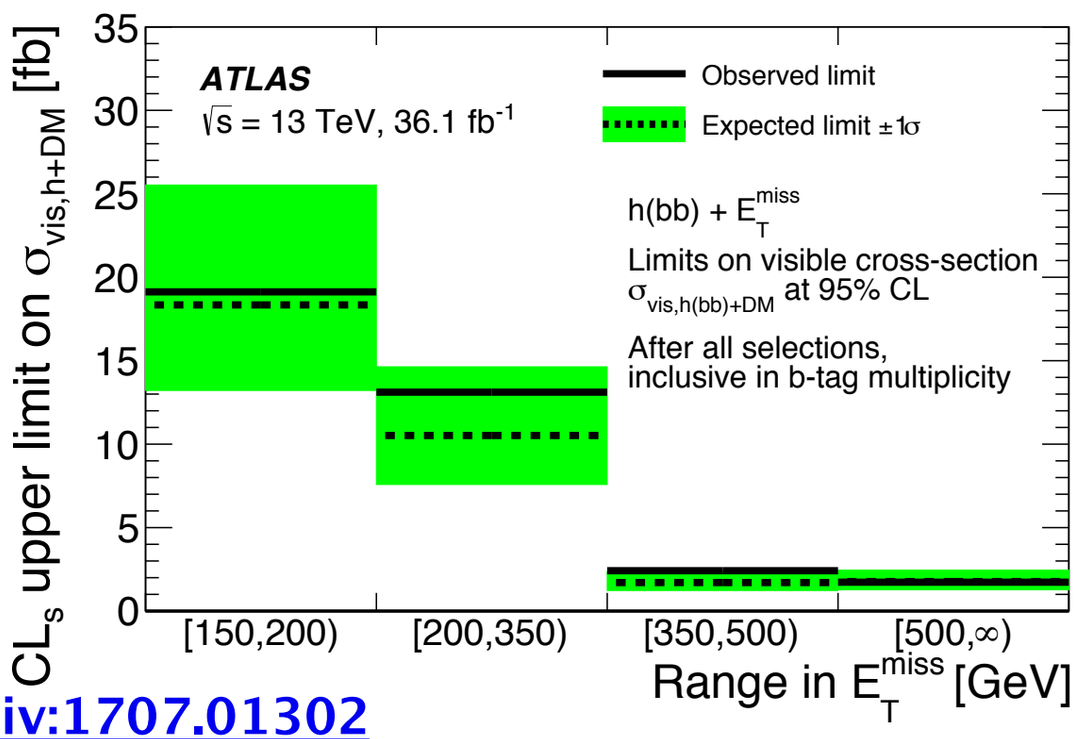
arXiv:1707.01302

Results

- Interpretation of limits without extra model assumptions:
  - Assume SM-like Higgs boson and a back-to-back topology of Higgs and E_T^{miss}.
  - Set limits on visible cross section:

$$\sigma_{\mathrm{vis},h+\mathrm{DM}} = \sigma_{h+\mathrm{DM}} \times \mathrm{BR}\left(h \to b\bar{b}\right) \times \mathcal{A} \times \varepsilon$$

  - Where $\mathcal{A}$ represents kinematic acceptance and $\mathcal{E}$ accounts for experimental efficiency.
    - $\mathcal{A} \times \varepsilon$ term quantifies the probability for an event to be reconstructed in the same E_T^{miss} bin as generated to pass all selections.



Range in E_T^{miss} [GeV]	$\sigma^{obs}_{\mathrm{vis},h(b\bar{b})+\mathrm{DM}}$ [fb]	$\sigma^{exp}_{\mathrm{vis},h(b\bar{b})+\mathrm{DM}}$ [fb]	$\mathcal{A} \times \varepsilon$ [%]
[150, 200)	19.1	$18.3^{+7.2}_{-5.1}$	15
[200, 350)	13.1	$10.5^{+4.1}_{-2.9}$	35
[350, 500)	2.4	$1.7^{+0.7}_{-0.5}$	40
[500, ∞)	1.7	$1.8^{+0.7}_{-0.5}$	55

arXiv:1707.01302

Conclusion

- A search for DM produced in association with a Higgs boson decaying to a $b\bar{b}$ pair was conducted using 36.1 fb^{-1} of *pp* collisions at $\sqrt{s}$ = 13 TeV recorded by the ATLAS detector.
- The results are in agreement with SM expectations and exclude a substantial region of the parameter space for *Z'*-2HDM models.
- Limits are also placed on the production cross section of non-SM events with large E_T^{miss} and a SM-like Higgs boson without extra model assumptions.

