Observation of the ⭐ ttH process at CMS

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(on behalf of the CMS Collaboration)

11th International Workshop on Top Quark Physics
Bad Neuenahr-Ahrweiler, Germany

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Phys. Rev. Lett. 120 (2018) 231801

Top-Higgs interaction

More on Top in all other talks

More on Higgs in Kevin Lannon's talk

top

- ★ The **heaviest elementary particle** (1995)
- ★ Almost exclusively decays to W boson and b quark
- ★ **Short lifetime** makes it decay before hadronization ($\tau \approx 4\times10^{-25}$ s)
- ★ Represents relatively clean experimental signature to study

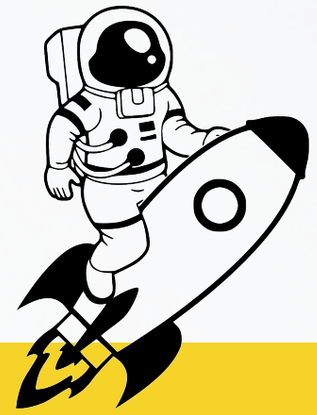
Higgs

- ★ The **second heaviest elementary particle** (2012)
- ★ The last predicted missing particle in SM was finally observed
- ★ **Gives mass to all particles**
- ★ Studies of its properties and implications for the SM ongoing

In the SM top is expected to strongly couple to Higgs ($y_t \approx 1$)

$$\mathcal{L} = \overline{Q}(\frac{m_Q}{v}H + m_Q)Q$$

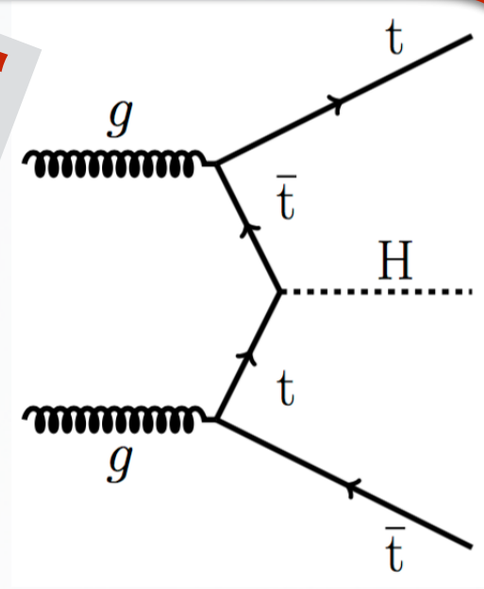
Where to find ?



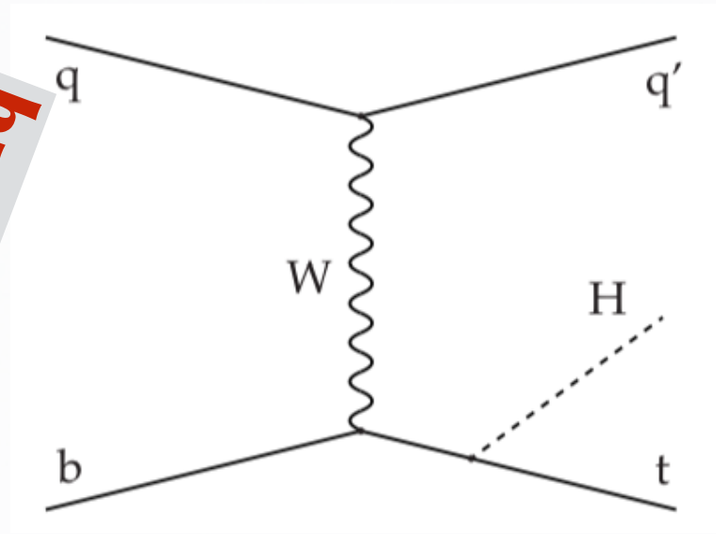
Not possible in Higgs decays - top quark is too heavy !

Directly

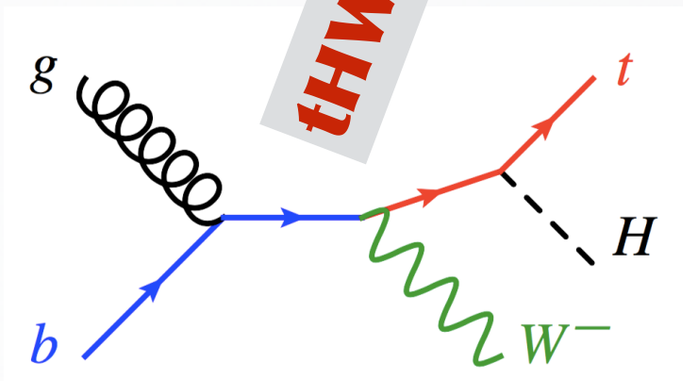
ttH



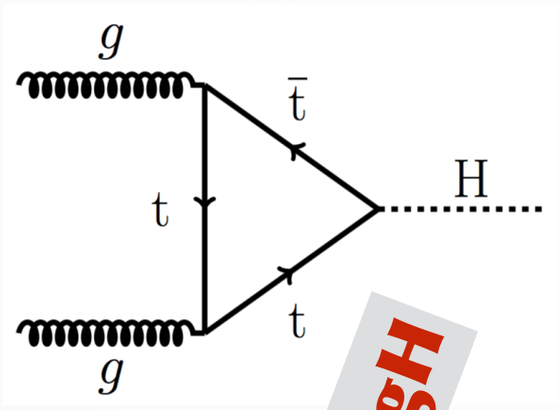
tHq



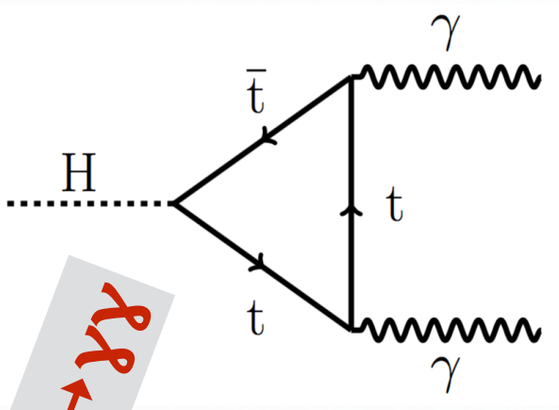
tHW



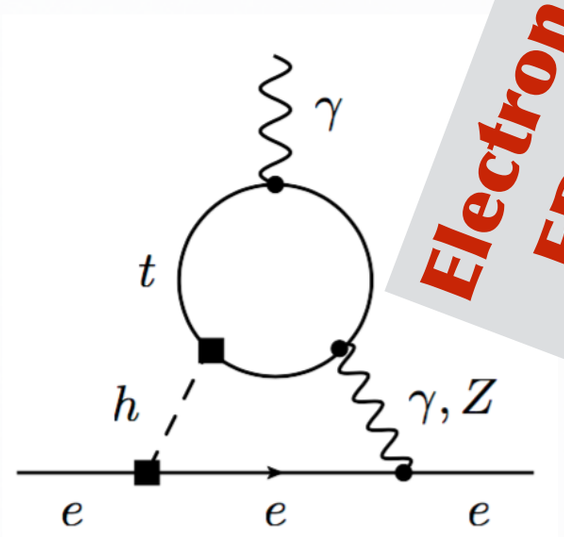
Indirectly



ggH



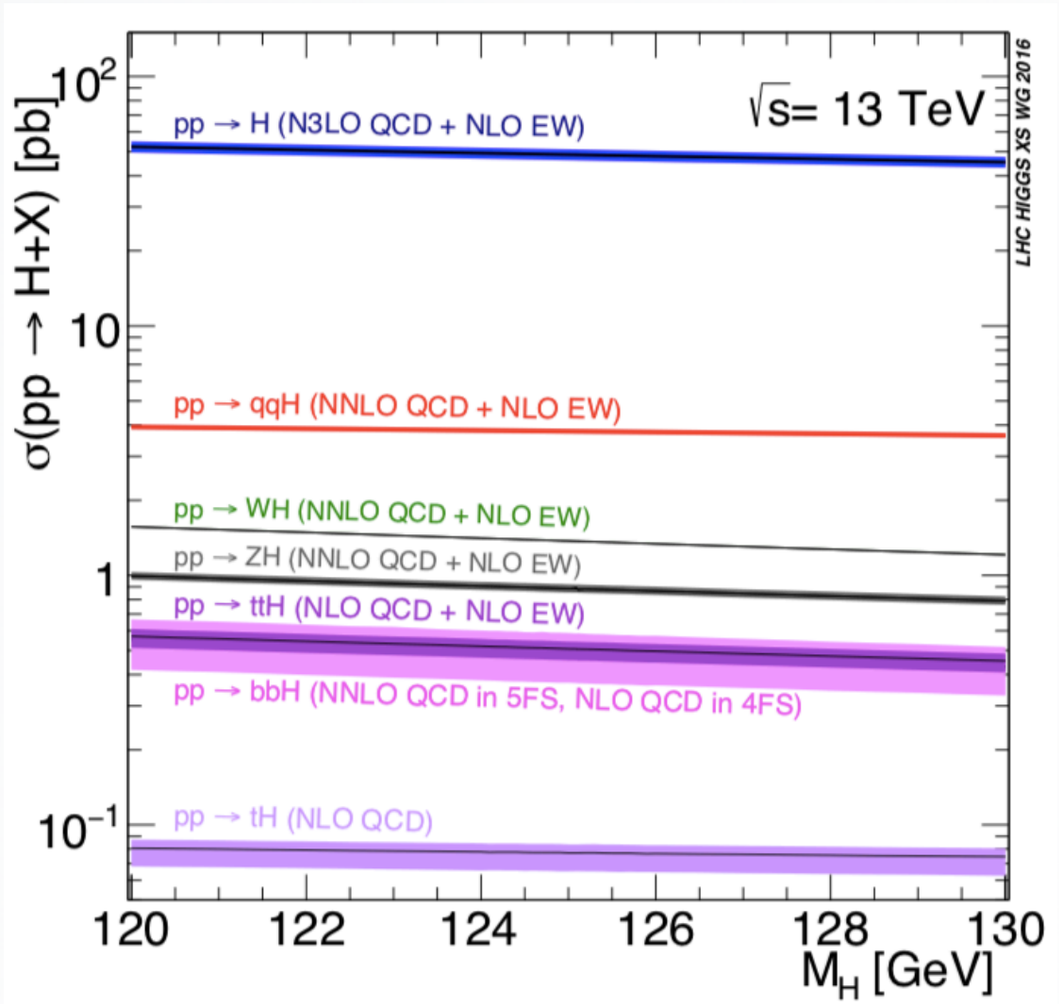
H→γγ



Electron EDM

***Caveat*: new particles can contribute in the loops !**

Production and decay modes



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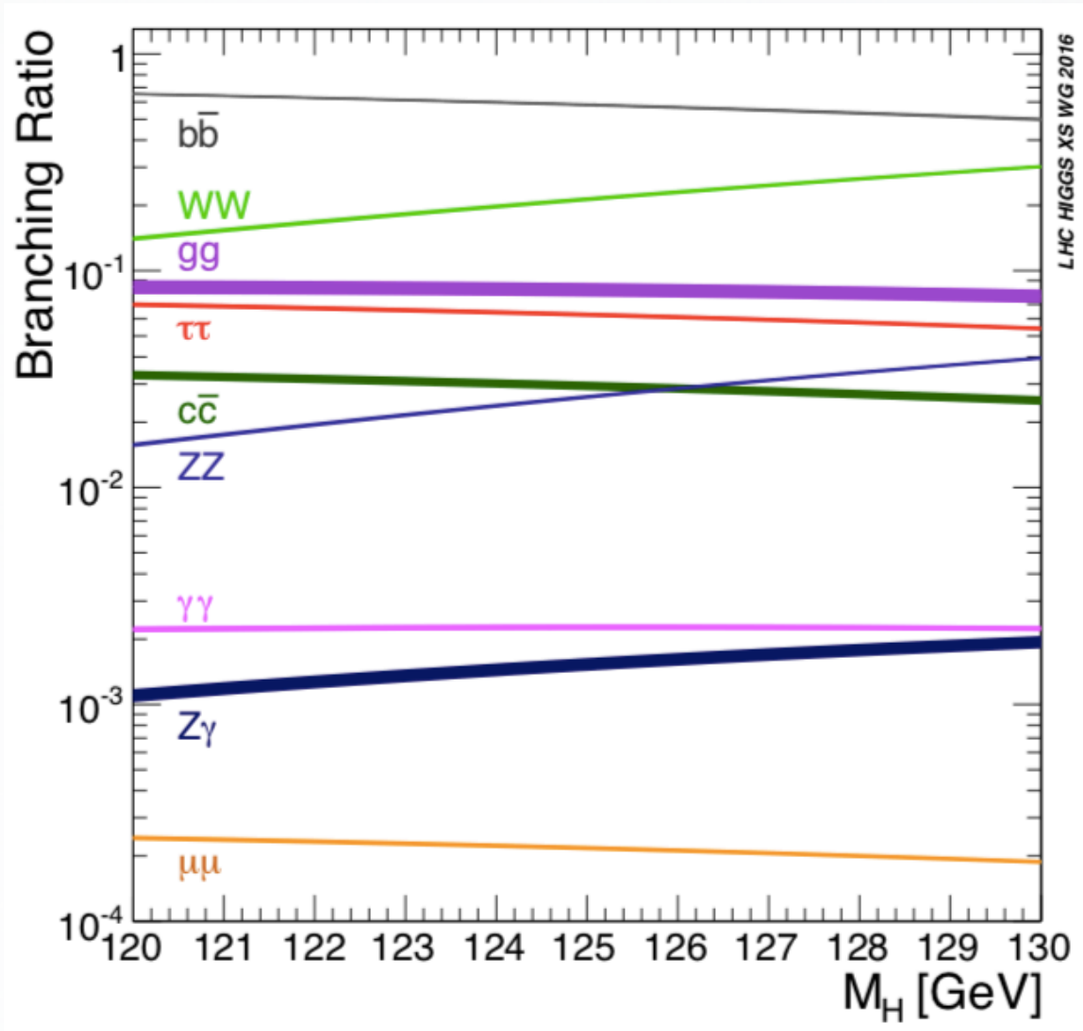
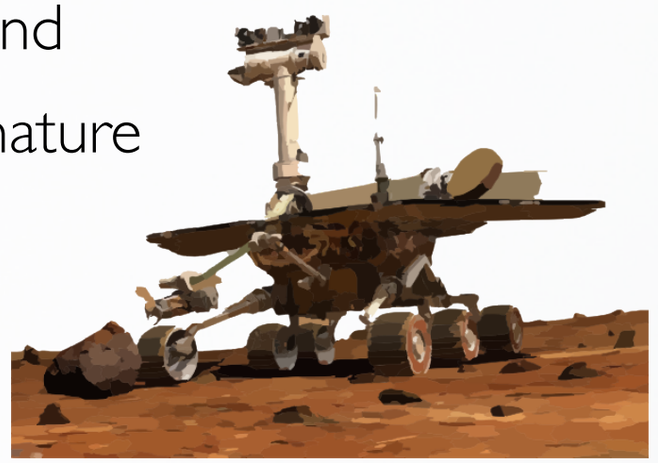
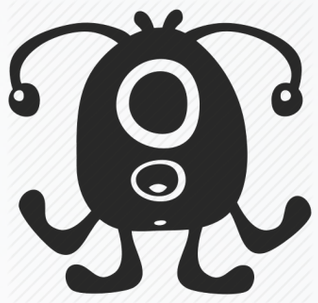


- ☆ Very small production cross section (≈0.5 pb NLO QCD + NLO EW @13 TeV)
- ☆ **H→bb**: large branching fraction (≈60%), but huge background
- ☆ **H→γγ**: very small branching fraction (≈0.1%), but clean signature
- ☆ **H→WW, ZZ, ττ**: (multileptons): overall very good sensitivity due to small background and clean final state

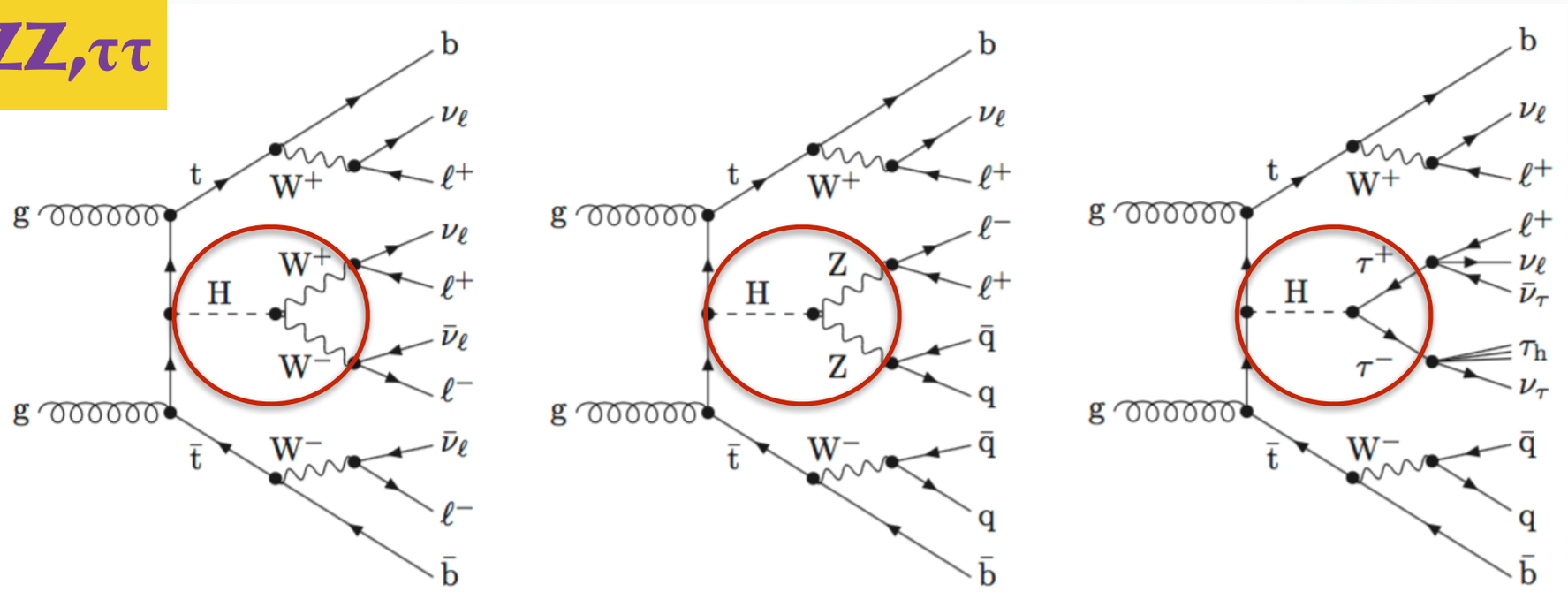


ttH production and analysis channels

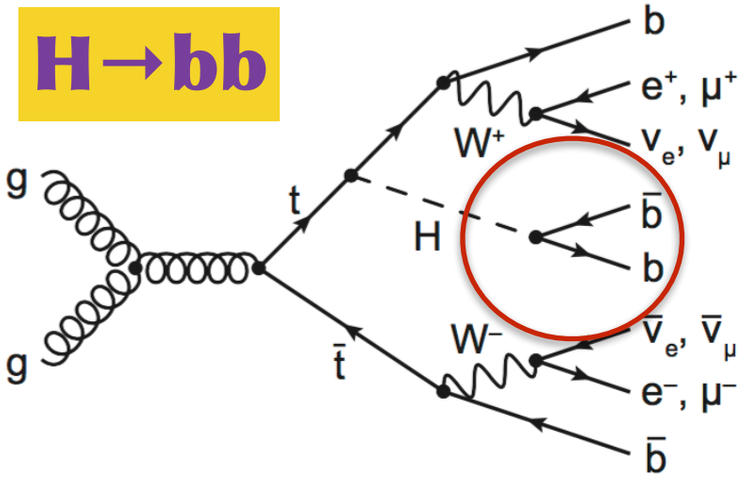
Golden channel to directly probe y_t but ... a very complex final state !



