Review of Higgs boson physics at the LHC

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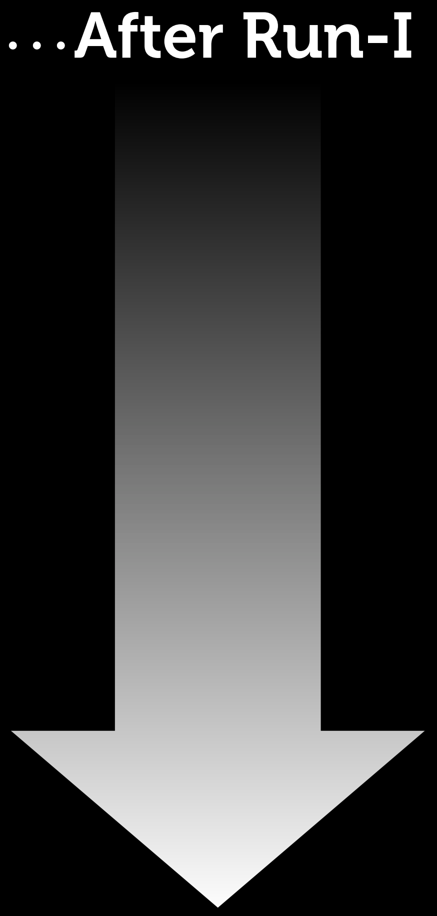
Outline

- I Introduction
- II Precision
- III Discovery
- IV Known unknown
- V Unknown unknown



I

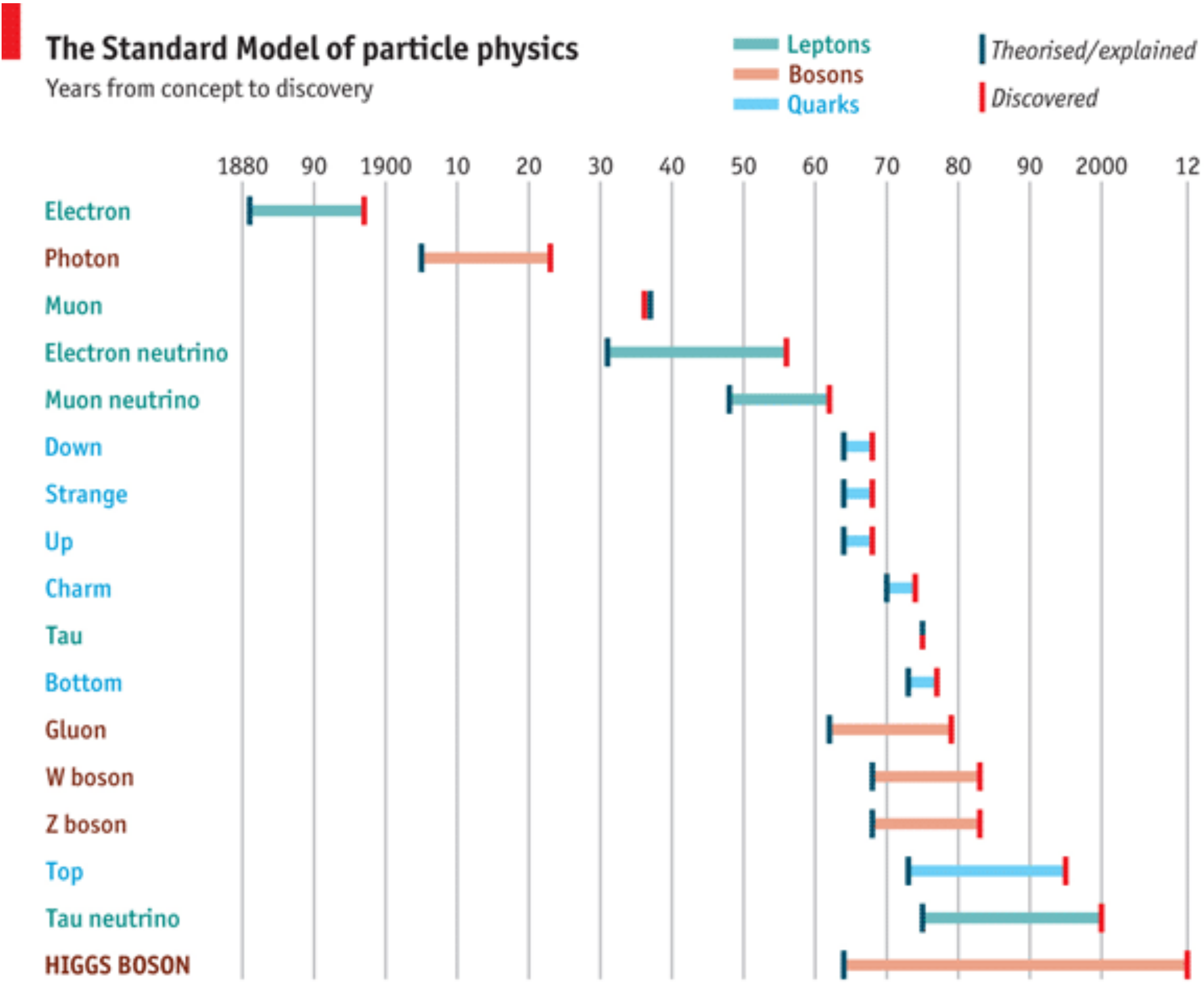
Introduction

Higgs sector

Run-I summary slide

Happy Birthday!

Today is the 5th birthday of the particle that had the longest "gestation" period



The Standard Model of particle physics

Years from concept to discovery

Source: *The Economist*

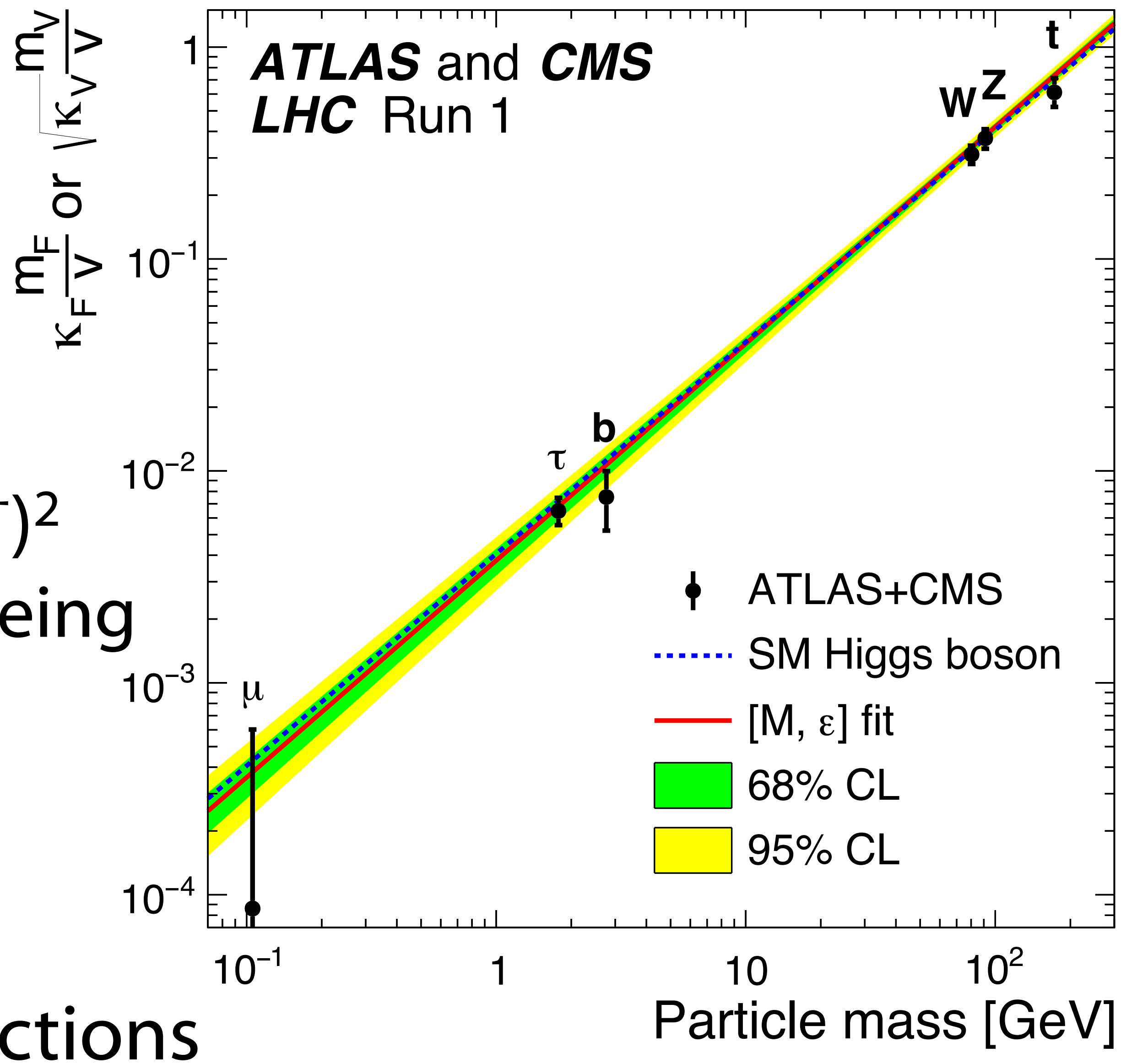
I

The Higgs sector is special

JHEP 08 (2016) 045

The particle and its theory are unlike anything we have seen in nature

➡ A fundamental scalar φ (spin 0)
all other particles are spin 1 or 1/2



➡ A potential $V(\varphi) \sim -\mu^2(\varphi\varphi^\dagger) + \lambda(\varphi\varphi^\dagger)^2$
before the discovery was limited to being theorists'"toy model" (φ^4)

➡ Mass of fermions from Yukawa interactions
couplings spanning 5 orders of magnitude

Run-I summary in a single figure

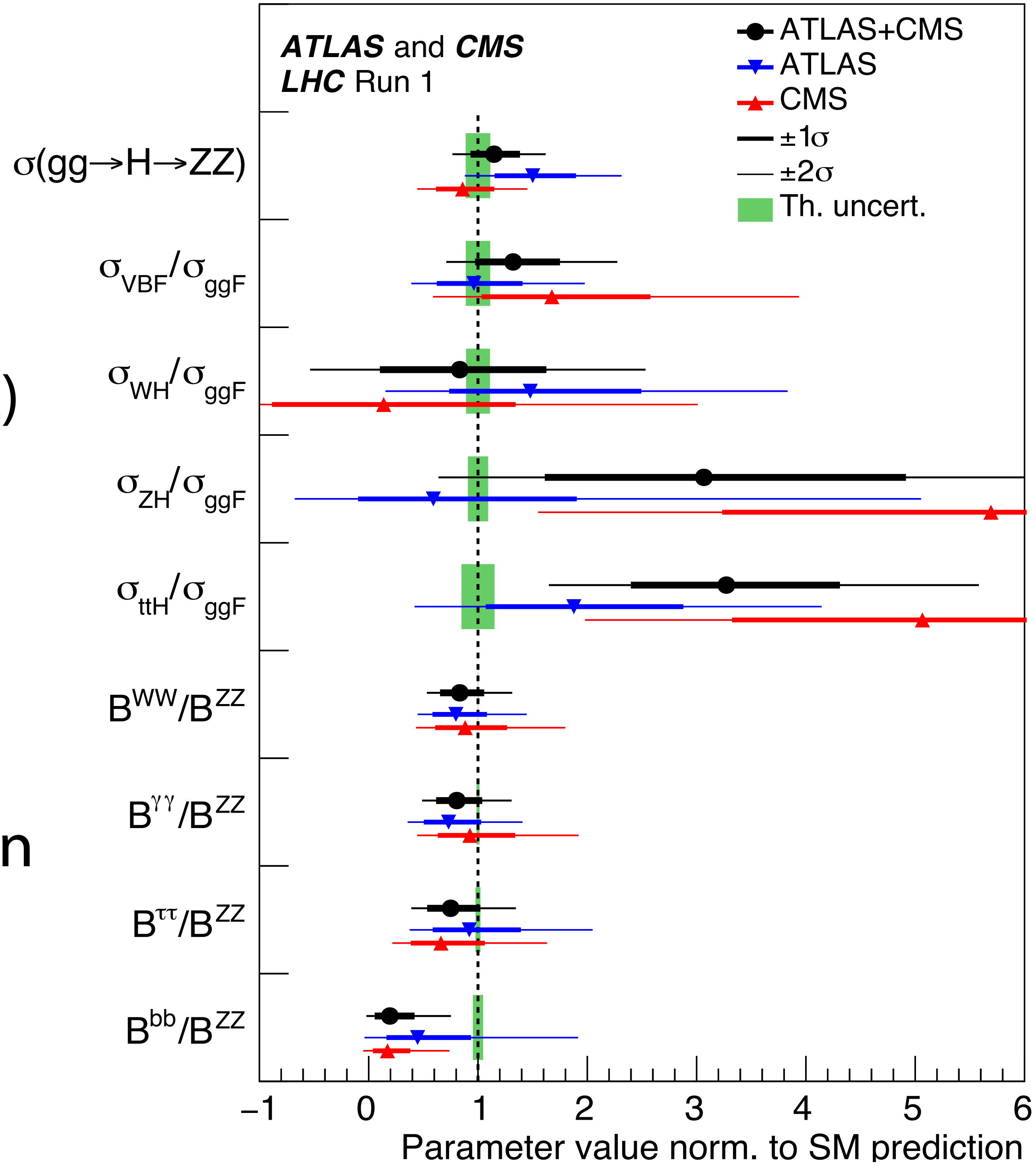
JHEP 08 (2016) 045

What we know after Run-I :

- ➡ Higgs discovery with bosonic decays
- ➡ m_H=125.09 GeV with 0.2% precision
- ➡ $J^{PC} = 0^+$ favoured
- ➡ Narrow width (Γ_H < 20 MeV @ 95%CL)
- ➡ Broad picture looks SM like

… but :

- ➡ Slight excess in σ_{ttH}
- ➡ Slight deficit in B^{bb}
- ➡ Couplings known at 10-30% precision



II

Precision

Mass

Spin-parity

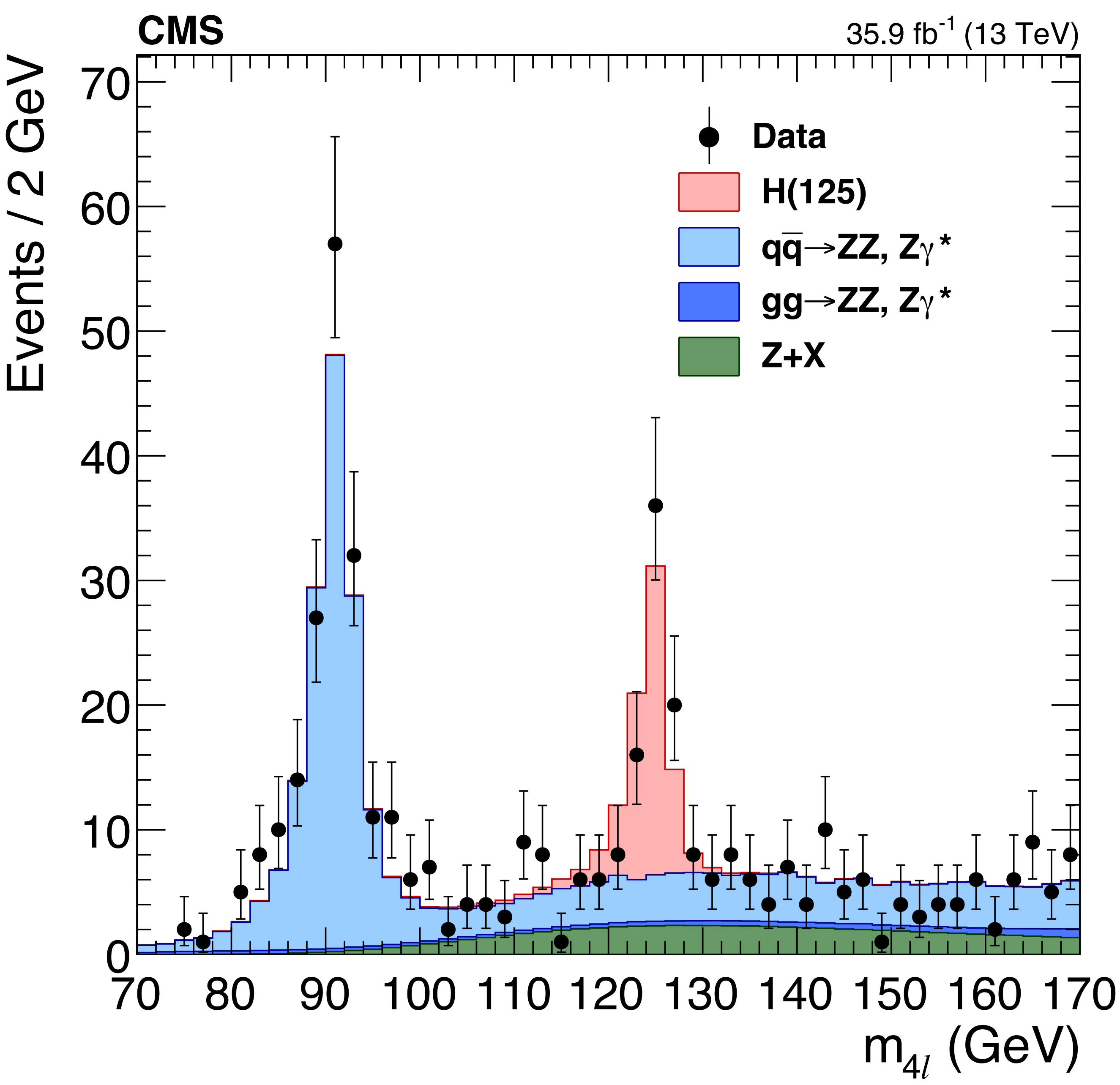
Coupling measurements

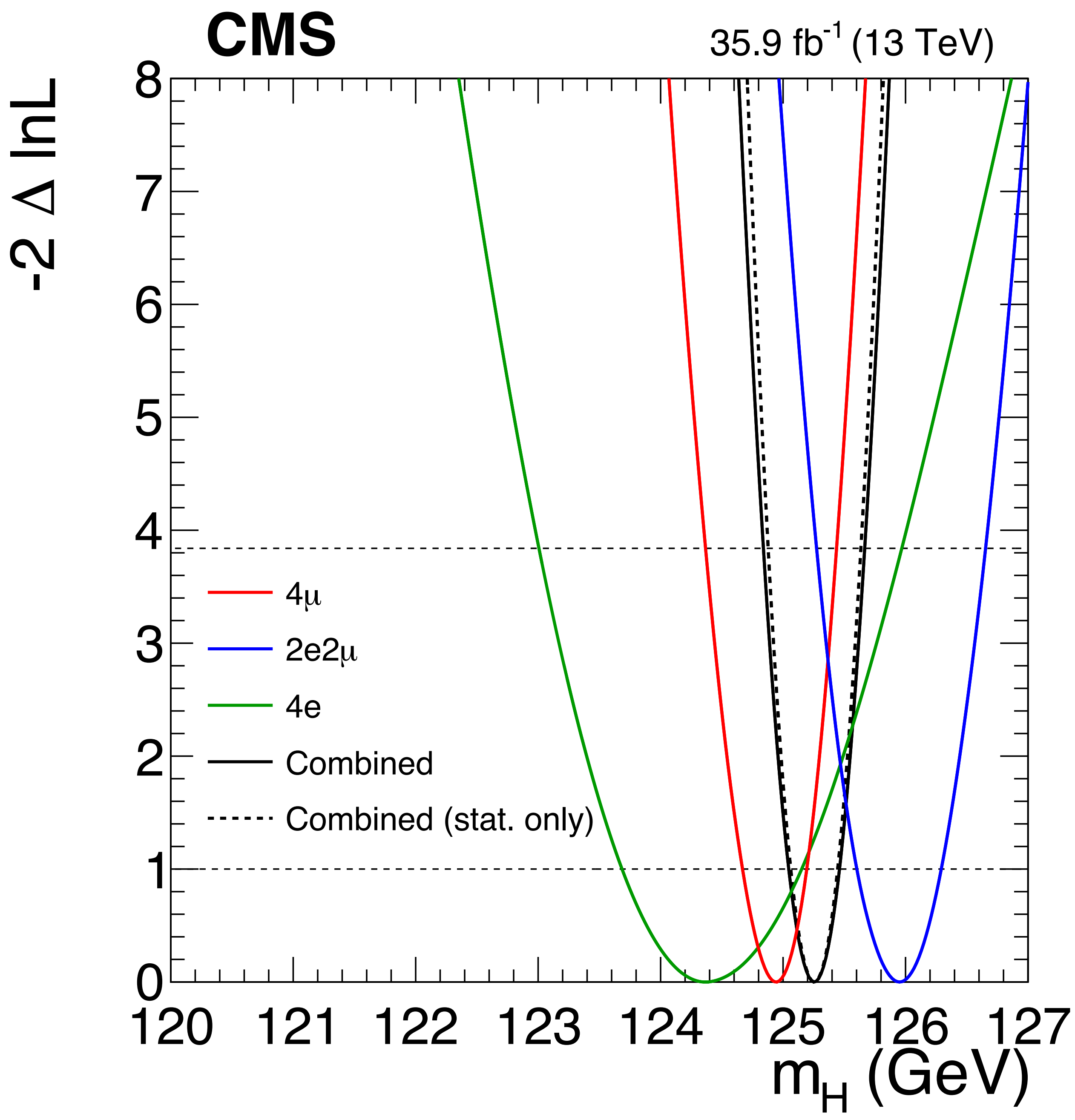
Cross sections measurements

II

Mass peaks : mass measurements

arXiv:1706.09936





Very precise **$m_H = 125.26 \pm 0.20^{(stat)} \pm 0.08^{(syst)}$ GeV**

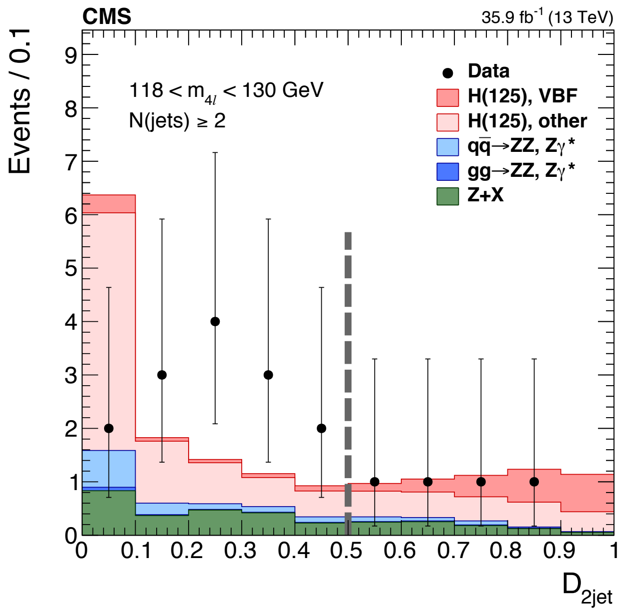
but, 49 MeV (~20%) better than expected,

