Higgs Boson Measurements in Fermionic Decay Modes

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On behalf of the ATLAS and CMS collaborations

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Higgs Couplings to the SM particles

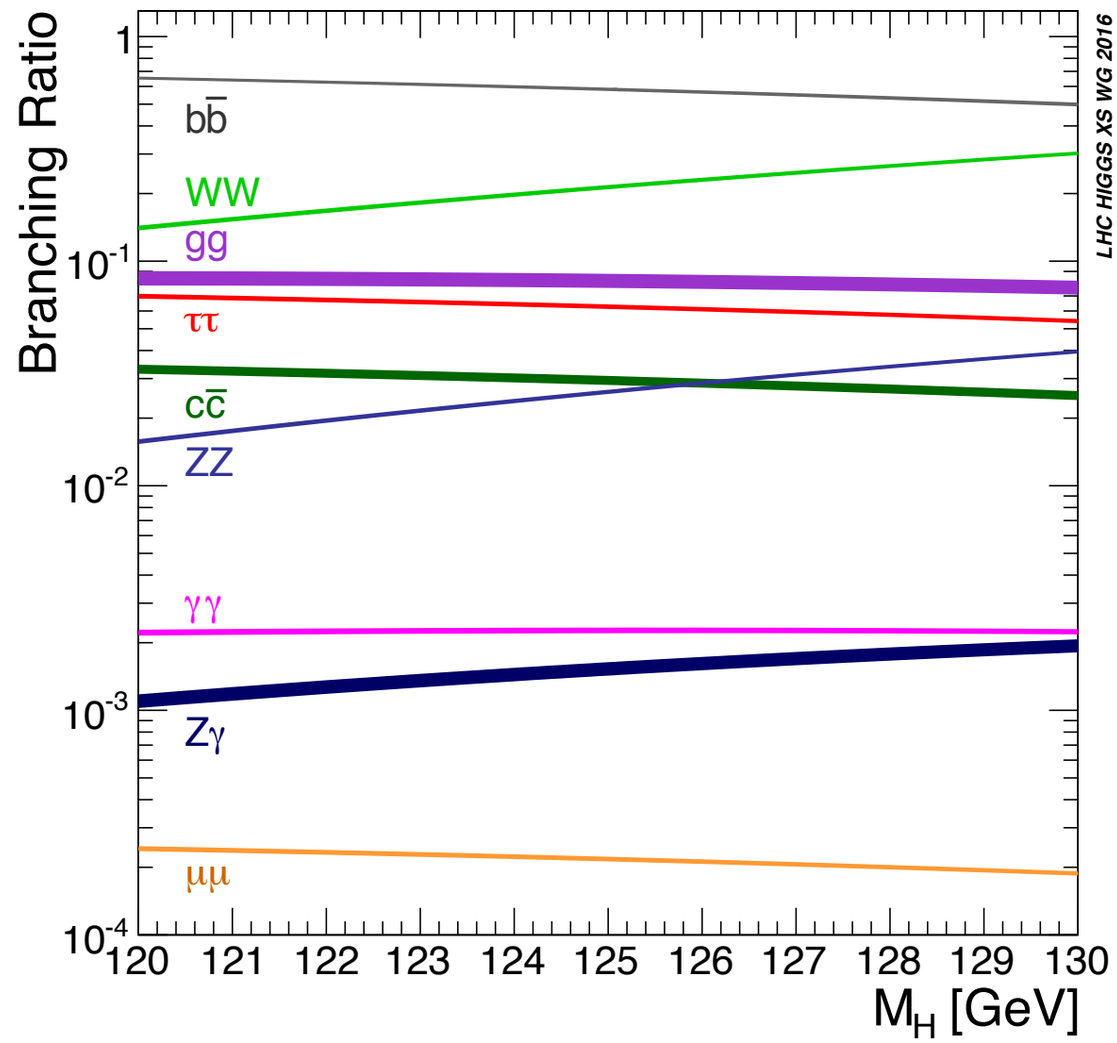
- In the standard model the Higgs mechanism provides mass to vector bosons
  - Fermions acquire mass via Yukawa interactions with the Higgs boson
- The SM predicts coupling between Higgs and bosons (fermions) proportional to M_V^2/v (M_f/v)

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\Psi} \not{D} \Psi + h.c.$$

$$+ \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c.$$

$$+ |D_\mu \phi|^2 - V(\phi)$$



Higgs Couplings to Fermions

- What we know so far:
  - By a single experiment Higgs was observed in decays to vector bosons
  - Higgs mass is measured to be ~125 GeV with 0.2% unc.
  - Pure scalar is favored with width less than 20 MeV at 95%CL
  - Our best knowledge of couplings as of at the end of Run I

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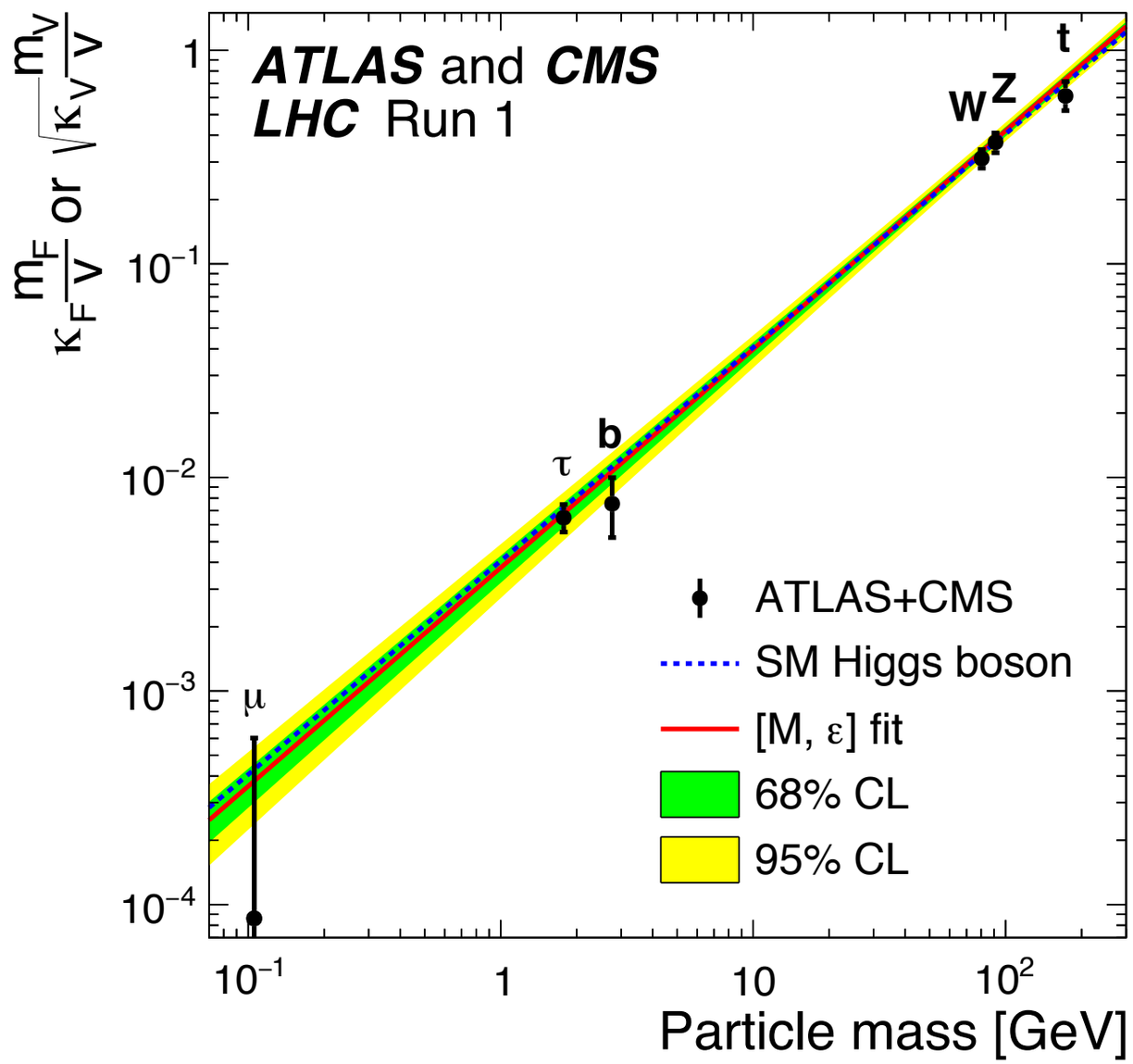
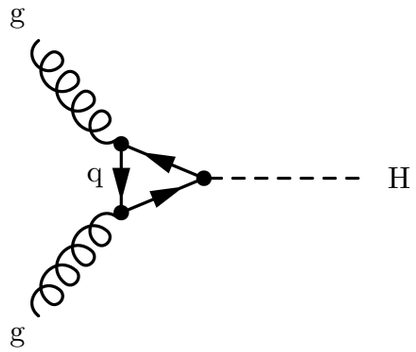
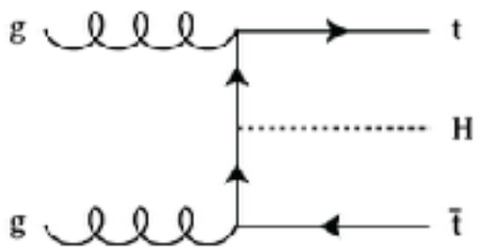


- Direct decay to fermions allow to probe Higgs Yukawa coupling independently from loop effects
  - Measurements of Higgs to fermions couplings are challenging
  - Any deviation from the SM prediction would hint to new phenomena

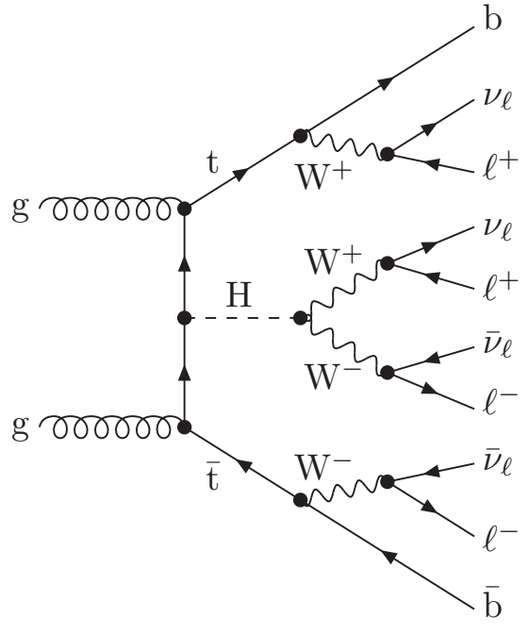
Higgs Coupling to Top Quark

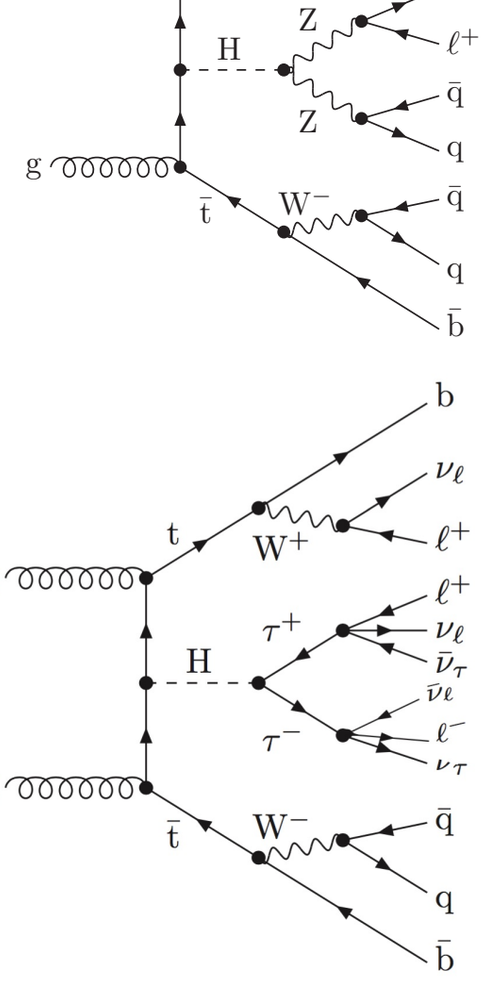
- Coupling to top quark can be probed via indirect and direct





- Use different decay modes
  - Multilepton: H→WW, ZZ, ττ, where τ→ℓνν



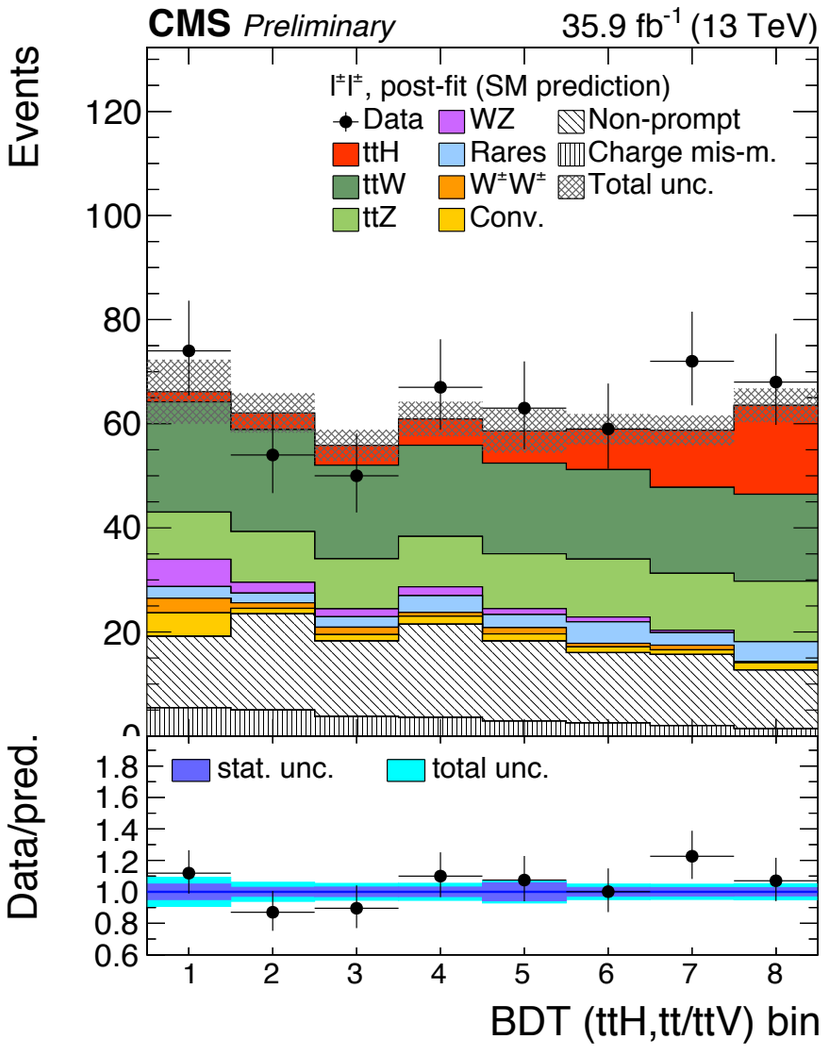


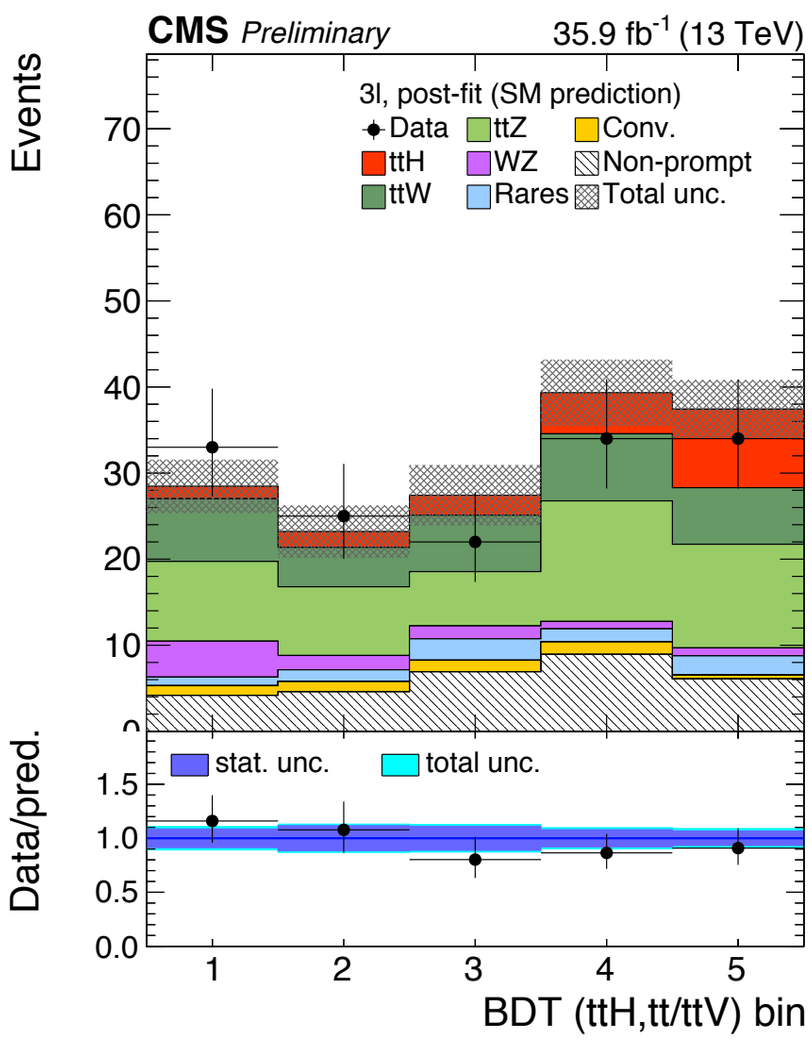
ttH with Multilepton Final State

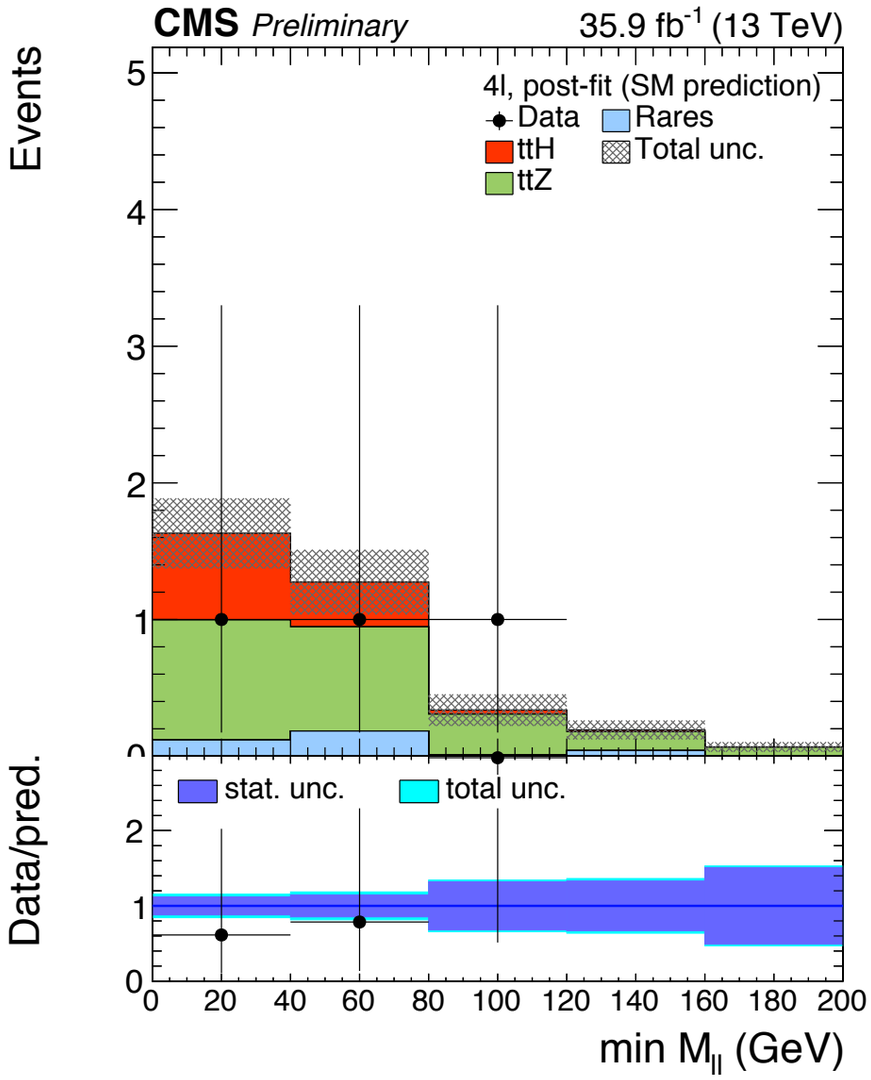
- Events are categorized by number of leptons

CMS-PAS-HIG-17-004

  - BDT is used to extract signal in high stats regions
  - Simpler approach is used in statistics limit 4ℓ category