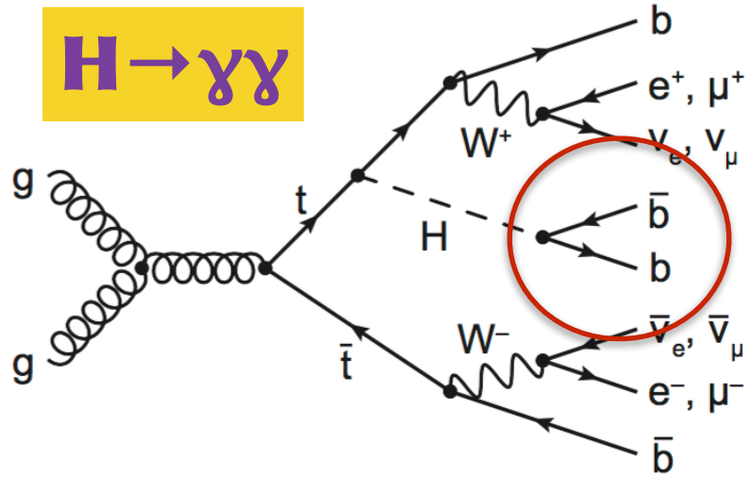
H→WW,ZZ,ττ

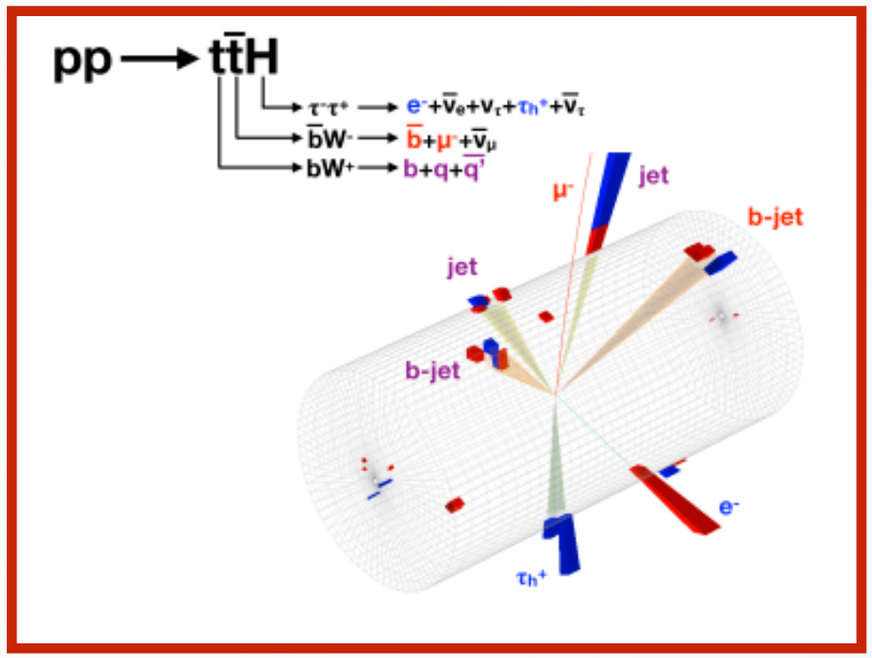


H→bb



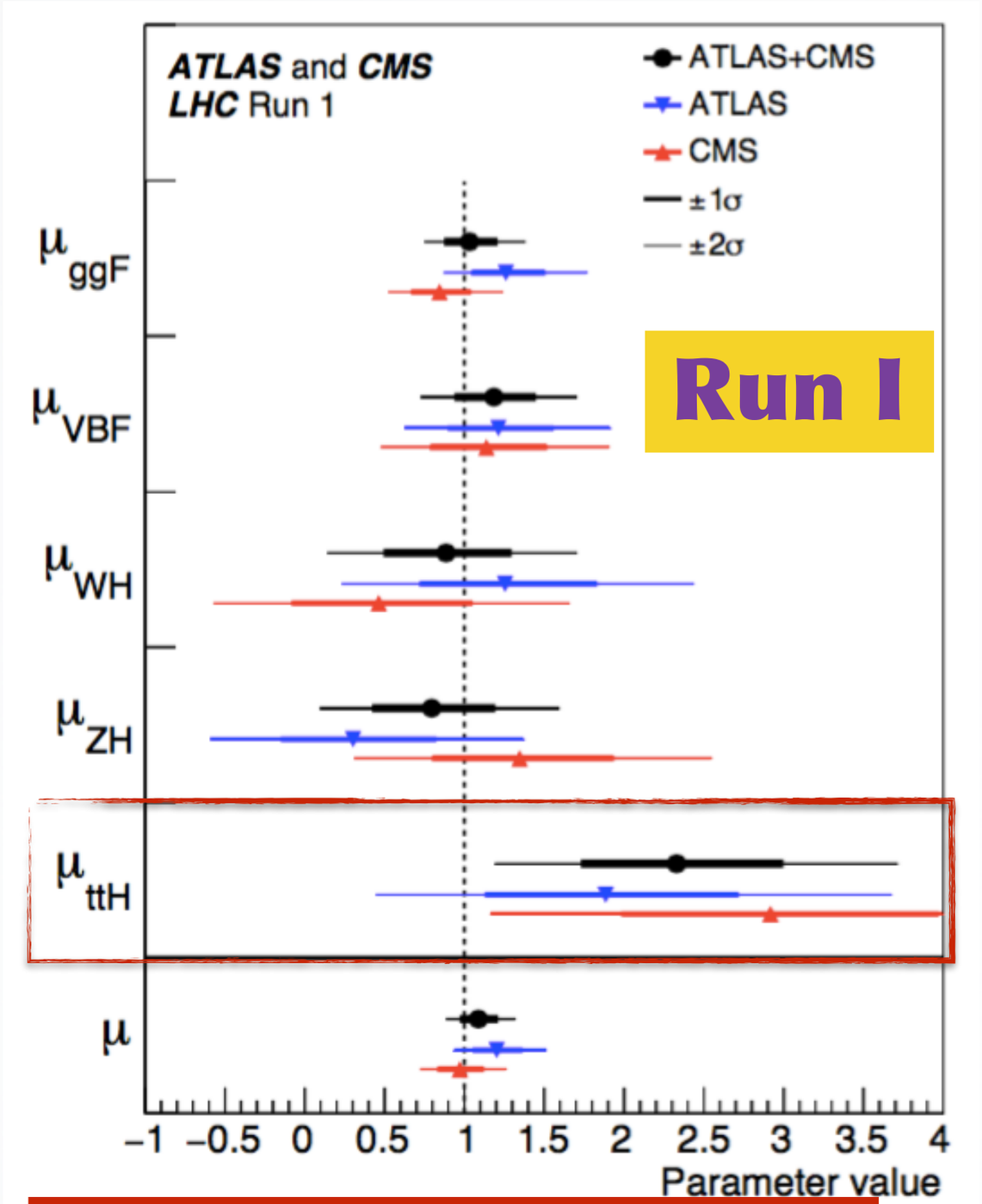
H→γγ





Hunt status before 2018

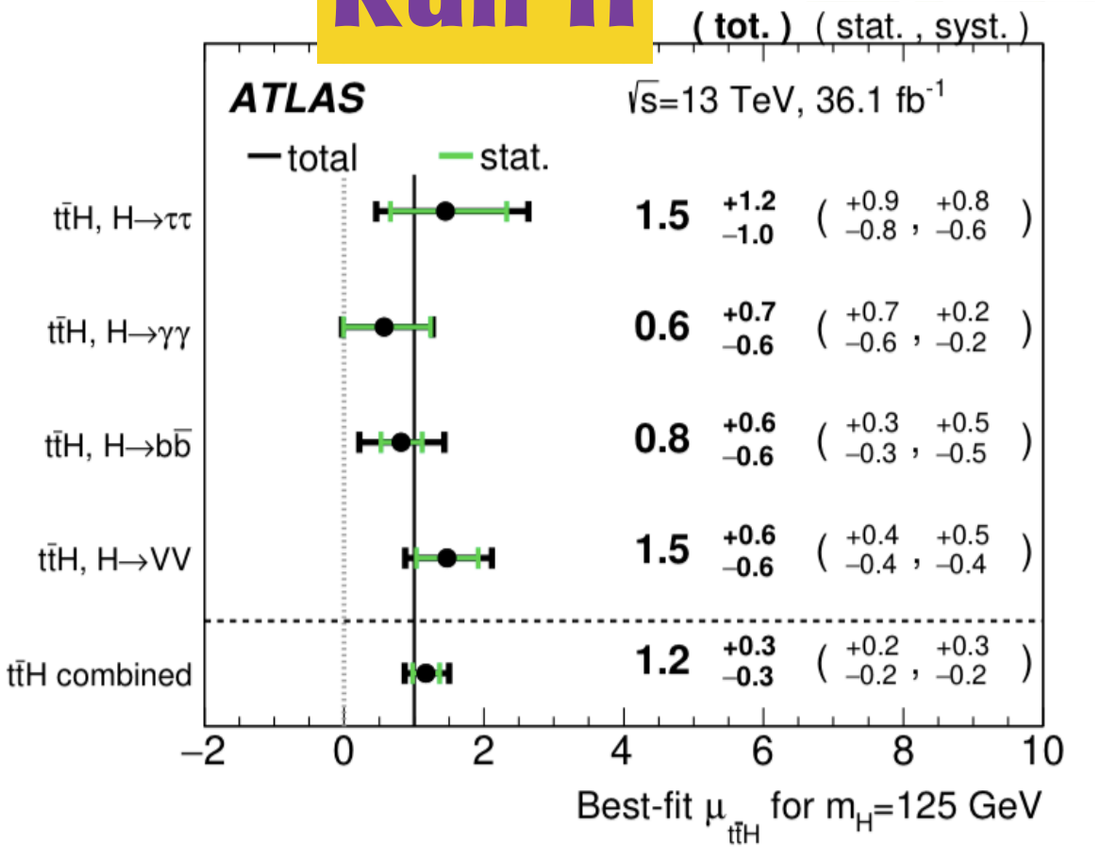
JHEP 08 (2016) 045



Run I

Significance@8 TeV = 4.4 (2.0) σ

Run II



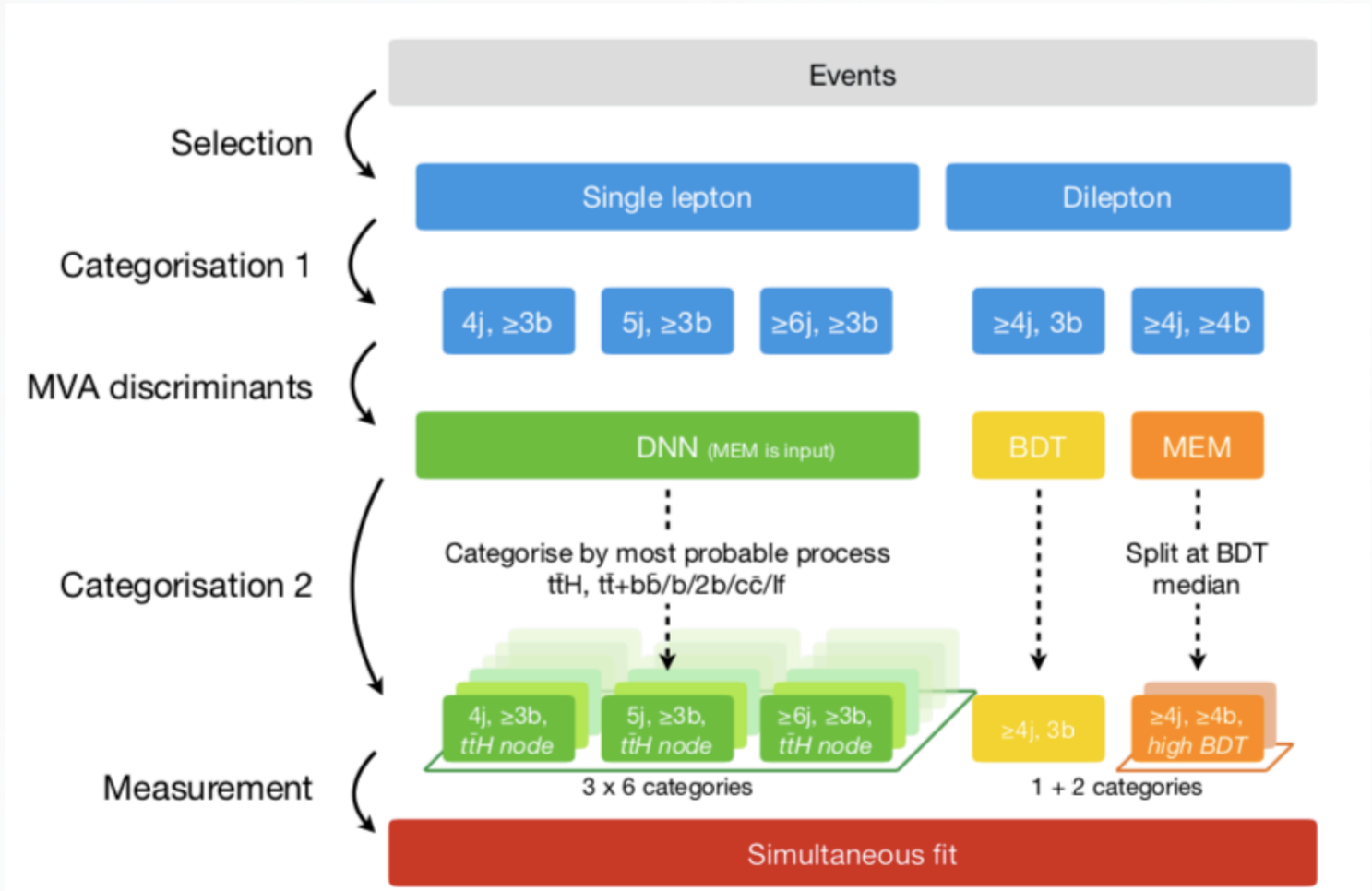
Significance@13 TeV = 4.2 (3.8) σ

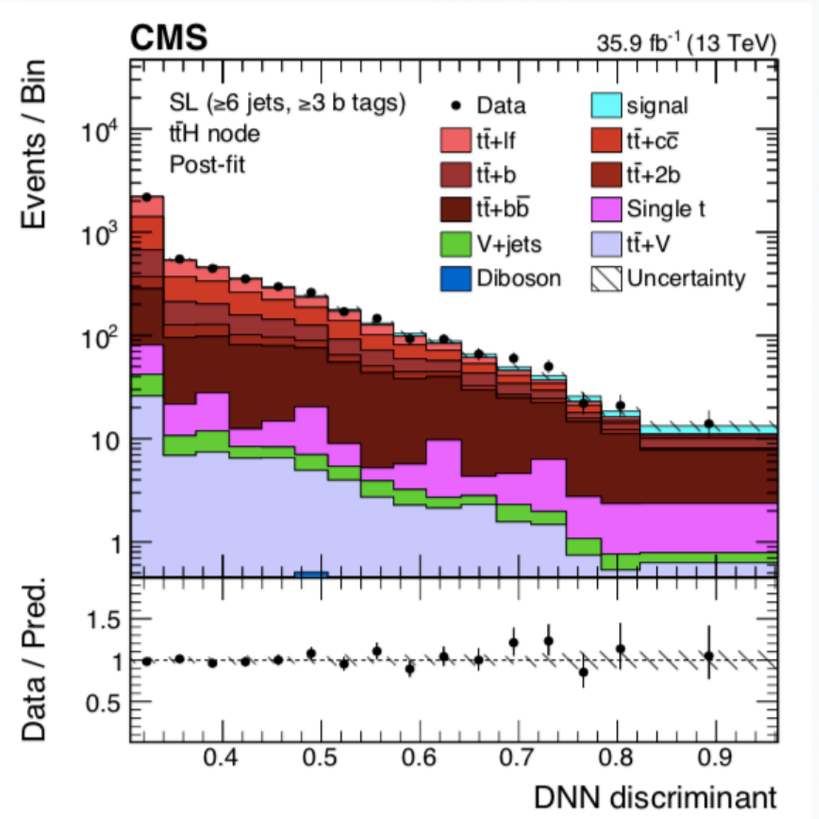
2016	2017	2018
3.3 (2.5)σ @13TeV	***4.4 (2.0)σ @8TeV***	***4.2 (3.8)σ @13TeV***
		> 5σ ?

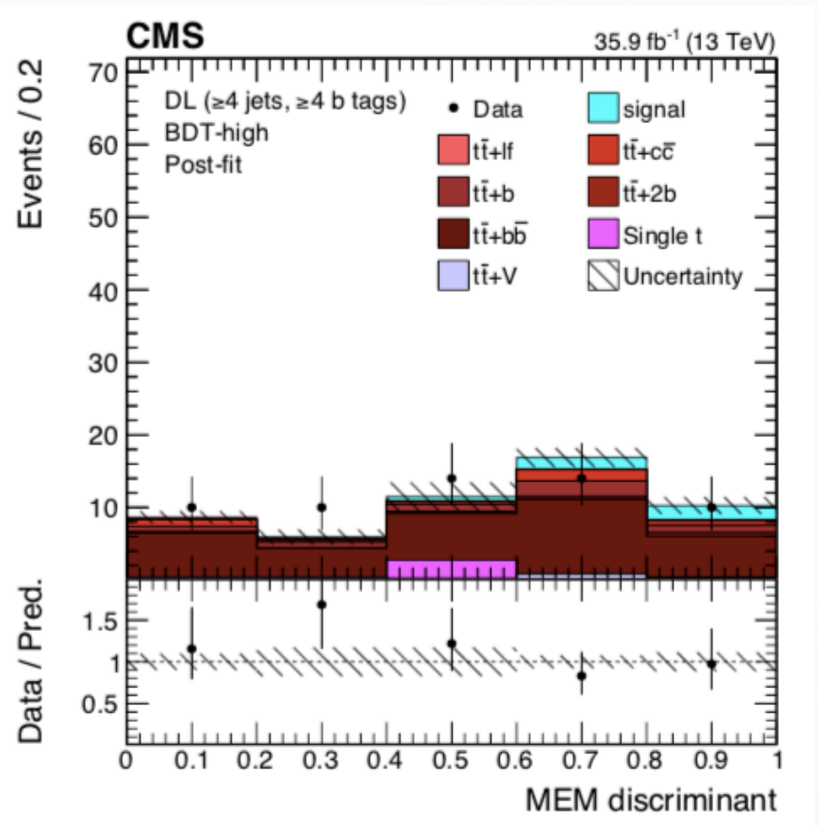
arXiv:1804.03682

ttH, H→bb

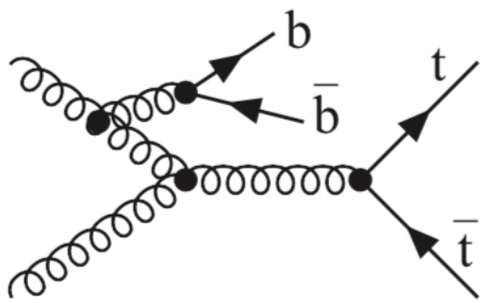
leptonic top decays







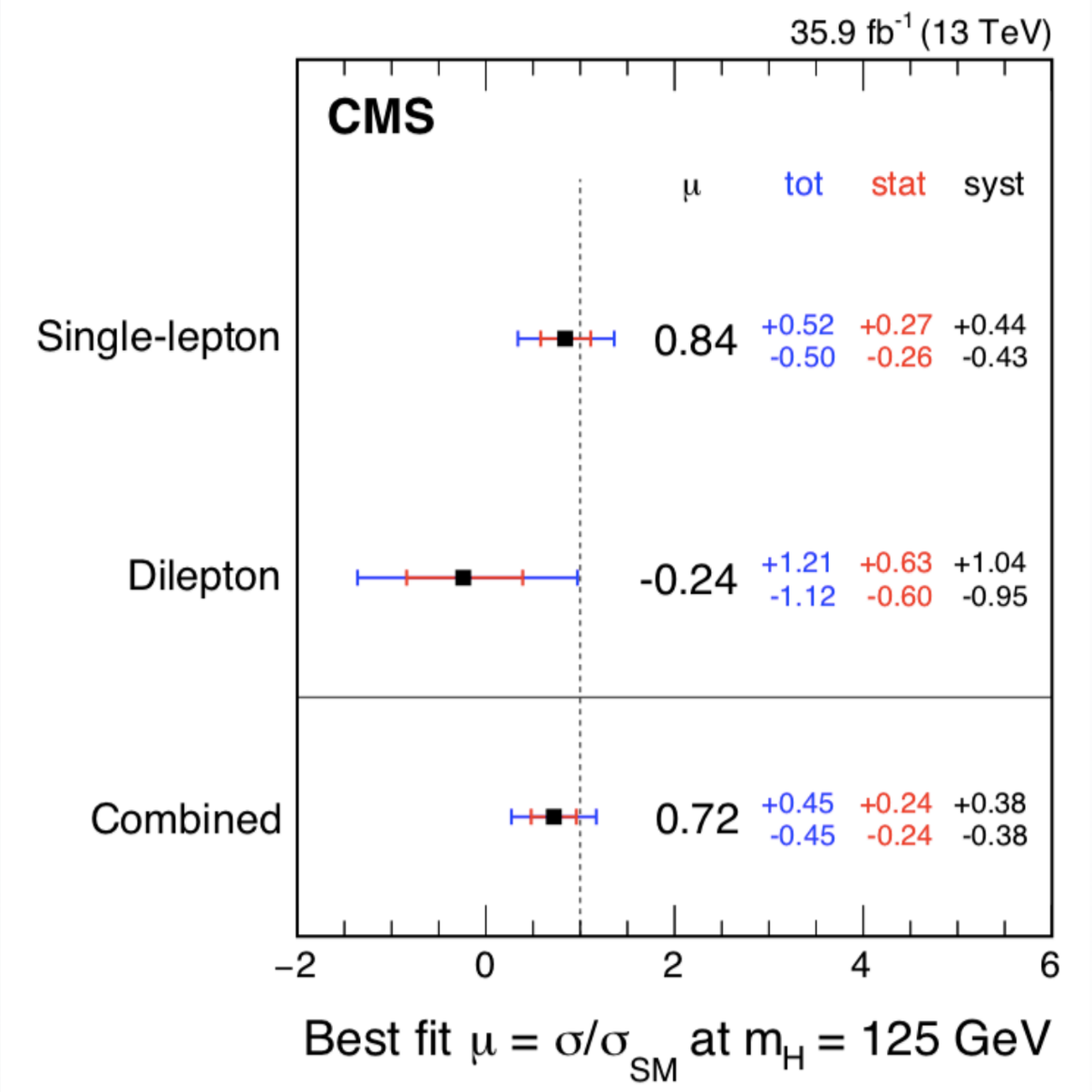
- Single lepton and dilepton channels
- At least three b-tagged jets
- Dominant background:
  tt+bb, tt+b, tt+cc, tt+c, tt+lf
- Sensitivity enhanced with DNN, BDT and MEM, and event categorisation

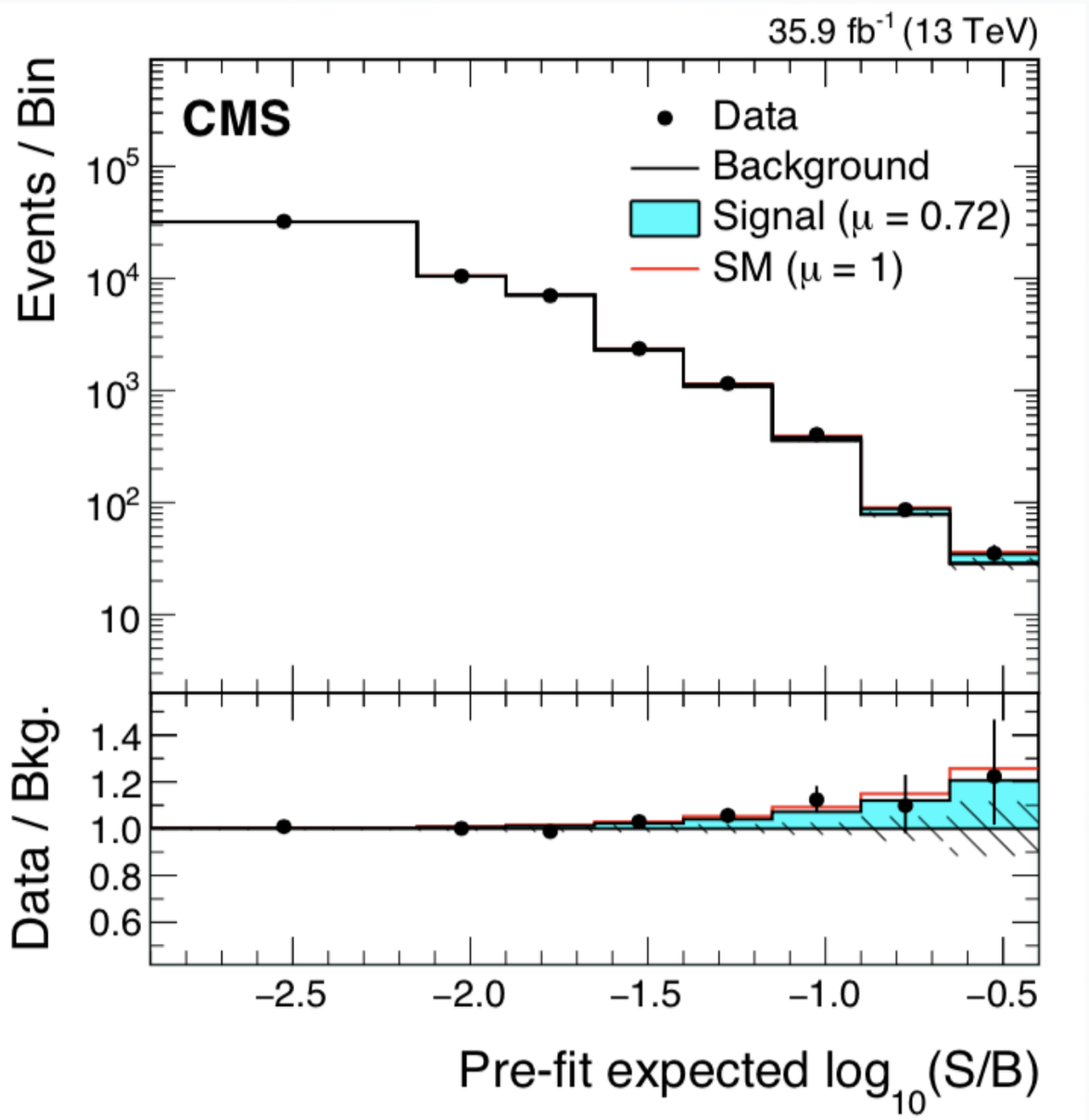


arXiv:1804.03682

ttH, H→bb

leptonic ttbar





Obs. (Exp.) Significance = 1.6σ (2.2σ)

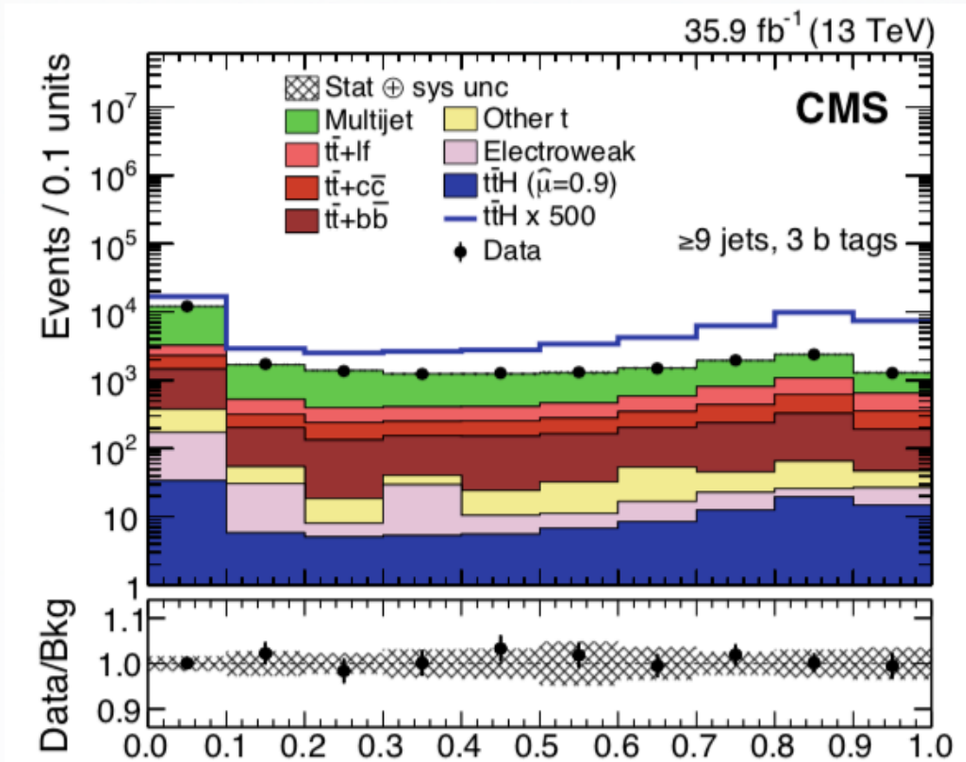
Want more ? Have a look at poster by Andrej Saibel

JHEP 06 (2018) 101

ttH, H→bb

fully hadronic

- Six exclusive event categories
- At least three b-tagged jets
- Full event reconstruction (no neutrinos in the final state)
- Dominant background: QCD multijet, tt+bb
- Data-driven estimate: QCD validation in the low b tag multiplicity control region
- Sensitivity enhanced with quark-gluon discriminant, MEM, and event categorisation

