Status of Higgs Boson Couplings and Searches

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FPCP, 26 May 2015

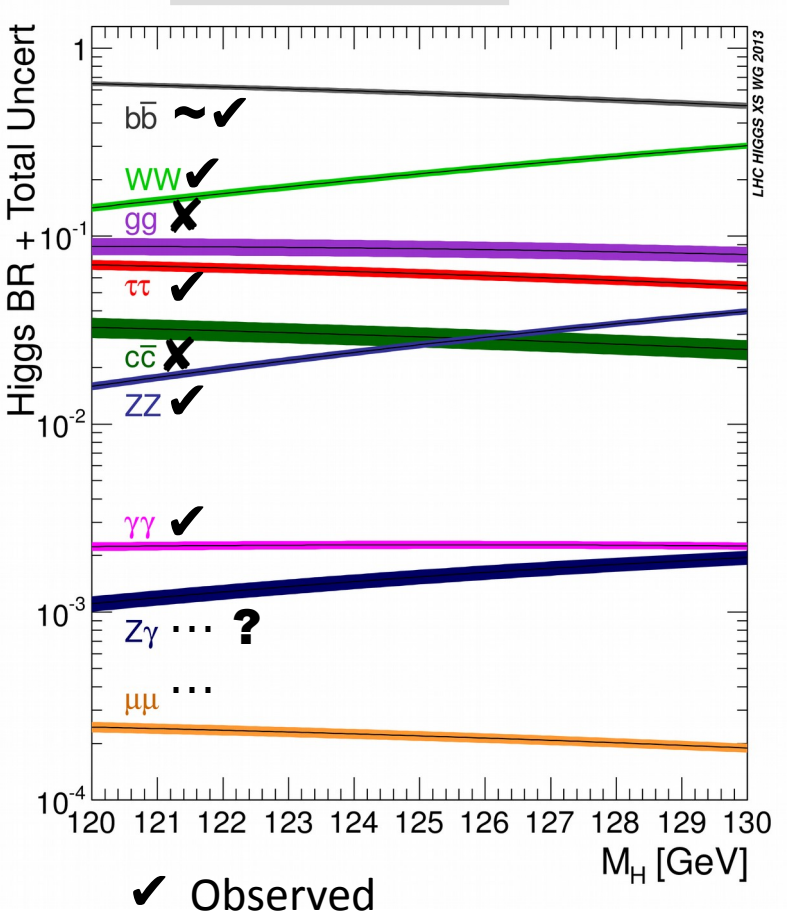
Outline

- H(125) coupling measurements
- Non-SM H(125) interactions
- Search for H^+
- Search for a light pseudoscalar a
- Search for di-Higgs resonances

Unable to cover full spectrum of BSM Higgs physics here!
In particular minimal discussion of searches for high mass states.

SM Higgs at the LHC

Decay Modes

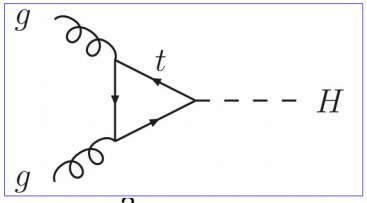


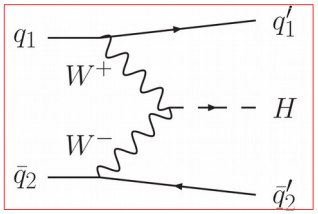
✔ Observed

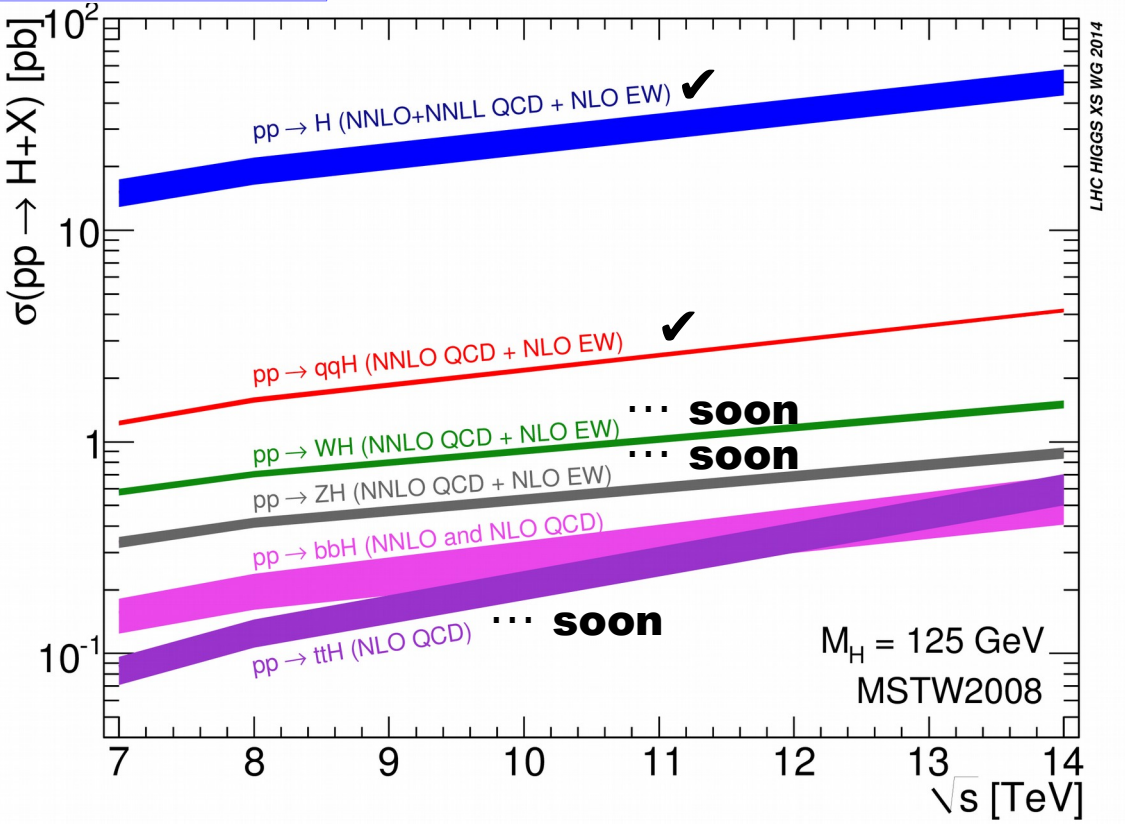
··· Expect observation at LHC

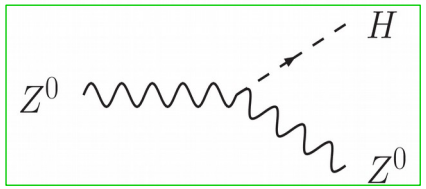
✘ Do not expect to observe at LHC

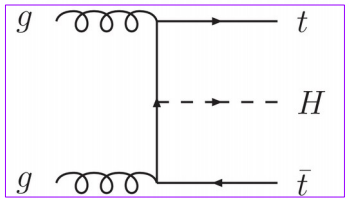
Production Modes





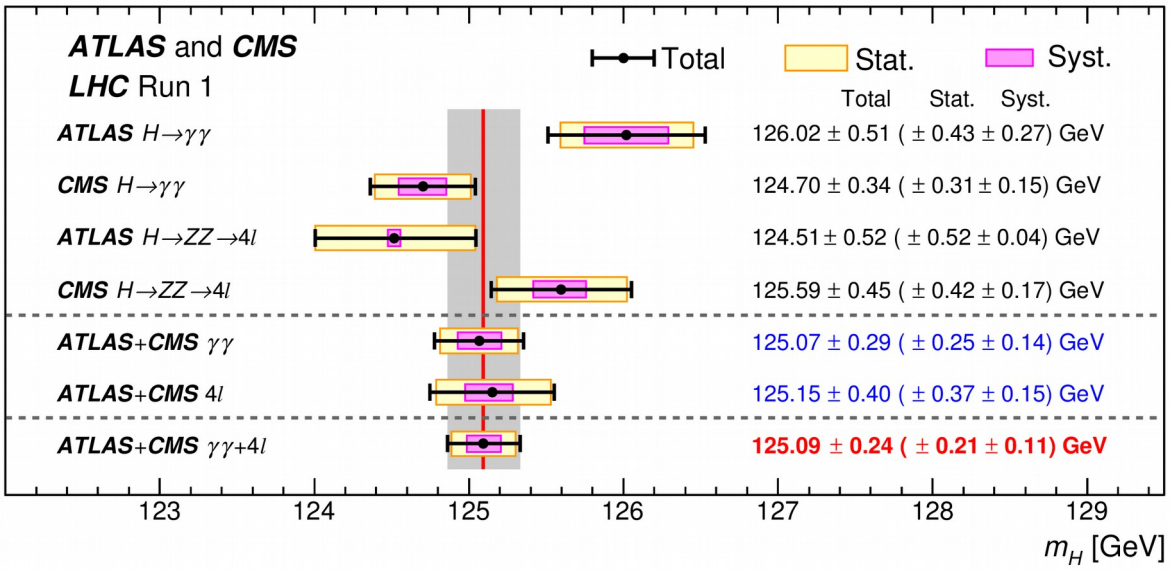


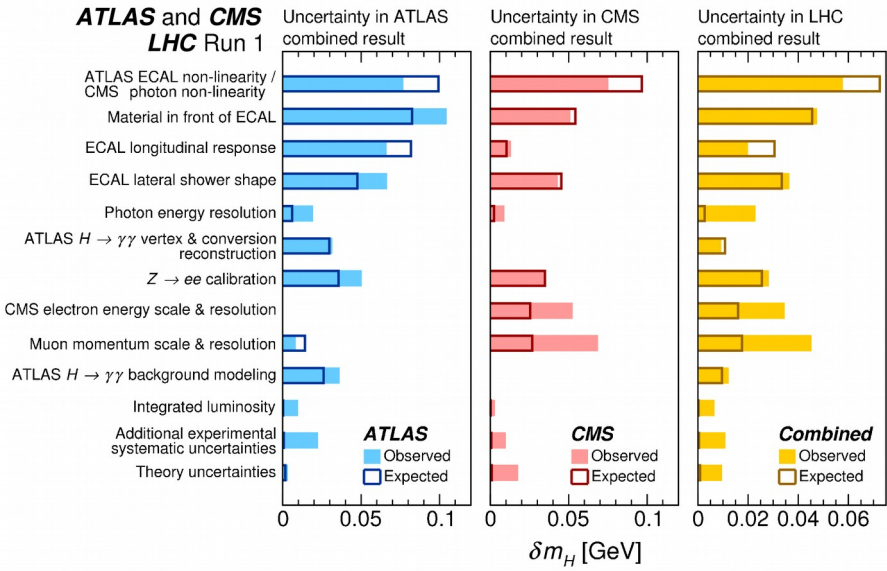




Higgs Mass

- Use high resolution decay modes H → γγ and H → ZZ → 4ℓ
  - diphoton has more statistical power, 4ℓ has (in principle) better systematics





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

0.2% measurement

PRL 114, 191803 (2015)

Coupling Formalism

- Allow scale factors κ_i for the couplings of the SM
  - and ratios $\lambda_{ij} = \kappa_i/\kappa_j$

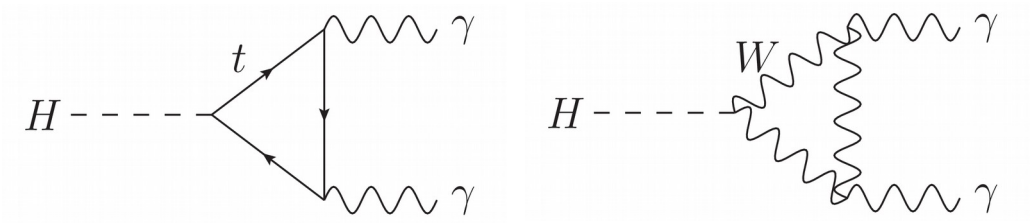
$$\Gamma(H \to X) = \kappa_X^2 \Gamma(H \to X)_{\rm SM}$$

- Invisible or undetected decays have branching fraction $BR_{i,u}$
- Overall width scales as $\Gamma_H = \frac{\kappa_H^2}{1 - \mathrm{BR_{i,u}}} \Gamma_H^{SM}$

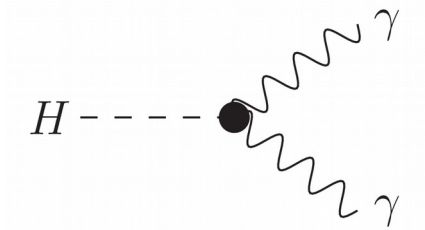
*coherently scale all κ, increase $BR_{i,u}$: no effect on observed **on-shell** μ*