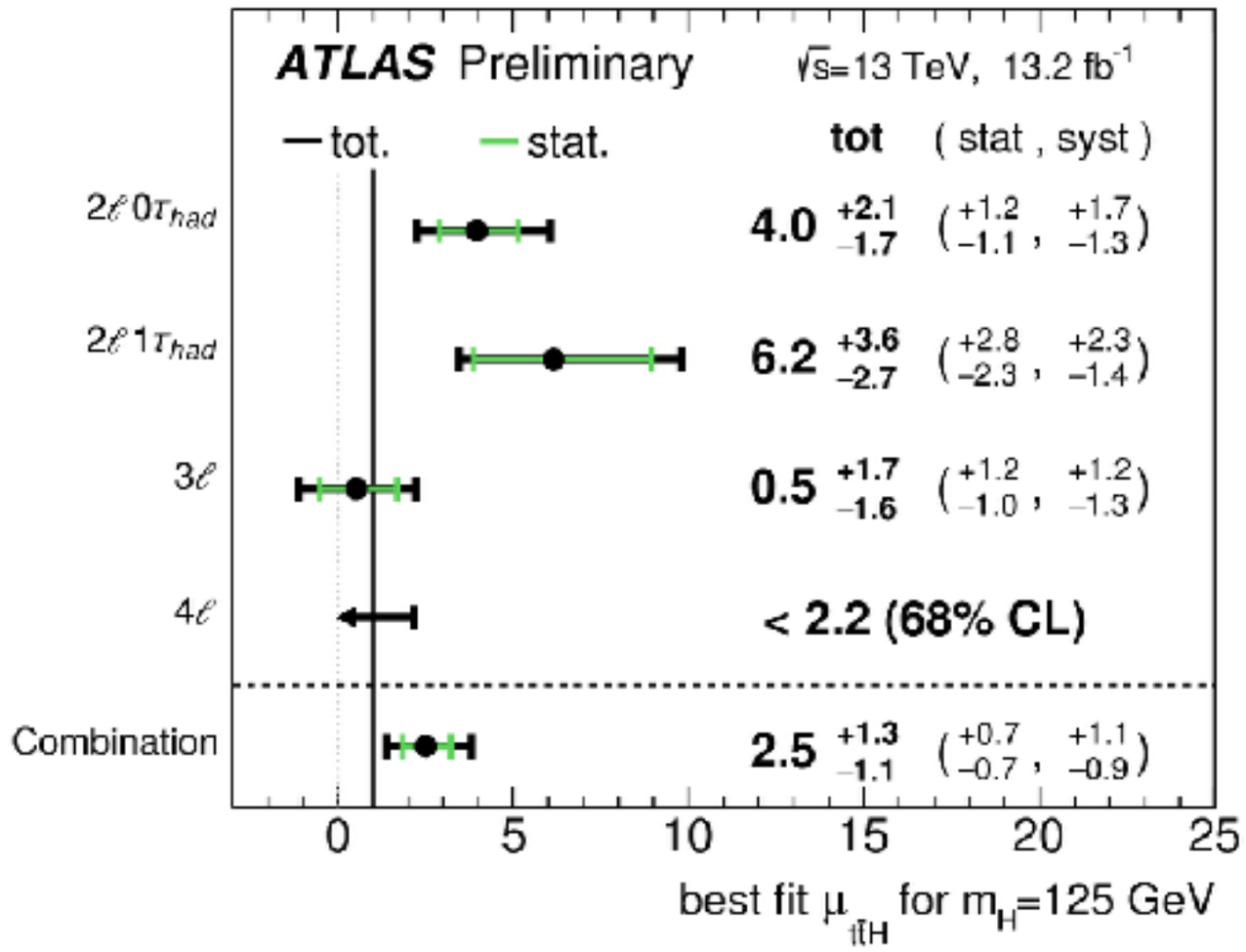


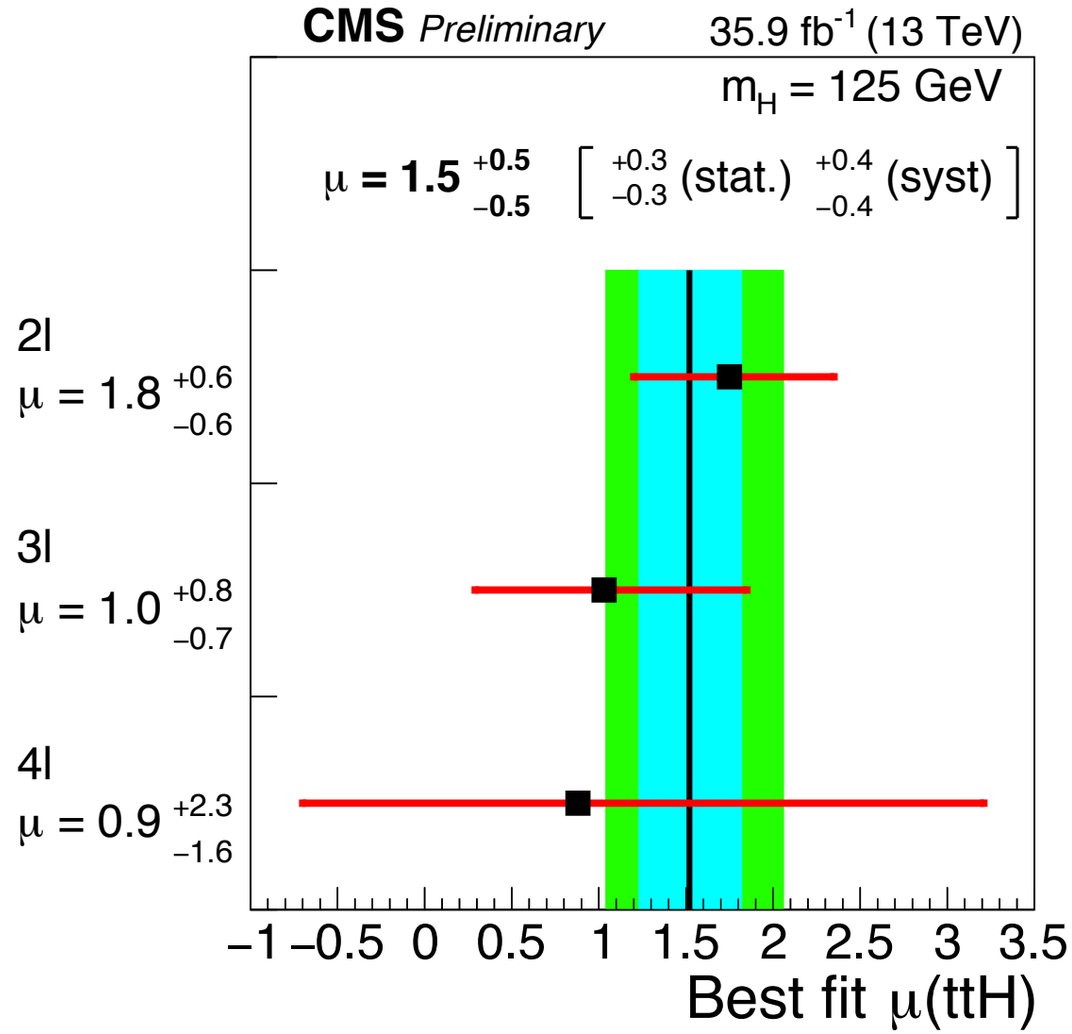




ttH with Multilepton Final State

ATLAS-CONF-2016-058
CMS-PAS-HIG-17-004





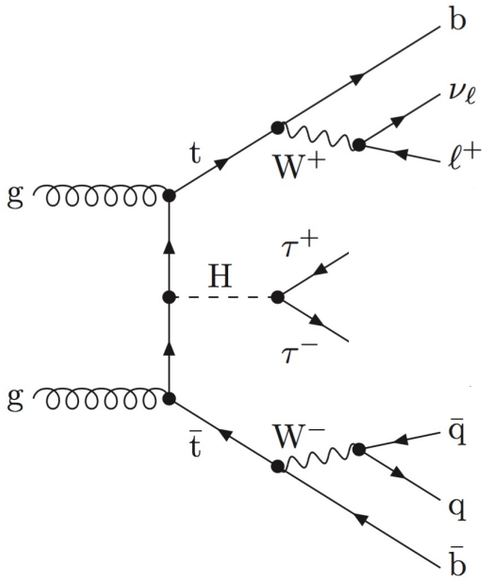
Combined results correspond to observed (expected) significance of 3.3σ (2.5σ)

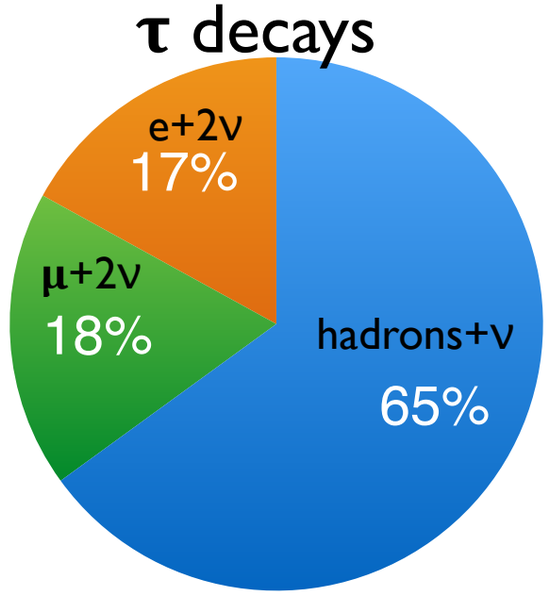
Category	Observed μ fit $\pm1\sigma$	Expected μ fit $\pm1\sigma$
Same-sign di-lepton	$1.7\,(-0.5)\,(+0.6)$	$1.0\,(-0.5)\,(+0.5)$
Three lepton	$1.0\,(-0.7)\,(+0.8)$	$1.0\,(-0.7)\,(+0.8)$
Four lepton	$0.9\,(-1.6)\,(+2.3)$	$1.0\,(-1.6)\,(+2.4)$
Combined (2016 data)	$1.5\,(-0.5)\,(+0.5)$	$1.0\,(-0.4)\,(+0.5)$
Combined (2015 data) [42]	$0.6\,(-1.1)\,(+1.4)$	$1.0\,(-1.1)\,(+1.3)$
Combined (2015+2016 data)	$1.5\,(-0.5)\,(+0.5)$	$1.0\,(-0.4)\,(+0.5)$

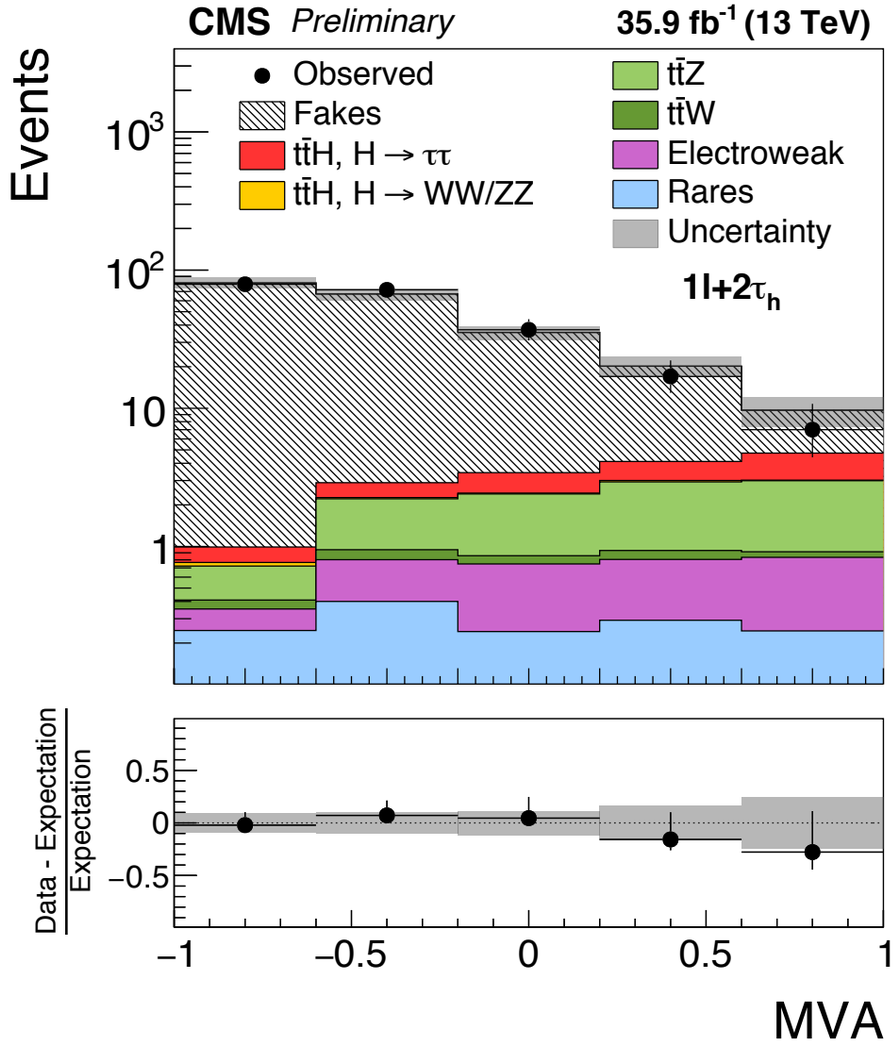
ttH with τ_h in final state

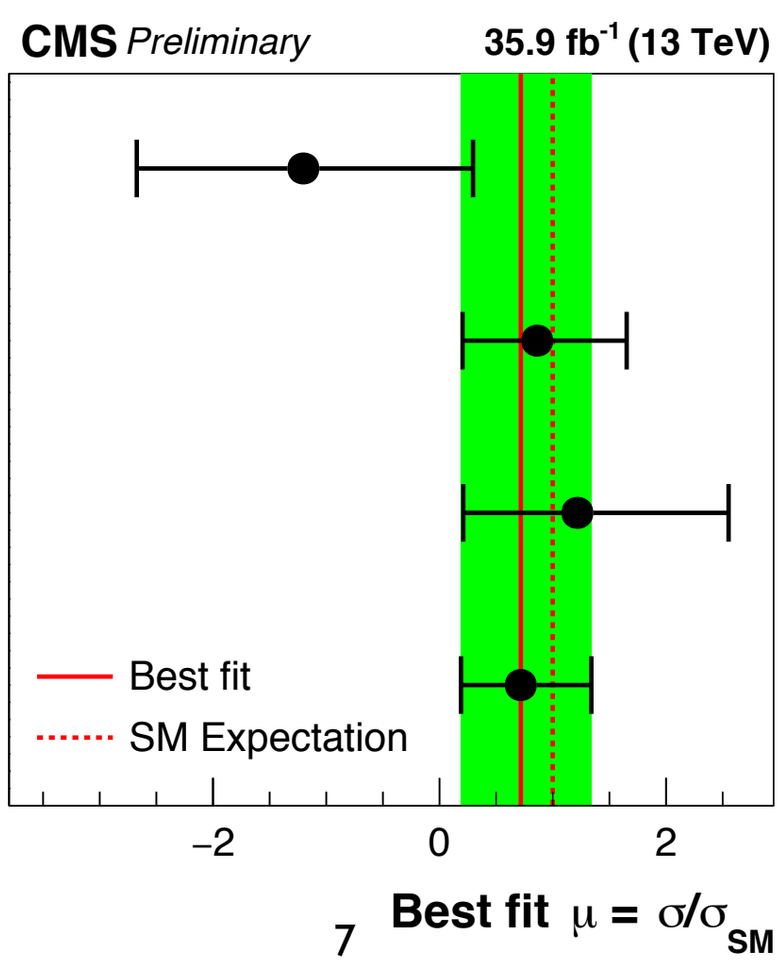
CMS-PAS-HIG-17-003

- Dedicated search involving τ_h
  - Categories: $1\ell 2\tau_h$, $2\ell 1\tau_h$, $3\ell 1\tau_h$
  - Using BDT or ME to discriminate between signal and backgrounds









1l+2τ_h
$\mu = -1.20^{+1.50}_{-1.47}$

2lss+1τ_h
$\mu = 0.86^{+0.79}_{-0.66}$

3l+1τ_h
$\mu = 1.22^{+1.33}_{-1.01}$

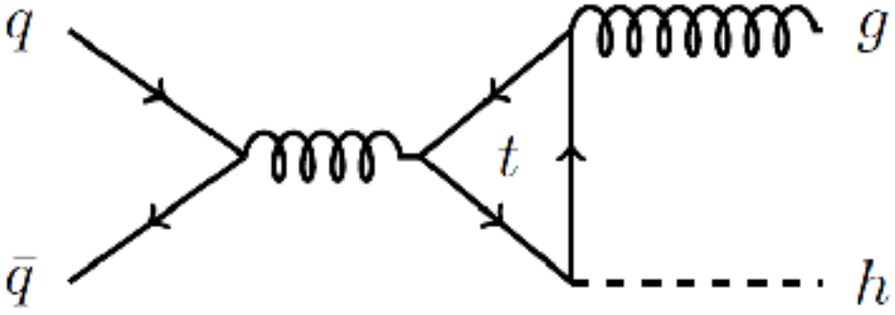
Combined
$\mu = 0.72^{+0.62}_{-0.53}$

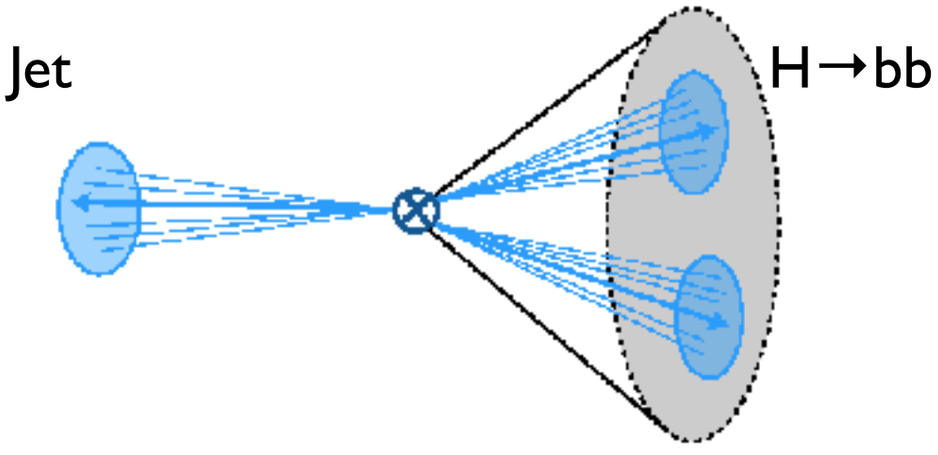
Significance
1.4σ (obs.)
1.8σ(exp.)

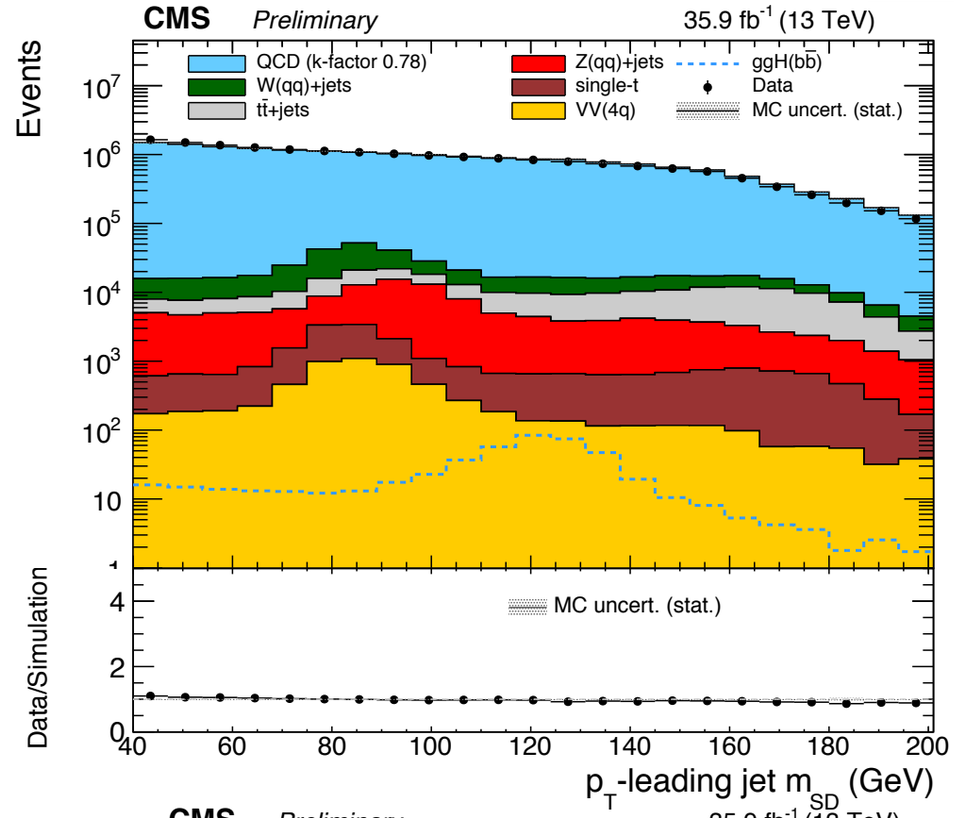
Boosted H→bb

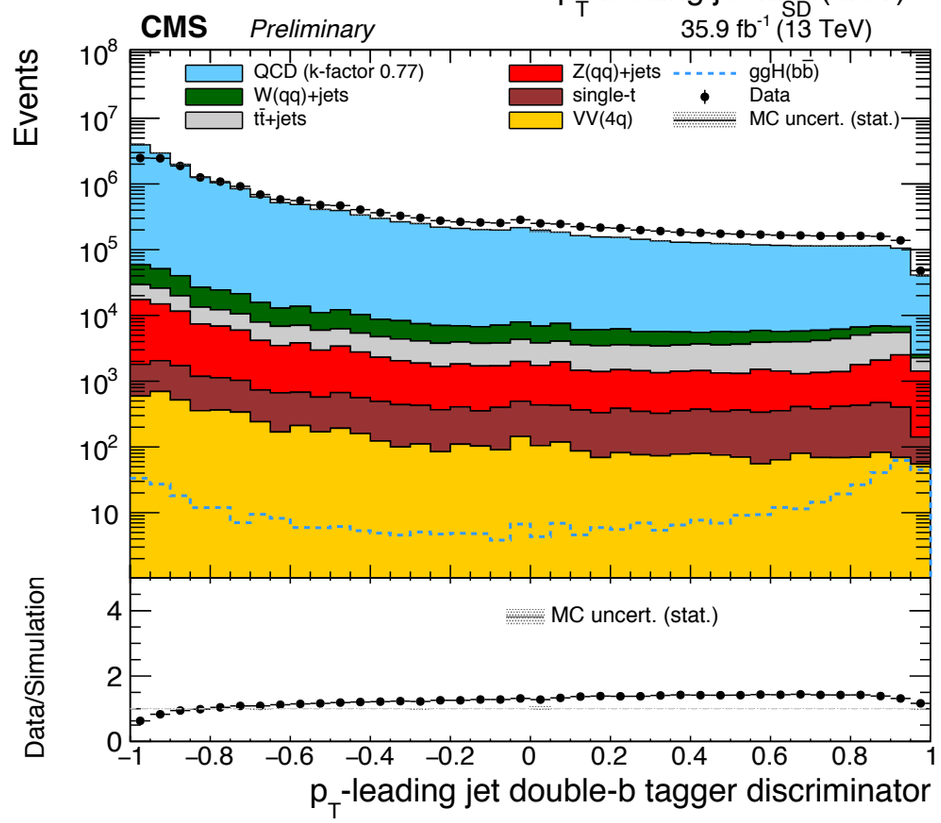
CMS-PAS-HIG-17-010

- Using boosted Higgs to directly probe top Yukawa coupling from gluon-gluon fusion production
  - Sensitive to new physics contribution



