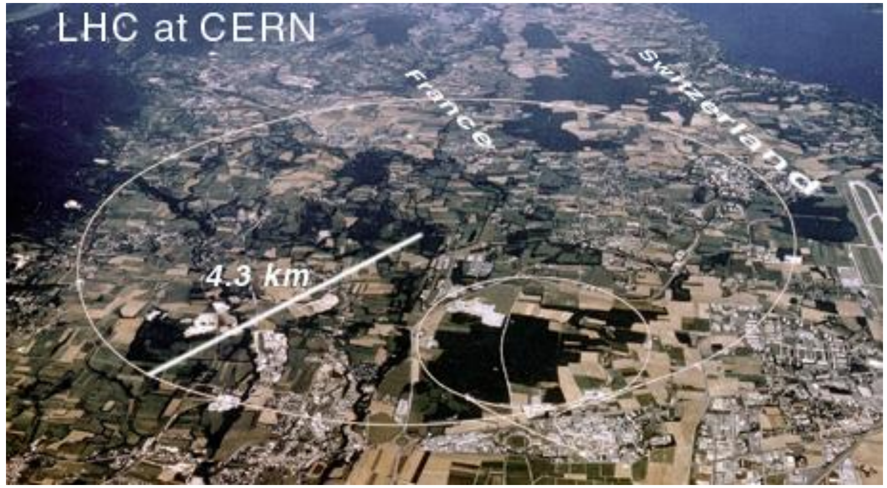
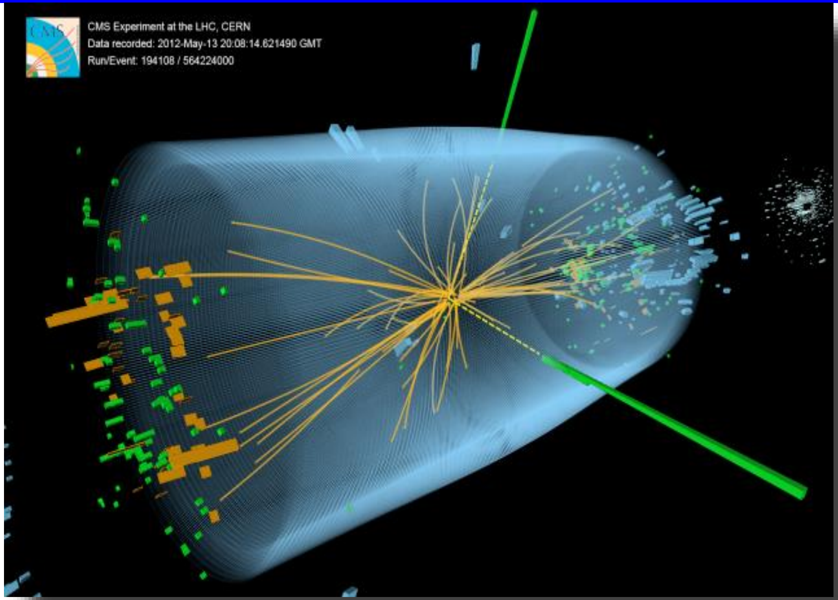


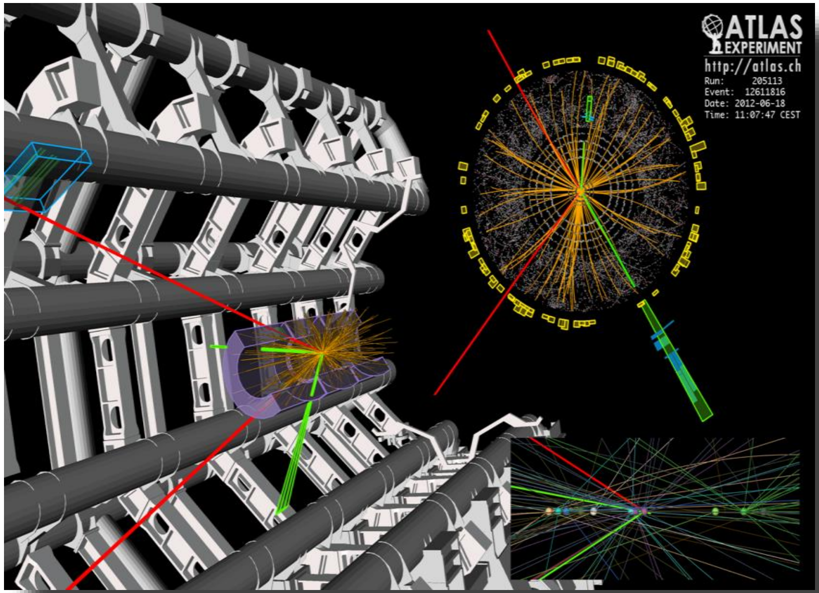
H->4l measurements at ATLAS and CMS

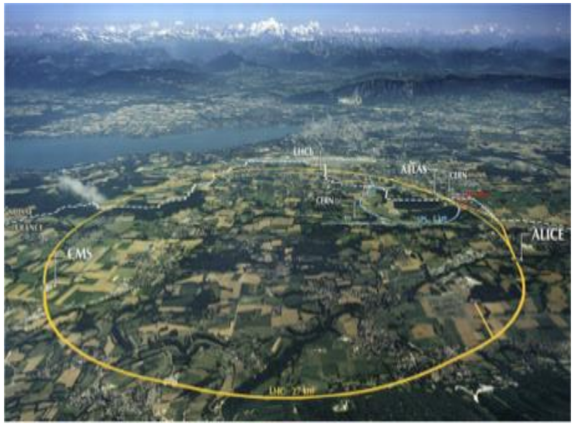
Guenakh Mitselmakher
University of Florida
on behalf of ATLAS and CMS Collaborations

QCD@LHC 2017 Conference, Debrecen, Hungary, August 28, 2017

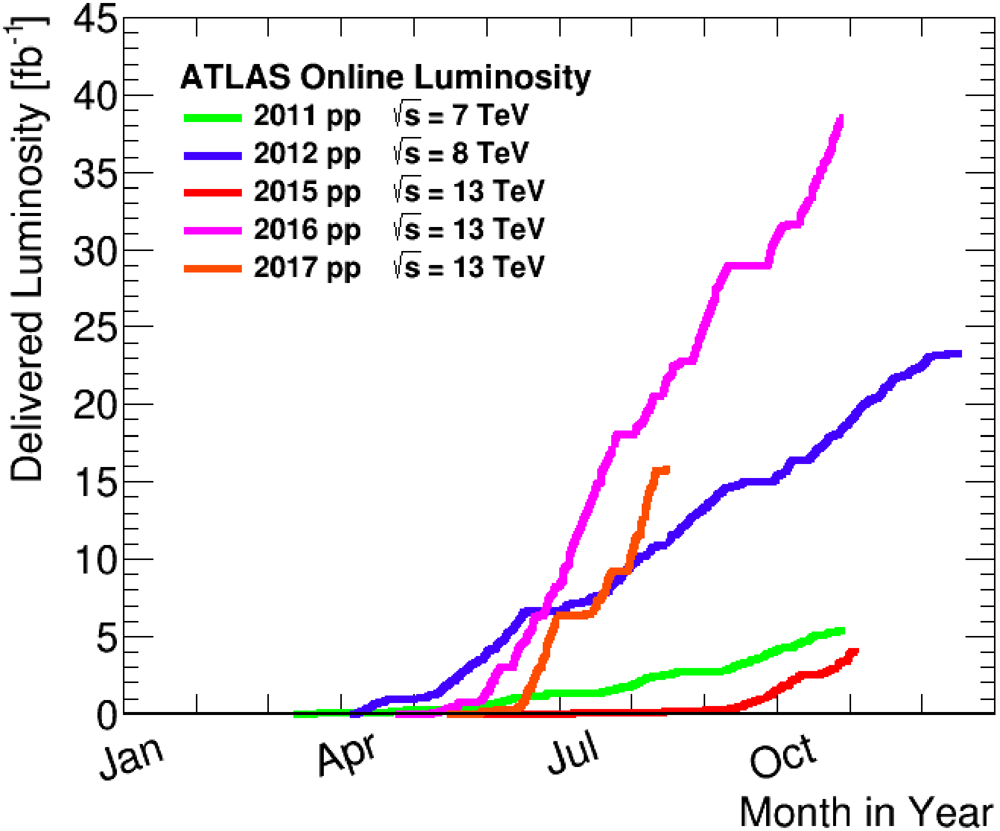
July 4, 2012. Higgs discovery announced by ATLAS and CMS







