

# Lectures on BSM and Dark Matter theory (1st class)

Stefania Gori  
UC Santa Cruz



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Hadron Collider Physics Summer School  
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# Overview

**Chapter 1:** Introduction:  
The Standard Model and its open problems

- \* SUSY theories.

**Chapter 2:** Direct & indirect searches of SUSY particles

- \* Twin Higgs theories.

Direct & indirect searches of the “twin Higgs”

TODAY

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**Chapter 3:** \* Introduction on Dark Matter  
\* WIMP Dark Matter; Complementarity of searches

**Chapter 4:** \* (Light) Dark Matter living in a dark sectors  
\* Complementarity of accelerator experiments  
(high energy vs. high intensity)

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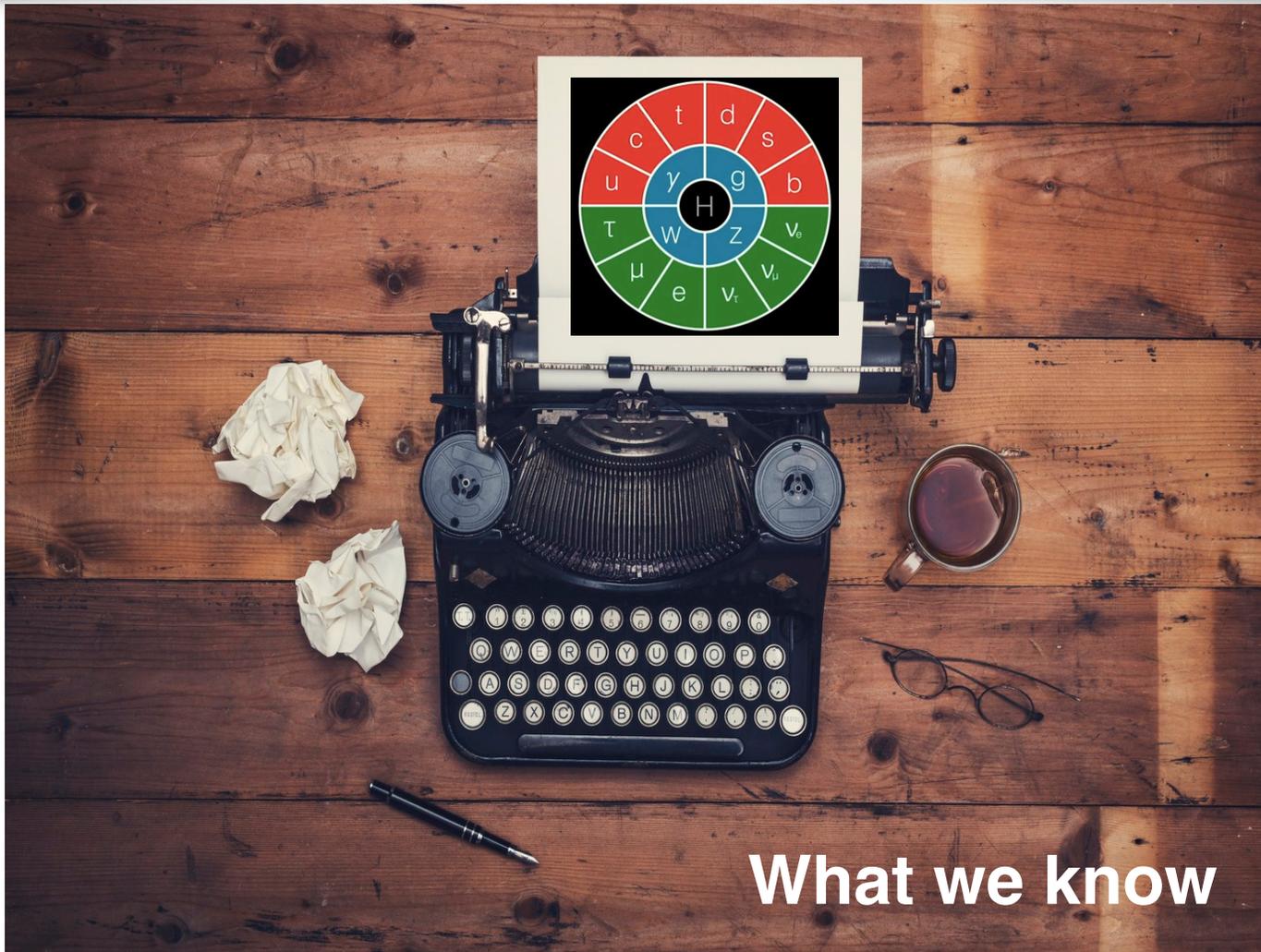
**Goal:** Some basics + overview of what I find exciting about BSM theories + pheno

**Disclaimer:** not comprehensive!

**Please interrupt to ask questions! We do not have to go through all slides! :)**

# Let us start!

## Chapter 1: Introduction: The Standard Model and its open problems



# First: what is the Standard Model (SM)?

The SM is

- \* a remarkably successful description of nature
- \* a Quantum Field Theory
- \* based on symmetry principles
- \* ~minimal
- \* a model with an enormous predictive power

But we do not understand why it works so well. . .



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Particle content:

2 ≠ electric charges	mass →	≈2.3 MeV/c <sup>2</sup>	≈1.275 GeV/c <sup>2</sup>	≈173.07 GeV/c <sup>2</sup>	0	≈126 GeV/c <sup>2</sup>
	charge →	2/3	2/3	2/3	0	0
	spin →	1/2	1/2	1/2	1	0
	<b>QUARKS</b>	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> Higgs boson
		<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>γ</b> photon	
		≈4.8 MeV/c <sup>2</sup>	≈95 MeV/c <sup>2</sup>	≈4.18 GeV/c <sup>2</sup>	0	0
2 ≠ electric charges		-1/3	-1/3	-1/3	0	0
		1/2	1/2	1/2	1	1
	<b>LEPTONS</b>	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>Z</b> Z boson	<b>W</b> W boson
		0.511 MeV/c <sup>2</sup>	105.7 MeV/c <sup>2</sup>	1.777 GeV/c <sup>2</sup>	91.2 GeV/c <sup>2</sup>	80.4 GeV/c <sup>2</sup>
		-1	-1	-1	0	±1
		1/2	1/2	1/2	1	1
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>W</b> W boson		
	<2.2 eV/c <sup>2</sup>	<0.17 MeV/c <sup>2</sup>	<15.5 MeV/c <sup>2</sup>	80.4 GeV/c <sup>2</sup>		
	0	0	0	±1		
	1/2	1/2	1/2	1		
	<b>3 ≠ generations/flavors</b>					
	<b>GAUGE BOSONS</b>					

# Fundamental principles of the SM

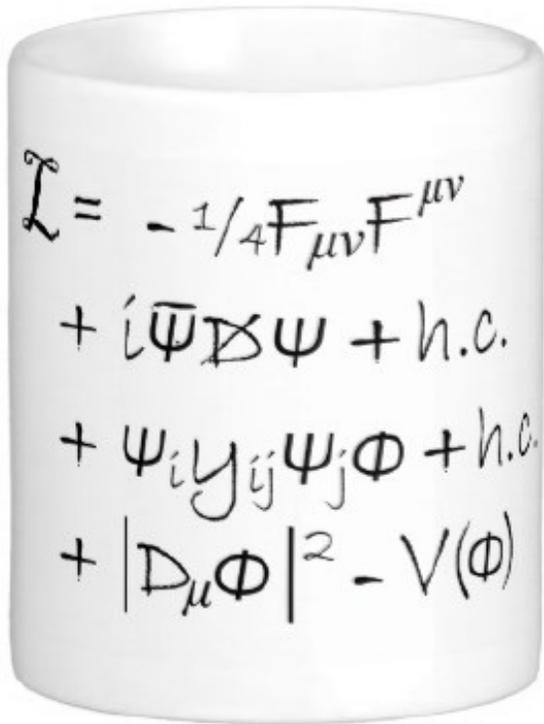
We write down a Lagrangian based on

- \* minimality: only observed and/or unavoidable objects
- \* unitarity
- \* renormalizability: finite predictions for the physical observables
- \* **symmetries**

**Symmetries:**

- \* **Lorentz** symmetry
- \* **Gauge** symmetries:  $SU(3)_C \times SU(2)_L \times U(1)_Y$
- \* we do not impose **global** symmetries. They are "accidental": e.g.
  - ✓  $SU(3)^5$  **flavor** symmetry broken by the Higgs interactions with fermions
  - ✓ Lepton and baryon number
  - ✓ ...

