Beyond the Standard Model Higgs bosons and dark sectors at the LHC

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UC Santa Cruz

4th annual meeting of the GRK 2044

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September 24-26, 2018

Overview

Topic of these lectures:

- is the 125 GeV Higgs boson the only scalar of nature?
- is it connected to a dark sector?

Aim: inspire young scientists to undertake new experimental searches/theory studies

Watch for the symbol ? for the open questions

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- is the 125 GeV Higgs boson the only scalar of nature?
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Chapter 1: phenomenology of 2HDMs type I-IV (focus on type II).
What are the open questions? Why are they interesting?

Chapter 2: new flavor structures for 2HDMs.
What does it change in terms of LHC searches?

Chapter 3: Models with singlet scalars
LHC challenges in searching for light particles

Chapter 4: Dark sectors at the LHC
What is a dark sector? The Higgs as a probe of dark sectors

Aim: inspire young scientists to undertake new experimental searches/theory studies

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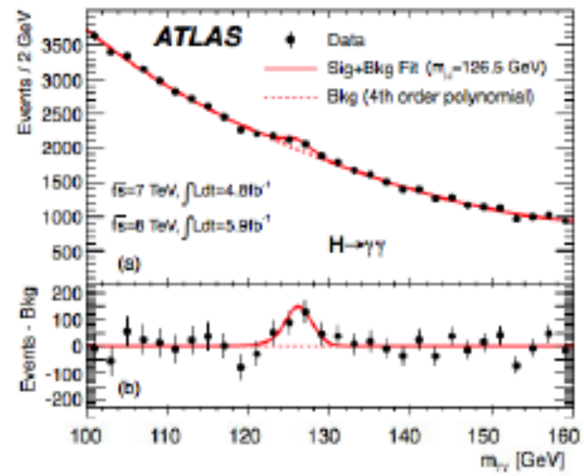
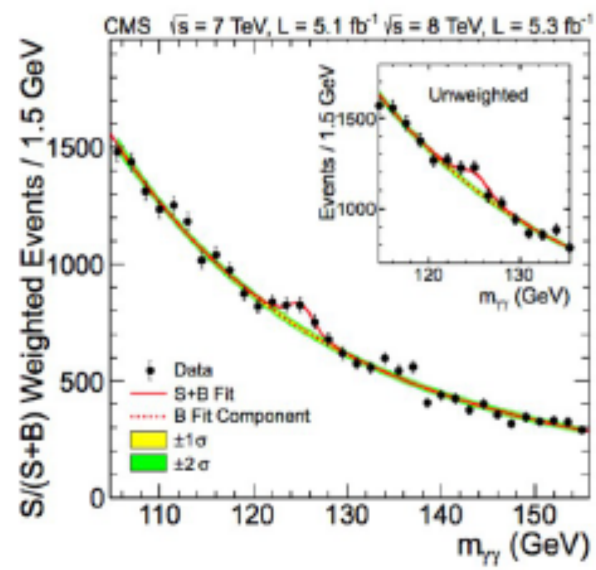
Discovery!

The first elementary particle discovery of 21st century



CERN, July 4th 2012, ~11am

After ~30 years of experimental searches
(LEP, SLC, Tevatron, LHC)



What we have learned so far

The Higgs we have discovered has SM-like properties

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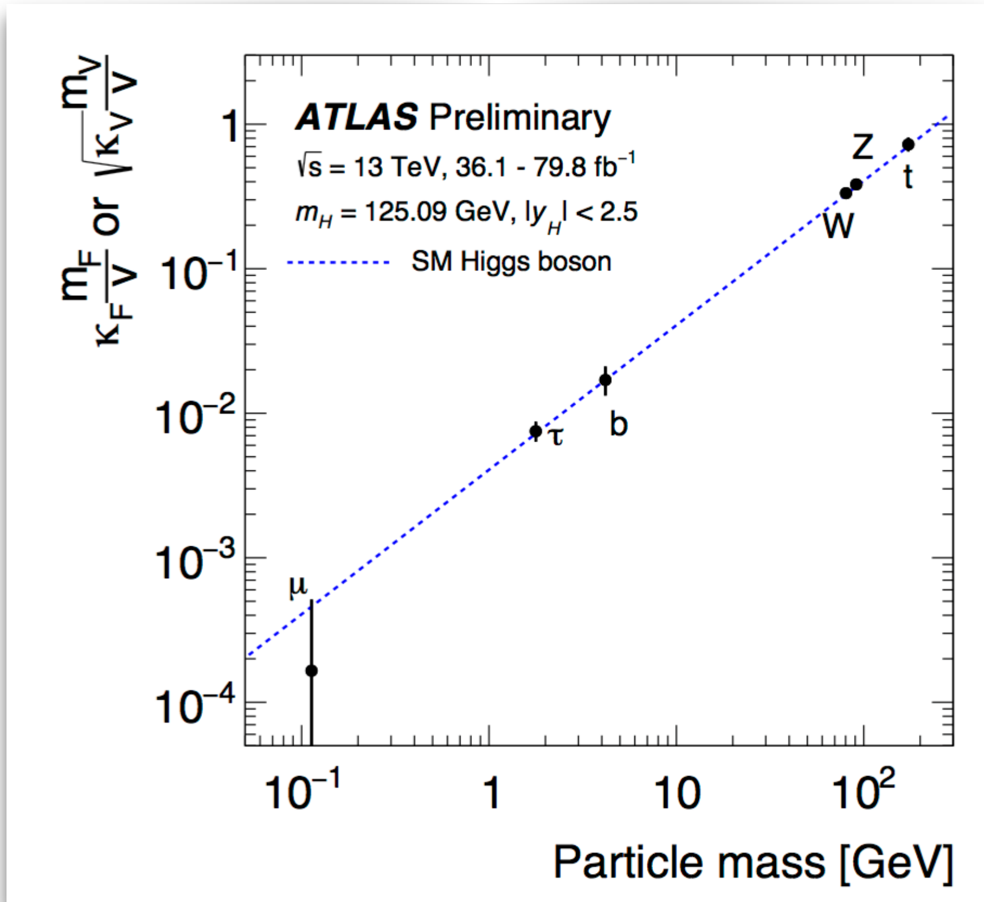

ATLAS-CONF-2018-031

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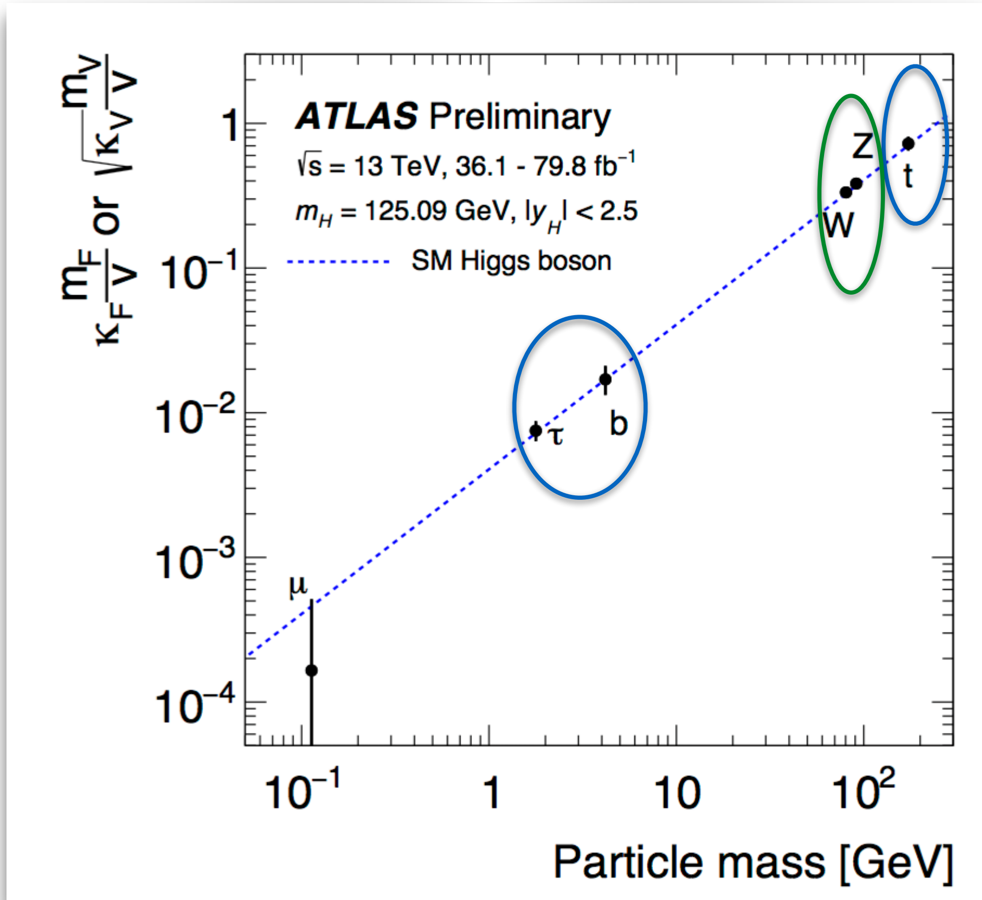

