Searches for new Higgs bosons at CMS

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on behalf of the CMS collaboration
University of Illinois at Chicago and Fermilab

Workshop on Baryon and Lepton Number Violation
May 16, 2017

Introduction

- Discovery and first characterization of ***a*** Higgs boson was defining achievement of CMS and ATLAS in Run 1 of the LHC

- Additional Higgs bosons well-motivated and generically present in extensions of the Standard Model
  - → *Doublets and/or singlets, including in supersymmetry*
  - → *Triplets as in left-right symmetric models (neutrino mass)*
  - → *Connection between additional scalars and electroweak baryogenesis*

- Extensive LHC searches, plus ever-improving measurements of the observed Higgs boson strongly constrain additional Higgs bosons

- Broad search program at CMS adapts accordingly
  - → *Cascades of multiple new Higgs bosons*
  - → *Production by and decay to fermions*
  - → *Invisible decays*
  - → *Triplet models, including doubly-charged Higgs boson*

Two-Higgs-doublet models

Two-Higgs-Doublet Model

- 2HDM is a workhorse of BSM Higgs physics
  - → *Second SU(2) doublet compared to the SM*
    - **Five physical particles: h, H, $H^{\pm}$, A**
  - → *Compatible with electroweak baryogenesis*
    - Can modify phase transition, include additional sources of CP violation
  - → *"Type 2" similar to Higgs sector of Supersymmetry*
- Parameterized by $\tan\beta = v_2/v_1$ ratio of VEVs, and α = angle of rotation that diagonalizes the mass matrix of CP-even states
- **h and H "share" couplings** to SM fermions and vector bosons

		type 1		**type 2**	
	W, Z	**up-type q**	**dn-type q**	**up-type q**	**dn-type q**
h	$\sin(\beta-\alpha)$	$\cos\alpha / \sin\beta$	$\cos\alpha / \sin\beta$	$\cos\alpha / \sin\beta$	$-\sin\alpha / \cos\beta$
H	$\cos(\beta-\alpha)$	$\sin\alpha / \sin\beta$	$\sin\alpha / \sin\beta$	$\sin\alpha / \sin\beta$	$\sin\alpha / \cos\beta$

Pragmatist's interpretation

2HDM strongly constrained by direct searches and indirectly by measurements of observed Higgs boson

→ *Very good agreement in vector boson couplings*

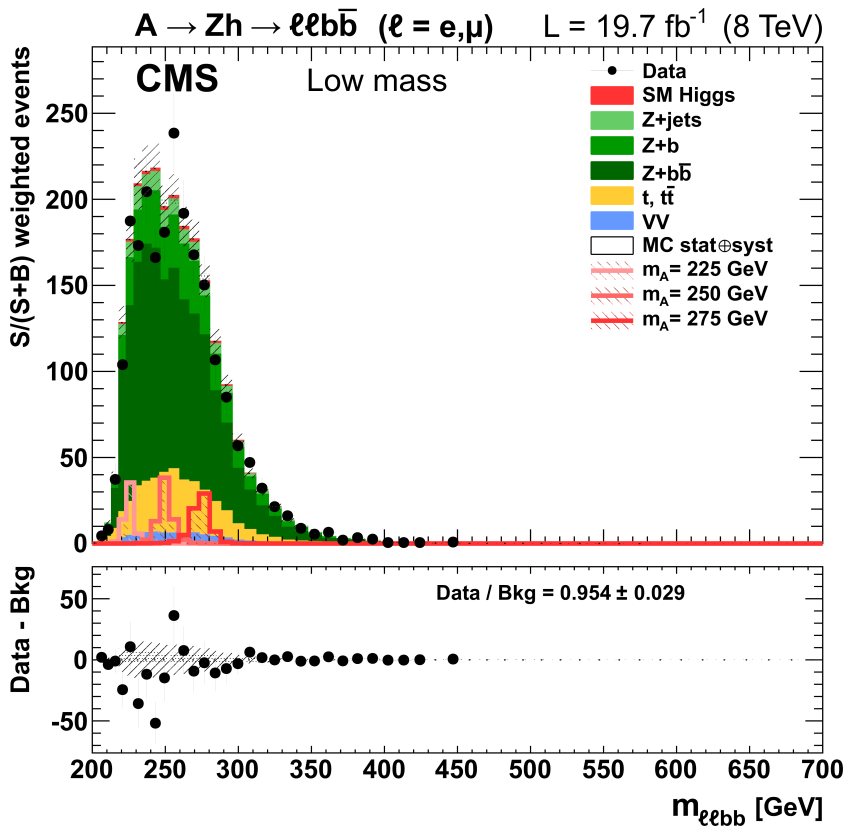
→ *Suggests "**alignment**": H → VV and $H^{\pm}$ → WZ suppressed*

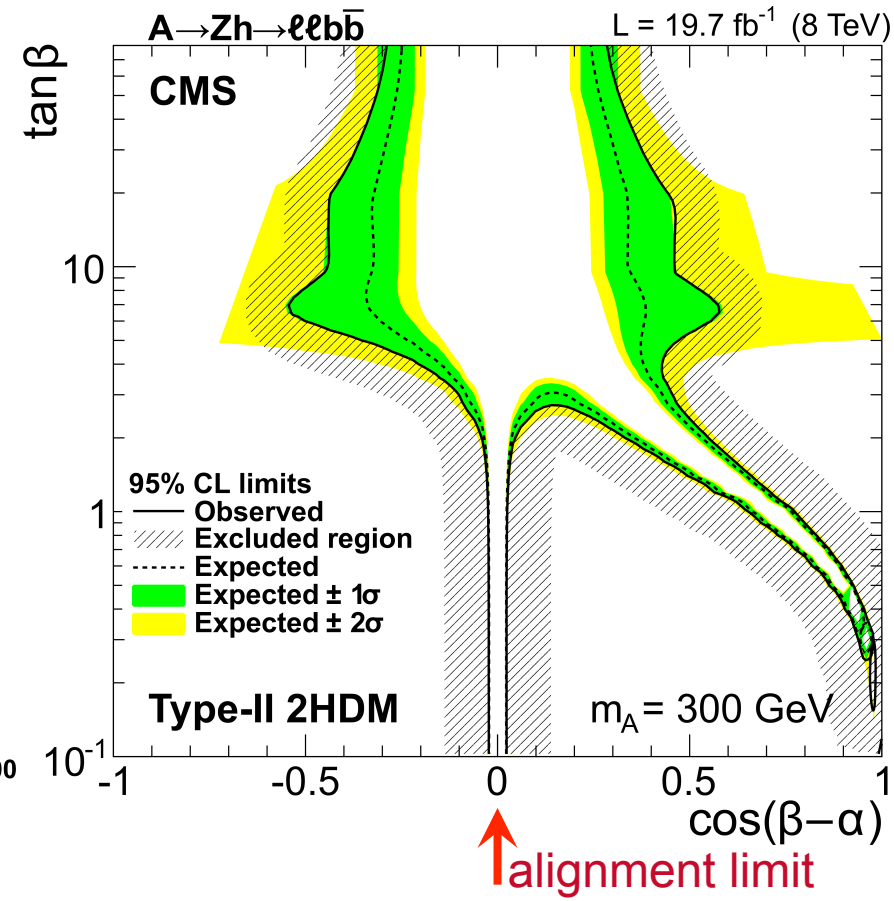
→ *and/or "**decoupling**": additional particles very massive*

	h	**H**	**$H^{\pm}$**	**A**
charge	neutral	neutral	charged	neutral
CP	even	even	even	**odd** ("pseudoscalar")
couplings	SM-like	tt, (hh)	$\tau\nu$, tb, bc	tt, bb, $\tau\tau$, (Zh)

A → Zh

- Classic search for 2HDM
- Use h → bb, largest branching ratio for light SM-like h
- Search for llbb resonance **1504.04710**

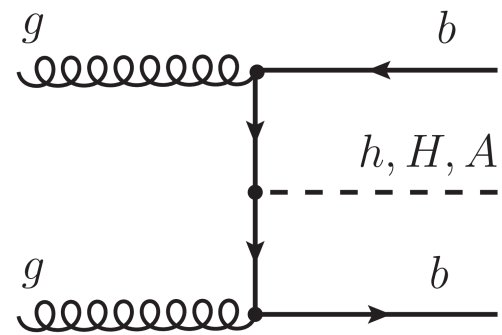


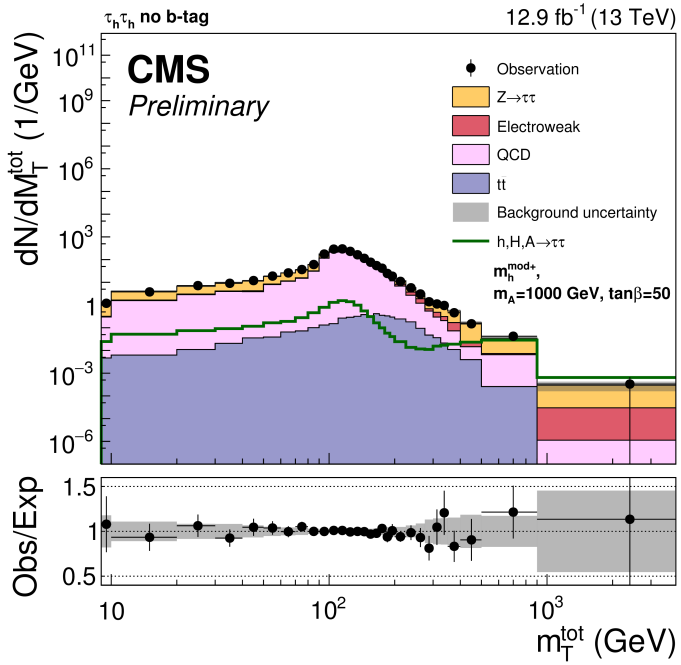


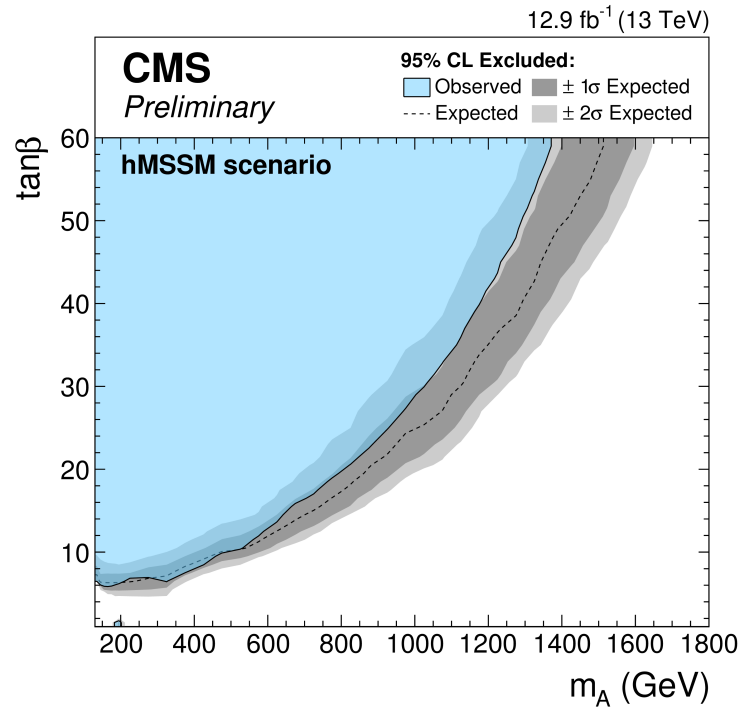
h,H,A → ττ

- Any of h, H, A (= φ) can decay to τ pair
- Hadronic and leptonic decays in analysis

