Top Quark Physics at the Precision Frontier

Curia II (WH2SW) (Fermilab, Wilson Hall)

15 May 2019, 17 May 2019

Search for Standard Model Higgs boson production in association with top quark pairs at CMS

Dr. Ram Krishna Dewanjee
Lab of High Energy and Computational Physics,
K.B.F.I, Tallinn

On behalf of the CMS collaboration

Motivation

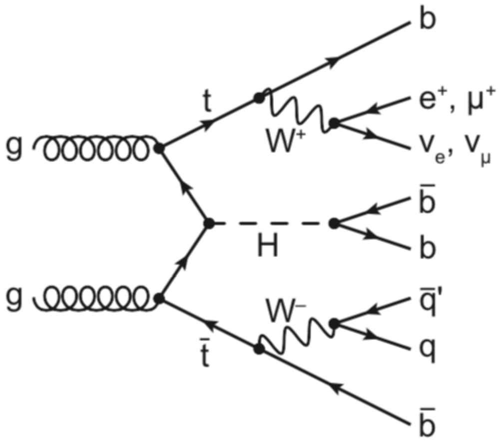
- After 125 GeV Higgs discovery, LHC experiments focused on studying the properties of this new particle (spin, couplings etc.).

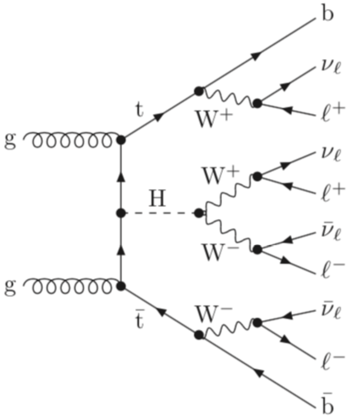
- Yukawa coupling b/w Higgs boson and top quark: important SM parameter that needs to be measured.

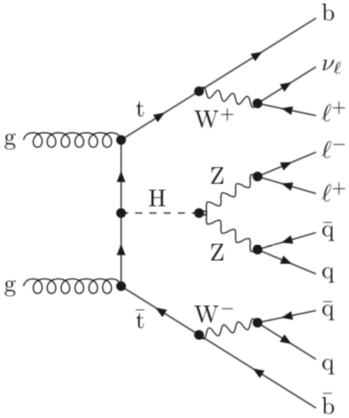
- Sensitive to BSM physics, may shed light on how top quark affects electroweak symmetry breaking.

- Although indirect constraints available (gluon fusion, H → $\gamma\gamma$ loop contribution), a direct measurement is possible only via studying top quark associated Higgs production ($t\bar{t}$H, tH).

- This talk overviews all major Run-2 $t\bar{t}$H searches:
  $t\bar{t}$H (H → $b\bar{b}$), $t\bar{t}$H (H → $\gamma\gamma$), $t\bar{t}$H (H → VV^*) and $t\bar{t}$H (H → $\tau^+\tau^-$).

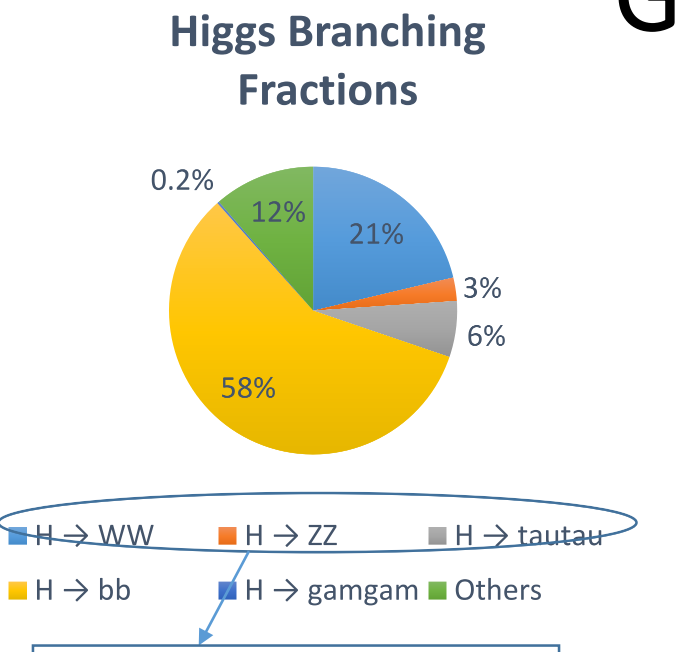






(*V= W/Z boson)

General strategy



Covered by $t\bar{t}$H Multi-lepton analysis

- **$t\bar{t}$H (H→$b\bar{b}$)**
  - Large BR, sensitivity limited by systematic uncert. (on irreducible $t\bar{t} + b\bar{b}$ background).
  - Shape analysis with **MEM*** to achieve optimal S/B.
- **$t\bar{t}$H (H → $\gamma\gamma$)**
  - High signal purity, small BR => analysis sensitivity statistically limited.
- **$t\bar{t}$H Multi-lepton**
  - Use of categories based on lepton and/or hadronic tau multiplicity.
  - Sufficient event yields, signal purities => most sensitive channel.
  - Mix of **H** → $\boldsymbol{VV^*}$ and **H** → $\boldsymbol{\tau^+\tau^-}$ contributing to each category.

- Categorization used to separate events with high S/B from those with low S/B.
- Reducible backgrounds determined directly from data, irreducible backgrounds taken from MC and checked in data control regions.
- Signal-background separation in each category performed by shape analysis. Maximum Likelihood fit on the distribution of one “discriminating observable” (typically output of **BDT** @), performed for signal extraction.
- Analysis sensitivity improved by using discriminants computed with **MEM** , **BDT** or **DNN**#.

*** Matrix element method** **@ Boosted Decision tree** **# Deep Neural Network**

Analysis level objects

GENERIC GUIDELINES FOLLOWED IN MOST OF THE SEARCHES

- Particle Flow (**PF**) algorithm used for global event reconstruction: full use of sub-detector information. ***arXiv:1706.04965***

- **Jets** reconstructed using anti-kT algorithm (R =0.4) using output of **PF** algorithm.

- **b-Jets** identified by likelihood based discriminator (**CSV**) including impact parameter significance and track based lifetime information. Most analysis use working point corresponding to 70% (1%) b-tagging efficiency (light jet mis-tag rate).

- **Muons** identified by PF based selections designed to reduce muons fakes from pions/kaons and punch through hadrons.

- **Electrons** identified via multi-variate (**BDT**) based discriminators which include electron shower shape variables.

- **Hadronic Taus (τ_h)** identified via reconstructing the individual hadronic tau decay modes: 1Prong-0π_0, 1Prong-1π_0, 1Prong-2π_0 and 3Prong-0π_0 inside **PF** jets and qualifying strict isolation criteria. Dedicated multi-variate selections further reduce e → τ_h and μ → τ_h fakes.

- **Photons (γ)** identified as ECAL energy clusters not linked to **PF** charged track. Dedicated shower shape based clustering and **MVA** regression is used to recover the full energy of both converted and unconverted photons inside the detector.

$t\bar{t}$H (H→$b\bar{b}$)

- Search performed in 2 distinct channels:

arXiv:1803.06986

JHEP 06 (2018) 101

Hadronic channel

- Events selected using multi-jet triggers and divided into 6 categories depending on jet and b-jet multiplicity: **(7Jet, 3b-tag), (7Jet, ≥4b-tag), (8Jet, 3b-tag), (8Jet, ≥4b-tag), (≥ 9Jet, 3b-tag) and (≥ 9Jet, ≥ 4b-tag)**

Backup (20,21)

- **MEM** employed in all categories to distinguish signal ($t\bar{t}$H) from background ($t\bar{t}$ + $b\bar{b}$) and used for signal extraction.

Leptonic channel

arXiv:1804.03682

- Events selected using lepton triggers and divided into single-lepton and di-lepton (split by lepton flavor).
- Di-lepton events divided into: **(≥4Jets, 3b-tag)** and **(≥4Jets, ≥4b-tag)** categories. **BDT**s trained to distinguish signal ($t\bar{t}$H) from background ($t\bar{t}$) in both. Backup (28-30)
- **BDT/BDT+MEM** used for signal extraction in **(≥4Jets, 3b-tag)/(≥4Jets, ≥4b-tag).** Backup (28-30)
- Single lepton events split into: **(4Jets, ≥3b-tag), (5Jets, ≥3b-tag)** and **(≥6Jets, ≥3b-tag)** categories.
- **DNN**s trained to distinguish signal ($t\bar{t}$H) from background ($t\bar{t}$ + **X**) processes used for signal extraction.

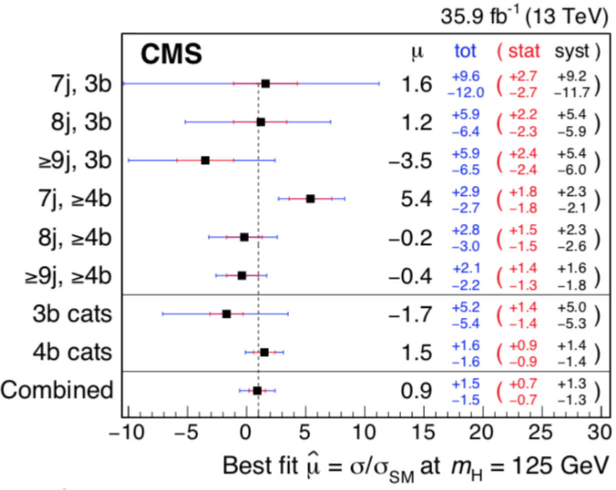
Backup (22-26)

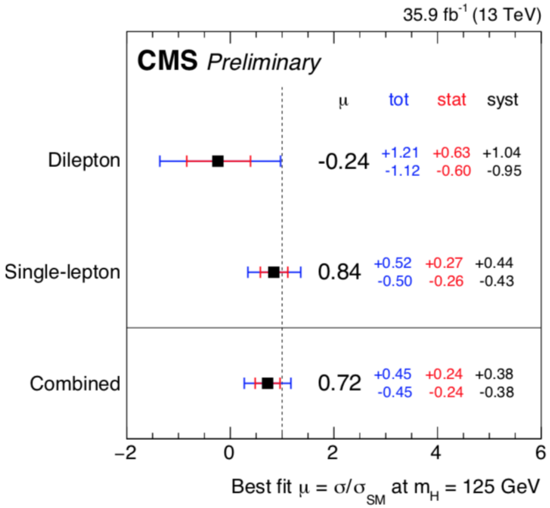
X = b$\bar{b}$, c$\bar{c}$, 2b, b, light flavors.

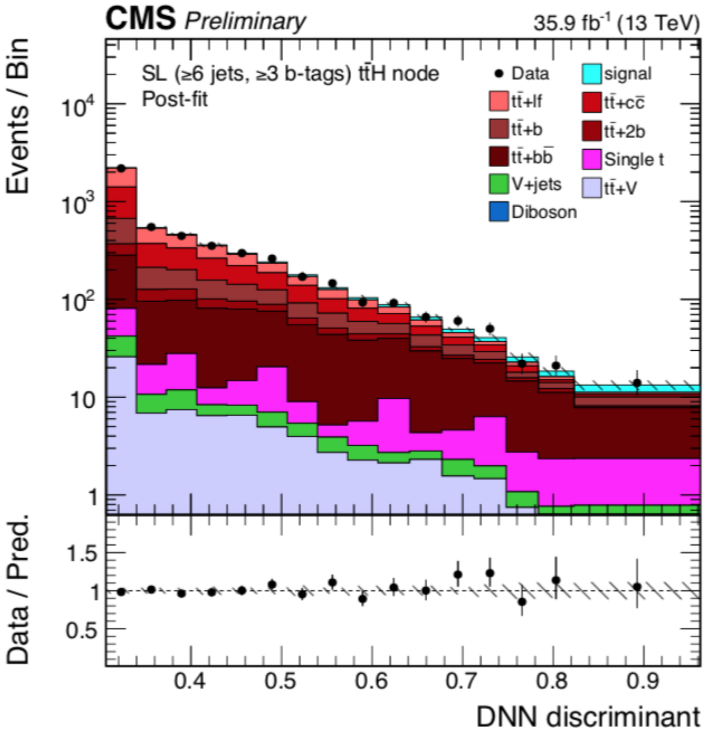
Full 2016 data
(35.9 fb^{-1})

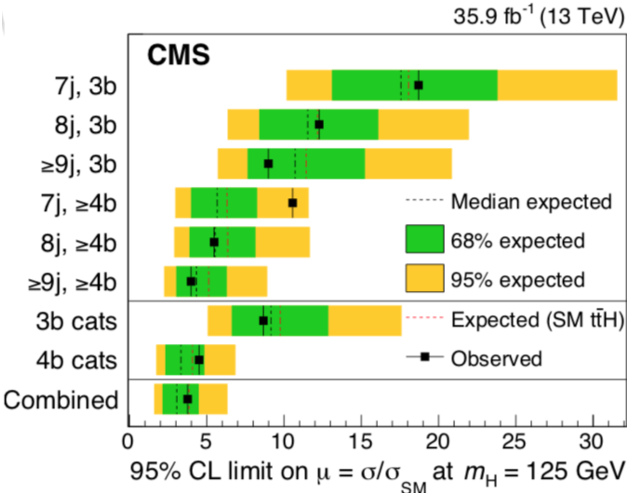
$t\bar{t}$H (H→$b\bar{b}$): Results

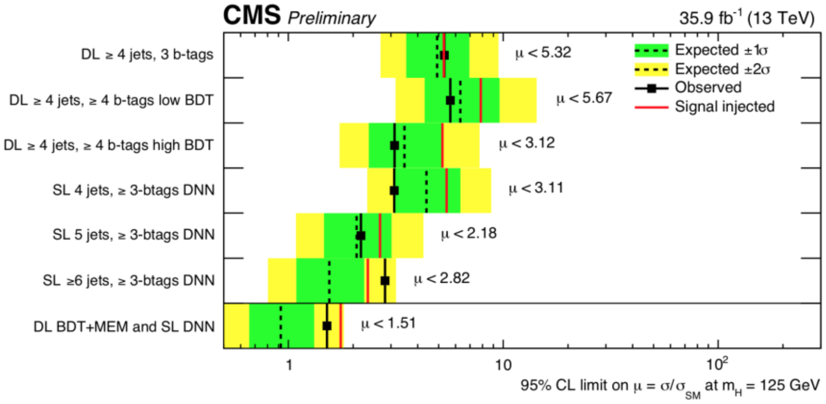
Systematics in Backup (27)











$t\bar{t}$H (H → $\gamma\gamma$)

arXiv:1804.02716

- Events triggered by asymmetric di-photon triggers with E_T thresholds of 30 and 18 GeV and loose ECAL based ID.
- Photon energy scale corrected and resolution smeared to match data using Z→ e^+e^-events ($e^\pm$ reconstructed as γ).
- Photons entering analysis required to satisfy pre-selection criteria and **BDT** (trained to separate prompt photons from mis-identified jet fragments). Backup (31)
- Additional **BDT**s are used for di-photon vertex assignment and vertex probability computation. Backup (32)
- Events split into categories based on Higgs production mechanism (ggH, VBF, VH and $t\bar{t}$H), $m_{\gamma\gamma}$ resolution and predicted S/B.
- Good $m_{\gamma\gamma}$ resolution allows determination of backgrounds from data sidebands in $m_{\gamma\gamma}$.
- Category targeting $t\bar{t}$H production employs **BDT** for tagging $t\bar{t}$H multi-jet events using:
  - Number of Jets with $p_T > 25$ GeV.
  - The leading jet p_T
  - 2 jets with the highest **CSV** b-tagging scores.
  - Contributions of SM H → $\gamma\gamma$ production via ggH, VBF, VH treated as background.

