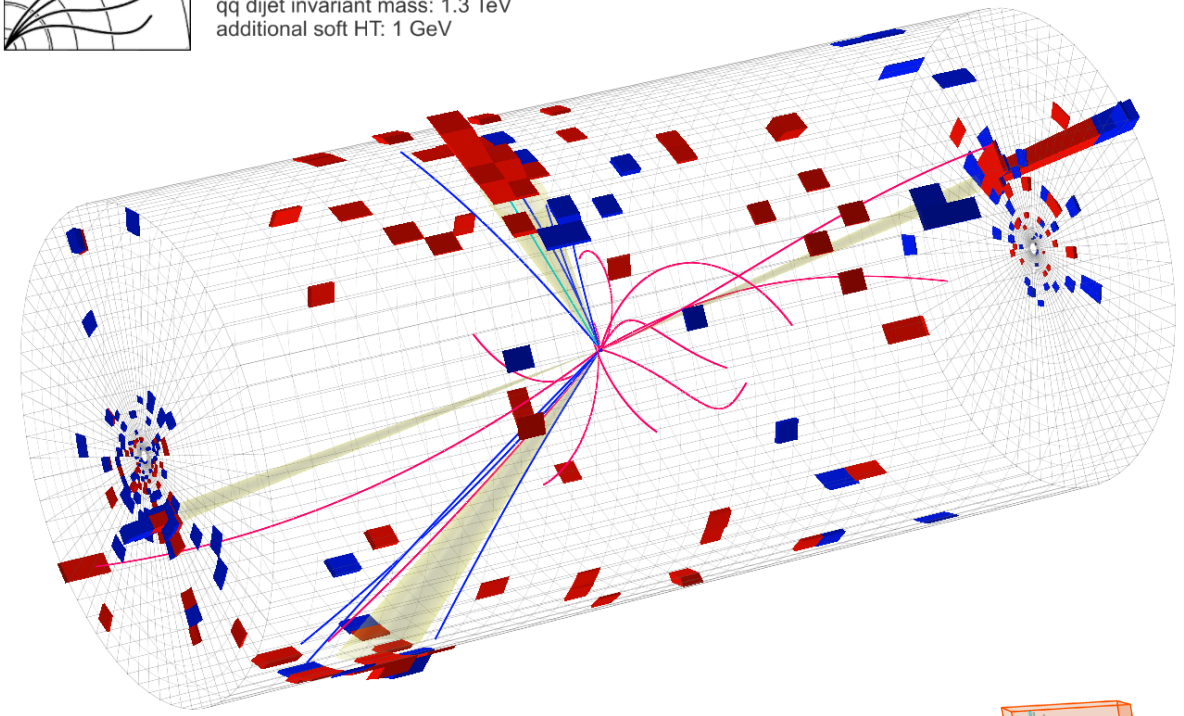
CMS Experiment at LHC, CERN
Data recorded: Sat Aug 4 21:17:51 2012 CEST
Run/Event: 200245 / 198478589
Lumi section: 175
bb dijet invariant mass: 114 GeV
qq dijet invariant mass: 1.3 TeV
additional soft HT: 1 GeV

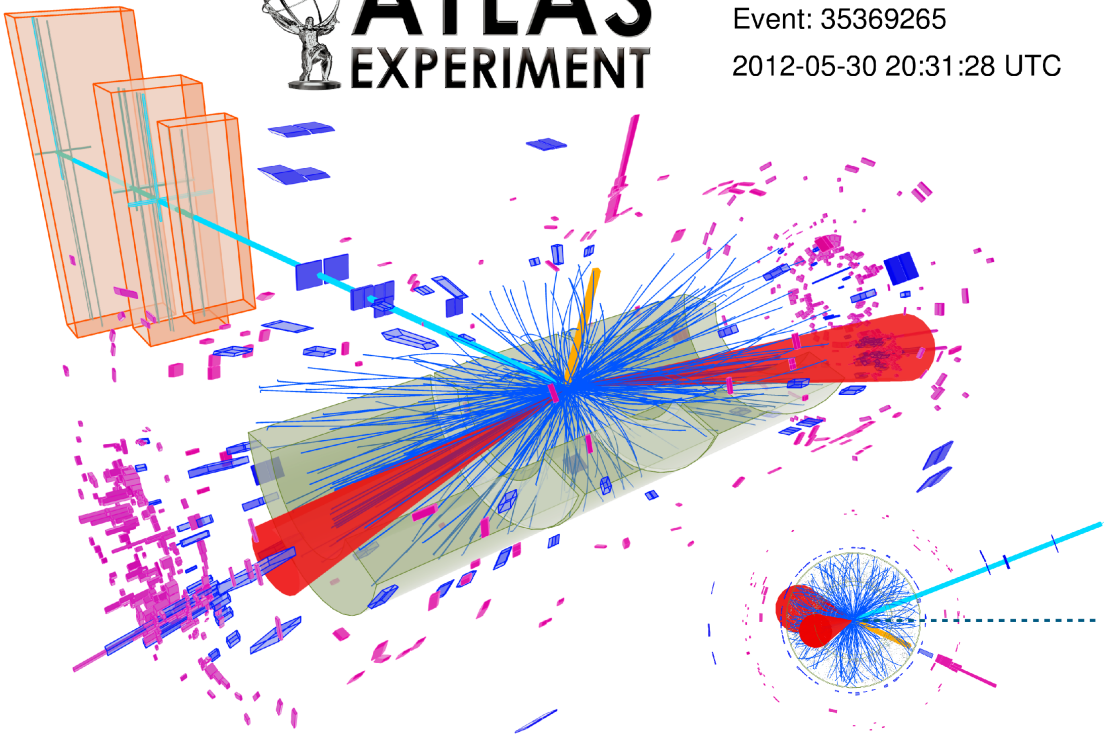


Higgs to fermions at LHC

Silvio Donato *(CERN, INFN and SNS Pisa)*
on behalf of the CMS and ATLAS collaborations

ATLAS EXPERIMENT

Run: 204153
Event: 35369265
2012-05-30 20:31:28 UTC



CERN

SCUOLA NORMALE SUPERIORE PISA

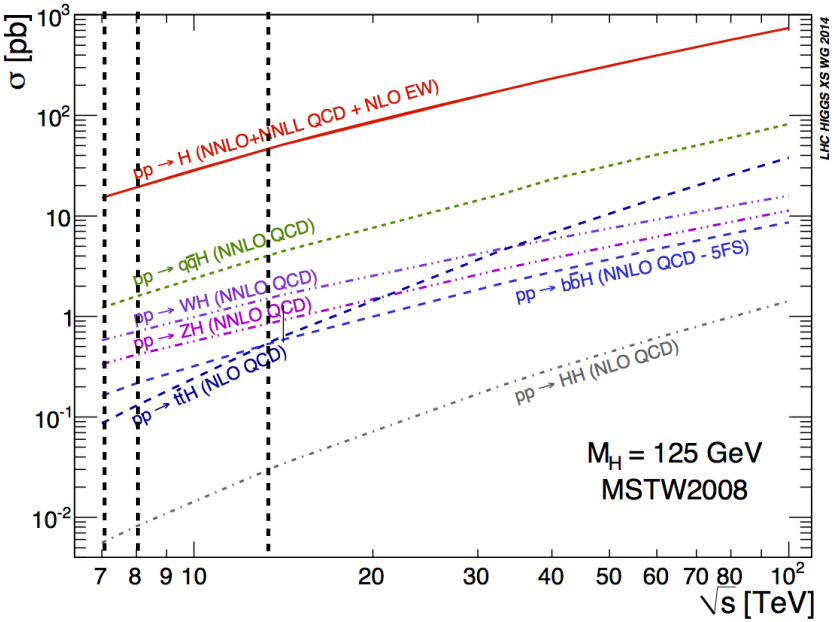
INFN

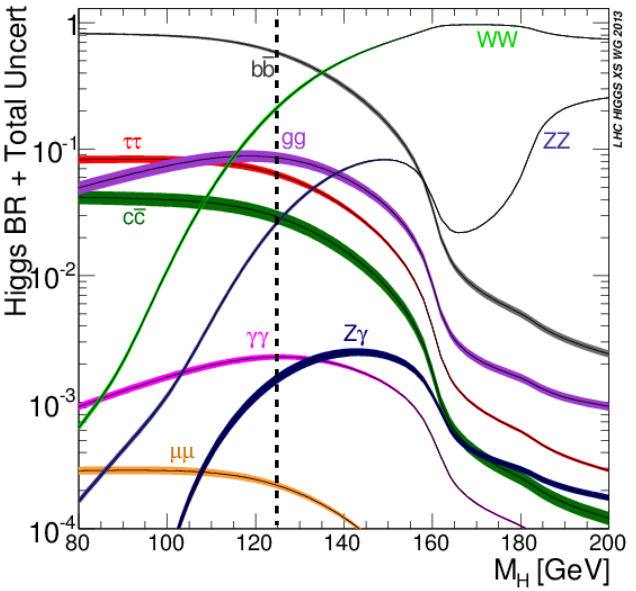
Outline

- Introduction.
- Higgs to ττ.
- Higgs to bb:
  - VH;
  - VBF **(new)**;
  - ttH.
- Higgs to fermions (combination).
- Higgs to μμ/ee.
- Run-2 prospective.
- Conclusion.

Introduction

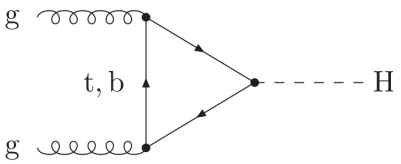
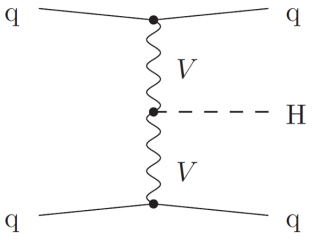
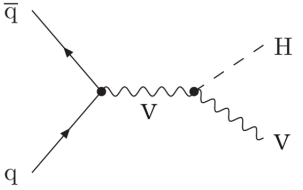
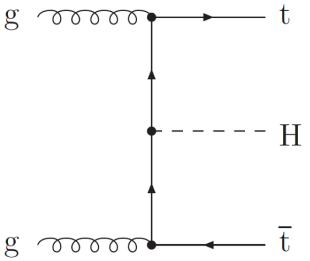
- Higgs cross section 8 TeV → 13 TeV for $m_H = 125$ GeV:
  - ggH: 19.3 pb → 43.9 pb; [x2.3]
  - VBF: 1.57 pb → 3.75 pb; [x2.3]
  - VH: 1.12 pb → 2.25 pb; [x2.0]
  - ttH: 0.13 pb → 0.51 pb; [x3.9]
- Higgs branching ratios for $m_H = 125$ GeV:
  - **H → bb (58%)**;
  - H → WW (21%) → 2l2ν (0.21%);
  - **H → ττ (6.3%)**;
  - H → ZZ (2.6%) → 4l (0.01%);
  - H → γγ (0.23%);
  - **H → μμ (0.022%)**;





