Experimental summary/conclusion of Higgs Hunting 2016

Marco Pieri
University of California San Diego

Higgs Hunting 2016

Paris, August 31st – September 2nd 2016

Outline

- Introduction
- SM-like Higgs measurements
- BSM Higgs bosons and decays
- Future perspectives
- Summary and outlook

Disclaimers

- I will not put emphasis on Run 1 results that were available since more than one year
  - We had quite some time to discuss them
- Will report the many latest results based on 13 TeV data
- We had very nice Young Scientist's talks that I will not be able to cover

- **Apologies for the contributions I may miss or not well represent**

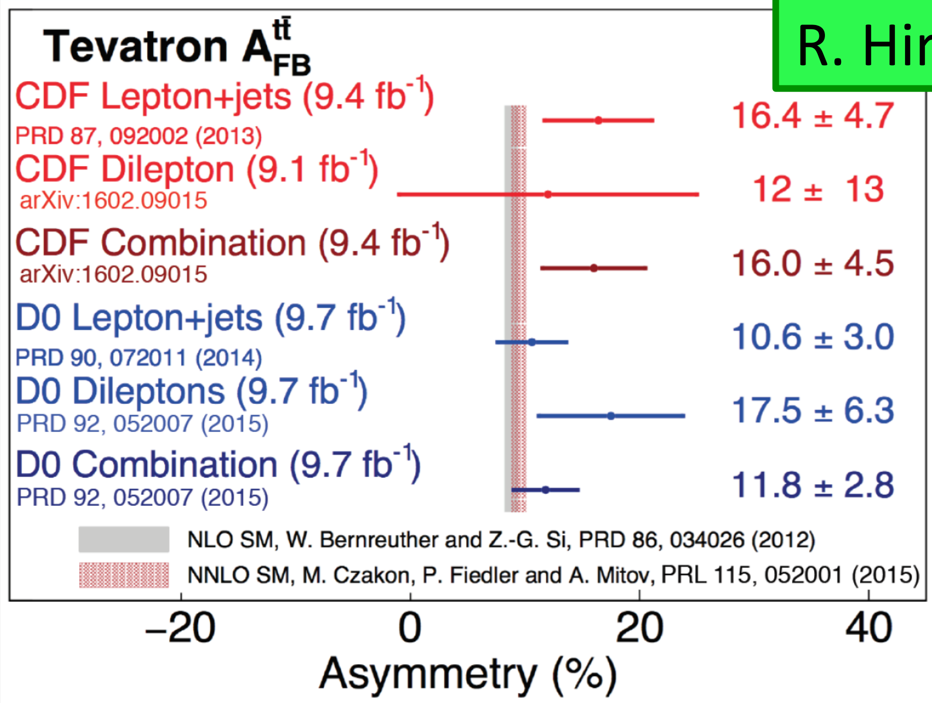
Tevatron

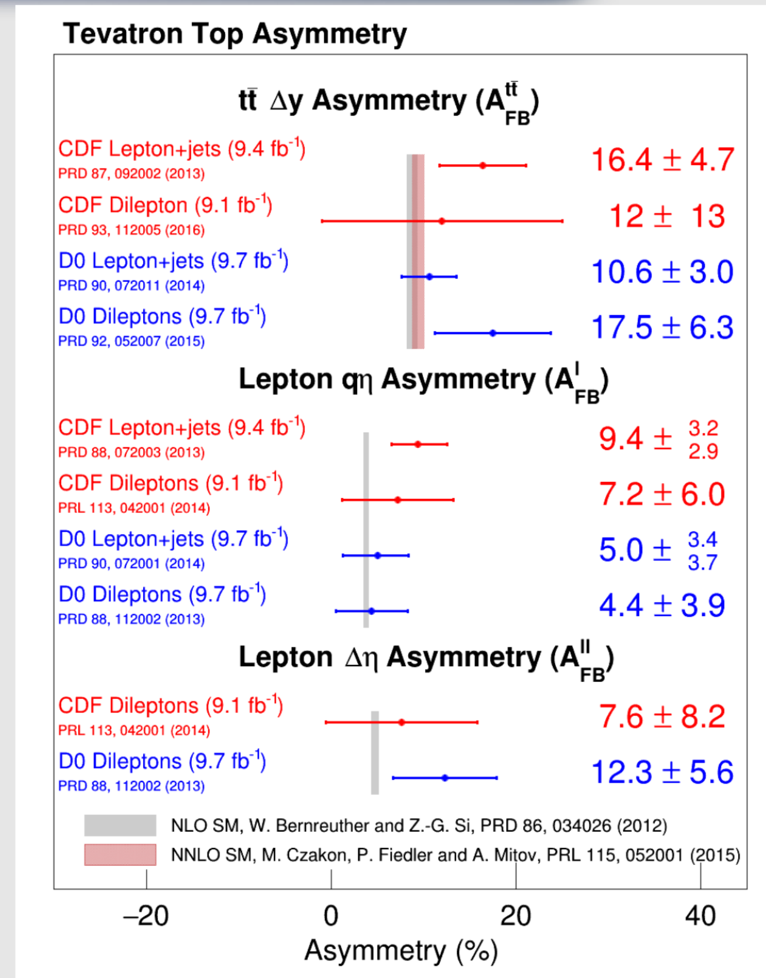
R. Hirosky

- Still carrying out precision measurements
  - New Tevatron top mass combined measurement updating 2014 result: M_t=174.30 ± 0.35 (stat) ± 0.54 (syst) GeV
  - Working on update of W mass
  - Continues to investigate on the excess reported in the measurement of tt A_{FB}

$t\bar{t}$ asymmetries at Tevatron

R. Hirosky

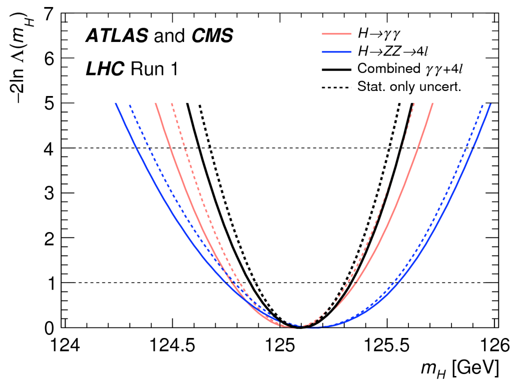


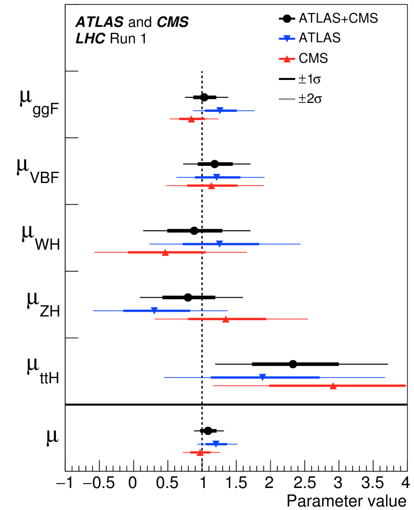


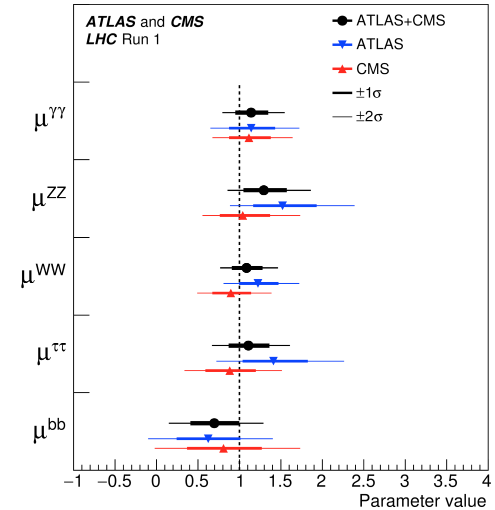
- Overall agreement with SM
- **Legacy Tevatron combination is underway**

Run 1 Results

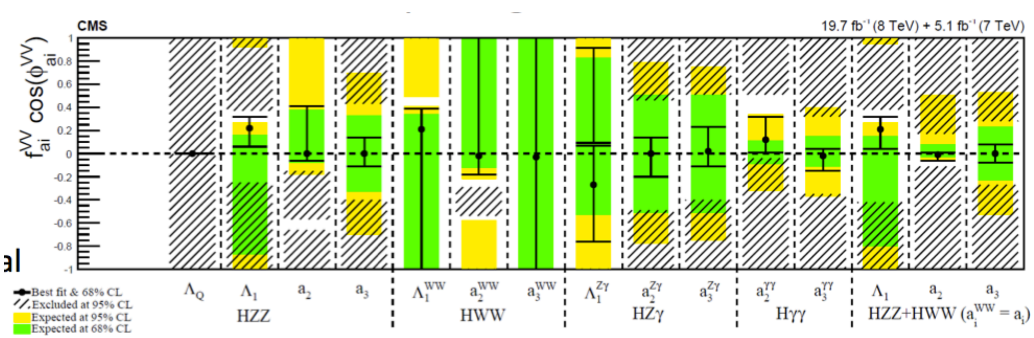
- Only recall the combined ATLAS + CMS results here (talk of **P. Francavilla**): mass and couplings

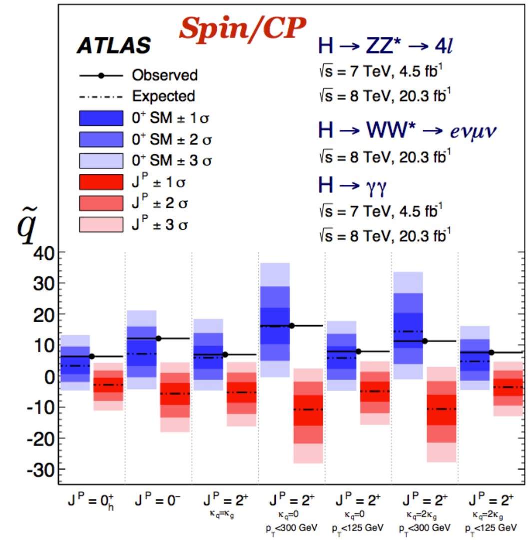






- Many more results from Run 1 on:
  - SM-like Higgs-CP studies





  - All measurements agree with the SM
  - BSM Higgs (additional Higgs bosons and decays)
    - Also no hints of any statistically significant excess

ATLAS + CMS final Run 1 results: mass

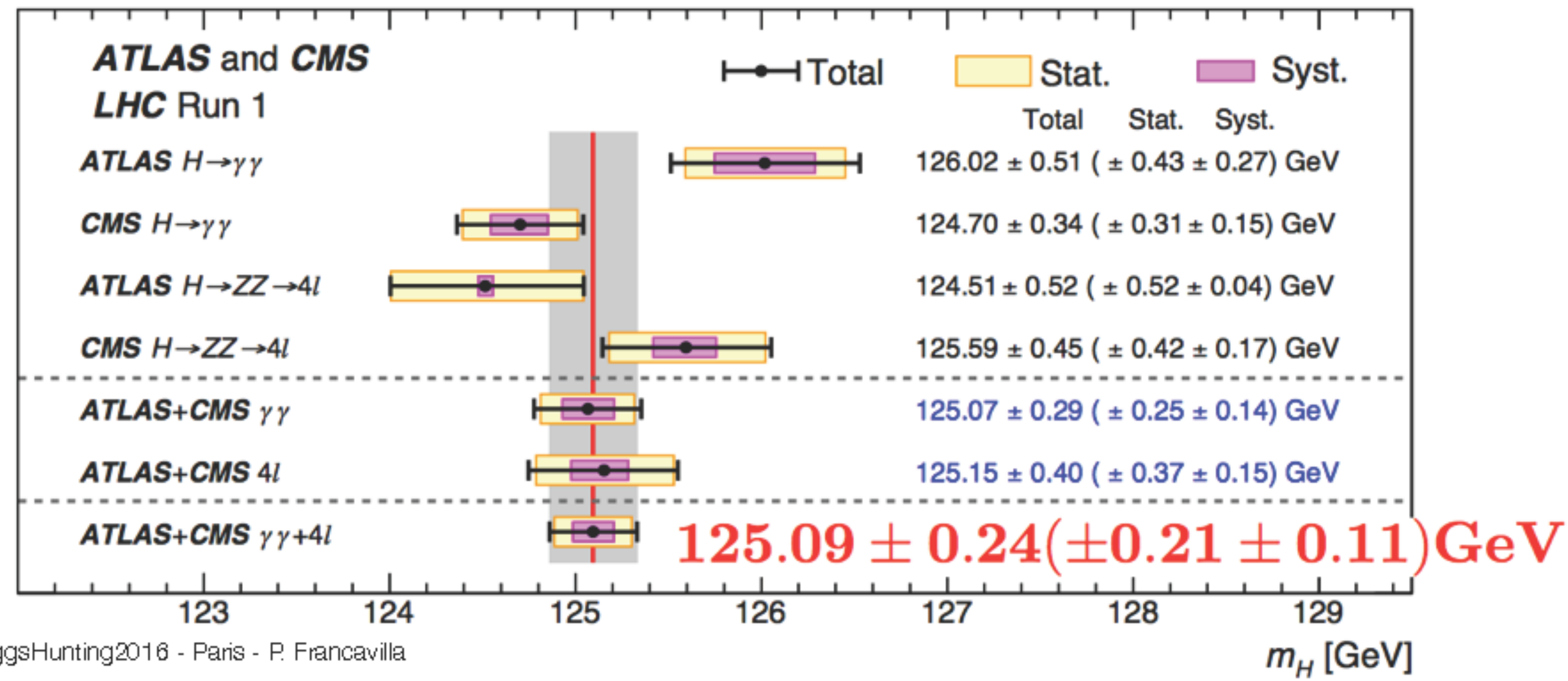
Measurement of the Higgs boson mass

P. Francavilla

- Mass of Higgs boson measured with <0.2% precision

PRL 114 (2015) 191803

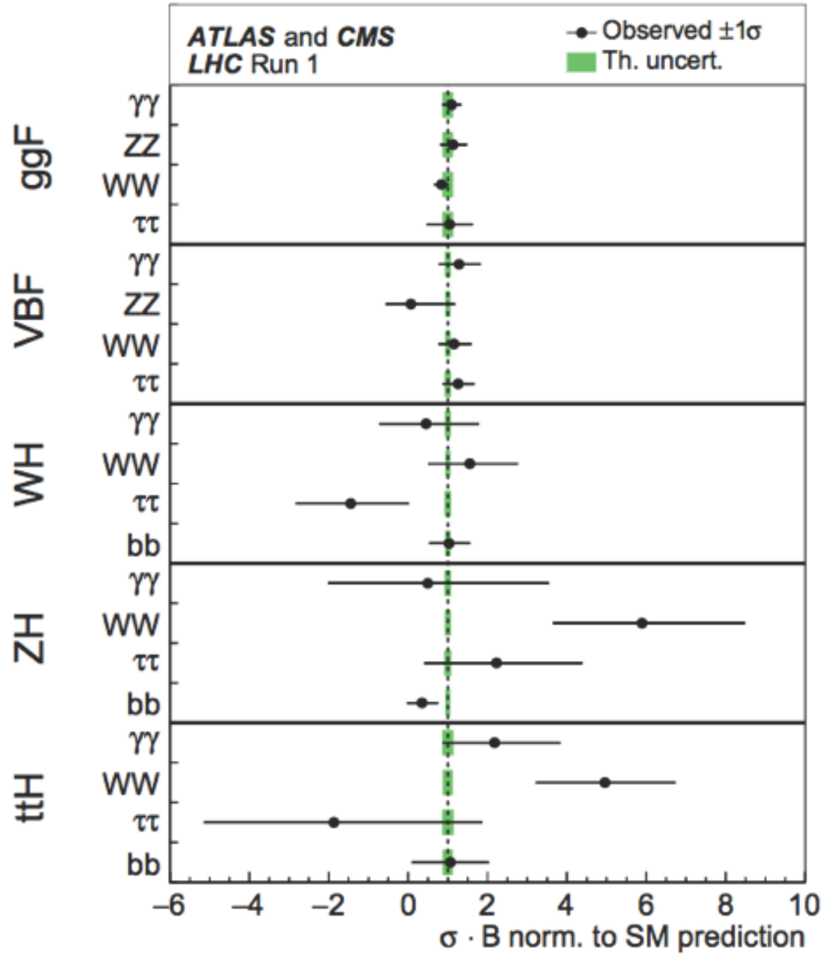
- MH = 125.09 ± 0.24 GeV [±0.21 (stat.) ±0.11(syst.)]
- Dominant systematics: energy or momentum scale and resolution for γ,e,μ

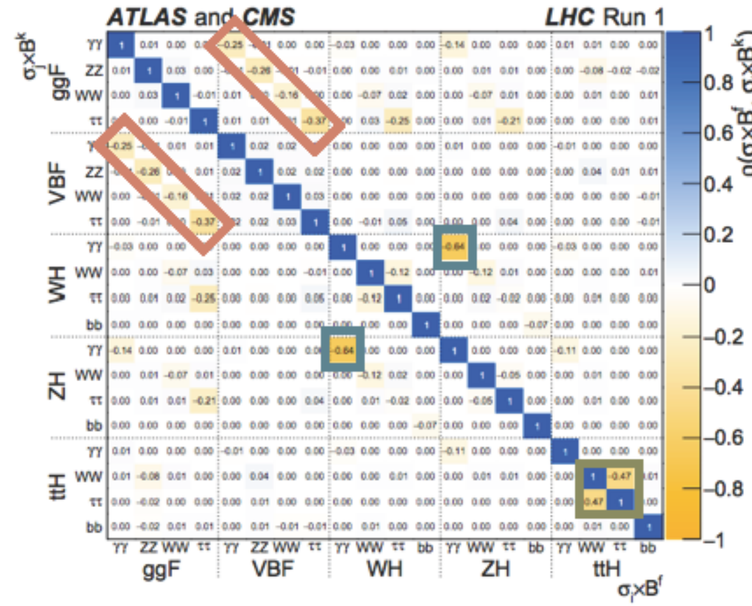


ATLAS + CMS final Run 1 results: couplings

JHEP 08 (2016) 045

P. Francavilla





- As expected, correlations due to signal mix of production modes in the analysis categories:
  - ggF VS VBF or WH VS ZH in H→γγ;
- and decay modes:
  - ττ VS WW in ttH

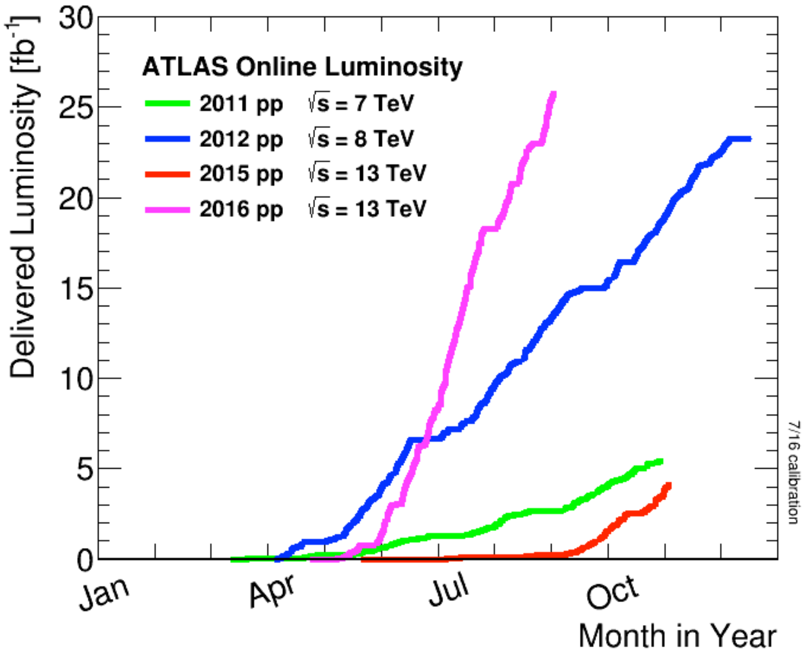
HiggsHunting2016 - Paris - P. Francavilla 13

With central values and covariance matrix it is possible to derive in an approximate way all other results

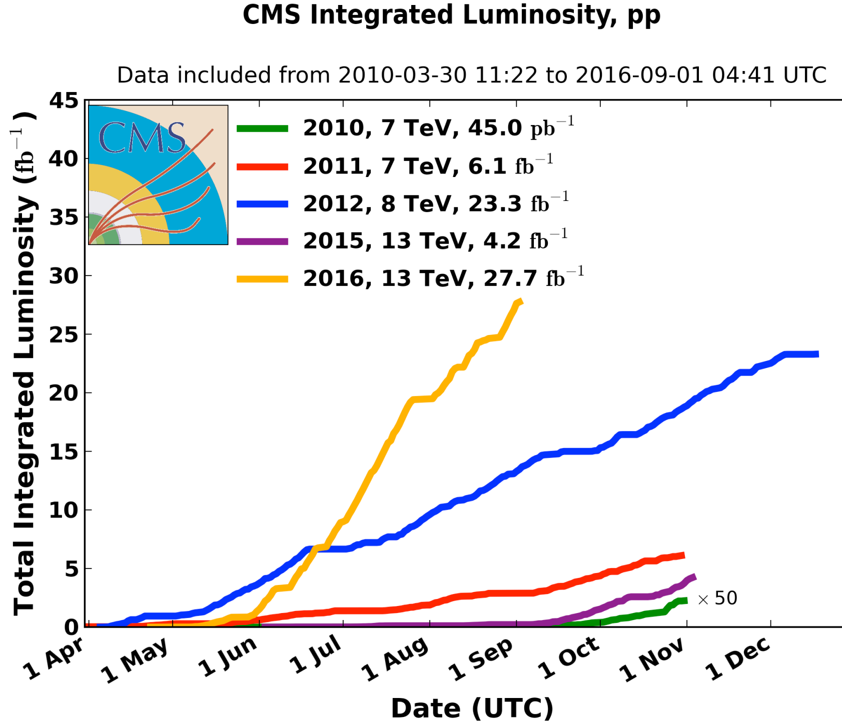
LHC is performing wonderfully in 2016

- Instantaneous luminosity same or more than expected
- Already delivered more than 25 fb^{-1} per experiment

ATLAS



CMS



Max instantaneous luminosity 1.2-1.3 x 10^{34} $cm^{-2}s^{-1}$

Status of main Higgs decay channels

- Almost all results of Run 1 are published
- Most of Run 2 results are preliminary and more work is needed to finalize them

Run 1: 7 – 8 TeV

Decay / Production	Untagged	VBF	VH	ttH
$H \rightarrow \gamma\gamma$	Done	Done	Done	Done
$H \rightarrow ZZ \rightarrow 4l$	Done	Done	Not done	Done
$H \rightarrow WW \rightarrow 2l2\nu$	Done	Done	Done	Done
$H \rightarrow \tau\tau$	Done	Done	Done	Done
$H \rightarrow bb$	Not done	Done	Done	Done
$H \rightarrow \mu\mu$	Done	Done	Not done	Not done
$H \rightarrow Z\gamma$	Done	Done	Not done	Not done
$H \rightarrow$ Invisible	Done	Done	Done	Not done

Green	Done
White	Not done

Run 2: 13 TeV

Decay / Production	Untagged	VBF	VH	ttH
$H \rightarrow \gamma\gamma$	A+C	A+C	Only A	A+C
$H \rightarrow ZZ \rightarrow 4l$	A+C	A+C	A+C	A+C
$H \rightarrow WW \rightarrow 2l2\nu$	Only CMS (2015)	Only CMS (2015)		A+C
$H \rightarrow \tau\tau$				A+C
$H \rightarrow bb$			Only A	C 2015
$H \rightarrow \mu\mu$	Only A	Only A		
$H \rightarrow Z\gamma$				
$H \rightarrow$ Invisible	Only C	Only C	Only C	

Green	2016 13 TeV data at least 1 exp
Yellow	2015 13 TeV data at least 1 exp
White	13 TeV data not used yet

Measurements of the SM-like Higgs boson

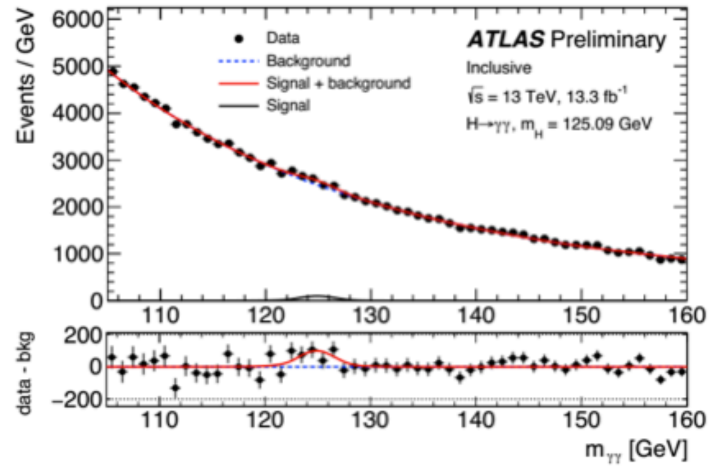
ATLAS H→γγ 13 TeV fiducial cross sections

