HOPES and WISHES on Higgs physics at the LHC

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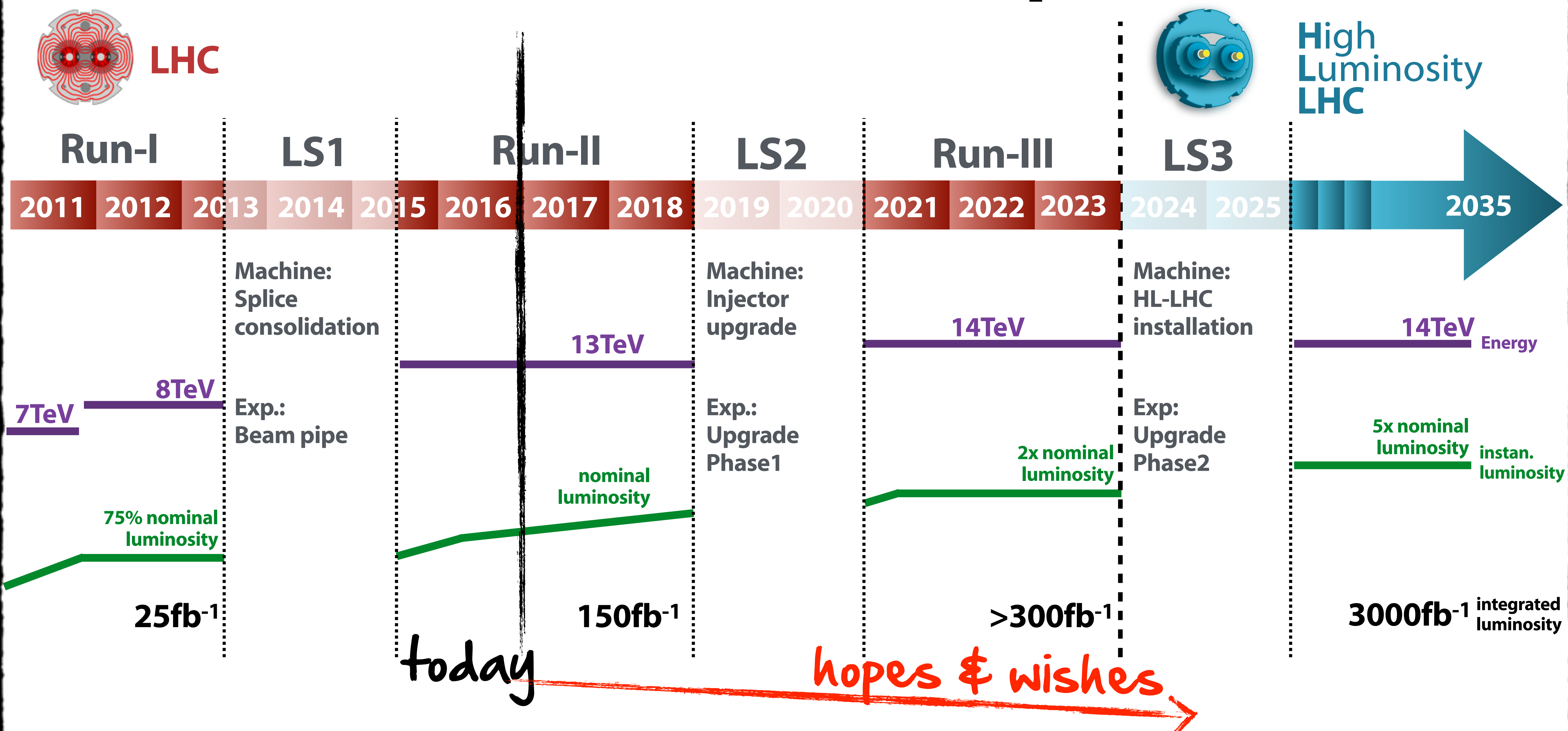
Outline

- **I** Summary of Run-I/Run-II results
- **II** Precision Higgs boson physics
- **III** Rare processes
- **IV** BSM Higgs boson searches

Timeline

LHC and HL-LHC plans



I Summary of Run-I/Run-II results

Higgs sector

Run-I summary slide

Run-II highlights

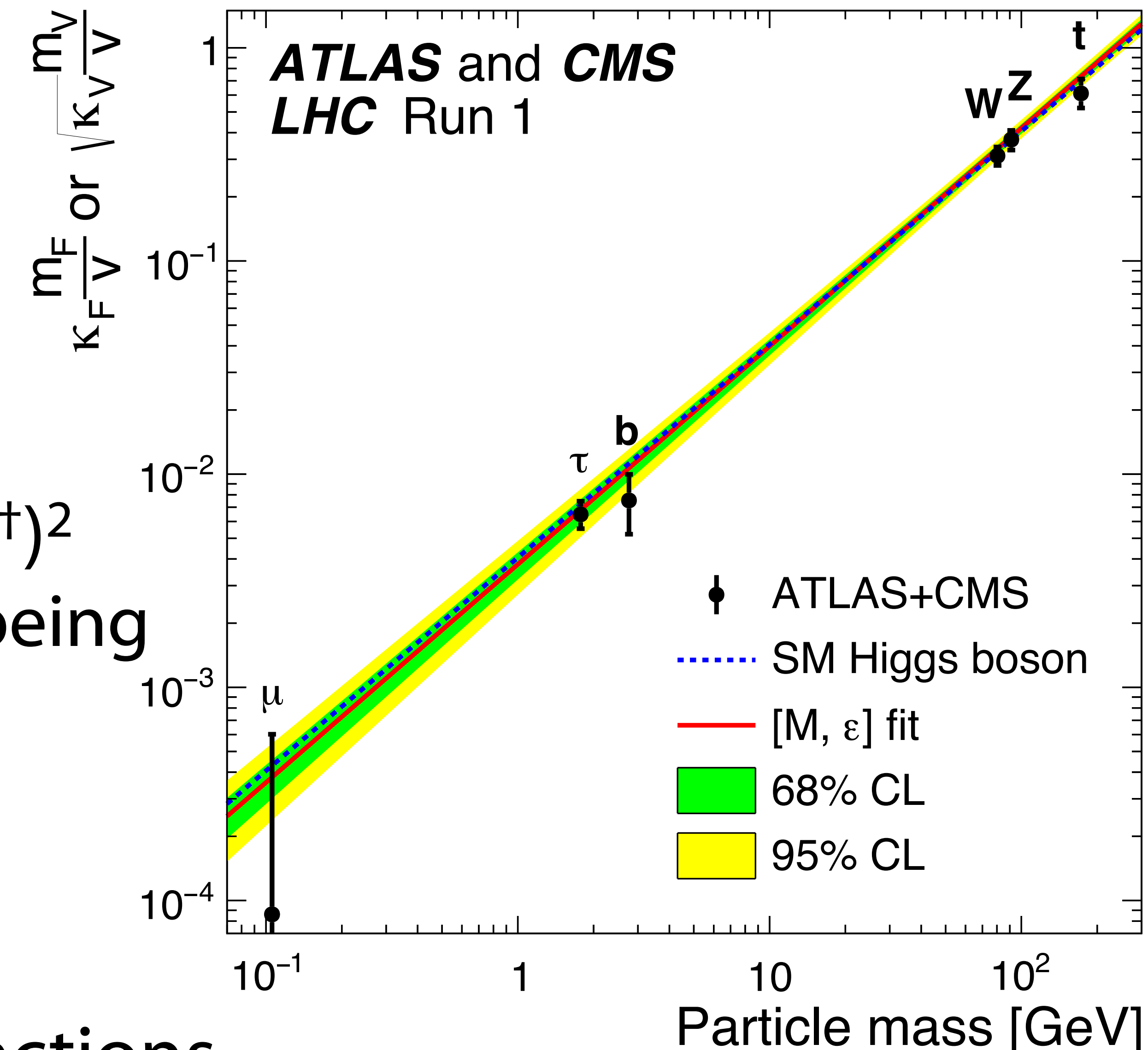
The Higgs sector is special

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



I

The Higgs sector needs stress-testing

- ➡ Is the Higgs boson fundamental or composite?
- ➡ If fundamental, is it "minimal"?
- ➡ Are Yukawa interactions responsible for masses of all generations?
- ➡ Is the associated potential really φ^4?
- ➡ Is it a portal to new physics?
- ➡ … … …

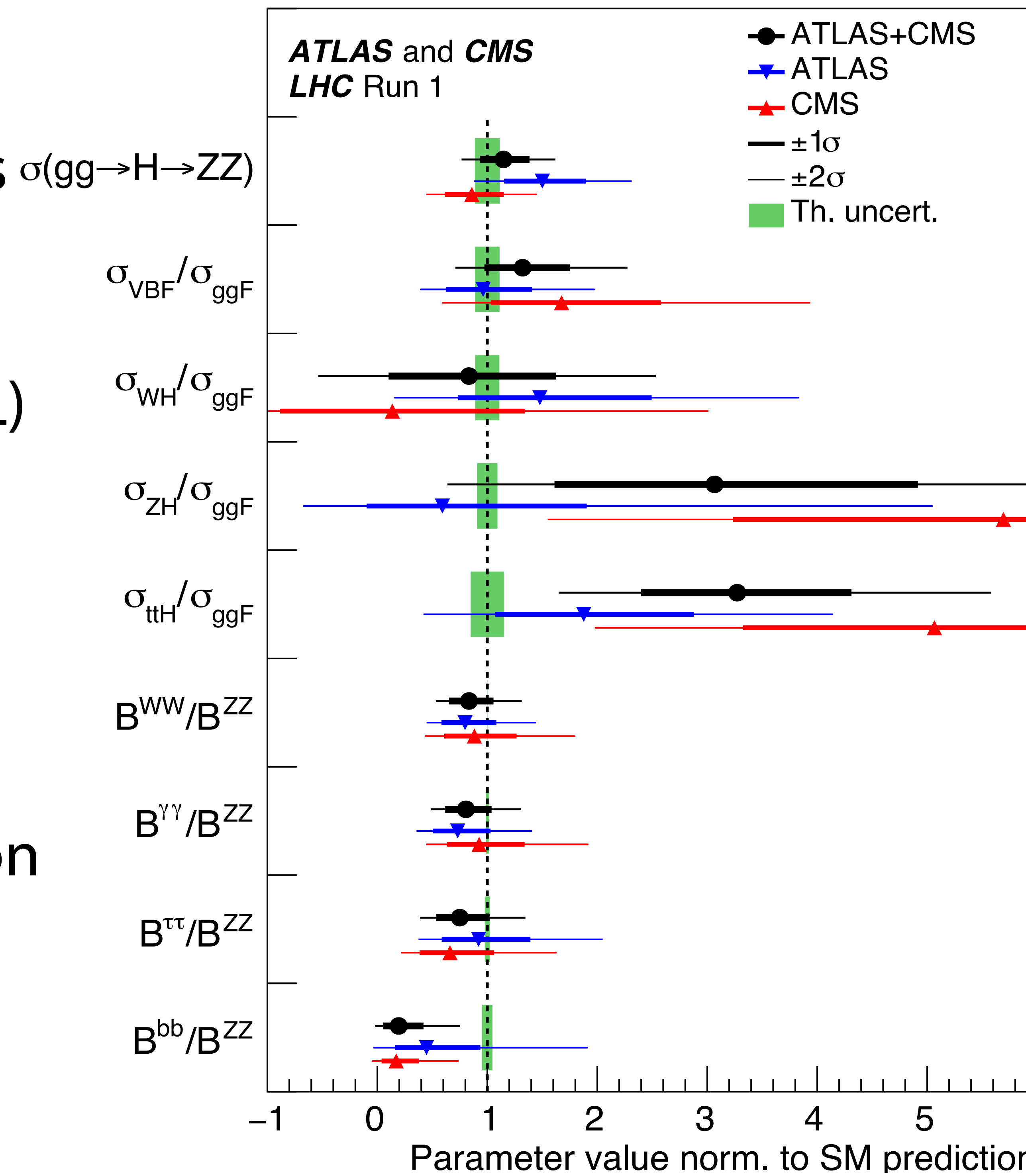
Run-I summary in a single figure

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

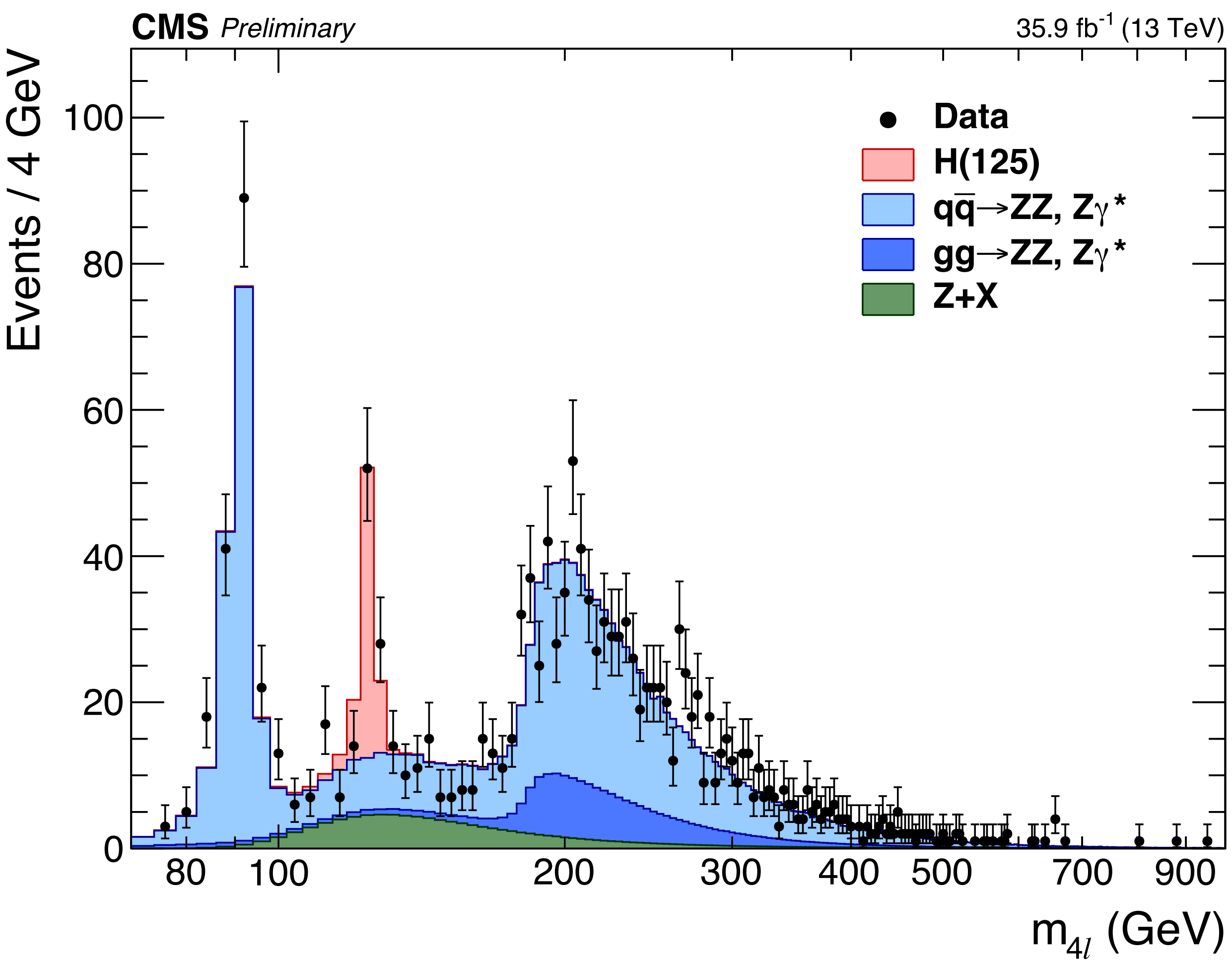
… but :

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

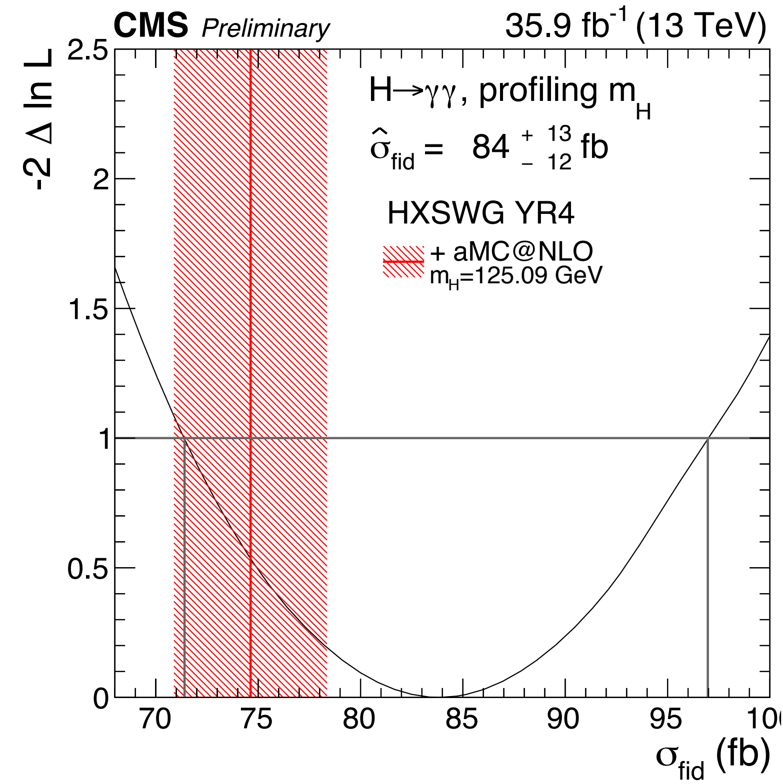


Run-II results

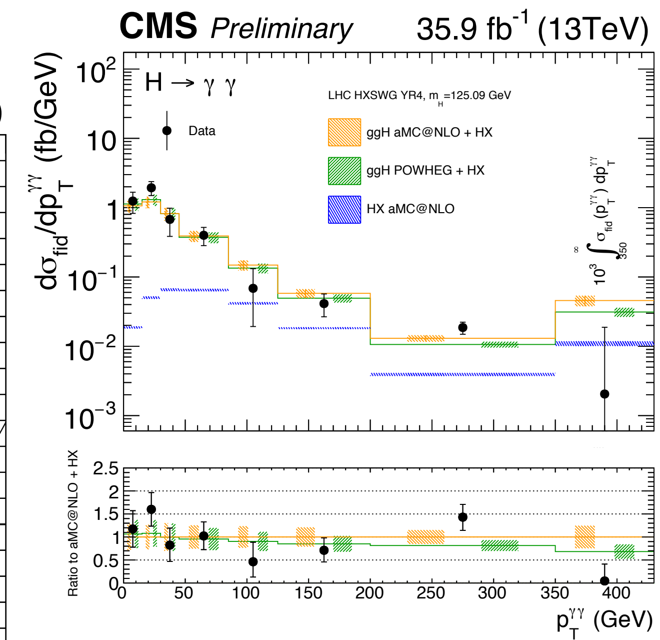
Great start of Run-II : focus on production side, cross sections, fermion couplings



