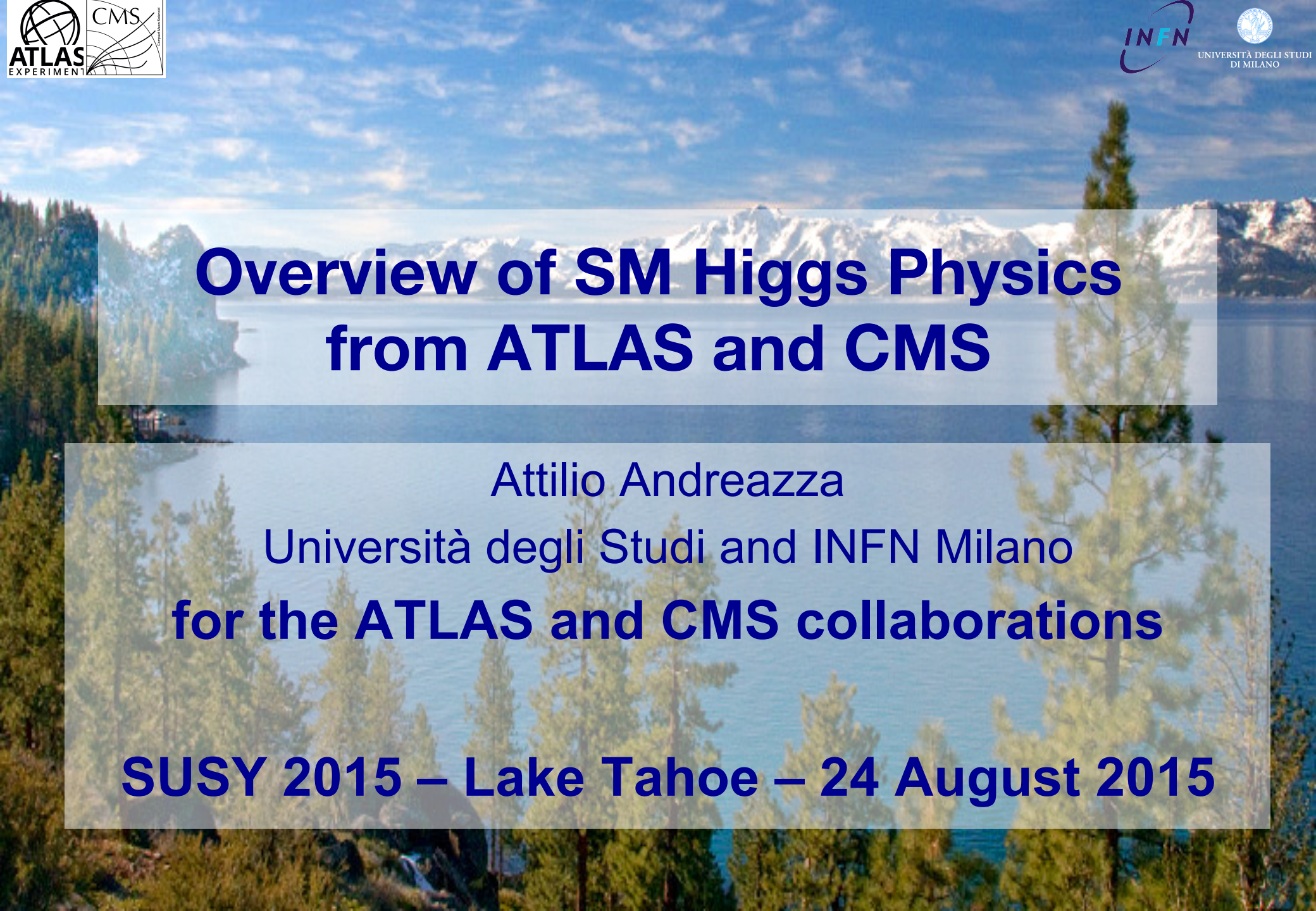


Overview of SM Higgs Physics from ATLAS and CMS

Attilio Andreazza

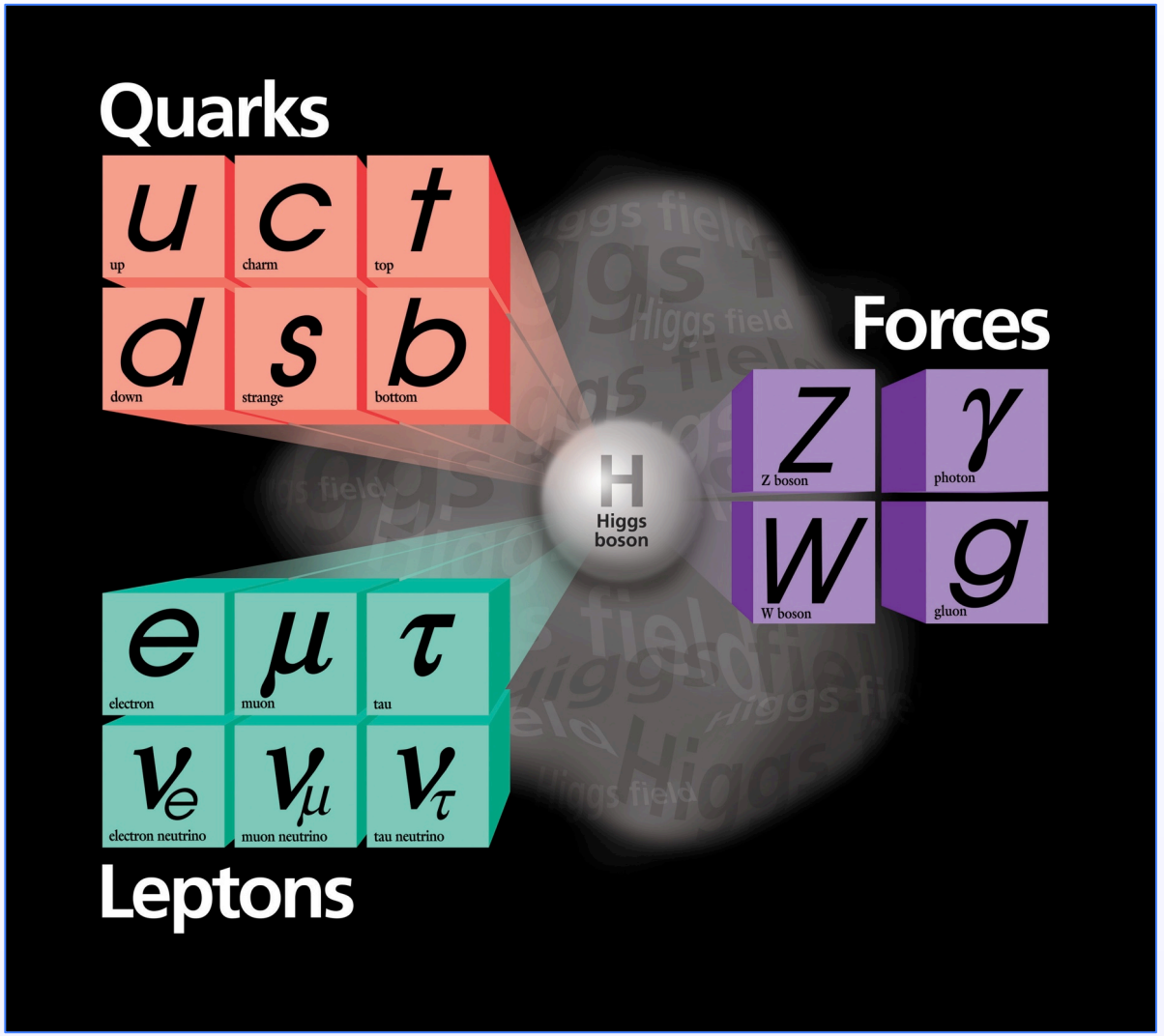
Università degli Studi and INFN Milano

for the ATLAS and CMS collaborations

SUSY 2015 – Lake Tahoe – 24 August 2015

Outline

- Introduction
- Higgs properties
  - Mass
  - Couplings
  - Width
  - Spin and Parity
- Differential and total cross sections
- Summary and outlook



The Higgs boson

H^0

$J = 0$

Mass $m = 125.7 \pm 0.4$ GeV

H^0 Signal Strengths in Different Channels

Combined Final States $= 1.17 \pm 0.17$ (S = 1.2)

$WW^* = 0.87^{+0.24}_{-0.22}$

$ZZ^* = 1.11^{+0.34}_{-0.28}$ (S = 1.3)

$\gamma\gamma = 1.58^{+0.27}_{-0.23}$

$b\bar{b} = 1.1 \pm 0.5$

$\tau^+\tau^- = 0.4 \pm 0.6$

$Z\gamma < 9.5$, CL = 95%

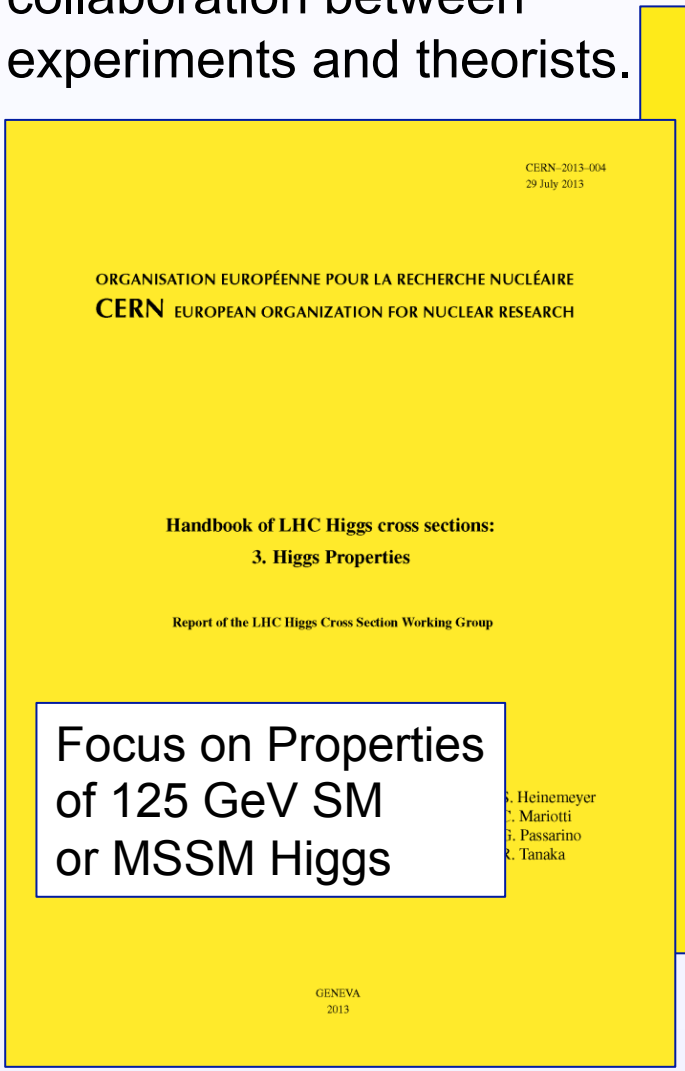
2014:
first printed PDG edition with Higgs boson data

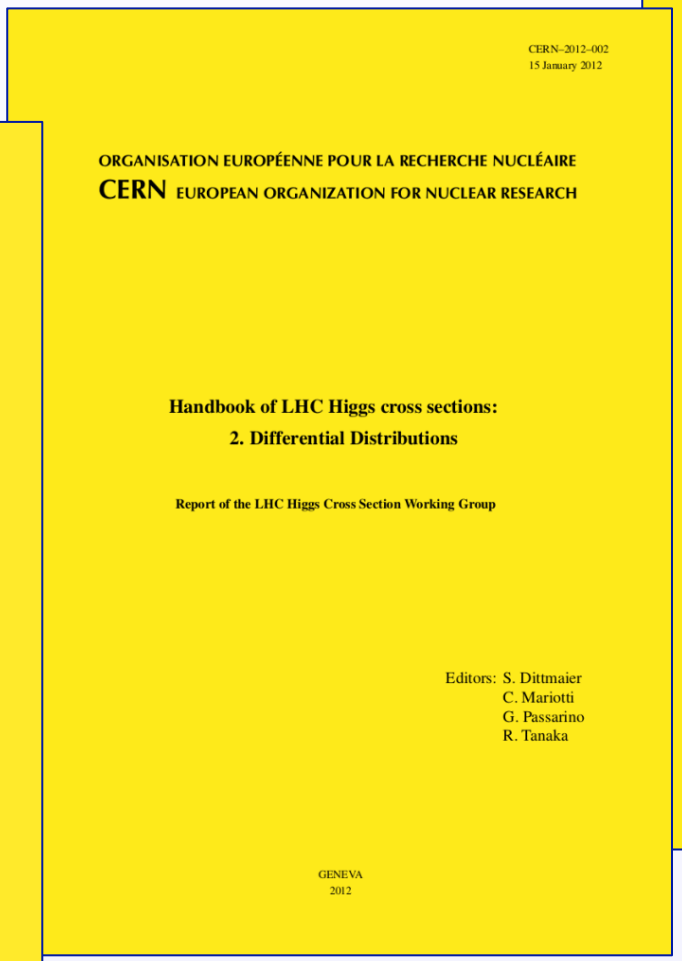
- Collaborations wrapping up analysis on LHC Run-1 data: ~5 fb^{-1} at $\sqrt{s}$=7 TeV, ~20 fb^{-1} at $\sqrt{s}$=8 TeV
- Legacy papers:
  - Couplings: ATLAS: **arXiv:1507.04548v1**
    CMS: **Eur. Phys. J. C (2015) 75:212**
  - Mass combination: **PRL 114, 191803 (2015)**
  - Extended bibliography in backup slides

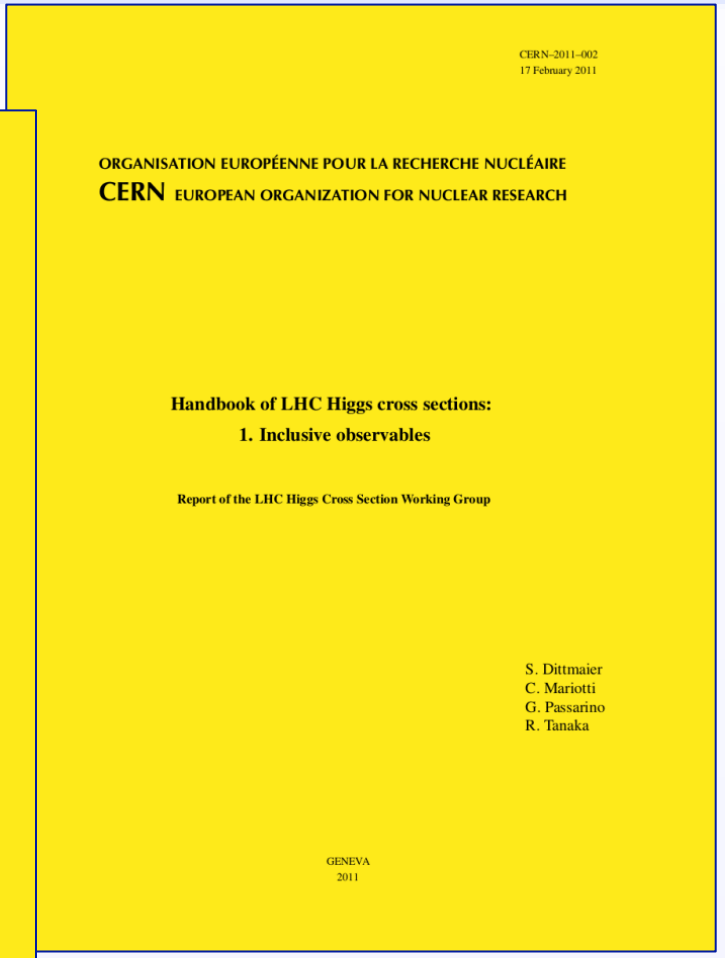
ATLAS+CMS combination in preparation

LHC Higgs Cross-section WG

Results and interpretation thanks to the long-term collaboration between experiments and theorists.





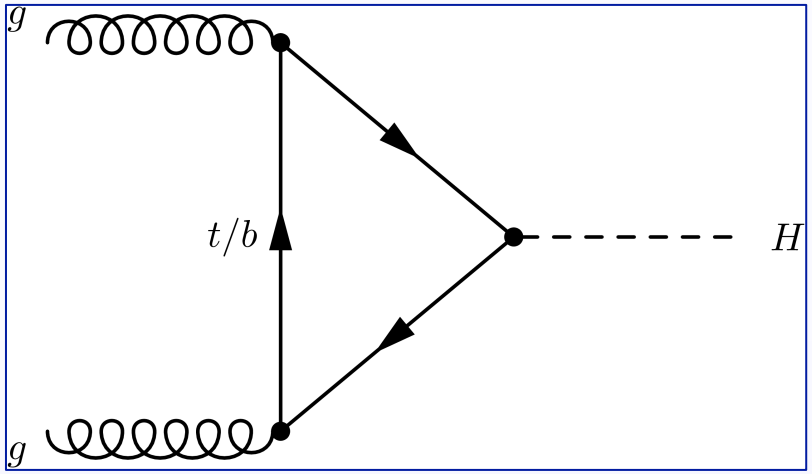


Focus on Properties of 125 GeV SM or MSSM Higgs

See theoretical talks in plenary and parallel sessions

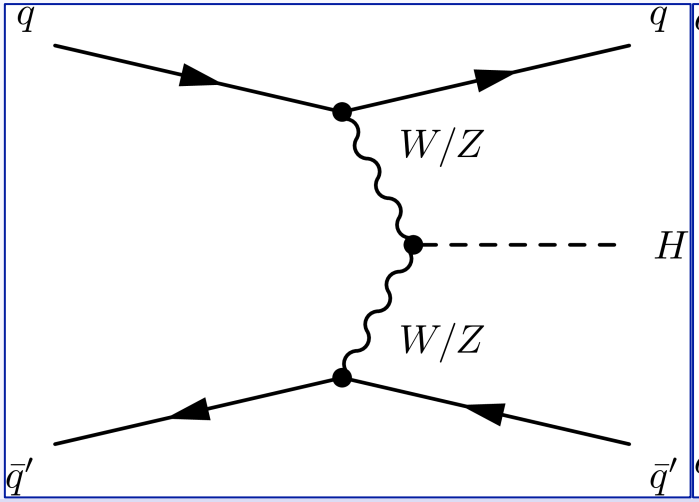
Higgs production at LHC

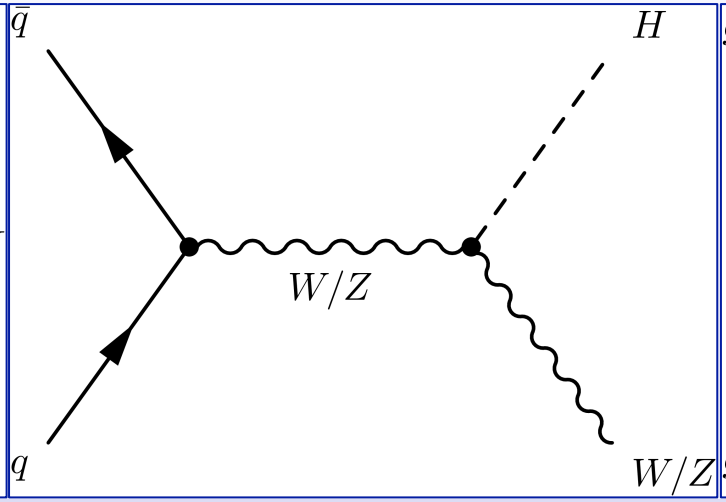
from LHCHXS WG

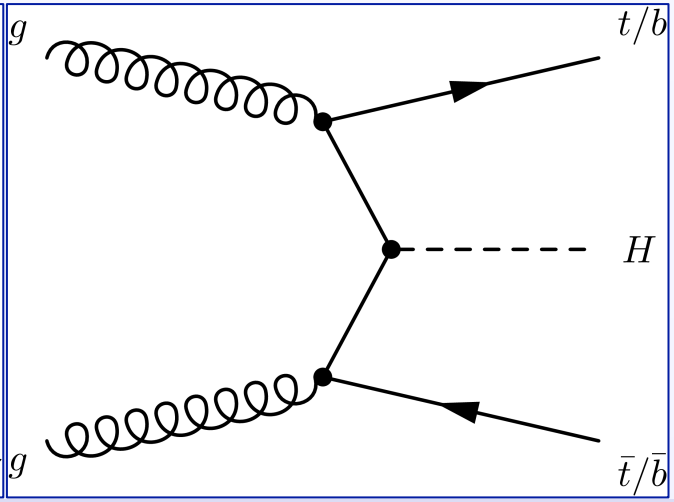


σ [pb]	√s=7 TeV	√s=8 TeV	Uncertainty at 8 TeV [%] QCD scale	PDF+α_S
ggH	15.1	19.2	+7.2 -7.8(**)	+7.5 -6.9
VBF	1.22	1.58	±0.2	+2.6 -2.8
WH	0.577	0.703	±1.0	±2.3
ZH	0.334	0.414	±3.1	±2.5
ttH(*)	0.086	0.129	+3.8 -9.3	±8.1
bbH(*)	0.156	0.203	+10.3 -14.8	±6.2

(*) *tqH/WtH non negligible w.r.t. ttH/bbH*
(**) *Improved by NNNLO calculations*

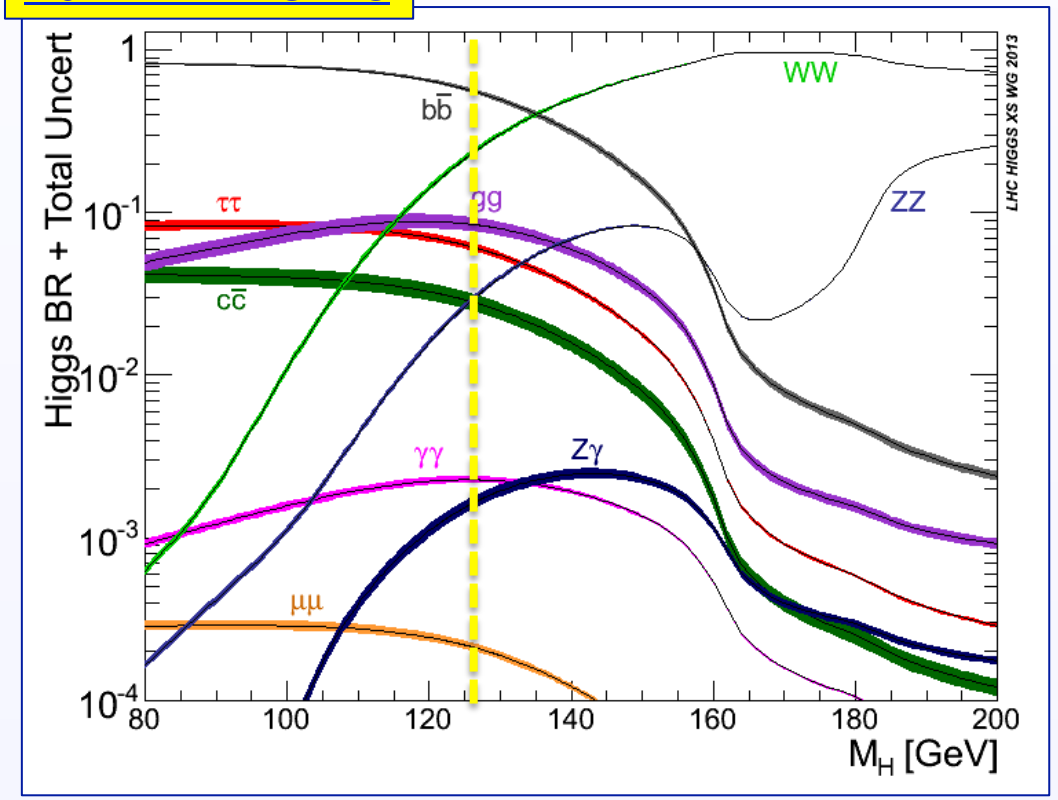


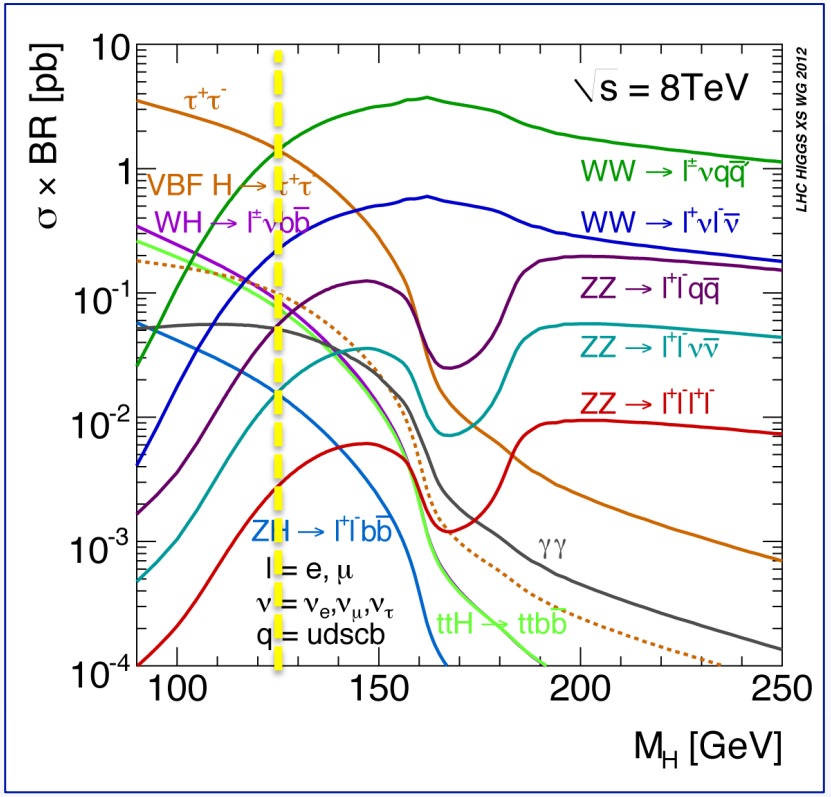




Higgs decay modes

from LHCHXS WG





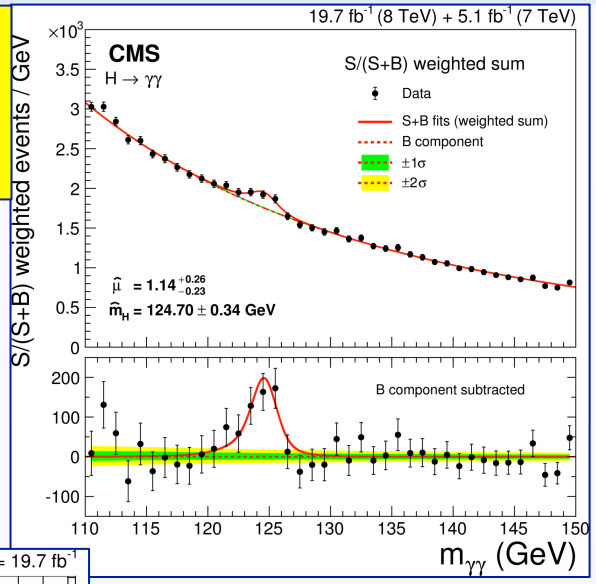
- m_H at 125 GeV is an exceptional opportunity:
  - many decay channels (also rare ones) are accessible.
  - narrow state: no widening w.r.t. detector resolution