Full 2016 data
(35.9 fb^{-1})

$t\bar{t}$H (H → $\gamma\gamma$): Analysis strategy

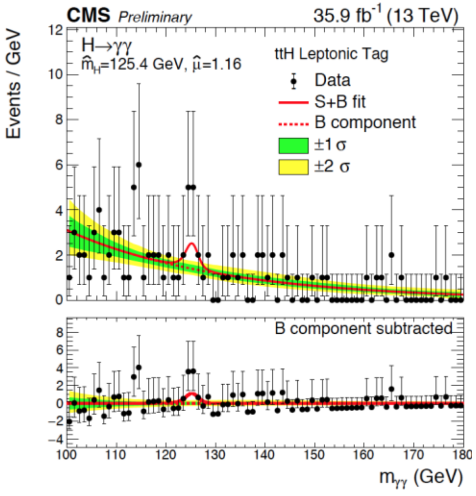
- The $t\bar{t}$H category is further split into 2 sub-categories:
  - ***$t\bar{t}$*H Leptonic**: targeting semi-Leptonic top decays. This sub-category applies the following selections.
    - $p_T^{\gamma 1} > \frac{m_{\gamma\gamma}}{2}, p_T^{\gamma 2} > \frac{m_{\gamma\gamma}}{4}$
    - Di-photon **BDT** score > 0.11
    - $\geq$ 1 lepton with p_T > 20 GeV satisfying loose (tight) ID for the case of electrons (muons).
    - ΔR(lepton,γ) > 0.35
    - $|m_{e,\gamma} - m_Z|$ > 5 GeV (for electrons only)
    - $\geq$ 2 jets, p_T > 25 GeV, $|\eta| < 2.4$, ΔR(jet,γ) > 0.4, ΔR(jet, lepton) > 0.4
    - $\geq$ 1 medium b-tagged jet

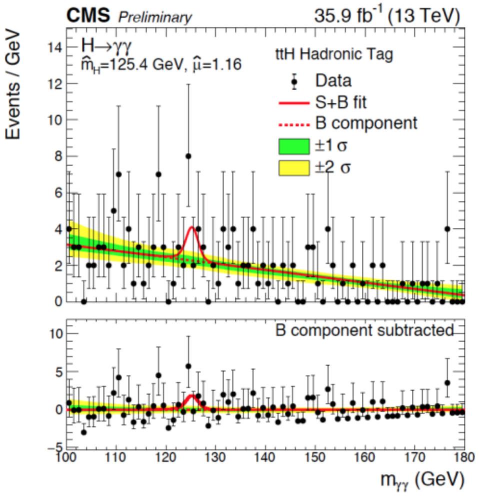
  - ***$t\bar{t}$*H Hadronic**: targeting hadronic top decays.
    - $p_T^{\gamma 1} > \frac{m_{\gamma\gamma}}{3}, p_T^{\gamma 2} > \frac{m_{\gamma\gamma}}{4}$
    - Di-photon **BDT** score > 0.4
    - Lepton veto (lepton ID similar to one used above)
    - $\geq$ 3 jets, p_T > 25 GeV, $|\eta| < 2.4$
    - $\geq$ 1 loose b-tagged jet
    - $t\bar{t}$H multi-jet tagger **BDT** score > 0.75

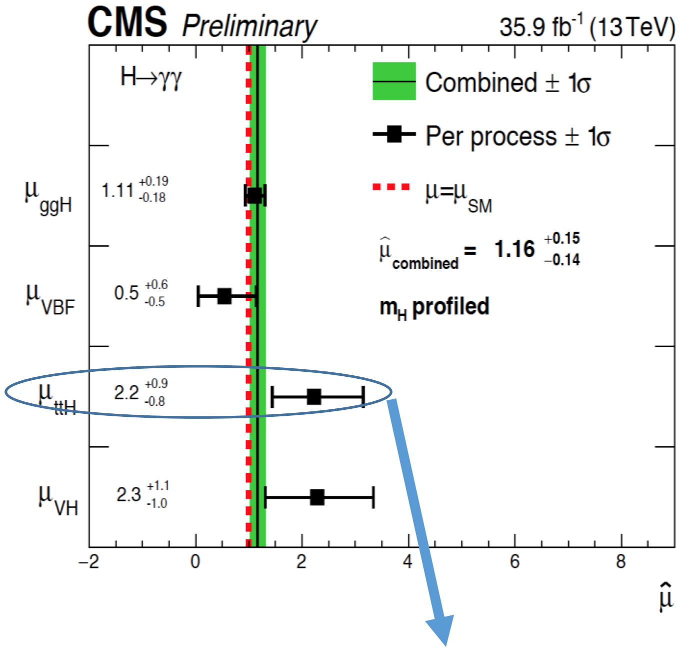
- Signal model is derived from simulation via. simultaneous fitting of Gaussians for each process, category and vertex scenario.

- Background model is derived from data via discreet profiling method wherein choice of background function is a nuisance parameter in the fit.

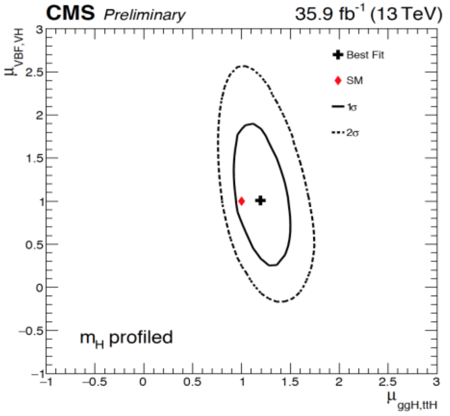
$t\bar{t}$H (H → $\gamma\gamma$): Results

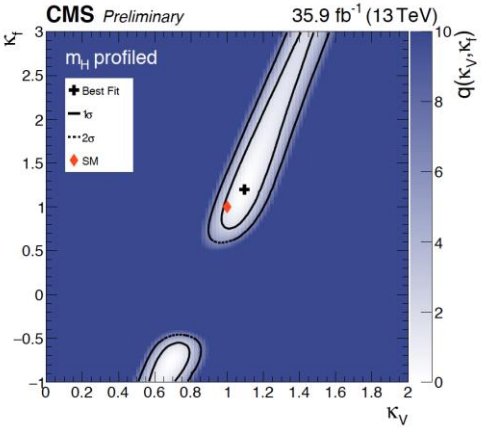






3.3 σ excess w.r.t b-only hypothesis
Compatible with SM $t\bar{t}$H prod. within 1.6 σ





Systematics in Backup (33)

$t\bar{t}$H Multi-lepton (H → VV^*/(H → $\tau^+\tau^-$)

arXiv:1803.05485
JHEP 08 (2018) 066

- Events are triggered based on the presence of electrons/muons/τ_h using lepton or lepton + τ_h triggers.
- Selected events required to have at least 2 “loose” b-tagged jets[$] out of which at least one is medium b-tagged.
- Events containing τ_h vetoed in $t\bar{t}$H (H → VV^*) analysis to keep it orthogonal to $t\bar{t}$H (H → $\tau^+\tau^-$) analysis.
- Special **BDT** used to distinguish “prompt” leptons (produced by W/Z/leptonic τ decays) from “non-prompt” ones (produced in b-hadron decays, decays-in-flight and photon conversions).
- This **BDT** is trained on simulated $t\bar{t}$H ($t\bar{t}$) events as signal (background). Leptons passing (failing) it are called tight (loose) leptons.
- Events with pair of loose leptons having $m_{ll} < 12$ GeV rejected due to mis-modelling by simulation.
- Events categorized as a function of (tight) lepton and/or τ_h multiplicity:
  - **$t\bar{t}$H (H → VV^*):** 2 same sign leptons (**2lSS**), 3 leptons (**3l**) and 4 leptons (**4l**). Backup (34)
  - **$t\bar{t}$H (H → $\tau^+\tau^-$):** 1 lepton + 2 Had. Taus ($\mathbf{1l + 2\tau_h}$), 2 same-sign leptons + 1 Had. Tau ($\mathbf{2lss + 1\tau_h}$) and 3 leptons + 1 Had. Tau ($\mathbf{3l + 1\tau_h}$). Backup (39)

Full 2016 data
(35.9 fb^{-1})

[$] p_T > 25 GeV, $|\eta|$ < 2.4, $\Delta R(lep, Jet)$ > 0.4

$t\bar{t}$H Multi-Lepton: Background Estimation

- Dominant reducible backgrounds arise from "non-prompt leptons"* passing "tight" selections and from lepton charge mis-identification.

- Non-prompt lepton contribution estimated from data via fake rate method:
  - Measure "Probability(non-prompt lepton→ tight lepton)" in QCD enriched regions in data collected by lepton, lepton+jet triggers as function of lepton (p_T, η).
  - Prompt lepton contamination either suppressed (by lepton vetoes) or subtracted (using m_T) prior to measurement.
  - Weigh events in sidebands defined by relaxed lepton ID criteria (w.r.t. signal region) with the above probability to get the final background contribution.

- Lepton charge mis-id estimated from Z→ ll events in data:
  - Measure the "charge mis-id probability" in sample of SS di-lepton events compatible with Z-boson decay.
  - Measurement done in bins of lepton (p_T, η).
  - Weigh events with OS leptons in signal region with the above measured probability to get the background estimate.

- Irreducible $t\bar{t}V$ and WZ/ZZ backgrounds modelled by MC and validated in control regions in data.

* Leptons not produced by W/Z decays e.g. leptons in semi-leptonic decays of b-hadrons

$t\bar{t}$H Multi-Lepton: Signal Extraction

- Pair of **BDTs** (trained against $t\bar{t}$V and $t\bar{t}$ as backgrounds) used to enhance sensitivity in **$2l$SS** and **$3l$** categories.

  Backup (35)

- **BDT**s for **$2l$SS** includes discriminators for "hadronic top tagging" and for identifying jets in Higgs decays.

  Backup (36)

- 1 dim. distributions derived via. "Likelihood based clustering" of the 2D space spanned by individual **BDT**s used for signal extraction.

- Minimum invariant mass of OS di-lepton pair used for signal extraction in **$4l$**.

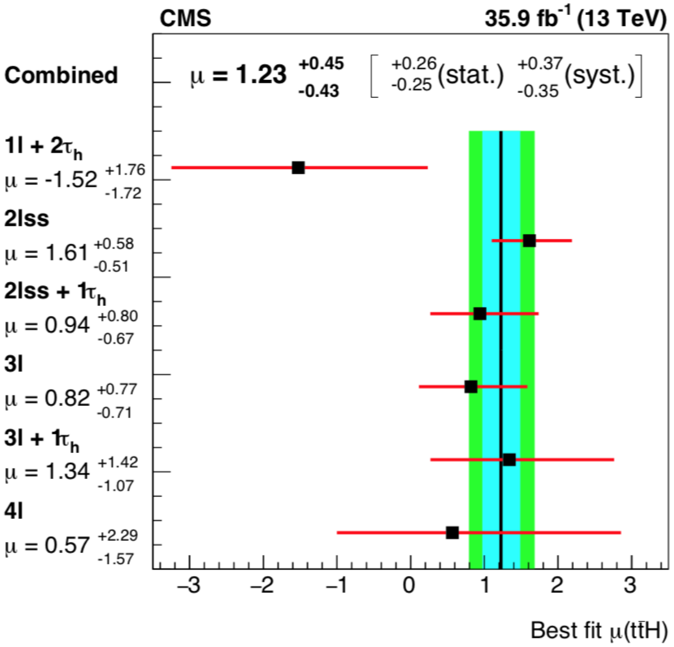
- **BDT** (trained to distinguish $t\bar{t}$H from $t\bar{t}$) used as final discriminant in $\mathbf{1l + 2\tau_h}$. Backup (40)

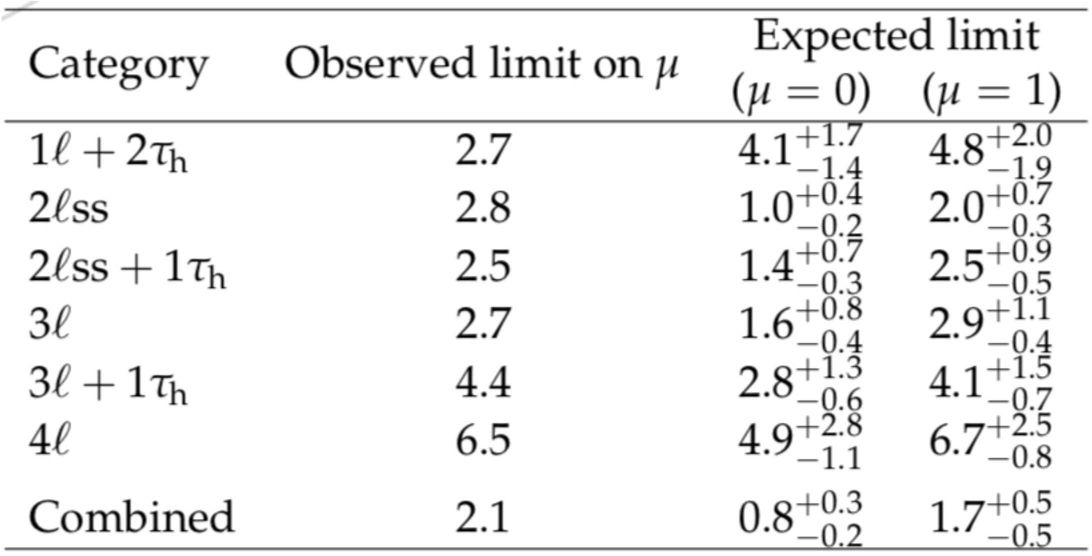
- **MEM** (useful in separating $t\bar{t}$H from $t\bar{t}$Z and $t\bar{t}$ backgrounds) used as final discriminant in the $\mathbf{2lss + 1\tau_h}$ category.

- 2 **BDT**s (one trained against $t\bar{t}$V other against $t\bar{t}$) which are later mapped into a 1 dim. discriminant (D_{MVA}) used in $\mathbf{3l + 1\tau_h}$ category. Backup (40)

$t\bar{t}$H Multi-Lepton: Results*

arXiv:1803.05485



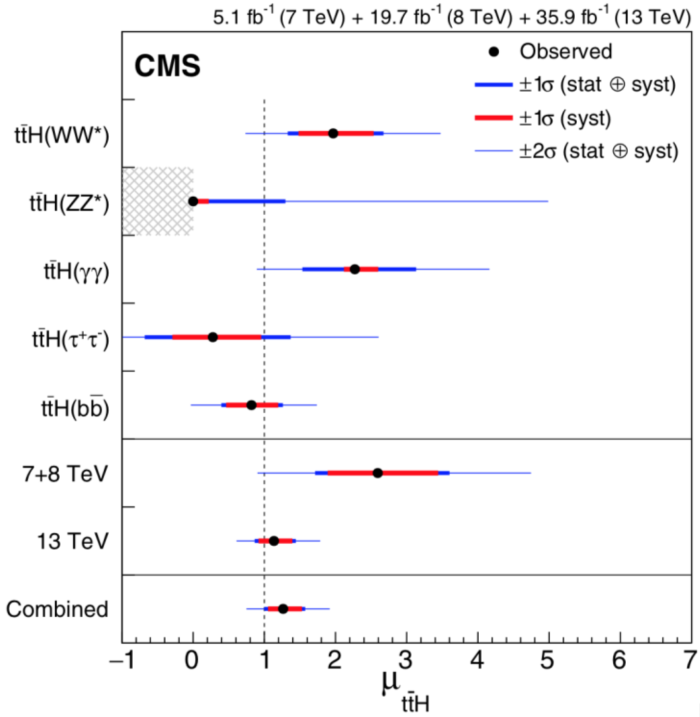


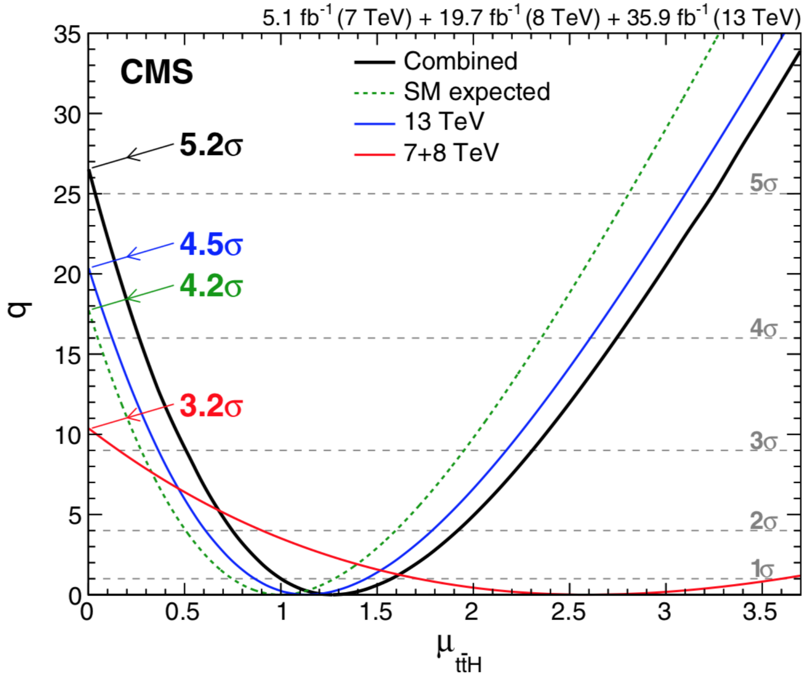
Category	Observed limit on μ	Expected limit $(\mu = 0)$	$(\mu = 1)$
$1\ell + 2\tau_h$	2.7	$4.1^{+1.7}_{-1.4}$	$4.8^{+2.0}_{-1.9}$
2ℓss	2.8	$1.0^{+0.4}_{-0.2}$	$2.0^{+0.7}_{-0.3}$
$2\ell\mathrm{ss} + 1\tau_h$	2.5	$1.4^{+0.7}_{-0.3}$	$2.5^{+0.9}_{-0.5}$
3ℓ	2.7	$1.6^{+0.8}_{-0.4}$	$2.9^{+1.1}_{-0.4}$
$3\ell + 1\tau_h$	4.4	$2.8^{+1.3}_{-0.6}$	$4.1^{+1.5}_{-0.7}$
4ℓ	6.5	$4.9^{+2.8}_{-1.1}$	$6.7^{+2.5}_{-0.8}$
Combined	2.1	$0.8^{+0.3}_{-0.2}$	$1.7^{+0.5}_{-0.5}$

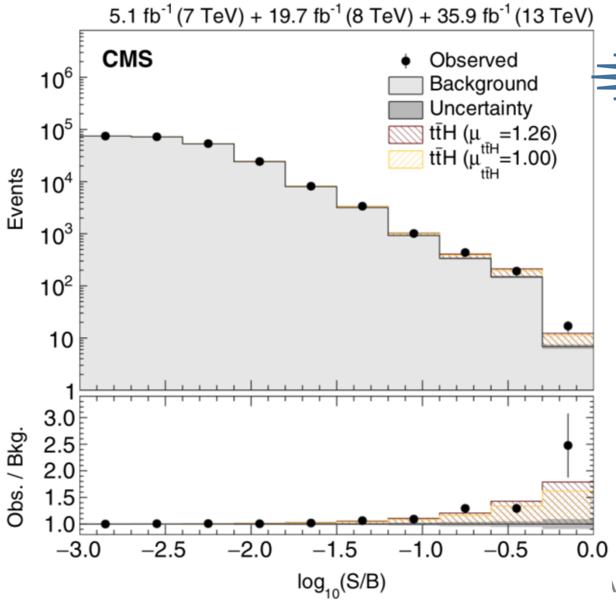
Observed (Expected) Significance: 3.2 σ (2.8 σ) !!!

