SLAC NATIONAL ACCELERATOR LABORATORY, NOVEMBER 9–12, 2016

HIGGS 2016 COUPLINGS

Higgs decaying to b quarks

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On behalf of the CMS Collaboration

CMS Compact Muon Solenoid

SLAC NATIONAL ACCELERATOR LABORATORY

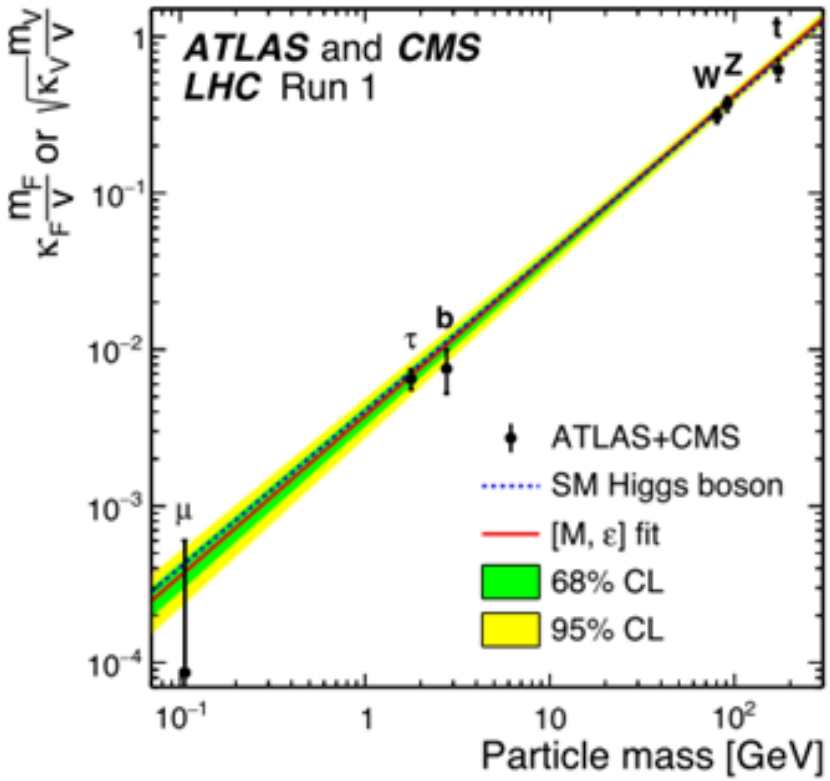
U.S. DEPARTMENT OF ENERGY Office of Science

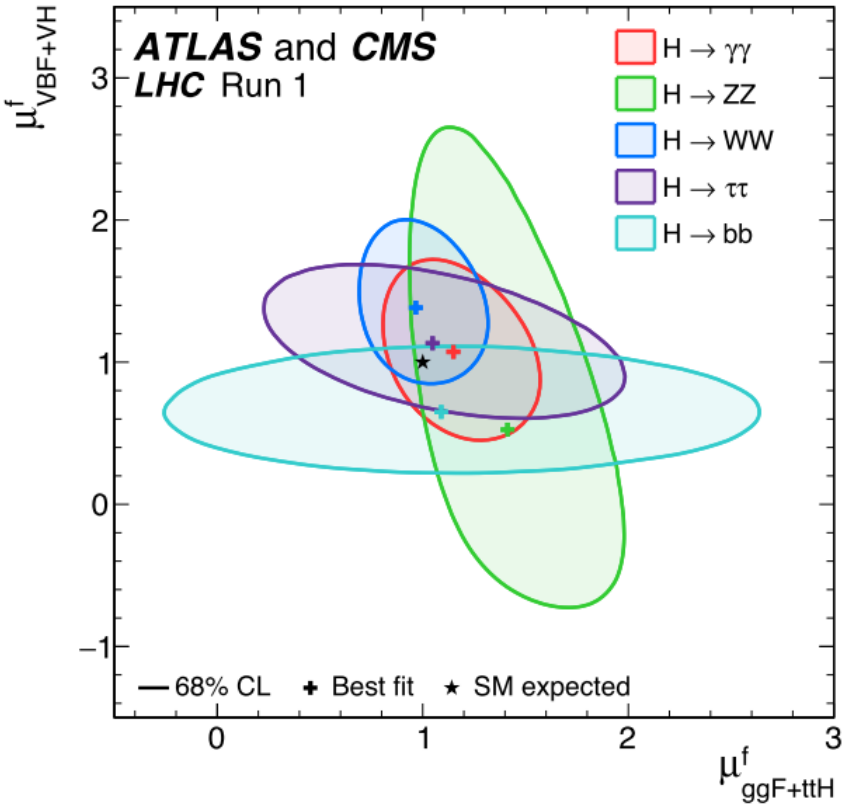
ETH Zürich

with respect to ICHEP…

Higgs to bottom Quarks

- Highest Higgs BR @ 125GeV: 58%
- Direct probe of the Higgs coupling to b-quarks

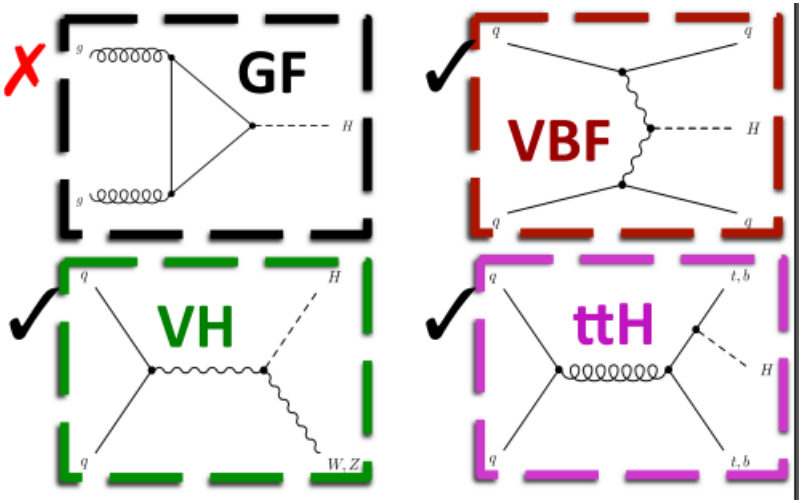




CMS Run1 H→bb Summary

- Given the large amounts of other SM processes containing two bottom quarks, the search **must use different production mechanism handles to reduce background**
  - Further discrimination is obtained in the VH channel by utilizing boosted Higgs topology
- **Total observed significance: 2.56σ** (2.70σ expected)
  - Most updated result in **Phys. Rev. D 92, 032008 (HIG-14-004)**