Higgs decay modes

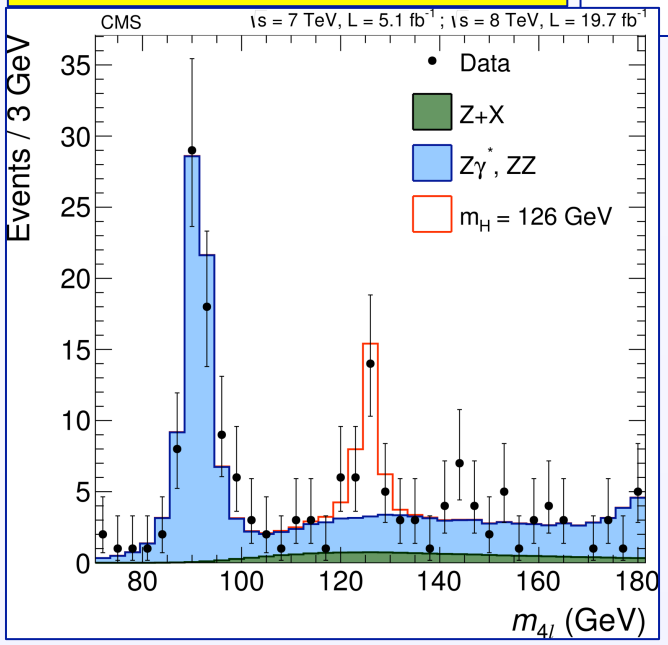
	BR	σ×BR √s=8 TeV [pb]	Most sensitive channel σ×BR [pb]		Events in 20 fb^{-1}
H→bb	0.575	12.8	VH	0.64	12765
H→WW*	0.216	4.8	WW→ℓνℓν (21.3%)	1.0	20000
H→ττ	0.063	1.4	VBF+VH	0.17	340
H→ZZ*	0.027	0.6	ZZ→ℓℓℓℓ (0.45%)	0.0027	54
H→γγ	2.3×10^{-3}	0.05			1000
H→Zγ	1.6×10^{-3}	0.036	Z→ℓℓ (6.73%)	0.0024	54
H→μμ	2.2×10^{-4}	0.0049			98

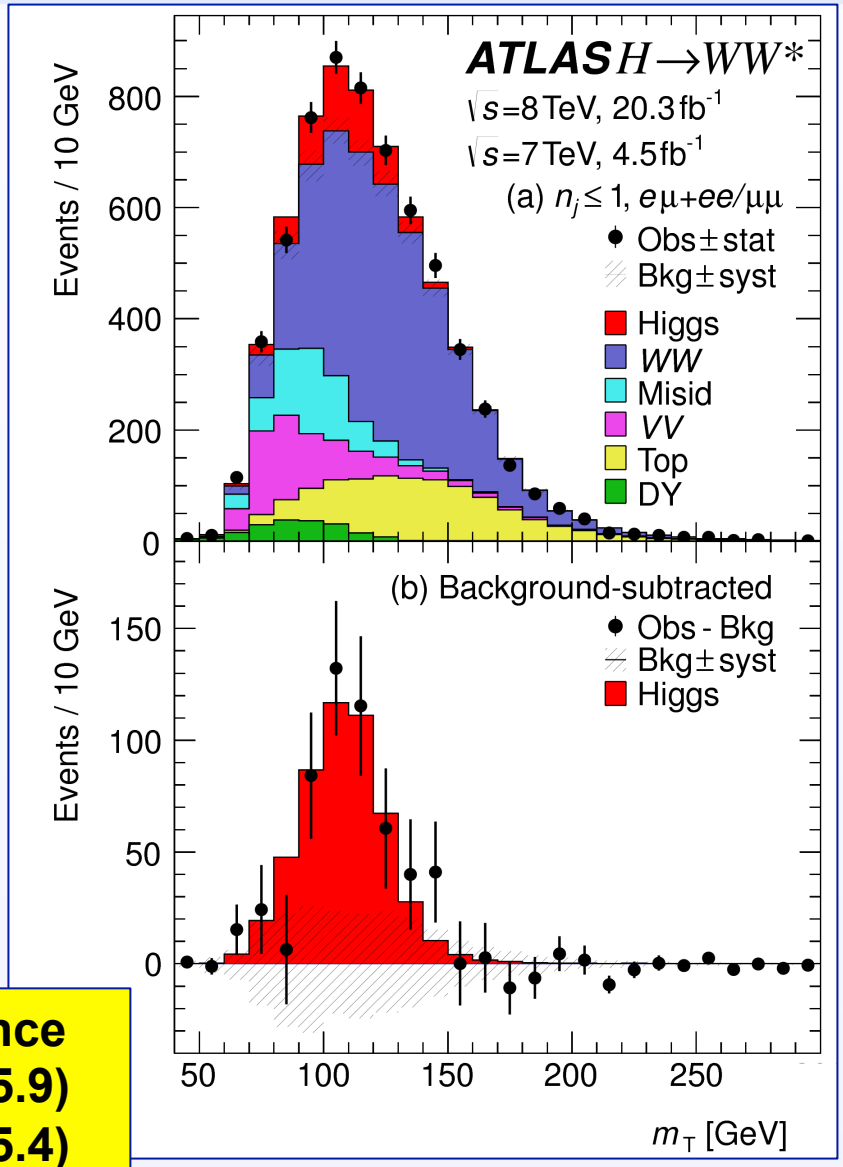
Higgs into di-bosons

H→γγ significance
ATLAS: 5.2 (exp. 4.6)
CMS: 5.6 (exp. 5.3)



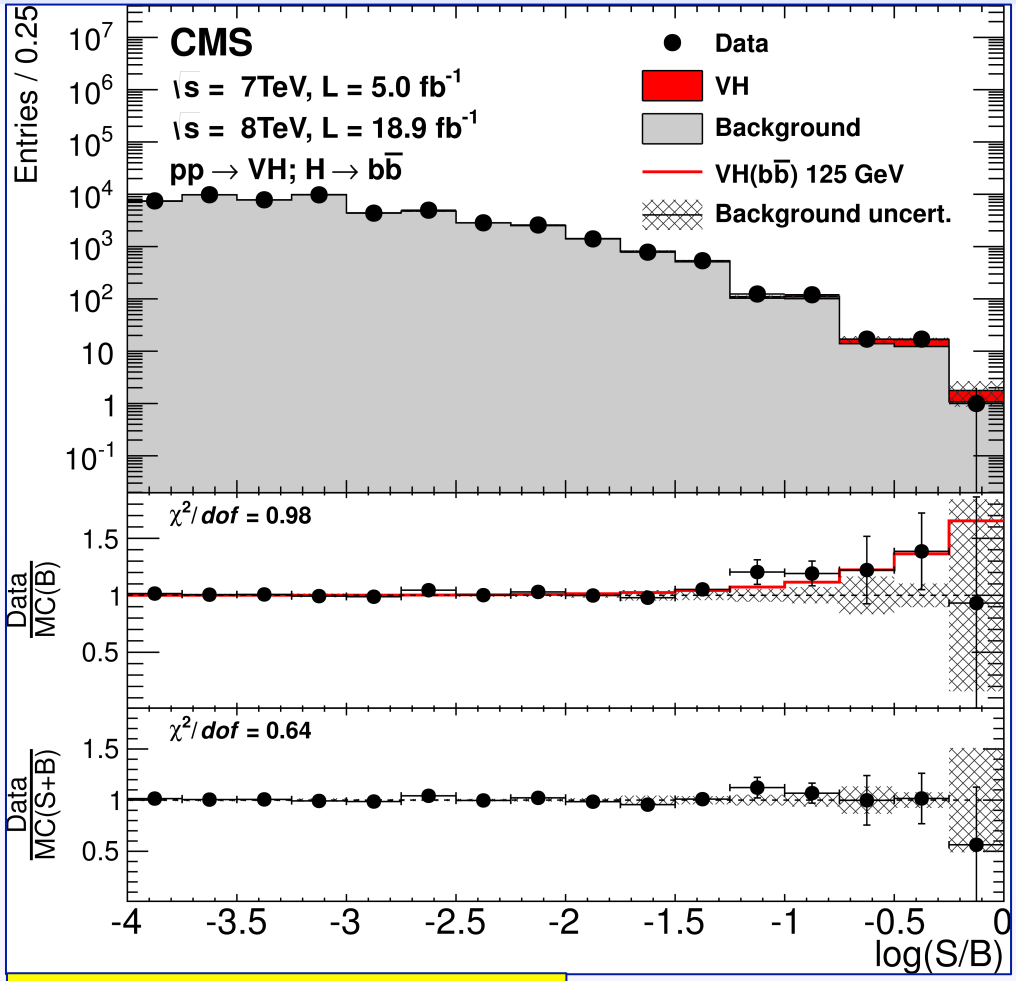
H→ZZ* significance
ATLAS: 8.1 (exp. 6.2)
CMS: 6.5 (exp. 6.3)





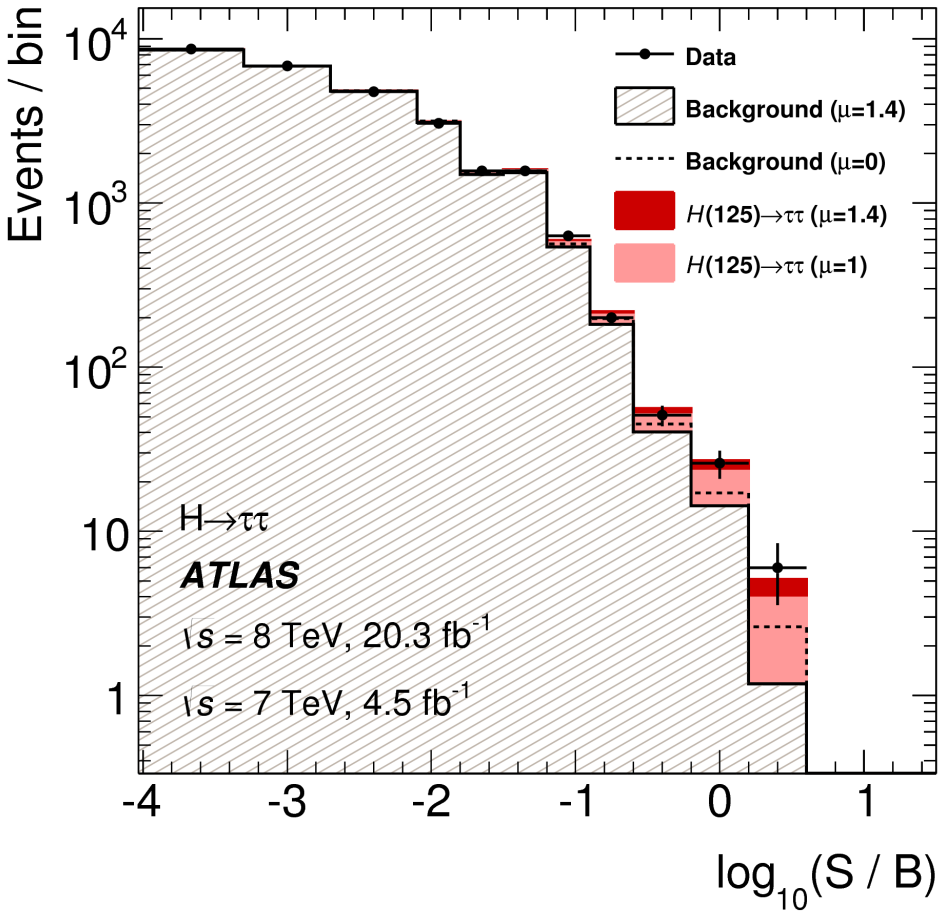
H→WW* significance
ATLAS: 6.5 (exp. 5.9)
CMS: 4.7 (exp. 5.4)

Higgs to fermions



H→bb significance
ATLAS: 1.8 (exp. 2.8)
CMS: 2.0 (exp. 2.6)

H→ττ significance
ATLAS: 4.5 (exp. 3.4)
CMS: 3.8 (exp. 3.9)



Related talks at SUSY2015

- Combinations of the 125 Higgs Boson Properties Measurements using the ATLAS Detectors *(P. K. Rados, Monday)*
- Study of Higgs bosons decaying to bottom quarks at CMS *(S. Alderweireldt, Monday)*
- Constraints on new phenomena through Higgs coupling measurements with the ATLAS detector *(L. Brenner, Tuesday)*
- Higgs boson properties in bosonic final states at CMS *(D. A. Belknap, Tuesday)*
- Latest results on the Higgs boson in the diphoton decay channel *(F. Bernlochner, Tuesday)*
- Search for the Higgs boson in the ttH production channel using the ATLAS detector *(J. Bouffard, Tuesday)*
- Status of Higgs coupling strength determination from ATLAS and CMS *(M. Moreno Llacers, Tuesday)*
- ATLAS and CMS Prospects for Higgs Physics at the HL-LHC *(A. Perieanu, Thursday)*
- Study of Higgs boson decay to leptons at *CMS (C. S. Caillol, Thursday)*
- Higgs flavor studies and rare decays *(H. Okawa, Plenary Saturday)*
- Overview of BSM Higgs Physics from the ATLAS and CMS *(T. A. Du Pree, Plenary Saturday)*

Mass Phys. Rev. Lett. 114, 191803

H^0

$J = 0$

Mass $m = 125.7 \pm 0.4$ GeV

H^0 Signal Strengths in Different Channels

Combined Final States $= 1.17 \pm 0.17$ (S = 1.2)

$WW^* = 0.87^{+0.24}_{-0.22}$

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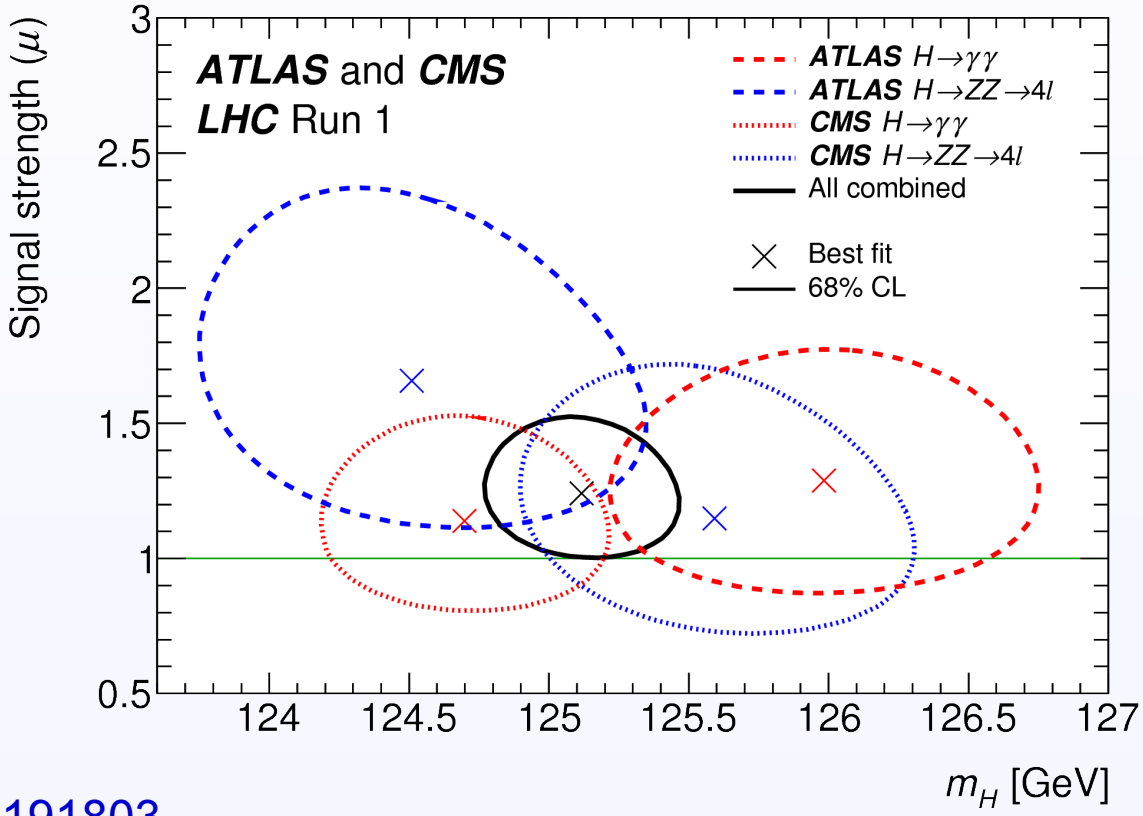


- **First combination of Higgs measurements between the LHC collaborations**

DOI: 10.1103/PhysRevLett.114.191803

m_H = 125.09 ± 0.21 (*stat*) ± 0.11 (*syst*) GeV

- Still statistically dominated
- Systematic uncertainties driven by detector energy scale.

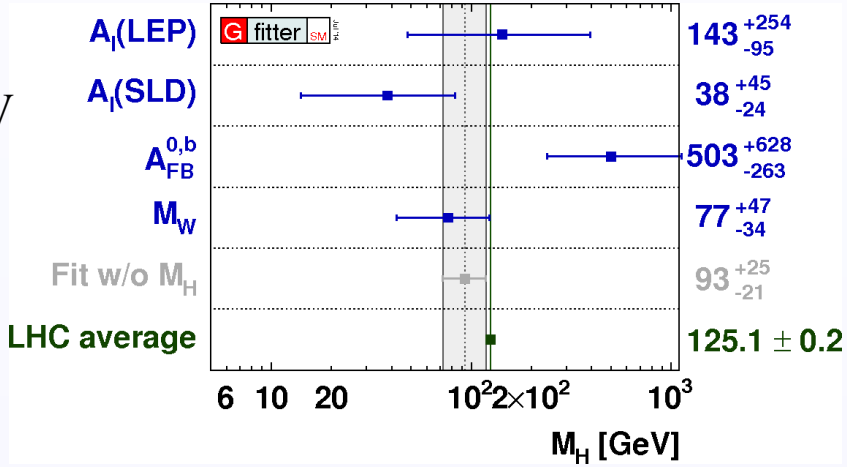
Mass

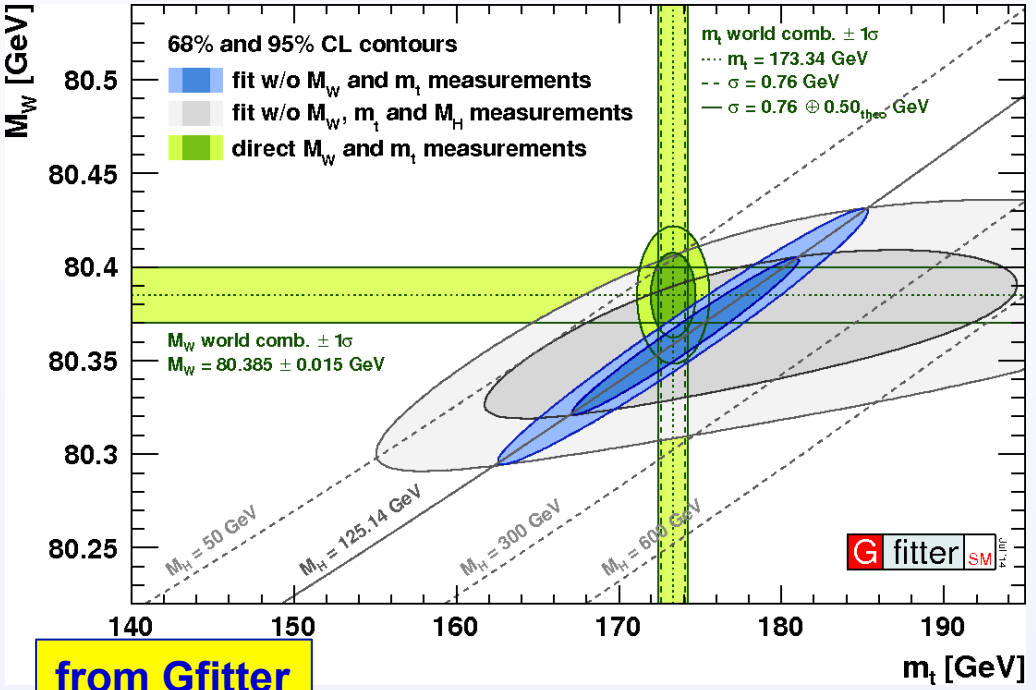
- Higgs mass is an arbitrary parameter in the SM

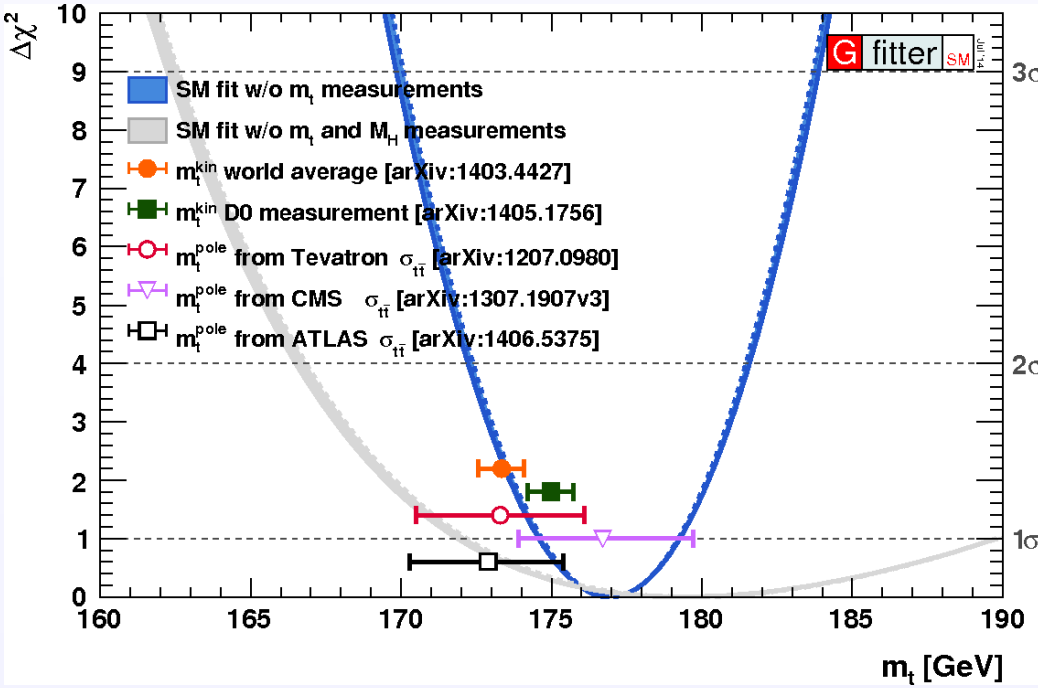
$$V(\phi) = m^2|\phi|^2 + \lambda|\phi|^4 \qquad \upsilon = \sqrt{-m^2/\lambda} = \left(\sqrt{2}G_F\right)^{-1/2} = 246\ \text{GeV}$$

$$m_H = \sqrt{2\lambda}\upsilon \Rightarrow \lambda = 0.13$$

  - constrains Electroweak fits
  - provides predictions on production and decay widths: couplings $\propto M/v$







from Gfitter

Signal strength

H^0 $J = 0$

Mass $m = 125.7 \pm 0.4$ GeV

H^0 Signal Strengths in Different Channels

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$WW^* = 0.87^{+0.24}_{-0.22}$