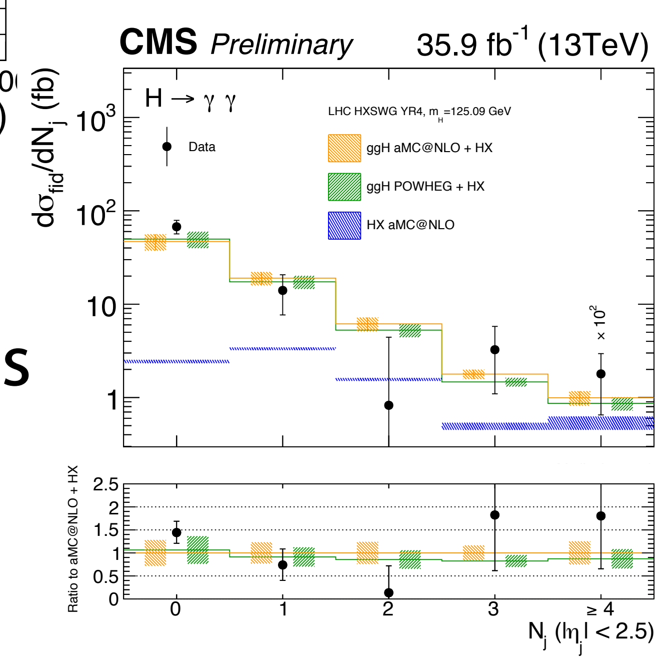
Most precise mass measurement:
$m_H = 125.26 \pm 0.20^{(stat.)} \pm 0.08^{(sys.)}$ GeV
0.17% precision



most precise cross section measurements



(a) $p_{T,\gamma\gamma}$ differential cross-section



(b) N_{jets} differential cross-section

II Precision Higgs boson physics

top-Higgs Yukawa coupling

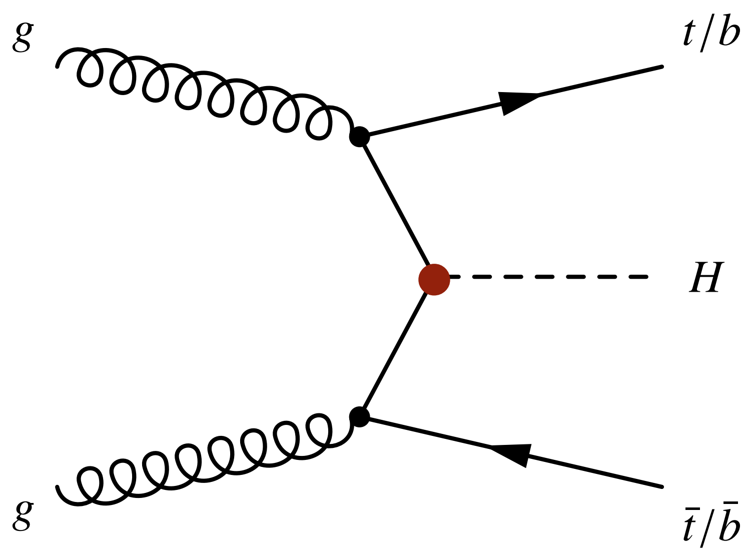
Observation of the 2^{nd} generation Higgs coupling

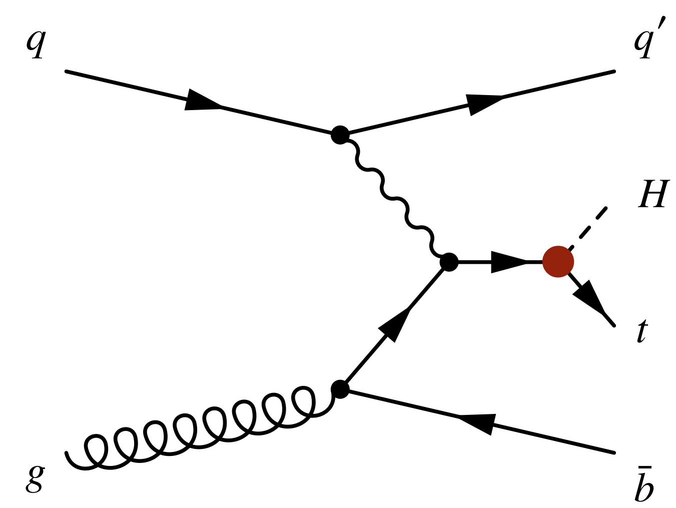
High precision coupling measurements

Cross sections measurements

top-Higgs Yukawa coupling

In SM the top-Higgs 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





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

~1/96th of ggH production

Probes the modulus of Y_t

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

~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

II 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.

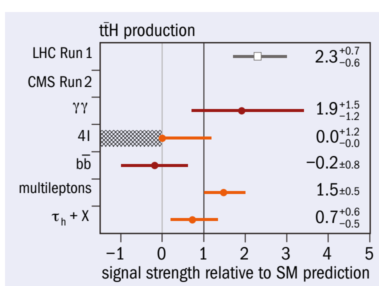
The top-Higgs coupling is crucial for the production of Higgs bosons at the LHC, since the process with the largest production cross-section (gluon–gluon fusion) proceeds via a virtual top-quark loop. In this sense, Higgs production itself provides indirect evidence for the top-Higgs coupling. Direct 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 $H \rightarrow bb$, $H \rightarrow WW$, and $H \rightarrow \tau\tau$. The search in the $H \rightarrow bb$ 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 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.

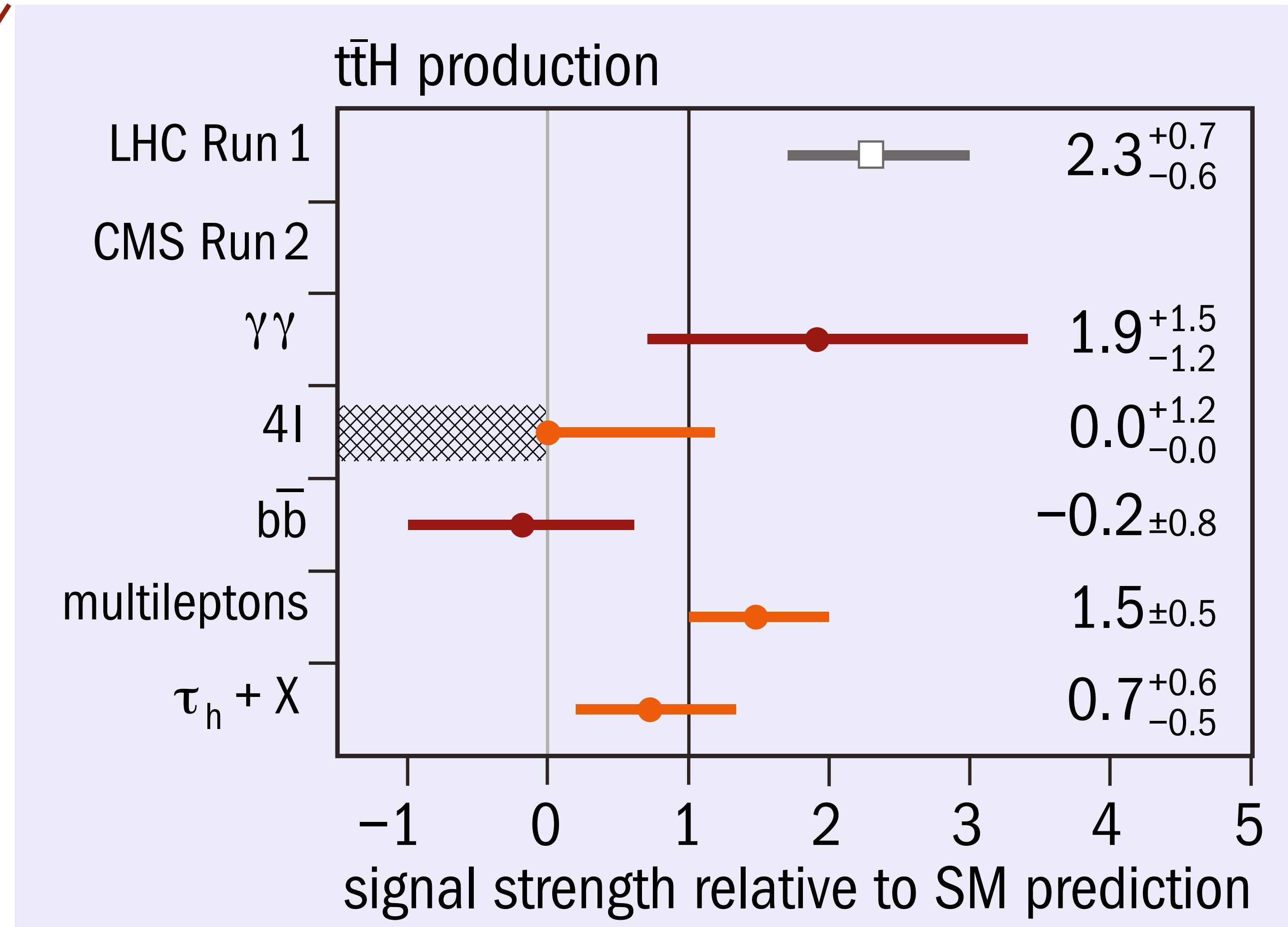


The top section summarises the ATLAS and CMS combined analysis of the Run 1 data, which exhibit a 2.3 standard-deviation excess above the SM prediction, while the lower section shows the latest CMS results from Run 2. Results that include the full 2016 data, presented for the first time in March, are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

Further reading

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

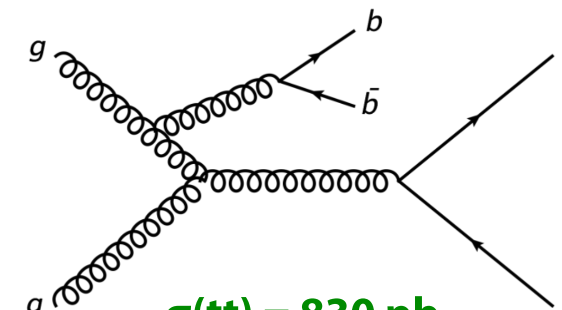
CMS Collaboration 2017 CMS-PAS-HIG-17-004.



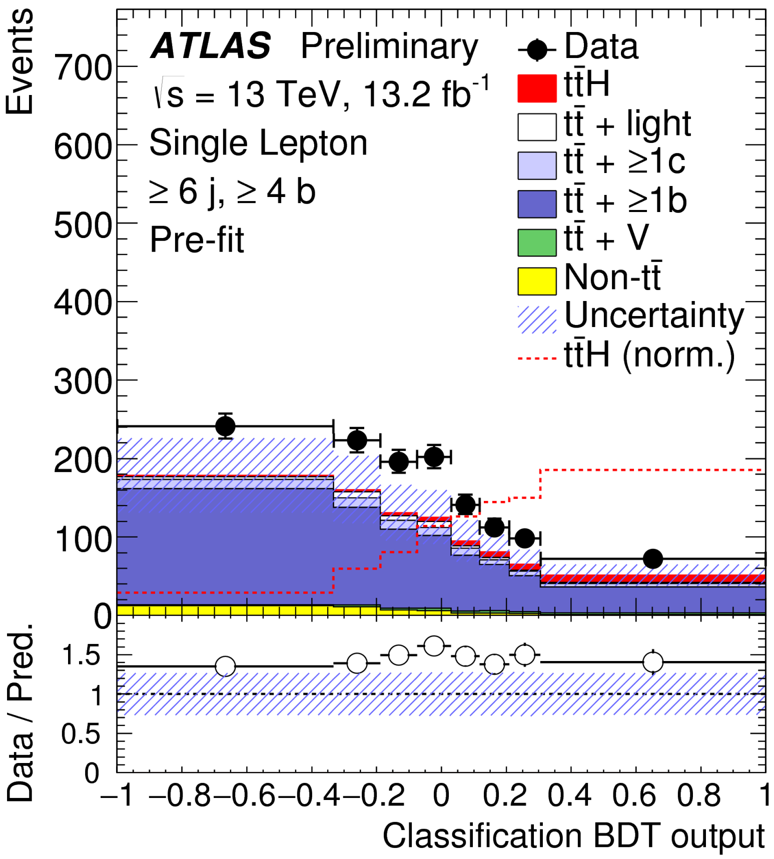
A combination of ATLAS and CMS ttH results would likely be incompatible with $\mu = 0$ but there is not yet a single analysis with a strong and unambiguous ttH signal

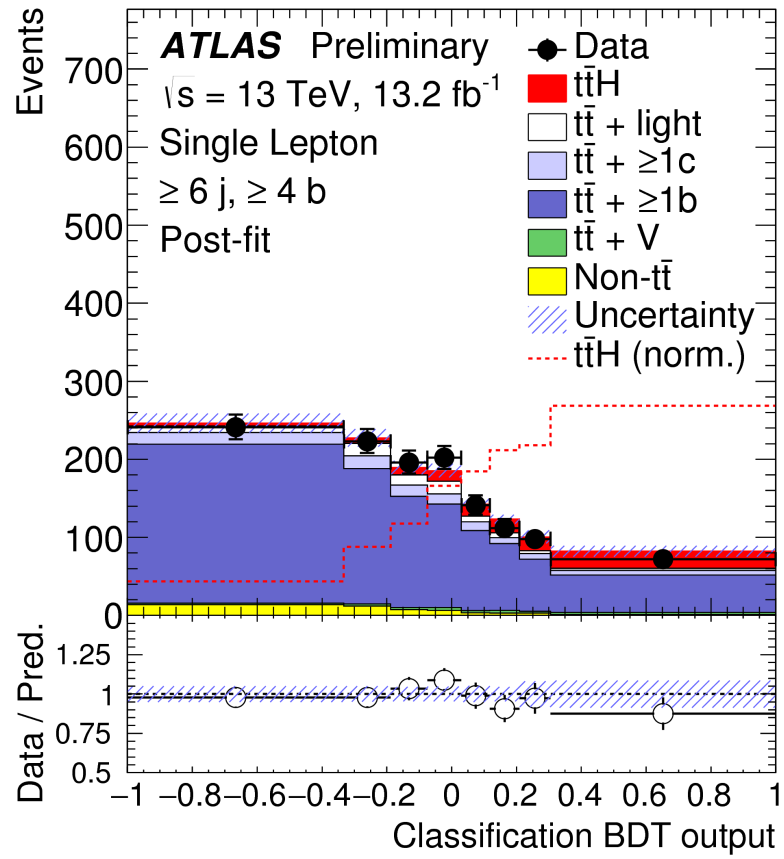
ttH with H→bb

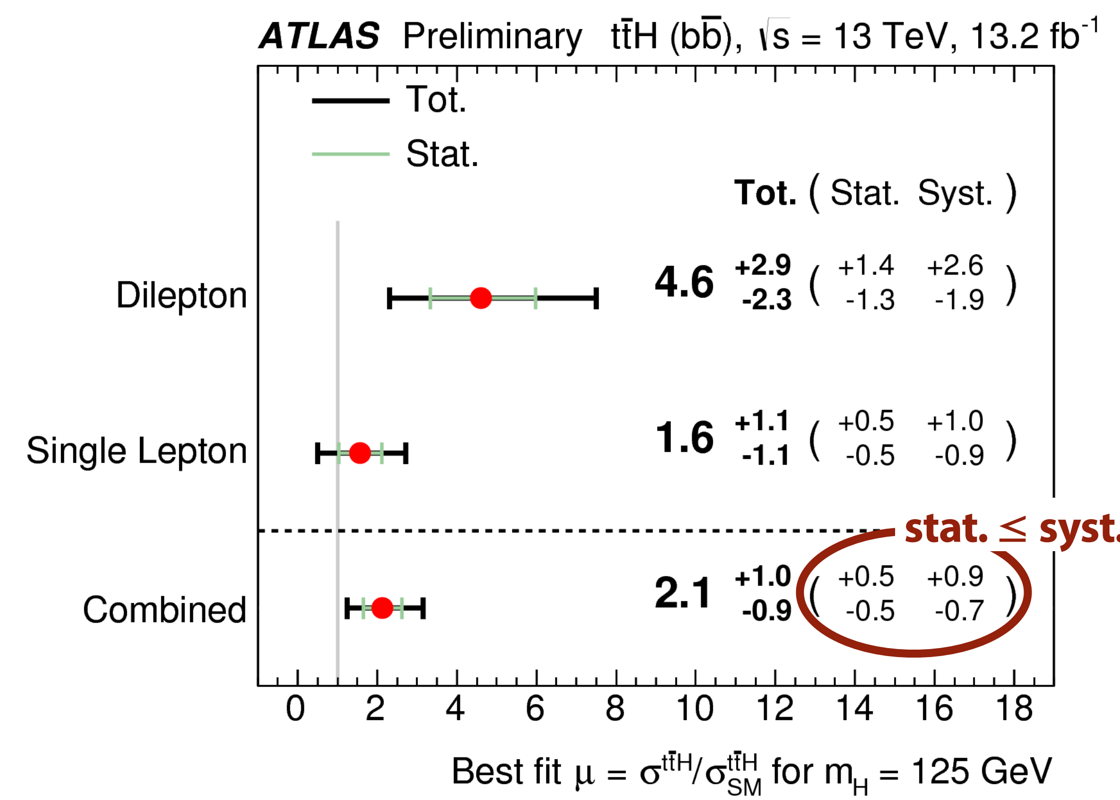
Overcome large background from tt+jets, especially tt+≥1b, associated large theory uncertainties on its modelling



