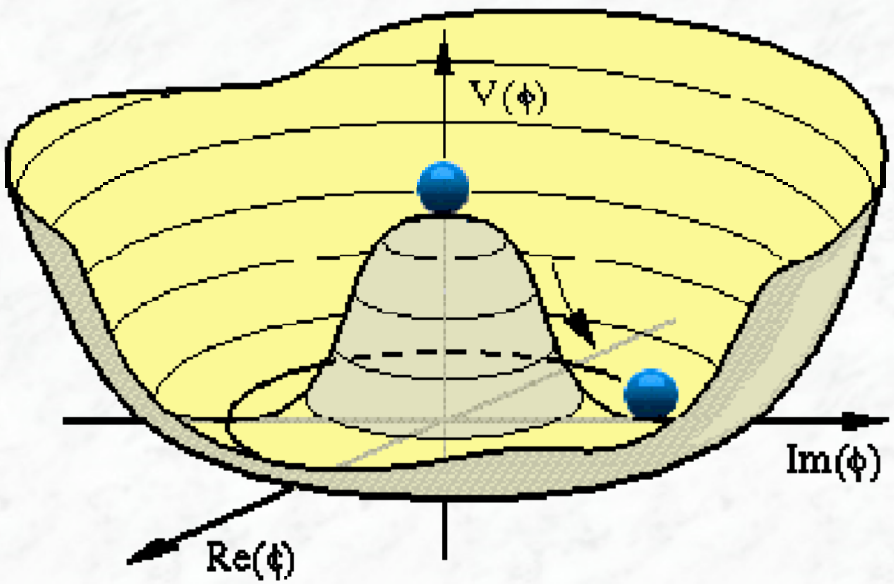
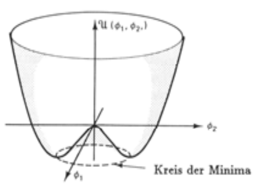
7.5 What are its properties?
Is it the Higgs boson of the Standard Model?





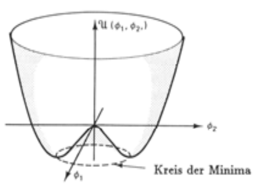
Is it a Higgs Boson ?

-can the LHC measure its parameters ?-

- Mass
- Couplings to bosons and fermions
- Spin and CP
- Higgs boson width, lifetime ?
- Higgs self coupling

Motivation:

- After a discovery of a Higgs-boson at the LHC one has to measure its parameters and consolidate that it matches the SM predictions
- As many parameters as possible have to be measured in as many different production and decay channels as possible ! (global fit, see later)
- Discriminate between: SM Higgs boson,
  MSSM like Higgs boson,
  Composite Higgs boson, ….



Summary: Is it a Higgs Boson ?

1. Mass

Higgs boson mass can be measured with high precision « 1%
using $\gamma\gamma$ and ZZ→ 4ℓ resonances

2. Couplings to bosons and fermions

Ratios of major couplings can be measured with reasonable (~10-30%) precision;
Absolute coupling measurements need further theory assumptions

3. Spin and CP

Angular correlations are sensitive to spin and CP
(achievable precision is statistics limited, requires high luminosity)

4. Higgs self coupling

No measurement possible at the LHC;
Very difficult at the HL-LHC

Higgs-boson mass

Combine H→4l and H→γγ:

•Full kinematic information in photons and leptons

•Need excellent understanding and calibration of muon, electron, photon momentum scale

New material description in front of the calorimeter

•Determined from detailed analysis of 6.6M Z→ee(γ) and 8M Z→μμ(γ)

•Calibrate individual layers in EM calorimeter with muons, electrons, unconverted photons

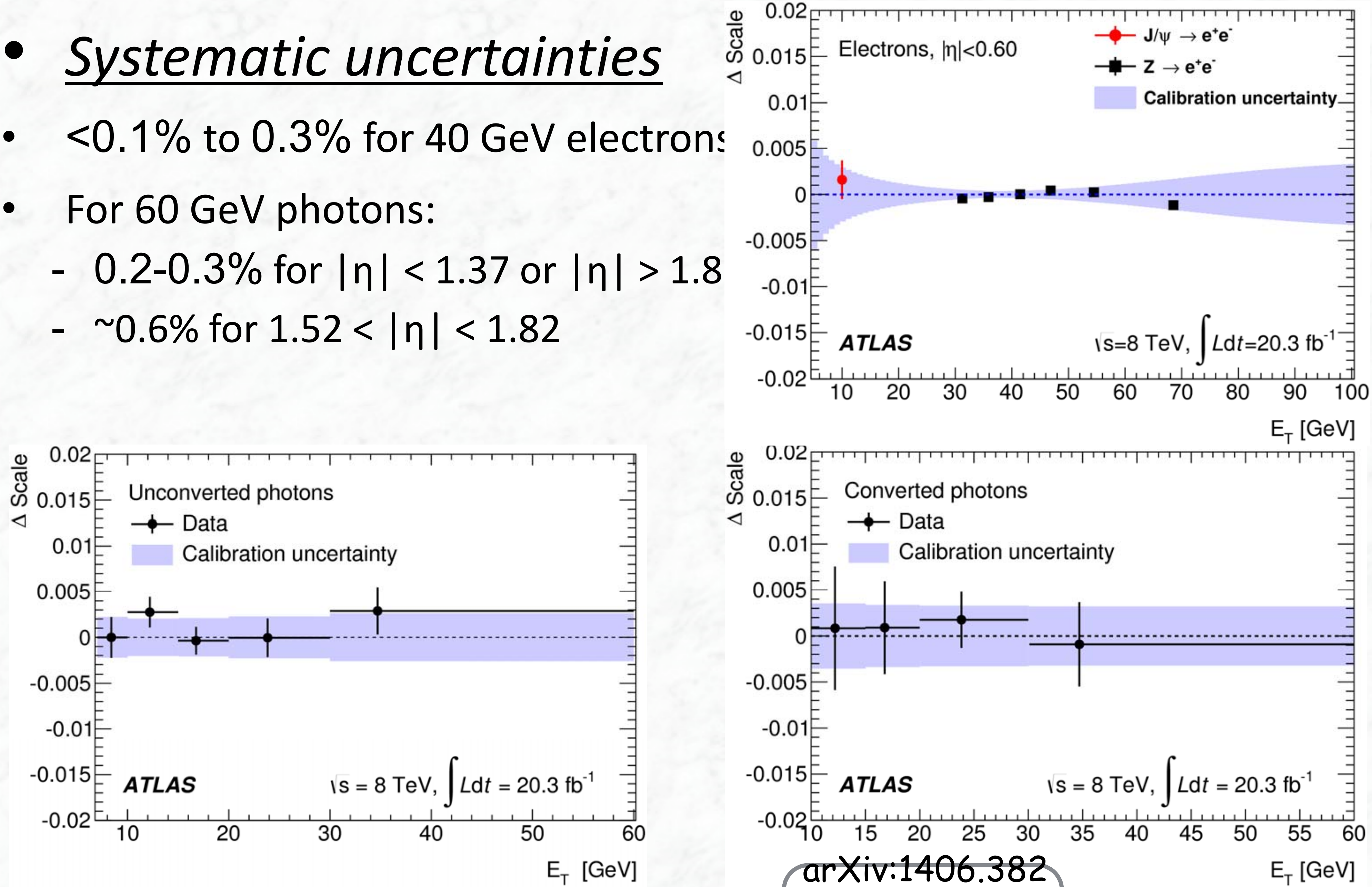
•$\Delta X_0/X_0 < 10\%$

Energy response of EM calorimeter

- Very stable vs. time and pileup
- RMS < 0.05%

Electron and Photon Energy Scale

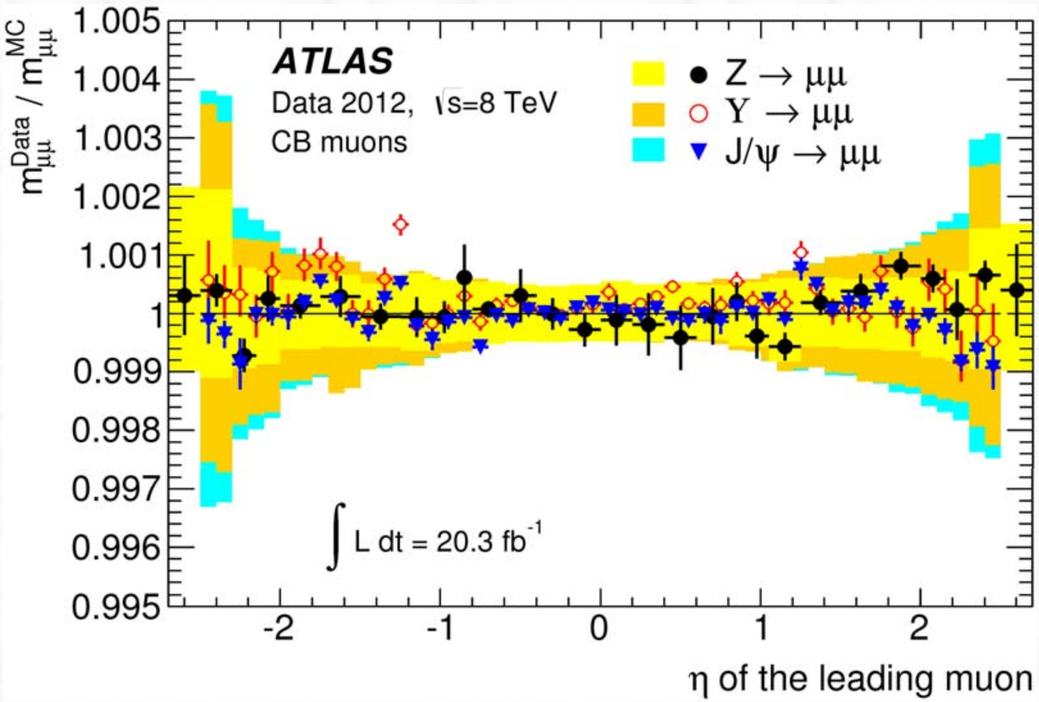
- ***Systematic uncertainties***
- <0.1% to 0.3% for 40 GeV electrons
- For 60 GeV photons:
  - 0.2-0.3% for |η| < 1.37 or |η| > 1.8
  - ~0.6% for 1.52 < |η| < 1.82

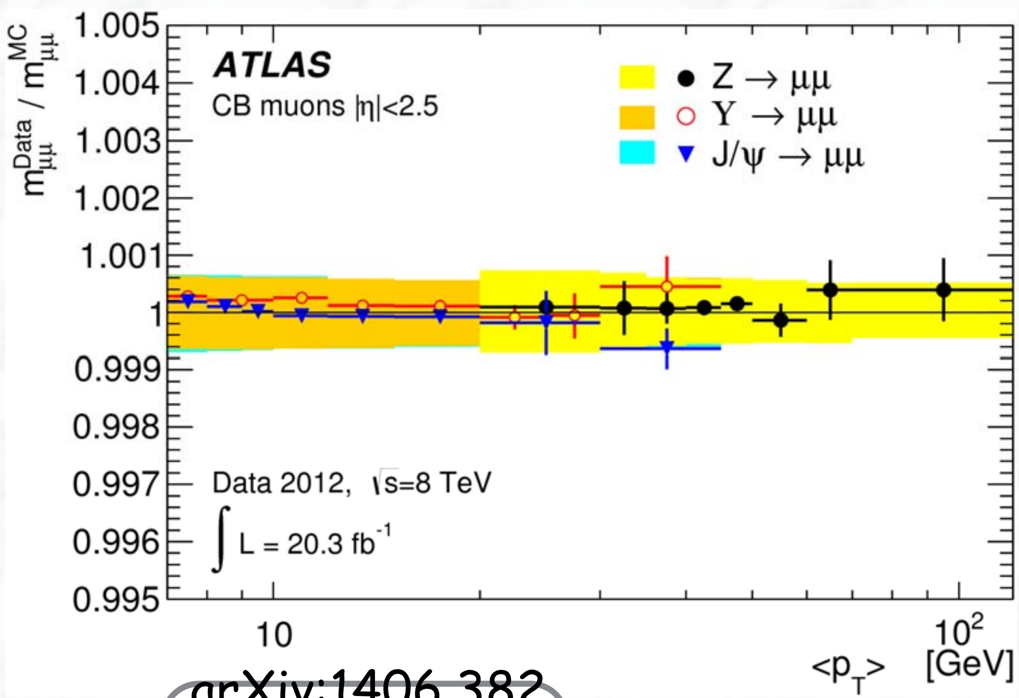


arXiv:1406.3827

Muon Momentum Calibration

- *New calibration for momentum scale and resolution:*
- Combination of two independent measurements (inner tracker and muon spectrometer)
- Using millions of Z→μμ, Y→μμ, and J/Ψ→μμ
- Impact on H→4μ mass measurement now <60 MeV





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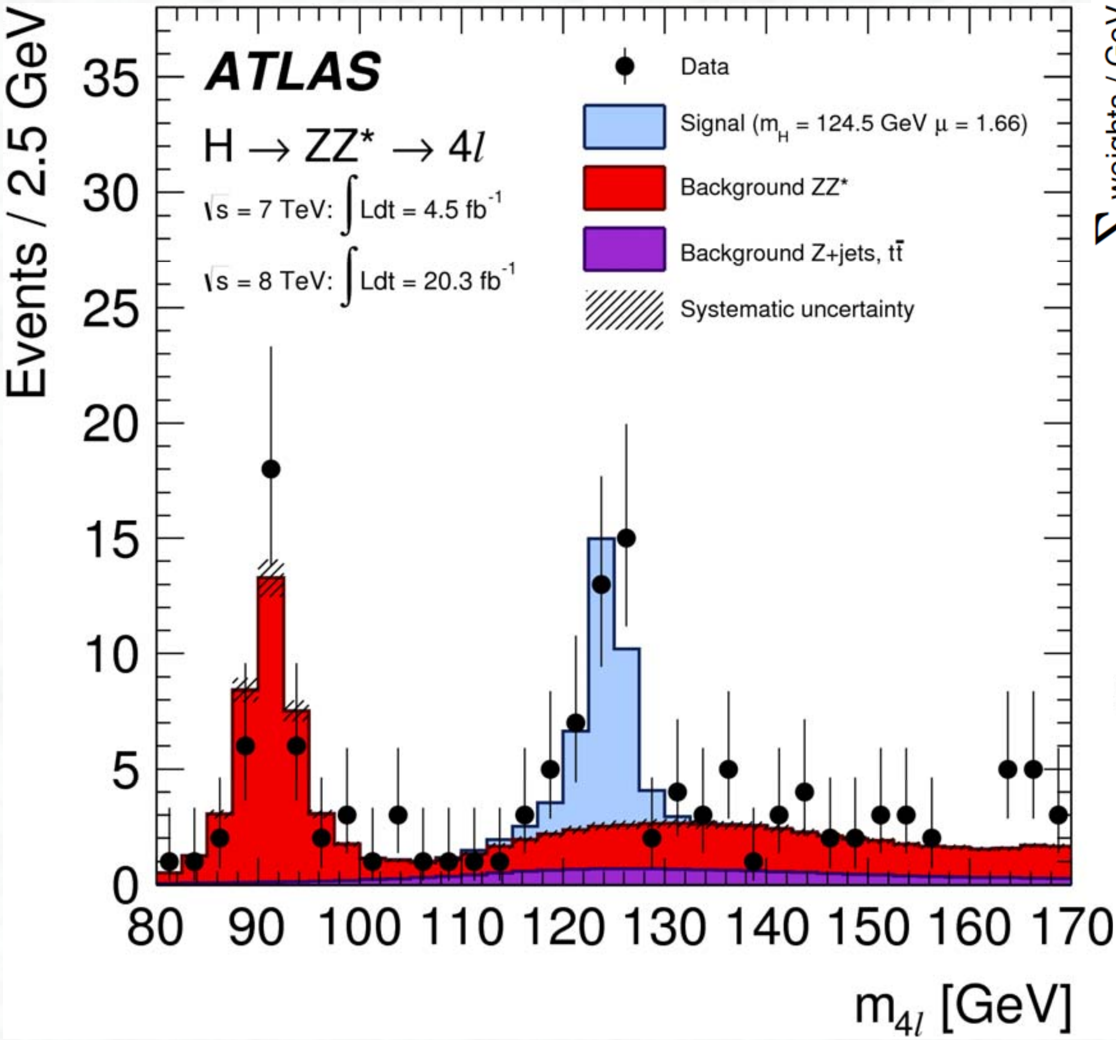
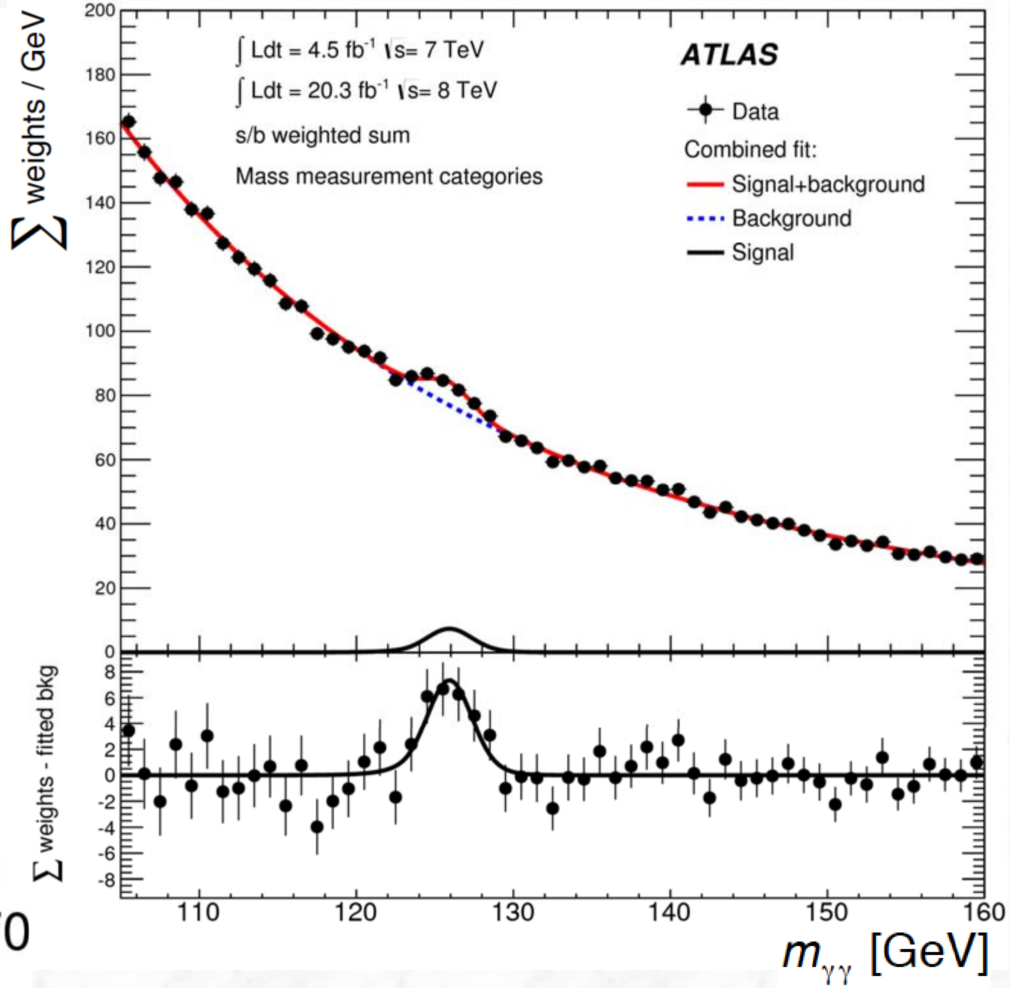
Higgs-Boson Mass