→ *All-hadronic ($\tau_h\tau_h$) most sensitive for m_φ > 200, $\mu\tau_h$ for m_φ < 200 GeV*







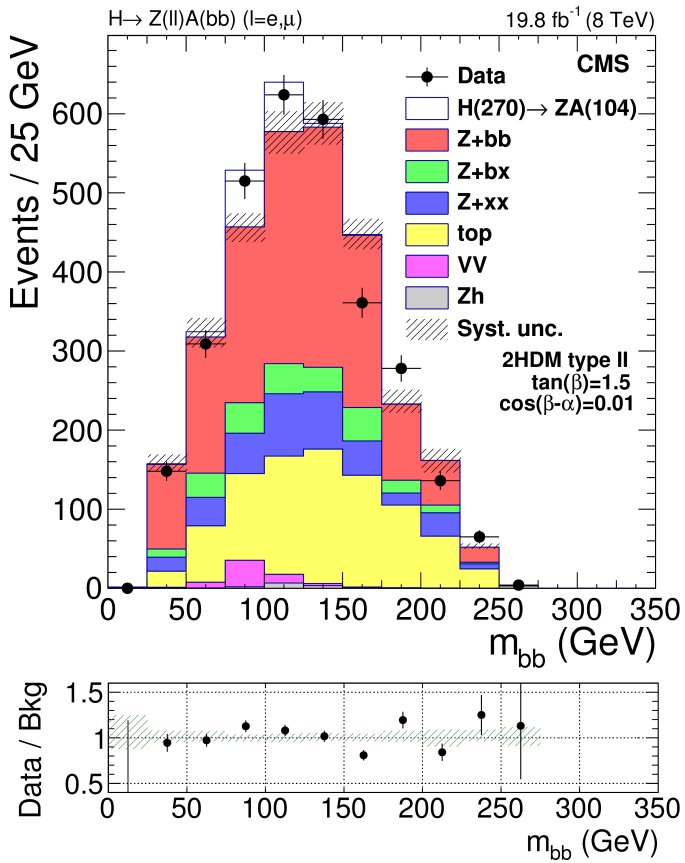
$$m_T^{tot} = \sqrt{m_T(E_T^{miss}, \tau_1^{vis})^2 + m_T(E_T^{miss}, \tau_2^{vis})^2 + m_T(\tau_1^{vis}, \tau_2^{vis})^2}$$

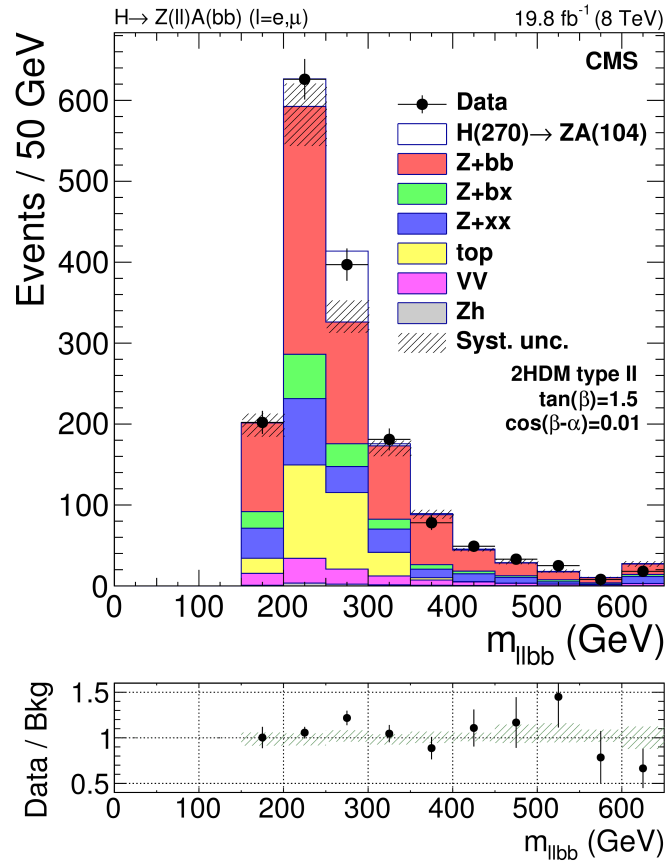
HIG-16-037-pas

General 2-scalar search

- EW baryogenesis: look for A → ZH, H → ZA, not just A → Zh
  - → *All of H, A, and h decay to b-bbar or ττ*
  - → ***Release mass constraint on m(bb) or m(ττ)***

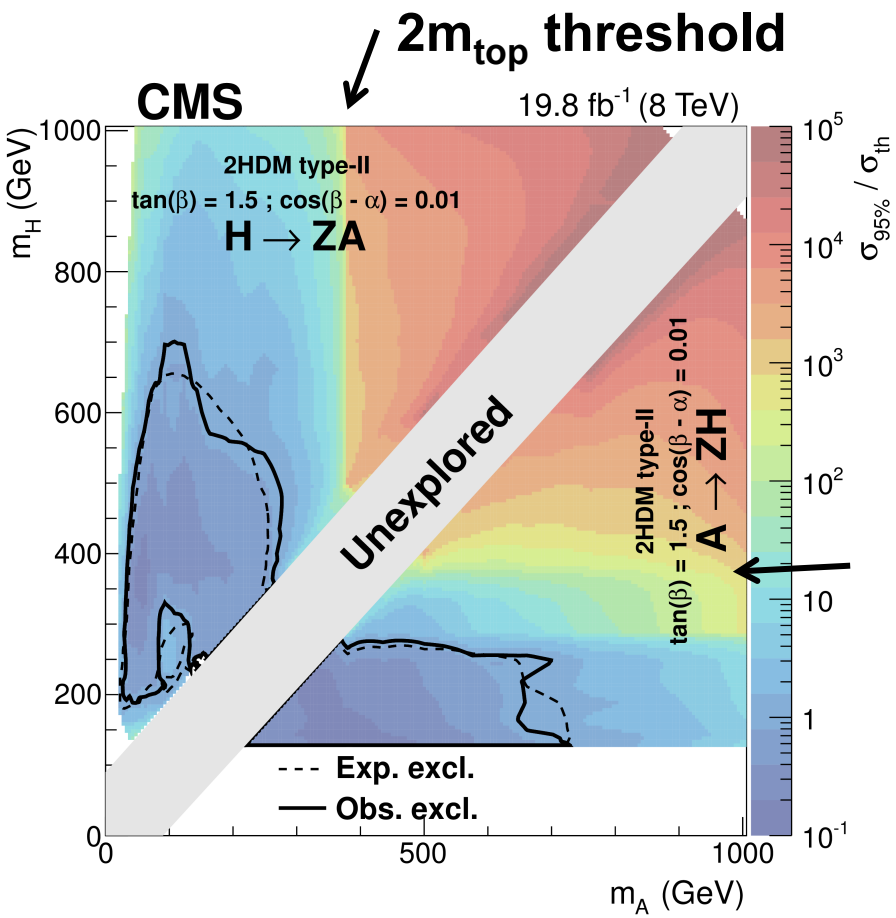
CMS, 8 TeV
1603.02991
~1.5σ excess



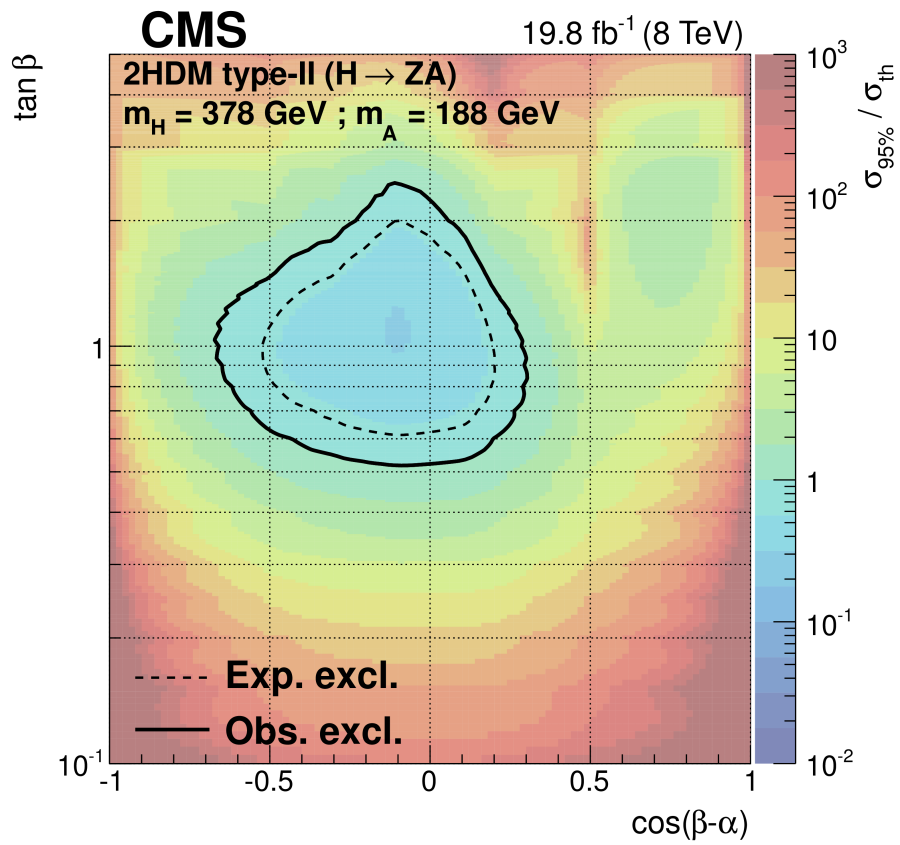


General 2-scalar search

for tan(β) = 1.5, cos(β−α) = 0.01,
scan mass:

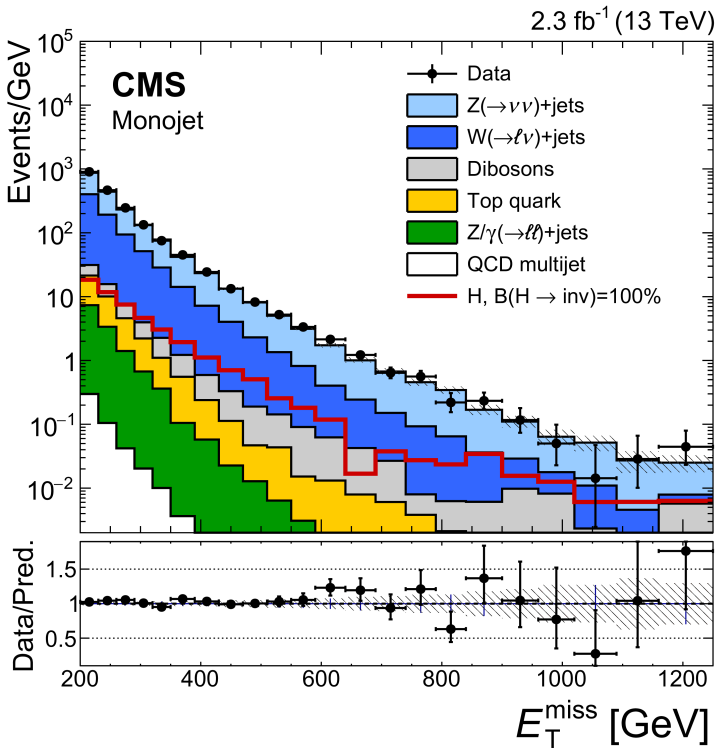


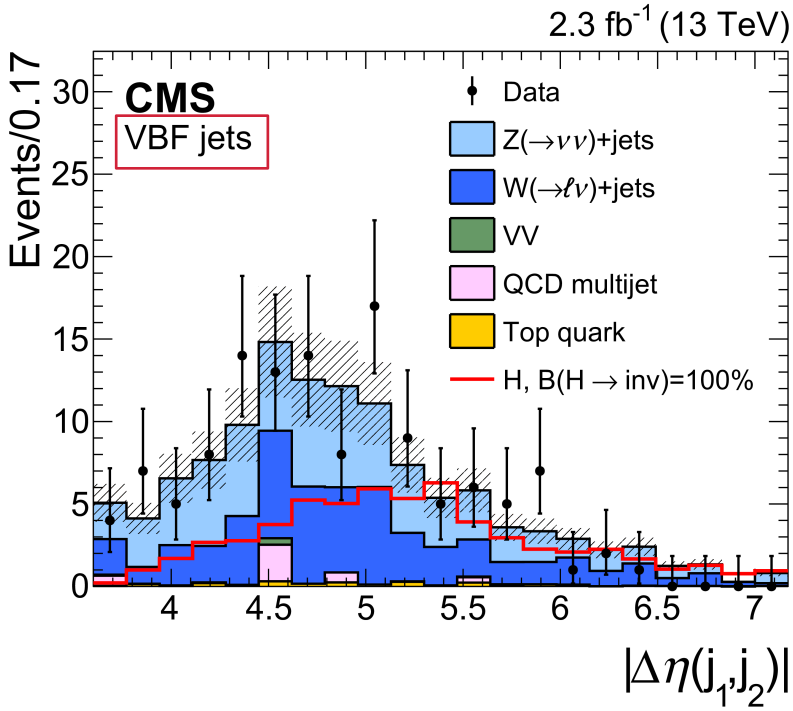
for a given mass,
scan parameter space:



H/A → invisible

- "Invisible" means missing transverse momentum
  - → *Identify as Higgs production via production mode*
- Designed for h[125], but sensitive to a pseudoscalar and/or heavy Higgs boson: discriminating variables sensitive to production mechanism but not mass of particle produced





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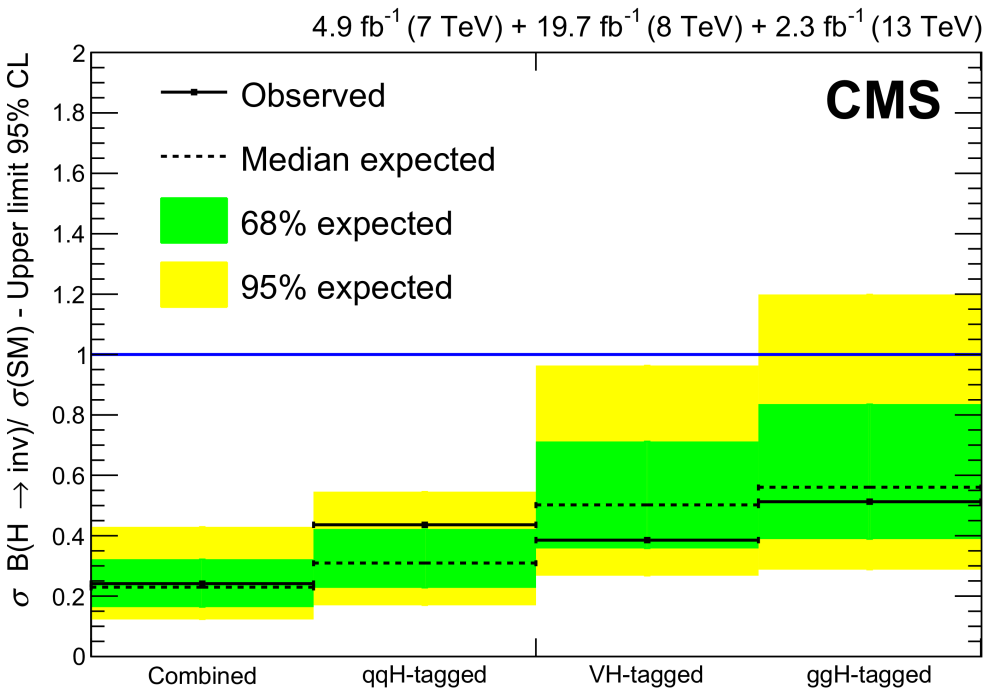
H/A → invisible

- Run 2: Raised trigger thresholds (pileup) limit 13 TeV analysis
  → *example: VBF-channel MET threshold raised 90 → 200 GeV*
- Leading systematics theoretical: BG extrapolation from control regions
- It will take some time for Run 2 to catch up



VBF ("qqH") channel most sensitive

BR (H → invis.) < 0.24 at 95% CL (0.23 expected)

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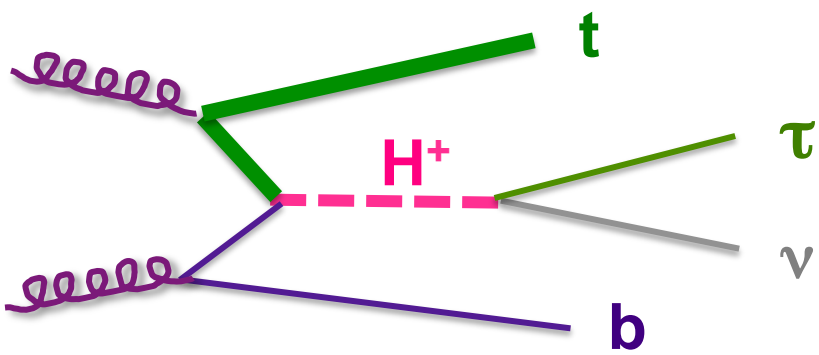
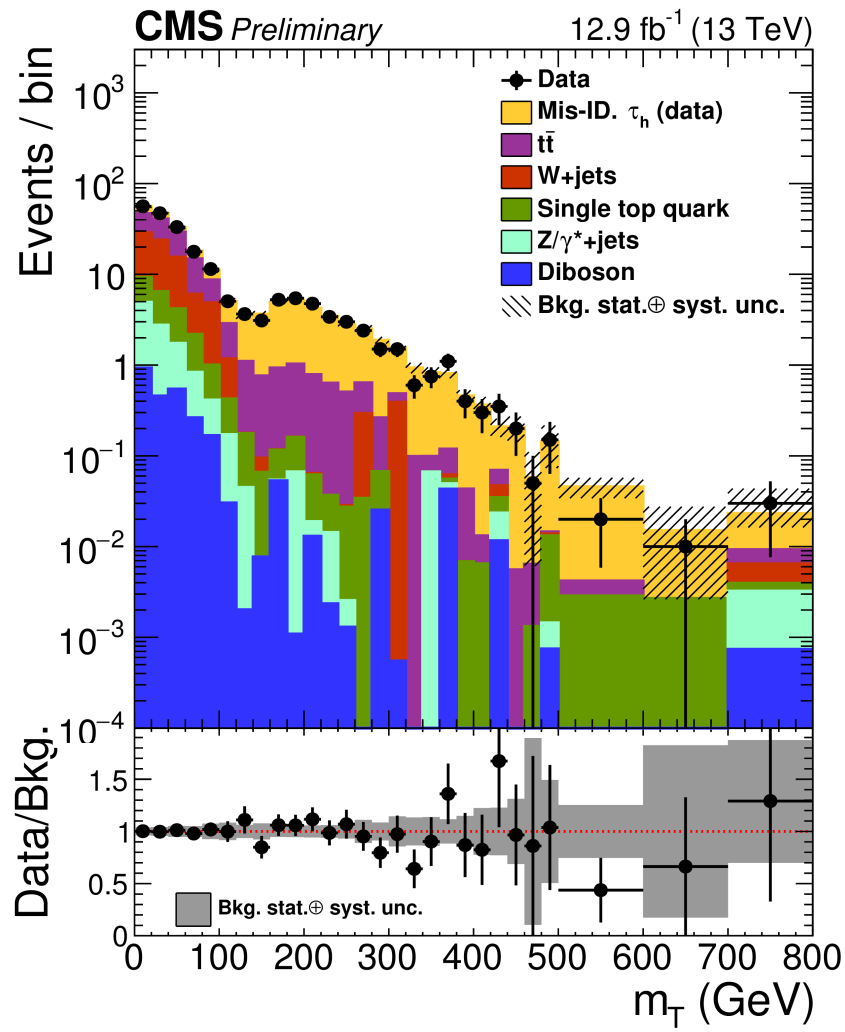
Charged Higgs to τν

