Search for supersymmetry in single lepton events with the full Run 2 data

Physics at the Terascale

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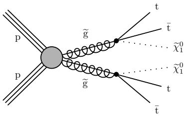
1-Lepton $\Delta\varphi$ Analysis

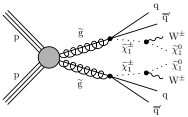
- Search for SUSY with 1 lepton in its final state

Multiple b-tags



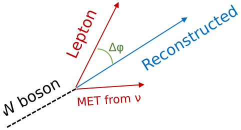
T1tttt

0b-tags



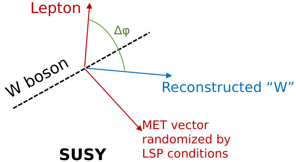
T5qqqqWW

SM events :
$\Delta\varphi$ between W and lepton
usually small
and max given by M_W, p_{TW})

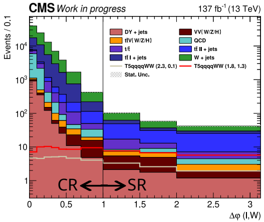


SM

SUSY events :
Flattish $\Delta\varphi$ distribution
(two missing particles)



SUSY



Object and Event selection

Objects

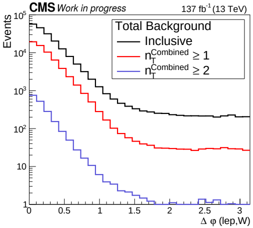
- Electrons:
  - $p_T > 25$ GeV
  - $|\eta| < 2.4$
  - Cut-based ID, tight WP
  - miniIso < 0.1
- Muons:
  - $p_T > 25$ GeV
  - $|\eta| < 2.4$
  - Cut-based ID, medium WP
  - miniIso < 0.2
- Jets:
  - AK4 with
  - $|\eta| < 2.4$
  - Latest JEC applied
  - b-tagging: DeepCSV, mediumWP

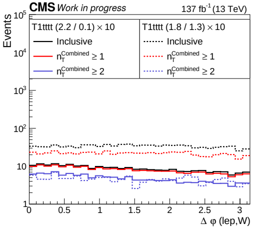
Event

- Exactly 1 lepton (e or μ)
- $H_T = \sum_{\text{jets}} p_T > 500$ GeV
- $L_T = p_T^{\text{lep}} + E_T^{\text{miss}} > 250$ GeV
- Sub-leading jet $p_T > 80$ GeV
- $n_{\text{jet}} \geq 3$
- **Multi-b:** $n_b \geq 1$
- **0b:** $n_b = 0$
- Additional MET filters are applied
- Isolated track veto to reduce dileptonic background
- Search bins defined by H_T, L_T, n_{jet}, n_b and either n_{Top} or n_W

Combined Top Tagger

- The multi-b signal has 3 hadronic top decays
- $n_{\text{Top}} \geq 1$ significantly reduces the dileptonic background
- DeepAK8 Top Tagger $[1]$
  - Dnn based for merged tops ($p_T > 400$ GeV)
- Resolved Top Tagger$[2]$
  - BDT based for resolved tops ($p_T < 400$ GeV)
- A combined top tagger (merged OR resolved) is used after performing cross-cleaning between the two types of top tags



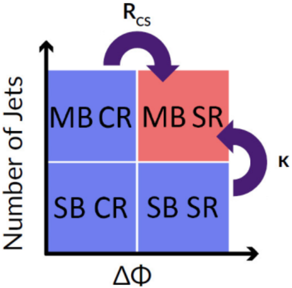


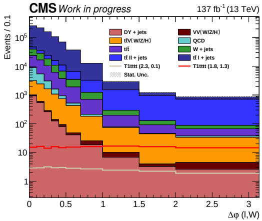
- $[1]$ CMS Collaboration, “Identification of heavy, energetic, hadronically decaying particles using machine-learning techniques”, JINST 15 (2020) P06005, arXiv:2004.08262.
- $[2]$ CMS Collaboration, “Search for direct production of supersymmetric partners of the top quark in the all-jets final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV”, JHEP 10 (2017) 005, arXiv:1707.03316