- Combination of H→4l and H→γγ





arXiv:1406.3827

Higgs-Boson Mass

- Systematic uncertainty on combined mass is ~180 MeV
  - (compared to ~540 MeV in PLB Summer 2013 publication)

Systematic	Uncertainty on m_H [MeV]
LAr syst on material before presampler (barrel)	70
LAr syst on material after presampler (barrel)	20
LAr cell non-linearity (layer 2)	60
LAr cell non-linearity (layer 1)	30
LAr layer calibration (barrel)	50
Lateral shower shape (conv)	50
Lateral shower shape (unconv)	40
Presampler energy scale (barrel)	20
ID material model ($\|\eta\| < 1.1$)	50
$H \to \gamma\gamma$ background model (unconv rest low p_{Tt})	40
$Z \to ee$ calibration	50
Primary vertex effect on mass scale	20
Muon momentum scale	10
Remaining systematic uncertainties	70
Total	180

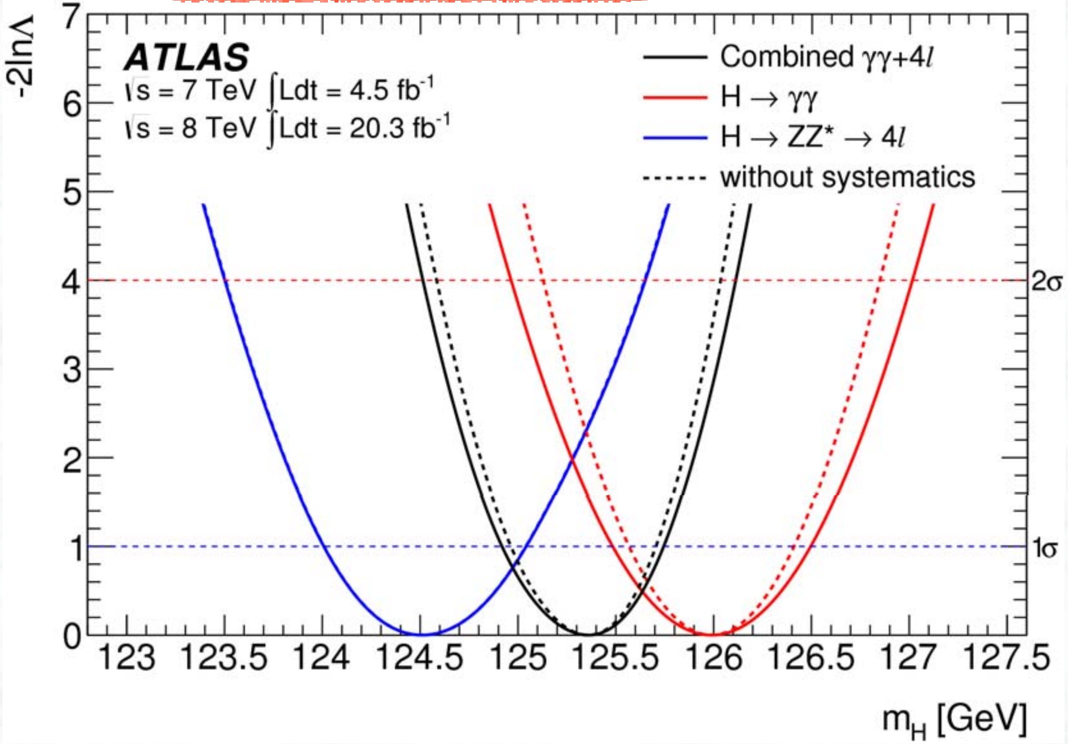
arXiv:1406.3827

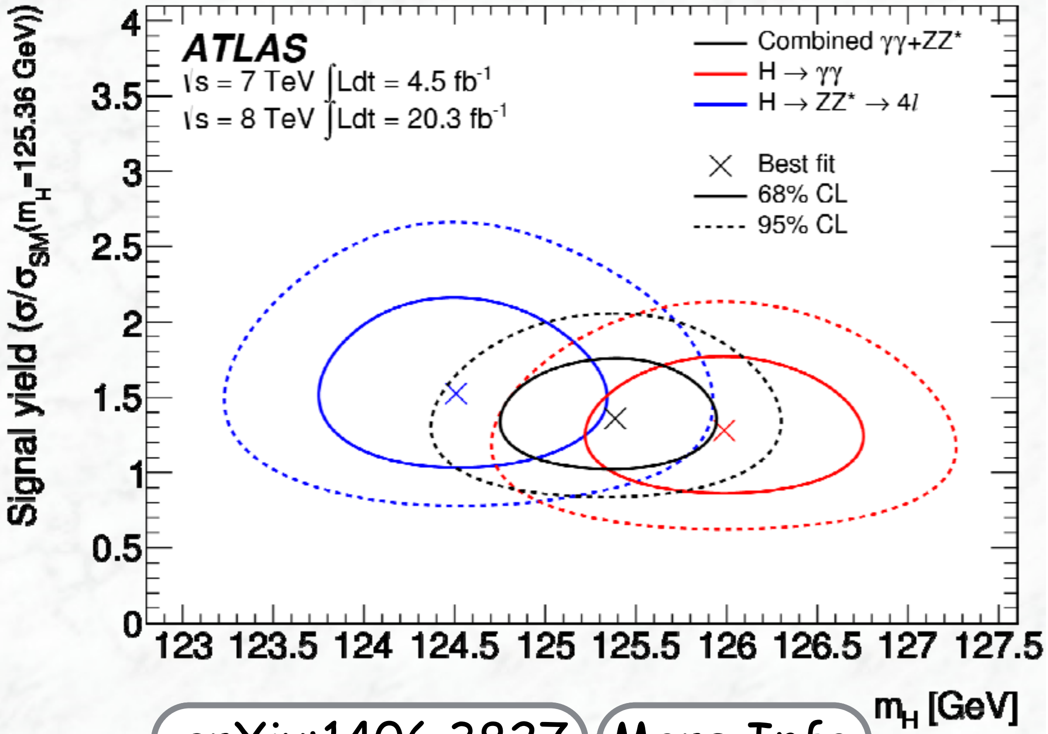
Higgs-Boson Mass

Channel	Mass measurement [GeV]
$H \to \gamma\gamma$	$125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{syst}) = 125.98 \pm 0.50$
$H \to ZZ^* \to 4\ell$	$124.51 \pm 0.52\,(\text{stat}) \pm 0.06\,(\text{syst}) = 124.51 \pm 0.52$
Combined	$125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst}) = 125.36 \pm 0.41$

$$\Delta m_H = 1.47 \pm 0.67\,(\text{stat}) \pm 0.28\,(\text{sys})\ \text{GeV} = 1.47 \pm 0.72\ \text{GeV}$$

- 2.0σ compatibility (compared to 2.5σ from Summer 2013 publication)





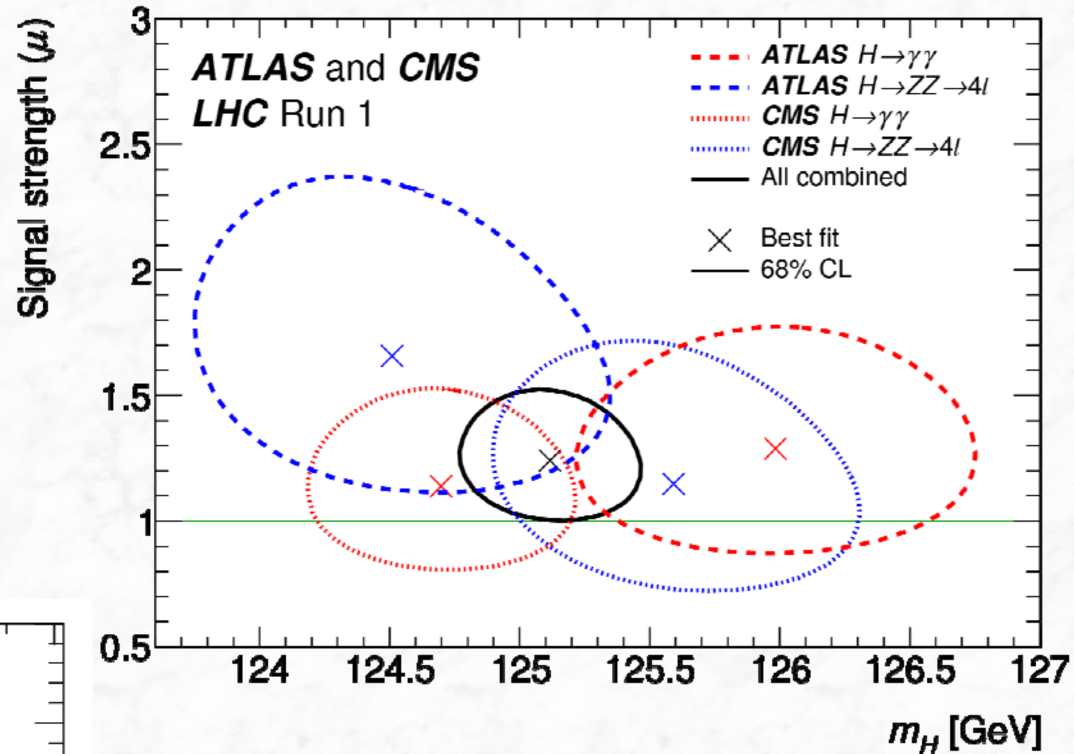
arXiv:1406.3827 More Info

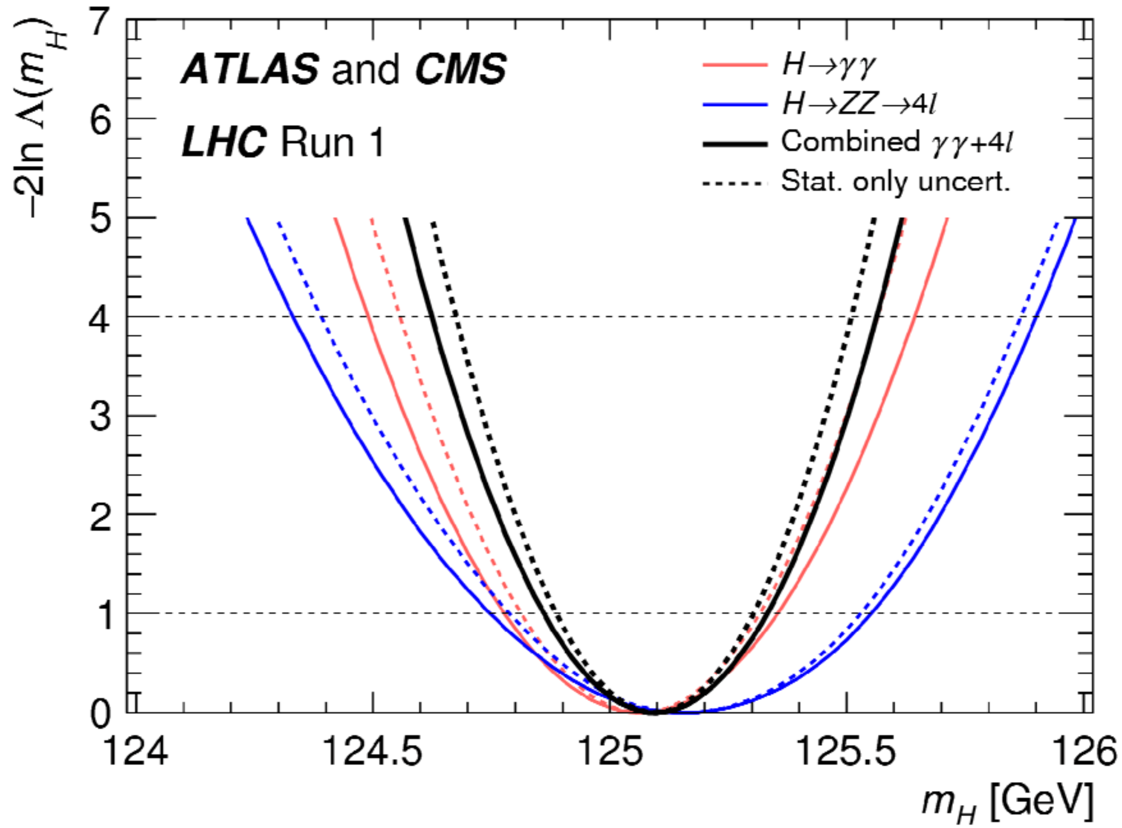
Higgs-boson mass: ATLAS&CMS combination

Combination paper

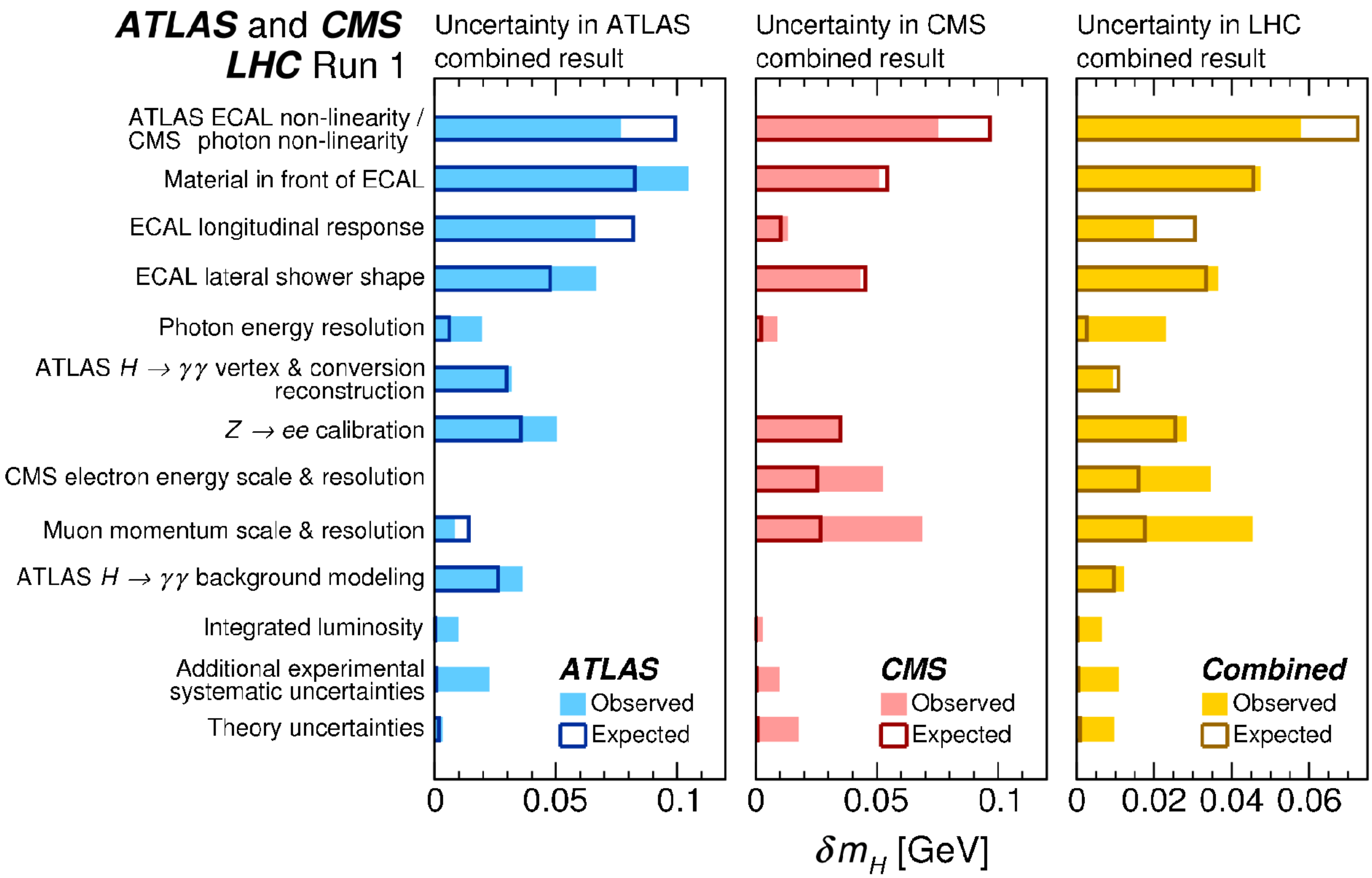
(5154 authors):

