Higgs physics with ATLAS at the LHC

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A bit of history

Why did we build LHC ?

1961-1968 - Glashow, Weinberg, Salam: formulation of the framework of the Standard Model providing a formalism for unification of the electromagnetic and weak interactions.

1970-1980 - verification of most of the predictions and observation of the neutral currents: short range → carriers of the weak force must be heavy

1983 - discovery of the W and Z bosons at CERN SPS

Persistent problem: electroweak symmetry is broken – photon is massless while W and Z are heavy

The Higgs mechanism: scalar field can differentiate the masses of carriers without breaking the symmetry of the interactions. Proposed in 1964 by Higgs, and Brout and Engler, and Kibble, Guralnik and Hagen (and earlier by Anderson in context of solid state)

Higgs boson - consequence of the scalar field. Its mass was unknown but esthetics implied it to be of the same order as W and Z triplet

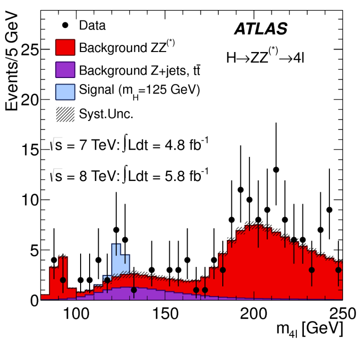
Searches for indirect effects in e+e- precision experiments were unsuccessful -> need a dedicated "discovery" machine.

A bit of recent history

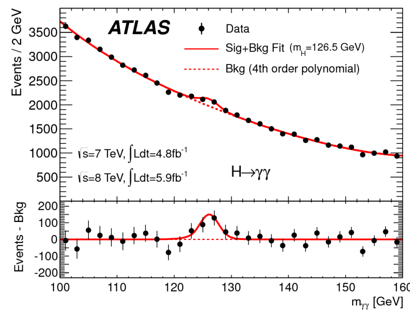
July 4th, 2012

Announcement of the Higgs discovery in bosonic channels H -> γγ, H -> ZZ* -> 4l consistent with production via gluon fusion.

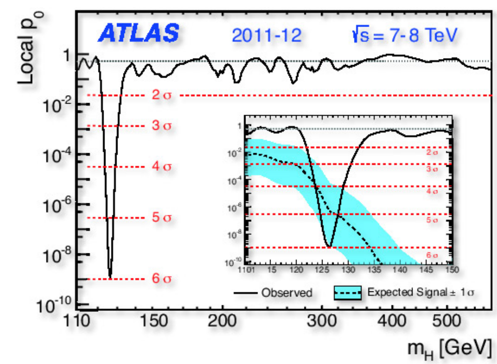
ATLAS, H -> 4 l



ATLAS, H -> γγ



ATLAS, combined



4 independent observations:
2 channels in 2 experiments – ATLAS + CMS

Probability of ~ 10^{-10} that these observations are due to background fluctuation

2012

- Further observation of H -> WW -> lνlν with l = electron or muon

consistent with production via gluon fusion

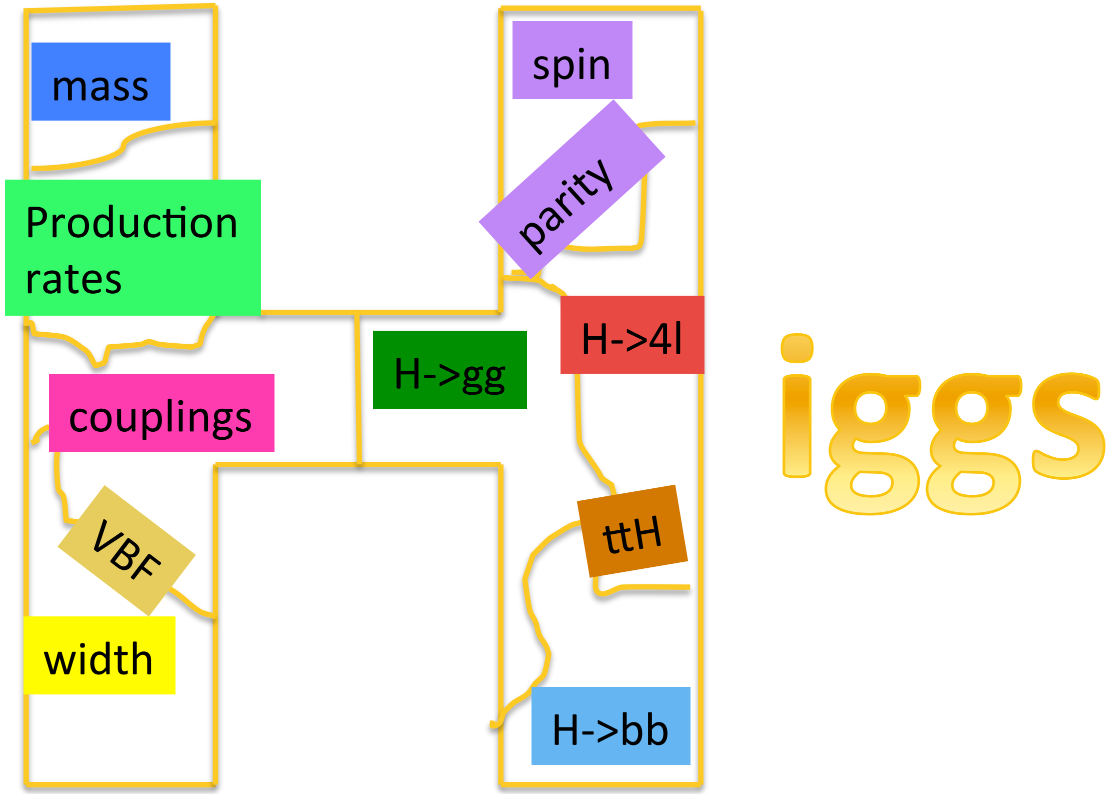
2013-2014

- Evidence for decays to fermions H -> ττ, VH -> bb
- First measurement of properties (mass, spin, couplings)
- Search for new production modes (VBF, ttH, ggH, VH…)

2015

- Final results from LHC Run 1 with improved detector calibrations and using complete data sets
- Evidence for VBF
- Greatly improved theoretical calculations including many interference effect
- June - Start of Run 2 – no results yet

As of May 2015: 56 publications, 98 conference papers, ~10 in preparation



Too many subjects -> selected topics from among recent ATLAS results
Concentrate on final analyses of Run 1

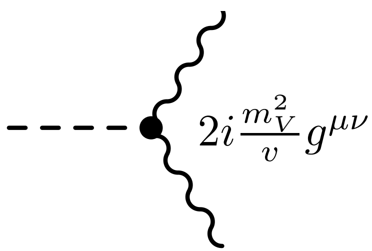
1. Higgs boson mass (M_H) & width (Γ_H)
2. Higgs boson couplings to gauge bosons (g_V) and fermions (g_F)
3. Higgs boson quantum numbers J^{PC}

Standard Model Lagrangian - Higgs sector

$$L_{SM} = D_\mu H^+ D_\mu + \mu^2 H^+ H - \frac{\lambda}{2}(H^+ H)^2 - (y_{ij} H \overline{\psi_i} \psi_j + h.c.)$$

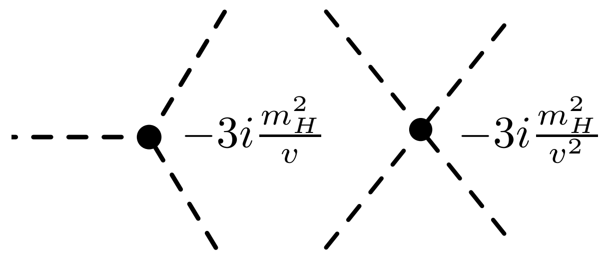
Couplings to EW gauge bosons

$$[m_W^2 W^{\mu+} W_\mu^- + \tfrac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0] \cdot (1 + \tfrac{h}{v})^2$$



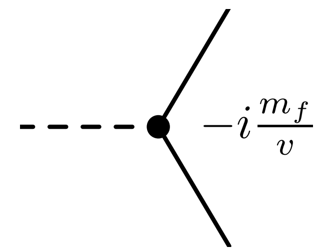
Higgs self-couplings

$$-\mu^2 h^2 - \tfrac{\lambda}{2} v h^3 - \tfrac{1}{8} \lambda h^4$$



Couplings to fermions

$$-\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$$



$$m_H = \sqrt{2}\mu = \sqrt{\lambda} v$$

$v =$ vacuum expectation value

m_H – only parameter not fixed in SM

LHC Goals

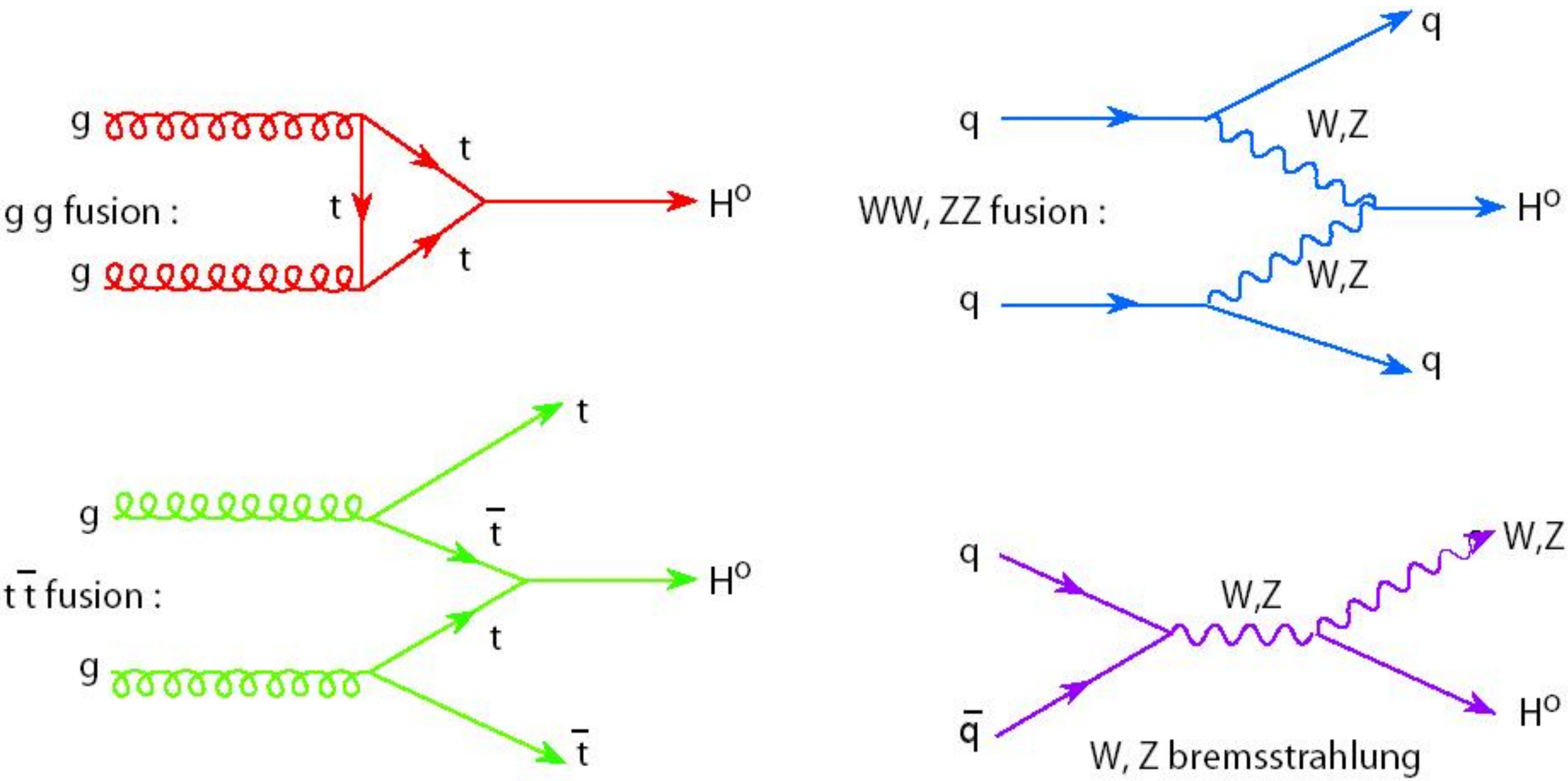
- verify Standard Model Lagrangian
- measure Higgs boson parameters
- search for physics beyond the Standard Model

Production

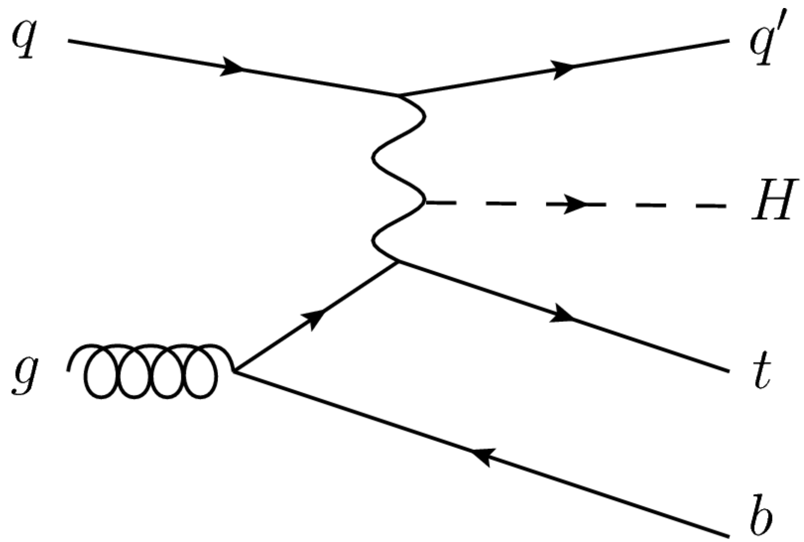
and

Decays

Production - dominant processes



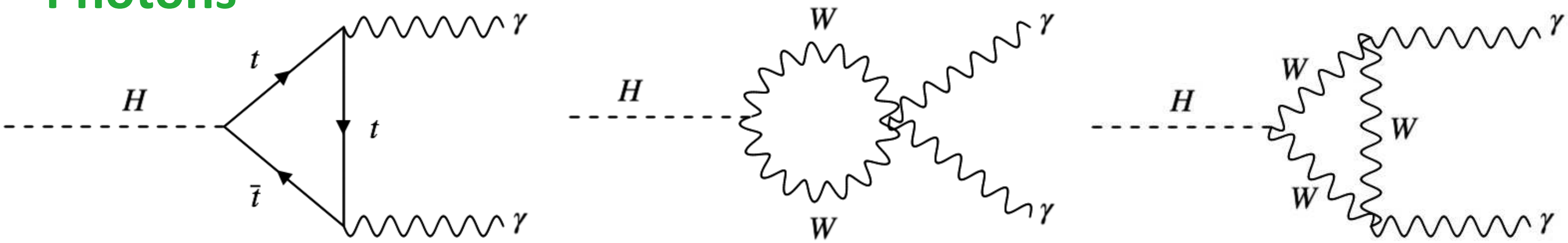
More complex diagram are possible with a penalty of multiple couplings