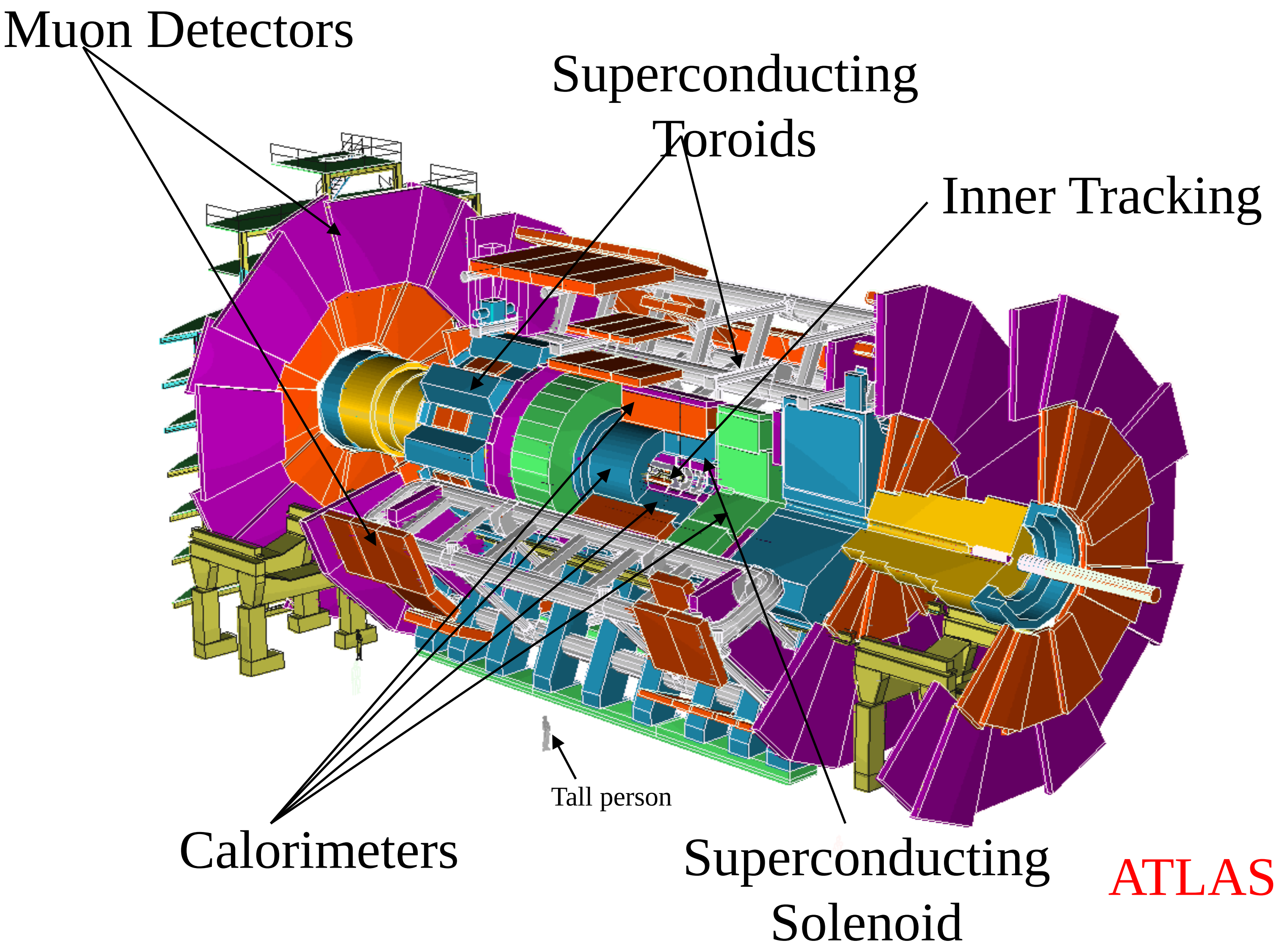
LHC performance over the years



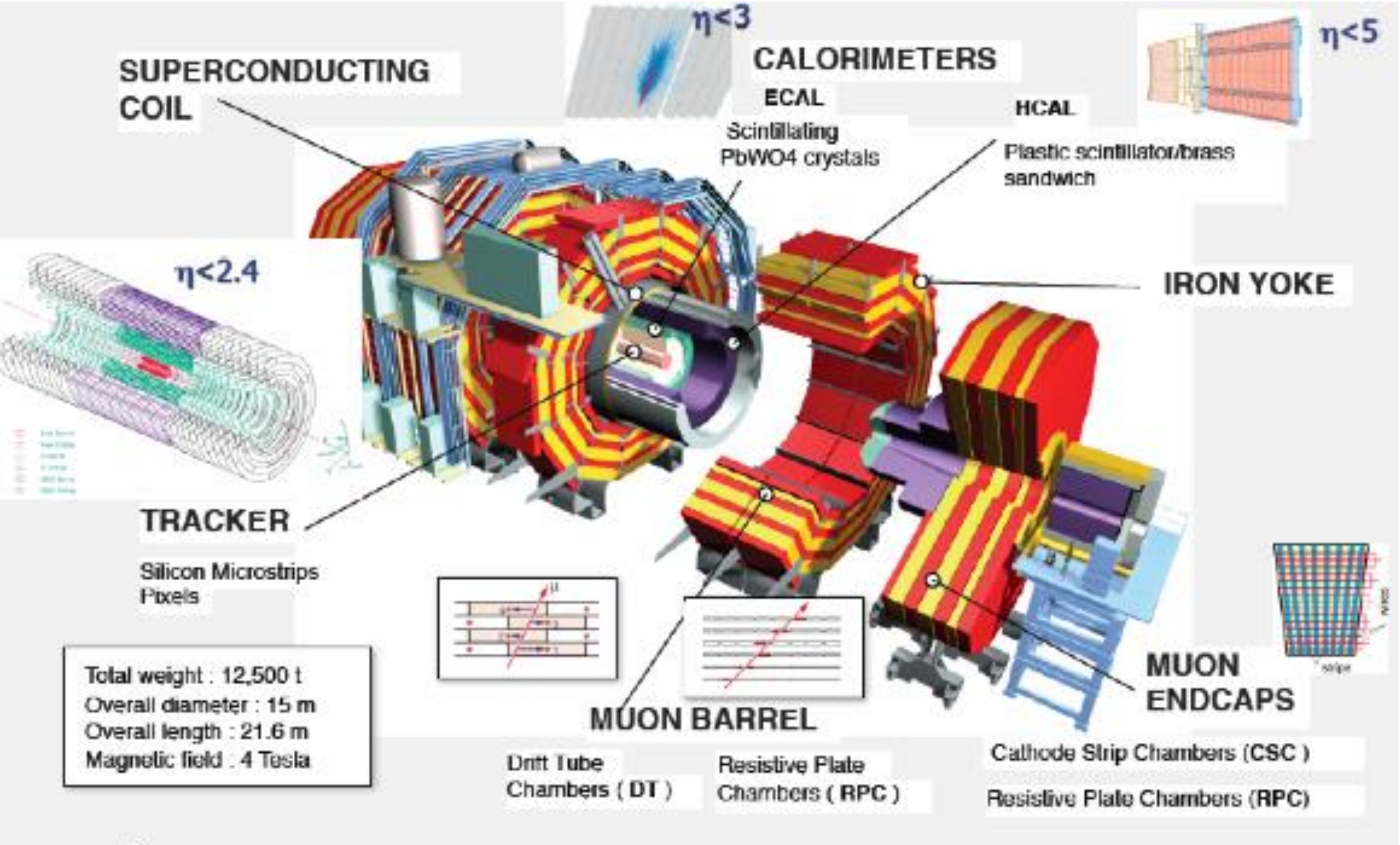
This talk is based on the results of the Higgs-> 4l analyses using LHC Run 2 statistics from 2015+2016 at 13 TeV

~ 40 fb^{-1} integrated luminosity in each experiment: ATLAS and CMS (most of the presented here results are based on ~ 36 fb^{-1} ,2016 data)

ATLAS: A Toroidal LHC ApparatuS

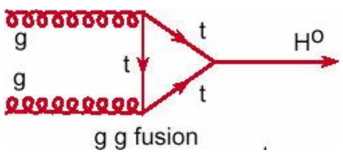


CMS: The Compact Muon Solenoid



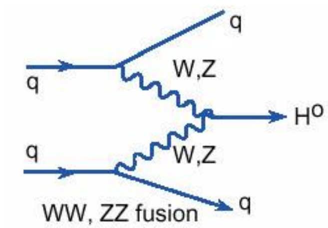
h(125) production modes 13 TeV (pb)

	ggF	VBF	WH	ZH	bbH	ttH
8 TeV	21.4	1.60	0.70	0.42	0.20	0.13
13 TeV	48.6	3.78	1.37	0.88	0.49	0.51
ratio	2.3	2.4	2.0	2.1	2.5	3.9



N3LO QCD + NLO EW

±3.9% (theory) ±3.2% (PDF+α_S)



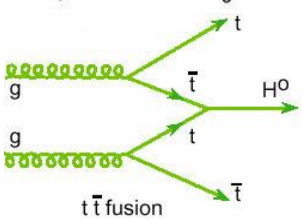
NNLO QCD + NLO EW

±0.4% (theory) ±2.1% (PDF+α_S)

NNLO QCD + NLO EW

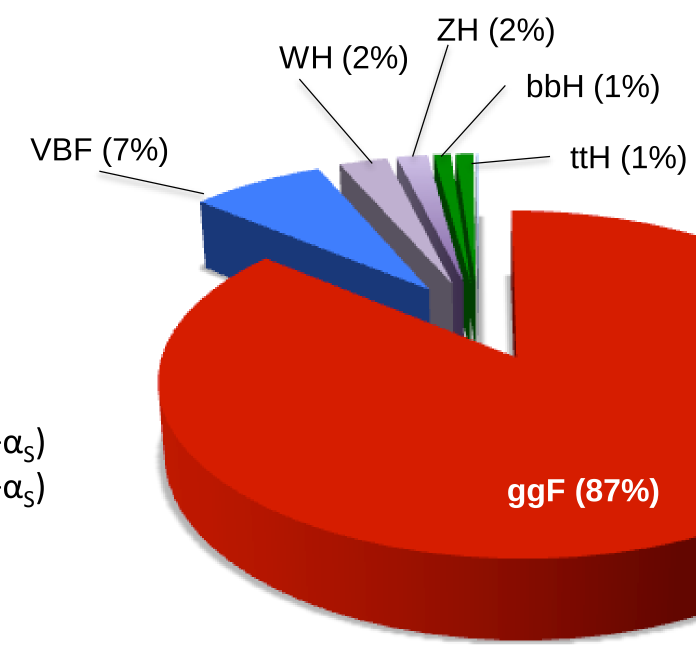
WH: ±0.6% (theory) ±1.8% (PDF+α_S)

ZH: ±3.5% (theory) ±1.6% (PDF+α_S)



NLO QCD + NLO EW

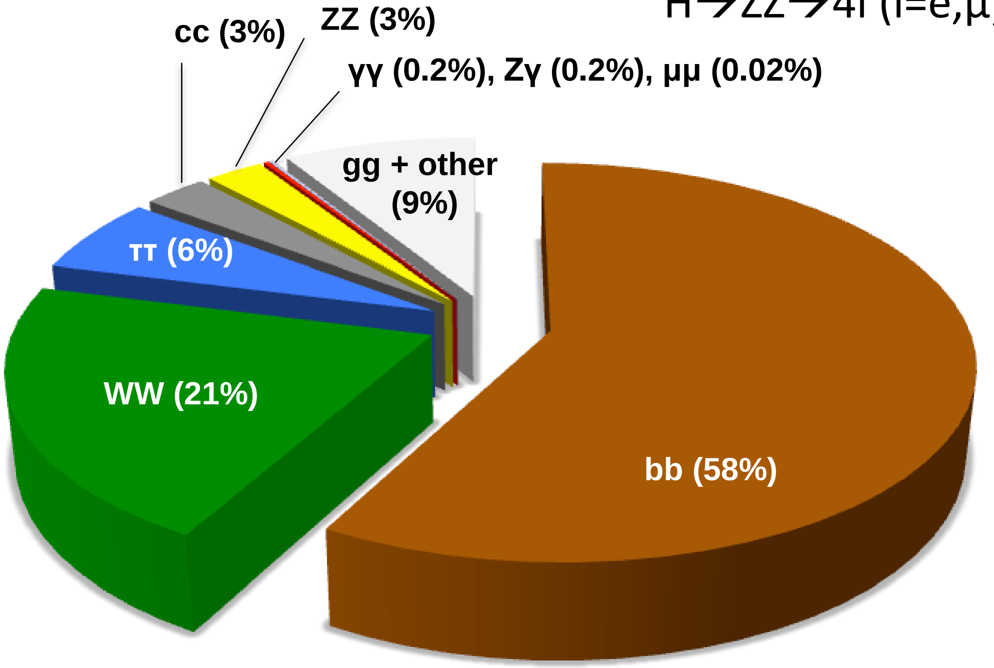
±7.5% (theory) ±3.6% (PDF+α_S)

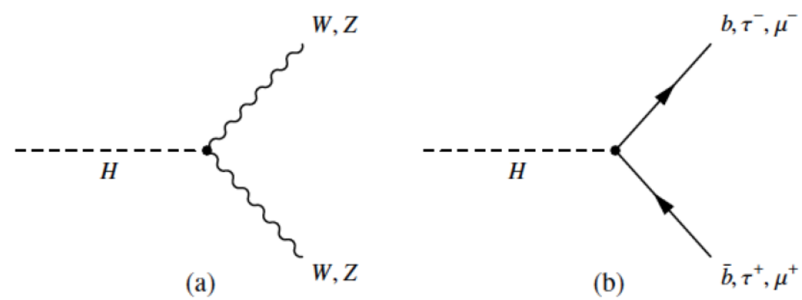


h(125) decay modes

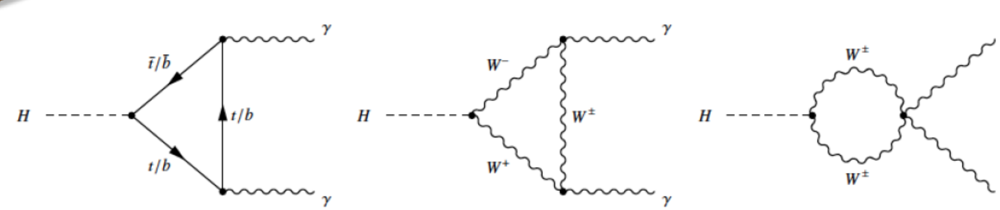
	bb	WW	ττ	cc	ZZ	γγ	Zγ	μμ	gg + …
all	58%	21%	6.3%	2.9%	2.6%	0.23%	0.15%	0.022%	9%
Leptonic (e.μ only)		0.76%			0.012%		0.009%		

H→ZZ→4l (l=e,μ) the very small, but convenient!