The R_{CS} Method for the Multi-b Channel

- Goal: Data driven prediction of the EWK background
- The signal sensitive region is defined by large $\Delta\phi$ and high n_{jet}
- Data is taken in $n_{\text{jet}} \in [4,5]$, $n_b \geq 1$
  $R_{\text{CS}} = \frac{N_{\text{SR}}}{N_{\text{CR}}^{\text{Data}} - N_{\text{CR}}^{\text{QCD}}}$
- Correction factors are calculated using MC
- $\kappa_{\text{EWK}} = \frac{R_{\text{CS}}(n_{\text{jet}} \text{ as in MB, EWK})}{R_{\text{CS}}(n_{\text{jet}} \in [4,5], \text{EWK})}$

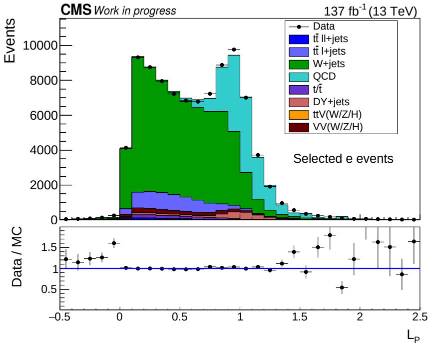
$$N_{\text{EWK}}^{\text{Pred.}} = \kappa_{\text{EWK}} \cdot R_{\text{CS}}\left(n_{\text{jet}} \in [4,5], \text{Data}\right) \cdot \left(N_{\text{CR, MB}}^{\text{Data}} - N_{\text{CR, MB}}^{\text{QCD}}\right)$$





Background Estimation: QCD

- Inverting the lepton selection gives a QCD enriched region
- $F_{\text{sel-to-anti}} = \dfrac{N^{\text{fit}}_{\text{QCD, selected}}}{N^{\text{data}}_{\text{QCD, anti-selected}}}$
- Fit performed in the $n_{\text{jet}} \in [3, 4]$ and $n_b = 0$ region
- EWK and QCD templates from selected MC
- determined in each of the L_T bins used in the search region
- To estimate the QCD in the search region, the data in the anti-selected region of each search bin is scaled by $F_{\text{set-to-anti}}$



$$Lp = \frac{p_T^{\ell}}{p_T^{\text{W}}} cos(\Delta\Phi) \; .$$

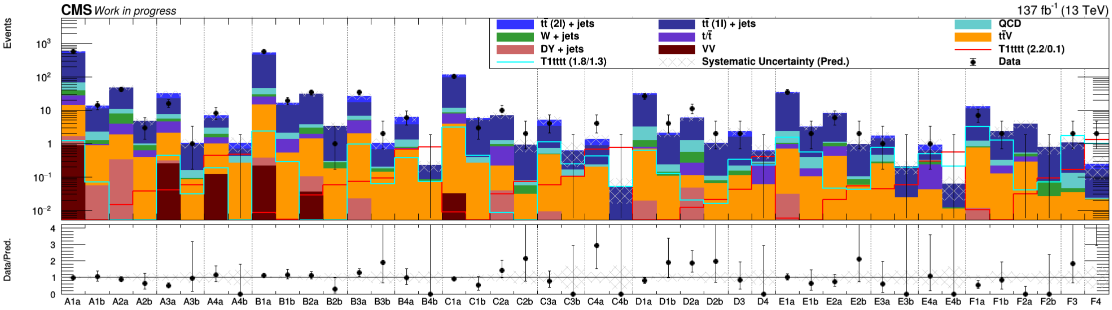
Systematics for the Multi-b Analysis

- Systematic uncertainties are propagated to the correction factor κ_{EWK} for the background
- The range of the uncertainties is quite large but the median value seems reasonable, meaning that only a few bins have very large uncertainties

Systematic	EWK (Median[Min., Max.] [%])
JEC	$3.8\,[0.2, 36.3]$
TTVxsec	$2.8\,[0.1, 22.6]$
nISR	$2.3\,[0.4, 20.3]$
PU	$2.3\,[0.1, 18.6]$
DLSlope	$2.2\,[0.4, 12.3]$
TTxsec	$1.6\,[0.1, 23.7]$
Wpol	$0.6\,[0.1, 4.4]$
btagHF	$0.6\,[0.1, 5.7]$
Wxsec	$0.4\,[0.1, 7.7]$
btagLF	$0.3\,[0.1, 8.4]$
DLConst	$0.2\,[0.1, 3.6]$
lepSF	$0.2\,[0.1, 1.6]$