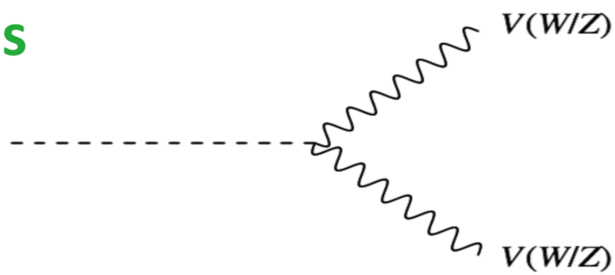
Important higher order corrections

Decays

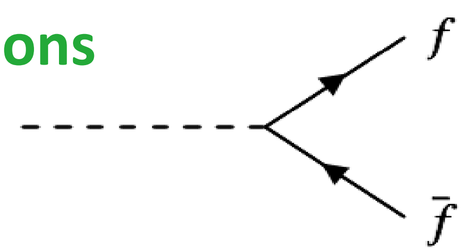
Photons



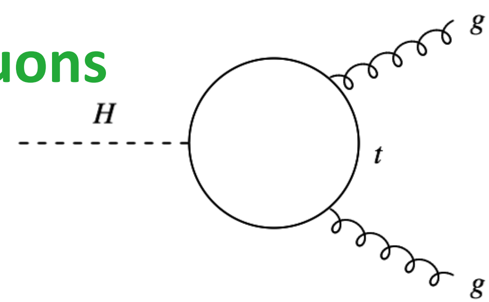
Vector bosons



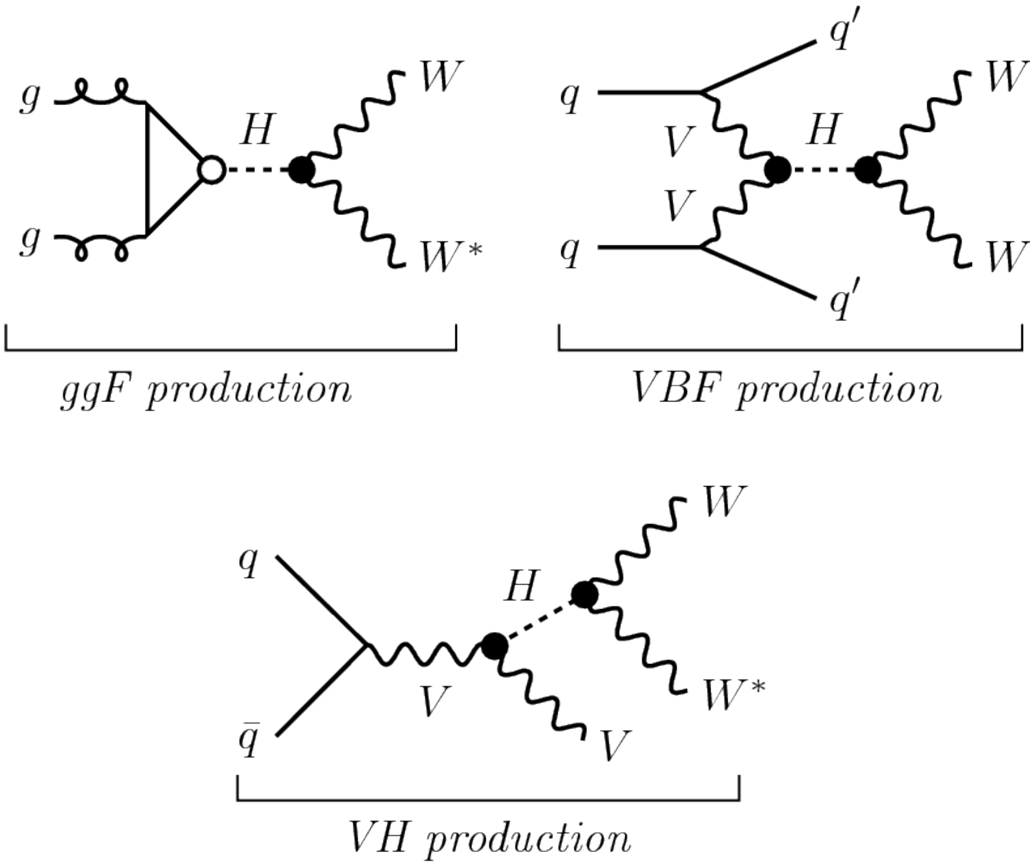
Fermions



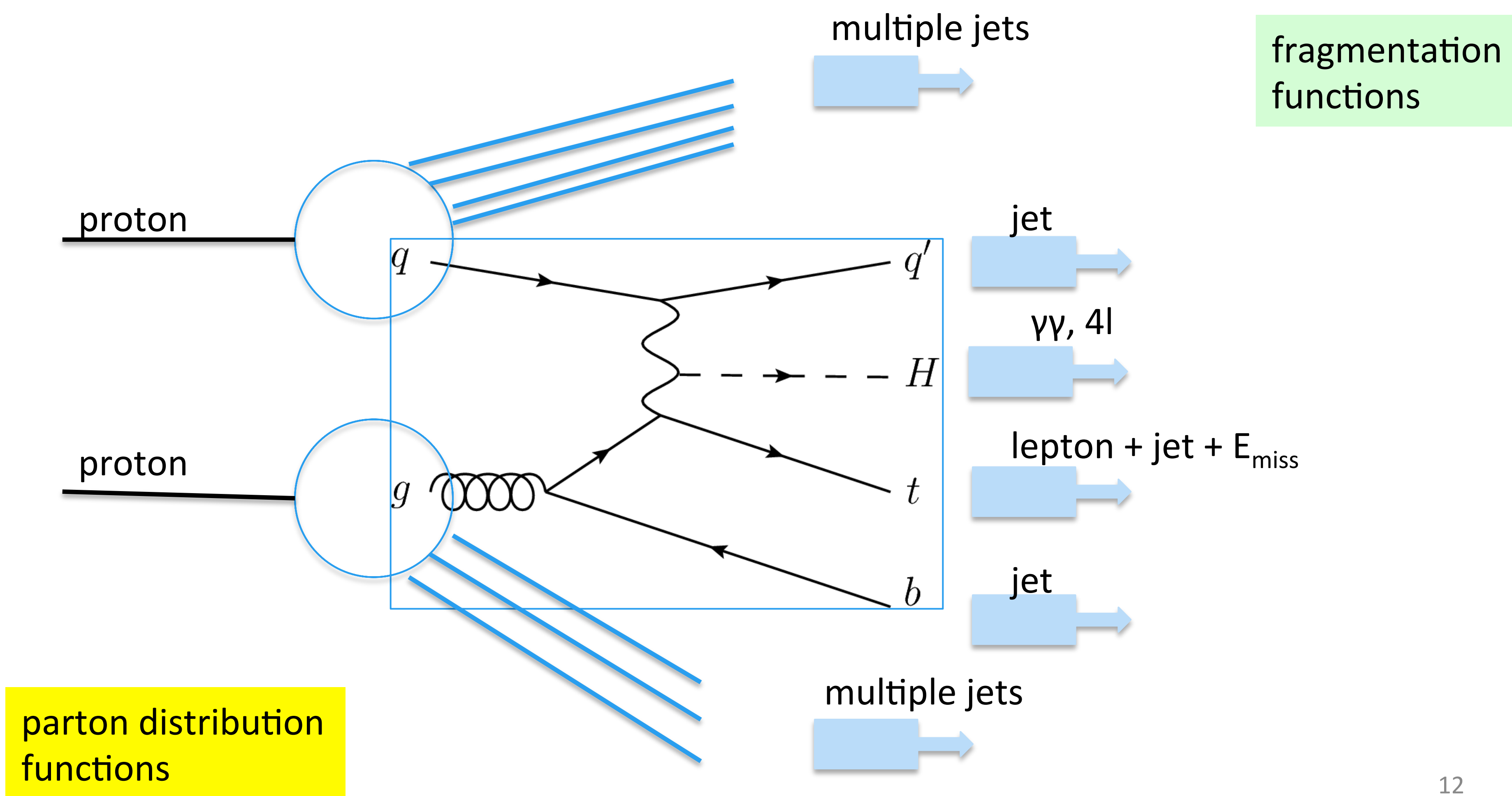
Gluons



Production + decay - theorist's view



Production + decays – experimenter's view



Event Classification

Higgs decay is independent of the production mechanism. However, different production mechanisms imply different kinematical distributions and therefore different acceptances and detection efficiencies.

→ For precision measurement it is important to separate Higgs production channels.

Difficult and possible only for a fraction of cases.

Topology of events (extra jets, additional leptons or missing energy) allows for partial separation of production mechanisms.

“Experimental” Tools

- Search for new physics – comparison of data with theoretical expectations

- “Hermetic” detectors ATLAS + CMS (2 experiments with different emphases on detection techniques)

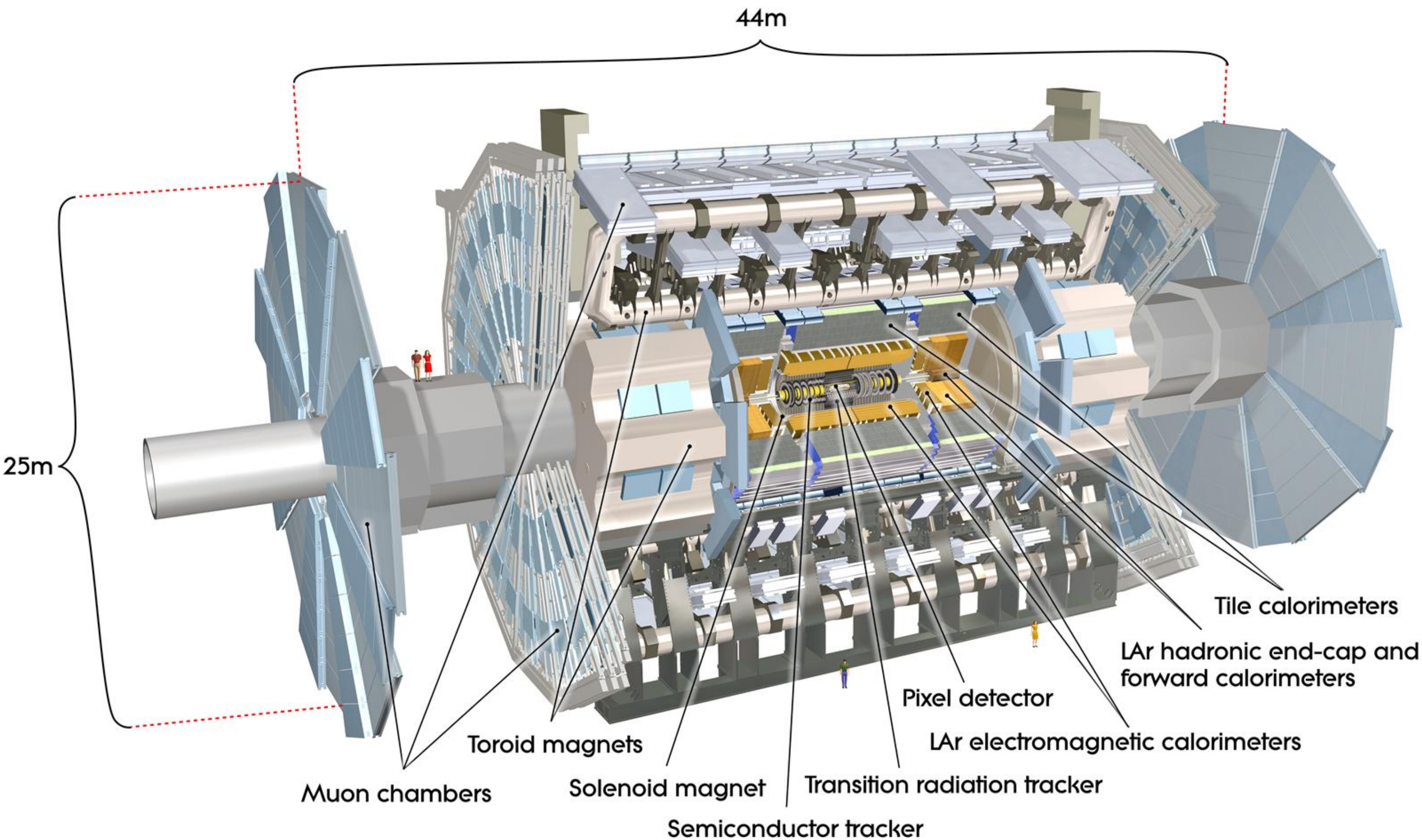
- Signature of new physics: photons, leptons, jets, missing energy

- Data provided by the detector signals from which we extract for each event:
  - hadronic jets – precision tracking in magnetic field
  - muon momentum measurement – muon spectrometer
  - photon/electron identification – electromagnetic calorimeter
  - energy measurements – hadronic and electromagnetic calorimeters
    - use production of known particles (J/ψ,Z) for calibration
  - missing energy – hermeticity requirement on the detector

- Theory – Monte Carlo simulations of known processes (many approaches)

- Small signals, many large backgrounds -> need statistical methods to asses significance of observations

ATLAS Detector



Statistical method

Extended likelihood function for (signal + background): *L*(α,ν)

signal pdf · background pdf · ancillary pdfs

$$-\ln L(\alpha,\nu) = (n_s + n_b) - \sum_e \ln[\underbrace{n_s \cdot f_s(x_e \mid \alpha, \nu_s)}_{\text{signal pdf}} + \underbrace{n_b \cdot f_b(x_e \mid \nu_b)}_{\text{background pdf}}] - \underbrace{\sum_k \ln \pi_k(\nu_k)}_{\text{ancillary pdfs}}$$

n_s, n_b - signal / background yields
x_e - observables
f_s, f_b - signal / background pdfs
α - parameter of interest (mass, couplings, cross-section,…)
ν - "nuisance parameters" (shape parameters, systematics,….)
π_k - pdfs obtained from auxiliary measurements

Many variables + many signal + background processes → many terms

Likelihood fits

Confidence intervals (value ± error), limits and significances are based on the **Profile Likelihood Ratio**

$$\Lambda(\alpha) = \frac{L(\alpha, \hat{\hat{\nu}}(\alpha))}{L(\hat{\alpha}, \hat{\nu})}$$

likelihood for fixed α and profiled ν

maximum likelihood for free α, ν

$\hat{\hat{V}}$ is the conditional best fit for a particular value of α

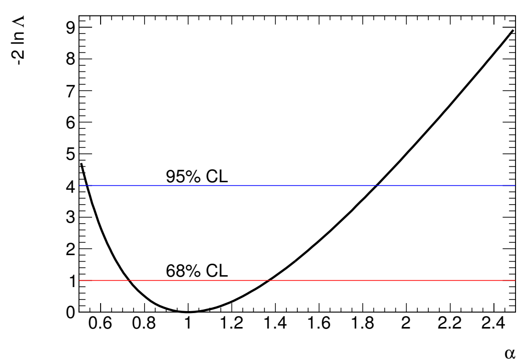
$\hat{\nu}$ is the best-fit α

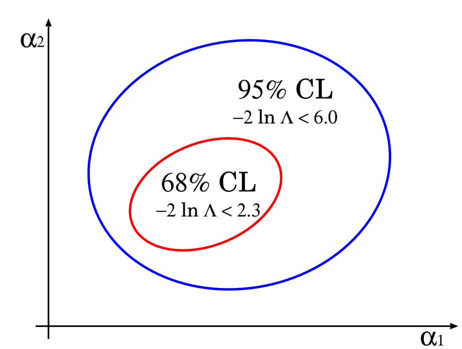
To **combine** – multiply the likelihood terms

Test statistics: $q_\alpha = -2 \ln \Lambda(\alpha)$

Wilks theorem: if $\alpha = \alpha_{true}$, then q_α follows a χ^2 distribution

compute **confidence interval**





Pseudo-experiments

Selected candidate events represent a small subsample of all produced signal events. They may all be in a tail of a distribution of a particular discriminant.

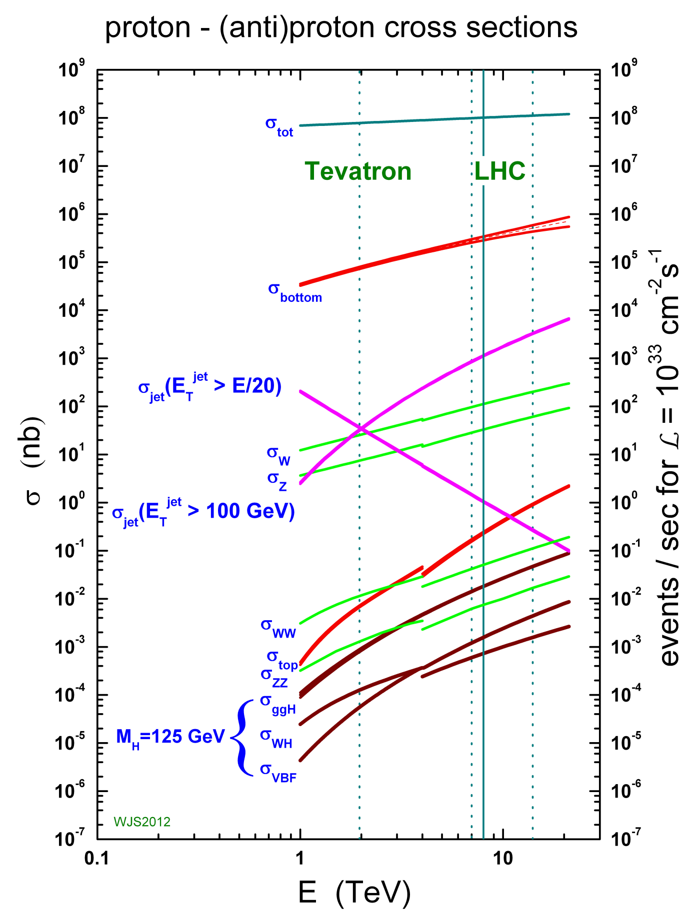
-> Need to estimate the probability of this selection, e.g., for VBF process how often there are two separated jets fulfilling selection criteria.

Estimated by generating large number (~10^4) of Monte Carlo data sets with the same number of events with full reconstruction and applying selection criteria.

Cross sections at LHC

Higgs cross section overwhelmed by QCD

process	cross section (pb) at √s = 8 TeV	events/s at L-10^{33} cm^{-2} s^{-1}
low-Q^2 QCD (minimum bias)	≈10^{11}	≈ 10^8
high-Q^2 QCD	≈10^9	≈ 10^6
W production	≈10^5	≈ 100
Z production	≈$5 \cdot 10^4$	≈ 50
ttbar production	≈240	≈ 0.24
SM Higgs	≈22	≈ 0.022



Need to apply several filters starting from the on-line trigger and then in off-line analysis

selection based on isolated leptons, photons, jets with high p_T and large missing energy

Higgs Boson Production Rates

Run 1 integrated luminosity: ~ 5 fb^{-1} at √7 TeV and ~20 fb^{-1} at √s = 8 TeV

At √8 TeV: total pp cross section ~ 70 mb

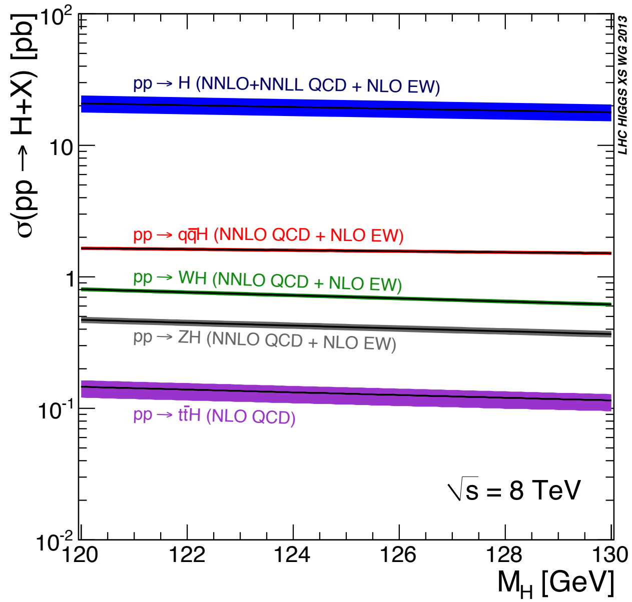
total Higgs production cross section ~ 22 pb

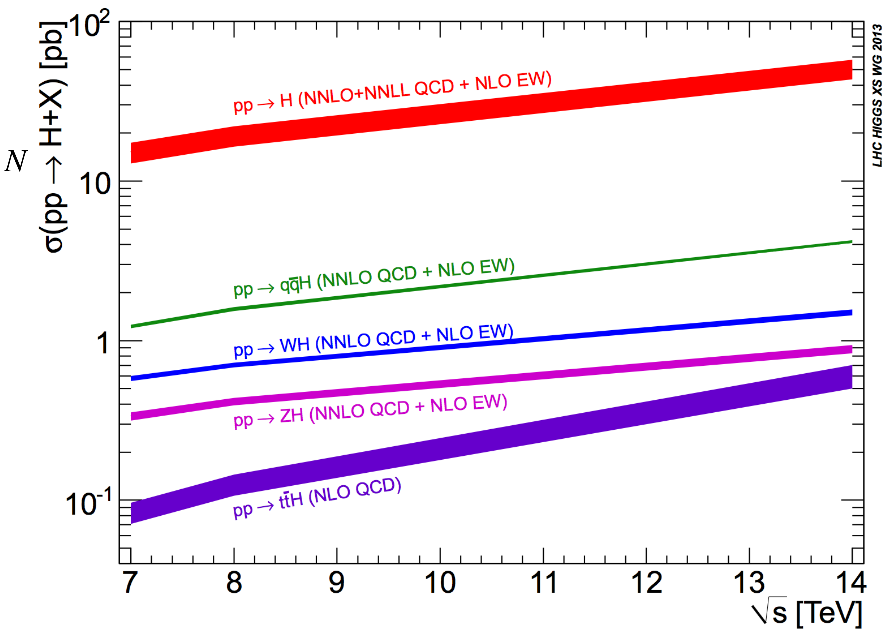
★ ~500,000 Higgs produced in Run 1

$$N_{ev} = \sigma \cdot \int L \cdot A \cdot E_{ff}$$

★ only 1 in 10^{10} events contains Higgs

8 TeV *pp* collisions





Small dependence on Higgs mass

Factor 2-4 increase with energy for Run 2.
Large phase space increase for ttH.