Tree level Higgs decay diagrams



Loop induced Higgs decay diagrams

Higgs particles produced in ATLAS + CMS in 2016 (rough estimate)

- **Number of SM Higgs particles produced in ATLAS and CMS in 2016 = 4,000,000 !!!**

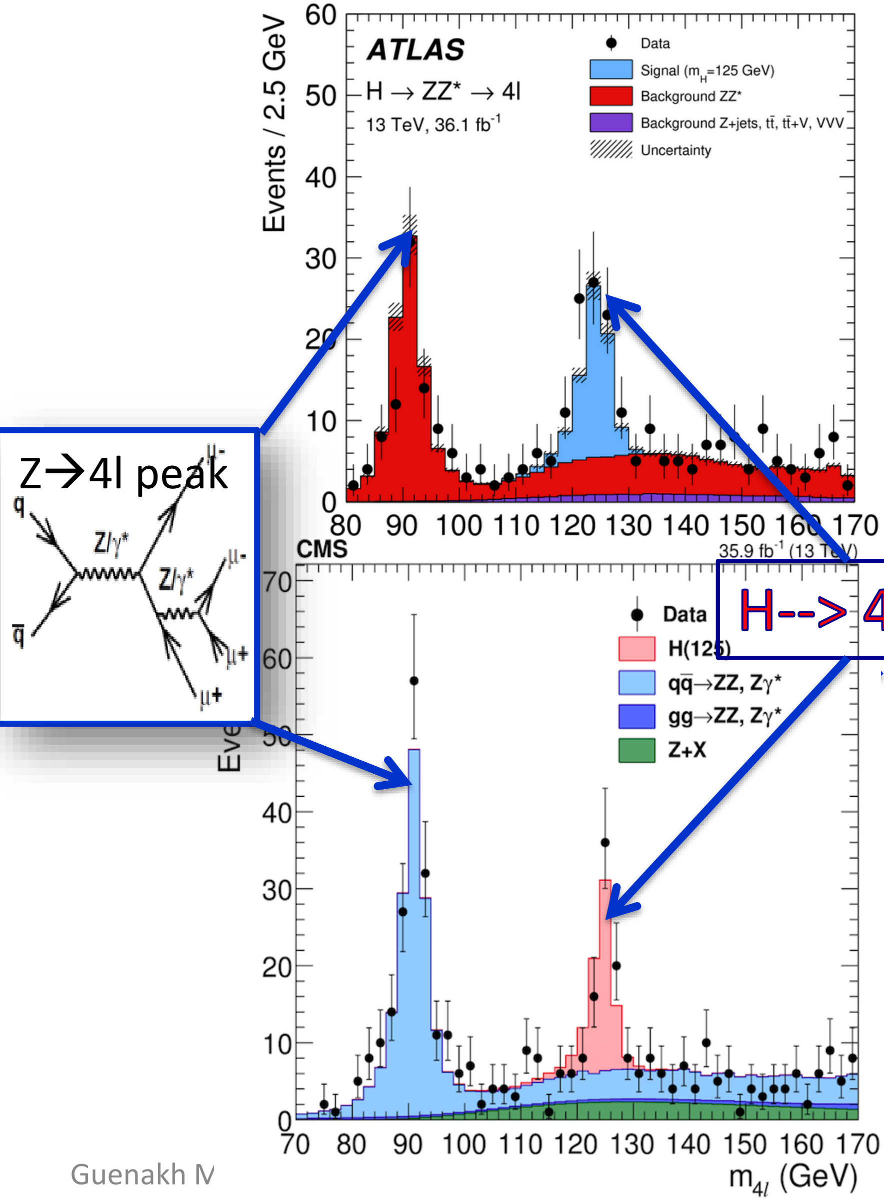
  (total Higgs production cross section at 13 Tev ~55 pb) x ($36\ fb^{-1}$ integrated luminosity) x (2 experiments)

But:

- Higgs decay to four leptons $H \rightarrow ZZ \rightarrow 4l$ is only $\sim 10^{-4}$ of 4,000,000, which is ~ 400 events: very small number
- Further the number of detected $H \rightarrow 4l$ becomes few times smaller (~ 100 in two experiments) due to acceptance and event selection losses

$H \to ZZ \to 4l$ “golden channel”

used for: discovery, mass, spin/parity, coupling to bosons



H→4l decay channel features:

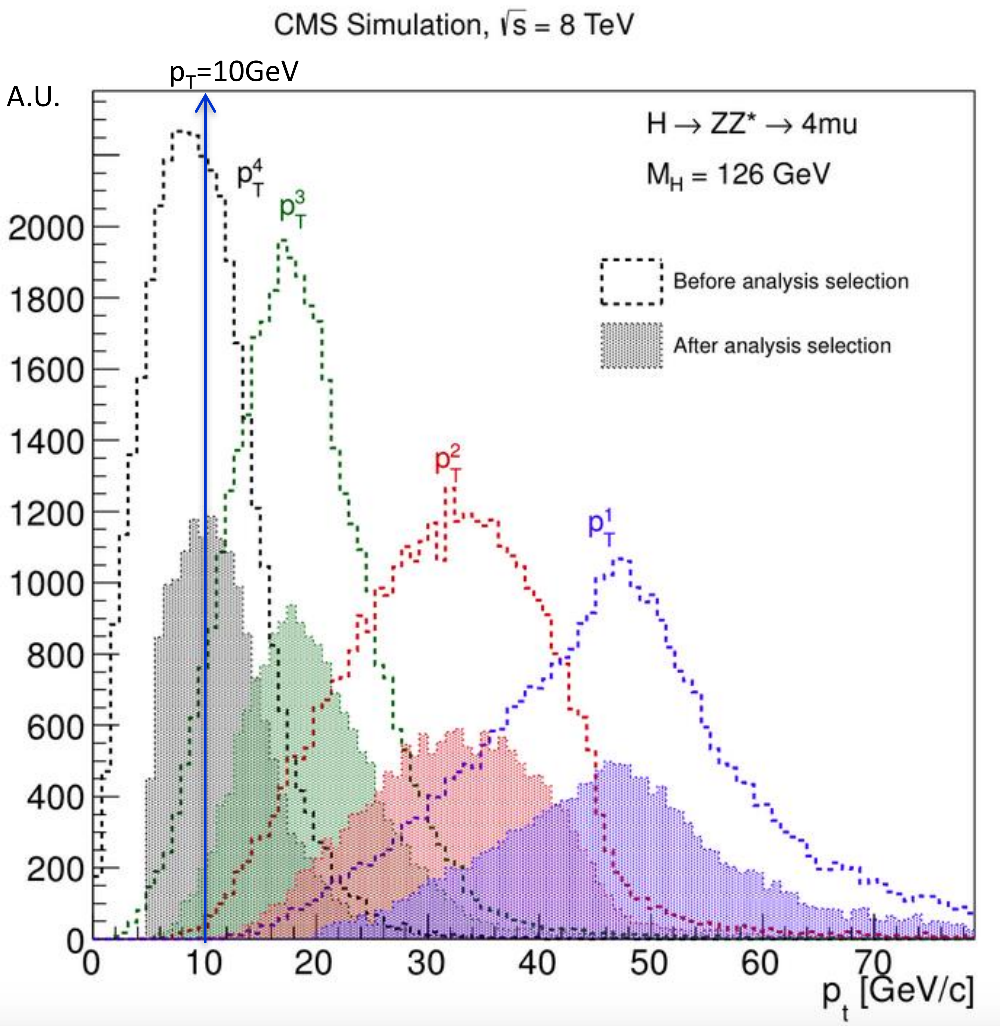
- high S/B-ratio (~2:1)
- but very small event yield
- Excellent mass resolution per event (1-2%),
- Excellent precision in Higgs mass measurements, (statistics limited, ~ 0.2 % now)
- Z→4l decay peak conveniently nearby,
  provides natural validation of the Higgs boson measurements

Analysis strategy:

Four-lepton mass is the key observable

- Select four leptons (muons or electrons)
- split events into 4e, 4μ, 2e2μ channels
- Exploit differences in differential distributions for separation from bkgd, and for spin-parity measurements
- Backgrounds:
  - irreducible ZZ (dominant): from theory (NLO, Monte Carlo)
  - reducible (with non-isolated or “fake” leptons): from control region

An example of experimental challenge: 4 Leptons selection



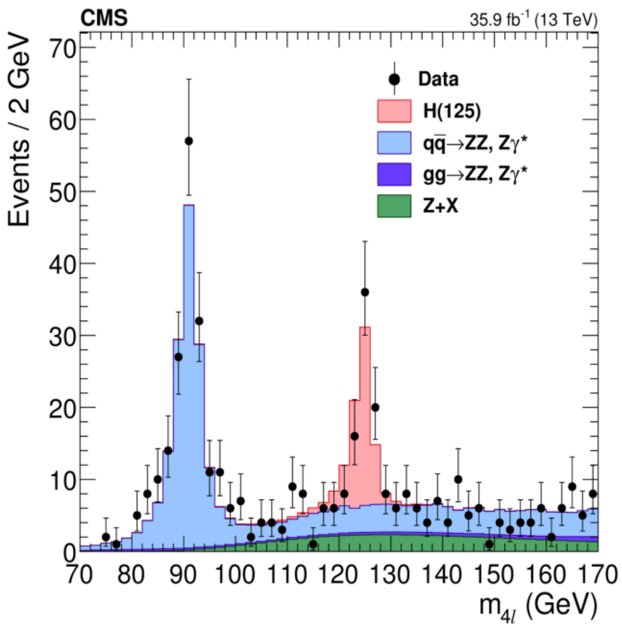
- Around 50% of events have a lepton with p_T less than 10 GeV. A challenge for the lepton selection in the analysis
- Control of background rate is difficult at low p_T
- Control of lepton selection efficiencies is also a challenge at low p_T

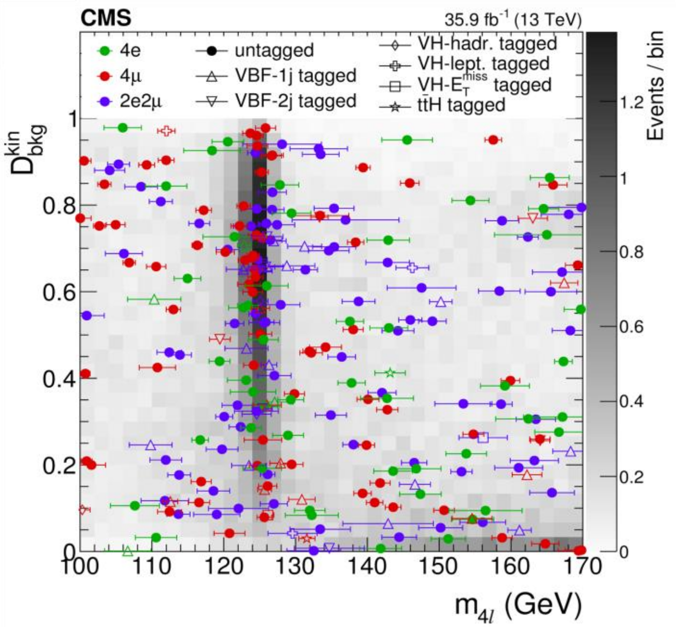
ATLAS and CMS results used in this talk, analysis of Ran II pp-collisions at 13 TeV, 2015+2016 data

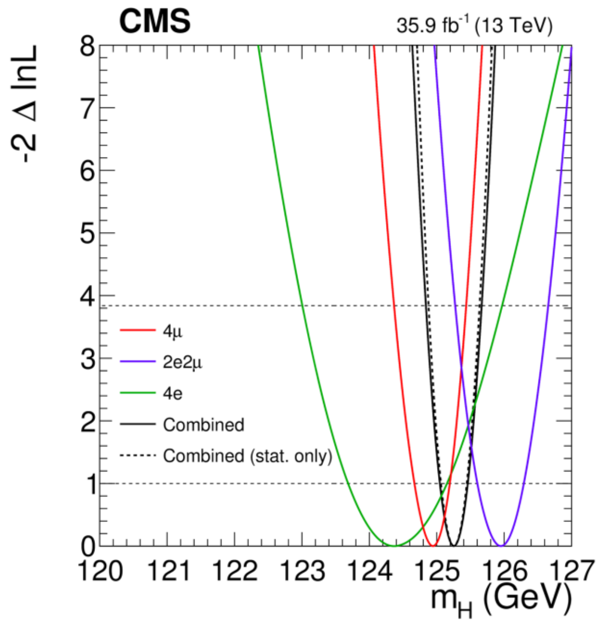
CMS is publishing two Run 2 papers on H->ZZ->4l:
"Measurements of properties of the Higgs boson…" *Submitted to JHEP*
http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-16-041/index.html
"Constraints on anomalous Higgs boson couplings…" *Submitted to Phys. Lett. B*
http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-17-011/index.html