Individual results for $t\bar{t}$H (H → VV)/(H → $\tau^+\tau^-$) shown in Slides 38/41

$t\bar{t}$H (Run-1 + Run-2) Combination: Results







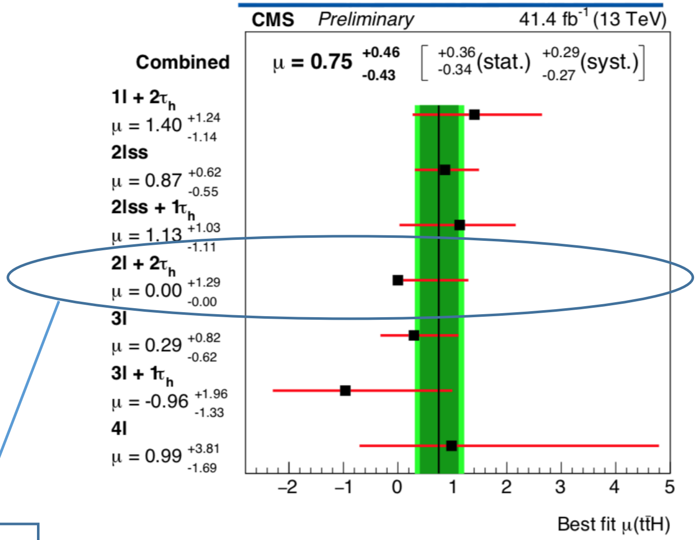
5 σ observation !!

Phys.Rev. Letts 120.23 (2018): 231801

Summary

- Comprehensive overview of all Run-2 $t\bar{t}$H searches with 2016 dataset was presented.
- $t\bar{t}$H production observed with significance of > 5 σ after combining 2016 data with Run-1 dataset.
- Updated results using 2017 data (41.4 fb^{-1}) already made public by some analyses e.g $t\bar{t}$H Multi-lepton and $t\bar{t}$H (H → $\gamma\gamma$) searches (See below).
- Work ongoing in all channels for Run-2 legacy papers with more channels and improved experimental methods that will further increase analysis sensitivity.

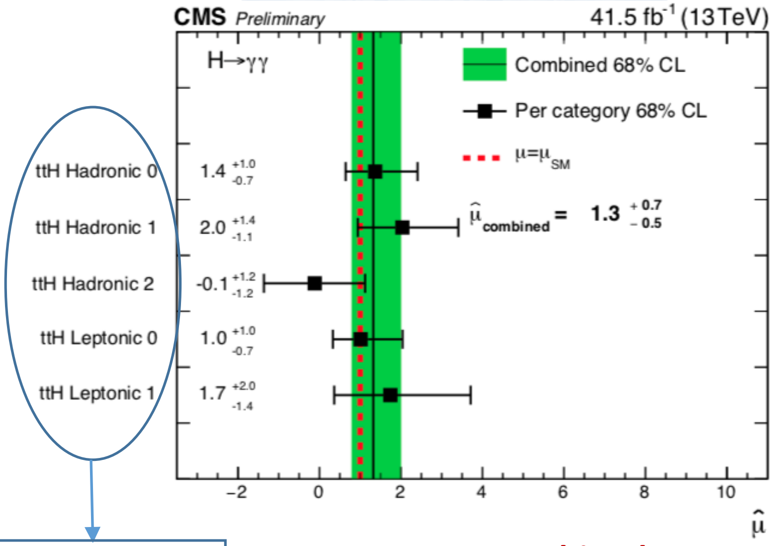
CMS PAS HIG-18-019



New Channel Added

2016+2017 combined best fit signal strength
$\mu = 0.96^{+0.34}_{-0.31}$

CMS PAS HIG-18-018



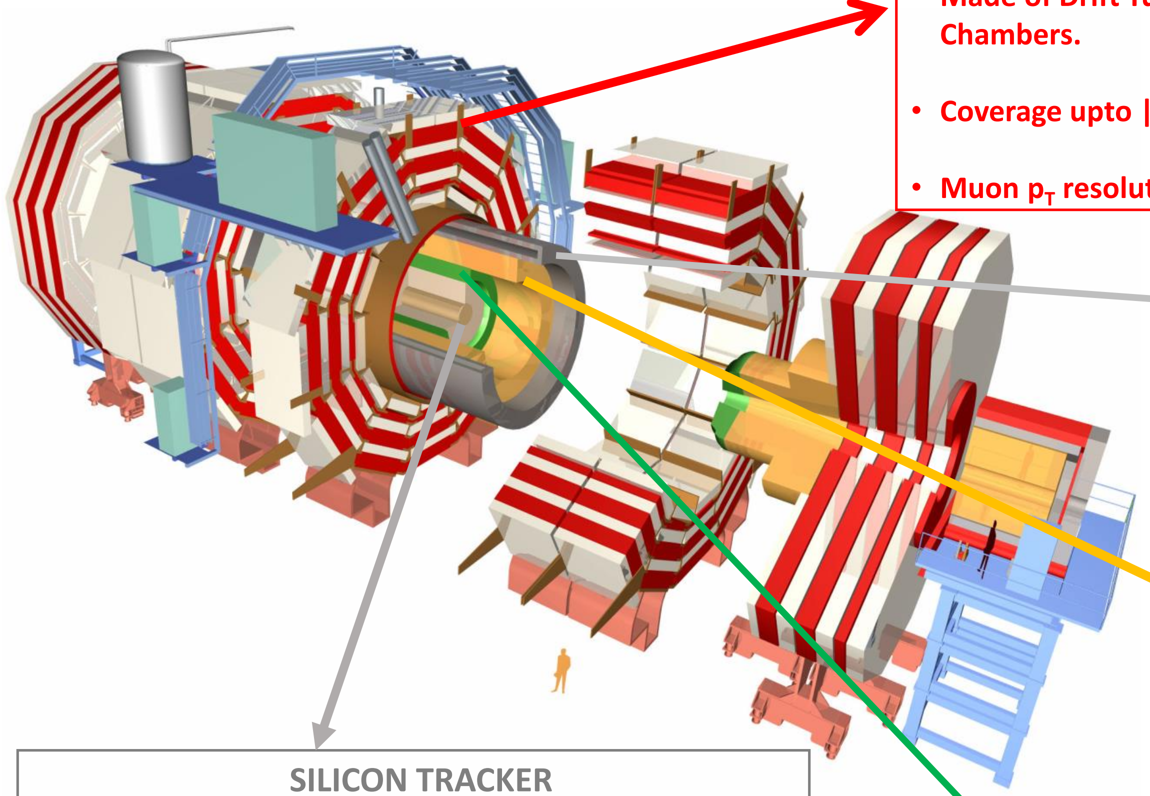
New BDT based Categorization

2016+2017 combined best fit signal strength
$\mu = 1.7^{+0.6}_{-0.5}$

THANK YOU

Backup Slides

CMS Detector



MUON CHAMBERS

- Made of Drift Tubes, Cathode Strip Chambers and Resistive Plate Chambers.
- Coverage upto $|\eta| < 2.4$
- Muon p_T resolution 1-1.5% upto $p_T^\mu = 1$ TeV

MAGNET

- Superconducting Nb-Ti coil , 12m long and 6m diameter.
- Design Magnetic field : 4 Tesla

HADRON CALORIMETER

- Sampling calorimeter made of alternating layers of Brass and plastic scintillator.
- WLS fibres used for collection of signal. measured by HPDs.
- Energy resolution 10% for 100 GeV pion.

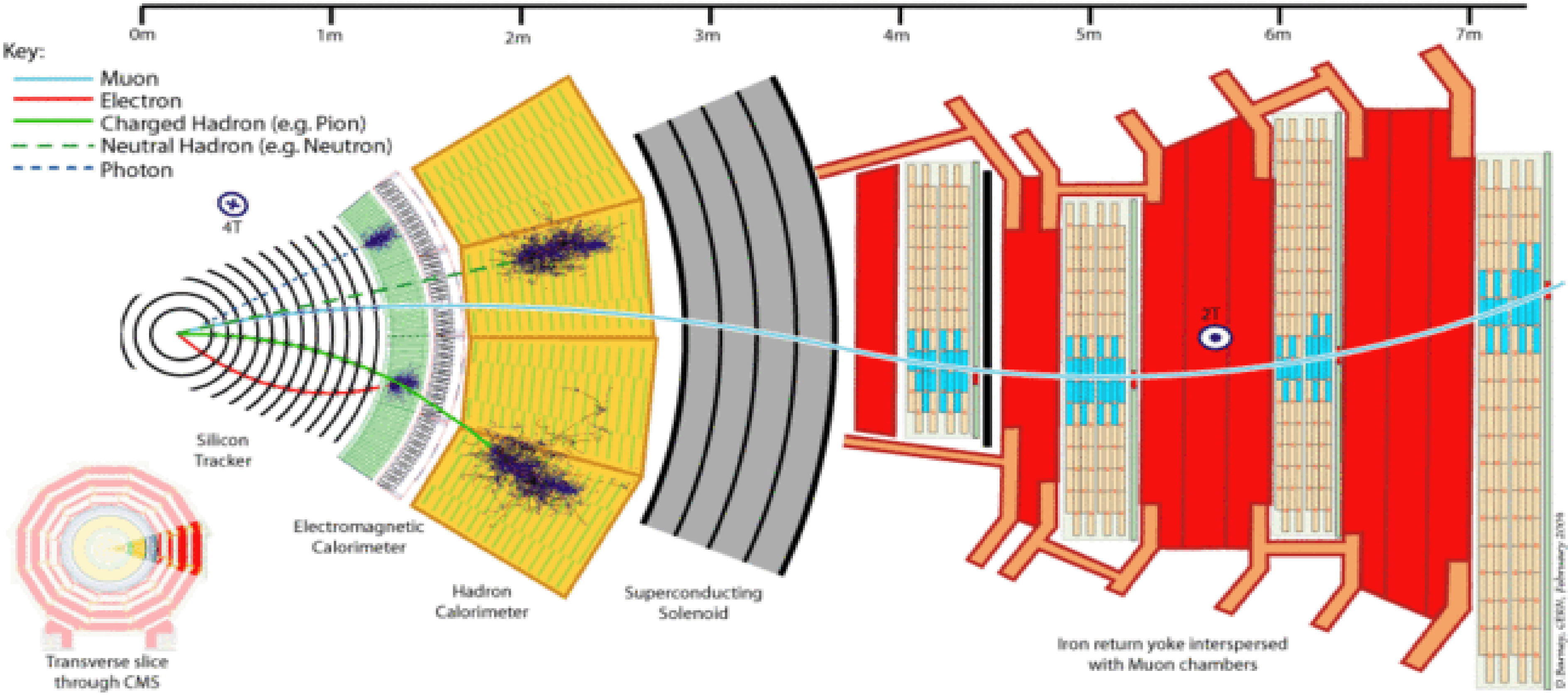
ELECTROMAGNETIC CALORIMETER

- Homogeneous calorimeter made of PbWO4 crystals .
- Signal measured by Avalanche Photo diodes.
- Energy resolution of 1% for 30 GeV e/γ.

SILICON TRACKER

- Inner most 3/2 layers in the Barrel/Endcap comprising 100 x 150 μm^2 pixels (66 million channels).
- Outermost 10/12 layers in the Barrel/Endcap made of strip detectors.
- p_T resolution 0.5% for 10 GeV charged track.

EVENT RECONSTRUCTION (PARTICLE FLOW)



- Muons: Tracker hits, Calo Energy deposits (ECAL + HCAL), Muon chamber hits
- Charged Hadrons: Tracker hits, Calo Energy deposits (ECAL + HCAL)
- Electron/Photon (Converted): Tracker hits, Calo Energy deposits (ECAL)
- Neutral Hadron: Calo Energy deposits (ECAL + HCAL)
- Photon (Unconverted): Calo Energy deposits (ECAL)

$t\bar{t}$H (H→$b\bar{b}$) Hadronic: CMS PAS HIG-17-022

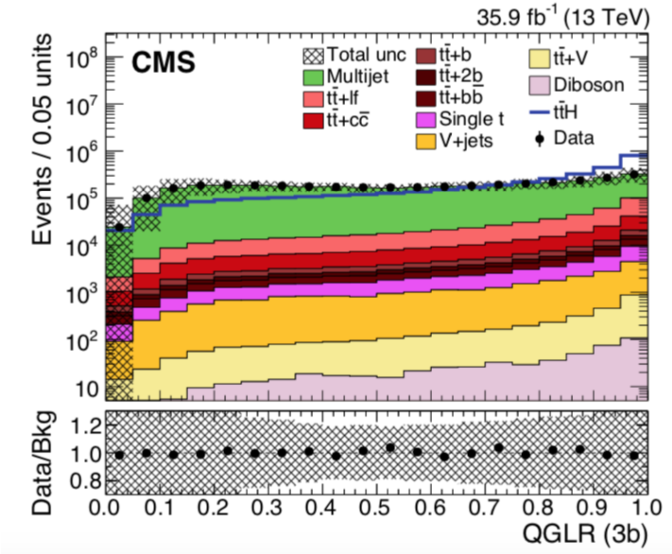
Events

≥ 6 Jets, p_T > 40 GeV, |η| < 2.6,
H_T *> 500 GeV, ≥ 2 b-tags (CSVM)

Lepton Veto
No e/μ: p_T> 15 GeV, |η| < 2.4

Events split into 6 categories:
(7 Jets, 3 b-tags); (7 Jets, ≥ 4 b-tags); (8 Jets, 3 b-tags);
(8 Jets, ≥ 4 b-tags); (≥ 9 Jets, 3 b-tags); (≥ 9 Jets, ≥ 4 b-tags);
QCD Multi-jet Control region: (≥ 7 Jets, 2 b-tags);

Non b-tag "Di-Jet" Mass window cuts:
60 GeV < m_{qq} < 100 GeV (7/8 Jet categories)
70 GeV < m_{qq} < 92 GeV (9 Jet categories)

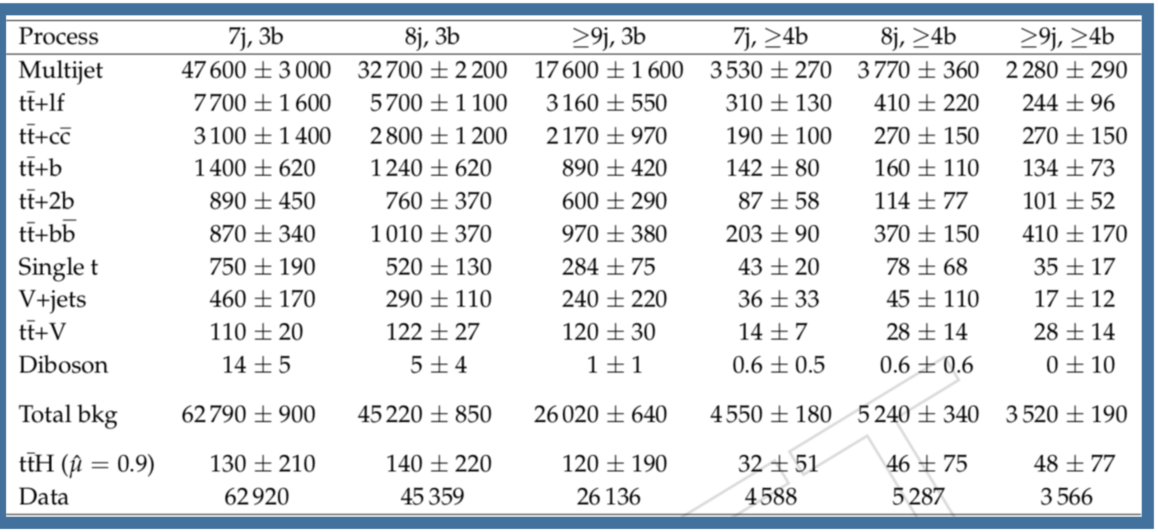


Quark-Gluon Likelihood ratio (QGLR) used for all Jets (except the 3 highest CSV score Jets) and used for Muli-Jet background validation

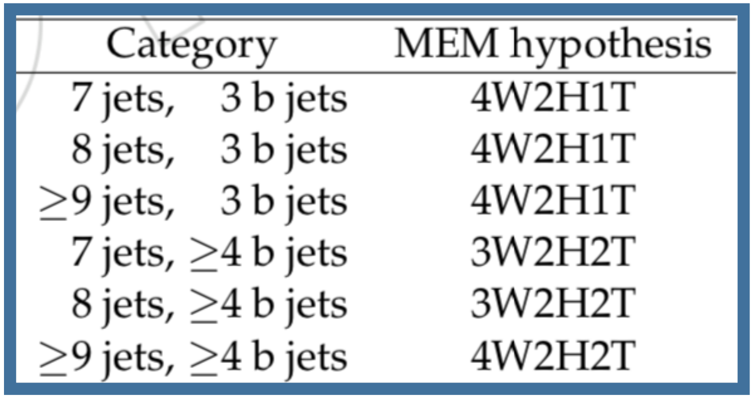
	$N_{\mathrm{CSVM}} = 2$ $N_{\mathrm{CSVL}} \geq 3$	$N_{\mathrm{CSVM}} \geq 3$
QGLR > 0.5	CR (to extract distribution)	SR (final analysis)
QGLR < 0.5	Validation CR (to validate distribution)	VR (comparison with data)