Systematic	T1tttt$(1800, 1300)$ (Median[Min., Max.] [%])	T1tttt$(2200, 100)$ (Median[Min., Max.] [%])
JEC	$10.4\,[0.1, 62.0]$	$8.8\,[0.1, 58.8]$
MET	$8.4\,[1.0, 73.3]$	$4.2\,[0.1, 129.2]$
nISR	$4.7\,[0.1, 50.9]$	$6.2\,[0.1, 27.1]$
btagHF	$4.6\,[0.1, 15.9]$	$7.3\,[0.1, 26.9]$
btagLF	$0.5\,[0.1, 8.9]$	$0.6\,[0.1, 7.4]$

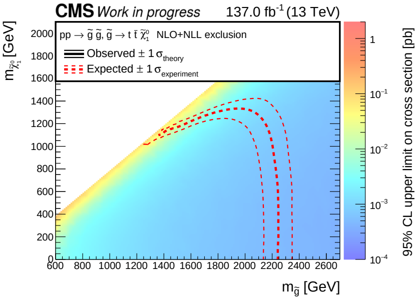
The Search Bins - Multi-b



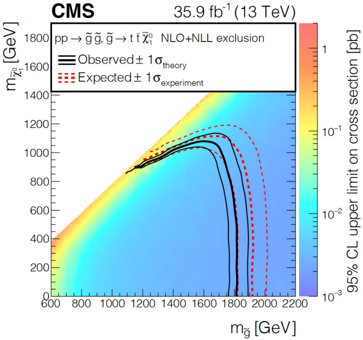
- Overall good agreement, i.e. no significant excess is observed

Results for the Multi-b Signal

Full Run 2 Analysis



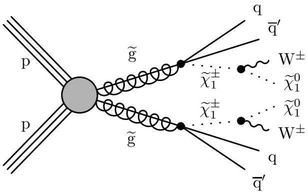
Previous Analysis
1709.09814



- Expected to exclude $m_{\tilde{g}} < 2240$ GeV and $m_{\text{LSP}} < 1300$ GeV
- Improvement compare to previous Analysis on 2016 Data

The 0b Analysis

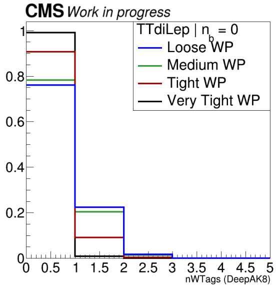
- The 0b analysis follows a very similar strategy
- The QCD estimation is the same, except for the bin of L_T
- Instead of using a Top tagger, the 0b analysis utilizes W tagging.
- The background consists mostly of W+jets and $t\bar{t}$ events
  - Two R_{CS} methods are used to predict both seperately

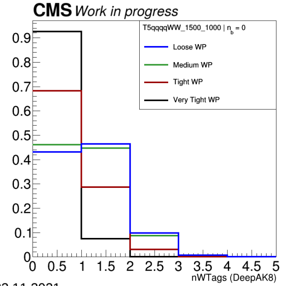


T5qqqqWW

Merged W Tagger

- The 0b Signal contains 2 W bosons from the chargino decay
- $n_{\mathrm{W}} \geq 1$ significantly reduces the dileptonic background
- DeepAK8 Tagger identifies the W bosons

