Higgs Beyond the Standard Model – theory (part 1)

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Outline

Lecture 1:
- Lightning review of SM Higgs
- Conceptual framework for extended Higgs sectors
- Higgs mixing: SM + Singlet
- New gauge structures: Georgi-Machacek model

Lecture 2: Two-Higgs-Doublet Model and its delights
- New fermion structures: Natural flavour cons. & 2HDM pheno
- More new fermion structures: Flavour violation
- New scalar potential options: CP violation
- Dark matter: Inert 2HDM

Standard Model Higgs: a quick review

SM is an SU(3)$_c\times$SU(2)$_L\times$U(1)$_Y$ gauge theory with chiral fermions and a spin-zero Higgs field in a doublet representation of SU(2)$_L$:

[Glashow, Weinberg, Salam 1967]

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

The part of the Lagrangian involving the Higgs field is:

$$\mathcal{L}_{Higgs} = \mathcal{L}_{gauge} + \mathcal{L}_{Yukawa} - V_{Higgs}$$

where

- $\mathcal{L}_{gauge} = (\mathcal{D}^\mu \Phi)^\dagger (\mathcal{D}_\mu \Phi)$ is the gauge-kinetic (covariant derivative) term involving Φ;
- $\mathcal{L}_{Yukawa}$ contains the Yukawa couplings of Φ to the fermions;
- V_{Higgs} is the scalar potential.

(For a refresher, see my TASI 2013 lectures, arXiv:1406.1786)

Standard Model Higgs: a quick review

Most general gauge-invariant, renormalizable scalar potential:

$$V_{Higgs} = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

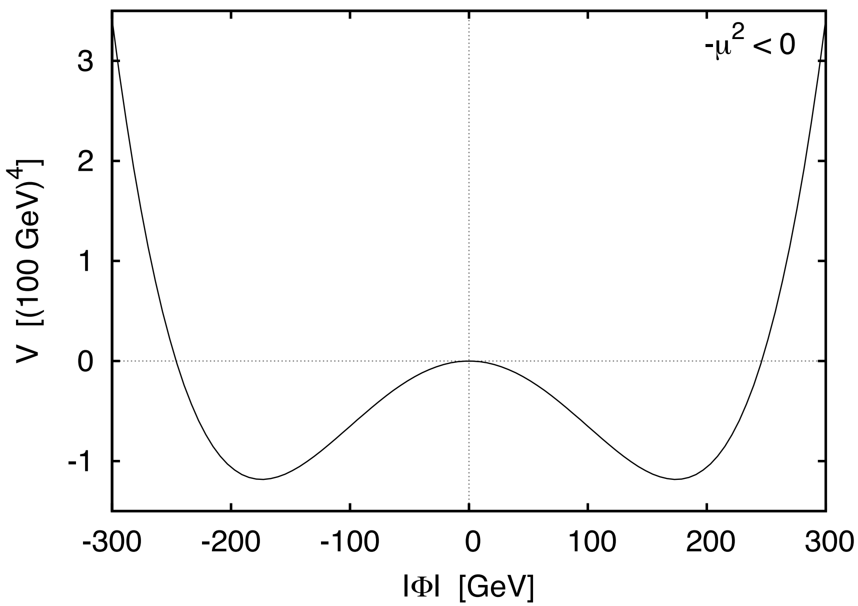
Spontaneous symmetry breaking:

minimum of potential is at $|\Phi| \neq 0 \quad \Rightarrow \quad \langle \Phi \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$

2 parameters in V_{Higgs} fixed by 2 observables:

- $v \simeq 246$ GeV from Fermi constant G_F
- $m_h = 2\lambda v^2 \simeq 125$ GeV from Higgs mass measurement

Prediction for triple-Higgs coupling $hhh \sim -6i\lambda v = -3im_h^2/v$



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Standard Model Higgs: a quick review

Gauge-kinetic terms completely determined by gauge invariance:

$$\mathcal{L}_{gauge} = (\mathcal{D}^\mu \Phi)^\dagger (\mathcal{D}_\mu \Phi)$$

Use covariant derivative for an SU(2)$_L$ doublet ($T^a = \sigma^a/2$) with hypercharge $Y = 1/2$:

$$\mathcal{D}_\mu = \partial_\mu - i\frac{g'}{2}B_\mu - igW_\mu^a T^a$$

Algebra → get W and Z boson masses (photon stays massless)

$$M_W^2 = \frac{g^2 v^2}{4} \qquad\qquad M_Z^2 = \frac{(g^2 + g'^2)v^2}{4}$$

These fix g and g' → predict W and Z couplings to the Higgs:

$$hW_\mu^+ W_\nu^- \sim i\frac{g^2 v}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v} g_{\mu\nu}$$
$$hZ_\mu Z_\nu \sim i\frac{(g^2 + g'^2)v}{2} g_{\mu\nu} = 2i\frac{M_Z^2}{v} g_{\mu\nu}$$