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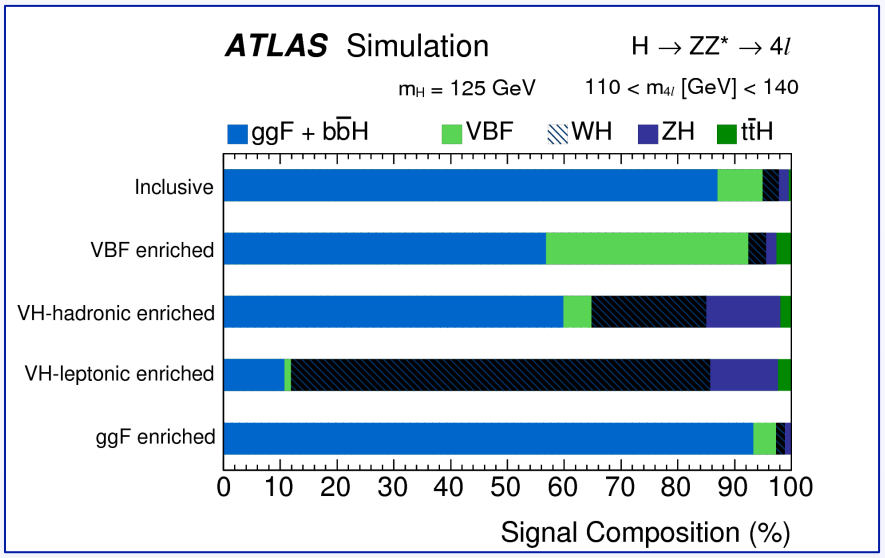
$b\bar{b} = 1.1 \pm 0.5$

$\tau^+\tau^- = 0.4 \pm 0.6$

$Z\gamma < 9.5$, CL = 95%

$$\mu = \frac{\sigma \times BR}{(\sigma \times BR)_{\mathrm{SM}}}$$



- Allow splitting in **categories** with different sensitivities:
  - background vs. acceptance trade-off
  - signal composition
- Combine categories fitting strength of different **processes** and different **final states**:

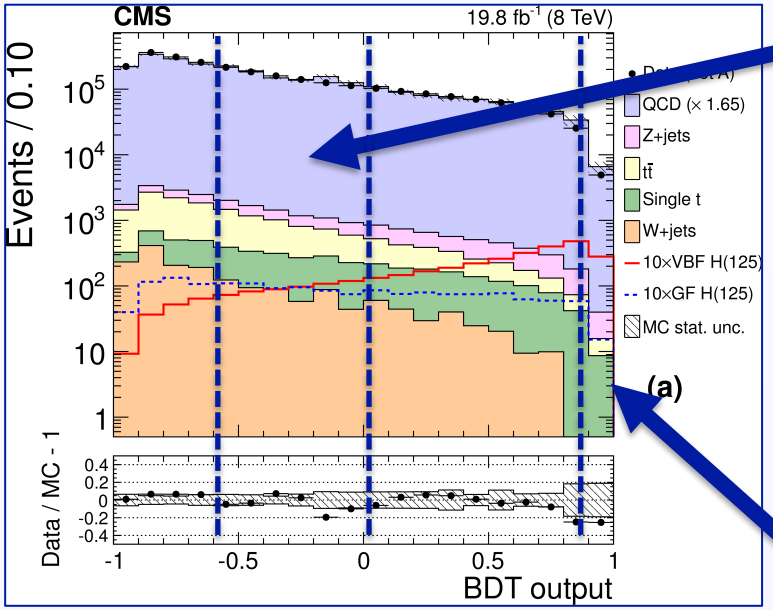
$$n^C_{\mathrm{Signal}} = \sum_{p,f} \mu^p \mu^f \left(\sigma_p \times BR_f\right)_{\mathrm{SM}} \times A^C_{p,f} \times \varepsilon^C_{p,f} \times \mathrm{Lumi}$$

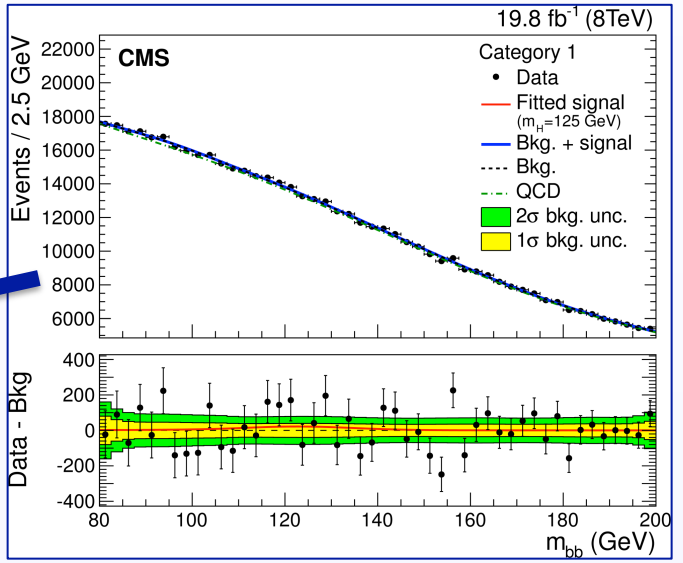
Channel matrix

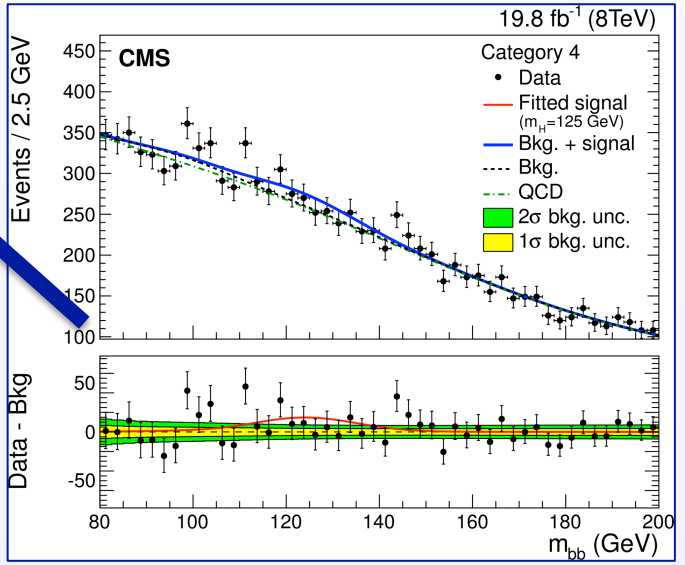
	WW	ZZ	γγ	bb	ττ
ggH	ATLAS CMS	ATLAS CMS	ATLAS CMS		ATLAS CMS
VBF	ATLAS CMS	ATLAS CMS	ATLAS CMS	**CMS**	ATLAS CMS
WH	ATLAS CMS	ATLAS CMS	ATLAS CMS	ATLAS CMS	CMS
ZH	ATLAS CMS	ATLAS CMS	ATLAS CMS	ATLAS CMS	CMS
ttH	**ATLAS** CMS	**ATLAS** CMS	ATLAS CMS	ATLAS CMS	**ATLAS** CMS

VBF $H \to bb$ arXiv:1506.01010

- Alternative approach for $H \to bb$ search.
  - BDT base on event kinematics and *b* content
  - fit to m_{bb} spectrum







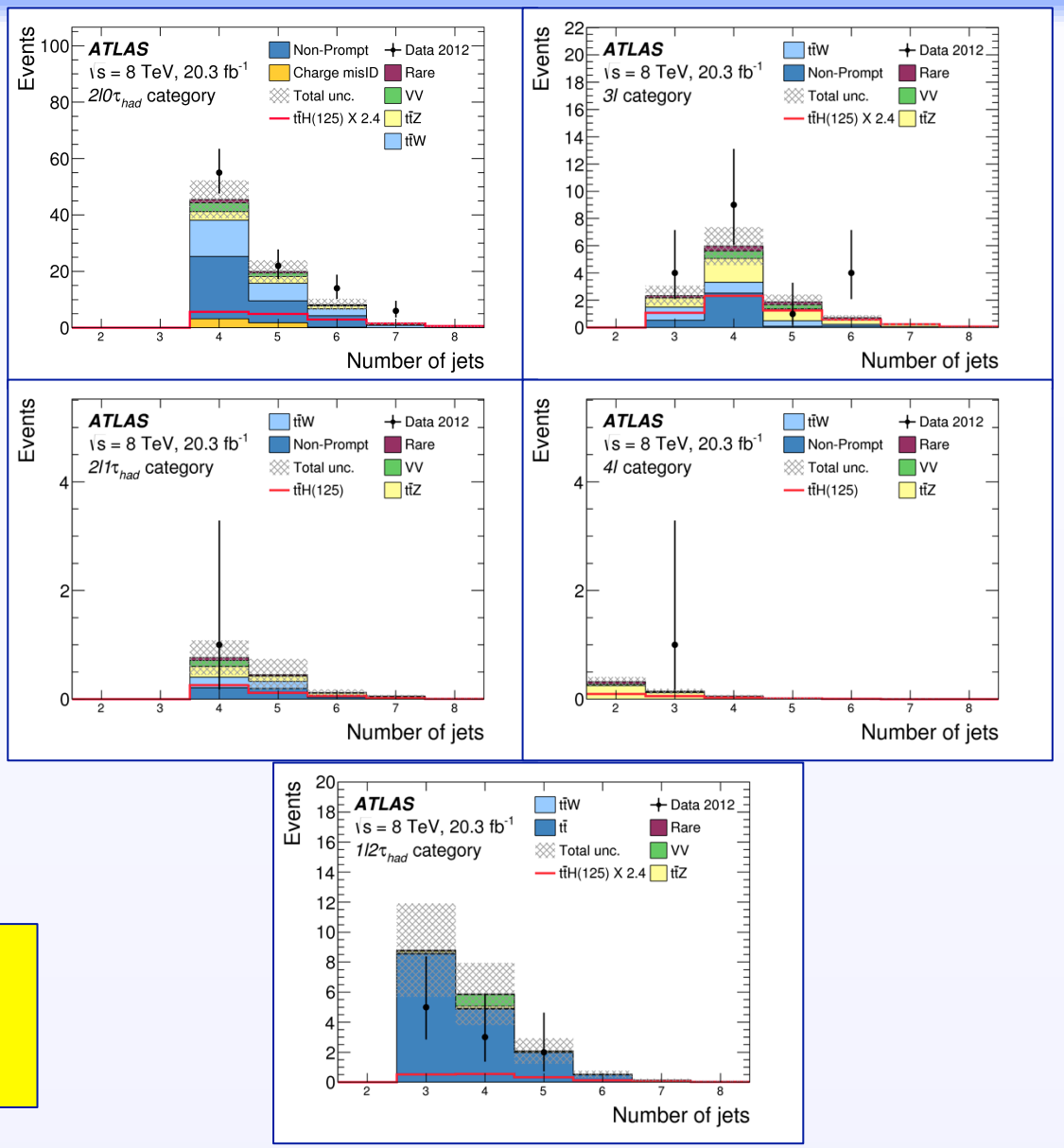
$H \to b\bar{b}$ Channel	Best fit (68% CL) Observed	Upper limits (95% CL) Observed	Upper limits (95% CL) Expected	Signal significance Observed	Signal significance Expected
VH	0.89 ± 0.43	1.68	0.85	2.08	2.52
$t\bar{t}H$	0.7 ± 1.8	4.1	3.5	0.37	0.58
VBF	$2.8^{+1.6}_{-1.4}$	5.5	2.5	2.20	0.83
Combined	$1.03^{+0.44}_{-0.42}$	1.77	0.78	2.56	2.70

ttH multileptons arXiv:1506.05988

- *ttH* has small cross section but spectacular final state.
- Multilepton final states targe *WW*+*ZZ*+*ττ* decay modes

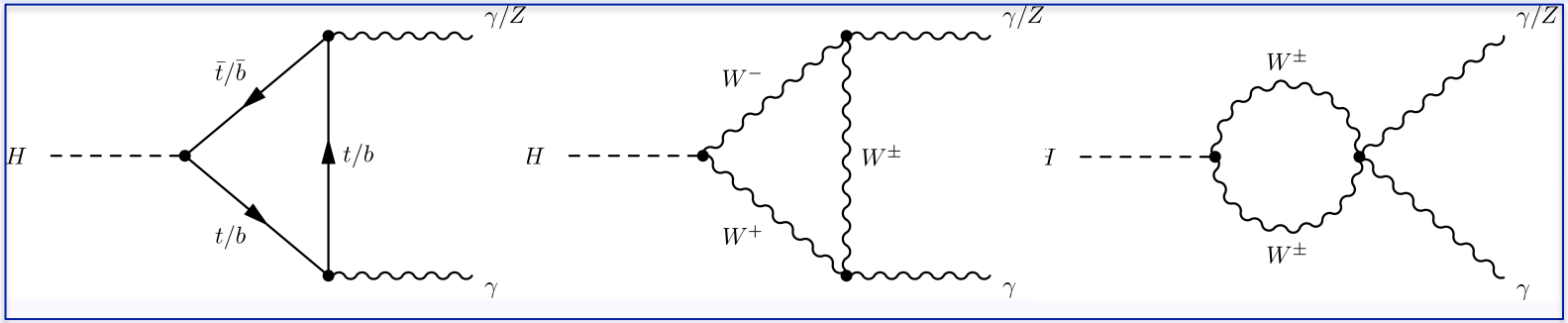
	Higgs boson decay mode			
Category	WW^*	$\tau\tau$	ZZ^*	Other
$2\ell 0\tau_{\rm had}$	80%	15%	3%	2%
3ℓ	74%	15%	7%	4%
$2\ell 1\tau_{\rm had}$	35%	62%	2%	1%
4ℓ	69%	14%	14%	4%
$1\ell 2\tau_{\rm had}$	4%	93%	0%	3%

- Background from *tt*(+*Z*/*W*)

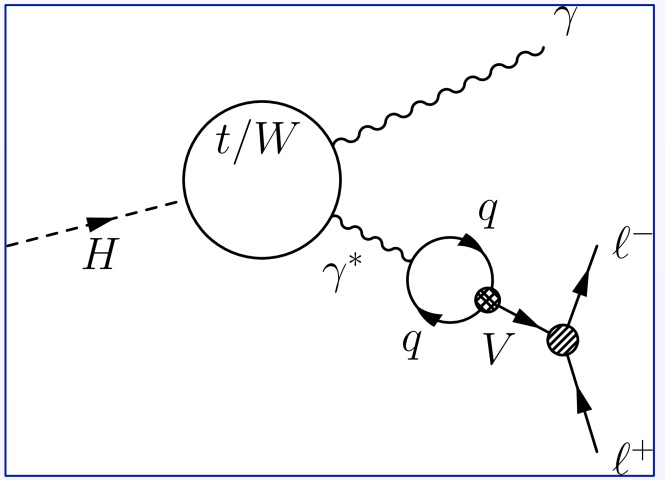


ATLAS (WW+ZZ+ττ)	**$\mu=2.1^{+1.4}_{-1.2}$**
ATLAS (bb)	μ=1.5±1.1
CMS (WW+ZZ+tt+bb+γγ)	μ=2.8±1.0

Rare decays



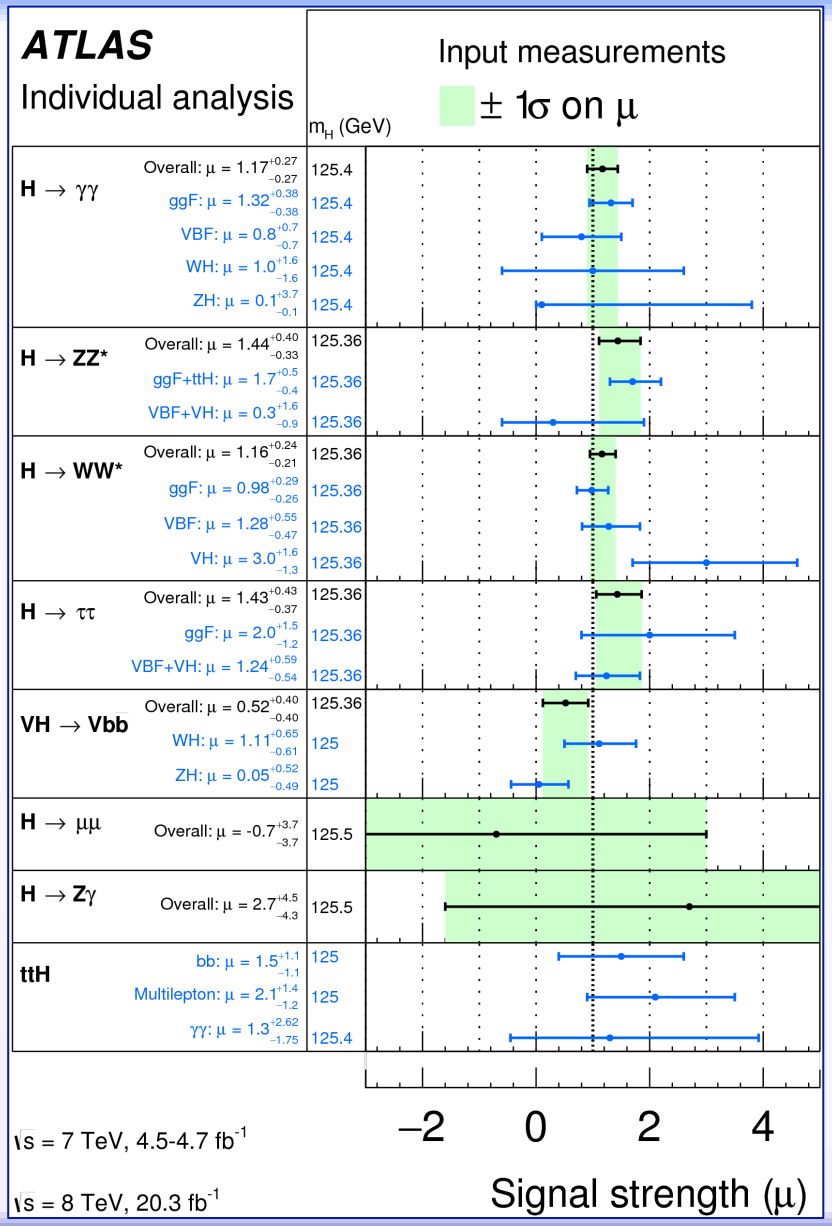
$(\sigma\times BR)/(\sigma\times BR)_{SM}$	ATLAS	CMS
$H\to Z\gamma$	<11 (9 exp.)	<9.5 (10 exp.)
$H\to\mu\mu$	<7.0 (7.2 exp.)	<7.4 (6.5 exp.)
$H\to ee^{(*)}$		$<3.7\times10^5$ (4.7×10^5 exp.)
$H\to\gamma^*\gamma\to\ell\ell\gamma$		<7.7 (6.4 exp.)
$H\to J/\psi\gamma^{(*)}$	<540 (430 exp.)	<540 (570 exp.)

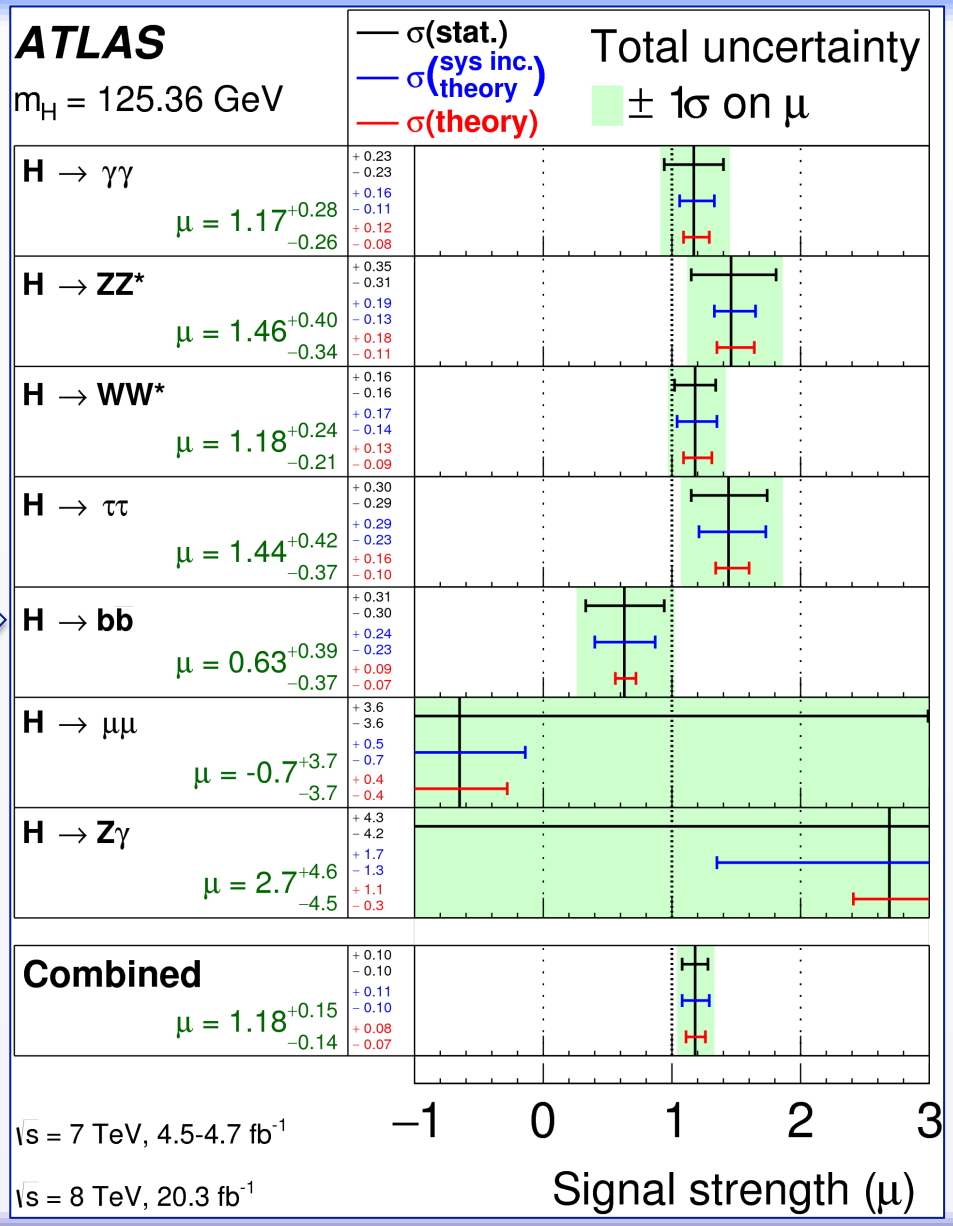


(*) *expected limits are my personal derivation from Phys. Lett. B744 184, Phys.Rev.Lett.114 121801, arXiv:1507.03031*