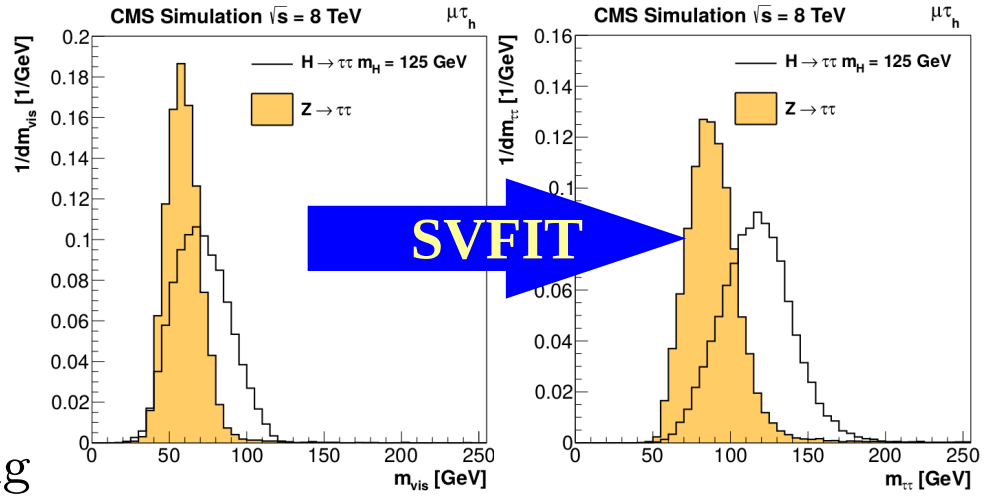
Introduction

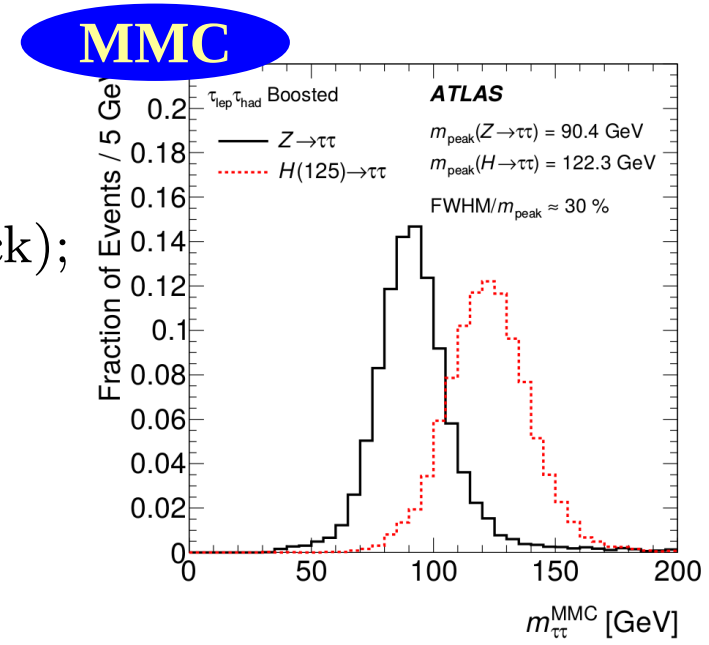
Searches for Higgs boson decaying into fermions

	ggH	VBF	VH	ttH
				
H → bb	(QCD bkg. too large)	Large QCD bkg. Low mass resolut.	Small x-sec∗BR VV, V+jets, tt bkg. Low mass resolution	Small x-sec∗BR tt+jets backgrounds Low mass resolution
H → ττ	Large Z→ττ bkg. Very low mass resol.	Small x-sec∗BR Z→ττ bkg. Low mass resolut.	Small x-sec∗BR Z→ττ bkg. Low mass resolut.	Very small x-sec. Low mass resolution
H → μμ	Small x-sec∗BR. Large Z→μμ bkg. High mass resol.	Very small x-sec∗BR. Small Z→μμ bkg. High mass resol.	Very small x-sec∗BR. Small Z→μμ bkg. High mass resol.	(x-section and BR are too small)

Higgs to ττ

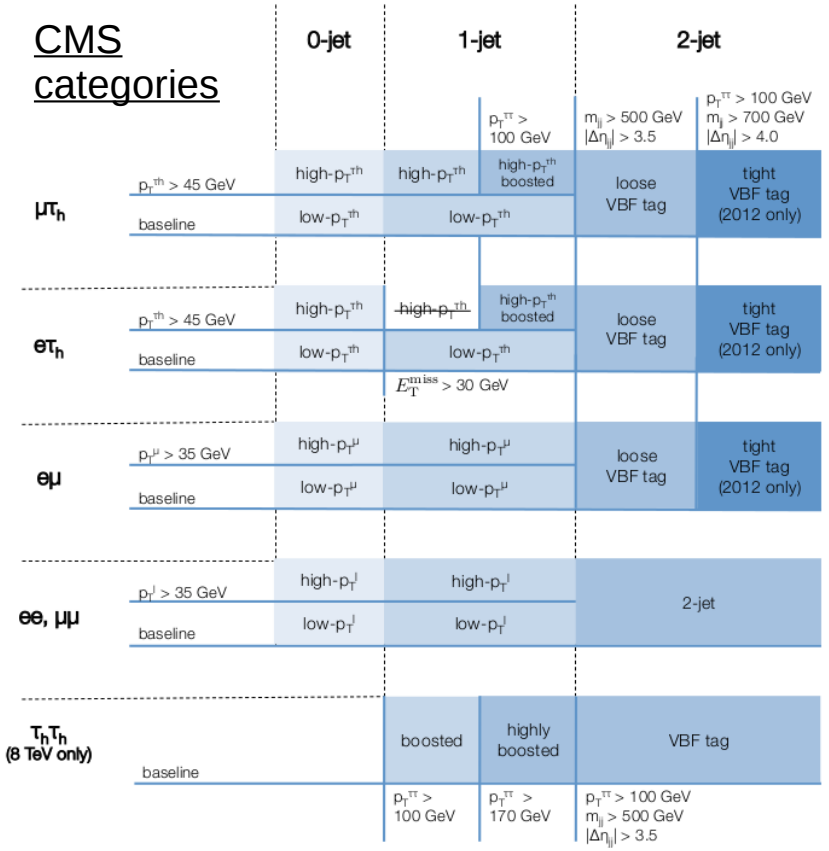
- ☺ Higgs to ττ BR ~ 6 %.
- ☺ Good τ ID → small QCD bkg.
- ☹ Large Z → ττ irreducible bkg.
- ☹ Neutrinos in final states:
  → di-tau invariant mass measured using maximum likelihood (MMC and SVFIT).
- ☺ All production modes available:
  - **ggH**: high cross-section, but low mass resolutions (neutrinos back-to-back);
  - **VBF**: specific topology, useful to reduce Z → tt background;
  - **VH**: low cross section, but better mass resolution (boosted taus);
  - **ttH**: very low cross section.





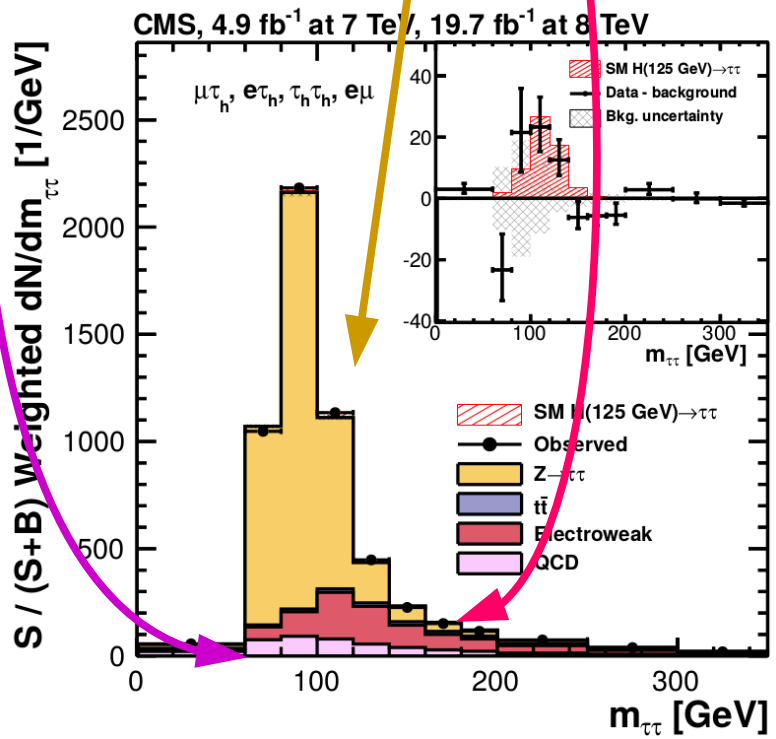
Higgs to ττ

- Analysis categories:
  - VBF category: two high-p_T jets with high $\Delta\eta(j_1,j_2)$ [ATLAS,CMS];
  - Boosted category: $p^H_T > 100$ GeV [ATLAS,CMS];
  - Other categories [CMS]:
    - VH ($\ell\ell$+LL' or ℓ+Lτ_h, where ℓ=e,μ and L=e,μ,τ);
    - 0-jet.
- Decay modes:
  - $\tau_h\tau_h$ (hadronic decay in 3/1-prongs);
  - $e\tau_h$, $\mu\tau_h$;
  - ee, eμ, μμ.

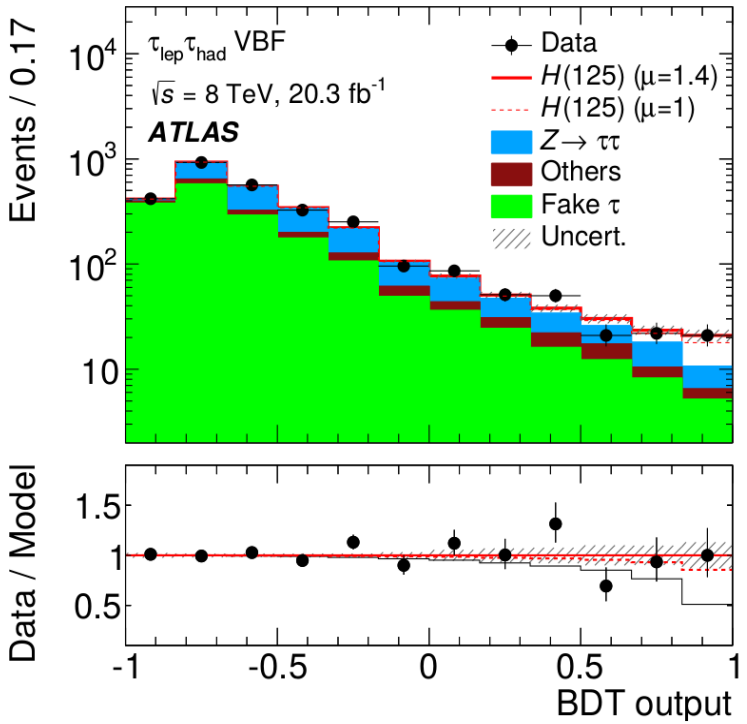


Higgs to ττ

- Background estimation:
  - misidentified hadrons, fake rate modeled from data;
  - EW from simulation;
  - $Z \to \tau\tau$, using $Z \to \mu\mu$ events from data.

