Search for production of a Higgs boson and a top quark pair at CMS in the H->bb Mode

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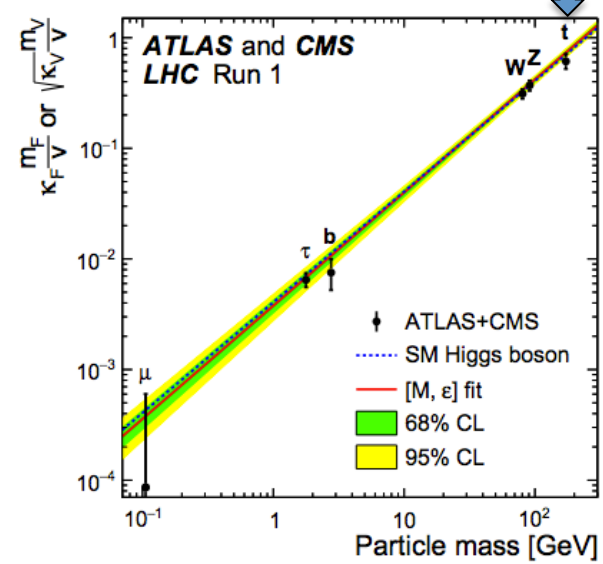
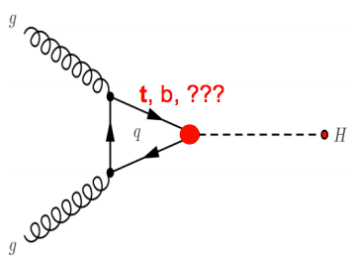
Introduction

- With discovery of 125 GeV Higgs in 2012 we now move from the era of **searching** to **characterization**
  - Thus far appears to be SM like…
- One of the most important characteristics that **remains to be measured** is the **coupling between the top quark and the Higgs**
  - Top is most massive fundamental particle we know of thus far…
  - Yukawa coupling may show **hints at BSM physics** if deviating from SM value
  - **ttH production allows direct probe at tree level where as gluon-gluon fusion requires loops**

Driven by Indirect Measurements



INDIRECT



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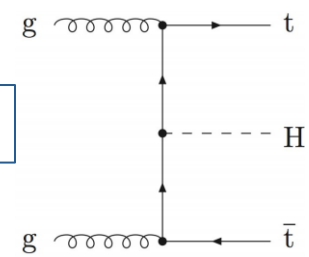
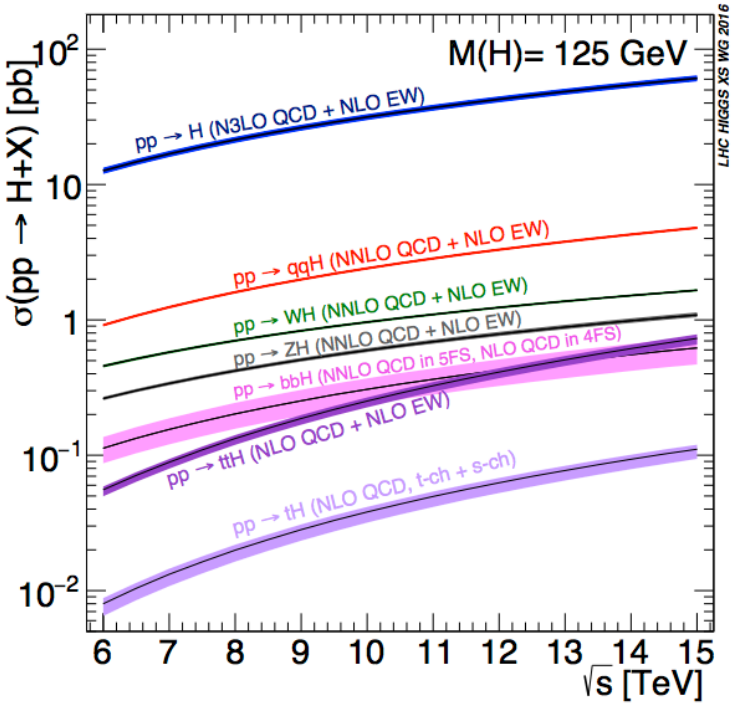
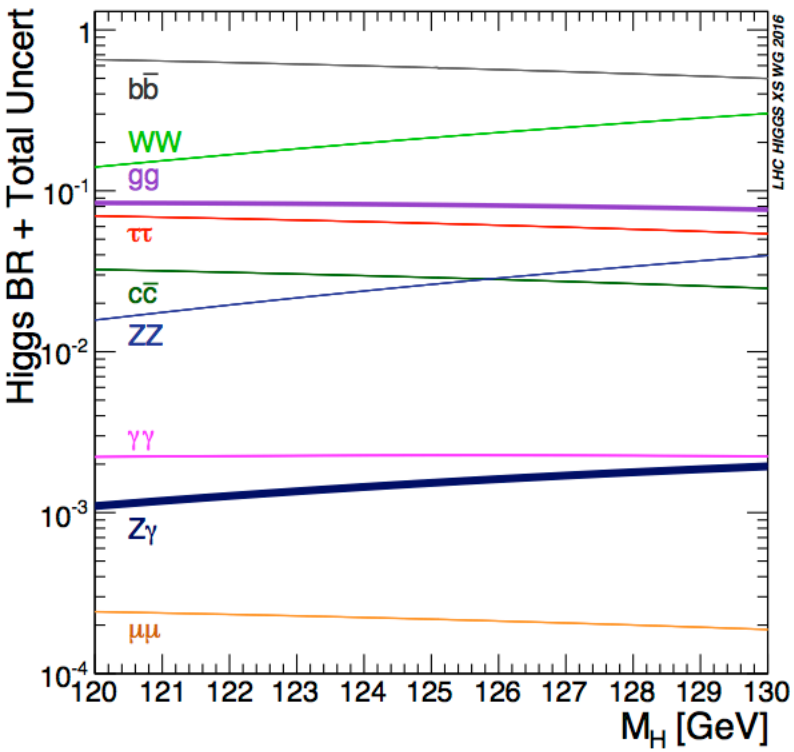


Higgs Production and Decay

- Cross section for ttH ~**510 fb @ 13 TeV**
  - This is an **increase of 3.8** from 8TeV
  - **Only 1%** of total cross section for Higgs production is ttH though…

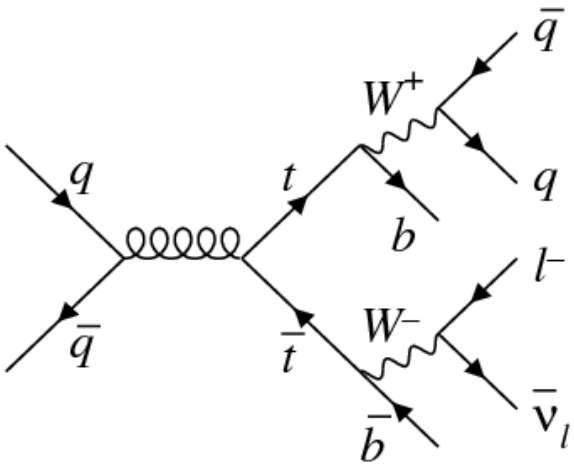


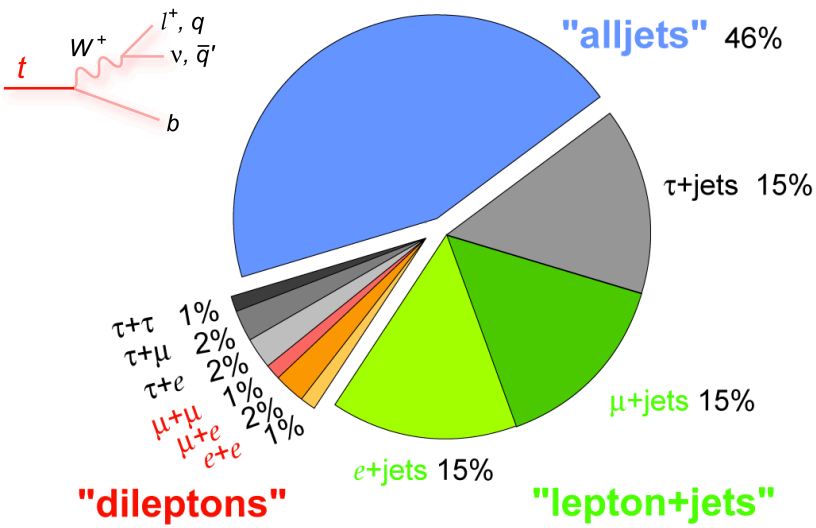


- Branching Ratio of Higgs to bb ~58%
  - **Largest decay mode** however it comes with **large background… ttbar**

Overcoming Background

- **ttbar background** goes up by **3.3** going from 8TeV → 13TeV
  - Challenging due to top decays to leptons and additional jets being present
- Combinations from **both top and Higgs** decays cause many complex final states and **combinatorial headaches**.





