The Higgs in the Standard Model & beyond

Stefania Gori
UC Santa Cruz

Lake Louise Winter Institute

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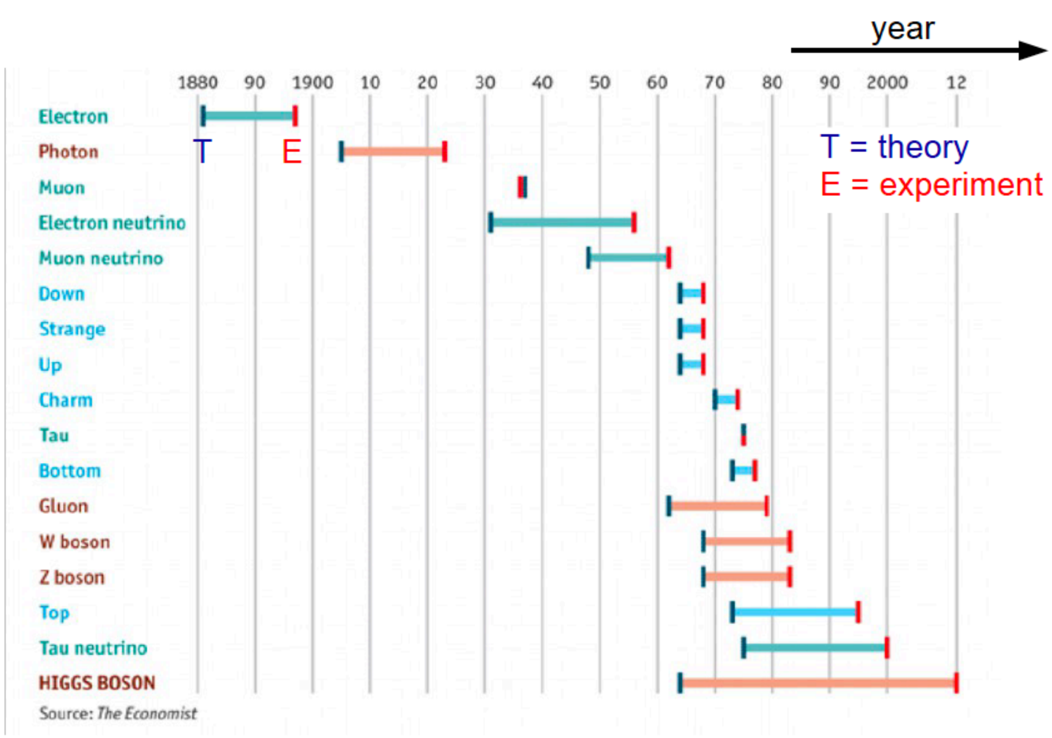
The Higgs is (almost) 10 years old!



- What have we learned?
- What do we still need to learn?
- Connection to the broader picture: can the Higgs help us addressing the most important **open problems in particle physics**? (dark matter, baryogengesis, flavor puzzle, …)

see also talk by R. Rusack on Monday

Outline

Open problems in particle physics:

- Flavor & CP
- Baryon-antibaryon asymmetry
- Dark Matter & dark sectors
- The hierarchy problem

The 125 GeV Higgs boson →

- Higgs precision program — **Chapter 1**
- Unknown properties of the Higgs — **Chapter 2**

New Higgs bosons? →

- New Higgs bosons and flavor physics
- New Higgs bosons and the hierarchy problem

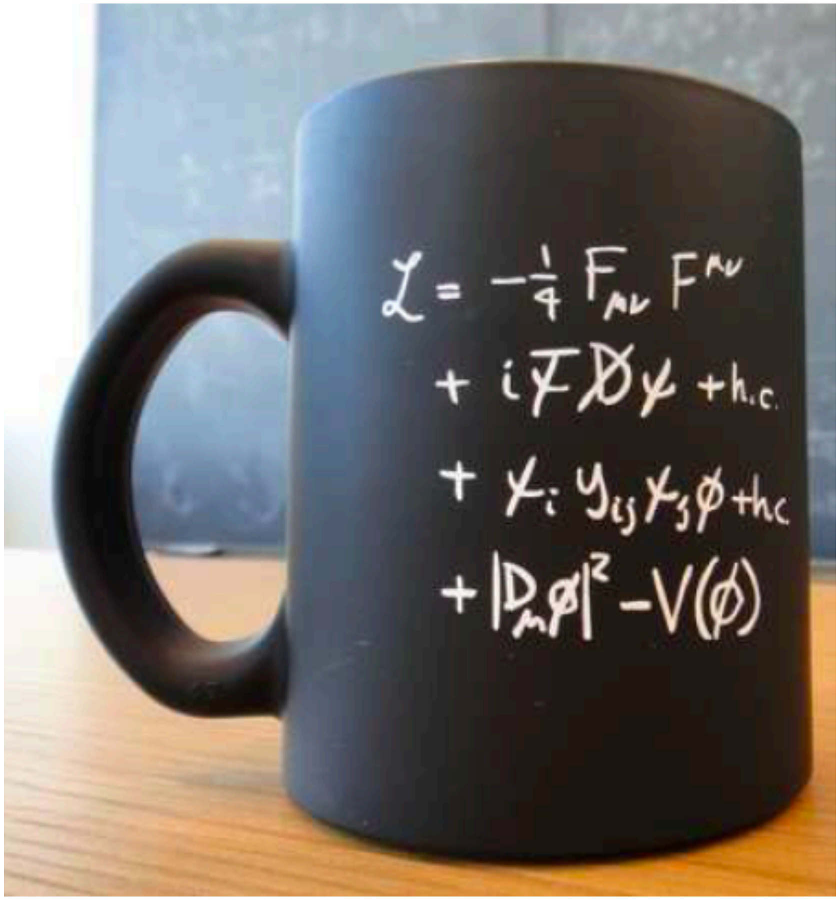
Chapter 3

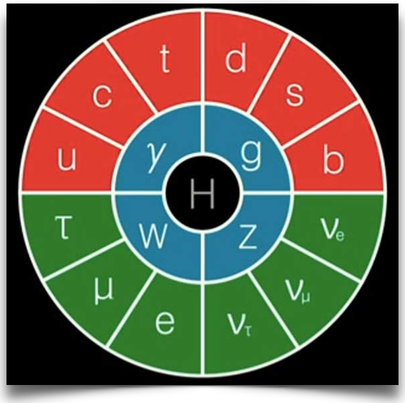
Highlight: signatures and models which have not been yet covered at the LHC

Caveat: this is a Higgs overview. I won't have the time to mention many other interesting aspects of Higgs physics.

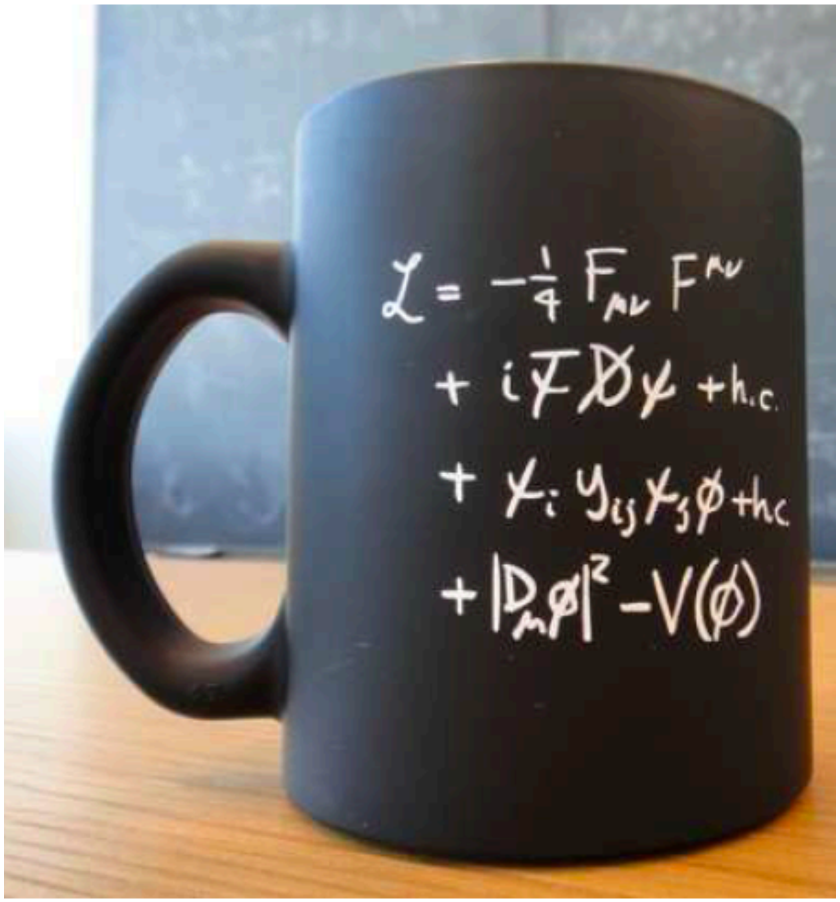

Chapter 1
The precision Higgs program

The Standard Model of particle physics





The Standard Model of particle physics



$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c.$ describes the gauge interactions of quarks & leptons.

Parametrized by 3 free parameters:
g_1, g_2, g_3 (gauge couplings)

$+ \psi_i y_{ij} \psi_j \phi + h.c.$ leads to masses & mixings of quarks & leptons.

Parametrized by 10+10 free parameters in the quark + lepton sector
(12 in the lepton sector in case of Majorana masses)

$+ |D_\mu \phi|^2 - V(\phi)$ gives mass to the W and Z bosons.

Parametrized by 2 free parameters:
Higgs vev; Higgs mass

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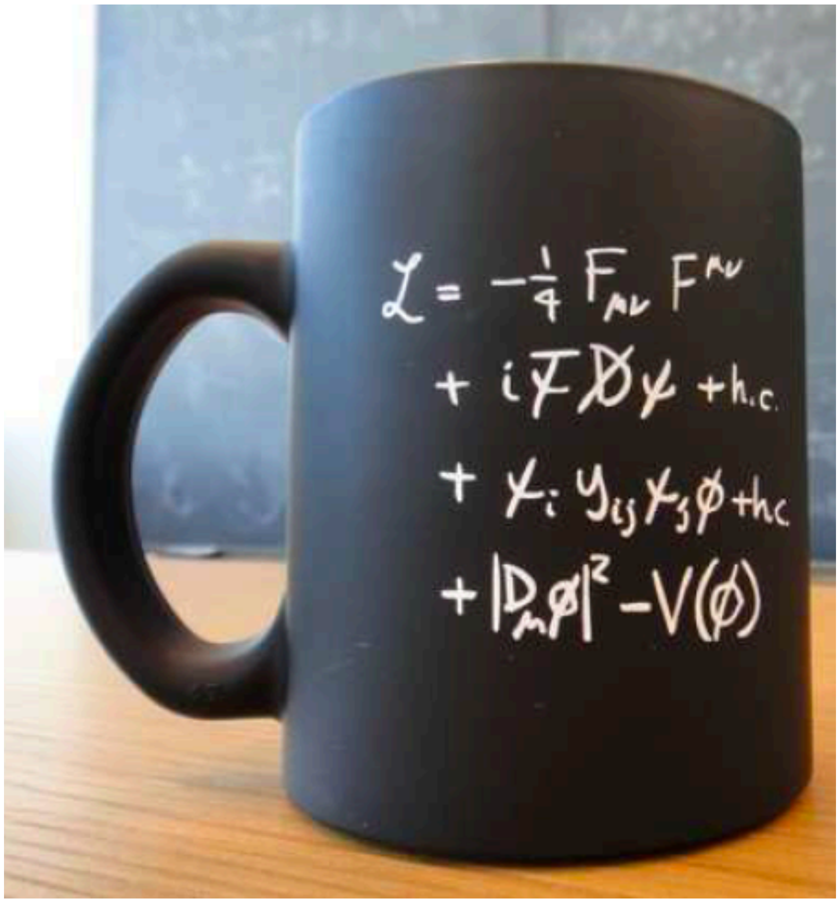

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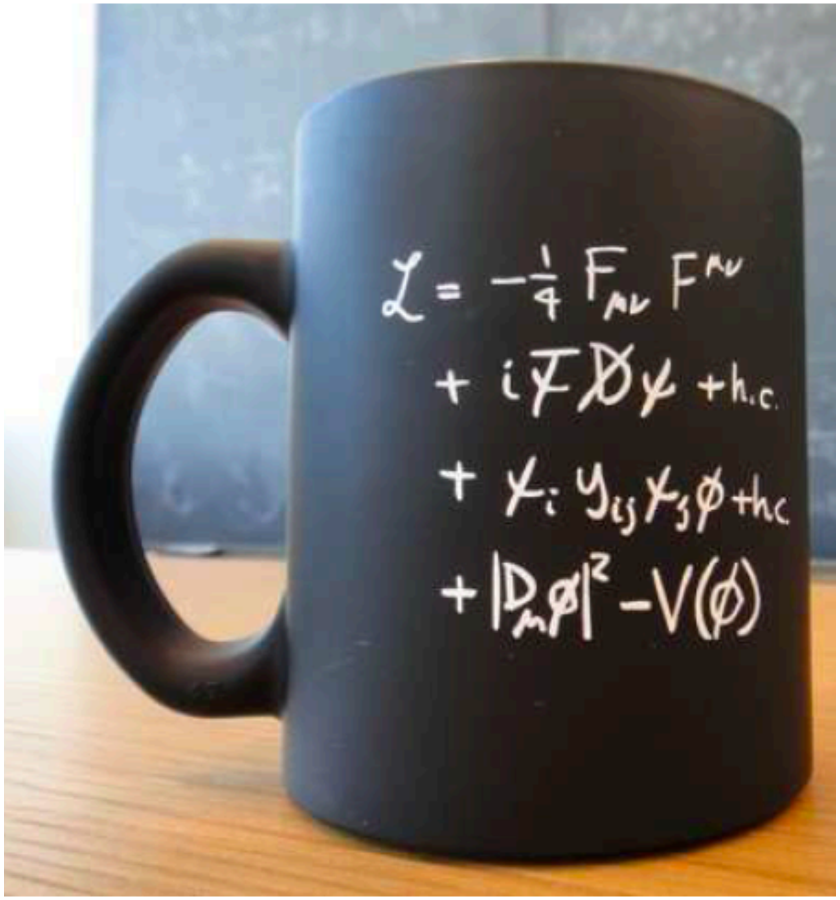
Higgs part of the Lagrangian

The Standard Model of particle physics



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Parametrized by 2 free parameters: Higgs vev; **Higgs mass**

Before 2012: The Higgs mass was the only free parameter left to be measured

The Higgs mass in the Standard Model

The historical perspective...