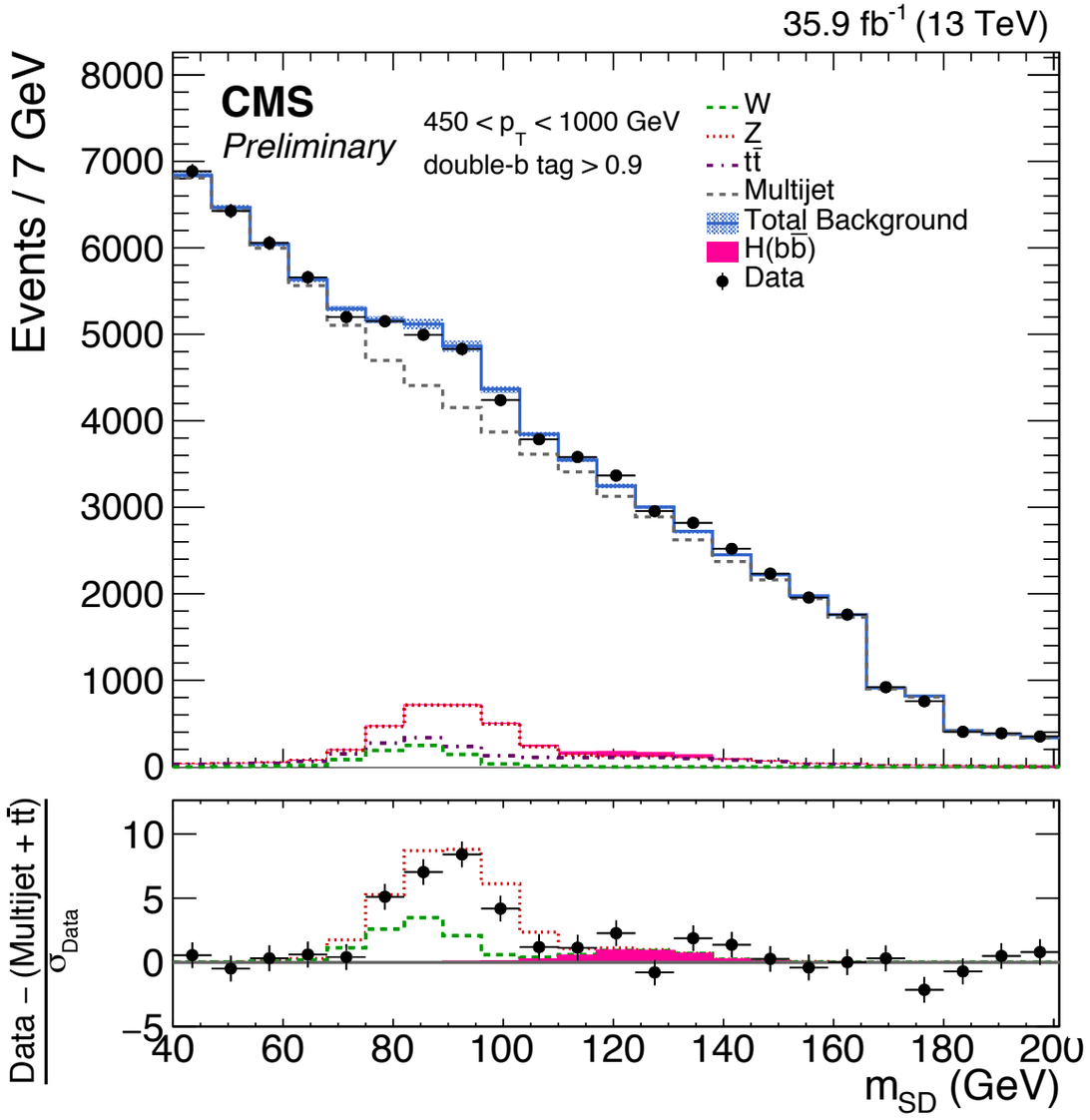


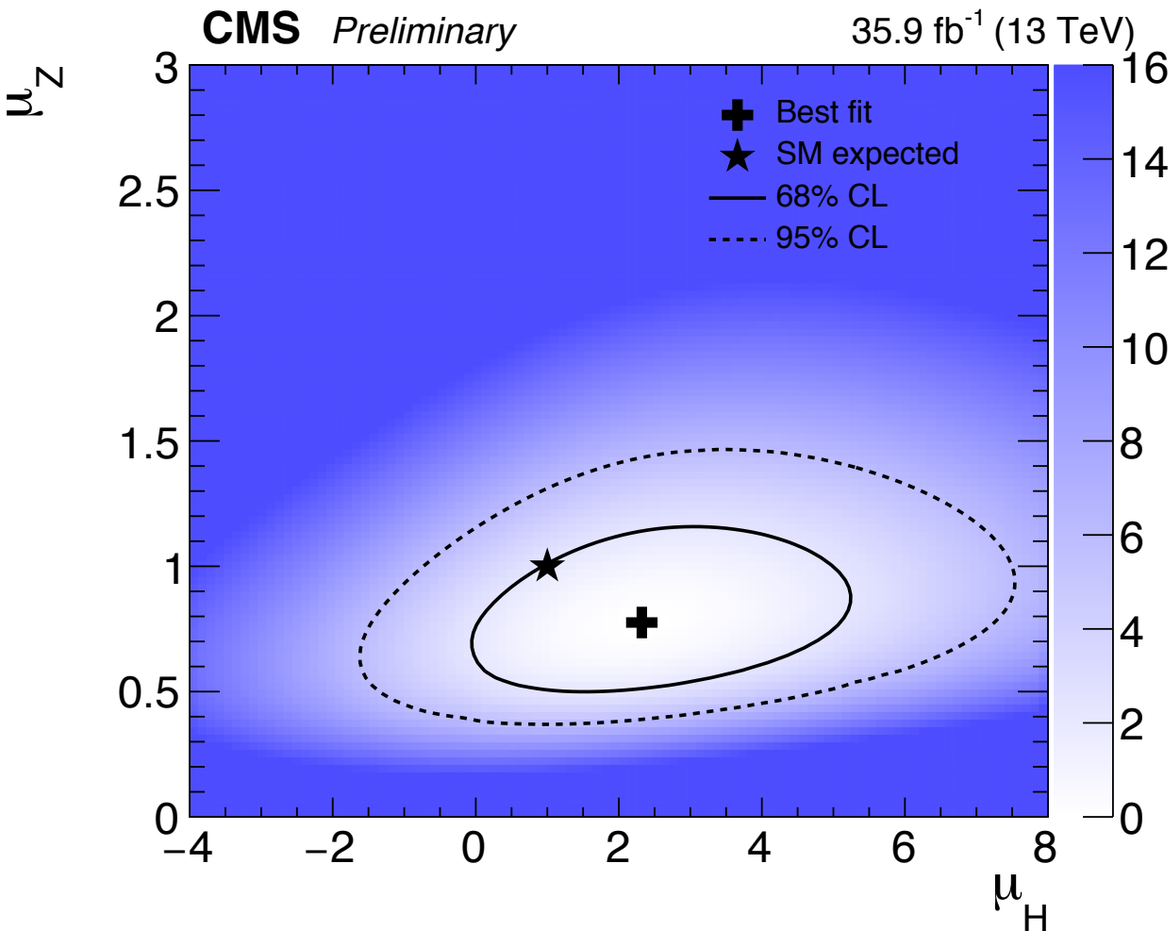




Boosted H→bb

CMS-PAS-HIG-17-010

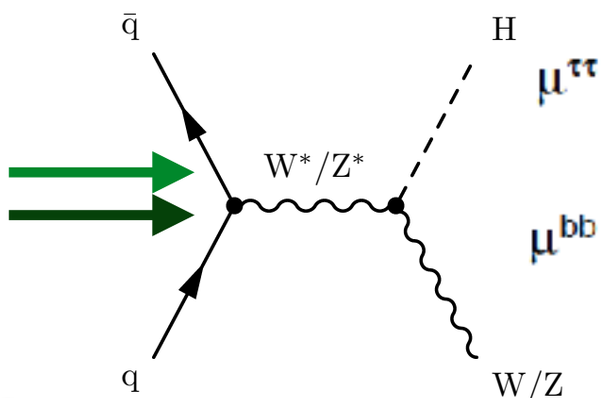




	H	H no p_T corrections	Z
Observed best fit	$\mu_H = 2.3^{+1.8}_{-1.6}$	$\mu'_H = 3.2^{+2.2}_{-2.0}$	$\mu_Z = 0.78^{+0.23}_{-0.19}$
Expected significance	0.7σ ($\mu_H = 1$)	0.5σ ($\mu'_{11} = 1$)	5.8σ ($\mu_Z = 1$)
Observed significance	1.5σ	1.6σ	5.1σ

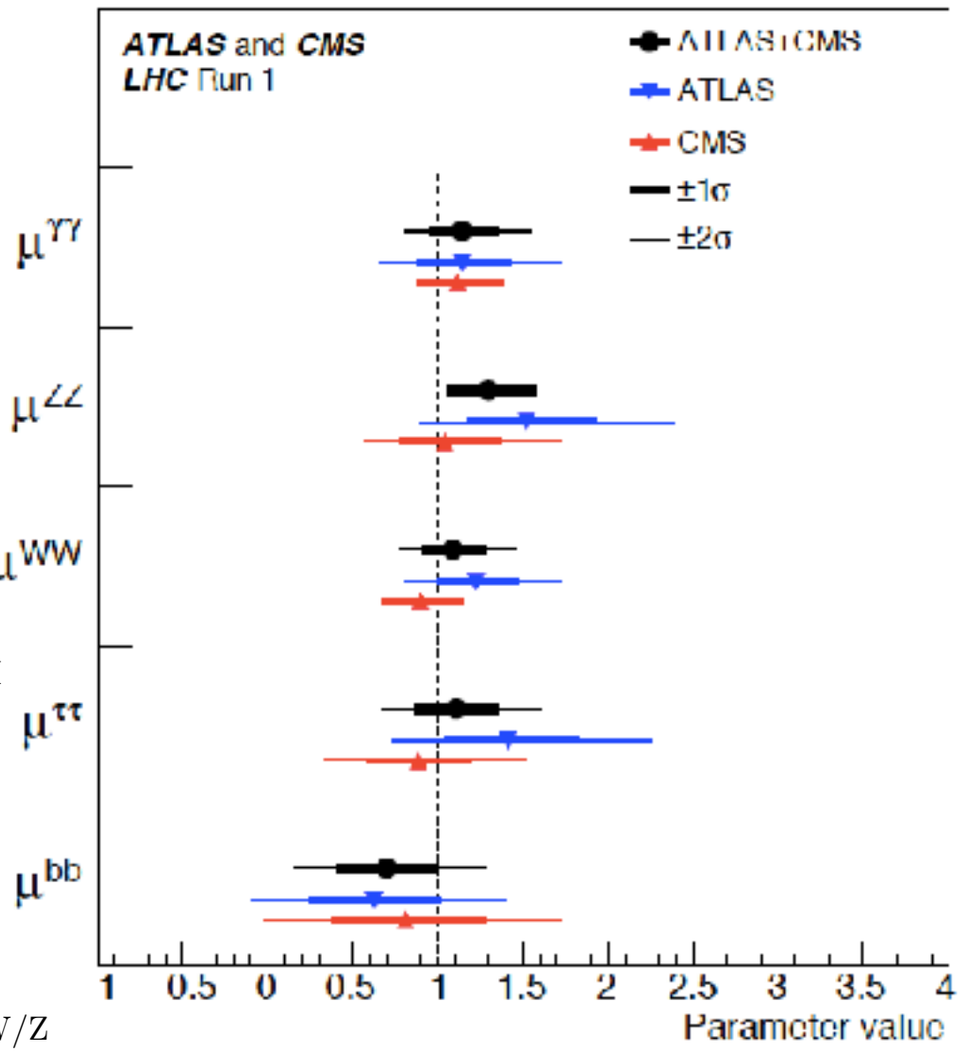
H→bb Decay

- H→bb decay
  - Largest decay rate
  - Direct probe of coupling to down type quarks
  - Best probe is using VH production



- At the end of Run I

Significance	Observed	Expected
H→bb	2.6	3.7

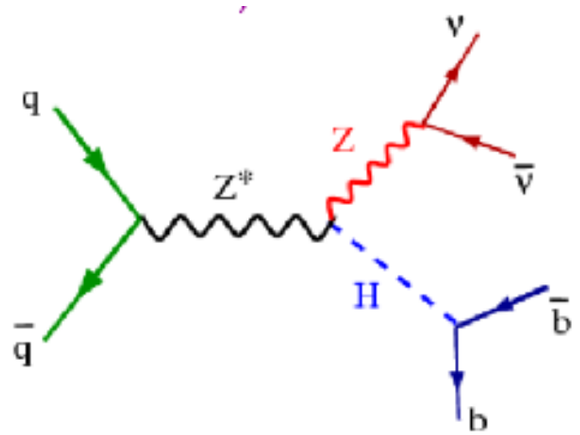


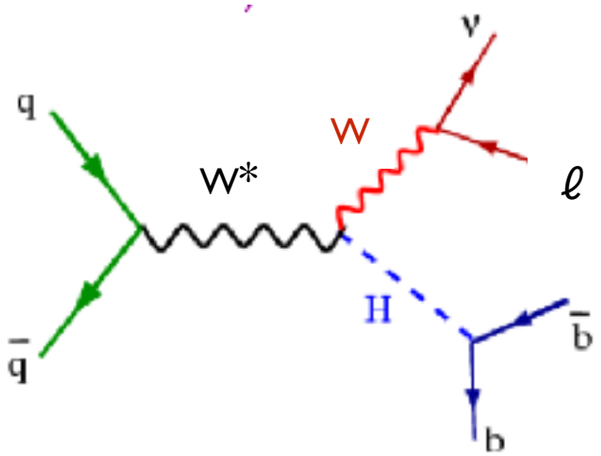
arXiv:1606.02266
JHEP08(2016)045

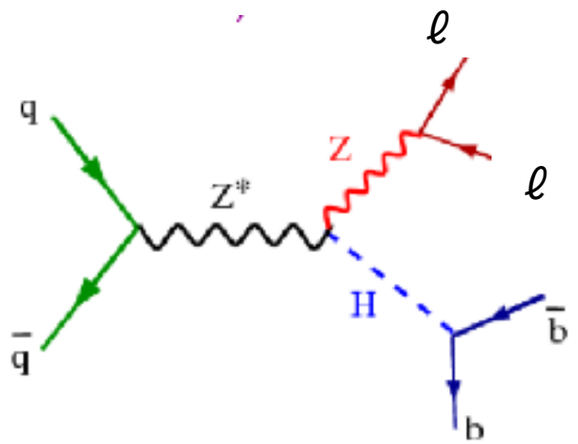
VH, H→bb

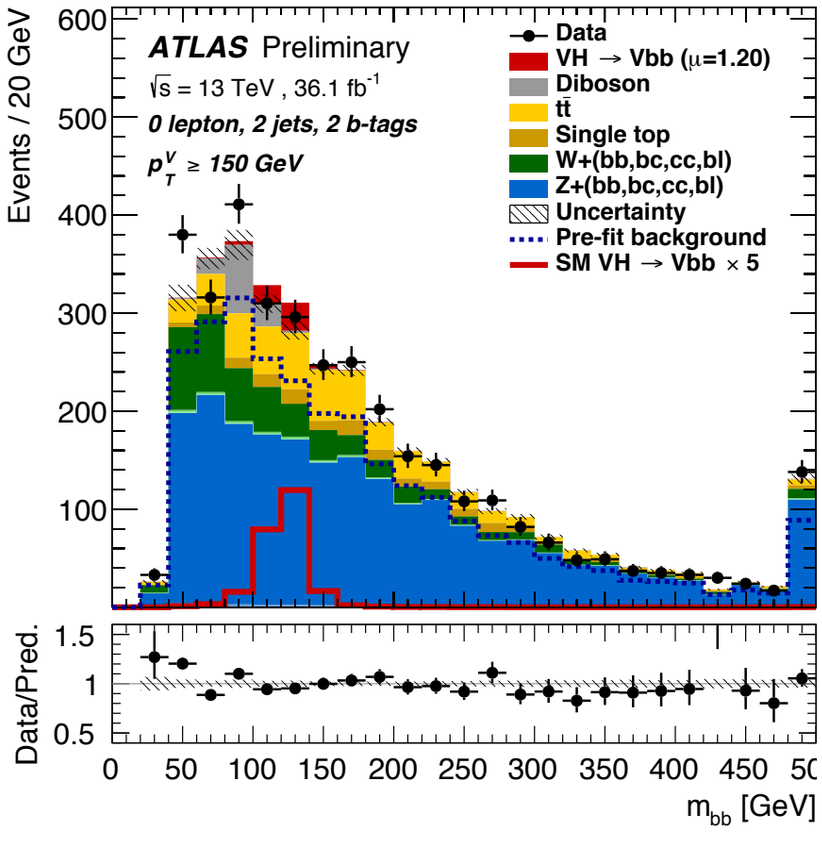
ATLAS-CONF-2017-041

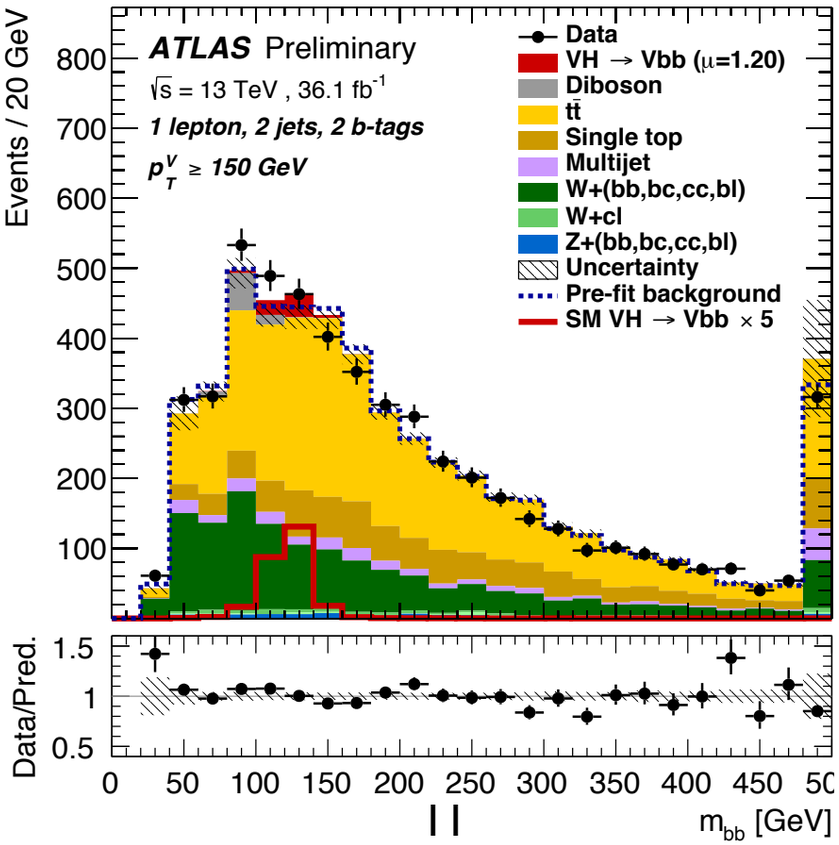
- Consider only leptonic decays of vector bosons for better background rejection
- Categorize events by p_T^V and number of jets