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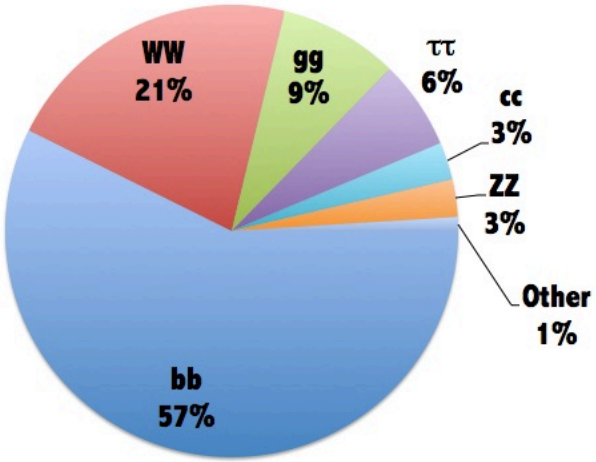
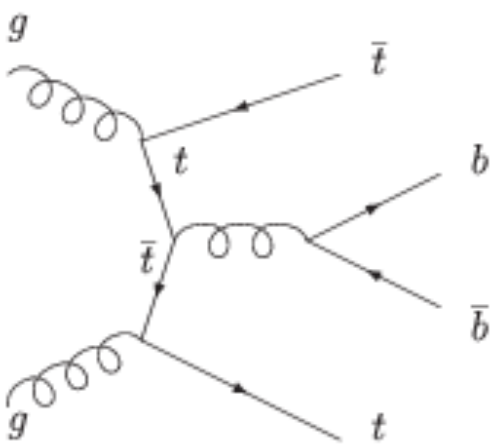


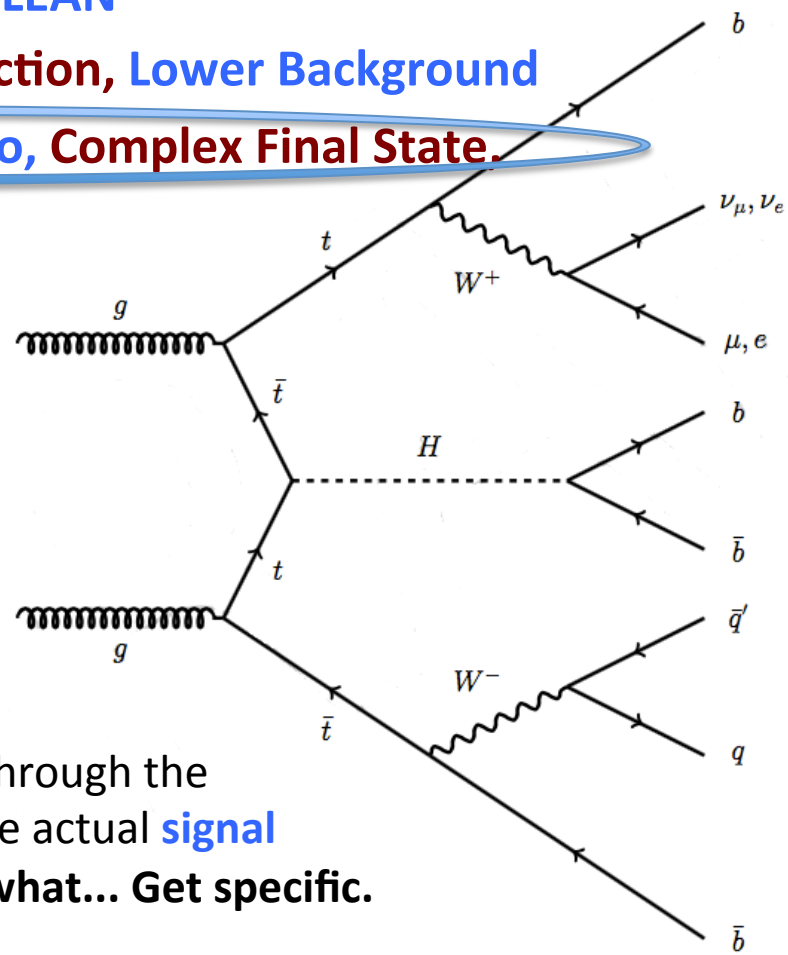
Searching for ttH

- Searches at CMS for ttH:
  - tt + ϒϒ: H→ϒϒ **Lower Production, VERY CLEAN**
  - tt + leptons: H→ WW,ZZ,ττ **Lower Production, Lower Background**
  - tt + b's: H→bb **Dominant Branching Ratio, Complex Final State.**



tt+bb

- In addition to standard **tt production**, gluon going to bb can mimic our signal



- Need to be able to sift through the **background** to get to the actual **signal**

How do we select what's what... Get specific.

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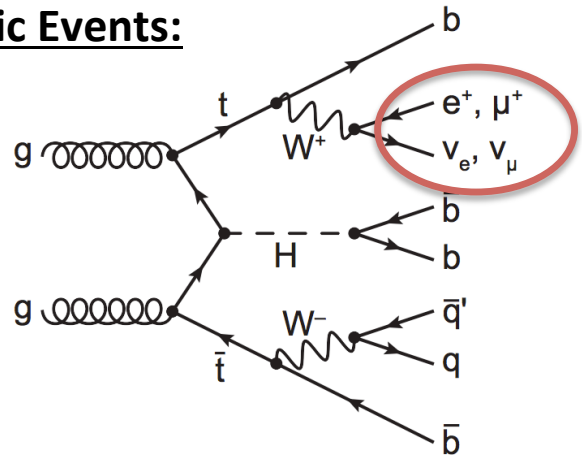
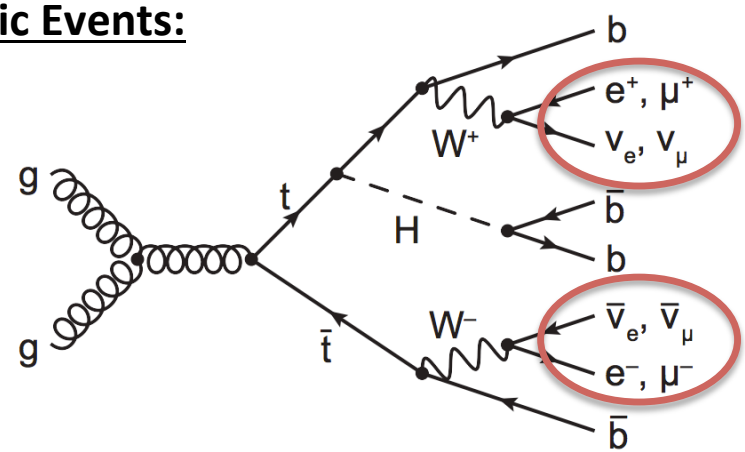
Event Selection: SL or DL

Semileptonic Events:



- Exactly 1 lepton(e or μ)
  - Veto events with additional identifed leptons to ensure no overlap with dileptonic events.
  - pt > 25GeV(e),30GeV(μ)
  - $|\eta| < 2.1$
  - $\Delta R = 0.3(e), 0.4(\mu)$ isolation
- At least 4 jets among which atleast 2 are b-tagged.
- OR fulfill boosted event selection
  - Boosted t and H (pt ≥ 200GeV)

Dileptonic Events:



- Exactly 2 oppositely charge leptons(e or μ)
  - Leading lepton pt > 20GeV
  - Subleading lepton pt > 15GeV
  - Both $|\eta|<2.4$
  - $\Delta R = 0.3$ isolation
- Invariant mass of lepton pair > 20 GeV
- Same flavor channels:
  - 76 GeV < m_{ll} < 106GeV
  - missing Et > 40 GeV
- At least 2 jets with p_T > 30GeV and $|\eta| < 2.4$
  - Other jets > 20GeV

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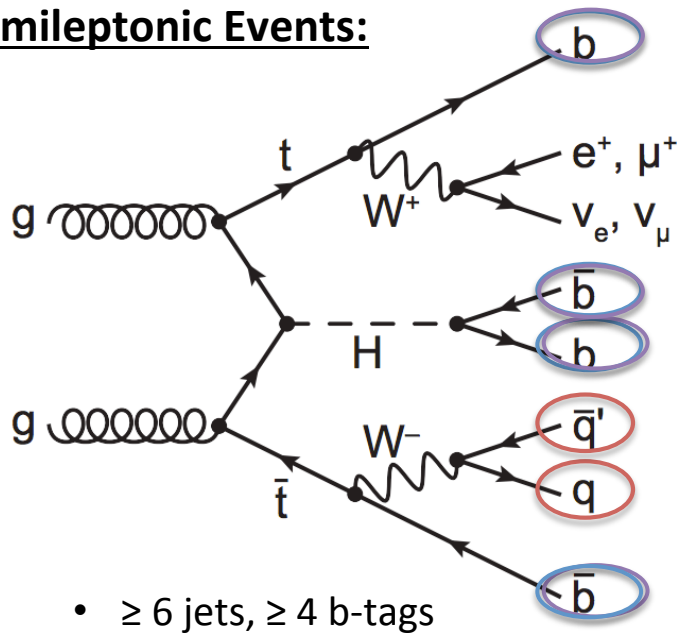
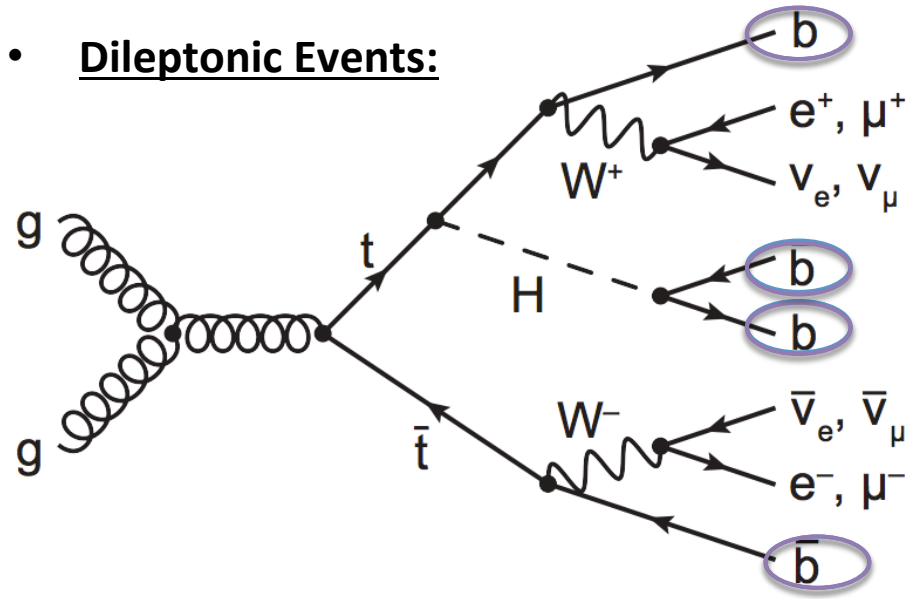
Event Classification: Njets & b-tags