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







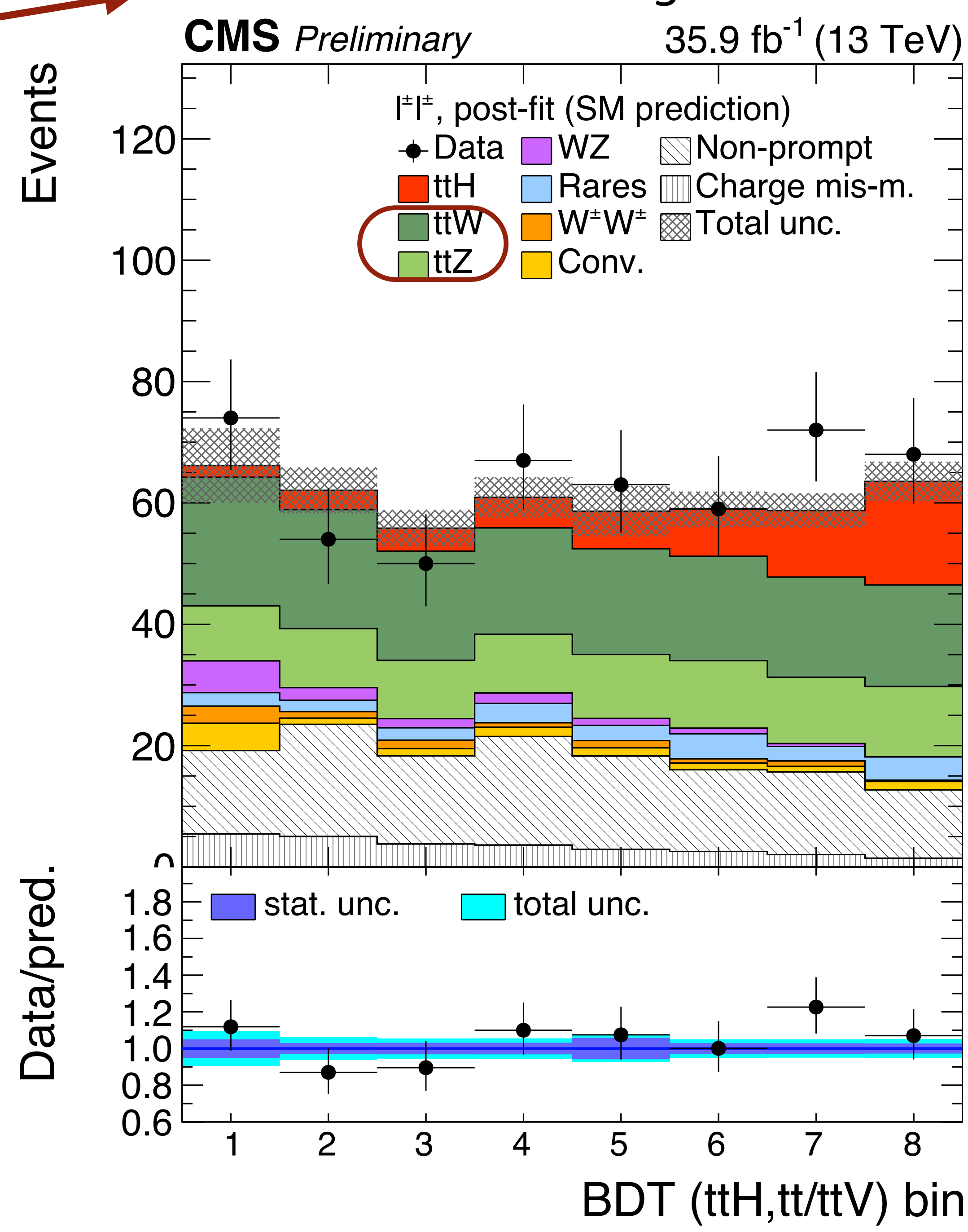
Sensitivity on μ: ~1·SM, limited by systematics dominated by those on tt+≥1b background

Improve the background modelling
Interaction with theory & MC experts

ttH in multilepton

Category	Observed μ fit $\pm 1\sigma$	Expected μ fit $\pm 1\sigma$
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)

BDT classifier used for signal extraction



Main ttW/ttZ irreducible backgrounds from NLO QCD+EWK cross section (YR4) + NLO QCD+PS MC (uncertainties ~10%)

ttW measurements (assuming μ(ttH) = 1)

μ(ttV) = 1.3 ± 0.6	CMS 5fb^{-1}	7 TeV	PRL 110 (2013) 172002
μ(ttW) = 1.7 ± 0.5	ATLAS 20fb^{-1}	8 TeV	JHEP 11 (2015) 172
μ(ttW) = 1.9 ± 0.6	CMS 20fb^{-1}	8 TeV	JHEP 01 (2016) 096
μ(ttW) = 2.5 ± 1.4	ATLAS 3fb^{-1}	13 TeV	EPJC77 (2017) 40
μ(ttW) = 1.6 ± 0.5	CMS 13fb^{-1}	13 TeV	CMS-PAS-TOP-16-017

Cross-check fit with free floating ttW and ttZ

Combined μ(ttH) = 1.3 ± 0.5

Maybe the ttW NLO cross section prediction does not capture all that we can see?

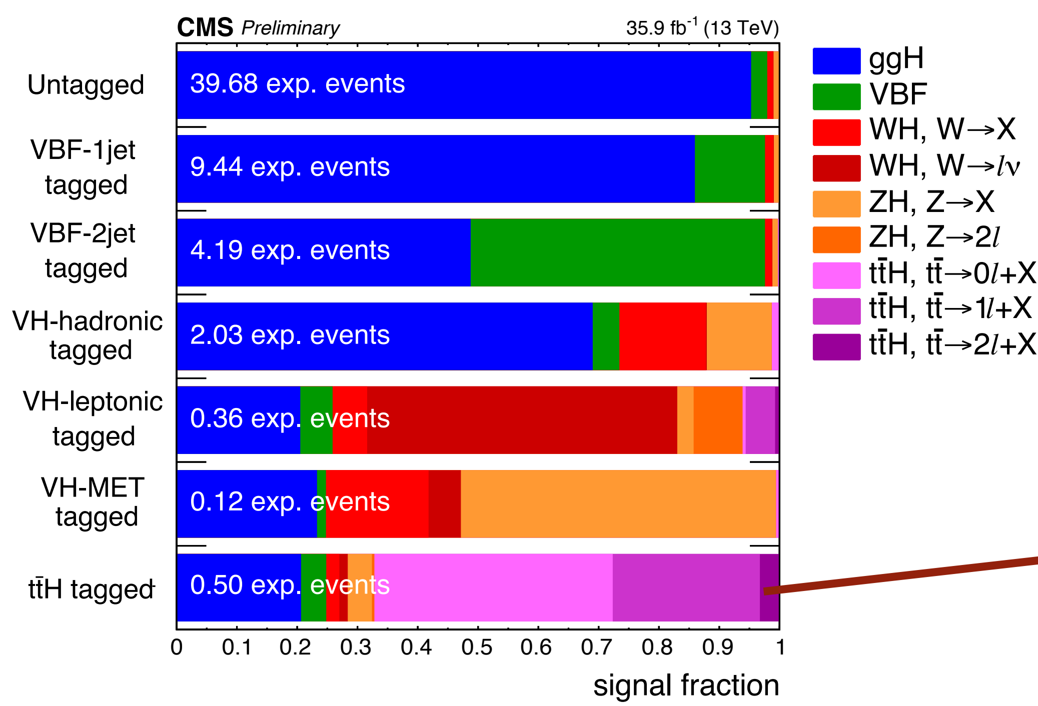
Improved handling of reducible backgrounds validation of ttV in data.

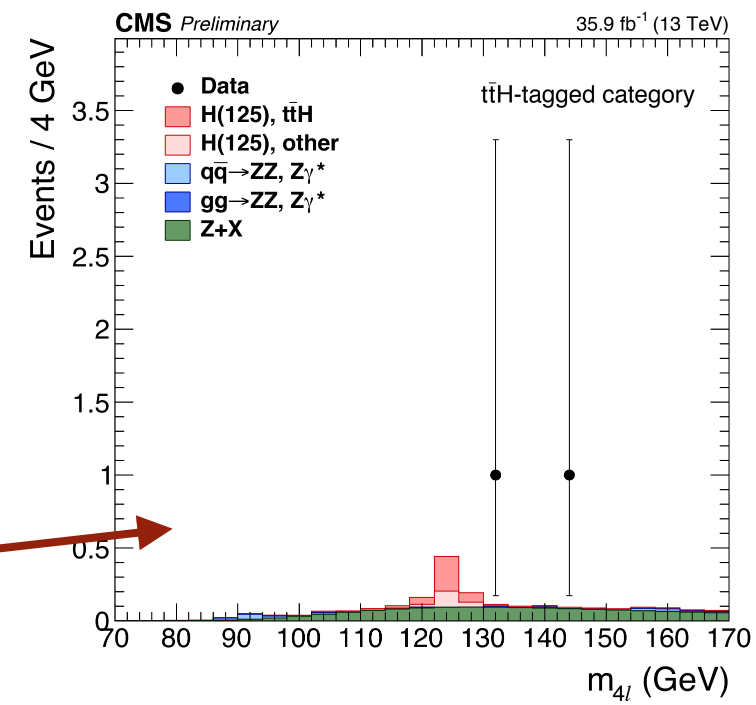
ttH with H→ZZ→4l or H→γγ

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)

4l : CMS started to target a dedicated category

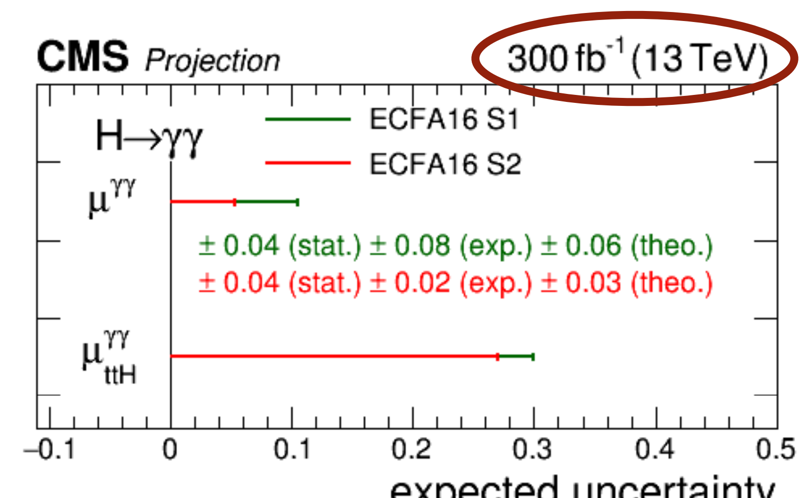




Events in 118<m$_{4l}$<130 GeV

	tt̄H
gg → H	0.10
VBF	0.02
WH	0.02
ZH	0.02
tt̄H	0.35
Signal	0.51
qq̄ → ZZ	0.01
gg → ZZ	< 0.01
Z+X	0.27
Total expected	0.79
Observed	0

Observe by the end of Run-III an unambiguous ttH signal

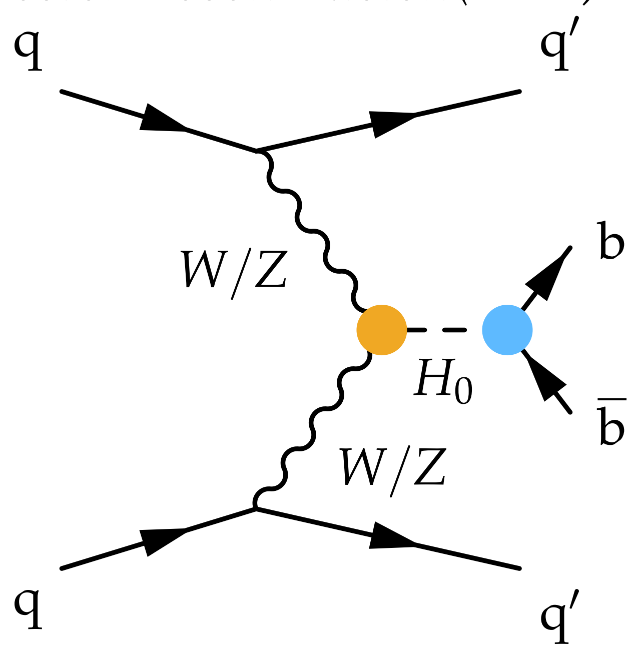


Observation of the 2nd generation Higgs coupling

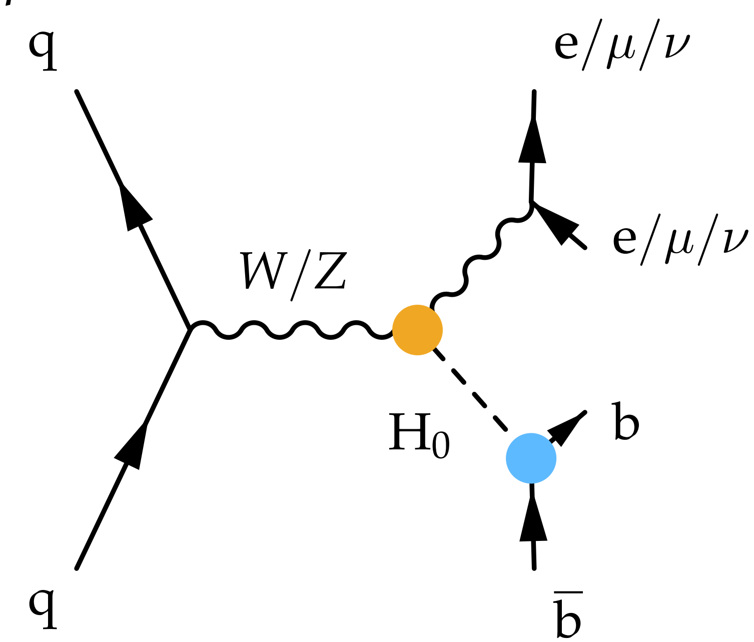
Despite being the dominant decay mode, Higgs coupling to bb is not yet observed

Used production mechanisms

Vector Boson Fusion(VBF)



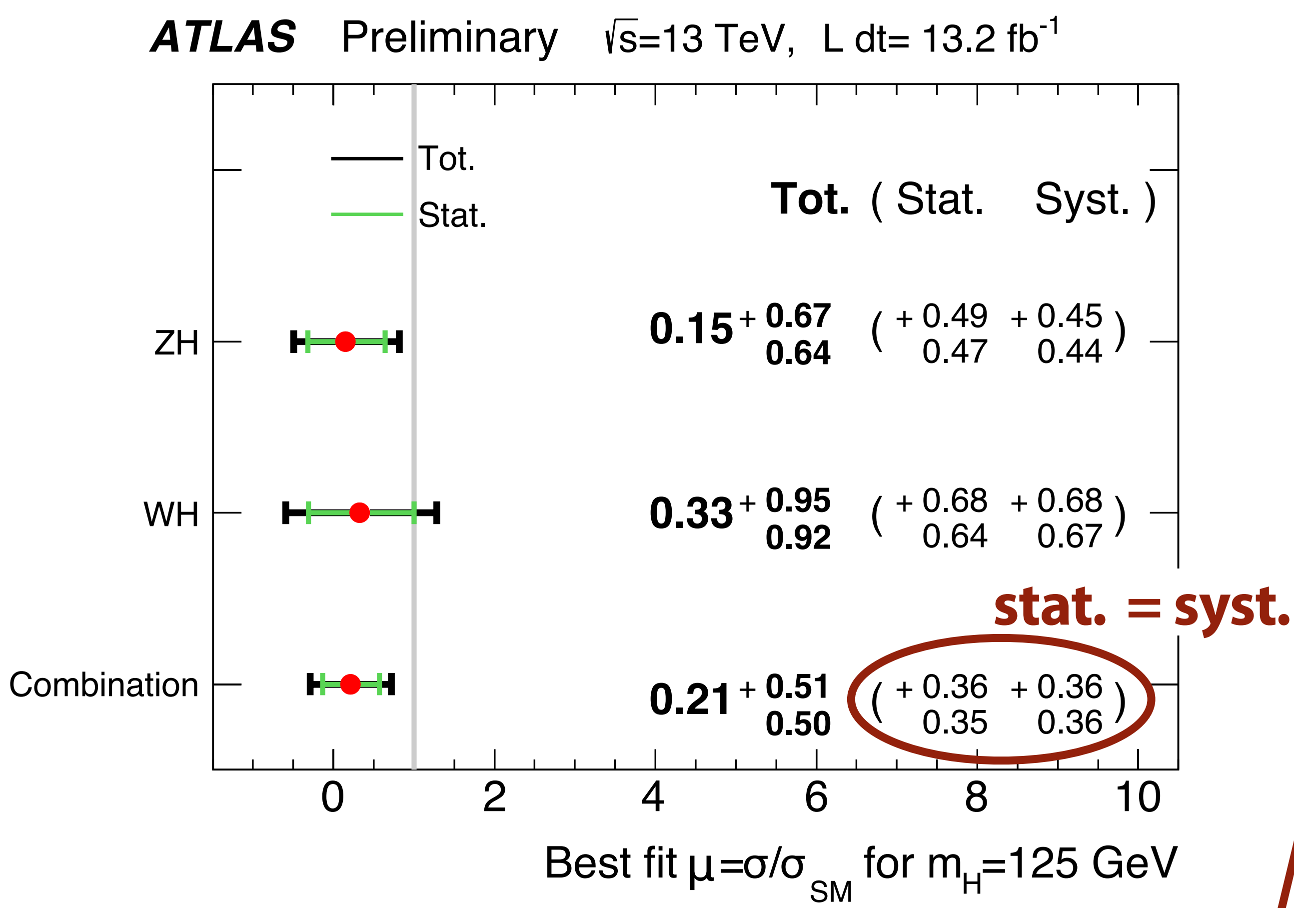
Associate production with vector bosons(VH)

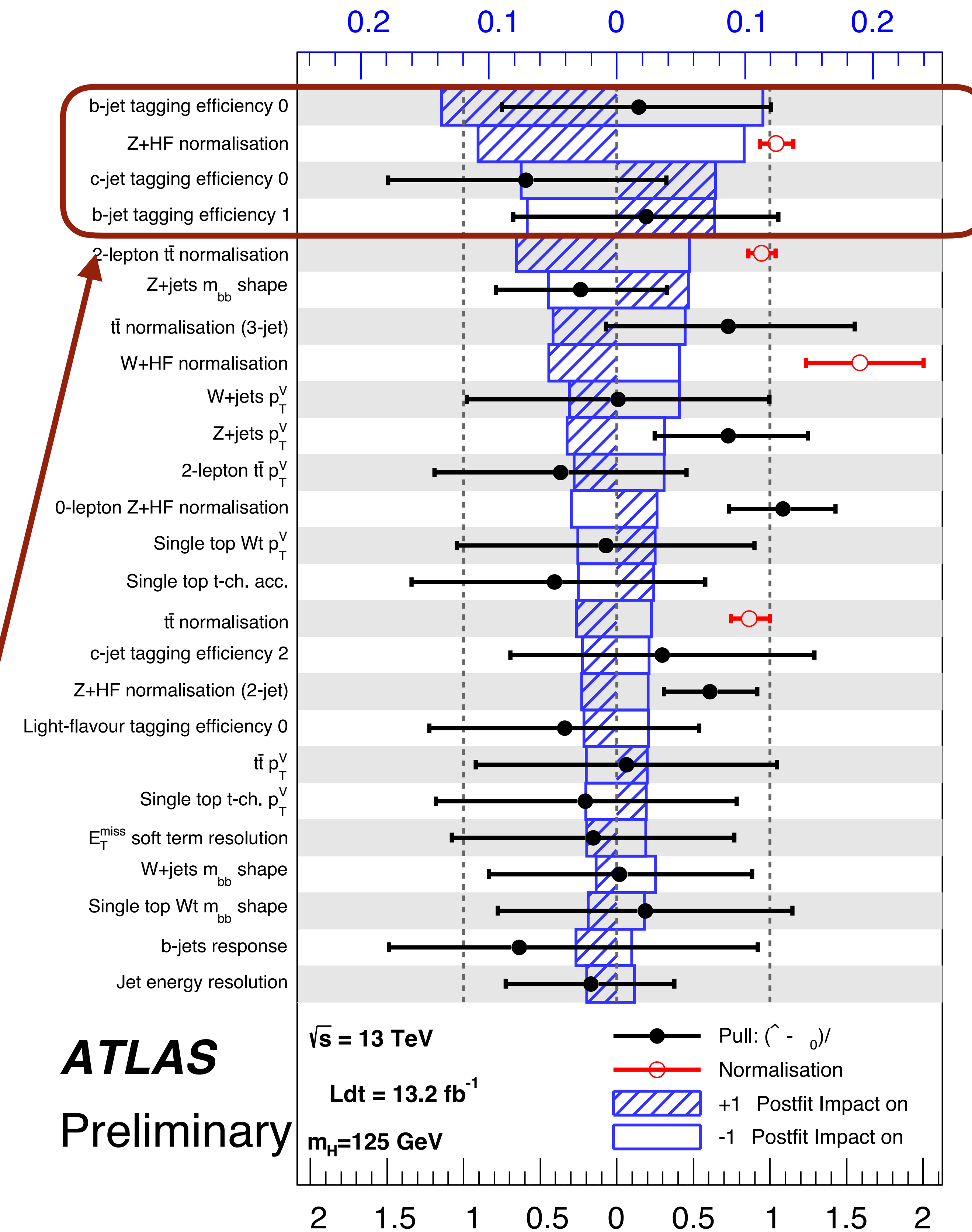


+ associated production with single-top two-tops (previously discussed)