Production cross sections and decay rates

Production process	Cross section (pb) $\sqrt{s} = 7$ TeV	Cross section (pb) $\sqrt{s} = 8$ TeV
ggF	15.0 ± 1.6	19.2 ± 2.0
VBF	1.22 ± 0.03	1.57 ± 0.04
WH	0.573 ± 0.016	0.698 ± 0.018
ZH	0.332 ± 0.013	0.412 ± 0.013
bbH	0.155 ± 0.021	0.202 ± 0.028
ttH	0.086 ± 0.009	0.128 ± 0.014
tH	0.012 ± 0.001	0.018 ± 0.001
Total	17.4 ± 1.6	22.3 ± 2.0

Decay channel	Branching ratio (%)
$H \to bb$	57.1 ± 1.9
$H \to WW^*$	22.0 ± 0.9
$H \to gg$	8.53 ± 0.85
$H \to \tau\tau$	6.26 ± 0.35
$H \to c\bar{c}$	2.88 ± 0.35
$H \to ZZ^*$	2.73 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.157 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

Handbook of LHC Higgs cross sections http://arxiv.org/pdf/1307.1347

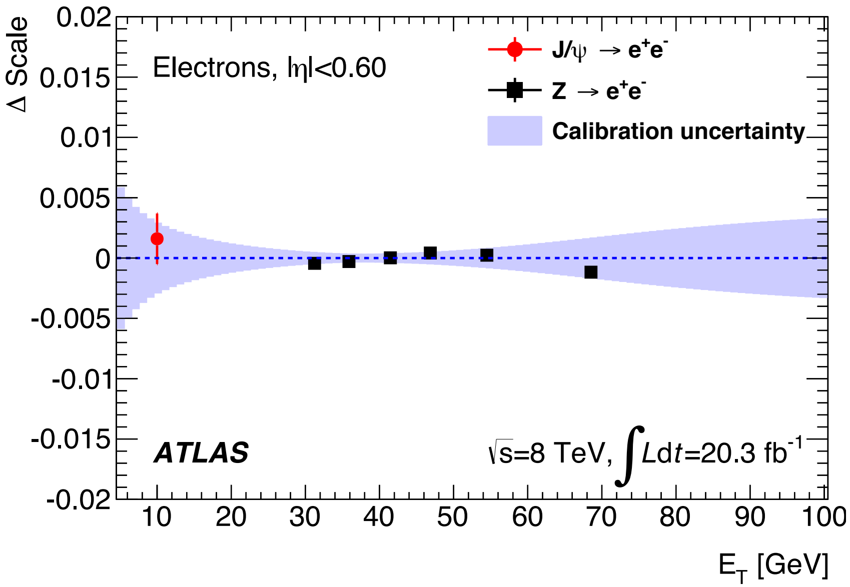
Each Higgs decay channel suffers (after filters) from QCD backgrounds with rates that are typically $10^5 - 10^6$ higher than rates expected for the signal.

Higgs Mass
and
Cross Section

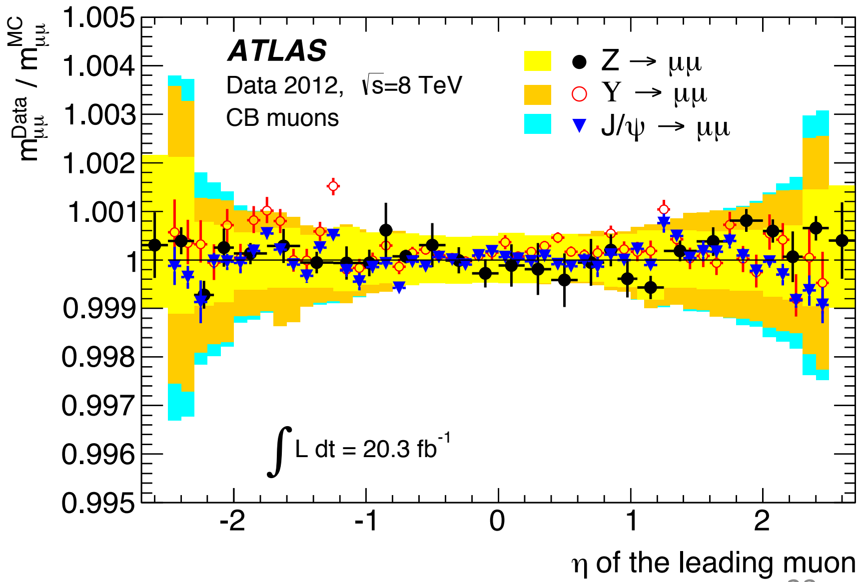
Higgs Mass and Production Rates Experimental Details

- Mass - Most precisely determined with H -> γγ and H –> 4 leptons channels
- Precise measurements of low p_T leptons down to 5-7 GeV are important
- Detector calibrations: ECAL (e/γ) and muon systems extremely important.
  ->ATLAS calibration reached precision below few per mille
- Energy scale from J/ψ, Y, Z decays to e+e- and μ+μ-

Electron calibration



Muon calibration



Phys. Rev. D. 90, 052004 (2014)

Event selection

H -> γγ - large signal, clean but with large irreducible background

- several categories of photons:
  - unconverted
  - converted to e+e- with two tracks reconstructed
  - converted with one track reconstructed
- several classes of production mechanisms

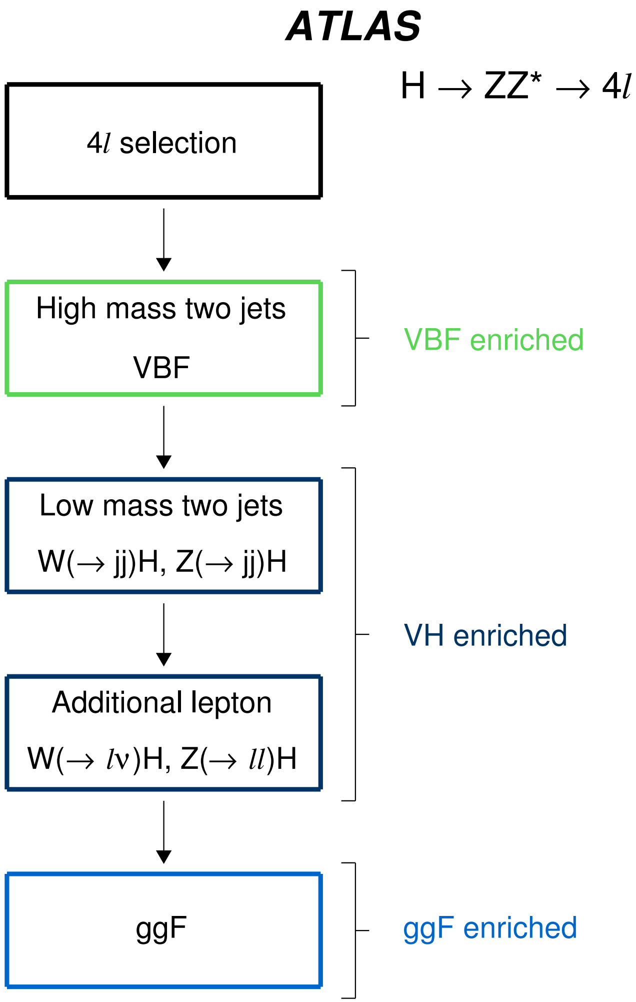
H -> ZZ*-> 4 leptons **-** small statistics but large signal/background ratio

- four separate final state channels:
  - ZZ* -> 4 electrons
  - ZZ* -> 4 muons
  - Z -> 2 electrons, Z* -> 2 muons
  - Z -> 2 muons, Z* -> 2 electrons
- Several classes of production mechanisms

For each category and decay channel there are different efficiencies, backgrounds and different systematic errors

Higgs -> 4 lepton event selection

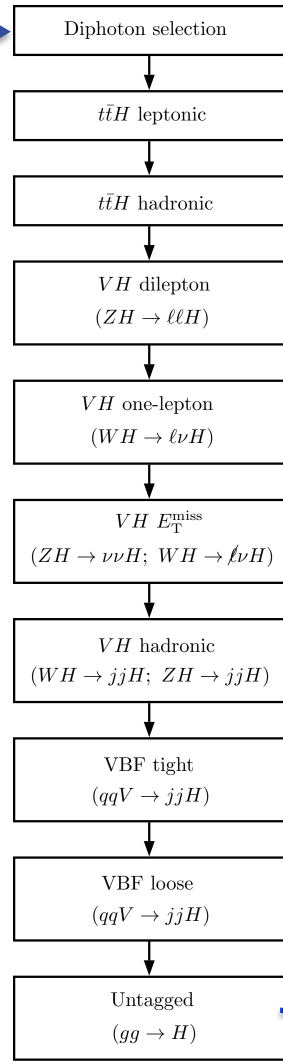
- Separate out most likely candidates for low-rate processes.
- Put everything else into dominant category.
- Introduce selection uncertainty into error estimate



Diphoton event selection and classification

photon selection

Unconverted photons
Two-track photon conversions
“One-track” photon conversions



event selection

detector region selection

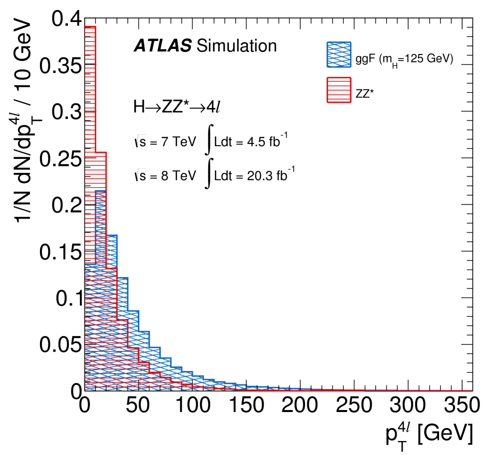
Central/forward
Low pt/high pt

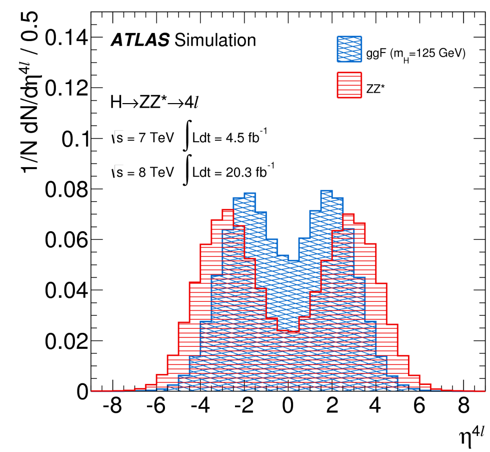
Sum individual contributions from 14 different categories with weights corresponding to selection efficiencies (see later ~300 fit parameters)

BDT -Multivariate discriminant construction

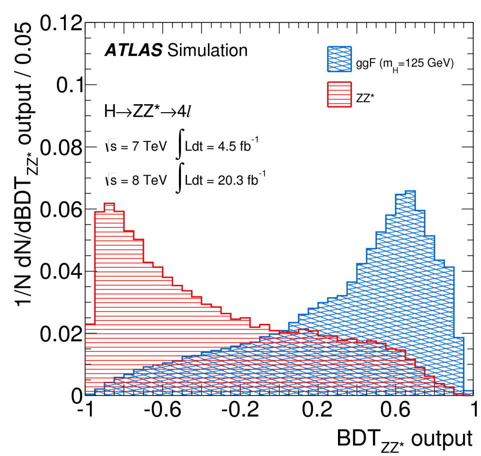
Need to separate H->ZZ* signal from ZZ* background and separate ggF production from VBF production mode. Use MC simulations using matrix element calculations (MadGraph5).

signal vs background distributions





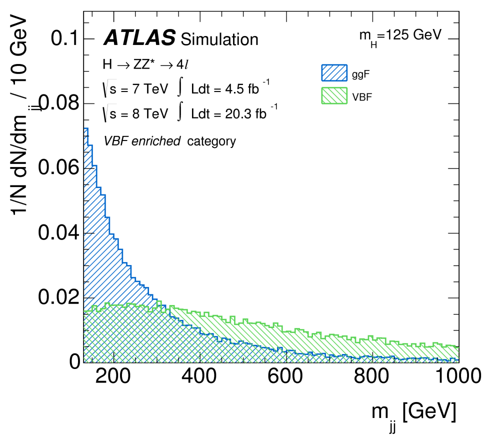
signal vs background separation

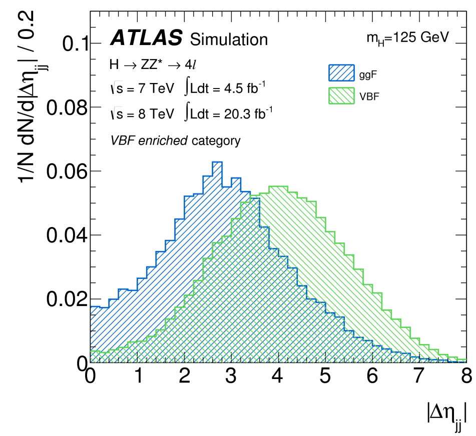


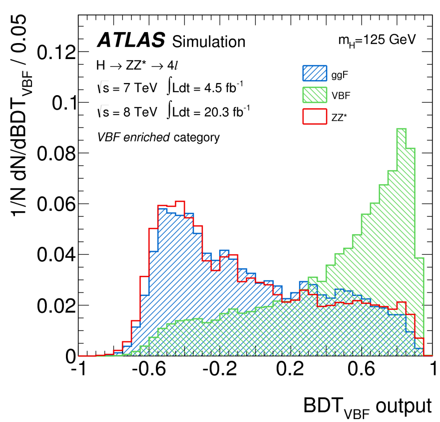
Discriminant of ggF vs VBF

VBF - 5 additional variables for extra jets:
invariant mass of two jets, Δη separation of jets, p_T of each jet, η of leading jet

simulated distributions for ggF vs VBF



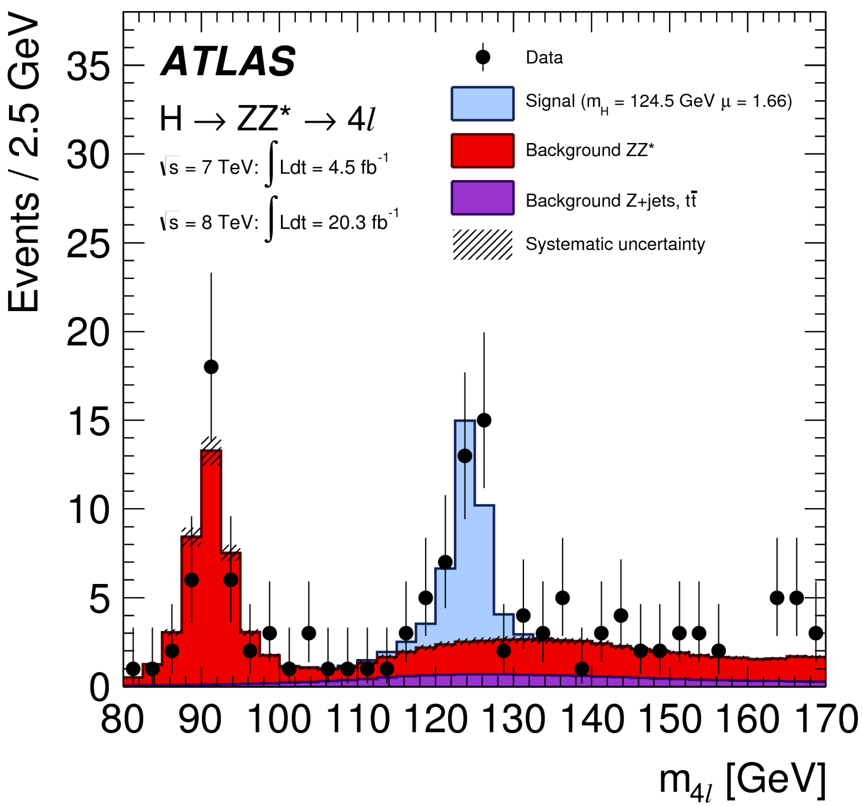


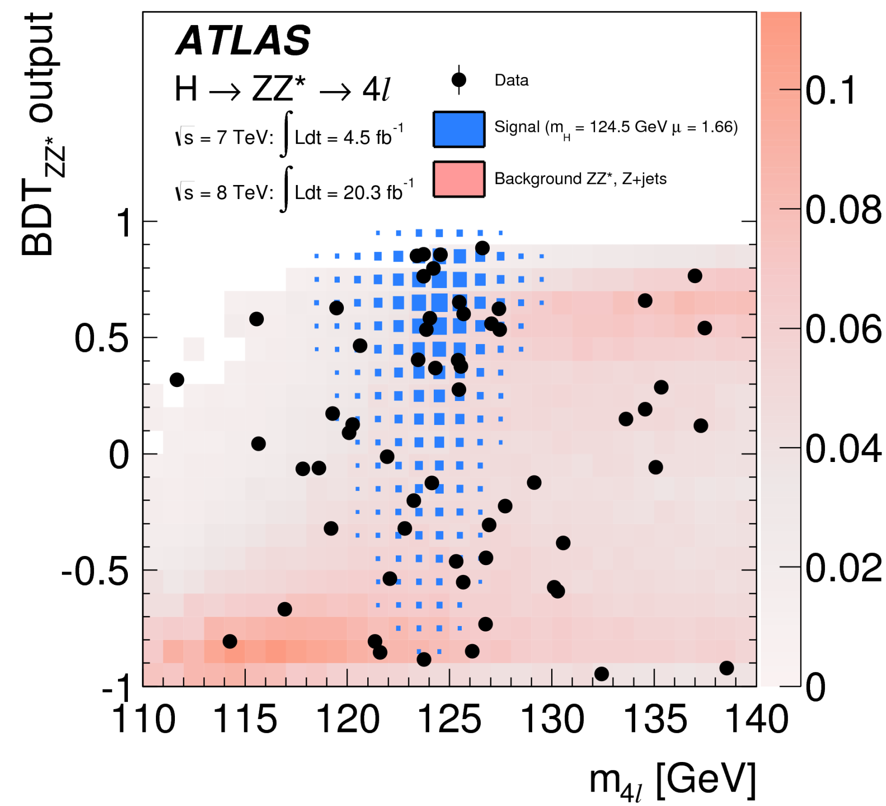


final discriminant

H→ ZZ* → 4l

Boosted Decision Tree (BDT) 2D analysis trained on simulated signal and ZZ* background events