http://arxiv.org/abs/1503.07589

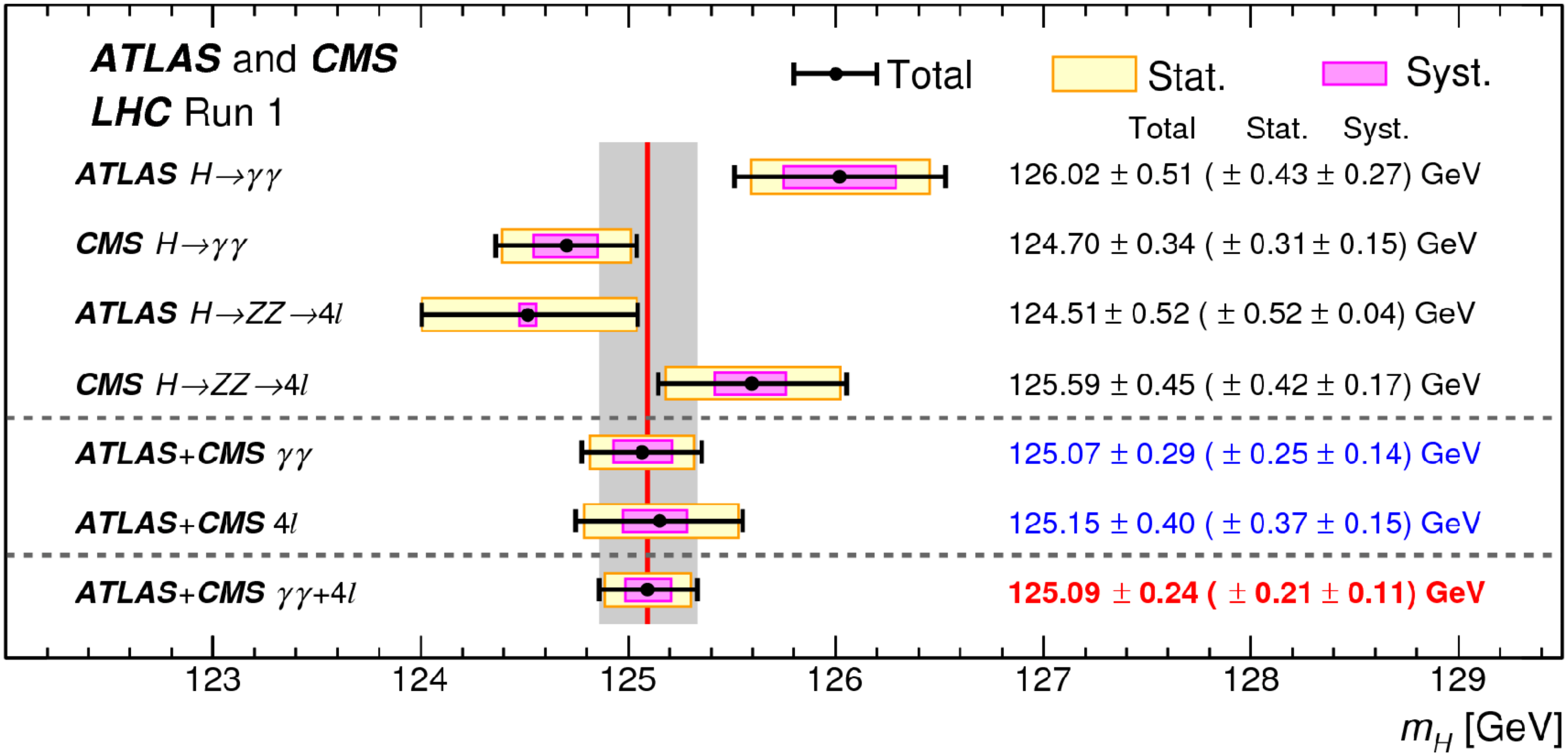




Higgs-boson mass: ATLAS&CMS combination



Higgs-boson mass: ATLAS&CMS combination

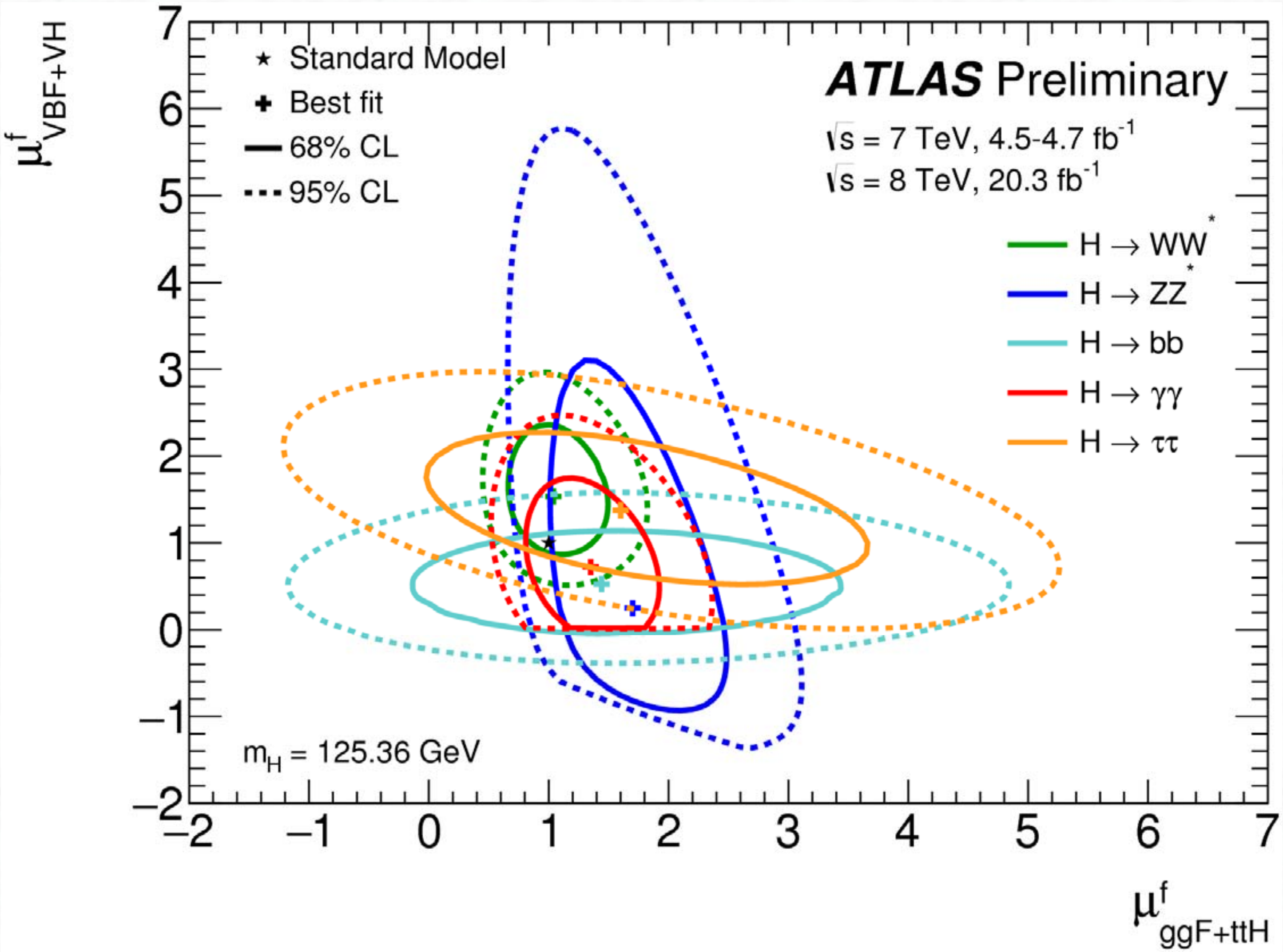


Better than 2 per-mille!!

Higgs-boson coupling combination

Combination framework:

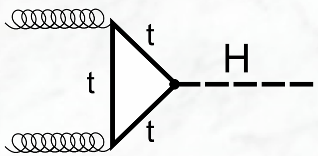
- Use all ATLAS Higgs-boson measurements in one global fit
- Fit for different combinations of parameters of interest

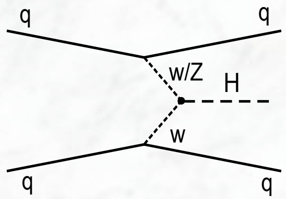


Higgs boson couplings

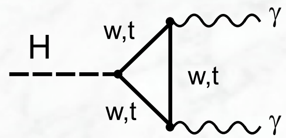
- Production and decay involve several couplings

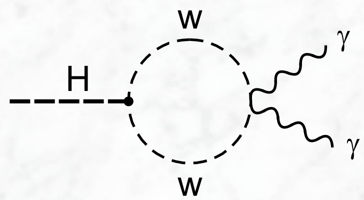
Production:





Decays: e.g. H → γγ (best example)
(Decay widths depends on W and top coupling,
destructive interference)





- Standard Model couplings are tested by introducing coupling scale factors κ

$$g_i = \kappa g_i^{SM}$$

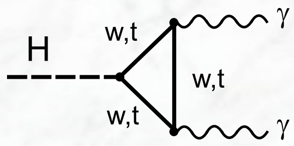
- Standard Model tree level amplitudes:

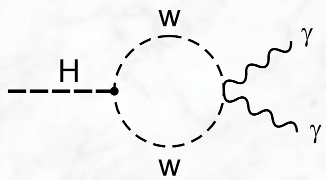
$$\Gamma_{ff} \propto \left(\kappa_f \frac{m_f}{v} \right)^2 = \kappa_f^2 \cdot \Gamma_{ff}^{SM}$$

$$\Gamma_{VV} \propto \left(\kappa_f \frac{m_V^2}{v} \right)^2 = \kappa_V^2 \cdot \Gamma_{VV}^{SM}$$

Higgs boson couplings

- Example: H → γγ $\Gamma_{\gamma\gamma} \propto \left|1.28\kappa_W - 0.28\kappa_t\right|^2 \cdot \Gamma_{\gamma\gamma}^{SM}$





– Loop scaling factors can be expressed in terms of κ_f and κ_V

- The analysis is also done in terms of effective loop couplings κ_g and κ_γ

Higgs boson couplings

- Benchmarks defined by LHC cross section working group (leading-order tree-level framework):

  - Signals observed originate from a single resonance; (mass assumed here is 125.5 GeV)

  - Narrow width approximation: → rates for given channels can be decomposed as:

$$\sigma \cdot B\,(i \rightarrow H \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

i, f = initial, final state
Γ_f, Γ_H = partial, total width

  - Modifications to coupling strength are considered (coupling scale factors κ), tensor structure of Lagrangian assumed as in Standard Model

Scaling of cross sections with k_F and k_V factors

$$\sigma \cdot \mathrm{BR}\,(\mathrm{gg} \to \mathrm{H} \to \gamma\gamma) \;=\; \sigma_{\mathrm{SM}}(\mathrm{gg} \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

$$\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{\kappa_F^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{\kappa_V^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(qq' \to qq'H, VH) * \mathrm{BR}(H \to \tau\tau, H \to b\bar{b}) \sim \frac{\kappa_V^2 \cdot \kappa_F^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

(i) Couplings to fermions and bosons

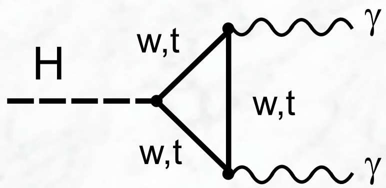
- Assume only one scale factor for fermion and vector couplings:

  $\kappa_V = \kappa_W = \kappa_Z$
  $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$

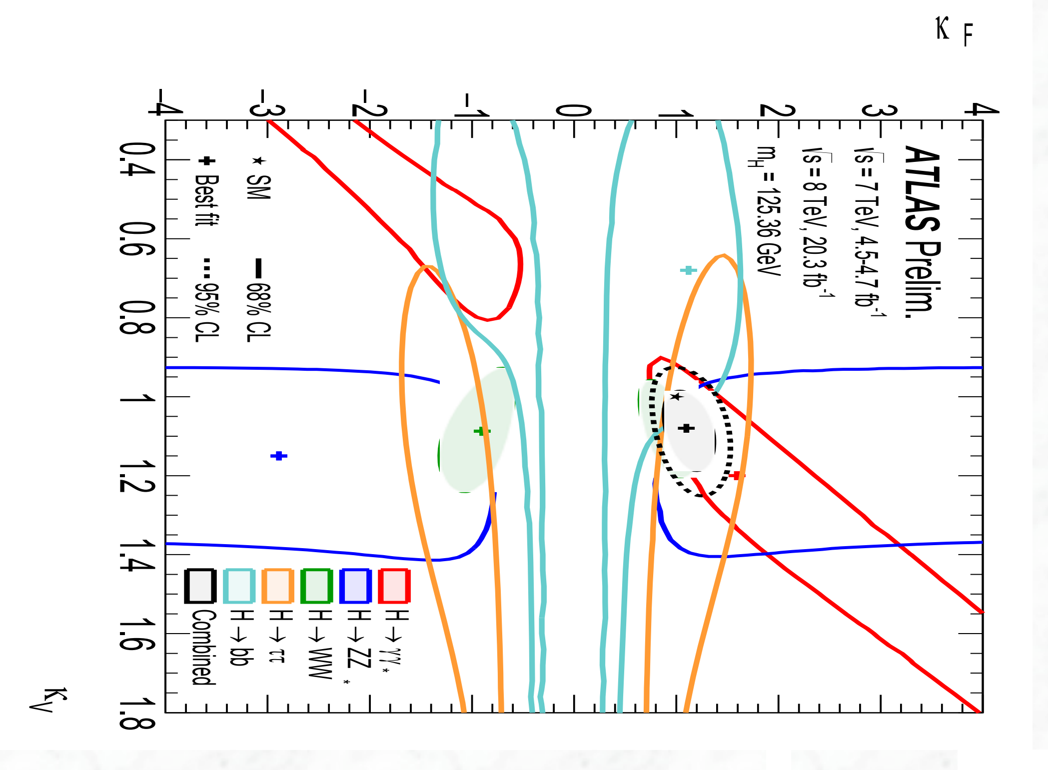
  The size of the current data set is insufficient to quantify all parameters

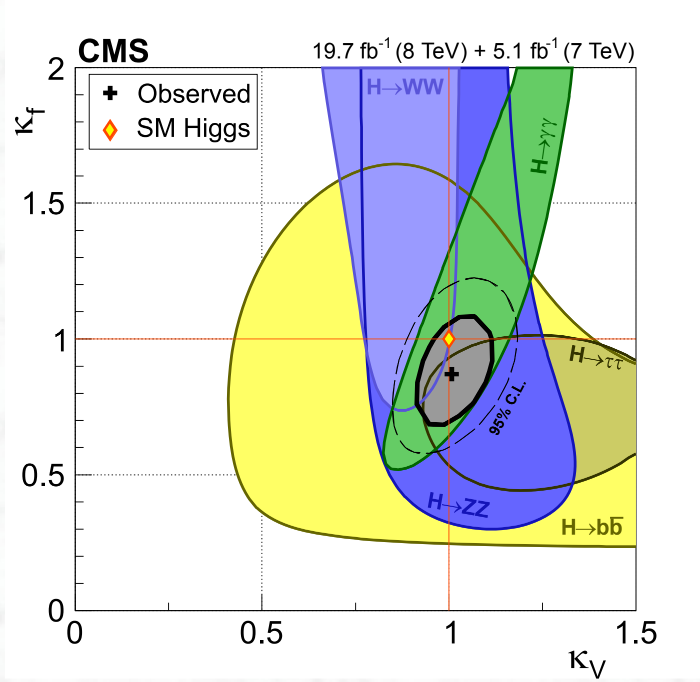
- Assume that $H \rightarrow \gamma\gamma$ and $gg \rightarrow H$ loops and the total Higgs boson width depend only on κ_V and κ_F
  (no contributions from physics beyond the Standard Model)

- Sensitivity to relative sign between κ_F and κ_V only from interference term in $H \rightarrow \gamma\gamma$ decays (assume $\kappa_V > 0$)



(i) Couplings to fermions and bosons (cont).





