Additional Higgs bosons

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Outline

Why additional Higgs bosons?

Models: SM + singlet(s)

Models: SM + doublet(s)

Models: SM + triplet(s), etc.

Conclusions

Why additional Higgs bosons?

SM Higgs is the minimal (perturbative) implementation of electroweak symmetry breaking: additional Higgses not necessary.

But there are many other "open questions" in the SM whose solutions may involve additional Higgs bosons:

- Hierarchy problem MSSM (2 doublets), NMSSM (2 doublets + singlet), ...; composite Higgs models (extra doublet(s), triplet(s), singlet(s)); Twin Higgs; ...

- Dark matter SUSY as above; complex singlet scalar DM; Inert Doublet Model; ...

- Neutrino masses Type 2 Seesaw (scalar triplet), more complicated neutrino mass models

- Baryon asymmetry Extended Higgs sector for strong 1st-order phase transition; extra CP violation in Higgs sector; ...

Why search for additional Higgs bosons?

Many different extended-Higgs models map onto the same types of additional-Higgs signatures. Lots of "bang" from each search.

Spin-zero Higgs bosons keep the kinematics simple: easy to interpret searches, reinterpret limits from one model to another. Searches hold their value well.

Excellent benchmark processes for resonant non-SM production and decay modes of h_{125}. Next frontier beyond usual SM Higgs measurements.

Low-rate electroweak production of additional Higgs bosons provides natural targets for high-luminosity LHC searches. Genuine opportunities for discovery.

Complementary to high-precision measurements of h_{125} couplings. Multiple experimental handles will allow to dig into model details.

Why search for additional Higgs bosons?

Additional Higgs bosons can be quite light $\mathcal{O}(100 - 200)$ GeV

- Electroweak production $\to$ cross sections generally fairly small

- Couplings to SM fermions can be suppressed depending on mixing

- Decays can be complicated leading to hard-to-reconstruct or soft final states

Low mass $\Rightarrow$ not captured cleanly by EFT framework!

Good targets for dedicated searches.

Models: SM + singlet(s)

Motivation is usually phenomenological ("simplest" extension of the Higgs sector), or for dark matter.

SM Higgs doublet Φ + real singlet S:

$$V = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 + \frac{m^2}{2} S^2 + \lambda_S S^4 + \lambda_{hS} \Phi^\dagger \Phi S^2$$

- imposed $S \to -S$ symmetry for simplicity: can be spontaneously broken by S vev (in which case h and S mix), or exact (in which case S is dark matter).

- $\lambda_{hS} \Phi^\dagger \Phi S^2$ is the "Higgs portal" coupling: controls most of the interesting physics.

Models: SM + real singlet: case where h and S mix:

$h_{125} = \cos\alpha \; h_{SM} - \sin\alpha \; S$ $\qquad\qquad$ $h_{new} = \sin\alpha \; h_{SM} + \cos\alpha \; S$

- All h_{125} couplings reduced by a factor of $\cos\alpha$:
if no $h_{125} \to h_{new} h_{new}$ decays, all signal strengths $\mu_{125} = \cos^2\alpha$.

- All h_{new} couplings to SM particles are just $\sin\alpha$ times SM Higgs couplings.