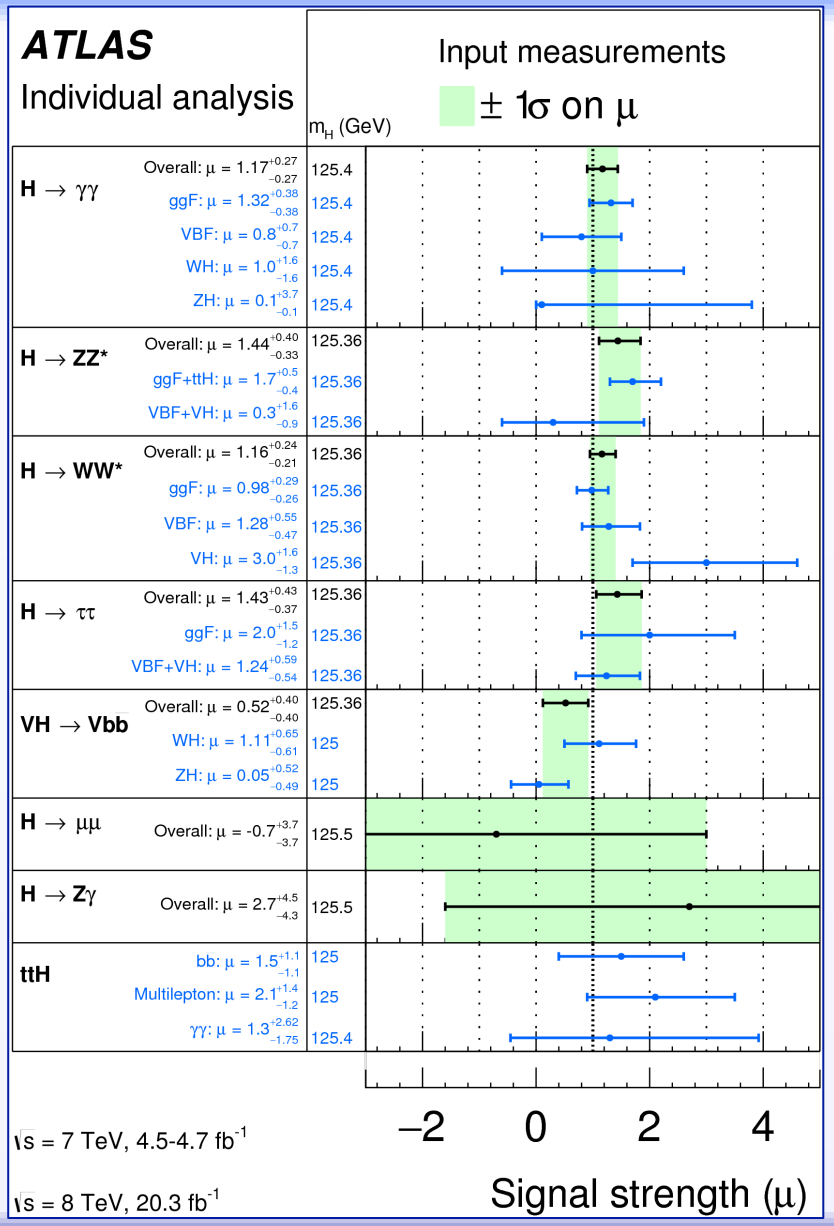
See H. Okawa's talk on Saturday

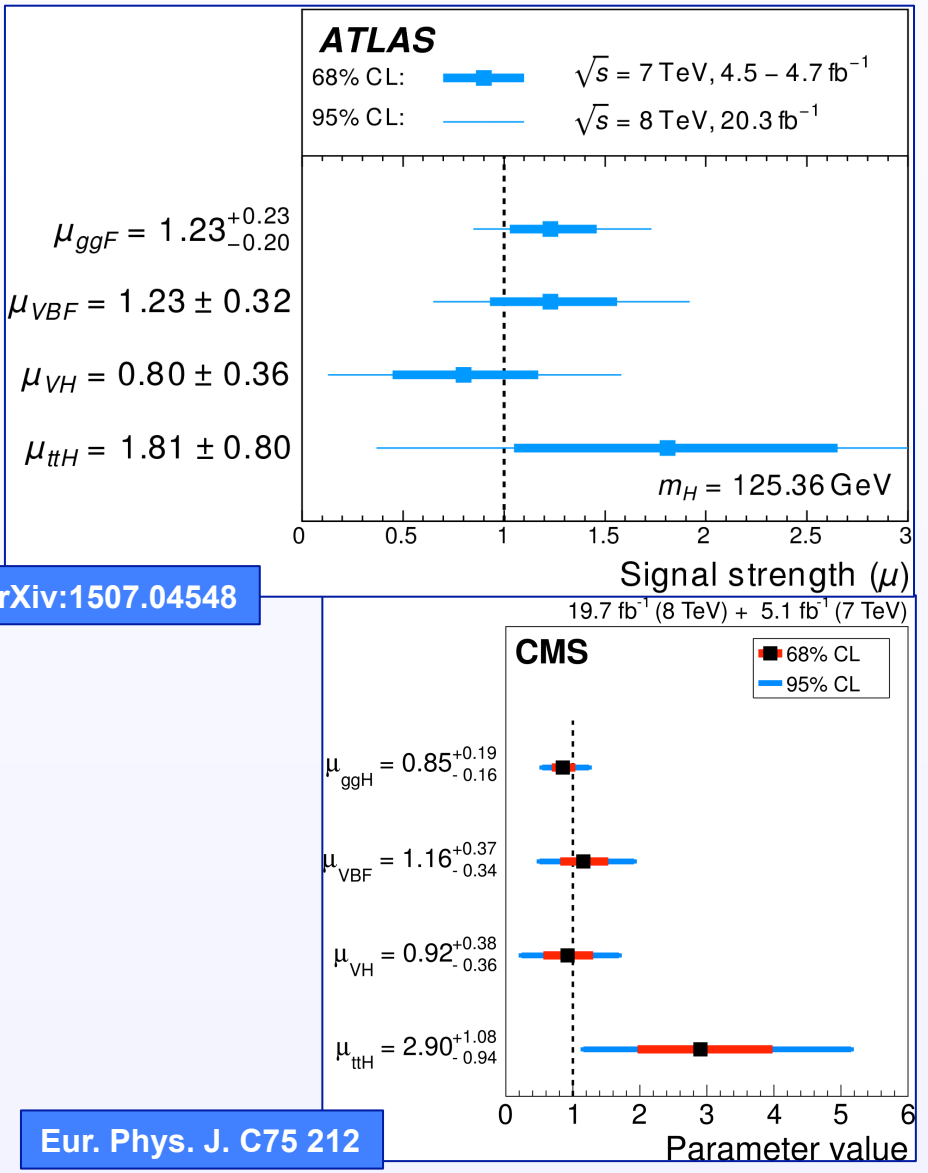
Combination: final states





Combination: production





Combination: production

Production process	Signal strength μ at $m_H = 125.36$ GeV			
	$\sqrt{s} = 8$ TeV		Combined $\sqrt{s} = 7$ and 8 TeV	
ggF	$1.23^{+0.25}_{-0.21}$	$^{+0.16\ +0.10\ +0.16}_{-0.16\ -0.08\ -0.11}$	$1.23^{+0.23}_{-0.20}$	$^{+0.14\ +0.09\ +0.16}_{-0.14\ -0.08\ -0.12}$
VBF	$1.55^{+0.39}_{-0.35}$	$^{+0.32\ +0.17\ +0.13}_{-0.31\ -0.13\ -0.11}$	1.23 ± 0.32	$^{+0.28\ +0.13\ +0.11}_{-0.27\ -0.12\ -0.09}$
VH	0.93 ± 0.39	$^{+0.37\ +0.20\ +0.12}_{-0.33\ -0.18\ -0.06}$	0.80 ± 0.36	$^{+0.31\ +0.17\ +0.10}_{-0.30\ -0.17\ -0.05}$
ttH	1.62 ± 0.78	$^{+0.51\ +0.58\ +0.28}_{-0.50\ -0.54\ -0.10}$	1.81 ± 0.80	$^{+0.52\ +0.58\ +0.31}_{-0.50\ -0.55\ -0.12}$

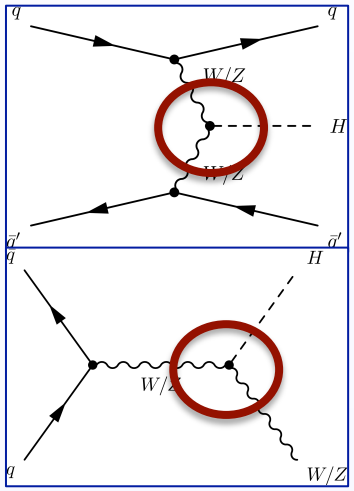
Stat. Syst. Theory

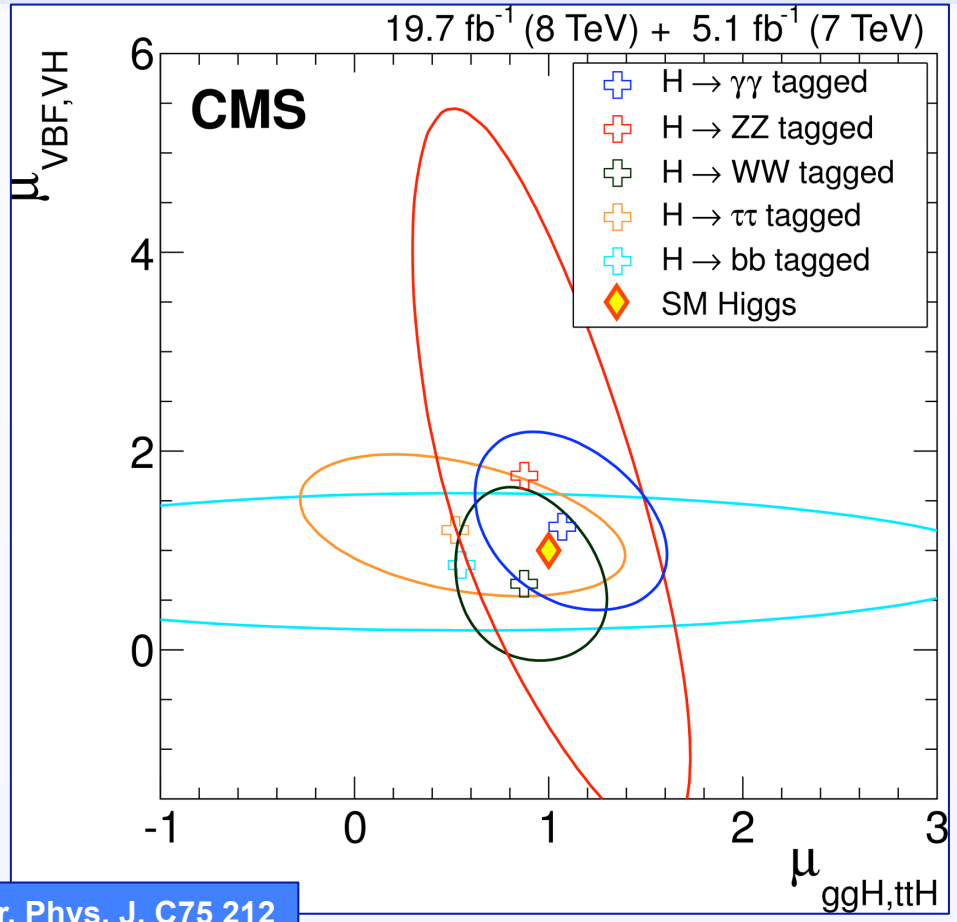
ATLAS: arXiv:1507.04548

Parameter	Best-fit result (68 % CL)			Significance (σ)		Pull to SM
	7 TeV	8 TeV	Combined	Observed	Expected	(σ)
μ_{ggH}	$1.03^{+0.37}_{-0.33}$	$0.79^{+0.19}_{-0.17}$	$0.85^{+0.19}_{-0.16}$	6.6	7.4	−0.8
μ_{VBF}	$1.77^{+0.99}_{-0.90}$	$1.02^{+0.39}_{-0.36}$	$1.16^{+0.37}_{-0.34}$	3.7	3.3	+0.4
μ_{VH}	<0.99	$0.96^{+0.41}_{-0.39}$	$0.92^{+0.38}_{-0.36}$	2.7	2.9	−0.2
μ_{ttH}	<2.19	$3.27^{+1.20}_{-1.04}$	$2.90^{+1.08}_{-0.94}$	3.5	1.2	+2.2

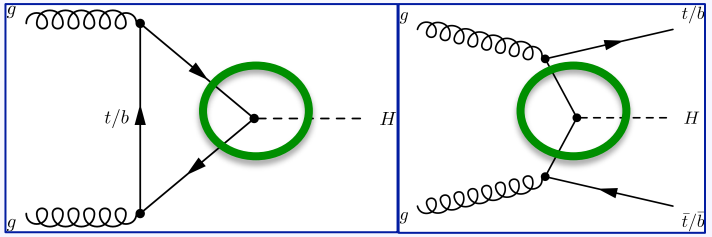
CMS: Eur. Phys. J. C75 212

$\mu_{VBF+VH}/\mu_{ggH+ttH}$





Eur. Phys. J. C75 212



$\mu_{VBF+VH}/\mu_{ggH+ttH}$: ATLAS $0.96^{+0.43}_{-0.31}$
CMS $1.25^{+0.62}_{-0.44}$

Coupling estimation

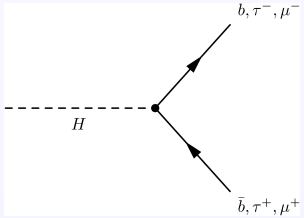
- Signal strength mix different elementary processed
- Direct comparison with SM based on elementary couplings
  - deviation from SM coded into **κ** factors [LHCHXS Report 3]

$$\sigma(i \to H \to f) = \frac{\sigma_i(\kappa_j)\Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}$$

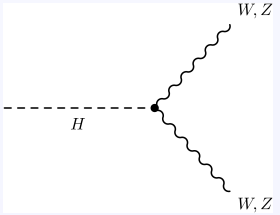
$$\sigma_i = \kappa_i^2 \sigma_i^{SM} \qquad \Gamma_f = \kappa_f^2 \Gamma_f^{SM} \qquad \Gamma_H = \frac{\kappa_H^2(\kappa_j)}{1 - BR_{i.,u.}} \Gamma_H^{SM}$$

invisible/undetected BR

  - At the level of the Feynman vertices:



$$\kappa_f \frac{m_f}{v}$$

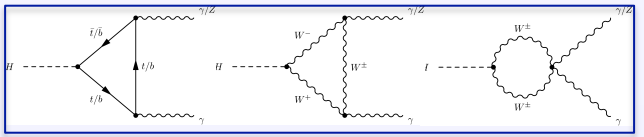


$$\kappa_Z \frac{m_Z^2}{v}, \kappa_W \frac{m_W^2}{v}$$

  - Composite:

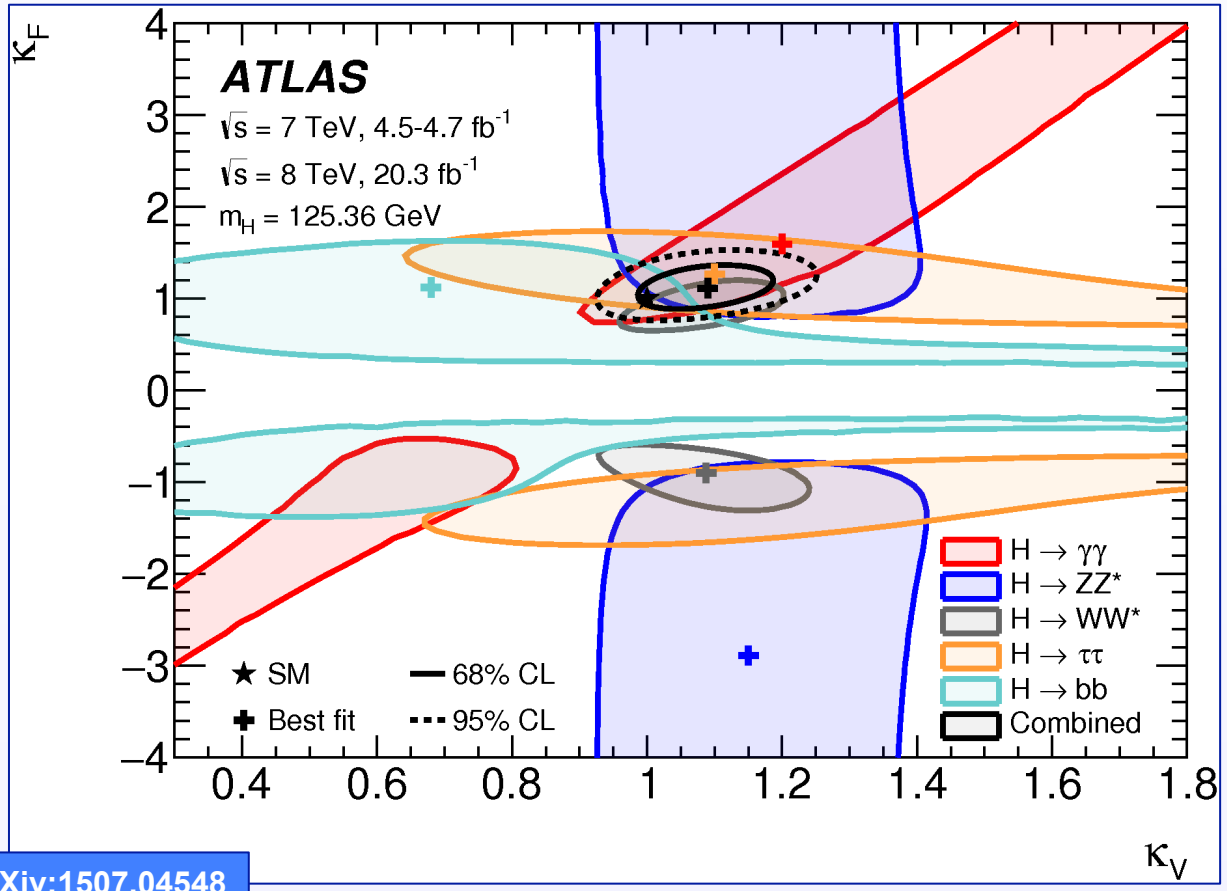
$$\kappa_\gamma^2 = 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t, \quad \kappa_H^2(\kappa_Z, \kappa_W, \kappa_t, \kappa_b, \kappa_g \ldots)$$

$$\kappa_g^2 = 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_b \kappa_t$$



Vector vs. Fermion couplings

- Simplified model: common parameter for *HVV* and *Hff* vertices.
- Similar to $\mu_{VBF+VH}/\mu_{ggH+ttH}$, but accounts for *b-t* and *V-t* interferences.



arXiv:1507.04548

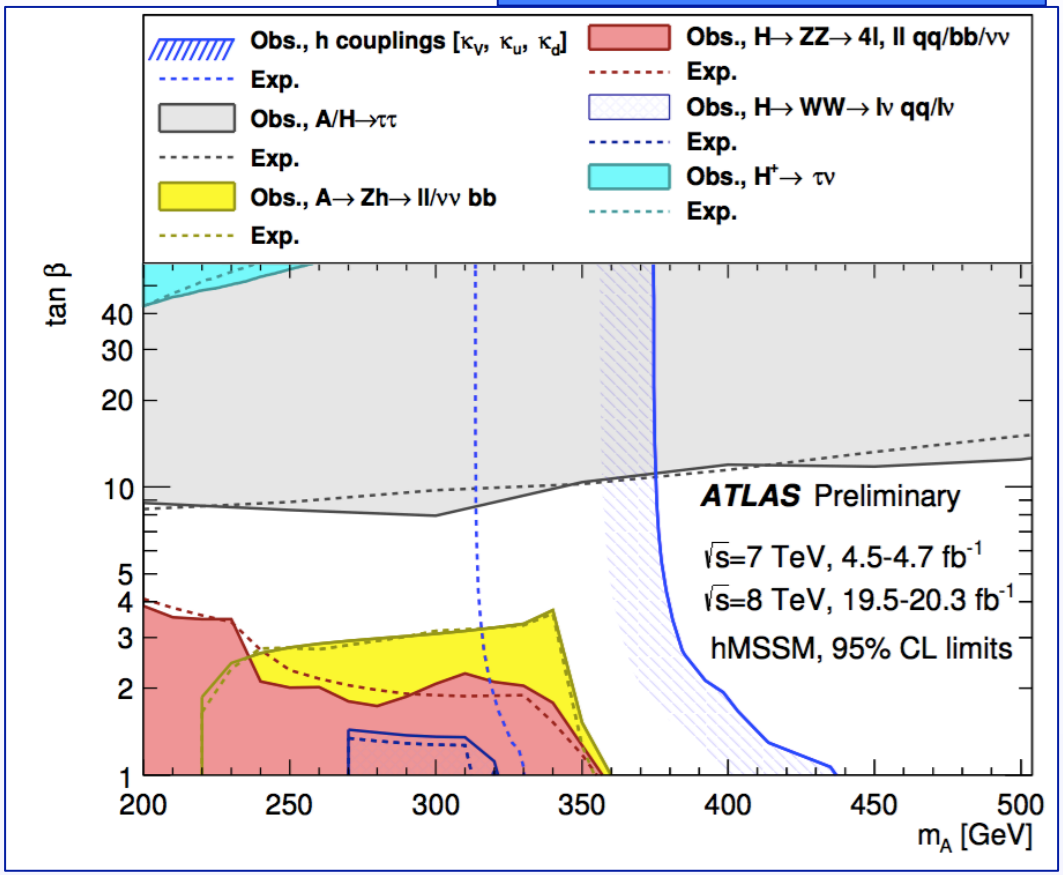
Fermion couplings

- Difference in strength in fermion couplings are expected in two Higgs doublets models
- Fit κ_V and two fermions couplings.

κ_d/κ_u:	**ATLAS**	**$[-1.08,-0.81] \cup [0.75,1.04]$**
	CMS	**$0.99^{+0.19}_{-0.18}$**
κ_ℓ/κ_q:	**ATLAS**	**$[-1.34,-0.94] \cup [0.94,1.34]$**
	CMS	**$1.03^{+0.23}_{-0.21}$**

- Results can be interpreted as constraints on BSM models.

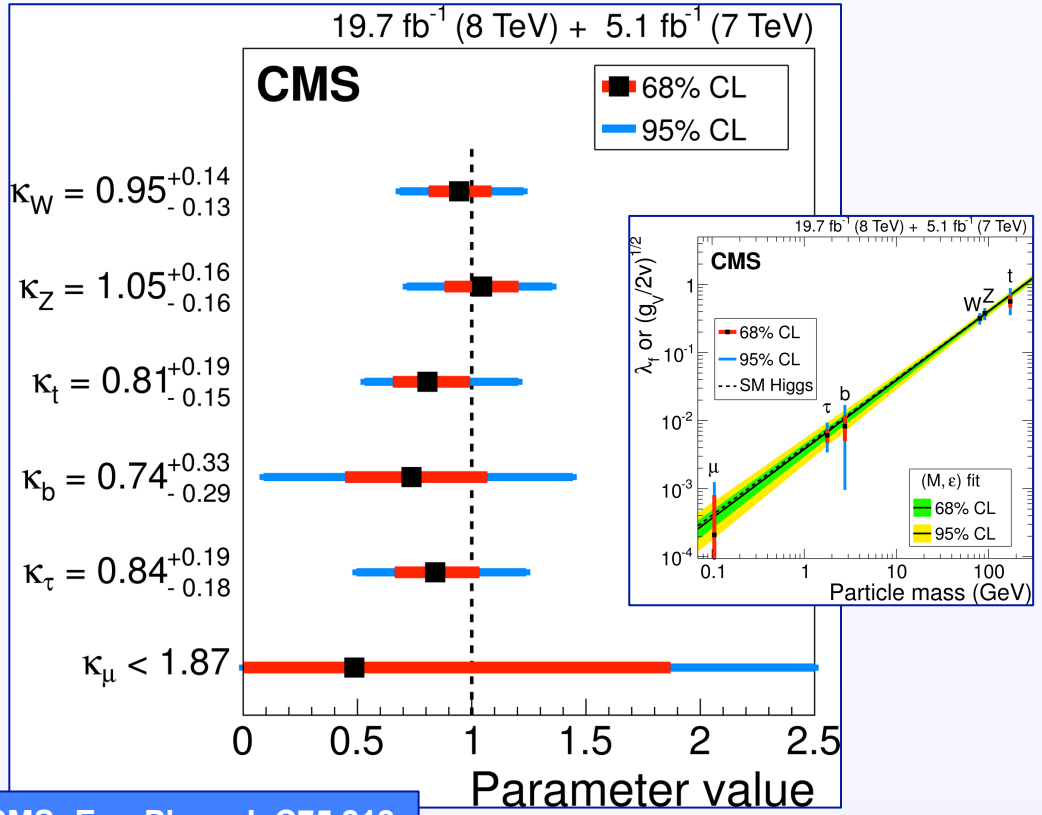
Update of ALTAS-CONF-2014-010



For example see L. Brenner this afternoon

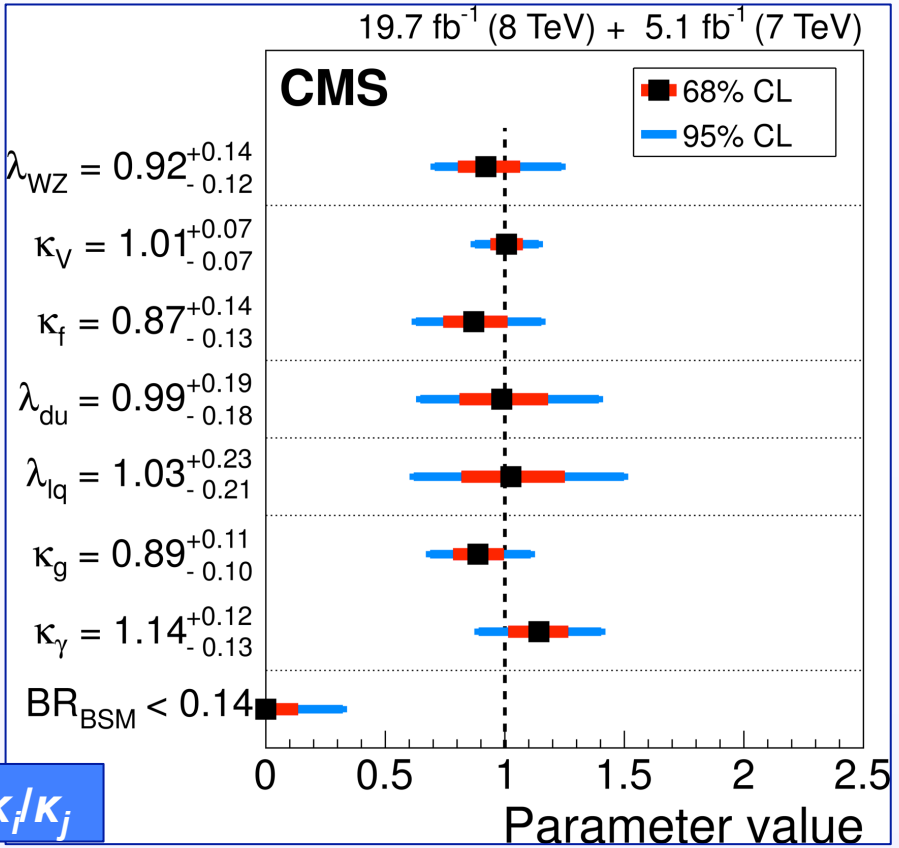
General models

- Standard Model
  - all couplings in SM lagrangian



CMS: Eur. Phys. J. C75 212

- BSM searches
  - contributions to loops, κ_g, κ_γ
  - exotics decay channels Γ_{BSM}