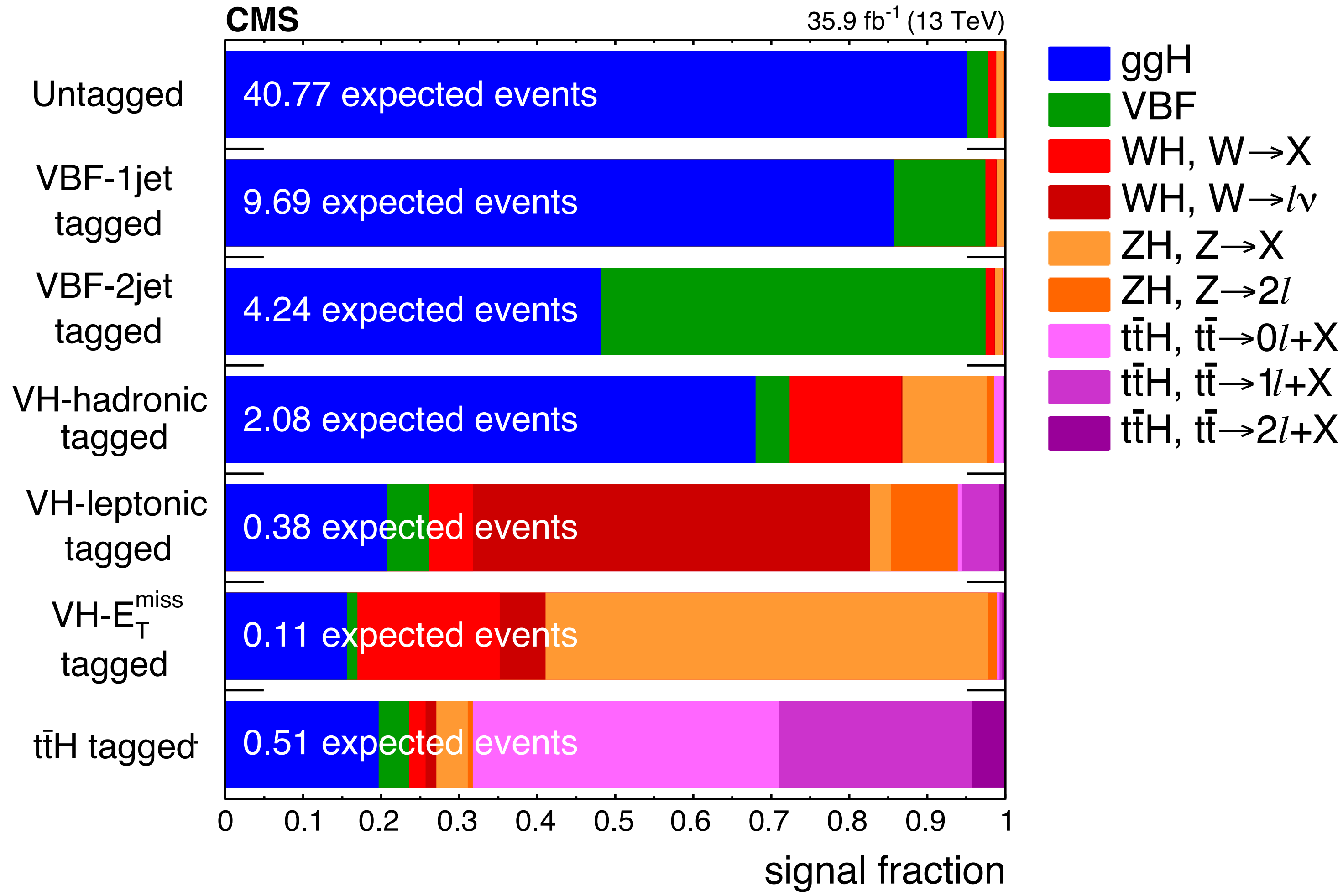
by chance, ~10% better than ATLAS+CMS Run-I combination.

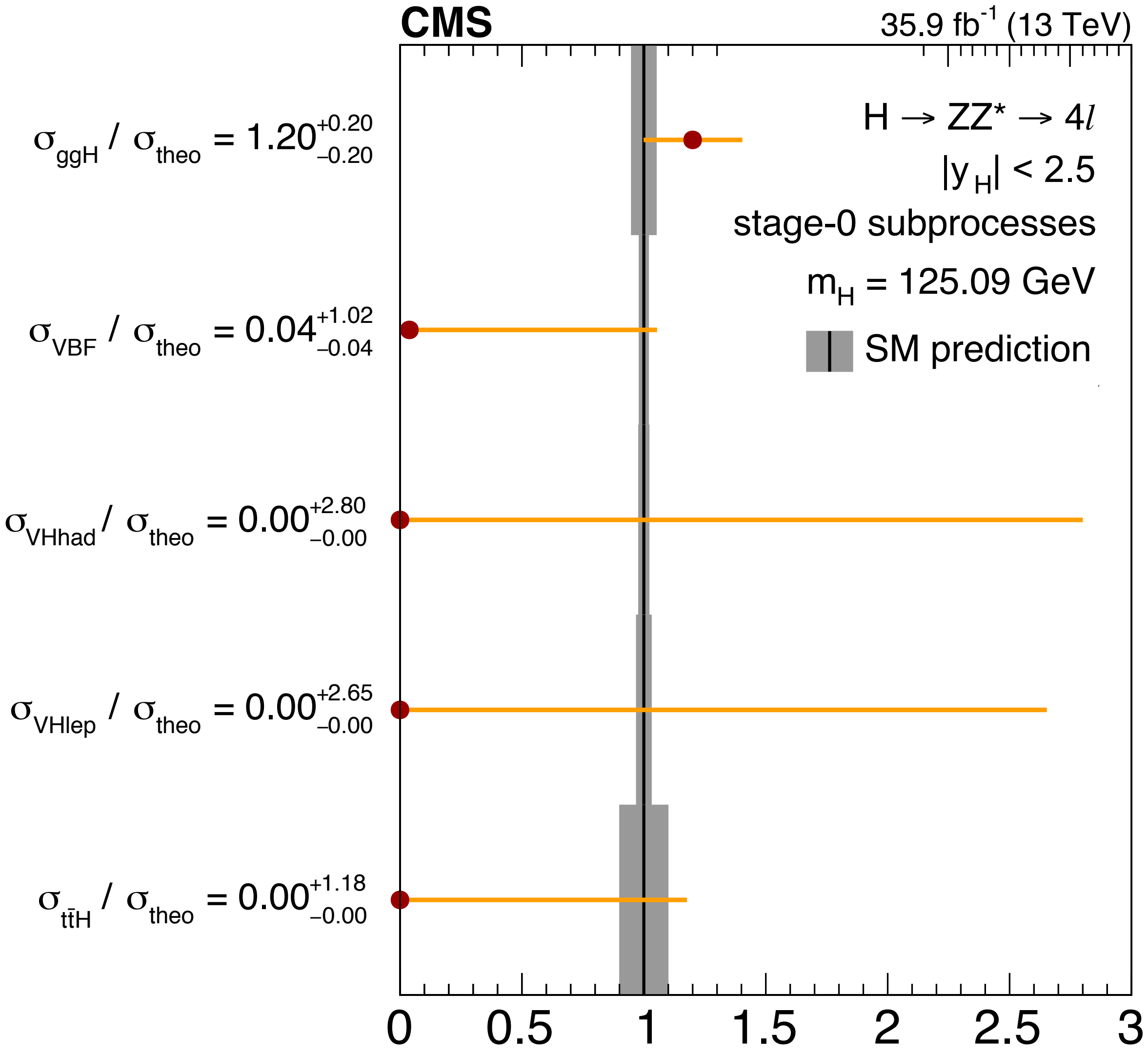
Coupling measurements

arXiv:1706.09936

Introduce productions tags (event categorisation) based on event topology and ME-based discriminants that are exploiting full decay- and production-information.







ggH still pervasive

Statistics low in most exclusive categories

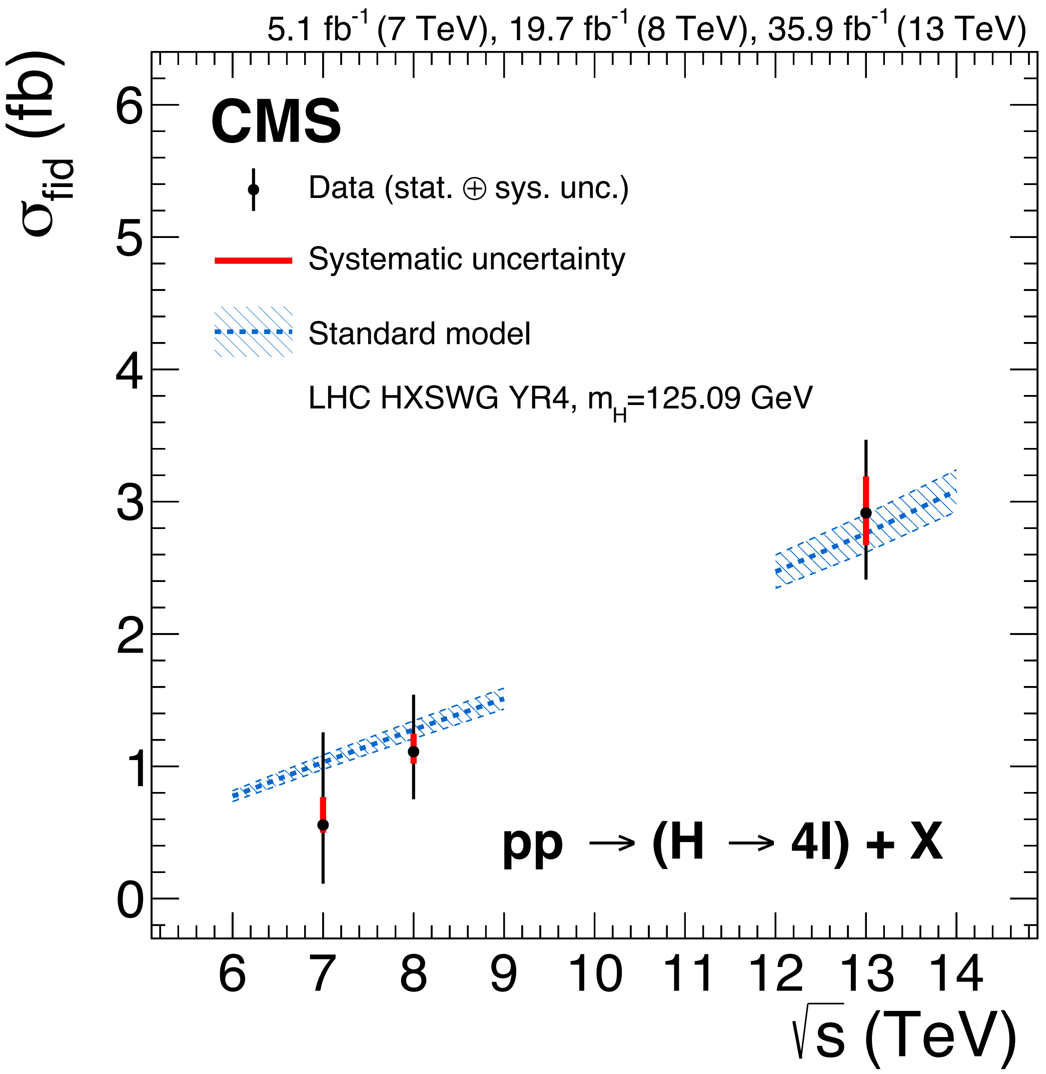
II

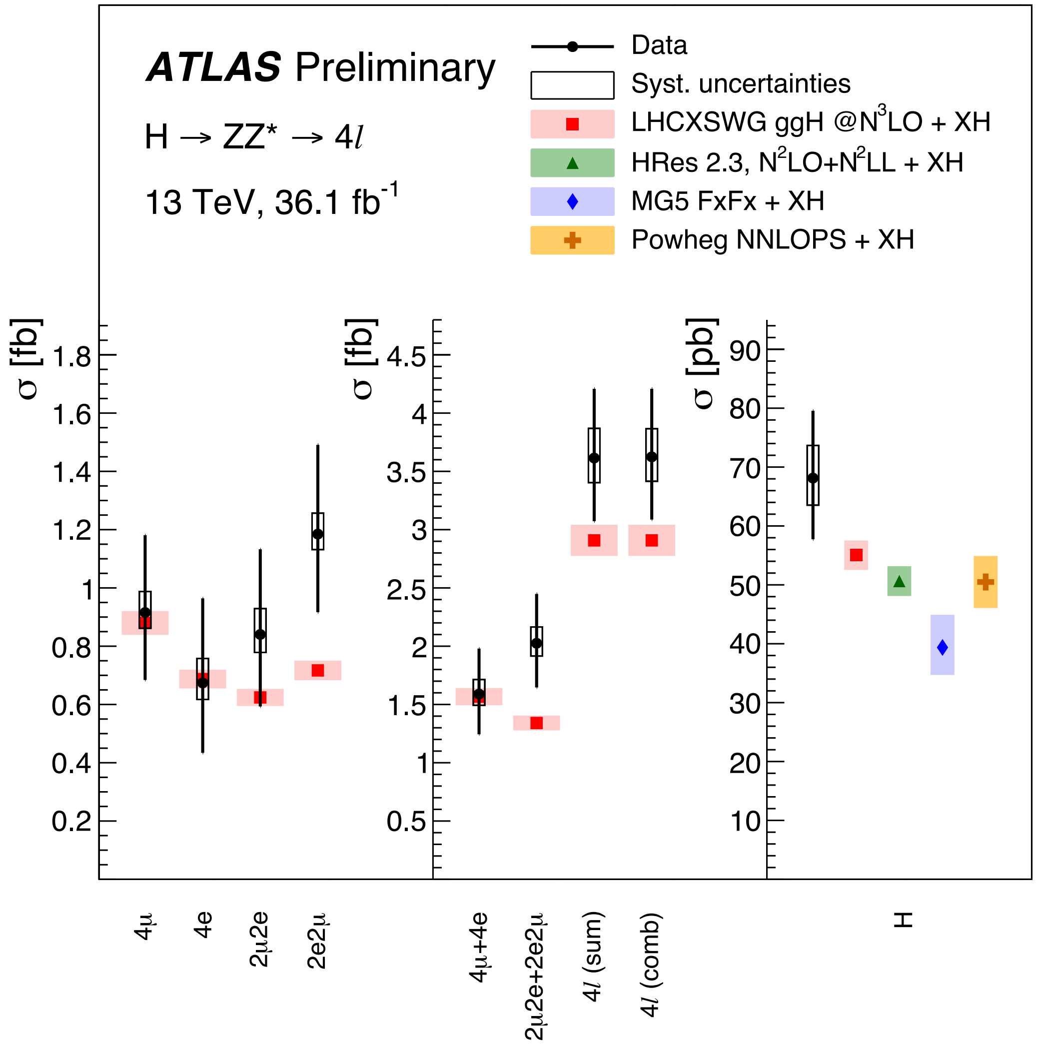
Integral fiducial cross sections

arXiv:1706.09936

ATLAS-CONF-2017-032

Measure within fiducial phase space to minimise model dependence



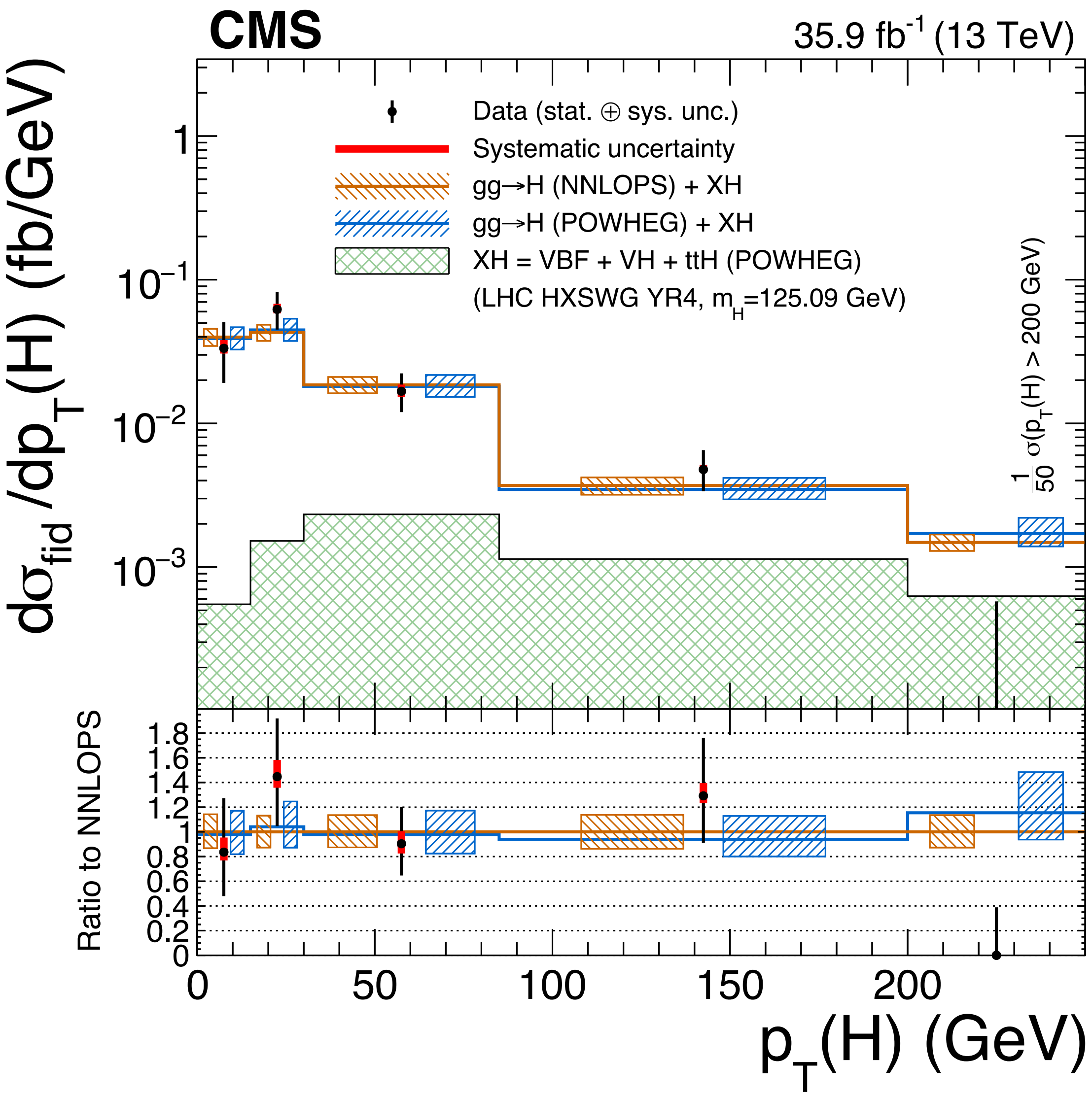


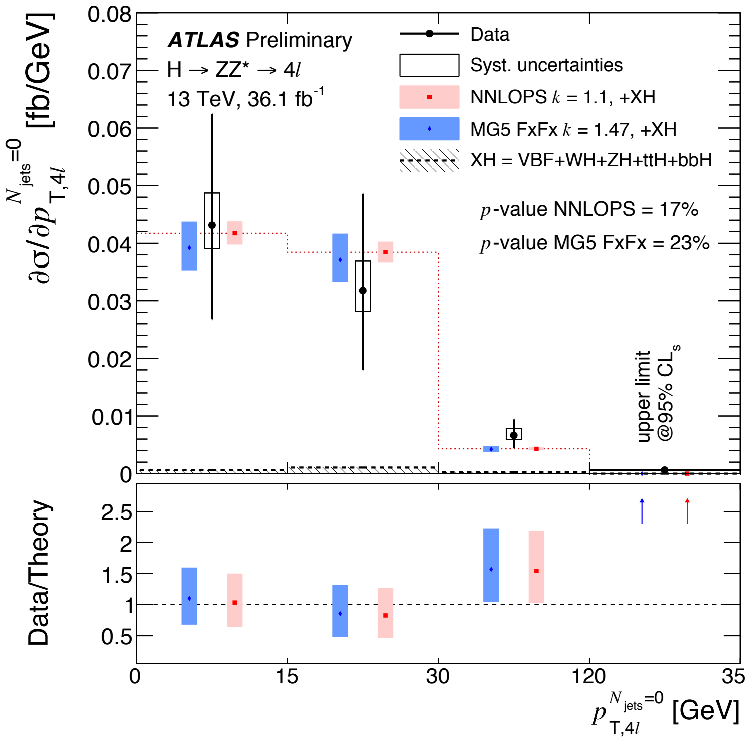
Cross section [fb]	Data (± (stat) ± (sys))	LHCXSWG prediction	*p*-value [%]
$\sigma_{4\mu}$	$0.92\ ^{+0.25}_{-0.23}\ ^{+0.07}_{-0.05}$	0.880 ± 0.039	88
σ_{4e}	$0.67\ ^{+0.28}_{-0.23}\ ^{+0.08}_{-0.06}$	0.688 ± 0.031	96
$\sigma_{2\mu 2e}$	$0.84\ ^{+0.28}_{-0.24}\ ^{+0.09}_{-0.06}$	0.625 ± 0.028	39
$\sigma_{2e2\mu}$	$1.18\ ^{+0.30}_{-0.26}\ ^{+0.07}_{-0.05}$	0.717 ± 0.032	7
$\sigma_{4\mu+4e}$	$1.59\ ^{+0.37}_{-0.33}\ ^{+0.12}_{-0.10}$	1.57 ± 0.07	65
$\sigma_{2\mu 2e+2e2\mu}$	$2.02\ ^{+0.40}_{-0.36}\ ^{+0.14}_{-0.11}$	1.34 ± 0.06	6
σ_{sum}	$3.61\ ^{+0.54}_{-0.50}\ ^{+0.26}_{-0.21}$	2.91 ± 0.13	19
σ_{comb}	$3.62\ ^{+0.53}_{-0.50}\ ^{+0.25}_{-0.20}$	2.91± 0.13	18
σ_{tot} [pb]	$69\ ^{+10}_{-9} \pm 5$	55.6 ± 2.5	19

