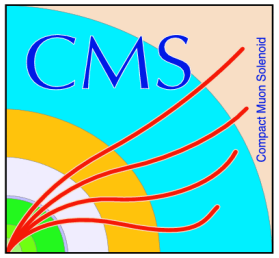


Search for Higgs bosons produced in association with top quark pairs in the CMS detector

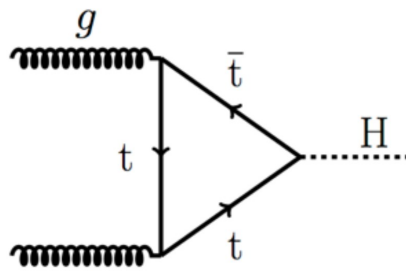
Gerrit Van Onsem (DESY)

LHC discussions DESY
Hamburg, Germany
February 13th, 2017

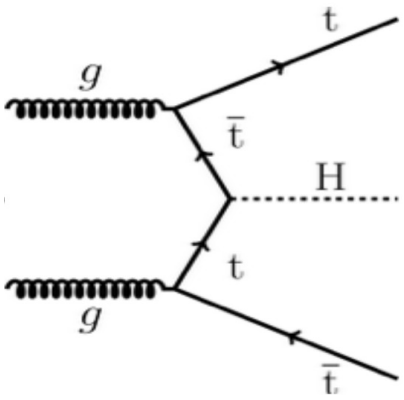
Probing the ttH coupling at the LHC

> **Top-Higgs Yukawa coupling y_t** probed at LHC

- H production via gluon fusion
  indirect measurement of y_t
  potential new particles in loop



- H production in association with top quarks (ttH)
  direct measurement of y_t



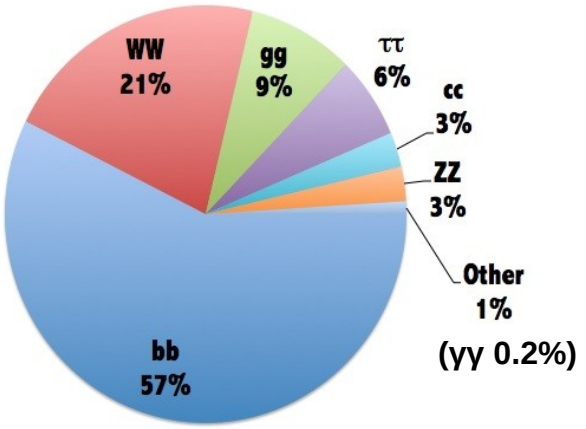
> **Experimental challenges** of search for ttH

- ttH cross section very small (~510 fb at 13 TeV)
  large backgrounds such as tt+jets, ttZ/ttW, ...
- H signature diluted by additional jets or leptons from t decays

> CMS analyzed **12.9 / fb of 13 TeV data** in 2016,
SM sensitivity of **ttH production getting into reach**

Signatures searched for in CMS

- Rich experimental program, final states depend on t→bW and H decay products



- **tt+(H→bb)** **CMS-PAS-HIG-16-038**
  - single lepton
  - opposite-sign dileptons DESY

large H branching ratio, large tt background

- **tt+(H→WW*, ZZ*, ττ)** **CMS-PAS-HIG-16-022**
  - same-sign dileptons
  - trileptons

small H branching ratio, relatively pure, difficult fake lepton background

- **tt+(H→ γγ)** **CMS-PAS-HIG-16-020**
  - inclusive tt decays

very small H branching ratio, pure, difficult fake photon background

tt + (H → bb)

selection and (jet,b-jet) event categorization
background vs signal separation (BDT, MEM)
signal extraction and results

tt + (H → WW*, ZZ*, ττ)

selection and non-prompt lepton rejection
background vs signal separation (BDT, MEM)
signal extraction and results

tt + (H → γγ)

selection
background estimation
signal extraction and results

Summary and outlook

tt + (H → bb)

selection and (jet,b-jet) event categorization
background vs signal separation (BDT, MEM)
signal extraction and results

tt + (H → WW*, ZZ*, ττ)

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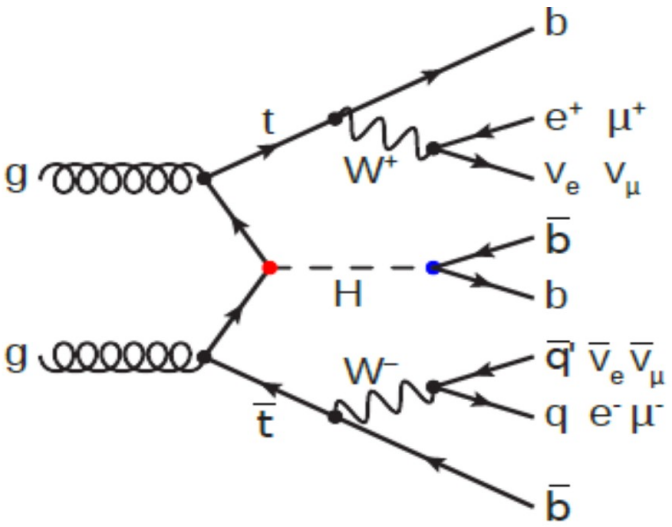
Summary and outlook

Strategy and selection



> Strategy

- Select events compatible with tt→ℓ+jets or tt → ℓℓ and H → bb decay
- Categorize by jets, b-tagged jets
- Separate signal from background using multivariate algorithms
- Signal extraction via fit to data

Single lepton channel

≥ 4 anti-k_T (R=0.4) jets with p_T > 30 GeV, |η| < 2.4

1 isolated electron p_T > 30 GeV or muon p_T > 25 GeV, |η| < 2.1

Dilepton channel

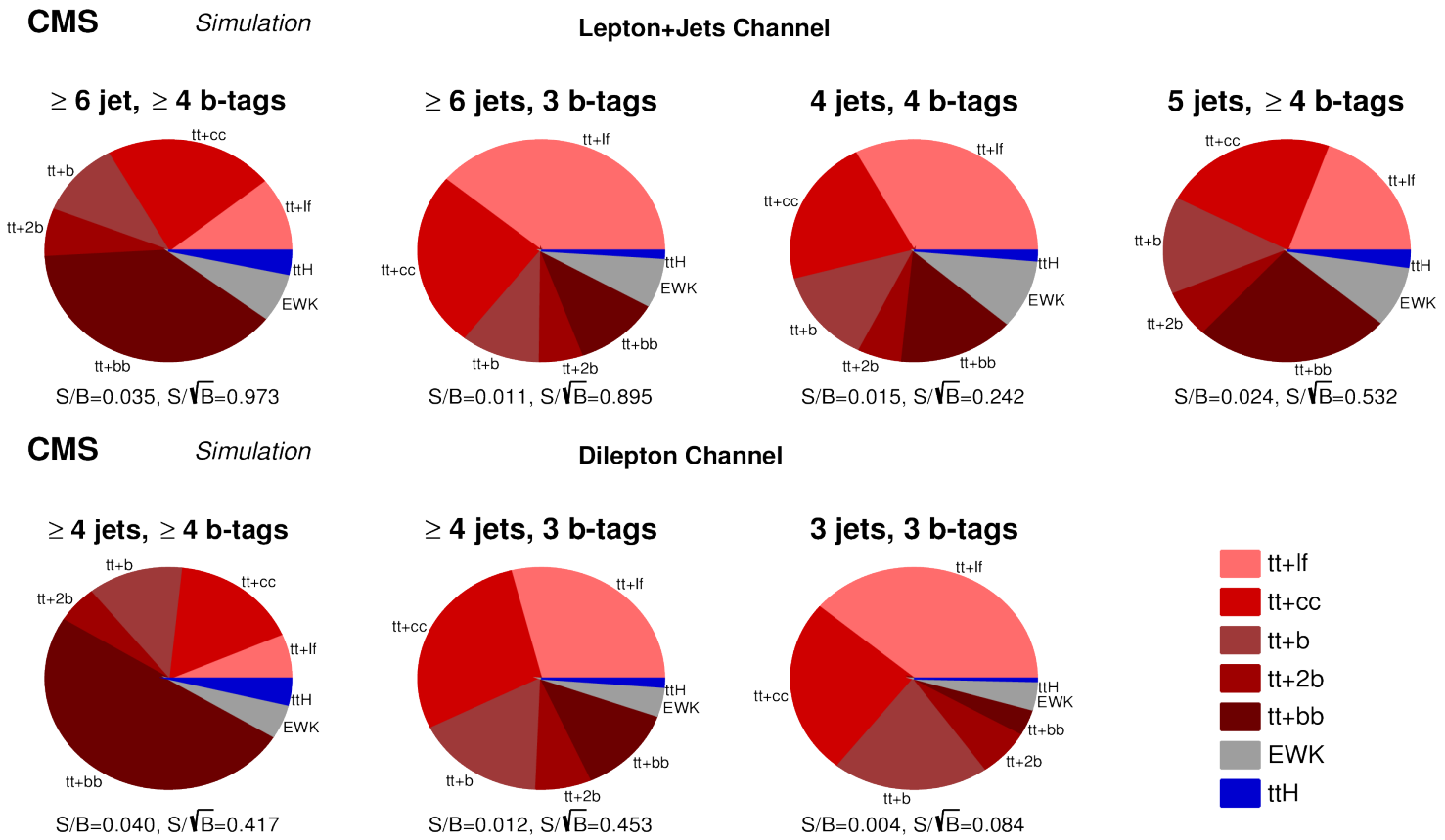
≥ 2 anti-k_T (R=0.4) jets with p_T > 30 GeV, |η| < 2.4

2 oppositely-sign electrons or muons, p^{lead}_T > 25 GeV, $p^{sublead}_T$ > 15 GeV |η| < 2.4

> **Corrections applied** in simulation and/or data (trigger, lepton, jet energy scale and resolutions, b-tagging efficiency, pileup)

Event categorization based on jet and b jets

- **Background simulation** using `POWHEG` (ttH signal, tt+jets, single top), `MG5_aMC@NLO` (V+jets, ttV), or `PYTHIA` (VV)
- **tt+jets sample separated in additional jet flavor components,** based on matching of reconstructed jet with generated hadrons: tt+bb, tt+b, tt+2b, tt+cc, tt+lf (tt+bb irreducible and theoretically challenging)

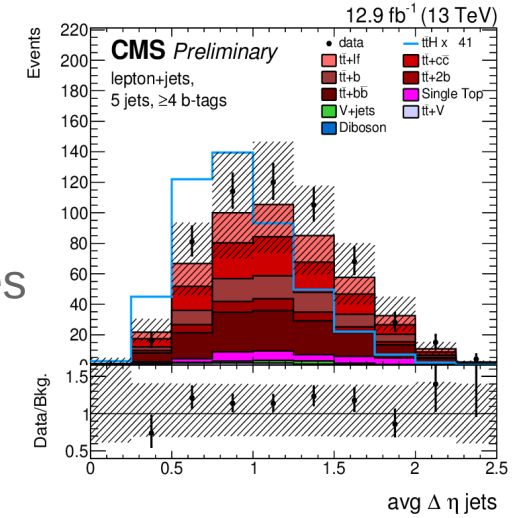


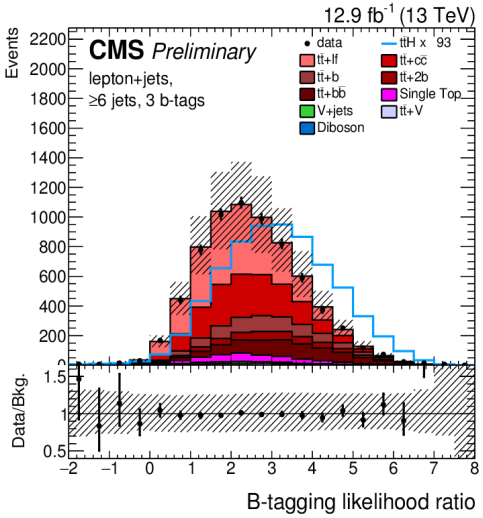
BDT input variable examples

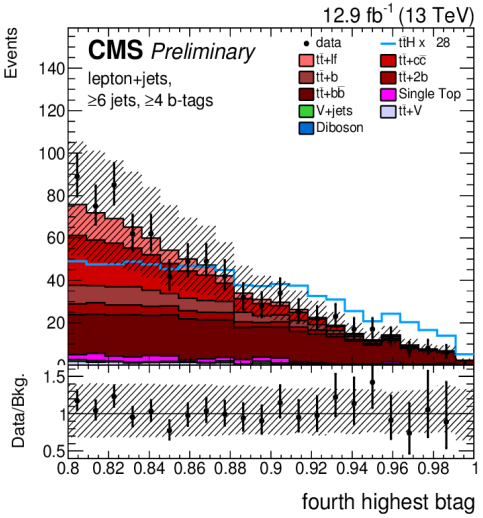
HIG-16-038

> In each (jet,b-jet) category, information from **kinematic, event shape and b-tagging variables** are combined using **Boosted Decision Trees** (BDT)

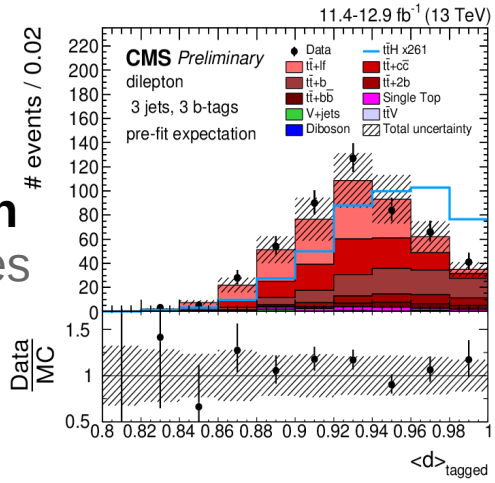
Single lepton examples

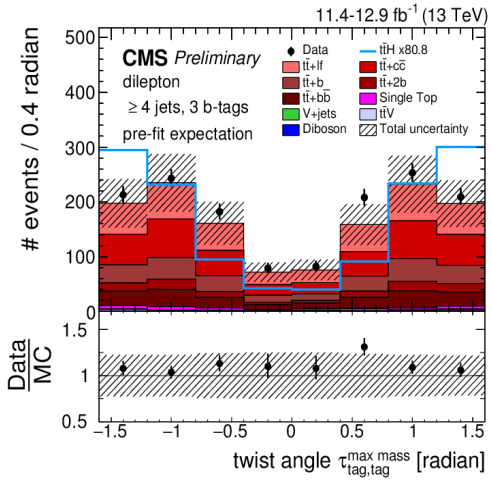


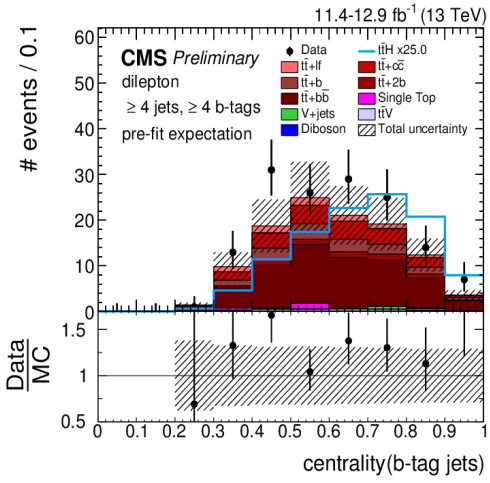




Dilepton examples



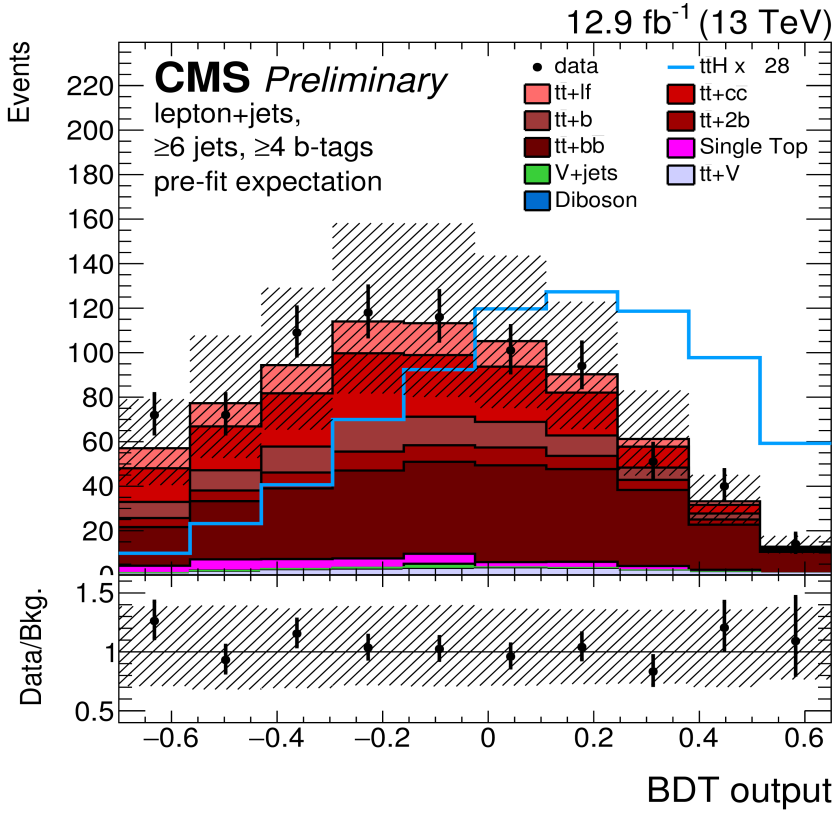




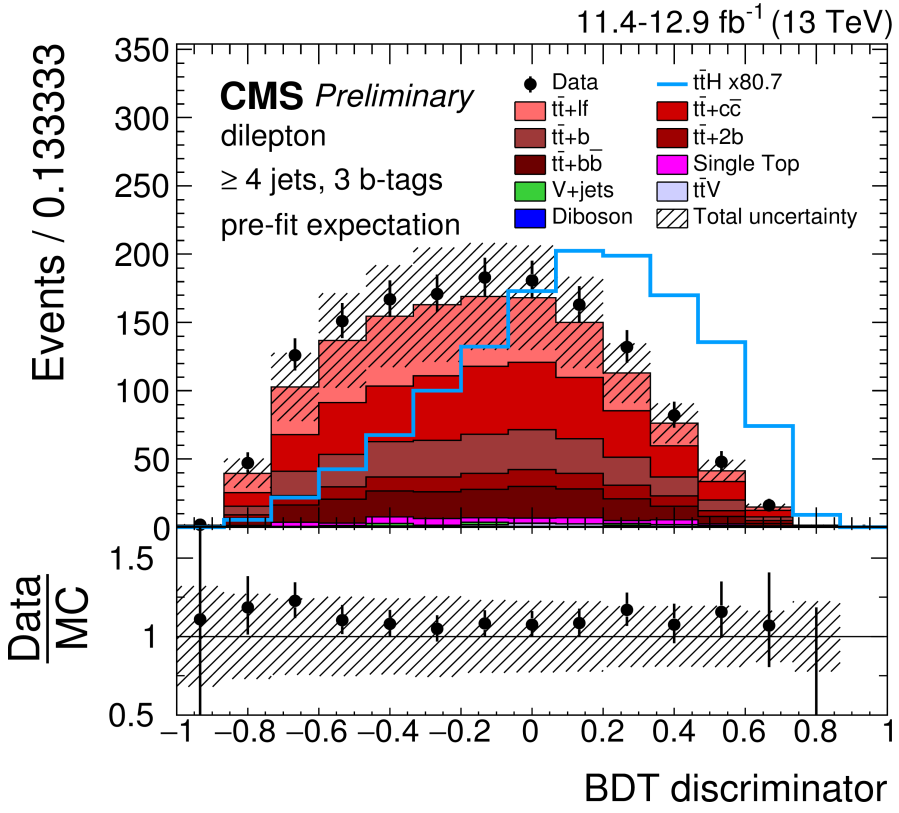
BDT output discriminant examples

HIG-16-038

Single lepton example
≥6 jets, ≥4 b-tags



Dilepton example
≥4 jets, 3 b-tags



Matrix element method (MEM)