$\lambda_{ij}=\kappa_i/\kappa_j$

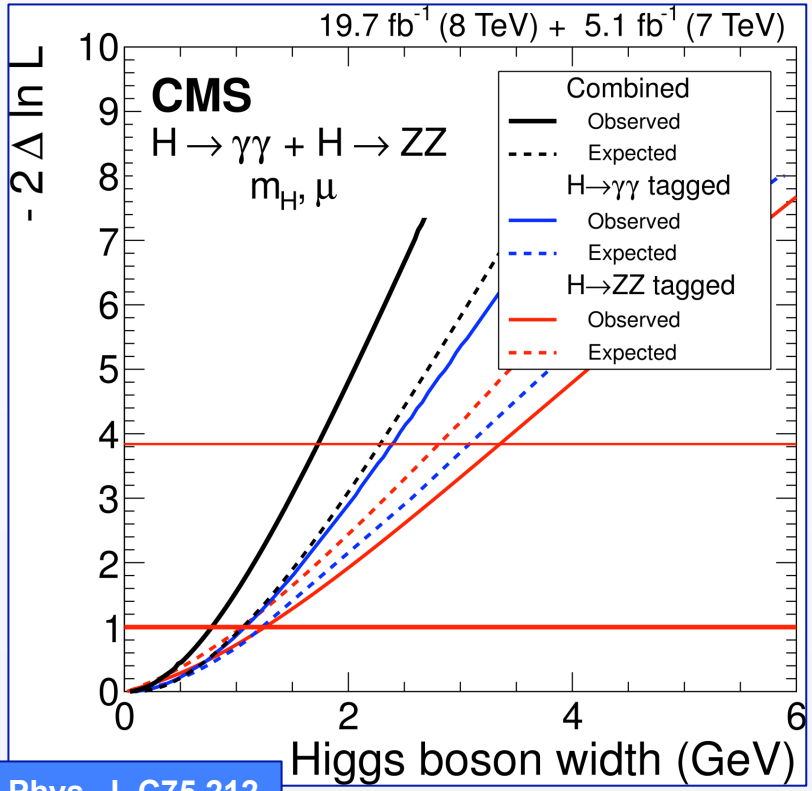
For more details on couplings see M. Moreno Llacer's talk this afternoon

Width

- SM width for m_H=125.1 GeV is Γ_H=4.1 MeV
- Width measurements:
  - discriminate one vs. multiple resonances
  - additional BSM contributions (invisible decay channels)
- Direct limits
  - compatibility of mass peak with detector resolution

Γ_H limits at 95% CL:

ATLAS γγ:	**<5.0 GeV (6.2 exp.)**
ATLAS ZZ:	**<2.6 GeV (6.2 exp.)**
CMS γγ+ZZ:	**<1.7 GeV (2.3 exp.)**



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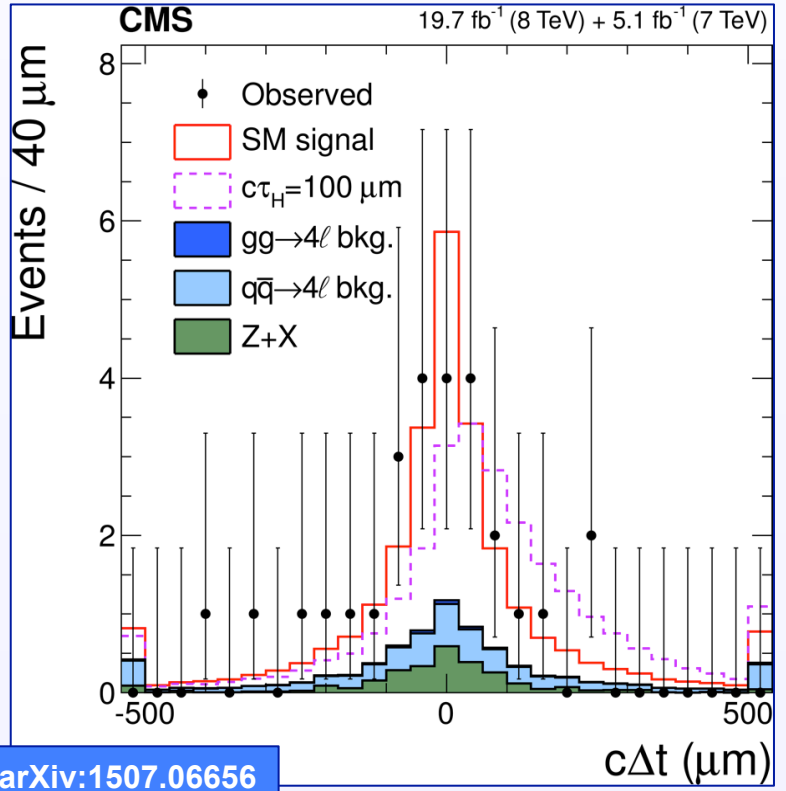
Width

- SM width for m_H=125.1 GeV is Γ_H=4.1 MeV
- Width measurements:
  - discriminate one vs. multiple resonances
  - additional BSM contributions (including invisible decay channels)
- Direct limits
  - compatibility of mass peak with detector resolution

Γ_H limits at 95% CL:
ATLAS γγ: <5.0 GeV (6.2 exp.)
ATLAS ZZ: <2.6 GeV (6.2 exp.)
CMS γγ+ZZ: <1.7 GeV (2.3 exp.)

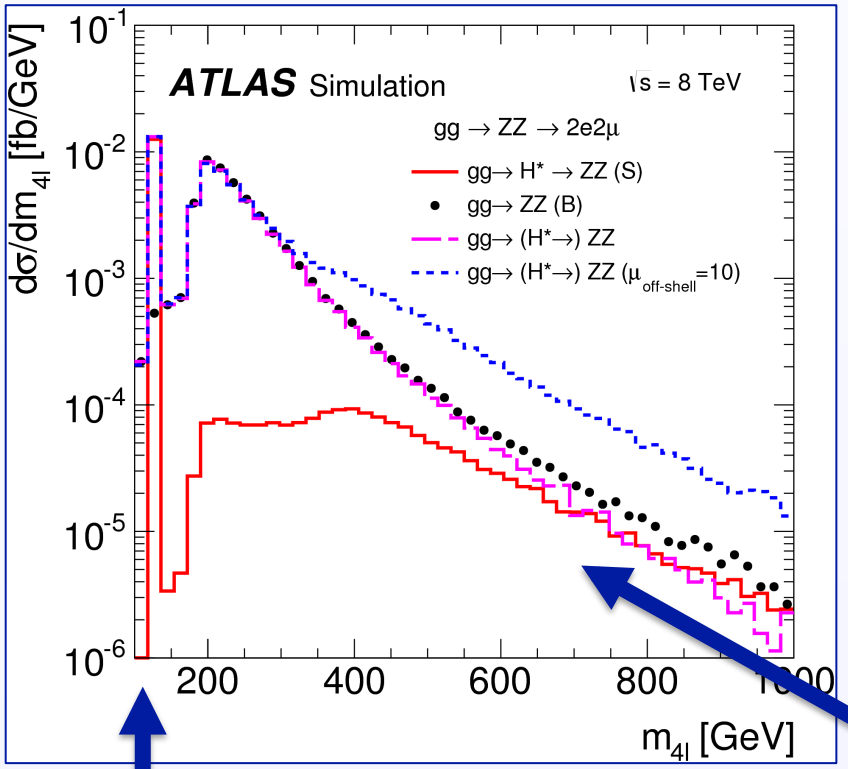
  - flight distance measurement

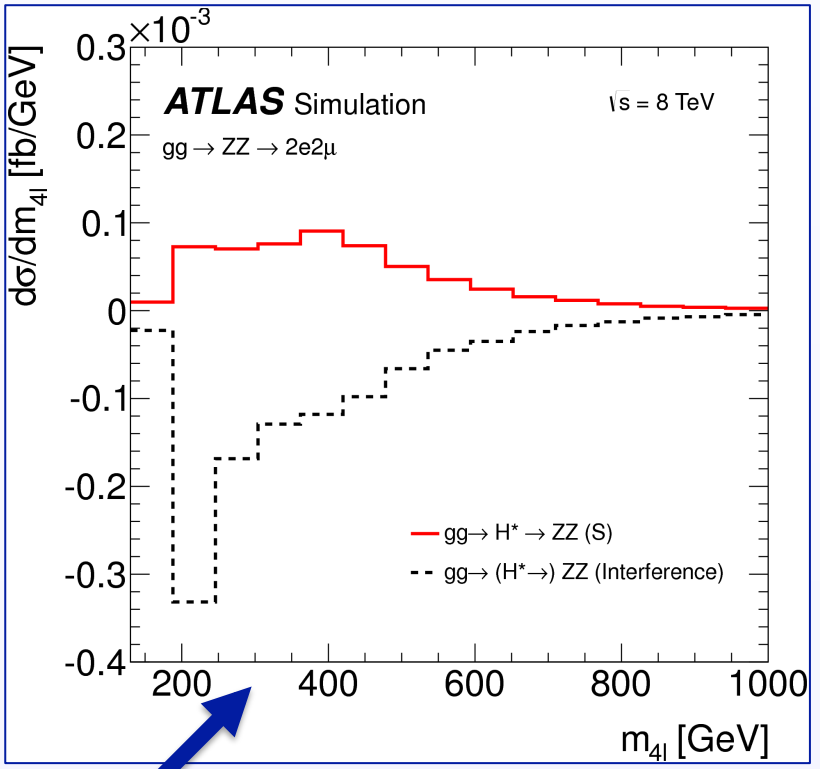
Γ_H limits at 95% CL:
CMS ZZ: >3.9×10^{-9} MeV



Width: off shell coupling

- Interplay between $gg \to H^* \to VV$ and other di-boson production mechanisms.





$$\sigma_{\text{on-shell}}\left(gg \to H \to VV\right) \propto \frac{\kappa^2_{g,\text{on-shell}}\kappa^2_{V,\text{on-shell}}}{\Gamma_H / \Gamma_{H,\text{SM}}}$$

$$\sigma_{\text{off-shell}}\left(gg \to H^* \to VV\right) \propto \kappa^2_{g,\text{off-shell}}\kappa^2_{V,\text{off-shell}}$$

Width: off shell coupling

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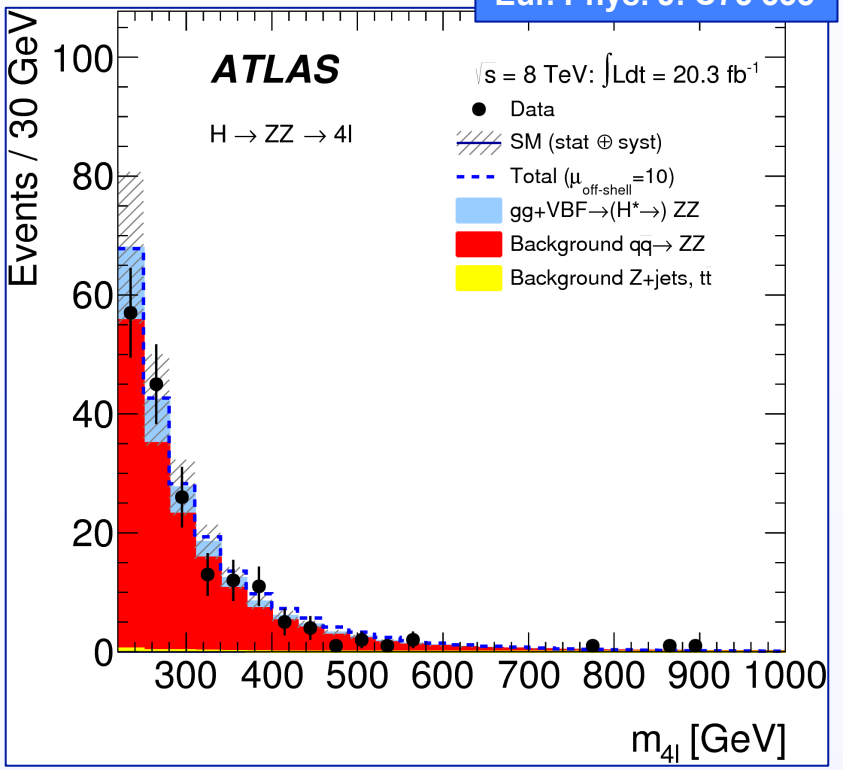
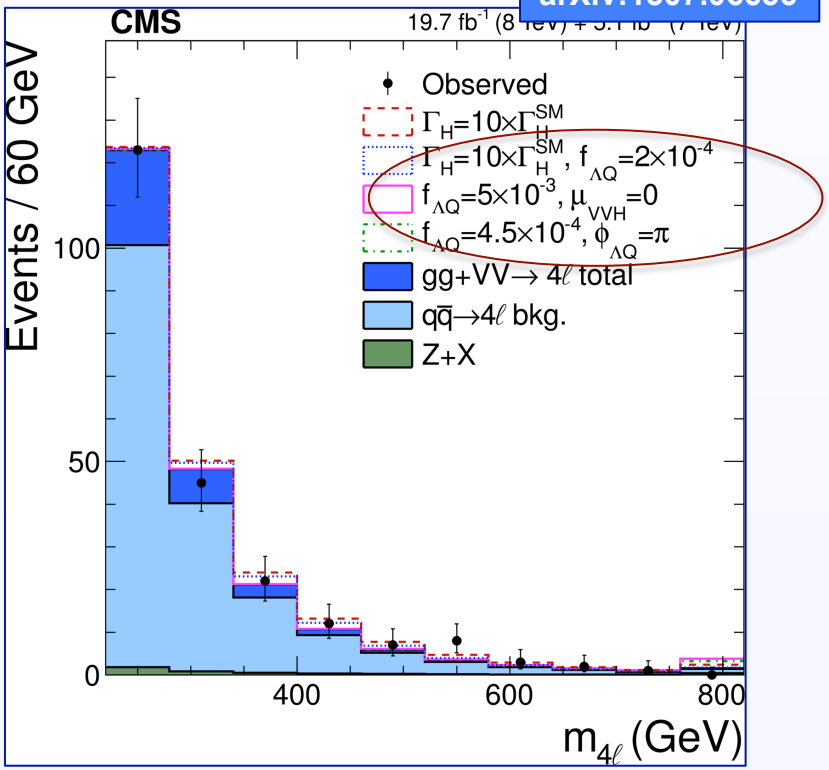


arXiv:1507.06656



- Upper limits at 95% CL, assuming $\kappa_{\text{on-shell}} = \kappa_{\text{off-shell}}$:

ATLAS (ZZ+WW): Γ_H <23 MeV (33 MeV)
CMS (ZZ): Γ_H <22 MeV (33 MeV)

- Alternative interpretations: limits on **anomalous couplings**

$$f_{\Lambda Q} = \frac{m_H^4/\Lambda_Q^4}{|a_1|^2 + m_H^4/\Lambda_Q^4}$$

$$A(\text{HVV}) \propto \left[a_1 - e^{i\phi_{\Lambda Q}} \frac{(q_{V1}+q_{V2})^2}{(\Lambda_Q)^2} - e^{i\phi_{\Lambda 1}} \frac{(q_{V1}^2+q_{V2}^2)}{(\Lambda_1)^2} \right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^*$$

Spin and P determination

H^0 $J = 0$

Mass $m = 125.7 \pm 0.4$ GeV

H^0 Signal Strengths in Different Channels

Combined Final States $= 1.17 \pm 0.17$ (S = 1.2)

$WW^* = 0.87^{+0.24}_{-0.22}$

$ZZ^* = 1.11^{+0.34}_{-0.28}$ (S = 1.3)

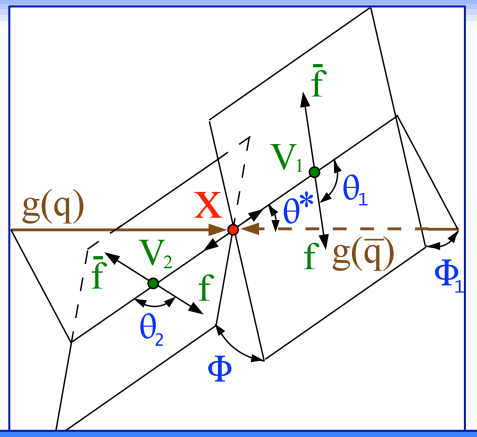
$\gamma\gamma = 1.58^{+0.27}_{-0.23}$

$b\bar{b} = 1.1 \pm 0.5$

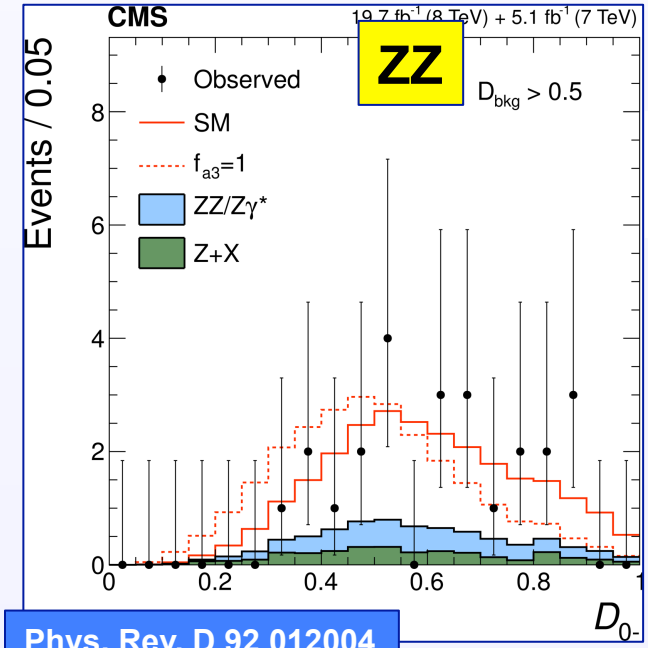
$\tau^+\tau^- = 0.4 \pm 0.6$

$Z\gamma < 9.5$, CL = 95%

- Kinematic variables in the final state sensitive to spin/parity of the decaying particle.
- Test alternative hypotheses against SM 0^+ hypothesis.



ZZ, full final state kinematics



Phys. Rev. D 92 012004

pdf for discriminator variable

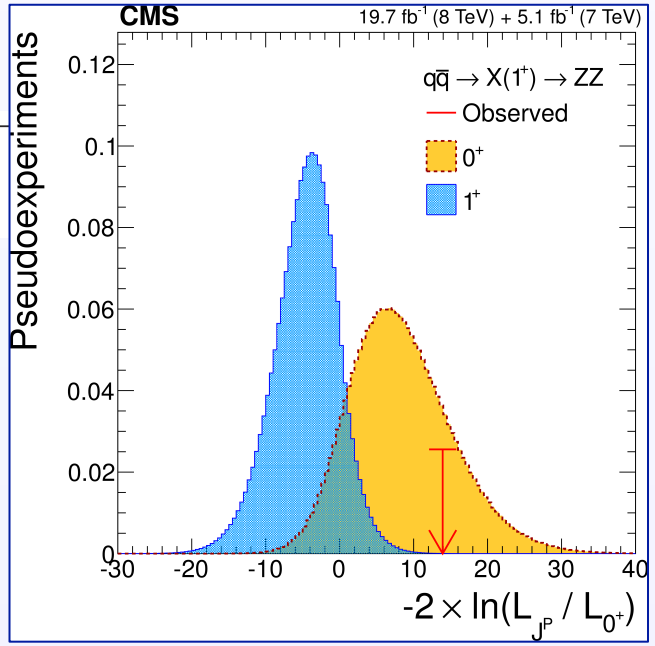
$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{\mathrm{SM}}}{\mathcal{P}_{\mathrm{SM}} + \mathcal{P}_{J^P}} = \left[1 + \frac{\mathcal{P}^{\mathrm{kin}}_{J^P}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}^{\mathrm{kin}}_{\mathrm{SM}}(m_1, m_2, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

Hypothesis estimator:

$$q = -2\ln\left(L_{J^P} / L_{0^+}\right)$$

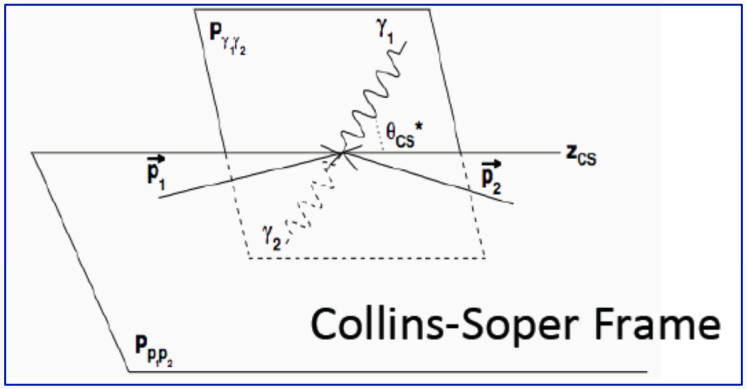
$$p = P\left(q < q_{\mathrm{obs}} \,|\, 0^+ + \mathrm{bkg}\right)$$