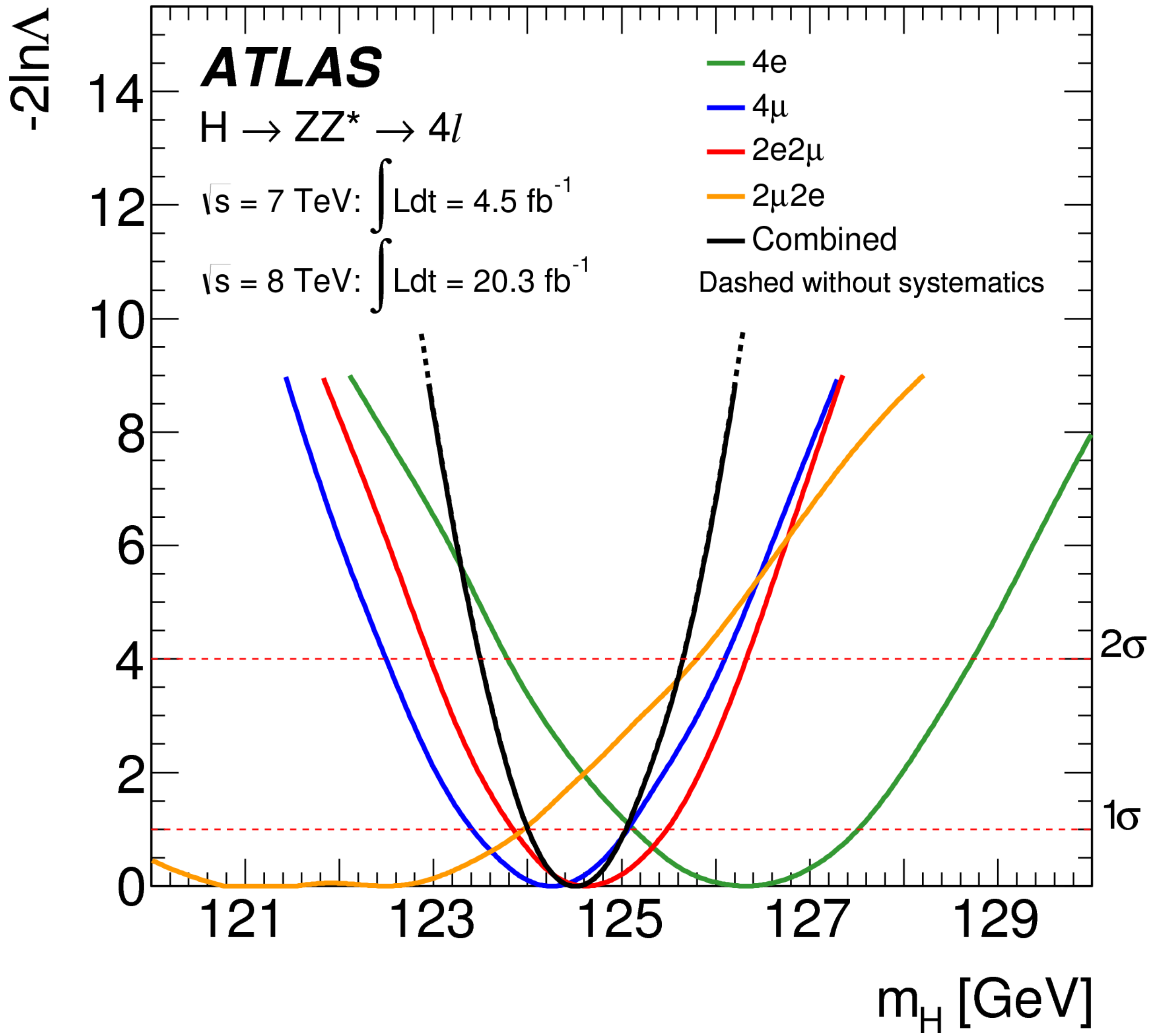


ATLAS **$m_H = 124.51 \pm 0.52$ ($\pm$ 0.52 (stat) $\pm$ 0.04 (syst)) GeV**

CMS $m_H = 125.59 \pm 0.45$ ($\pm$ 0.42 (stat) $\pm$ 0.17 (syst)) GeV

ATLAS: Phys. Rev. D. 90, 052004 (2014)
CMS: Phys. Rev. D. 89, 092007 (2014)

Detail check - Does mass depend on the 4l decay mode?
→No significant mass difference between different 4 lepton channels

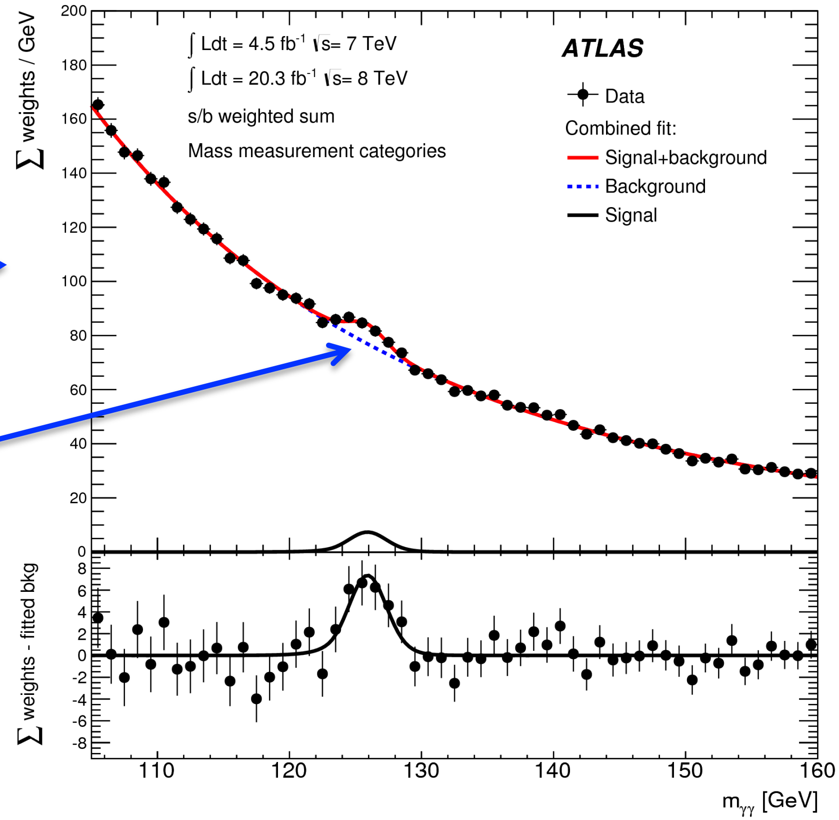


H→γγ

weights derived independently for each category

~300 events

observed weighted signal - background

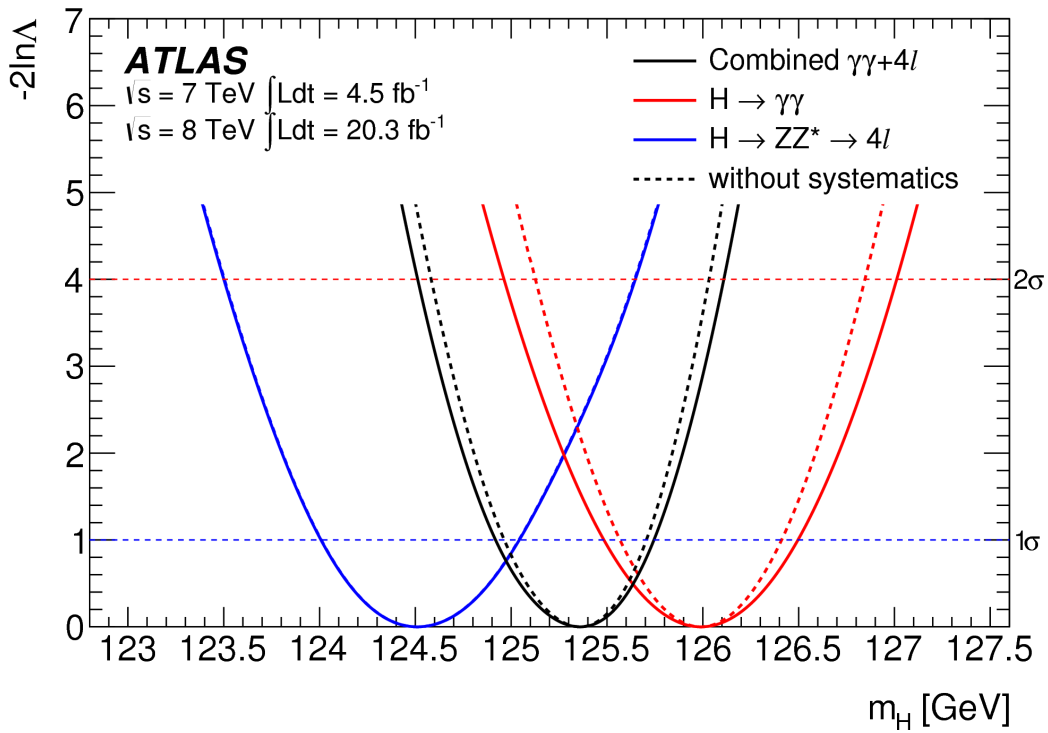


ATLAS **m_H = 126.02 ± 0.51 (± 0.43 (stat) ± (0.27 (syst)) GeV**

CMS m_H = 124.70 ± 0.45 (± 0.31 (stat) ± (0.15 (syst)) GeV

ATLAS: Phys. Rev. D. 90, 052004 (2014)
CMS: Eur. Phys. J. C. 74, 3076 (2014)

H→ZZ* + H→γγ combination



No significant mass difference between H→γγ and 4 lepton channels

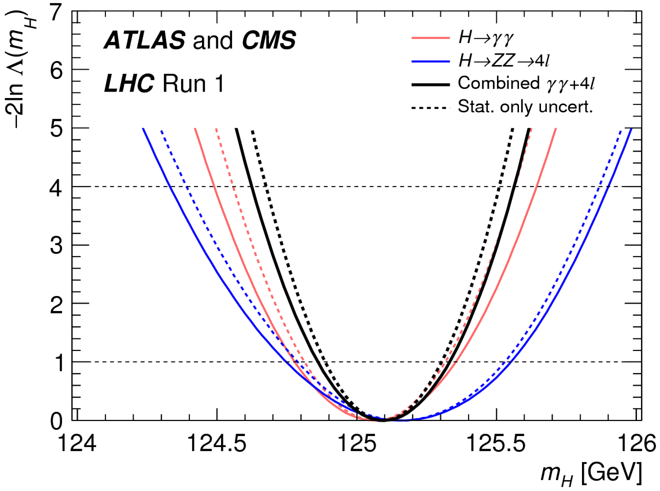
ATLAS: Δm_H(γγ-4l) = +1.47 ± 0.67 (stat.) ± 0.28 (syst.) GeV (1.98σ)
CMS: Δm_H(γγ-4l) = - 0.89 ± 0.57 GeV (1.6σ)

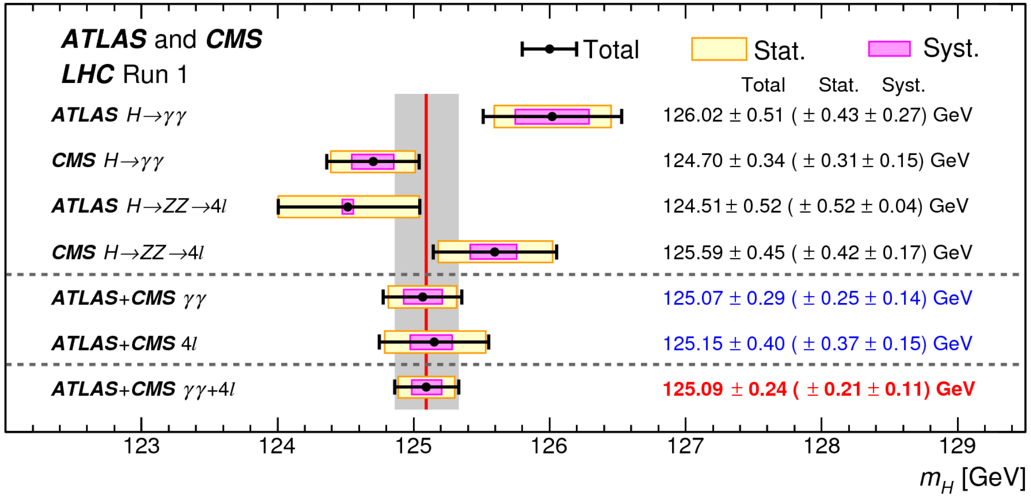
ATLAS m_H = 125.36 ± 0.37 (stat) ± 0.18 (syst) GeV
CMS $m_H = 125.03^{+0.26}_{-027}$ (stat) $^{+0.13}_{-0.15}$ (syst) GeV

New: ATLAS/CMS combination

- Maximum of the profile-likelihood fits using signal probability density functions derived from modeling and background probability distributions derived from the data
- Includes interference between signal and backgrounds (EW only)

arXiv:1503.07589



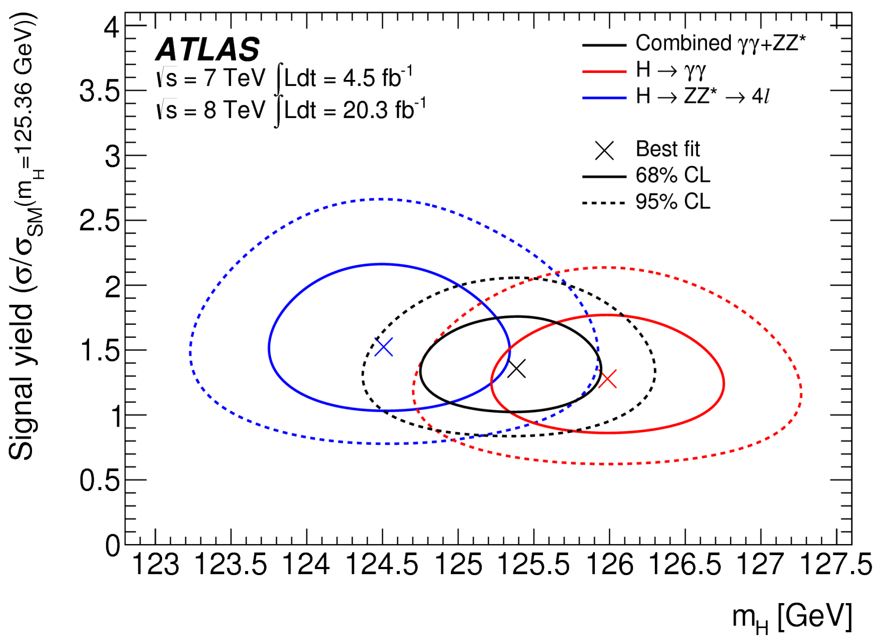


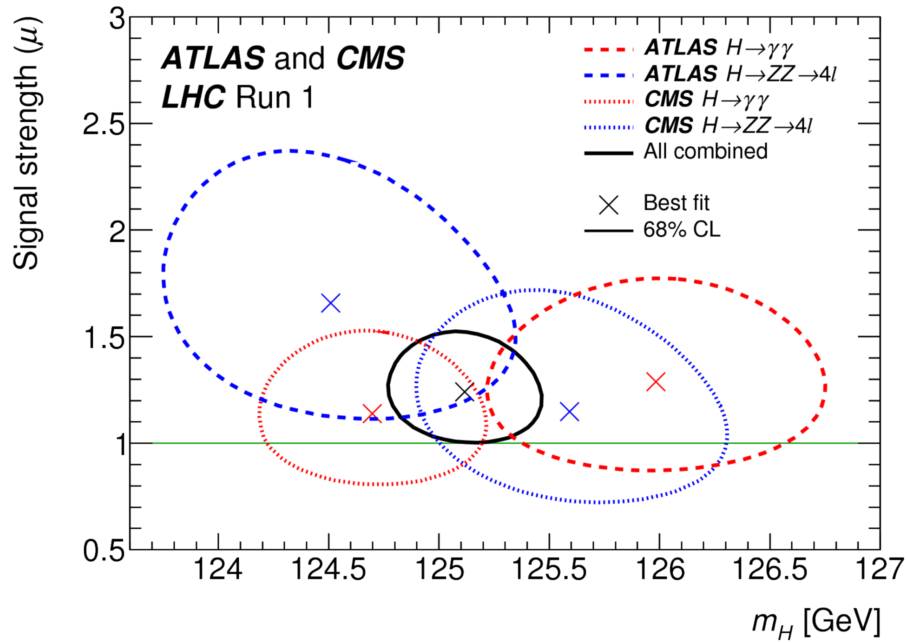
$m_H = 125.09 \pm 0.24\ (\pm 0.21\ (\text{stat.}) \pm 0.11\ (\text{syst.}))$ GeV

★ **I offer a beer for best/craziest explanation why this value is so close to 5^3 in GeV**

Production rate

- Derived from the same 2D fit as the Higgs mass using 4l and γγ decays.
- **Caution:** For photon channel there are about 300 nuisance parameters with about 100 fitted parameters describing shapes and normalization of background models and about 200 parameters describing experimental and theoretical systematic uncertainties.