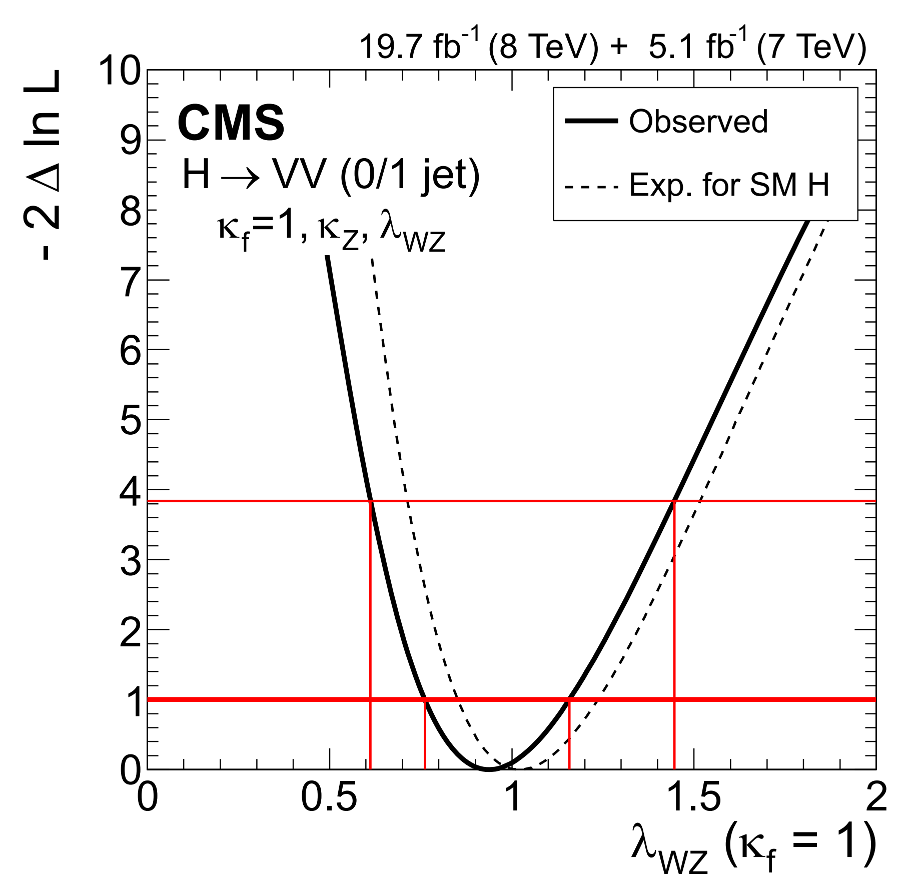
Results: Data are consistent with the SM expectation;

Fit results: $k_V = 1.09 \pm 0.07$
$k_F = 1.11 \pm 0.16$

Fit results: $k_V \in [0.87, 1.14]$ (95% CL)
$k_F \in [0.63, 1.15]$ (95% CL)

(ii) Ratio of couplings to the W and Z bosons

- Relation between m_W and m_Z in the Standard Model requires $\lambda_{WZ} := \kappa_W/\kappa_Z = 1$ (ρ parameter required to be 1)
- Sensitivity via VBF and VH production and $H \rightarrow WW$ and $H \rightarrow ZZ$ rates



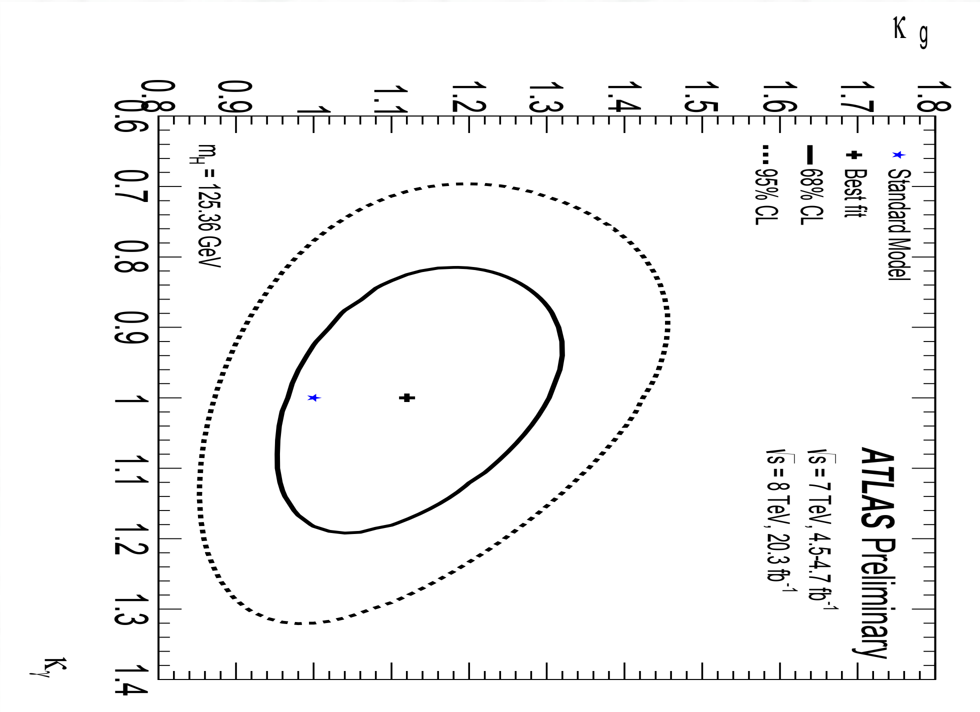
Data are consistent with $\lambda_{WZ} := \kappa_W / \kappa_Z = 1$

(iii) Constraints on production and decay loops

- Test on contributions from other particles contributing to loop-induced processes

- Assume nominal couplings for all SM particles $\kappa_i = 1$
  and that the new particles do not contribute to the Higgs boson width

- Fit for effective scale factors κ_g and κ_γ

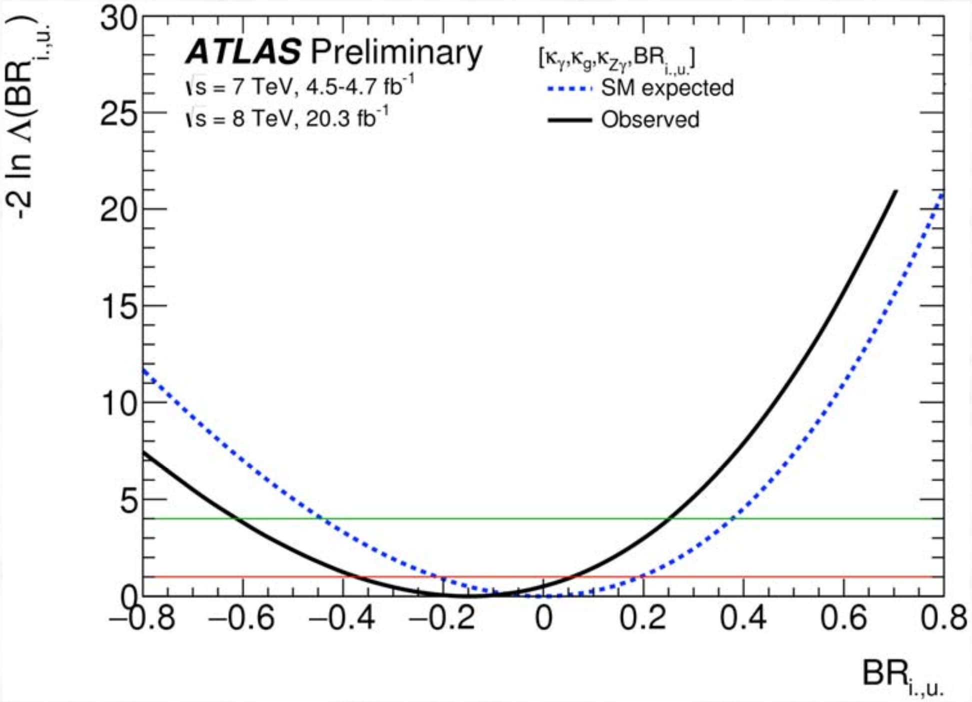


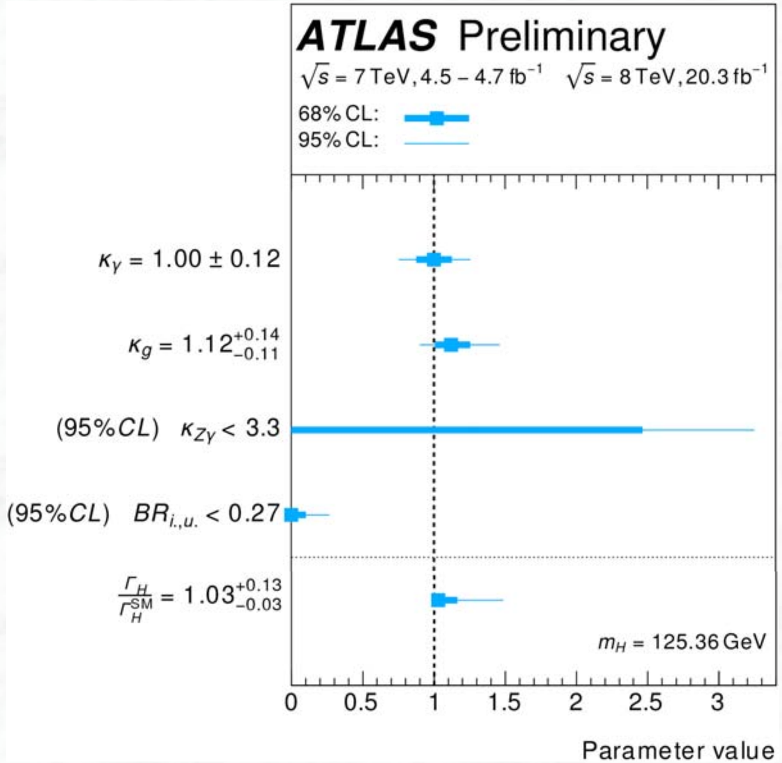
Best fit values: $k_\gamma = 1.00 \pm 0.12$
(ATLAS) $k_g = 1.12 \pm 0.12$

(iv) Constraints on invisible decays (BR_{BSM})

- There might be invisible decays that would increase the total decay width:
- $\Gamma_H = \Gamma_{SM} + \Gamma_{BSM}$ ($BR_{BSM} = \Gamma_{BSM} / \Gamma_H$)

Assume nominal couplings for all SM particle $\kappa_i = 1$
Three fitted parameters: k_g, k_γ and BR_{BSM}





$BR_{BSM} < 0.27$ (95% CL)

Higgs boson couplings

- Fit all coupling scale factors for relevant particles (W, Z, t, b, t, m) independently;
- Loop factors expressed in terms of these scale factors, assume SM particle content

λ = Yukawa coupling for fermions
√g/2v = couplings for W/Z bosons

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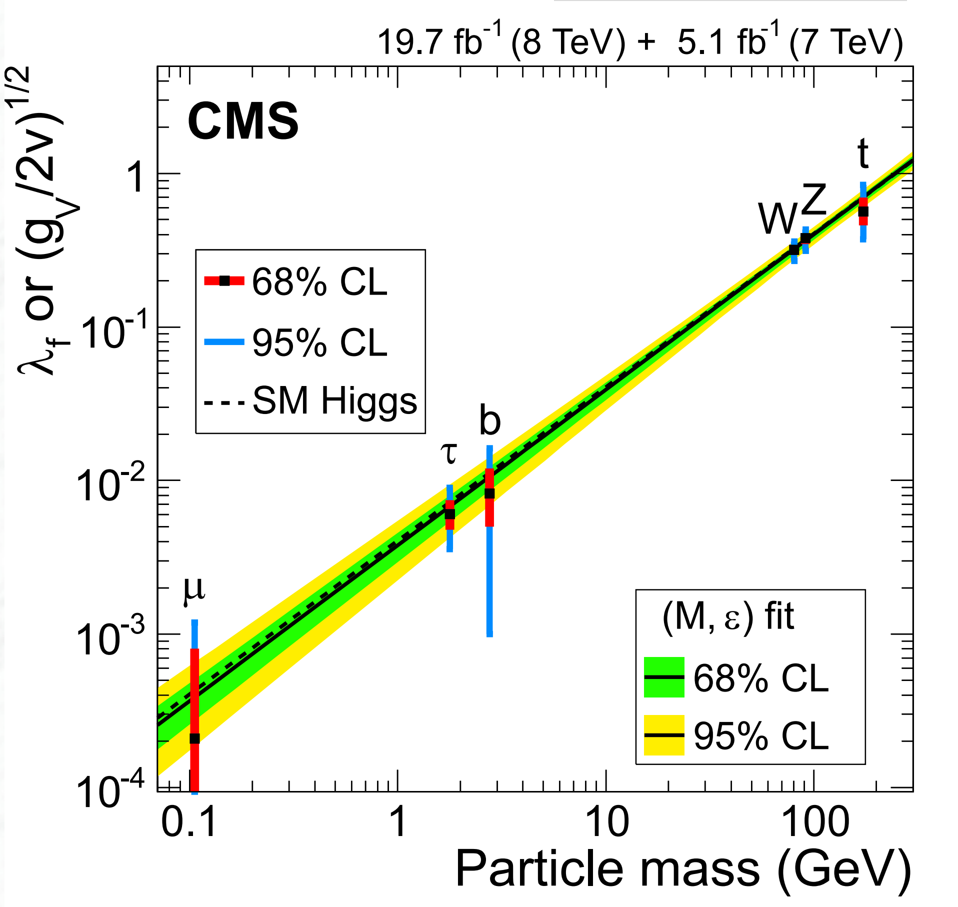

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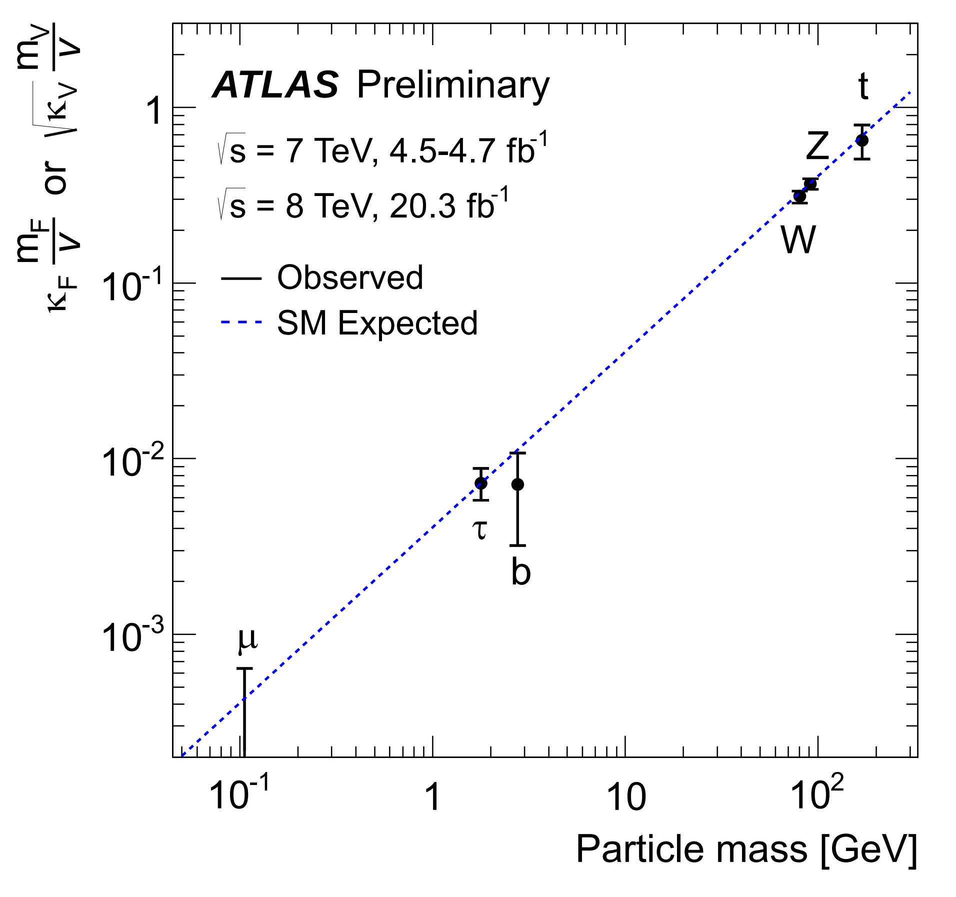

For the first time, non-universal, mass-dependent couplings observed

Ratios of Higgs boson couplings (model independent)

- In the most general model, only ratios of couplings can be measured independently on any assumptions on the total width (allowing also deviations in vertex loop coupling strength)

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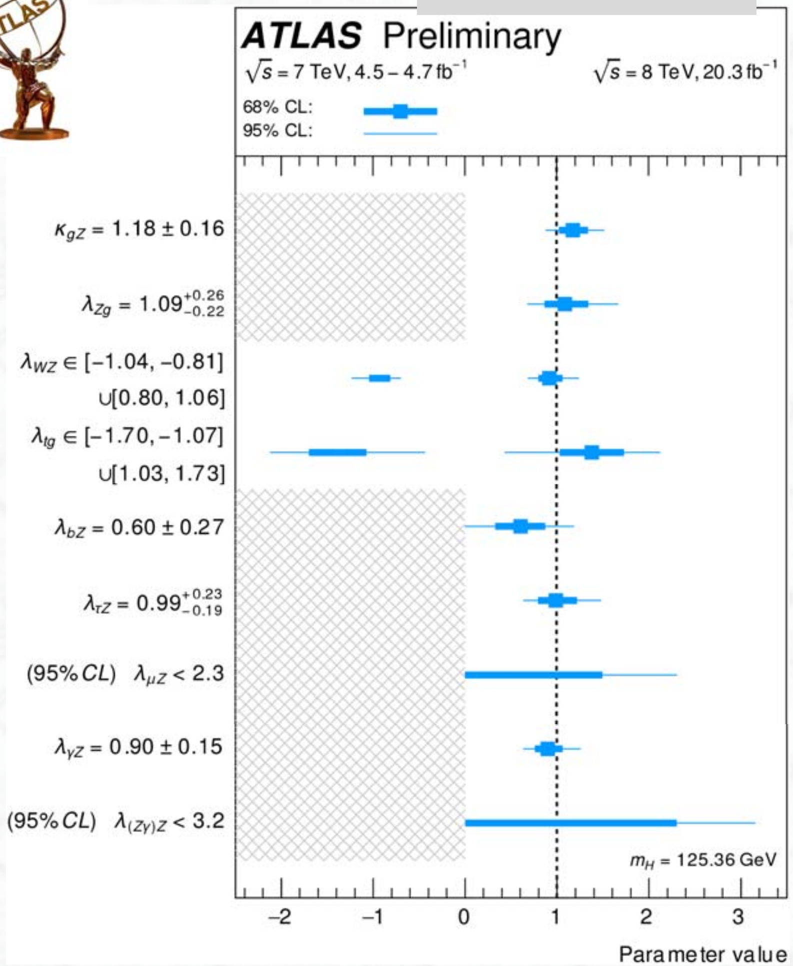

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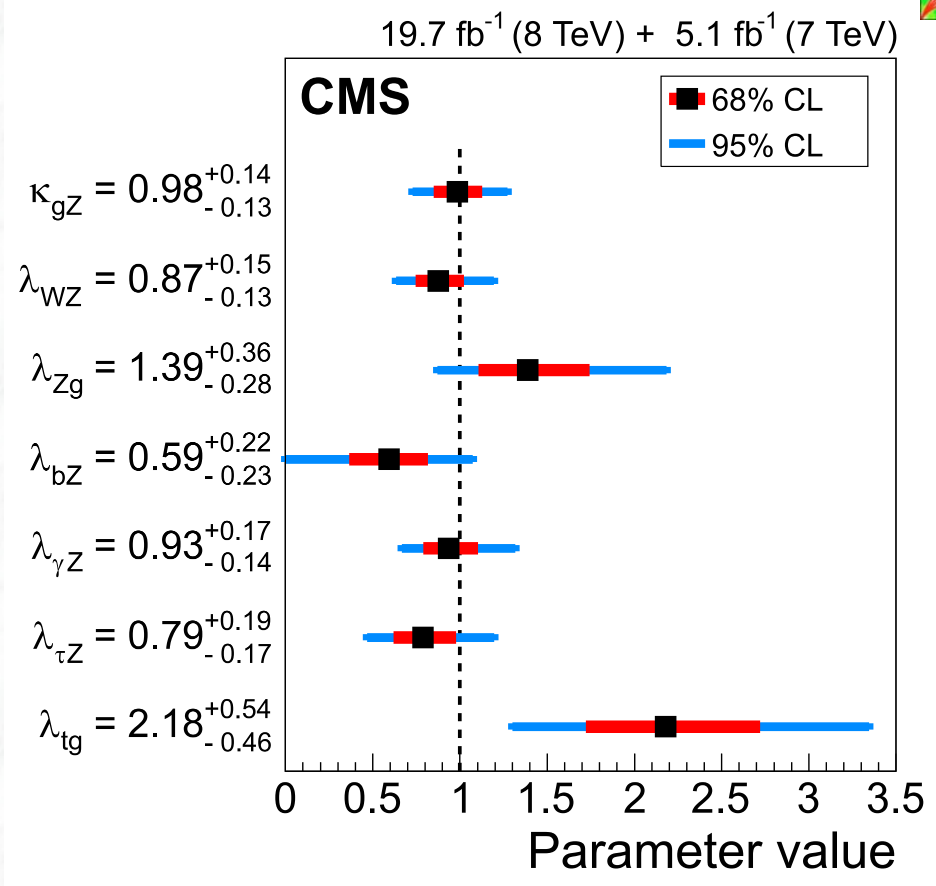