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.

The LHC tells us: $\mathbf{m_{Higgs} = 125\ GeV}$

Precision theoretical predictions for the Higgs

Now that we have measured this last free parameter of the Standard Model,
we can make **accurate predictions** for the Higgs phenomena

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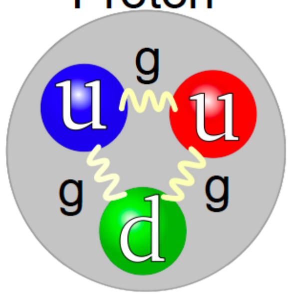
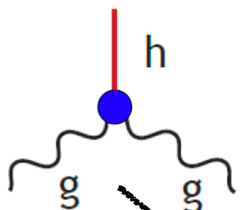
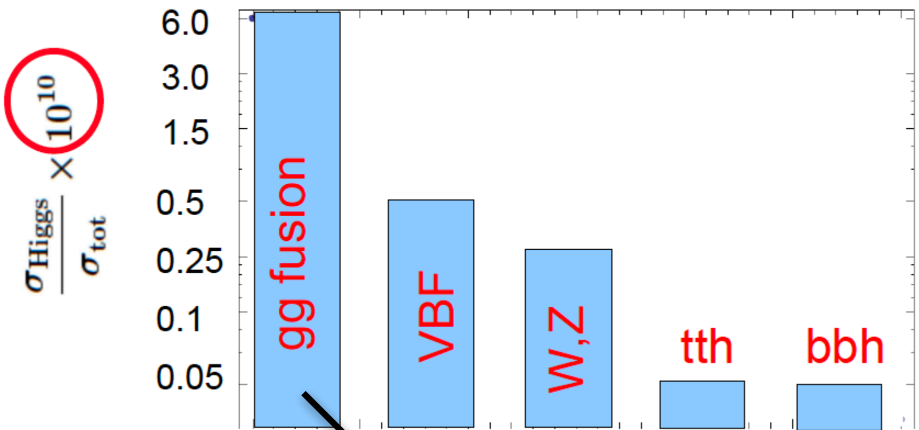
- We predict how many Higgs bosons are produced at the LHC

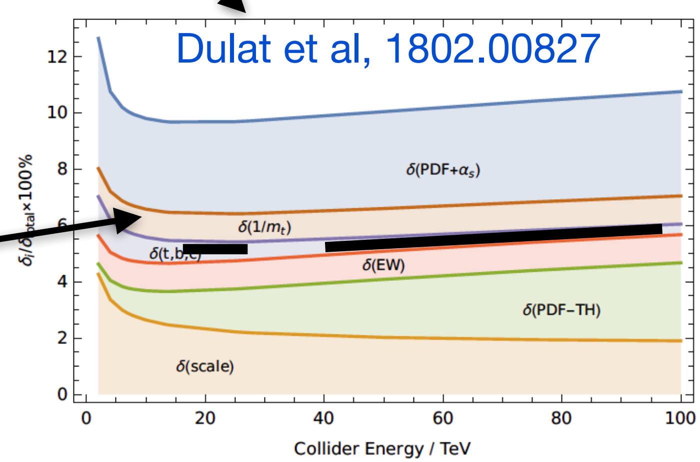
Proton







Calculation of
finite top-quark mass corrections
Czakon et al, 2105.04436



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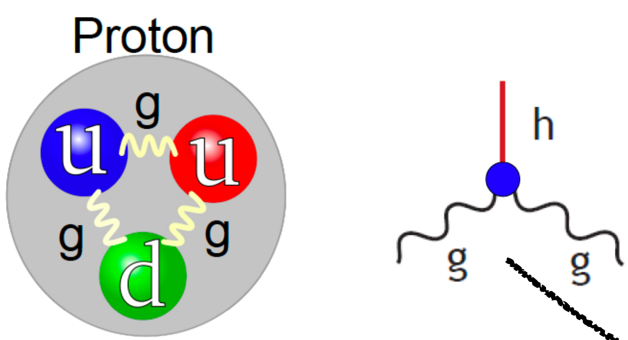
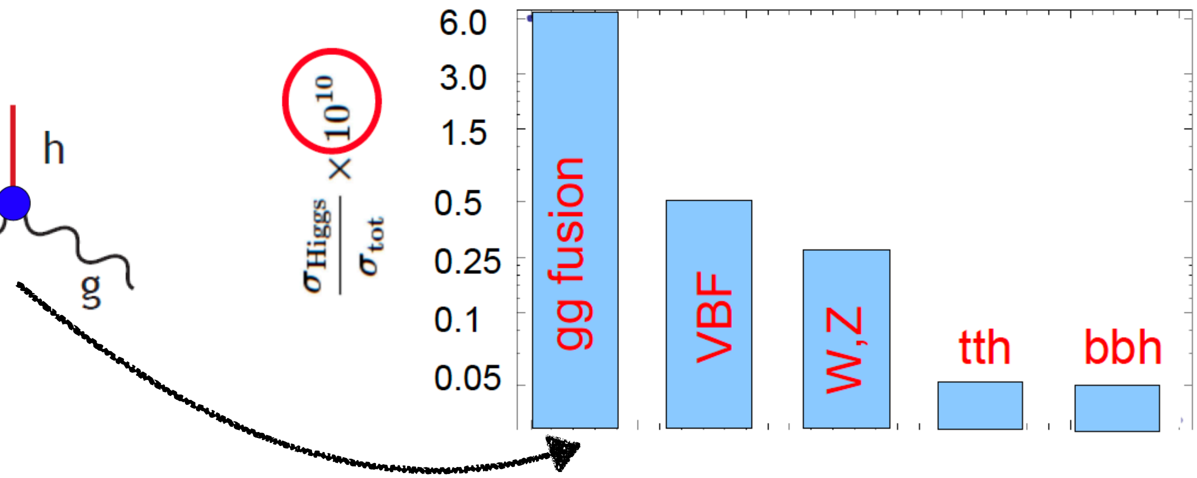
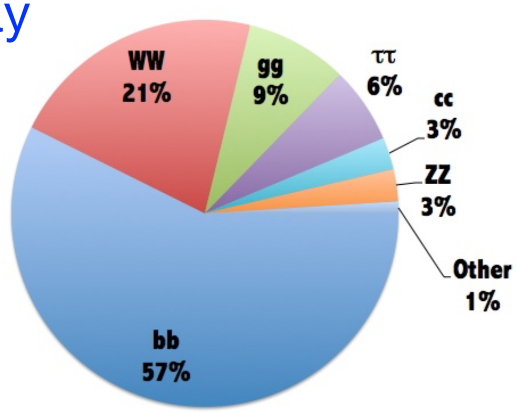




✱ We predict what is the probability for the Higgs to decay to other Standard Model particles



Precision determination of the Higgs couplings

"k framework":

all New Physics (NP) is encoded in the modification of the Higgs couplings to SM particles

In any NP model,

$$\kappa \equiv \frac{\mathrm{Coupling}_{\mathrm{Higgs}}^{\mathrm{NP}}}{\mathrm{Coupling}_{\mathrm{Higgs}}^{\mathrm{SM}}}$$

We can extract these via measuring the Higgs rates at the LHC

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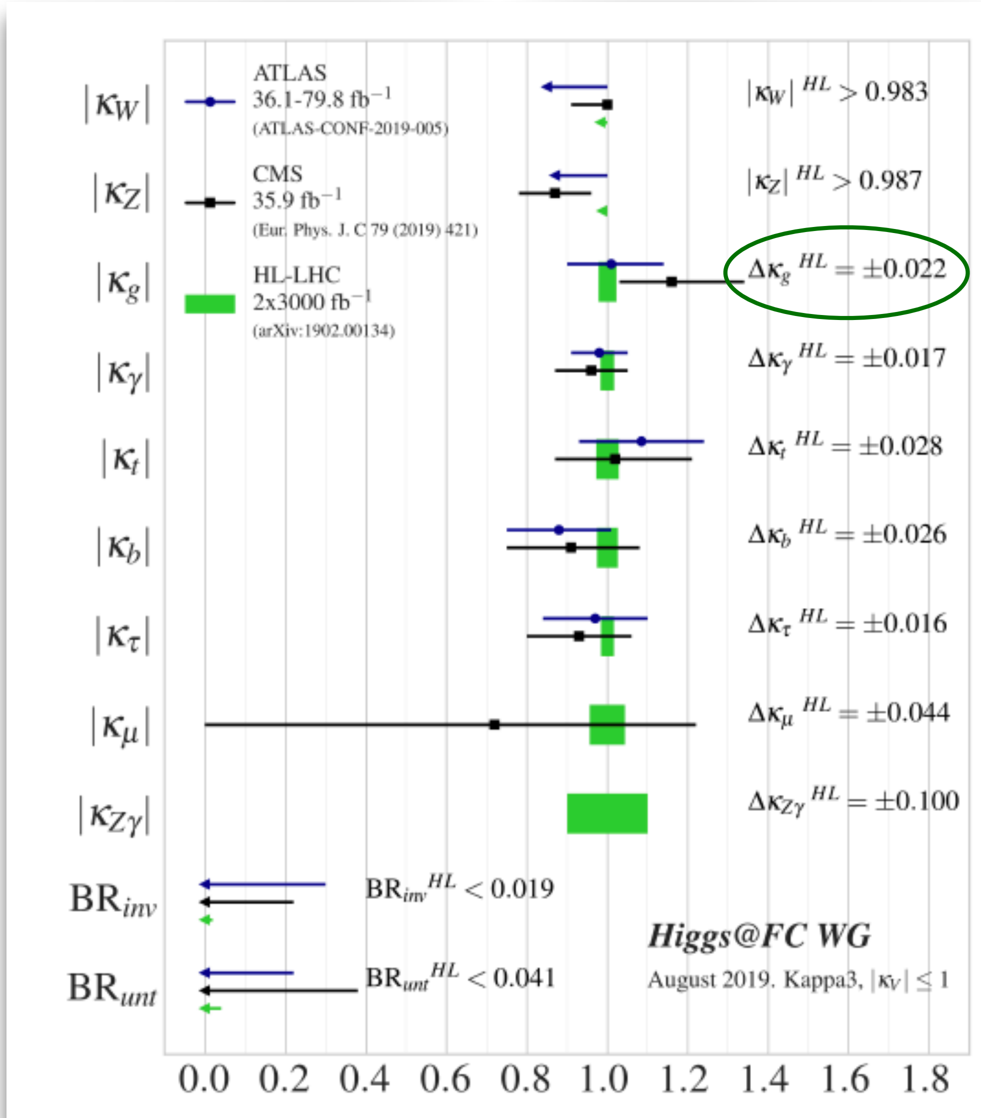

"Physics briefing book", European physics strategy, 1910.11775

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Expected precision with HL-LHC:
k_g → 2 % TH+STAT+SYS.

Enormous challenge for TH to reach this level!

Probing Higgs distributions

The LHC not only measures Higgs rates but also Higgs event distributions

These can be used to set bounds on the SMEFT Lagrangian.
(The idea is to write the most general Lagrangian containing SM particles up to dimension 6 satisfying the SU(2) gauge symmetry and flavor universal)

EWPO:	$\mathcal{O}_{HWB}\,,\ \mathcal{O}_{HD}\,,\ \mathcal{O}_{ll}\,,\ \mathcal{O}_{Hl}^{(3)}\,,\ \mathcal{O}_{Hl}^{(1)}\,,\ \mathcal{O}_{He}\,,\ \mathcal{O}_{Hq}^{(3)}\,,\ \mathcal{O}_{Hq}^{(1)}\,,\ \mathcal{O}_{Hd}\,,\ \mathcal{O}_{Hu}\,,$
Bosonic:	$\mathcal{O}_{H\Box}\,,\ \boxed{\mathcal{O}_{HG}}\,,\ \mathcal{O}_{HW}\,,\ \mathcal{O}_{HB}\,,\ \mathcal{O}_{W}\,,\ \mathcal{O}_{G}\,,$
Yukawa:	$\mathcal{O}_{\tau H}\,,\ \mathcal{O}_{\mu H}\,,\ \mathcal{O}_{bH}\,,\ \mathcal{O}_{tH}\,.$