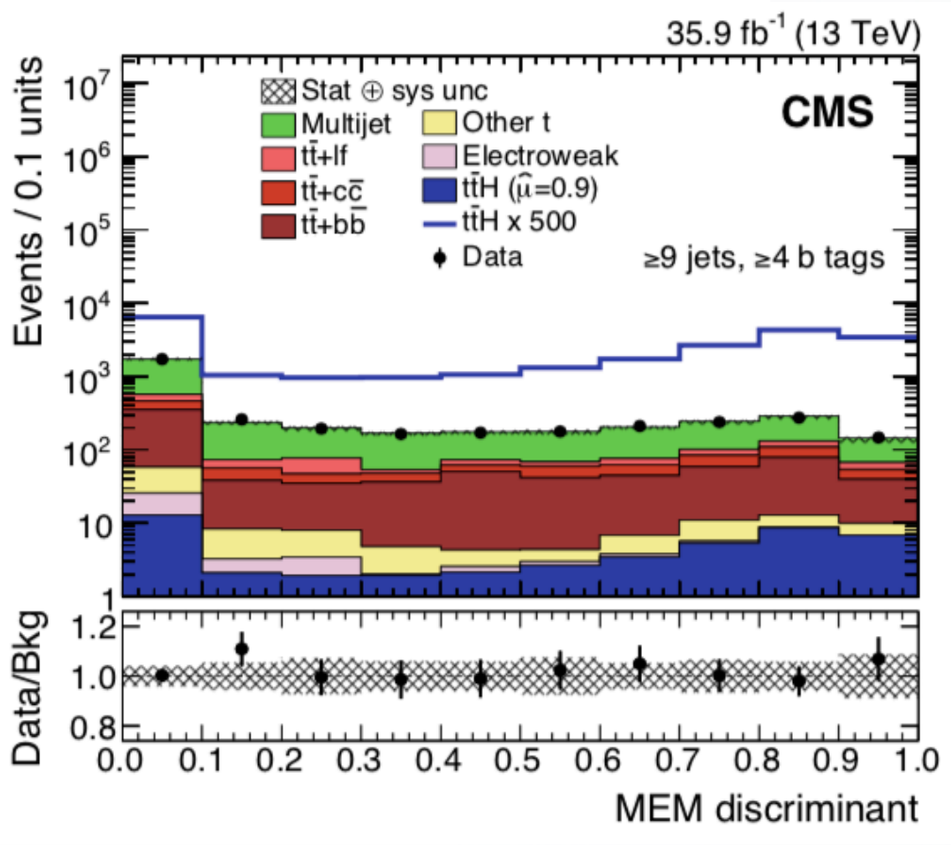


MEM

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

ttH

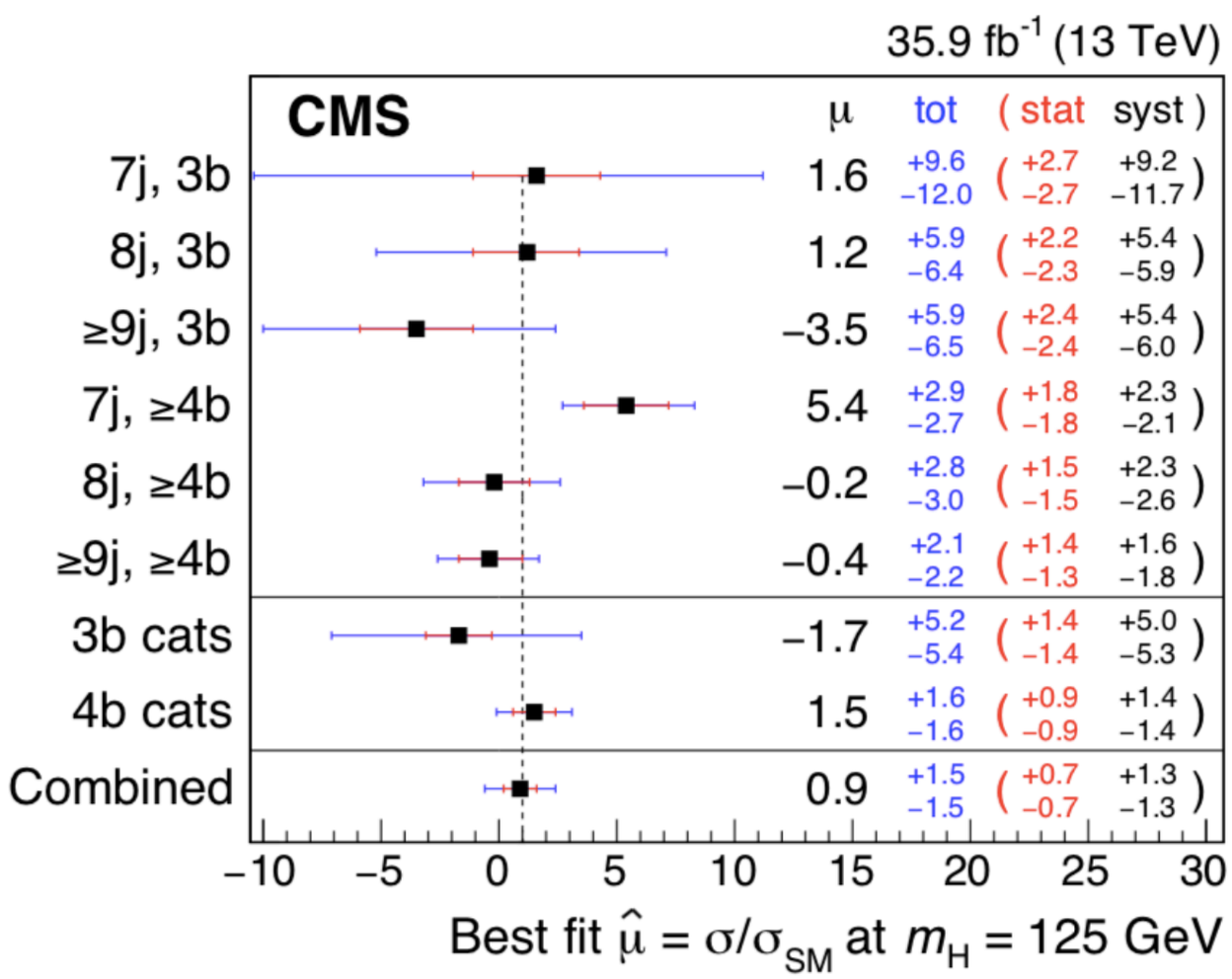
tt+bb

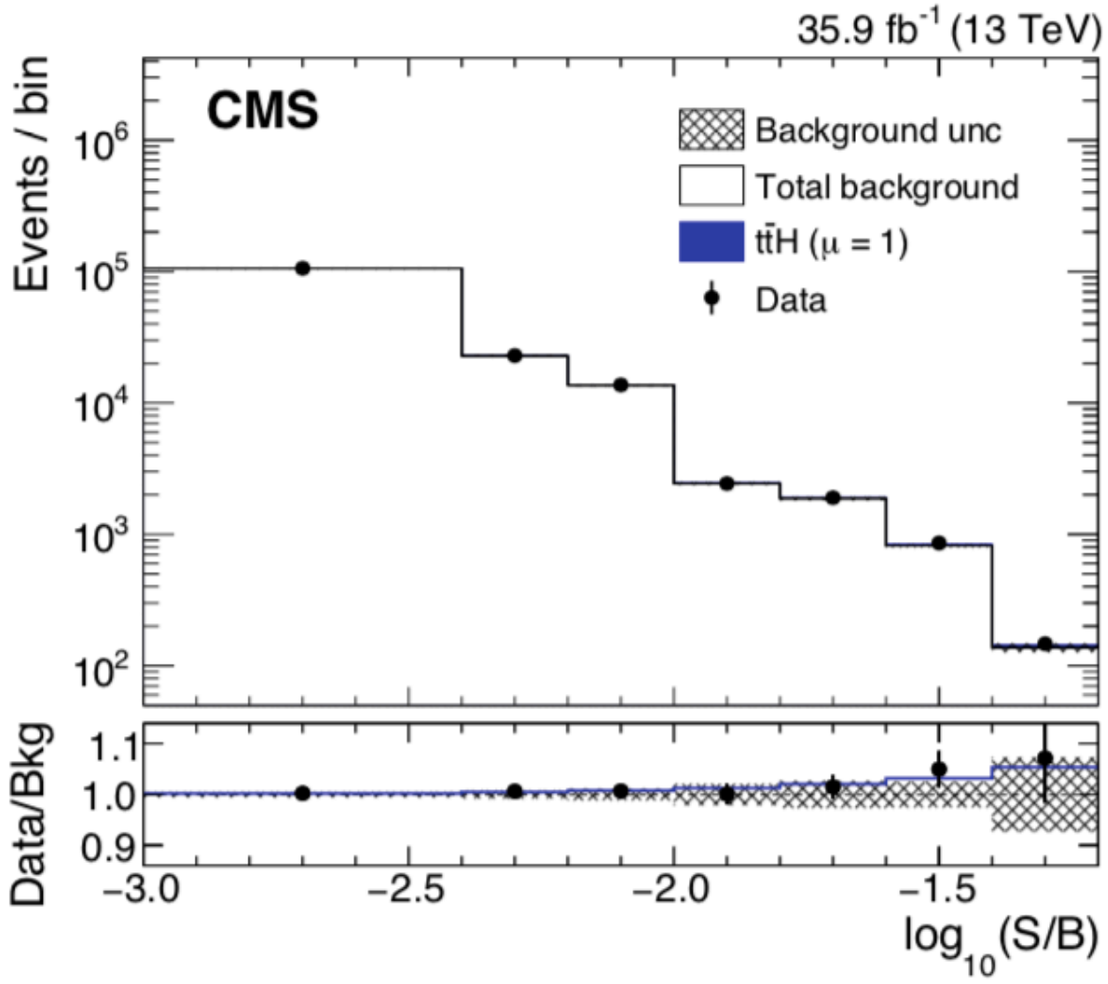


JHEP 06 (2018) 101

ttH, H→bb

fully hadronic



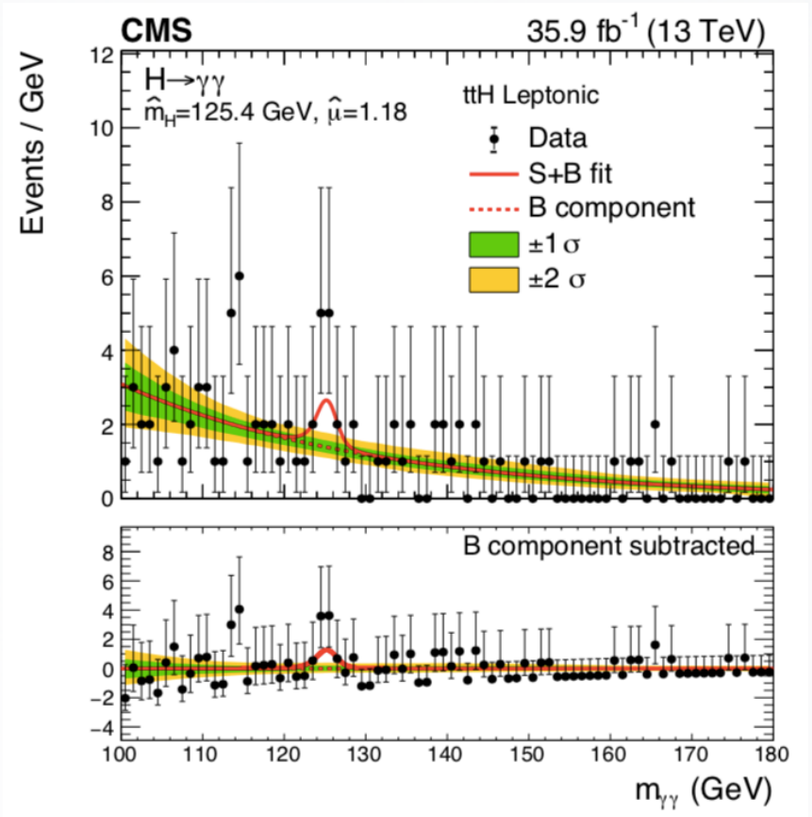


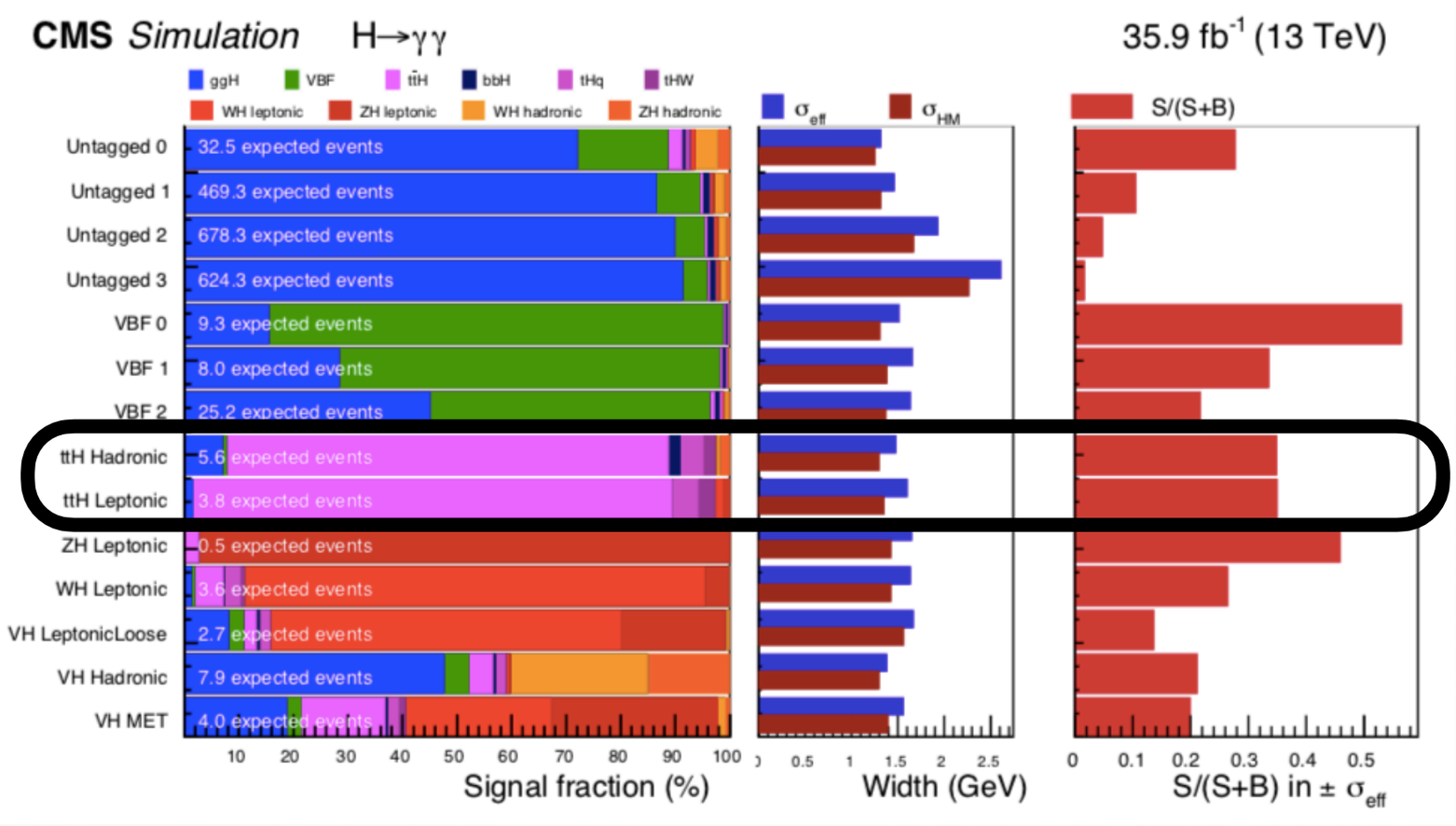
Obs. (exp.) μ < 3.8 (3.1) @95% CL

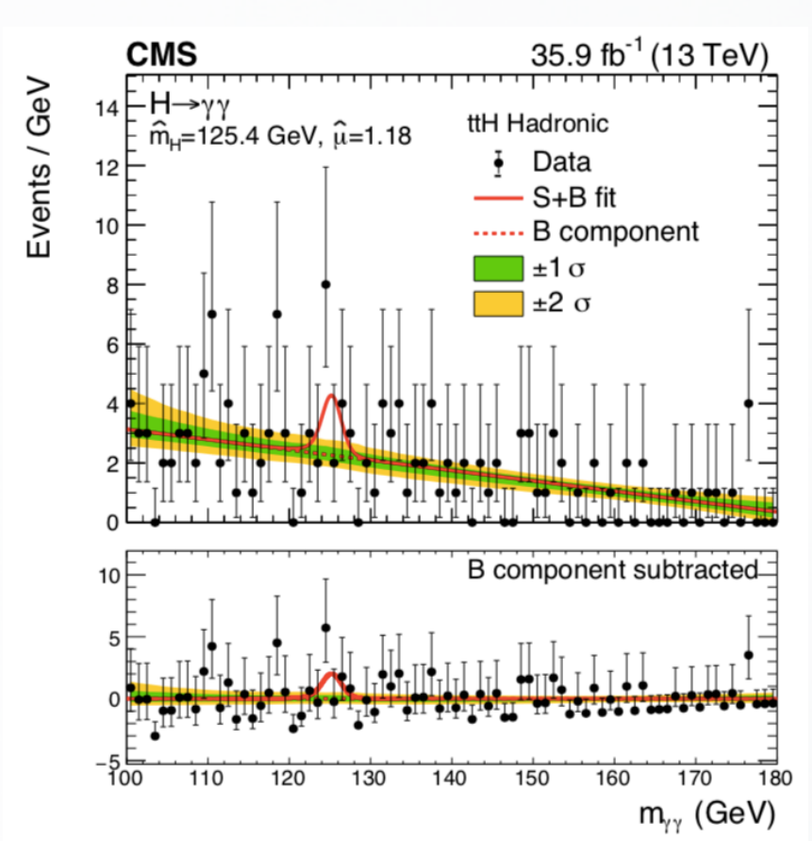
ttH, H→γγ

arXiv:1804.02716

- Two exclusive categories with semileptonic (at least one lepton) and hadronic ttbar
- At least two b-tagged jets
- Diphoton vertex assignment with BDT
- Dominant background: QCD multijet, γ+jets, γγ+jets
- Data-driven estimate: All backgrounds extracted from the fit to data

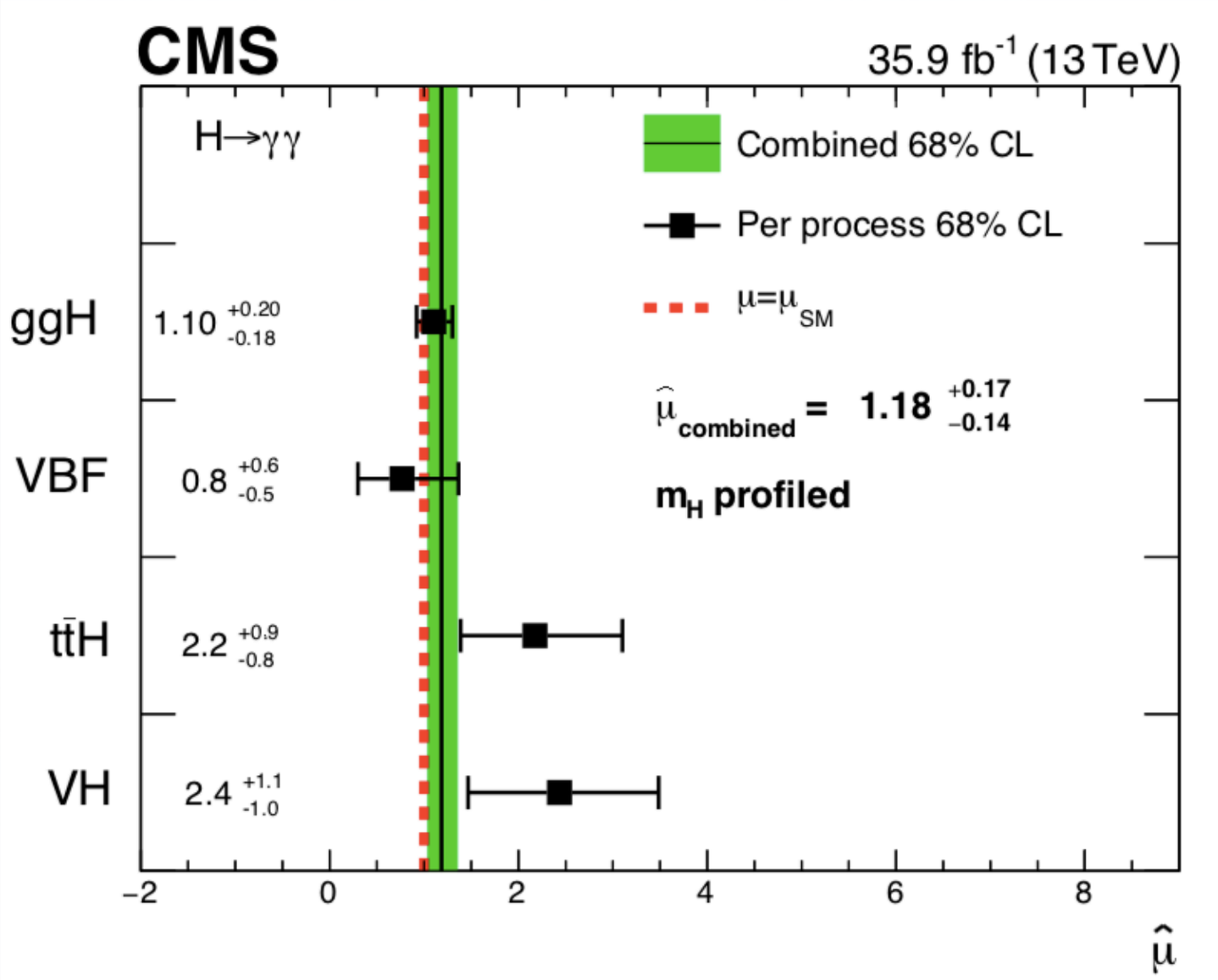






ttH, H→γγ

arXiv:1804.02716



Obs. (Exp.) Significance = 3.3σ (1.5σ)

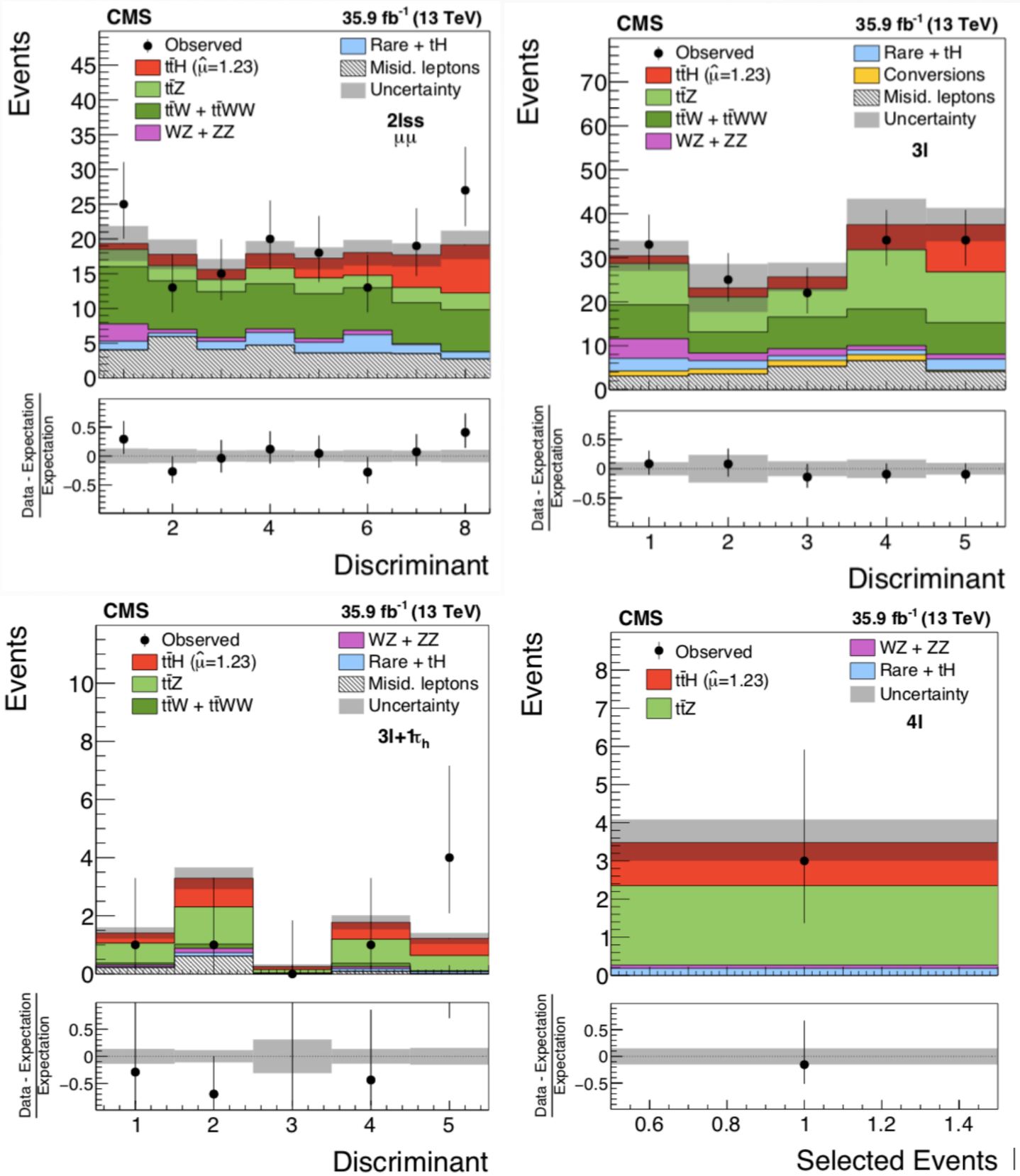
Evidence for ttH in diphotons !

ttH, H→WW/ZZ/ττ

JHEP 08 (2018) 066

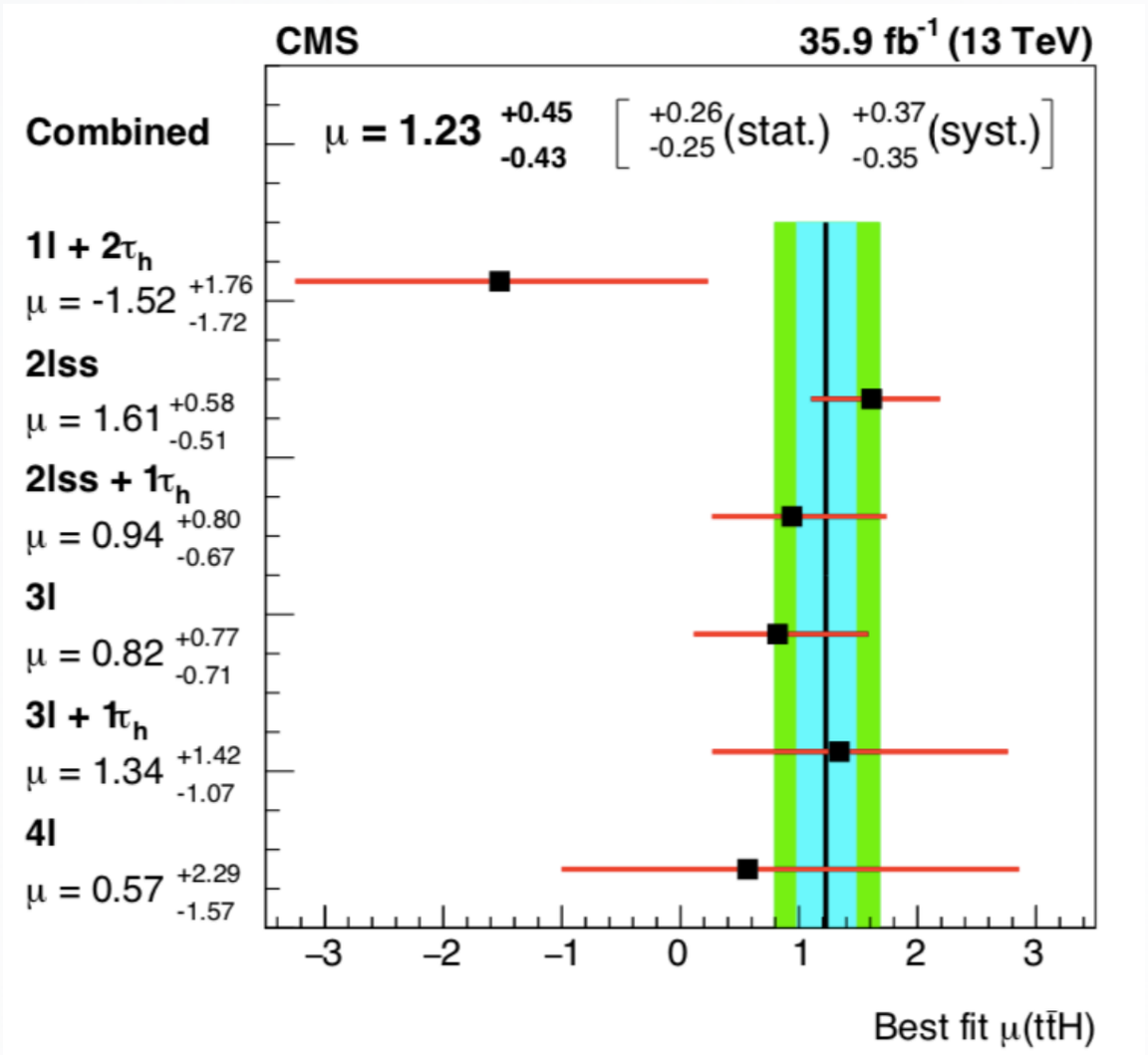
- Six exclusive event categories:
  - 1ℓ+2τ
  - 2ℓss, 2ℓss+τ
  - 3ℓ, 3ℓ+τ
  - 4ℓ
- Increased sensitivity to H→$\tau\tau$
- At least one tight or two loose b-tagged jets
- Dominant background: ttZ, ttW, misidentified leptons
- Data-driven estimate: misidentified leptons, lepton charge sign-flip
- Sensitivity enhanced with dedicated lepton MVA selection, event MEM and BDT

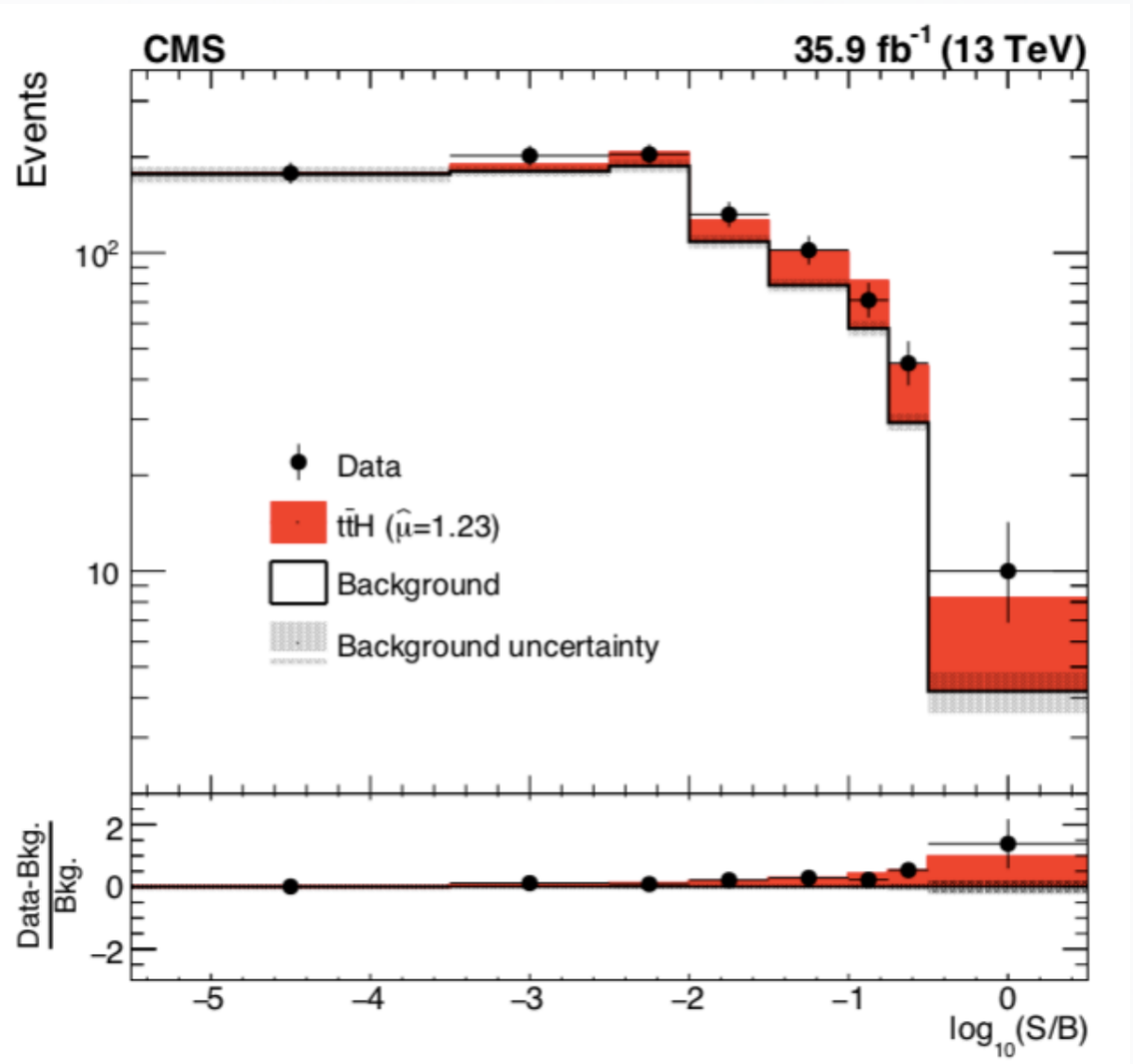
$$\mathrm{LR}(\mathbf{y}) = \frac{w_{\mathrm{t\bar{t}H}}(\mathbf{y})}{w_{\mathrm{t\bar{t}H}}(\mathbf{y}) + \sum_{\mathrm{B}} \kappa_{\mathrm{B}}\, w_{\mathrm{B}}(\mathbf{y})}$$



ttH, H→WW/ZZ/ττ

JHEP 08 (2018) 066



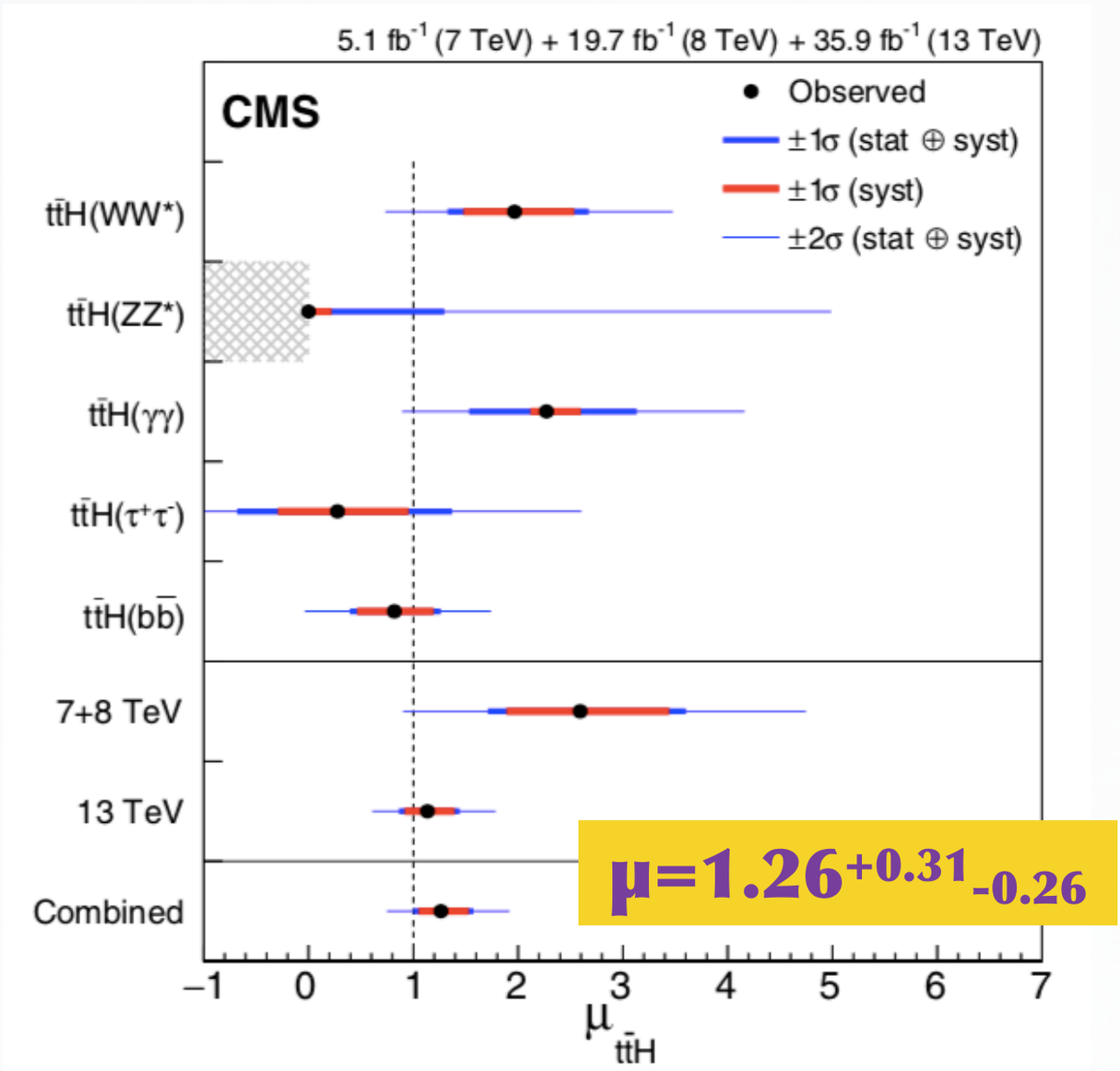


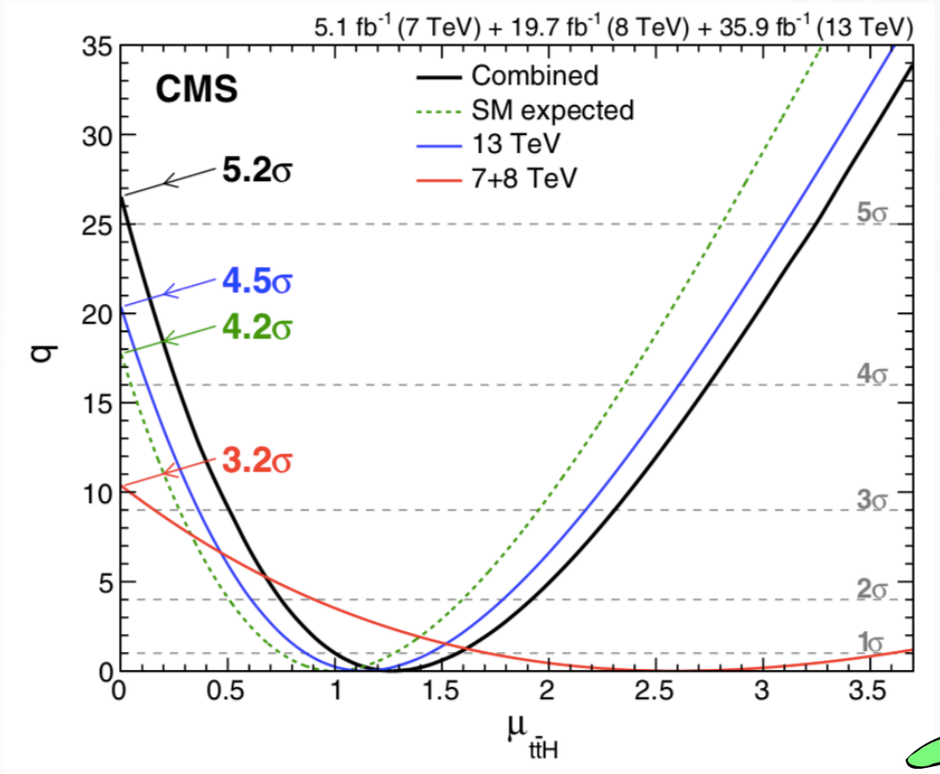
Obs. (Exp.) Significance = 3.2σ (2.8σ)

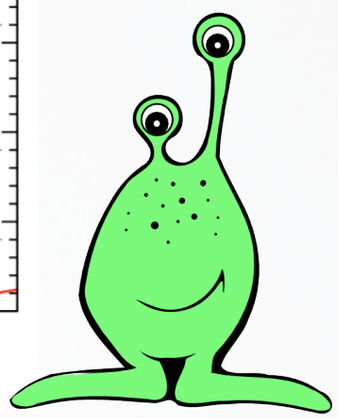
Evidence for ttH in multileptons !

