Yukawa Couplings of the Higgs boson at LHC

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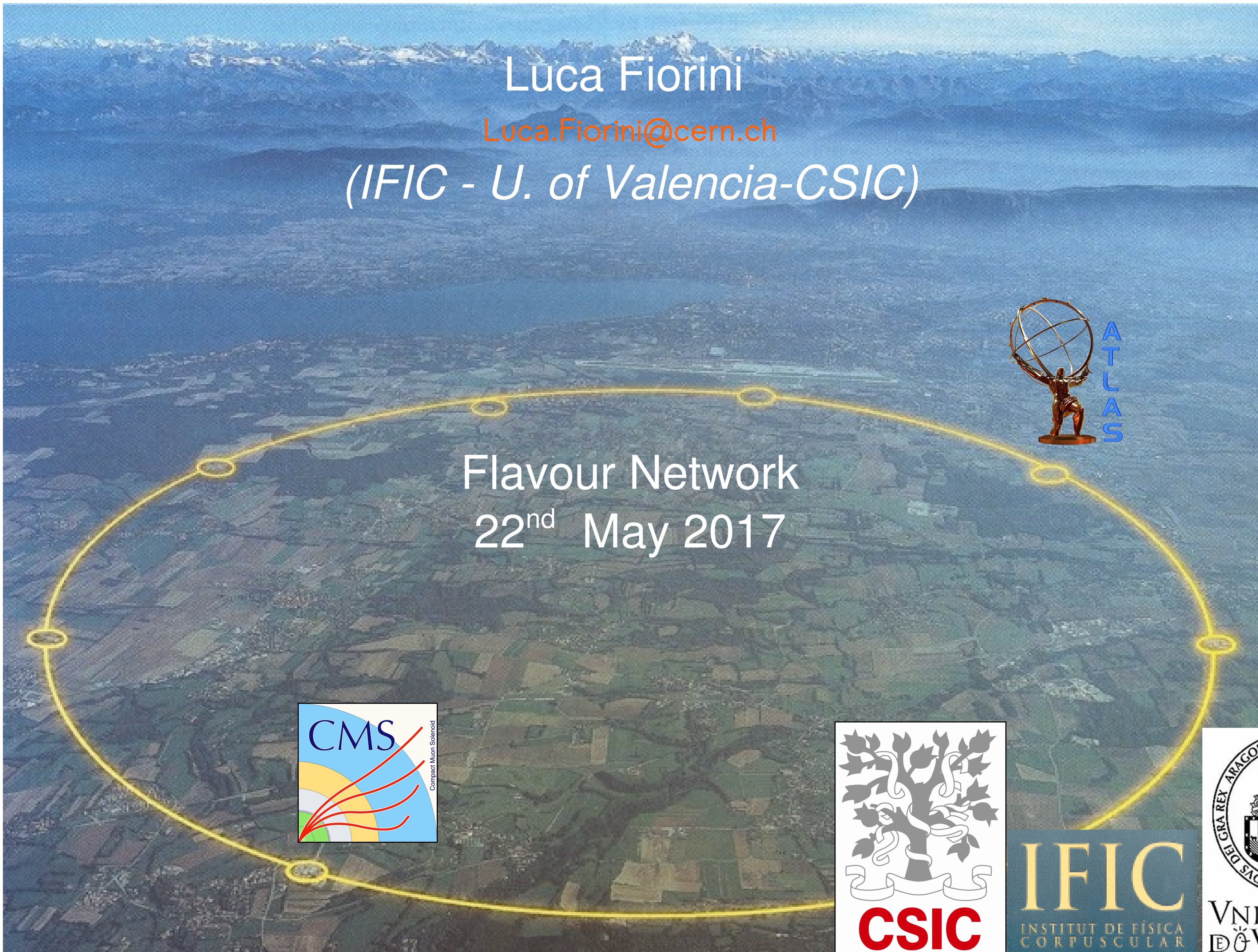
Flavour Network
22nd May 2017

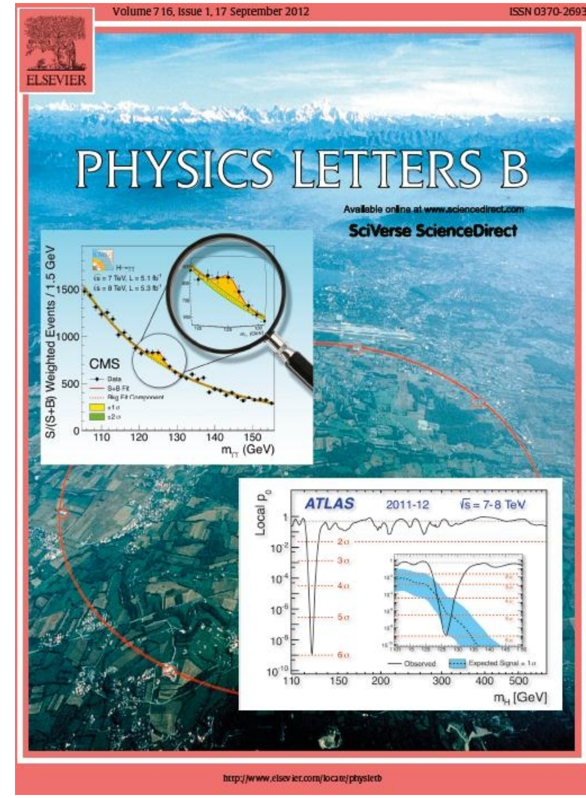


Outline

- Higgs boson Yukawa couplings
- Experimental performance
- Higgs Physics Results @ LHC:
  - Diagonal terms:
    - $H \to \tau\tau$
    - VH/VBF $H \to bb$
    - $H \to \mu\mu$
    - $H \to J/\psi\,\gamma$, $H \to \Upsilon\gamma$ and $H \to \phi\gamma$
    - ttH production
    - Combination
  - Off-diagonal terms:
    - LFV $H \to \tau e/\mu$, $\to e\mu$
    - FCNC $t \to Hc/u$

Green := 13 TeV results

- Not covered here:
  - Indirect access to fermions couplings e.g. $H \to \gamma\gamma$ and ggH production
  - Future Prospects for LHC upgrades



Higgs couplings to fermions

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

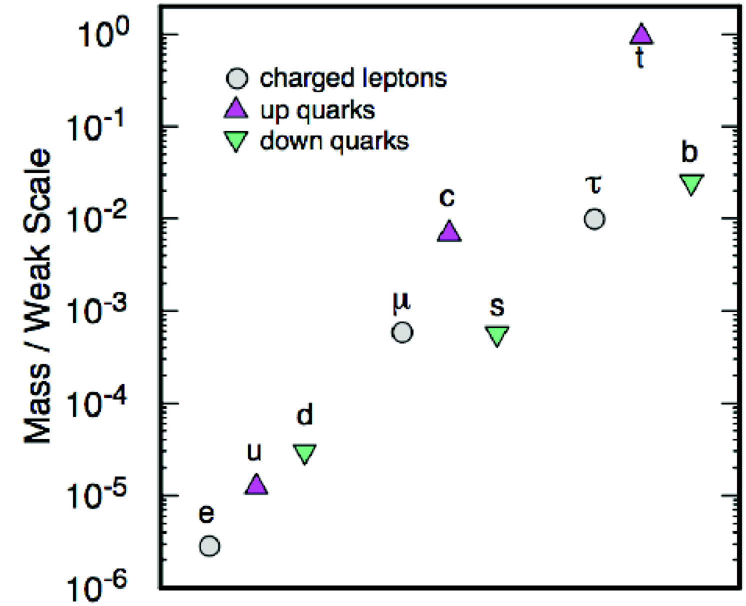
Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

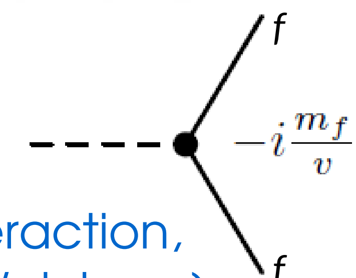
A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)



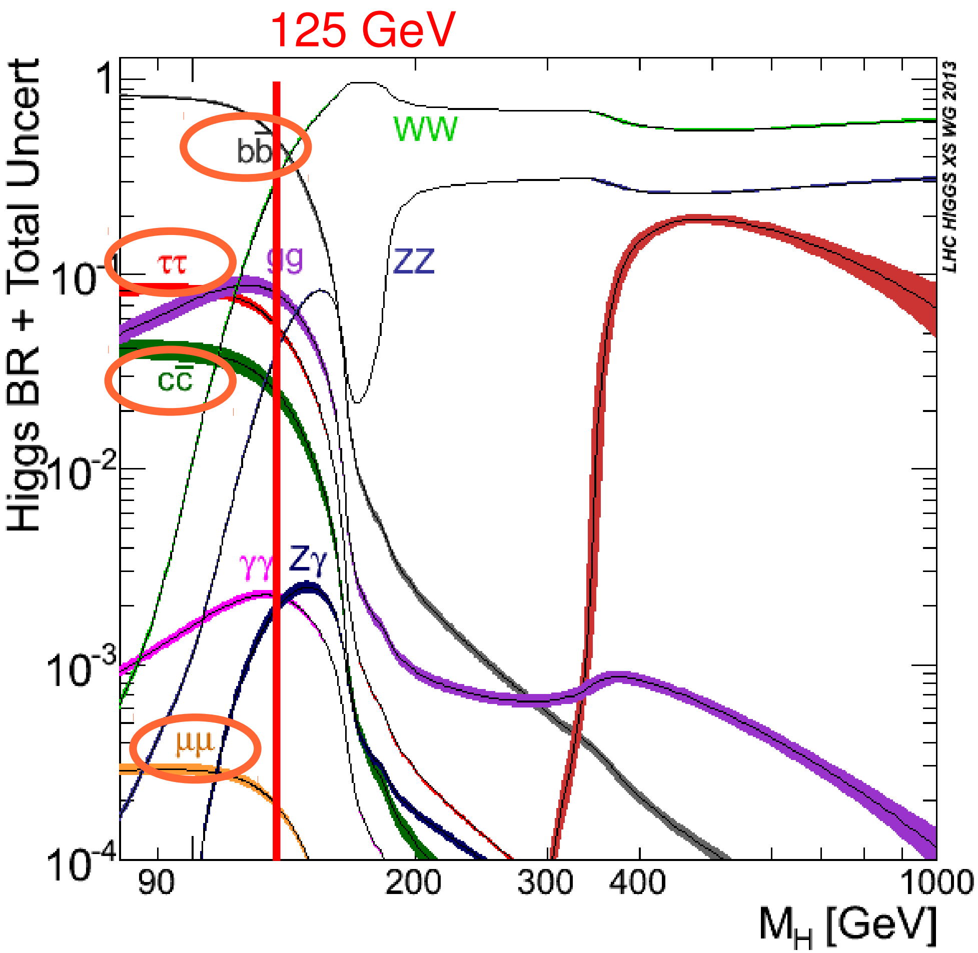
$$\mathcal{L}_{\rm Yuk} = -\sum_f \left(m_f + \frac{m_f}{v} H\right) \overline{\psi}_f \psi_f + \cdots$$

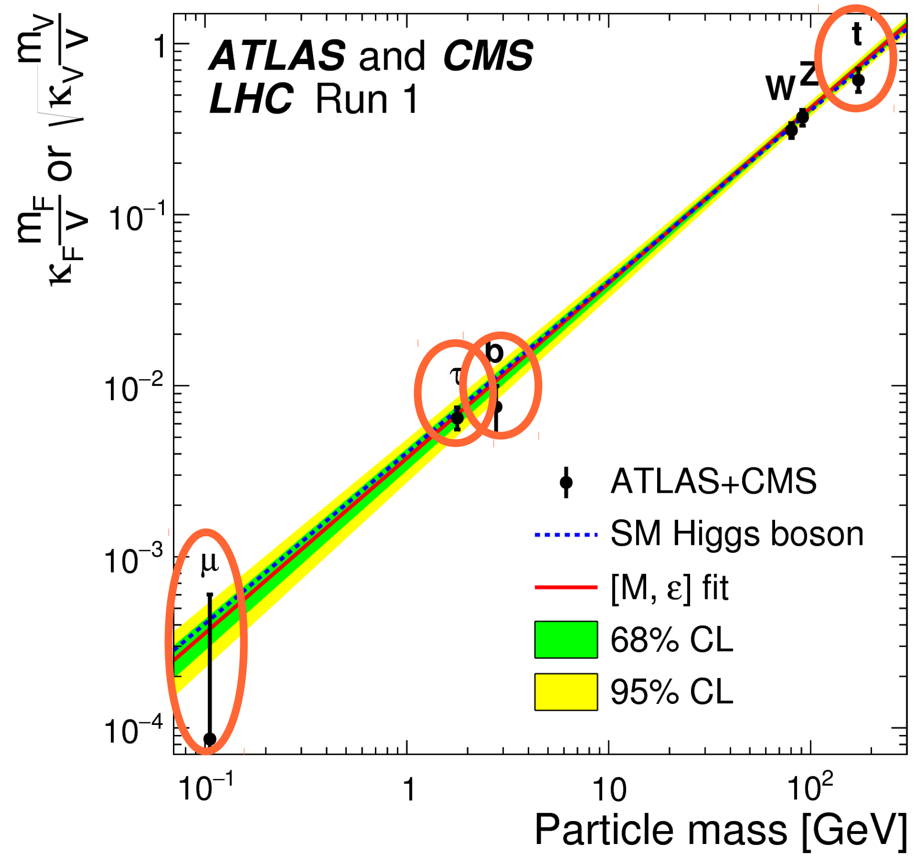
Yukawa coupling



- In the SM the Higgs field couples to fermions through a Yukawa interaction, which was not formalzied in first seminal papers (introduced by S. Weinberg).
- Coupling strength between the SM Higgs boson and fermions is proportional to the mass of the fermion.
- Deviation of couplings, asymmetries in up/down type quarks, evidence of (large) lepton flavour violation or flavour changing neutral current would be sings of new physics.

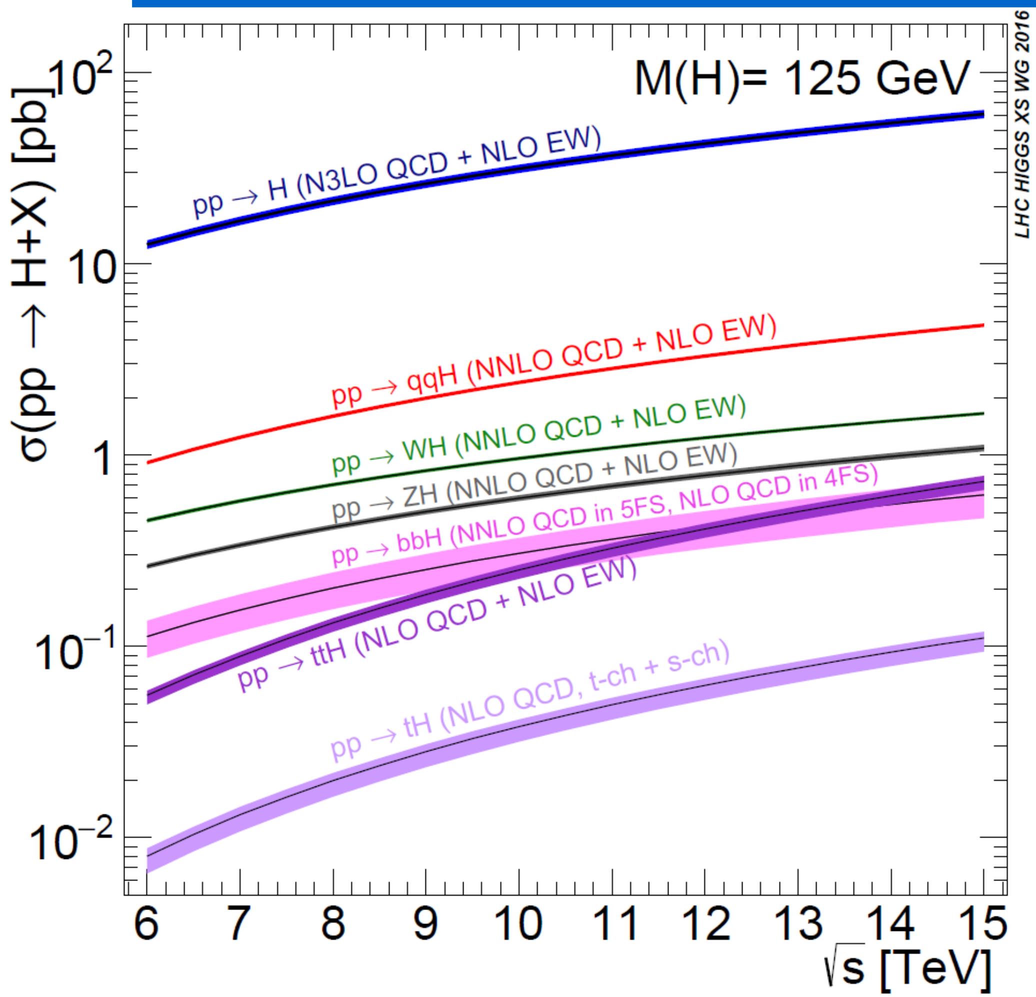
Higgs Decay Modes





Fermionic decay modes provide direct measurement of the Yukawa coupling.
Bosonic modes can also provide indirect measurement of couplings to quarks at LHC (via virtual loops).

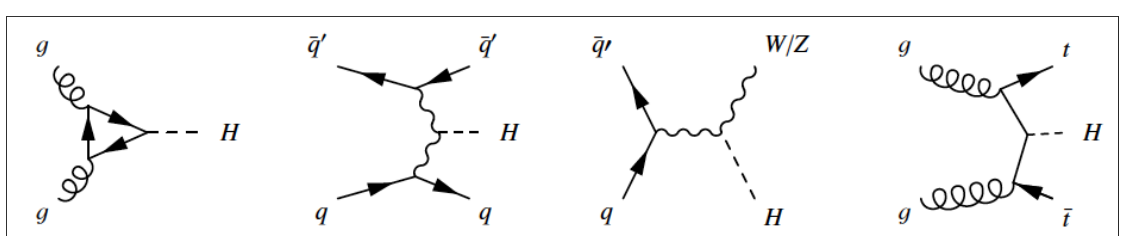
Higgs Production Modes at LHC



Total x-section:

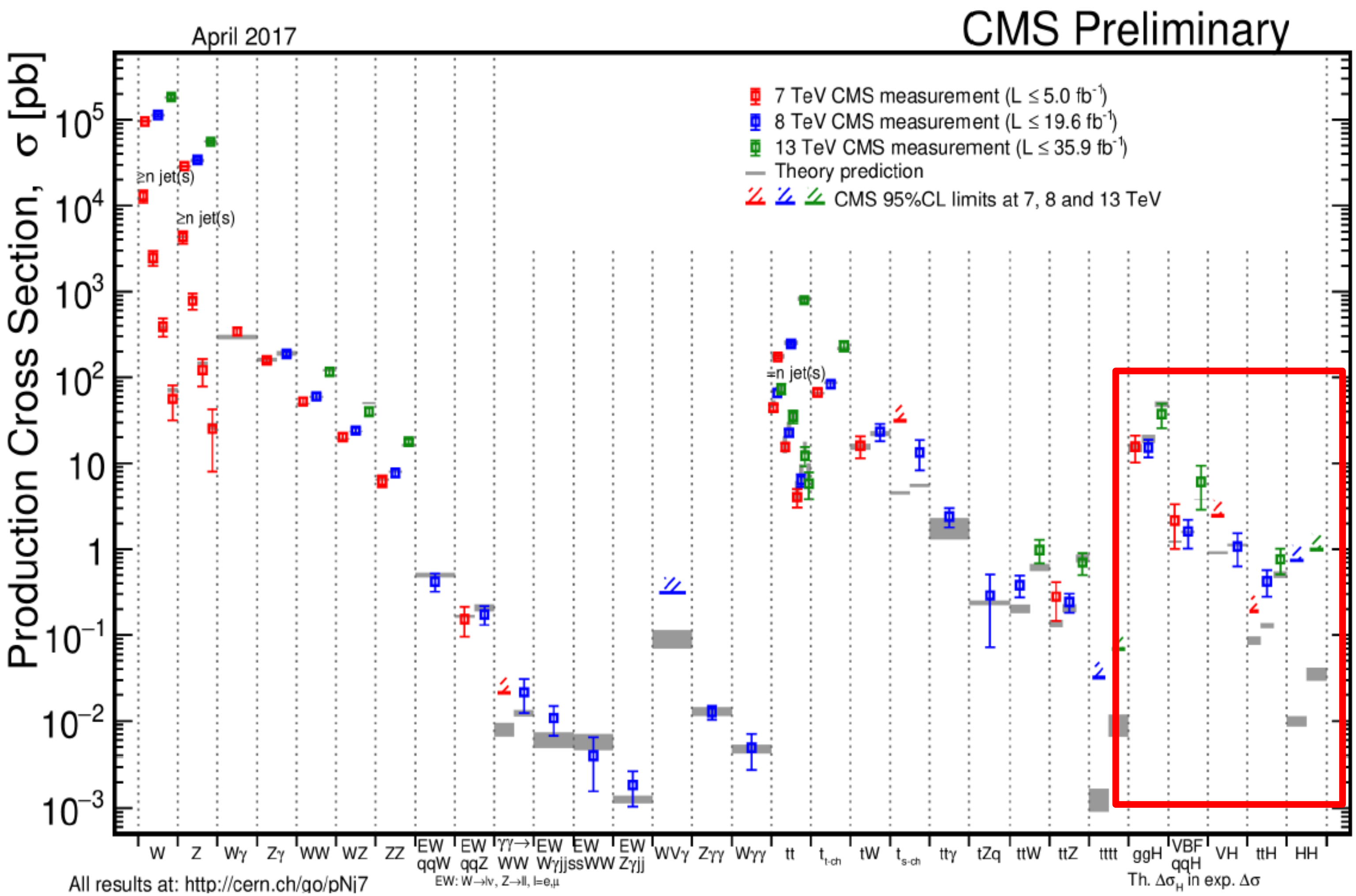
17 pb (17000 evts/fb^{-1}) @7 TeV
22 pb (22000 evts/fb^{-1}) @8 TeV
55 pb (55000 evts/fb^{-1}) @13TeV

- ttH and bbH provide direct measurement of Yukawa coupling, but they are not easily accessible.
- ggH provides indirect measurement of couplings to quarks at LHC via virtual loops.



(a) $gg \to H$	(b) VBF	(c) VH	(d) $t\bar{t}H$
87%	7%	5%	<1%

Summary of SM results

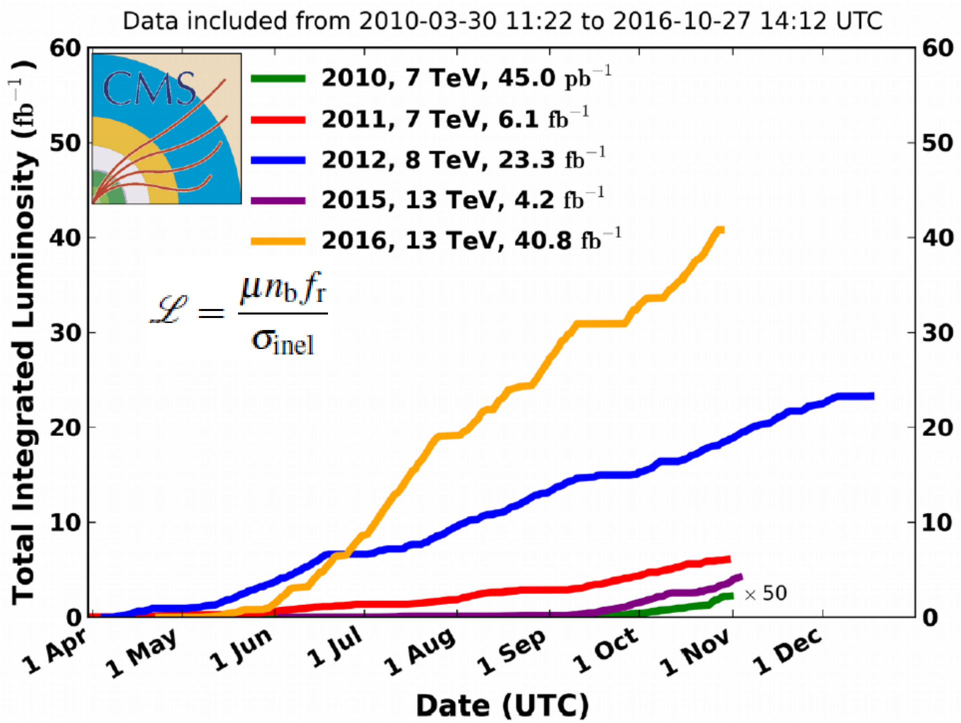


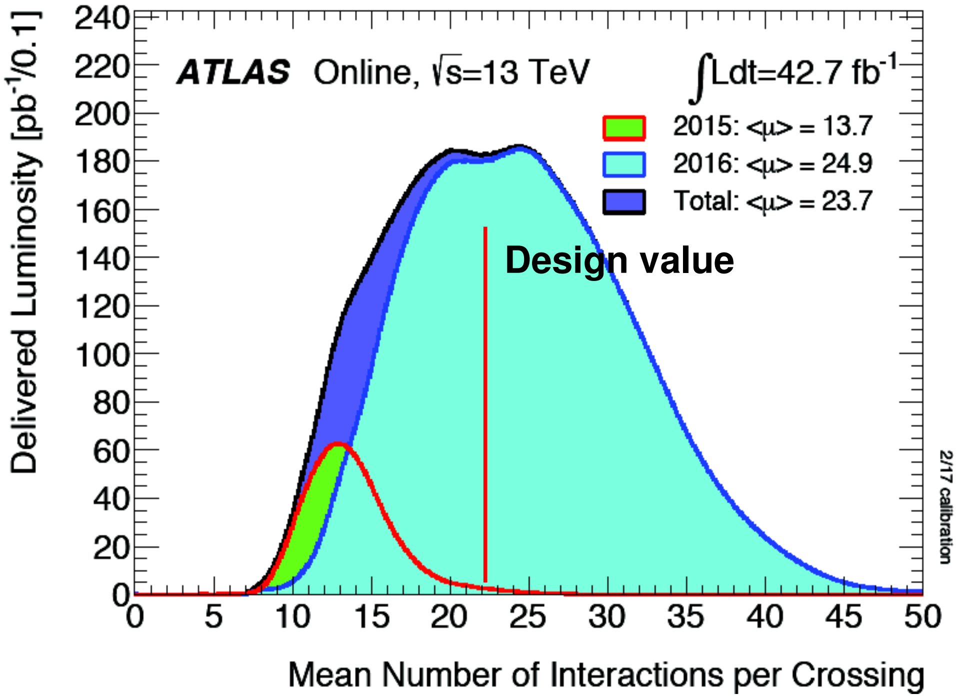
- Good agreement with SM expectations within uncertainties.
- Experimental uncertainties are in some cases at the level of the theor. predictions

Measurements of the Higgs cross-sections down to few pb (~tens of fb in some cases if we include also the BR).

LHC Luminosity and interactions per bunch crossing

Luminosity is measured with forward/tracking detectors and calibrated with beam separation scans





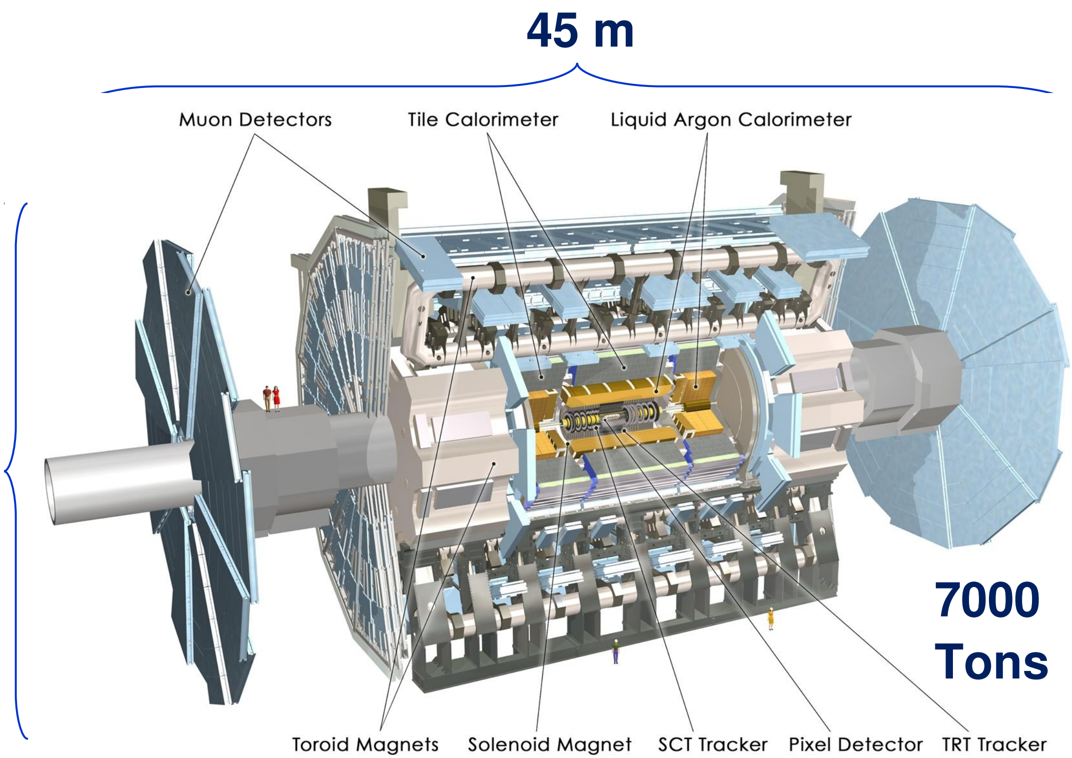
~29 fb^{-1} of data delivered during Run 1 and about 45 fb^{-1} during Run 2 so far.

- Pileup already above design level,thanks to excellent performance of the LHC.
- Peak luminosity ($cm^{-2} s^{-1}$): 7.7×10^{33} (2012), 1.4×10^{34} (2016).