Example:

$$\boxed{\mathcal{O}_{HG}} = H^\dagger H G^A_{\mu\nu} G^{\mu\nu A}$$

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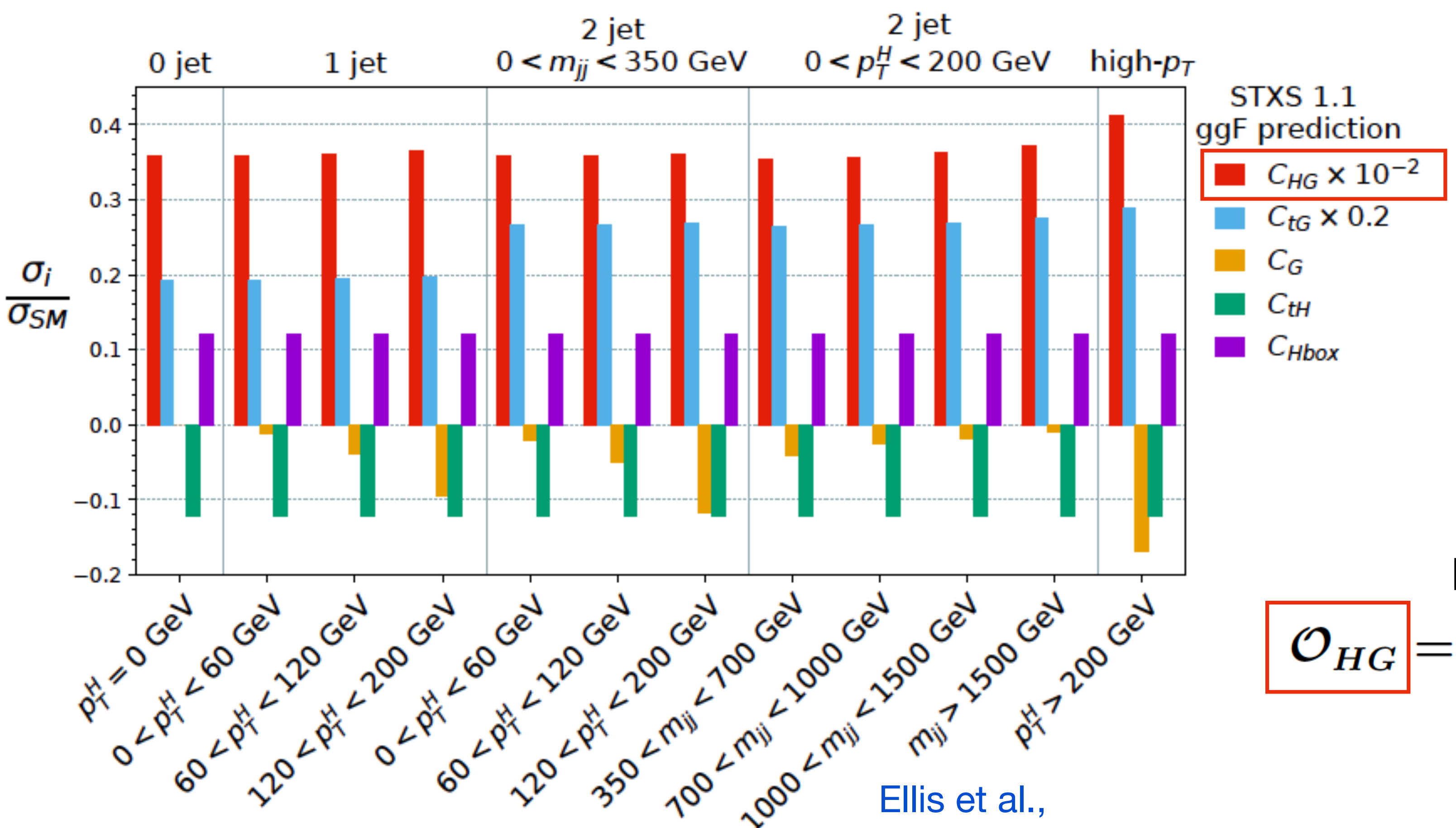

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Ellis et al., 2012.02779

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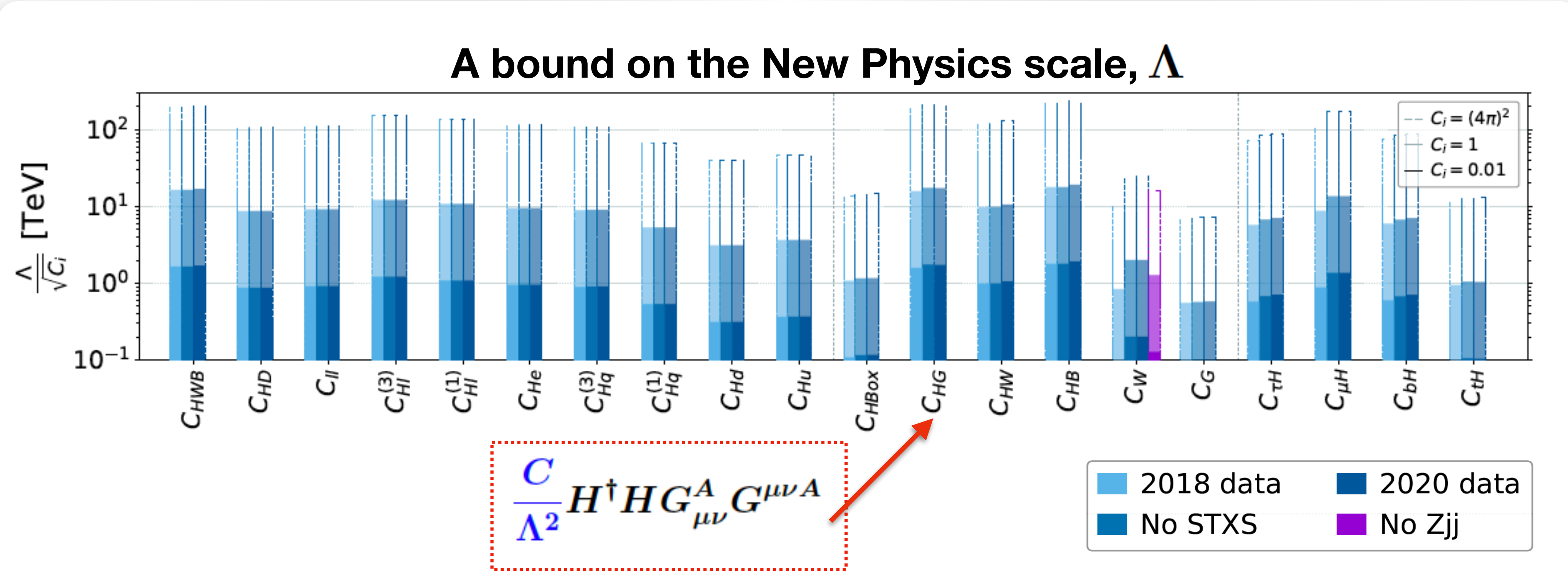

Ellis et al.,
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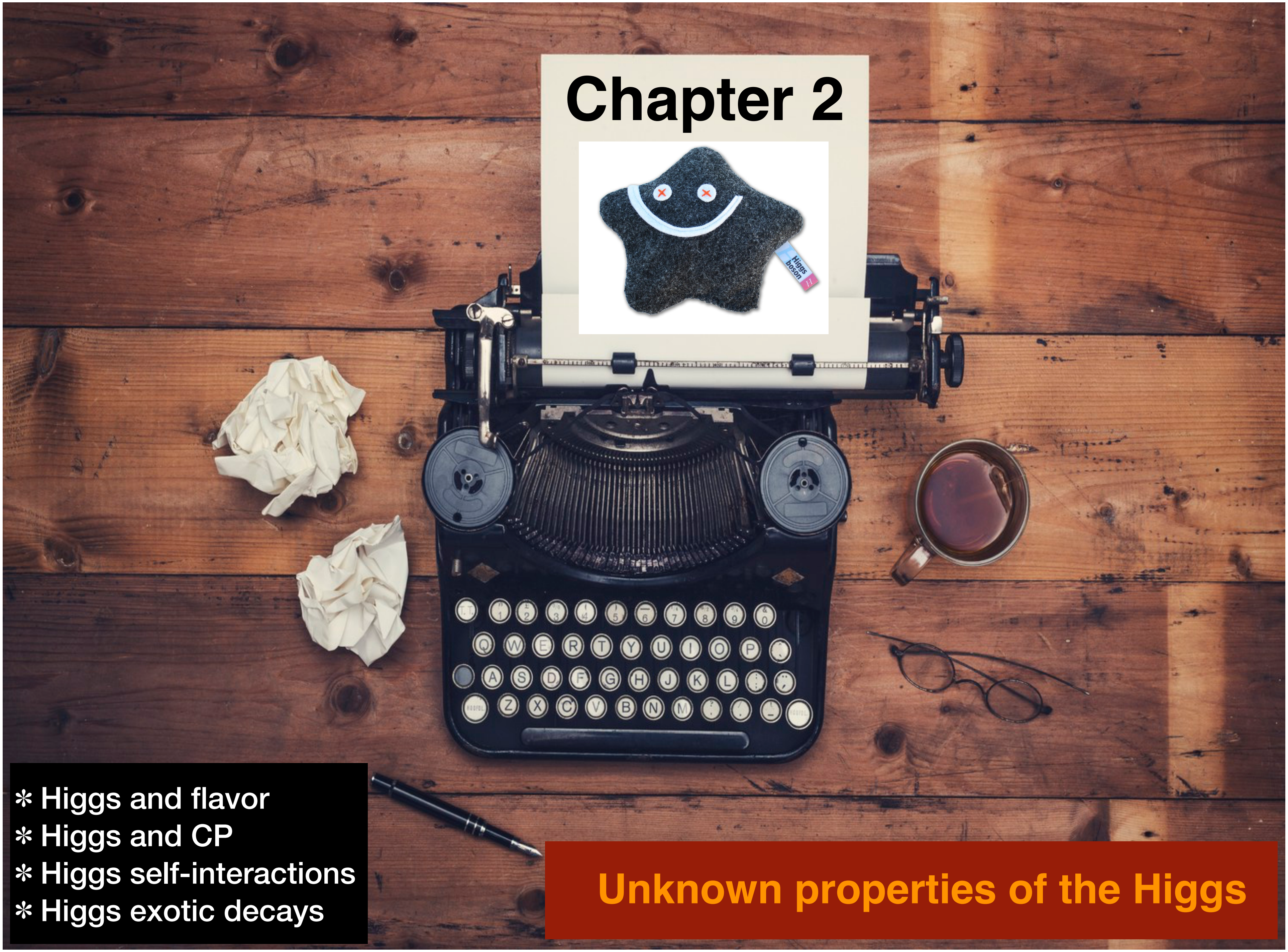
Chapter 2



* Higgs and flavor
* Higgs and CP
* Higgs self-interactions
* Higgs exotic decays

Unknown properties of the Higgs

Higgs and flavor

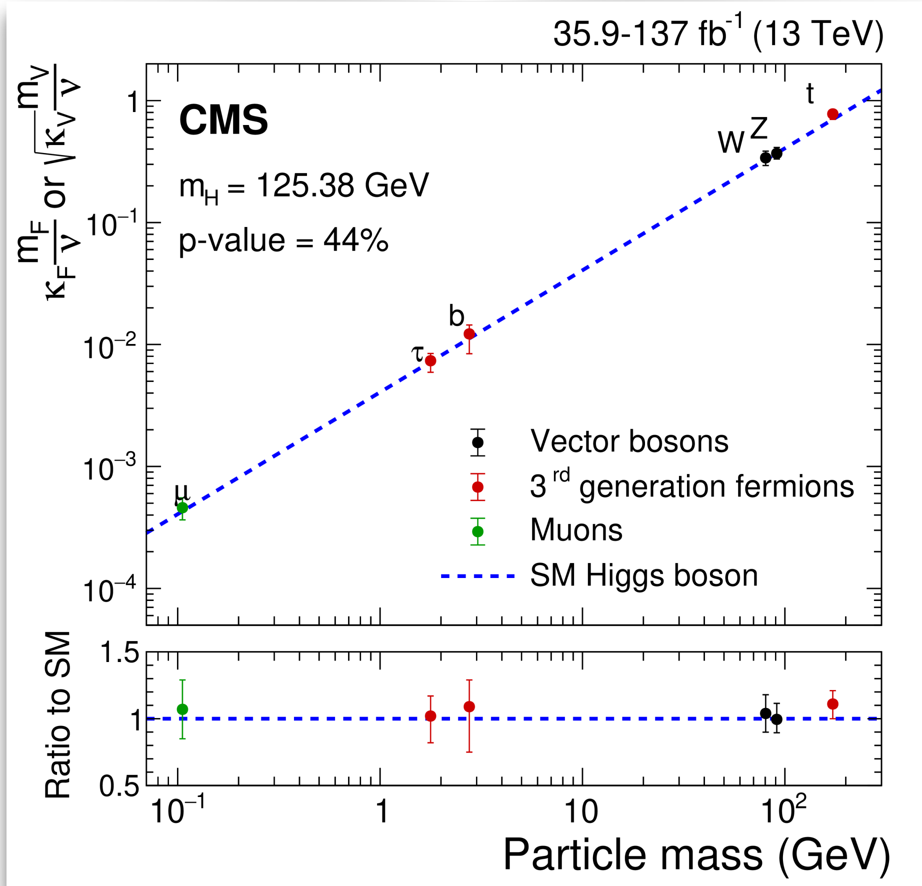
We do not know if the 125 GeV Higgs is coupled/gives mass to all flavors

Evidence for the Higgs decaying into muons!

$$\mu = 1.2 \pm 0.6$$ (ATLAS, 2007.07830)

$$\mu = 1.19^{+0.40}_{-0.39}(\text{stat})^{+0.15}_{-0.14}(\text{syst})$$ (CMS, 2009.04363)

Run III discovery?