- Decay to fermions preferred in alignment limit
- Produce via tHb coupling if $m_{H+} > M_t$
- In top-quark decay if $m_{H+} < M_t$
- All-hadronic: $\tau_h + E_T^{miss}$ + 3 jets
  - → *$\tau_h + E_T^{miss}$ trigger*
  - → *Discriminant: $\tau_h + E_T^{miss}$ transverse mass (m_T)*
  - → *Key background τ from mis-ID at high transverse mass*

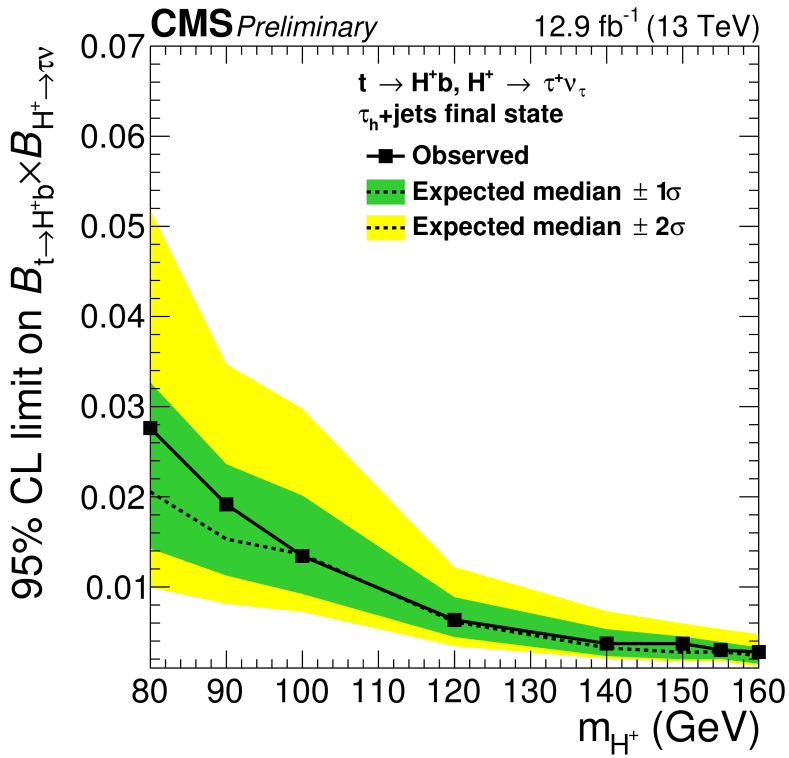


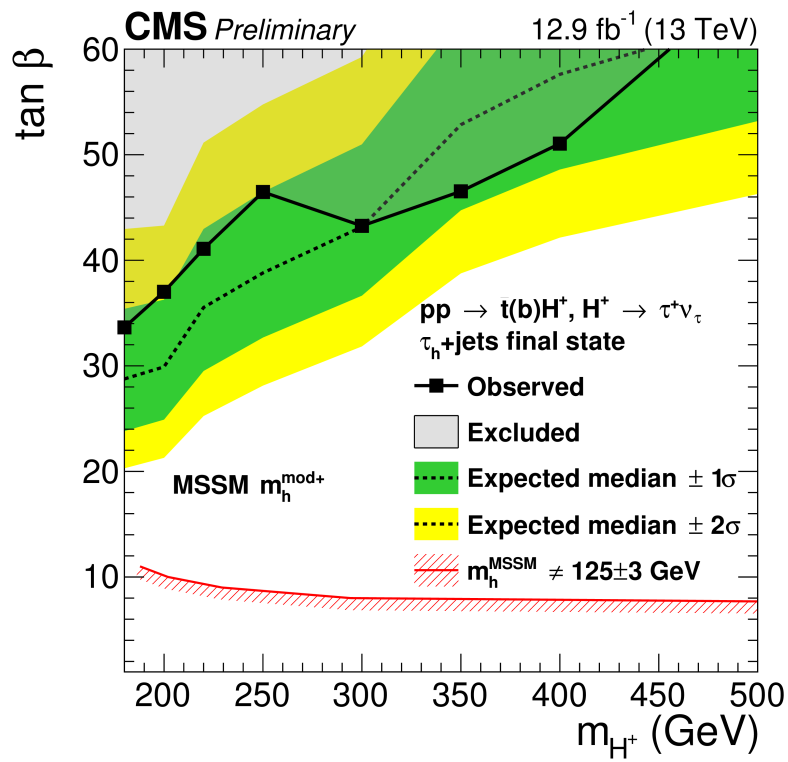


HIG-16-031-PAS

Charged Higgs to τν

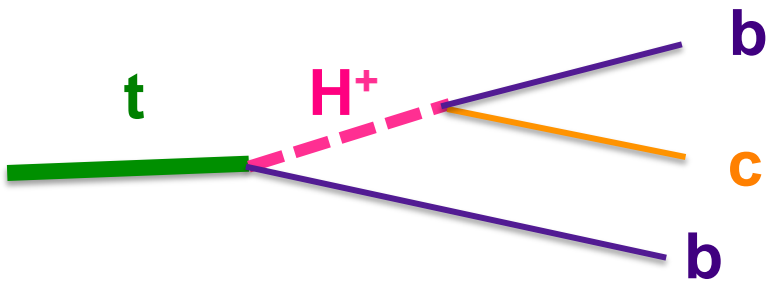
- Heavy H+: limits out to mH+ = 3 TeV (σ x BR < 3 fb @ 95% CL)
- Challenging interpretation for light H^+: constraints from b → sγ and Higgs mass in SUSY interp.



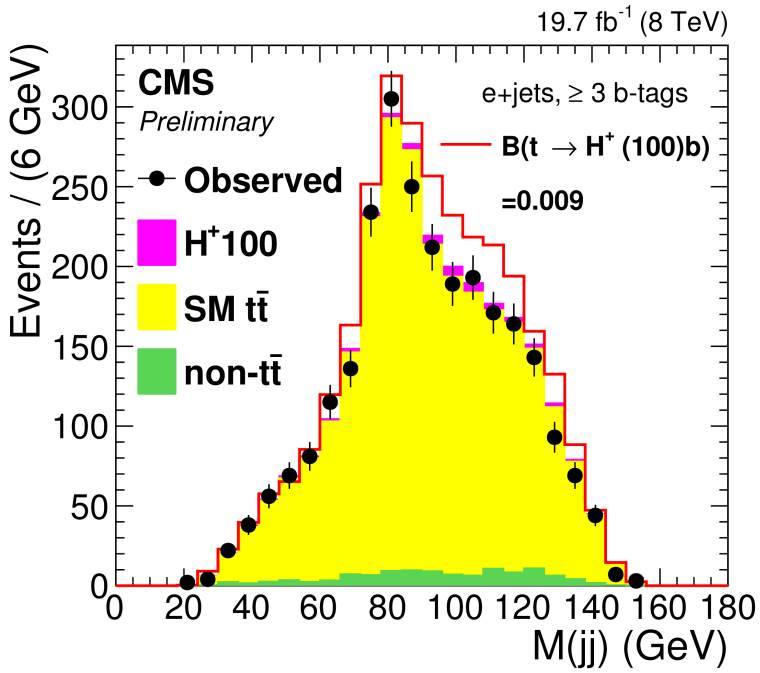


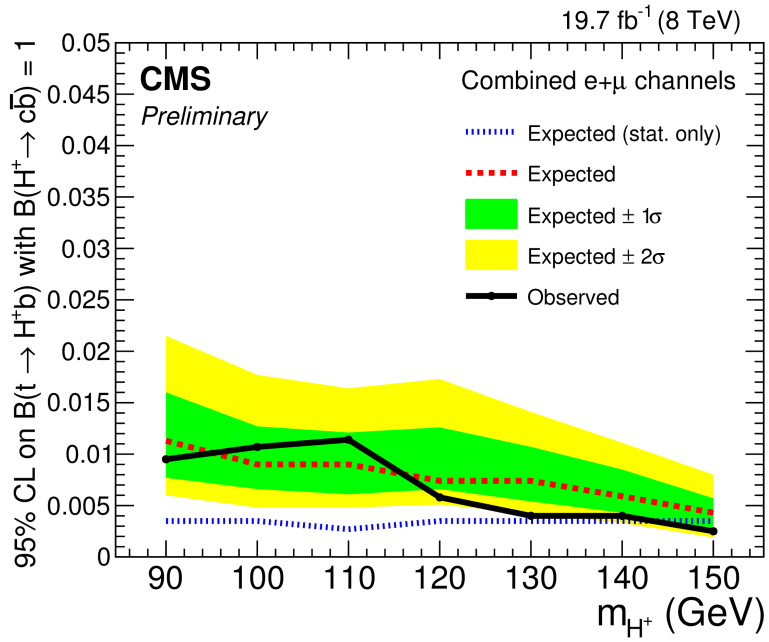
HIG-16-031-PAS

Light H^+ in top quark decays



- Leptonic decay of other top quark
  - → *e/μ + E_T^{miss} + 4 jets (2 or more b-tagged)*
  - → *Background almost all t-tbar*
    - Signal has one more b-jet (3 total)
- Kinematic fitter assigns jets to quarks
  - → *No W-mass constraint on hadronic side*
  - → *top-specific jet energy corrections*