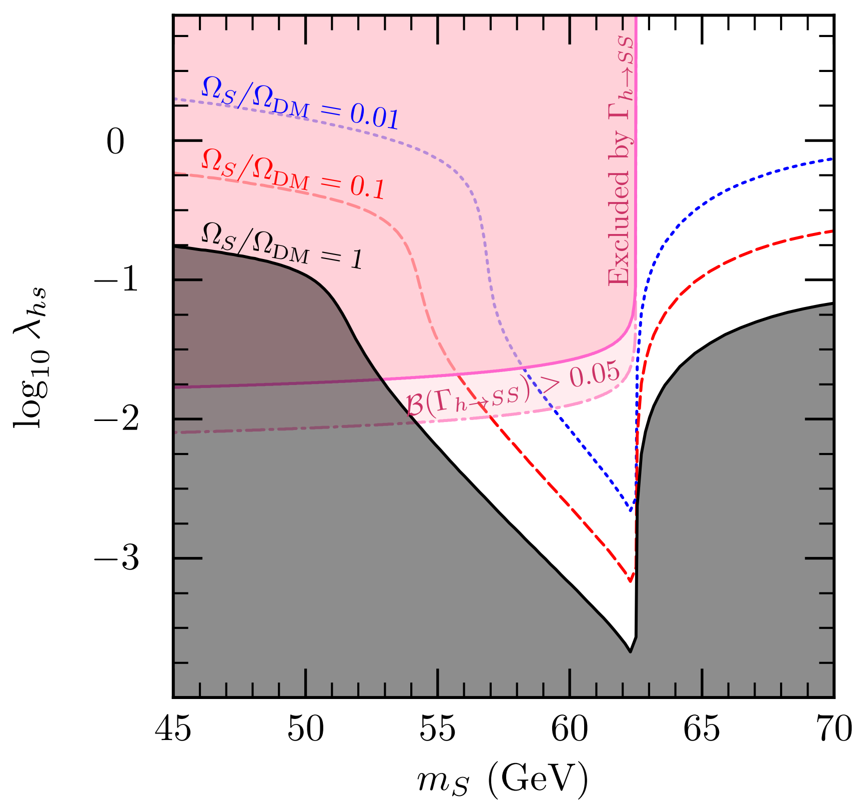
- Interesting signatures:
$h_{125} \to h_{new} h_{new} \to f\bar{f} \; f\bar{f}$ (exotic Higgs decays)
and/or SM $\to h_{new} \to$ SM (SM searches, $\mu_{new} = \sin^2\alpha$)
and/or $h_{new} \to h_{125} h_{125}$ (resonant di-Higgs production)

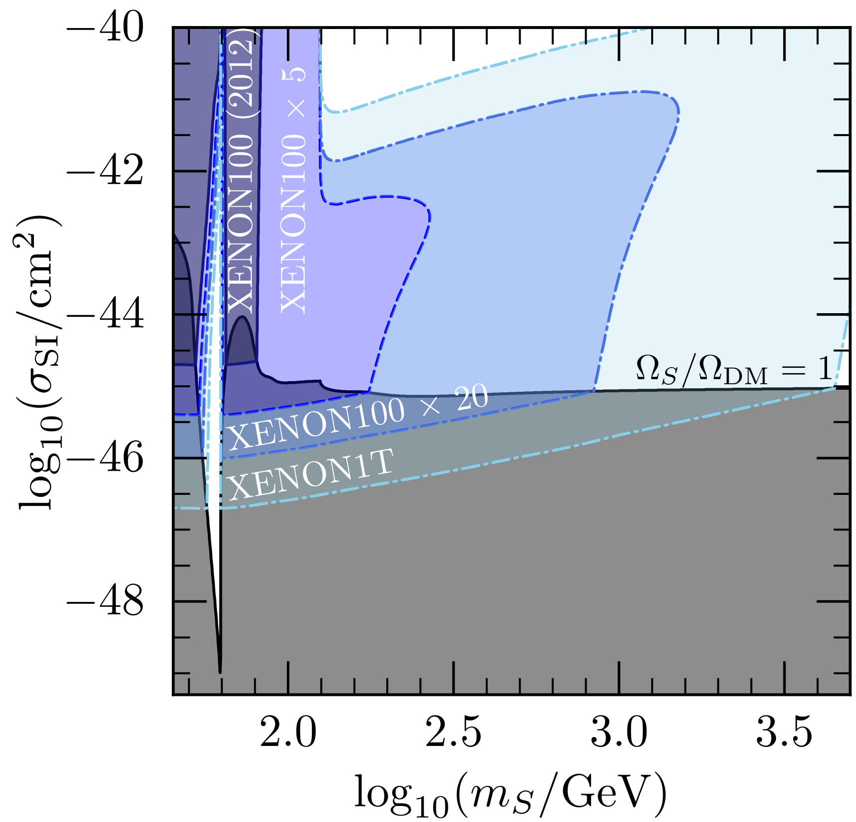
Few free parameters (m_{new}, α) + precision electroweak + existing searches $\Rightarrow$ quite constrained. Recent summary: 1611.03007

Models: SM + real singlet: case where S is dark matter:

$h_{125} = h_{SM}$; only possible new signature is $h \to SS$ (i.e., $h \to$ invisible)

Very constrained by relic density and direct-detection DM searches (e.g. XENON-1T) if S is to be all the dark matter. 1306.4710





Models: SM + singlet(s)

SM Higgs doublet Φ + complex singlet $S = (s + v_s + ia)/\sqrt{2}$:

Dark matter phenomenology significantly more interesting.

