Higgs boson studies with the ATLAS detector at the Large Hadron Collider

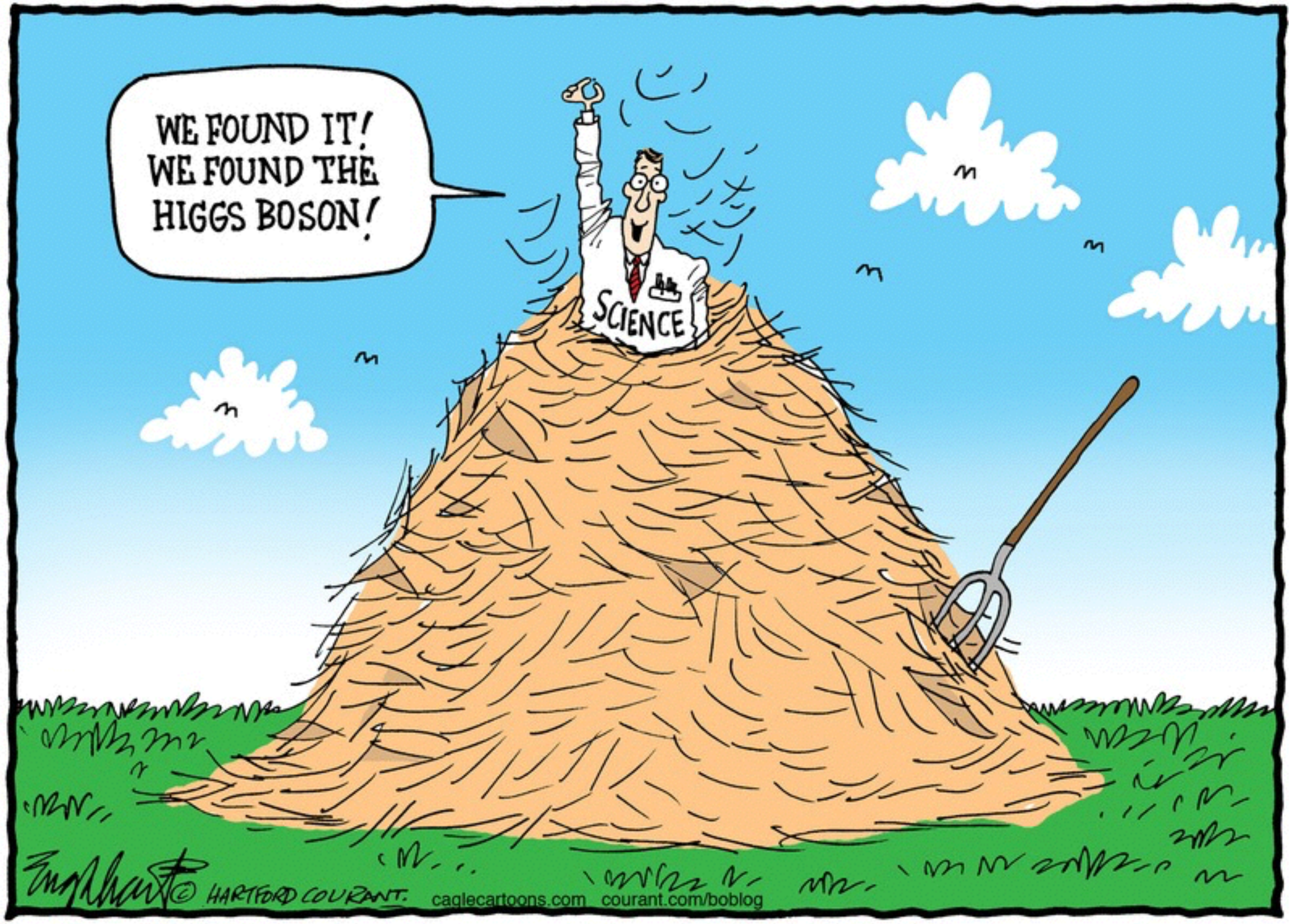
Giovanni Marchiori (LPNHE-Paris)
ATLAS Collaboration

Corfu 2015 Summer School and Workshop
8 September 2015

Outline

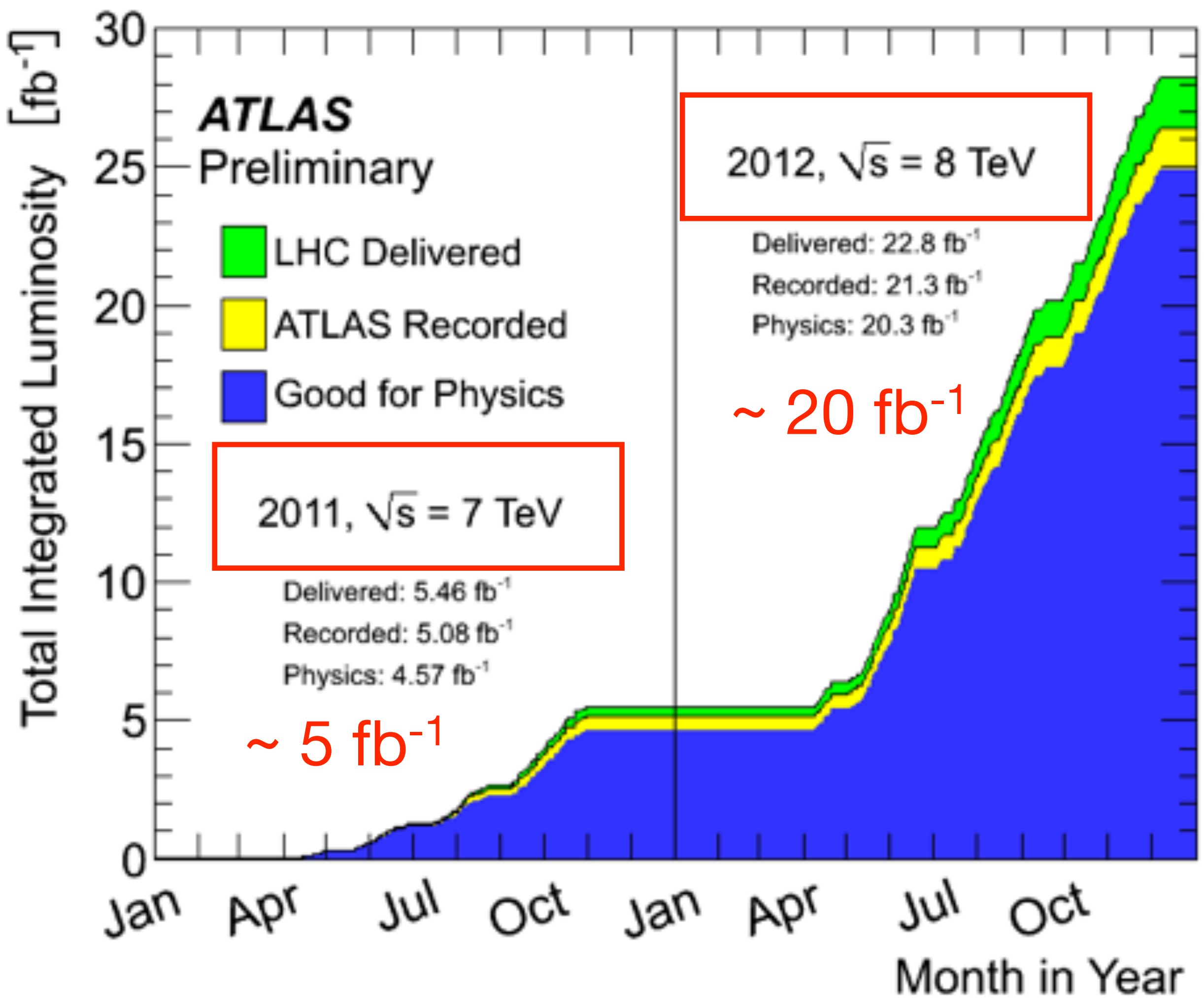
- Higgs boson discovery
  - experimental setup
  - experimental features of Higgs boson production and decay at the LHC
  - observation of a Higgs boson with m~125 GeV
- Higgs boson characterisation with the full ATLAS data from LHC Run1
  - mass
  - production and decay strength
  - couplings
  - width
  - spin and CP
  - differential cross sections
  - beyond-SM (BSM) decays
- Future perspectives

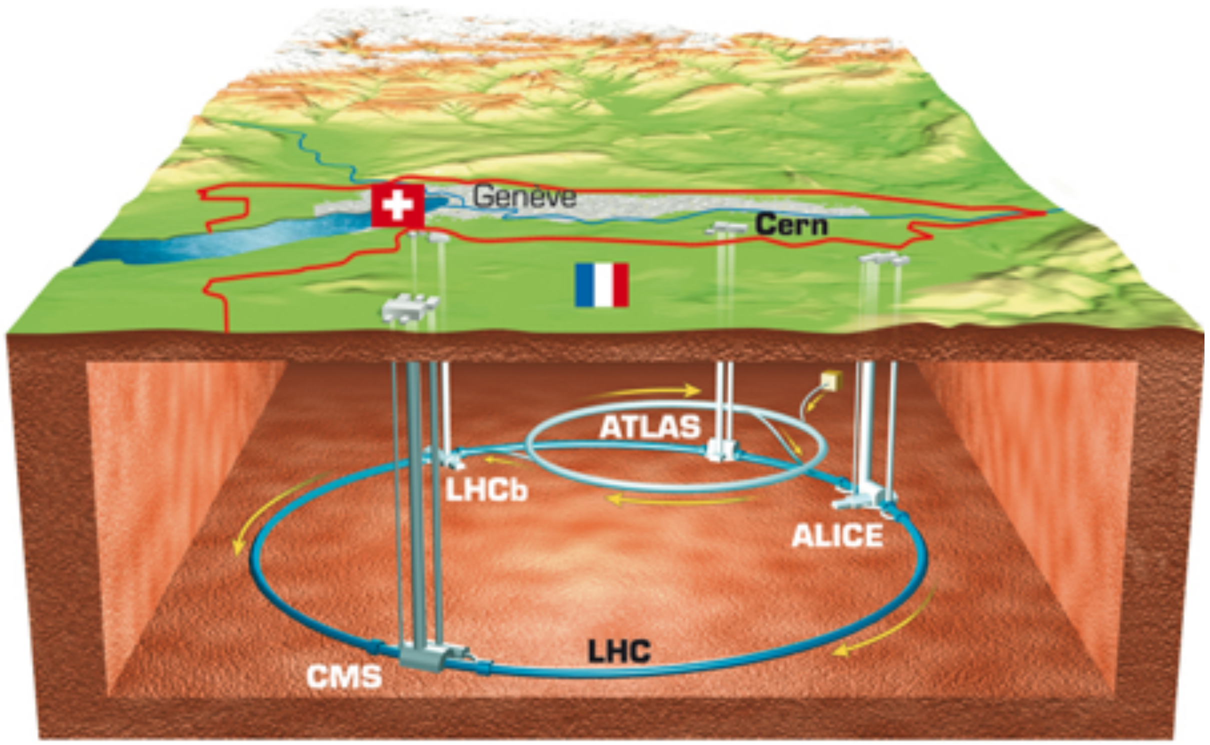
1. The Higgs boson discovery



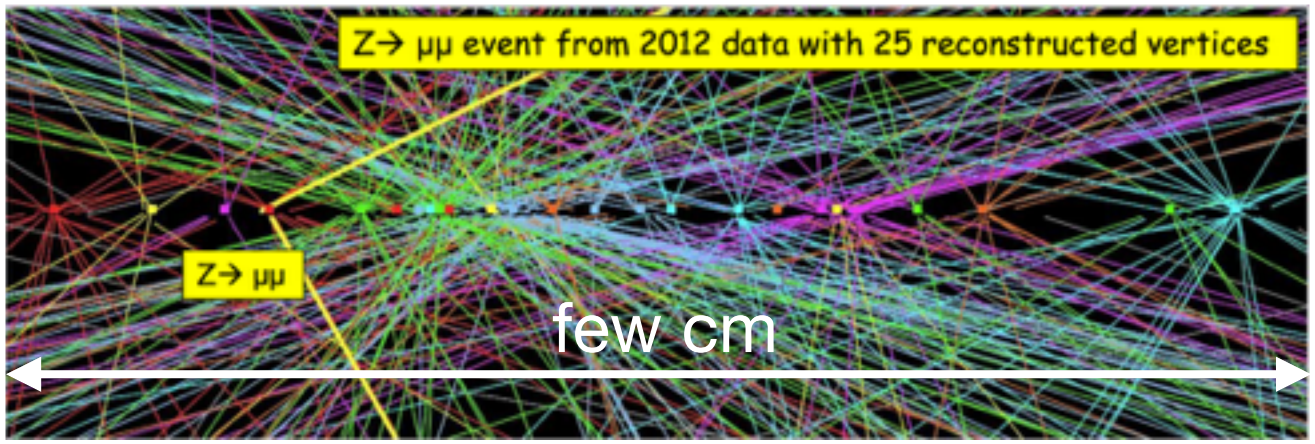
The **L**arge **H**adron **C**ollider at CERN

- LHC is a proton and heavy ion collider
- Run1: ~25 fb^{-1} of pp collisions at $\sqrt{s}$=7,8 TeV



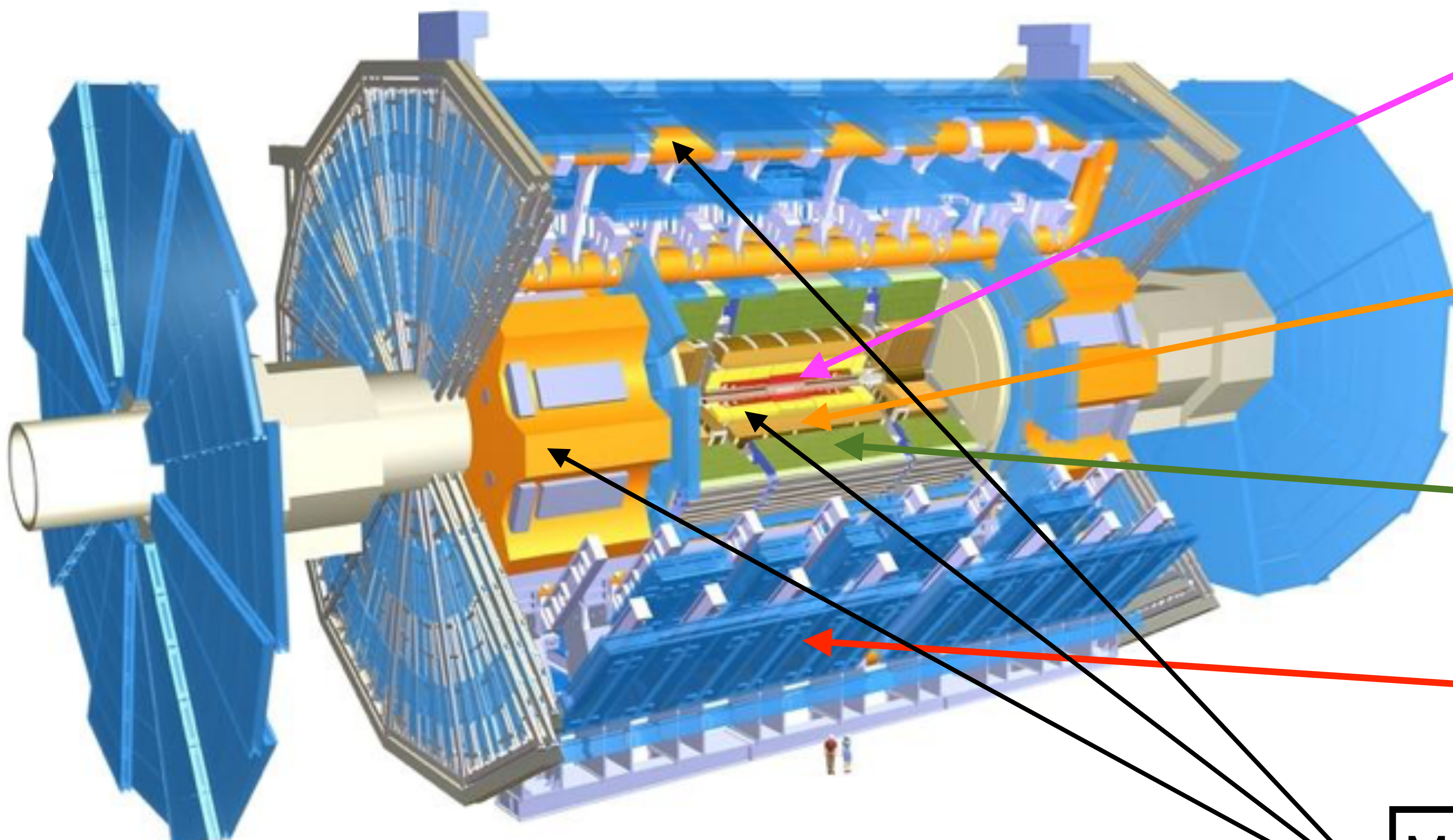


- Bunches of ~1.5e11 p cross every 50 ns
- More than 25 pp interactions per bunch crossing on average



The **ATLAS** experiment at the LHC

- General purpose detector optimised for diboson final states, considered in 90's most promising for Higgs boson discovery: $\gamma\gamma$, ZZ^*, WW^*, $Z^{(*)}\to\ell\ell$, $W^{(*)}\to\ell\nu$ (ℓ=e,μ)
  - **e, μ**: inner detector (tracker) with high precision, even at low transverse momentum
  - **e,γ**: e.m. calorimeter with excellent energy resolution and direction reconstruction
  - **ν** (E_T^{miss}), **jets**: calorimeters with large acceptance and good jet energy resolution for reconstruction of missing energy in transverse plane
  - **μ**: muon system with good precision up to 1 TeV



Inner Detector
- $|\eta|<2.5$
- $\sigma_{p_T}/p_T \sim 0.05\% p_T \oplus 1\%$

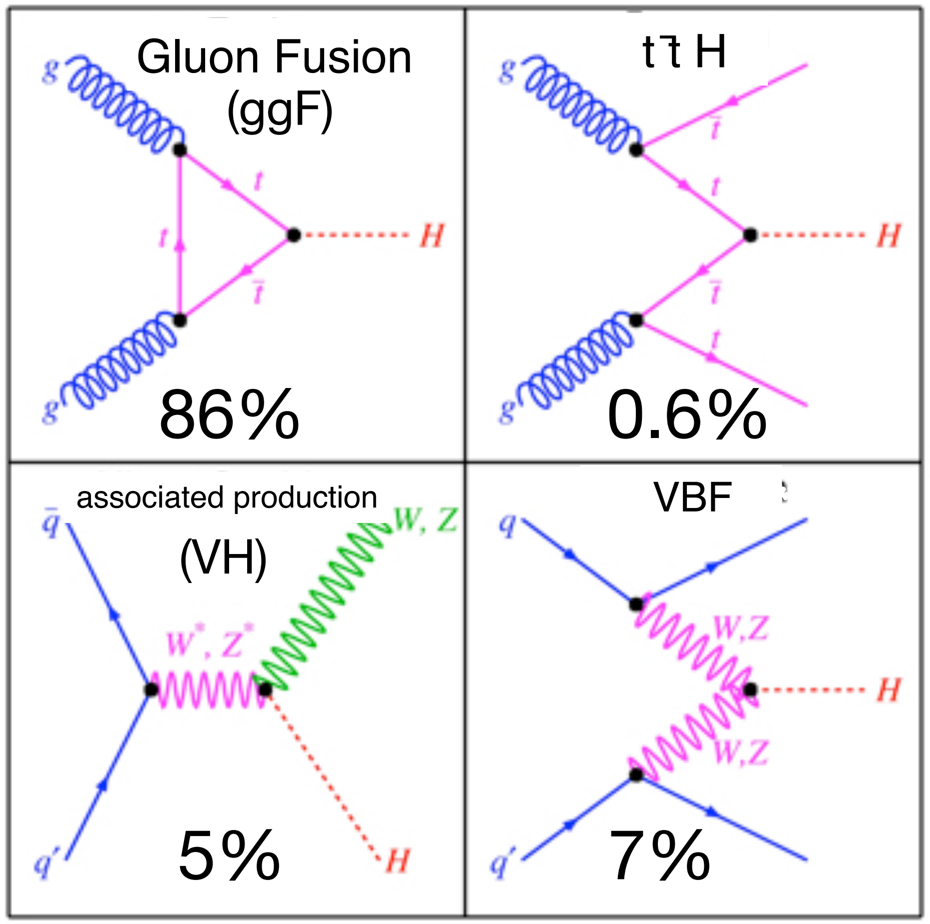
E.M. Calorimeter
- $|\eta|<3.2$
- $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.7\%$ (barrel)

Hadron Calorimeter
- $|\eta|<4.9$
- $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 3\%$ (barrel)

Muon Spectrometer
- $|\eta|<2.7$
- $\sigma_p/p<10\%$ up to 1 TeV

Magnets: solenoid (2T) & toroids (0.5T & 1T)

SM Higgs boson production @ LHC (m_H~125 GeV)

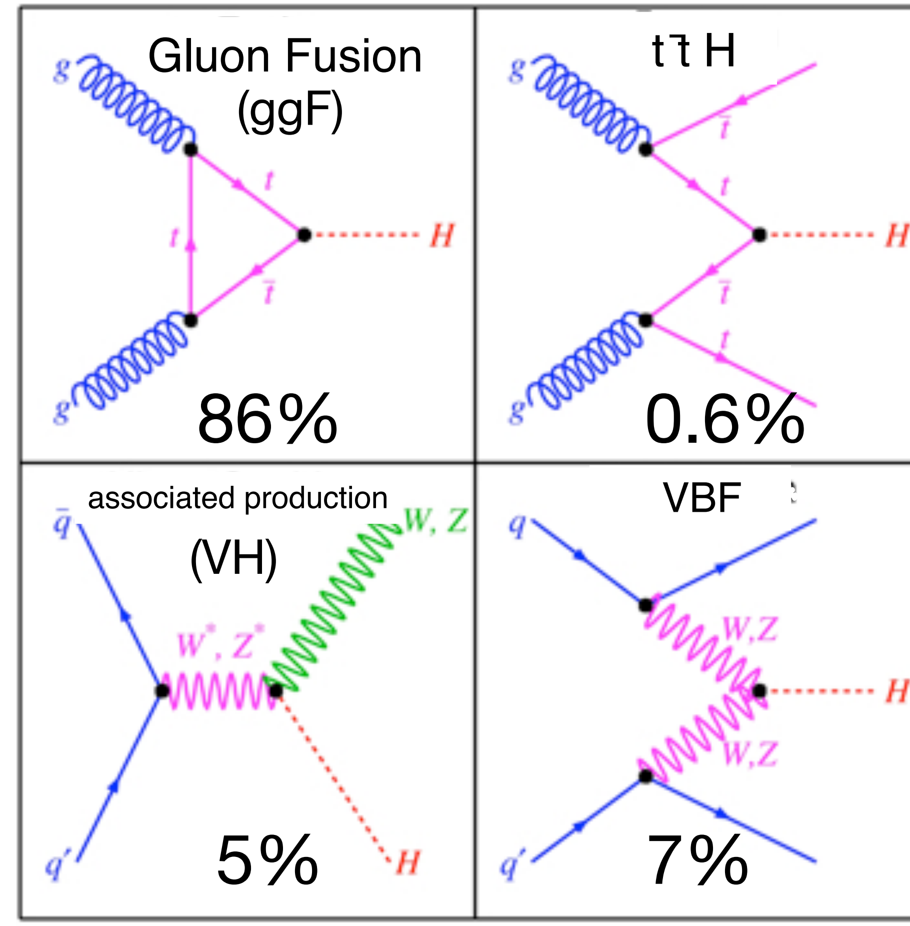


Production process	Cross section [pb] $\sqrt{s} = 7$ TeV	Cross section [pb] $\sqrt{s} = 8$ TeV	Relative fraction
ggF	15.0 ± 1.6	19.2 ± 2.0	86%
VBF	1.22 ± 0.03	1.57 ± 0.04	7%
WH	0.573 ± 0.016	0.698 ± 0.018	5%
ZH	0.332 ± 0.013	0.412 ± 0.013	
bbH	0.155 ± 0.021	0.202 ± 0.028	0.9%
ttH	0.086 ± 0.009	0.128 ± 0.014	0.6%
tH	0.012 ± 0.001	0.018 ± 0.001	
Total	17.4 ± 1.6	22.3 ± 2.0	

~500k Higgs bosons in ATLAS interaction point in Run1 collisions
(before reconstruction)

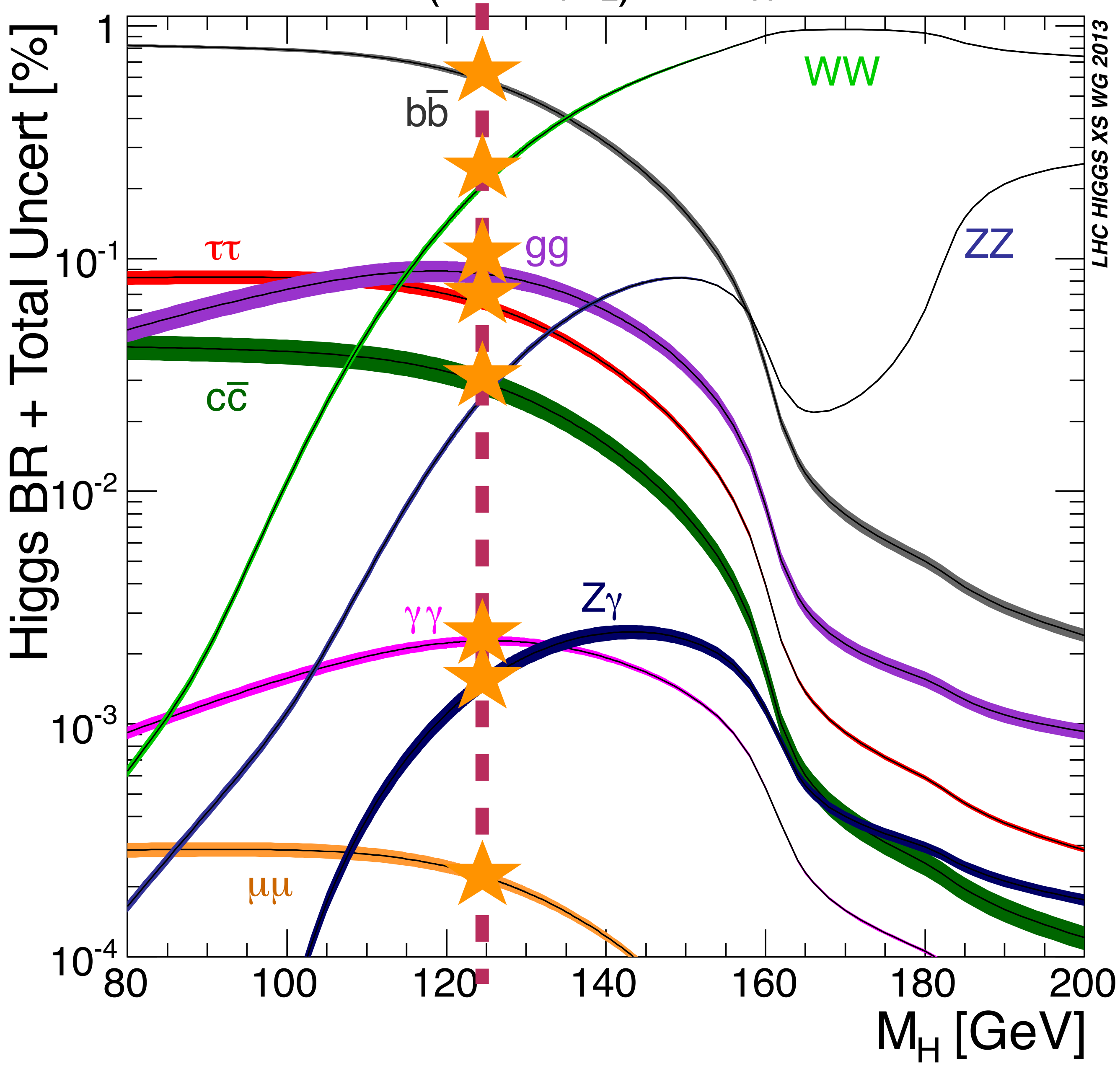
SM Higgs boson production @ LHC (m_H~125 GeV)