(For a refresher, see my TASI 2013 lectures, arXiv:1406.1786)

Standard Model Higgs: a quick review

Most general gauge-invariant Yukawa couplings:

$$\mathcal{L}_{Yukawa} = -y_d \bar{Q}_L \Phi d_R - y_u \bar{Q}_L \tilde{\Phi} u_R - y_\ell \bar{L}_L \Phi e_R + \text{h.c.}$$

Three fermion generations: y_d, y_u, y_ℓ are 3×3 complex matrices in flavour space.

Insert $\langle \Phi \rangle$ and diagonalize the resulting fermion mass matrices $\rightarrow$ get fermion masses (except for neutrinos) and CKM matrix from mismatch of up and down diagonalizations:

$$m_f = \frac{y_f v}{\sqrt{2}}$$

These fix the elements of the Yukawa matrices in the mass basis $\rightarrow$ predict fermion couplings to the Higgs:

$$h \bar{f} f \sim \frac{-i y_f}{\sqrt{2}} = \frac{-i m_f}{v}$$

(For a refresher, see my TASI 2013 lectures, arXiv:1406.1786)

Why study BSM Higgs?

Two practical reasons:

(1) We know that the Standard Model does not fully explain nature.

- Dark matter?
- Baryon asymmetry of the universe?
- Cosmic inflation?
- Origin of neutrino masses?
- Absence of CP violation in strong interactions?
- Hierarchy problem?
- [your favourite open question here]

Why study BSM Higgs?

Two practical reasons:

(2) Experimental searches designed to look for particular signatures of new particles are always (much!) more sensitive than generic tests of consistency with Standard Model predictions.

- Extended Higgs models give us a class of fairly generic new-physics signatures to design searches around

Why study BSM Higgs?

And one opportunistic reason:

(3) The Higgs boson is here, and the LHC is a good machine to study its properties! Let's do the best and most thorough job we can with the LHC data!

Close cooperation between theorists and experimentalists makes this possible.

Conceptual framework for extended Higgs sectors

- Work in a perturbative framework ⇒ add scalar(s) in specific representations of SU(2)$_L$×U(1)$_Y$

(Nonperturbative: composite Higgs models)

(Scalars charged under QCD: not normally called “Higgs”)

3 classes of things that can happen:

- New gauge coupling structures – SU(2)$_L$×U(1)$_Y$ reps other than doublet

- New fermion coupling structures – SU(2)$_L$ doublets only (due to the known gauge charges of left- and right-handed fermions)

- Additional states and mixing – SU(2)$_L$ singlet(s), and/or any of the above

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  2. Georgi-Machacek model
- New fermion coupling structures – SU(2)$_L$ doublets only (due to the known gauge charges of left- and right-handed fermions)
  3. Two-Higgs-doublet models (tomorrow)
- Additional states and mixing – SU(2)$_L$ singlet(s), and/or any of the above
  1. SM + Singlet

Higgs mixing: SM + singlet

Simplest possible extension of the SM Higgs sector is to add a single real scalar field S, which is uncharged under any gauge symmetry (i.e., transforms as a singlet under SU(2)$_L$).

Build the most general renormalizable scalar potential by requiring gauge invariance:

$$\begin{aligned} V_{Higgs} &= -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 && \leftarrow \text{ SM part} \\ &\quad +\kappa\Phi^\dagger\Phi S + \lambda_{hS}\Phi^\dagger\Phi S^2 && \leftarrow \ \Phi\text{–}S \text{ couplings} \\ &\quad +\kappa_1 S + \mu_S^2 S^2 + \kappa_3 S^3 + \lambda_S S^4 && \leftarrow \ S\text{–only terms} \end{aligned}$$

Notes:

- S can get a vev, or not. This has no collider consequences other than to reshuffle the meanings of the various terms in the scalar potential.
- Could impose a discrete Z_2 symmetry, $S \to -S$; this sets κ, κ_1, and κ_3 to zero. If S gets a vev, this has collider consequences only in Higgs-to-Higgs couplings. If S doesn't get a vev, this prevents mixing with h and makes S a dark matter candidate.