- Loop-induced couplings either *resolved* (expressed in terms of SM particle κ) or *unresolved* (have their own κ to capture possible new physics)

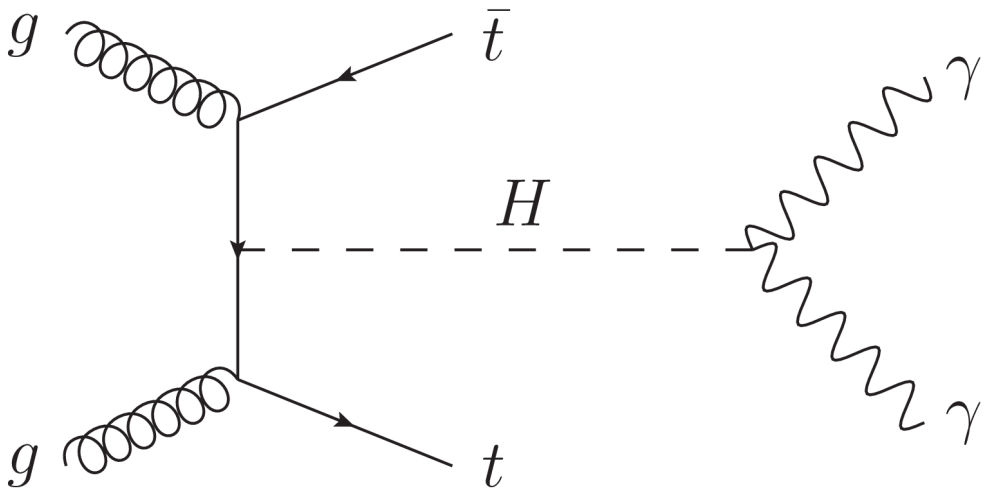
resolved



unresolved



Example of κ-formalism



$$\frac{\Gamma_{\gamma\gamma}/\Gamma_H}{\Gamma_{\gamma\gamma,SM}/\Gamma_{H,SM}}$$

On-shell!

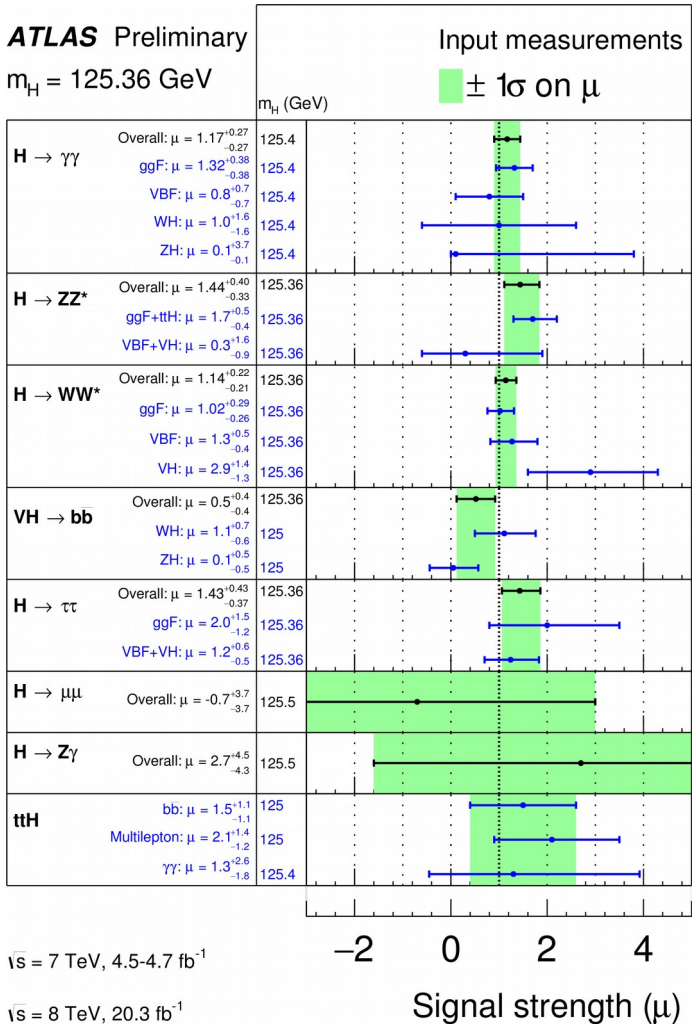
$$\mu = \frac{\text{Rate}}{\text{SM Rate}} = \kappa_t^2 \times \frac{\mathcal{B}(H \to \gamma\gamma)}{\mathcal{B}(H \to \gamma\gamma)_{\text{SM}}}$$

unresolved $\quad \kappa_t^2 \times \kappa_\gamma^2 \times \frac{\Gamma_{H,SM}}{\Gamma_H}$

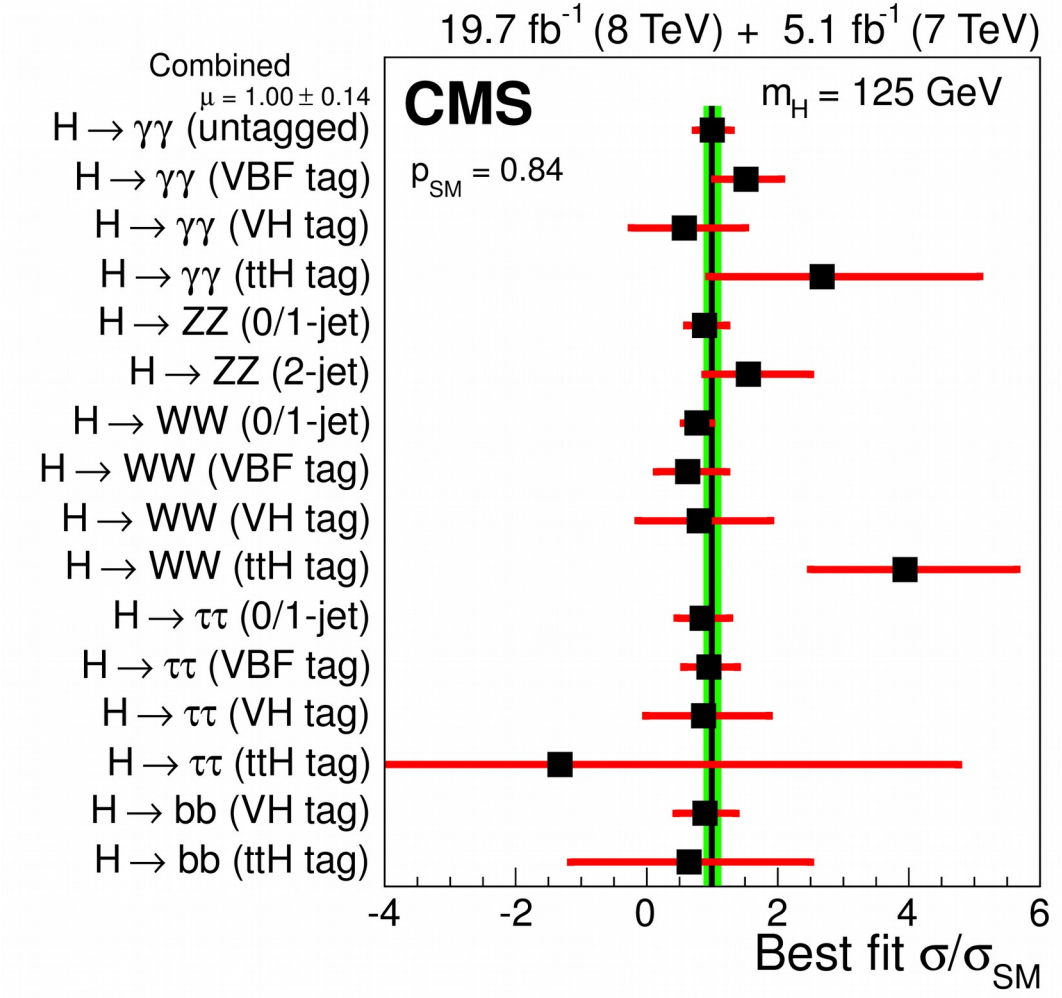
resolved $\quad \kappa_t^2 \times \left(1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.66\kappa_W\kappa_t\right) \times \frac{\Gamma_{H,SM}}{\Gamma_H}$

Can increase all κ coherently and keep same on-shell μ
if increase Γ_H to compensate (invisible/undetected decays)

Inputs to the Coupling Measurements



ATLAS-CONF-2015-007



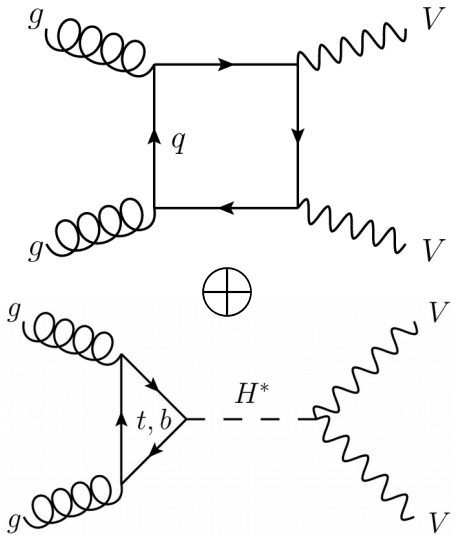
arxiv:1412.8662
sub. to EPJC

Off-shell Measurements

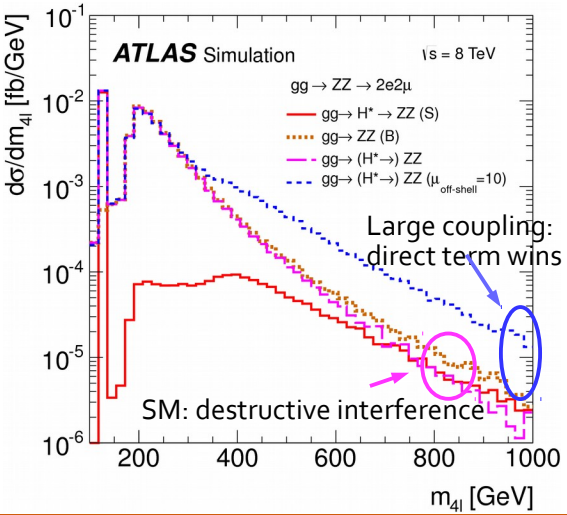
- Production of off-shell H gives access to couplings independent of Higgs width

$$\frac{g_i^2 g_f^2}{(s - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

dominates off-shell — dominates on-shell



- $H \rightarrow VV$ increases dramatically once $m_{H^*} \geq 2m_V$
- For SM-like Higgs, biggest effect is destructive interference with $gg \rightarrow VV$



No excess: interpret as limit on couplings or width, *assuming couplings s-independent*

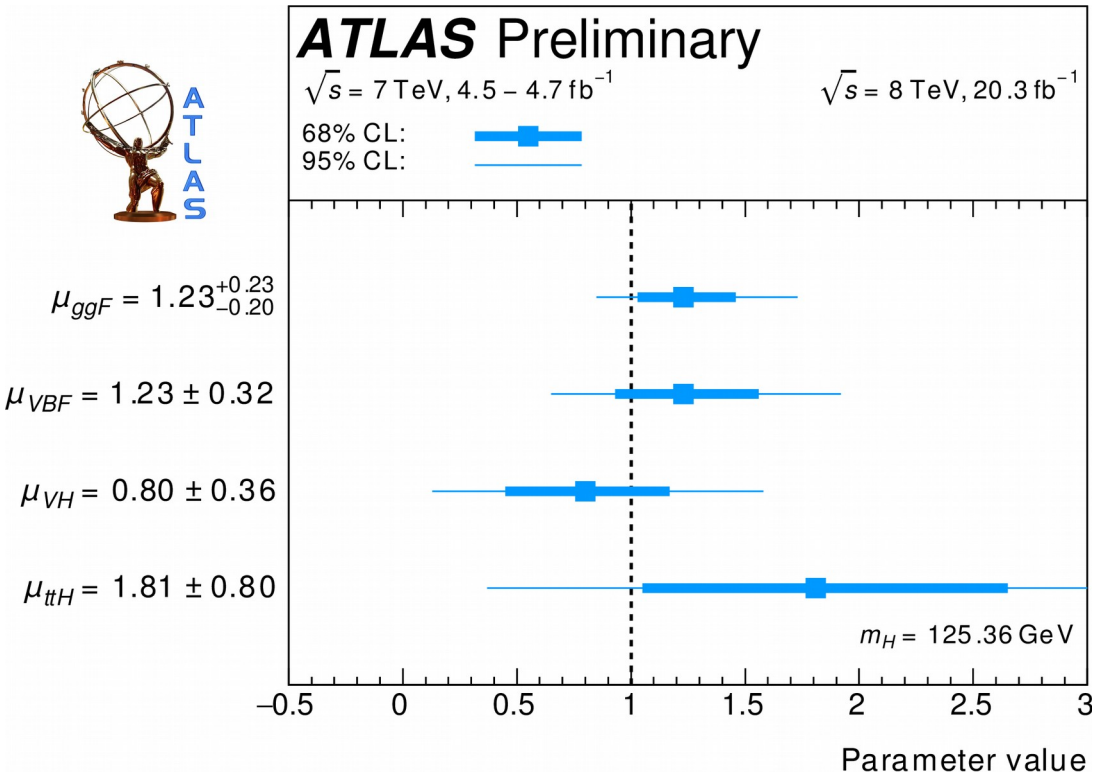
Indirect limits on Γ_H:

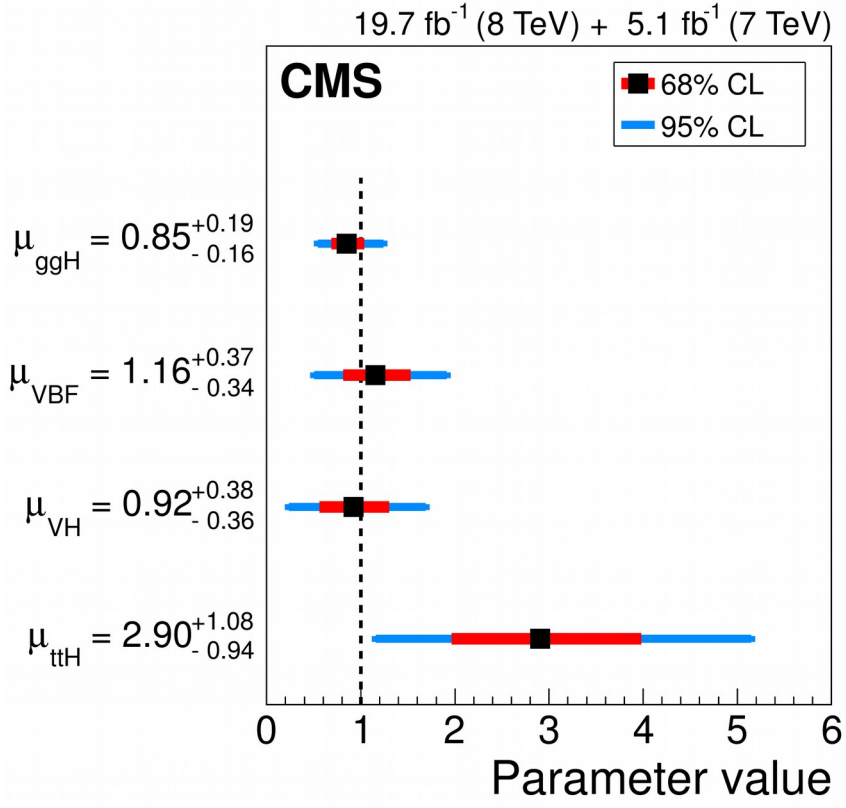
$\Gamma_H/\Gamma_H^{SM} < 5.5$ (8.0 exp) : ATLAS arxiv:1503.01060, sub. to EPJC

< 5.4 (8.0 exp) : CMS PLB 736 (2014) 64

Direct limits are ~ 2 orders of magnitude worse

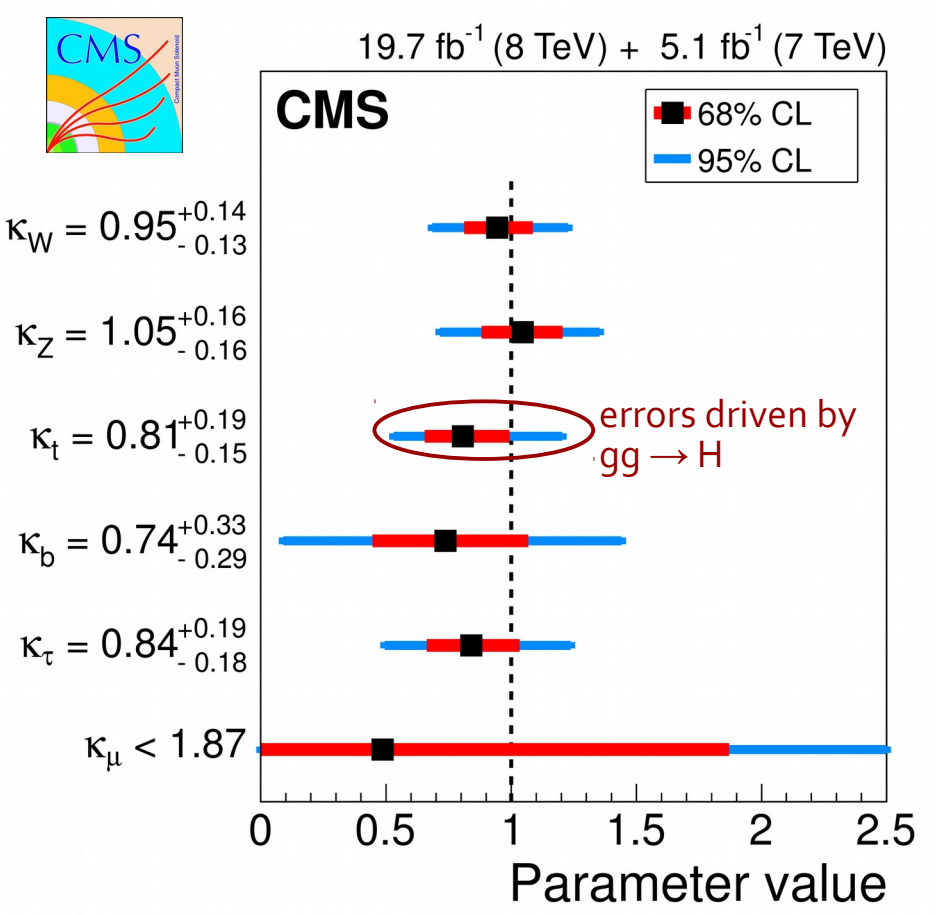
Production Process Significance

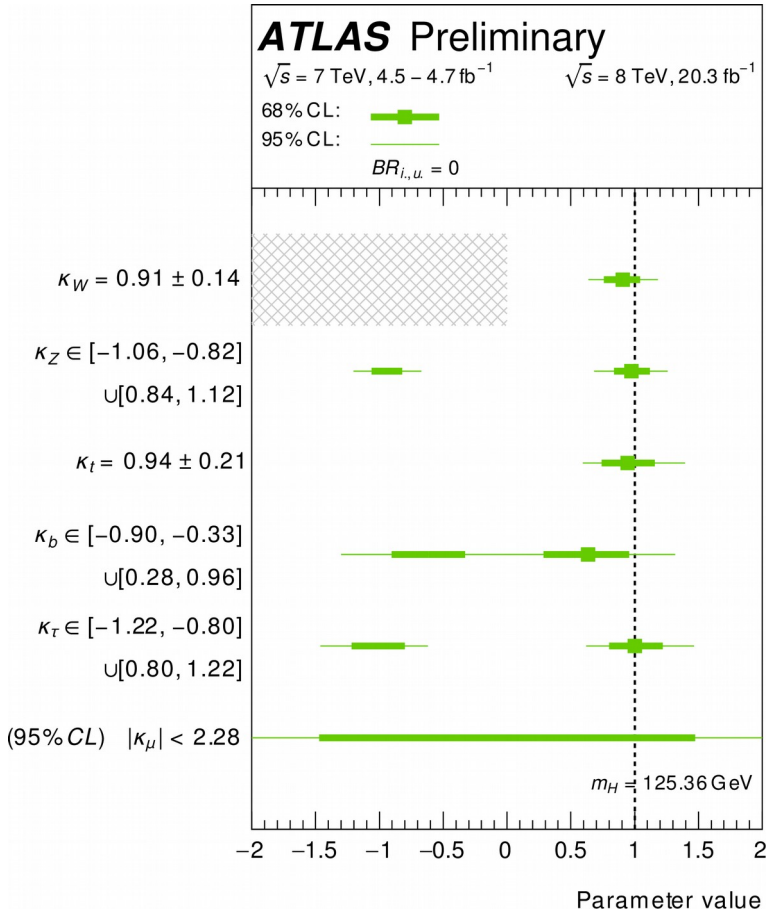




	Significance			
	ATLAS		**CMS**	
Mechanism	Obs	Exp	Obs	Exp
VBF	4.3	3.8	3.7	3.3
VH	2.6	3.1	2.7	2.9
ttH	2.4	1.5	3.5	1.2

Couplings: SM content, decays

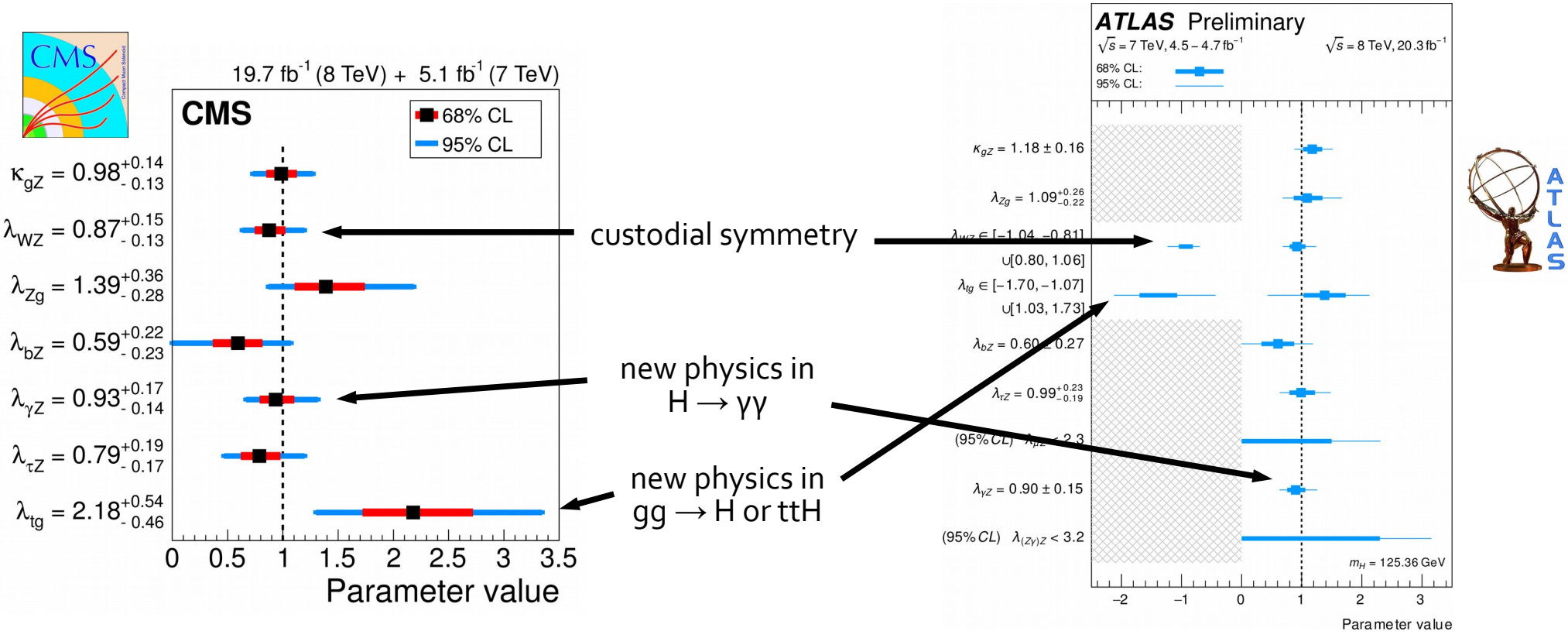




Assume only SM particles, no new Higgs decay modes
Best constraints ~ ±14% of SM coupling