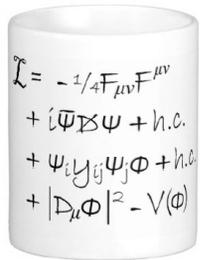
# Free parameters of the SM Lagrangian

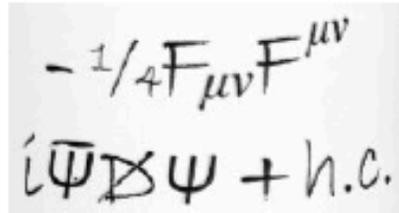


The image shows a white ceramic mug with the Standard Model Lagrangian written on it in black marker. The text is as follows:

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & + i\bar{\Psi}\not{D}\Psi + h.c. \\ & + \Psi_i y_{ij} \Psi_j \Phi + h.c. \\ & + |D_\mu\Phi|^2 - V(\Phi)\end{aligned}$$

# Free parameters of the SM Lagrangian

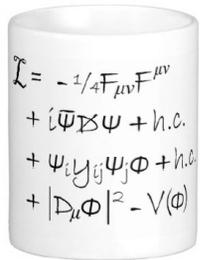

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$$\begin{aligned}& -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & i\bar{\Psi}\not{D}\Psi + h.c.\end{aligned}$$

- Describes the gauge interactions of quarks and leptons
- Parametrized by **3 gauge couplings**  
 $g_1, g_2, g_3$
- Stable with respect to quantum corrections
- Highly symmetric

Gauge sector

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$$+ |D_\mu \tilde{\Phi}|^2 - V(\Phi)$$

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Gauge sector

- Breaks electro-weak symmetry and gives mass to the  $W$  and  $Z$  bosons
- **2 free parameters:**  
Higgs mass  
Higgs vev
- Not stable with respect to quantum corrections

Higgs sector

# Free parameters of the SM Lagrangian

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi + h.c. + \psi_i y_{ij} \psi_j \Phi + h.c. + |D_\mu \Phi|^2 - V(\Phi)$$

$$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi + h.c.$$

$$+ |D_\mu \Phi|^2 - V(\Phi)$$

$$+ \psi_i y_{ij} \psi_j \Phi + h.c.$$

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Gauge sector

- Breaks electro-weak symmetry and gives mass to the  $W$  and  $Z$  bosons
- **2 free parameters:** Higgs mass, Higgs vev
- Not stable with respect to quantum corrections

Higgs sector

- Leads to masses and mixings of the quarks and leptons
- **10+10 free parameters in the quark+lepton sector** (12 in the lepton sector in case of Majorana masses)
- Stable with respect to quantum corrections

Flavor sector

# Open problems/questions for the SM

Let us re-write the SM Lagrangian allowing also for operators up to dimension 6 in the SM fields

$$\begin{aligned}\mathcal{L}_{\text{SM}} &\sim \Lambda^4 - \Lambda_H^2 H^2 + \lambda H^4 \\ &+ \bar{\psi} \not{D} \psi + (D_\mu H)^2 + (F_{\mu\nu})^2 \\ &+ F_{\mu\nu} \tilde{F}_{\mu\nu} + Y H \bar{\psi} \psi \\ &+ \frac{1}{\Lambda} (LH)^2 + \frac{1}{\Lambda^2} \sum_i O_i(\text{dim}6)\end{aligned}$$

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**Cosmological constant problem**

$$\left( \frac{\Lambda}{M_{\text{Planck}}} \right)^4 \sim 10^{-120}$$

**Hierarchy problem**

$$\left( \frac{m_h}{M_{\text{Planck}}} \right)^2 \sim 10^{-36}$$

**Vacuum stability problem**

see next slide

**Strong CP problem**

$$\frac{\Theta}{16\pi^2} F_{\mu\nu} \tilde{F}_{\mu\nu}, \quad \Theta \leq 10^{-10}$$

**Flavor puzzle**

$$\frac{y_t}{y_u} \sim 10^{-5}$$

Z. Ligeti lectures

**Origin of neutrino masses**

**New Physics flavor puzzle**



**Beyond the Standard Model (BSM) physics?**

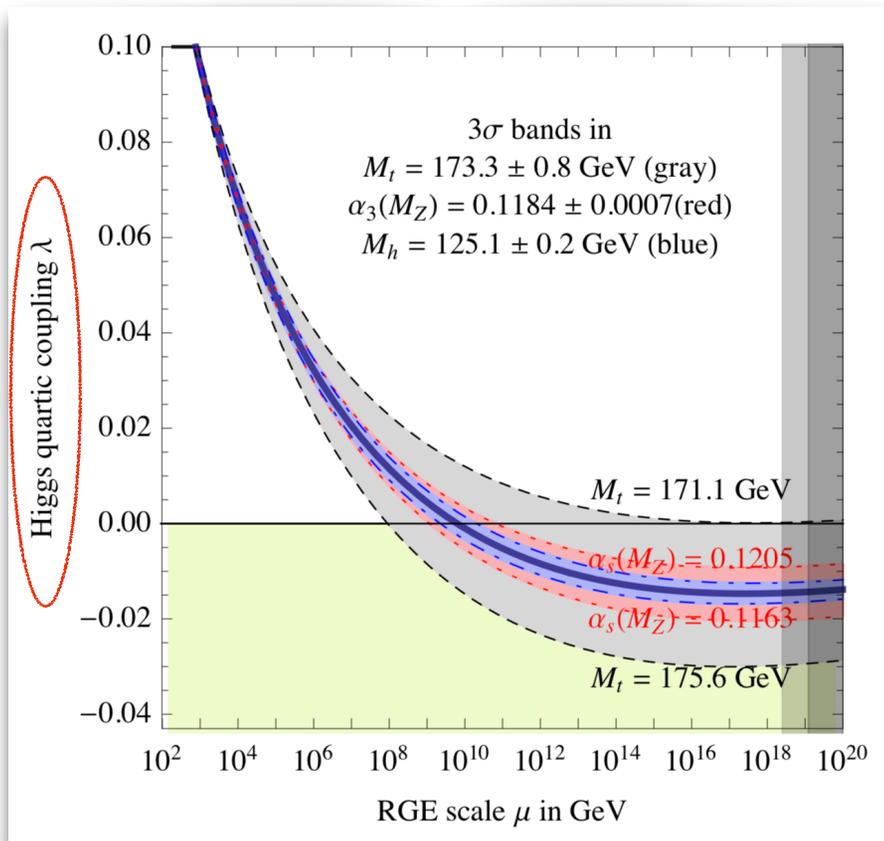
# Vacuum stability

Once we fix the two free parameters of the Higgs potential, we can compute the **running of the quartic coupling,  $\lambda$** , as a function of the energy scale