Results from different channels are consistent within 2σ and are consistent with signal strength expected from Standard Model.

Higgs Production Rates - other channels

Similar procedures as that for ZZ and γγ:

- Signal selection using leptons, b-jets, missing energy and tau hadronic decays
- Background minimization using kinematic properties
- Comparison with signal expected from various Monte Carlos
- Identification of systematic and theoretical uncertainties

Channels studied (tags)

H→W W→lν lν (l = e or μ, missing energy carried by neutrinos)

H→τ τ (τ hadronic and leptonic decays: lepton-lepton, lepton-jet, jet-jet topology)

H→b b (b jets tagged by 70% likelihood of identifying separated vertices)

H→Z γ (reconstructed Z ->ee and Z->μμ)

VBF (Higgs reconstruction applied in all decay channels + 2 separated hadronic jets)

VH (Higgs reconstructed in all channels, W tagged by lepton + missing energy, Z reconstructed from leptonic decays)

ttH (Higgs reconstructed in bb, γγ, WW->lνlν, additional leptons from top decays)

Evidence for VBF process

- Second largest expected rate, low theory uncertainty.
- Distinctive topology with two jets widely separated in η and suppressed QCD activity between them
- Hints consistent with SM expectations in several channels.
- Combined analysis based o profile likelihood ratio test statistics Probability densities used for in are derived from MC for the signal and MC and data for the backgrounds.

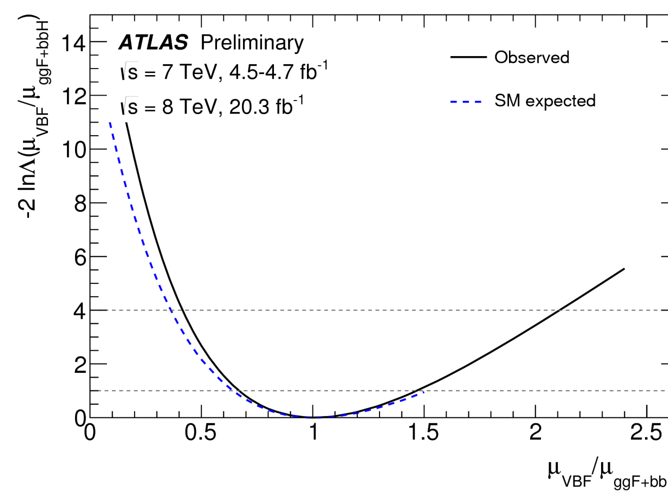
H->γγ 2 photons with $E_T/m_{\gamma\gamma}$ > 0.35 and 0.25 plus 2 jets

H->4l 2 pairs of same flavor, opposite charge leptons plus 2 jets with m_{jj} 130 GeV

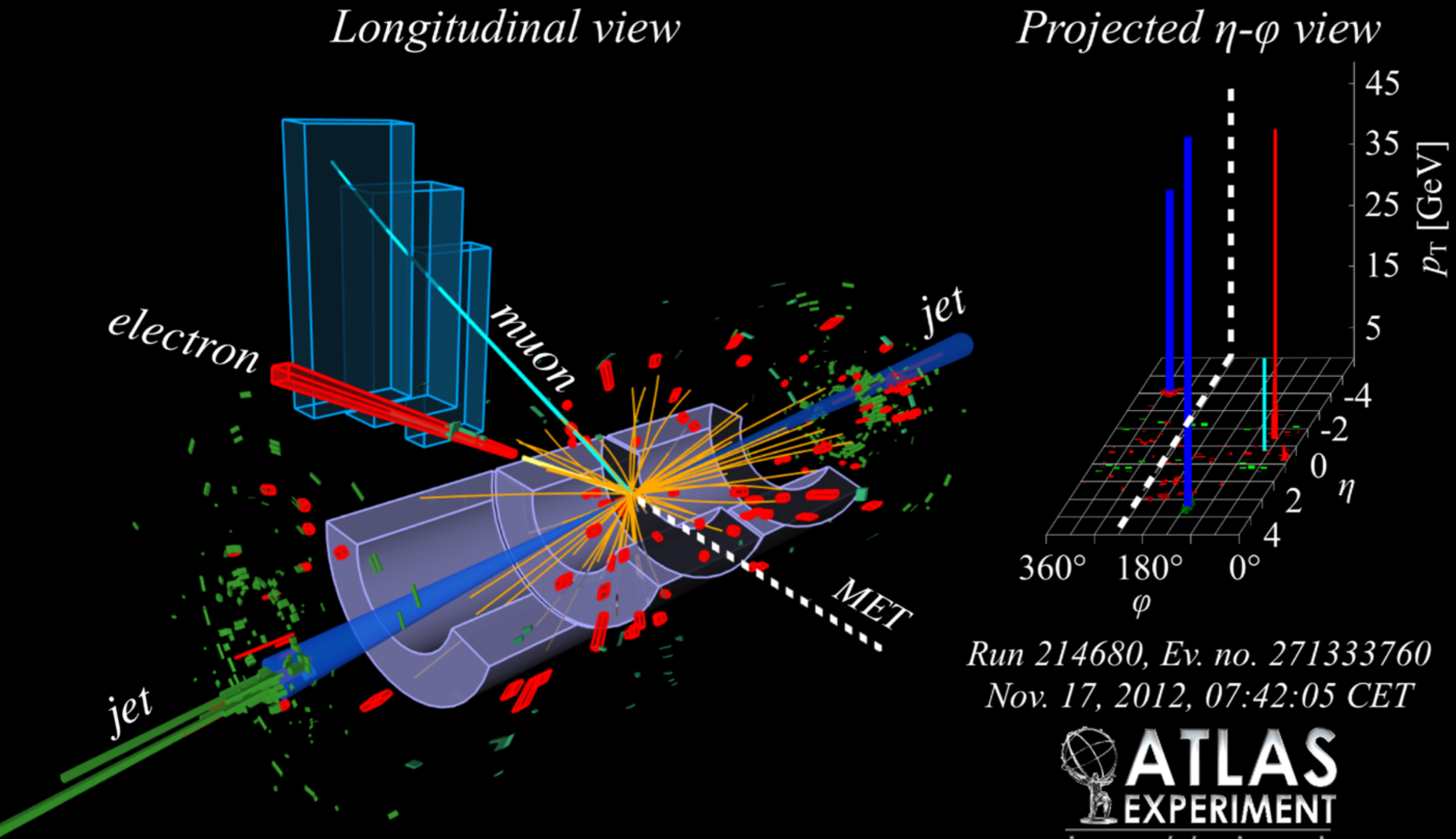
H->WW* leptonic W decays - lνlν (same and opposite lepton charges) plus N_{jet}> 2

H->ττ leptonic and hadronic tau decays plus 2 jets separated by pseudorapidity

H->μμ opposite charged muon pair plus N_{jet}> 2



$H \rightarrow WW^* \rightarrow e\nu\mu\nu$ candidate and two jets with VBF topology



Exp. signal yield	S/B
~500	~15%

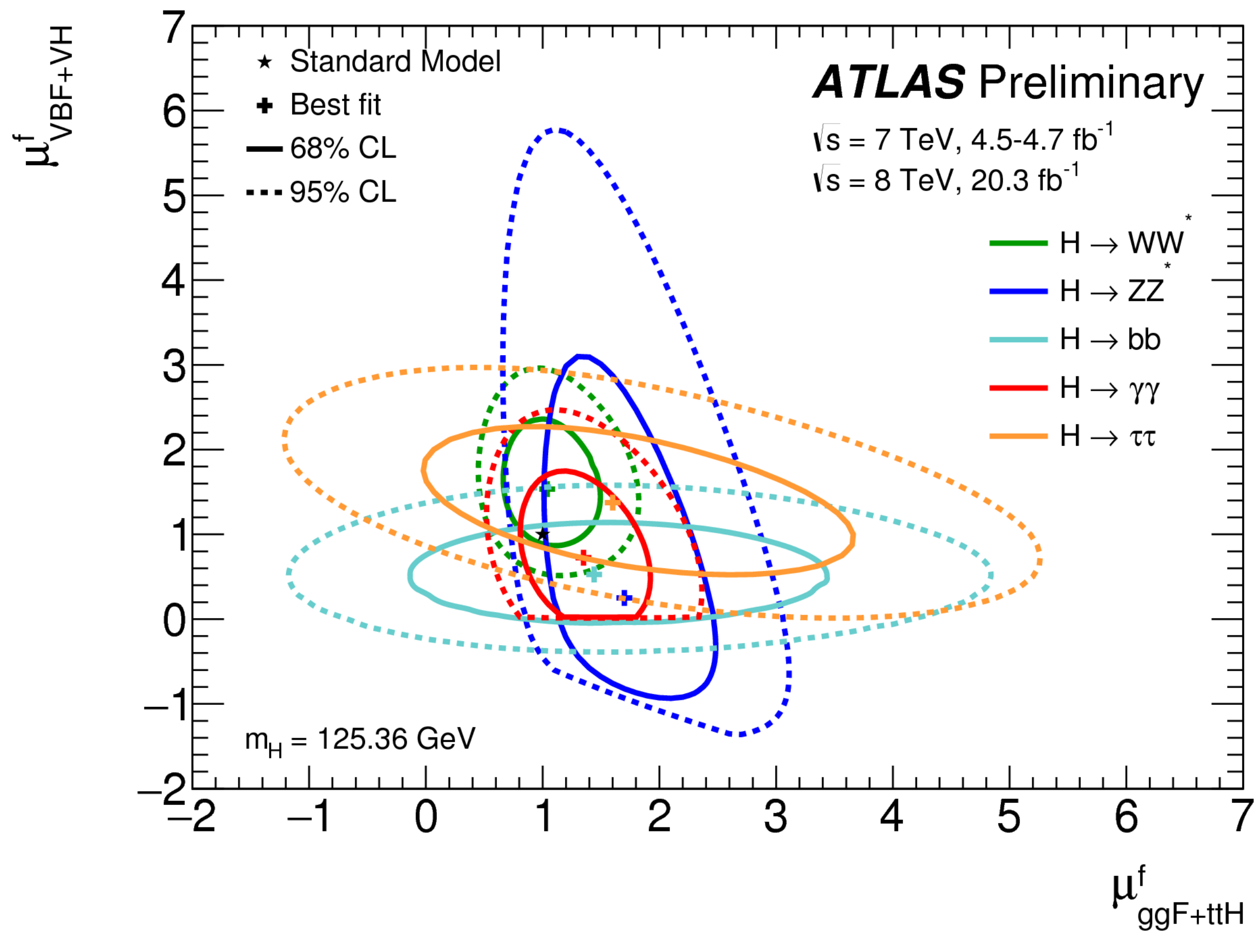
Likelihood contours

($\mu^f_{ggF+ttH}$, μ^f_{VBF+VH}) plane for Higgs mass m_H=125.36 GeV.

μ – ration of observed yield wrt SM expectation

Solid lines - 68% CL contours, dashed lines – 95% CL contours.

Standard Model expectation - star at (1,1).



Higgs Boson Couplings

Higgs Couplings

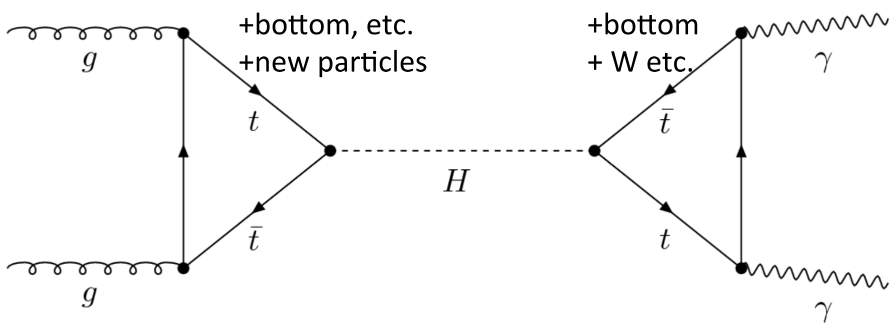
ATLAS-CONF_2015-007

The coupling of Standard Model particle to Higgs boson scales with particle mass

$$g_f = \sqrt{2}\frac{m_f}{v}, g_V = 2\frac{m_V^2}{v}$$

We know masses. Introduce coupling scale factor κ and signal strength μ, e.g.,

$$\mu = \frac{(\sigma \cdot BR)(gg \to H \to \gamma\gamma)}{\sigma_{SM}(gg \to H)\cdot BR_{SM}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$



LO Standard Model

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

$$\kappa_\gamma^2 \approx 1.59 \cdot \kappa_W^2 - 0.66 \cdot \kappa_W \cdot \kappa_t + 0.07 \cdot \kappa_t^2$$

Destructive interference top-bottom in gg->H loop and W-top in H->γγ loop

Input and assumptions:

- Single narrow boson with mass = 125.4 GeV
- Narrow width approximation →

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

Γ_f – partial decay width

$\kappa_{j,off} = \kappa_{j,on}$

- Signal strength off-shell depends only on coupling strength (not on total width)

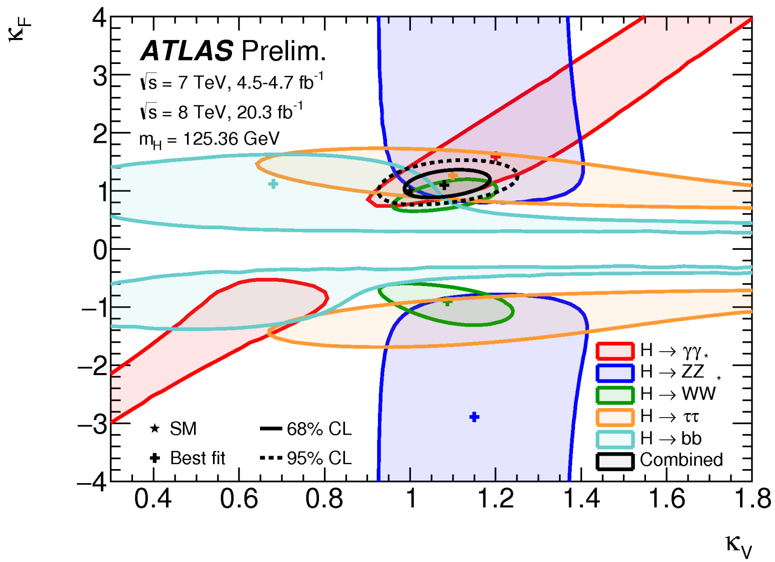
- Coupling constant does not run (approximation for off-shell H->WW and H-> ZZ

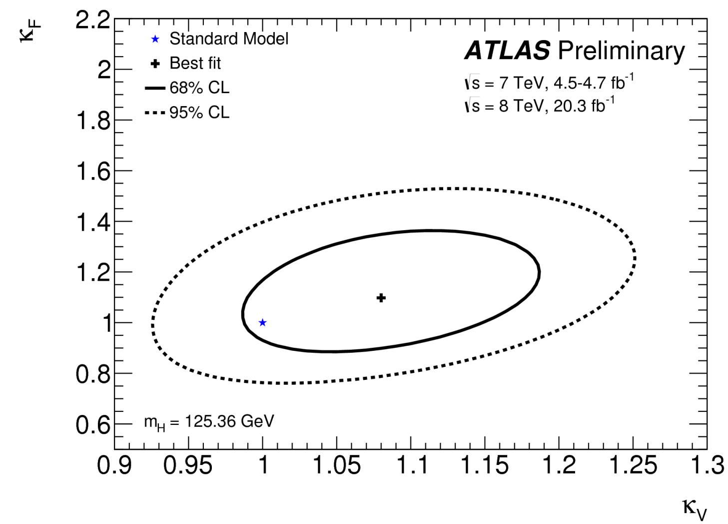
$$\kappa_{j,off} = \kappa_{j,on}$$

- Use bb, WW, ZZ, ττ, μμ, Zγ, γγ decays
- Use ggF, VBF, ZH, bbH, ttH, WtH, tHq production mechanisms

Benchmark Model

- only SM particles contribute (total width - sum of known possible decays)
- all coupling to vector bosons have the same scale factors: $\kappa_V = \kappa_W = \kappa_Z$
- all couplings to fermions have the same scale factors: $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \ldots$
- Sign ambiguity due to quadratic relation –> positive sign selected – (preferred by electroweak precision data)





Data consistent with SM predictions

$$\kappa_V = 1.09^{+0.07}_{-0.07}$$

$$\kappa_F = 1.11^{+0.17}_{-0.15}$$

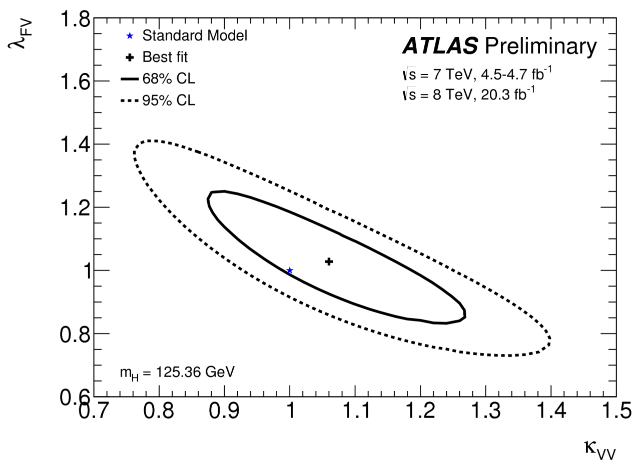
Higgs Couplings

Repeat **analysis without assumption on the total width**

i.e., allow for unknown decay modes.