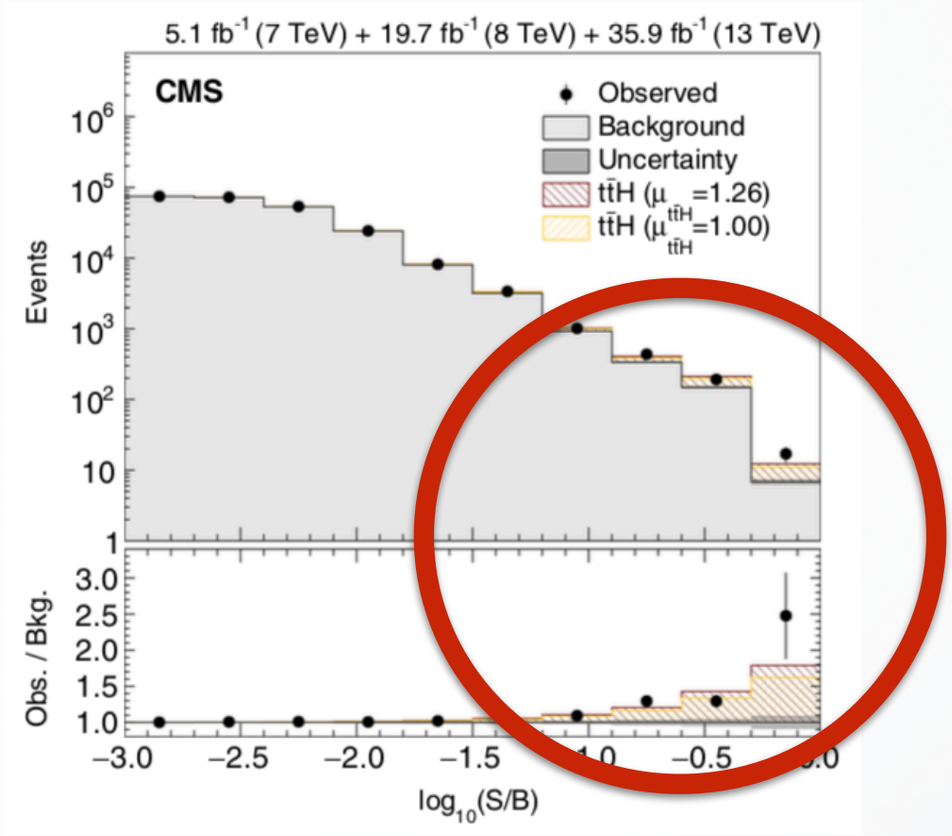
7+8+13 = Observation !

Phys. Rev. Lett. 120 (2018) 231801









- ★ Combination of results from 7 publications (≈ 20 exclusive search channels)
- ★ **Excess observed with the obs. (exp.) significance of 5.2σ (4.2σ)**

Uncertainties

Experimental

Lepton and b jet identification

Hadronic tau and jet energy scales

Theory

ttW, ttZ, tt+bb/cc modelling

ttH cross section (PDF, scale)

Statistical

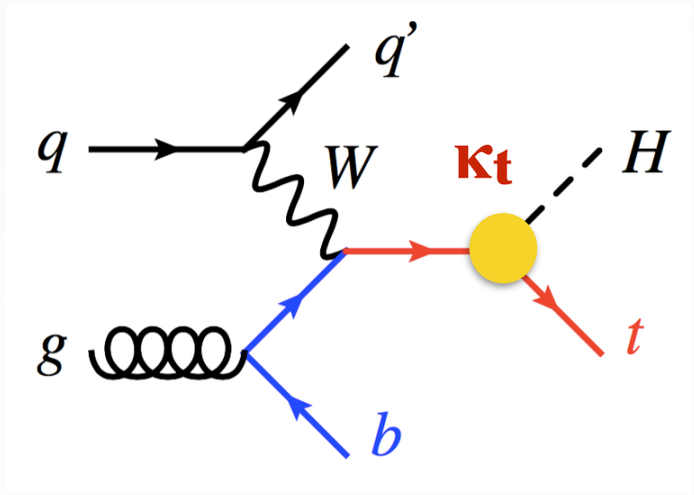
comparable to experimental and theory uncertainties

Parameter	Best fit	Uncertainty: Statistical	Experimental	Background theory	Signal theory
$\mu_{t\bar{t}H}^{WW^*}$	$1.97^{+0.71}_{-0.64}$	$^{+0.42}_{-0.41}$	$^{+0.46}_{-0.42}$	$^{+0.21}_{-0.21}$	$^{+0.25}_{-0.12}$
	$(^{+0.57}_{-0.54})$	$(^{+0.39}_{-0.38})$	$(^{+0.36}_{-0.34})$	$(^{+0.17}_{-0.17})$	$(^{+0.12}_{-0.03})$
$\mu_{t\bar{t}H}^{ZZ^*}$	$0.00^{+1.30}_{-0.00}$	$^{+1.28}_{-0.00}$	$^{+0.20}_{-0.00}$	$^{+0.04}_{-0.00}$	$^{+0.09}_{-0.00}$
	$(^{+2.89}_{-0.99})$	$(^{+2.82}_{-0.99})$	$(^{+0.51}_{-0.00})$	$(^{+0.15}_{-0.00})$	$(^{+0.27}_{-0.00})$
$\mu_{t\bar{t}H}^{\gamma\gamma}$	$2.27^{+0.86}_{-0.74}$	$^{+0.80}_{-0.72}$	$^{+0.15}_{-0.09}$	$^{+0.02}_{-0.01}$	$^{+0.29}_{-0.13}$
	$(^{+0.73}_{-0.64})$	$(^{+0.71}_{-0.64})$	$(^{+0.09}_{-0.04})$	$(^{+0.01}_{-0.00})$	$(^{+0.13}_{-0.05})$
$\mu_{t\bar{t}H}^{\tau^+\tau^-}$	$0.28^{+1.09}_{-0.96}$	$^{+0.86}_{-0.77}$	$^{+0.64}_{-0.53}$	$^{+0.10}_{-0.09}$	$^{+0.20}_{-0.19}$
	$(^{+1.00}_{-0.89})$	$(^{+0.83}_{-0.76})$	$(^{+0.54}_{-0.47})$	$(^{+0.09}_{-0.08})$	$(^{+0.14}_{-0.01})$
$\mu_{t\bar{t}H}^{b\bar{b}}$	$0.82^{+0.44}_{-0.42}$	$^{+0.23}_{-0.23}$	$^{+0.24}_{-0.23}$	$^{+0.27}_{-0.27}$	$^{+0.11}_{-0.03}$
	$(^{+0.44}_{-0.42})$	$(^{+0.23}_{-0.22})$	$(^{+0.24}_{-0.23})$	$(^{+0.26}_{-0.27})$	$(^{+0.11}_{-0.04})$
$\mu_{t\bar{t}H}^{7+8\ \mathrm{TeV}}$	$2.59^{+1.01}_{-0.88}$	$^{+0.54}_{-0.53}$	$^{+0.53}_{-0.49}$	$^{+0.55}_{-0.49}$	$^{+0.37}_{-0.13}$
	$(^{+0.87}_{-0.79})$	$(^{+0.51}_{-0.49})$	$(^{+0.48}_{-0.44})$	$(^{+0.50}_{-0.44})$	$(^{+0.14}_{-0.02})$
$\mu_{t\bar{t}H}^{13\ \mathrm{TeV}}$	$1.14^{+0.31}_{-0.27}$	$^{+0.17}_{-0.16}$	$^{+0.17}_{-0.17}$	$^{+0.13}_{-0.12}$	$^{+0.14}_{-0.06}$
	$(^{+0.29}_{-0.26})$	$(^{+0.16}_{-0.16})$	$(^{+0.17}_{-0.16})$	$(^{+0.13}_{-0.12})$	$(^{+0.11}_{-0.05})$
$\mu_{t\bar{t}H}$	$1.26^{+0.31}_{-0.26}$	$^{+0.16}_{-0.16}$	$^{+0.17}_{-0.15}$	$^{+0.14}_{-0.13}$	$^{+0.15}_{-0.07}$
	$(^{+0.28}_{-0.25})$	$(^{+0.15}_{-0.15})$	$(^{+0.16}_{-0.15})$	$(^{+0.13}_{-0.12})$	$(^{+0.11}_{-0.05})$

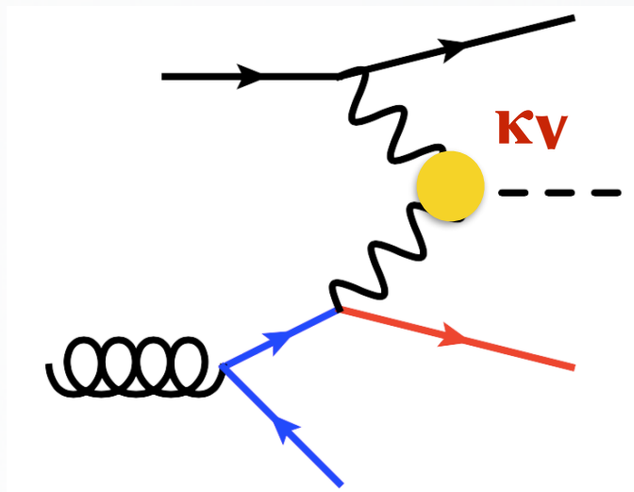
Phys. Rev. Lett. 120 (2018) 231801

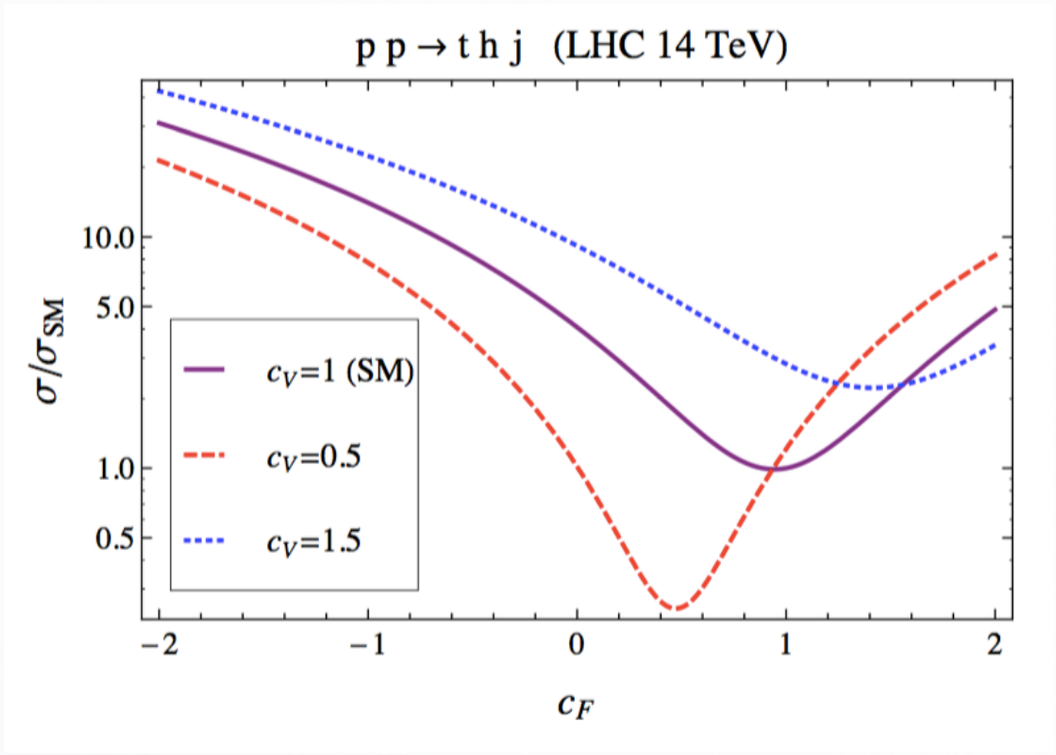
And what about tHq ?

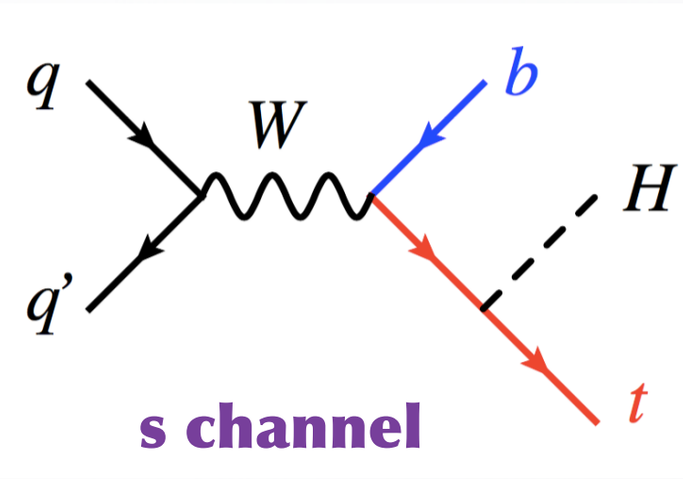
- Suppressed in SM by destructive interference: $\kappa_t \cdot \kappa_V < 0$
- **tHq is sensitive to both magnitude and sign of κ_t**
- BSM can be looked for by probing **negative κ_t** still allowed from global fits
- 15x increase in tHq cross section assuming inverted coupling scenario, $\kappa_t = -1$



t channel



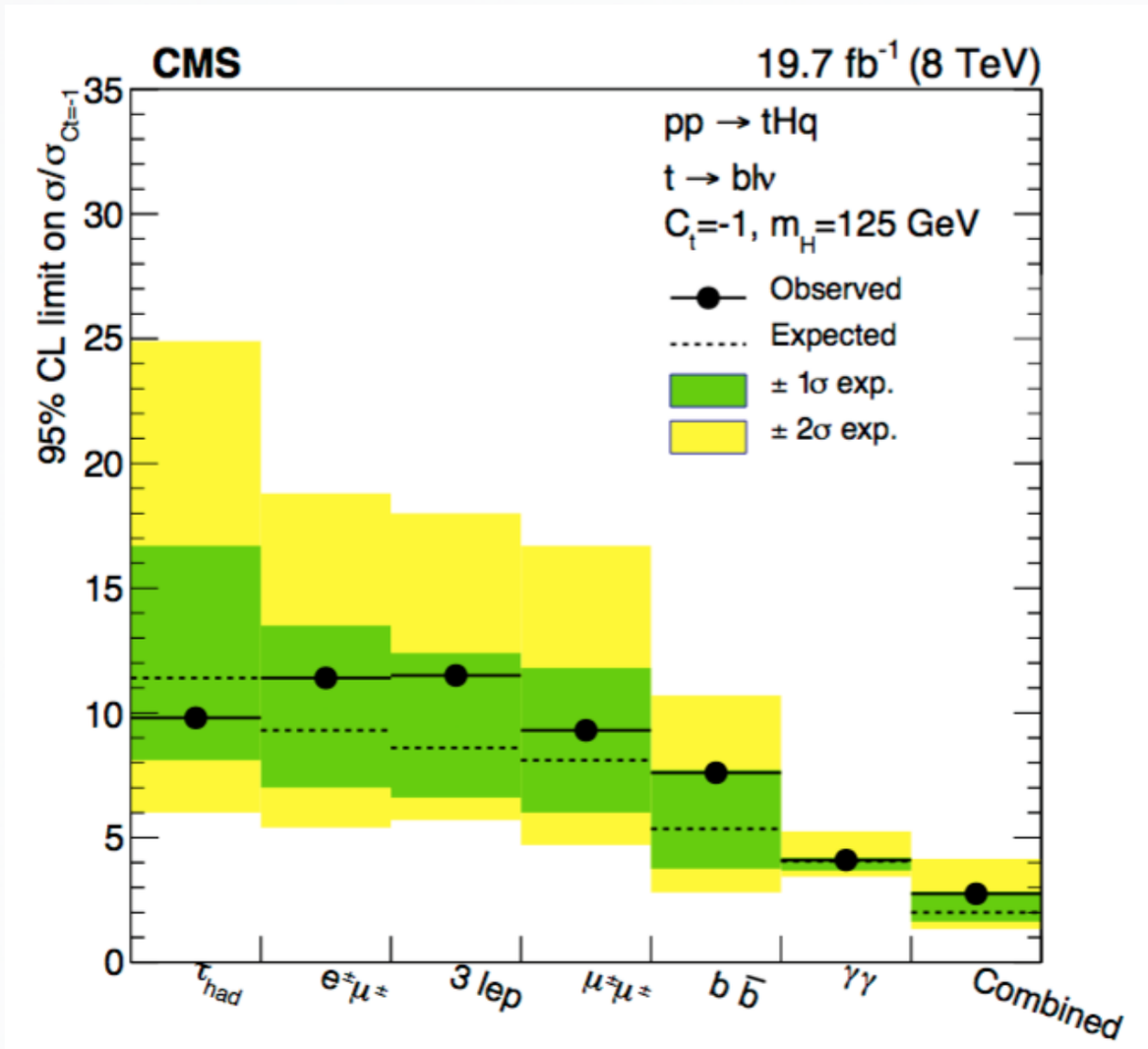


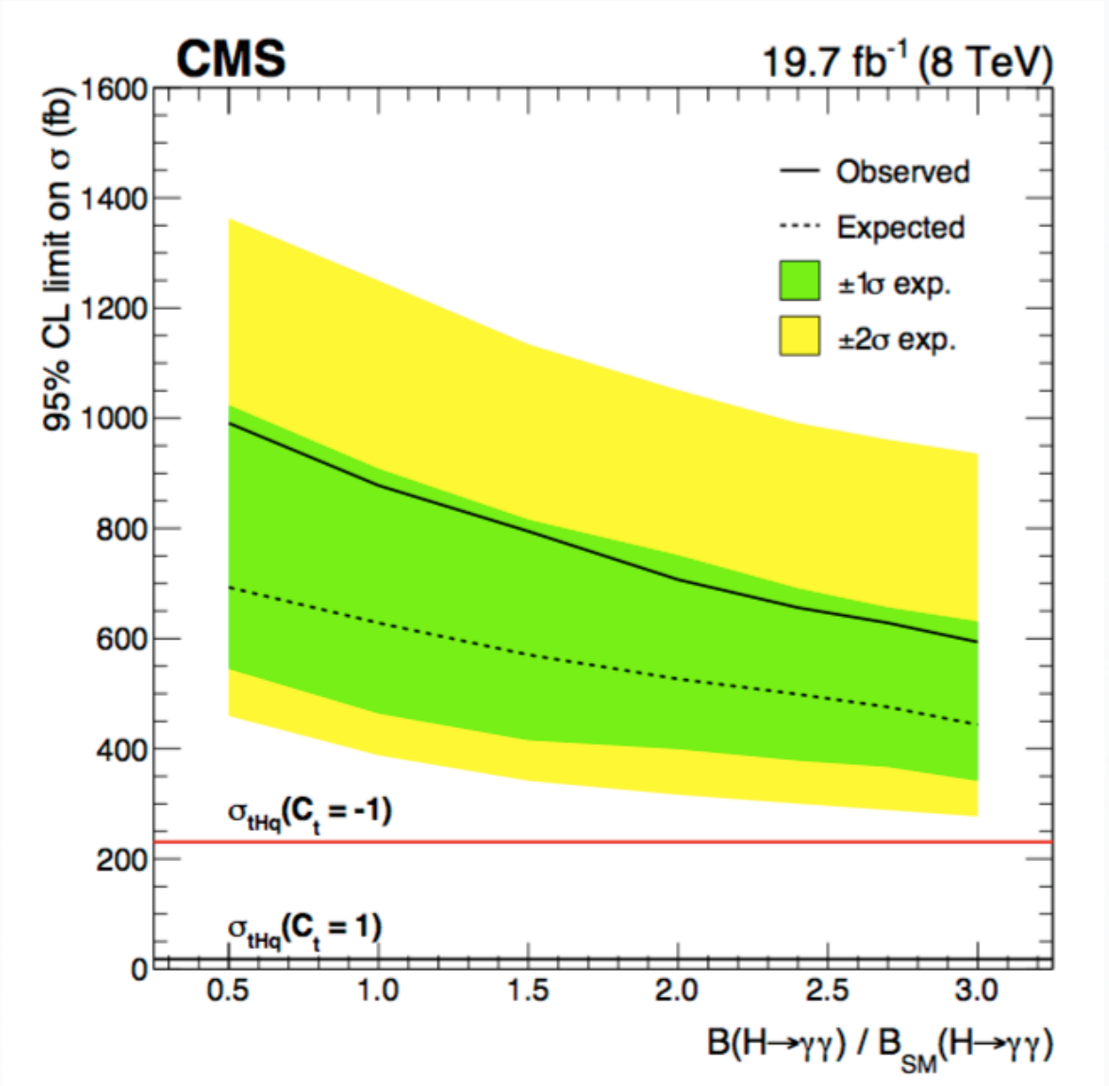


s channel

J. High Energ. Phys. (2013) 2013: 22

tHq at 8 TeV



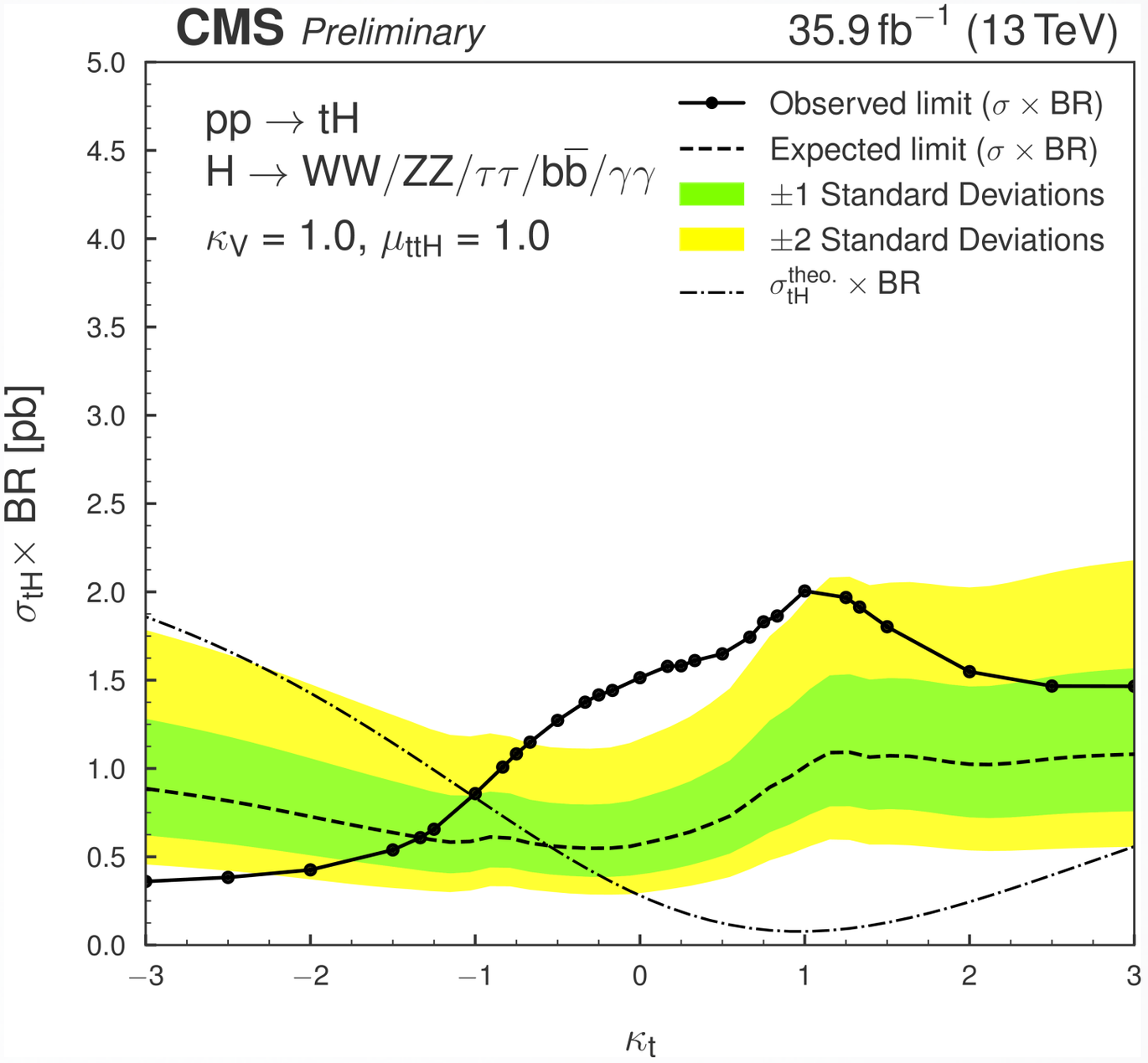


JHEP06 (2016) 177

tHq at 13 TeV

CMS PAS HIG-18-009

- Dedicated analysis in H→WW/ZZ/ **ττ** and H→bb channels, and reinterpretation of the ttH (H→**γγ**) result
- The observed excess over the non-Higgs background compatible with the tHq+ttH SM prediction within two s.d.
- Excluding the cross section of 26 x SM tHq x BR = 2.0 pb (95% CL)



Conclusion

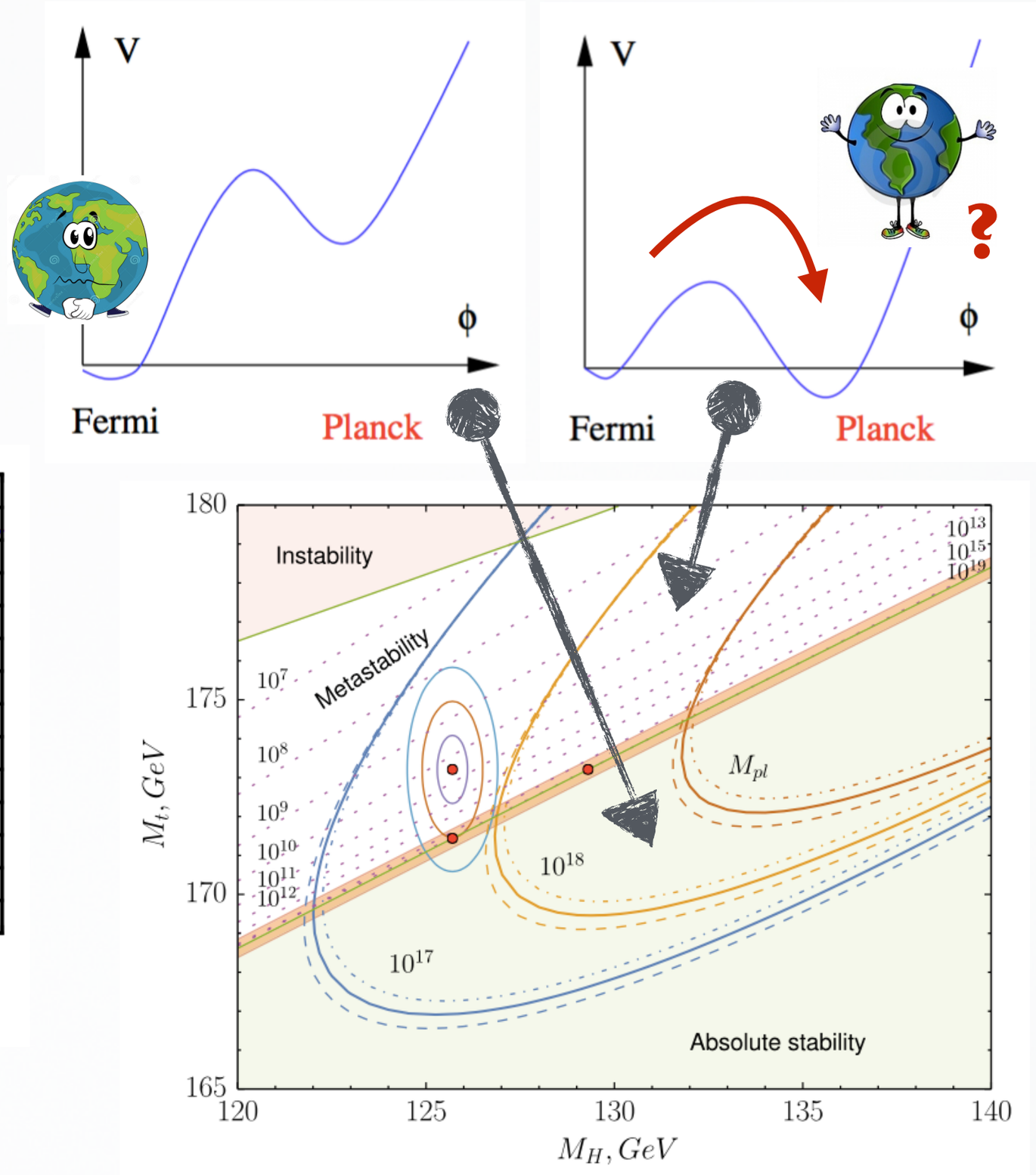
- ★ The observation of the ttH production is our very first step towards the direct study of the top-Higgs interaction
- ★ These two heaviest elementary particles of the standard model may open heavy doors to new discoveries
- ★ Still have more CMS data to analyse before the LHC long shutdown
- ★ From the first ttH observation to differential cross section measurements and precise y_t determination possible at future colliders !

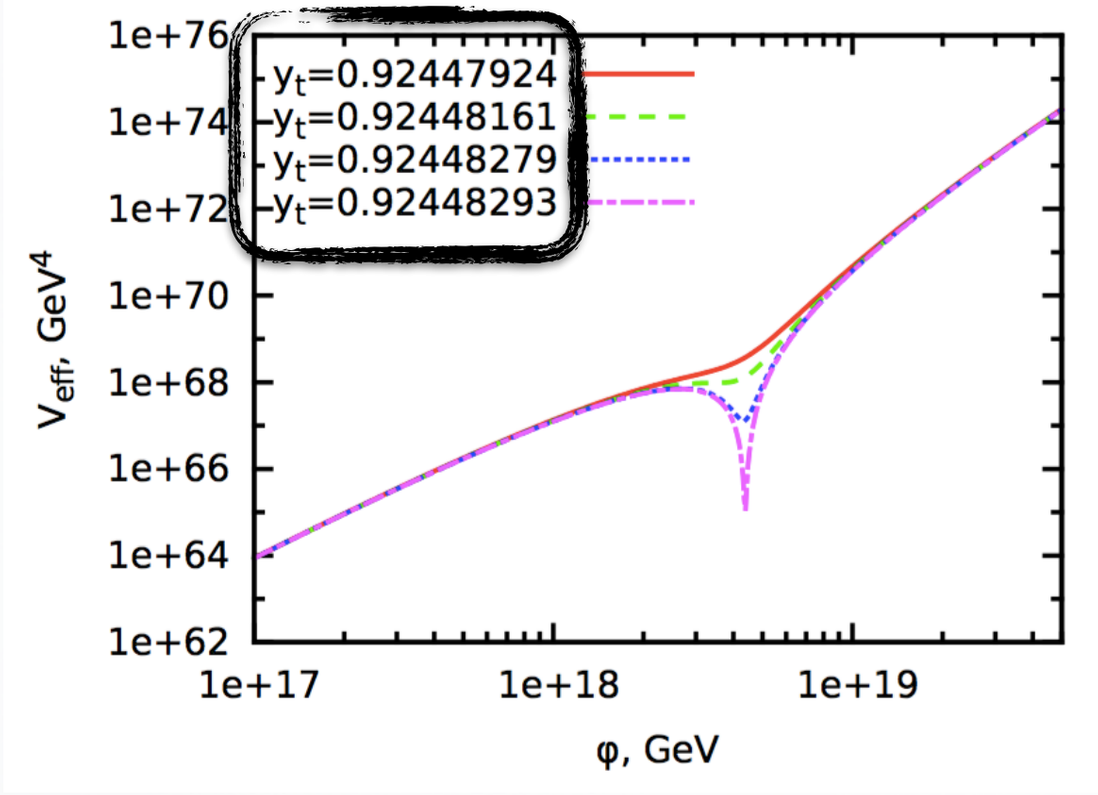
Backup

Why to study ?