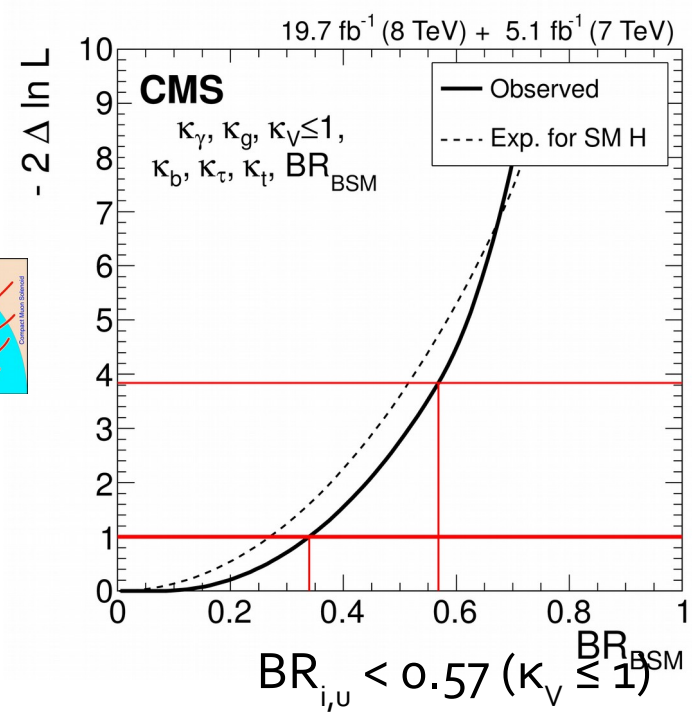
Couplings: New Physics Tests

- Relax assumptions on the width, do not resolve any loops (κ_γ, κ_g, $\kappa_{Z\gamma}$ float independently)
  - Look only at ratios (λ_{ij}) and an overall scale $\kappa_{gZ} = \kappa_g\kappa_Z/\kappa_H$
  - no information on invisible/undetected decays

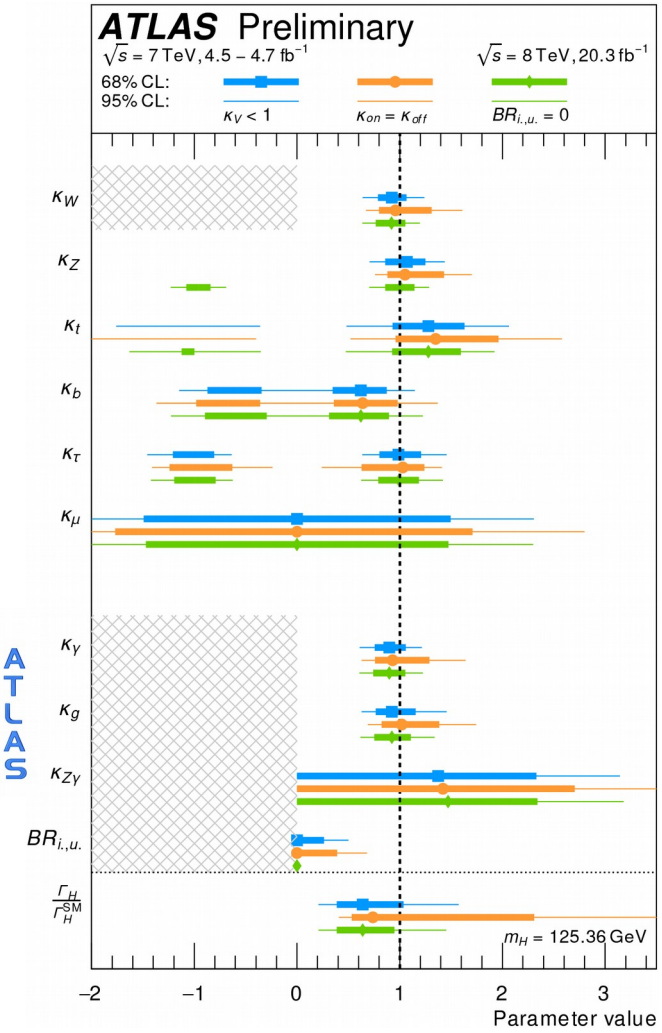


BSM Higgs decays

- Allow $BR_{i,u} > 0$
  - additional info needed to break μ-scaling degeneracy: either assume $\kappa_V \leq 1$ or use off-shell couplings



$BR_{i,u} < 0.57$ ($\kappa_V \leq 1$)

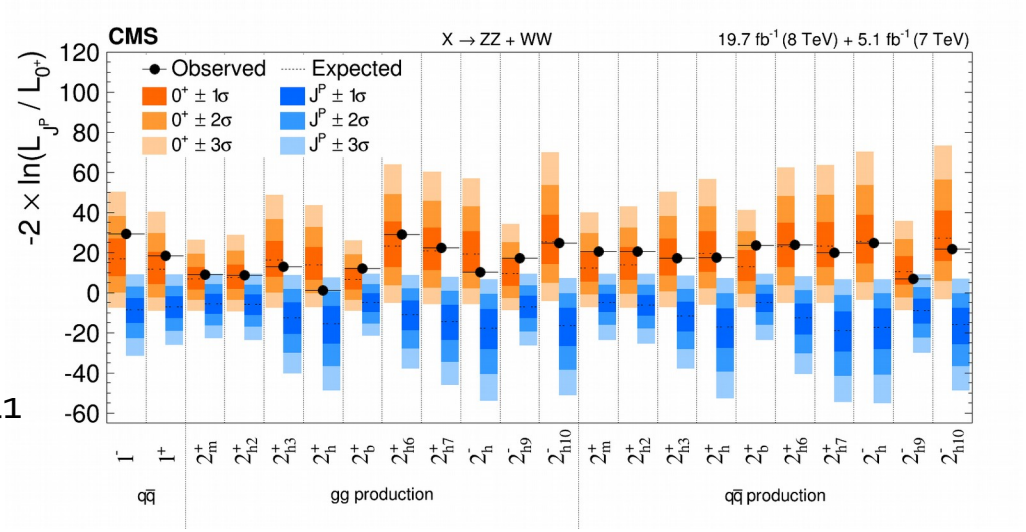


Direct BR(inv) measurements also!
CMS combines to get BR(inv) < 0.32 (if BR(undet) = 0)

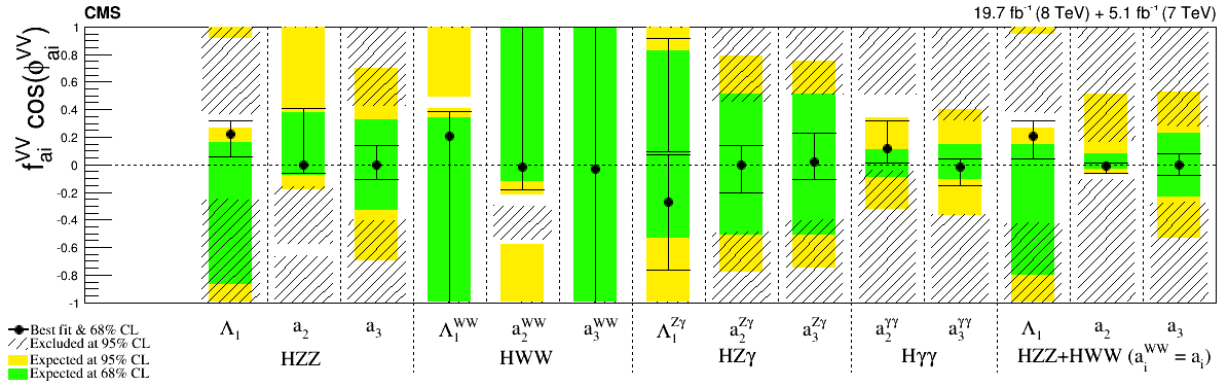
$BR_{i,u} < 0.49$ ($\kappa_V \leq 1$)
< 0.68 ($\kappa_{off} = \kappa_{on}$)

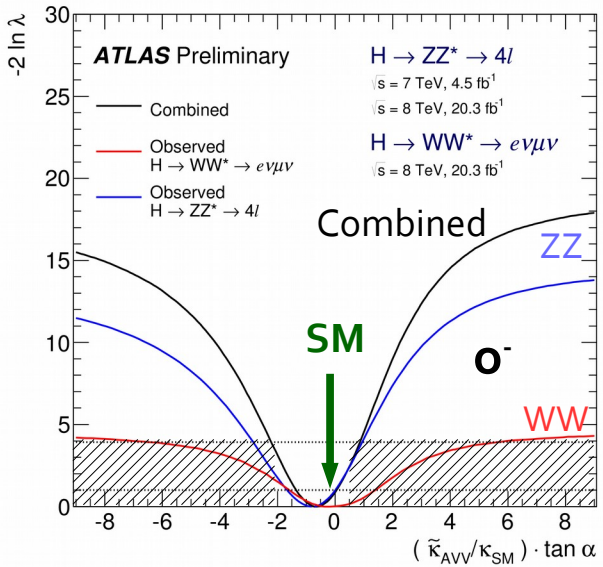
Higgs Boson Spin/CP

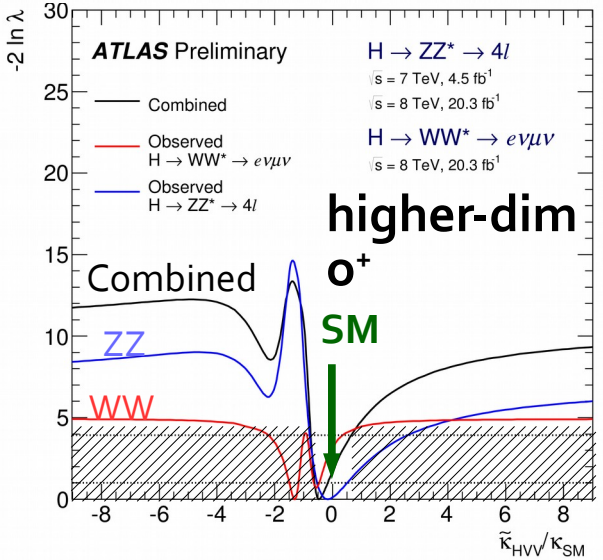
- pure spin 2, 1, 0^- particle excluded at > 99% in almost all models
- limit non-minimal 0^+ couplings, mixture with 0^-



arxiv:1411.3441
sub to PRD



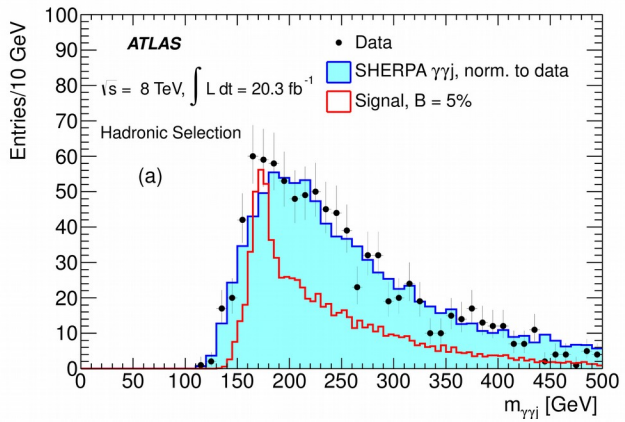


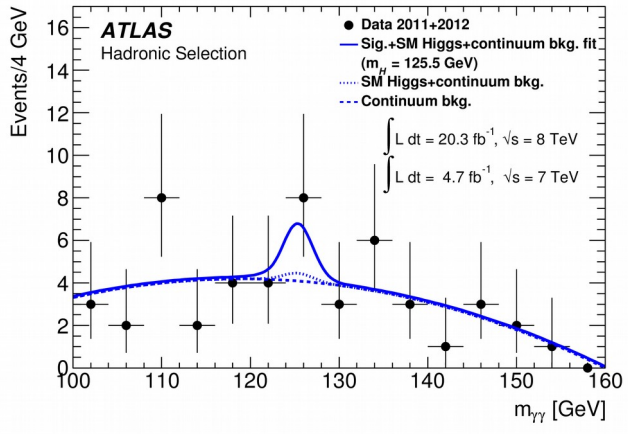


ATLAS-CONF-2015-008

FCNC: t → cH

- Search in H → γγ [ATLAS, CMS] and H → WW/ZZ/ττ [CMS]