- **Semileptonic Events:**



  - ≥ 6 jets, ≥ 4 b-tags
  - ≥ 6 jets, ≥ 3 b-tags
  - ≥ 6 jets, ≥ 2 b-tags
  - 5 jets, ≥ 4 b-tags
  - 5 jets, 3 b-tags
  - 4 jets, 3 b-tags

- **Dileptonic Events:**



  - ≥ 4 jets, ≥ 4 b-tags
  - ≥ 4 jets, 3 b-tags
  - 4 jets, 2 b-tags
  - 3 jets, 3 b-tags
  - 3 jets, 2 b-tags

With events categorized, easier to compare signal and background for differences …

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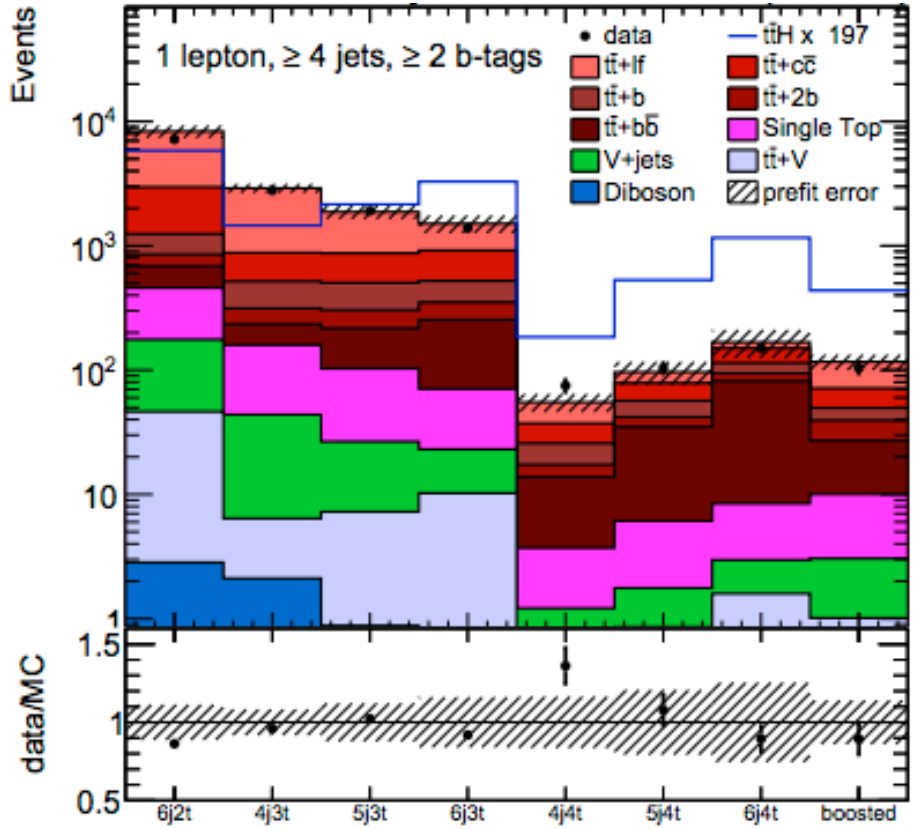
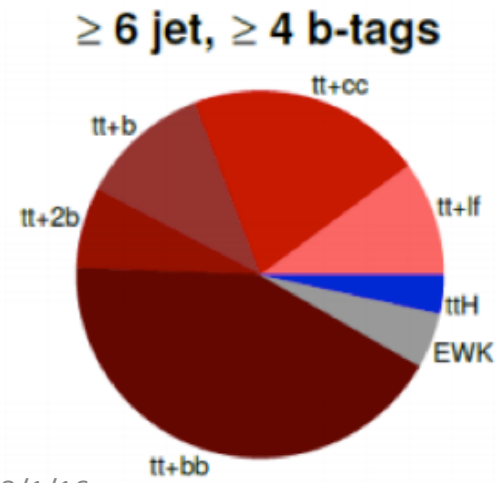
Data MC Comparison

- **Signal** and **Background** both modeled with Monte Carlo
  - ttH Signal modeled with PYTHIA8
  - ttW,ttZ,W+jets modeled with MADGRAPH
  - tt background modeled with POWHEG and PYTHIA8 (More on this…)
- Simulated and observed event yields with expected **signal(scaled up)** overlaid showed for lepton+jets categories



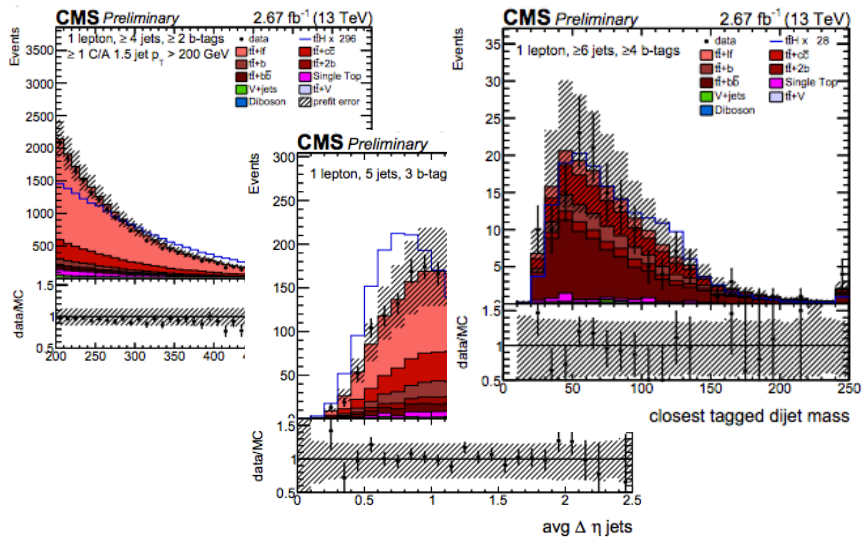
HIG-16-038

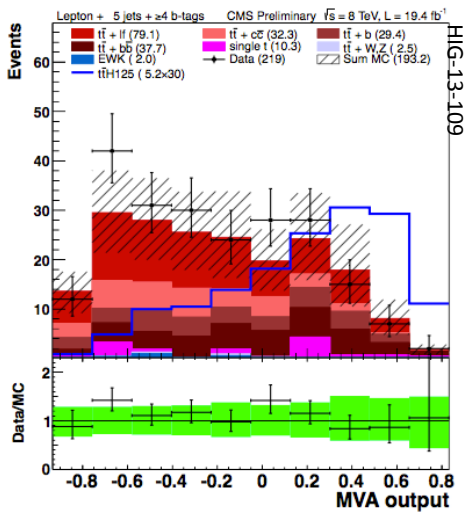


Simulated breakdown for **signal** rich region in semileptonic…

Analysis Strategy

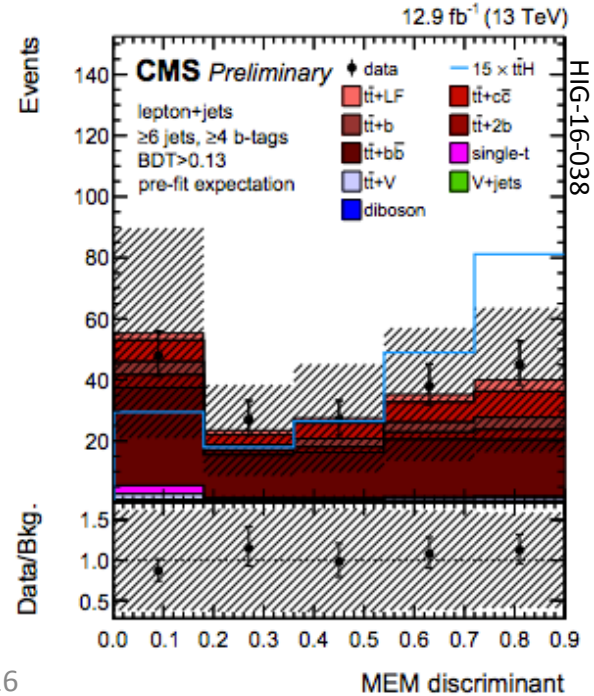
- ttH signal **drowned out** by large tt+jets background.
  - No one powerful separating variable
  - Use Multivariate analysis techniques such as Boosted Decision Trees (BDT) to exploit higher dimensional correlations among them.
  - Training on MC with each category using separate variables
- BDT input variables combined
  - Use physics objects kinematic information (Pt, event shape…)
  - BDT can further resolve these events → Inclusion of MEM into BDT