ATLAS has released the following Run 2 H->ZZ->4l results:
"Measurement of inclusive and differential cross sections…" arXiv:1708.02810
https://inspirehep.net/record/1615206 ,
plots: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2016-25/
"Measurement of the Higgs boson coupling properties…"
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2017-043
"The ATLAS combined Higgs→4l + Higgs→γγ mass measurement in Run 2"
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2017-046
"Combined measurements of Higgs boson production and decay in the $H \to 4\ell$ and $H \to \gamma\gamma$…"
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2017-047

Higgs mass measurement : CMS







$$m_{\mathrm{H}} = 125.26 \pm 0.20(\mathrm{stat.}) \pm 0.08(\mathrm{sys.})\ \mathrm{GeV}$$

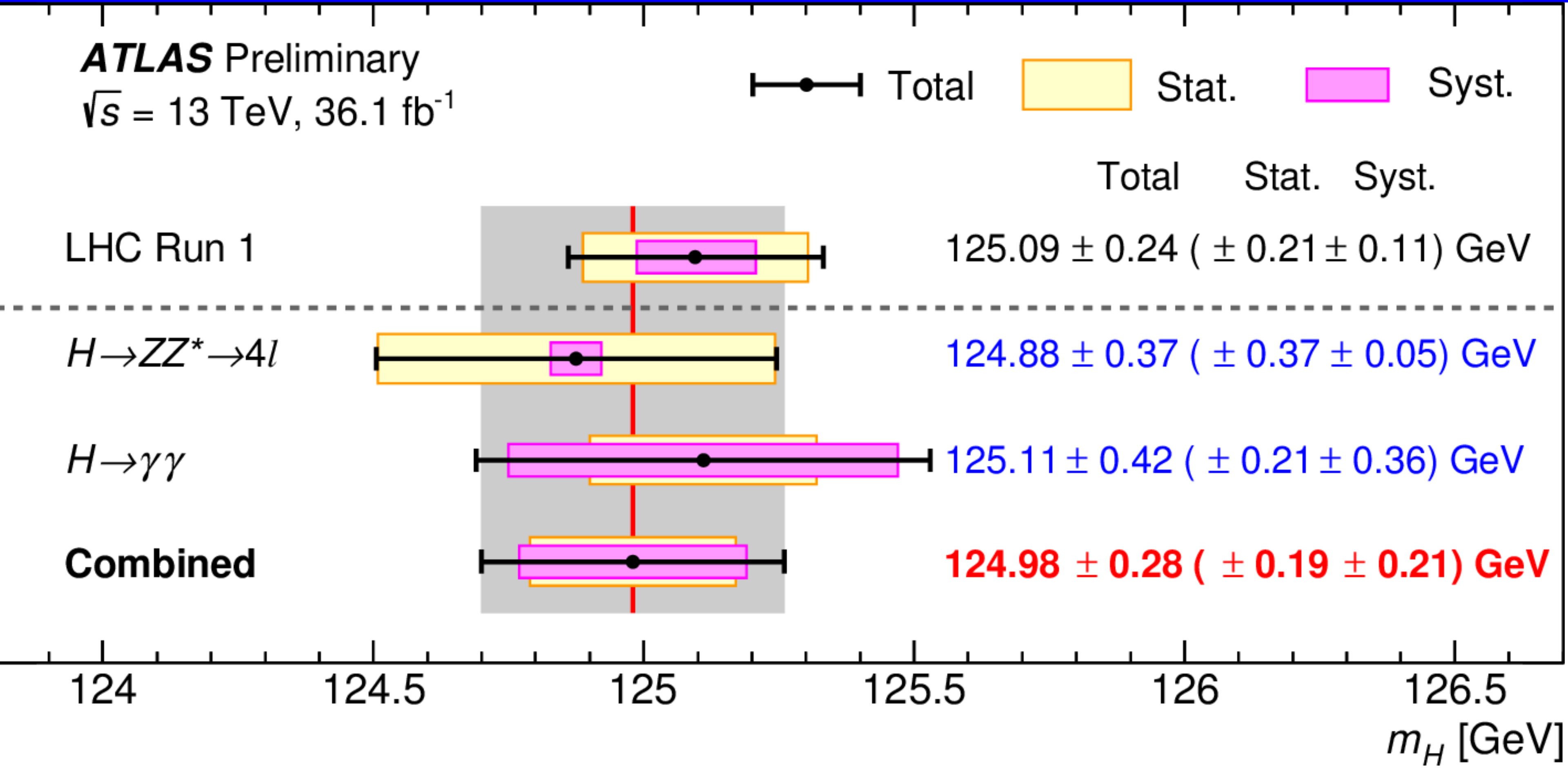
New CMS mass measurement (above) in the H->4l channel is more precise than the published Run1 average of ATLAS+CMS:

$$m_H = 125.09 \pm 0.21\ (\mathrm{stat.}) \pm 0.11\ (\mathrm{syst.})\ \mathrm{GeV}.$$

To get the new Run 2 mass result CMS used 3D fit (Higgs mass, Kinematic Discriminant D^{kin}, per-event mass uncertainty) with M_{Z1} mass constraint, related to H→ZZ* decay

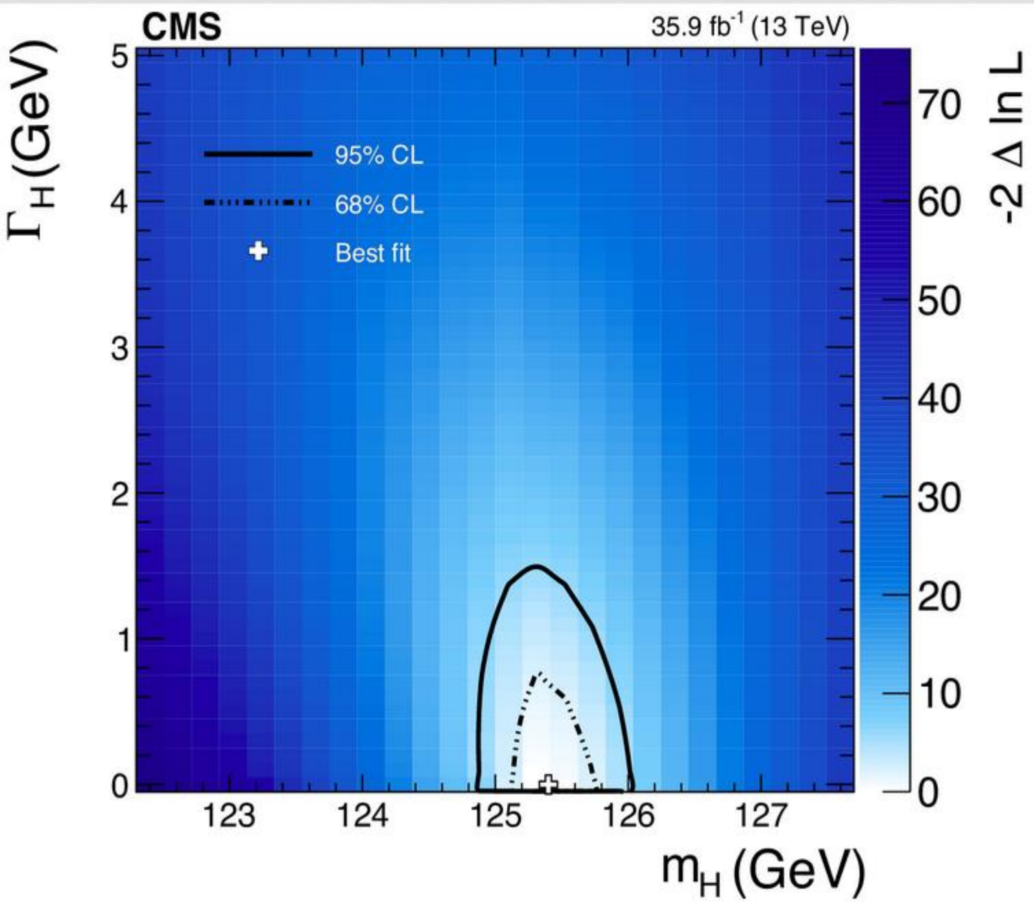
Higgs mass measurement (ATLAS)

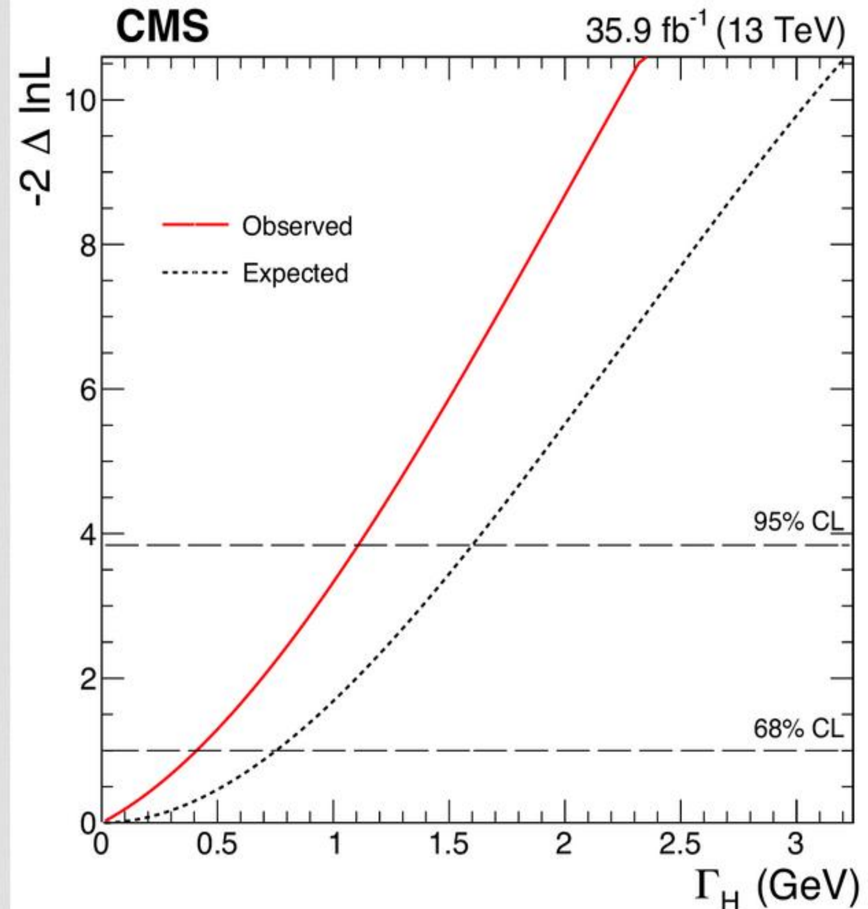
H→4l +H→γγ combined



ATLAS combination measurements of the Higgs boson mass in $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ decay channels

New limit on Higgs width (CMS)