- Different production processes
  - sensitive to different couplings
    - ggF, ttH: fermions (t, b)
    - VBF, VH: bosons (W, Z)
  - different signatures
  - sub-dominant modes have cleaner signatures with better S/B than ggF
    - VBF: two jets with large m_{jj}, large rapidity gap, little hadronic activity in between
    - WH, ZH: V boson decay to
      - charged leptons ($W\to\ell\nu$, $Z\to\ell\ell$)
      - neutrinos ($W\to\ell\nu$, $Z\to\nu\nu$)
      - jet pairs w/ m_{jj}~80-90 GeV ($W,Z\to qq$)
    - ttH: $tt\to WbWb$, $W\to\ell\nu$ or $W\to qq$: many jets (≥4-6), b-jets, leptons, neutrinos



SM Higgs boson decays

BR(H→X_1X_2) vs m_H

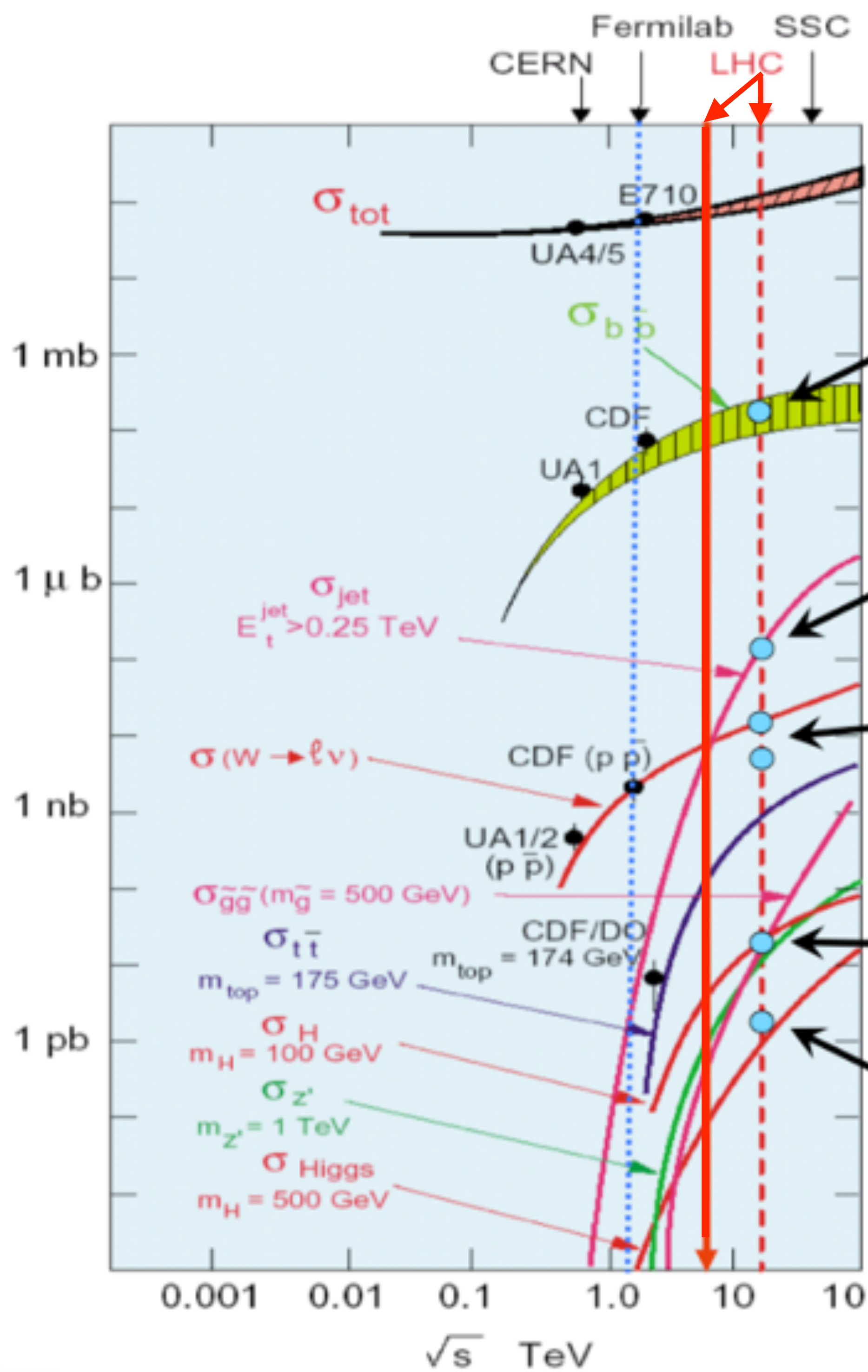


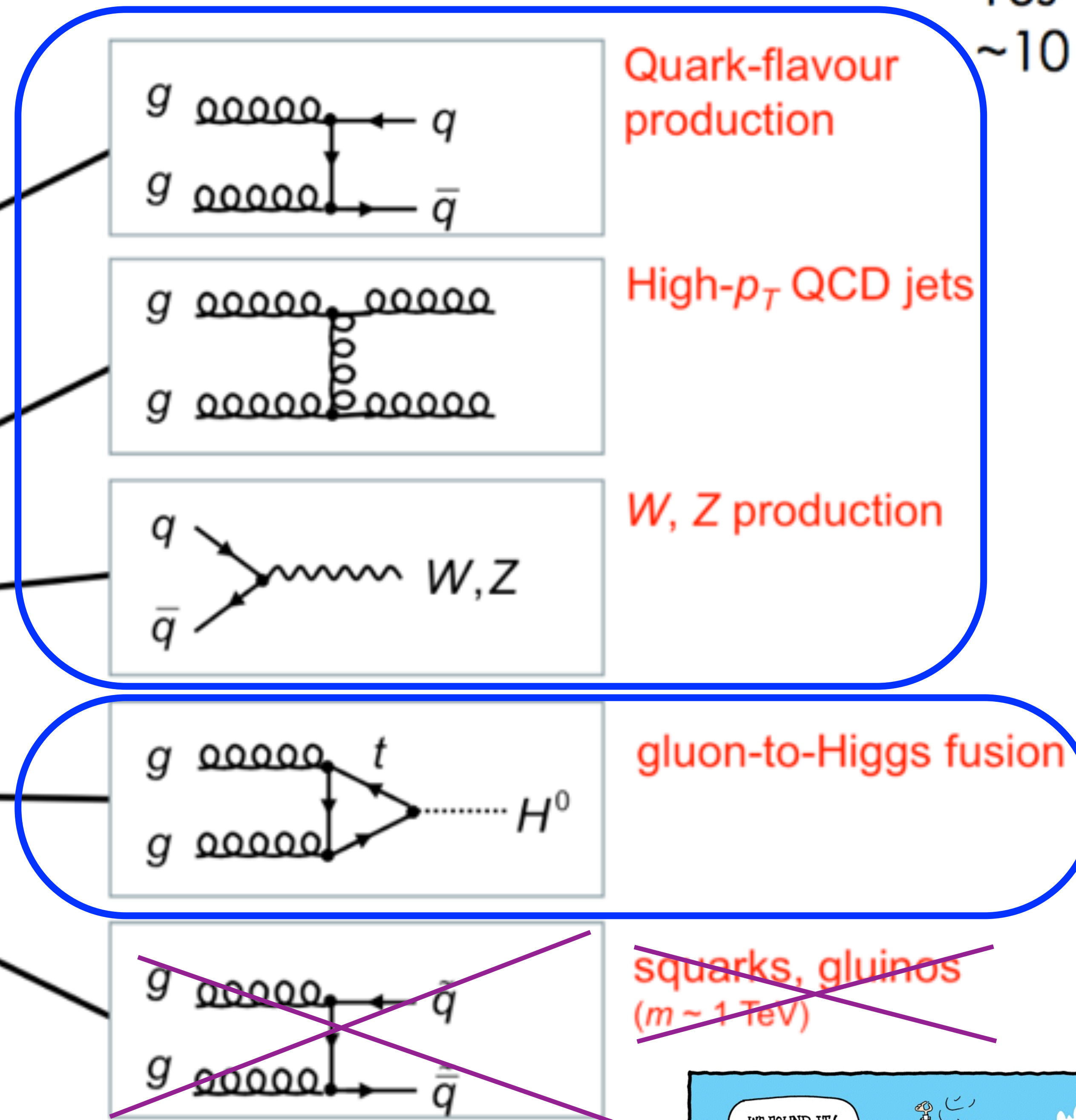
BR(H->X_1X_2) for m_H=125.36 GeV

Decay channel	Branching ratio [%]
$H \to b\bar{b}$	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
Total width Γ_H	4.12 MeV

- Many final states with non negligible branching ratios @ m_H~125 GeV
  - not all of them can be cleanly identified (cc, gg..)

Backgrounds in pp collisions



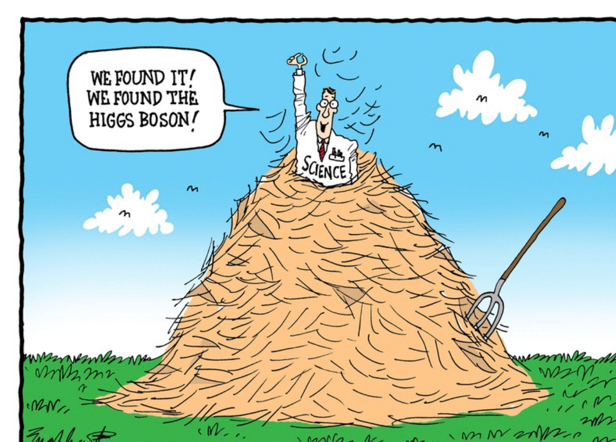


10s at LHC:
~10 billions evts

≈ 100 millions
b quarks

≈ 200 000
W bosons

≈ 3 Higgs
bosons



- that's indeed like searching a needle in a haystack!

SM Higgs boson decays exploited at the LHC

- To reduce QCD backgrounds or get best invariant mass resolution, privilege
  - photons
  - $W \to \ell\nu$ (ℓ=e,μ) (BR_{WW} = 4.7%)
  - $Z \to \ell\ell$ (BR_{ZZ} = 0.45%, $BR_{Z\gamma}$ = 6.7%)
  - $VH \to Vbb$, $V \to \ell\ell/\ell\nu/\nu\nu$ (σ_{VH}/σ_{H}*BR_V = 1.15%)

  but reconstruct also other final states (like W,Z→jj) to increase stat or access specific Higgs boson couplings

$H_{125} \to$	$\gamma\gamma$	$WW^* \to \ell\nu\ell\nu$	$ZZ^* \to 4\ell$	$\tau\tau$	Vbb $V \to \ell\ell,\ell\nu,\nu\nu$	$\mu\mu$	$Z\gamma \to \ell\ell\gamma$
σ*BR/σ_{TOT}	2.28E-03	1.06%	1.25E-04	6.3%	6.4E-03	2.2E-04	1.03E-04

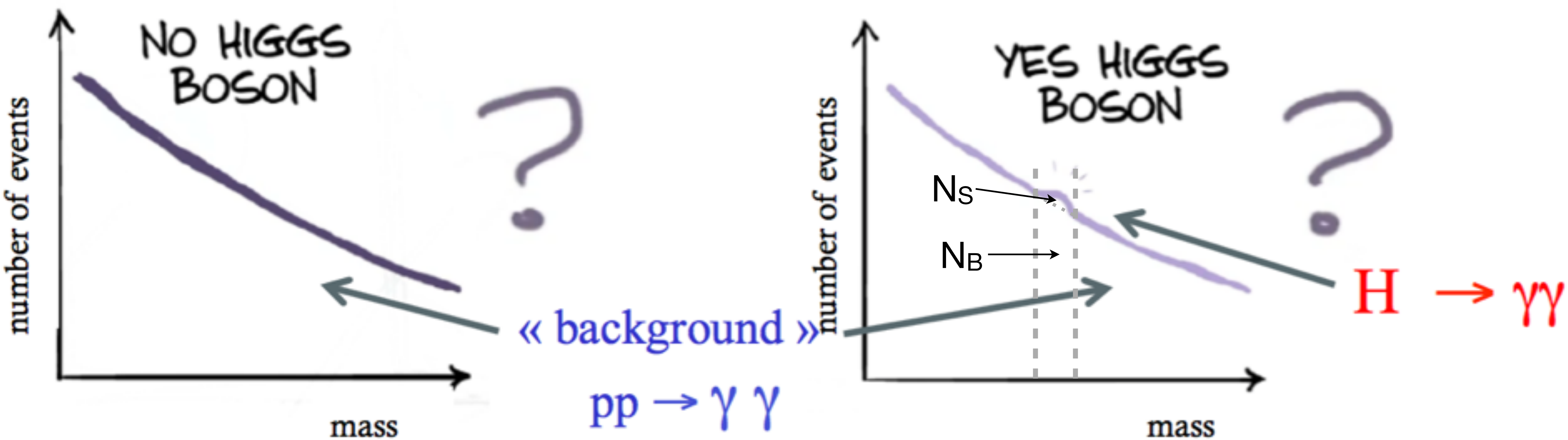
- A*ε ~30–40% for modes without ν ($\gamma\gamma/4\ell/\ell\ell\gamma/\mu\mu$), 2–10% for the others
  - ~1.5k Higgs bosons (m_H=125 GeV) in full 8 TeV sample after selection

Higgs boson search strategy: the H→γγ example

- Reconstruct final state of interest: two photons in the detector
- Apply selection optimised based on expected properties of signal (S) and background (B) to improve S/B while keeping good signal efficiency
- Define (at least) 1 discriminating variable between S and B: the di-photon invariant mass

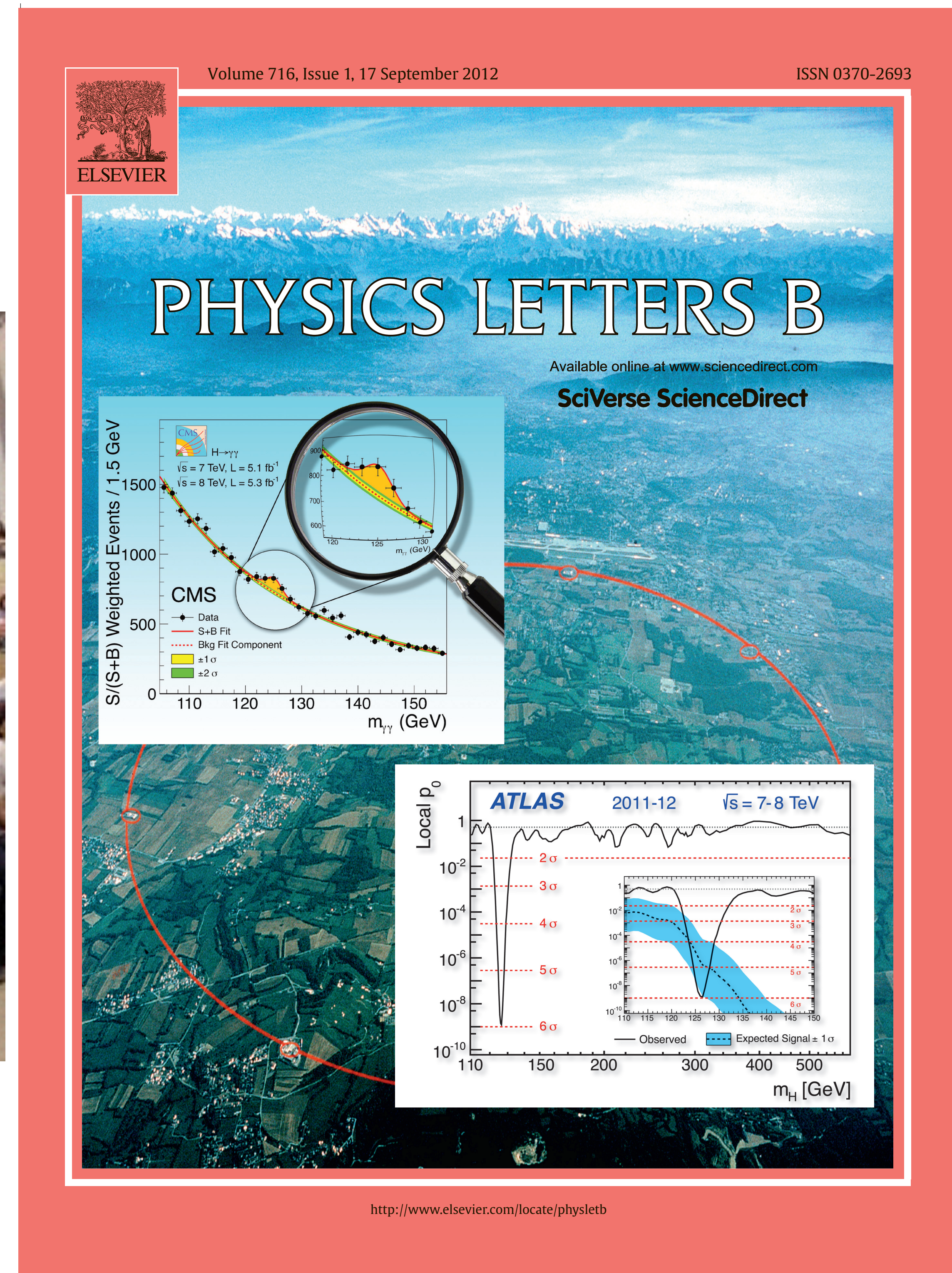
$$m_{\gamma\gamma} = \sqrt{(E_1+E_2)^2 - (\vec{p}_1+\vec{p}_2)^2} = \sqrt{2E_1E_2(1-\cos\theta)}$$

- Fit $m_{\gamma\gamma}$ distribution to estimate S and B yields, N_S and N_B
  - signal and background distributions from simulation and data control samples



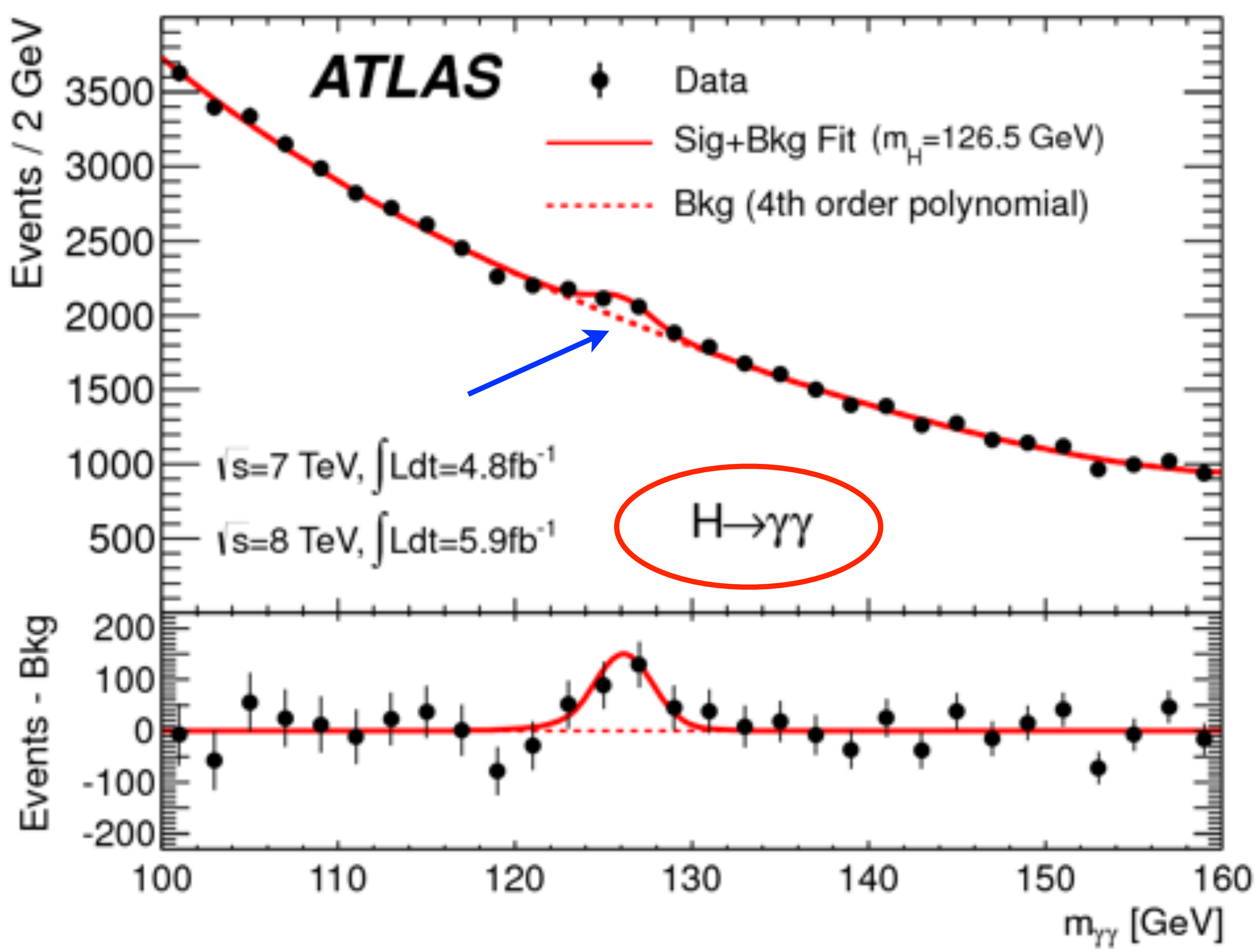
- Claim discovery if ">5σ significance": $N_S/\sqrt{N_B} > 5$ or some equivalent but more complicated criteria. The probability ("p-value") that B fluctuates to yield a fake S that large is $3 \cdot 10^{-7}$
- Search in as many final states as possible to increase sensitivity

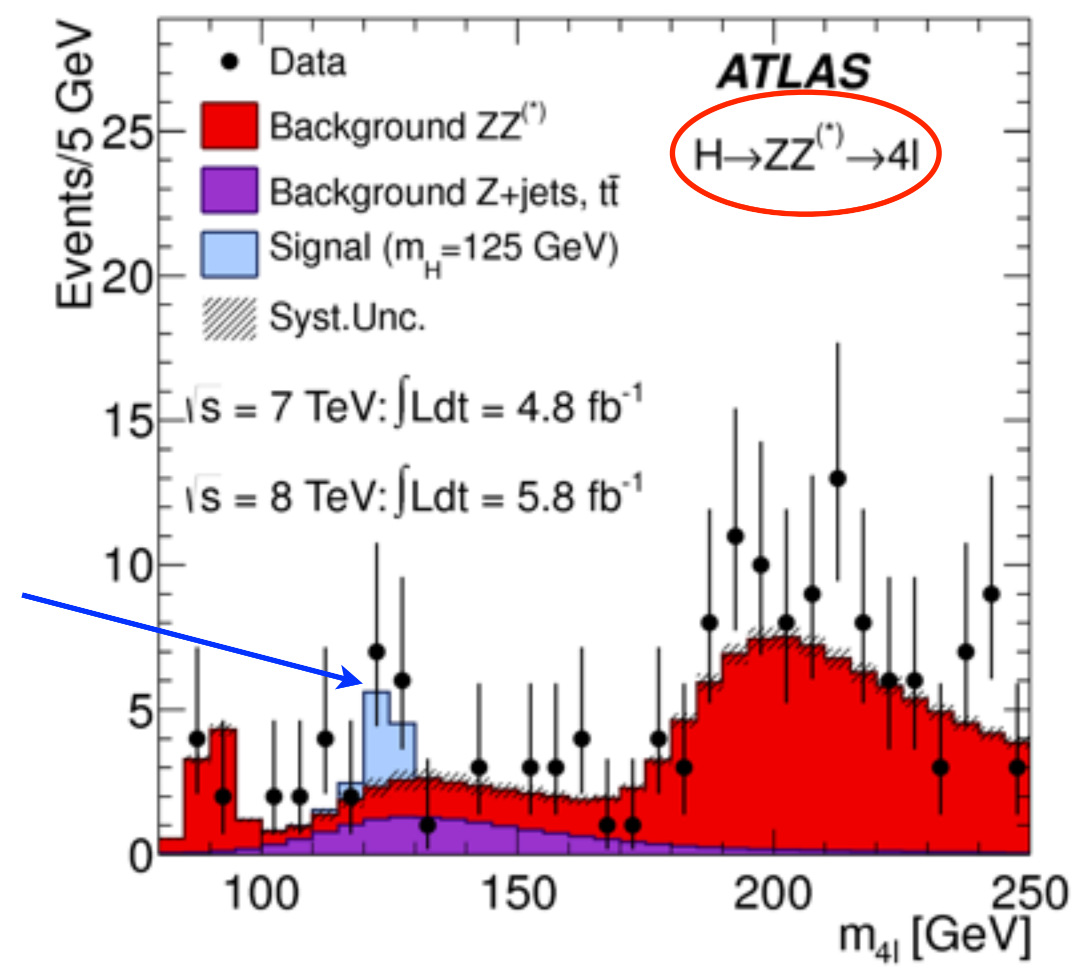
Higgs boson discovery: CERN, 4th July 2012