λ_{WZ}: test of custodial symmetry

$\lambda_{\gamma Z}$: sensitive to new charged particles in H → γγ loop w.r.t H→ZZ decays

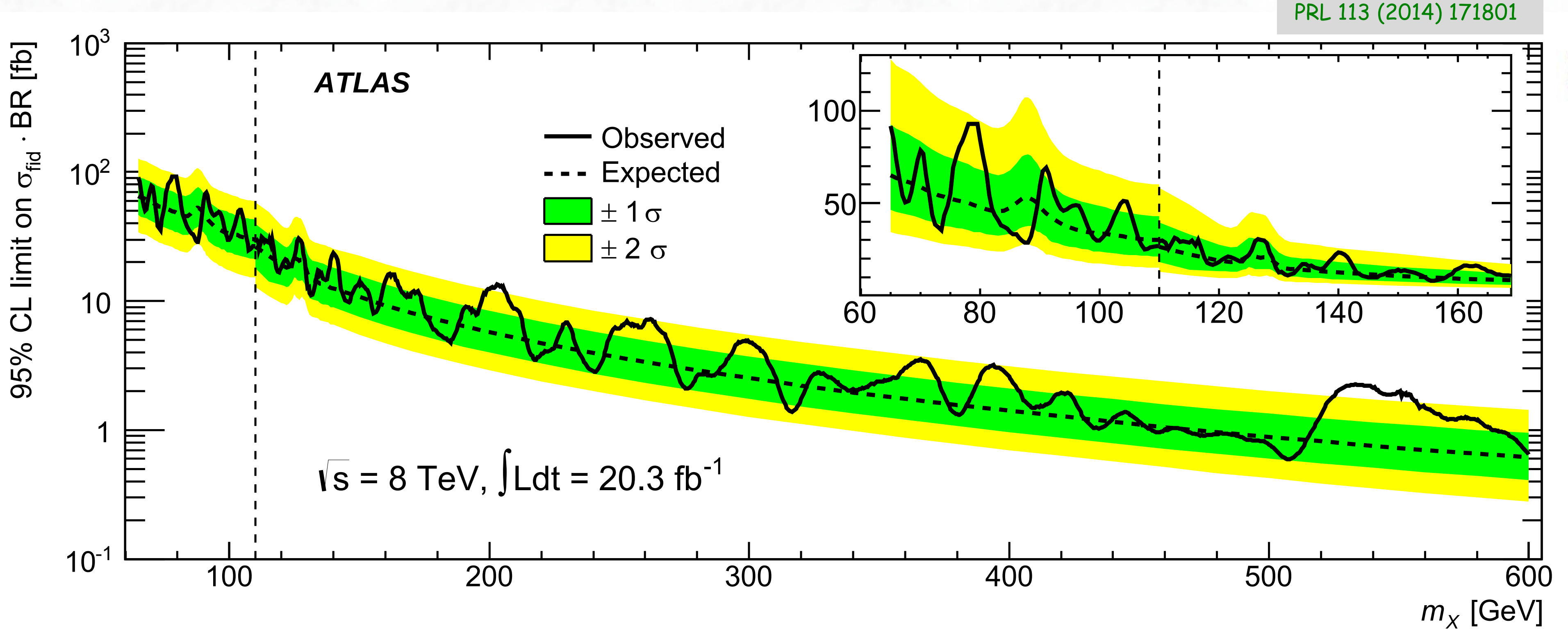
λ_{tg}: sensitive to new coloured particles contributing to gg → H production w.r.t. ttH production

Good consistency with the Standard Model Higgs boson hypothesis

Search for Additional Higgs Bosons
-a few examples-

(i) Results of an ATLAS search on additional resonances X decaying into $\gamma\gamma$

PRL 113 (2014) 171801



Observed and expected 95% CL limits on the fiducial cross section times branching ration BR(X → $\gamma\gamma$) as a function of mass

(note: 125 GeV signal was treated as “background” and contribution was subtracted)

Outlook towards Run 2

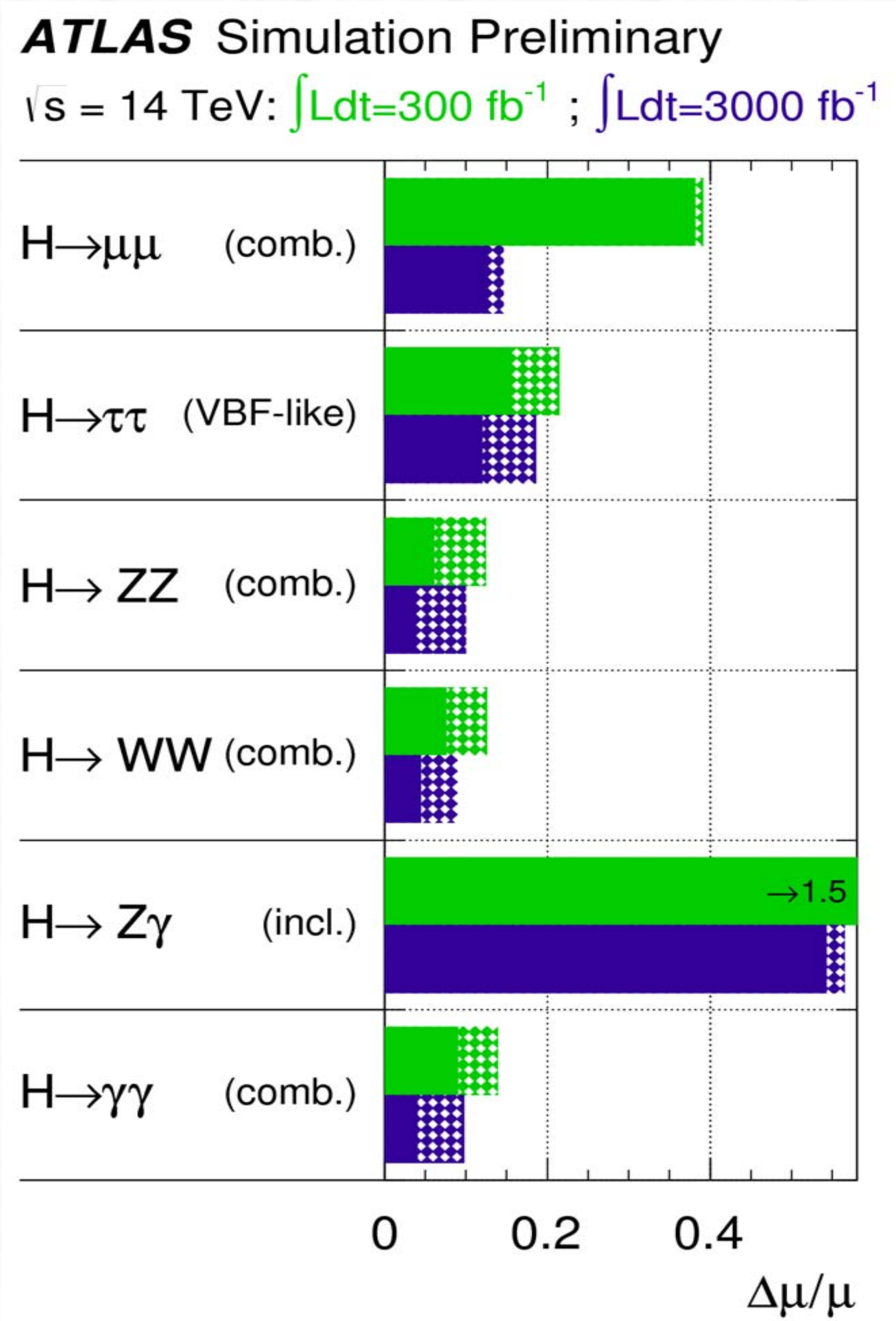
Expectations from LHC:

- ~100 fb^{-1} at 13-14 TeV
  - ⇒ Expect 10 times more Higgs-bosons compared to Run 1

Consequences for Higgs boson parameter extractions:

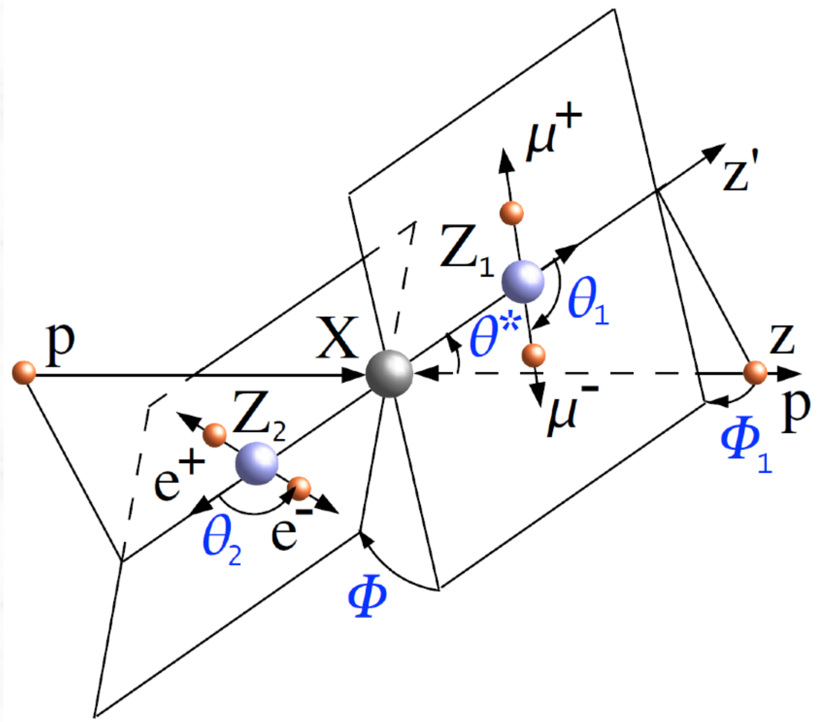
- κ-framework has shortcomings:
  - Neglects completely tensor structure of coupling operators
  - Strictly only interpretable for κ=1
- New approach: Effective Field Theori $\mathcal{L}_{eff} = \mathcal{L}_{\rm SM}^{(4)} + \sum_i \frac{1}{\Lambda^{d_i-4}} c_i \mathcal{O}_i$
  - Full tensor structure
    - Use Spin-CP measurements in the same framework
    - Can take differential measurements into account
  - Interpretable for all values of the parameters to high precision

Outlook towards HL-LHC



Spin and Parity

- <u>*Standard Model Higgs boson: $J^P = 0^+$*</u>
  - Strategy is to *falsify other hypothesis* (0^-, 1^+, 1^-, 2^+, 2^-) and *demonstrate consistency with SM 0^+ hypothesis*
  - Spin 1 already strongly disfavoured by observed $H \rightarrow \gamma\gamma$ and Landau-Yang theorem
  - Use angular variables and build a combined discriminant
  - Calculate likelihood ratio between alternative hypothesis and standard 0^+ hypothesis

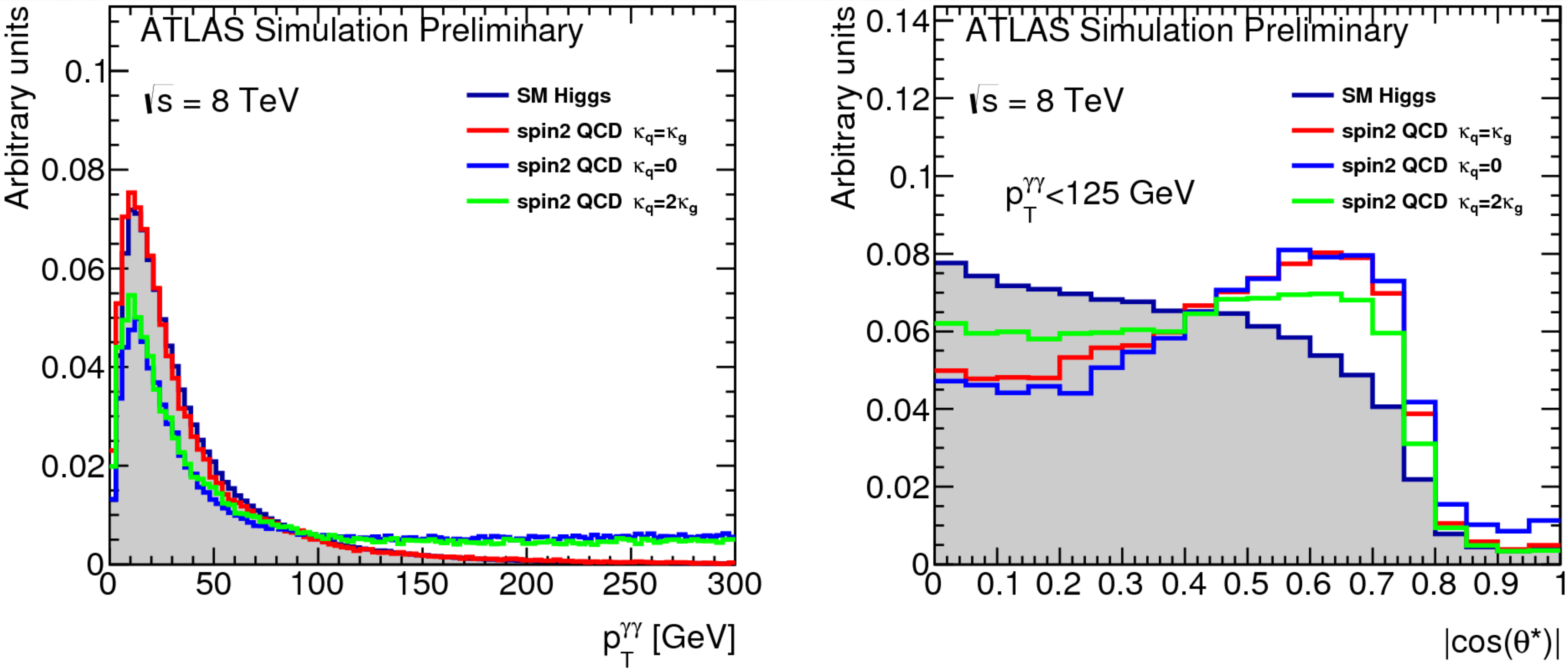


Spin und CP

General:

•Use $H\rightarrow\gamma\gamma$, $H\rightarrow ZZ^*$, and $H\rightarrow WW^*$ decays

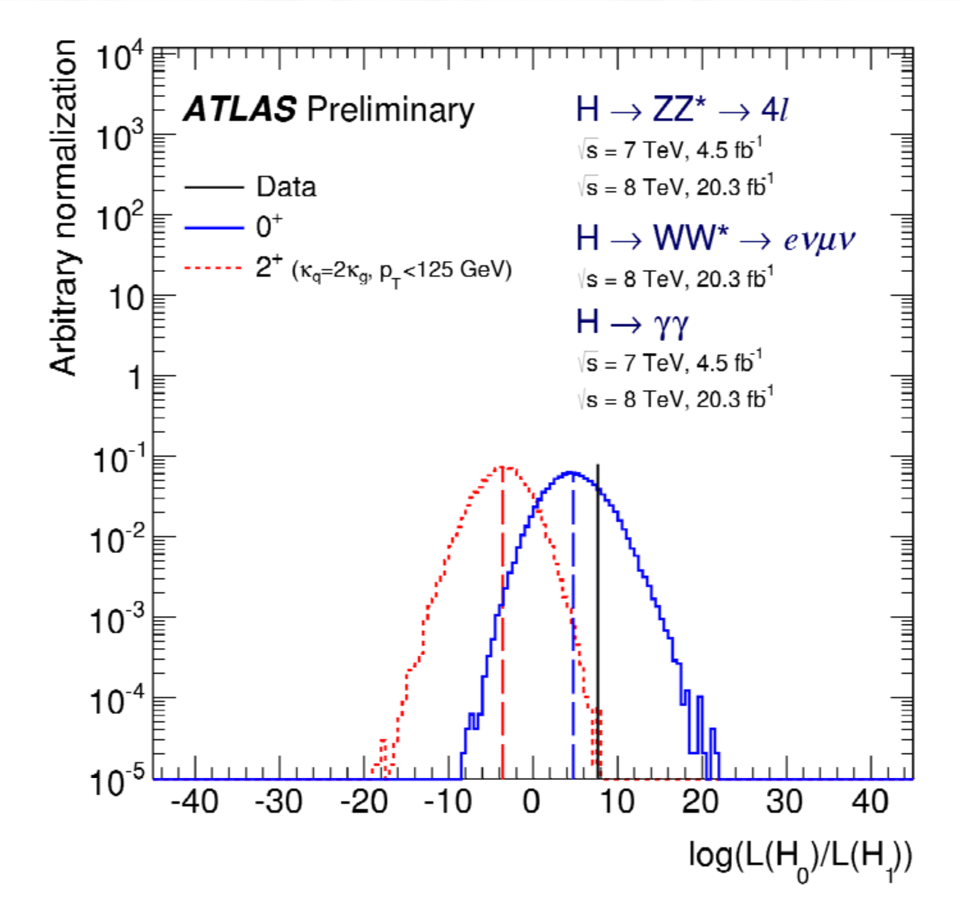
•Build boosted-decision-trees or matrix-element-discriminants to combine distributions within one channel into one variable