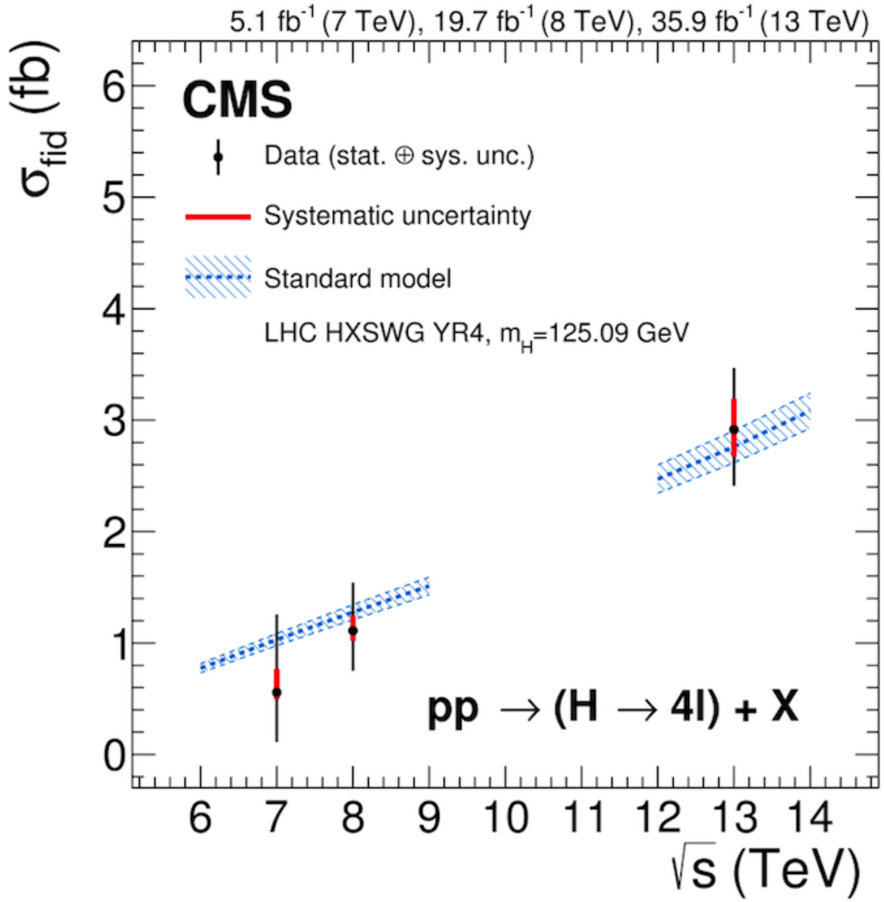


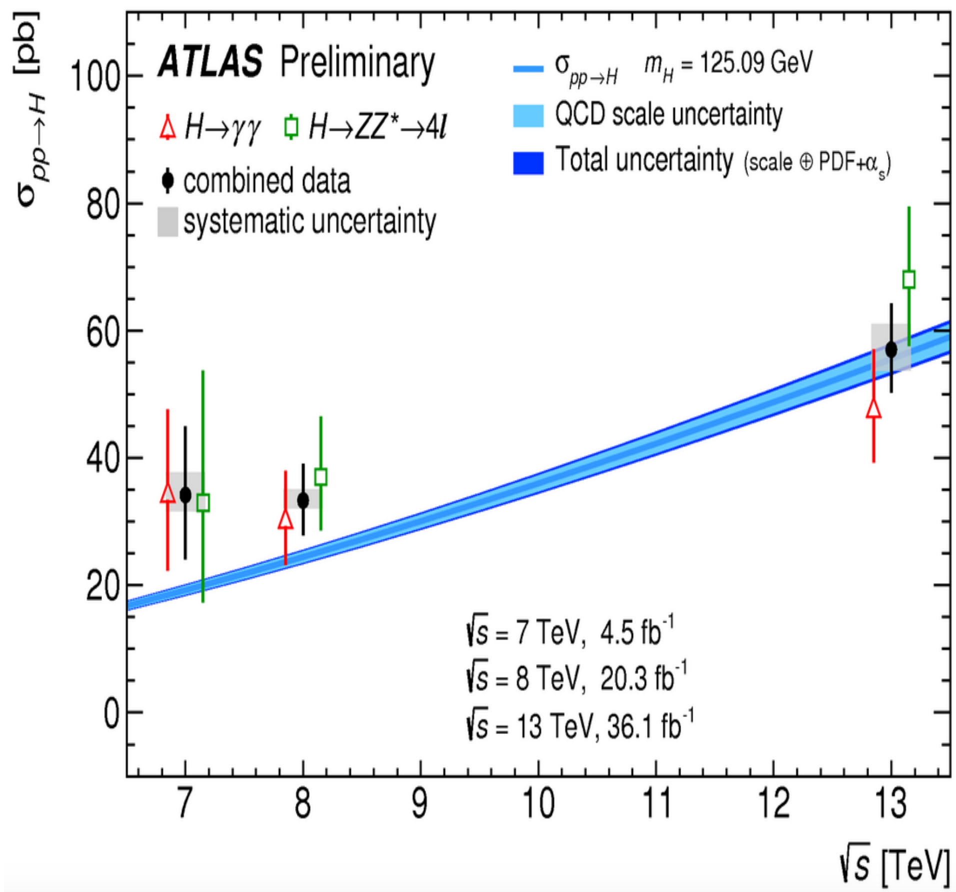


Likelihood scan of m_H and $\Gamma_{H.}$ Measured Γ_H < 1.10 GeV,
Results for Γ_H in agreement with the SM prediction Γ_H ~ 4 MeV.

(Earlier Run I more model dependant off-shell production limit on $\Gamma_{H.}$ from ATLAS and CMS is few times the SM prediction, see backup).

Higgs total cross section





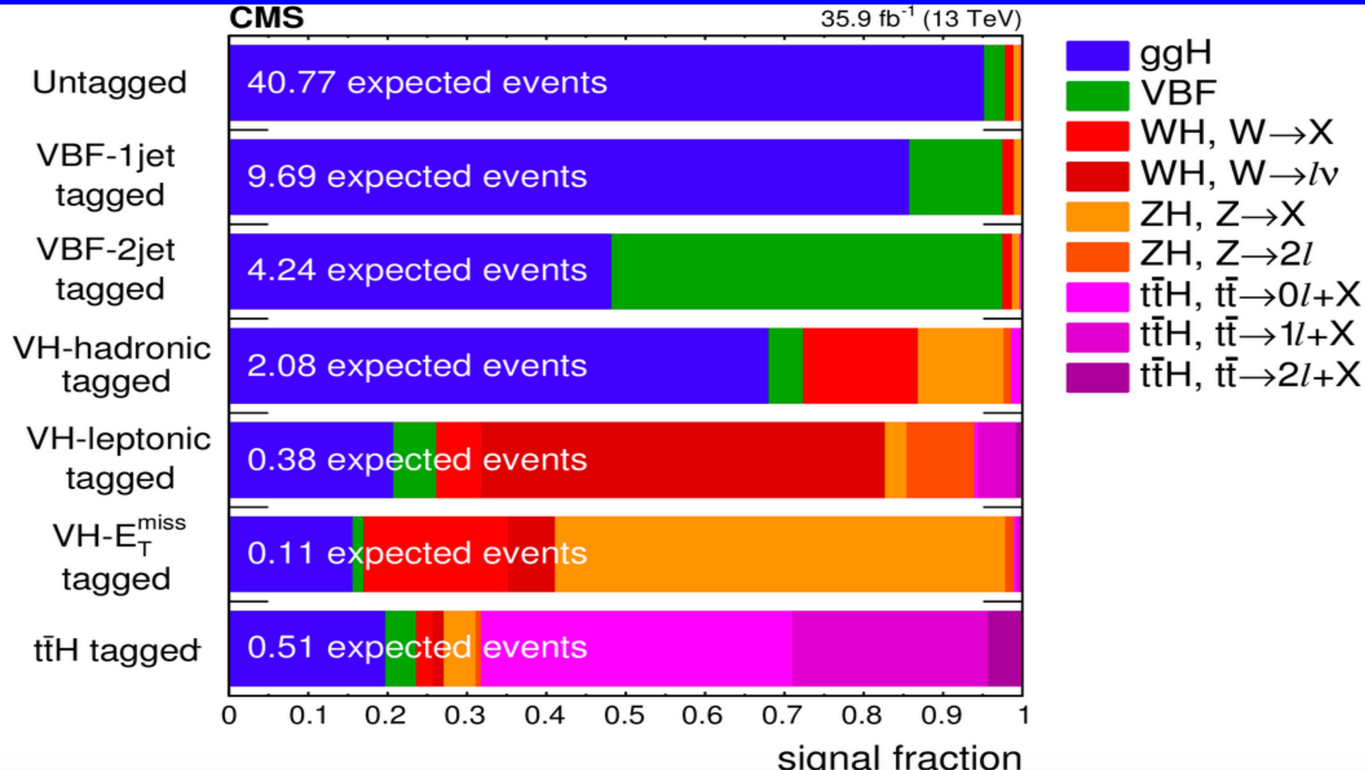
Higgs cross section as a function of pp- collisions energy.

(Fiducial cross sections defined and measured in ATLAS and CMS)

Measurements agree with the SM predictions

Higgs→4l: event categories

Expected signal purity for different event categories in CMS, similar in ATLAS

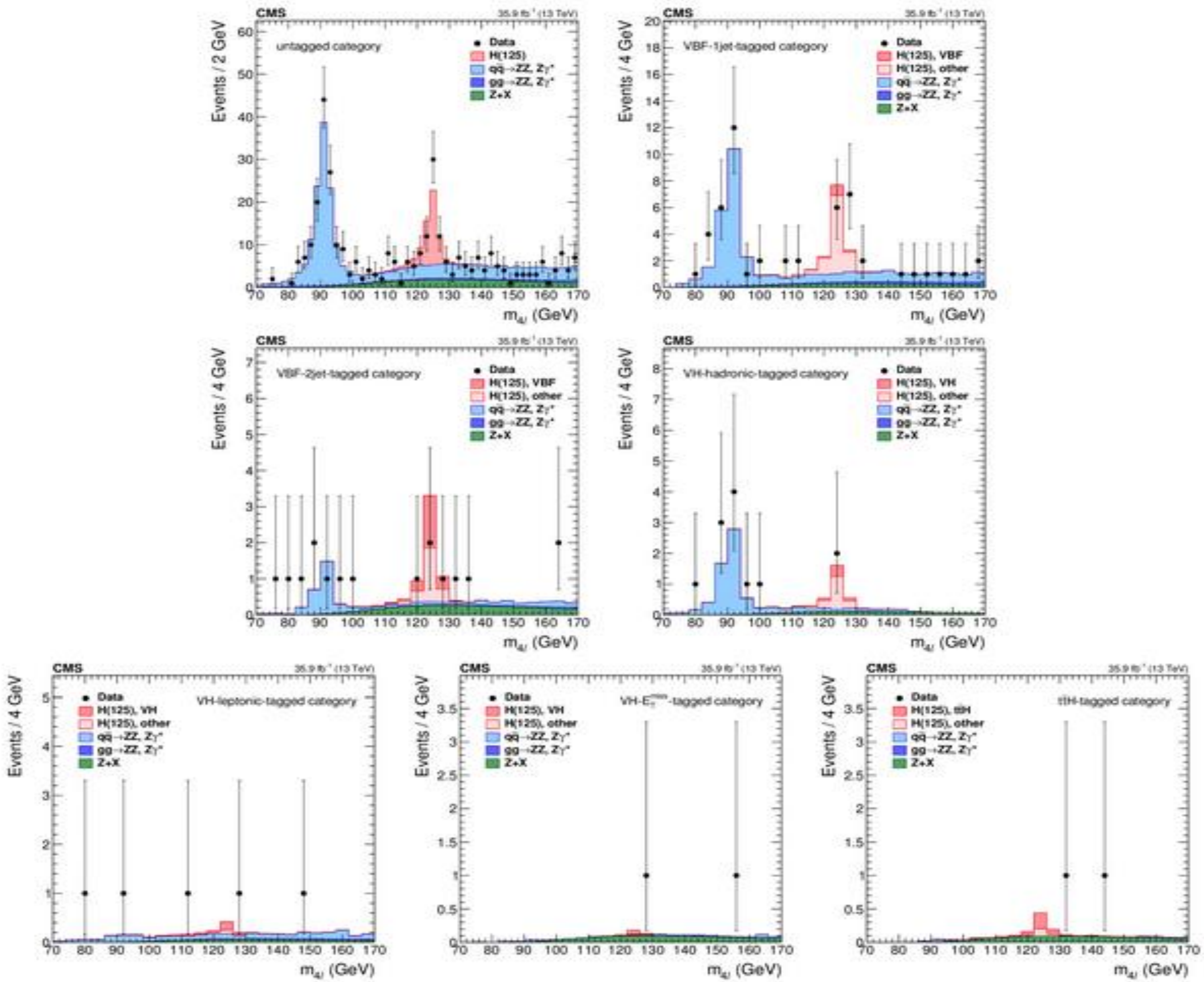


Expected signal purity in different event categories,

Unfortunately a mixture of different Higgs production mechanisms, hard to separate