Y. Wu

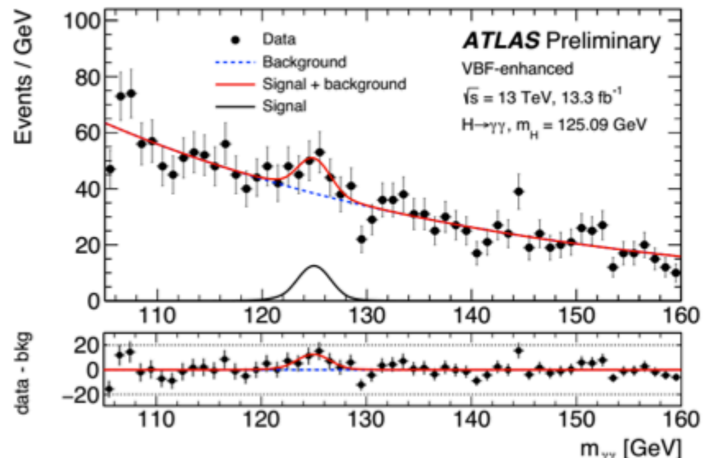
	diphoton baseline	VBF enhanced	single lepton
Photons	$\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.37$ $p_T^{\gamma_1} > 0.35\, m_{\gamma\gamma}$ and $p_T^{\gamma_2} > 0.25\, m_{\gamma\gamma}$		
Jets	- - -	$p_T > 30\,\text{GeV}$, $\lvert y\rvert < 4.4$ $m_{jj} > 400\,\text{GeV}$, $\lvert\Delta y_{jj}\rvert > 2.8$ $\lvert\Delta\phi_{\gamma\gamma,jj}\rvert > 2.6$	- - -
Leptons	-	-	$p_T > 15\,\text{GeV}$ $\lvert\eta\rvert < 2.47$

Fiducial region	Measured cross section (fb)	SM prediction (fb)	
Baseline	43.2 ± 14.9 (stat.) ± 4.9 (syst.)	$62.8^{+3.4}_{-4.4}$	[N³LO + XH]
VBF-enhanced	4.0 ± 1.4 (stat.) ± 0.7 (syst.)	2.04 ± 0.13	[NNLOPS + XH]
single lepton	1.5 ± 0.8 (stat.) ± 0.2 (syst.)	0.56 ± 0.03	[NNLOPS + XH]

Diphoton baseline region



VBF enhanced region

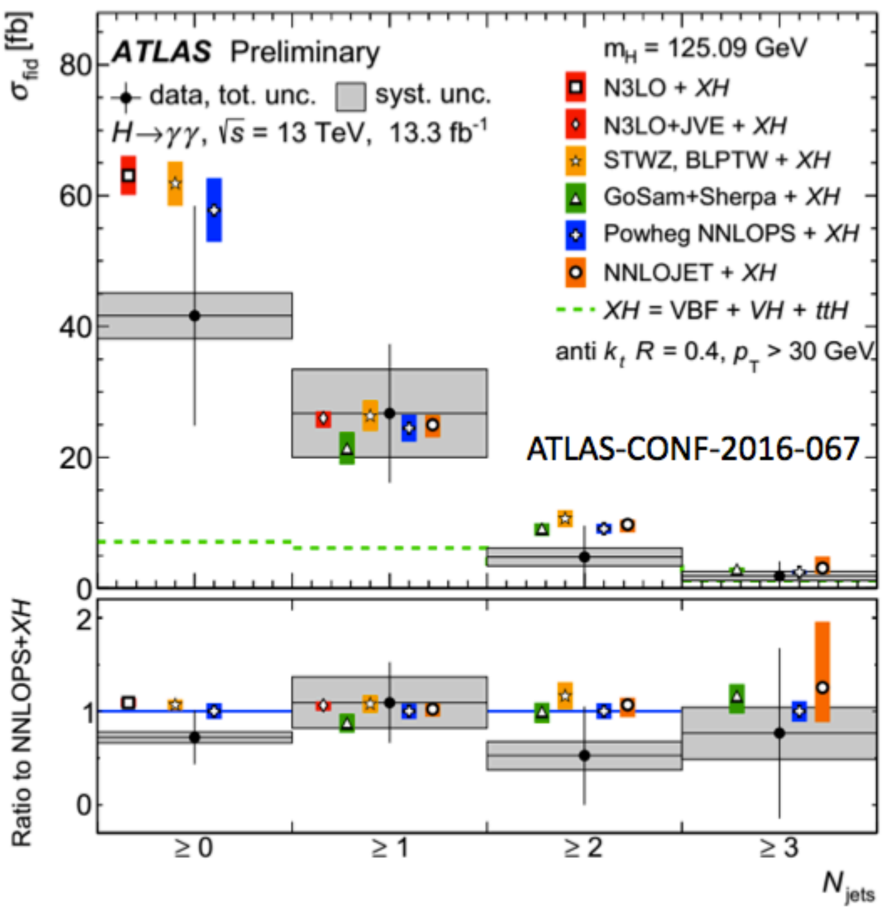


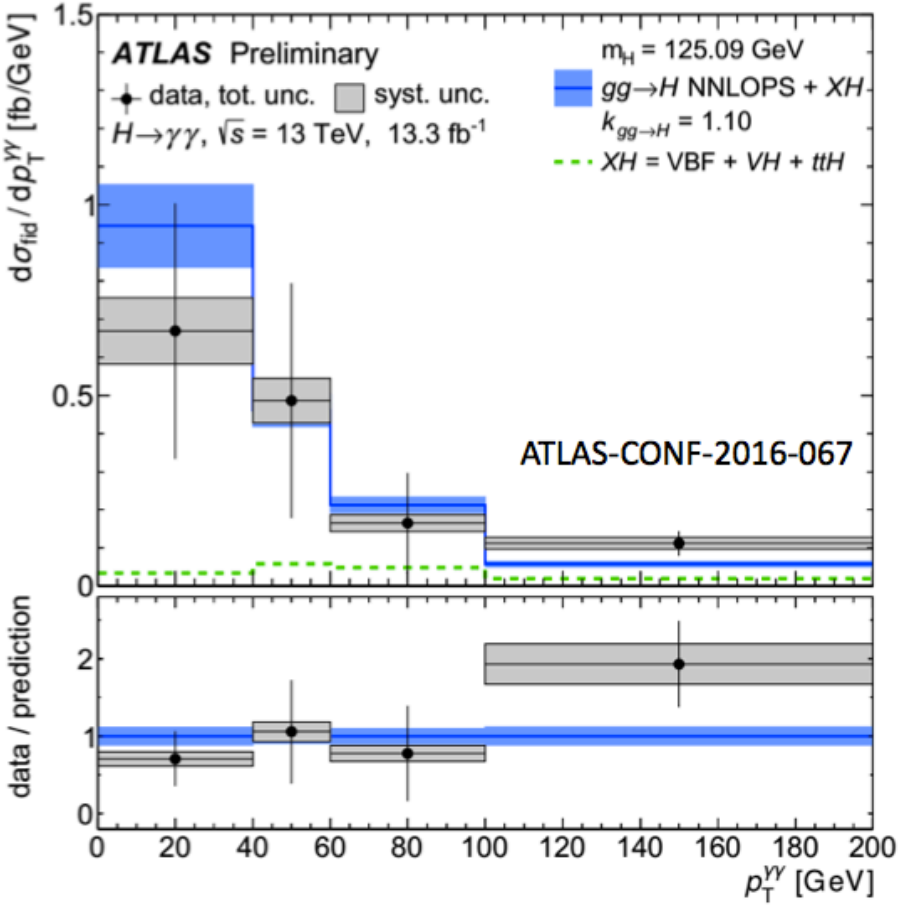
ATLAS-CONF-2016-067

ATLAS H→γγ 13 TeV differential distributions

Y. Wu

- In diphoton baseline region

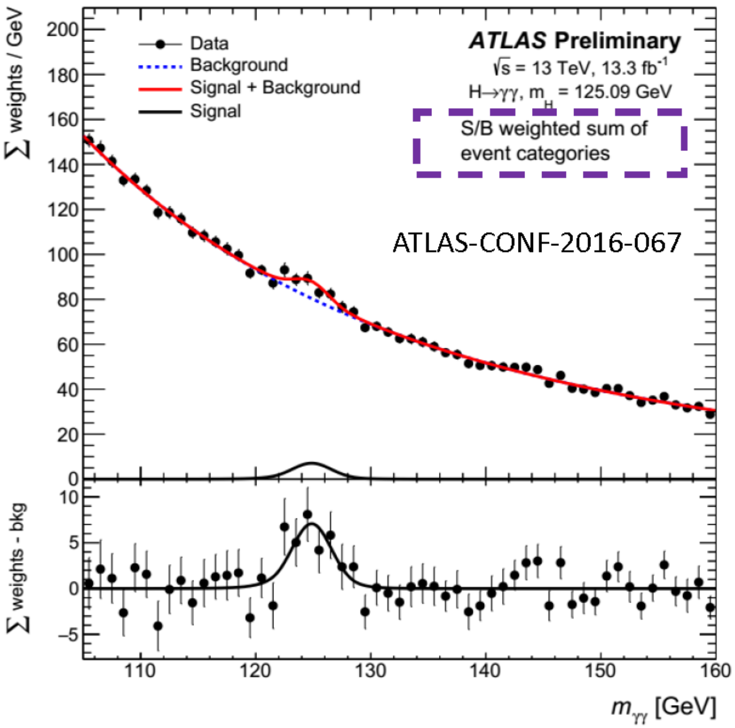


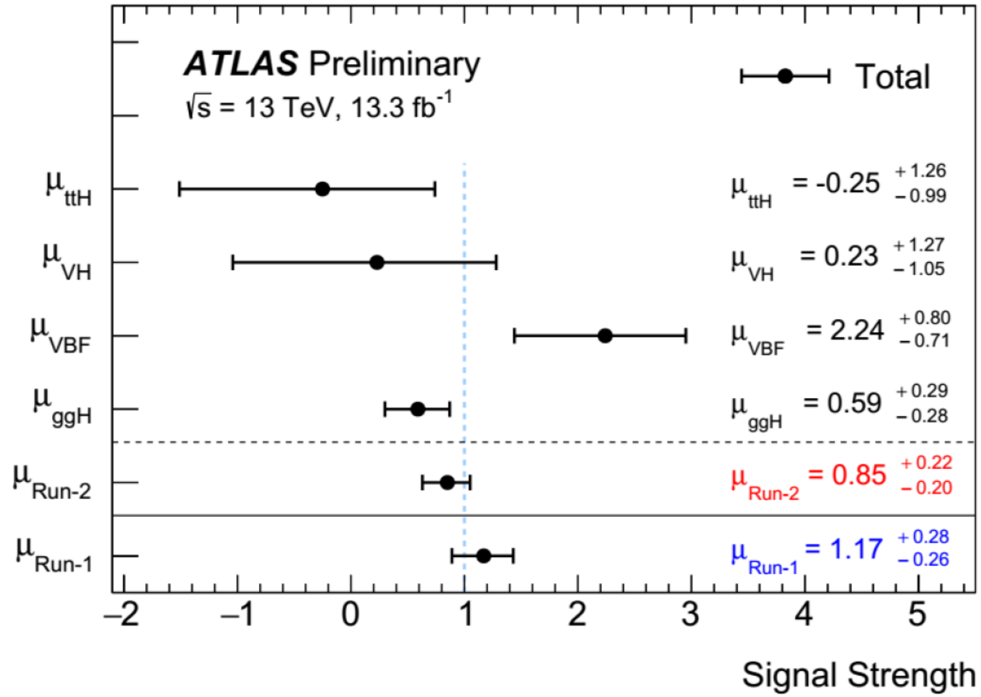


ATLAS H→γγ 13 TeV signal strengths

Y. Wu

Main sensitivity from high-pT ggF and VBF categories





Total observed (expected) detection significance of H->γγ is about 4.7 (5.4) σ

Comparable to Run I significance*: 5.0 (4.6) σ

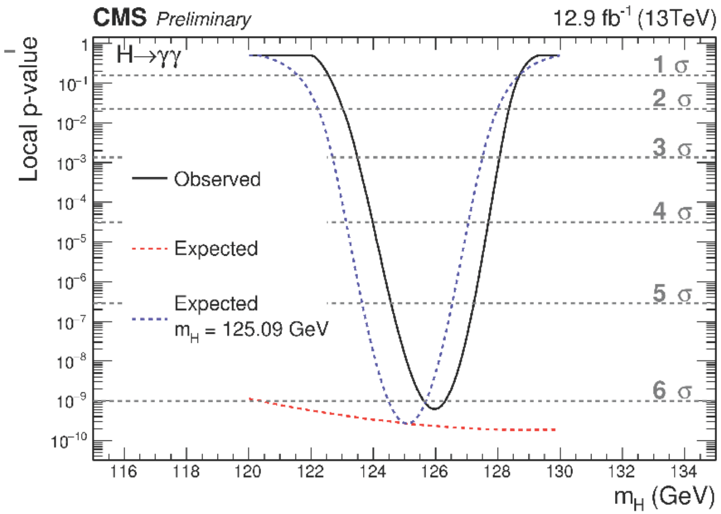
* JHEP 08 (2016) 045

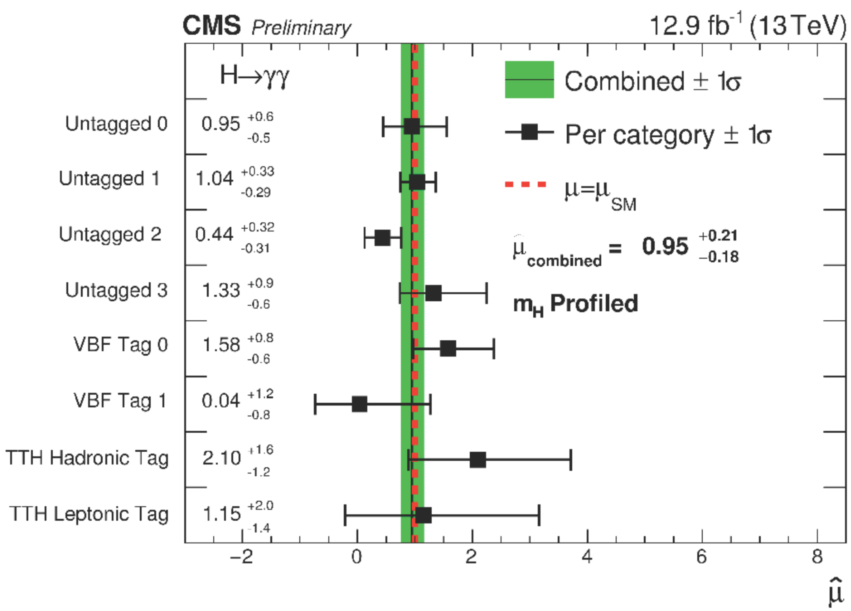
CMS H→γγ

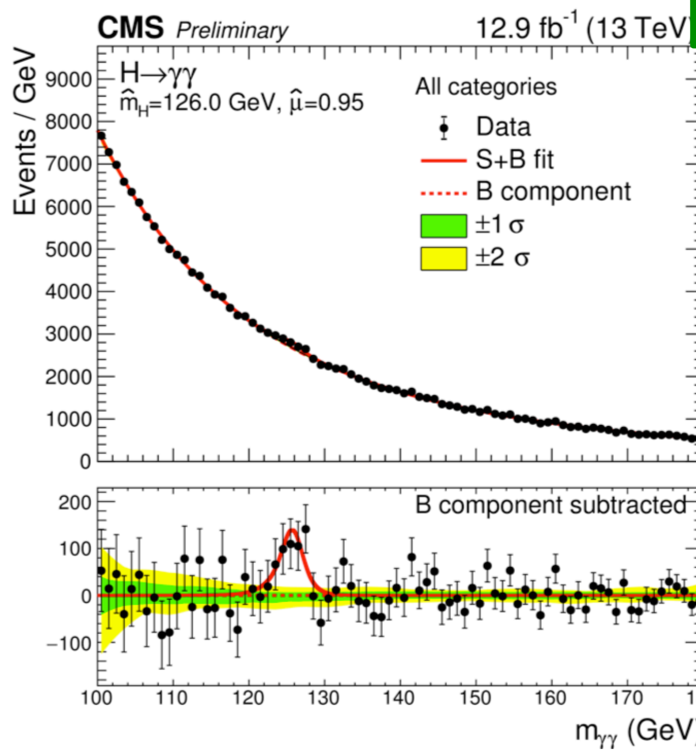
- Significance @ 125.09 GeV: 5.6σ observed (6.2σ expected)
- Maximum observed significance is 6.1σ at 126.0 GeV
- Best-fit signal strength @ 125.09 GeV:

$$\sigma_{obs}/\sigma_{SM} = 0.91 \pm 0.20 = 0.91 \pm 0.17\,(\text{stat.})\ ^{+0.09}_{-0.07}\,(\text{syst.})\ ^{+0.08}_{-0.05}\,(\text{theo.})$$

A. Calderon, L. Corpe







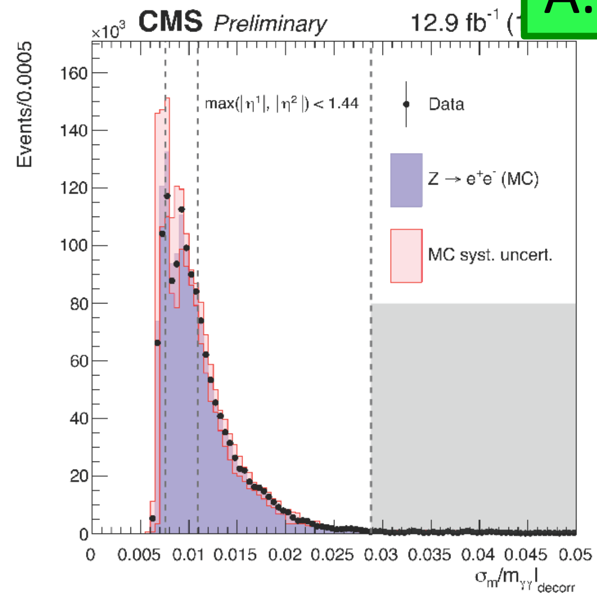
30 $^{+0.14}_{-0.18}$

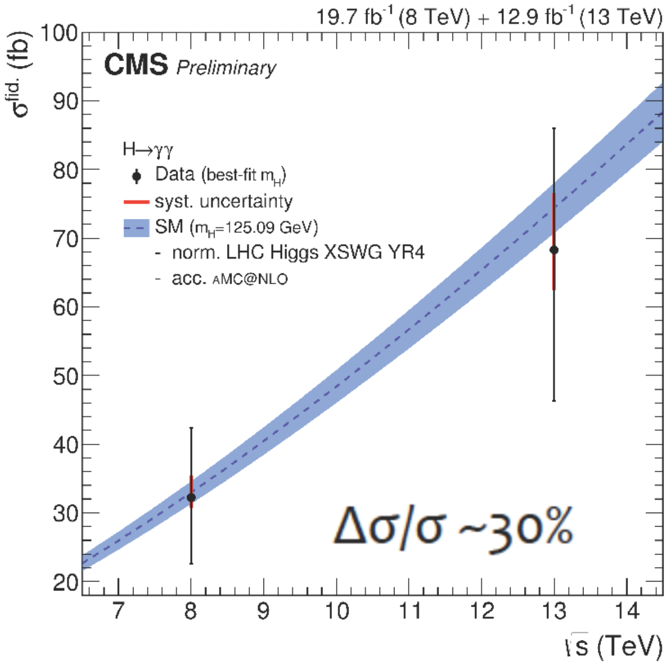
59 $^{+0.73}_{-0.45}$

CMS H→γγ fiducial cross section

A. Calderon

- Different event categorization: 3 mass resolution categories.
- Event yields corrected for detector inefficiency and resolution
  - Minimal dependence on theoretical modeling





- Fiducial cross section measured profiling m_H

$$\hat{\sigma}_{fid} = 69^{+18}_{-22}\text{fb} = 69^{+16}_{-22}(\text{stat.})^{+8}_{-6}(\text{syst.})\text{fb}$$

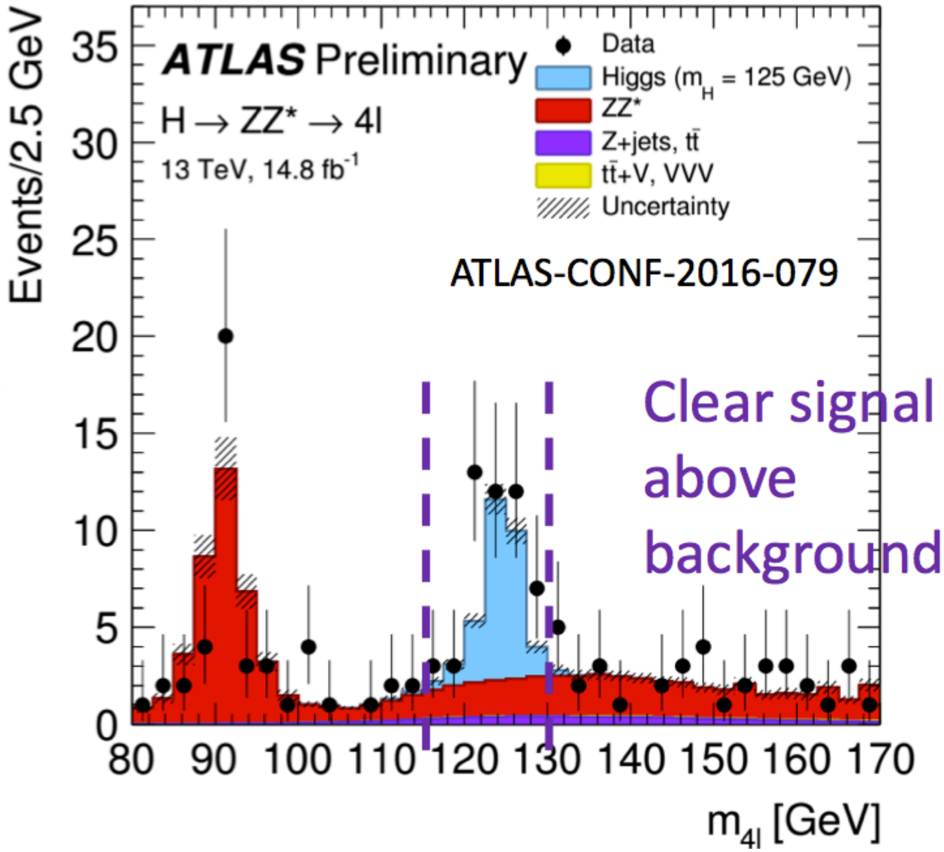
- Theoretical prediction for m_H=125.09 GeV

$$\hat{\sigma}_{fid} = 73.8 \pm 3.8 \text{ fb}$$

6

ATLAS H→ZZ→4l 13 TeV

Y. Wu



Fiducial and total cross-sections for pp→H with mH=125.09 GeV

Measured	Predicted
$\sigma^{4\ell}_{\text{fid,comb}} = 4.54^{+1.02}_{-0.90}$ fb	$\sigma^{4\ell}_{\text{fid,SM}} = 3.07^{+0.21}_{-0.25}$ fb [1)]
$\sigma_{\text{tot}} = 81^{+18}_{-16}$ pb	$\sigma_{\text{tot,SM}} = 55.5^{+3.8}_{-4.4}$ pb

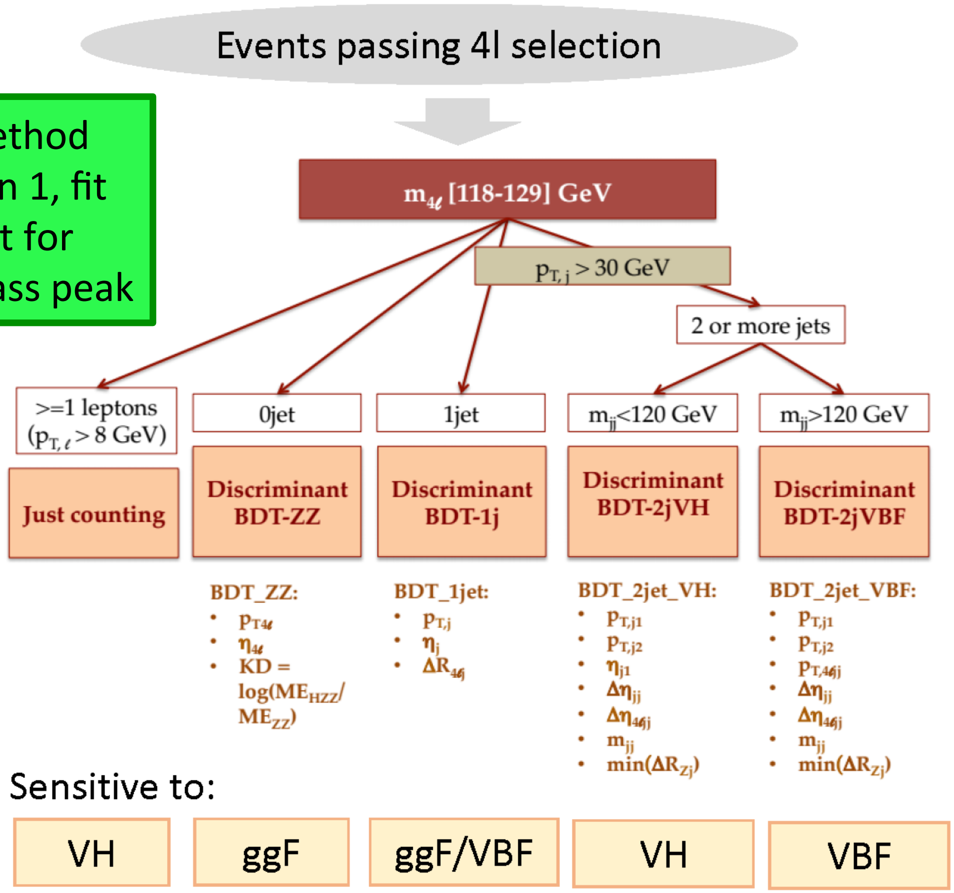
- Measured σ higher than SM prediction
- Total uncertainty O(20%), dominated by the data statistical unc.