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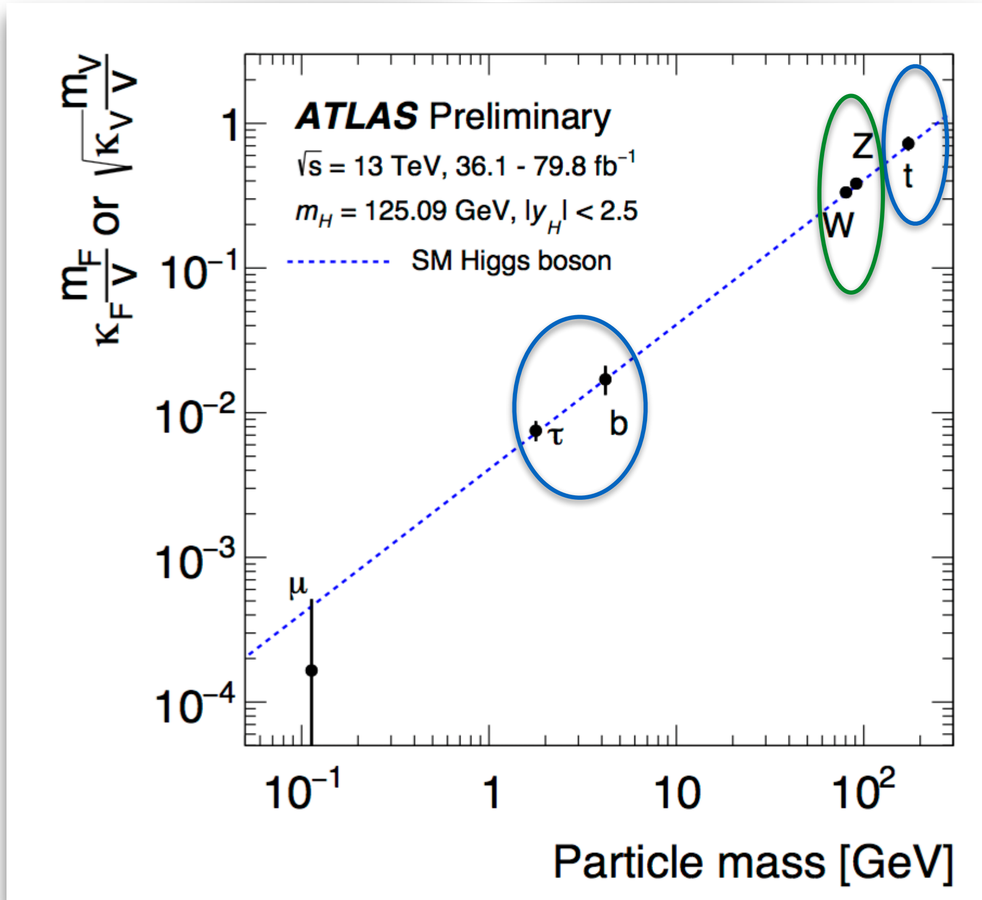

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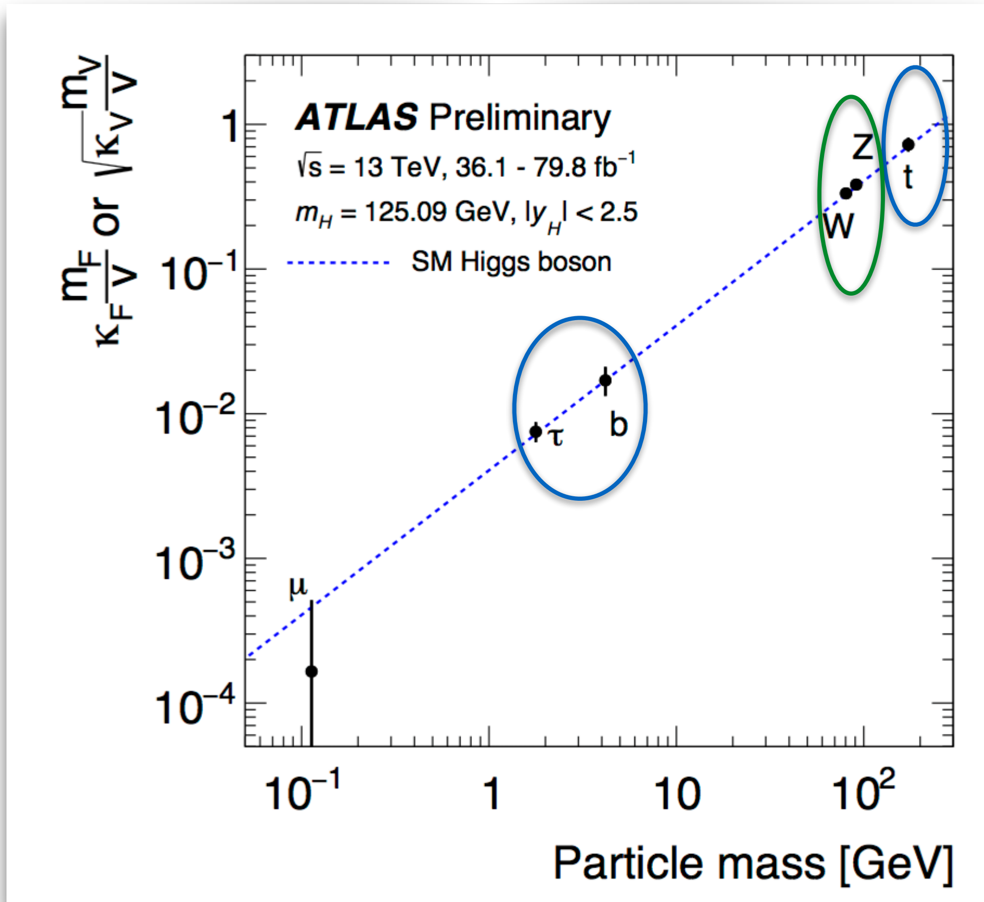

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Substantial improvement in the precision of the extraction of the couplings at future LHC runs.

Many couplings are not yet measured!
Eg. light generations, self-coupling, …

Let us step back in time…

Testing the electro-weak theory

Symmetry Magazine

Weak force carriers:

www.particlezoo.net

Discovery

- Discovery of Z and W bosons at Super Proton Synchrotron, at CERN in 1983.

Precision measurements

Z boson properties at the
- Large Electron–Positron Collider at CERN in 1989-2000
- Stanford Linear Collider in 1989-1998

Experiments

Z properties depend on the Higgs mass

Standard Model Prediction

The Higgs mass in the Standard Model

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John Ellis, Mary K. Gaillard [*] and D.V. Nanopoulos [+]

CERN -- Geneva

Nucl. Phys. B 106, 292 (1976)

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

We need to measure the Higgs mass!