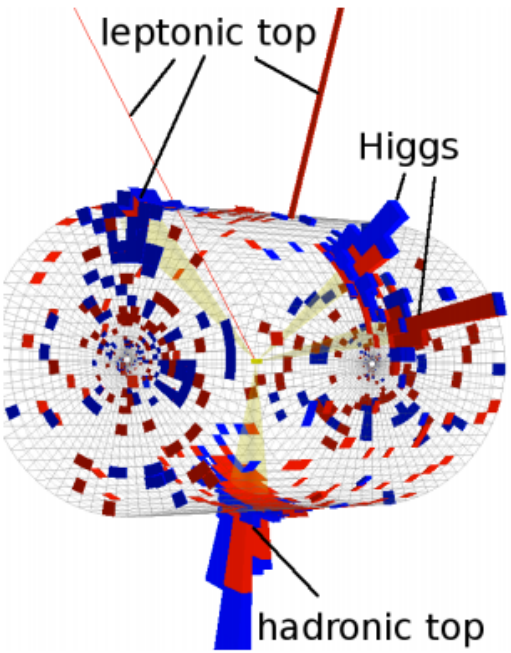




Matrix Element Method (MEM)

- Calculates the differential probability density of measuring a set of observables (y) under the hypothesis that the event is generated by a specific process (i)
- Provides separation between null hypothesis (signal) and the alternative hypothesis (background)
- Parton showering and detector response simulated with transfer functions from simulation (GEANT4)

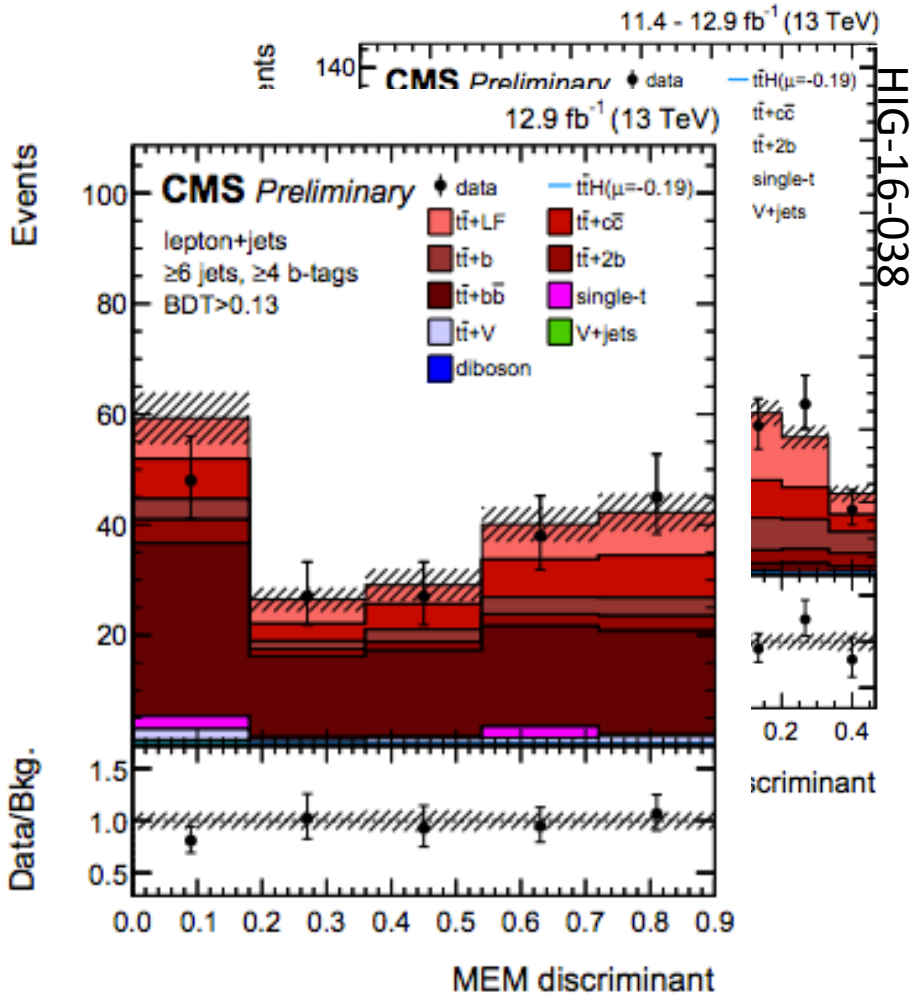




$$P(\mathbf{y}|\lambda) = \frac{w_0(\mathbf{y}|\lambda)}{w_0(\mathbf{y}|\lambda) + w_1(\mathbf{y}|\lambda)}$$

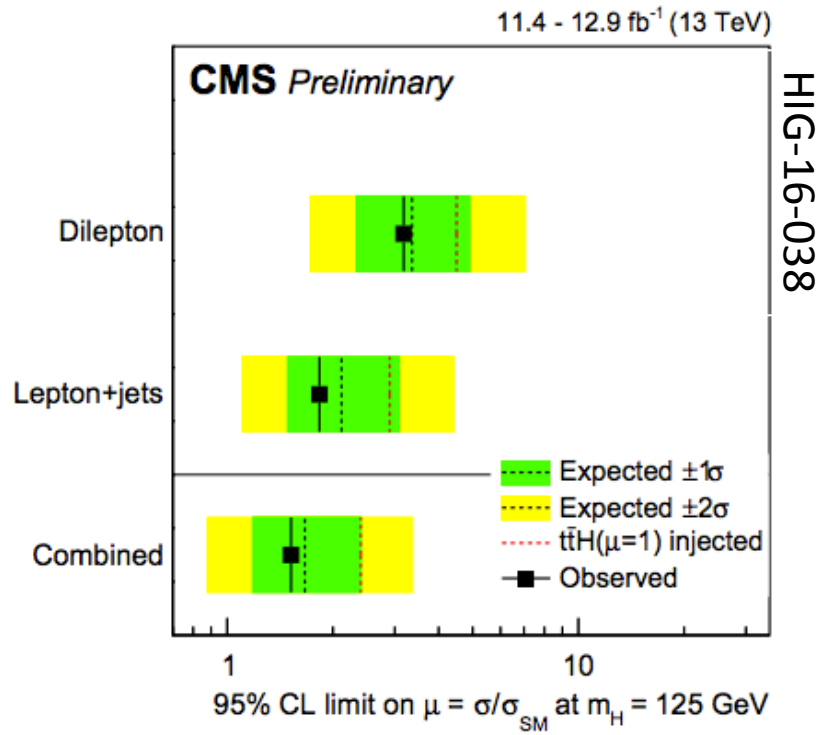
Final Discriminants

- Final discriminator shape for lepton + jets
  - 6jets, ≥4 b-tags shown right
- Final discriminant outputs provide better separation than any single input variable.
  - Performed across all event categories…



Results from 13TeV

- We incorporate BDT discriminate shapes from each category and perform a **simultaneous fit** across all.
- Seeing no excess, and without sufficient sensitivity to probe the expected-SM-level content, we place upper limits using up to 12.9 fb $^{-1}$ of pp collision data



Combining results from Semileptonic and Dileptonic

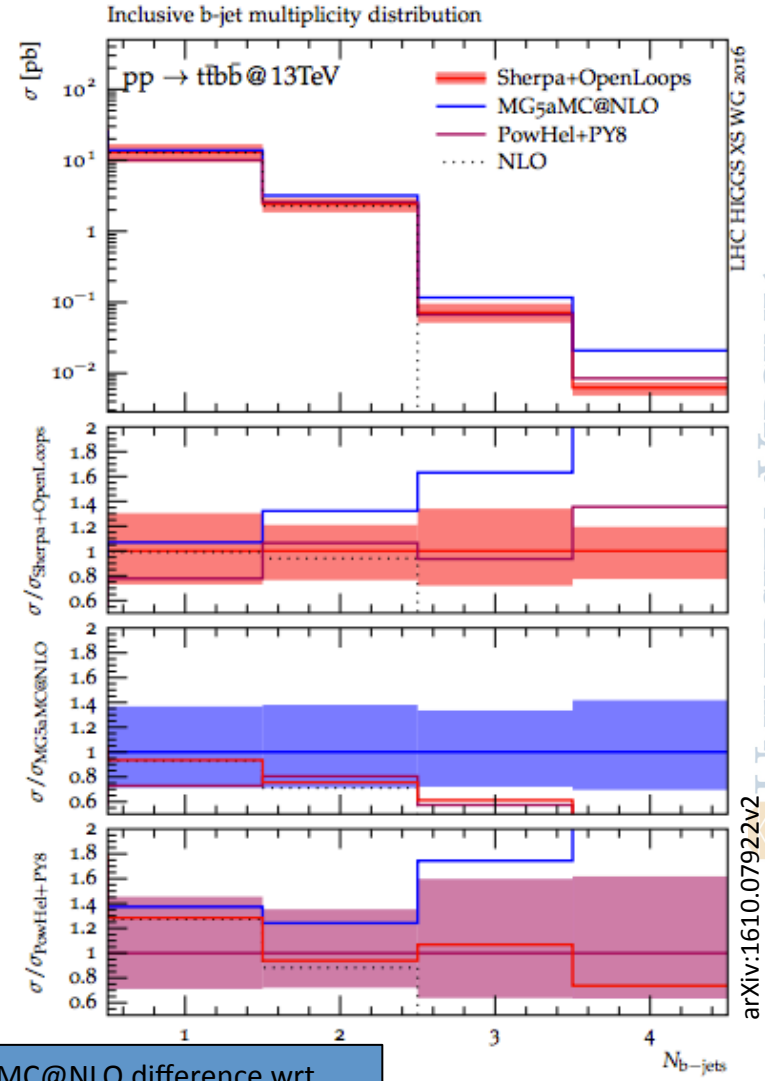
Channel	Observed UL	Expected UL	Best-fit μ
Dilepton	3.2	$3.4^{+1.5}_{-1.0}$	$-0.04^{+1.50}_{-1.39}$(tot.) $^{+1.05}_{-0.96}$(stat.) $^{+1.01}_{-1.06}$(syst.)
Lepton+jets	1.8	$2.1^{+1.0}_{-0.6}$	$-0.43^{+1.02}_{-1.02}$(tot.) $^{+0.51}_{-0.52}$(stat.) $^{+0.88}_{-0.87}$(syst.)
Combined	1.5	$1.7^{+0.7}_{-0.5}$	$-0.19^{+0.80}_{-0.81}$(tot.) $^{+0.45}_{-0.44}$(stat.) $^{+0.66}_{-0.68}$(syst.)

