Using $t\bar{t}$ and missing energy to search for new physics

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Motivation

- We know that new physics exists (dark matter, SUSY…) but we don't know where it might appear
- Top quarks are a good place to look due to their mass (strong coupling to Higgs or new scalar particles)
- Useful to test the feasibility of doing a general search for this new physics through $t\bar{t}$ decays to invisible particles to see if this is actually possible at the LHC

Method

- Use the existing search for SUSY particles and adapt it to look for $\mathbf{t\bar{t}Z(\rightarrow \nu\bar{\nu})}$ decays
- Can reduce the associated uncertainties by taking the ratio of $\frac{\sigma(t\bar{t}Z(\rightarrow \nu\bar{\nu}))}{\sigma(t\bar{t}Z(\rightarrow l\bar{l}))}$ because the uncertainties are correlated, so $\mathbf{t\bar{t}Z(\rightarrow l\bar{l})}$ was also investigated
- This can also be compared to branching ratios to indicate whether the Standard Model is incomplete...

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DESY

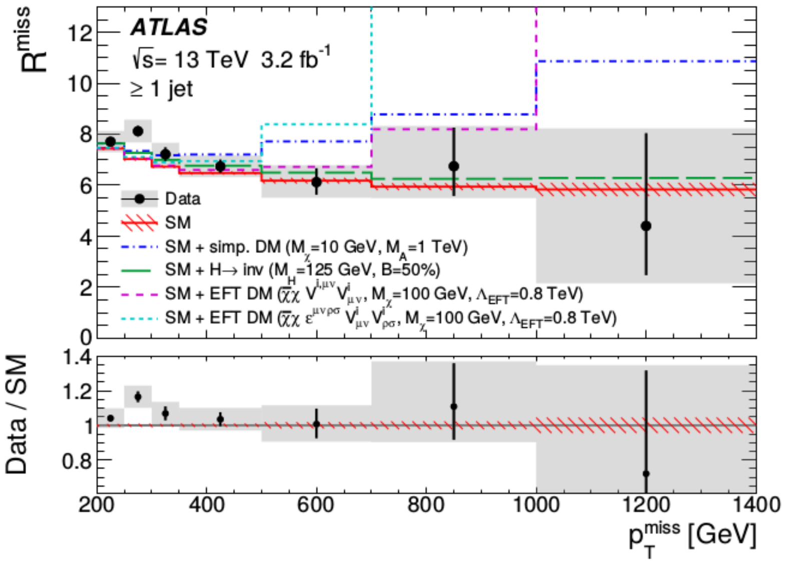
Theory

A hint at new physics

- If the Standard Model holds, then $\frac{\sigma(t\bar{t}Z(\rightarrow \nu\bar{\nu}))}{\sigma(t\bar{t}Z(\rightarrow l\bar{l}))} = \frac{BR(t\bar{t}Z(\rightarrow \nu\bar{\nu}))}{BR(t\bar{t}Z(\rightarrow l\bar{l}))} \approx 6$

- If invisible particles are produced (e.g. dark matter via **t $\bar{\mathbf{t}}$ $\mathbf{m_{\Phi}}$(→X $\bar{\mathbf{X}}$)**), then

$$\frac{\sigma(t\bar{t}Z(\rightarrow \nu\bar{\nu}))}{\sigma(t\bar{t}Z(\rightarrow l\bar{l}))} = \frac{BR(t\bar{t}Z(\rightarrow \nu\bar{\nu})) + BR(t\bar{t}m_{\phi}(\rightarrow \chi\bar{\chi}))}{BR(t\bar{t}Z(\rightarrow l\bar{l}))} \neq 6$$

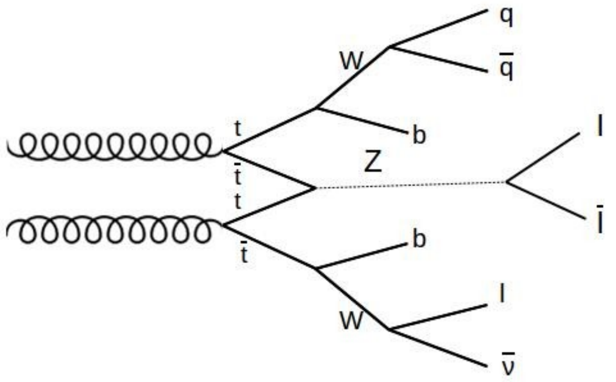


- Inspired by a similar study in which $\frac{\sigma(jet + Z(\rightarrow \nu\bar{\nu}))}{\sigma(jet + Z(\rightarrow l\bar{l}))}$ was measured and compared to the branching ratio

- Want to test the feasibility of using $\frac{\sigma(t\bar{t}Z(\rightarrow \nu\bar{\nu}))}{\sigma(t\bar{t}Z(\rightarrow l\bar{l}))}$ to find new physics

So t$\bar{\text{t}}$Z(→ l $\bar{\text{l}}$) was also studied (where l = electron or muon)

- Background interactions include single top, t$\bar{\text{t}}$, diboson, Z + jets and t$\bar{\text{t}}$Z
- Used to look for the decay
- Similar signature (jets and missing transverse energy)



