Search for electroweak production of a vectorlike quark decaying to a top quark and a Higgs or Z boson using boosted topologies in an all-hadronic final state

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Vector like Quarks

Heavy quark, spin ½
- Chiralities transform the same under SM gauge group

Contained in various SM extensions
- Such as Little Higgs, Composite Higgs

Why VLQs?
- Potential solution to hierarchy problem
- Conventional 4th generation is excluded
- Mass not constrained by Yukawa coupling

For this talk:
- top partner, charge +2/3

VLQ Type	Charge	Decays
T	+2/3	$\mathrm{bW^+}, \mathrm{tH}, \mathrm{tZ}$
B	-1/3	$\mathrm{tW^-}, \mathrm{bH}, \mathrm{bZ}$
X	5/3	$\mathrm{tW^+}$
Y	-4/3	$\mathrm{bW^-}$

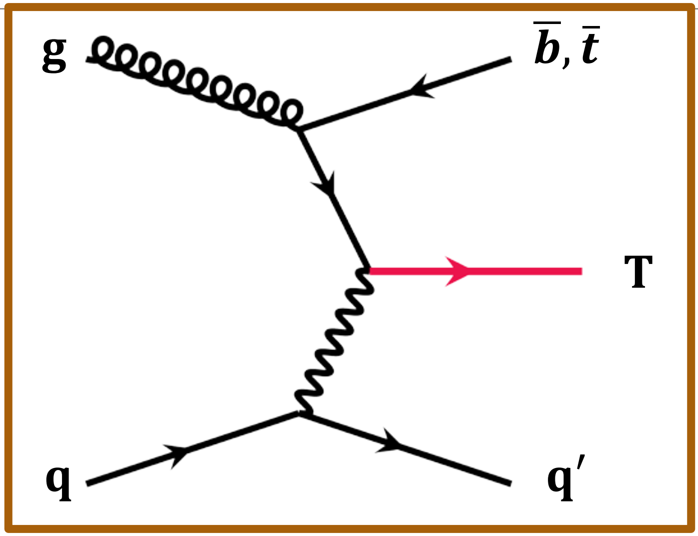
Types of Production

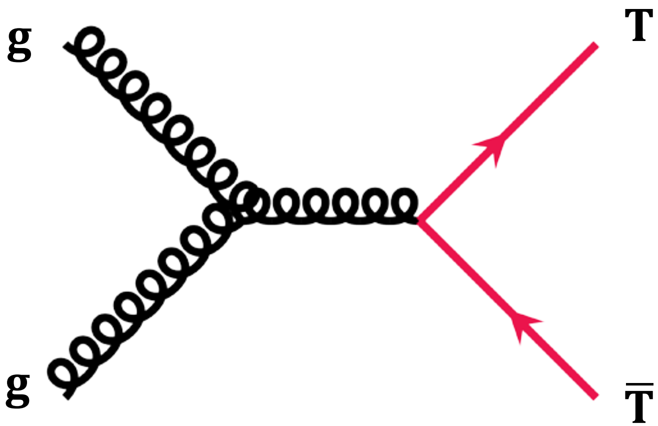
Single

- Mediated by electroweak interaction
- Model dependent cross section
  - Relies on coupling at production vertex
- Dominates with higher masses (above 1 TeV)
- Our range → M(T) = 1000-1800 GeV

In Pairs

- Mediated by strong interaction
- Model independent cross sections
  - Relies on strong coupling