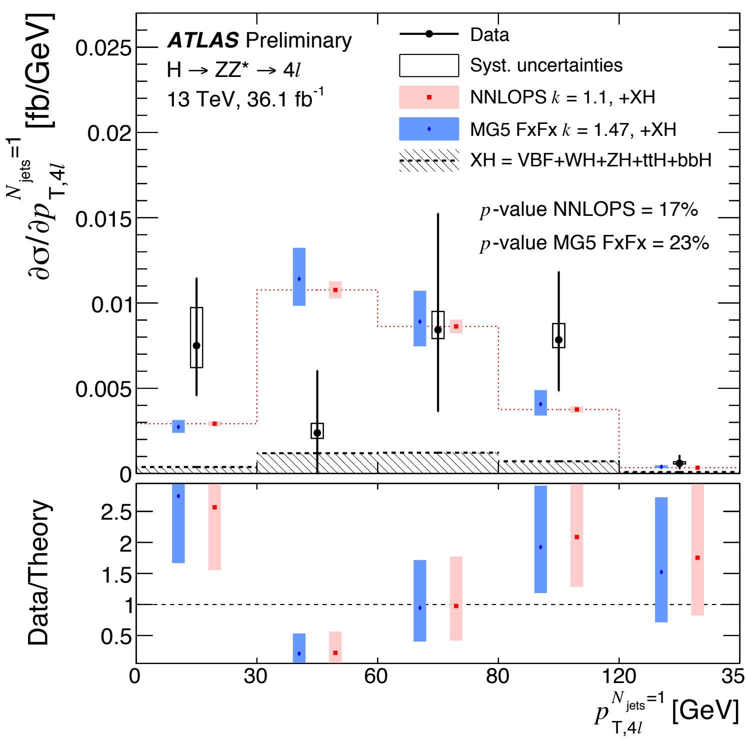
For the fiducial cross section predictions : LHCXSWG ggH prediction accurate to N^{3}LO in QCD is multiplied the acceptance determined using the NNLOPS

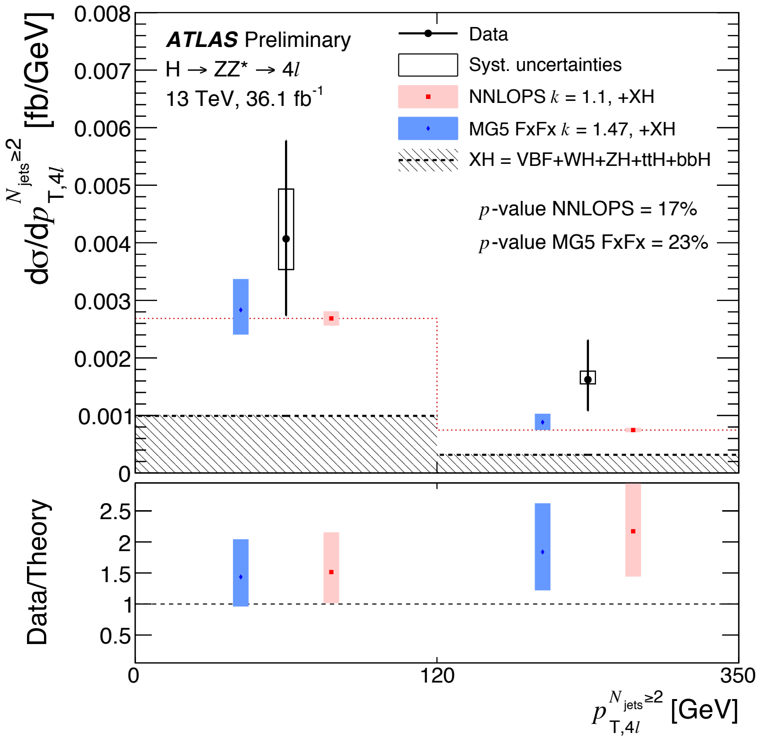
Differential fiducial cross sections

arXiv:1706.09936
ATLAS-CONF-2017-032









No particular deviations

III

Discovery

coupling to leptons

tau lepton coupling

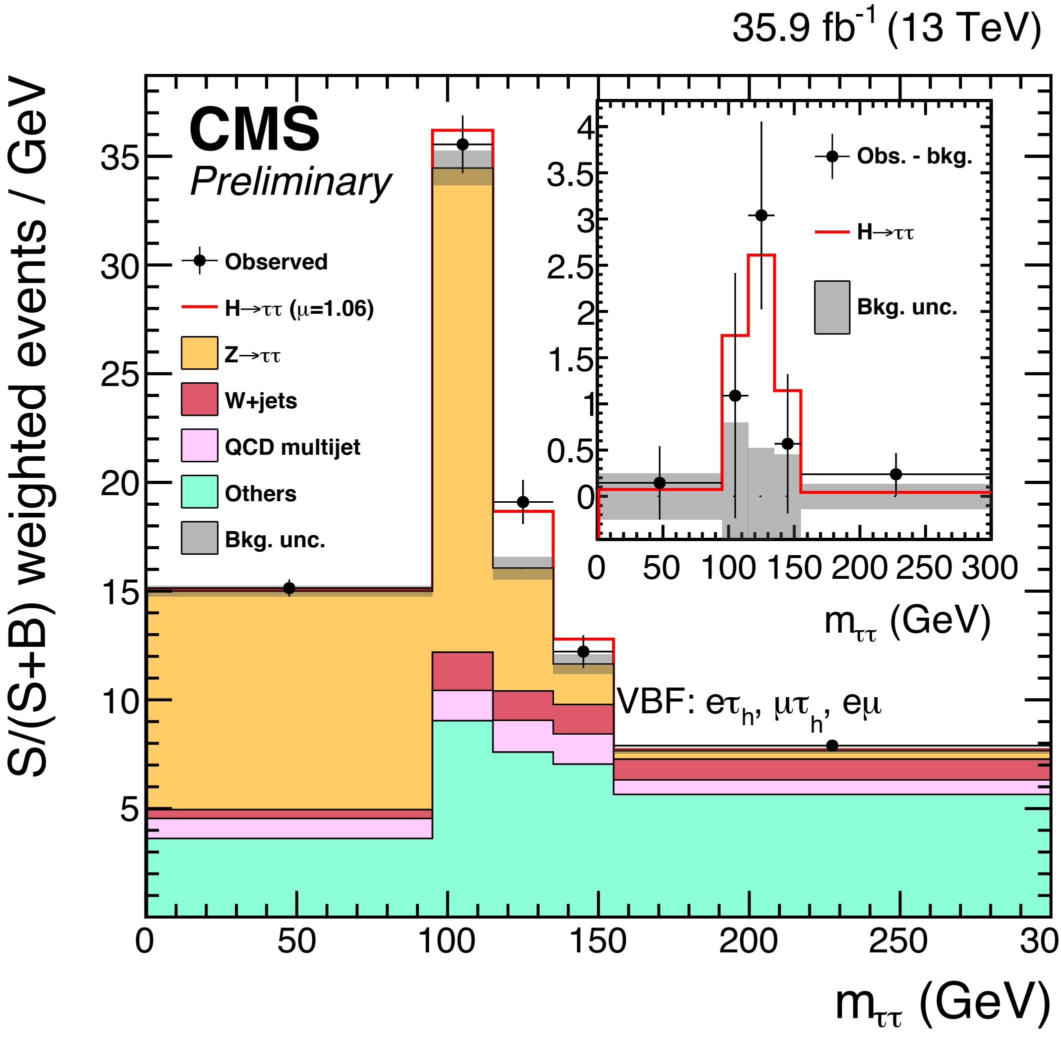
bottom quark coupling

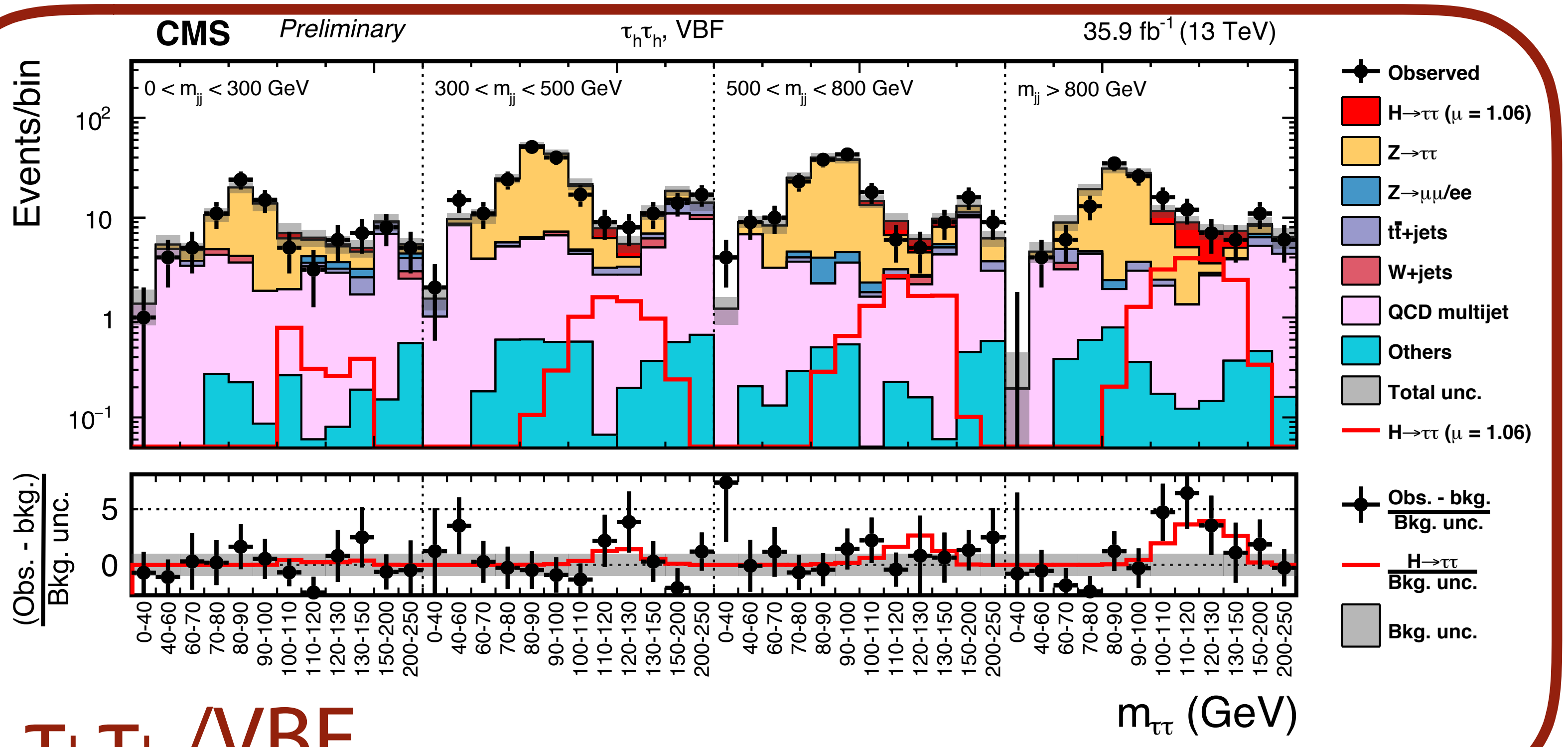
top quark coupling

Observation of H→$\tau\tau$

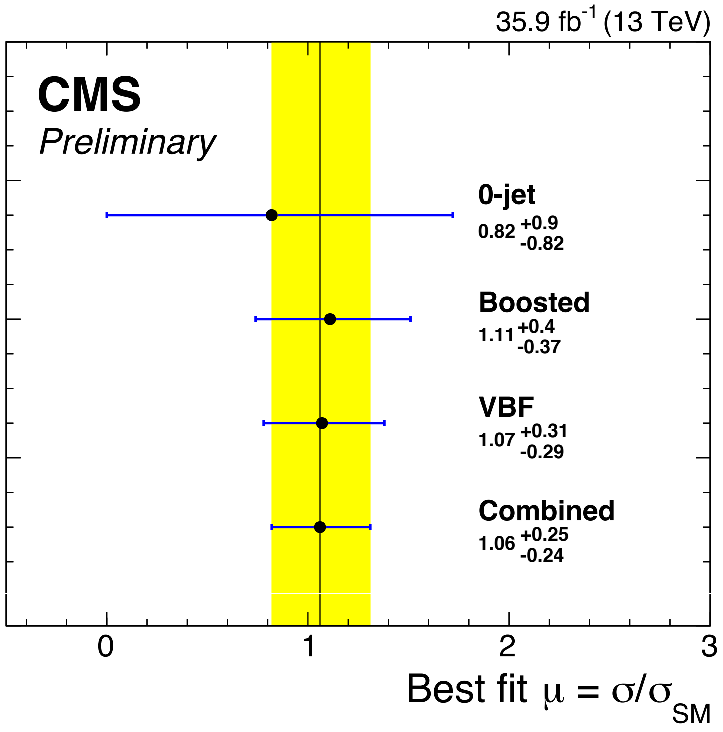
4 decay channels ($e\tau_h$, $\mu\tau_h$, $e\mu$, $\tau_h\tau_h$) x 3 event categories (0-jet, VBF, Boosted)

Simultaneous fit in two kinematical observables





$\tau_h\tau_h$/VBF



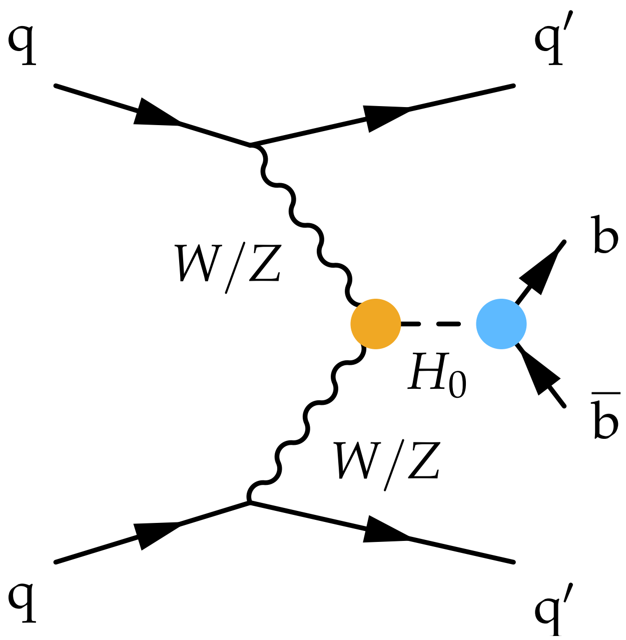
Observed (Expected) significance is 4.9(4.7)σ

bottom quark Yukawa coupling

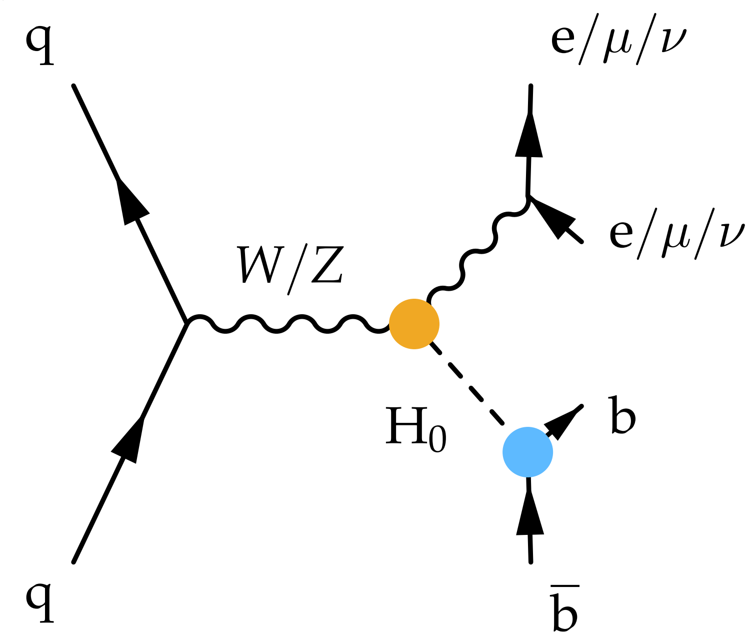
Despite being the largest BR for SM H (~58%), the b quark Yukawa coupling is not yet observed !

The most sensitive production mechanisms used so far

Vector Boson Fusion(VBF)



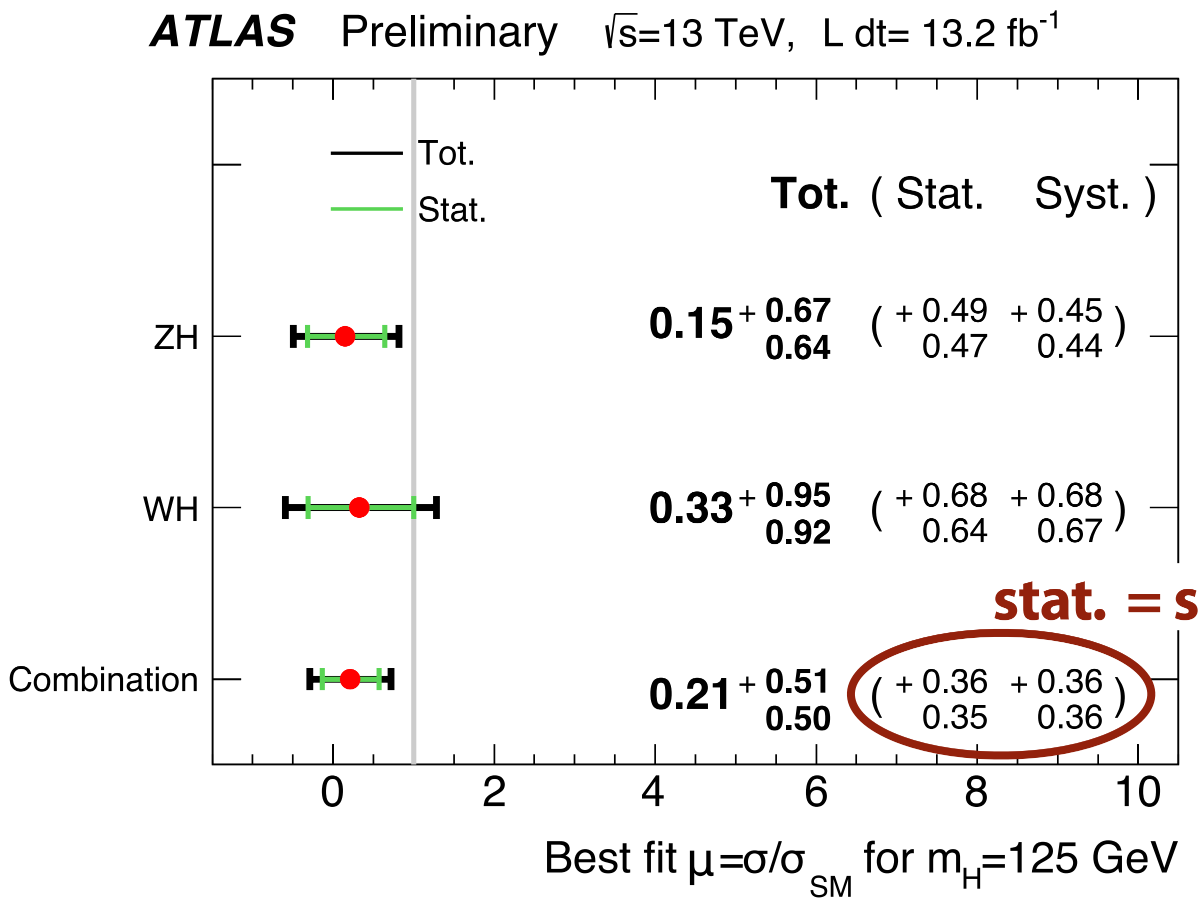
Associate production with vector bosons(VH)



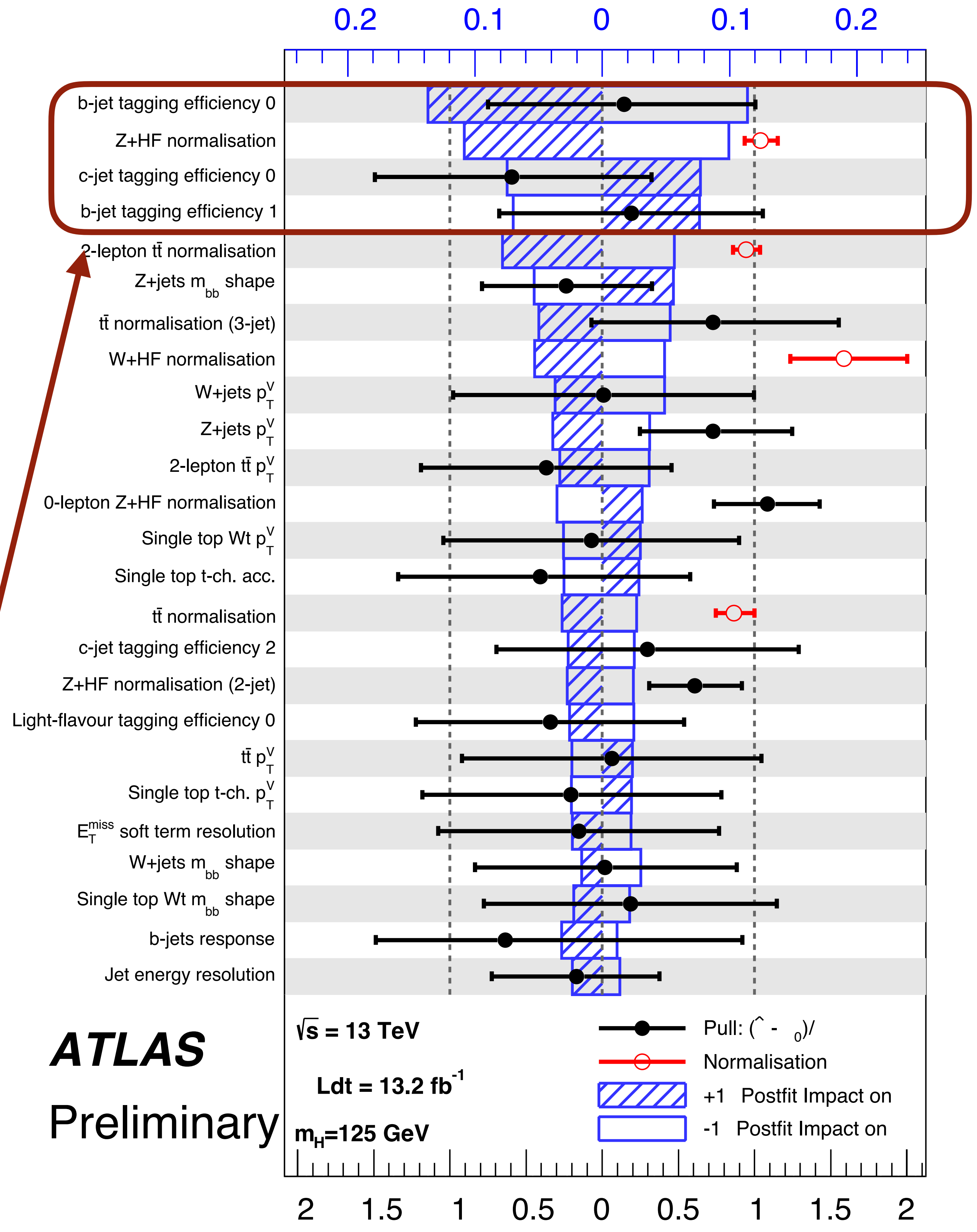
+ associated production with single-top/two-tops (previously discussed)
+ ggH (see later!!)