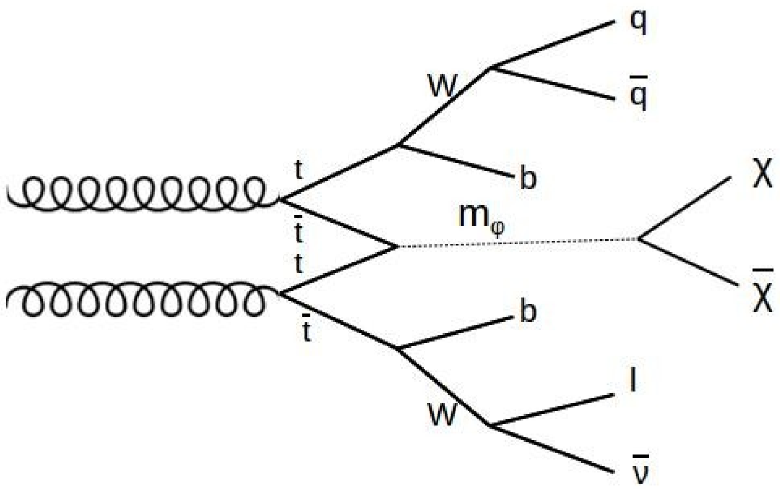
Channels of interest

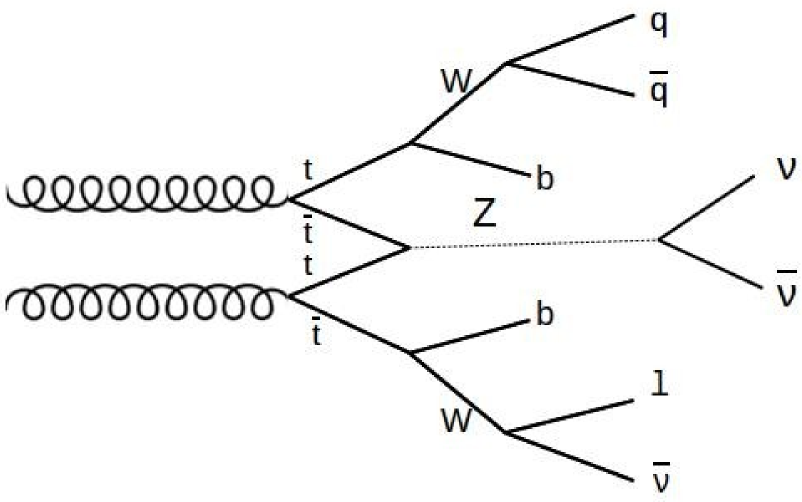
Production of dark matter

- Mediated by a spin 0 or spin 1 boson (m_Φ)
- $X\bar{X}$ are a pair of dark matter fermions

$t\bar{t}Z(\rightarrow \nu\bar{\nu})$

- Background interaction
- Used to look for the decay
- Similar signature (jets and missing transverse energy)





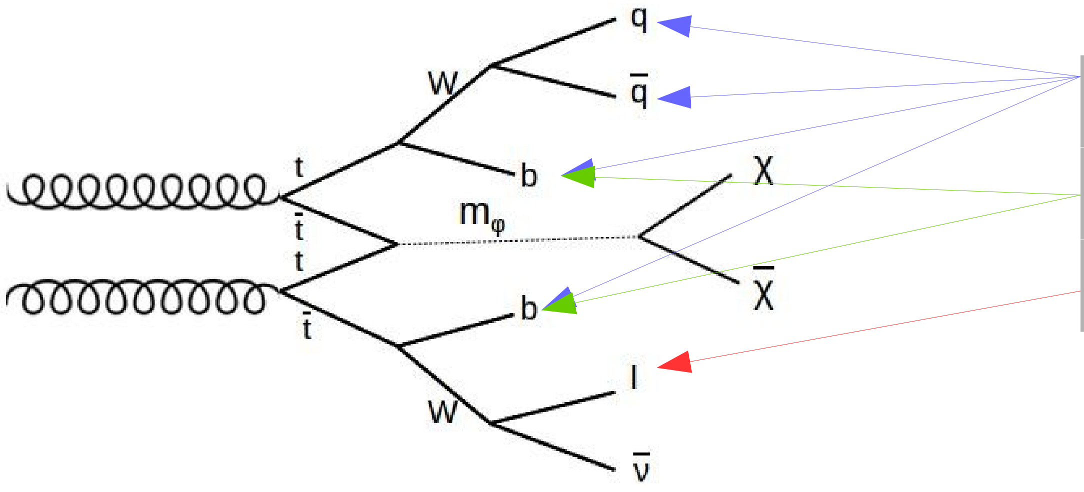
Other background decays

- Decays to a single top, $t\bar{t}$, diboson, W + jets, Z + jets and $t\bar{t}V$ (where V is a W or Z boson)

Analysis

Preselection level

- These are the first selections applied and they are applied to all signal regions.