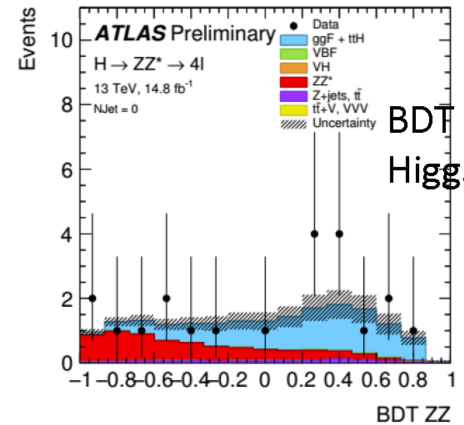
ATLAS H→ZZ→4l 13 TeV

ATLAS-CONF-2016-079

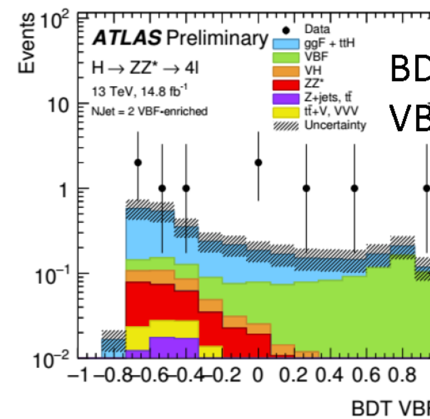
Y. Wu

New analysis method compared to Run 1, fit BDT discriminant for events in the mass peak





BDT in 0j: Higgs v.s. ZZ



BDT in VBF: VBF v.s. ggF

Measured

$$\sigma_{ggF+b\bar{b}H+t\bar{t}H} \cdot \mathcal{B}(H \to ZZ^*) = 1.80^{+0.49}_{-0.44}\ \text{pb}$$

$$\sigma_{VBF} \cdot \mathcal{B}(H \to ZZ^*) = 0.37^{+0.28}_{-0.21}\ \text{pb}$$

$$\sigma_{VH} \cdot \mathcal{B}(H \to ZZ^*) = 0^{+0.15}\ \text{pb}$$

Predicted

$$\sigma_{SM,ggF+b\bar{b}H+t\bar{t}H} \cdot \mathcal{B}(H \to ZZ^*) = 1.31 \pm 0.07\ \text{pb}$$

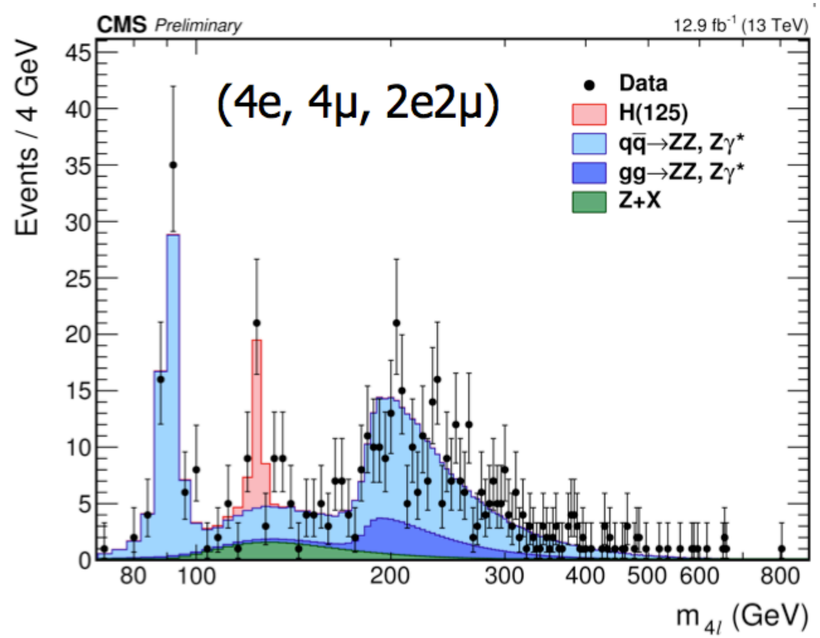
$$\sigma_{SM,VBF} \cdot \mathcal{B}(H \to ZZ^*) = 0.100 \pm 0.003\ \text{pb}$$

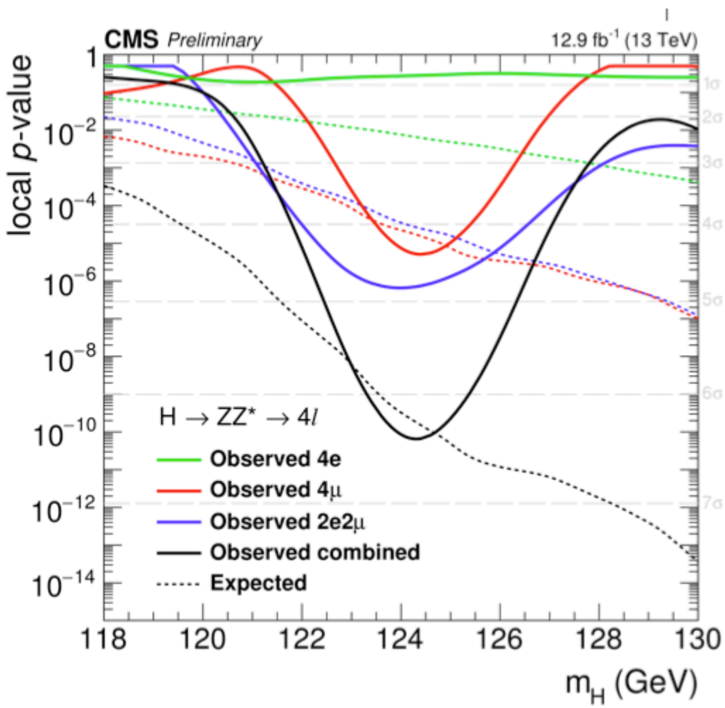
$$\sigma_{SM,VH} \cdot \mathcal{B}(H \to ZZ^*) = 0.059 \pm 0.002\ \text{pb}$$

CMS H→ZZ→4l 13 TeV

A. Calderon

- Similar analysis strategy as Run 1
  - Kinematic discriminant: M_{Z1}, M_{Z2}, 5 angles from decay chain, matrix element, used to enhance the signal purity of different production modes
  - Extraction of signal through 2D fit of m4l and the discriminant gg/qq (D^{kin}_{bkg})





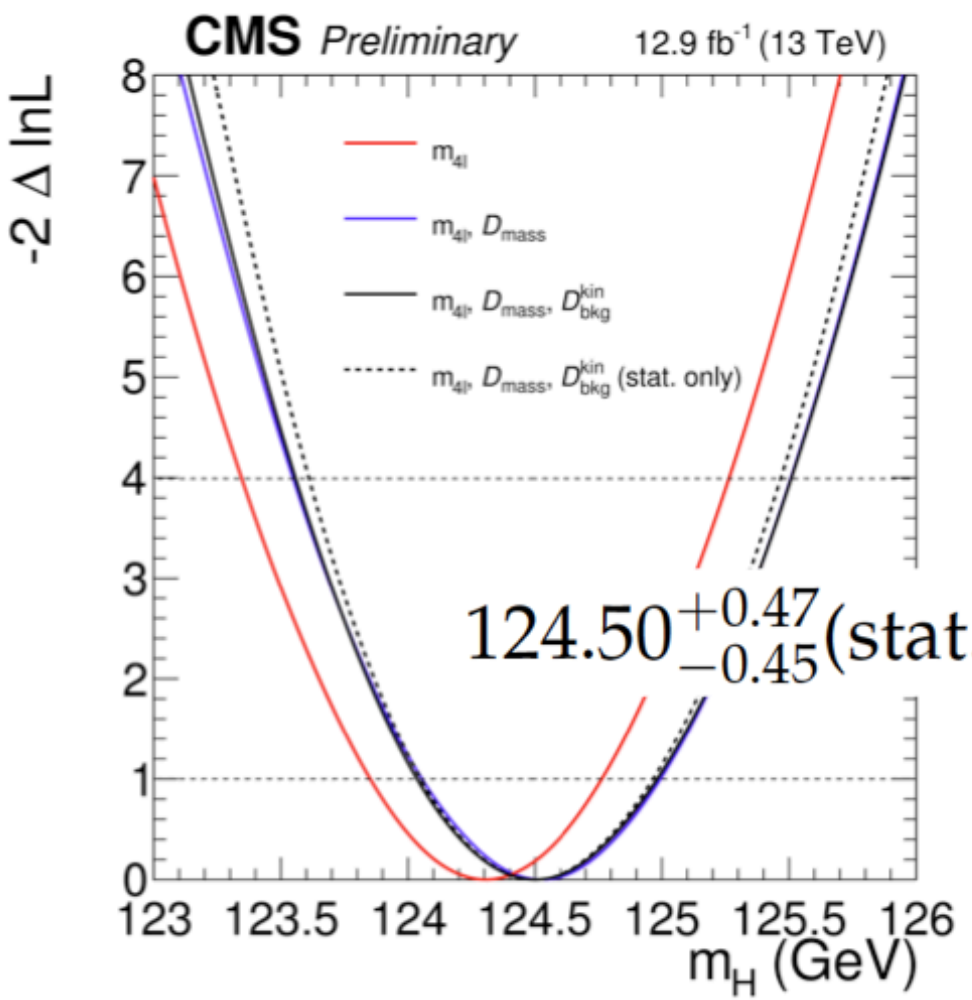
Maximum observed significance is 6.4σ at 124.3 GeV

Best-fit signal strength @ 125.09 GeV:

$$\mu = \sigma/\sigma_{SM} = 0.99^{+0.33}_{-0.26}$$

- First Higgs boson mass measurement at 13 TeV

A. Calderon



$$124.50^{+0.47}_{-0.45}(\text{stat.})^{+0.13}_{-0.11}(\text{sys.})$$

7

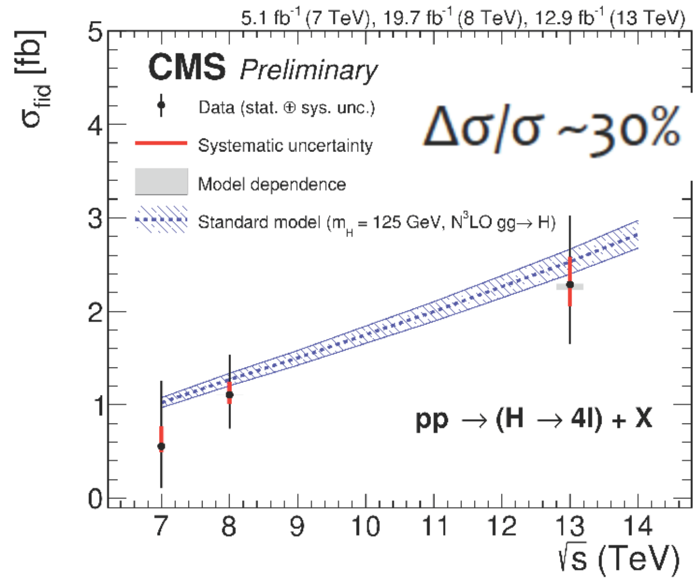
CMS H→ZZ→4l 13 TeV

A. Calderon

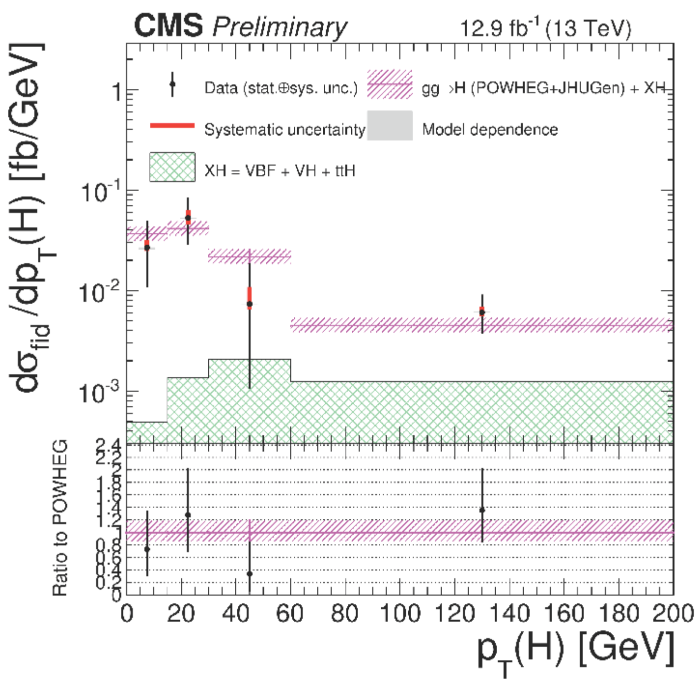
- Fiducial volume closely matches reconstruction level
  - Minimal dependence on theoretical modeling
- Maximum likelihood fit to the uncategorized m_{4l} distribution, assuming m_H = 125.0 GeV

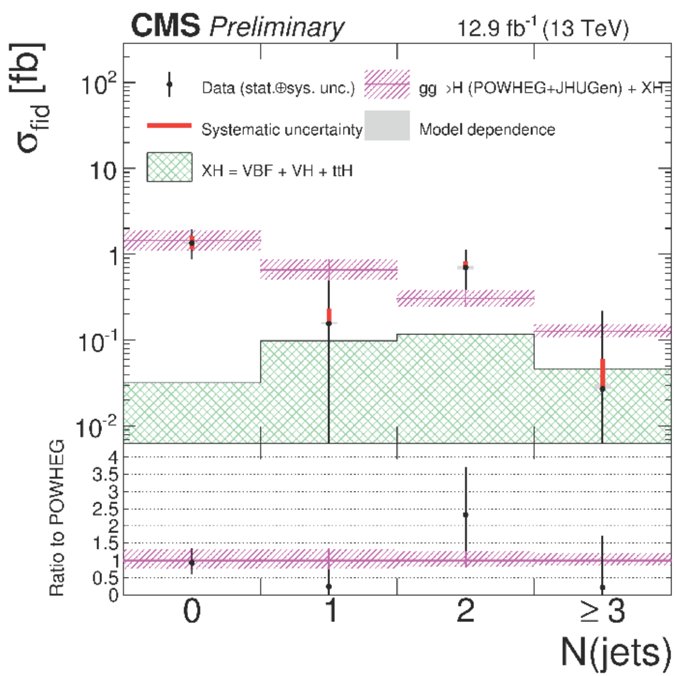
$$\sigma_{\text{fid.}} = 2.29^{+0.74}_{-0.64}(\text{stat.})^{+0.30}_{-0.23}(\text{sys.})^{+0.01}_{-0.05}(\text{model dep.})\ \text{fb}$$

SM prediction: $\sigma^{\text{SM}}_{\text{fid.}} = 2.53 \pm 0.13$ fb



Δσ/σ ~30%





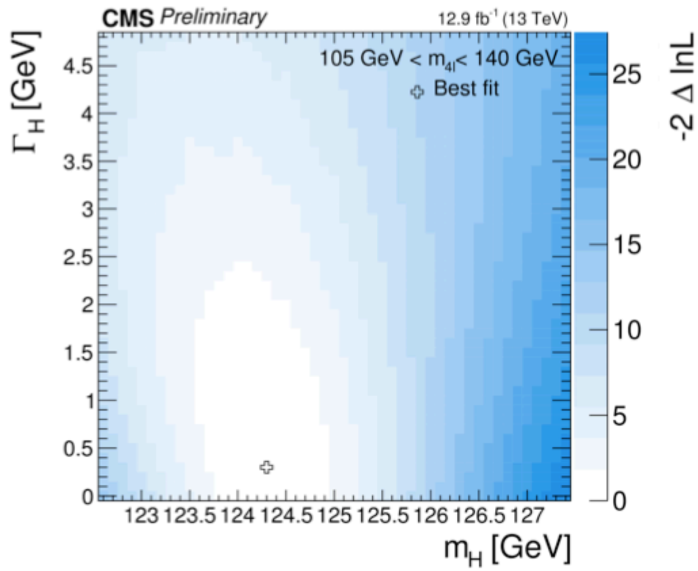
CMS H→ZZ→4l 13 TeV, width

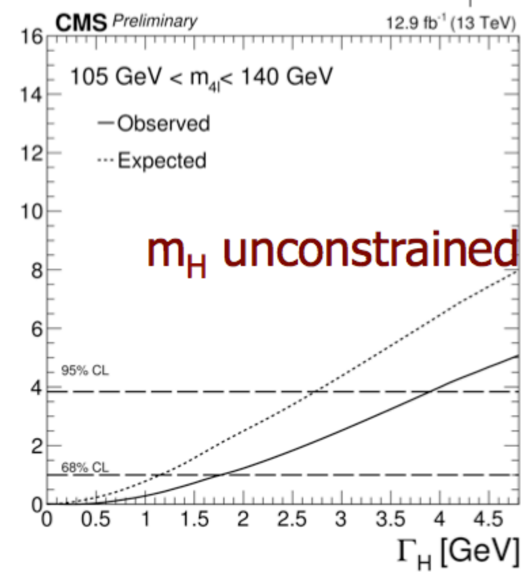
A. Calderon,
U. Sarica

- Using on-shell only
  (105 < m4l < 140 GeV)

$\Gamma_H = 0.3^{+1.4}_{-0.0}$ GeV (68% CL)

Γ_H < 3.9 GeV (95% CL)



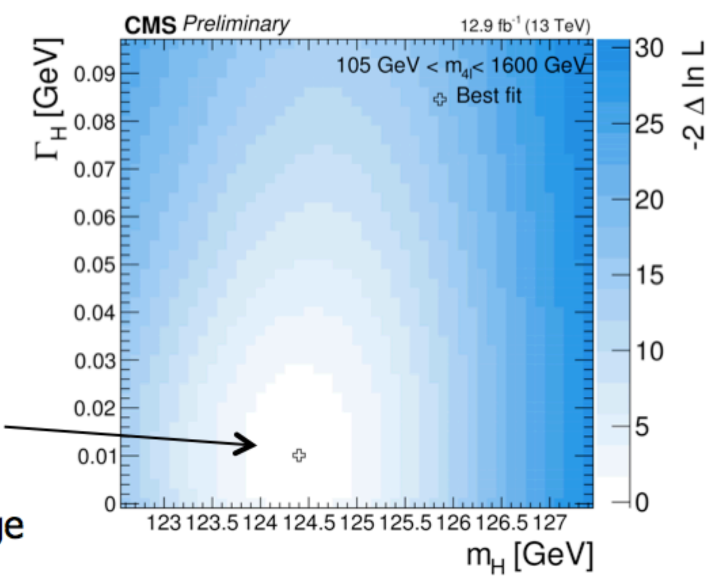


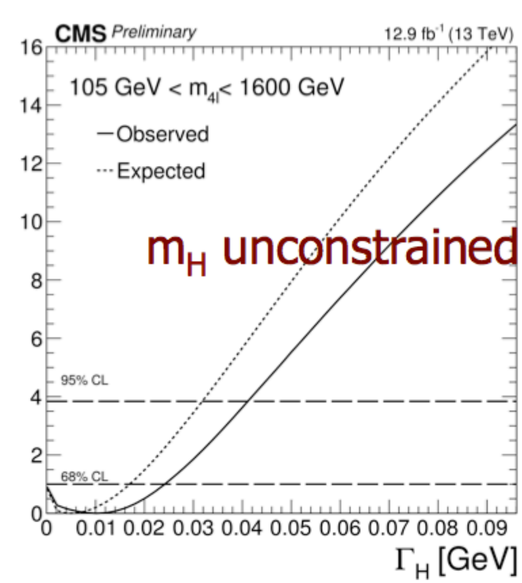
- Using on-shell & off-shell
  (100 < m4l < 1600 GeV)

$\Gamma_H = 0.010^{+0.014}_{-0.010}$ GeV (68% CL)

Γ_H < 41 MeV (95% CL)

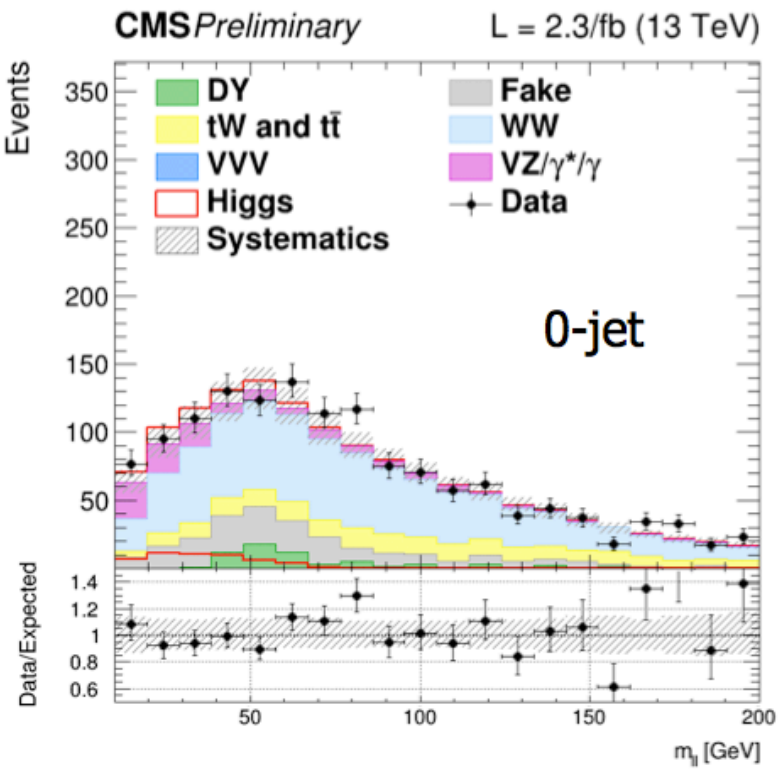
Mass fit not dependent on the mass range





$H \rightarrow WW \rightarrow 2l2\nu$

- Both experiments are working hard but analysis is more complicated than γγ and ZZ
- ATLAS and CMS analysis on 2016 data are in progress
- Only results from CMS based on 2015 data shown at Moriond eμ in the 0- and 1-jet channels



A. Calderon

- Analysis strategy:
  - Using 0-jet and 1-jet categories only for now (2.3/fb 2015 dataset)
  - Perform a 2D fit: mll vs. mT