BACKUP

Event Selection

Region	SR	1μ-CR	2ℓ-CR
Trigger	E_T^{miss}	E_T^{miss}	Single lepton
Leptons	No e or μ	Exactly one μ	Exactly two e or μ 83 GeV $< m_{ee} <$ 99 GeV 71 GeV $< m_{\mu^\pm\mu^\mp} <$ 106 GeV
Resolved	$E_T^{miss} \in [150, 500)$ GeV $p_T^{miss,trk} > 30$ GeV (1 b-tag only) $\min\left[\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{j}\right)\right] > \pi/9$ $\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{miss,trk}\right) < \pi/2$ –	$p_T(\mu, E_T^{miss}) \in [150, 500)$ GeV $p_T(\mu, \vec{p}_T^{miss,trk}) > 30$ GeV $\min\left[\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{j}\right)\right] > \pi/9$ $\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{miss,trk}\right) < \pi/2$ –	$p_T(\ell, \ell) \in [150, 500)$ GeV – – – $E_T^{miss} \times \left(\sum_{jets,leptons} p_T\right)^{-1/2} < 3.5$ GeV$^{1/2}$
	Number of central small-R jets ≥ 2 Leading Higgs candidate small-R jet $p_T > 45$ GeV $H_{T,2j} > 120$ GeV for 2 jets, $H_{T,3j} > 150$ GeV for > 2 jets $\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_{T,h}\right) > 2\pi/3$ Veto on τ-leptons $\Delta R\left(\vec{p}_h^{j_1}, \vec{p}_h^{j_2}\right) < 1.8$ Veto on events with > 2 b-tags Sum of p_T of two Higgs candidate jets and leading extra jet $> 0.63 \times H_{T,\text{all jets}}$ b-tagging : one or two small-R calorimeter jets **Final discriminant = Dijet mass**		
Merged	$E_T^{miss} \geq 500$ GeV $p_T^{miss,trk} > 30$ GeV $\min\left[\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{j}\right)\right] > \pi/9$ $\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{miss,trk}\right) < \pi/2$	$p_T(\mu, E_T^{miss}) \geq 500$ GeV $p_T(\mu, \vec{p}_T^{miss,trk}) > 30$ GeV $\min\left[\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{j}\right)\right] > \pi/9$ $\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{miss,trk}\right) < \pi/2$	$p_T(\ell, \ell) \geq 500$ GeV – – –
	Number of large-R jets ≥ 1 Veto on τ-lepton not associated to large-R jet Veto on b-jets not associated to large-R jet H_T-ratio selection (<0.57) b-tagging : one or two ID track jets matched to large-R jet **Final discriminant = Large-R jet mass**		

Selection Efficiency - Resolved

- The signal region selection efficiency in the resolved regime for three representative Z'-2HDM signal points:
  - (a) with ($m_{Z'}$, m_A) = (0.6 TeV, 0.3 TeV)
  - (b) with ($m_{Z'}$, m_A) = (1.4 TeV, 0.6 TeV)
  - (c) with ($m_{Z'}$, m_A) = (2.6 TeV, 0.3 TeV)

Selections (resolved)	(a)	(b)	(c)
$E_T^{miss} < 500$ GeV	0.997	0.606	0.022
$E_T^{miss} > 150$ GeV	0.890	0.604	0.022
$p_T^{miss,trk} > 30$ GeV (not for 2 b-tags)	0.711	0.546	0.020
$\min\left[\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{j}\right)\right] > \pi/9$	0.685	0.497	0.017
$\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{miss,trk}\right) < \pi/2$	0.671	0.480	0.016
$N_j \geq 2$	0.658	0.460	0.014
$p_{T,h}^{leading\ j} \geq 45$ GeV	0.655	0.459	0.014
$H_T > 120$ GeV or 150 GeV	0.651	0.459	0.014
$\Delta\phi\left(\vec{p}_h^{j_1}, \vec{p}_h^{j_2}\right) < 7\pi/9$	0.633	0.441	0.012
$\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_{T,h}\right) > 2\pi/3$	0.620	0.439	0.012
τ veto	0.603	0.424	0.012
$\Delta R\left(\vec{p}_h^{j_1}, \vec{p}_h^{j_2}\right) < 1.8$	0.506	0.385	<0.01
b-jet Veto	0.503	0.383	<0.01
H_T-Ratio Cut (0.63)	0.499	0.382	<0.01
$50 < m_{h,reco}/\text{GeV} < 280$	0.481	0.378	<0.01
$N(b\text{-tags}) = 2$	0.246	0.177	<0.01
$N(b\text{-tags}) = 1$	0.197	0.164	<0.01

Selection Efficiency - Merged

- The signal region selection efficiency in the merged regime for three representative Z'-2HDM signal points:
  - (a) with ($m_{Z'}$, m_A) = (0.6 TeV, 0.3 TeV)
  - (b) with ($m_{Z'}$, m_A) = (1.4 TeV, 0.6 TeV)
  - (c) with ($m_{Z'}$, m_A) = (2.6 TeV, 0.3 TeV)

Selections (merged)	(a)	(b)	(c)
$E_T^{miss} > 500$ GeV	<0.01	0.394	0.977
$p_T^{miss,trk} > 30$ GeV (not for 2 b-tags)	<0.01	0.375	0.934
$\min\left[\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{j}\right)\right] > \pi/9$	<0.01	0.358	0.834
$\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{miss,trk}\right) < \pi/2$	<0.01	0.356	0.822
$N_J \geq 1$	<0.01	0.353	0.818
τ Veto	<0.01	0.343	0.798
b-jet Veto	<0.01	0.326	0.782
H_T-Ratio Cut (0.57)	<0.01	0.325	0.782
$50 < m_{h,reco}/\text{GeV} < 270$	<0.01	0.282	0.705
$N(b\text{-tags}) = 2$	<0.01	0.136	0.150
$N(b\text{-tags}) = 1$	<0.01	0.147	0.442

Expected and Observed Yields - 1 *b*-tags

- Numbers of expected background events, and observed data yields for events with 1 *b*-tags are shown.
- The multijet background in the two highest-E_T^{miss} regions is negligible and not included in the fit.
- Statistical and systematic uncertainties are combined.
- The expected signal for a Z'-2HDM model with ($m_{Z'}$, m_A)=(1.4 TeV, 0.6 TeV) for tanβ = 1, $g_{Z'}$=0.8, and m_χ=100 GeV, assuming a production cross-section of 3.75 fb, is also shown.