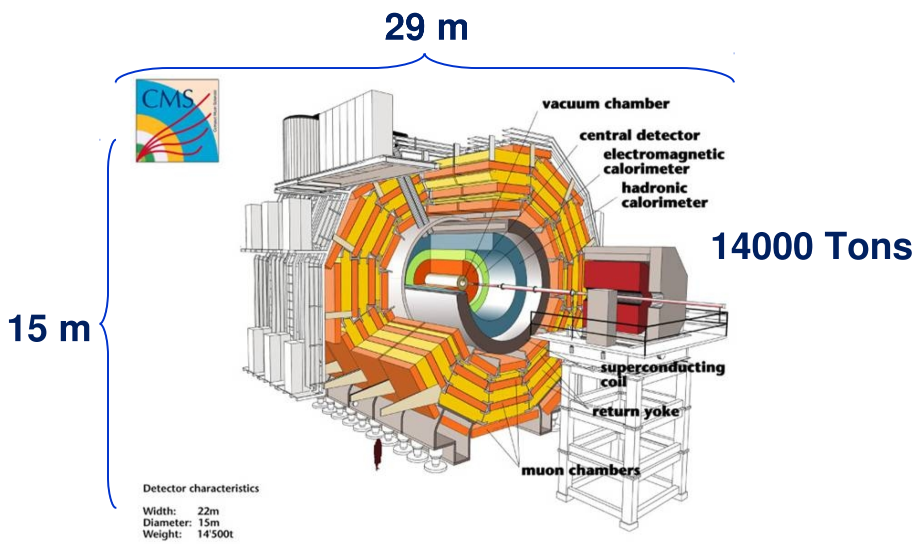
ATLAS Detector

	ATLAS
Magnetic field	2 T solenoid + toroid: 0.5 T (barrel), 1 T (endcap)
Tracker	Silicon pixels and strips + transition radiation tracker $\sigma/p_T \approx 5 \cdot 10^{-4} p_T + 0.01$
EM calorimeter	Liquid argon + Pb absorbers $\sigma/E \approx 10\%/\sqrt{E} + 0.007$
Hadronic calorimeter	Fe + scintillator / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)
Trigger	L1 + HLT (L2+EF)

ATLAS Collaboration
38 Countries
175 Institutions
3000 Scientific Authors total
(~2000 with a PhD)



CMS Detector



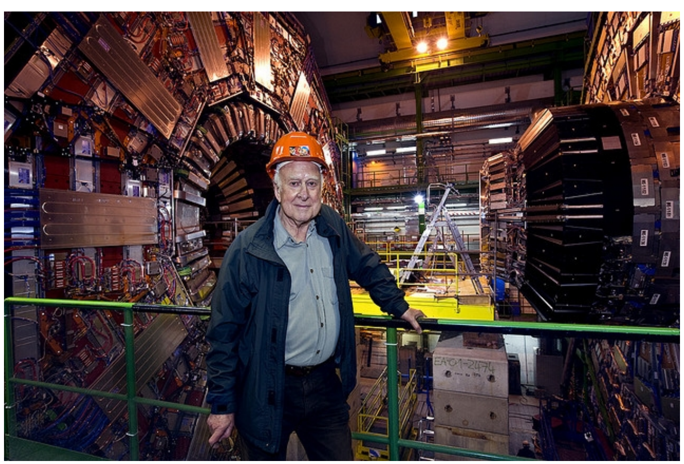
CMS Collaboration

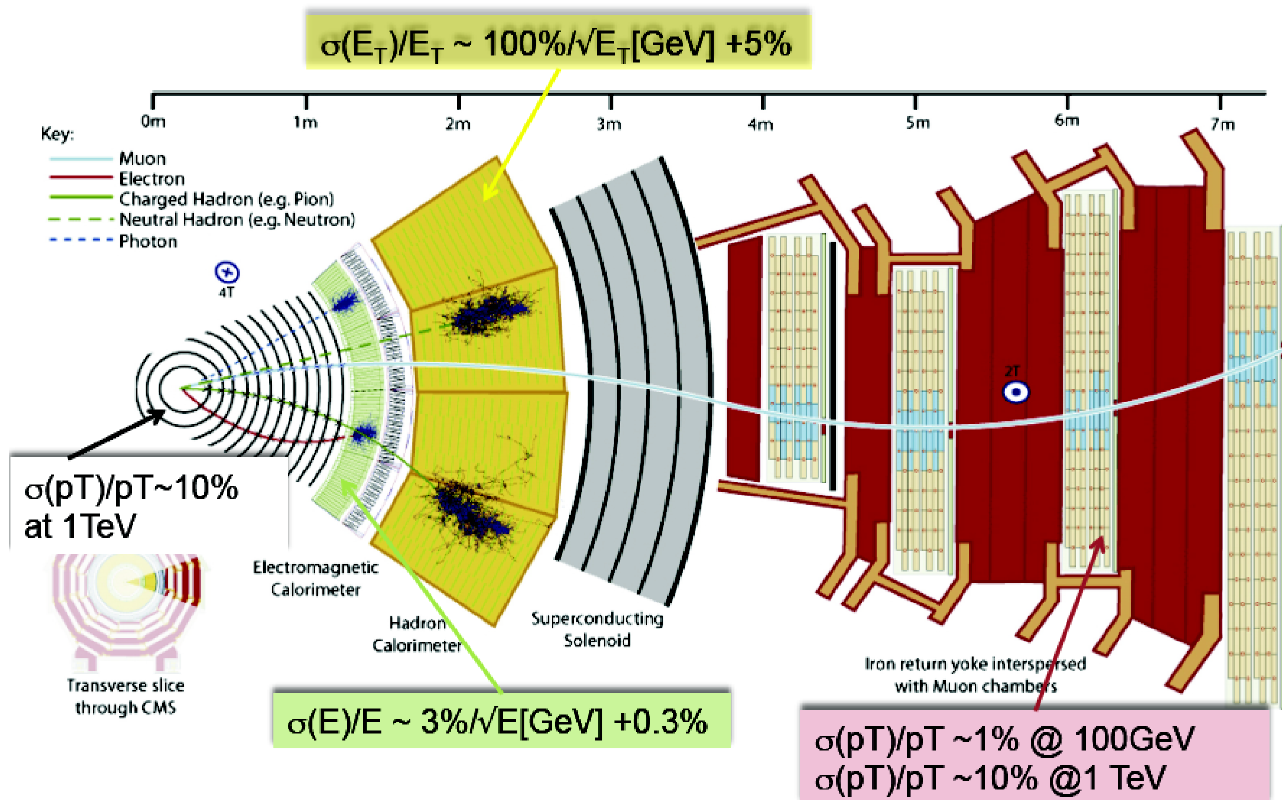
42 Countries

182 Institutions

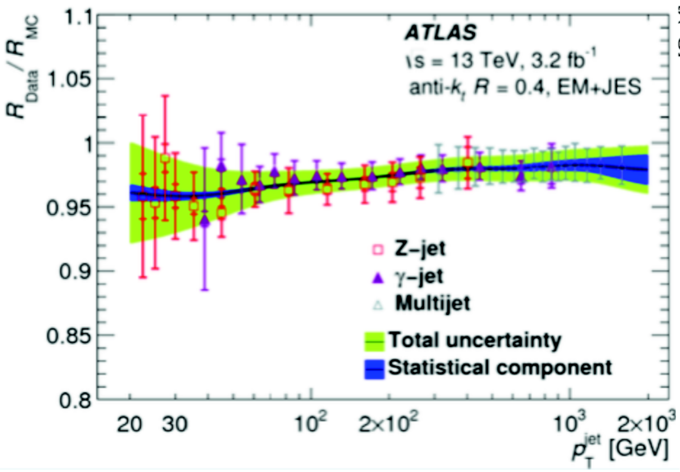
3300 Scientific Authors total

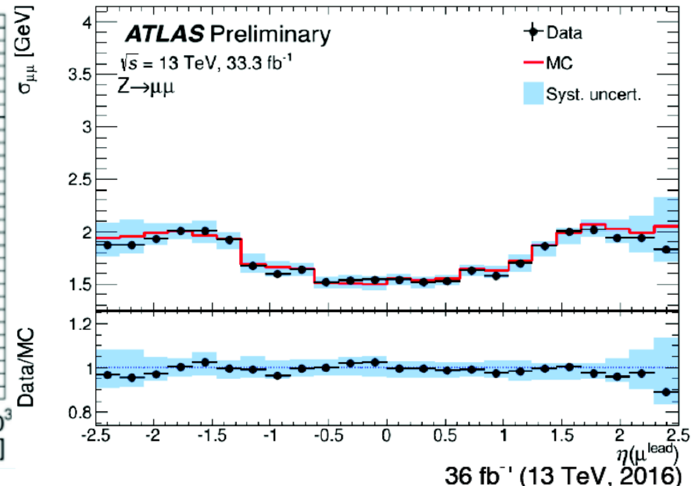
(~900 students)

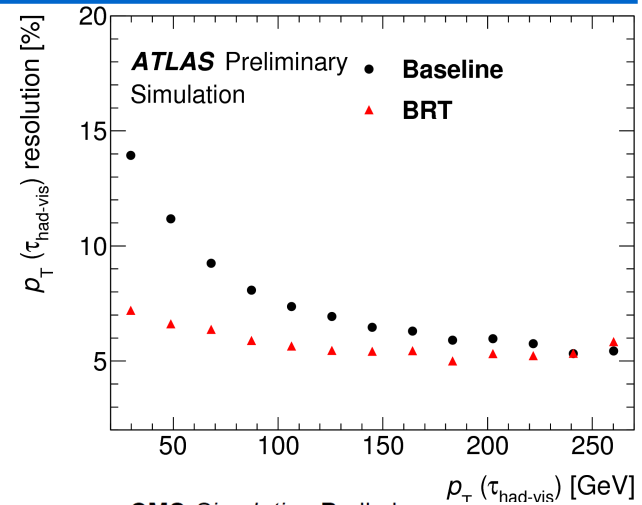


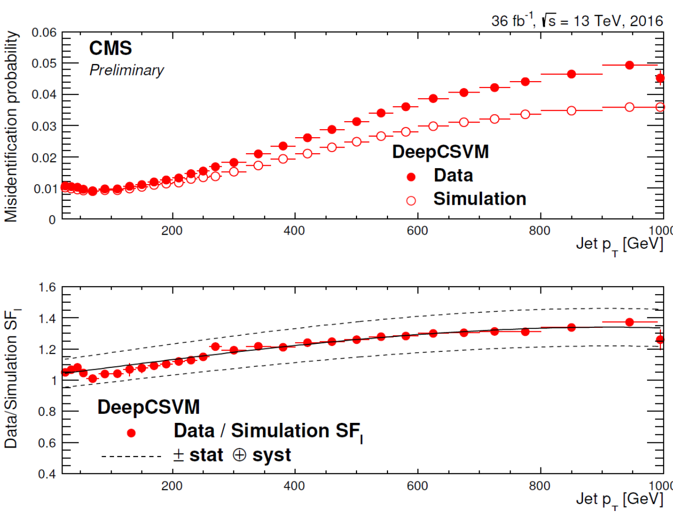


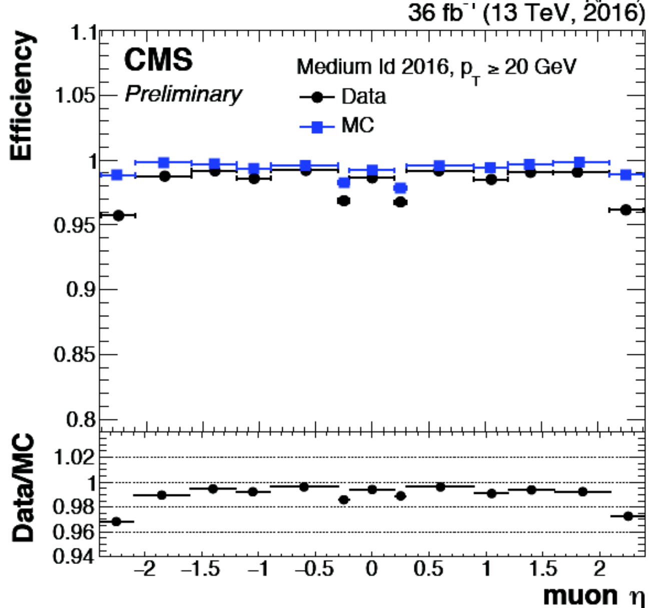
Reconstruction Performance

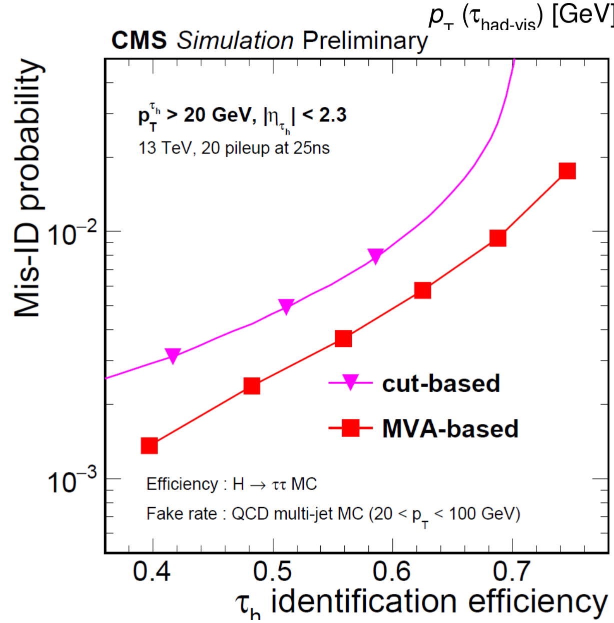






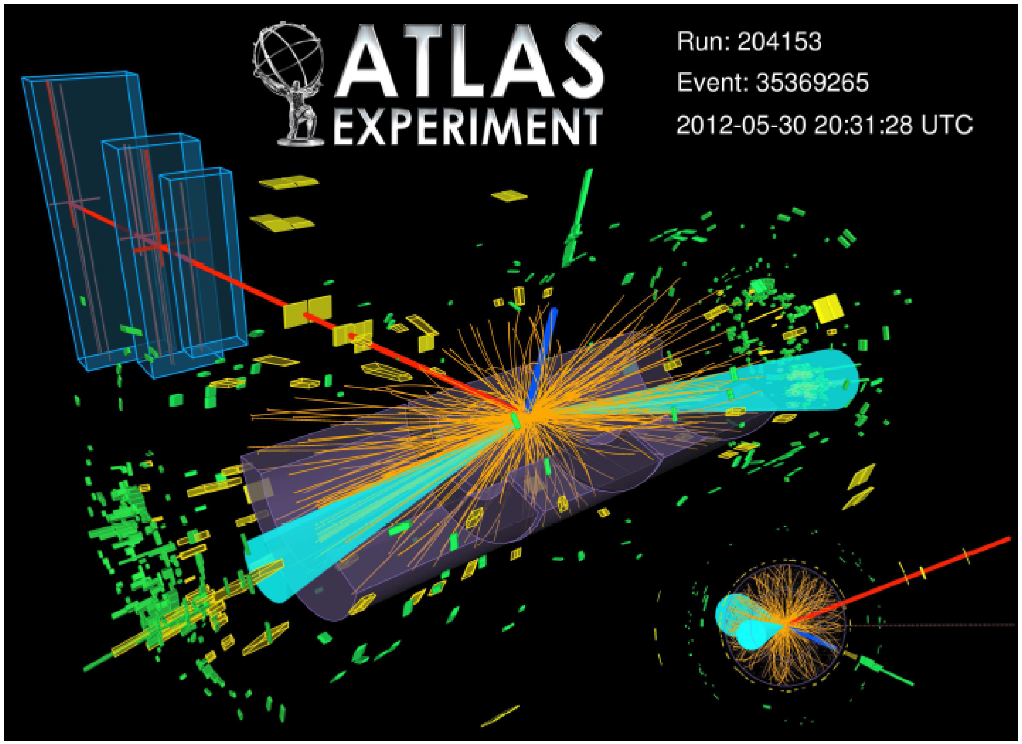


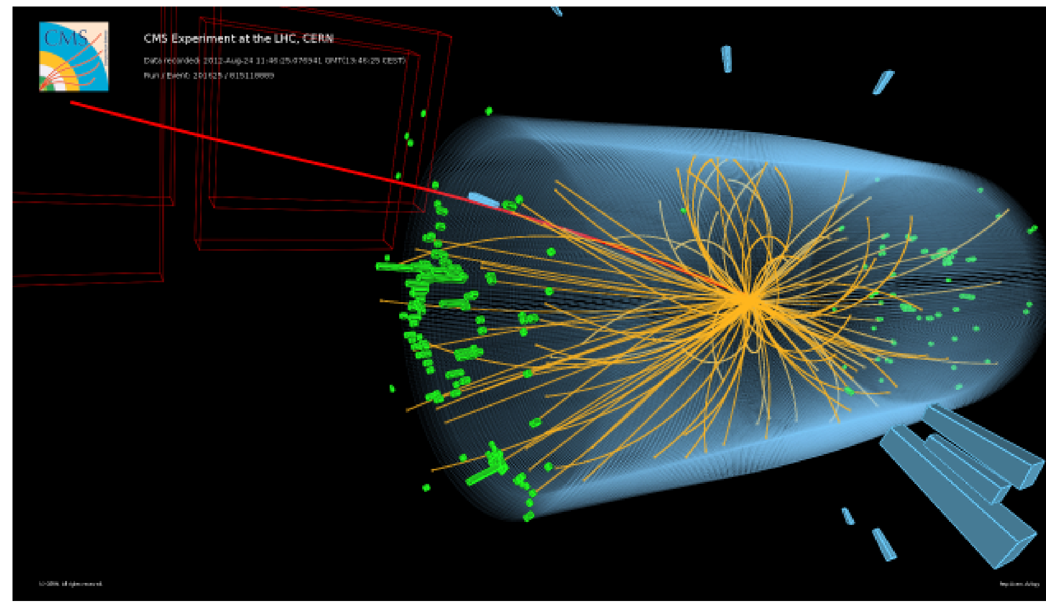




- Despite using different techniques, both experiments achieved a precise knowledge of the Jet Energy scale and its uncertainties.
- Isolation requirements are frequently applied to leptons to reduce the fake rate.
- The experiments succeeded in obtaining a low dependence wrt pileup observables.

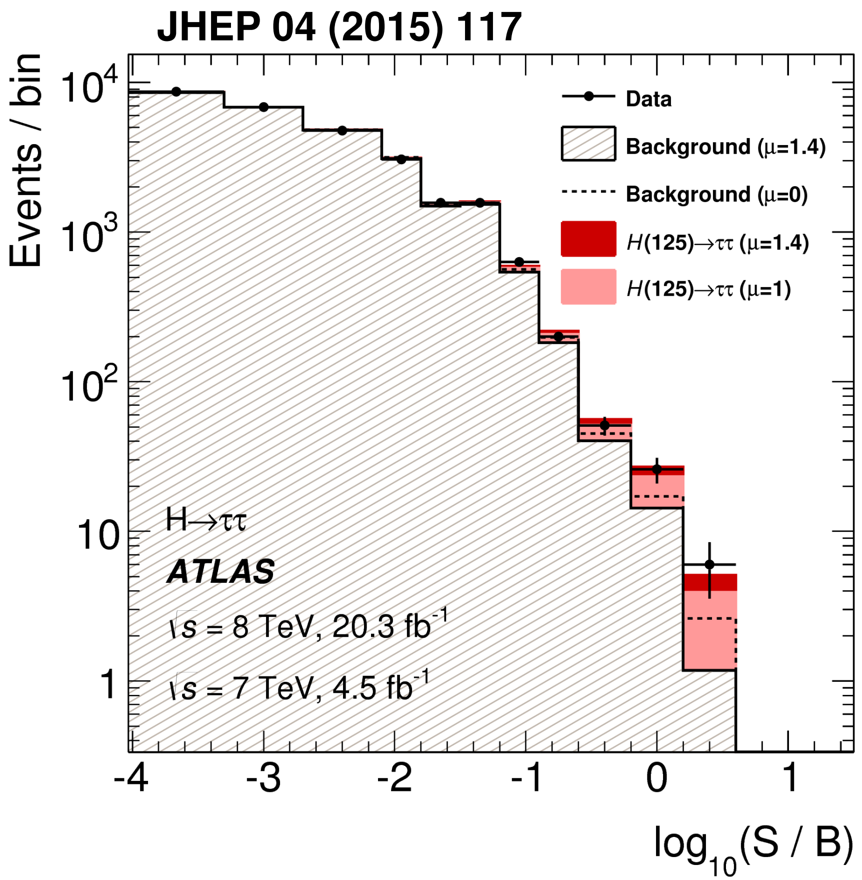
Higgs decays

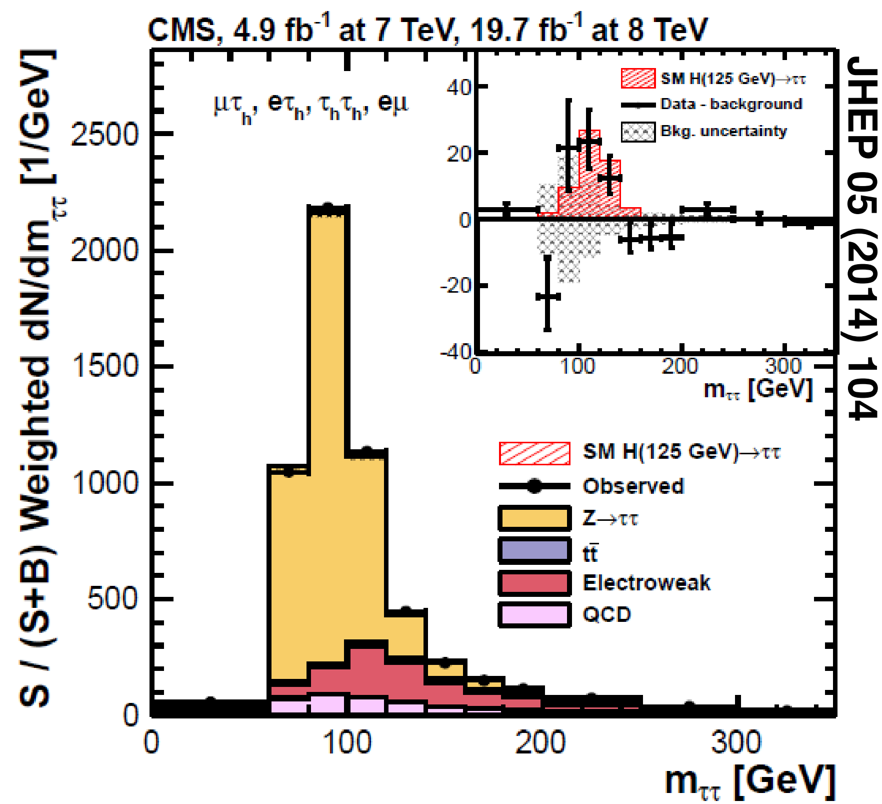




Run 1 $H \rightarrow \tau\tau$

- Evidence of Higgs fermionic decays:
  - Excess wrt expected background observed by both experiments





ATLAS Results

Significance 4.5 obs (3.4 exp) σ

$$\mu = 1.43 \, ^{+0.43}_{-0.37}$$

CMS Results

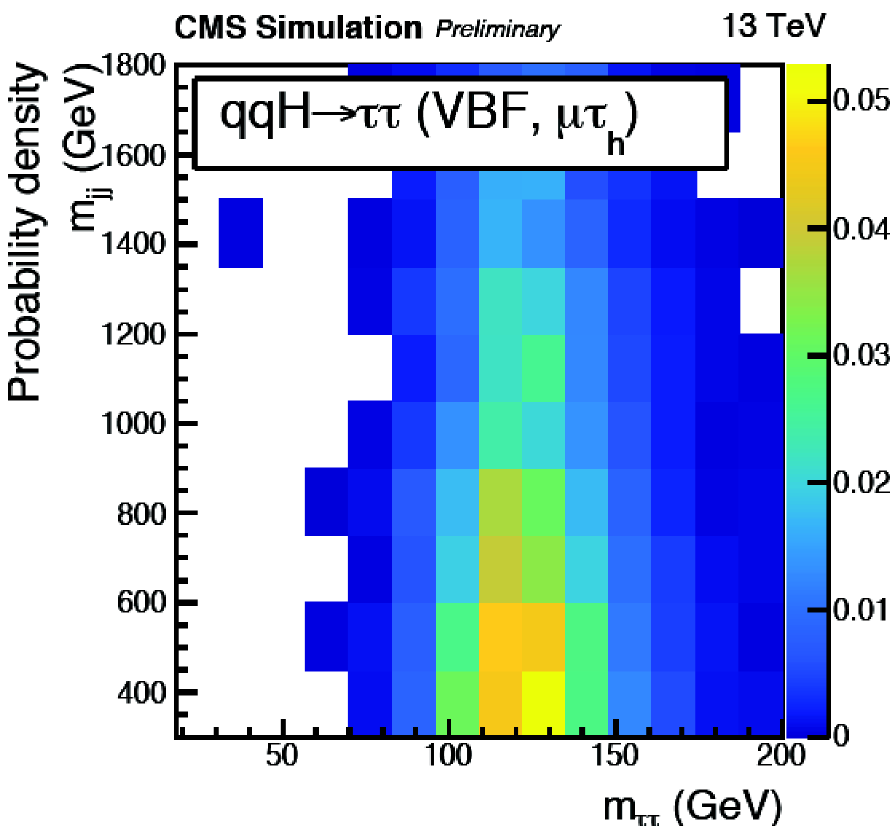
Significance 3.2 obs (3.7 exp) σ

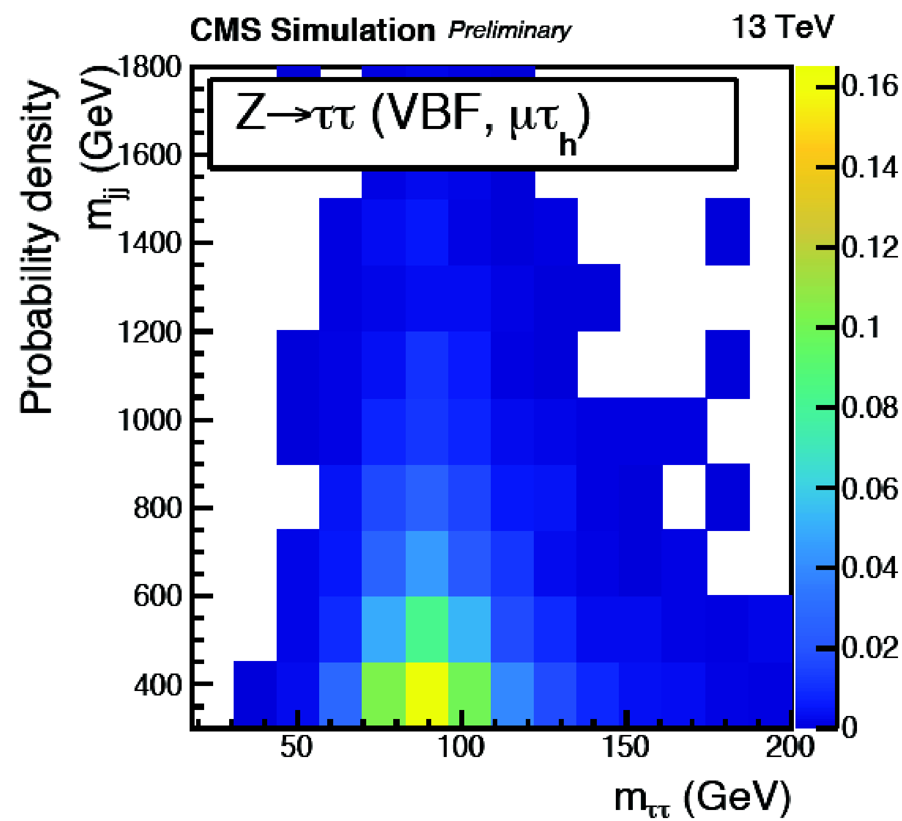
$$\mu = 0.78 \pm 0.27$$

Run 2 $H \to \tau\tau$ Analysis

CMS PAS-HIG-16-043

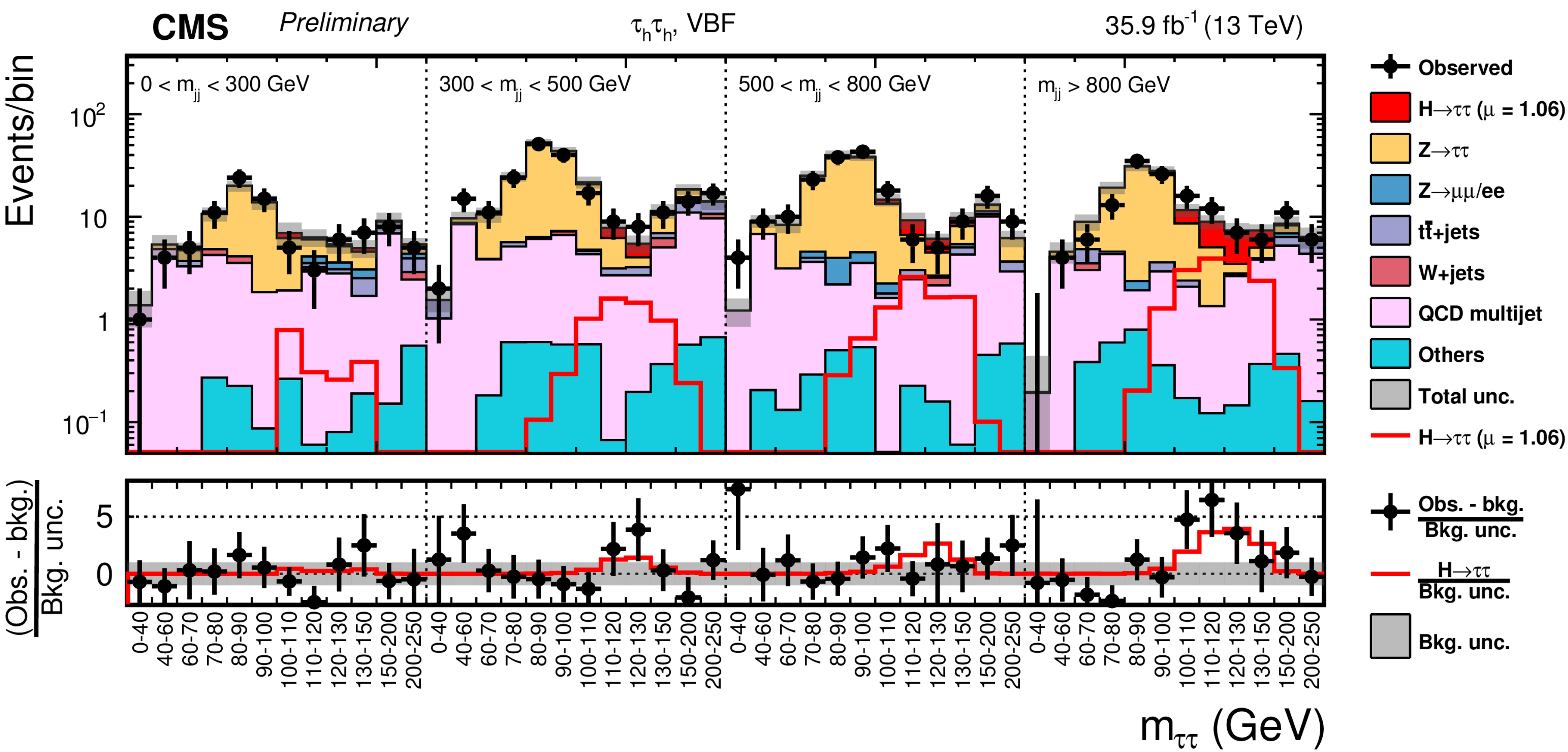
- Main background is $Z \to \tau\tau$ modelled by MC simulation.
- Cut-based analysis employing 0-jet, boosted and VBF event categories
- Analysis includes leptonic and hadronic decay channels of the taus: ($e\tau_{had}$, $\mu\tau_{had}$, $e\mu$, $\tau_{had}\tau_{had}$)





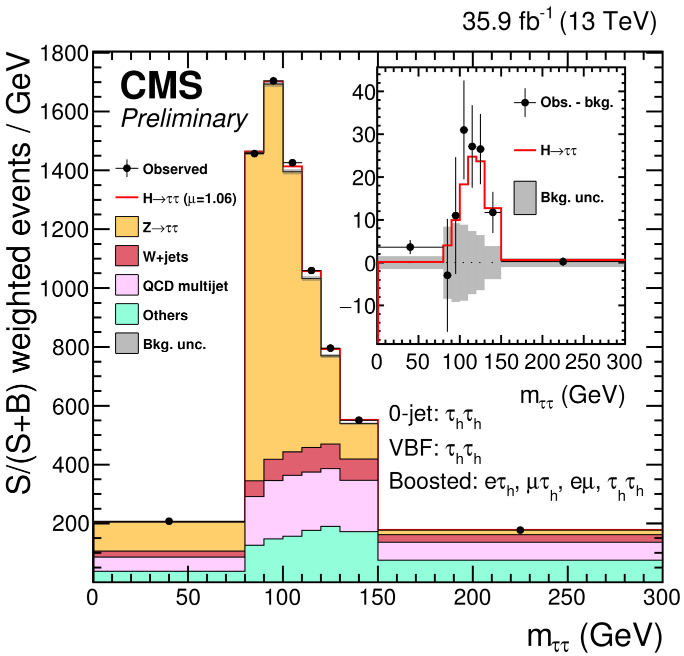
- Extracting the signal in 2-dimensions : one dim is always di-tau mass (m_{vis} for 0jet) and other dimension (tau decay mode,di-jet mass, higgs p_T, ...) is chosen targeting specific prod modes.

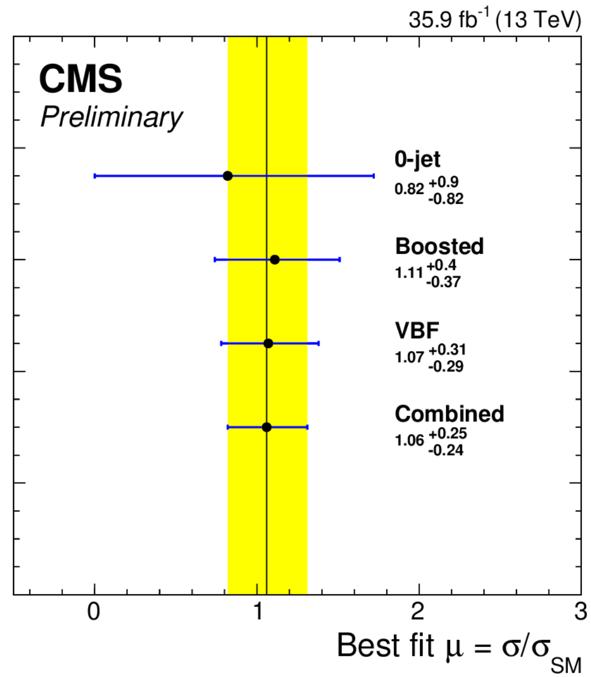
$H \to \tau\tau$ Background

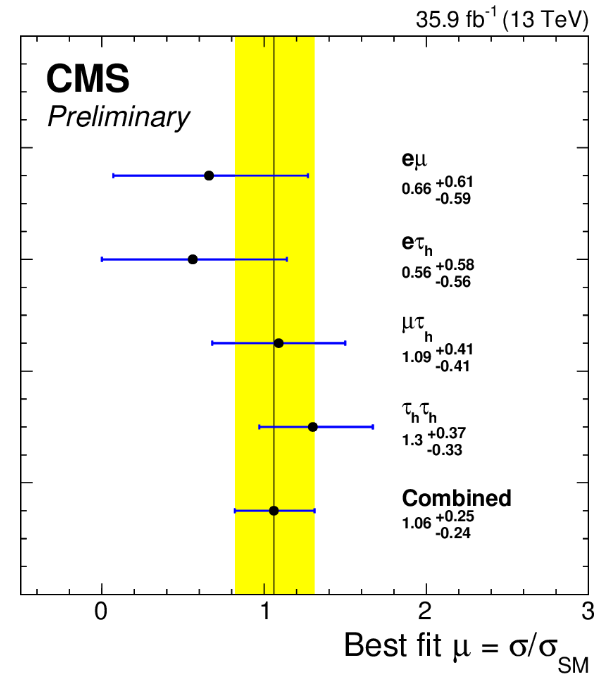


- $Z \to \tau\tau$: MadGraph MC, with corrections from $Z \to \mu\mu$ CR
- QCD MJ: data-driven from CR
- Other: lepton $\to \tau$ fake and EW

$H \to \tau\tau$ Results

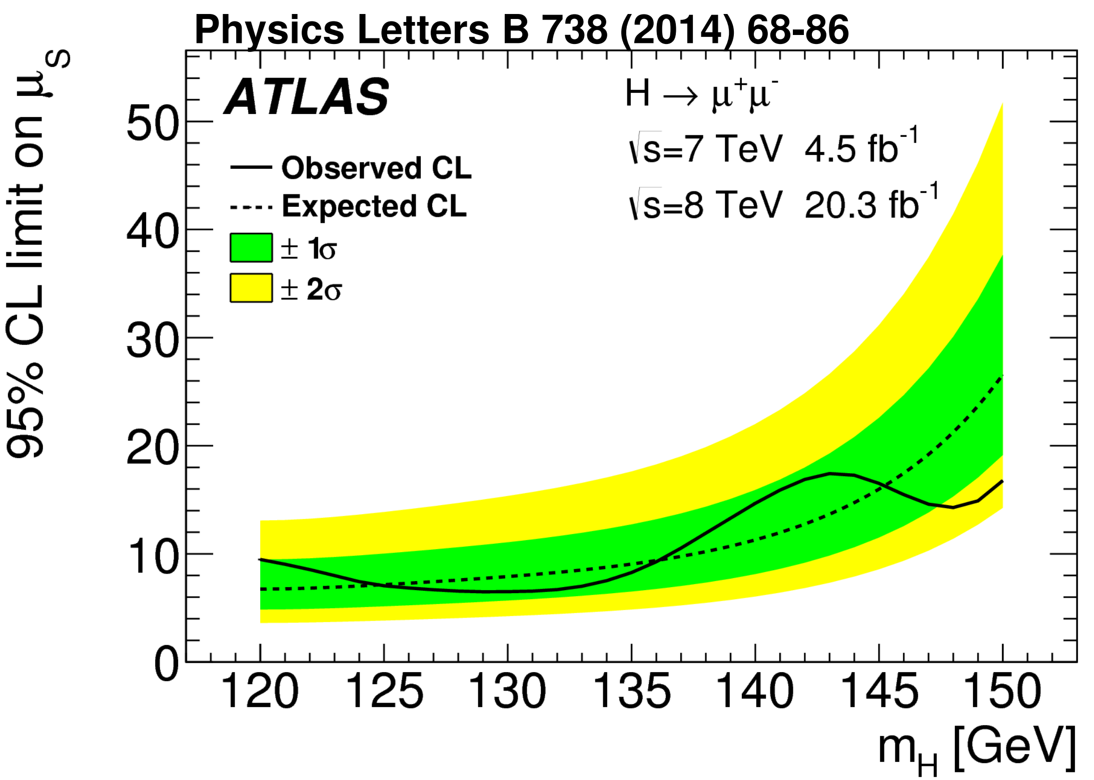


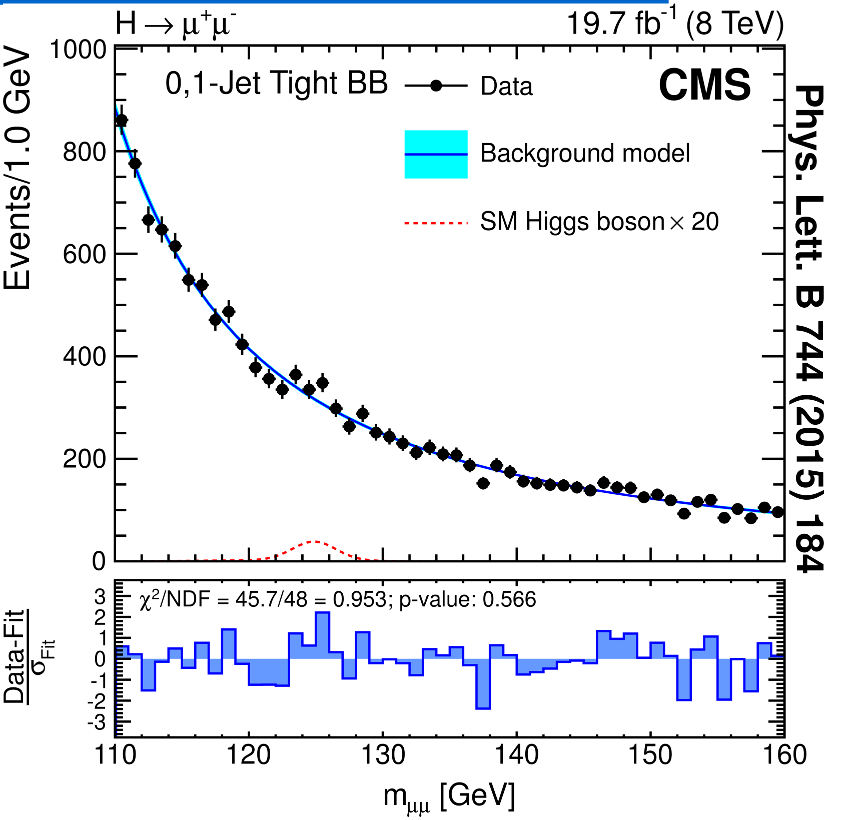




- Excess compatible with the 125 GeV SM Higgs
- Expected (postfit) significance is 4.7 σ
- Observed significance is 4.9 σ
- 0jet and boosted: mostly ggH, VBF: mostly qqH
- 0jet: little signal sensitivity, but it allows to control background and systematics.