Ongoing Studies

- Background uncertainties (….background itself) still dominate our systematics
- Specifically tt+bb produced FAR more often than ttH(Hbb) and appear seemingly identical in final state
- Dependency on MC background modeling to help identify discriminating variables in kinematics

<u>Accurate Predictions from MC ARE A MUST!</u>

- Several new NLO predictions are now available in ME+PS event generators
- Studying the state of the art ME+PS tools is crucial. Two-fold approach:
  - Examine consistency when tested under equivalent conditions (ttH/tH portion of HXSWG YR4, and followups)
  - Compare to ttbb-enriched control regions -- how do the predictions compare to observations of this process?

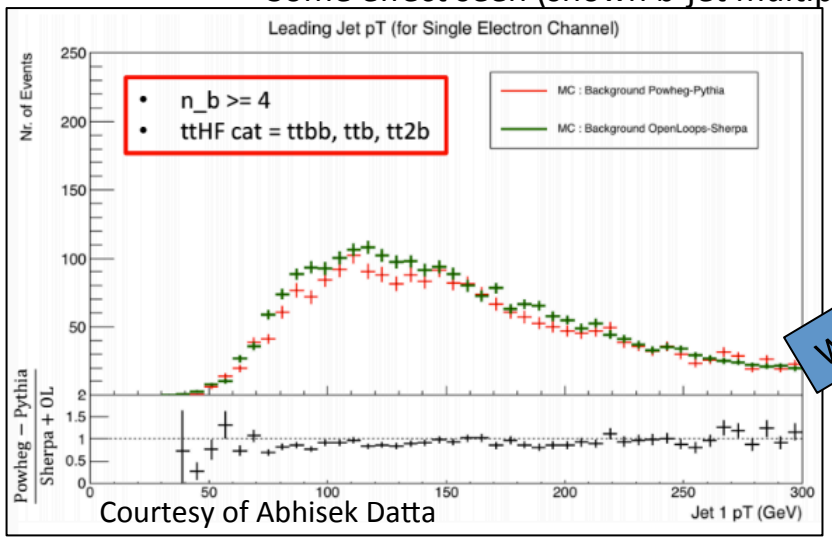


arXiv:1610.07922v2

MG5_aMC@NLO difference wrt Sherpa+OpenLoops in YR4 puzzling

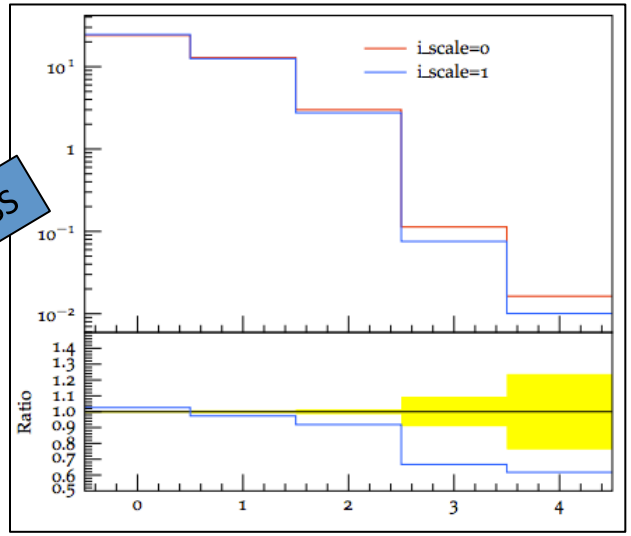
MC Modeling and Comparisons

- POWHEG+PYTHIA8 for ttbar modelling
  - tt+bb events make up small fraction of events(< 1%)
  - More statistics required for kinematic studies, modeling validation
- Sherpa+OpenLoops sample for comparisons
  - Dedicated tt+bb sample recently generated
  - ttbar inclusive sample underway…
- MadGraph5_aMC@NLO
  - MG5_aMC@NLO difference wrt Sherpa+OpenLoops in YR4 puzzling… Dissimilar shower starting scale values hypothesized
  - At UVA testing new version of MG5_aMC@NLO allowing for adjustment of shower starting scale
  - Some effect seen (shown b-jet multiplicity) but more remains



Courtesy of Abhisek Datta

WORK IN PROGRESS



Courtesy of Andrew Orvedahl

Data Driven Studies Not YetPublic

Outlook for End of 2017

- Improvements for analysis already underway:
  - Increased luminosity… MORE DATA
  - MC samples incorporating tunes with refined α_s and h_{damp} variables for better agreement to data
    - Njet distribution, jet pt…
  - Constraining background uncertainties

Formal Write Up Coming SOON…

Going forward with plans to make first observation of ttH(Hbb) production at 13TeV with Run II dataset at CMS

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THANK YOU

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BACKUP

- BDT Input Variables
  - Object and Event Kinematics:
    - Mass and pt variables
      - 4 highest transverse jet momenta
      - Scalar Sum of all jet transverse momenta (HT)
    - Angular Variables
      - ΔR between b-tagged jets, ΔR between lepton and closest jet
      - $\Delta\eta$ between b-tagged jets
    - Event Reconstruction related variables
      - Best Higgs Mass
      - Median Invariant Mass of all combinations of b-tagged jet pairs
      - Scalar Sum of transverse momentum of all b-tagged jets and leptons
      - Invariant mass of 3-jet system with largest tansverse momentum where atleast 2 jets are b-tagged
      - Centrality
      - Twist Angle
    - CSVv2IVF b-tag
    - MEM Discriminator
      - Lepton+Jets uses as input

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Event Yields: Semileptonic

Table 1: $t\bar{t}H$ and background event yields for lepton+jets categories. The processes and the separation of the $t\bar{t}$ +jets sample are described in Section 3. The uncertainties in the expected yields include the statistical as well as all the systematic contributions. Cases where no events pass the event selection are marked as "—".

Process	≥ 6 jets, 3 b-tags	4 jets, 4 b-tags	5 jets, ≥ 4 b-tags	≥ 6 jets, ≥ 4 b-tags
$t\bar{t}$+LF	2710.6 ± 1027.1	91.4 ± 69.9	96.9 ± 75.8	86.2 ± 71.9
$t\bar{t}$+$c\bar{c}$	1771.9 ± 1099.0	59.3 ± 47.0	112.5 ± 88.9	175.8 ± 141.6
$t\bar{t}$+b	717.6 ± 406.8	37.6 ± 23.1	69.6 ± 42.4	86.3 ± 57.0
$t\bar{t}$+2b	401.4 ± 237.1	16.0 ± 9.9	33.8 ± 20.6	54.9 ± 37.3
$t\bar{t}$+$b\bar{b}$	777.0 ± 468.4	42.2 ± 23.8	126.5 ± 71.6	306.3 ± 183.2
Single t	331.9 ± 77.2	19.2 ± 7.8	29.5 ± 11.4	30.0 ± 10.8
V+jets	79.5 ± 30.9	5.7 ± 6.8	7.7 ± 5.1	7.2 ± 3.9
$t\bar{t}$+V	81.4 ± 17.0	2.2 ± 0.6	6.3 ± 1.7	18.1 ± 5.2
Diboson	4.3 ± 2.3	0.5 ± 0.5	—	—
Total bkg.	6875.6 ± 2776.8	274.1 ± 153.0	482.9 ± 239.7	764.8 ± 365.3
$t\bar{t}H$	74.2 ± 9.7	4.0 ± 0.8	11.7 ± 2.2	26.9 ± 5.6
Data	6811	376	551	787

Event Yields: Dilepton

Table 2: $t\bar{t}H$ and background event yields for dilepton categories. The processes and the separation of the $t\bar{t}$ +jets sample are described in Section 3. The uncertainties in the expected yields include the statistical as well as all the systematic contributions. Cases where no events pass the event selection are marked as "—".