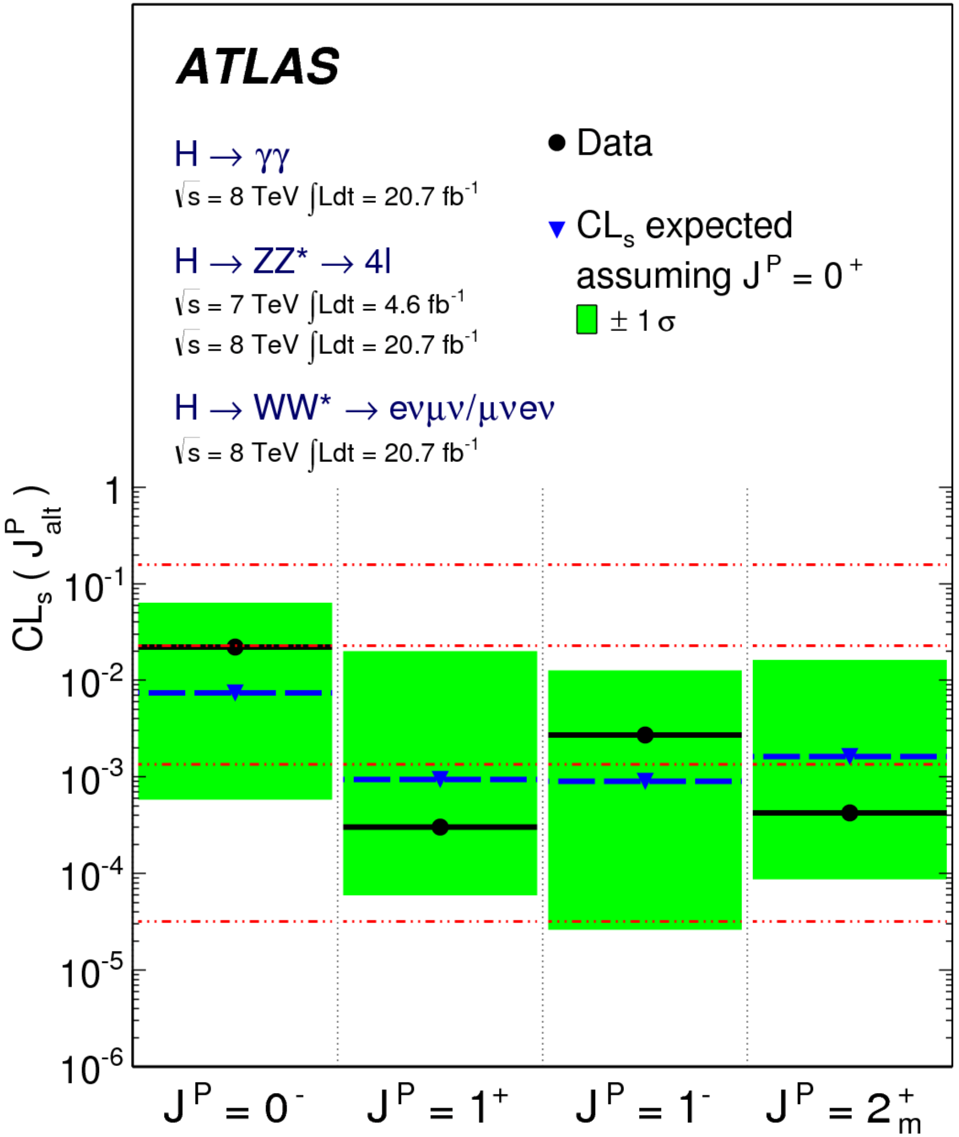
Spin und CP

General:

- Build the likelihood ratio for SM and competing hypthesis
- Extract BSM coupling limits

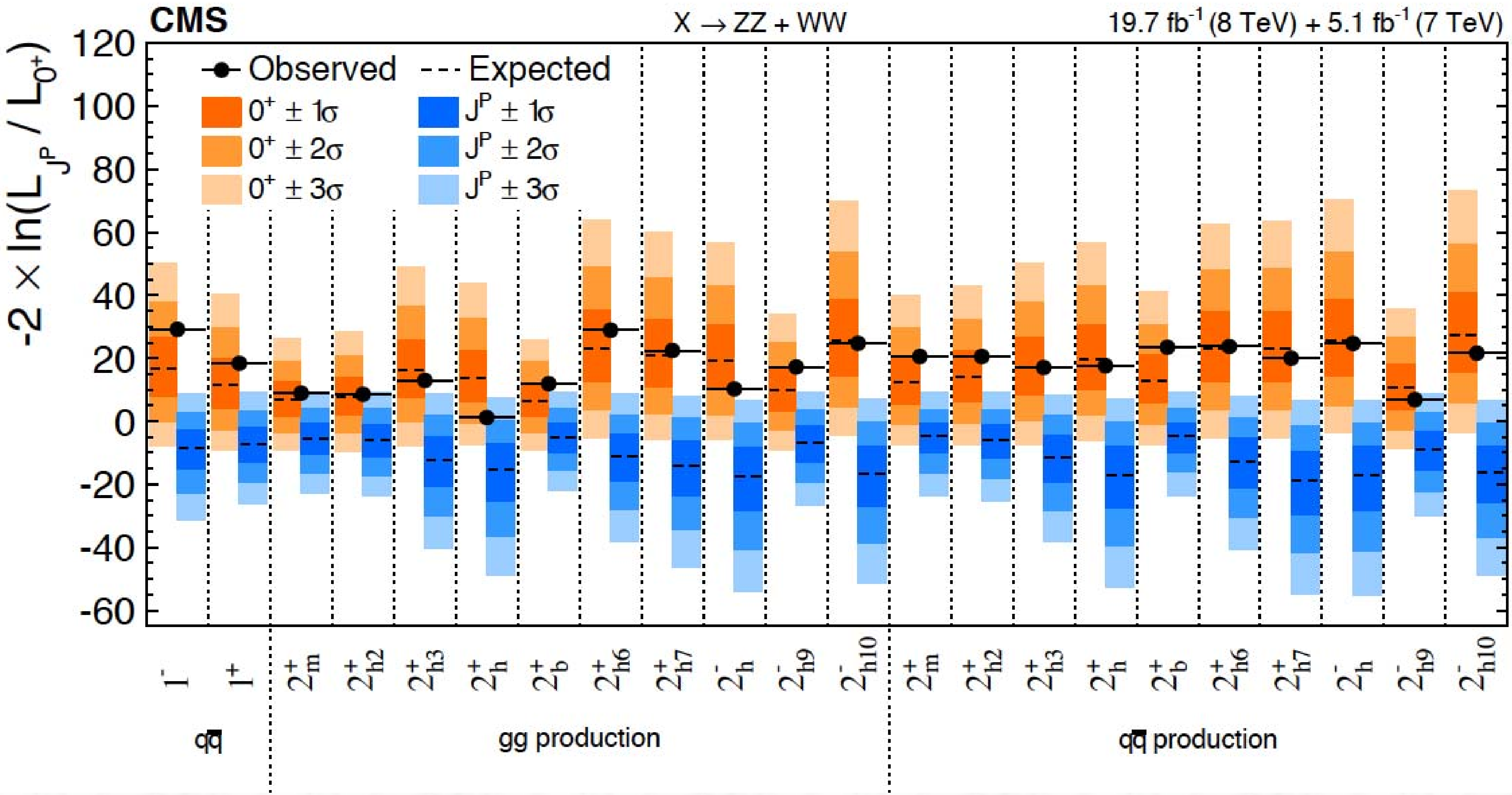


Spin und CP Summary



- SM $J^P = 0^+$ favored
- 1^+, 1^-, 2^+ are disfavored at the 3σ level
- 0^- excluded at 97.8% CL

Spin und CP Summary



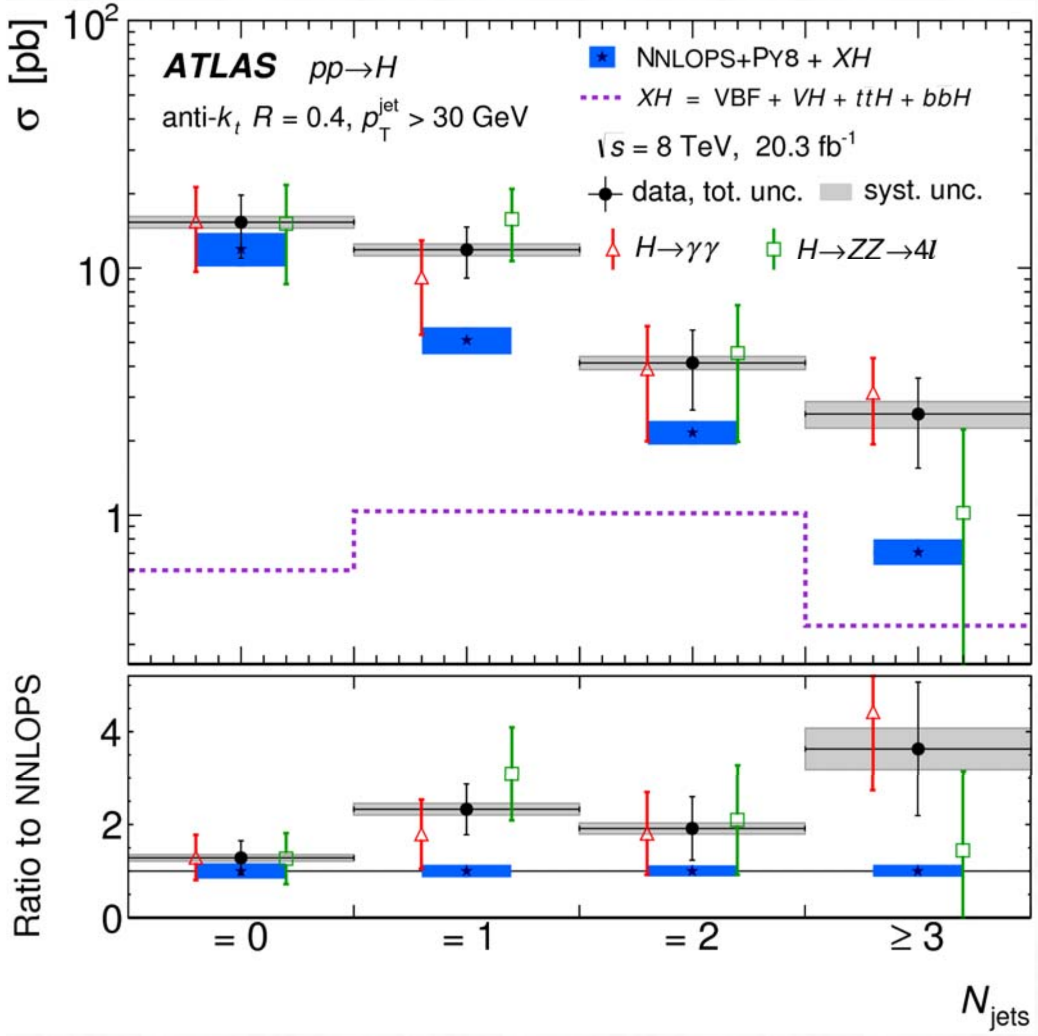
Differential cross sections

General:

- Unfold measured distributions to true distributions using response matrix from MC
- Needed matrix inversion (with proper uncertainty propagation) non-trivial

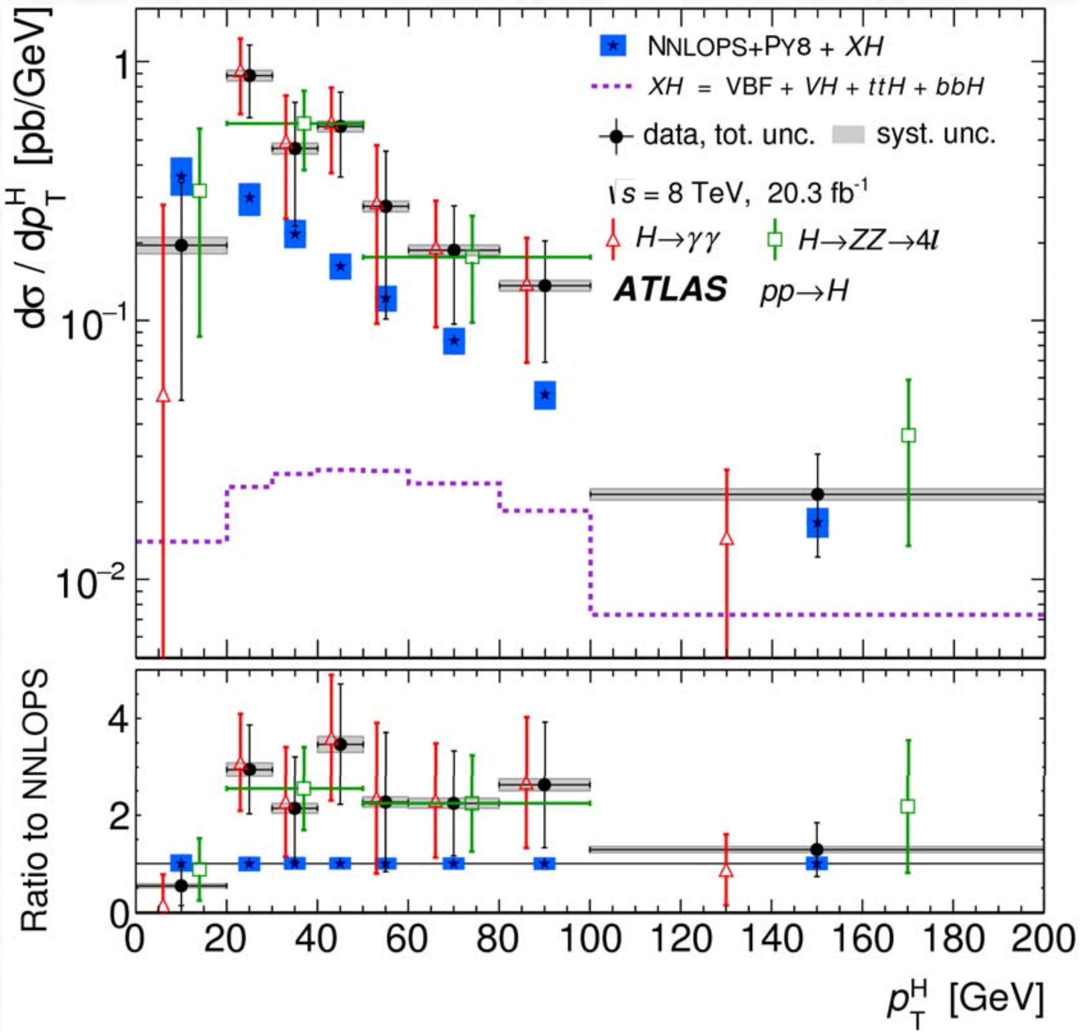
Number of associated jets:

- Test QCD



Higgs-boson p_T:

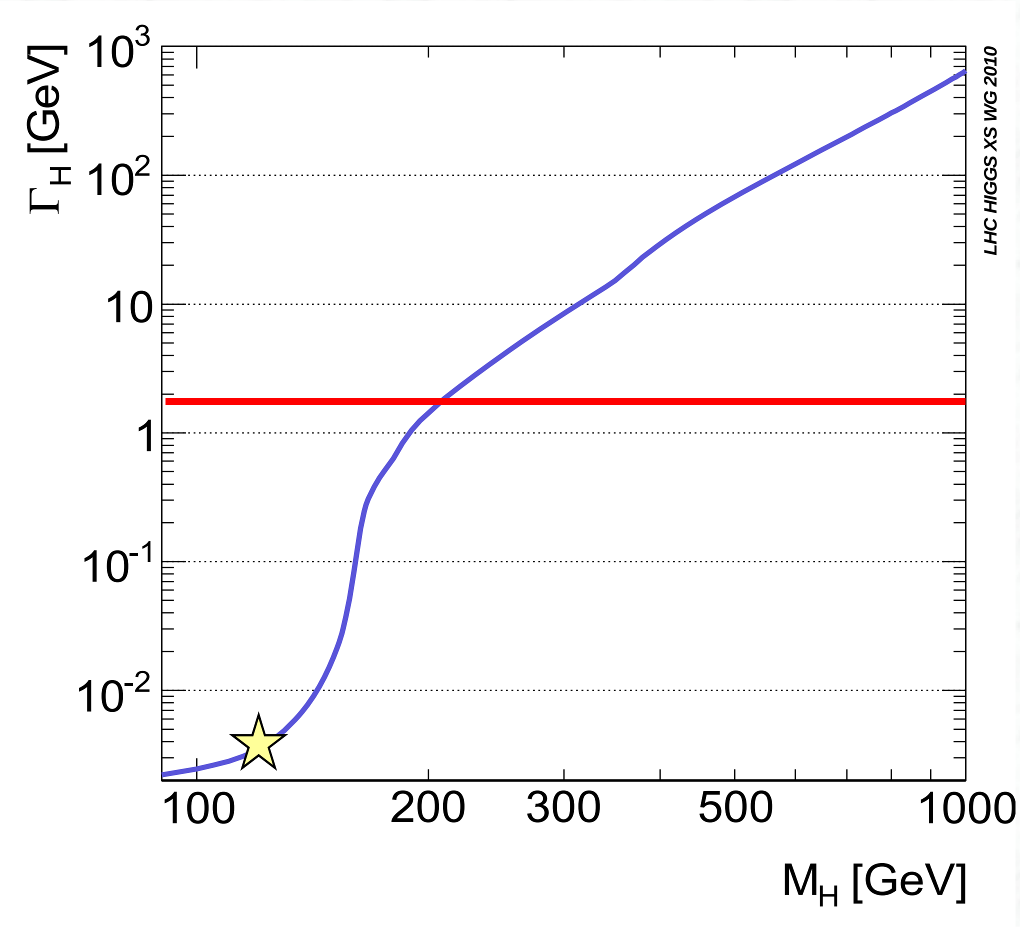
- Test theoretical modeling



Higgs boson width

- The Standard Model Higgs boson width is expected to be small: $\Gamma_H \sim 4$ MeV
- Experimental mass resolution in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ channel ~1 - 2 GeV

→ only upper limits can be extracted from the observed mass peaks



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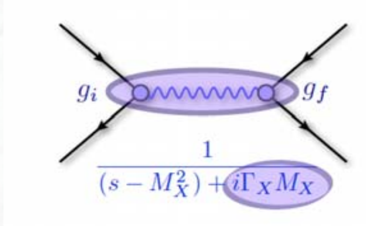
Results: 95% CL limits