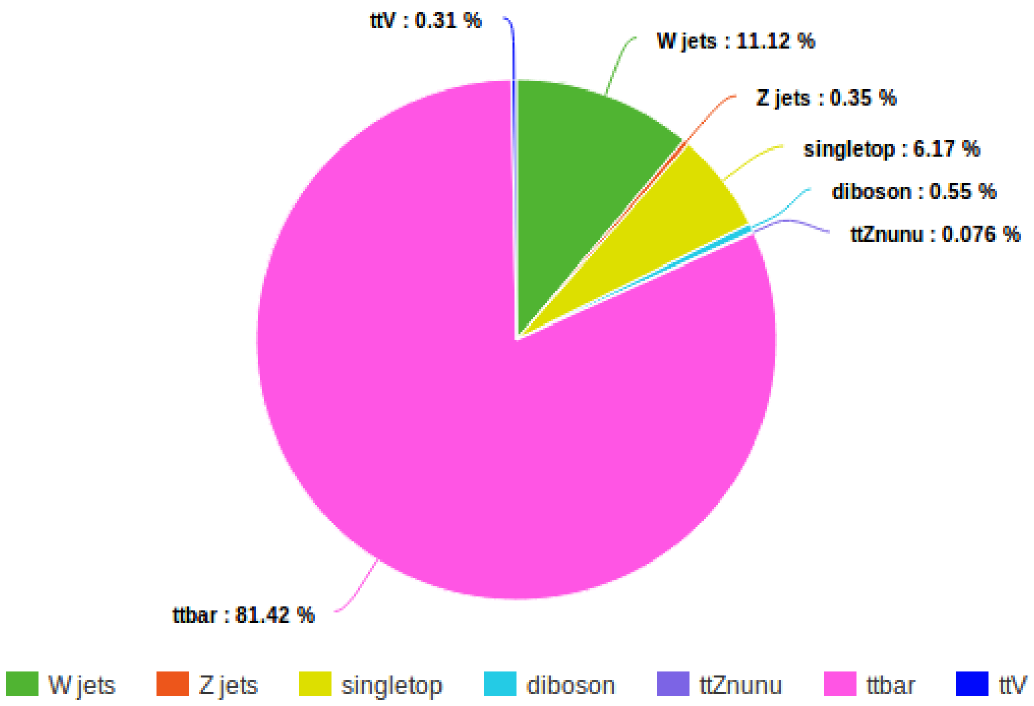
Number of jets	> 4
Number of b-tags	> 1
Number of leptons	1

- This selection ensures one W boson decays leptonically and one to a quark/antiquark pair to make signal clearer.

Analysis

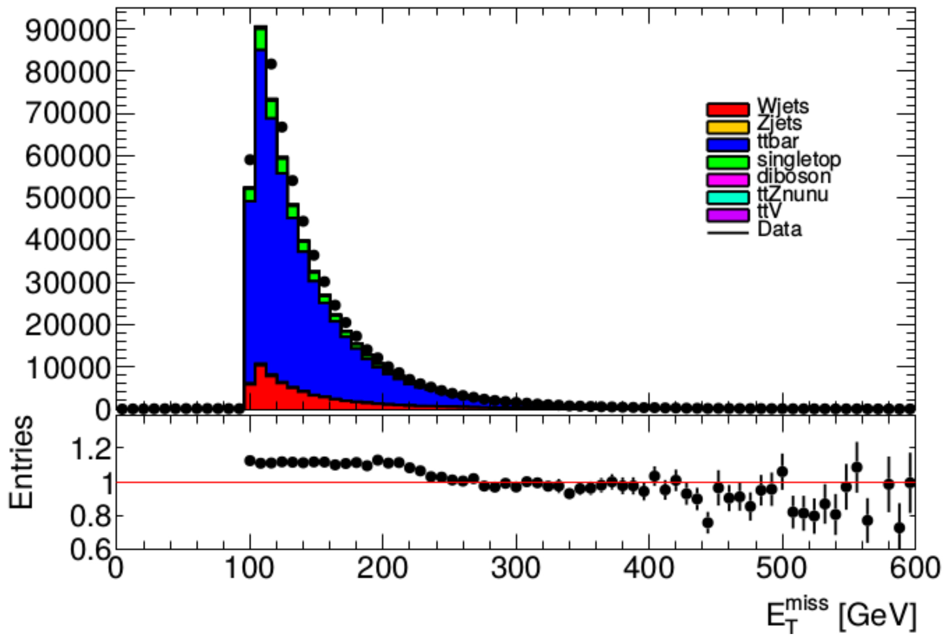
Preselection level

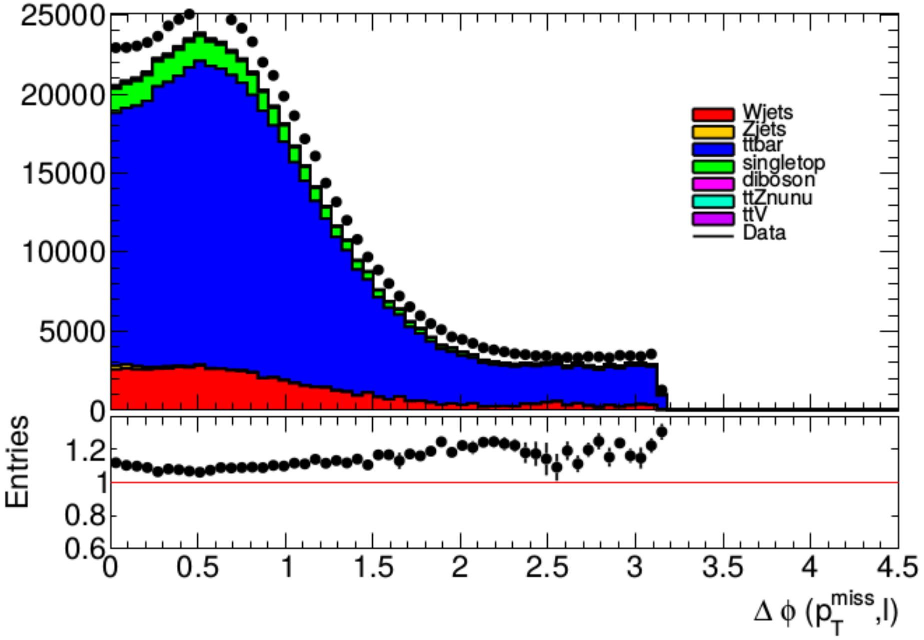
- A total of ~560,000 events were expected using Monte Carlo with the below proportions
- The dominant background decay is to $t\bar{t}$