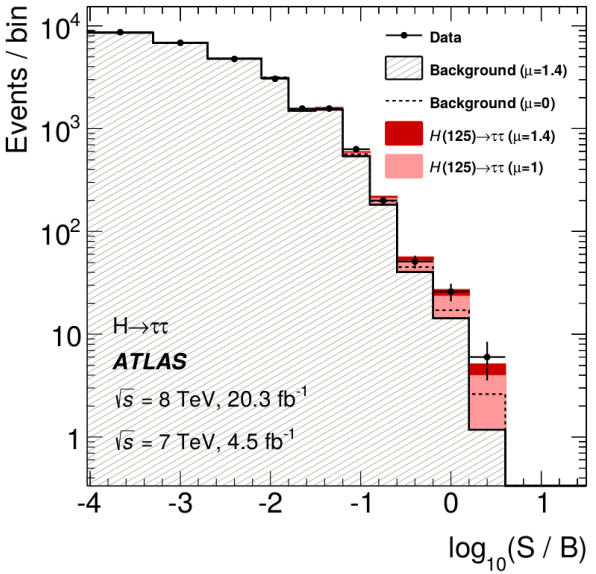


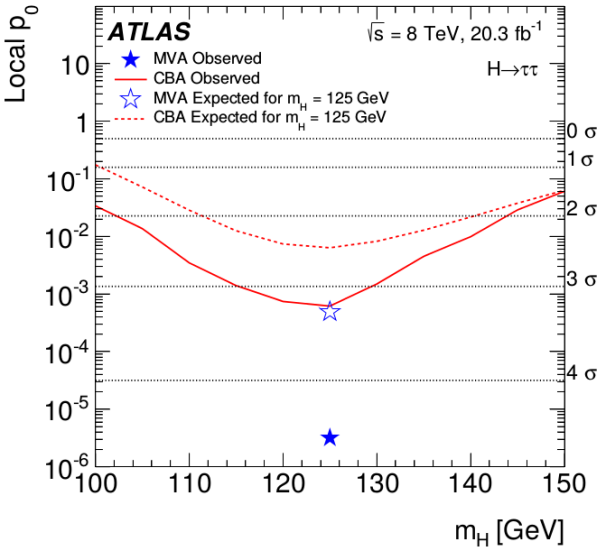
- Signal extraction:
  - Fit on m_{tt} distribution [CMS];
  - Fit on a multivariate discriminant [ATLAS].

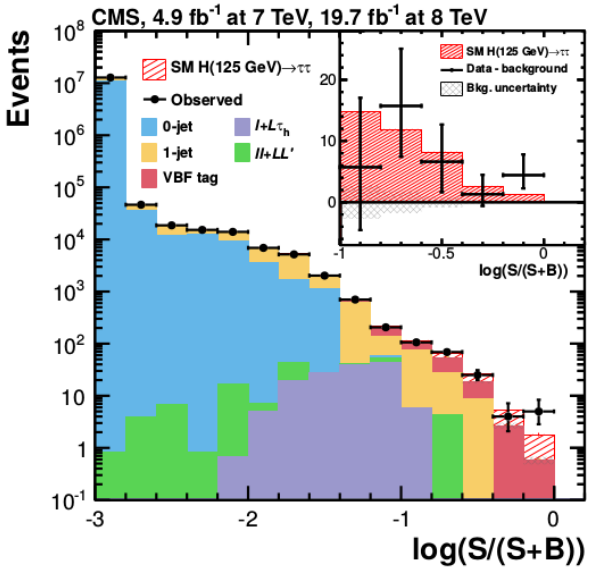


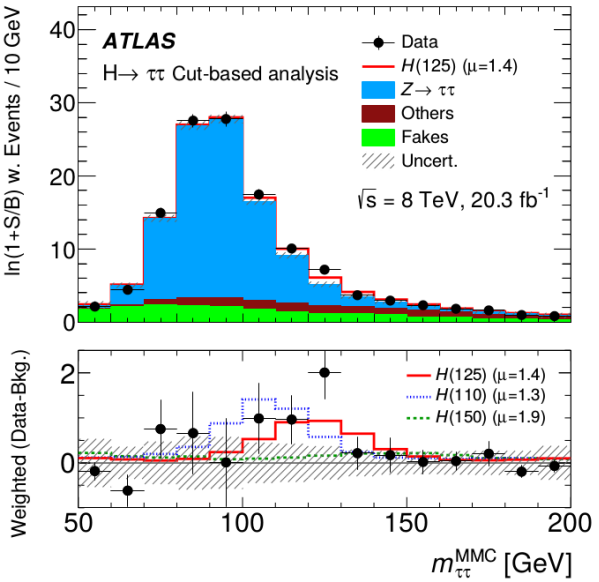
Higgs to ττ

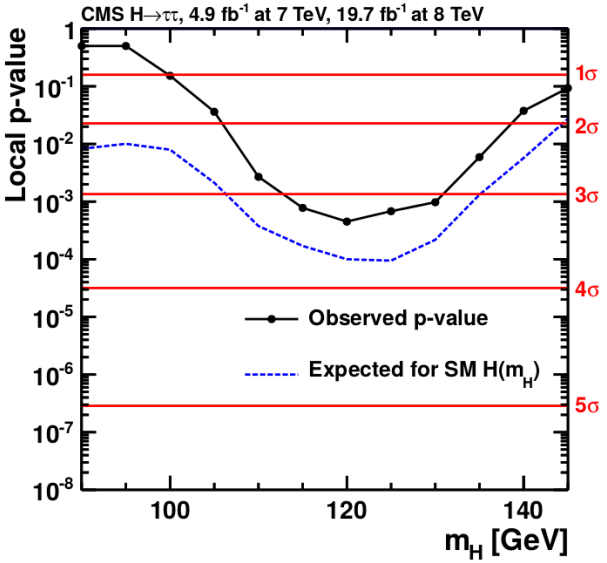
- Signal strength:
  - ATLAS: $\boldsymbol{\mu = 1.43^{+0.43}_{-0.37}}$;
  - CMS: $\boldsymbol{\mu = 0.78^{+0.27}_{-0.27}}$.
- Observed (expected) p-value:
  - ATLAS: **4.5σ (3.4σ)**;
  - CMS: **3.2σ (3.7σ)**.











Higgs to bb

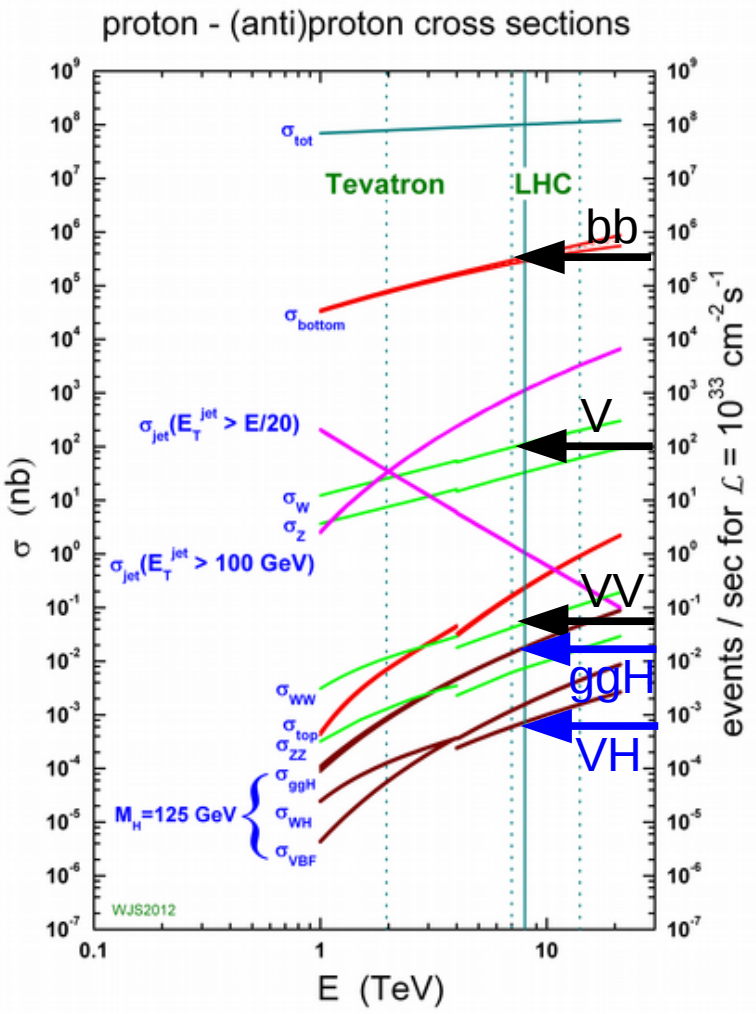
☺ Highest branching ratio ~ 60 %;

☹ Low mass resolution (jets as final state):

- possible missing energy from: B → ℓν + hadr.

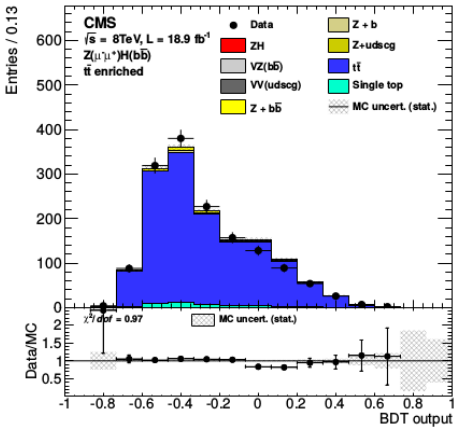
☹ Some production modes are overwhelmed by QCD:

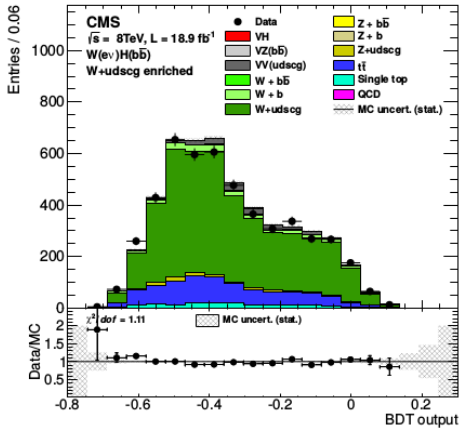
- in **ggH** QCD 10^7 times larger → no sensitivity;
- **VBF** topology is useful to reduce QCD bkg.;
- **VH** is almost QCD free thanks to V → ℓℓ,ℓν,νν but it has low cross section → high sensitivity;
- **ttH** channel has a very low cross-section → low sensitivity.

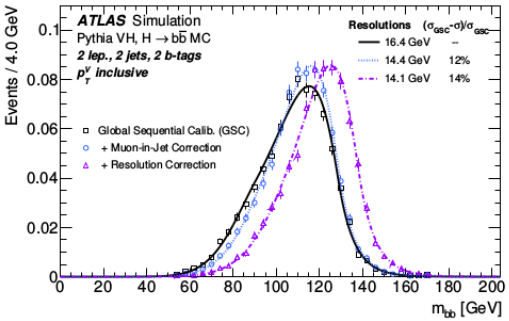


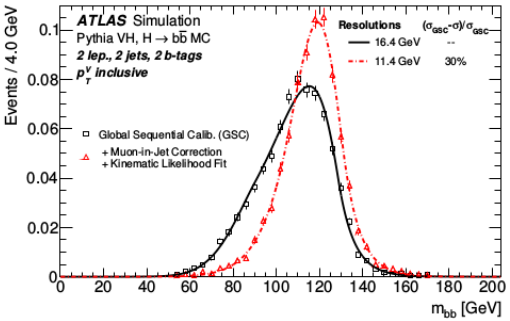
$VH \to \ell\ell,\ell\nu,\nu\nu + b\bar{b}$

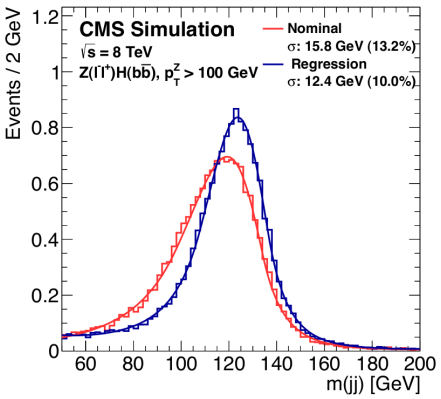
- Backgrounds:
  - Leptonic V decay rejects QCD backgrounds;
  - Main backgrounds: Z+jets, W+jets and $t\bar{t}$;
  - Shapes are from simulation and normalization from data.
- Improvement on mass resolution:
  - b-jet energy regression [CMS];
  - resolution correction, for soft muon B decay, and kinematic fit [ATLAS].