Only ration of scale factors can be measured. Fit parameters:

$$\lambda_{FV} = \kappa_F / \kappa_V$$
$$\kappa_{VV} = \kappa_V \times \kappa_V / \kappa_H$$

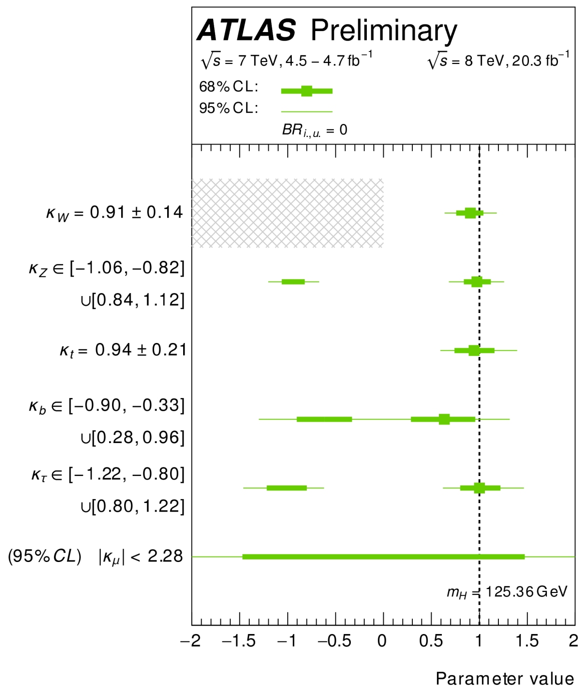


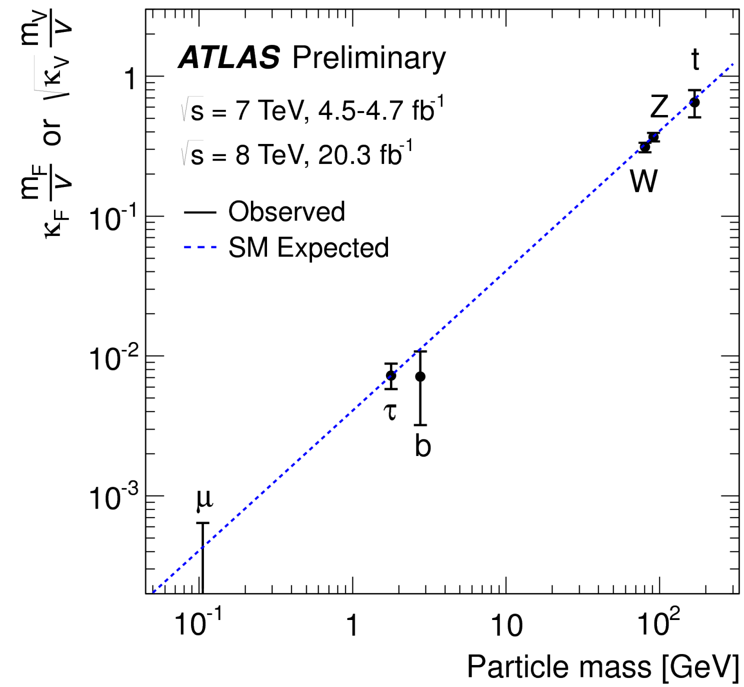
$$\lambda_{FV} = 1.02^{+0.15}_{-0.13}$$
$$\kappa_{VV} = 1.07^{+0.14}_{-0.13}$$

Result consistent with SM predictions at 41%CL

Higgs couplings – generic model

Repeat analysis for **independent scale factors** for couplings to W, Z, t, b, τ and μ.
Assume Standard Model particle content.
Free parameters: κ_W, κ_Z, κ_t, κ_b, κ_τ, κ_μ



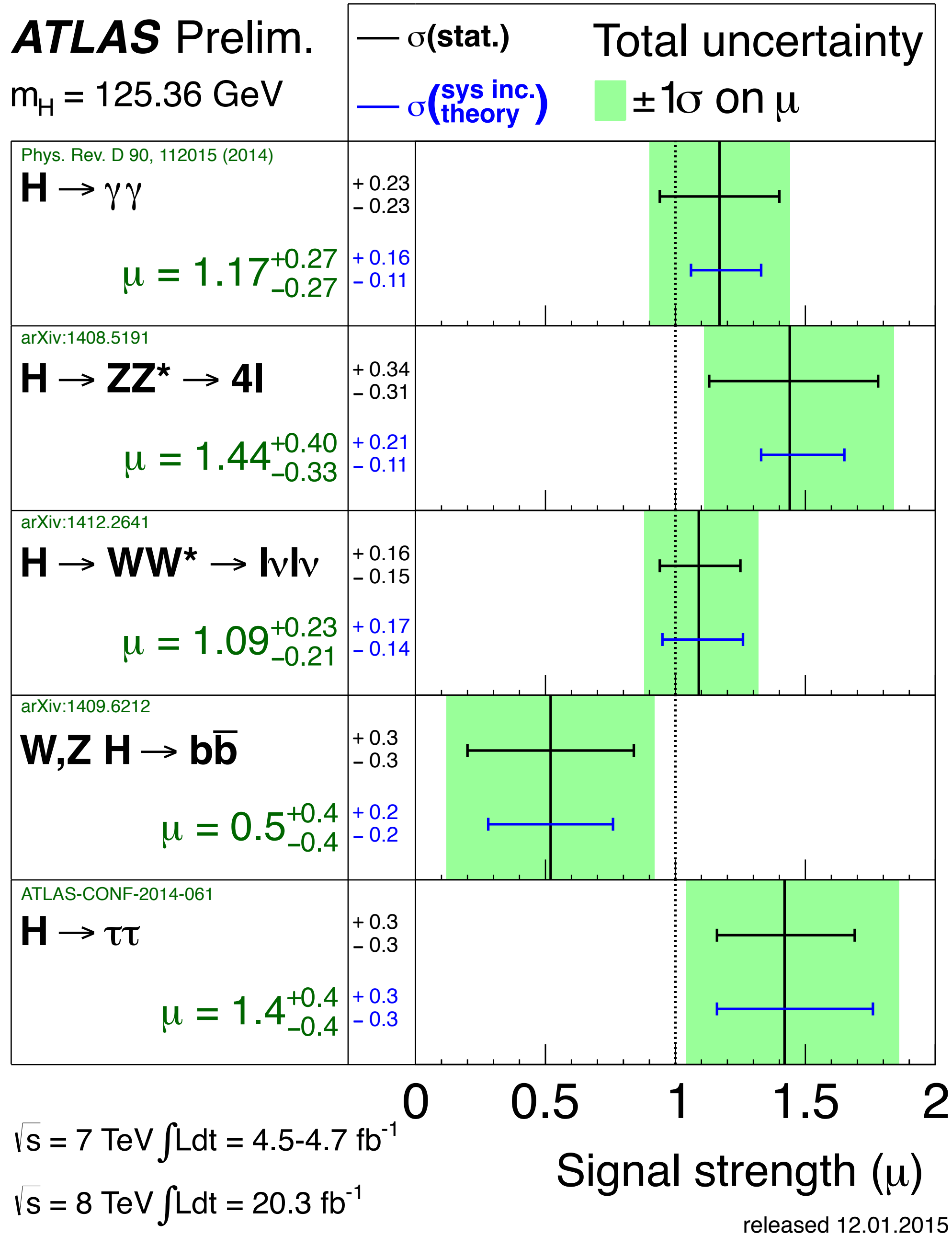


All measured coupling strengths consistent with SM within 1σ !

Signal strength

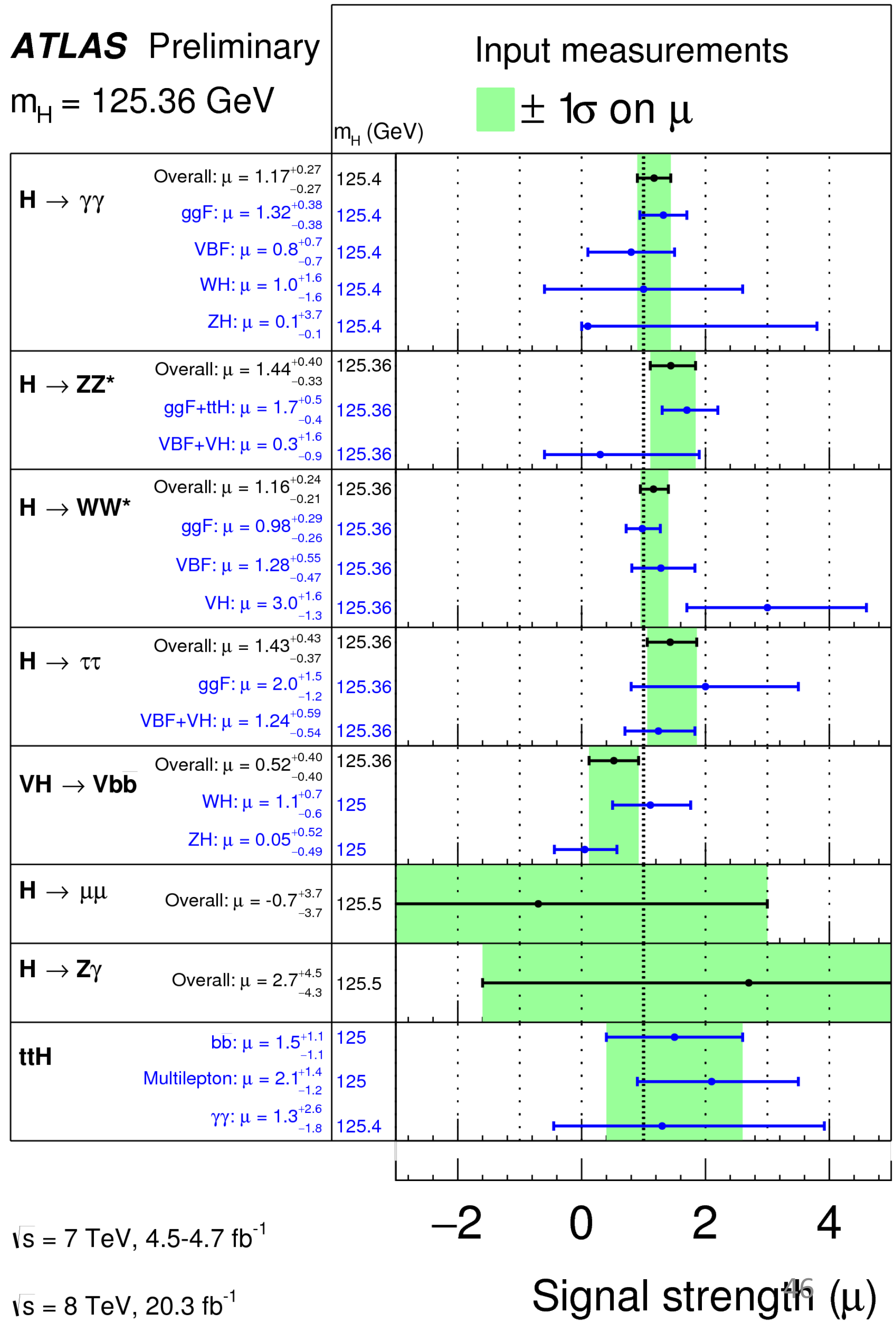
μ = ratio: observed/SM expectation

ALL consistent with SM predictions



Separated by production mode

- Error bars represent ± 1σ total uncertainties, combining statistical and systematic contributions.
- Green shaded bands are the overall uncertainty of the signal strength.
- Combined Hγγ signal strength includes the ttH contribution, which is listed separately.

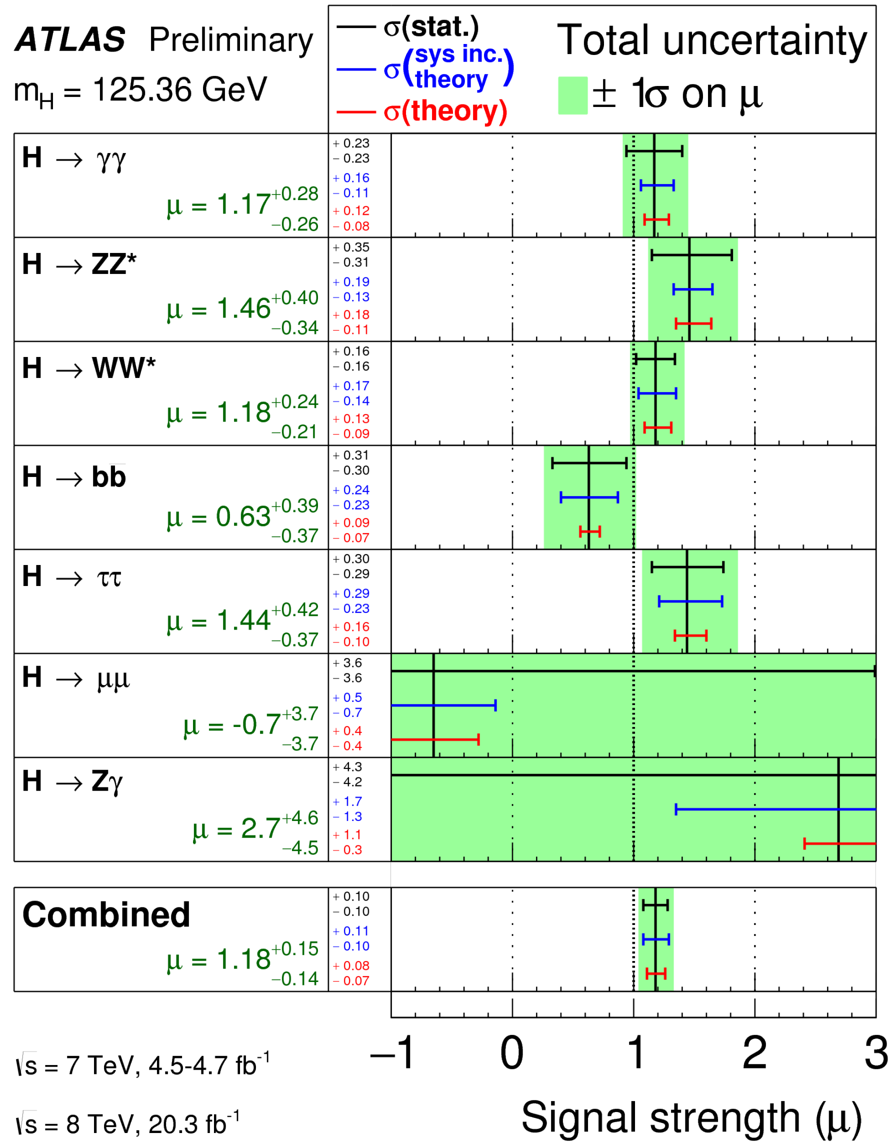


Experimental vs theoretical uncertainties

Theory uncertainty is comparable to experimental and statistical uncertainties

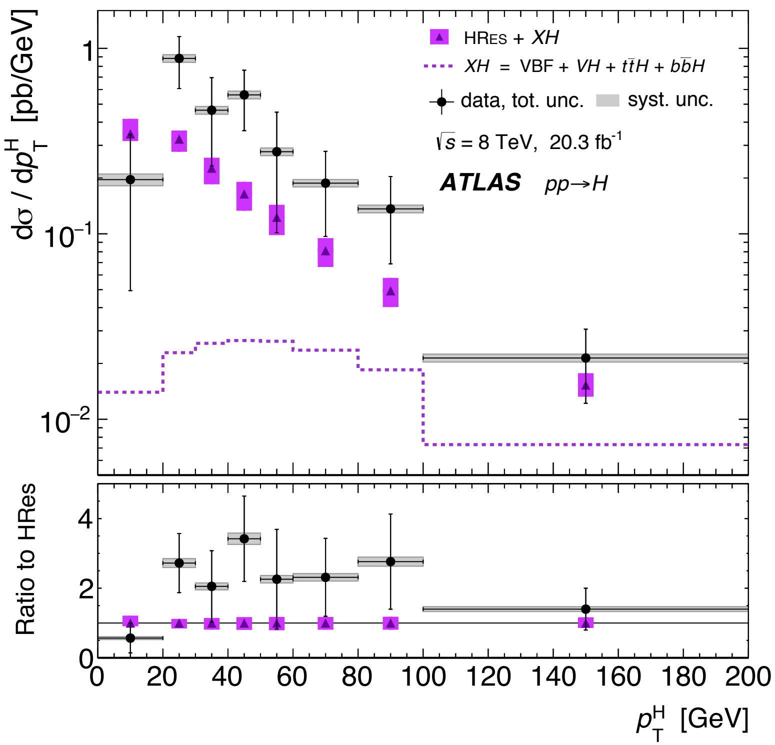
QCD scale ~±8% @NNLO

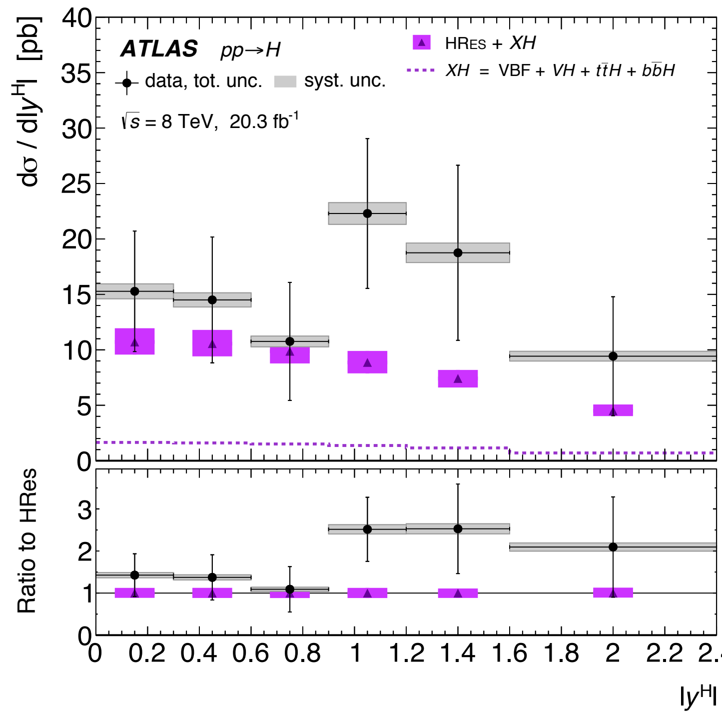
PDF+α_s ~±8%



Differential cross section distributions

- **Obtained from measured yields of γγ and 4l final states**
- **Corrected for detector efficiencies, acceptance and branching fractions**





s_{tot} : NNLO+NNLL , N^3LO
Differential: NNLO+NNLL (HRES 2.2. STWZ, BLPTW, JetVHeto 2.0)
Monte Carlo: NLO (SHERPA 2.1.1, MG5_aMC@NLO, POWHEG) NNLOPS
Higgs: Hres 2.2

CERN-PH-EP-2015-048
Submitted to PRL

Higgs Boson Width

Higgs Boson Width

SM expectation Γ_{tot}= 4.15 MeV for M_H=125 GeV

- The **event yield** for each production × decay mode:

$$(\sigma \cdot \mathcal{B})\,(x \to \mathrm{H} \to f\!f) = \frac{\sigma_x \cdot \Gamma_{f\!f}}{\Gamma_{\mathrm{tot}}}$$

$\Gamma_{f\!f}$ - Partial decay width into *ff* final state (ZZ, WW, bb, γγ, ττ, …)

- Direct measurement of the width is limited by the resolution of the detector response to photons, electrons, muons, jets, ..