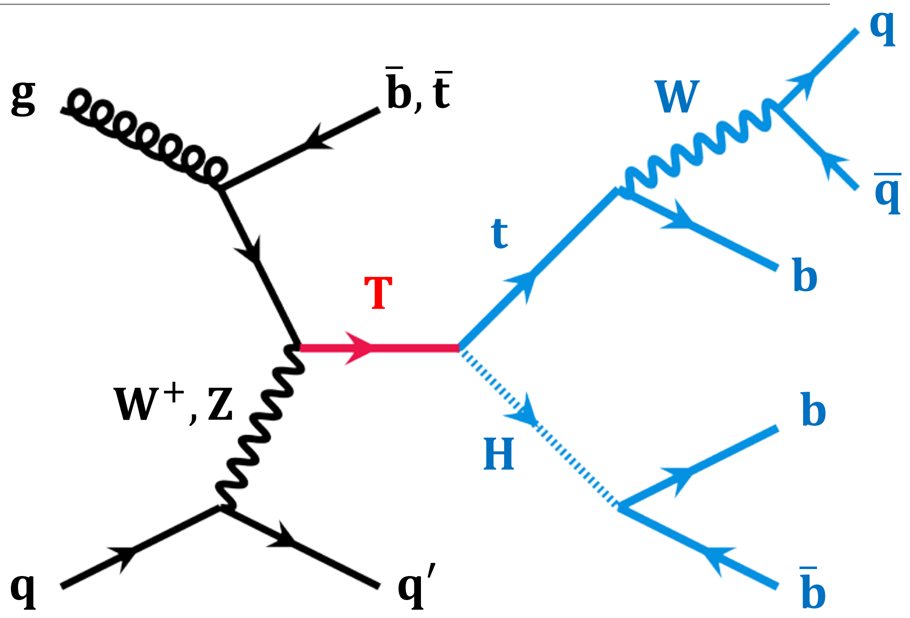
Single T→tH/Z

Two single production modes explored:

- **pp→Tbq,** charged current
- **pp→Ttq,** neutral current
- **All hadronic decay**: H/Z→ $b\bar{b}$, t→bW
- Left and Right handed couplings

Cross sections:

- Evaluated using Simplest Simplified Model, arXiv:1409.0100
- Depends quadratically on scaling factors: c^{bW}, c^{tZ} (for tH case)
- **pp→Tbq**: 0.174-1.950 pb for M(T) = 1000-1800 GeV
- **pp→Ttq**: 0.0324-0.285 pb for M(T) = 1000-1800 GeV



Full decay mode

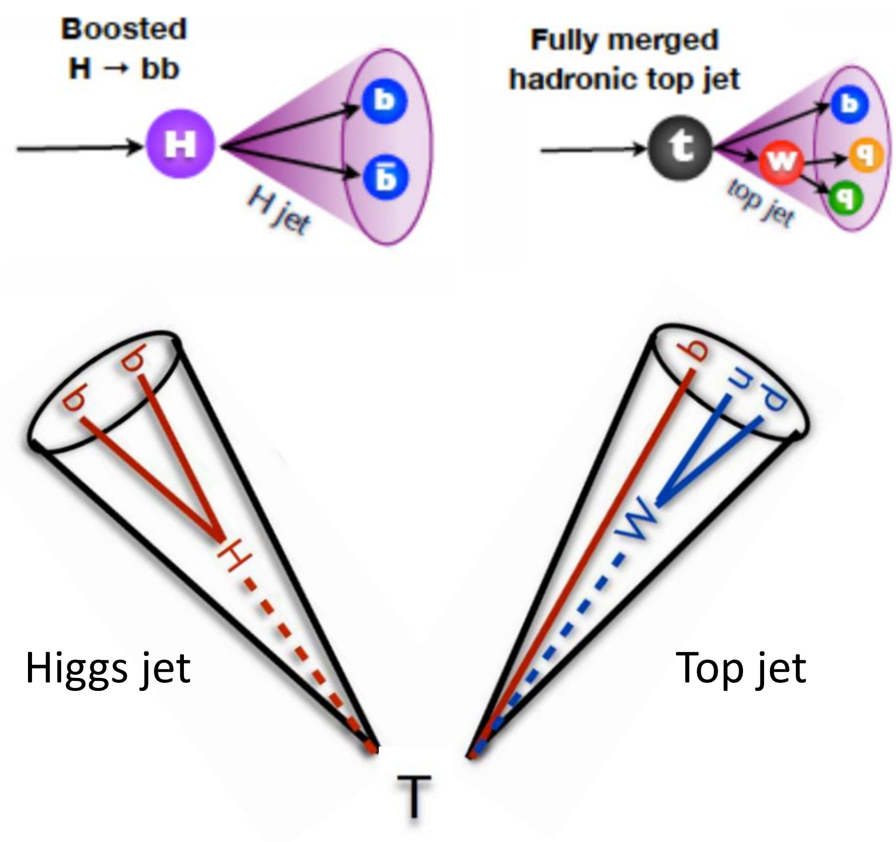
Boosted Jets with Fully Hadronic Decay Mode

Above 1 TeV masses, jets become Lorentz boosted

- Decays are fully merged into a single jet
- Can use substructure techniques for tagging jets

Substructure Used:

- Jet mass grooming
- N-subjettiness (τ_2/τ_1, τ_3/τ_2)
  - Higgs → two hard subjets (small τ_2/τ_1)
  - top → three hard subjets (small τ_3/τ_2)