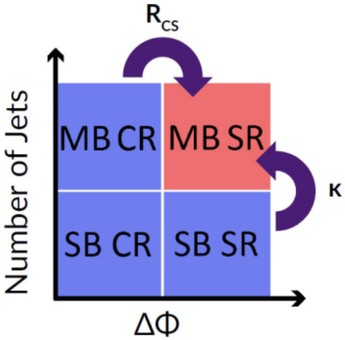


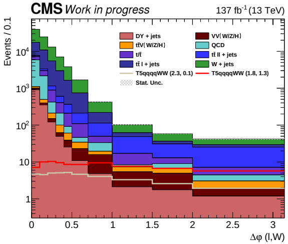


The R_{CS} Method for the 0b channel

- The two main backgrounds are estimated with independent transfer factors
- For $t\bar{t}$, data is taken in $n_{\text{jet}} \in [4,5]$, $n_b \geq 1$
- Correction factors are calculated using MC
- $$\kappa_b = \frac{R_{\text{CS}}\left(n_{\text{jet}}{\in}[4{,}5],\, n_b{=}0,\, t\bar{t}\right)}{R_{\text{CS}}\left(n_{\text{jet}}{\in}[4{,}5],\, n_b{\geq}1,\, \text{EWK}\right)}$$
- $$\kappa_{t\bar{t}} = \frac{R_{\text{CS}}\left(n_{\text{jet}} \text{ as in MB},\, t\bar{t}\right)}{R_{\text{CS}}\left(n_{\text{jet}}{\in}[4{,}5],\, t\bar{t}\right)}$$
- $$f_i^{\text{MB,CR}} = \frac{N_{\text{fit},i}^{\text{MB,CR}}}{N_{\text{data}}^{\text{MB,CR}}}, \text{ with } i \in [t\bar{t}, \text{W+jets}] \ .$$

$$N_{t\bar{t}}^{\text{Pred.}} = f_{t\bar{t}} \cdot \kappa_b \cdot \kappa_{t\bar{t}} \cdot R_{\text{CS}}\left(n_{\text{jet}} \in [4,5]\,,\, n_b \geq 1,\, \text{Data}\right) \cdot N_{\text{CR, MB}}^{\text{Data}}$$

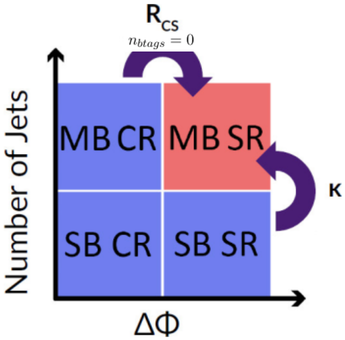


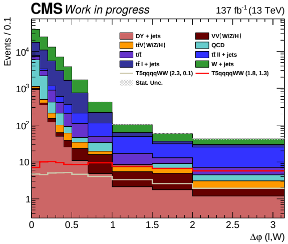


Differences for the W+Jets Prediction

- The signal sensitive region is defined by large $\Delta\phi$ and high n_{jet}
- For W+Jets, data is taken in $n_{\text{jet}} \in [3,4]$, $n_b = 0$
- Correction factor is calculated using MC
- $\kappa_W = \dfrac{R_{\text{CS}}(n_{\text{jet}} \text{ as in MB, W+Jets})}{R_{\text{CS}}(n_{\text{jet}}\in[3,4], W\text{+Jets and Rare})}$
- $R_{\text{CS}}^{\text{corr}} = \dfrac{N_{\text{SR}} - f_{t\bar{t}} \cdot R_{\text{CS}}^{t\bar{t}} \cdot N_{\text{CR}}}{(1-f_{t\bar{t}}) \cdot N_{\text{CR}}}$

$$N_W^{\text{Pred.}} = f_W \cdot \kappa_W \cdot R_{\text{CS}}^{\text{corr.}}\left(n_{\text{jet}} \in [3,4], n_b = 0, Data\right) \cdot N_{\text{CR, MB}}^{\text{Data}}$$





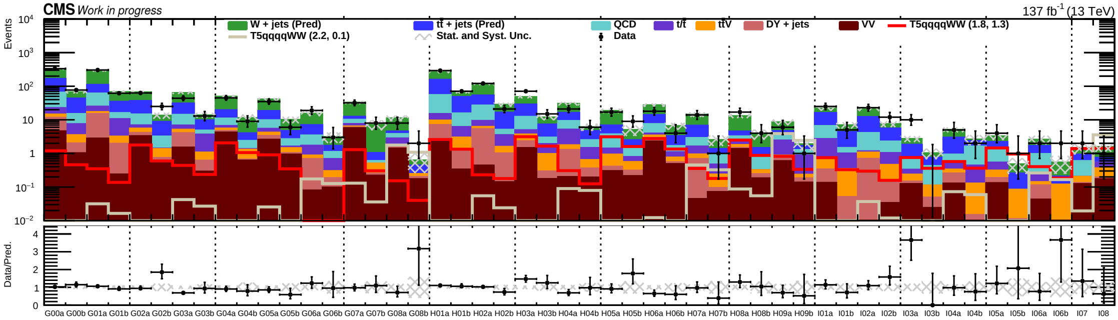
Systematics for the 0b Analysis

- Systematic uncertainties are propagated to the correction factors for the background
- The range of the uncertainties is quite large but the median value seems reasonable