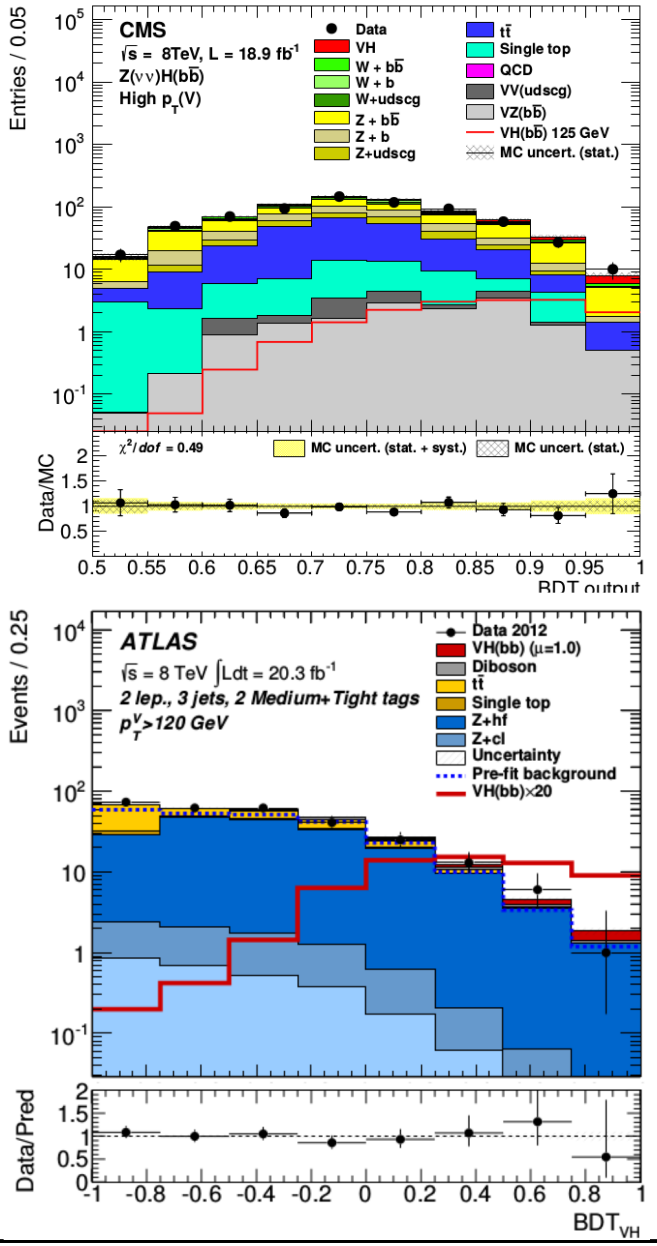






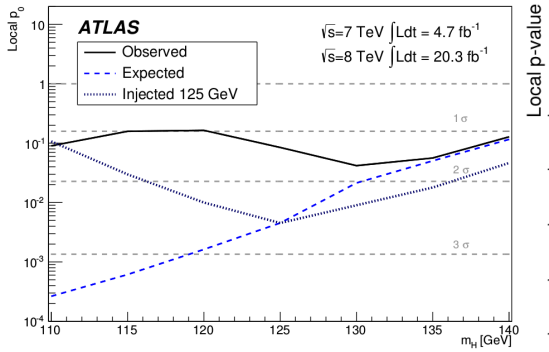
$VH \to \ell\ell,\ell\nu,\nu\nu + bb$

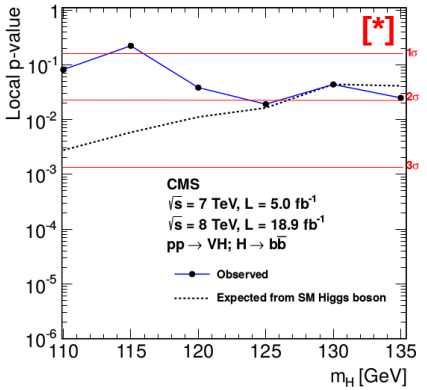
- Analysis categories based on:
  - vector boson decays: $Z\to\mu\mu$, $Z\to ee$, $Z\to\nu\nu$, $W\to\mu\nu$, $W\to e\nu$, $(W\to\tau\nu)$.
  - vector boson p_T;
  - other categories [ATLAS only]:
    - jets multiplicity;
    - b-tag discriminants.
- Signal extraction:
  - fit of multivariate discriminant distribution.

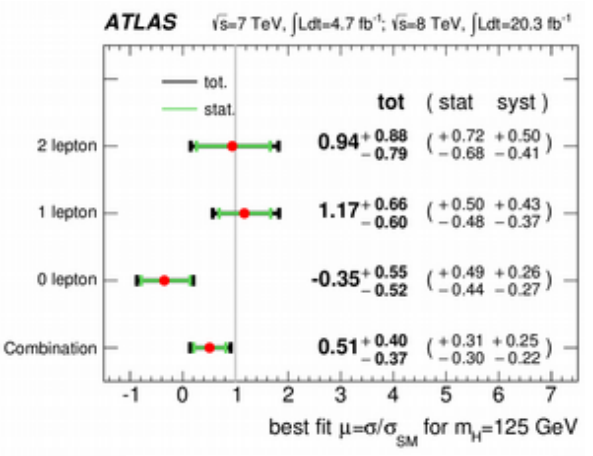


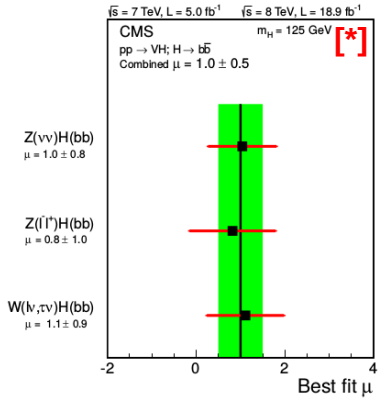
$VH \to \ell\ell,\ell\nu,\nu\nu + bb$

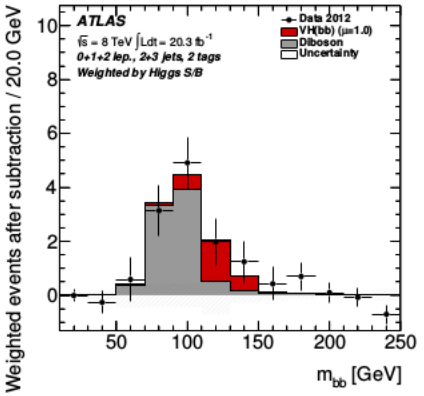
- Observed (expected) p-value:
  - ATLAS: **1.4σ (2.6σ)**;
  - CMS: **2.1σ (2.5σ)**.
- Signal strength:
  - ATLAS: $\boldsymbol{\mu = 0.52 \pm 0.40}$;
  - CMS: $\boldsymbol{\mu = 0.89 \pm 0.43}$.

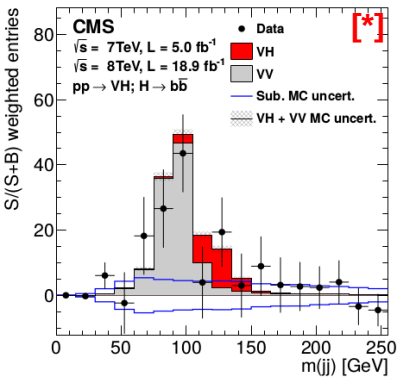










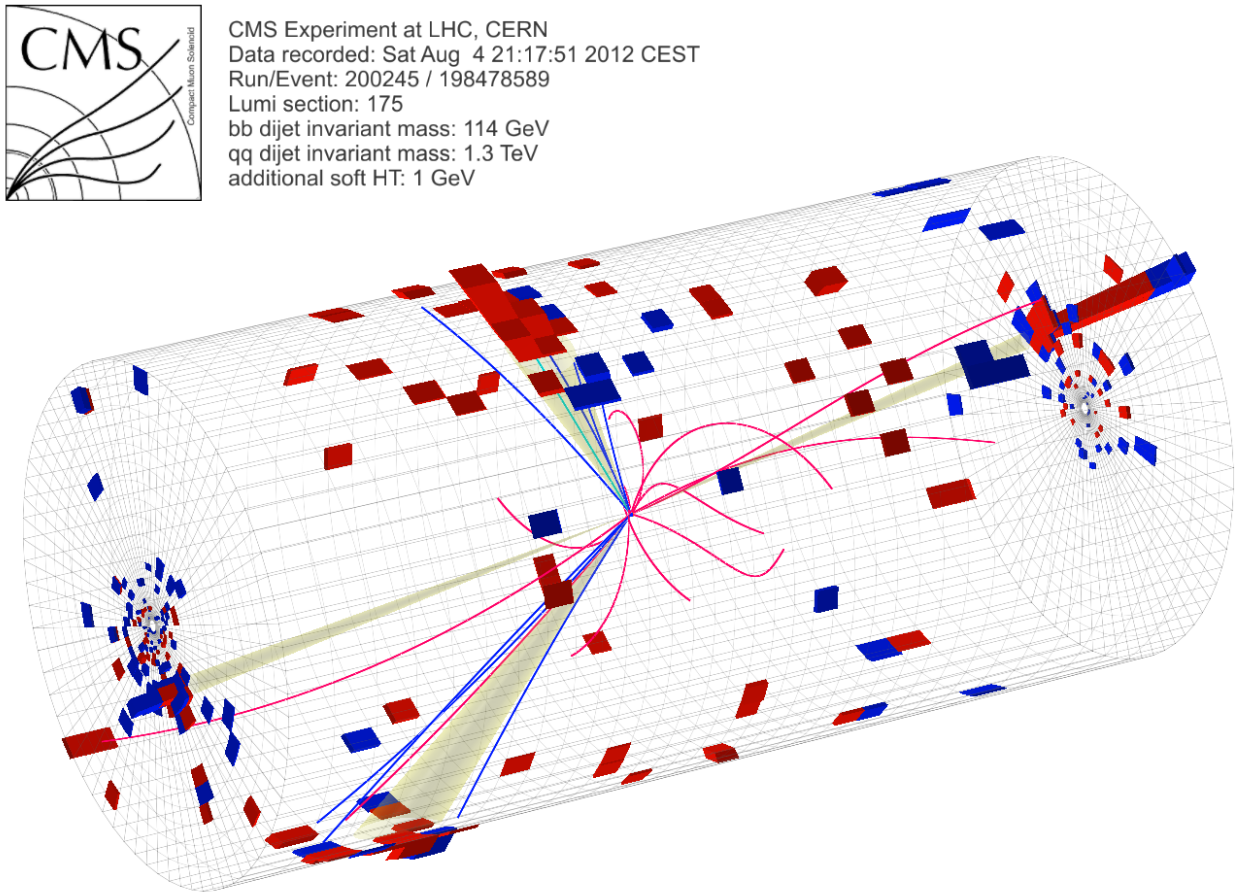


[*] : plots obtained excluding gg → ZH contribution.

[new!] VBF H → bb

☺ Highest branching ratio ~ 60 % and large cross section;

☹ Fully hadronic final state → large QCD background.