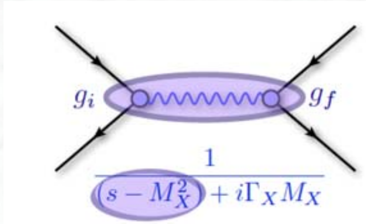
Γ_H < 1.7 GeV (2.3 expected)

Indirect constraint on the Higgs boson width from "off-shell cross sections"

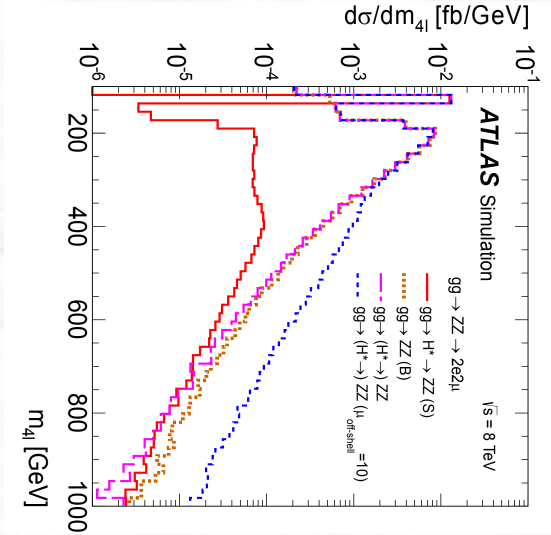
- Different sensitivity of on-shell and off-shell cross sections on the Higgs boson width
- However, model dependent: assumes that on-shell and off-shell couplings are the same
- Dependence on K-factors for signal and backgrounds (gg → VV)



$$\sigma^{on}_{i\to X\to f} \sim \frac{g_i^2 g_f^2}{\Gamma_X}$$



$$\sigma^{off}_{i\to X\to f} \sim g_i^2 g_f^2$$



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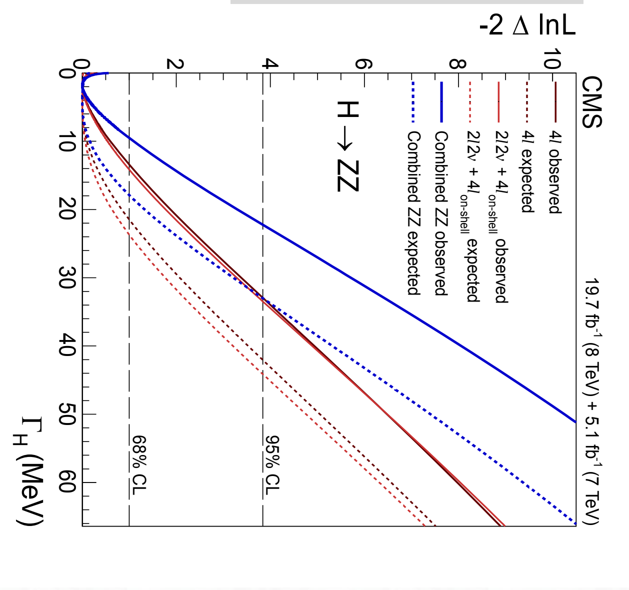
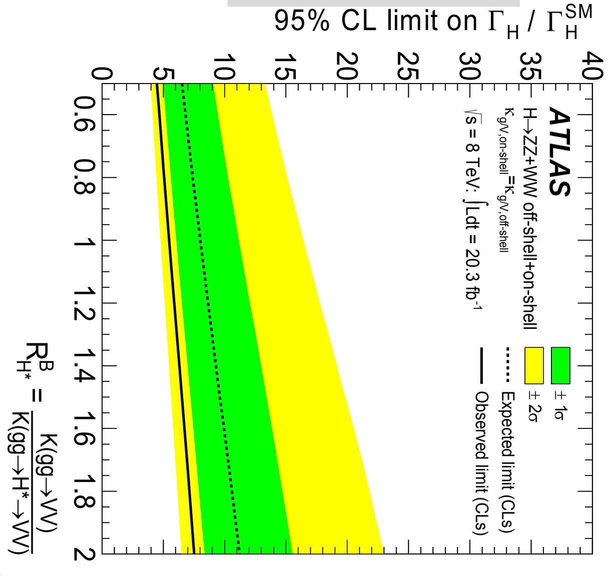


arXiv: 1503.01060



Results: 95% CL limits

CMS: Γ_H / Γ_{SM} < 5.4 (= 22 MeV)

ATLAS: Γ_H / Γ_{SM} < 5.5 ($R_B^{H^*}$ = 1)

Additional Higgs bosons?

Composite Higgs bosons

MSSM Higgs bosons

Dark Higgs

More Higgs bosons

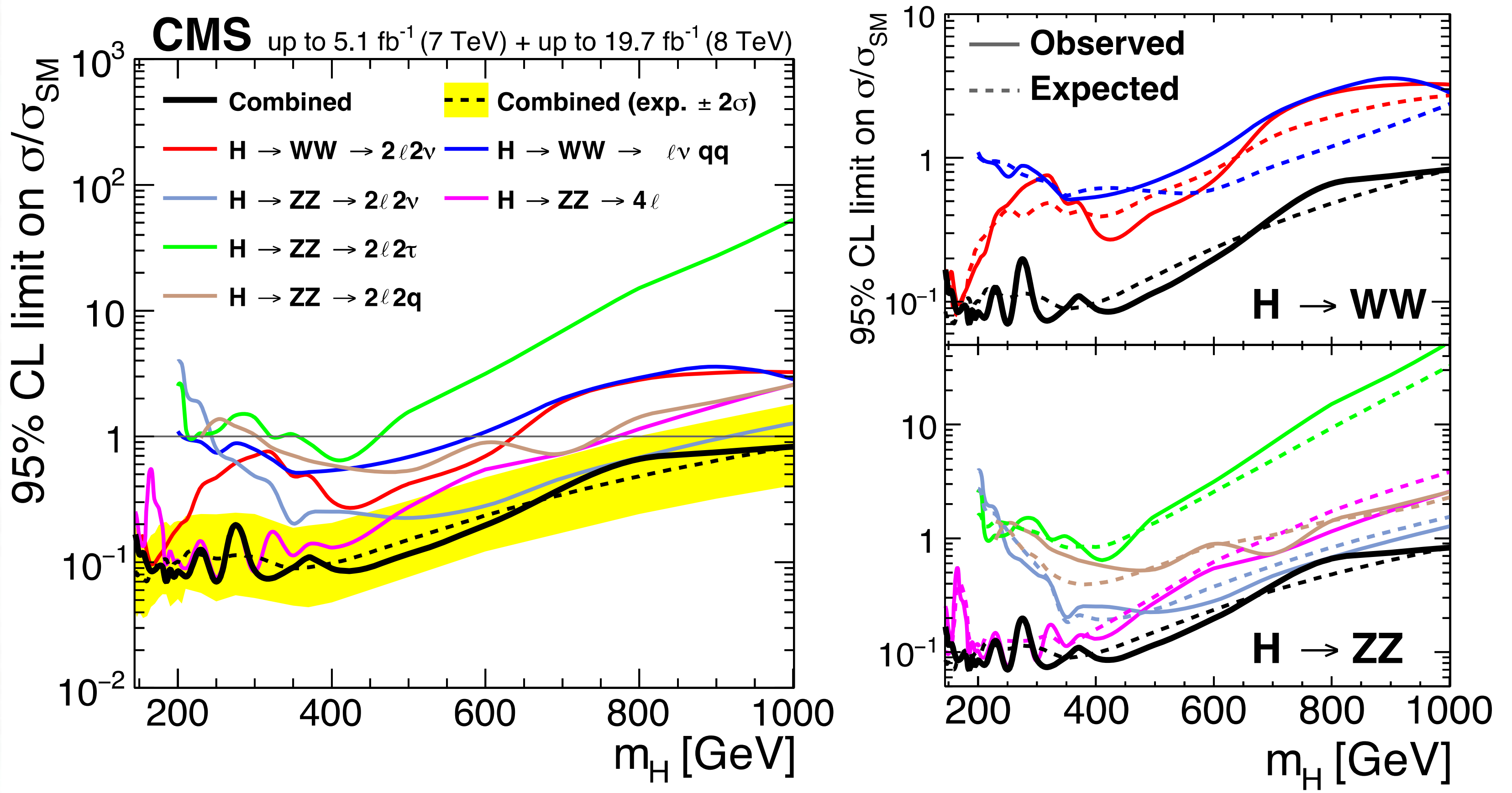
SUSY Higgs

Heidi Higgs

No Higgs at the LHC

(ii) Results of a CMS search on additional SM-like Higgs bosons decaying into ZZ and WW

arXiv:1504.00936



Observed and expected 95% CL limits on the cross section normalised to the SM value for individual channels and their combination

(iii) Search for charged and heavy neutral MSSM Higgs bosons

Search for $H^{\pm} \rightarrow \tau\nu$ decays via
tt production or $tH^{\pm}$ associated production

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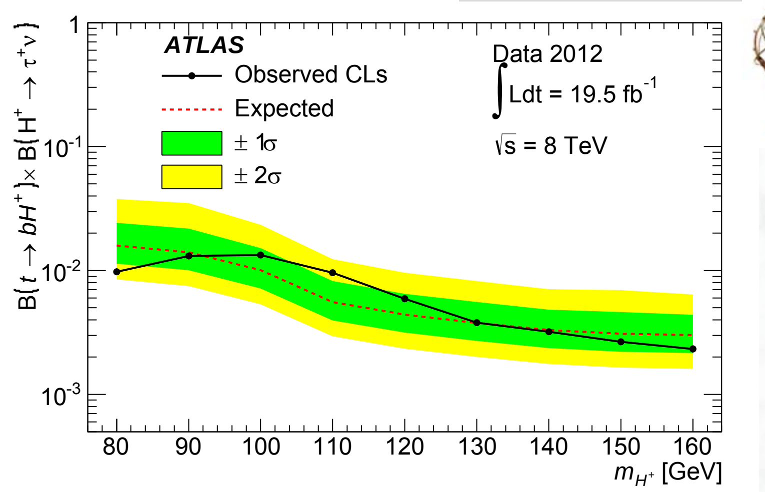

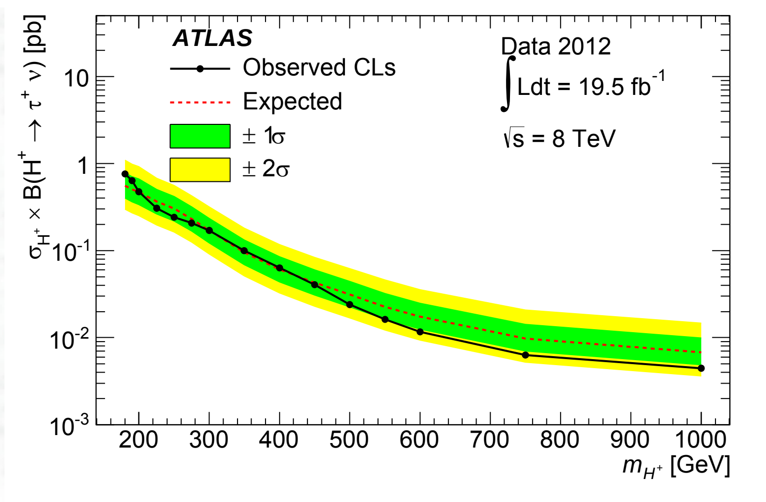

95% CL exclusion limits on branching ratios or cross sections times branching ratio

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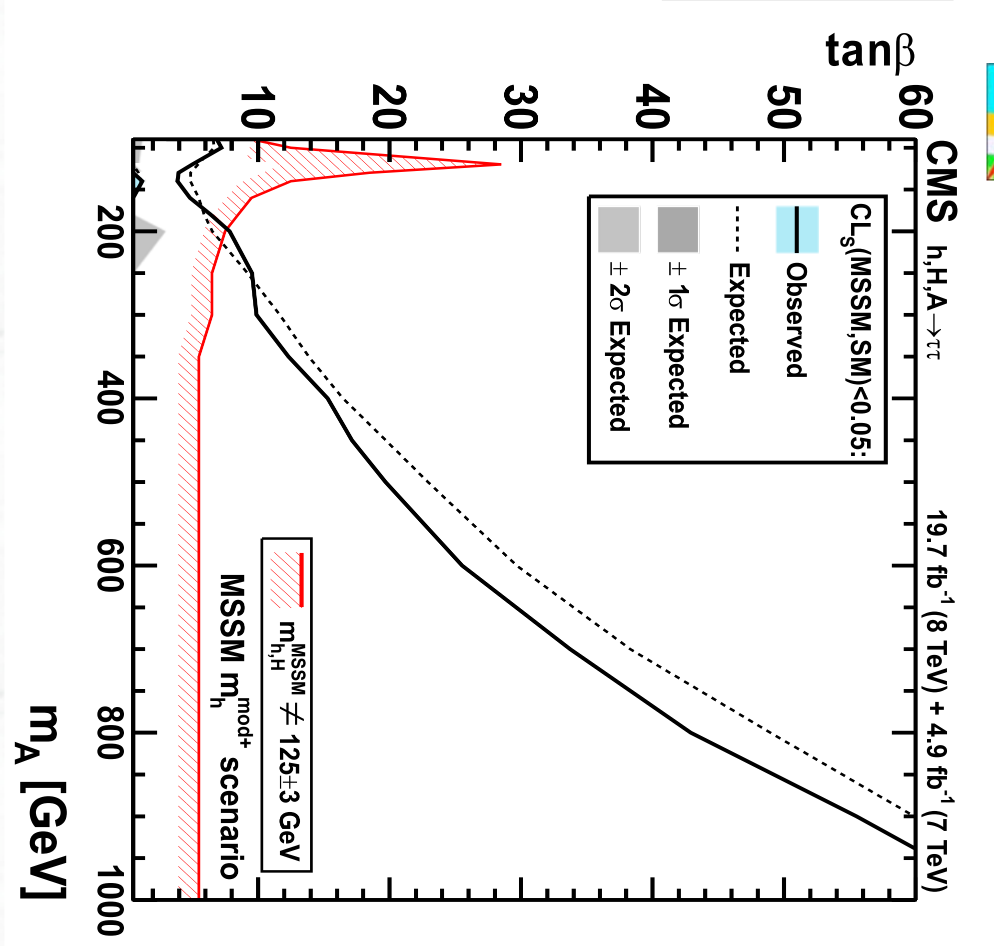
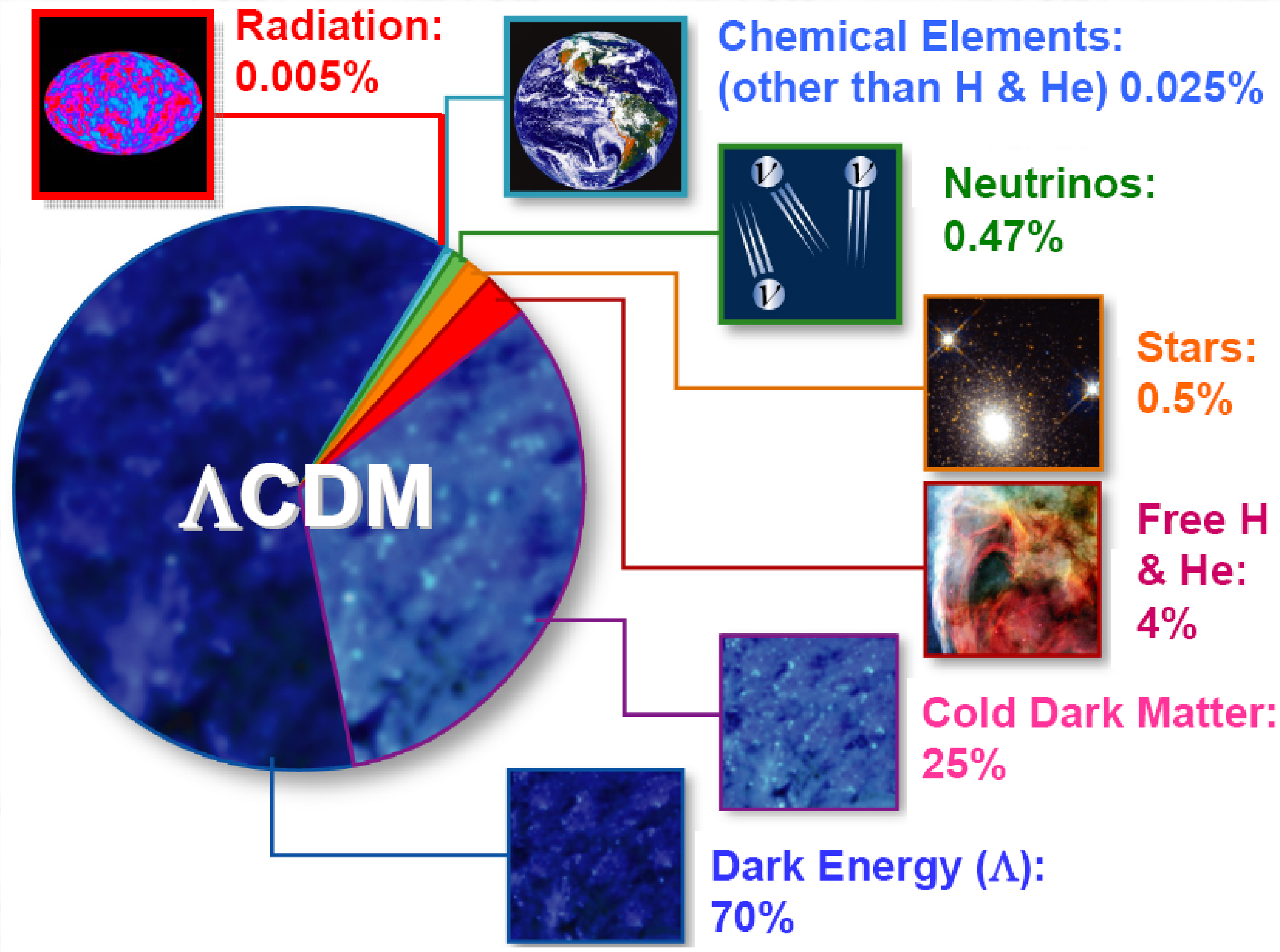
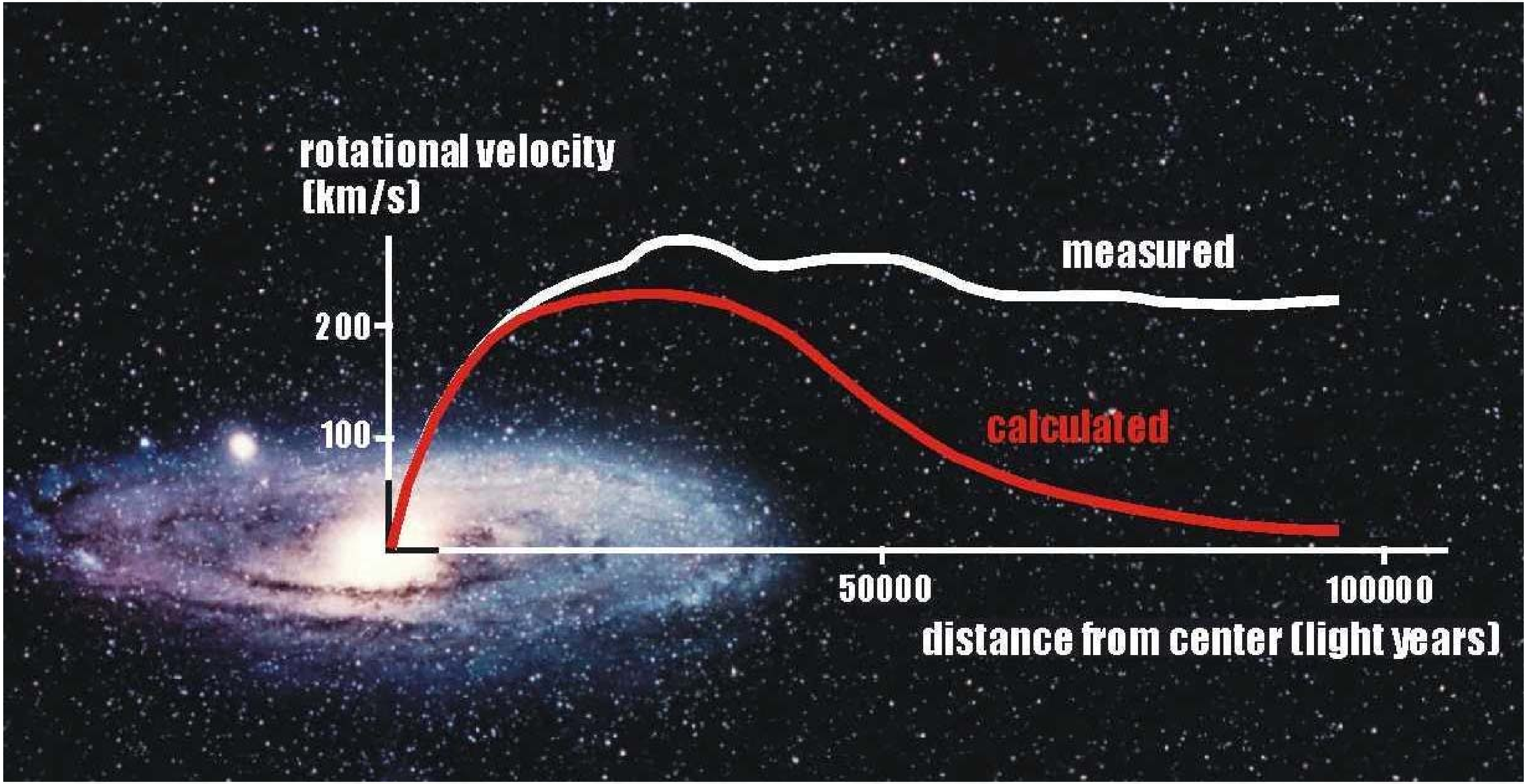