Systematic	Total Bkg. (Median[Min., Max.] [%])
Luminosity	$15.6\,[6.5, 58.2]$
JEC	$1.1\,[0.1, 11.8]$
TTVxsec	$1.0\,[0.2, 7.1]$
DLSlope	$0.7\,[0.1, 5.6]$
PU	$0.6\,[0.1, 3.1]$
TTxsec	$0.4\,[0.1, 4.6]$
Wpol	$0.4\,[0.1, 4.5]$
Wxsec	$0.8\,[0.1, 5.0]$
btagHF	$0.3\,[0.1, 2.5]$
DLConst	$0.2\,[0.1, 1.0]$
lepSF	$0.2\,[0.1, 0.9]$
nISR	$0.1\,[0.1, 6.4]$
btagLF	$0.1\,[0.1, 0.2]$

Systematic	T5qqqqW$(1800, 1300)$ (Median[Min., Max.] in %)	T5qqqqW$(2200, 100)$ (Median[Min., Max.] [%])
JEC	$6.2\,[0.8, 72.5]$	$5.1\,[0.1, 50.0]$
MET	$4.0\,[0.1, 28.4]$	$4.9\,[0.1, 63.9]$
Luminosity	$3.0\,[2.4, 3.5]$	$3.0\,[2.5, 3.5]$
ISR	$1.8\,[0.1, 11.3]$	$1.7\,[0.1, 14.8]$
btagHF	$0.5\,[0.2, 5.9]$	$1.3\,[0.2, 6.0]$
btagLF	$0.2\,[0.1, 0.9]$	$0.4\,[0.1, 1.1]$

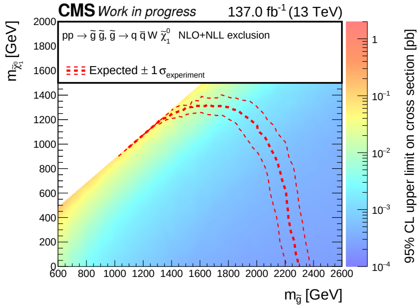
The Search Bins - 0b



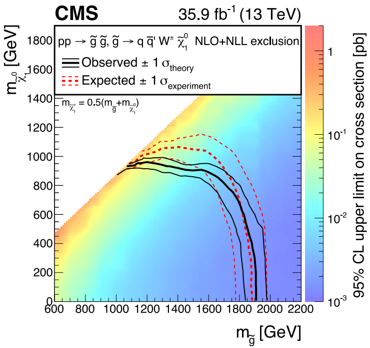
- Three bins show excess of data but these are not very sensitive to the signal
- Investigations have shown that this is just fluctuation in the SB that leads to predicting less background events
- These bins do not have a large impact on the final limit

Results for the Zero-b Signal

Full Run 2 Analysis



Previous Analysis: 1709.09814



- New expected upper limit in cut and count analysis using full Run 2 systematics
- Expected to exclude $m_{\tilde{g}} < 2300$ GeV and $m_{\tilde{\chi}_0^1} < 1300$ GeV

Summary and Outlook

- A search for SUSY in two different signal regions has been performed
- Multi-b:
  - No significant excess was observed in data compared to the SM prediction
- 0b:
  - A complex 6 bin factorization approach is required
  - To ensure proper statistical behavior one has to carefully construct the likelihood and an Asimov dataset that is statistically equivalent to evaluating on real observed events
- New expected and improved limits are presented in both regions
- Analysis is on its way to be published in a paper
- Paper Review committee has been formed and will start reviewing this analysis soon

Thank you!