Analysis

Preselection level





- These plots show that $t\bar{t}$ is the most dominant background process
- The data line shows that the Monte Carlo simulation of the shape is good
- There is an offset between the data and the Monte Carlo by ~10%, this is the same as ATLAS-CONF-2017-037 before background fits (likely due to an inaccurate scaling of background)
- Validates later simulation usage

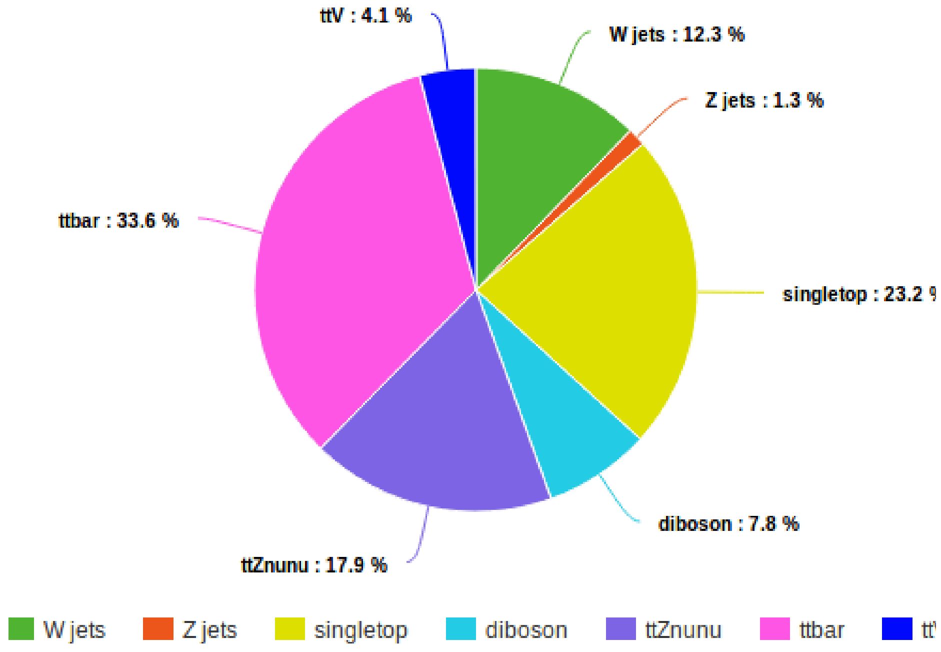
Decay analysis

- The DM high and DM low signal regions from the SUSY search were also investigated
- $t\bar{t}$ less dominant than with just the preselection

Variable	DM low	DM high
Jet p_T [GeV]	> (120, 85, 65, 25)	> (125, 75, 65, 25)
b jet p_T [GeV]	> 60	> 25
E_T^{miss} [GeV]	> 300	> 380
m_T [GeV]	> 170	> 225
am_{T2} [GeV]	> 160	> 190
$H_{T,sig}^{miss}$	> 14	-
$\Delta\Phi(p_T^{miss}, l)$	> 1.2	> 1.2
$\Delta\Phi(p_T^{miss}, jet_{1,2})$	> 1.0	> 1.0