*** H_T = Scalar sum of p_T of all Jets in the event**

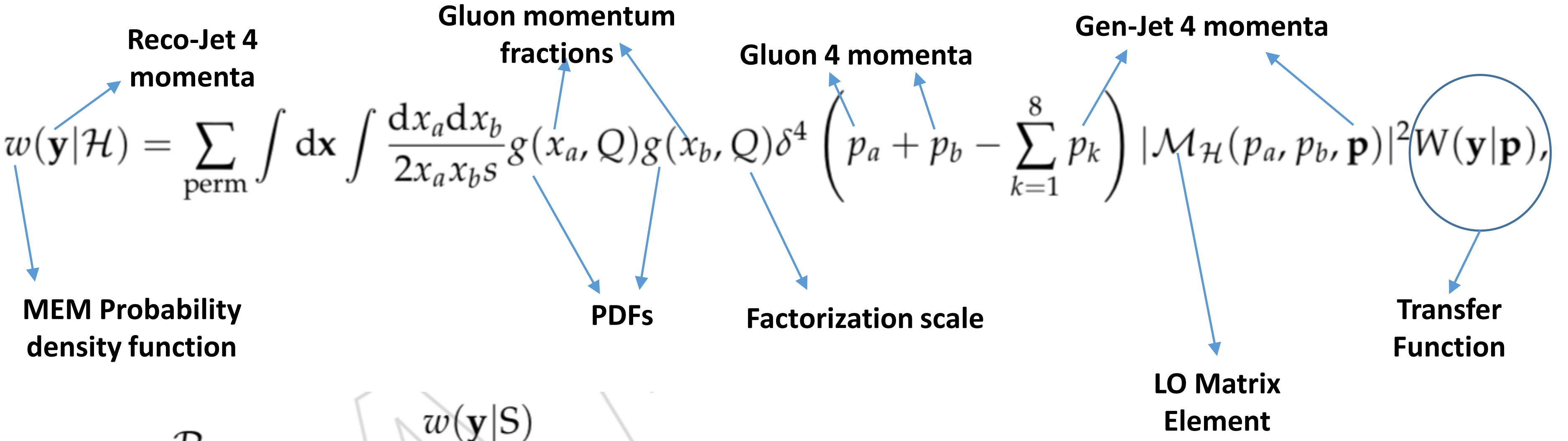
$t\bar{t}$H (H→$b\bar{b}$) Hadronic: MEM & Event yields



Process	7j, 3b	8j, 3b	≥9j, 3b	7j, ≥4b	8j, ≥4b	≥9j, ≥4b
Multijet	47 600 ± 3 000	32 700 ± 2 200	17 600 ± 1 600	3 530 ± 270	3 770 ± 360	2 280 ± 290
$t\bar{t}$+lf	7 700 ± 1 600	5 700 ± 1 100	3 160 ± 550	310 ± 130	410 ± 220	244 ± 96
$t\bar{t}$+$c\bar{c}$	3 100 ± 1 400	2 800 ± 1 200	2 170 ± 970	190 ± 100	270 ± 150	270 ± 150
$t\bar{t}$+b	1 400 ± 620	1 240 ± 620	890 ± 420	142 ± 80	160 ± 110	134 ± 73
$t\bar{t}$+2b	890 ± 450	760 ± 370	600 ± 290	87 ± 58	114 ± 77	101 ± 52
$t\bar{t}$+$b\bar{b}$	870 ± 340	1 010 ± 370	970 ± 380	203 ± 90	370 ± 150	410 ± 170
Single t	750 ± 190	520 ± 130	284 ± 75	43 ± 20	78 ± 68	35 ± 17
V+jets	460 ± 170	290 ± 110	240 ± 220	36 ± 33	45 ± 110	17 ± 12
$t\bar{t}$+V	110 ± 20	122 ± 27	120 ± 30	14 ± 7	28 ± 14	28 ± 14
Diboson	14 ± 5	5 ± 4	1 ± 1	0.6 ± 0.5	0.6 ± 0.6	0 ± 10
Total bkg	62 790 ± 900	45 220 ± 850	26 020 ± 640	4 550 ± 180	5 240 ± 340	3 520 ± 190
$t\bar{t}$H ($\hat{\mu} = 0.9$)	130 ± 210	140 ± 220	120 ± 190	32 ± 51	46 ± 75	48 ± 77
Data	62 920	45 359	26 136	4 588	5 287	3 566



Category	MEM hypothesis
7 jets, 3 b jets	4W2H1T
8 jets, 3 b jets	4W2H1T
≥9 jets, 3 b jets	4W2H1T
7 jets, ≥4 b jets	3W2H2T
8 jets, ≥4 b jets	3W2H2T
≥9 jets, ≥4 b jets	4W2H2T



Reco-Jet 4 momenta

Gluon momentum fractions

Gluon 4 momenta

Gen-Jet 4 momenta

$$w(\mathbf{y}|\mathcal{H}) = \sum_{\text{perm}} \int d\mathbf{x} \int \frac{dx_a dx_b}{2x_a x_b s} g(x_a, Q) g(x_b, Q) \delta^4 \left(p_a + p_b - \sum_{k=1}^{8} p_k \right) |\mathcal{M}_{\mathcal{H}}(p_a, p_b, \mathbf{p})|^2 W(\mathbf{y}|\mathbf{p}),$$

MEM Probability density function

PDFs

Factorization scale

Transfer Function

LO Matrix Element

$$\mathcal{P}_{S/B} = \frac{w(\mathbf{y}|S)}{w(\mathbf{y}|S) + \kappa_{S/B} w(\mathbf{y}|B)},$$

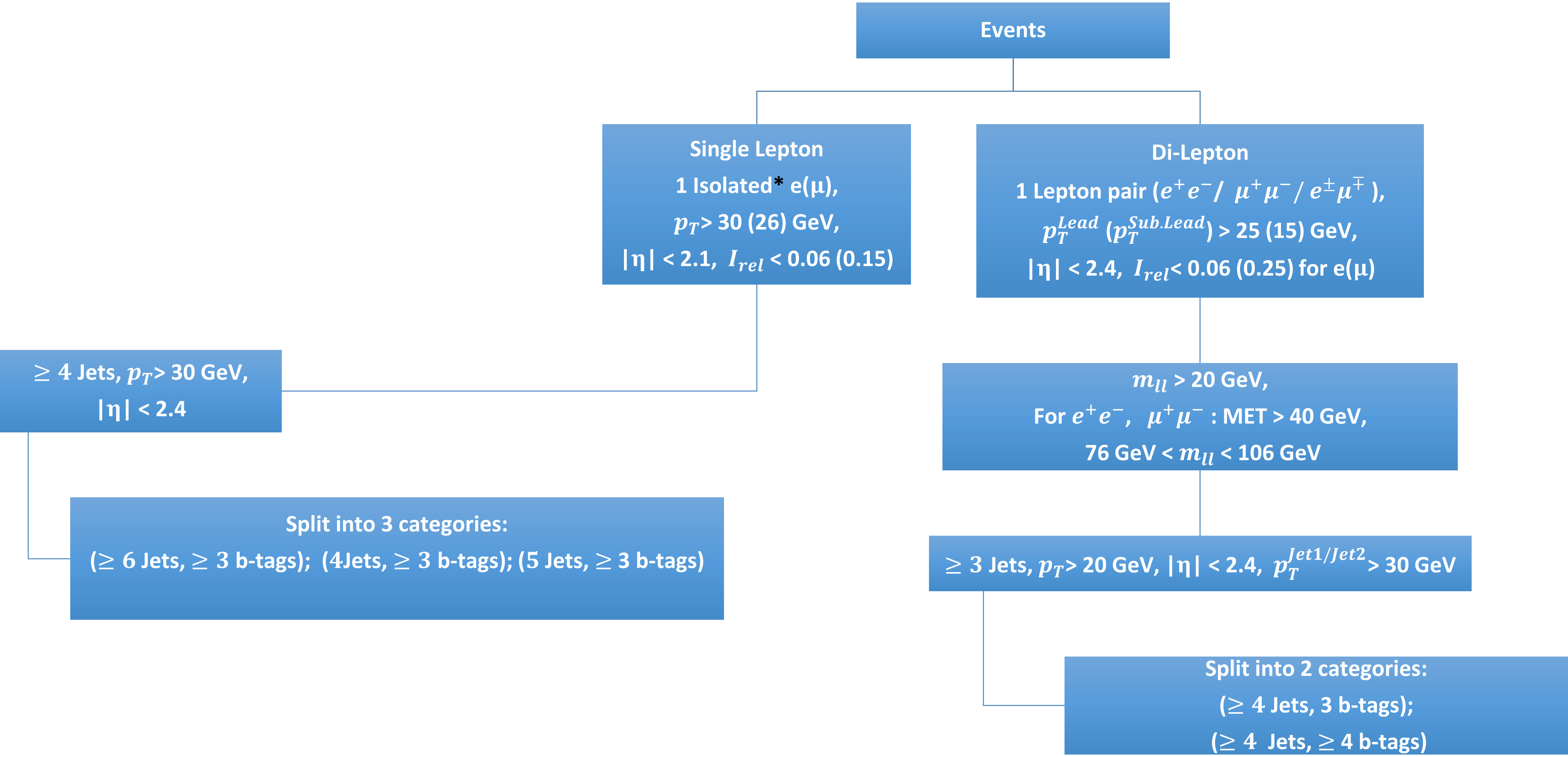
$\mathcal{H}$ = $t\bar{t}$H (S) or $\mathcal{H}$ = $t\bar{t}$+$b\bar{b}$ (B)

MEM discriminant

(Sensitivity optimizing) scale factor

Hypothesis

$t\bar{t}$H (H→$b\bar{b}$) Leptonic: CMS PAS HIG-17-026



Events

Single Lepton

1 Isolated* e(μ),

p_T> 30 (26) GeV,

|η| < 2.1, I_{rel} < 0.06 (0.15)

≥ 4 Jets, p_T> 30 GeV,

|η| < 2.4

Split into 3 categories:

(≥ 6 Jets, ≥ 3 b-tags); (4Jets, ≥ 3 b-tags); (5 Jets, ≥ 3 b-tags)

Di-Lepton

1 Lepton pair (e^+e^-/ $\mu^+\mu^-$/ $e^\pm\mu^\mp$),

p_T^{Lead} ($p_T^{Sub.Lead}$) > 25 (15) GeV,

|η| < 2.4, I_{rel}< 0.06 (0.25) for e(μ)

m_{ll} > 20 GeV,

For e^+e^-, $\mu^+\mu^-$: MET > 40 GeV,

76 GeV < m_{ll} < 106 GeV

≥ 3 Jets, p_T> 20 GeV, |η| < 2.4, $p_T^{Jet1/Jet2}$> 30 GeV

Split into 2 categories:

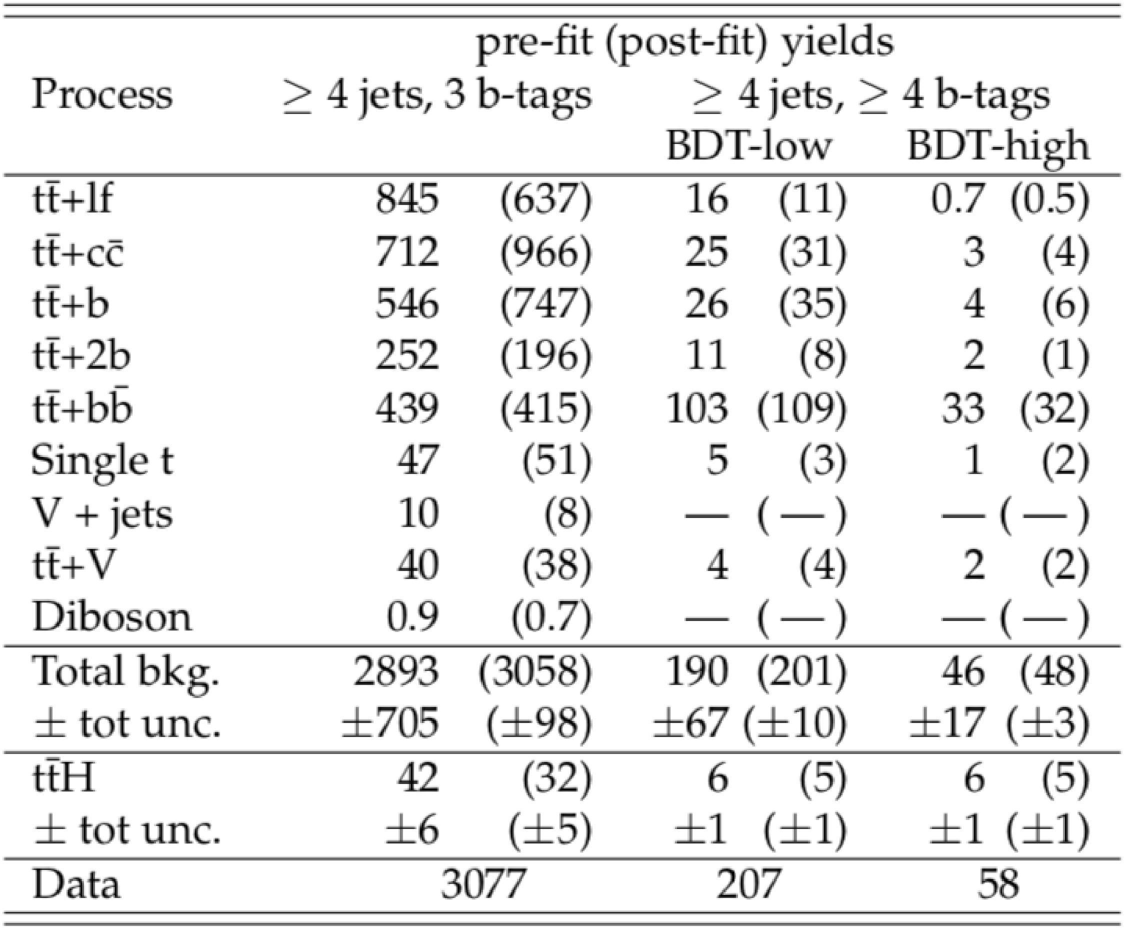
(≥ 4 Jets, 3 b-tags);

(≥ 4 Jets, ≥ 4 b-tags)

*** Relative Isolation (I_{rel}) cone radius for e (μ) : ΔR = 0.3 (0.4)**

$t\bar{t}$H (H→$b\bar{b}$) Leptonic: Event yields-1

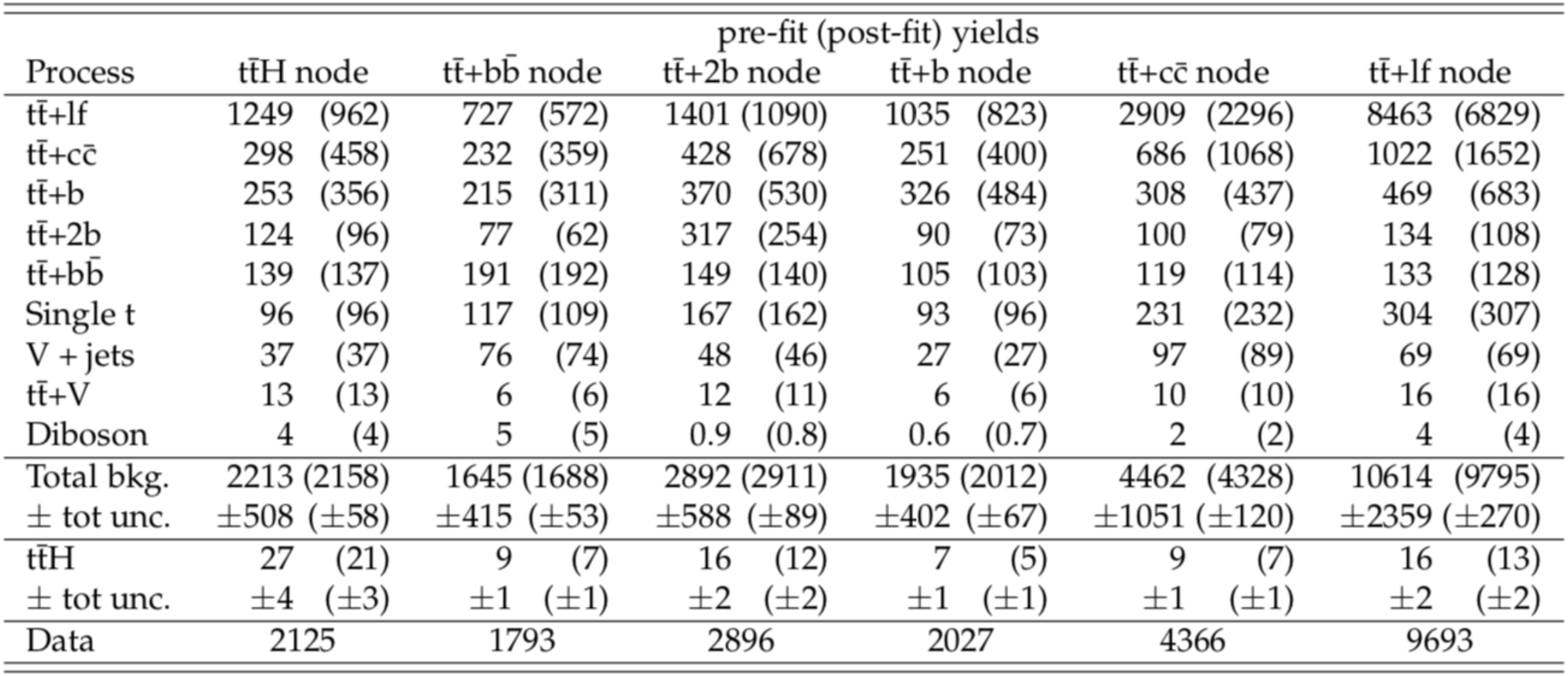
Di-Lepton



	pre-fit (post-fit) yields		
Process	≥ 4 jets, 3 b-tags	≥ 4 jets, ≥ 4 b-tags	
		BDT-low	BDT-high
$t\bar{t}$+lf	845 (637)	16 (11)	0.7 (0.5)
$t\bar{t}$+$c\bar{c}$	712 (966)	25 (31)	3 (4)
$t\bar{t}$+b	546 (747)	26 (35)	4 (6)
$t\bar{t}$+2b	252 (196)	11 (8)	2 (1)
$t\bar{t}$+$b\bar{b}$	439 (415)	103 (109)	33 (32)
Single t	47 (51)	5 (3)	1 (2)
V + jets	10 (8)	— (—)	— (—)
$t\bar{t}$+V	40 (38)	4 (4)	2 (2)
Diboson	0.9 (0.7)	— (—)	— (—)
Total bkg.	2893 (3058)	190 (201)	46 (48)
± tot unc.	±705 (±98)	±67 (±10)	±17 (±3)
$t\bar{t}$H	42 (32)	6 (5)	6 (5)
± tot unc.	±6 (±5)	±1 (±1)	±1 (±1)
Data	3077	207	58