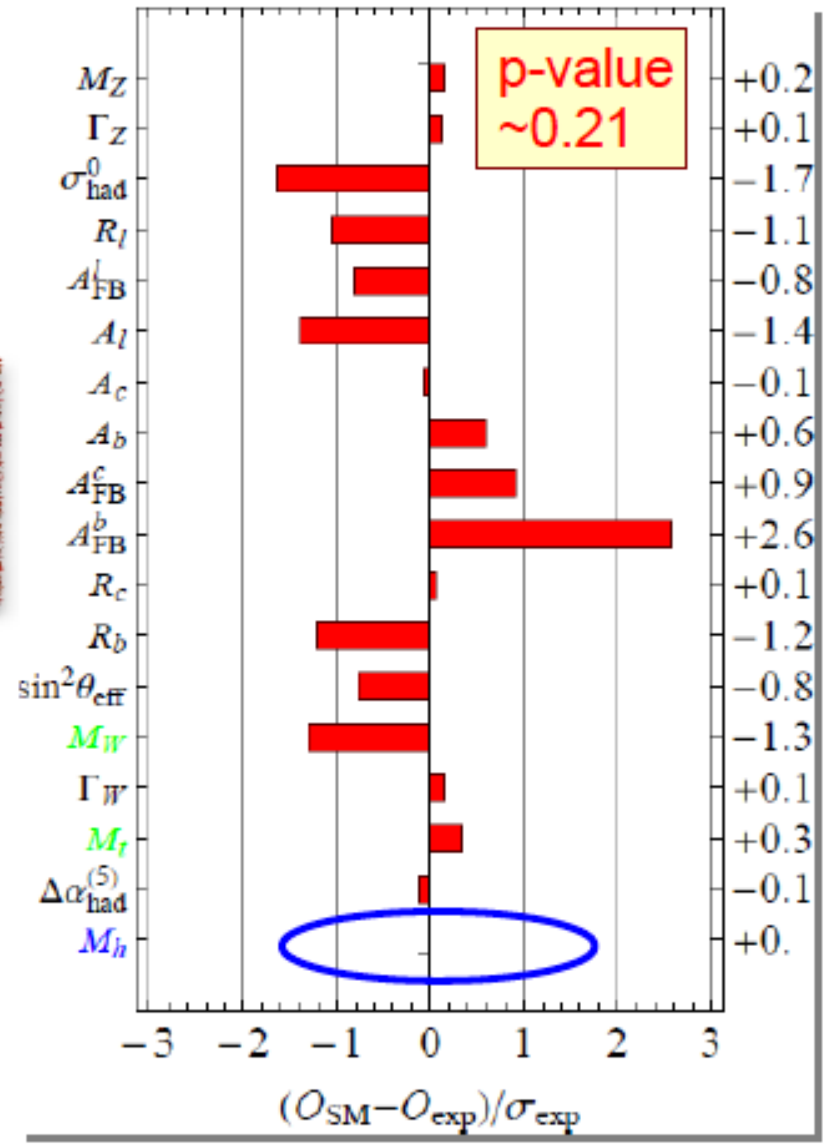
Self-consistency

Higgs mass
Z properties

If the Higgs is the one of the SM...

For the first time we have
the measurement of
a self-consistent electro-weak sector

Result of decades of
experimental & theory efforts



Batell, SG, Wang, 1209.6382

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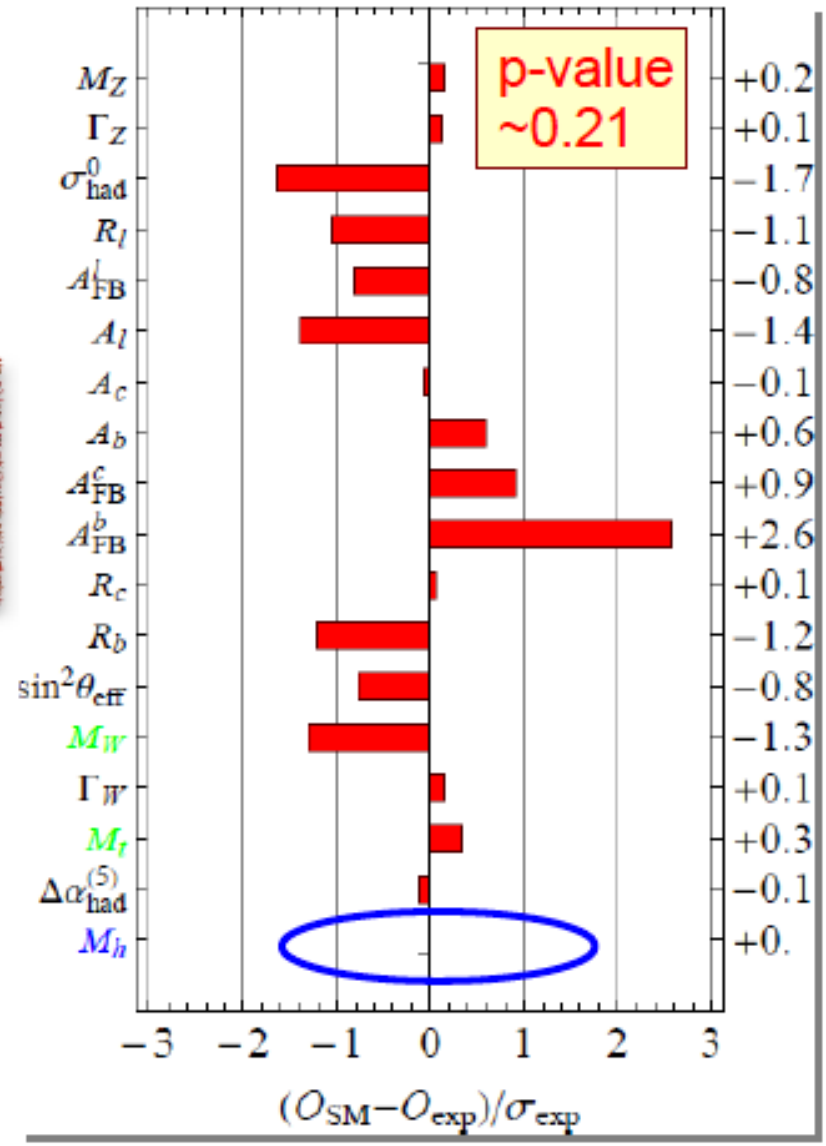
It would not be the case if the Higgs was heavier:

eg. M_h = 300 GeV → $p_{value} \sim 3 \times 10^{-5}$



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One or more Higgs bosons?

- Extended Higgs sectors arise in several well motivated theories beyond the Standard Model (SUSY, neutral naturalness models, models for baryogenesis, DM models, …)

- The discovery of new Higgs boson(s) would be revolutionary. They are “not needed” anymore

- Essential experimental program for the LHC

or

?

How to see new Higgs bosons?

1. LHC direct searches → Heavy Higgs bosons ($M_H > 125$ GeV)
→ Light Higgs bosons ($M_H < 125$ GeV)

2. Modification of the 125 GeV Higgs couplings to SM particles
→ Higgs precision program!

3. Indirect flavor effects at low energy

Organization principles (bottom-up approach)

Not all Higgs bosons are "good" Higgs bosons

1. Electro-weak precision tests (EWPTs):

in principle, there is an infinite number of SU(2)*U(1)$_Y$ Higgs representations. In practice…

$$\rho_{\rm tree} = \frac{\sum_{T,Y}\left(T(T+1)-Y^2\right)|v_{T,Y}|^2 C_{T,Y}}{\sum_{T,Y} 2Y^2 |v_{T,Y}|^2}$$

$$\begin{aligned} C_{T,Y} &= 1 \quad \text{(complex representation)} \\ &= 1/2 \quad \text{(real representation)} \end{aligned}$$

reminder

$$\rho_{\rm tree} \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta}$$

Experimentally: $\rho = 1.0007 \pm 0.001$

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= 1 for doublets of SU(2) (T=1/2, Y= ±1/2)
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2. Flavor transitions:

Constraints from low energy flavor physics limit the possible Yukawa couplings we can write down

Natural flavor conservation,
Minimal flavor violation, U(2) symmetries, …

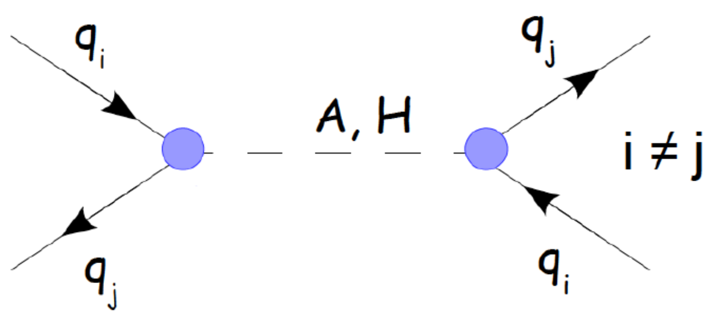
The flavor structure of 2HDMs

* In all generality, we can write

$$\mathcal{H}_Y^{\rm gen} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2 + {\rm h.c.}$$

(H_1, H_2 with hypercharge ±1/2)

If X_{d1}, X_{u1}, X_{d2}, X_{u2} are generic 3*3 matrices in flavor space:
Flavor changing neutral currents (FCNCs) at the tree-level!



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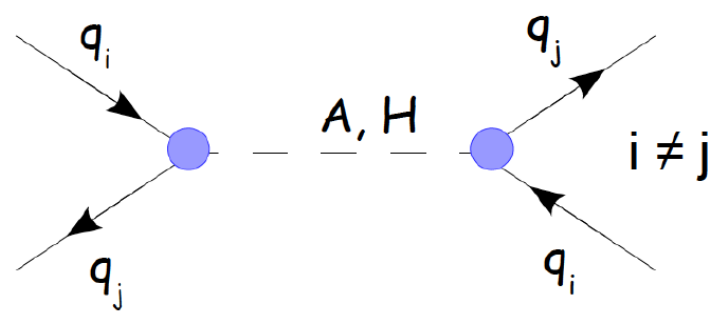

- How to see this?