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

VH→(ll/lν/νν)bb





The pull plot shows the systematics and their impact

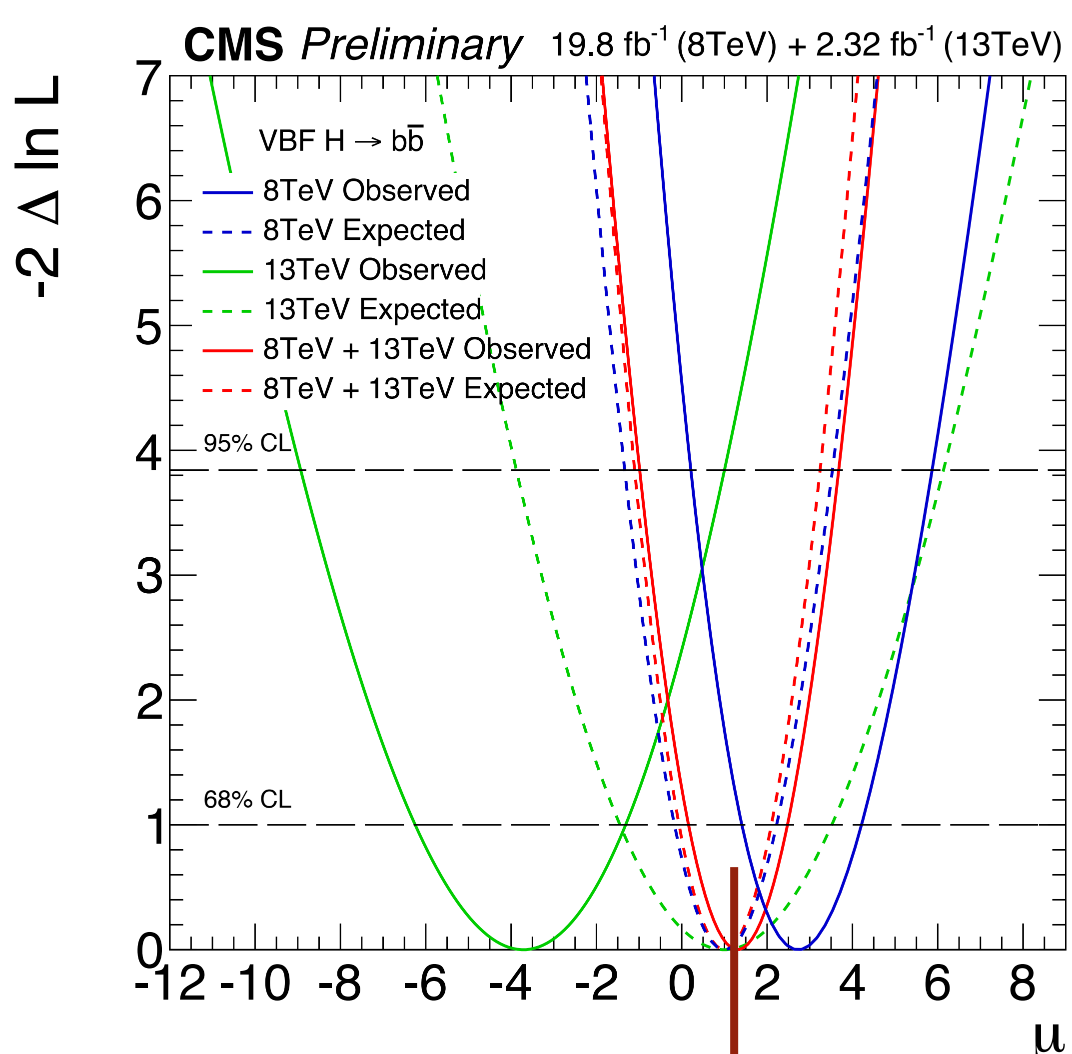
Main ones : b/c tag efficiencies and Z+HF normalization

II

VBF(+γ), H→bb

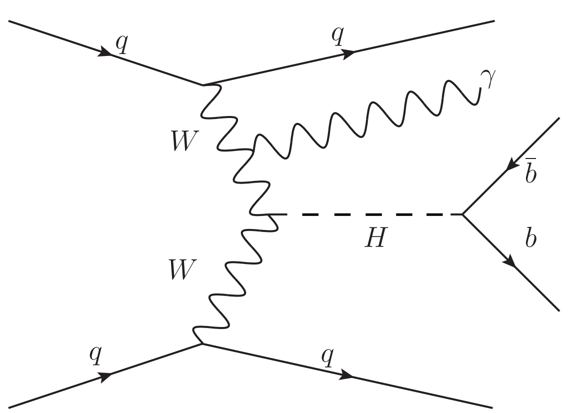
A channel that currently lag in sensitivity but it will catch up the main VH channel → **trigger is critical**

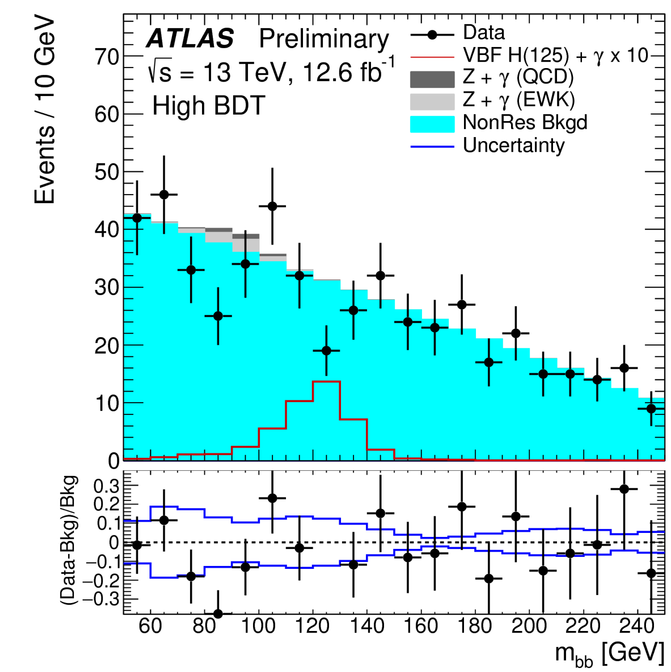
Highest rate analysis attempted
3/4 jets at L1/HLT (high background)



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

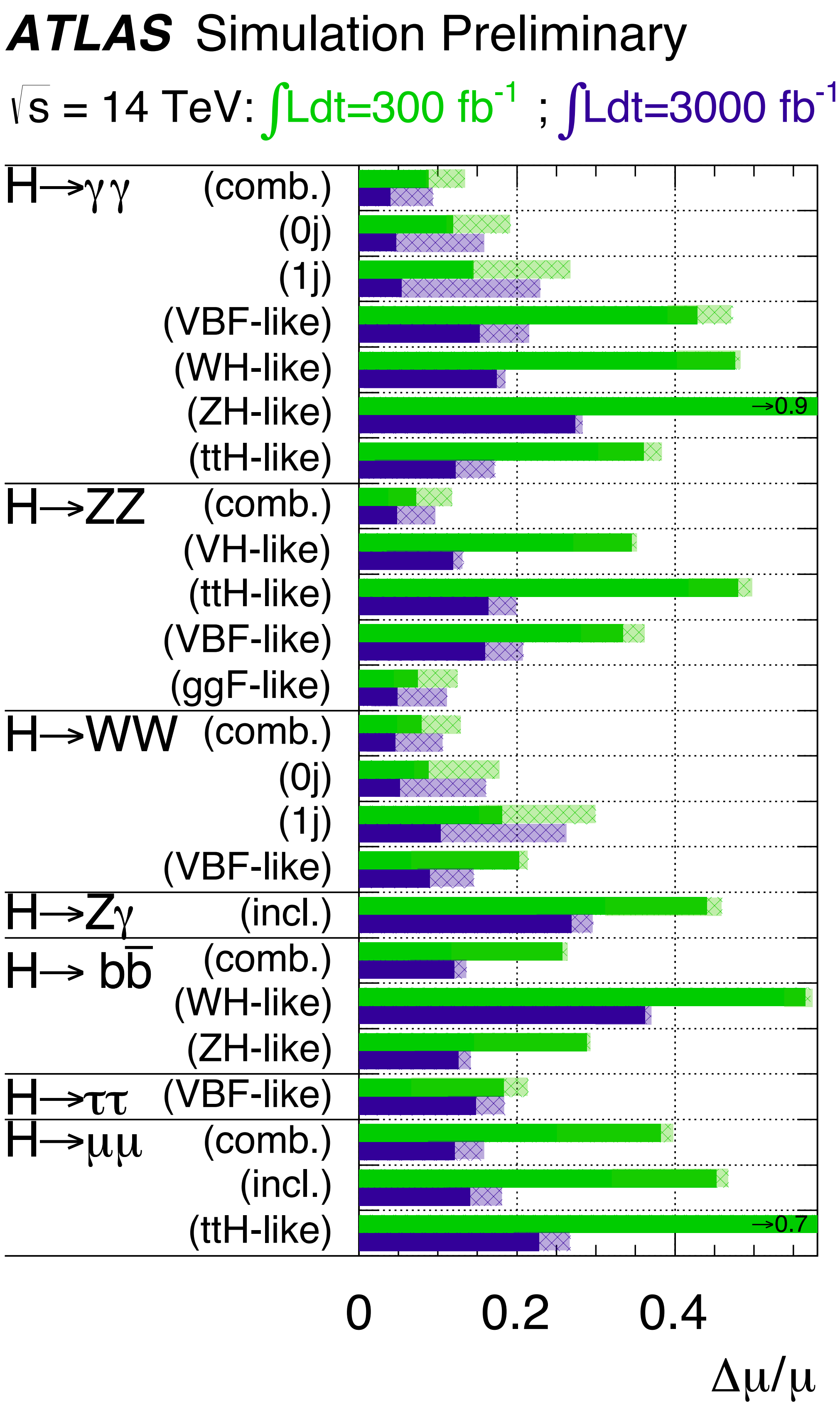
Lowest rate analysis attempted
photon as a tag

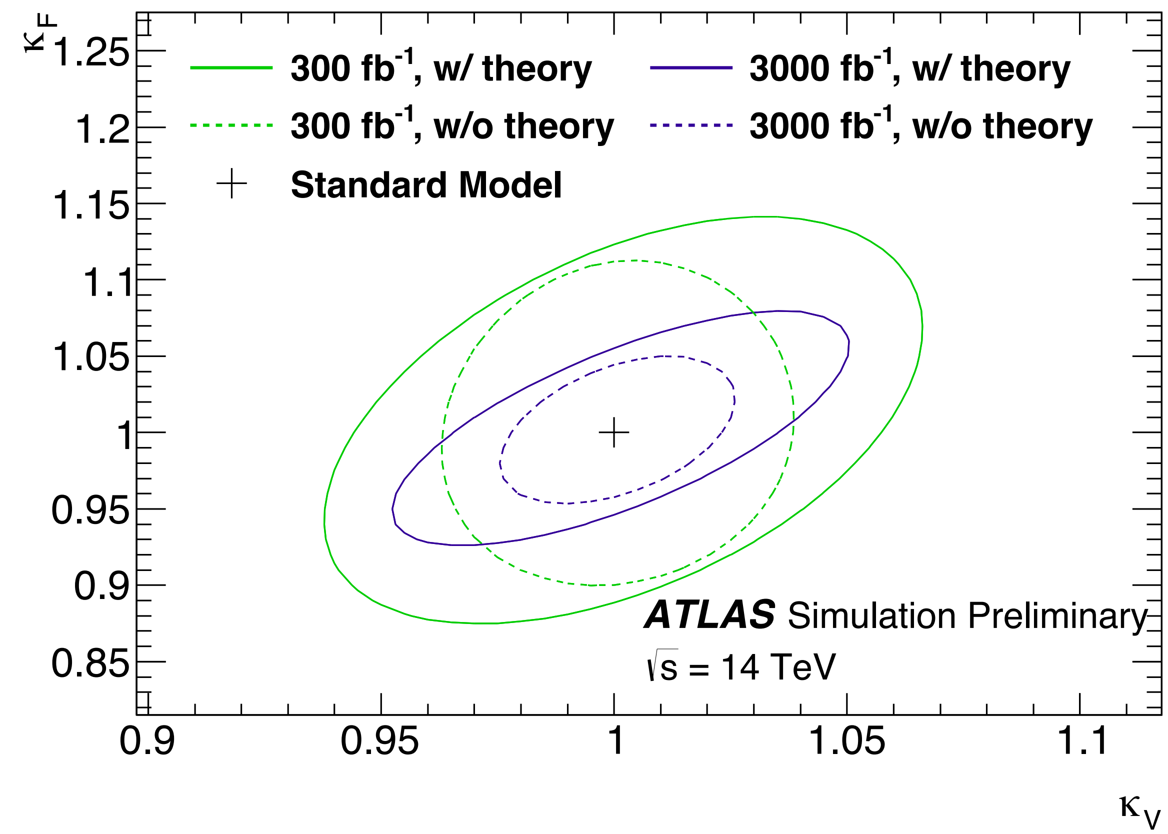




Result	$H(\to b\bar{b})+\gamma jj$	$Z(\to b\bar{b})+\gamma jj$
Expected significance	0.4	1.3
Expected p-value	0.4	0.1
Observed p-value	0.9	0.4
Expected limit	$6.0^{+2.3}_{-1.7}$	$1.8^{+0.7}_{-0.5}$
Observed limit	4.0	2.0
Observed signal strength μ	$-3.9^{+2.8}_{-2.7}$	0.3 ± 0.8

Higgs boson coupling measurements



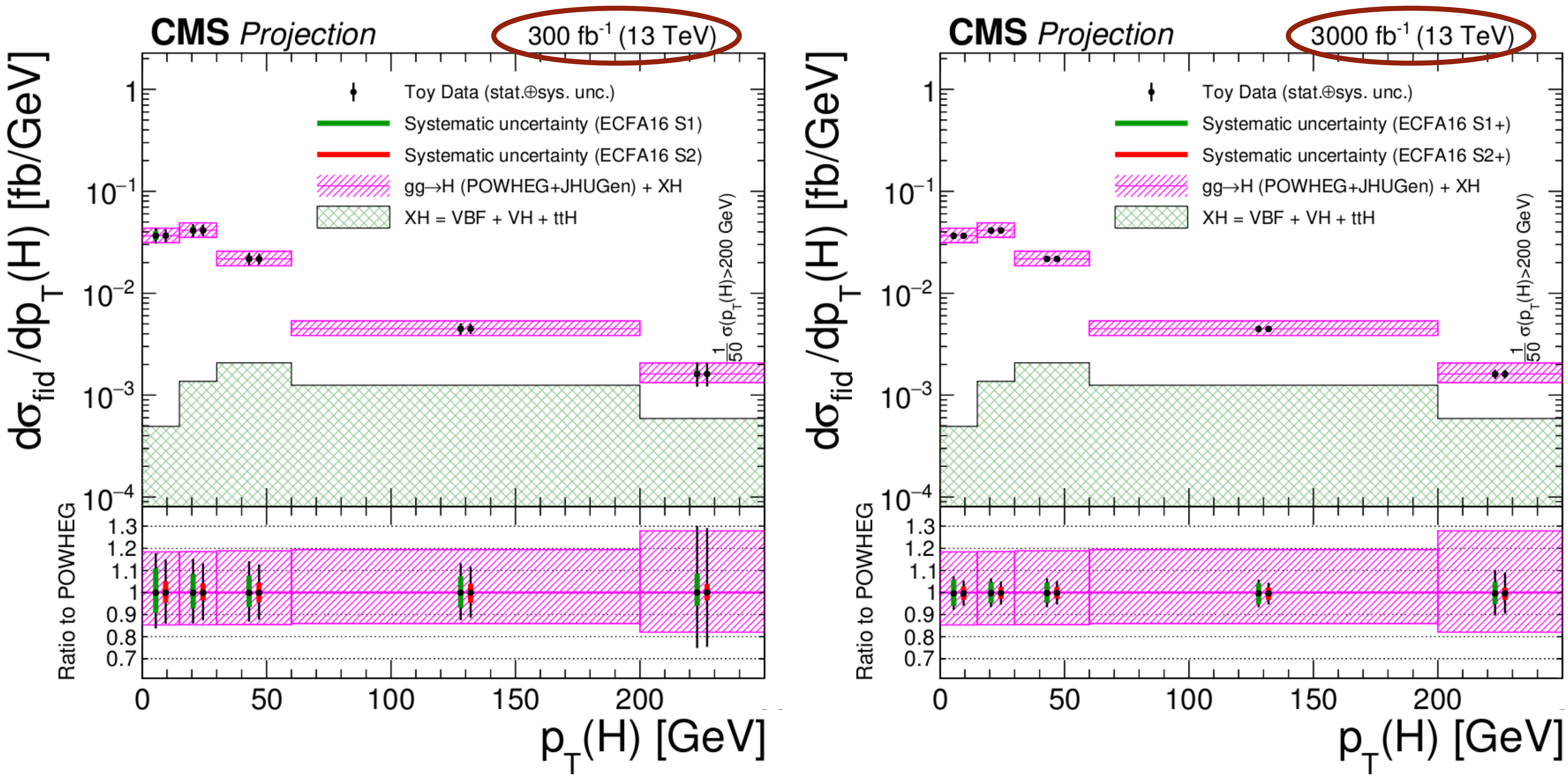


Theory uncertainties give a sizeable contribution to the expected total uncertainty and even dominate the uncertainty in some cases.