Main challenges: b-tag (eff, misID), E^{miss}_T, back. modelling (Z+HF),trigger, …

VH→(ll/lν/νν)bb



stat. = syst.



The pull plot shows the systematics and their impact

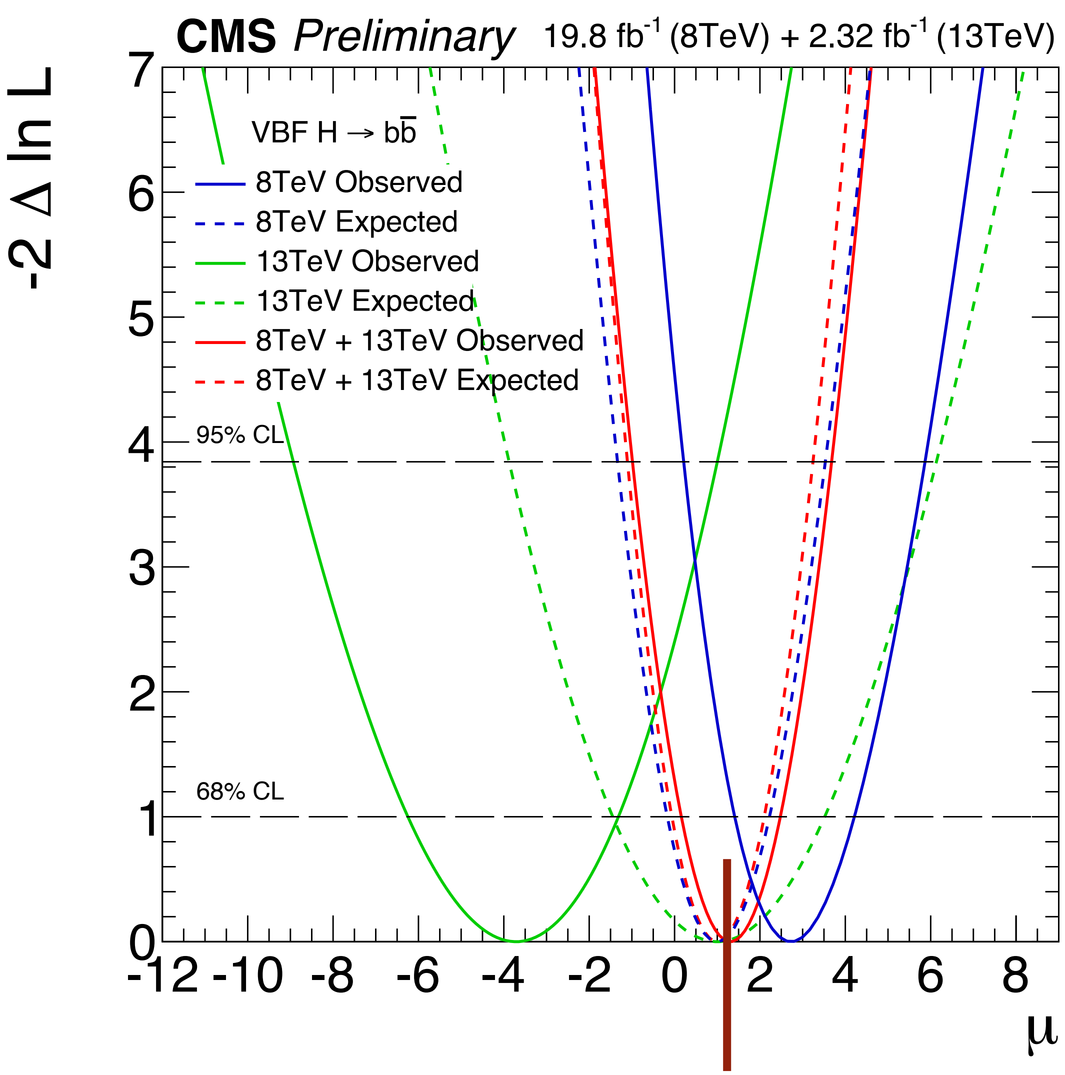
Main ones : b/c tag efficiencies and Z+HF normalization

VBF(+γ), H→bb

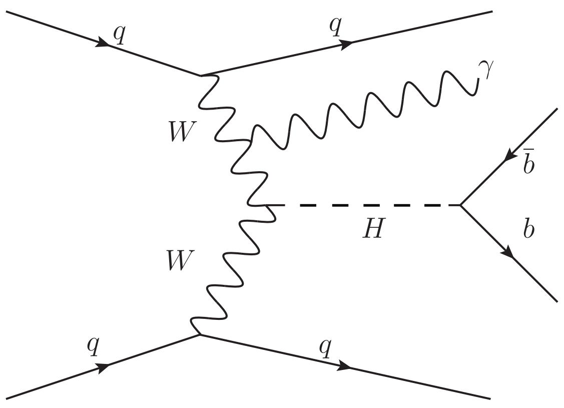
A channel that currently lag in sensitivity but it will catch up the main VH channel → **trigger is critical**

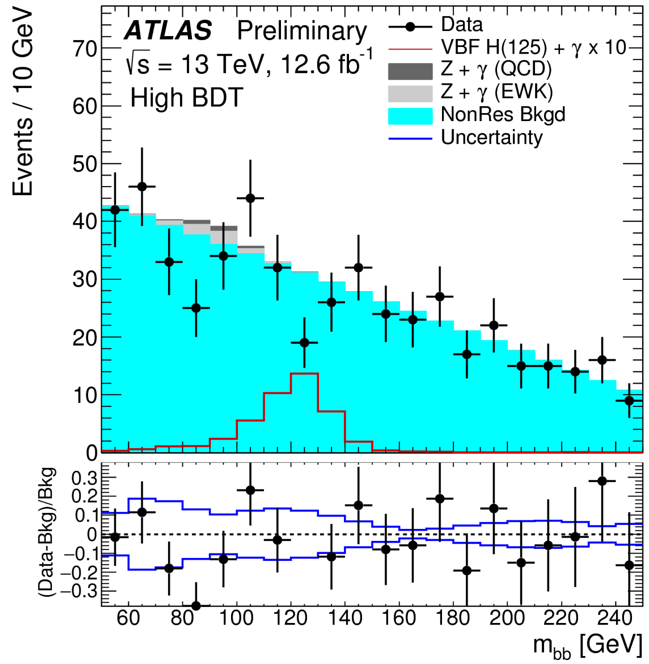
Highest rate analysis attempted
3/4 jets at L1/HLT (high background)

Lowest rate analysis attempted
photon as a tag



μ : $1.3^{+1.2}_{-1.1}$
significance : 1.2σ





Result	$H(\to b\bar{b})+\gamma jj$	$Z(\to b\bar{b})+\gamma jj$
Expected significance	0.4	1.3
Expected p-value	0.4	0.1
Observed p-value	0.9	0.4
Expected limit	$6.0^{+2.3}_{-1.7}$	$1.8^{+0.7}_{-0.5}$
Observed limit	4.0	2.0
Observed signal strength μ	$-3.9^{+2.8}_{-2.7}$	0.3 ± 0.8

III

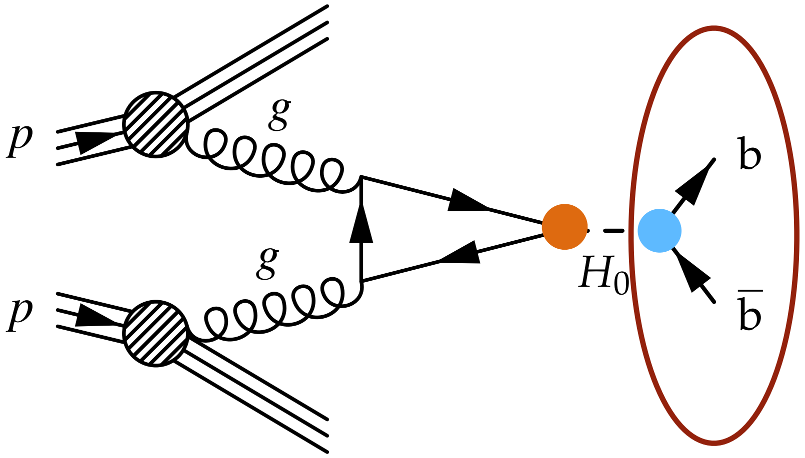
H→bb in boosted topology

CMS-PAS-HIG-17-010

First time at LHC!

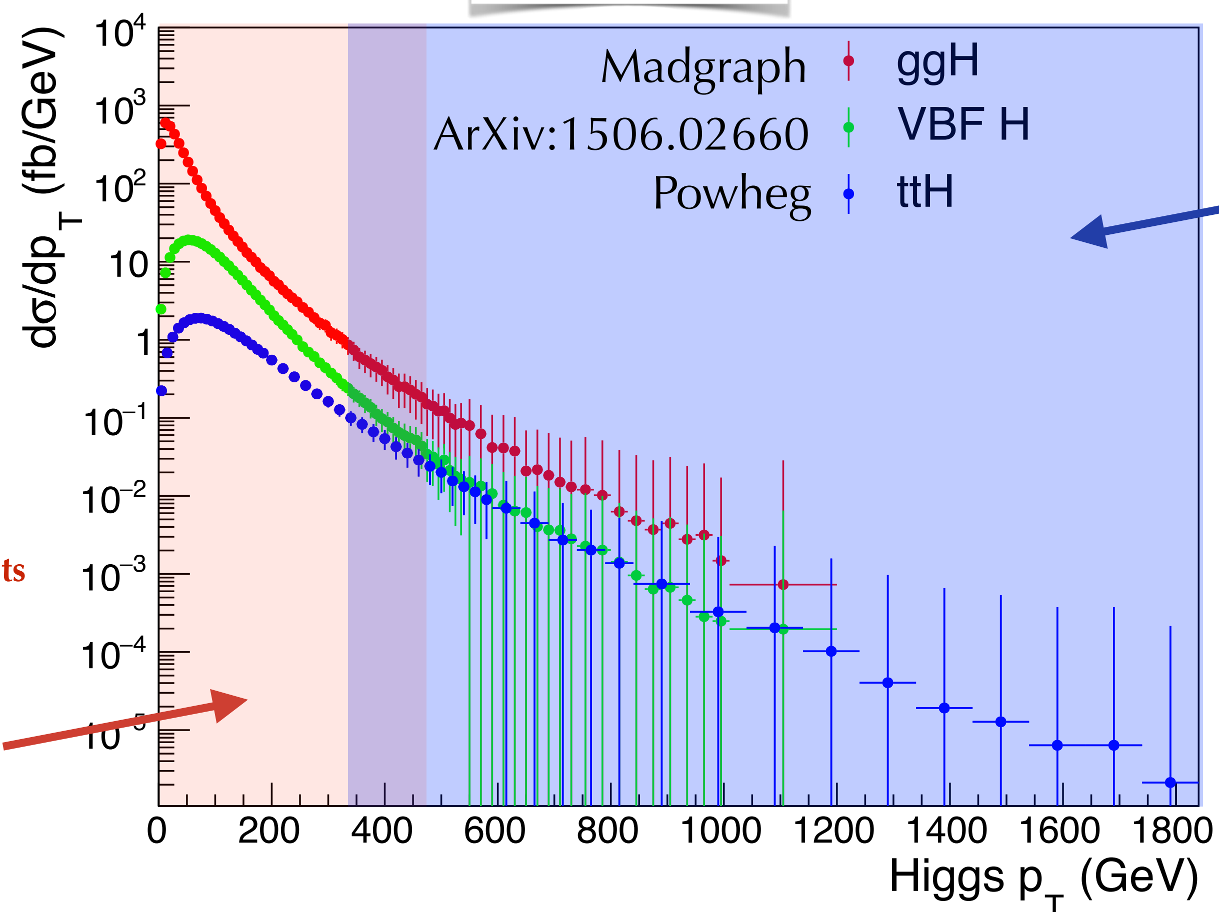
Inclusive H→bb : historically deemed impossible because overwhelming background from QCD production (10^7 larger)

Look for **boosted H boson** in a single jet mass distribution

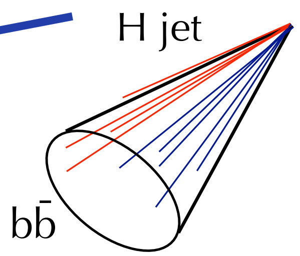


single jet

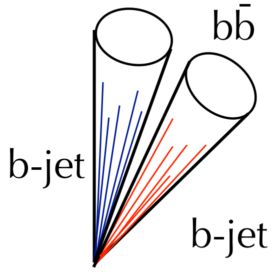
dR($b\bar{b}$) ~ $2m_H/p_T$



one single large-cone (fat) jet (R = 0.8)



two-separate b-jets (R = 0.4)

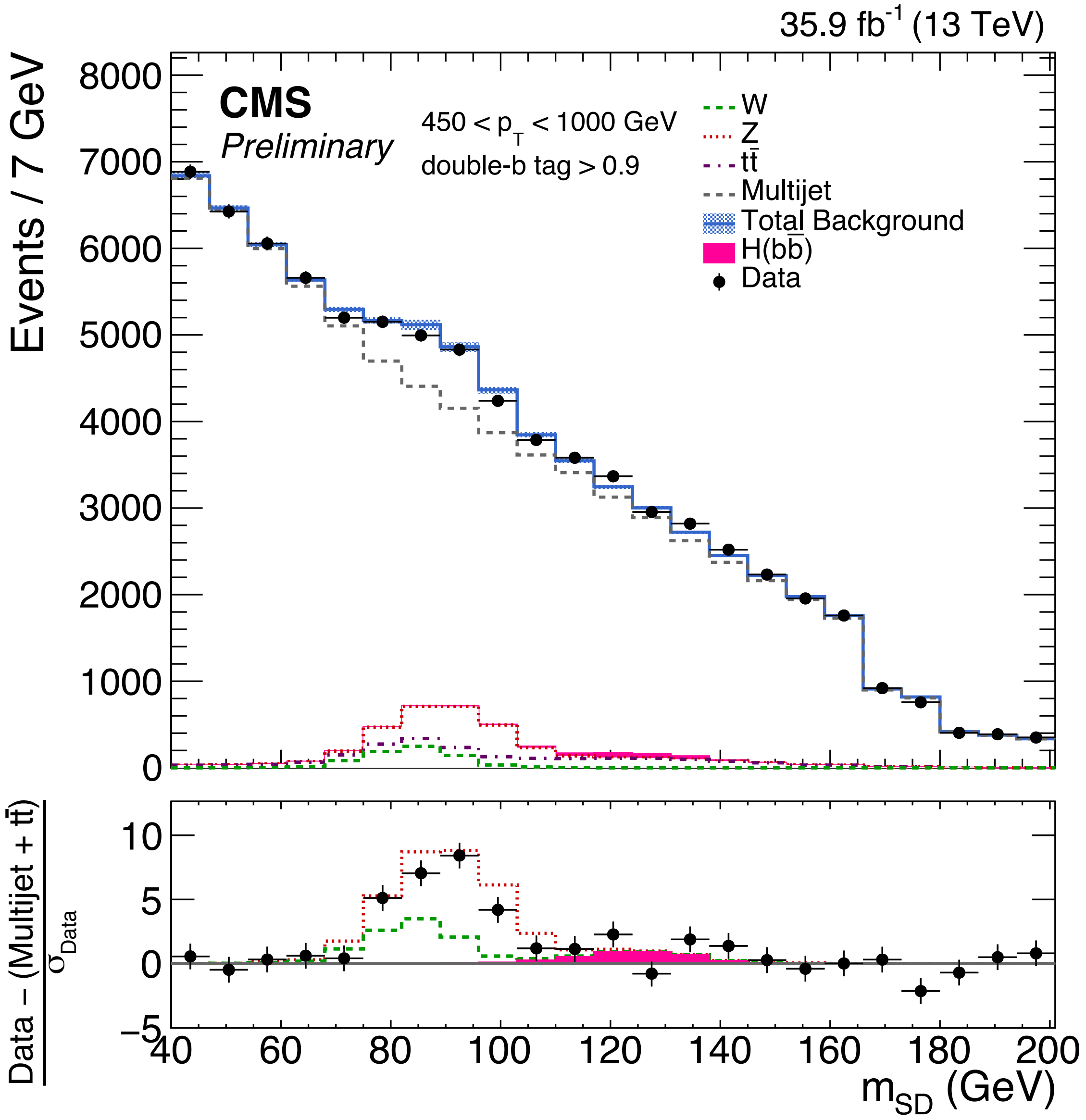


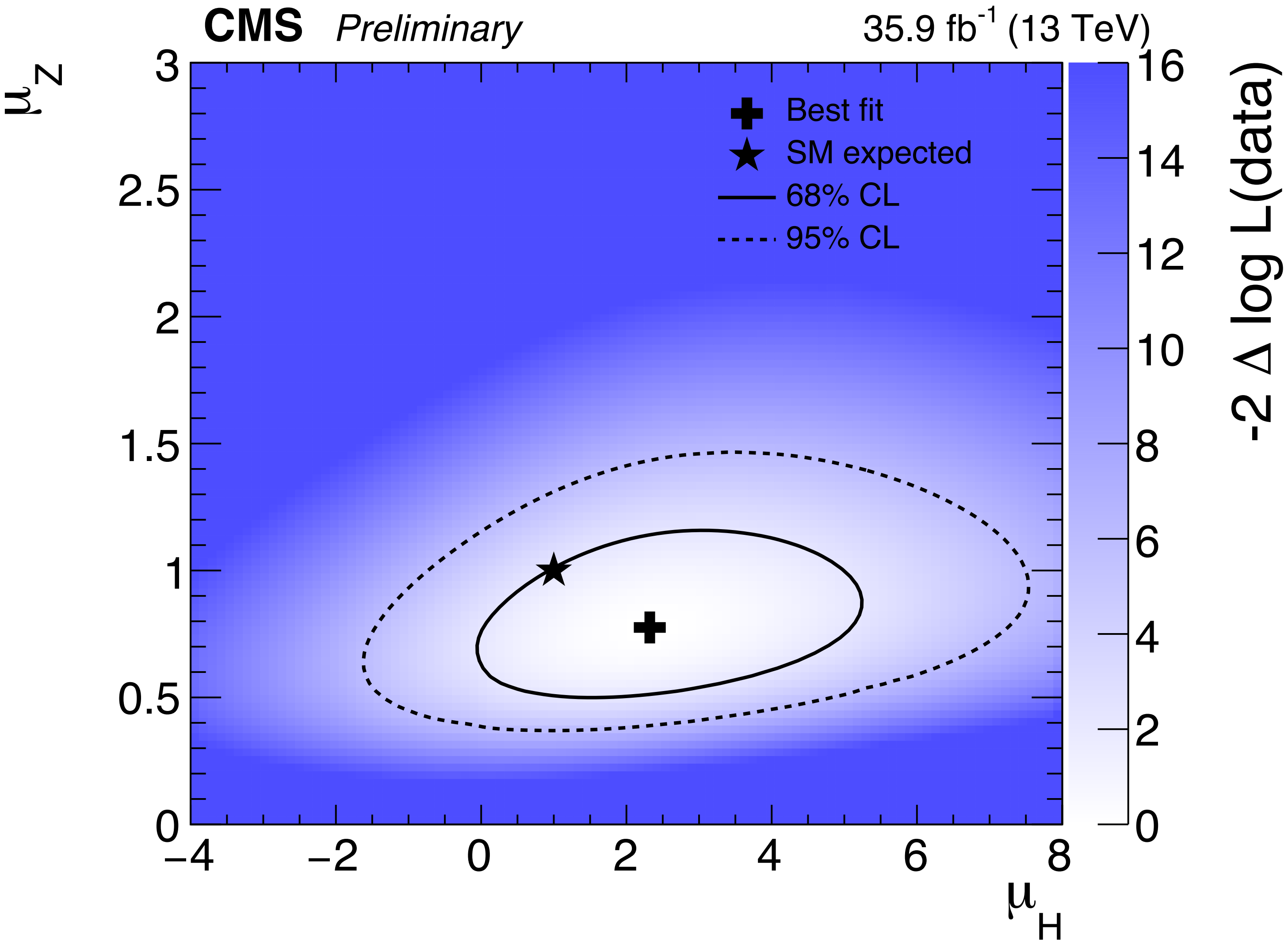
Main challenges: signal ID in large cone jets, b-tag (eff, misID), jet mass and substructure, usage of initial state jet to get above the trigger, …