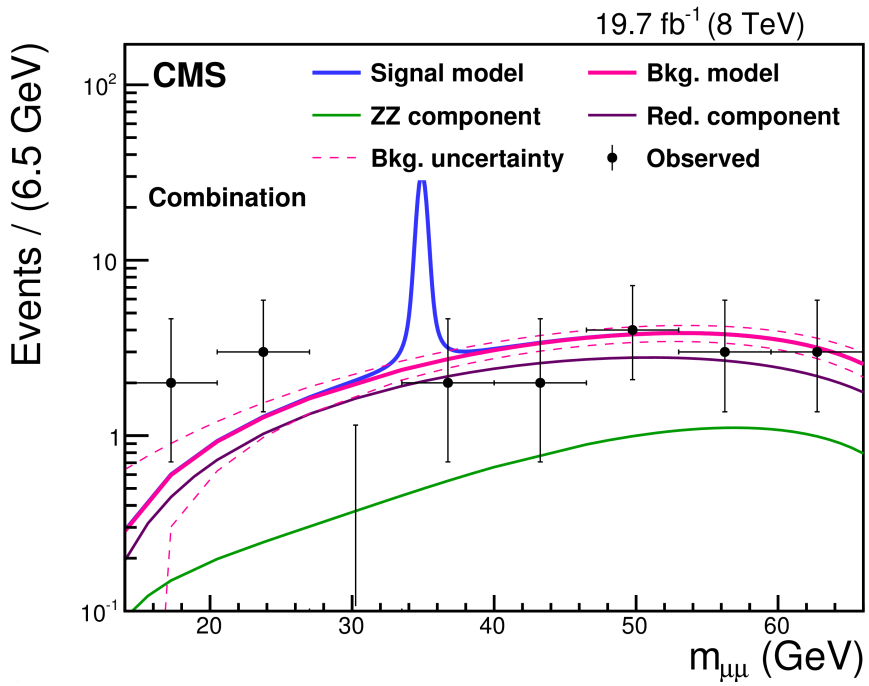


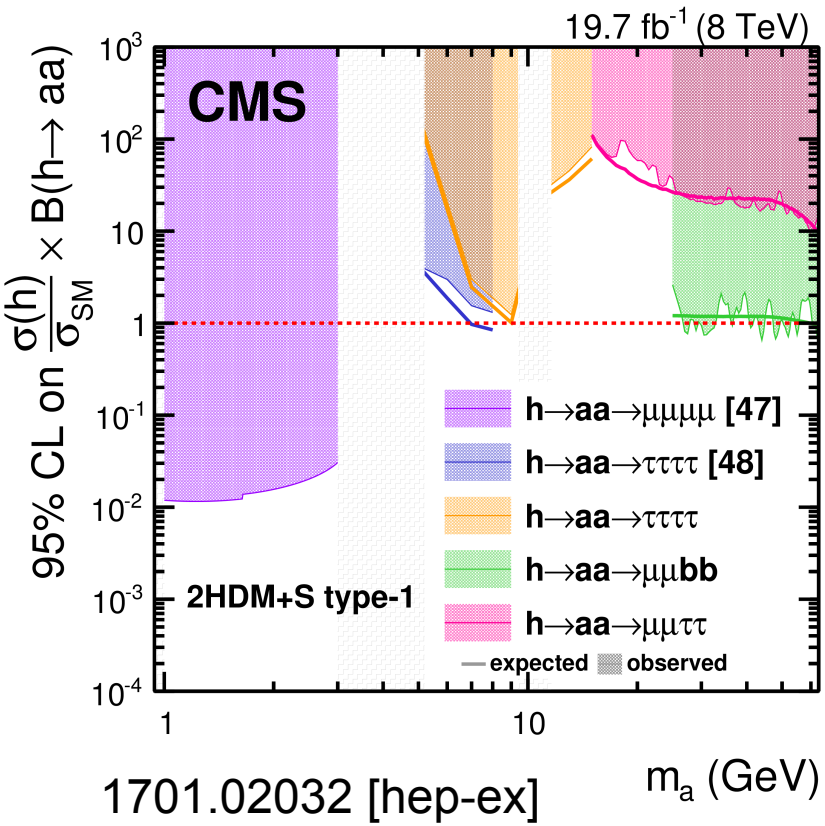
HIG-16-030-PAS

beyond the 2HDM-scape

h decay to light singlet

- Light (pseudo)scalar appears in many models: nMSSM, 2HDM+S, technically possible in 2HDM alone
- Decays to fermions ($\mu\mu$, $\tau\tau$, bb) have challenging backgrounds
- For $m_a < 2m_h$, workaround: look for h[125] → aa



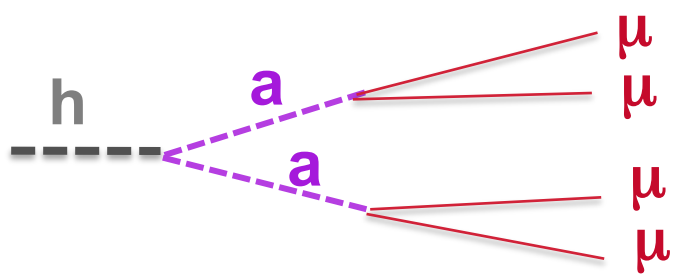


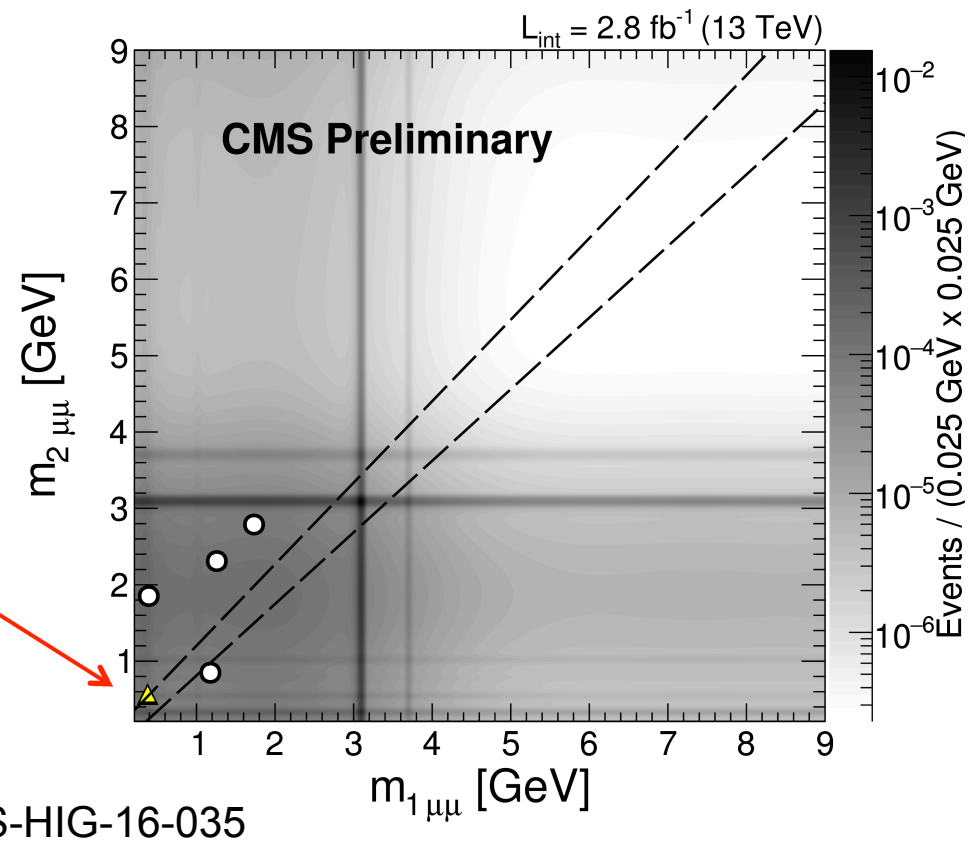
stats-limited, much to be learned in Run 2 and beyond

1701.02032 [hep-ex]

Light scalar decay to muons

- $h \rightarrow 2a \rightarrow 4\mu$ motivated by nMSSM; 13 TeV update of result in prev. slide
  - → *Require consistent invariant mass for the muon pairs but no constraint on $m_{4\mu}$*
  - → *Scan dimuon mass $0.25 < m_{2\mu} < 8.5$ GeV and four-μ mass $86 < m_{4\mu} < 150$ GeV*



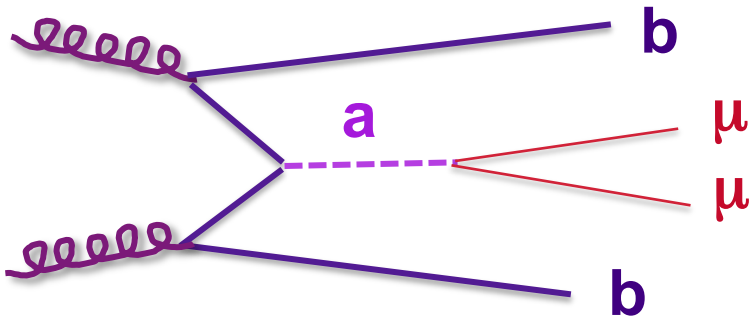


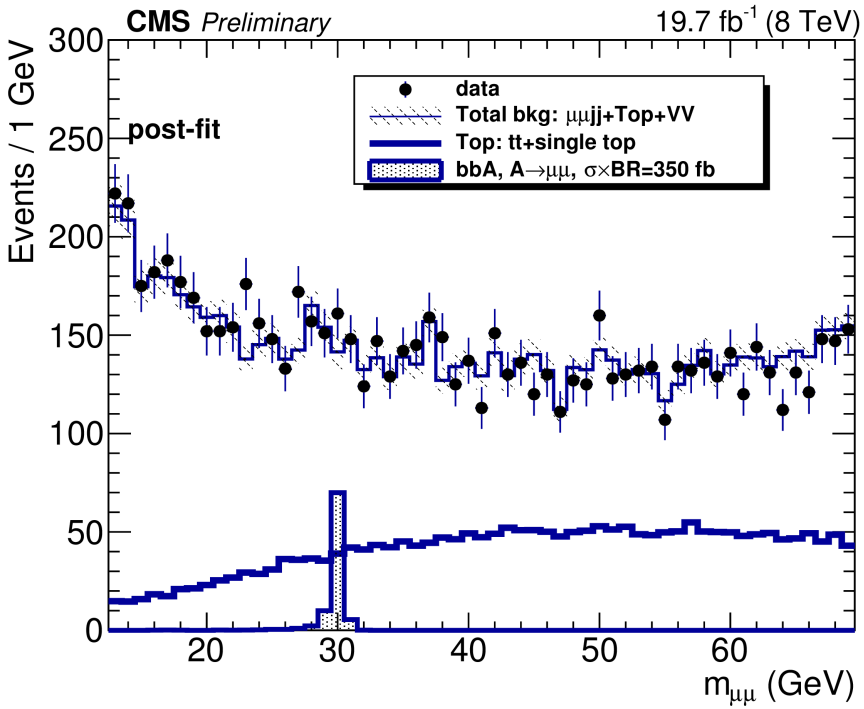
- One candidate event at $(m_1, m_2) = (0.40, 0.56)$ GeV
- $0.74\ ^{+0.46}_{-0.35}$ background events expected (dominant background is b-bbar)