Category	Range in E_T^{miss} [GeV]			
	[150, 200)	[200, 350)	[350, 500)	[500, ∞)
$t\bar{t}$+single top	23 060 ± 530	13 190 ± 310	614 ± 32	53.7 ± 5.1
W+jets	10 500 ± 1 300	6 620 ± 810	458 ± 58	84.5 ± 14
Z+jets	20 000 ± 1 300	16 200 ± 1 100	1 800 ± 120	383 ± 40
Diboson	644 ± 82	605 ± 79	87.8 ± 12	25.0 ± 3.6
SM $Vh(b\bar{b})$	40 ± 13	39 ± 14	6.3 ± 2.3	1.8 ± 0.7
Multijet	2 310 ± 240	80 ± 99	negligible	negligible
Total Bkg.	56 570 ± 240	36 710 ± 190	2 965 ± 42	548 ± 19
Data	56 611	36 584	3 015	551
Exp. signal	0.2	5.0	18.2	16.9

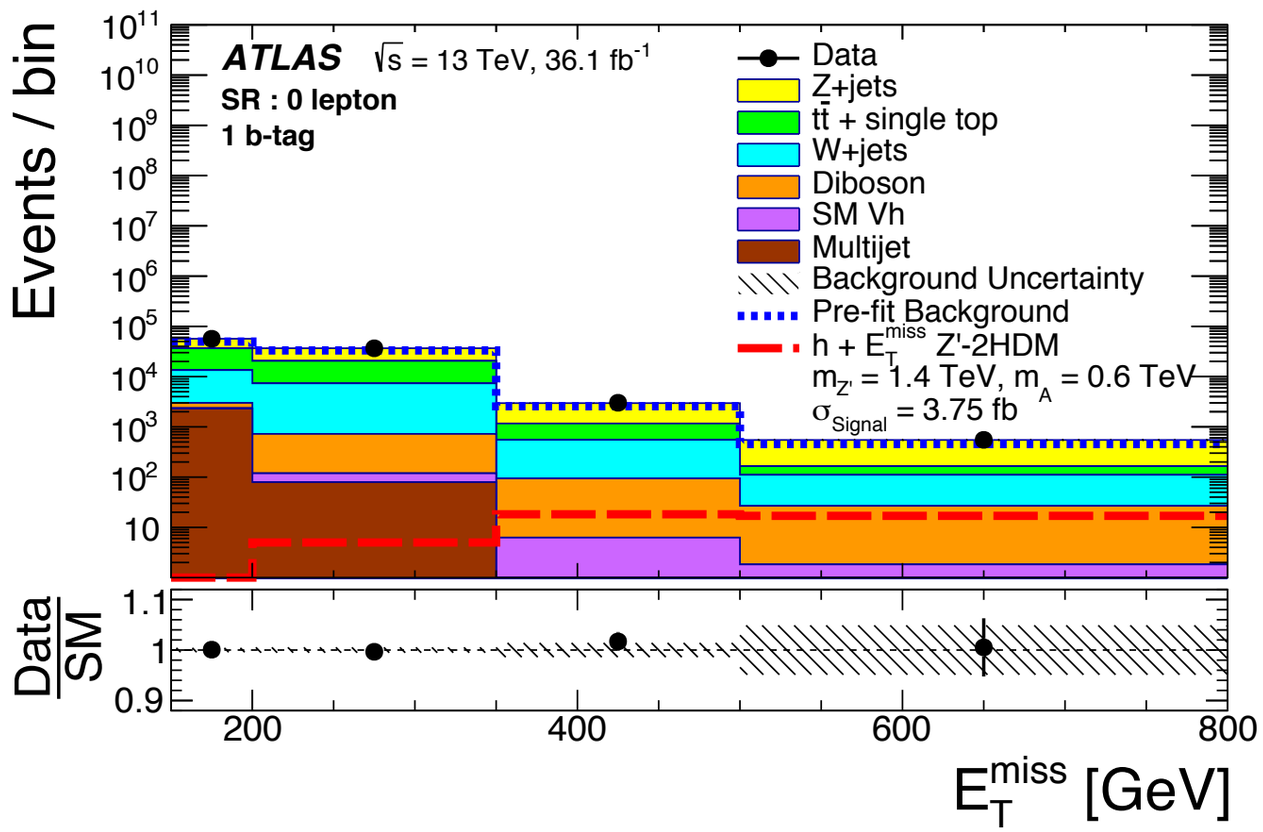
Expected and Observed Yields - 2 *b*-tags