- Analytical signal and background probabilities constructed using **full kinematic information of event**
  - *LO matrix elements* from signal tt+(H→bb), background tt+bb
  - Four jets most likely originating from b-quarks considered as *b-quark candidates* in hypotheses
  - *Detector transfer functions* map reconstructed four-vectors of final state particles to generated ones
  - Numerical *integration over phase space*

- Final **MEM variable**: likelihood ratio of weights under different hypotheses

$$P_{\mathrm{s/b}} = \frac{w(\vec{y}|\mathrm{t\bar{t}H})}{w(\vec{y}|\mathrm{t\bar{t}H}) + k_{\mathrm{s/b}} w(\vec{y}|\mathrm{t\bar{t}{+}b\bar{b}})}$$

Systematic uncertainties

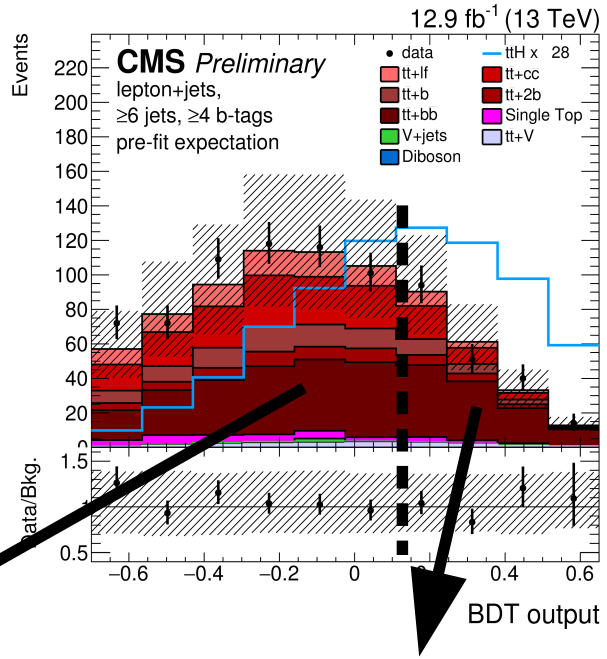
- Uncertainties affecting **shape** (and rate) of BDT and MEM distributions
  - B-tag scale factor uncertainties
  - Jet energy scale and resolution
  - Lepton ID/isolation, trigger efficiency, pileup
  - Q^2 renormalization and factorization scale
  - Bin-by-bin statistical uncertainty on prediction (limited sample size)
- Uncertainties affecting **rate**
  - Normalization of (sub)processes (e.g. 50% additional uncertainty for each tt+heavy flavor component)
  - PDF for different production modes (gg, qq, qg)
  - Parton shower renormalization and factorization scale of tt (1-9% depending on jet flavor component)
  - Luminosity 6.2%
- Systematic uncertainties treated as **nuisance parameters** in fit

Signal extraction using fit

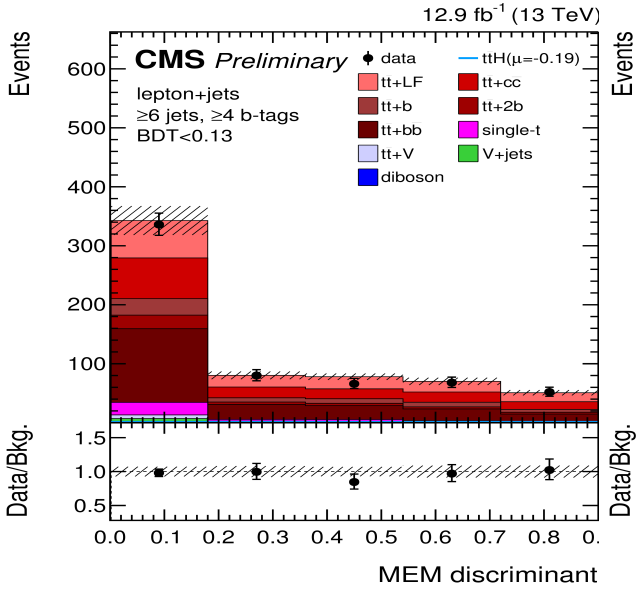
HIG-16-038

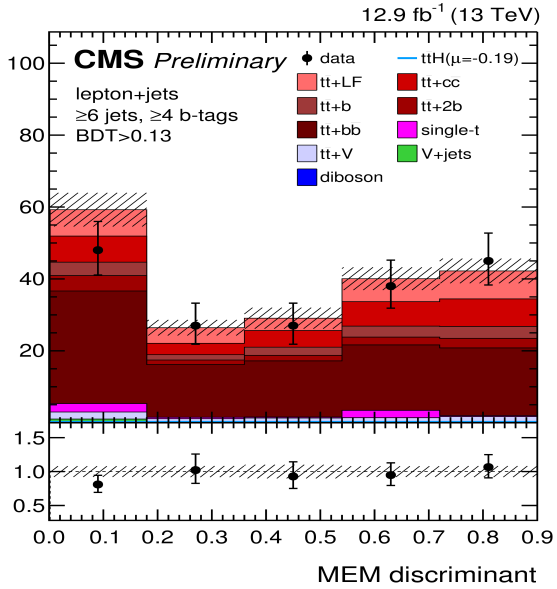
Single lepton channel

	4 jets	5 jets	≥6 jets
3 b-tags			MEM in low and high BDT
≥4 b-tags	MEM in low and high BDT	MEM in low and high BDT	MEM in low and high BDT



- **Split at median ttH** BDT value
- **Fit MEM in each region to data** in bkg and bkg+signal hypotheses



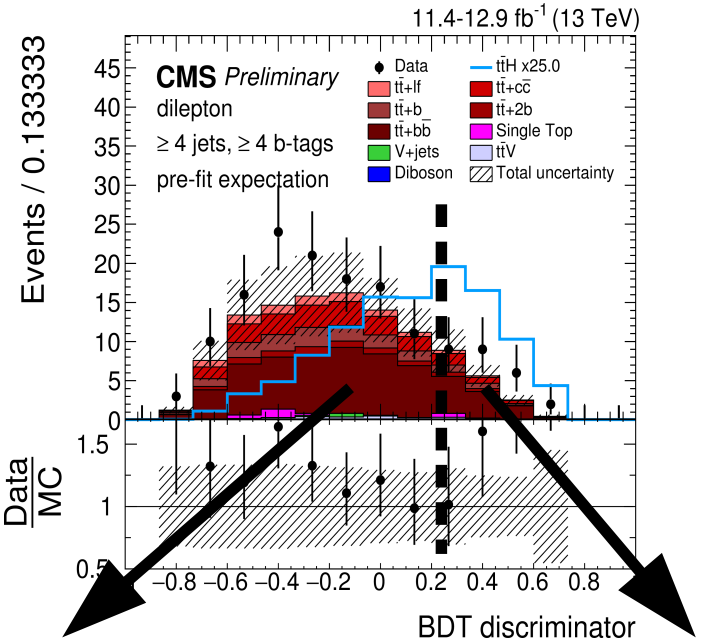


Signal extraction using fit

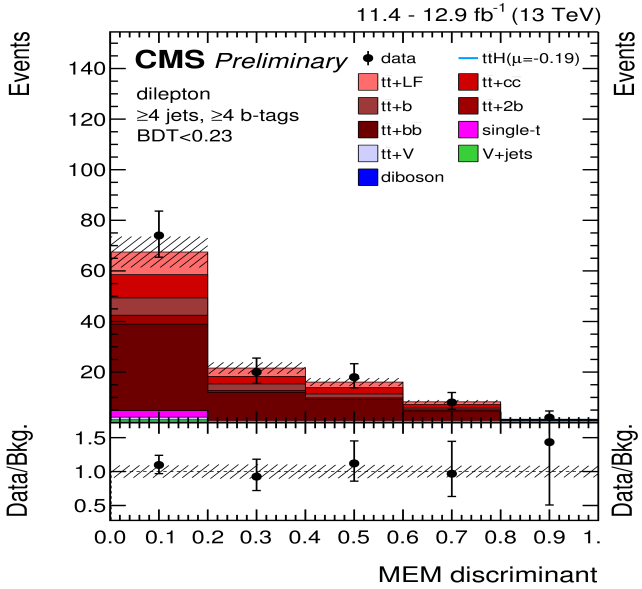
HIG-16-038

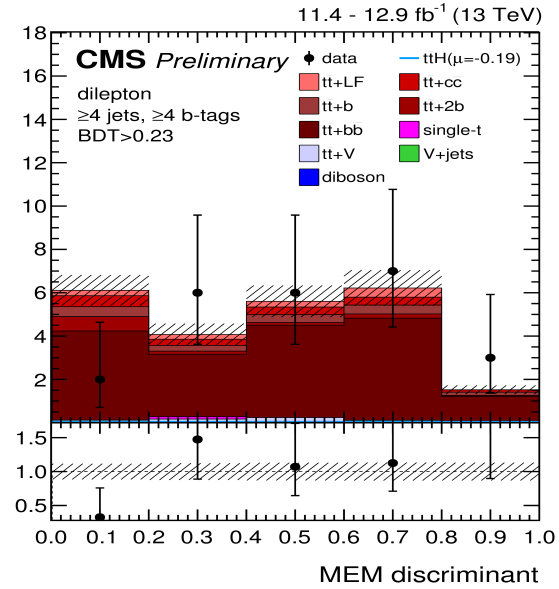
Dilepton channel

	3 jets	≥4 jets
3 b-tags	BDT only	MEM in low and high BDT
≥4 b-tags		MEM in low and high BDT



- **Split at median ttH** BDT value
- **Fit BDT or MEM in each region to data** in bkg and bkg+signal hypotheses

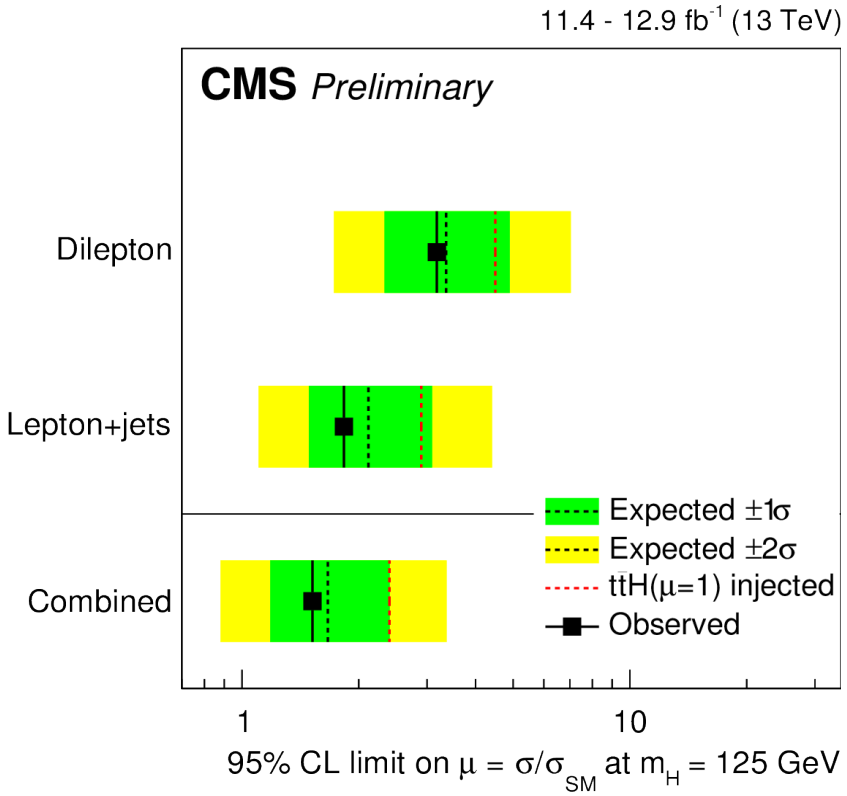


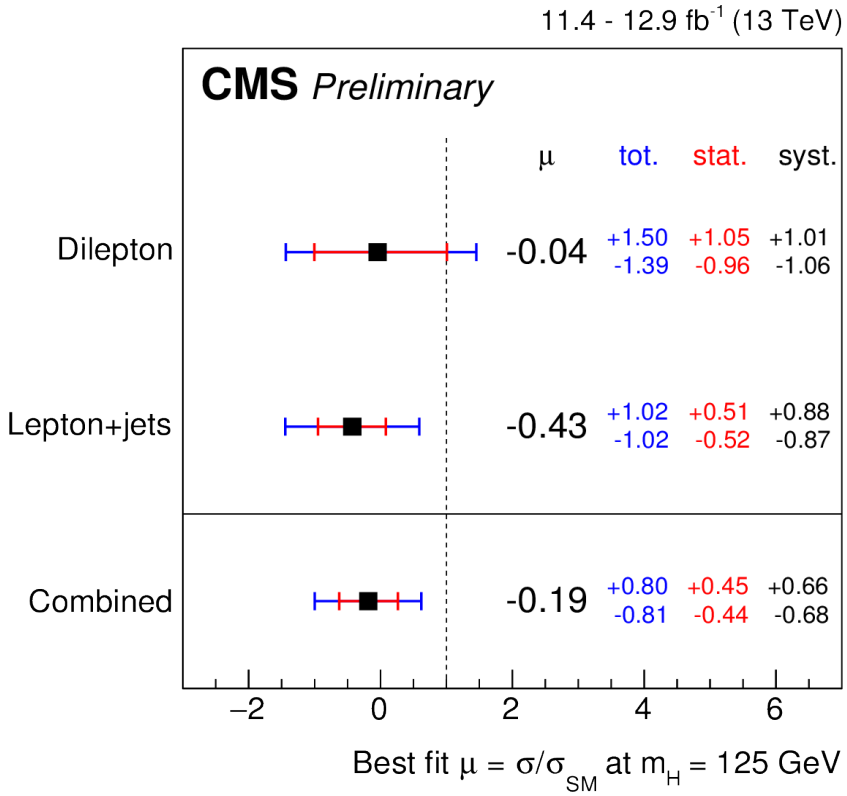


Limits and fit results

> **Simultaneous binned likelihood fit** in both channels

- Combined observed ttH cross section **upper limit = 1.5 σ_{SM}**
- Combined **best-fit ttH signal strength $\sigma/\sigma_{SM} = -0.19^{+0.80}_{-0.81}$**





tt + (H → bb)

selection and (jet,b-jet) event categorization
background vs signal separation (BDT, MEM)
signal extraction and results

tt + (H → WW^{*}, ZZ^{*}, ττ)

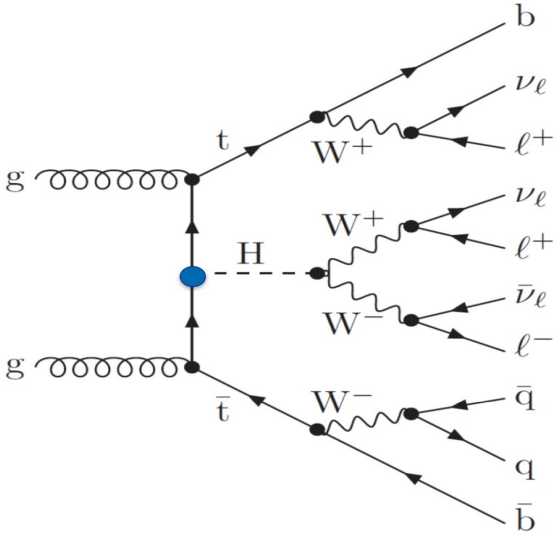
selection and non-prompt lepton rejection
background vs signal separation (BDT, MEM)
signal extraction and results

tt + (H → γγ)

selection
background estimation
signal extraction and results

Summary and outlook

Strategy and selection



> Strategy

- Select events with multilepton final states from Higgs decays to WW^*, ZZ^*, $\tau\tau$
- Dedicated algorithm to identify prompt leptons
- Separate signal from background using multivariate algorithms
- Signal extraction via fit to data

Same-sign dilepton channel

≥ 4 anti-k_T (R=0.4) jets
with p_T > 25 GeV, $|\eta|$ < 2.4

≥ 2 loose or 1 medium b-tag

2 oppositely-sign electrons/muons
p^{lead}_T > 25 GeV, $p^{sublead}_T$ > 15/10 GeV

Z mass window veto
0.6 E^{miss}_T + 0.4 H^{miss}_T > 30 GeV

Three lepton channel

≥ 2 anti-k_T (R=0.4) jets
with p_T > 25 GeV, $|\eta|$ < 2.4

≥ 2 loose or 1 medium b-tag

≥ 3 electrons or muons
p_T > 10 GeV (p^{lead}_T > 25 GeV)

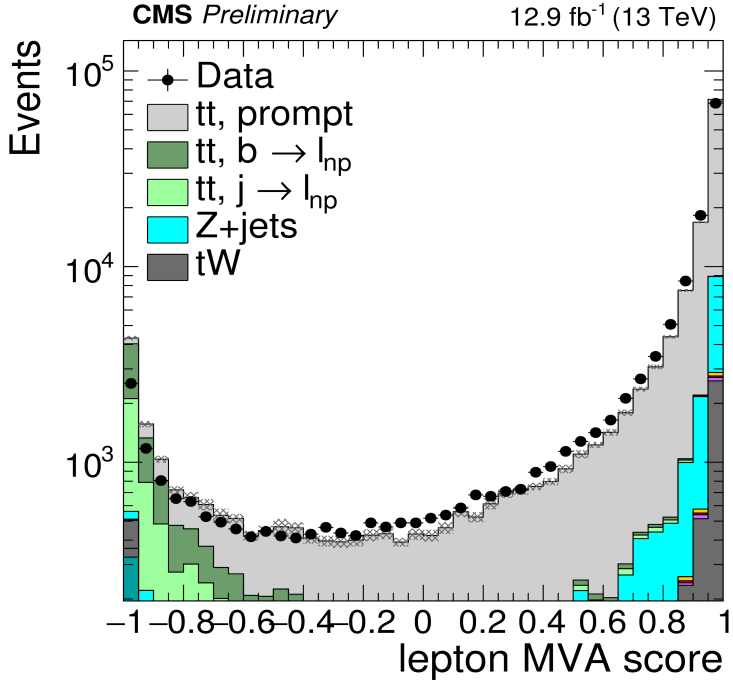
Z mass window veto
[+ cut on 0.6 E^{miss}_T + 0.4 H^{miss}_T]

Rejecting non-prompt leptons

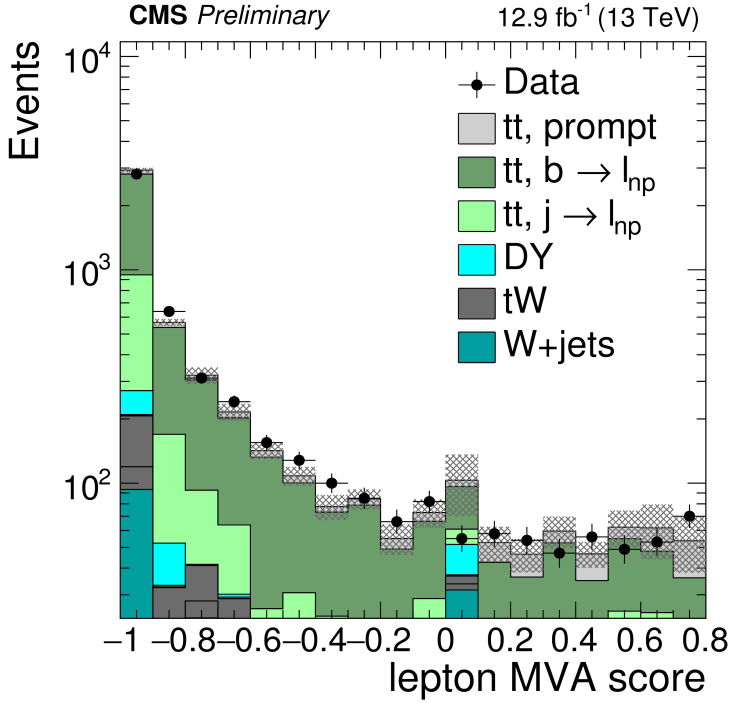
HIG-16-022

- **Non-prompt leptons** from b jets in tt, or mis-identified light jets
- Dedicated **multivariate discriminant** developed, based on isolation, vertex and identification observables