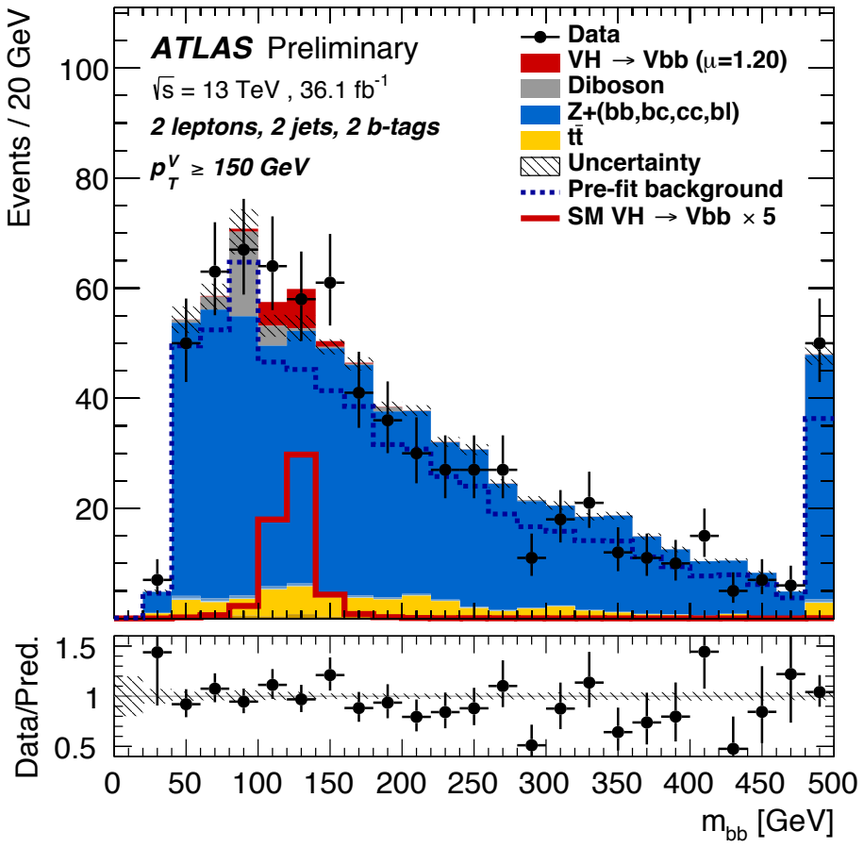












VH, H→bb

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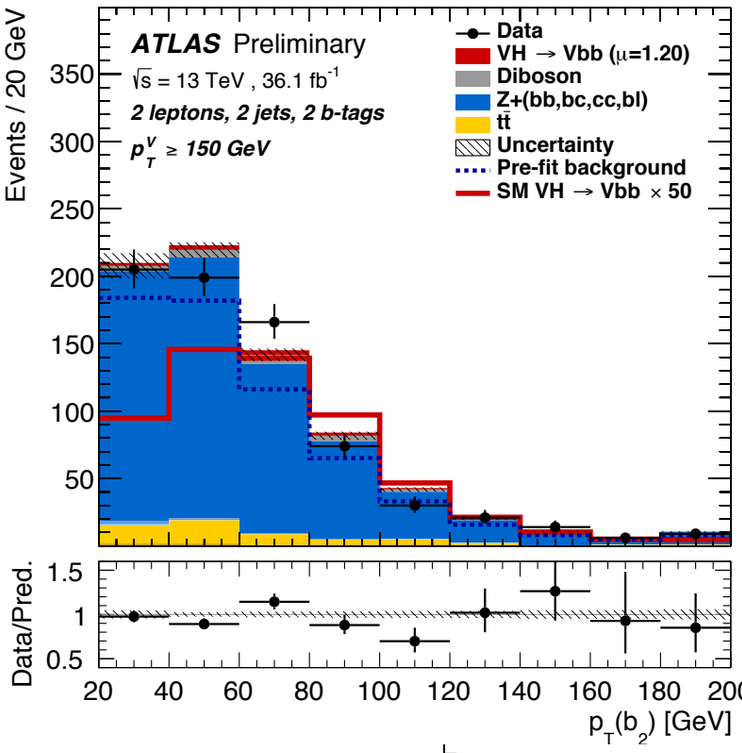
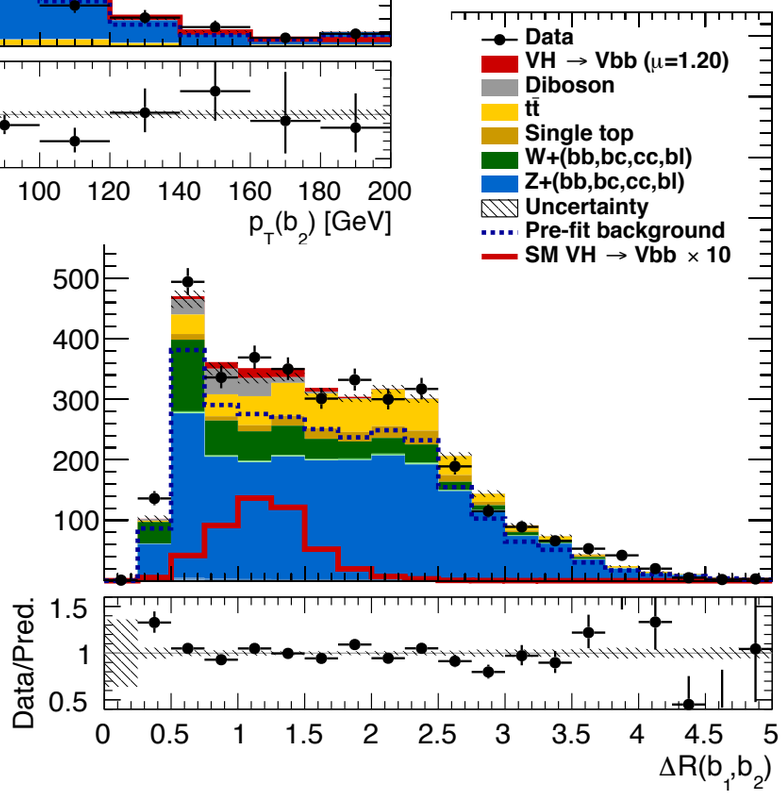
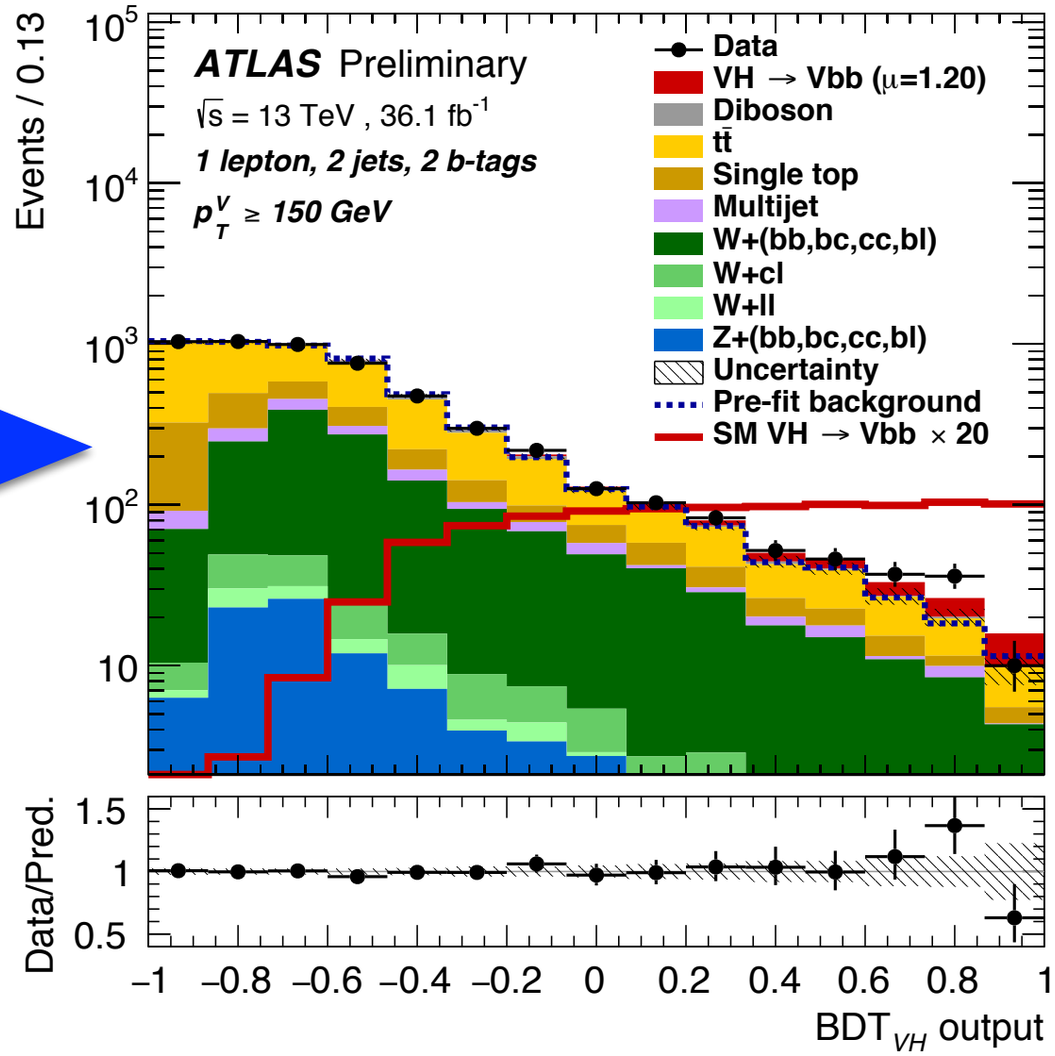
- Using BDT discriminator in each signal region
- Use number of background yields from control samples together with final distribution in signal region to perform simultaneous fit







VH, H→bb

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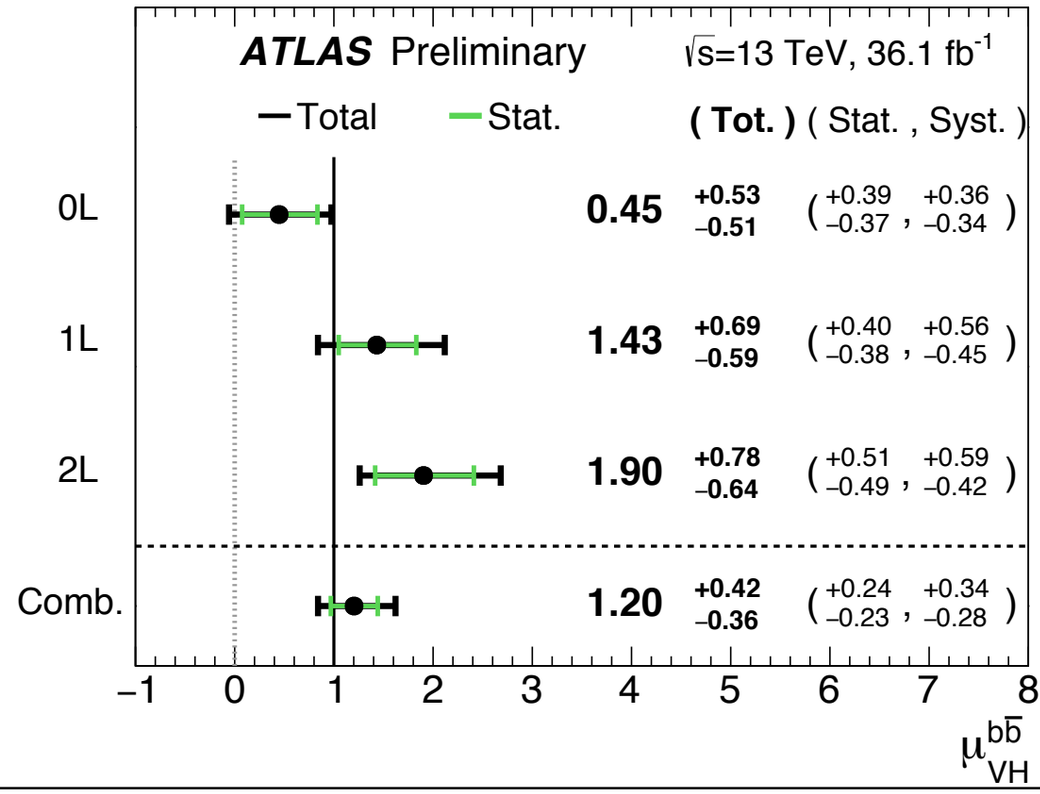
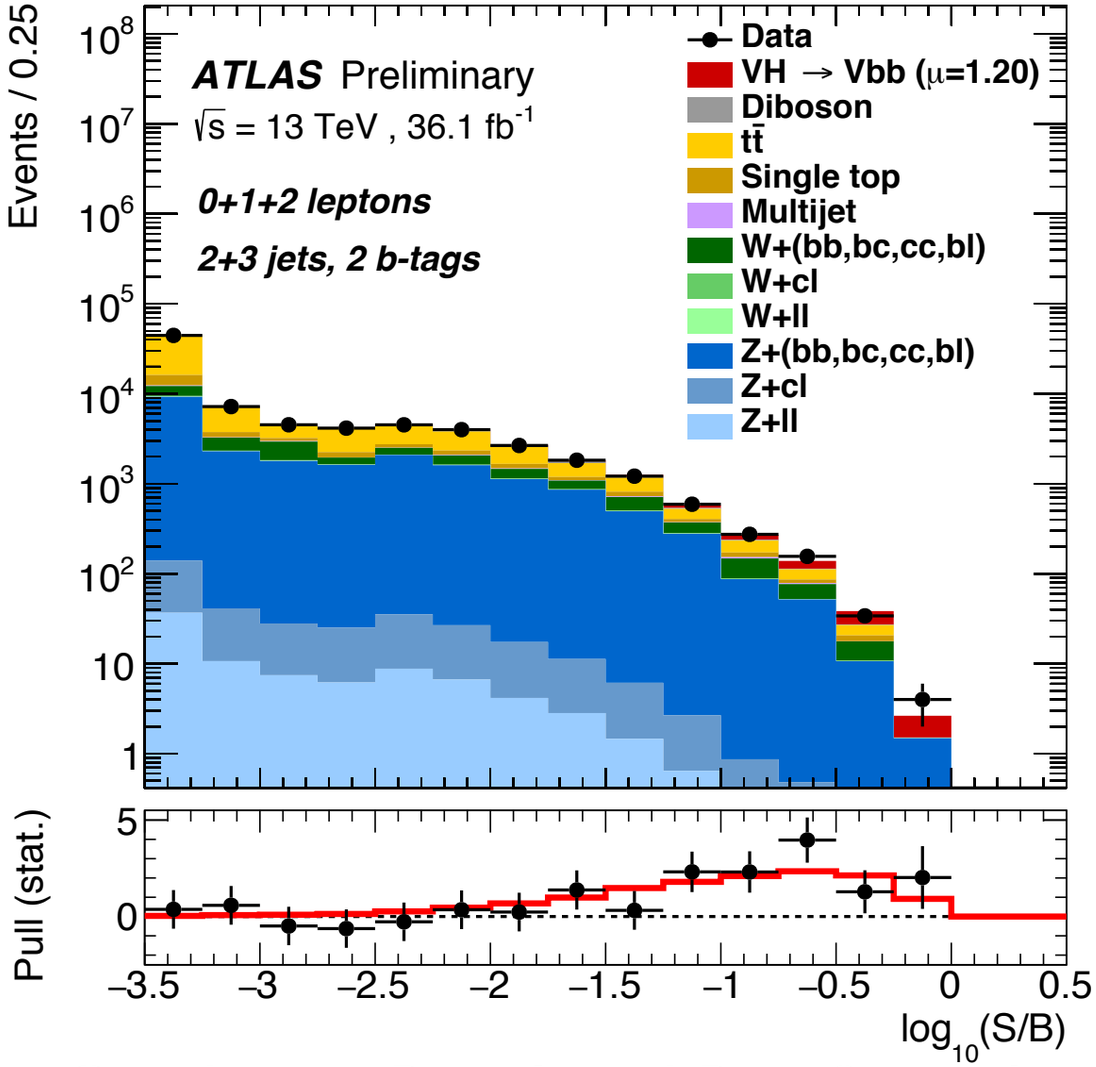


Dataset	p_0		Significance	
	Exp.	Obs.	Exp.	Obs.
0-lepton	4.2%	30%	1.7	0.5
1-lepton	3.5%	1.1%	1.8	2.3
2-lepton	3.1%	0.019%	1.9	3.6
Combined	0.12%	0.019%	3.0	3.5



Combining Run 1 and Run 2 results:

$$\mu = 0.90 \pm 0.18(stat.)^{+0.21}_{-0.19}(stat.)$$

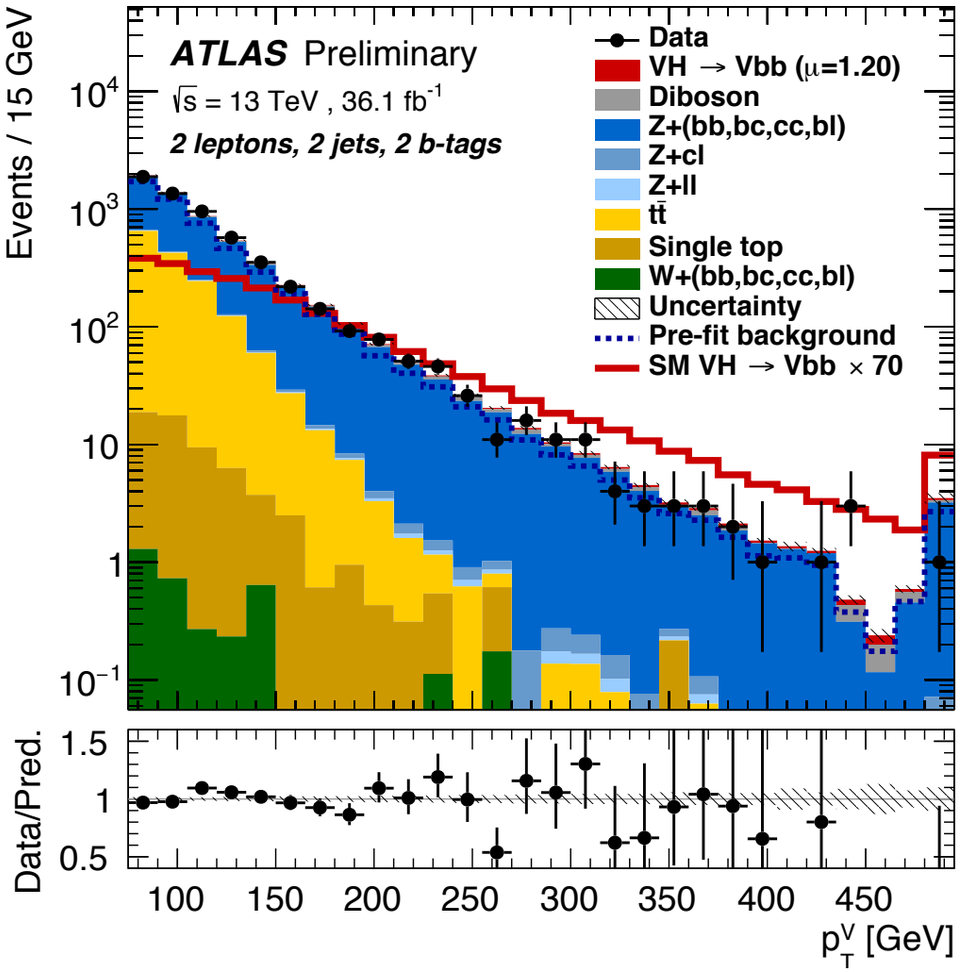
$$significance: \ 3.6\sigma(obs.), \ 4.0\sigma(exp.)$$

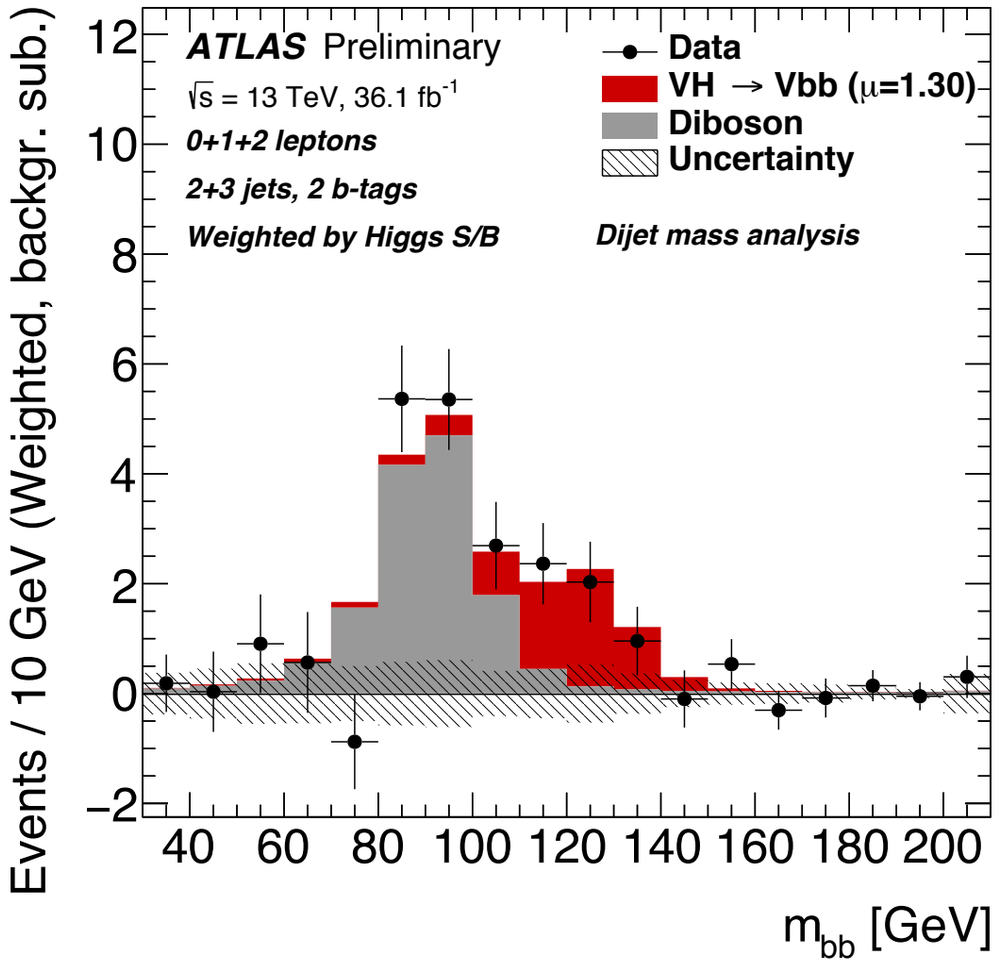
VZ, Z→bb signal is observed with $\mu = 1.11^{+0.12}_{-0.11}(stat.)^{+0.22}_{-0.19}(syst.)$ @ 5.8σ

VH, H→bb

ATLAS-CONF-2017-041

- Di-jet mass based analysis
  - Adjust final selection criteria to better discriminate signal from background





$$significance:\ 3.5\sigma(obs.),\ 2.8\sigma(exp.)$$

$$\mu = 1.30^{+0.28}_{-0.27}(stat.)^{+0.37}_{-0.29}(syst.)$$

VH, H→bb @ CMS

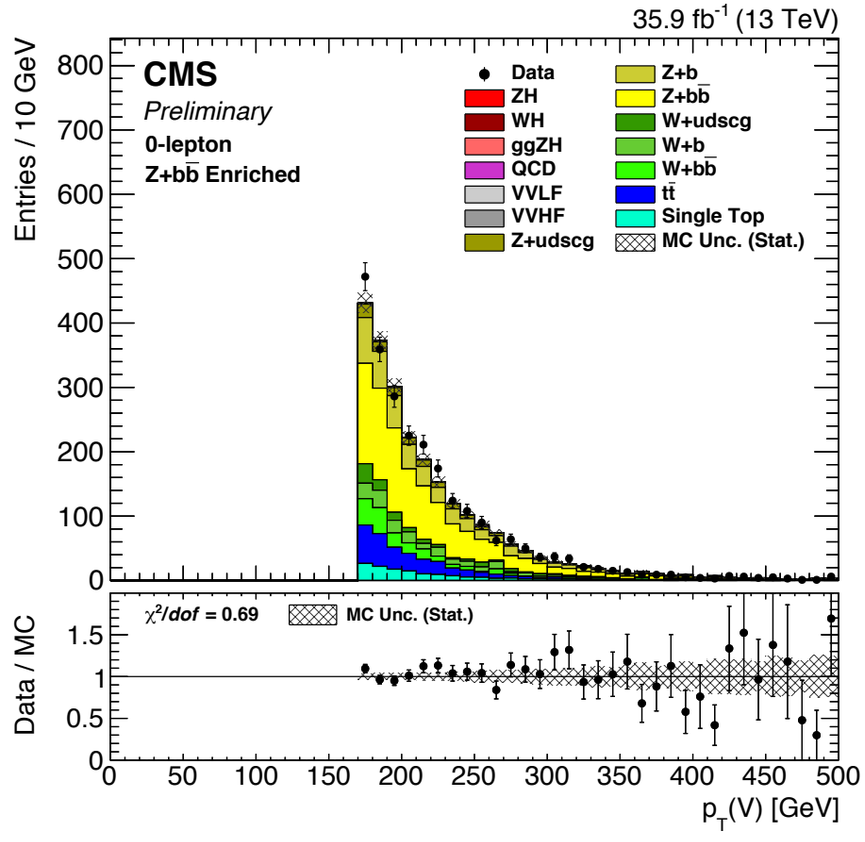
- Categorize events with number of leptons and p_T^V
- Define background control sample for each category and each type of background