Process	3 jets, 3 b-tags	$\geq$ 4 jets, 3 b-tags	$\geq$ 4 jets, $\geq$ 4 b-tags
$t\bar{t}$+LF	179.0 ± 68.7	390.1 ± 167.9	7.6 ± 3.6
$t\bar{t}$+$c\bar{c}$	117.5 ± 73.8	382.6 ± 237.7	19.4 ± 15.5
$t\bar{t}$+b	94.2 ± 51.9	228.0 ± 127.7	14.4 ± 9.2
$t\bar{t}$+2b	31.7 ± 17.3	99.1 ± 54.3	6.2 ± 3.8
$t\bar{t}$+$b\bar{b}$	17.1 ± 9.4	172.5 ± 92.9	57.9 ± 32.6
Single t	16.0 ± 4.6	38.4 ± 11.9	2.4 ± 1.2
V+jets	1.6 ± 2.2	1.6 ± 4.1	0.7 ± 0.5
$t\bar{t}$+V	1.4 ± 0.5	16.6 ± 3.4	2.6 ± 0.8
Diboson	—	0.4 ± 0.4	—
Total bkg.	458.3 ± 197.0	1329.3 ± 503.1	111.2 ± 49.8
$t\bar{t}H$	1.8 ± 0.4	16.5 ± 3.4	4.4 ± 1.3
Data	498	1469	146

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Systematic Uncertainties

Source	Type	Notes
Luminosity	lnN	Signal and all backgrounds
Lepton ID/trigger efficiency	shape	Signal and all backgrounds
Pileup	shape	Signal and all backgrounds
Jet Energy Scale	shape	Signal and all backgrounds
b-Tag HF fraction	shape	Signal and all backgrounds
b-Tag HF stats (linear)	shape	Signal and all backgrounds
b-Tag HF stats (quadratic)	shape	Signal and all backgrounds
b-Tag LF fraction	shape	Signal and all backgrounds
b-Tag LF stats (linear)	shape	Signal and all backgrounds
b-Tag LF stats (quadratic)	shape	Signal and all backgrounds
b-Tag Charm (linear)	shape	Signal and all backgrounds
b-Tag Charm (quadratic)	shape	Signal and all backgrounds
QCD Scale ($t\bar{t}H$)	lnN	Scale uncertainty for NLO $t\bar{t}H$ prediction
QCD Scale ($t\bar{t}$)	lnN	Scale uncertainty for NLO $t\bar{t}$ prediction
QCD Scale ($t\bar{t}$+HF)	lnN	Additional scale uncertainty for NLO $t\bar{t}$+HF predictions
QCD Scale (t)	lnN	Scale uncertainty for NLO single top prediction
QCD Scale (V)	lnN	Scale uncertainty for NNLO W and Z prediction
QCD Scale (VV)	lnN	Scale uncertainty for NLO diboson prediction
pdf (gg)	lnN	Pdf uncertainty for gg initiated processes except $t\bar{t}H$ ($t\bar{t}$, $t\bar{t}Z$)
pdf ($gg t\bar{t}H$)	lnN	Pdf uncertainty for $t\bar{t}H$
pdf ($q\bar{q}$)	lnN	Pdf uncertainty for $q\bar{q}$ initiated processes ($t\bar{t}W$, W, Z).
pdf (qg)	lnN	Pdf uncertainty for qg initiated processes (single top)
Q2 Scale ($t\bar{t}$)	shape	Renormalization and factorization scale uncertainties of the $t\bar{t}$ ME generator, independent for additional jet flavors
PS Scale ($t\bar{t}$)	shape	Renormalization and factorization scale uncertainties of the parton shower (for $t\bar{t}$ events), independent for additional jet flavors

DRAFT

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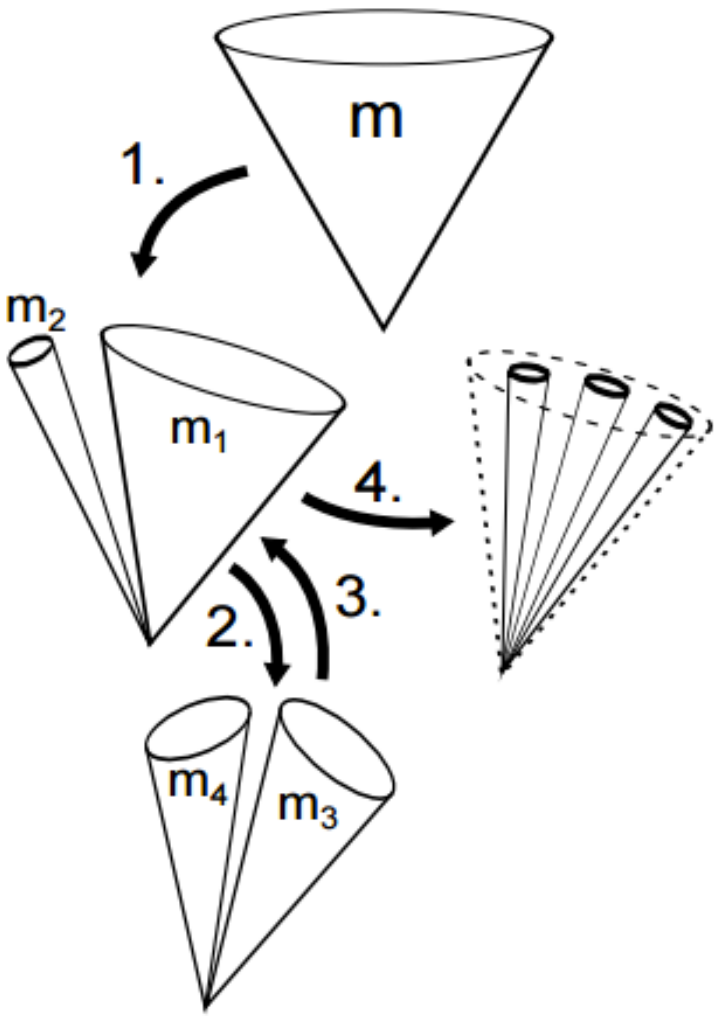
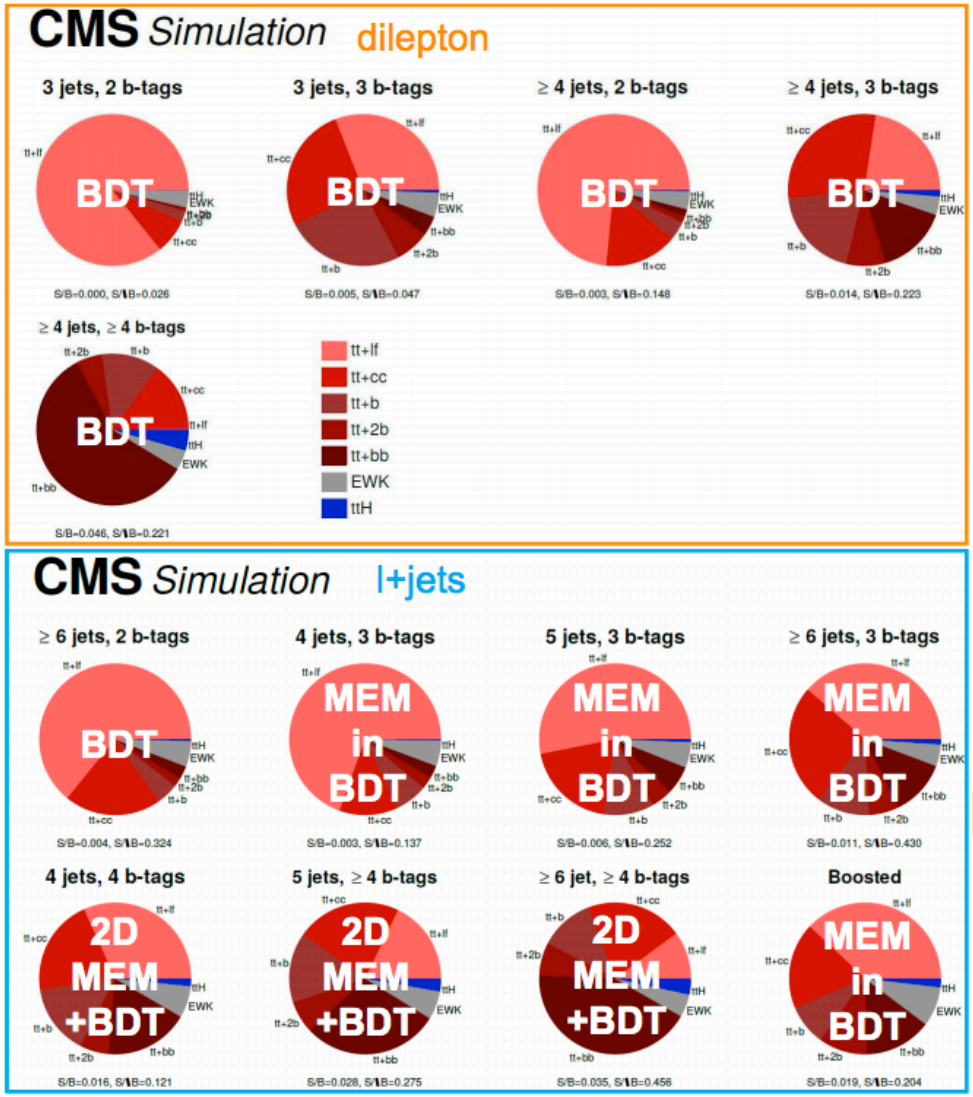
Boosted Analysis: Higgs

- Declustering fat jets
- Find subjets from invariant mass
- Jet Grooming
- Returns number of jets



BDT and MEM: Final Discriminants

- In lepton + jets (semileptonic) events the BDT and MEM discriminants are combined
- Boosted Category events (both top and Higgs)
  - BDT used as final discriminant
  - Sensitivity increases from reduced combinatorics in reconstructed objects from both top and Higgs



References

- "Search for ttH production in the H → bb decay channel with s = 13TeV pp collisions at the CMS experiment" - CMS PAS HIG-16-004
- "First results on ttH with H→bb at 13 TeV" – CMS AN-15-216
- "Search for the associated ttH(→bb) production using the Matrix Element Method" – CMS AN-13-313
- "Search for ttH production in boosted topologies" – GRK Plenary Workshop 2015, Shawn Williamson
- "Results and Prospects for ttH at CMS" – 51st Rencontres de Moriond EW 2016, Johannes Hauk

