Higgs physics experimental status

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Disclaimers:

- ATLAS rather than CMS results (performances are in general very similar)
- not doing justice to the huge effort expended on theoretical as well as experimental side

Nikhef Topical Lectures, June 17, 2020

Contents

Experimental aspects

- physics analysis at the LHC
- generalities of analyses in main Higgs decay modes

Higgs boson properties

- coupling strengths
- mass
- CP nature of couplings to bosons and fermions
- decay width
- differential cross section measurements

Searches

- probing the Higgs potential
- Beyond-the-Standard Model Higgs bosons

Experimental aspects

The path to the energy frontier: the LHC

LHC built to discover a SM Higgs boson of any mass in the range
100 GeV $\lesssim m_H <$ 1 TeV

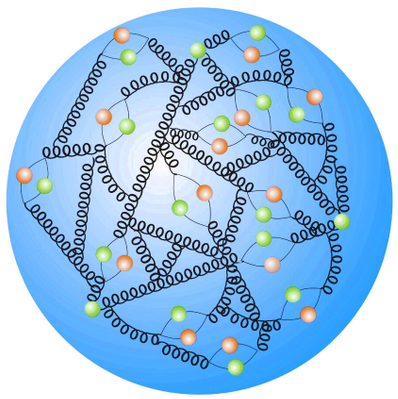
- or to discover BSM physics — "no-lose theorem"

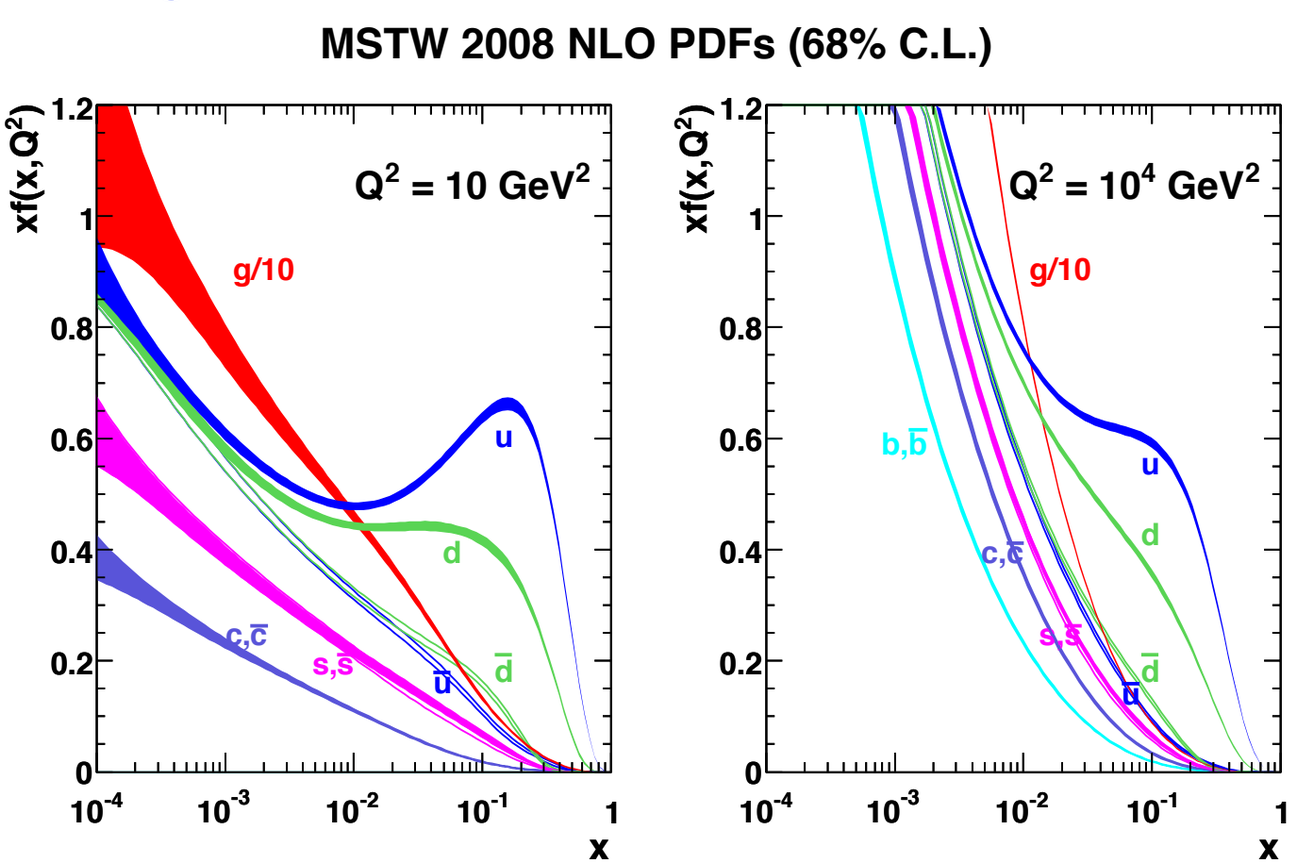
Protons are the standard vehicle for the highest-energy colliders:

- heavy (or at least $m_p \gg m_e$) ➠ synchrotron radiation not an issue at $\sqrt{s}$ = 14 TeV
- protons are stable ➠ high intensity possible (nominal $\mathscr{L} = 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$)

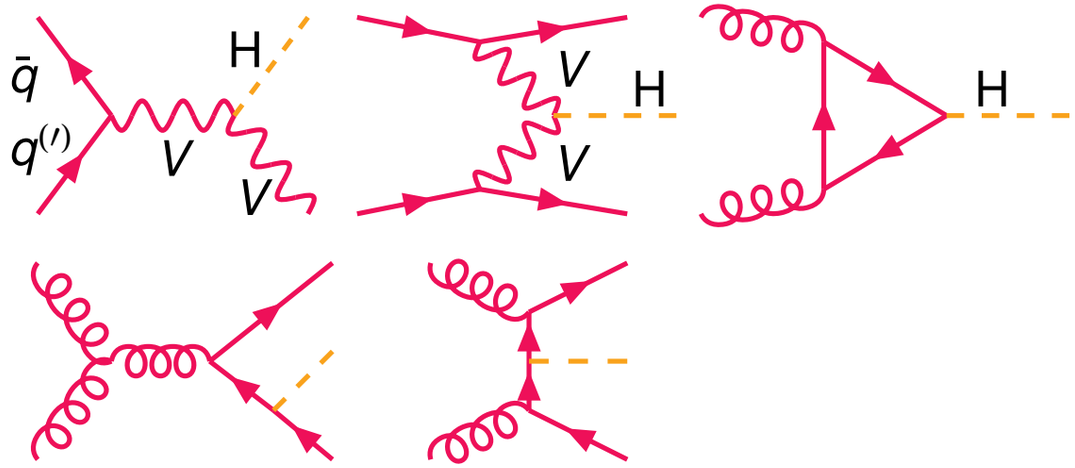
Protons are a rich source of quarks & gluons

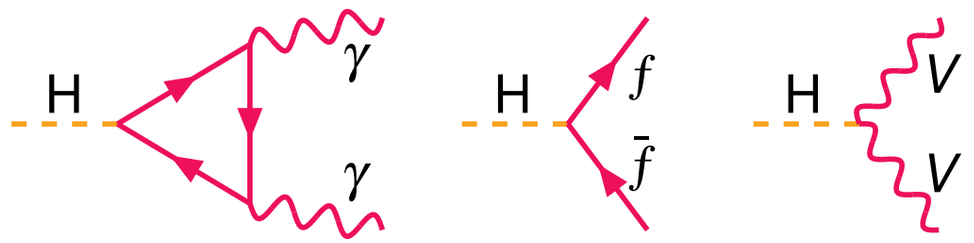
- both a bliss and a curse!
- $\sigma_{\text{tot}} \sim 10^{10}\sigma(H)$

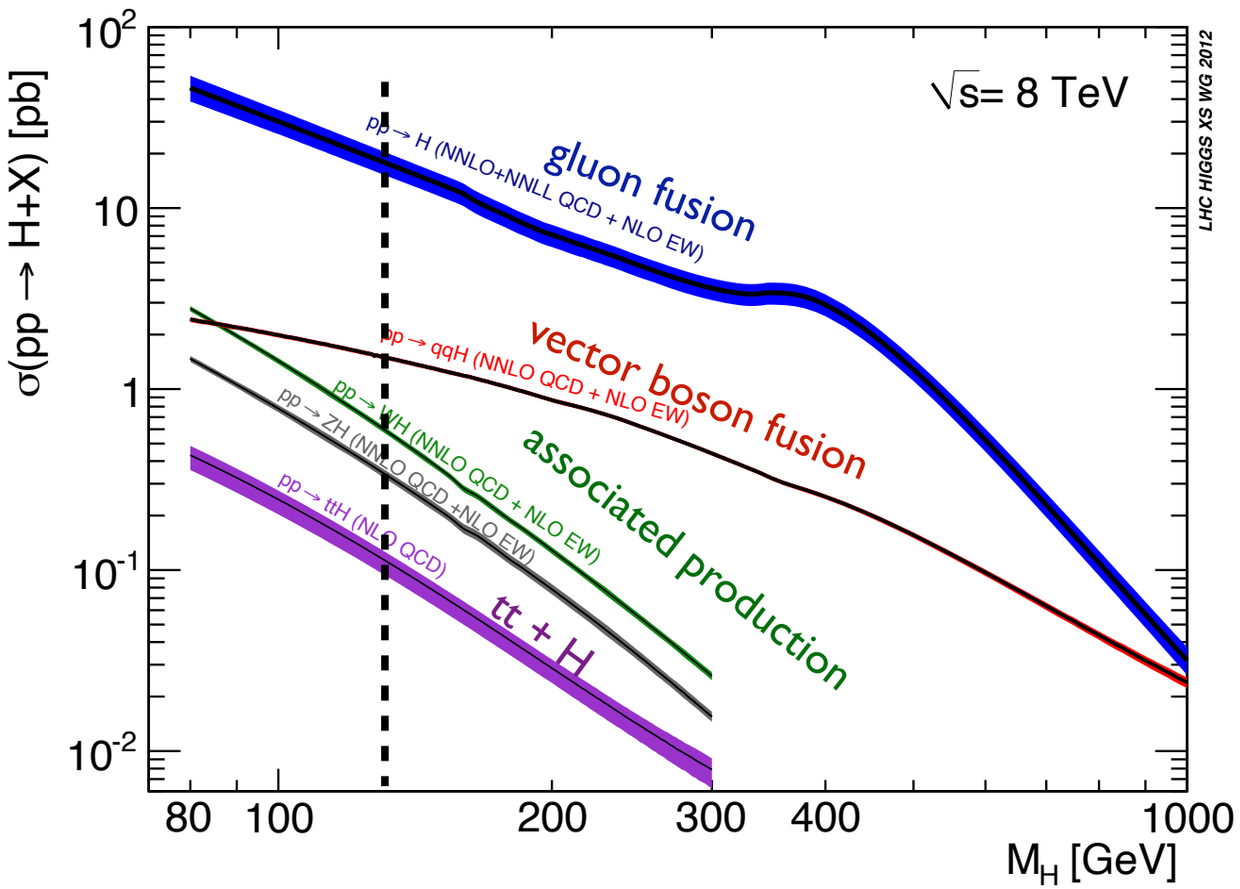


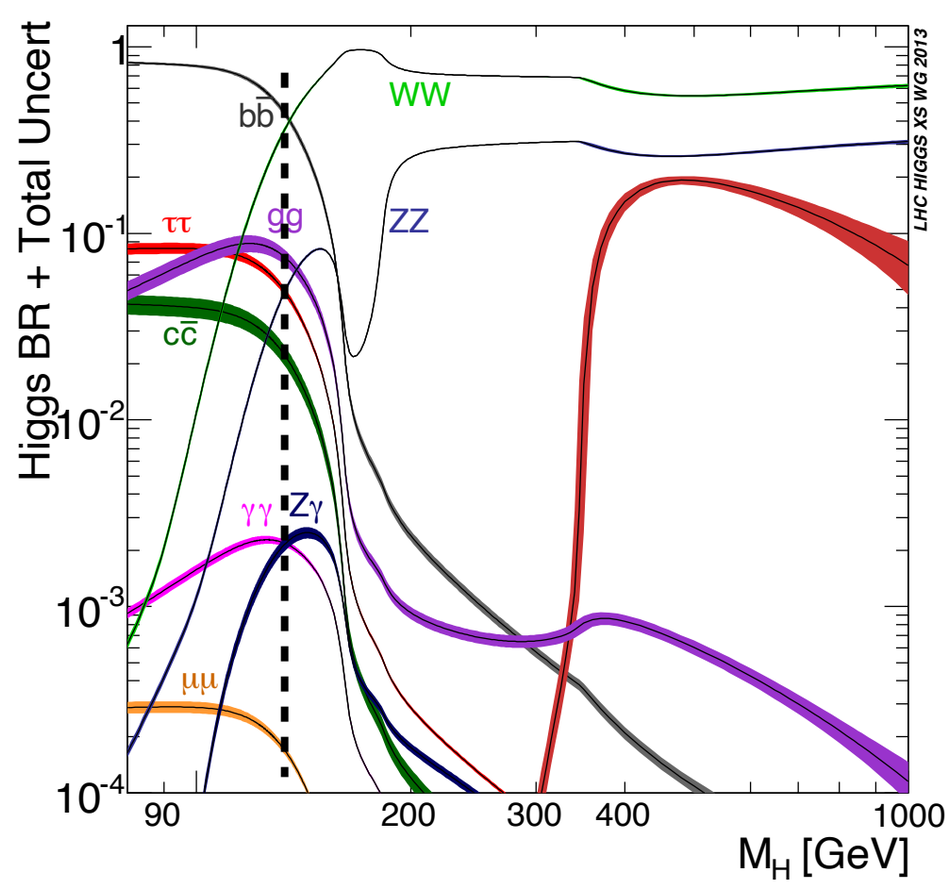


Higgs boson production & decay









figures from https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

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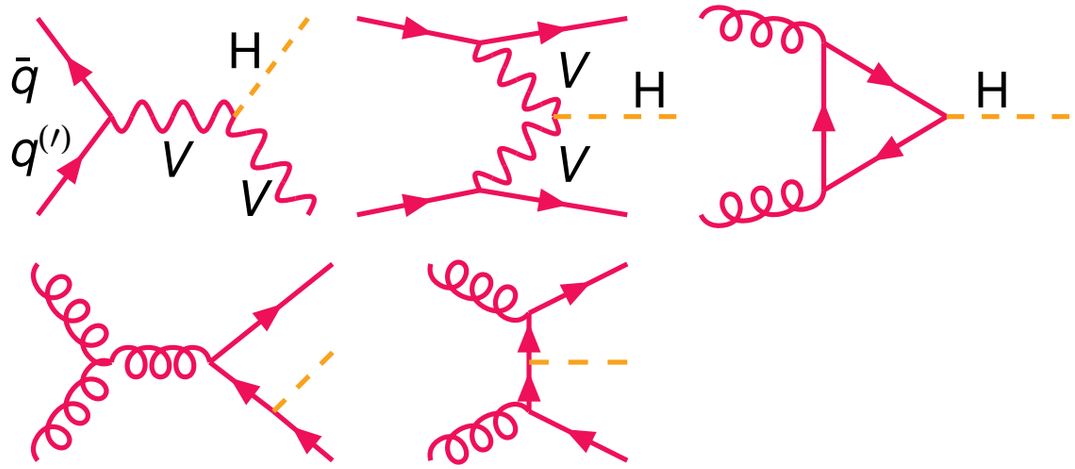
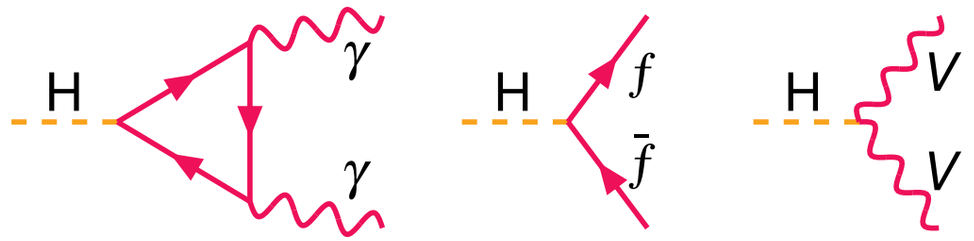
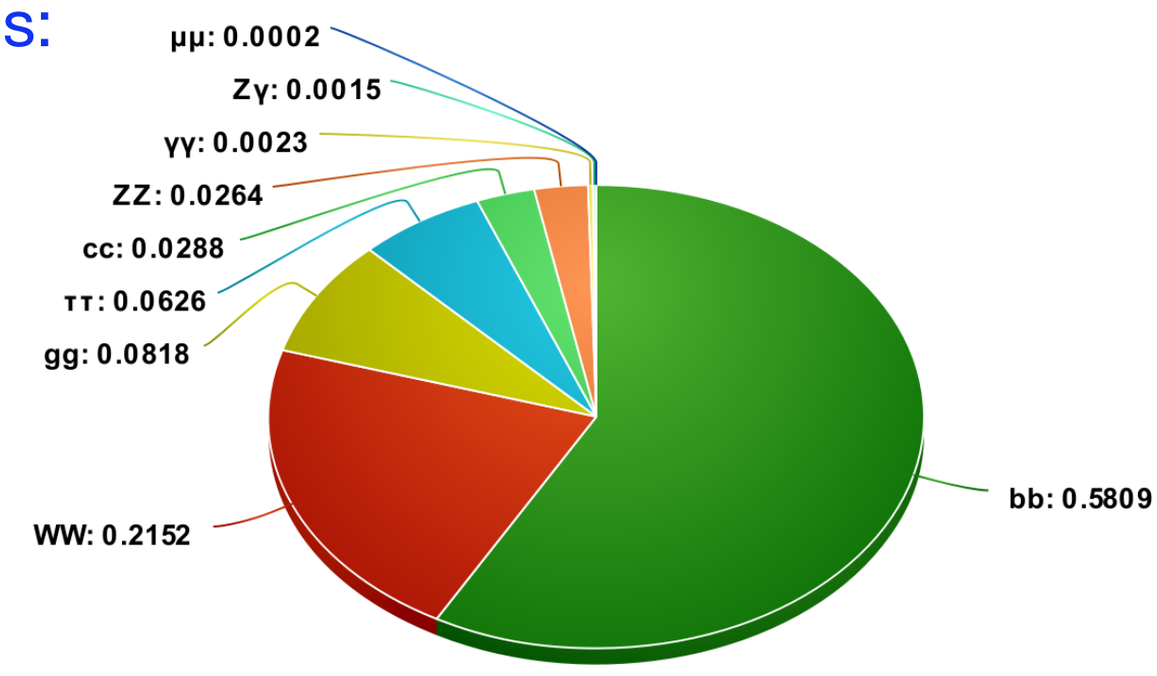




Different modes probe different couplings:

- production:
  - ggF, $t\bar{t}H$: coupling to fermions
  - VBF, VH: coupling to W, Z
- decay:
  - clear for decays to $f\bar{f}$, VV
  - $H \to \gamma\gamma$: coupling to both W boson and fermions



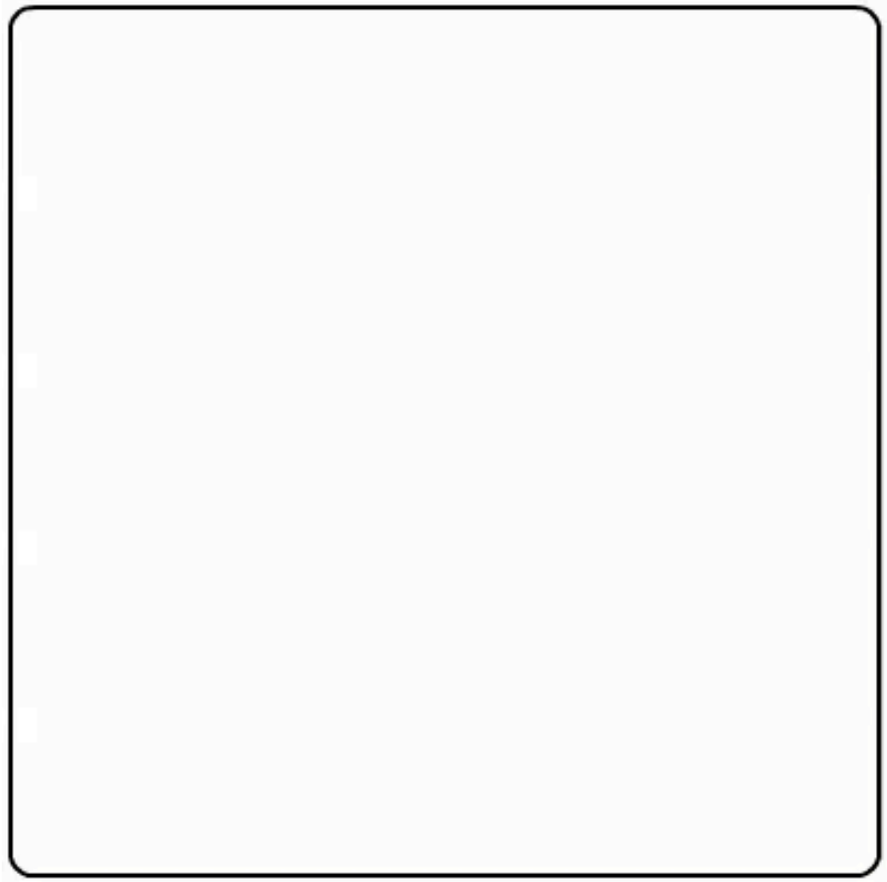
For $m_H = 125$ GeV: $\Gamma = 4.1$ MeV

Detection techniques

Always start from “stable” particles!