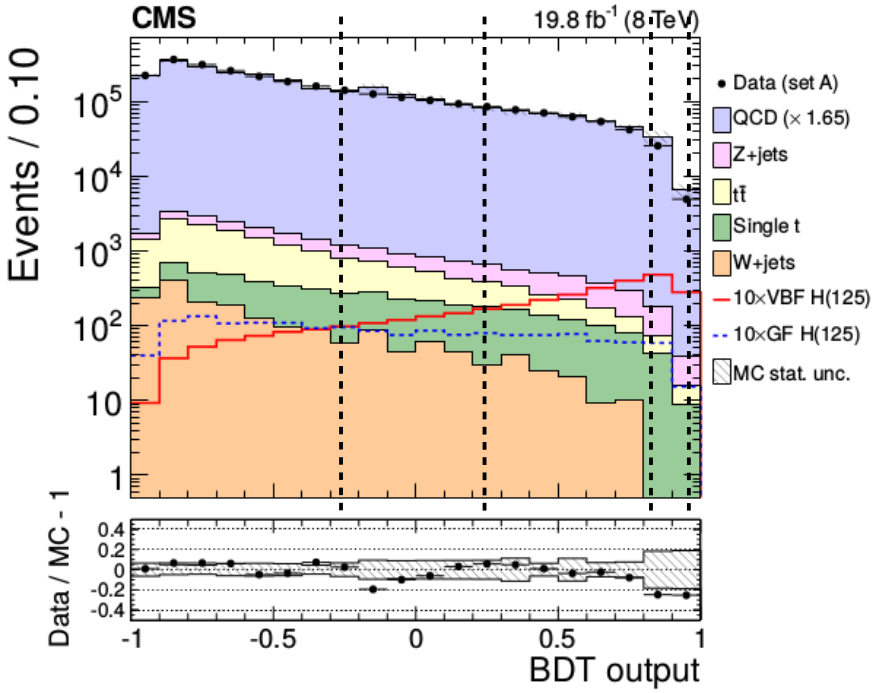
☺ Peculiar final states:

- Two b-jets;
- Two quark-jets with large $\Delta\eta$;
- No additional hadronic activity between them.

[new!]

VBF H → bb

- Events are divided in 7 categories, with different S/B, using a multivariate discriminator (uncorrelated with m_{bb}).
- Signal is extracted with a simultaneous fit on m_{bb} in all categories.
- QCD is fitted in all categories with a common fifth order polynomial.
- QCD shape corrected with a category-dependent quadratic transfer function.



Signal strength

Normalization and shapes of signal, Z and top

Free parameter

Fixed parameter (simulation)

$$f_i(m_{bb}) = \mu_H \cdot N_{i,H} \cdot H_i(m_{bb}; k_{JES}, k_{JER}) + N_{i,Z} \cdot Z_i(m_{bb}; k_{JES}, k_{JER}) + N_{i,t} \cdot T_i(m_{bb}; k_{JES}, k_{JER}) + N_{i,QCD} \cdot K_i(m_{bb}) \cdot B(m_{bb}; \vec{p}_{set}),$$

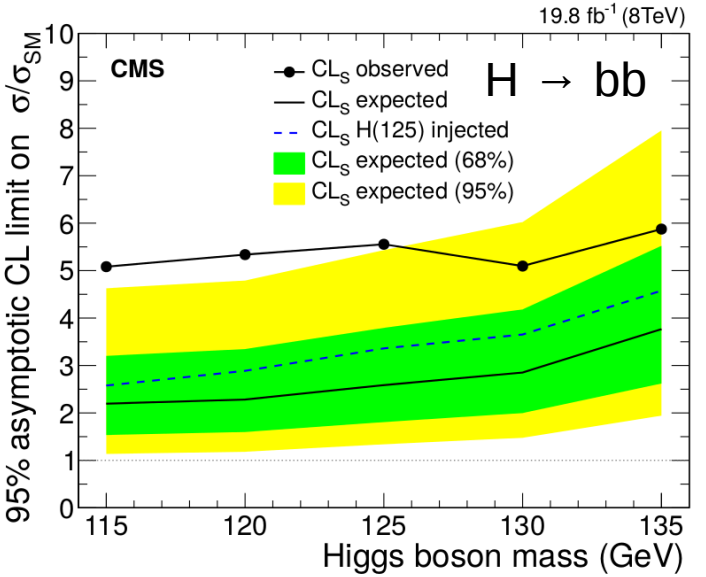
QCD normalization

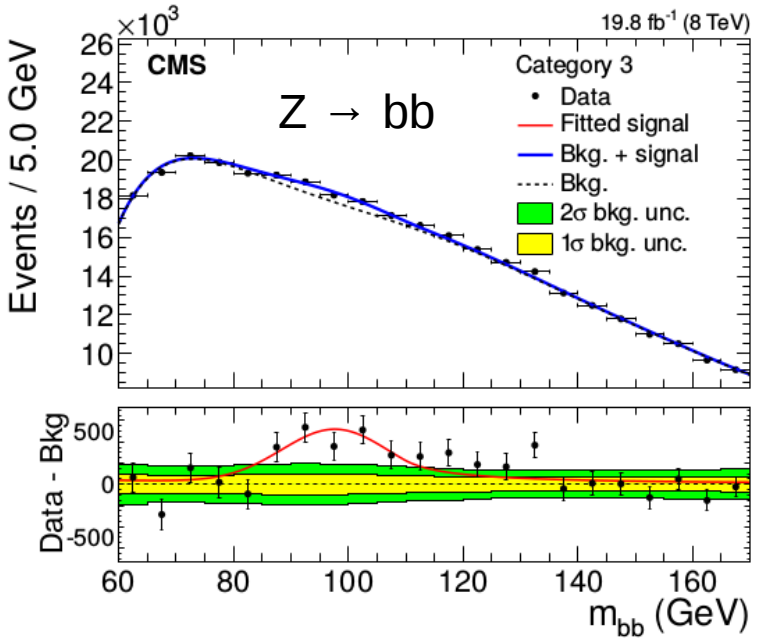
Transfer function (linear or quadratic)

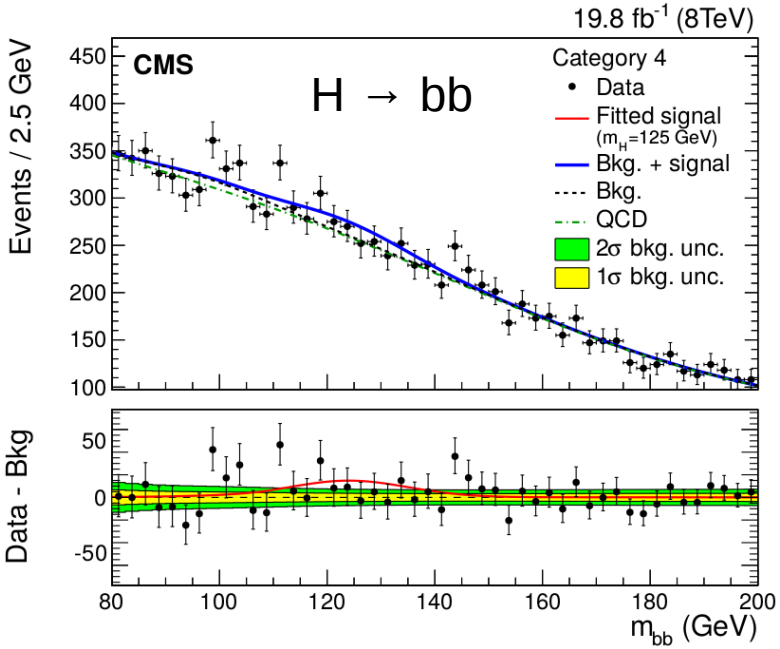
Polynomial QCD shape with free parameters.

[new!] VBF H → bb

- Signal strength: $\boldsymbol{\mu = 2.8\ ^{+1.6}_{-1.4}}$.
- Observed (exp.) 95% CL upper limit: **5.5 (2.5).**
- Observed p-value (exp.): **2.2σ (0.8σ).**
- Cross-check Z→bb resonance:
  - $\mu_Z = 1.10\ ^{+0.44}_{-0.33}$; p-value$_Z$ 3.6σ (3.3σ).



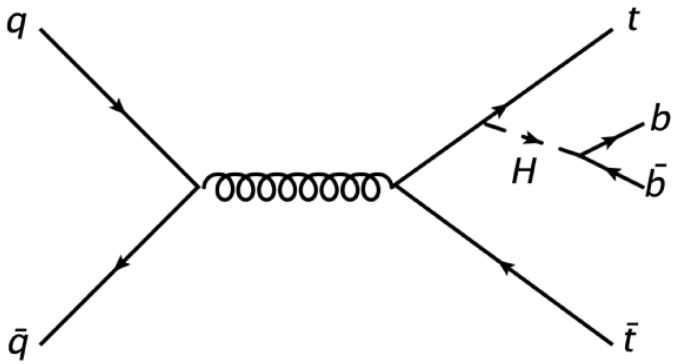




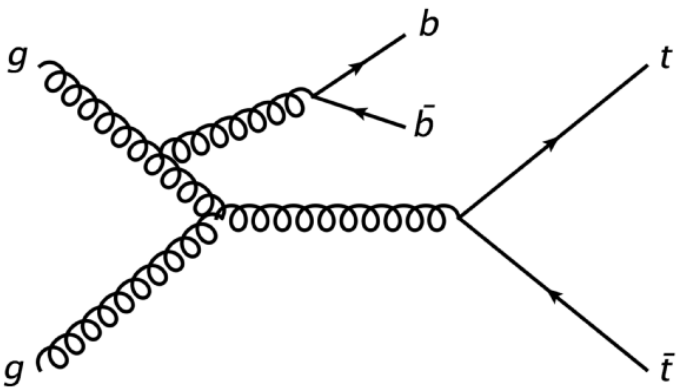
ttH → bb

- ttH production has a low cross section:
  - H → bb: best sensitivity (high BR).
- At least one leptonic top decay is required to remove QCD background.
- Two main categories:
  - Single lepton (ttH → 2b+2j+ℓ+ν+2b);
  - Double lepton (ttH → 2b+2ℓ+2ν+2b).
- Complex final state: 4 b-jets (+ 2 jets).
- Main background is $t\bar{t}$+b-jets (irreducible).

ttH



tt+b-jets



$ttH \rightarrow bb$

- A likelihood ratio is used to discriminate signal vs background.
- The probability that an event is ttH or tt+jets has been evaluated using the Matrix Element Method (MEM).

Probability of a final state x to be compatible with the process i with the set of parameter α

Normalization

Integral over the phase space of the initial-state particles

$$P_i(\boldsymbol{x}|\boldsymbol{\alpha}) = \frac{(2\pi)^4}{\sigma_i^{\exp}(\boldsymbol{\alpha})} \int \mathrm{d}p_{\mathrm{A}}\mathrm{d}p_{\mathrm{B}}\, \boldsymbol{f}(p_{\mathrm{A}})\, \boldsymbol{f}(p_{\mathrm{B}}) \frac{|\mathcal{M}_i(\boldsymbol{y}|\boldsymbol{\alpha})|^2}{\mathcal{F}} W(\boldsymbol{y}|\boldsymbol{x})\, \mathrm{d}\Phi_N(\boldsymbol{y})$$

Matrix element

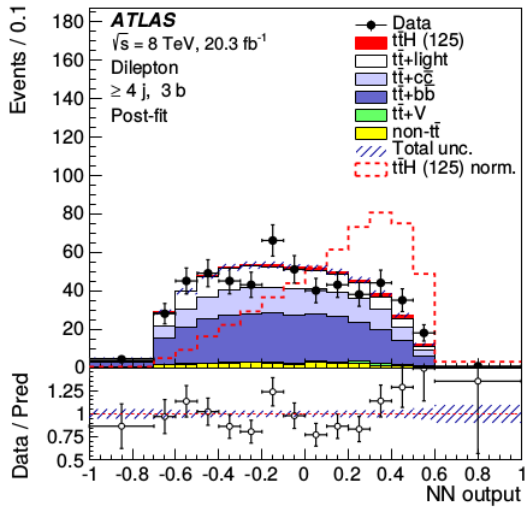
Flux factor

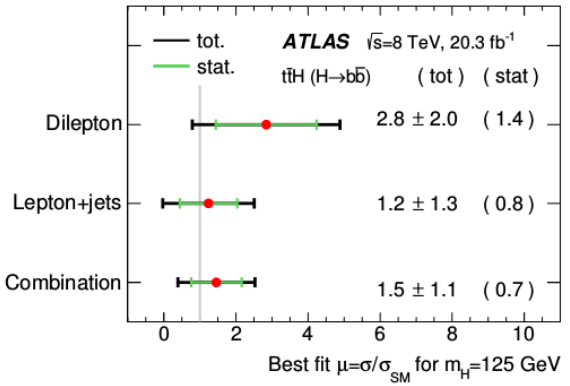
Map between the reconstructed final state y and the parton level x