$H \to b\bar{b}$ Channel	Best fit (68% CL) Observed μ/μ_{SM}
VH	0.89 ± 0.43
$t\bar{t}H$	0.7 ± 1.8
VBF	$2.8^{+1.6}_{-1.4}$
Combined	$1.03^{+0.44}_{-0.42}$



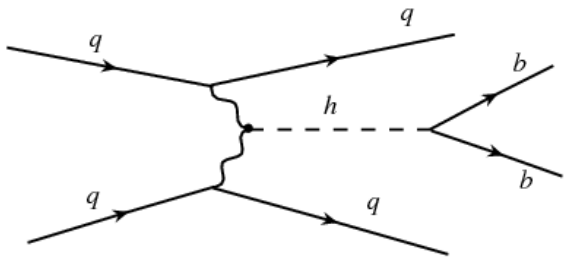
Run2: the search resumes

- H→bb searches with 13 TeV data:
  - **VBF**
  - **Single top plus Higgs** (sensitive to inverted top couplings)
  - **Non-resonant di-Higgs→bb bb (see Olivier's talk)**
  - **ttH (see Gregor's talk)**
  - **VH…**

VBF H→bb: Signature

HIG-16-003

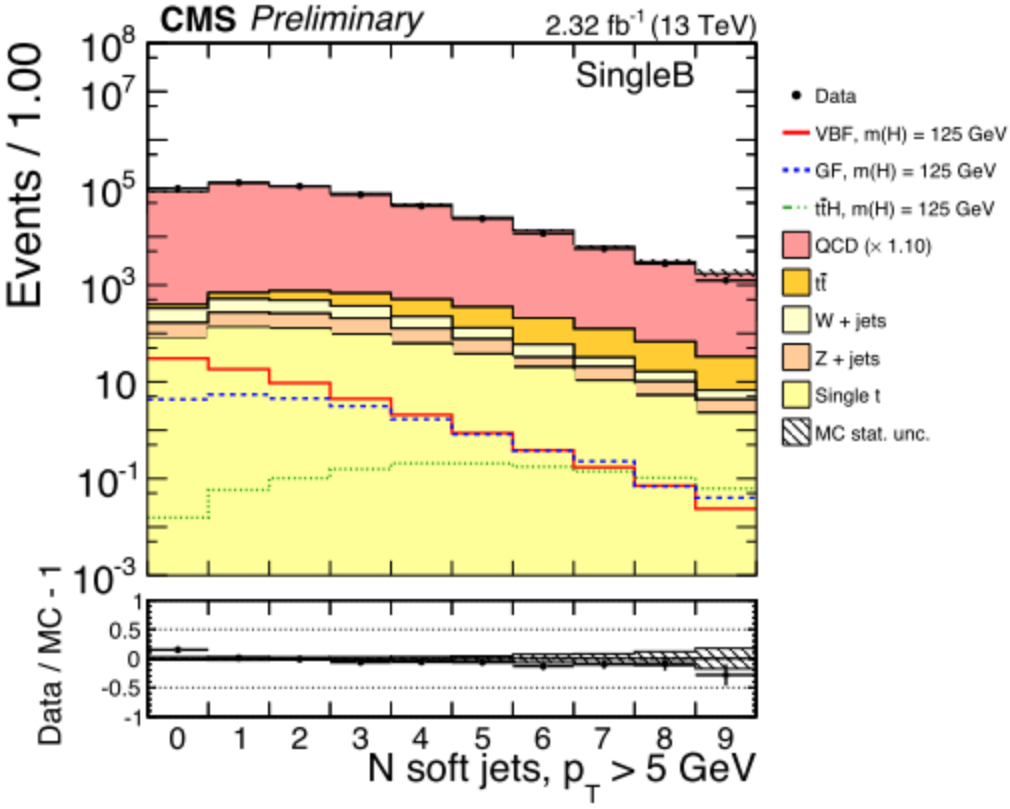
- **Signal signature:**
  - 2 central b-jets from Higgs decay
  - 2 fwd VBF jets with large Δn_{jj} and m_{jj}



- **Main background: multi-jet QCD**

- **Two independent search region from complementary triggers**
  - Both require 3 p_T jets at level 1 trigger
  - At HLT we require four jets, 2 fwd VBF jets and **one or two b-tags**

- **Discriminating variables**
  - **1 or 2 b-tagged jets**
  - VBF di-jet signature (tighter selection for 1 b-jet)
  - Rapidity gap with track jet counting ("soft activity")