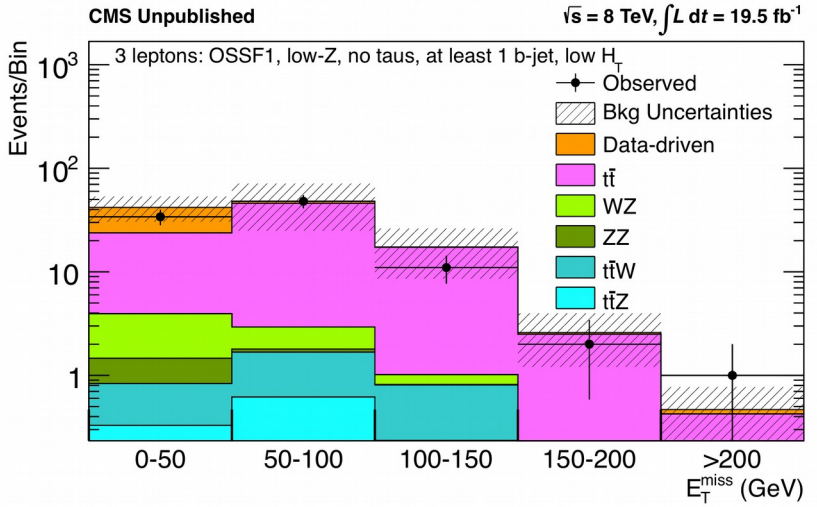




B(t → qH) < 0.79% (0.51%)

JHEP 06 (2014) 008

Leptonic channels reinterpreted from CMS-SUS-13-002, sub to PRD



95% CL upper limits on B(t → cH)

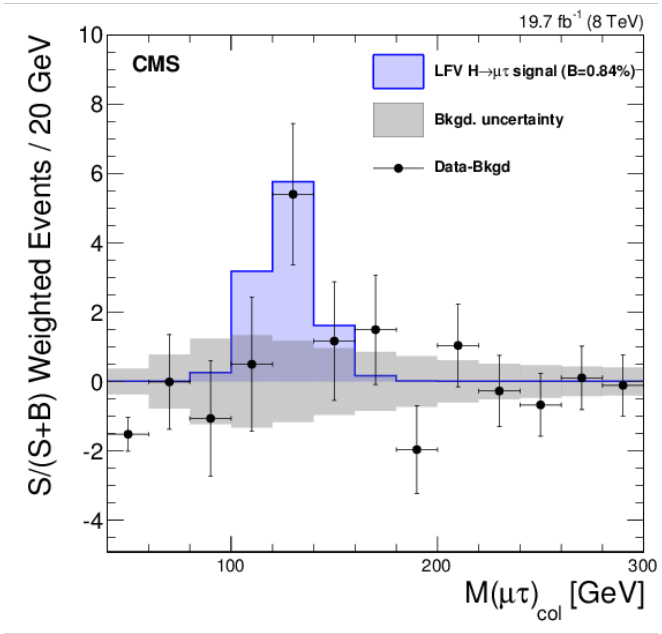
Higgs Decay Mode	observed	expected	1σ range
$H \to WW^*$ ($\mathcal{B}$ = 23.1 %)	1.58 %	1.57 %	(1.02–2.22) %
$H \to \tau\tau$ ($\mathcal{B}$ = 6.15 %)	7.01 %	4.99 %	(3.53–7.74) %
$H \to ZZ^*$ ($\mathcal{B}$ = 2.89 %)	5.31 %	4.11 %	(2.85–6.45) %
combined multileptons (WW^*, $\tau\tau$, ZZ^*)	1.28 %	1.17 %	(0.85–1.73) %
$H \to \gamma\gamma$ ($\mathcal{B}$ = 0.23 %)	0.69 %	0.81 %	(0.60–1.17) %
combined multileptons + diphotons	0.56 %	0.65 %	(0.46–0.94) %

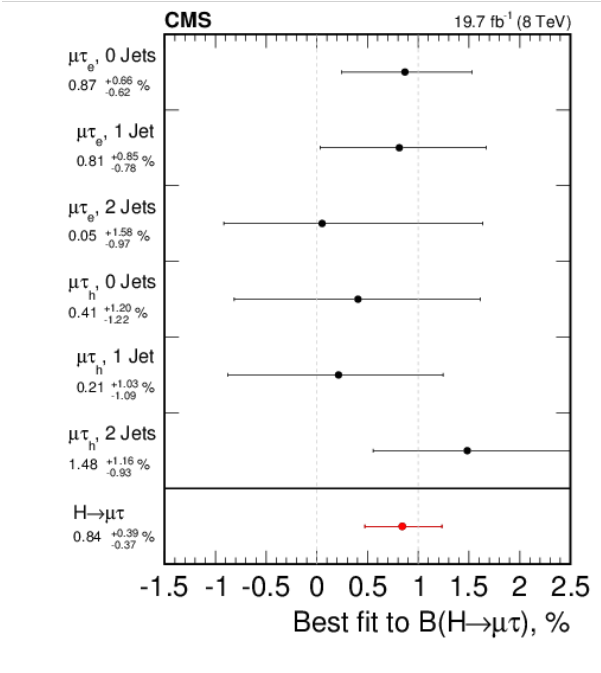
PRD 90 (2014) 112013

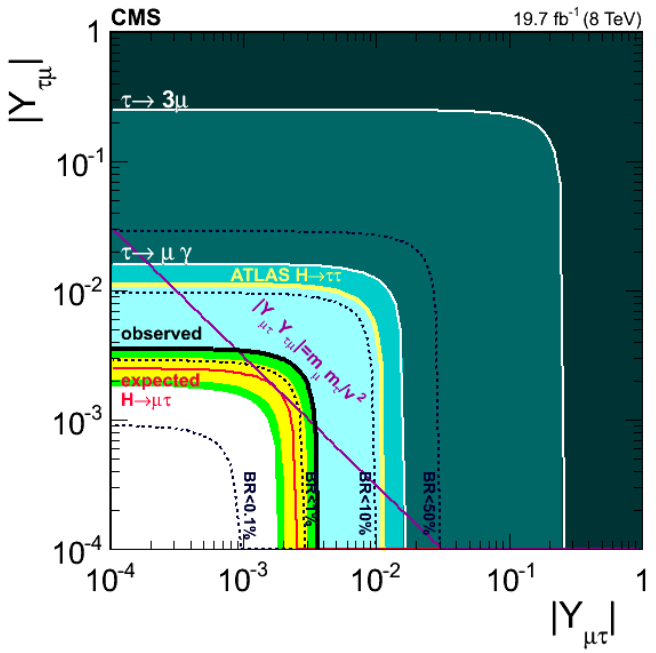
LFV: H → τμ

- Search using gg → H, vector boson fusion production (select by # jets)
- Look for H → τμ, τ → evv or τ → hadrons
- Very good constraints compared to rare τ decays (e.g. τ → μγ)
- Slight excess of events
  - B(H → μτ) < 1.51% @95% CL, best fit 0.84%

arxiv:1502.07400, sub. to PLB

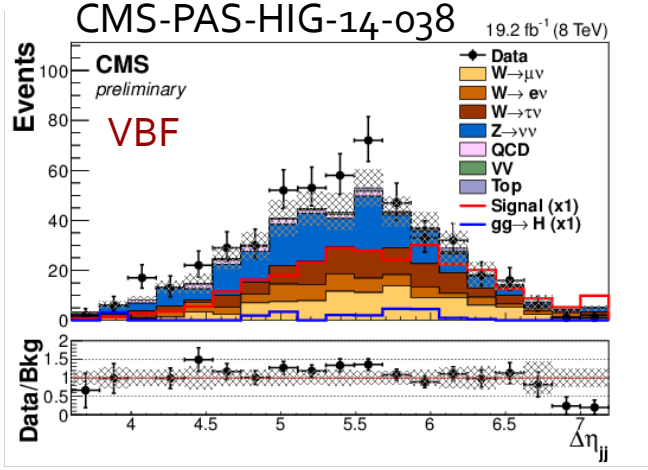


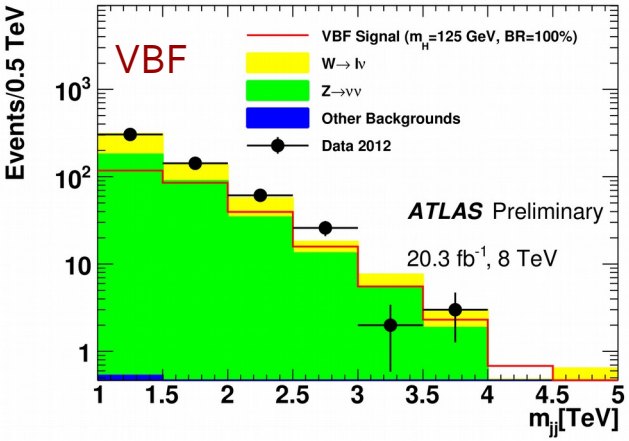




Explicit H → invisible

- Does the Higgs interact with a dark sector?
  - total width badly known: can have unseen decays
  - look for "invisible" Higgs production
  - need a *tag*: characteristic production mechanism. Higgs recoil provides E_T^{miss}
- Tags:
  - vector boson fusion production with two high energy forward jets
  - WH/ZH production





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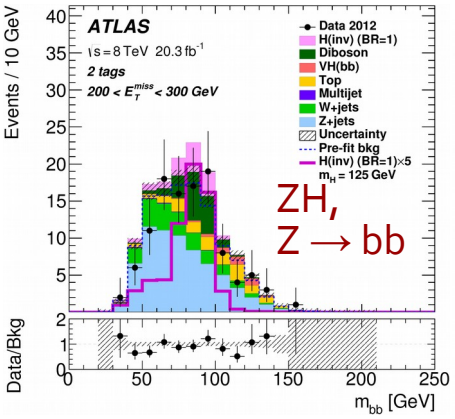
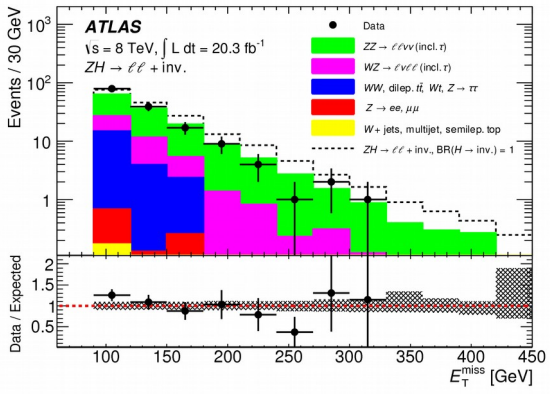
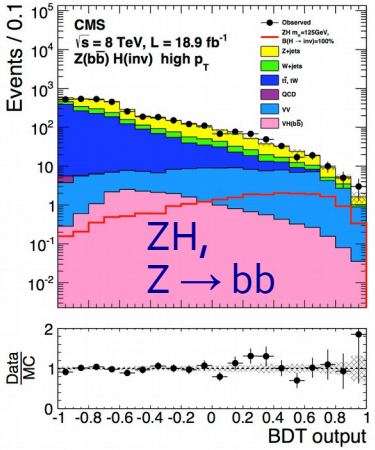


arxiv:1504.04324, sub to EPJC

ZH, Z → ℓℓ



PRL 112 (2014) 201802



EPJC 74 (2014) 2980

H → invisible results

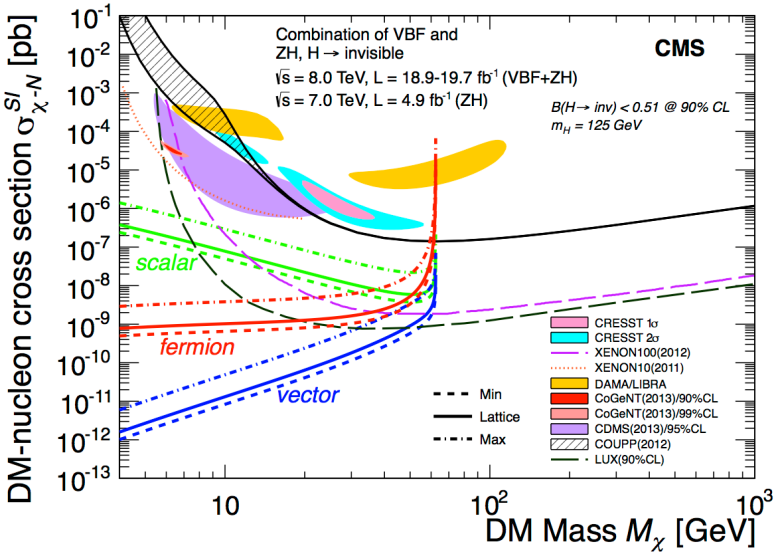
95% CL observed (expected) limits on B(H → inv)

Channel	ATLAS	CMS
Z → ℓℓ	< 0.75 (0.62)	< 0.83 (0.86)
W/Z → jj	< 0.78 (0.86)	< 1.82 (1.99)
VBF	< 0.29 (0.35)	< 0.57 (0.40)
From coupling analysis*	< 0.49	< 0.58 (0.44)