➢ **Results with 2015 data:**

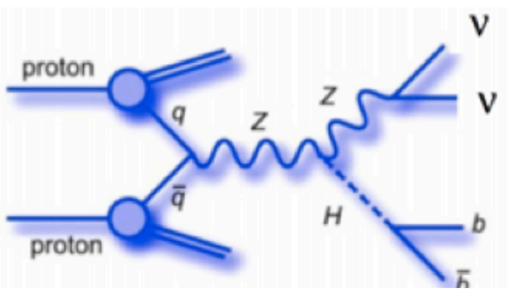
- Significance @ 125 GeV: 0.7σ observed (2.0σ expected)
- Best-fit signal strength @ 125 GeV: 0.3 ± 0.5

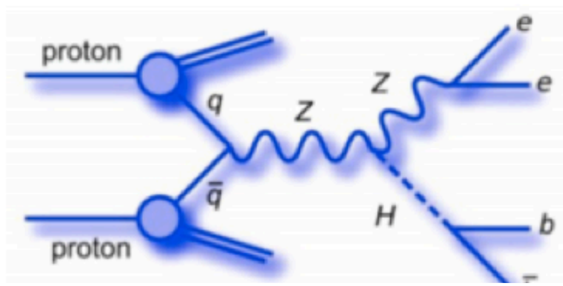
ATLAS VH H→bb

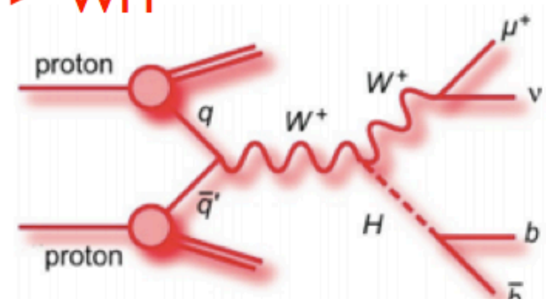
E. Shabalina

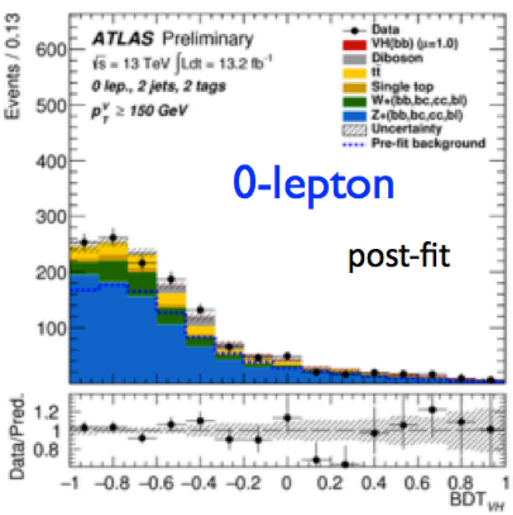
	p_T^V<150 GeV		p_T^V>150 GeV		
	2 jets	≥3 jets	2 jets	3 jets	≥3 jets
0-lepton	-	-	BDT	BDT	-
1-lepton	-	-	BDT	BDT	-
2-lepton	BDT	BDT	BDT	-	BDT

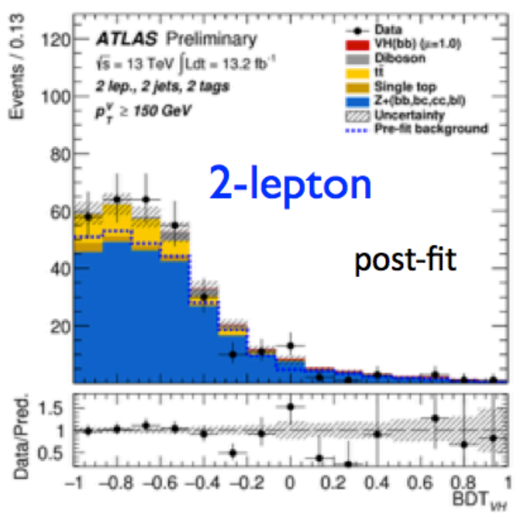
ZH ← → WH

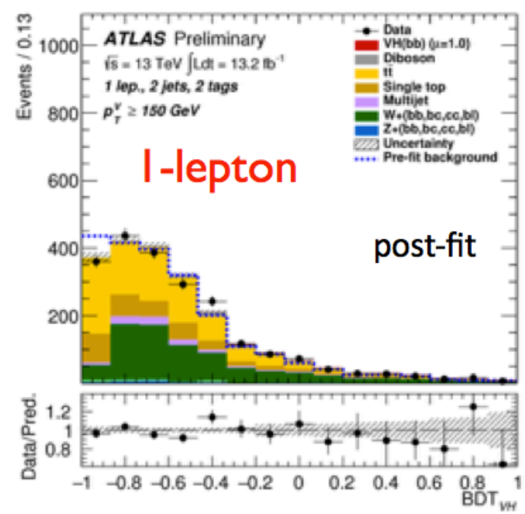








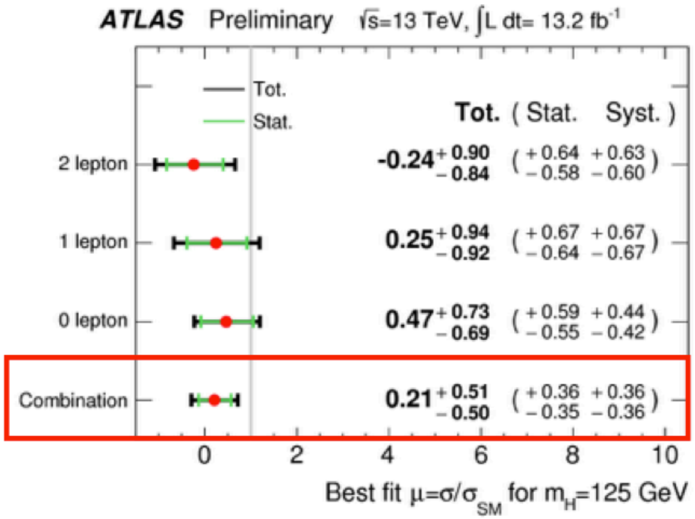




E. Shabalina

ATLAS VH H→bb results

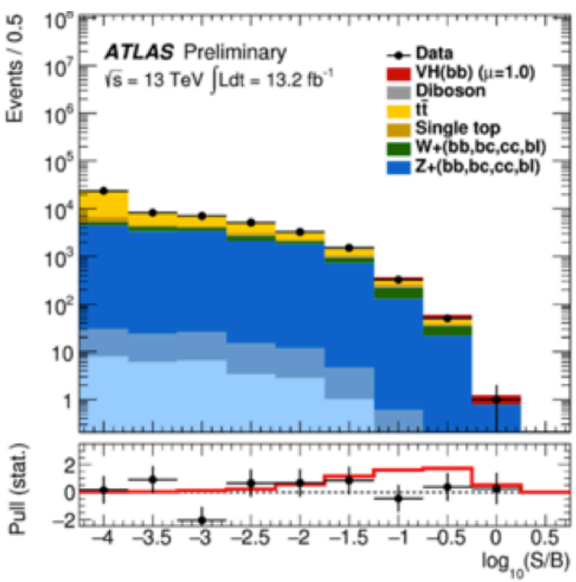
Systematic uncertainties of similar size as statistical ones



VZ fit result

$\mu_{VZ} = 0.91 \pm 0.17(\text{stat})^{+0.32}_{-0.27}(\text{syst})$

significance obs (exp) 3.0 (3.2) SD

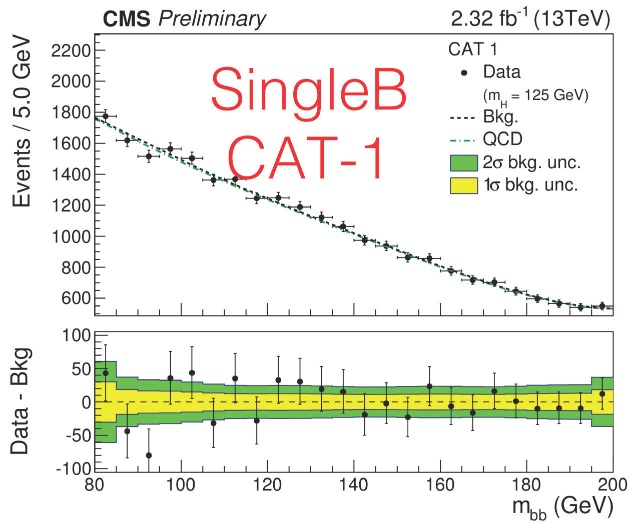


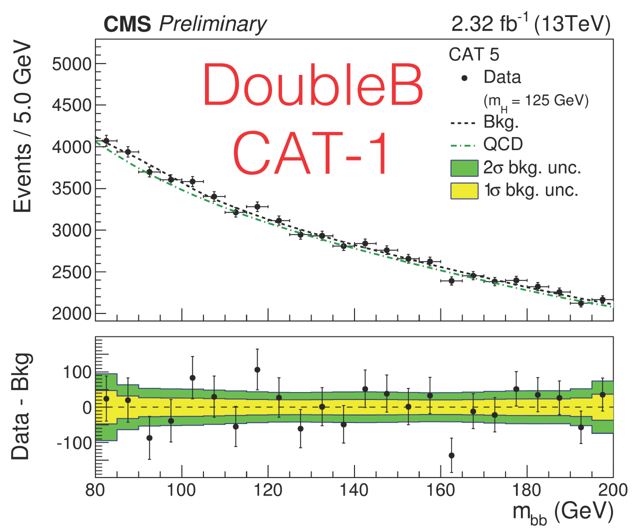
	significance obs (exp) [σ]	μ
ATLAS run I	1.4 (2.6)	$0.51^{+0.40}_{-0.37}$
ATLAS run 2	0.42 (1.94)	$0.21^{+0.51}_{-0.50}$
CMS run I	2.1 (2.5)	0.89 ± 0.43
ATLAS+CMS run I	2.6 (3.7)	$0.70^{+0.29}_{-0.27}$

CMS VBF H→bb

A. Nayak

- Analysis strategy is the same as in Run 1



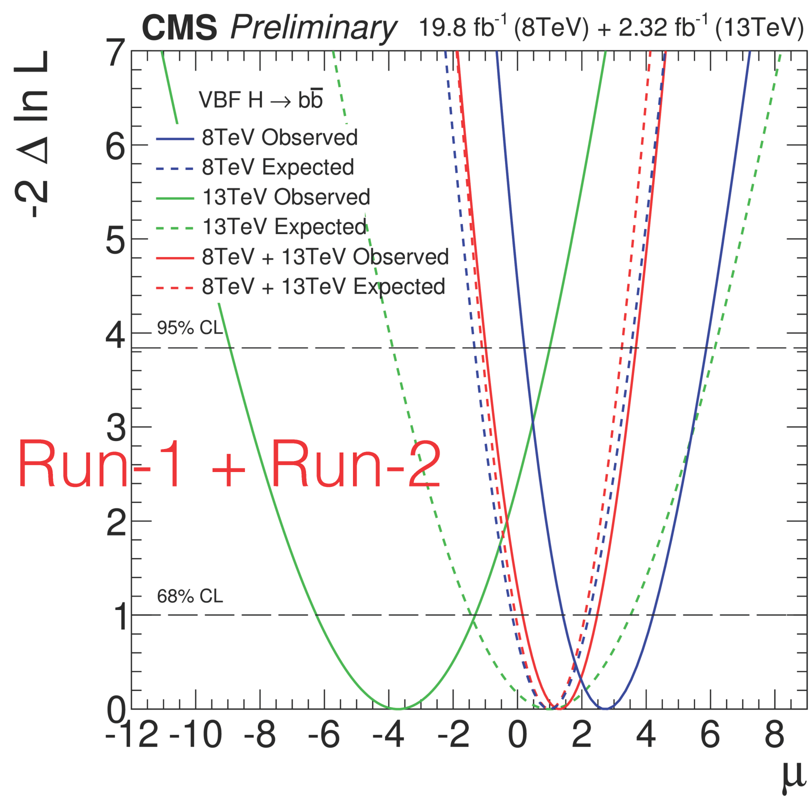


13 TeV results (2.32 fb^{-1} of 2015 data)

$\mu = \sigma/\sigma_{SM} = -3.7\ (+2.4, -2.5)$

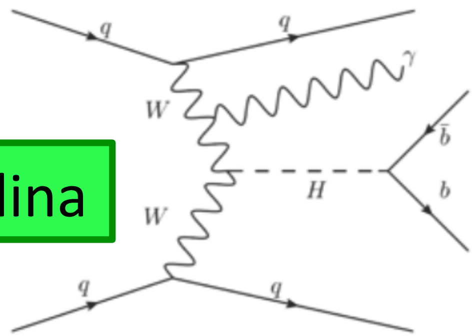
Run-1 + Run-2 Combination:

$\mu = \sigma/\sigma_{SM} = 1.3\ (+1.2, -1.1)$

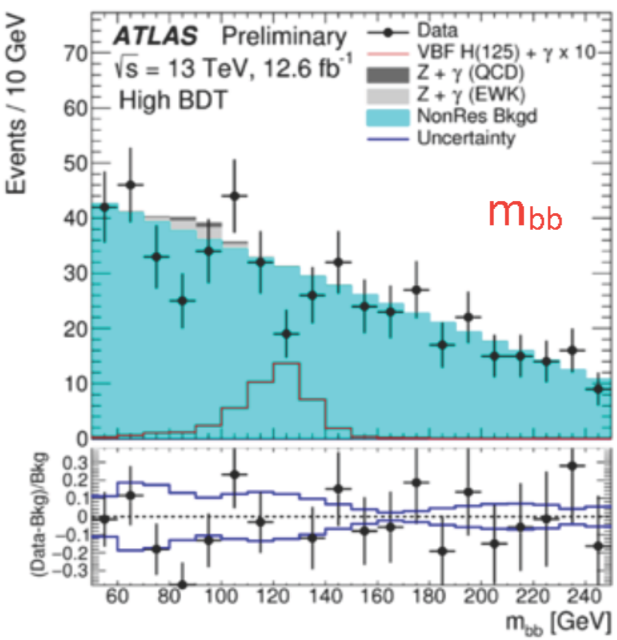


ATLAS VBF H→bb (plus photon)

E. Shabalina



- Require high p_T photon in the final state
  - provides a clean signature for efficient triggering
  - gluon-induced component of non-resonant bbjjγ is suppressed
  - destructive interference further suppresses central photon emissions
- Dramatically increases S/B in VBF mode



deficit of events near 125 GeV in high BDT region

upper limit @95% CL	obs (exp)	μ
ATLAS run I	4.4 (5.4)	-0.8 ± 2.3
ATLAS (VBF with γ) run 2	4.0 (6.0)	$-3.9^{+2.8}_{-2.7}$
CMS run I	5.5 (2.5)	$2.8^{+1.6}_{-1.4}$
CMS run 2	3.0 (5.0)	$-3.7^{+2.4}_{-2.5}$
CMS run I+run 2	3.4 (2.2)	$1.3^{+1.2}_{-1.1}$

Z+γ measurement with the same signature
obs (exp) limit: 2.0 (1.8), μ = 0.3±0.8

ATLAS ttH multi-lepton

- **Great interest in ttH because cross section increases at 13 TeV by a factor 4 (similar increase for main BGs)**

Best-fit μ_{ttH} $2.5 \pm 0.7\ (\text{stat})\ ^{+1.1}_{-0.9}\ (\text{syst})$

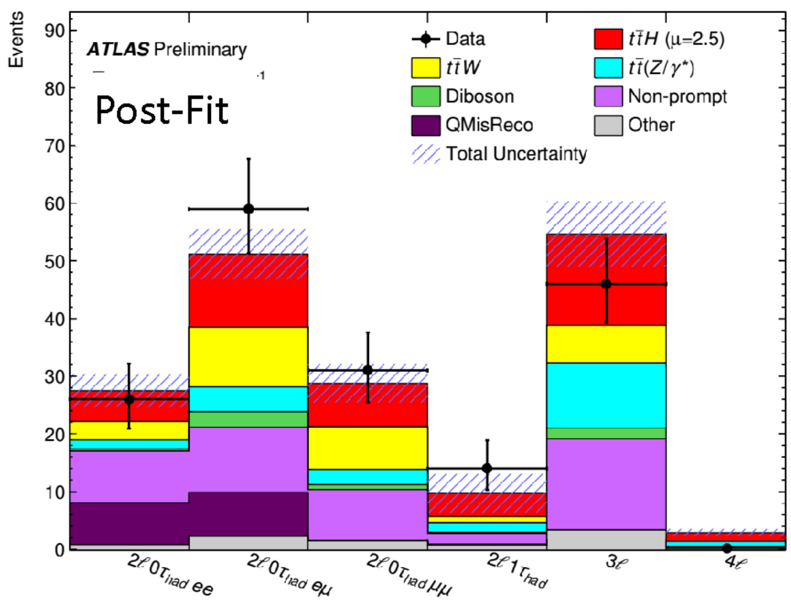
- Main systematic uncertainty: fake backgrounds, jets, pile-up
- Observed (expected) significance to non-ttH hypothesis is 2.2 (1.3) σ

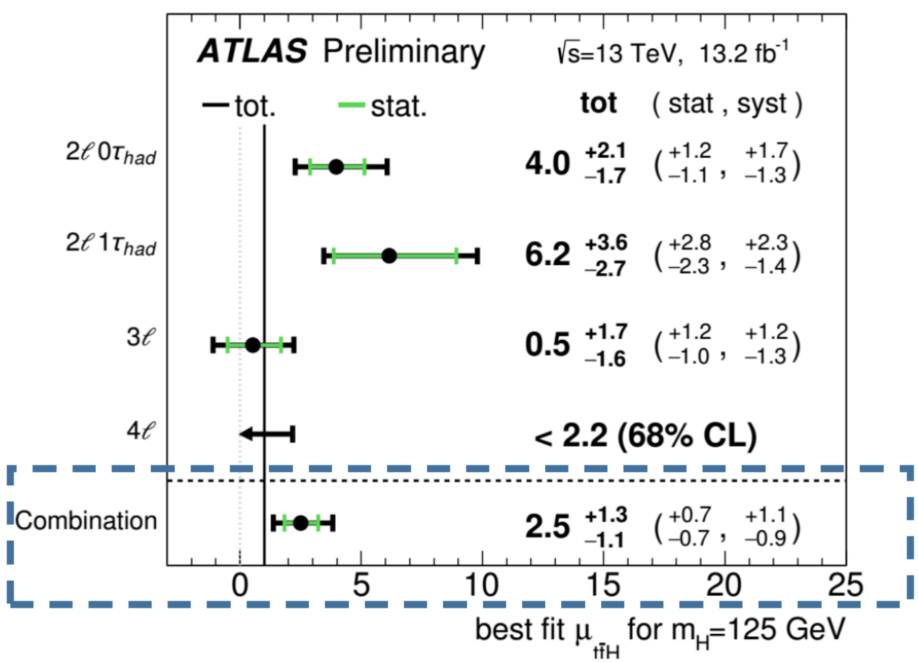
  comparable to Run 1 significance in the same final state: 1.8 (0.9) σ
  Phys. Lett. B **749** (2015) 519

E. Shabalina

Observed (expected) Upper limit on μ_{ttH} (95% CL) is 4.9 (2.3)

ATLAS-CONF-2016-058

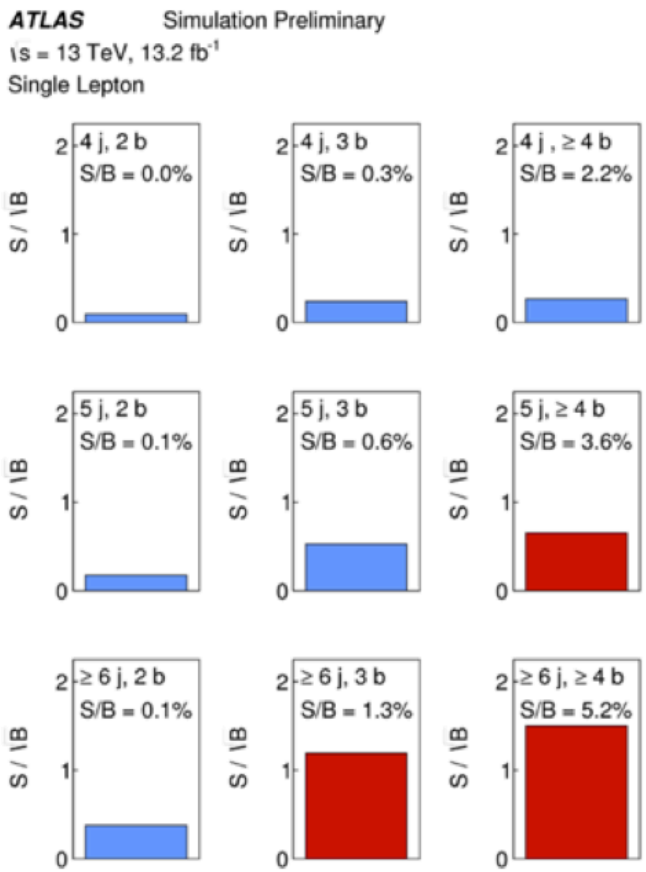


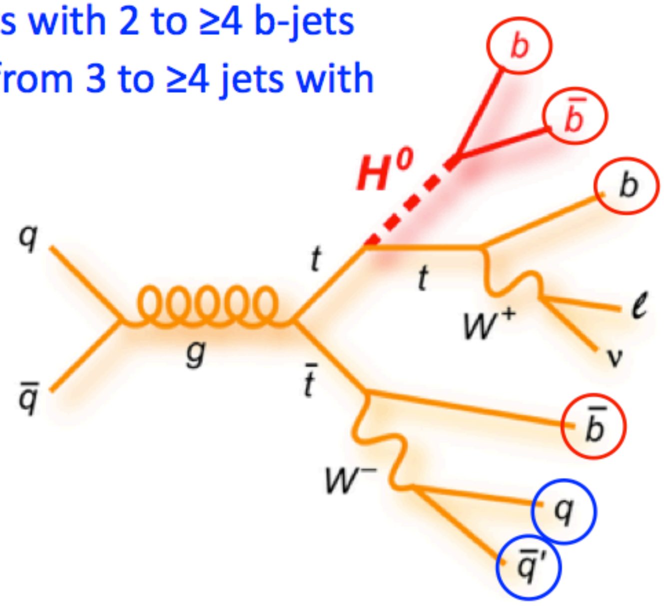


ATLAS ttH H→bb

E. Shabalina

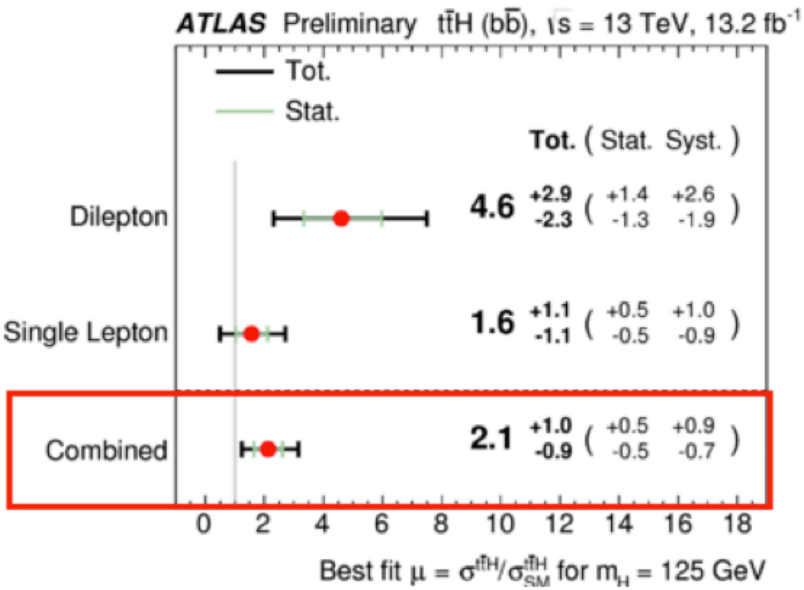
- Event selection
  - Single lepton channel: 1 lepton (e or μ), from 4 to ≥6 jets with 2 to ≥4 b-jets
  - Dilepton channel: 2 opposite-sign leptons (ee, μμ, eμ), from 3 to ≥4 jets with 2 to ≥4 b-jets