Run 1 H → μμ





- Excellent mass resolution provides a clean signature.
- Result extracted from the fit of the $m_{\mu\mu}$ mass spectrum, similar to H → γγ
- Evidence of H → ττ and limit on H → μμ means no universal coupling of the Higgs to leptons, as expected.
- Need significantly more statistics to reach sensitivity to the SM rate of H → μμ

ATLAS:
Limit @ m_H=125 GeV: 7.0xSM
(7.2 exp)

CMS:
Limit @ m_H=125 GeV: 7.4xSM
(6.5 exp)

Run 2 $H \rightarrow \mu\mu$

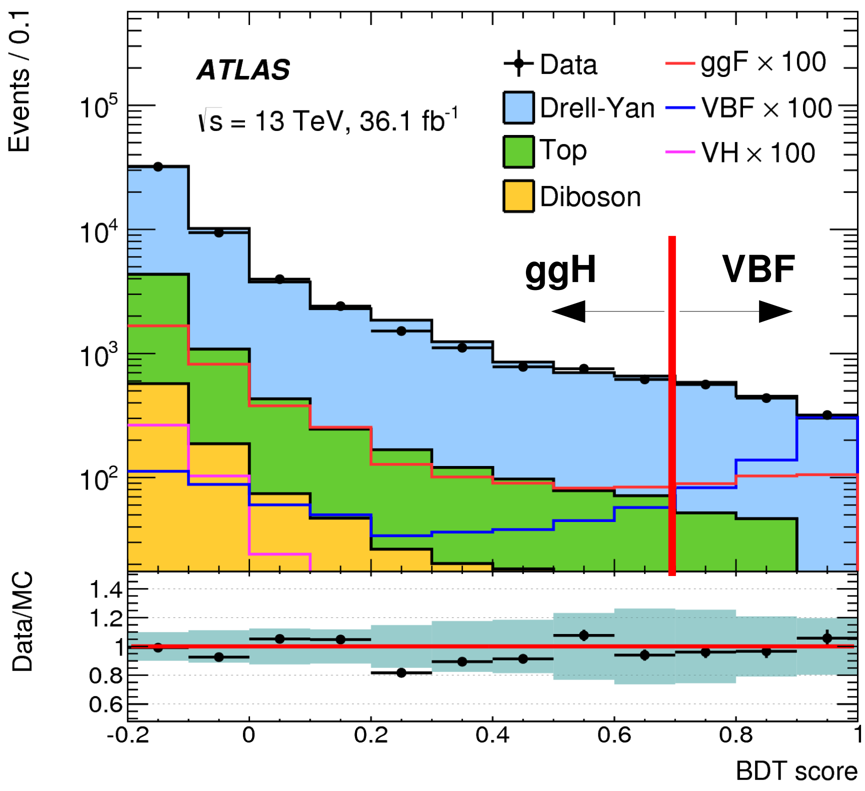
- Dominant background is $Z \rightarrow \mu\mu$, several order of magnitudes larger than Higgs signal.

- Selection:
  - Two muons with p_T>15 GeV
  - E_T^{miss} < 80 GeV
  - b-jet veto
  - $110 < m_{\mu\mu} < 160$ GeV

- In Run 2, a BDT is used to define two VBF-enriched Signal Region (loose, tight).

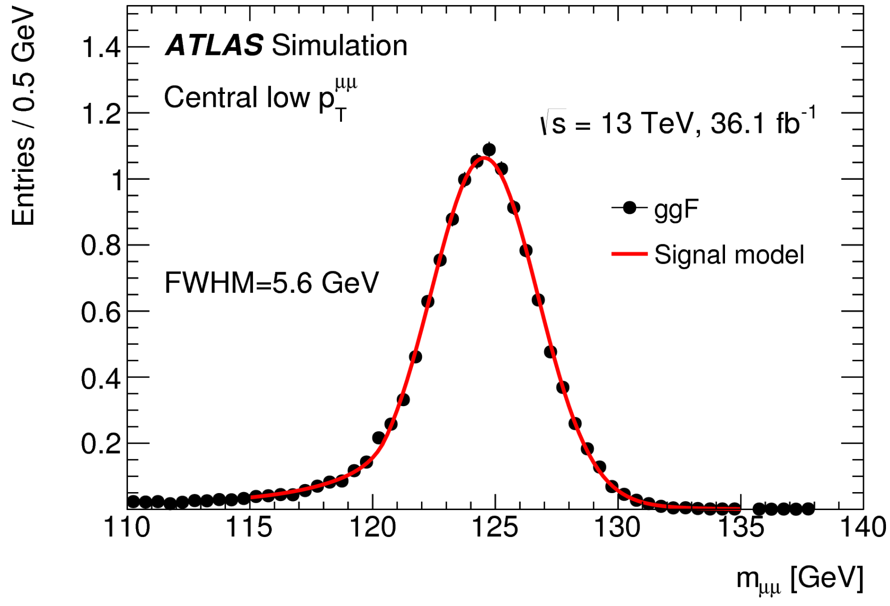
- Event failing the selection are reused for 6 ggH categories, based on η_μ and $p_T^{\mu\mu}$

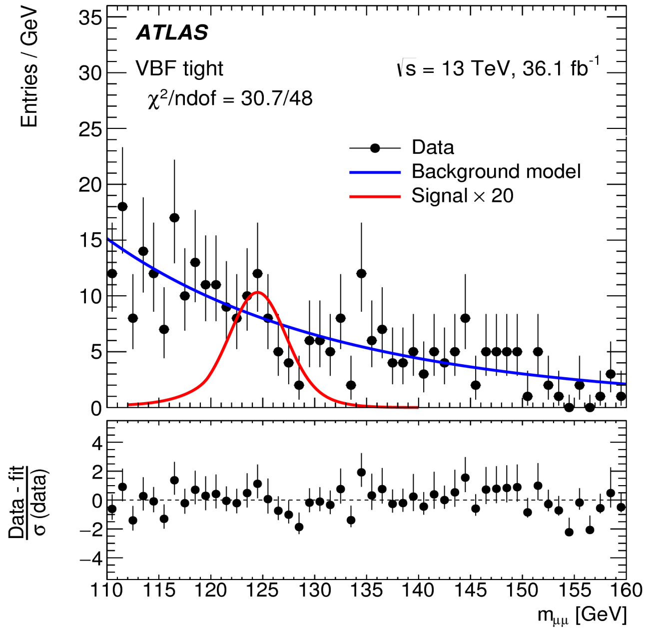
arxiv:1705.04582

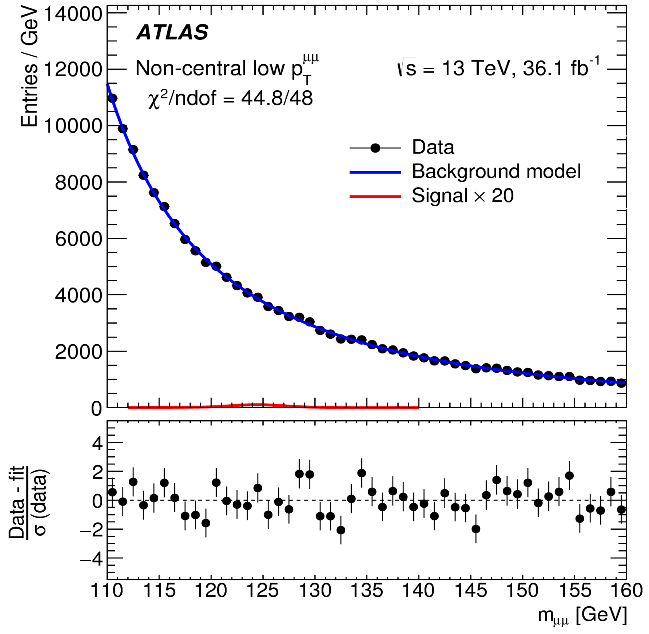


Run 2 H → μμ Signal

- Signal is parametrized with a Crystal-Ball+Gaussian shape
- Signal FWHM between 5.6-7.7 GeV
- Background is parameterized with a Breit-Wigner+exponential fit to data in sidebands







Run 2 $H \rightarrow \mu\mu$ Results

- 2015+2016 limit greatly improves the Run 1 result.

- Results are in agreement with SM so far, some gap to be closed still to reach sensitivity to SM predicted cross-section.

- Expect to measure $H \rightarrow \mu\mu$ (second generation fermions) during the lifetime of the 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

	best fit value for σ/σ_{SM}	95% CL upper limit on σ/σ_{SM}
Run 2	-0.1±1.5	3.0 (exp 3.1)
Run 1 + Run 2	-0.1±1.4	2.8 (2.9)

$Run\ 1\ H \rightarrow ee$

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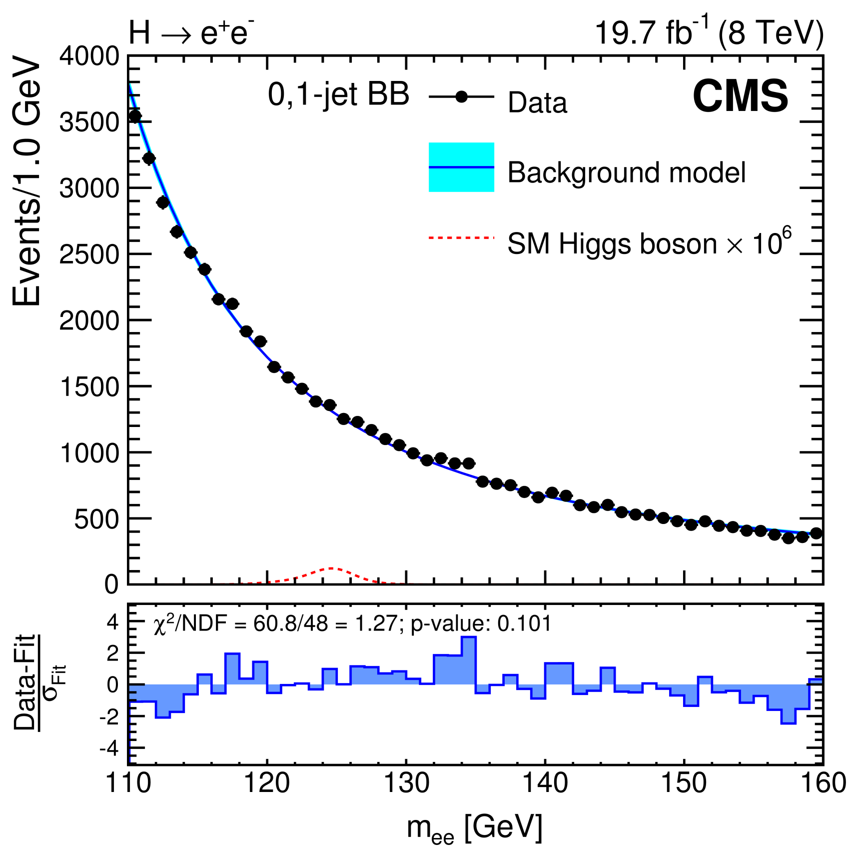
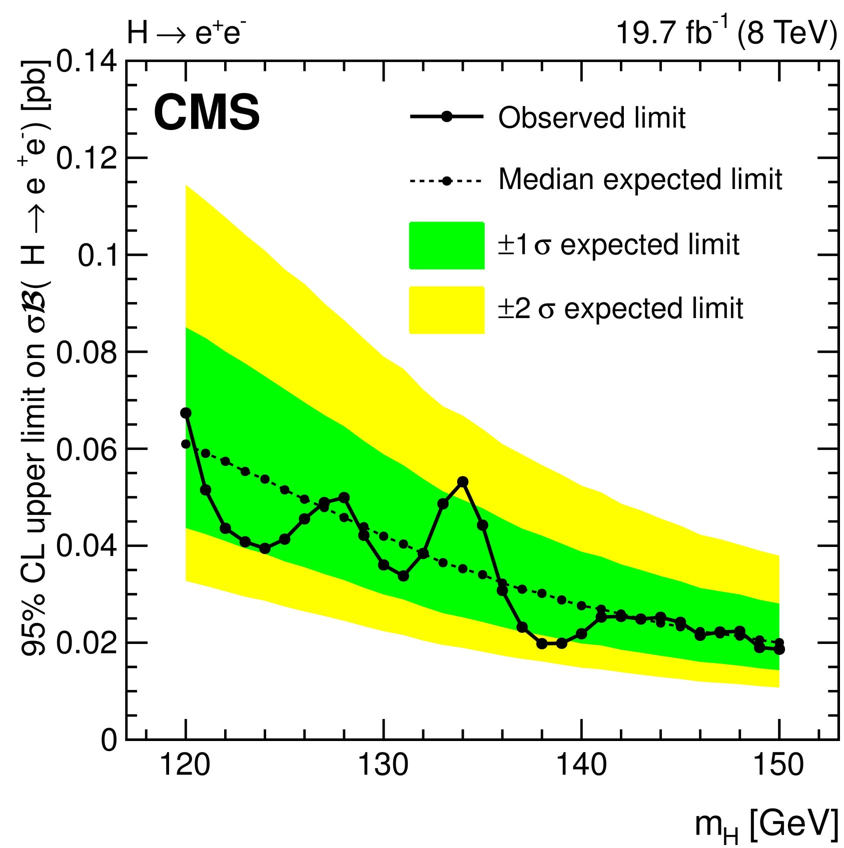
- Extremely low BR predicted by the SM
- Leave no stone unturned
- BR limit <0.19%, 3.7 • 10^5 times the standard model value.





Run 1 VH → bbar

- Most abundant decay mode (58%), but challenging due to the multi-jet background.
- Tag VH production mode and use MVA analysis to boost sensitivity.
- VZ → bbar is used as benchmark.
- CMS included the search for VBF production qqH(→bb) with Run 1 data.
- TeVatron has a combined significance of 2.8σ @125 GeV in the H → bb channel.

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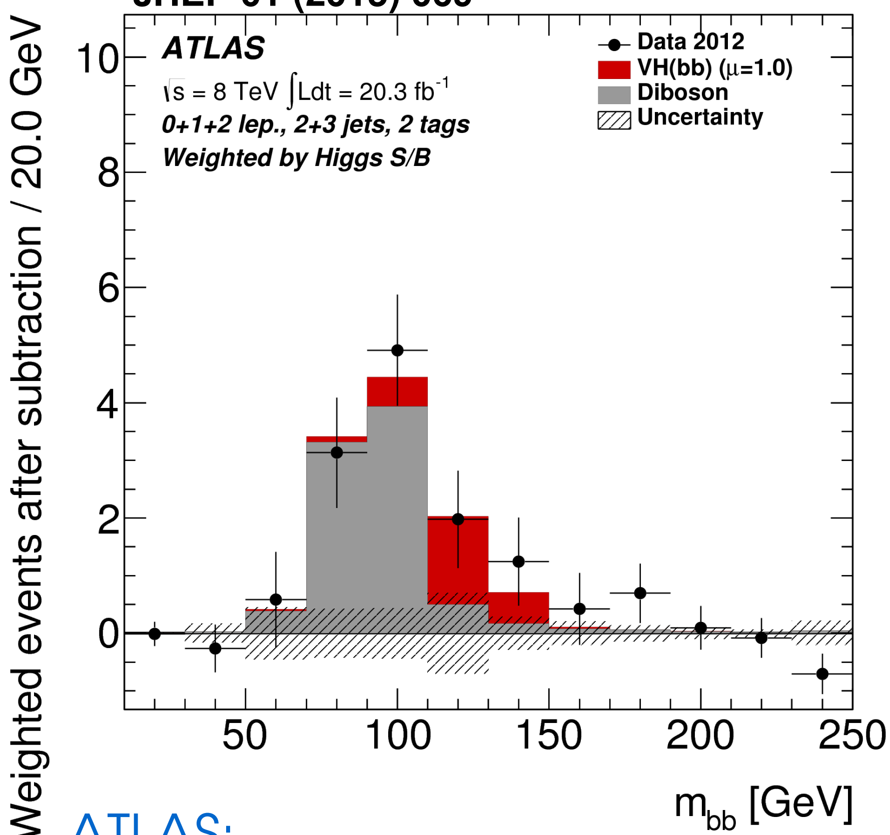
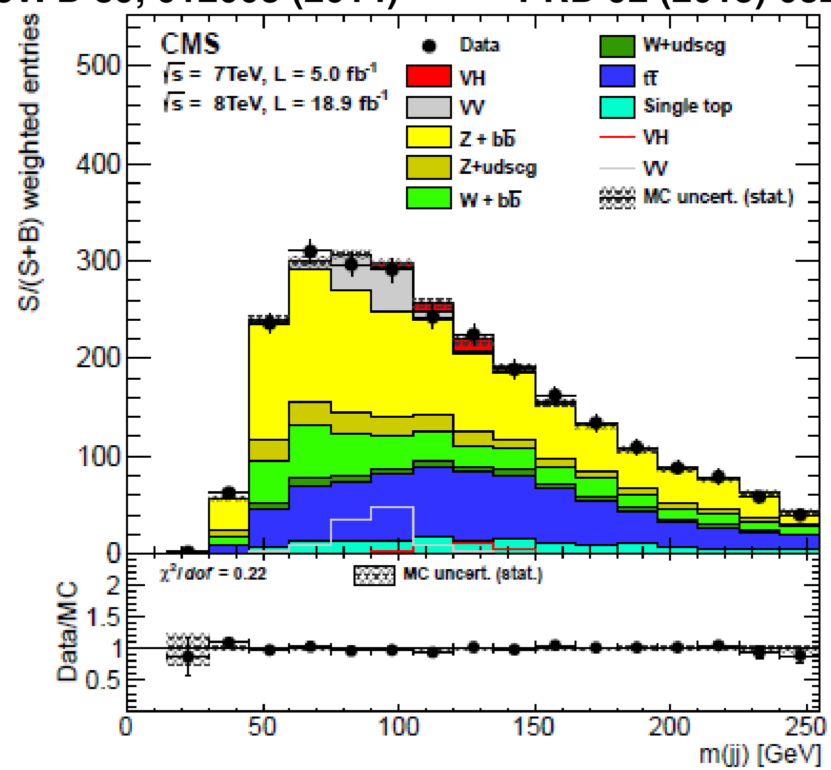


Phys. Rev. D 89, 012003 (2014) PRD 92 (2015) 032008



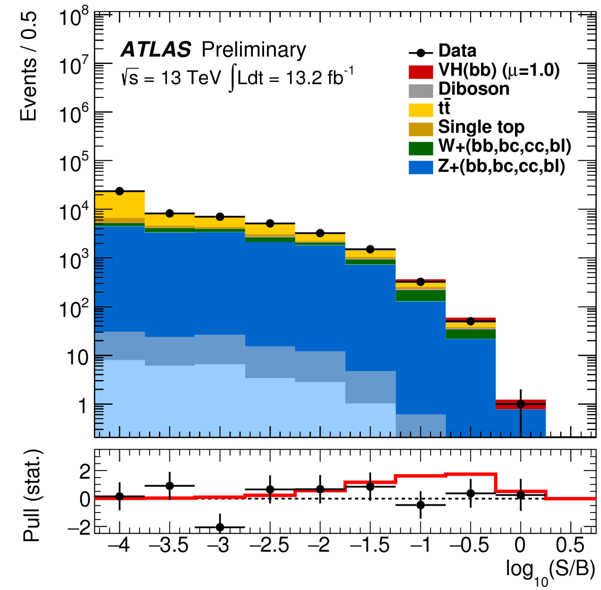
ATLAS:
μ=0.52±0.32(stat)±0.26(syst) @125.36 GeV
Significance 1.4 (2.6) σ

CMS (VH and VBF combination):
μ=1.0±0.4 @125.0 GeV
Significance 2.0 (2.7) σ

Run 2 VH → bbar

ATLAS-CONF-2016-091

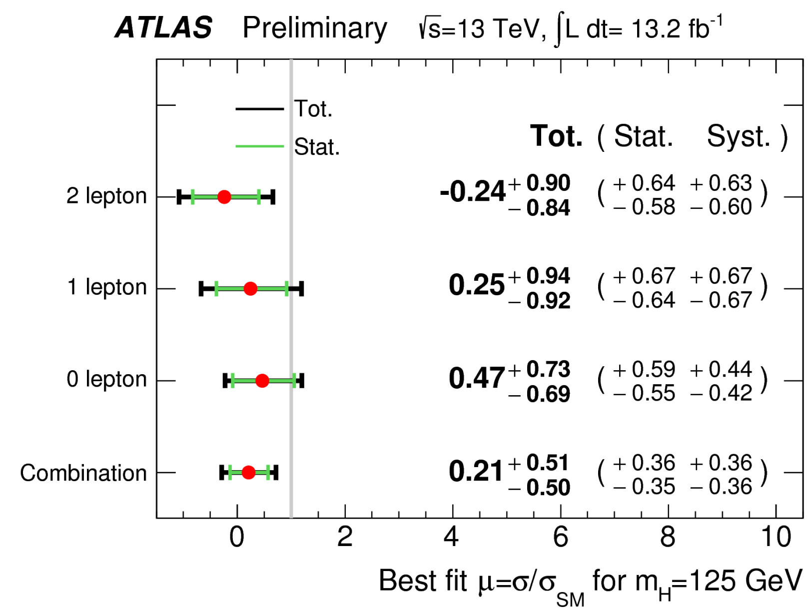
- Preselection: >= 2 jets, 2 b-jets
- Categories defined according to number of leptons to tag W/Z decays:
  - 0 leptons: tagging $Z \rightarrow \nu\nu$
    - $E_T^{miss} > 150$ GeV
    - 2 or 3 jets
  - 1 lepton
    - $E_T^{miss} > 30$ GeV
    - $p_T(W) > 150$ GeV
    - 2 or 3 jets
  - 2 leptons
    - $71 < m_{ll} < 121$ GeV
    - $p_T(Z)$ > or < 150 GeV (2 categories)
    - =2 or >2 jets



- BDT is used in each of the categories
- Signal is extracted from a simultaneous fit

$\mu = 0.21^{+0.36}_{-0.35}(\text{stat}) \pm 0.36(\text{syst})$ @125 GeV

Significance 0.42 (1.94) σ



Run 1 & Run 2 qqH → bbar

- Using forward and b-jet triggers to select events. Different choices by the experiment, both achieving ~6% acceptance for signal.
- MVA selection is used to select VBF final states: 4 categories for ATLAS and 7 categories for CMS.
- Both experiments fit m_{bb} distribution to extract signal

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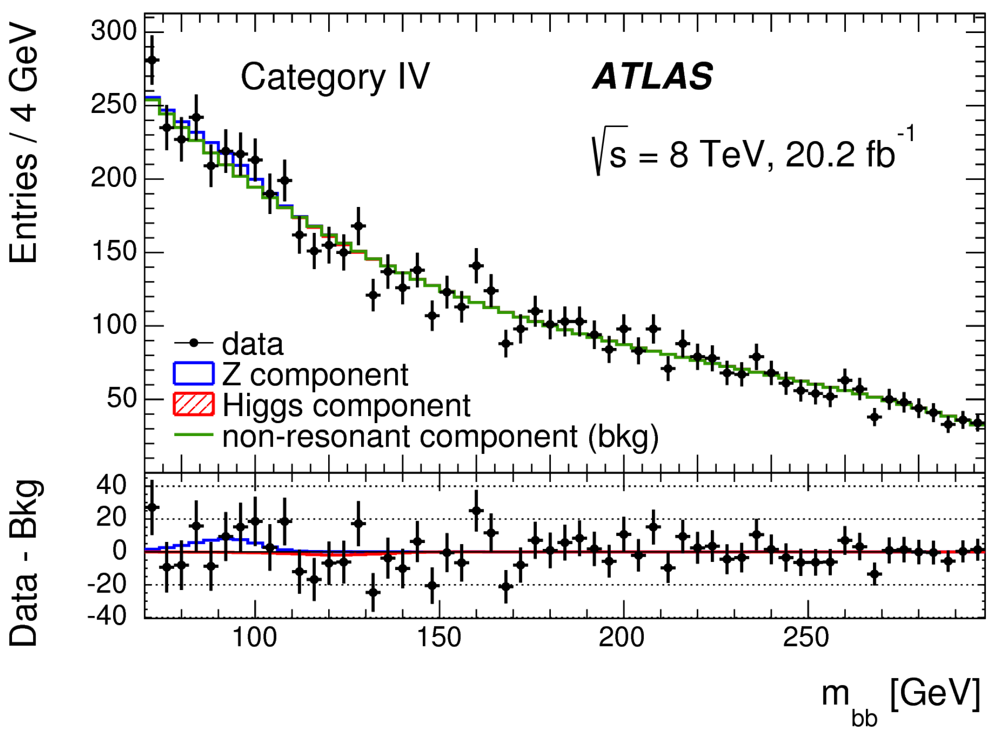
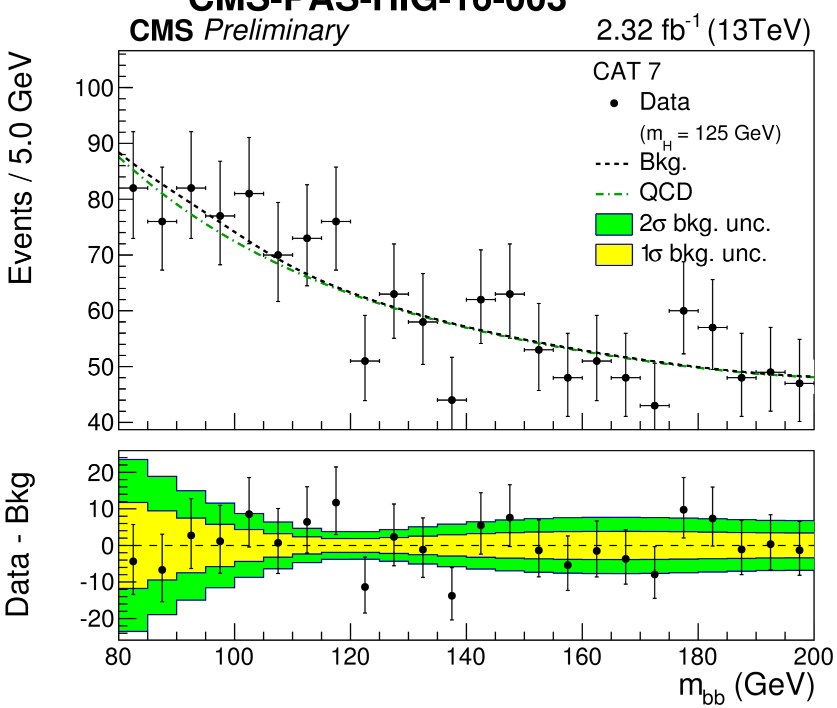


CMS-PAS-HIG-16-003



ATLAS:

μ=-0.8±2.3 @125 GeV

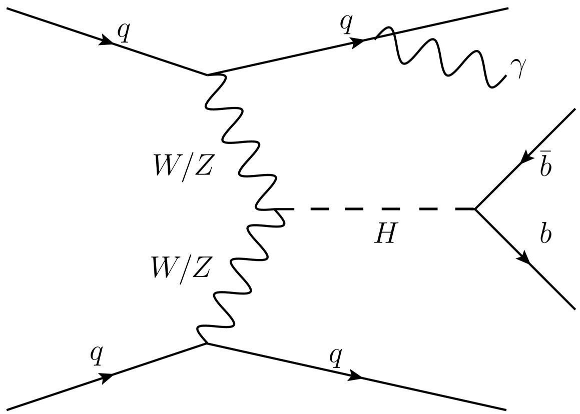
95% CL Limit: 4.4 (5.4 exp.) x SM

CMS:

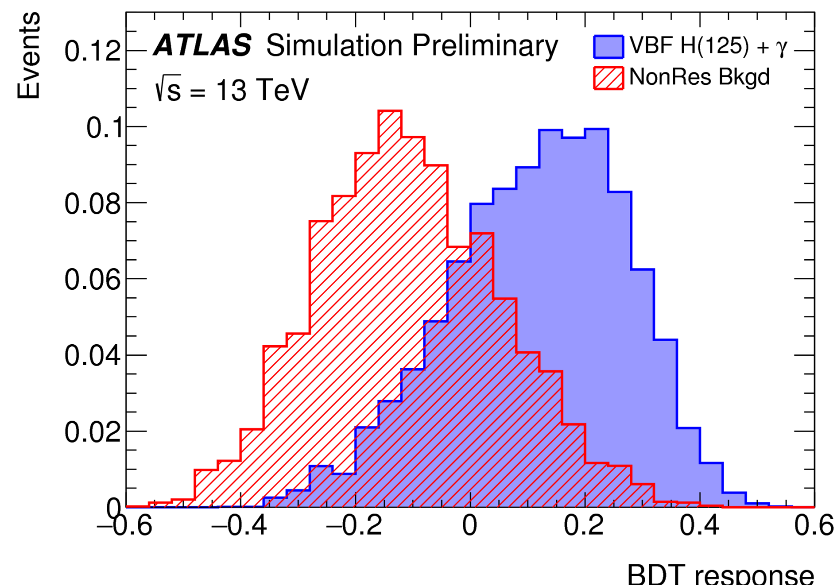
μ=1.3±1.2 Run1+2015

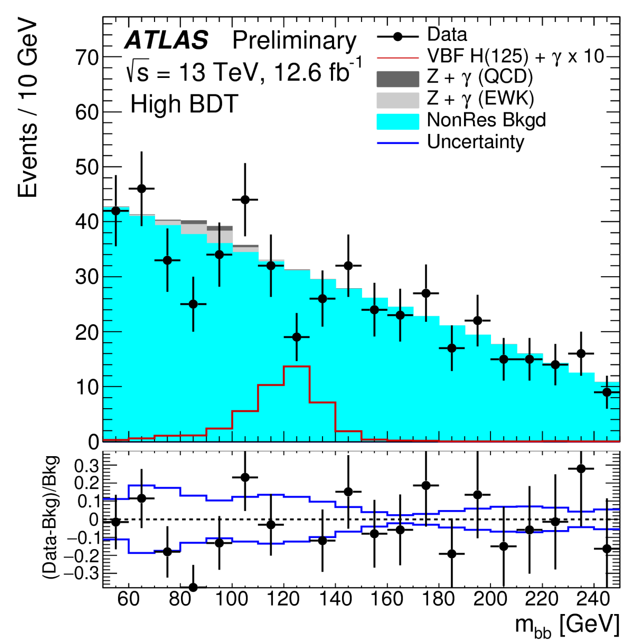
95% CL Limit: 3.4 (2.3 exp.) x SM

Run 2 $qqH \rightarrow bbar + \gamma$



ATLAS-CONF-2016-063



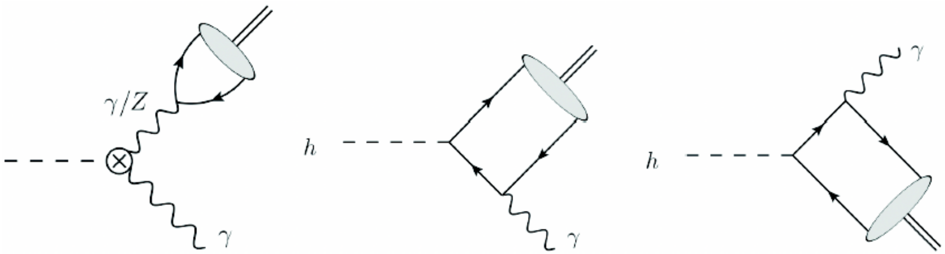


- Trigger on photons, 4 jets and mjj>700 GeV
- Main backgrounds are γ+4 jets production and Z → bb + jets
- BDT is used too reject multi-jet background
- Events are separated in 3 categories according to the BDT
- Signal is extracted from a fit of the m_{bb} mass, limited by statistical uncertainty.