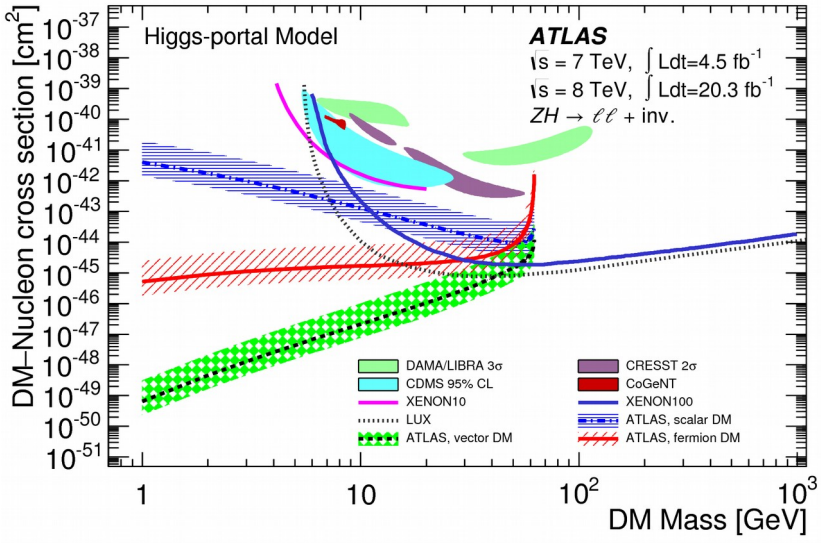
* $\kappa_V \leq 1$

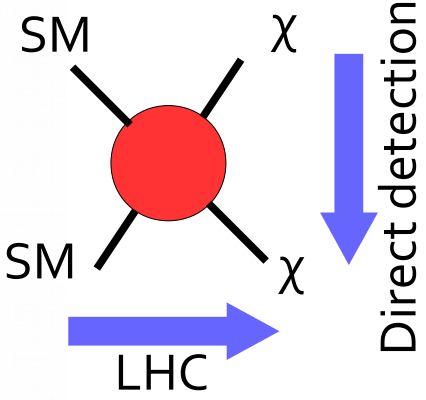
Higgs Portal Dark Matter interpretation

VBF + Z(ℓℓ, bb)H



Z → ℓℓ only

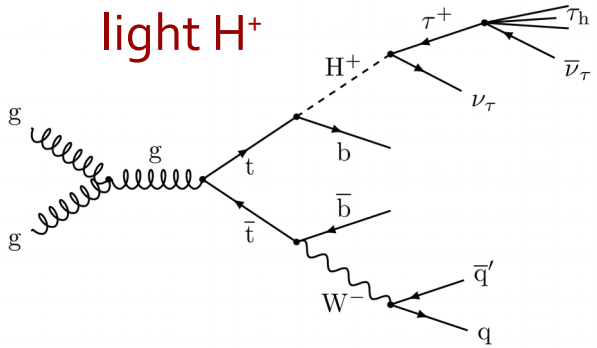




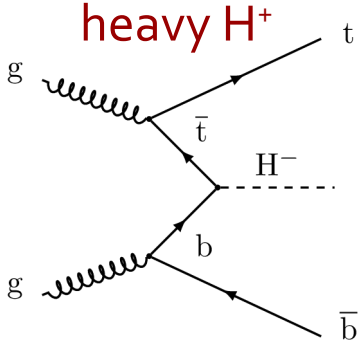
Search for H^+

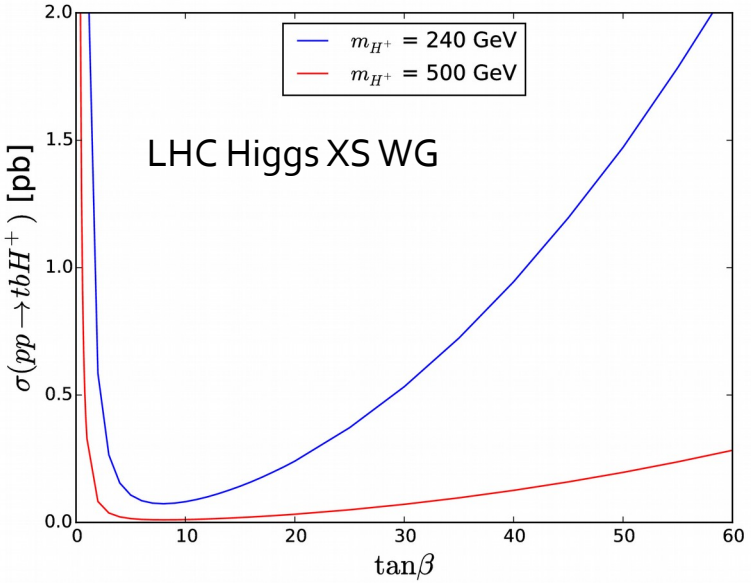
- Searches for $H^+ \rightarrow \tau\nu$, cs [both], tb [CMS]
  - decays cover different regions of tan β
- Search strategy changes if H^+ is lighter or heavier than top quark
  - m(H+) < m(t) : use tt, $t \rightarrow H^+b$
  - m(H+) > m(t) : use associated production $gg \rightarrow tbH^+$
  - $m(H^+) \sim m(t)$: no reliable calculation of production yet

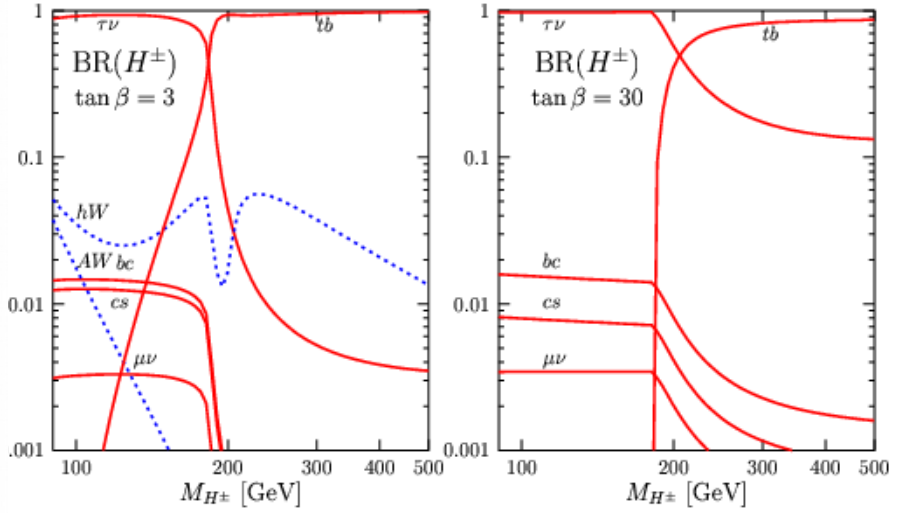
light H^+



heavy H^+







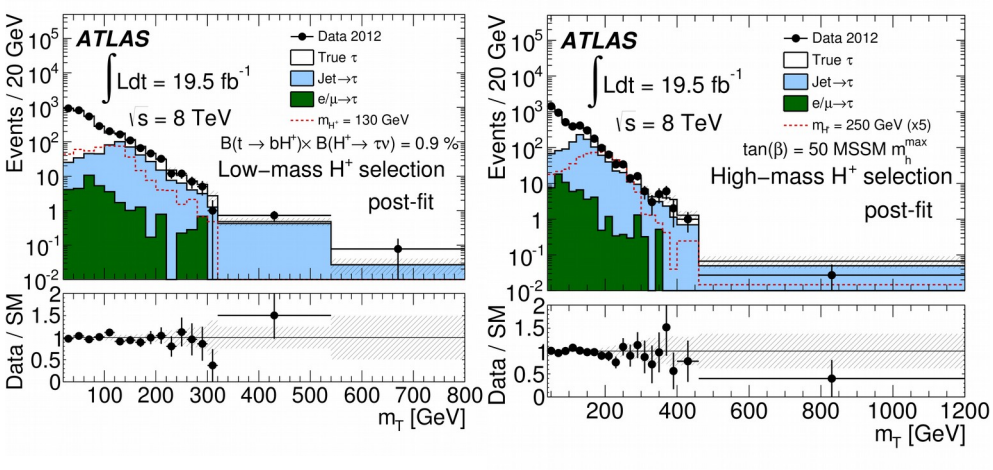
Type II 2HDM

Djouadi, Godbole arxiv:0901.2030

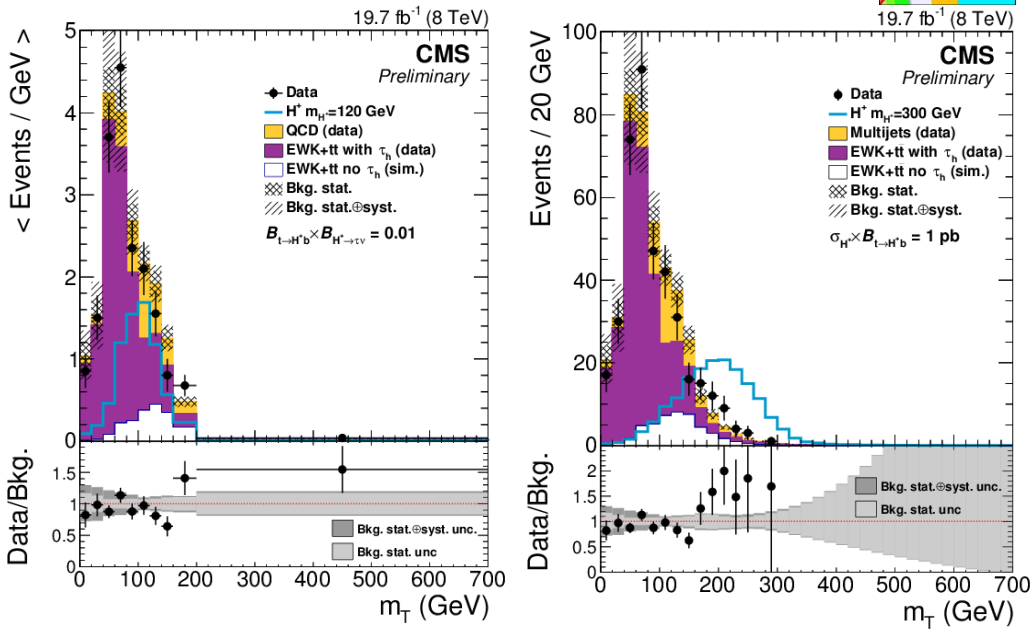
$H^+ \rightarrow \tau\nu$

- Produced in top decay (if light) or in association with top (if heavy)
  - Fully hadronic top decays: E_T^{miss} from H^+ neutrino, can reconstruct H^+ transverse mass. Large background from τ_h fakes
  - CMS also searches in tbH^+ using top leptonic decays

JHEP03 (2015) 088

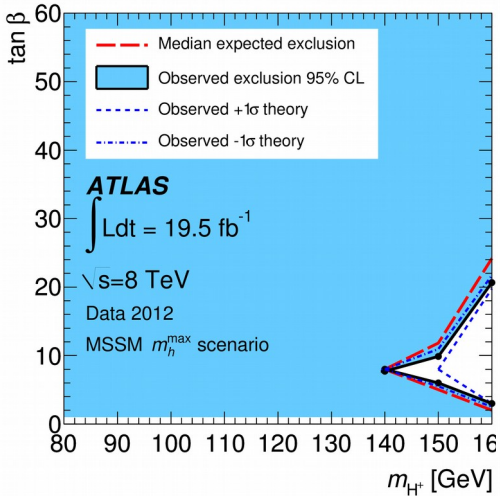


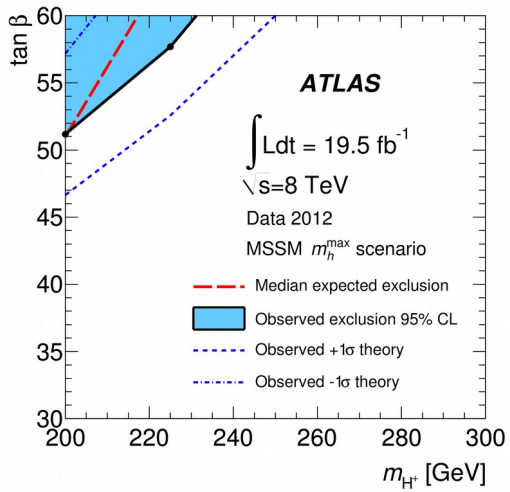
CMS-PAS-HIG-14-020

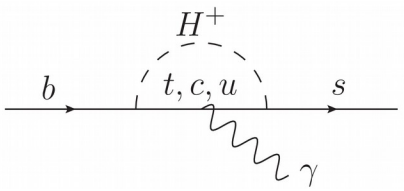


$H^+ \to \tau\nu$ exclusions

- Quite similar in different MSSM scenarios ← different NLO corrections
- In MSSM, only a small corner for $m(H^+) < m(t)$ still open