$t\bar{t}$H (H→$b\bar{b}$): Event yields-2

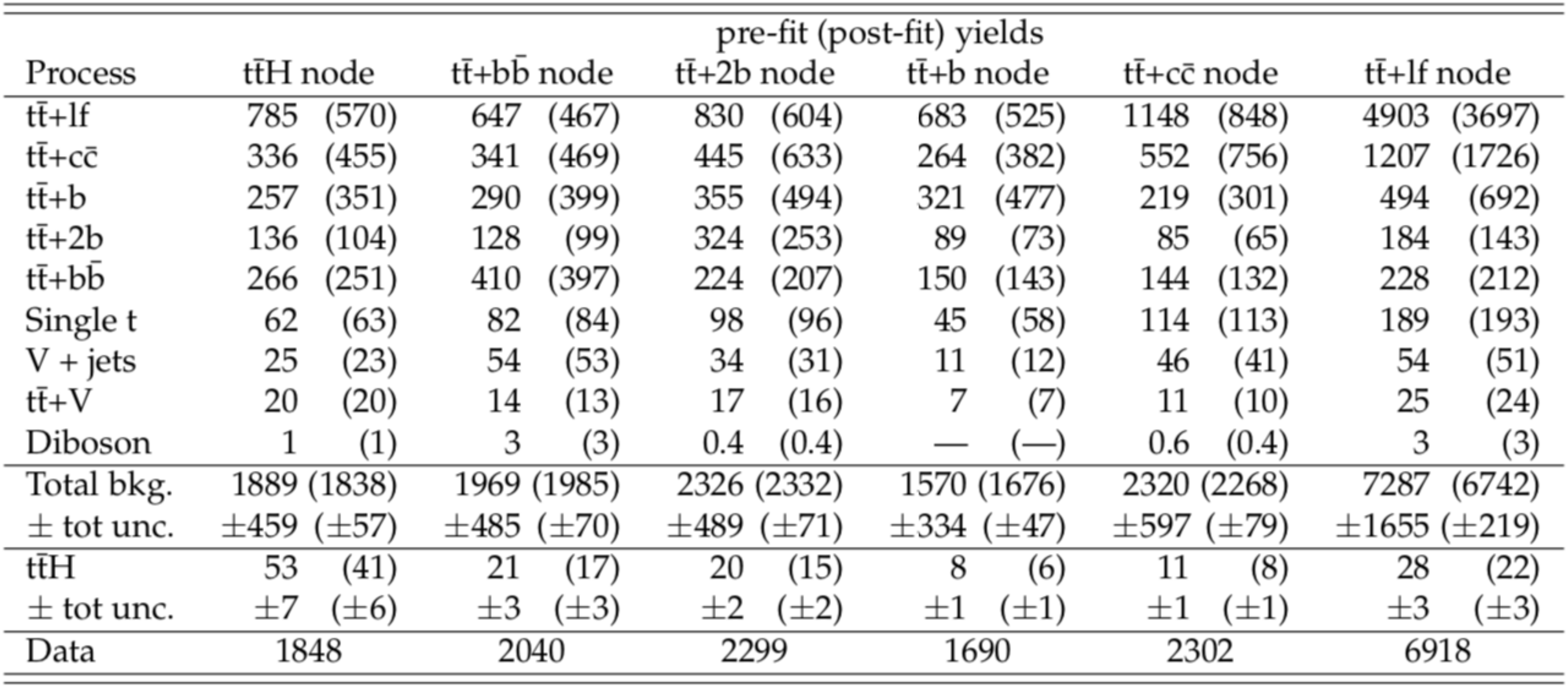
Single Lepton
(4Jet, ≥3b-tag)
DNN Output



	pre-fit (post-fit) yields					
Process	$t\bar{t}$H node	$t\bar{t}$+$b\bar{b}$ node	$t\bar{t}$+2b node	$t\bar{t}$+b node	$t\bar{t}$+$c\bar{c}$ node	$t\bar{t}$+lf node
$t\bar{t}$+lf	1249 (962)	727 (572)	1401 (1090)	1035 (823)	2909 (2296)	8463 (6829)
$t\bar{t}$+$c\bar{c}$	298 (458)	232 (359)	428 (678)	251 (400)	686 (1068)	1022 (1652)
$t\bar{t}$+b	253 (356)	215 (311)	370 (530)	326 (484)	308 (437)	469 (683)
$t\bar{t}$+2b	124 (96)	77 (62)	317 (254)	90 (73)	100 (79)	134 (108)
$t\bar{t}$+$b\bar{b}$	139 (137)	191 (192)	149 (140)	105 (103)	119 (114)	133 (128)
Single t	96 (96)	117 (109)	167 (162)	93 (96)	231 (232)	304 (307)
V + jets	37 (37)	76 (74)	48 (46)	27 (27)	97 (89)	69 (69)
$t\bar{t}$+V	13 (13)	6 (6)	12 (11)	6 (6)	10 (10)	16 (16)
Diboson	4 (4)	5 (5)	0.9 (0.8)	0.6 (0.7)	2 (2)	4 (4)
Total bkg.	2213 (2158)	1645 (1688)	2892 (2911)	1935 (2012)	4462 (4328)	10614 (9795)
± tot unc.	±508 (±58)	±415 (±53)	±588 (±89)	±402 (±67)	±1051 (±120)	±2359 (±270)
$t\bar{t}$H	27 (21)	9 (7)	16 (12)	7 (5)	9 (7)	16 (13)
± tot unc.	±4 (±3)	±1 (±1)	±2 (±2)	±1 (±1)	±1 (±1)	±2 (±2)
Data	2125	1793	2896	2027	4366	9693

$t\bar{t}$H (H→$b\bar{b}$): Event yields-3

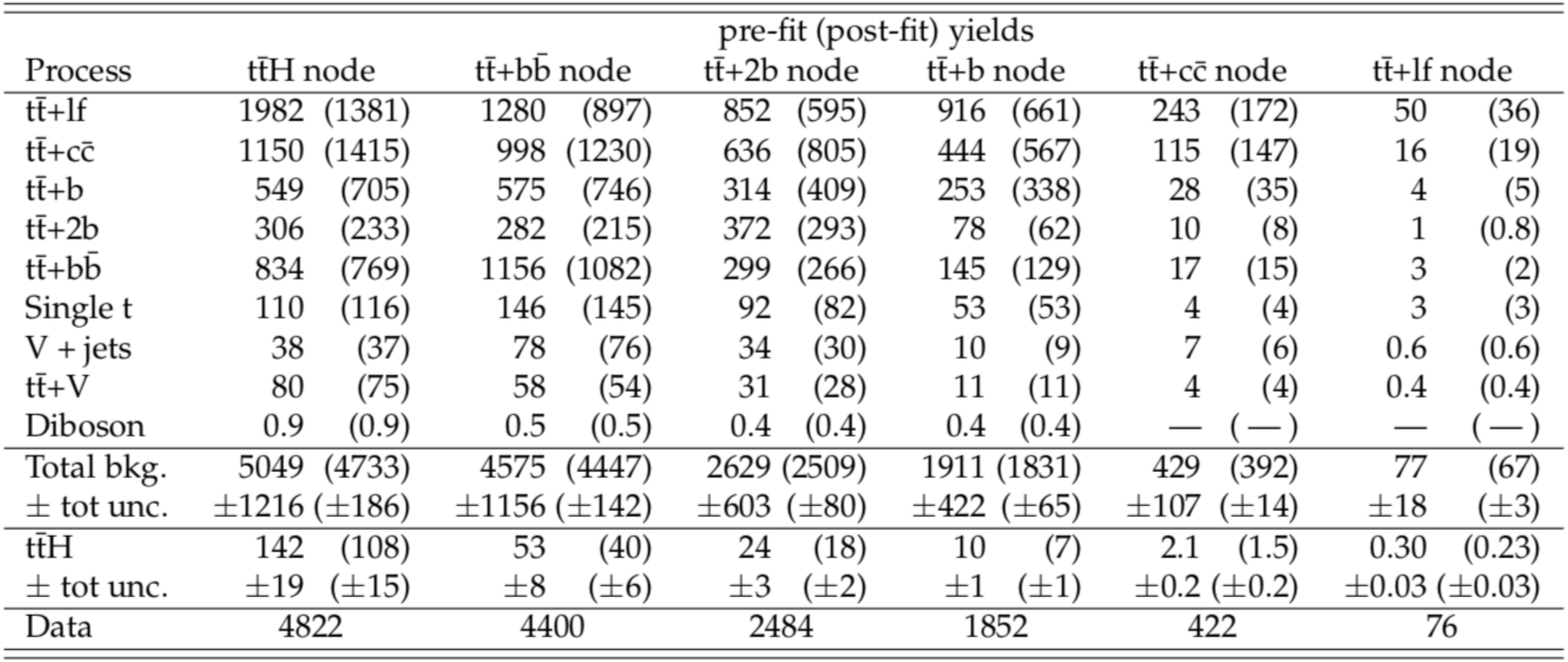
Single Lepton
(5Jet, ≥3b-tag)
DNN Output



	pre-fit (post-fit) yields					
Process	$t\bar{t}$H node	$t\bar{t}$+$b\bar{b}$ node	$t\bar{t}$+2b node	$t\bar{t}$+b node	$t\bar{t}$+$c\bar{c}$ node	$t\bar{t}$+lf node
$t\bar{t}$+lf	785 (570)	647 (467)	830 (604)	683 (525)	1148 (848)	4903 (3697)
$t\bar{t}$+$c\bar{c}$	336 (455)	341 (469)	445 (633)	264 (382)	552 (756)	1207 (1726)
$t\bar{t}$+b	257 (351)	290 (399)	355 (494)	321 (477)	219 (301)	494 (692)
$t\bar{t}$+2b	136 (104)	128 (99)	324 (253)	89 (73)	85 (65)	184 (143)
$t\bar{t}$+$b\bar{b}$	266 (251)	410 (397)	224 (207)	150 (143)	144 (132)	228 (212)
Single t	62 (63)	82 (84)	98 (96)	45 (58)	114 (113)	189 (193)
V + jets	25 (23)	54 (53)	34 (31)	11 (12)	46 (41)	54 (51)
$t\bar{t}$+V	20 (20)	14 (13)	17 (16)	7 (7)	11 (10)	25 (24)
Diboson	1 (1)	3 (3)	0.4 (0.4)	— (—)	0.6 (0.4)	3 (3)
Total bkg.	1889 (1838)	1969 (1985)	2326 (2332)	1570 (1676)	2320 (2268)	7287 (6742)
± tot unc.	±459 (±57)	±485 (±70)	±489 (±71)	±334 (±47)	±597 (±79)	±1655 (±219)
$t\bar{t}$H	53 (41)	21 (17)	20 (15)	8 (6)	11 (8)	28 (22)
± tot unc.	±7 (±6)	±3 (±3)	±2 (±2)	±1 (±1)	±1 (±1)	±3 (±3)
Data	1848	2040	2299	1690	2302	6918

$t\bar{t}$H (H→$b\bar{b}$): Event yields-4

Single Lepton
(6Jet, ≥3b-tag)
DNN Output



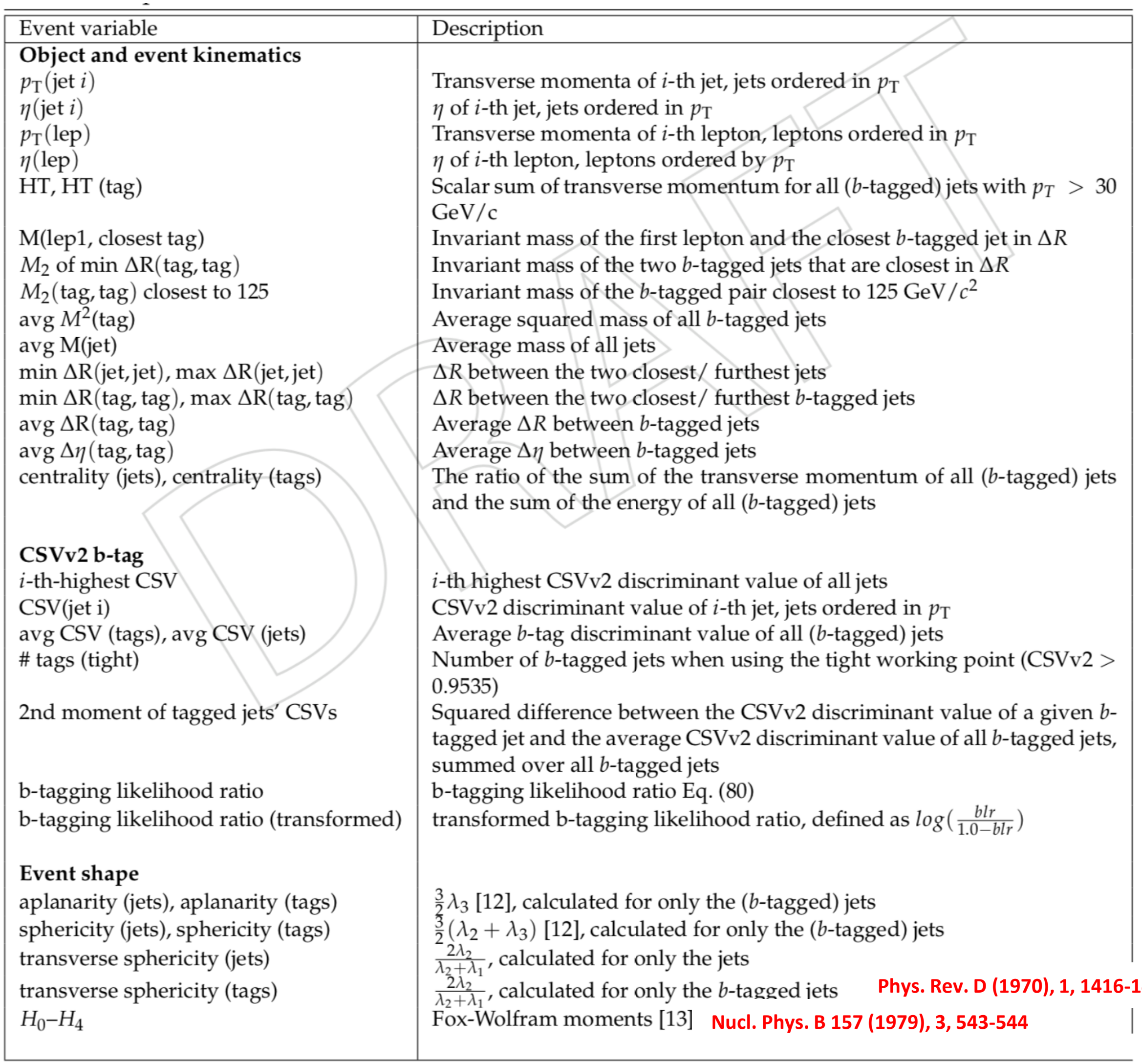
	pre-fit (post-fit) yields					
Process	tt̄H node	tt̄+bb̄ node	tt̄+2b node	tt̄+b node	tt̄+cc̄ node	tt̄+lf node
tt̄+lf	1982 (1381)	1280 (897)	852 (595)	916 (661)	243 (172)	50 (36)
tt̄+cc̄	1150 (1415)	998 (1230)	636 (805)	444 (567)	115 (147)	16 (19)
tt̄+b	549 (705)	575 (746)	314 (409)	253 (338)	28 (35)	4 (5)
tt̄+2b	306 (233)	282 (215)	372 (293)	78 (62)	10 (8)	1 (0.8)
tt̄+bb̄	834 (769)	1156 (1082)	299 (266)	145 (129)	17 (15)	3 (2)
Single t	110 (116)	146 (145)	92 (82)	53 (53)	4 (4)	3 (3)
V + jets	38 (37)	78 (76)	34 (30)	10 (9)	7 (6)	0.6 (0.6)
tt̄+V	80 (75)	58 (54)	31 (28)	11 (11)	4 (4)	0.4 (0.4)
Diboson	0.9 (0.9)	0.5 (0.5)	0.4 (0.4)	0.4 (0.4)	— (—)	— (—)
Total bkg.	5049 (4733)	4575 (4447)	2629 (2509)	1911 (1831)	429 (392)	77 (67)
± tot unc.	±1216 (±186)	±1156 (±142)	±603 (±80)	±422 (±65)	±107 (±14)	±18 (±3)
tt̄H	142 (108)	53 (40)	24 (18)	10 (7)	2.1 (1.5)	0.30 (0.23)
± tot unc.	±19 (±15)	±8 (±6)	±3 (±2)	±1 (±1)	±0.2 (±0.2)	±0.03 (±0.03)
Data	4822	4400	2484	1852	422	76