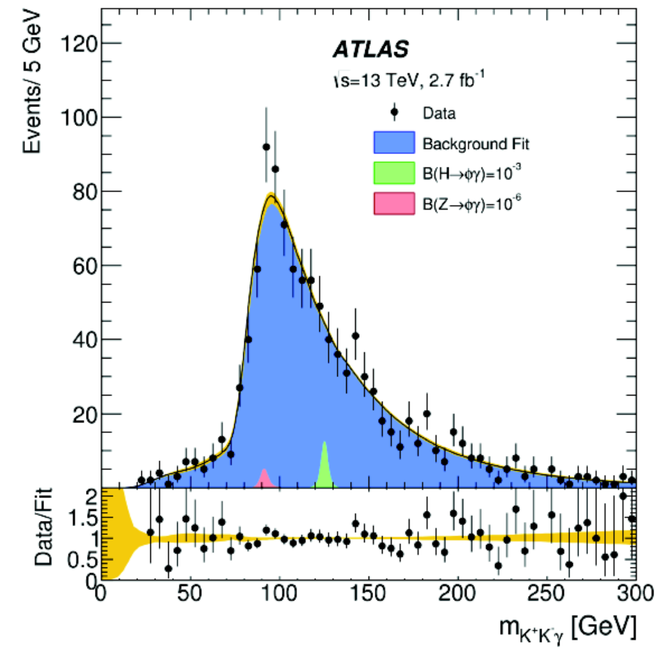
ATLAS:
μ=-3.9±2.8 @125 GeV
95% CL Limit: 4.0 (6.0 exp.) x SM

$H \to \gamma X\ (\to ff)$

ATLAS: Phys.Rev.Lett.117, 111802 (2016), Phys.Rev.Lett.114, 121801 (2015) CMS: Phys.Lett.B 753 (2016) 341



- Final states with ϕ, J/ψ and $\Upsilon(nS) + \gamma$ are sensitive to s,c,b-quark Yukawa couplings
- A dedicated trigger is used for the $H \to \gamma\phi(\to K^+K^-)$ search.
- $\mu\mu\gamma$ final state is used by both experiments, CMS also adds $ee\gamma$ events.

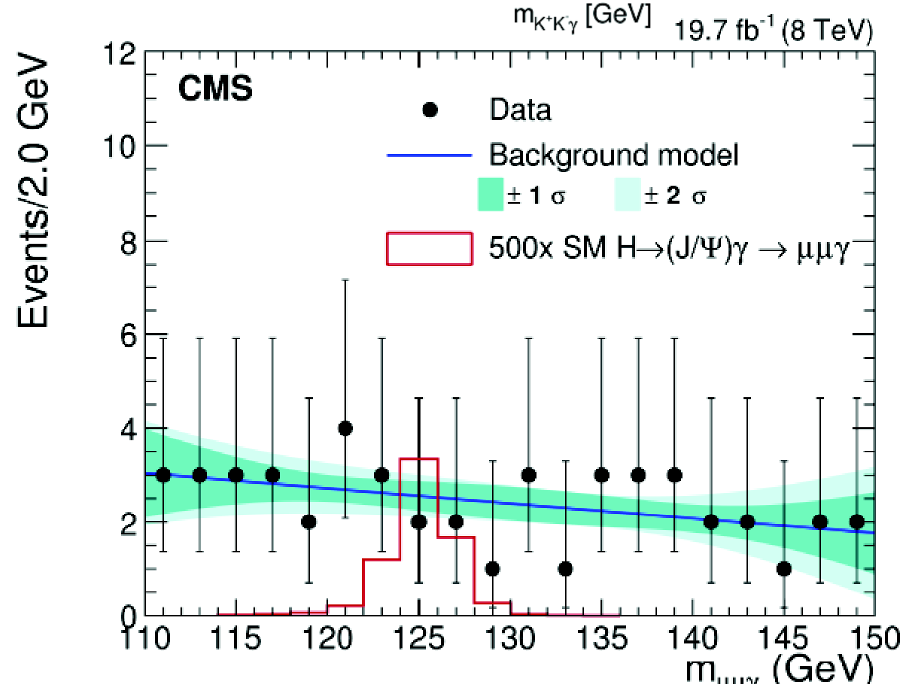


95% CL Limit ATLAS:

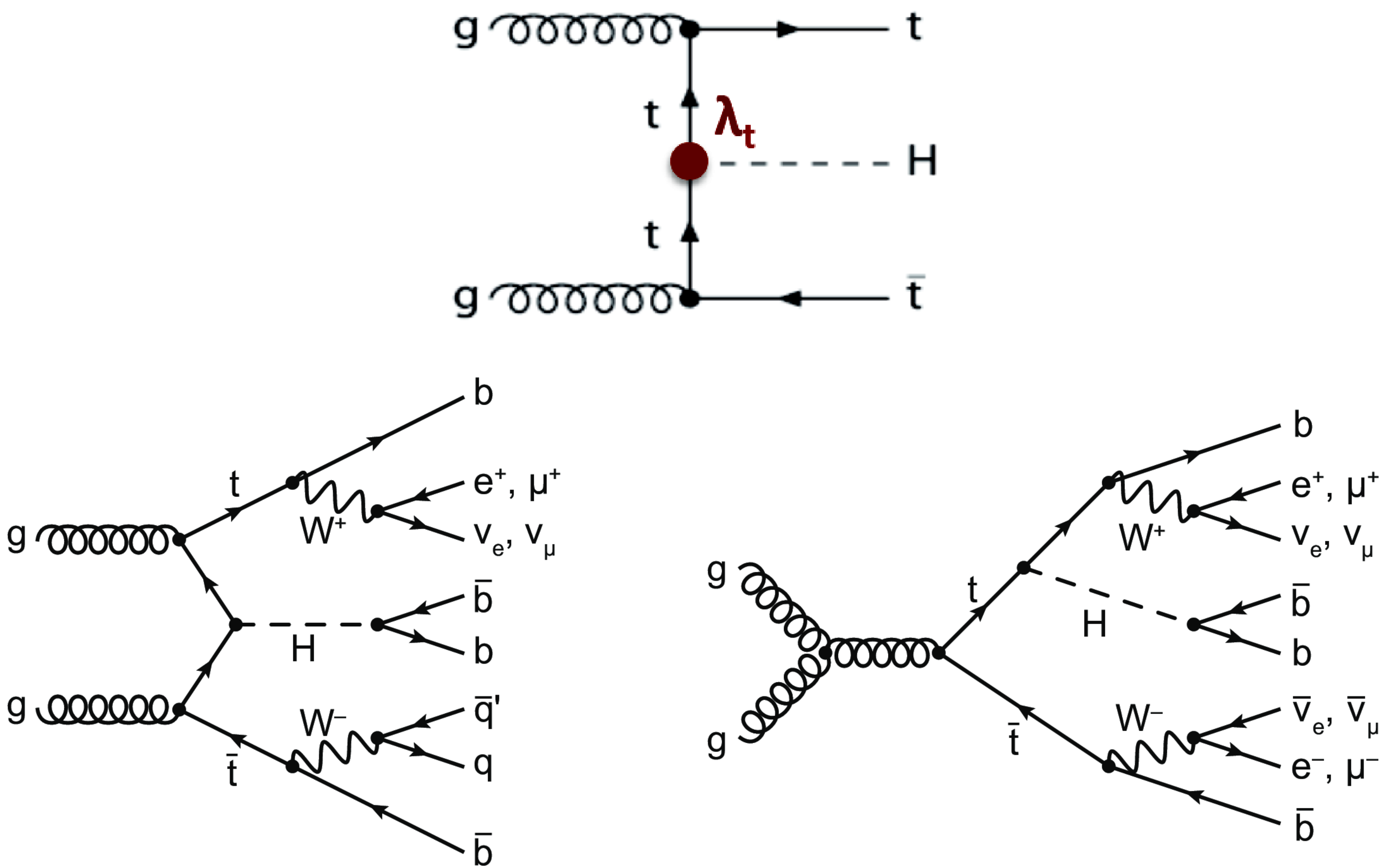
- BR $(H \to \gamma\phi)$: 0.14%
- BR $(H \to \gamma J/\psi)$: 0.15%
- BR $(H \to \gamma\Upsilon(1,2,3S))$: 0.13%, 0.19%, 0.13%

95% CL Limit CMS:

- BR $(H \to \gamma J/\psi)$: 0.15%
- BR $(H \to \gamma^*\gamma)$: 6.7xSM



Higgs production



Run 1ttH (H->bb, WW, ZZ, ττ, γγ)

- ATLAS and CMS covered broad range of Higgs boson final states and ttbar decay modes, grouped by decay products:
  - H → bb, Multileptons (WW, ττ, ZZ), H → γγ
- b-tagging and top-tagging used to suppress backgrounds.
- The analyses are characterised by large number of categories and control region.
- These analyses require an excellent modelling and control of tt+HF and ttV

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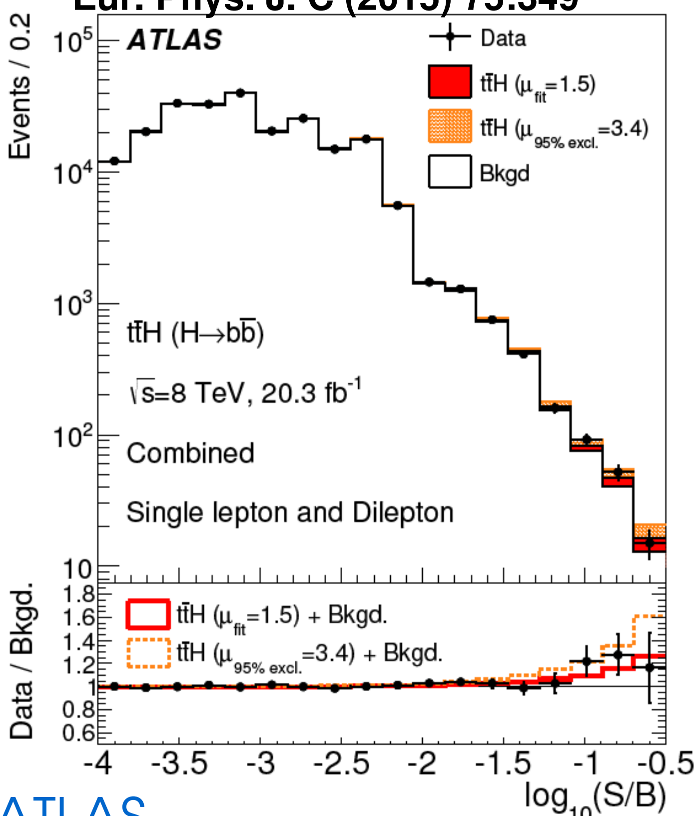

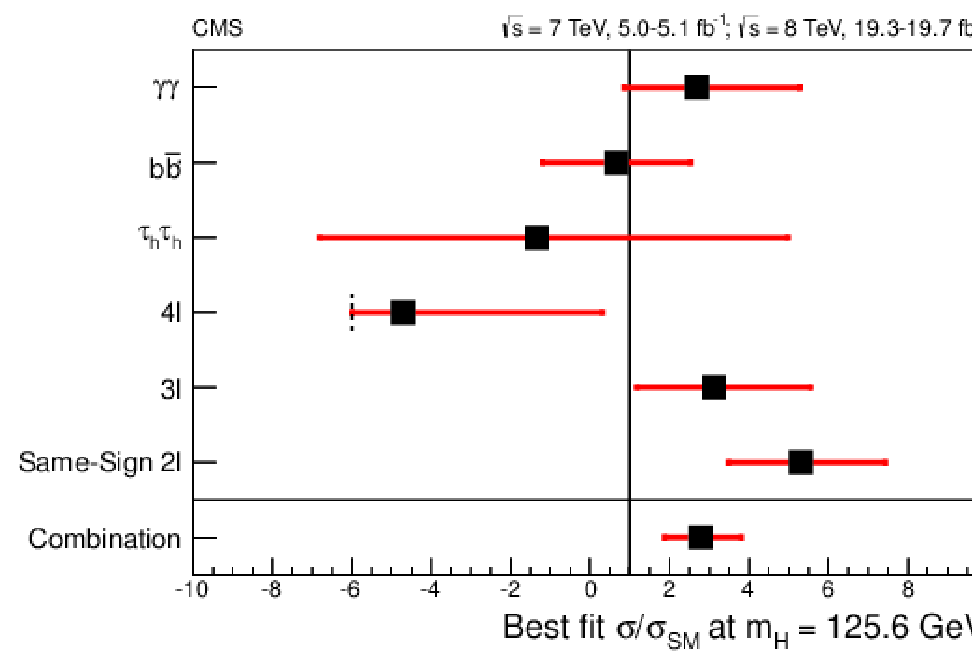

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ATLAS

μ=1.7±0.8 @125.36 GeV

Local Significance: 2.5 obs (1.5 exp) σ

CMS

8 TeV: μ=2.8±1.0 @125.6 GeV

Local Significance: 3.4 obs (1.2 exp) σ

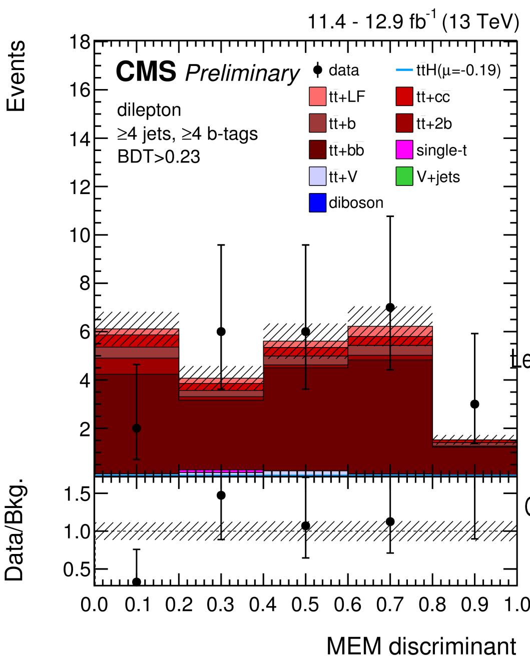
13 TeV ttH(bb) Results

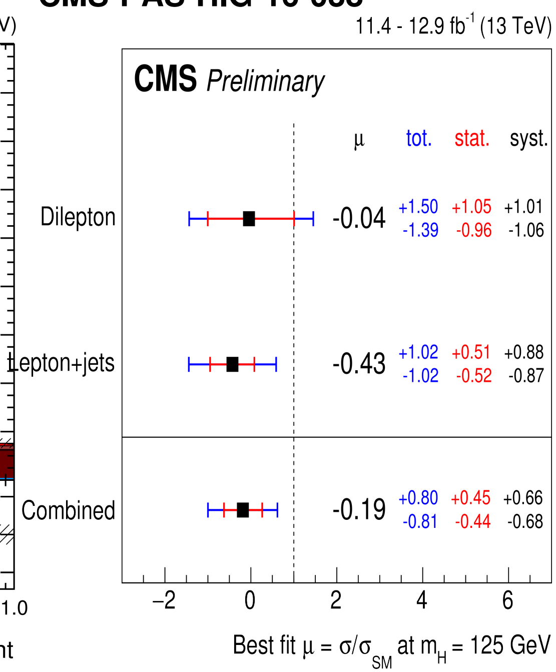
- 13TeV/8TeV Cross-section ~3.9: sensitive to potential new physics and quickly approaching Run-1 sensitivity to SM production.

CMS ttH(bb)
- Bkg. Discrimination from BDT and MEM
- MEM discriminant used to extract signal.

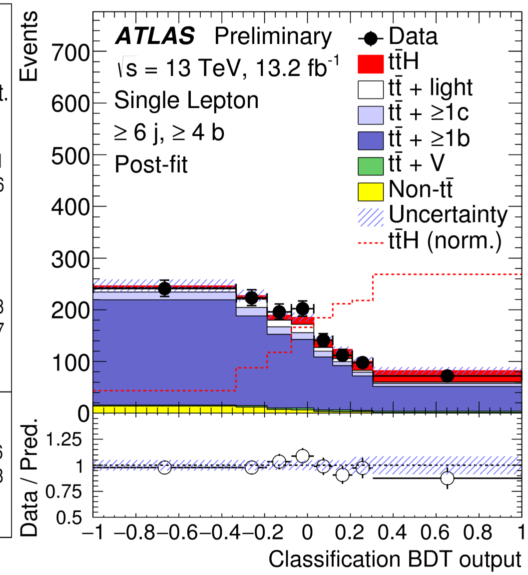
ATLAS ttH(bb)
- BDT to decide jet assignement
- Classification BDT to separate signal from background.

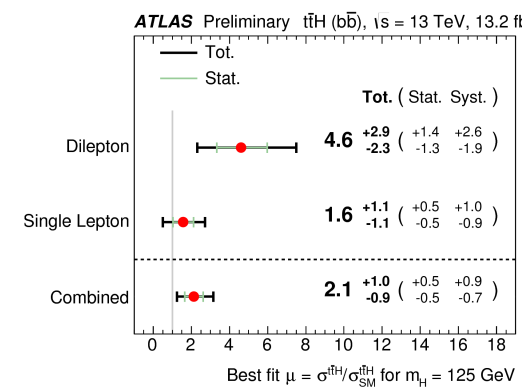
CMS-PAS-HIG-16-038





ATLAS-CONF-2016-080





CMS ttH(bb) @13 TeV
95% CL Upper Limit:
1.5 (1.7) x SM

ATLAS ttH(bb) @13TeV
95% CL Upper Limit:
4.0 (1.9) x SM

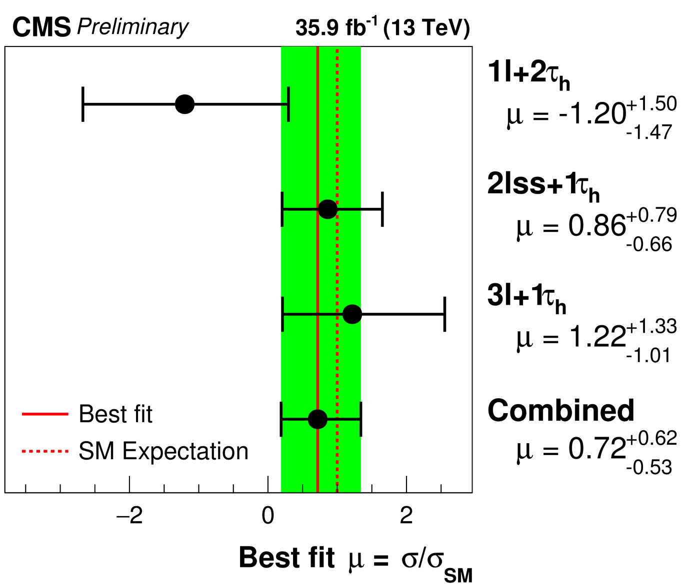
13 TeV ttH(H->WW, ZZ, ττ)

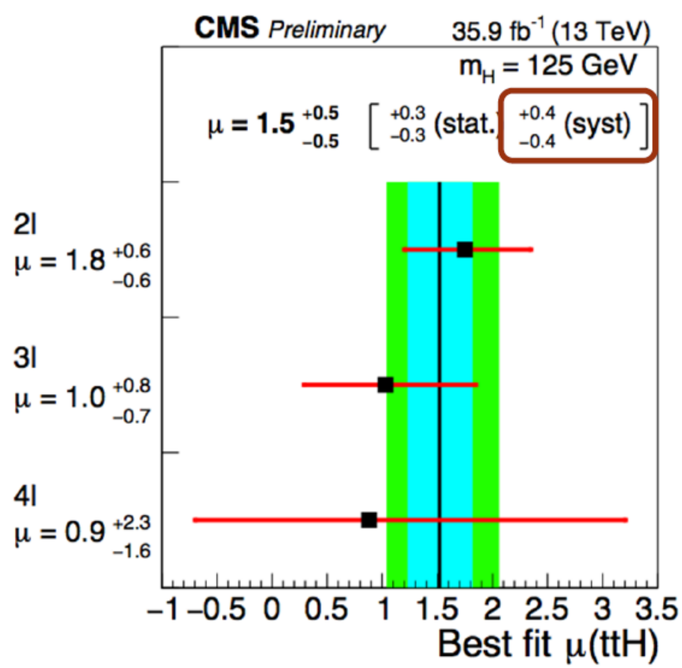
- Split according to number of leptons.

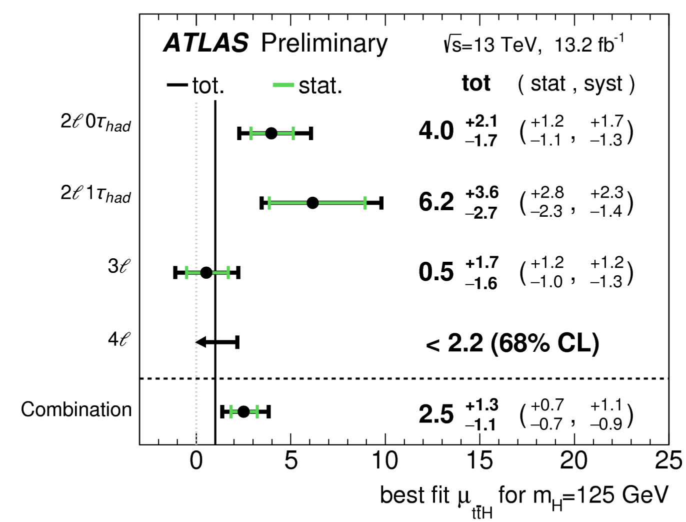
CMS ttH(multi-leptons)
- Use MVA to further improve signal separation
- ttH(4l) object of a separate analysis

ATLAS ttH(multi-leptons)
- Counting experiment in 6 categories.
- ttV and ttbar are main backgrounds

CMS-PAS-HIG-17-003 **CMS-PAS-HIG-17-004** **ATLAS-CONF-2016-058**







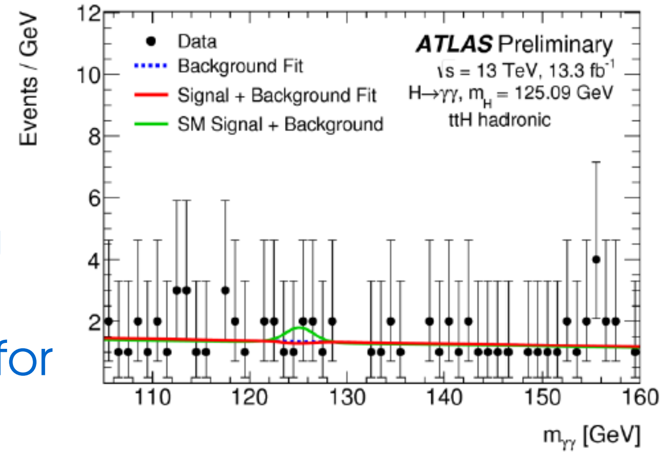
- CMS: 3.3σ (2.5σ) significance with 2015+2016 dataset
- ATLAS: 2.2 (1.5σ) significance with 13.2 fb^{-1} dataset

13 TeV ttH(H->γγ) and summary

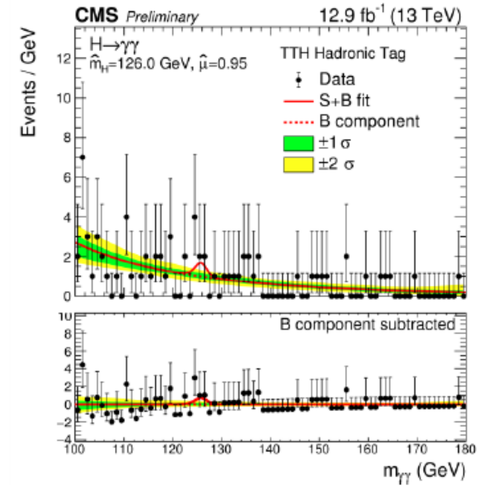
- ttH(γγ) very pure final state with low yields
- Fit to the $m_{\gamma\gamma}$ mass distribution to extract signal
- Statistical Uncertainty is dominating

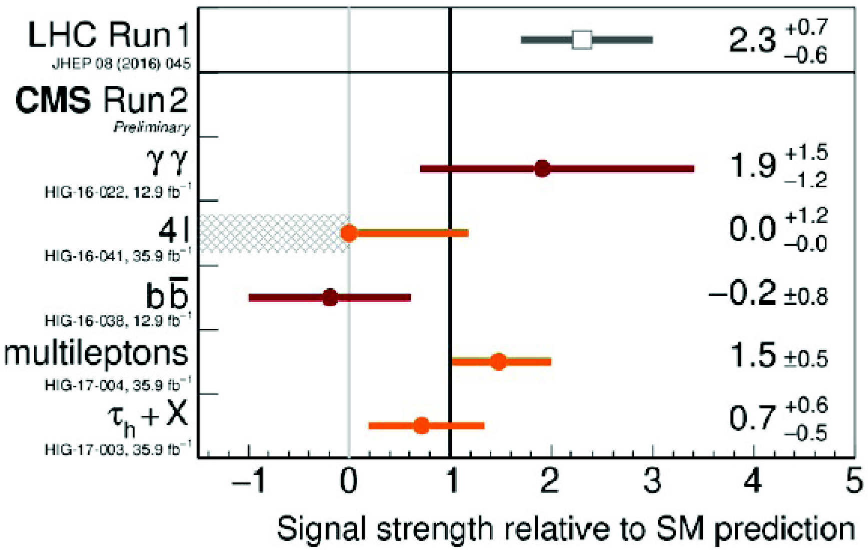
- CMS has recently added a search for tH production.

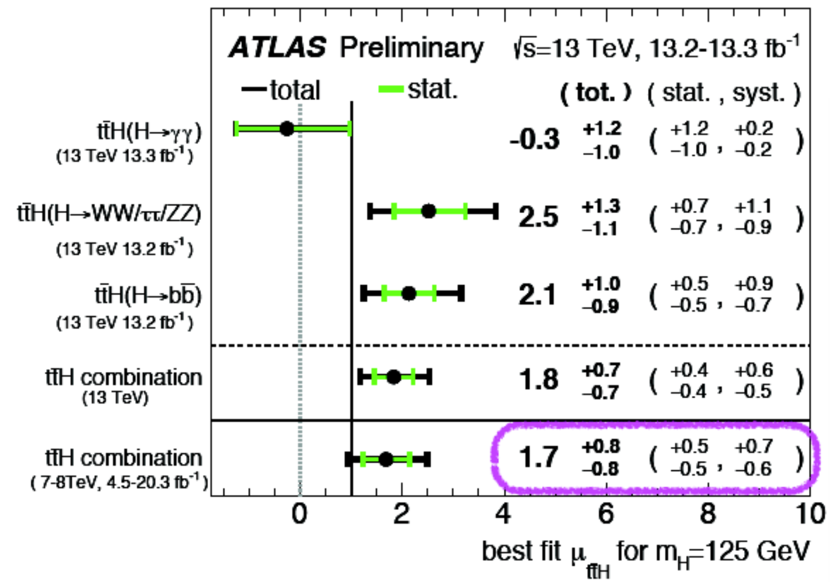
ATLAS-CONF-2016-067



CMS PAS HIG-16-020







- ttH results with 13 TeV are already improving Run 1 precision
- ttH(bb) and ttH multi-leptons starts to be limited by systematics: JES, HF-tag, data-driven backgrounds as well as Q^2, PS, tt+(HF,V) modelling.
- CMS has also first results for tH production.

Run 1 Combined Measurements

- Higgs Yukawa couplings to ττ established already from Run 1.
- H → ττ is still the only leptonic channel accessible for few more years and it is the fermionic channel with the best sensitivity.
- ttH measurements are among the most interesting topics of LHC Run 2.
- H → bb sensitivity already above 3σ during Run 1, but observed value was lower than that.

Production process	Observed Significance(σ)	Expected Significance (σ)
VBF	**5.4**	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
H→ττ	**5.5**	5.0
H→bb	2.6	3.7

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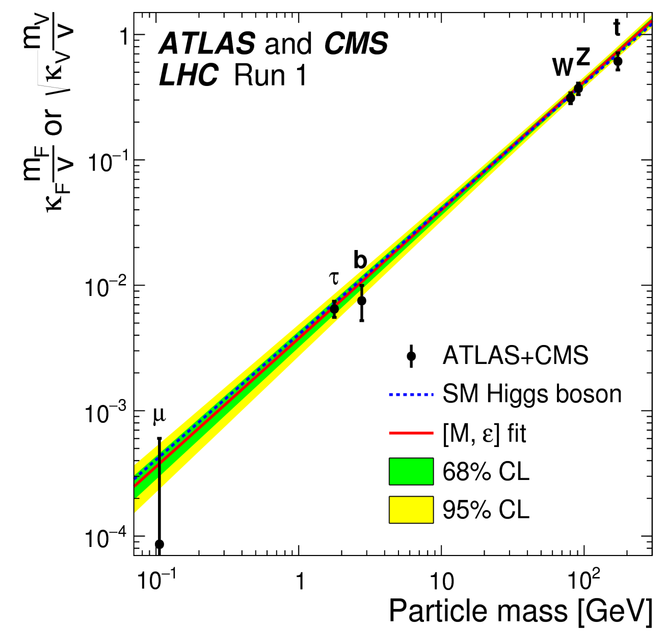
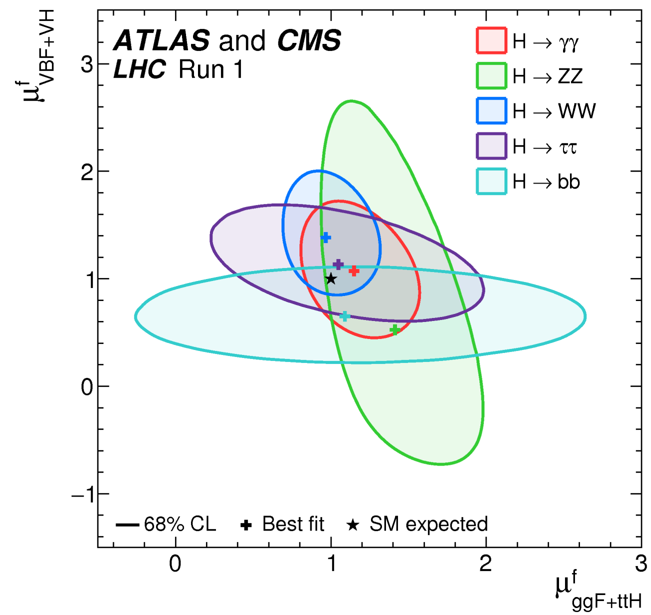




Run 1 Combined Measurements (2)

$$\kappa = \frac{g}{g_{\mathrm{SM}}}$$

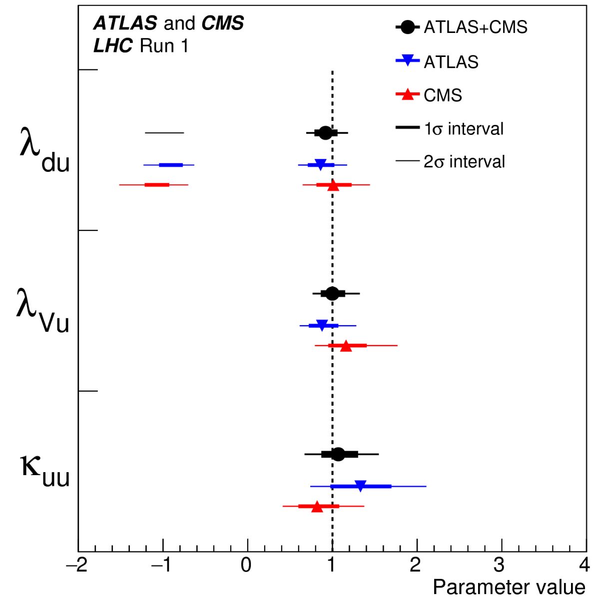
$$\sigma_i \times \mathrm{BF}^f = \frac{\sigma_i(\vec{\kappa}) \times \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

$$\lambda_{du} = \kappa_d/\kappa_u$$

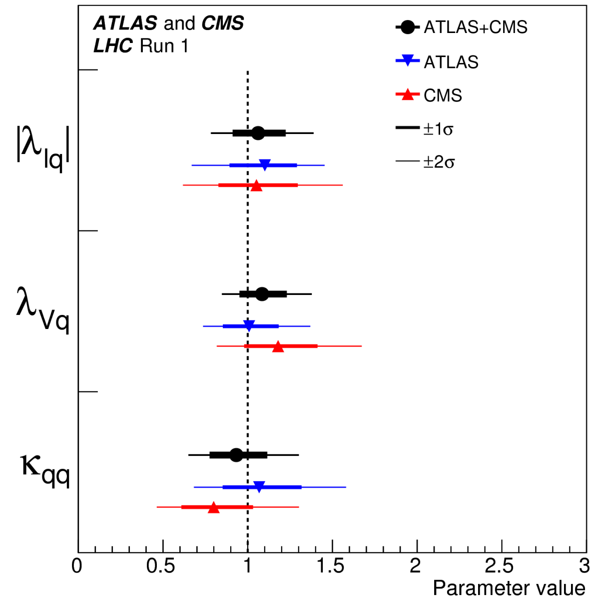
$$\lambda_{Vu} = \kappa_V/\kappa_u$$

$$\kappa_{uu} = \kappa_u \cdot \kappa_u/\kappa_H$$

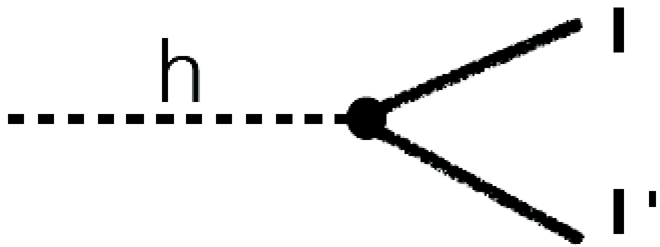
$$\lambda_{\ell q} = \kappa_\ell/\kappa_q$$

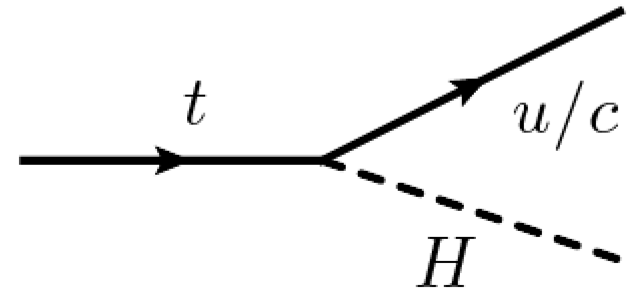


- Several BSM models predict λ_{lq} and $\lambda_{ud} \neq 1$
- Quark couplings probed mainly by ggH, $H \to bb$
- Lepton couplings from $H \to \tau\tau$
- Precision:
  - $|\lambda_{ud}| \in (0.80, 1.04)$
  - $|\lambda_{ud}| \in (0.88, 1.21)$



Off-diagonal terms





$$\mathcal{L}_Y = -m_i \bar{f}^i_L f^i_R - Y_{ij}(\bar{f}^i_L f^j_R)h + h.c. + \cdots ,$$

In the SM: $Y_{ij} = (m_i/v)\delta_{ij}$

- Lepton flavor violation exists in Nature (neutrino oscillations), but LFV in the charged sector is extremely suppressed in the SM.