Step 1: go to the "Higgs basis"

$$\begin{pmatrix} \Phi_v \\ \Phi_H \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} H_1 \\ H_2^c \end{pmatrix}$$

$$\tan\beta \equiv \frac{v_2}{v_1}$$

$$\langle \Phi_v^\dagger \Phi_v \rangle = v^2/2, \quad \langle \Phi_H^\dagger \Phi_H \rangle = 0$$

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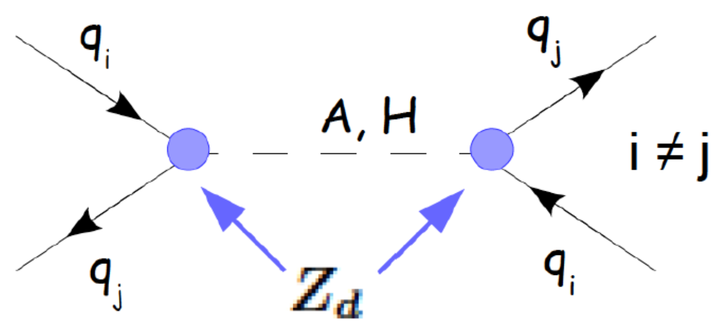

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Step 2: write the Lagrangian in this basis

$$\mathcal{H}_Y^{\rm gen} = \bar{Q}_L \left[\frac{\sqrt{2}}{v} M_d \Phi_v + Z_d \Phi_H \right] D_R + \text{h.c.}$$

with

$$Z_d = \cos\beta X_{d2} - \sin\beta X_{d1}$$

$$M_d = \frac{v}{\sqrt{2}} (\cos\beta X_{d1} + \sin\beta X_{d2})$$

Not proportional!

The flavor structure of 2HDMs

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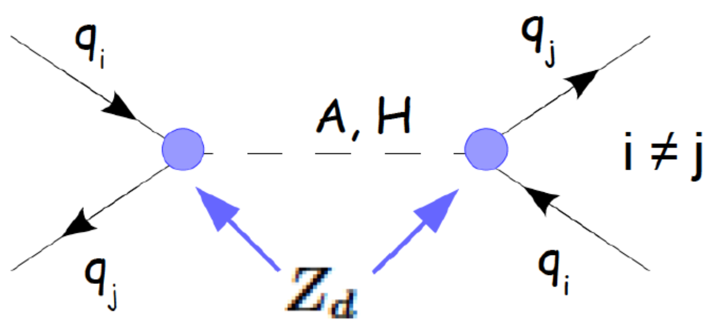

- Result: 2HDMs with a generic flavor structure have

Very stringent bounds from low energy flavor measurements!

e.g. the H, A Higgs bosons should have a mass ≥ **O(10^4 TeV)**,
to agree with measurements of Kaon mixings

Chapter 1

New Higgs bosons in
Type I-IV 2HDMs

(focus on type II)

1. Type I-IV 2HDMs…

How to address the problem with flavor?

Natural conservation laws for neutral currents*

Sheldon L. Glashow and Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 20 August 1976)

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How: Z_2 symmetry

Result: no FCNCs at the tree level (and therefore weaker constraints)

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* Imposing this principle, we get the Type I-IV 2HDMs:

Type I: H_1 gives mass to all quarks and leptons.

Type II: H_2 gives mass to up quarks; H_1 to down quarks and leptons (~MSSM).

Type III (IV): H_2 gives mass to up & down quarks (leptons), H_1 to leptons (down quarks)

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The physical couplings are dictated by the type:

	Z_d	Z_u	Z_ℓ
Type I	$-\cot\beta$	$\cot\beta$	$-\cot\beta$
Type II	$\tan\beta$	$\cot\beta$	$\tan\beta$
Type III (lepton-specific)	$-\cot\beta$	$\cot\beta$	$\tan\beta$
Type IV (flipped)	$\tan\beta$	$\cot\beta$	$-\cot\beta$

The “wrong Yukawa” in the MSSM

The MSSM is a theoretically very well motivated Type II-like 2HDM at the tree level: $X_{d2}=X_{u1}=0$

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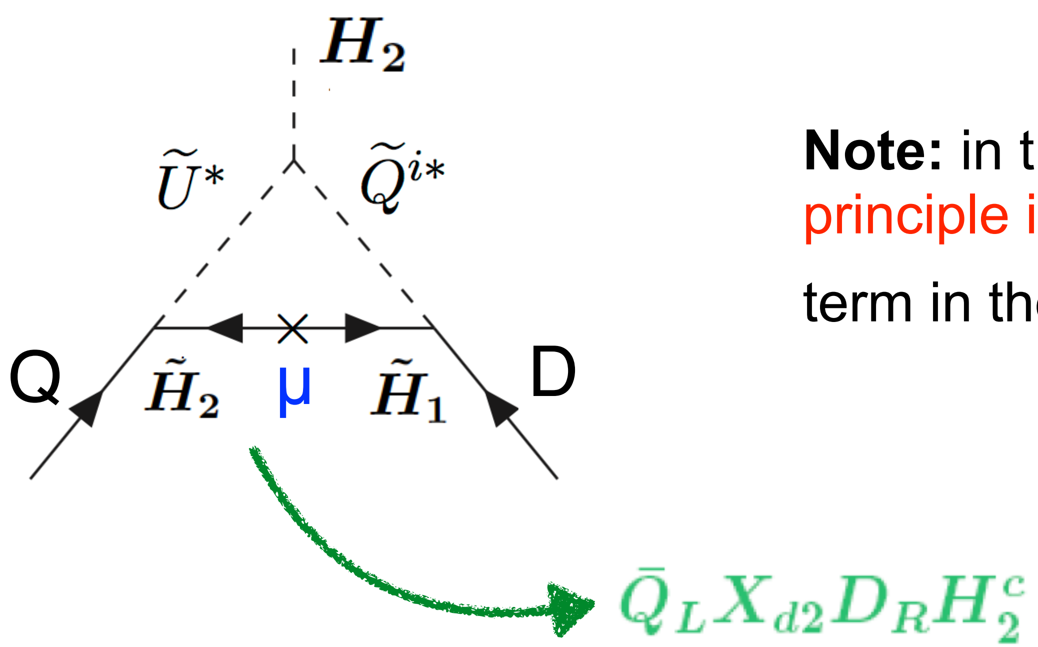
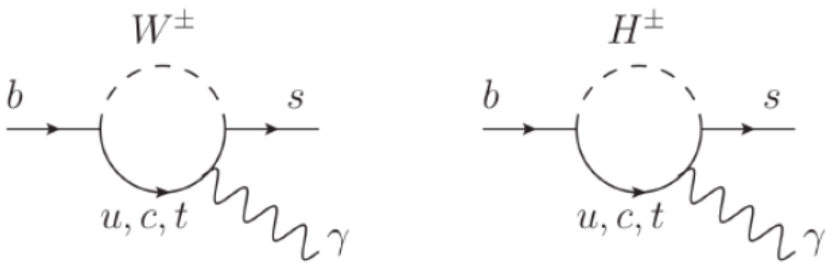


Note: in the MSSM the NFC principle is broken by the **μ H$_1$ H$_2$** term in the Higgs potential

Appearance of FCNCs at the one loop level

Low energy flavor constraints on type-II 2HDMs

$b \to s\gamma$



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$$\mathrm{BR}(b \to s\gamma)_{\mathrm{exp}} = (3.49 \pm 0.19) \times 10^{-4}$$

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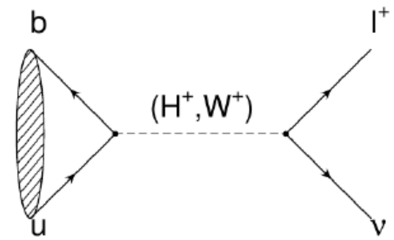

More “solid” being at the tree-level

$$\mathrm{BR}(B \to \tau\nu)_{\mathrm{SM}} = (0.807 \pm 0.061) \times 10^{-4}$$
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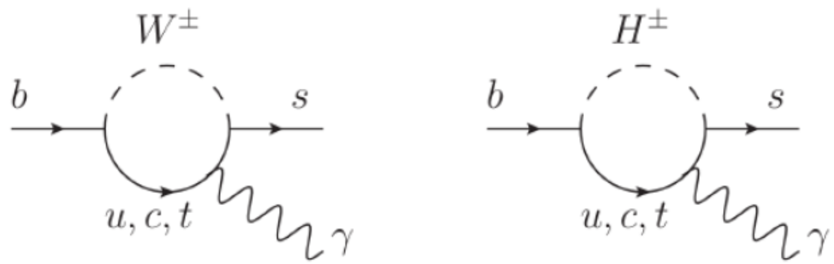

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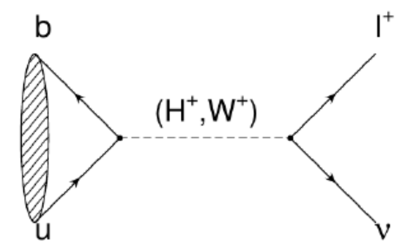