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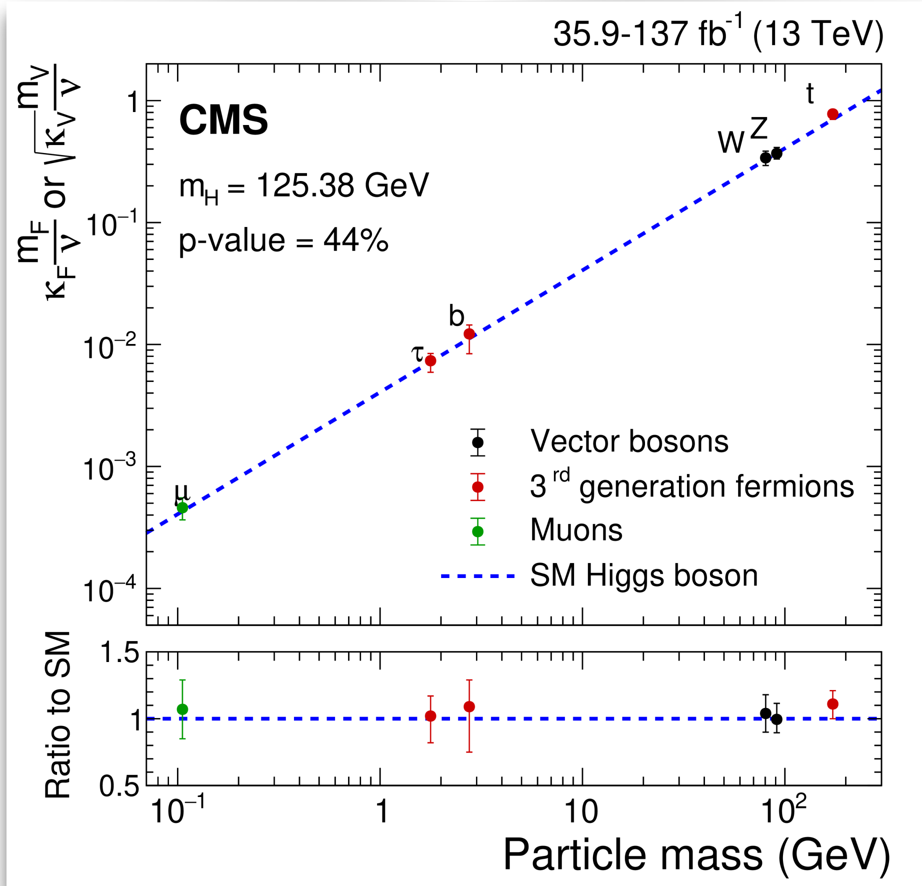

What about light quarks? (electrons?)

Strategies to probe light quark Yukawas (warning: not exhaustive)

- Higgs + charm production (Brivio, Isidori, Goertz 1507.02916)
- Higgs + jet production (Bishara, Haisch, Monni, Re, 1606.09253)
- Higgs η & p_T distributions (Soreq, Zhu, Zupan, 1606.09621)
- Rare Higgs decays (Bodwin, Petriello, Stoynev, Velasco,1306.5770)
- Charge asymmetry in $W^\pm h$ production (Yu,1609.06592) discovery with 300/fb
- Higgs + photon production (Aguilar-Saavedra, Cano, No, 2008.12538)

Higgs and CP violation

In the Standard Model (SM),

- The only source of CP violation comes from the electroweak sector (CKM phase).
- The Higgs has scalar couplings with SM particles.

We need to test these two statements!

From the experimental point of view,

- The Higgs CP nature is one of the **least known properties** of the Higgs boson.
- By now, the CP-odd hypothesis is strongly disfavored.

What if the Higgs is a CP even - CP odd admixture?

Generically, UV scenarios (e.g. 2HDMs) involve extended Higgs sectors
and the possibility of CPV Higgs couplings.
Constraints from electric dipole moments?

Baryon asymmetry (typically) requires new sources of CPV

CPV Higgs in a complex 2HDM

Most general Higgs potential for a 2HDM with a softly broken Z_2 symmetry:

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \frac{1}{2}(m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2$$
$$+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}(\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}),$$

Set of free parameters (phenomenological):

$m_{h_1},\ m_{h_2},\ m_{h_3},\ m_{H^\pm},\ \alpha\ (\text{or } x),\ \alpha_2,\ \nu,\ \tan\beta$

CP admixture of the 125 GeV Higgs

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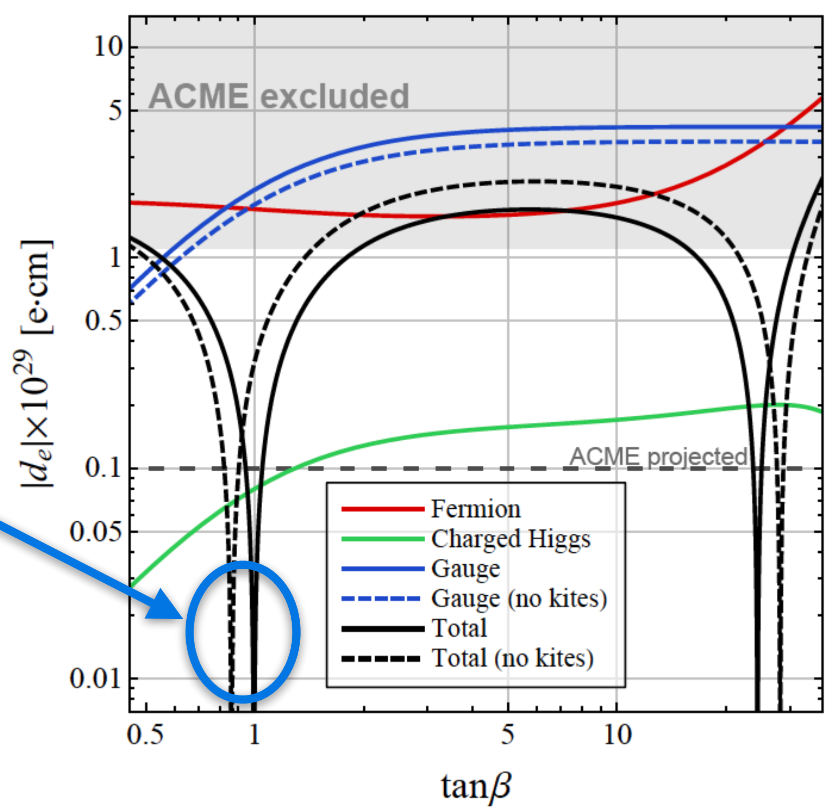
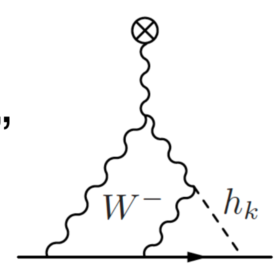
Altmannshofer, SG, Hamer, Patel, 2009.01258

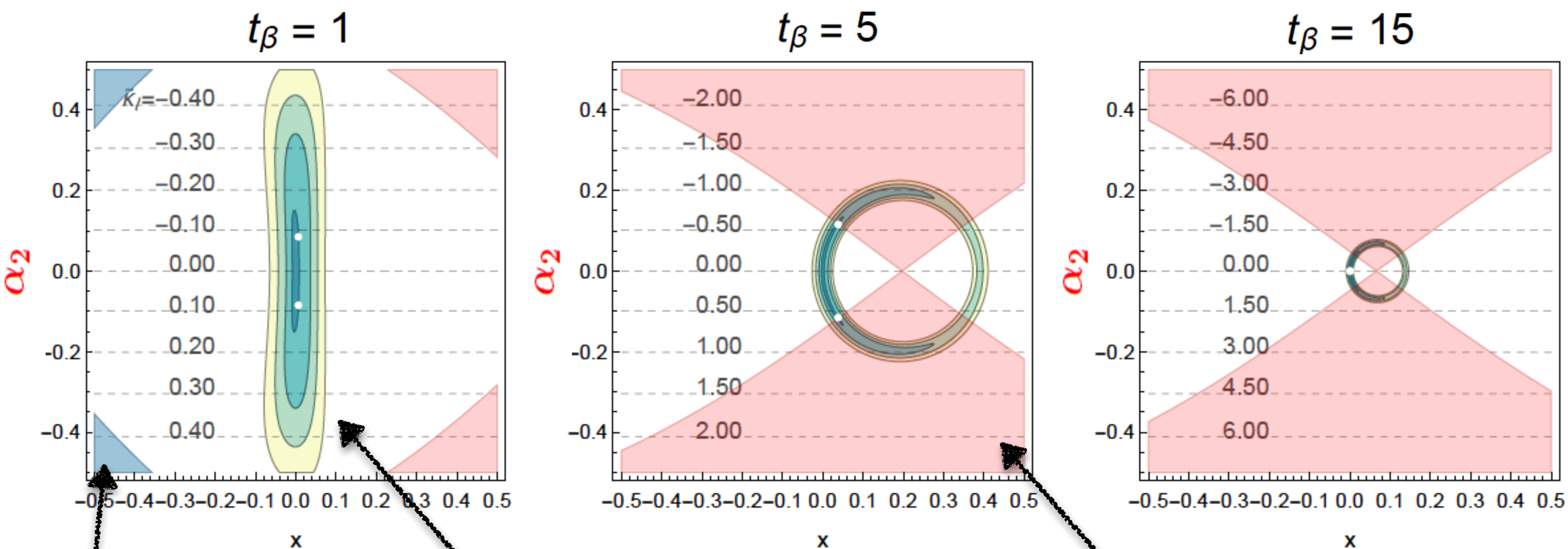


Searches for EDMs strongly constrain the parameter space but…

Latest calculation of electron EDM that includes "kite diagrams"



Direct & indirect constraints on a CPV Higgs



(Indirect) constraint from Higgs rate measurements
(we need to be in this region)

Exclusion from direct searches for CPV in $h \to \tau\bar{\tau}$

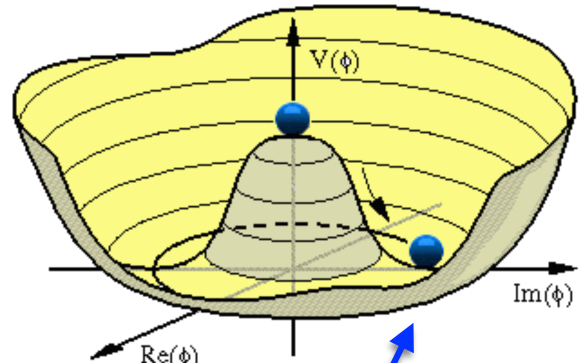
Exclusion from direct searches for CPV in $ht\bar{t}$

Higgs self-interactions

In the SM, the Higgs **self-interactions are fully determined**:

$$V_0 + \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4}\frac{m_h^2}{2v^2} h^4$$

v, m_h are the only two free parameters of the Higgs potential



Well motivated theories beyond the SM predict **modifications** to this picture.
Classic example: theories to explain the baryon-antibaryon asymmetry

What’s the shape of the potential at around the minimum?

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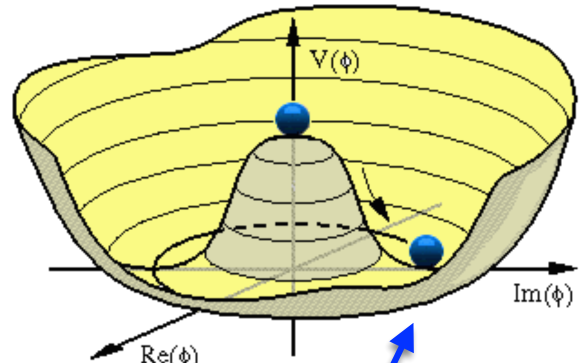

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It is very important to test the Higgs self-interactions!

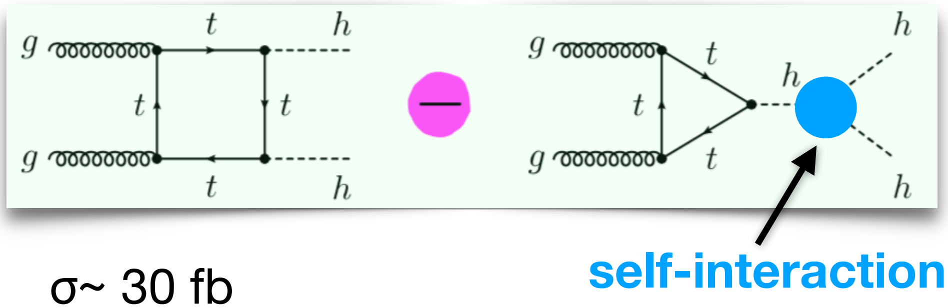
How to measure it?

1. di-Higgs production

2. Higgs rate measurements

1. Di-Higgs production

The measurement is challenging since the **SM di-Higgs cross section is small**



σ~ 30 fb
(~1000 smaller than single production)

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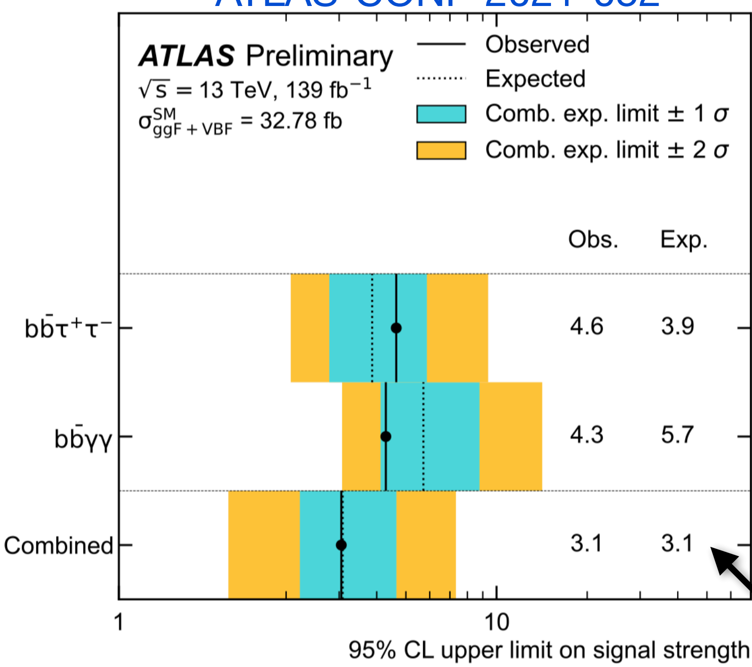
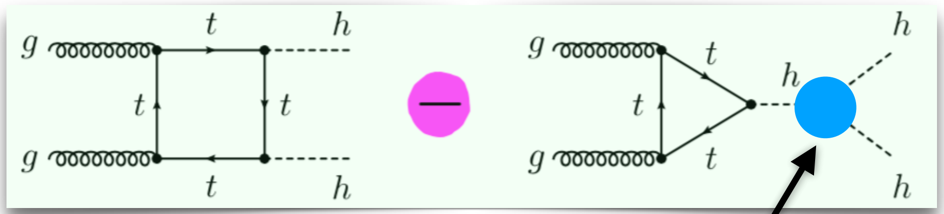
Several di-Higgs searches performed at Run II:

ATLAS-CONF-2021-052



see also talk by M.Swiatlowski

times the SM cross section



self-interaction

σ~ 30 fb
(~1000 smaller than single production)

HL: bbττ, bbγγ (and bbbb) will provide the best sensitivity (combined sensitivity of ~4-4.5σ)

We should prepare in view of the HL-LHC!