Extrapolation based on old analyses, Run-II analyses are doing better than the ones used

Higgs boson cross sections measurements

… fiducial, differential, simplified …



The theoretical uncertainty on the differential gluon fusion cross section is taken at NLO

The statistical uncertainty of the measurement ranges from 10-29% (4-9%) for 300 (3000) fb^{-1}

III Rare processes

Yukawa coupling to 2nd generation fermions

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

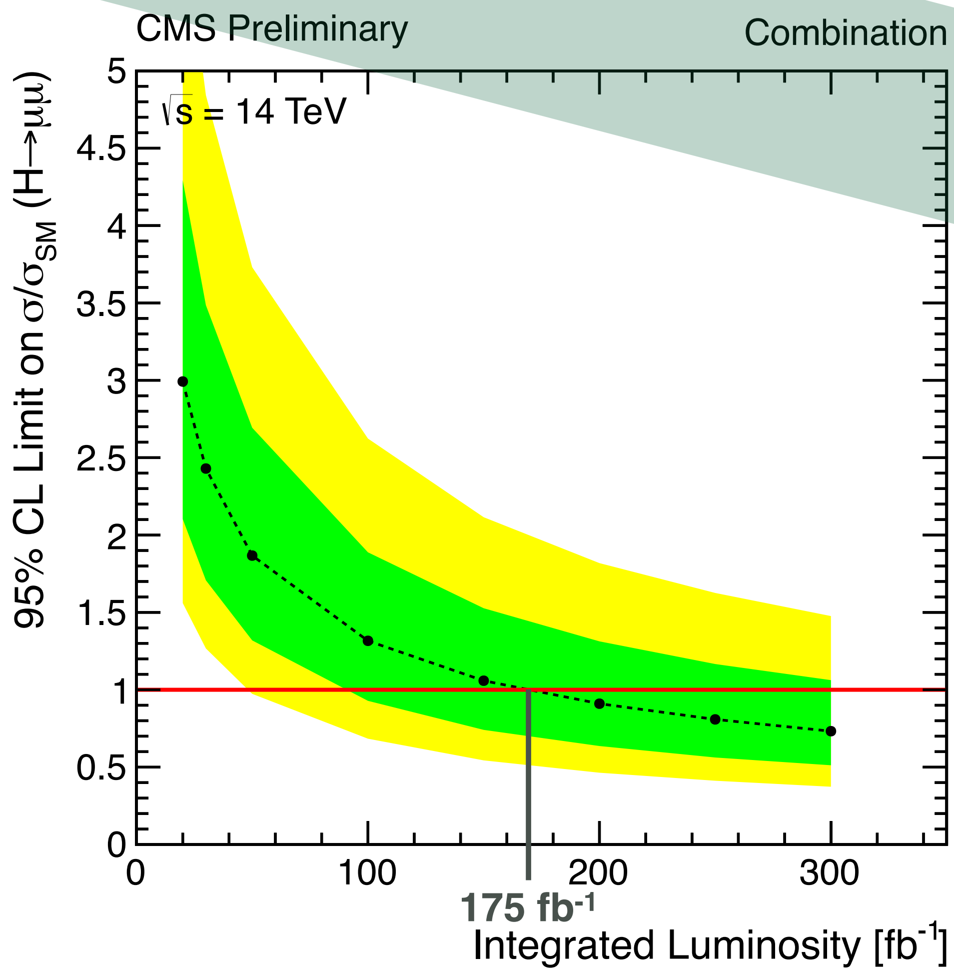
175 fb^{-1} : excluded SM

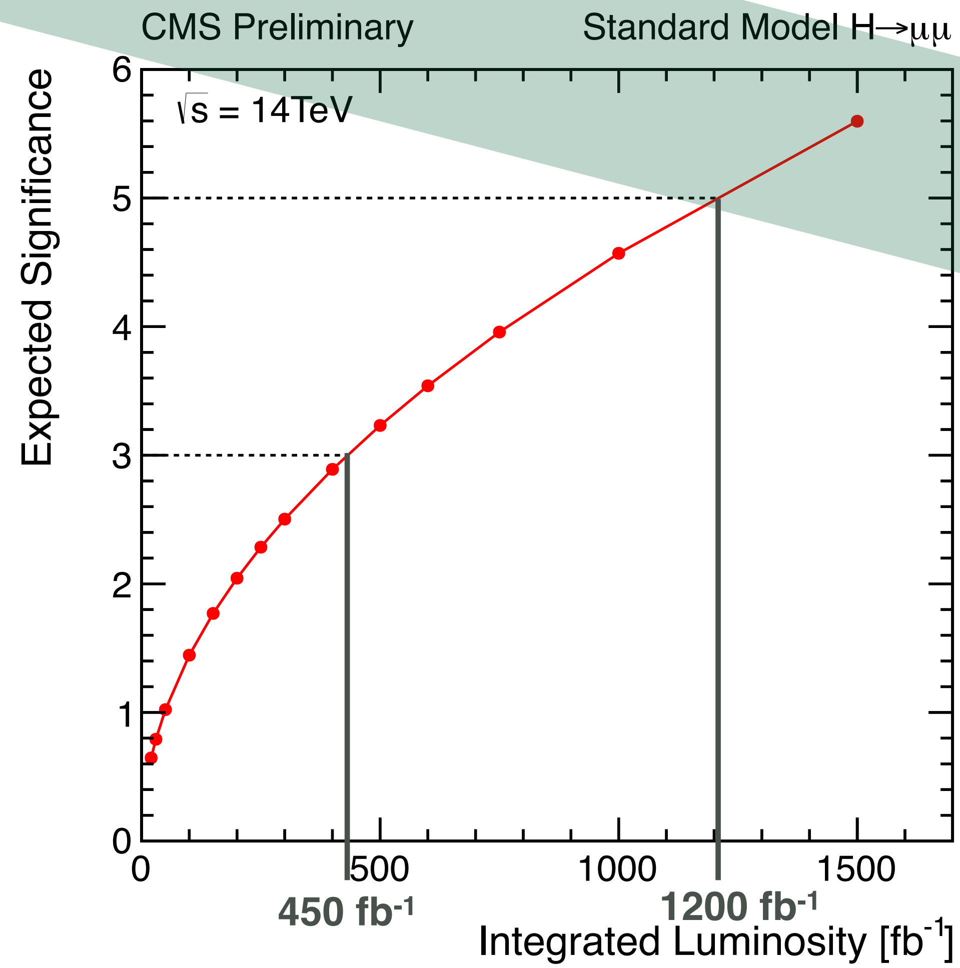
300 fb^{-1} : 20% on K_μ

450 fb^{-1} : reach 3σ significance

1200 fb^{-1} : reach 5σ significance

3000fb^{-1} : 5% on K_μ



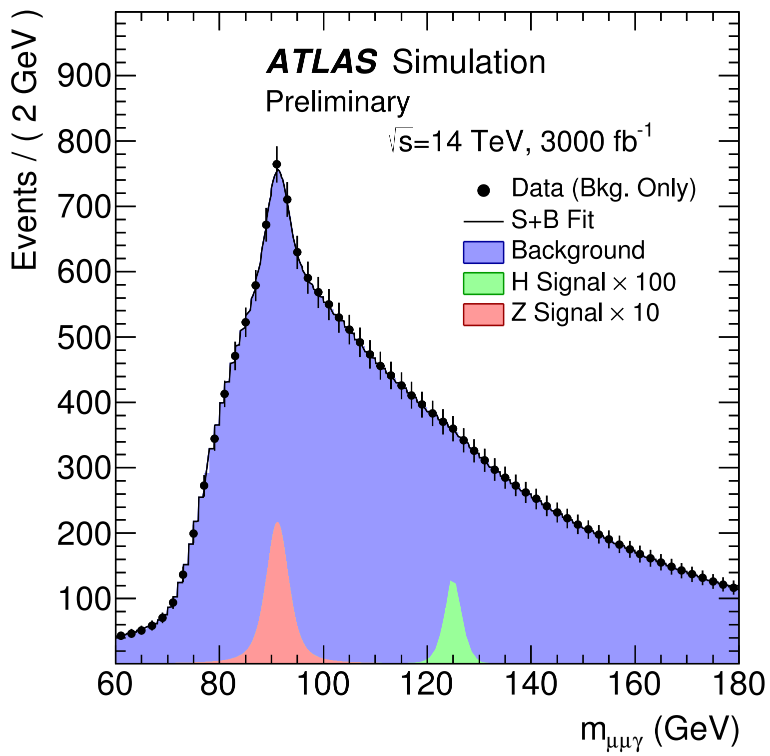


charm-Higgs Yukawa coupling

Hcc coupling : another test to measure coupling to **2[nd] generation fermions**

Main focus on $H \to J/\psi\gamma$: $BR_{H\to J/\psi\gamma} = (2.9 \pm 0.2)\times 10^{-6}$

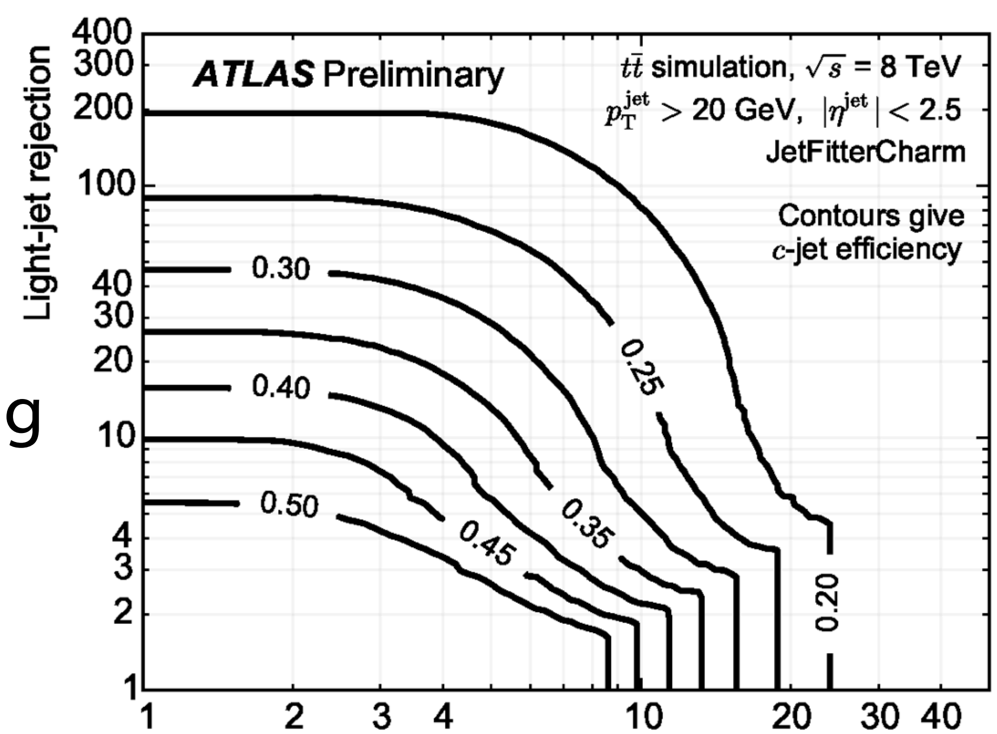
This is a nice and, relatively, clean final state but small branching ratio and significant contribution from non-resonant $H \to \mu\mu\gamma$ and $Z \to \mu\mu\gamma$



	Expected branching ratio limit at 95% CL		
	$\mathcal{B}(H \to J/\psi\gamma)$ [10^{-6}]		$\mathcal{B}(Z \to J/\psi\gamma)$ [10^{-7}]
	Cut Based	Multivariate Analysis	Cut Based
$300\ fb^{-1}$	185^{+81}_{-52}	153^{+69}_{-43}	$7.0^{+2.7}_{-2.0}$
$3000\ fb^{-1}$	55^{+24}_{-15}	44^{+19}_{-12}	$4.4^{+1.9}_{-1.1}$
	Standard Model expectation		
	$\mathcal{B}(H \to J/\psi\gamma)$ [10^{-6}]		$\mathcal{B}(Z \to J/\psi\gamma)$ [10^{-7}]
	2.9 ± 0.2		0.80 ± 0.05

What about $H \to cc$: $BR_{H\to cc} = 2.9\times 10^{-2}$

Huge QCD background + signal sits on top of large (×20) $H \to bb$ "background" but a dedicated c-tagging exist and is already applied some searches

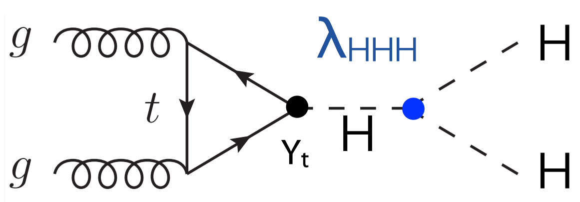


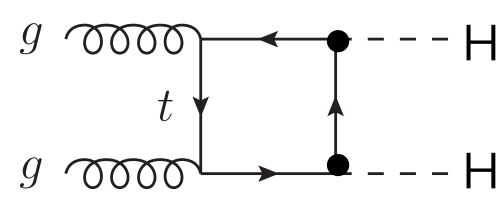
ATL-PHYS-PUB-2015-001

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

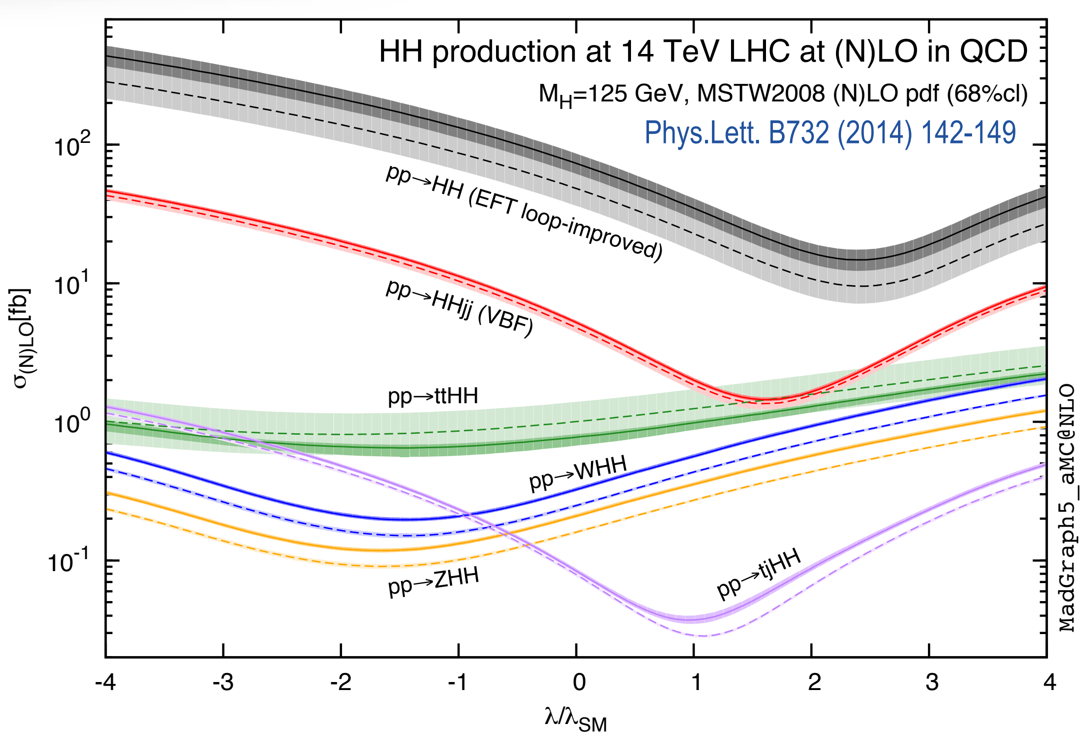
Problem : to measure *n*H coupling need to measure (*n-1*)H production

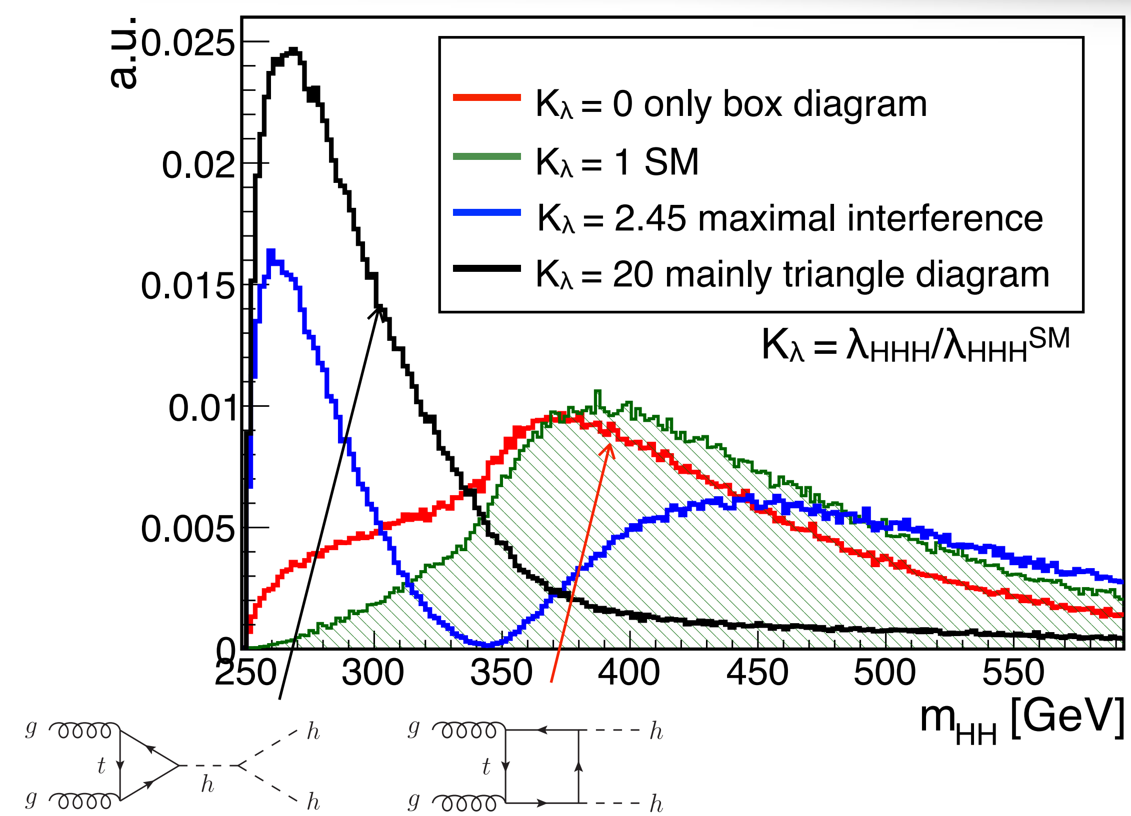




$\sigma_{gg\to HH} = 33.49^{+4.3}_{-6.0}$ (scale) ± 2.1 (PDF) ± 2.3 (α_s) fb

[13 TeV, NNLO + NNLL with top mass effects, HXSWG, 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