Jet Tagging with Substructure

Jet Mass grooming → help identify H, t jets

- Pruned
  - $\frac{(\min(p_{T1}, p_{T2}))}{p_{Tp}} > 0.1;\ \Delta R_{12} < 0.5 \times \frac{m_{jet}}{p_T}$
- Soft Drop
  - $\frac{(\min(p_{T1}, p_{T2}))}{p_{T1}+p_{T2}} > z_{cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta};\ z_{cut} = 0.1,\ \beta = 0$

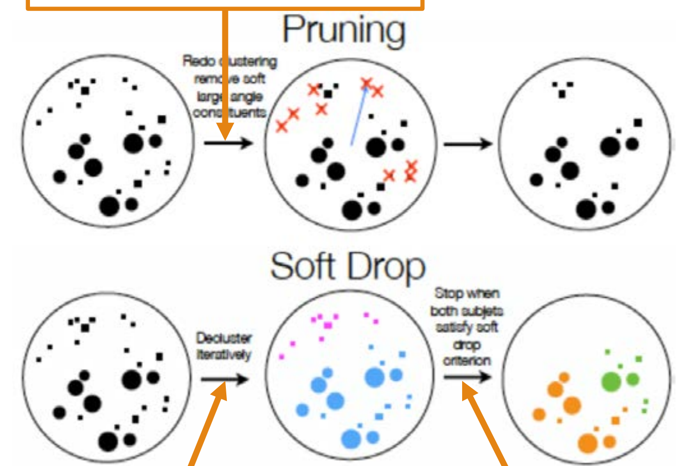
N-subjettiness

- Discriminate against multijet background
- Multijet → large τ_2/τ_1 and τ_3/τ_2

Subjet b-tagging

- Combined Secondary Vertex algorithm
- Combination of track, secondary vertex variables

Re-clustering removes soft large angle constituents



De-cluster iteratively

Stop when criterion satisfied

Analysis Cuts

2.3 fb^{-1} pp collision data at $\sqrt{s}$ = 13 TeV collected in 2015 by CMS

Events selected by 2-stage trigger
- Level 1 → loose jet requirements
- High Level Trigger (HLT)
  - Scalar sum of jet p_T > 800 GeV required

Jet candidates from HLT reconstructed with anti-k$_T$ algorithm, R=0.4, 0.8 (labeled AK4, AK8 respectively)

Main Selection:

At least 4 AK4 jets → p_T > 30 GeV, $|\eta|$ < 5

At least 1 AK8 jet → p_T > 300 GeV, $|\eta|$ < 2.4

Scalar sum of AK4 jet p_T ($\mathrm{H_T}$) > 1100 GeV

1 Higgs tagged jet:
- Pruned Mass→ 105-135 GeV (Z → 65-105 GeV)
- τ_2/τ_1 < 0.6
- 2 subjet b-tags

1 Top tagged jet:
- Soft drop mass→ 110-210 GeV
- τ_3/τ_2< 0.54
- 1 subjet b-tag

$\Delta\mathrm{R}(\mathrm{Higgs, top})$ > 2.0

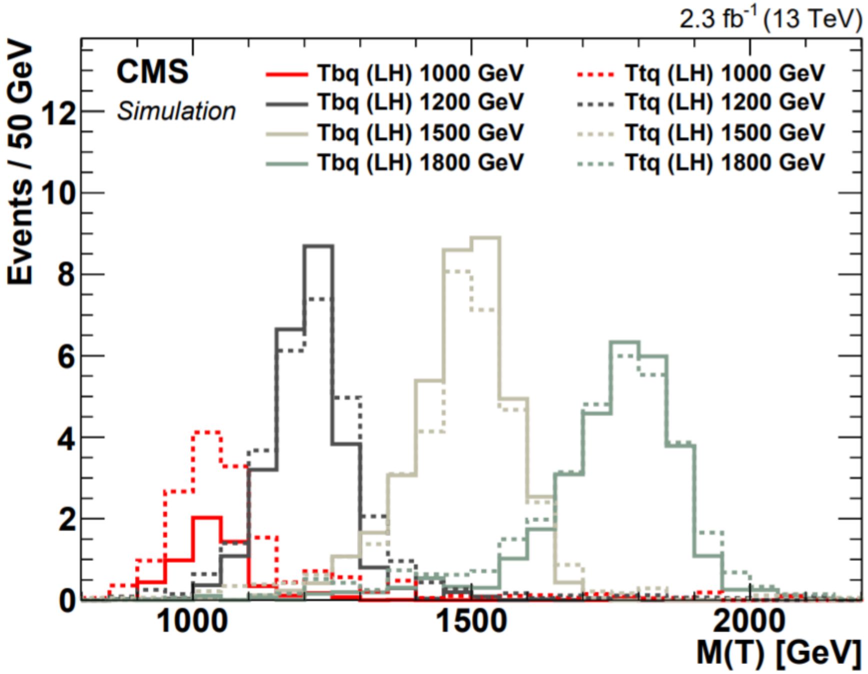
Mass of T after selection

Shown is the simulated M(T) distribution for 1000, 1200, 1500, and 1800 GeV mass points, after all cuts;

$\sigma\mathcal{B}(\mathrm{T} \rightarrow \mathrm{tH})$ set to 1 pb

pp→Tbq on solid lines; pp→Ttq on dotted

Left handed coupling shown, which uses the $\mathrm{c_L^{bW}}$ scaling factor



Background Estimation

Backgrounds Considered

- **QCD Multijets** → estimated with data
- $\boldsymbol{t\bar{t}}$ **+ jets** → estimated with MC
- W + jets
- tW Single Top

Bold → main backgrounds

ABCD Method used to estimate QCD background from data

- Predicts QCD background number and shape
- N → MC background subtracted from data in each region

Number Prediction:

$$\frac{N_D}{N_B} = \frac{N_C}{N_A} \rightarrow N_D = N_B \times \frac{N_C}{N_A}$$

Shape Prediction:

$$\mathcal{F}_D = \mathcal{F}_B \times \frac{N_C}{N_A}$$

Anti-Higgs jet → same as Higgs jet, but failing subjet b-tagging

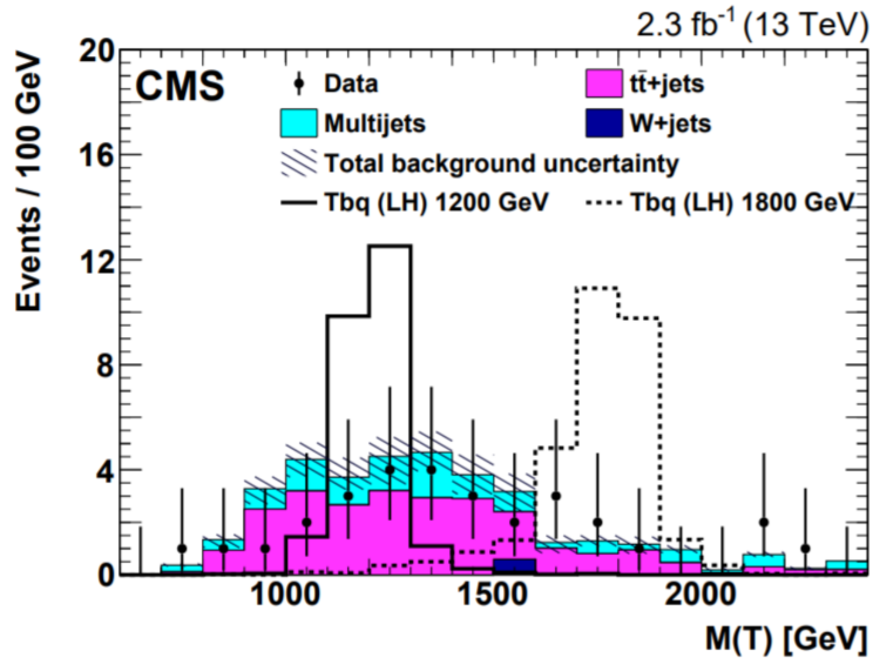
Region	N(Higgs tag)	N(anti-Higgs tag)	N(top tag)
A	0	>0	0
B	0	>0	>0
C	>0	≥0	0
D	>0	≥0	>0