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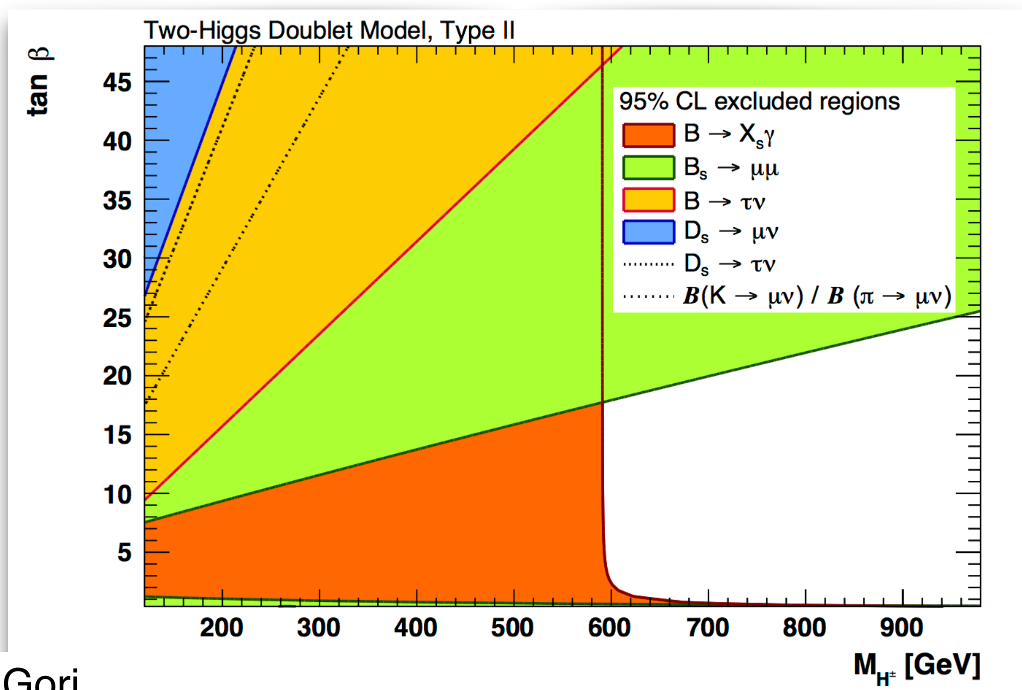

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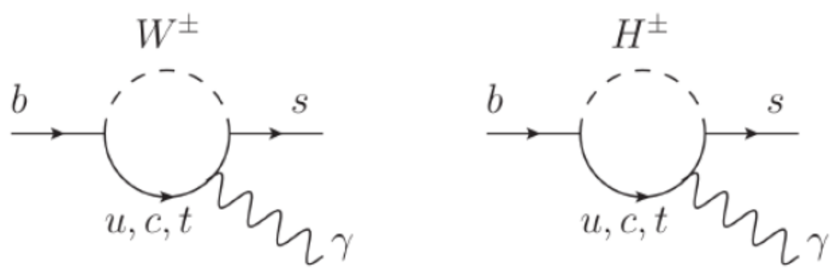

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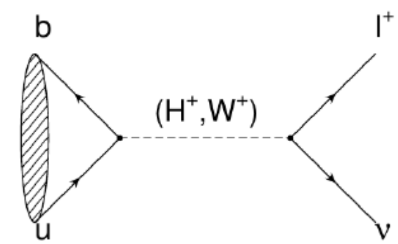

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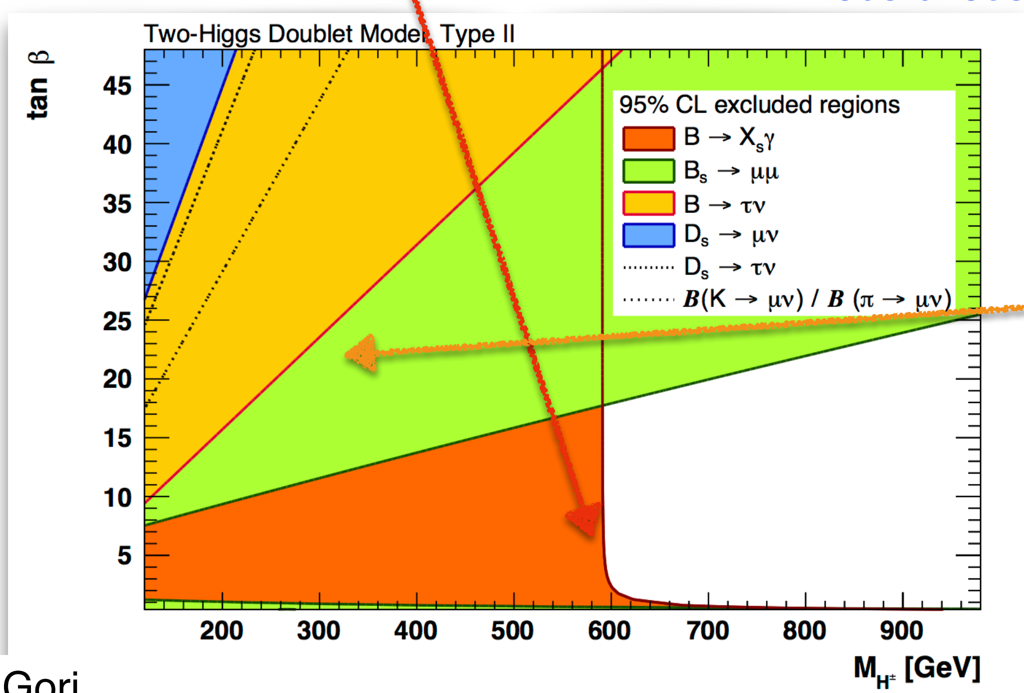

NP effects enhanced by tanβ as

$H^\pm b_R u_L \sim m_b \tan\beta / v$

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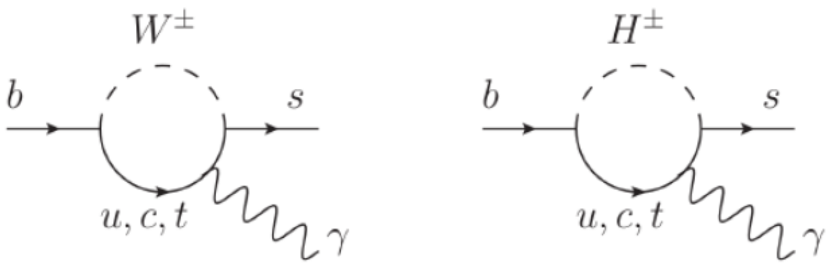

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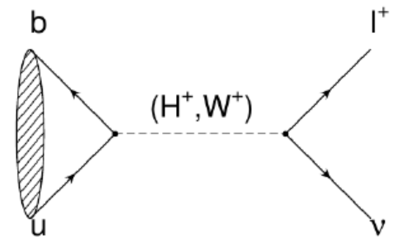

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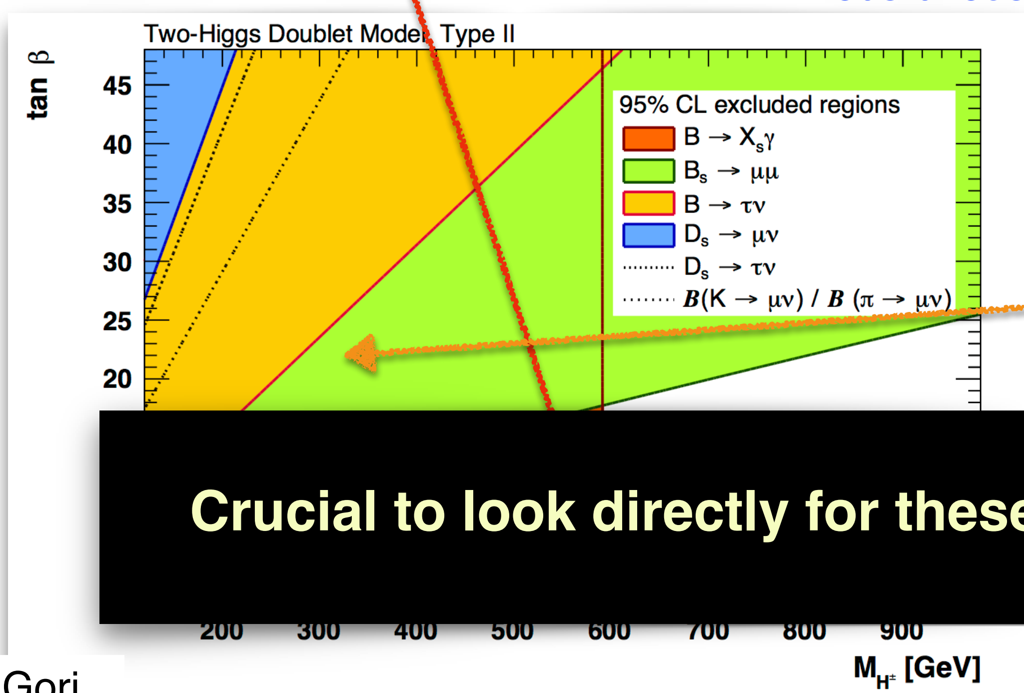

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Crucial to look directly for these new Higgs bosons at the LHC!