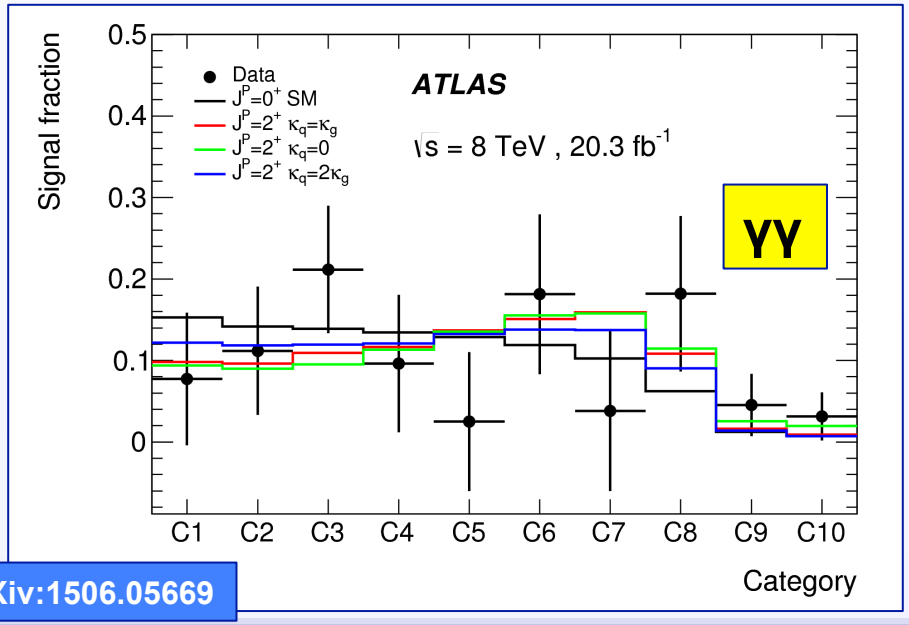
Determination of final *p* value



Spin and P determination

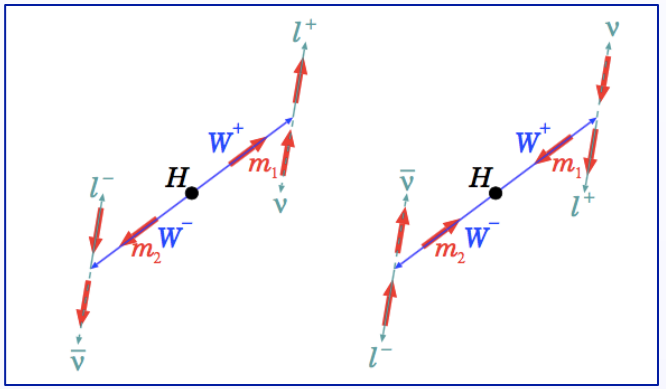
γγ, use $\cos\theta^*_{CS}$

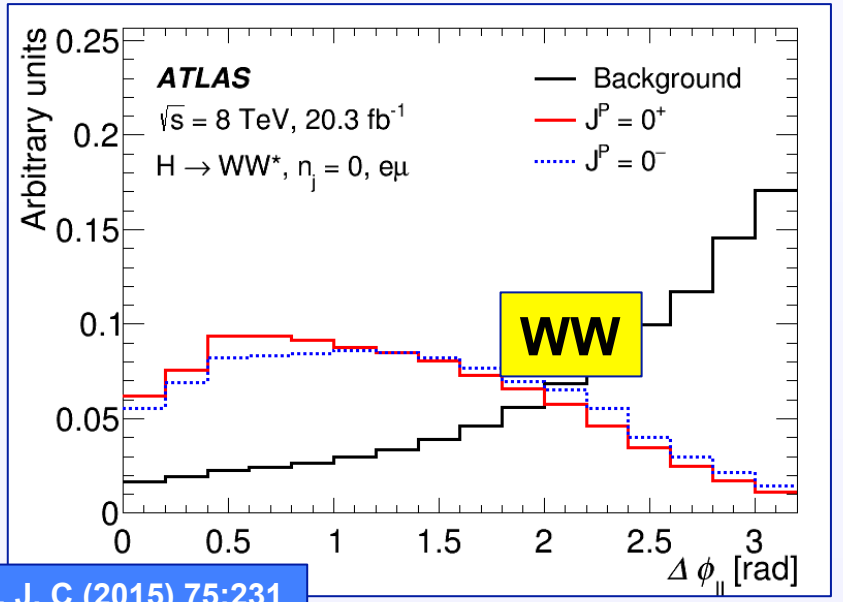




arXiv:1506.05669

WW, Correlation between final state leptons





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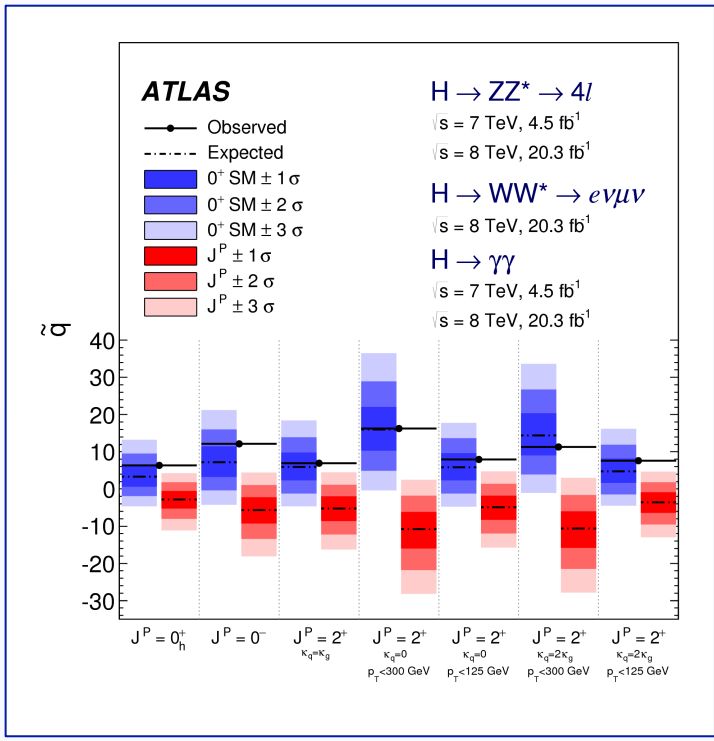
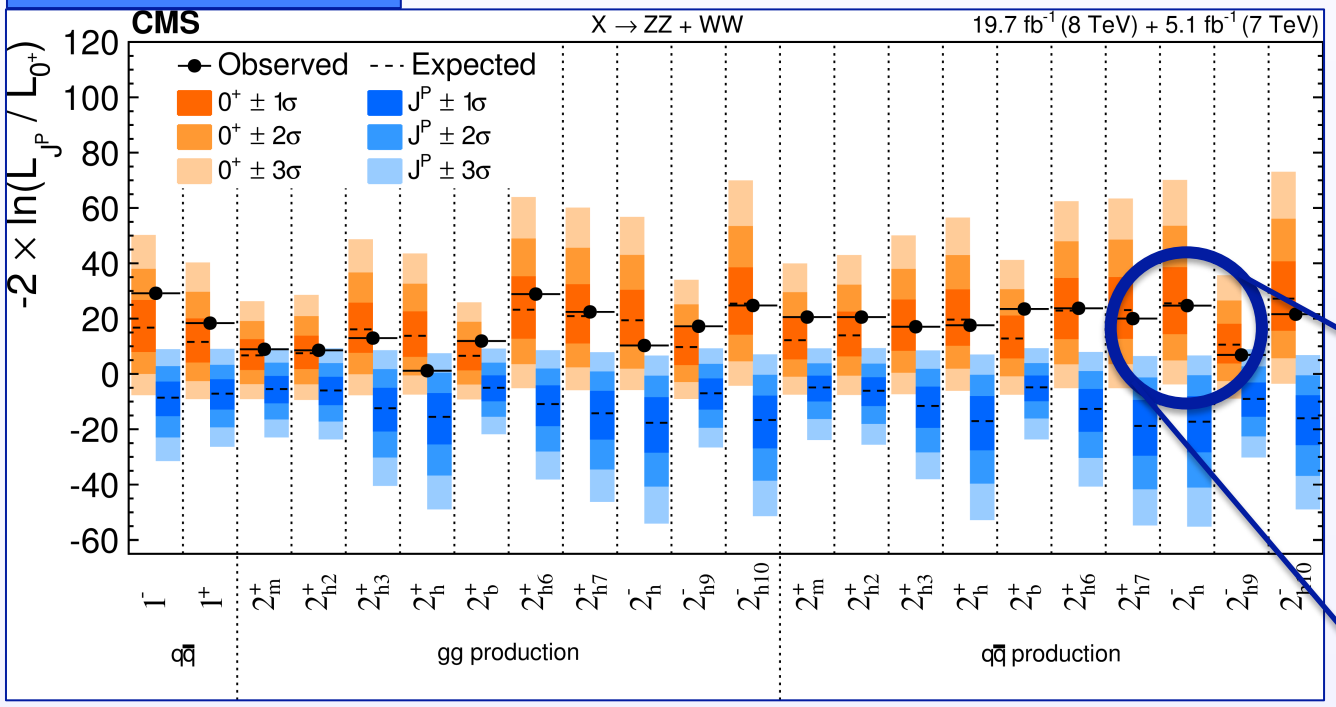
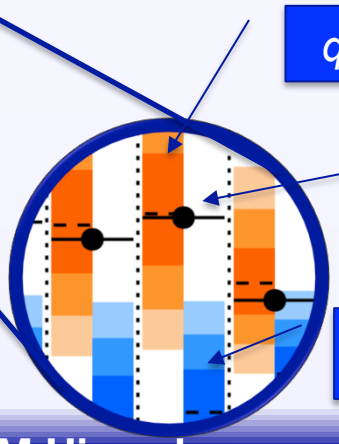
Spin and P determination

- Many tested models: different spin (0,1,2) parity (+,-), Lorentz structure, production process...
- **0^+ with SM coupling** structure almost always preferred to alternative hypotheses.



Phys. Rev. D 92 012004





q distribution for 0^+

q observed

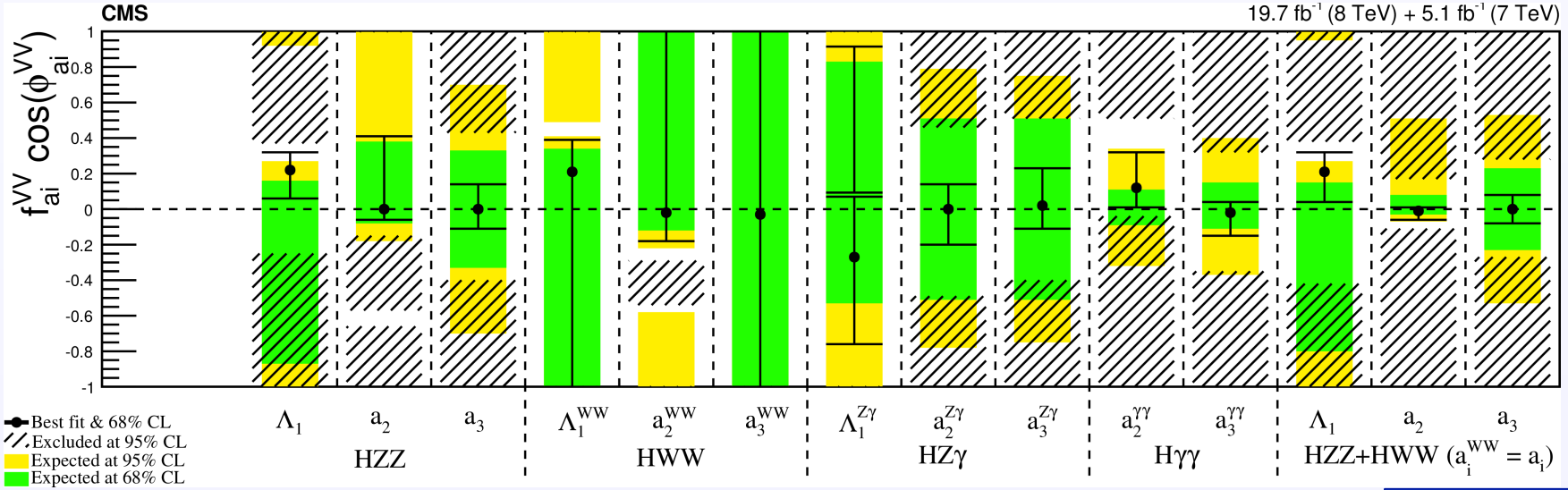
q distribution alternative model

Spin and P determination

- State completely different from SM 0^+ excluded.
- Now look for anomalous couplings giving mixed states.

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{(\Lambda_1^{\mathrm{VV}})^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

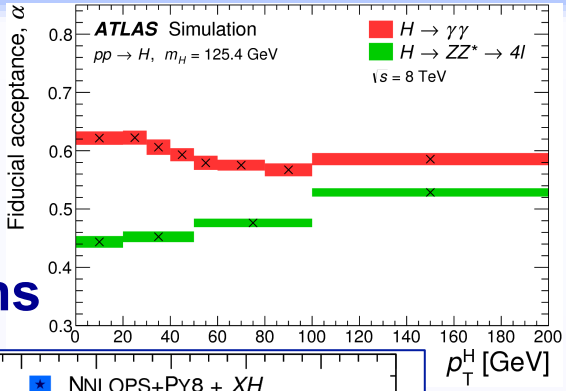
SM — BSM CP-even — BSM CP-odd

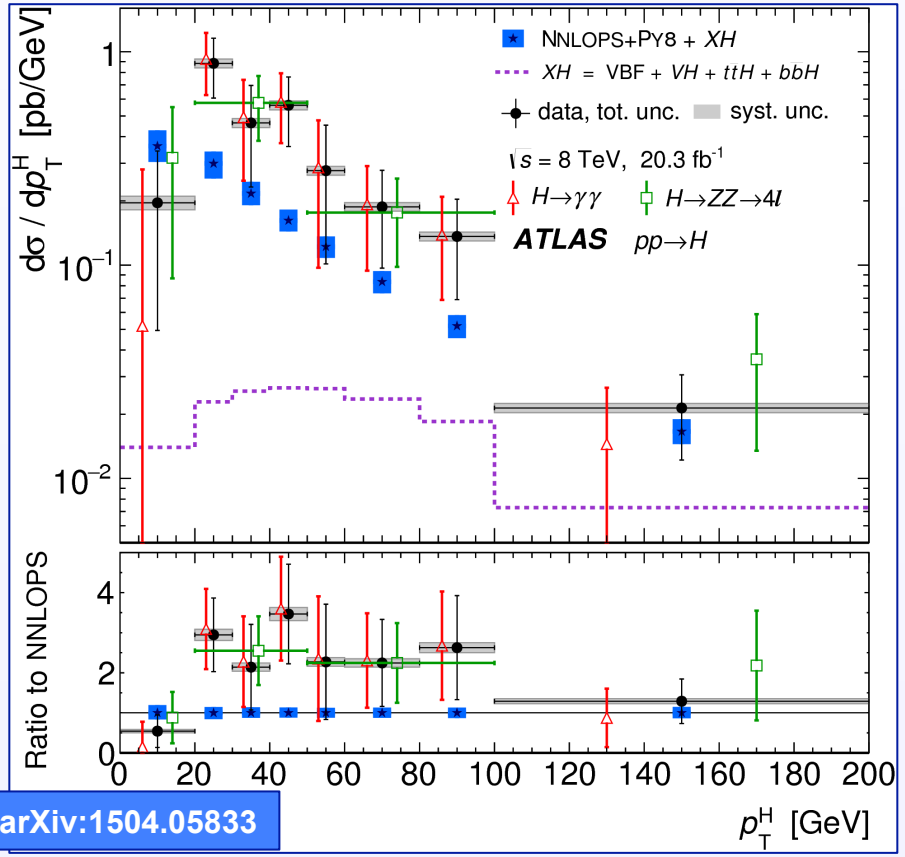


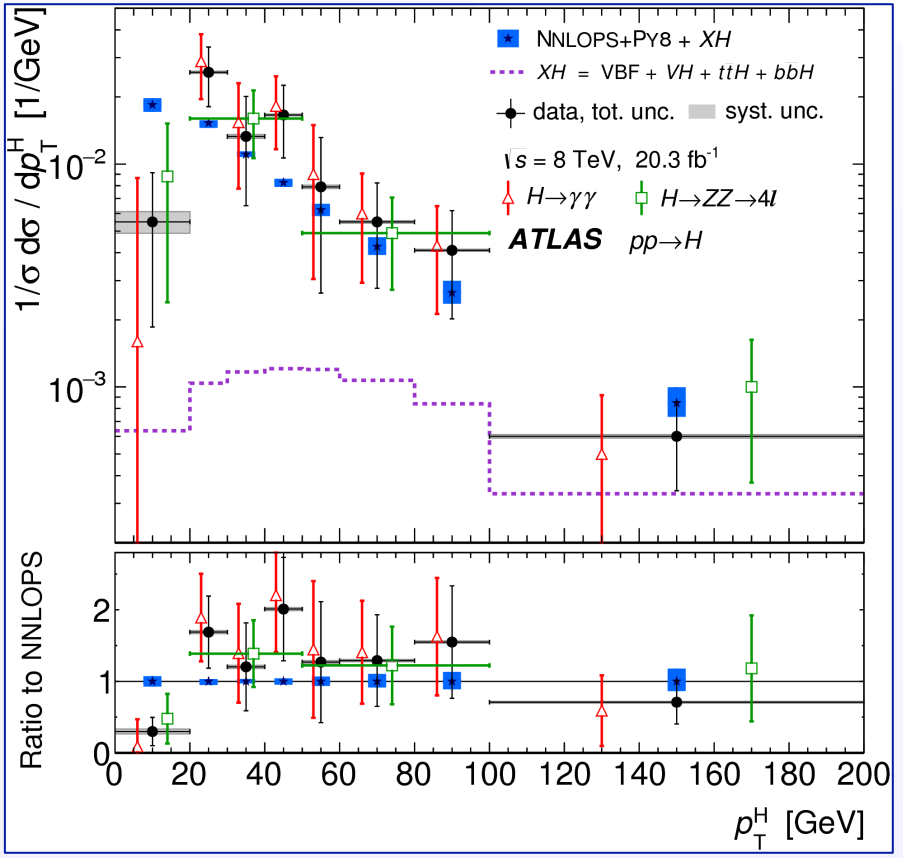
Phys. Rev. D 92 012004

Differential distributions

- Moving beyond relative SM comparisons:
  - Event yield
    × Acceptance correction
  - **Differential cross sections** and **Shape distributions**





