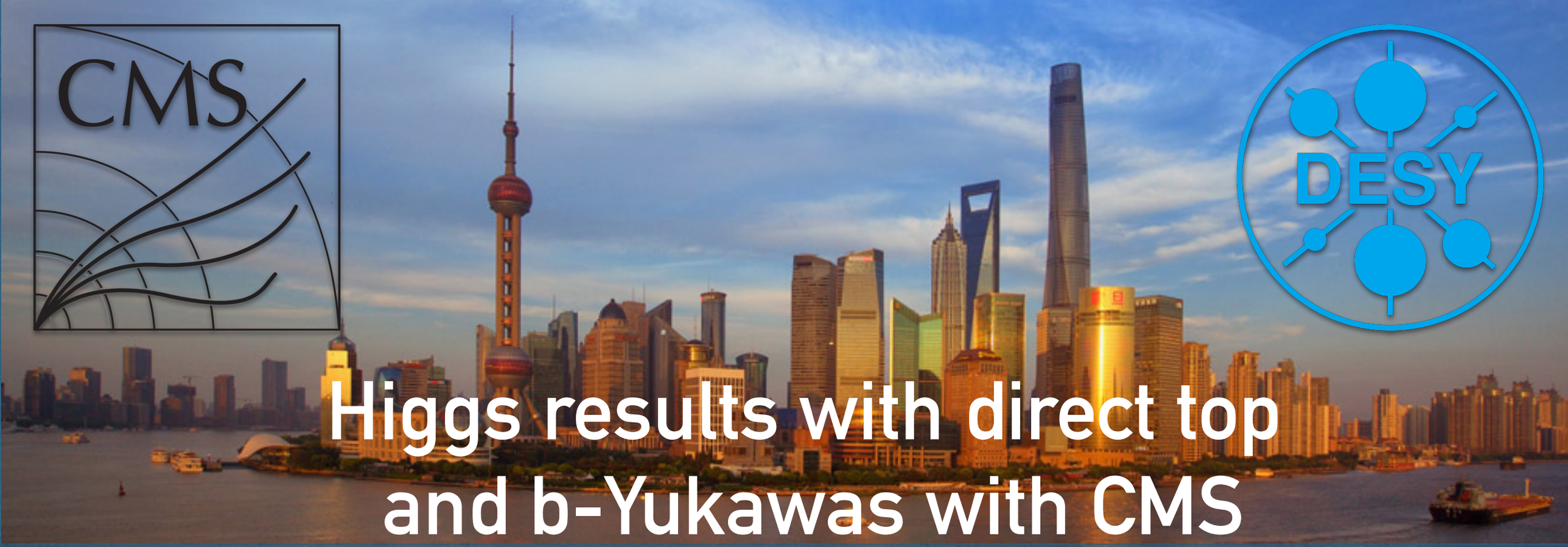


Higgs results with direct top and b-Yukawas with CMS

LHCP 2017
SHANGHAI

Christian Contreras (DESY)
on behalf of the CMS collaboration

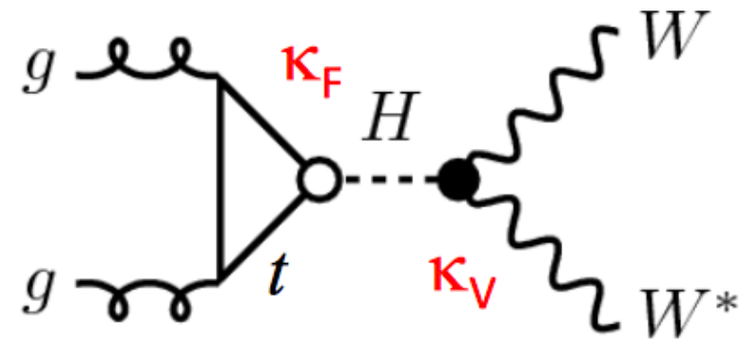
May 16, 2017

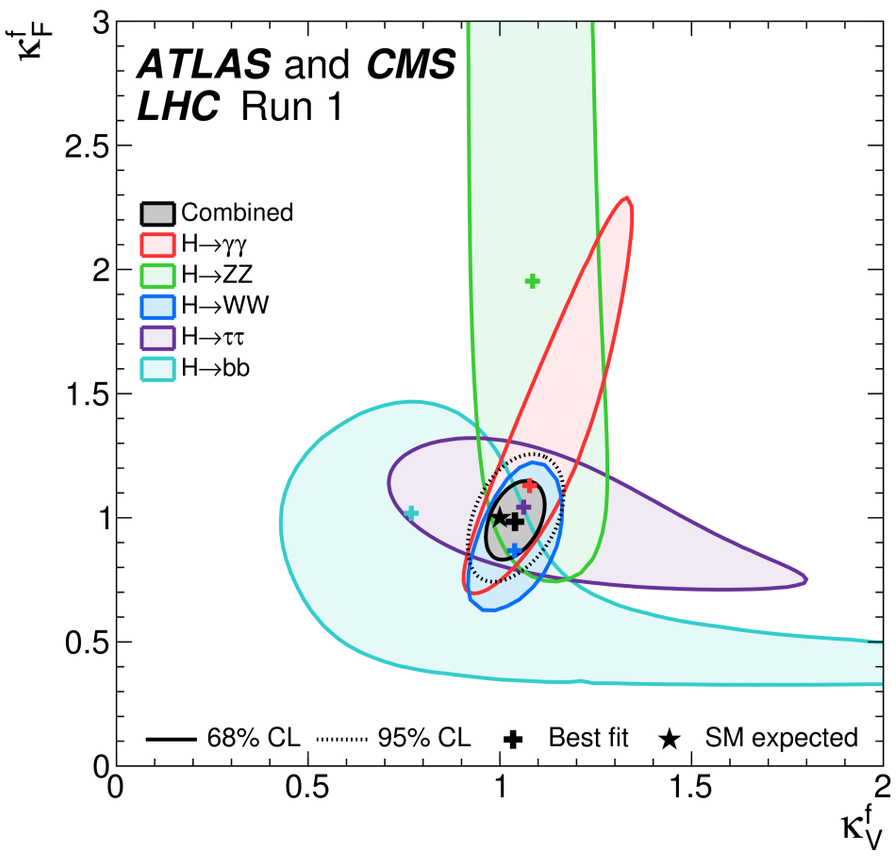
Overview

- Search for the Higgs boson decaying to 2 b quarks is performed at CMS in 3 production channels:
  - Associate production with top quarks ($t\bar{t}$ H, tH)
  - Vector boson fusion (VBF)
  - Associate production with a vector boson (VH)
- The search for $t\bar{t}$ H production is performed in 3 broad decay channels:
  - H→$b\bar{b}$: Analysis targeting production in the leptonic, dilepton final states (PAS HIG-16-038, presented @ Higgs Coupling 16')
  - H→ multileptons: Analysis targeting in leptonic (e,μ) final states from H→WW, ττ, ZZ (PAS HIG-17-004, presented @ Moriond 17')
  - H→ γγ: Analysis targeting in leptonic & hadronic final states (PAS HIG-16-020, presented @ LHC Day 16')
  - H→ττ: Analysis targeting in the hadronic tau final states (PAS HIG-17-003)

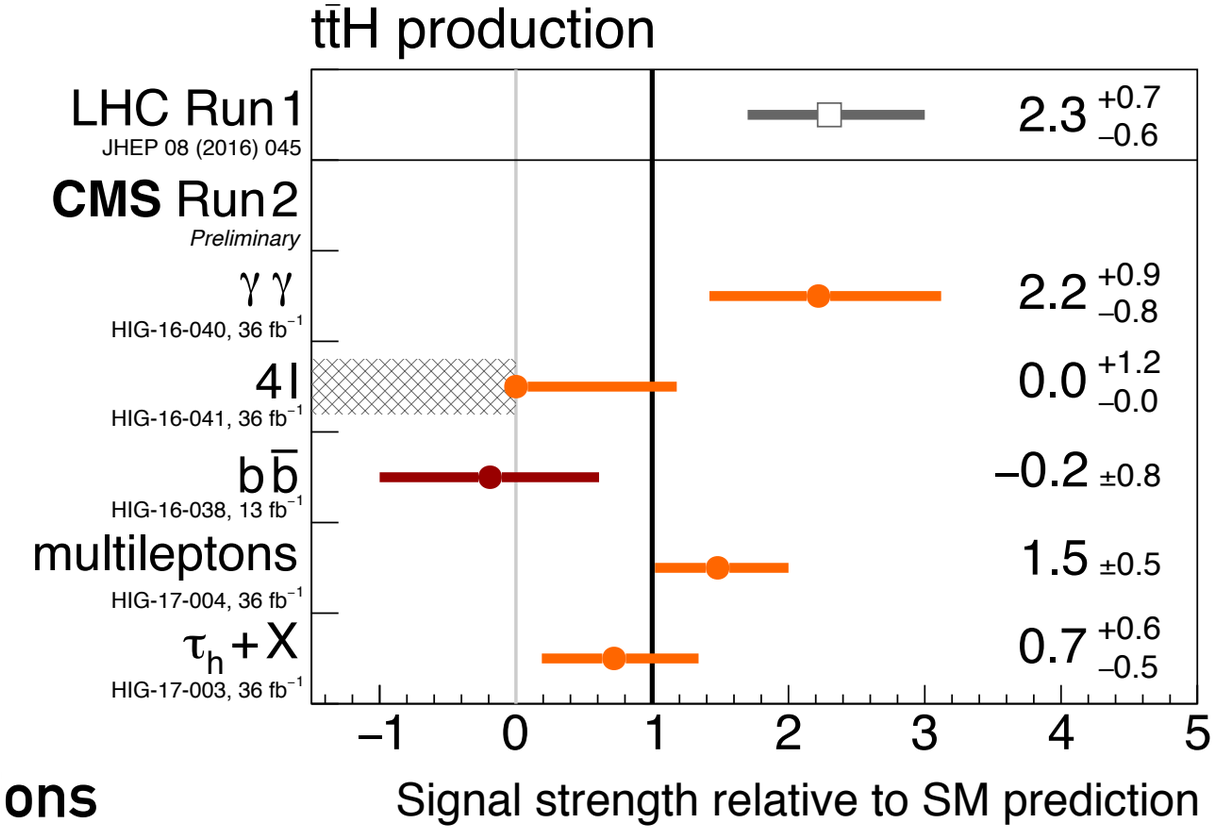
Run 1 coupling results

- Couplings to fermions and boson strongly constrained by Run-I measurements
- Scale factors k_j introduced to quantify deviation from SM
- One benchmark uses 2 scale factors k_V for vector boson and k_F for fermions