Control region enriched in prompt leptons



Control region enriched in non-prompt leptons

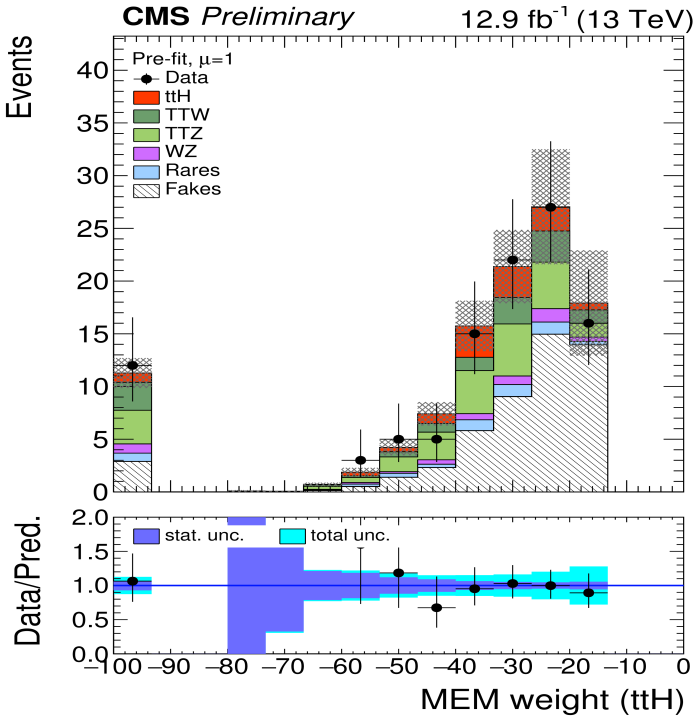


MVA score > 0.75: "tight" lepton selection

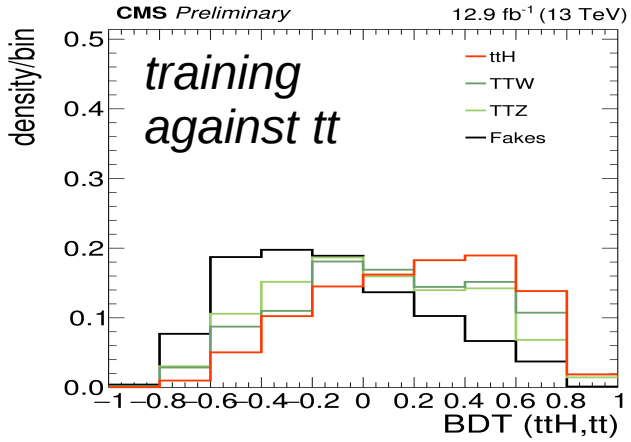
- **Data-driven estimate** of residual non-prompt lepton background using **tight-to-loose method**

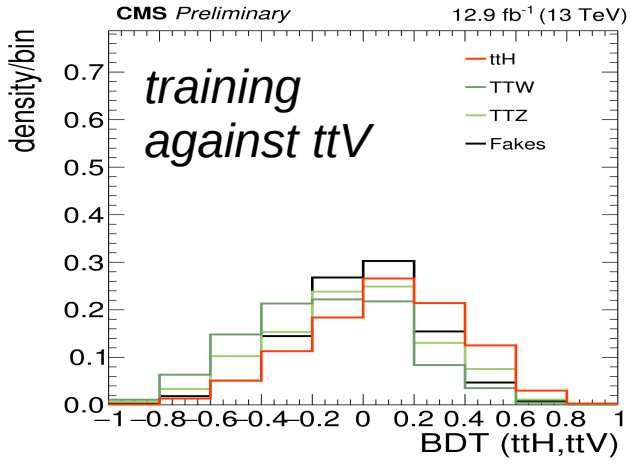
Multivariate analysis

- **Kinematic observables** (jet multiplicity, lepton/jet angular separation, E^{miss}_T, lepton p_T, ...)
- In three lepton channel: **matrix element weights** for ttH, ttW, ttZ hypotheses



Combined in **BDT to discriminate ttH against**
tt *(reducible bkg)*
ttV *(irreducible bkg)*



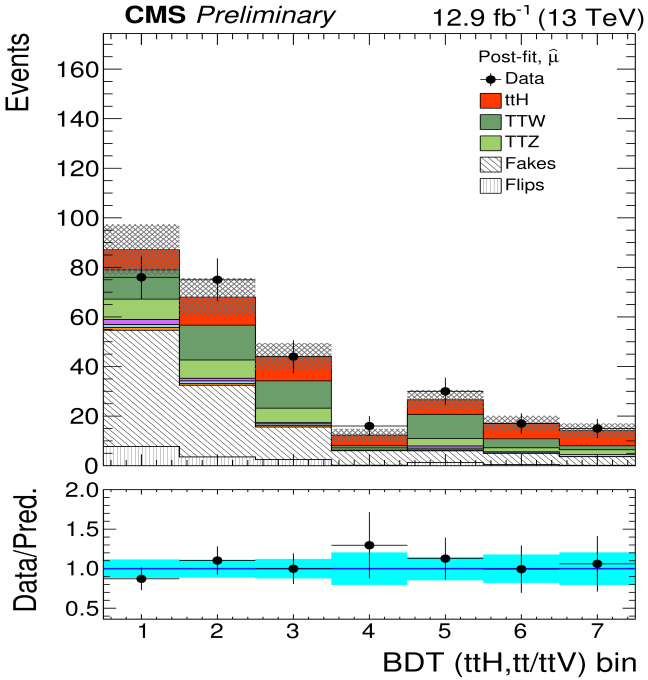


Signal extraction using fit

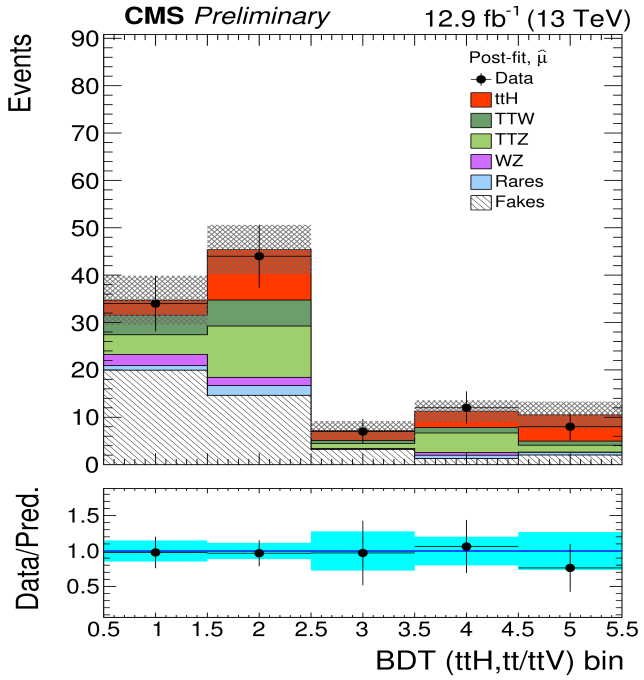
HIG-16-022

- **Two-dimensional fit** to BDT(ttH,tt) and BDT(ttH,ttV) discriminants
- **Systematic uncertainties** (lepton, trigger, b-tagging scale factors, non-prompt lepton prediction 30-50%, jet energy corrections, PDF, Q^2 scale, cross sections) treated as **nuisance parameters**

Same-sign dilepton channel



Three lepton channel

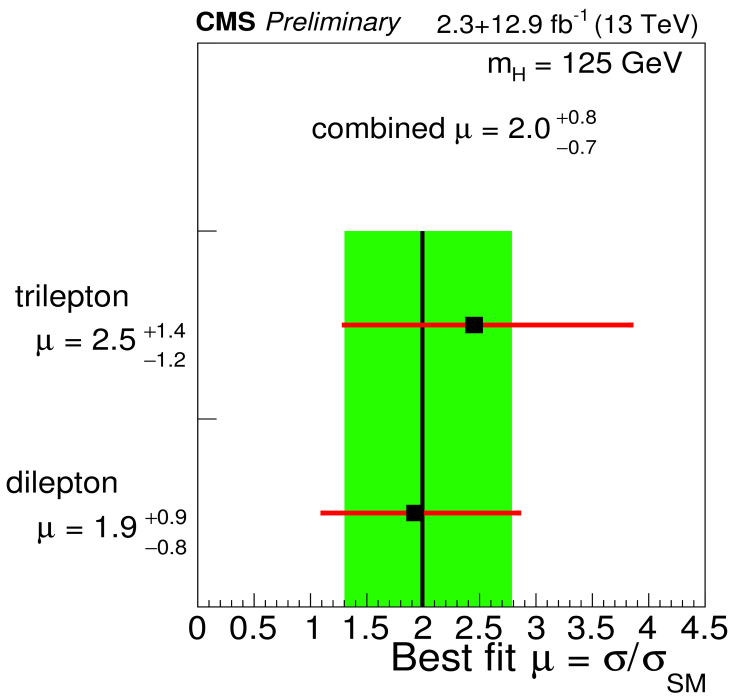


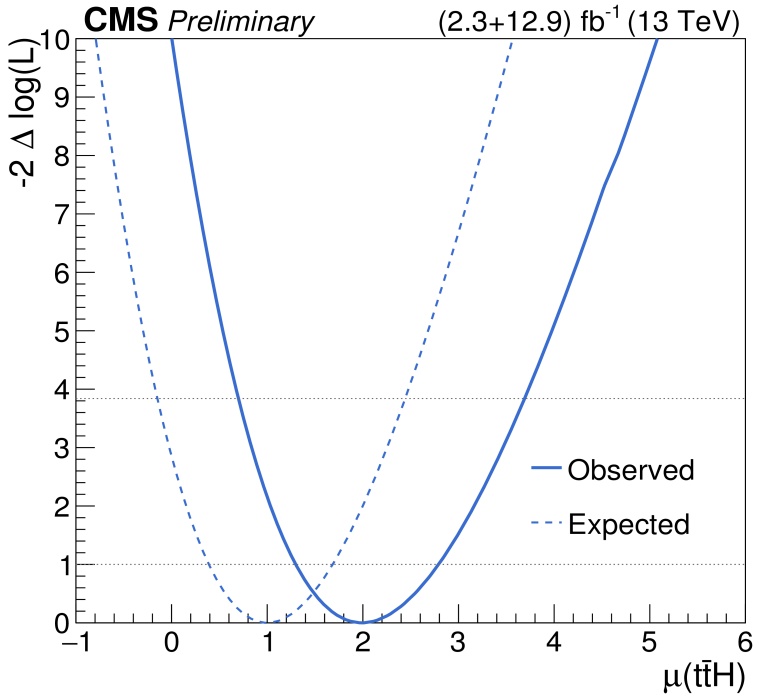
- **Further event categorization** based on lepton flavor, presence of b-tagged jets, hadronically decaying τ leptons

Limits and fit results

> **Simultaneous binned likelihood fit** in all categories and combined with 2015 analysis (CMS-PAS-HIG-15-008)

Category	Obs. limit	Exp. limit $\pm1\sigma$	Best fit μ $\pm1\sigma$
Same-sign dileptons	4.6	$1.7^{+0.9}_{-0.5}$	$2.7^{+1.1}_{-1.0}$
Trileptons	3.7	$2.3^{+1.2}_{-0.7}$	$1.3^{+1.2}_{-1.0}$
Combined categories	3.9	$1.4^{+0.7}_{-0.4}$	$2.3^{+0.9}_{-0.8}$
Combined with 2015 data	3.4	$1.3^{+0.6}_{-0.4}$	$2.0^{+0.8}_{-0.7}$





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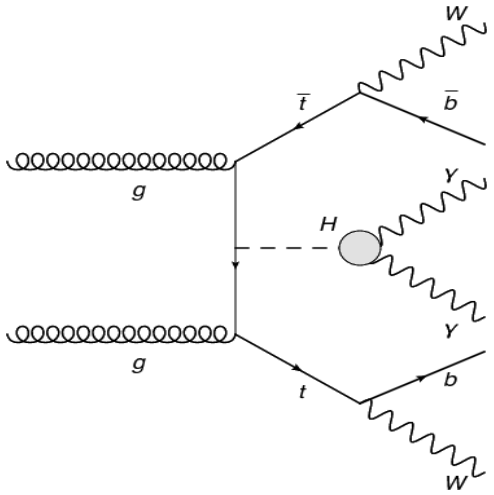
Summary and outlook

Strategy and selection



> Strategy

- Select events compatible with inclusive tt decays and H → γγ decay
- Search for narrow diphoton peak on falling background in mass distribution
- Signal extraction via fit to data

ttH leptonic tag

≥ 2 anti-k_T (R=0.4) jets
with p_T > 25 GeV, |η| < 2.4

≥ 1 medium b-tag

≥ 1 isolated electron/muon
p_T > 20 GeV, |η| < 2.4, not Z peak

2 photons
$p^{lead}_T > m_{\gamma\gamma} / 2$, $p^{sublead}_T > m_{\gamma\gamma} / 4$

ttH hadronic tag

≥ 5 anti-k_T (R=0.4) jets
with p_T > 25 GeV, |η| < 2.4

≥ 1 medium b-tag

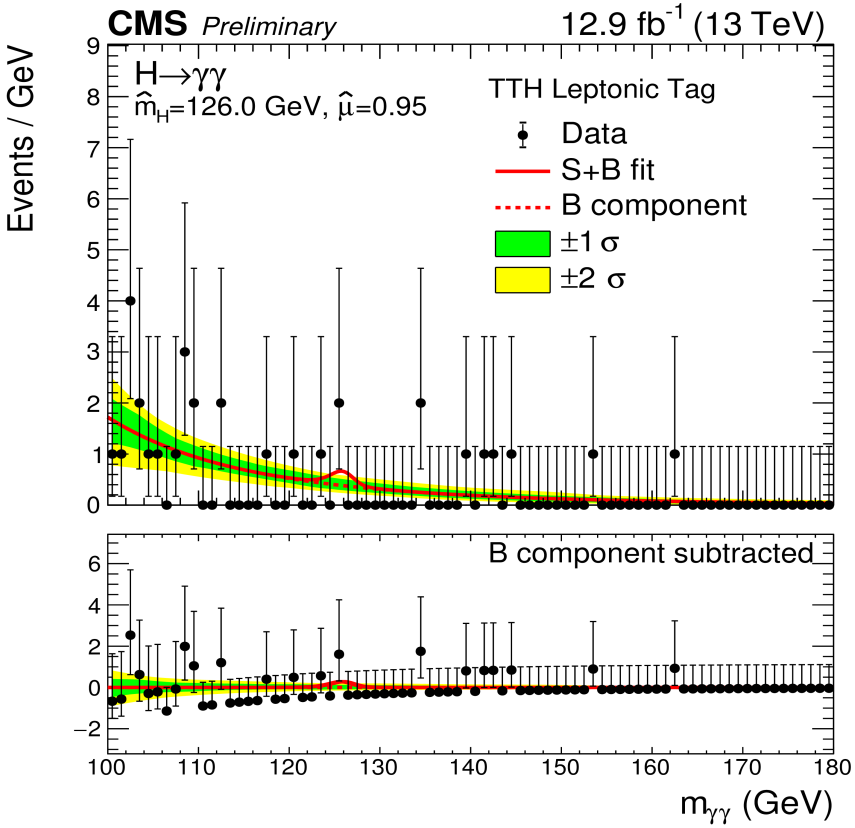
no leptons

2 photons
$p^{lead}_T > m_{\gamma\gamma} / 2$, $p^{sublead}_T > m_{\gamma\gamma} / 4$

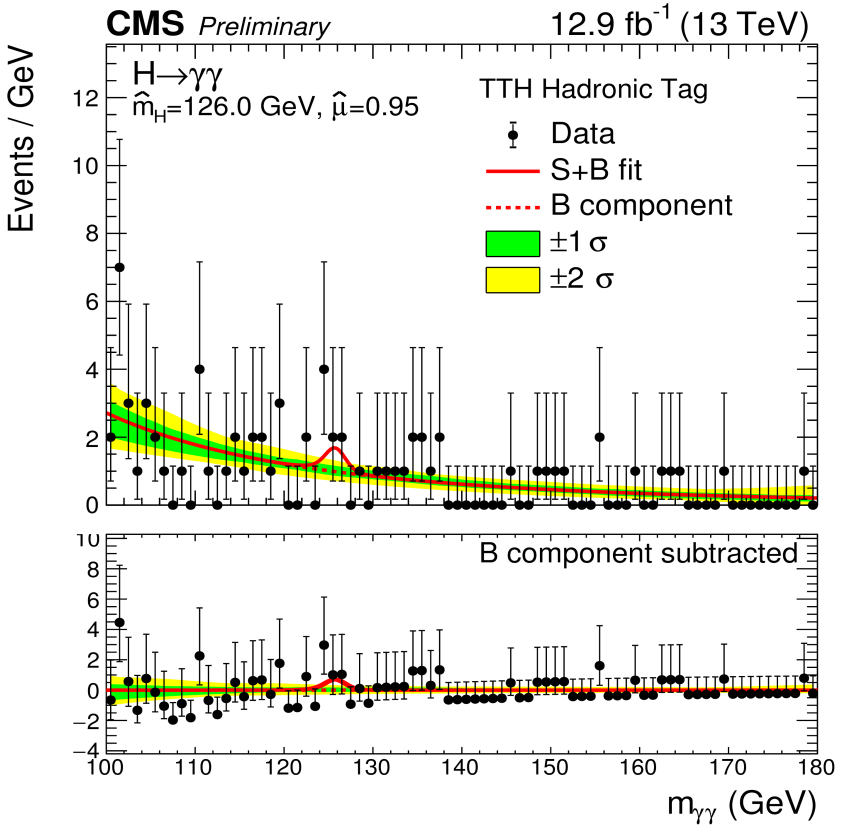
Diphoton mass spectrum

- Background consists of *reducible* **fake photon** backgrounds, and *irreducible* **prompt diphoton backgrounds; data-driven**
- **Diphoton mass** $m_{\gamma\gamma}$ observable used to extract signal
- Signal shape parametrized as sum of gaussian functions

ttH leptonic tag

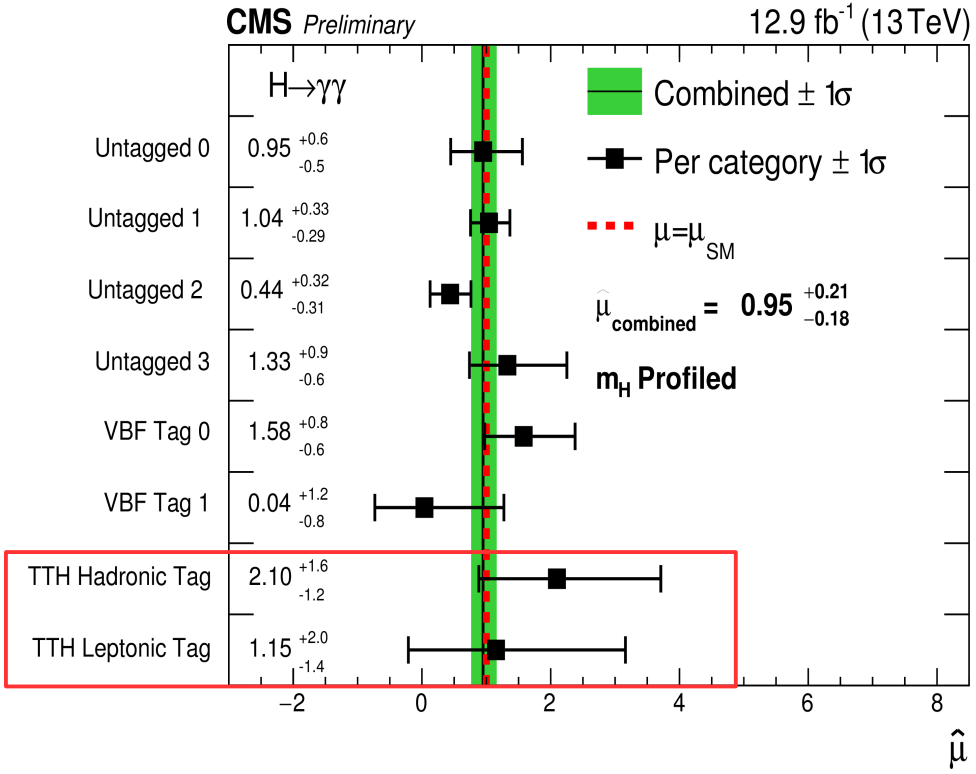


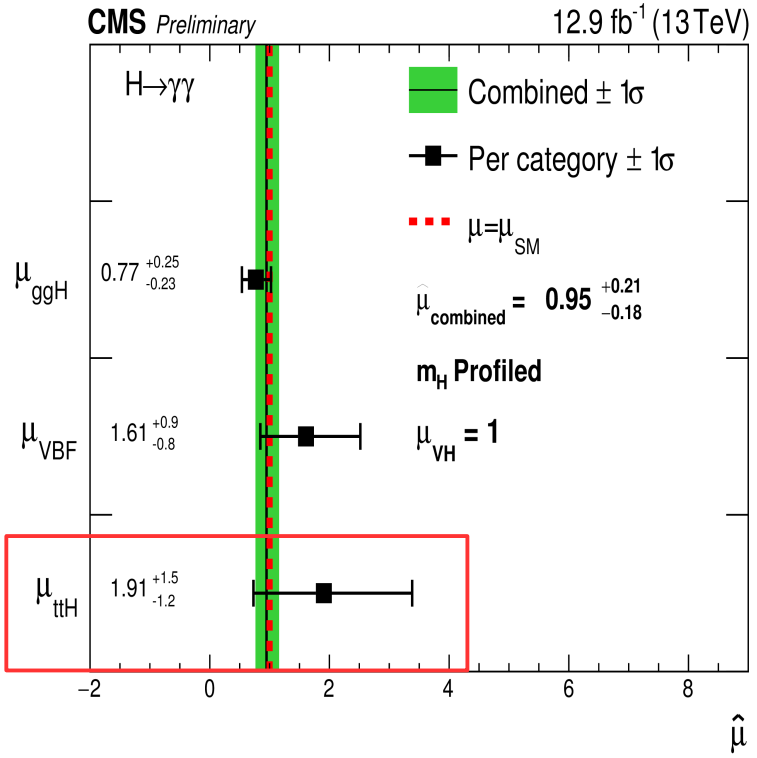
ttH hadronic tag



Fit results

- **Systematic uncertainties** (Parton shower, Q^2 scale, jet energy scale, photon energy resolution, gluon fusion contamination in ttH category, …)
- **Best-fit ttH signal strength $\sigma/\sigma_{SM} = 1.91^{+1.5}_{-1.2}$**