Other indirect probes: the Higgs precision program

After the Higgs discovery, we have learned that the 125 GeV Higgs boson has SM-like properties

→ towards a precision program to assess the nature of the Higgs boson we have discovered

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At the LHC, we measure **Higgs rates**:

For example, we look for the Higgs decaying into two photons

$$\sigma(pp \to h \to \gamma\gamma)_{\rm exp} \;=\; \sigma(pp \to h)_{\rm theory} \times {\rm BR}(h \to \gamma\gamma)_{\rm theory}$$

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$$= \sigma(pp \to h \to \gamma\gamma)_{\rm SM} \times \frac{\sigma(pp \to h)_{\rm theory}}{\sigma(pp \to h)_{\rm SM}} \times \frac{{\rm BR}(h \to \gamma\gamma)_{\rm theory}}{{\rm BR}(h \to \gamma\gamma)_{\rm SM}}$$

— computed to high precision

Other indirect probes: the Higgs precision program

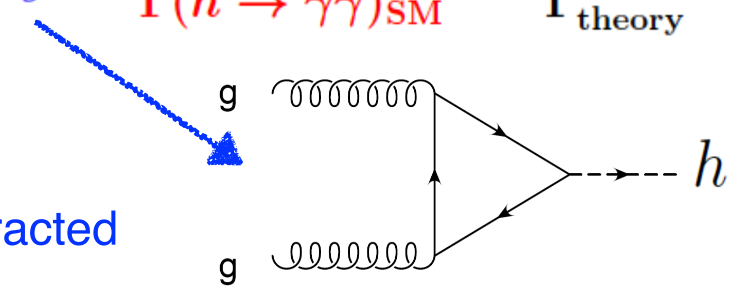
After the Higgs discovery, we have learned that the 125 GeV Higgs boson has SM-like properties

→ towards a precision program to assess the nature of the Higgs boson we have discovered

At the LHC, we measure **Higgs rates**:

For example, we look for the Higgs decaying into two photons

$$\begin{aligned}\sigma(pp\to h\to\gamma\gamma)_{\rm exp} &= \sigma(pp\to h)_{\rm theory}\times {\rm BR}(h\to\gamma\gamma)_{\rm theory}\\ &= \sigma(pp\to h\to\gamma\gamma)_{\rm SM}\times\frac{\sigma(pp\to h)_{\rm theory}}{\sigma(pp\to h)_{\rm SM}}\times\frac{{\rm BR}(h\to\gamma\gamma)_{\rm theory}}{{\rm BR}(h\to\gamma\gamma)_{\rm SM}}\\ &= \sigma_{\rm SM}\times\kappa_g^2\times\frac{\Gamma(h\to\gamma\gamma)_{\rm theory}}{\Gamma(h\to\gamma\gamma)_{\rm SM}}\times\frac{\Gamma^{\rm tot}_{\rm SM}}{\Gamma^{\rm tot}_{\rm theory}} = \sigma_{\rm SM}\times\kappa_g^2\times\kappa_\gamma^2\times\frac{\Gamma^{\rm tot}_{\rm SM}}{\Gamma^{\rm tot}_{\rm theory}}\end{aligned}$$



computed to high precision (red)

reduced couplings to be extracted (blue)

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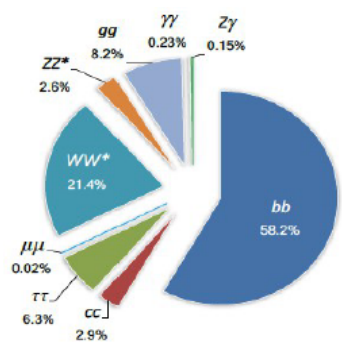
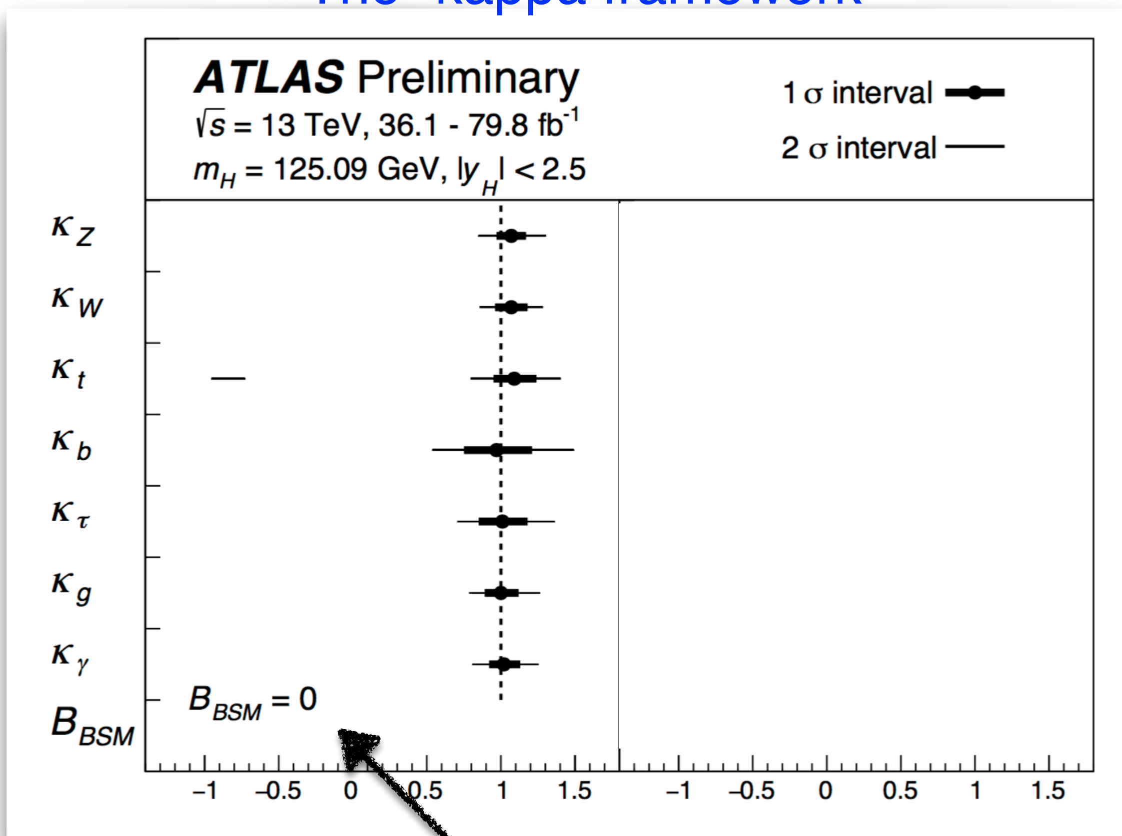


We need to make some assumption.
e.g. $\Gamma^{\rm tot}_{\rm theory} = \Gamma^{\rm tot}_{\rm SM}(\kappa_i)$

Status & prospects for the Higgs measurements

The "kappa framework"



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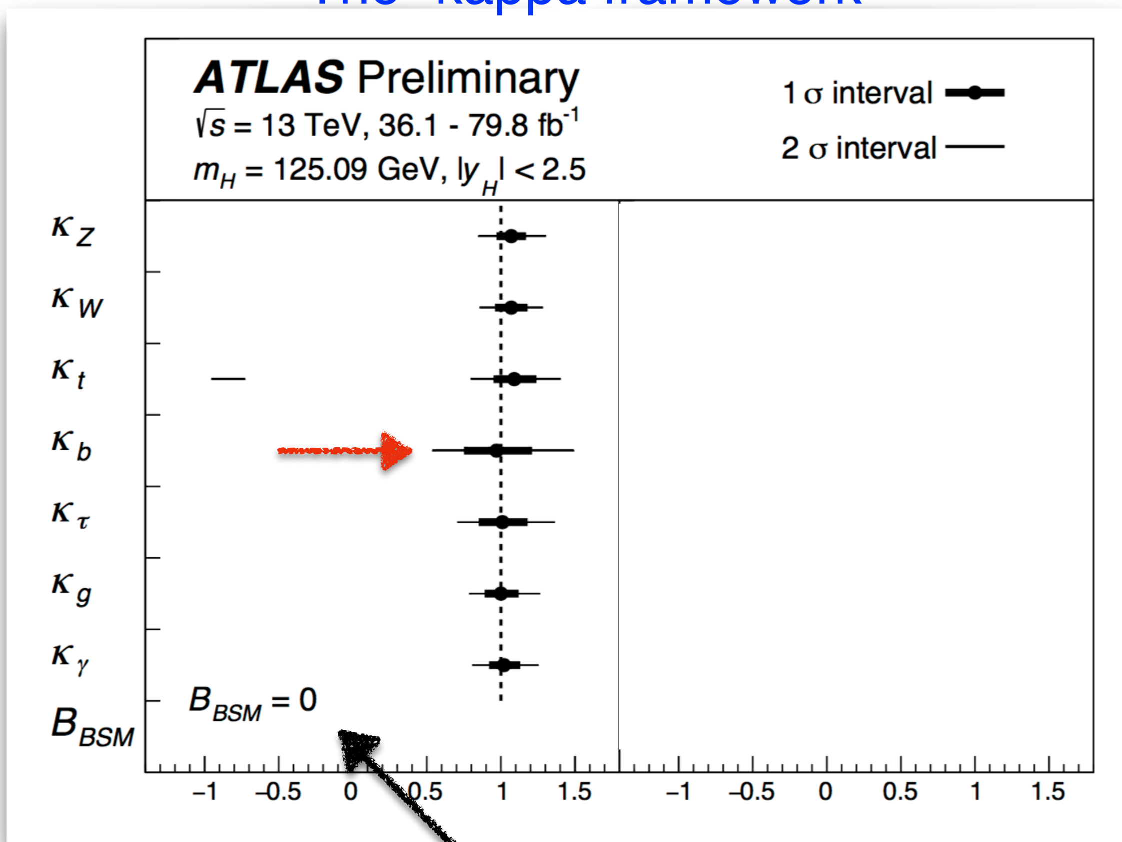