h_{SM} and s mix to give two "Higgs portal" mediators.
$h_{new} \to h_{125} h_{125}$ signature

a becomes dark matter; direct detection cross section can be heavily suppressed at tree level by natural cancellation between h_{125} and h_{new} exchanges. 1808.01598
$h_{125} \to$ invisible generally small, but $h_{new} \to$ invisible can be interesting

Models: SM + doublet(s): 2HDM

Original motivations to study 2HDM are SUSY (require an even number of Higgs doublets for anomaly cancellation among fermionic partners) and spontaneous parity or CP violation (from spontaneous misalignment of the vevs of the two doublets, now very constrained by EDMs).

Fabulous playground for additional-Higgs phenomenology!

Two doublets − Goldstone bosons = h^0, H^0, A^0, $H^\pm$

- h_{125} couplings: characteristic patterns of deviations depending on "Type" of fermion coupling structure.

- New CP-even (H^0) and CP-odd (A^0) neutral Higgs bosons, production in SM-like processes plus $b\bar{b}$-fusion, new decays including $t\bar{t}$ (interference w/ continuum!), $H \to h_{125}h_{125}$, $A \to Zh_{125}$; strong constraint from $H/A \to \tau\tau$ at larger $\tan\beta$ (Type II).

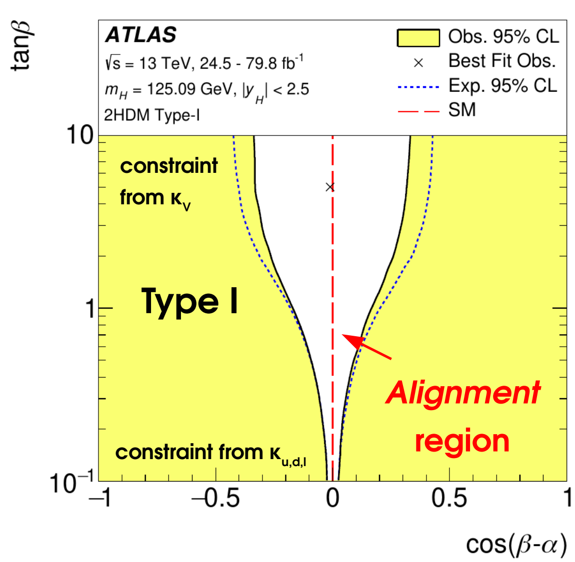
- Charged Higgs $H^\pm$ production in top decays or tH^- associated production, decays to $\tau\nu$, tb, etc.

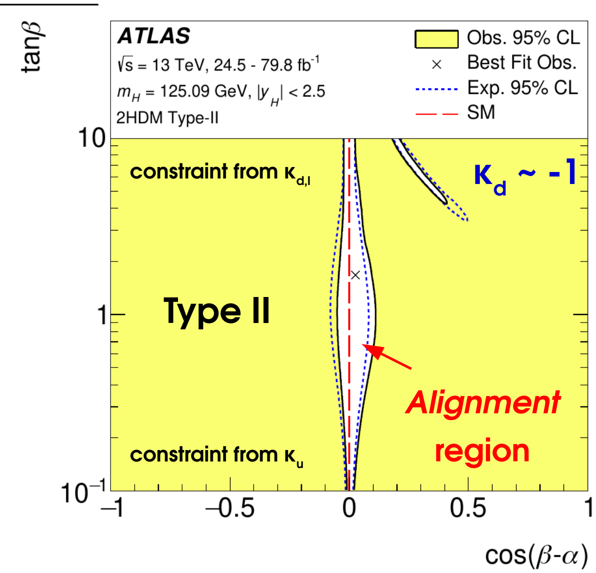
Models: SM + doublet(s): 2HDM

Natural flavour conservation Glashow, Weinberg 1977 dictates structure of Higgs doublet couplings to fermions. Enforce with Z_2 symmetry.

Type	Φ_2	Φ_1
I	u, d, ℓ	$-$
II (MSSM)	u	d, ℓ
X/leptonic	u, d	ℓ
Y/flipped	u, ℓ	d

Or: allow fermions to get mass from both doublets $\rightarrow$ framework for lepton flavour violating Higgs decays.





Type I is interesting: large $\tan\beta$ dials down fermion couplings of $H, A, H^{\pm}$; can be quite light $<$ 200 GeV! $t \to H^+ b$ still relevant!