$$V = -\mu^2 |H|^2 + \lambda |H|^4$$

See lectures by H. Logan

Buttazzo et al, 1307.3536



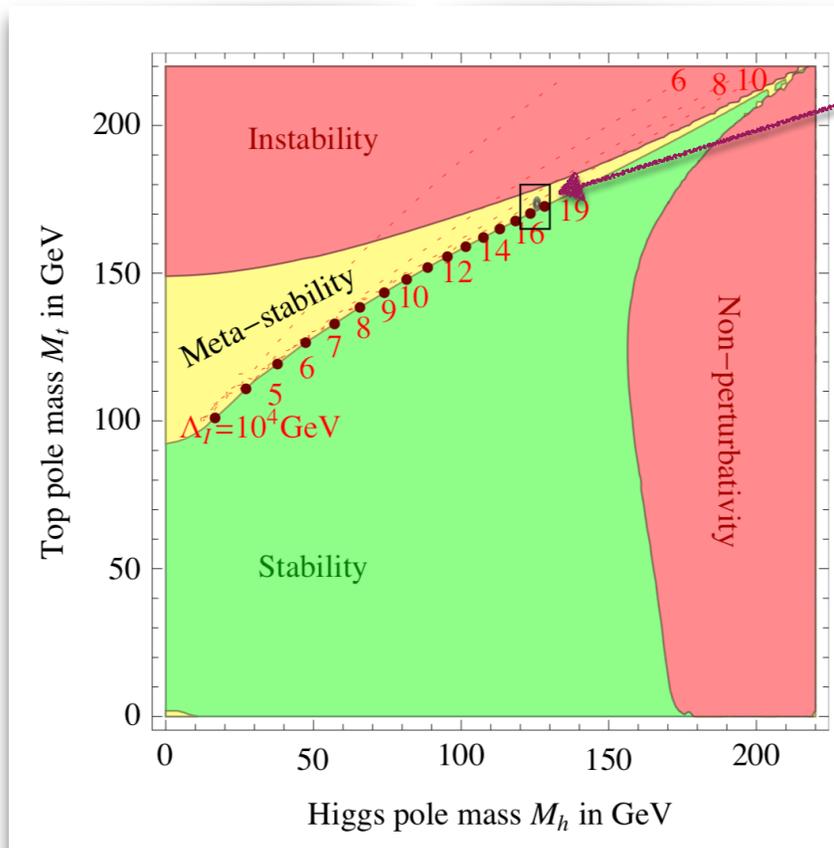
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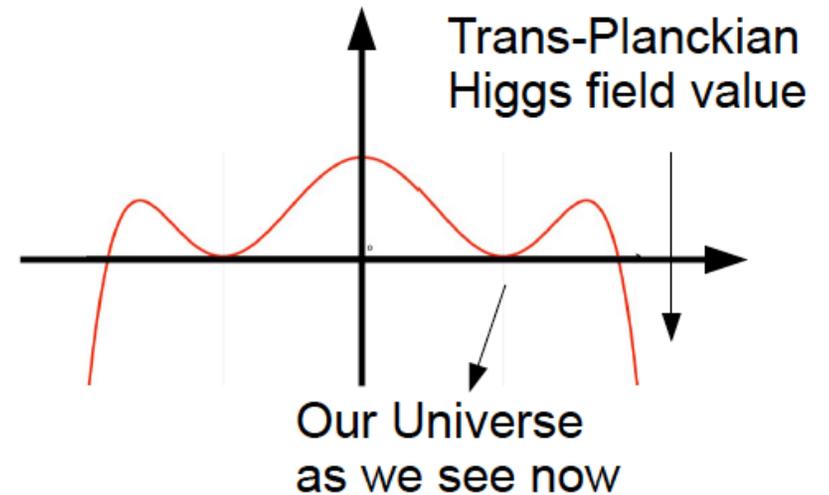
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We are here.  
Is this a coincidence?



Stability condition:  
 $M_h > (129.6 \pm 1.5) \text{ GeV}$

# The hierarchy problem

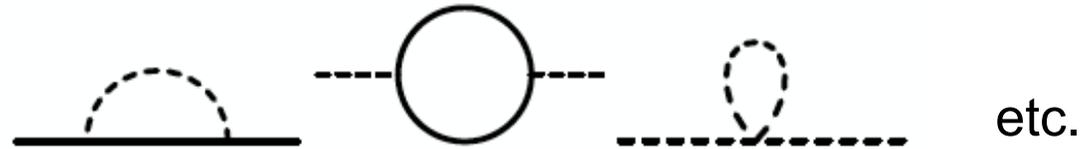
Let us take a generic theory of scalars,  $\phi$ , and fermions,  $\psi$ :

$$\mathcal{L} = |\partial_\mu \phi|^2 + \bar{\psi} i \not{\partial} \psi - m_f^0 \bar{\psi} \psi - y \phi \bar{\psi} \psi + \mu_0^2 |\phi|^2 - \lambda |\phi|^4$$

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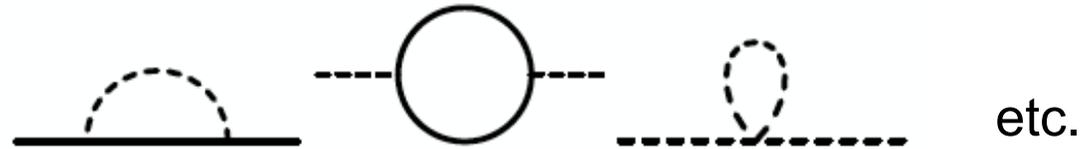


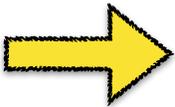
$\Delta m_f \sim -\frac{y^2}{16\pi^2} m_f \log\left(\frac{\Lambda}{m_f}\right)$   
 $\Delta \mu^2 \sim \frac{y^2 - \lambda}{16\pi^2} \Lambda^2 + \dots \quad \mu^2 = \mu_0^2 + \Delta \mu^2 = \mathcal{O}((100 \text{ GeV})^2)$

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**Scalars are very sensitive to the highest scale of the theory**

Generically, we would expect some New Physics at the scale

$$\Lambda = \mathcal{O}\left(\frac{4\pi}{g} m_h\right)$$

$m_h \sim 125 \text{ GeV}$ $M_{\text{Planck}} \sim 10^{19} \text{ GeV}$
--



# Principles to build a “good” BSM theory

- \* Take a **local, lorentz invariant, unitary** field theory;
- \* Preserve **gauge invariance** ( $SU(3) \times SU(2)_L \times U(1)_Y$ ), **anomaly free**;
- \* (Typically) do not introduce too large sources of breaking of the **accidental / approximate symmetries** of the SM classical Lagrangian



- \* Not be ruled out by experiments!

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  - baryon and lepton number  
 $B_{\text{quark}} = 1/3$ ,  $B_{\text{anti-quark}} = -1/3$ ,  $B_{\text{lepton}} = 0$  ( $L_{\text{lepton}} = 1$ ,  $L_{\text{anti-lepton}} = -1$ ,  $L_{\text{quark}} = 0$ )
  - Individual lepton families  
 $L_e, L_\mu, L_\tau$  (these are broken by neutrino masses in the SM (tiny))
  - Custodial symmetry:  $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$  (diagonal)  
(this is broken by hypercharge and Yukawas in the SM)
  - $SU(3)^5$  flavor symmetry (this is broken by the Yukawas in the SM)
- \* **Not be ruled out by experiments!**



# Addressing the hierarchy problem

Most studied

**Supersymmetry**

Composite Higgs models or, equivalently, extra-dimensional models

More recently:

**Neutral naturalness models (twin Higgs, [Chacko et al, 0506256](#)),**

Relaxation models ([Graham et al, 1504.07551](#)),

Nnaturalness ([Arkani-Hamed et al, 1607.06821](#)), ...



**Signals  
at the LHC**

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**Signals  
at the LHC**

## **SUSY (basic principle)**

Introduce **new scalar degrees of freedom** that are related to the fermions of the SM

$$\Delta\mu^2 \sim \frac{y^2 - \lambda}{16\pi^2} \Lambda^2 + \dots$$

Cancel the quadratic sensitivity of the Higgs mass to the New Physics scale

## **Twin Higgs (basic principle)**

Introduce **new fermionic degrees of freedom** that are related to the fermions of the SM but **not charged under the SM gauge symmetries**

Cancellation of the quadratic sensitivity is ensured by a **global symmetry** (e.g.  $SU(4) \times Z_2$ ).

**Chapter 1:** Introduction:  
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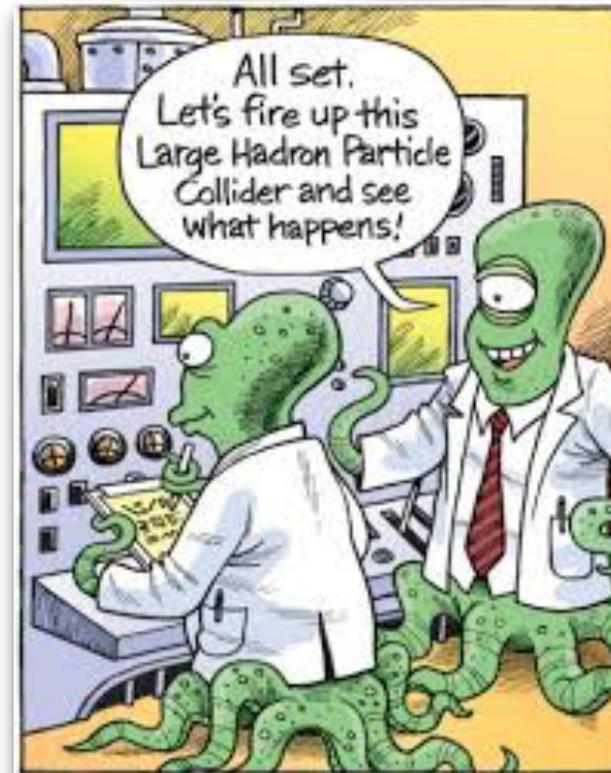
\* SUSY theories.