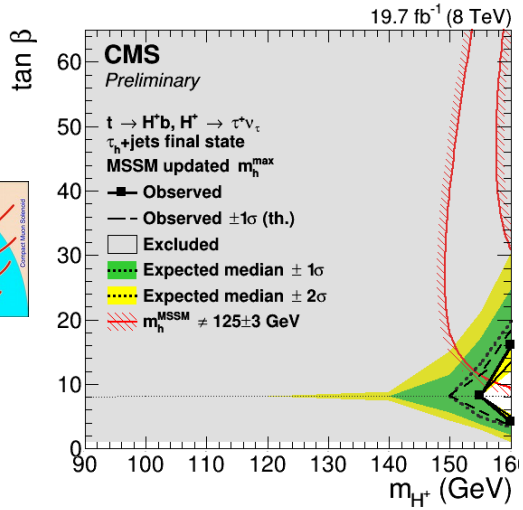


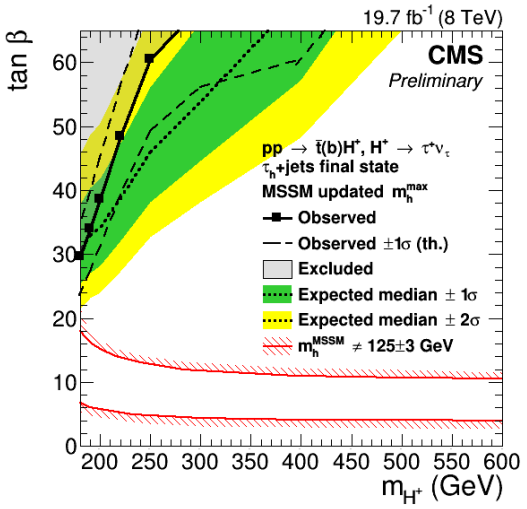


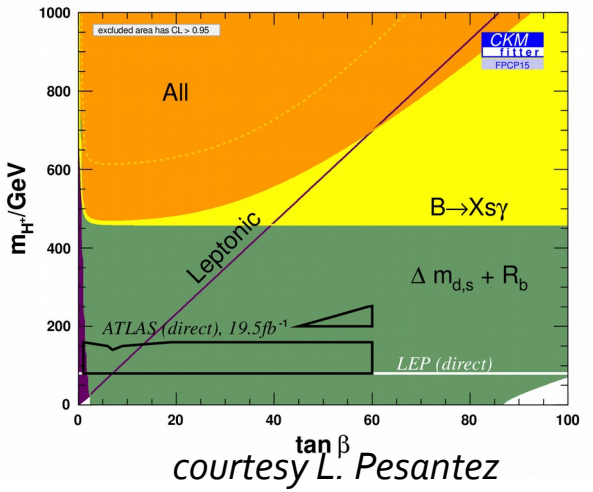
m(H⁺) > 360~480 GeV (2HDM Type II)

complementary to $b \to s\gamma$ limits since less sensitive to other new physics

complements $B \to \tau\nu$, $B \to D^{(*)}\ell\nu$





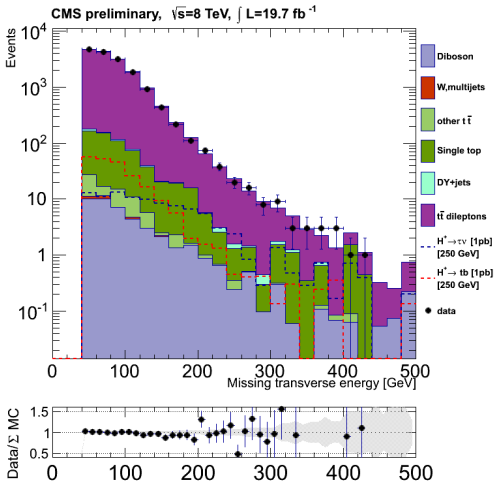


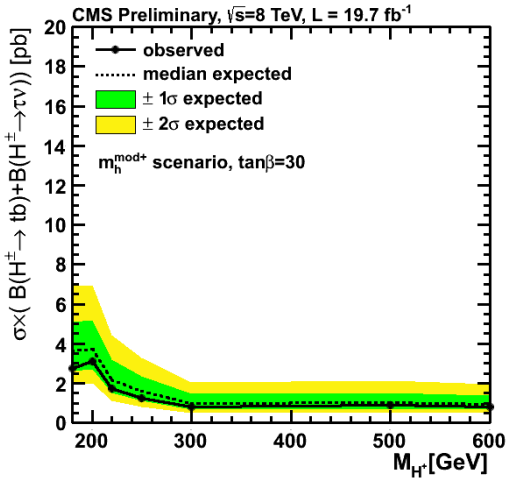
courtesy L. Pesantez

Other H^+ Searches

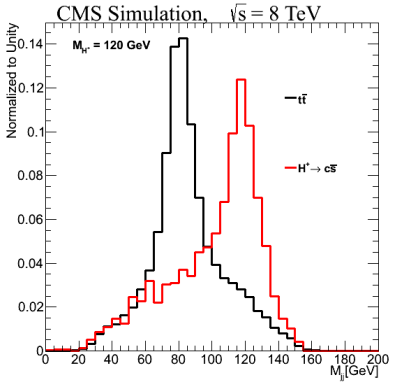
$H^+ \to tb$: high mass H^+

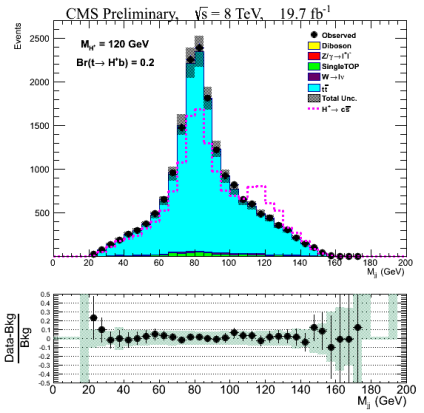
CMS-PAS-HIG-13-026





$H^+ \to cs$: low mass, low tan β

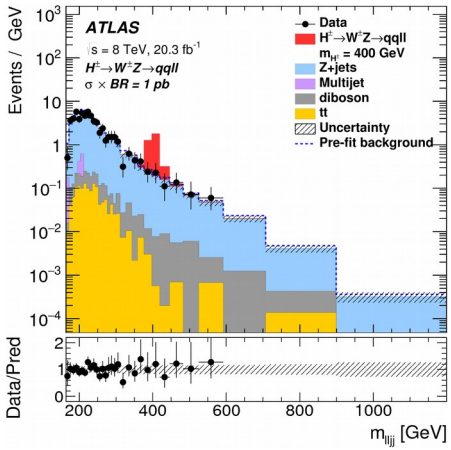


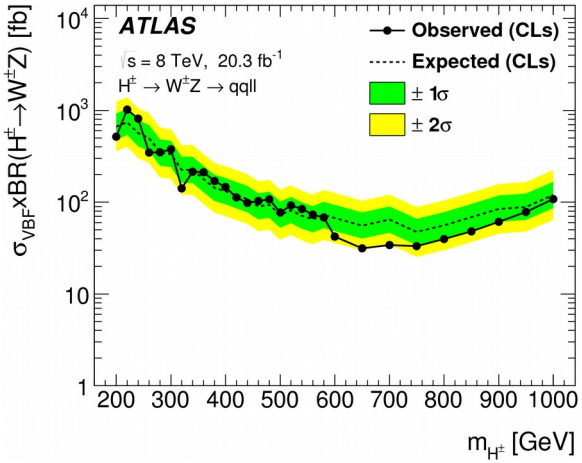


CMS-PAS-HIG-13-035

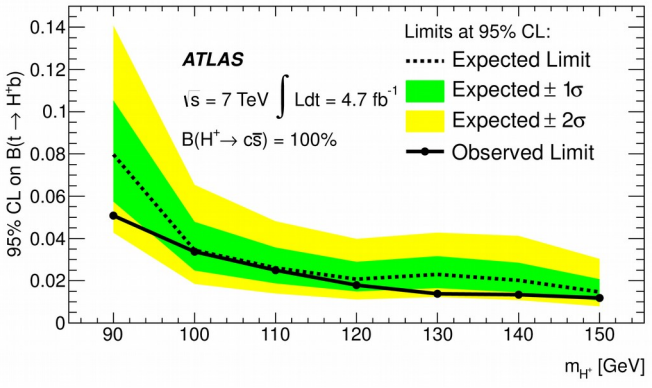
$H^+ \to WZ$: allowed in Higgs triplet models

arxiv:1503.04233
acc. by PRL





EPJC 73 (2013) 2465

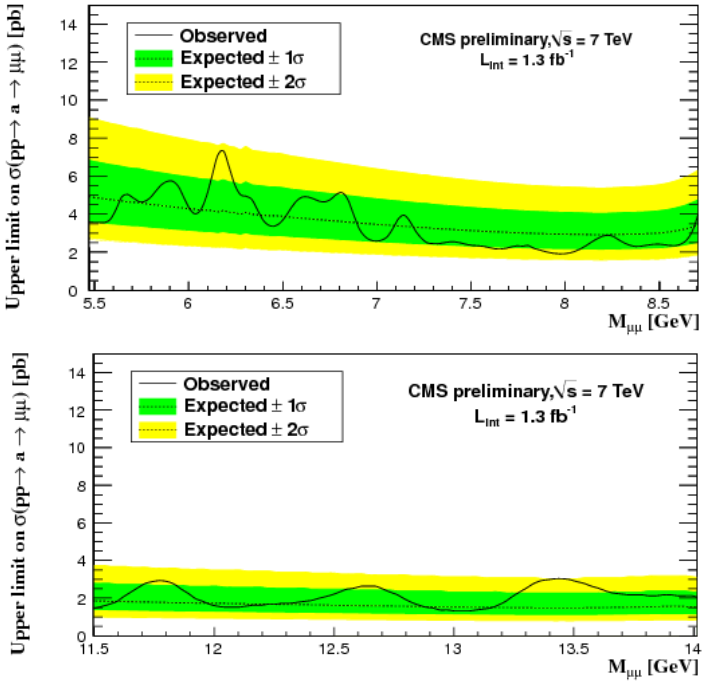


Search for light pseudoscalar

- NMSSM: address "μ-problem" fine-tuning by introducing an additional singlet field
  - allows a very light pseudoscalar *a* with mass ~ few GeV, decaying to accessible fermions with mass coupling
  - relieves some tension in the "high" H(125) mass in MSSM
- Motivates searches for light particle decaying to μμ, ττ

ATLAS: $H \rightarrow aa \rightarrow \mu\mu\tau\tau$

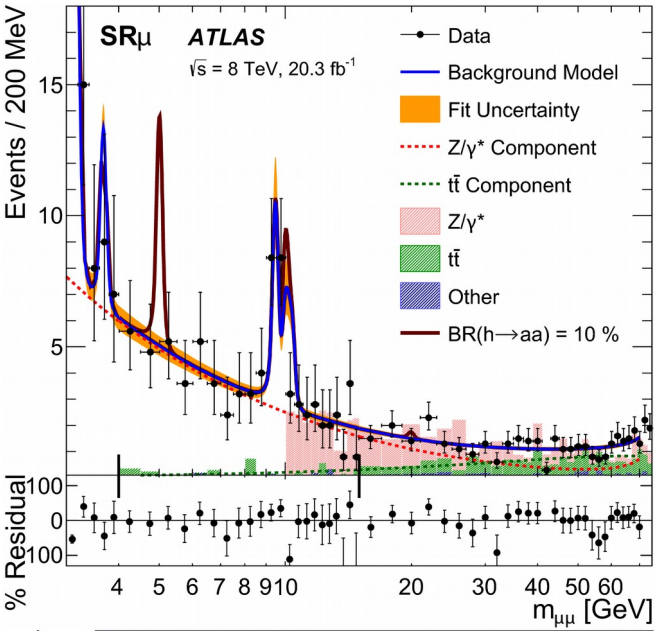
CMS: $gg \rightarrow a \rightarrow \mu\mu$