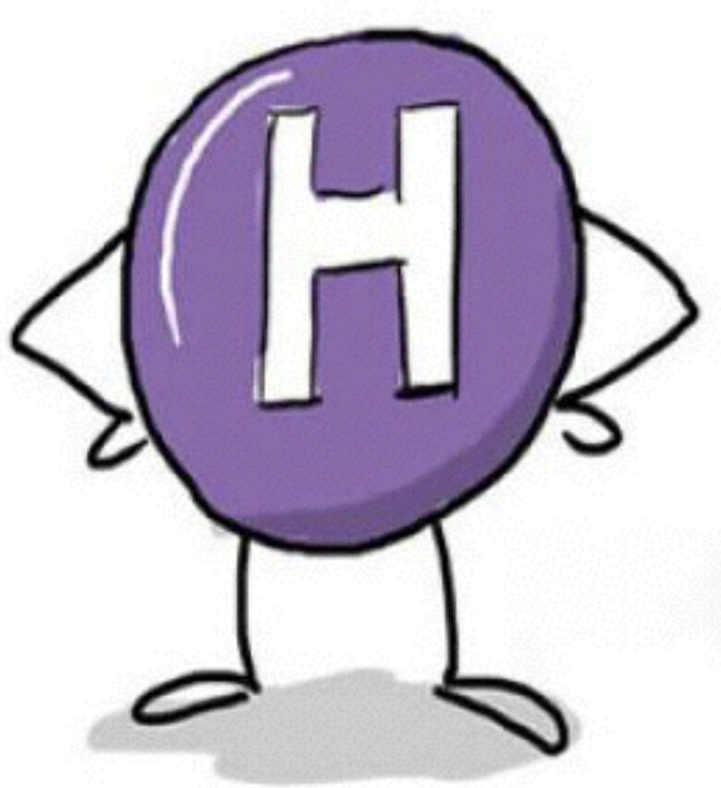
Higgs boson discovery

- ~10 fb^{-1} for each experiment (5 fb^{-1} @ 7 TeV + ~5 fb^{-1} @ 8 TeV)
- Maximum deviation of data from B-only hypothesis near m_H=125 GeV
- ~5σ/experiment mainly from largest-sensitivity (i.e. best $N_S/\sqrt{N_B}$) final states





2. Higgs boson characterisation with full Run1 data



Name: Higgs boson

Date of birth: 04/07/2012

Weight: 125.36 GeV

Blood type (J^P): 0^+

Address: Route de Meyrin 385,
1217 Meyrin, CH

Reconstructed production and decay modes

Productions →

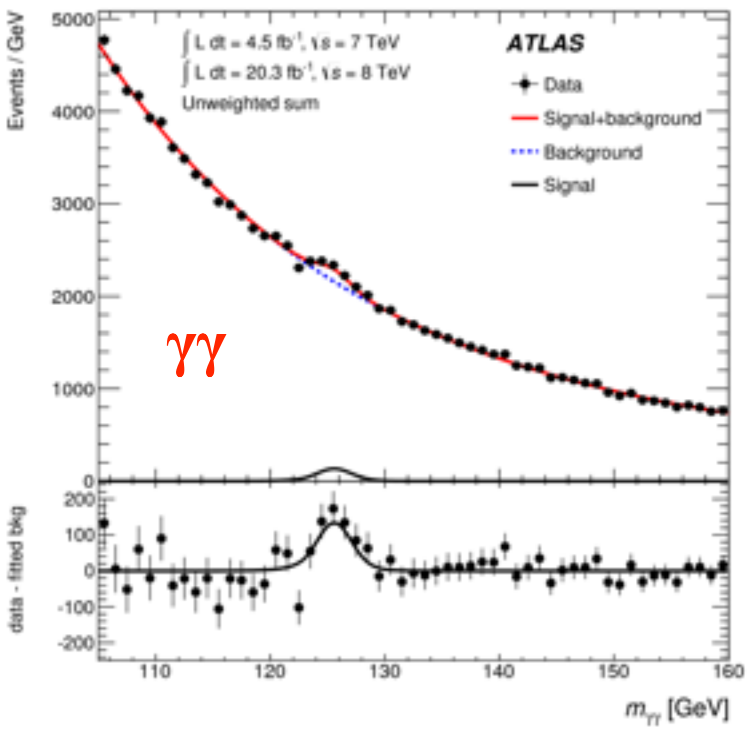
Decays ↓

	ggF	VBF	VH	ttH	σ_m/m	S/B	S	Observed (expected) significance or limit
$\gamma\gamma$	✔	✔	✔	✔	1.3%	0.03	~400	5.2σ (4.6σ)
$ZZ^*\rightarrow 4\ell$	✔	✔	✔	✔	1–2%	1.5	~15	8.1σ (6.2σ)
WW^*	✔	✔	✔	✔	15%	0.02	~1000	6.5σ (5.9σ)
$\tau\tau$	✔	✔			15–20%	0.03	~100	4.5σ (3.4σ)
bb			✔	✔	15%	0.03	~160	1.4σ (2.6σ)
$Z\gamma$	✔				1.4%	0.003	~15	<11 (9) * SM
$\mu\mu$	✔	✔			2%	0.002	~35	<7.0 (7.2) * SM

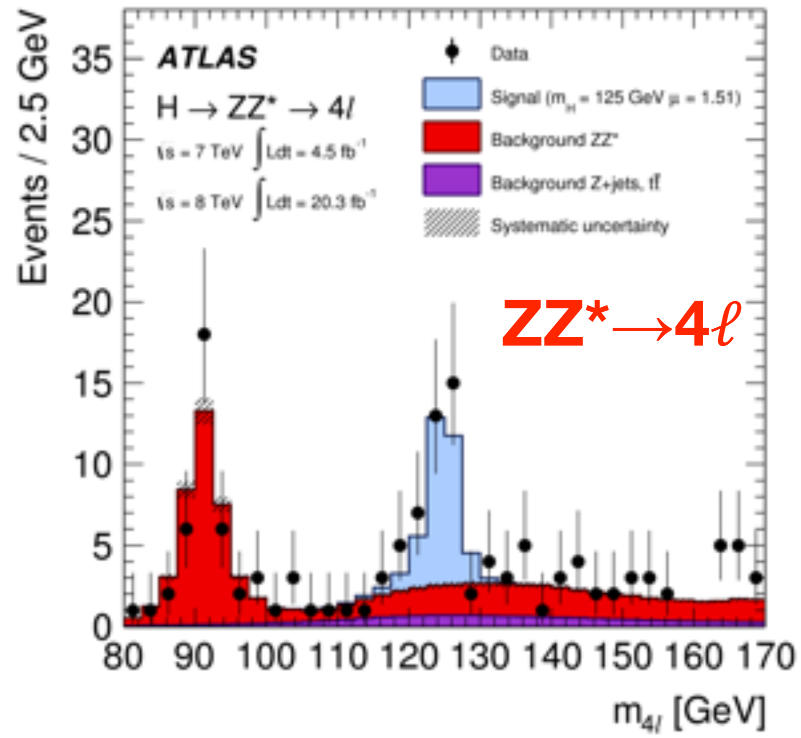
- plus searches for rarer/forbidden decay modes (see later)

Invariant mass distributions of main decay modes

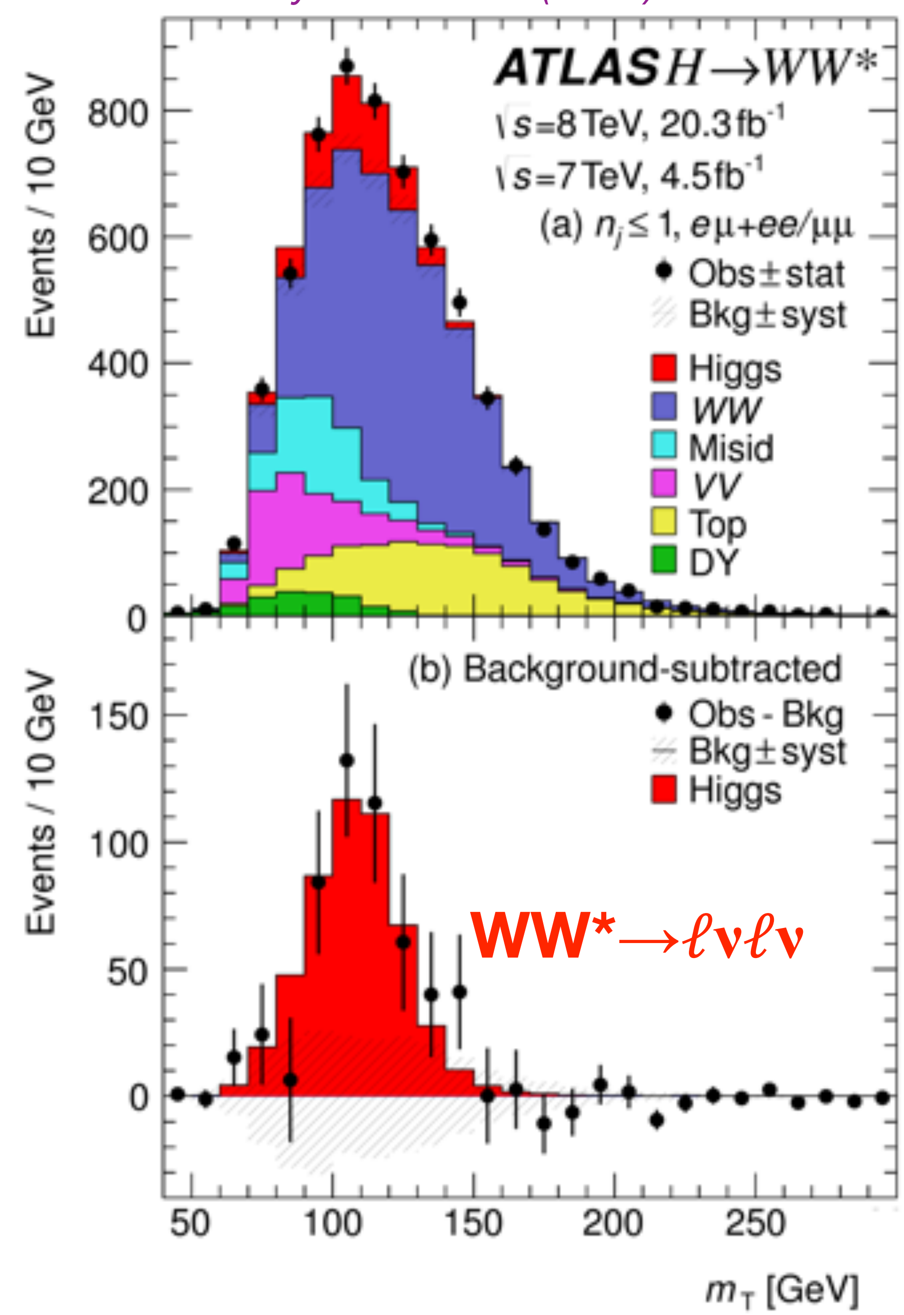
Phys. Rev. D90 (2014) 112015



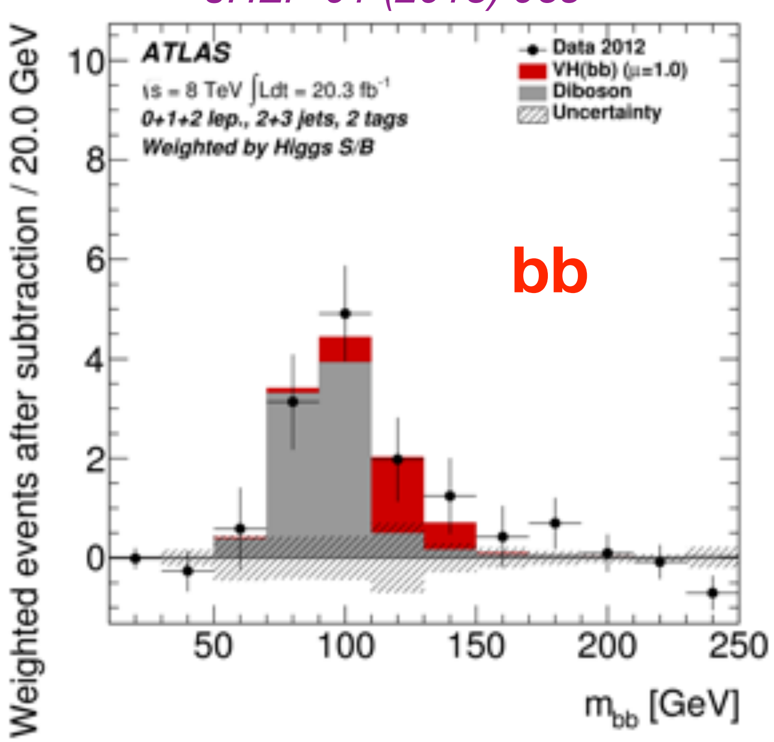
Phys. Rev. D91 (2015) 012006



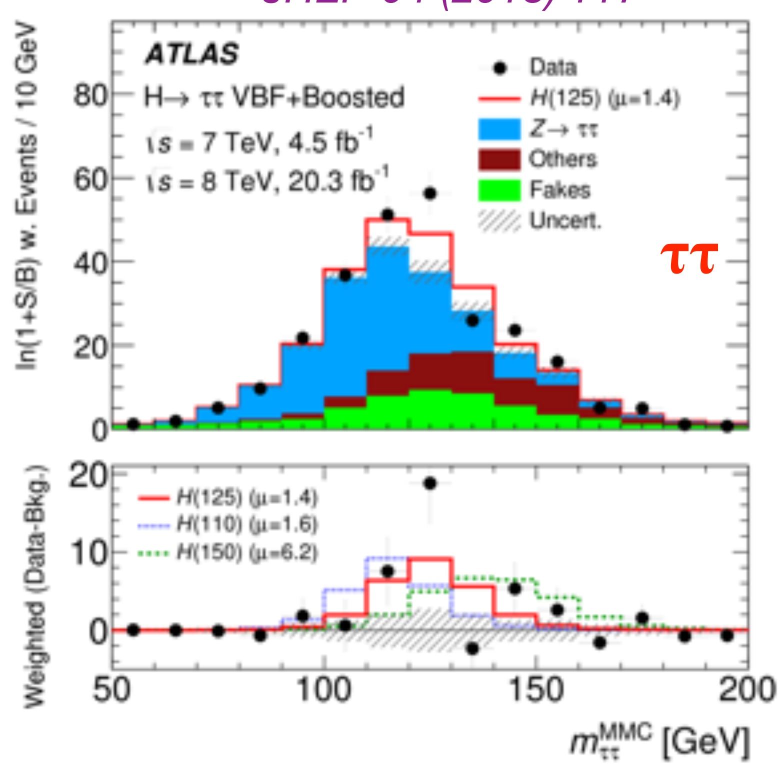
Phys. Rev. D92 (2015) 012006



JHEP 01 (2015) 069



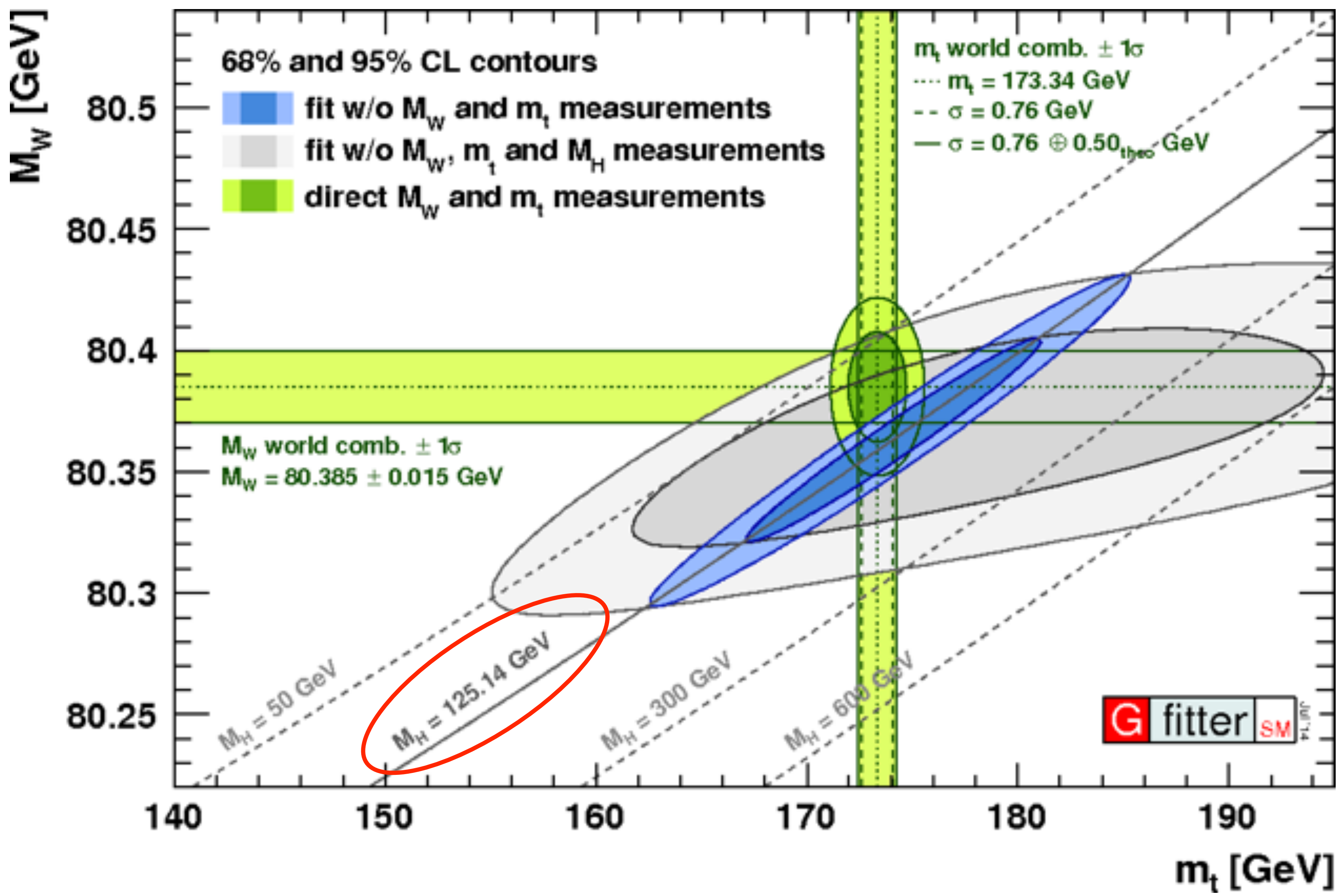
JHEP 04 (2015) 117



- no hint of peak at 125 GeV in Zγ and μμ channels (not shown here)

Higgs boson mass

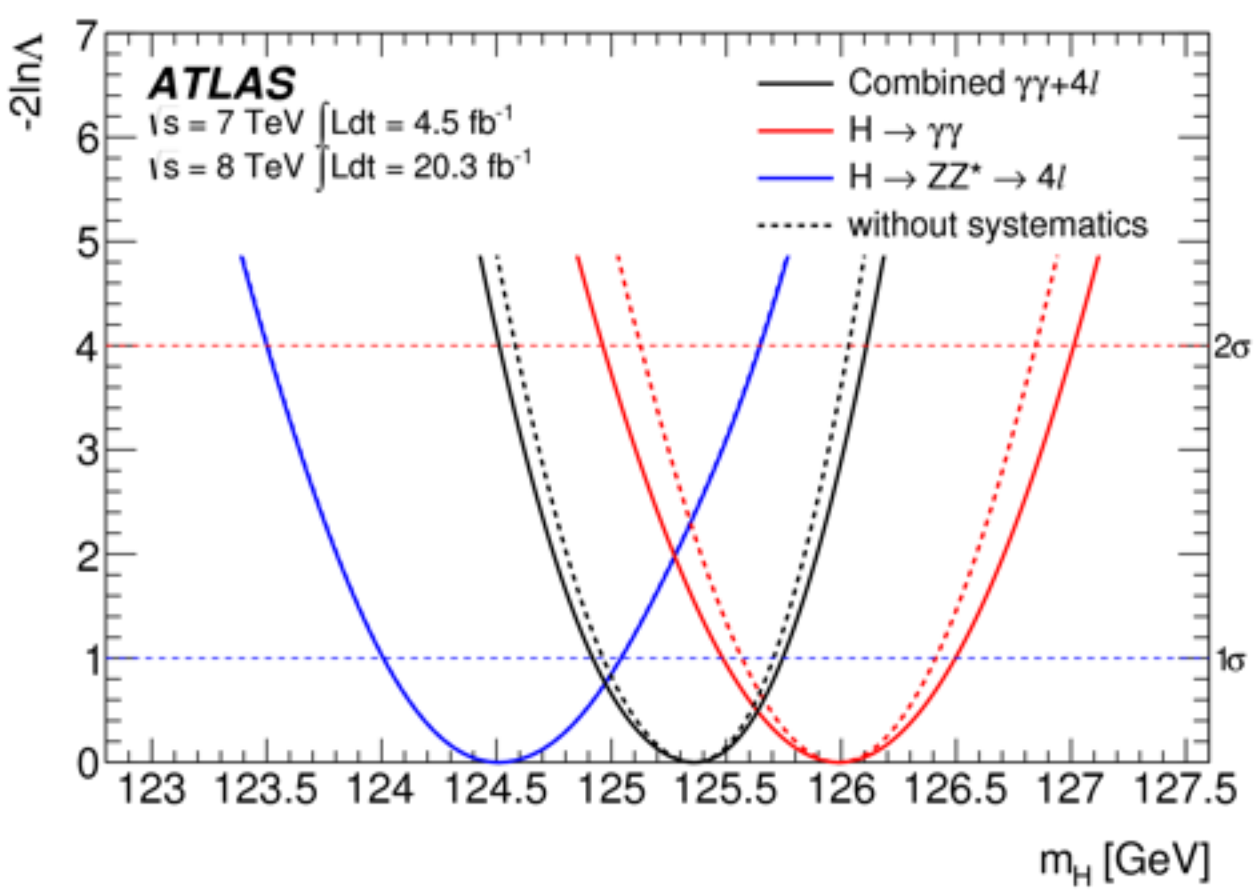
- In SM, Higgs sector is determined by a single parameter, m_H (+vev~245 GeV)
    - need to know m_H to predict couplings to all other SM particles
- In SM, quantum corrections to many observables depend on m_H, m_t and m_W
    - test consistency of SM by comparing direct m_t, m_W measurements to indirect constraints from fits of SM observables after fixing m_H



Phys. Rev. D90 (2014) 052004

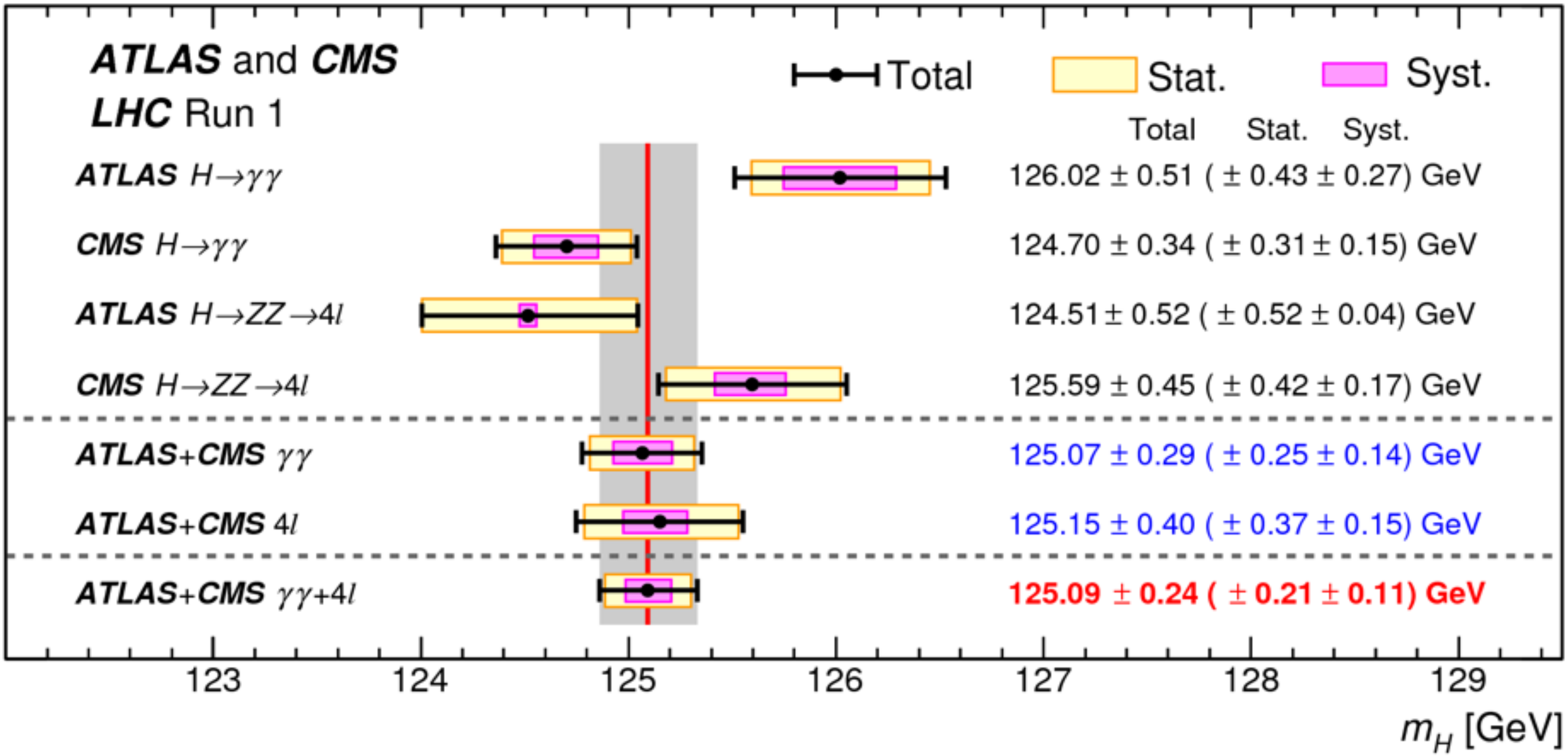
Higgs boson mass from H→γγ and H→4ℓ

- From position of invariant mass peak in channels with best resolution σ_m/m
- Through maximisation of profile likelihood ratio $$\Lambda(\alpha) = \frac{L(data|\alpha, \hat{\hat{\theta}}(\alpha))}{L(data|\hat{\alpha}, \hat{\theta})}$$
  - L = likelihood function
  - α = parameter of interest = m_H
  - θ = nuisance parameters (systematic uncertainties, bkg and signal model parameters, signal cross section*BR)
  - $\hat{\alpha}, \hat{\theta}$ maximise L; $\hat{\hat{\theta}}(\alpha)$ maximises L for given α