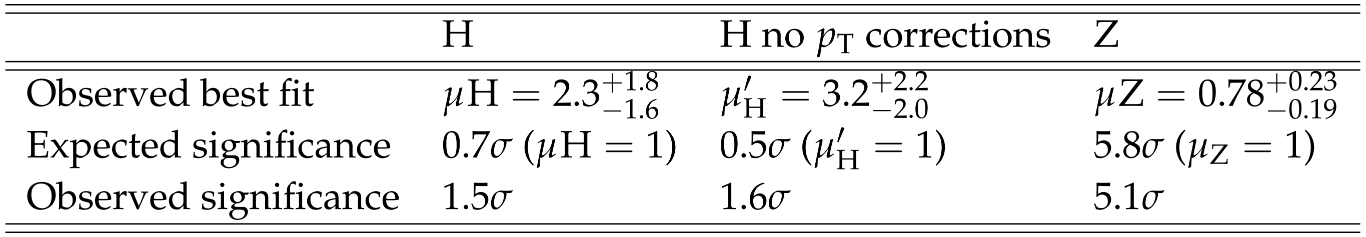
Boosted H→bb

CMS-PAS-HIG-17-010

This is the first time an (approximate) NLO H+0,1,2 jet merged with finite top mass is attempted





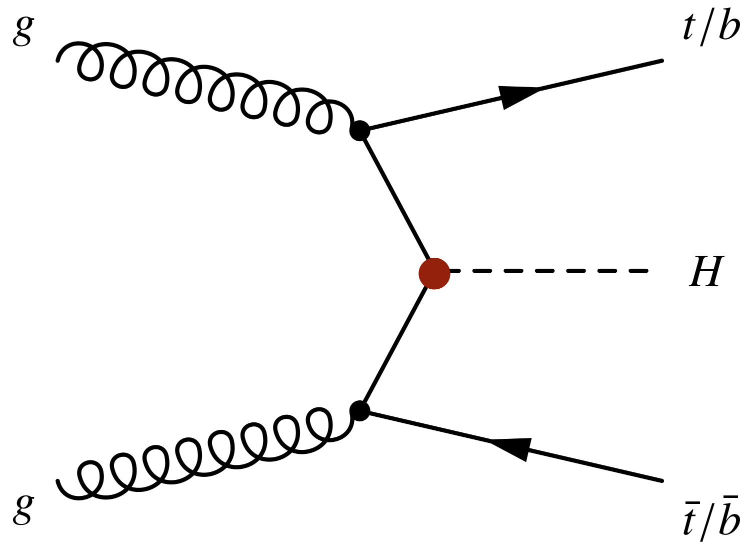


	H	H no p_T corrections	Z
Observed best fit	$\mu H = 2.3^{+1.8}_{-1.6}$	$\mu'_H = 3.2^{+2.2}_{-2.0}$	$\mu Z = 0.78^{+0.23}_{-0.19}$
Expected significance	0.7σ ($\mu H = 1$)	0.5σ ($\mu'_H = 1$)	5.8σ ($\mu_Z = 1$)
Observed significance	1.5σ	1.6σ	5.1σ

Possible to probe BSM contributions to the Higgs at very high p_T

top quark Yukawa coupling

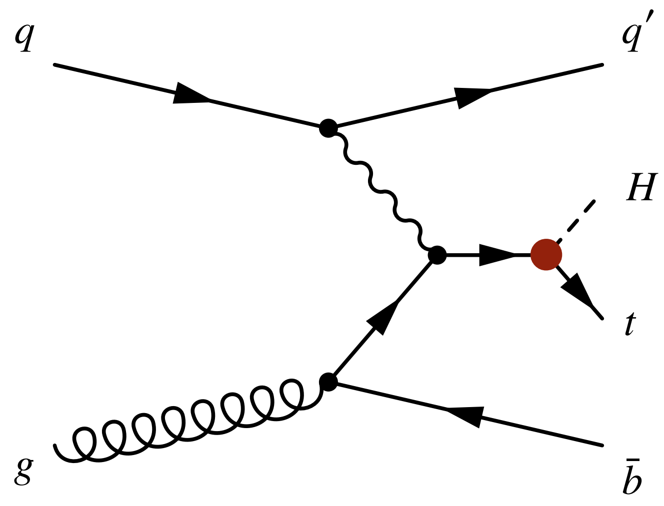
In SM the top quark Yukawa coupling is strongest one ($Y_t \propto m_{top}/v \approx 1$)
The top-Higgs vertex (●) is only directly accessible when H is produced in association with one or more top quarks



$\sigma(pp \rightarrow ttH)\begin{cases} 0.133\ \text{pb @ 8 TeV} \\ 0.507\ \text{pb @ 13 TeV} \end{cases}$

~1/96th of ggH production

Probes the modulus of Y_t



$\sigma(pp \rightarrow tH)\begin{cases} 0.019\ \text{pb @ 8 TeV} \\ 0.074\ \text{pb @ 13 TeV} \end{cases}$

~1/15th of ttH production

Probes the relative sign of Y_t

The comparison of the precise direct measurement of Y_t with the one from the loop-induced ggH (which in the SM is also dominated by the Y_t) can constrain contributions from new physics in the gluon fusion loop

III Experimental path to top quark Yukawa coupling

Systematics-limited → **Statistical-limited**

$H \longrightarrow b\bar{b}$

- High yield
- Theory-limited tt+HF backgrounds

$H \longrightarrow (WW,\tau\tau)$ multileptons

- Moderate yield
- Reducible background from non-prompt leptons

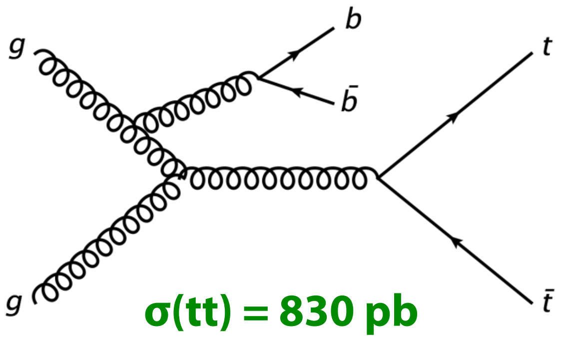
$H \longrightarrow ZZ \longrightarrow 4l$

$H \longrightarrow \gamma\gamma$

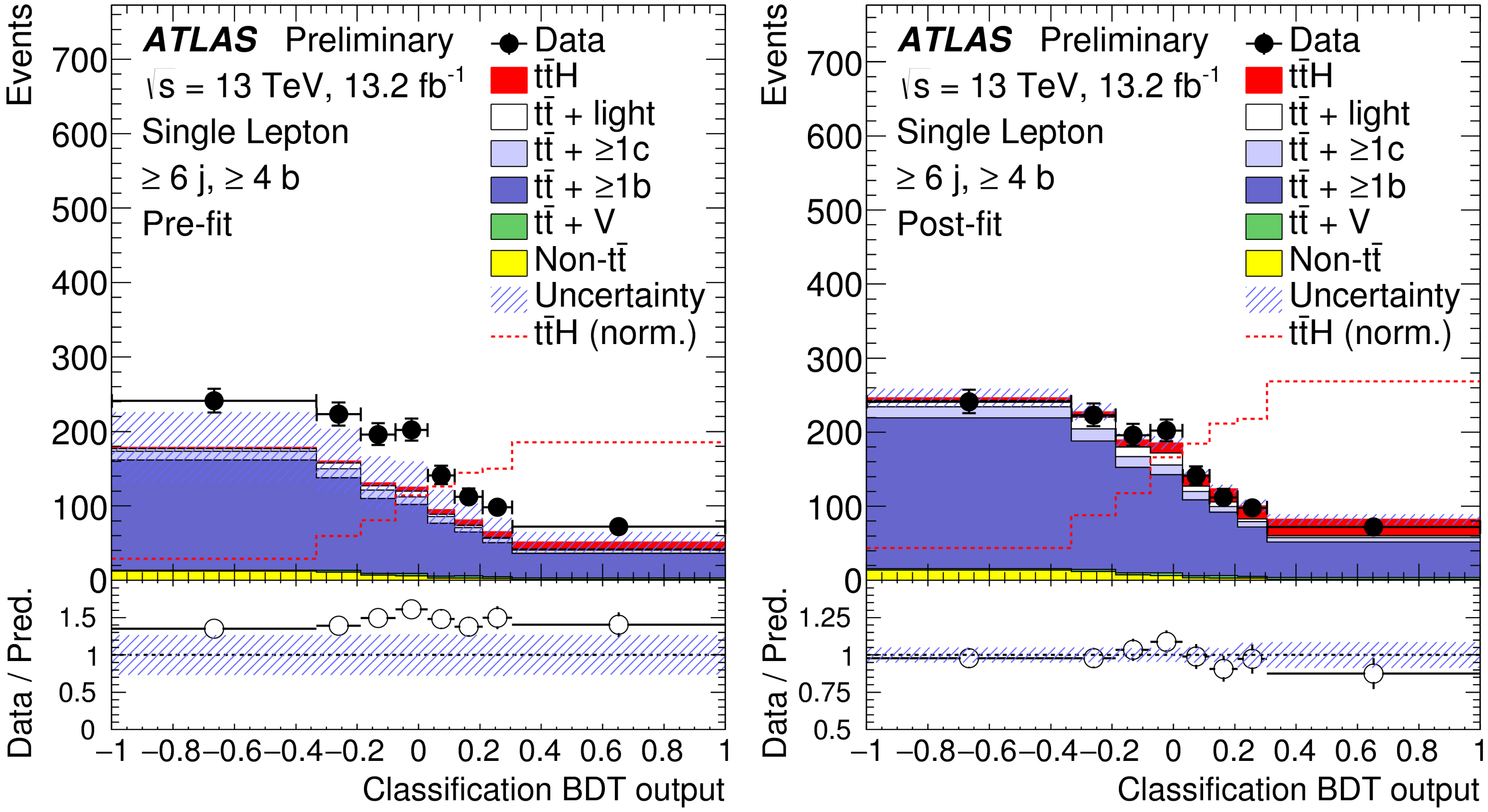
ttH with H→bb

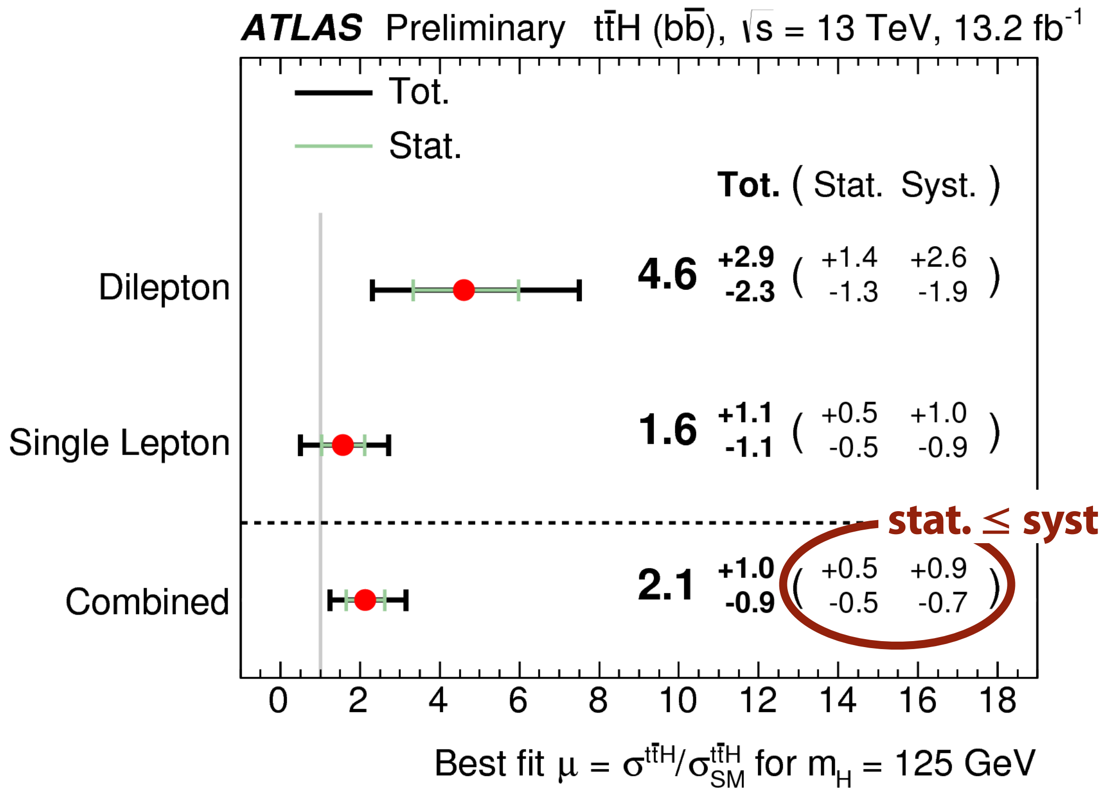
ATLAS-CONF-2016-080

Overcome large background from tt+jets, especially tt+≥1b, associated large theory uncertainties on its modelling



σ(tt) = 830 pb
σ(tt + b-jets) ~ O(10) pb





stat. ≤ syst.

Sensitivity on μ: ~1·SM, limited by systematics dominated by those on tt+≥1b background

Need in the close future to improve the background modelling
Interaction with theory & MC experts

III

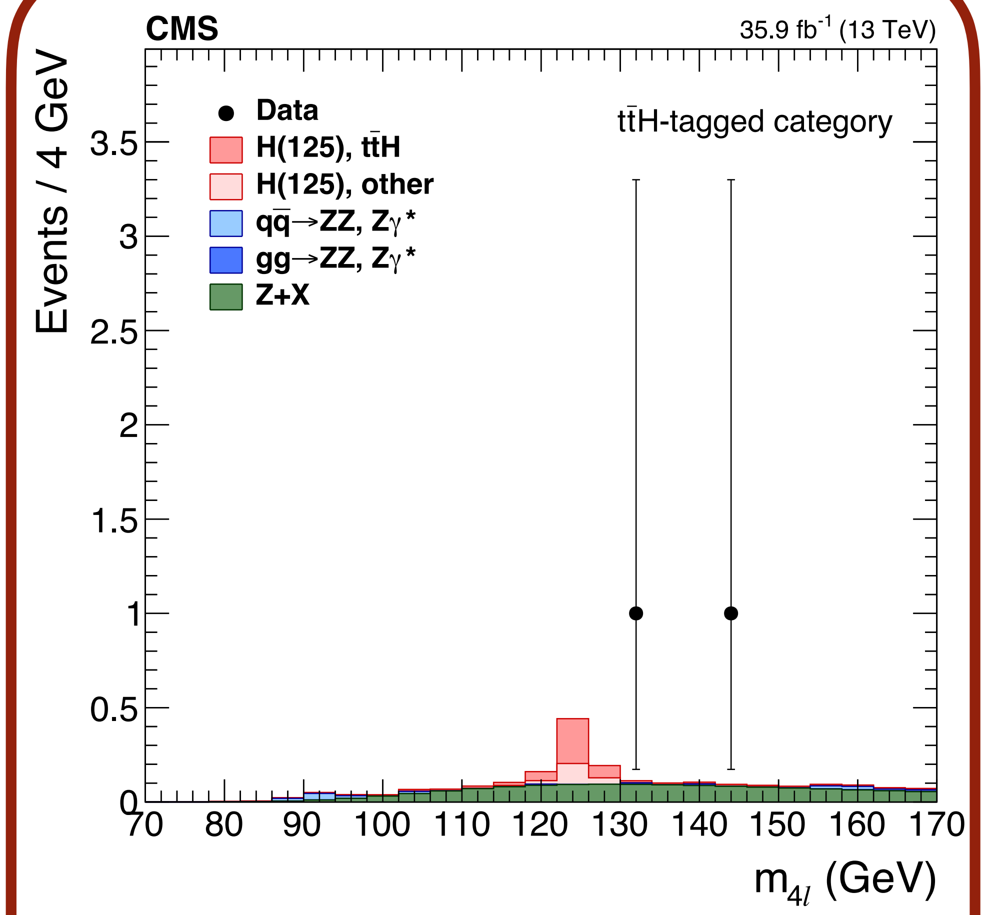
$t\bar{t}H$ with $H\to ZZ\to 4l$ or $H\to\gamma\gamma$

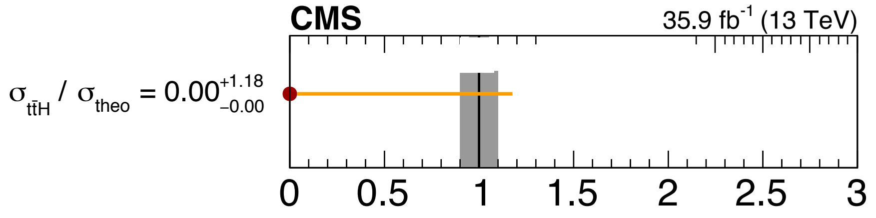
arXiv:1706.09936
CMS-PAS-HIG-16-040

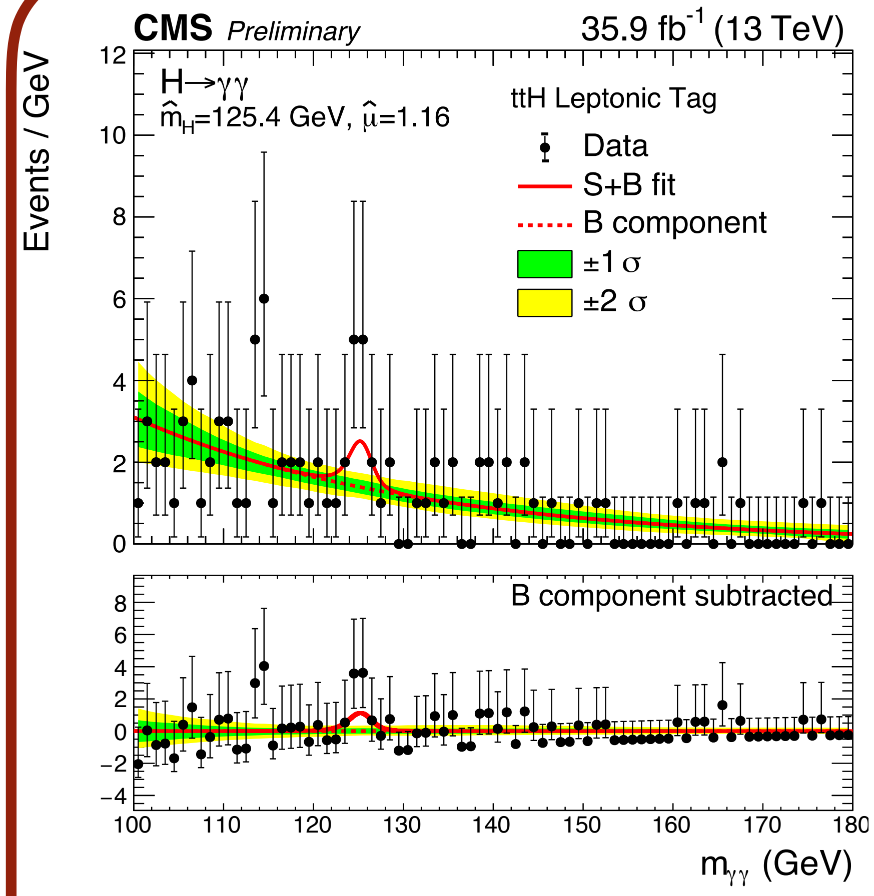
The cleanest Higgs decays, and will provide the best observation for ttH

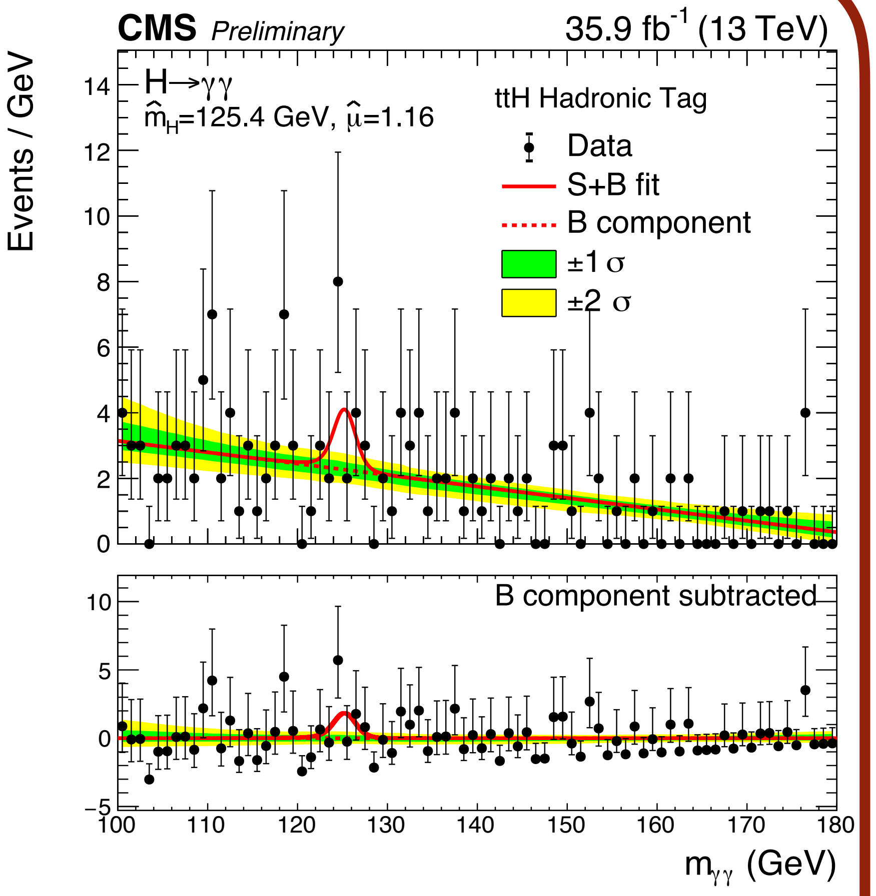
Main challenge: small signal yield σ×BR: ~0.14 fb(4l) ~1 fb(γγ)