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selection
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Summary and outlook

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- The CMS experiment analyzed **12.9 / fb of data in 2016** searching for ttH
  - **tt+(H→bb)** single and opposite-sign dilepton final state

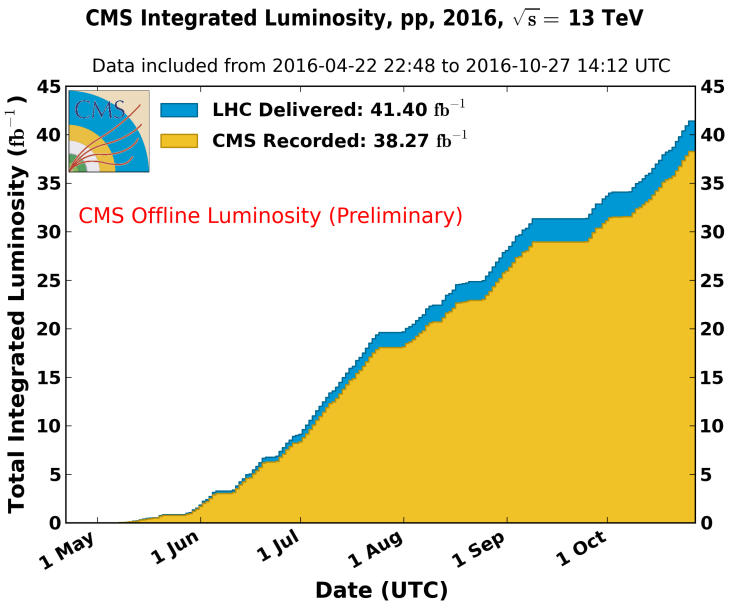
    Best fit $\mu_{ttH} = -0.19^{+0.80}_{-0.81}$
  - **tt+(H→WW*, ZZ*, ττ)** same-sign dilepton and trilepton final states

    Best fit $\mu_{ttH} = 2.0^{+0.8}_{-0.7}$ *combined with 2015 data*
  - **tt+(H→γγ)** diphoton final states

    Best fit $\mu_{ttH} = 1.91^{+1.5}_{-1.2}$

- About **3 times more data being analyzed**, results at Moriond 2017 conference and beyond

SM sensitivity getting in reach, exciting ttH times ahead!



BACKUP

tt + (H → bb)

tt + (H → WW*, ZZ*, ττ)

tt + (H → γγ)

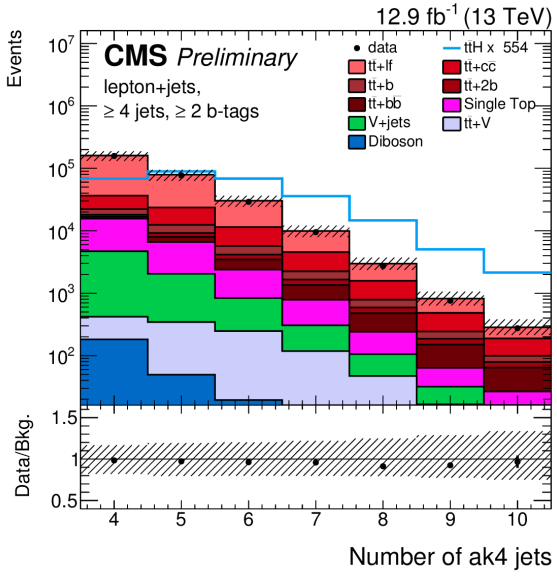
Single lepton event yields

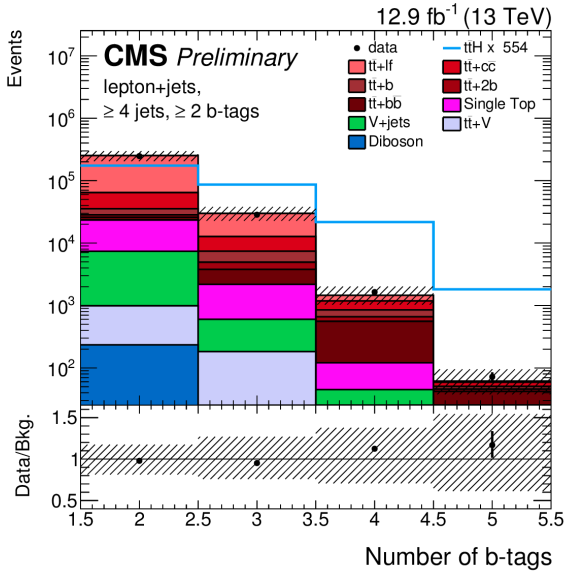
Process	≥ 6 jets, 3 b-tags	4 jets, 4 b-tags	5 jets, ≥ 4 b-tags	≥ 6 jets, ≥ 4 b-tags
$t\bar{t}$+LF	2710.6 ± 1027.1	91.4 ± 69.9	96.9 ± 75.8	86.2 ± 71.9
$t\bar{t}$+c$\bar{c}$	1771.9 ± 1099.0	59.3 ± 47.0	112.5 ± 88.9	175.8 ± 141.6
$t\bar{t}$+b	717.6 ± 406.8	37.6 ± 23.1	69.6 ± 42.4	86.3 ± 57.0
$t\bar{t}$+2b	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

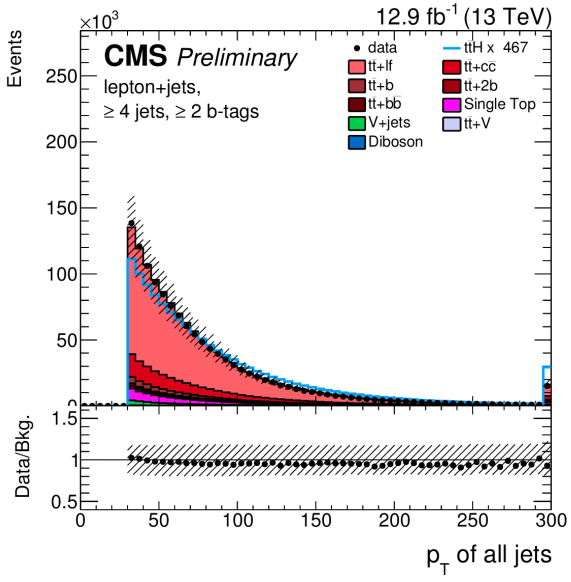
Dilepton event yields

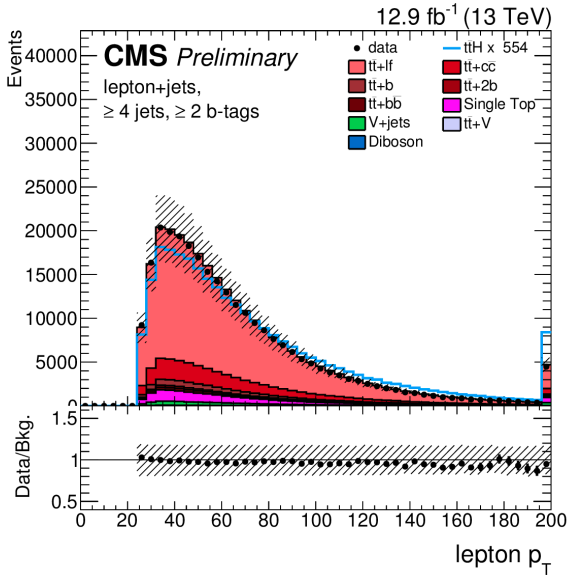
Process	3 jets, 3 b-tags	$\geq$ 4 jets, 3 b-tags	$\geq$ 4 jets, $\geq$ 4 b-tags
$t\bar{t}$+LF	179.0 ± 68.7	390.1 ± 167.9	7.6 ± 3.6
$t\bar{t}$+$c\bar{c}$	117.5 ± 73.8	382.6 ± 237.7	19.4 ± 15.5
$t\bar{t}$+b	94.2 ± 51.9	228.0 ± 127.7	14.4 ± 9.2
$t\bar{t}$+2b	31.7 ± 17.3	99.1 ± 54.3	6.2 ± 3.8
$t\bar{t}$+$b\bar{b}$	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

Single lepton control plots

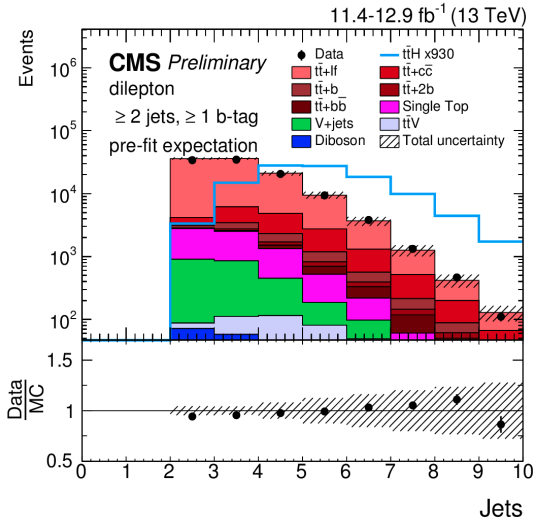


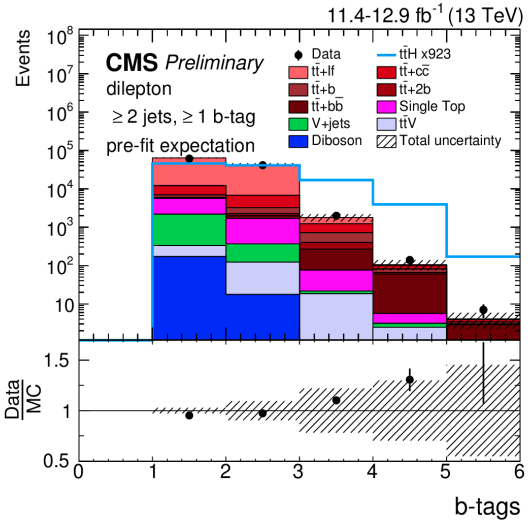


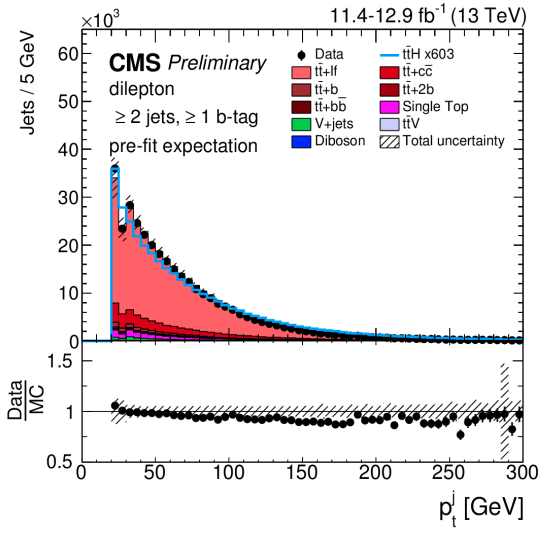


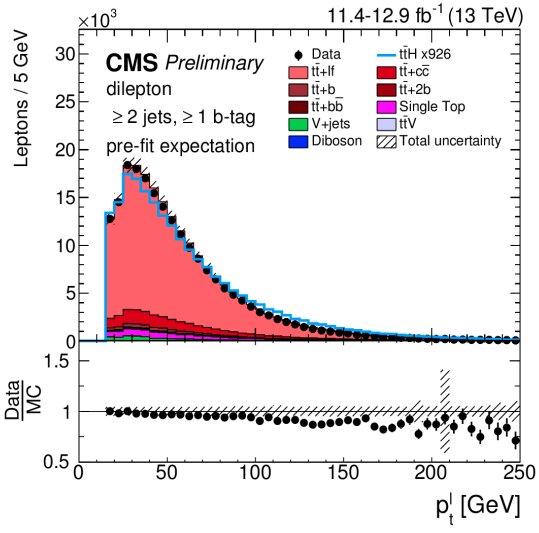


Dilepton control plots









Systematic uncertainties

Source	Type	Remarks
Luminosity	rate	Signal and all backgrounds
Lepton ID/Iso	shape	Signal and all backgrounds
Trigger efficiency	shape	Signal and all backgrounds
Pileup	shape	Signal and all backgrounds
Jet energy scale	shape	Signal and all backgrounds
Jet energy resolution	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 ($t\bar{t}H$)	rate	Scale uncertainty of NLO $t\bar{t}H$ prediction
QCD scale ($t\bar{t}$)	rate	Scale uncertainty of NLO $t\bar{t}$ prediction
QCD scale ($t\bar{t}$+HF)	rate	Additional 50% rate uncertainty of $t\bar{t}$+HF predictions
QCD scale (t)	rate	Scale uncertainty of NLO single t prediction
QCD scale (V)	rate	Scale uncertainty of NNLO W and Z prediction
QCD scale (VV)	rate	Scale uncertainty of NLO diboson prediction
pdf (gg)	rate	PDF uncertainty for gg initiated processes except $t\bar{t}H$
pdf (gg $t\bar{t}H$)	rate	PDF uncertainty for $t\bar{t}H$
pdf ($q\bar{q}$)	rate	PDF uncertainty of $q\bar{q}$ initiated processes ($t\bar{t}$ W, W, Z)
pdf (qg)	rate	PDF uncertainty of qg initiated processes (single t)
Q^2 scale ($t\bar{t}$)	shape	Renormalization and factorization scale uncertainties of the $t\bar{t}$ ME generator, independent for additional jet flavors
PS Scale ($t\bar{t}$)	rate	Renormalization and factorization scale uncertainties of the parton shower (for $t\bar{t}$ events), independent for additional jet flavors
Bin-by-bin statistics	shape	statistical uncertainty of the signal and background prediction due to the limited sample size

Systematic uncertainties yield effect

Effect in ≥6 jet, 3 b-tags single lepton channel

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 ($t\bar{t}$+$c\bar{c}$)	$-3.9/+3.0$	–

BDT input variable list

Single lepton channel

Event variable	Description
Object and event kinematics	
$\langle \Delta R_{\text{tag,tag}} \rangle$	Average ΔR between b-tagged jets
$\sum p_{T\text{jets,leptons}}$	Sum of the p_T of all jets and leptons
$\tau_{\text{jet,jet}}^{\text{max mass}}$	Twist angle between jet pair
min $\Delta R_{\text{tag,tag}}$	ΔR between the two closest b-tagged jets
max $\Delta\eta_{\text{tag,tag}}$	$\Delta\eta$ between the two furthest b-tagged jets
$M_{\text{jet,jet}}^{\text{min}\Delta R}$	Invariant mass of jet pair with minimum ΔR
$M_{\text{higgs-like}}^{\text{jj}}$	Invariant mass of a jet pair ordered in closeness to the Higgs mass
$M_{\text{tag,tag}}^{\text{min}\Delta R}$	Mass of b-tagged jet pair with minimum ΔR
$p_{T\ \text{tag,tag}}^{\text{min}\Delta R}$	Sum of the p_T of b-tagged jet pair with minimum ΔR
Centrality (tags)	Ratio of the sum of the transverse momentum of all b-tagged jets and the sum of the energy of all b-tagged jets
Centrality (jets, leptons)	Ratio of the sum of the transverse momentum of all jets and leptons, and the sum of the energy of all jets and leptons
H_T	Scalar sum of transverse momentum for all jets
min $\Delta R_{\text{jet,jet}}$	ΔR between the two closest jets
median $M_{\text{jet,jet}}$	Median invariant mass of all combinations of jet pairs
$M_{\text{tag,tag}}^{\text{max mass}}$	Mass for b-tagged jet pair with maximum invariant mass combination
$\langle \Delta R_{jet,tag} \rangle$	Average ΔR between jets (with at least one b-tagged jet)
$p_{T\ jet,tag}^{\text{min}\Delta R}$	Sum of the p_T of jet pair with minimum ΔR (with at least one b-tagged jet)
$\tau_{\text{jet,tag}}^{\text{max mass}}$	Twist angle between jet pair (with at least one b-tagged jet)
$\text{m}_{\text{jet,jet,jet}}^{\text{max } p_T}$	Invariant mass of the 3-jet system with the largest transverse momentum.
$M_{\text{higgs-like}}^{\text{bj}}$	Invariant mass of a jet pair (with at least one b-tagged jet) ordered in closeness to the Higgs mass
CSVv2 b-tag	
$\langle d \rangle_{\text{tagged/untagged}}$	Average CSVv2 b-tag discriminant value for b-tagged/un-b-tagged jets
Event shape	
H_0, H_1, H_2, H_3, H_4	Fox-Wolfram moments [**?**]
C(jets)	3 $(\lambda_1\lambda_2 + \lambda_1\lambda_3 + \lambda_2\lambda_3)$ [**?**]

BDT input variable list

Dilepton channel

3 jets, 3 tags	≥4 jets, 3 tags	≥4 jets, ≥4 tags
$\langle d \rangle_{\text{tagged}}$	Centrality(jets & leptons)	Centrality(jets & leptons)
$H_1(\text{jets})$	C(jets)	Centrality(tags)
$M^{\text{bj}}_{\text{higgs-like}}$	$H_2(\text{tags})$	H_T^{tags}
$M^{\text{max mass}}_{\text{tag,tag}}$	$M^{\text{jj}}_{\text{higgs-like}}$	$M^{\text{jj}}_{\text{higgs-like}}$
$\min \Delta R_{\text{tag,tag}}$	$M^{\text{max}p_T}_{\text{jet,jet,jet}}$	$\min \Delta R_{\text{jet,jet}}$
$\max \Delta\eta_{\text{jet,jet}}$	$M^{\text{min}\Delta R}_{\text{tag,tag}}$	$M^{\text{min}\Delta R}_{jet,tag}$
$\min \Delta R_{\text{jet,jet}}$	$\min \Delta R_{\text{tag,tag}}$	$M^{\text{max mass}}_{\text{tag,tag}}$
$\sum p_{T\text{jets,leptons}}$	$\max \Delta\eta_{\text{tag,tag}}$	$M^{\text{min}\Delta R}_{\text{tag,tag}}$
$\text{H}_4/\text{H}_0(\text{tags})$	$\tau^{\text{max mass}}_{\text{tag,tag}}$	$\max \Delta\eta_{\text{jet,jet}}$
		$\max \Delta\eta_{\text{tag,tag}}$
		$\text{median } M_{\text{jet,jet}}$