Contact

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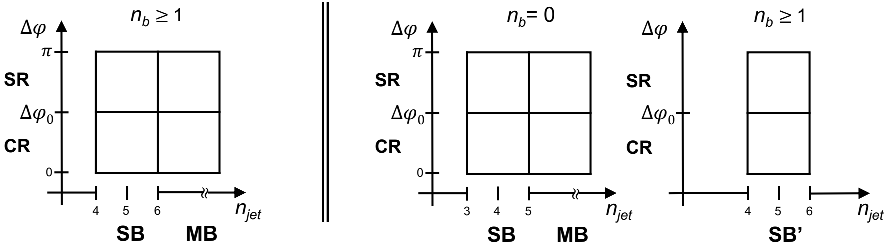
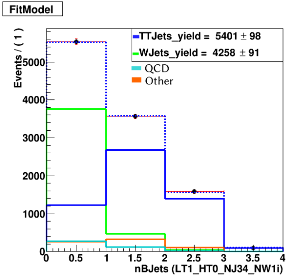
Detailed background prediction

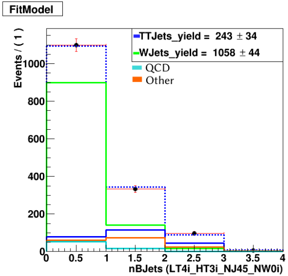


$$N^{\text{MB,SR}}_{\text{Pred,}} = \underbrace{\kappa_{\text{W}} \cdot R^{\text{CS, corr}}_{\text{data}}\left(n_{\text{jet}\in[3,4],n_b=0,n=1}\right)}_{\text{transfer factor}} \cdot \underbrace{f^{\text{MB,CR}} \cdot N^{\text{MB,CR}}_{\text{data}}}_{\text{contribution in the control region}} .$$

Template Fit of n_b

- Fit is done in control region $\Delta\phi < \phi_0\,(L_T)$
- QCD and other background are set constant, so the fit only adjusts the TTJets and WJets yields
- $f_W\,(n_b = 0) = \frac{N_W^{\text{fit}}}{N_{\text{Total}}}$
- $f_{t\bar{t}}\,(n_b = 0) = \frac{N_{t\bar{t}}^{\text{fit}}}{N_{\text{Total}}}$

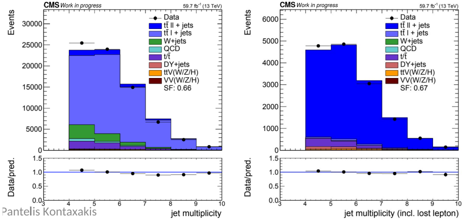


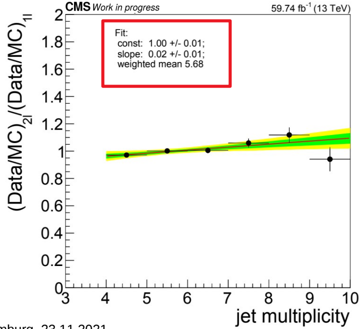


Dileptonic Correction as Event Weight

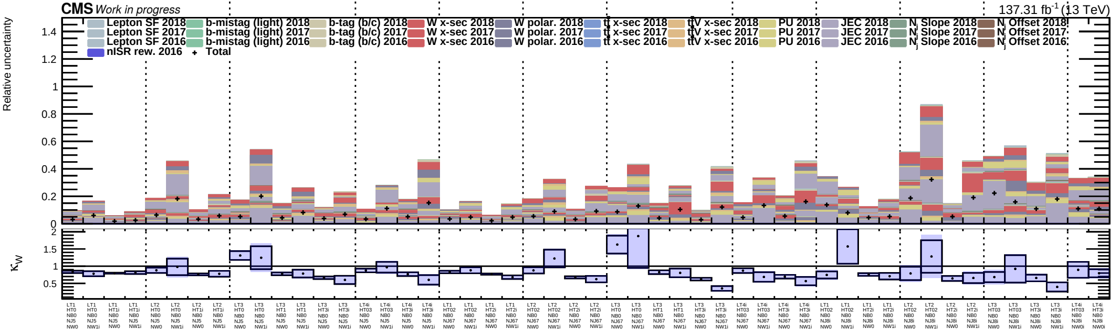
- R_{CS} factor is sensitive to lost leptons
- Select two tight leptons of opposite charge
- $(|m_{\ell\ell} - m_Z| > 10$ GeV$)$
- Emulate lost lepton
  - 1/3 of lepton p_T added to MET
  - 2/3 of lepton p_T counted as additional jet
- Scale MC to data so only the shape is corrected
- $w_{\mathrm{DL}} = a + b \cdot (n_{\mathrm{jet}} - \langle n_{\mathrm{jet}} \rangle)$
- Applied to events that are generated with two leptons