- Despite being the dominant decay mode, coupling to $b\bar{b}$ not yet observed (2.6σ LHC Run 1)



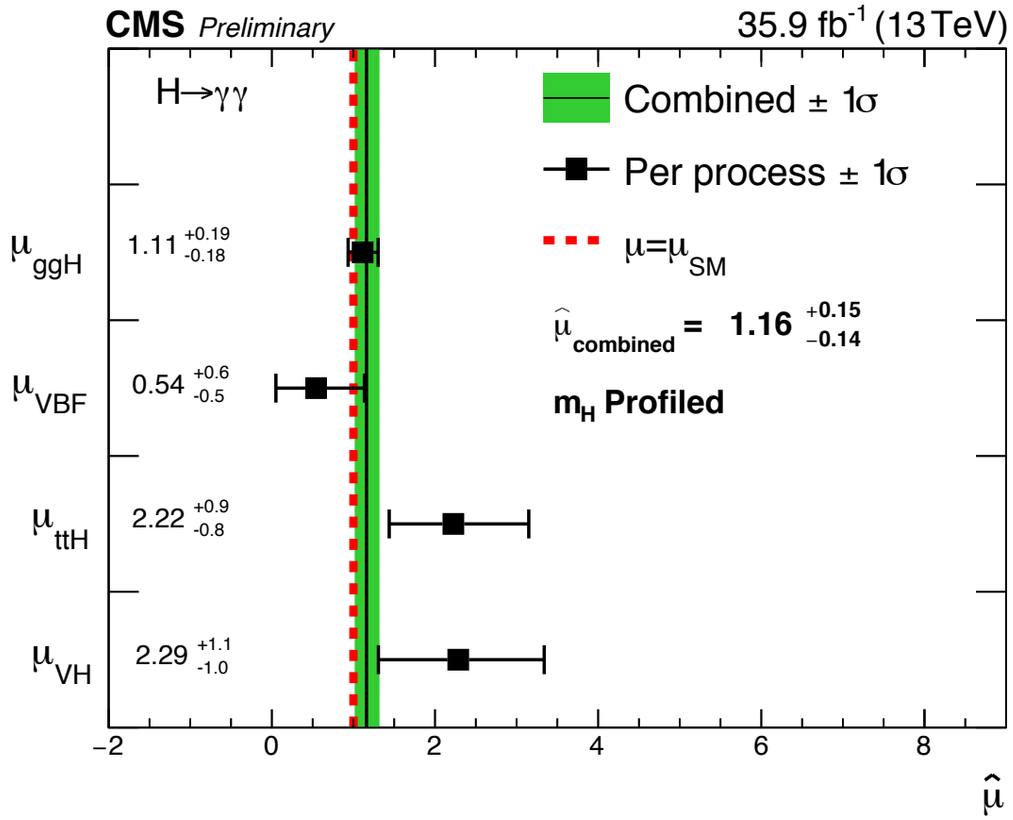
- All channels compatible with k_V=1 and k_F=1
  - Result is consistent with the SM expectations

The Hunt for $t\bar{t}$ H @ 13 TeV

$t\bar{t}$ H why so relevant, why now?

- The combined H($b\bar{b}$) and H($\tau\tau$) result establishes strong evidence for coupling of the Higgs boson to down-type 3rd generation fermions
- Indirect and direct results on $t\bar{t}$ H coupling is also evident for a coupling to up-type fermions [arXiv:1401.6527]
- The $t\bar{t}$ H cross section increases by a factor of ~4 @ 13 TeV
  - Grows substantially from 7 to 8 and to 13 TeV for Higgs @ 125 GeV (NLO QCD+EW):

→ $\sqrt{s}$=7 TeV: σ(ttH)≃89 fb^{-1}
→ $\sqrt{s}$=8 TeV: σ(ttH)≃133 fb^{-1}
→ $\sqrt{s}$=13 TeV: σ(ttH)≃507 fb^{-1}

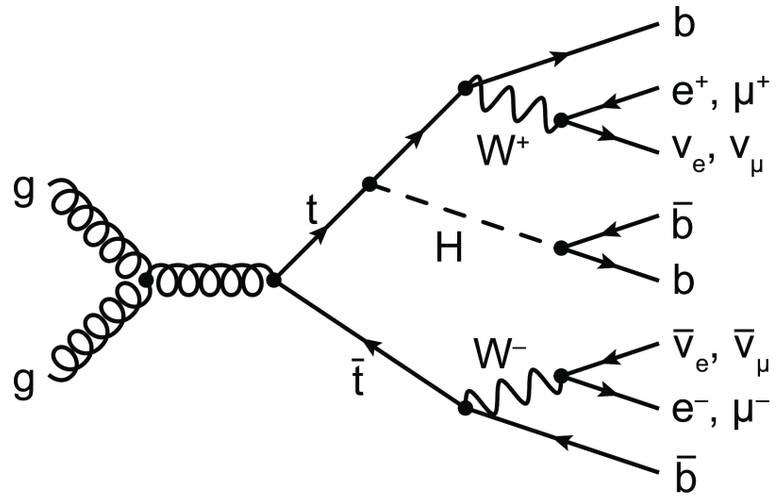


- Direct measurement of the process is a key to determine top Yukawa coupling

$t\bar{t}$ H(b$\bar{\text{b}}$)

CMS-PAS-HIG-16-038

- Large branching fraction H → b$\bar{\text{b}}$
- Dominant background: tt+jets
  - Irreducible contribution: tt+bb (theoretically challenging)
- Many jets with similar kinematics and limited mass resolution for H → b$\bar{\text{b}}$



Analysis strategy

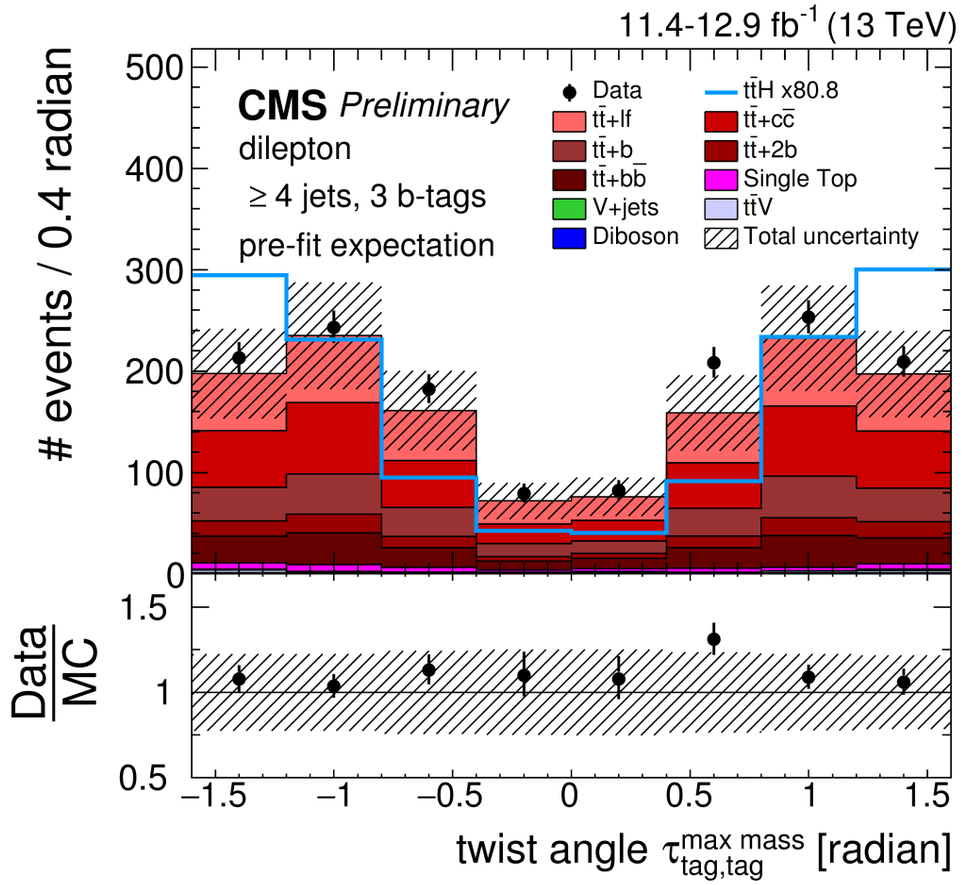
- Obtain good signal separation & constrain background
- Event categories: 11 (5) lepton+jets (dilepton)