Matrix element method weights

Details of method in arXiv:1502.02485

Weight *w* for hypothesis *H*

4-momenta of reconstructed particles

Phase space element, momentum conservation enforced

Resolution function

$$w(\vec{y}|\mathcal{H}) = \sum_{i=1}^{N_a} \int \frac{\mathrm{d}x_a \mathrm{d}x_b}{2x_a x_b s} \int \prod_{k=1}^{8} \left(\frac{\mathrm{d}^3\vec{p}_k}{(2\pi)^3 2E_k} \right) (2\pi)^4 \delta^{(E,z)} \left(p_a + p_b - \sum_{k=1}^{8} p_k \right) \mathcal{R}^{(x,y)} \left(\vec{p}_{\mathrm{T}}, \sum_{k=1}^{8} p_k \right) \times$$
$$g(x_a, \mu_{\mathrm{F}}) g(x_b, \mu_{\mathrm{F}}) |\mathcal{M}_{\mathcal{H}}(p_a, p_b, p_1, \ldots, p_8)|^2 W(\vec{y}, \vec{p}),$$

Parton density functions

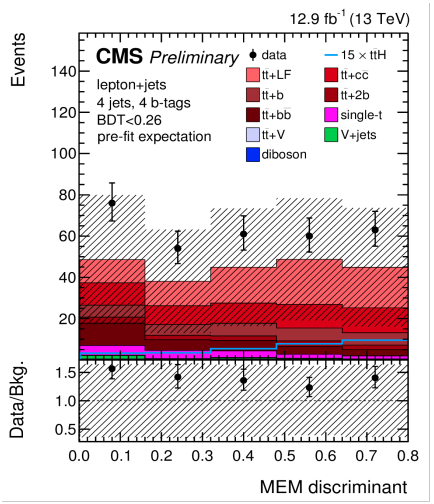
Squared matrix element (Open Loops)

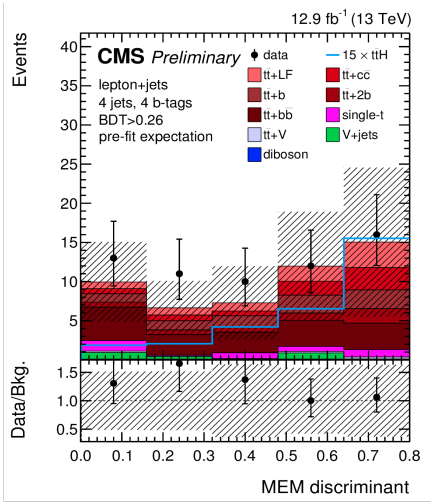
Detector transfer functions

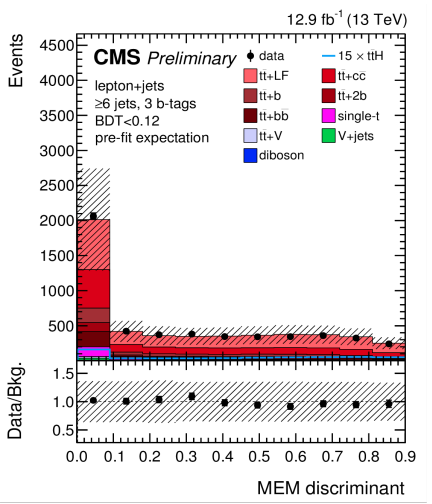
- Four jets assigned to two b quarks in matrix element, selected using likelihood ratio between hypotheses that 4 or 2 jets arose from b quarks, based on b-tagging discriminant probability densities
- All permutations considered of 4 b-jets, and of 4 W decay products

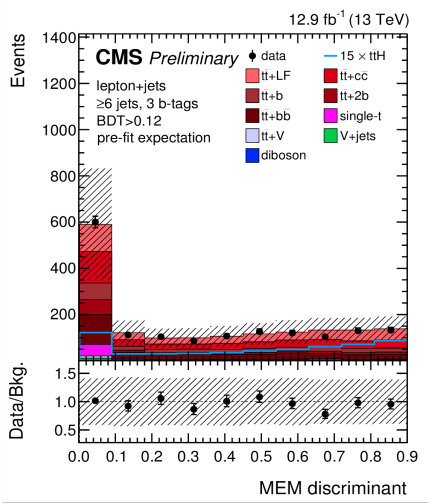
MEM discriminants in single lepton channel

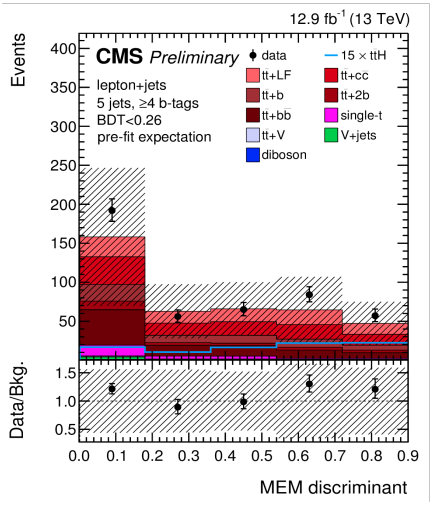
Pre-fit

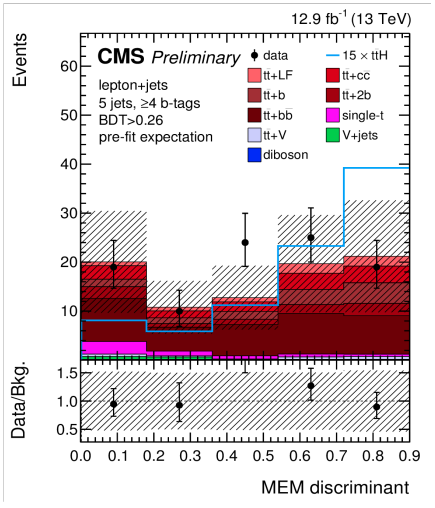


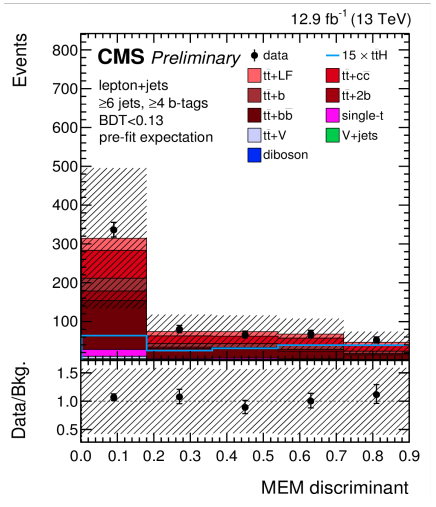


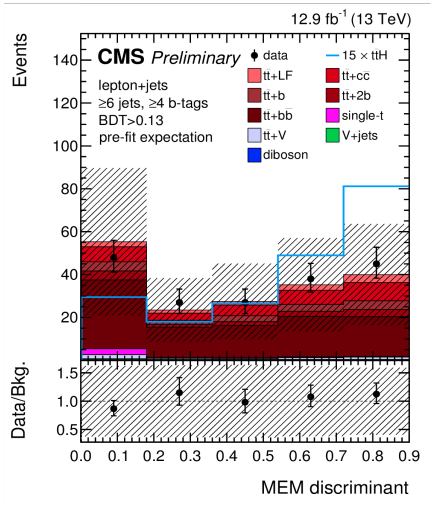








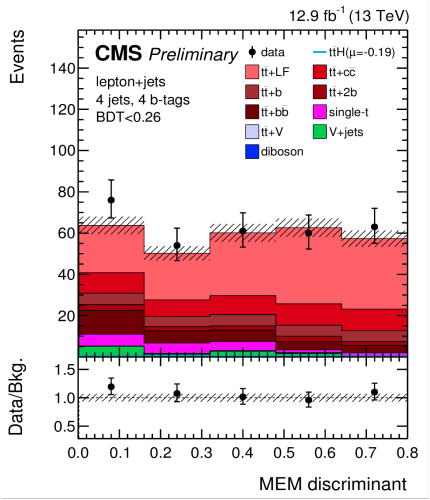


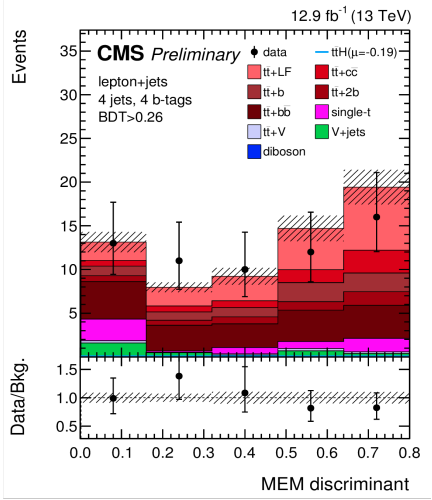


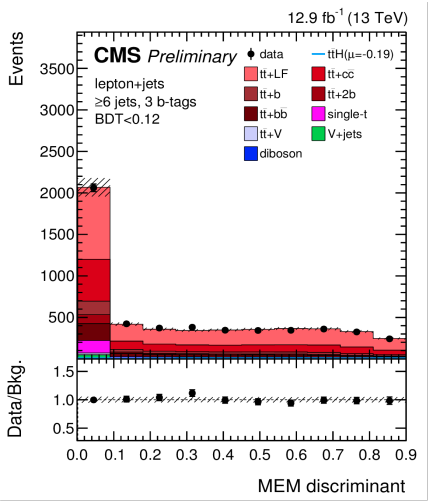
MEM discriminants in single lepton channel

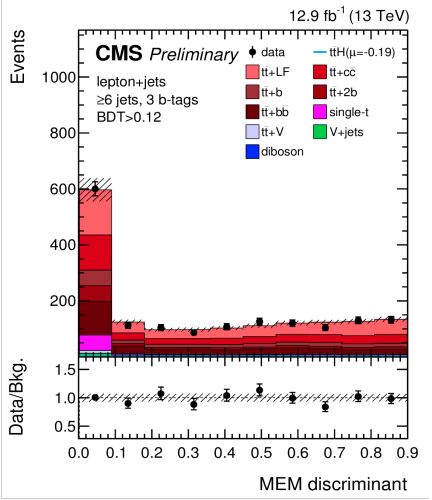
ttH(bb)
HIG-16-038

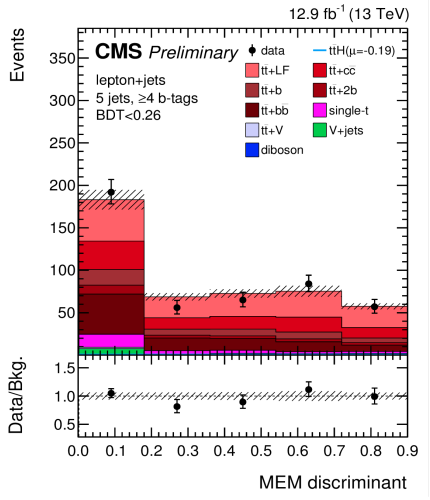
Post-fit

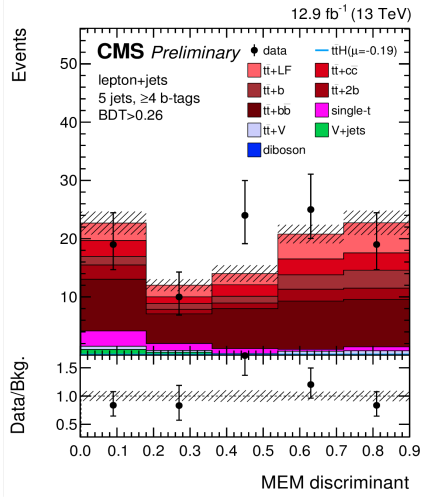


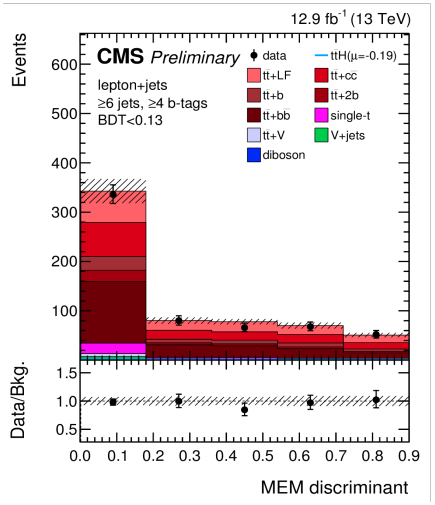


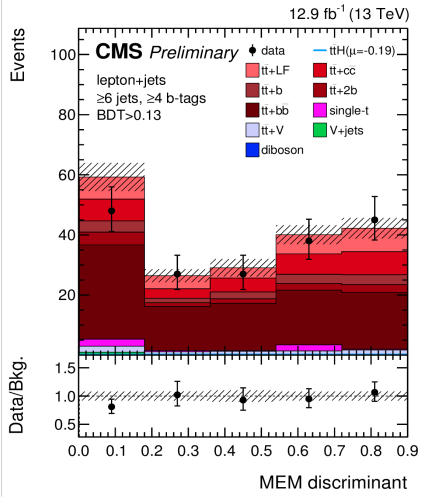








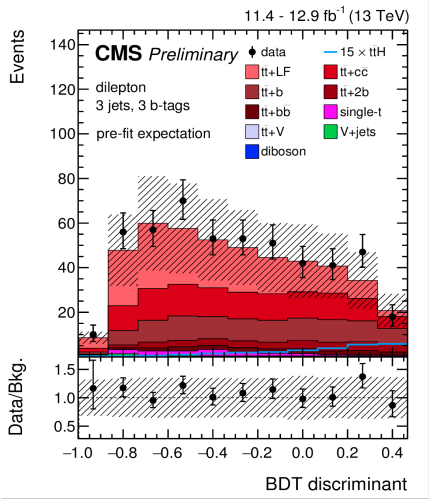


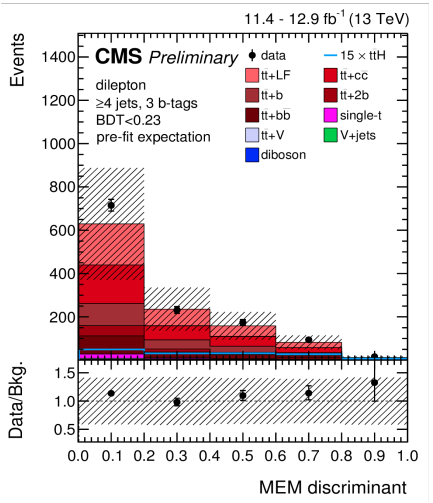


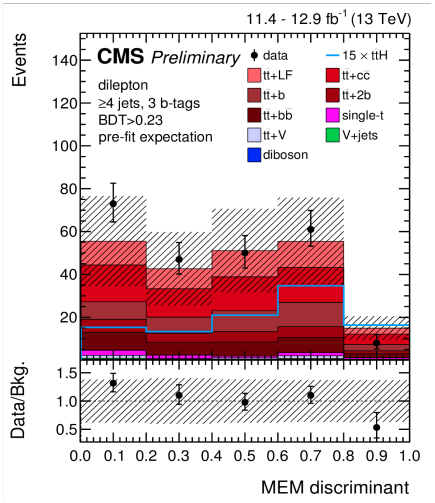
BDT & MEM discriminants in dilepton channel

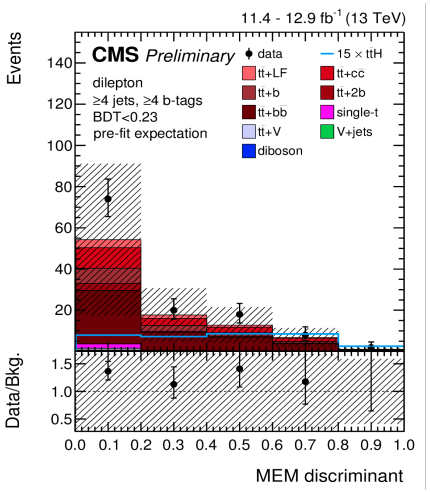
ttH(bb)
HIG-16-038

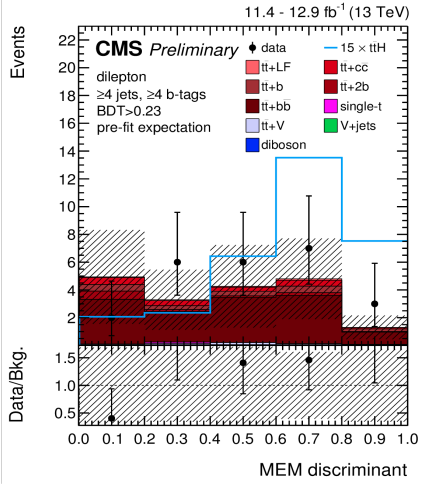
Pre-fit











BDT & MEM discriminants in dilepton channel

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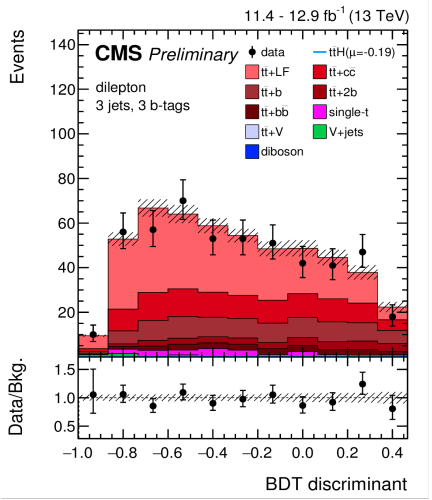
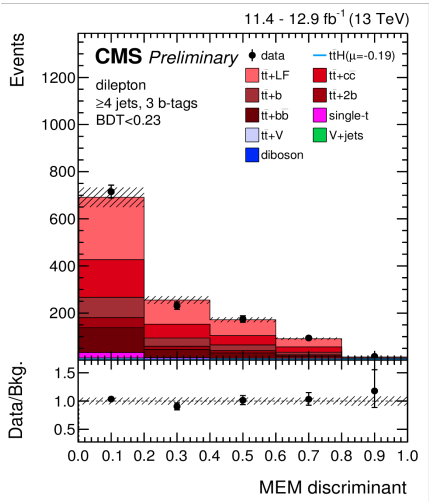
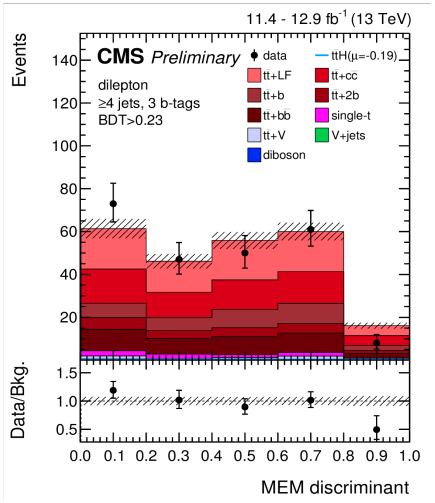
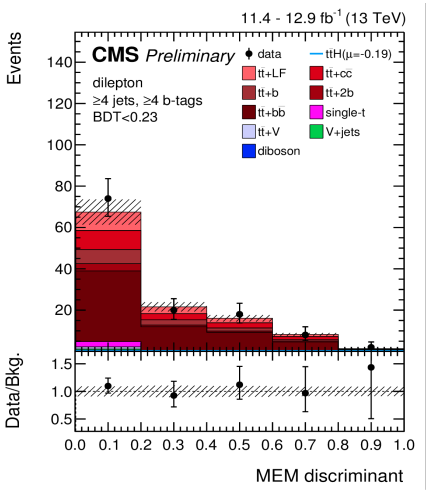
HIG-16-038