- $m_H = 125.36 \pm 0.37 \pm 0.18$ GeV
- 2.0σ compatibility between the two channels
  - ($m_H^{\gamma\gamma} - m_H^{4\ell} = 1.47 \pm 0.67 \pm 0.28$ GeV)
- Limited by statistical uncertainty
- Systematic uncertainty dominated by energy and momentum scale and resolution

ATLAS+CMS mass combination



- $m_H = 125.09 \pm 0.24$ GeV (2‰ uncertainty!)
- Compatibility (p-value) between the 4 masses: 10%
- Expected uncertainties for same values of nuisance parameters: ±0.19 ±0.10 GeV

Production and decay rate strengths

- Production and decay "signal strengths": $\boxed{\mu_i = \frac{\sigma_i}{(\sigma_i)_{\rm SM}} \text{ and } \mu_f = \frac{{\rm BR}_f}{({\rm BR}_f)_{\rm SM}}}$

  can be inferred correlating the signal rates measured in all channels c

$$n_s^c = \sum_i \sum_f \mu_i (\sigma_i)_{\rm SM} \times \mu_f ({\rm BR}_f)_{\rm SM} \times A_{if}^c \times \varepsilon_{if}^c \times \mathcal{L}^c$$

Measured

Estimated

Predicted

  via maximisation of profile likelihood ratio $\Lambda(\mu_i,\mu_f)$

  Asymptotically $-2\ln\Lambda(\alpha)$ distribution $\sim \chi^2$ with n d.o.f., n = size(α)

- $\mu \neq 1 \Rightarrow$ deviation from SM assuming that production and decay kinematics are similar to SM expectation
  - corroborated by measurements of differential x-sections and tests of spin/CP

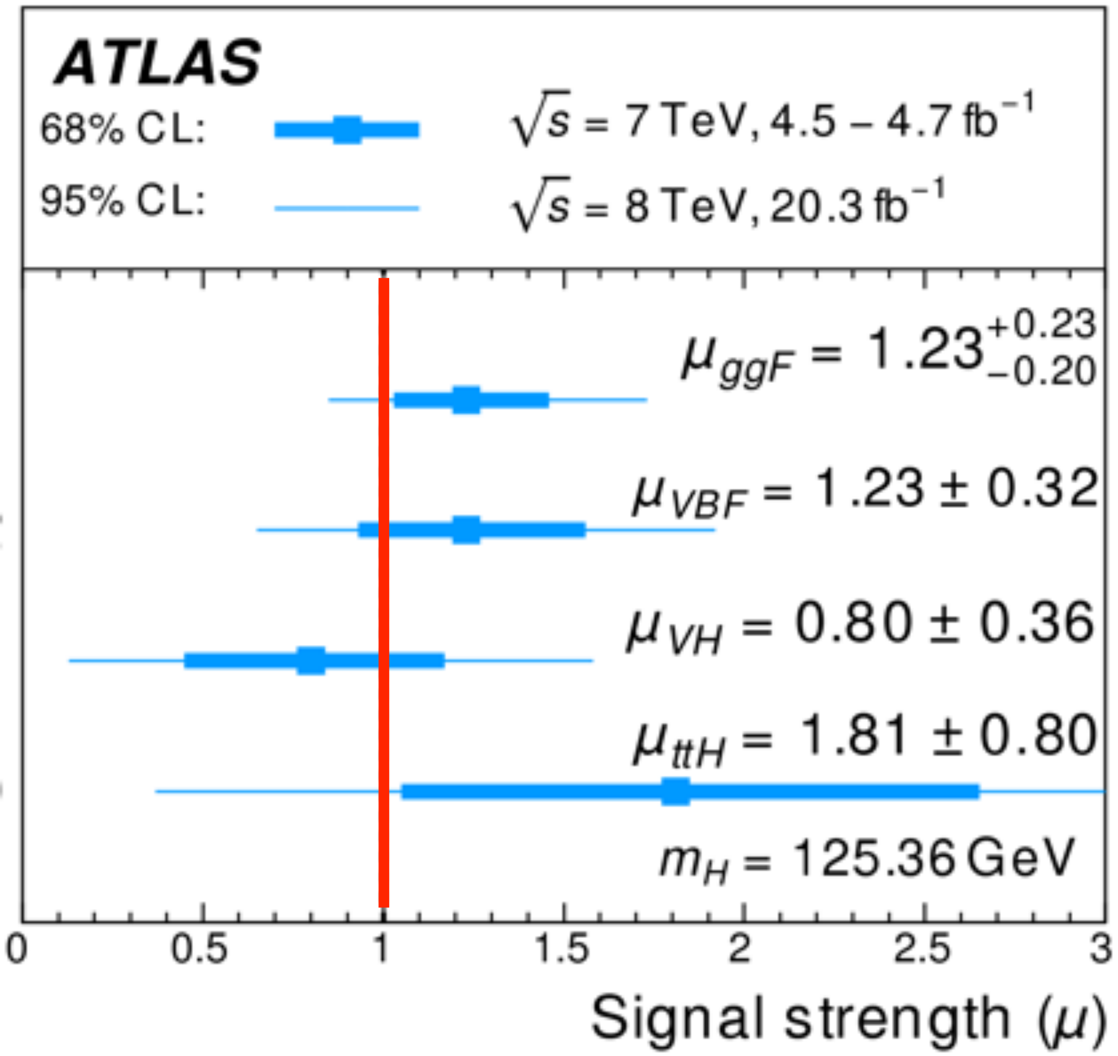
- Simplest model: one overall μ
  - $\boldsymbol{\mu = 1.18^{+0.15}_{-0.14}}$ [±0.10 (stat) ±0.07 (syst) $^{+0.08}_{-0.07}$ (theo)]
  - systematic error dominated by background estimates; theory error due to uncertainty on SM x-sections, BRs and kinematic distributions

p-value of SM (μ = 1): 18%

Signal strength parameters

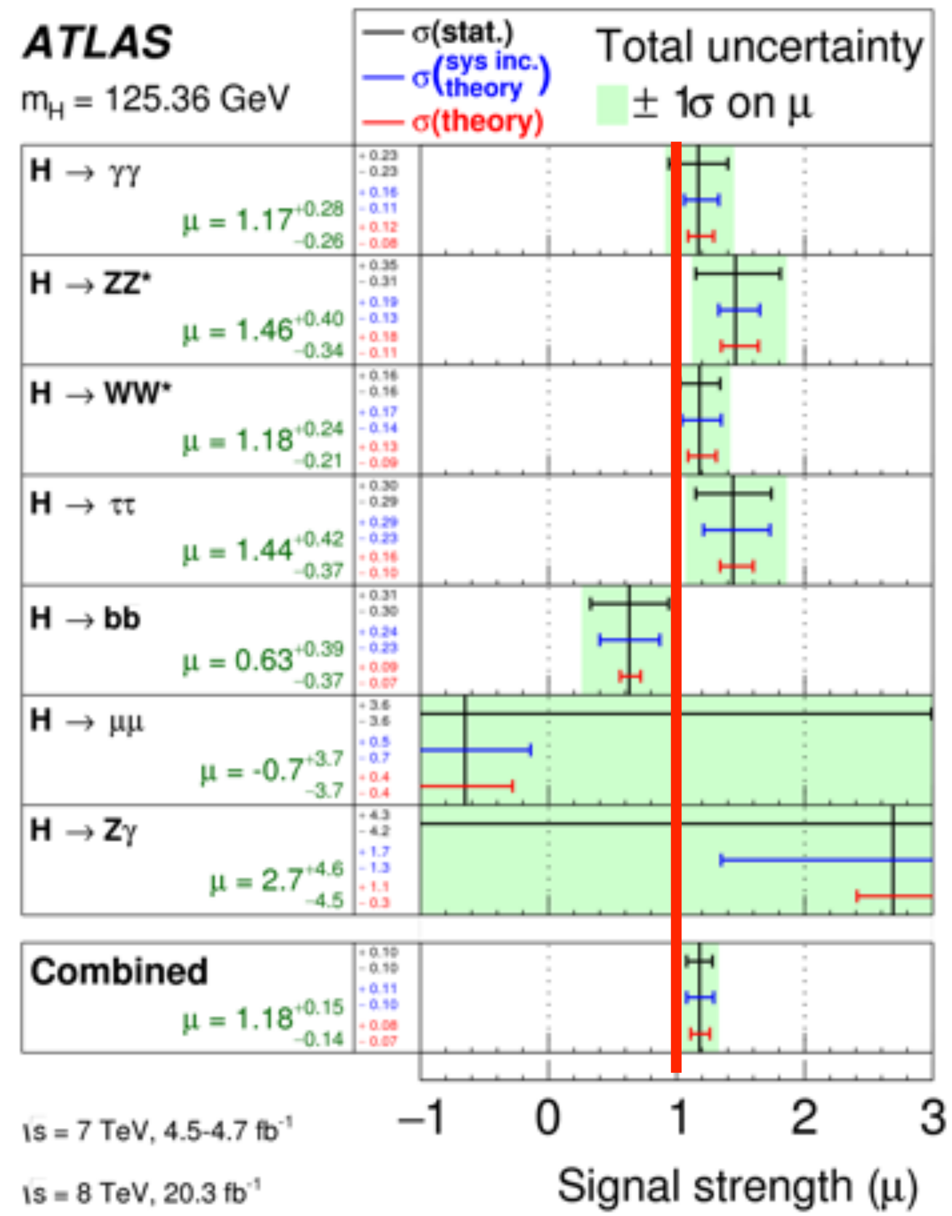
by production mode

(*assuming μ_f=1, μ_{bbH}=μ_{ggF}, μ_{tH}=μ_{ttH}, $\mu_{WH=ZH}$*)



by decay mode

(*assuming μ_i=1*)



- All μ's consistent with SM expectation = 1
- VBF evidence > 4σ
- VH, ttH not firmly established yet (but evidence of VH at Tevatron); μ_{ttH}<3.2@95% C.L.

Total cross section

- From SM predictions and measured μ_i (removing σ_{SM} uncertainty from μ_i)

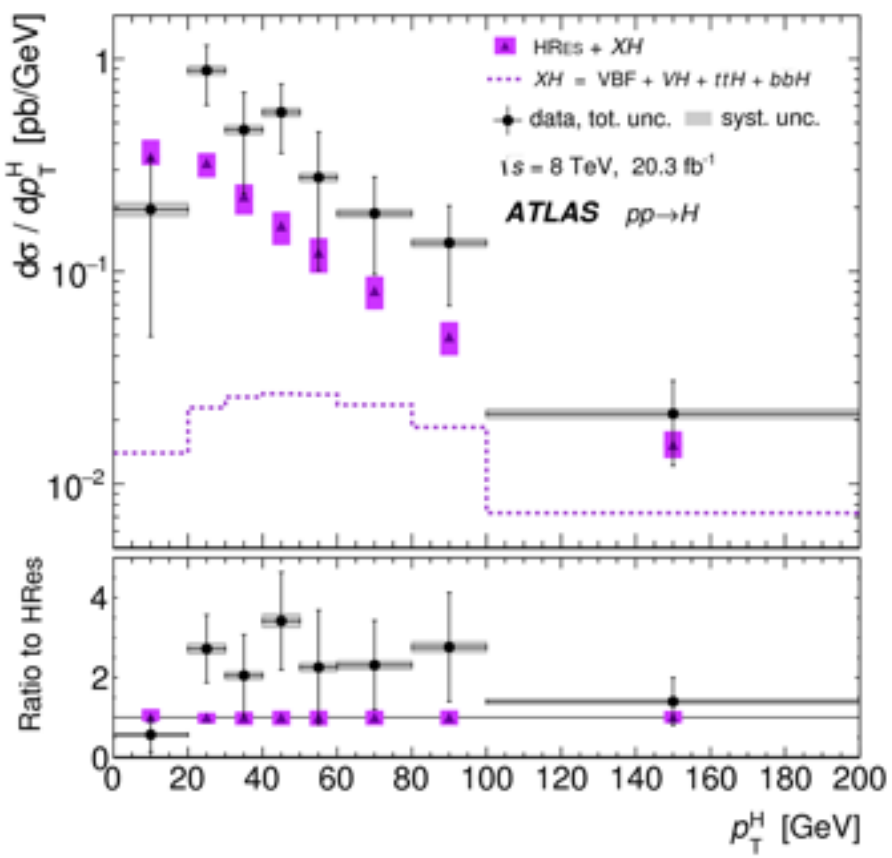
Measured x-section	σ_{SM} [pb]
$\sigma_H(7\ \text{TeV}) = 22.1\,^{+7.4}_{-6.0}\ \text{pb} = 22.1\,^{+6.7}_{-5.3}\,(\text{stat.})\,^{+2.7}_{-2.3}\,(\text{syst.})\,^{+1.9}_{-1.4}\,(\text{theo.})\ \text{pb}$	17.4±1.6
$\sigma_H(8\ \text{TeV}) = 27.7 \pm 3.7\ \text{pb} = 27.7 \pm 3.0\,(\text{stat.})\,^{+2.0}_{-1.7}\,(\text{syst.})\,^{+1.2}_{-0.9}\,(\text{theo.})\ \text{pb}$	22.3±2.0

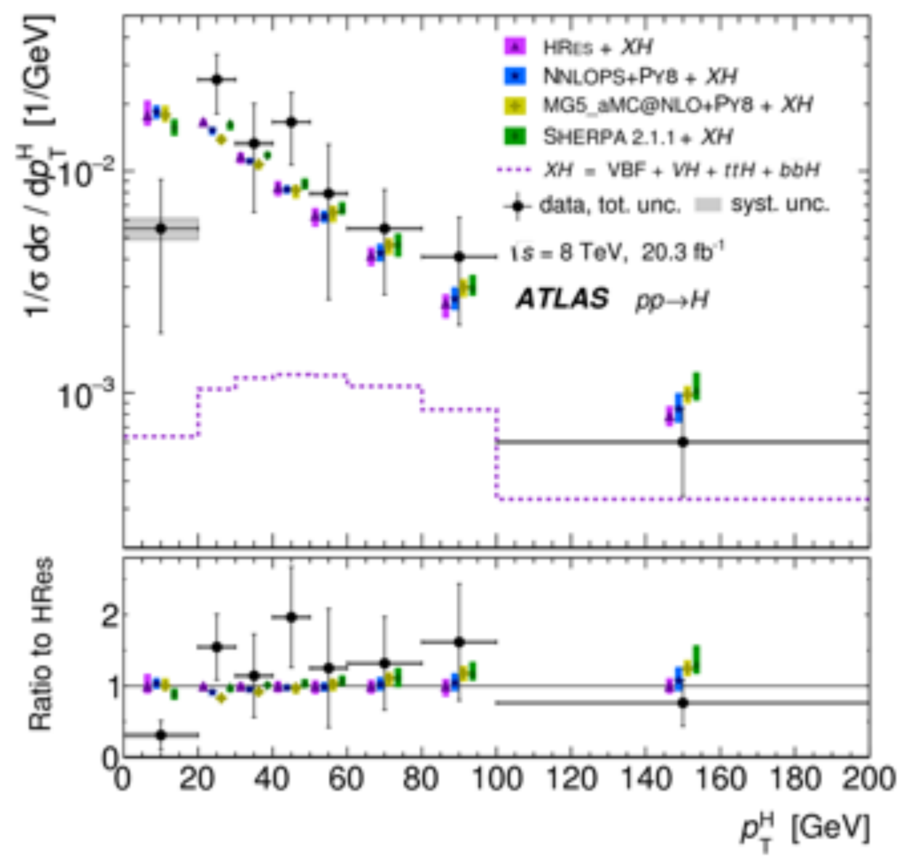
  - uncertainty dominated by gluon-fusion contribution
  - ~1σ higher than theoretical prediction

Phys. Rev. Lett. 115 (2015) 091801

Differential cross-sections from H→γγ and H→4ℓ

- Several distributions sensitive to various theoretical effects: QCD modelling in ggF production (p_T^H, y^H), ratios of different production mechanisms (N_{jets}), modelling of partonic radiation in ggF and of jets in VBF and VH events (p_T of leading jet, p_T^{j1})
- Measured separately in 2 channels from differential yields, efficiencies and BR
- Two combinations: absolute xsections (assume SM BR) and normalised ones (shapes only; no assumptions on BR), vs analytical calculations and MC generators





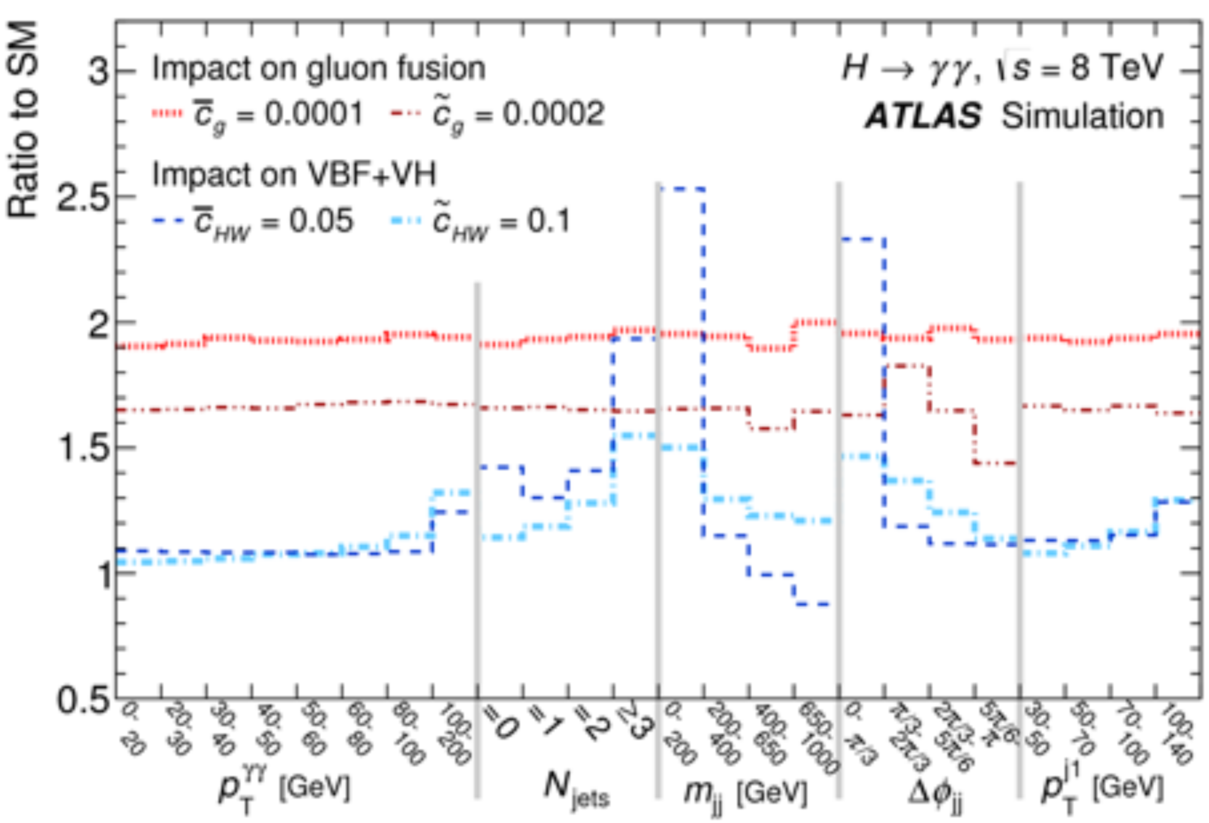
- Total xsection larger than SM but shapes in good agreement with prediction (p-values between 8% and 88%)
- Statistical uncertainties (23%-75%) dominate

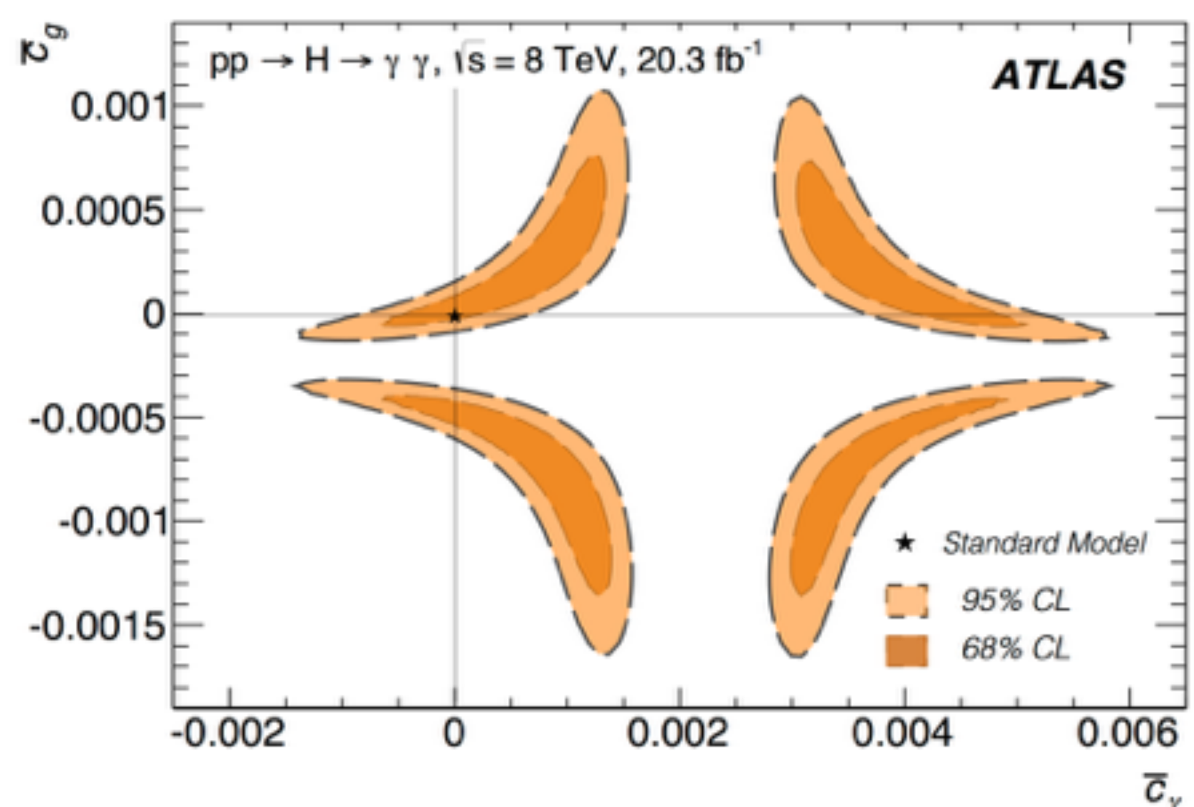
Constraints on BSM in EFT using differential xsections in Hγγ

- SM lagrangian augmented with dim-6 operators of Strongly Interacting Light Higgs
- Differential xsections in Hγγ mainly sensitive to CP-even and CP-odd operators affecting interactions with: photons (c_γ); gluons, via ggF (c_g); WW and ZZ via VBF and associated production (c_{HW}, c_{HB}). Other operators have very small impact

$$\mathcal{L} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB},$$

- Particle-level predictions with Madgraph5 reweighted to account for higher-order QCD and EW corrections, assuming factorisation wrt EFT effects
- 2D limits after setting other coefficients to SM (c=0)





arXiv:1507.04548

Coupling-strength fits

- Scale strength of SM coupling to particle *j* by factor k_j (SM: k_j=1)
- Parametrise x-sections and partial widths in terms of {k_j}, e.g. $\frac{\sigma_{\mathrm{WH}}}{\sigma_{\mathrm{WH}}^{\mathrm{SM}}} = \kappa_W^2$, $\frac{\Gamma_{\mathrm{ZZ}}}{\Gamma_{\mathrm{ZZ}}^{\mathrm{SM}}} = \kappa_Z^2$

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

- *k* of loop-induced couplings (g, γ..) defined either:
  - as function of scale factors for fields in the loop (t, W, ..)
  - as additional free parameter
- Total width depends on invisible/undetected decays: $\Gamma_H(\kappa_j, \mathrm{BR}_{\mathrm{i.,u.}}) = \frac{\kappa_H^2(\kappa_j)}{(1-\mathrm{BR}_{\mathrm{i.,u.}})}\Gamma_H^{\mathrm{SM}}$
  - make some assumptions: $\mathrm{BR}_{\mathrm{i,u}}$=0, or $k_W \leq 1$, $k_Z \leq 1$, ..
  - or measure ratios of coupling strengths
- Assumptions:
  - observed signals come from single resonance with m=125.36 GeV, Γ=0
  - production and decay kinematics compatible with SM expectation
  - tensor structure of the couplings same as in SM (pure CP-even state)