- $e^{\pm}, \mu^{\pm}, \gamma$
- charged particles (mostly $\pi^{\pm}$)
- energy deposits in calorimeters

ATLAS animation, but techniques are general for high-energy collider experiments



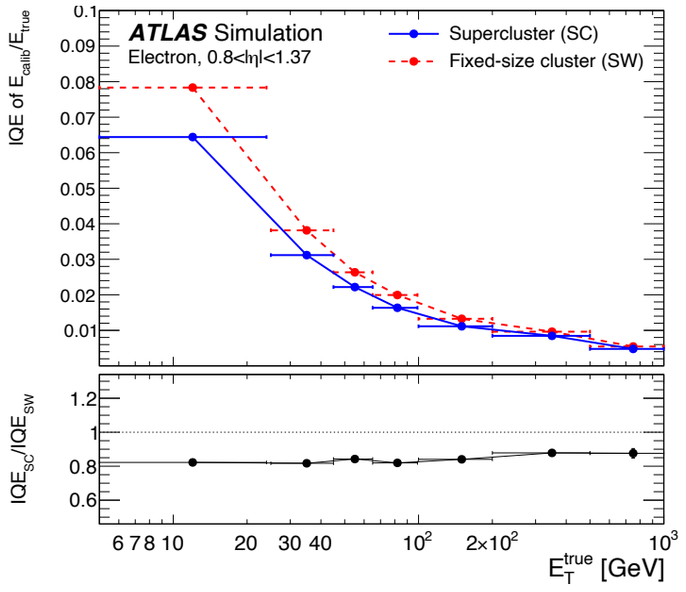
Beyond these:

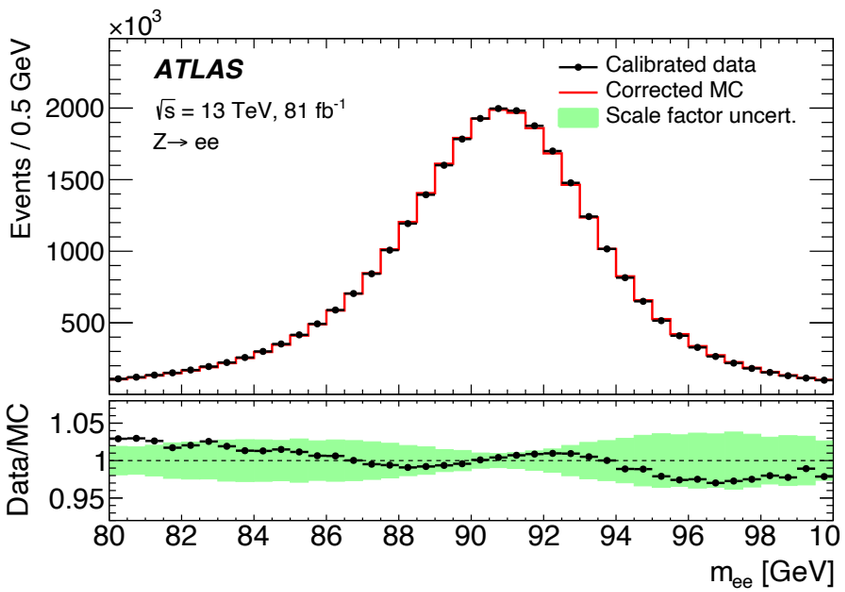
- jets: collimated streams of hadrons, representative of high-energy $q/\bar{q}/g$
  - LHC: anti-k_t algorithm (ATLAS: $R = 0.4$)
- b-quark jets: identified from τ(b hadrons) ~ 1.5 ps; decays reconstructed using tracking information (ATLAS: for $\epsilon_b = 70\,\% : \epsilon_c = 20\,\%$, $\epsilon_l = 0.2\,\%$)
- τ leptons: τ_τ ~ 300 fs; hadronic decays → narrow jets (difficult to distinguish from jets)
- ν: seen as apparent lack of momentum balance in the transverse plane
  - no constraint possible along the beam direction

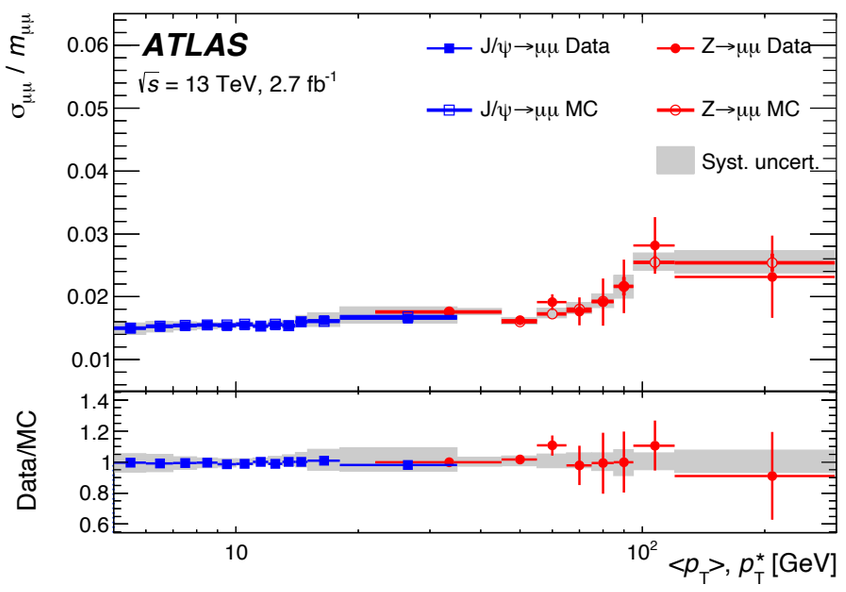
Resolutions: general guideline

$e^{\pm}, \mu^{\pm}, \gamma$: excellent momentum resolution, "easy" to identify

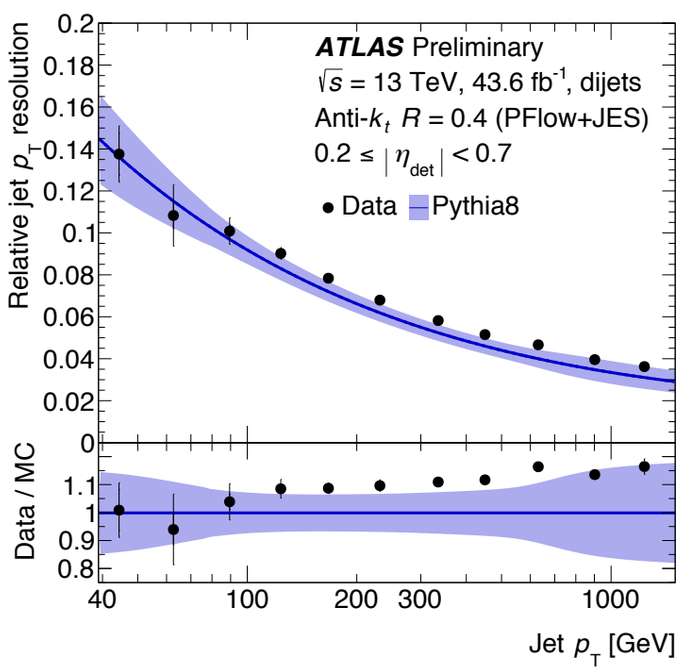
- but beware of HF decays, jets fragmenting to π^0

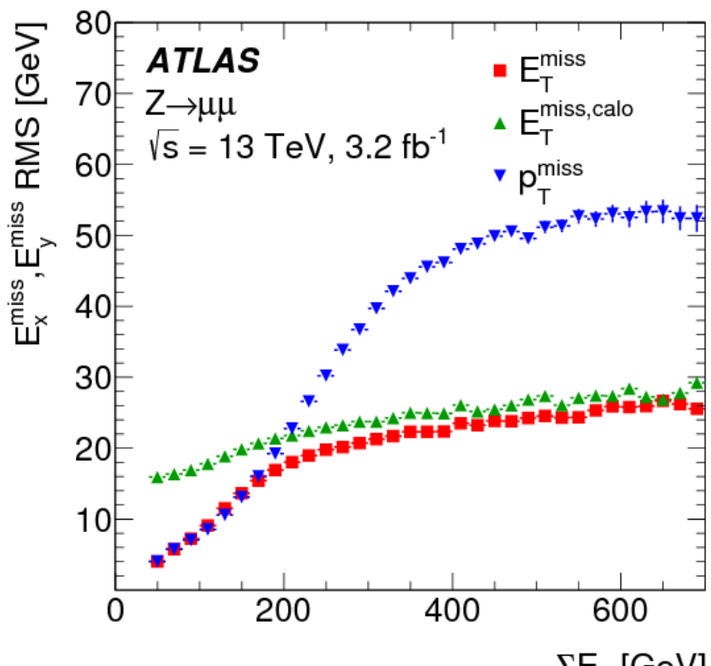






jets: resolution significantly worse; missing E_T: relatively poor

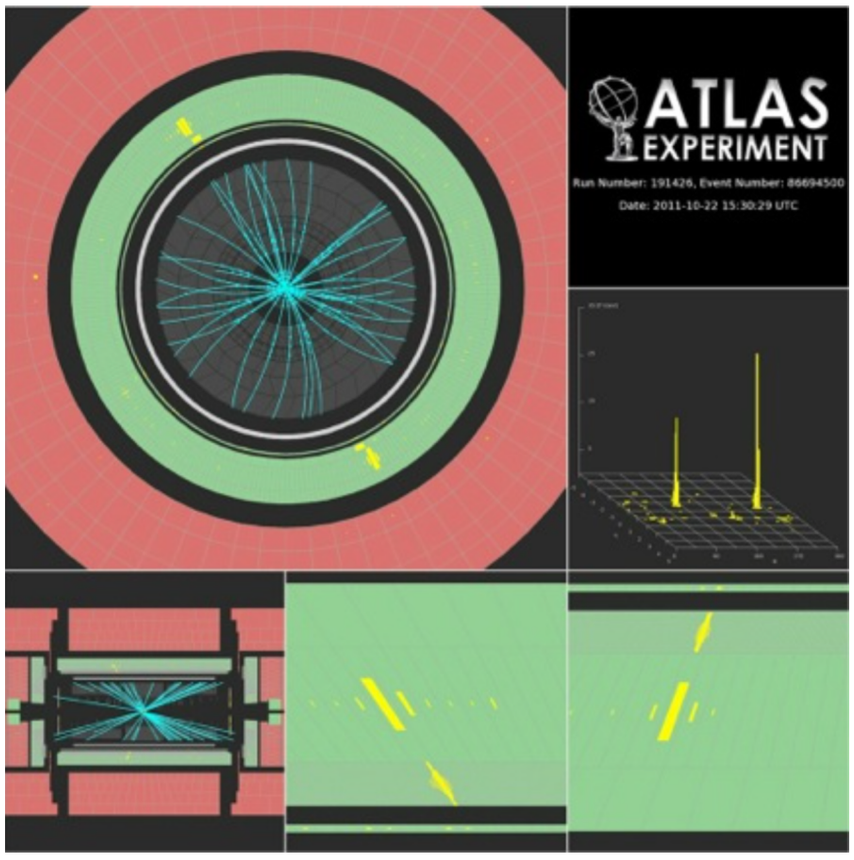


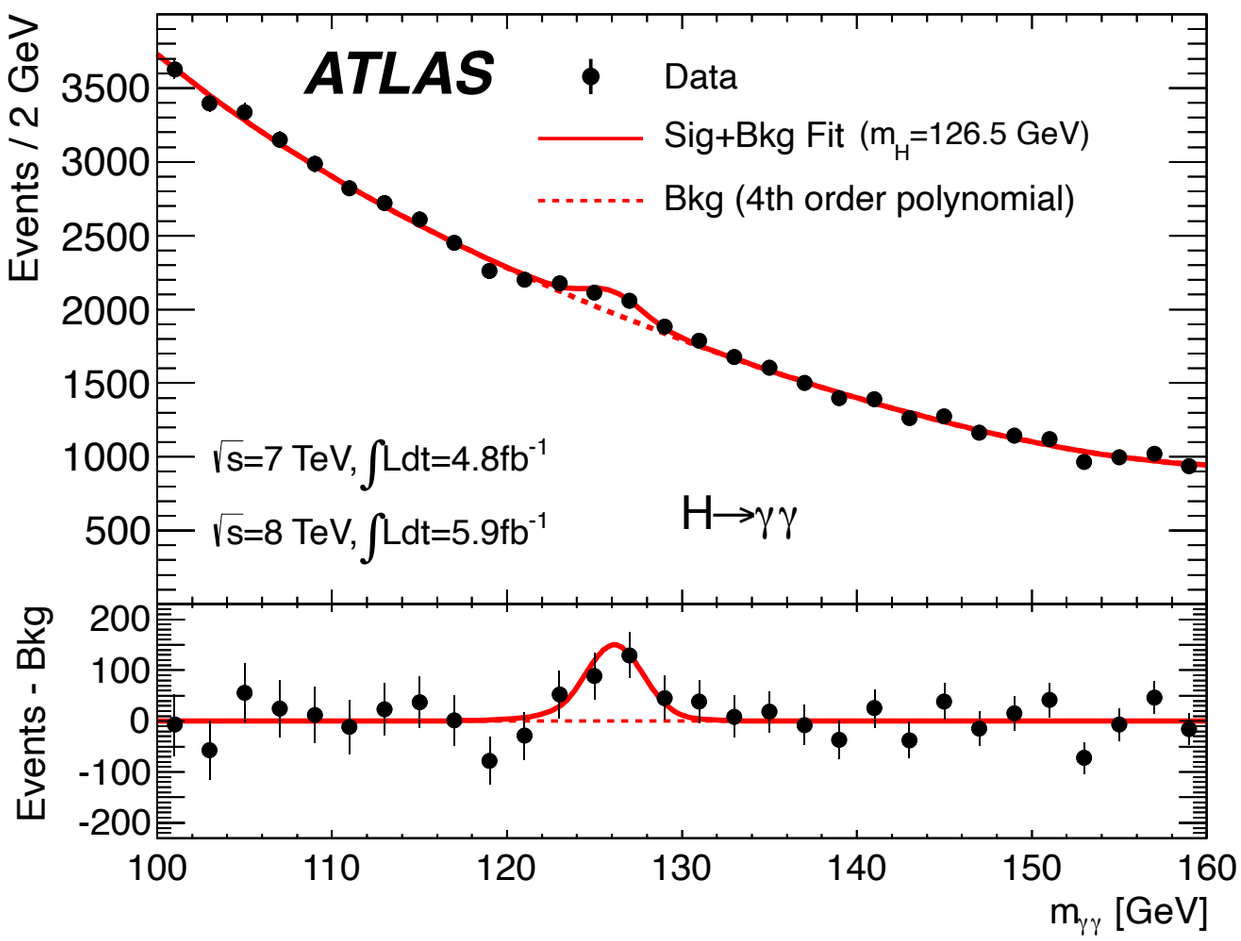


$H \to \gamma\gamma$

Typically, large (or at least substantial) background from γ+jet and jet+jet processes

- need a statistical background subtraction
  - common to all production modes





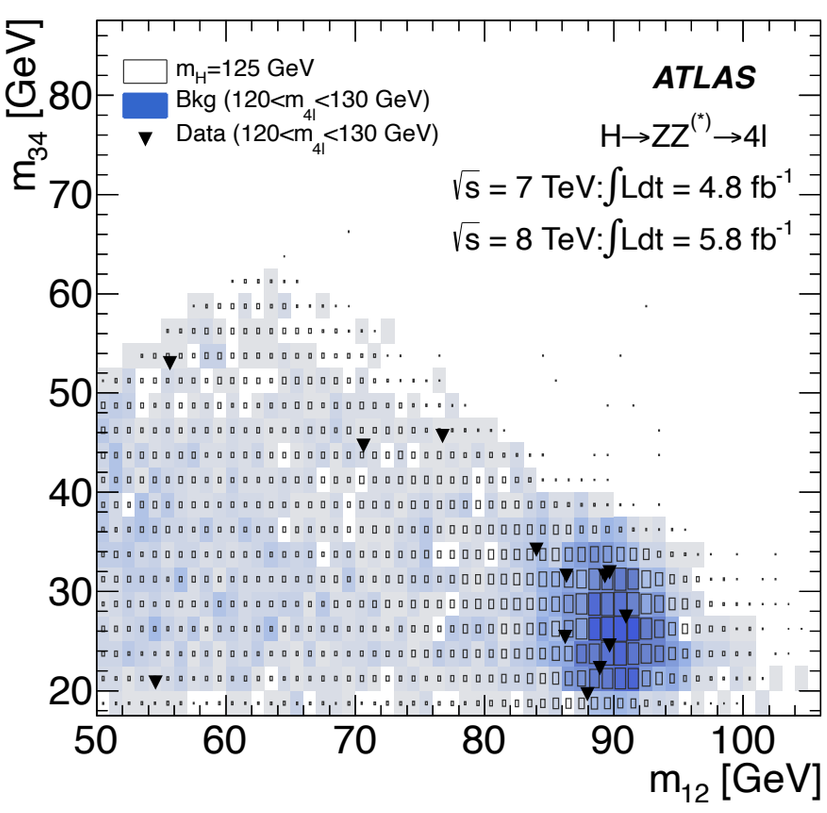
Note: observation of this decay mode precludes spin-1 hypothesis

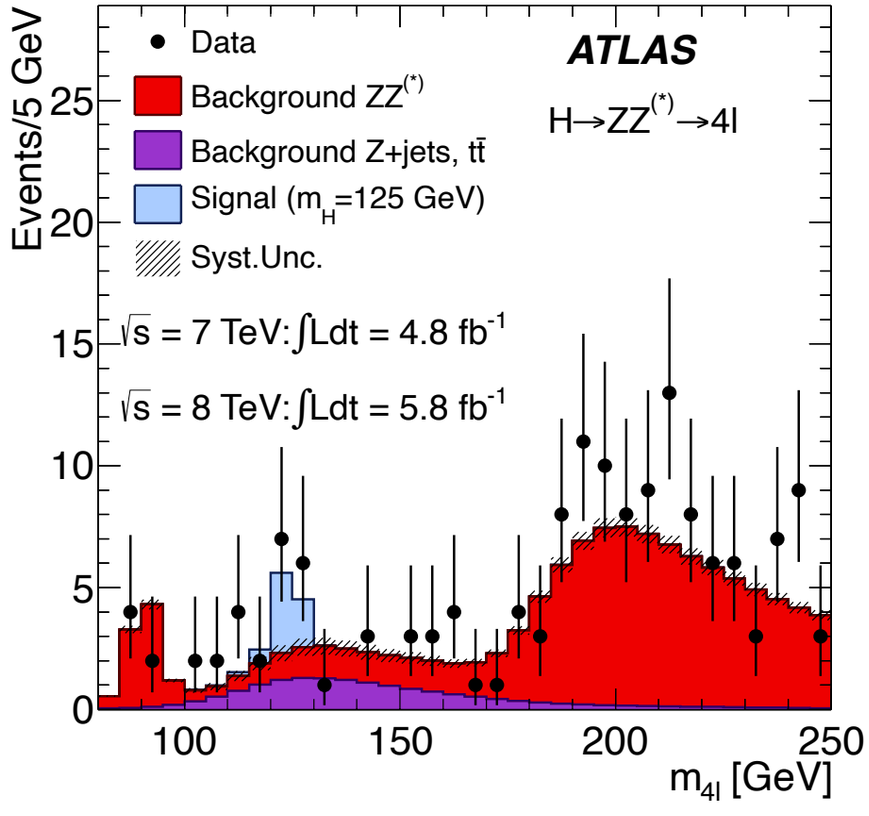
- Landau-Yang theorem

H → ZZ → 4 leptons (*eeee*, *eeμμ*, *μμμμ*)

"Golden mode": select four isolated electrons / muons

- drawback: low $Z \to \ell^+\ell^-$ branching fractions (3.4%)
- one off-shell Z boson ➠ one pair of very soft leptons ($p_{\mathrm{T}}(\ell) > 6$ GeV)
  - control regions to constrain background normalisations
- irreducible $ZZ^{(*)}$ background not an issue due to good mass resolution





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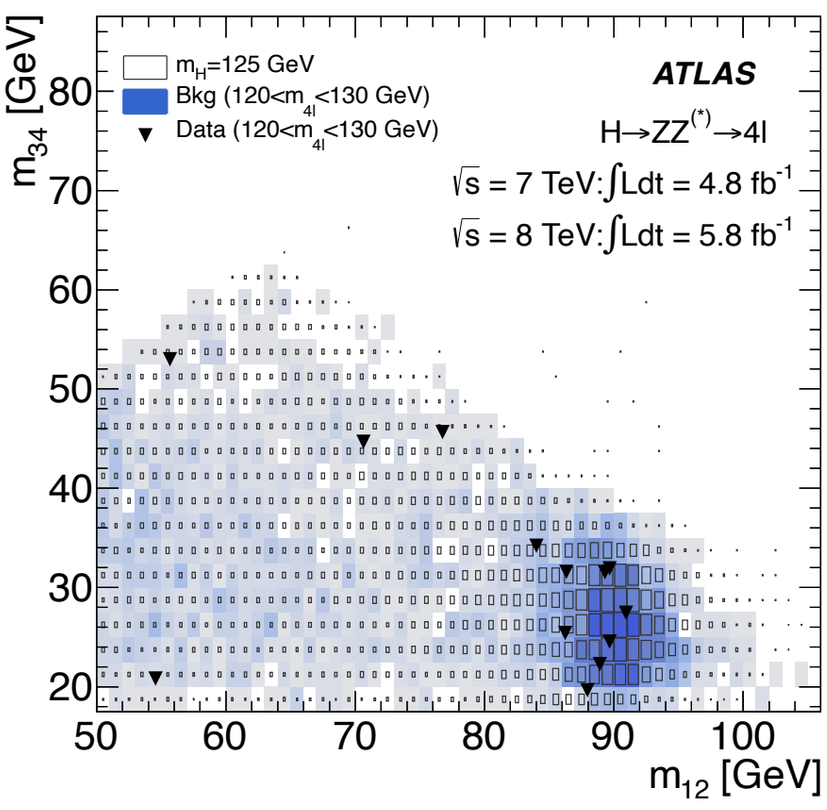
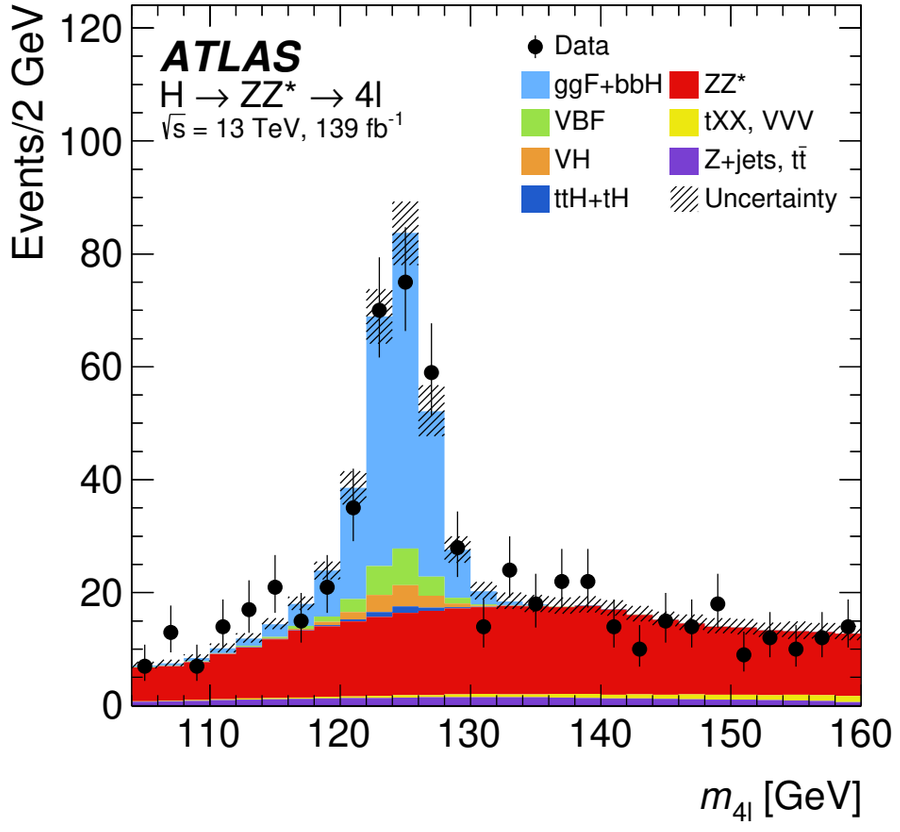
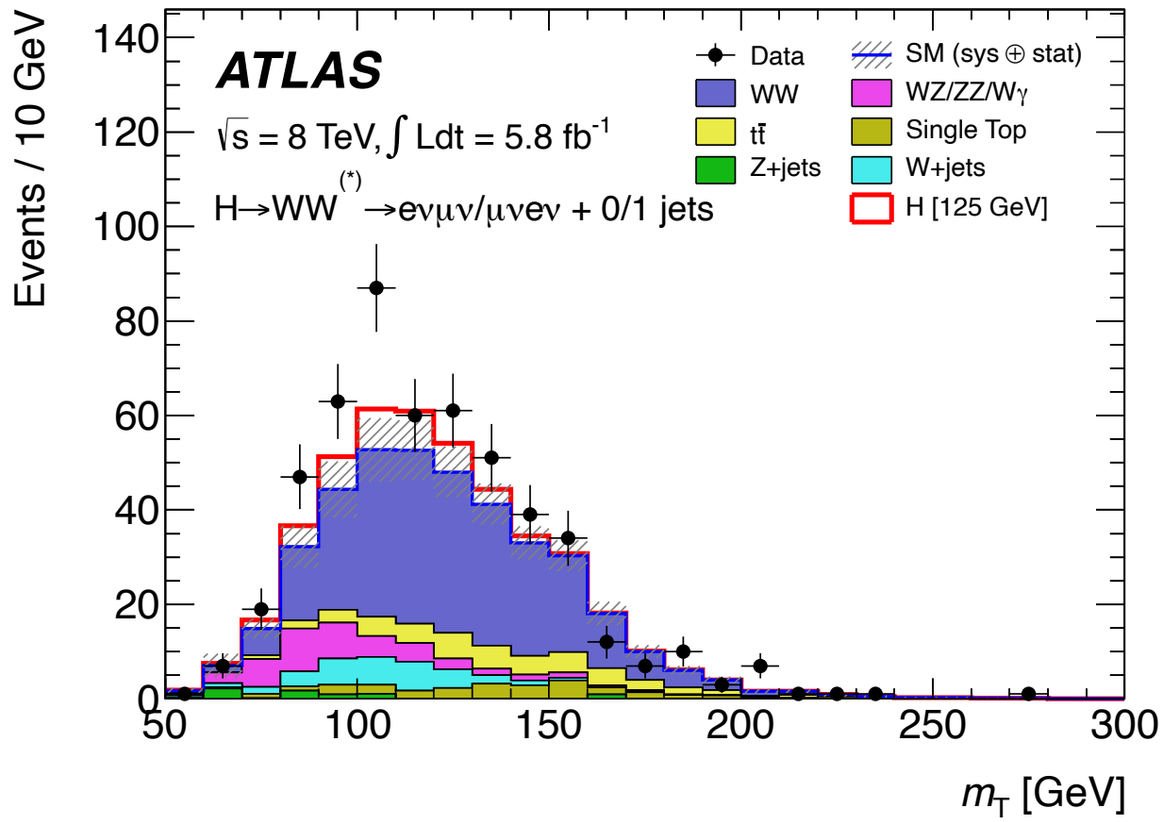