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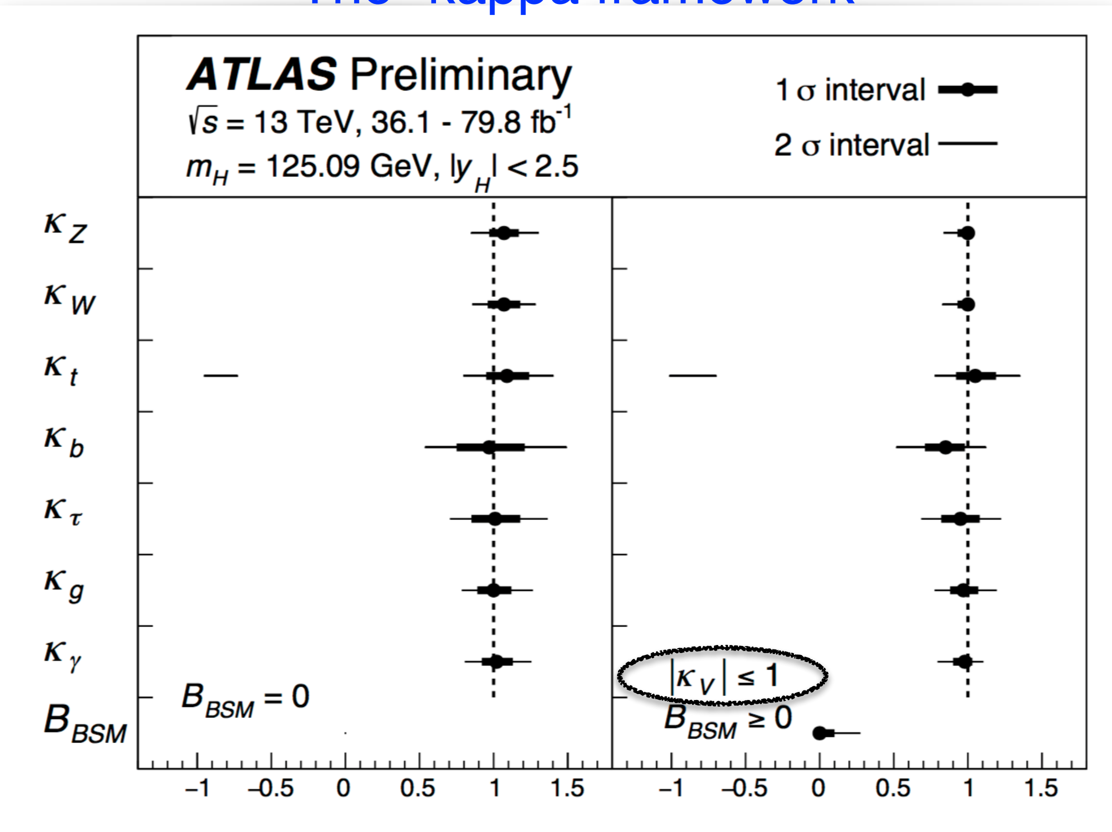

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Status & prospects for the Higgs measurements

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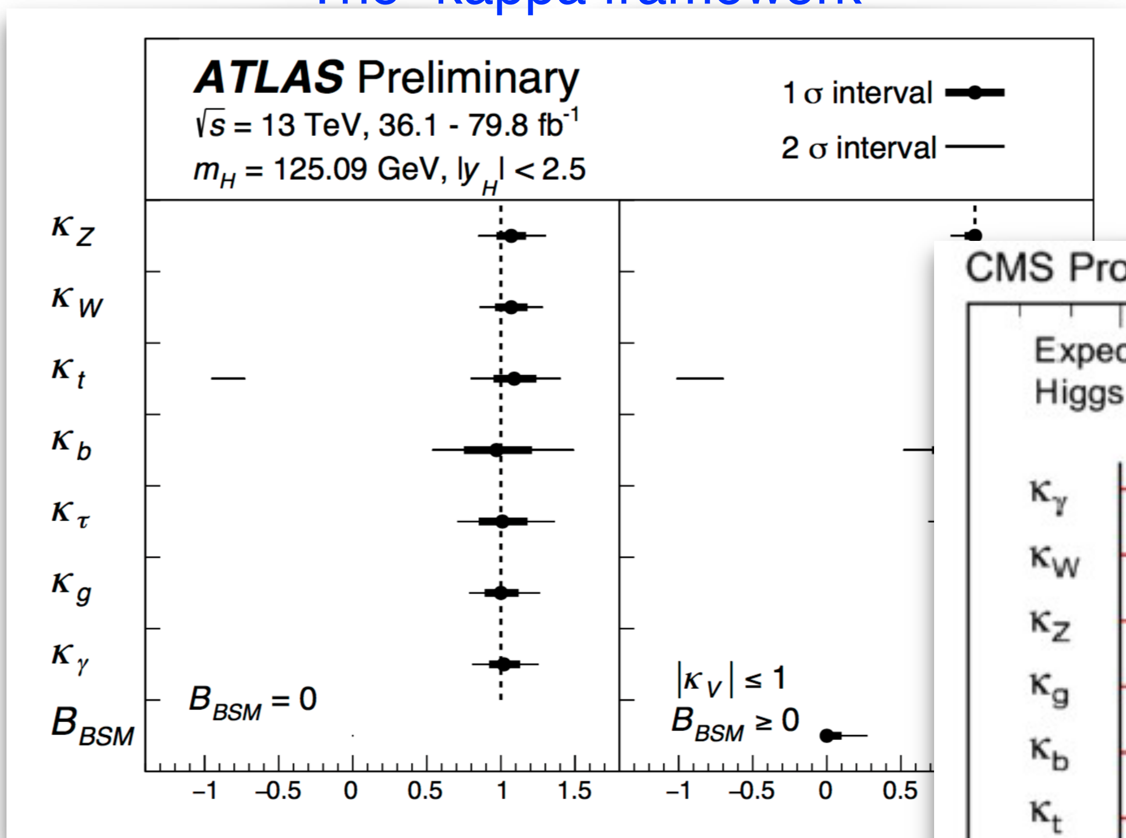