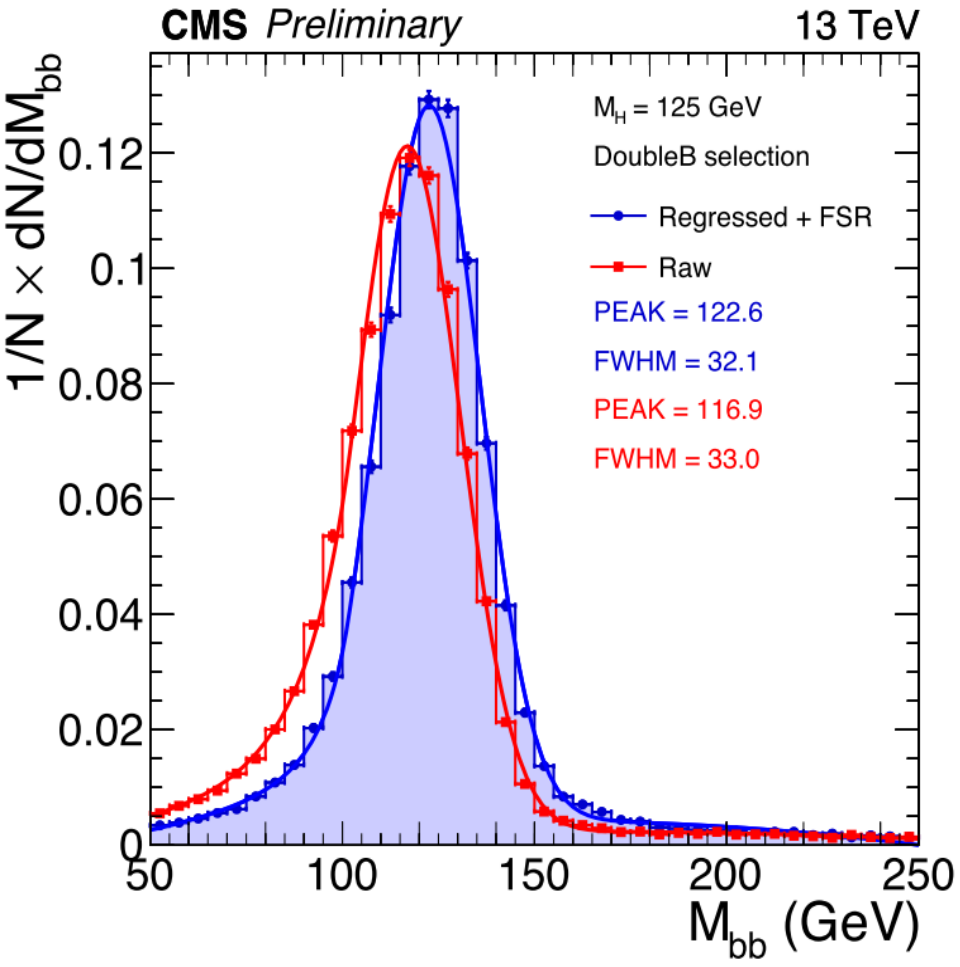


Improved H→bb resolution

- **Jet energy regression trained on VBF signal events (5% improvement) using:**
  - Jet kinematics
  - Sub-jet quantities
    - Leading track p_T
    - Energy fraction from hadrons and photons
  - Secondary vertex information (where available)
  - Estimate of pile-up contribution

- **Final state radiation recovery (2% improvement)**
  - Addition of jet near but outside b-jet reconstruction cone (dR<0.8)