$H \to W^+W^- \to \ell^+\nu_\ell \ell'^-\bar{\nu}_{\ell'}$

Two escaping ν ➠ mass reconstruction not possible

- but some sensitivity retained: $m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{\text{miss}}|^2}, \quad E_T^{\ell\ell} = \sqrt{|\mathbf{p}_T^{\ell\ell}|^2 + m_{\ell\ell}^2}$



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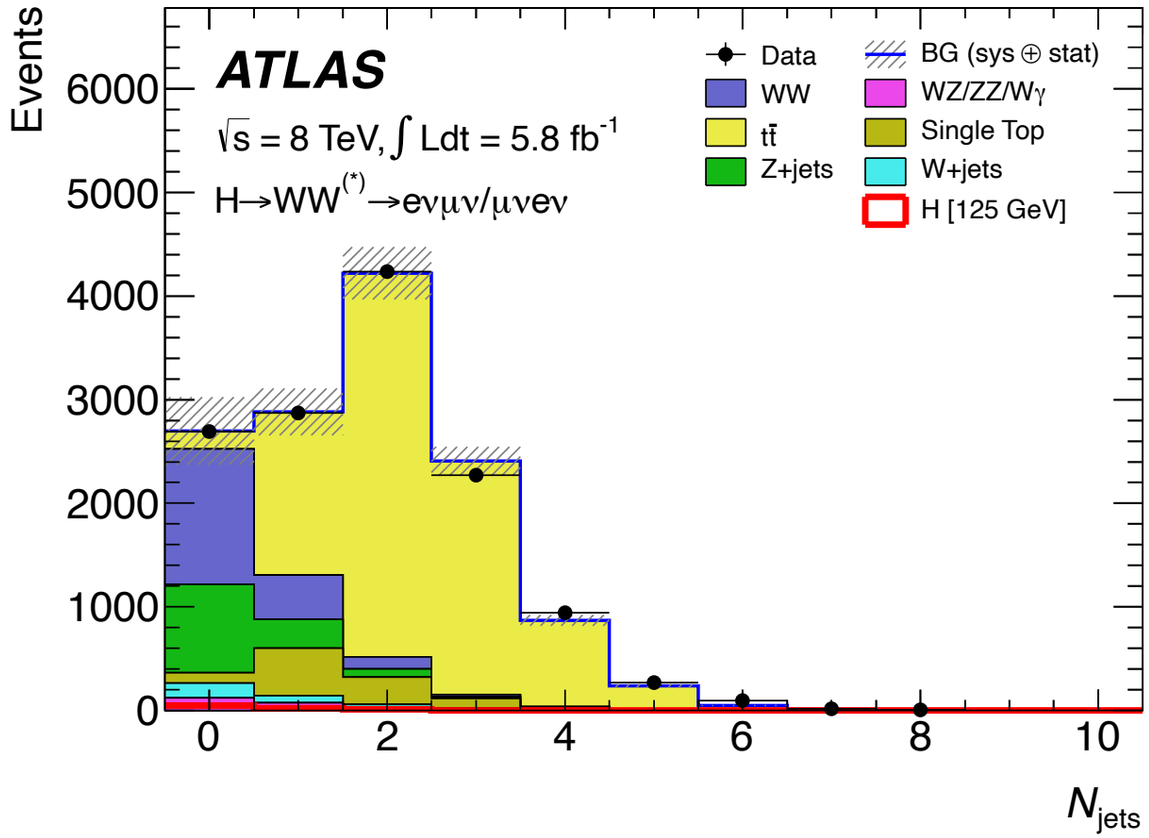
Large branching fraction (22%), but large irreducible (W^+W^-) and reducible backgrounds ($t\bar{t}$, W+jets, …)

- use of control regions critical
- jet multiplicity dependent ➠ analysis carried out in separate 0,1, ≥ 2 jet multiplicity bins
- substantial uncertainties related to QCD radiative corrections



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- use of control regions critical
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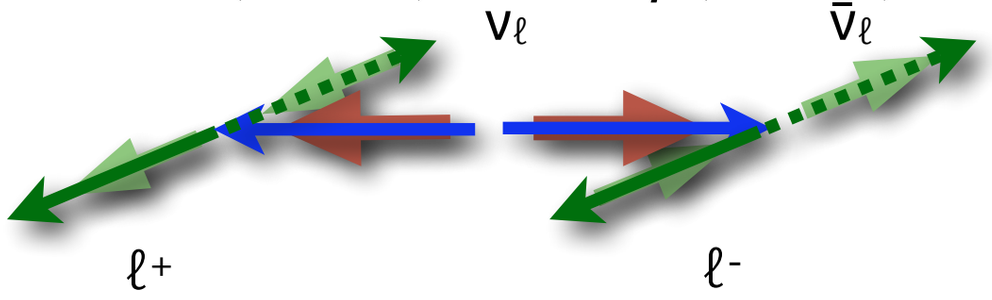
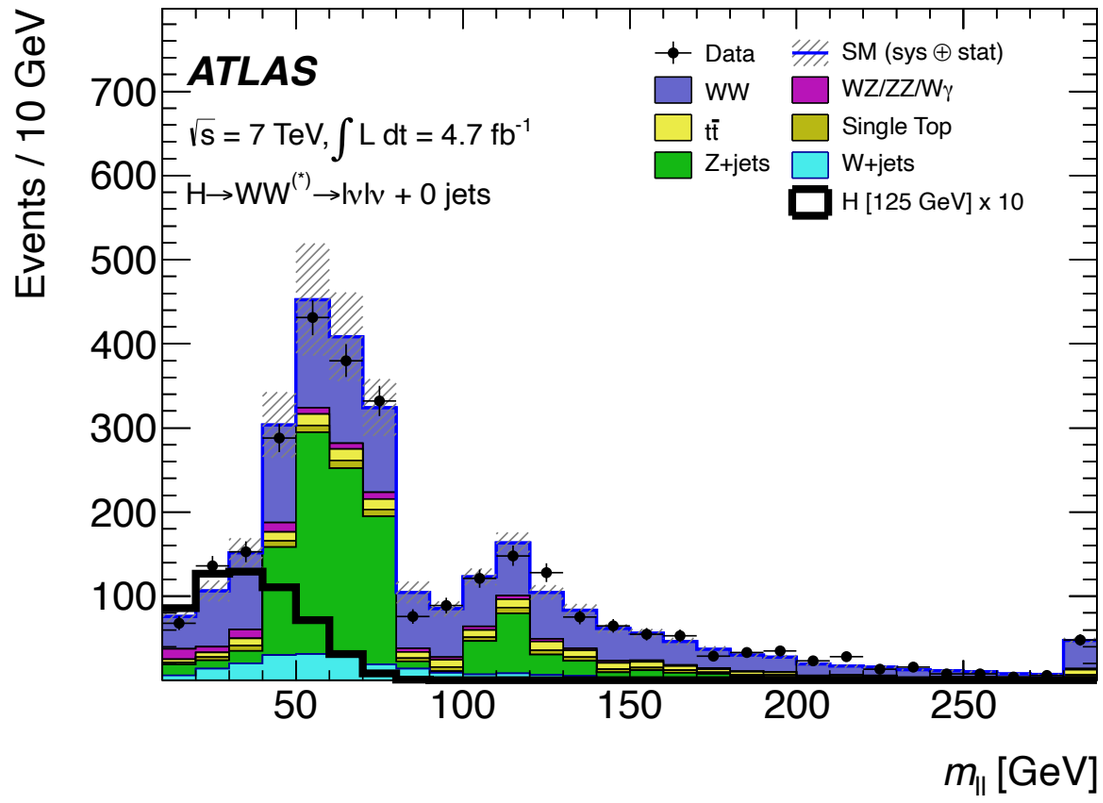
The Higgs boson's (expected) spin-0 nature is (typically) exploited

- small $m(\ell^+\ell'^-)$ and $\Delta\phi(\ell^+\ell'^-)$

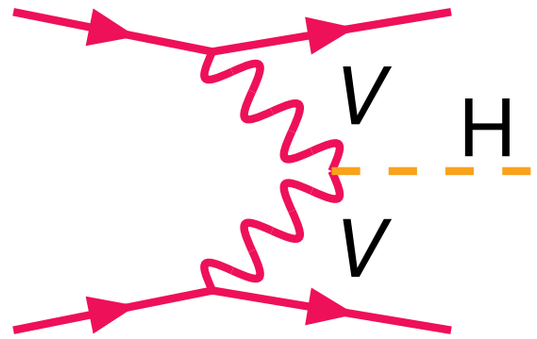


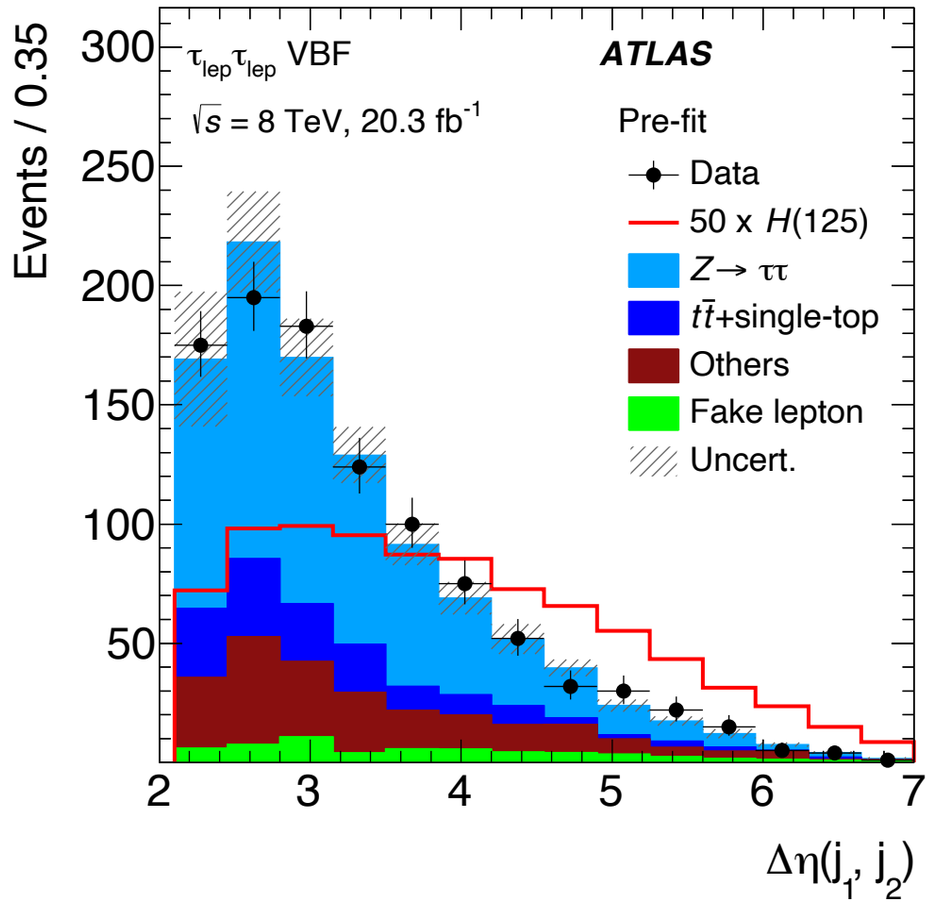


$H \to \tau^+\tau^-$

Analyses complicated by many τ decay modes and escaping ν

- poor mass resolution
  - ➠ in ggF, suffer from large $Z \to \tau^+\tau^-$ background
  - ➠ highest sensitivity achieved in VBF production mode





large $|y|$ ➠ ~ along beam direction

- rapidity differences invariant under boost along beam direction

$$y \equiv \frac{1}{2} \ln\left(\frac{E - p_z}{E + p_z}\right)$$

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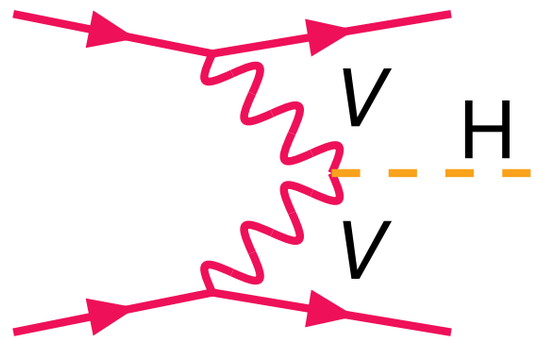
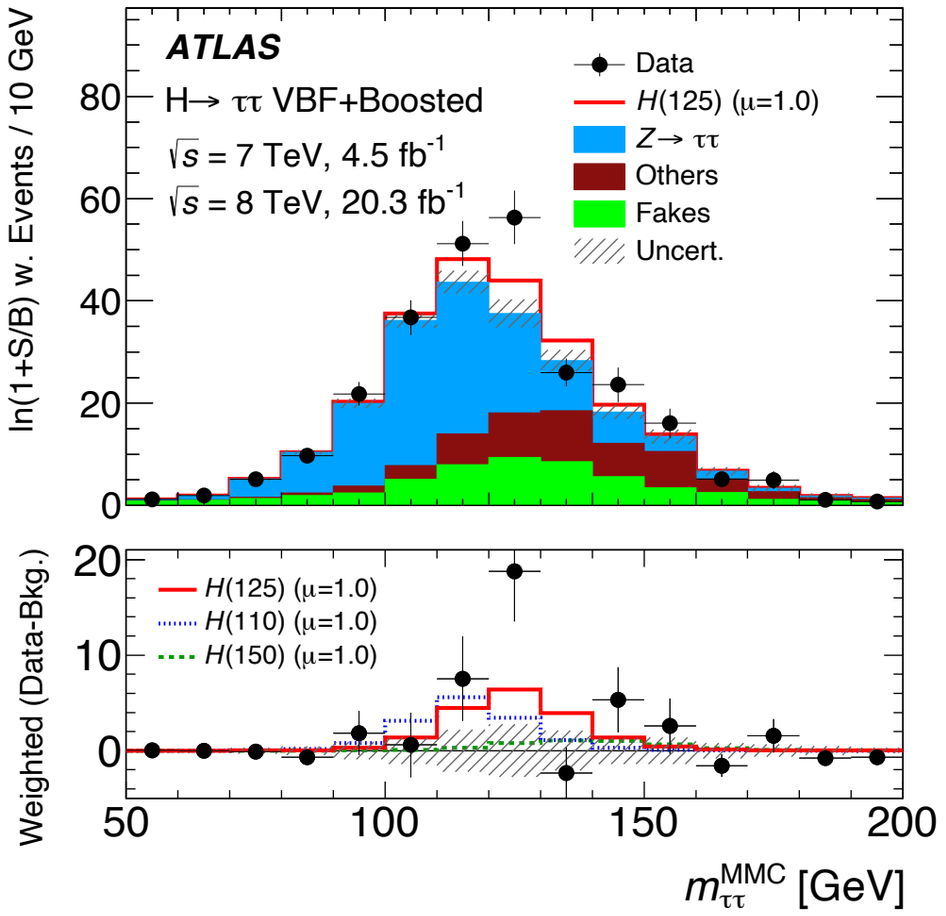
Analyses complicated by many τ decay modes and escaping ν

- poor mass resolution
  - ➠ in ggF, suffer from large $Z \to \tau^+\tau^-$ background
  - ➠ highest sensitivity achieved in VBF production mode
- using m_τ as a constraint allows to mitigate resolution effects somewhat



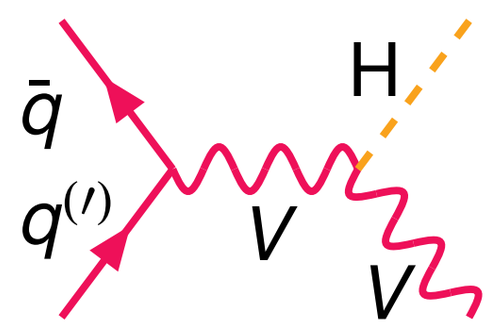


$H \to b\bar{b}$

Overwhelming background from $b\bar{b}$ through strong interaction

➠ only observed in associated production so far

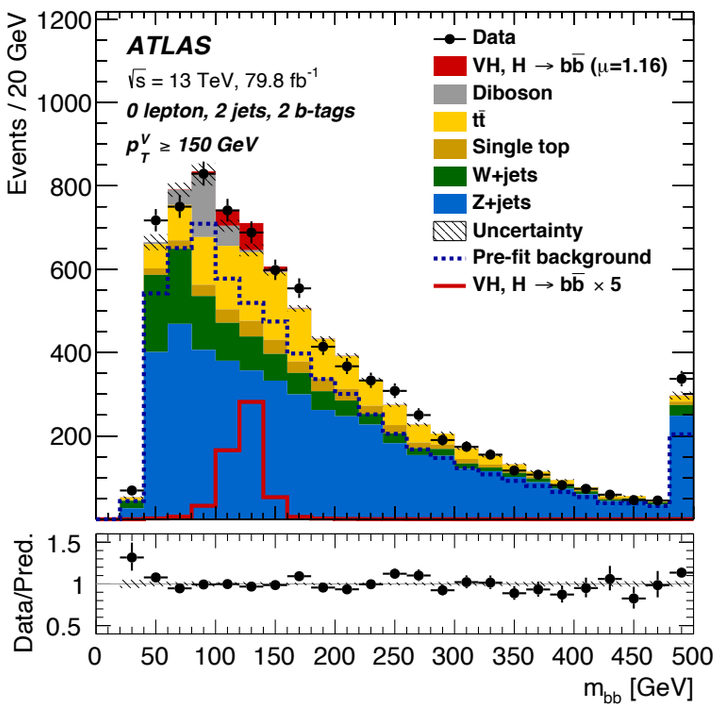
- $Z \to \ell^+\ell^-, \nu\bar{\nu}$; $W \to \ell\nu$