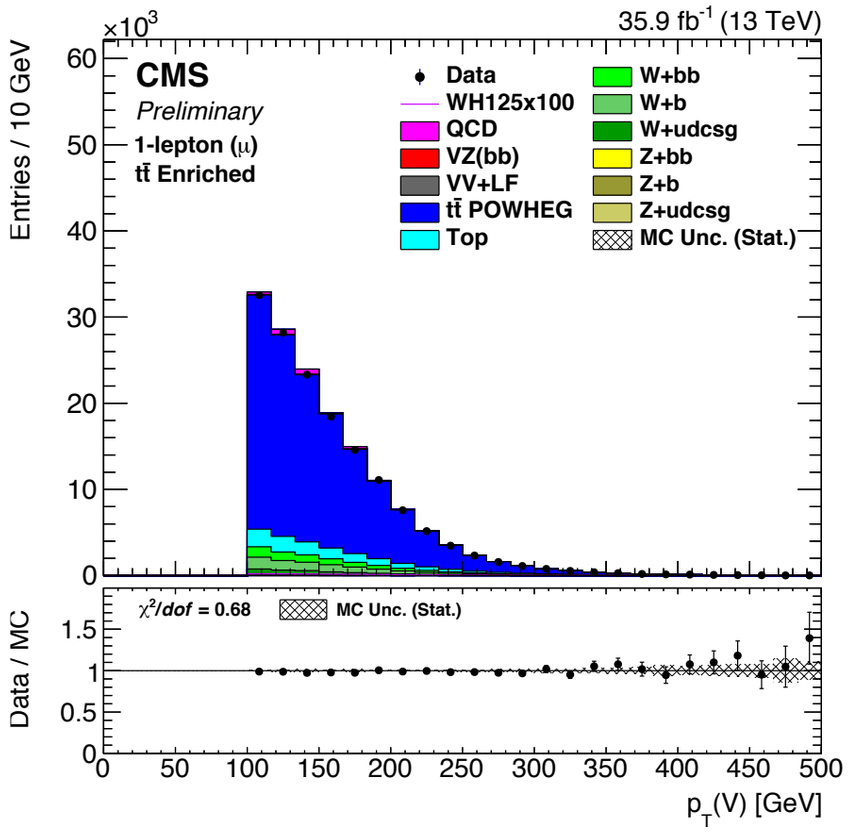
New CMS-PAS-HIG-16-044

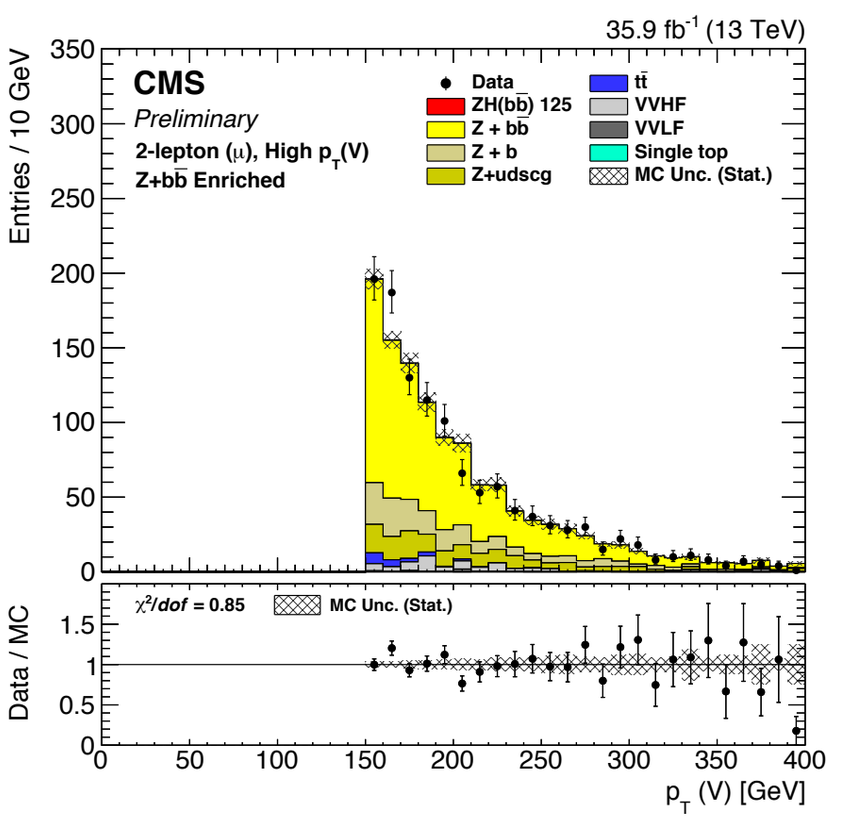
0 lepton:
ttbar, Z+LF, Z+HF

1 lepton:
ttbar, W+LF, W+HF

2 lepton:
ttbar, Z+LF, Z+HF







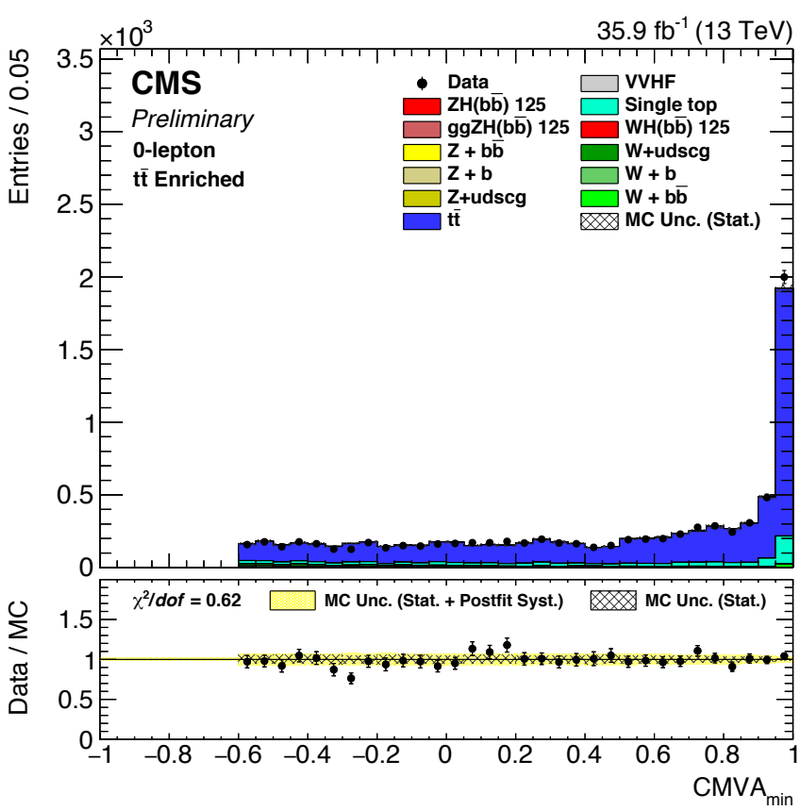
VH, H→bb @ CMS

- Distribution of b-tag discriminator of the second jet in background control sample is used in simultaneous fit in combination with final observable in signal region

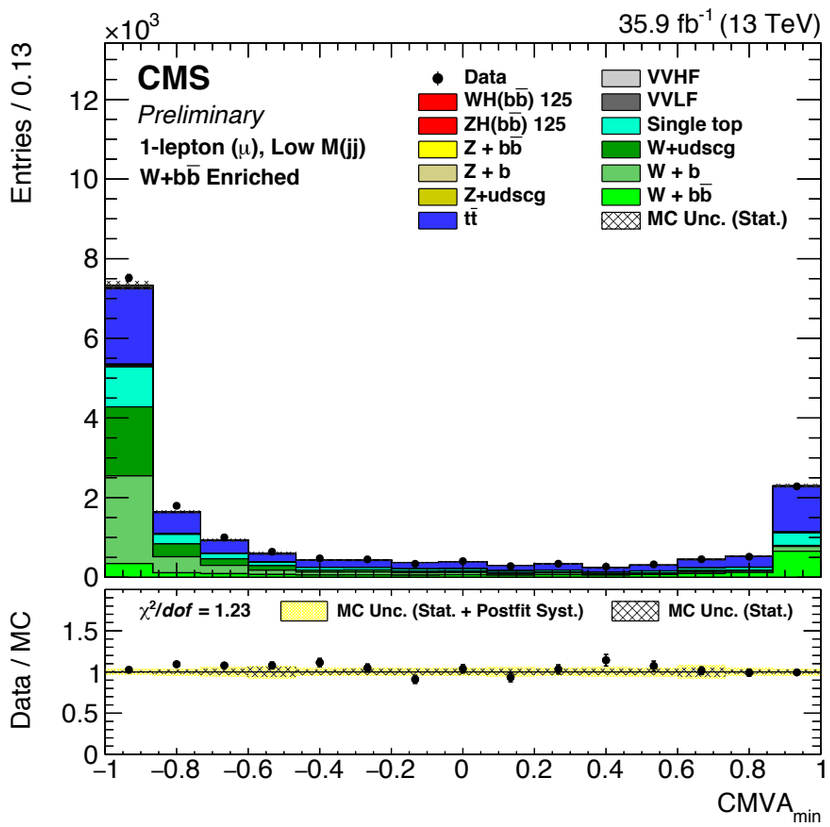
New

CMS-PAS-HIG-16-044

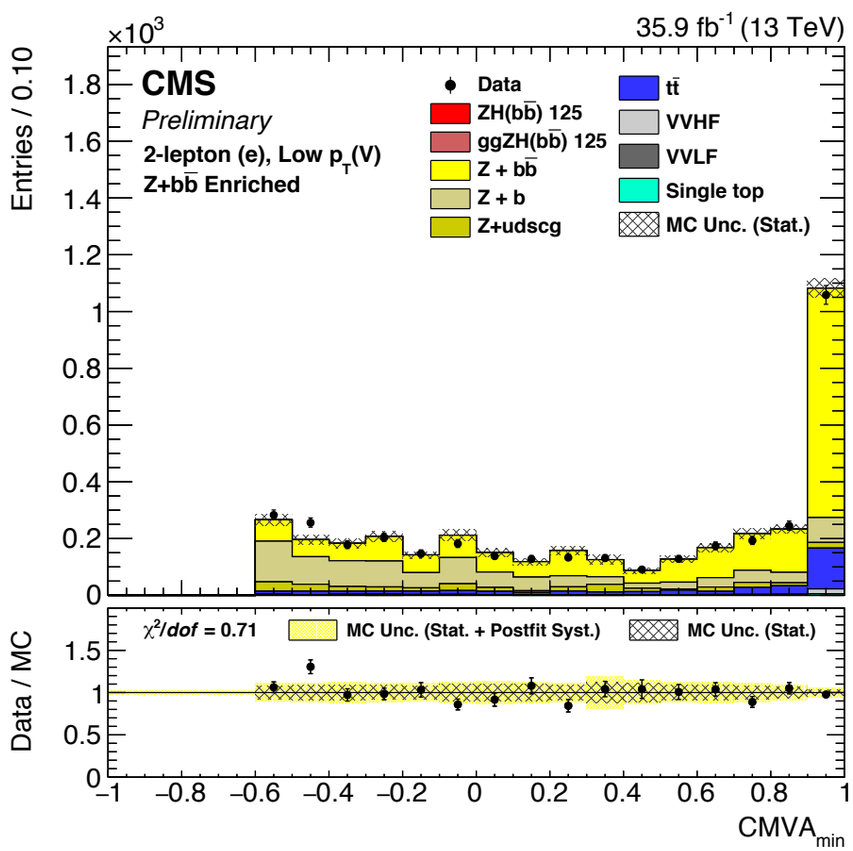
0 lepton:
ttbar, Z+LF, Z+HF



1 lepton:
ttbar, W+LF, W+HF



2 lepton:
ttbar, Z+LF, Z+HF

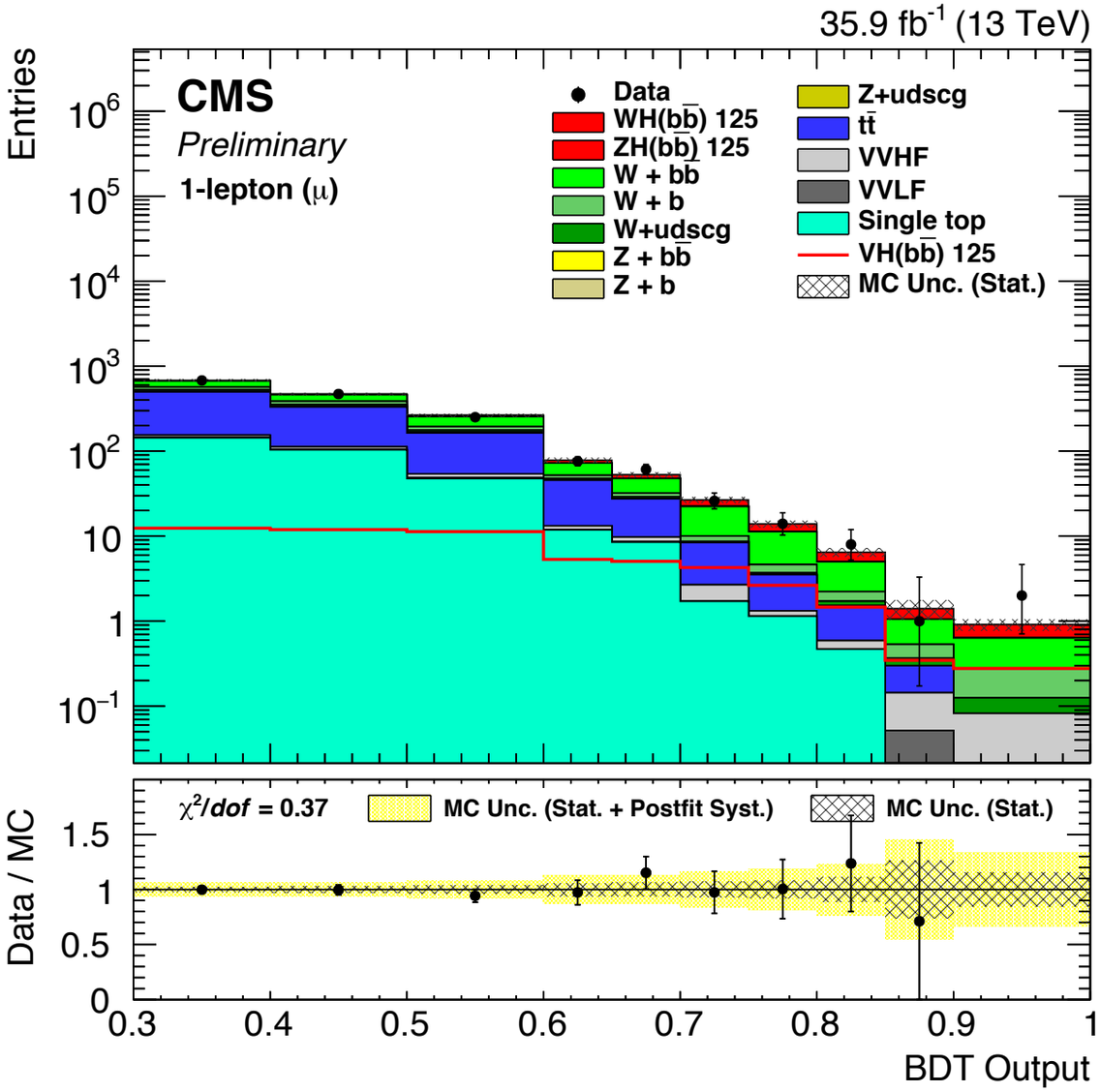


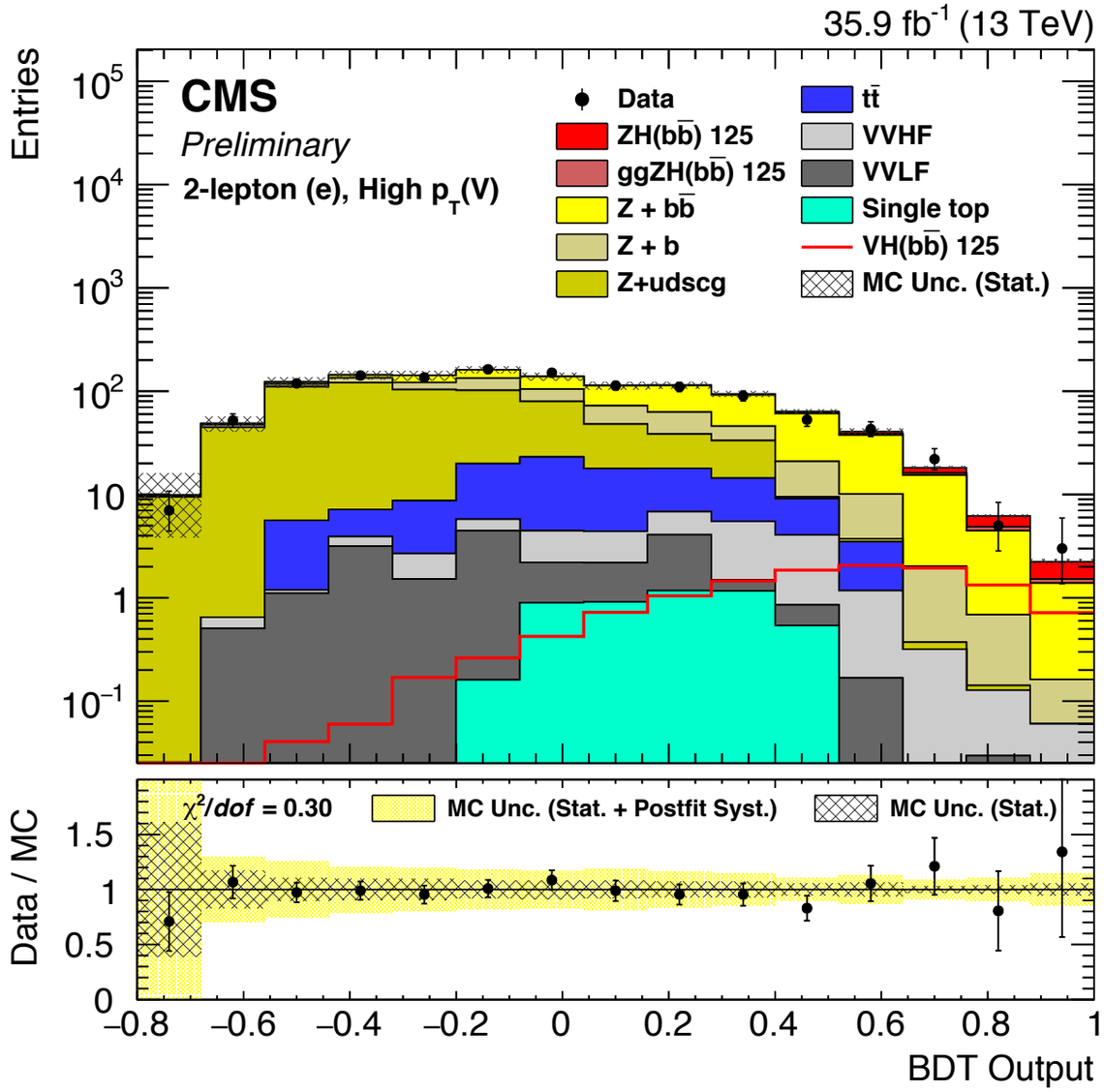
VH, H→bb @ CMS

- Use most sensitive variables to build event BDT
  - M_{jj}, b-tag discriminator for the second jet from Higgs, ΔR_{jj}, number of additional jets, etc.

New

CMS-PAS-HIG-16-044



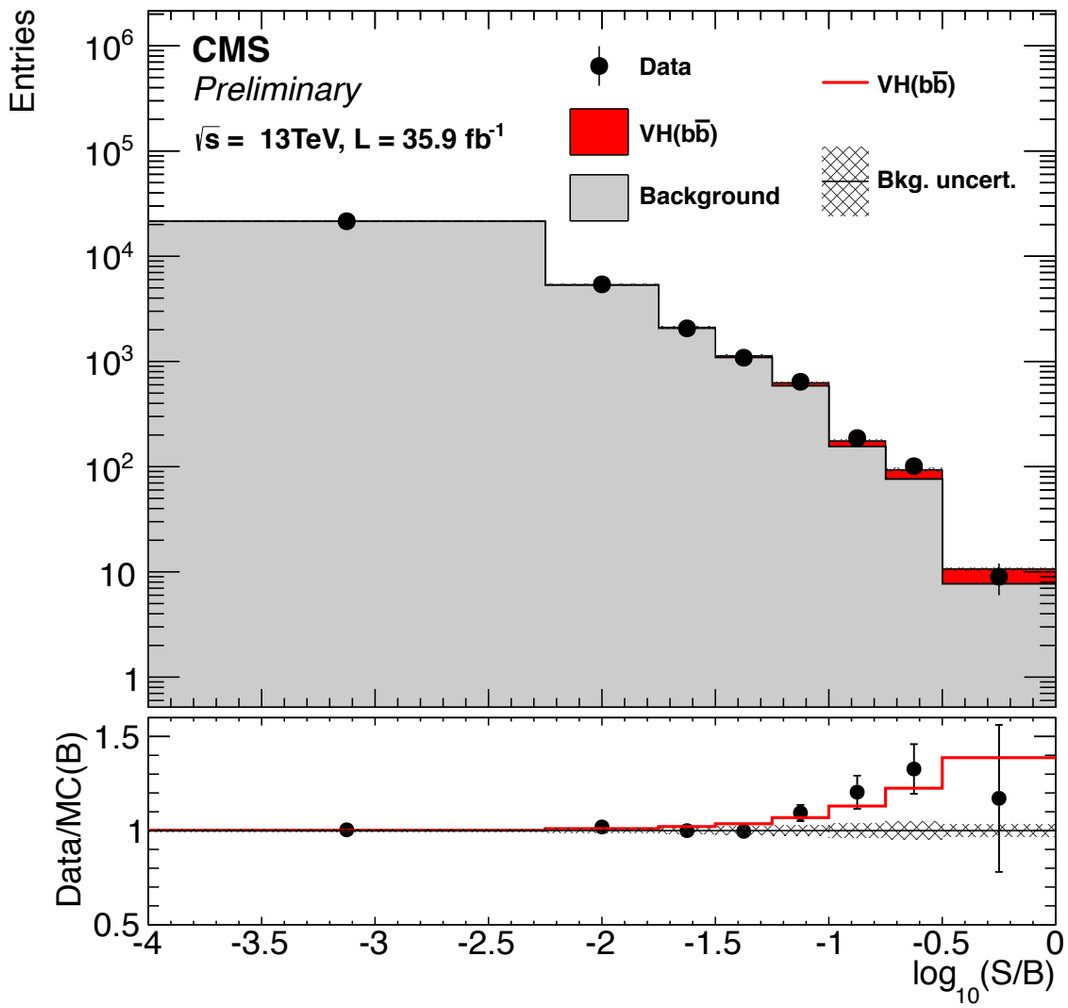


VH, H→bb @ CMS

New

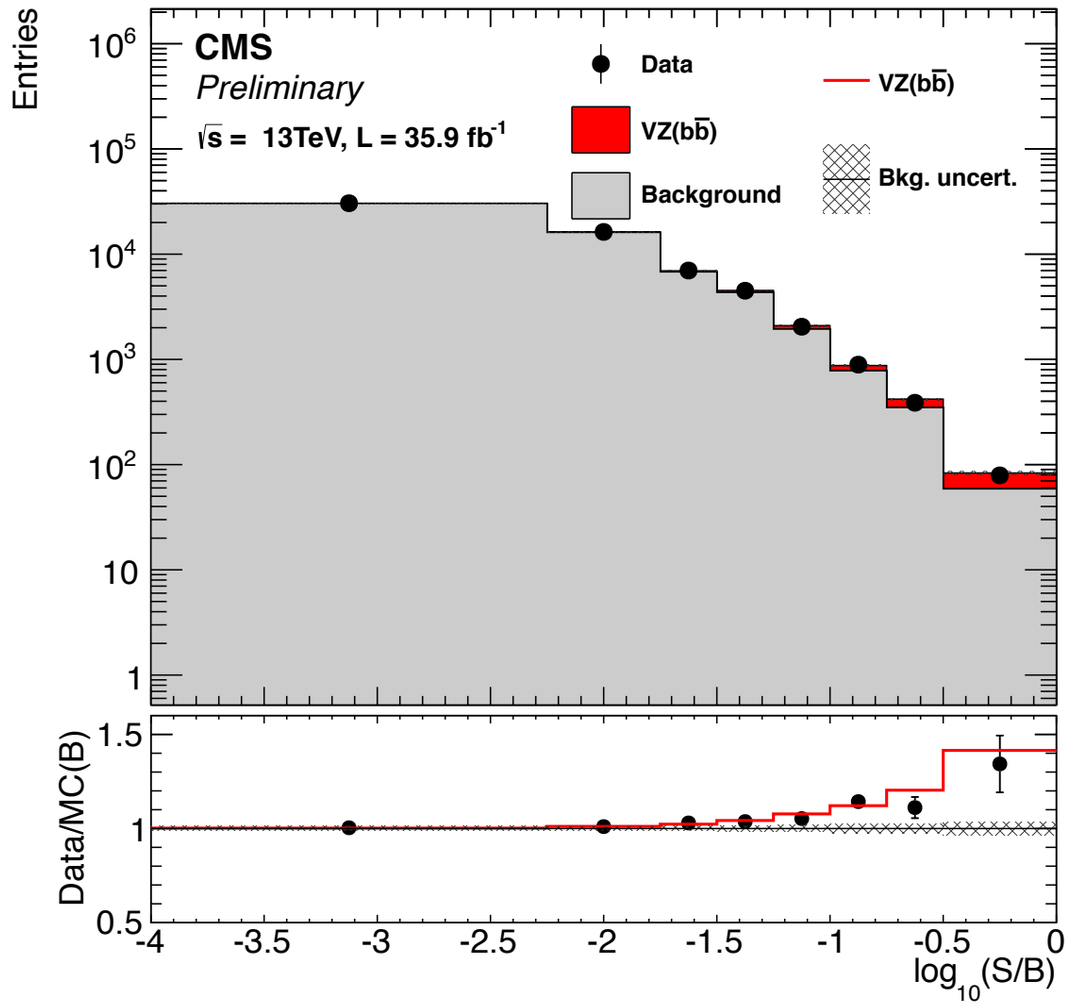
CMS-PAS-HIG-17-044

- Evidence of VH, H→bb signal



	Exp. sign.	Obs. sign.	Sig. strength
Run 1	2.5	2.1	$0.89^{+0.44}_{-0.42}$
Run 2	2.8	3.3	$1.19^{+0.40}_{-0.38}$
Comb.	3.8	3.8	$1.06^{+0.31}_{-0.29}$