single lepton dilepton



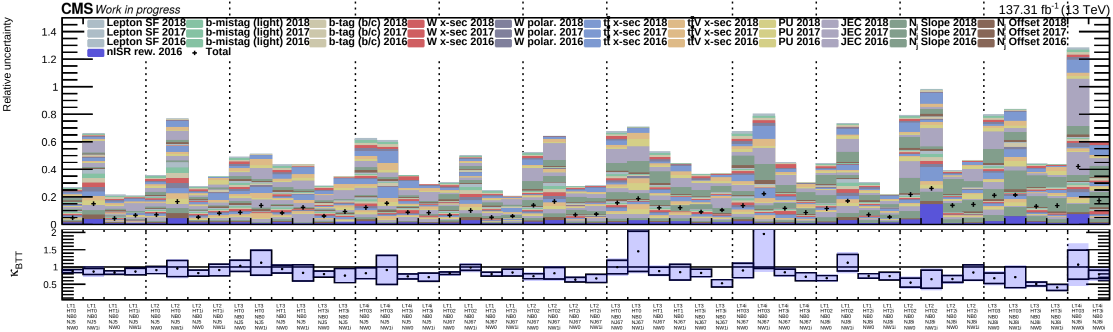


Correction Factor κ_W for W+jets Prediction



The corrections are close to 1 within the statistics availiable

Correction Factor κ_{BTT} for $t\bar{t}$ Prediction



The corrections are close to 1 within the statistics availiable

Search Bins - Multi-b

n_{jet}	Bin name (old)	Bin name	L_T [GeV]	H_T [GeV]	N_b	N_{top}
$[6,8]$	LT12, HT03, NB1, NJ68, NT1	A01a	$[250,450]$	$[500,1500]$	$=1$	$=1$
	LT12, HT03, NB1, NJ68, NT2i	A01b				≥ 2
	LT12, HT03, NB2, NJ68, NT1	B01a			$=2$	$=1$
	LT12, HT03, NB2, NJ68, NT2i	B01b				≥ 2
	LT12, HT03, NB3i, NJ68, NT1	C01a			≥ 3	$=1$
	LT12, HT03, NB3i, NJ68, NT2i	C01b				≥ 2
	LT12, HT4i, NB1, NJ68, NT1	A02a		≥ 1500	$=1$	$=1$
	LT12, HT4i, NB1, NJ68, NT2i	A02b				≥ 2
	LT12, HT4i, NB2, NJ68, NT1	B02a			$=2$	$=1$
	LT12, HT4i, NB2, NJ68, NT2i	B02b				≥ 2
	LT12, HT4i, NB3i, NJ68, NT1	C02a			≥ 3	$=1$
	LT12, HT4i, NB3i, NJ68, NT2i	C02b				≥ 2
	LT3, HT03i, NB1, NJ68, NT1	A03a	$[450,600]$	≥ 500	$=1$	$=1$
	LT3, HT03i, NB1, NJ68, NT2i	A03b				≥ 2
	LT3, HT03i, NB2, NJ68, NT1	B03a			$=2$	$=1$
	LT3, HT03i, NB2, NJ68, NT2i	B03b				≥ 2
	LT3, HT03i, NB3i, NJ68, NT1	C03a			≥ 3	$=1$
	LT3, HT03i, NB3i, NJ68, NT2i	C03b				≥ 2
	LT4i, HT03i, NB1, NJ68, NT1	A04a	≥ 600	≥ 500	$=1$	$=1$
	LT4i, HT03i, NB1, NJ68, NT2i	A04b				≥ 2
	LT4i, HT03i, NB2, NJ68, NT1	B04a			$=2$	$=1$
	LT4i, HT03i, NB2, NJ68, NT2i	B04b				≥ 2
	LT4i, HT03i, NB3i, NJ68,NT1	C04a			≥ 3	$=1$
	LT4i, HT03i, NB3i, NJ68,NT2i	C04b				≥ 2