Improved b-tagging performance and improved b-jet triggers would be very important!

2. Higgs self-couplings and single Higgs

A value of k_λ different from the SM prediction will modify the Higgs couplings the other SM particles and, therefore, single Higgs measurements.

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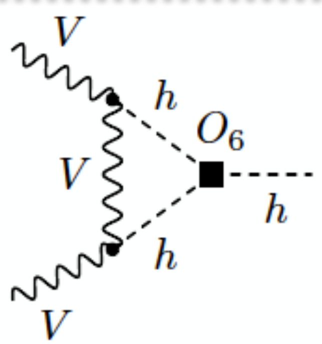
For example, the coupling to W and Z bosons:

example diagram:



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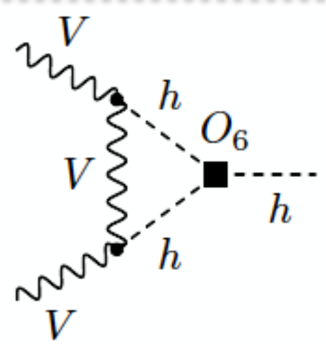
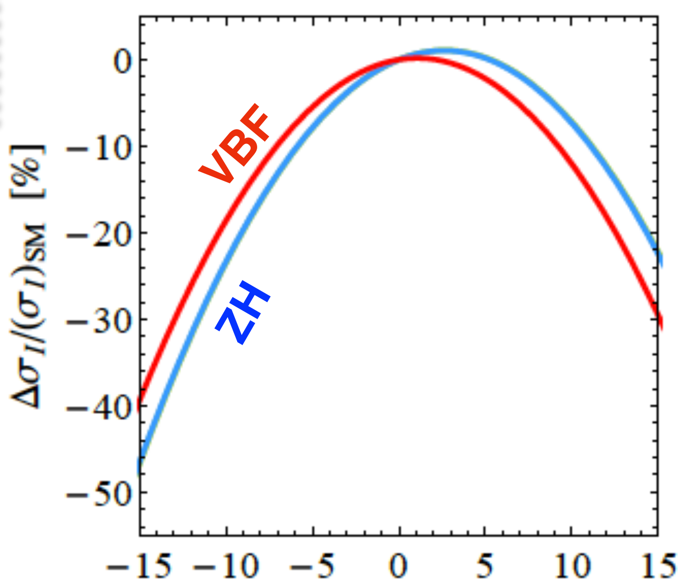
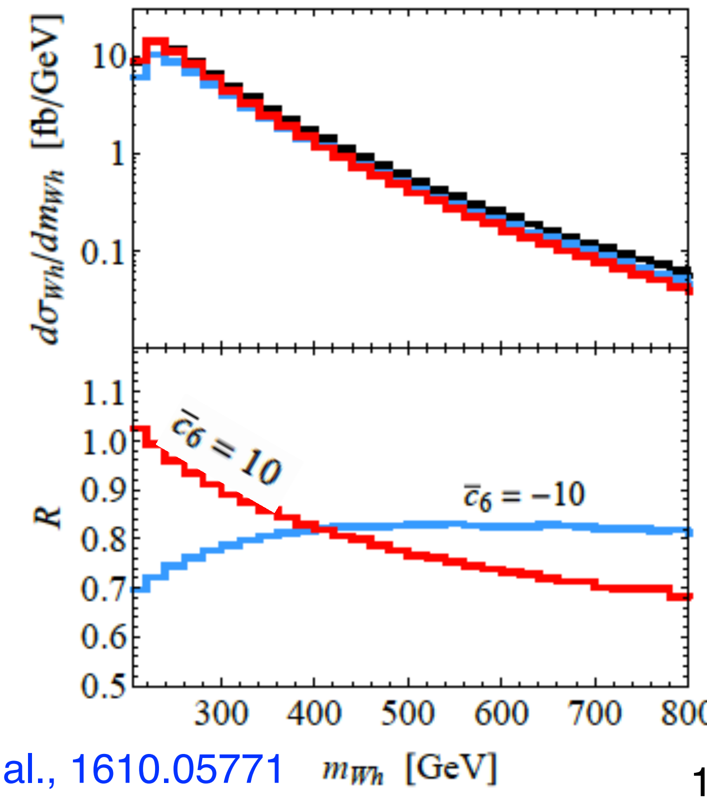


1. VBF and Z/W Higgs associated production cross section will be affected



$(-\lambda c_3 v h^3)$ $\bar{c}_6$ = c_3 -1

2. NP effects in differential distributions, as well



Extracted k_λ is **competitive** with the one extracted from di-Higgs searches

Bizon et al., 1610.05771

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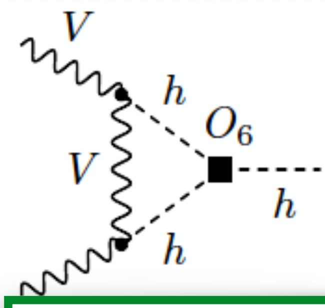

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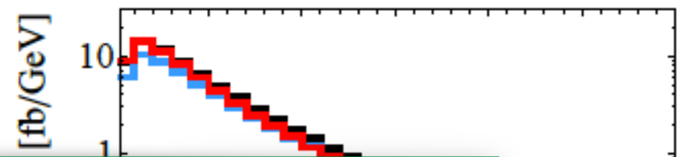
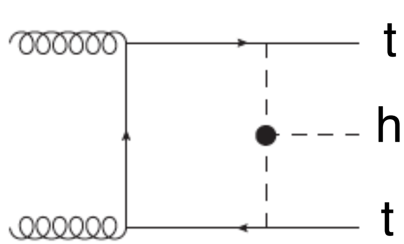
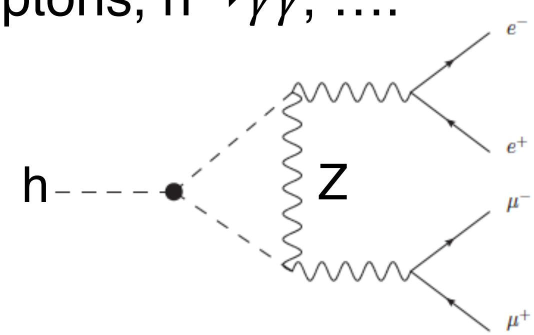


Extracted k
with the one
from di-Higg

Maltoni et al., 1709.08649

Many additional single Higgs measurements will be affected:
tth production, h → 4leptons, h→$\gamma\gamma$, ….





$(-\lambda c_3 v h$ $)$

Bizon et al., 1610.05771

Global fits (di-Higgs + single Higgs)

Importance of global fits to extract the maximum amount of information on **k_λ**

EFT fit performed in the 10-dimensional space: $\delta y_t,\ \delta y_b,\ \delta y_\tau,\ \delta c_z,\ c_{gg},\ c_{\gamma\gamma},\ c_{zz},\ c_{z\Box},\ c_{z\gamma},\ \kappa_\lambda$

$$\mathcal{L} \supset (1-\kappa_\lambda)\frac{m_h^2}{2v}h^3$$

Global fits (di-Higgs + single Higgs)

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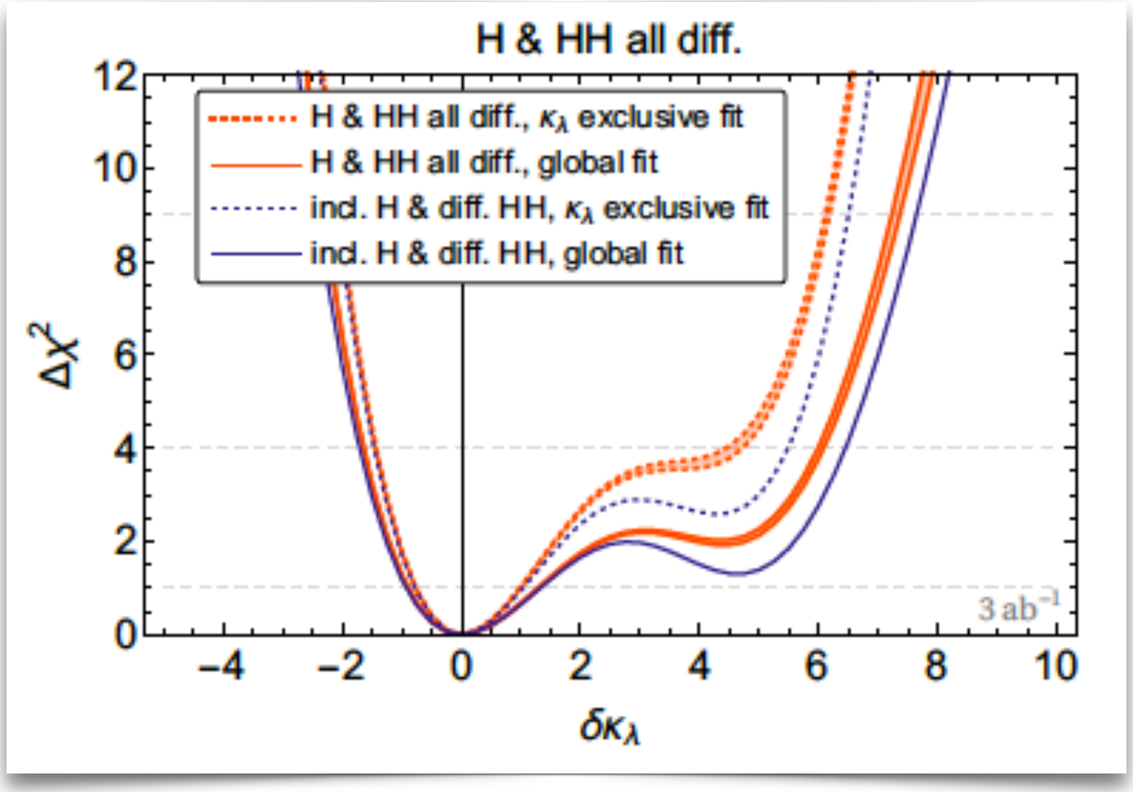

Di Vita et al., 1704.01953

HL-LHC

Dark sectors

Dark sector particles (= particles not charged under any SM gauge interaction) are theoretically very well-motivated:

- Models for thermal Dark Matter with a mass below a few GeV
- Several anomalies in data can be addressed by dark sectors
  (eg. $(g\text{-}2)_{\mu}$, B-physics anomalies, Dark Matter anomalies (galactic center excess), …)
- Neutrino mass model building

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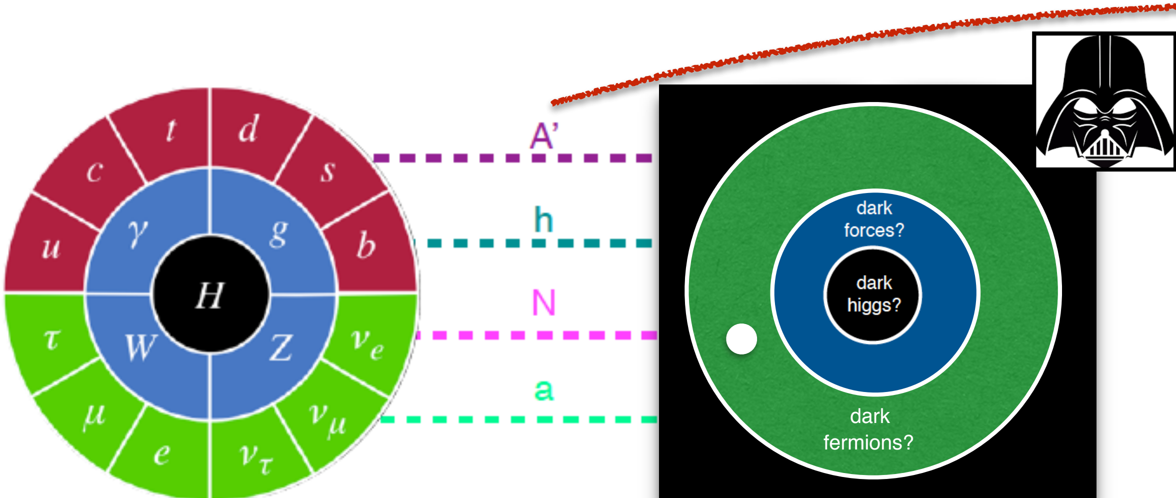
How to test this emerging paradigm?