- Observation of VZ, Z→bb signal

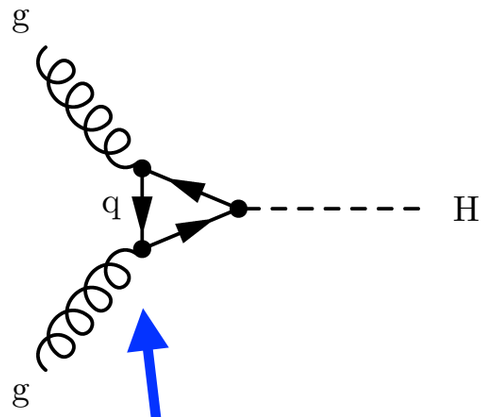


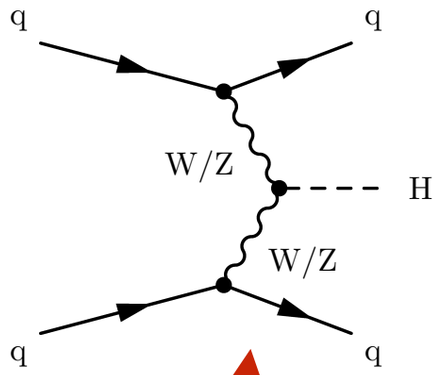
CMS-PAS-HIG-16-044

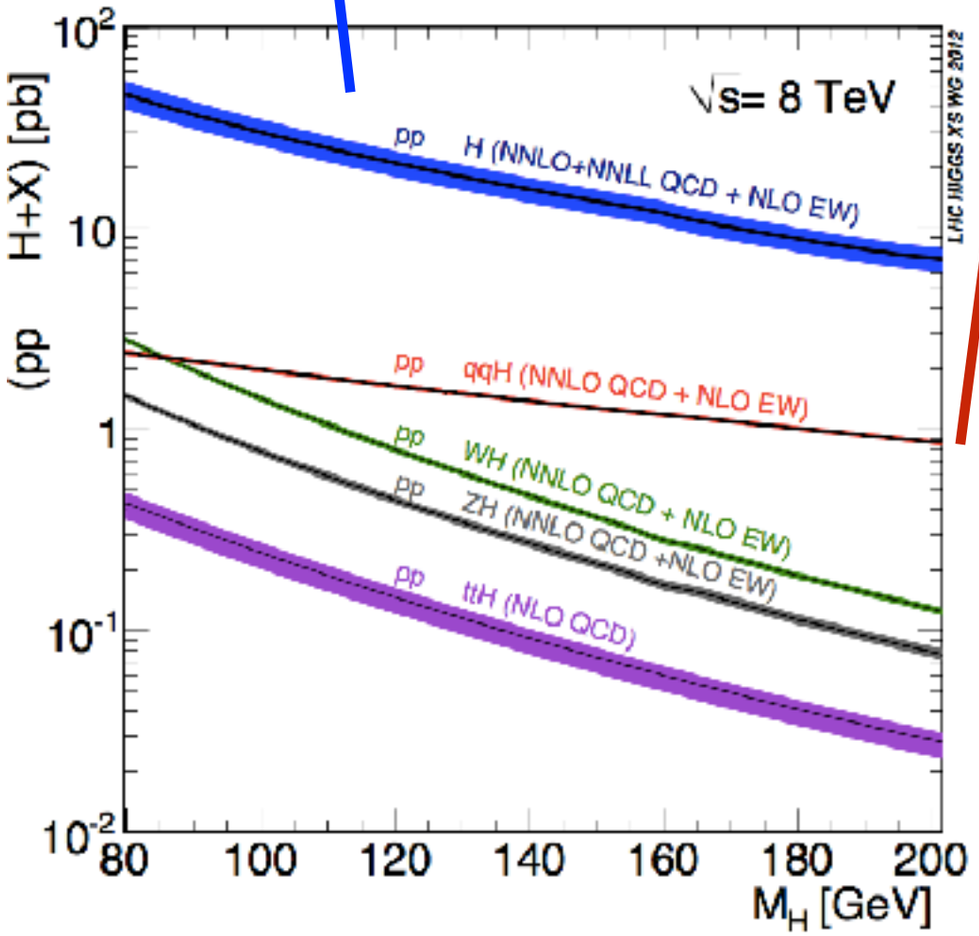
VZ Signal is observed with
$\mu = 1.02 \pm 0.22$ @ 5σ

H→ττ Decay

- Largest leptonic decay

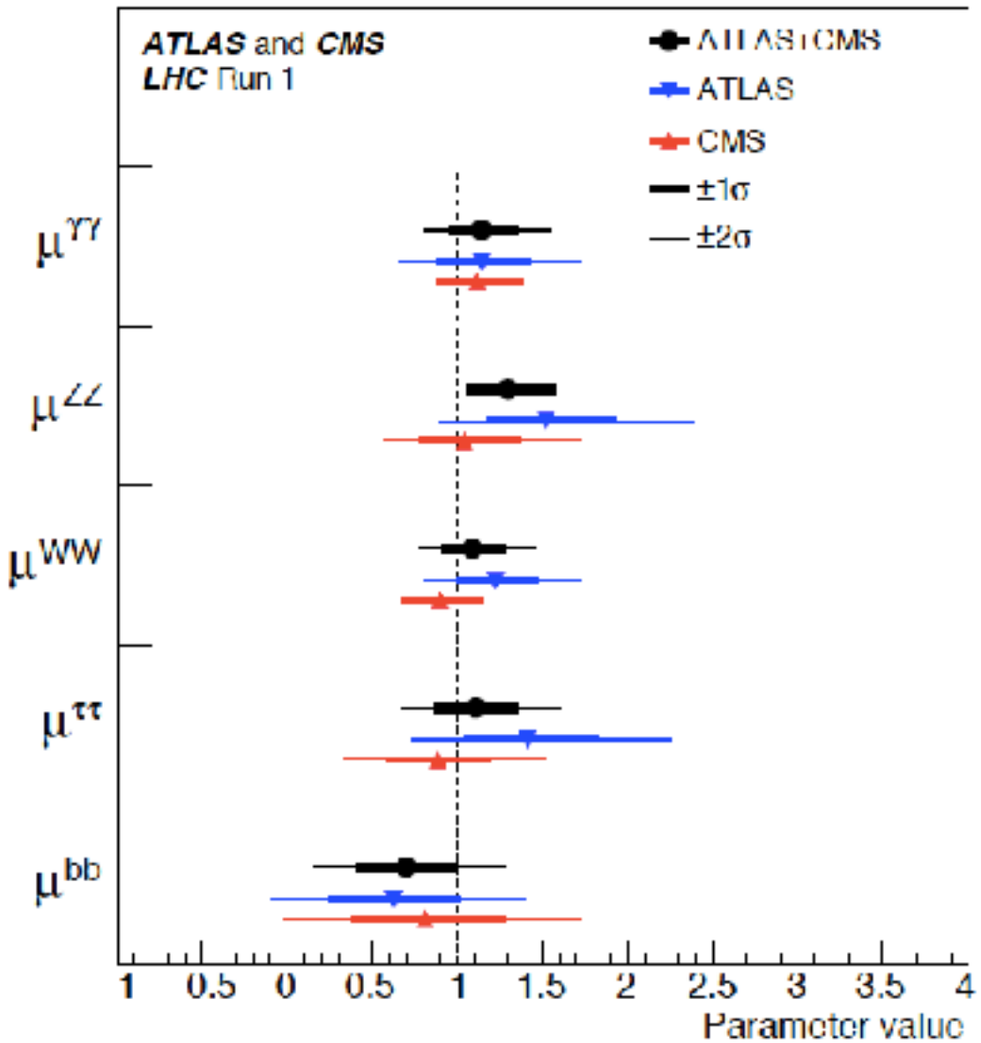






- At the end of Run I

Significance	Observed	Expected
H→ττ	5.5	5.0



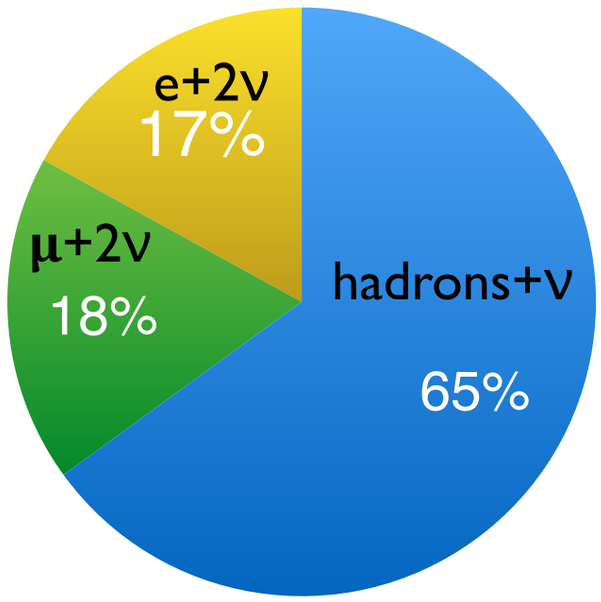
arXiv:1606.02266
JHEP08(2016)045

H→ττ Decay

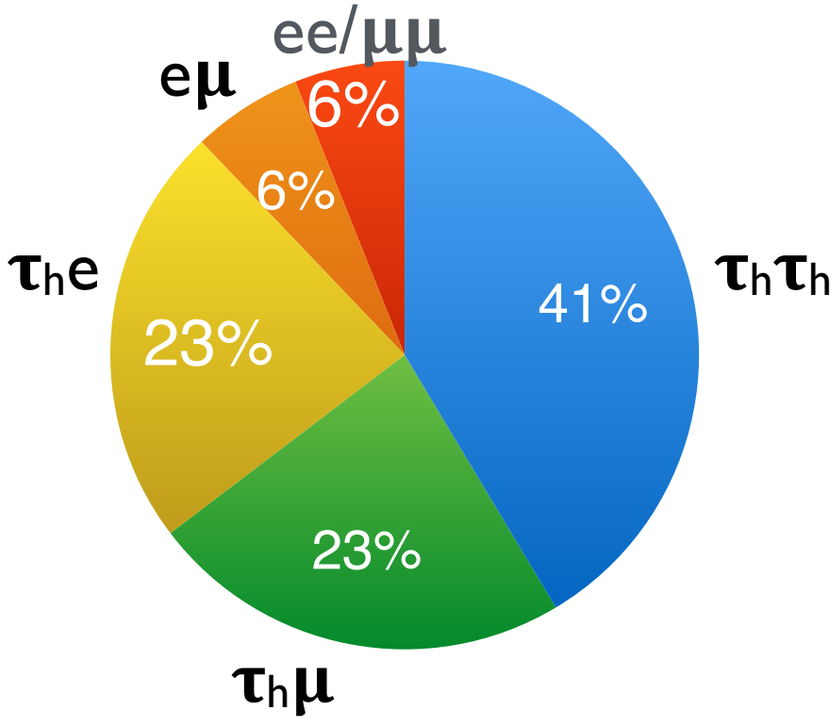
CMS, arXiv:1708.00373

- Different decay modes

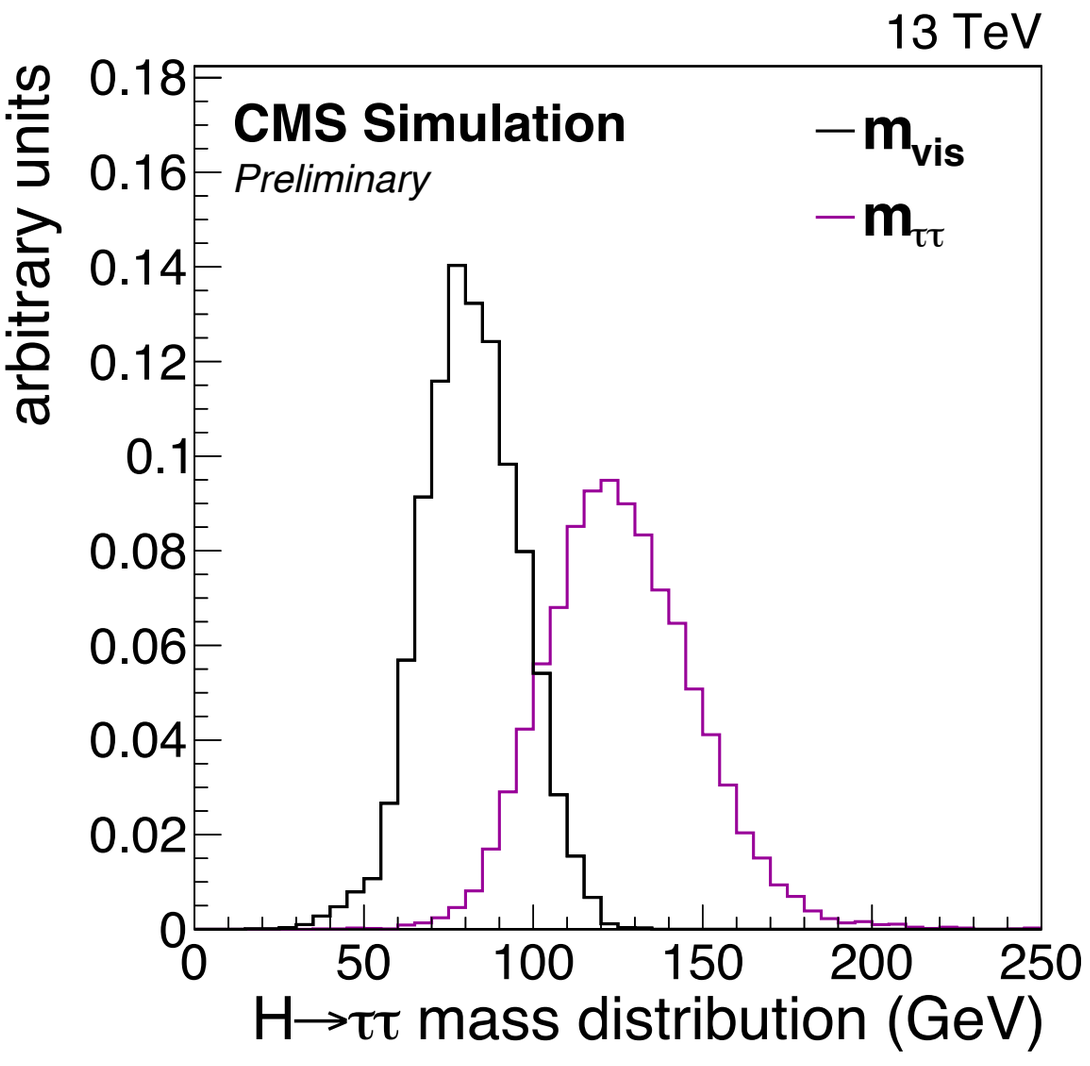
τ decays:



H→ττ decays:



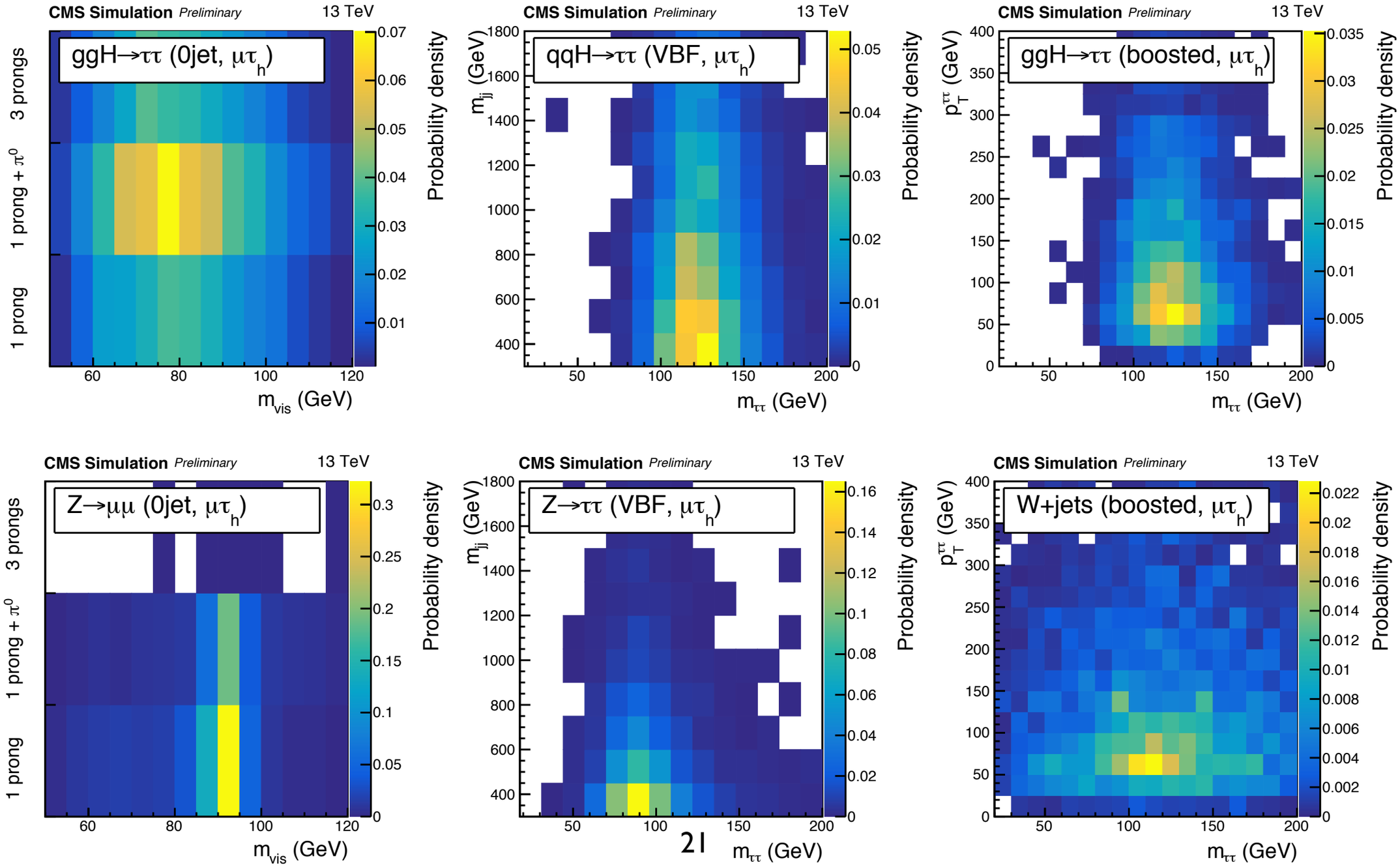
- Di-tau mass reconstruction
  - Using kinematics of tau decay products and imbalance of transverse momentum



H→ττ Decay

CMS, arXiv:1708.00373

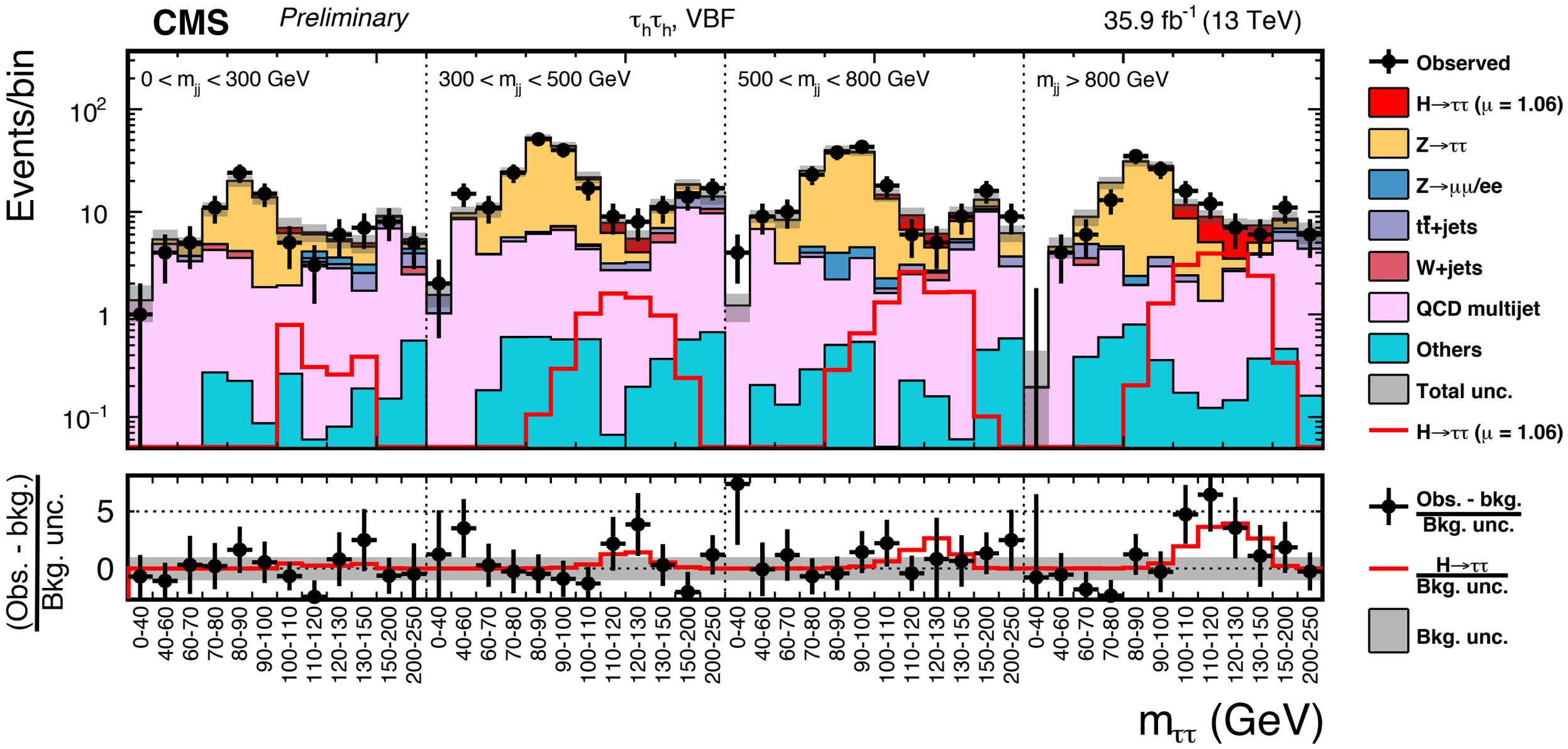
- Categorize events in number of jets
- Identify two sensitive variable per category