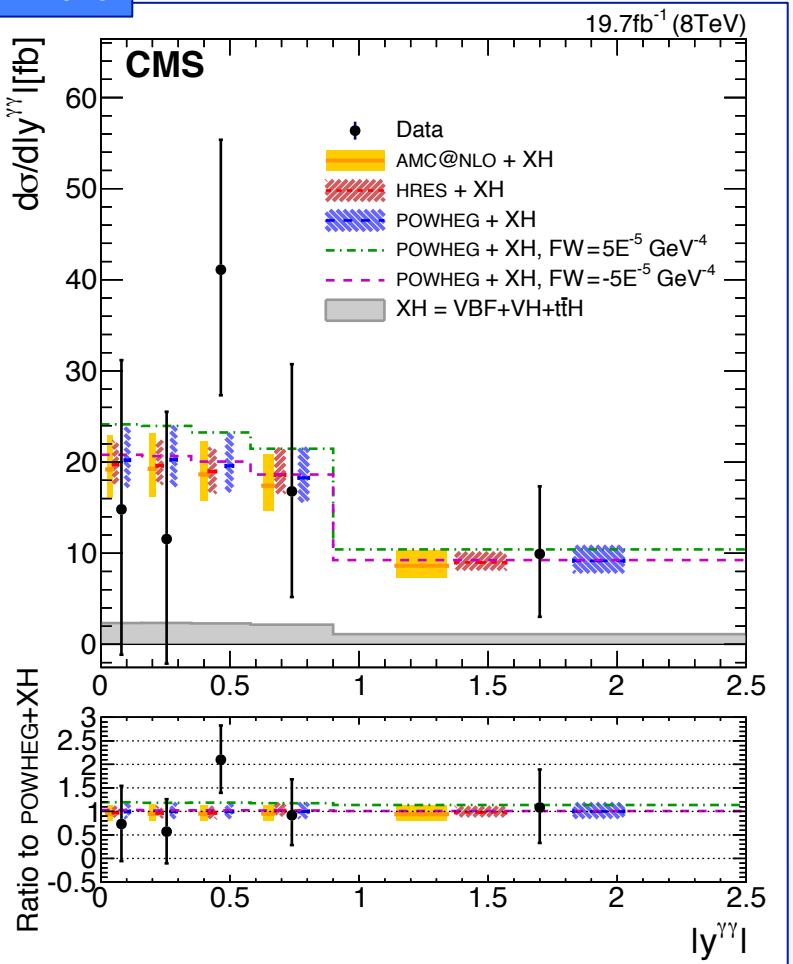


arXiv:1504.05833

Differential distributions

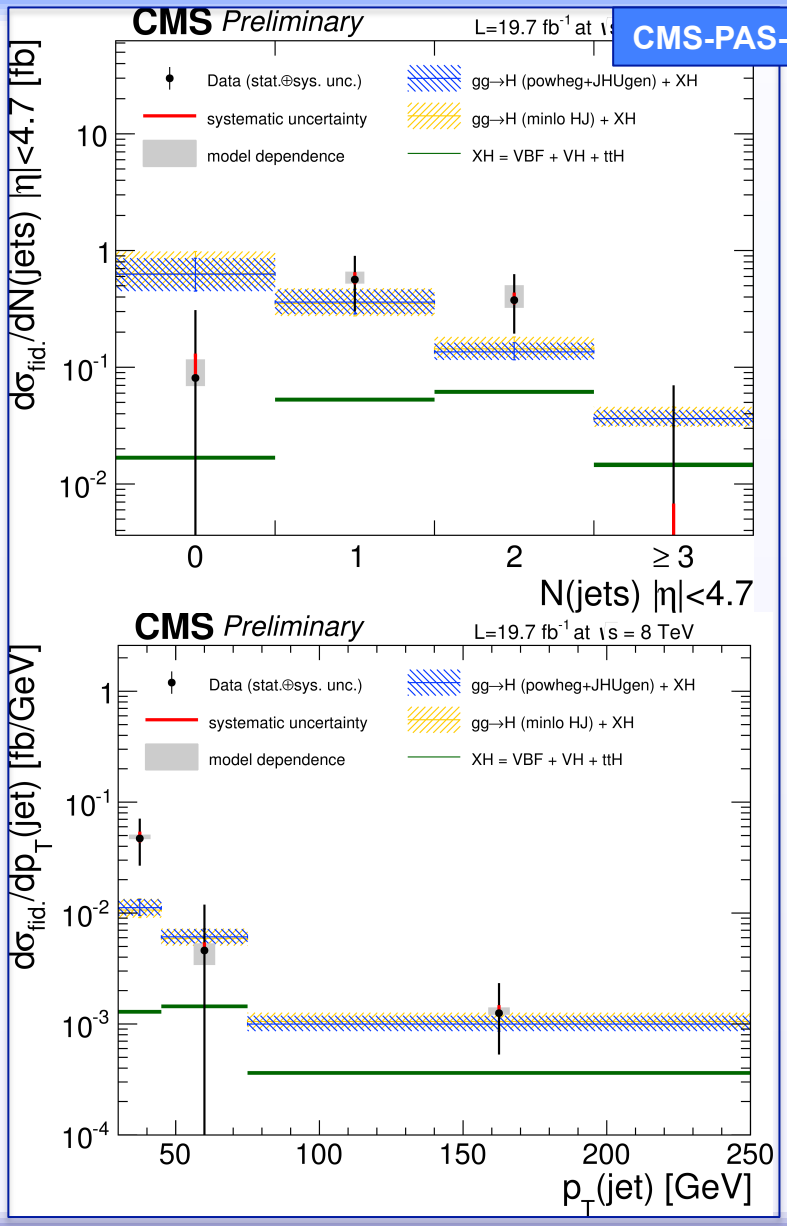
Higgs production properties

HIG-14-016



Jet production

CMS-PAS-HIG-14-028

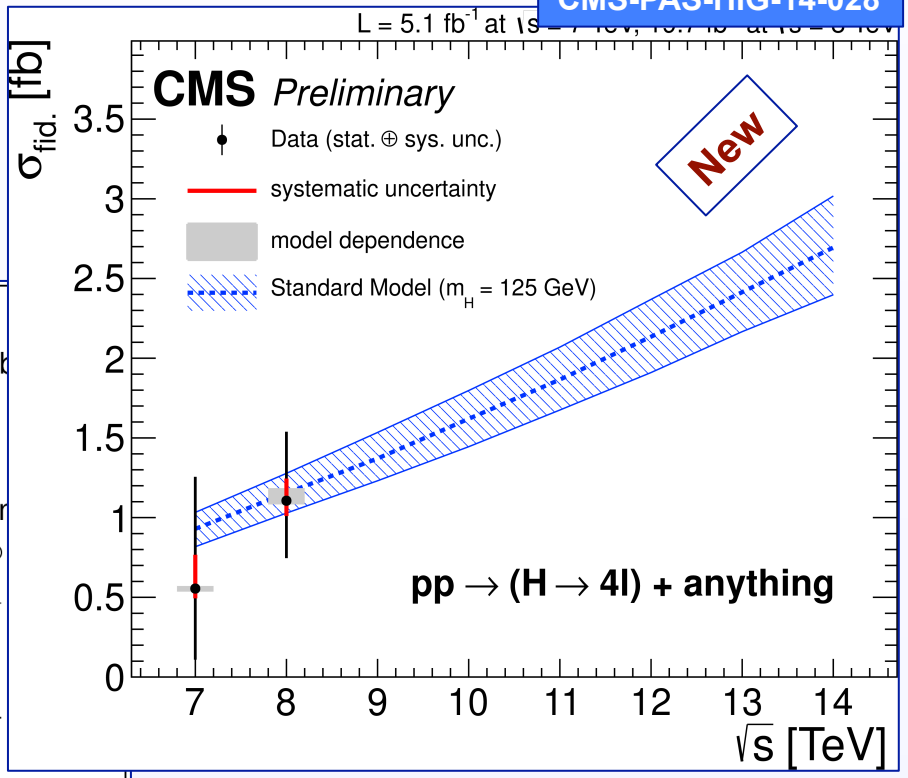


Cross-sections

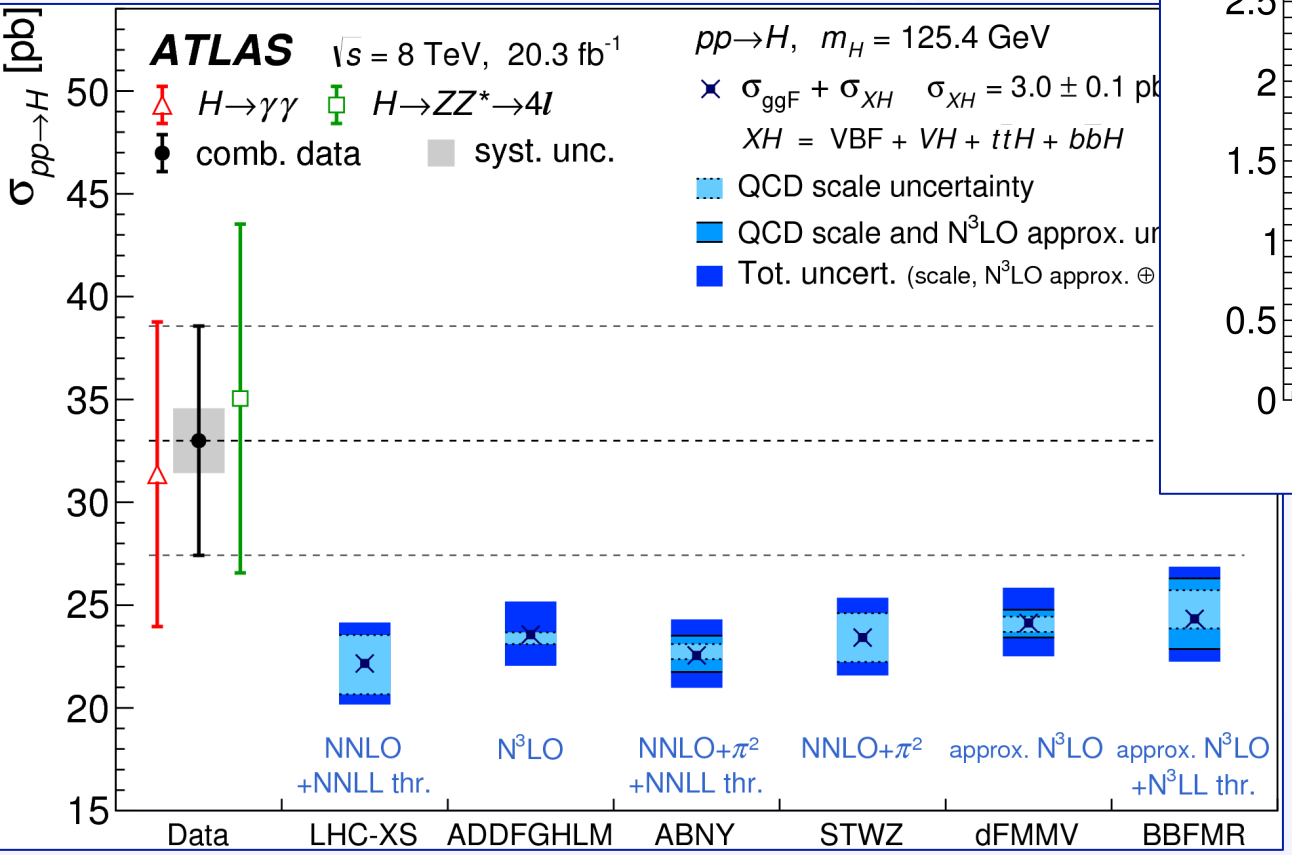
Fiducial cross section →

Total cross section ↓

CMS-PAS-HIG-14-028



arXiv:1504.05833



Summary

H^0

$J = 0$

$J^P = 0^+$

But mixed states are under investigation

Mass $m = 125.7 \pm 0.4$ GeV

m = 125.09 ± 0.24 GeV

H^0 Signal Strengths in Different Channels

Combined Final States $= 1.17 \pm 0.17$

$WW^* = 0.87^{+0.24}_{-0.22}$

$ZZ^* = 1.11^{+0.34}_{-0.28}$ $(S = 1.3)$

$\gamma\gamma = 1.58^{+0.27}_{-0.23}$

$b\bar{b} = 1.1 \pm 0.5$

$\tau^+\tau^- = 0.4 \pm 0.6$

$Z\gamma < 9.5$, CL = 95%

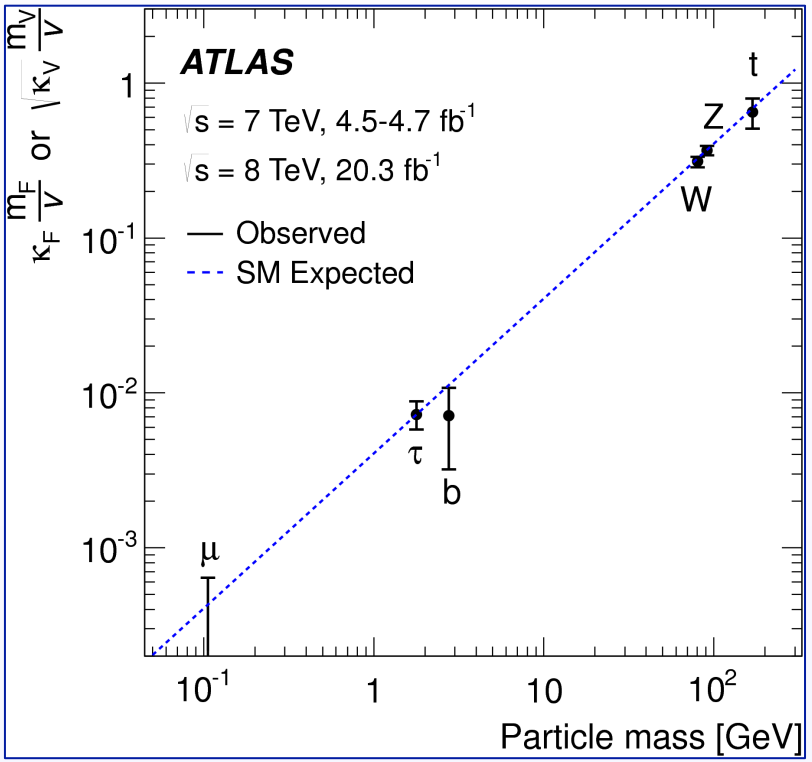
ATLAS	CMS
1.18±0.15	1.00±0.14
1.18±0.23	0.82±0.21
1.46±0.36	1.00±0.29
1.17±0.27	1.12±0.24
0.63±0.38	0.84±0.44
1.44±0.40	0.91±0.28
<11	<9.5

ATLAS+CMS combination coming soon!

+ more rare decay, width measurement, anomalous couplings...

Summary

- At the beginning of LHC Run-2 the 125 GeV Higgs boson properties appear well established:
  - only major decay mode missing evidence is *bb*
  - most production processes investigated
  - couplings consistent with SM expectation
  - $J^P=0^+$ favourite against alternative J^P eigenstates (still room for mixed states)



Is it another Standard Model triumph?

- Approach is already shifting towards Higgs as probe for BSM physics:
  - Precision EW measurements (deviations from SM couplings)
  - Flavour physics (rare or forbidden decays)

Outlook

- In the next years LHC Run-2 will provide:
  - 100 fb^{-1} integrated luminosity
  - at higher centre-of-mass energy
  - ~10 times Run-1 statistics
    - ~20 for ttH
- Potential highlights:
  - establishment of bb and ττ channels
  - detailed investigation of ttH process
  - precision tests on couplings and Lorentz structure

σ [pb]	√s=8 TeV	√s=13 TeV
ggH	19.2	43.9
VBF	1.58	3.77
WH	0.703	1.38
ZH	0.414	8.868
ttH(*)	**0.129**	**0.507**
bbH(*)	0.203	0.511

Plenty of room for new results, new ideas ...and, maybe, surprises!

Beyond run-2, see A. Perieanu's talk on Thursday

Only summary and some most recent papers

BIBLIOGRAPHY

Mass, Spin and Parity

- **Mass**
  - **Combined Measurement of the Higgs Boson Mass in *pp* Collisions at $s\sqrt{}$=7 and 8 TeV with the ATLAS and CMS Experiments**
    Phys. Rev. Lett. 114, 191803

- **Spin determination**
  - **Study of the spin and parity of the Higgs boson in diboson decays with the ATLAS detector**
    arXiv:1506.05669
  - **Determination of spin and parity of the Higgs boson in the WW* →evμv decay channel with the ATLAS detector**
    Eur. Phys. J. C (2015) 75:231
  - **Constraints on the spin-parity and anomalous *HVV* couplings of the Higgs boson in proton collisions at 7 and 8 TeV**
    PhysRev D 92 012004

Couplings

- **Couplings**
  - **Handbook of LHC Higgs Cross Sections: 3. Higgs Properties** CERN-2013-004
  - **Measurements of the Higgs boson production and decay rates and coupling strengths using *pp* collision data at $\sqrt{s}$=7 and 8 TeV in the ATLAS experiment** arXiv:1507.04548
  - **Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV** Eur. Phys. J. C75 212

Off shell measurements

- **Off-shell measurements**
  - **Limits on the Higgs boson lifetime and width from its decay to four charged leptons**
    arXiv:1507.06656
  - **Constraints on the off-shell Higgs boson signal strength in the high-mass *ZZ* and *WW* final states with the ATLAS detector**
    Eur. Phys. J. C75 335

Differential distributions

- **Differential distributions**
  - **Measurements of the Total and Differential Higgs Boson Production Cross Sections Combining the $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^{*}\rightarrow 4\ell$ Decay Channels at $\sqrt{s}$=8 TeV with the ATLAS Detector**
    arXiv:1504.05833
  - **Measurement of inclusive and differential fiducial cross sections for Higgs boson production in the $H\rightarrow 4\ell$ decay channel in p-p collisions at 7 TeV and 8 TeV**
    CMS-PAS-HIG-14-028

Rare Decays

- **Search for Higgs boson decays to a photon and a *Z* boson in *pp* collisions at $\sqrt{s}$=7 and 8 TeV with the ATLAS detector**
  Phys. Lett. B732 8
- **Search for Higgs and *Z* Boson Decays to *J/ψγ* and Υ(*nS*)*γ* with the ATLAS Detector**
  Phys. Rev. Lett. 114 121801
- **Search for the Standard Model Higgs boson decay to $\mu^+\mu^-$ with the ATLAS detector**
  Phys. Lett. B738 68
- **Search for a Higgs boson decaying into a Z and a photon in pp collisions at 7 TeV and 8 TeV**
  Phys. Lett. B726 587
- **Search for a Higgs boson decaying into γ* γ→ℓℓγ with low dilepton mass in pp collisions at $\sqrt{s}$ = 8 TeV**
  arXiv:1507.03031
- **Search for a standard model-like Higgs boson in the $\mu^+\mu^-$ and e^+e^- decay channels at the LHC**
  Phys. Lett. B744 184

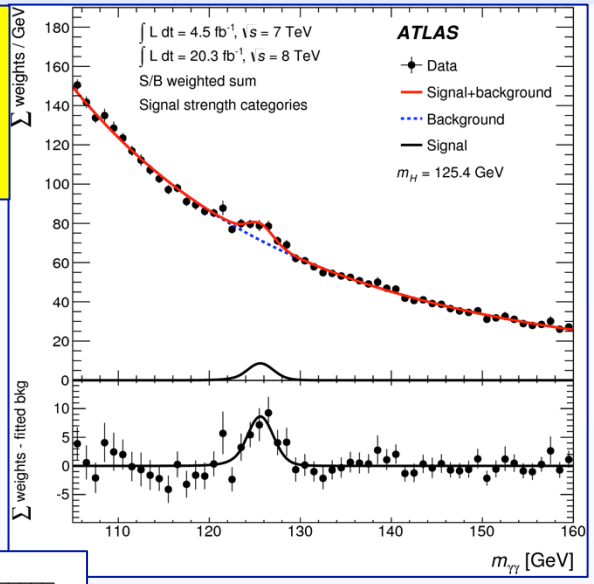
Other recent papers

- **Search for the standard model Higgs boson produced through vector boson fusion and decaying to *bb***
  arXiv:1506.01010
- **Search for the associated production of the Higgs boson with a top quark pair in multilepton final states with the ATLAS detector**
  arXiv:1506.05988

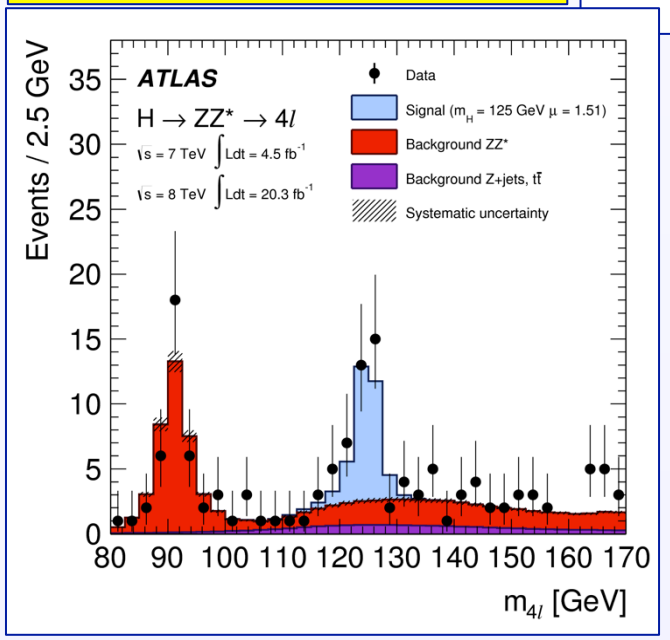
BACKUP

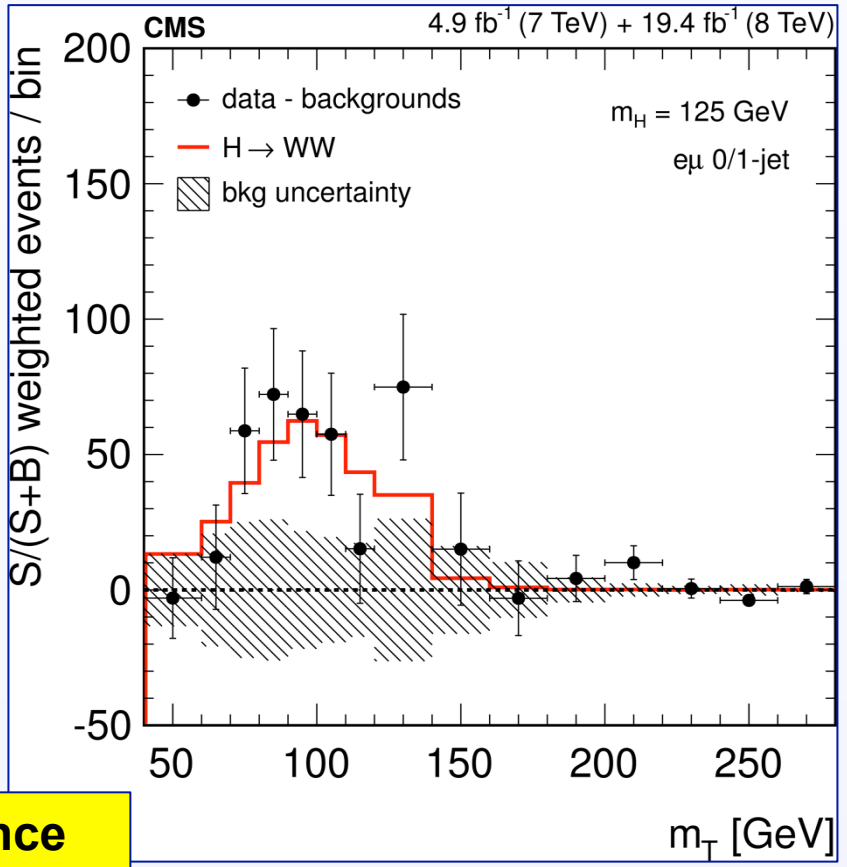
Higgs into di-bosons

H→γγ significance
ATLAS: 5.2 (exp. 4.6)
CMS: 5.6 (exp. 5.3)



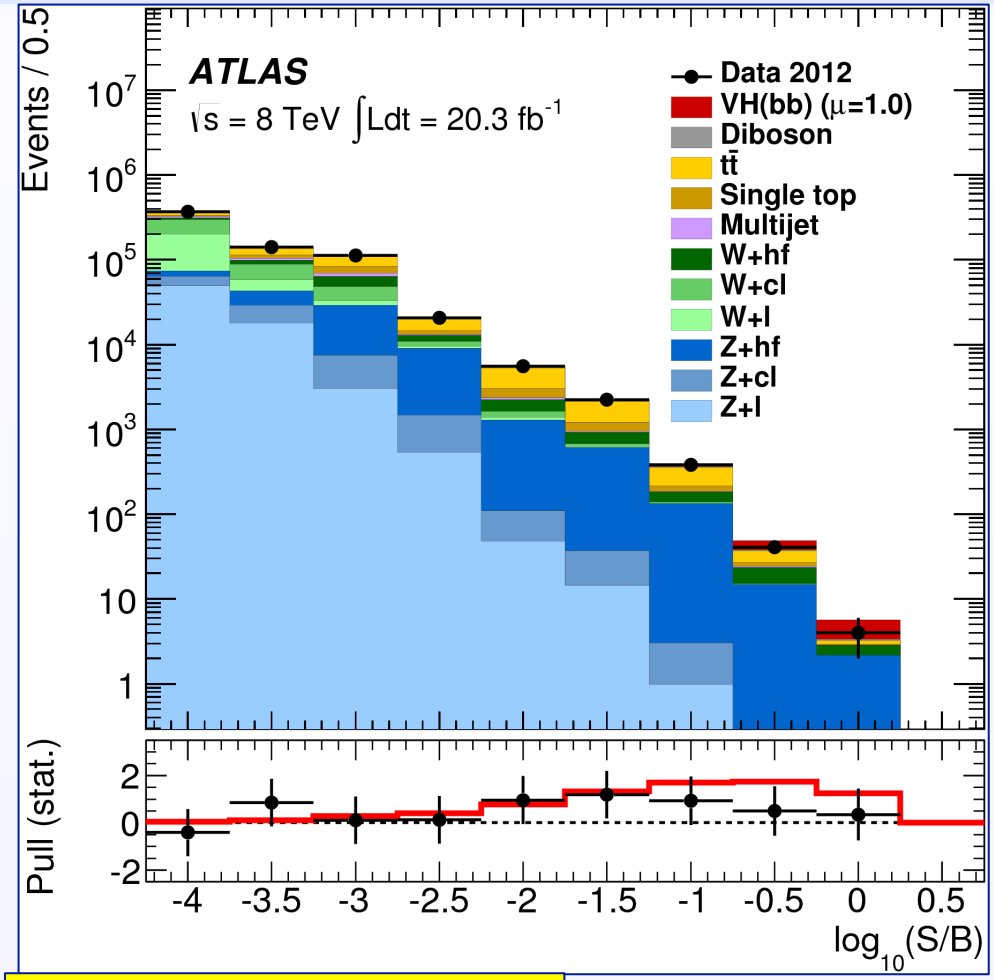
H→ZZ* significance
ATLAS: 8.1 (exp. 6.2)
CMS: 6.5 (exp. 6.3)





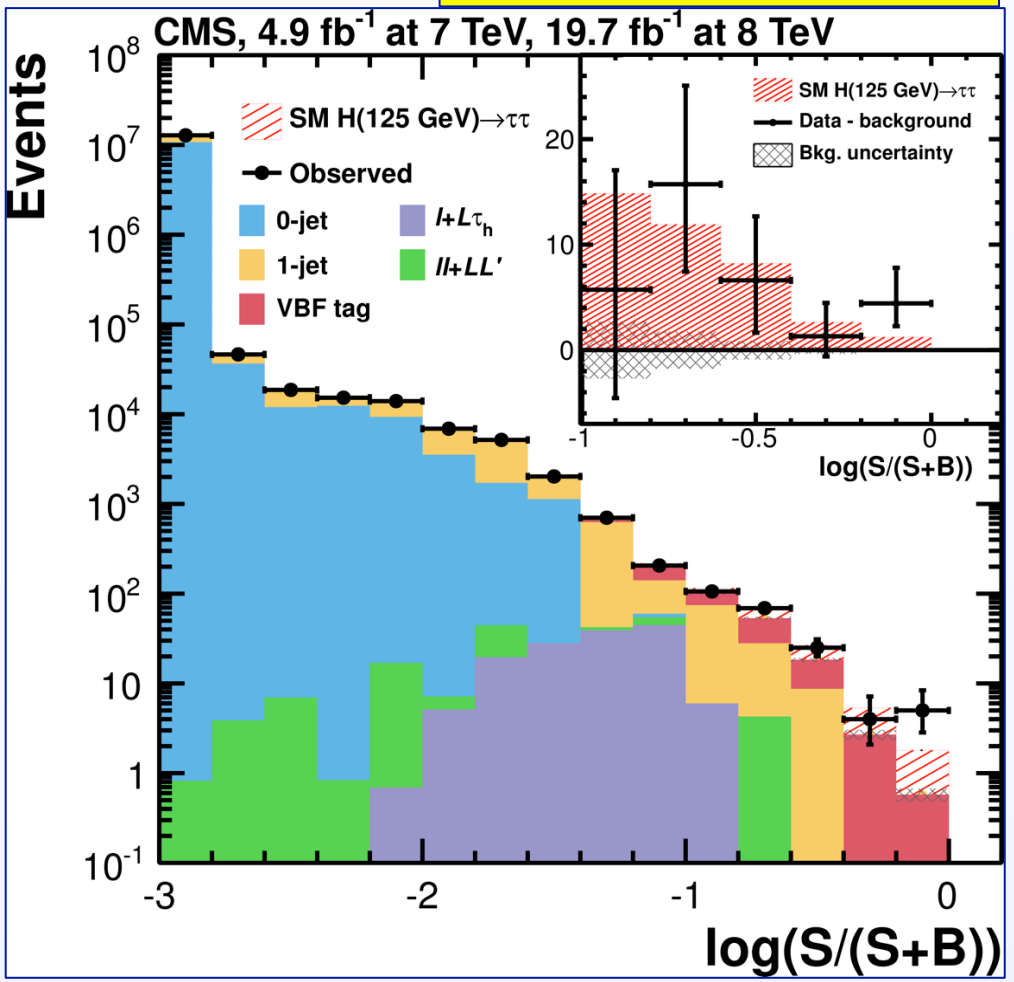
H→WW* significance
ATLAS: 6.5 (exp. 5.9)
CMS: 4.7 (exp. 5.4)

Higgs to fermions

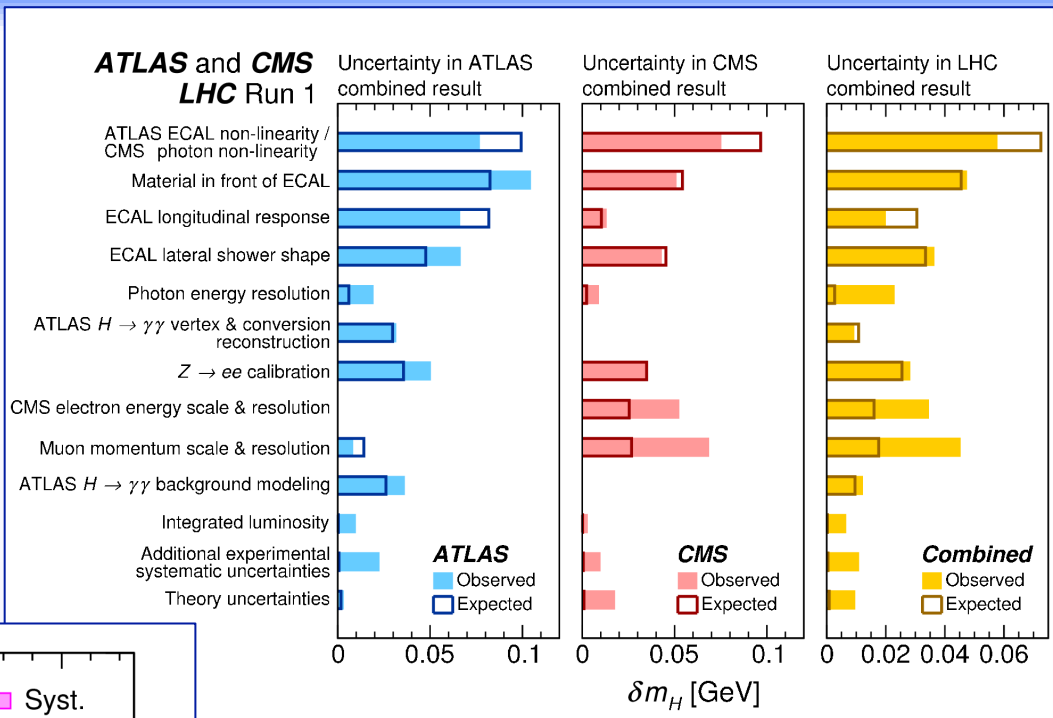


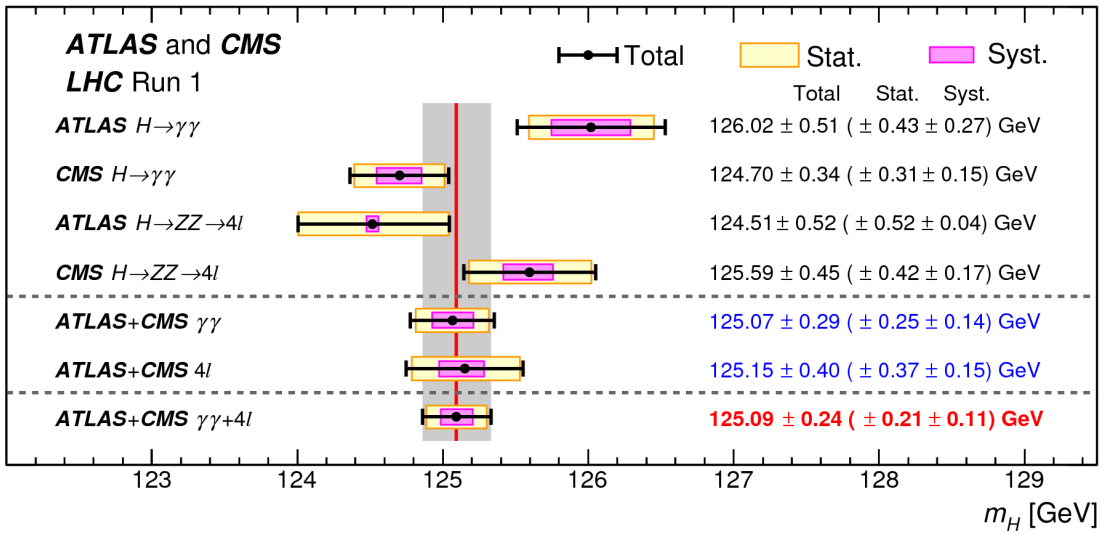
H→ττ significance
ATLAS: 1.8 (exp. 2.8)
CMS: 2.0 (exp. 2.6)

H→ττ significance
ATLAS: 4.5 (exp. 3.4)
CMS: 3.8 (exp. 3.9)