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Event Yields: Lepton+Jets

Process	≥ 6 jets, 2 b-tags	4 jets, 3 b-tags	5 jets, 3 b-tags	≥ 6 jets, 3 b-tags
$t\bar{t}$+lf	5359.3 ± 1226.3	2026.1 ± 651.4	1000.2 ± 352.9	589.5 ± 199.7
$t\bar{t} + c\bar{c}$	1722.2 ± 849.5	363.2 ± 190.9	368.1 ± 191.3	396.6 ± 209.5
$t\bar{t}$+b	393.7 ± 188.2	203.1 ± 92.5	199.6 ± 90.8	170.8 ± 81.4
$t\bar{t}$+2b	165.2 ± 81.2	78.9 ± 38.0	87.2 ± 40.7	97.3 ± 46.8
$t\bar{t} + b\bar{b}$	226.4 ± 113.2	75.8 ± 35.3	114.1 ± 52.3	183.7 ± 86.7
Single Top	283.0 ± 49.0	115.3 ± 30.8	76.2 ± 19.5	47.5 ± 12.7
V+jets	130.5 ± 35.2	38.6 ± 17.8	22.8 ± 10.4	13.6 ± 6.4
$t\bar{t}$+V	43.5 ± 8.2	4.3 ± 1.2	6.4 ± 1.8	10.0 ± 2.7
Diboson	2.8 ± 1.3	2.1 ± 1.3	0.9 ± 0.5	0.2 ± 0.3
Total bkg	8326.7 ± 1788.6	2907.4 ± 836.5	1875.5 ± 534.7	1509.1 ± 423.7
$t\bar{t}H$	29.6 ± 2.1	7.4 ± 1.0	10.9 ± 1.2	16.7 ± 2.1
Data	7185	2793	1914	1386
S/B	0.0036	0.0026	0.0059	0.011
Data/B	0.9 ± 0.2	1.0 ± 0.3	1.0 ± 0.3	0.9 ± 0.3

Process	4 jets, ≥ 4 b-tags	5 jets, ≥ 4 b-tags	≥ 6 jets, ≥ 4 b-tags	boosted
$t\bar{t}$+lf	17.8 ± 10.8	17.7 ± 10.9	17.6 ± 11.3	45.1 ± 9.4
$t\bar{t} + c\bar{c}$	11.6 ± 8.2	22.1 ± 15.4	35.9 ± 24.9	21.8 ± 12.0
$t\bar{t}$+b	8.4 ± 4.4	14.8 ± 7.7	20.0 ± 10.9	10.3 ± 5.5
$t\bar{t}$+2b	3.5 ± 1.9	6.9 ± 3.7	12.3 ± 6.9	12.3 ± 6.6
$t\bar{t} + b\bar{b}$	10.1 ± 4.9	28.8 ± 13.9	73.4 ± 36.6	17.0 ± 8.4
Single Top	2.5 ± 1.1	4.3 ± 1.4	5.5 ± 2.0	7.0 ± 1.7
V+jets	1.0 ± 0.8	0.9 ± 0.8	1.4 ± 0.7	2.5 ± 0.8
$t\bar{t}$+V	0.3 ± 0.1	0.7 ± 0.3	1.6 ± 0.6	0.9 ± 0.3
Diboson	0.0 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	0.1 ± 0.1
Total bkg	55.2 ± 23.0	96.5 ± 37.6	167.6 ± 65.7	117.0 ± 24.9
$t\bar{t}H$	0.9 ± 0.2	2.7 ± 0.6	5.9 ± 1.4	2.2 ± 0.3
Data	75	104	150	104
S/B	0.017	0.028	0.035	0.019
Data/B	1.4 ± 0.5	1.1 ± 0.4	0.9 ± 0.4	0.9 ± 0.2

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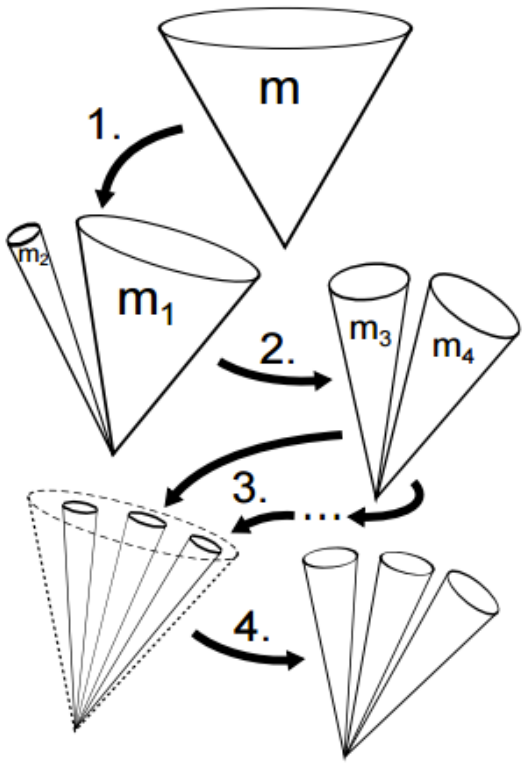
Event Yields: Dilepton

	3 jets, 2 b-tags	3 jets, 3 b-tags	$\geq$ 4 jets, 2 b-tags	$\geq$ 4 jets, 3 b-tags	$\geq$ 4 jets, $\geq$ 4 b-tags
$t\bar{t}$+lf	2558.6 ± 542.7	26.6 ± 10.5	2271.6 ± 505.0	60.3 ± 25.6	0.9 ± 0.8
$t\bar{t} + c\bar{c}$	220.9 ± 103.4	22.7 ± 13.6	478.4 ± 234.4	78.4 ± 45.4	3.4 ± 2.9
$t\bar{t}$+b	65.4 ± 28.5	21.4 ± 10.2	126.2 ± 57.7	52.2 ± 25.1	2.7 ± 1.6
$t\bar{t}$+2b	16.9 ± 7.6	6.6 ± 3.1	42.9 ± 20.2	22.3 ± 10.7	1.2 ± 0.7
$t\bar{t} + b\bar{b}$	8.6 ± 4.2	3.6 ± 1.8	48.9 ± 23.7	39.8 ± 18.8	13.4 ± 7.1
Single Top	93.2 ± 16.7	3.0 ± 1.0	87.6 ± 15.8	7.3 ± 2.5	0.4 ± 0.4
V+jets	14.5 ± 11.0	1.3 ± 0.8	16.0 ± 7.4	0.0 ± 0.0	0.0 ± 0.0
$t\bar{t}$+V	3.6 ± 0.9	0.3 ± 0.2	16.4 ± 3.2	3.2 ± 0.9	0.5 ± 0.2
Diboson	1.7 ± 0.9	0.0 ± 0.0	1.2 ± 1.0	0.1 ± 0.0	0.0 ± 0.0
Total bkg	2983.4 ± 590.4	85.6 ± 25.6	3089.2 ± 650.6	263.6 ± 79.9	22.5 ± 9.8
$t\bar{t}H$	1.4 ± 0.2	0.4 ± 0.1	8.1 ± 1.1	3.6 ± 0.6	1.0 ± 0.3
Data	3123	115	2943	319	27
S/B	0.00047	0.0051	0.0026	0.014	0.046
Data/B	1.0 ± 0.2	1.3 ± 0.4	1.0 ± 0.2	1.2 ± 0.3	1.2 ± 0.5

Boosted Analysis

- Large fraction of events at 13TeV include top quarks and Higgs bosons with $p_T \geq 200$ GeV
  - Boosted jet reconstruction techniques favorable
  - Implements HEP Top Tagger + sub-jet filtering
- Candidates require:
  - Exactly one selected lepton (only semi-leptonic)
  - $|\eta| < 2.0$
  - No sharing of subjets between hadronic top and Higgs