**Chapter 2:** Direct & indirect searches of SUSY particles

\* **Twin Higgs theories.**

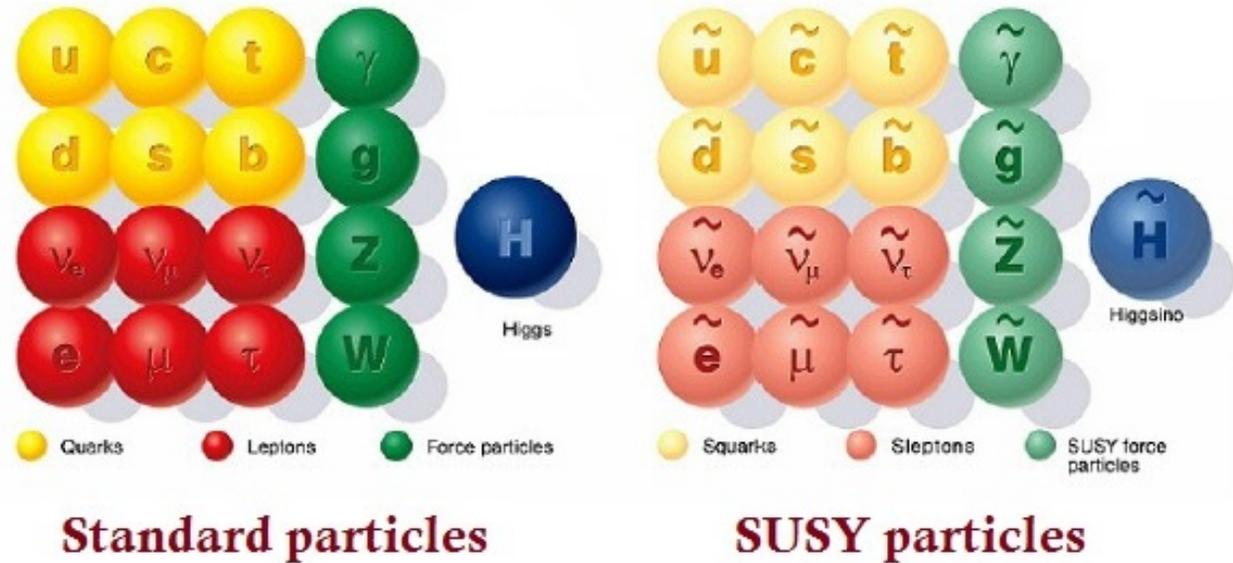
Direct & indirect searches of the “twin Higgs”

## BSM @ the LHC



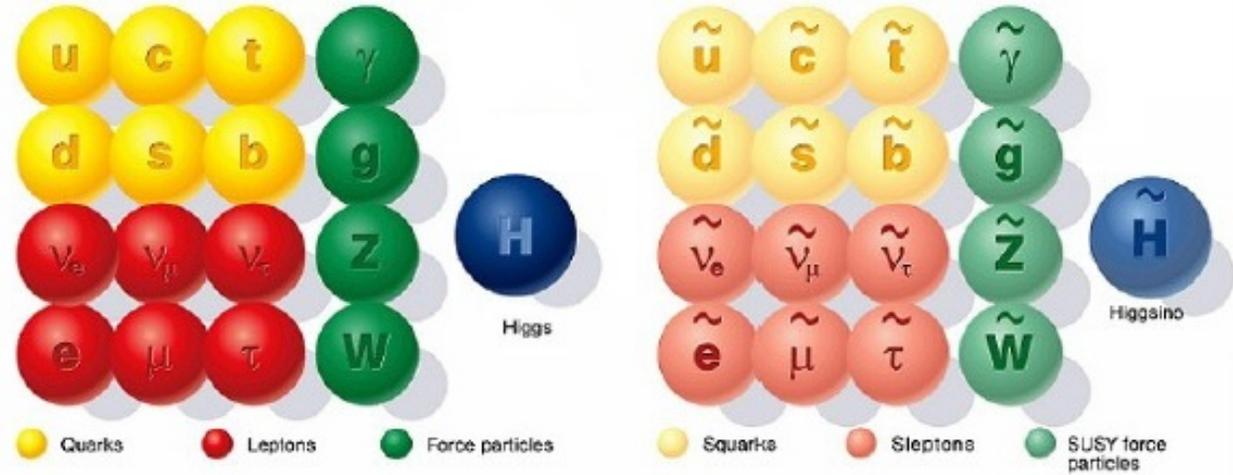
# Supersymmetry

Minimal Supersymmetric  
Standard Model  
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# Supersymmetry

Minimal Supersymmetric Standard Model (MSSM)



Standard particles

SUSY particles

**SUSY is broken**

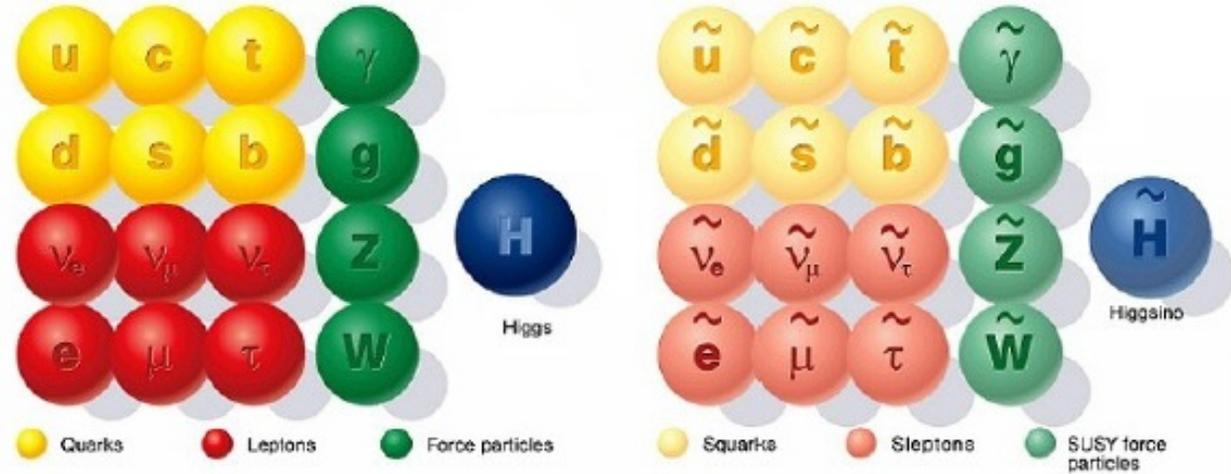
(in fact, we know that e.g. the sbottom cannot have the same mass as the bottom quark)

Log sensitivity of the Higgs mass to the New Physics scale:

$$\Delta\mu_h^2 \sim \frac{C^2}{4\pi^2} m_{\text{SUSY}}^2 \log\left(\frac{\Lambda}{m_t}\right) \quad \text{TeV-scale SUSY?}$$

# Supersymmetry

## Minimal Supersymmetric Standard Model (MSSM)



Standard particles

SUSY particles

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(in fact, we know that e.g. the sbottom cannot have the same mass as the bottom quark)

Log sensitivity of the Higgs mass to the New Physics scale:

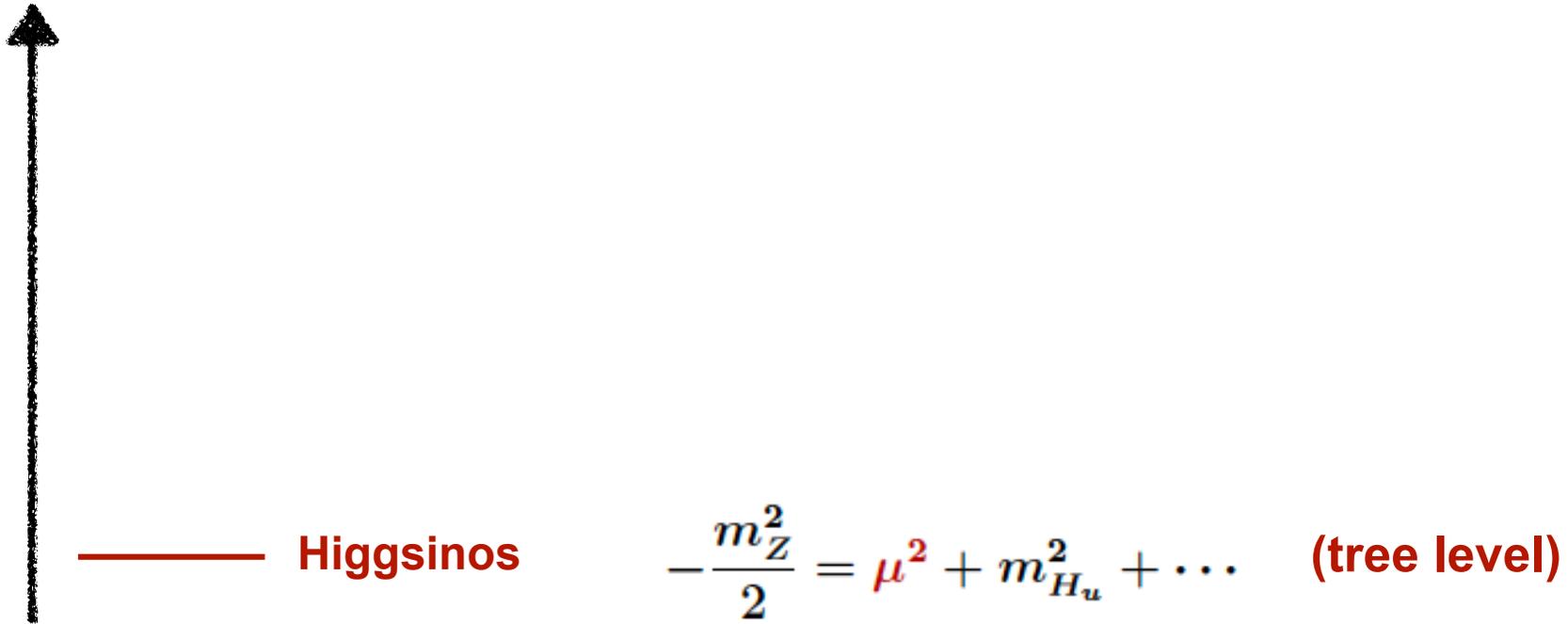
$$\Delta\mu_h^2 \sim \frac{C^2}{4\pi^2} m_{\text{SUSY}}^2 \log\left(\frac{\Lambda}{m_t}\right) \quad \text{TeV-scale SUSY?}$$

## Additional remarkable properties:

- \* **Gauge coupling unification**: if SUSY particles are not too heavy,  $g_3 \sim g_2 \sim g_1$  at  $M_{\text{GUT}}$
- \* If we impose R-parity (sparticles with R-parity = -1, SM particles with R-parity = +1), the lightest SUSY particle can be **WIMP Dark Matter** (see class of tomorrow)

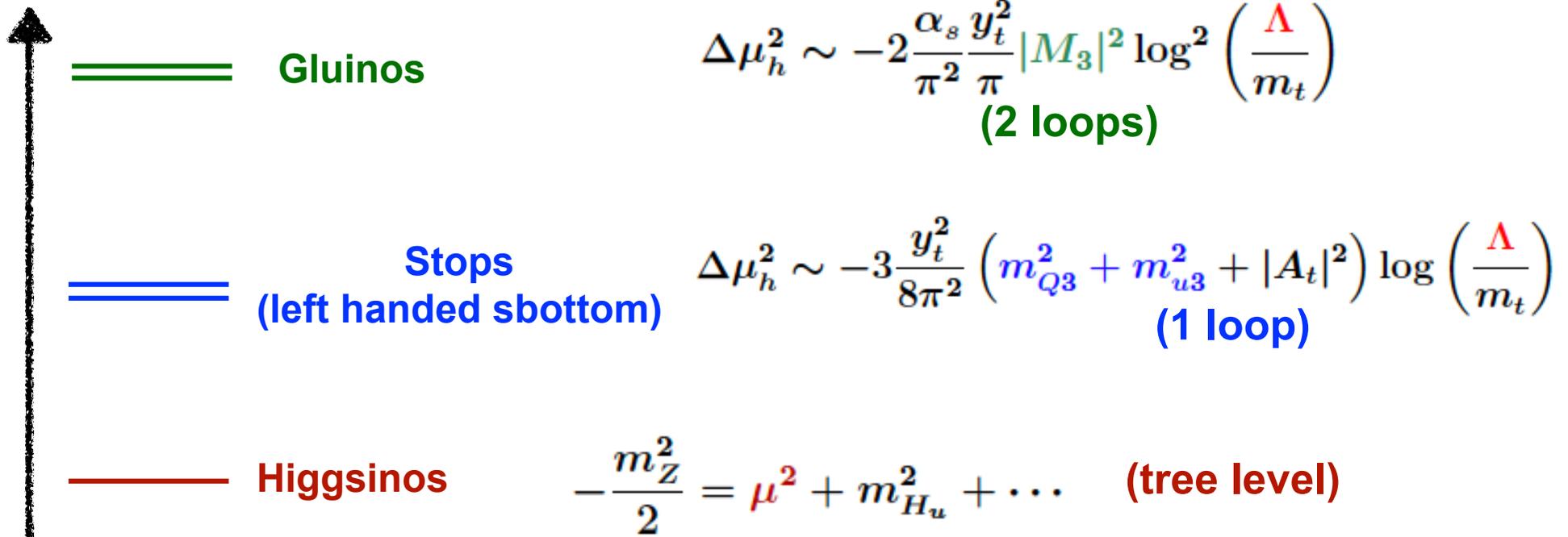
# The SUSY mass scale

The “natural spectrum”:



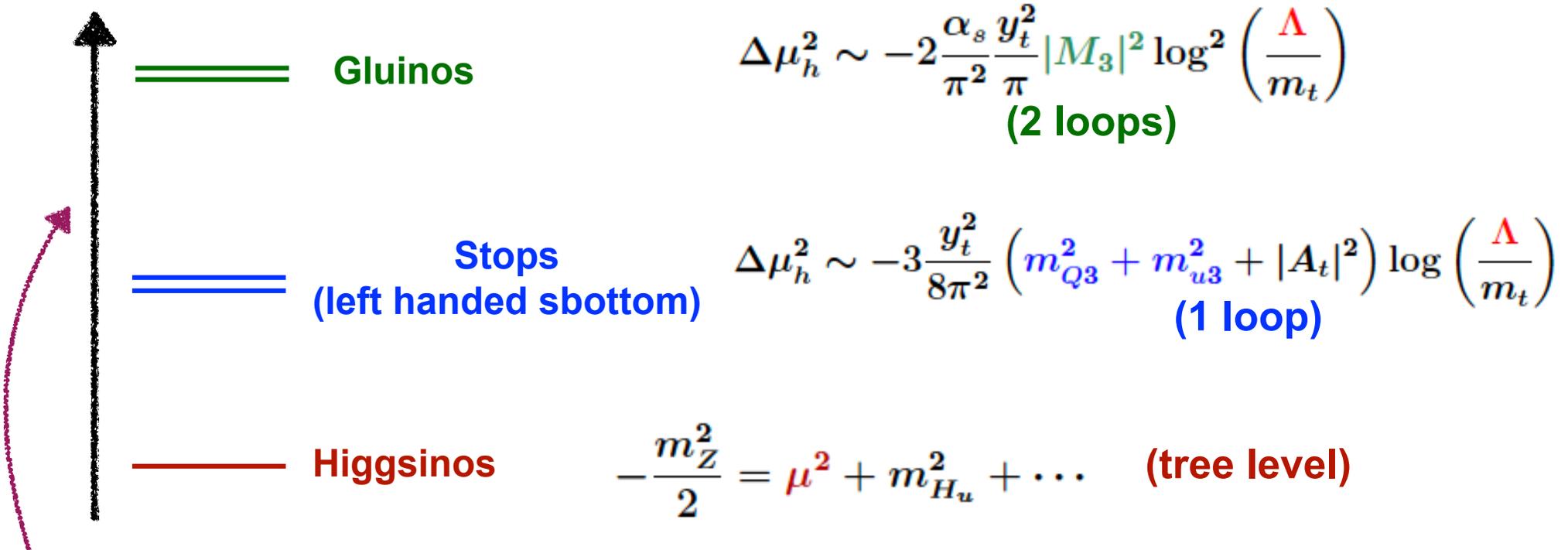
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# The SUSY mass scale

The “natural spectrum”:



**What is the exact scale?**

Said in other words: what is the level of “fine tuning” we are comfortable allowing?