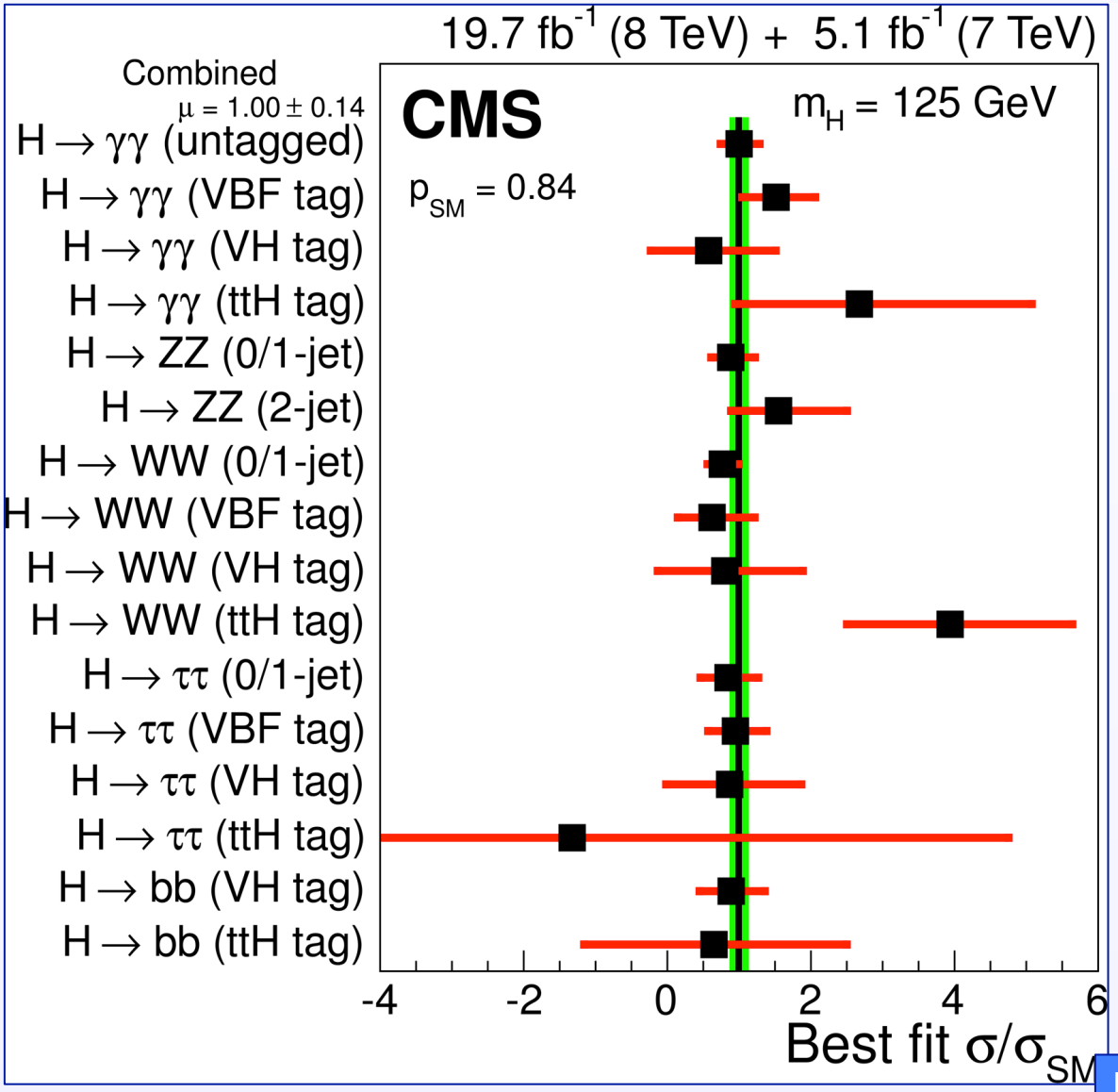


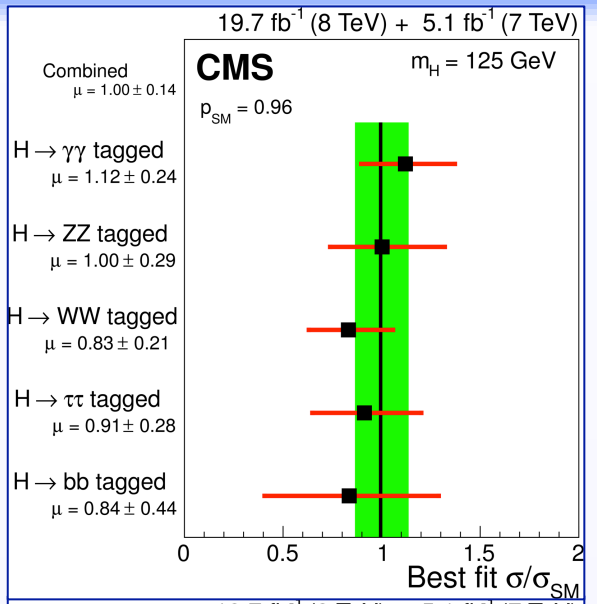
Mass combinations

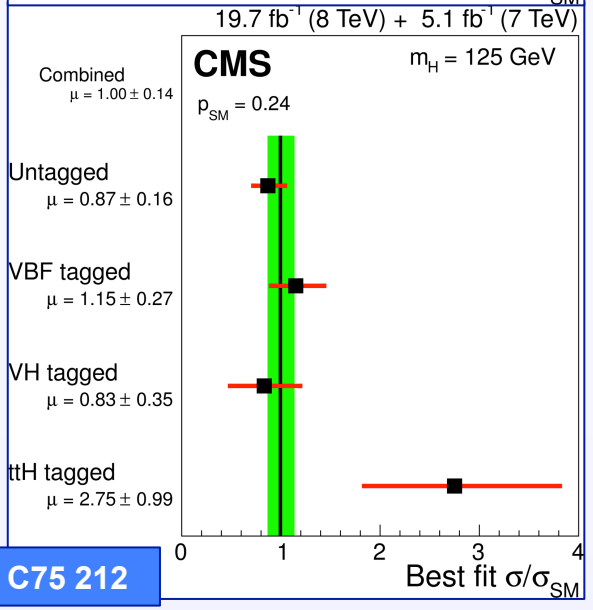




Signal strength CMS







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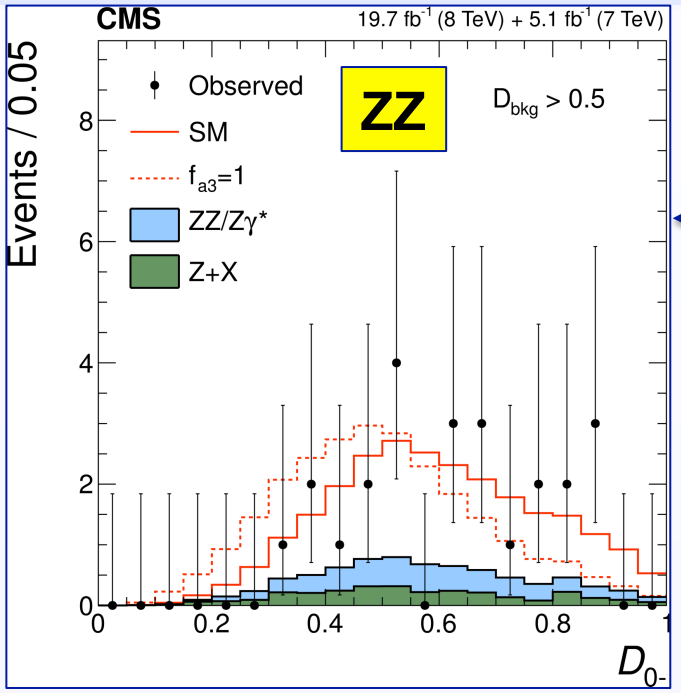
Spin and P determination



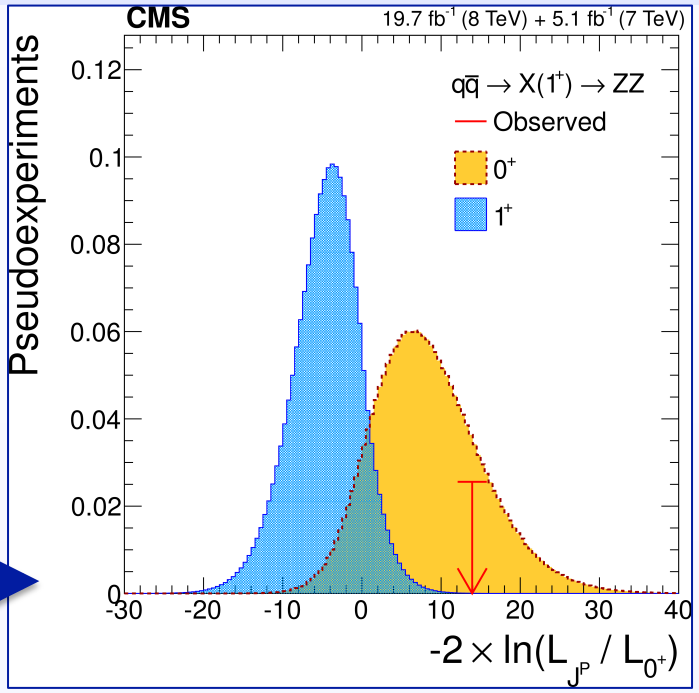
pdf for combined discriminator variable

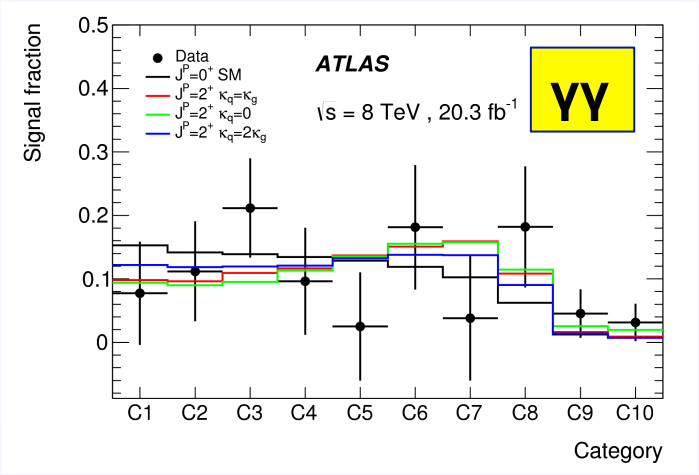
Hypothesis estimator:

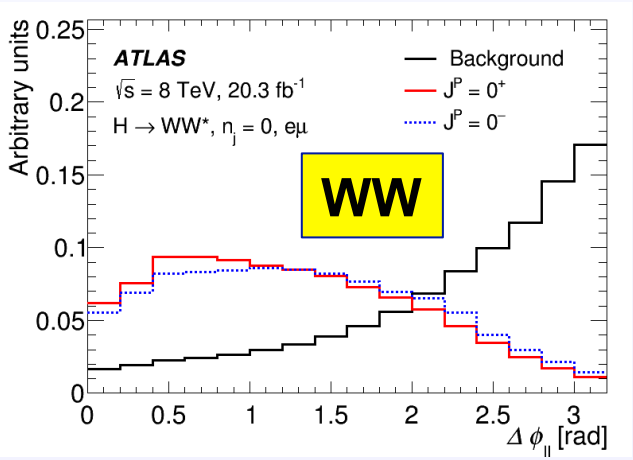
$$q = -2\ln\left(L_{J^P} / L_{0^+}\right)$$

$$p = P\left(q < q_{\text{obs}} \,|\, 0^+ + \text{bkg}\right)$$

Determination of final *p* value







Spin and CP determination

H^0 $J = 0$

Mass $m = 125.7 \pm 0.4$ GeV

H^0 Signal Strengths in Different Channels

Combined Final States $= 1.17 \pm 0.17$ (S = 1.2)

$WW^* = 0.87^{+0.24}_{-0.22}$

$ZZ^* = 1.11^{+0.34}_{-0.28}$ (S = 1.3)

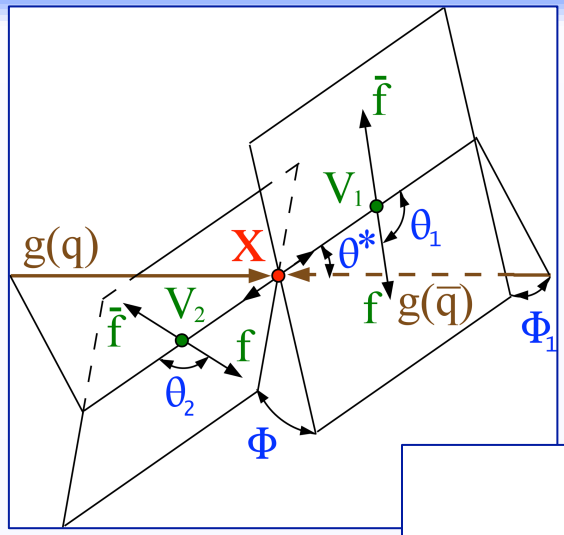
$\gamma\gamma = 1.58^{+0.27}_{-0.23}$

$b\bar{b} = 1.1 \pm 0.5$

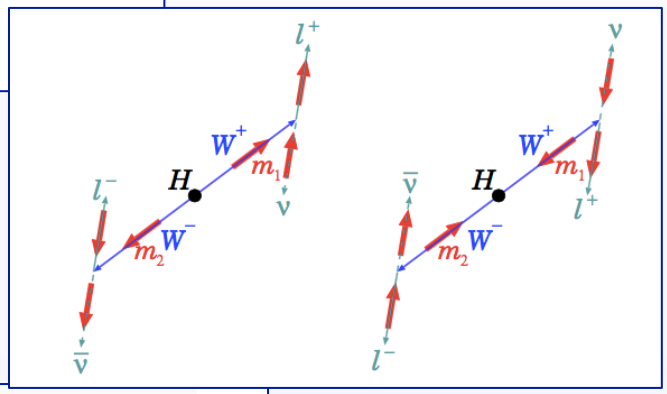
$\tau^+\tau^- = 0.4 \pm 0.6$

$Z\gamma < 9.5$, CL = 95%

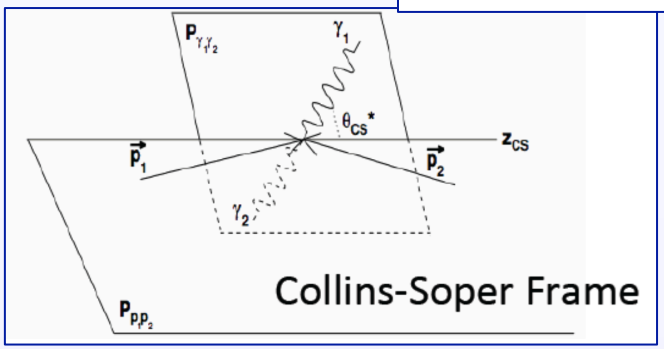
- Kinematic variables in the final state sensitive to spin/parity of the decaying particle.
- Test alternative hypotheses against SM 0^+ hypothesis.
- Likelihood ratio estimator



ZZ, full final state kinematics available



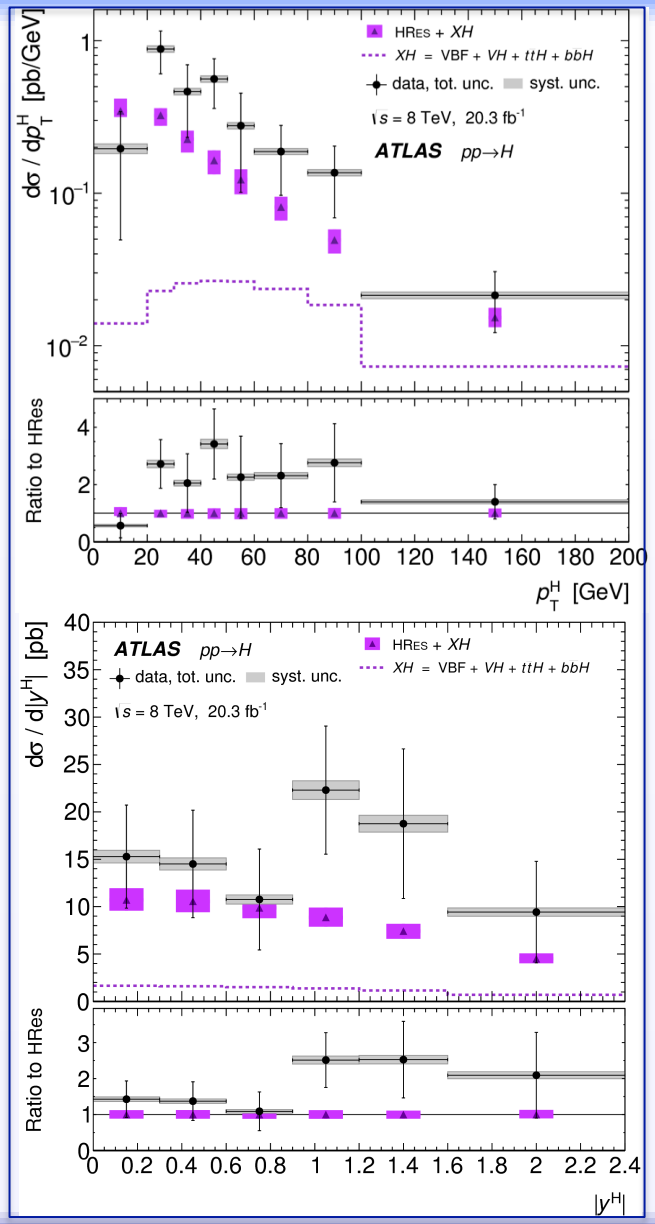
WW, Correlation between final state leptons



γγ, use $\cos\theta^*_{CS}$

Differential distributions

Higgs production properties



Jet production

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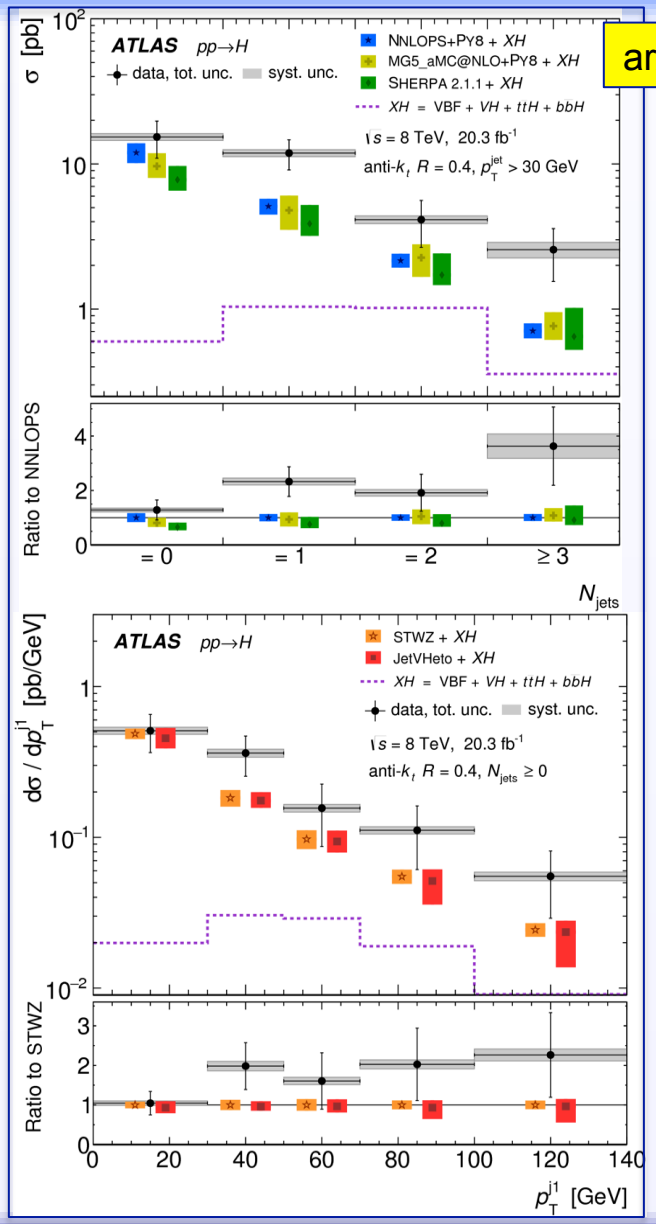
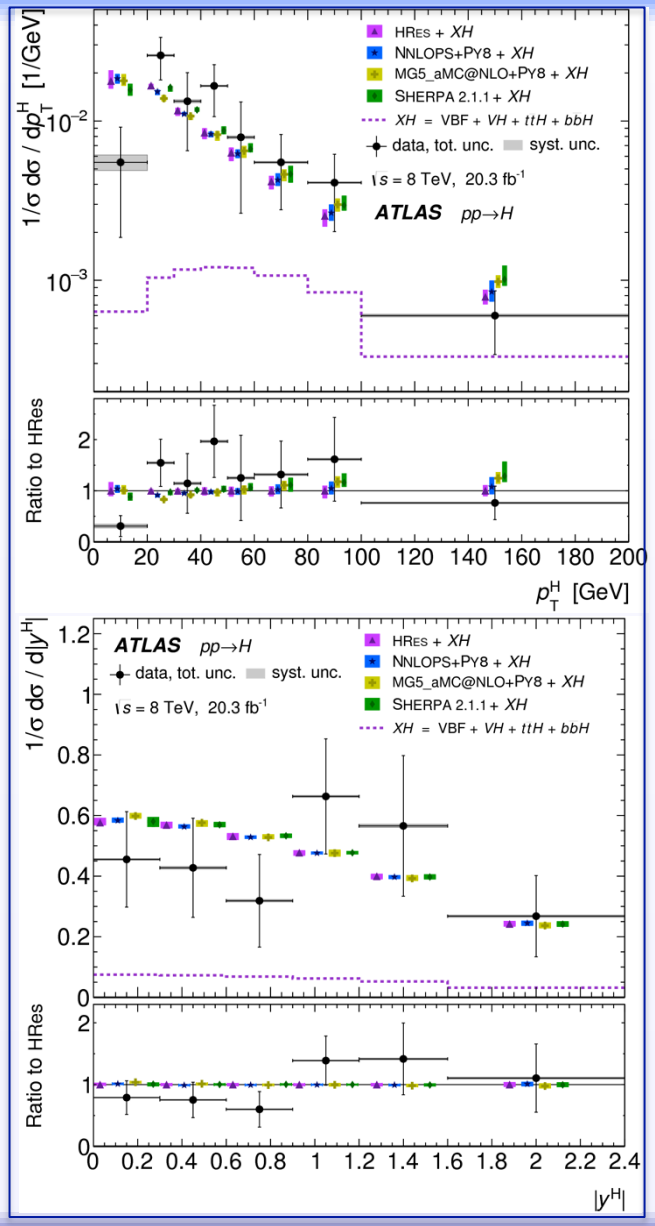
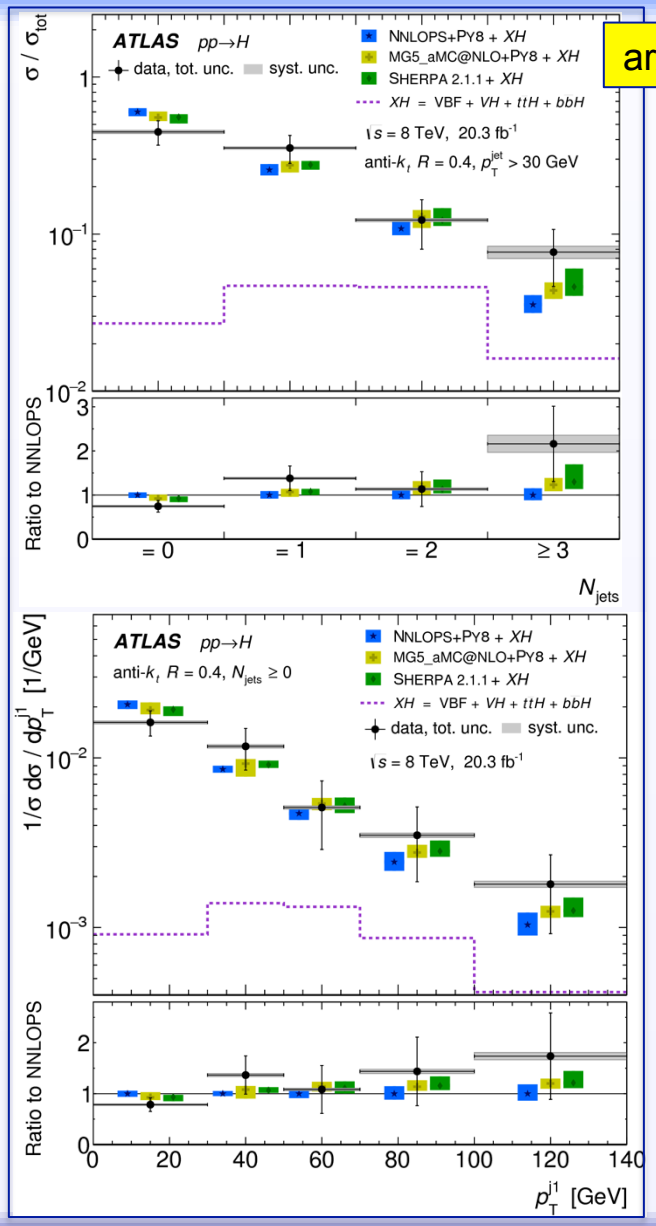


Differential distributions

Higgs production properties



Jet production



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