Parametrisation of x-sections and partial widths

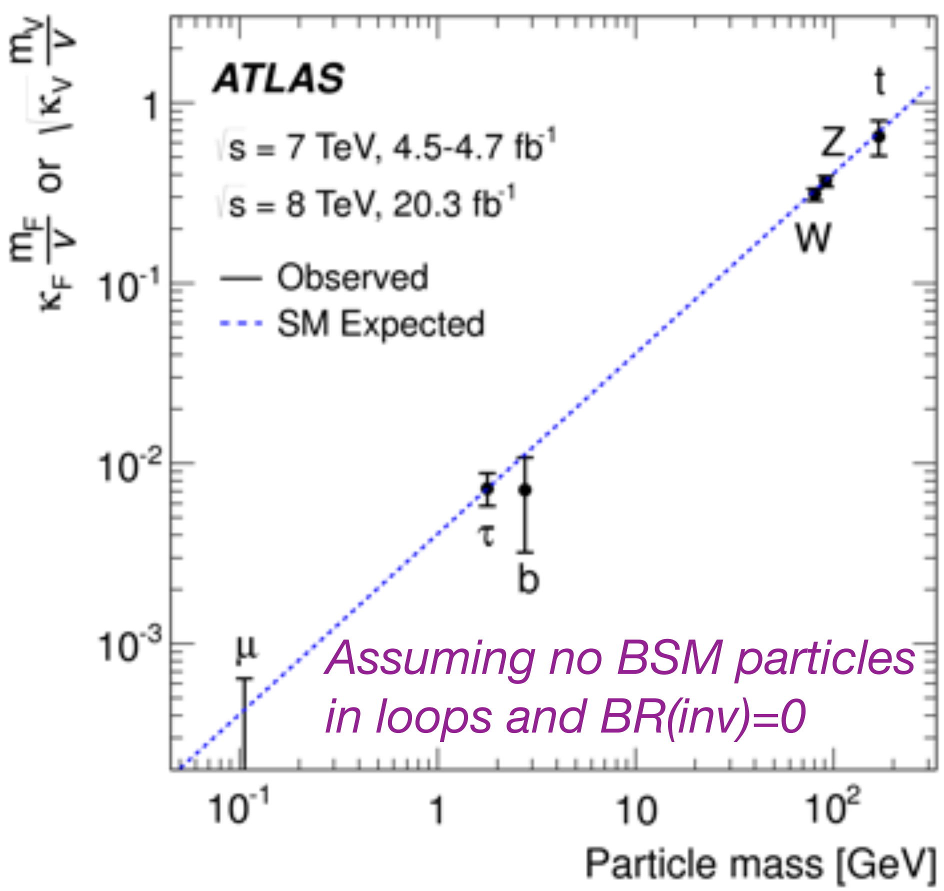
Production	Loops	Interference	Expression in fundamental coupling-strength scale factors
$\sigma(\mathrm{ggF})$	✓	b–t	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\mathrm{VBF})$	-	-	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	-	-	$\sim \kappa_W^2$
$\sigma(q\bar{q} \to ZH)$	-	-	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	Z–t	$\kappa_{ggZH}^2 \sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(bbH)$	-	-	$\sim \kappa_b^2$
$\sigma(ttH)$	-	-	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	-	W–t	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq')$	-	W–t	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
Partial decay width			
$\Gamma_{b\bar{b}}$	-	-	$\sim \kappa_b^2$
Γ_{WW}	-	-	$\sim \kappa_W^2$
Γ_{ZZ}	-	-	$\sim \kappa_Z^2$
$\Gamma_{\tau\tau}$	-	-	$\sim \kappa_\tau^2$
$\Gamma_{\mu\mu}$	-	-	$\sim \kappa_\mu^2$
$\Gamma_{\gamma\gamma}$	✓	W–t	$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma_{Z\gamma}$	✓	W–t	$\kappa_{Z\gamma}^2 \sim 1.12 \cdot \kappa_W^2 + 0.00035 \cdot \kappa_t^2 - 0.12 \cdot \kappa_W \kappa_t$
Total decay width			
Γ_H	✓	$W-t$ $b-t$	$\kappa_H^2 \sim$ $0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2$

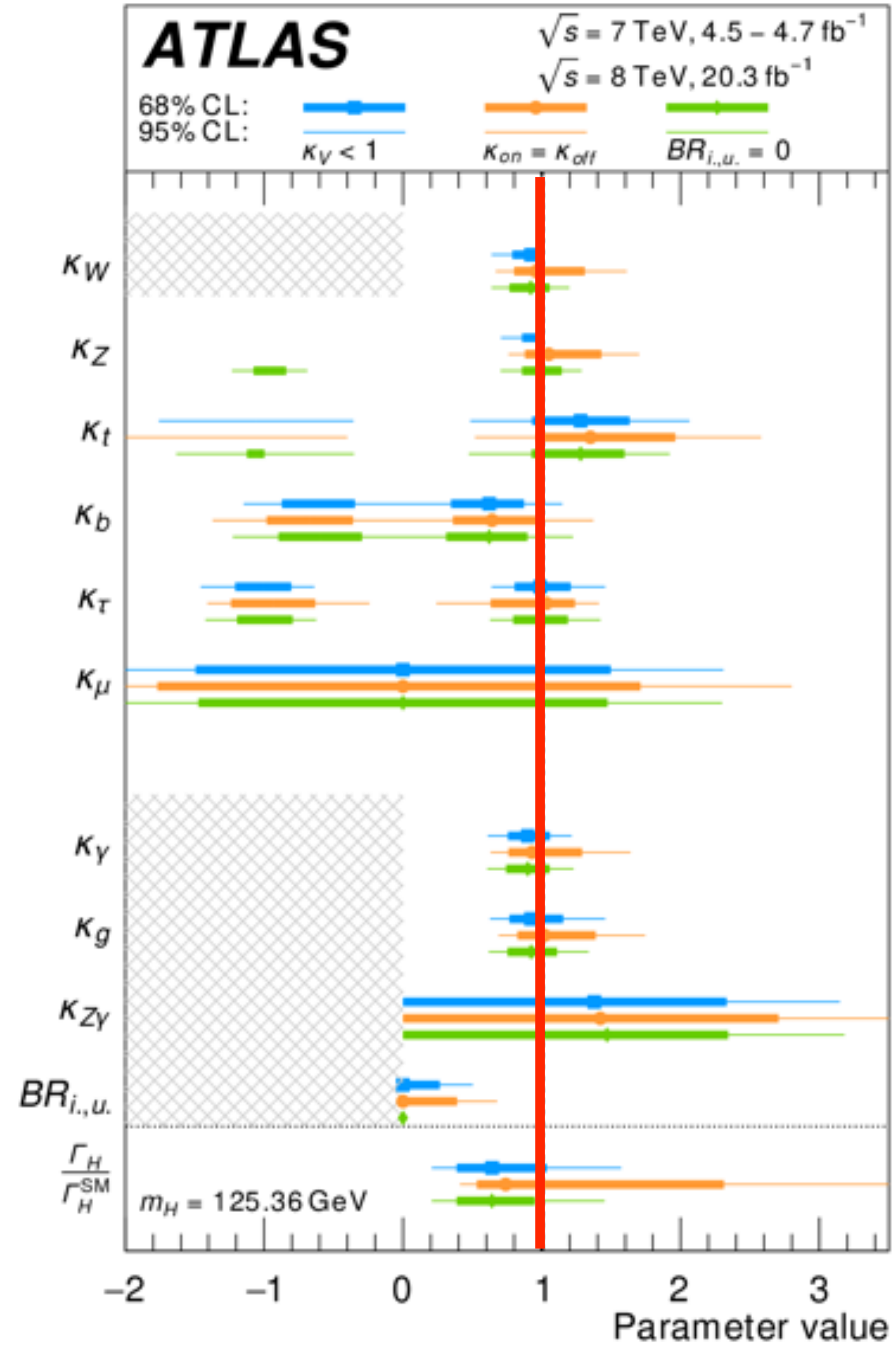
- Interference terms allows the determination of the sign of k_t, k_Z, k_b relative to k_W
- Negligible effect by approximating the xsections with inclusive expression (neglecting kinematic dependence of interference for ggF, gg→ZH), except for tH, explicitly modelled

arXiv:1507.04548

Many models explored

- Custodial Symmetry (k_W vs k_Z)
- Fermion vs vector-boson couplings (k_F vs k_V)
- Up-type vs down-type fermion couplings (k_d vs k_u)
- Quark vs lepton couplings (k_q vs k_ℓ)
- BSM contributions in loops and decays (k_g, k_γ, $k_{Z\gamma}$)
- Generic models w/ or w/o new particles in loops and assumptions on Γ_H





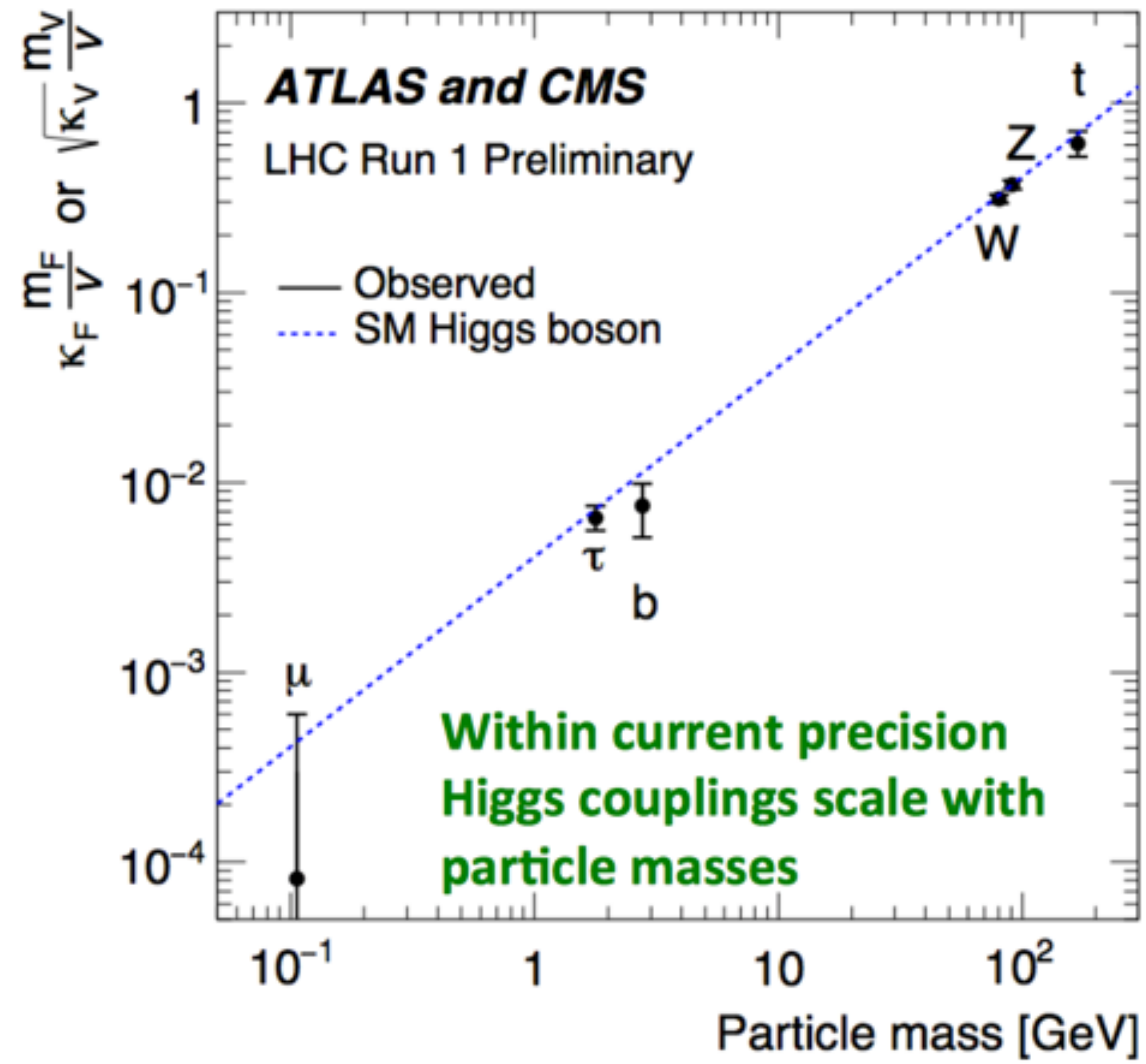
- All tested configurations consistent with SM
- Negative sign of k_t disfavoured

ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

New! ATLAS+CMS coupling combination

$\mu = 1.09^{+0.11}_{-0.10}$

Production process	Observed Significance(σ)	Expected Significance (σ)
VBF	**5.4**	**4.7**
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
H→ττ	**5.5**	**5.0**
H→bb	2.6	3.7



- VBF and H→ττ now established at over 5σ (like ggF and γγ, ZZ*, WW*)
- couplings measured to: ~10% (W,Z); 14% (t,τ); 21% (b)
  - assuming no BSM particles in loops and BR(inv)=0

Total width and off-shell couplings from H→ZZ,WW

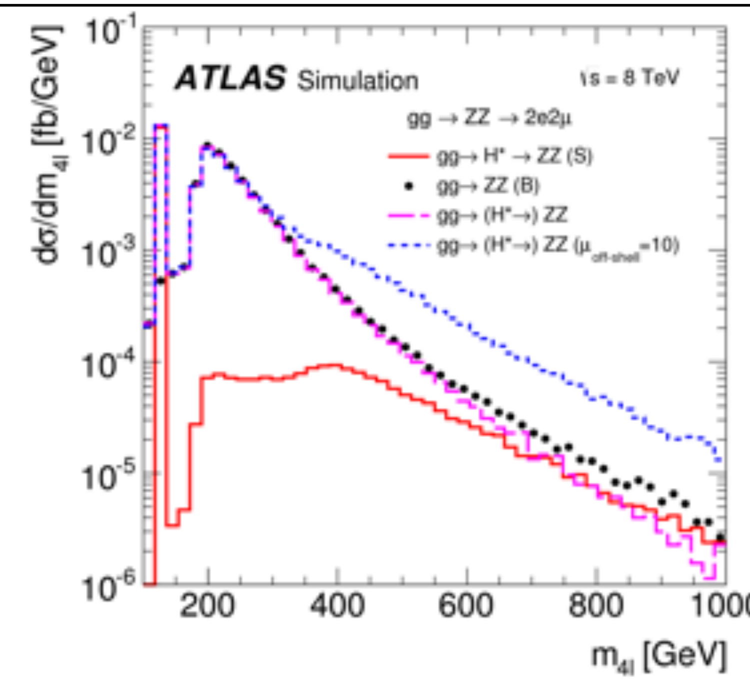
- Γ_H=4.12 MeV in SM for m_H=125.36 GeV, could be increased by BSM contributions
- Direct determination from width of $m_{\gamma\gamma}$ and $m_{4\ell}$ peaks limited by detector resolution (1-2 GeV) being deconvoluted *Phys. Rev. D90 (2014) 052004*

decay	95% C.L. observed (expected) upper limit on Γ_H from direct method
$\gamma\gamma$	<5.0 (4.2) GeV
4ℓ	<2.6 (3.5) GeV

- Indirect constraint from ratio between off-shell / on-shell strengths

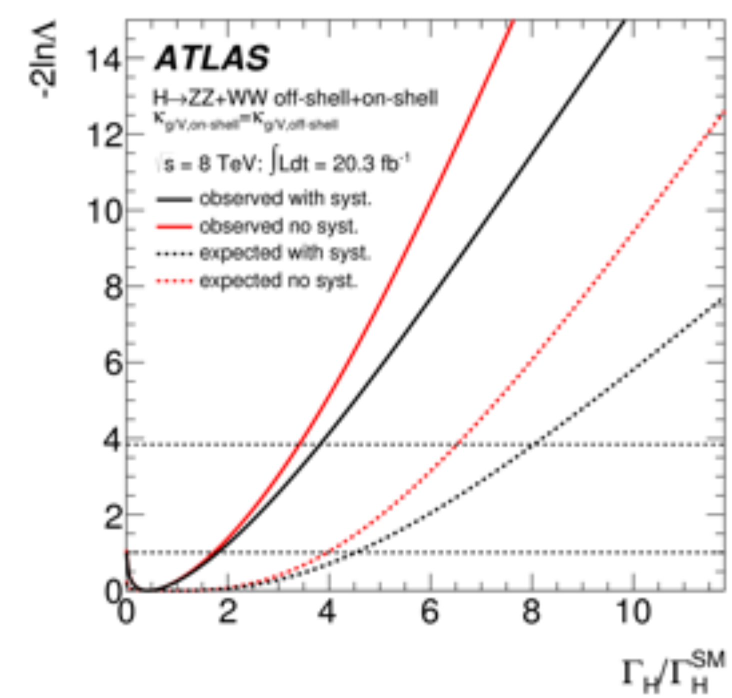
$$\frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s}) \qquad \frac{\sigma^{gg\to H\to VV}_{\text{on-shell}}}{\sigma^{gg\to H\to VV}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$

  - sizeable off-shell x-section at high mass (>200 GeV)
  - measure with WW ($e\nu\mu\nu$), ZZ (4ℓ, $2\ell2\nu$) events @ large m_{VV} after accounting for interference with VV bkg



decay	95% C.L. observed (expected) upper limit on Γ_H from indirect method
$WW^{(*)}+ZZ^{(*)}$	<22.7 (33.0) MeV

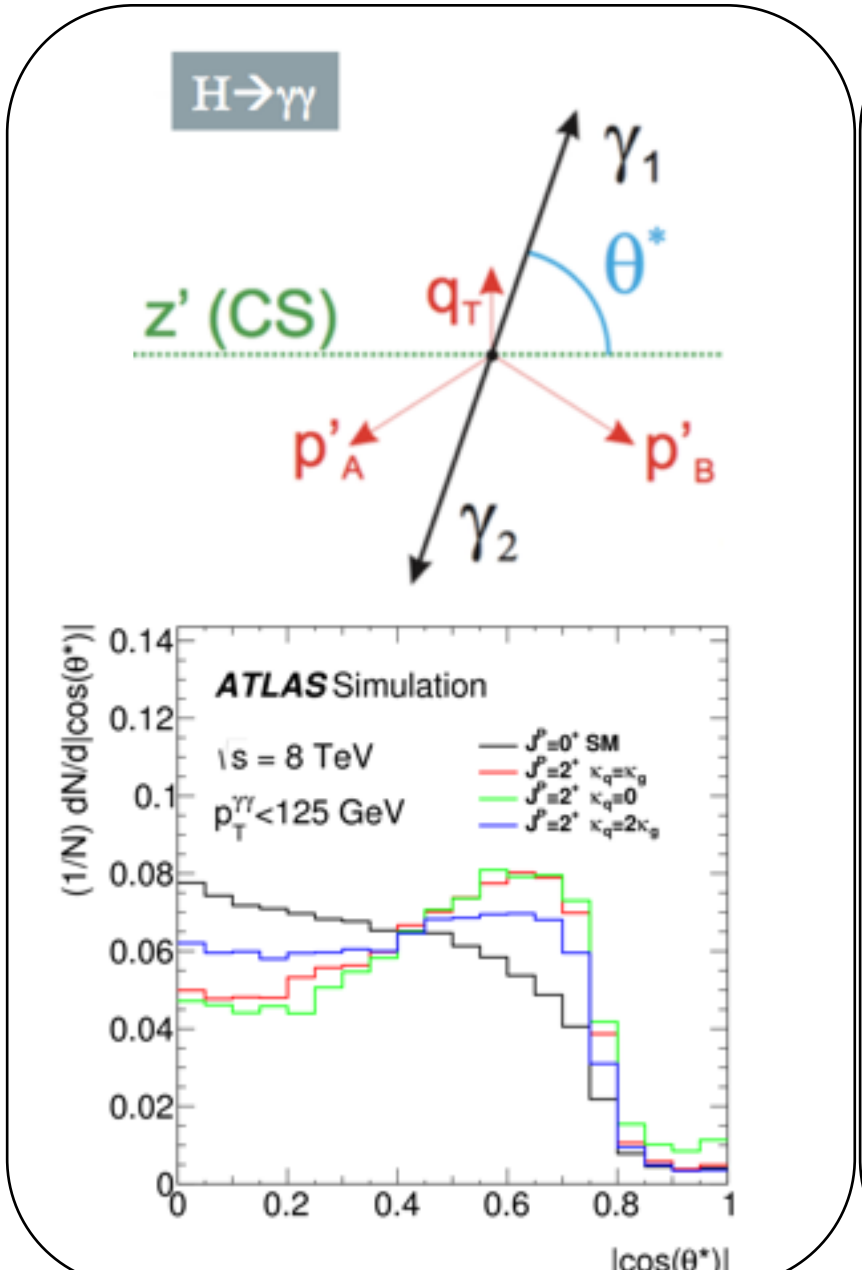
Eur. Phys. J. C 75 (2015) 335

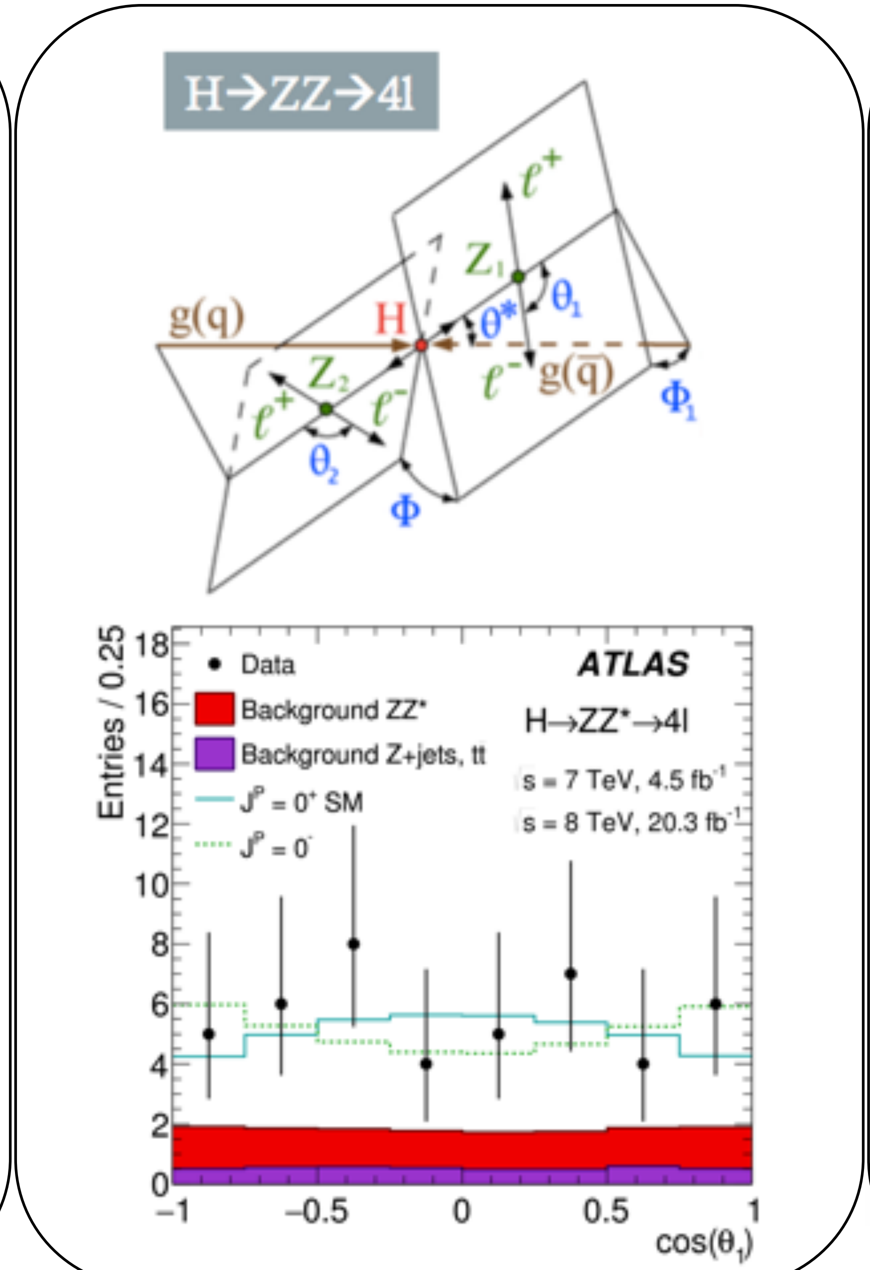


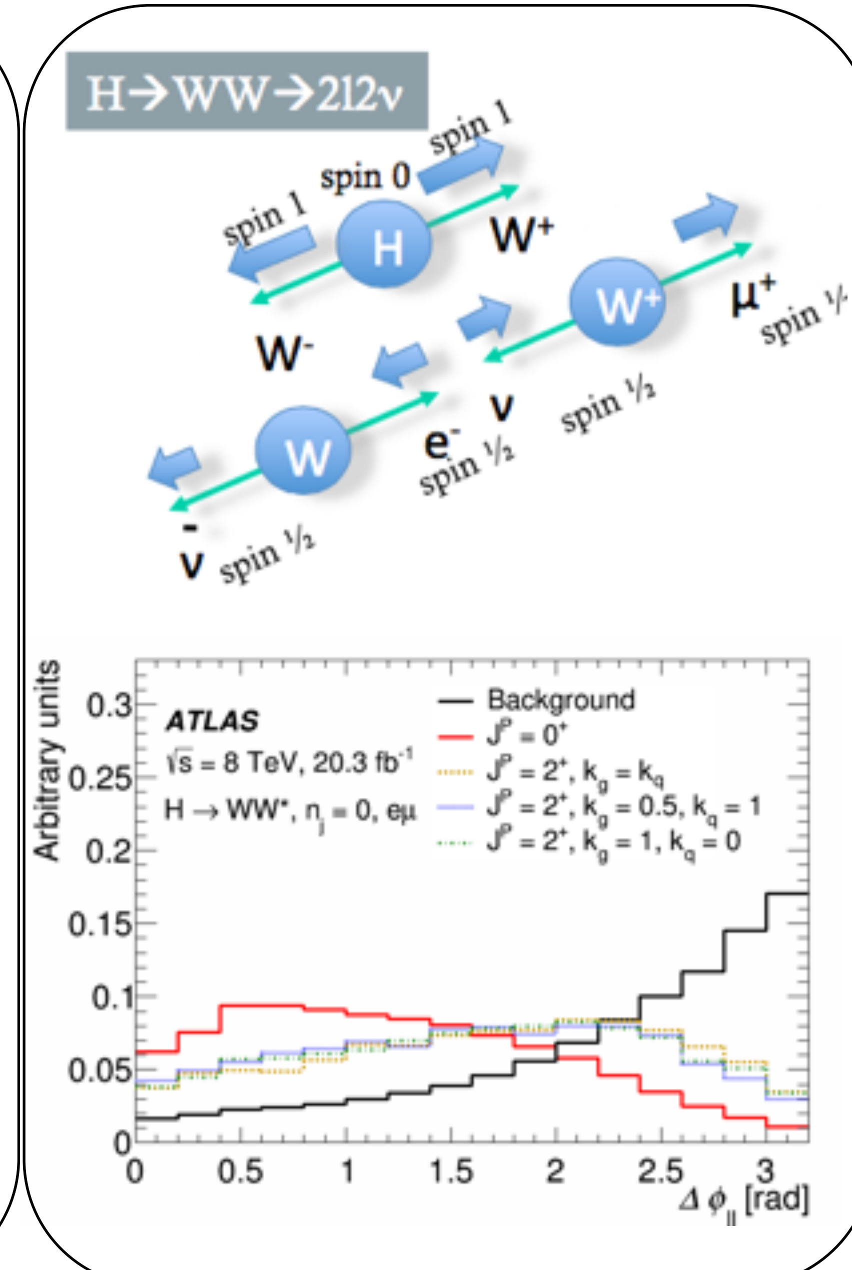
CAVEAT: neglect dependence on $\hat{s}$ and assume
- same off-shell/on-shell couplings
- background not affected by new physics affecting k_{off}
- no sizeable kinematic modifications to off-shell signal or new signals in search region
- ratio of k-factors for gg→VV (unknown) and gg→H*→VV (calculated) in 0.5—2.0
- ZZ/WW xsection ratio as in SM for both on-shell and off-shell (for combination)