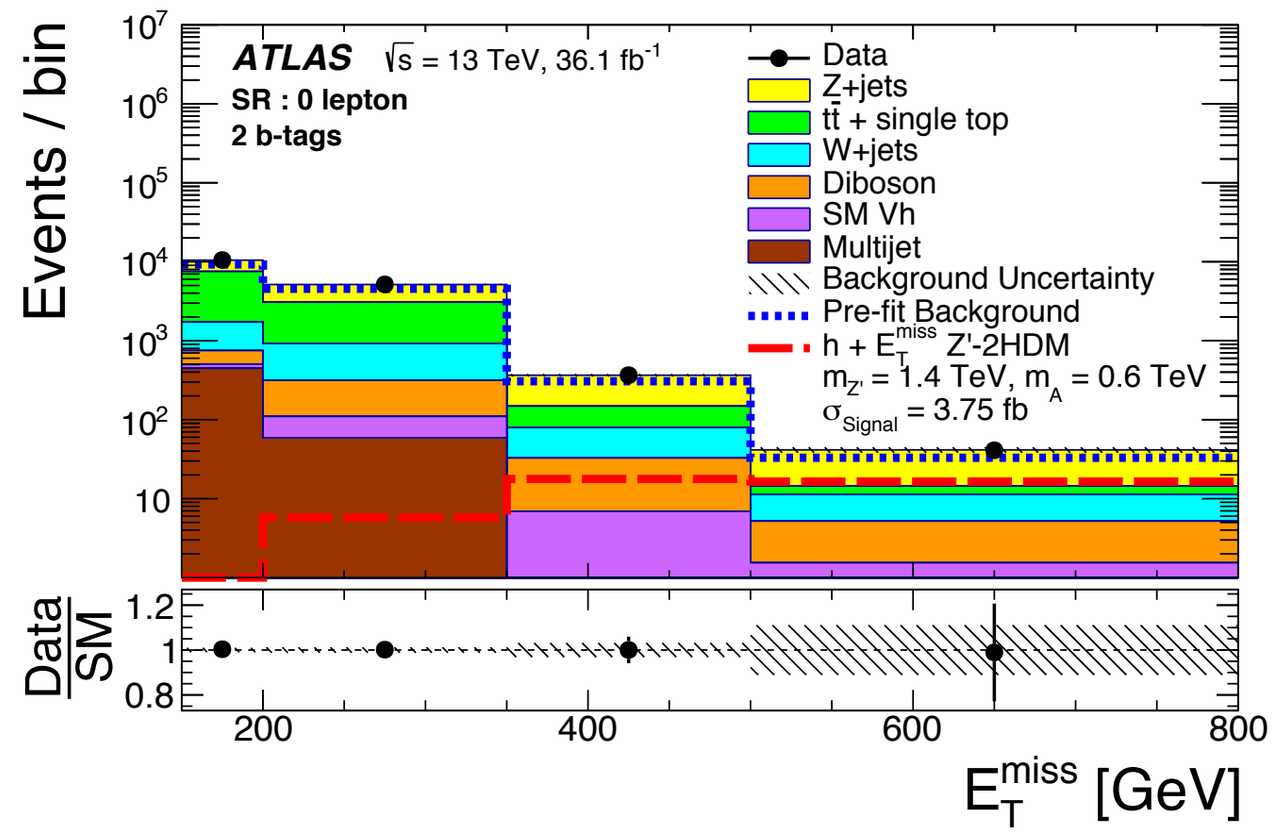
- Numbers of expected background events, and observed data yields for events with 2 *b*-tags are shown.
- The multijet background in the two highest-E_T^{miss} regions is negligible and not included in the fit.
- Statistical and systematic uncertainties are combined.
- The expected signal for a Z'-2HDM model with ($m_{Z'}$, m_A)=(1.4 TeV, 0.6 TeV) for tanβ = 1, $g_{Z'}$=0.8, and m_χ=100 GeV, assuming a production cross-section of 3.75 fb, is also shown.

Category	Range in E_T^{miss} [GeV]			
	[150, 200)	[200, 350)	[350, 500)	[500, ∞)
$t\bar{t}$+single top	5 820 ± 170	2 160 ± 76	69.2 ± 4.8	3.17 ± 0.66
W+jets	973 ± 170	605 ± 110	46.6 ± 8.7	6.1 ± 1.2
Z+jets	2 940 ± 190	2 070 ± 130	217 ± 13	27.0 ± 2.4
Diboson	247 ± 30	205 ± 25	25.8 ± 3.2	3.65 ± 0.62
SM $Vh(b\bar{b})$	56 ± 17	51 ± 18	6.9 ± 2.6	1.54 ± 0.64
Multijet	448 ± 120	59 ± 46	negligible	negligible
Total Bkg.	10 500 ± 100	5 150 ± 62	366 ± 12	41.4 ± 3.3
Data	10 514	5 160	366	41
Exp. signal	0.3	5.8	17.7	16.4