- Test of the standard model
- Strongly connected to the vacuum stability
- Precise determination of the top quark Yukawa coupling is important

stability **metastability/instability**

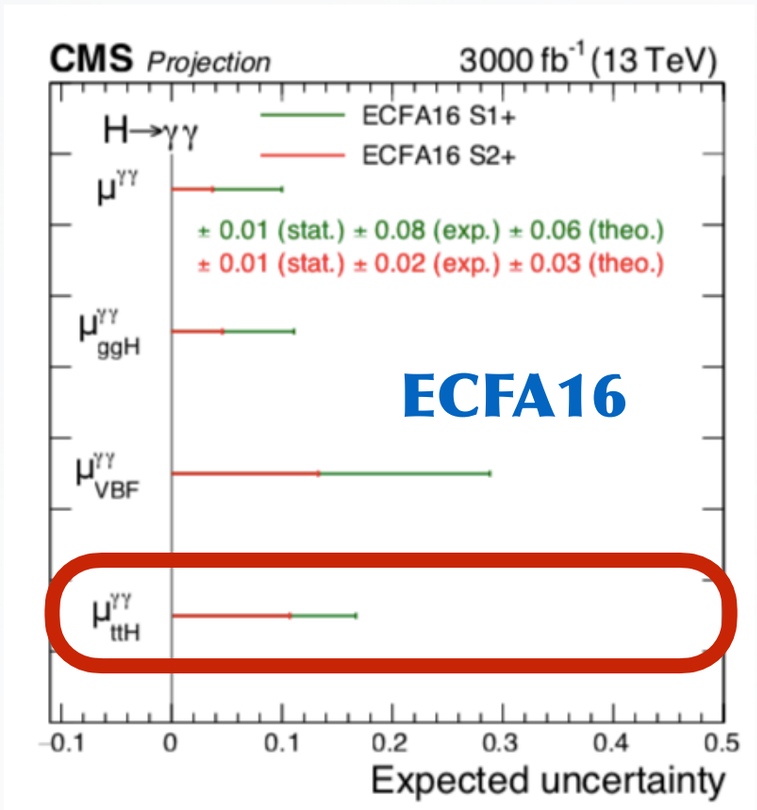


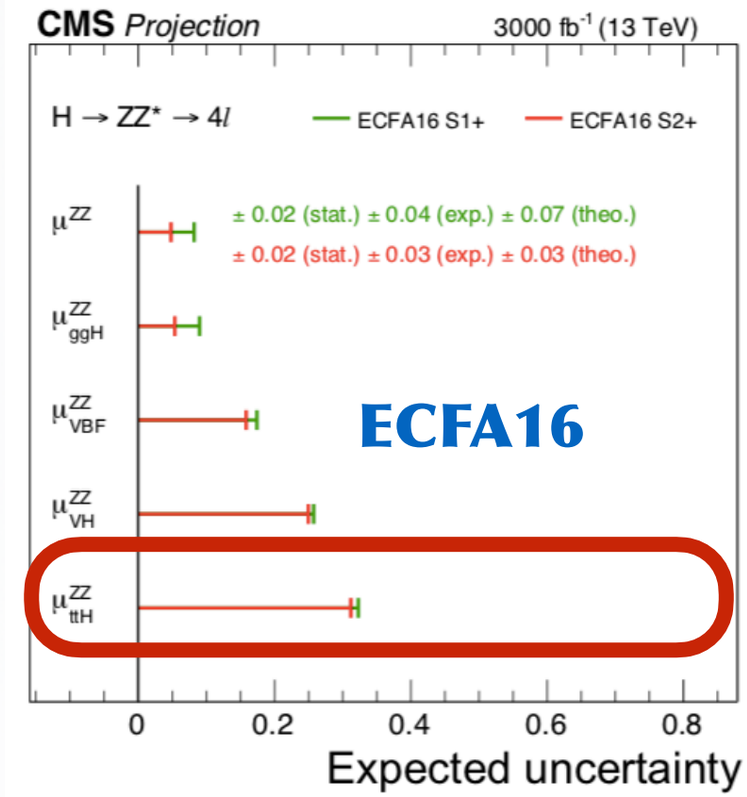


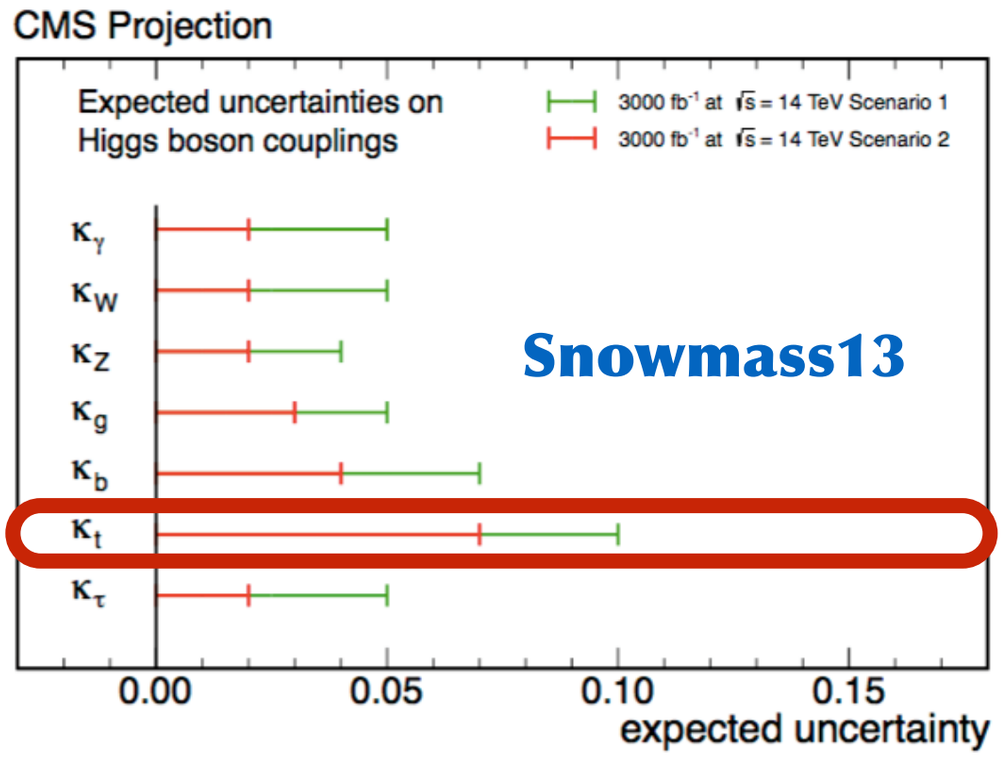
JHEP 10 (2012) 140

J. Exp. Theor. Phys. 120 (2015) 335

Future prospects







CMS PAS FTR-16-002

arXiv:1307.7135

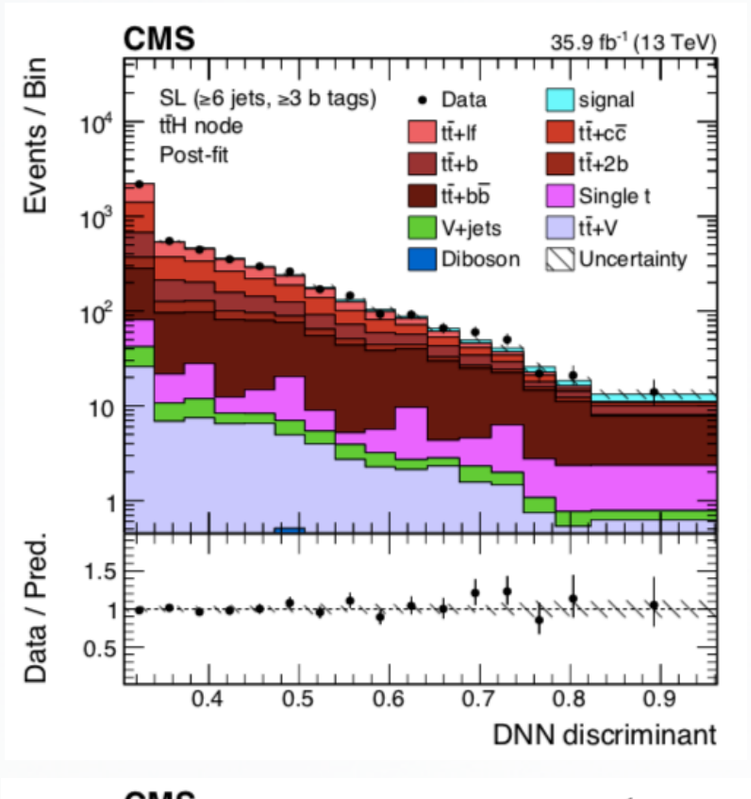
- ☆ The top-Higgs interaction can be studied at various future machines: HL-LHC, FCC, ILC, etc.
- ☆ Possible to reach ≈5% uncertainty in y_t at HL-LHC !

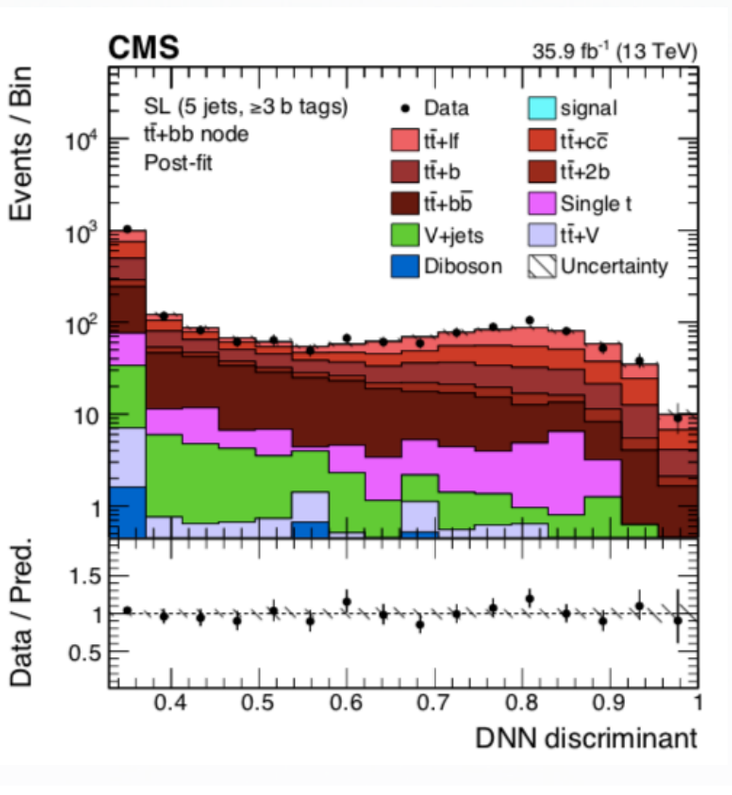
- ***Scenario 1***: systematics unchanged
- ***Scenario 2***: scale theoretical uncertainties by 1/2, others are scaled by IL

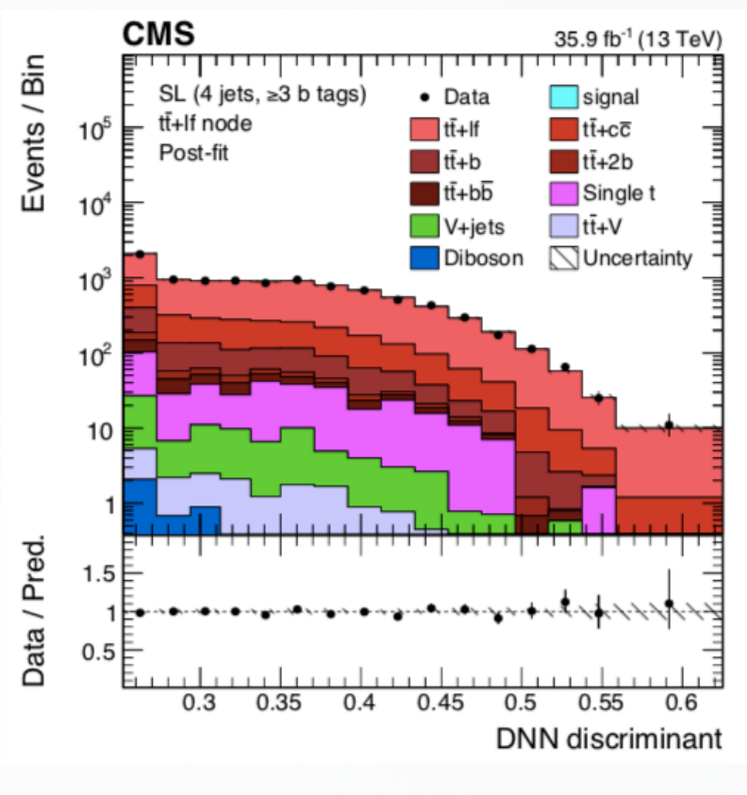
Collider	HL-LHC	ILC	LC 1-3 TeV	FCC-ee+hh
λ_t	4%	14%	2 – 4%	1 – 2%
λ_H	50%	83%	10 – 15%	5 – 10%

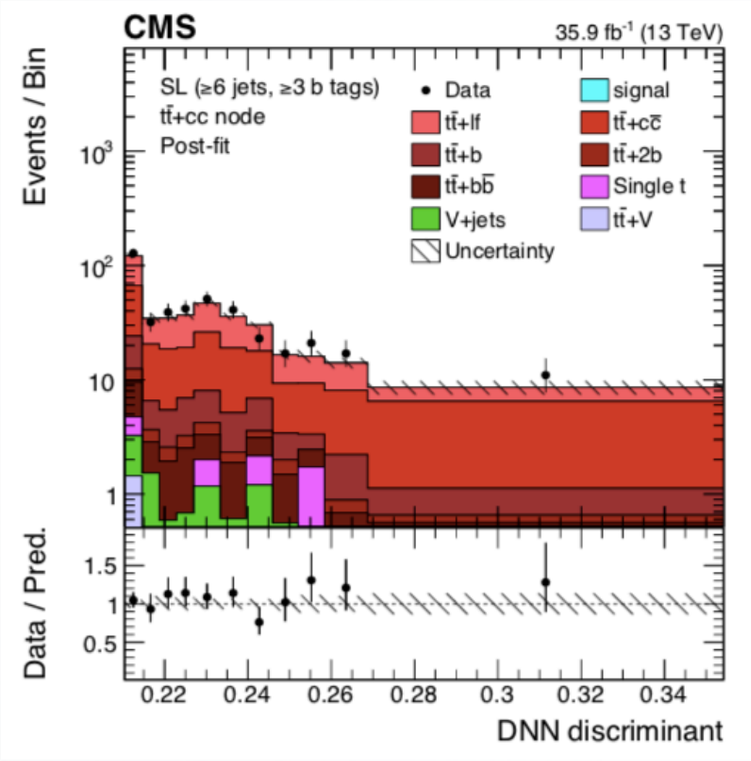
arXiv:1510.09056

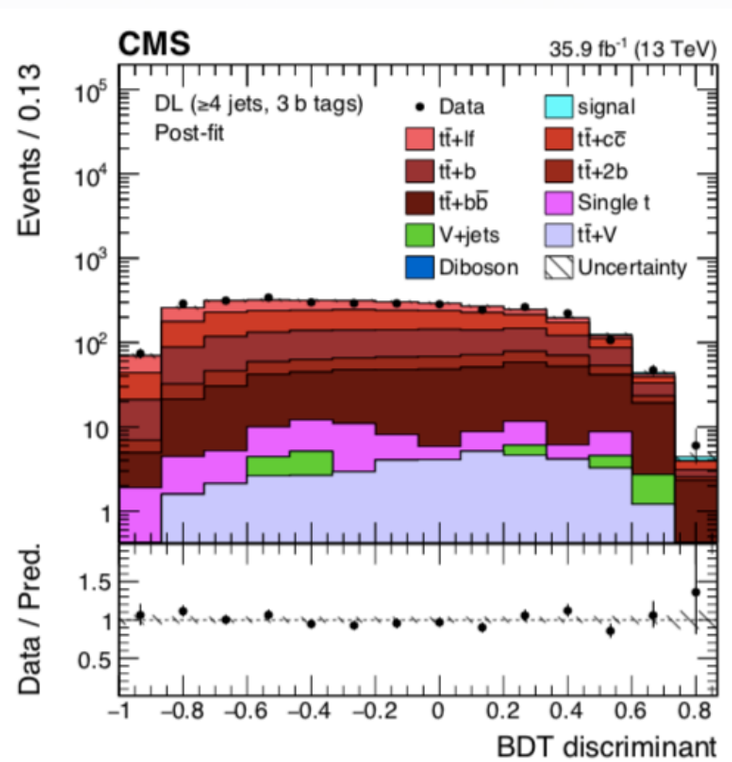
ttH, H→bb (leptonic)

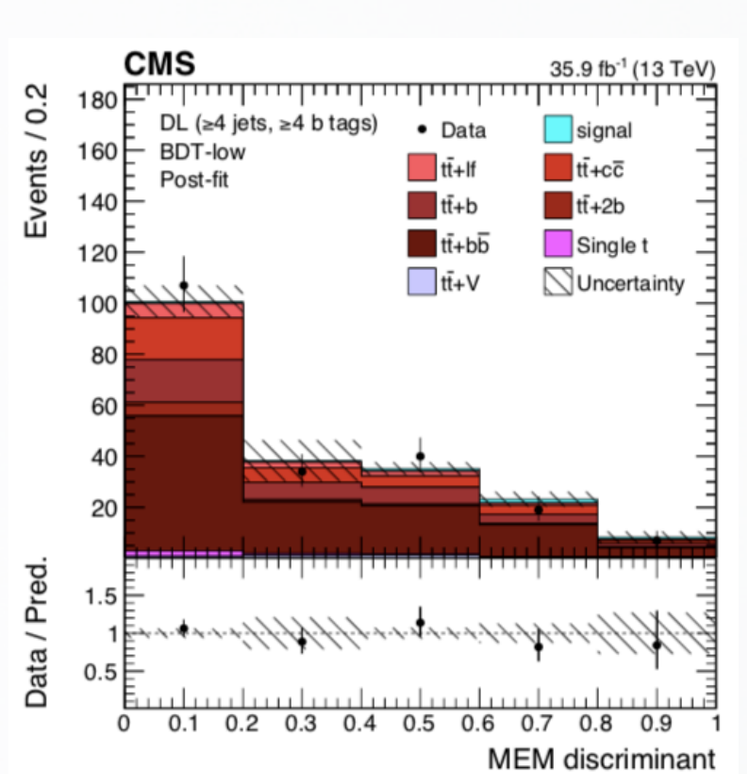




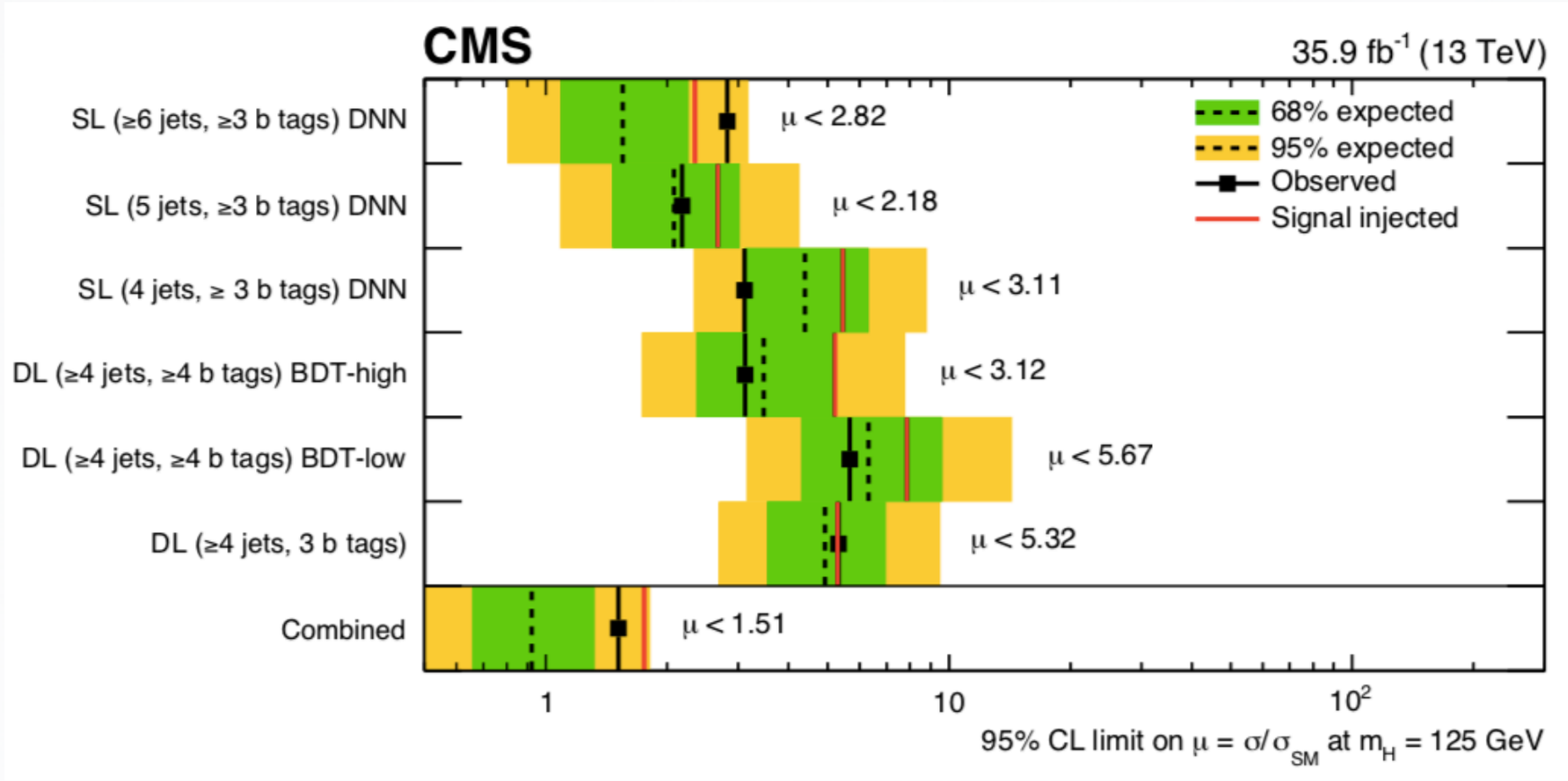








ttH, H→bb (leptonic)

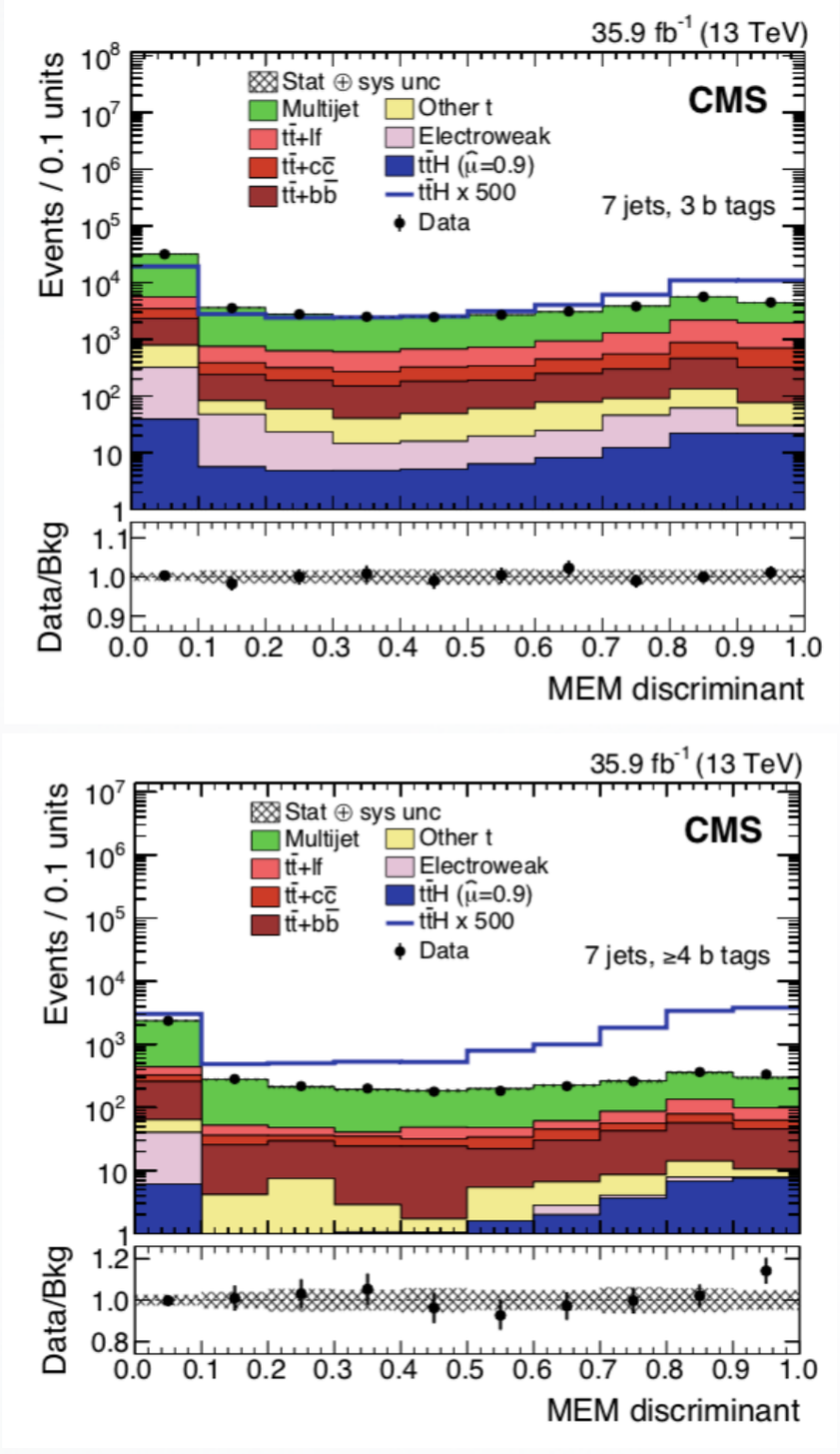


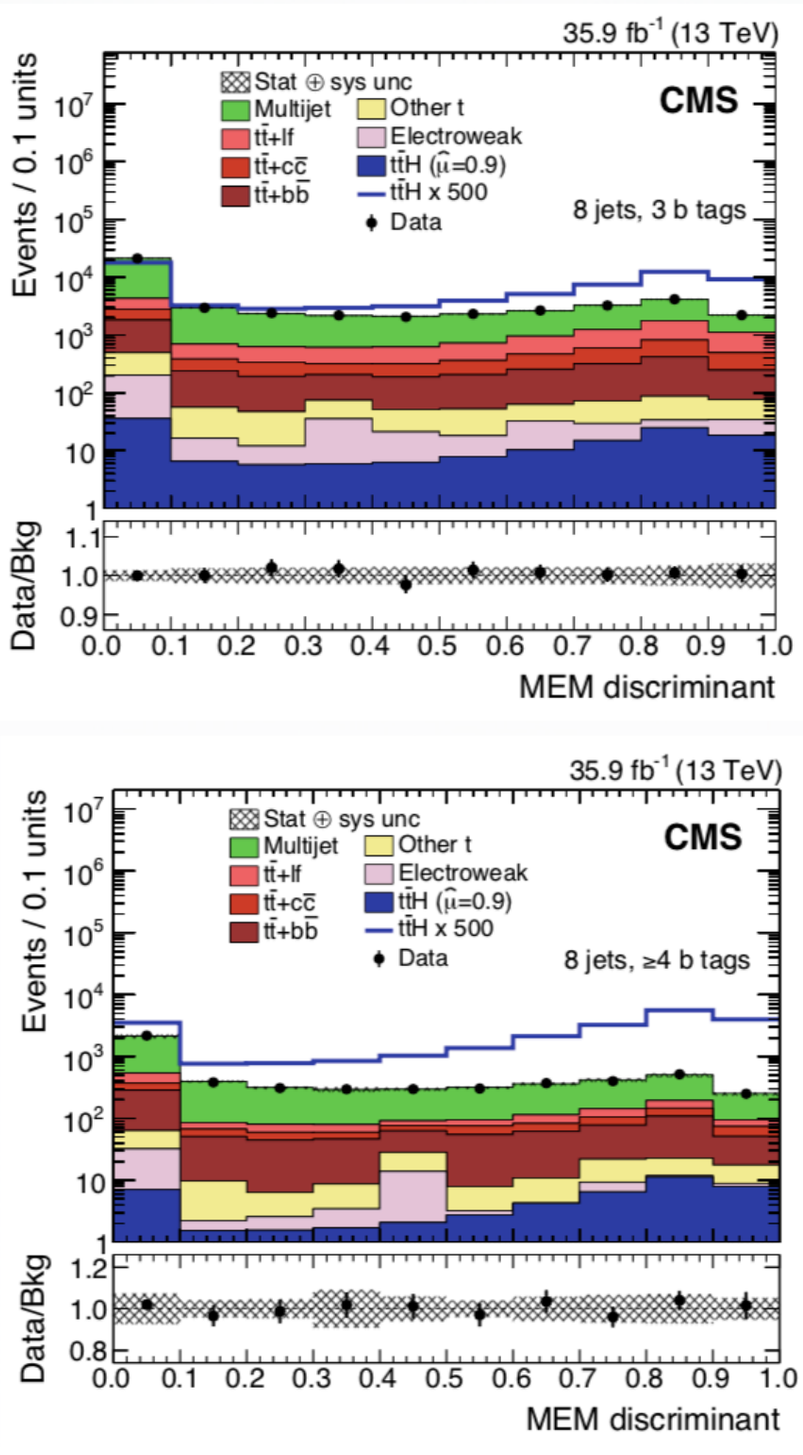
Channel	95% CL upper limit		Best-fit μ
	observed	expected	$\pm$tot ($\pm$stat $\pm$ syst)
Single-lepton	1.75	$1.03^{+0.44}_{-0.29}$	$0.84^{+0.52}_{-0.50}$ $\left(^{+0.27\ +0.44}_{-0.26\ -0.43}\right)$
Dilepton	2.34	$2.48^{+1.17}_{-0.76}$	$-0.24^{+1.21}_{-1.12}$ $\left(^{+0.63\ +1.04}_{-0.60\ -0.95}\right)$
Combined	1.51	$0.92^{+0.39}_{-0.26}$	$0.72^{+0.45}_{-0.45}$ $\left(^{+0.24\ +0.38}_{-0.24\ -0.38}\right)$