- FCNC is also highly suppressed in the SM by GIM mechanism.

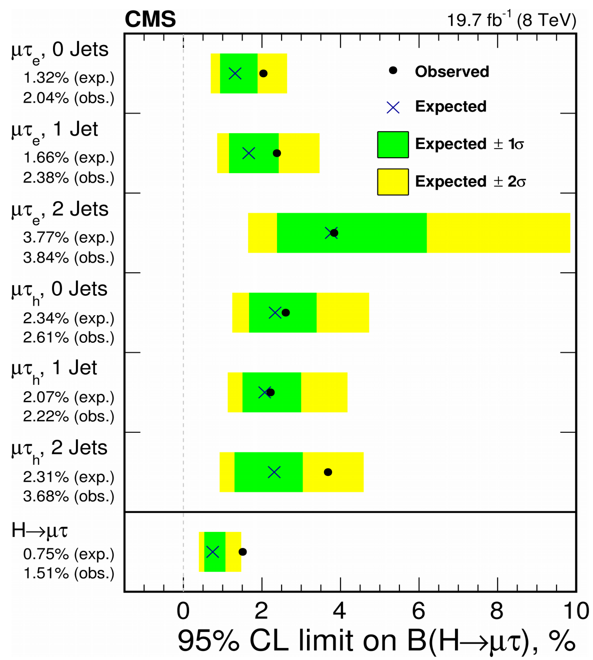
- A number of models beyond SM predict LFV in charged sector and FCNC related to the Higgs sector at levels observable at LHC.

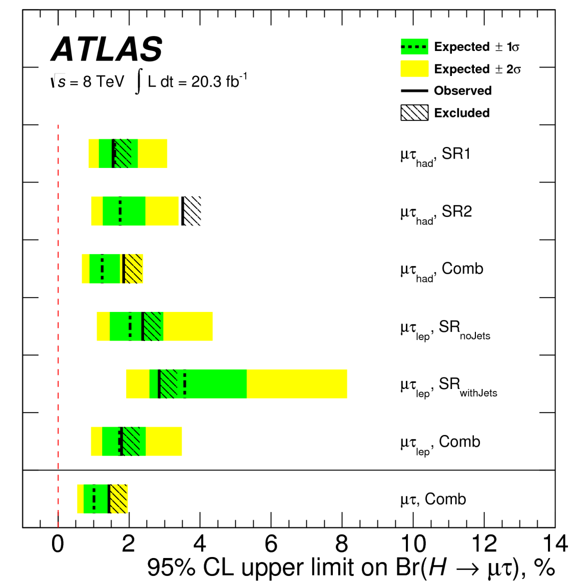
- Low energy results (e.g. $\mu \to e\gamma$, $\tau \to eee$, μ-e conversion, etc.) provide indirect constraints, but there are often assumptions.

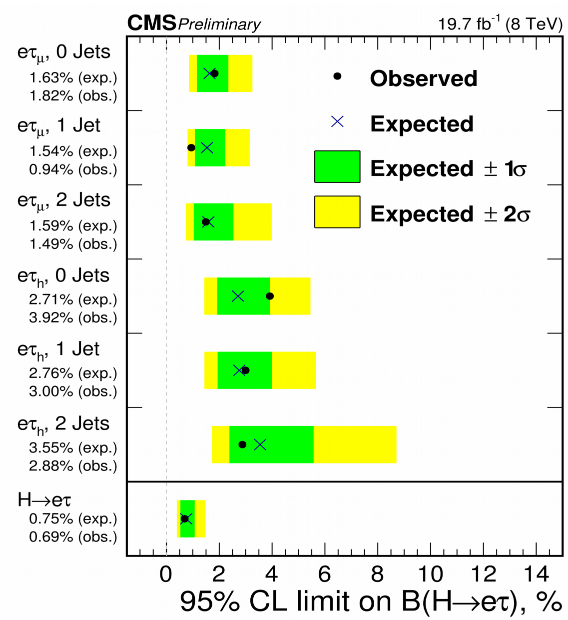
Run 1 search for $h \to \tau \ell'$

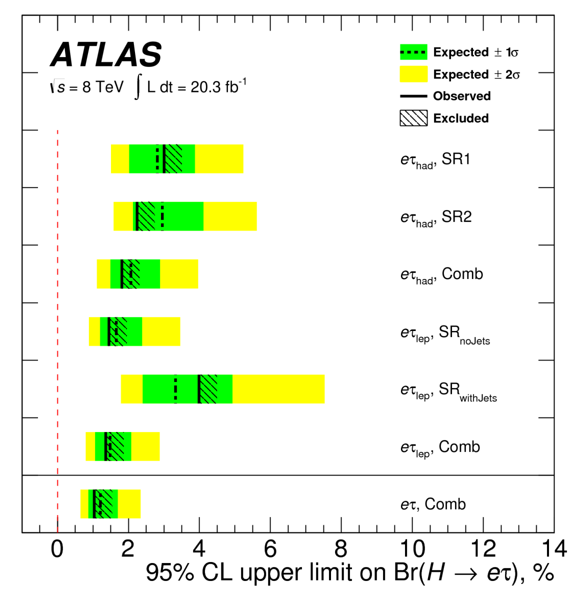
- The search for LFV decays of the Higgs boson are an interesting door to New Physics, $H \to \tau\mu, \tau e$.
- ATLAS searches for LFV $H \to \tau l$ decays are in part adapted from the $H \to \tau\tau$ analyses.
- A data-driven method is used by ATLAS for $l\tau_l$ channel, relying on symmetry of the SM bkg processes between $e\mu$ and μe final states.
- Collinear mass used by CMS and by ATLAS in $l\tau_l$ channel. ATLAS uses MMC reconstruction in the $l\tau_{had}$ channel.

- Small excess observed by CMS in 3 out of 6 categories:
  - 2.4 σ excess



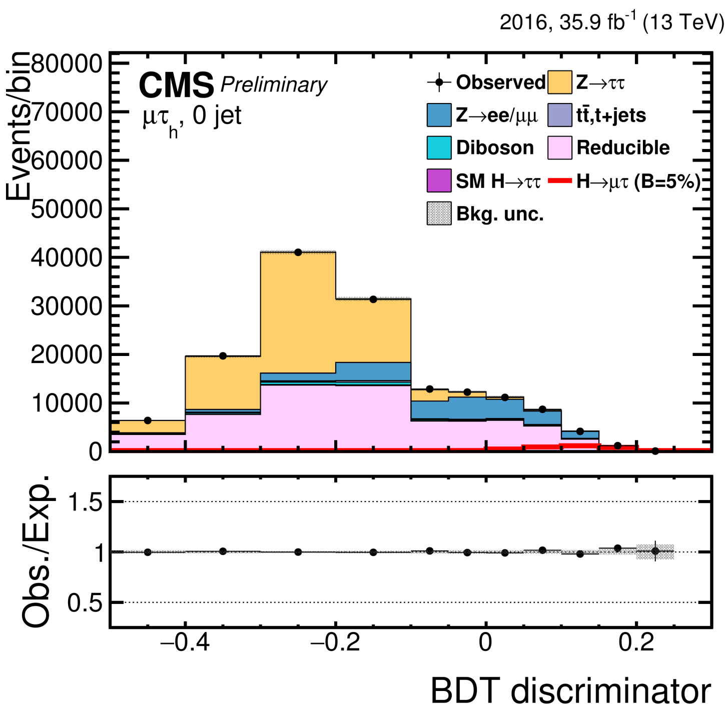


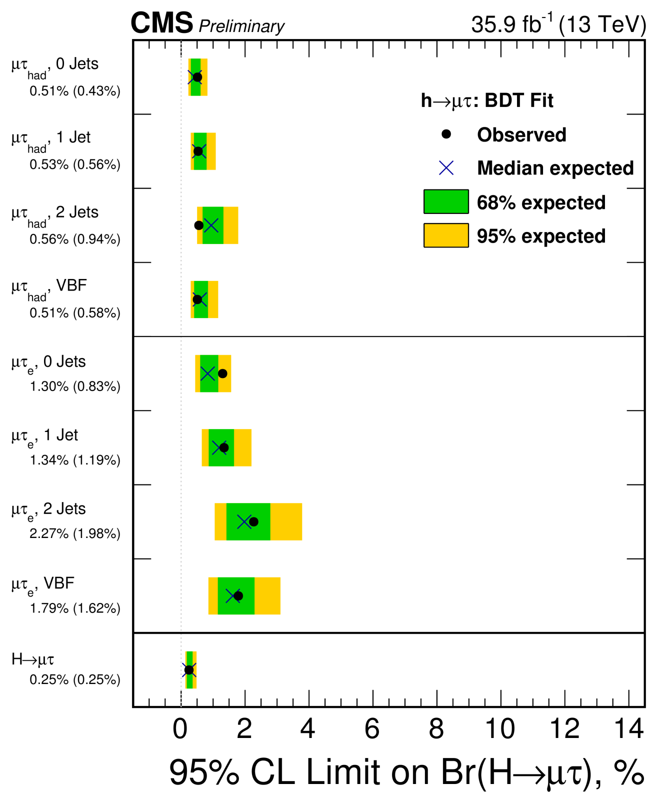


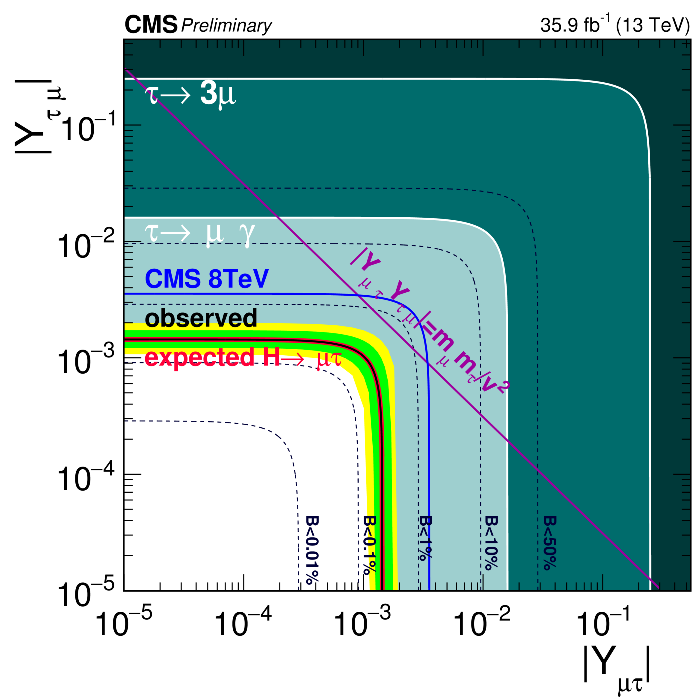


Run 2 $H \to \tau\mu$ Search

- Main backgrounds are the $Z \to \tau\tau$, W+jets and QCD production.
- Analysis employs categorization in 0-jet, 1-jet, 2-jet VBF and no VBF final states
- Both BDT and collinear mass fit analyses are used.



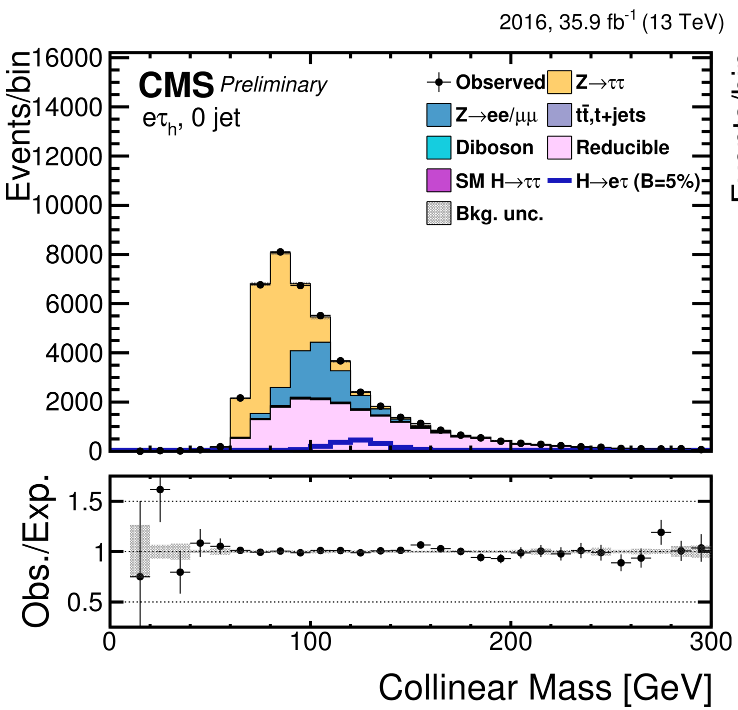


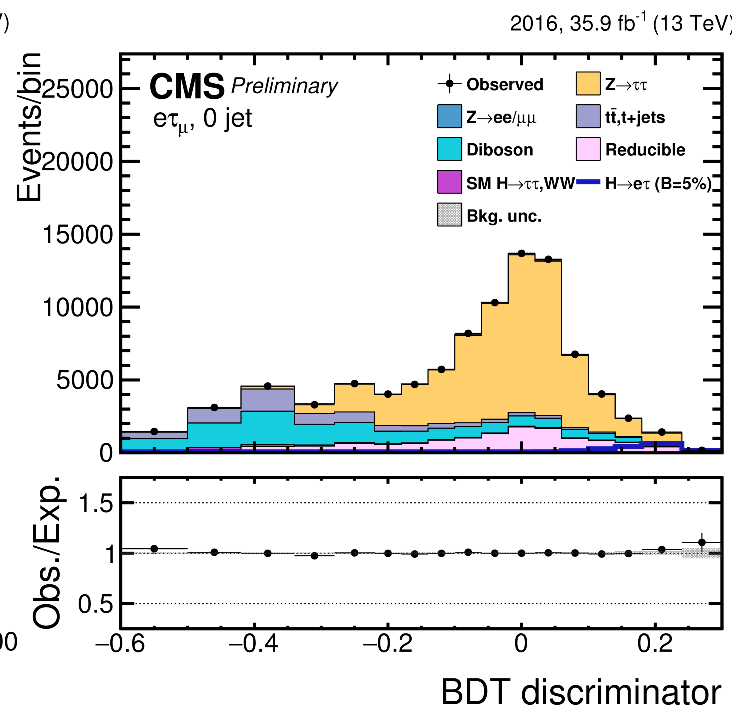


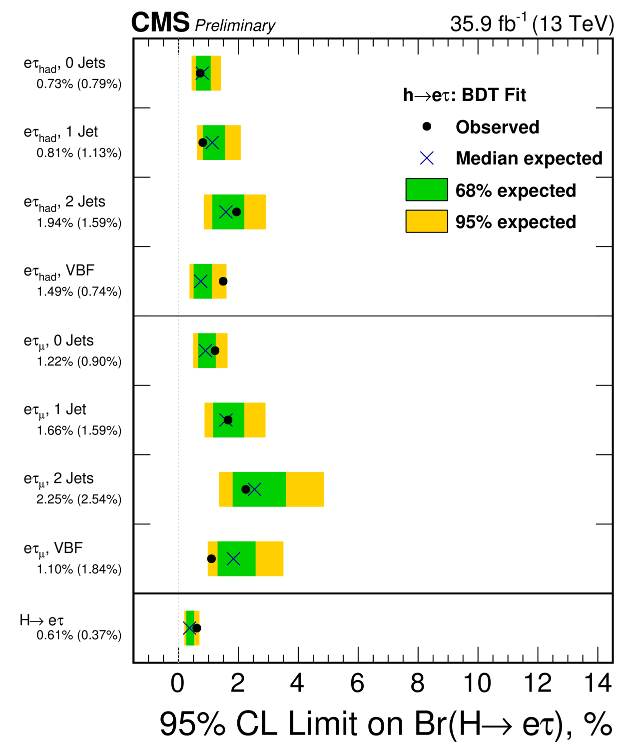
- BDT analysis significantly better than mass fit
- Best-fit BR($H \to \tau\mu$) = 0.00 ±0.12%
- No excess found, this result excludes the BR corresponding to the CMS Run 1 excess

Run 2 $H \to \tau e$ Search

- Same strategy used also for the $H \to \tau e$ search with only small differences in the choice of input variables to the BDT.
- With respect to $H \to \tau\mu$, additional $Z \to \mu\mu$ background



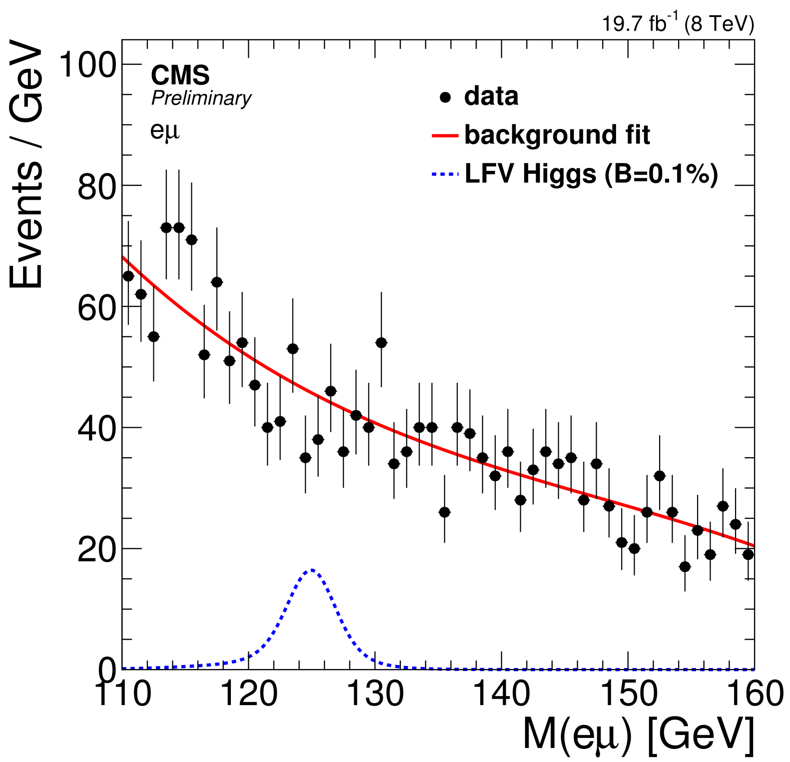


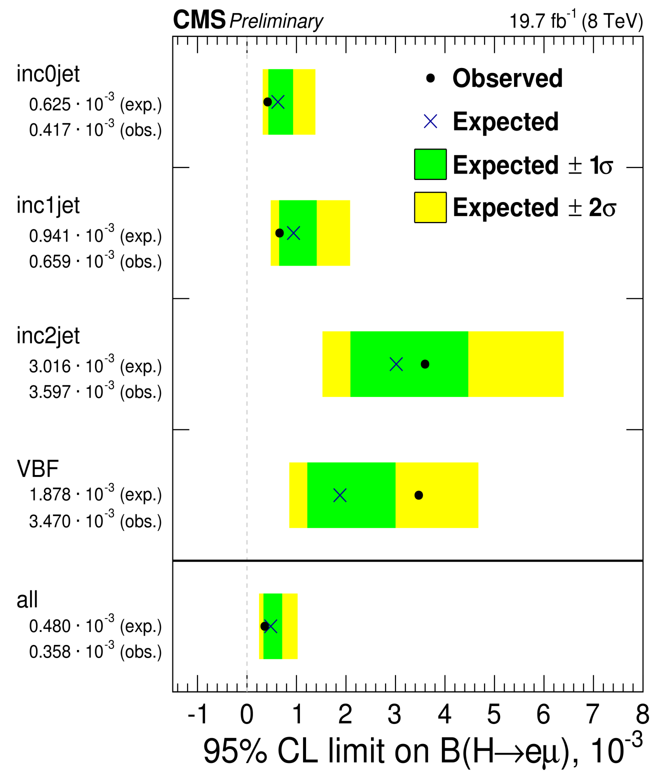


- Best-fit BR($H \to \tau e$) = 0.30 ±0.18%
- No excess found

Run 1 H →eμ

- CMS uses unbinned fit of the eμ mass spectrum.
- 11 categories (2 VBF + 3x3 barrel/endcap combination x number of jets), similar to H → μμ and H → γγ analyses
- Background modeled by polynomial, exponential and power law (category dependent).
- Signal modeled by the sum of two gaussians.





No excess observed: 95% CL limit is BR(H→eμ)<0.036%

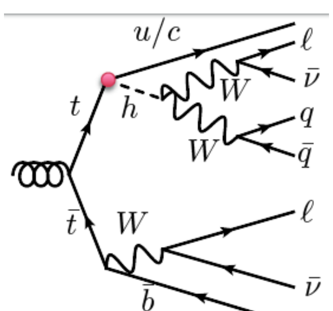
$FCNC\ t \rightarrow u/c+H$

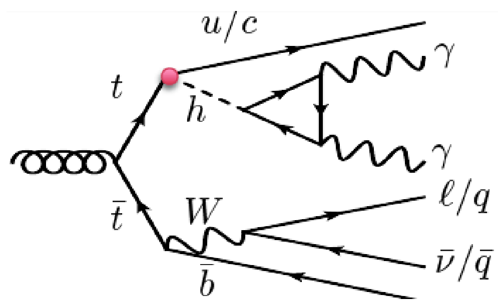
Modeling via anomalous couplings in effective Lagrangians

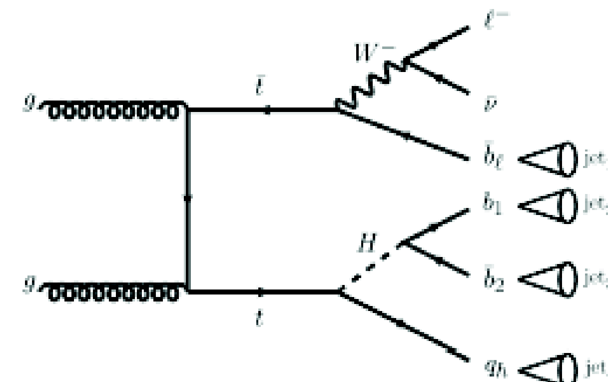
$$\mathcal{L}_{Htc} = -\frac{1}{\sqrt{2}}\,\bar{c}\left(\eta^{L}_{ct}P_L + \eta^{R}_{ct}P_R\right) t\, H + \mathrm{H.c.}$$

In the SM: $\mathrm{SM:}\ \mathcal{B}\left(t \to u/c + H\right) \lesssim 10^{-15}$

ATLAS and CMS analyzed ttbar decays with final states with H → γγ, H → bb and "multi-leptons" final states (H → ZZ, WW, ττ) and t → bW(→ℓν,→qq).







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PRD 90 (2014) 112013

JHEP 1406 (2014) 008

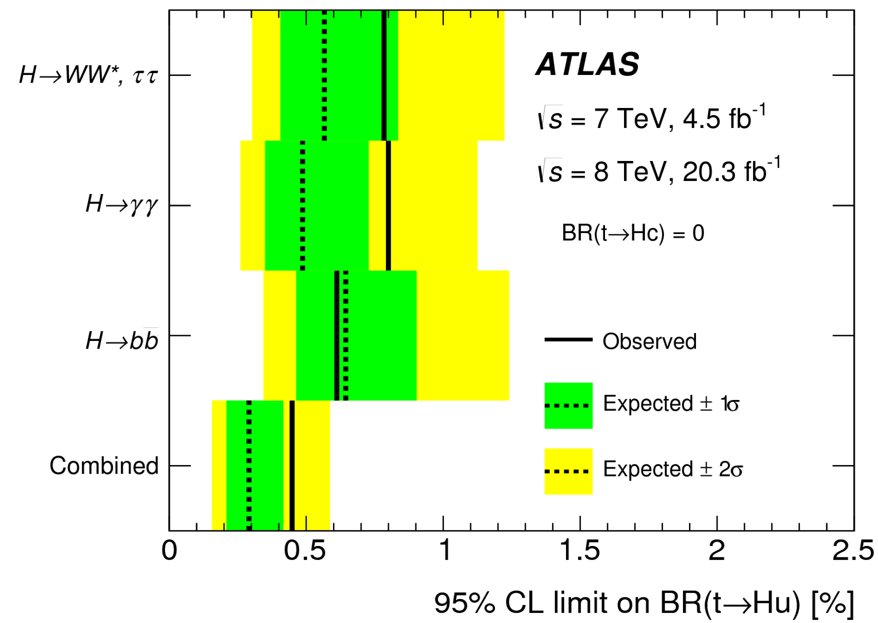
PRD 90 (2014) 112013

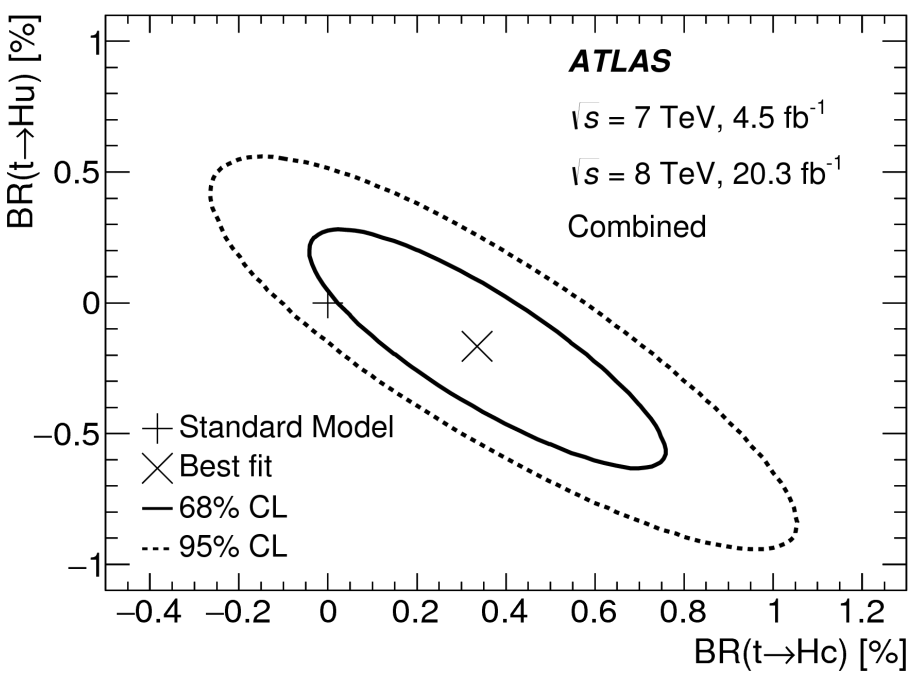
JHEP 12 (2015) 061

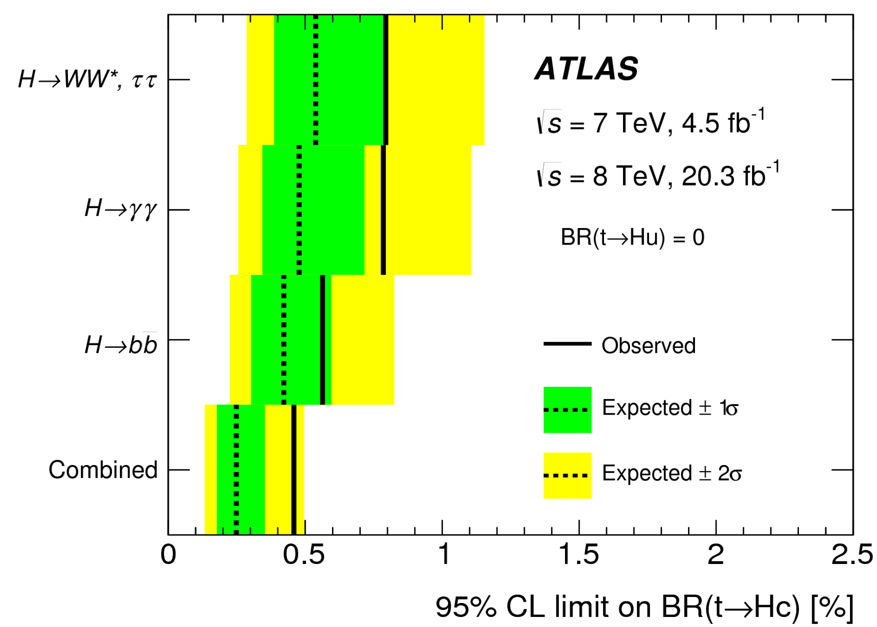
JHEP 02 (2017) 079

ATLAS FCNC $t \to u/c+H$ combination

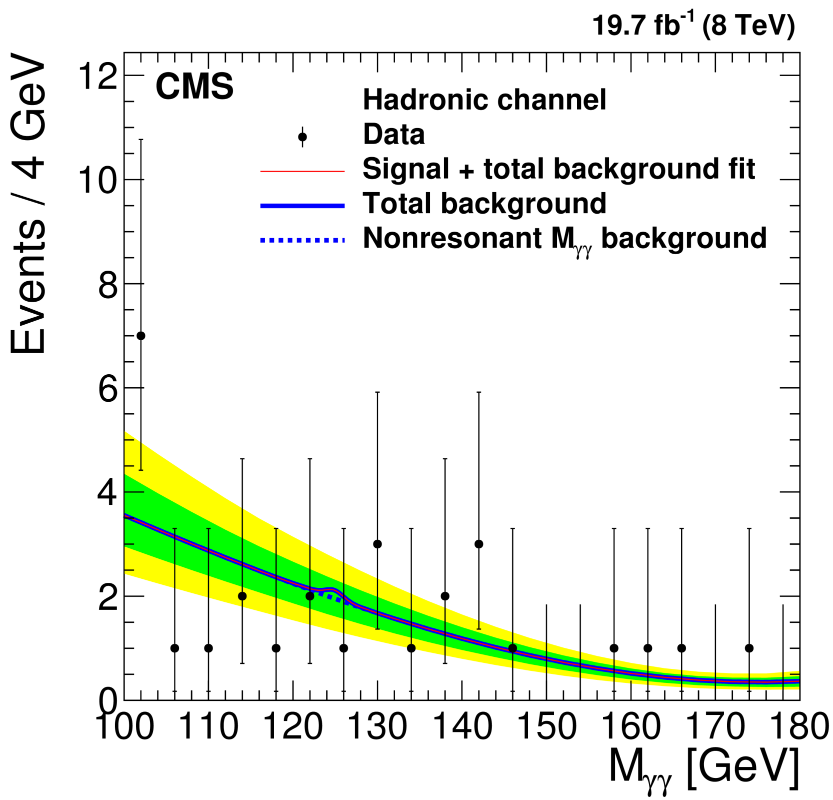
- Combination of ATLAS searches in $H \to bb$, $H \to \gamma\gamma$ and multi-lep
- 95% CL upper limits:
  - BR($t \to uH$) < 0.45% (0.29% exp)
  - BR($t \to cH$) < 0.46% (0.25% exp)
- Best fit of BR($t \to uH$) vs BR($t \to cH$) compatible within ~1σ with null hypothesis.