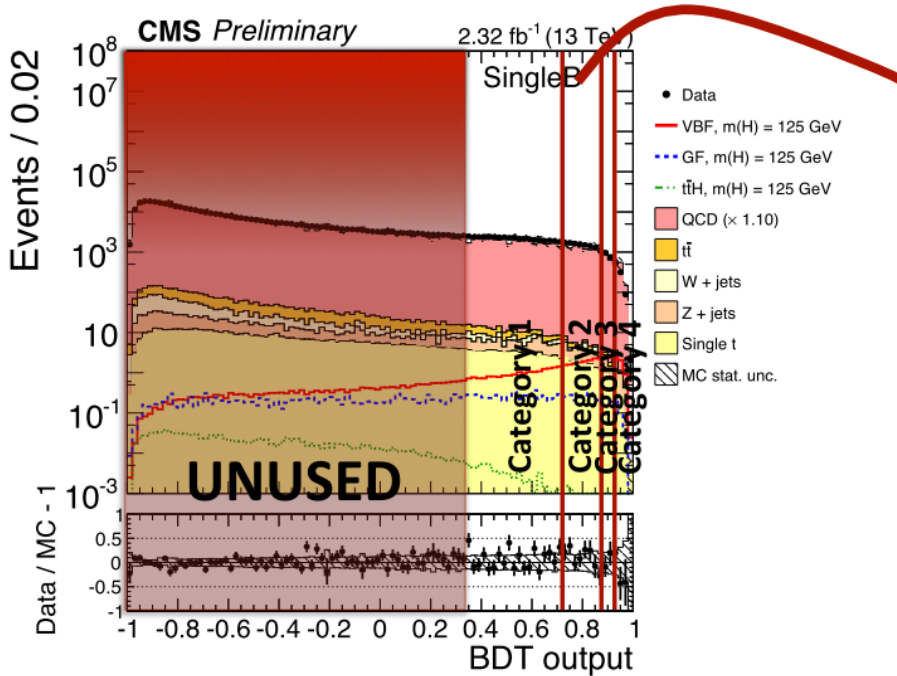
HIG-16-003

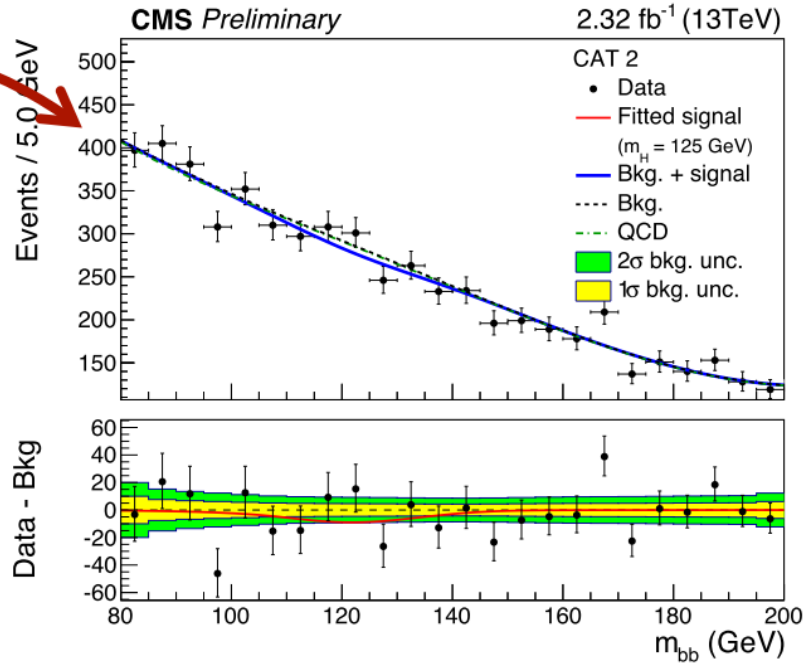


VBF H→bb analysis

HIG-16-003

- **All of the discriminating variables used in a boosted decision tree (BDT)**
  - Variables need to be uncorrelated with b-jet invariant mass
  - Separate training for one or two b-tagged categories
- **BDT output sliced in optimized categories (9 total)**
  - 5 for the single b-jet sample, 4 for the double b-jet sample
  - Lowest BDT category dropped (UNUSED) in both samples
- **Simultaneous fit of the m_{bb} distributions in the best categories of both samples (4+3)**
  - QCD background modeled with polynomial functions: common polynomial for each sample, plus transfer functions from the lowest used BDT category to the higher ones, to account for residual shape differences





VBF H→bb – Run1 + 2015 Data

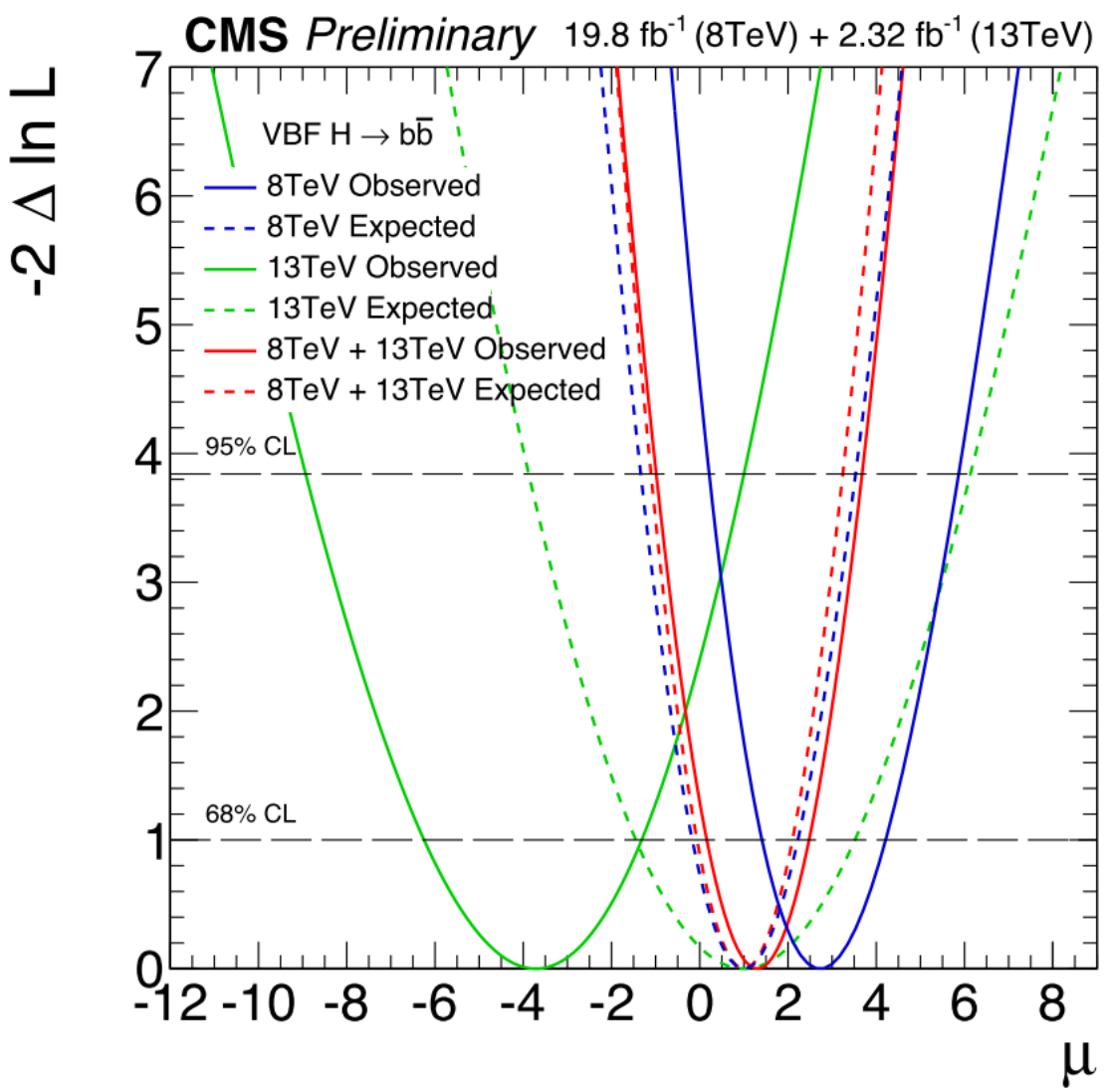
- Using **2.3/fb of 2015 data at 13 TeV**, the analysis results in a deficit of data at m_{bb} =

$$\mu_{2015} = \frac{\sigma}{\sigma_{SM}} = -3.7^{+2.4}_{-2.5}$$

- In **combination with the Run1** analysis signal strength is:

$$\mu_{\text{Run 1+2015}} = 1.3^{+1.2}_{-1.1}$$

HIG-16-003

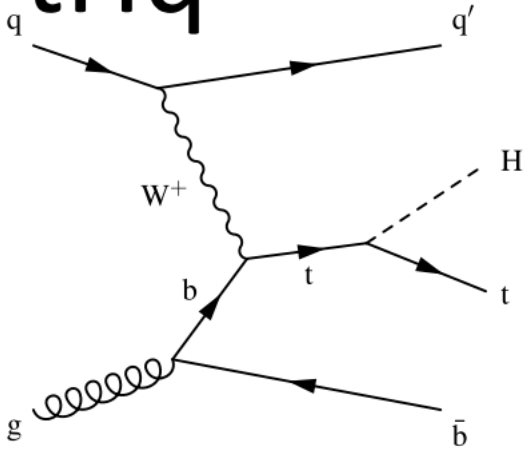


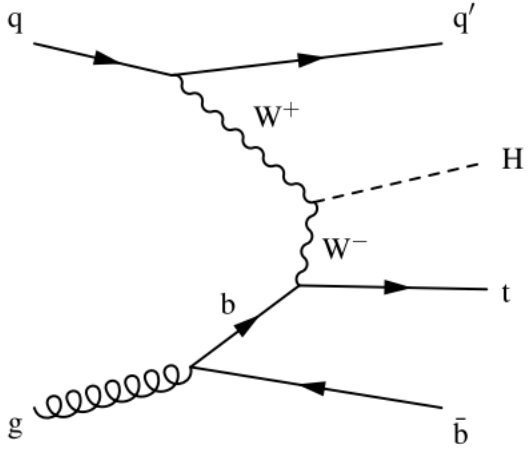
Probing the top-Higgs coupling

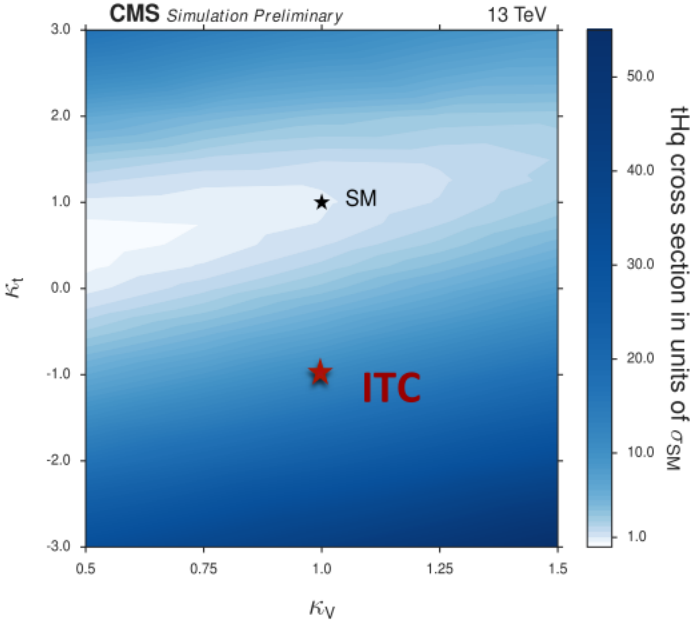
HIG-16-019

- **Top+Higgs interference in tHq diagrams is destructive in SM, while it is constructive for inverted top coupling (ITC) k_{top} = -1**
  - σ_{SM}=71 fb **σ_{ITC}~ 10*σ_{SM}**=739 fb
  - Analysis potentially sensitive to the sign of the Yukawa coupling, unique of its kind
- **Other diagrams (tHW) contribute in a similar manner, but with a smaller cross section**
  - They are considered as signal (10-20%) but not used during optimization

tHq



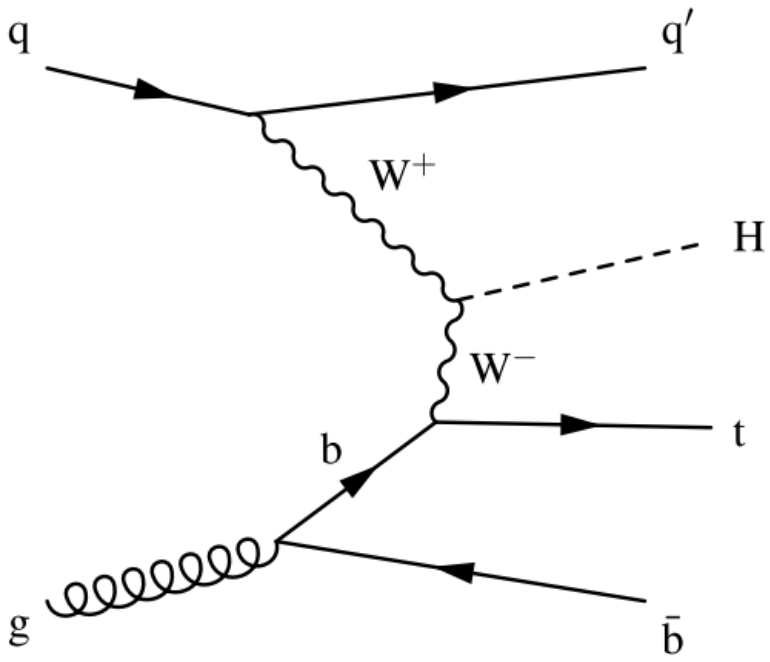




Top-Higgs Selection

HIG-16-019

- **Final state topology**
  - Top quark decaying to b quark + W boson
  - H→bb
  - Additional b-quark
  - Additional light quark