**No guaranteed discovery. Exploration of the SUSY paradigm!**

(TeV-scale stops imply  $\sim O(1\%)$  fine tuning)

# **(Some) pheno of SUSY particles**

**SUSY provides a remarkably rich set of signatures for the LHC**

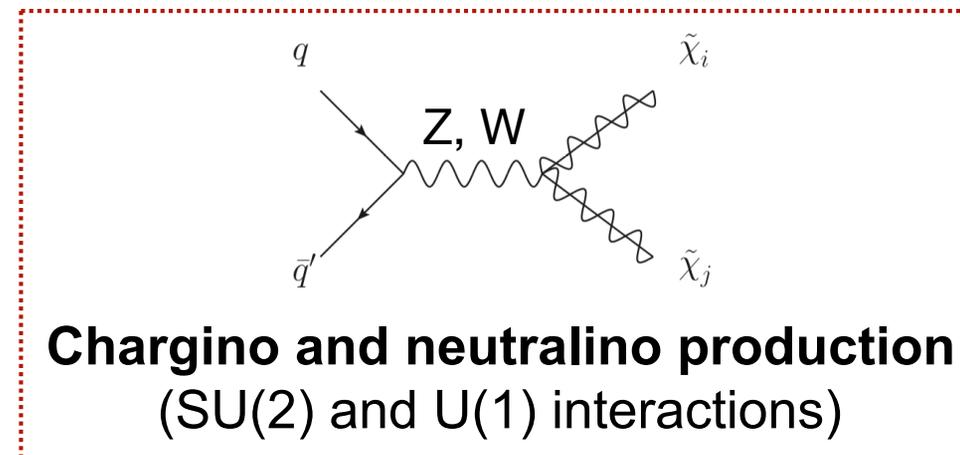
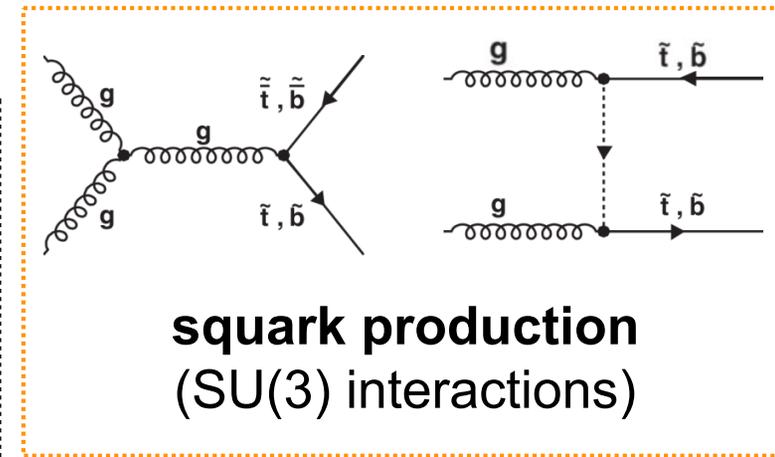
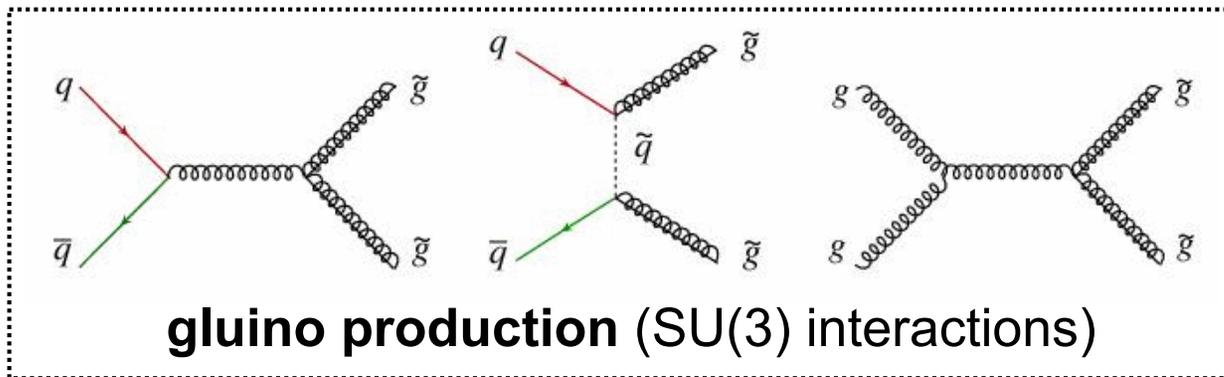
# (Some) pheno of SUSY particles

SUSY provides a remarkably rich set of signatures for the LHC

All SUSY particles are **charged under the SM gauge symmetries**.

That means that SUSY particles will be copiously produced at the LHC

In the case of R-parity conservation:



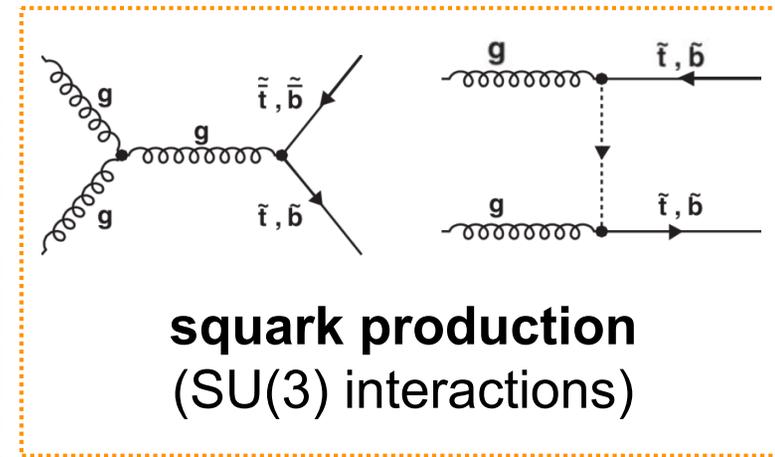
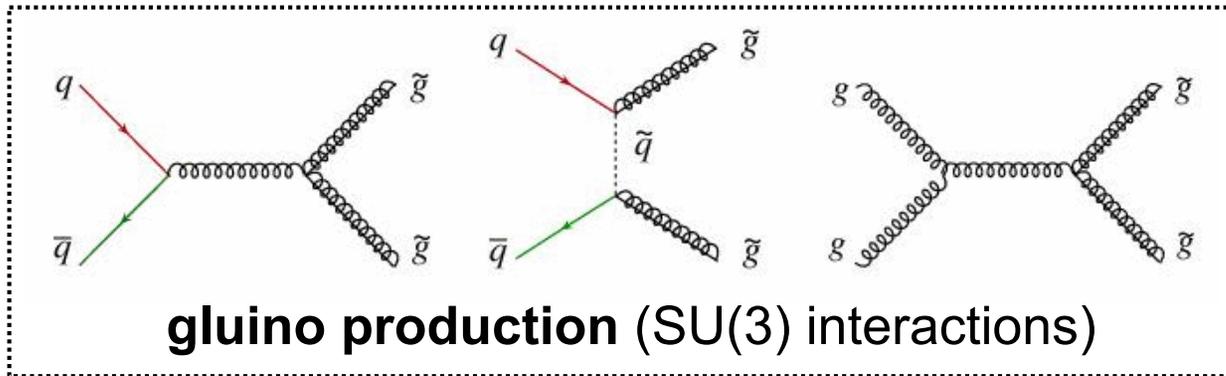
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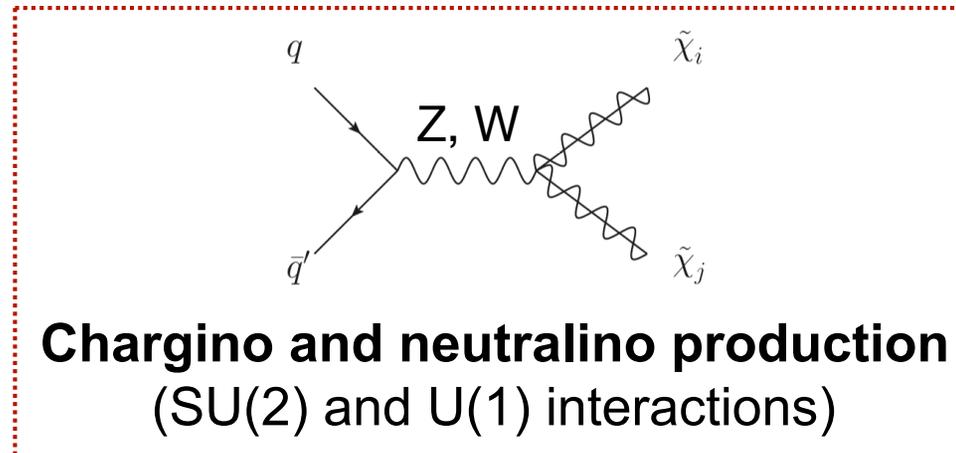
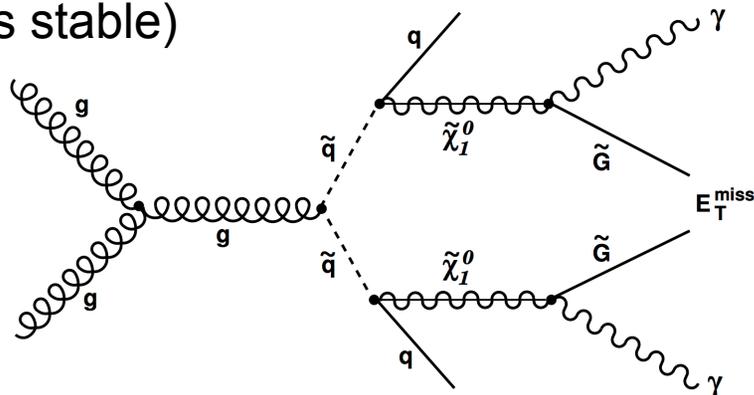
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## Missing energy-enriched signatures