CMS FCNC $t \to u/c+H$ combination



	$\mathcal{B}_{obs}(t \to Hc)$	$\mathcal{B}_{exp}(t \to Hc)$	$\mathcal{B}_{exp}+\sigma$	$\mathcal{B}_{exp}-\sigma$
Trilepton	1.26	1.33	1.87	0.95
Same-sign dilepton	0.99	0.93	1.26	0.68
Multilepton combined	0.93	0.89	1.22	0.65
Diphoton hadronic	1.26	1.33	1.87	0.95
Diphoton leptonic	0.99	0.93	1.26	0.68
Diphoton combined	0.47	0.67	1.06	0.44
b jet + lepton	1.16	0.89	1.37	0.60
Full combination	0.40	0.43	0.64	0.30

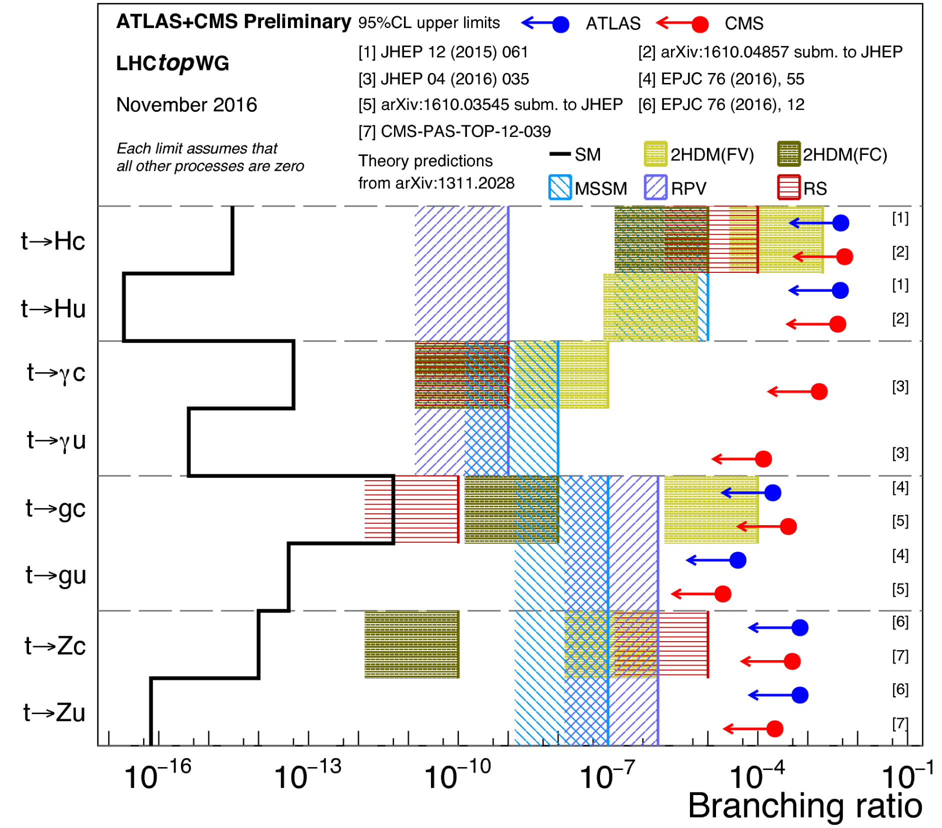
	$\mathcal{B}_{obs}(t \to Hu)$	$\mathcal{B}_{exp}(t \to Hu)$	$\mathcal{B}_{exp}+\sigma$	$\mathcal{B}_{exp}-\sigma$
Trilepton	1.34	1.47	2.09	1.05
Same-sign dilepton	0.93	0.85	1.16	0.62
Multilepton combined	0.86	0.82	1.14	0.60
Diphoton hadronic	1.26	1.33	1.87	0.95
Diphoton leptonic	0.99	0.93	1.26	0.68
Diphoton combined	0.42	0.60	0.96	0.39
b jet + lepton	1.92	0.84	1.31	0.57
Full combination	0.55	0.40	0.58	0.27

- Combination of CMS searches in $H \to bb$, $H \to \gamma\gamma$ and multi-lep
- 95% CL upper limits:
  - BR($t \to uH$) < 0.55% (0.40% exp)
  - BR($t \to cH$) < 0.40% (0.43% exp)
- No excess wrt SM found

LHC FCNC $t \to u/c+H$ combination

Collab	Decay mode	Limit BR($t \to Hc$) [%] Observed	Limit BR($t \to Hc$) [%] Expected	Limit BR($t \to Hu$) [%] Observed	Limit BR($t \to Hu$) [%] Expected
CMS	$H \to \gamma\gamma$	0.47	0.67	0.42	0.60
	$H \to WW, ZZ, \tau\tau$ (SS 2ℓ, 3ℓ, 4ℓ)	0.93	0.89	0.82	0.82
	$H \to bb$	1.16	0.89	1.92	0.84
	Combination	0.40	0.43	0.55	0.40
ATLAS	$H \to \gamma\gamma$	0.79	0.51	0.79	0.51
	$H \to WW, \tau\tau$ (SS 2ℓ, 3ℓ)	0.79	0.54	0.78	0.57
	$H \to bb$	0.56	0.42	0.61	0.64
	Combination	0.46	0.25	0.45	0.29

- **Strategies:**
- $H \to \gamma\gamma$: small BR(~0.2%)
  - Very small background, excellent mass resolution
- $H \to WW^*$, $\tau\tau$: sizeable BR(WW^*: 21.5%, $\tau\tau$: 6.3%); SS 2ℓ, 3ℓ.
  - Small background, poor mass resolution
- $H \to bb$: largest BR(~58%); lepton+jets.
  - Large background, some mass resolution.



Summary

- Outstanding performance from the LHC team and experiments is allowing to deliver an impressive amount of updates on the Higgs Yukawa couplings.

- Couplings to tau-leptons established in Run 1.

- Couplings to quark still hasto reach the observation level.

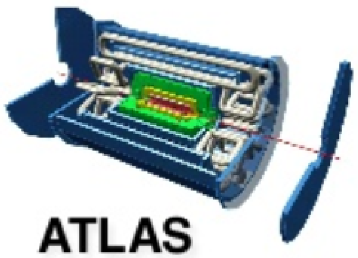
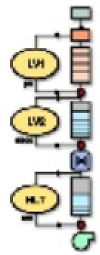
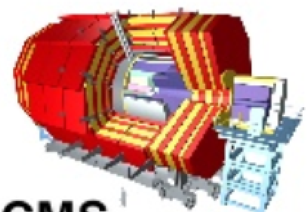
- Small CMS excess on $H \rightarrow \tau\mu$ has been excluded with more statistics.

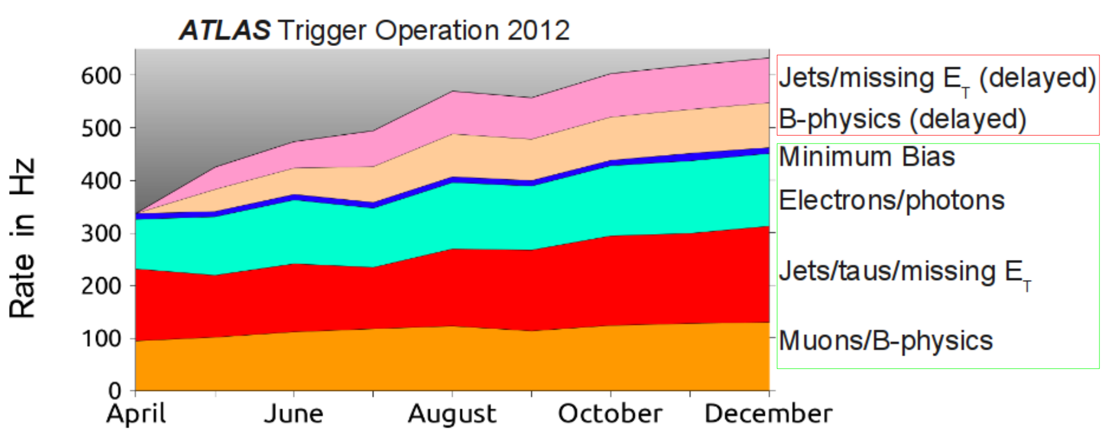
- LHC Run 2 is the opportunity to improve Yukawa couplings measurements:
    - ttH analyses start to be more sensitive than Run 1.
    - Run 1 sensitivity for VH(bb) not surpassed yet.
    - Search for rare channels and production modes continues:
        - $H \rightarrow \mu\mu$, quarkonia+γ and tH
        - FCNC and LFV decay modes

Thanks for the attention

Bonus Slides

DAQ and Trigger

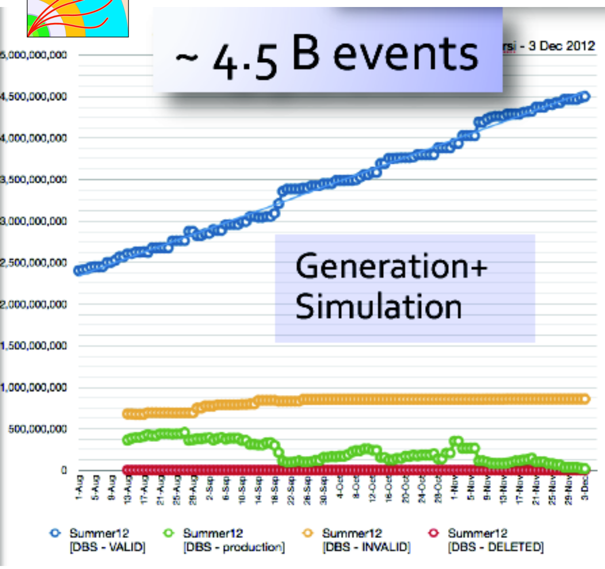
	Trigger No. Levels	Level-0,1,2 Rate (Hz)	Event Size (Byte)	Readout Bandw.(GB/s)	HLT Out MB/s (Event/s)
 ATLAS	3 	LV-1 10^5 LV-2 $3\text{x}10^3$	$1.5\text{x}10^6$	4.5	600+300 ($4\text{x}10^2+2\text{x}10^2$)
 CMS	2 	LV-1 10^5	10^6	100	O(1000) (10^3)

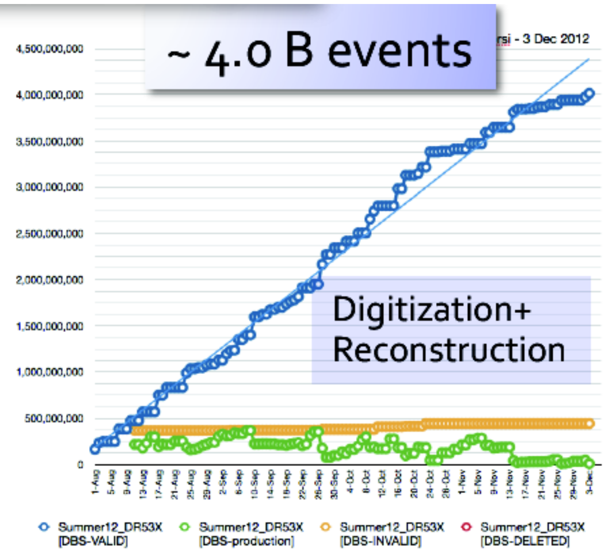


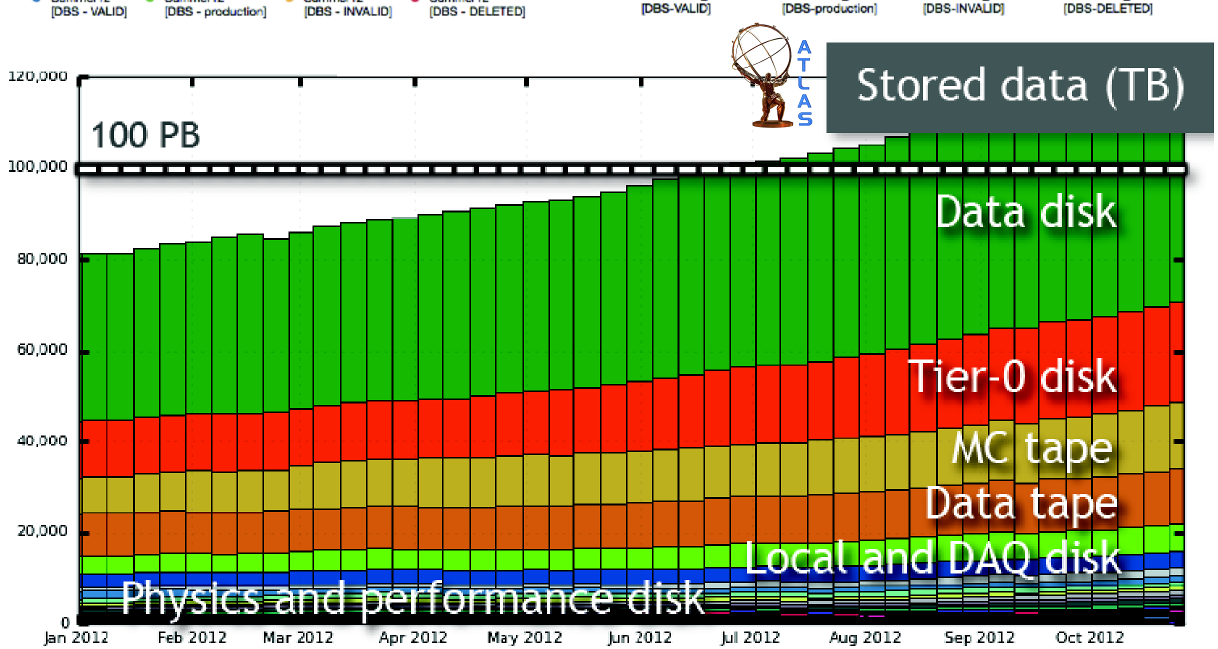
Both experiments have improved their DAQ and trigger systems for Run-2.
Current DAQ Performance
- >= 100 kHz at L1
- >= 1 kHz HLT output

Computing and Simulation

The fast duty cycle of the LHC analyses is possible thanks to the Tier0 and GRID resources





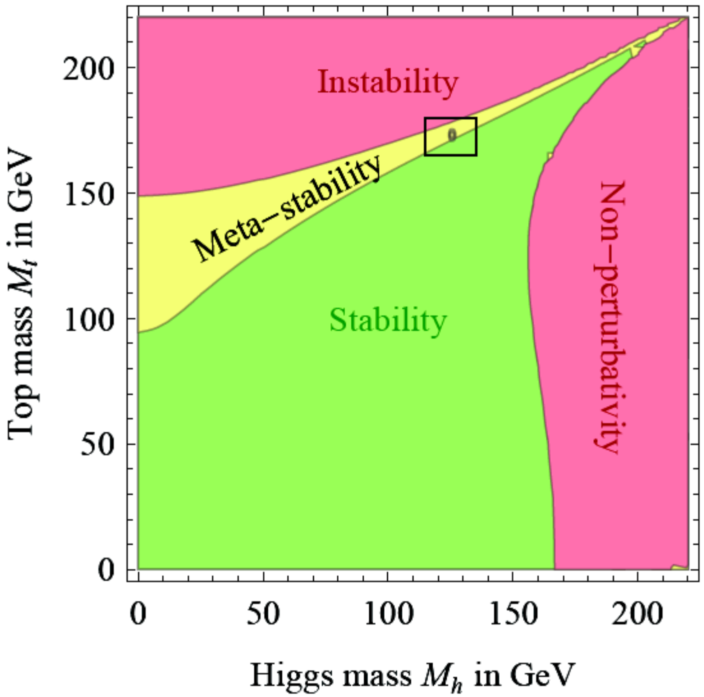


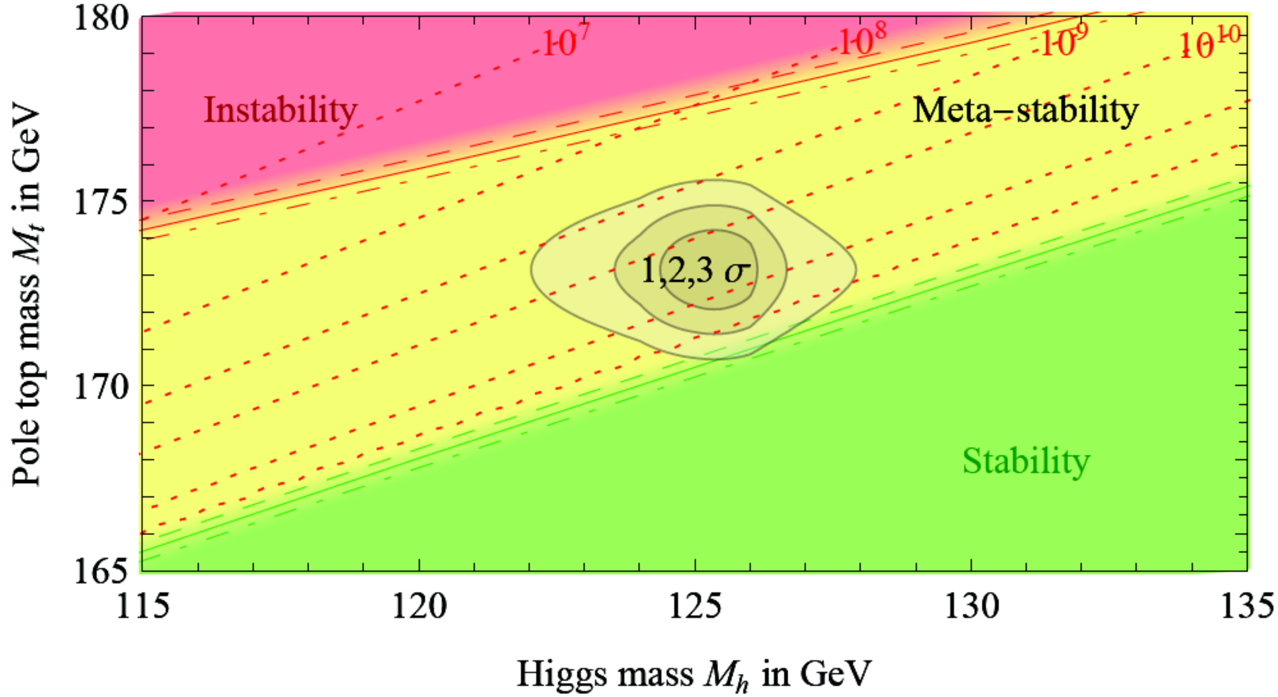
- Just in 2012, both CMS and ATLAS experiments have produced 3-4 billions of MC events on the GRID and processed ~3 billions of data events at Tier0.

- On a single machine, it would require more than 15 thousands years (without considering user and group analyses, calibrations, reprocessings, ...).

- GRID is a crucial asset of the LHC experiments to provide physics results in a timely manner.

Higgs Mass measurement

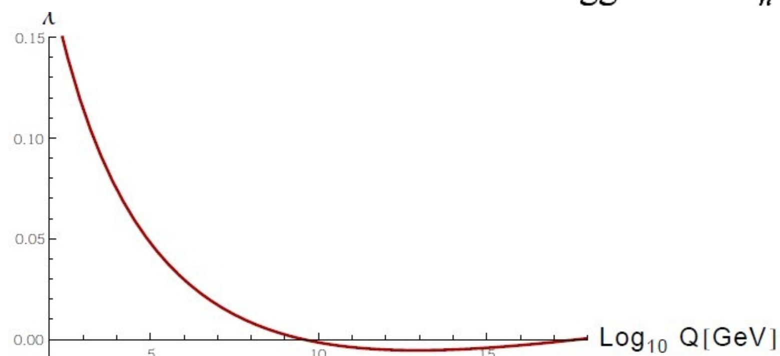


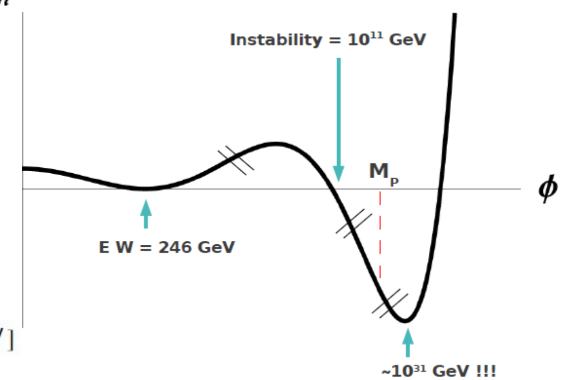


$$L = (\partial\Phi)(\partial\Phi^*) - V(\Phi)$$

$$V = \mu^2\Phi\Phi^* + \lambda(\Phi\Phi^*)^2$$

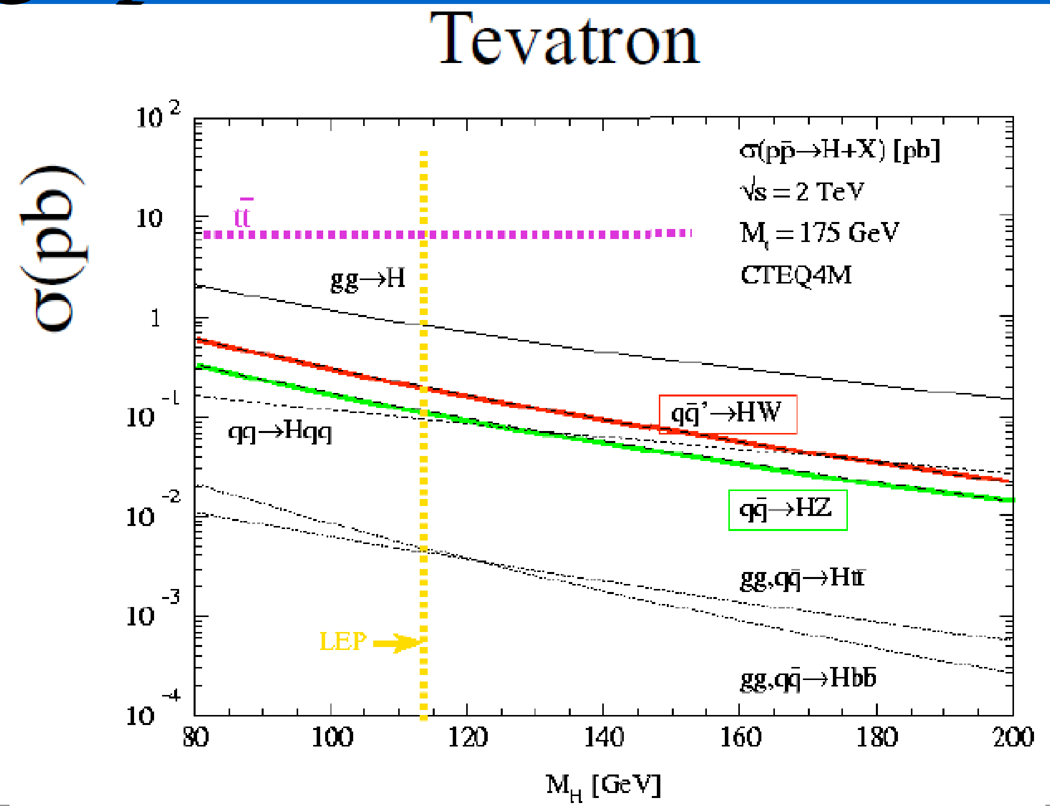
At EW scale λ~0.13

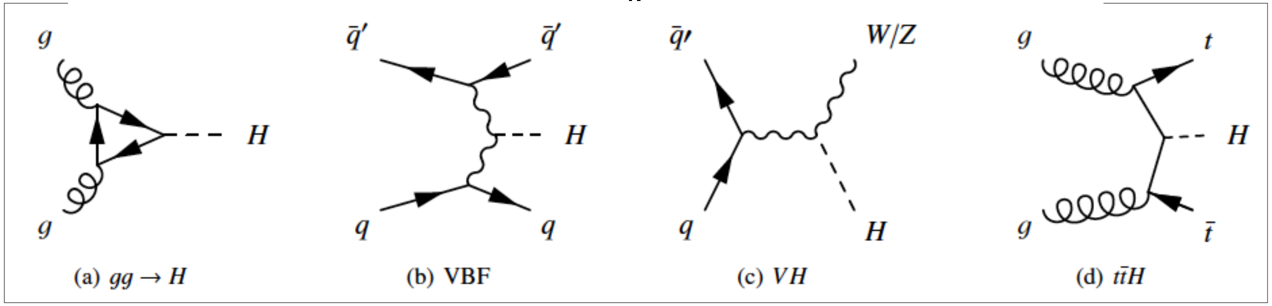




- Higgs quartic coupling λ can become negative for energies of $O(10^{10})$ GeV. Main corrections depends on m_{top} and m_H precise values.
- EW Vacuum stability up to Planck scaled excluded @ 95 C.L. <u>without NP</u>
- G.Degrassi et al. (arXiv:1205.6497, arXiv:1307.3536)

Higgs prod. Rates at TeVatron



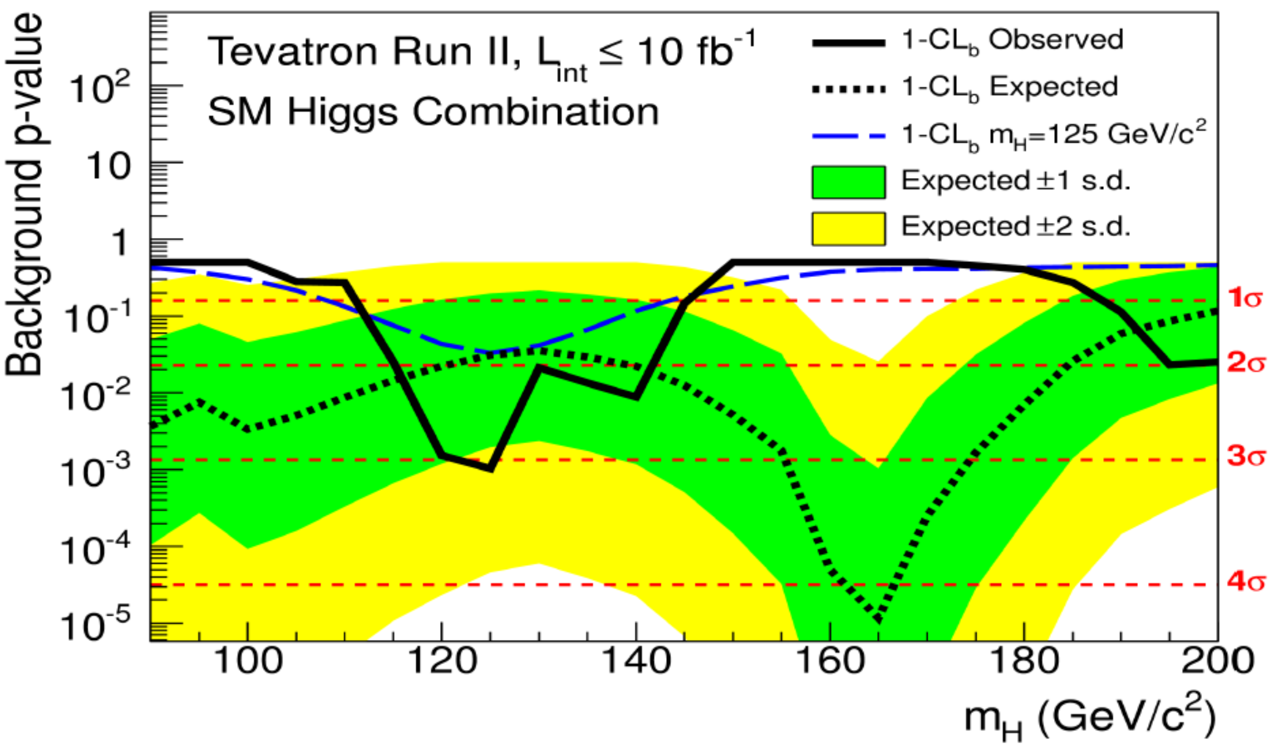


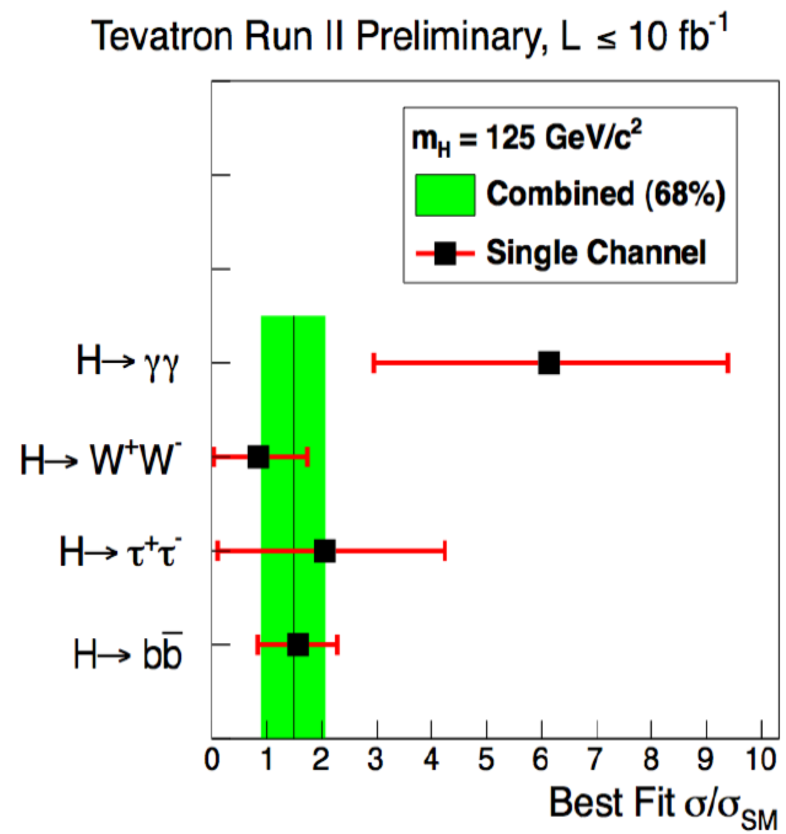
78%	7%	15%	<1%

ggH is the dominant production mode.
VH is the subleading production mode

TeVatron Results

TeVatron updated their Higgs boson search results with ~10 fb^{-1}
Most sensitive channels are (V)H → (V)bb, H → WW. Analyses of H → γγ and H → ττ are also included.

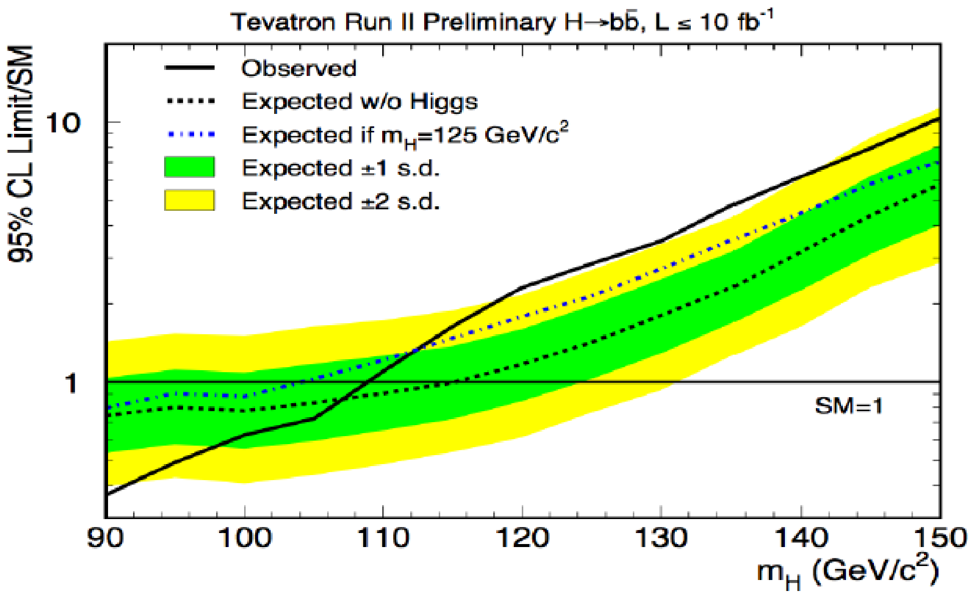


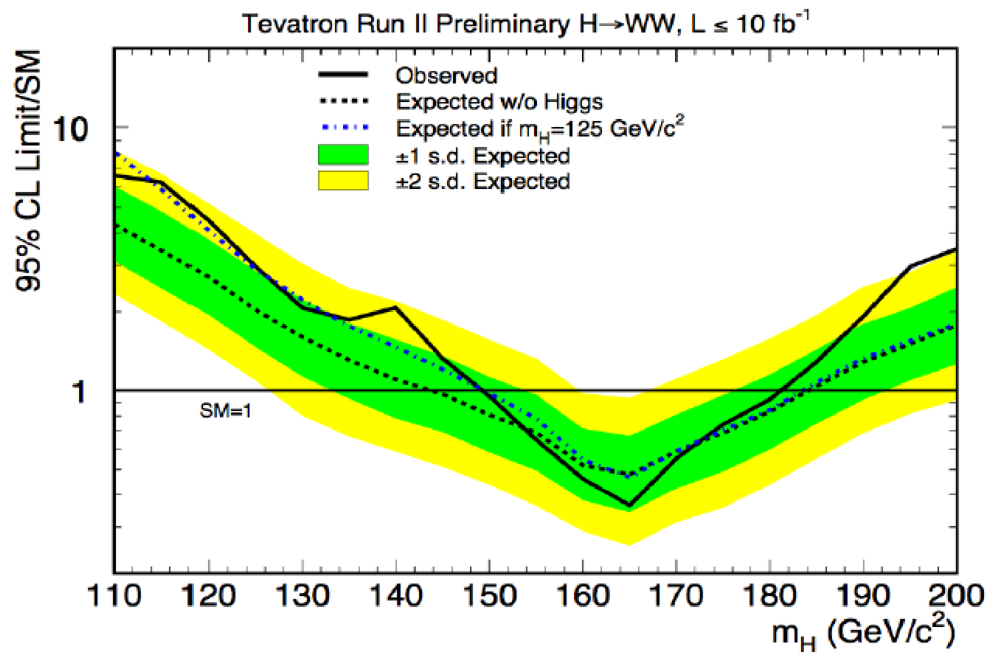


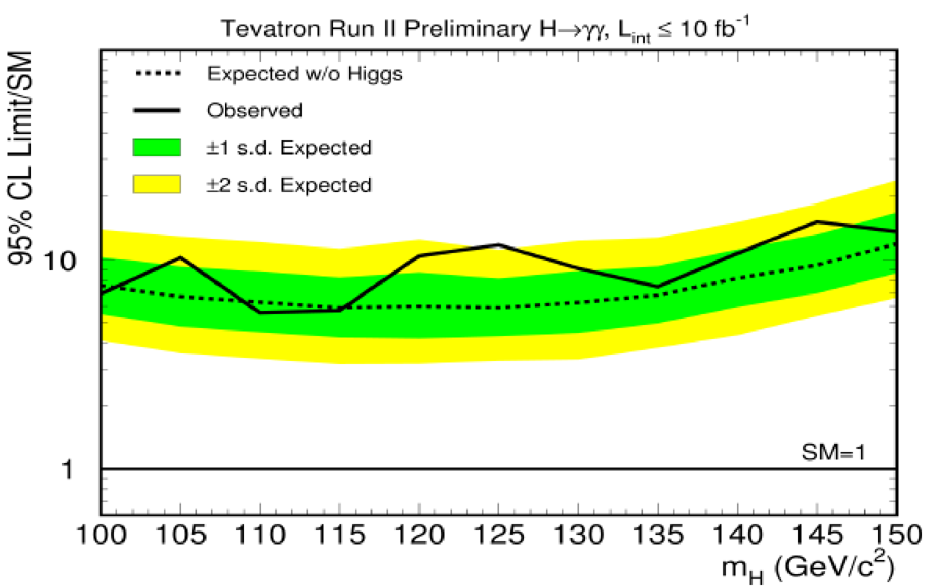
The minimum p-value is found to be 3.0σ at mH =125GeV.