  H->γγ: 5.0 GeV 95% CL upper limit on width from observed mass spectrum
  - assumes no interference with background

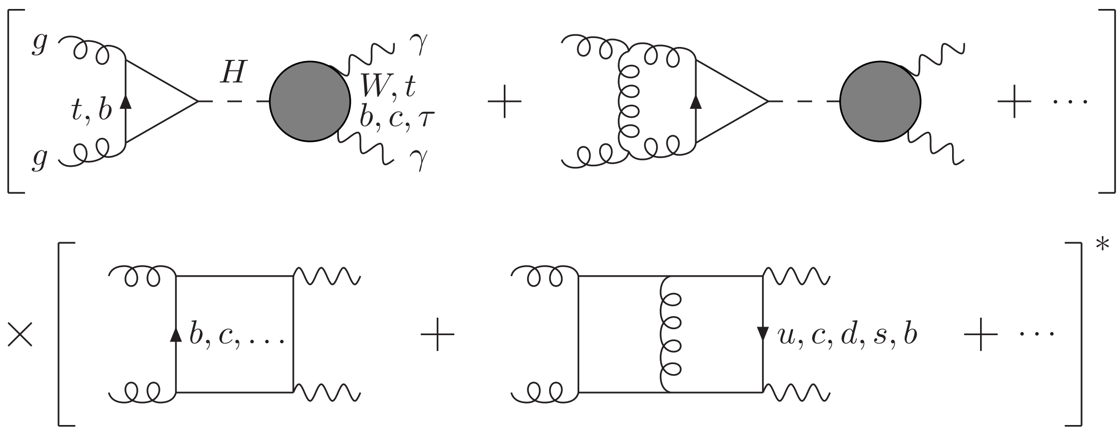
  H->ZZ* 2.6 GeV 95% CL upper limit
  - measurement resolution different for each lepton.
  For each event 4-lepton mass is obtained by convolution of detector response with Breit-Wigner function.
  No Z-mass constraint applied.

New idea – interference between Higgs signal and SM background

Interference for Higgs -> γγ

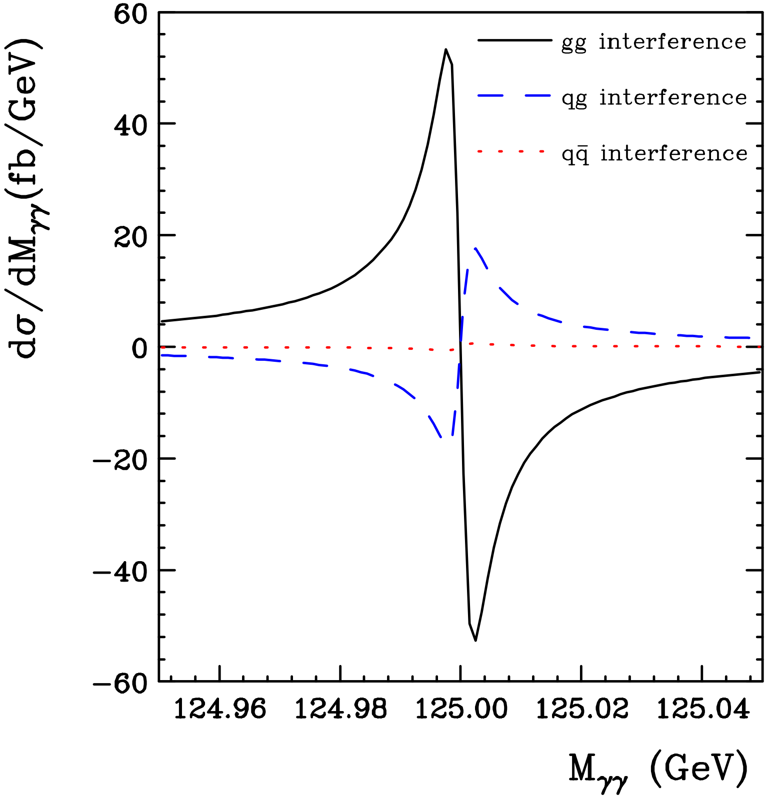
S.P. Martin, arXiv:1208.1533(2012)
L.J.Dixon,Y.Li, arXiv: 1305.3854(2013)
F.Coradeschi et al., arXiv:1504.05215(2015)

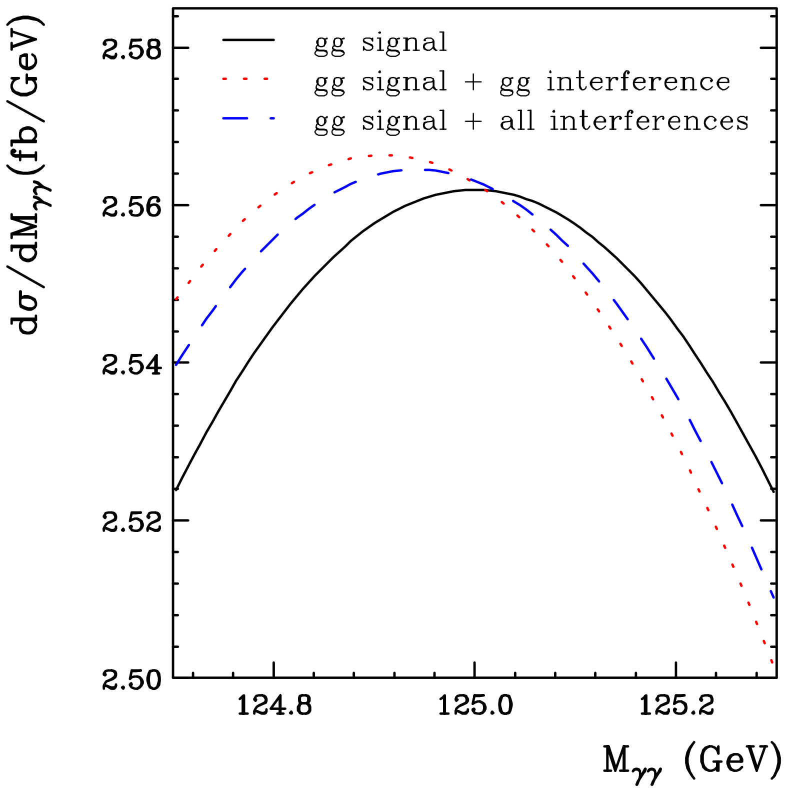
- Destructive interference between H->γγ signal and continuum background induces a shift of the mass peak.
- Mass shift depends on Higgs p_T, $\Delta M_{\gamma\gamma}$= -120 MeV at LO and -70 MeV at NLO



No experimental results yet

De Florian et al., EPJ **C73** (2013) 2387





Interference for H -> 4l

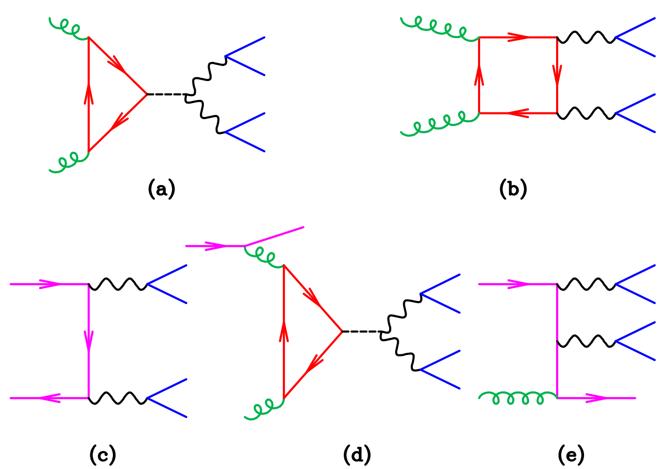
- F.Caola, K.Melnikov, Phys.Rev.D88(2013)054024
- N.Kauer, G.Passarino, JHEP08(2012) 116
- J.M.Campbel, R.K.Ellis, C. Williams, JHE04 (2014) 060, FERMILAB-PUB-13-508-T

Off-shell Higgs boson signal strength is independent of the width, while on-shell cross section is proportional to $1/\Gamma_{tot}$

$$\frac{d\sigma(pp \to H \to ZZ)}{dM_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

On-resonance $M^2_{4l} \cong m_H$ and $\sigma \approx 1/\Gamma_H$

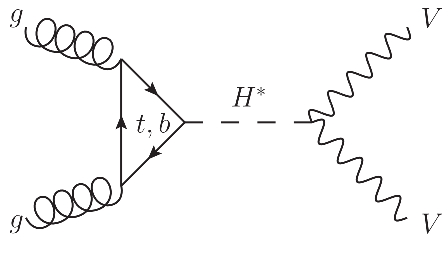
Off-resonance the term $(M^2_{4l} - m^2_H)$ in denominator is large -> width can be neglected.



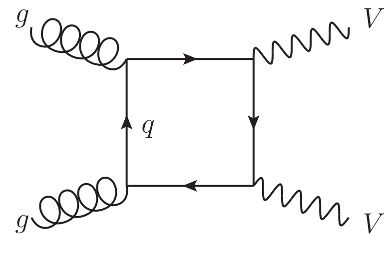
Use the ratio of signal and background cross sections on and off resonance to estimate width.

Interference for H -> 4l

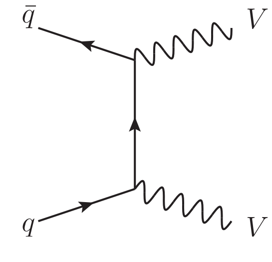
- ATLAS: arXiv1503.01060 (2015)



signal



background



background

For zero-width approximation

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

κ_j - scale factor of the Higgs coupling to particles j, for SM $\kappa_j = 1$
For off-shell measurement assume non-running coupling strength

$$\sigma^{off}(i \to H^* \to f) \sim \kappa_{i,off}^2 \cdot \kappa_{f,off}^2$$

Interference effects (signal-background) due to real part of the amplitudes are negative throughout whole mass region > $2M_V$.

Interference for H -> 4l

$$\mu_{off-shell} \equiv \frac{\sigma^{gg\to H^*\to VV}_{off-shell}}{\sigma^{gg\to H^*\to VV}_{SM,off-shell}} = \kappa^2_{goff-shell} \cdot \kappa^2_{Voff-shell}$$

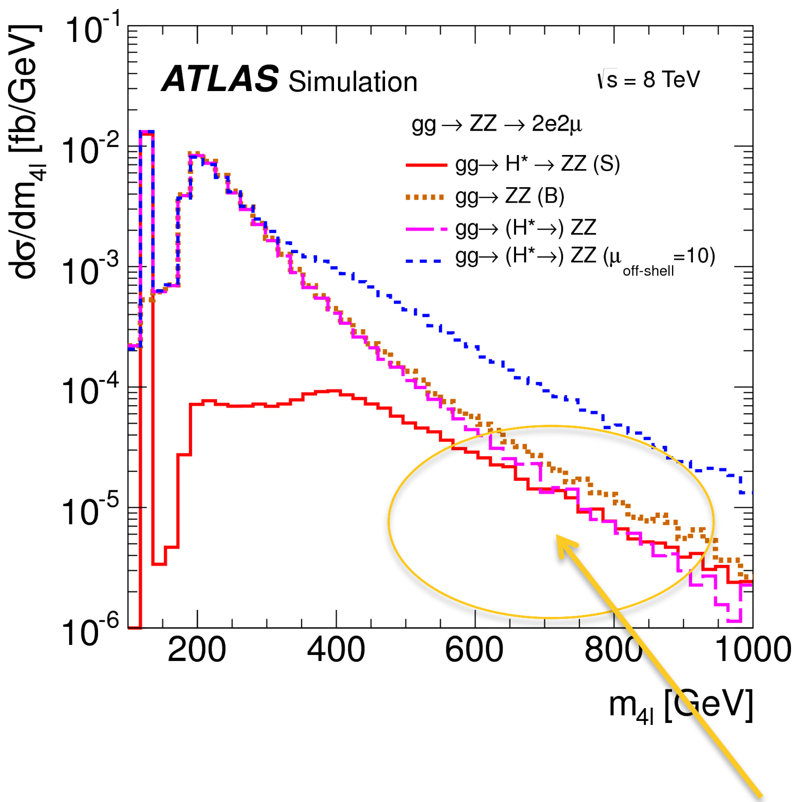
$$\mu_{on-shell} \equiv \frac{\sigma^{gg\to H\to VV}_{on-shell}}{\sigma^{gg\to H\to VV}_{SM,on-shell}} = \frac{\kappa^2_{g,on-shell} \cdot \kappa^2_{V,on-shell}}{\Gamma_H / \Gamma_H^{SM}}$$

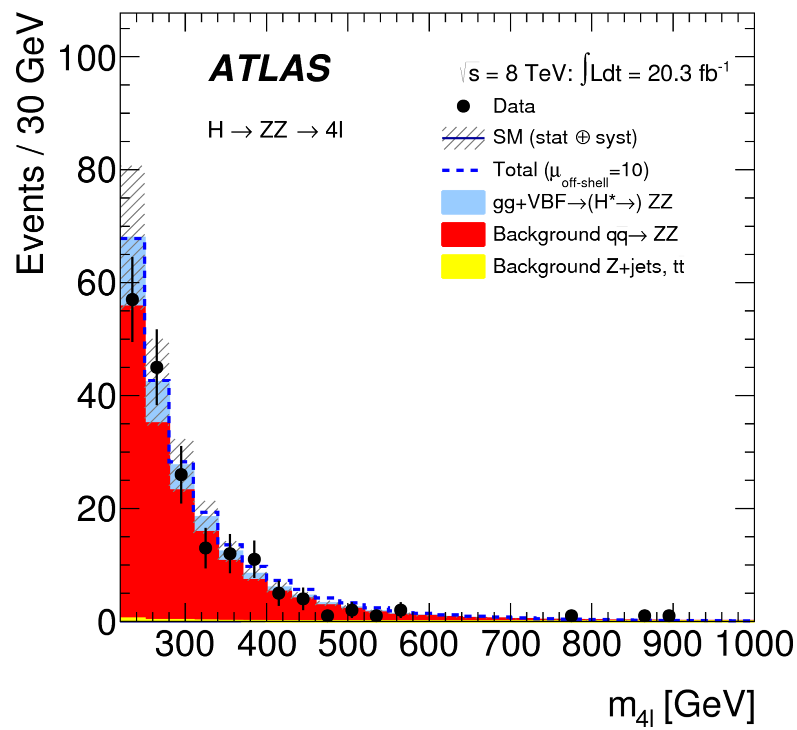
$$\frac{\mu_{off-shell}}{\mu_{on-shell}} \cong \frac{\Gamma_H^{SM}}{\Gamma_H}$$

Interference for H -> 4l

Simulation: gg -> H -> ZZ and gg -> ZZ

Data: 4 lepton invariant mass





Region of expected interference

Higgs decays to 4 leptons including 2 neutrinos

2 neutrino present in the final state -> no reconstruction of the 4 lepton mass

- for ZZ use transverse mass m_T^{ZZ} reconstructed from p_T^{ll} and E_T^{miss}

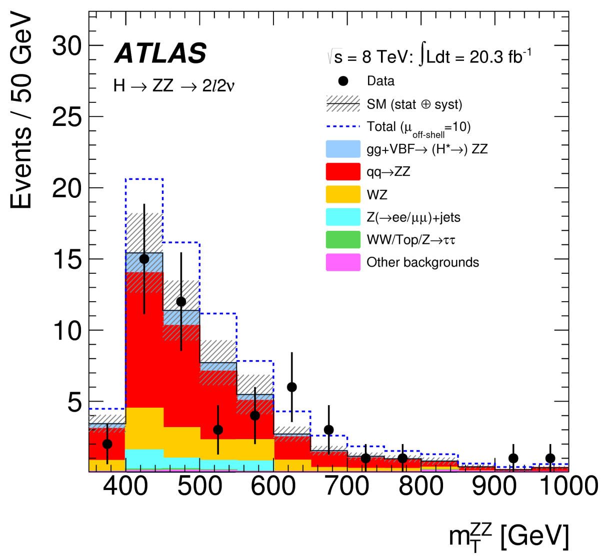
$$m_{\mathrm{T}}^{ZZ} \equiv \sqrt{\left(\sqrt{m_Z^2 + |\boldsymbol{p}_{\mathrm{T}}^{\ell\ell}|^2} + \sqrt{m_Z^2 + |\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}|^2}\right)^2 - |\boldsymbol{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}|^2},$$

- for WW use m_T^{WW} to form a variable R_8 with $p_T^{\nu\nu}$ is p_T^{miss} obtained from tracks only