Not charged under the SM gauge symmetries

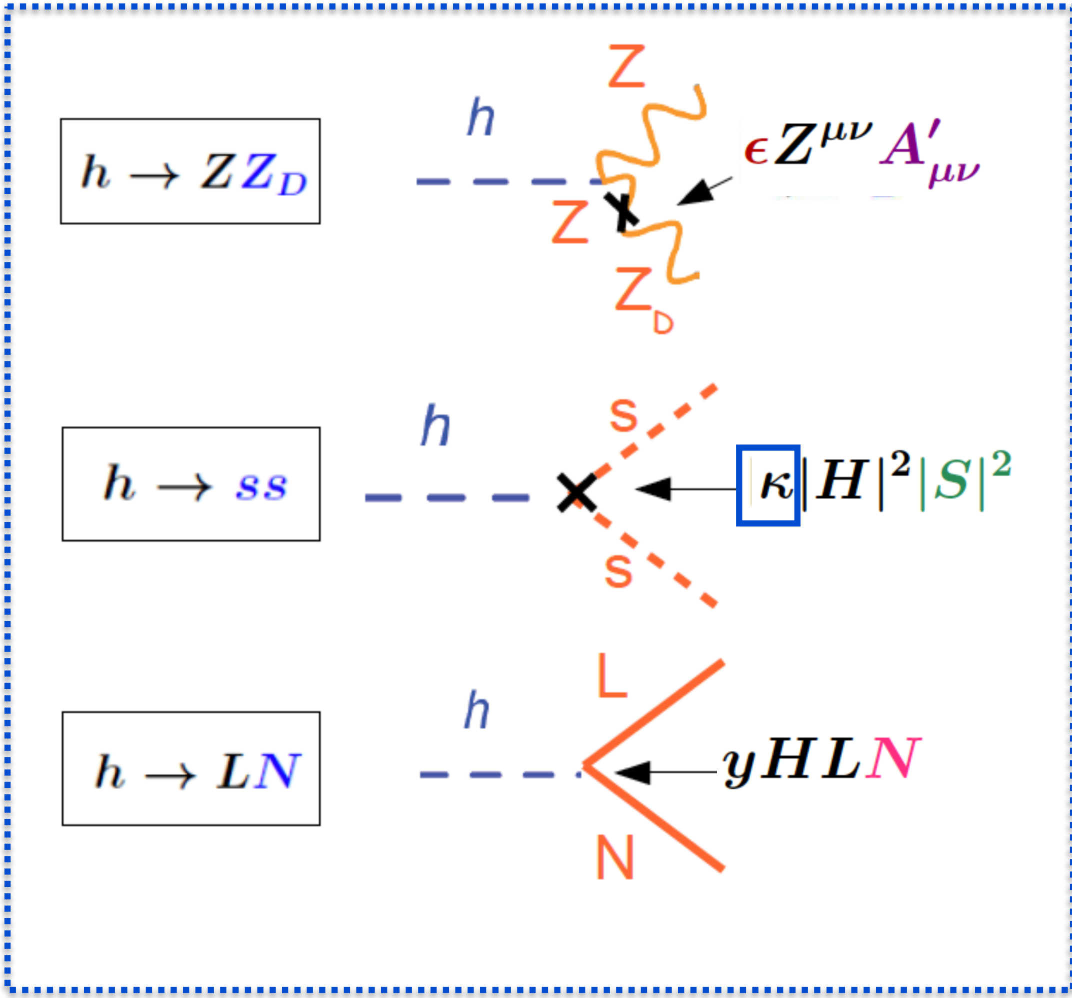
“Portals”:

Dark photon	$\epsilon Z^{\mu\nu} A'_{\mu\nu}$
Higgs	$\kappa \lvert H \rvert^2 \lvert S \rvert^2$
Neutrino	$y H L N$

generically small parameters

Dark sectors and Higgs exotic decays

Each "portal" leads to exotic decays of the Higgs boson, if the dark particles are light enough!



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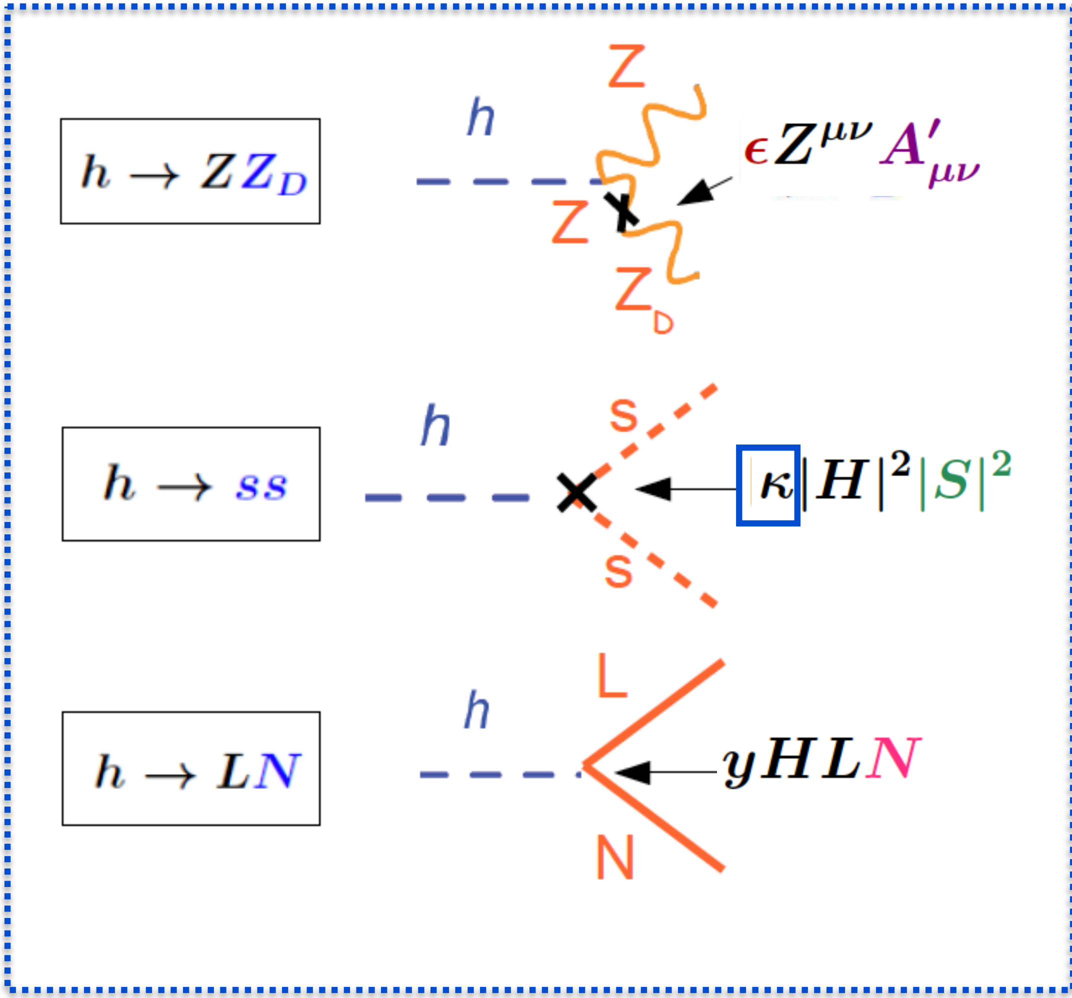
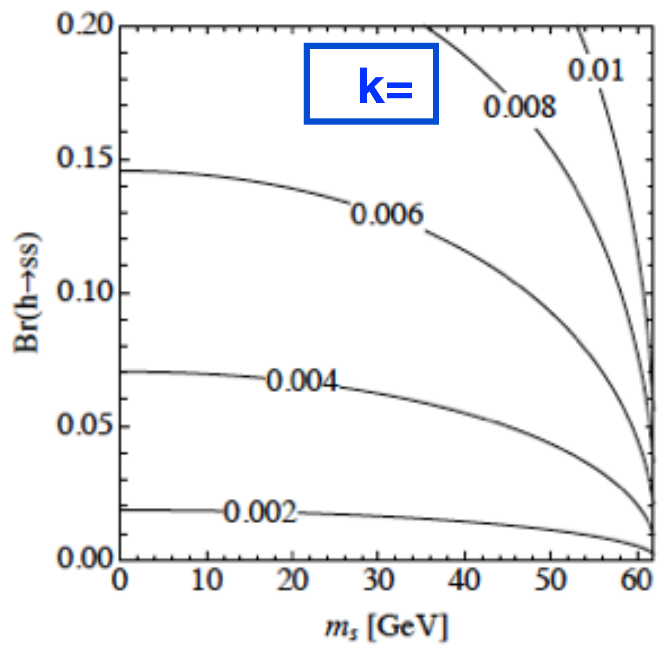
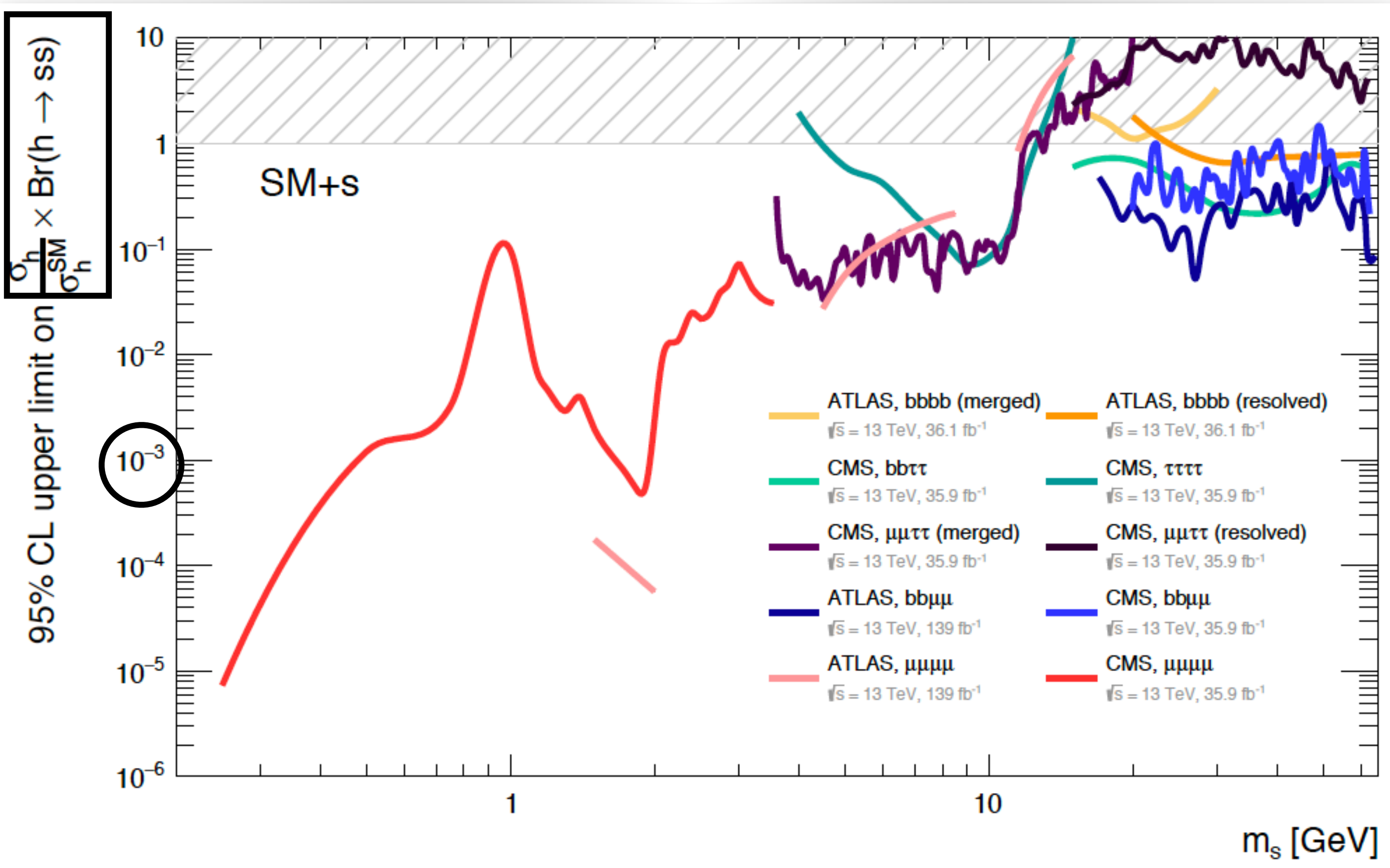


The Higgs exotic branching ratios can be sizable, even with small couplings
(the SM Higgs width is very small!)



Searches for Higgs exotic decays



Cepeda, SG, Martinez-Outschoorn, Shelton, 2111.12751

$h \to ss \to (ff)(f'f')$

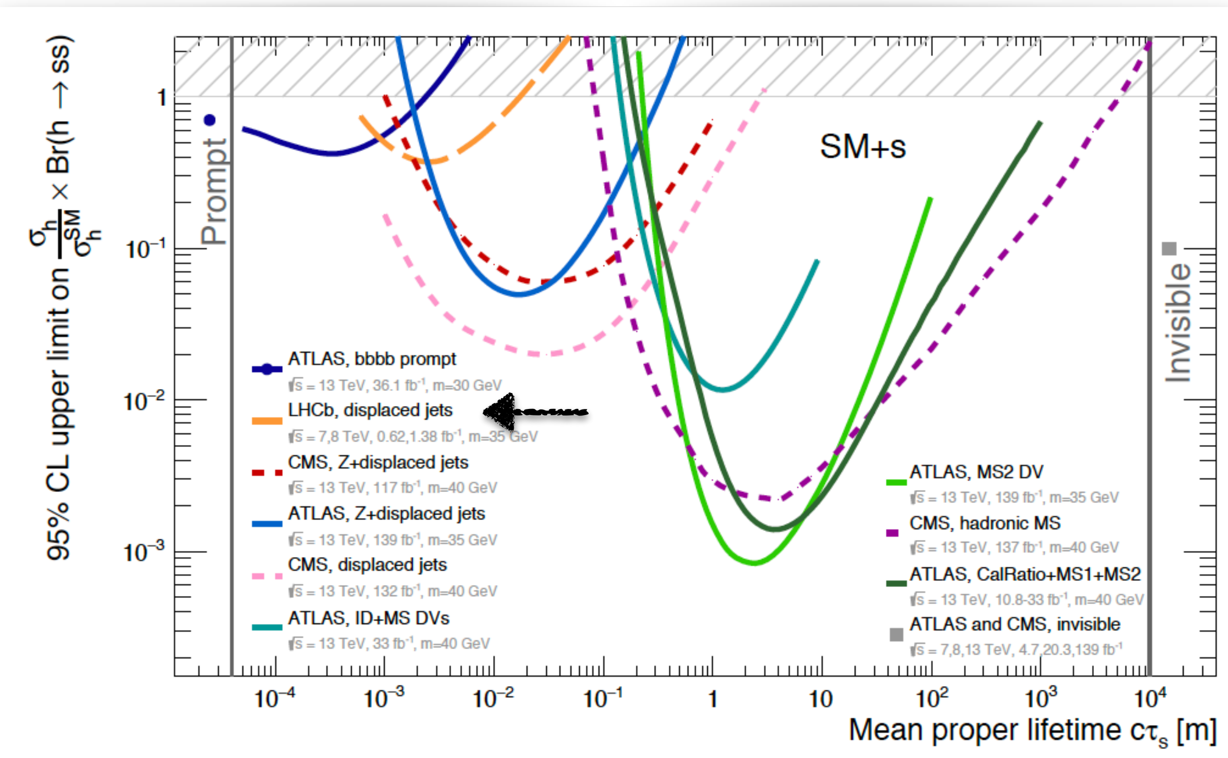
Other searches for
$h \to ss \to (\gamma\gamma)(\gamma\gamma)$
$h \to ss \to (gg)(\gamma\gamma)$
do not appear here since small
$s \to \gamma\gamma, gg$
branching ratios

See axion-like-particle models, though!