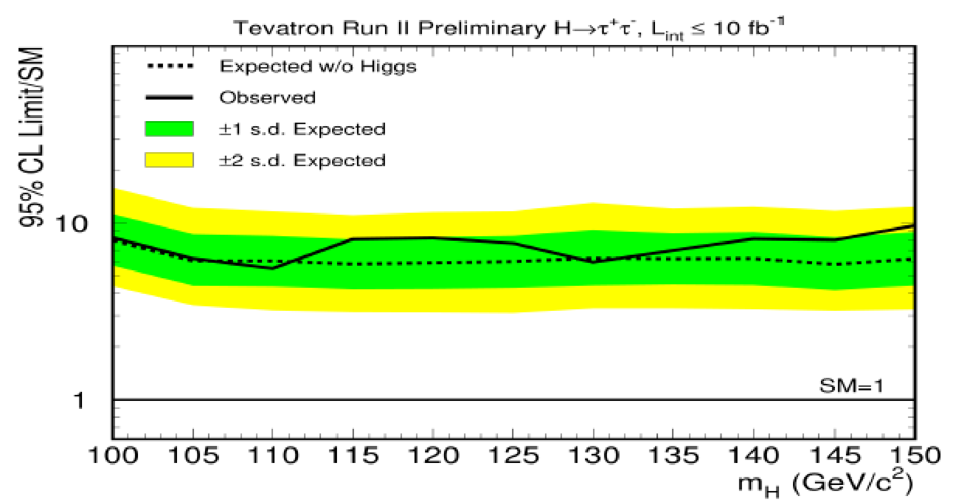
Fit to signal strength (1.4±0.6)xSM @125 GeV

TeVatron Limits by channel

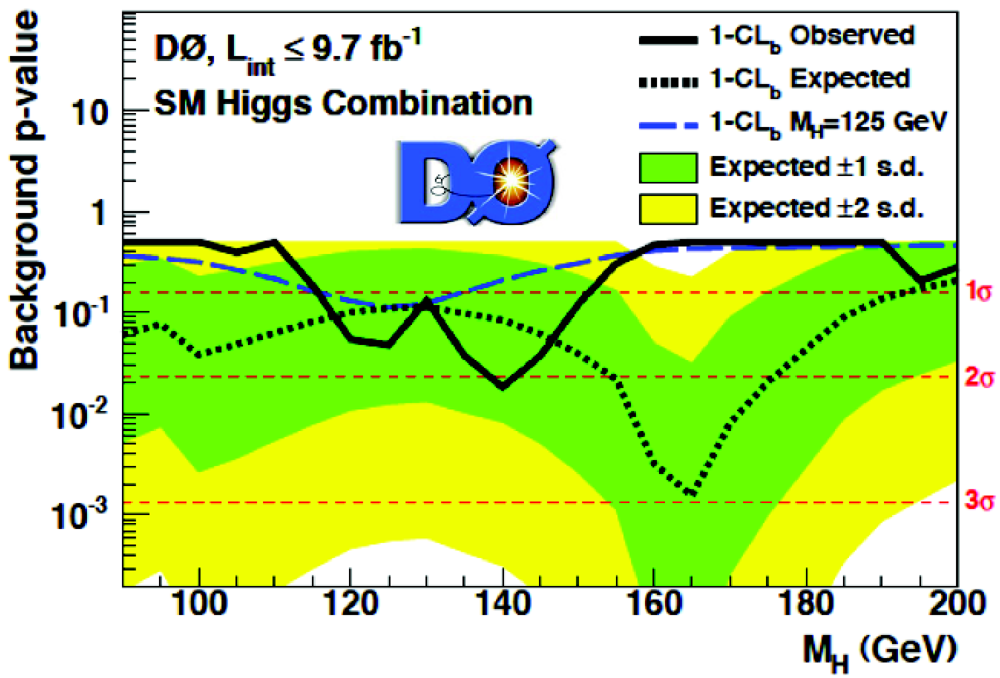


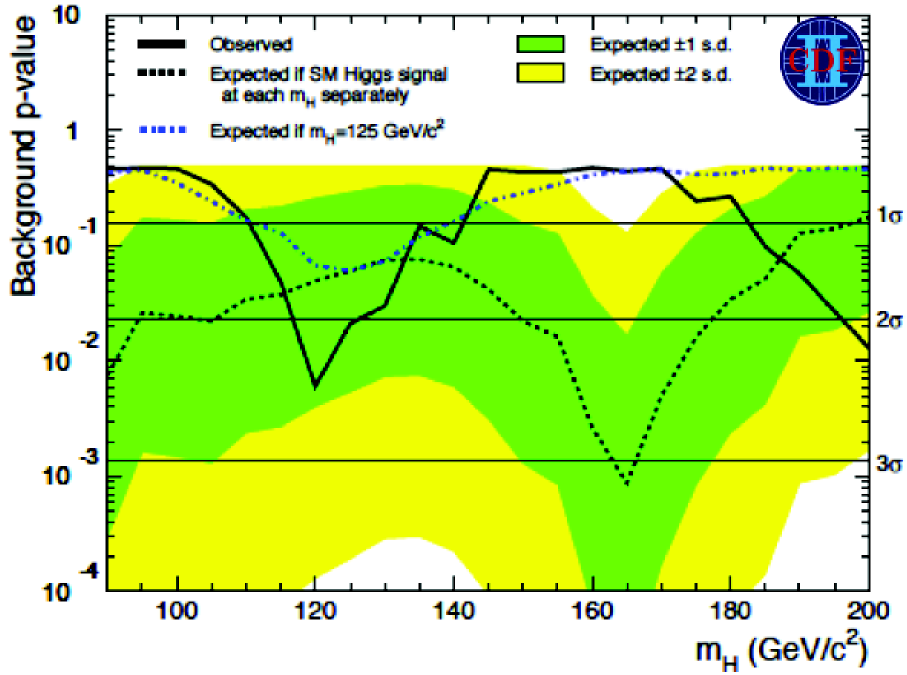






TeVatron Results by experiment

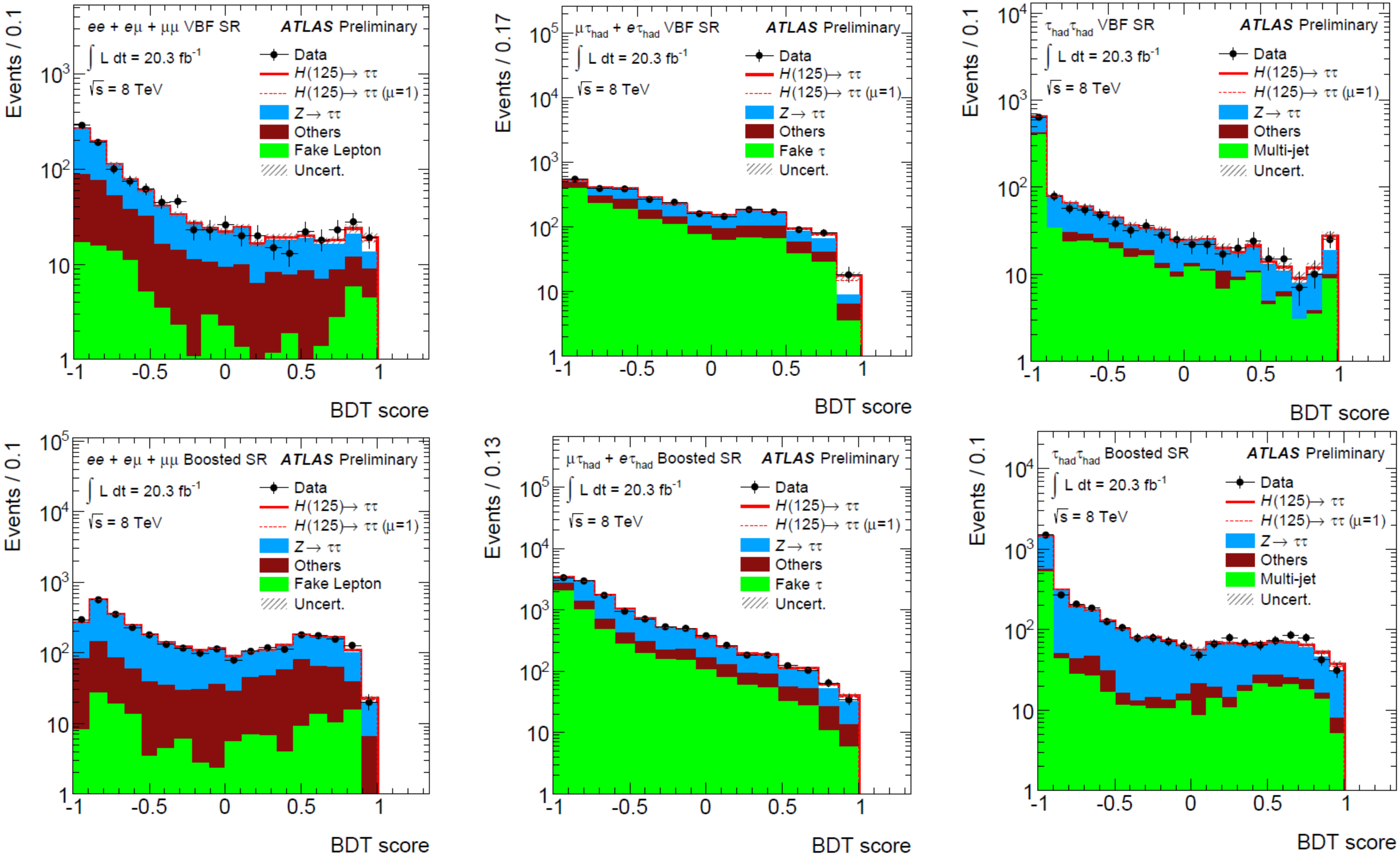




Local p-value distributions as a function of the Higgs mass for D0 and CDF experiments:

- D0: 1.7 σ @ m_H=125 GeV
- CDF: 2.0 σ @ m_H=125 GeV

$H \to \tau\tau$ Analysis BDT



- Data is divided in 6 signal regions and 9 control region to simultaneously fit signal and backgs.

Higgs Potential (2)

The minima of the potential are on a circumference of radius:

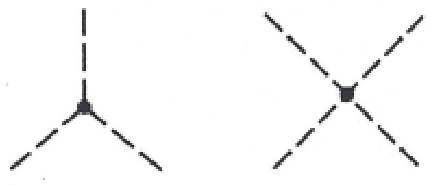
$$|\Phi| = \sqrt{\frac{-\mu^2}{2\lambda}} \equiv v/\sqrt{2}$$

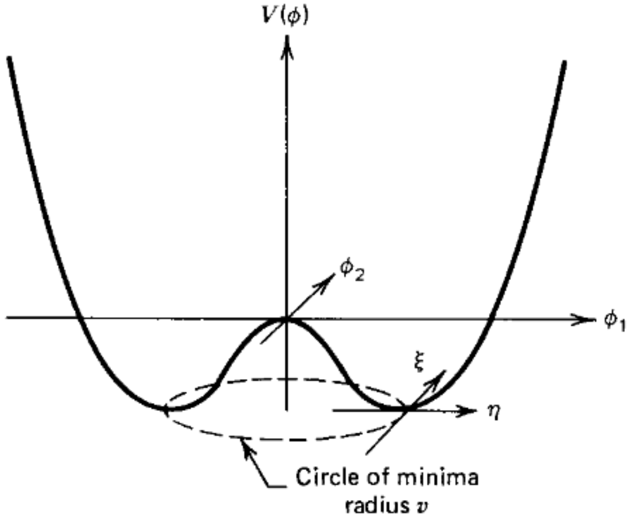
We rewrite the Lagrangian around a minimum: $\frac{v}{\sqrt{2}} + \eta(x)$

The Lagrangian now becomes:

$$\mathscr{L} = \tfrac{1}{2}(\partial_\mu \eta)(\partial^\mu \eta) - \mu^2\eta^2 \pm \mu\lambda\eta^3 - \tfrac{1}{4}\lambda^2\eta^4 + \tfrac{1}{4}(\mu^2/\lambda)^2$$

where the third and forth terms represent
the self coupling of the Higgs field:

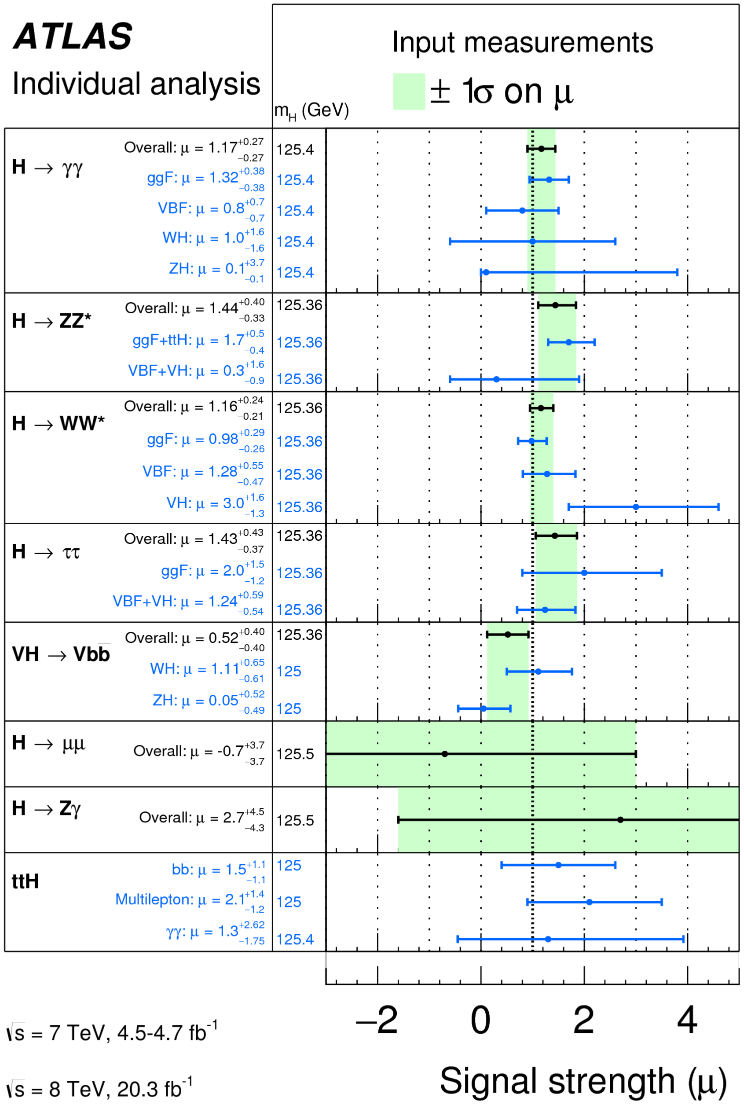




21/05/17

LHC Couplings Combination

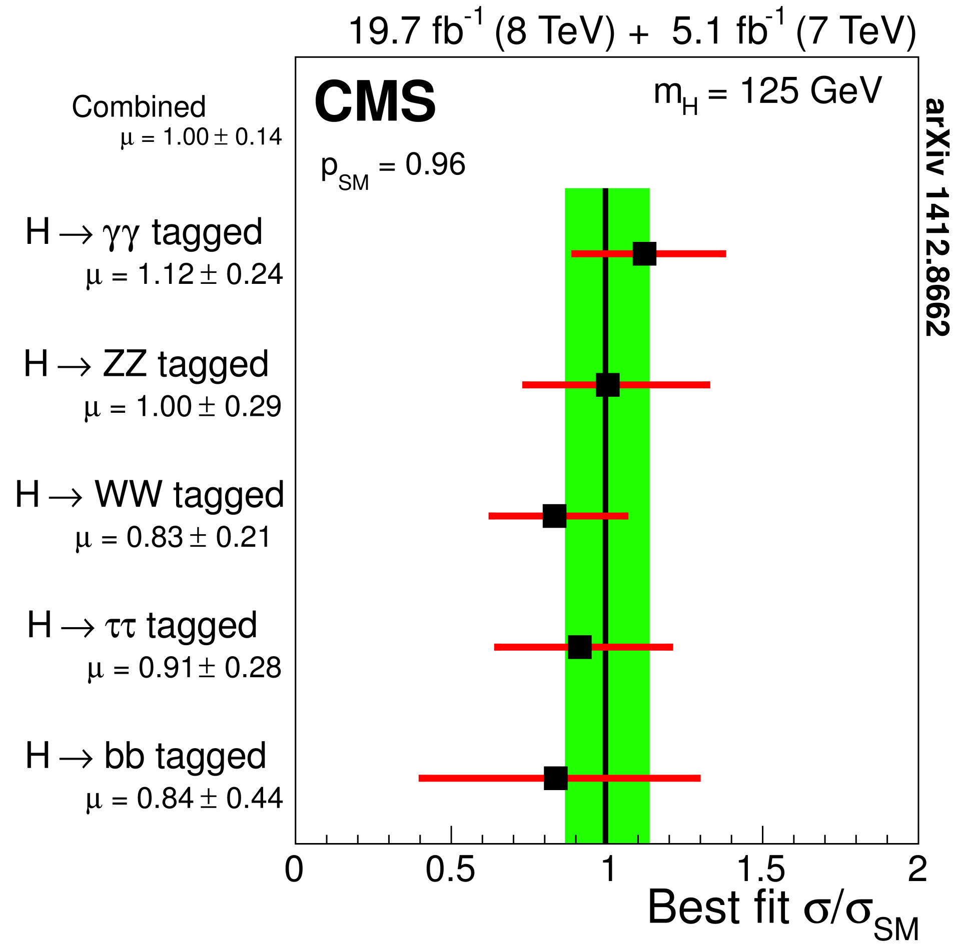
arXiv 1507.04548



$\mu=\sigma/\sigma_{SM}$

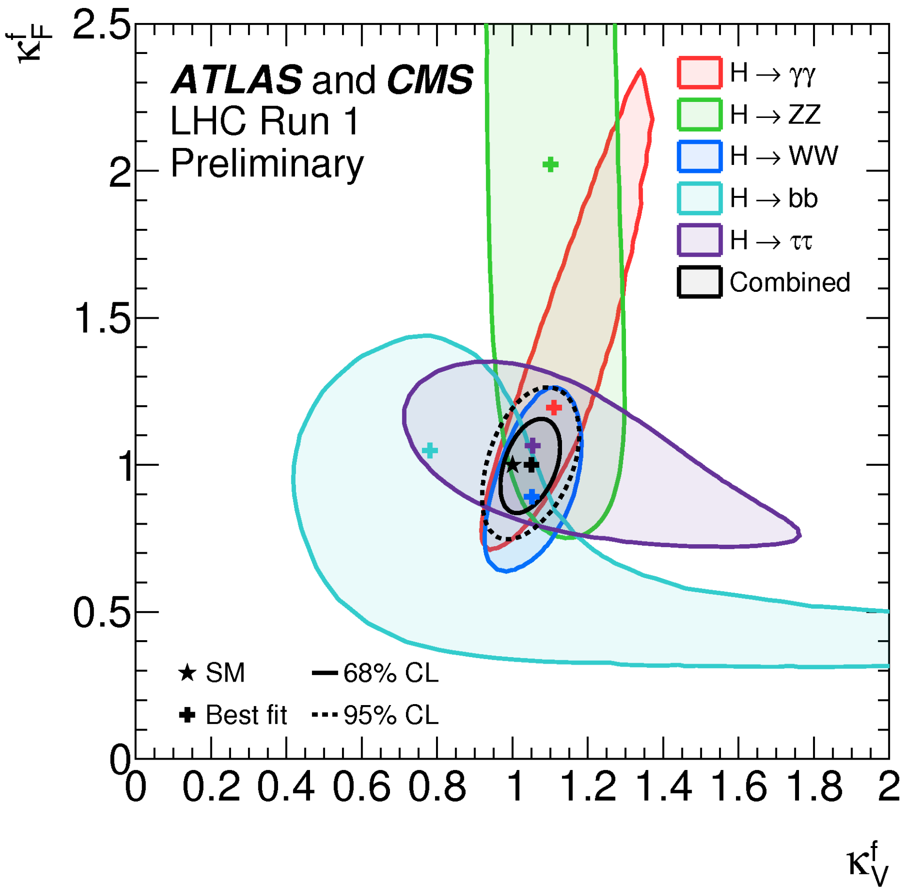
μ=0 no Higgs

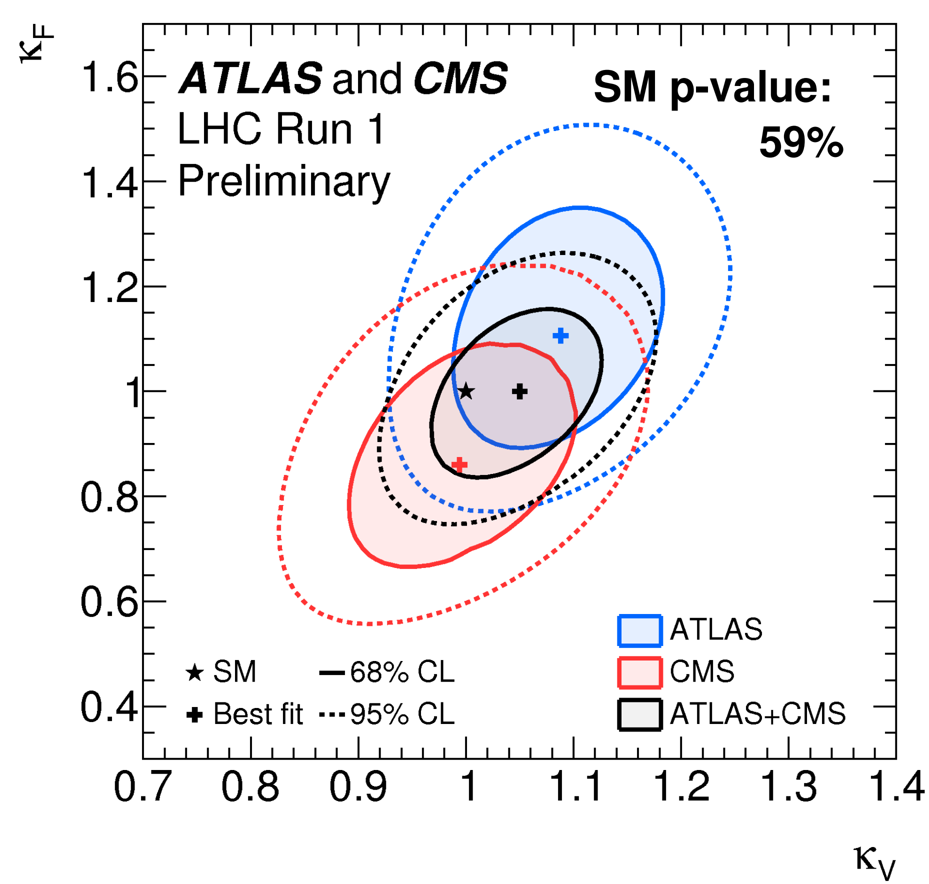
μ=1 SM Higgs



- Combination of ATLAS and CMS coupling measurements.
- Inputs sensitive to ggF, VBF, W/ZH and ttH production modes and to $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, $H \rightarrow WW$, $H \rightarrow \tau\tau$, $H \rightarrow \mu\mu$ and $H \rightarrow bb$ decay modes.

κ_V vs κ_F Contour





- Couplings are grouped: $\kappa_V = \kappa_W = \kappa_Z$; $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$
- Assumptions:

– gg → H and H → γγ only through SM particles

→ only SM particles contribute to decay

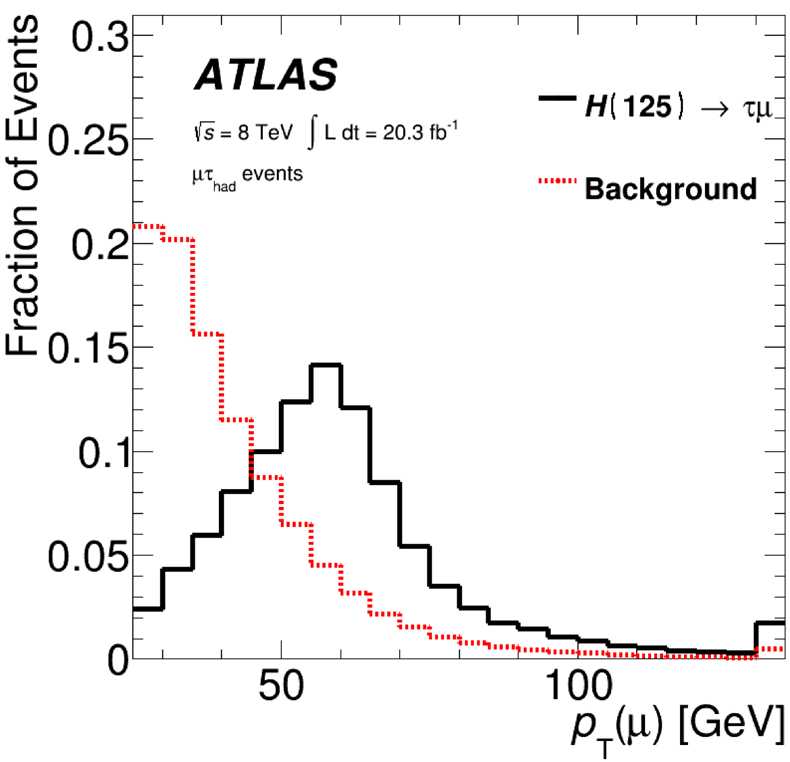
- All results in agreement with SM ($\kappa_V = \kappa_F = 1$) within 1σ

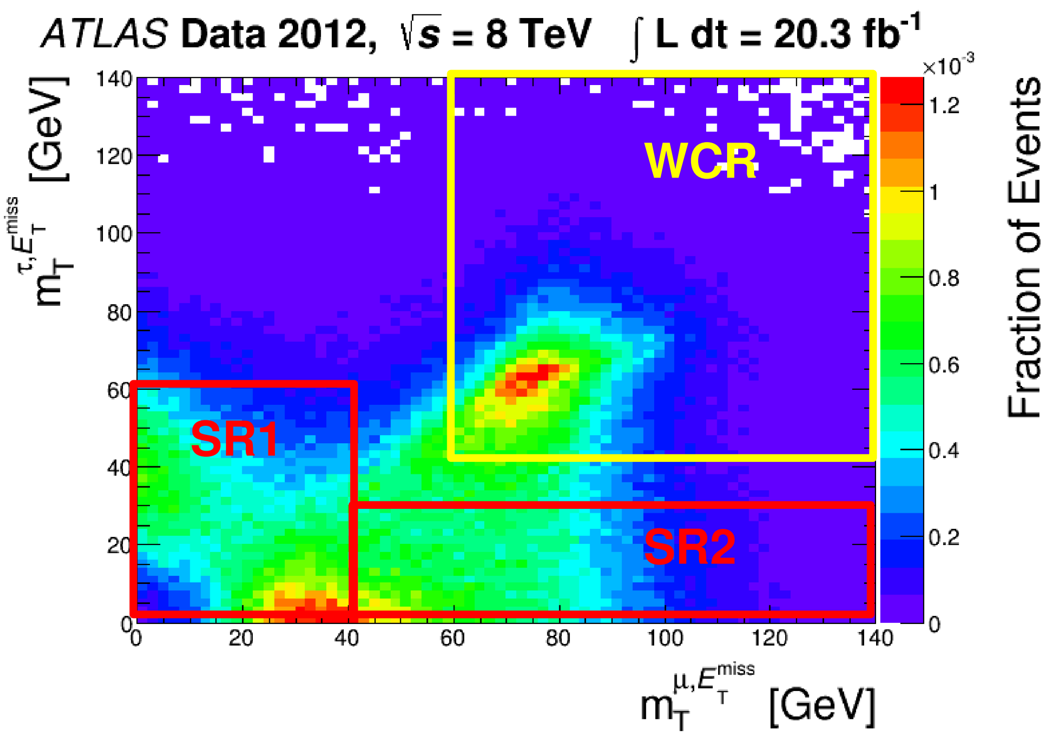
$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_\mathrm{H}},$$

$$\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}} \quad \text{or} \quad \kappa_j^2 = \Gamma^j / \Gamma_{\mathrm{SM}}^j.$$

ATLAS H →μτ

- ATLAS analyzed the $\mu\tau_{had}$ final states
- Analysis employs 2 signal categories and 1 control region
- Using binned MMC (missing mass calculator) spectrum for the statistical analysis.
- Main backgrounds:
  - W+jets main backgrond in SR1
  - $Z \rightarrow \tau\tau$ main background in SR2





Run 1 search for $h \to \ell\ell'$

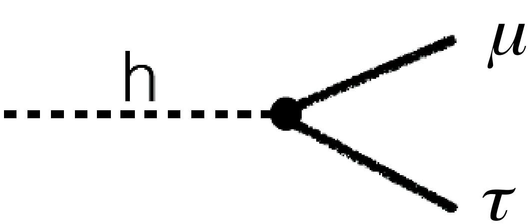
General Higgs interaction to fermions in mass basis.

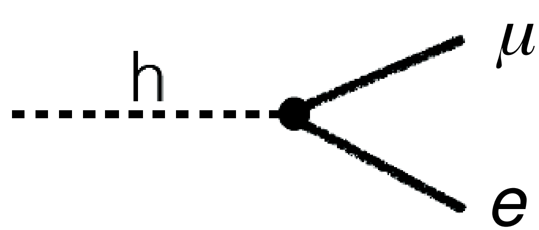
$$\mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - Y_{ij}(\bar{f}_L^i f_R^j)h + h.c. + \cdots ,$$

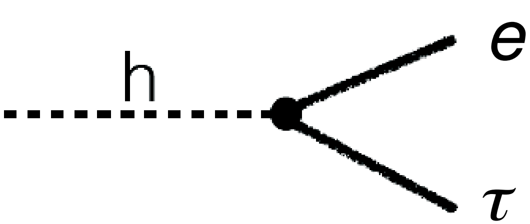
In the SM: $Y_{ij} = (m_i/v)\delta_{ij}$

Indirect limit on BR($H \to \ell\tau$) are loose O(10%)

Stringent indirect limits on $Y_{e\mu}$ from $\mu \to e\gamma$ BR($H \to e\mu$)< 10^{-8}, but with assumptions on NP contributions in the loop.