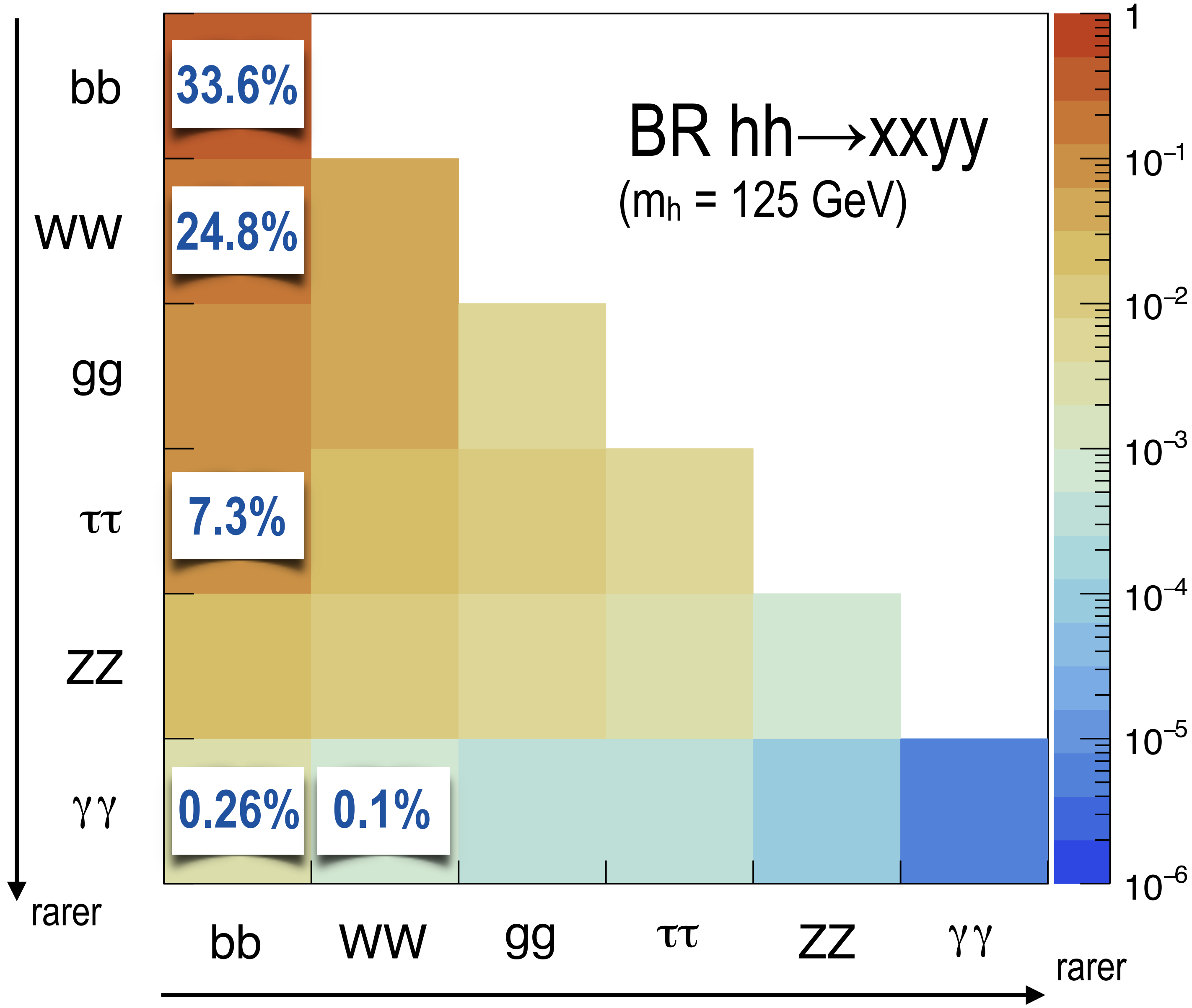
large branching ratio,
large tt contamination

bbττ

tradeoff between purity and branching ratio

bbγγ

high purity,
low branching ratio



III

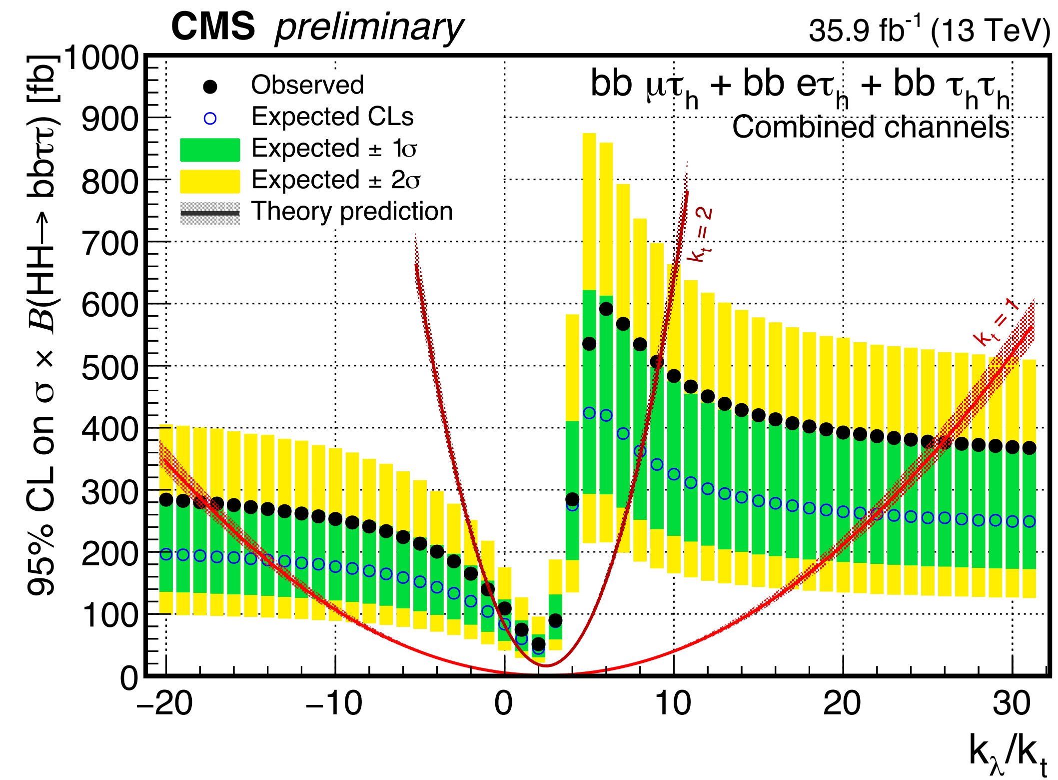
HH production : Run-II results overview

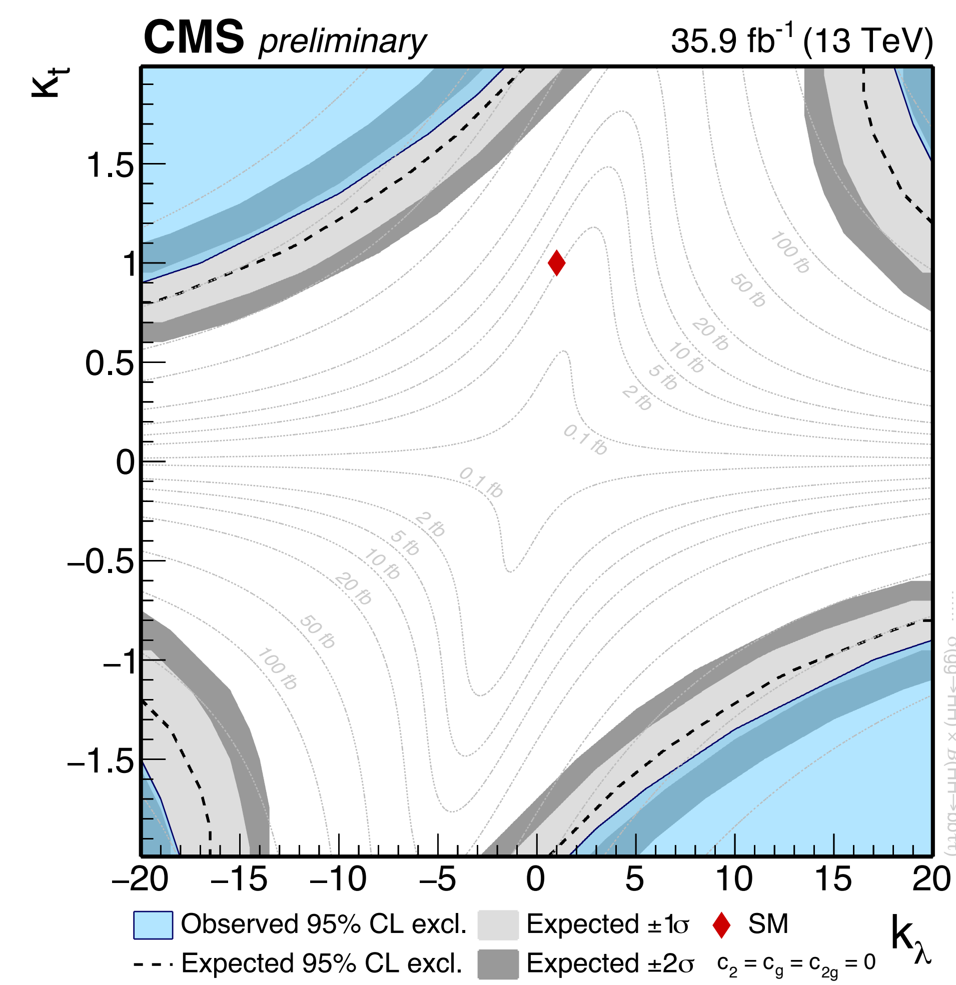
Several HH final states already explored at 13 TeV

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



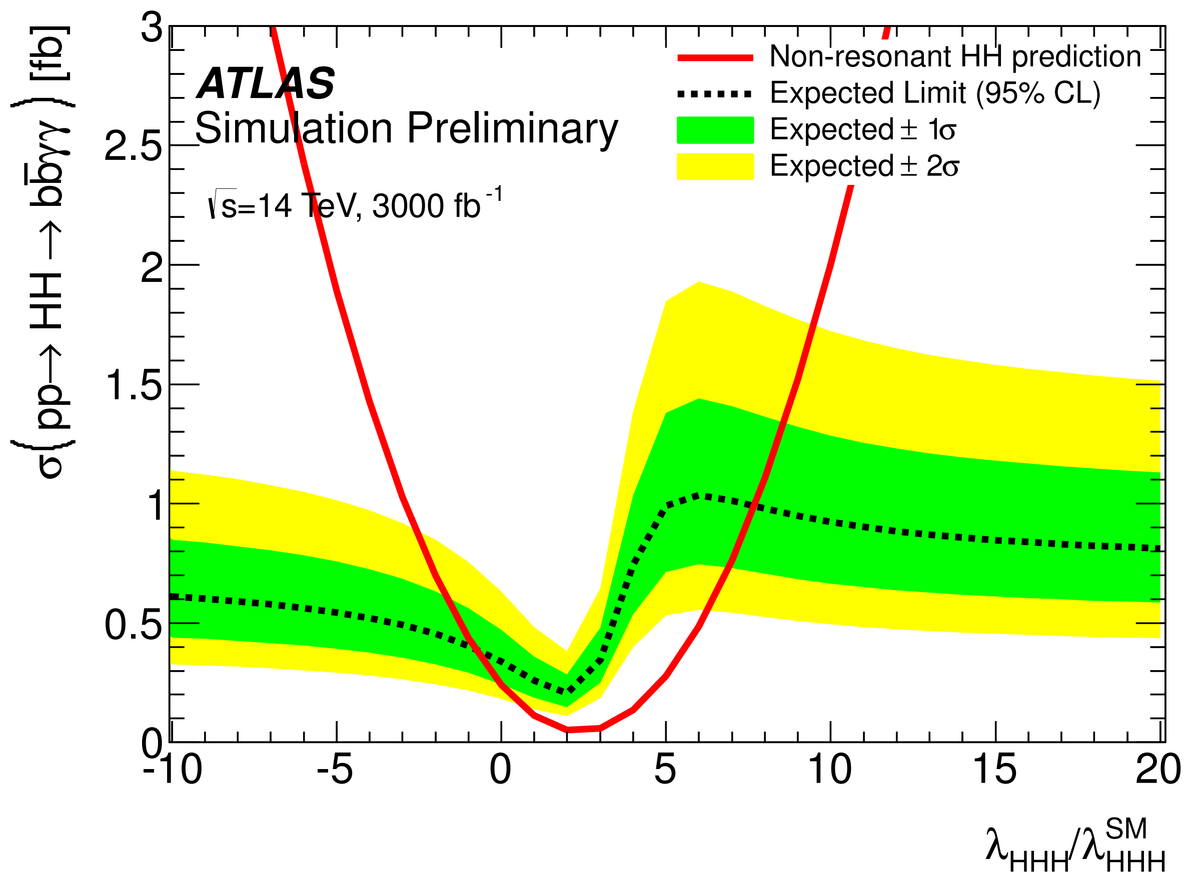


HH production : prospects

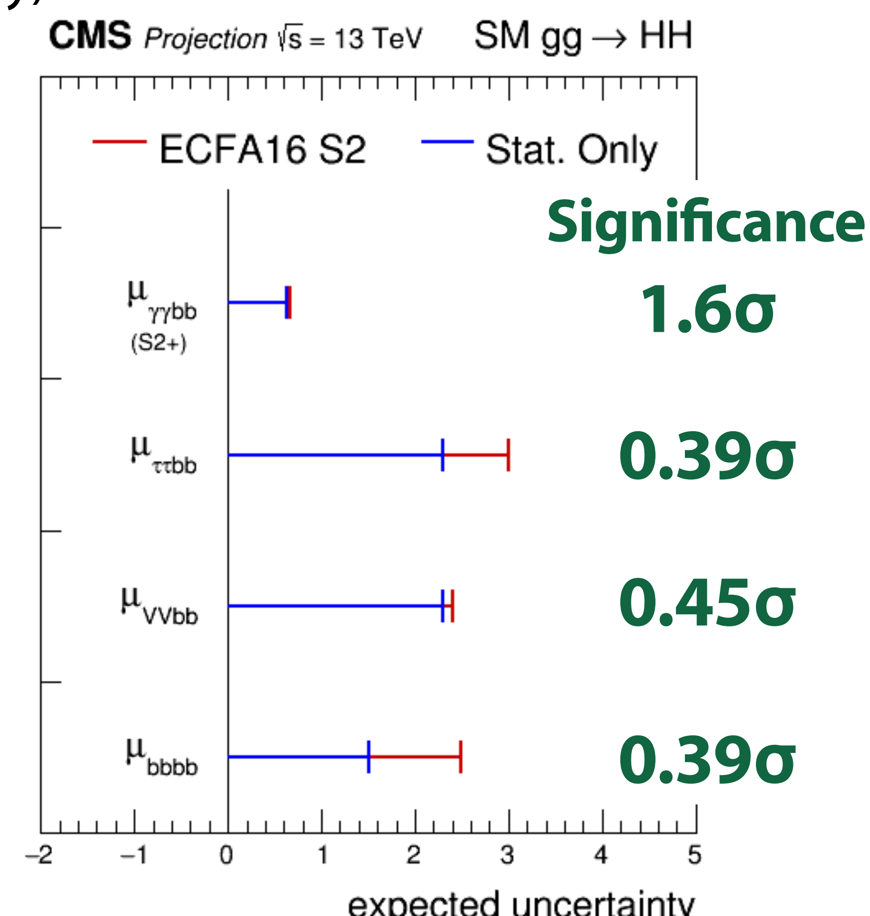
Measurement of σ_{HH} and determination of λ_{HHH} are one of the main points of the physics programme at the HL-LHC (3 ab^{-1} of data)

Two alternative approaches to estimate the sensitivity to HH production

parametric simulation of upgraded detector response



extrapolation of results from 13 TeV ~3fb^{-1} to HL-LHC (conservative: used results not optimal for high luminosity)



Analyses are evolving quickly, and we expect to do better!

Observe HH production with combination of final states and experiments

IV BSM Higgs boson searches

Exotic Higgs boson decays

Invisible Higgs boson decays

Additional Higgs-like particles

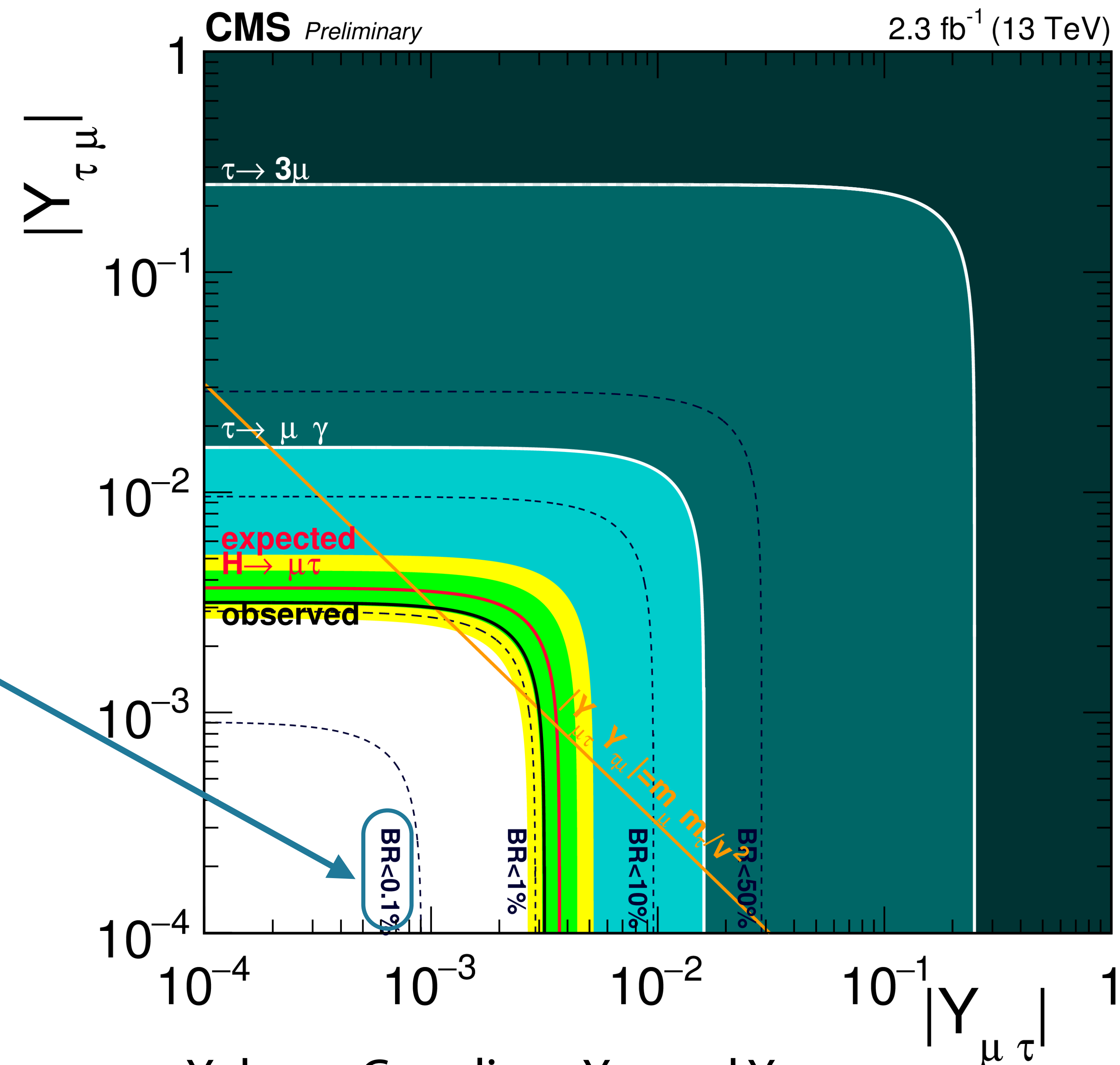
Exotic decays

Lepton Flavour Violating decays ($h \to \mu\tau$) are not allowed in SM

- exception can occur in case it is a theory valid only to a finite mass scale
- LFV decays can occur in 2HDM, and others…