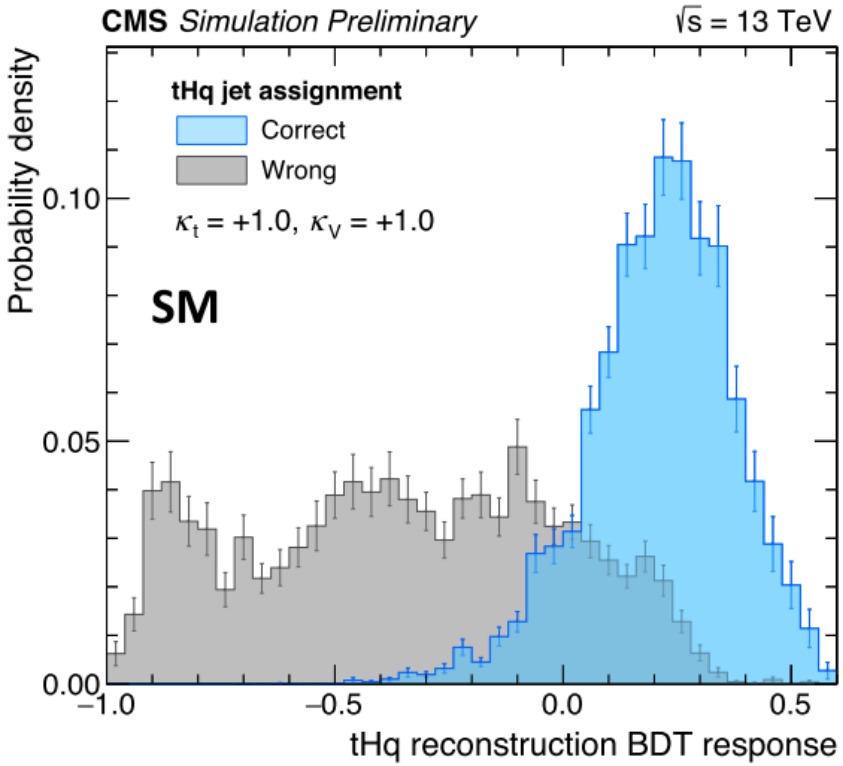


- **Analysis requirements**
  - W boson
    - High p_T lepton (electron or muon)
    - Minimal missing transverse energy required to reject QCD background
  - Events with additional leptons rejected to eliminate Drell-Yan
  - Three or four identified b-jets required
  - One additional light quark jet

Top-Higgs Reconstruction

HIG-16-019

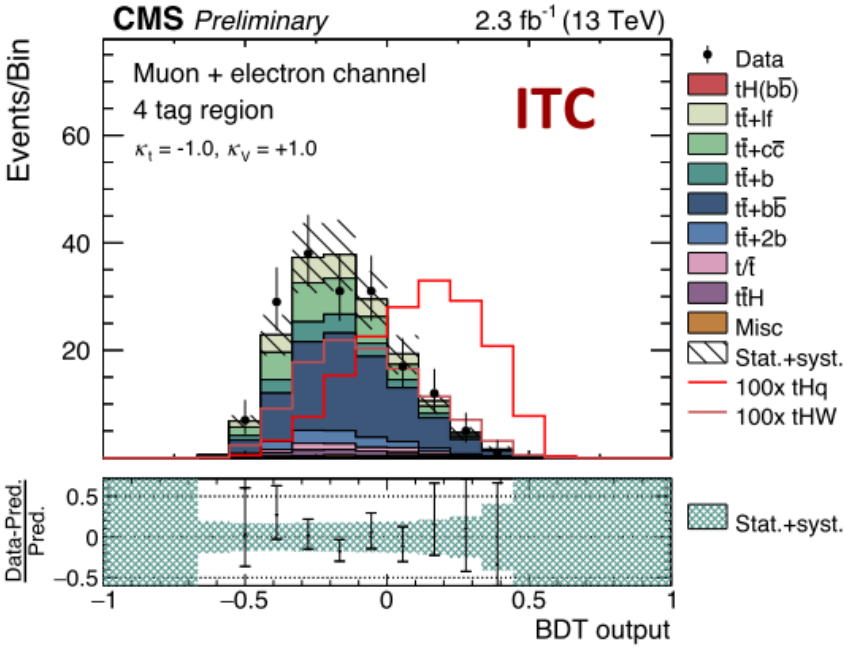
- **Many ways to associate four jets to three objects (Higgs, top and additional quark)**
- **BDT trained on the correct matching in MC (using generator level truth info) to optimize the assignment of the jets to the proper object**
  - Trained against making random assignment
- **Most discriminating reconstruction response input variables**
  - Log(M_{bb})
  - Log($M_{reco\ top}$)
  - B-tagging discriminators for Higgs candidate b-jets and b-jet from top
  - Jet kinematics
- **Configuration yielding to the best tHq reconstruction response selected for analysis**

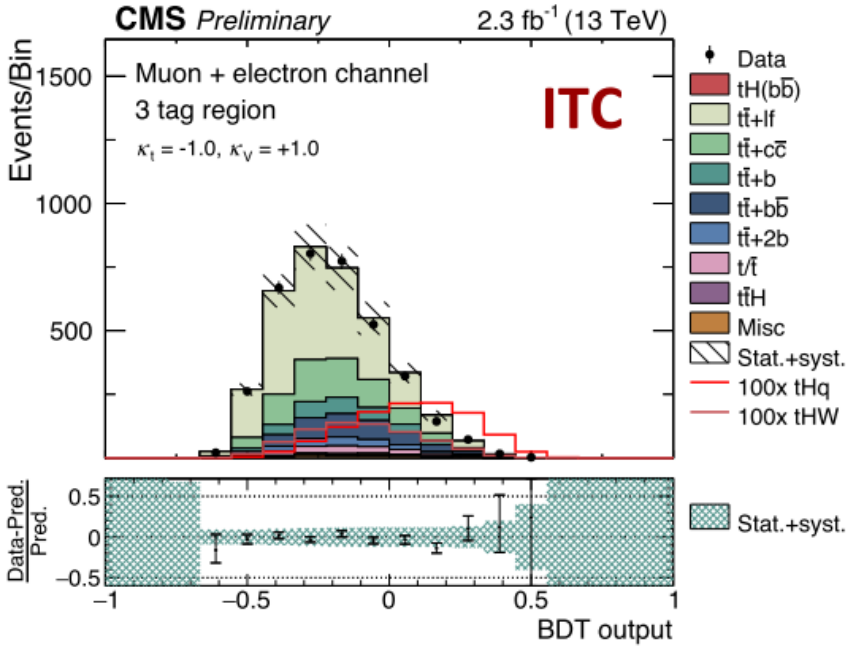


Top-Higgs Analysis

HIG-16-019

- **BDT shape analysis is performed**
  - BDTs are trained for each k_{top} assumption to take int account variation on kinematic distributions
- **Most discriminating BDT input variables**:
  - B-tagging discriminators for Higgs candidate b-jets and b-jet from top
  - Jet kinematics