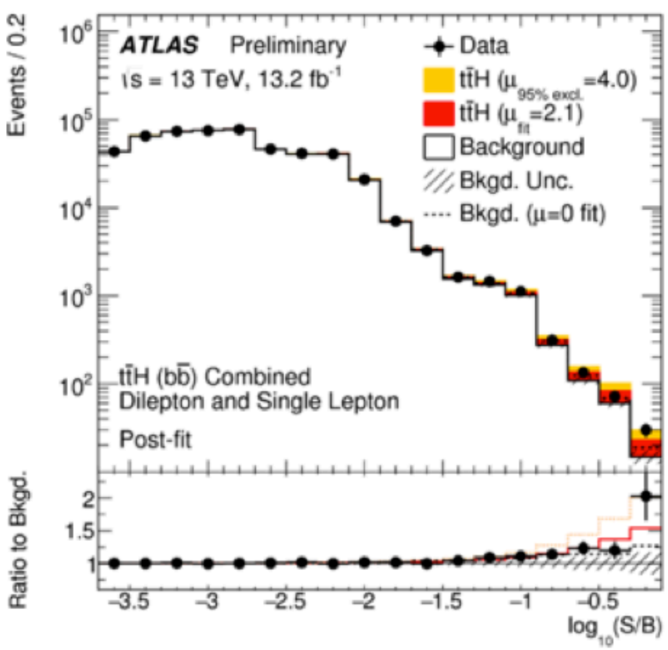




- Categorise events by jet and b-jet multiplicity
  - take advantage of low S/B regions to constrain systematic uncertainties
  - maximise sensitivity by separating regions with different S/√B
- Build MVA discriminant to separate signal from background in signal-rich regions

ATLAS ttH H→bb





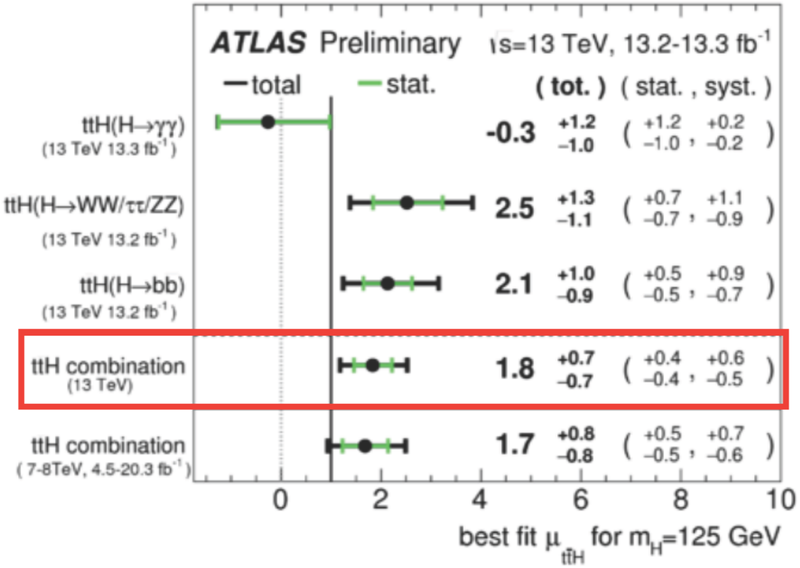
Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	$+0.53$	-0.53
Jet flavour tagging	$+0.26$	-0.26
$t\bar{t}H$ modelling	$+0.32$	-0.20
Background model statistics	$+0.25$	-0.25
$t\bar{t}+\geq 1c$ modelling	$+0.24$	-0.23
Jet energy scale and resolution	$+0.19$	-0.19
$t\bar{t}$+light modelling	$+0.19$	-0.18
Other background modelling	$+0.18$	-0.18
Jet-vertex association, pileup modelling	$+0.12$	-0.12
Luminosity	$+0.12$	-0.12
$t\bar{t}Z$ modelling	$+0.06$	-0.06
Light lepton (e, μ) ID, isolation, trigger	$+0.05$	-0.05
Total systematic uncertainty	$+0.90$	-0.75
$t\bar{t}+\geq 1b$ normalisation	$+0.34$	-0.34
$t\bar{t}+\geq 1c$ normalisation	$+0.14$	-0.14
Statistical uncertainty	$+0.49$	-0.49
Total uncertainty	$+1.02$	-0.89

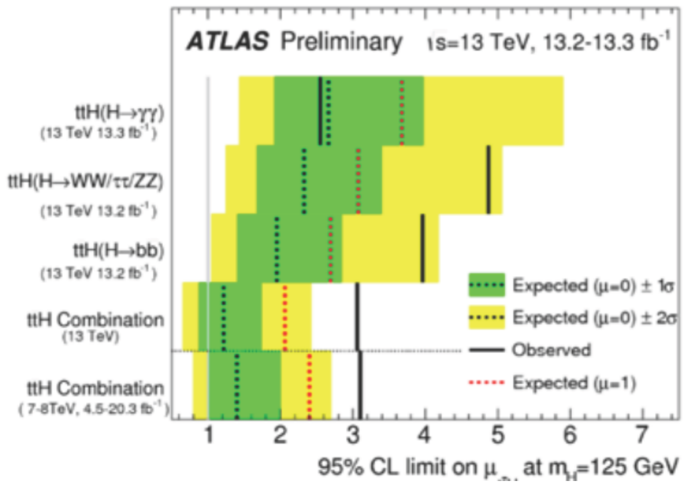
	significance obs (exp) [σ]	μ
ATLAS run I	1.4 (1.1)	1.5 ± 1.1
ATLAS run 2	2.4 (1.2)	$2.1^{+1.0}_{-0.9}$
CMS run 2 (2.7 fb^{-1})		-2.0 ± 1.8

ATLAS ttH combination

E. Shabalina

ATLAS-CONF-2016-068





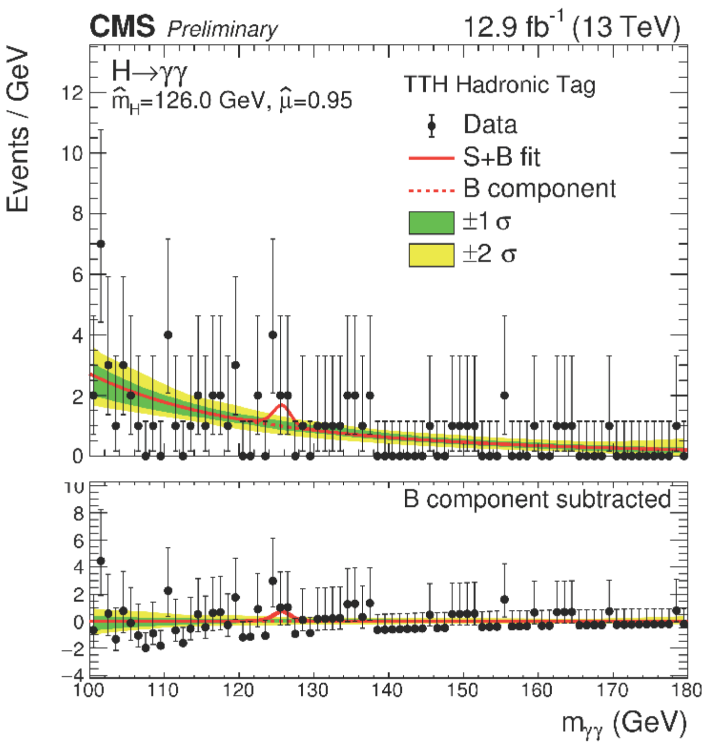
Channel	Significance	
	Observed [σ]	Expected [σ]
$t\bar{t}H,\ H \to \gamma\gamma$	-0.2	0.9
$t\bar{t}H,\ H \to (WW, \tau\tau, ZZ)$	2.2	1.0
$t\bar{t}H,\ H \to b\bar{b}$	2.4	1.2
$t\bar{t}H$ combination	2.8	1.8

	significance obs (exp) [σ]	μ
ATLAS run I	2.33 (1.53)	1.7 ± 0.8
ATLAS run 2	2.8 (1.8)	1.8 ± 0.7
CMS run I	3.4 (1.2)	$2.8^{+1.0}_{-0.9}$
ATLAS+CMS run I	4.4 (2.0)	$2.3^{+0.7}_{-0.6}$

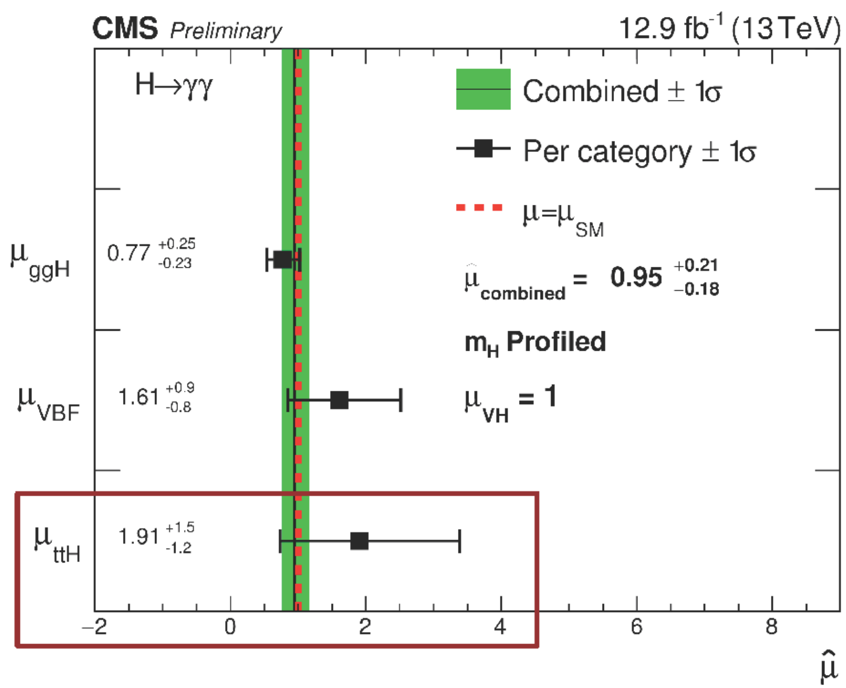
CMS ttH, H→γγ

A. Calderon

- ttH(γγ), through H→γγ event categorisation
  - small branching ratio, but very clean final state (small systematic uncertainty)
  - tagged H→γγ categories selecting hadronic and leptonic top decays



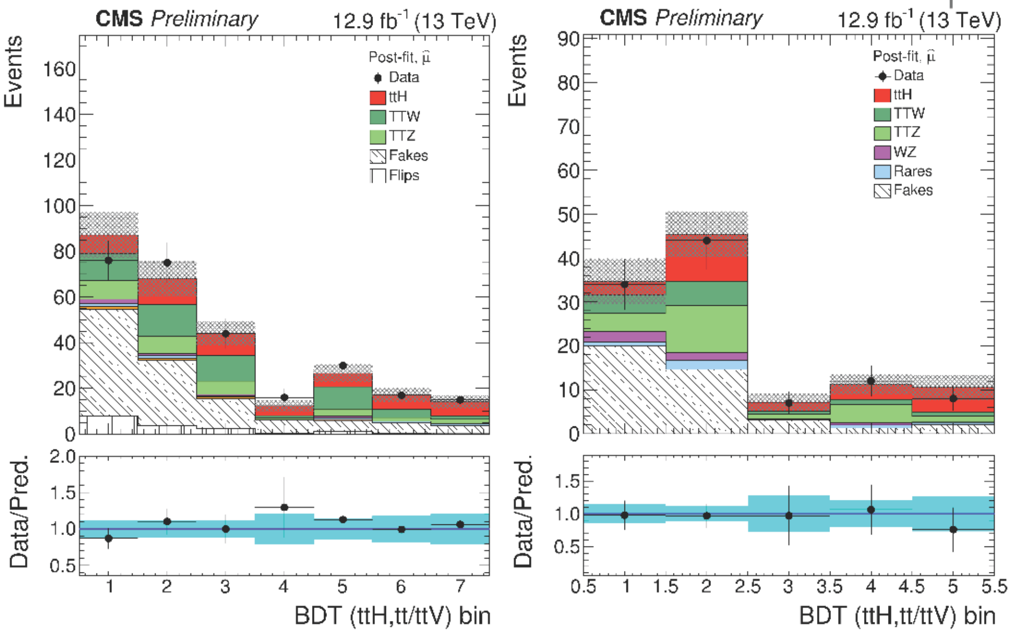
$\mu = 1.9^{+1.5}_{-1.2}$ (2016 dataset)



CMS ttH multi-lepton

A. Calderon

- ttH(multileptons) targeting Higgs decays to WW*, ZZ*, $\tau\tau$
  - lower rate, low background multi-lepton final state
- Further categorization based on lepton flavor, presence of b-jets, hadronically-decaying τ, lepton charge
- The signal is extracted via a 2-dimensional fit to the BDT discriminators.
- Dominant systematic uncertainty: non-prompt background estimates in some channels.



➢ Observed and expected asymptotic 95% CL upper limits on and best t value of the signal strength (2015+2016 datasets)

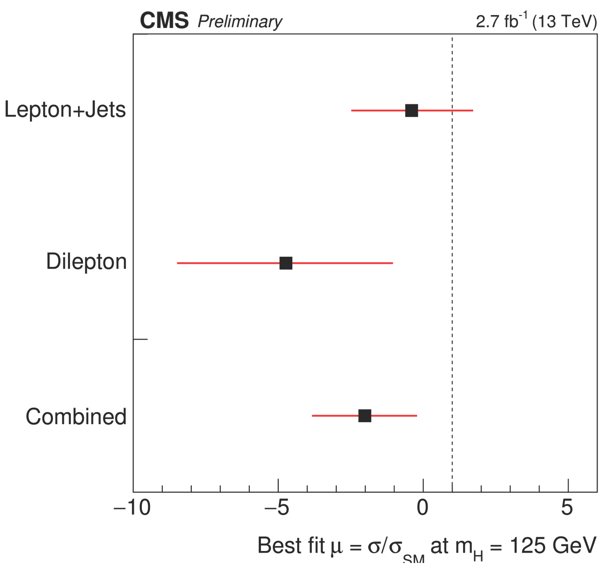
Category	Obs. limit	Exp. limit $\pm 1\sigma$	Best fit $\mu \pm 1\sigma$
Same-sign dileptons	4.6	$1.7^{+0.9}_{-0.5}$	$2.7^{+1.1}_{-1.0}$
Trileptons	3.7	$2.3^{+1.2}_{-0.7}$	$1.3^{+1.2}_{-1.0}$
Combined categories	3.9	$1.4^{+0.7}_{-0.4}$	$2.3^{+0.9}_{-0.8}$
Combined with 2015 data	3.4	$1.3^{+0.6}_{-0.4}$	$2.0^{+0.8}_{-0.7}$

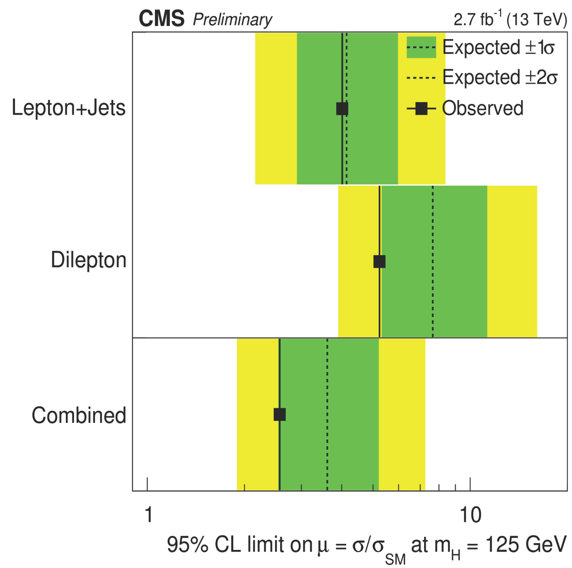
CMS ttH H→bb with 2015 data

A. Nayak

Best fit μ = -2.0 ±1.8

95% CL upper limit on μ
2.6 (3.6 exp.)



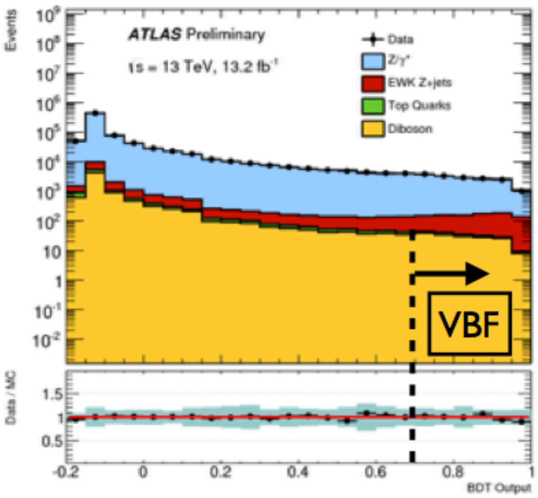


Summary of CMS results

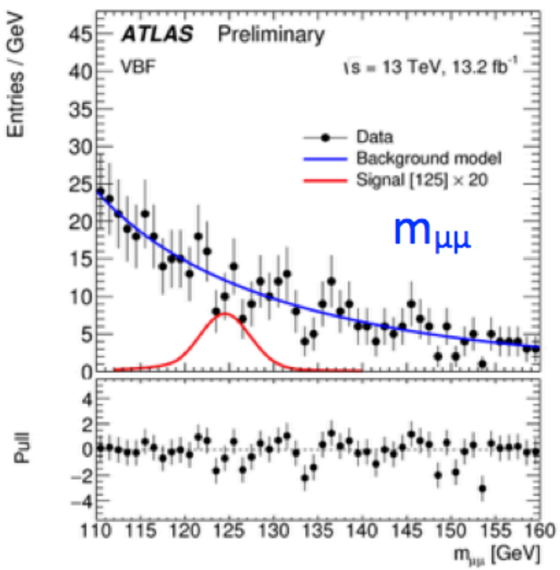
	ttH (H→bb)	ttH (H→γγ)	ttH multi-lepton
CMS	-2.0±1.8	$1.9^{+1.5}_{-1.2}$	$2.0^{+0.8}_{-0.7}$

ATLAS H→μμ

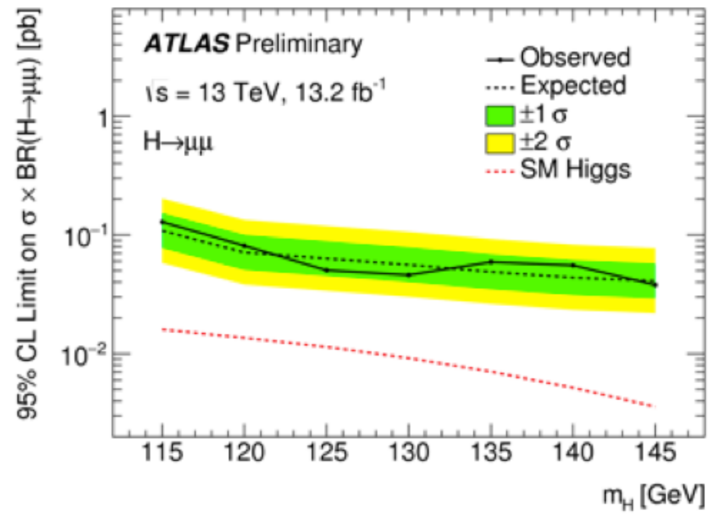
E. Shabalina



51.3% (2.4%) eff for VBF signal (total bckg)



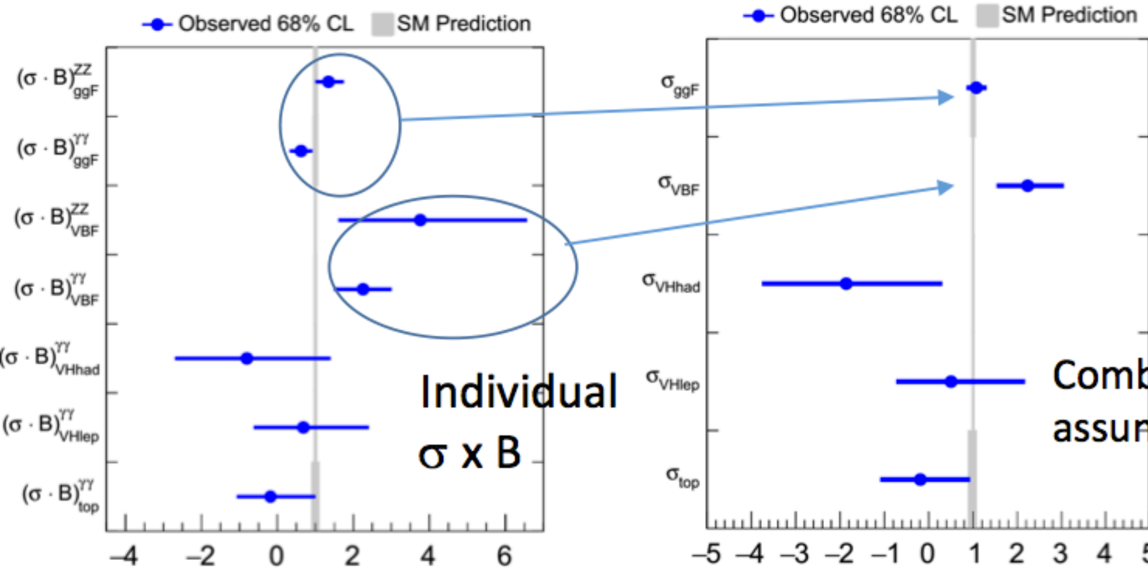
- Analysis strategy
  - split in categories with different S/B
  - VBF category defined first using MVA discriminant
    - new in run 2: ~10% improvement of sensitivity
  - the rest is split into 6 categories in muon η and $p_T(\mu\mu)$ to take advantage of different dimuon mass resolution
- Signal extracted from simultaneous fit to $m_{\mu\mu}$ distribution in 7 categories



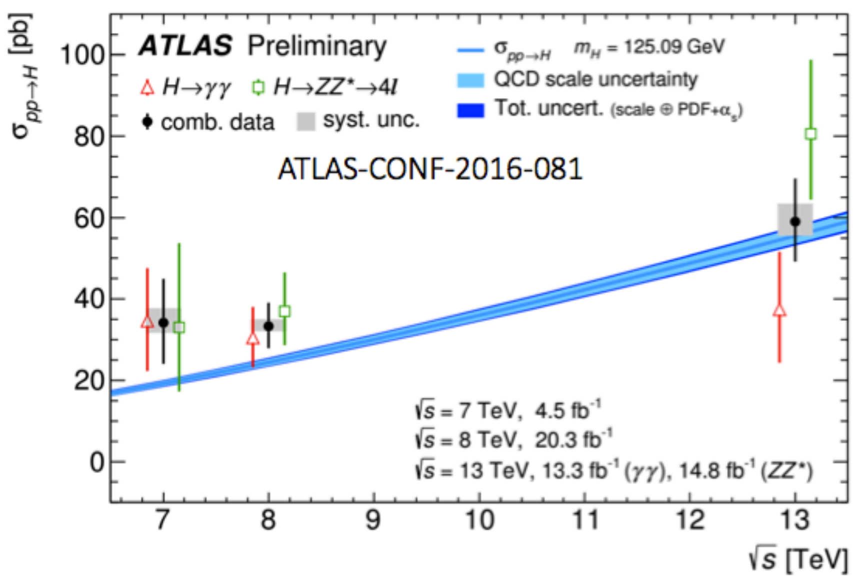
upper limit @95% CL	obs (exp)
ATLAS run 1+run 2	3.5 (4.5)
ATLAS run 2	4.4 (5.5)
ATLAS run 1	7.1 (7.2)
CMS run 1	7.4 (6.5)