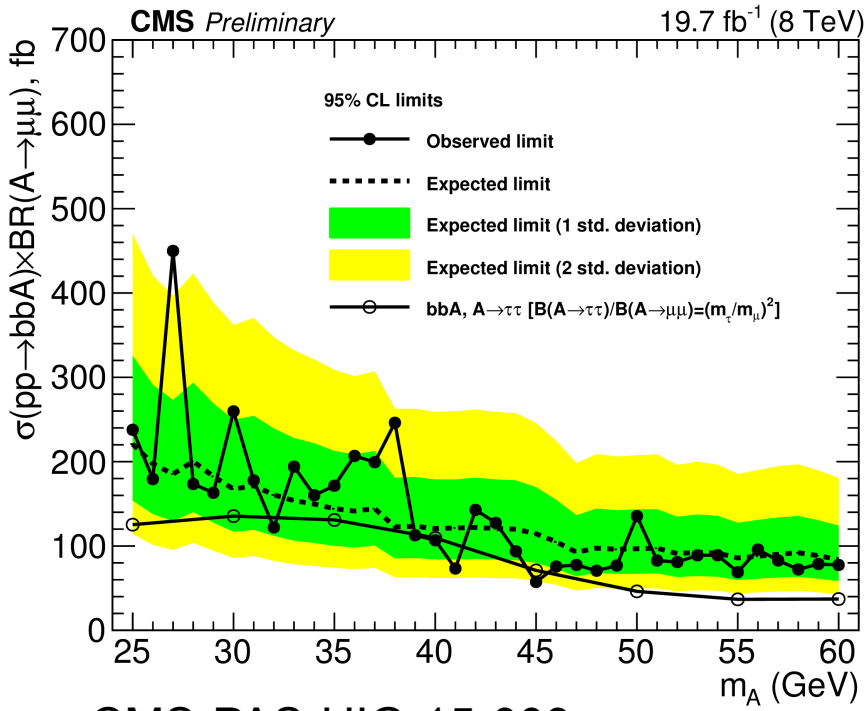
CMS-PAS-HIG-16-035

Light scalar decay to muons

- b-associated production, new 8 TeV analysis
  - → *2 muons, one may be soft (p_T > 5 GeV), one b-jet (second may be soft)*
  - → *Competitive with a → ττ even if lower BR*







CMS-PAS-HIG-15-009

Higgs triplet models

- SU(2) triplet rather than doublet or singlet
  → *Need UV completion, issues w/custodial symmetry*

- Appears in Left-Right symmetric models
  → *Higgs sector may be kinematically out of reach in proper L-R symmetric model (1612.09146)*
- Also in "type II seesaw models" for generating **neutrino masses**…
- Extra scalar content / VEV can affect the **electroweak phase transition** (see 1108.4416)

- Distinctive particle content:

H $H^{\pm}$ $H^{\pm\pm}$

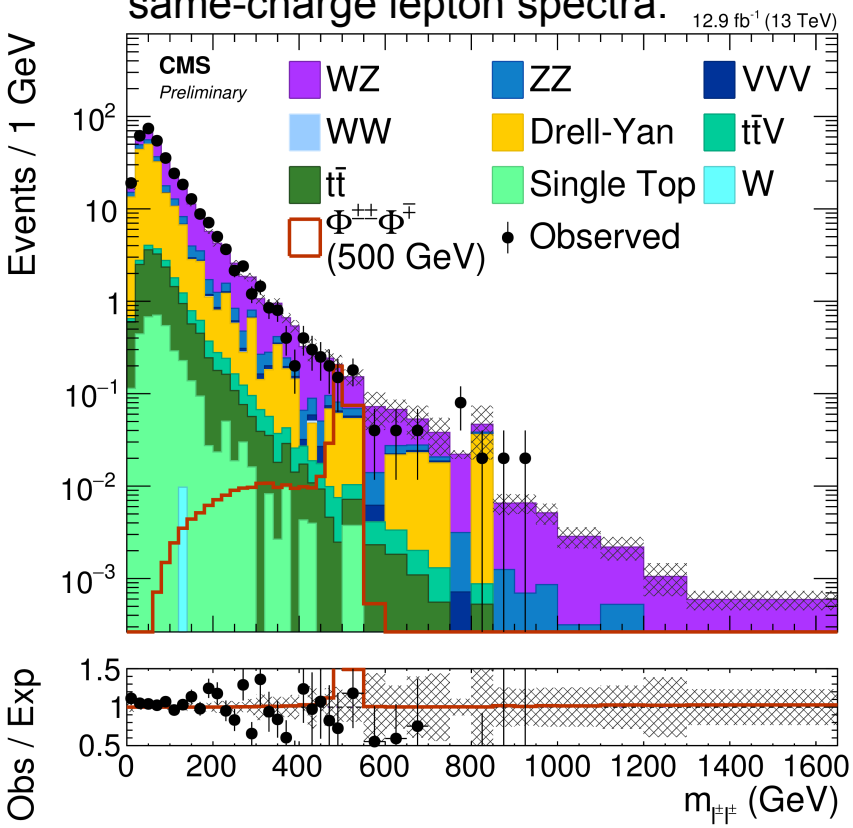
Doubly-charged H @CMS

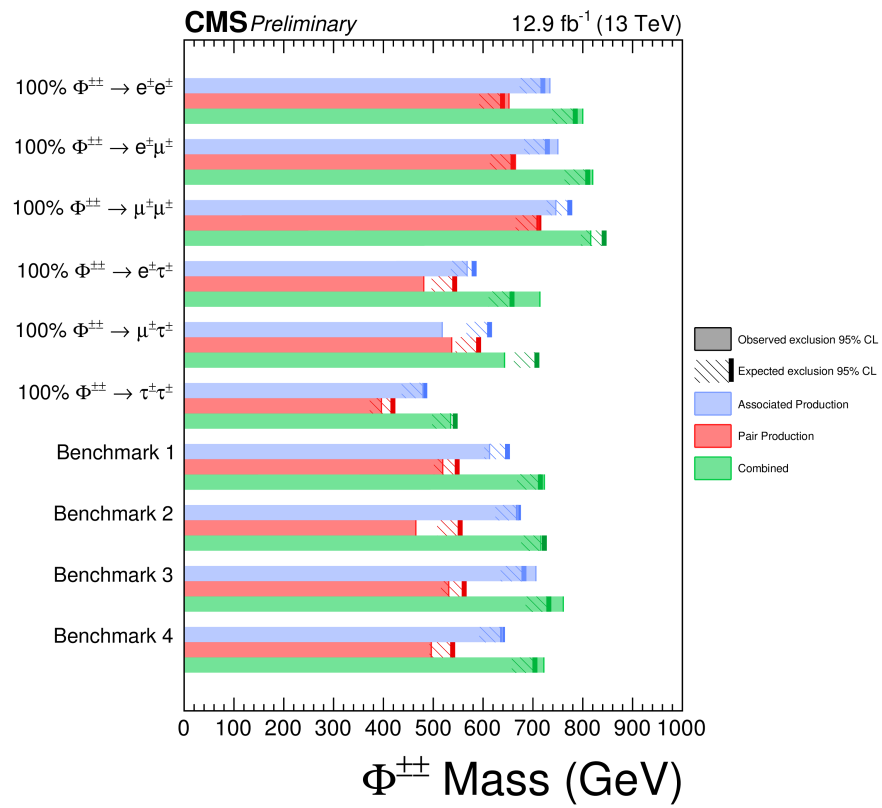
- Analysis using in same-charge leptons, 3- and 4-lepton events
- Also sensitive to $H^{++} \rightarrow W^+W^+$, but not explicitly targeted

→ *Semi-leptonic searches for heavy $H \rightarrow WW \rightarrow l\nu jj$ also in principle sensitive*

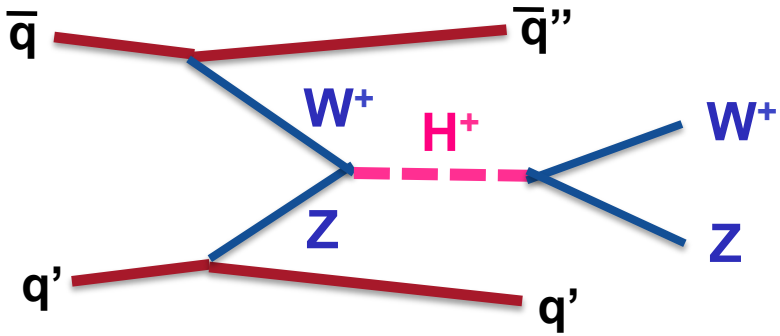
CMS PAS HIG-16-036

same-charge lepton spectra:





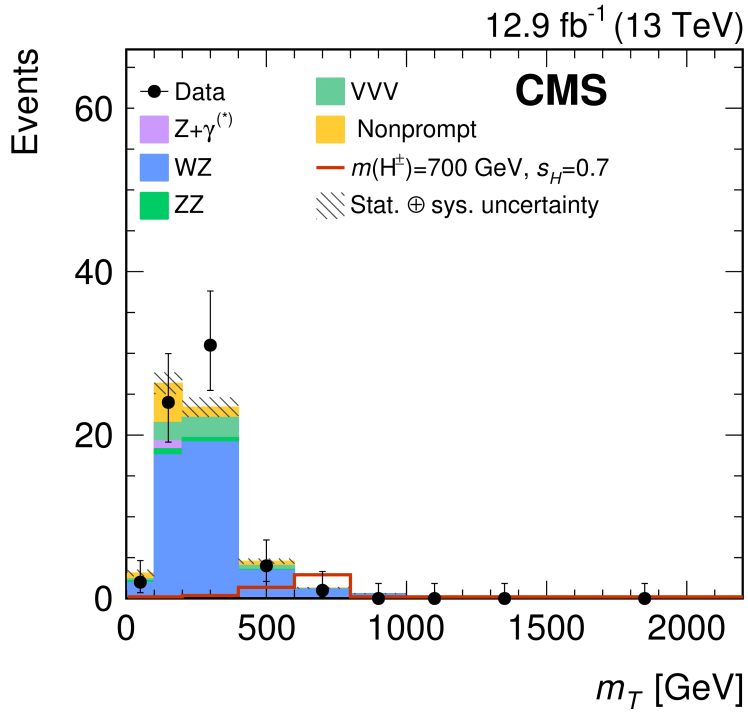
H^+ via vector-boson fusion

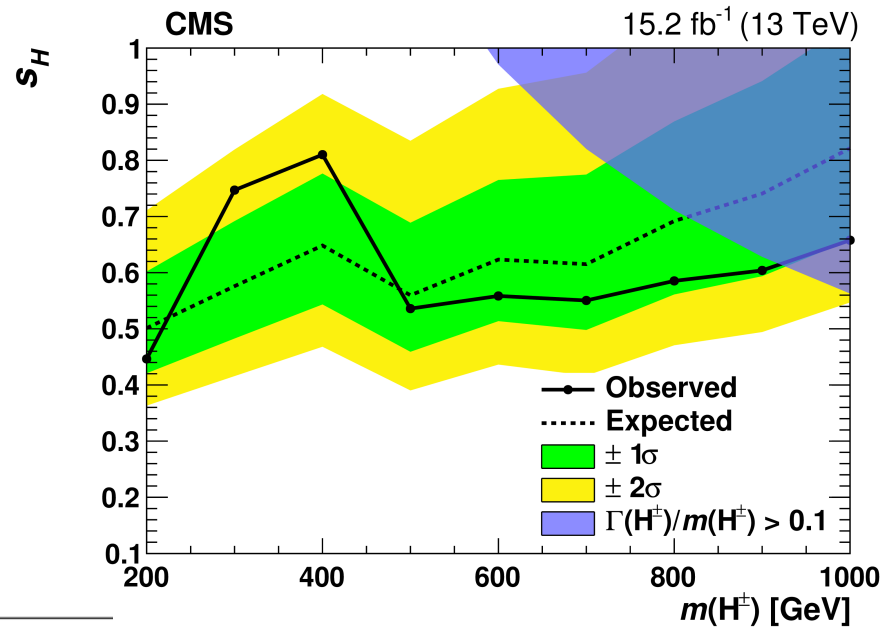


- 3 charged leptons → dominant WZ background (QCD and EWK)
- Interpretation in triplet model