≥ 9	LT12, HT03, NB1, NJ9i, NT1	A05a	$[250,450]$	$[500,1500]$	$=1$	$=1$
	LT12, HT03, NB1, NJ9i, NT2i	A05b				≥ 2
	LT12, HT03, NB2, NJ9i, NT1	B05a			$=2$	$=1$
	LT12, HT03, NB2, NJ9i, NT2i	B05b				≥ 2
	LT12, HT03, NB3i, NJ9i, NT1	C05a			≥ 3	$=1$
	LT12, HT03, NB3i, NJ9i, NT2i	C05b				≥ 2
	LT12, HT4i, NB1, NJ9i, NT1	A06a		≥ 1500	$=1$	$=1$
	LT12, HT4i, NB1, NJ9i, NT2i	A06b				≥ 2
	LT12, HT4i, NB2, NJ9i, NT1	B06a			$=2$	$=1$
	LT12, HT4i, NB2, NJ9i, NT2i	B06b				≥ 2
	LT12, HT4i, NB3i, NJ9i, NT1	C06a			≥ 3	$=1$
	LT12, HT4i, NB3i, NJ9i, NT2i	C06b				≥ 2
	LT3, HT03i, NB1, NJ9i, NT1i	A07	$[450,600]$	≥ 500	$=1$	≥ 1
	LT3, HT03i, NB2, NJ9i, NT1	B07a			$=2$	$=1$
	LT3, HT03i, NB2, NJ9i, NT2i	B07b				≥ 2
	LT3, HT03i, NB3i, NJ9i, NT1i	C07			≥ 3	≥ 1
	LT4i, HT03i, NB1, NJ9i, NT1i	A08	≥ 600	≥ 500	$=1$	≥ 1
	LT4i, HT03i, NB2, NJ9i, NT1	B08a			$=2$	$=1$
	LT4i, HT03i, NB2, NJ9i, NT2i	B08b				≥ 2
	LT4i, HT03i, NB3i, NJ9i, NT1	C00			≥ 3	≥ 1

Search Bins - Zero-b part 1

n_{jet}	L_T [GeV]	H_T [GeV]	$\Delta\phi$ [rad]	N_W	Bin Name
5	$[250, 350]$	$[500, 750]$	1.00	0	G00a
				≥ 1	G00b
		≥ 750		0	G01a
				≥ 1	G01b
	$[350, 450]$	$[500, 750]$	1.00	0	G02a
				≥ 1	G02b
		≥ 750		0	G03a
				≥ 1	G03b
	$[450, 650]$	$[500, 750]$	0.75	0	G04a
				≥ 1	G04b
		$[750, 1250]$		0	G05a
				≥ 1	G05b
		≥ 1250		0	G06a
				≥ 1	G06b
	≥ 650	$[500, 1250]$	0.50	0	G07a
				≥ 1	G07b
		≥ 1250		0	G08a
				≥ 1	G08b

n_{jet}	L_T [GeV]	H_T [GeV]	$\Delta\phi$ [rad]	N_W	Bin Name
$[6, 7]$	$[250, 350]$	$[500, 1000]$	1.00	0	H01a
				≥ 1	H01b
		≥ 1000		0	H02a
				≥ 1	H02b
	$[350, 450]$	$[500, 1000]$	1.00	0	H03a
				≥ 1	H03b
		≥ 1000		0	H04a
				≥ 1	H04b
	$[450, 650]$	$[500, 750]$	0.75	0	H05a
				≥ 1	H05b
		$[750, 1250]$		0	H06a
				≥ 1	H06b
		≥ 1250		0	H07a
				≥ 1	H07b
	≥ 650	$[500, 1250]$	0.50	0	H08a
				≥ 1	H08b
		≥ 1250		0	H09a
				≥ 1	H09b

Search Bins - Zero-b part 2

n_{jet}	L_T [GeV]	H_T [GeV]	$\Delta\phi$ [rad]	N_W	Bin Name
≥ 8	$[250, 350]$	$[500, 1000]$	1.00	0	I01a
				≥ 1	I01b
		≥ 1000		0	I02a
				≥ 1	I02b
	$[350, 450]$	$[500, 1000]$	1.00	0	I03a
				≥ 1	I03b
		≥ 1000		0	I04a
				≥ 1	I04b
	$[450, 650]$	$[500, 1250]$	0.75	0	I05a
				≥ 1	I05b
		≥ 1250		0	I06a
				≥ 1	I06b
	≥ 650	$[500, 1250]$	0.50	≥ 0	I07
		≥ 1250			I08