Phys. Lett. B 749 (2015) 337

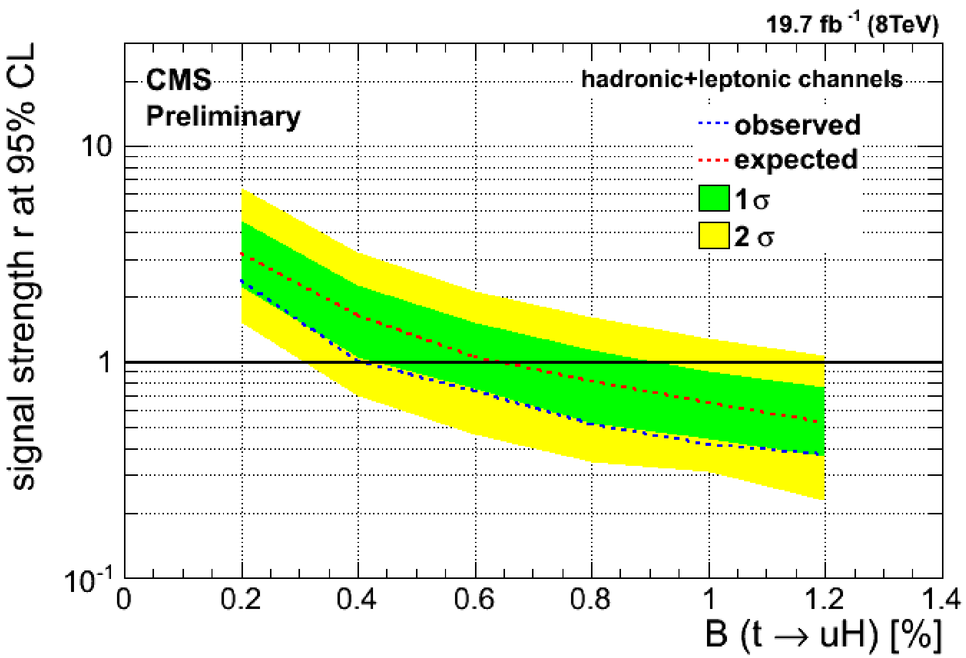
arXiv:1508.03372

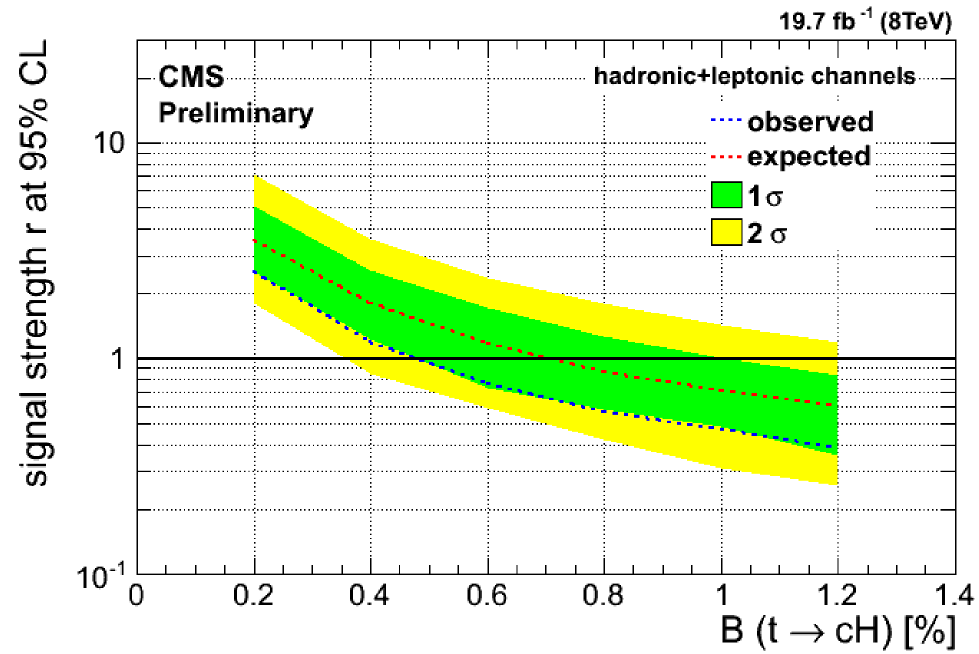
CMS-PAS-HIG-14-040

CMS-PAS-HIG-14-040

CMS FCNC $t \to u/c+H(\gamma\gamma)$

- 8 TeV datasets is used.
- Similar approach to ATLAS analysis, considering both hadronic and leptonic final states of the W decay:



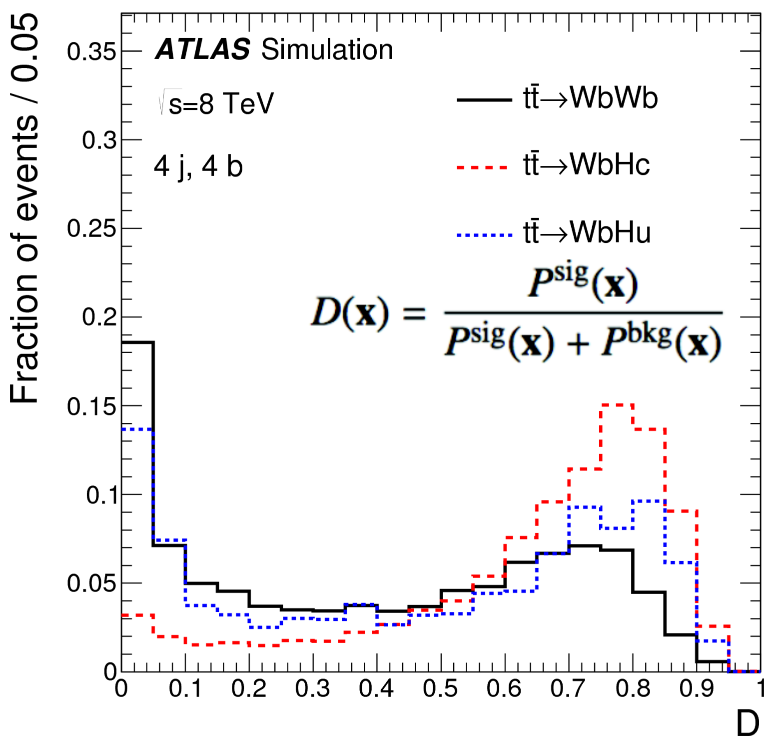


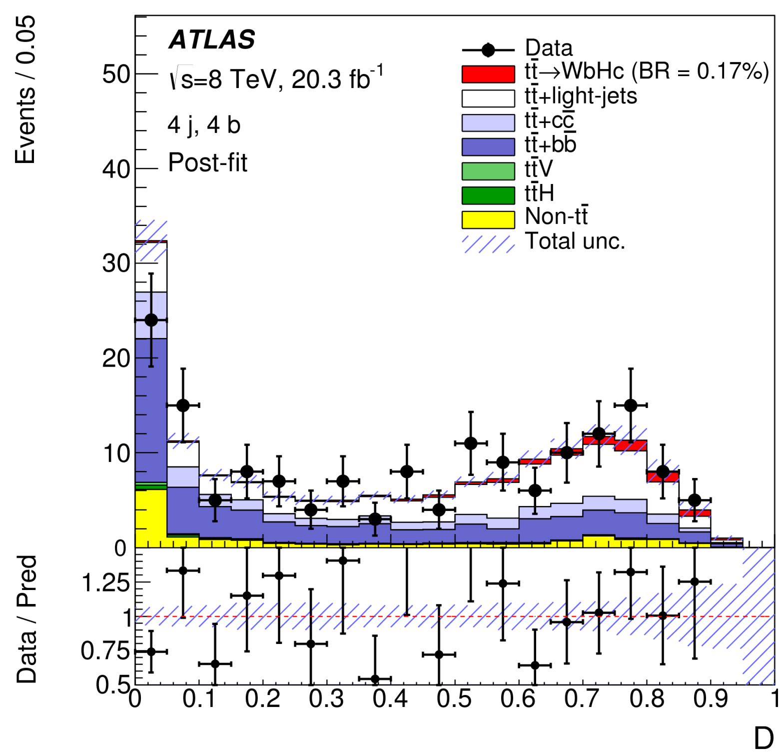
Observed (expected) 95% CL upper limits on the branching ratios:

- $BR(t \to Hu) < 0.42\%$ (0.65%)
- $BR(t \to Hc) < 0.47\%$ (0.71%)

ATLAS FCNC t → u/c+H(bb)

- Search for ttbar→WbHq→(ℓν)b(bb)q
- Requiring one light lepton, >= 4 jets and >=2 b-jets
- 9 signal- and bkg-enriched event categories:
  - (4j, 5j, ≥6j) x (2b, 3b, ≥4b)
- main background is SM ttbar(→WbWb)+jets
- Using Likelihood discriminant including mass constraints and b-tagging information for signal and bkg hypotheses.



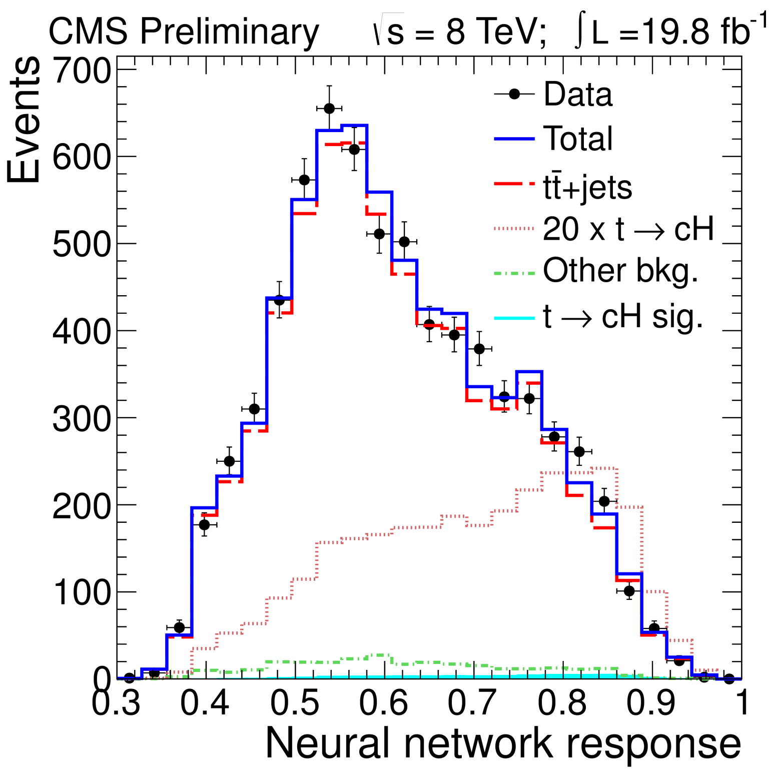


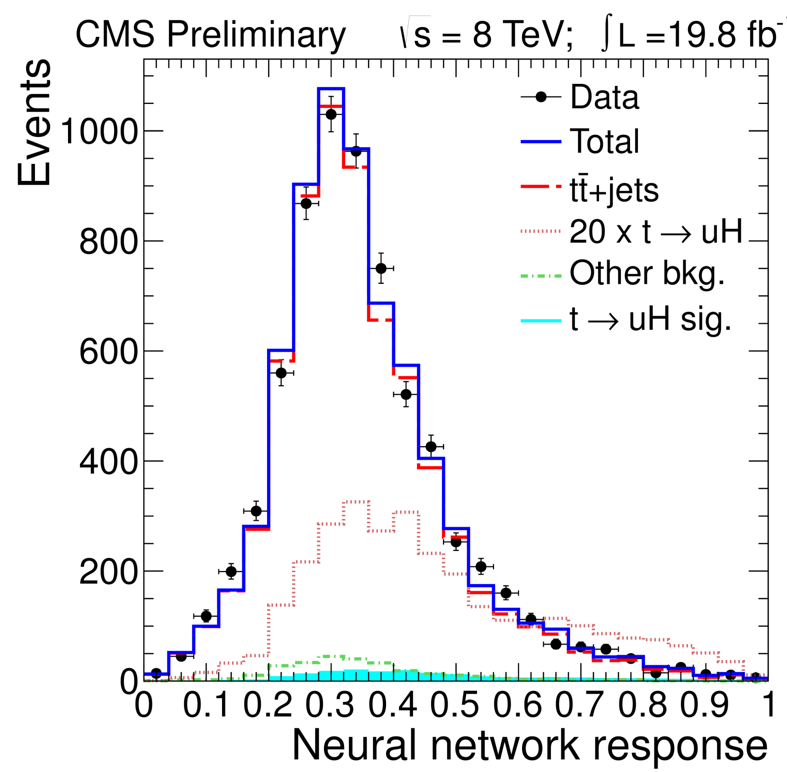
Observed (expected) 95% CL upper limits on the branching ratios:

- BR(t → Hu) < 0.61% (0.64%)   BR(t → Hc) < 0.56% (0.42%)

CMS FCNC $t \to u/c+H(bb)$

- Result released 5 days ago!
- Requiring one light lepton, >=4 jets and >= 2-bjets
- Using Boosted decision Tree discriminant with kinematic variables of the Higgs and top candidates and and combining it in a Neural-Network Likelihood discriminant including b-tagging information of the jets.

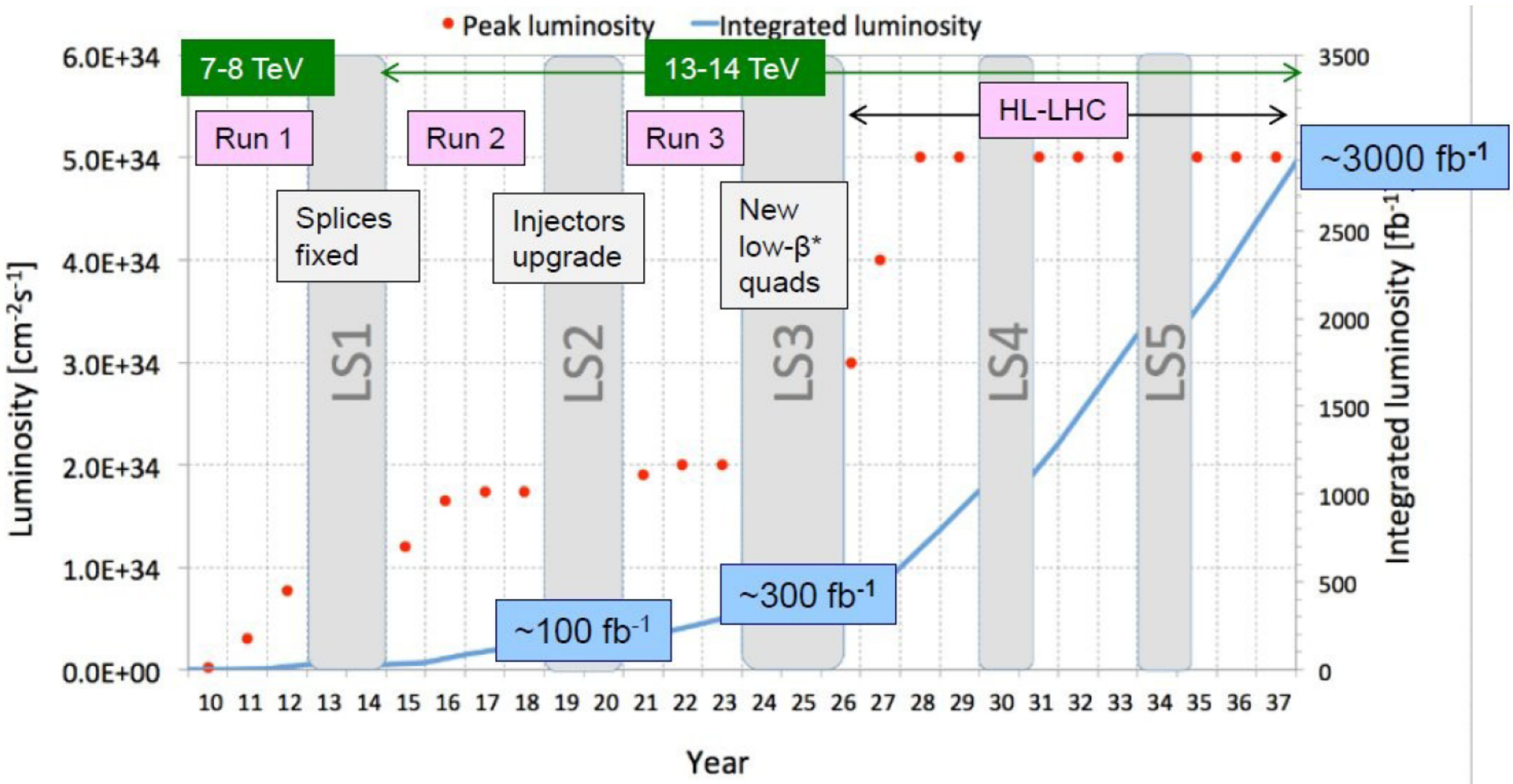




Observed (expected) 95% CL upper limits on the branching ratios:

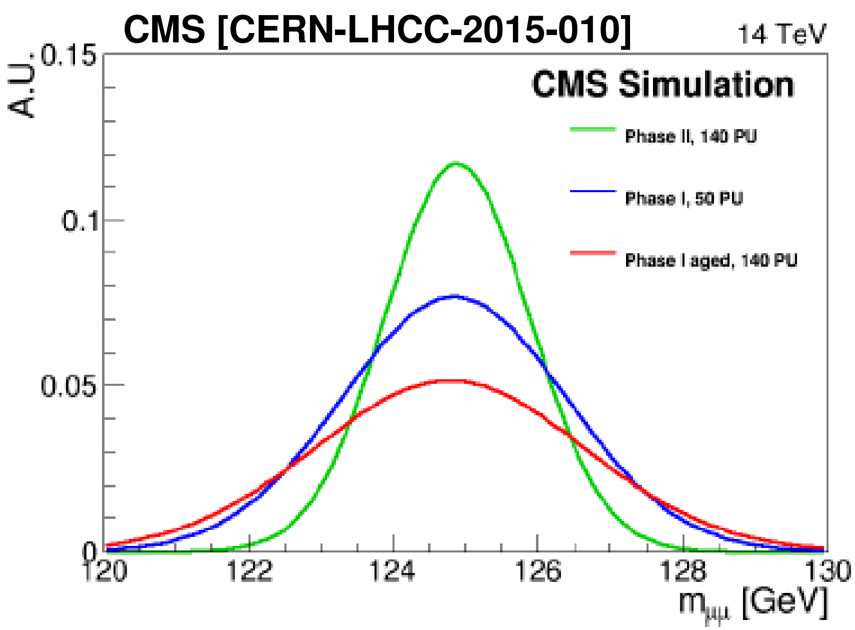
- $BR(t \to Hu) < 1.92\%$ (0.85%) $BR(t \to Hc) < 1.16\%$ (0.89%)

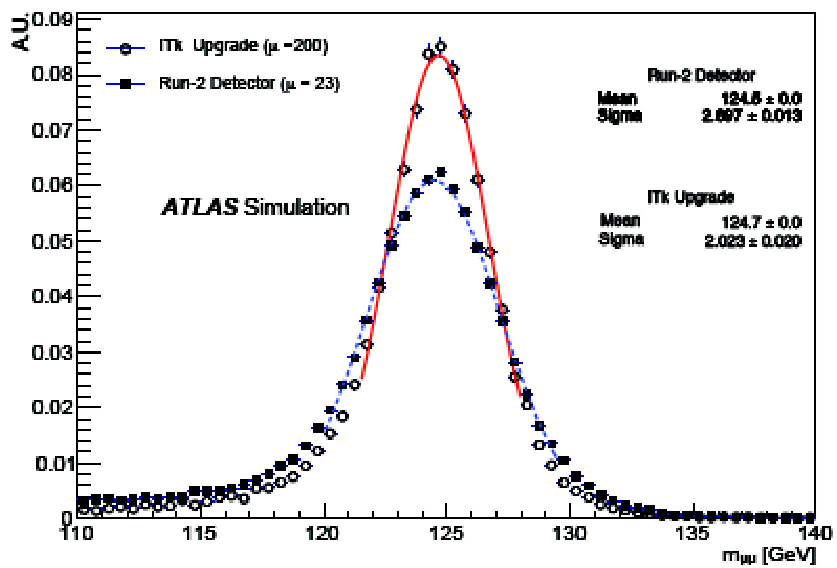
LHC Upgrade



- In parallel design of electron-positron linear colliders ILC, CLIC
- At CERN for >2035: HE-LHC, VHE-LHC, TLEP,...

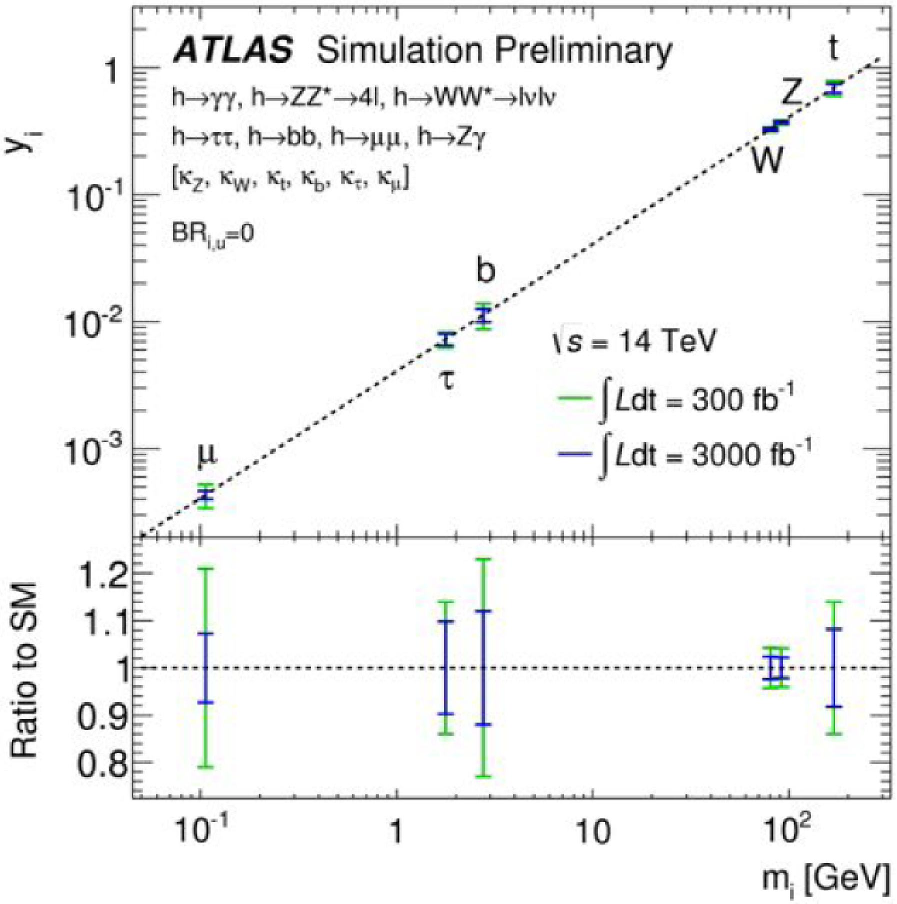
Projections of $H \to \mu\mu$

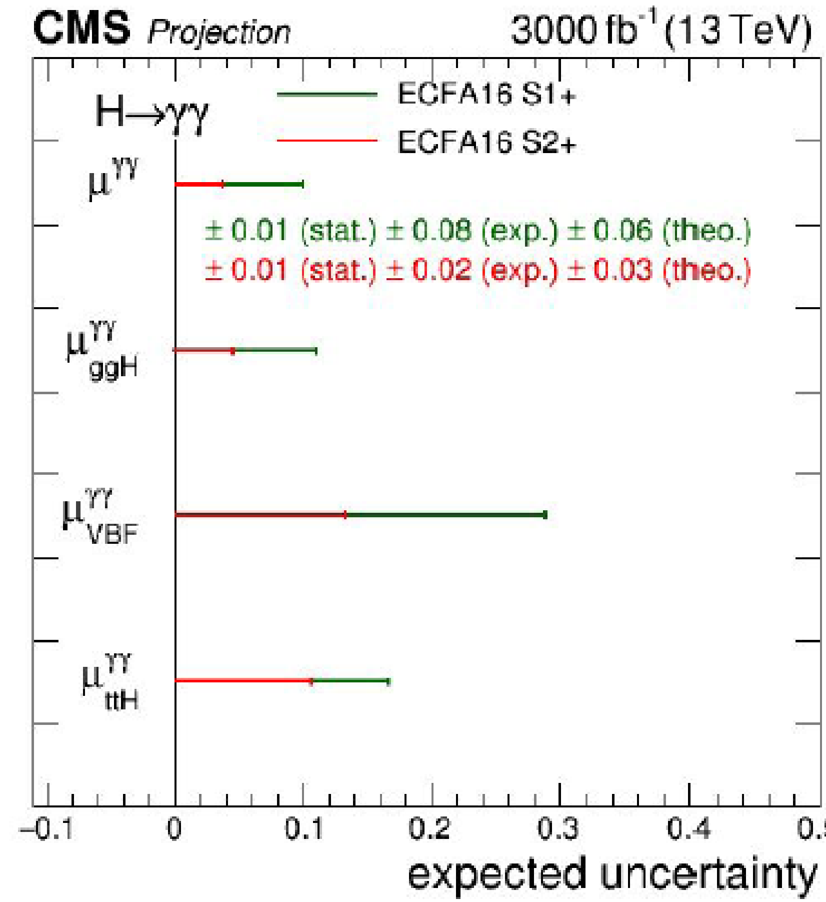




- CMS: revised projection, expect 5% uncertainty on $H \to \mu\mu$ coupling measurement at HL-LHC (only a few tens produced during LHC Run-1, according to SM prediction.

Sensitivity for Phase-1 and Phase-2

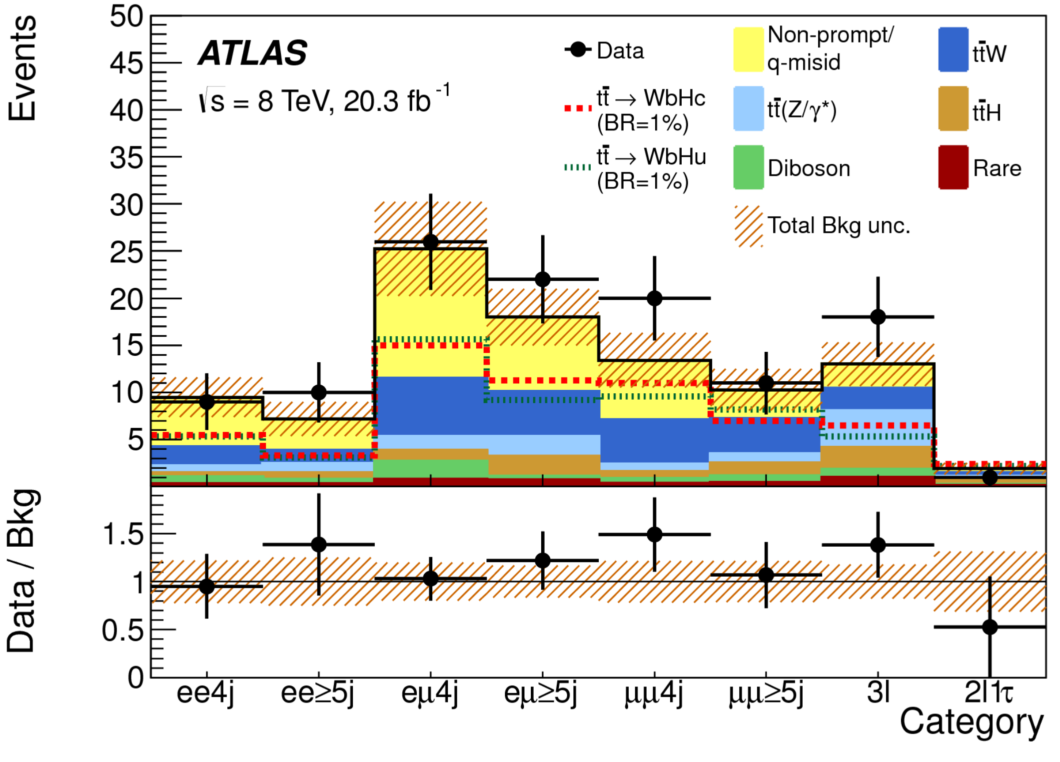




- Phase-1 and phase-2 will allow to measure rare decays (H → μμ) in addition to the main 5 and perhaps HH production.
- Some some production modes, projections indicate accuracy below 10% for the main decay modes.

ATLAS FCNC t → u/c+H (multi-lep)

- Re-interpretation of ATLAS ttH analysis in multi-lepton final states
- 8 different categories defined by lepton multiplicity and jet multiplicity:
  - (ee, μμ, eμ) x (4j,>=5j)
  - 3 light leptons
  - 2 light leptons + 1 tau



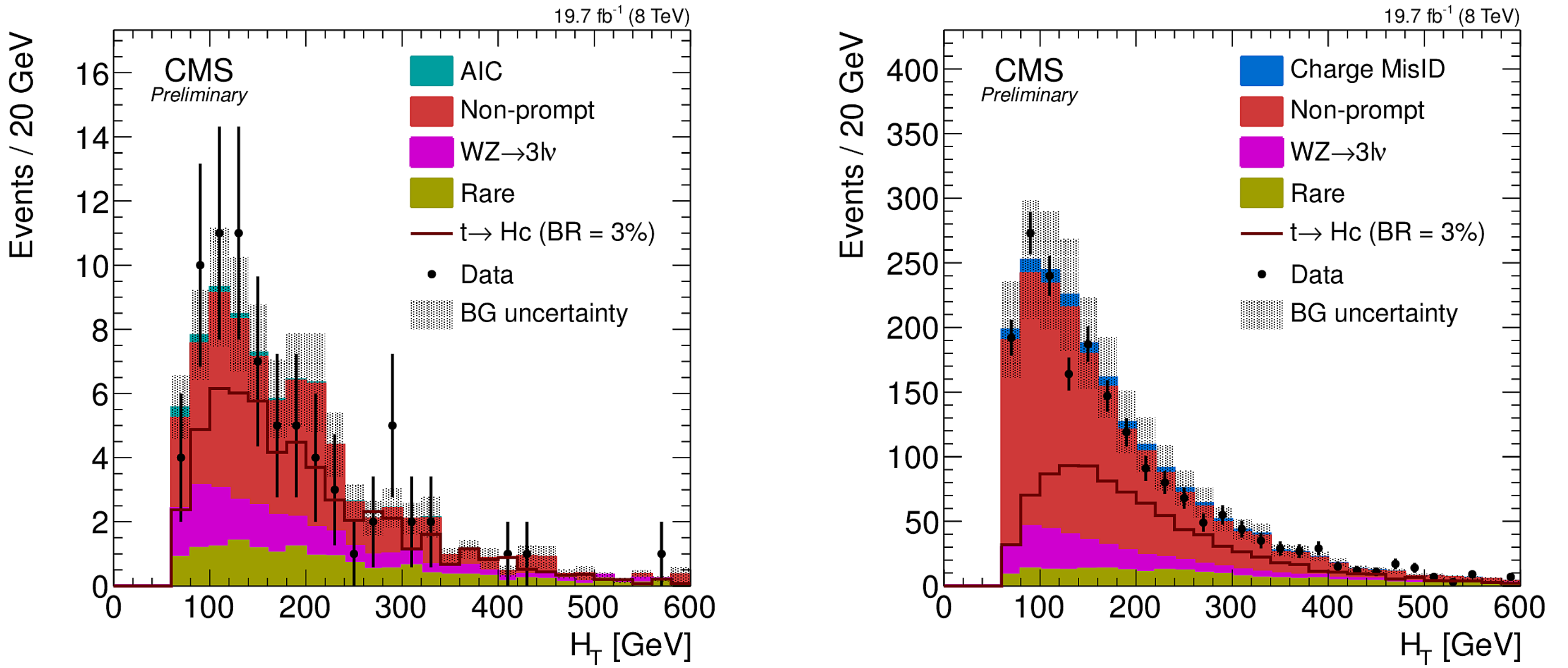
The observed (expected) 95% CL upper limits on the branching ratios are:

- BR(t → Hc) < 0.79% (0.54%)
- BR(t → Hu) < 0.78% (0.57%),

assuming BR(t → Hu), BR(t → Hc) =0 respectively

CMS FCNC $t \to c+\mathcal{H}$

- Analysis of 3 light leptons or 2 same sign leptons events, selecting the final states ($H \to ZZ, WW, \tau\tau$) and $t \to bW(\to \ell\nu)$
- Two categories, no jet splitting:
  - 2 light leptons SS
  - 3 light leptons

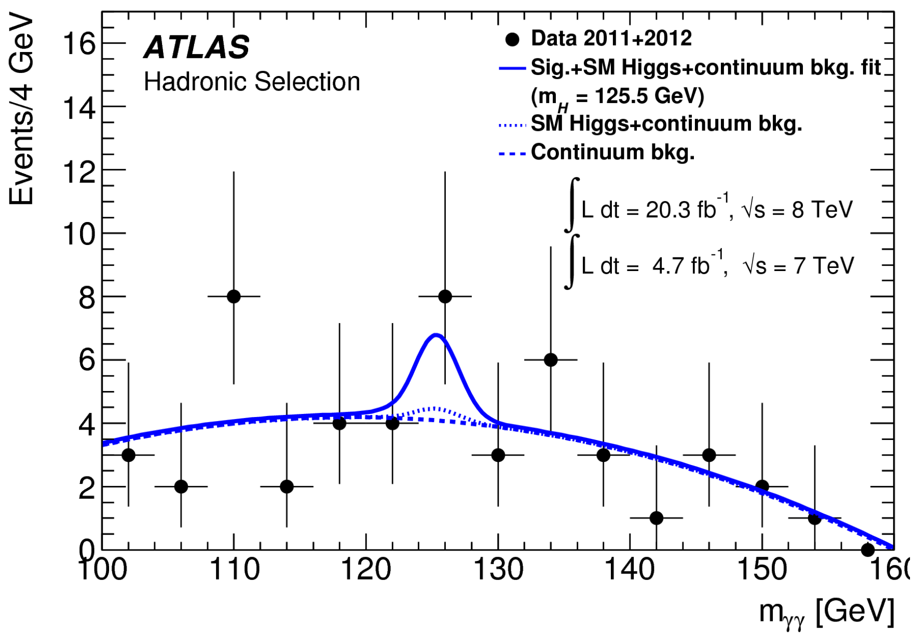


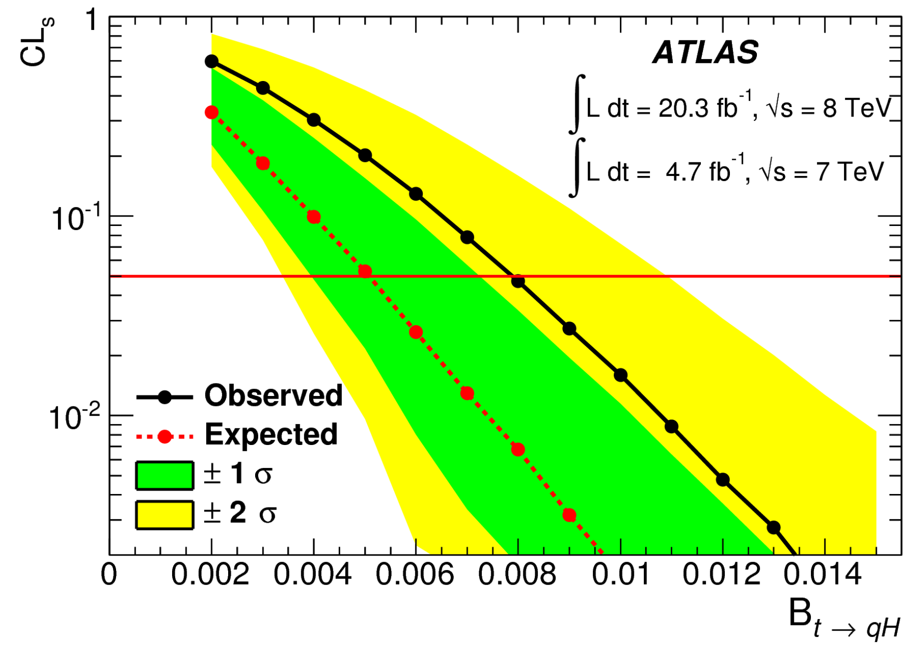
The observed (expected) 95% CL upper limits on the branching ratio is:

- $BR(t \to Hc) < 0.93\%$ (0.89%)

ATLAS FCNC $t \rightarrow u/c + H(\gamma\gamma)$

- 7 TeV and 8 TeV datasets are used.
- Main backgrounds are di-photon non-resonant background and ttH
- Analysis considers both hadronic and leptonic final states of the W decay:
  - diphoton+jets (cut on m_{top})
  - diphoton+lepton+jets (cut on $m_T(W)$)





Observed (expected) 95% CL upper limits on the branching ratios:

- BR($t \rightarrow Hq$) < 0.79% (0.51%)