Lepton+jets

- exactly 1 lepton
- At least 4 jets
- At least 2 b-tagged jets

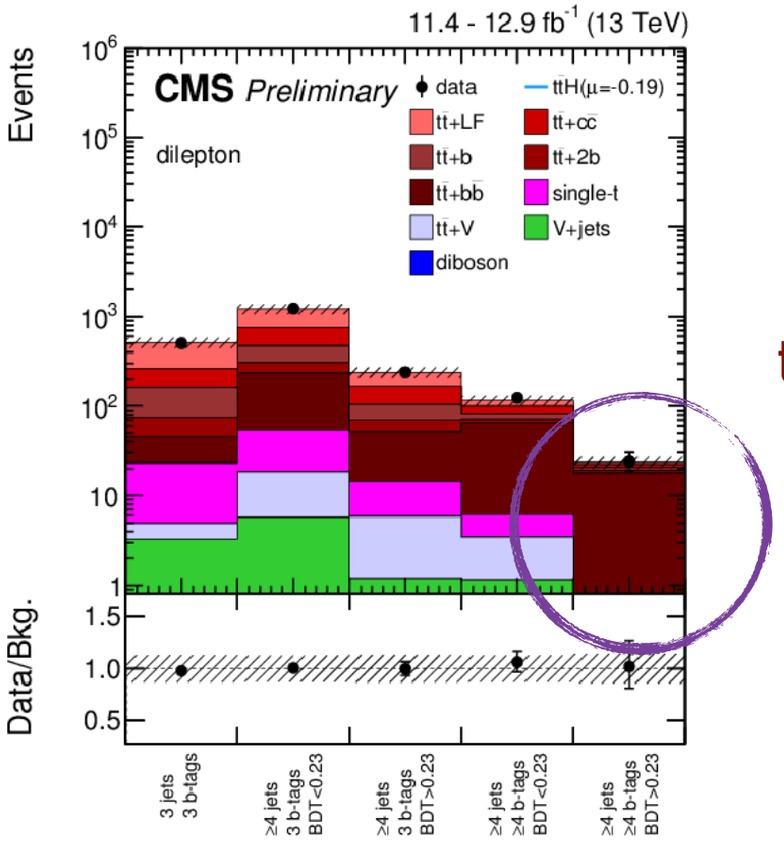
Dileptons

- 2 opposite sign leptons
- At least 3 jets
- At least 2 b-tagged jets

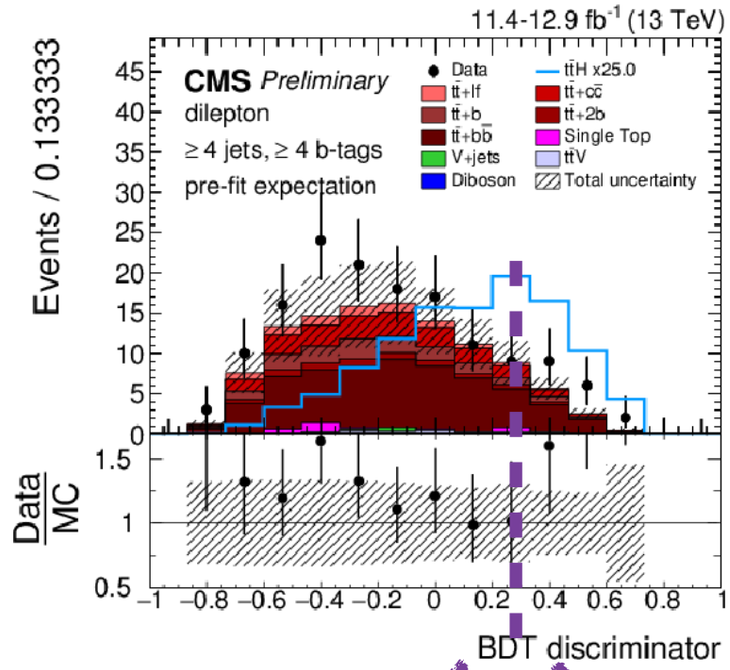


- Leptons + jets: high statistics
- Dilepton: minimal non-$t\bar{t}$ background, and jet combinatorics
- Classify events based on jet, b-tag multiplicities optimized to improve sensitivity

$t\bar{t}$ H($b\bar{b}$) signal extraction



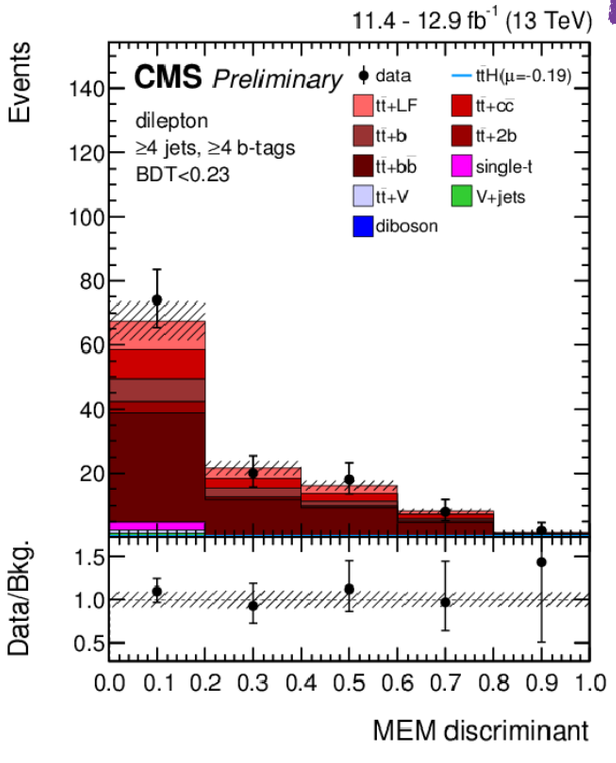
Split category at the median of ttH BDT output

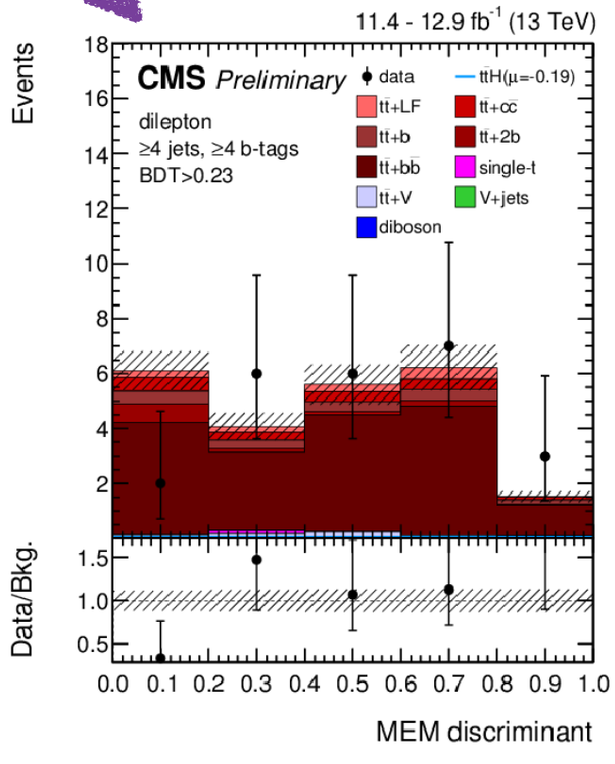


low purity

high purity

- Boosted Decision Tree (BDT)
- Matrix Element Method (MEM)
  - Separate $t\bar{t}$ H vs $t\bar{t}$ +bb at LO built Likelihood ratio between signal & bkg hypotheses
    - Include all measured jets by permuting over possible jet-quark associations