Expected and observed exclusion limits at 95% CL in the (m_A–tan β) parameter plane for the MSSM m_h^{mod+} benchmark scenario

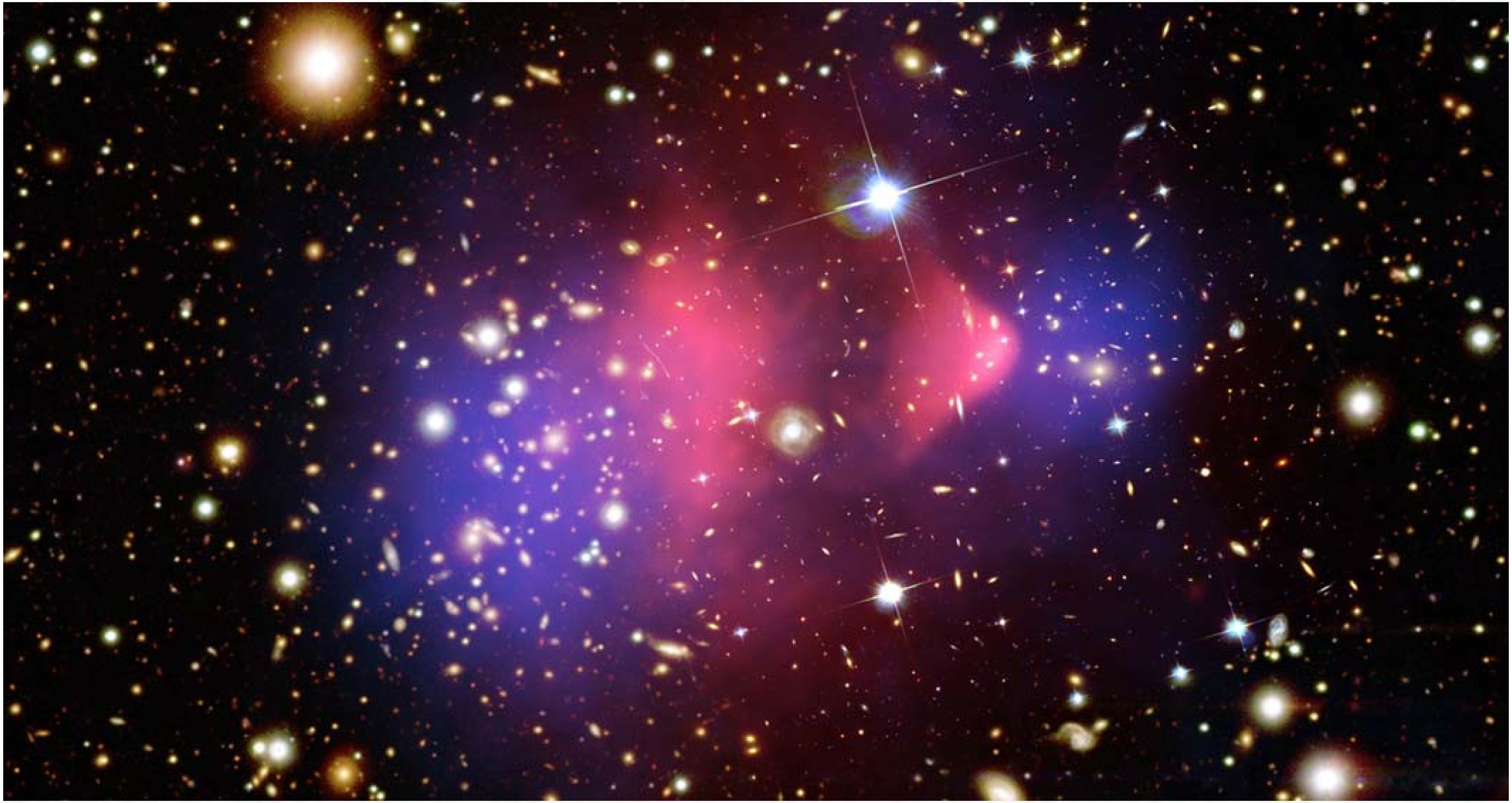
Mass in our Universe



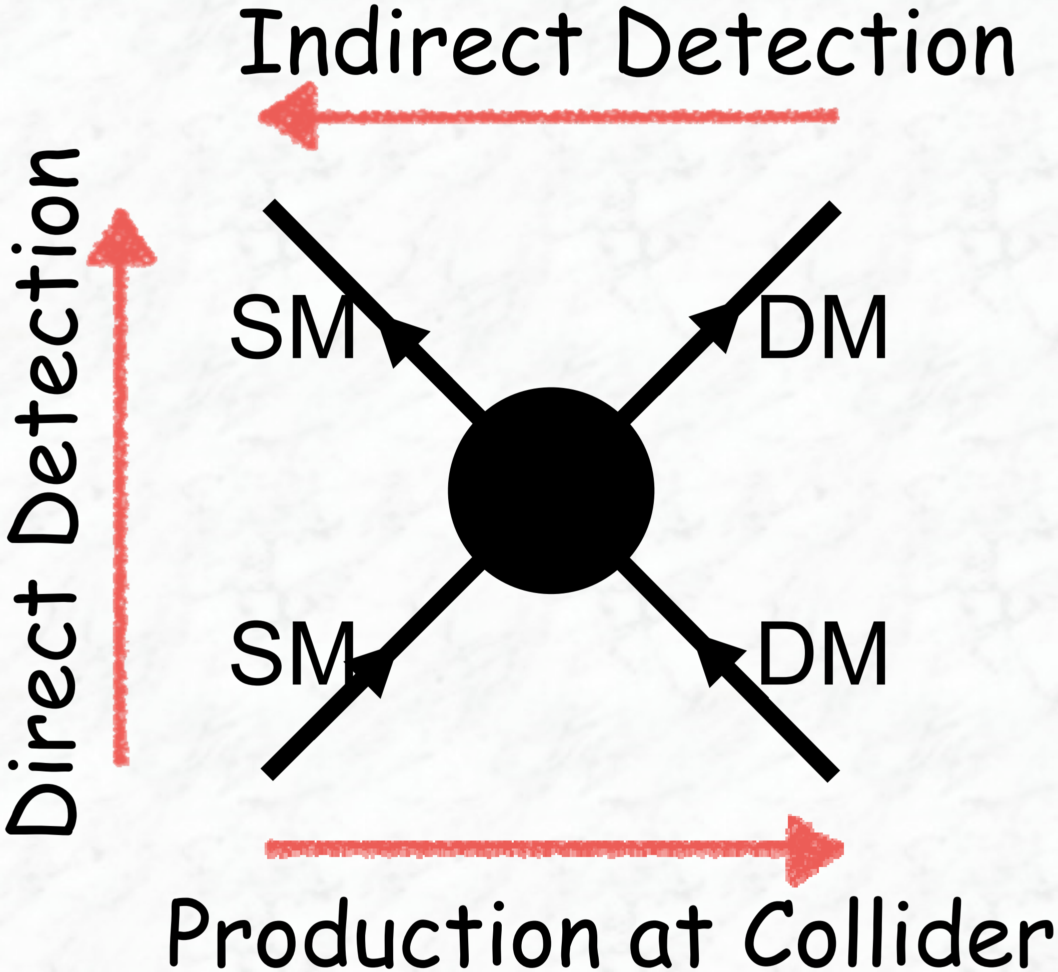
Dark matter


rotational velocity
(km/s)
200
100
measured
calculated
50000
100000
distance from center (light years)

Dark Matter

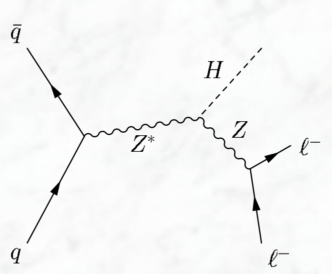


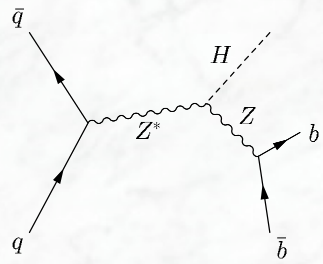
Dark Matter

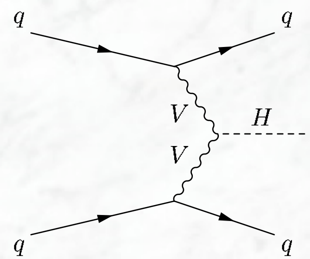

Indirect Detection
Direct Detection
SM
DM
SM
DM
Production at Collider

Search for invisible Higgs boson decays

- Some extensions of the Standard Model allow a Higgs boson to decay to stable or long-lived particles







- Search for excess in ZH associated production and VBF production

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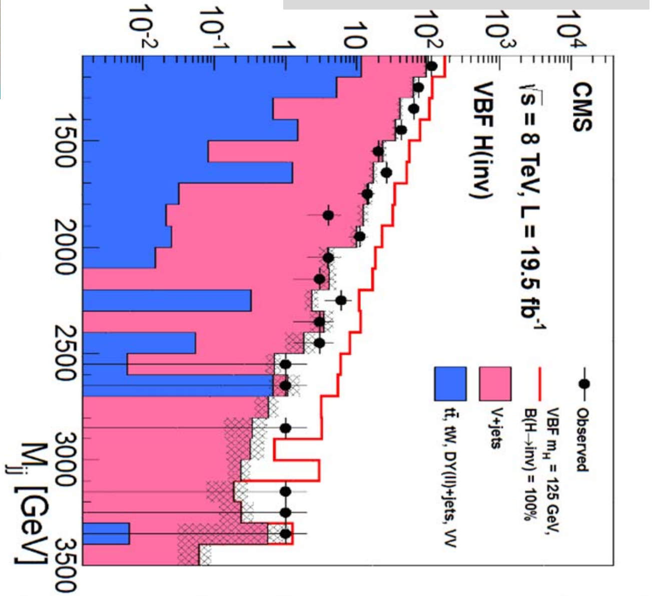
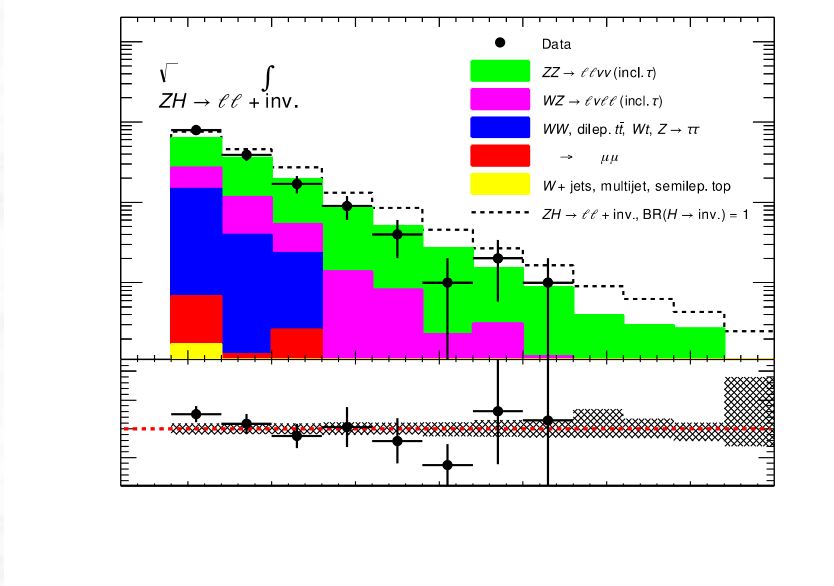


VBF

ZH

PRL 112 (2014) 201802



Assuming the ZH and VBF production rates for m_H = 125 GeV:

ATLAS: 95% CL on BR (H → inv.) < 0.75 (from ZH production)

95% CL on BR (H → inv.) < 0.29 (from VBF production) [ATLAS-CONF-2015-004]

CMS: 95% CL on BR (H → inv.) < 0.58 (from ZH + VBF combination)

Interpretation in Higgs-portal models

-Stable dark matter particles with couplings to the Higgs boson-

- For $m_\chi < m_H/2$, limits on invisible branching ratios can be translated to the spin-independent DM-nucleon elastic cross section for scalar, vector and fermionic DM particles

- Higgs-nucleon coupling, model dependent: assume $0.33^{+0.30}_{-0.07}$ (lattice calculations)

- Within this model, interesting limits for low m_χ masses

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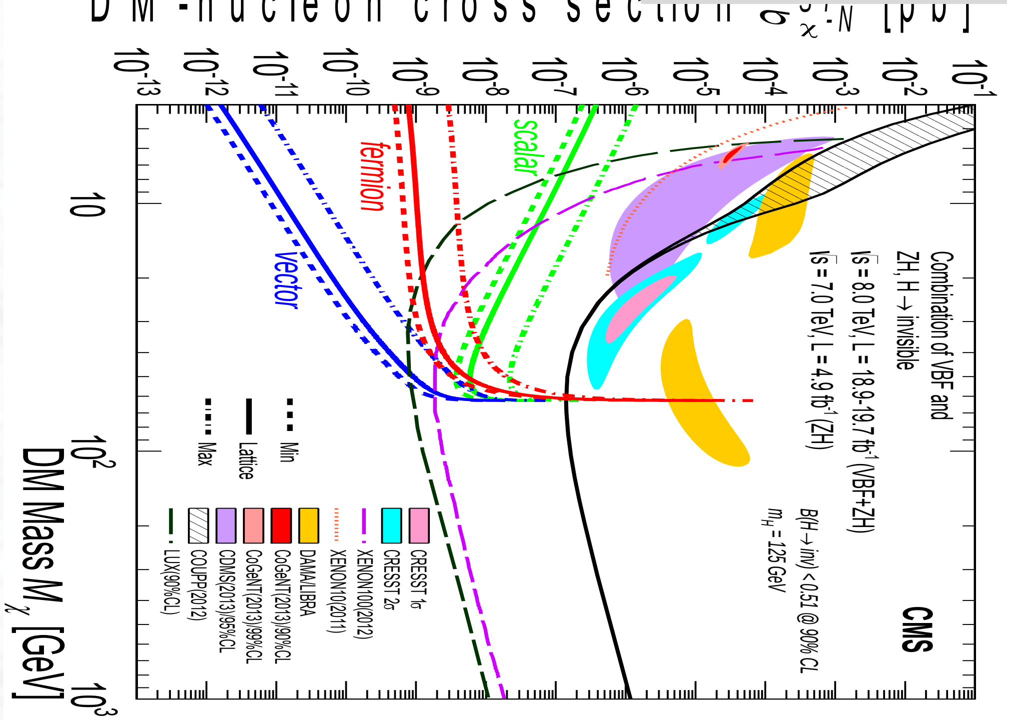

PRL 112 (2014) 201802