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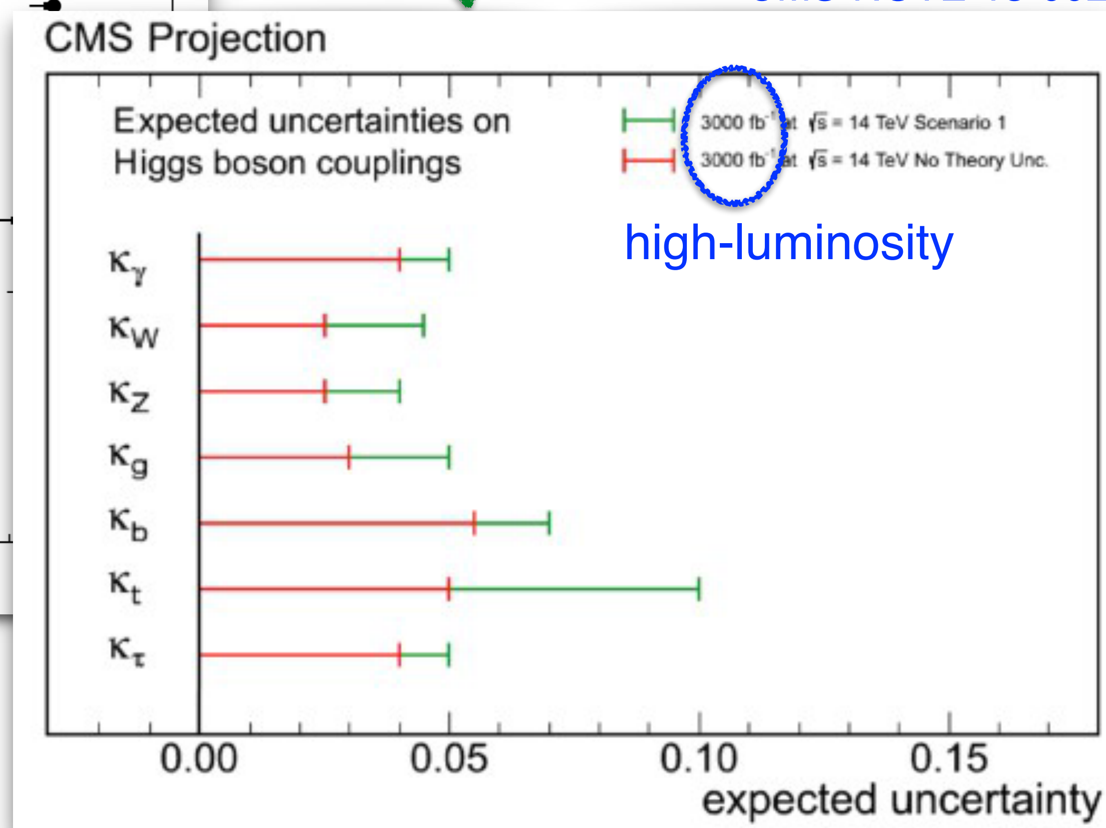

need to have more and more precise SM predictions & measurements

updates will be available soon for the Yellow Report of the high-luminosity/high-energy workshop

Implications on the heavy Higgs bosons

Do the measurements of the 125 GeV Higgs boson tell us something about new Higgs bosons?

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In particular, the coupling with massive gauge bosons:

$$\kappa_V = \sin(\beta - \alpha)$$

(normalized coupling to the SM value)

Measured to be close to 1

reminder

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos(\alpha-\beta) & \sin(\alpha-\beta) \\ -\sin(\alpha-\beta) & \cos(\alpha-\beta) \end{pmatrix} \begin{pmatrix} \Phi_v \\ \Phi_H \end{pmatrix}$$

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Generically, we have an upper bound on the value of |x| with α = β – π/2 + x

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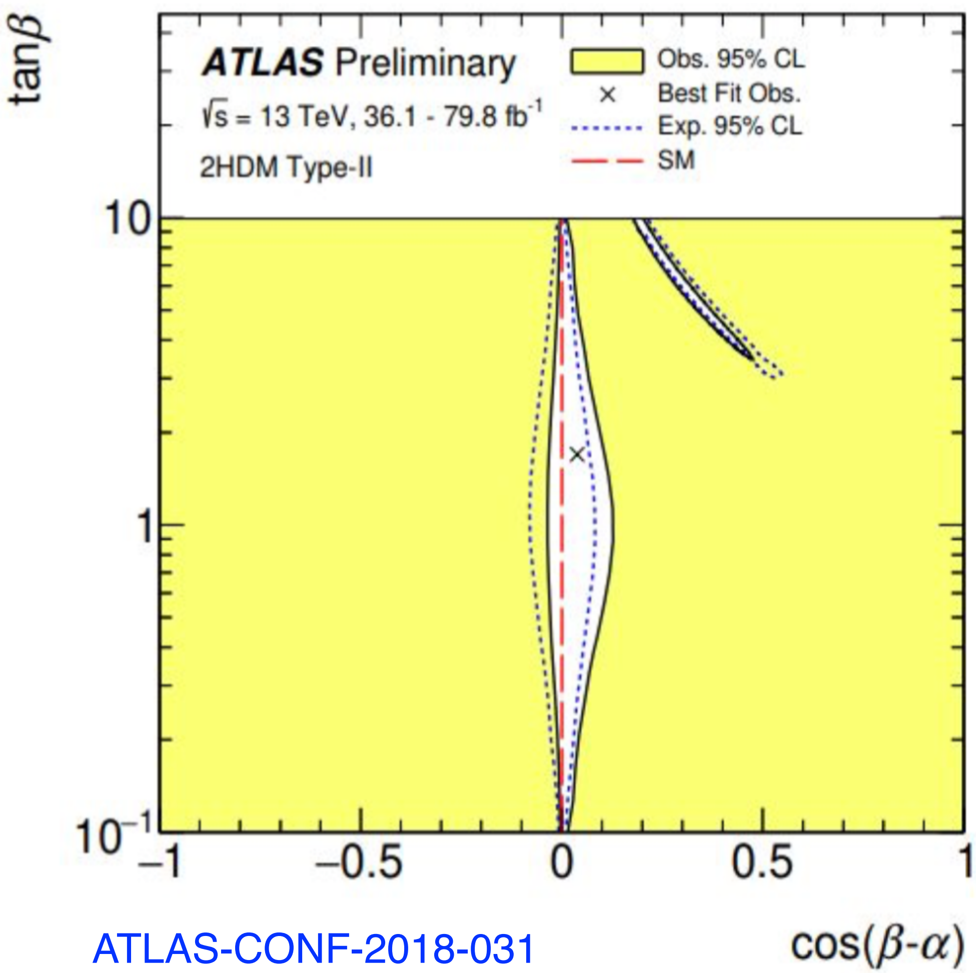
(125 GeV) Higgs coupling measurements

Putting all measurements together…



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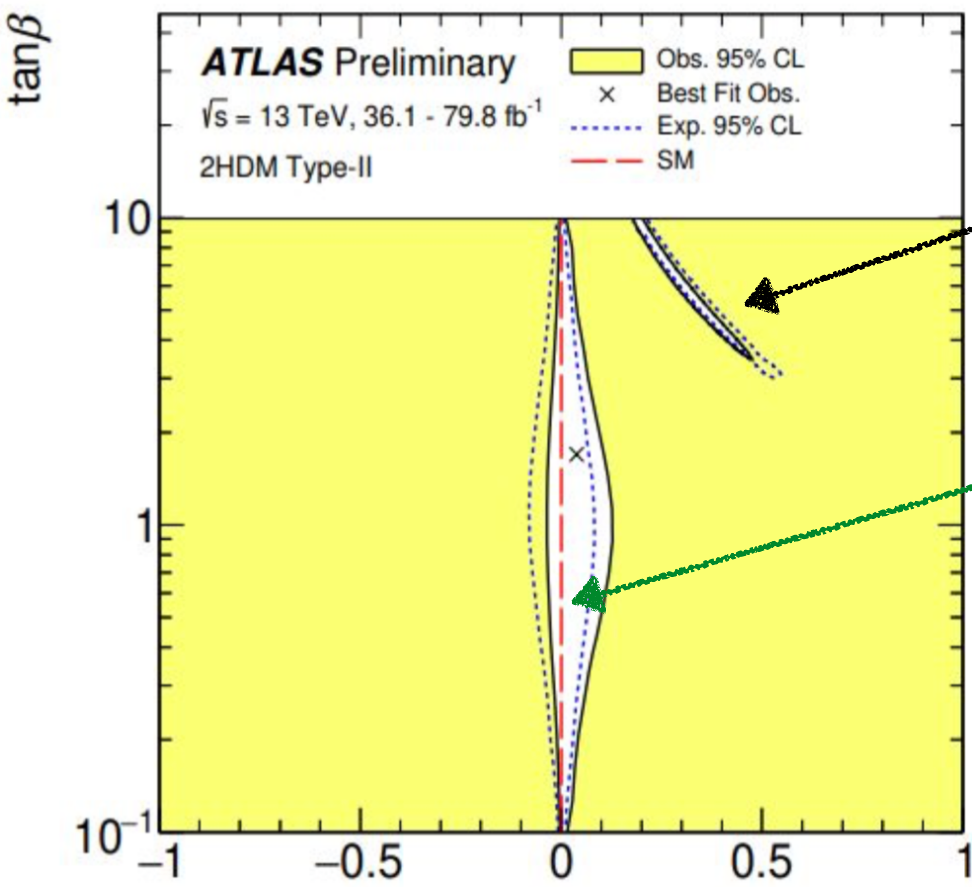

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What is this additional region? 🤔

Alignment (or decoupling) limit

$$\sin(\beta - \alpha) = 1$$

In this limit, the 125 GeV Higgs has the same properties as in the SM

Why 2 names? (alignment/decoupling)

$$\alpha = \beta - \pi/2 + O(\lambda_i v^2/M_A^2)$$

What do we learn on the new H bosons? (1)

So far we have considered the couplings of the 125 GeV Higgs boson

$$\kappa_V = \sin(\beta - \alpha)$$

The couplings of the heavy Higgs bosons are related:

→ Upper bound on the coupling of the heavy Higgses with gauge bosons:

$$\kappa_V^H = \cos(\alpha - \beta) \simeq x$$