Results - E_T^{miss}

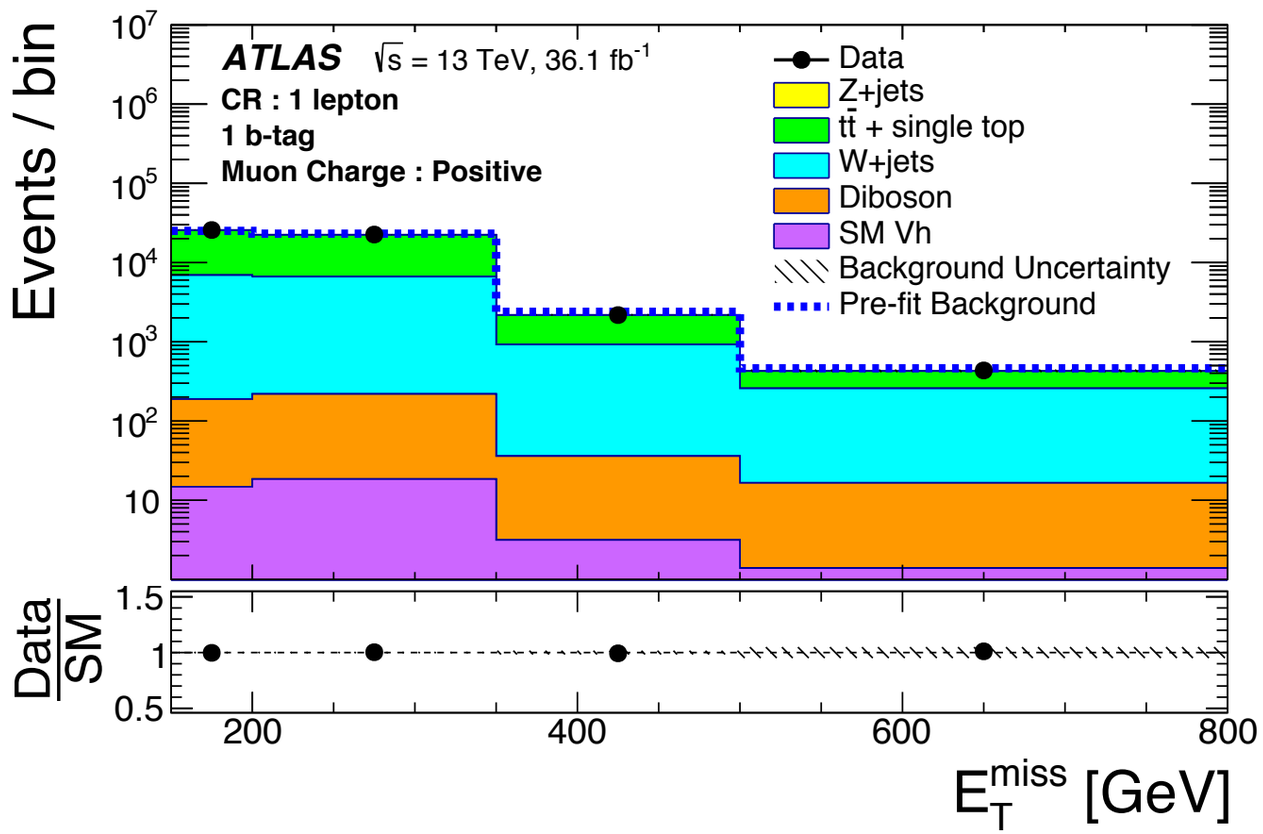
- Postfit E_T^{miss} distributions for 0 Lepton SR using events with 1 *b*-tags (left) or 2 *b*-tags (right):