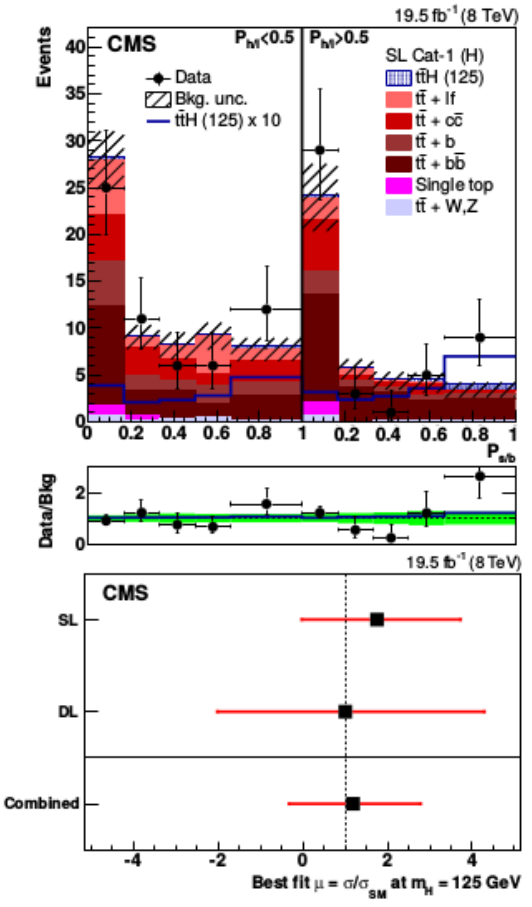
Integral over the phase space of the final-state particles

ttH → bb

- Signal extraction:
  - Fit on multivariate discriminant that includes MEM [ATLAS];
  - 2D fit using MEM and a heavy/light jets discriminant [CMS].
- Observed (expected) 95% CL upper limit:
  - ATLAS: **3.4 (2.2)**;
  - CMS: **4.2 (3.3)**.
- Signal strength:
  - ATLAS: $\boldsymbol{\mu = 1.5\,^{+1.1}_{-1.1}}$;
  - CMS: $\boldsymbol{\mu = 1.2\,^{+1.6}_{-1.5}}$.

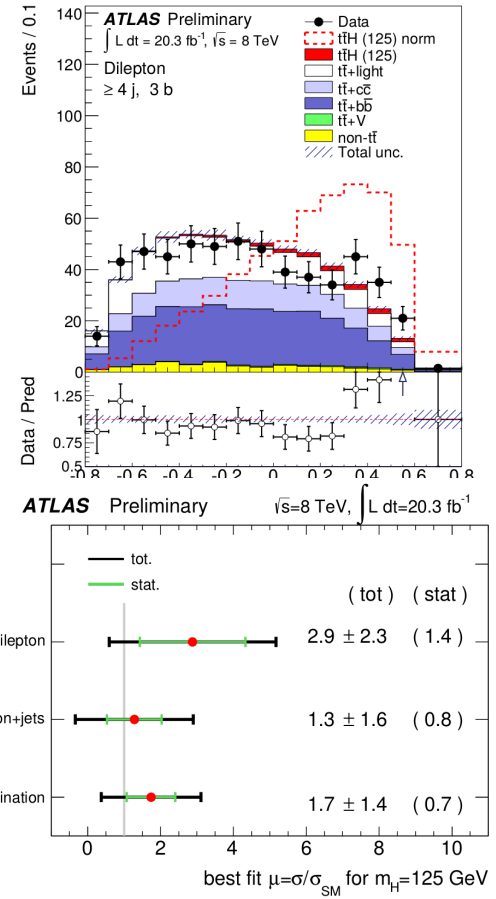


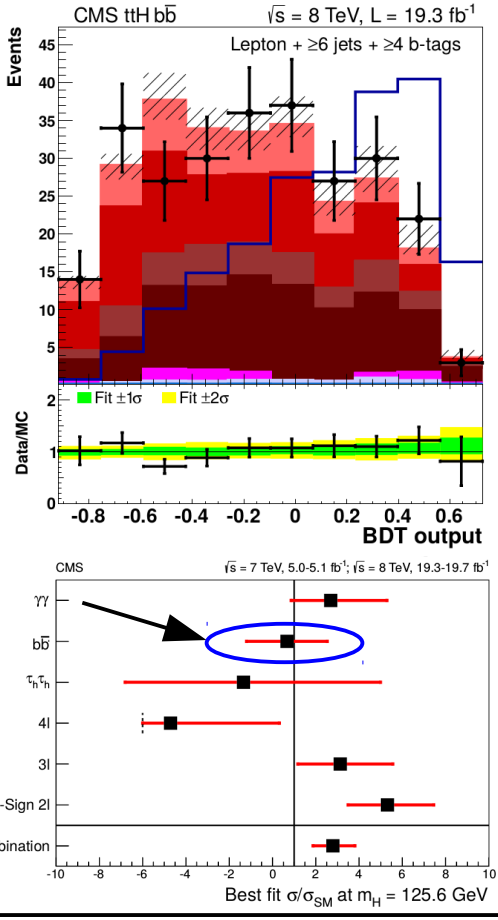




ttH → bb (legacy)

- Previous analysis without using Matrix Element method.
- Signal extraction:
  - Fit on multivariate discriminant distribution [ATLAS,CMS].
- Observed (expected) 95% CL upper limit:
  - ATLAS: **4.1 (2.6)**;
  - CMS: **4.1 (3.5)**.
- Signal strength:
  - ATLAS: $\boldsymbol{\mu = 1.7^{+1.4}_{-1.4}}$;
  - CMS: $\boldsymbol{\mu = 0.7^{+1.9}_{-1.9}}$.



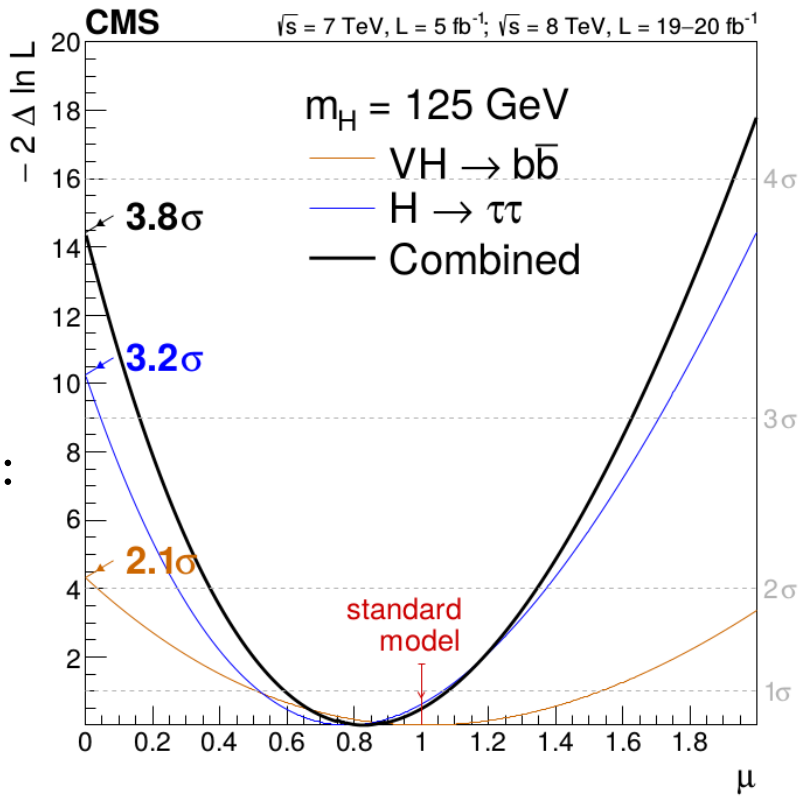


H → fermions combination

- Combination of all H → bb analysis, signal strength:

[new!]
  - CMS (VH, VBF, ttH(*)): $\boldsymbol{\mu = 1.03^{+0.44}_{-0.42}}$.
  - ATLAS (VH, ttH): $\boldsymbol{\mu = 0.63^{+0.39}_{-0.37}}$.

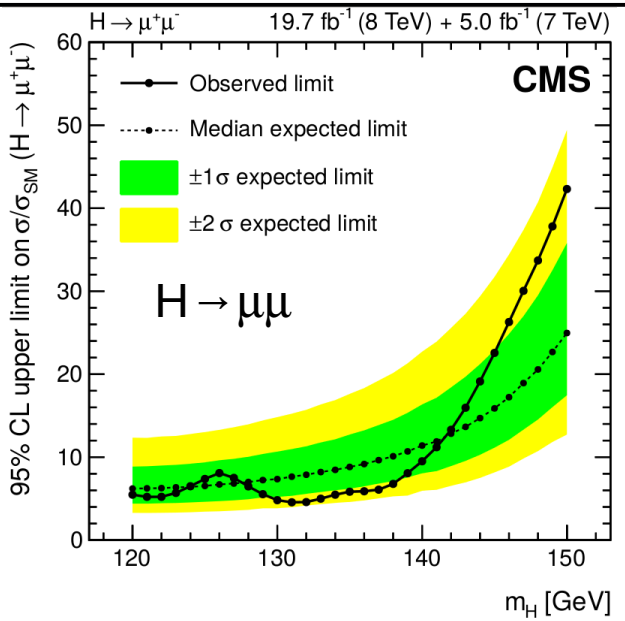
- Higgs to fermions (H→ττ, VH→bb) p-value:
  - Observed (exp.), CMS: **3.8σ (4.4σ)**.
  - Observed, ATLAS: **~4.5σ**.