→ *alignment limit → no 2HDM*

→ *s_H^2 = fraction of W boson mass squared generated by triplet vev*





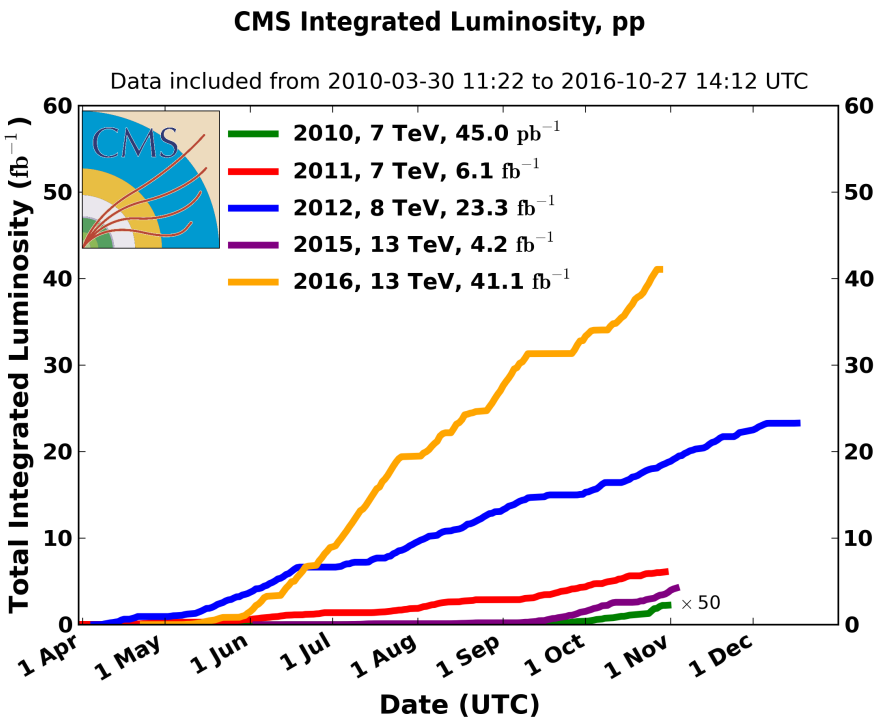
$$m_T(WZ) = \sqrt{(E_T(W) + E_T(Z))^2 - (\vec{p}_T(W) + \vec{p}_T(Z))^2}$$

1705.02942

Summary

- Strong motivations to search for extended Higgs sector
  - → *Cover all decay and production modes*
  - → *2HDM constraints suggest focus on fermions*
  - → *Doesn't have to look like the 2HDM*
    - Singlets and triplets may also have a role

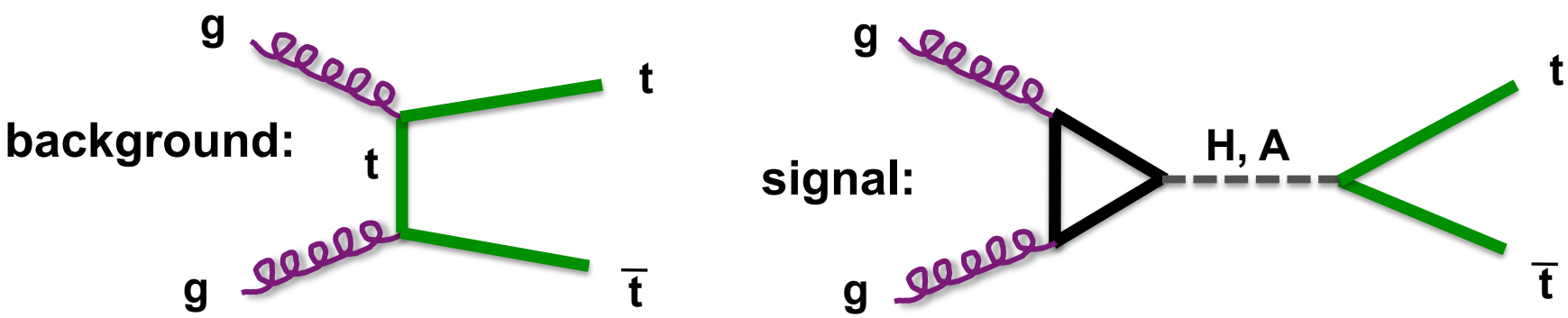
- Will be a rich program for the life of the LHC – many measurements just getting interesting
  - → *Detailed Run 1 analysis mostly complete*
  - → *Many Run 2 analyses in place*
  - → *50x the data yet to come*