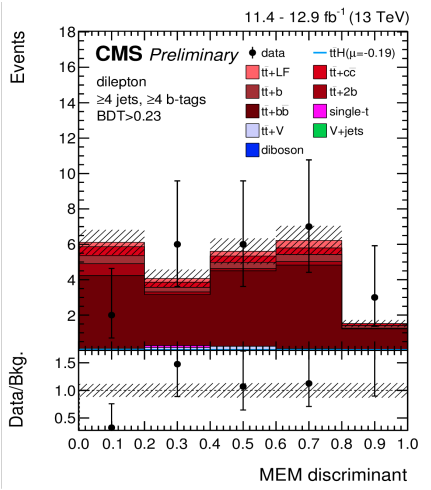
Post-fit



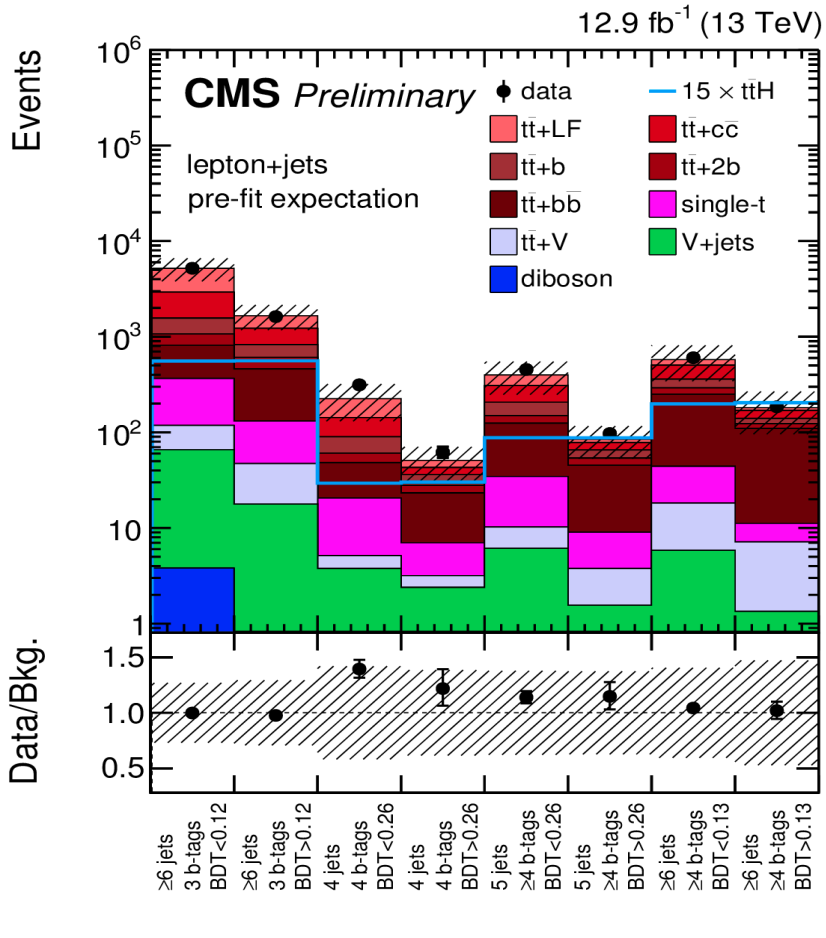


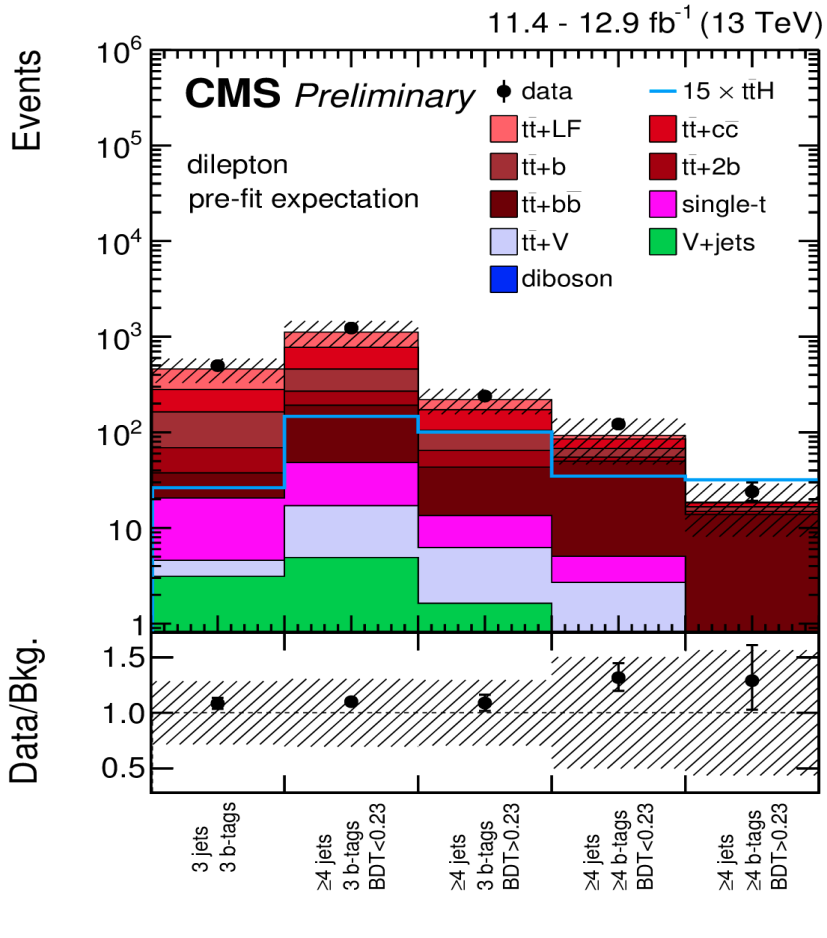




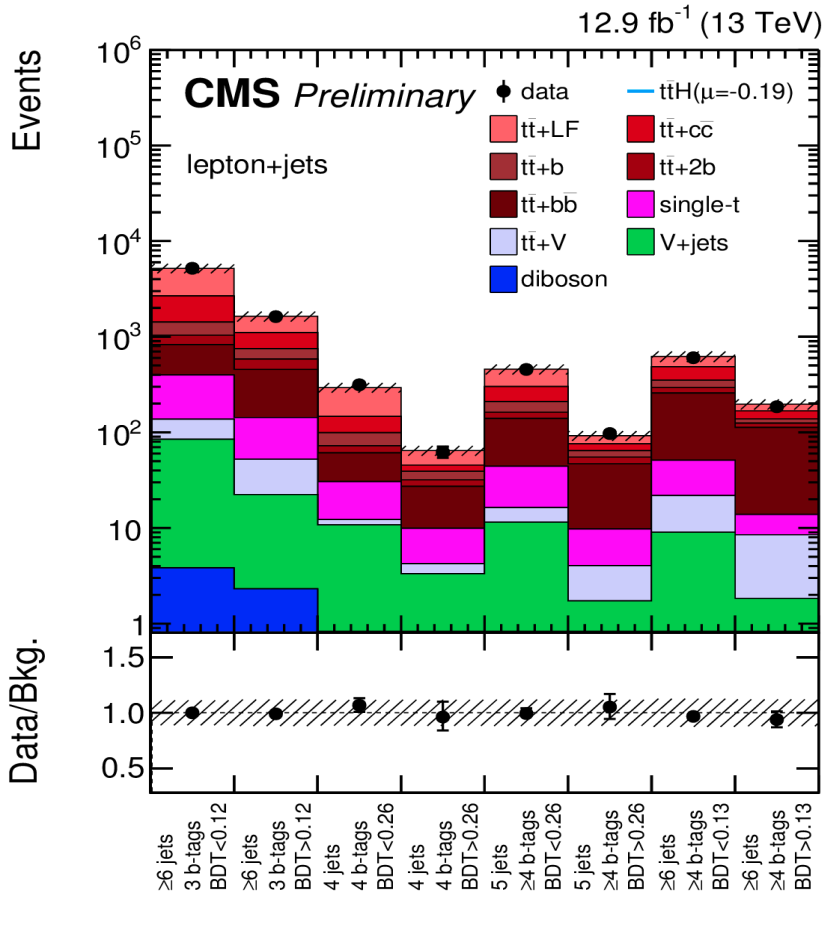


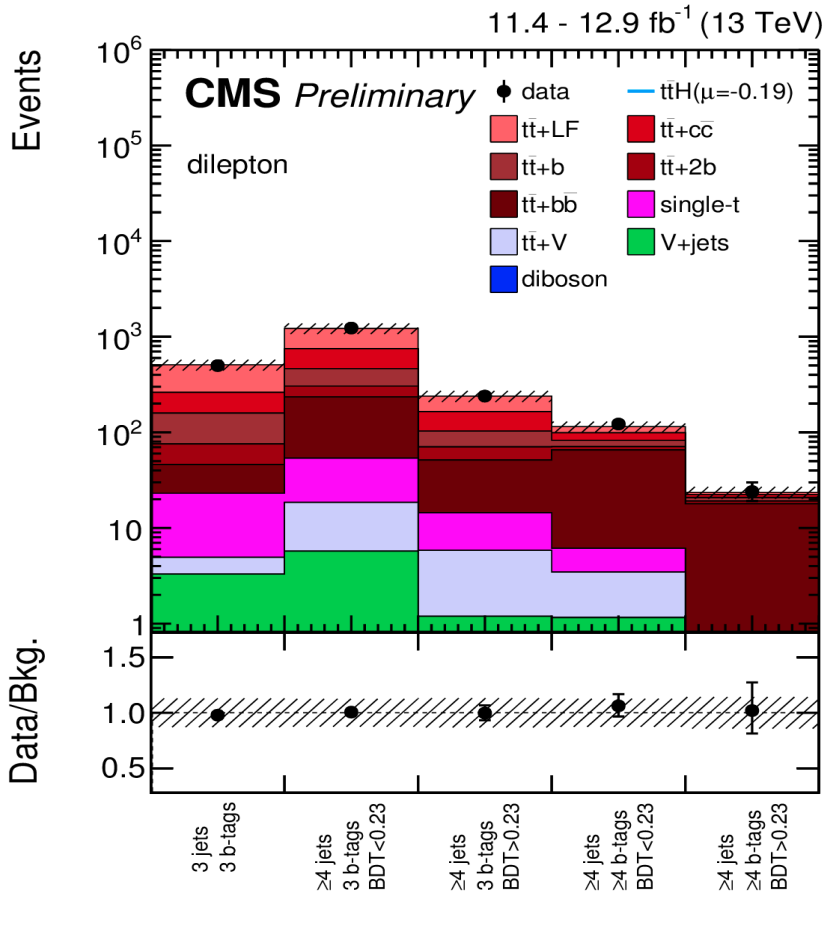
Event yields pre-fit





Event yields post-fit

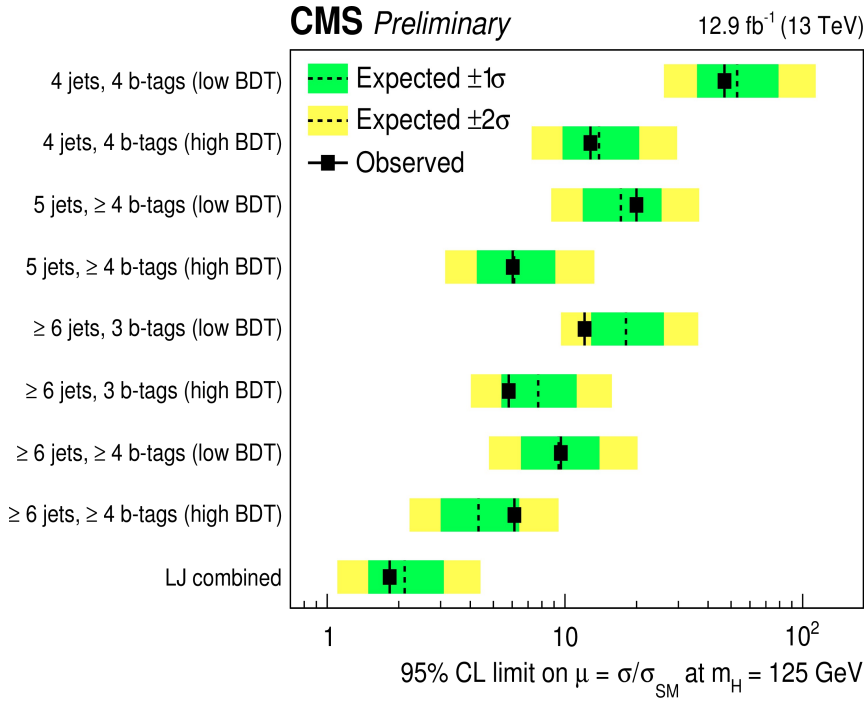




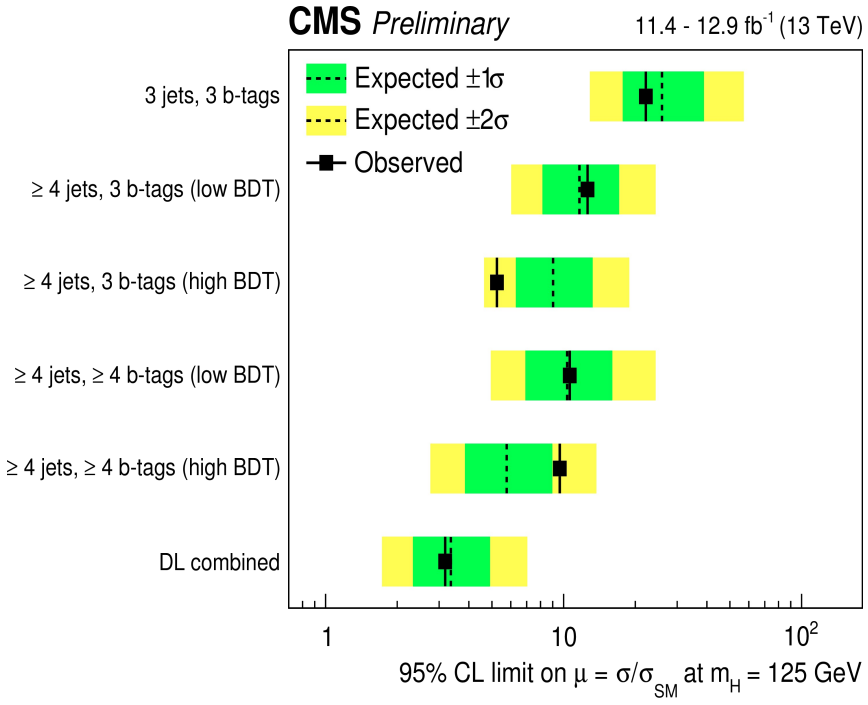
Limits in (jet,b-jet) categories

ttH(bb)
HIG-16-038

Single lepton categories



Dilepton categories

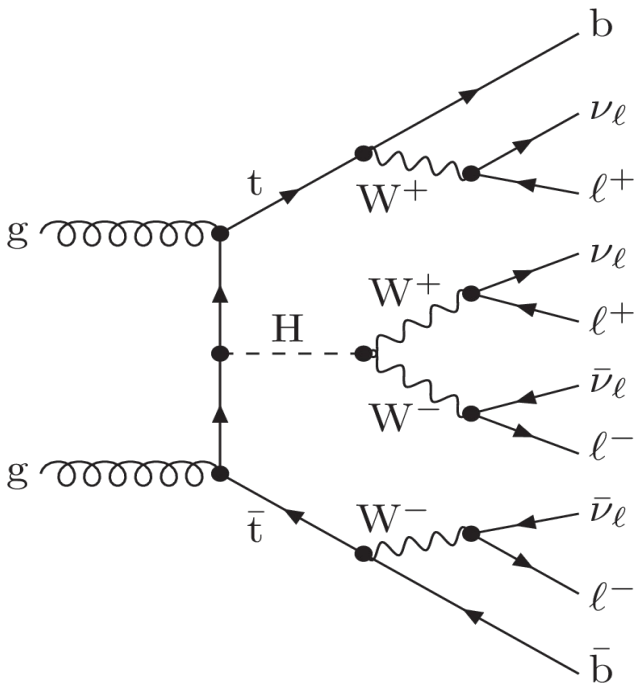


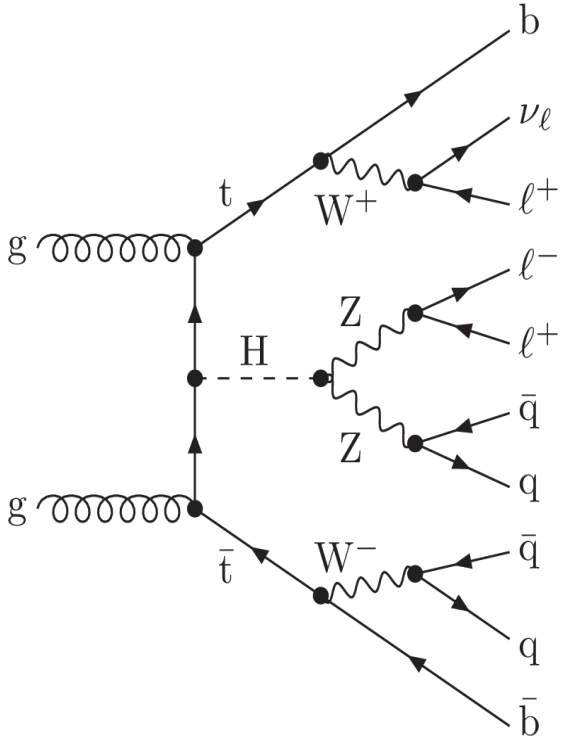
$tt + (H \rightarrow bb)$

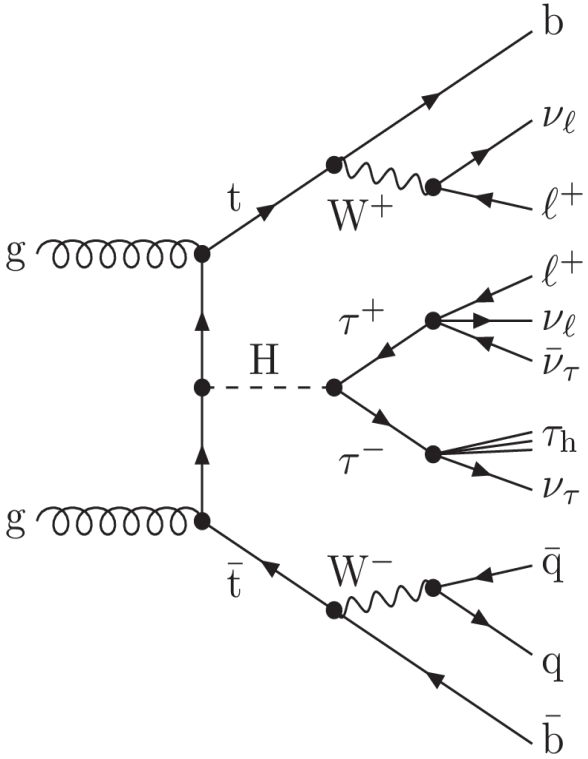
$tt + (H \rightarrow WW^{*}, ZZ^{*}, \tau\tau)$