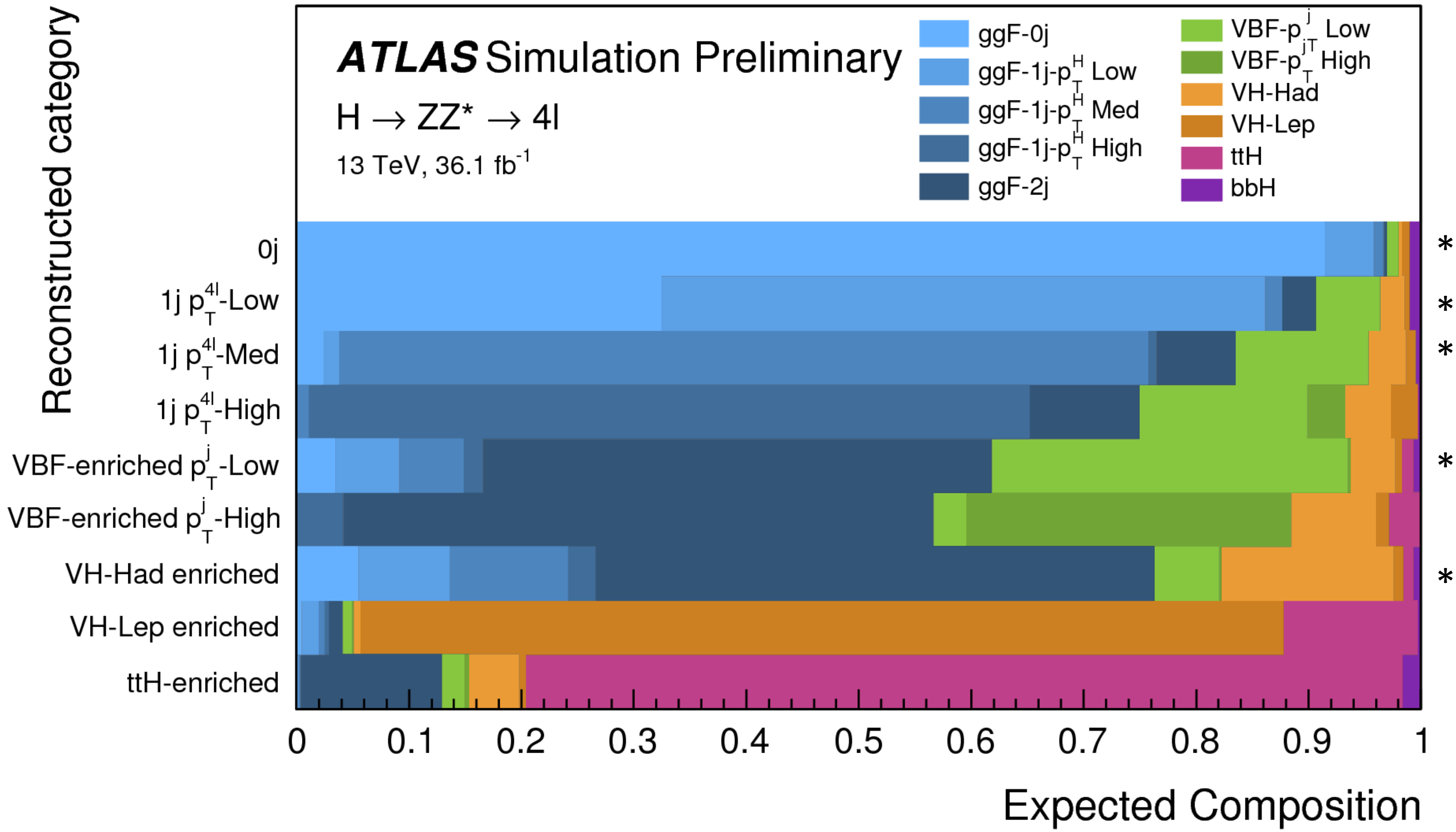
Notes: Numbers indicate the expected signal event yields in each category (integral for 118-130 GeV window)
WH, ZH, and tt¯H processes are split according to the decay of the associated particles,
where X is anything other than an electron or muon.

CMS: Reconstructed 4L invariant mass in the seven event categories

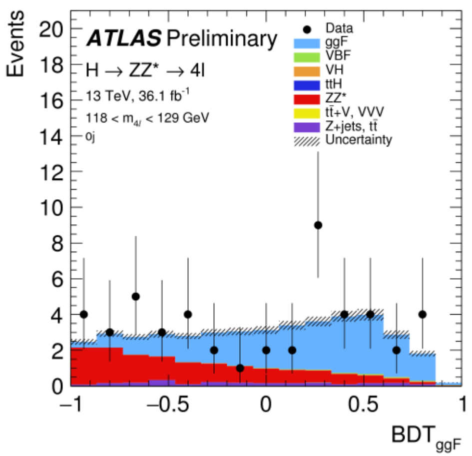


Distribution of the reconstructed four-lepton invariant mass in the seven event categories (low 4leptons mass range).

Event categories in ATLAS

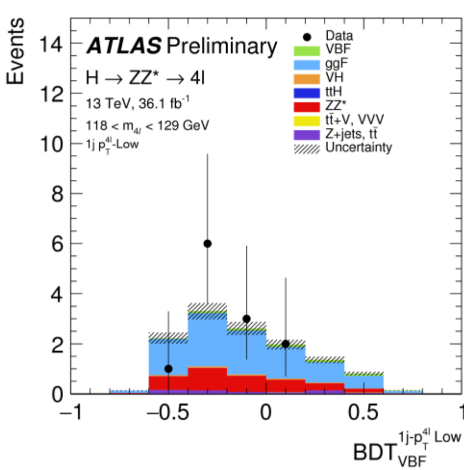


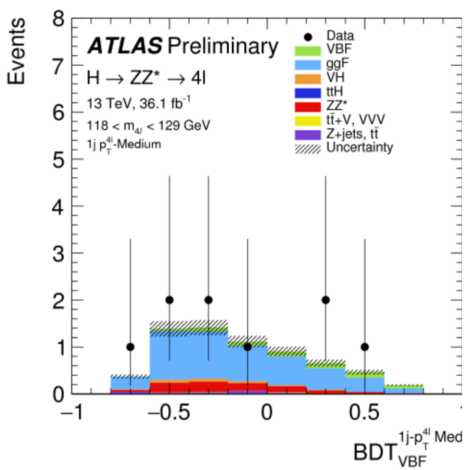
Discriminants in 5 event categories (ATLAS)

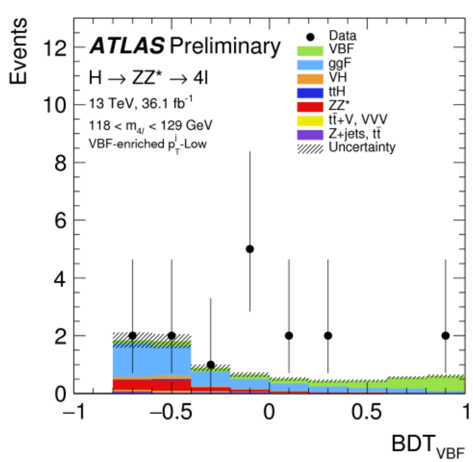


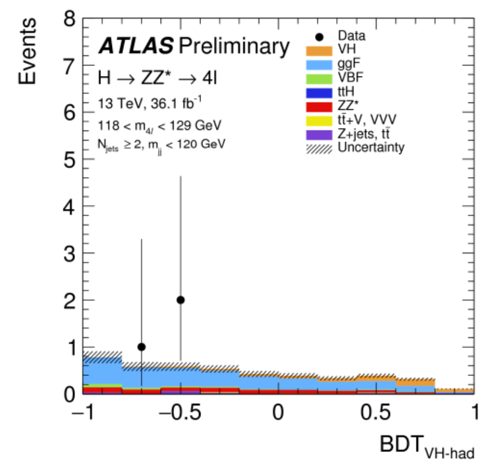
In order to further increase the sensitivity of
the cross section measurements for different production modes,
BDT discriminants are introduced in reconstructed event categories
with a sufficiently high number of events:

- (top left): ggF vs ZZ bkg
- (three on the bottom left): VBF vs ggF
- (bottom right): VH vs ggF+VBF