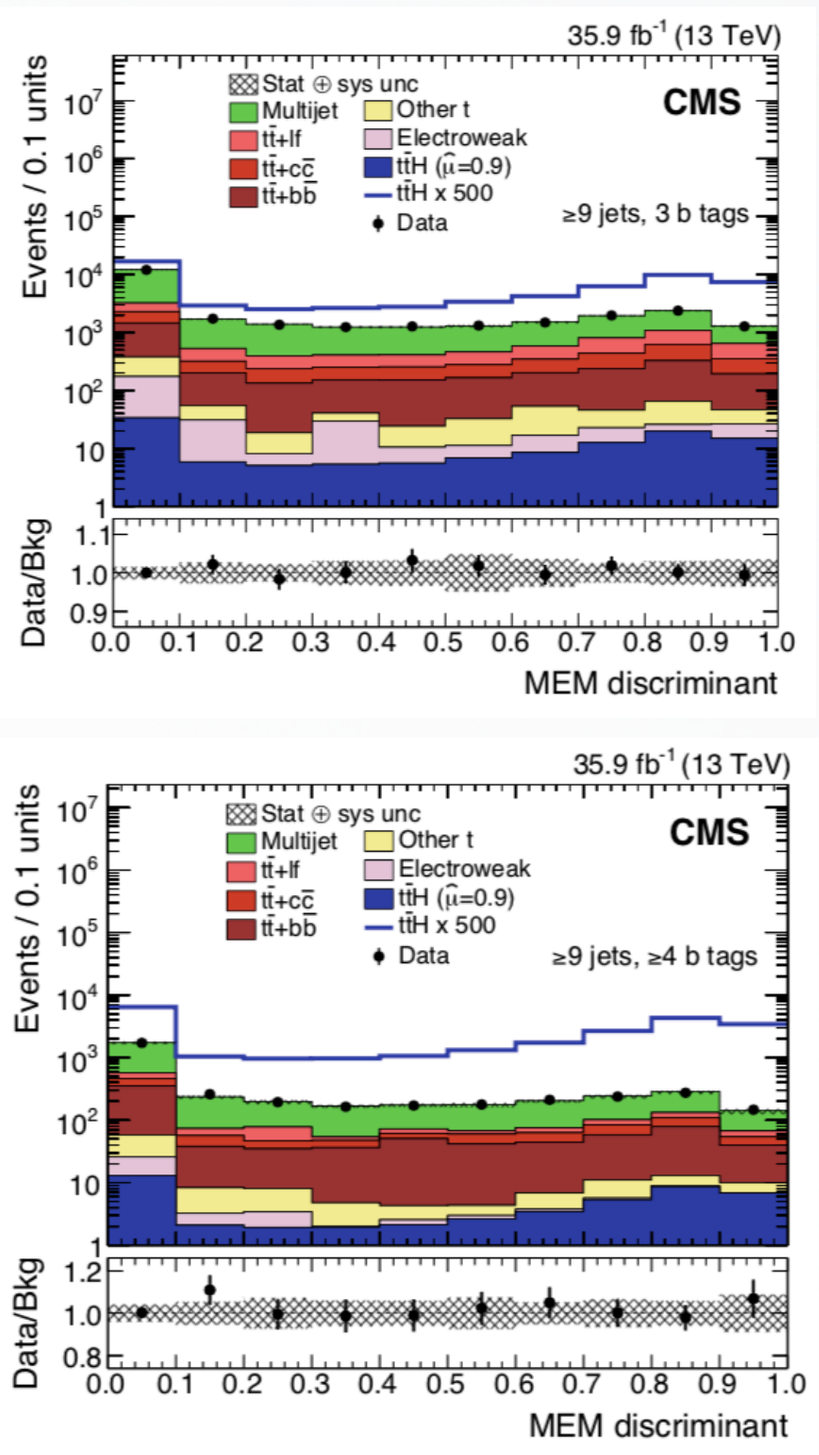
ttH, H→bb (fully hadronic)

Source	Range of uncertainty (%)	Distribution	Process			
			$t\bar{t}H$	Multijet	$t\bar{t}$+jets	Other
Experimental uncertainties						
Integrated luminosity	2.5	No	✓	*	✓	✓
Trigger efficiency	1–2	Yes	✓	*	✓	✓
Pileup	0.2–5	Yes	✓	*	✓	✓
JES	3–11	Yes	✓	*	✓	✓
JER	2–11	Yes	✓	*	✓	✓
b tagging	4–40	Yes	✓	*	✓	✓
QGL reweighting	4–11	Yes	✓	*	✓	✓
Top quark p_T reweighting	1–2	Yes	—	*	✓	—
Multijet estimation						
CSVL correction	—	Yes	—	✓	—	—
MEM first bin	—	Yes	—	✓	—	—
H_T reweighting	—	Yes	—	✓	—	—
Normalization	∞	No	—	✓	—	—
Theoretical uncertainties						
$t\bar{t}$+$b\bar{b}$ normalization	50	No	—	*	✓	—
$t\bar{t}$+2b normalization	50	No	—	*	✓	—
$t\bar{t}$+b normalization	50	No	—	*	✓	—
$t\bar{t}$+$c\bar{c}$ normalization	50	No	—	*	✓	—
μ_F/μ_R scales for signal	6–9	No	✓	—	—	—
μ_F/μ_R scales for background	1–13	No	—	*	✓	✓
PDFs	2–4	No	✓	*	✓	✓
Simulated sample size	2–40	Yes	✓	*	✓	✓

ttH, H→bb (fully hadronic)

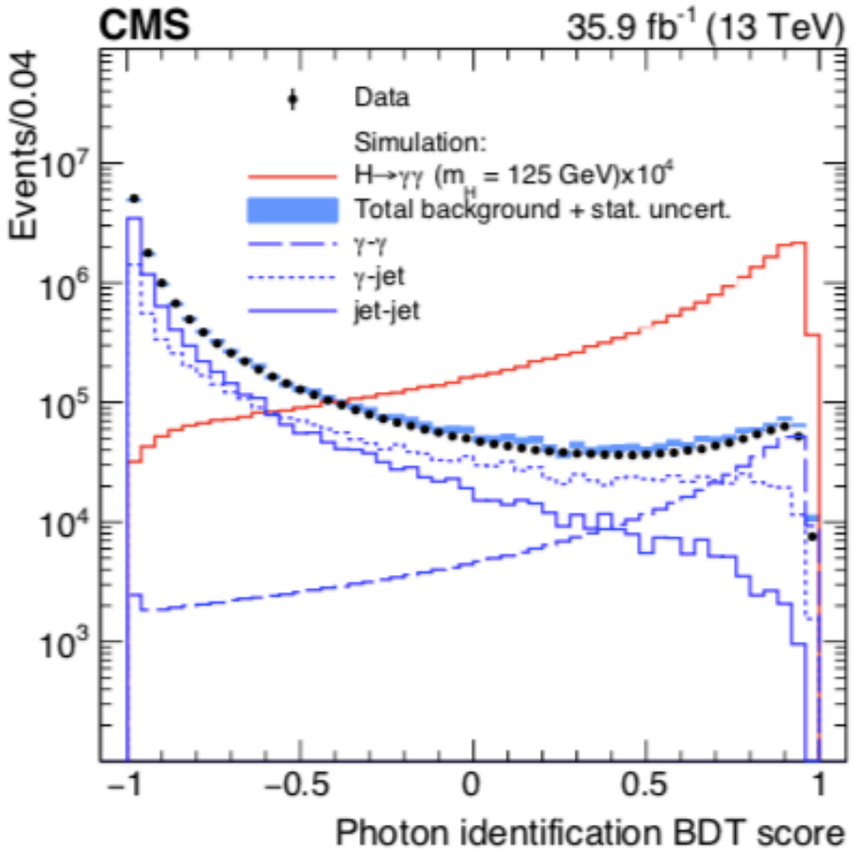


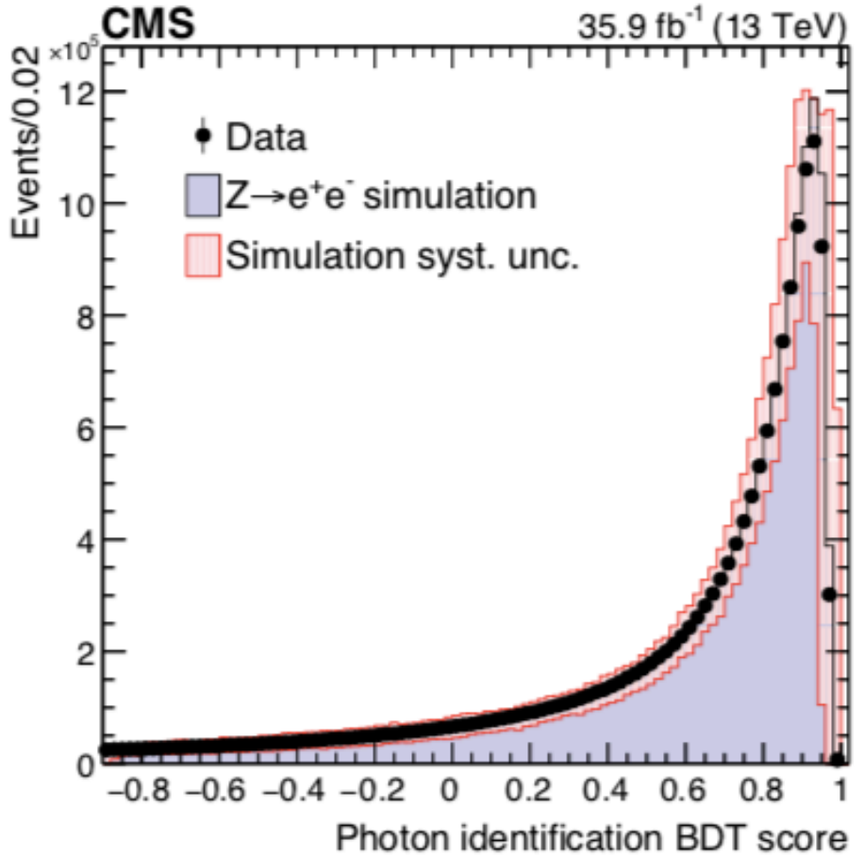




ttH, H→γγ: photon selection

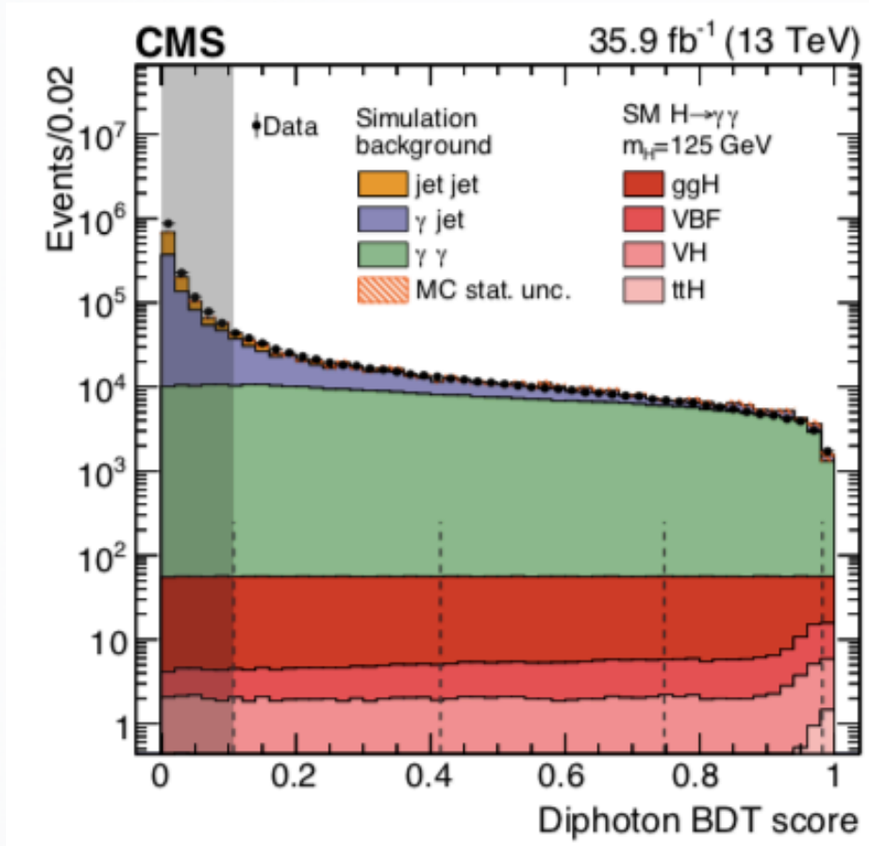
- shower shape observables, corrected to mitigate data and simulation discrepancies;
- isolation variables, $\mathcal{I}_{\text{ph}}$ and $\mathcal{I}_{\text{ch}}$; two kinds of $\mathcal{I}_{\text{ch}}$ are computed, including hadrons associated with the chosen primary vertex (described in Section 6), and including hadrons associated with the vertex providing the largest isolation sum; the latter is effective in rejecting misidentified photon candidates originating from jets coming from a vertex other than the chosen one;
- photon η and energy, 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.

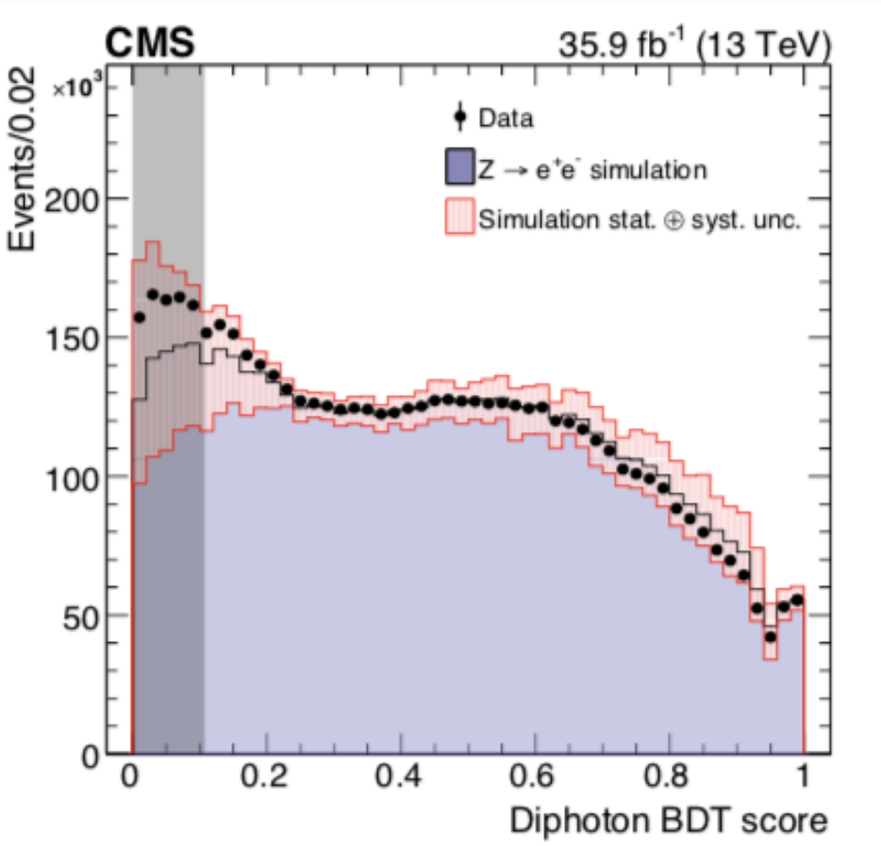




ttH, H→γγ: diphoton selection

- $p_{\mathrm{T}}^{\gamma}/m_{\gamma\gamma}$ for each photon;
- the pseudorapidity of the two photons;
- the cosine of the angle between the two photons in the transverse plane;
- photon identification BDT scores for both photons;
- two per-event relative mass resolution estimates, one under the hypothesis that the mass has been reconstructed using the correct primary vertex, and the other under the hypothesis that the mass has been reconstructed using an incorrect vertex;
- the per-event probability estimate that the correct primary vertex has been assigned to the diphoton.





ttH, H→γγ (leptonic)

- semileptonic top quark decays (ttH Leptonic):
  - leading photon $p_T > m_{\gamma\gamma}/2$, subleading photon $p_T > m_{\gamma\gamma}/4$;
  - diphoton classifier BDT score greater than 0.11;
  - at least one lepton with $p_T > 20\,\text{GeV}$; electrons must satisfy loose requirements on the same observables as described in Ref. [37]; muons are required to pass a tight selection based on the quality of the track, the number of hits in the tracker and muon system, and the longitudinal and transverse impact parameters of the track with respect to the muon vertex, and to satisfy a requirement on the relative isolation (after correction for pileup) based on transverse energy of the charged hadrons, neutral hadrons, and photons, in a cone around the muon with a radius between 0.05 and 0.2, depending on the p_T of the muon;
  - all selected leptons ℓ are required to have $R(\ell, \gamma) > 0.35$, where R is the distance between the objects in the $\eta - \phi$ plane;
  - specifically for electrons: $|m_{e,\gamma} - m_Z| > 5\,\text{GeV}$, where $m_{e,\gamma}$ is the invariant mass of any pair of electron and photon and m_Z refers to the mass of the Z boson;
  - at least two jets in the event with $p_T > 25\,\text{GeV}$, $|\eta| < 2.4$, and $R(\text{jet}, \gamma) > 0.4$ and $R(\text{jet}, \ell) > 0.4$;
  - at least one of the jets in the event identified as a b jet according to the CSV tagger medium requirement;

ttH, H→γγ (hadronic)

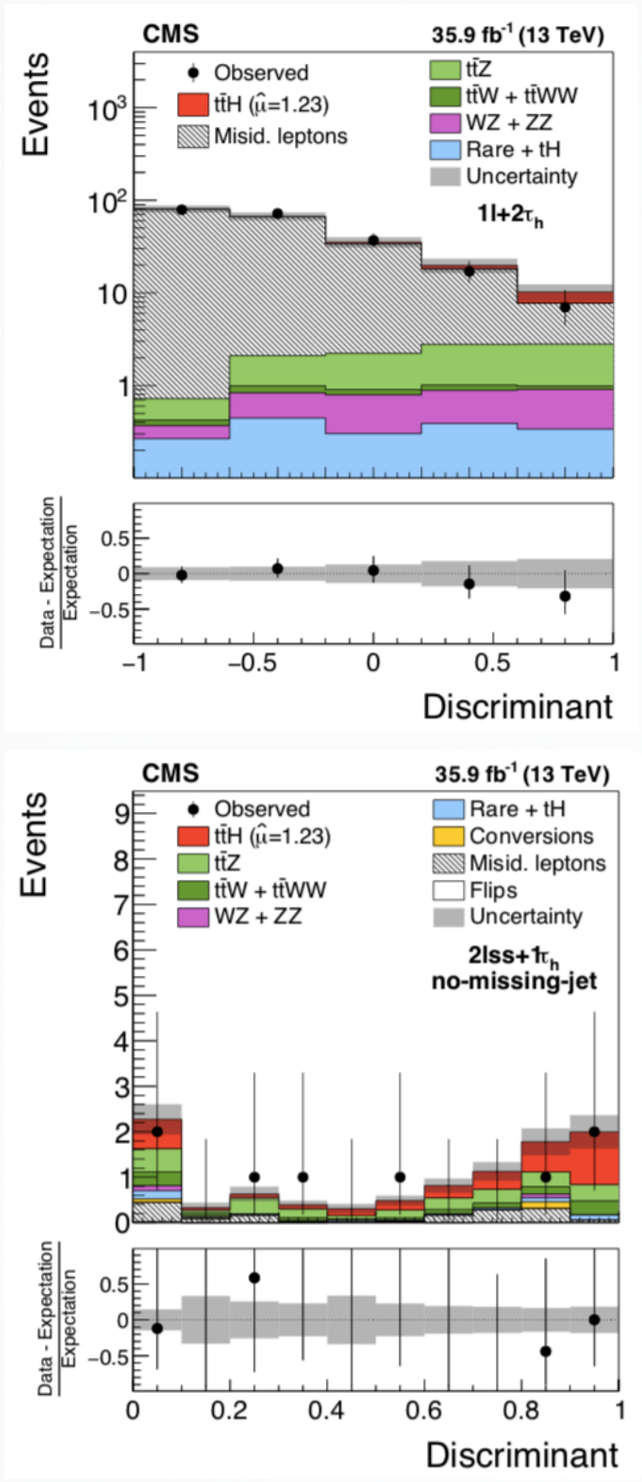
- hadronic top quark decays (ttH Hadronic):
  - leading photon $p_{\mathrm{T}} > m_{\gamma\gamma}/3$, subleading photon $p_{\mathrm{T}} > m_{\gamma\gamma}/4$;
  - diphoton classifier BDT score greater than 0.58;
  - no leptons, defined according to the criteria of the ttH Leptonic category;
  - at least three jets in the event with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $|\eta| < 2.4$;
  - at least one of the jets in the event identified as a b jet according to the CSV tagger loose requirement;
  - score from the ttH Hadronic multivariate discriminant greater than 0.75.

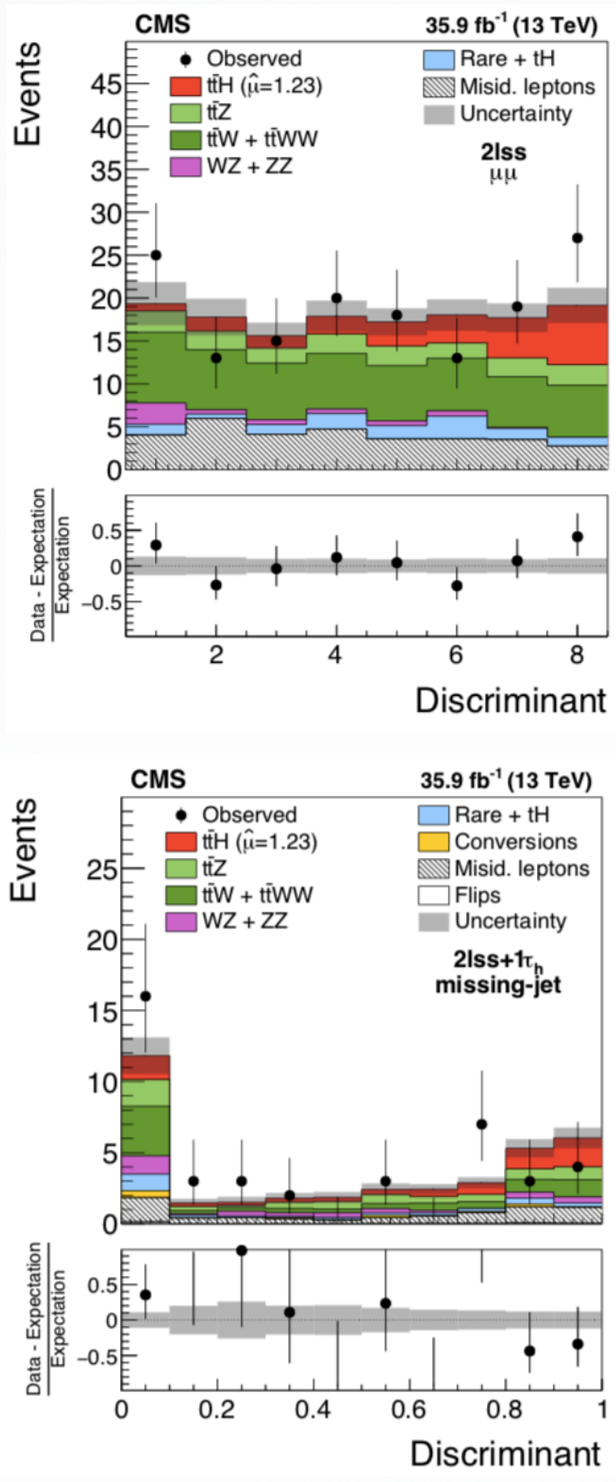
ttH, H→WW/ZZ/ττ

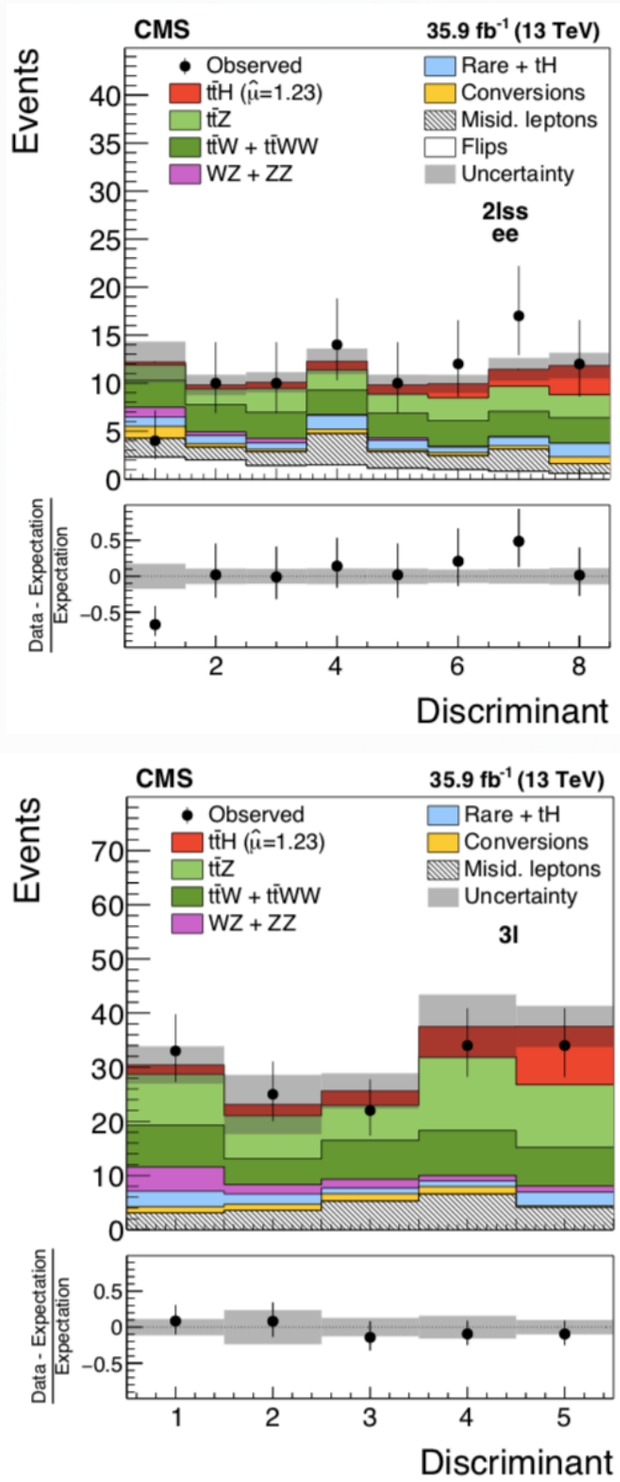
Observable	$1\ell + 2\tau_h$	2ℓss	3ℓ	$3\ell + 1\tau_h$
$\Delta R(\ell_1, j)$	—	√	√	√
$\Delta R(\ell_2, j)$	—	√	√	√
$\langle \Delta R_{jj} \rangle$	√	—	—	√[2]
$\Delta R_{\tau\tau}$	√	—	—	—
$\max(\lvert\eta^{\ell 1}\rvert, \lvert\eta^{\ell 2}\rvert)$	—	√	√	√
H_T^{miss}	√	—	—	√[2]
N_j	√	√	√	√
N_b	√	—	—	—
$m_{\tau\tau}^{vis}$	√	—	—	—
$m_T^{\ell 1}$	—	√	√	√
$p_T^{\ell 1}$	—	√[1]	√[1]	√[1]
$p_T^{\ell 2}$	—	√[1]	-	-
$p_T^{\ell 3}$	—	—	√[1]	√[1]
$p_T^{\tau 1}$	√	—	—	—
$p_T^{\tau 2}$	√	—	—	—
LR(3ℓ)	—	—	√[1]	—
MVA_{thad}^{max}	—	√[2]	—	—
MVA_{Hj}^{max}	—	√[1]	—	—

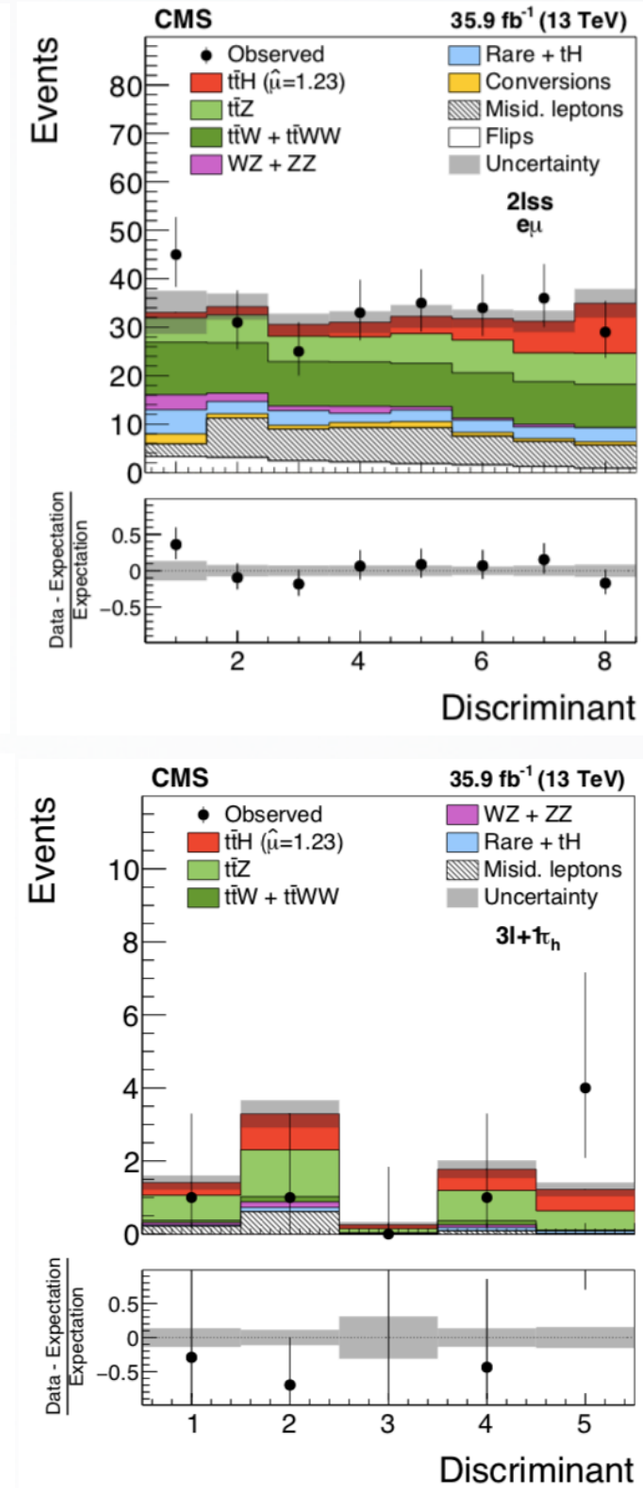
[1] Used only in BDT that separates $t\bar{t}H$ signal from $t\bar{t}V$ background.
[2] Used only in BDT that separates $t\bar{t}H$ signal from $t\bar{t}$+jets background.