(MET arises from the lightest SUSY particle that is stable)



# (Some) pheno of SUSY particles

SUSY

All That In t

q q̄

Mis (ME) that

S.Gor

## ATLAS SUSY Searches\* - 95% CL Lower Limits July 2020

ATLAS Preliminary  
 $\sqrt{s} = 13 \text{ TeV}$

Model	Signature	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference			
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0 e, $\mu$ mono-jet	$E_T^{\text{miss}}$ 139 $E_T^{\text{miss}}$ 36.1	$\tilde{q}$ [10x Degen] $\tilde{q}$ [1x, 8x Degen] 0.43 0.71 1.9	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ $m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	ATLAS-CONF-2019-040 1711.03301	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0 e, $\mu$	$E_T^{\text{miss}}$ 139	$\tilde{g}$ $\tilde{g}$ 2.35 Forbidden 1.15-1.95	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$ $m(\tilde{g}) = 1000 \text{ GeV}$	ATLAS-CONF-2019-040 ATLAS-CONF-2019-040	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{\chi}_1^0$	1 e, $\mu$	2-6 jets	139	$\tilde{g}$ 2.2	$m(\tilde{\chi}_1^0) < 600 \text{ GeV}$	ATLAS-CONF-2020-047
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$	ee, $\mu\mu$	2 jets	$E_T^{\text{miss}}$ 36.1	$\tilde{g}$ 1.2	$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 50 \text{ GeV}$	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	0 e, $\mu$	7-11 jets	$E_T^{\text{miss}}$ 139	$\tilde{g}$ 1.97	$m(\tilde{\chi}_1^0) < 600 \text{ GeV}$	ATLAS-CONF-2020-002
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	SS e, $\mu$	6 jets	$E_T^{\text{miss}}$ 139	$\tilde{g}$ 1.15	$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200 \text{ GeV}$	1909.08457
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 e, $\mu$ SS e, $\mu$	3 b 6 jets	$E_T^{\text{miss}}$ 79.8 139	$\tilde{g}$ 2.25 $\tilde{g}$ 1.25	$m(\tilde{g}) < 200 \text{ GeV}$ $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300 \text{ GeV}$	ATLAS-CONF-2018-041 1909.08457
3 <sup>rd</sup> gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0 / \tilde{\chi}_1^\pm$	Multiple Multiple	36.1 139	$\tilde{b}_1$ Forbidden $\tilde{b}_1$ 0.9 Forbidden 0.74	$m(\tilde{\chi}_1^0) = 300 \text{ GeV}, \text{BR}(\tilde{\chi}_1^\pm) = 1$ $m(\tilde{\chi}_1^0) = 200 \text{ GeV}, m(\tilde{\chi}_1^\pm) = 300 \text{ GeV}, \text{BR}(\tilde{\chi}_1^\pm) = 1$	1708.09266, 1711.03301 1909.08457	
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow bh\tilde{\chi}_1^0$	0 e, $\mu$	6 b	$E_T^{\text{miss}}$ 139	$\tilde{b}_1$ 0.23-1.35	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}, m(\tilde{\chi}_1^0) = 100 \text{ GeV}$	1908.03122
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow bh\tilde{\chi}_1^0$	2 $\tau$	2 b	$E_T^{\text{miss}}$ 139	$\tilde{b}_1$ 0.13-0.85	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}, m(\tilde{\chi}_1^0) = 0 \text{ GeV}$	ATLAS-CONF-2020-031
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0-1 e, $\mu$	$\geq 1$ jet	$E_T^{\text{miss}}$ 139	$\tilde{t}_1$ 1.25	$m(\tilde{\chi}_1^0) = 1 \text{ GeV}$	ATLAS-CONF-2020-003, 2004.14060
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	1 e, $\mu$	3 jets/1 b	$E_T^{\text{miss}}$ 139	$\tilde{t}_1$ 0.44-0.59	$m(\tilde{\chi}_1^0) = 400 \text{ GeV}$	ATLAS-CONF-2019-017
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tau b\tilde{\chi}_1^0, \tilde{t}_1 \rightarrow \tau\tilde{G}$	1 $\tau + 1$ e, $\mu, \tau$	2 jets/1 b	$E_T^{\text{miss}}$ 36.1	$\tilde{t}_1$ 1.16	$m(\tilde{\chi}_1^0) = 800 \text{ GeV}$	1803.10178
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 e, $\mu$	2 c	$E_T^{\text{miss}}$ 36.1	$\tilde{t}_1$ 0.46 $\tilde{t}_1$ 0.85	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$ $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 50 \text{ GeV}$	1805.01649 1805.01649
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h\tilde{\chi}_1^0$	0 e, $\mu$	mono-jet	$E_T^{\text{miss}}$ 36.1	$\tilde{t}_1$ 0.43	$m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	1711.03301
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h\tilde{\chi}_1^0$	1-2 e, $\mu$	1-4 b	$E_T^{\text{miss}}$ 139	$\tilde{t}_1$ 0.067-1.18	$m(\tilde{\chi}_1^0) = 500 \text{ GeV}$	SUSY-2018-09
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e, $\mu$	1 b	$E_T^{\text{miss}}$ 139	$\tilde{t}_2$ Forbidden 0.86	$m(\tilde{\chi}_1^0) = 360 \text{ GeV}, m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 40 \text{ GeV}$	SUSY-2018-09
EW direct	$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via WZ	3 e, $\mu$ ee, $\mu\mu$	$E_T^{\text{miss}}$ 139 $E_T^{\text{miss}}$ 139	$\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$ 0.205 $\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$ 0.64	$m(\tilde{\chi}_1^0) = 0$ $m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	ATLAS-CONF-2020-015 1911.12606	
	$\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$ via WW	2 e, $\mu$	$E_T^{\text{miss}}$ 139	$\tilde{\chi}_1^\pm$ 0.42	$m(\tilde{\chi}_1^0) = 0$	1908.08215	
	$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via Wh	0-1 e, $\mu$	2 b/2 $\gamma$	$E_T^{\text{miss}}$ 139	$\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$ Forbidden 0.74	$m(\tilde{\chi}_1^0) = 70 \text{ GeV}$	2004.10894, 1909.09226
	$\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e, $\mu$		$E_T^{\text{miss}}$ 139	$\tilde{\chi}_1^\pm$ 1.0	$m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$	1908.08215
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	2 $\tau$		$E_T^{\text{miss}}$ 139	$\tilde{\tau}$ [F.L., F.R.L.] 0.16-0.3 0.12-0.39	$m(\tilde{\chi}_1^0) = 0$	1911.06660
	$\tilde{\ell}_L\tilde{\ell}_L, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 e, $\mu$	0 jets	$E_T^{\text{miss}}$ 139	$\tilde{\ell}$ 0.7	$m(\tilde{\chi}_1^0) = 0$	1908.08215
	$\tilde{\ell}_L\tilde{\ell}_L, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	ee, $\mu\mu$	$\geq 1$ jet	$E_T^{\text{miss}}$ 139	$\tilde{\ell}$ 0.256	$m(\tilde{\ell}) - m(\tilde{\chi}_1^0) = 10 \text{ GeV}$	1911.12606
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, $\mu$ 0 jets	$\geq 3$ b 0 jets	$E_T^{\text{miss}}$ 36.1 $E_T^{\text{miss}}$ 139	$\tilde{H}$ 0.13-0.23 0.55 0.29-0.88	$\text{BR}(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 1$ $\text{BR}(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$	1806.04030 ATLAS-CONF-2020-040
Long-lived particles	Direct $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet $E_T^{\text{miss}}$ 36.1	$\tilde{\chi}_1^\pm$ 0.15 0.46	Pure Wino Pure higgsino	1712.02118 ATL-PHYS-PUB-2017-019	
	Stable $\tilde{g}$ R-hadron	Multiple	36.1	$\tilde{g}$ 2.0		1902.01636, 1808.04095	
	Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	Multiple	36.1	$\tilde{g}$ [ $\tau(\tilde{g}) = 10 \text{ ns}, 0.2 \text{ ns}$ ] 2.05 2.4	$m(\tilde{\chi}_1^0) = 100 \text{ GeV}$	1710.04901, 1808.04095	
RPV	$\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm / \tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow Z\ell\ell$	3 e, $\mu$	139	$\tilde{\chi}_1^\pm / \tilde{\chi}_1^0$ [BR(Z $\tau$ )=1, BR(Ze)=1] 0.625 1.05	Pure Wino	ATLAS-CONF-2020-009	
	L $\bar{\nu}$ $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu/\mu\tau$	ee, $e\tau, \mu\tau$	3.2	$\tilde{\nu}_\tau$ 1.9	$\lambda_{311} = 0.11, \lambda_{132/133/233} = 0.07$	1607.08079	
	$\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm / \tilde{\chi}_2^0 \rightarrow W\tilde{W}/Z\ell\ell\nu\nu$	4 e, $\mu$	0 jets $E_T^{\text{miss}}$ 36.1	$\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$ [ $\lambda_{133} \neq 0, \lambda_{124} \neq 0$ ] 0.82 1.33	$m(\tilde{\chi}_1^0) = 100 \text{ GeV}$	1804.03602	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}q$	4-5 large-R jets	Multiple	36.1 36.1	$\tilde{g}$ [ $m(\tilde{\chi}_1^0) = 200 \text{ GeV}, 1100 \text{ GeV}$ ] $\tilde{g}$ [ $\lambda_{112} = 2e-4, 2e-5$ ] 1.05 1.3 1.9 2.0	Large $\lambda'_{12}$ $m(\tilde{\chi}_1^0) = 200 \text{ GeV}$ , bino-like	1804.03568 ATLAS-CONF-2018-003
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$	Multiple	36.1	$\tilde{t}_1$ [ $\lambda'_{232} = 2e-4, 1e-2$ ] 0.55 1.05	$m(\tilde{\chi}_1^0) = 200 \text{ GeV}$ , bino-like	ATLAS-CONF-2018-003	
	$\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow bbs$	$\geq 4$ b	139	$\tilde{t}_1$ Forbidden 0.95	$m(\tilde{\chi}_1^0) = 500 \text{ GeV}$	ATLAS-CONF-2020-016	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	2 jets + 2 b	36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 e, $\mu$	2 b	36.1	$\tilde{t}_1$ 0.4-1.45	$\text{BR}(\tilde{t}_1 \rightarrow b\ell/\ell b) > 20\%$	1710.05544
	1 $\mu$	DV	136	$\tilde{t}_1$ [1e-10 < $\lambda'_{232} < 1e-8, 3e-10 < \lambda'_{232} < 3e-9$ ] 1.0 1.6	$\text{BR}(\tilde{t}_1 \rightarrow q\mu) = 100\%, \cos\theta = 1$	2003.11956	