Higgs mixing: SM + singlet

Since S is a gauge singlet, its gauge-kinetic term is just a kinetic term:

$$\mathcal{L}_{gauge} = (\mathcal{D}^\mu \Phi)^\dagger (\mathcal{D}_\mu \Phi) + \frac{1}{2}(\partial^\mu S)(\partial_\mu S)$$

- Φ is responsible for electroweak symmetry breaking just as in the SM.
- The real neutral component of Φ (call it $\phi^{0,r}$) gets the same couplings to gauge bosons as the SM Higgs.
- S does not couple to gauge bosons at all.

Note that $\phi^{0,r}$ and S are going to mix to form the physical mass eigenstates... more on this in a moment!

Higgs mixing: SM + singlet

Since S is a gauge singlet, it cannot have Yukawa couplings to SM fermions; $\mathcal{L}_{Yukawa}$ is exactly the same as in the SM:

$$\mathcal{L}_{Yukawa} = -y_d \bar{Q}_L \Phi d_R - y_u \bar{Q}_L \tilde{\Phi} u_R - y_\ell \bar{L}_L \Phi e_R + \text{h.c.}$$

(We know the SU(2)$_L \times$U(1)$_Y$ gauge charges of the SM fermions from direct measurements of their couplings to W and Z bosons – need a scalar doublet to couple left-handed doublet fermions to right-handed singlet fermions).

- Φ is responsible for fermion masses just as in the SM.
- The real neutral component of Φ (call it $\phi^{0,r}$) gets the same couplings to fermions as the SM Higgs.
- S does not couple to fermions at all.

Note that $\phi^{0,r}$ and S are going to mix to form the physical mass eigenstates... more on this in a moment!

Higgs mixing: SM + singlet

Up to now this sounds very boring... until we look back at the scalar potential! Simplest version: no vev for S:

$$V_{Higgs} \supset \kappa \Phi^\dagger \Phi S \to \text{EWSB} \to \kappa v \phi^{0,r} S$$

... an off-diagonal (or mixing) term in the mass matrix for $\phi^{0,r}$ and S:

$$\begin{pmatrix} m^2_{\phi^{0,r}} & \kappa v/2 \\ \kappa v/2 & m^2_S \end{pmatrix} \qquad \to \text{diagonalize, mixing angle } \theta$$

Physical mass eigenstates are linear combinations of $\phi^{0,r}$ and S:

$$\begin{aligned} h &= \cos\theta\,\phi^{0,r} - \sin\theta\, S \\ H &= \sin\theta\,\phi^{0,r} + \cos\theta\, S \end{aligned}$$

- Convention: h is lighter and H is heavier (either one can be the SM Higgs)
- Mixing angle θ is a free parameter (trade one of the scalar potential parameters for it)

Higgs mixing: SM + singlet

Re-express the gauge and fermion couplings in terms of the mass eigenstates h and H:

$$hV_\mu V_\nu \sim 2i\frac{M_V^2}{v}g_{\mu\nu} \times \cos\theta \qquad HV_\mu V_\nu \sim 2i\frac{M_V^2}{v}g_{\mu\nu} \times \sin\theta$$

$$h\bar{f}f \sim \frac{-im_f}{v} \times \cos\theta \qquad H\bar{f}f \sim \frac{-im_f}{v} \times \sin\theta$$

$\Rightarrow$ A second Higgs boson H with SM-like couplings, but all scaled down by a factor of $\sin\theta$. (Sum rule: $\sin^2\theta + \cos^2\theta = 1$)

In the early days [years] after the Higgs boson discovery, this model provided a theoretically well-defined benchmark to search for a second Higgs resonance at higher mass – particularly important when the Higgs width has to be taken into account.

This structure of "sharing" of couplings due to mixing of the underlying scalar fields will show up again in more complicated models.

Higgs mixing: SM + singlet

Two other bits of interesting phenomenology:

- If h is the 125 GeV Higgs and H is heavy enough, can have resonant di-Higgs production from $pp \to H \to h_{125} h_{125}$.

$\Rightarrow$ Variant of search for SM di-Higgs production, with potential for earlier discovery.

- If H is the 125 GeV Higgs and h is light enough, can have exotic Higgs decays $H_{125} \to hh$.