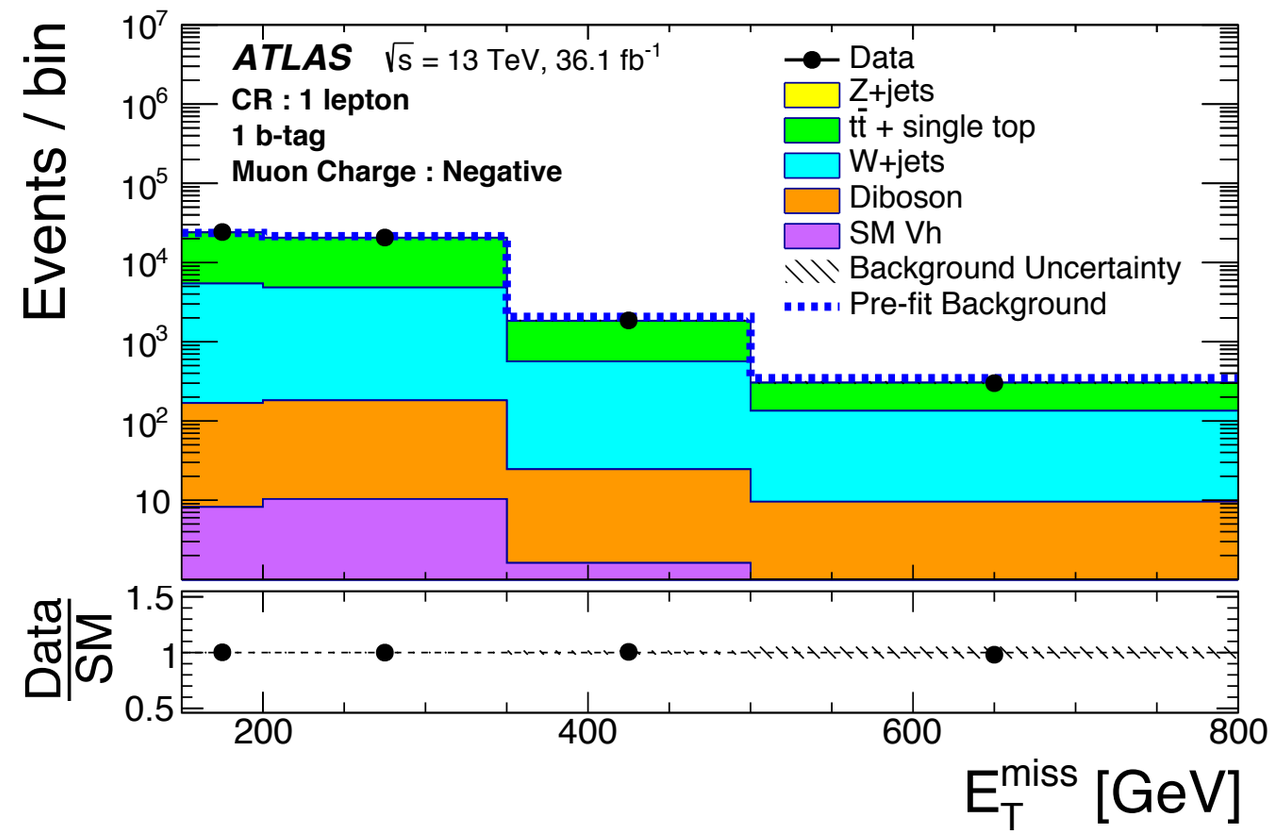




Results - E_T^{miss} - 1 Muon CR

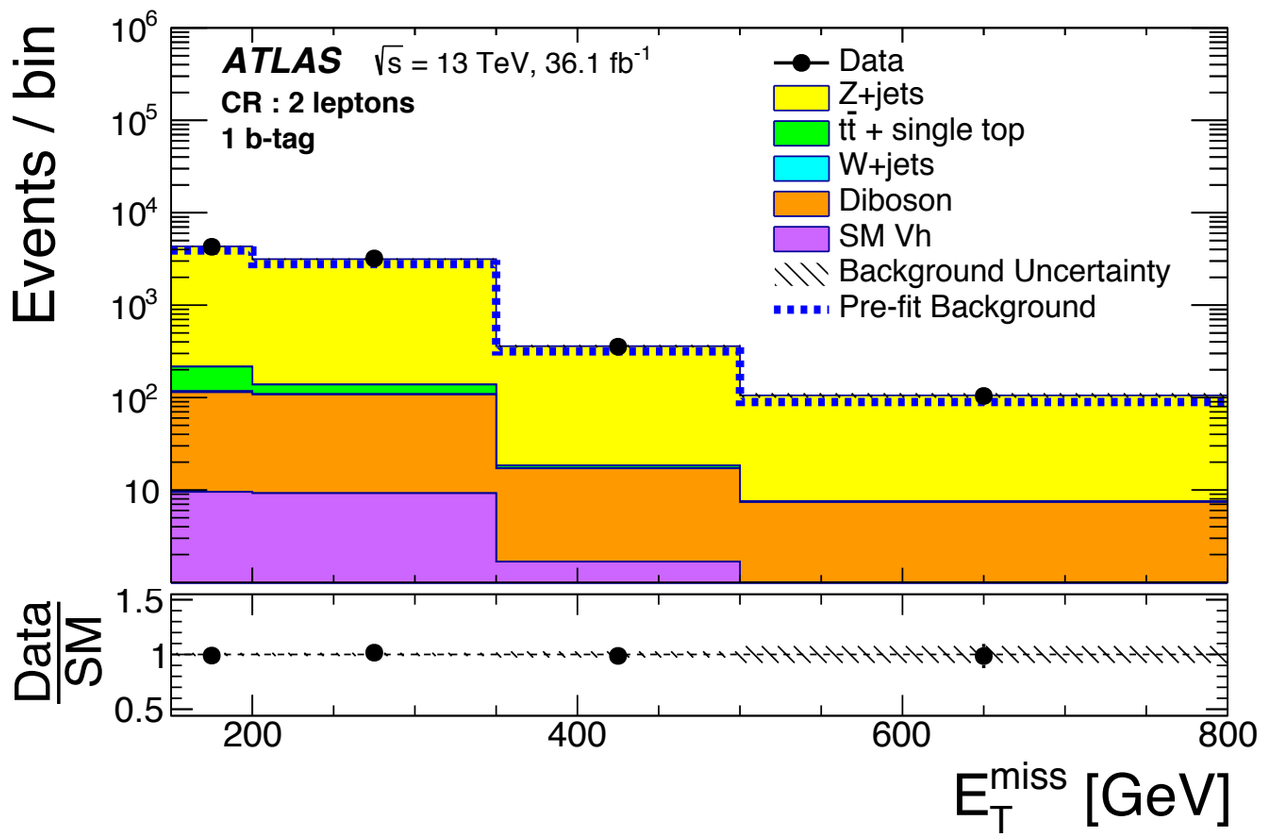
- Postfit E_T^{miss} distributions for 1 Muon CR using events with 1 *b*-tags and when muon charge is positive (left) or negative (right):