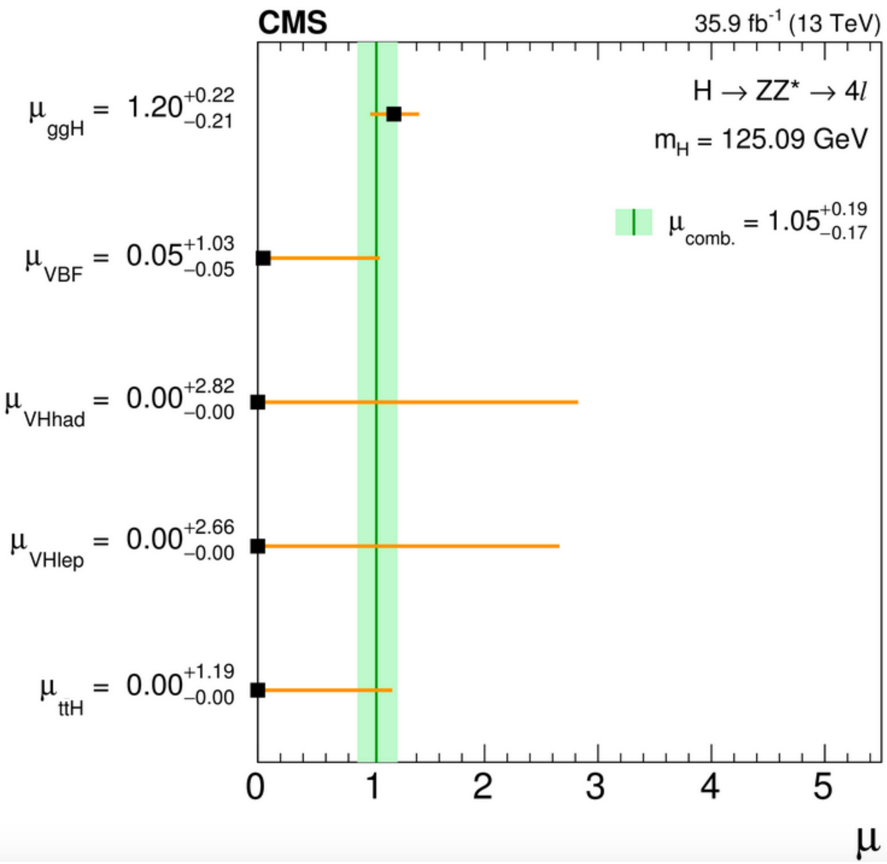


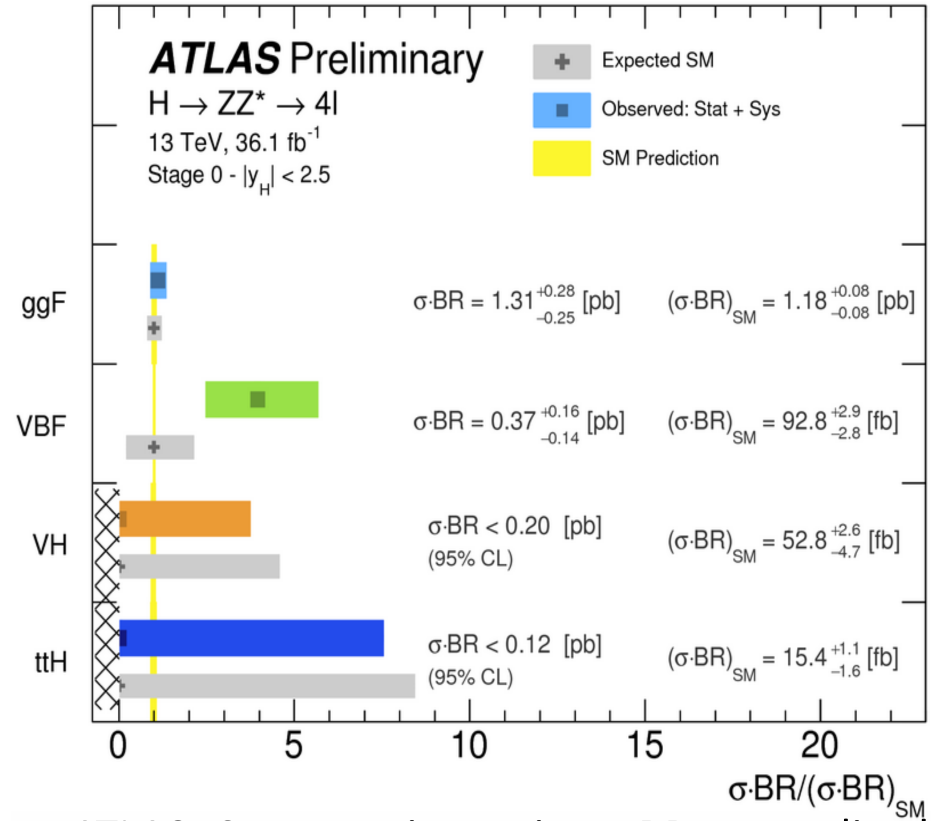






Measured signal strength for different production modes



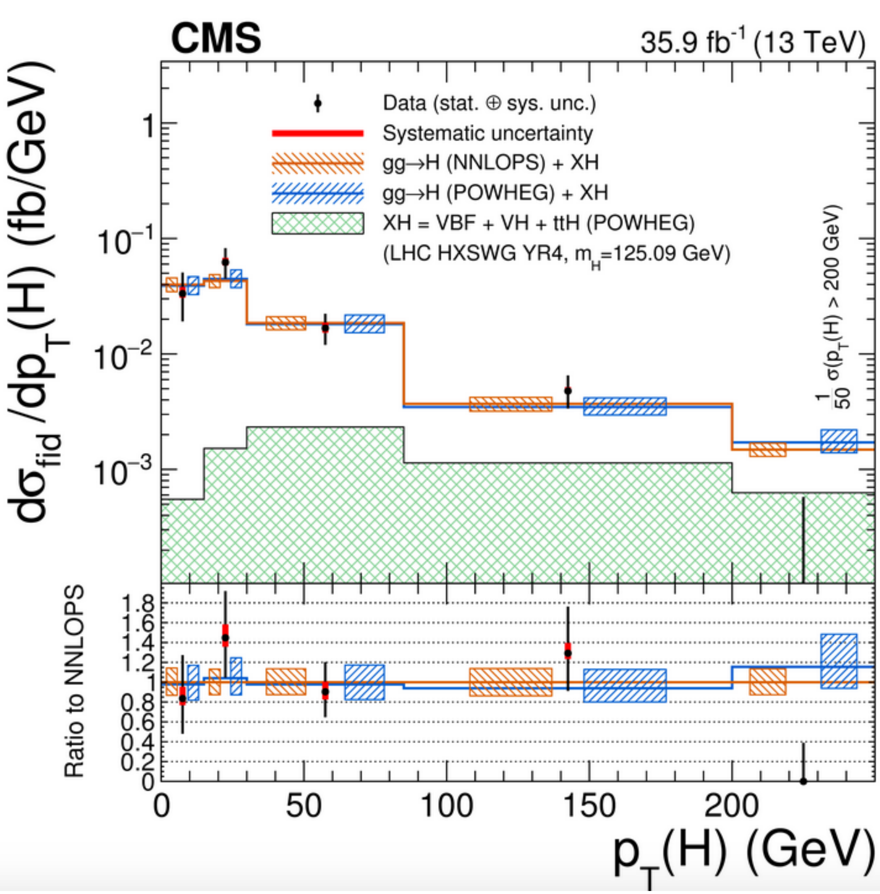


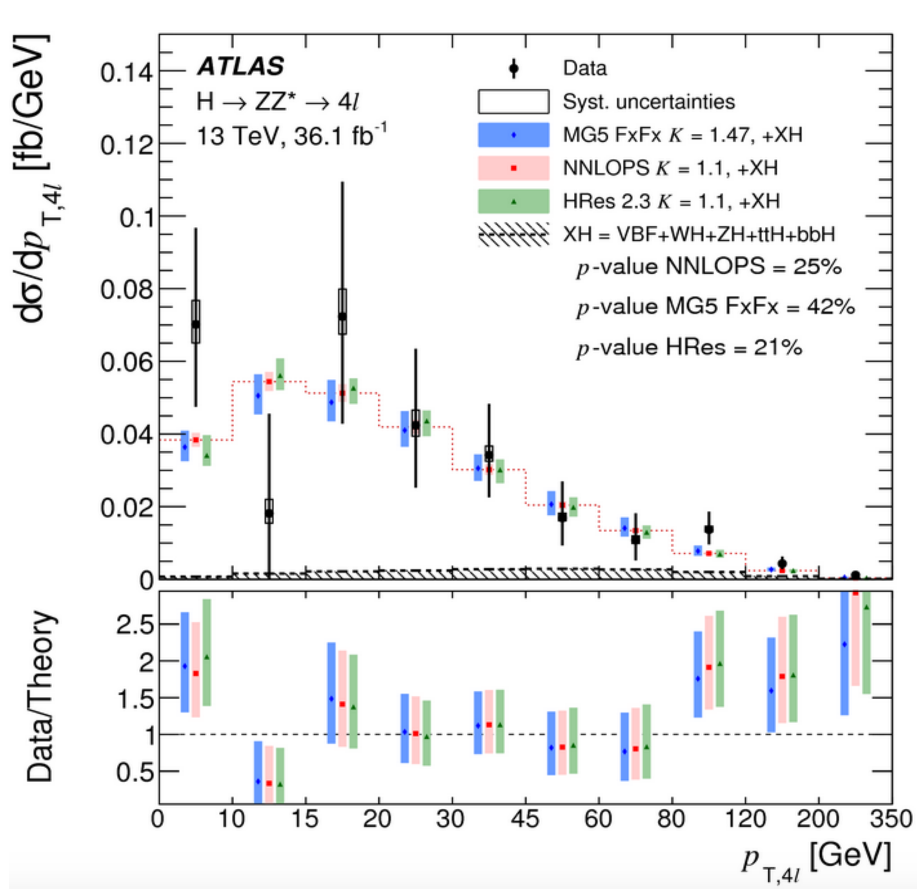
CMS: Signal strength modifiers $\mu=\sigma/\sigma_{SM}$ for the main SM Higgs boson production modes with ±1σ uncertainties.

ATLAS: Cross section ratios σ·BR, normalized by SM expectation $(\sigma \cdot BR)_{SM}$ for the main Higgs production modes.

Note: VH and ttH parameters are constrained to positive values (indicated by hashed area)

Higgs transverse momentum



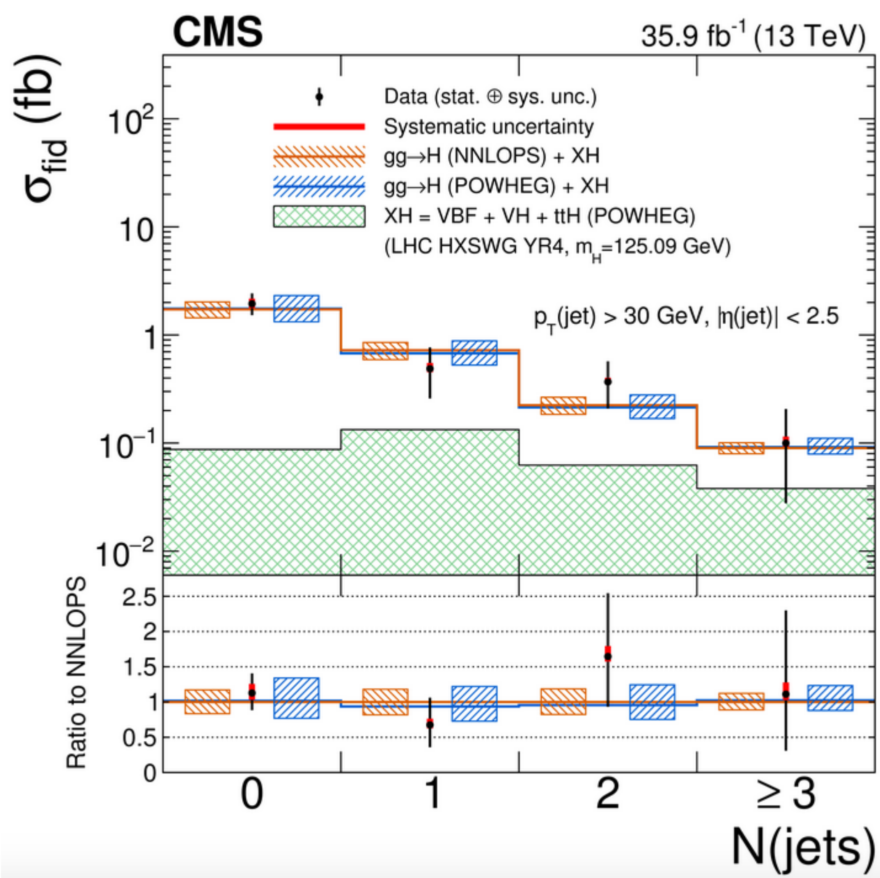


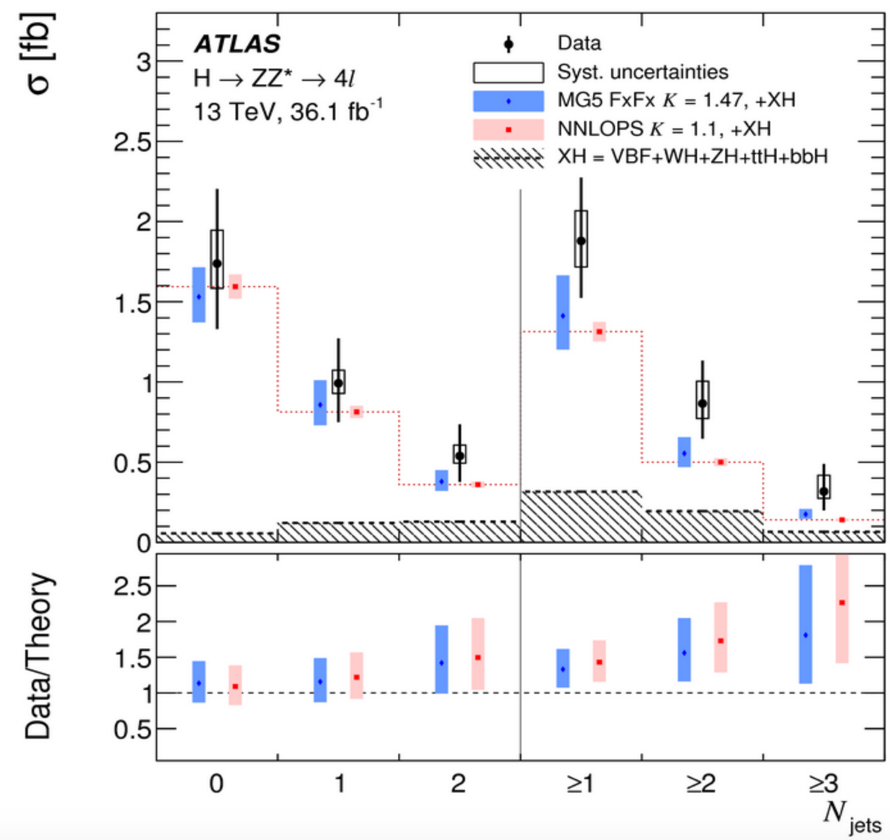
Differential cross section measurements as a function of the Higgs transverse momentum p_T(H).