Spin and parity in H→diboson decays

- Kinematic distributions of production and decay are sensitive to J^P
  - $\gamma\gamma$: $p_T^{\gamma\gamma}$ and photon production angle (sensitive to spin only)
  - $ZZ^* \to 4\ell$: production and decay angles
  - $WW^* \to e\nu\mu\nu$: $m_{\ell\ell}$, $p_T^{\ell\ell}$, $\Delta\phi_{\ell\ell}$, m_T







Spin and parity in H→diboson decays

- SM (0^+) tested against alternative hypotheses w/ EFT approach
  - pure 0^-
  - pure (BSM) 0^+ with anomalous couplings to vector bosons
  - pure 2^+ with universal or non-universal couplings to quarks and gluons
  - mixture of 0^+ (SM-like) and 0^+,0^- (BSM)
- Assumptions:
  - single resonance with m~125 GeV, narrow width, negligible interference with background
  - any other BSM particle has m>1 TeV
- Hypotheses discriminated based on ratio

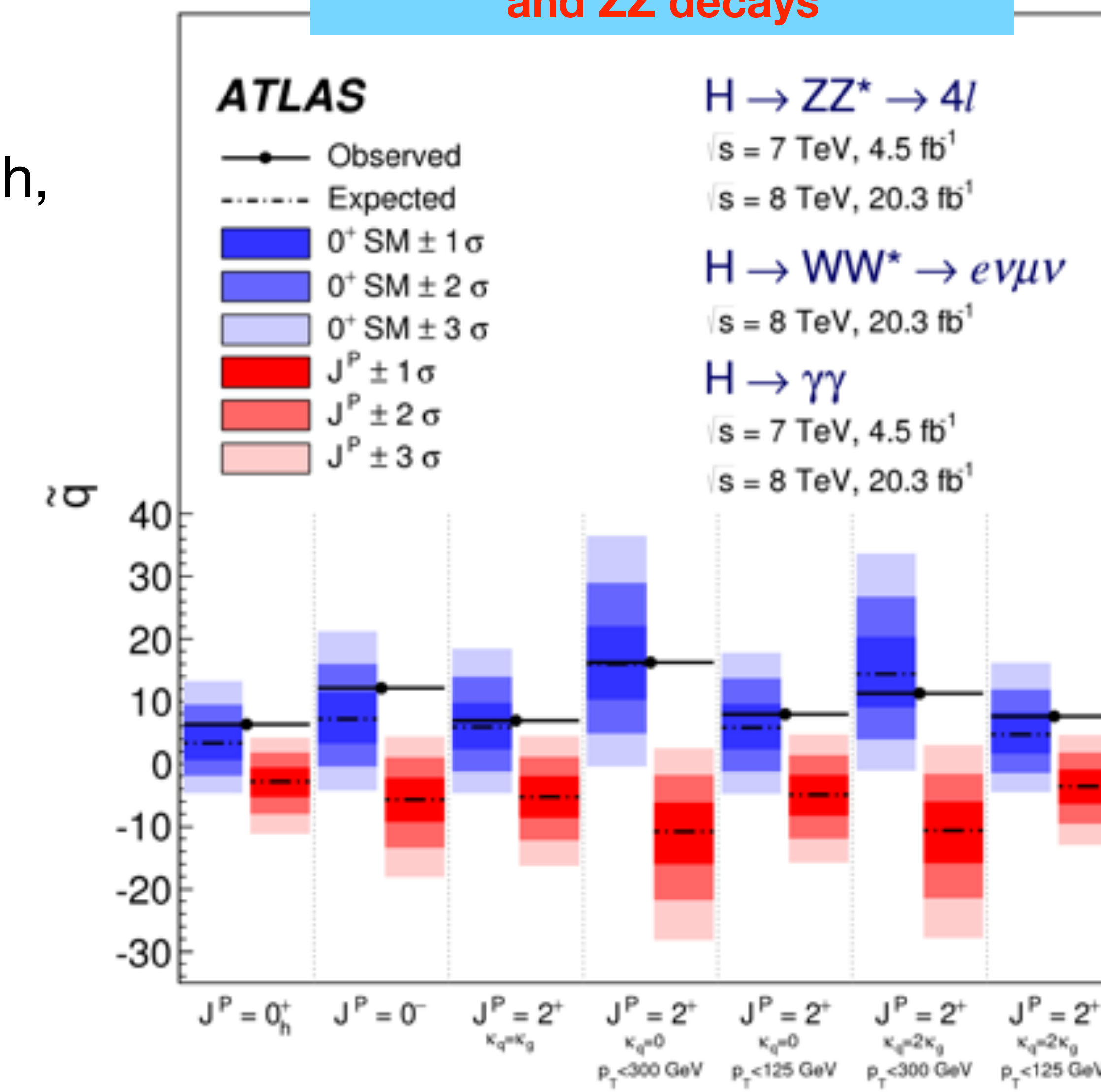
$$\tilde{q} = \log \frac{\mathcal{L}(J^P_{\rm SM}, \hat{\hat{\mu}}_{J^P_{\rm SM}}, \hat{\hat{\theta}}_{J^P_{\rm SM}})}{\mathcal{L}(J^P_{\rm alt}, \hat{\hat{\mu}}_{J^P_{\rm alt}}, \hat{\hat{\theta}}_{J^P_{\rm alt}})}$$

- Alternative hypotheses excluded based on

$$\mathrm{CL_s}(J^P_{\rm alt}) = \frac{p(J^P_{\rm alt})}{1 - p(J^P_{\rm SM})}$$

- All alternative hypotheses rejected at >99.9% CL

J=1 excluded by observation of H→γγ (Landau-Yang theorem) and previous studies of WW and ZZ decays

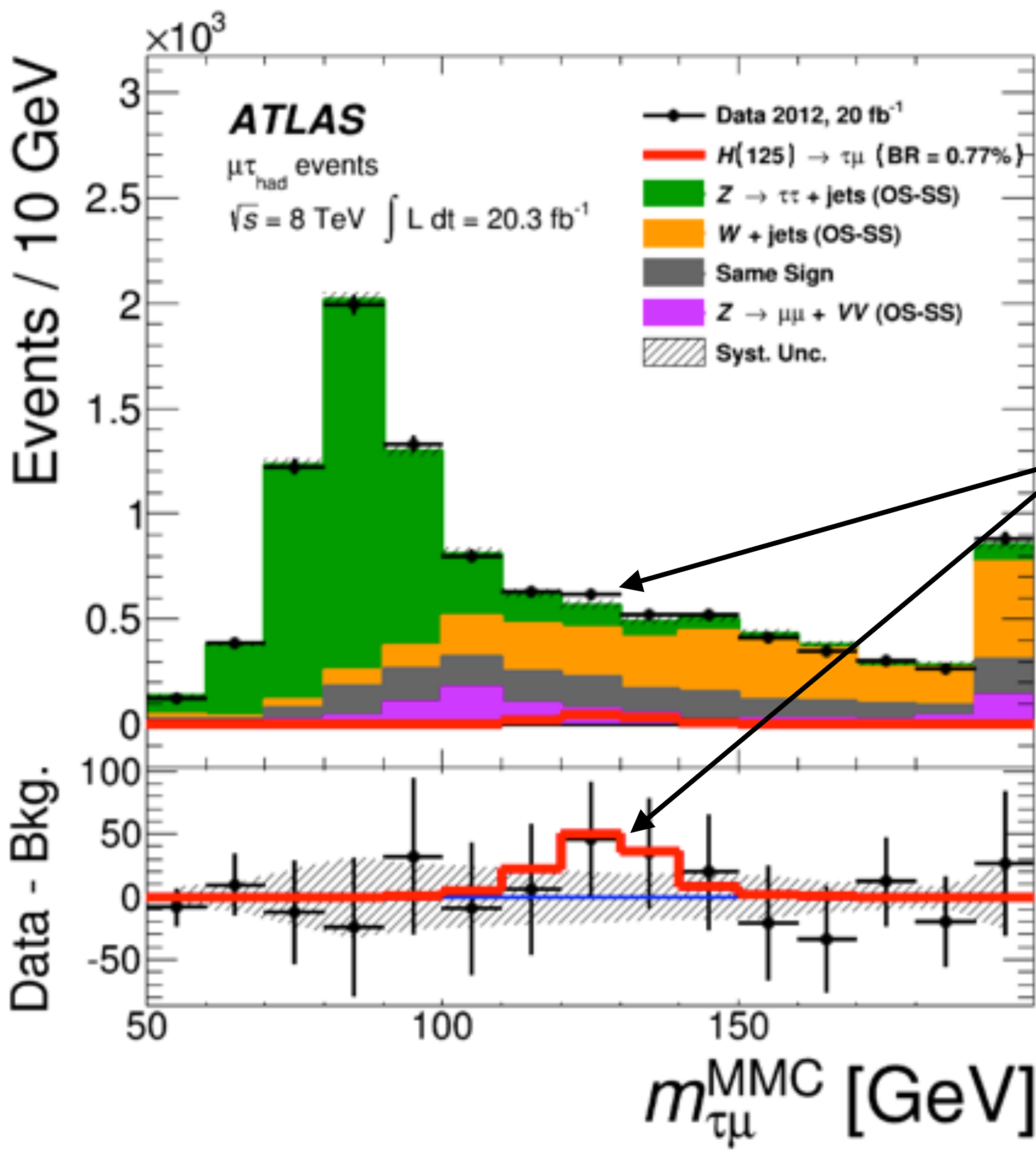


BSM Higgs boson searches

- So far the discovered Higgs boson look like the SM one, but:
  - the level of precision which we know the Higgs sector is still limited
  - the SM cannot be the ultimate theory
- Beyond-SM theories predict a richer Higgs boson sector (more final states accessible or more Higgs bosons) ⇒ Higgs boson searches as portal to BSM
  - Exotic decays of H_{125}
    - lepton flavour violating decays
    - invisible decays
    - decays to $J/\psi\gamma$ and $\Upsilon\gamma$
    - decays to "dark" gauge bosons ($H \to ZZ_D \to 4\ell$)
  - Additional low/high-mass Higgs bosons
    - pseudoscalar A boson decaying to ZH_{125}
    - scalar boson decaying to ZZ
    - scalar boson decaying to diphotons
    - charged Higgs bosons decaying to WZ and $\tau\nu$

Lepton Flavor Violating decays: $H\to\tau\mu$

- Not allowed in the SM
- CMS observes a 2.5σ excess in 8 TeV data in $H\to\tau\mu$
- Indirect constraints by LFV μ,τ decays: $BR(H\to\mu e)<O(10^{-8})$; $BR(H\to\tau\mu, H\to\tau e)<10\%$



- 1.3σ excess in 8 TeV data
- $BR(H\to\tau\mu) = (0.77\pm0.62)\%$
  - BR<1.85% at 95% C.L.

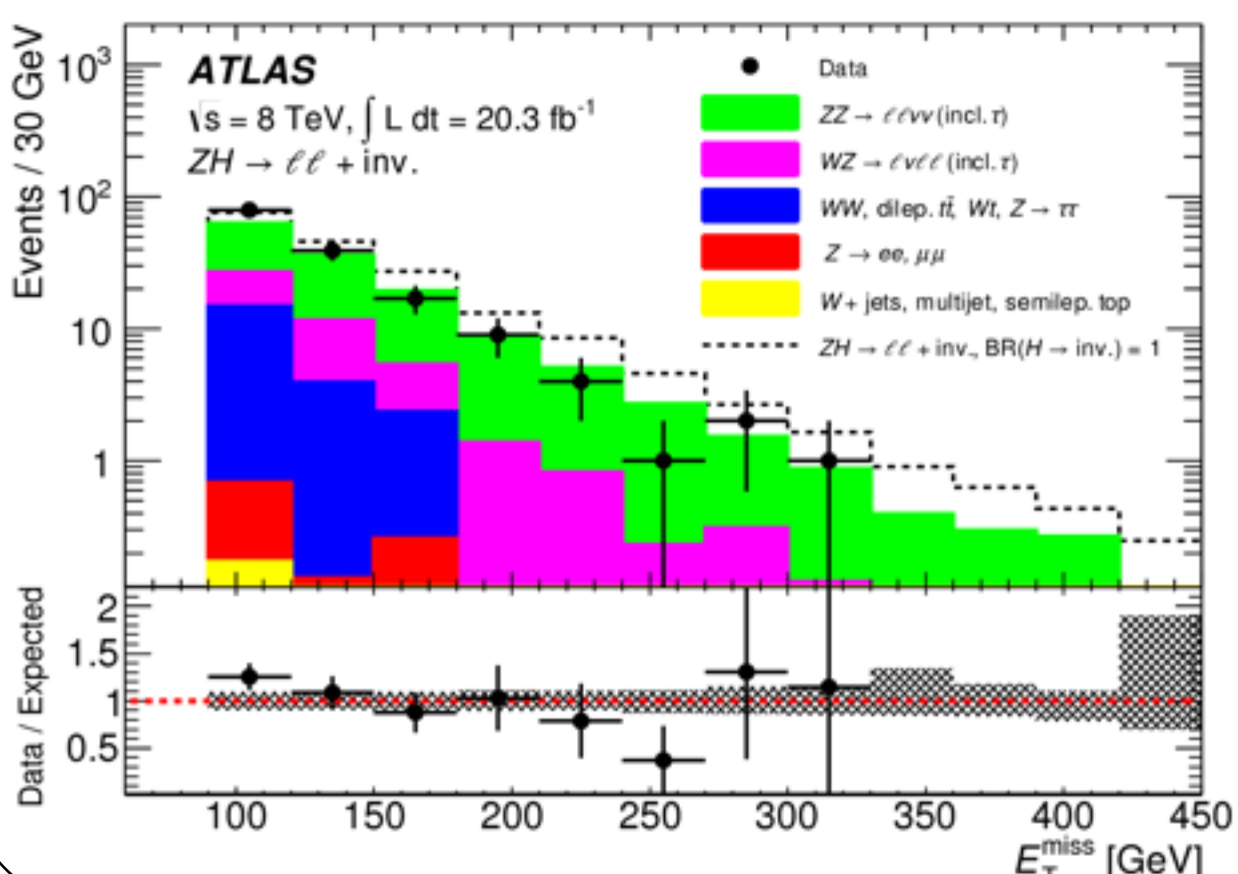
Phys. Rev. Lett. 112 (2014) 201802
Eur. Phys. J. C75 (2015) 337

Invisible decays: VH, H→invisible, V→ℓℓ or qq'

- BR(H→ZZ*→νν)<0.1% in SM; BR(inv.) enhanced if H coupled to BSM WIMPs
- Final states: E_T^{miss} + 2 leptons or 2 jets, m_{12}~$m_{W,Z}$
- No excess in E_T^{miss} distributions ⇒ 95% CL limits:

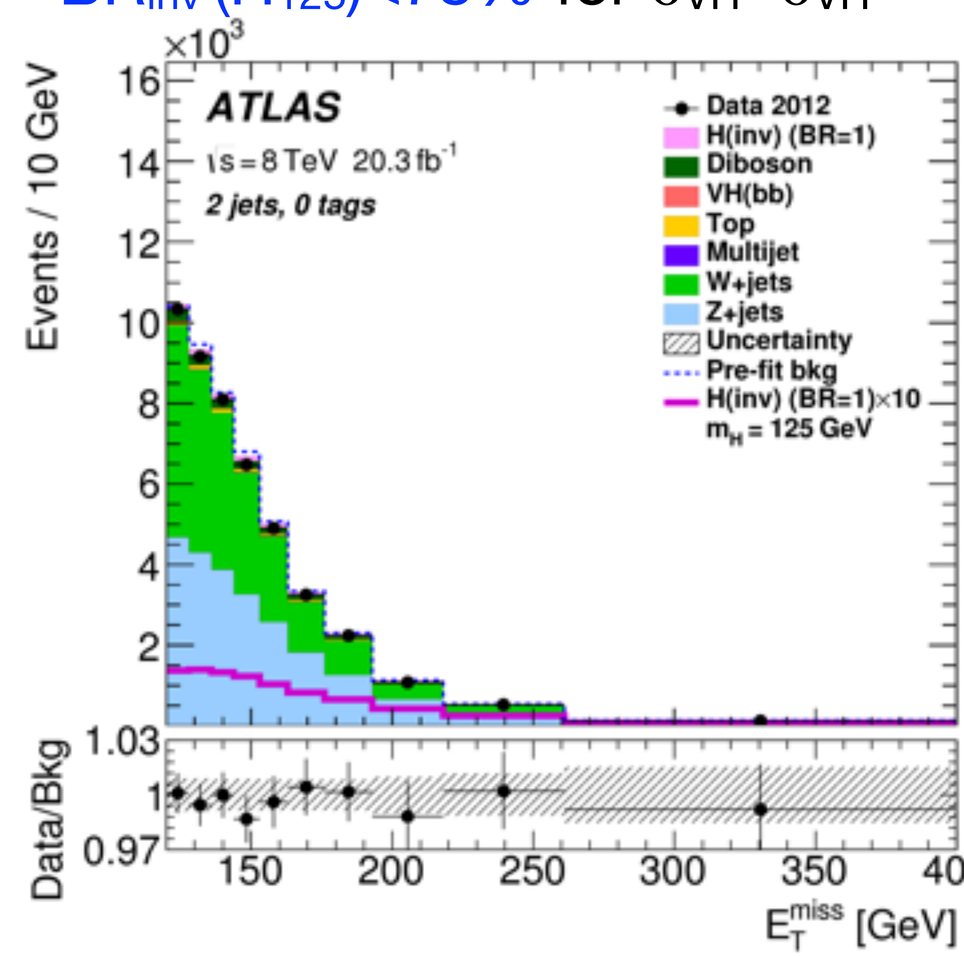
ℓℓ:

- σ_{ZH}*BR_{inv}<0.03–0.4 pb (m_H=110–400 GeV)
- BR_{inv} (H_{125})<75% for $\sigma_{ZH}=\sigma_{ZH}^{SM}$



qq (assuming σ_{WH}/σ_{ZH} as in SM):

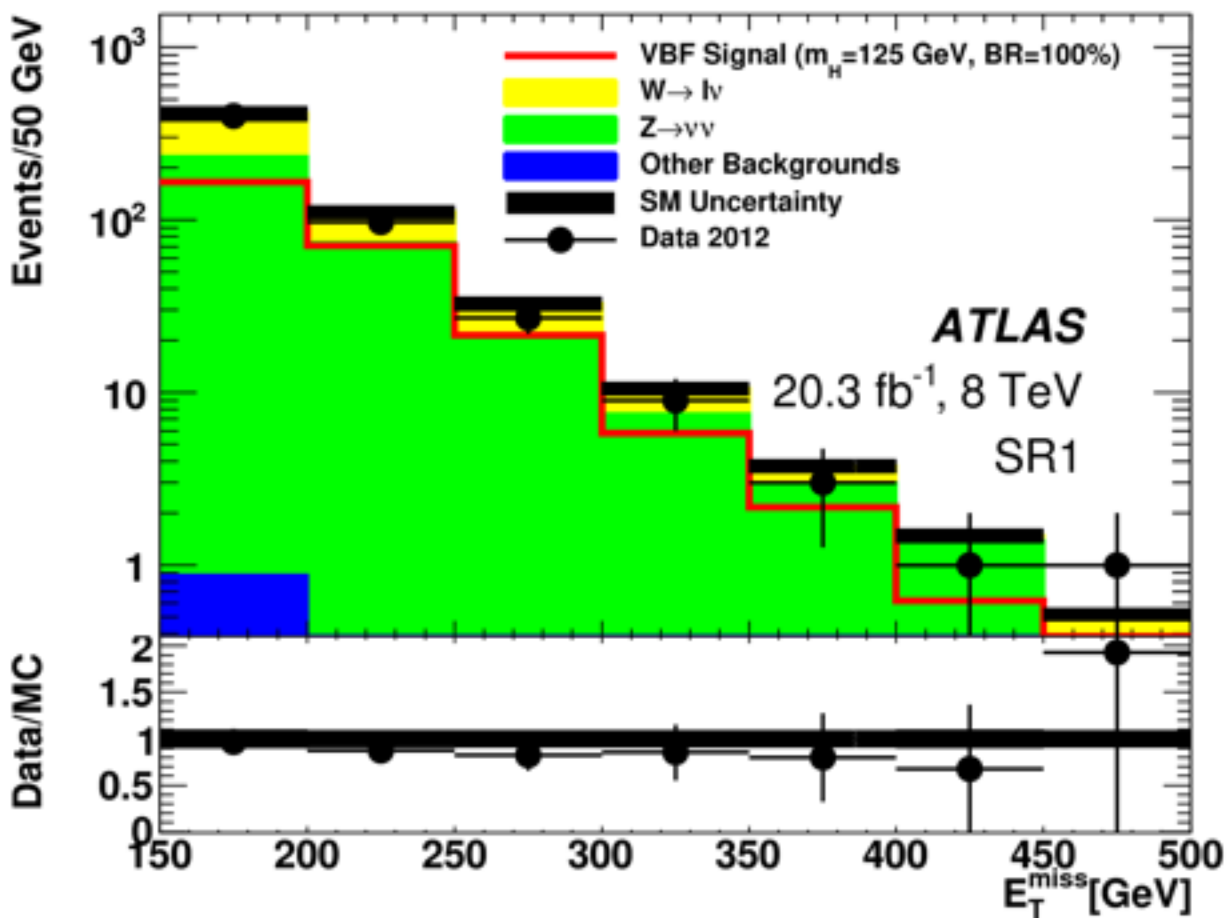
- σ_{VH}*BR_{inv}<0.13–1.6 pb (m_H=115–300 GeV)
- BR_{inv} (H_{125})<78% for $\sigma_{VH}=\sigma_{VH}^{SM}$



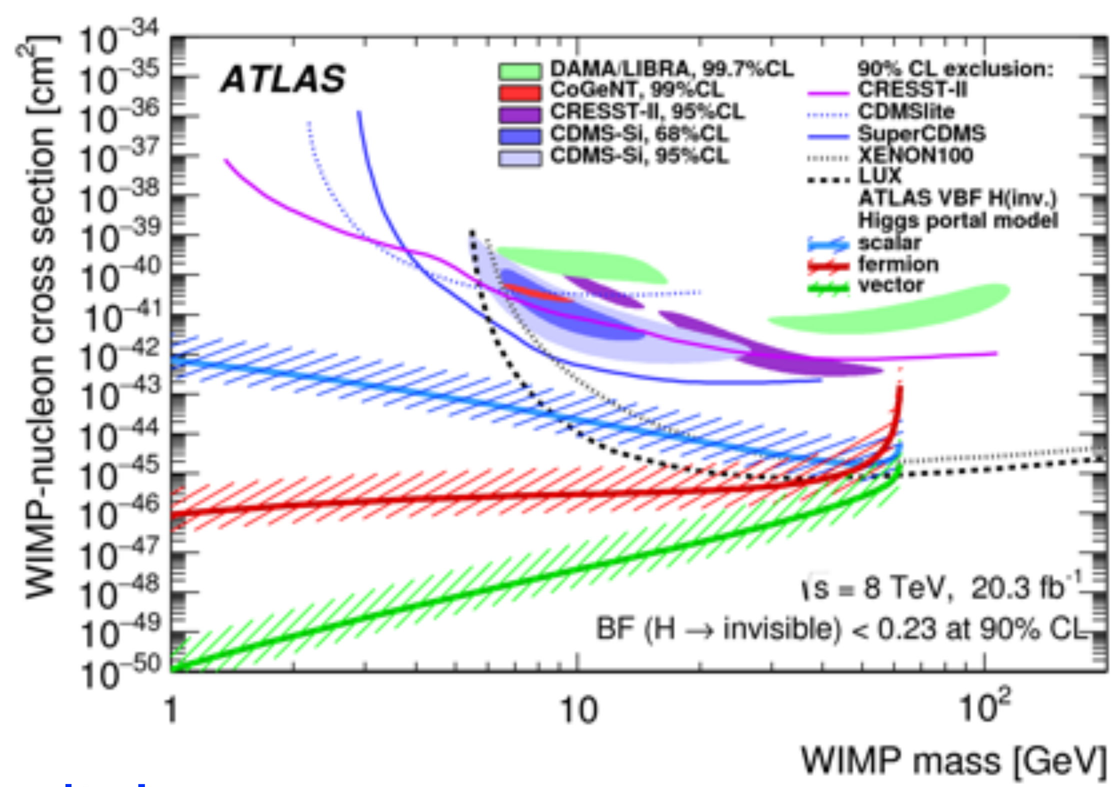
arXiv:1508.07869
arXiv:1509.00672

Invisible decays in VBF (and ggF+2jets)

- Final states: E_T^{miss} + 2 VBF-tagged jets
- No excess in E_T^{miss} distribution
  - $BR_{inv}(H_{125})<28\%$ assuming SM for ggF and VBF x-sections, acceptance*efficiency ⇒ better than global coupling analysis!