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

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



Yukawa Couplings $Y_{\mu\tau}$ and $Y_{\tau\mu}$

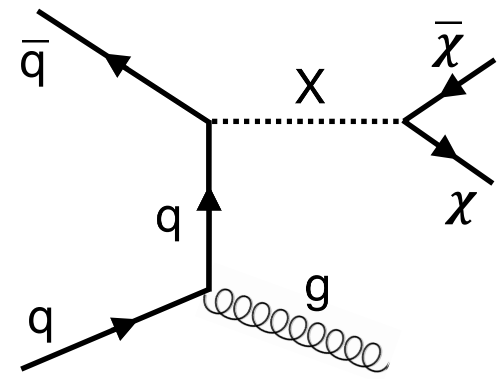
97% C.L.: $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.6 \times 10^{-3}$

The mystery of dark matter

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

Mono-mania

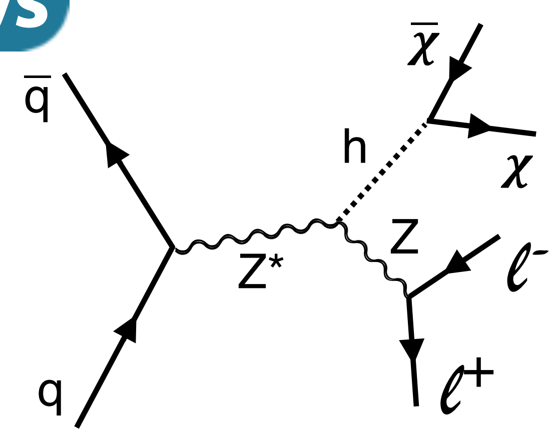
For every m_{DM} value



X is a mediator here example of a spin-1 mediator

Higgs bosons invisible decays

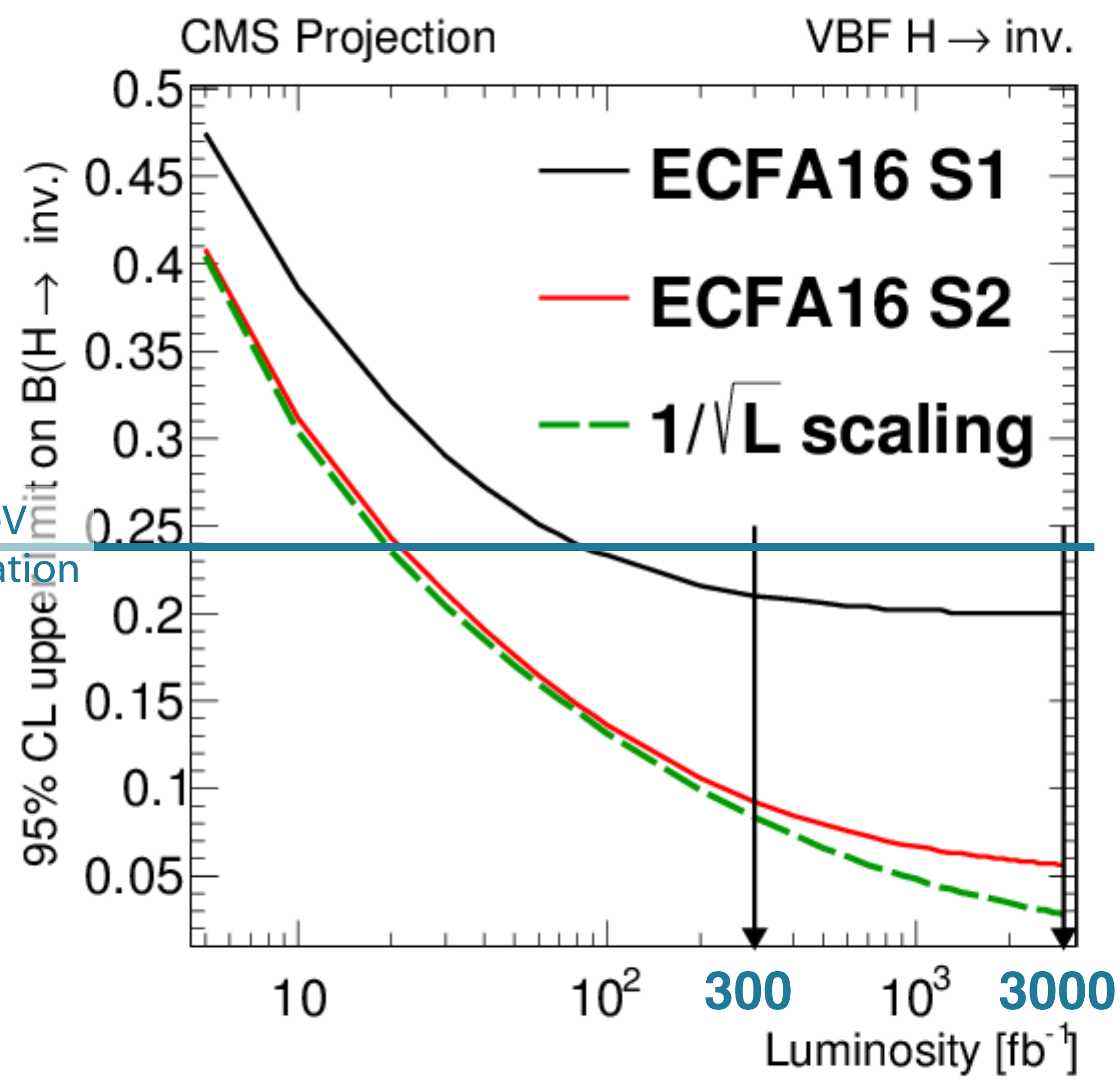
For $m_{DM} < m_h/2$

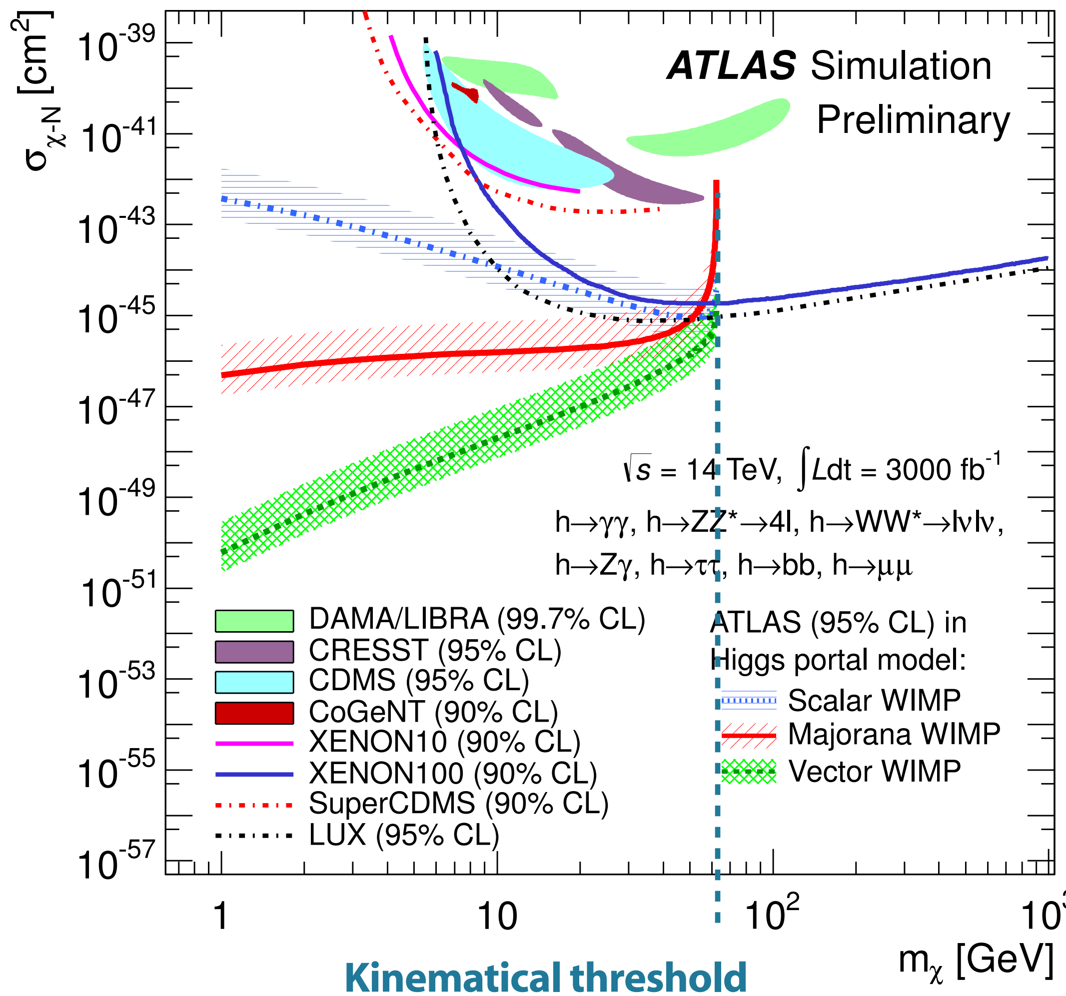


profiting of VBF and VH production modes

Dark matter : prospects

The Higgs to invisible BR is interpreted to WIMP constraint assuming that H→invisible goes to WIMPs all the time (Higgs-portal model)



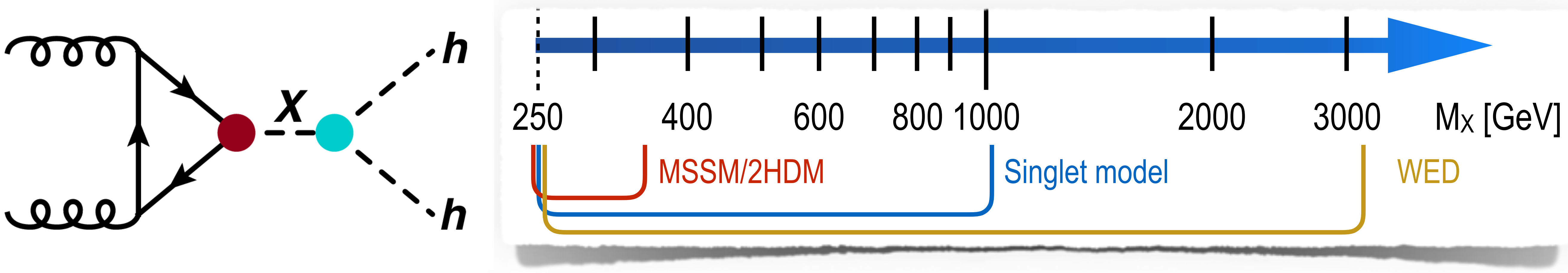


Kinematical threshold
$m_{DM} = m_H/2 = 62.5$ GeV

Models for the Higgs potential also solve the dark matter problem

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 tanβ region of the MSSM plane where BR (H→hh) is sizable

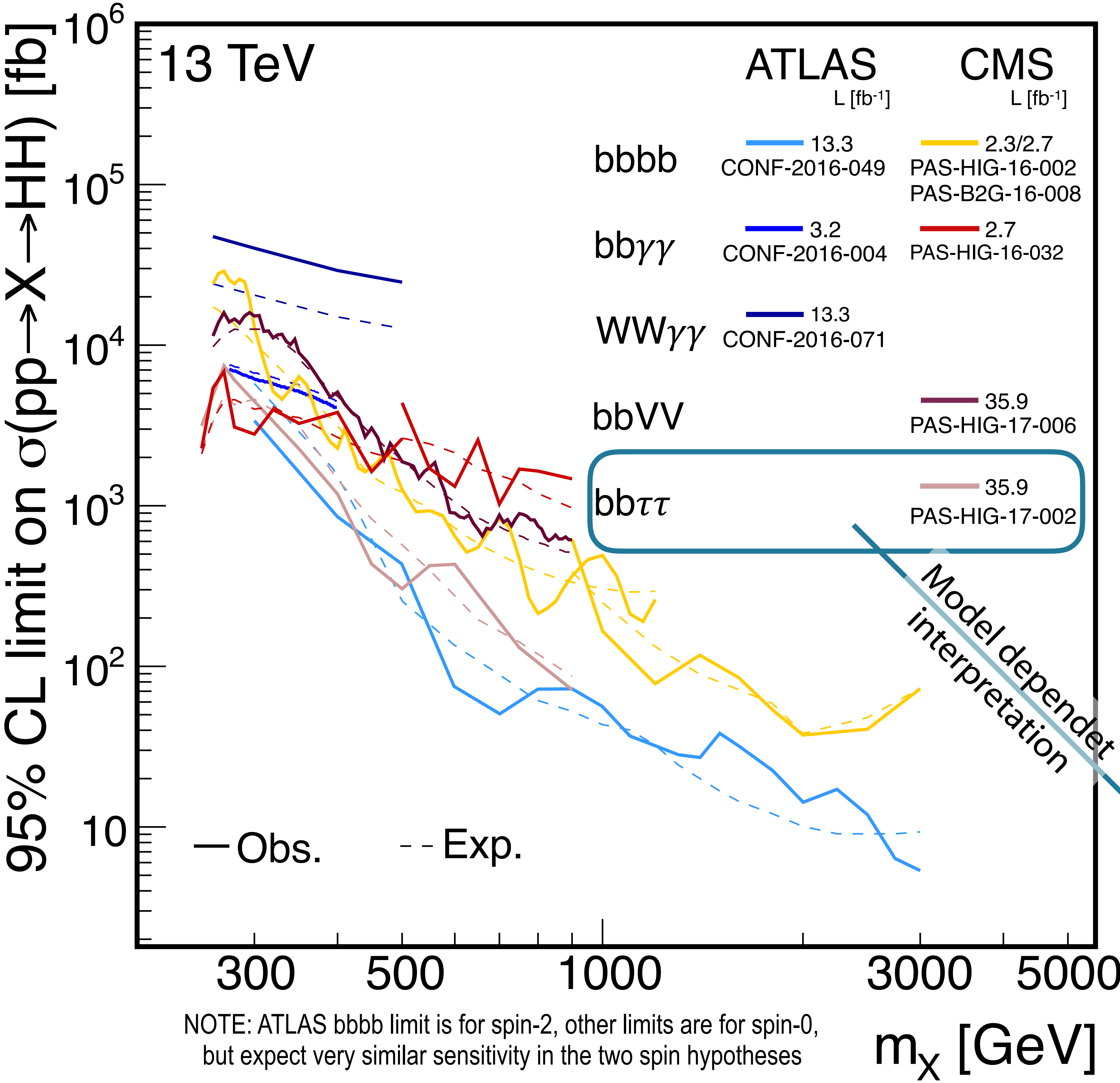
Singlet model: additional Higgs singlet S gives an extra scalar H

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

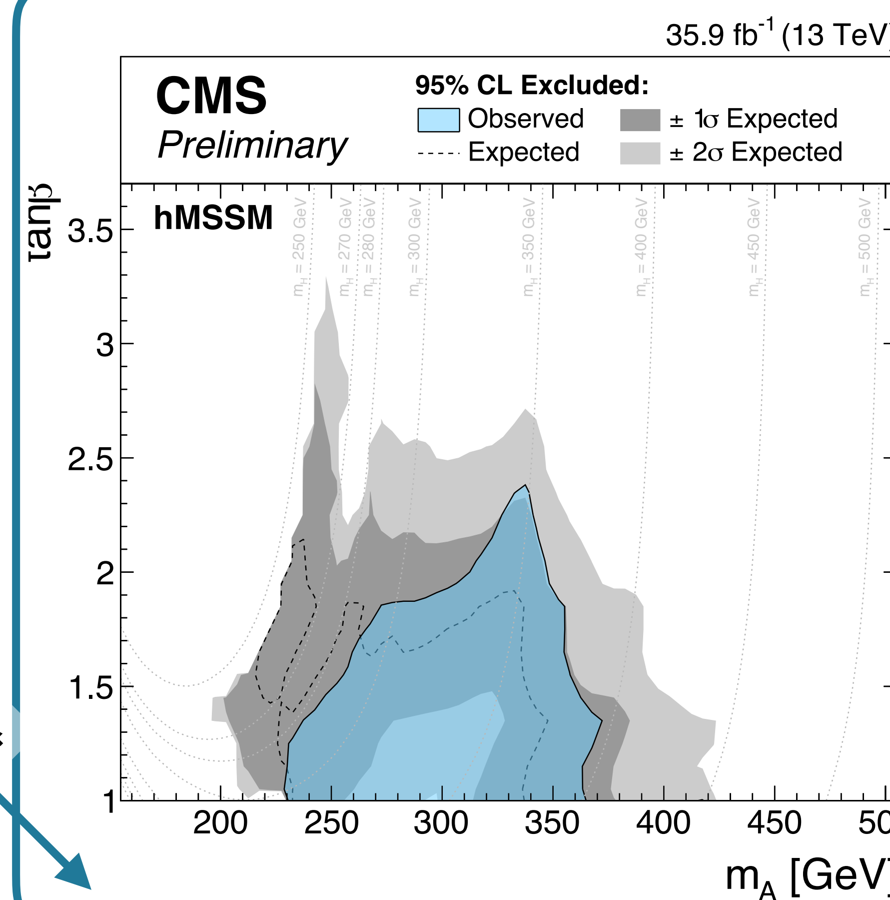
Warped Extra Dimensions: spin-2 (KK-graviton) and spin-0 (radion) resonances

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

X→HH : Run-II results overview



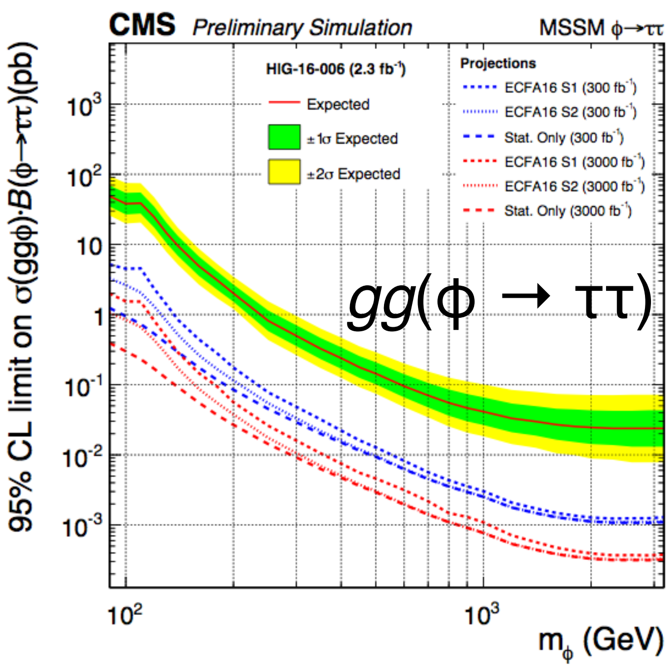
NOTE: ATLAS bbbb limit is for spin-2, other limits are for spin-0, but expect very similar sensitivity in the two spin hypotheses