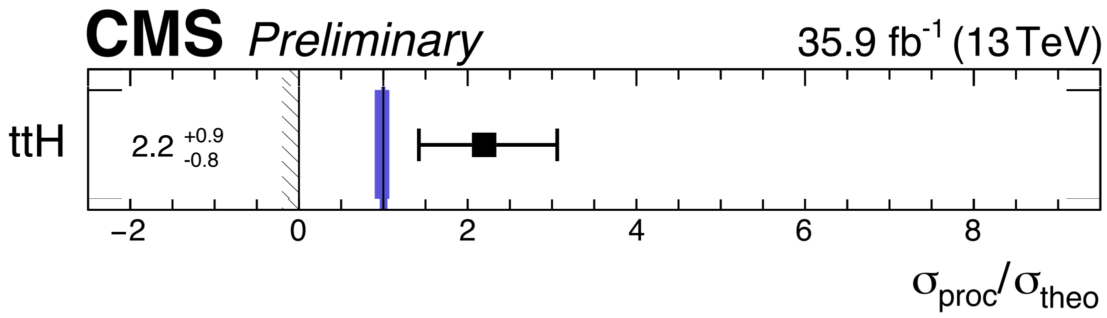
Dedicated categories





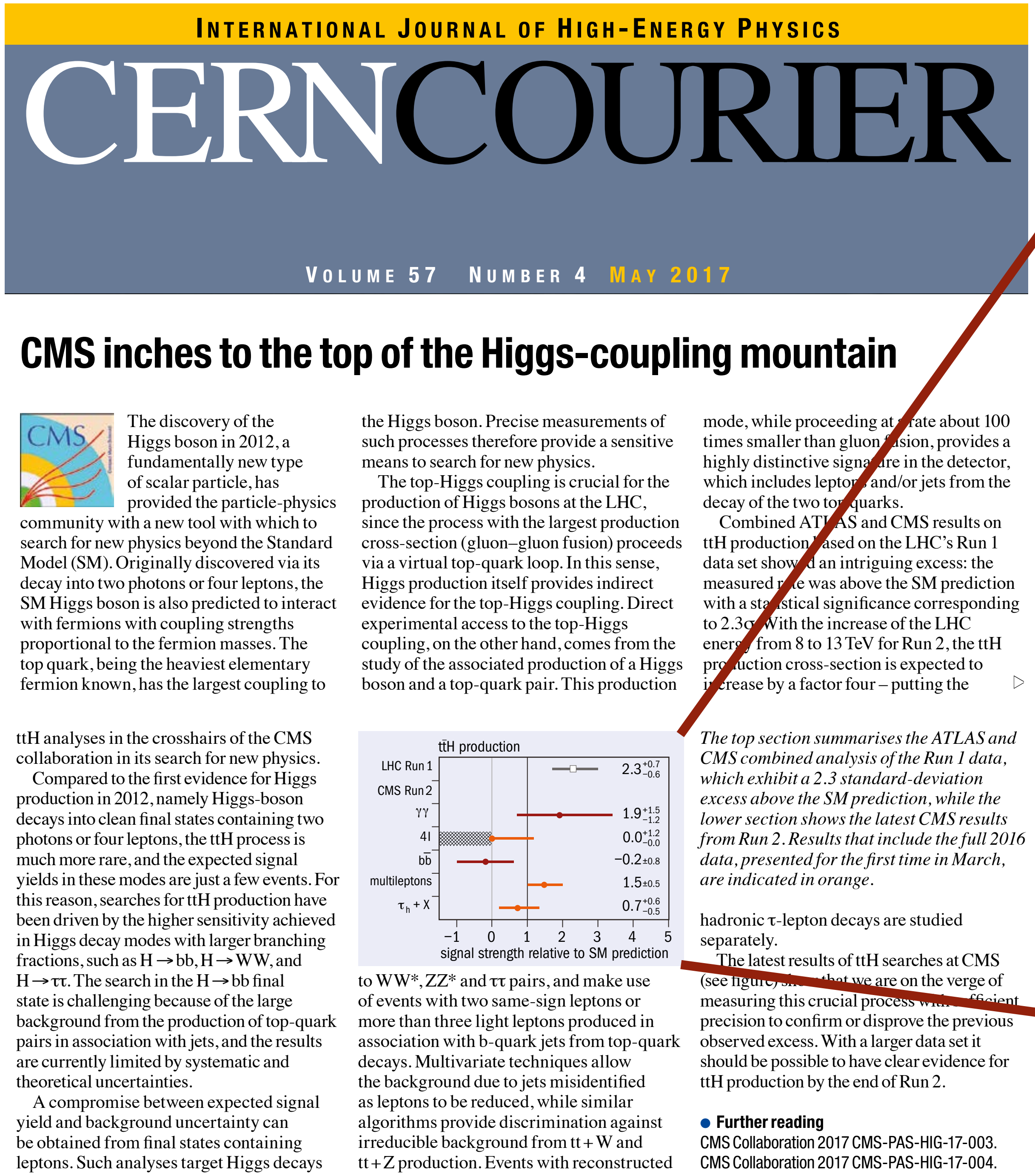






Hope to observe by the end of Run-III an unambiguous ttH signal

III Evidence for ttH production with 13 TeV data



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CMS inches to the top of the Higgs-coupling mountain

The discovery of the Higgs boson in 2012, a fundamentally new type of scalar particle, has provided the particle-physics community with a new tool with which to search for new physics beyond the Standard Model (SM). Originally discovered via its decay into two photons or four leptons, the SM Higgs boson is also predicted to interact with fermions with coupling strengths proportional to the fermion masses. The top quark, being the heaviest elementary fermion known, has the largest coupling to the Higgs boson. Precise measurements of such processes therefore provide a sensitive means to search for new physics.

The top-Higgs coupling is crucial for the production of Higgs bosons at the LHC, since the process with the largest production cross-section (gluon–gluon fusion) proceeds via a virtual top-quark loop. In this sense, Higgs production itself provides indirect evidence for the top-Higgs coupling. Direct experimental access to the top-Higgs coupling, on the other hand, comes from the study of the associated production of a Higgs boson and a top-quark pair. This production mode, while proceeding at a rate about 100 times smaller than gluon fusion, provides a highly distinctive signature in the detector, which includes leptons and/or jets from the decay of the two top quarks.

Combined ATLAS and CMS results on ttH production based on the LHC's Run 1 data set showed an intriguing excess: the measured rate was above the SM prediction with a statistical significance corresponding to 2.3σ. With the increase of the LHC energy from 8 to 13 TeV for Run 2, the ttH production cross-section is expected to increase by a factor four – putting the ttH analyses in the crosshairs of the CMS collaboration in its search for new physics.

▷

Compared to the first evidence for Higgs production in 2012, namely Higgs-boson decays into clean final states containing two photons or four leptons, the ttH process is much more rare, and the expected signal yields in these modes are just a few events. For this reason, searches for ttH production have been driven by the higher sensitivity achieved in Higgs decay modes with larger branching fractions, such as H → bb, H → WW, and H → ττ. The search in the H → bb final state is challenging because of the large background from the production of top-quark pairs in association with jets, and the results are currently limited by systematic and theoretical uncertainties.

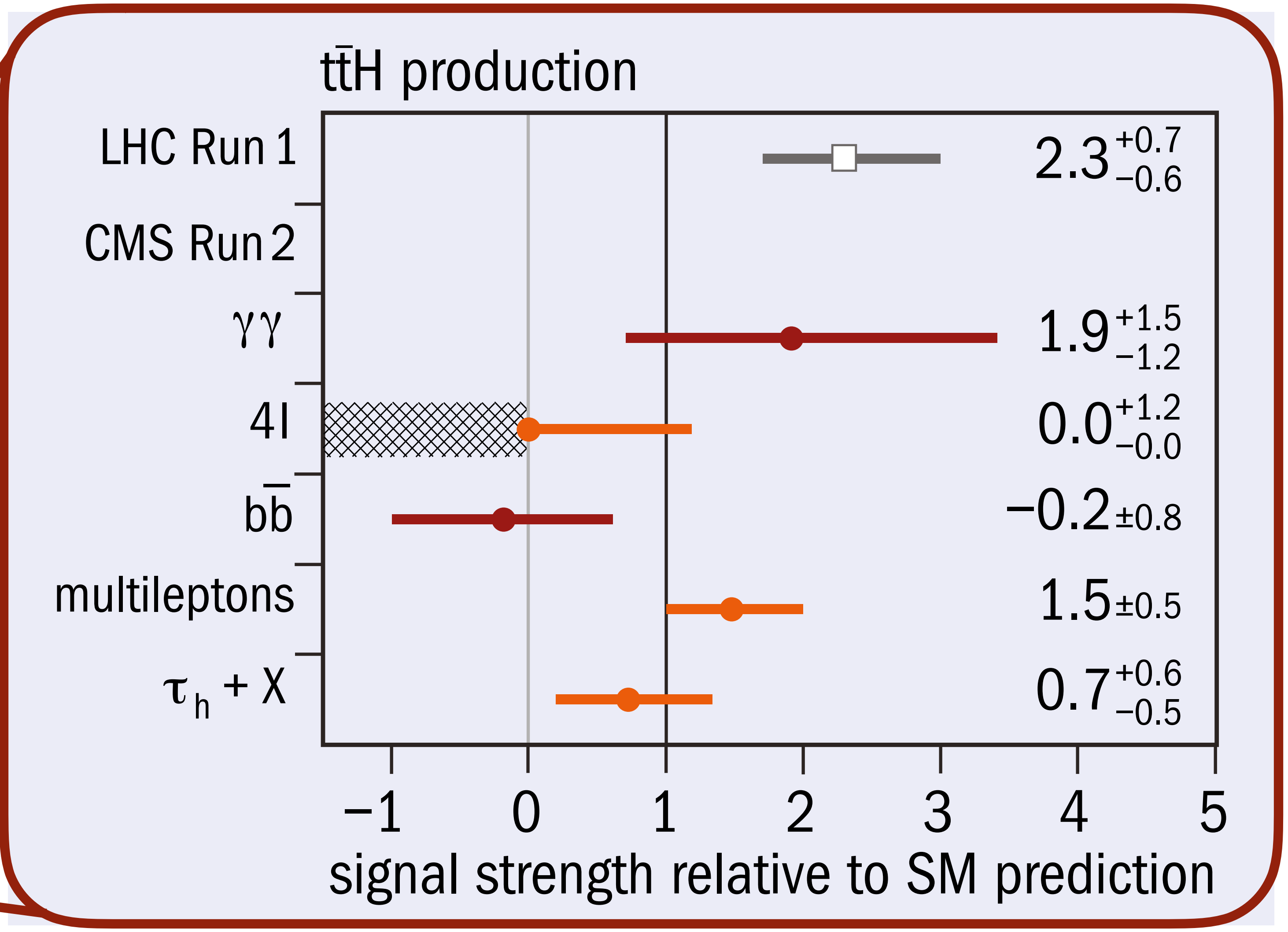
A compromise between expected signal yield and background uncertainty can be obtained from final states containing leptons. Such analyses target Higgs decays to WW*, ZZ* and ττ pairs, and make use of events with two same-sign leptons or more than three light leptons produced in association with b-quark jets from top-quark decays. Multivariate techniques allow the background due to jets misidentified as leptons to be reduced, while similar algorithms provide discrimination against irreducible background from tt + W and tt + Z production. Events with reconstructed hadronic τ-lepton decays are studied separately.

The top section summarises the ATLAS and CMS combined analysis of the Run 1 data, which exhibit a 2.3 standard-deviation excess above the SM prediction, while the lower section shows the latest CMS results from Run 2. Results that include the full 2016 data, presented for the first time in March, are indicated in orange.

The latest results of ttH searches at CMS (see figure) show that we are on the verge of measuring this crucial process with sufficient precision to confirm or disprove the previous observed excess. With a larger data set it should be possible to have clear evidence for ttH production by the end of Run 2.

Further reading

CMS Collaboration 2017 CMS-PAS-HIG-17-003.
CMS Collaboration 2017 CMS-PAS-HIG-17-004.



A combination of ATLAS and CMS ttH results would likely be incompatible with μ = 0 but there is not yet a single analysis with a strong and unambiguous ttH signal

IV

Known Unknown

Rare processes

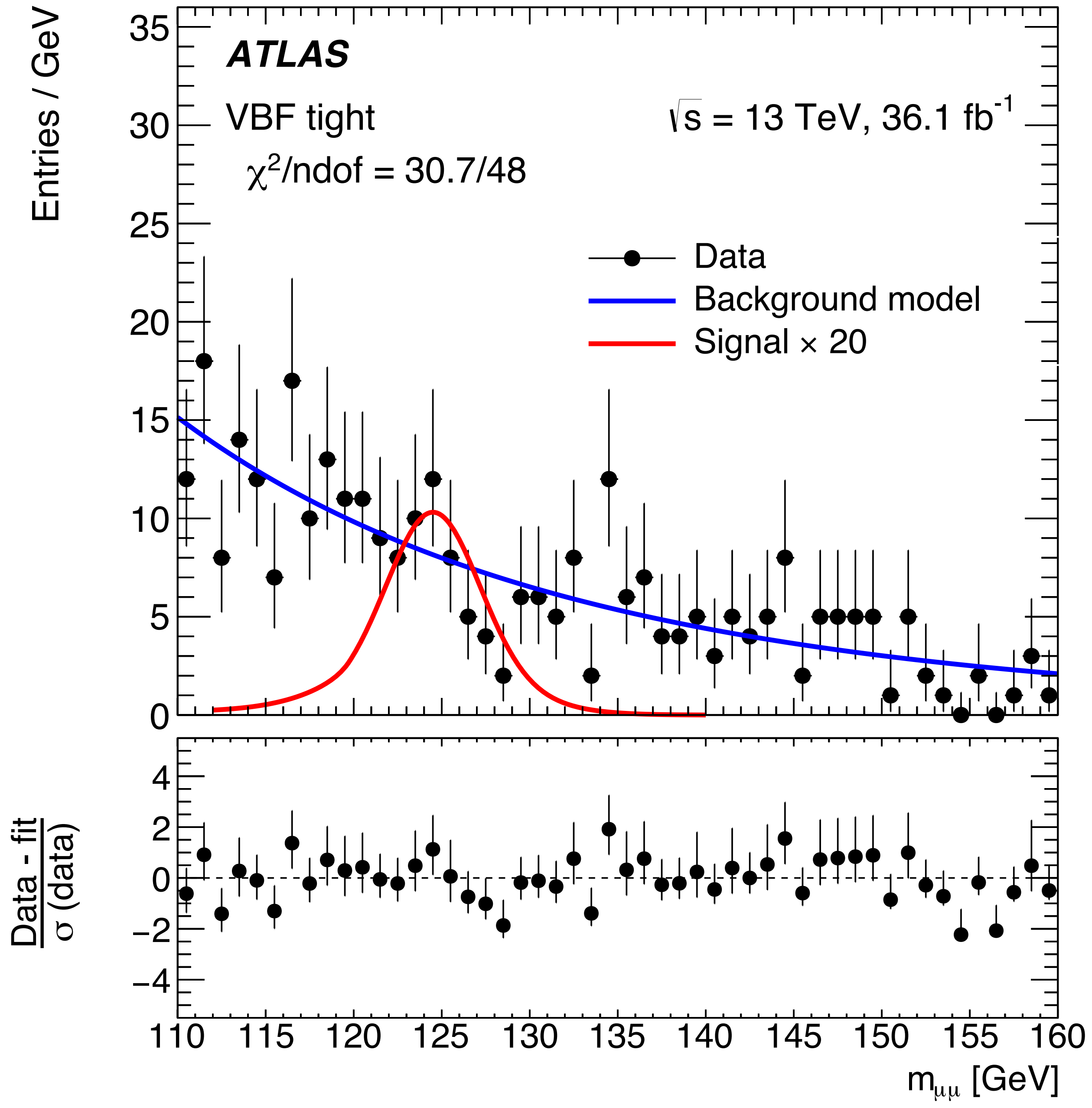
2nd generation fermion Yukawa coupling

HH production

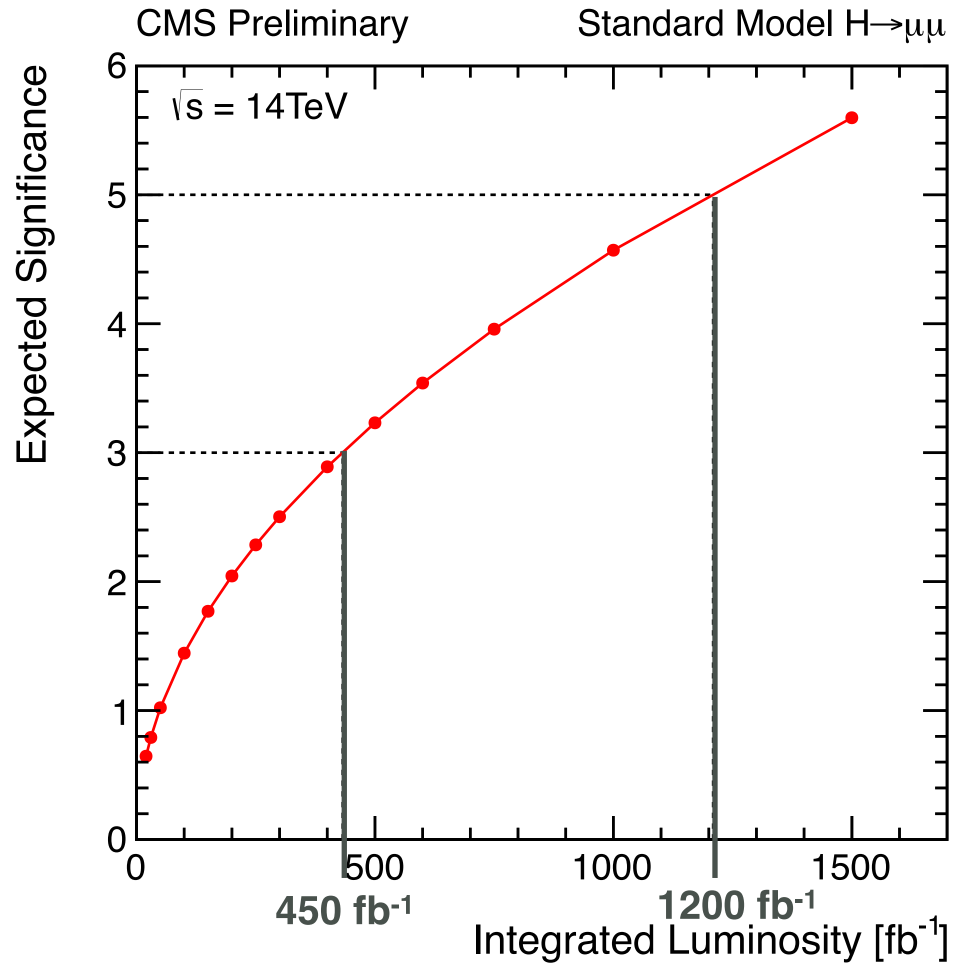
H→μμ

Main channel to measure Yukawa coupling to **2nd generation fermions**

$BR_{H\rightarrow\mu\mu} = 0.021\%$: ~100 events produced during Run-I w.r.t. 3.4k events at LHC



	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



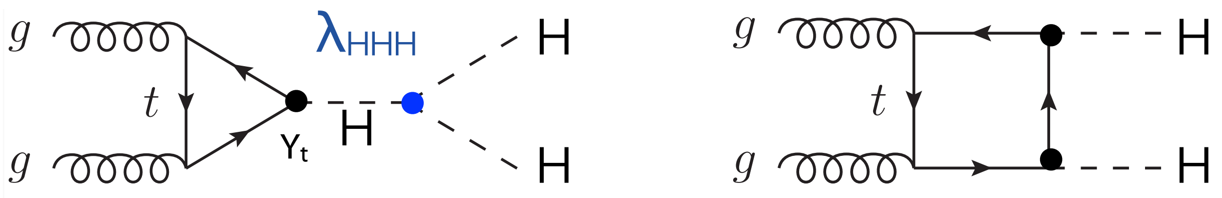
$\mu_S = -0.1 \pm 1.5$

Observed (expected) 95% CL UL on μ_S is 3.0 (3.1)