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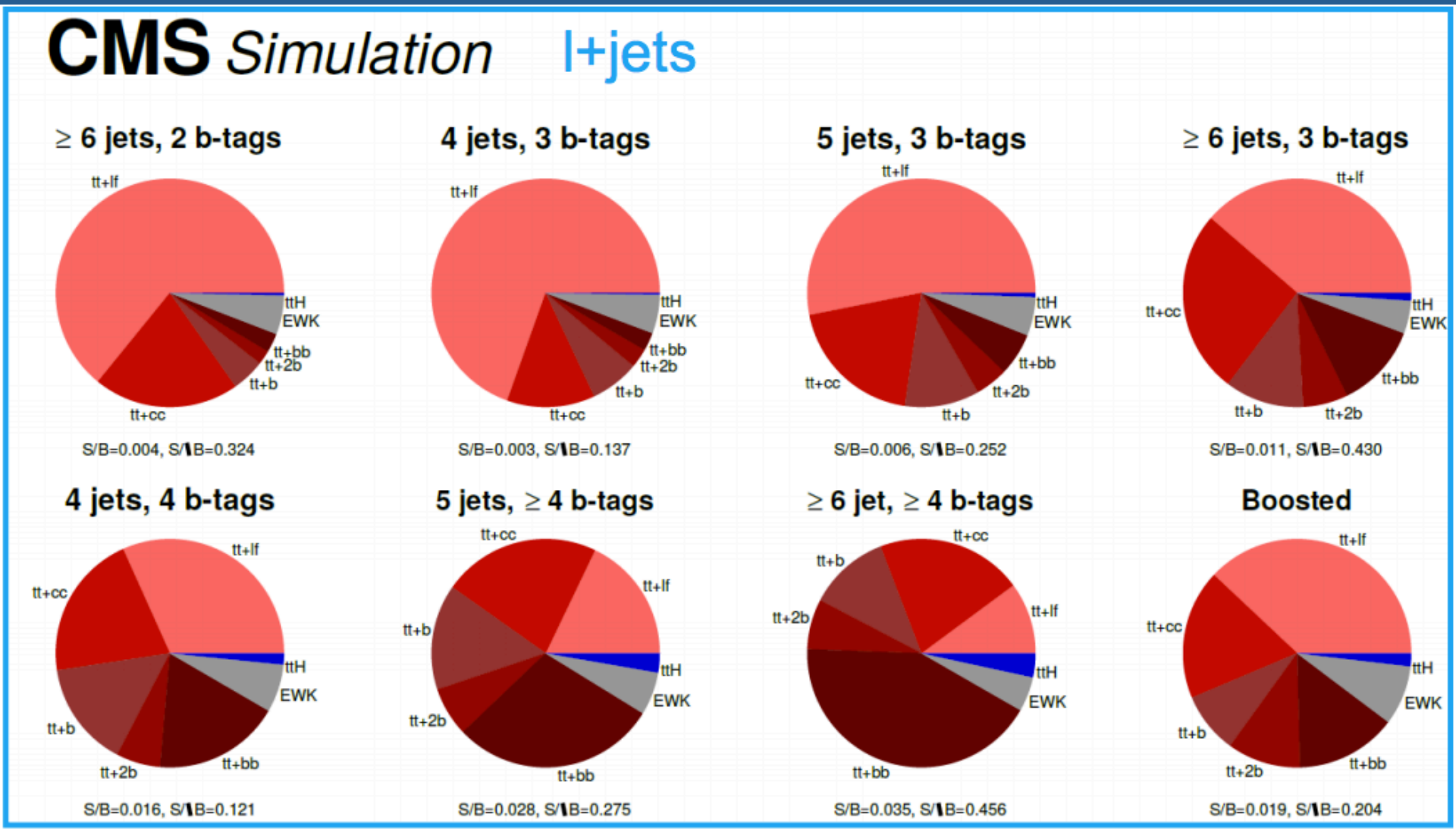
Event Classification



BDT Input Variables: Semileptonic

4 jets, 3 tags	4 jets, 4 tags
avg CSV (tags) jet 2 p_T $\sum p_T$(jets,lepton,MET) b-tagging likelihood ratio H_1 jet 4 p_T avg CSV (all)	closest tagged dijet mass $\sum p_T$(jets,lepton,MET) b-tagging likelihood ratio avg ΔR(tag,tag) H_3 jet 1 p_T

5 jets, 3 tags	5 jets, $\geq$ 4 tags
H_1 b-tagging likelihood ratio third-highest CSV avg ΔR(tag,tag) avg $\Delta\eta$(jet,jet) min ΔR(lepton,jet) max $\Delta\lvert\eta\rvert$ (tag, avg tags $\lvert\eta\rvert$) avg CSV (tags)	b-tagging likelihood ratio jet 3 p_T tagged dijet mass closest to 125 avg $\Delta\eta$(jet,jet) avg ΔR(tag,tag) H_1 fifth-highest CSV (Σ jet p_T)/(Σ jet E)

$\geq$ 6 jets, 2 tags	$\geq$ 6 jets, 3 tags	$\geq$ 6 jets, $\geq$ 4 tags
avg $\Delta\eta$(tag,tag) avg ΔR(tag,tag) ΔR(jet1, jet2) b-tagging likelihood ratio max $\Delta\lvert\eta\rvert$ (tag, avg tags $\lvert\eta\rvert$) third-highest CSV sphericity fourth-highest CSV max $\Delta\lvert\eta\rvert$ (tag, avg jet $\lvert\eta\rvert$) min ΔR(tag,tag)	avg CSV (tags) min ΔR(lepton,jet) H_1 $\sum p_T$(jets,lepton,MET) b-tagging likelihood ratio HT $\sqrt{\Delta\eta(t^{lep}, bb) \times \Delta\eta(t^{had}, bb)}$ third-highest CSV fourth-highest CSV	$\sum p_T$(jets,lepton,MET) H_3 best higgs mass b-tagging likelihood ratio tagged dijet mass closest to 125 fifth-highest CSV (Σ jet p_T)/(Σ jet E) jet 4 p_T sphericity max $\Delta\lvert\eta\rvert$ (tag, avg tag $\lvert\eta\rvert$) second-highest CSV

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BDT Input Variables: Dileptonic

3 jets, 2 tags	3 jets, 3 tags	≥4 jets, 2 tags	≥4 jets, 3 tags	≥4 jets, ≥4 tags
$\langle d \rangle_{untagged}$	$\langle d \rangle_{tagged}$	median $m_{jet,jet}$	min $\Delta R_{tag,tag}$	min $\Delta R_{tag,tag}$
$\sum p_{T\,jets,leptons}$	$m^{min\Delta R}_{tag,tag}$	H_1/H_0(tags)	$\langle d \rangle_{untagged}$	median $m_{jet,jet}$
$\tau^{\text{max mass}}_{jet,jet}$	$m^{\text{max mass}}_{tag,tag}$	$m^{min\Delta R}_{jet,jet}$	$\langle d \rangle_{tagged}$	max $\Delta\eta_{tag,tag}$
min $\Delta R_{tag,tag}$	max $\Delta\eta_{jet,jet}$	$\langle d \rangle_{untagged}$	$m^{min\Delta R}_{tag,tag}$	$M^{jj}_{higgs-like}$
max $\Delta\eta_{tag,tag}$	H_4/H_0(tags)	$H_2(jets)$	$M^{jj}_{higgs-like}$	H_T^{tags}
$m^{min\Delta R}_{jet,jet}$	$H_1(jets)$	$\sum p_{T\,jets,leptons}$	max $\Delta\eta_{tag,tag}$	$\langle d \rangle_{tagged}$
$M^{jj}_{higgs-like}$	$\tau^{\text{max mass}}_{jet,jet}$	$\langle \Delta R_{jet,tag} \rangle$	$\langle \Delta R_{jet,tag} \rangle$	$m^{min\Delta R}_{jet,tag}$
$m^{min\Delta R}_{tag,tag}$	$\sum p_{T\,jets,leptons}$	H_T^{jets}	$H_2(tags)$	$m^{min\Delta R}_{jet,jet}$
	min $\Delta R_{jet,jet}$	$m^{min\Delta R}_{tag,tag}$	$\sum p_{T\,jets,leptons}$	$m^{\text{max mass}}_{tag,tag}$
	$M^{bj}_{higgs-like}$	$p_{T\,jet,tag}^{min\ \Delta R}$	$\tau^{\text{max mass}}_{tag,tag}$	max $\Delta\eta_{jet,jet}$
			Centrality(jets & leptons)	Centrality(jets & leptons)
			$m^{\text{max } p_T}_{jet,jet,jet}$	Centrality(tags)

Boosted Analysis: Higgs Discriminator

- CSV(B2) shows highest discriminator value in identifying true boosted Higgs over fake candidates.

Systematic Uncertainties

- Sources of systematic uncertainty affecting event yields (signal or background), discriminant shape, or both.

Process	$t\bar{t}$ rate up/down [%]	$t\bar{t}H$ rate up/down [%]
Jet energy scale	$+12.6/-11.8$	$+8.4/-8.0$
Jet energy resolution	$+0.2/-0.3$	$-0.0/-0.1$
Pile-up	$+0.1/-0.1$	$-0.2/+0.1$
Electron efficiency	$+0.5/-0.5$	$+0.5/-0.5$
Muon efficiency	$+0.4/-0.4$	$+0.4/-0.4$
Electron trigger efficiency	$+1.2/-1.2$	$+1.3/-1.3$
Muon trigger efficiency	$+0.8/-0.8$	$+0.9/-0.9$
b-Tag HF contamination	$-9.4/+9.8$	$-2.6/+2.8$
b-Tag HF stats (linear)	$-3.1/+3.3$	$-2.5/+2.7$
b-Tag HF stats (quadratic)	$+2.6/-2.4$	$+2.4/-2.2$
b-Tag LF contamination	$+7.1/-5.2$	$+5.8/-4.5$
b-Tag LF stats (linear)	$-2.0/+4.4$	$+0.5/+1.5$
b-Tag LF stats (quadratic)	$+2.1/+0.2$	$+1.5/+0.5$
b-Tag charm Uncertainty (linear)	$-11.1/+14.9$	$-3.1/+4.1$
b-Tag charm Uncertainty (quadratic)	$+0.5/-0.5$	$-0.0/+0.0$
Q^2 scale ($t\bar{t}$+LF)	$-6.2/+7.5$	–
Q^2 scale ($t\bar{t}$+b)	$-1.7/+2.0$	–
Q^2 scale ($t\bar{t}$+2b)	$-1.1/+1.4$	–
Q^2 scale ($t\bar{t}$+$b\bar{b}$)	$-2.0/+2.5$	–
Q^2 scale ($t\bar{t}$+$c\bar{c}$)	$-4.3/+5.4$	–
PS scale ($t\bar{t}$+LF)	$+4.8/-9.0$	–
PS scale ($t\bar{t}$+b)	$-0.9/+0.7$	–
PS scale ($t\bar{t}$+2b)	$-0.8/+0.9$	–
PS scale ($t\bar{t}$+$b\bar{b}$)	$-1.5/+2.7$	–
PS scale ($t\bar{t}$+$c\bar{c}$)	$-3.9/+3.0$	–

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