ATLAS γγ + ZZ combination

Y. Wu, D. Gillberg



Observed local significance for total Higgs production: 10σ, for VBF-only: 4σ



Combined cross-section agrees better with prediction

Total unc. ~ 18%

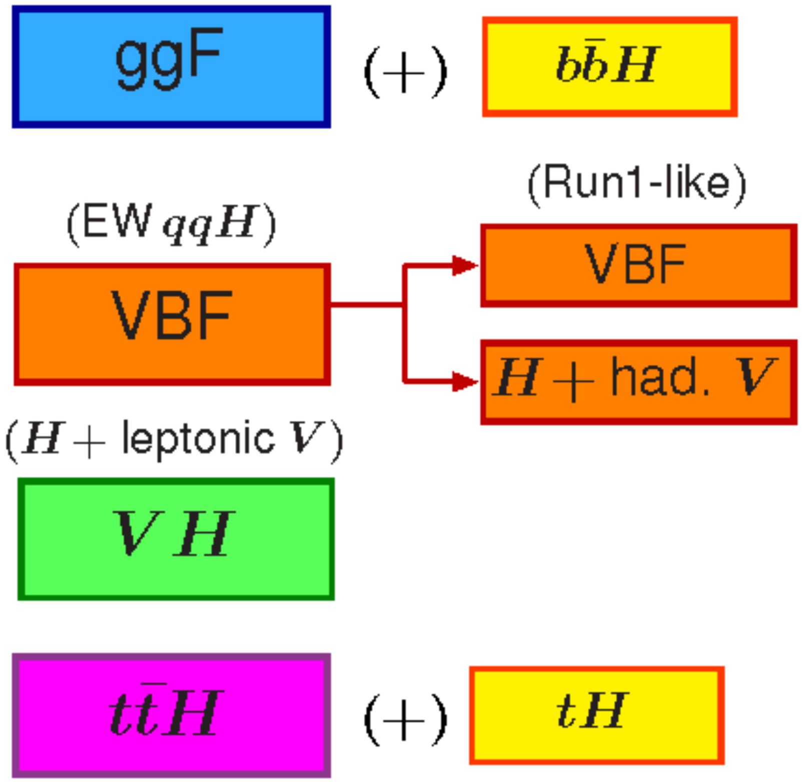
Similar to the precision at 8 TeV

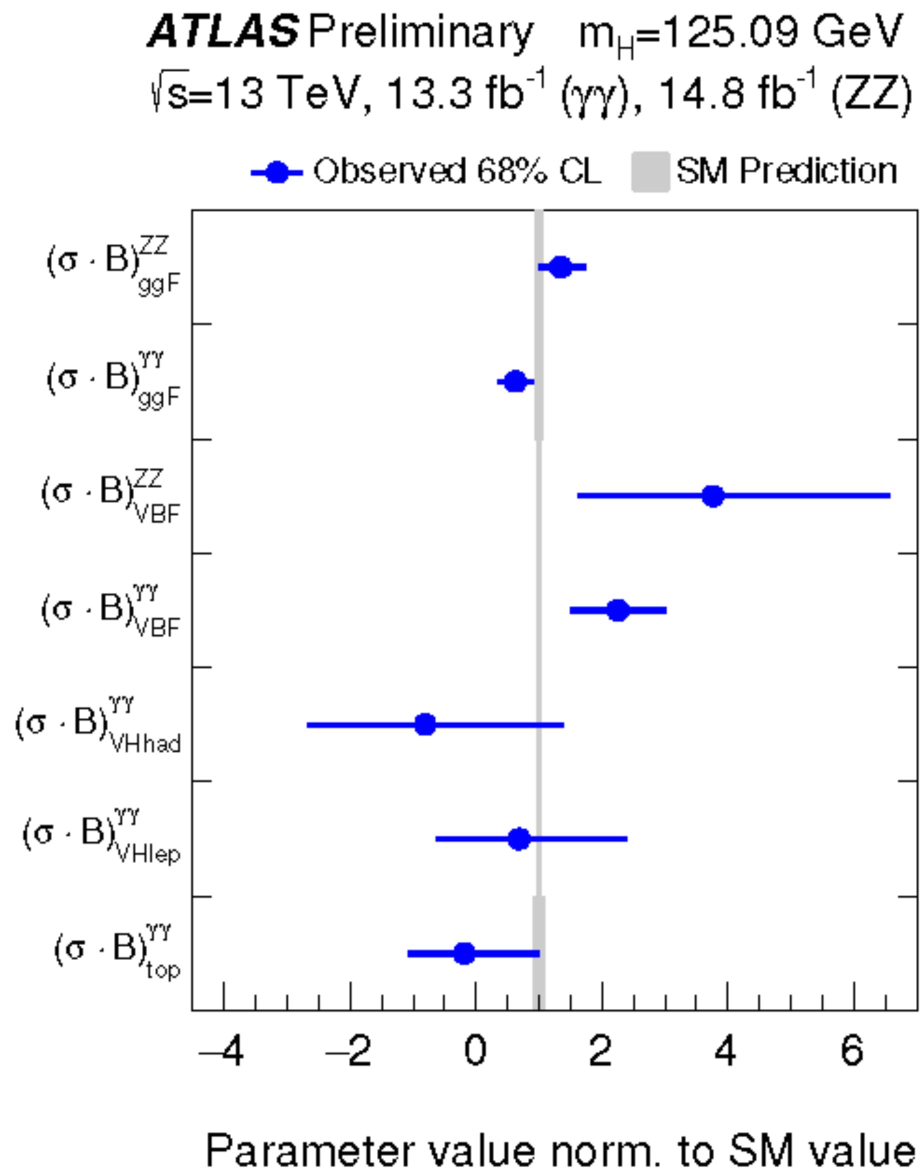
31/08/2016 12

ATLAS γγ + ZZ combination

F. Tackmann

First fits with simplified template cross sections





BSM

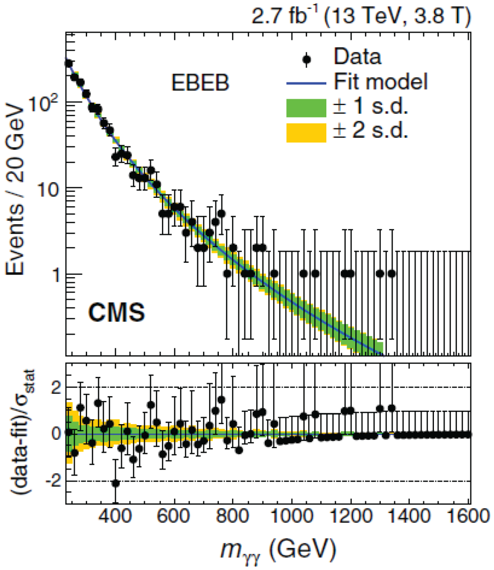
Diphoton excess at 750 GeV

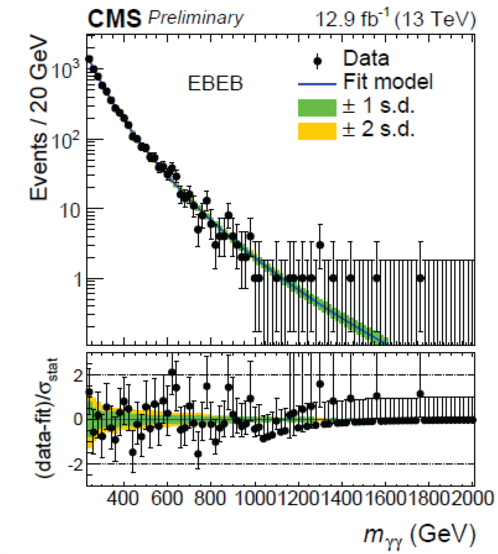
- Lot of excitement and lots of work from both experiments during the first months of the year, until ICHEP

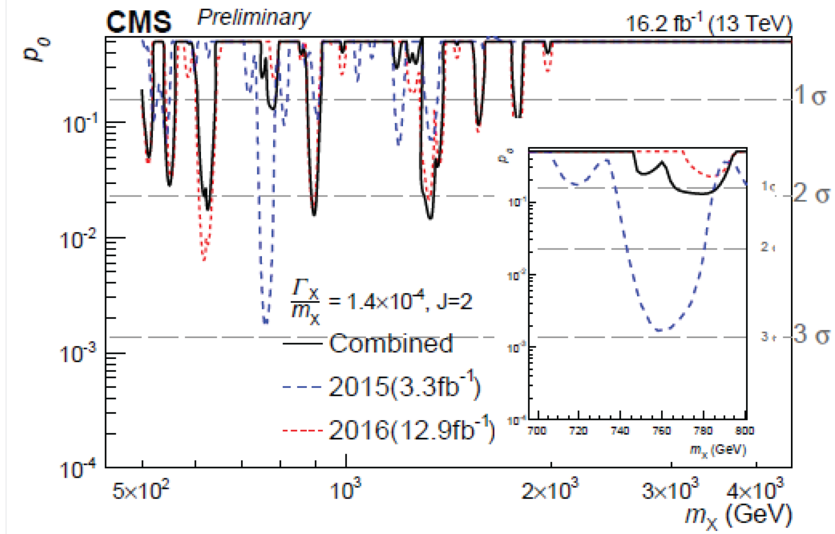
R. Covarelli, K. Grevtsov

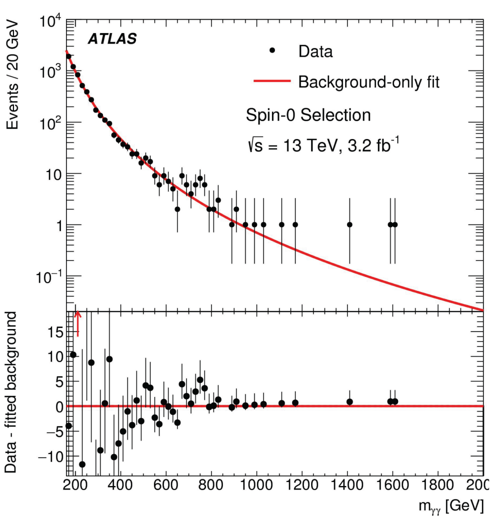
- Some excess was observed in 2015 data
  - 3.9 σ ATLAS at 750 GeV (3.4 at 734 GeV after reprocessing)
  - 3.4 sigma at 750 GeV CMS (combined with 8 TeV)
  - Global significances below ~2 sigma
  - Mass was the same at Moriond
- No excess seen in γγ in 13 fb^{-1} of 2016 data and all related channels (e.g. Zγ) and limits derived

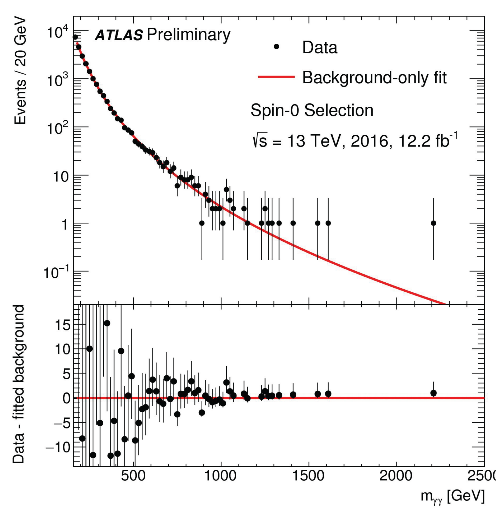
Born in 2015; deceased in 2016

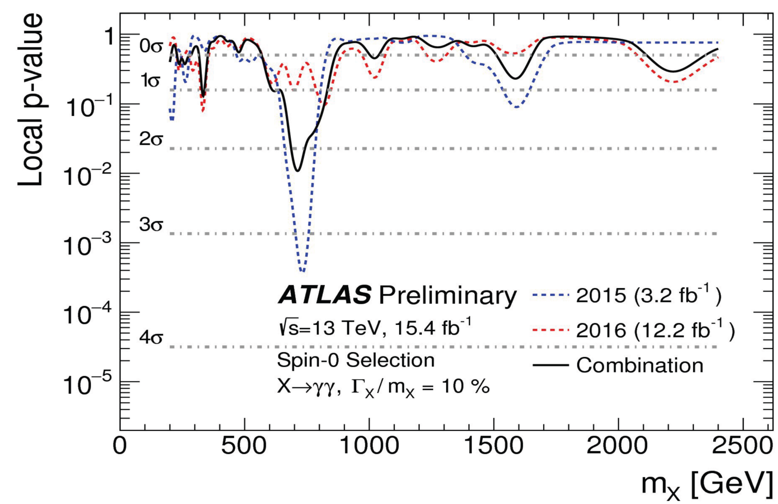




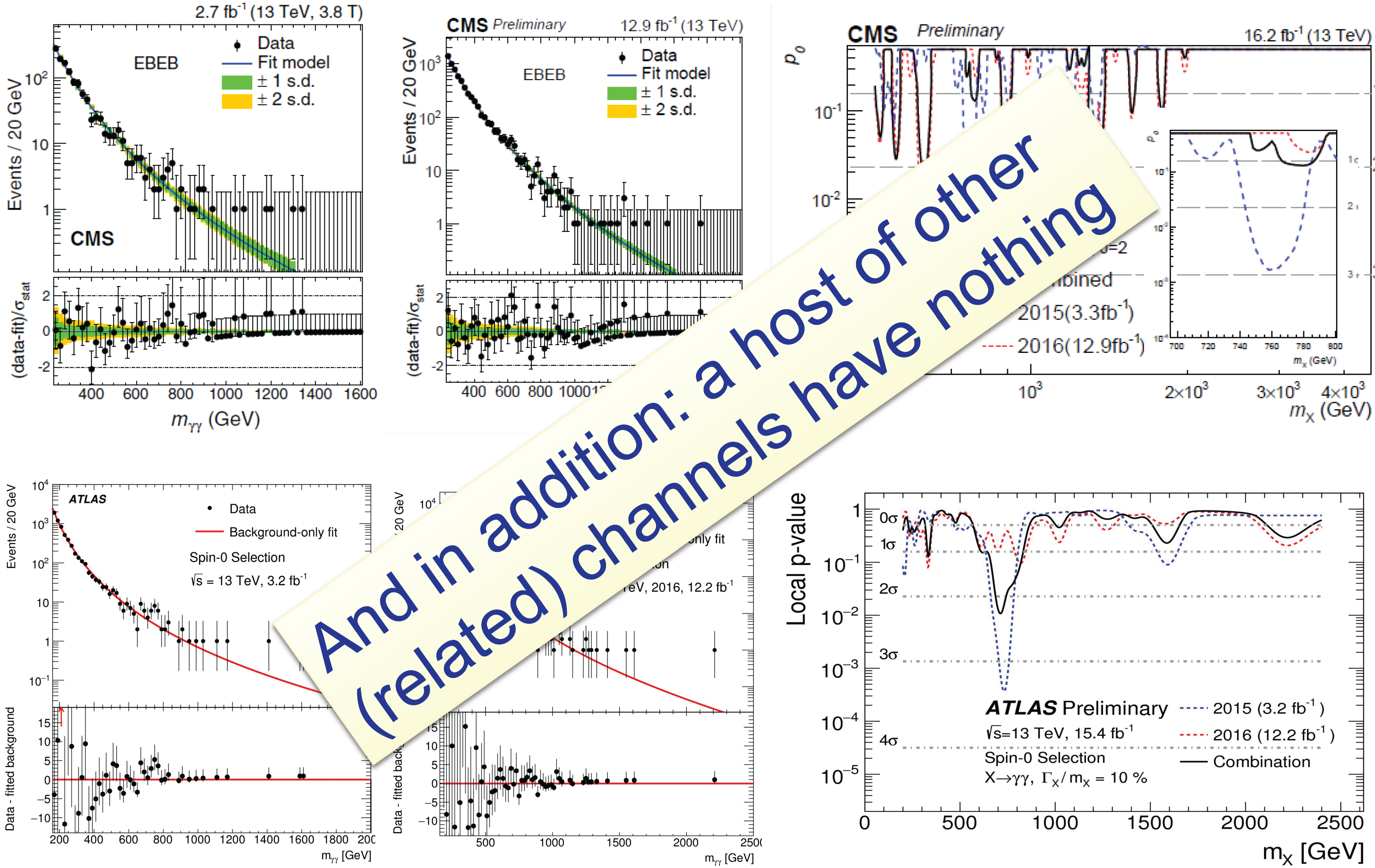








Born in 2015; deceased in 2016



And in addition: a host of other (related) channels have nothing

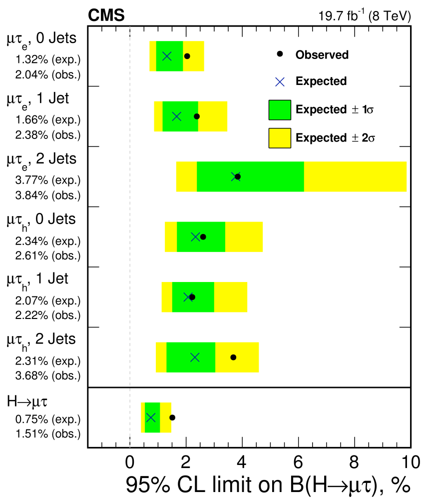
BSM Higgs searches

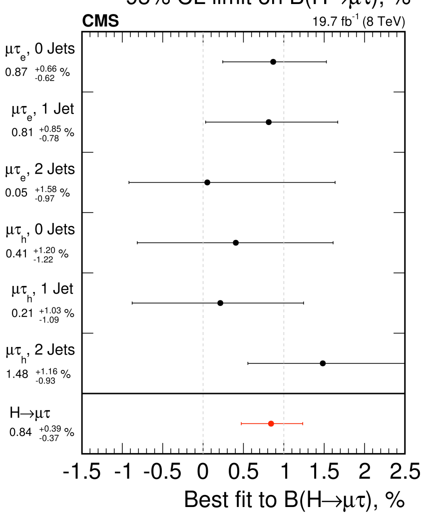
- Searches for BSM physics in the Higgs sector
  - BSM decays
  - Direct searches for additional Higgs boson
  - Higgs properties modifications (non SM couplings, CP studies, Higgs width) from SM-like Higgs bosons measurements

CMS LFV decays

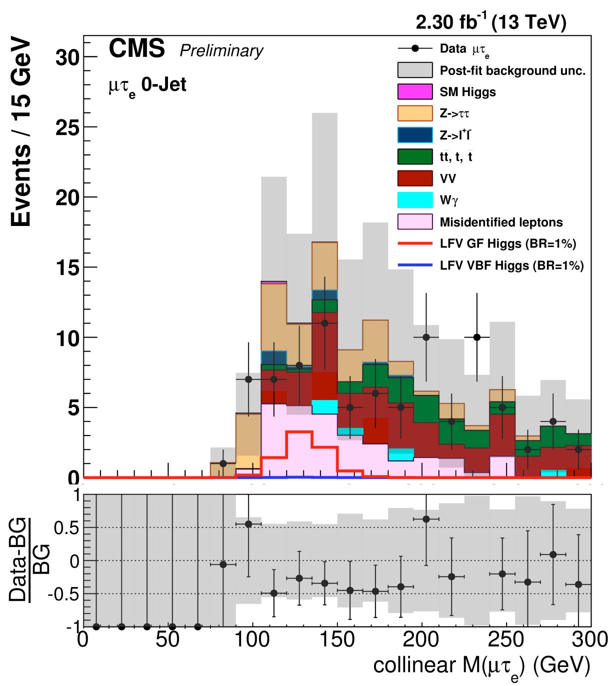
- Some small excess (~2.4σ) in H->μτ was reported by CMS in Run 1
- As in Run 1 $\mu\tau_e$ and $\mu\tau_h$ are analyzed (2015 data only)

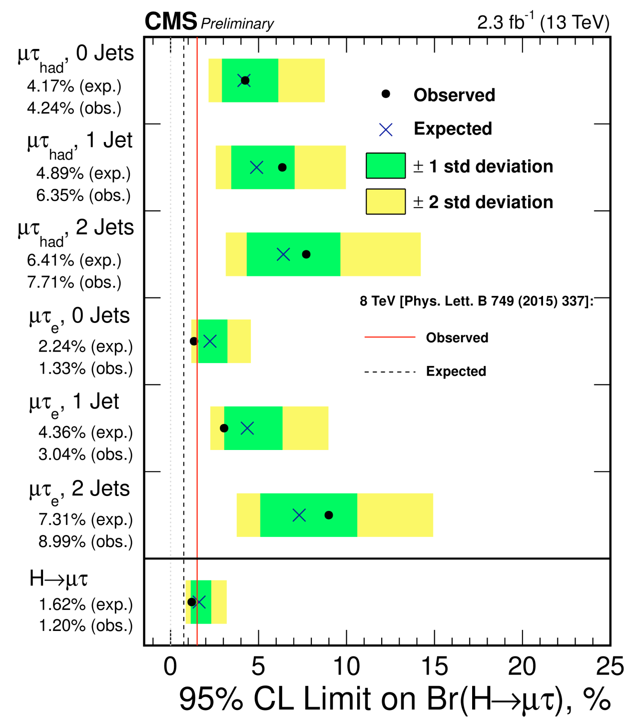
D. Taylor





13 TeV



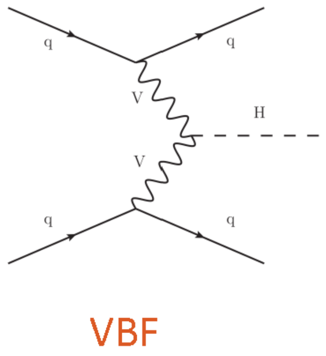


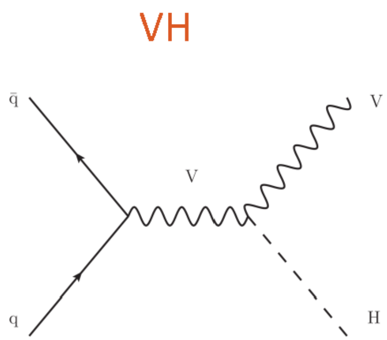
No excess observed but previous excess not excluded yet

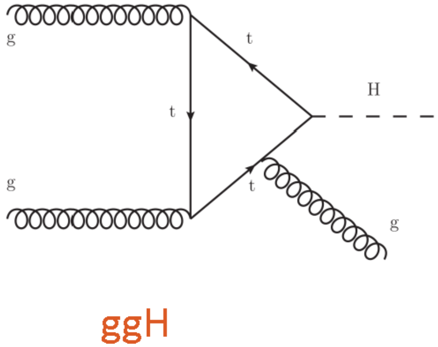
CMS Higgs invisible decays

D. Taylor

- SM BR(H → inv.) ~1.2e-3
  - H → 4ν

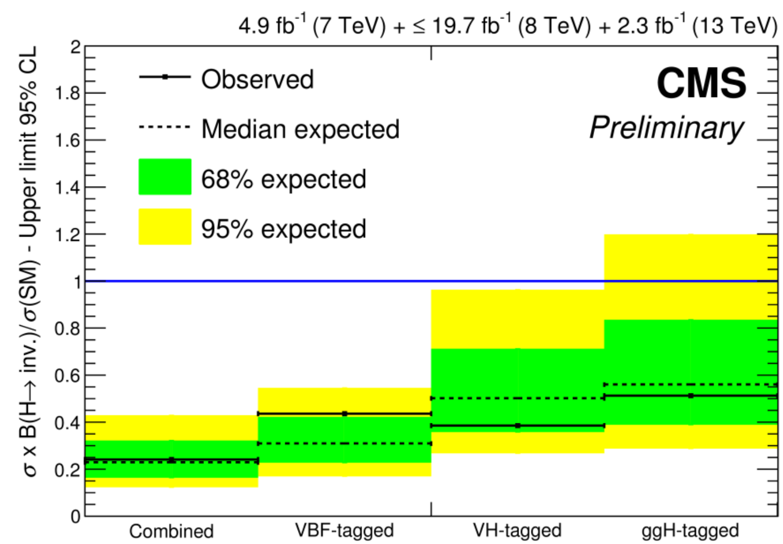






- Dedicated VBF trigger
  - Large η separation
  - High dijet invariant mass

Combination of several analyses in 7, 8, and 13 TeV

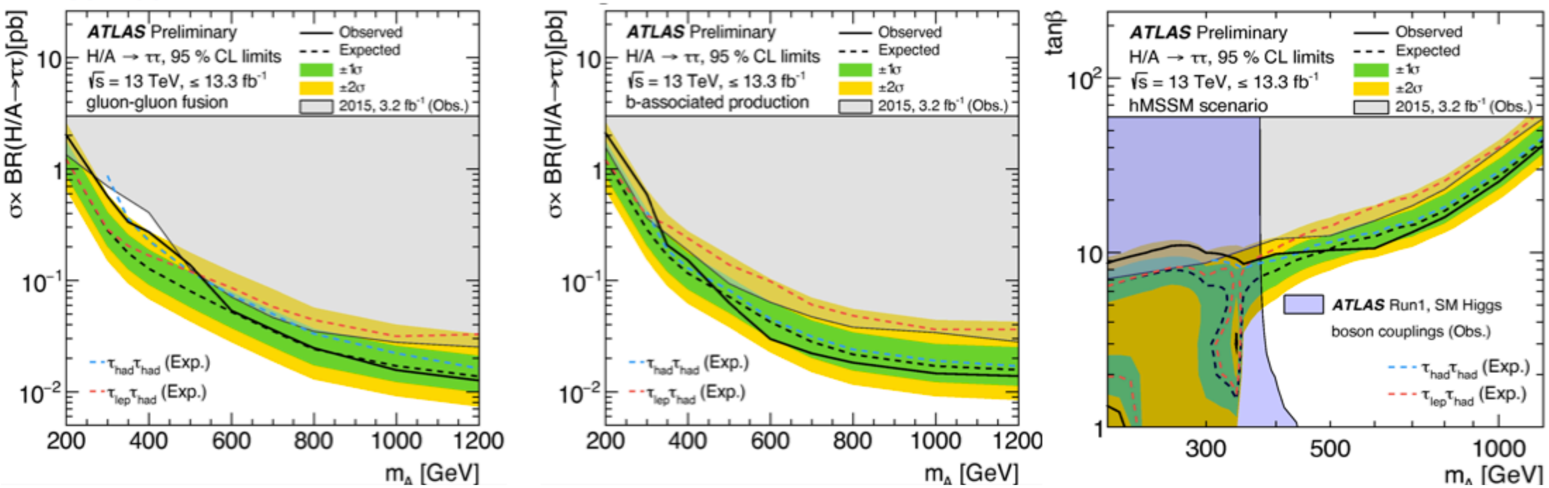


Combined: BR_{inv}<0.24 (0.23) at 95% CL

ATLAS Neutral Higgs searches: $H/A \to \tau\tau$

L. Fiorini,
P. de Bruin

- $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channels (they dominate the sensitivity at high mass)
- *b*-tag and *b*-veto categories. High-E_T^{miss} category also used for $\tau_{lep}\tau_{had}$
- m_T^{tot} variable used in both channels $m_T^{tot} = \sqrt{m_T^2(E_T^{miss},\tau_1) + m_T^2(E_T^{miss},\tau_2) + m_T^2(\tau_1,\tau_2)}$,
- **Backgrounds:**
  - $\tau_{lep}\tau_{had}$: multi-jet and W-jets/top estimated with data-driven methods.
  - $\tau_{had}\tau_{had}$: multi-jet and fake taus in other backgrounds: data-driven methods