H→ττ Decay

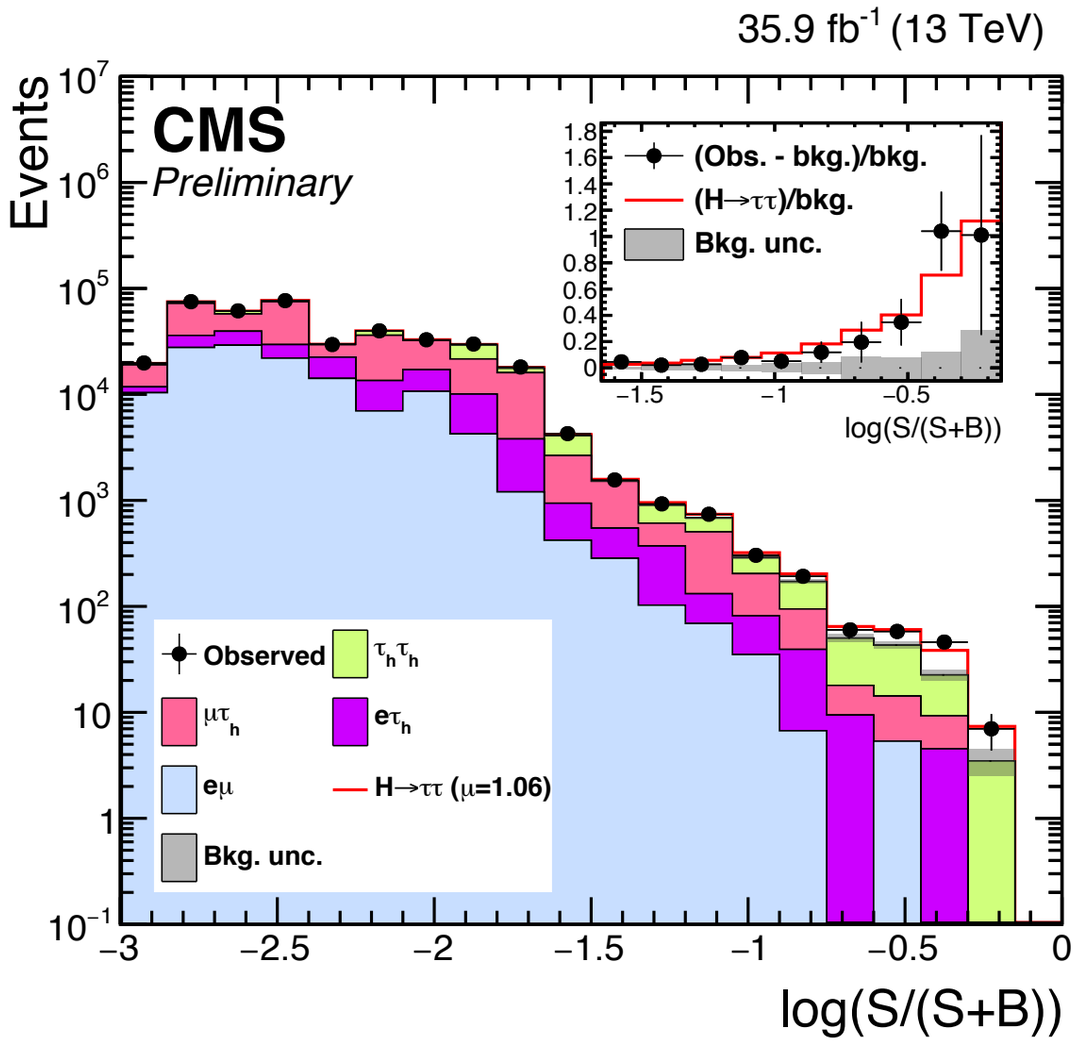
CMS, arXiv:1708.00373

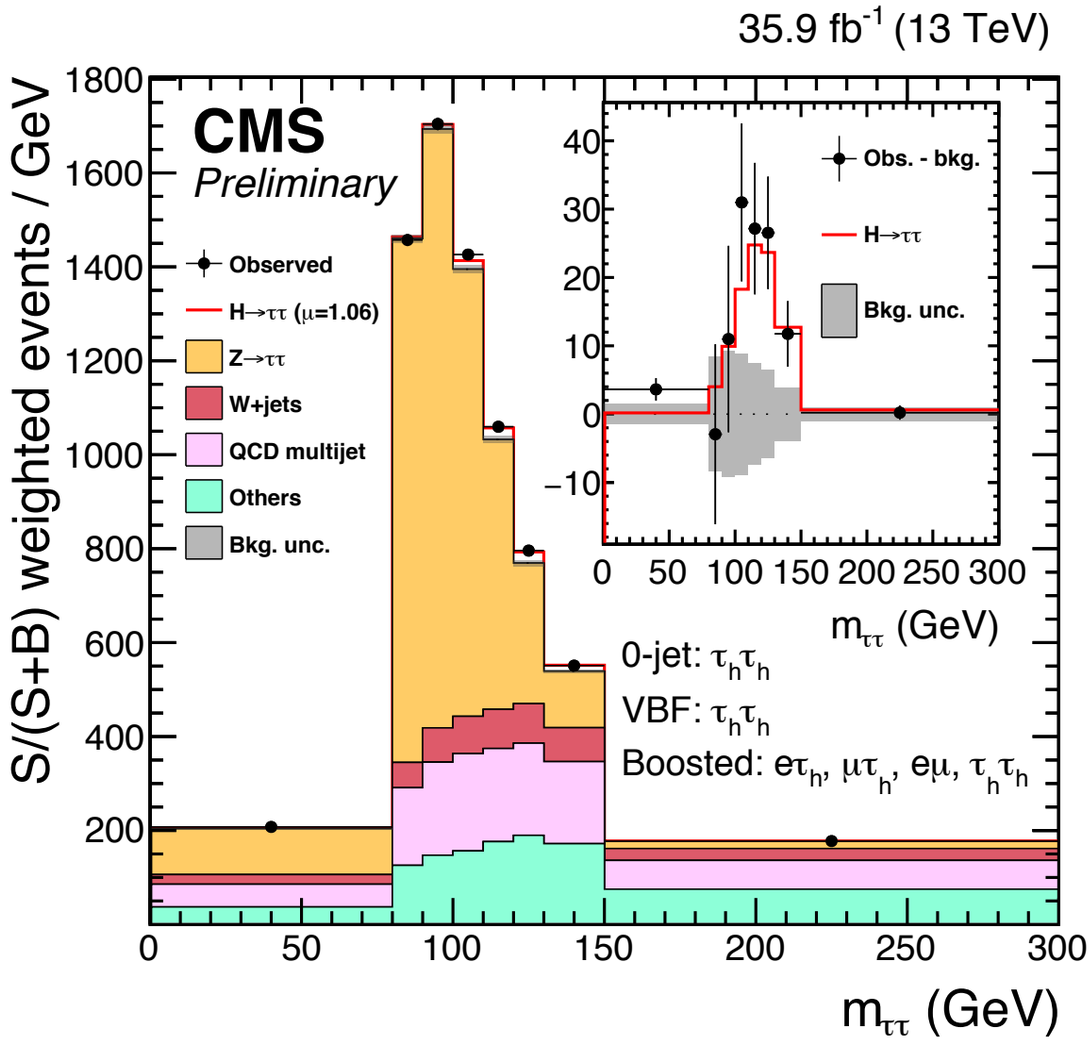
- Use unfolded di-τ mass distribution to extract signal



H→ττ Decay

CMS, arXiv:1708.00373



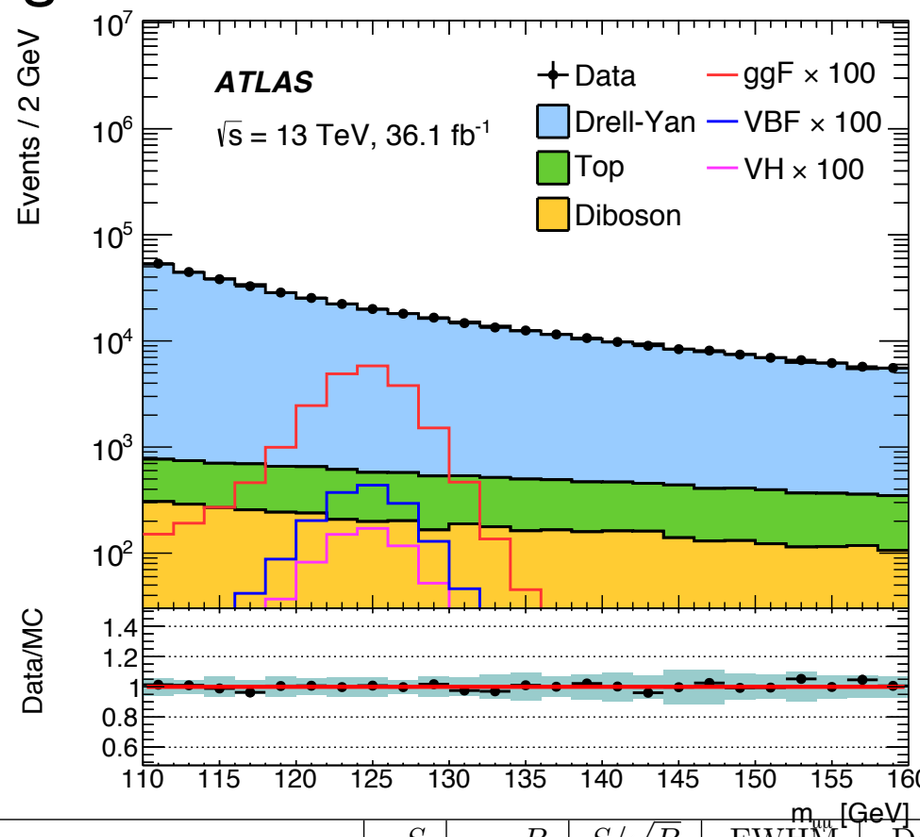


	Signal Strength	Obs. significance	Exp. significance
Run 2	$1.09^{+0.27}_{-0.26}$	4.9σ	4.7σ
Run 1 & 2	0.98±0.18	5.9σ	5.9σ

H→μμ Decay

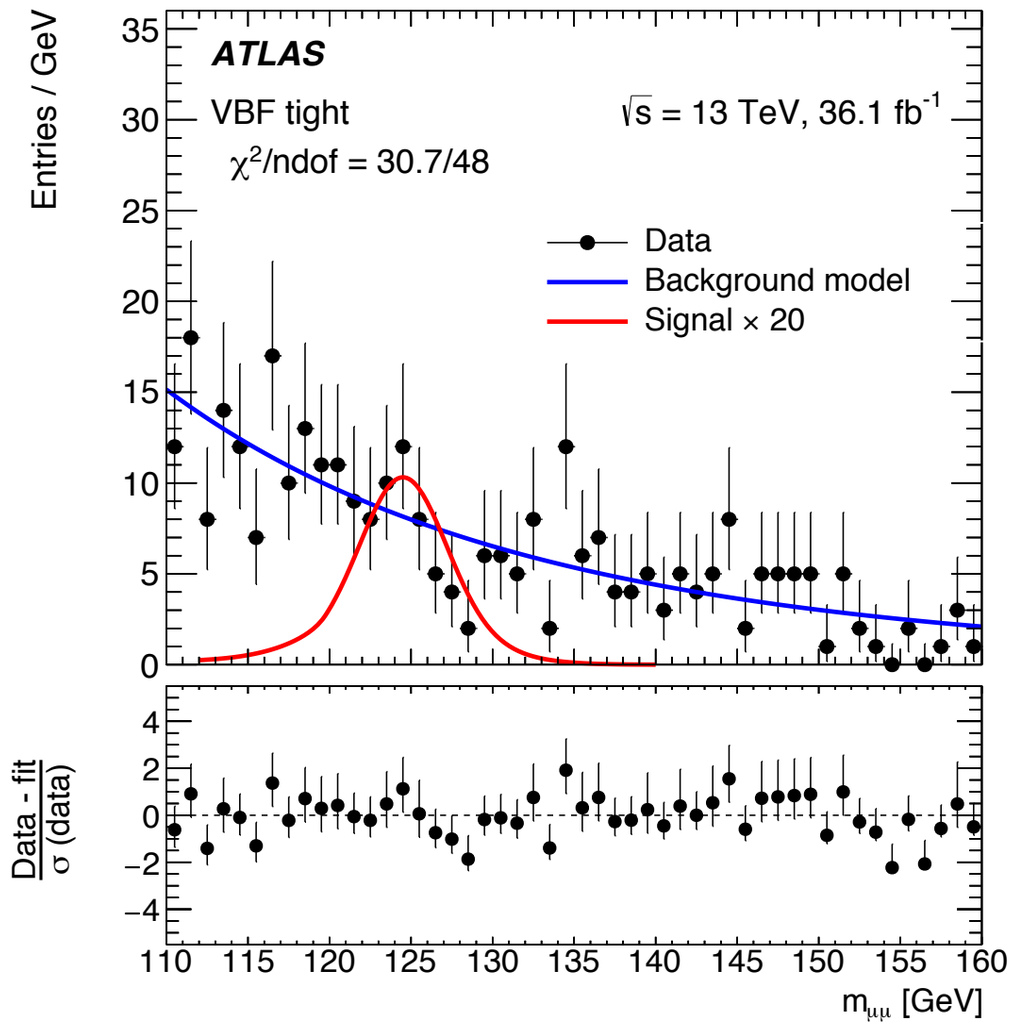
ATLAS, arXiv:1705.04582

- Search for narrow $M_{\mu\mu}$ mass peak
  - Use BDT to select VBF-like events
  - Remaining events split $p_T(\mu)$-based categories



	S	B	$S/\sqrt{B}$	FWHM	Data
Central low $p_T^{\mu\mu}$	11	8000	0.12	5.6 GeV	7885
Non-central low $p_T^{\mu\mu}$	32	38000	0.16	7.0 GeV	38777
Central medium $p_T^{\mu\mu}$	23	6400	0.29	5.7 GeV	6585
Non-central medium $p_T^{\mu\mu}$	66	31000	0.37	7.1 GeV	31291
Central high $p_T^{\mu\mu}$	16	3300	0.28	6.3 GeV	3160
Non-central high $p_T^{\mu\mu}$	40	13000	0.35	7.7 GeV	12829
VBF loose	3.4	260	0.21	7.6 GeV	274
VBF tight	3.4	78	0.38	7.5 GeV	79

- Fit $M_{\mu\mu}$ with analytical S+B model



Upper limit on signal strength

μ < 3.0 obs. (3.1 exp.)

Run 1&2: **μ< 2.8 obs. (2.9 exp.)**

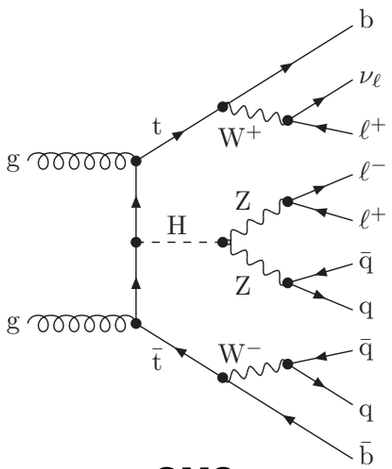
Summary

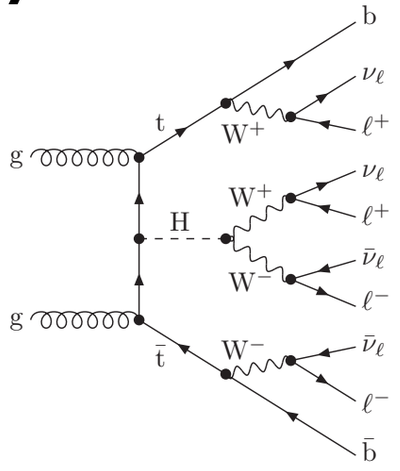
- Both ATLAS and CMS experiments have made significant move forward with Run 2 data
  - There is substantial progress towards establishing fermion couplings
  - The first evidence of ttH production by the CMS experiment
  - The evidence of VH, H→bb signal independently by the ATLAS and CMS experiments
  - The first observation of H→$\tau\tau$ signal by the CMS experiment
  - Improved limits on H→$\mu\mu$ signal strength by the ATLAS experiment; More data needed until the first evidence of this process
- Already ~10 fb^{-1} of luminosity was delivered in 2017
- Stay tuned for more exciting results in near future!

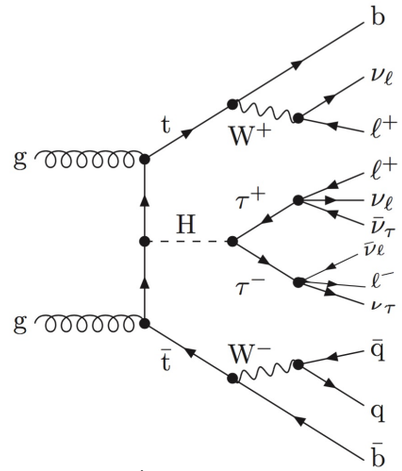
BACKUP

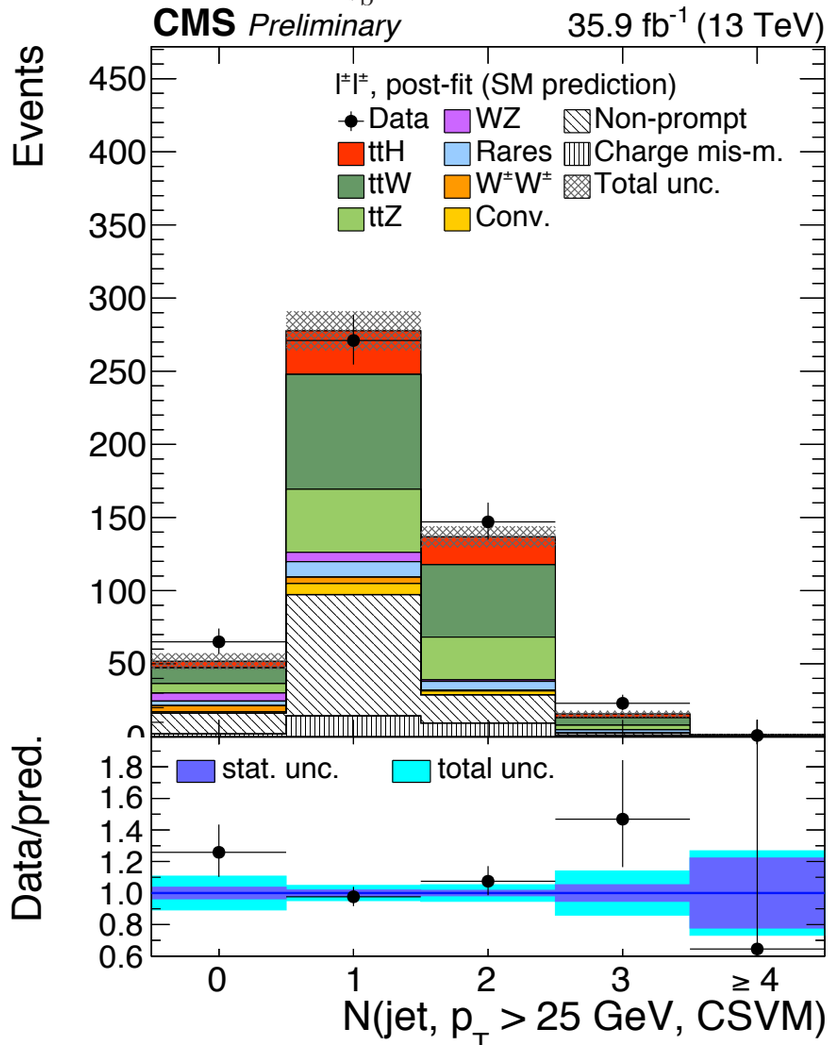
ttH with Multilepton Final State

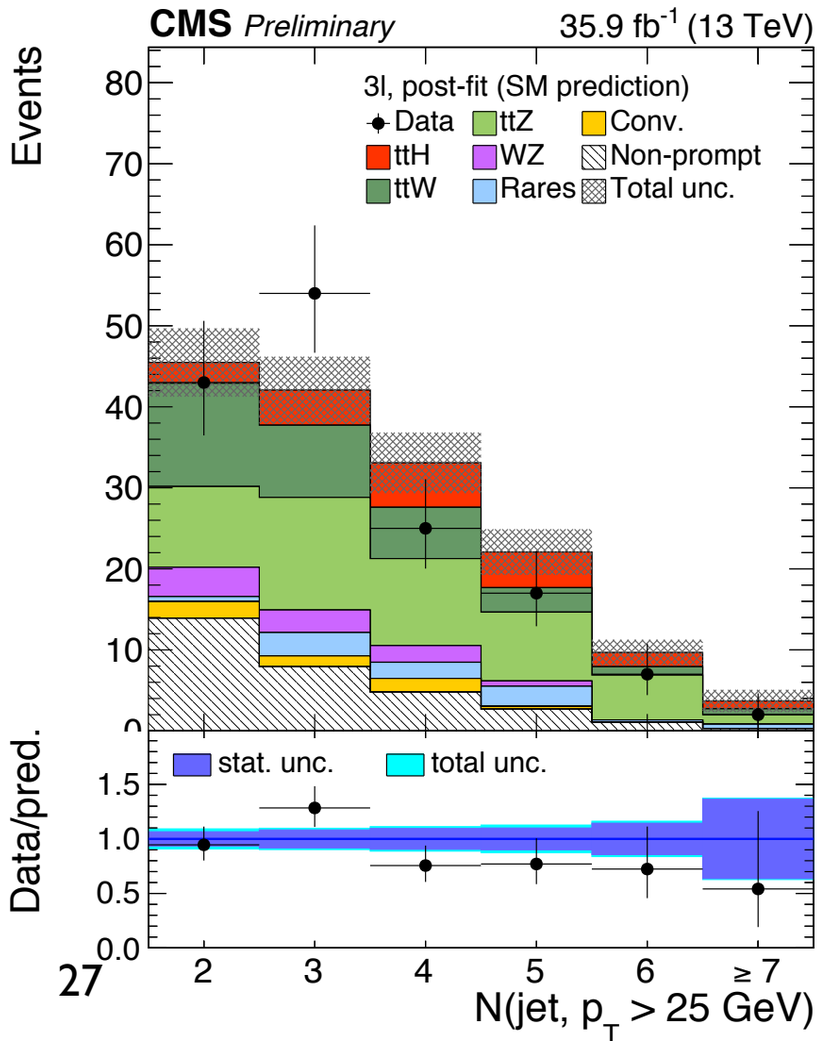
- Events are categorized by number of observed leptons