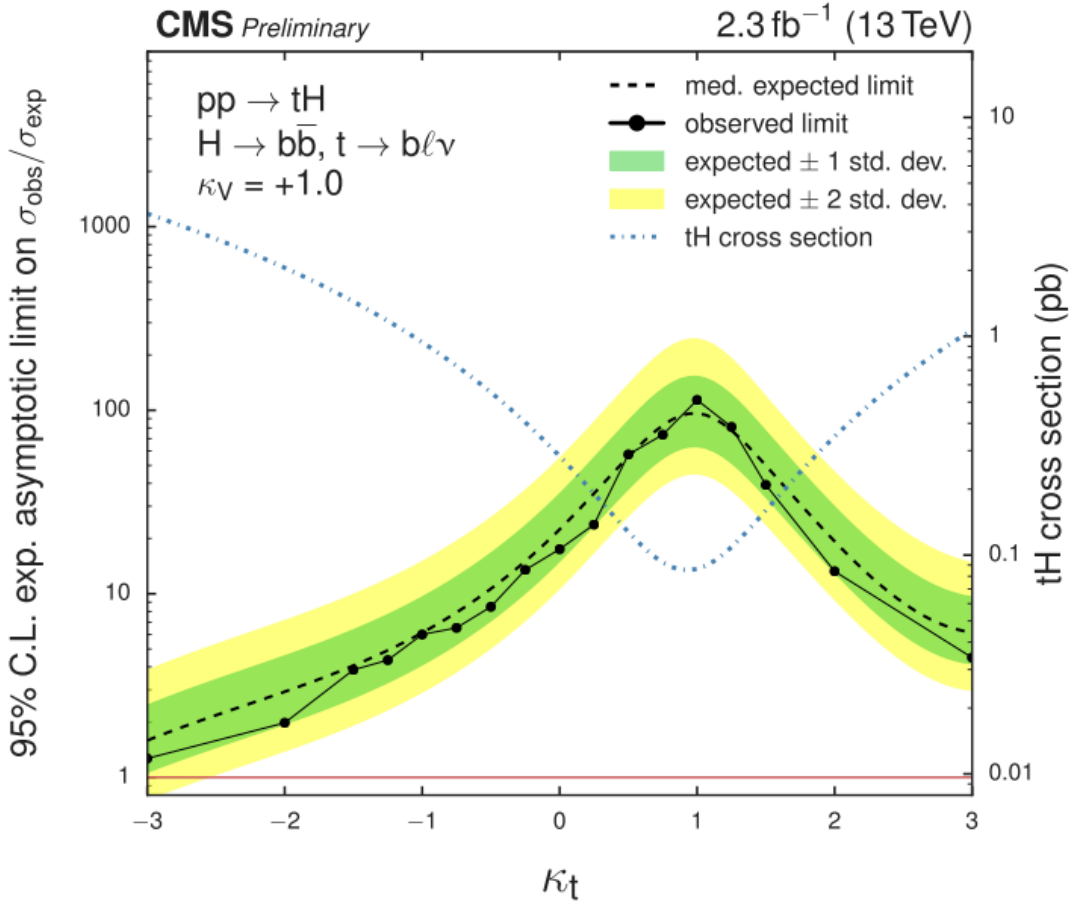


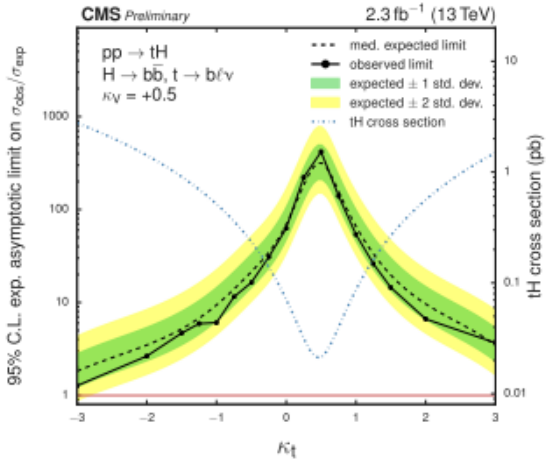


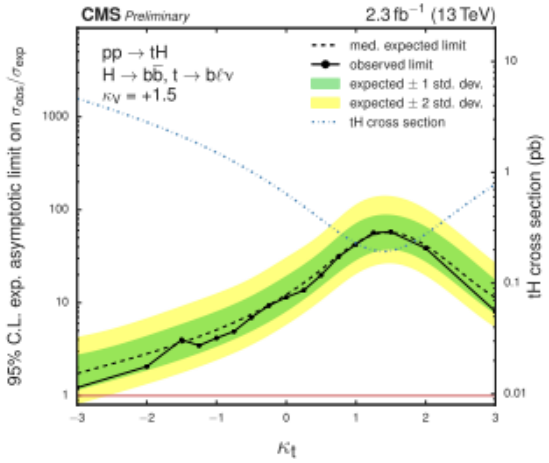
Exclusion limits at 95% C.L.

HIG-16-019

- **Upper limits @95% CL provided on tH scenarios with different k_V = [0.5 ; 1.0 ; 1.5] together with the tH cross sections**
  - **Observed (expected) limit for SM is 113.7 (98.6) times the predicted value, and 6.0 (6.4) with negative Yukawa coupling of the top quark**







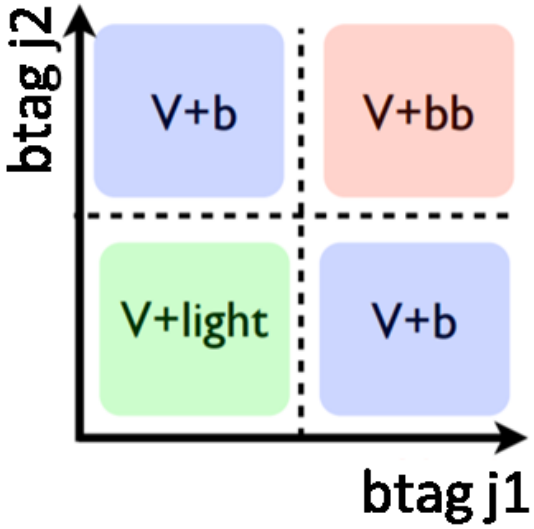
VH and VBF discussion topics

- **VH and VBF are particularly relevant for Higgs decaying to b quarks**
  - **But not only**