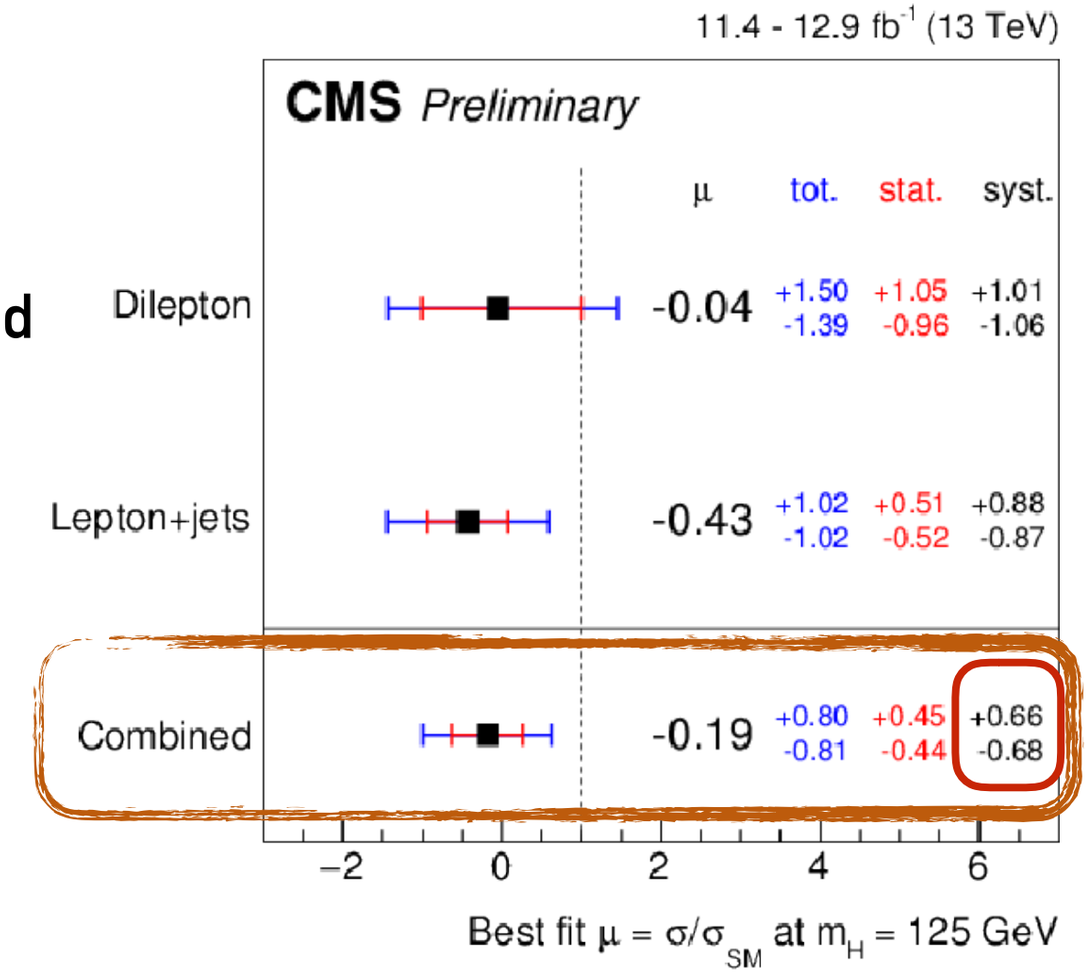




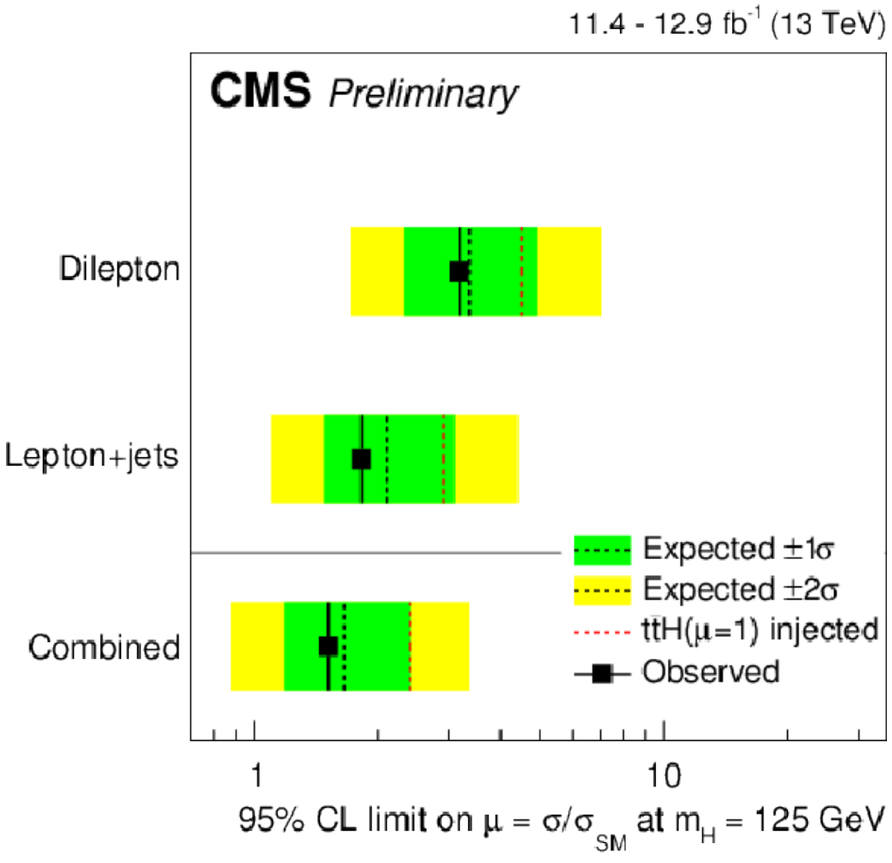
$t\bar{t}$ H(b$\bar{\text{b}}$) results

Simultaneous Maximum Likelihood combined fit of BDT score cross all event categories is performed

- No significant excess observed
- Dominated by systematic uncertainties
  - Primarily those from $t\bar{t}$ +(b-)jets background



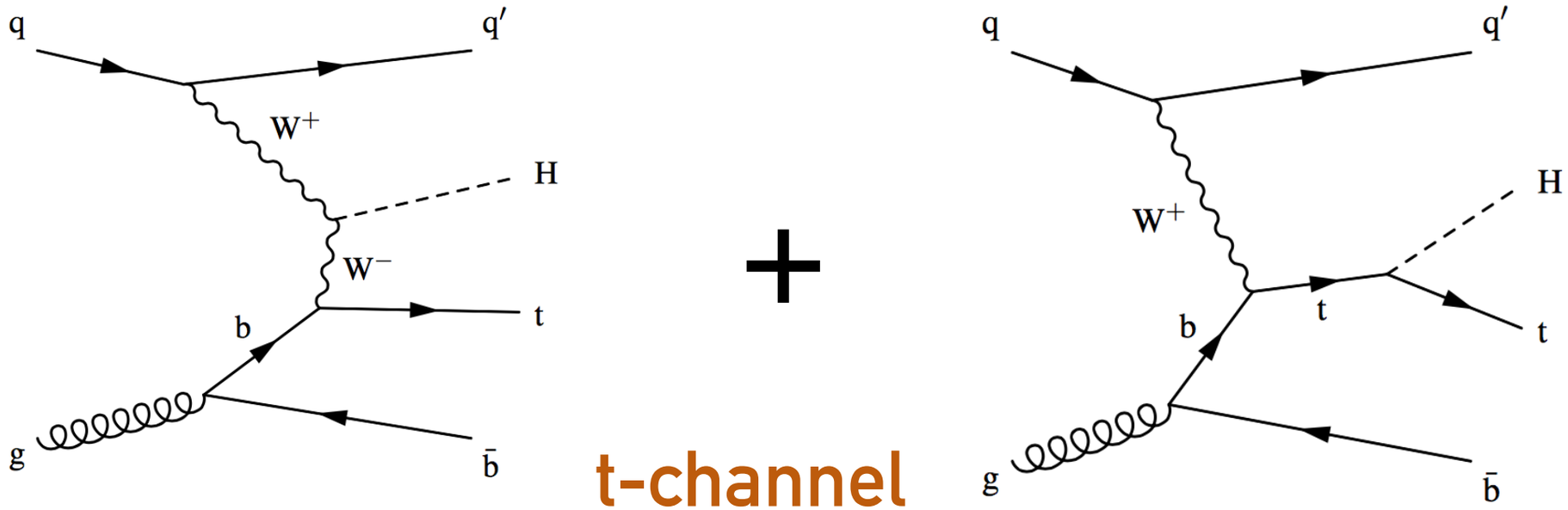
Upper limit at 95% CL



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

Higgs production with single top

- At LO tH can be separated into 3 production modes:
  - t-channel (tHq) (diagrams destructive interference in SM)
  - Associated tW production (tHW)
  - s-channel (negligible cross section at the LHC)



t-channel

- Sensitive to both the magnitude and sign of top Yukawa coupling

  $\sigma_{SM(\kappa V = \kappa t = 1)} = 70.96$ fb ($\sqrt{s} = 13$ TeV)

  $\sigma_{SM}(tHW) = 15.61$ fb ($\sqrt{s} = 13$ TeV)

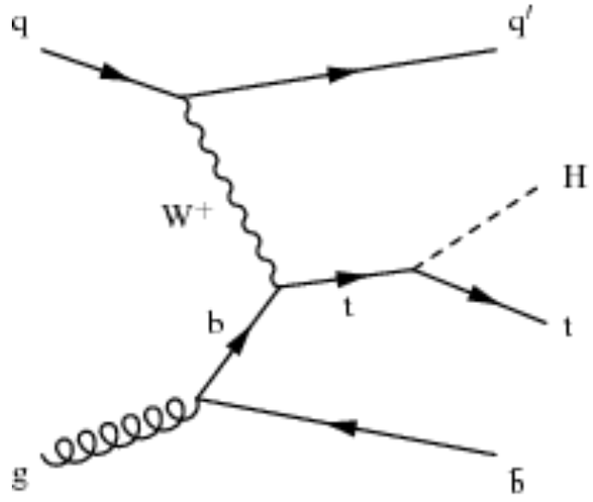
- In BSM scenarios not necessarily destructive interference, e.g. Inverted Top Coupling scenario (large enhancement σ_{ITC} ($\kappa V = -\kappa t = 1$) = 792.7 fb)

  → Effective theory with possibly CP violating top Yukawa couplings,
  & modified couplings to vector bosons (Eur. Phys. J. C 75 (2015), no. 6, 267)