ATLAS-CONF-2016-085 results: both model independent and MSSM scenarios:

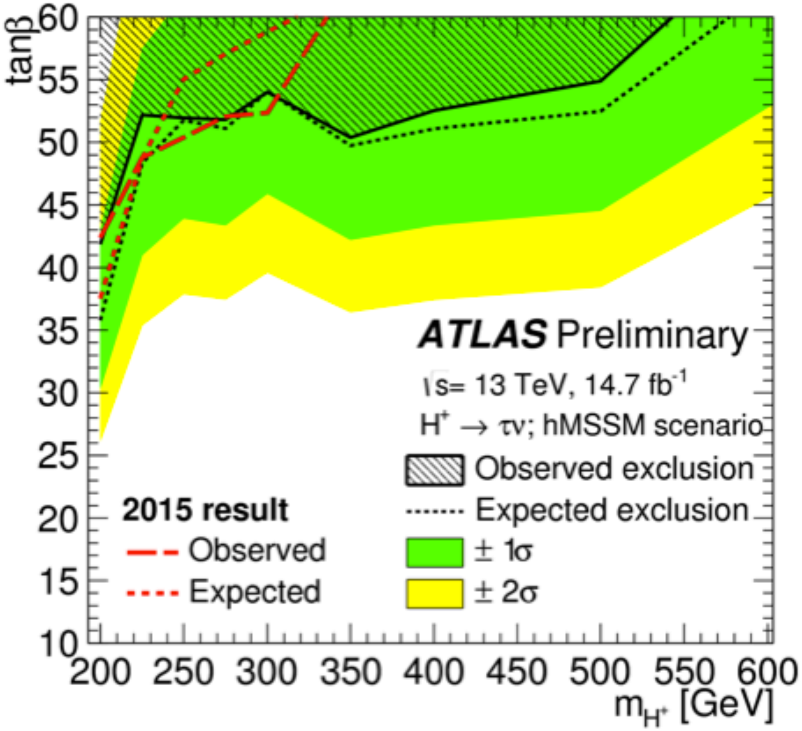
- ggH limits: 2.0-0.013 pb for m_A=200-1200 GeV
- bbH limits: 2.1-0.014 pb for m_A=200-1200 GeV

- **ATLAS also reported the results of the search of H/A->tt based on Run 1 data and taking into account the interference**

ATLAS Charged Higgs searches

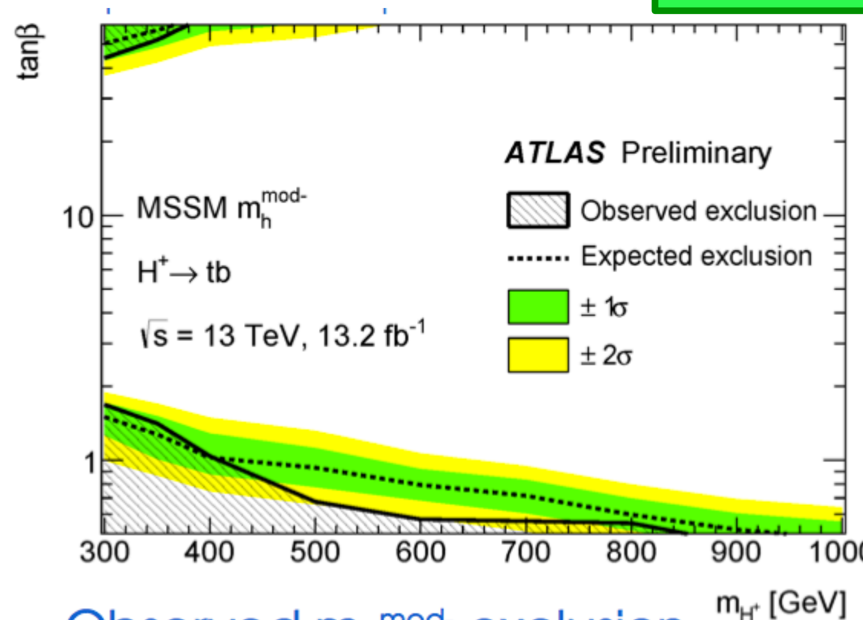
L. Fiorini

$H^{\pm} \to \tau\nu$



Observed hMSSM exclusion:
$\tan\beta > 42\text{-}60$ @ $m_{H^{\pm}}$ = 200-540 GeV

$H^{\pm} \to tb$



Observed m_h^{mod-} exclusion:
$\tan\beta < 1.7\text{-}0.5$ @ $m_{H^{\pm}}$ = 300-855 GeV

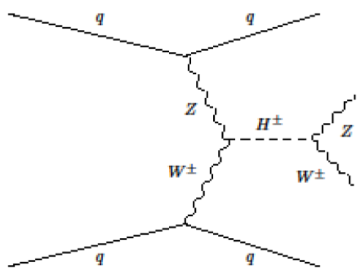
No signal observed and improved exclusion limits obtained

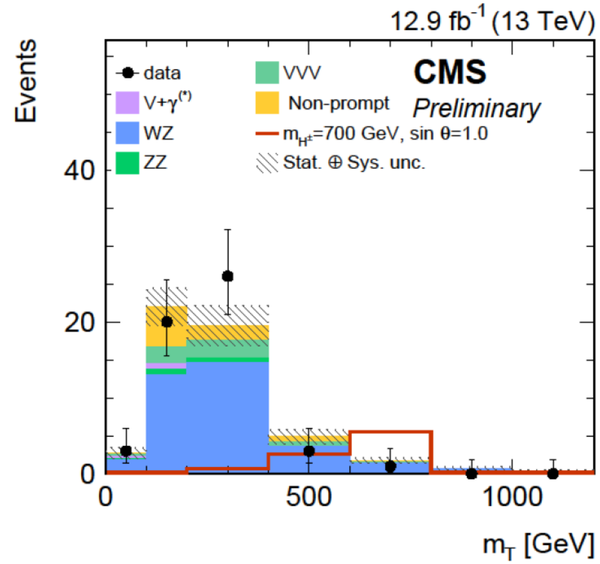
Next for ATLAS and CMS will be to address the intermediate region ~160-180 GeV (calculations now available)

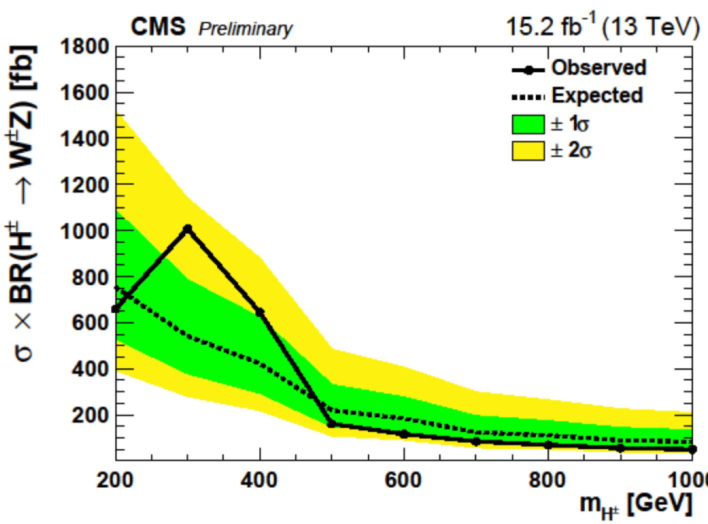
CMS $H^{\pm} \to WZ$

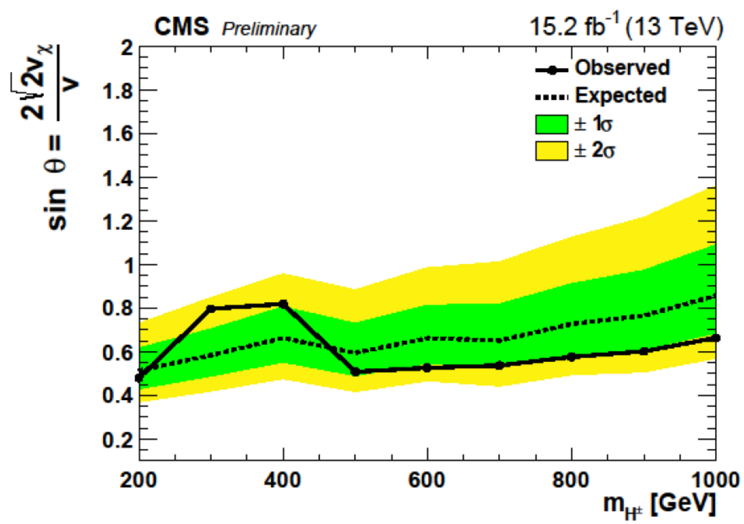
D. Taylor

- H+ decays predicted at tree level in Higgs triplet models
  - Georgi-Machacek
- Leptonic WZ
- VBS topology
  - High dijet mass



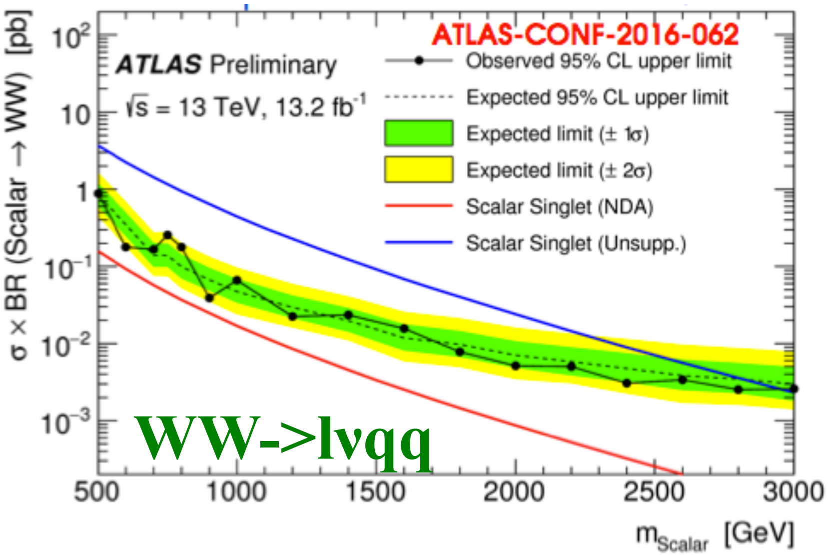


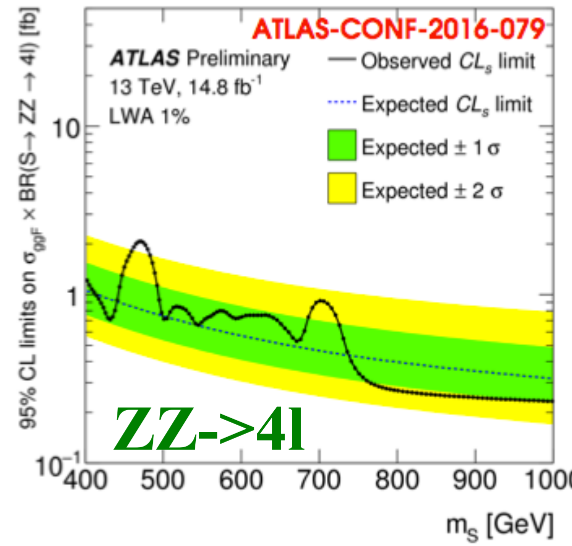


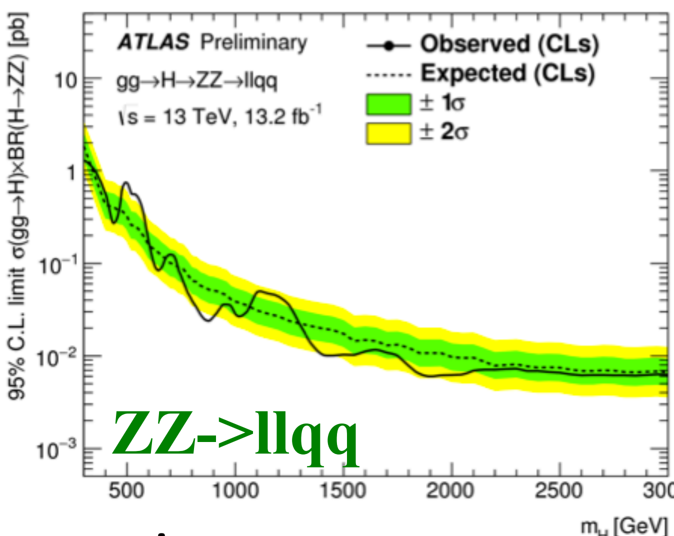


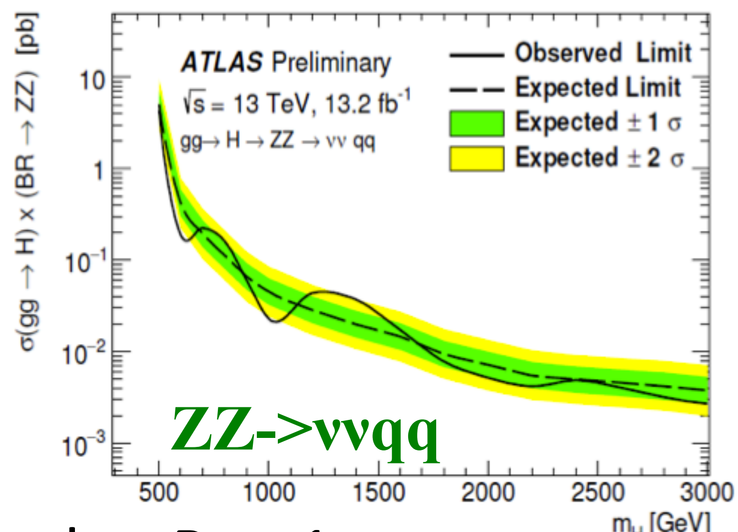
ATLAS: high mass searches

- Largely exploit jet substructure in many different channels







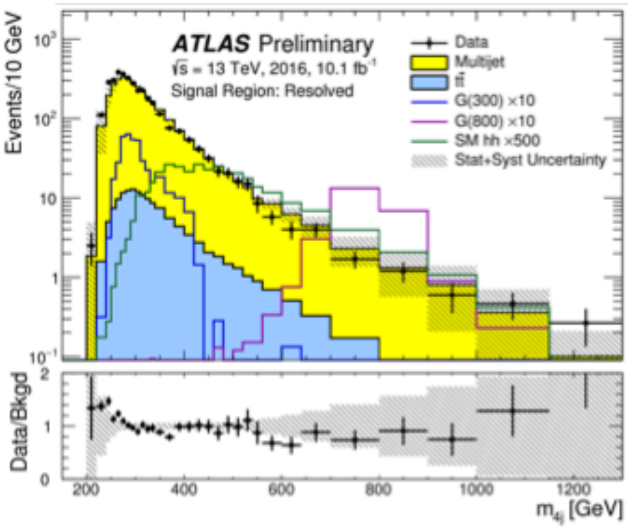


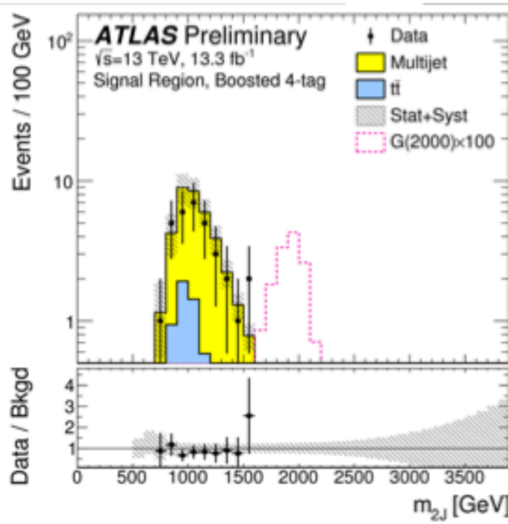
- Large improvements compared to Run 1

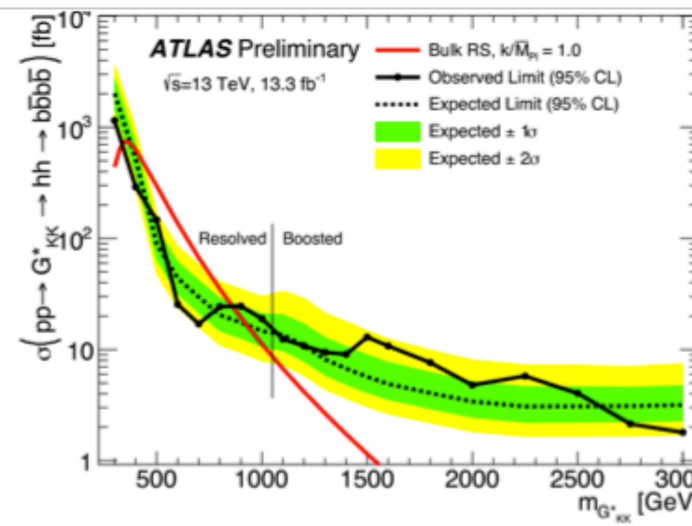
ATLAS results on hh→bbbb

Combine resolved and unresolved exploiting IBL detector for b-tagging

- **Main backgrounds**: multi-jet and ttbar for both searches
- **Resolved Analysis:**
  - multi-jet: data-driven
  - ttbar: modelled with MC
- **Boosted Analysis:**
  - multi-jet: data-driven
  - ttbar: data-driven normalization, shape from MC
- **Systematic Uncertainties:**
  - *b*-tagging is the main systematic uncertainty for both analyses.





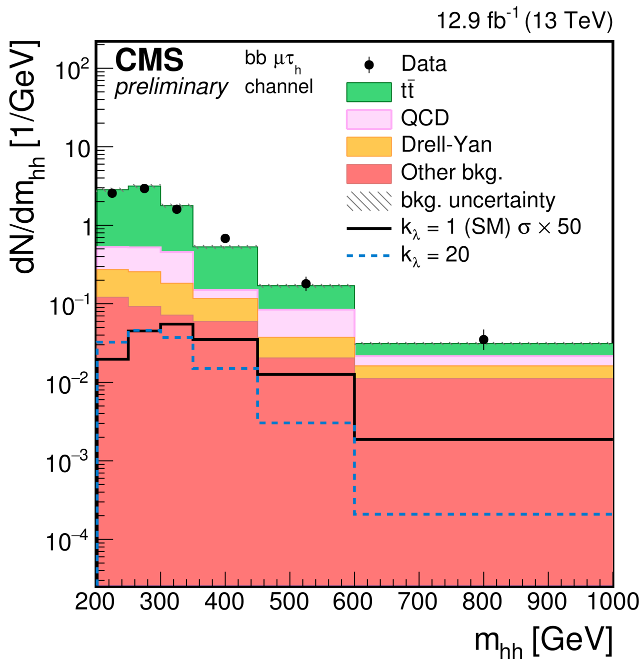


- **Results:**
- 95% CL limit is (pp → hh → bbbb) < 330 fb
- **Excluded mass range:**
- observed: 360 GeV < m(G_{KK})< 860 GeV

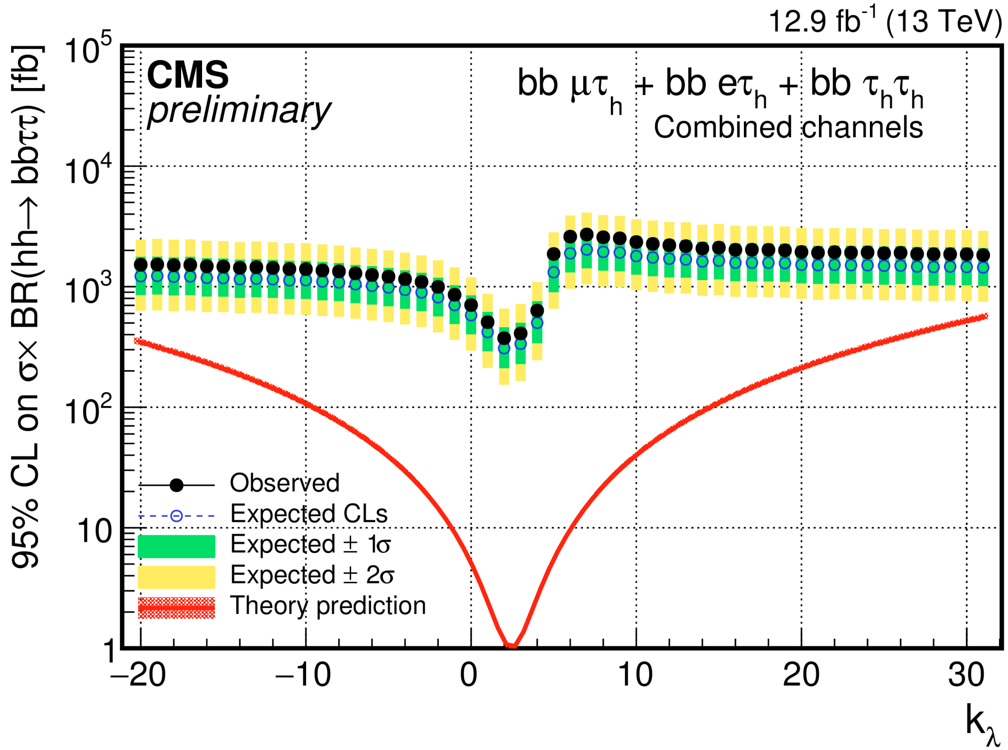
29 x the SM, expected may be somewhat larger

CMS double Higgs searches

- Resonant and non-resonant searches have been performed at 13 TeV in different channels using 2015 data
- bbττ has been updated with the full statistics before ICHEP



95% CL upper limits as function of the anomalous triliear couplings (~200 x the SM)