$t\bar{t}$H (H→$b\bar{b}$): Systematics

Systematic Uncert. Name	Value (%)
Luminosity	2.5%
e/μ Identiifcation	(2-4)%
Trigger efficiency	(1-2)%
Pile-Up	(0.2-5)%
PDF	(2-4)%
μ_R/μ_F signal	(6-9)%
μ_R/μ_F background	(1-13)%
Jet Energy scale/resolution	shape (3-11)%
b-tagging efficiency	shape (4-40)%
$t\bar{t}$+heavy flavor	50%
QGLR Reweighting	(4-11)%

$t\bar{t}$H (H→$b\bar{b}$) Leptonic: BDT/DNN inputs-1

Common in both Single and Di-Lepton



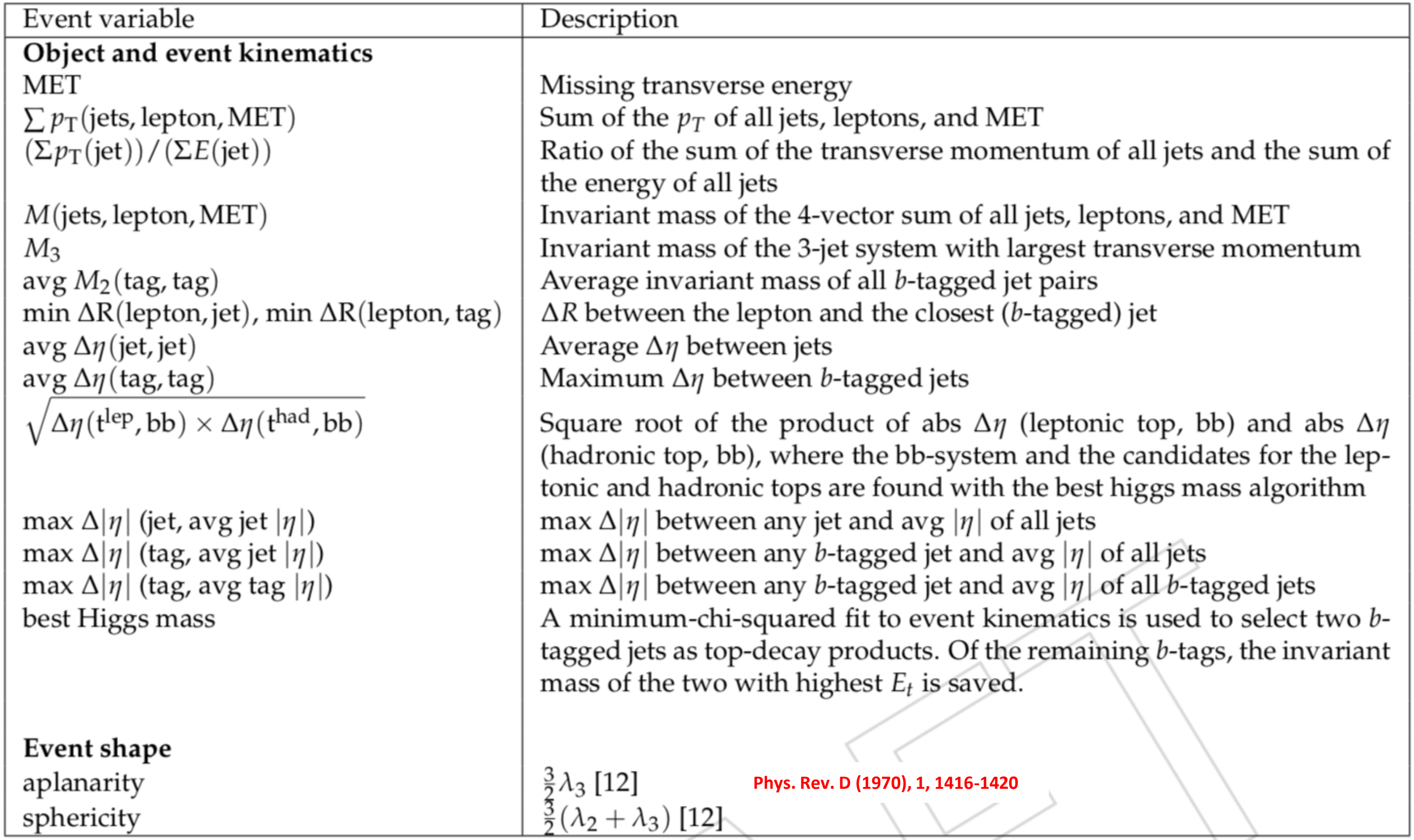
Event variable	Description
Object and event kinematics	
p_T(jet i)	Transverse momenta of i-th jet, jets ordered in p_T
η(jet i)	η of i-th jet, jets ordered in p_T
p_T(lep)	Transverse momenta of i-th lepton, leptons ordered in p_T
η(lep)	η of i-th lepton, leptons ordered by p_T
HT, HT (tag)	Scalar sum of transverse momentum for all (b-tagged) jets with $p_T > 30$ GeV/c
M(lep1, closest tag)	Invariant mass of the first lepton and the closest b-tagged jet in ΔR
M_2 of min ΔR(tag, tag)	Invariant mass of the two b-tagged jets that are closest in ΔR
M_2(tag, tag) closest to 125	Invariant mass of the b-tagged pair closest to 125 GeV/c^2
avg M^2(tag)	Average squared mass of all b-tagged jets
avg M(jet)	Average mass of all jets
min ΔR(jet, jet), max ΔR(jet, jet)	ΔR between the two closest/ furthest jets
min ΔR(tag, tag), max ΔR(tag, tag)	ΔR between the two closest/ furthest b-tagged jets
avg ΔR(tag, tag)	Average ΔR between b-tagged jets
avg $\Delta\eta$(tag, tag)	Average $\Delta\eta$ between b-tagged jets
centrality (jets), centrality (tags)	The ratio of the sum of the transverse momentum of all (b-tagged) jets and the sum of the energy of all (b-tagged) jets
CSVv2 b-tag	
i-th-highest CSV	i-th highest CSVv2 discriminant value of all jets
CSV(jet i)	CSVv2 discriminant value of i-th jet, jets ordered in p_T
avg CSV (tags), avg CSV (jets)	Average b-tag discriminant value of all (b-tagged) jets
# tags (tight)	Number of b-tagged jets when using the tight working point (CSVv2 > 0.9535)
2nd moment of tagged jets' CSVs	Squared difference between the CSVv2 discriminant value of a given b-tagged jet and the average CSVv2 discriminant value of all b-tagged jets, summed over all b-tagged jets
b-tagging likelihood ratio	b-tagging likelihood ratio Eq. (80)
b-tagging likelihood ratio (transformed)	transformed b-tagging likelihood ratio, defined as $log(\frac{blr}{1.0-blr})$
Event shape	
aplanarity (jets), aplanarity (tags)	$\frac{3}{2}\lambda_3$ [12], calculated for only the (b-tagged) jets
sphericity (jets), sphericity (tags)	$\frac{3}{2}(\lambda_2 + \lambda_3)$ [12], calculated for only the (b-tagged) jets
transverse sphericity (jets)	$\frac{2\lambda_2}{\lambda_2+\lambda_1}$, calculated for only the jets
transverse sphericity (tags)	$\frac{2\lambda_2}{\lambda_2+\lambda_1}$, calculated for only the b-tagged jets
H_0–H_4	Fox-Wolfram moments [13]

Phys. Rev. D (1970), 1, 1416-1420

Nucl. Phys. B 157 (1979), 3, 543-544

$t\bar{t}$H (H→$b\bar{b}$) Leptonic: BDT/DNN inputs-2

Single Lepton



Event variable	Description
Object and event kinematics	
MET	Missing transverse energy
$\sum p_{\mathrm{T}}(\text{jets, lepton, MET})$	Sum of the p_T of all jets, leptons, and MET
$(\Sigma p_{\mathrm{T}}(\text{jet}))/(\Sigma E(\text{jet}))$	Ratio of the sum of the transverse momentum of all jets and the sum of the energy of all jets
$M(\text{jets, lepton, MET})$	Invariant mass of the 4-vector sum of all jets, leptons, and MET
M_3	Invariant mass of the 3-jet system with largest transverse momentum
avg $M_2(\text{tag, tag})$	Average invariant mass of all b-tagged jet pairs
min $\Delta\mathrm{R}(\text{lepton, jet})$, min $\Delta\mathrm{R}(\text{lepton, tag})$	ΔR between the lepton and the closest (b-tagged) jet
avg $\Delta\eta(\text{jet, jet})$	Average $\Delta\eta$ between jets
avg $\Delta\eta(\text{tag, tag})$	Maximum $\Delta\eta$ between b-tagged jets
$\sqrt{\Delta\eta(\mathrm{t^{lep}, bb}) \times \Delta\eta(\mathrm{t^{had}, bb})}$	Square root of the product of abs $\Delta\eta$ (leptonic top, bb) and abs $\Delta\eta$ (hadronic top, bb), where the bb-system and the candidates for the leptonic and hadronic tops are found with the best higgs mass algorithm
max $\Delta\|\eta\|$ (jet, avg jet $\|\eta\|$)	max $\Delta\|\eta\|$ between any jet and avg $\|\eta\|$ of all jets
max $\Delta\|\eta\|$ (tag, avg jet $\|\eta\|$)	max $\Delta\|\eta\|$ between any b-tagged jet and avg $\|\eta\|$ of all jets
max $\Delta\|\eta\|$ (tag, avg tag $\|\eta\|$)	max $\Delta\|\eta\|$ between any b-tagged jet and avg $\|\eta\|$ of all b-tagged jets
best Higgs mass	A minimum-chi-squared fit to event kinematics is used to select two b-tagged jets as top-decay products. Of the remaining b-tags, the invariant mass of the two with highest E_t is saved.
Event shape	
aplanarity	$\frac{3}{2}\lambda_3$ [12]
sphericity	$\frac{3}{2}(\lambda_2 + \lambda_3)$ [12]

Phys. Rev. D (1970), 1, 1416-1420

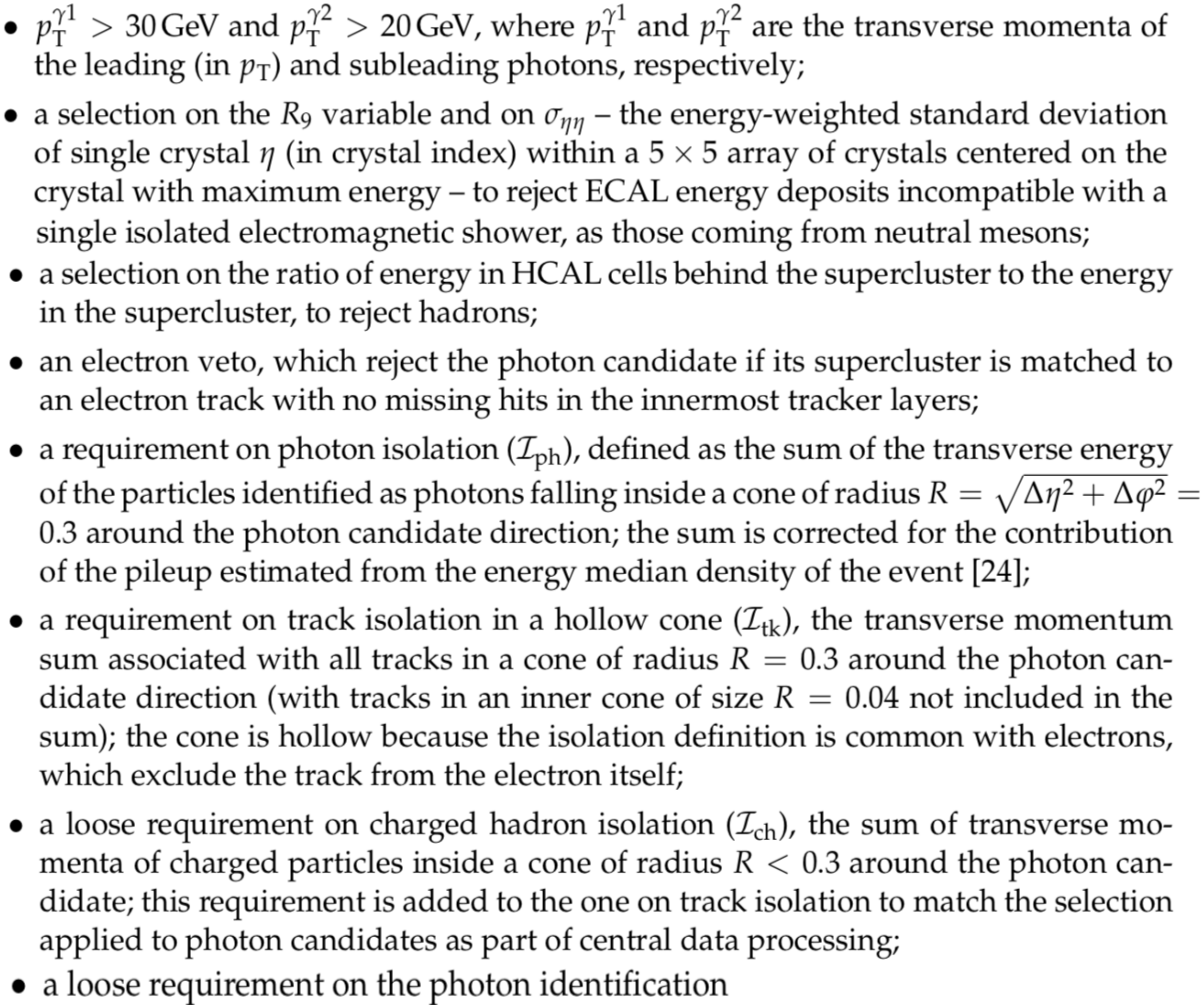
$t\bar{t}$H (H→$b\bar{b}$) Leptonic: BDT/DNN inputs-3

Di-Lepton

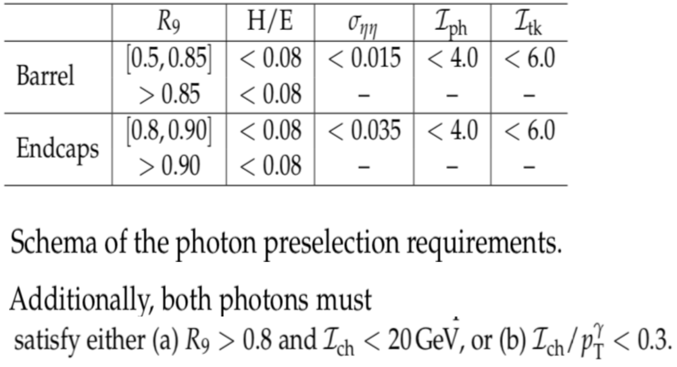
Event variable	Description
Object and event kinematics	
$\tau^{\text{max mass}}_{\text{jet,jet}}$	Twist angle between jet pair with maximum mass
max $\Delta\eta_{\text{jet,jet}}$	The $\Delta\eta$ between the two furthest jet pairs
max $\Delta\eta_{\text{tag,tag}}$	The $\Delta\eta$ between the two furthest b-tagged jet pairs
min $\Delta R_{\text{jet,jet}}$	The ΔR between the two closest jets
$\langle \Delta R_{\text{jet,tag}} \rangle$	Average ΔR between jets (with at least one b-tagged)
$\text{m}^{\text{max mass}}_{\text{tag,tag}}$	Mass for b-tagged jet pair with maximum invariant mass combination
$\text{m}^{min\Delta R}_{\text{jet,tag}}$	Invariant mass of jet pair with minimum ΔR (with at least one b-tag jet)
$\text{m}^{min\Delta R}_{\text{tag,tag}}$	Mass for b-tag jet pair with minimum ΔR
median $\text{m}_{\text{jet,jet}}$	Median invariant mass of all combinations of jet pairs
H_{T}(jets)	Scalar sum of transverse momentum for all jets
$\text{p}^{min\Delta R}_{T}$(tag, tag)	Sum p_T of b-tag jet pair with minimum ΔR
$\text{p}^{min\Delta R}_{T}$(jet, tag)	Sum p_T of jet pair with minimum ΔR between them (with at least one b-tag jet)
m(lep, lep)	The invariant mass of the system of the two leptons
N^{jj}	Multiplicity of Higgs-like di-jet
CSVv2 b-tag	
$\langle d \rangle_{\text{tagged/untagged}}$	Average CSV b-tag discriminant value for b-tagged/un-b-tagged jets
Event shape	
H_3(tags)	The 3rd Fox-Wolfram moments for all b-tagged jets in the event [13]
R_3(jets)	Ratio between Fox-Wolfram moments, H_3/H_0(jets) [13]
Isotropy(tags)	A measure of how spherical or linear in r-ϕ space b-tagged jets are in the event

$t\bar{t}$H (H → $\gamma\gamma$)

Photon Pre-selection



- $p_T^{\gamma 1} > 30\,\text{GeV}$ and $p_T^{\gamma 2} > 20\,\text{GeV}$, where $p_T^{\gamma 1}$ and $p_T^{\gamma 2}$ are the transverse momenta of the leading (in p_T) and subleading photons, respectively;
- a selection on the R_9 variable and on $\sigma_{\eta\eta}$ – the energy-weighted standard deviation of single crystal η (in crystal index) within a 5×5 array of crystals centered on the crystal with maximum energy – to reject ECAL energy deposits incompatible with a single isolated electromagnetic shower, as those coming from neutral mesons;
- a selection on the ratio of energy in HCAL cells behind the supercluster to the energy in the supercluster, to reject hadrons;
- an electron veto, which reject the photon candidate if its supercluster is matched to an electron track with no missing hits in the innermost tracker layers;
- a requirement on photon isolation ($\mathcal{I}_{\text{ph}}$), defined as the sum of the transverse energy of the particles identified as photons falling inside a cone of radius $R = \sqrt{\Delta\eta^2 + \Delta\varphi^2} = 0.3$ around the photon candidate direction; the sum is corrected for the contribution of the pileup estimated from the energy median density of the event [24];
- a requirement on track isolation in a hollow cone ($\mathcal{I}_{\text{tk}}$), the transverse momentum sum associated with all tracks in a cone of radius $R = 0.3$ around the photon candidate direction (with tracks in an inner cone of size $R = 0.04$ not included in the sum); the cone is hollow because the isolation definition is common with electrons, which exclude the track from the electron itself;
- a loose requirement on charged hadron isolation ($\mathcal{I}_{\text{ch}}$), the sum of transverse momenta of charged particles inside a cone of radius $R < 0.3$ around the photon candidate; this requirement is added to the one on track isolation to match the selection applied to photon candidates as part of central data processing;
- a loose requirement on the photon identification



	R_9	H/E	$\sigma_{\eta\eta}$	$\mathcal{I}_{\text{ph}}$	$\mathcal{I}_{\text{tk}}$
Barrel	[0.5, 0.85]	< 0.08	< 0.015	< 4.0	< 6.0
	> 0.85	< 0.08	–	–	–
Endcaps	[0.8, 0.90]	< 0.08	< 0.035	< 4.0	< 6.0
	> 0.90	< 0.08	–	–	–

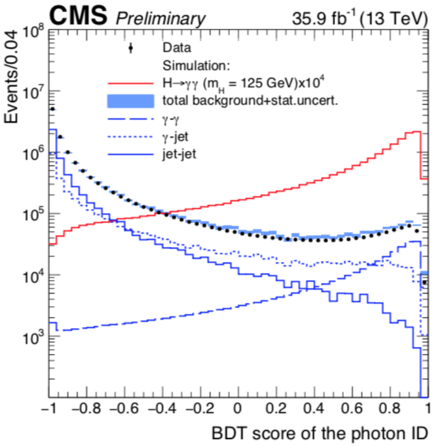
Schema of the photon preselection requirements.