M(T) After Full Selection

Background and Data in good agreement, within estimated uncertainties

Uncertainty shown in table is the combined statistical and systematic

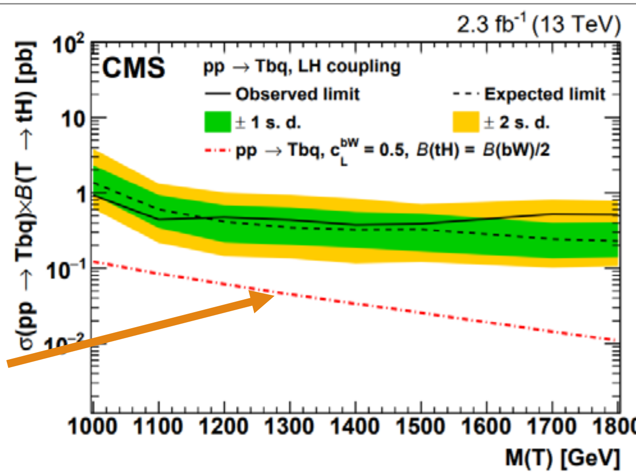
Process	Events
Estimated QCD	10.8±5.5
Estimated $t\bar{t}$+jets	24.3±8.1
Estimated W+jets	0.6±0.6
Estimated Background	35.7±5.6
Observed Events	30

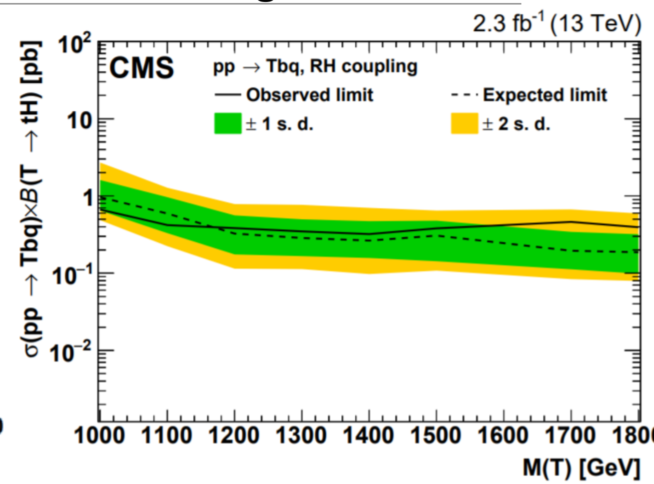


T→tH, Limits

Left Handed   Right Handed

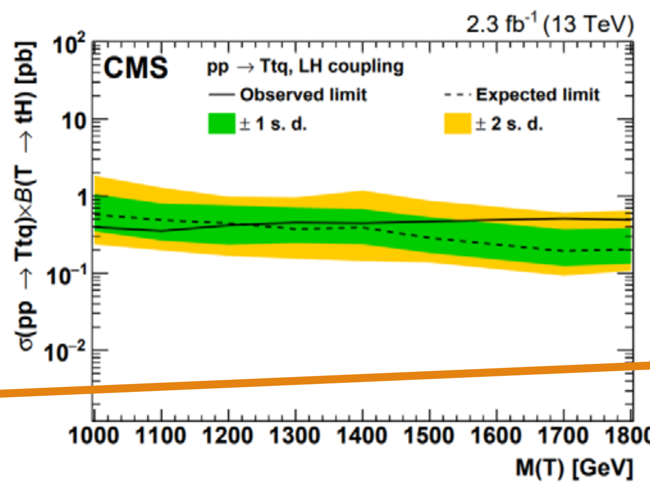
$\sigma(\mathrm{pp} \rightarrow \mathrm{Tbq})BR(\mathrm{T} \rightarrow \mathrm{tH})$

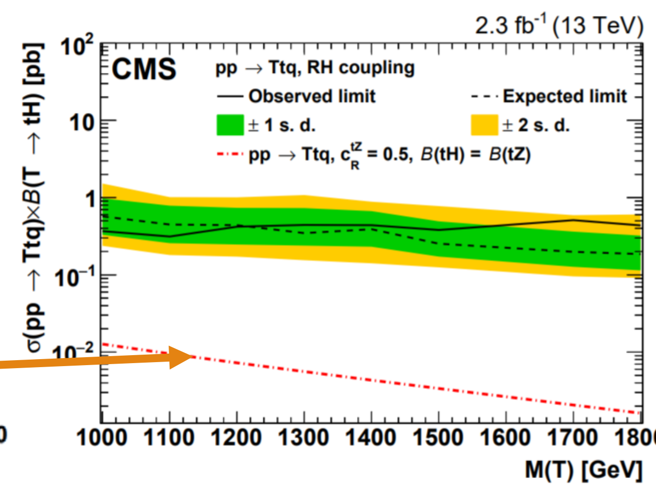




Model:
c_L^{bW}=0.5, BR(tH) = BR(bW)/2

$\sigma(\mathrm{pp} \rightarrow \mathrm{Ttq})BR(\mathrm{T} \rightarrow \mathrm{tH})$