ttH, H→WW/ZZ/ττ


CMS
35.9 fb-1 (13 TeV)
Observed
tt̄H (μ̂=1.23)
tt̄Z
tt̄W + tt̄WW
WZ + ZZ
Rare + tH
Misid. leptons
Uncertainty
1l+2τh
Events
Data - Expectation / Expectation
Discriminant


CMS
35.9 fb-1 (13 TeV)
Observed
tt̄H (μ̂=1.23)
tt̄Z
tt̄W + tt̄WW
WZ + ZZ
Rare + tH
Misid. leptons
Uncertainty
2lss
μμ
Events
Data - Expectation / Expectation
Discriminant


CMS
35.9 fb-1 (13 TeV)
Observed
tt̄H (μ̂=1.23)
tt̄Z
tt̄W + tt̄WW
WZ + ZZ
Rare + tH
Conversions
Misid. leptons
Flips
Uncertainty
2lss
ee
Events
Data - Expectation / Expectation
Discriminant


CMS
35.9 fb-1 (13 TeV)
Observed
tt̄H (μ̂=1.23)
tt̄Z
tt̄W + tt̄WW
WZ + ZZ
Rare + tH
Conversions
Misid. leptons
Flips
Uncertainty
2lss
eμ
Events
Data - Expectation / Expectation
Discriminant

CMS
35.9 fb-1 (13 TeV)
Observed
tt̄H (μ̂=1.23)
tt̄Z
tt̄W + tt̄WW
WZ + ZZ
Rare + tH
Conversions
Misid. leptons
Flips
Uncertainty
2lss+1τh
no-missing-jet
Events
Data - Expectation / Expectation
Discriminant

CMS
35.9 fb-1 (13 TeV)
Observed
tt̄H (μ̂=1.23)
tt̄Z
tt̄W + tt̄WW
WZ + ZZ
Rare + tH
Conversions
Misid. leptons
Flips
Uncertainty
2lss+1τh
missing-jet
Events
Data - Expectation / Expectation
Discriminant

CMS
35.9 fb-1 (13 TeV)
Observed
tt̄H (μ̂=1.23)
tt̄Z
tt̄W + tt̄WW
WZ + ZZ
Rare + tH
Conversions
Misid. leptons
Uncertainty
3l
Events
Data - Expectation / Expectation
Discriminant

CMS
35.9 fb-1 (13 TeV)
Observed
tt̄H (μ̂=1.23)
tt̄Z
tt̄W + tt̄WW
WZ + ZZ
Rare + tH
Misid. leptons
Uncertainty
3l+1τh
Events
Data - Expectation / Expectation
Discriminant

Systematics

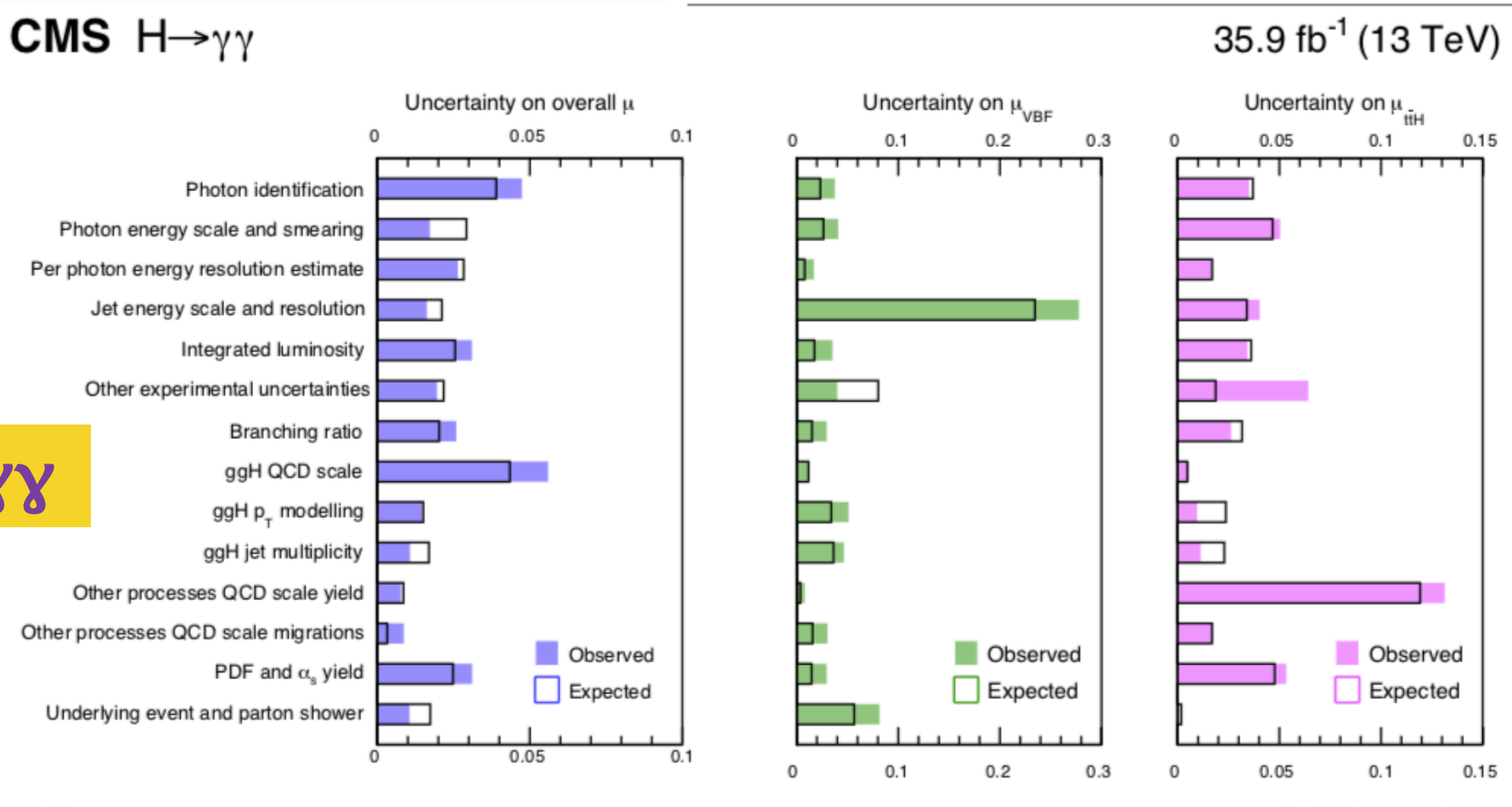
H→WW/ZZ/ττ

Source	Uncertainty [%]	Δμ/μ [%]
e, μ selection efficiency	2–4	11
τ_h selection efficiency	5	4.5
b tagging efficiency	2–15 [57]	6
Reducible background estimate	10–40	11
Jet energy calibration	2–15 [65]	5
τ_h energy calibration	3	1
Theoretical sources	≈10	12
Integrated luminosity	2.5	5

H→bb (leptonic)

Uncertainty source	±Δμ (observed)	±Δμ (expected)
Total experimental	+0.15/−0.16	+0.19/−0.17
b tagging	+0.11/−0.14	+0.12/−0.11
jet energy scale and resolution	+0.06/−0.07	+0.13/−0.11
Total theory	+0.28/−0.29	+0.32/−0.29
$t\bar{t}$+hf cross section and parton shower	+0.24/−0.28	+0.28/−0.28
Size of the simulated samples	+0.14/−0.15	+0.16/−0.16
Total systematic	+0.38/−0.38	+0.45/−0.42
Statistical	+0.24/−0.24	+0.27/−0.27
Total	+0.45/−0.45	+0.53/−0.49

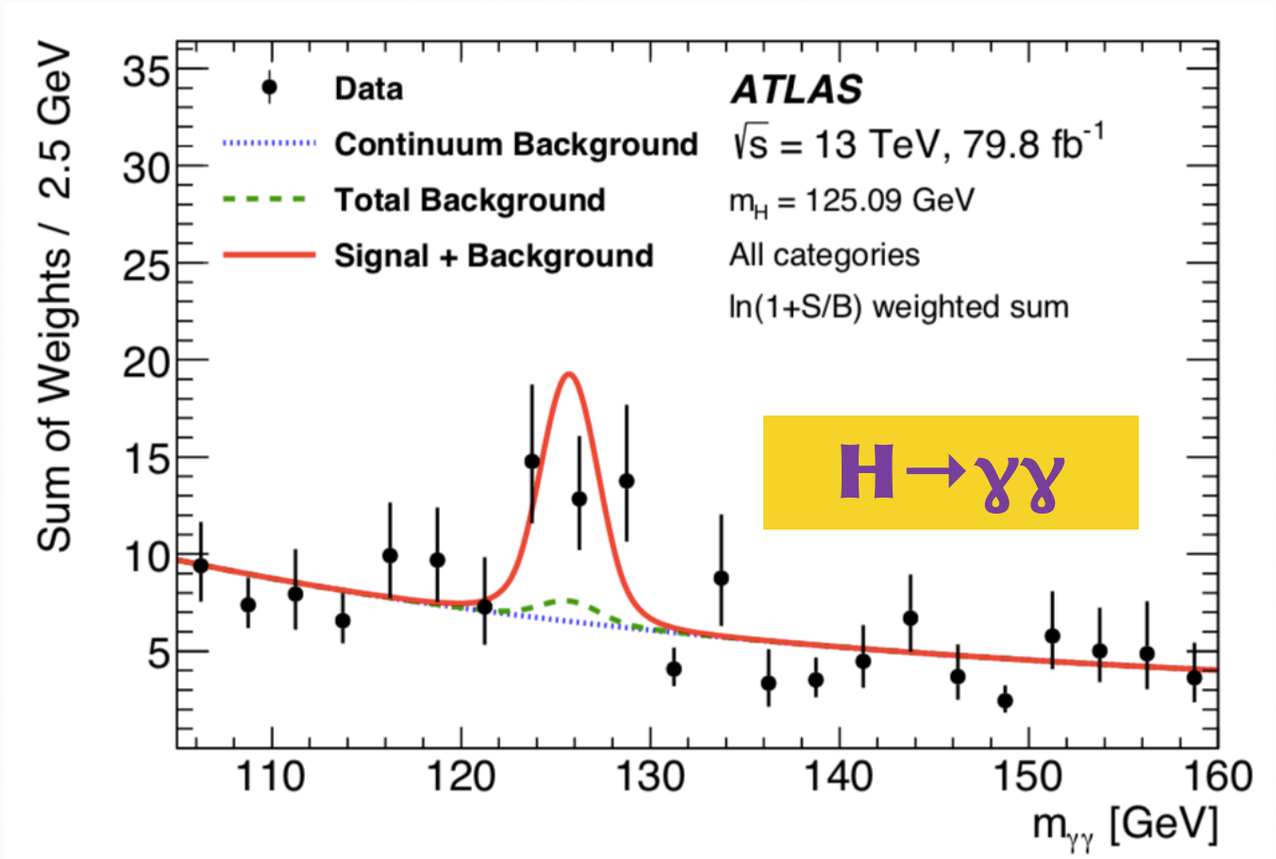
H→γγ

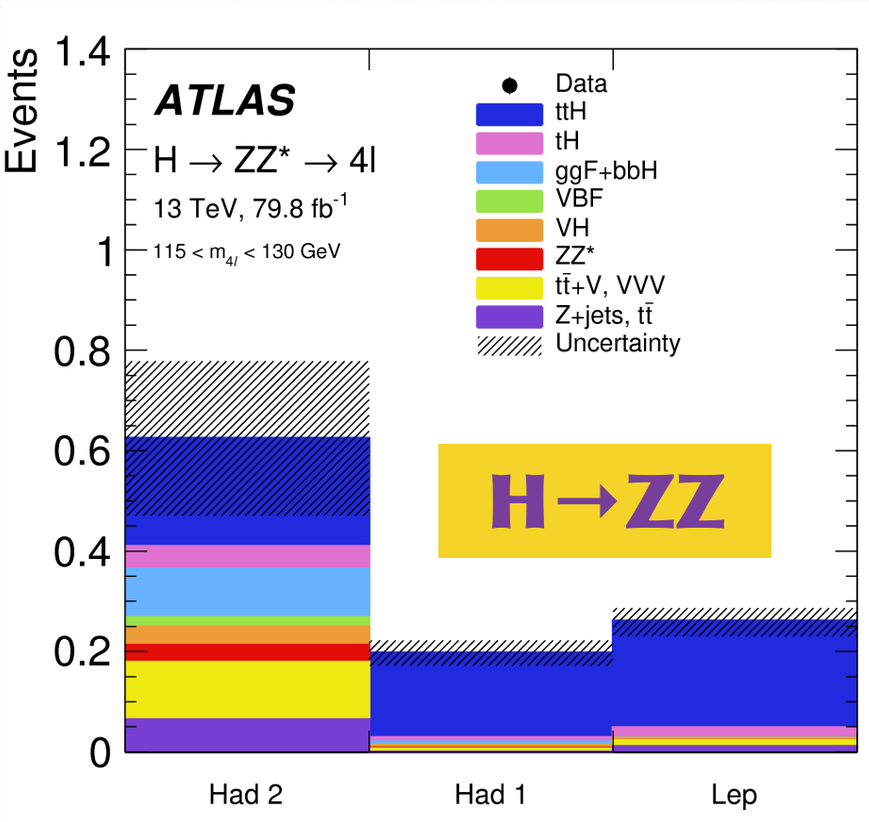


Observation of ttH at ATLAS

arXiv:1806.00425

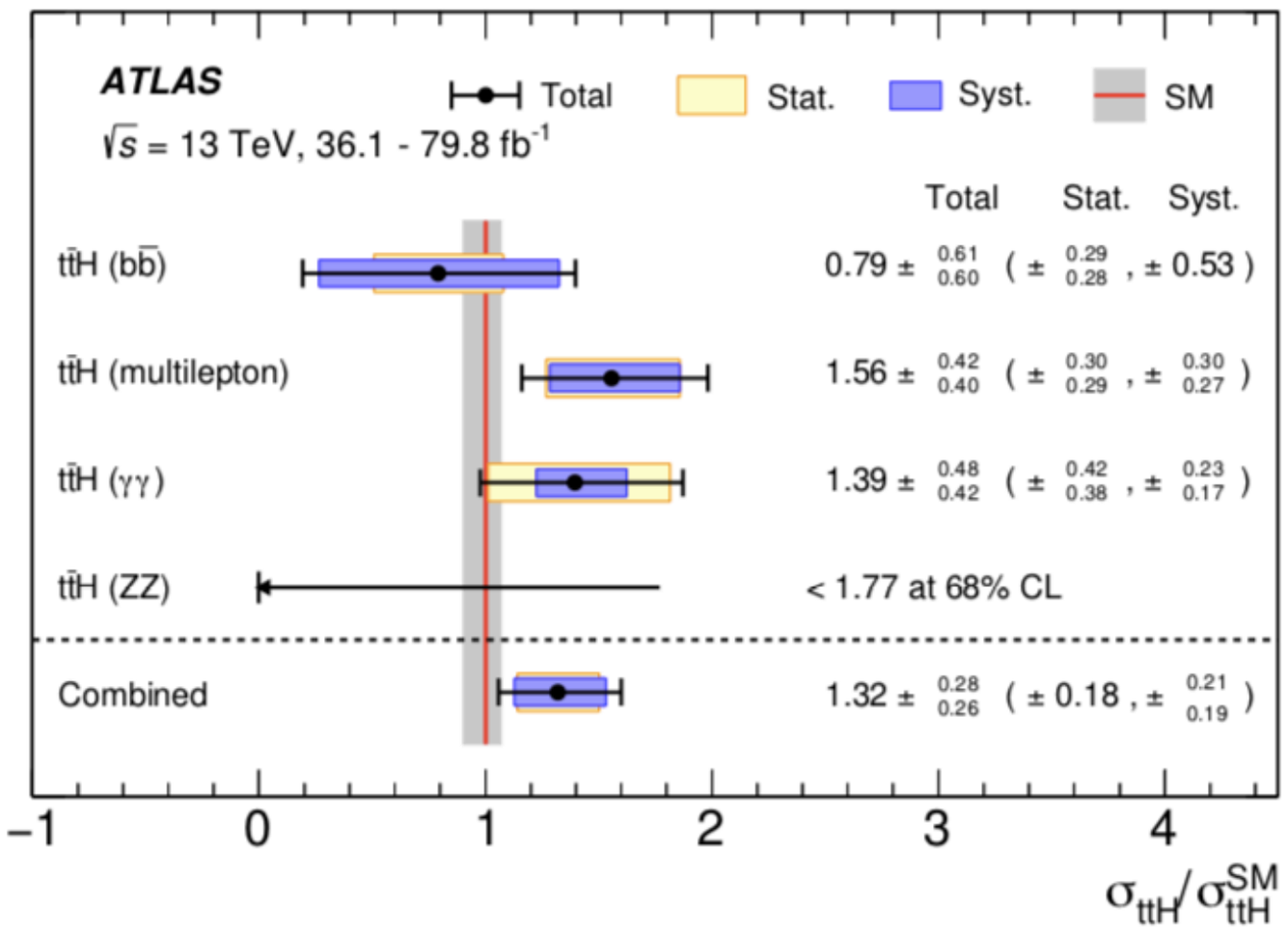
- ☆ New results in H→γγ and H→ZZ (4 leptons) channels
- ☆ Larger data set at 13 TeV than used by CMS (79.8 fb^{-1} vs 35.9 fb^{-1})
- ☆ Combination with previously published H→bb and H→multileptons (13, 8 and 7 TeV)

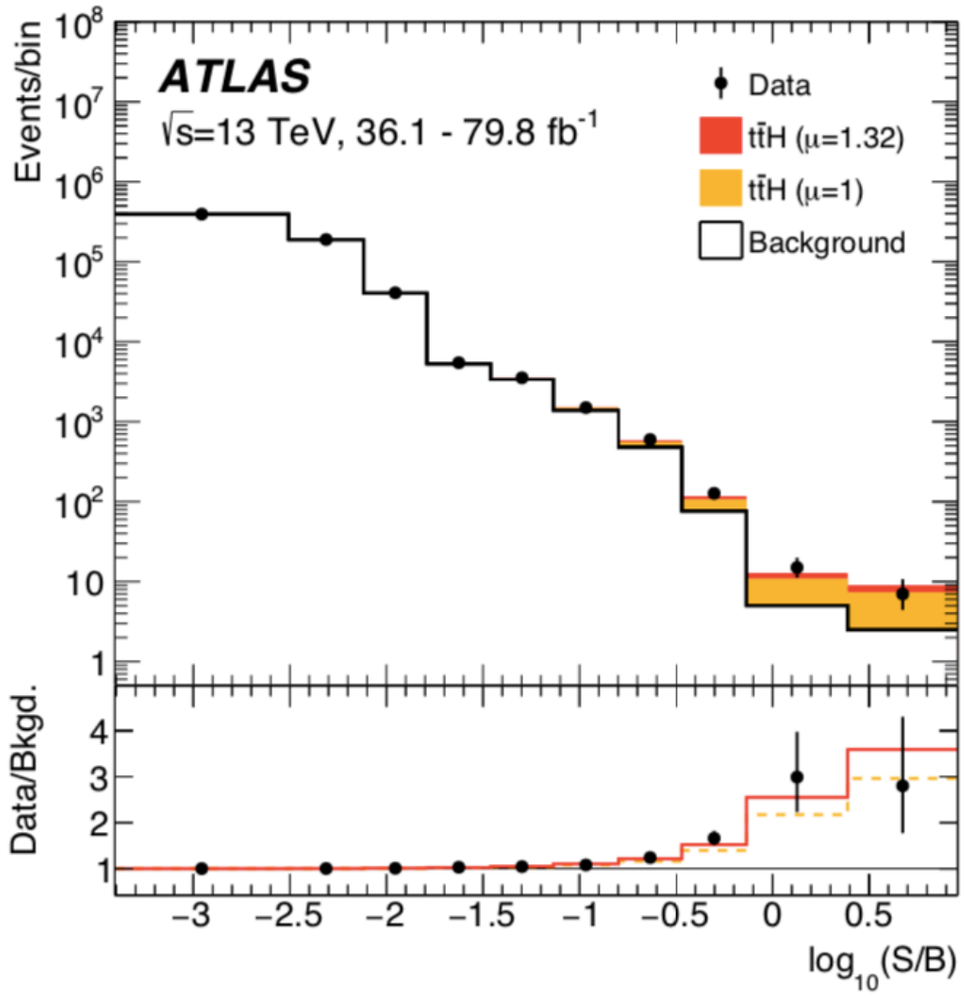




Observation of ttH at ATLAS

arXiv:1806.00425





Obs. (Exp.) Significance = 6.3σ (5.1σ)

Observation !

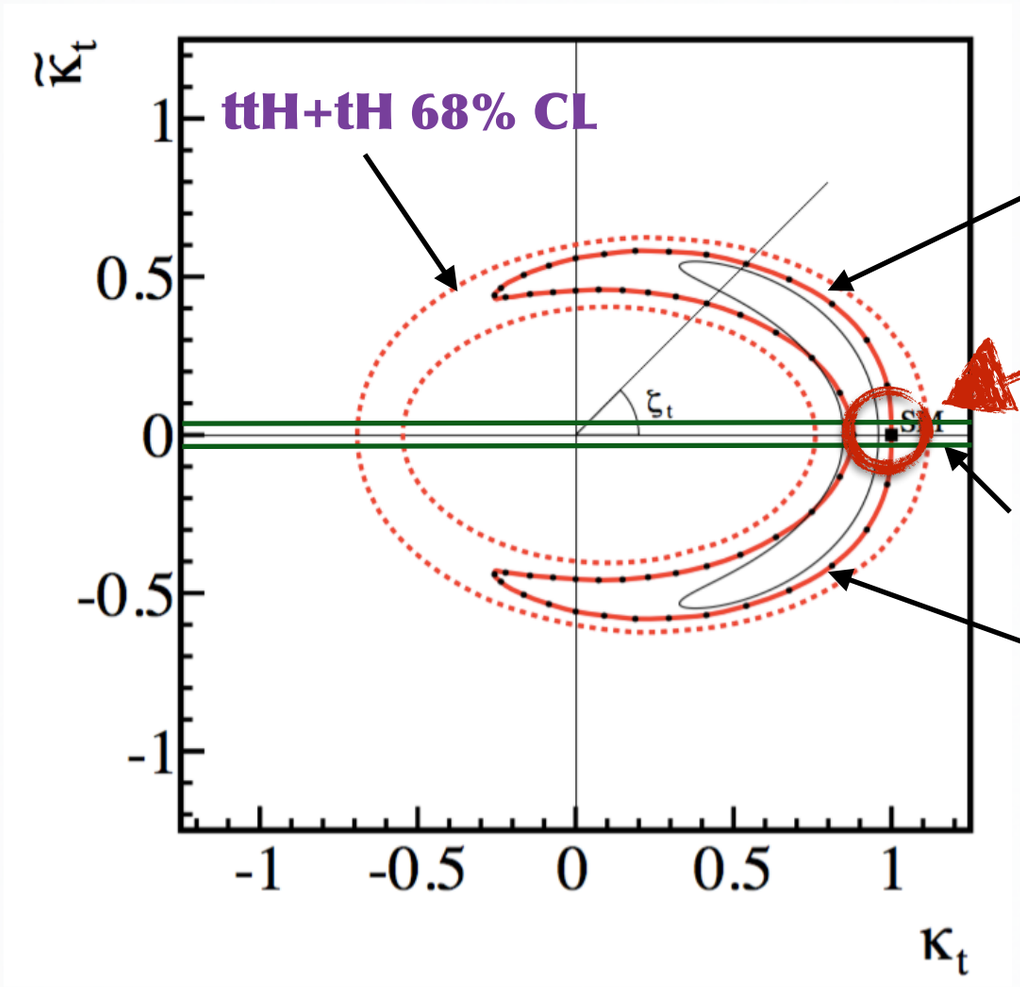
y_t and CP violation

Top-Higgs interaction

scalar pseudoscalar

$$\mathcal{L}_t = -\frac{m_t}{v}\left(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t\right) H$$

CP violation phase: $\zeta_t = arctan(\tilde{\kappa}_t/\kappa_t)$



SM: $\kappa_t = 1$, $\tilde{\kappa}_t = 0$

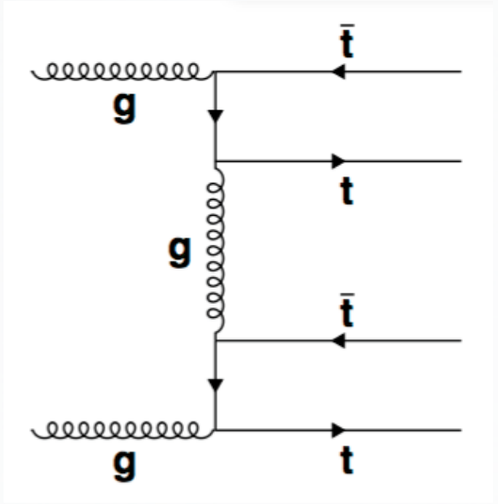
Electron EDM (indirect): $|\tilde{\kappa}_t| < 0.01$

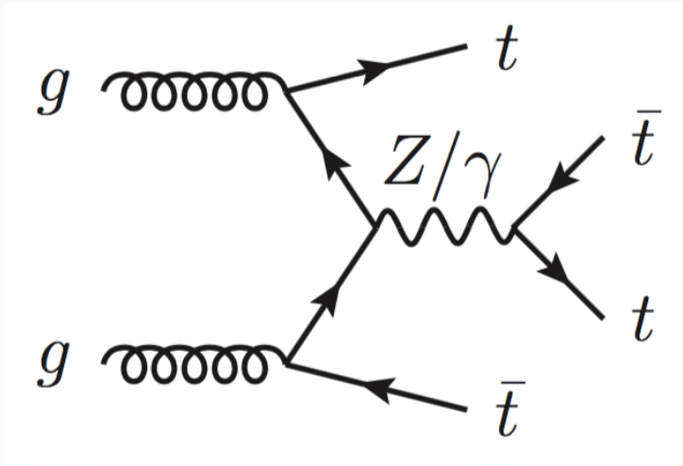
All Higgs results

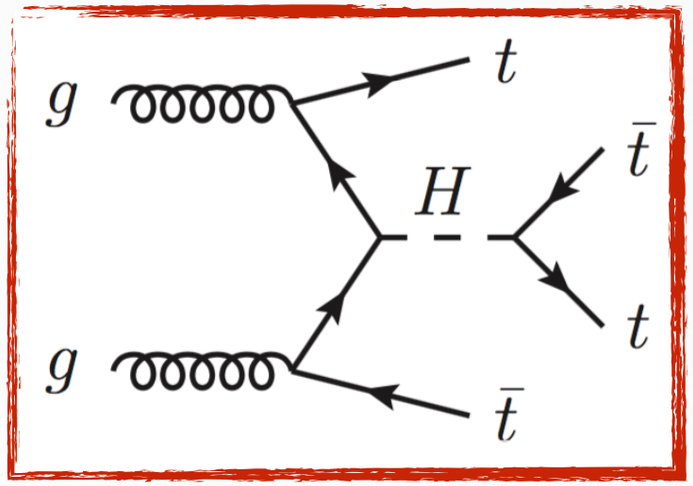
JHEP04 (2014) 004

JHEP 1311 (2013) 180

Indirect probe of y_t in four tops



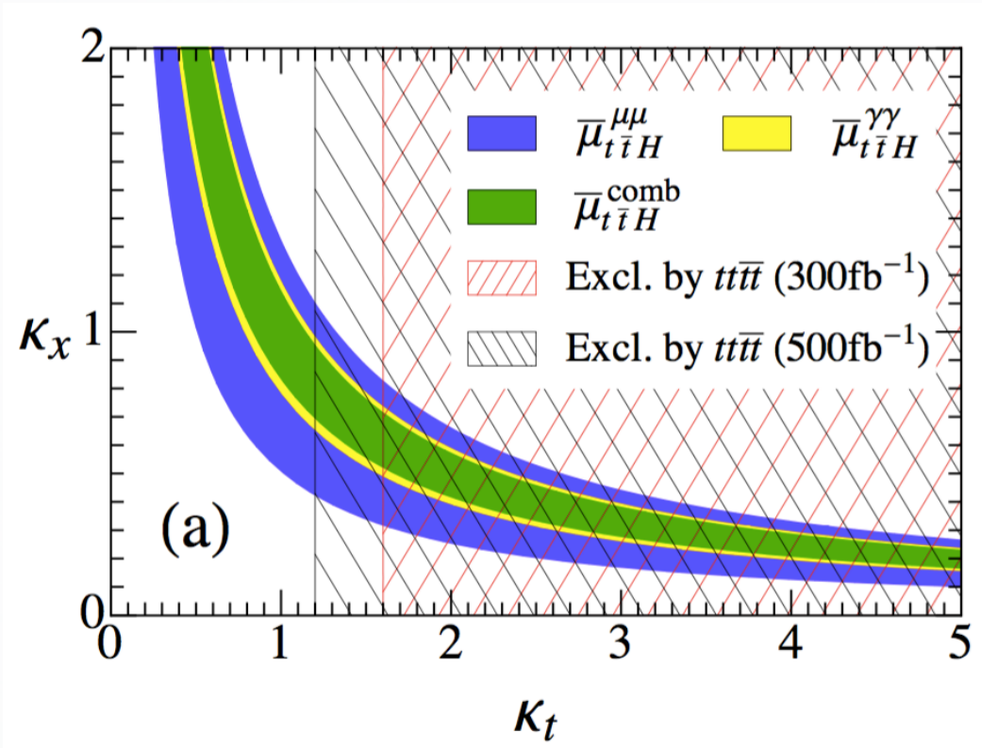




$$\sigma(t\bar{t}t\bar{t}) = \sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{g+Z/\gamma} + \kappa_t^2\sigma^{\mathrm{SM}}_{\mathrm{int}} + \kappa_t^4\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_H$$

arXiv:1602.01934

$$\kappa_x \equiv y_{Hxx}/y^{\mathrm{SM}}_{Hxx}$$



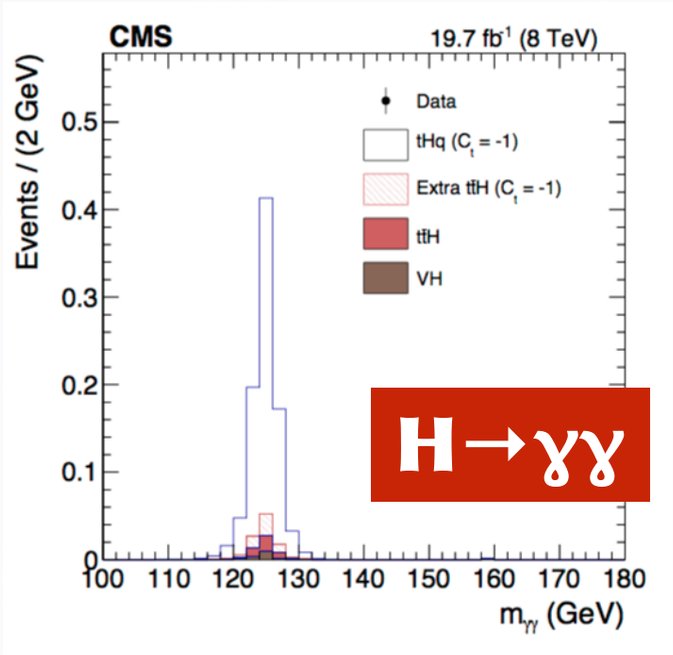
	8 TeV	14 TeV
$\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{g+Z/\gamma}$:	1.193 fb,	12.390 fb,
$\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_H$:	0.166 fb,	1.477 fb,
$\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{\mathrm{int}}$:	−0.229 fb,	−2.060 fb.