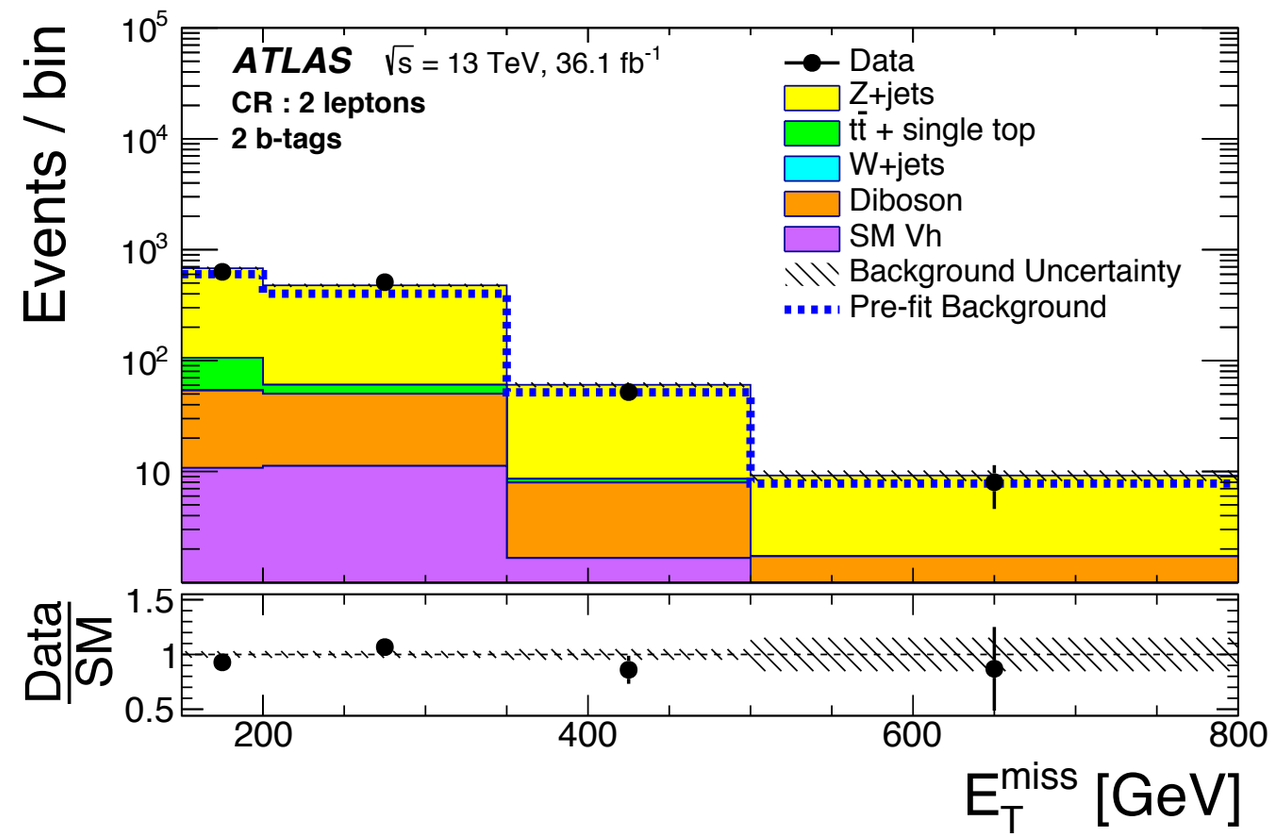




Results - E_T^{miss} - 2 Lepton CR

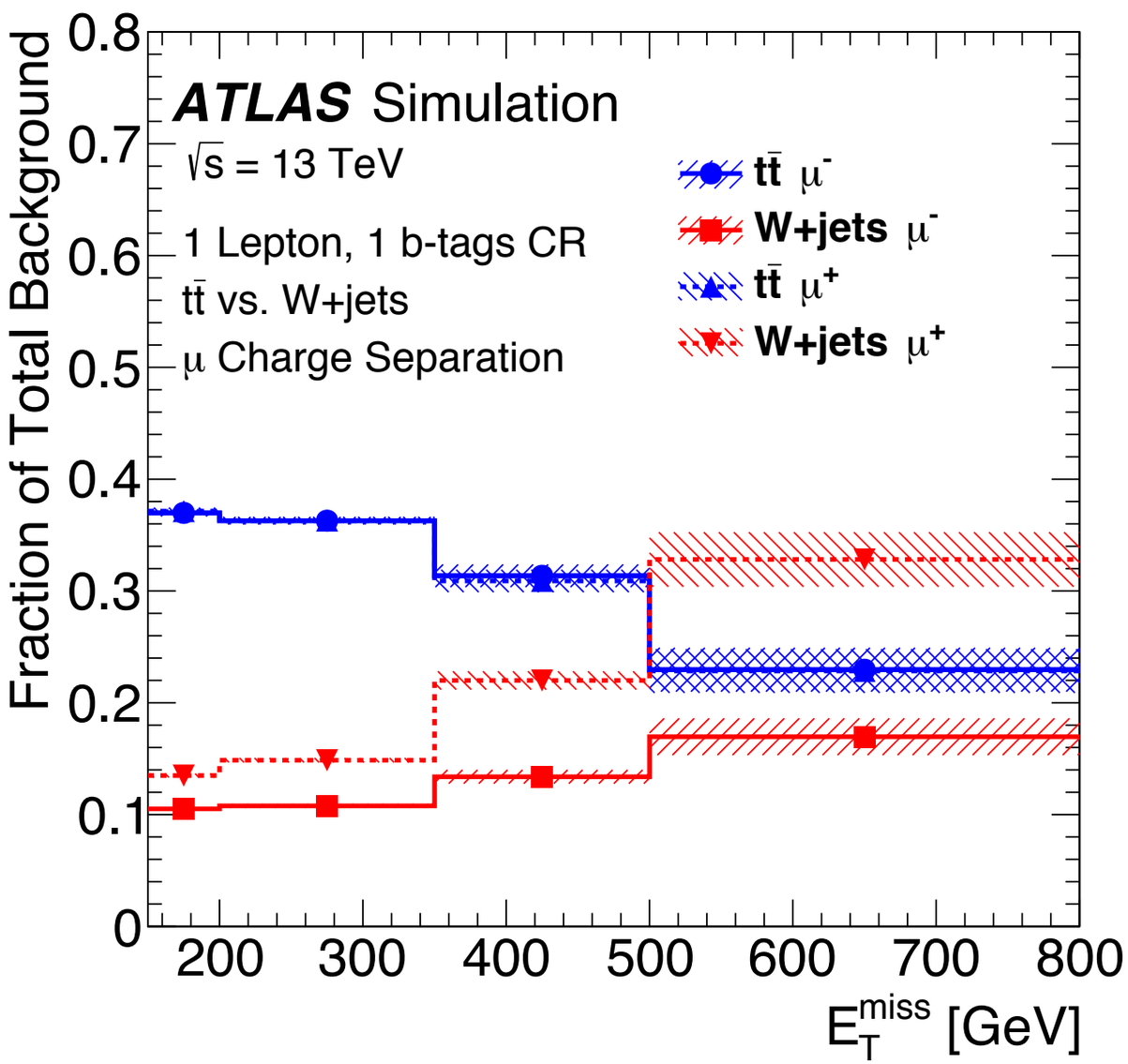
- Postfit E_T^{miss} distributions for 2 Lepton CR using events with 1 *b*-tags (left) and 2 *b*-tags (right):