tHq+tHW, H→b$\bar{b}$

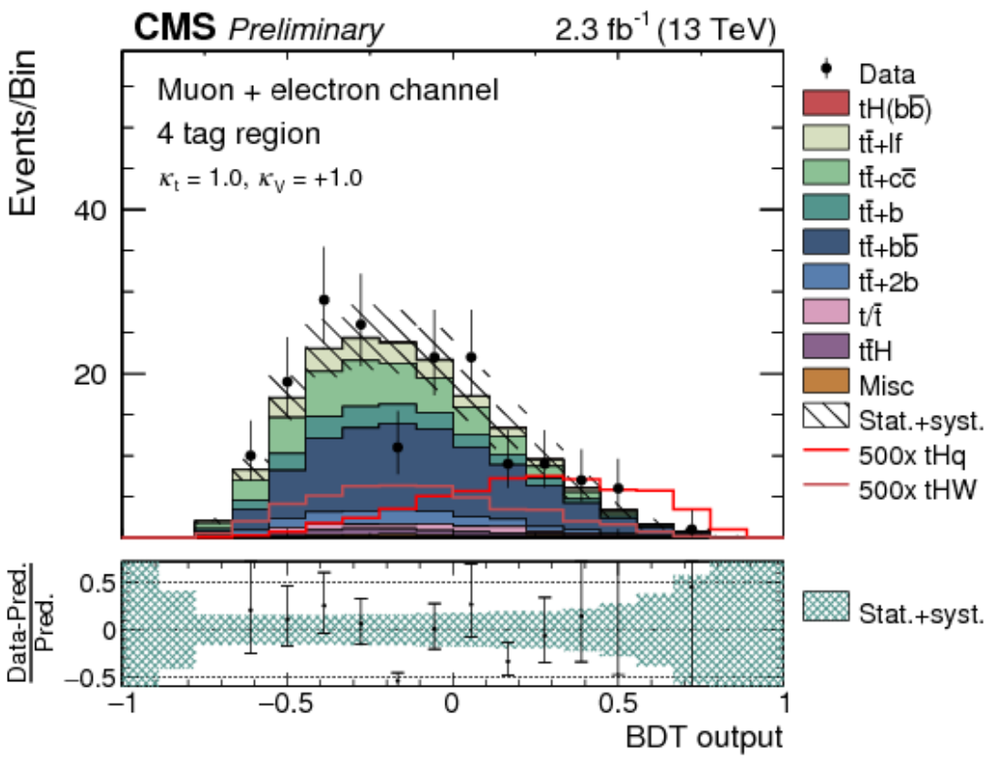
CMS-PAS-HIG-16-019

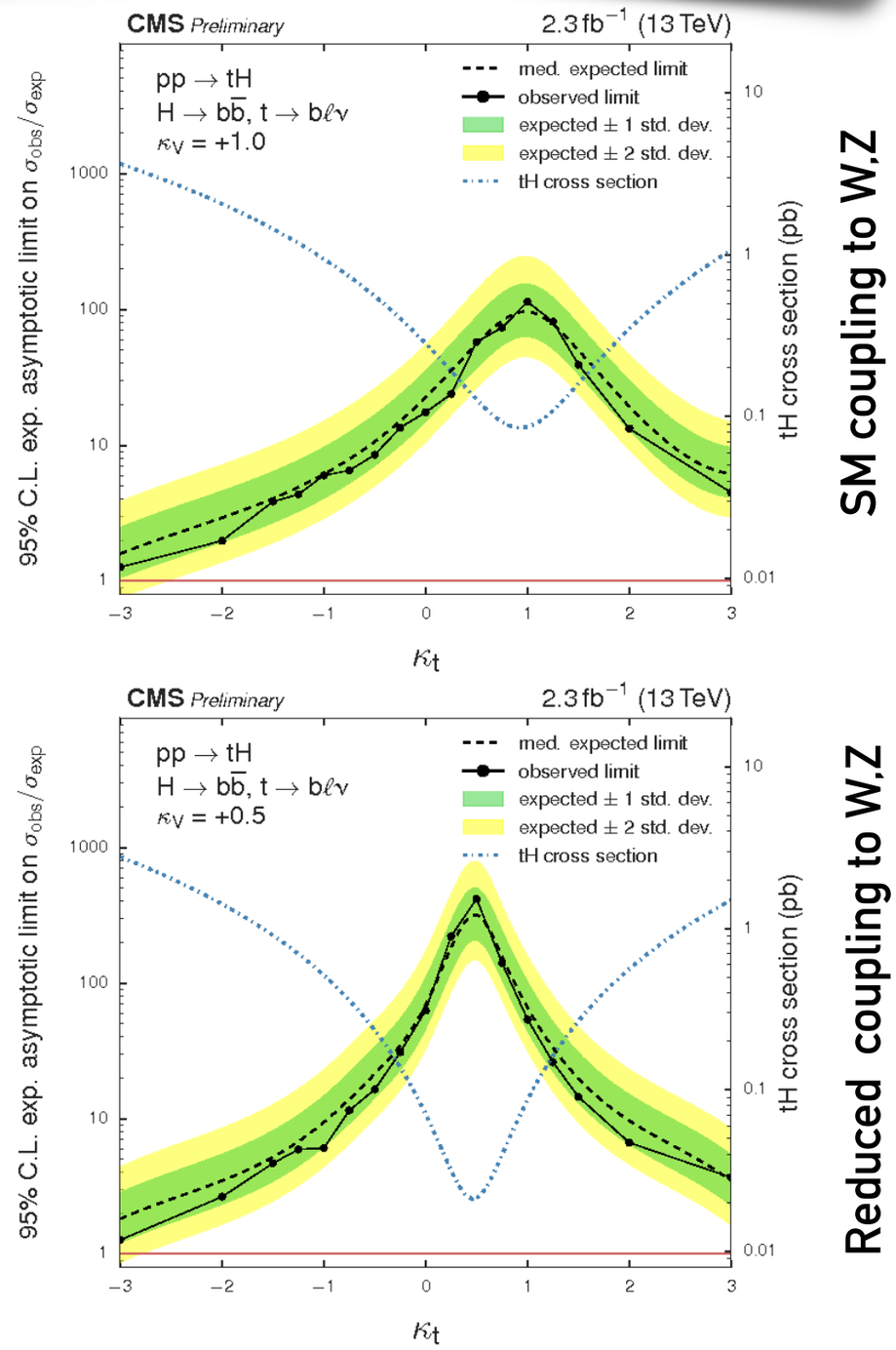
Search for H → b$\bar{b}$ in association with a single top (t → b ev/b μv)



Signal region:

- e/mu + 3 or 4 b-tagged jets, 1 non-tagged jet final state
- BDT to find jet assignment for $t\bar{t}$ and tHq hypotheses
- Final BDT discriminant exploits reconstruction properties (jet assignment) + additional kinematic properties





Observed (expected) 95% CL upper limit for the SM is 113.7 × σ_{SM} (98.6 × σ_{SM}) & 6.0 × σ_{SM} (6.4 × σ_{SM}) for ITC

tHq+tHW, H→multileptons

CMS-PAS-HIG-17-005

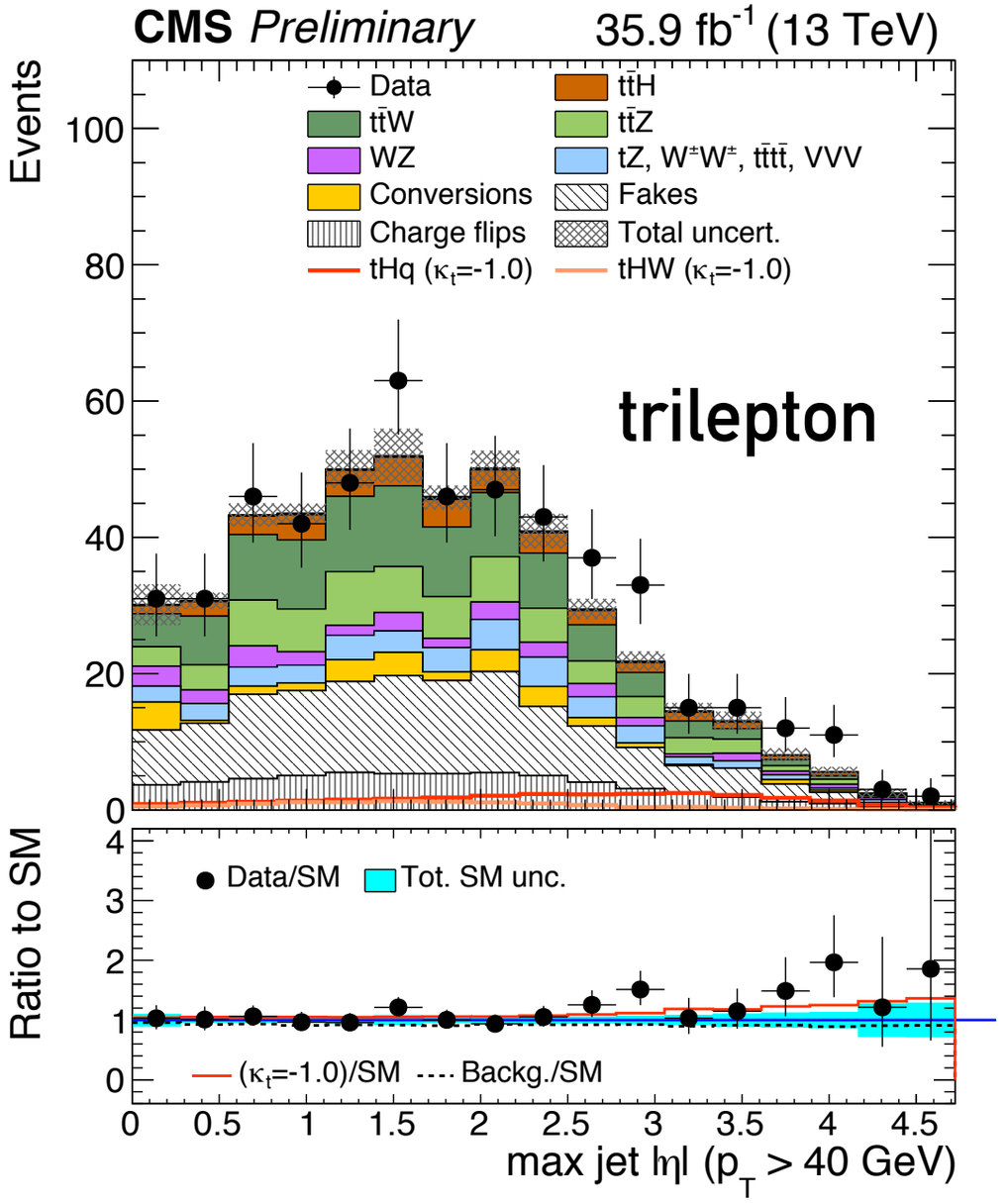
The process exposes relative sign of top-Higgs and W-Higgs couplings via interference

- Irreducible bkg (MC):
  - $t\bar{t}$ +X (X=W/Z/H/γ^*)
  - Photon conversions
  - Rare SM tZq, tWZ, tri-bosons, WWqq, tttt
  - Di-bosons WZ, ZZ
- Reducible bkg (data-drive):
  - Fakes due to non-prompt leptons & miss-ID of jets passing lepton selection
  - Charge flips:
    - Charge mis-ID (2lss)
    - Opposite-sign processes (e.g $t\bar{t}$/Z+jets)

Analysis strategy

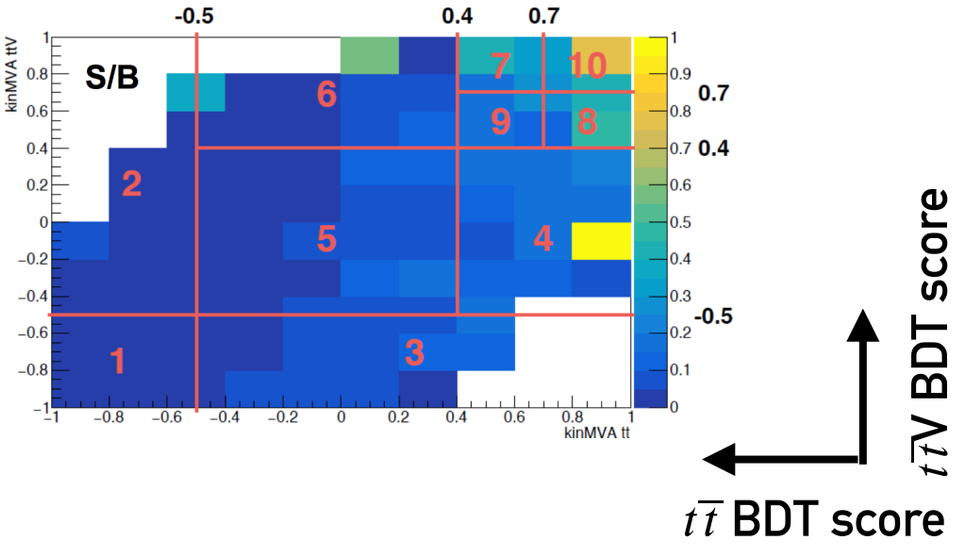
- Same-sign dilepton (2lss): 1 W from Higgs decays hadronically, others decay leptonically
- Trilepton (3l): H→ WW/ττ/ ZZ, & where top's W decays leptonically