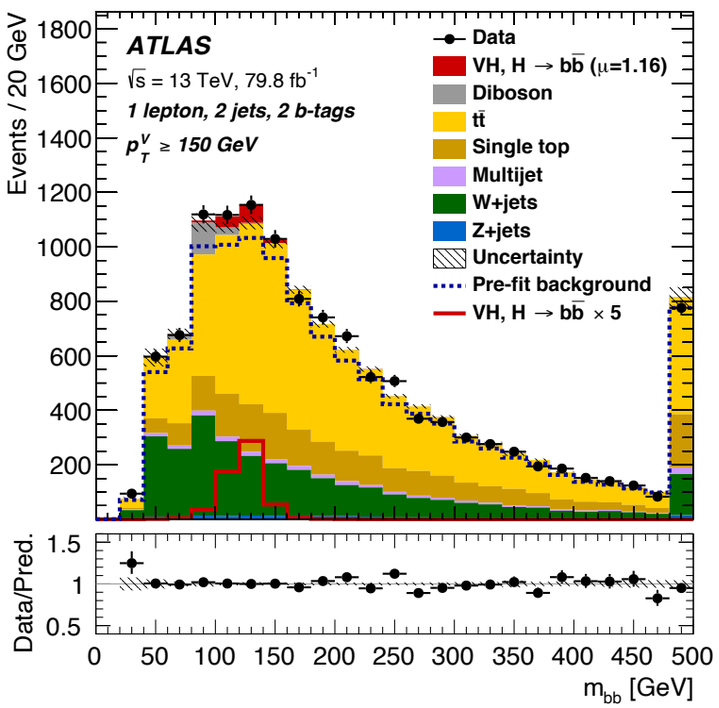


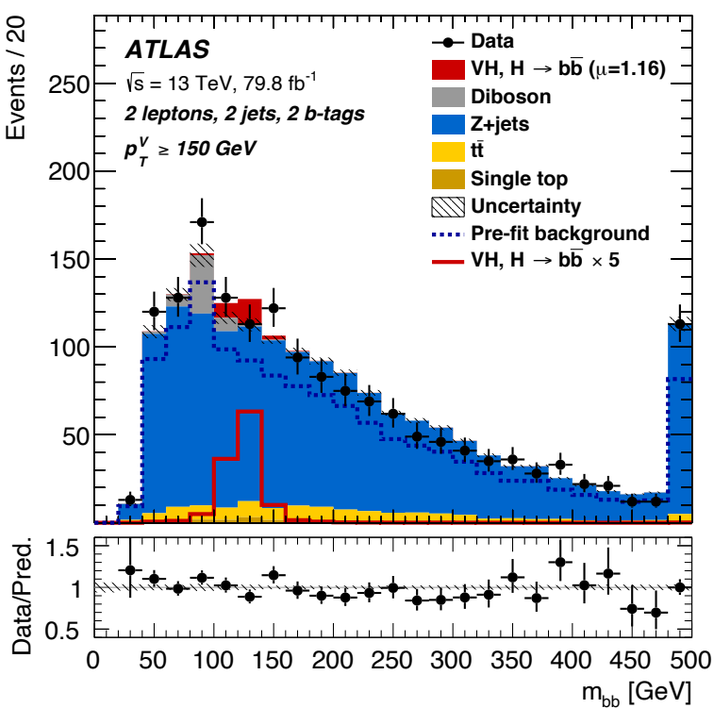
Sensitivity limited by dominant irreducible ($W/Z + b\bar{b}$) and reducible ($t\bar{t}$) backgrounds

- multivariate analysis techniques necessary (also used in other Higgs analyses)

- binning in jet and b-tag multiplicity







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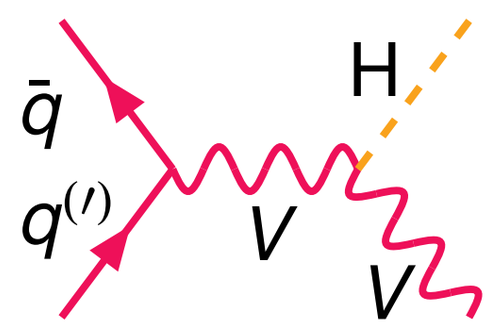

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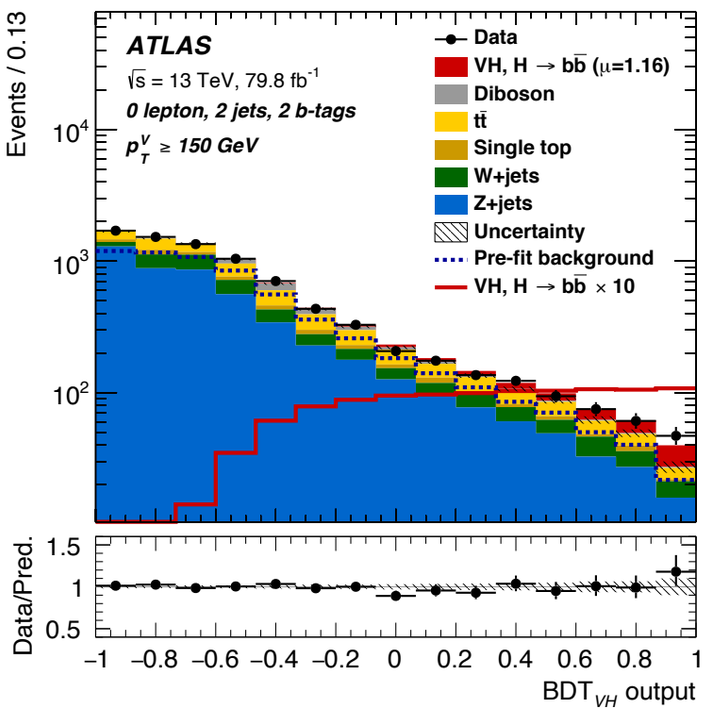
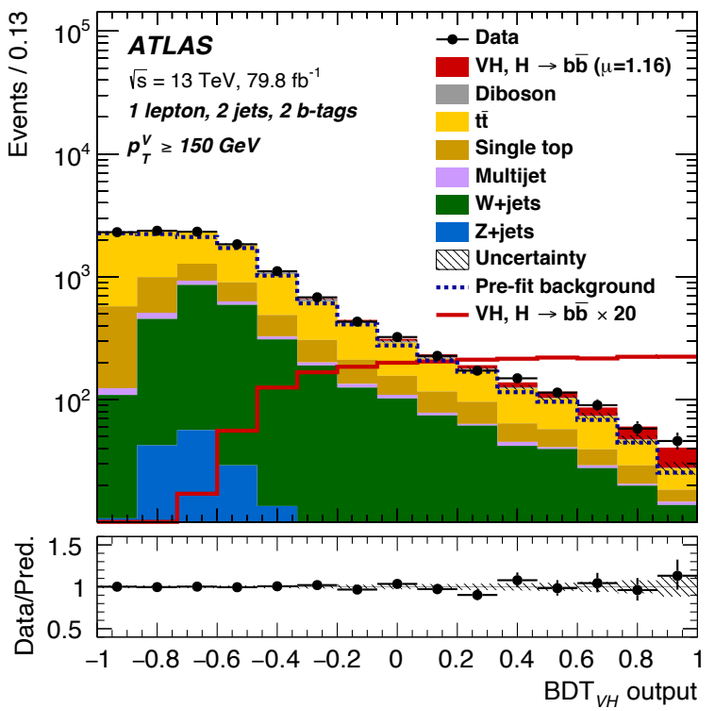
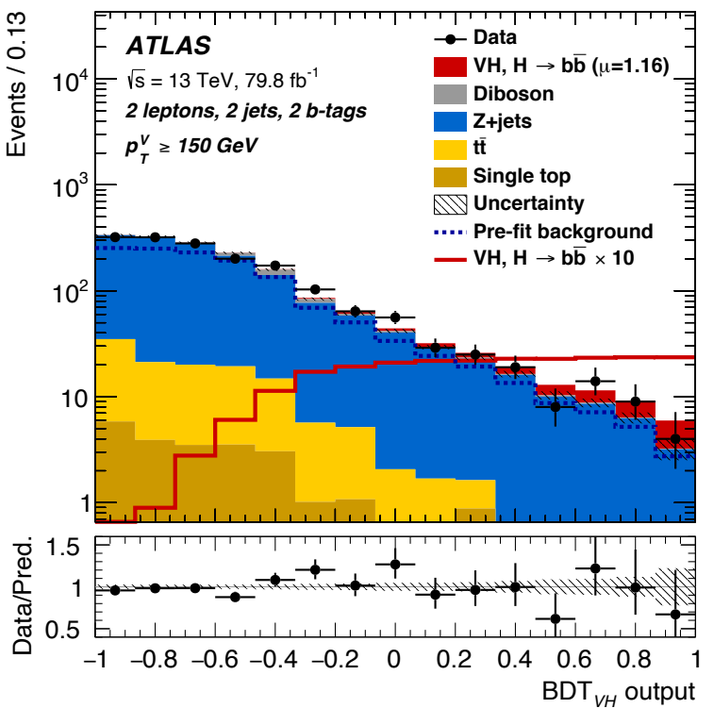




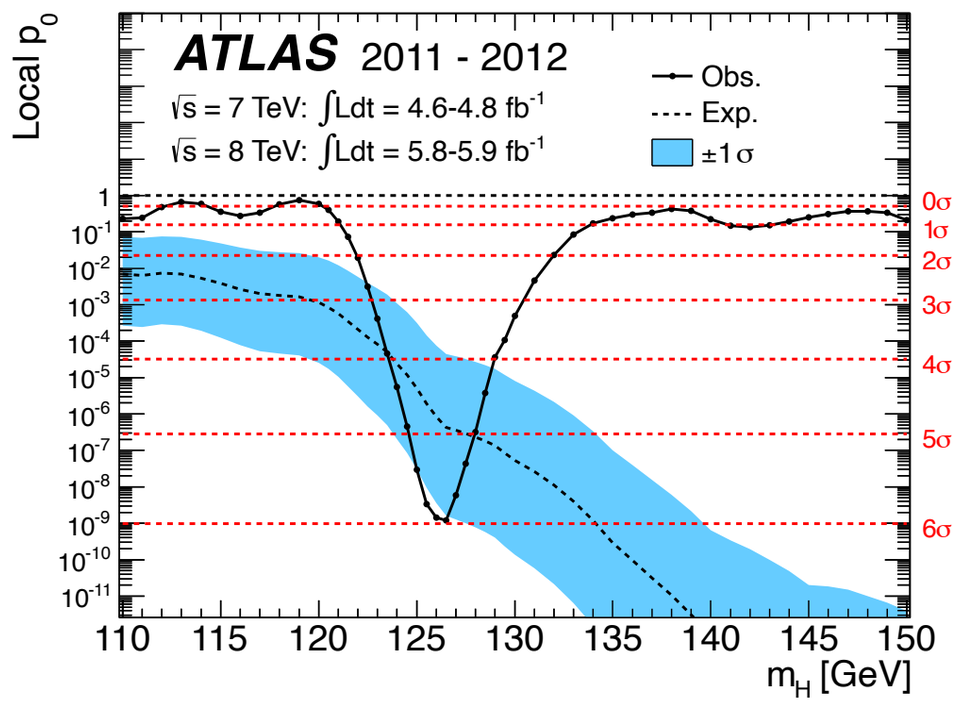


Statistical analysis

Basic approach: use (binned or unbinned) likelihood ratio ("profile LH")

$$\lambda(\mu) = L\left(\mu, \hat{\hat{\vec{\theta}}}(\mu)\right) / L\left(\hat{\mu}, \hat{\vec{\theta}}\right)$$

- μ: assumed signal strength
  - also other parameters of interest possible
- $\vec{\theta}$: nuisance parameters parameterising effect of systematic uncertainties on predictions
  - per channel or combined (allowing for proper accounting of correlations)
  - multiple μ parameters when relaxing assumptions

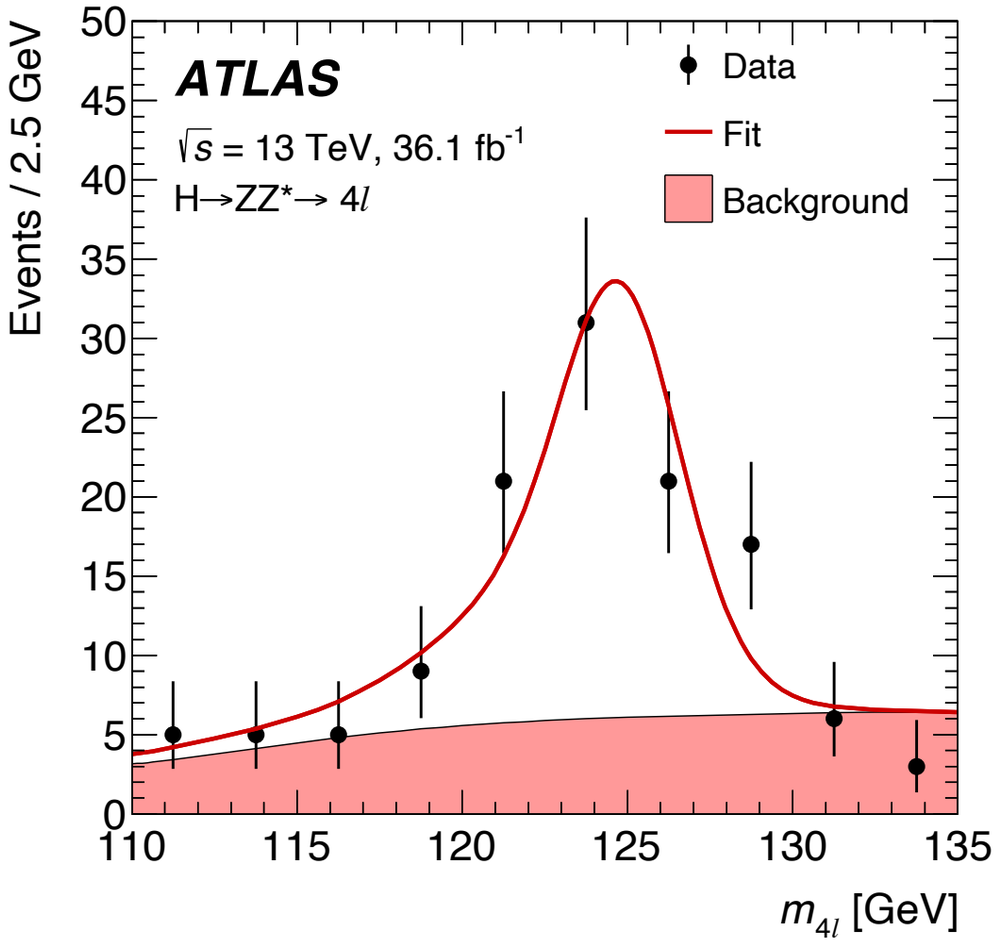


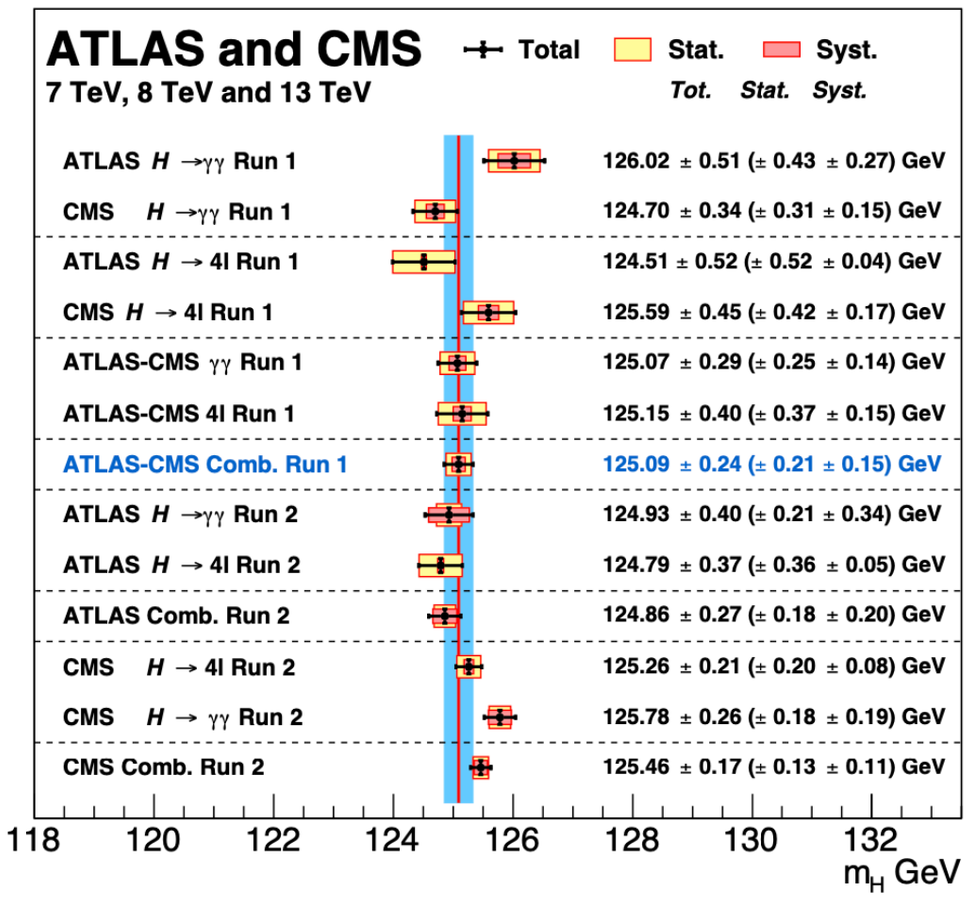
Higgs boson properties

Higgs boson mass

Exploit high-resolution channels ($H \to \gamma\gamma, H \to \ell^+\ell^-\ell'^+\ell'^-$)

- relative precision approaching 1‰



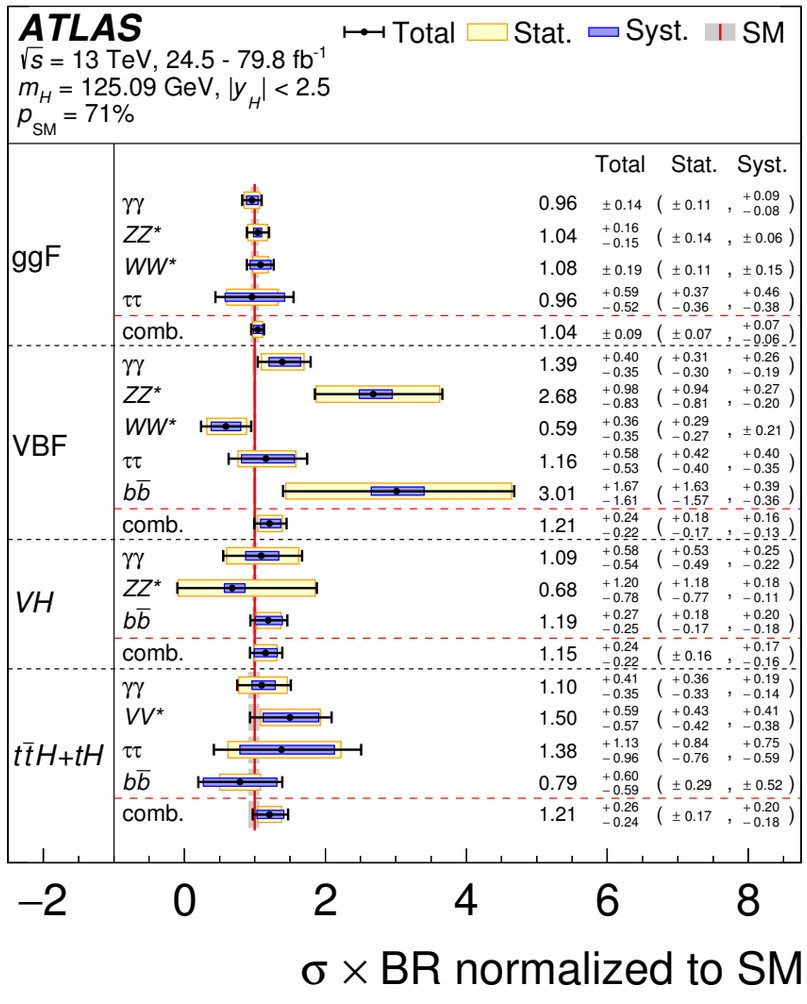


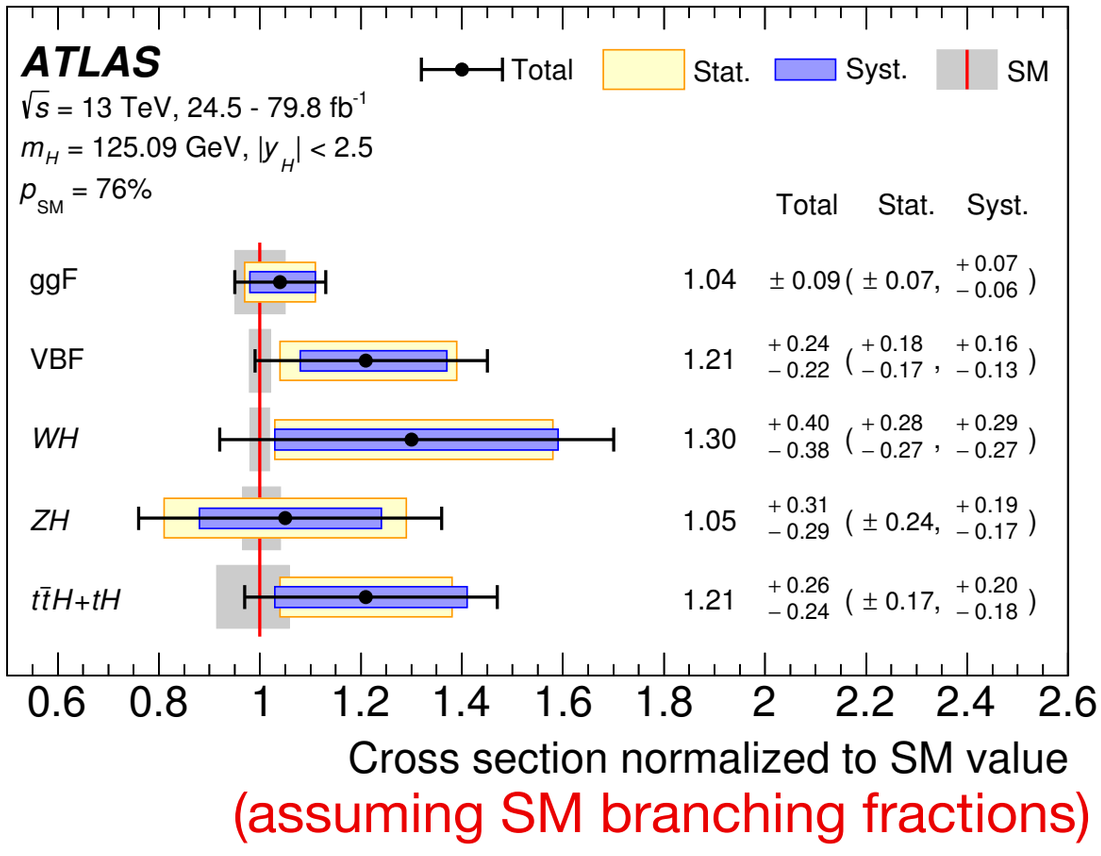
Cross sections and branching fractions

Assuming a single, common μ:

- Run 1 combination: $\mu = 1.09 \pm 0.11$
- Run 2 ATLAS: $\mu = 1.11 \pm 0.09$
- Run 2 CMS: $\mu = 1.17 \pm 0.10$