Models: 2HDM + (complex) singlet

Higgs sector of the NMSSM.

Light pseudoscalar gets fermion couplings by mixing with A^0:
Prototype model for $h_{125} \to aa \to 4f$ searches

3 CP-even neutral Higgs bosons:
$H_3 \to H_1 H_2$ signatures (any of $H_{1,2,3}$ can be h_{125}; the other two have different masses)
- $H \to h_{125} h_{new}$
- $h_{125} \to h_1 h_2$

On the theorist "wish list" from HXSWG :)

Models: SM + doublet(s): 3HDM

More choices for structure of fermion mass generation.

E.g., can have Type Y/flipped style decays (e.g., dominant $H^+ \to cb$) while evading $b \to s\gamma$ constraint.

Options for dark matter:
- 2 active + 1 inert doublet (less constrained than Inert 2HDM)
- 1 active + 2 inert doublets (CPV in dark sector)

Models: SM + triplet(s), etc.

Two main reasons to add SU(2)-triplet Higgs bosons:

1) Neutrino mass generation (Type-2 Seesaw) from a complex triplet $(\chi^{++}, \chi^{+}, \chi^{0})$: $\mathcal{L} \supset (y_\nu)_{ij} \bar{L}_i^c \tau^a L_j \chi^a$

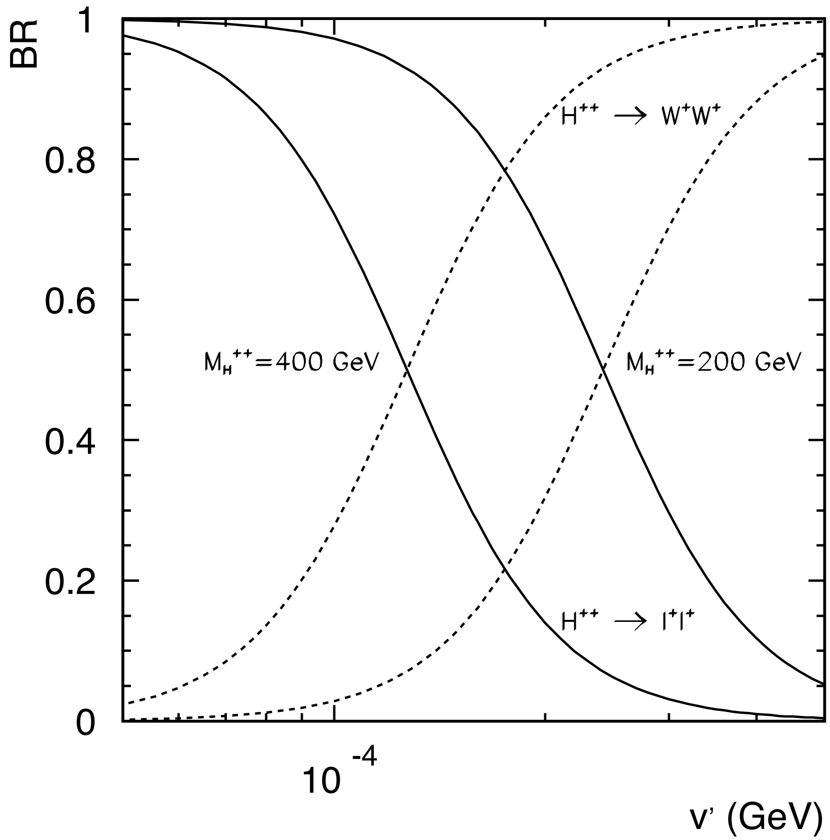
Yukawa couplings $y_\nu v_\chi = m_\nu \sim 0.1$ eV

Triplet vev v_χ drives $\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} < 1$: constrained to be less than a couple of GeV.

Novel signature: Doubly-charged Higgs $\chi^{\pm\pm}$

Pair production via Drell-Yan $q\bar{q} \to \chi^{++}\chi^{--}$, etc.
(Single production cross sections all $\propto v_\chi^2$: very suppressed.)

Models: SM + triplet(s), etc.



e.g. Han et al, 0706.0441

$y_\nu v_\chi = m_\nu \sim 0.1$ eV

- Small vev: couples to $\ell_i^\pm \ell_j^\pm \propto y_\nu$. Very clean signature, measure left-handed neutrino Majorana mass matrix; limit $m_{\chi^{++}} \gtrsim 500 - 800$ GeV.