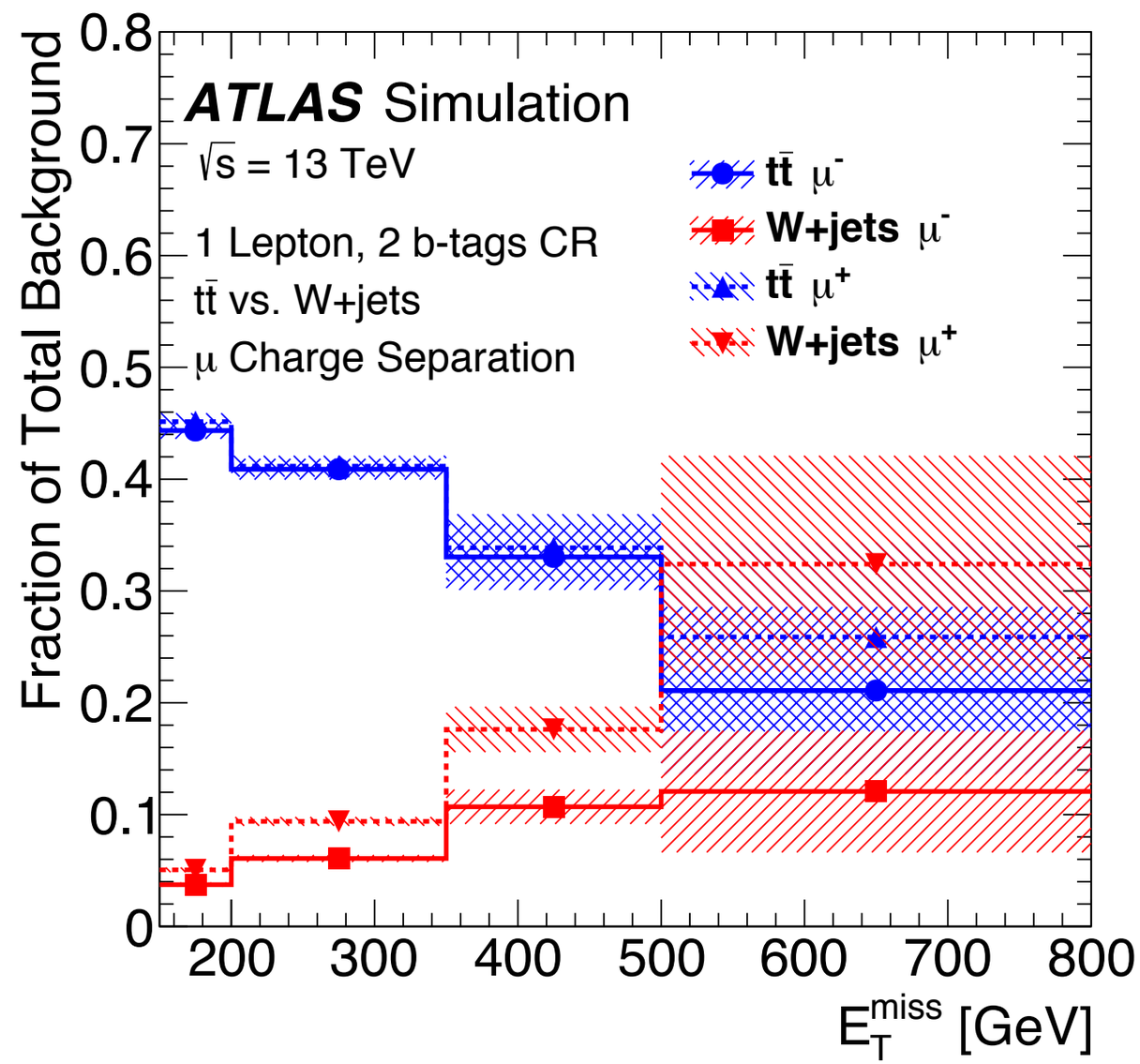




1 Muon CR

- Fraction of the $t\bar{t}$ and W+jets processes to the total sum of backgrounds as a function of E_T^{miss} for events with 1 (left) and 2 (right) b-tags in the 1μ-CR. While $t\bar{t}$ is symmetric in the muon charge, W+jets shows an asymmetry which allows to separate the two processes.





Limits Without Model Assumptions

- Product of kinematic acceptance and experimental efficiency, however without the requirement that an event be reconstructed in the same E_T^{miss} range as generated, for three representative Z'-2HDM models considered in this analysis.

$(m_{Z'}, m_A)$ [GeV]	Range in E_T^{miss} [GeV]			
	$[150, 200)$	$[200, 350)$	$[350, 500)$	$[500, \infty)$
(600, 300)	18.3%	12.9%	0.3%	< 0.1%
(1400, 600)	0.4%	8.4%	28.5%	31.7%
(2600, 300)	< 0.1%	0.2%	0.7%	77.5%