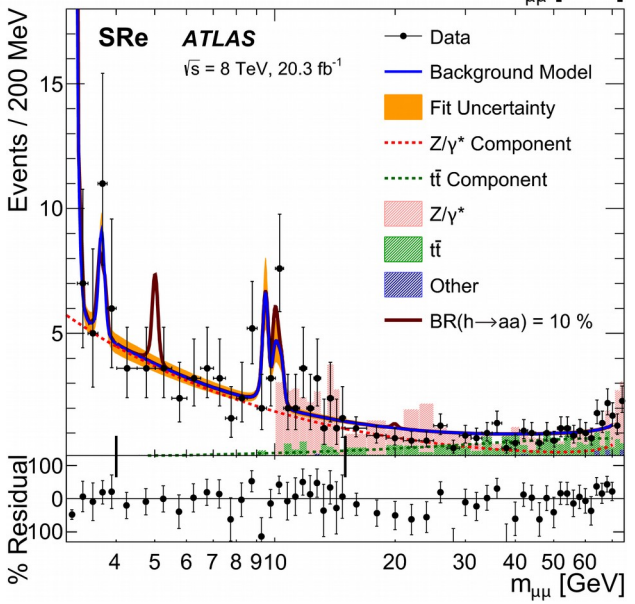


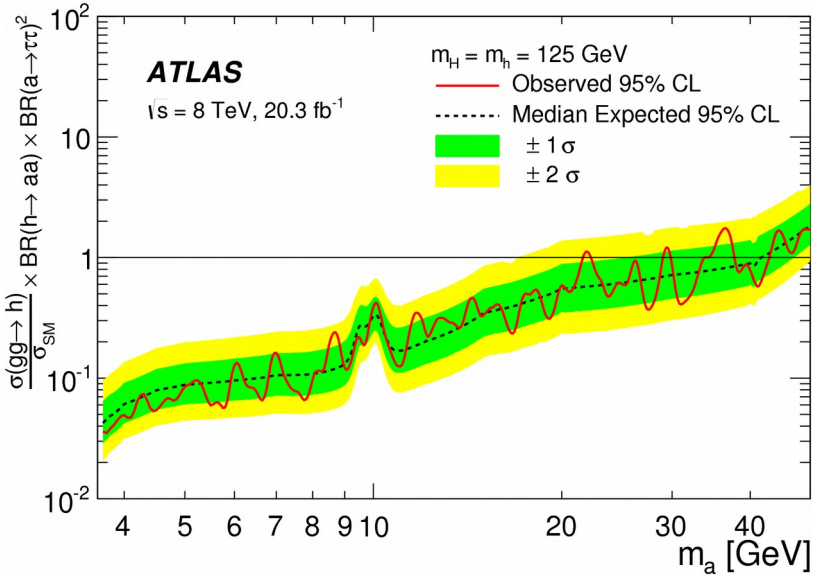
PRL 109 (2012) 121801

H → *aa* → μμττ

- Final state μμ + (e,μ)τ_h
- Two *a* candidates should be back to back; $p_T(a) > 40$ GeV



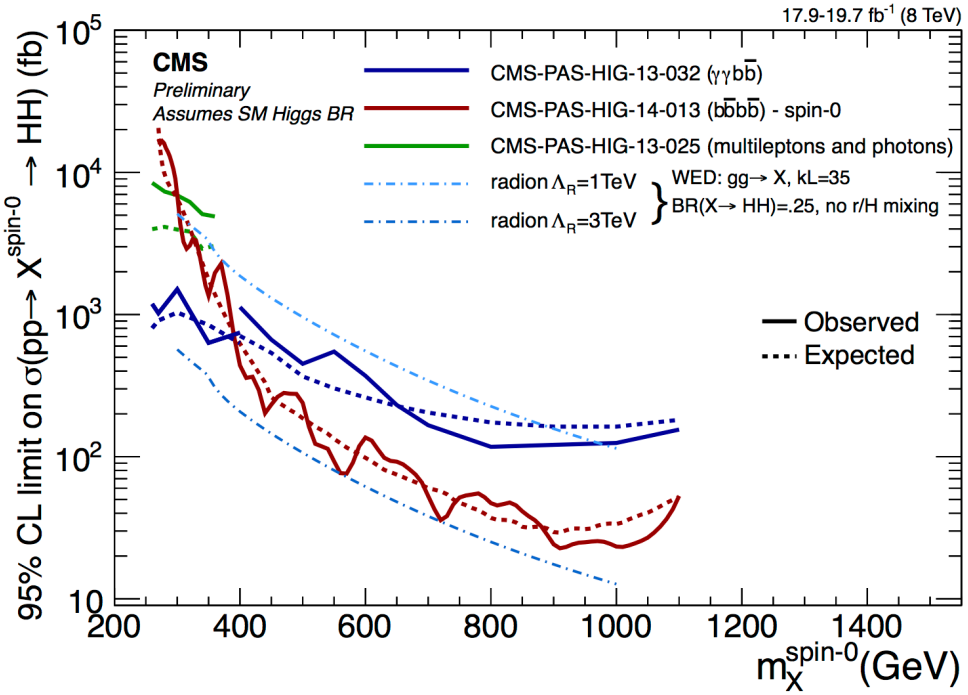




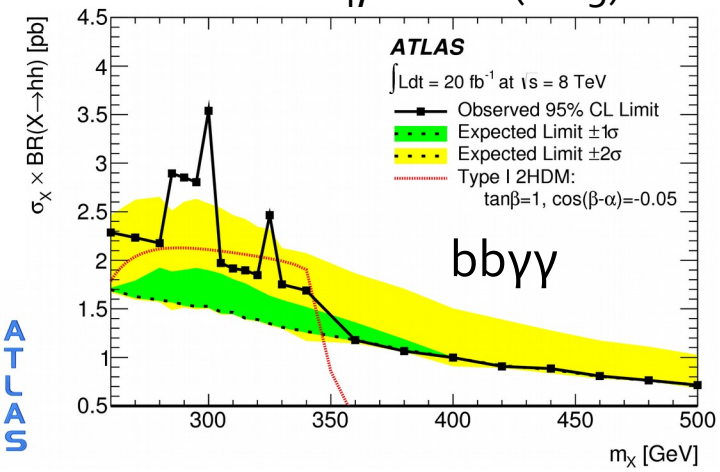
arxiv:1505.01609
sub. to PRD

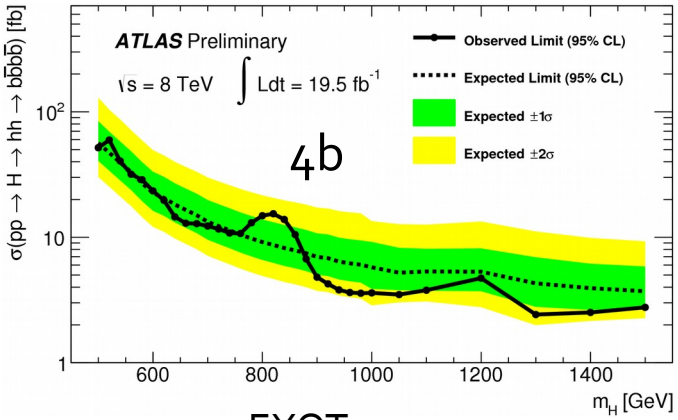
Di-Higgs Production

- Production of two h(125) bosons
  - Resonant: expected in 2HDM, etc. [H → hh]
  - Non-resonant: SM rate requires HL-LHC
  - Channels: bbγγ, 4b, γγ + leptons



PRL 114, 081802 (2015)





EXOT-2014-11

(Some) 2HDM Limits

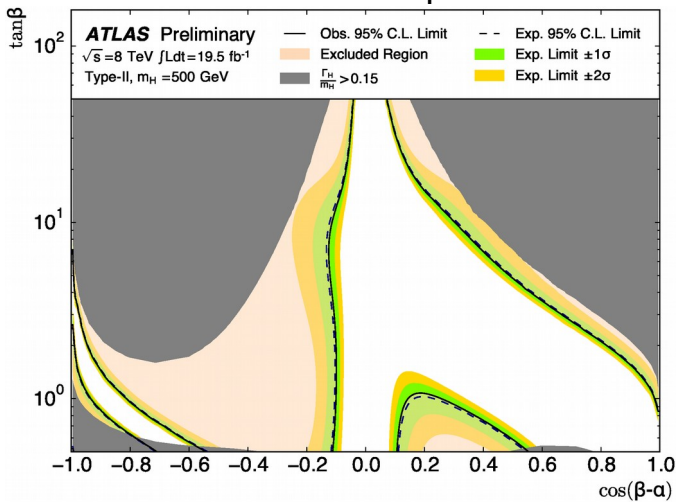
Two Higgs doublet model particle content:

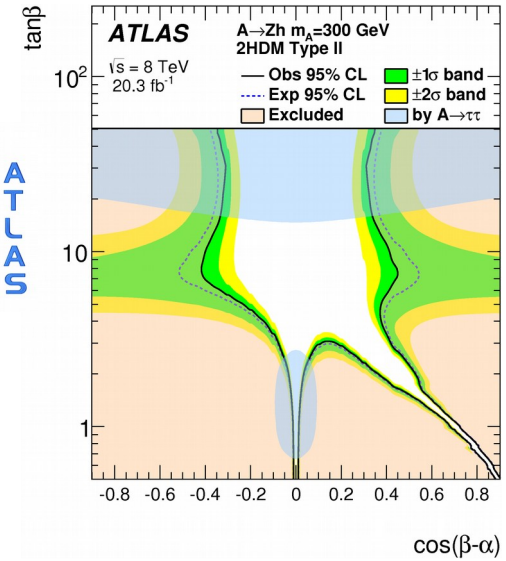
light, heavy scalars h, H
charged scalars H^+, H^-
pseudoscalar A

Avoid FCNC at tree level:
→ four classes of fermion coupling structure

Plots here are for Type II (the Higgs sector in SUSY)

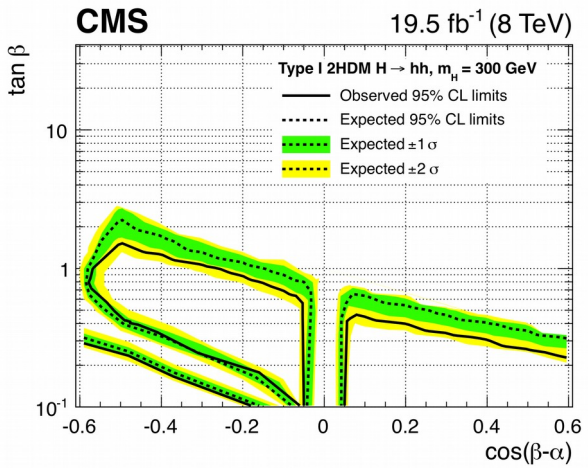
H → hh → 4b
EXOT-2014-11

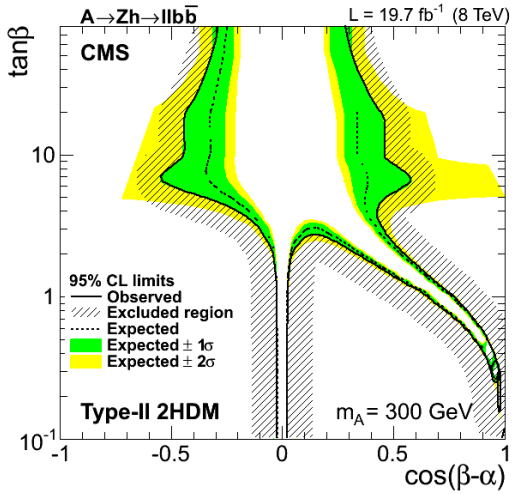




A → Zh → ℓℓττ/ℓℓbb/νvbb
PLB 744 163 (2015)

H → hh → γγ + leptons
PRD 90 112013 (2014)





A → Zh → ℓℓbb
arxiv:1504.04710, sub to PLB

Summary

- 125 GeV Higgs boson looks similar to SM prediction
  - mass precisely measured
  - ATLAS+CMS coupling combination ongoing
- Many searches for anomalous couplings of H(125): no new behavior found yet
- Searches for H^+, light pseudoscalar *a*, resonant di-Higgs production negative so far
- Complementarity with lower-energy probes
  - e.g. $B \to D^{(*)} \tau\nu$, $B \to \tau\nu$, $\tau \to \mu\gamma$, direct DM searches …

HH → 4b candidate