- Larger vev: couples to $W^\pm W^\pm \propto v_\chi$. More complicated final states, W branching fractions $\rightarrow$ much harder to probe.

Mass dependence: $\Gamma(\ell\ell) \propto y_\nu^2 m_{\chi^{++}}$ while $\Gamma(WW) \propto v_\chi^2 m_{\chi^{++}}^3 / M_W^4$ due to longitudinal W polarization contribution.

Models: SM + triplet(s), etc.

Two main reasons to add SU(2)-triplet Higgs bosons:

2) Experimentally test whether part of electroweak-breaking condensate comes from representations larger than doublet.

Have to model-build to evade ρ parameter constraint on larger representation's vev:
- Build in global SU(2)$_L\times$SU(2)$_R$ symmetry in scalar potential; preserves custodial symmetry after EWSB.
    $\Rightarrow$ Georgi-Machacek model (2 triplets) + generalizations
- Use septet representation $T = 3, Y = 2$; gives $\rho = 1$ by accident.
    $\Rightarrow$ Scalar septet model

Novel feature: $|\kappa_V| > 1$ is possible! (favoured by current data!)
Cannot be obtained in models with Higgs doublets/singlets only.

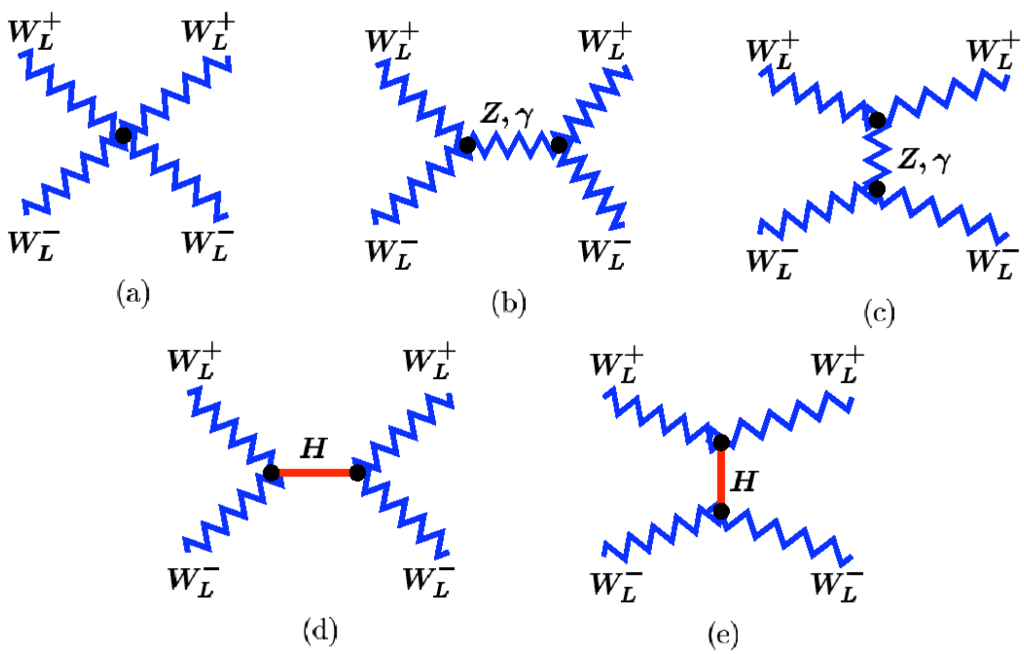
hVV coupling:

$$\kappa_V^h = \cos\alpha \cos\theta_H - \sqrt{A} \sin\alpha \sin\theta_H, \qquad A = \frac{4}{3} T(T+1)$$

holds in GM, GM-generalizations, and scalar septet model

α is h–H mixing angle; θ_H is analogous to β in 2HDM.
$\sin^2\theta_H$ = fraction of $M_{W,Z}^2$ from larger representation's vev.

$|\kappa_V| > 1$ is intertwined with doubly-charged Higgs $H^{\pm\pm}$ via the unitarization of the longitudinal W^+W^- scattering amplitude.