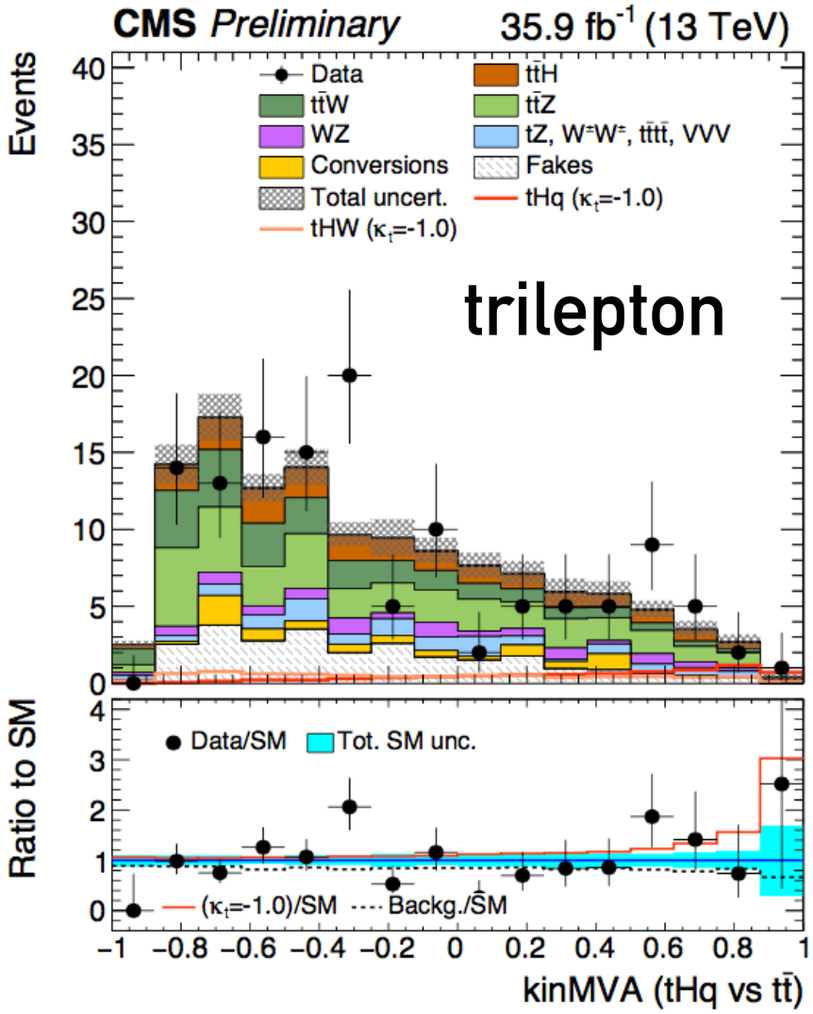
Integrated luminosity of 35.9 fb^{-1}

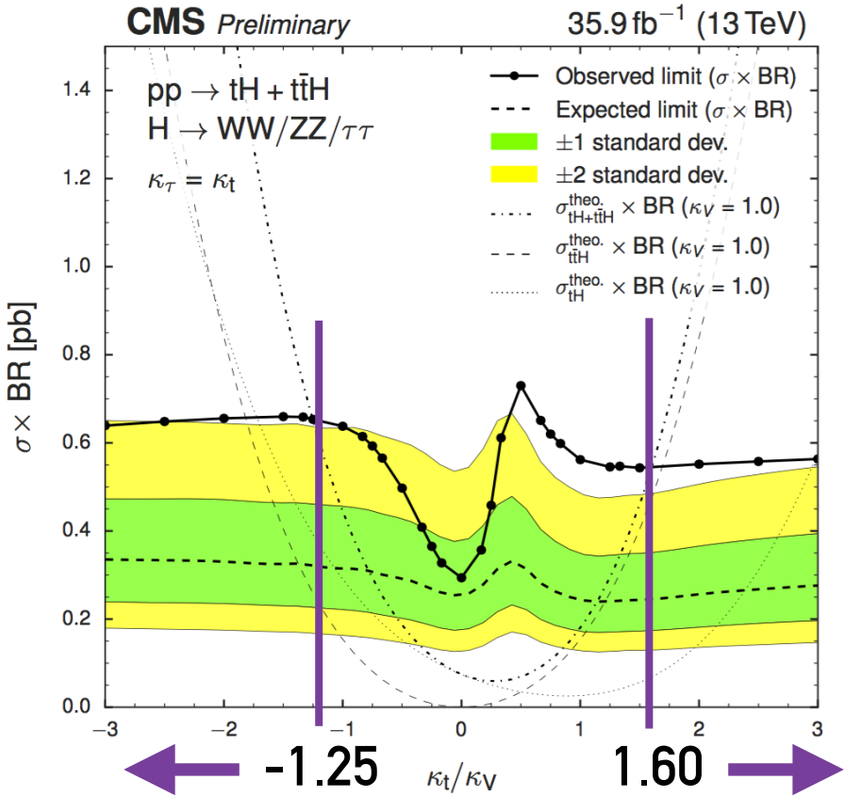


tHq+tHW, H→multileptons signal extraction

- 2 BDT classifiers train tHq against $t\bar{t}$ or $t\bar{t}$V
  - Divide the plane of BDT $t\bar{t}$ vs BDT $t\bar{t}$V into bins for signal & background
  - Shape fit the MVA binned output to extract the signal yield combine for final 1D discriminant







Expected (incl. SM Higgs) & observed limit on σxBR as function of κ_t/κ_V

- Excess of about 1 σ of expected SM-like tHq+tHW+ttH signal observed
- Best-fit signal strength for SM: μ = 1.8 ± 0.3 stat. ± 0.6 syst.