- **Recent, dedicated studies included in the Yellow Report 4 from the LHC Higgs Cross Section Working Group (arXiv:1610.07922)**
  - Differential NNLO QCD corrections combined with NLO EWK for both VH and VBF
    - VBF corrections are not negligible, need to be properly incorporated in the experimental analysis
    - NNLOPS for VH soon available
  - Updated cross section for gluon induced ZH at NLO+NLL
    - ggZH contribution relevant in the boosted regime, LO prediction available also at generator level, higher order corrections large (factor 2) but only available as inclusive
  - Distribution of central jets for VBF Higgs
    - Central jet veto aimed at increasing the discrimination power with respect to ggH
  - Systematic uncertainties due to parton shower modelling in VH
    - To be extended to background modelling

Background scale factors in VH(bb)

- **VH(bb) events categorized by number of leptons and V pT**
- **Main irreducible background is V+jets, arising from real b and misidentified jets (charm/light)**
- **Data/MC agreement checked in control regions enriched in 0, 1, or 2 b-jets**
  - Residual normalization differences treated as background scale factors, and propagated to the signal region
- **No unique approach between ATLAS and CMS**
  - Sub-processes V+bb, V+b, V+light either treated as independent or correlated, different systematic uncertainties assigned



	CMS Run-I	ATLAS Run-I
Floating parameter	μ_{V+bb} μ_{V+b} $\mu_{V+light}$	μ_{V+bb} μ_{V+cl}
Constrain with prior	-	μ_{V+cc} / μ_{V+bb} μ_{V+bc} / μ_{V+bb} μ_{V+bl} / μ_{V+bb} μ_{3jet} / μ_{2jet}

Sensitive to s/c quark PDF

Uncorrelated between categories

Summary

- Using **2015 data CMS** has updated the **H→bb search** in the VBF production mode
  - Measurement of the signal strength agrees with the SM expectation, no significant excesses or deviations can be reported… yet

- A specialized **analysis of single top plus H→bb** has set limits at the 95% C.L. for the SM scenario and inverted k_{top} coupling for k_V coupling between 0.5 and 1.5 times the SM
  - Sensitivity similar to Run1 results (tHW now treated as signal)

- Using the full 2016 dataset and combining with Run1 data **expected significance for VH > 3σ**
  - Points for discussion between experimental and theory communities

Backup

Bibliography

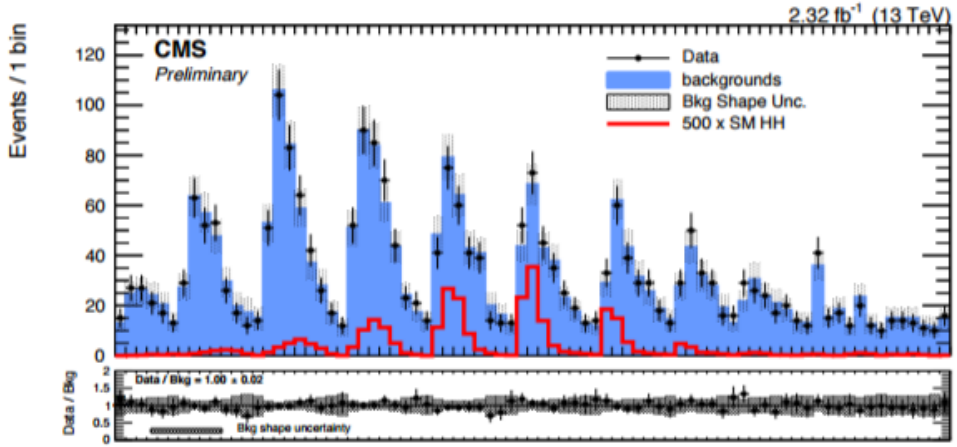
- HIG-15-002 – LHC Run1 combination
- HIG-14-004 – Run 1 VBF Hbb with final Hbb combination
- HIG-16-003 – VBF with 2015 data
- HIG-16-019 – Single top plus SM Hbb with 2015 data

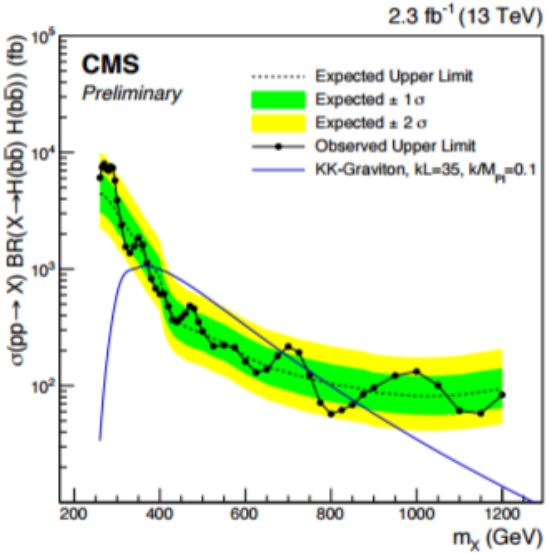
di-Higgs→bb bb

CMS PAS HIG-16-026
CMS PAS HIG-16-002

- ✓ Non-Resonant production:
  - binned shape fit to the 2D $m(b_1b_2)$, $m(b_3,b_4)$ distribution
  - Pairing chosen minimizing $|m(b_ib_j) - m(b_nb_m)|$
- ✓ Resonant production:
  - Search for model independent narrow-width resonance.
  - Triggers with online b-tagging for multi-jet background rejection.
  - Invariant mass of 4 b-tagged jets used for signal extraction.

Non-Resonant production



Category	Observed	Expected	-2σ	-1σ	$+1\sigma$	$+2\sigma$
			[fb]			
SM $H(b\bar{b})H(b\bar{b})$	3880	3490	2140	2540	5350	8350

Resonant production