$\Rightarrow$ New SM Higgs decay process; requires dedicated experimental search and modifies SM branching ratios (already constrained to be rare).

(Note: with an unbroken $S \to -S$ symmetry, S is dark matter and there's no mixing; then $H_{125} \to SS$ is an invisible decay of the Higgs.)

These processes can show up again in more complicated models.

New gauge structures

Singlet model is especially simple because the singlet does not couple to gauge bosons or contribute to electroweak symmetry breaking (nor does it contribute to fermion masses).

Let's move on and consider scalars in nontrivial representation(s) of SU(2)$_L$.

We'll look at multi-doublet models extensively tomorrow.

Now, let's consider "exotic" representations of SU(2)$_L$ (i.e., larger than the doublet).

Going to focus on the situation in which the "exotic" representations get a vev.

New gauge structures: exotic reps

The first challenge is to avoid messing up the W and Z masses! Mass terms from the gauge-kinetic Lagrangian:

$$\begin{aligned}\mathcal{L}_{gauge} \supset\ & \frac{g^2}{2}\left\{\langle X\rangle^\dagger(T^+T^- + T^-T^+)\langle X\rangle\right\} W^+_\mu W^{-\mu} \\ & + \frac{(g^2+g'^2)}{2}\left\{\langle X\rangle^\dagger(T^3T^3 + Y^2)\langle X\rangle\right\} Z_\mu Z^\mu + \cdots\end{aligned}$$

Must also have ≥ 1 Higgs doublet to give masses to SM fermions:

$$\begin{aligned}M_W^2 &= \left(\frac{g^2}{4}\right)[v_\phi^2 + a\langle X^0\rangle^2] \\ M_Z^2 &= \left(\frac{g^2+g'^2}{4}\right)[v_\phi^2 + b\langle X^0\rangle^2]\end{aligned}$$

where $\langle \Phi_{\rm SM}\rangle = (0, v_\phi/\sqrt{2})^T$ and

$$\begin{aligned}a &= 4\left[T(T+1) - Y^2\right]c \\ b &= 8Y^2\end{aligned}$$

$c = 1$ for complex, $c = 1/2$ for real multiplet

New gauge structures: exotic reps

Extremely strong constraint from electroweak precision measurements (including low-energy weak interaction strength measurements):

$$\rho \equiv \frac{\text{weak neutral current}}{\text{weak charged current}} = \frac{(g^2 + g'^2)/M_Z^2}{g^2/M_W^2} = \frac{v_\phi^2 + a\langle X^0\rangle^2}{v_\phi^2 + b\langle X^0\rangle^2}$$

$$\begin{aligned} a &= 4\left[T(T+1) - Y^2\right] c \\ b &= 8Y^2 \end{aligned}$$

Experiment: (PDG 2024 [Erler & Freitas])

$$\rho = 1.000\,31 \pm 0.000\,19$$

Two options:
- $\langle X^0\rangle$ is really small or zero (kind of boring)
- Choose representation(s) so that $a = b$ (or $\sum a_i \langle X_i^0\rangle = \sum b_i \langle X_i^0\rangle$)

New gauge structures: exotic reps

1) Doublet + septet $(T, Y) = (3, 2)$: Scalar septet model

Hisano & Tsumura, 1301.6455; Kanemura, Kikuchi & Yagyu, 1301.7303

2) Doublet + triplets $(1, 0) + (1, 1)$: Georgi-Machacek model

(ensure triplet vevs are equal using a global "custodial" symmetry)

Georgi & Machacek 1985; Chanowitz & Golden 1985

3) Doublet + quartets $\left(\frac{3}{2}, \frac{1}{2}\right) + \left(\frac{3}{2}, \frac{3}{2}\right)$: Generalized Georgi-
4) Doublet + quintets $(2, 0) + (2, 1) + (2, 2)$: Machacek models
5) Doublet + sextets $\left(\frac{5}{2}, \frac{1}{2}\right) + \left(\frac{5}{2}, \frac{3}{2}\right) + \left(\frac{5}{2}, \frac{5}{2}\right)$:

(ensure exotics' vevs are equal using a global "custodial" symmetry)

Galison 1984; Robinett 1985; HEL 1999; Chang et al 2012; HEL & Rentala 2015

Larger than sextets $\rightarrow$ too many large multiplets, violates perturbativity!

Looks like a lot to tackle... but all these models have a key phenomenological feature in common! Choose one as a benchmark to design expt searches.