LHC data results @8TeV:

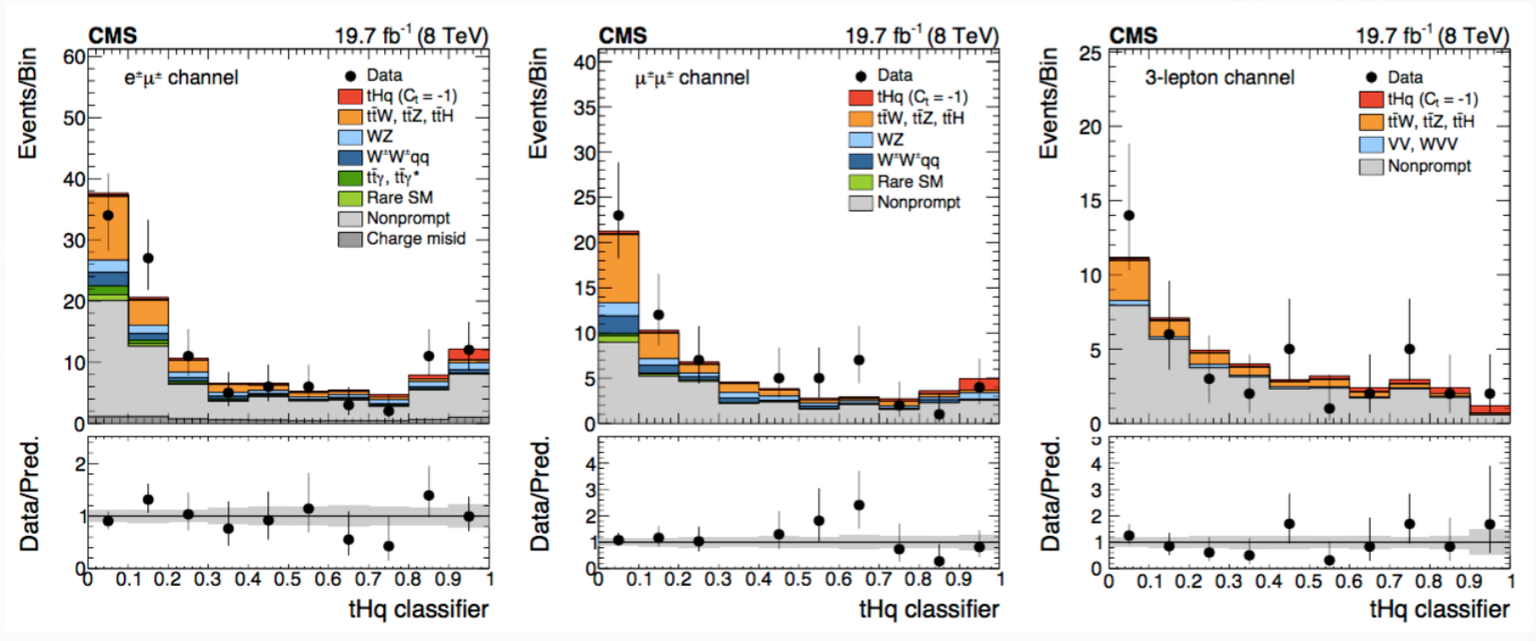
$$\sigma(t\bar{t}t\bar{t}) \leq 23 \text{ fb} \rightarrow \kappa_t \leq 3.49$$

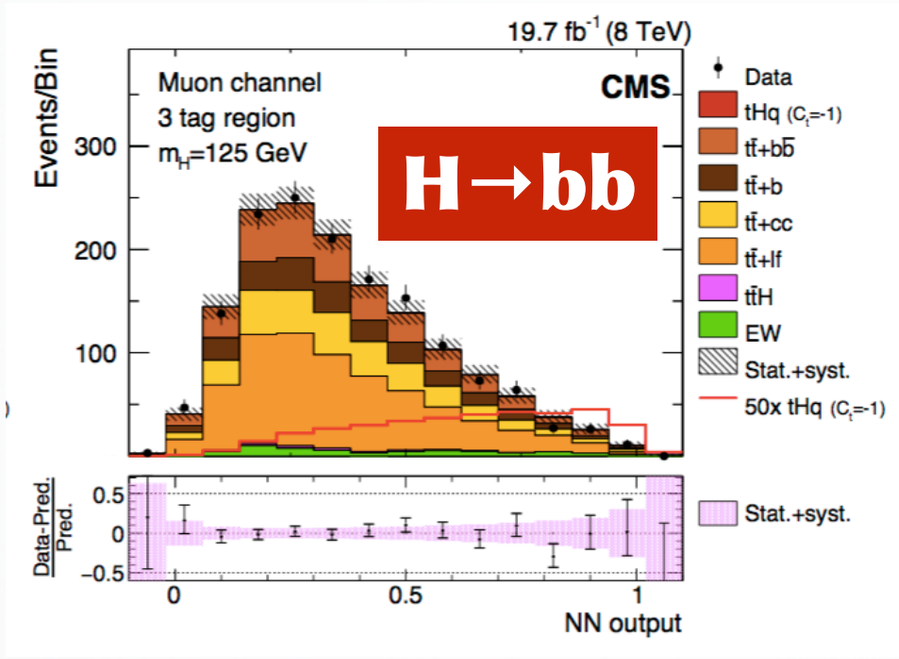
tHq at 8 TeV

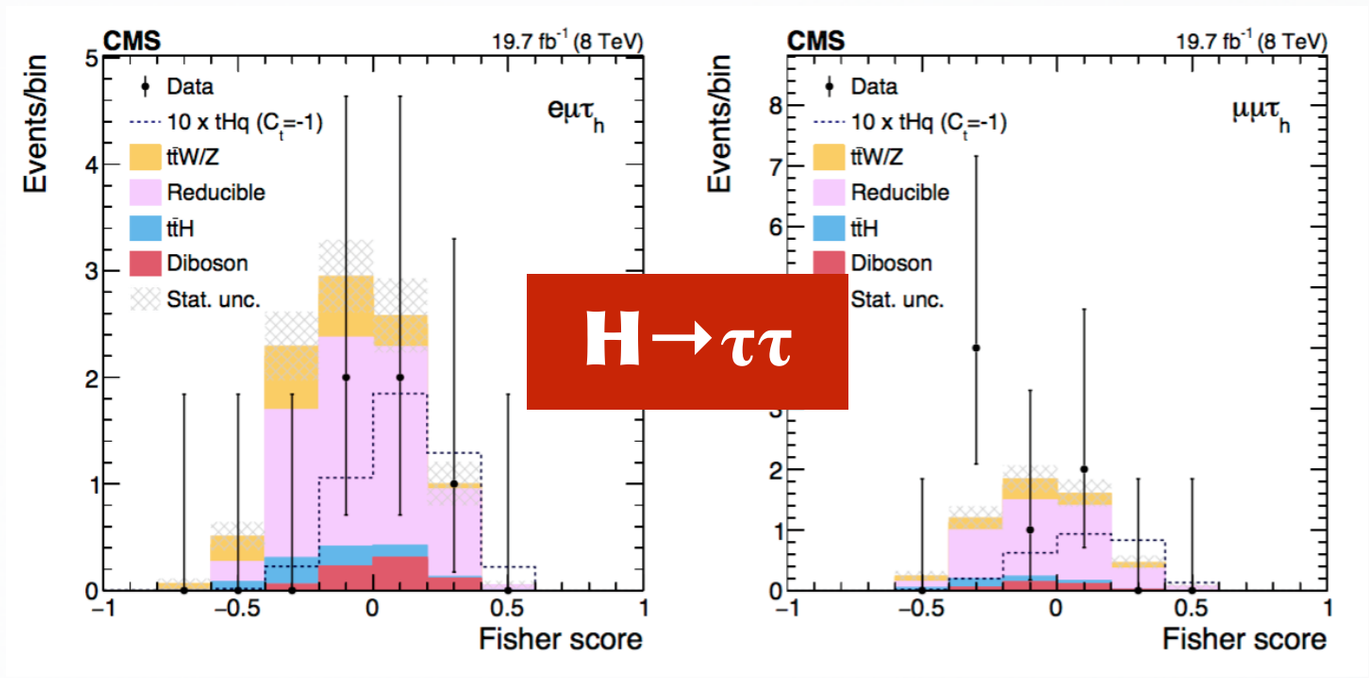
JHEP06 (2016) 177



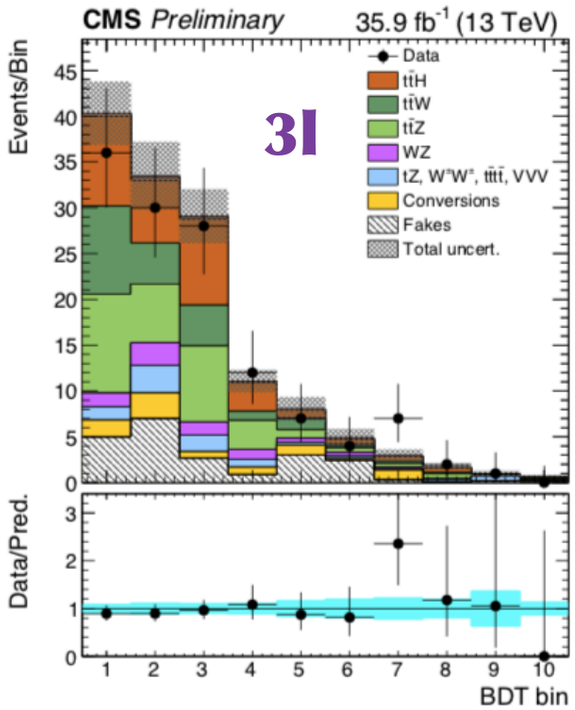
H→WW

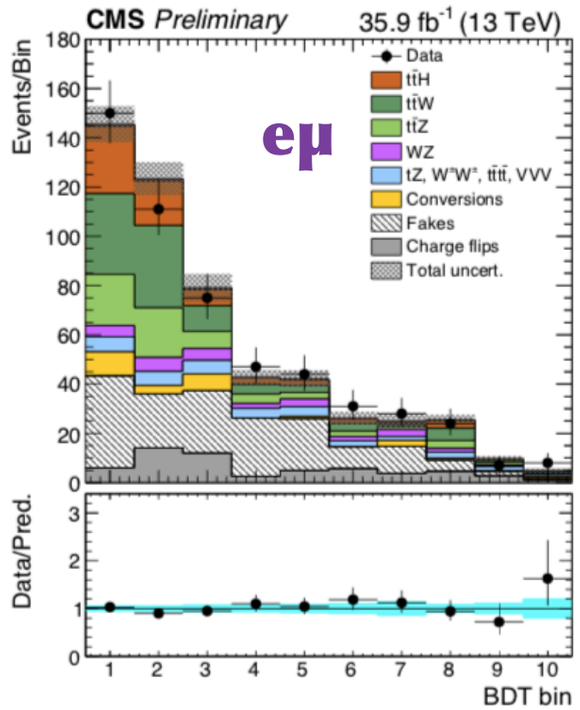


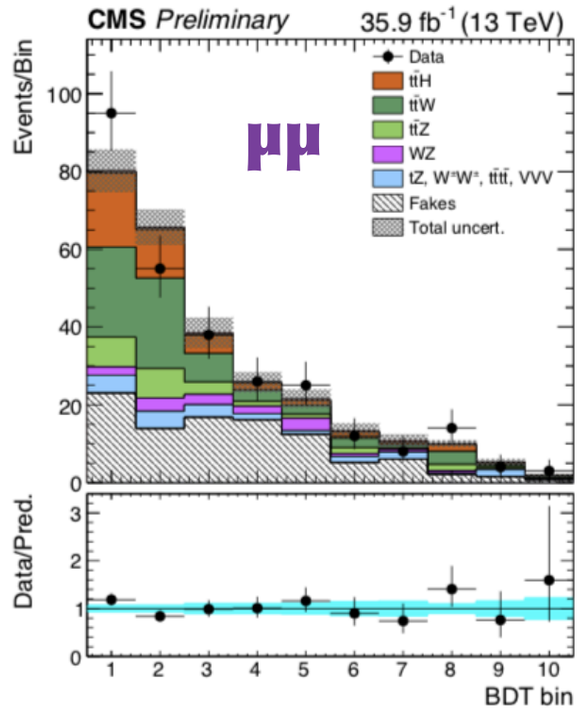


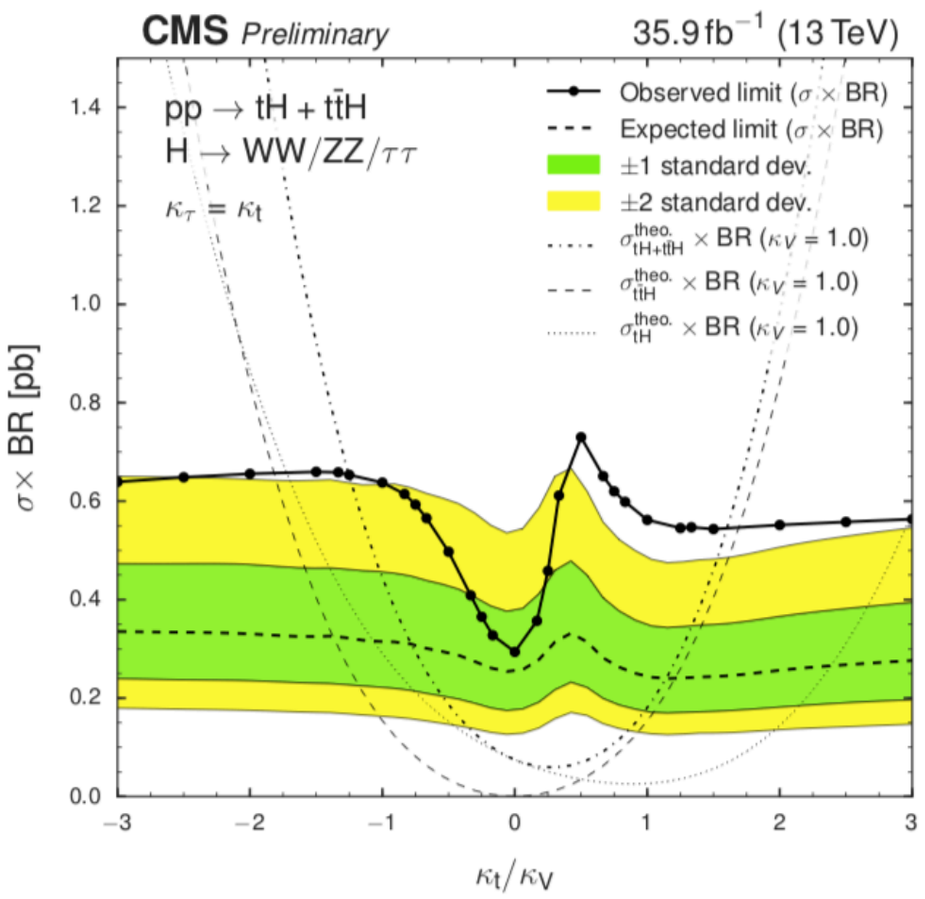


tHq at 13 TeV (H→WW/ZZ/ττ)



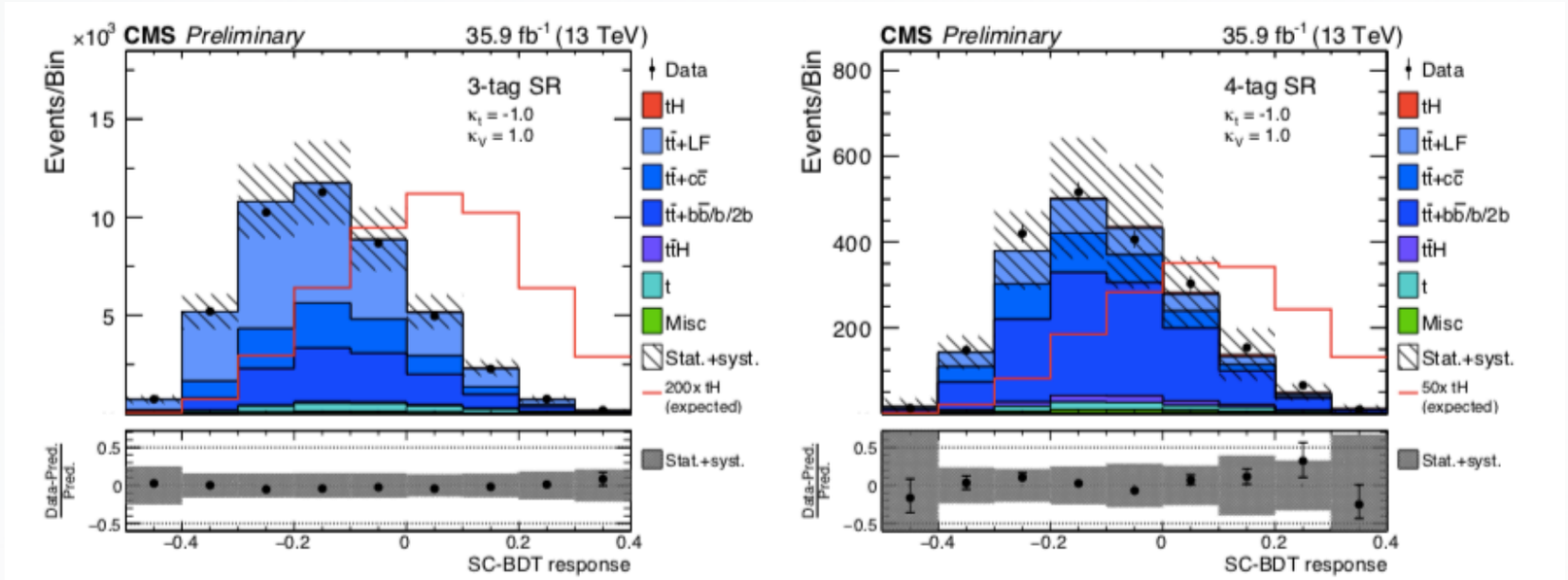


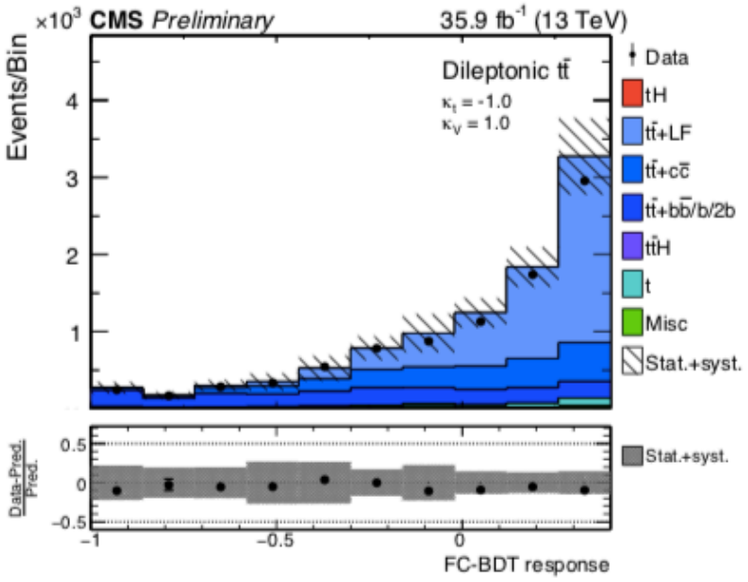


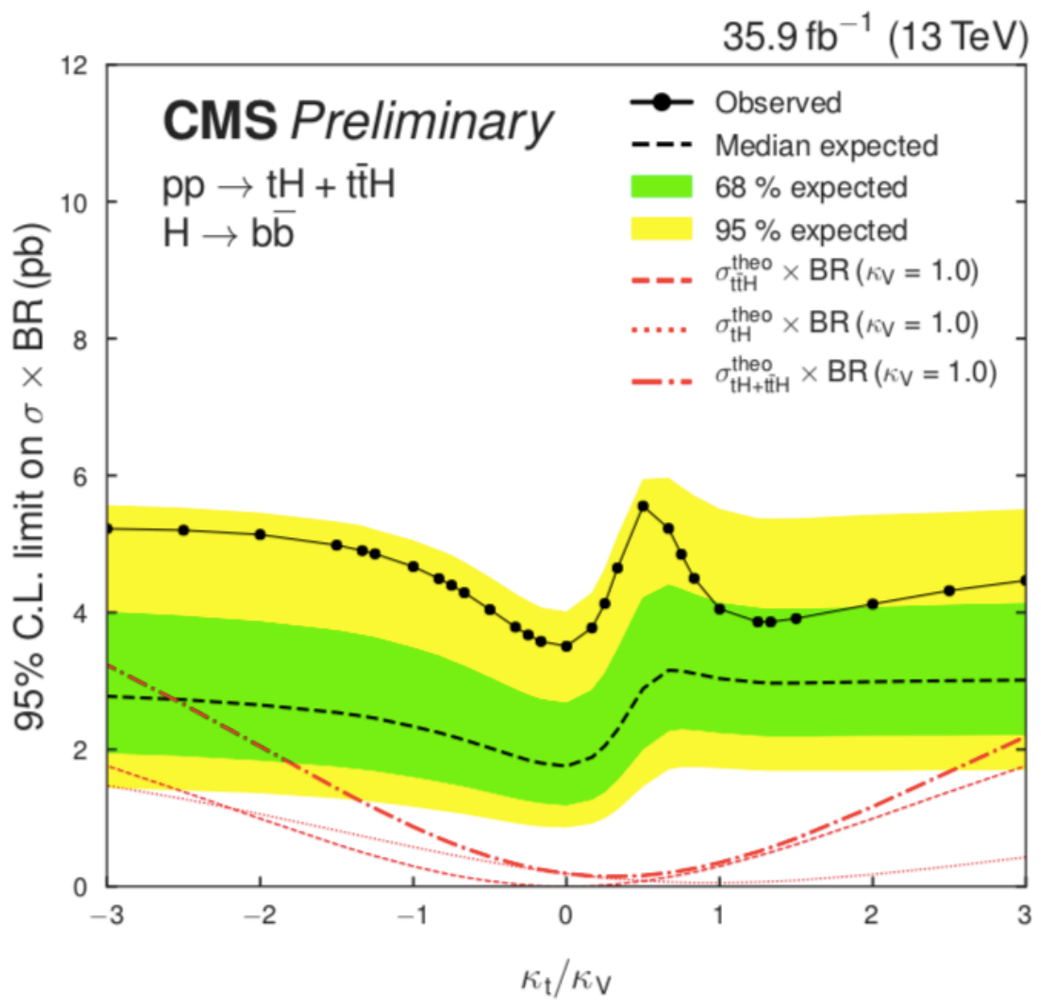


CMS PAS HIG-17-005

tHq at 13 TeV (H→bb)

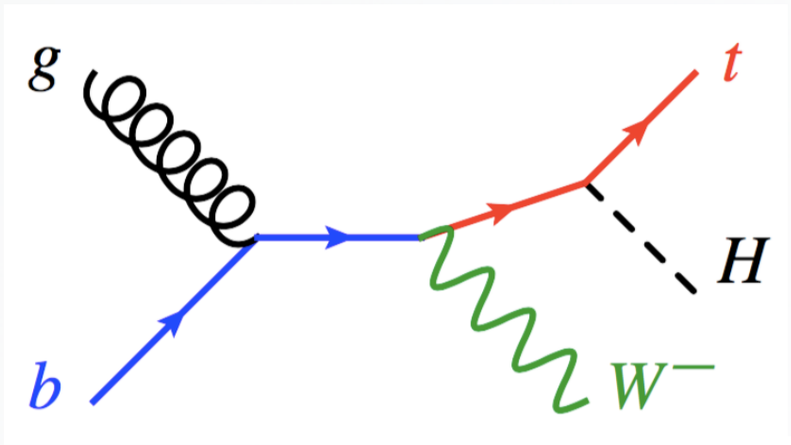


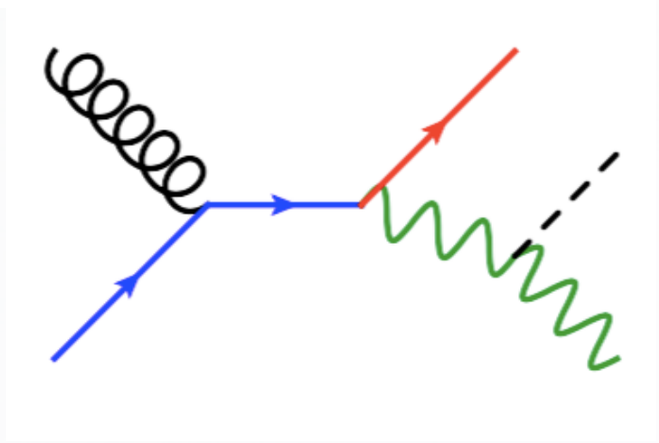


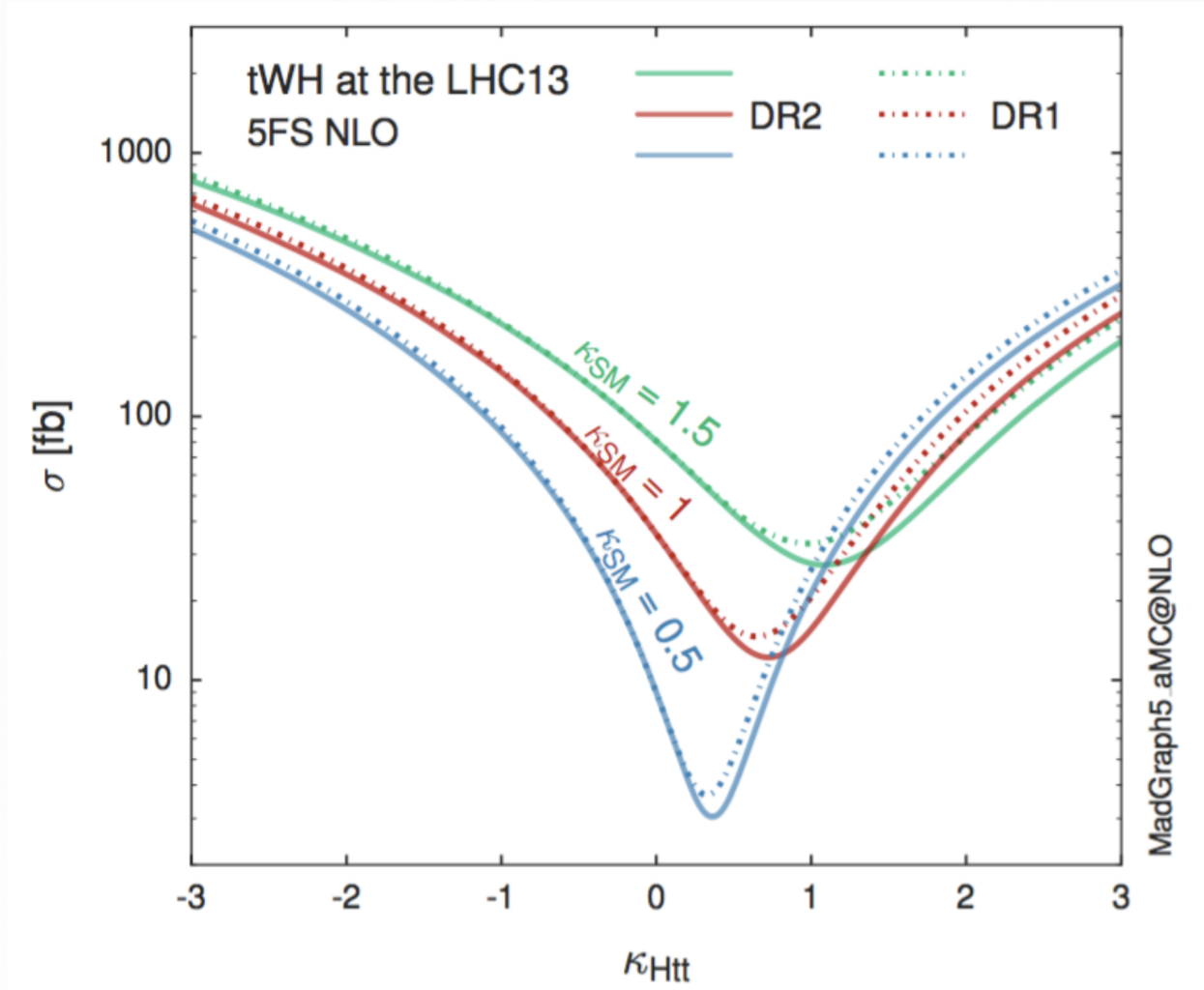


CMS PAS HIG-17-016

tHW







- As tHq, suppressed in SM by destructive interference: $\mathbf{y_t \cdot y_W < 0}$
- **Sensitive to both magnitude and sign of y_t**
- Significant increase in tHW cross section (up to 50x) in some phase space of (y_t,y_W)

Eur. Phys. J. C (2017) 77: 34

No experimental results yet