$tt + (H \rightarrow \gamma\gamma)$

Example diagrams



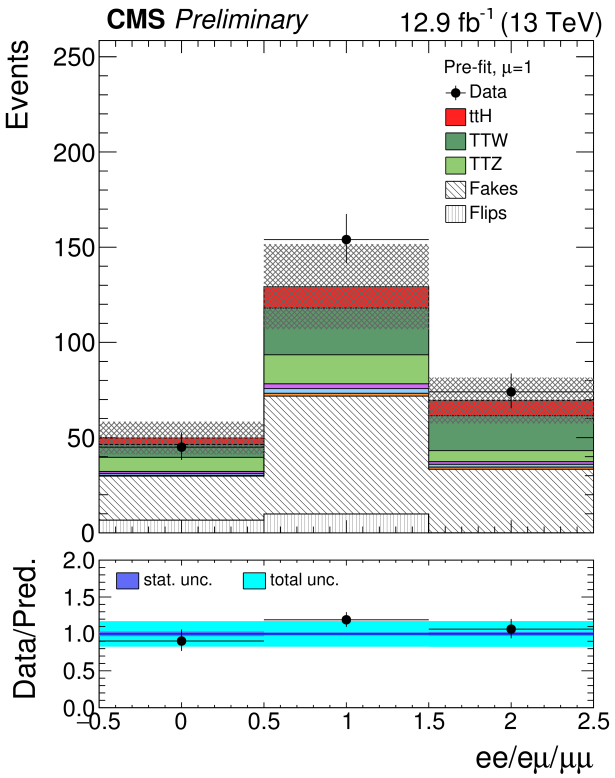


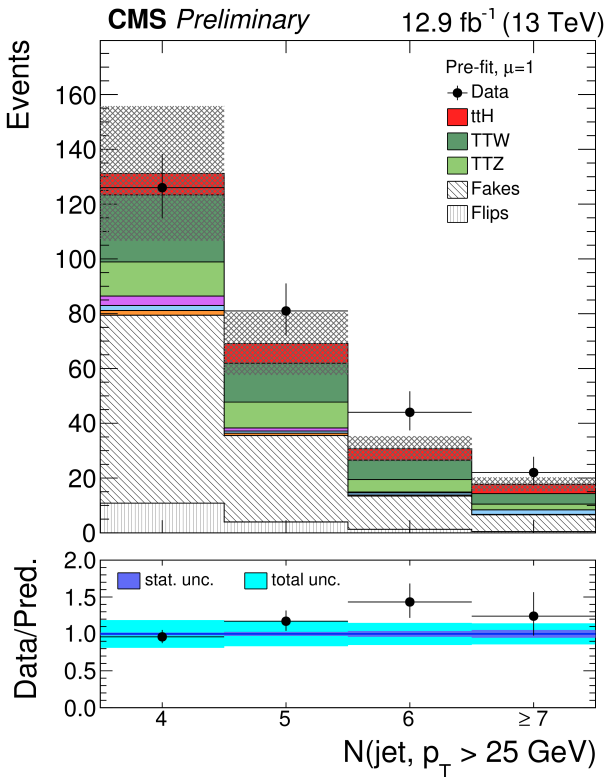


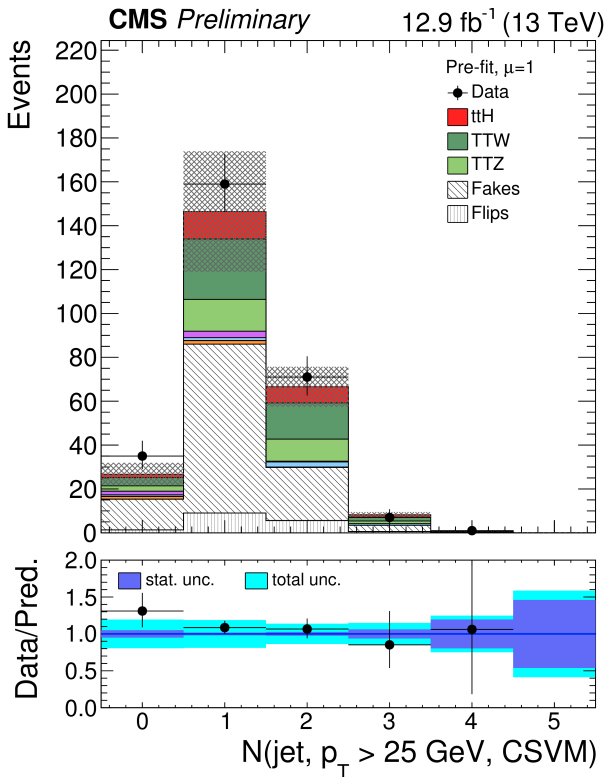
Event yields

	$\mu\mu$	ee	eμ	3ℓ
$t\bar{t}W$	18.3 ± 0.9	6.8 ± 0.6	24.5 ± 1.1	12.2 ± 0.7
$t\bar{t}Z/\gamma^*$	5.8 ± 0.6	7.4 ± 0.6	15.3 ± 1.3	22.6 ± 1.0
Di-boson	1.4 ± 0.2	1.1 ± 0.2	2.6 ± 0.3	5.7 ± 0.4
tttt	0.8 ± 0.2	0.4 ± 0.1	1.5 ± 0.2	1.2 ± 0.1
tqZ	0.2 ± 0.3	0.4 ± 0.4	0.6 ± 0.6	2.7 ± 0.8
Rare SM bkg.	1.6 ± 0.3	0.5 ± 0.1	1.8 ± 0.1	0.3 ± 0.1
Charge mis-meas.		6.7 ± 0.1	10.0 ± 0.1	
Non-prompt leptons	33.4 ± 1.2	23.1 ± 1.1	61.9 ± 1.7	51.0 ± 1.8
All backgrounds	61.5 ± 1.7	46.4 ± 1.5	118.0 ± 2.5	95.7 ± 2.3
$t\bar{t}H$ ($H \to WW^*$)	6.3 ± 0.2	2.6 ± 0.1	8.5 ± 0.2	8.0 ± 0.2
$t\bar{t}H$ ($H \to \tau\tau$)	1.6 ± 0.1	0.7 ± 0.1	2.5 ± 0.1	2.1 ± 0.1
$t\bar{t}H$ ($H \to ZZ^*$)	0.2 ± 0.0	0.1 ± 0.0	0.3 ± 0.0	0.5 ± 0.0
Data	74	45	154	105

Same-sign dilepton channel control plots

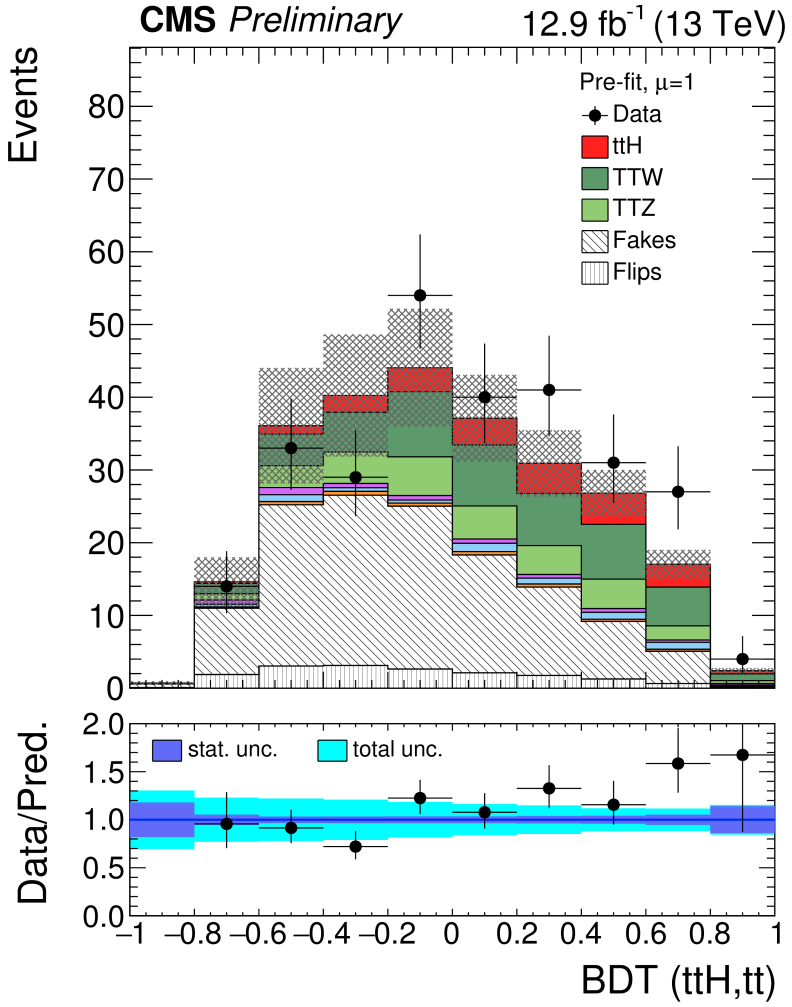




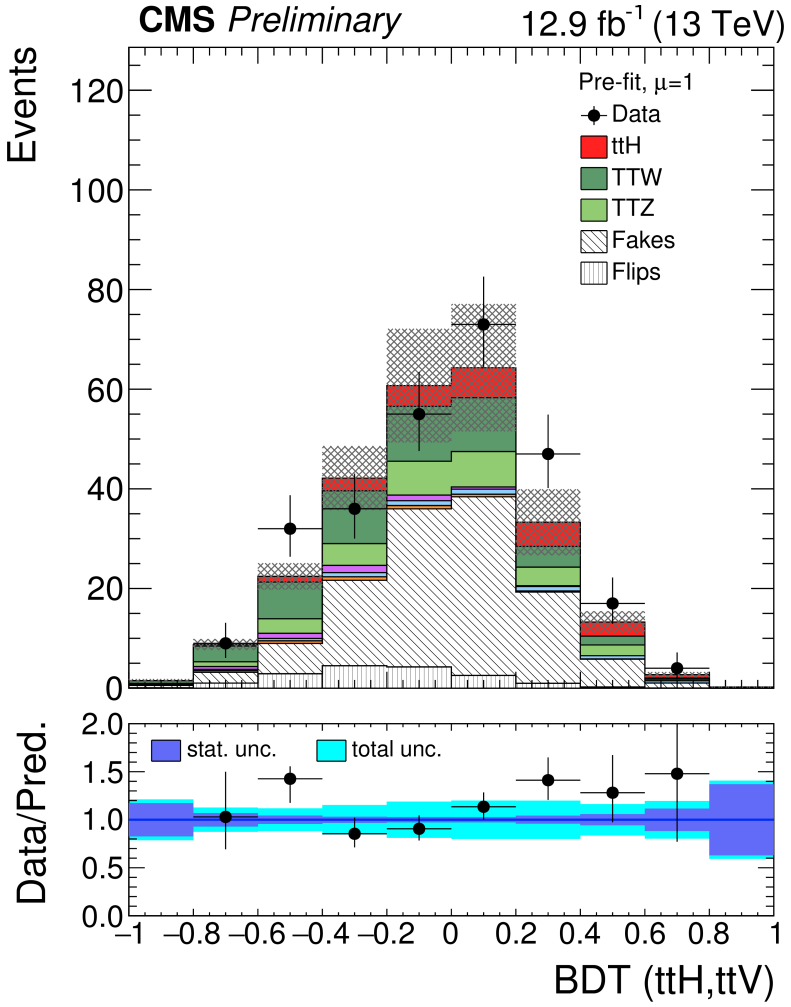


Same-sign dilepton channel BDT

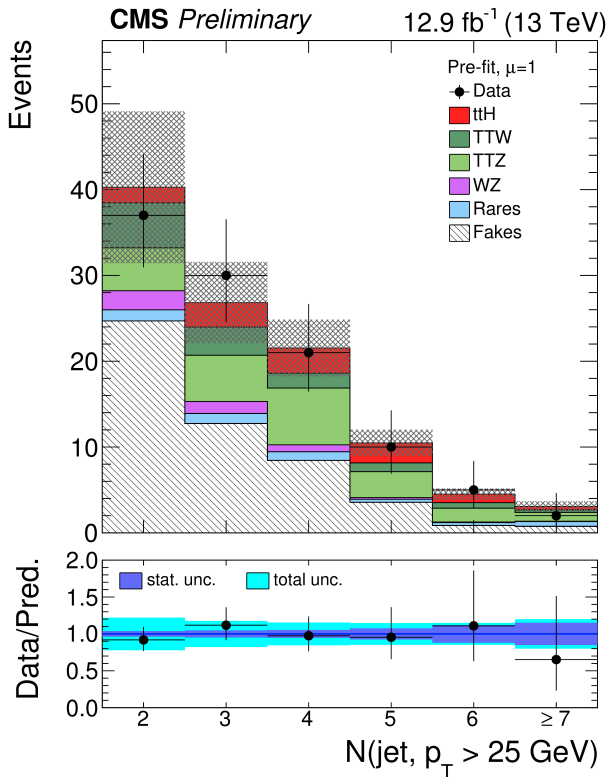
Training against tt



Training against ttV



Same-sign trilepton channel control plots



Matrix element method weights

Weight $w_{i,\alpha}$ for hypothesis α and event i

4-momenta of reconstructed particles

Phase space element corresponding to unmeasured quantities, momentum conservation enforced

Squared matrix element

$$w_{i,\alpha}(\Phi') = \frac{1}{\sigma_\alpha} \int d\Phi_\alpha \cdot \delta^4\left(p_1^\mu + p_2^\mu - \sum_{k\geq 2} p_k^\mu\right) \cdot \frac{f(x_1,\mu_F) f(x_2,\mu_F)}{x_1 x_2 s} \cdot \left|\mathcal{M}_\alpha(p_k^\mu)\right|^2 \cdot W(\Phi'|\Phi_\alpha)$$

Cross section

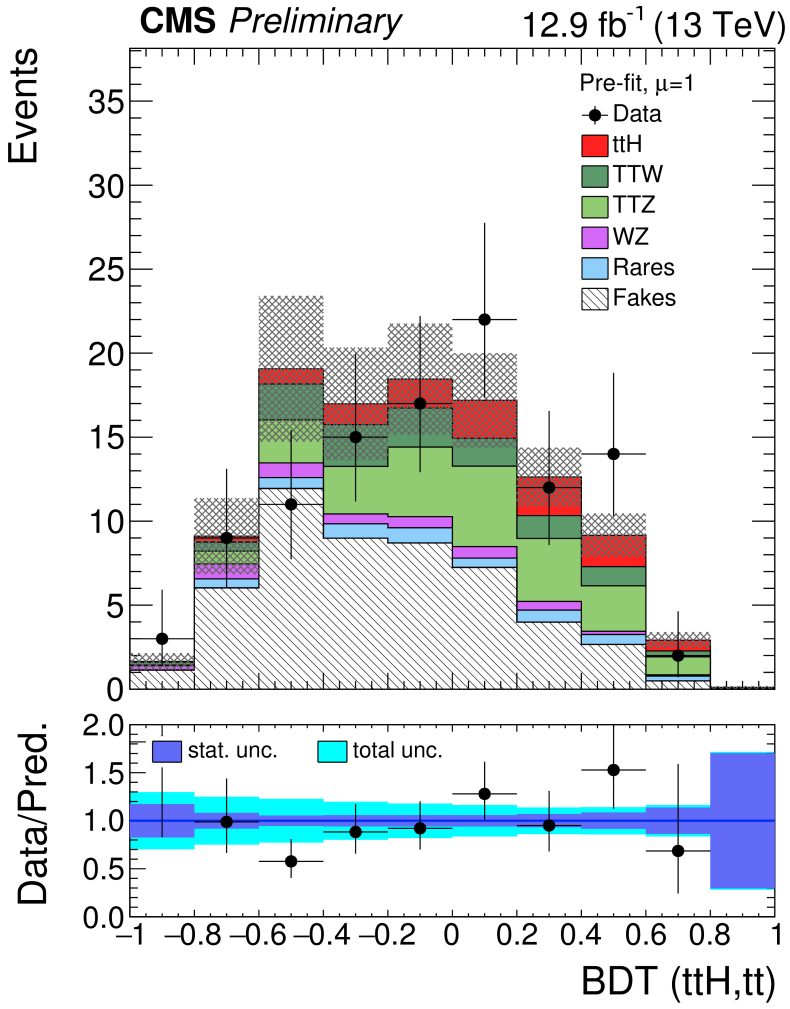
Parton density functions (NNPDF2.3 LO)

Transfer functions

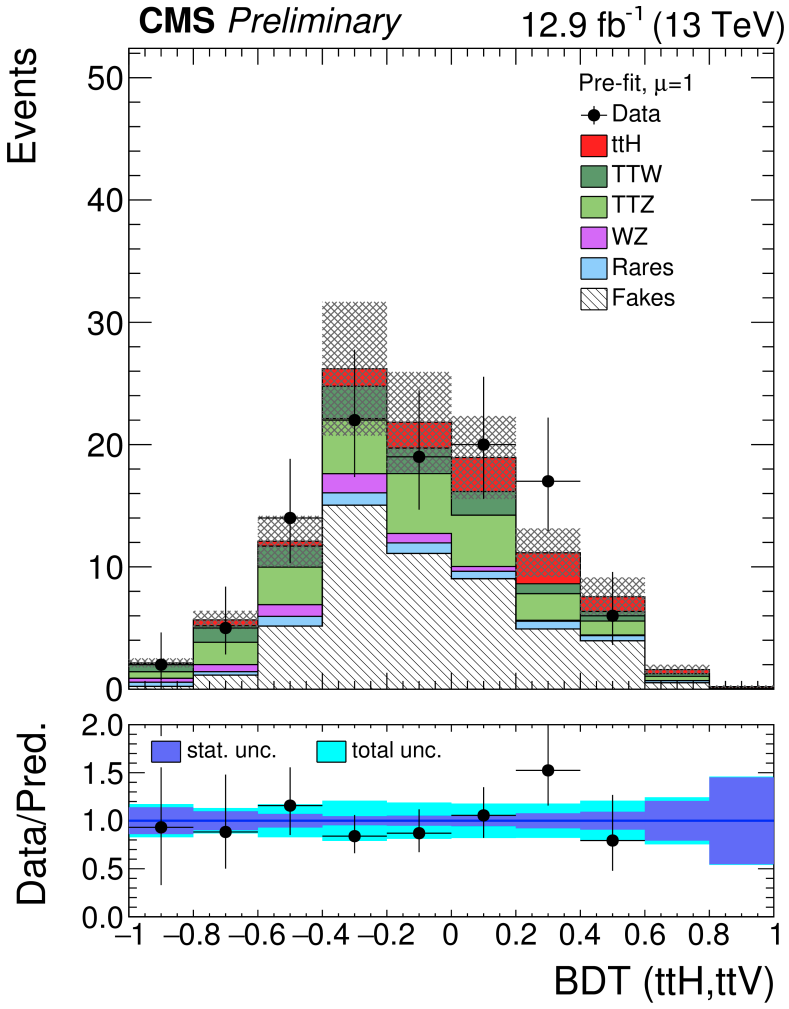
- Two jets with highest b-tagging discriminant assigned to two b quarks in matrix element
- Among remaining jets, pair with dijet mass closest to m_W selected
- **Final weight** = average of weights for each lepton, jet permutation