Agreement with the SM observed

In the future statistics will allow to measure high P_T tail, potentially sensitive to BSM physics

Higgs differential cross section function of number of accompanying jets



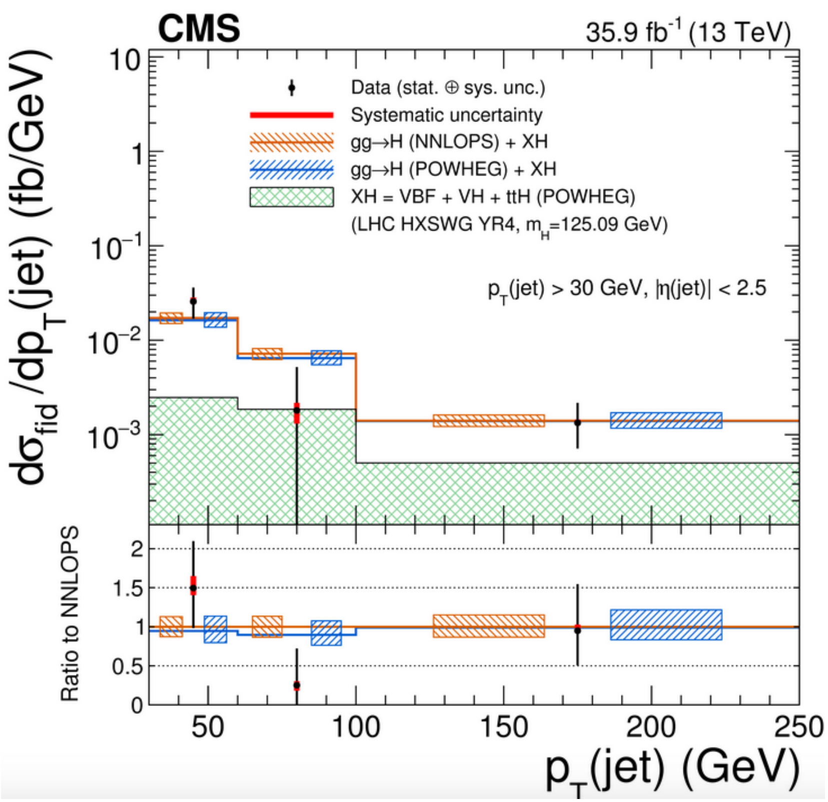


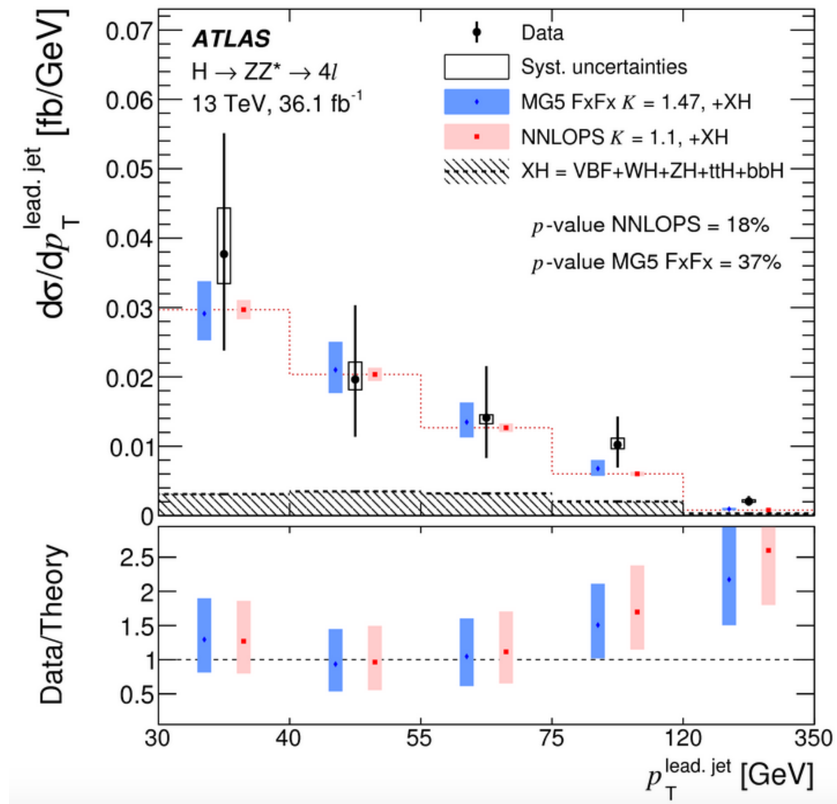
Differential cross sections shown for different number of jets in the events

Results are in agreement with SM calculations

Such a measurement allows to find a fraction in zero jets bin = experimental jet veto, used e.g. in H→WW measurements to suppress Top quark backgrounds

Higgs differential cross section, as a function of PT of the leading associated jet





Differential cross section for p_T(jet) of leading associated jet.
Results in agreement with SM

CMS: anomalous couplings from H→4l (2015+2016 datasets at 13 TeV)

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

Most generic amplitude of spin 0 decay to two Z particles.
a_1=2 describes SM Higgs decays to ZZ.
a_3 is CP violating term, very small in the SM
.

Measurements results for possible anomalous couplings:

Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$0.00^{+0.26}_{-0.09}$ $[-0.38, 0.46]$	$0.000^{+0.010}_{-0.010}$ $[-0.25, 0.25]$
$f_{a2}\cos(\phi_{a2})$	$0.01^{+0.12}_{-0.02}$ $[-0.04, 0.43]$	$0.000^{+0.009}_{-0.008}$ $[-0.06, 0.19]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.02^{+0.08}_{-0.06}$ $[-0.49, 0.18]$	$0.000^{+0.003}_{-0.002}$ $[-0.60, 0.12]$
$f_{\Lambda1}^{Z\gamma}\cos(\phi_{\Lambda1}^{Z\gamma})$	$0.26^{+0.30}_{-0.35}$ $[-0.40, 0.79]$	$0.000^{+0.019}_{-0.022}$ $[-0.37, 0.71]$

Here $f_{ai} = |a_i|^2\sigma_i \big/ \sum |a_j|^2\sigma_j$, and $\phi_{ai} = \arg\left(a_i/a_1\right)$

All measured parameters are consistent with SM.
Possible fraction of pseudo-scalar is less than ~40% at 95% conf level

ATLAS: anomalous couplings from H→4l

$$\mathcal{L}_0^V = \Big\{\kappa_{\rm SM}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W_\mu^+ W^{-\mu}\right]$$
$$-\tfrac{1}{4}\left[\kappa_{Hgg}g_{Hgg}G_{\mu\nu}^a G^{a,\mu\nu} + \tan\alpha\,\kappa_{Agg}g_{Agg}G_{\mu\nu}^a \tilde{G}^{a,\mu\nu}\right]$$
$$-\tfrac{1}{4}\tfrac{1}{\Lambda}\left[\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \tan\alpha\,\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right]$$
$$-\tfrac{1}{2}\tfrac{1}{\Lambda}\left[\kappa_{HWW}W_{\mu\nu}^+ W^{-\mu\nu} + \tan\alpha\,\kappa_{AWW}W_{\mu\nu}^+ \tilde{W}^{-\mu\nu}\right]\Big\}X_0.$$

Effective Lagrangian extension of the SM for Higgs, including possible BSM extensions of the SM.

K_{SM}, K_{Hgg} - modifiers for SM couplings to vector bosons and gluons, resp., = 1 in SM

K_{HVV}, K_{AVV} are CP even/odd BSM/anomalous couplings to vector bosons

K_{Agg} - CP odd BSM/anomalous coupling to gluons

Measurements results for possible anomalous couplings:

BSM coupling $\kappa_{\rm BSM}$	Fit configuration	Expected limit	Observed limit	Best-fit $\hat{\kappa}_{\rm BSM}$	Best-fit $\hat{\kappa}_{\rm SM}$	Deviation from SM
κ_{Agg}	$(\kappa_{Hgg}=1, \kappa_{\rm SM}=1)$	[-0.47, 0.47]	[-0.68, 0.68]	±0.43	-	1.8σ
κ_{HVV}	$(\kappa_{Hgg}=1, \kappa_{\rm SM}=1)$	[-2.9, 3.2]	[0.8, 4.5]	2.9	-	2.3σ
κ_{HVV}	$(\kappa_{Hgg}=1, \kappa_{\rm SM}$ free)	[-3.1, 4.0]	[-0.6, 4.2]	2.2	1.2	1.7σ
κ_{AVV}	$(\kappa_{Hgg}=1, \kappa_{\rm SM}=1)$	[-3.5, 3.5]	[-5.2, 5.2]	±2.9	-	1.4σ
κ_{AVV}	$(\kappa_{Hgg}=1, \kappa_{\rm SM}$ free)	[-4.0, 4.0]	[-4.4, 4.4]	±1.5	1.2	0.5σ

The data are consistent with the SM, with the largest deviations of about 2σ.

Exclusion limits are set on the CP-even and CP-odd BSM couplings of the Higgs to vector bosons, and on the CP-odd BSM Higgs coupling to gluons.

Summary

The H125 GeV properties at Run II pp-collisions energy of 13 TeV, using 2015+2016 datasets, are measured for Higgs→4l decays with statistics larger than in Run I

All the measurements agree with the Standard Model predictions.

The H125 boson still looks like the SM Higgs, no deviations observed.

Still plenty of room for deviations from SM Higgs (within errors) exist. We are at the beginning of the program of precision measurements of the H125 GeV particle, with a hope to find BSM physics via deviations from the SM predictions.

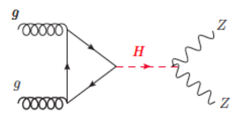
Higgs boson is very unusual, and studying it may be a good way to look for the new physics Beyond the Standard Model.

Backup

Off-shell production (Γ and couplings)

- Breit-Wigner production gg→H→ZZ:

$$\boxed{\frac{d\sigma}{dm^2} \sim g_g^2 g_Z^2 \frac{F(m)}{(m^2 - m_{\rm H}^2)^2 + m_{\rm H}^2\Gamma_{\rm H}^2}}$$

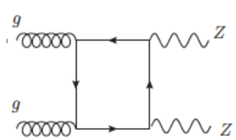


- <u>On-peak</u> and <u>off-peak</u> cross sections:

$$\boxed{\sigma^{\rm on-shell} = \int_{|m-m_{\rm H}|\leq n\Gamma_{\rm H}} \frac{d\sigma}{dm}\cdot dm \sim \frac{g_g^2 g_Z^2}{m_{\rm H}\Gamma_{\rm H}}}$$

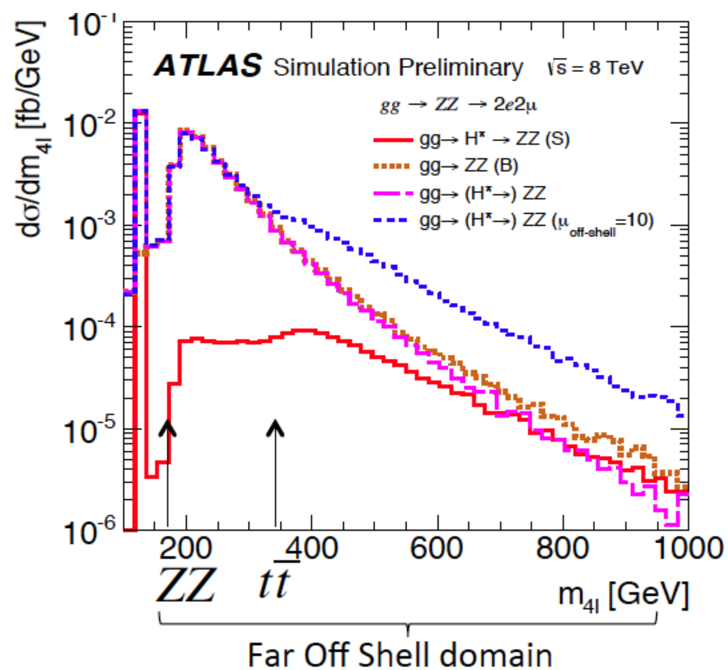
$$\boxed{\sigma^{\rm off-shell} = \int_{m-m_{\rm H}\gg\Gamma_{\rm H}} \frac{d\sigma}{dm}\cdot dm \sim g_g^2 g_Z^2}$$

- <u>**Off-peak to on-peak ratio**</u> ~ $\boxed{\frac{\sigma^{\rm off-shell}}{\sigma^{\rm on-shell}} \sim \Gamma_{\rm H}}$
- (red curve on the plot)
- **The picture** gets **more complicated due interference with non-resonant gg→ZZ**



F(m) depends on:

- phase space for H→ZZ
- partonic gg-luminosity
- Hgg coupling evolution with m_{H^*}
- tensor structure Hgg coupling



	ATLAS (ZZ)	CMS (ZZ+WW)
limits on off-shell production rate $\mu = \sigma^{\rm off\text{-}shell}/\sigma^{\rm off\text{-}shell}_{\rm SM}$	**< 6.7**	**< 2.4**
limits on $\Gamma/\Gamma_{\rm SM}$ ($\Gamma_{\rm SM}$ = 4.1 MeV)	**< 4.8 (20 MeV)**	**< 3.2 (13 MeV)**