~ equal contributions from statistical, experimental, theoretical uncertainties





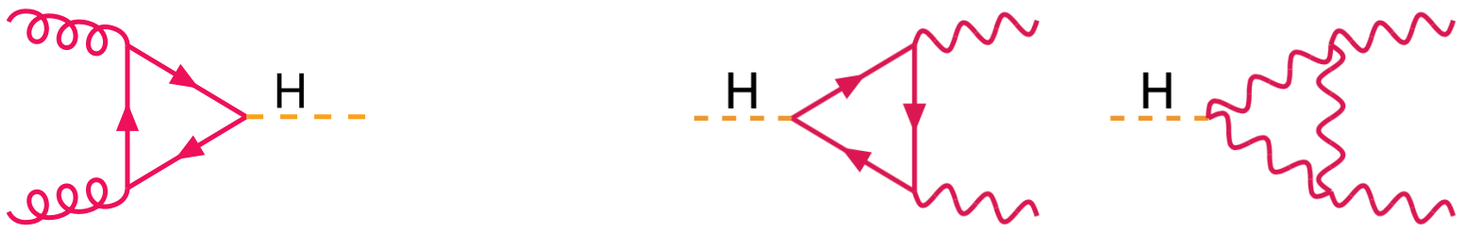
(assuming SM branching fractions)

Coupling constants ("κ framework") (1)

Going beyond interpretation in "mere" terms of cross sections, branching fractions:

- obvious framework for interpretation: coupling constant modifiers
  - fermions: $y_f \to \kappa_f y_f$
    vector bosons: $g_{W/Z} \to \kappa_{W/Z}\, g_{W/Z}$
  - simplifying assumptions possible
- $gg \to H$ and $H \to \gamma\gamma$: loops so also sensitive to new physics contributions

➠ retain also κ_g, κ_γ interpretations



- "resolved" interpretation: $\kappa_g^2 = 1.04\kappa_t^2 + 0.002\kappa_b^2 - 0.04\kappa_t\kappa_b$

  $\kappa_\gamma^2 = 1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.67\kappa_W\kappa_t$

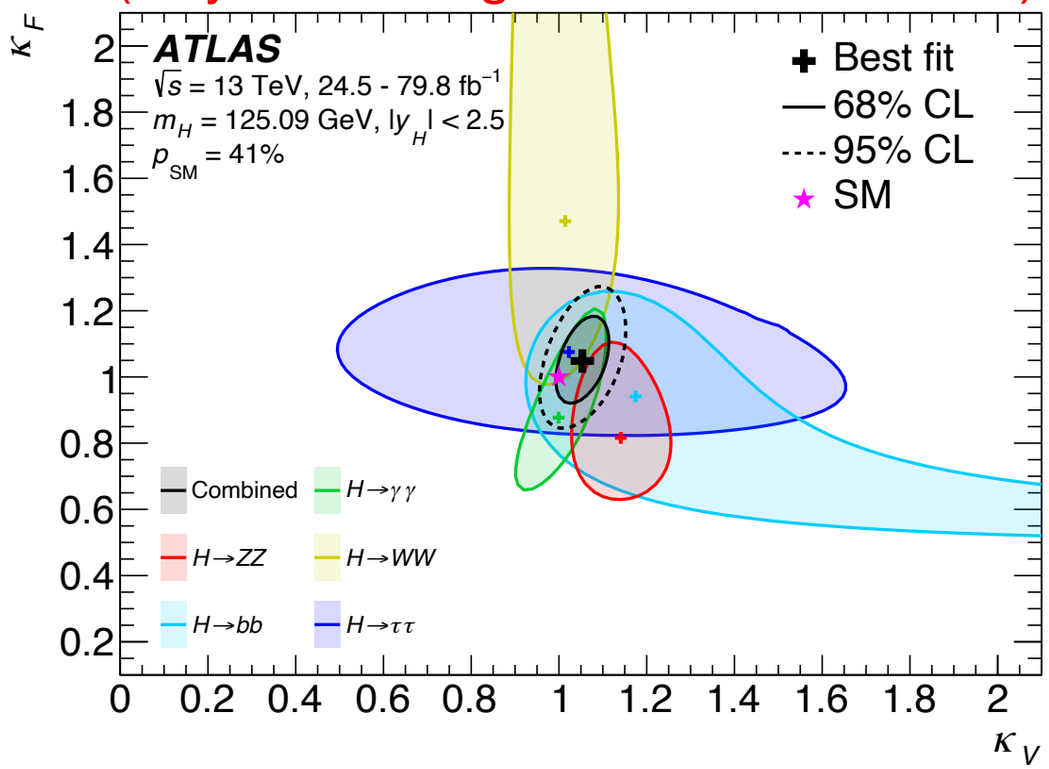
- N.B.: $\sigma(gg \to H)$ excludes 4th quark family with "usual" Yukawa couplings
  - contributions become ~ mass independent for high mass

Coupling constants ("κ framework") (2)

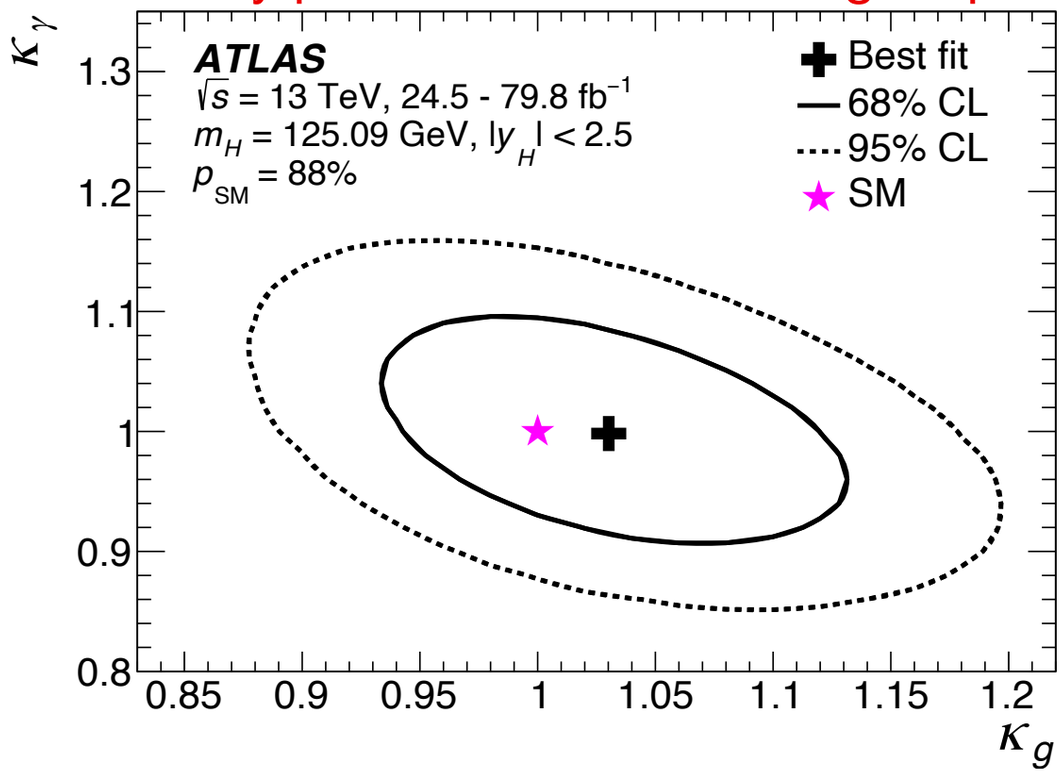
Cross section for production process i, decay j: $\sigma_i \mathrm{Br}_j = \sigma_i \Gamma_j / \Gamma_H$, with $\Gamma_H = \sum_j \Gamma_j$ ➠ sensitivity not to just products of κ_i

- Γ_H could have contributions from non-standard decays
  - weak constraints from limits on explicit $H \rightarrow$ invisible searches in VBF, VH production ($\mathrm{Br}(H \rightarrow \text{invisible}) < \sim 0.2$); but mostly assumed to be 0

assuming common κ_f, κ_V
(only relative sign can be determined)



assuming $\kappa_f = \kappa_V = 1$ for production / decay processes not involving loops

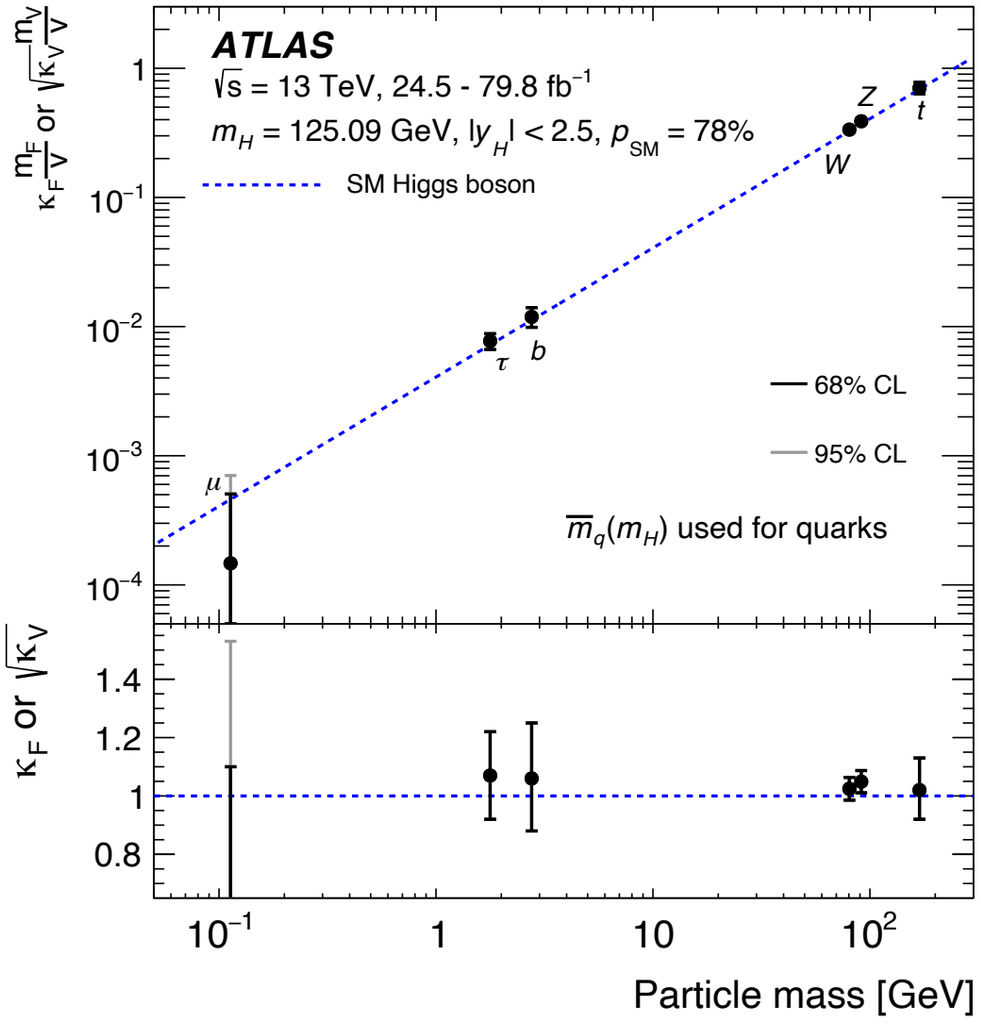


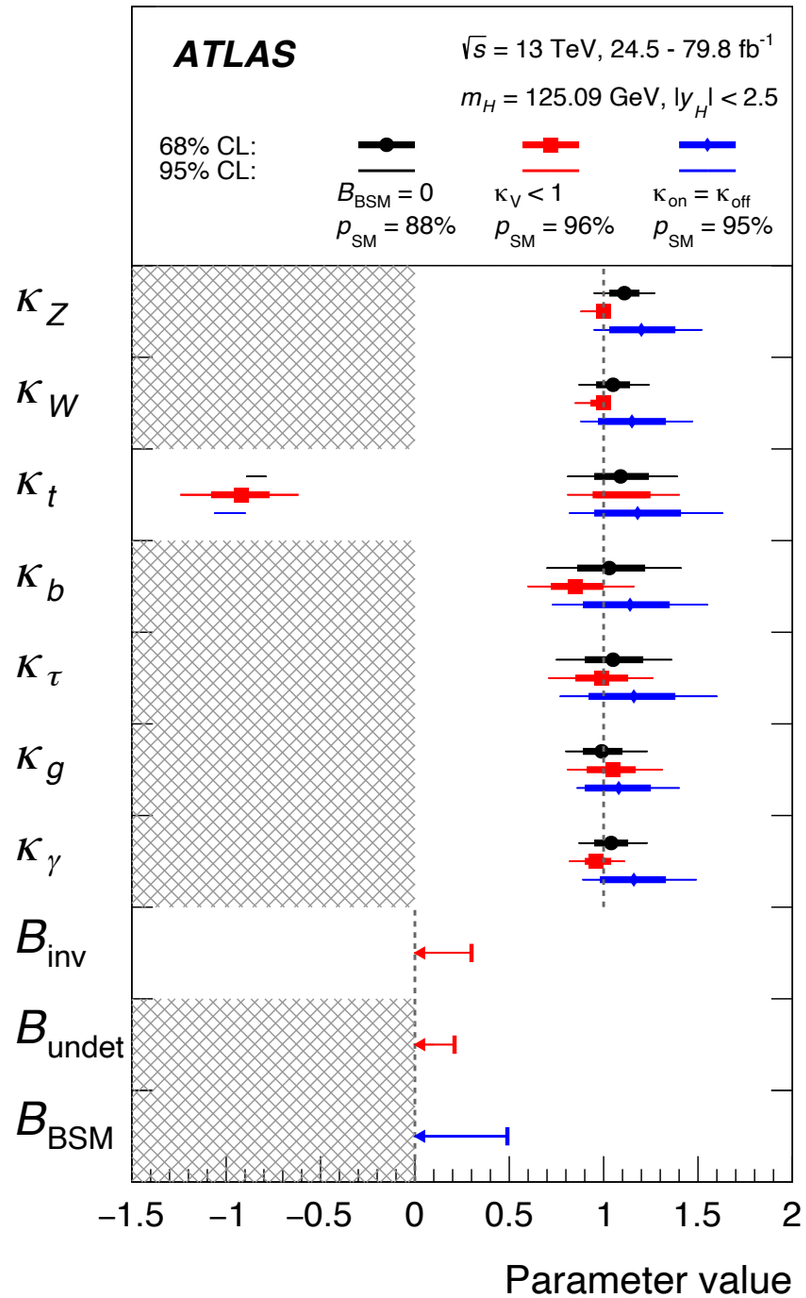
Coupling constants ("κ framework") (3)

Relaxing assumptions about relations between κ_i

- using "resolved" expression for κ_g, κ_γ (left) or not (right)
  - precision ~ 10% (W/Z), ~ 15% (t, b, τ)

not straight plots of y_f, $\sqrt{g_{W/Z}}$ as couplings evaluated at scale m_H





Spin/parity determination (1)

Relax and test assumptions about Higgs spin and parity properties.
Sensitivity especially in decay angular distributions. For W, Z:

- spin 0: $A(X \to VV) = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}\left(a_1 g_{\mu\nu} m_X^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta\right)$ $0^+, 0^-$
- spin 2:

$$A(X \to VV) = \Lambda^{-1}\Big[2g_1^{(2)} t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2g_2^{(2)} t_{\mu\nu}\frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu,\beta}$$
$$+ g_3^{(2)}\frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu}(f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}) + g_4^{(2)}\frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta}$$
$$+ m_V^2\left(2g_5^{(2)} t_{\mu\nu}\epsilon_1^{*\mu}\epsilon_2^{*\nu} + 2g_6^{(2)}\frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu}\left(\epsilon_1^{*\nu}\epsilon_2^{*\alpha} - \epsilon_1^{*\alpha}\epsilon_2^{*\nu}\right) + g_7^{(2)}\frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu}\epsilon_1^*\epsilon_2^*\right)$$
$$+ g_8^{(2)}\frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta}\tilde{f}^{*(2)}_{\alpha\beta} + g_9^{(2)} t_{\mu\alpha}\tilde{q}^\alpha \epsilon_{\mu\nu\rho\sigma}\epsilon_1^{*\nu}\epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha}\tilde{q}^\alpha}{\Lambda^2}\epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma\left(\epsilon_1^{*\nu}(q\epsilon_2^*) + \epsilon_2^{*\nu}(q\epsilon_1^*)\right)\Big]$$

graviton-like tensor:
$g_1^{(2)} = g_5^{(2)}$

- only polarisation states ±1 ($q\bar{q}$), ±2 (gg) possible ➠ predictions depend on fraction of events produced from each initial state

- spin 1 also considered but excluded by Landau-Yang theorem ($H \to \gamma\gamma$)

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Not an exhaustive list of options!

- CP admixtures in principle possible (property of the coupling, not the particle)

Spin/parity determination (2)

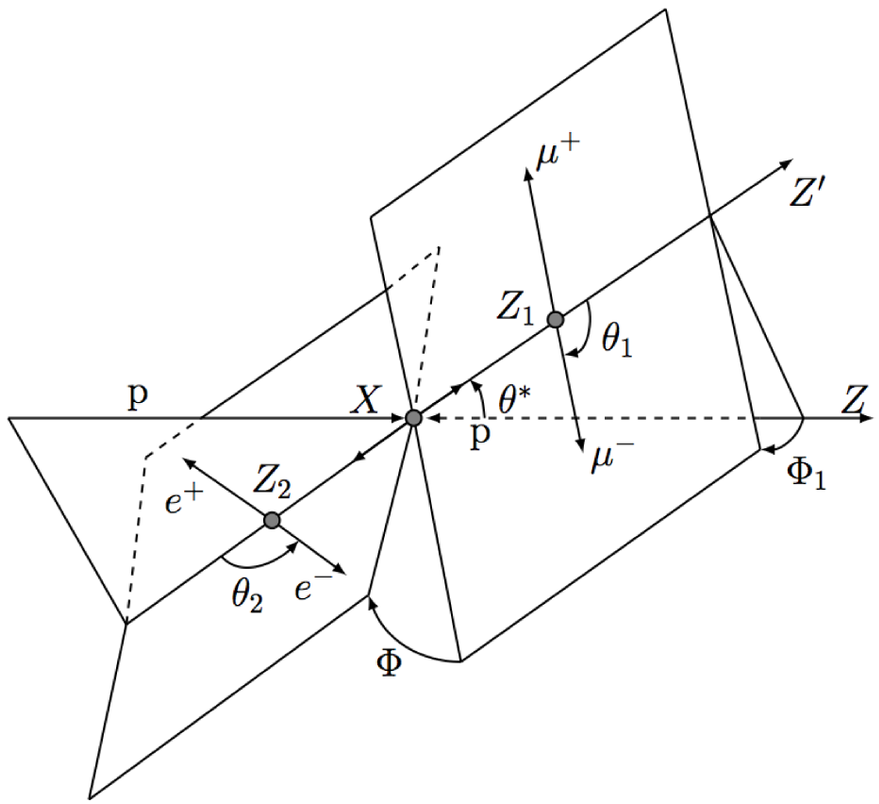
Maximum information can be obtained from H→WW, ZZ analyses (leptons carry information about W, Z spins)

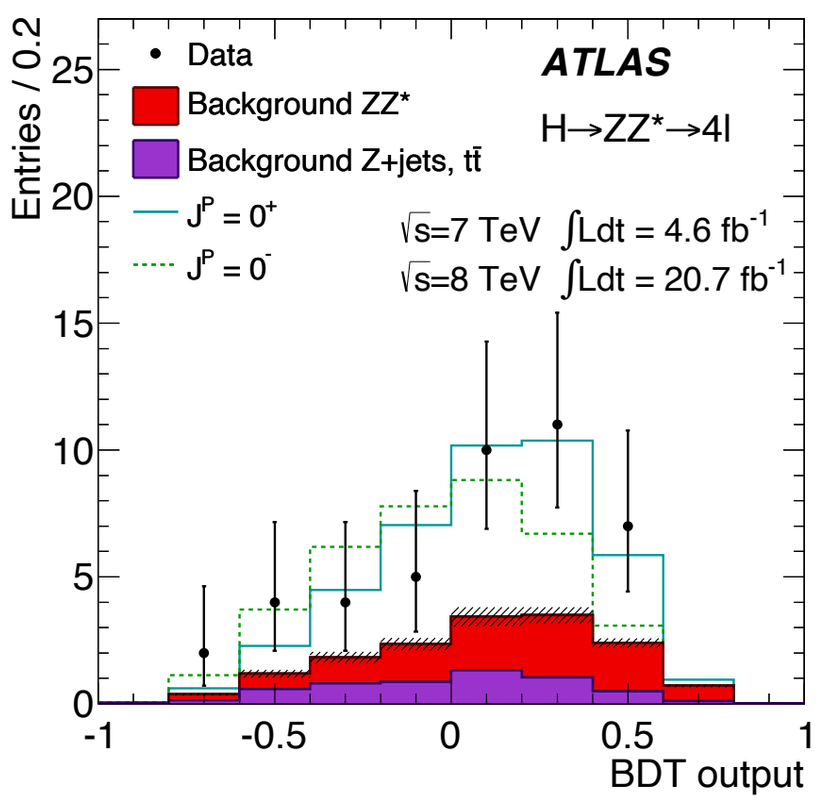
- some information also from angular distribution in $H \to \gamma\gamma$ & from VBF production (studied in $H \to \tau^+\tau^-$)

Example: $H \to ZZ^*$: 5 angles in addition to m_{12}, m_{34}

- build BDTs using all information, trained to distinguish each spin/parity hypothesis from the 0^+ one

Other <u>pure</u> J^P hypotheses than the Standard Model's $J^P = 0^+$ ruled out





Spin/parity determination (3)

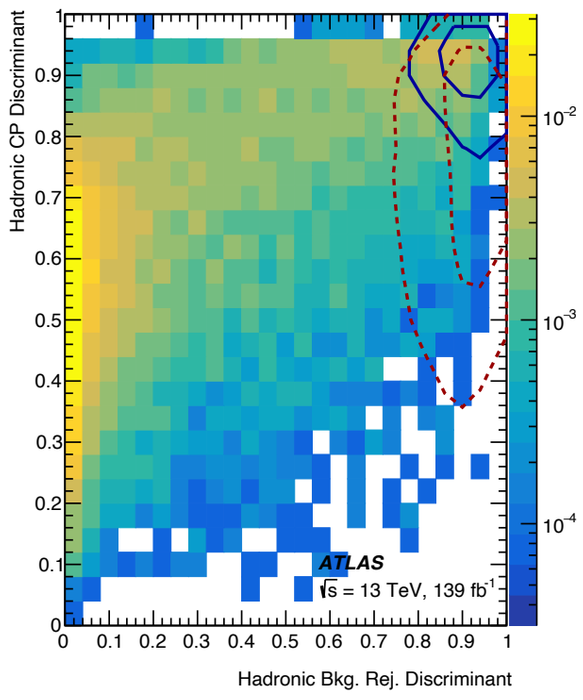
As parity is a property of the coupling, it must be investigated separately for couplings to fermions. General formulation:

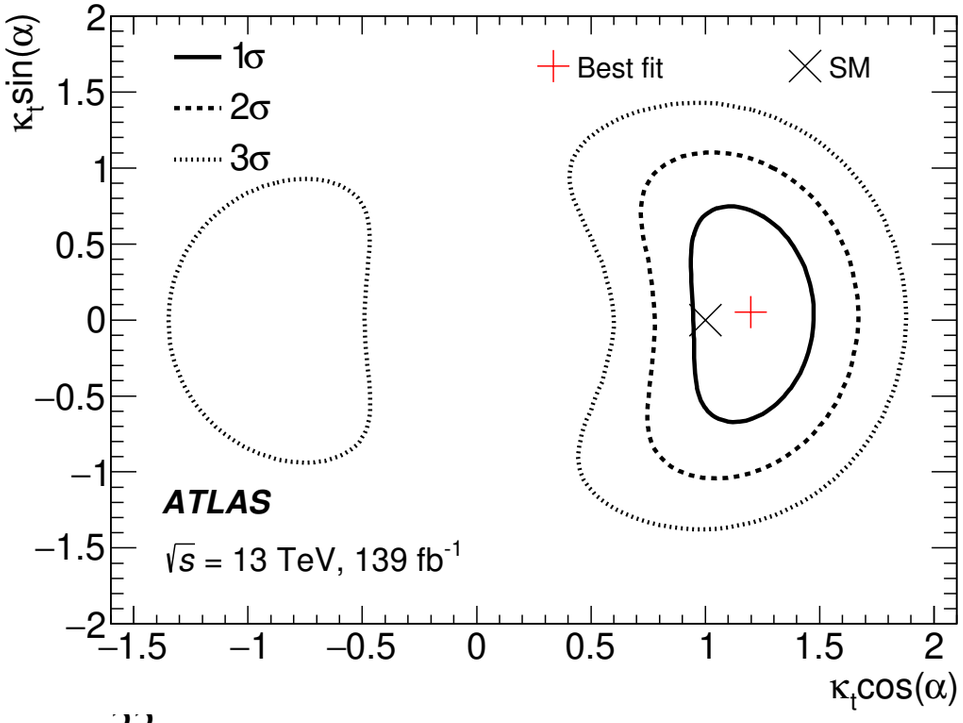
$$\mathscr{L}_{ffH} = -\kappa_f y_{f,\mathrm{SM}} \bar{f}(\cos\alpha + i \sin\alpha\gamma^5) f\, h$$

Studied: ttH

- $t, \bar{t}$ polarisation analysed using decay products' angular information
- $H \to \gamma\gamma$ cleanest as little confusion with other objects in final state
- still a complex analysis with highest sensitivity using multivariate analysis

Combined ATLAS & CMS results exclude pure CP-odd hypothesis with ~ 5σ





Total decay width (1)

Using on-shell Higgs boson production only, it is not possible to obtain independent information on Γ_H ➠ use also off-shell production

- off-shell: $\sigma \propto \kappa_i^2 \, \kappa_f^2$
- on-shell: $\sigma \propto \dfrac{\kappa_i^2 \, \kappa_f^2}{(s - m_H)^2 + m_H^2 \Gamma_H^2} \xrightarrow{\text{NWA}} \dfrac{\pi}{m_H \Gamma_H} \delta(s - m_H^2) \kappa_i^2 \, \kappa_f^2$

  ➠ ratio sensitive to Γ_H

} assumes that on- and off-shell κ are identical

Studied notably in $gg \to H \to ZZ^{(*)}$

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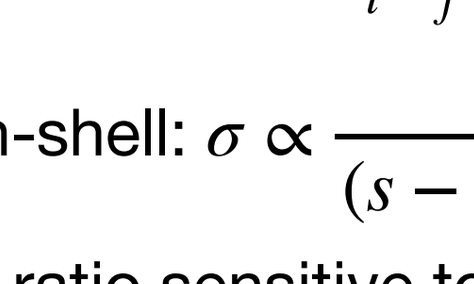
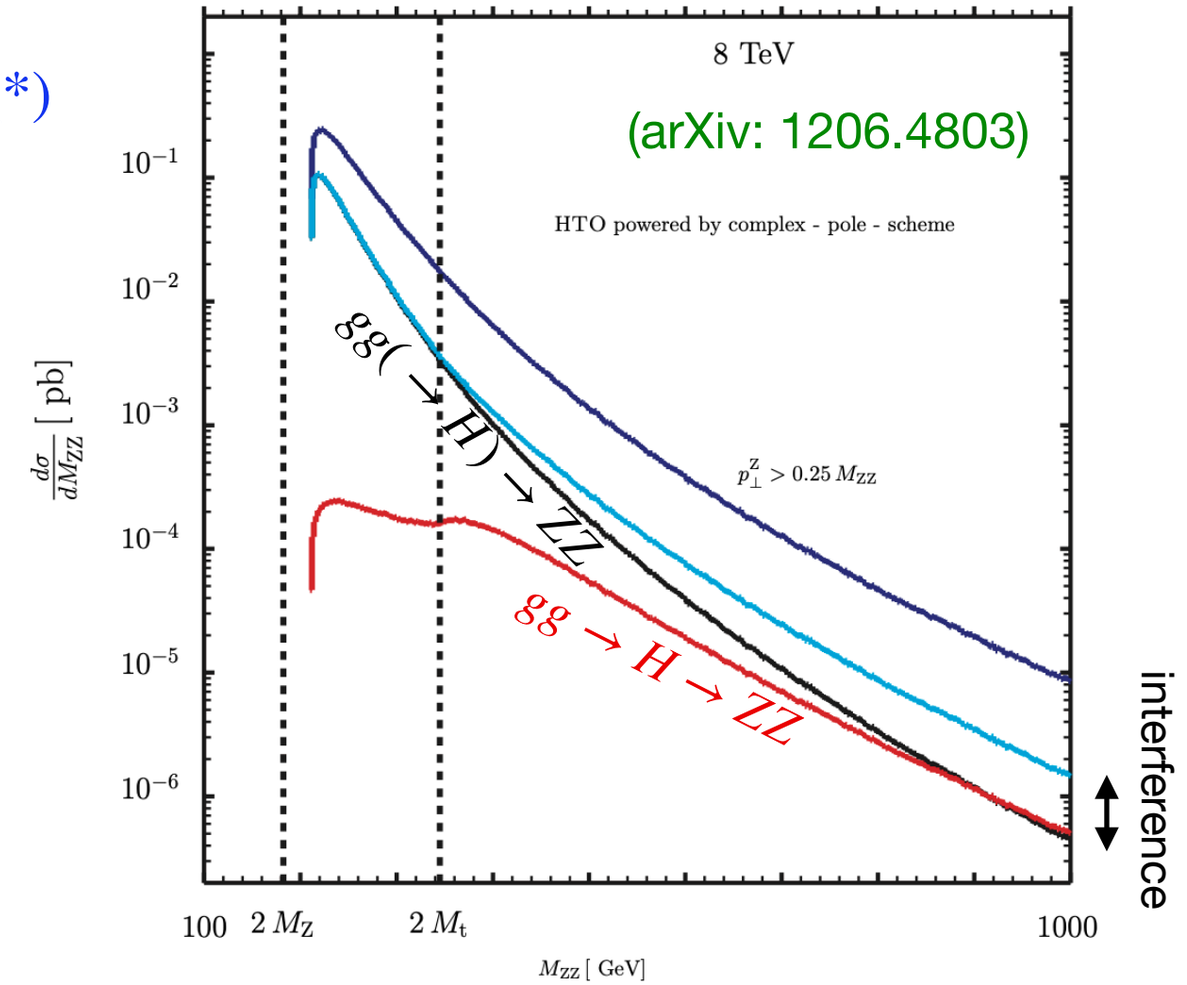
  - interference > pure H contribution





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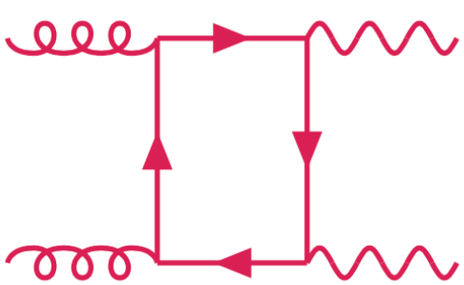
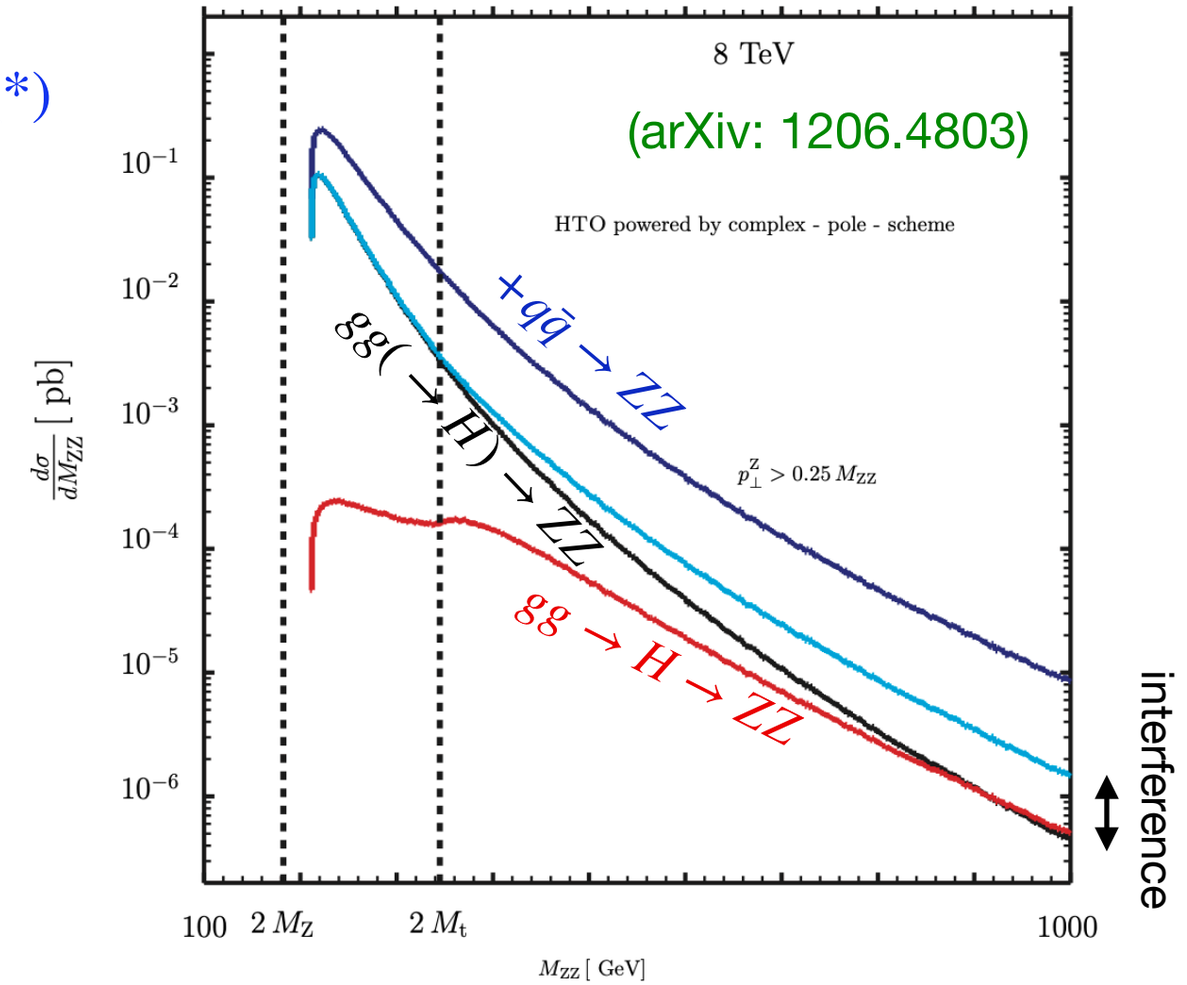


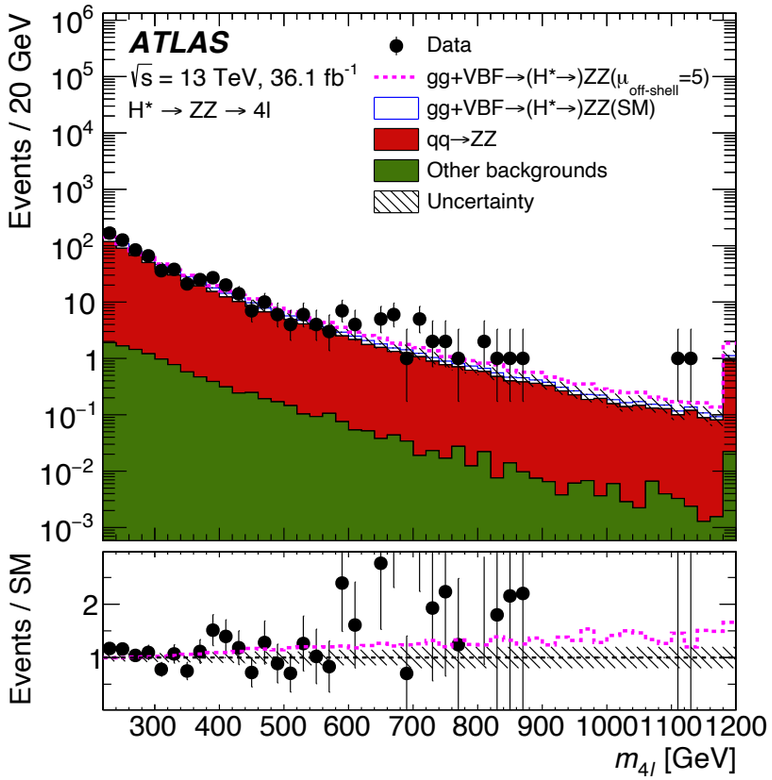
  - $q\bar{q} \to ZZ$ bkg

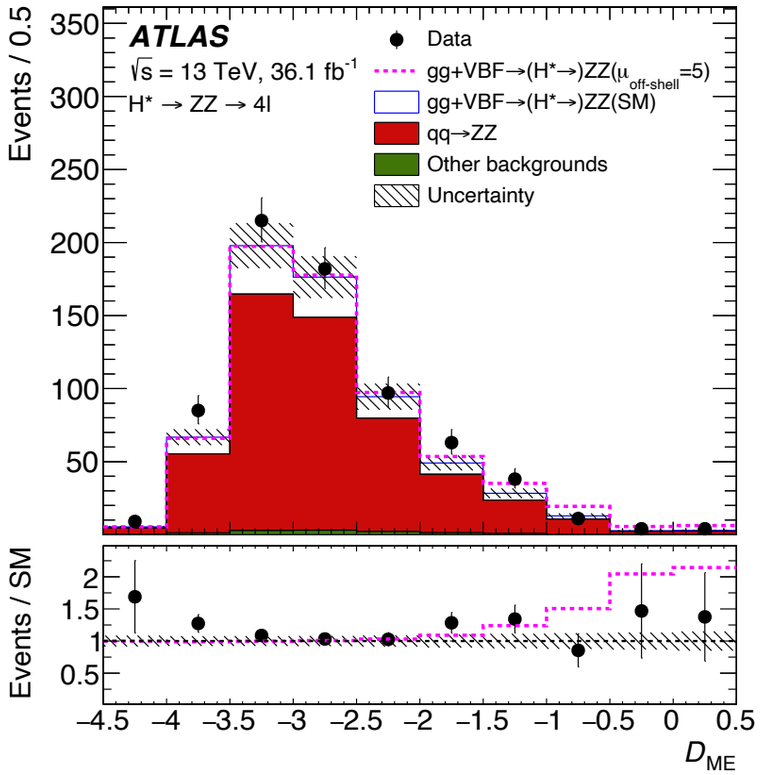


Total decay width (2)

ATLAS Analysis is designed to distinguish signal $gg \to H \to ZZ$ from continuum $gg \to ZZ$ & $q\bar{q} \to ZZ$

- discriminating power despite $gg \to ZZ$ forming irreducible background





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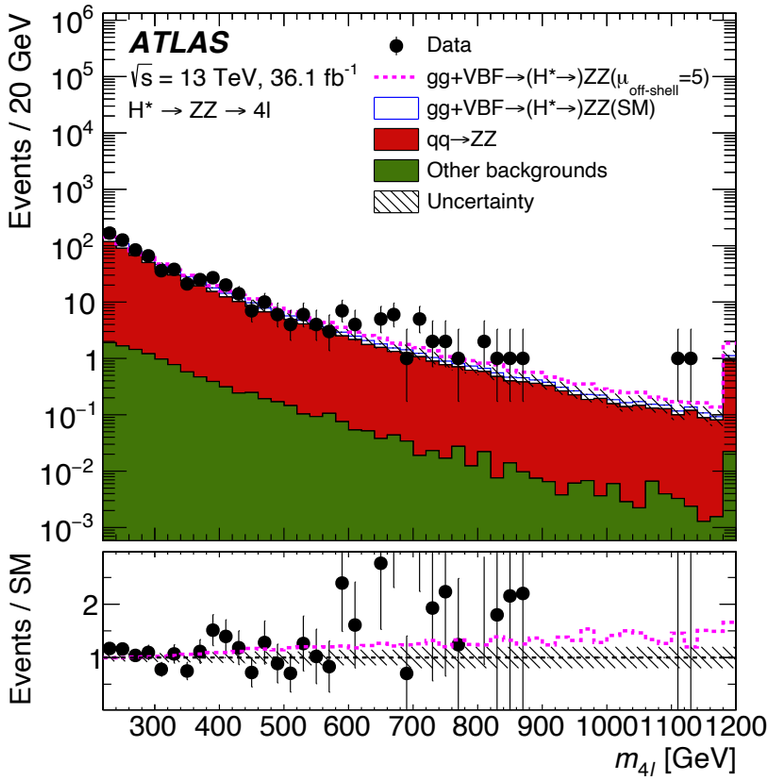
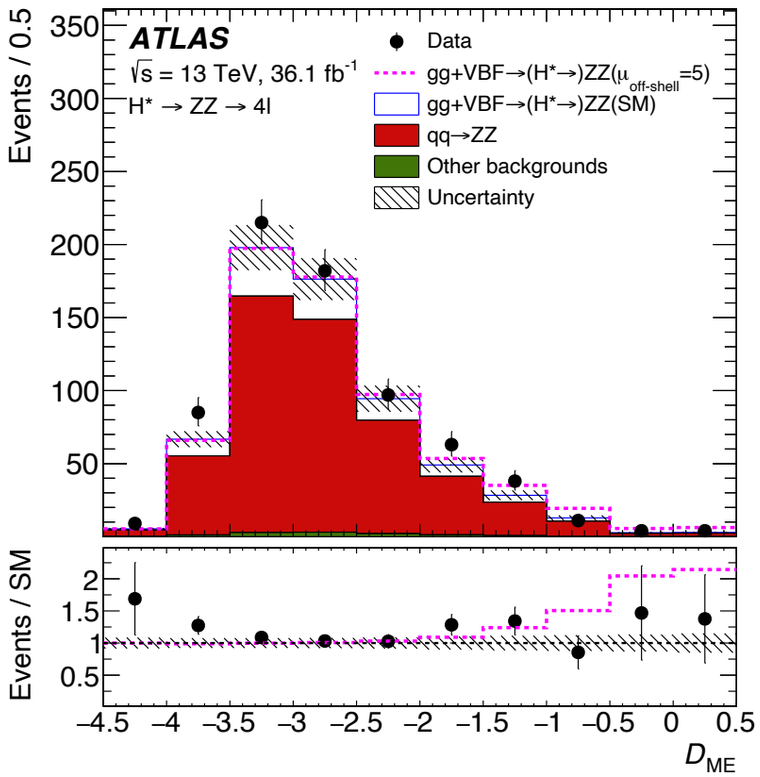
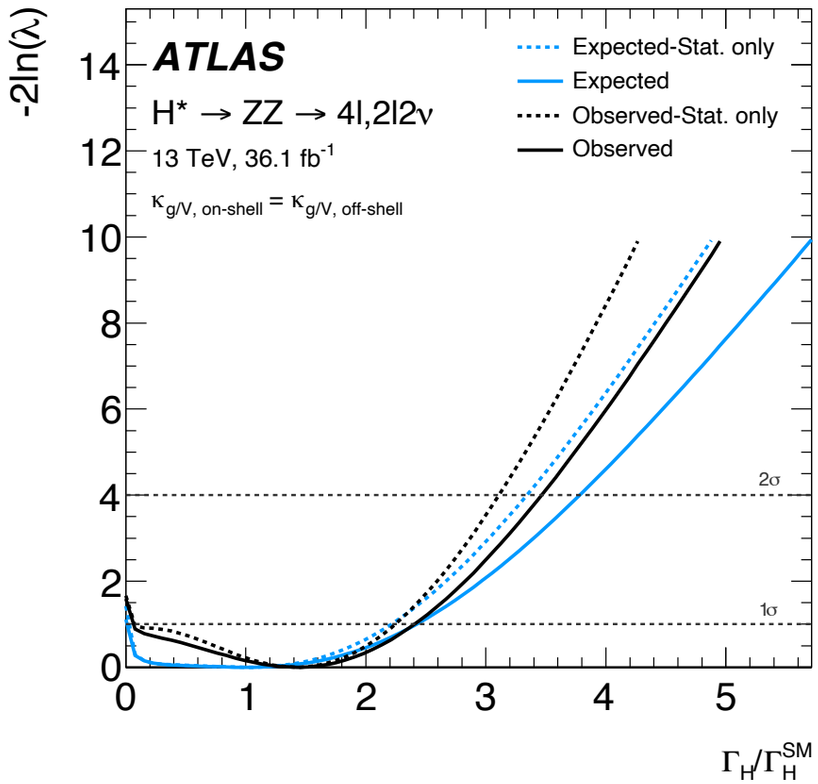






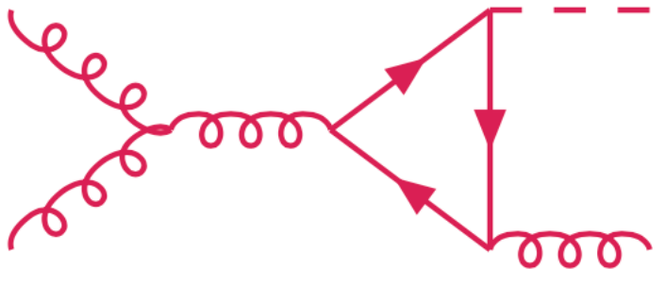
$\Gamma_H < 14.2$ MeV at 95% CL

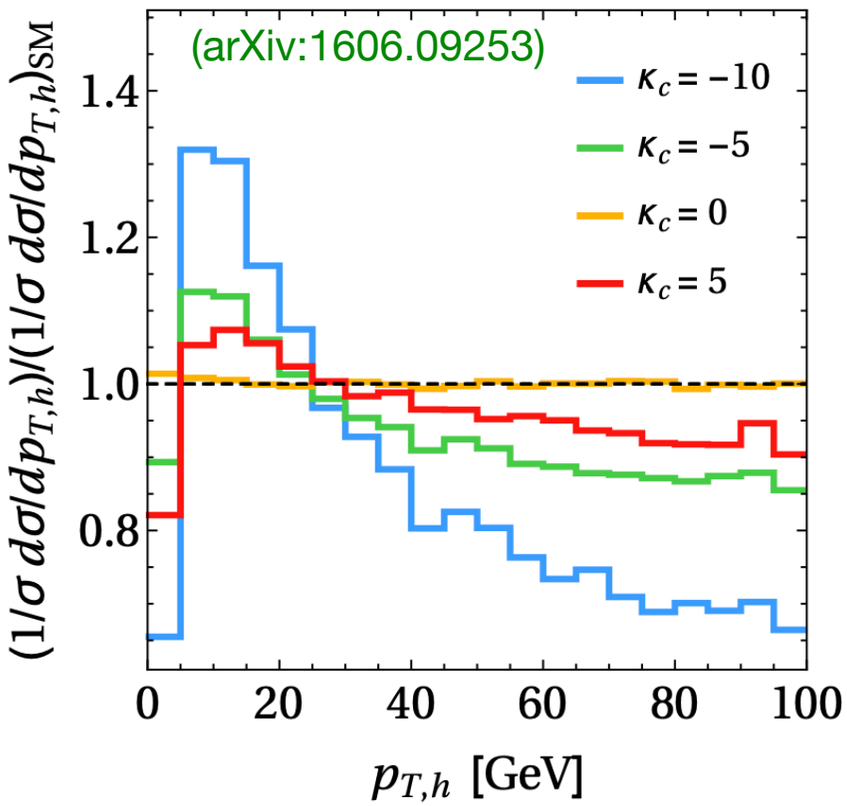
- result also includes $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$, $H \to W^+W^- \to \ell^+\nu_\ell\ell'^-\bar{\nu}_{\ell'}$
- CMS analysis is significantly more precise ($\Gamma_H = 3.2^{+2.8}_{-2.2}$ MeV) but makes more specific assumptions as well

Differential cross section measurements (1)

Access to properties beyond those discussed before, e.g.