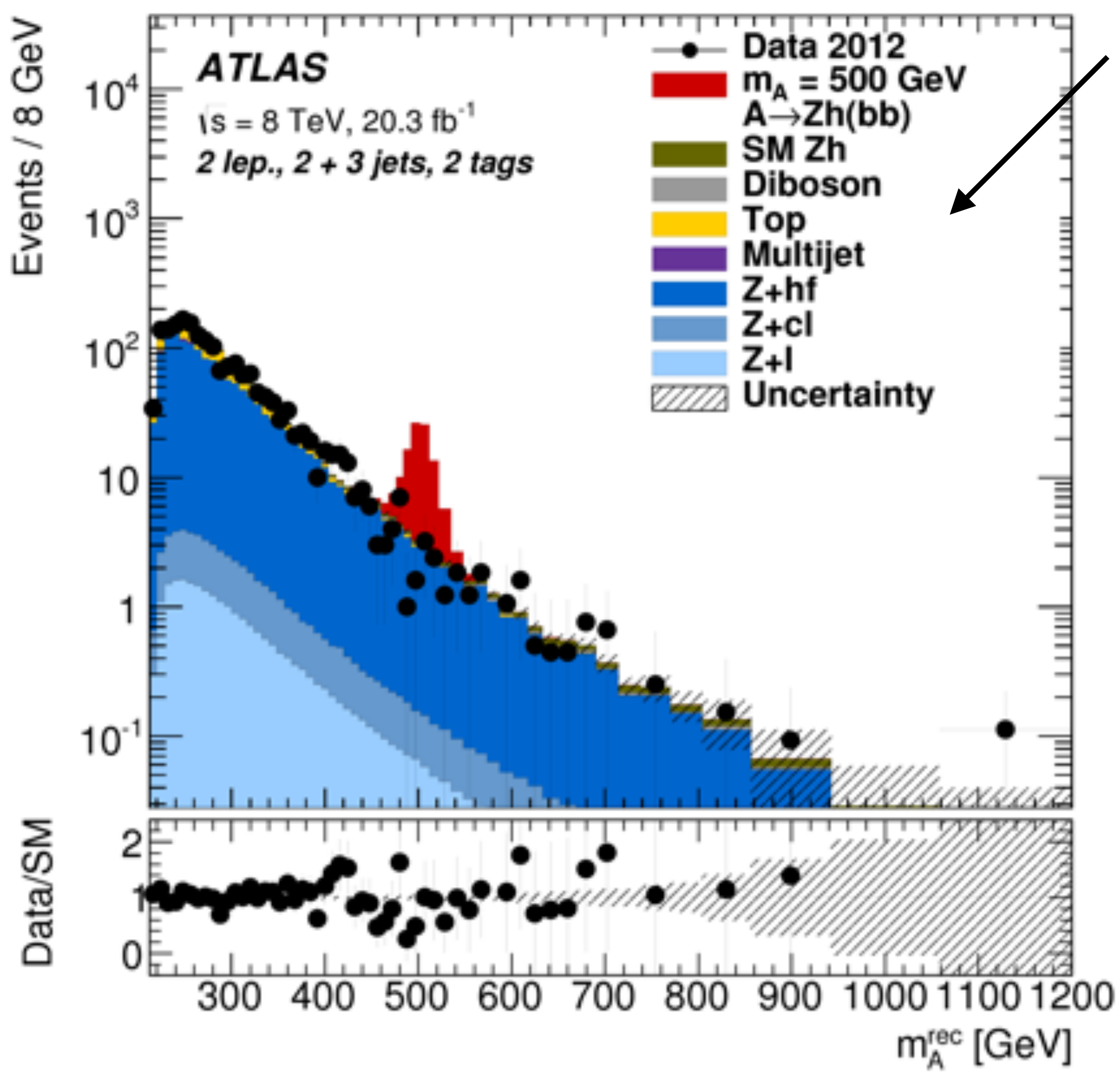
- also translated into limits on WIMP-nucleon cross section in Higgs portal models



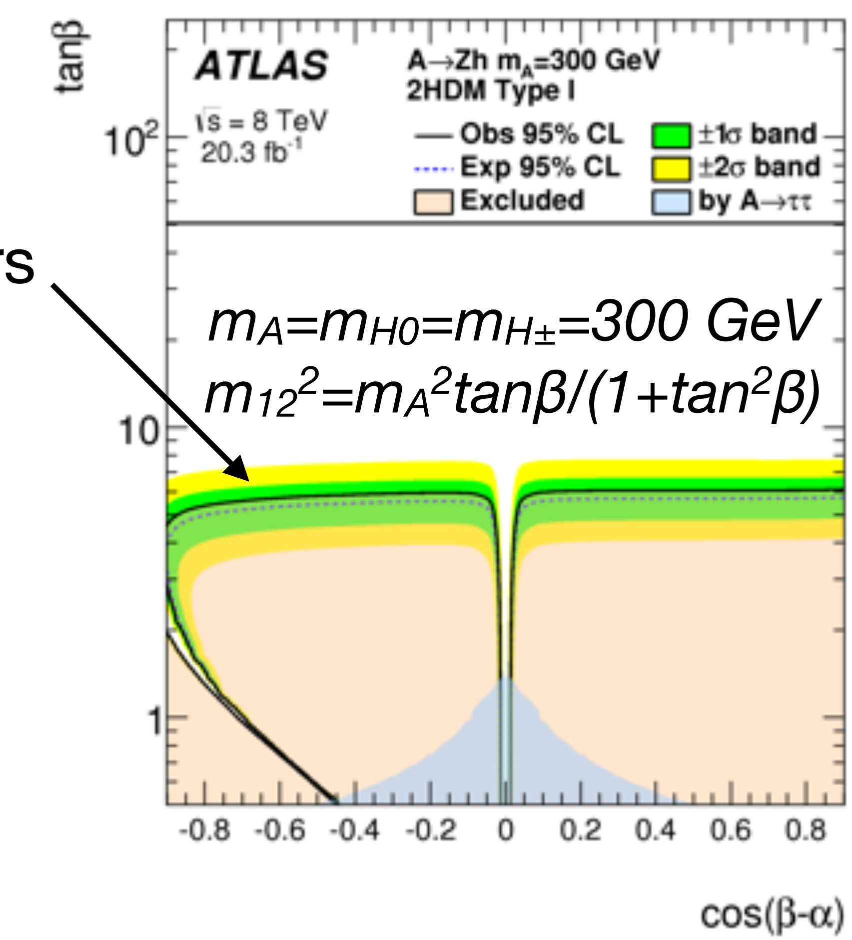
- $BR_{inv}<23\%$ combining VBF and VH results!

Pseudoscalar Higgs boson $A \to ZH_{125}$, $H_{125} \to \tau\tau$, bb

- A^0 ($J^P=0^-$) appears in many models with extended Higgs sector like 2HDM
- Reconstructed final states: $\ell\ell\tau\tau$, $\ell\ell$bb, $\nu\nu$bb
- Search for narrow resonance (Γ_A/m_A<few %) for 220<m_A<1000 GeV
- Improve invariant mass resolution (~few %) by constraining $m_{\ell\ell}=m_Z$, $m_{bb}=m_H$
- Similar to SM Higgs boson searches with additional cuts on m_{bb}, $m_{\tau\tau}$ and p_T^Z

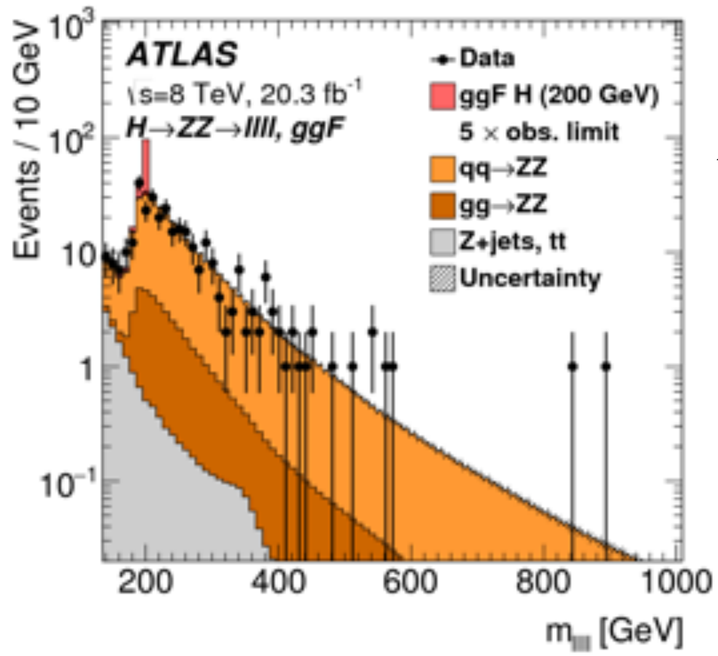


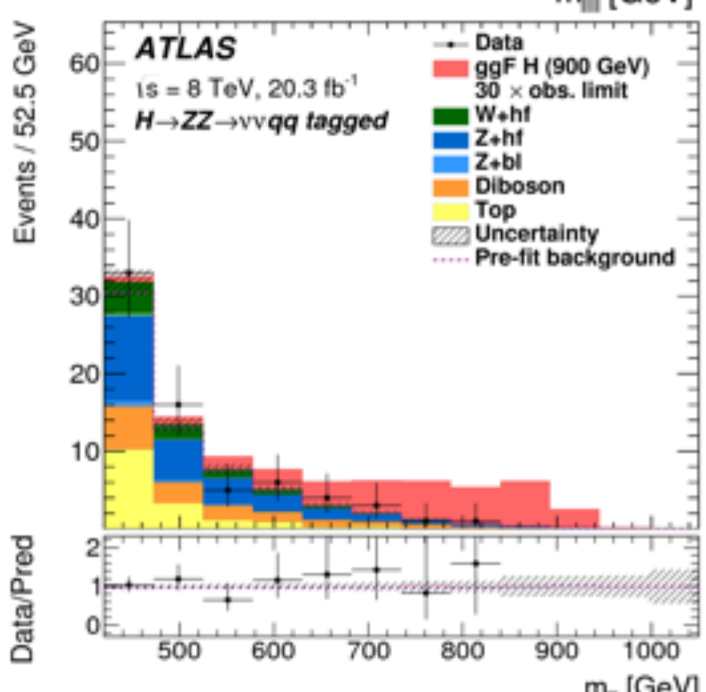
- No excess in data, upper limits @ 95% CL:
  - $\sigma(pp\to A)$*BR($A\to ZH$)*BR($H\to\tau\tau$)<0.098–0.013 pb
  - $\sigma(pp\to A)$*BR($A\to ZH$)*BR($H\to bb$)<0.57–0.014 pb
- also combined and translated into limits on 2HDM parameters



Heavy neutral Higgs boson $H\to ZZ\to 4\ell$, $2\ell 2\nu$, $2\ell 2q$, $2\nu 2q$

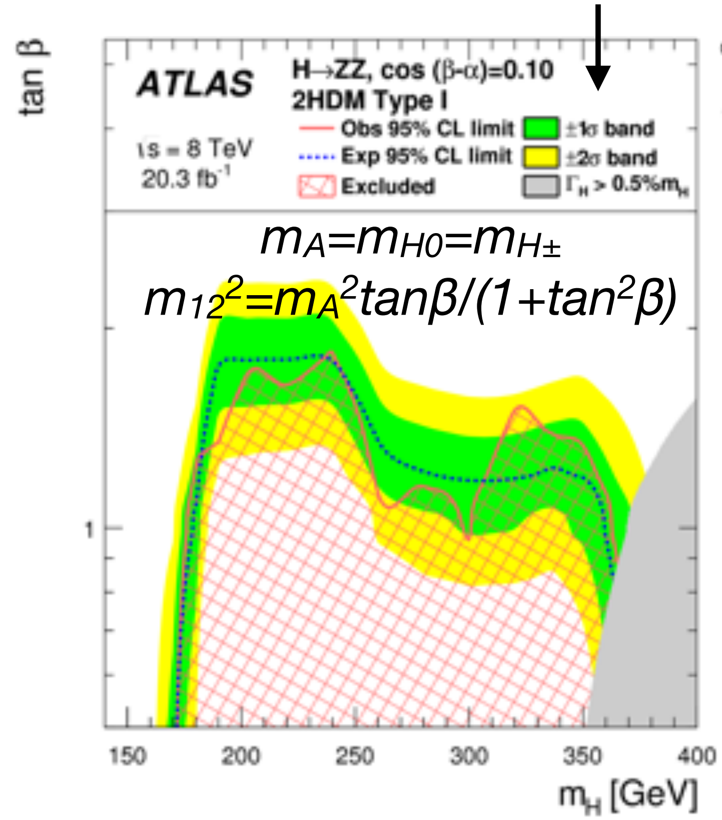
- Search narrow resonance, 140<m<1000 GeV, produced in ggF, VBF (all) or VH (4ℓ)
- No assumption on ratios of production cross sections ⟹ separate limits
- Similar selection to SM Higgs boson searches, but include H_{125} (+ off-shell production and interference with continuum) as additional bkg

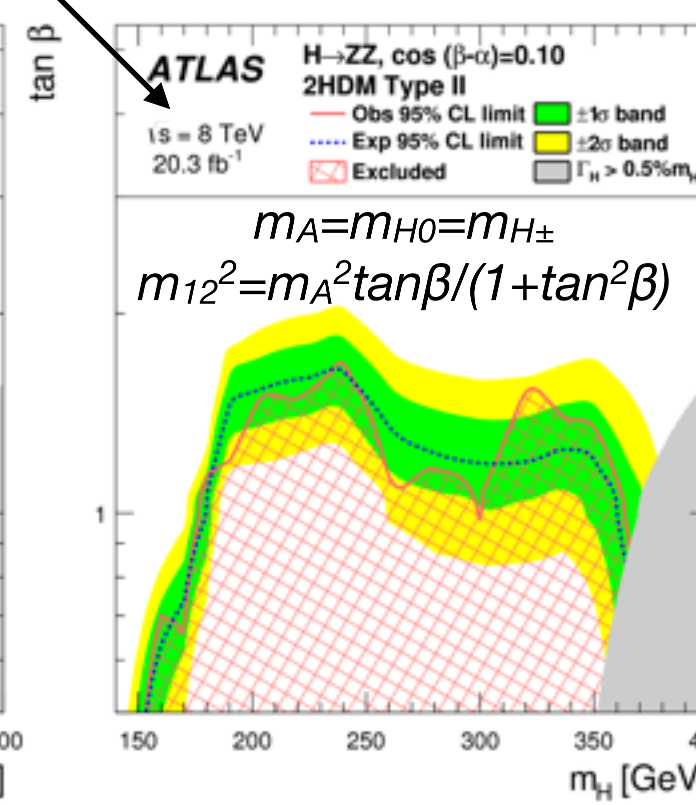




- No excess in data: @ 95 CL σ_{ggF}<0.008—0.53 pb, σ_{VBF}<0.009—0.31 pb

- also combined and translated into limits on 2HDM parameters



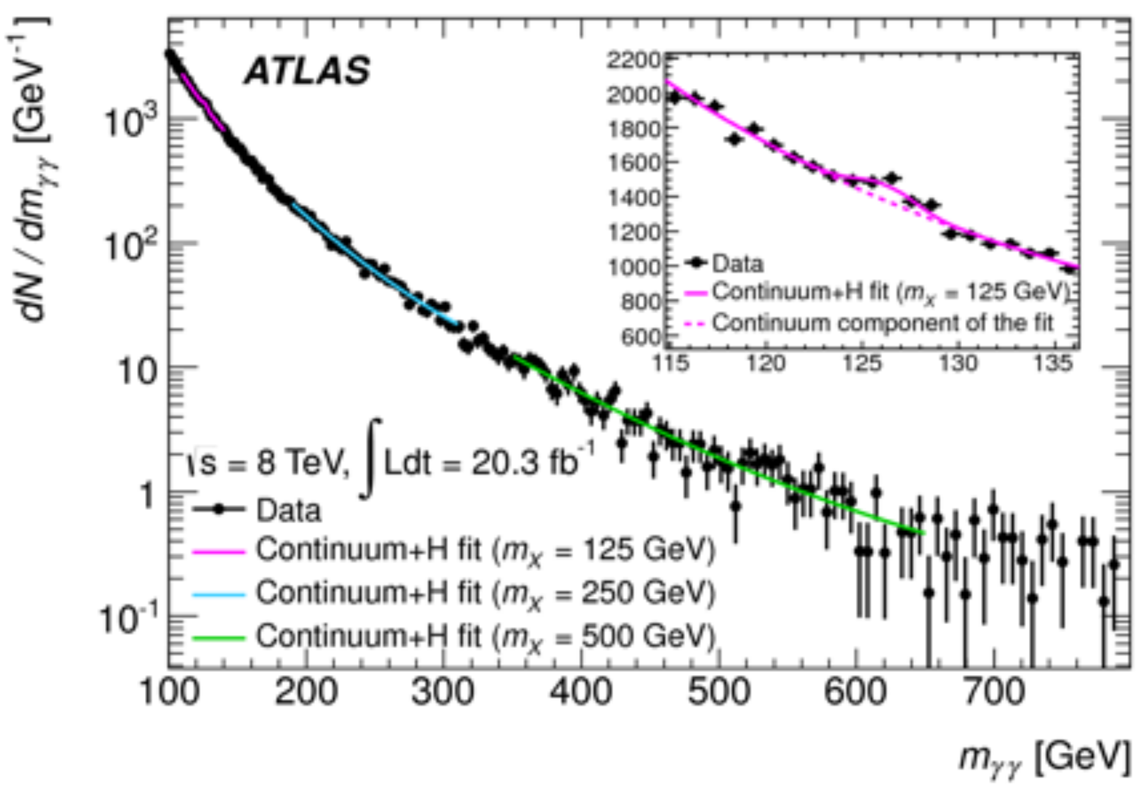


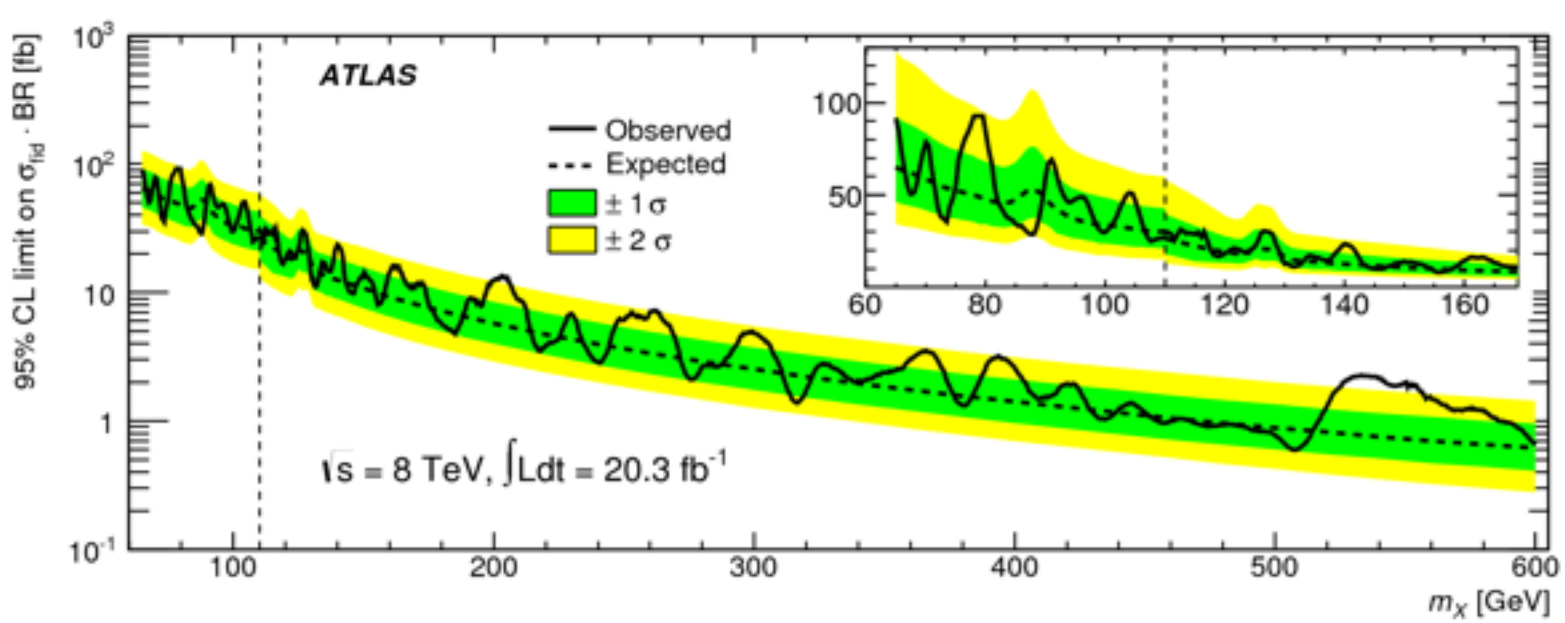
$m_A=m_{H0}=m_{H\pm}$

$m_{12}^2=m_A^2\tan\beta/(1+\tan^2\beta)$

Low/high-mass scalar di-photon resonances

- Search for narrow di-photon resonance, 65<m<600 GeV in fiducial region where reconstruction efficiency ~independent of event topology
- Similar selection to SM Higgs boson search, but include H_{125} as additional bkg
- Interference with background neglected
- At low-mass, contribution from Drell-Yan included ($Z \to ee$ data + $e \to \gamma$ MC corrections)
- No excess in data, σ<1—90 fb @ 95% CL

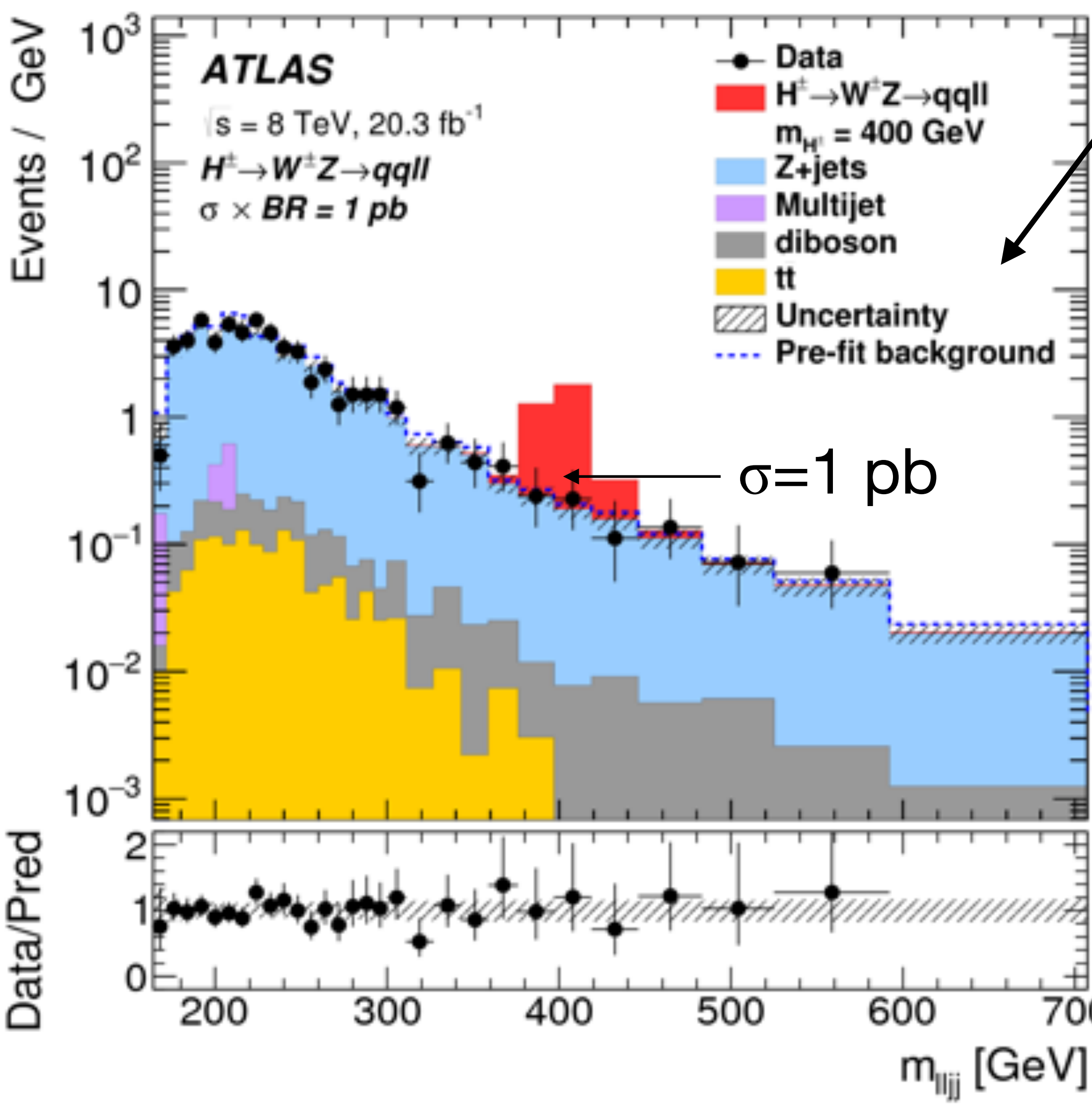




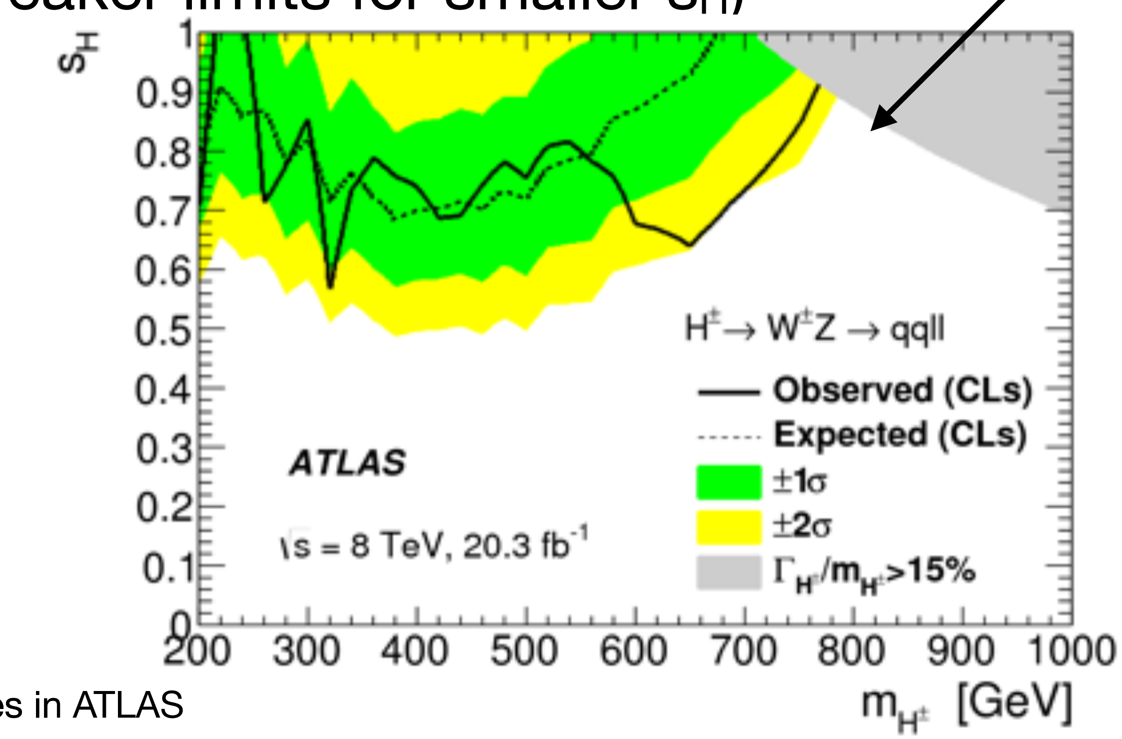
Phys. Rev. Lett. 114, 231801 (2015)