The least investigated Higgs exotic decays

1. A particularly interesting (and challenging) case:
Higgs decaying to **long-lived particles**

- Some searches will greatly benefit from the increase in luminosity (case of low/negligible backgrounds)



Cepeda, SG, Martinez-Outschoorn, Shelton, 2111.12751

- Significant improvements in sensitivity of many searches could be possible in future LHC runs with potential improvements in
  - timing (Liu, Liu, Wang, 1805.05957);
  - triggers (Gershtein, 1705.04321);
  - analysis strategies (e.g. Csaki et al, 1508.01522).

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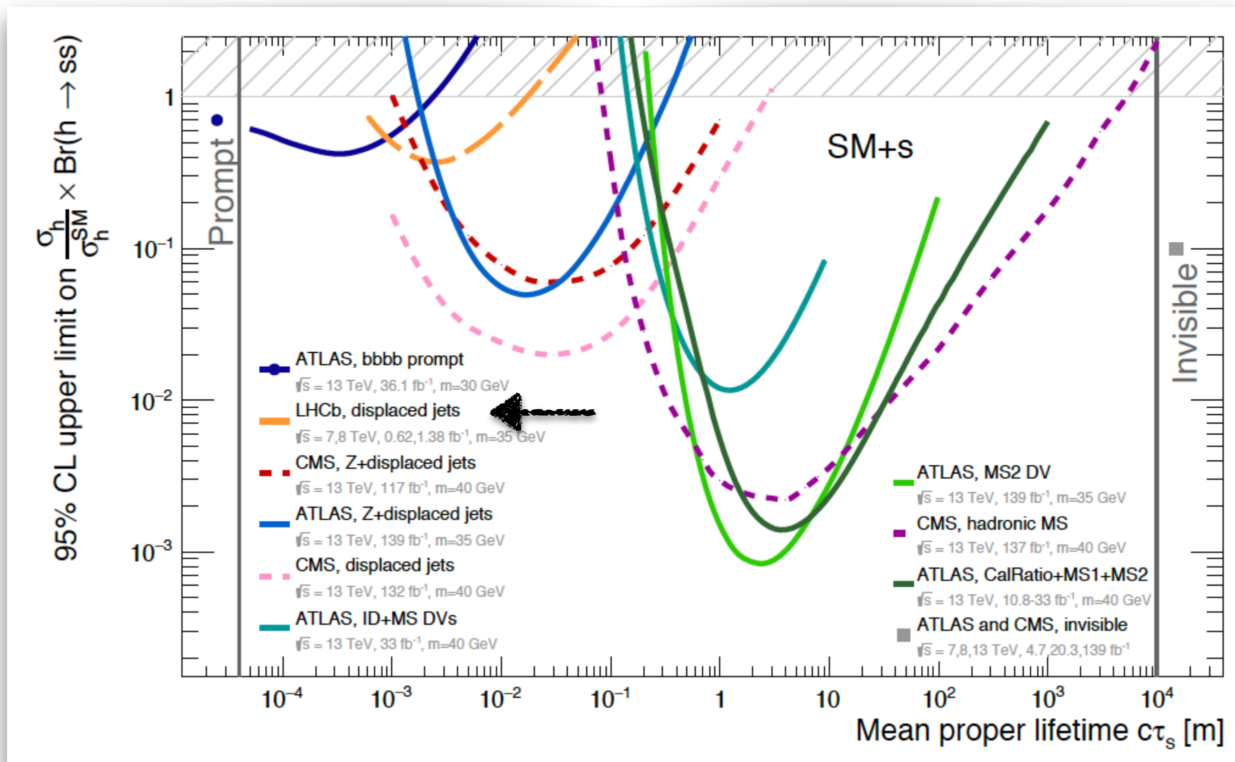

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2. Higgs decaying to **visible + invisible particles**
(example: $h \to X_1 X_2$,
$X_2 \to (f\bar{f})$ + MET and X_1 invisible)


Chapter 3
* The flavor puzzle
* The hierarchy problem
New Higgs bosons

New Higgs bosons

Many theoretically well-motivated theories beyond the Standard Model predict the existence of new Higgs bosons.

For example,

- theories that ameliorate the hierarchy problem
  (SUSY theories, twin Higgs theories, relaxion theories, …)
- models for electroweak baryogenesis

generically contain an extended Higgs sector

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Guiding principles

1. Electro-weak precision tests (EWPTs):

in principle, there is an infinite number of SU(2)*U(1)$_Y$ Higgs representations. Generically, Higgs SU(2) triplet models need some additional mechanism to fit EWPTs

2. Flavor transitions:

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

3. LHC direct searches

One of the simplest model: a Two Higgs Doublet Model (2HDM)

The flavor structure of a 2HDM

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)

Up quarks, down quarks, and leptons are only coupled to one Higgs doublet

→ Type I-IV Two-Higgs-Doublet-Models (2HDMs)

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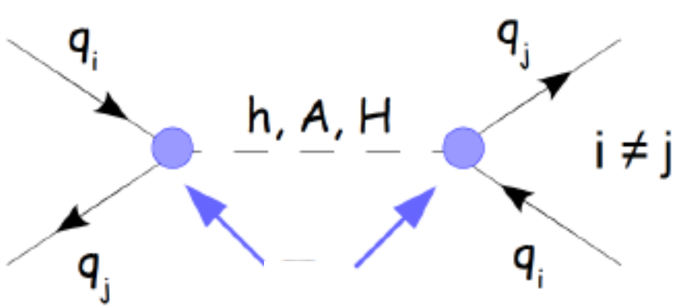
Indeed, generic 2HDMs are "dangerous" for flavor changing neutral currents:

$$\mathcal{H}_Y \supset \bar{Q}_L Y D_R H + \bar{Q}_L Y' D_R H'$$



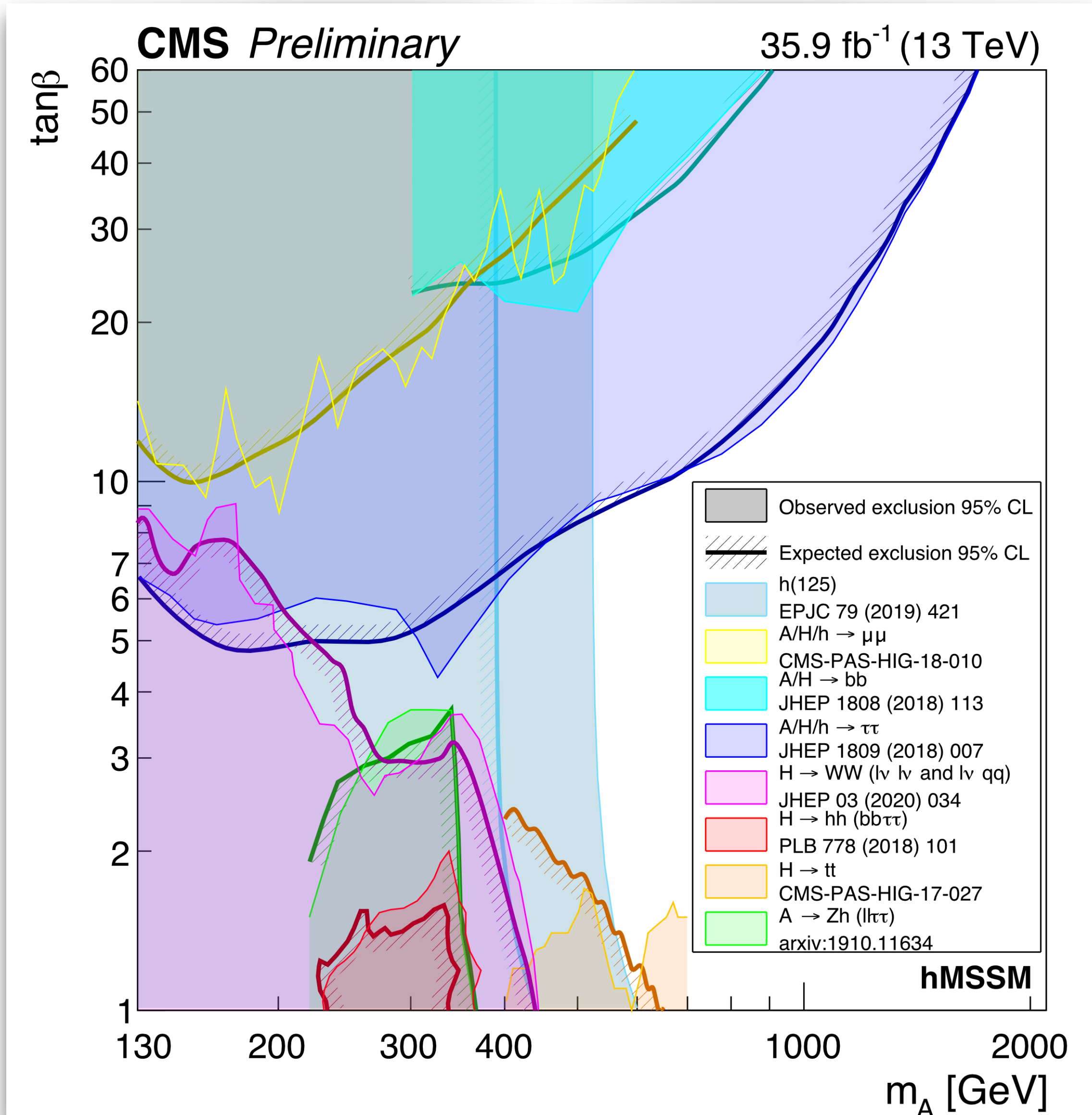
Stringent constraints from low energy flavor measurements:

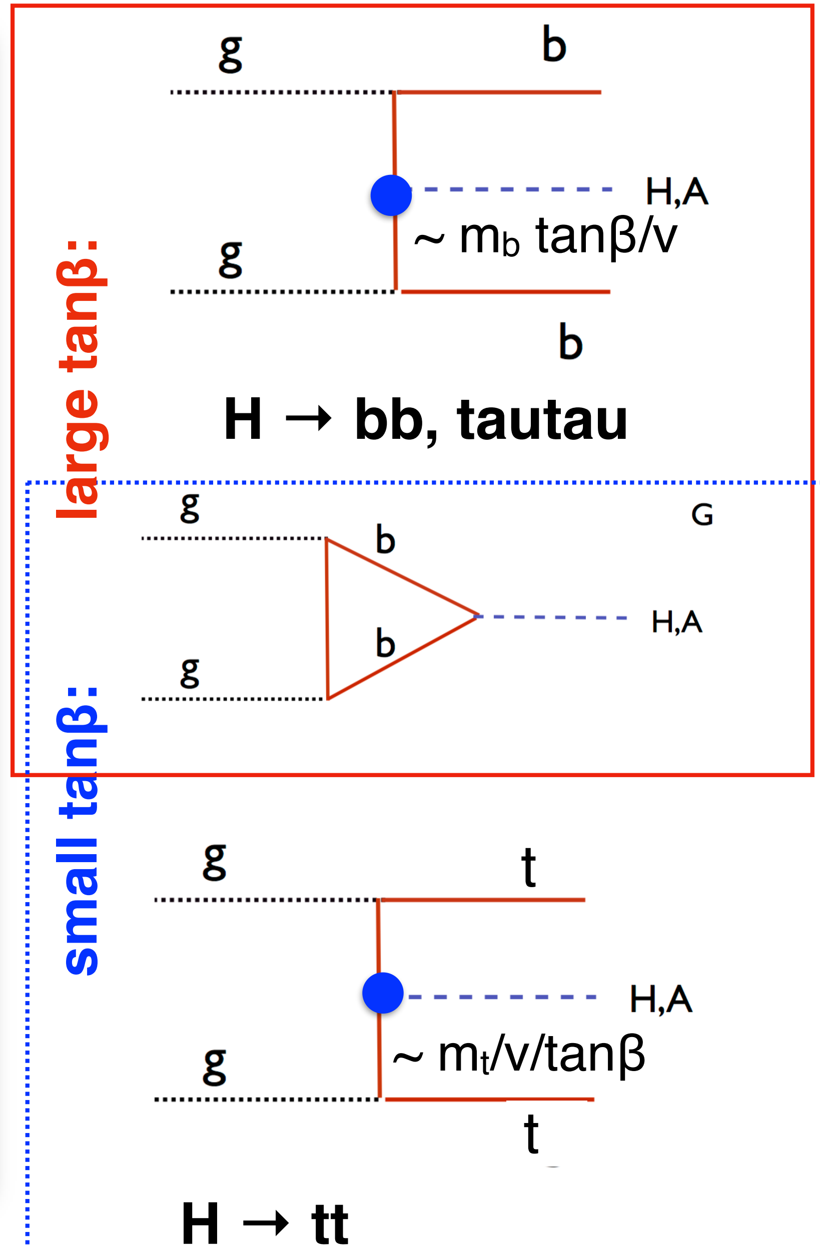
Kaon mixing → $m_H \geq \mathcal{O}(10^5 \text{ TeV})$

Conclusion:

We need a "clever" flavor structure

LHC searches motivated by type II 2HDMs





New flavorful structures

Models with an extended Higgs sector that
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Example

$$\mathcal{L} = \bar{f} Y f H + \bar{f} Y' f H' \rightarrow \mathcal{M} = vY + v'Y'$$