- y_H (in $gg \to H$): sensitive in particular to $g(x)$
- $p_{\mathrm{T},H}$ (in H+jets): non-negligible contribution from b, c quarks
  - at LO: $\kappa_i \frac{m_i^2}{m_H^2} \ln^2(p_{\mathrm{T}}^2/m_i^2)$
    - access to Hcc coupling
    - as an alternative to direct search for $H \to c\bar{c}$ (e.g. in VH production)

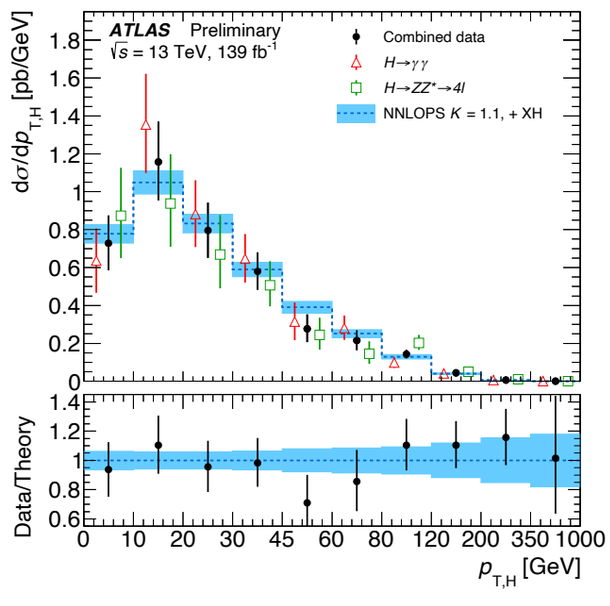


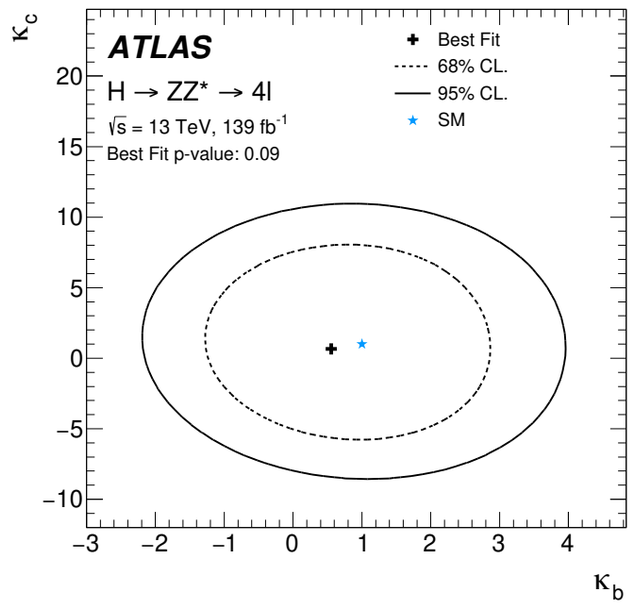


Differential cross section measurements (2)

"Cleanest" measurements possible in $H \to 4\ell, H \to \gamma\gamma$

- unfold in order to compare with detailed theoretical predictions





assuming SM cross section modified by κ_b, κ_c only

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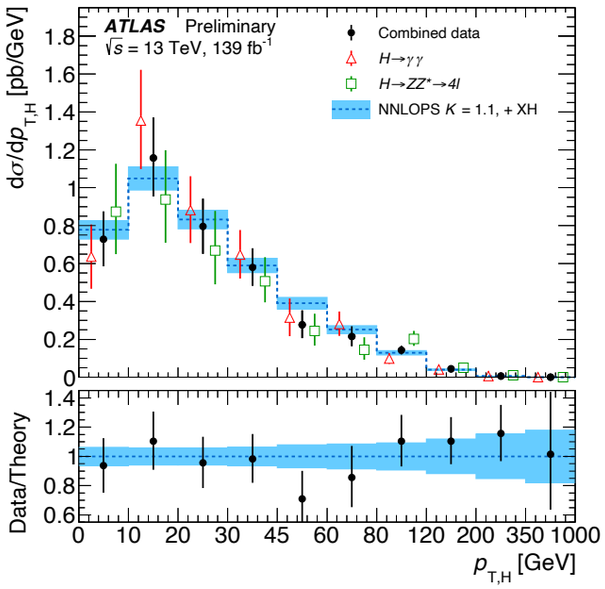

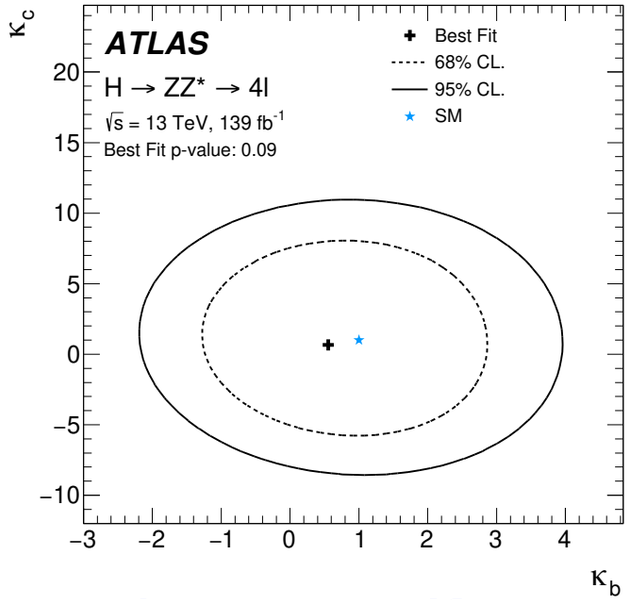

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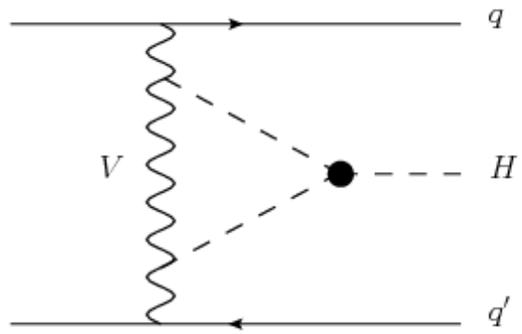
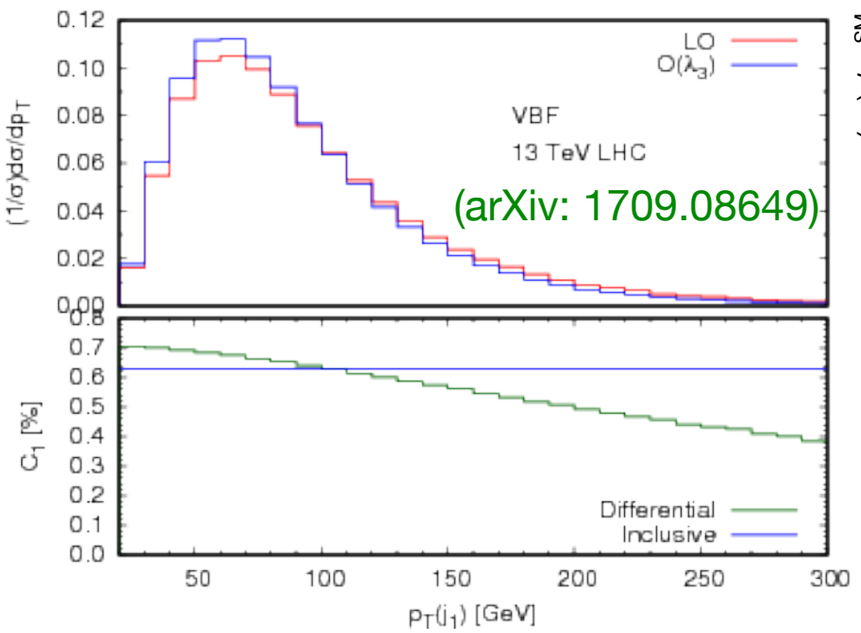
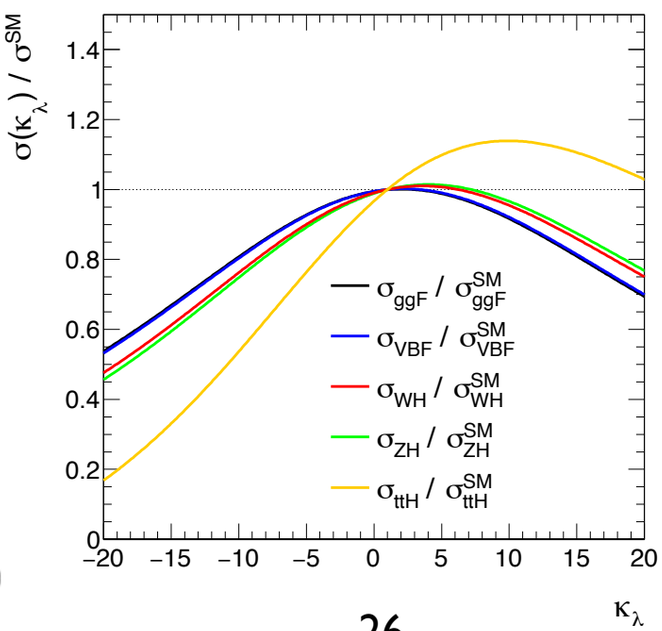
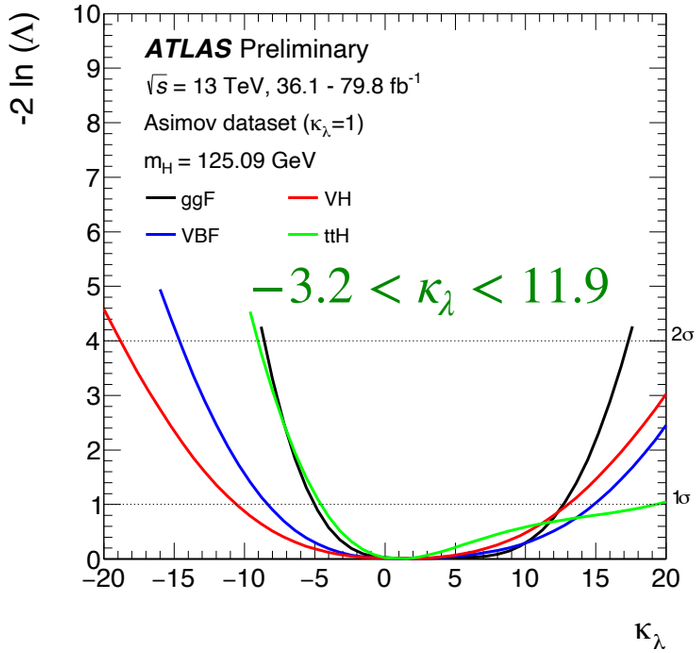


Alternative interpretation: Higgs-boson self-coupling

- also affects overall rates & branching fractions







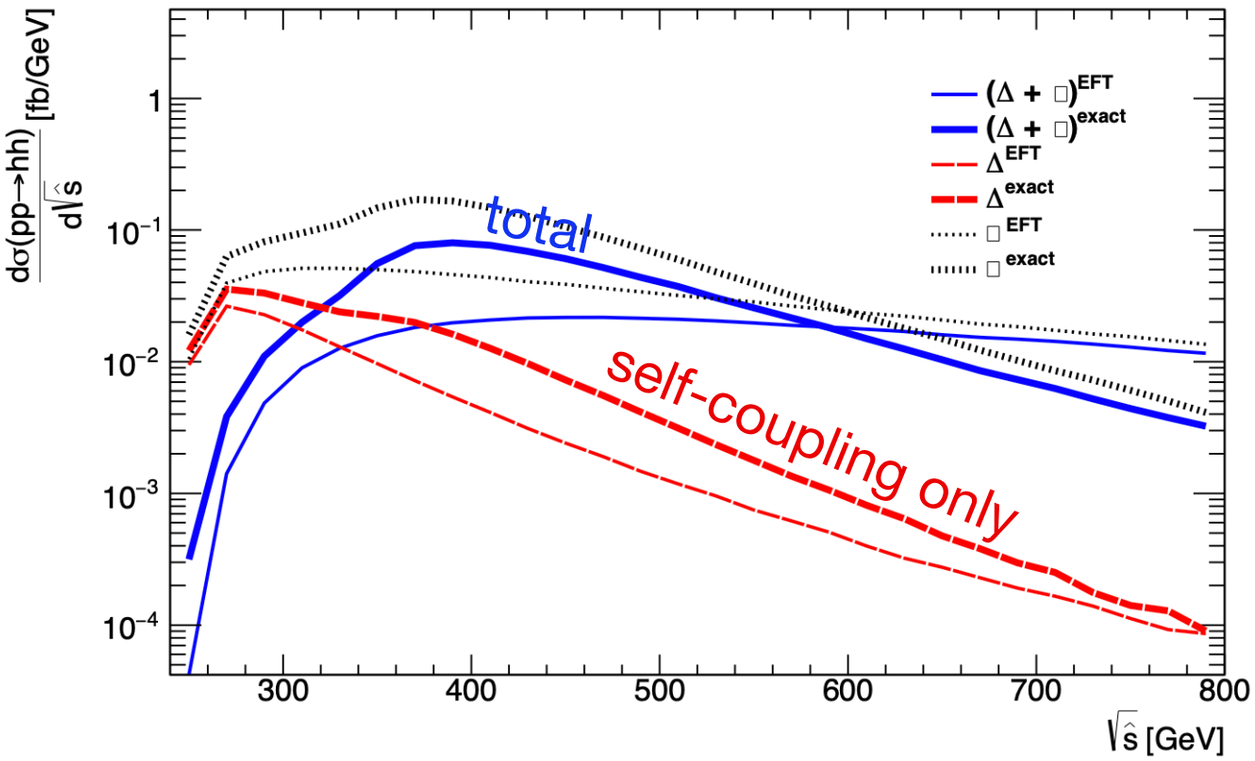
Searches

Higgs boson pair production (1)

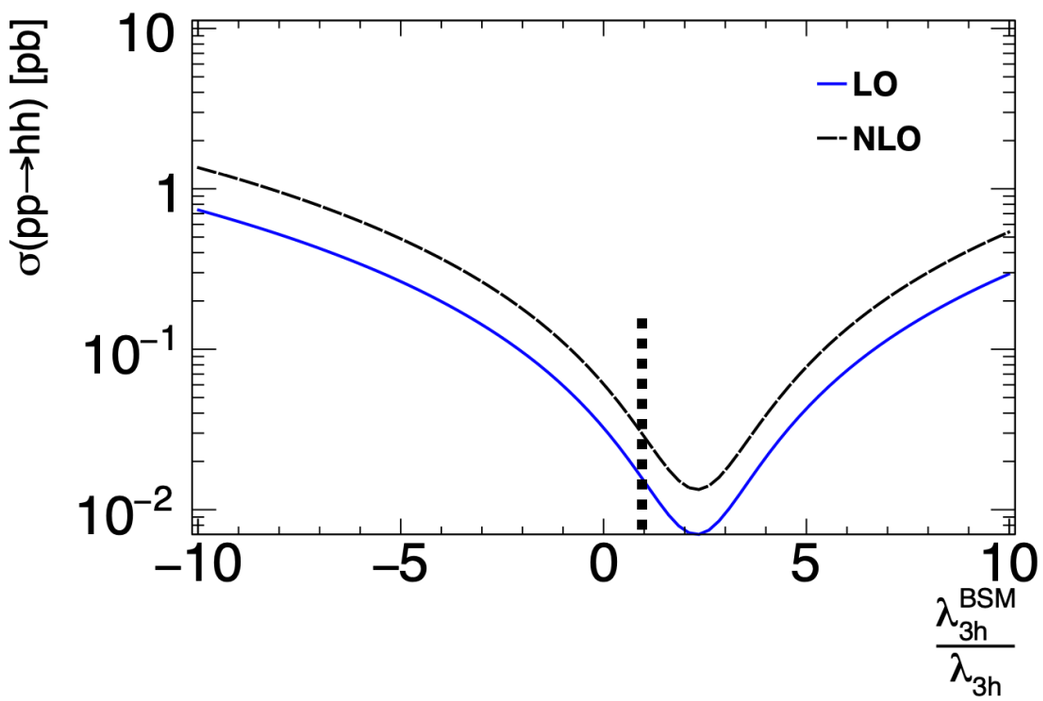
HH production is a much more direct way to probe the Higgs boson's self-coupling

- cross section dominated by $H^* \rightarrow HH$
  - as opposed to $H \rightarrow H^*H^*$

- large (destructive) interference effects between self-coupling, box diagrams
- significant dependence on κ_λ



(plots from PhD thesis Wouter van den Wollenberg)

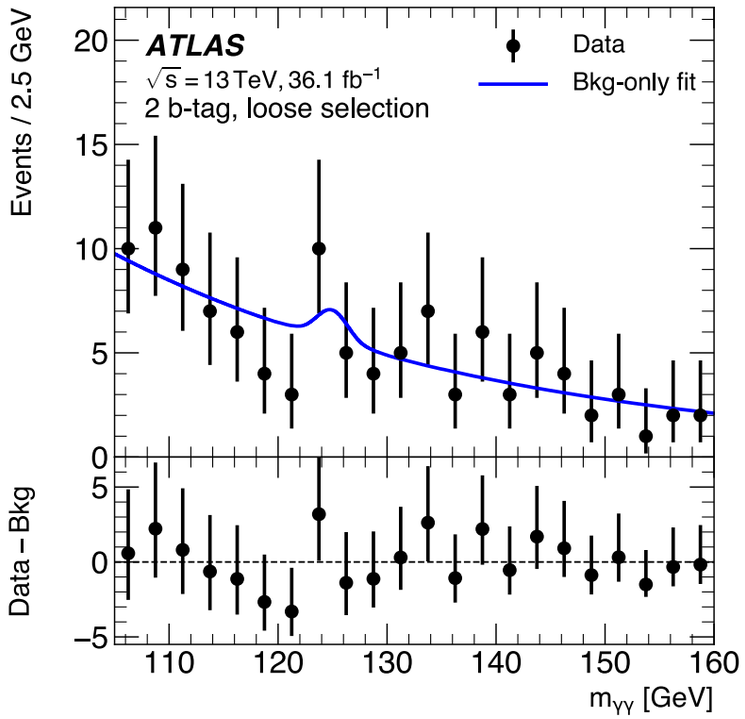


Higgs boson pair production (2)

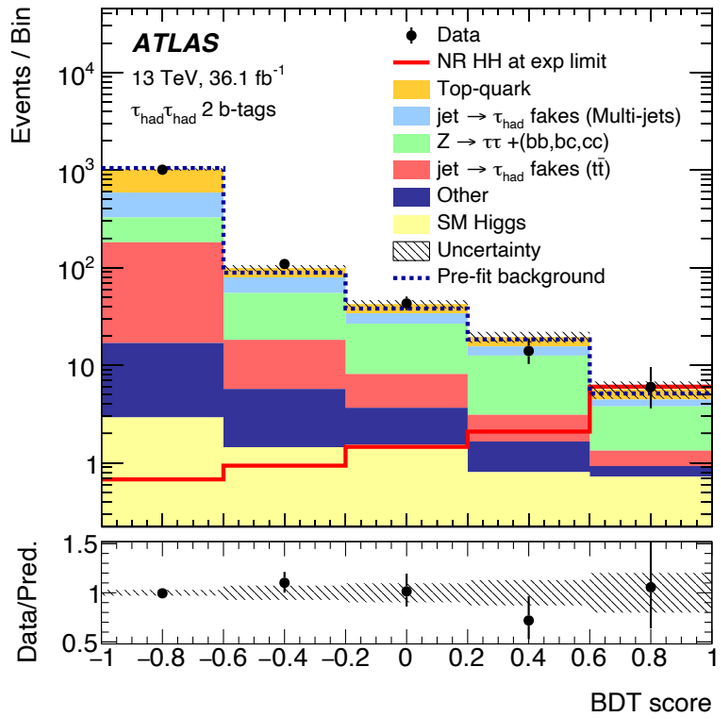
Tiny cross section (~ 30 fb in SM) ➠ need combination of (relatively) clean decay modes with sufficiently high branching fractions

- studied so far: $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}b\bar{b}$, $b\bar{b}W^+W^-$, $W^+W^-W^+W^-$, $W^+W^-\gamma\gamma$
  - generally complex analyses, but with large analysis dependence

fit $m(\gamma\gamma)$ in $b\bar{b}\gamma\gamma$ final state;
use SM $H(\rightarrow\gamma\gamma) + b\bar{b}$ prediction



MVA in $b\bar{b}\tau^+\tau^-$ final state,
trained against $t\bar{t}$ (~ irreducible)