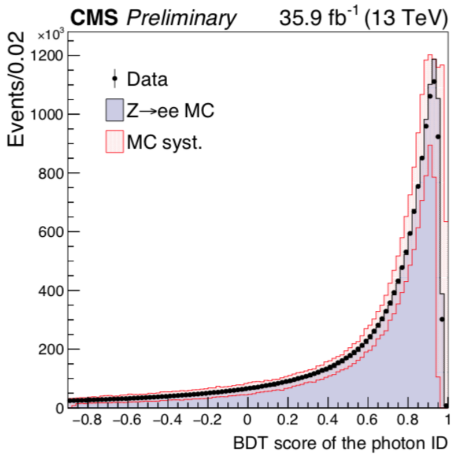
Additionally, both photons must satisfy either (a) $R_9 > 0.8$ and $\mathcal{I}_{\text{ch}} < 20\,\text{GeV}$, or (b) $\mathcal{I}_{\text{ch}}/p_T^{\gamma} < 0.3$.

$t\bar{t}\mathrm{H}\ (\mathrm{H} \rightarrow \gamma\gamma)$

Photon ID BDT

- shower shape observables,
- isolation variables, $\mathcal{I}_{\mathrm{ph}}$ and $\mathcal{I}_{\mathrm{ch}}$.
- photon η and E, which are correlated with the shower topology and isolation variables;
- the median energy density per unit area in the event, ρ, to minimize the impact of pileup on the above inputs.





Di-Photon BDT

The diphoton vertex assignment relies on a boosted decision tree, whose inputs are observables related to tracks recoiling against the diphoton system:

- $\sum_i |\vec{p_T^i}|^2$,
- $-\sum_i (\vec{p_T}^i \cdot \frac{\vec{p_T}^{\gamma\gamma}}{|\vec{p_T}^{\gamma\gamma}|})$,
- $(|\sum_i \vec{p_T}^i| - p_T^{\gamma\gamma})/(|\sum_i \vec{p_T}^i| + p_T^{\gamma\gamma})$,

where $\vec{p_T}^i$ is the transverse momentum of the i-th track associated with a given vertex and $\vec{p_T}^{\gamma\gamma}$ is the transverse momentum of the diphoton system. The sum runs over all charged particle flow candidates associated with the given vertex.

In the presence of tracks from photons converted in the tracker material, two additional input variables are used:

- the number of conversions,
- the pull $|z_{\mathrm{vtx}} - z_{\mathrm{e}}|/\sigma_z$ between the longitudinal position of the reconstructed vertex, z_{vtx}, and the longitudinal position of the vertex estimated using conversion track(s), z_{e}, where the variable σ_z denotes the uncertainty on z_{e}.

Vertex Probability BDT

- the number of vertices in each event,
- the values of the vertex identification BDT score for the three most probable vertices in each event,
- the distances between the chosen vertex and the second and third choices,
- the transverse momentum of the diphoton system, $p_T^{\gamma\gamma}$,
- the number of photons with an associated conversion track.

$t\bar{t}$H (H → $\gamma\gamma$)

Systematics

Systematic Unc. Name	Value (%)
PDF uncert.s	< 1 %
α_S uncert.	2.6 %
Underlying Event Parton Shower	(7-9) %
ggH contamination of $t\bar{t}$H	(10-50) %
H → $\gamma\gamma$ branching fraction uncert.	2 %
Photon energy scale	(0.15 - 0.5) %
Trigger efficiency	0.1 %
Jet Energy scale (resolution)	5 % (3 %)
PileUp Jet ID	1%
Lepton ID and iso.	1 %
b-tagging efficiency	2 % ($t\bar{t}$H Leptonic), 5 % ($t\bar{t}$H Hadronic)
Luminosity	2.5 %
Vertex finding	2 %

$t\bar{t}$H (H → VV^*)

2LSS

- $p_T^{l1} > 25\ GeV$, $p_T^{l2} > 15\ GeV$, $\geq$ 4 Jets
- $|m_{ee} - m_Z|$ > 10 GeV, @LD > 30 GeV
- Events split in lepton flavor: ee,$\mu\mu$, $e\mu$

  Each of which is split further into:

  b-tight and

  b-loose depending on whether they have $\geq$ 2 medium b-tagged Jets or not

3L

- $p_T^{l1} > 25\ GeV$, $p_T^{l2} > 15\ GeV$, $p_T^{l3} > 15\ GeV$, $\geq$ 2 Jets
- $|m_{ll} - m_Z|$ > 10 GeV, LD > 30 GeV (45 GeV for OS same flavor)
- Events split into b-loose and

  b-tight like 2LSS

4L

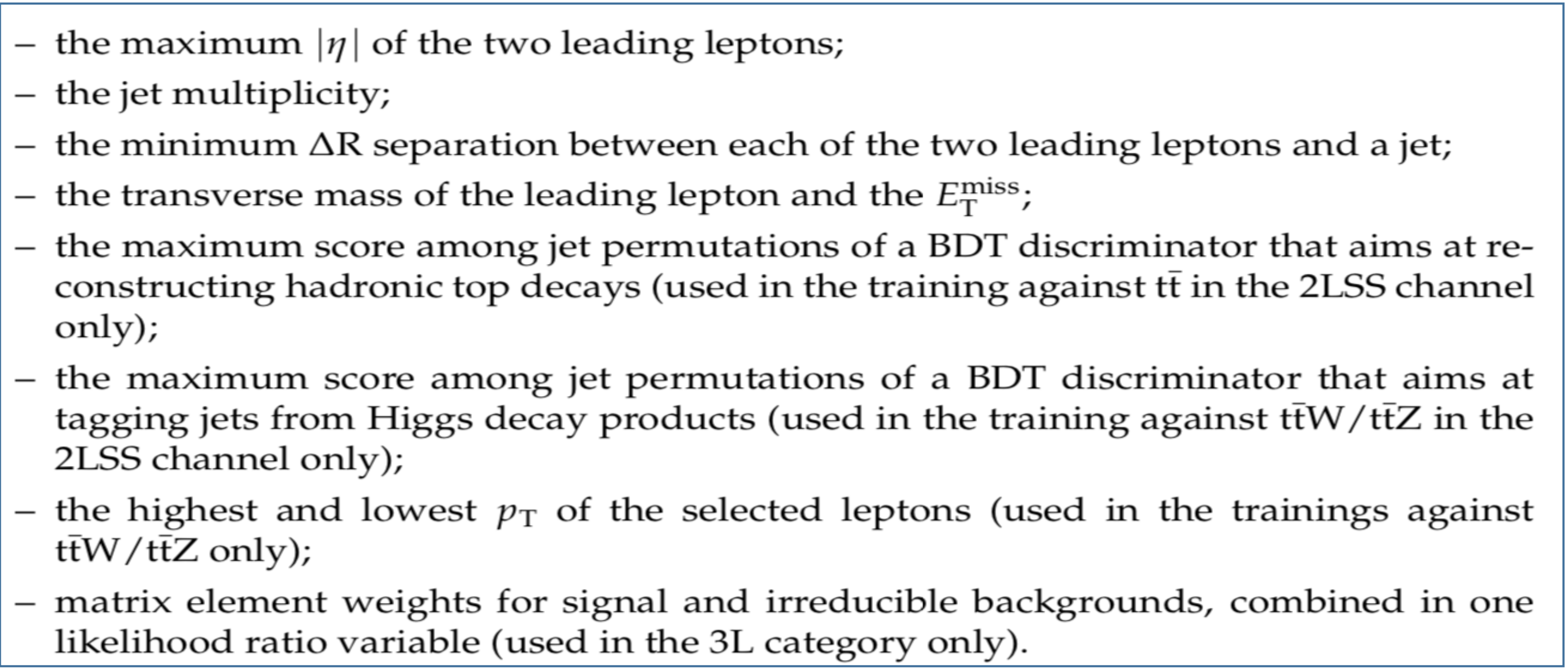
- Same as 3L but having 1 extra lepton p_T > 10 GeV
- Minimum invariant mass of OS di-lepton pair used for signal extraction

➢ **2LSS** and **3L** further split by lepton charge sum to exploit charge asymmetry b/w signal and backgrounds.

@LD = $0.6 \times E_T^{miss} + 0.4 \times H_T^{miss}$

$t\bar{t}$H (H → $VV*$)

Kinematic discriminators for 2lss and 3l



- the maximum $|\eta|$ of the two leading leptons;
- the jet multiplicity;
- the minimum ΔR separation between each of the two leading leptons and a jet;
- the transverse mass of the leading lepton and the $E_{\mathrm{T}}^{\mathrm{miss}}$;
- the maximum score among jet permutations of a BDT discriminator that aims at reconstructing hadronic top decays (used in the training against $\mathrm{t\bar{t}}$ in the 2LSS channel only);
- the maximum score among jet permutations of a BDT discriminator that aims at tagging jets from Higgs decay products (used in the training against $\mathrm{t\bar{t}W/t\bar{t}Z}$ in the 2LSS channel only);
- the highest and lowest p_{T} of the selected leptons (used in the trainings against $\mathrm{t\bar{t}W/t\bar{t}Z}$ only);
- matrix element weights for signal and irreducible backgrounds, combined in one likelihood ratio variable (used in the 3L category only).

$t\bar{t}$H (H → VV^*)

Hadronic top tagger for 2lss

Mass and p_T of the reconstructed hadronic top
Mass of the W boson
CSV score of the b-jet originating from the hadronic top decay
(p_T of Lepton from Higgs)/(p_t of lepton from top)
$\Delta R(lepton, bjet)$ from the $t\bar{t}$ system

Tests jet compatibility with top decay. Trained against incorrectly matched lept. & Jet permut.s in $t\bar{t}$H events. Hypotheses up to 2 non-reconstructed Jets are tested.

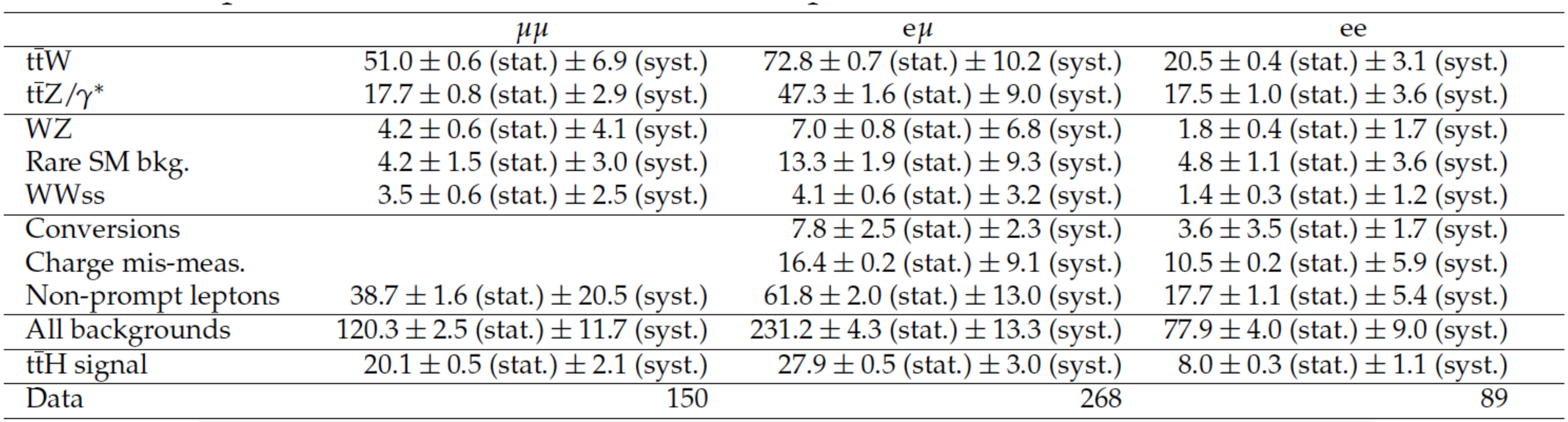
Higgs Jet tagger for 2lss

CSV Jet score
quark-gluon Jet likelihood
$\Delta R(lepton, jet)$

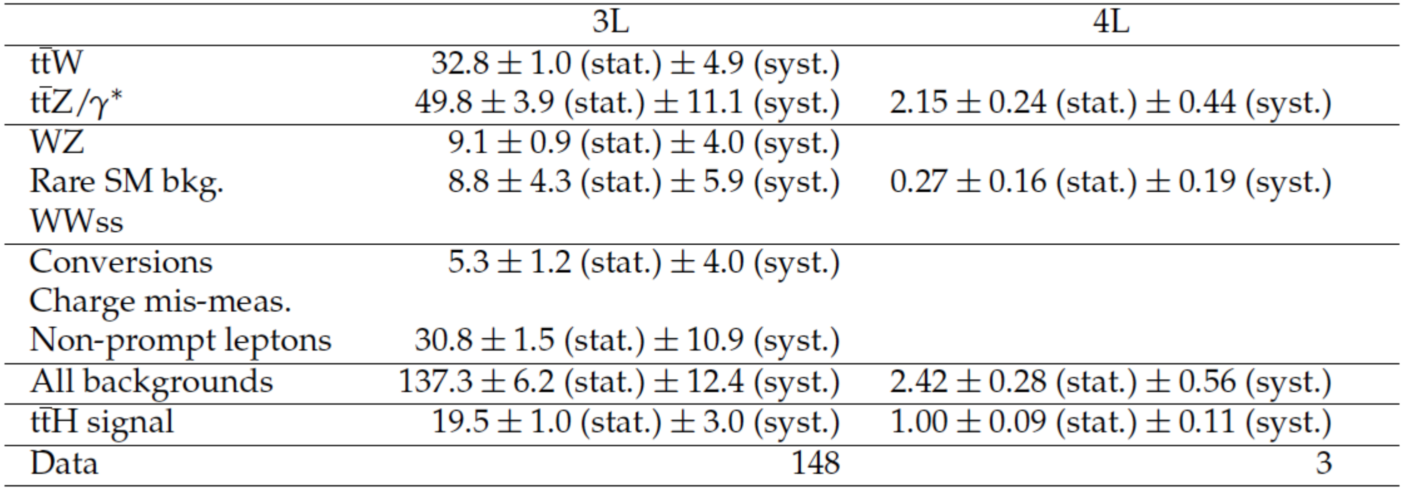
Trained against jets in $t\bar{t}$V events in 2lss category (except jets tagged as “top decay prod.s” by the top tagger above).