125 Higgs (h) Additional Higgses (H, A, $H^{\pm}$)

$$(\mathcal{M}_0 + \Delta\mathcal{M})$$

Altmannshofer, SG, Kagan, Silvestrini, Zupan, 1507.07927;

see also Ghosh, Gupta, Perez, 1508.01501

$$\mathcal{M}_0 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix}, \quad \Delta\mathcal{M} = \begin{pmatrix} m_e & \mathcal{O}(m_e) & \mathcal{O}(m_e) \\ \mathcal{O}(m_e) & m_\mu & \mathcal{O}(m_\mu) \\ \mathcal{O}(m_e) & \mathcal{O}(m_\mu) & \mathcal{O}(m_\mu) \end{pmatrix}$$

(analogous structure in the quark sector)

The ``flavorful 2HDM”

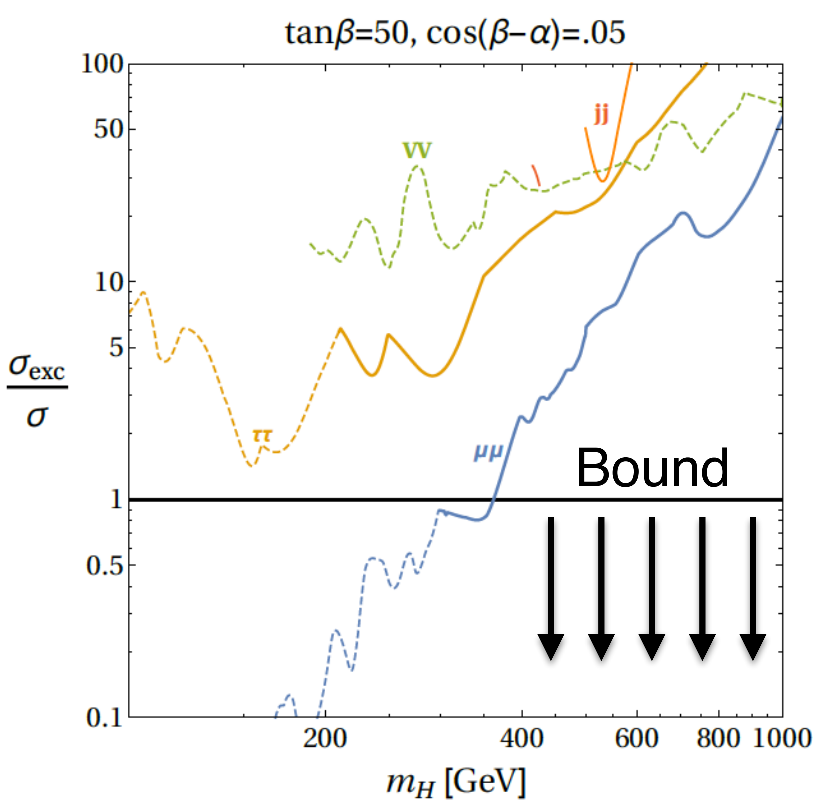
- Hierarchies obtained through v>>v’
- Flavor constraints under control thanks to an approximate U(2) symmetry
- New Higgs decays (flavor violating decays)

Heavy Higgs signatures of the flavorful 2HDM

Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398

Relatively weak LHC constraints

The "golden channels" are,
in fact, suppressed in this model



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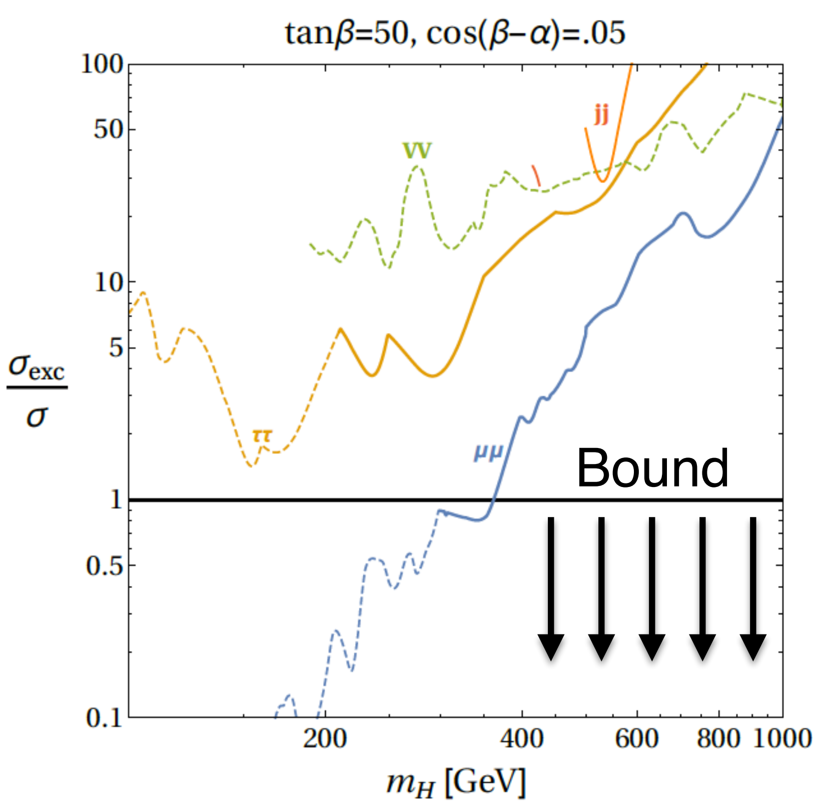

Several un-explored signatures

Top-charm resonances $pp \to H \to tc$

Boosted regime or leptonic top to trigger on the events.

Top-charm (or top-top) resonances

fully leptonic: $pp \to t(c)H,\ H \to tc$

same-charge dilepton plus bottom and charm jets

Tau-mu resonances $pp \to t(c)H,\ H \to \tau\mu$

Light di-jet resonances

$pp \to t(c)H,\ H \to cc$

Charm-bottom and charm-strange resonances (also above the top threshold).

Data scouting with bottom (charm)-tagging?

$pp \to H^{\pm} \to cs,\ cb$

New Higgs bosons and the hierarchy problem

Models that ameliorate the hierarchy problem often predict the existence of many new particles, in addition to new Higgs bosons.

⇨ Possible **exotic decays of the new Higgs**!

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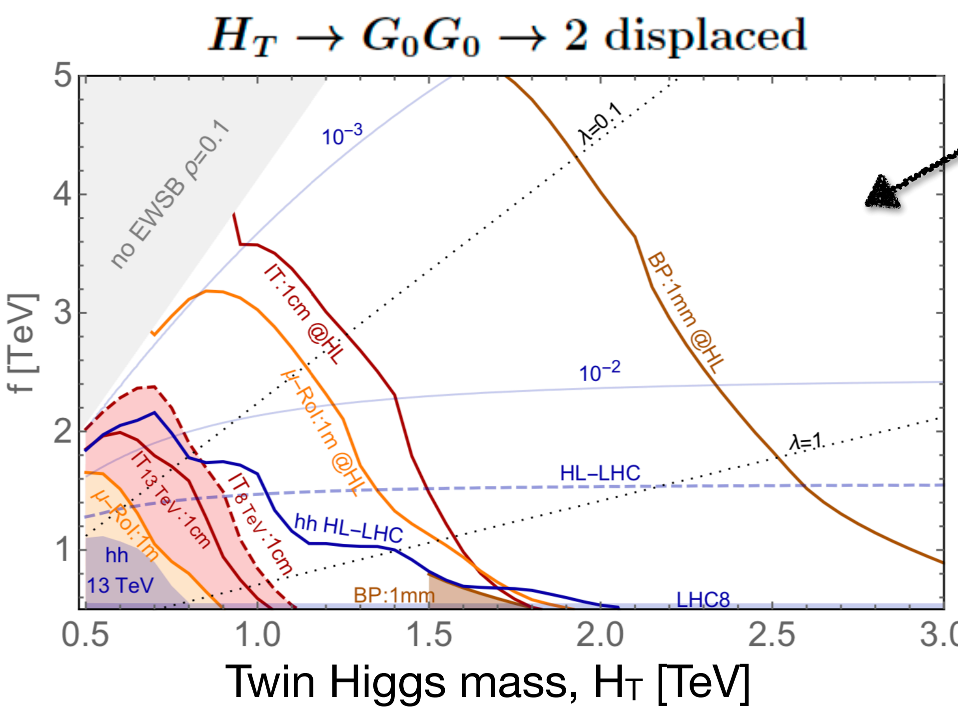
➡ Possible **exotic decays of the new Higgs**!

An interesting example: **twin Higgs models** predict the decay of the **new Higgs bosons to long lived particles**



Alipour-Fard, Craig, SG, Koren, Redigolo, 1812.09315

(G_0 = dark glueball of the twin sector)

This is the result of recasting existing searches for displaced resonance pair production and extrapolating them to the HL-LHC
(under the hypothesis of 0 background)

Many opportunities for the LHC:

- what about H_T - bb or H_T - tt associated production?
- What about only one displaced G_0 and the other one prompt?

Take home messages

The 125 GeV Higgs is still the least known particle of the Standard Model

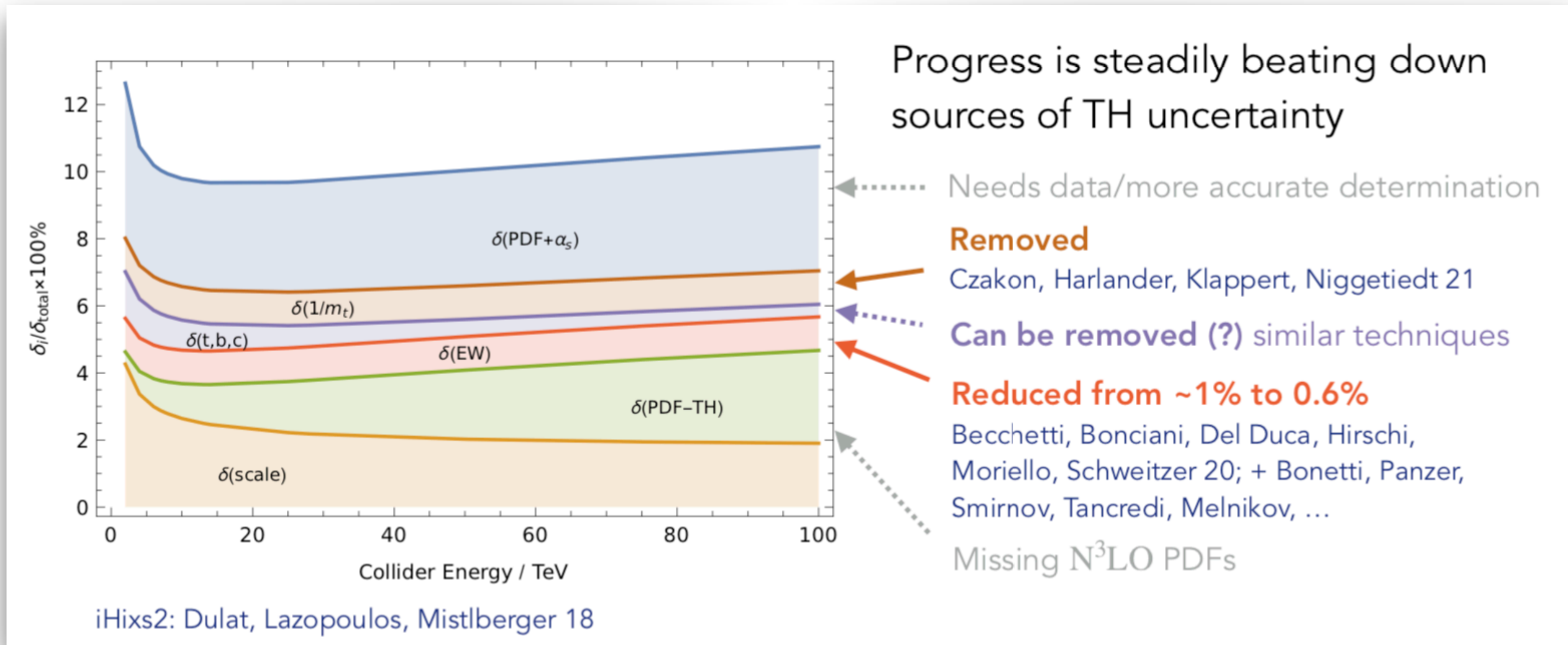
- LHC precision program (Higgs rates, distributions)
- (Almost) completely unknown properties (CP, flavor, self-interactions, exotic decays)

Extended Higgs sectors are a very generic aspect of theories beyond the Standard Model

Plenty of new signatures to look for!

Error budget

Inclusive Higgs gluon fusion cross section:



S. Jones talk at the general meeting LHC Higgs working group, Dec. 2021

Heavy Higgs couplings & non-universality

Comparing to the other flavor structures…

Neutral Heavy Higgs

	W,Z κ_V^H	up quarks $\kappa_t^H, \kappa_c^H, \kappa_u^H$	down quarks $\kappa_b^H, \kappa_s^H, \kappa_d^H$	leptons $\kappa_\tau^H, \kappa_\mu^H, \kappa_e^H$
2HDM type 1	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$
2HDM type 2	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta}$
Flavorful 2HDM	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta},\ t_\beta\frac{c_\alpha}{s_\beta},\ t_\beta\frac{c_\alpha}{s_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta},\ t_\beta\frac{c_\alpha}{s_\beta},\ t_\beta\frac{c_\alpha}{s_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta},\ t_\beta\frac{c_\alpha}{s_\beta},\ t_\beta\frac{c_\alpha}{s_\beta}$

Charged Higgs

	$H^\pm \bar{d}_L^i u_R^j$	$H^\pm \bar{u}_L^i d_R^j$	$H^\pm \bar{\nu}_L^i \ell_R^j$
Type 1	$\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$
Type 2	$\frac{1}{t_\beta}$	t_β	t_β
Flavorful	$\frac{1}{t_\beta},\ t_\beta,\ t_\beta$	$\frac{1}{t_\beta},\ t_\beta,\ t_\beta$	$\frac{1}{t_\beta},\ t_\beta,\ t_\beta$
	j=3,2,1	j=3,2,1	j=3,2,1