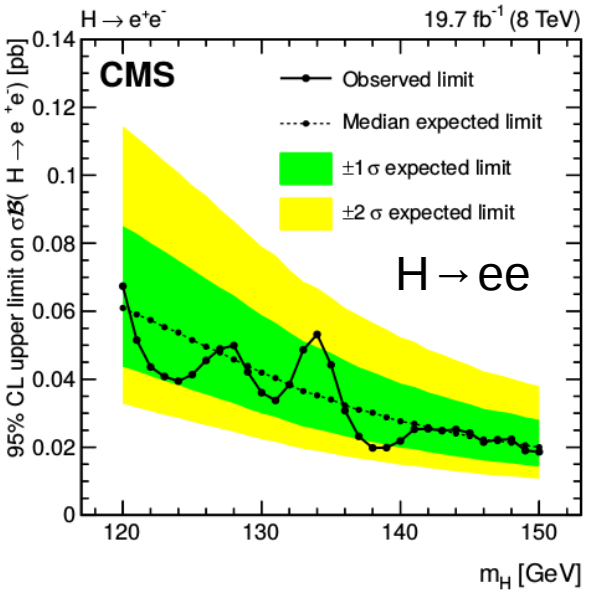


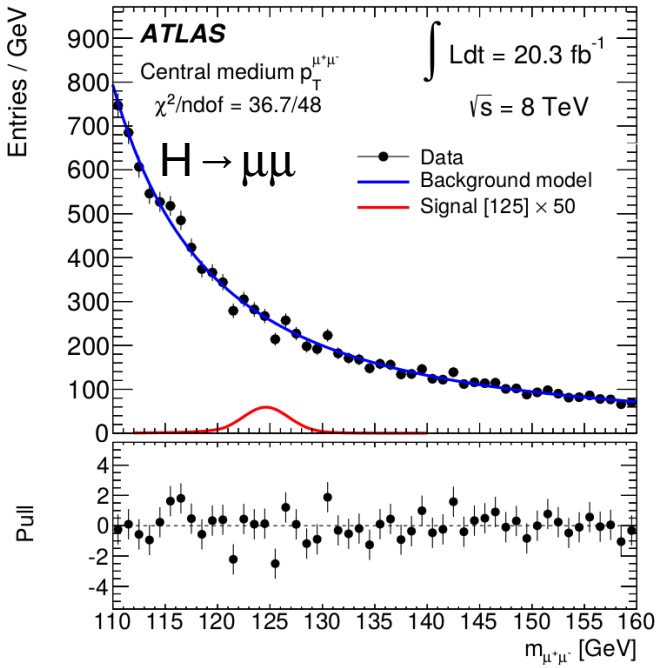
(*) Legacy analysis (no Matrix Element)

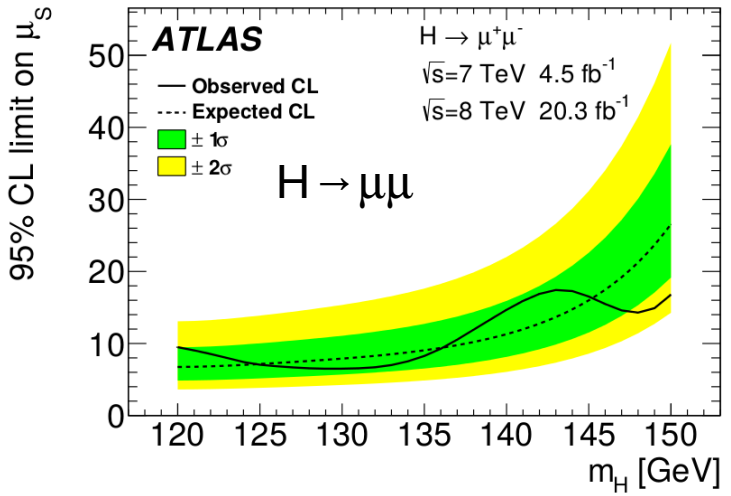
H → μμ, ee

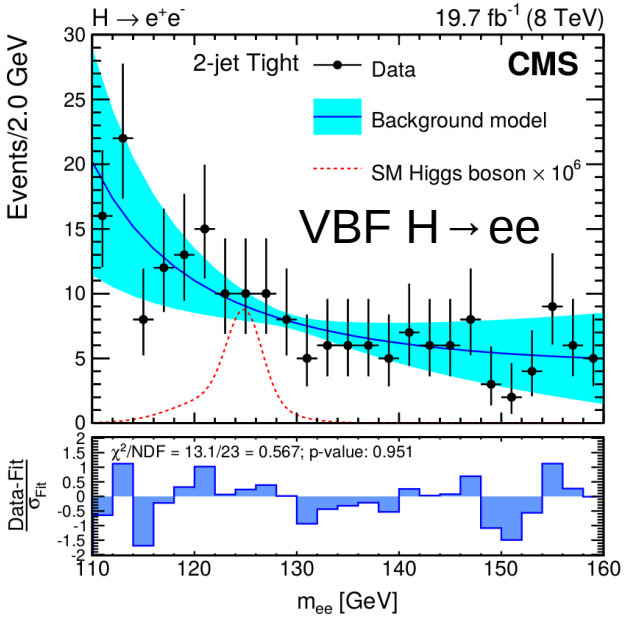
- Standard Model predicts small BR for H→μμ,ee:
  - good probe to look for New Physics with at 125 GeV.
- No excess has been found.











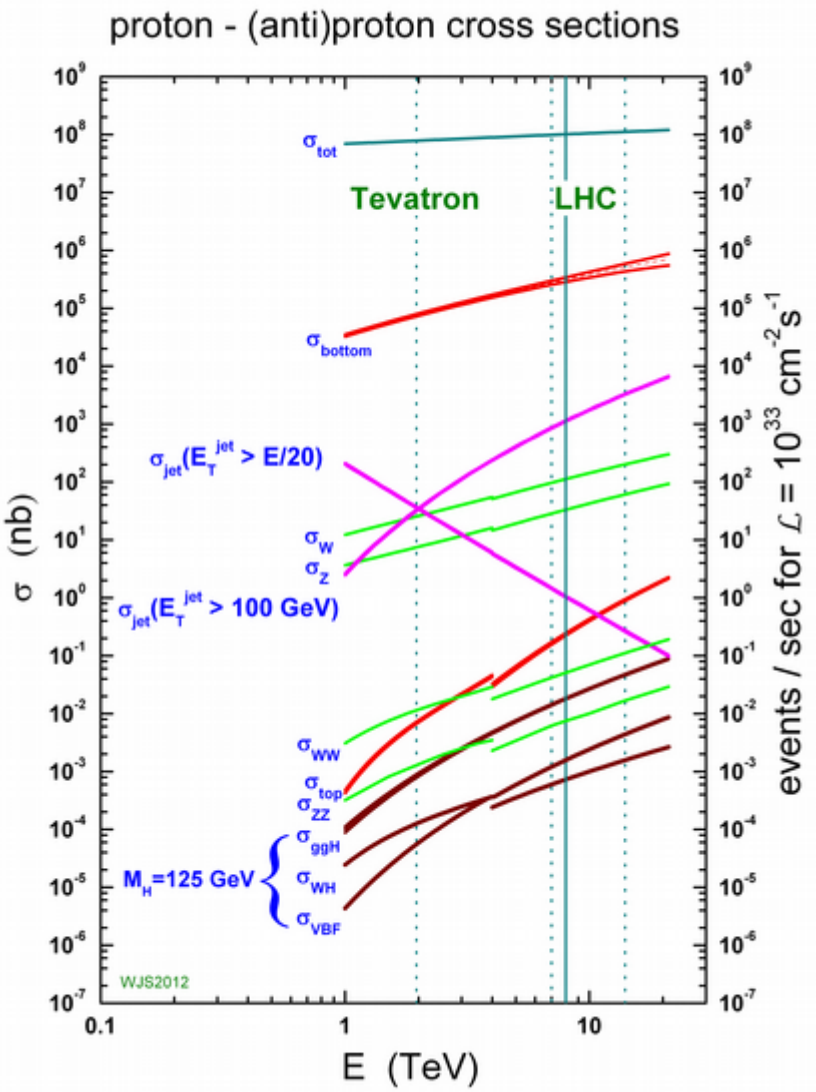
Run2 prospective

- In Run-2 we have:
  - more energy (13 TeV);
  - more luminosity ($\sim 2 \cdot 10^{34}\,\mathrm{cm^{-2}s^{-1}}$);
- At the new energy cross-sections increase

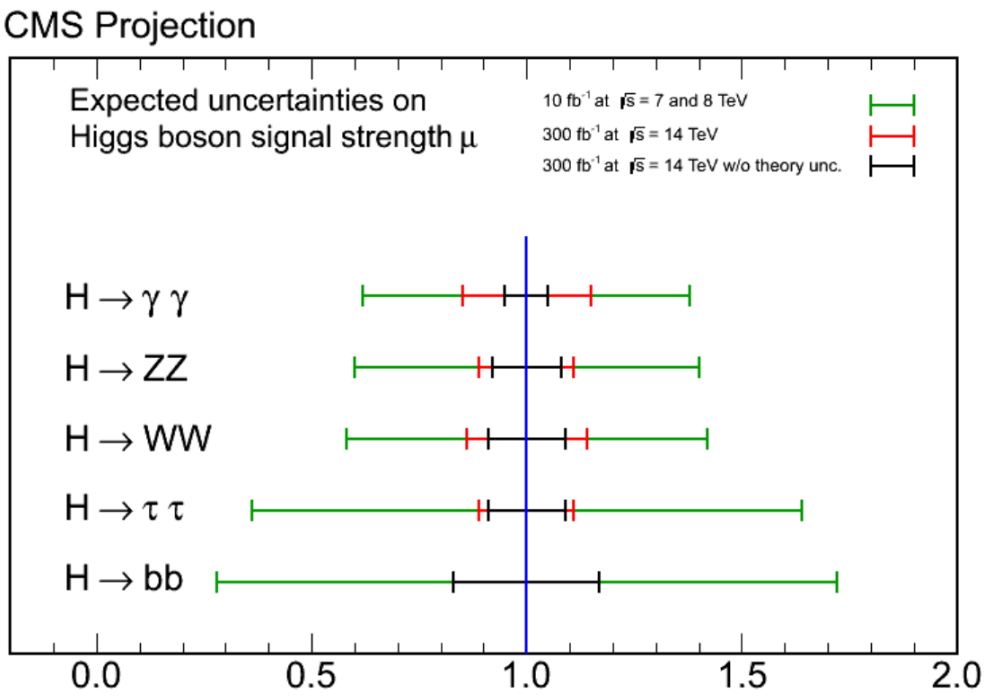
  ☺ ttH: x4;

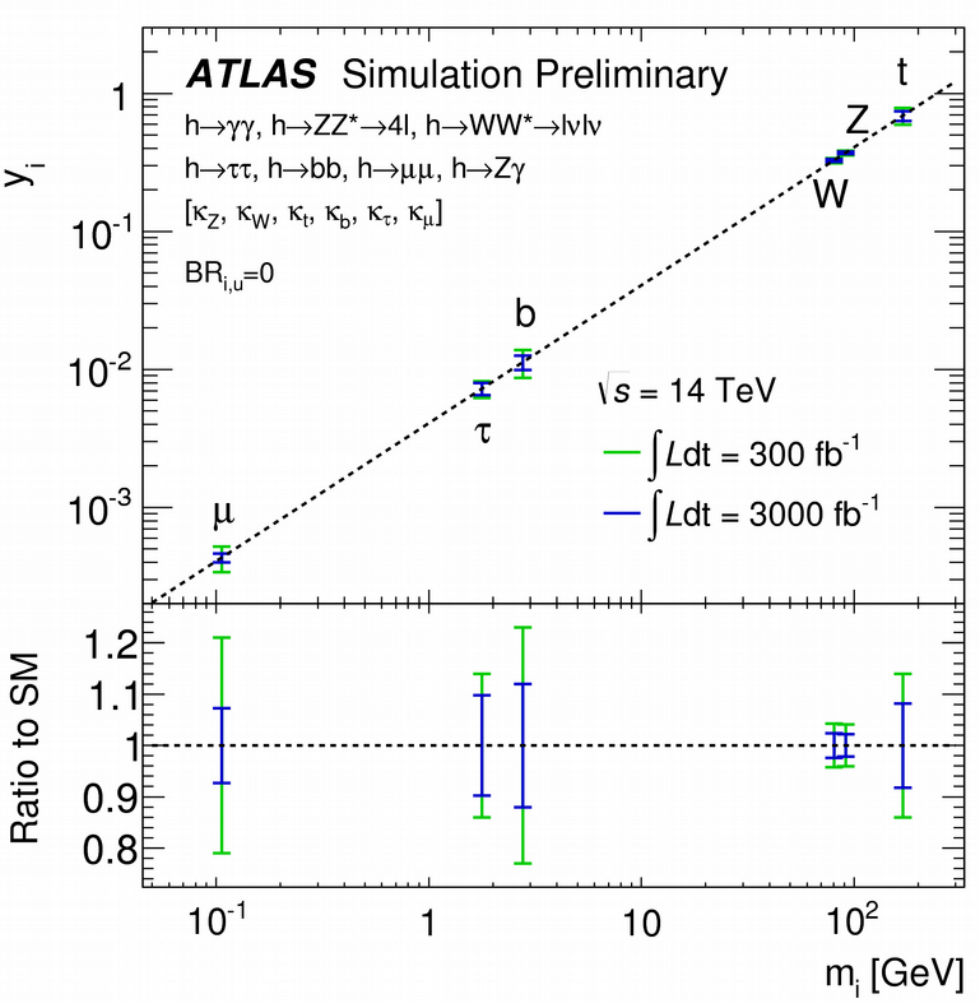
  ☺ ggH, VH, VBF: x2;

  ☹ tt: x4.
- With more luminosity we aim to improve the signal strength resolution...