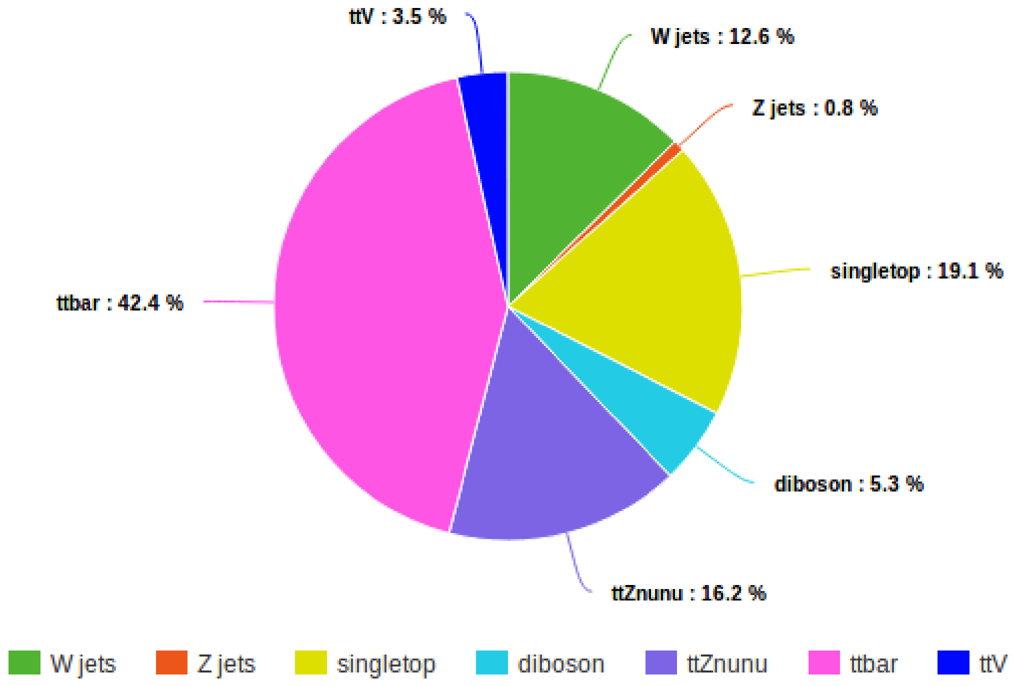
DM high

- 37 events in total with the below proportions



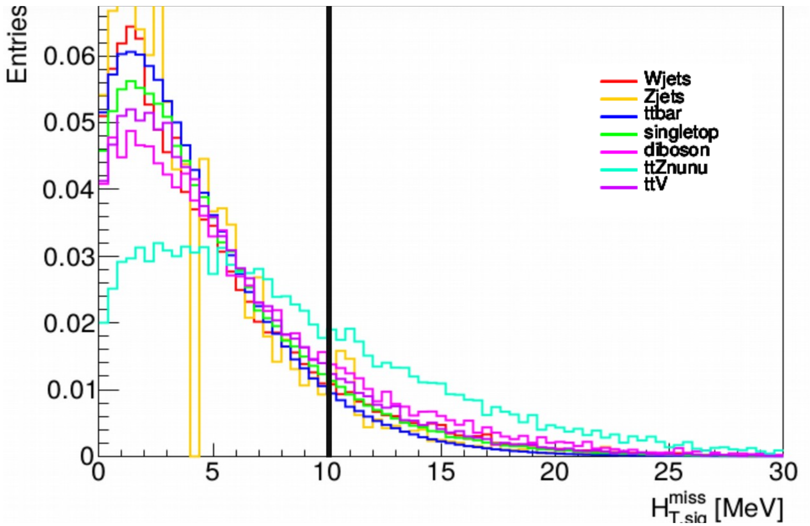
DM low

- 67 events in total with the below proportions

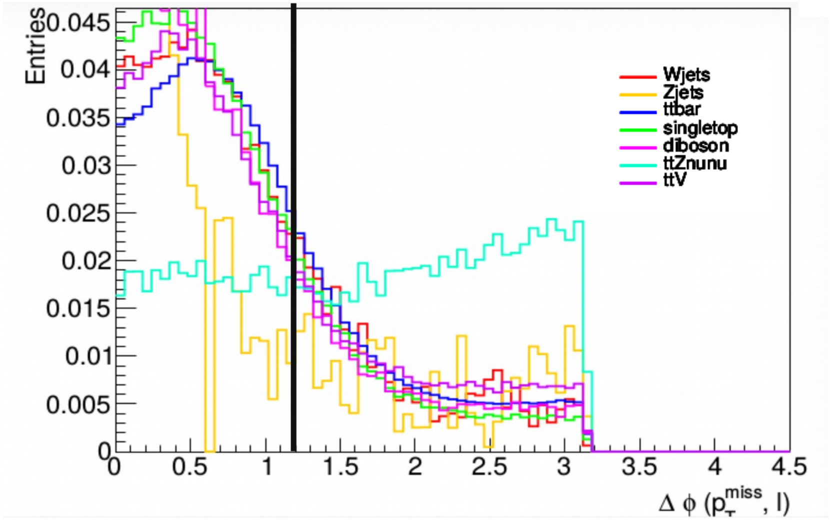


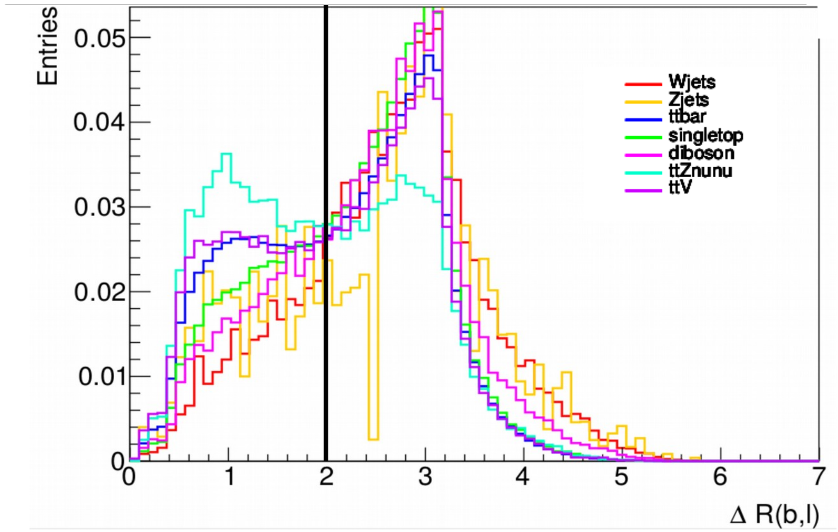
Analysis

Signal region for $t\bar{t}Z(\rightarrow \nu\bar{\nu})$ optimisation



- Signal regions that maximised the number of ttZnunu events and the purity of ttZnunu events were defined
- This was done by analysing the overlaid plots from the preselection
- Three examples of this are shown for $H_{T,sig}^{miss}$, ΔR(b-jet, l) and $\Delta\Phi(p_T^{miss}, l)$
- Cuts were also made to m_T, am_{T2}, $\Delta\Phi(p_T^{miss}, jet_{1,2})$ and E_t^{miss}