Charged Higgs bosons: VBF $H^{\pm} \to WZ \to qq\ell\ell$

- $H^{\pm}$ appears in models with extended Higgs sector (additional doublets, triplets ..)
- Search for $H^{\pm}$ coupled to W and Z: VBF production followed by $H^{\pm} \to WZ$ decay
- Final state: VBF jets + $jj\ell\ell$ (σ_m/m~2.4%) from $W \to qq$, $Z \to \ell\ell$
- Assume narrow width, 200<m<1000 GeV



- No excess in data
  - σ<31-1020 fb @ 95% CL
- also translated into limits on Higgs triplet model (s_H^2 = fraction of m_V^2 generated by vev of triplet)
  - 240<m_H<700 GeV excluded for s_H=1 (weaker limits for smaller s_H)

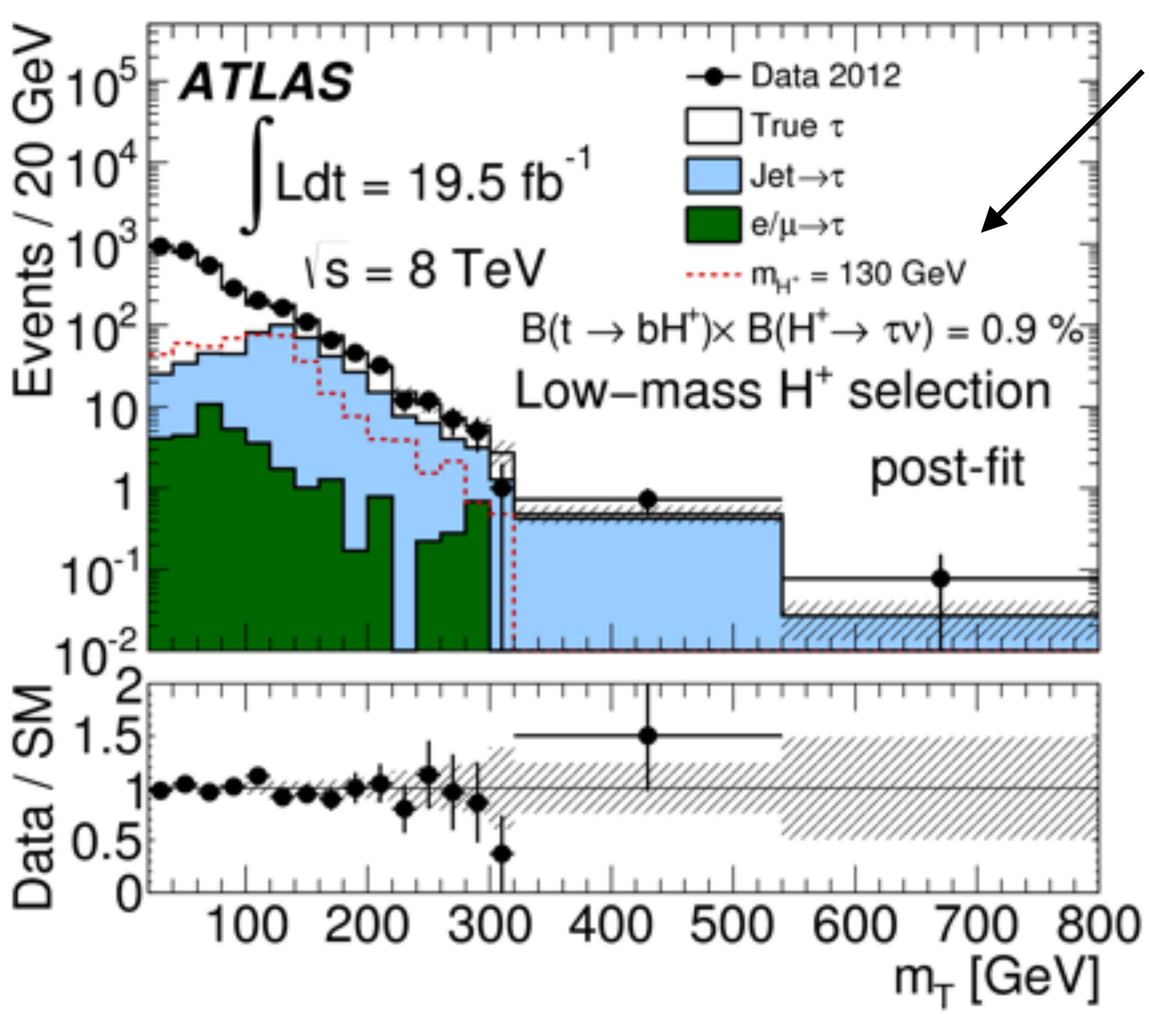


JHEP 03 (2015) 088

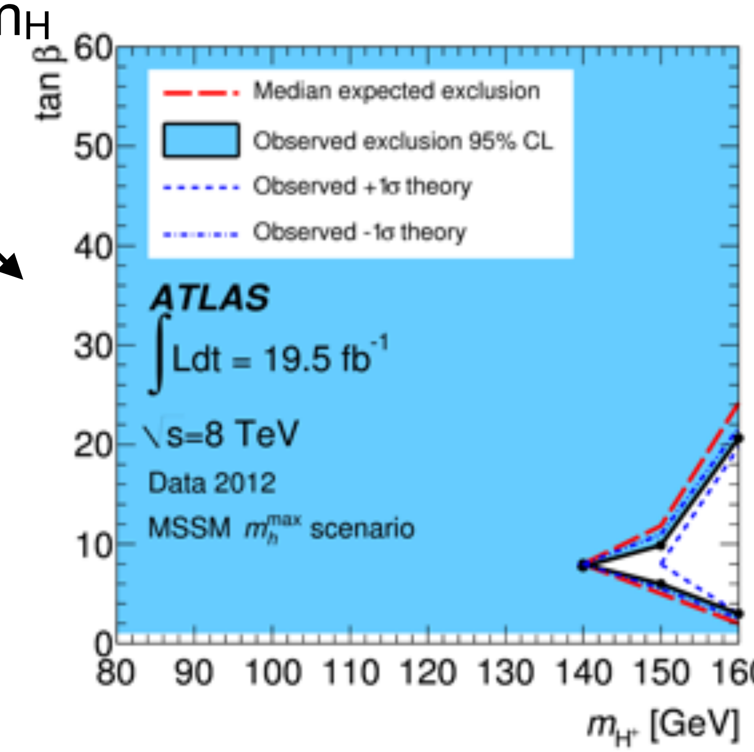
Charged Higgs bosons: $H^{\pm}\to\tau^{\pm}\nu$

- Search for narrow $H^{\pm}$ coupled to fermions: decaying to $\tau^{\pm}\nu$ and produced either in
  - top decays in ttbar events ($pp\to tt\to HbWb$) $\Rightarrow$ low-mass: $80<m_H<160$ GeV
  - association with top ($pp\to tHX\to WbHX$) $\Rightarrow$ high-mass: $180<m_H<1000$ GeV

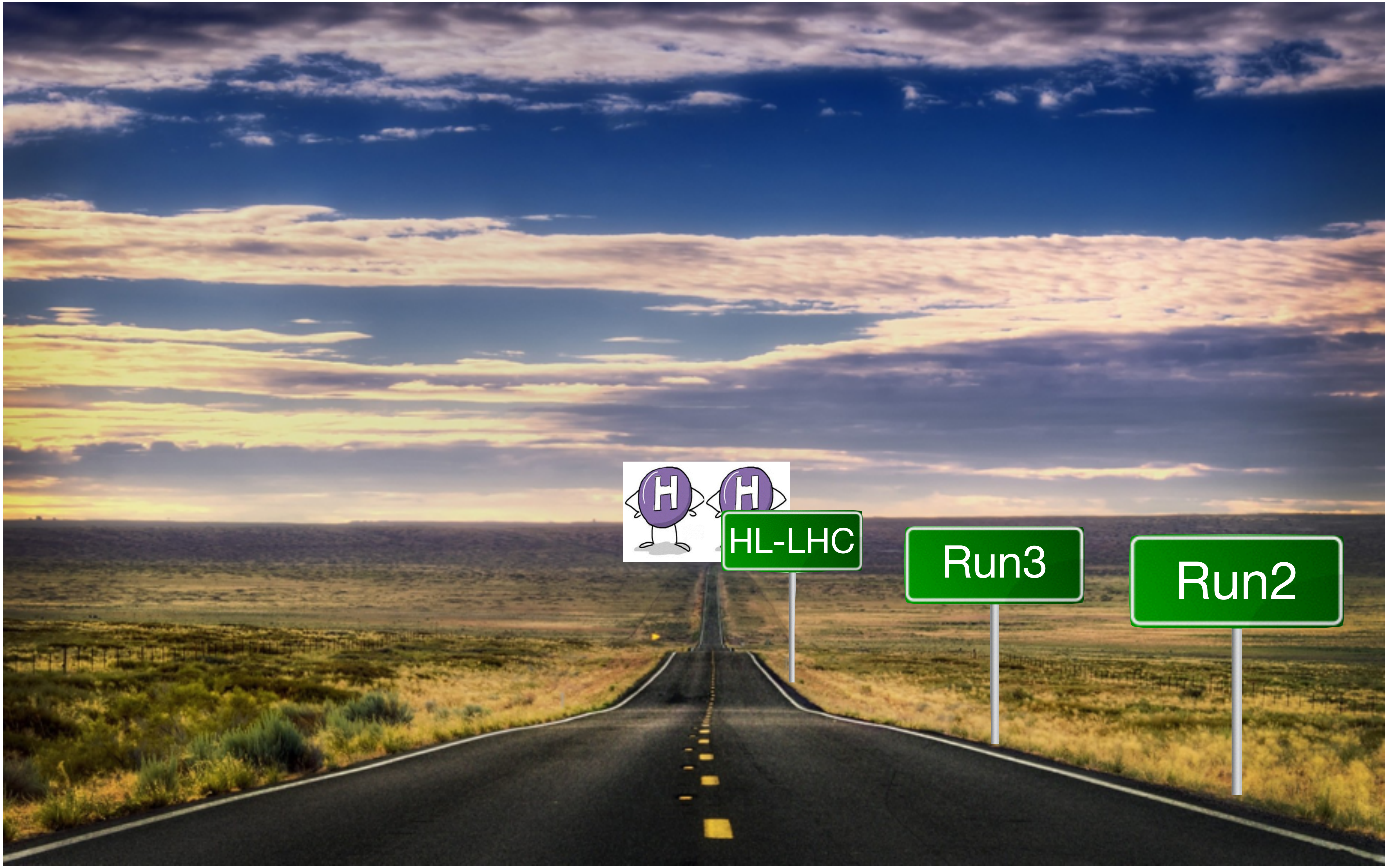
  (main production modes of $H^{\pm}$ in type-II 2HDM like MSSM)
- Final state: a hadronic τ decay, E_T^{miss}, b-jets, a hadronic W decay, no isolated ℓ



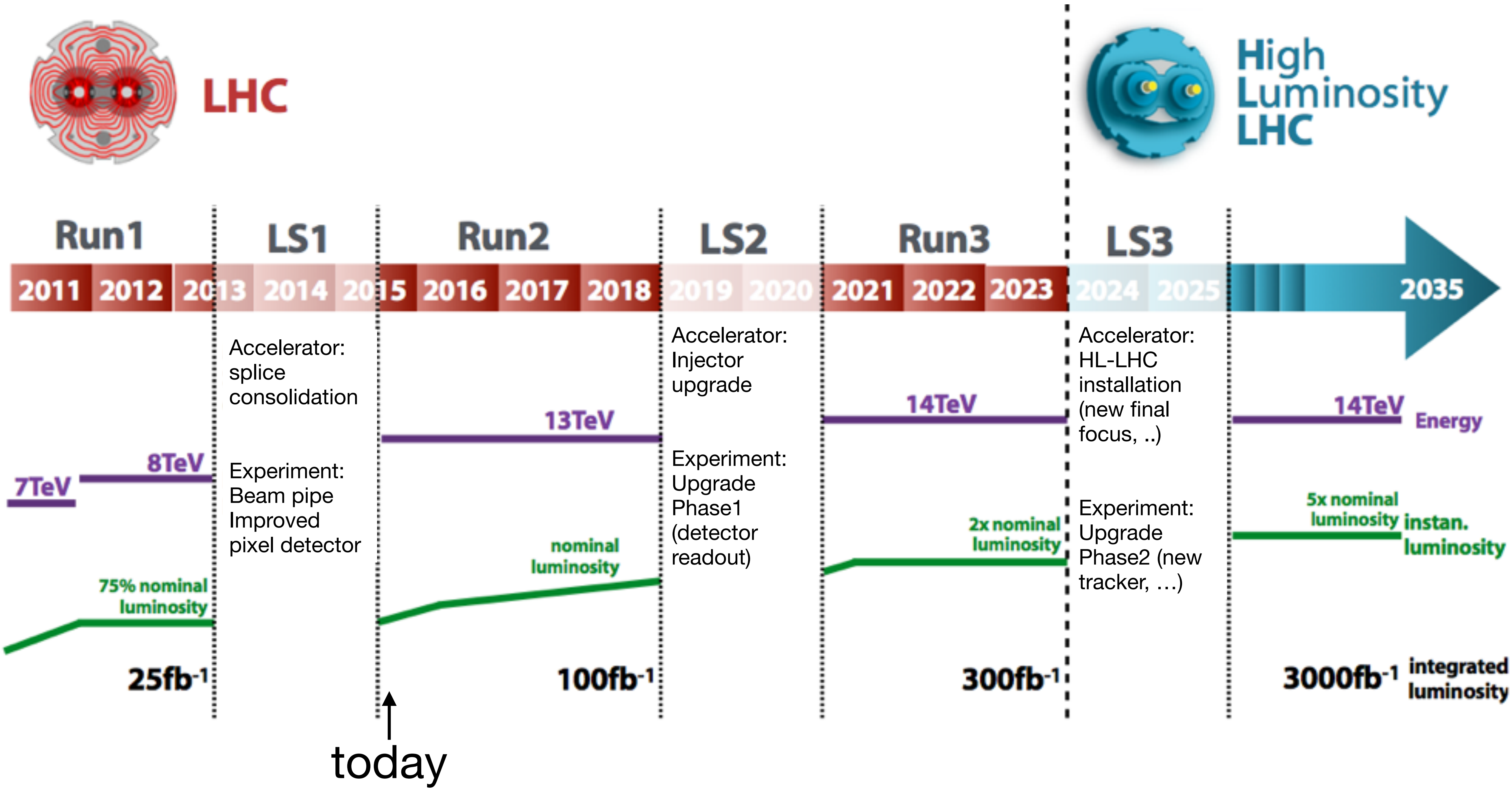
- No excess in data, upper limits @ 95% CL:
  - Low m_H: $BR(t\to bH)*BR(H\to\tau\nu)<0.23\%-1.3\%$
  - High m_H: $\sigma(pp\to tHX)*BR(H\to\tau\nu)<0.76pb-4.5fb$
- also translated into limits on MSSM parameters
  - e.g. $\tan\beta>1$ ~completely excluded in 3 benchmark scenarios for low m_H



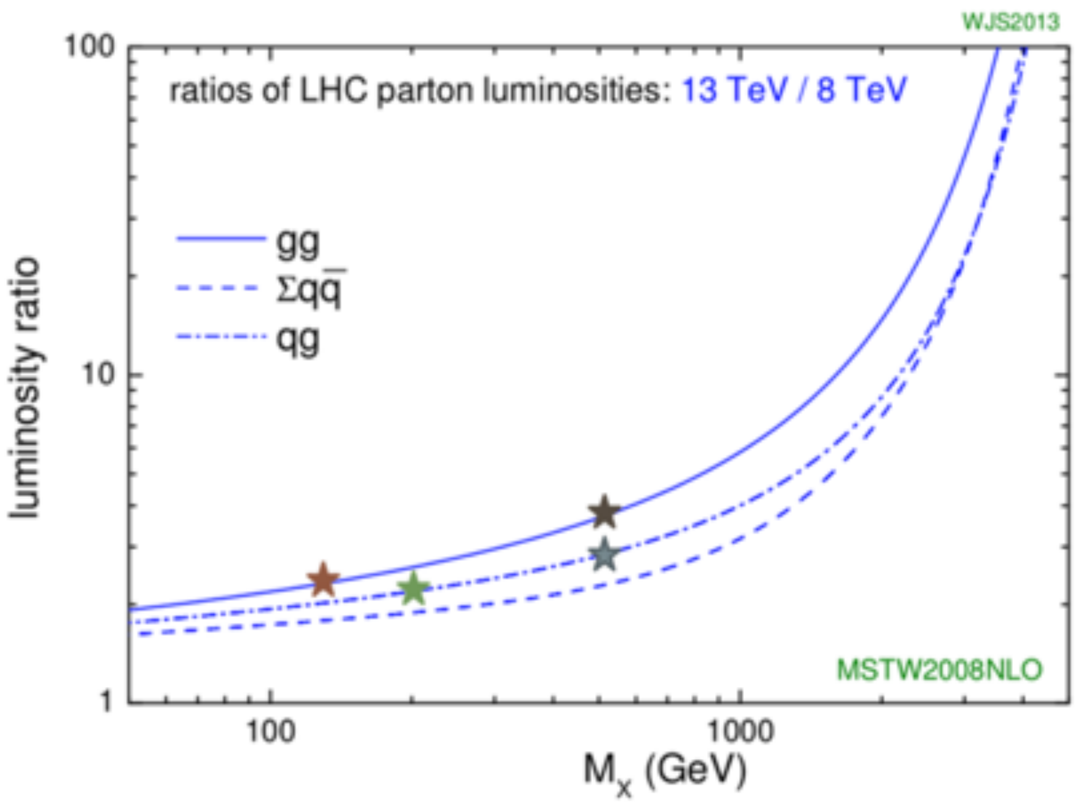
3. Future perspectives



LHC schedule (with caveats..)



Run2 plans (100 fb^{-1} at 13 TeV)

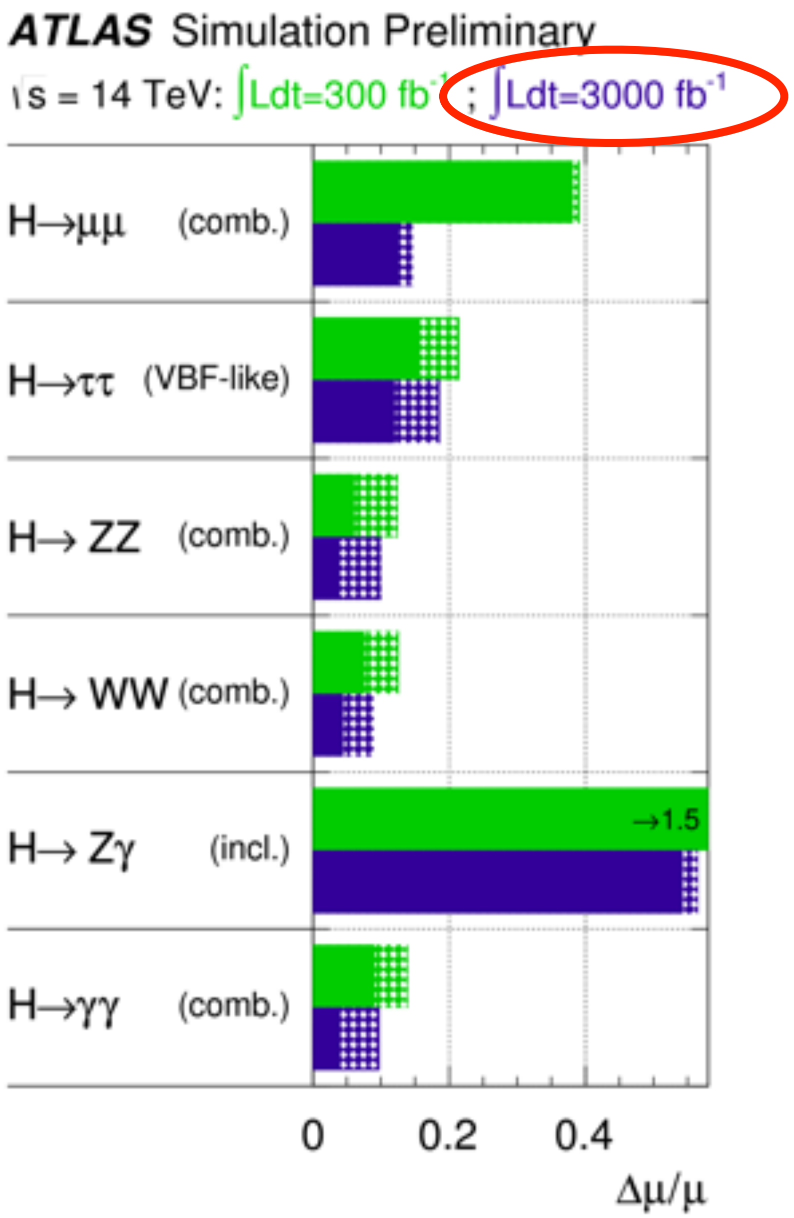


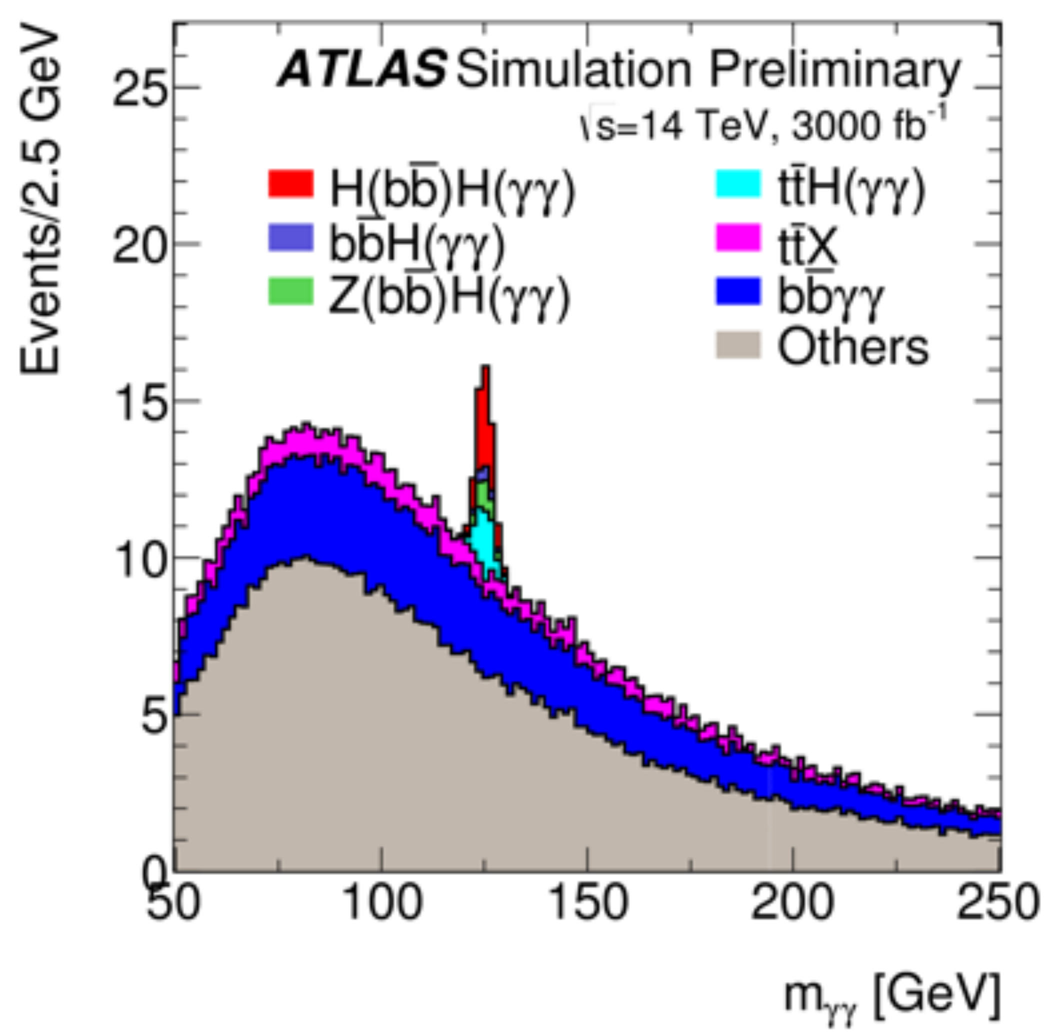
production process	gg/qq	M_X	σ(13TeV) /σ(8TeV)
gg fusion	gg	m_H	2.3
VBF	qq	m(H+jets) ~500GeV	2.4
VH	qq	$m_V + m_H$	2.0
ttH	gg	m(H+2tops) ~500GeV	3.9
bbH	gg	m(H+2tops) ~150GeV	2.5

- Exploit larger sample (4x more luminosity, 2–4x higher cross section) to
  - Re-establish signals observed in Run1
  - More fiducial/differential cross-section measurements, at 13 TeV
  - Observe more exclusive production (VH, ttH) and decay modes (bb)
  - Investigate in more depth few excesses observed in Run1 ($\tau\mu$, ttH, ..)
  - More in-depth look for richer BSM Higgs-boson sector

NOTE: also bkg x-sections increase by ~2 (W,Z,$\gamma\gamma$)—3.3 (ttbar)

HL-LHC perspectives (3000 fb^{-1} at 14 TeV)





- Enter precision era. Search for BSM in coupling deviations from SM (σ_κ~few %)
- Establish coupling to 2nd generation fermions (Hμμ: >7σ)
- Strong evidence of loop-induced rare decay to Zγ (~4σ)
- Higgs-boson self coupling (λ): through di-Higgs production. In bbγγ S~8, B=47: ~1.2σ significance ⇒ more channels and ingenuity needed. Aim for σ_λ/λ~30%

Conclusion

- Higgs boson discovery
  - ATLAS and CMS have observed the existence of a Higgs boson (>5σ)
- Higgs boson characterisation with the full LHC Run1 data
  - mass (~125 GeV) measured with 0.2% precision
  - no significant deviation from SM
    - in spin, parity, width, couplings, rare or forbidden decays, extra bosons
    - $\sigma/\sigma_{SM} = 1.18^{+0.15}_{-0.14}$
- Future perspective for Run2 and beyond
  - rich program of searches for deviations from SM or for extra states in the scalar sector exploiting larger datasets. Towards a precision era measurement