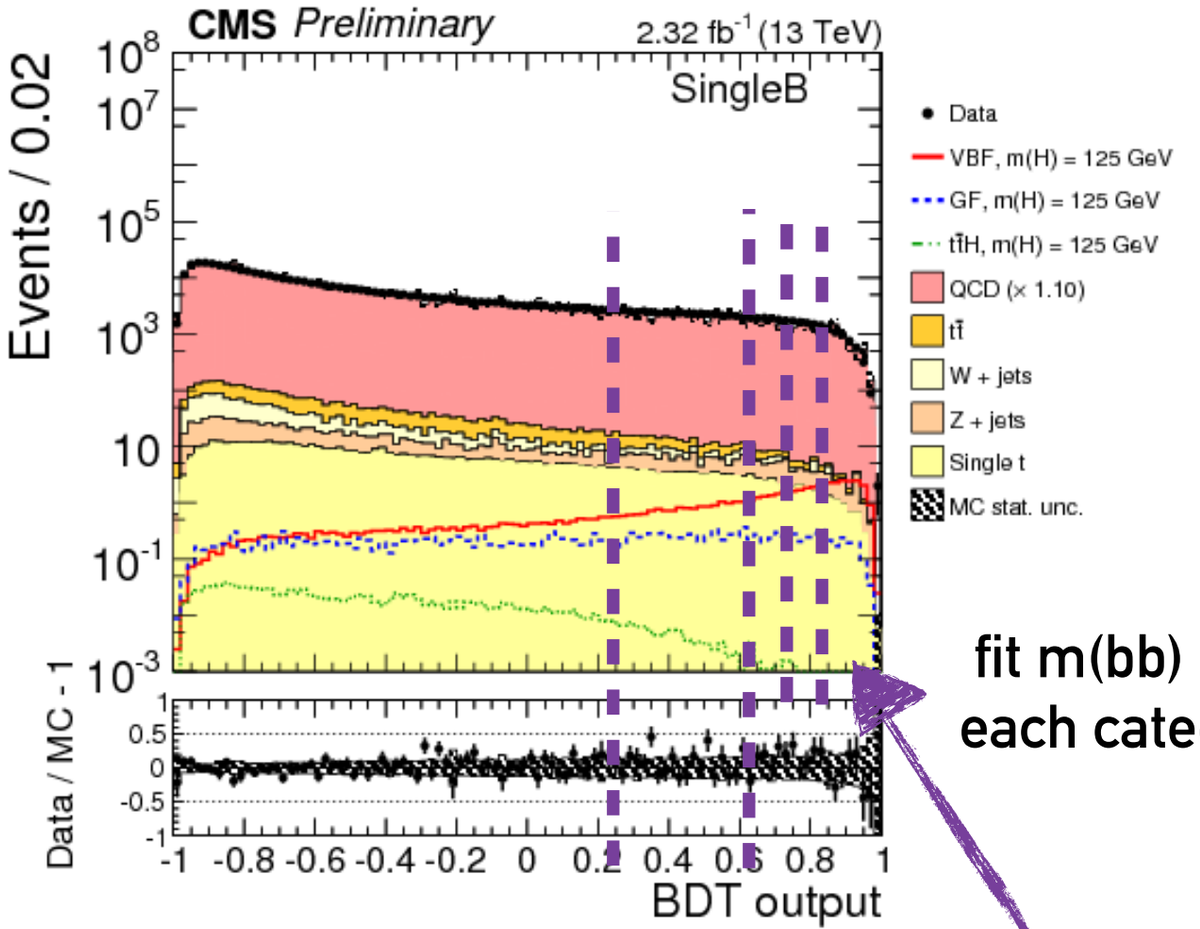
VBF, $H \to b\bar{b}$

CMS-PAS-HIG-16-003

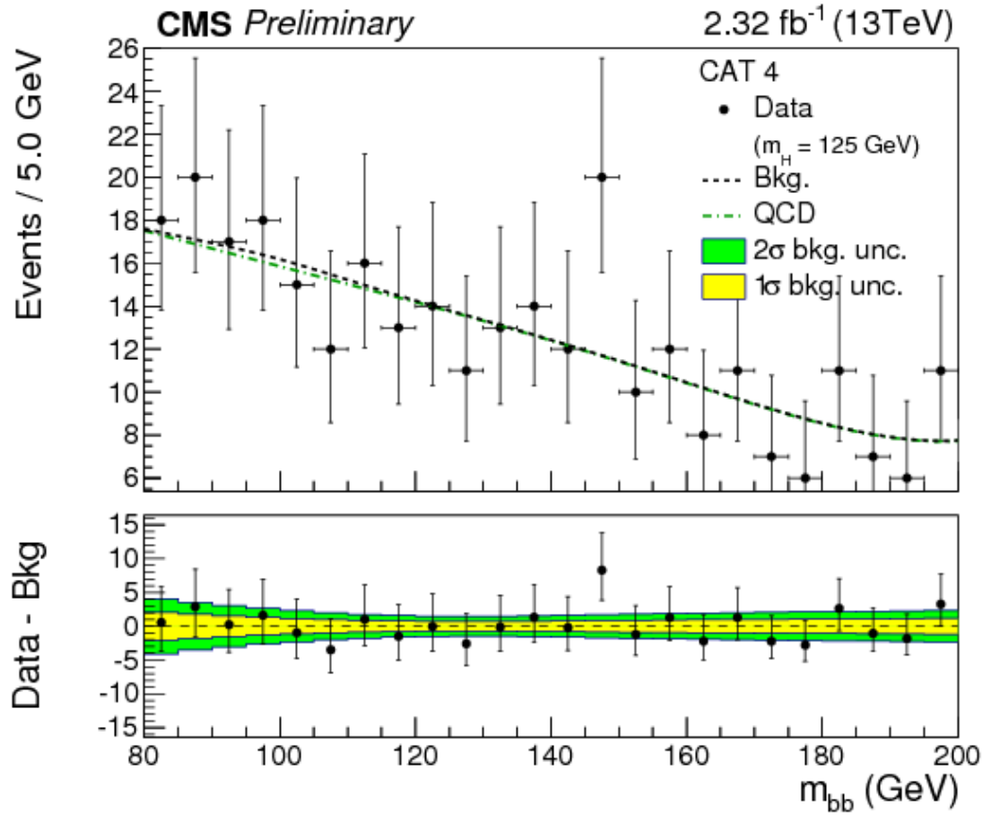
Properties of the VBF $H \to b\bar{b}$ channel:

- Cross section significantly larger than VH or ttH production
- Very large QCD production of multijet background events

- BDT to ID VBF-like events in 4-jet signal event topology with 1 or 2 b tag jets



fit m(bb) in each category



m_{bb} resolution worsened by semi-leptonic b-decays
→ improve b-jet energy resolution with BDT regression

CAT 1 . . . CAT 4

- Signal extraction in simultaneous fit to m_{bb} spectrum in all categories
- Result using 2.3 fb^{-1} @ $\sqrt{s}$ = 13 TeV:
  $\mu = -3.7^{+2.4}_{-2.5}$
- Combination with Run I (18 -19 fb^{-1} @ 8 TeV):
  $\mu = 1.3^{+1.2}_{-1.1}$

Summary and Outlook

- Presented searches performed for $H \rightarrow b\bar{b}$ using 2-39 fb^{-1} analyzed data @ 13 TeV
- Run-2 sensitivity exceeded Run-1 result
- Probes Top-Higgs Yukawa coupling directly accessible through associated t(t)H production
  - Important for understanding loop contributions
- Studies involve complex final states with leptons, jets, photons etc.
- Multiple analysis channels contribute sensitivity
- No deviation from the SM prediction observed

Outlook

- Not all analyses updated to all available data
  - updates in the very near future
- Excellent prospects for establishing $t\bar{t}H$, VBF signal with complete Run-2 data set
- Continuous improvement of the signal extraction methods & modeling of $t\bar{t}$ + (b-)jets (indispensable collaboration with theory & MC experts)

References

Publication

- CMS-PAS-HIG-16-038
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-16-038/index.html
- CMS-PAS-HIG-16-003
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-16-003/index.html
- CMS-PAS-HIG-16-019
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-16-019/index.html
- CMS-PAS-HIG-17-005
  - http://cms.cern.ch/iCMS/analysisadmin/cadilines?id=1868&ancode=HIG-17-005&tp=an&line=HIG-17-005

Conference talks

- https://indico.cern.ch/event/505065/contributions/2166376/attachments/1339192/2019944/LHC-Day-Split_2016_ChristianJCC.pdf
- https://indico.in2p3.fr/event/13763/session/0/contribution/79/material/slides/0.pdf
- https://indico.cern.ch/event/477407/contributions/2200113/subcontributions/198573/attachments/1369935/2077138/ttH_Hbb_CMS_Kasieczka.pdf

Backup

m_{bb} resolution

m_{bb} resolution significantly worsened by semi-leptonic b-decays and gluon radiation outside jet "cone"

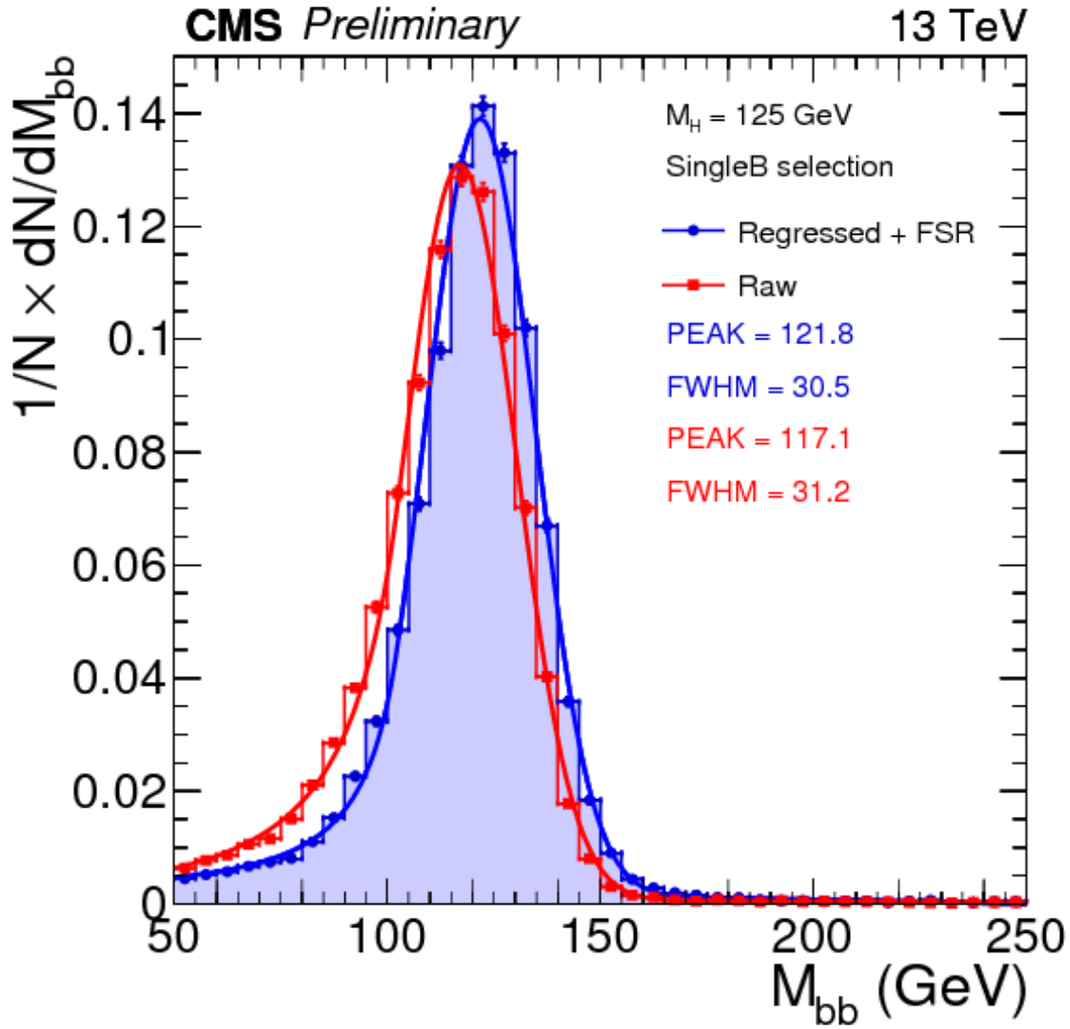
→ improve b-jet energy resolution with regression

BDT Regression inputs

- Jet kinematic
- EM energy fraction
- Information about soft leptons in the jet
- Secondary vertex information
- Pileup

FSR correction:

Add jets within $\Delta R < 0.8$.