HH production

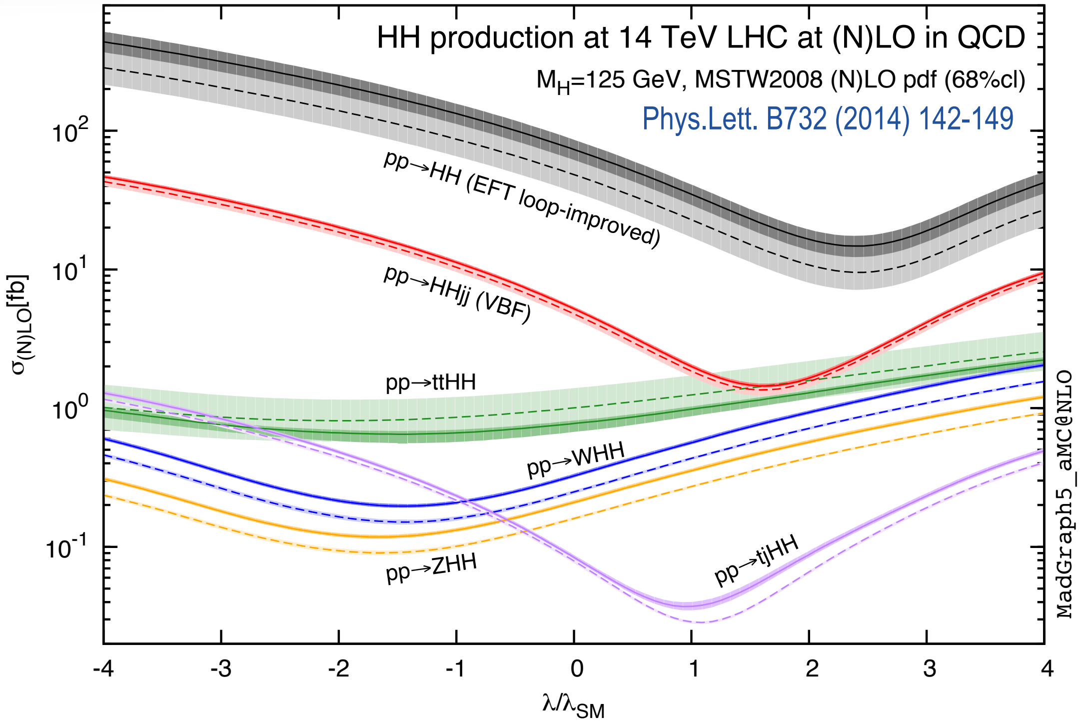
The principal way to extract the Higgs boson trilinear coupling (**λ_{HHH}**) to probe EWSB and measure the shape of the Higgs potential

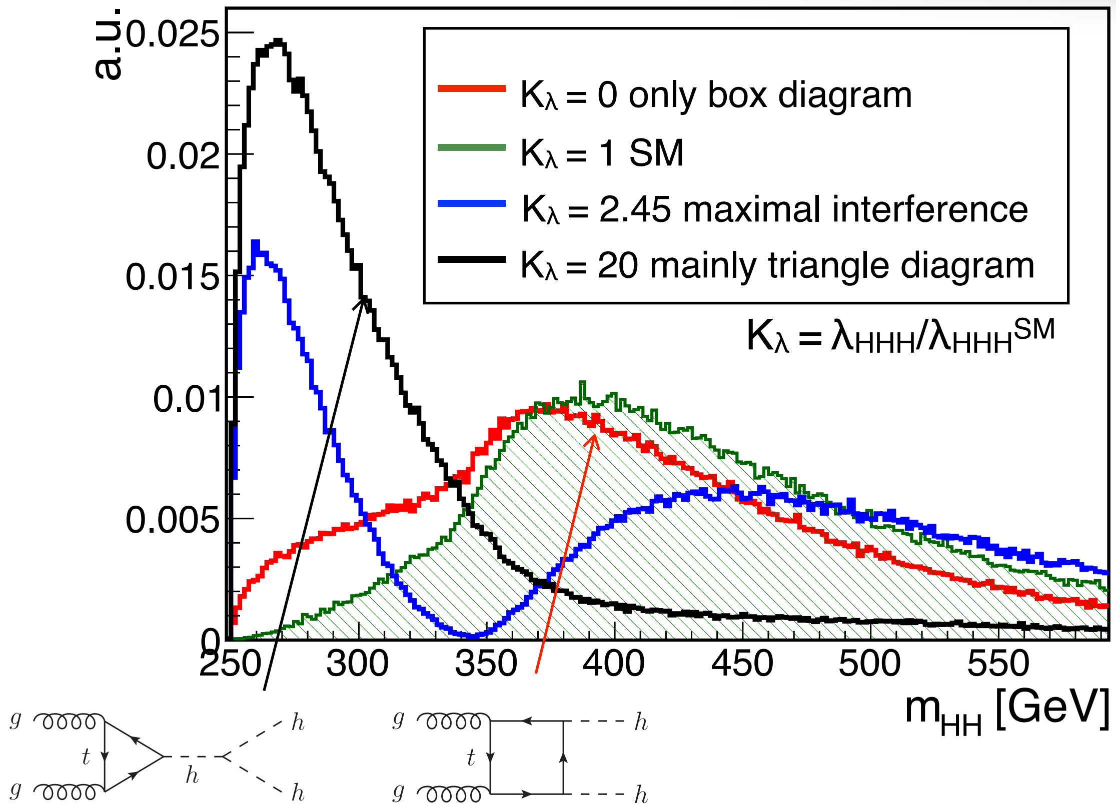
Problem : to measure *n*H coupling need to measure (*n-1*)H production



$\sigma_{gg\to HH} = 33.49^{+4.3}_{-6.0}$ (scale) ± 2.1 (PDF) ± 2.3 (α_s) fb

[13 TeV, NNLO + NNLL with top mass effects, LHXSWG, arXiv:1610.07922]





Corrections due to the exchange of new heavy states can be parametrized by low-energy effective Lagrangian EFT.

Enhancements in the cross-section can happen : $[10^{-1},10^{4}]\times\sigma(pp\to HH)^{SM}$

Signal shape can be significantly different from SM

HH production : which final state?

Tradeoff between BR and background contamination!

various channels are complementary

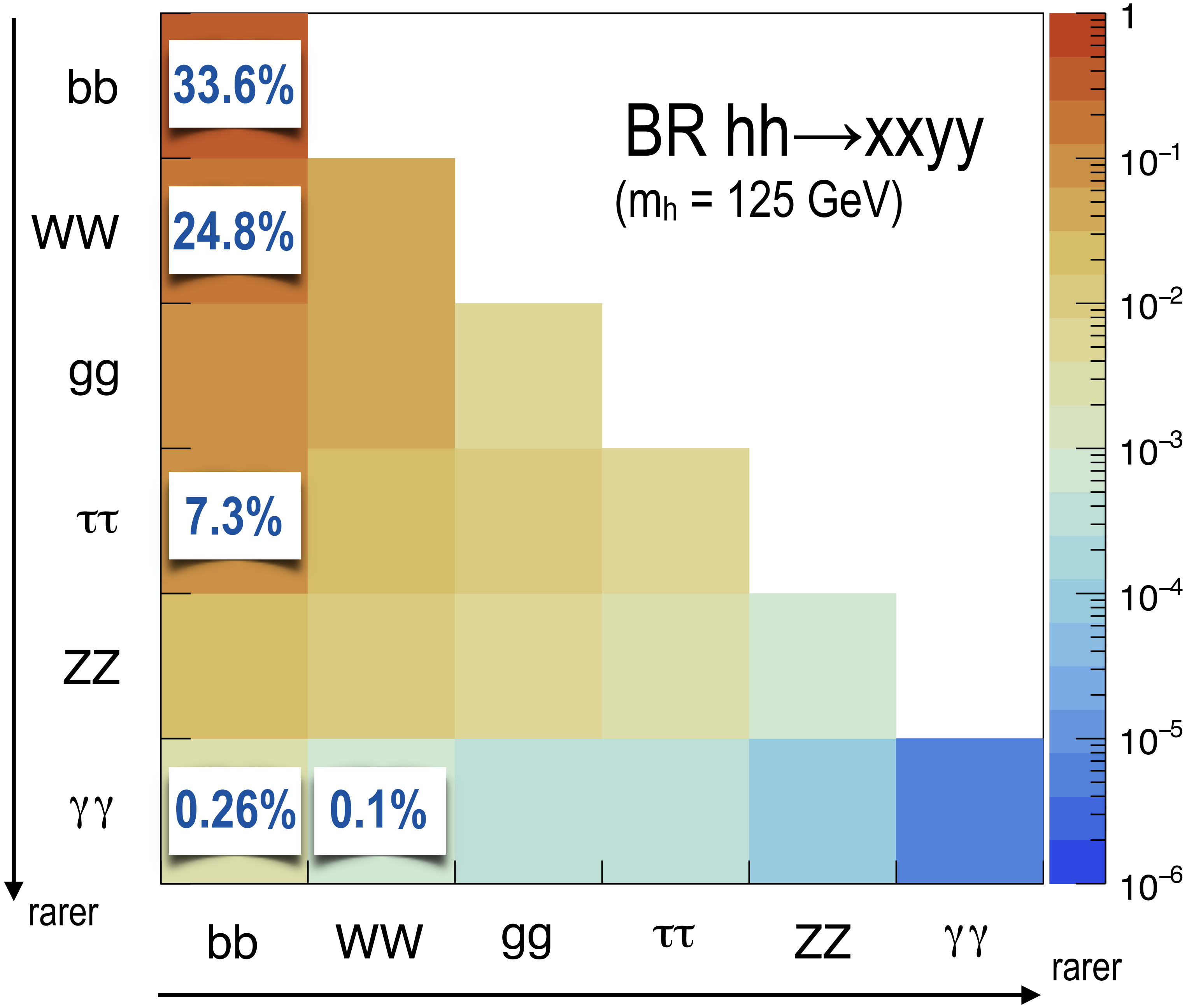
different sensitivities in different mass ranges

bbbb
large branching ratio,
large QCD and tt bkg

bbWW
large branching ratio,
large tt contamination

bbττ
tradeoff between purity
and branching ratio

bbγγ
high purity,
low branching ratio



HH : Run-II results overview

Several HH final states already explored at 13 TeV

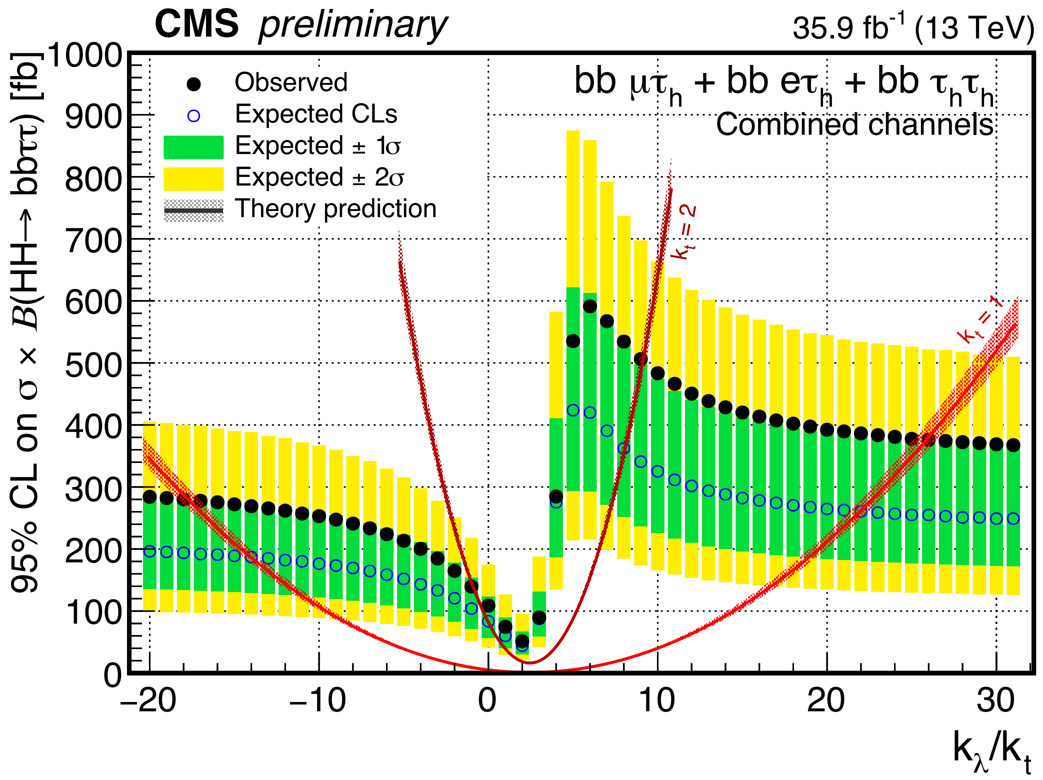
Chan.	Obs. (exp.) 95% C.L. limit on σ/	
	ATLAS EXPERIMENT	CMS
bbbb	29 (38)	342 (308)
bbVV	-	79 (89)
$bb\tau\tau$	-	28 (25)
$bb\gamma\gamma$	117 (161)	91 (90)
$WW\gamma\gamma$	747 (386)	-

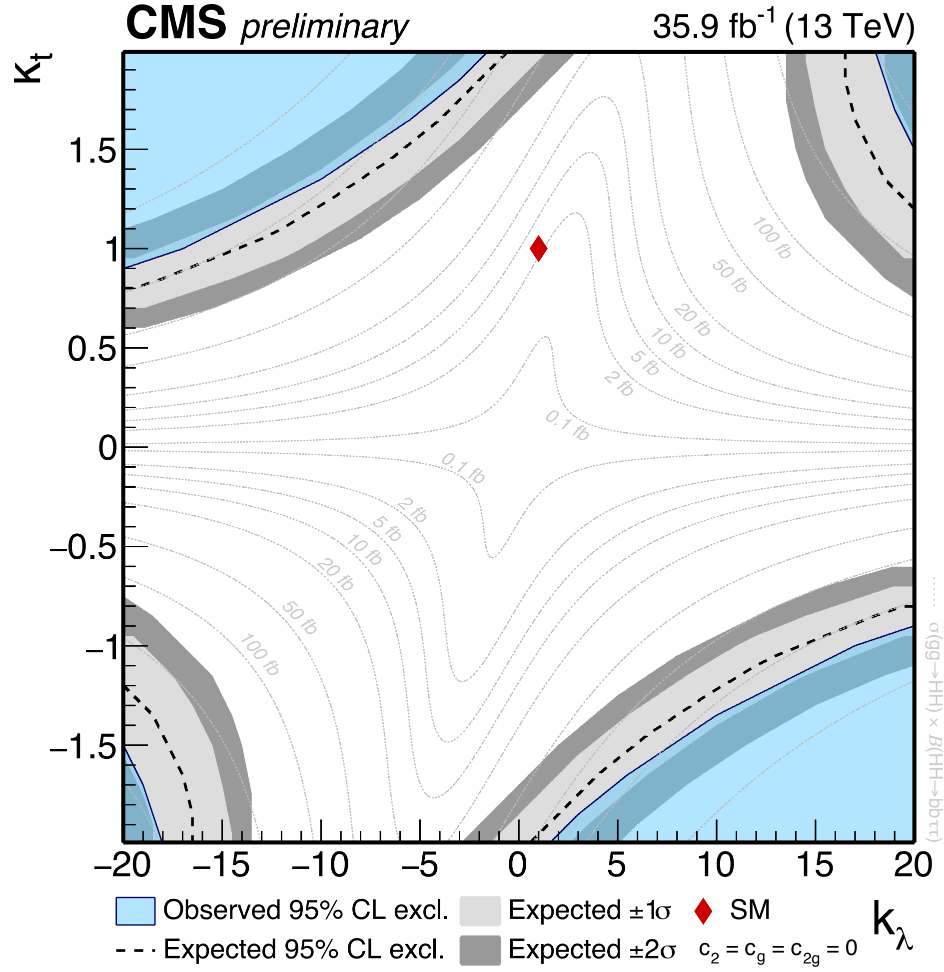
~3 fb^{-1}

13.3 fb^{-1}

35.9 fb^{-1}

Test of anomalous HH couplings





V

Unknown Unknown

Exotic Higgs boson decays

Higgs boson and dark matter

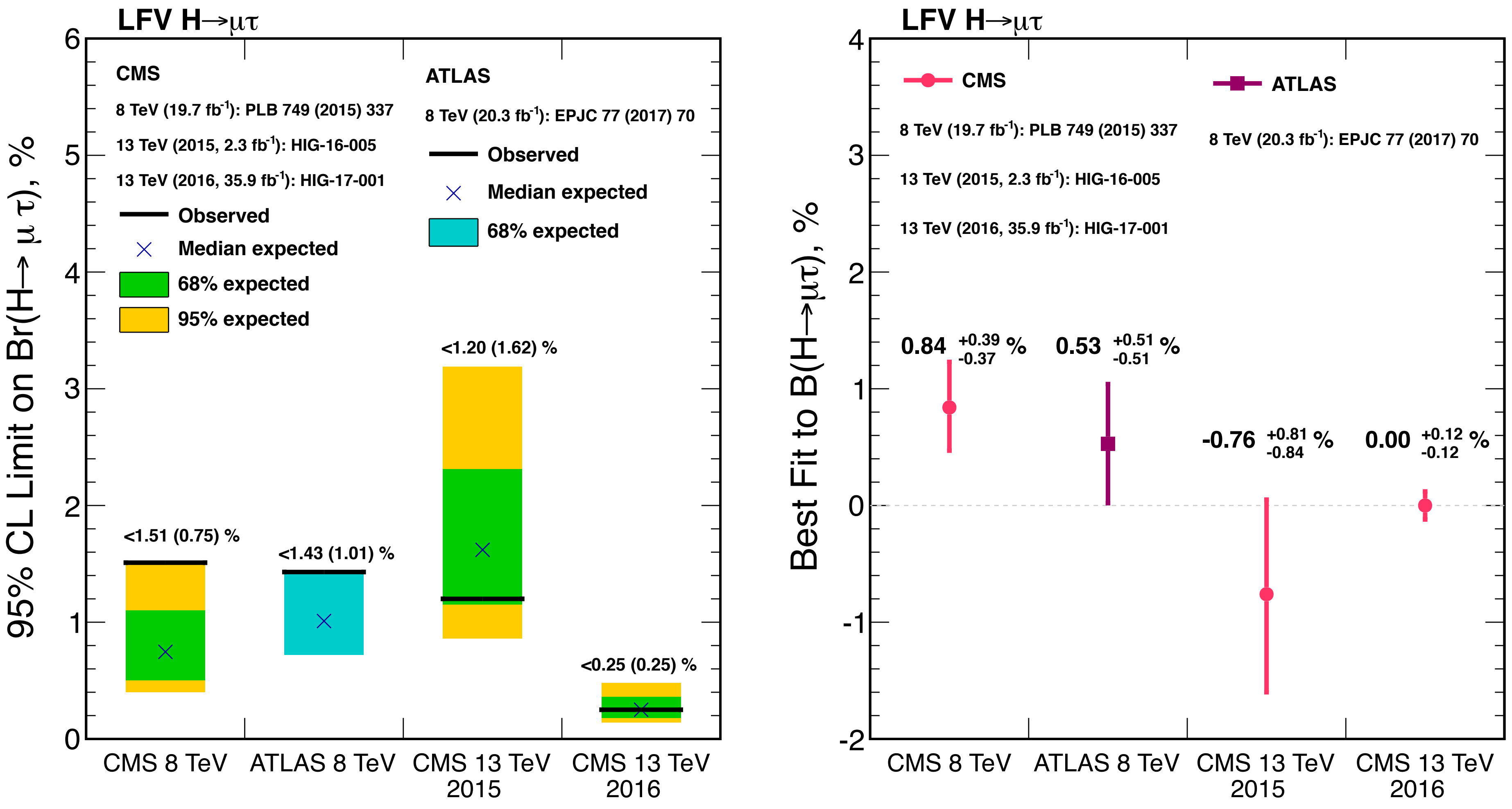
Additional Higgs-like particles (charged, heavy, light)

Exotic decays

Lepton Flavour Violating decays (H→μe/μτ/eτ) are not allowed
exception can occur in case it is a theory valid only to a finite mass scale

$$\begin{pmatrix} y_{ee} & y_{e\mu} & y_{e\tau} \\ & y_{\mu\mu} & y_{\mu\tau} \\ & & y_{\tau\tau} \end{pmatrix}$$

H→μτ



→ Yukawa Couplings $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.43 \times 10^{-3}$ at 95% C.L.

H→eτ

→ Yukawa Couplings $\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 2.26 \times 10^{-3}$ at 95% C.L.