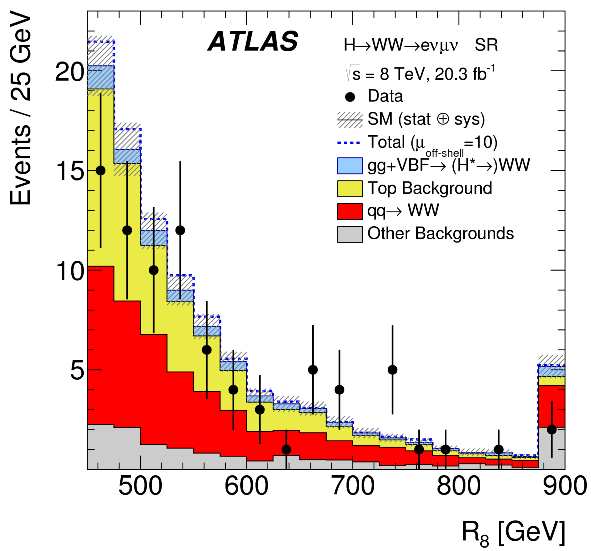
$$m_{\mathrm{T}}^{WW} = \sqrt{\left(E_{\mathrm{T}}^{\ell\ell} + p_{\mathrm{T}}^{\nu\nu}\right)^2 - |\boldsymbol{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{p}_{\mathrm{T}}^{\nu\nu}|^2}, \text{ where } E_{\mathrm{T}}^{\ell\ell} = \sqrt{(p_{\mathrm{T}}^{\ell\ell})^2 + (m_{\ell\ell})^2}$$

$$\mathrm{R}_8 = \sqrt{m_{\ell\ell}^2 + \left(a \cdot m_{\mathrm{T}}^{WW}\right)^2}.$$

H → ZZ → 2l2ν



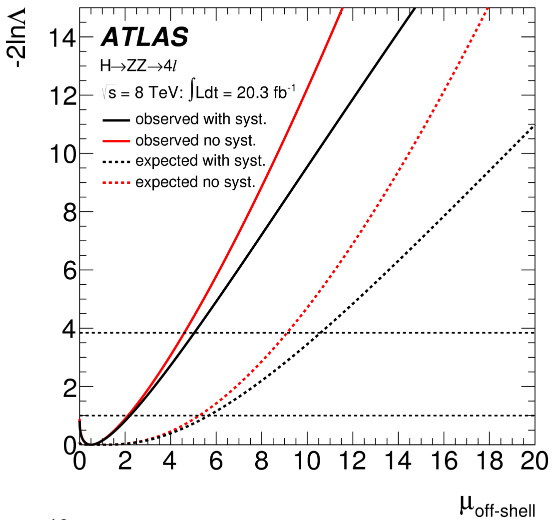
H → WW → eνμν



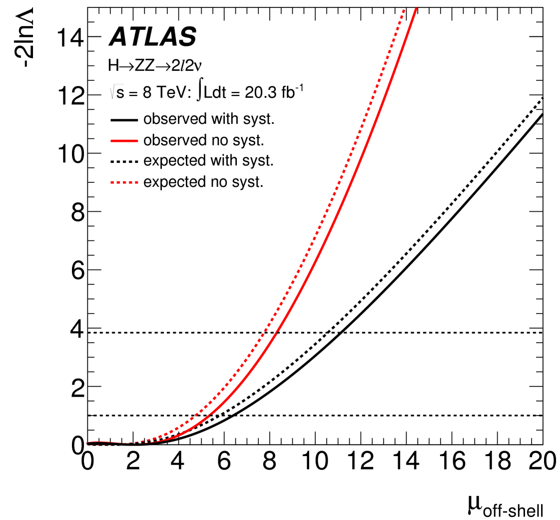
arXiv:1503.01060

Interference for H -> 4l: Likelihood fits

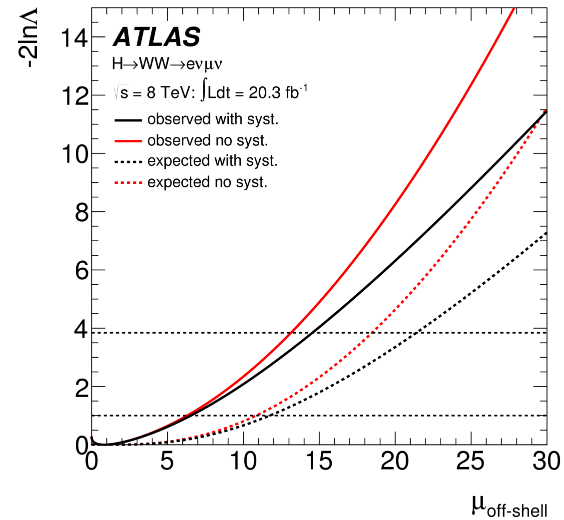
H->ZZ->4l

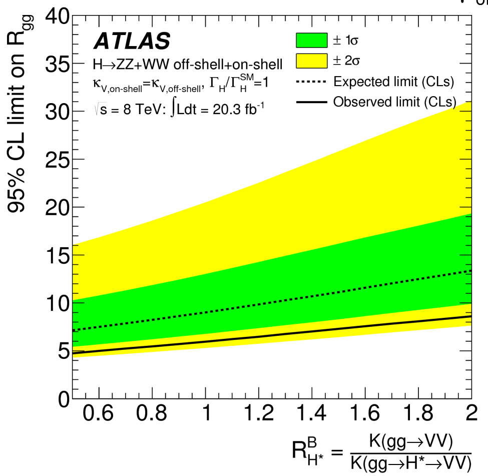


H->ZZ->2l2ν



H->WW->eνμν





Combined observed and expected 95% upper limits

ATLAS

Γ_H < 22.7 MeV (observed)

Γ_H < 33.0 MeV (expected)

Interference for H →4l - comments

- Similar results for ATLAS and CMS
- Similar sensitivity for Higgs decays to 4 charged leptons and to llνν
- Assumption - couplings are independent of energy scale
  - on-shell coupling and off-shell couplings are the same

ATLAS

Γ_H < 22.7 MeV (observed)

Γ_H < 33.0 MeV (expected)

CMS

Γ_H < 22 MeV (observed)

Γ_H < 33 MeV (expected)

-> 7÷8 times Standard Model expectation

Question to theory experts: Do we understand phases of the amplitudes involved here ?

Higgs Boson Spin-Parity

Spin and parity

Spin 0: - Standard Model Higgs boson is a scalar with $J^{CP} = 0^{++}$
- CP mixing and CP violation is permitted but small in some BSM models

Spin 1: - Landau-Yang theorem forbids the direct decay of an on-shell spin1 particle into two photons. It applies to on-shell (small width) resonance.
- Observation of $H \rightarrow \gamma\gamma$ eliminates spin 1 assignment and fixes C=1 (in absence of C violating effects)

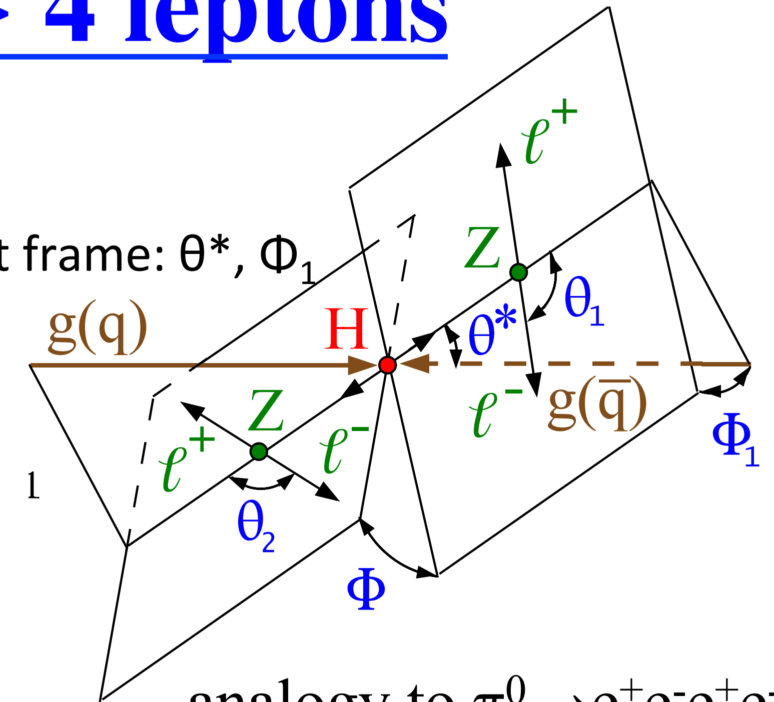
Spin 2: - possible assignment for graviton inspired tensor coupling

All studies assume single particle.
Test of $J^P = 0^-$ hypothesis done in H->ZZ* mode
Tests of 1^- and 1^+ hypothesis use H->ZZ* and H->WW* channels
Studies of 2^+ hypothesis use ZZ*, WW* and γγ final states

Example: H -> ZZ* -> 4 leptons

Full reconstruction gives 7 variables:

- masses of vector bosons: m_{Z1}, m_{Z2}
- production angles of vector bosons in H rest frame: θ^*, Φ_1
- decay angles: Φ, θ_1, θ_2



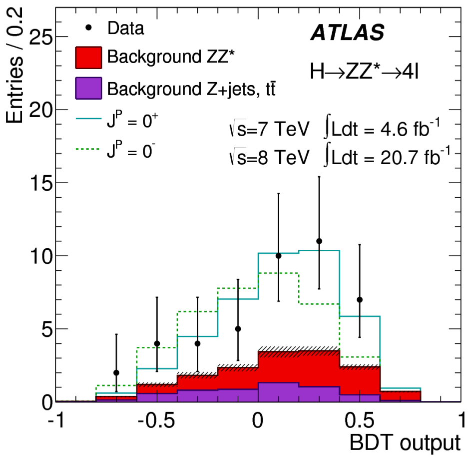
analogy to $\pi^0 \rightarrow e^+e^-e^+e^-$

- Data studied in 4l rest frame using a likelihood function for each spin hypothesis that describes a probability of observing N signal events in a bin defined by the observables given the expected number of signal and background events.
- Boosted Decision Tree approach to define discriminants. Small data sample requires additional sampling of test statistics for the probability of selecting N(observed) out of N(tot) events. Systematics effects must be included.
- Probability is defined by the ratio of the likelihoods. The exclusion of alternative hypothesis is evaluated by the Confidence Level

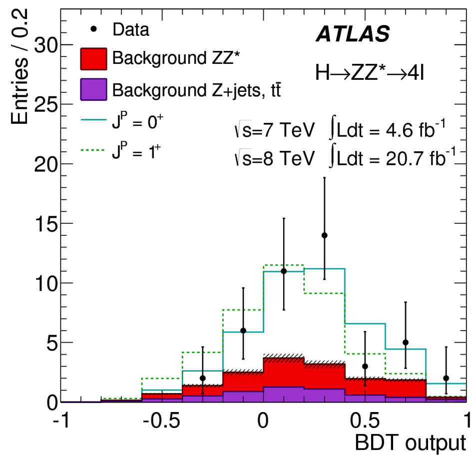
$$CL(J^P_{alt}) = \frac{p_0(J^p_{alt})}{1 - p_0(0^+)}$$

Example: H -> ZZ* -> 4 leptons

BDT for 0^- vs 0^+



BDT for 0^- vs 1^+



Final results included data for H->WW and H->γγ

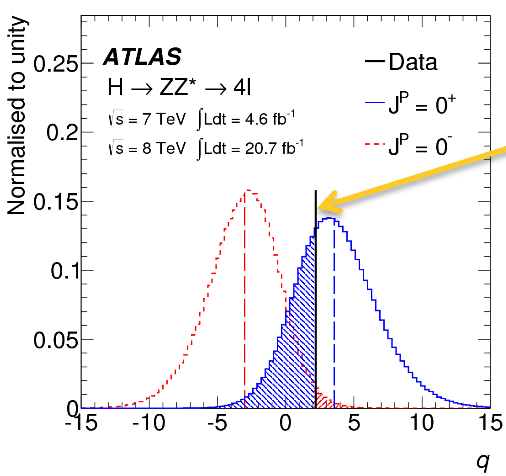
Phys. Lett. B 726 (2013)

0^- excluded at 97.8% CL

1^+ excluded at 99.97% CL

1^- excluded at 99.7% CL

Expected distributions of profiled likelihoods



observed likelihood

New studies extend the analysis to BSM models using Effective Field Theory approach. All non-SM spin-0 and spin-2 models are excluded at 99% CL. The tensor-like structure of BSM couplings remains allowed only in the small ranges

$-0.55 < \kappa_{HVV}/\kappa_{SM} < 4.80$

$-2.33 < \kappa_{AVV}/\kappa_{SM} \times \tan\alpha < 2.30$

ATLAS-CONF-2015-008

Higgs physics in Run 2

- **So far, the observed signal has all properties consistent with Standard Model expectations.**

- Run 2 has started – no results yet. Expect factor ~10 increase in data statistics
  - cross section increase with energy by a factor 2- 4 depending on the mode.
  - luminosity increase by a factor of 2-3
  - length of the run – my guess: factor ~2 (?)
- Improved performance of tracking, trigger and software
  - new tracking layer close to the interaction vertex improves b-tagging efficiency

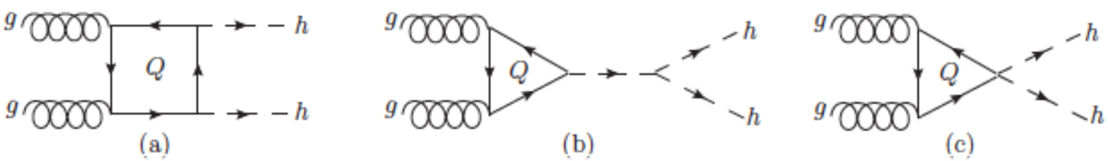
	σ(14TeV)/σ(8TeV)
gg->H	2.6
qq->WH	2.2
gg->ttH	4.7
gg->bbH	2.9
qq->qqH	2.7

Higgs physics in Run 2

First step - repeat past analyses to verify detector performance

Long term

- **Improve precision** of parameters measured: mass, width, couplings….
- **Search for rare decays**
  $B(H\rightarrow \mu^+\mu^-) = 2.2 \times 10^{-4}$; $B(H\rightarrow e^+e^-) = 4.9\times10^{-9}$ for m_H = 125 GeV
- **Search for Higgs Dalitz decays:** $H\rightarrow\gamma ff$ *(f = e, μ, τ, b, c, s, d, u)*
- **Search for BSM physics** in Higgs sector
- **Higgs self-coupling** - Standard Model HH production may become accessible by the end of Run 2
  - In Standard Model Higgs pair production suppressed by a factor ~100 ÷ 1000

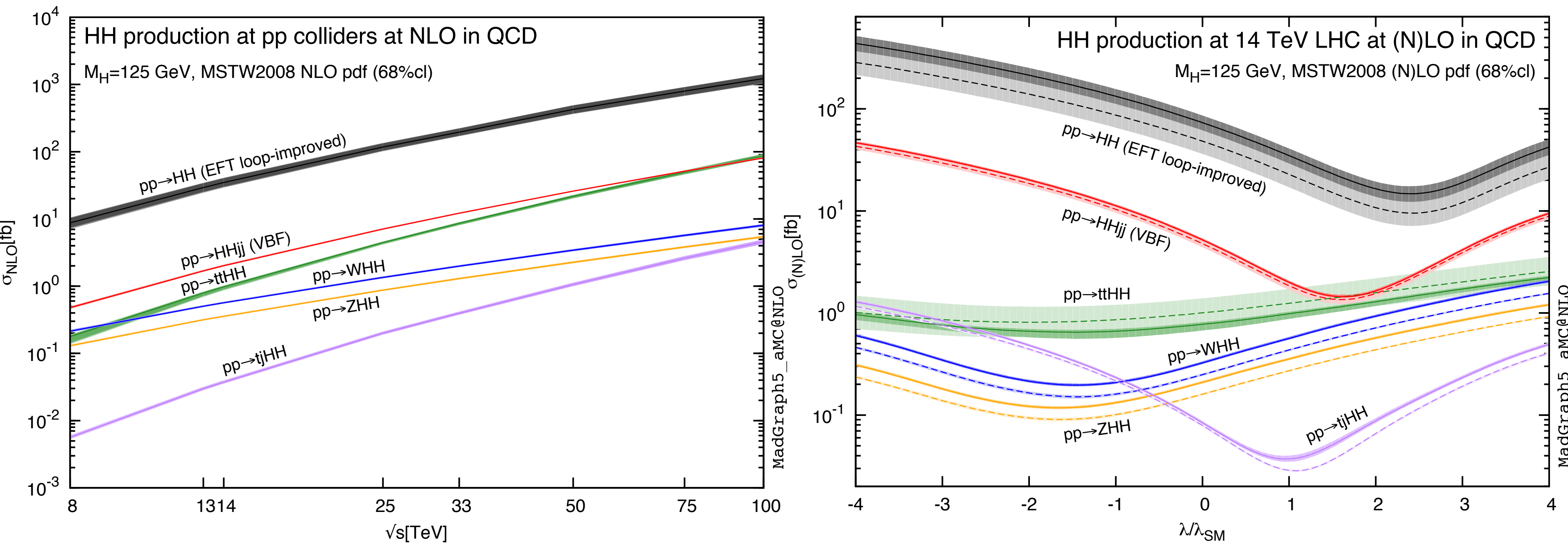


- Interference effects (a)+(b) reduce expected cross section
- BSM - Large number of possible sources of enhancements: 2HDM, composite Higgs, new couplings, dark matter portal,…

Two Higgs Production Cross Section

Benchmark processes: HH->bbγγ, bbττ, bbbb

R. Frederix et al., PLB **732** (2014) 142



Interference between box and triangle diagram has been calculated.
Is there an interference with QCD e.g., bbbb production ?
Plenty of work for theorists to calculate EW and QCD interference effects needed for precision measurements.

Summary

“It” looks like a Standard Model Higgs

- Need to improve precision
- Need to understand couplings to fermions and bosons
  Old question: why the mass of the muon is ~200 time greater than the mass of electron?
  New question” why the Higgs coupling to the muon is ~200 times greater than Higgs coupling to the electron?
- Need to measure Higgs self couplings

- Is there a new physics that can show up in the Higgs sector?