New gauge structures: Georgi-Machacek model

Georgi & Machacek 1985; Chanowitz & Golden 1985

SM Higgs (bi-)doublet + triplets $(1,0)+(1,1)$ in a bi-triplet:

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ -\phi^{+*} & \phi^0 \end{pmatrix} \qquad X = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ -\chi^{+*} & \xi^0 & \chi^+ \\ \chi^{++*} & -\xi^{+*} & \chi^0 \end{pmatrix}$$

Global $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ → custodial symmetry $\langle \chi^0 \rangle = \langle \xi^0 \rangle \equiv v_\chi$

Physical spectrum:

Bidoublet: $2 \otimes 2 \to 1 \oplus 3$ Bitriplet: $3 \otimes 3 \to 1 \oplus 3 \oplus 5$

- Two custodial singlets mix → h^0, H^0 m_h, m_H
  Usually identify $h^0 = h(125)$

- Two custodial triplets mix → (H_3^+, H_3^0, H_3^-) m_3 + Goldstones
  Phenomenology very similar to $H^\pm, A^0$ in 2HDM Type I, $\tan\beta \to \cot\theta_H$

- Custodial fiveplet $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$ m_5 ⟵ ★ new!
  Fermiophobic; H_5VV couplings $\propto s_H \equiv \sqrt{8} v_\chi / v_{\mathrm{SM}}$
  $s_H^2 \equiv$ exotic fraction of M_W^2, M_Z^2

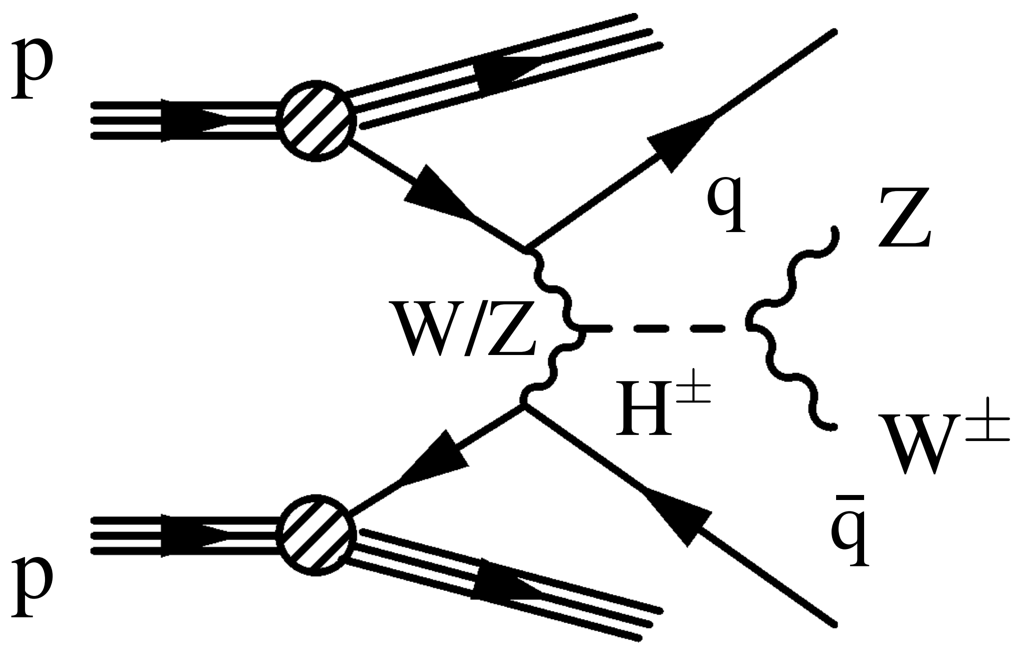
New gauge structures: Georgi-Machacek model

Novel collider processes in vector boson fusion (VBF):

VBF $\rightarrow H_5^{\pm\pm} \rightarrow W^\pm W^\pm$ — VBF + like-sign dileptons + MET