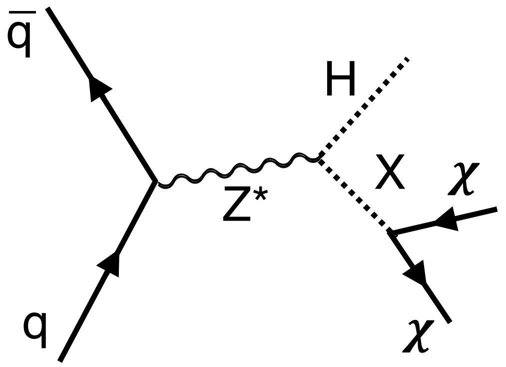
By the end of Run-III (300/fb) BR < 0.1% will be probed

The mystery of dark matter

Dark matter exists : it is most likely a neutral, weakly-interacting, and massive particle (WIMP)
Two ways to detect it at LHC involving Higgs boson:

Mono-mania

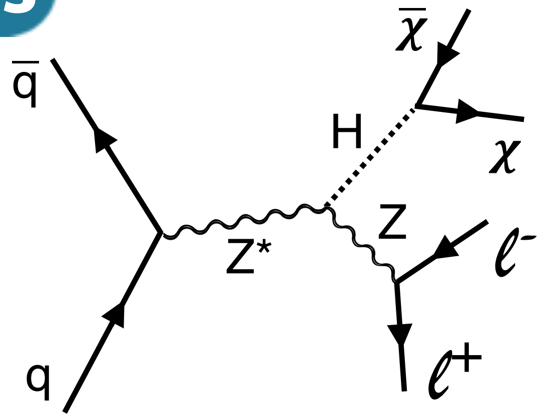
For every m_{DM} value



X is a mediator

Higgs bosons invisible decays

For $m_{DM} < m_H/2$



profiting of VBF and VH production modes

mono-H(125)

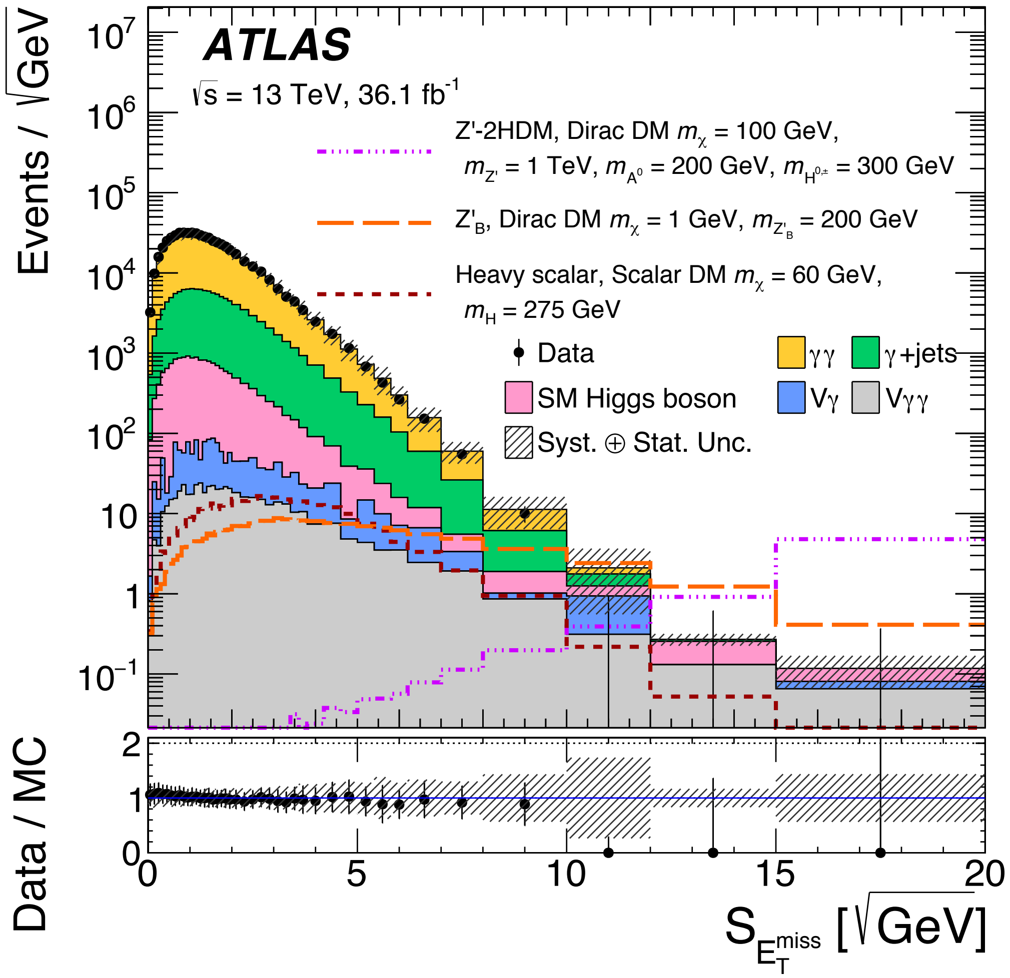
arXiv:1706.03948

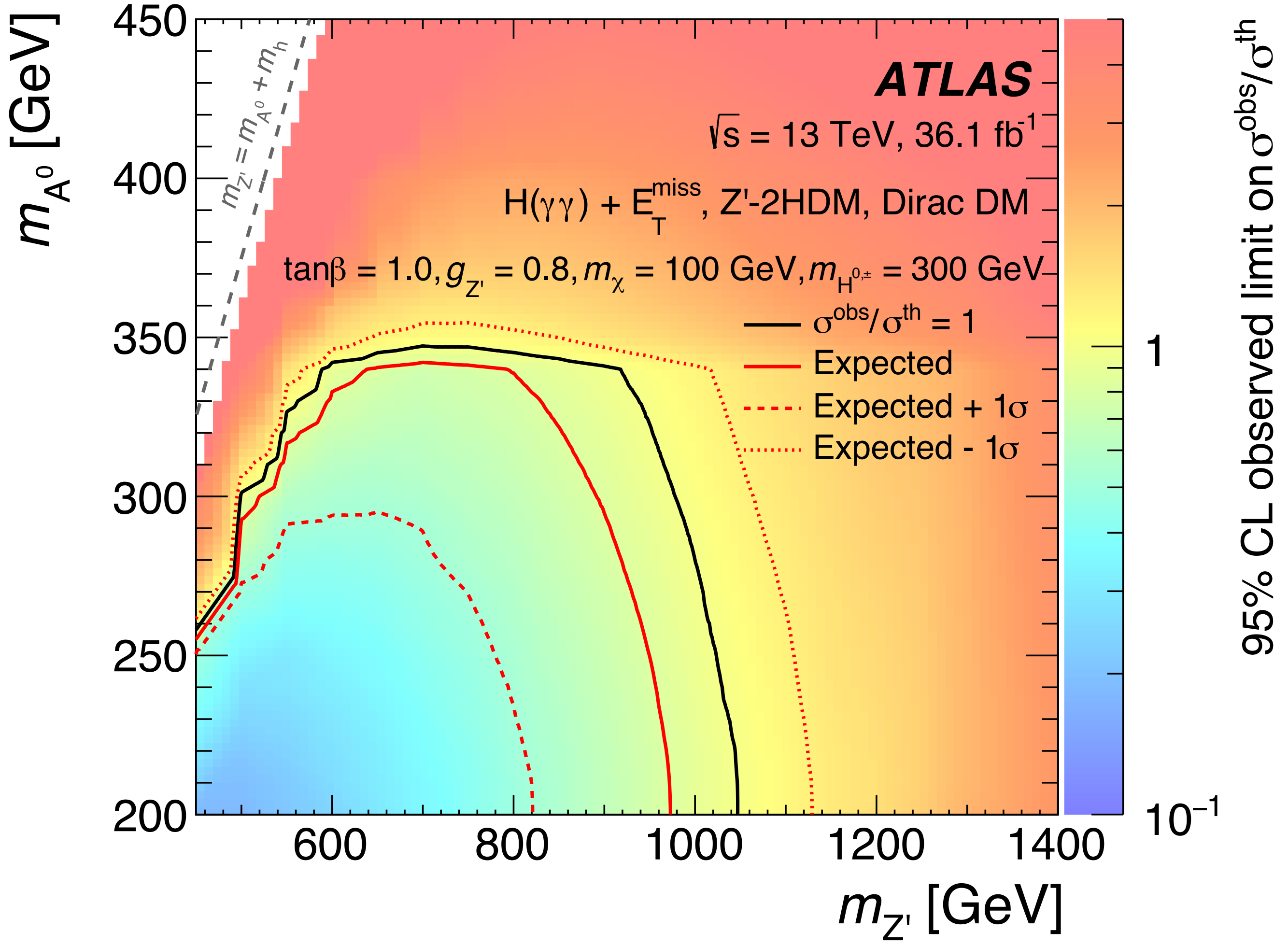
Special role of mono-H(125)

→ negligible coupling to incoming partons : not from ISR (contrary to e.g. gluon or photon) ⇒ direct probe of the dark sector interactions

→ interpretation in benchmark simplified models designed to cover a large wealth of topologies

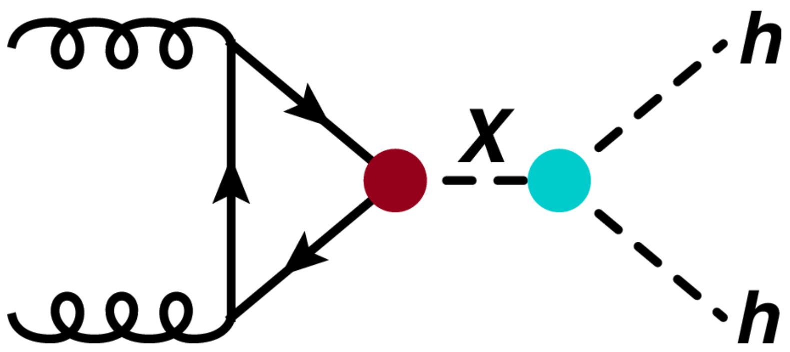
H→bb search is limited below E_T^{miss} = 150 GeV by the trigger
⇒ recover sensitivity with the cleaner and easier-to-trigger-on H → γγ

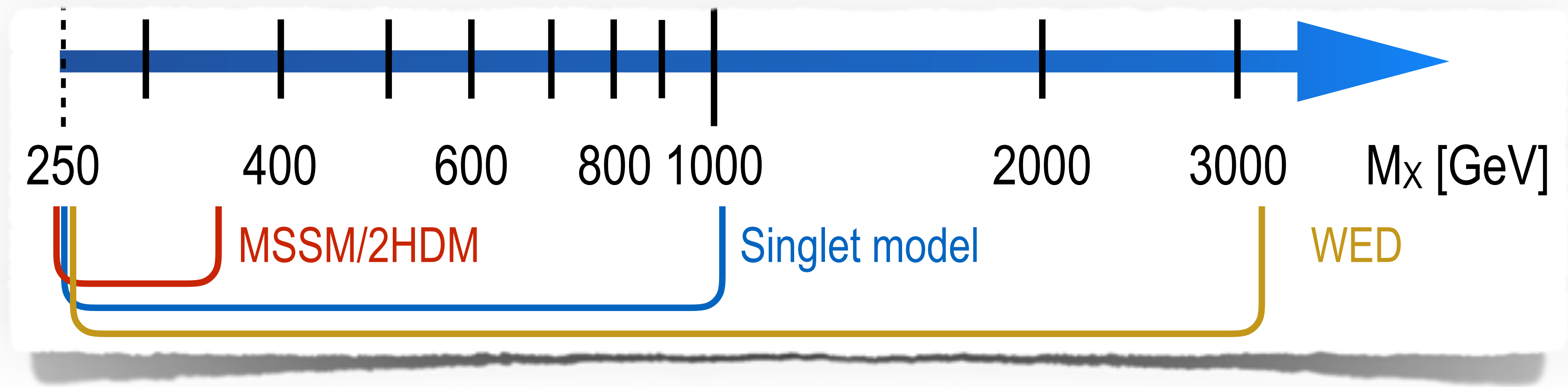




X→HH

The resonant HH production (X→HH) is not predicted in the SM any observation would be a sing of new Physics





MSSM/2HDM: additional Higgs doublet gives CP-even scalar H

probe the low m_H- low $\tan\beta$ region of the MSSM plane where BR (H→hh) is sizable

Singlet model: additional Higgs singlet S gives an extra scalar H

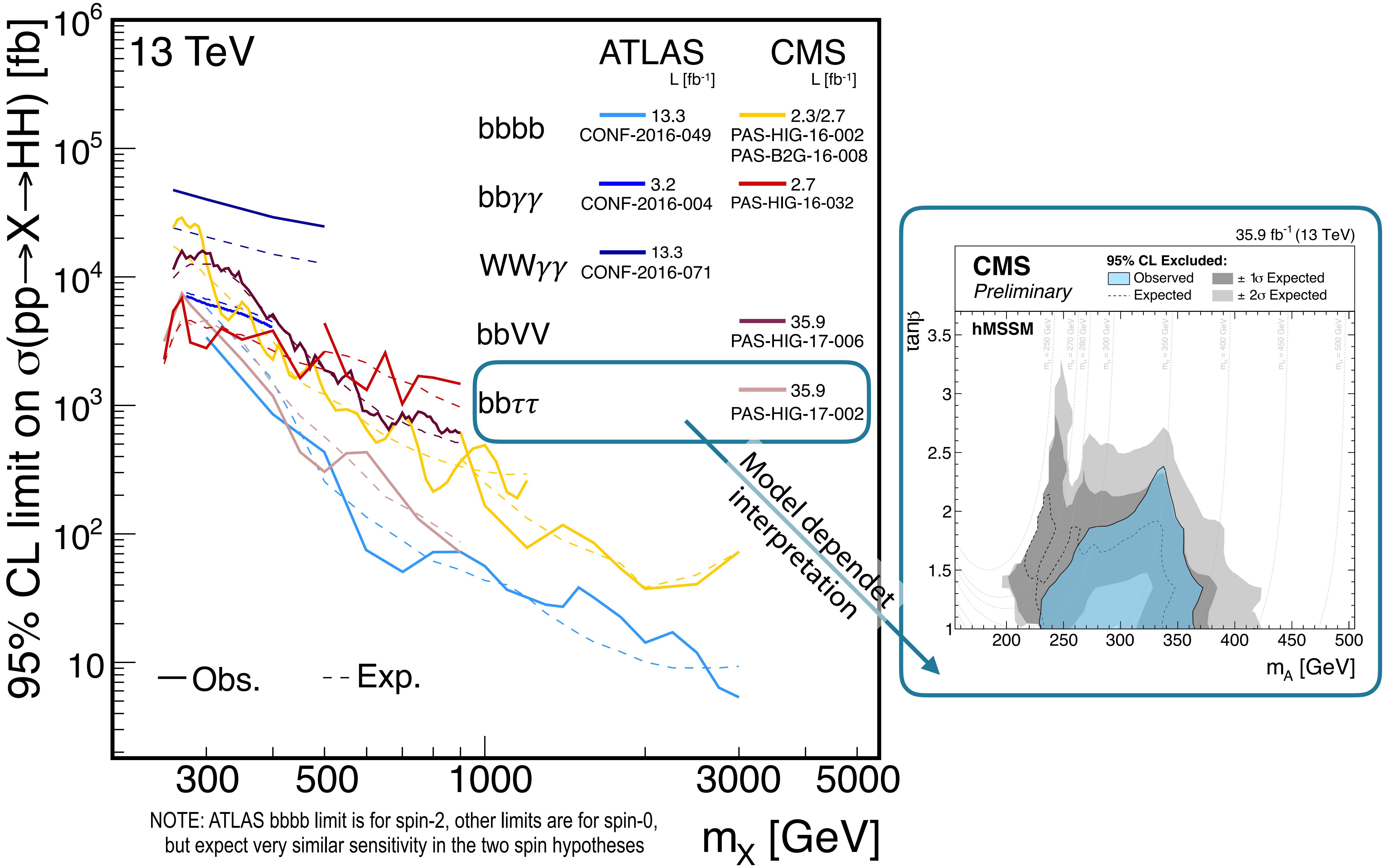
sizable BR beyond $2xm_{top}$, non negligible width at high m_H

Warped Extra Dimensions: spin-2 (KK-graviton) and spin-0 (radion) resonances

different phenomenology if SM particles are allowed (bulk RS) or not (RS1 model) to propagate in the extra-dimensional bulk

X→HH : results overview

CMS-PAS-HIG-17-002



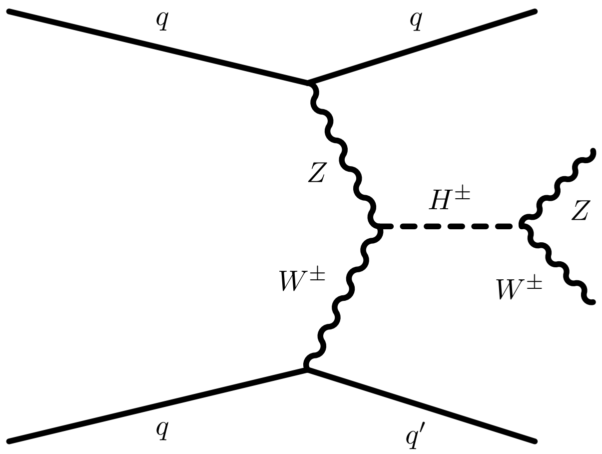
NOTE: ATLAS bbbb limit is for spin-2, other limits are for spin-0, but expect very similar sensitivity in the two spin hypotheses

Charged Higgs boson

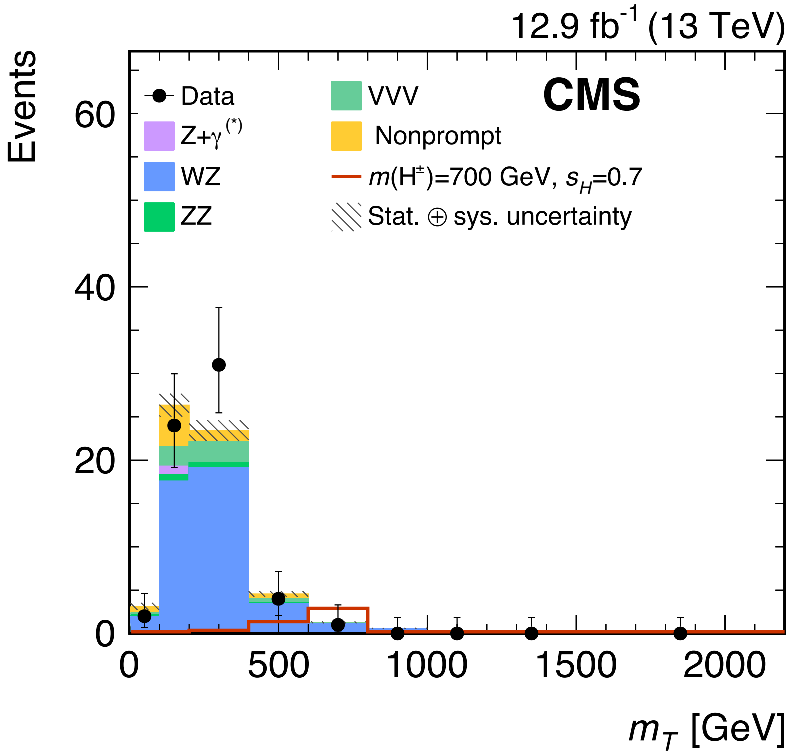
arXiv:1705.02942

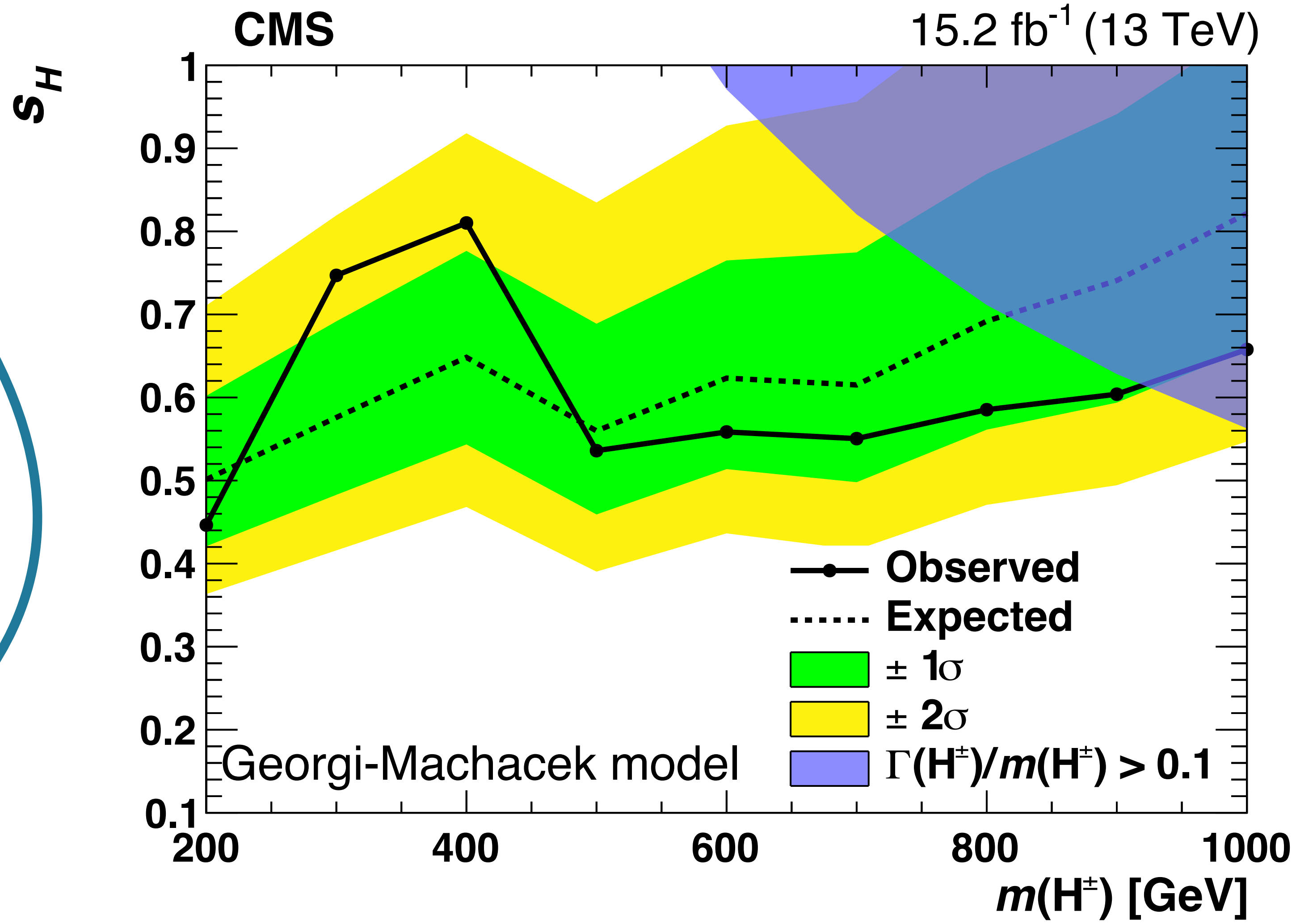
In MSSM, couplings of H± to W/Z are suppressed, fermiophobic H± bosons appear in Higgs Triple Model

Search for H± → WZ via VBF : very clean 3-lepton signatures + VBF jets



Dataset	2015	2016
Data	9	62
WZ	7.5 ± 0.5	44.4 ± 2.5
ZZ	0.2 ± 0.1	1.6 ± 0.1
VVV	0.8 ± 0.1	5.5 ± 0.3
$Z\gamma$	0.2 ± 0.1	1.0 ± 0.4
Nonprompt	1.3 ± 0.5	7.4 ± 2.0
Total bkg.	10.0 ± 0.8	59.9 ± 3.5
Signal ($m(\mathrm{H}^{\pm}) = 700\,\mathrm{GeV}$)	0.9 ± 0.1	4.7 ± 0.5





Conclusions

The Higgs boson is the first fundamental scalar. It was discovered with only <0.1% of the final HL-LHC integrate luminosity

The future is in the precision for discovery, and (yet) unknown new physics ...

Experiments' pages on Higgs results

http://cern.ch/go/7lDT

http://cern.ch/go/6qmZ