$t\bar{t}$H (H $\rightarrow VV^*$)

Event Yields

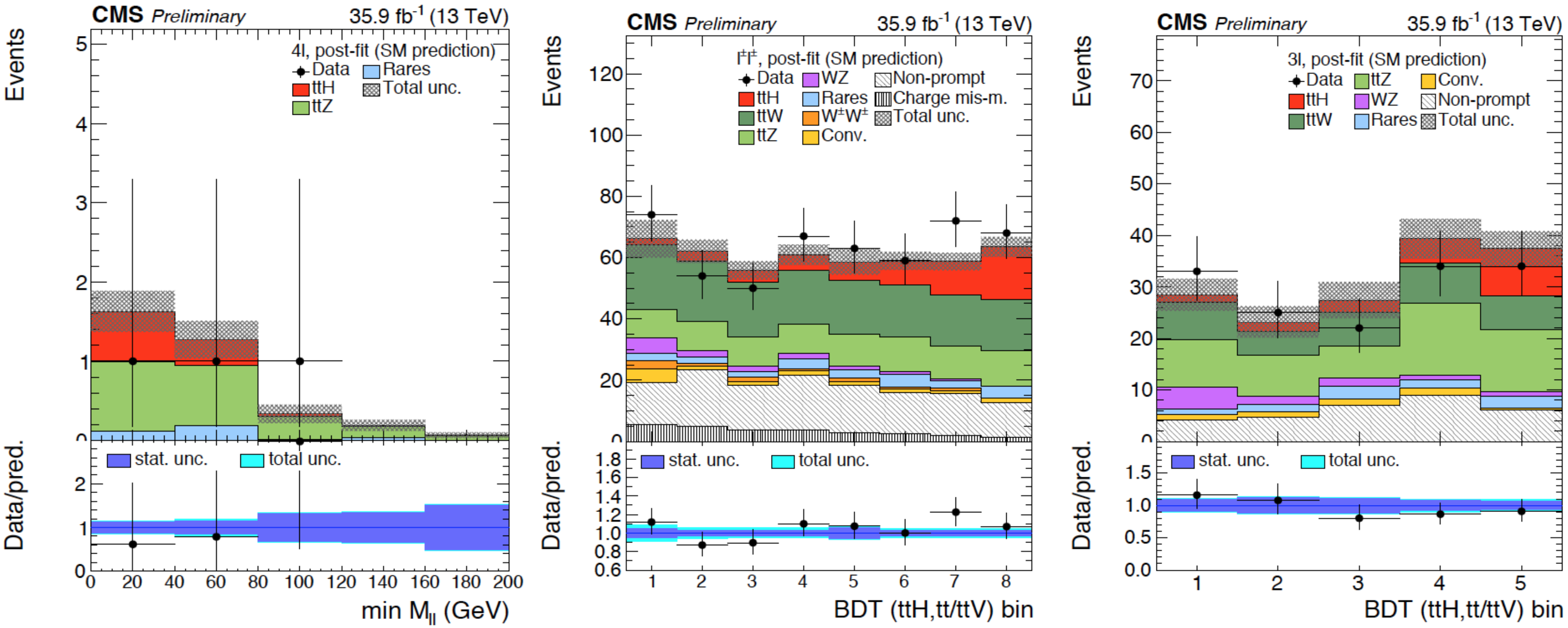


	$\mu\mu$	eμ	ee
$t\bar{t}$W	51.0 ± 0.6 (stat.) ± 6.9 (syst.)	72.8 ± 0.7 (stat.) ± 10.2 (syst.)	20.5 ± 0.4 (stat.) ± 3.1 (syst.)
$t\bar{t}Z/\gamma^*$	17.7 ± 0.8 (stat.) ± 2.9 (syst.)	47.3 ± 1.6 (stat.) ± 9.0 (syst.)	17.5 ± 1.0 (stat.) ± 3.6 (syst.)
WZ	4.2 ± 0.6 (stat.) ± 4.1 (syst.)	7.0 ± 0.8 (stat.) ± 6.8 (syst.)	1.8 ± 0.4 (stat.) ± 1.7 (syst.)
Rare SM bkg.	4.2 ± 1.5 (stat.) ± 3.0 (syst.)	13.3 ± 1.9 (stat.) ± 9.3 (syst.)	4.8 ± 1.1 (stat.) ± 3.6 (syst.)
WWss	3.5 ± 0.6 (stat.) ± 2.5 (syst.)	4.1 ± 0.6 (stat.) ± 3.2 (syst.)	1.4 ± 0.3 (stat.) ± 1.2 (syst.)
Conversions		7.8 ± 2.5 (stat.) ± 2.3 (syst.)	3.6 ± 3.5 (stat.) ± 1.7 (syst.)
Charge mis-meas.		16.4 ± 0.2 (stat.) ± 9.1 (syst.)	10.5 ± 0.2 (stat.) ± 5.9 (syst.)
Non-prompt leptons	38.7 ± 1.6 (stat.) ± 20.5 (syst.)	61.8 ± 2.0 (stat.) ± 13.0 (syst.)	17.7 ± 1.1 (stat.) ± 5.4 (syst.)
All backgrounds	120.3 ± 2.5 (stat.) ± 11.7 (syst.)	231.2 ± 4.3 (stat.) ± 13.3 (syst.)	77.9 ± 4.0 (stat.) ± 9.0 (syst.)
$t\bar{t}$H signal	20.1 ± 0.5 (stat.) ± 2.1 (syst.)	27.9 ± 0.5 (stat.) ± 3.0 (syst.)	8.0 ± 0.3 (stat.) ± 1.1 (syst.)
Data	150	268	89



	3L	4L
$t\bar{t}$W	32.8 ± 1.0 (stat.) ± 4.9 (syst.)	
$t\bar{t}Z/\gamma^*$	49.8 ± 3.9 (stat.) ± 11.1 (syst.)	2.15 ± 0.24 (stat.) ± 0.44 (syst.)
WZ	9.1 ± 0.9 (stat.) ± 4.0 (syst.)	
Rare SM bkg.	8.8 ± 4.3 (stat.) ± 5.9 (syst.)	0.27 ± 0.16 (stat.) ± 0.19 (syst.)
WWss		
Conversions	5.3 ± 1.2 (stat.) ± 4.0 (syst.)	
Charge mis-meas.		
Non-prompt leptons	30.8 ± 1.5 (stat.) ± 10.9 (syst.)	
All backgrounds	137.3 ± 6.2 (stat.) ± 12.4 (syst.)	2.42 ± 0.28 (stat.) ± 0.56 (syst.)
$t\bar{t}$H signal	19.5 ± 1.0 (stat.) ± 3.0 (syst.)	1.00 ± 0.09 (stat.) ± 0.11 (syst.)
Data	148	3

$t\bar{t}$H (H → VV^*): Results (CMS PAS HIG-17-004)



Category	Observed limit	Expected limit $\pm 1\sigma$
Same-sign di-lepton	2.8	$0.9\,(-0.3)\,(+0.4)$
Three lepton	2.5	$1.4\,(-0.4)\,(+0.7)$
Four lepton	5.9	$4.9\,(-1.7)\,(+3.1)$
Combined	2.5	$0.8\,(-0.2)\,(+0.3)$

Category	Observed μ fit $\pm 1\sigma$	Expected μ fit $\pm 1\sigma$
Same-sign di-lepton	$1.7\,(-0.5)\,(+0.6)$	$1.0\,(-0.5)\,(+0.5)$
Three lepton	$1.0\,(-0.7)\,(+0.8)$	$1.0\,(-0.7)\,(+0.8)$
Four lepton	$0.9\,(-1.6)\,(+2.3)$	$1.0\,(-1.6)\,(+2.4)$
Combined (2016 data)	$1.5\,(-0.5)\,(+0.5)$	$1.0\,(-0.4)\,(+0.5)$
Combined (2015 data)	$0.6\,(-1.1)\,(+1.4)$	$1.0\,(-1.1)\,(+1.3)$
Combined (2015+2016 data)	$1.5\,(-0.5)\,(+0.5)$	$1.0\,(-0.4)\,(+0.5)$

$t\bar{t}$H (H → $\tau^+\tau^-$)

$1l + 2\tau_h$

$\boldsymbol{p_T^e > 25\ GeV (p_T^\mu > 20\ GeV)}$,
$|\eta^{e/\mu}|$<2.1

2 OS τ_h s (p_T > 30 GeV) , ≥ 3 jets

$2lss + 1\tau_h$

$\boldsymbol{p_T^{e/\mu} > 25\ GeV}$,

$\boldsymbol{p_T^e > 15\ GeV\ (p_T^\mu > 10\ GeV)}$

$1\tau_h$ (p_T > 30 GeV) OS w.r.t leptons,
≥ 3 jets,

$|m_{ee} - m_Z|$> 10 GeV,

(MET – LD) > 30 GeV

Events further split into missing Jet (no missing Jet) depending on presence (absence) of jet pair compatible with W decay.

$3l + 1\tau_h$

$\boldsymbol{p_T^{lep1} > 20\ GeV \left(p_T^{lep2,3} > 10\ GeV\right)}$

$1\tau_h$ (p_T > 30 GeV) , ≥ 2 jets,

$\sum_{i=1}^{3} q_{lepi} + q_{\tau_h}$ = 0

$|m_{ll} - m_Z|$> 10 GeV,

(MET – LD) > 30 GeV (> 45 GeV for OS same flavor leptons)

- While events in $\boldsymbol{2lss + 1\tau_h}$ and $\boldsymbol{3l + 1\tau_h}$ use triggers similar to the ones used in HIG-17-004, the $\boldsymbol{1l + 2\tau_h}$ category selects events using single lepton and lepton + tau triggers (p_T^e > 24 GeV, $p_T^{\tau_h}$ > 30 GeV; p_T^μ > 19 GeV, $p_T^{\tau_h}$ > 20 GeV).

$t\bar{t}$H (H $\rightarrow \tau^+\tau^-$)

BDT for $1l$+$2\tau_h$

- The invariant mass and ΔR separation of the two reconstructed τ_h.
- The transverse momenta of the two reconstructed τ_h.
- The observable H_T^{miss}, computed according to Eq. (1).
- The average ΔR separation between any pair of jets.
- The multiplicity of jets, with and without b-tagging criteria applied.

BDT for $3l$+$1\tau_h$

- The transverse momenta of the leading lepton and of the trailing lepton.
- The maximum $|\eta|$ of the two leading leptons.
- The multiplicity of jets.
- The ΔR separation of the leading and of the subleading lepton with respect to the nearest jet.
- The transverse mass of the leading lepton and the missing transverse energy vector.
- The observable H_T^{miss}.
- The average ΔR separation between any pair of jets.

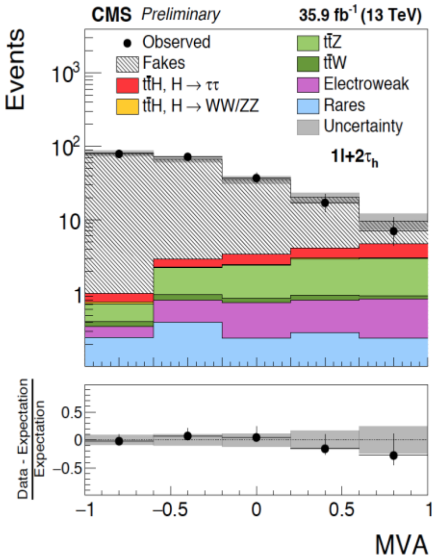
The observable H_T^{miss} and the average ΔR separation between jets (the p_T of the leading and third lepton) are used in case of the BDT that separates the tt̄H signal from the tt̄ (tt̄W and tt̄Z) background only.

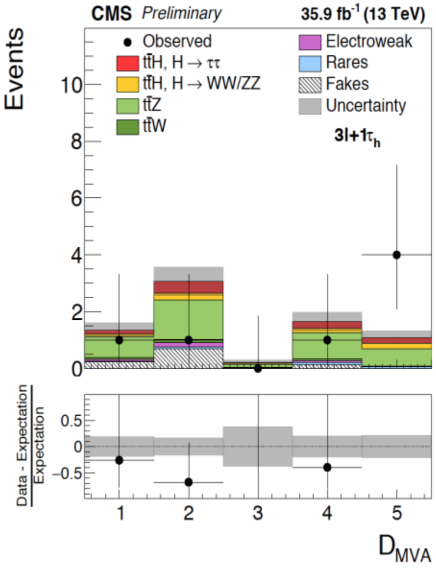
Event Yields

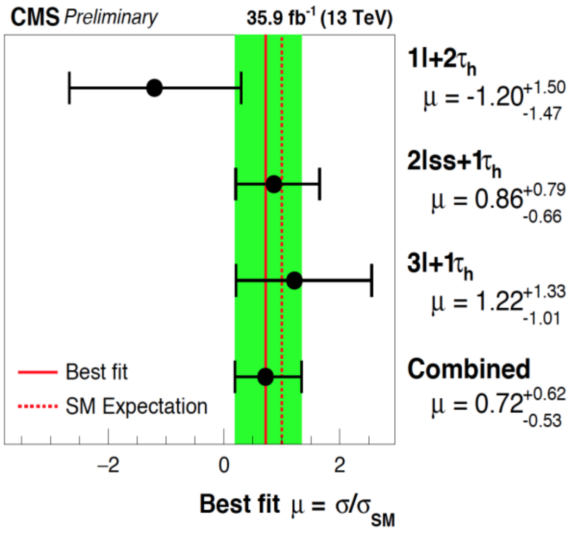
Process	$1\ell + 2\tau_h$	$3\ell + 1\tau_h$
tt̄H, H → $\tau\tau$	2.84 ± 1.35	1.01 ± 0.65
tt̄H, H → WW	0.07 ± 0.04	0.63 ± 0.29
tt̄H, H → ZZ	0.02 ± 0.01	0.09 ± 0.04
tt̄Z	4.07 ± 0.56	3.78 ± 0.62
tt̄W	0.21 ± 0.05	0.24 ± 0.05
Electroweak	1.10 ± 1.05	0.32 ± 0.05
Fake	20.98 ± 3.87	1.07 ± 0.34
Other	0.54 ± 0.23	0.24 ± 0.08
Total expected background	26.91 ± 3.84	5.65 ± 0.85
SM expectation	29.85 ± 4.07	7.38 ± 1.10
Observed data	24	7

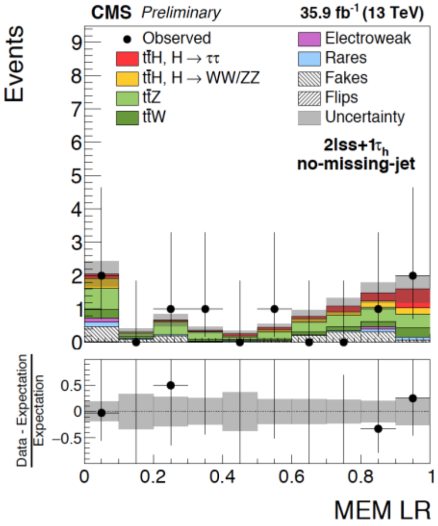
Process	$2\ell ss + 1\tau_h$	
	"no-missing-jet"	"missing-jet"
tt̄H, H → $\tau\tau$	1.38 ± 0.89	2.86 ± 1.68
tt̄H, H → WW	1.03 ± 0.47	2.09 ± 1.01
tt̄H, H → ZZ	0.06 ± 0.03	0.06 ± 0.04
tt̄Z	3.07 ± 0.46	8.33 ± 1.08
tt̄W	1.10 ± 0.15	7.18 ± 0.80
Electroweak	0.21 ± 0.19	3.73 ± 3.39
Fake	1.66 ± 0.52	7.80 ± 2.51
Charge flip	0.05 ± 0.01	0.39 ± 0.10
Other	0.50 ± 0.20	2.44 ± 1.01
Total expected background	6.59 ± 0.88	29.87 ± 4.75
SM expectation	9.06 ± 1.33	34.88 ± 5.05
Observed data	8	41

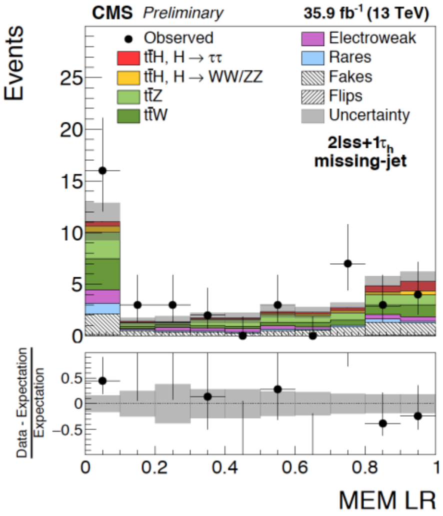
$t\bar{t}$H (H → $\tau^+\tau^-$): Results (CMS PAS HIG-17-003)

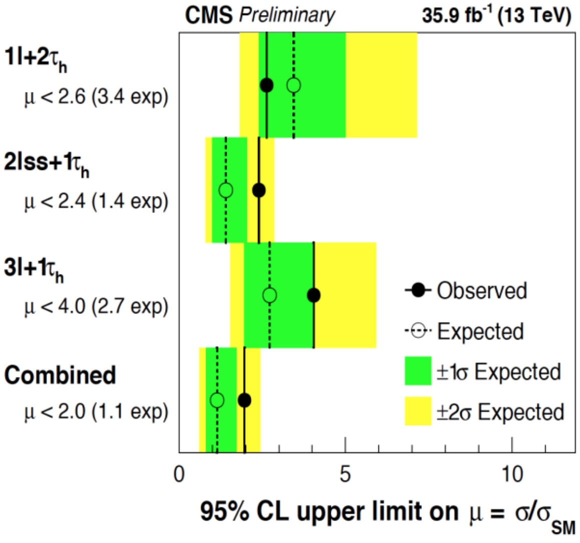












$t\bar{t}\text{H}\ (\text{H} \rightarrow \tau^{+}\tau^{-})/t\bar{t}\text{H}\ (\text{H} \rightarrow VV^{*})$

Systematics

Systematic Unc. Name	Value (%)
Charge Mis-identification	30%
Tau energy scale	3 %
Trigger efficiency	(1-3)%
Jet Energy scale	(1-4) %
Lepton ID and iso.	(2-3) % for e/μ, 5% for τ_{h}
b-tagging efficiency (mistag rate) uncert.s	3 % (10 %)
Luminosity	2.6 %
SM $t\bar{t}$H signal uncert.	+5.8%/-9.1% (missing higher orders), 3.6% (PDF and α_S)
WZ+Jets rate uncert.	Upto 100% depending on category
$t\bar{t}\text{W}$ rate uncert.	12% (missing higher orders), 4% (PDF and α_S)
$t\bar{t}\text{Z}$ rate uncert.	11% (missing higher orders), 3% (PDF and α_S)