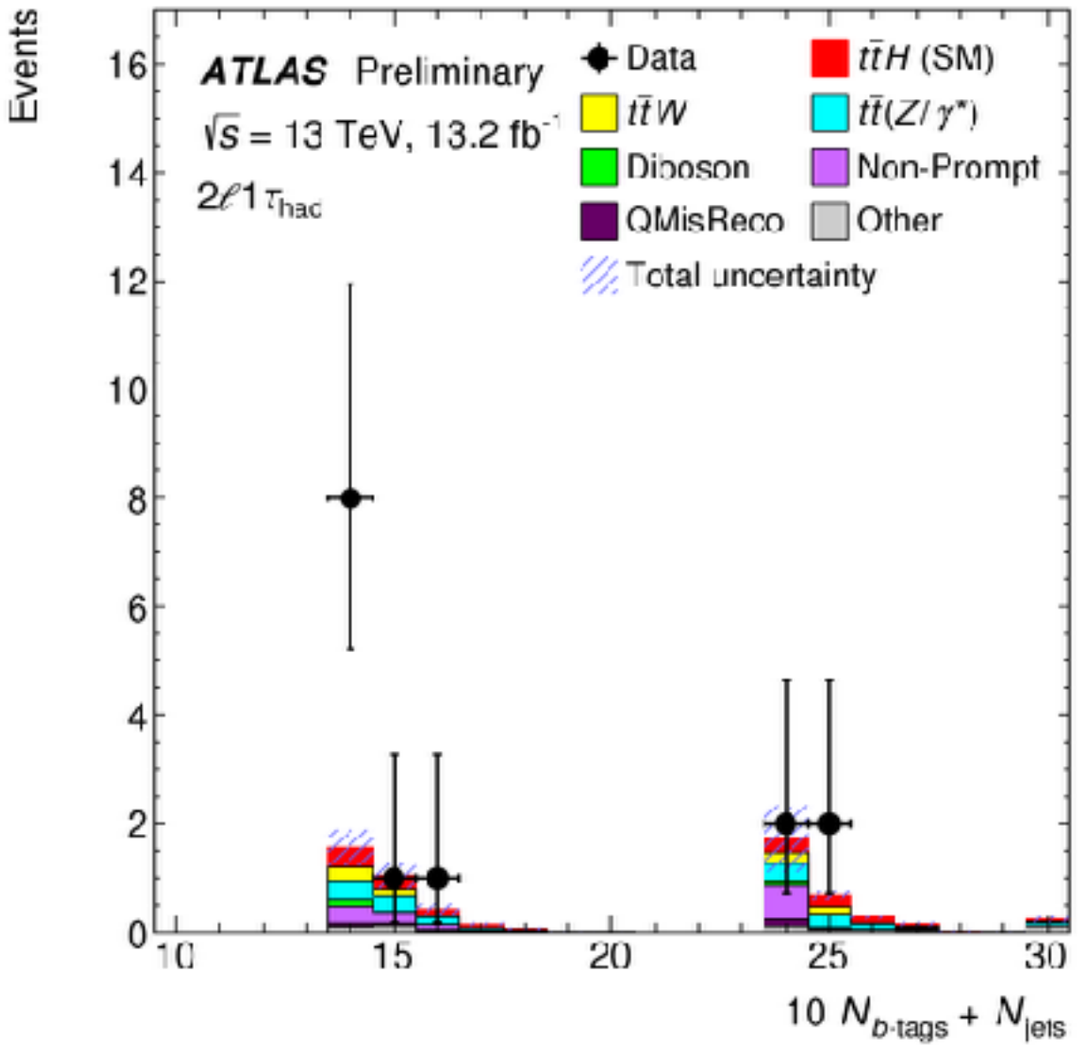


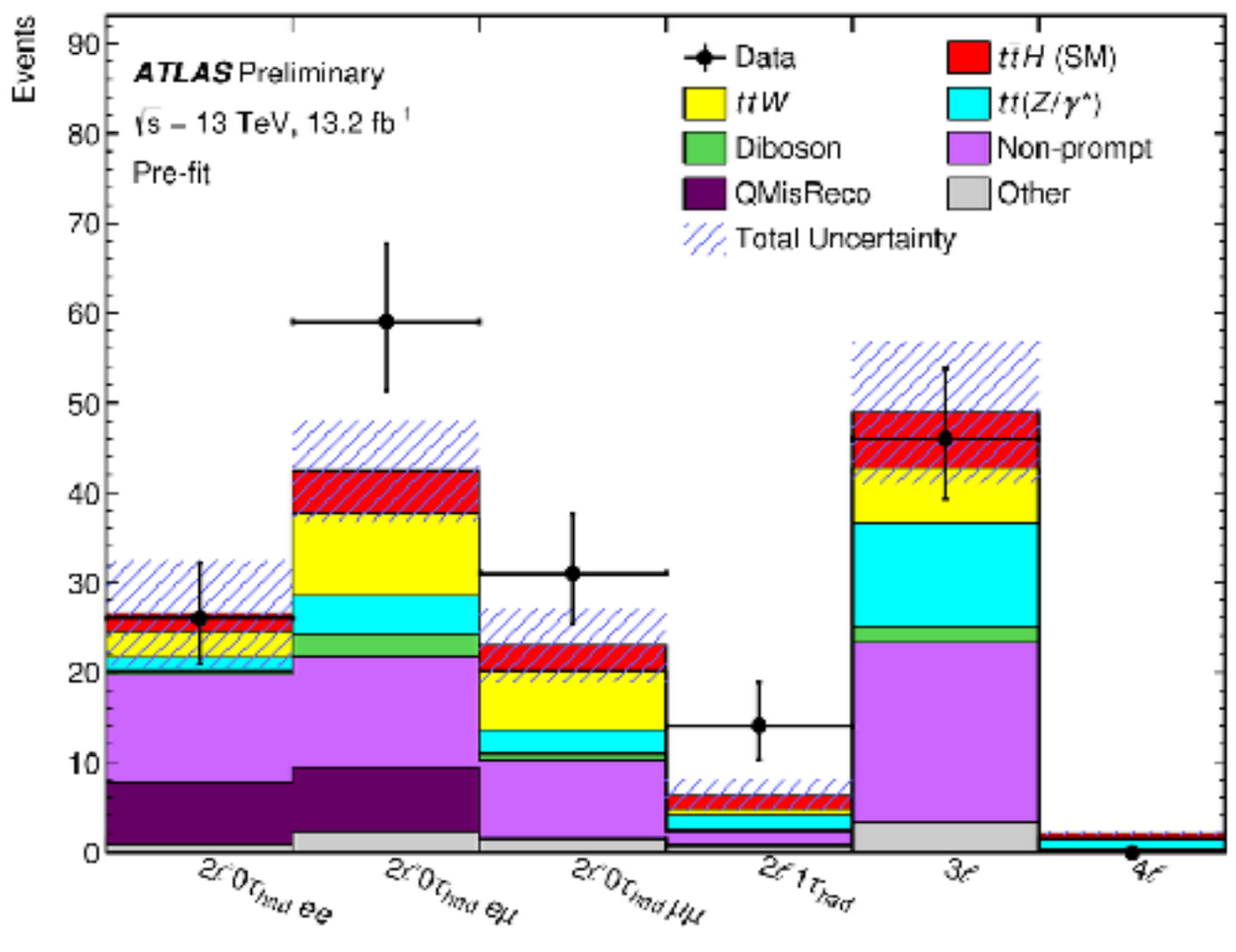
CMS-PAS-HIG-17-004

ttH with Multilepton Final State

- Very similar search was performed by ATLAS using part of 2016 dataset
  - Including additional category with one hadronic tau: $2\ell 1\tau_h$

ATLAS-CONF-2016-058

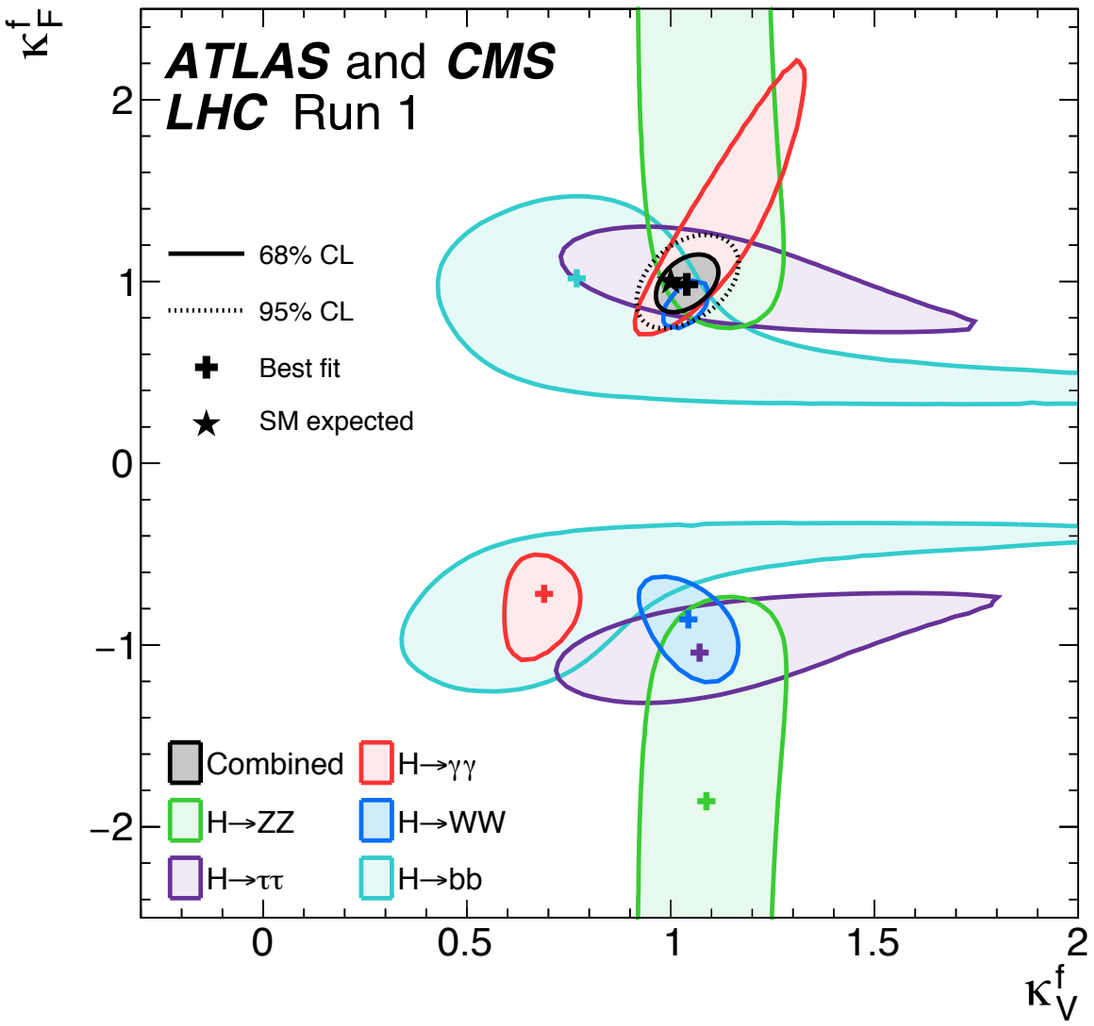




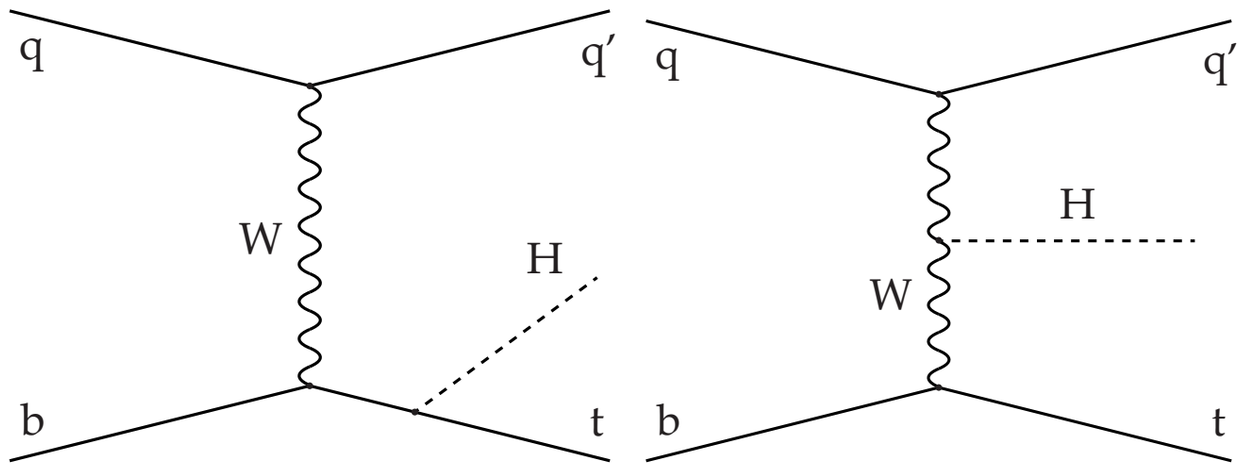
tHq Production

CMS-PAS-HIG-17-005

- Relative sign of coupling to boson and fermions could be still affected by some statistical fluctuations
- Single top and Higgs production is sensitive to sign of Y_t coupling



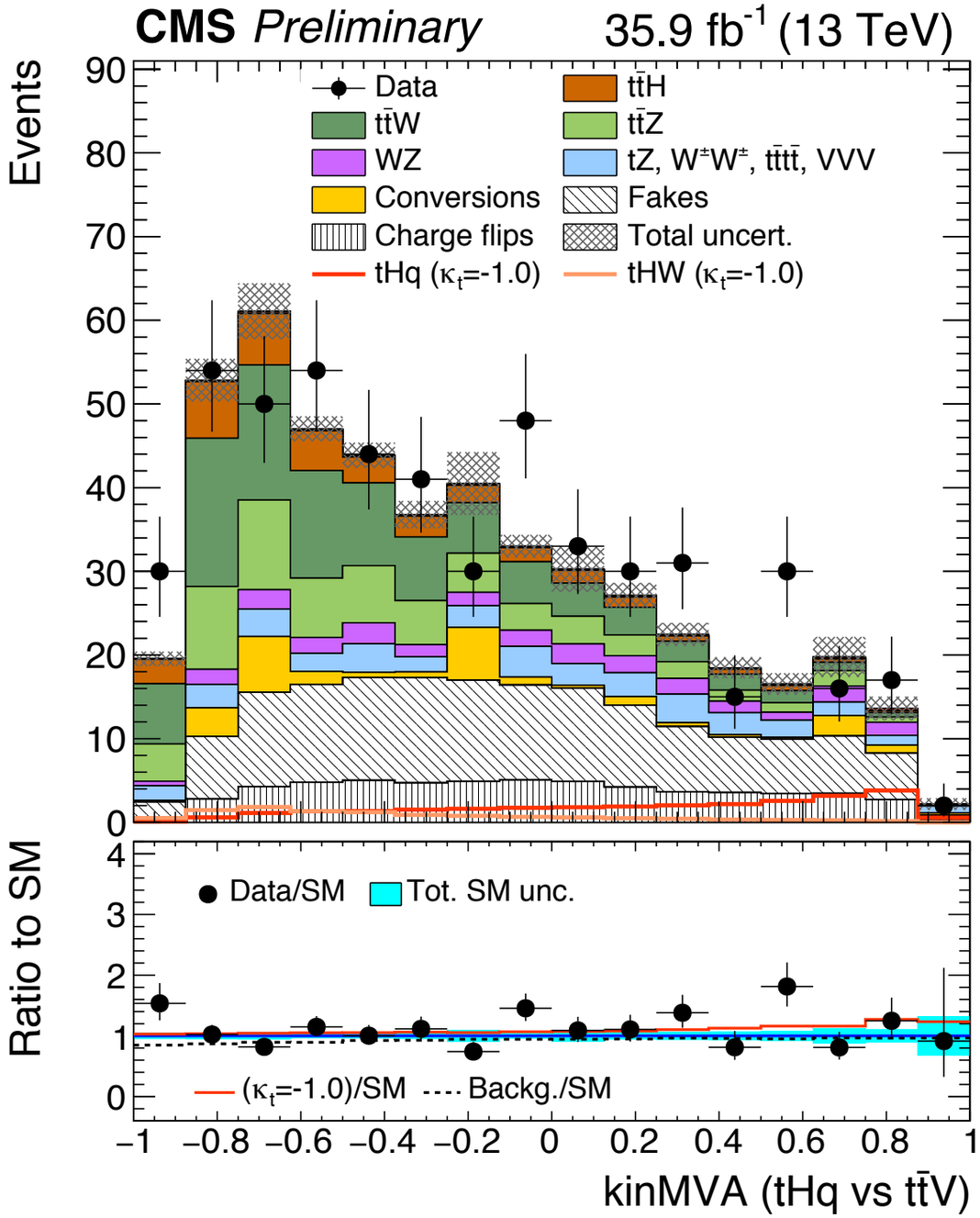
In the SM, tHq is suppressed due to due to distractive interference of t-channel productions

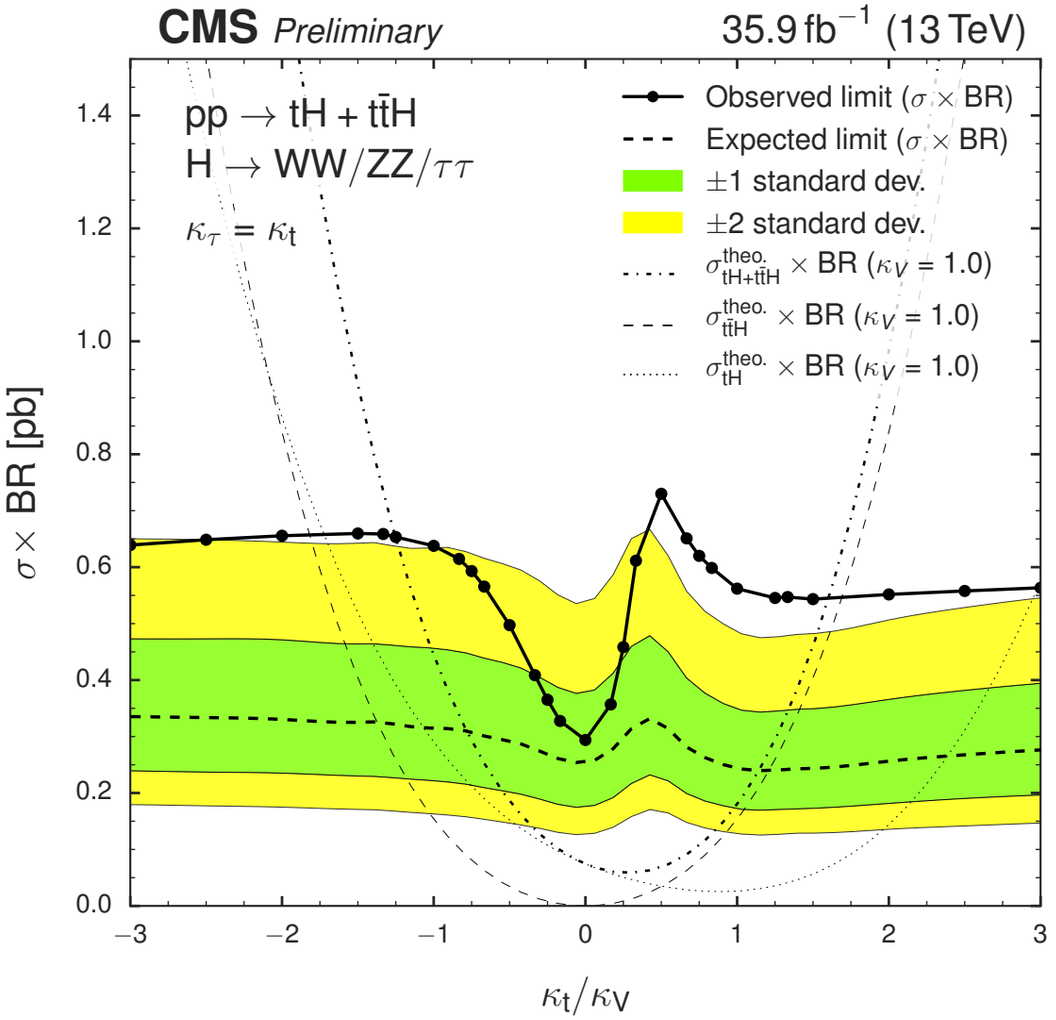


tHq Production

CMS-PAS-HIG-17-005

- Using multivariate technique to distinguish low cross-section tHq and tHW signal from backgrounds in ee, eμ, and 3ℓ channels





Scenario	Obs. Limit (pb)	Exp. Limit (pb)
κ_t/κ_V=-1	0.64	0.32
κ_t/κ_V=1	0.56	0.24

VH, H→bb @ CMS

- Final yields in the 20% most-sensitive region of BDT

	0-lepton	1-lepton	2-lepton	
Process			Low p_T(V)	High p_T(V)
Vbb	216.8	102.5	617.5	113.9
Vb	31.8	19.9	141.1	17.2
V + udscg	10.2	9.8	58.4	4.1
$t\bar{t}$	34.7	98.0	157.7	3.2
Single-top-quark	11.8	44.6	2.0	0.2
VV(udscg)	0.4	1.5	6.4	0.6
VZ(bb)	7.7	6.9	22.9	3.8
Total backgrounds	267.0	283.3	1005.9	142.9
VH	34.7	26.0	33.5	22.1
Data	334	320	1030	179
S/B	0.13	0.11	0.033	0.156

CMS-PAS-HIG-17-044

- Effect of each source of uncertainty on signal strength

Source	Type	Individual contribution to μ uncertainty (%)	Effect of removal on μ uncertainty (%)
Scale factors (tt,V+jets)	norm.	9.4	3.5
Size of simulated samples	shape	8.1	3.1
Simulated samples' modeling	shape	4.1	2.9
Btag	shape	7.9	1.8
Jet energy scale	shape	4.2	1.8
Signal cross sections	norm.	5.3	1.1
Cross section uncertainties (single-top, VV)	norm.	4.7	1.1
Jet energy resolution	shape	5.6	0.9
Mistag	shape	4.6	0.9
Luminosity	norm.	2.2	0.9
Missing transverse energy	shape	1.3	0.2
Lepton efficiency and trigger	norm.	1.9	0.1

VH, H→bb @ CMS

- Signal strength