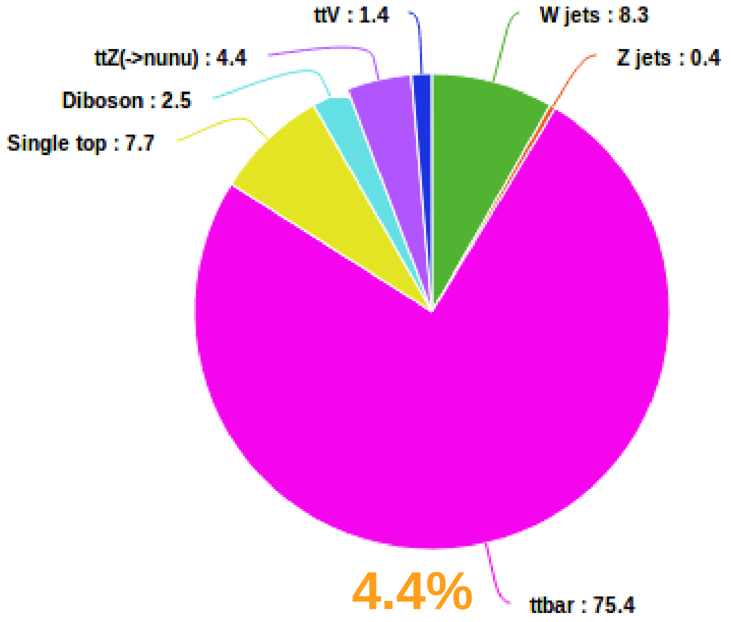


Analysis

Three possible signal regions were considered and the one with the smallest uncertainty chosen