Model:
c_R^{tZ}=0.5, BR(tH) = BR(tZ)

Conclusion

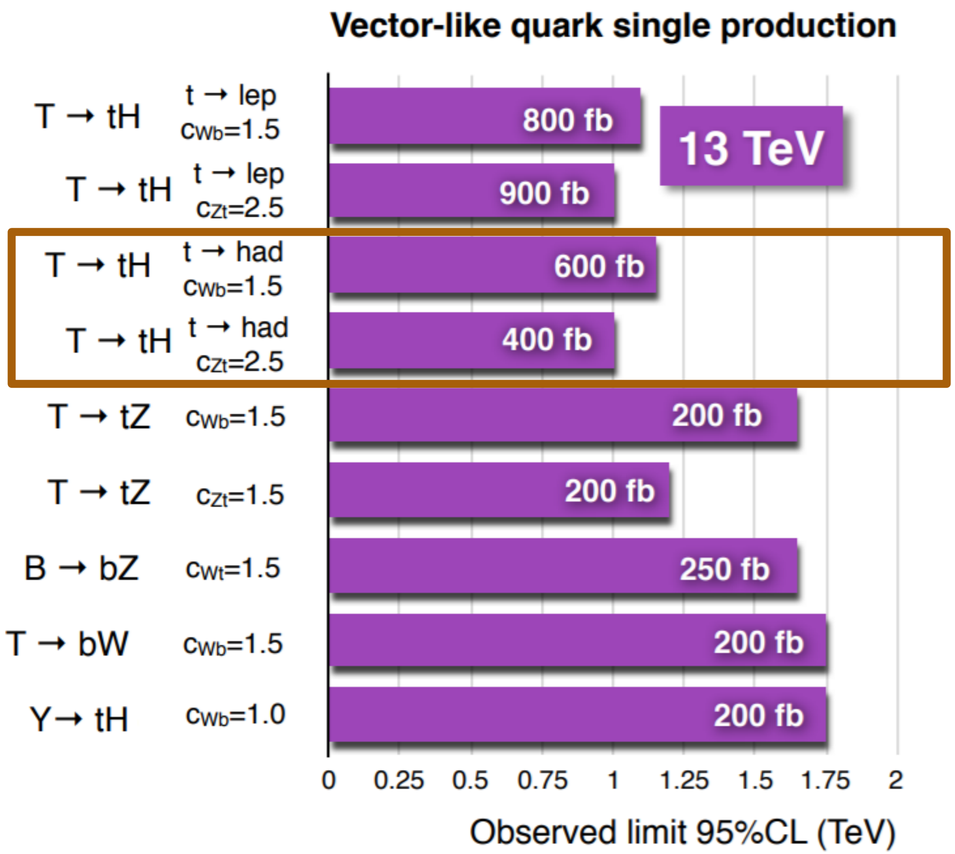
Search performed for a single T quark, T→tH, all hadronic decay

Using 3.2 fb^{-1} pp collision data at 13 TeV collected by CMS, upper limits placed on $\sigma\mathcal{B}(T \rightarrow tH)$

- 0.31-0.93 pb for M(T) ranging from 1000-1800 GeV
- arXiv:1612.05336v2

Future analysis in this channel planned for combined 2016, 2017 datasets

Single VLQ Public Results



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

Backup

Systematic Uncertainties

Dominant Sources

Shape Uncertainties
→ affects the shape of the M(T) distribution

Other Uncertainties:
→ Overall effect on event yield

JES → Jet Energy Scale
JER → Jet Energy Resolution

Uncertainty	Variation	Signal	Background
Luminosity	2.7%	Yes	Yes
PU reweighting	5%	Yes	Yes
$t\bar{t}$+jets cross section	6%	No	Yes
W+jets cross section	3.8%	No	Yes
PDF	1-3%	Yes	Yes
Higgs jet selection	10%	Yes	No
$\tau 2/\tau 1$ scale factor	12.5%	Yes	Yes
Higgs mass JES	2%	Yes	Yes
Top mass JES	2%	Yes	Yes
JES and JER	Shape (1-2%)	Yes	Yes
Top-tagging	Shape (15-30%)	Yes	Yes
H_T reweighting	Shape (1-3%)	No	Yes
B-tag scale factor	Shape (2-5%)	Yes	Yes