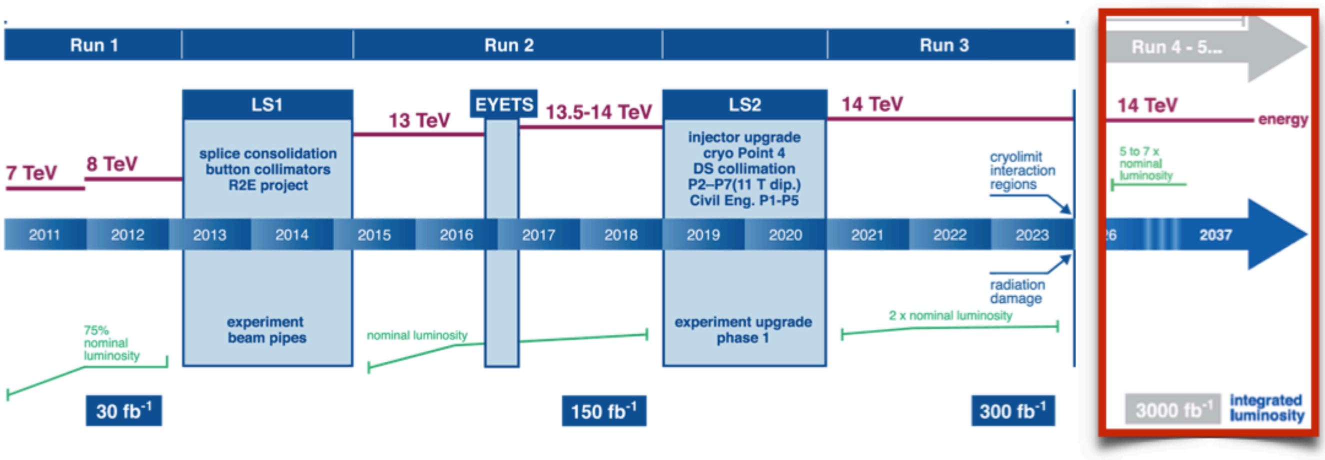
In summary, still

no deviations from SM expectations

Future

Future prospects

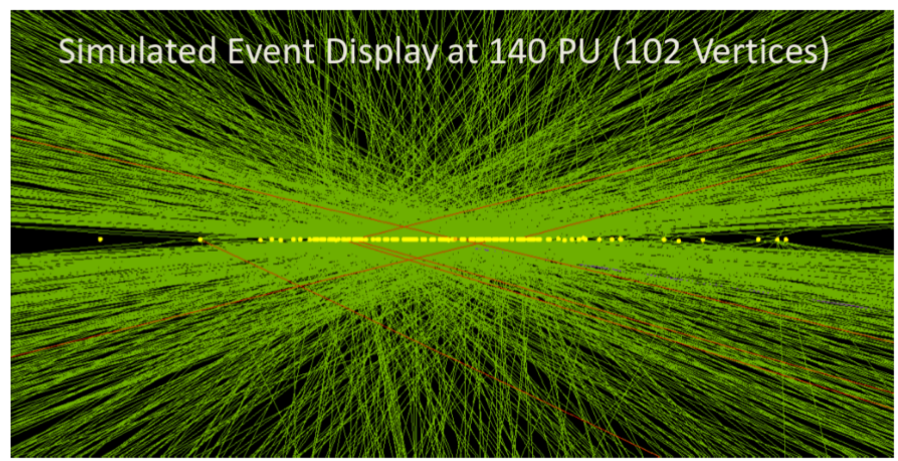
D. Gillberg, D. Sperka



HL-LHC

- During the HL-LHC beam intensity will increase to ×7.5 the design intensity
- Major detector detector upgrades needed

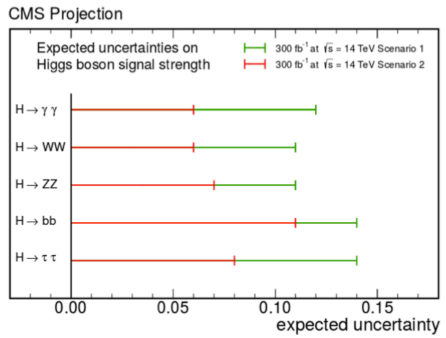
Higher PU, up to 140 interactions
Per beam crossing and more

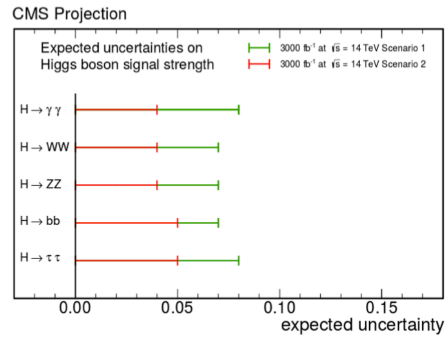


Signal strength and couplings projections

- Based on 8 TeV analyses, next iteration will surely be more accurate
- With Yellow Report 4 the LHCHXSWG has already improved the theory uncertainties
  by a factor 2
- **Important to also make projections on some ratios that have reduced theory errors, lumi error and others…**

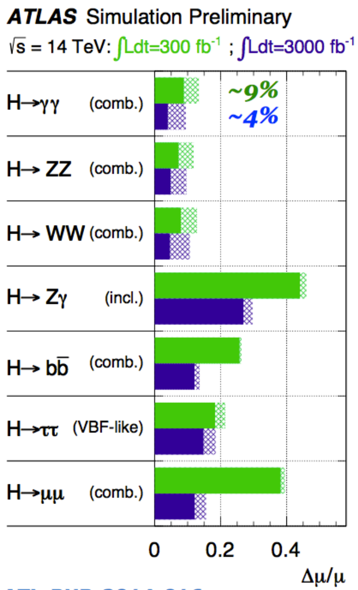
- Two scenarios for systematic uncertainties were considered:
  - Scenario 1: systematic unc. unchanged
  - Scenario 2: theoretical unc. scaled by 1/2, experimental unc. scaled by $1/\sqrt{\int \mathcal{L}}$





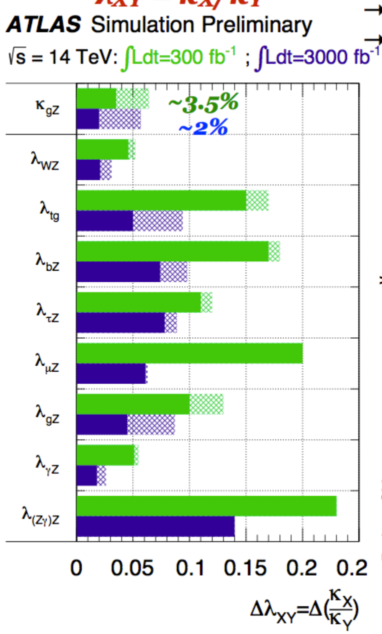
End of Run 3 (300 fb⁻¹): 6-14% uncertainty on signal strengths
HL-LHC (3000 fb⁻¹): 4-8% uncertainty on signal strengths

Precision on signal strength

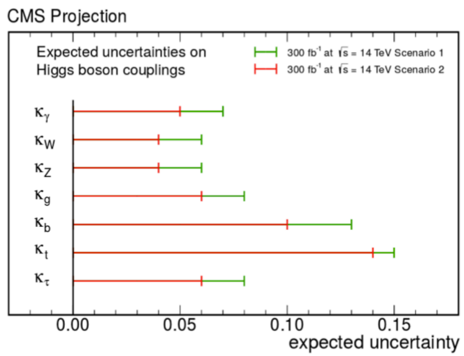


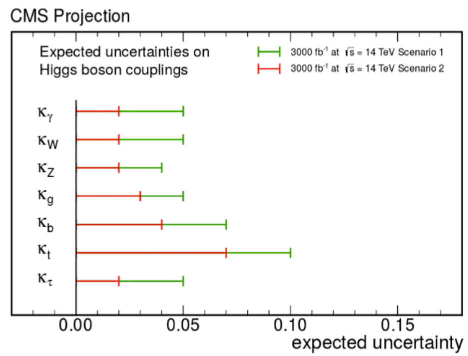
ATL-PUB-2014-016

Precision on Higgs coupling ratios: $\lambda_{XY} = \kappa_X/\kappa_Y$



rate
→ I(
→ R
→ R
→ H





End of Run 3 (300 fb⁻¹): 5-15% uncertainty on couplings
HL-LHC (3000 fb⁻¹): 4-8% uncertainty on couplings

H→μμ and rare decays

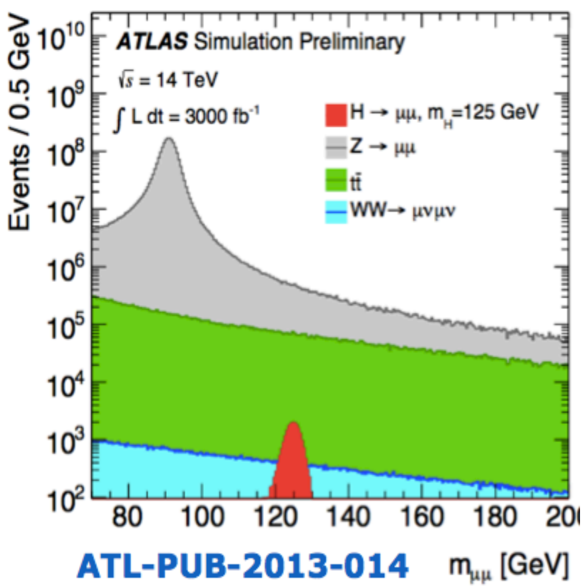
- H→μμ is the most promising channel to test the Higgs couplings to the second generation fermions

D. Gillberg, D. Sperka

ATLAS H→μμ and H→Zγ

H→μμ,
7.0σ **excess expected in 3 ab**$^{-1}$
~21% error on rate

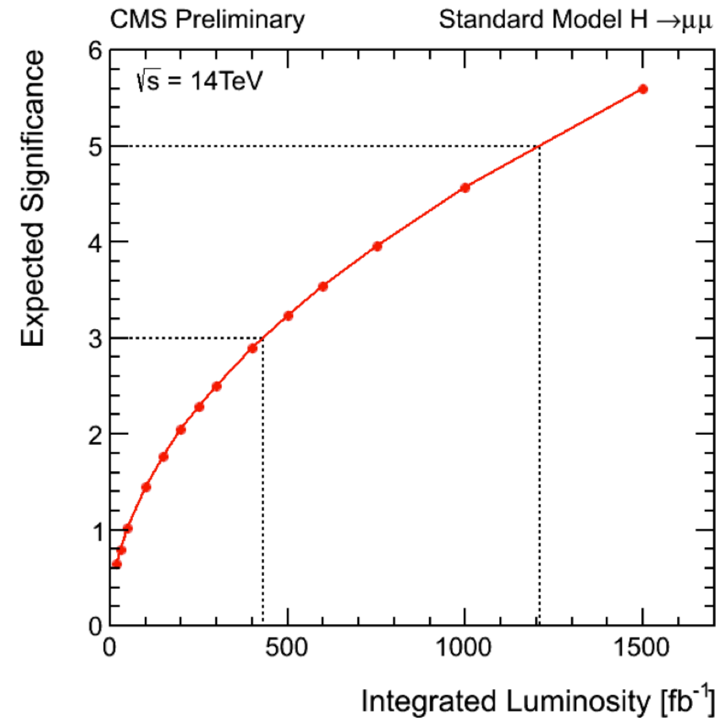
SM sensitivity (1σ) expected with ~70 fb^{-1} **(2018)**



ATL-PUB-2013-014

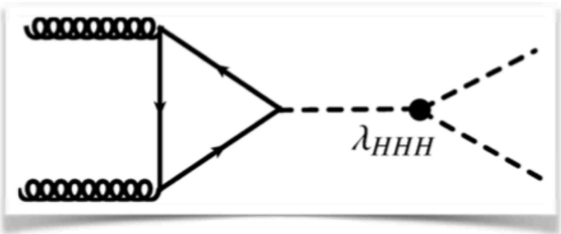
H→Zγ→eeγ, 3.9σ **excess expected in 3 ab**$^{-1}$
~25% uncertainty on rate

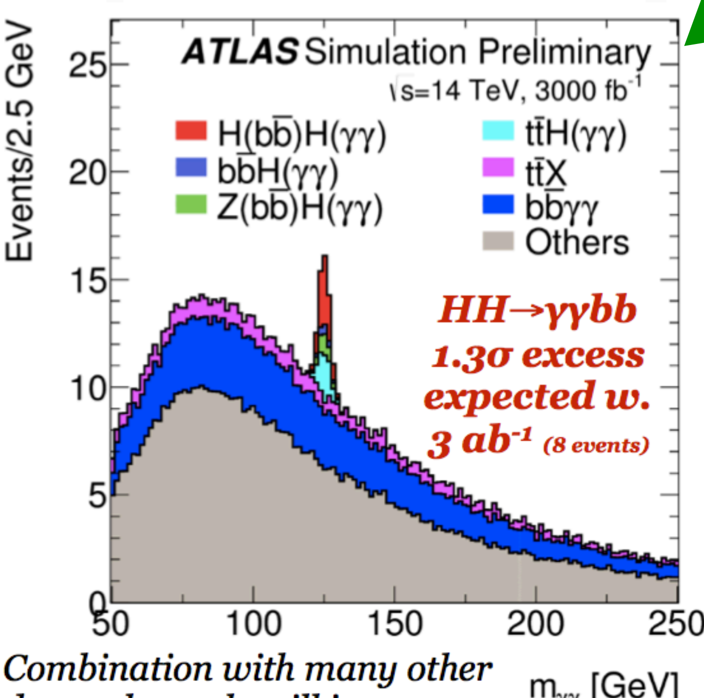
CMS: significance as function of IntL
Similar conclusion



Double Higgs production

The Higgs boson self coupling





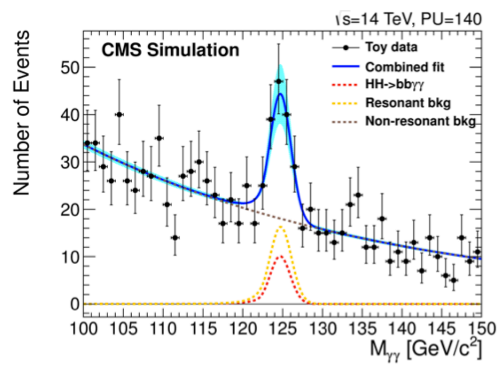
Combination with many other decay channels will improve the sensitivity.

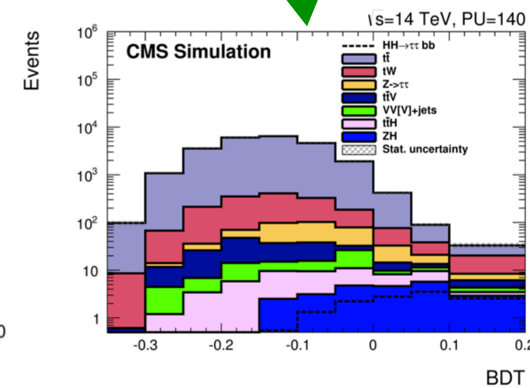
ATL-PUB-2014-019

ATLAS, simple cut and count analysis, can be improved

CMS uses bbγγ and bbττ

- Projections carried out using dedicated simulation of upgraded CMS detector
  - Combination of bbγγ and bbττ channels

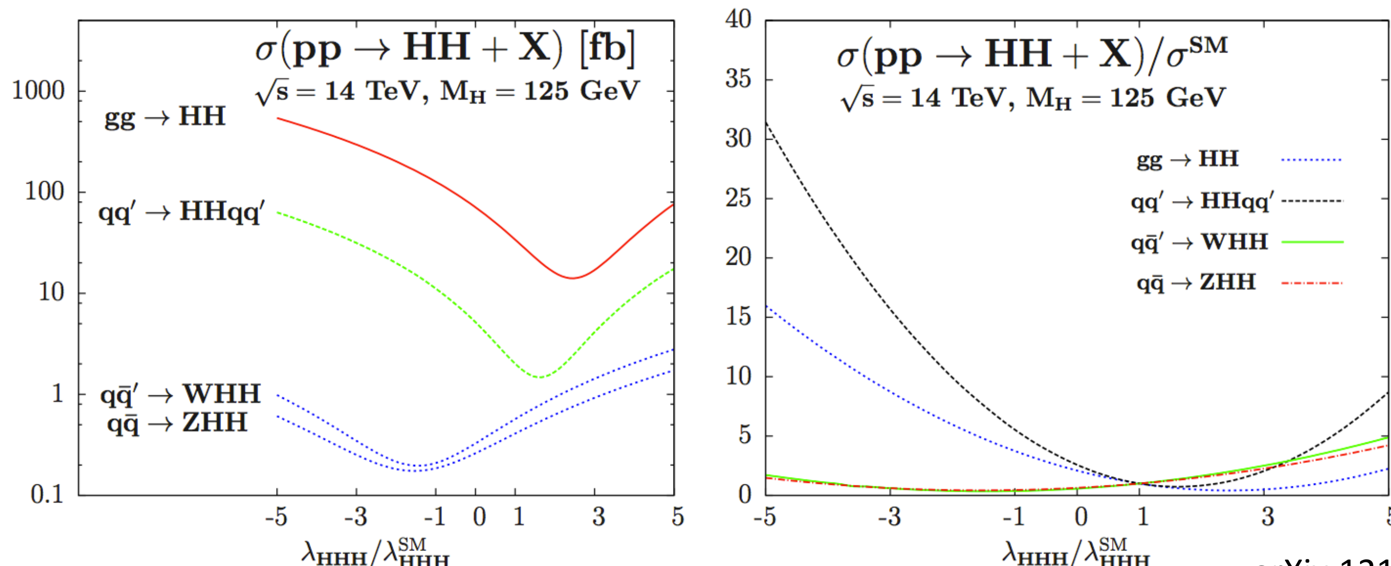




HL-LHC (3000 fb⁻¹): ~2σ significance, ~54% unc. on cross section

Final reach for Higgs self coupling

- We currently estimate 1.5-2 σ per experiment at the end of HL-LHC, more channels, improvements in the analysis…
- Generic statements that we may reach 3σ with 3 ab^{-1}
  - A complete analysis should be made at some point to clarify the issue
- But note that the sensitivity is expressed for double Higgs production, NOT for triple Higgs coupling
- Still we will be sensitive to large deviations



arXiv:1212.5581 [hep-ph]

Summary

and

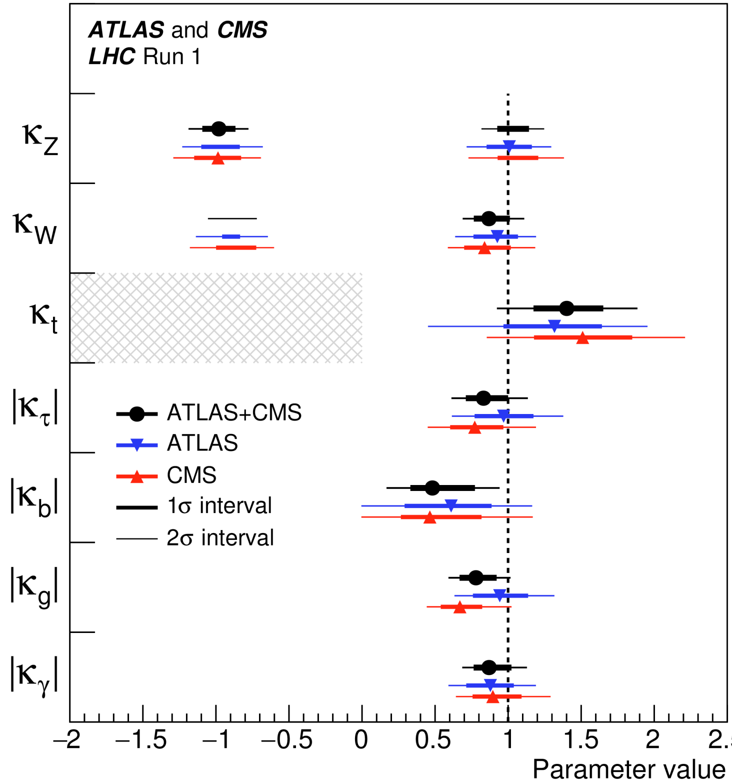
Outlook

What to keep an eye on

- Largest discrepancies observed (only at the 10% level and fully compatible with statistics) were in ttH and H->bb
- Analyses of Run 2 data for now seem to go in the same direction

p-values of combined ATLAS+CMS fits

Parameterisation	p-value	DOF	Parameters
Global signal strength	40%	1	μ
Production processes	24%	5	$\mu_{ggF}, \mu_{VBF}, \mu_{WH}, \mu_{ZH}, \mu_{ttH}$
Decay modes	65%	5	$\mu^{\gamma\gamma}, \mu^{ZZ}, \mu^{WW}, \mu^{\tau\tau}, \mu^{bb}$
Decay modes with $H \to \mu\mu$	75%	6	$\mu^{\gamma\gamma}, \mu^{ZZ}, \mu^{WW}, \mu^{\tau\tau}, \mu^{bb}, \mu^{\mu\mu}$
μ_V and μ_F per decay	90%	10	$\mu_V^{\gamma\gamma}, \mu_V^{ZZ}, \mu_V^{WW}, \mu_V^{\tau\tau}, \mu_V^{bb}, \mu_F^{\gamma\gamma}, \mu_F^{ZZ}, \mu_F^{WW}, \mu$
μ_V/μ_F ratio	75%	6	$\mu_V/\mu_F, \mu_F^{\gamma\gamma}, \mu_F^{ZZ}, \mu_F^{WW}, \mu_F^{\tau\tau}, \mu_F^{bb}$
$\sigma_i \cdot B^f$ product	20%	23	$(\sigma\cdot B)_{ggF}^{\gamma\gamma}, (\sigma\cdot B)_{ggF}^{ZZ}, (\sigma\cdot B)_{ggF}^{WW}, (\sigma\cdot B)_{ggF}^{\tau\tau}, (\sigma\cdot B)_{VBF}^{ZZ}, (\sigma\cdot B)_{VBF}^{WW}, (\sigma\cdot B)_{VBF}^{\tau\tau}, (\sigma\cdot B)_{WH}^{ZZ}, (\sigma\cdot B)_{WH}^{WW}, (\sigma\cdot B)_{WH}^{\tau\tau}, (\sigma\cdot B)_{ZH}^{\gamma\gamma}, (\sigma\cdot B)_{ZH}^{ZZ}, (\sigma\cdot B)_{ZH}^{WW}, (\sigma\cdot B)_{ZH}^{\tau\tau}, (\sigma\cdot B)_{ttH}^{\gamma\gamma}, (\sigma\cdot B)_{ttH}^{ZZ}, (\sigma\cdot B)_{ttH}^{WW}, (\sigma\cdot B)_{ttH}^{\tau\tau},$
Ratios of σ and BR relative to $\sigma(gg \to H \to ZZ)$	16%	9	$\sigma(gg \to H \to ZZ), \sigma_{VBF}/\sigma_{ggF}, \sigma_{WH}/\sigma_{ggF}, \sigma_{ttH}/\sigma_{ggF}, B^{WW}/B^{ZZ}, B^{\gamma\gamma}/B^{ZZ}, B^{\tau\tau}/B^{ZZ},$
Ratios of σ and BR relative to $\sigma(gg \to H \to ZZ)$ and 7/8 TeV	26%	14	$\sigma(gg \to H \to ZZ), \sigma_{VBF}/\sigma_{ggF}, \sigma_{WH}/\sigma_{ggF}, \sigma_{ttH}/\sigma_{ggF}, B^{WW}/B^{ZZ}, B^{\gamma\gamma}/B^{ZZ}, B^{\tau\tau}/B^{ZZ}$ $\sigma_{ggF}^{7TeV}/\sigma_{ggF}^{8TeV}, \sigma_{VBF}^{7TeV}/\sigma_{VBF}^{8TeV}, \sigma_{WH}^{7TeV}/\sigma_{WH}^{8TeV}, \sigma$ $\sigma_{ttH}^{7TeV}/\sigma_{ttH}^{8TeV}$
Coupling ratios	12%	7	$\kappa_{gZ}, \lambda_{Zg}, \lambda_{tg}, \lambda_{WZ}, \lambda_{\gamma Z}, \lambda_{\tau Z}, \lambda_{bZ}$
Couplings, SM loops	74%	6	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b, \kappa_\mu$
Couplings vs mass	55%	2	M, ϵ
Couplings, BSM loops	11%	7	$\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_b, \kappa_g, \kappa_\gamma$
BSM loops only	87%	2	κ_g, κ_γ
Fermion and vector couplings	64%	2	$\lambda_{FV}, \kappa_{VV}$
Up vs down couplings	72%	3	$\lambda_{du}, \lambda_{Vu}, \kappa_{uu}$
Lepton vs quark couplings	79%	3	$\lambda_{lq}, \lambda_{Vq}, \kappa_{qq}$



Interesting NMSSM model proposed by C. Wagner and collaborators with stop quarks in the gluon fusion loop would account for it

Summary

- Thanks to the excellent performance of the LHC, ATLAS and CMS are collecting a lot of data and analyzing them promptly
- Lots of measurements and searches have been reported by ATLAS and CMS
- New interpretations are starting to be carried out (**simplified template cross sections)**
- Fiducial and differential measurements will become more important with higher statistics

- **No significant deviations observed (yet)**

Outlook

- Higgs boson properties are among the most interesting measurements at the LHC
- After discovering the Higgs boson, we should measure its properties as well as we can
- Precise measurements may reveal BSM physics:
  - SM extensions, dark matter, …
- Keep searching for BSM effects in the Higgs sector
  - BSM decays, additional Higgs bosons
- It may take longer that we are used to, in some cases precision physics takes time
  - in many cases systematic uncertainties will start to dominate soon (did not happen in Run 1)
  - theory community will play a major role in the understanding of signal and backgrounds
- **I believe that we have a very exciting experimental program ahead of us**