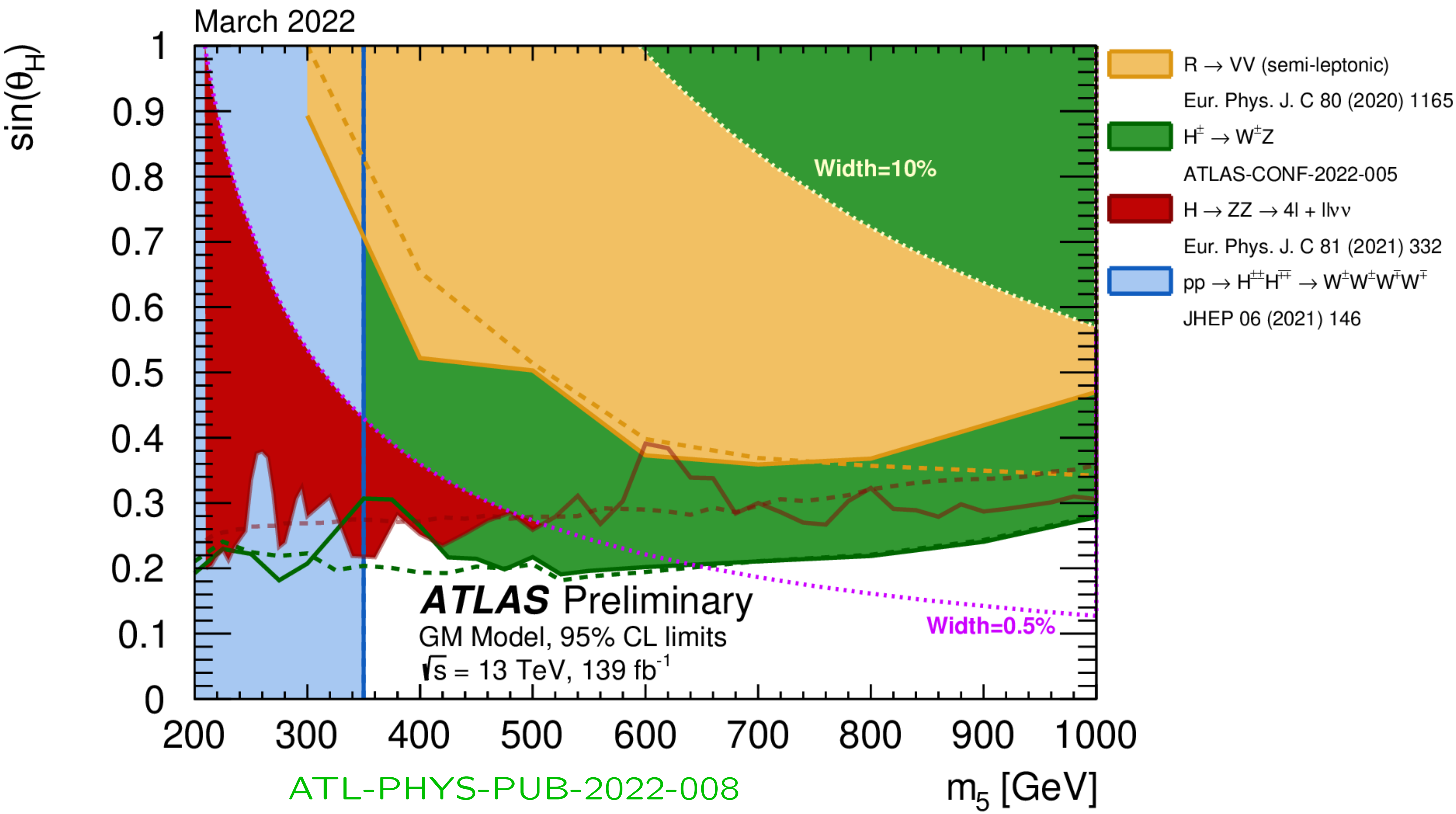
VBF $\rightarrow H_5^{\pm} \rightarrow W^\pm Z$ — VBF + $qq\ell\ell$; VBF + 3ℓ + MET

(tree-level $H^\pm W^\mp Z$ absent in models with Higgs doublets only!)



Cross section $\propto s_H^2 \equiv$ fraction of M_W^2, M_Z^2 due to exotic scalars

New gauge structures: Georgi-Machacek model



Custom-designed searches for specific new-physics signatures.

Summary of lecture 1

- Review of SM Higgs
- Motivation for BSM Higgs
- Mixing; SM + singlet
- New gauge structures; GM model

Our motivation here was not a Theory Of Everything.

Instead, collect a set of benchmarks around which one can design sensible and useful experimental searches.

Along the way, learn the inner workings of theories so that *if/when* a new particle is discovered, we're equipped to build consistent model(s) that incorporate it.

Tomorrow: two-Higgs-doublet models... and a bit more theoretical motivation.