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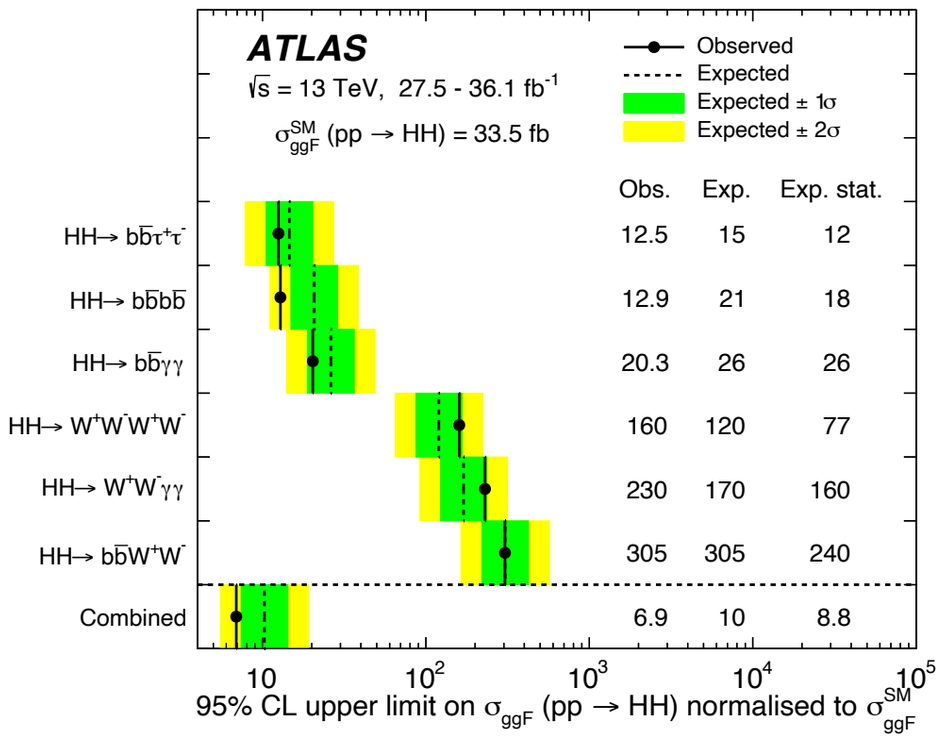
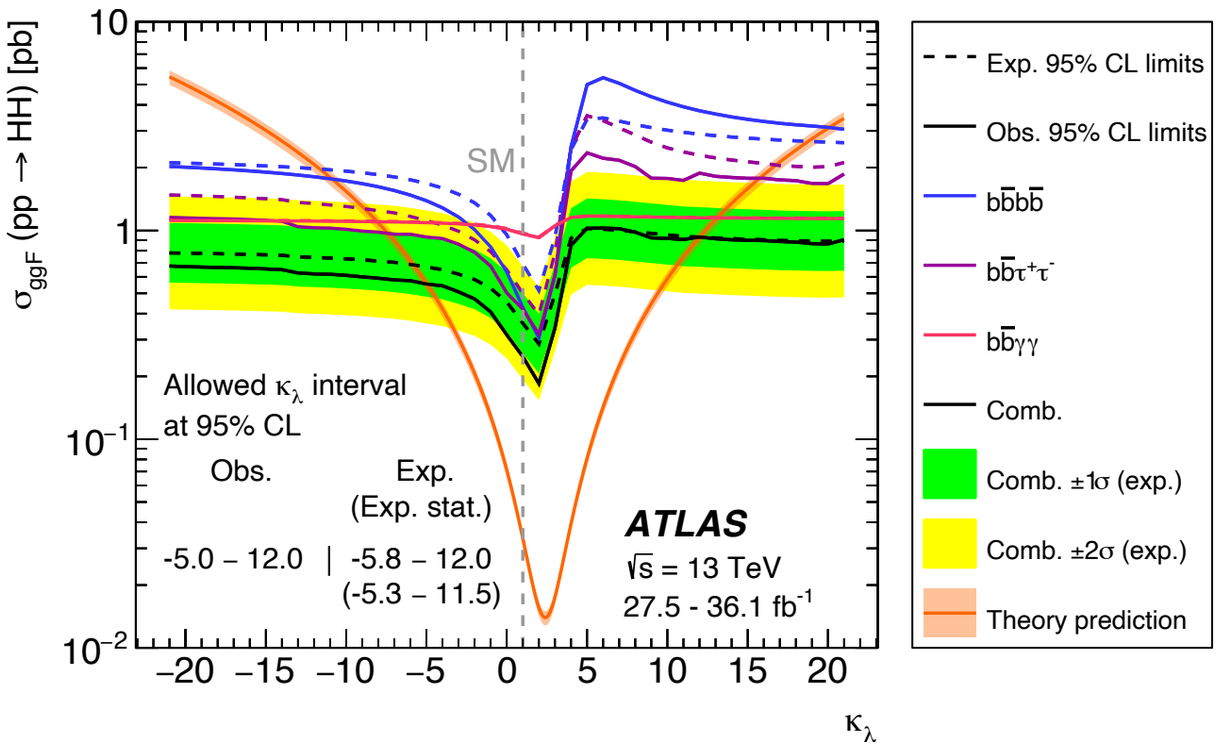




experimental cross section depends on κ_λ through event kinematics (m_{HH})

Constraint $-5 < \kappa_\lambda < 12$ weaker than from single-Higgs measurements

- but less model dependent

The MSSM Higgs sector

The MSSM features 2 complex Higgs doublets H_u, H_d

➠ after symmetry breaking, 5 physical Higgs bosons: $h, H, A, H^{\pm}$

Neutral Higgs boson modified couplings to SM particles:

SM particle type	*h* coupling	*H* coupling	*A* coupling
up-type quarks	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\cot\beta$
down-type quarks, $\ell^{\pm}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\tan\beta$
W, *Z* bosons	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	0

- $\tan\beta \equiv v_u/v_d$ (vevs)
- mixing angle α diagonalises neutral Higgs boson mass matrix

Lightest CP-even Higgs boson h has $m_h < M_Z$ at tree level, only SUSY radiative corrections can make it heavier:

- $m_h^2 \lesssim M_Z^2 \cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 M_W^2}\left(\ln(M_S^2/m_t^2) + \frac{X_t^2}{M_S^2}(1 - X_t^2/12M_S^2)\right), \; X_t \equiv A_t - \mu\cot\beta$

  ➠ hMSSM: SUSY parameters tuned for $m_h = 125$ GeV

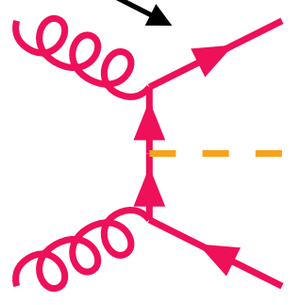
- effective description just in terms of $m_A, \tan\beta$
- decoupling limit: for $m_A \gg M_Z$, h becomes SM-like

- μ: $H_u - H_d$ interaction
- A_t: tri-linear coupling
- M_S: SUSY breaking scale

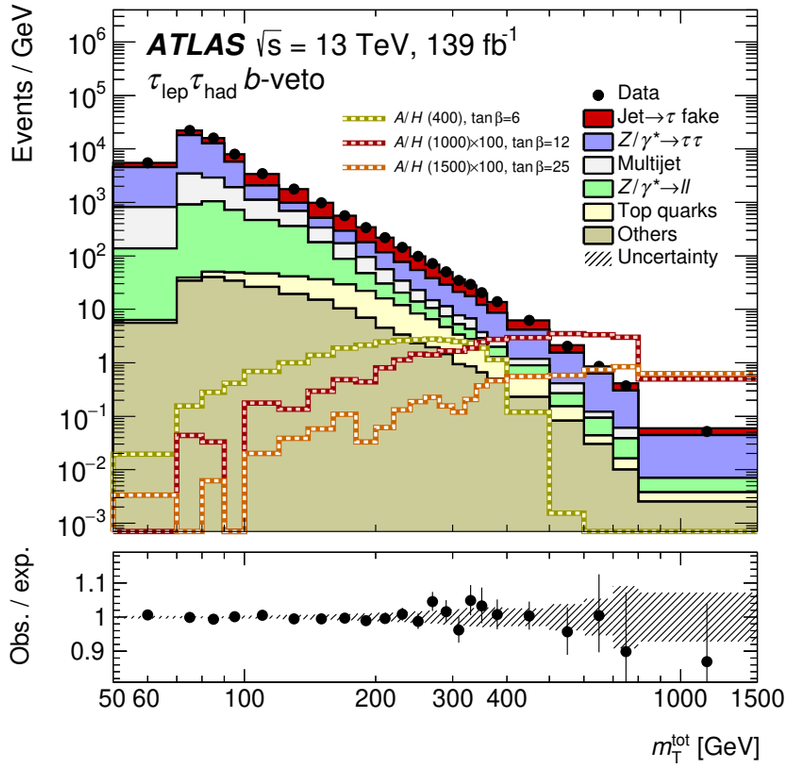
Neutral MSSM Higgs boson searches

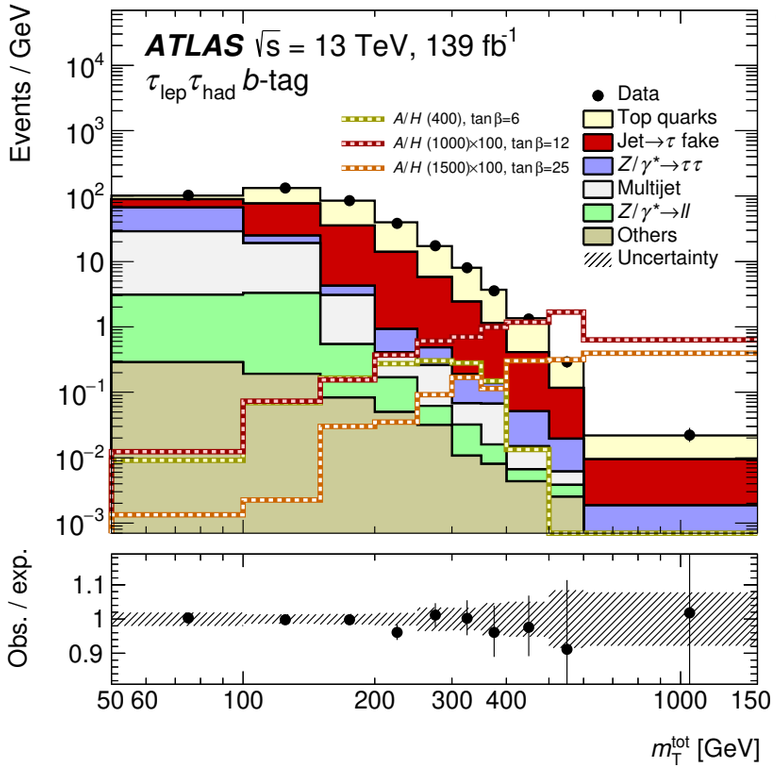
Searches for H, A focused mostly on high $\tan\beta$ (motivated by LEP)
➠ enhanced couplings to down-type quarks, charged leptons

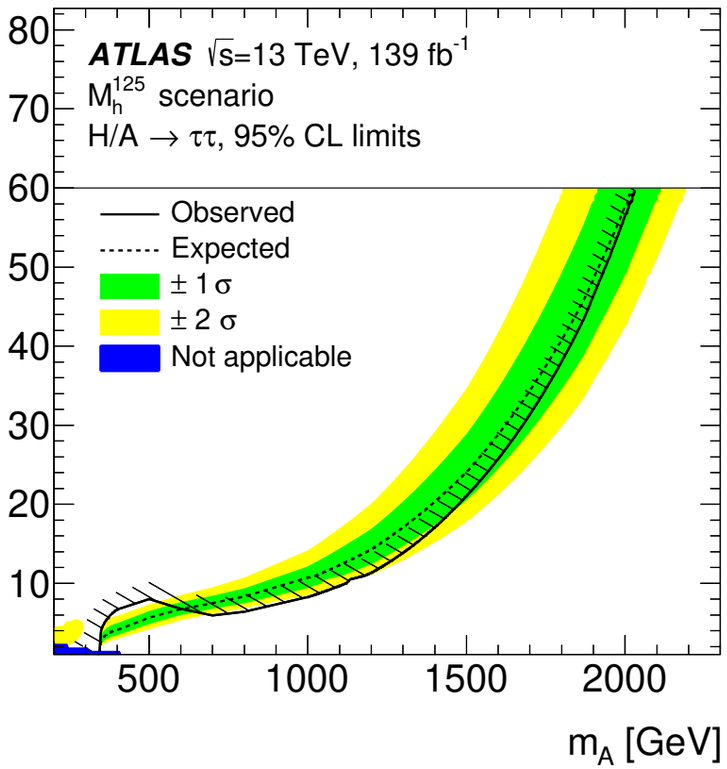
- cleanest: $H/A \to \tau^+\tau^-$, produced in gluon fusion or $b\bar{b} + H/A$
  - high $\tan\beta$ ➠ $m_H \approx m_A$ and large Γ ➠ seen as single resonance



Huge reduction in allowed $\tan\beta$ range compared to Run 1 results







Charged MSSM Higgs boson searches

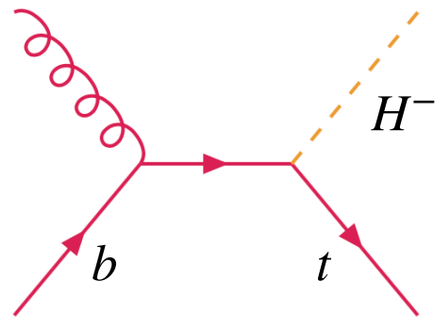
Charged Higgs boson coupling to fermions (e.g. tb):

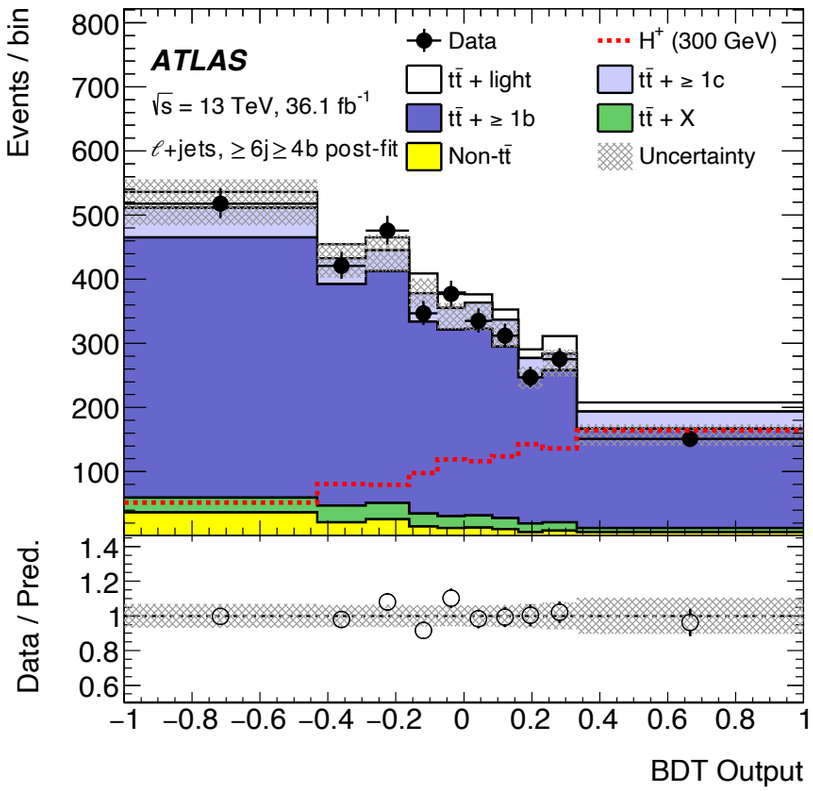
$$g_{Htb} = m_t \cot\beta \frac{1}{2}(1+\gamma^5) + m_b \tan\beta \frac{1}{2}(1-\gamma^5)$$

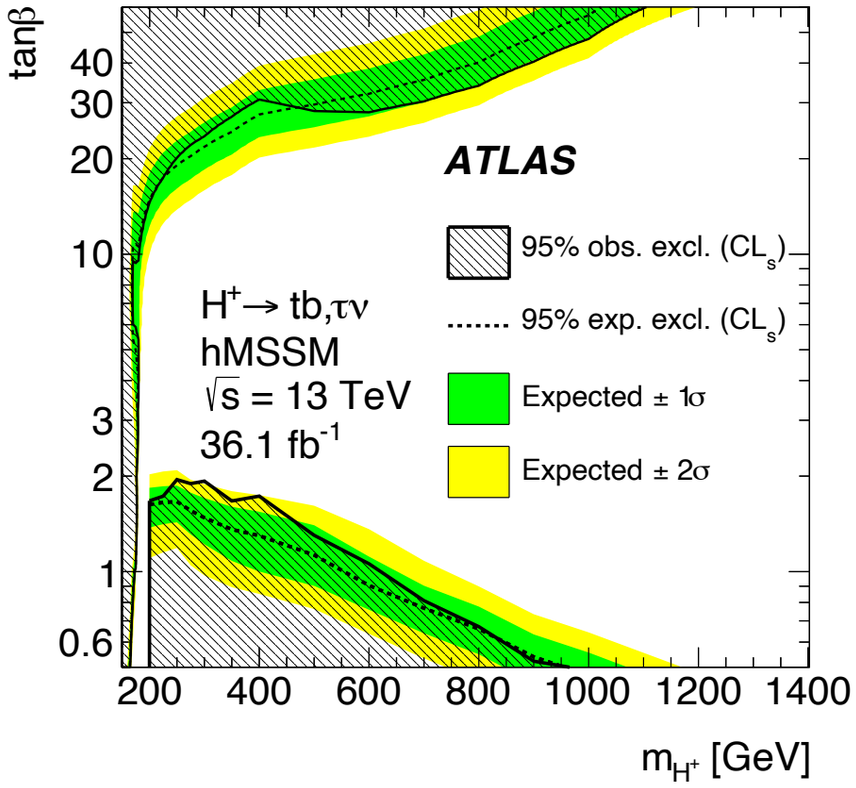
- sensitivity at both low and high values of $\tan\beta$

Focus on high-mass $H^- \to \bar{t}b$ ($t\,\bar{t}b\,\bar{b}$ final state)

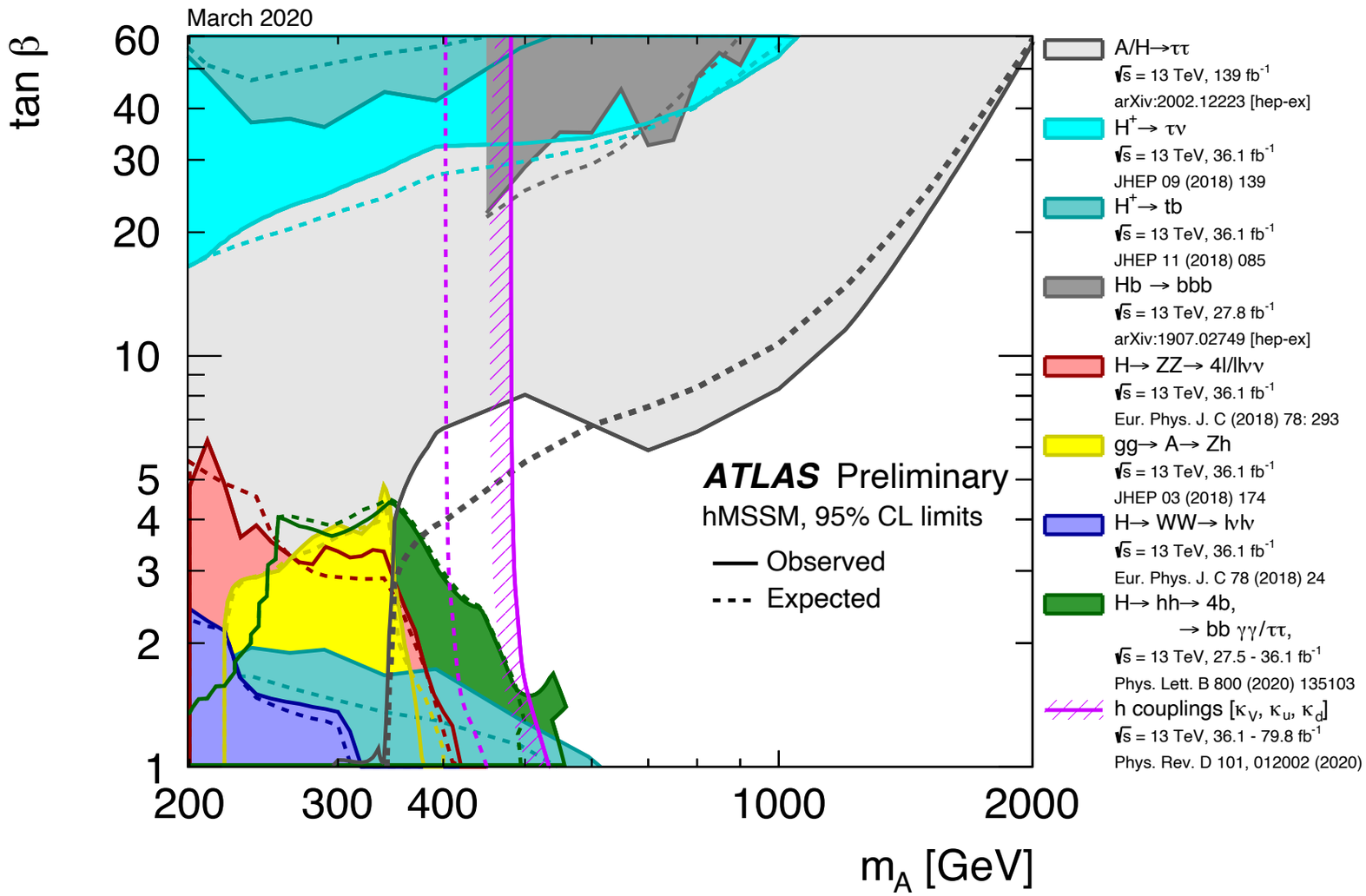
- alternative: $H^- \to \tau^- \bar{\nu}_\tau$ (and also $B \to D^{(*)}\tau\nu$)
- significant exclusion of low $\tan\beta$ regime







MSSM Higgs status



Many explicit searches, but also strong constraints from measurements of h couplings

- $m_A > 500$ GeV ➠ approaching decoupling limit: MSSM is being pushed where it does not want to go!

Finally

Many topics (especially BSM Higgs physics) not discussed; e.g.

- decays of heavy Higgs bosons to W^+W^- or ZZ, $A \to Zh$
- NMSSM (additional, possibly very light) Higgs bosons
- lepton flavour violating Higgs boson decays
- other BSM models involving couplings to Higgs bosons

LHC luminosity will increase further

- challenges for precision Higgs physics (especially couplings measurements) but plenty of improvements are still possible
- techniques optimised for the heaviest new (Higgs) particles