SRA

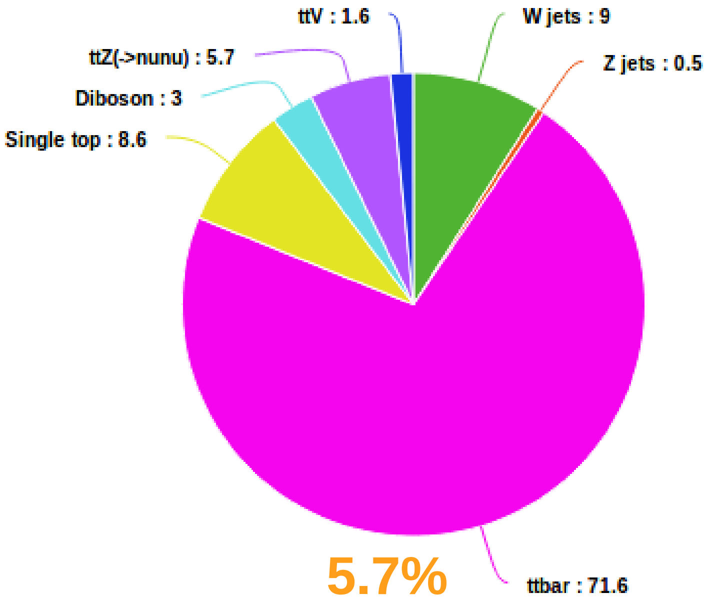
- 61 out of 1398 events



4.4%

SRB

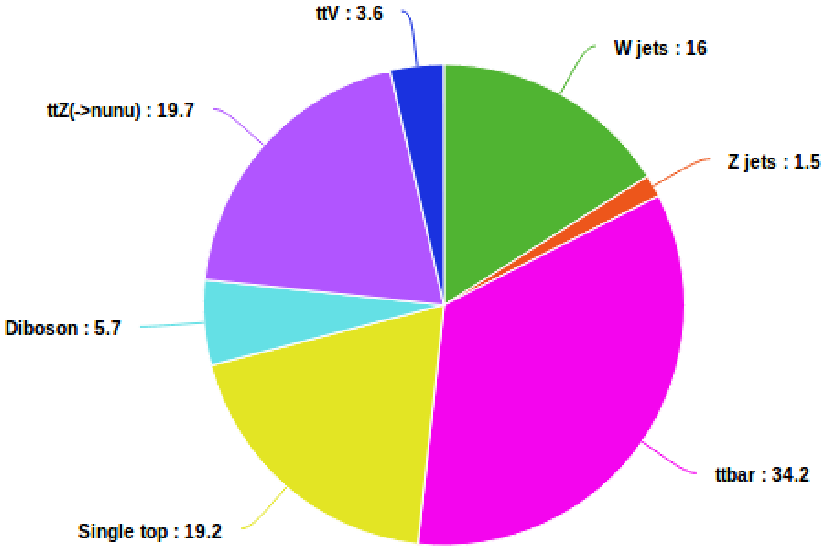
- 43 out of 1557 events



5.7%

SRC

- 7.4 out of 39.6 events

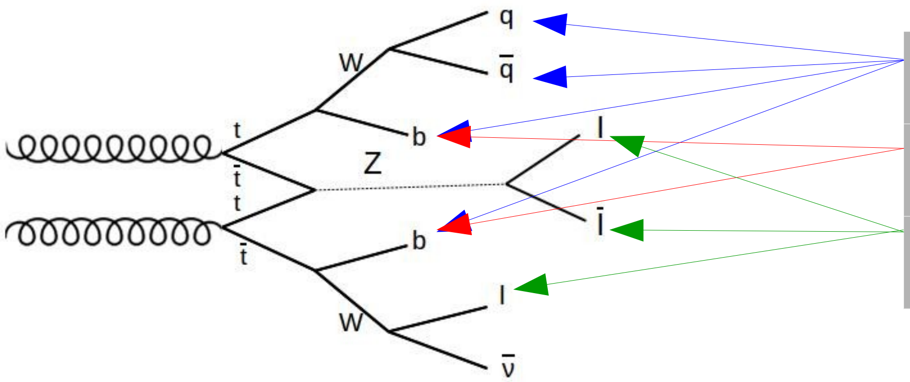


19.7%

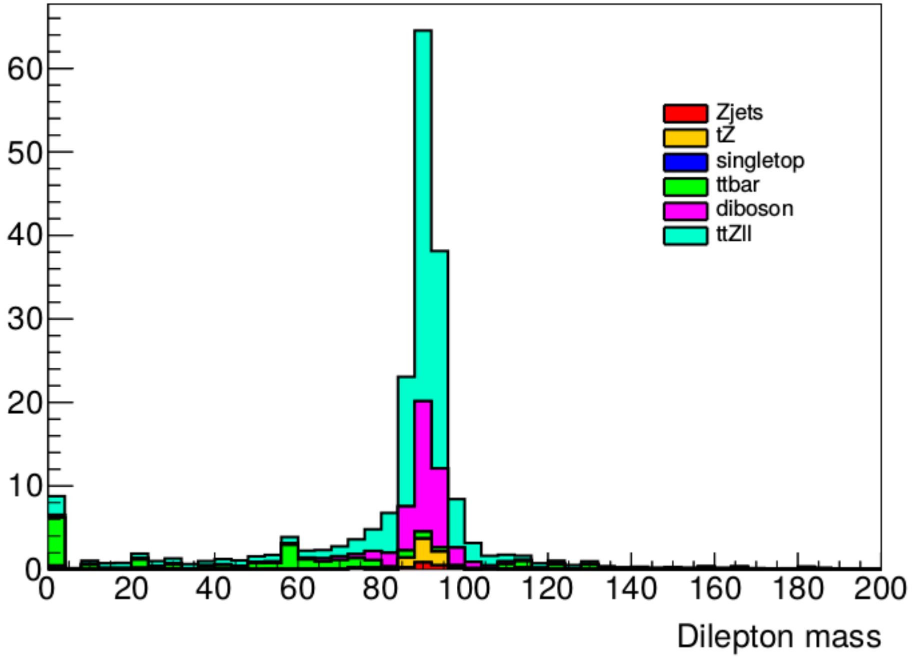
- To reduce the uncertainty, a compromise between number of events and purity has to be made
- SRC had the lowest percentage uncertainty

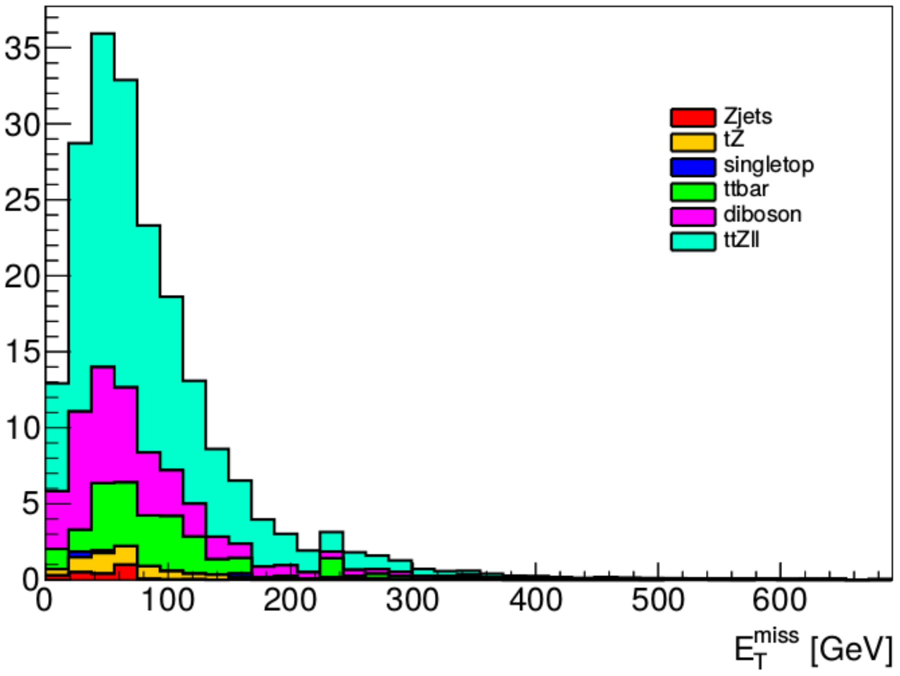
Analysis

Studying $t\bar{t}Z(\rightarrow l\bar{l})$ at preselection level



Number of jets	> 4
Number of b-tags	> 1
Number of leptons	3





The future

Investigating $t\bar{t}Z(\to \ell\bar{\ell})$ and $t\bar{t}Z(\to \nu\bar{\nu})$ in SRC