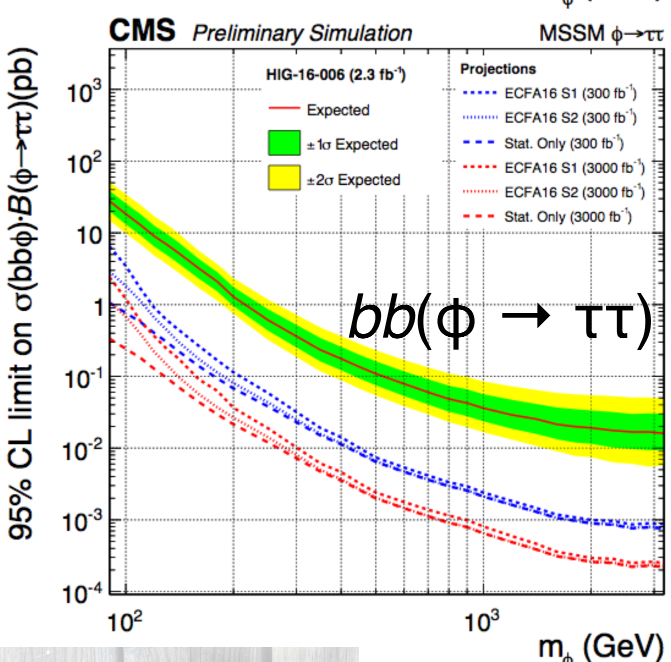


Search for additional Higgs bosons : H → ττ

One of the most sensitive channels for constraining extended Higgs sectors

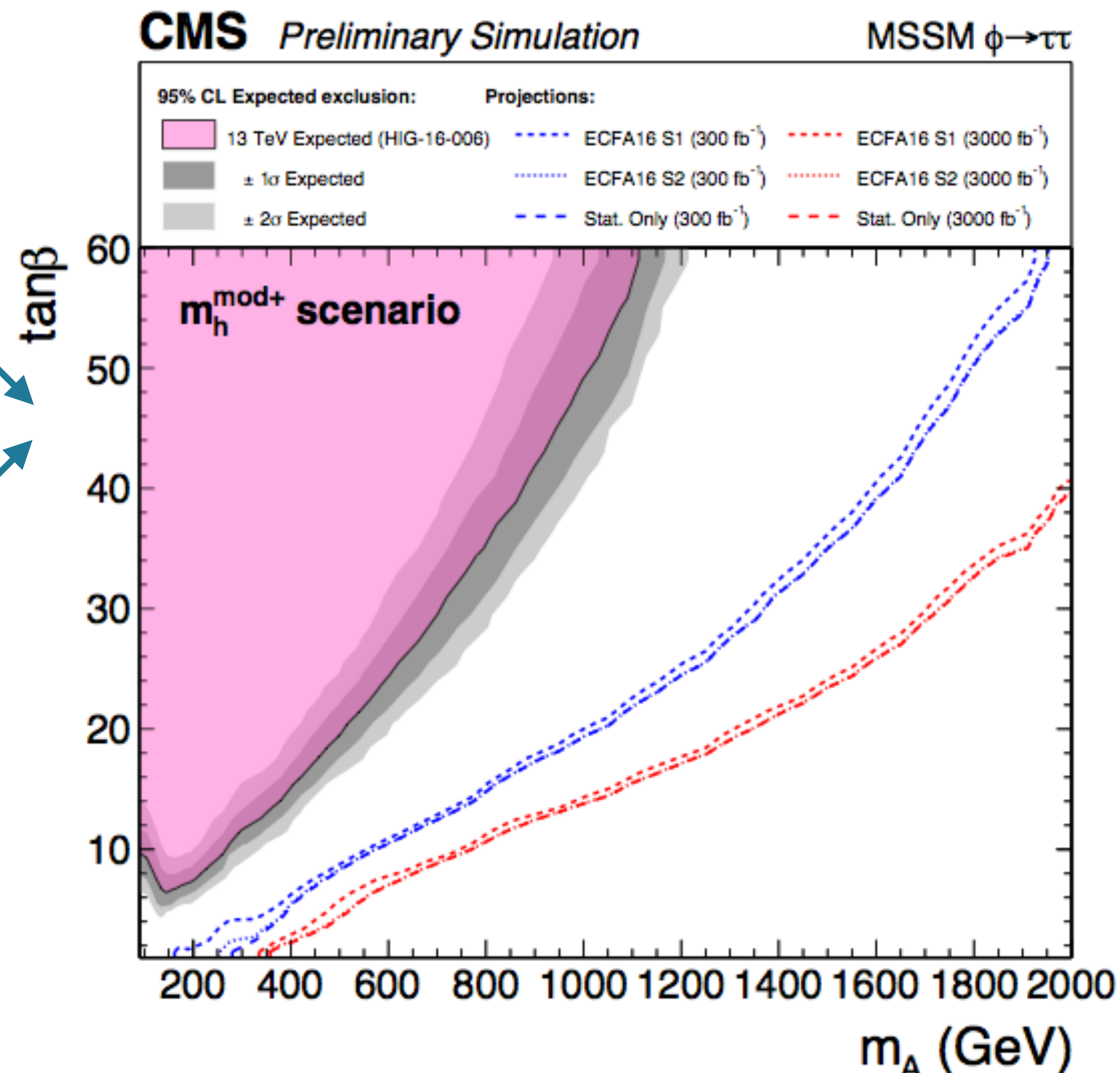
Cross sections limits





Model dependent limits

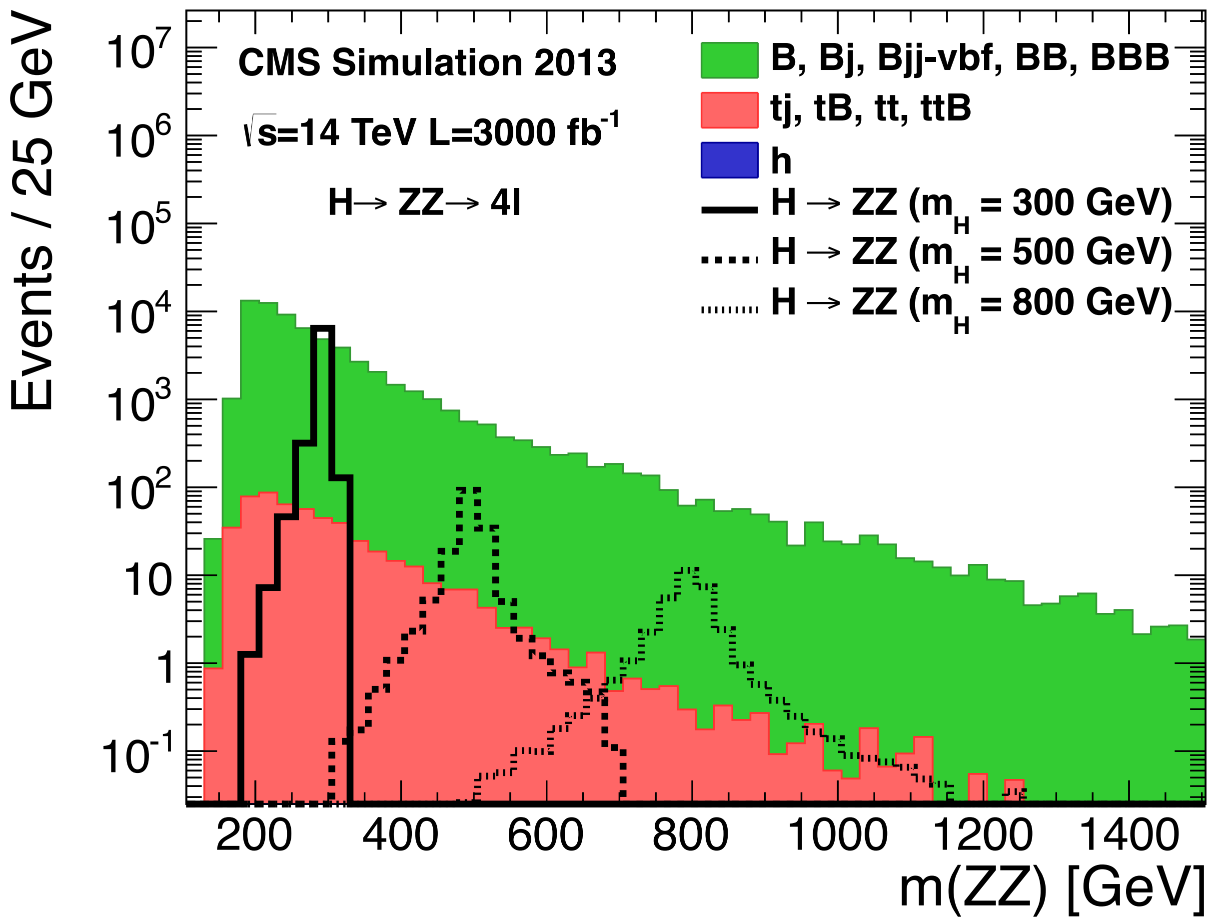
Sensitivity at high m_A still dominated by statistics



IV

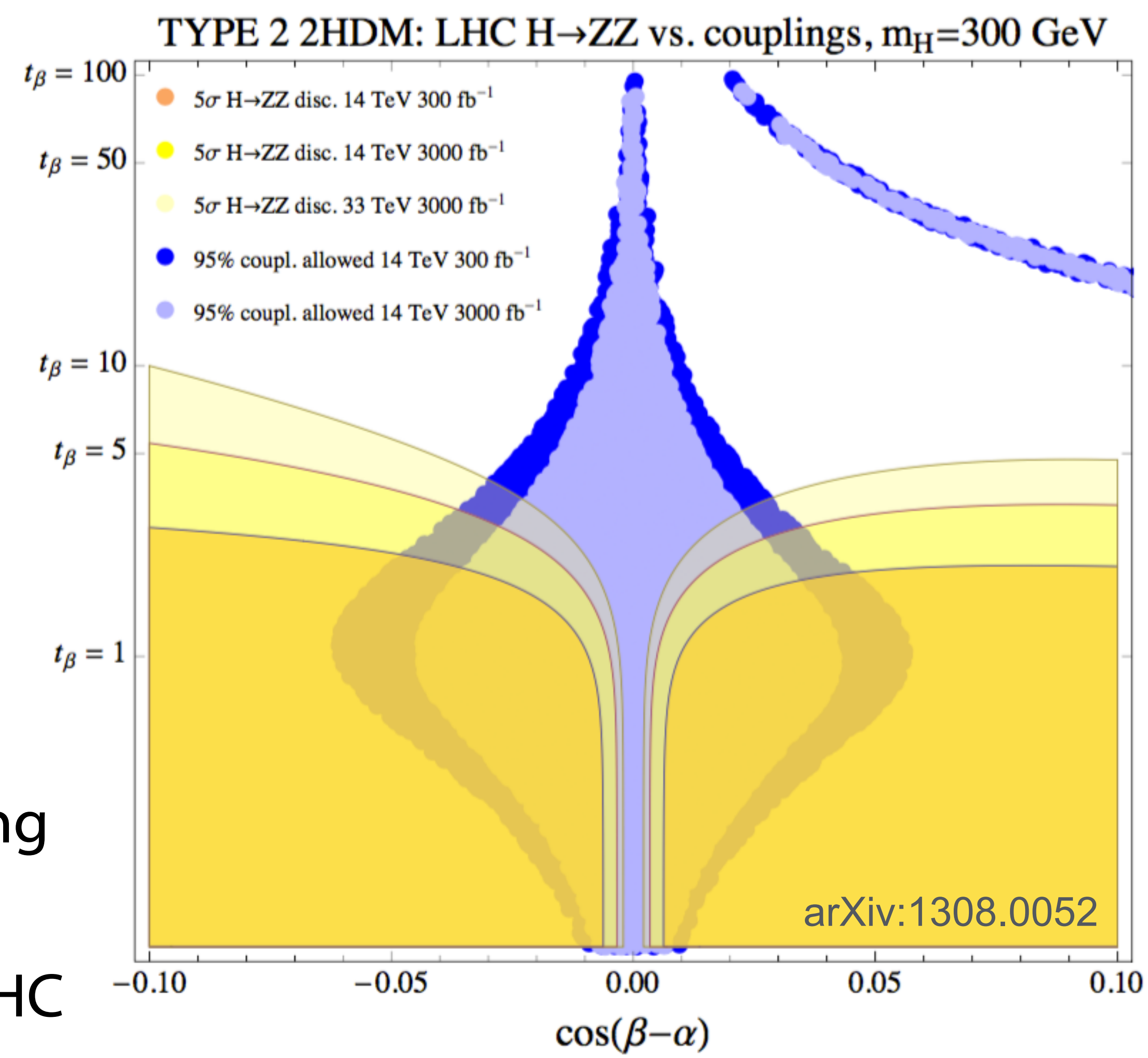
Search for additional Higgs bosons : H → ZZ

Potential to exclude or discover heavy (scalar/pseudo-scalar) neutral Higgs bosons in the context of 2HDM



Regions allowed at 95%CL by very constraining precision Higgs coupling measurements

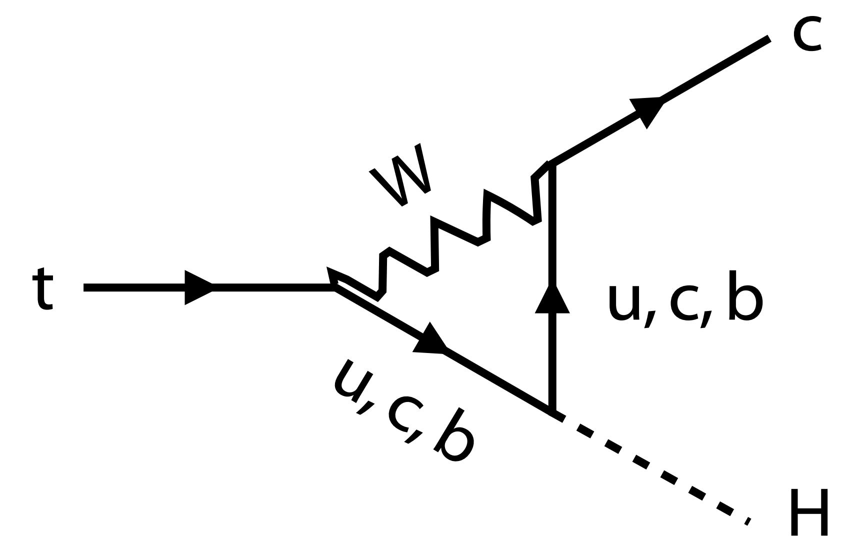
5σ discovery reach in direct searches at the LHC for a 300 GeV H decaying via H→ZZ→4l for the Type II 2HDM, this probes significant additional parameter space



Type-II model includes supersymmetry

FCNC in t →qH

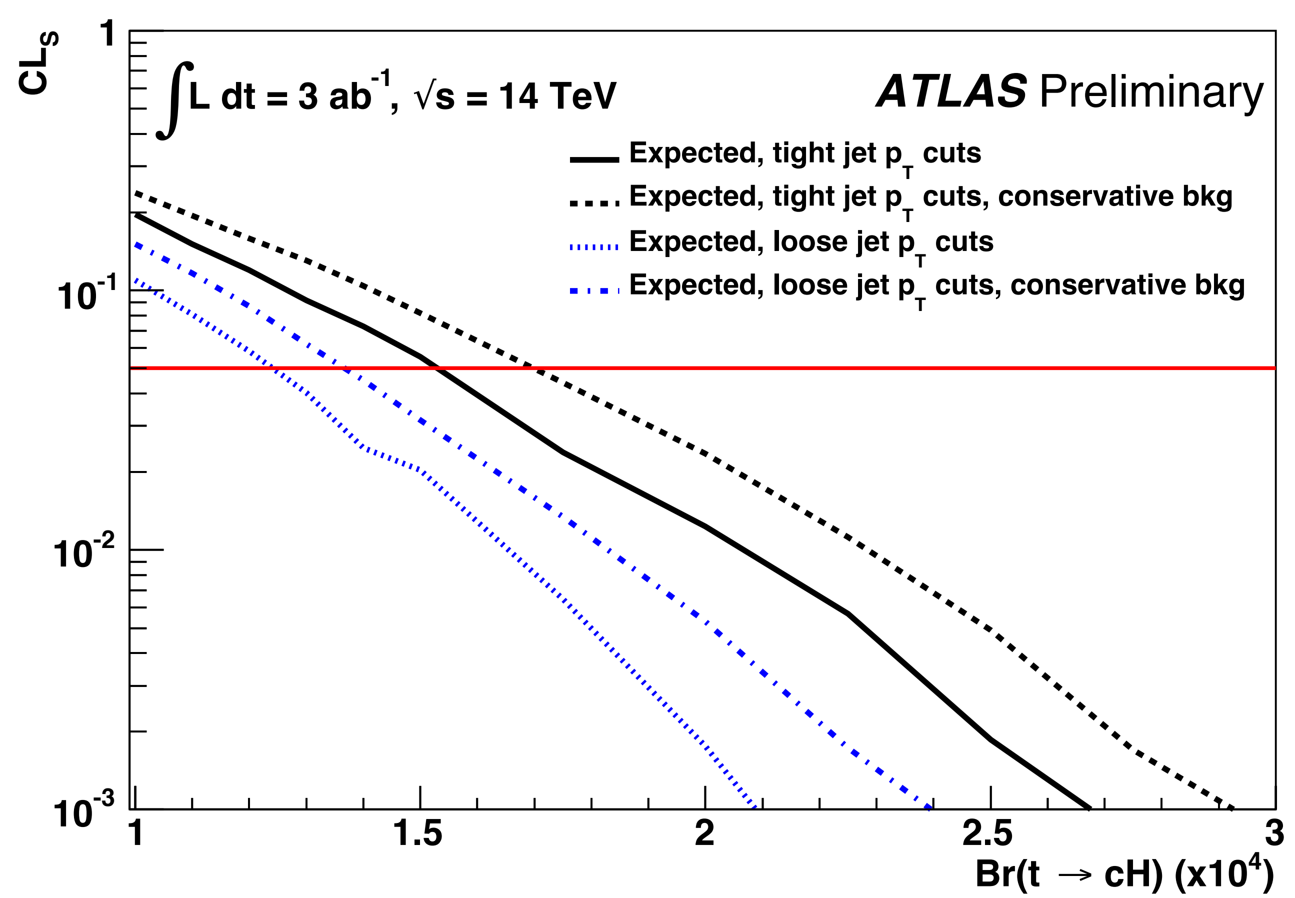
Higgs-induced flavour-changing neutral currents (FCNC) can be probed with rare top decays



In SM FCNC processes are forbidden at tree level and strongly suppressed at higher order due to GIM mechanism : $BR_{t\to cH} \sim 3\times10^{-15}$

$BR_{t\to cH}$ up to 10^{-5} in various BSM models (and up to 1.5×10^{-3} in 2HDM type III)

Evolution of CL_s as a function of BR for the expectation in the absence of signal



Conclusions

The Higgs boson is the first fundamental scalar that we have discover with only <0.1% of the final HL-LHC integrate luminosity

In the next years the Higgs physics program will be super dense
-> precision measurements
-> rare processes
-> BSM searches in the scalar sector