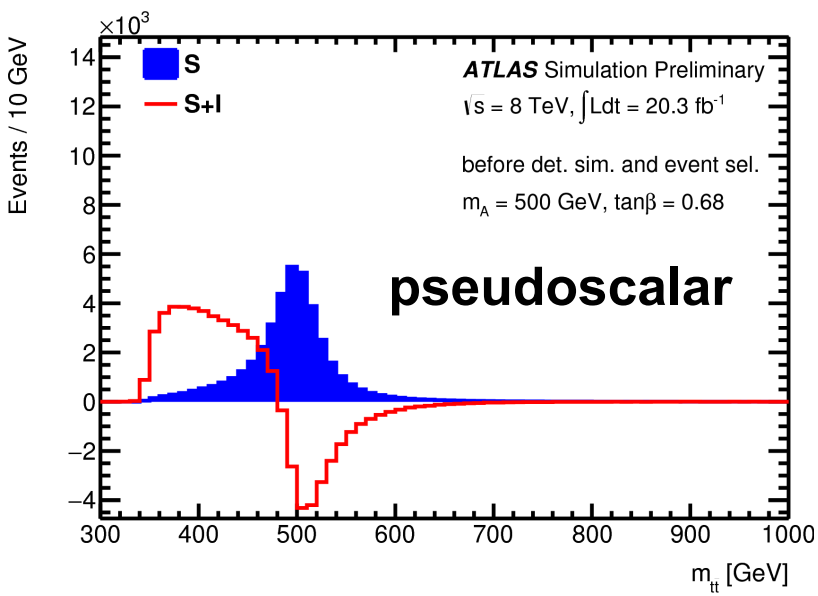


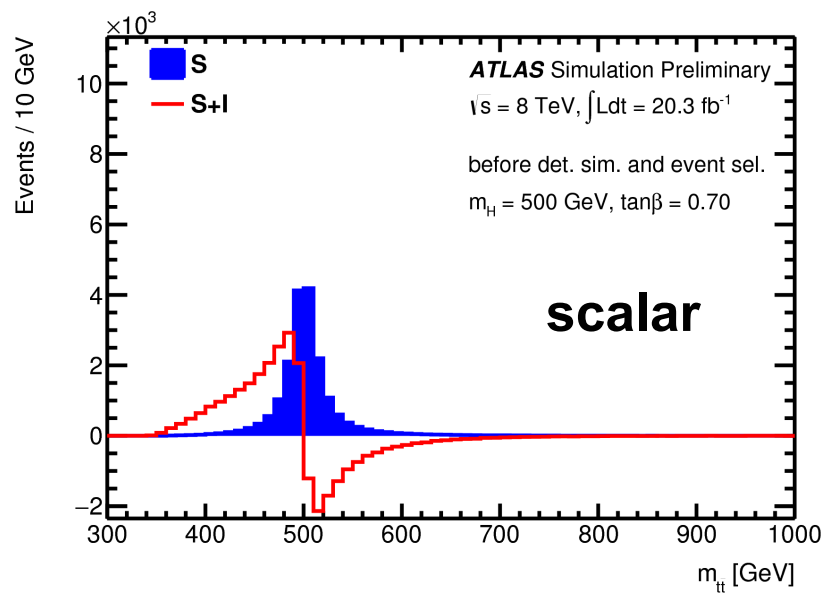
backup

H/A → ttbar

- Cannot be interpreted as a heavy Higgs search

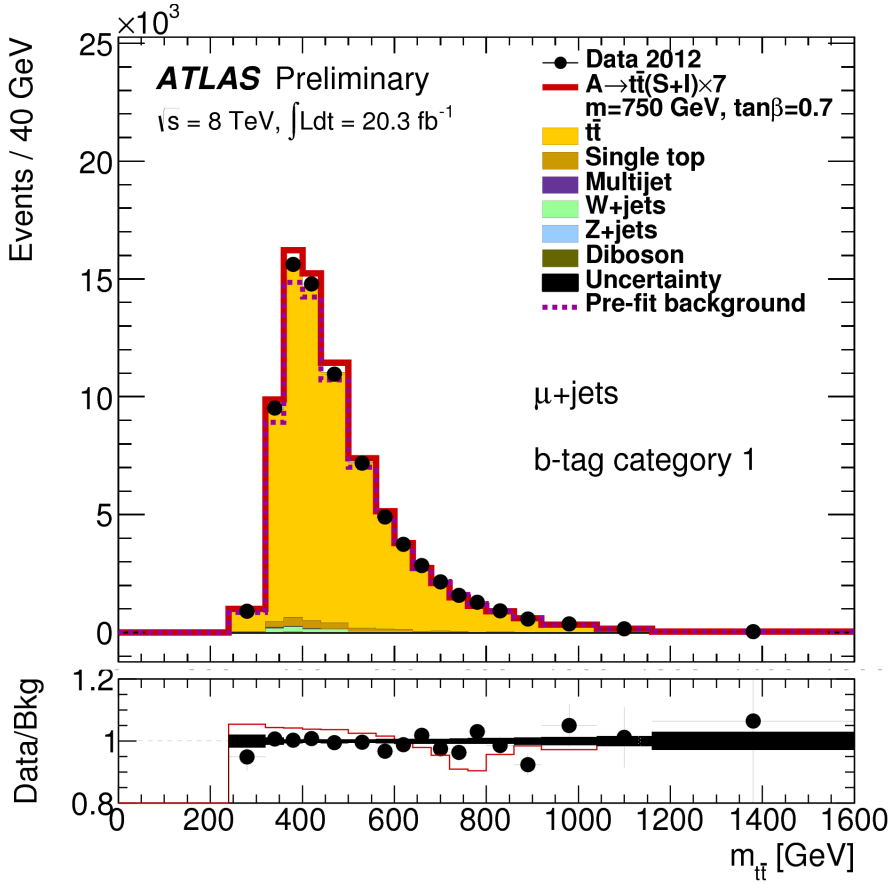


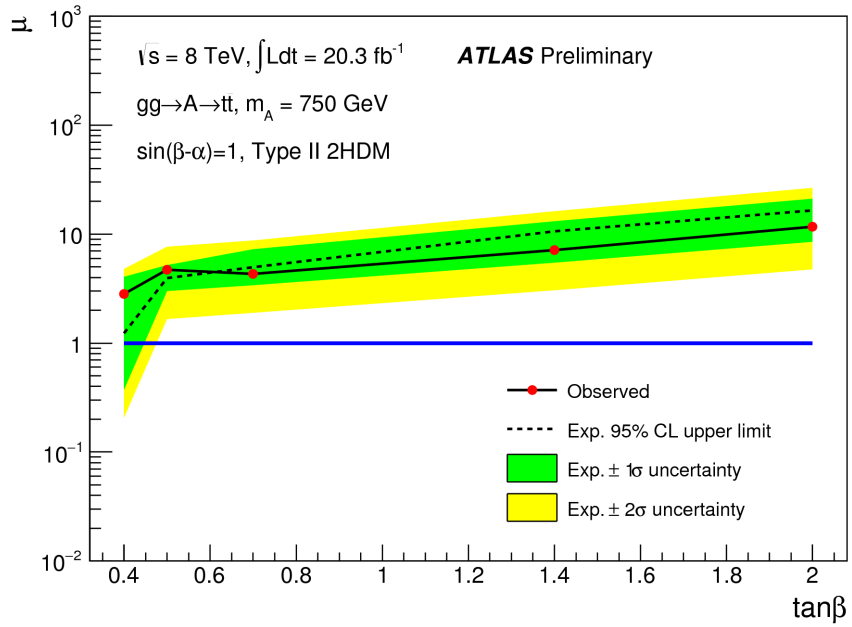




ATLAS-CONF-2016-073

H/A → ttbar





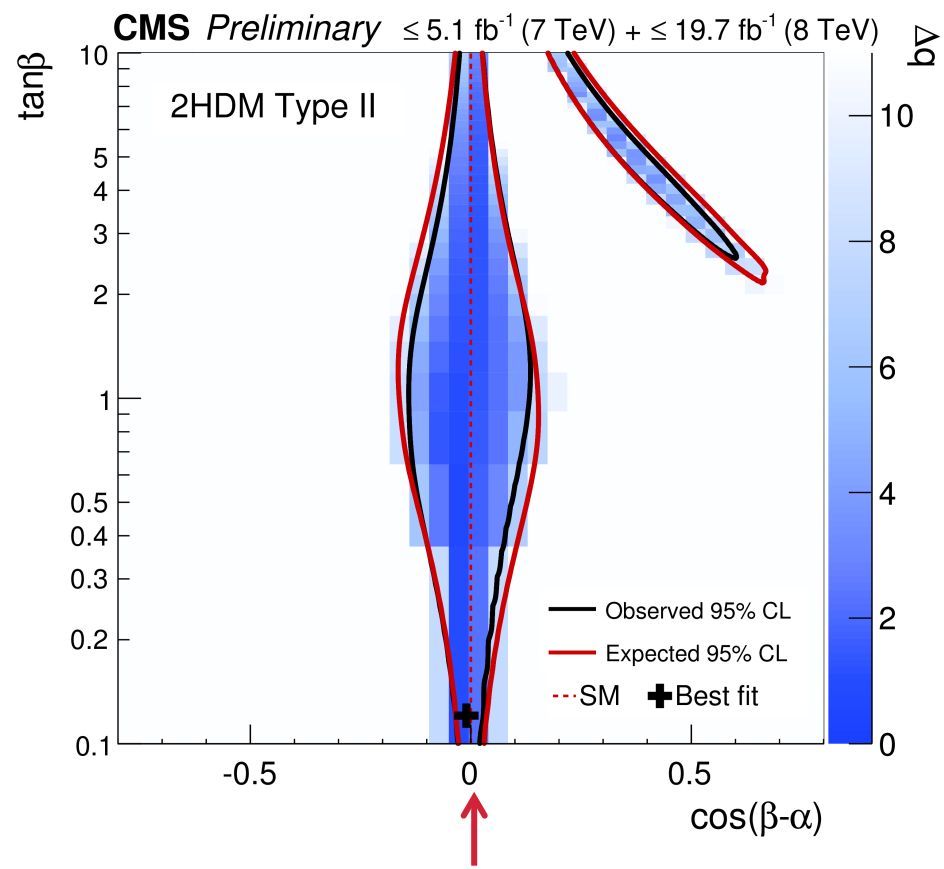
m_A = 750 GeV
from ATLAS-CONF-2016-073

- Just starting to dip into relevant parameter space
- Exclude tan β < 0.85 for m_A = 500 GeV
- Exclude tan β < 0.45 for m_H = 500 GeV

Indirect Constraints

- Implication of "shared" couplings: observed Higgs boson must be one of h or H
- Compatibility with SM constrains parameters
  - → *The better the measurement, the stronger the constraint for the corresponding channel*
- "alignment" = **cos(β−α) = 0** and h is SM-like
- Many such studies covering the parameter space….

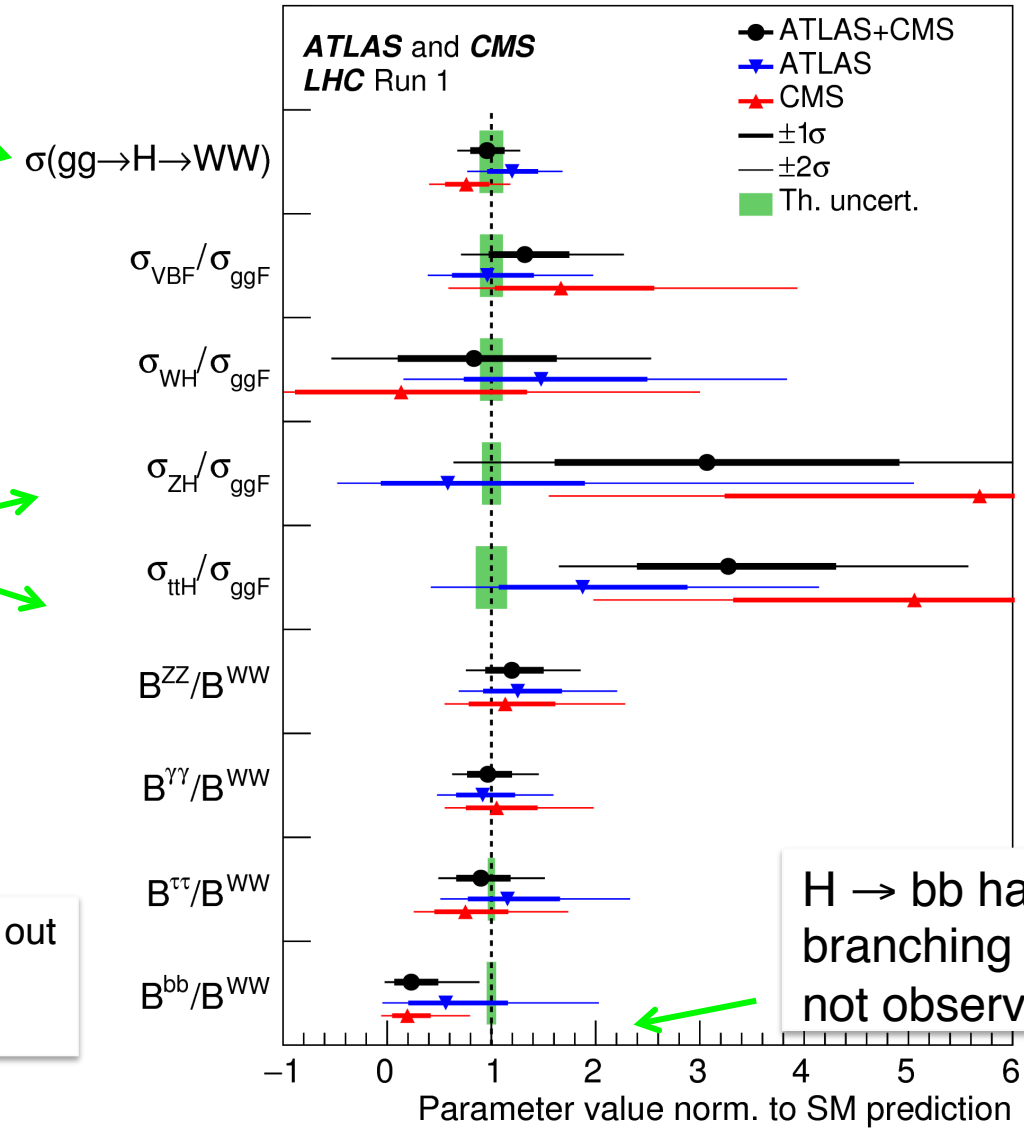
CMS-PAS-HIG-16-007



Run 1 is just the beginning

H → WW, the most precise single-channel measurement*, **total uncertainty ~20%**

Rare but important ZH, ttH production modes still to be established



H → bb has highest branching ratio, still not observed

* Just recently edged out by Run 2 preliminary measurement

The CMS Detector