2 b-jet candidates before & after the jet p_T regression (for VBF signal events)

$t\bar{t}$ H(multileptons)

CMS-PAS-HIG-17-004

Dominant backgrounds:

- Irreduicbl: $t\bar{t}$+V (from MC)
- Reducible: $t\bar{t}$+jets (from data)

2 same sign leptons

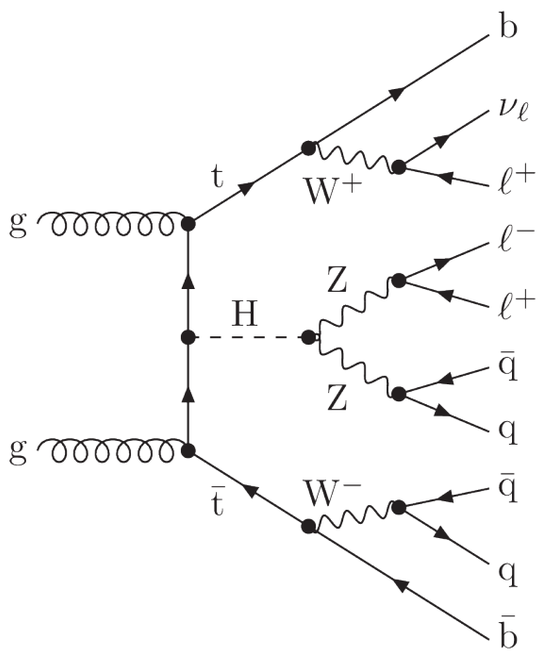
- At least 4 jets
- At least 1 b-tagged jets

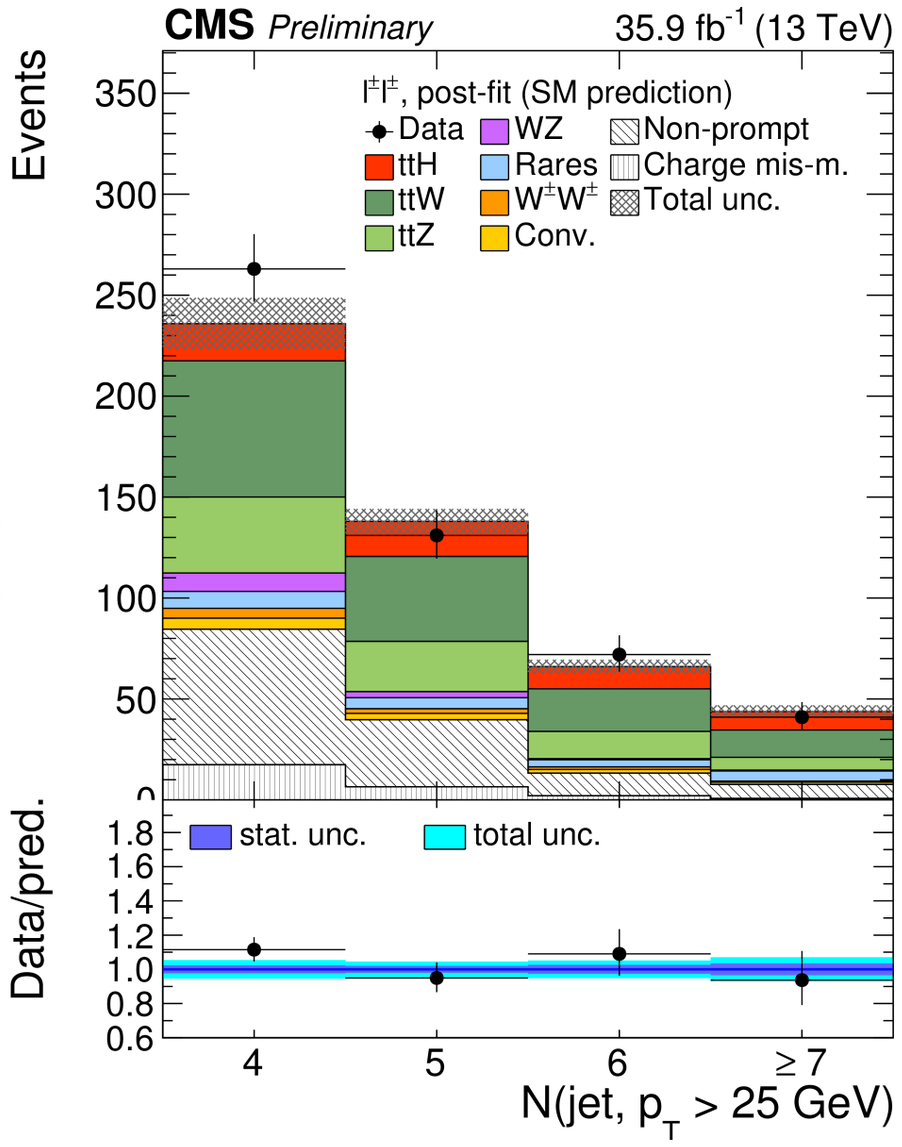
Tri-leptons

- 2 opposite sign leptons
- At least 3 jets
- At least 1 b-tagged jets

Sub-classification:

- Lepton charge
- Presence of hadronic taus
- Lepton flavor
- Presence of at least 2 b-tags
- Signal/Background bins

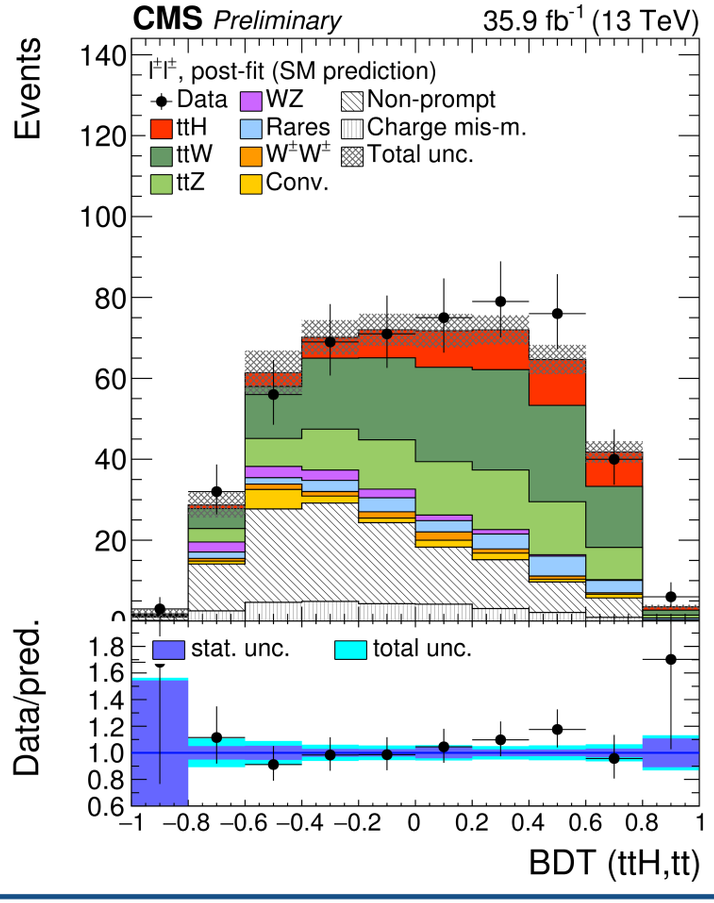




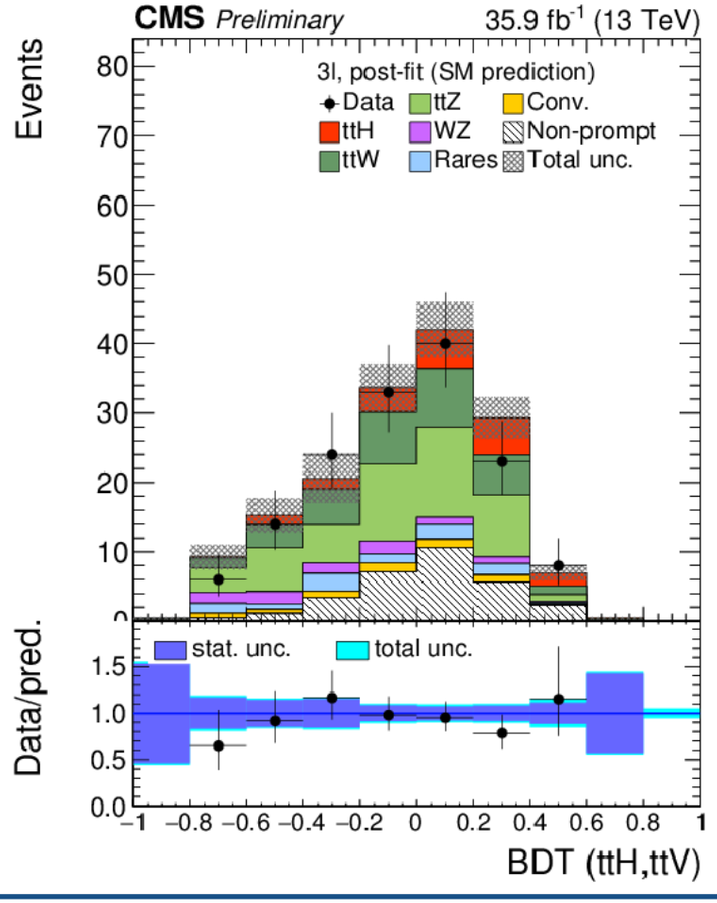
$t\bar{t}$ H(multileptons) results

- Relies on BDT method to separate signal from tt, and ttV backgrounds
- Modeling of fake lepton backgrounds based on control regions by relaxing lepton selection
  - Charge mis-assignment of electrons
  - Jet mis-identification, B-hadron decay
  - Categories based on signal/back bins
- Combined best-fit over all sub-categories
  - best fit ttH yield of 1.5±0.5 x the standard model prediction
  - observed (expected) significance of 3.3σ(2.5σ) (results combined with 2015 dataset)

dilepton



trilepton



Matrix Element method for $t\bar{t}$H(bb) vs $t\bar{t}$bb

- Signal extraction via Matrix Element Methods (MEM):
  - Event-by-event discriminator build upon matrix elements, combined with reconstruction-level information

Numerical integration

Momentum conservation

Resolution function (allow ISR)

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

Parton density functions

LO scattering amplitude (Open Loops)

Detector transfer function

- Construct per-event signal/background probabilities using full kinematic information in an analytic approach

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

- $t\bar{t}$+bb take as background hypothesis, permuting overall jet assignments
- Works best for final states with multiple reconstructed jets

Particle Swarm Optimization

- See: Particle swarm optimization (J. Kennedy, R. Eberhart)
  Proceedings of the IEEE International Conference on Neural Networks, 1995.
- Optimization algorithm
- Different BDT setting (i.e. tree structure and variables) form the search-space
- A specific setting corresponds to one point in this search space
- Algorithm:
  - Create swarm of candidate BDTs
  - Each BDT is initialized with a random set of input variables and position in parameter-space
  - Do N iterations
    - Repeatedly train/test at current position.
    - Vary input variables to maximize ROC while KS > threshold
    - Then the BDTs move to new positions, based on their own and