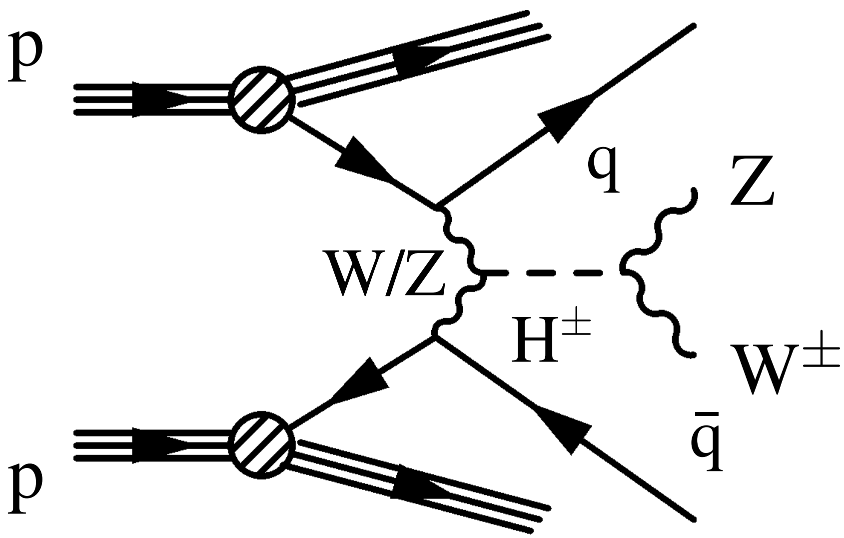


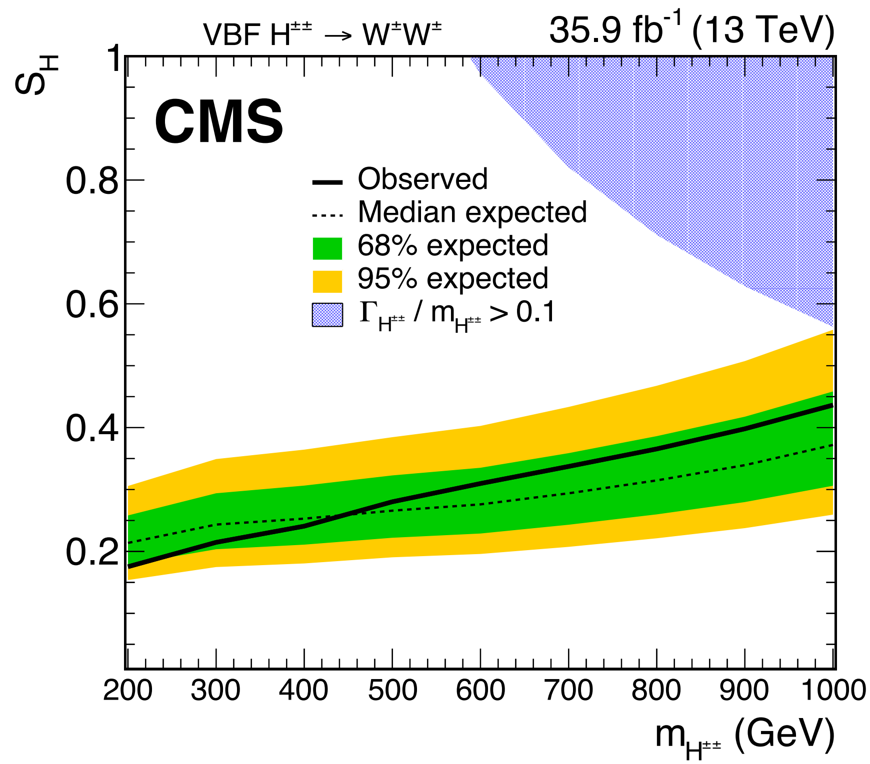
u-channel diagram with H^{++} comes in with opposite sign, cancels $\kappa_V^2 > 1$ contribution from h (and also H).

$H^{++}W^-W^-$ coupling $\propto \sin\theta_H$: probe in VBF!