Run2 prospective





Conclusion

- The searches for the SM Higgs boson decaying into fermions have been presented.
- The most sensitive search is $H \to \tau\tau$, where ATLAS and CMS collaborations reported excess with respect to SM background processes equal to:
  - ATLAS: **4.5σ (exp. 3.4σ)**;
  - CMS: **3.2σ (exp. 3.7σ)**.
- In Run-2 we expect to collect more signal events thanks to:
  - higher energy → higher cross-section;
  - higher luminosity.
- With 300 fb^{-1} of collected luminosity we expect to measure Higgs coupling with b,τ and μ with 10% — 20% of uncertainty.

References

- ATLAS:
  - Higgs to ττ: JHEP 04 (2015) 117;
  - Higgs to bb (VH): JHEP 01 (2015) 069;
  - Higgs to bb (ttH): arxiv.1503.05066, (legacy): ATLAS-CONF-2014-011;
  - Higgs to μμ: Physics Letters B 738 (2014) 68-86;
  - Higgs production and decay rates and coupling: ATLAS-CONF-2015-007;
  - Run2 prospective: ATL-PHYS-PUB-2014-016.
- CMS:
  - Higgs to ττ: JHEP 05 (2014) 104;
  - Higgs to bb (VH): Phys. Rev. D 89 (2014) 012003;
  - Higgs to fermions (VHbb+ττ): Nature Physics 10, 557–560 (2014);
  - Higgs to bb (VBF): CMS-HIG-14-004;
  - Higgs to bb (ttH): CMS-HIG-14-010; (legacy) JHEP 09 (2014) 087;
  - Higgs to μμ/ee: Physics Letters B 744 (2015) 184-207;
  - Run2 prospective: CMS-NOTE-2012-006;

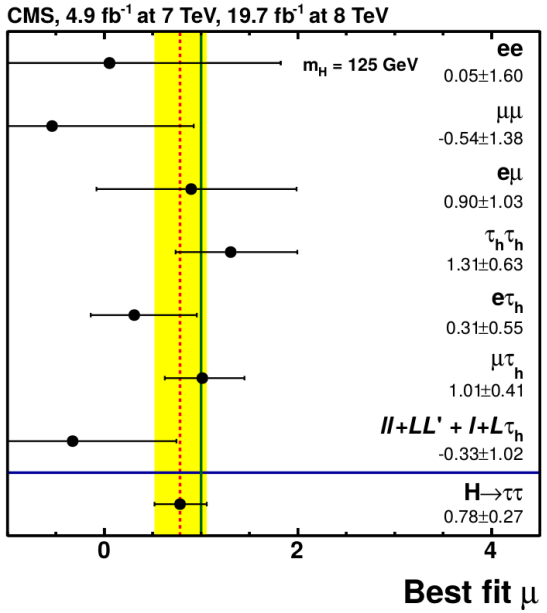
Backup

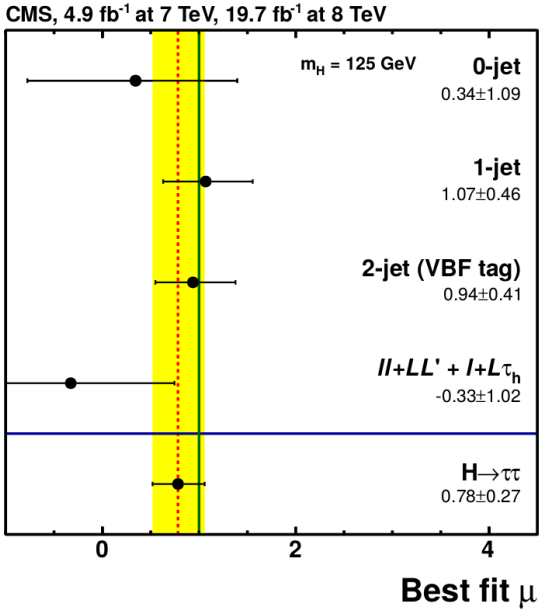
Higgs to ττ

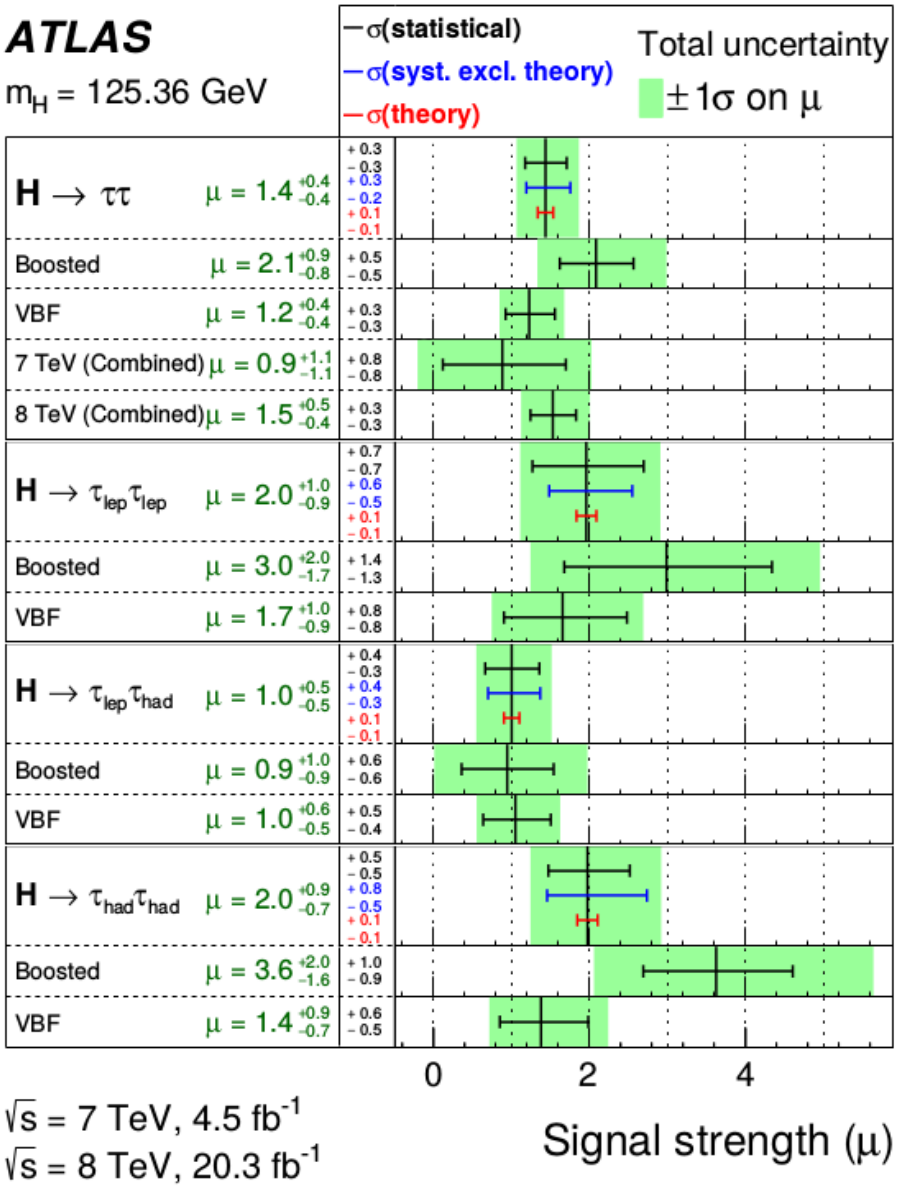
ATLAS

Process/Category	VBF			Boosted		
BDT output bin	All bins	Second to last bin	Last bin	All bins	Second to last bin	Last bin
Fake background	370 ± 18	2.3 ± 0.9	0.57 ± 0.29	645 ± 26	35 ± 4	0.65 ± 0.33
Others	37 ± 5	0.67 ± 0.22	< 0.1	89 ± 11	15.9 ± 2.0	0.92 ± 0.22
$Z \to \tau\tau$	475 ± 16	0.6 ± 0.7	0.6 ± 0.4	2230 ± 70	93 ± 4	5.4 ± 1.6
ggF: $H \to \tau\tau$ ($m_H = 125$ GeV)	8.0 ± 2.7	0.67 ± 0.23	0.53 ± 0.20	21 ± 8	9.1 ± 3.3	1.6 ± 0.6
VBF: $H \to \tau\tau$	12.0 ± 3.1	1.8 ± 0.5	3.4 ± 0.9	6.3 ± 1.6	2.8 ± 0.7	0.52 ± 0.13
$WH : H \to \tau\tau$	0.25 ± 0.07	< 0.1	< 0.1	4.0 ± 1.1	1.9 ± 0.5	0.41 ± 0.11
$ZH : H \to \tau\tau$	0.16 ± 0.04	< 0.1	< 0.1	2.4 ± 0.6	1.13 ± 0.30	0.23 ± 0.06
Total background	883 ± 18	3.6 ± 1.3	1.2 ± 1.0	2960 ± 50	143 ± 6	7.0 ± 1.8
Total signal	20 ± 5	2.5 ± 0.6	3.9 ± 1.0	34 ± 10	15 ± 4	2.7 ± 0.8
Data	892	5	6	3020	161	10

CMS







Higgs to ττ

ATLAS – BDT inputs

Variable	VBF			Boosted		
	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
$m_{\tau\tau}^{\text{MMC}}$	•	•	•	•	•	•
$\Delta R(\tau_1, \tau_2)$	•	•	•		•	•
$\Delta\eta(j_1, j_2)$	•	•	•			
m_{j_1,j_2}	•	•	•			
$\eta_{j_1} \times \eta_{j_2}$		•	•			
$p_{\text{T}}^{\text{Total}}$		•	•			
Sum p_{T}					•	•
$p_{\text{T}}^{\tau_1}/p_{\text{T}}^{\tau_2}$					•	•
$E_{\text{T}}^{\text{miss}}\phi$ centrality		•	•	•	•	•
m_{ℓ,ℓ,j_1}				•		
m_{ℓ_1,ℓ_2}				•		
$\Delta\phi(\ell_1, \ell_2)$				•		
Sphericity				•		
$p_{\text{T}}^{\ell_1}$				•		
$p_{\text{T}}^{j_1}$				•		
$E_{\text{T}}^{\text{miss}}/p_{\text{T}}^{\ell_2}$				•		
m_{T}		•			•	
$\min(\Delta\eta_{\ell_1\ell_2,\text{jets}})$	•					
$C_{\eta_1,\eta_2}(\eta_{\ell_1}) \cdot C_{\eta_1,\eta_2}(\eta_{\ell_2})$	•					
$C_{\eta_1,\eta_2}(\eta_{\ell})$		•				
$C_{\eta_1,\eta_2}(\eta_{j_3})$	•					
$C_{\eta_1,\eta_2}(\eta_{\tau_1})$			•			
$C_{\eta_1,\eta_2}(\eta_{\tau_2})$			•			