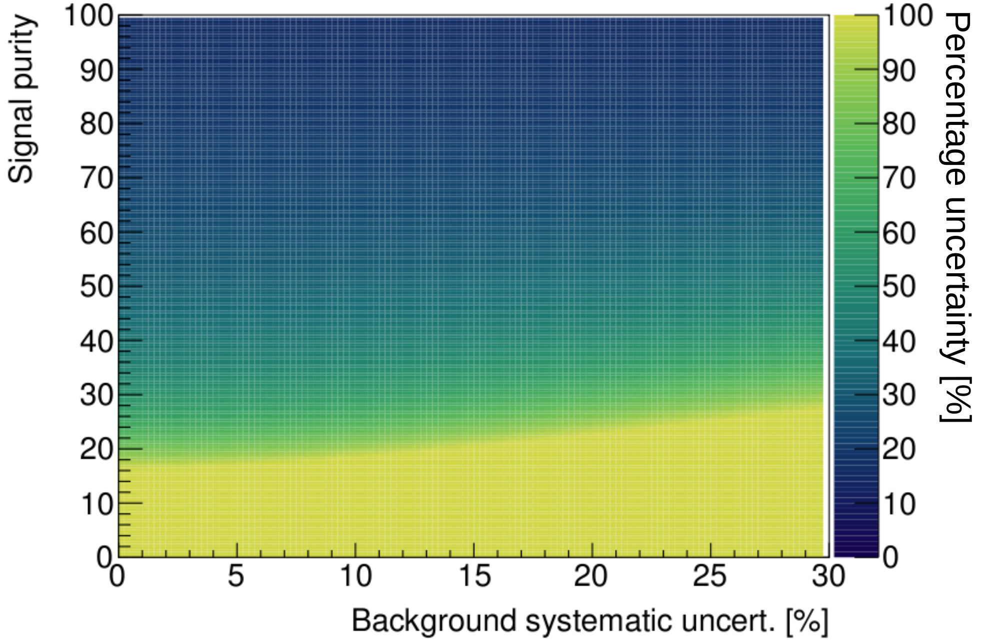
- The current luminosity of the LHC is 36.5fb^{-1} (2015 + 2016)
- By the end of Run 2 in 2018, this will have increased to ~100fb^{-1}
- The high luminosity LHC will begin running in 2025 and will have a luminosity of ~3000fb^{-1}

$t\bar{t}Z(\to \nu\bar{\nu})$:

Luminosity (fb^{-1})	Total expected number of events	Number of signals	Number of background events	Percentage uncertainty
36.5	37.3	7.4	29.9	92%
100	102.2	20.3	81.9	64%
3000	3065.8	608.2	2457	41%

$t\bar{t}Z(\to \ell\bar{\ell})$:

Luminosity (fb^{-1})	Total expected number of events	Number of signals	Number of background events	Percentage uncertainty
36.5	1.65	0.70	0.95	184%
100	4.52	1.9	2.6	113%
3000	136	58	78	24%



- Using a systematic uncertainty of 10%, the percentage uncertainty on **$t\bar{t}Z(\to \nu\bar{\nu})$** and **$t\bar{t}Z(\to \ell\bar{\ell})$** was determined for SRC
- The uncertainty is shown to decrease with the increased luminosity
- Demonstrates that due to the difficulty separating **$t\bar{t}Z(\to \nu\bar{\nu})$** from the background that a ratio to **$t\bar{t}Z(\to \ell\bar{\ell})$** is not yet useful

Conclusion

- $t\bar{t}Z(\rightarrow \nu\bar{\nu})$ and $t\bar{t}Z(\rightarrow l\bar{l})$ were isolated and studied to look for new physics in the form of invisible decays
- A new signal region was defined with the optimal cuts for achieving maximum purity and most events of $t\bar{t}Z(\rightarrow \nu\bar{\nu})$
- Despite this, the background signals were still dominant causing large percentage uncertainties
- This particular ratio could be useful only with a significantly increased luminosity and a significantly decreased systematic uncertainty
- The same method could however be applied to other decays with better purity
- Hopefully this could lead the way to the discovery of new physics

Notes (ttZnunu files)

Preselection

Background	Number of events
W jets	62,698
Z jets	1,954
Single top	459,178
Diboson	34,783
ttbar	3,082
ttV	429
ttZnunu	1,771

SRA

Background	Number of events
W jets	116
Z jets	6
Single top	107
Diboson	35
ttbar	1054
ttV	19
$t\bar{t}Z(\rightarrow \nu\bar{\nu})$	61

SRC

Background	Number of events
W jets	6.0
Z jets	0.6
Single top	12.7
Diboson	7.2
ttbar	2.1
ttV	3.6
$t\bar{t}Z(\rightarrow \nu\bar{\nu})$	7.4

SRB

Background	Number of events
W jets	868
Z jets	4
Single top	65
Diboson	23
ttbar	542
ttV	12
$t\bar{t}Z(\rightarrow \nu\bar{\nu})$	43

DM high

Background	Number of events
W jets	4.5
Z jets	0.5
Single top	12.4
Diboson	8.6
ttbar	2.9
ttV	6.6
ttZnunu	1.5

DM low

Background	Number of events
W jets	8.4
Z jets	0.5
Single top	28.2
Diboson	12.7
ttbar	3.5
ttV	10.8
ttZnunu	2.3

Variable	SRB	SRA	SRC
E_t^{miss} [GeV]	> 280	> 250	> 380
m_T [GeV]	> 125	> 100	> 225
am_{T2} [GeV]	-	-	> 190
$H_{T,sig}^{miss}$	> 10	> 10	> 10
$\Delta\Phi(p_T^{miss}, l)$	> 1.0	> 0.9	> 1.2
$\Delta\Phi(p_T^{miss}, jet_{1,2})$	> 0.7	> 0.6	> 1.0
ΔR(b jet, l)	-	-	< 2.0