Same-sign dilepton channel BDT

Training against tt

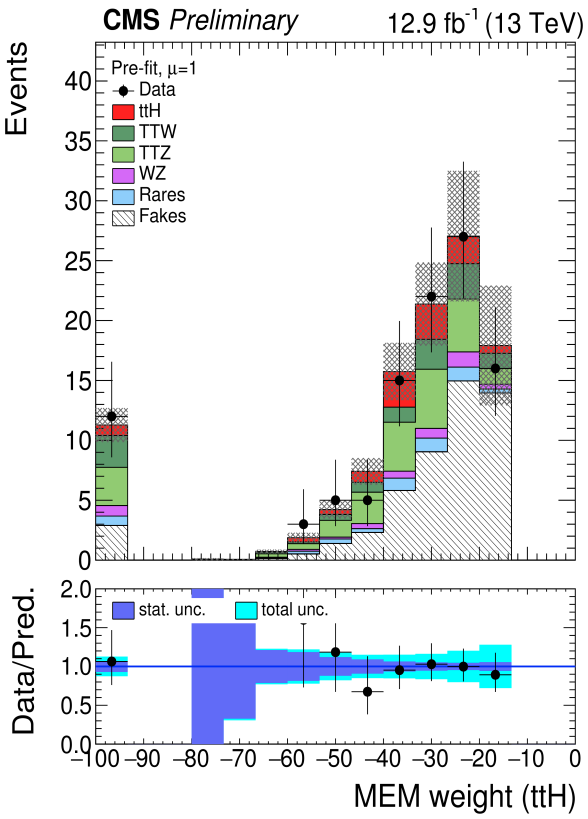


Training against ttV

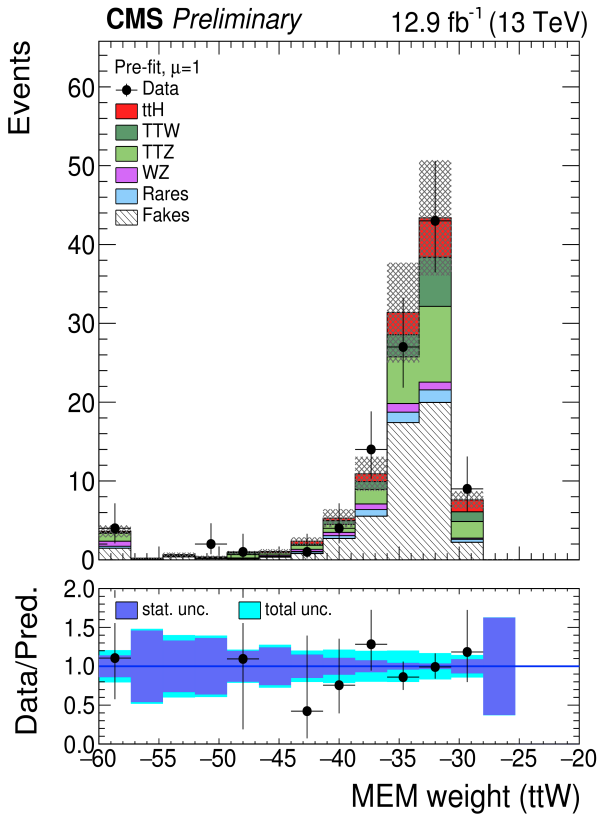


Trilepton channel MEM weights in BDT

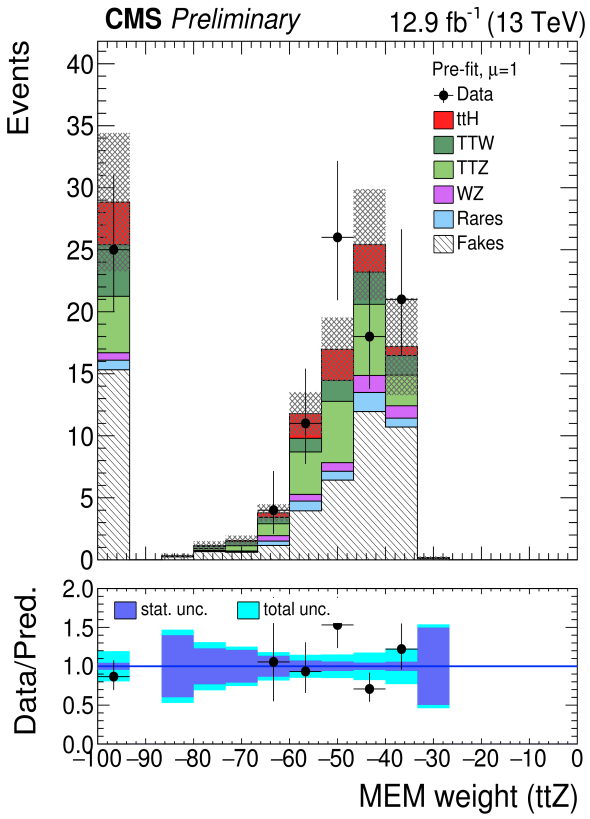
MEM weight for ttH



MEM weight for ttW

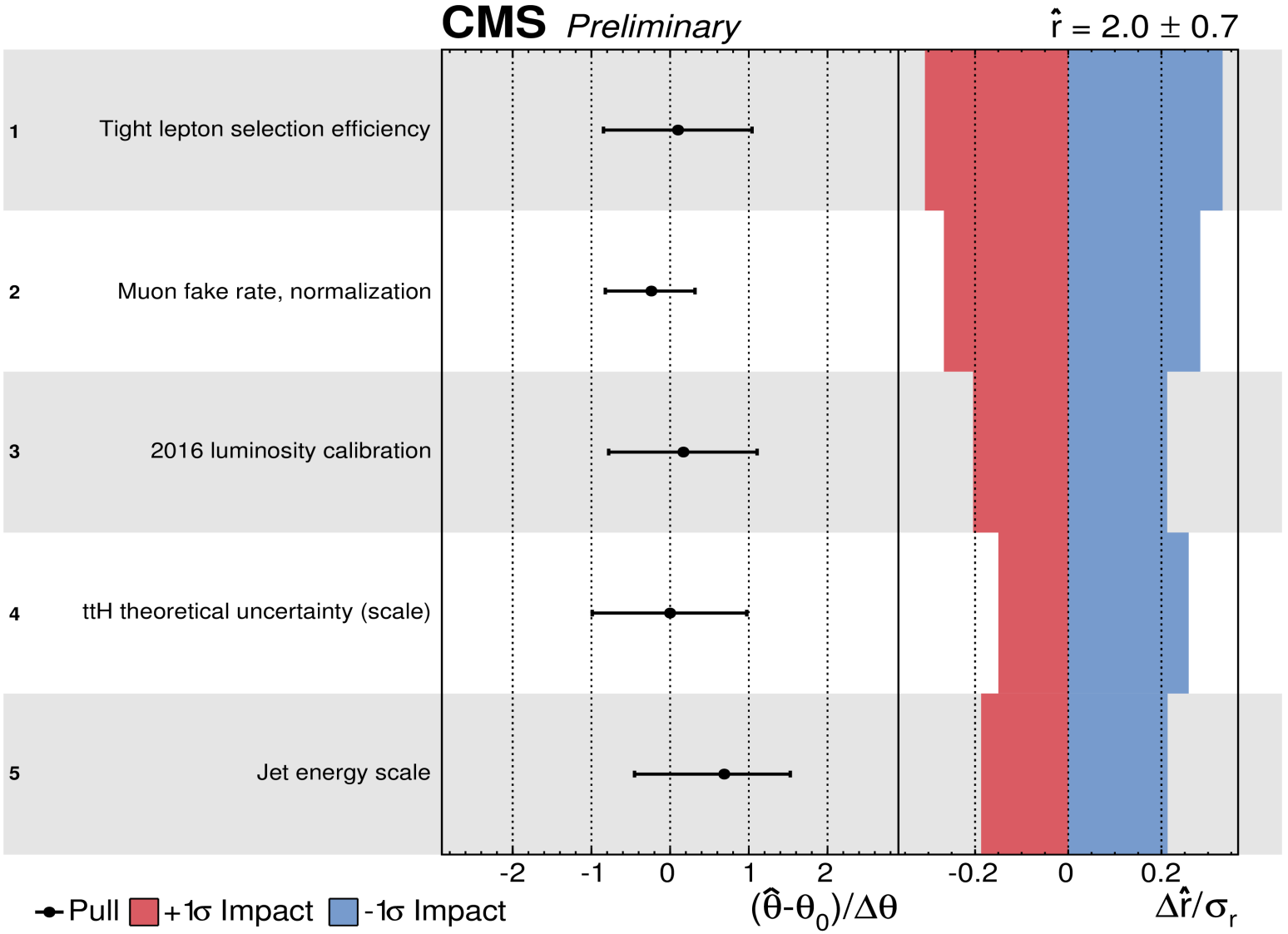


MEM weight for ttZ



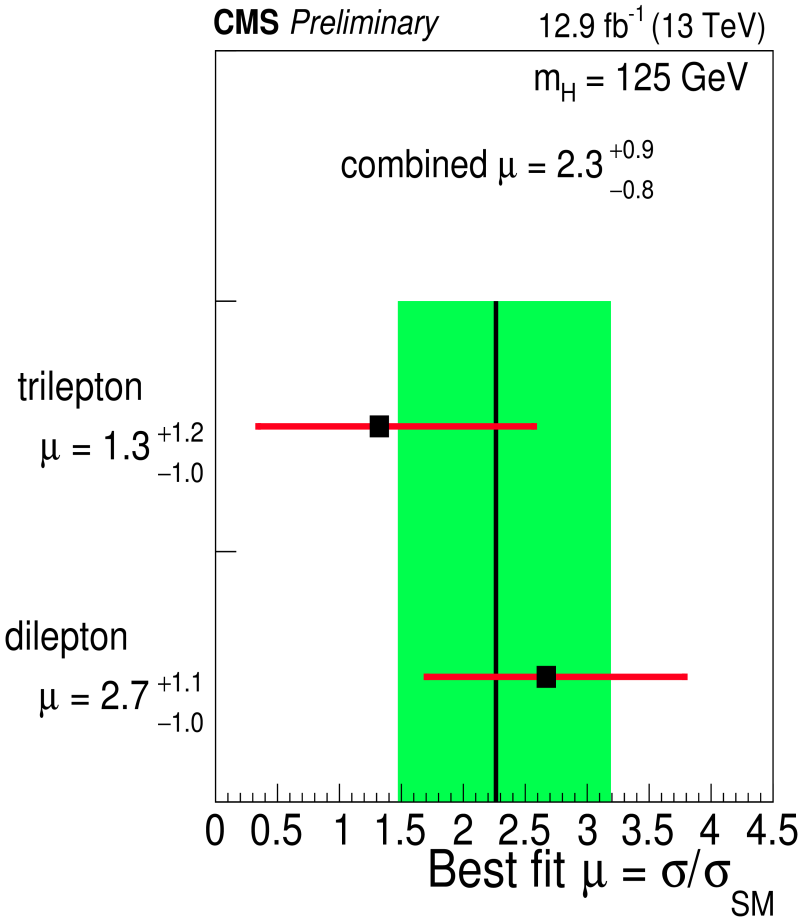
Most important systematic uncertainties

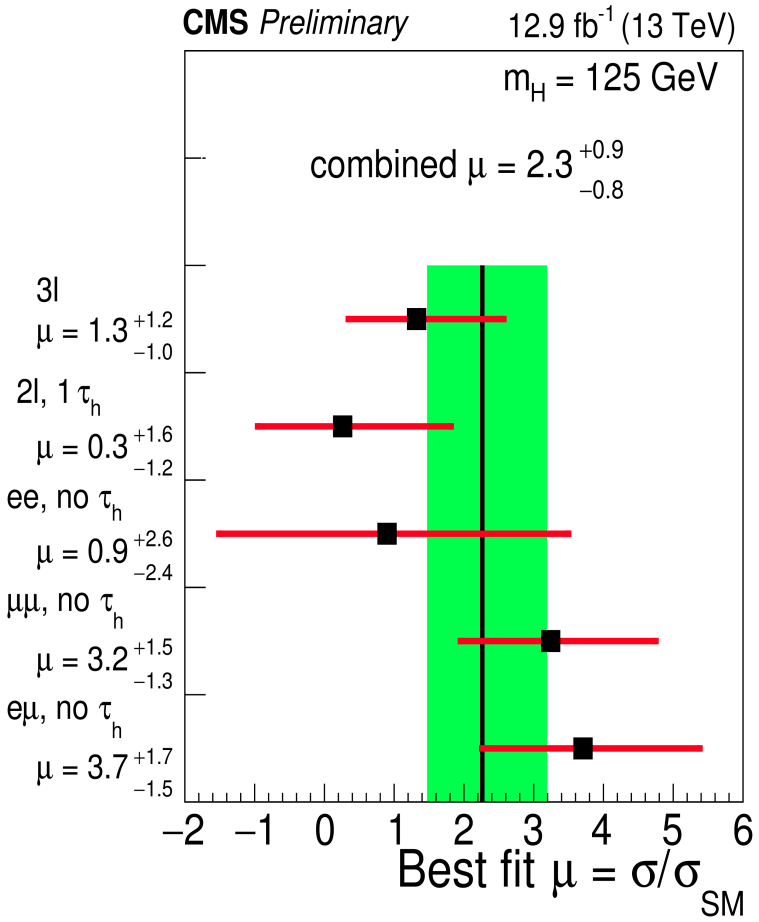
ttH(multilep)
HIG-16-022



Best-fit signal strengths: 2016 data

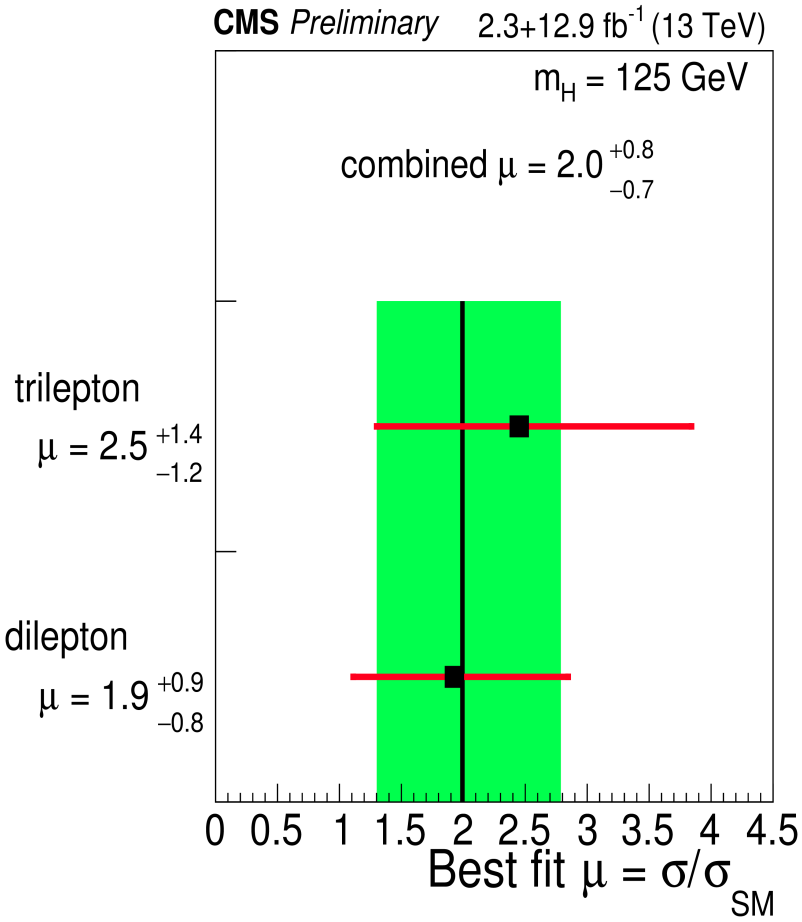
ttH(multilep)
HIG-16-022

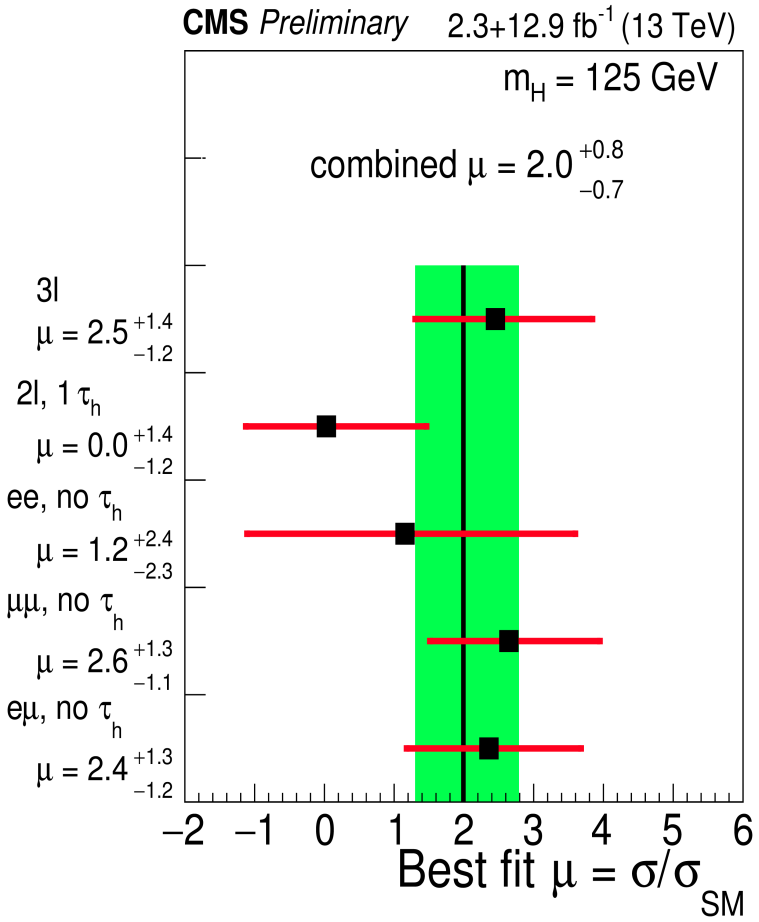




Best-fit signal strengths: 2015 + 2016 data

ttH(multilep)
HIG-16-022





$tt + (H \rightarrow bb)$

$tt + (H \rightarrow WW^{*}, ZZ^{*}, \tau\tau)$

$tt + (H \rightarrow \gamma\gamma)$

Photon selection and expected signal yields

Photon preselection requirements

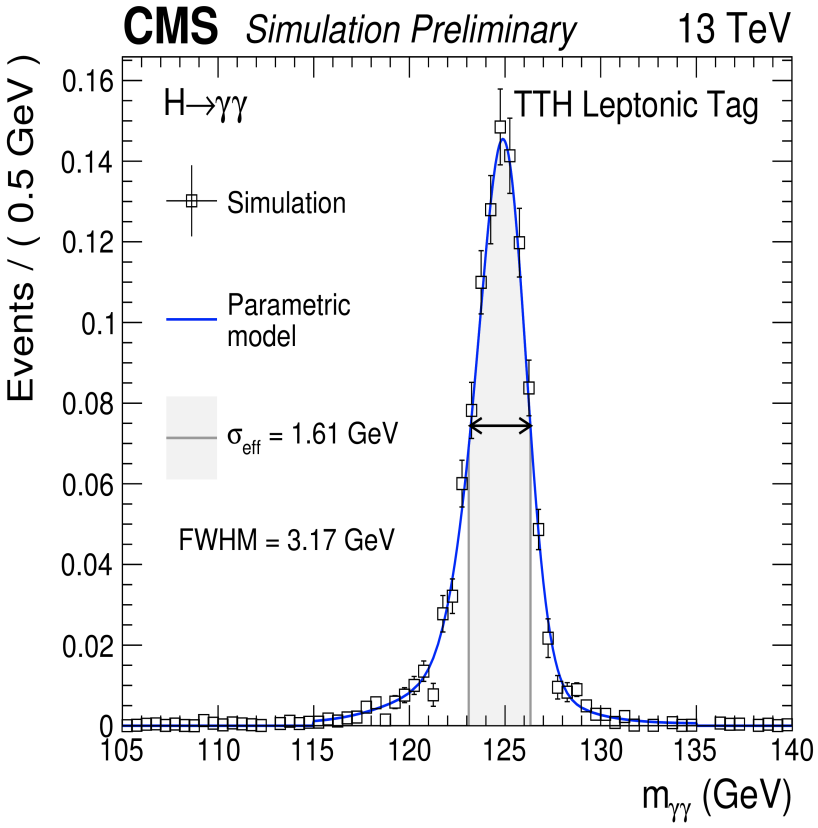
	H/E	$\sigma_{\eta\eta}$	R_9	photon iso.	tracker iso.
ECAL barrel; $R_9 > 0.85$	<0.08	–	>0.5	–	–
ECAL barrel; $R_9 \leq 0.85$	<0.08	<0.015	>0.5	< 4.0	< 6.0
ECAL endcaps; $R_9 > 0.90$	<0.08	–	>0.8	–	–
ECAL endcaps; $R_9 \leq 0.90$	<0.08	<0.035	>0.8	< 4.0	< 6.0

Expected signal event yields

Event Categories	SM 125GeV Higgs boson expected signal								Bkg (GeV^{-1})
	Total	ggh	vbf	wh	zh	tth	σ_{eff}	σ_{HM}	
Untagged Tag 0	11.92	79.10 %	7.60 %	7.11 %	3.59 %	2.60 %	1.18	1.03	4.98
Untagged Tag 1	128.78	85.98 %	7.38 %	3.70 %	2.12 %	0.82 %	1.35	1.20	199.14
Untagged Tag 2	220.12	91.11 %	5.01 %	2.18 %	1.23 %	0.47 %	1.70	1.47	670.44
Untagged Tag 3	258.50	92.35 %	4.23 %	1.89 %	1.06 %	0.47 %	2.44	2.17	1861.23
VBF Tag 0	9.35	29.47 %	69.97 %	0.29 %	0.07 %	0.20 %	1.60	1.33	3.09
VBF Tag 1	15.55	44.91 %	53.50 %	0.86 %	0.38 %	0.35 %	1.71	1.40	22.22
TTH Hadronic Tag	2.42	16.78 %	1.28 %	2.52 %	2.39 %	77.02 %	1.39	1.21	1.12
TTH Leptonic Tag	1.12	1.09 %	0.08 %	2.43 %	1.06 %	95.34 %	1.61	1.35	0.42
Total	647.77	87.93 %	7.29 %	2.40 %	1.35 %	1.03 %	1.88	1.52	2762.65

Signal diphoton mass shape

ttH leptonic tag



ttH hadronic tag