VBF $\to H^{\pm\pm} \to W^{\pm}W^{\pm}$ VBF + like-sign dileptons + MET

VBF $\to H^{\pm} \to W^{\pm}Z$ VBF + $qq\ell\ell$; VBF + 3ℓ + MET



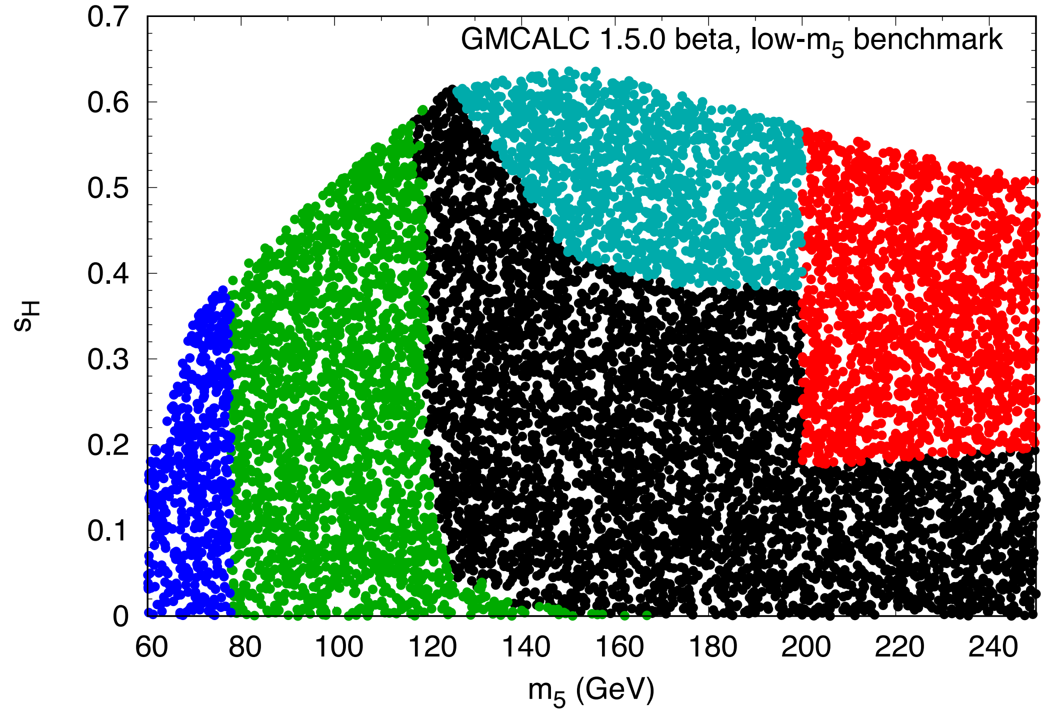


CMS, arXiv:1709.05822

Cross sections $\propto \sin^2\theta_H \equiv$ fraction of $M^2_{W,Z}$ due to exotic scalars.

Below 200 GeV constraints on $H^{\pm\pm}$ are mainly theory-recast:

Recast ATLAS Run1 VBF $\to W^{\pm}W^{\pm}$, 1407.5053



(Preliminary)

CMS VBF $\to H^{\pm\pm} \to W^{\pm}W^{\pm}$

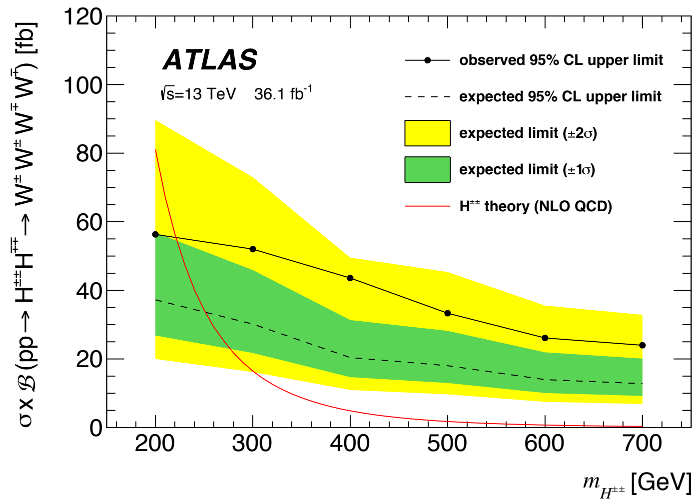
1709.05822

Allowed

Recast ATLAS Run1 dimuons, 1412.7603, 1502.01275

Recast ATLAS Run1 $\gamma\gamma$ resonance, in prep

Drell-Yan $H^{++}H^{--} \to 4W$ should have sensitivity over this whole region – important to extend search below 200 GeV!



Conclusions

Additional Higgs bosons appear in many well-motivated extensions of the SM.

Additional Higgs boson(s) can be light: can't fold into SMEFT approach at LHC energies.

Searches require few assumptions and are easily reinterpretable in related models.

Excellent well-motivated opportunity to dig deep into small signal cross sections with high-luminosity LHC data.

BACKUP SLIDES