\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models. c.f. refs. for the assumptions made.

10<sup>-1</sup> 1 Mass scale [TeV]

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# (Some) pheno of SUSY particles

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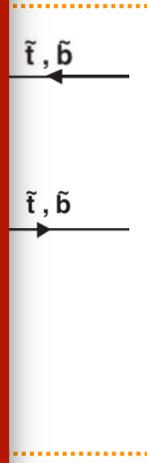
## ATLAS SUSY Searches\* - 95% CL Lower Limits July 2020

ATLAS Preliminary  
 $\sqrt{s} = 13 \text{ TeV}$

Model	Signature	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference							
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0 e, $\mu$ mono-jet	2-6 jets 1-3 jets	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$	139 36.1	$\tilde{q}$ [10x Degen] $\tilde{q}$ [1x, 8x Degen]	0.43 0.71	1.9	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ $m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	ATLAS-CONF-2019-040 1711.03301	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0 e, $\mu$	2-6 jets	$E_T^{\text{miss}}$	139	$\tilde{g}$ $\tilde{g}$	Forbidden 1.15-1.95	2.35	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$ $m(\tilde{g}) = 1000 \text{ GeV}$	ATLAS-CONF-2019-040 ATLAS-CONF-2019-040	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{\chi}_1^0$	1 e, $\mu$	2-6 jets		$E_T^{\text{miss}}$	139	$\tilde{g}$	2.2	$m(\tilde{\chi}_1^0) < 600 \text{ GeV}$	ATLAS-CONF-2020-047	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$	ee, $\mu\mu$	2 jets		$E_T^{\text{miss}}$	36.1	$\tilde{g}$	1.2	$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 50 \text{ GeV}$	1805.11381	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	0 e, $\mu$	7-11 jets		$E_T^{\text{miss}}$	139	$\tilde{g}$	1.97	$m(\tilde{\chi}_1^0) < 600 \text{ GeV}$ $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200 \text{ GeV}$	ATLAS-CONF-2020-002 1909.08457	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 e, $\mu$ SS e, $\mu$	3 b 6 jets		$E_T^{\text{miss}}$	79.8 139	$\tilde{g}$ $\tilde{g}$	15 2.25	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$ $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300 \text{ GeV}$	ATLAS-CONF-2018-041 1909.08457	
3 <sup>rd</sup> gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0 / \tilde{\chi}_1^\pm$	Multiple Multiple	Multiple Multiple		36.1 139	$\tilde{b}_1$ $\tilde{b}_1$	Forbidden Forbidden	0.9 0.74	$m(\tilde{\chi}_1^0) = 300 \text{ GeV}, \text{BR}(\tilde{\chi}_1^0) = 1$ $m(\tilde{\chi}_1^\pm) = 200 \text{ GeV}, m(\tilde{\chi}_1^\pm) = 300 \text{ GeV}, \text{BR}(\tilde{\chi}_1^\pm) = 1$	1708.09266, 1711.03301 1909.08457	
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow bh\tilde{\chi}_1^0$	0 e, $\mu$	6 b	$E_T^{\text{miss}}$	139	$\tilde{b}_1$	Forbidden	0.23-1.35	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \text{ GeV}, m(\tilde{\chi}_1^0) = 100 \text{ GeV}$ $\Delta m(\tilde{\chi}_2^\pm, \tilde{\chi}_1^\pm) = 130 \text{ GeV}, m(\tilde{\chi}_1^\pm) = 0 \text{ GeV}$	1908.03122 ATLAS-CONF-2020-031	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0-1 e, $\mu$	$\geq 1$ jet	$E_T^{\text{miss}}$	139	$\tilde{t}_1$		1.25	$m(\tilde{\chi}_1^0) = 1 \text{ GeV}$	ATLAS-CONF-2020-003, 2004.14060	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	1 e, $\mu$	3 jets/1 b	$E_T^{\text{miss}}$	139	$\tilde{t}_1$		0.44-0.59	$m(\tilde{\chi}_1^0) = 400 \text{ GeV}$	ATLAS-CONF-2019-017	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tau\tilde{b}, \tilde{t}_1 \rightarrow \tau\tilde{G}$	1 $\tau + 1$ e, $\mu, \tau$	2 jets/1 b	$E_T^{\text{miss}}$	36.1	$\tilde{t}_1$		1.16	$m(\tilde{t}_1) = 800 \text{ GeV}$	1803.10178	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 e, $\mu$	2 c	$E_T^{\text{miss}}$	36.1	$\tilde{t}_1$ $\tilde{t}_1$		0.46 0.85	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$ $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 50 \text{ GeV}$ $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	1805.01649 1805.01649 1711.03301	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h\tilde{\chi}_1^0$	0 e, $\mu$	mono-jet	$E_T^{\text{miss}}$	36.1	$\tilde{t}_1$		0.067 1.18	$m(\tilde{\chi}_1^0) = 500 \text{ GeV}$	SUSY-2018-09	
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	1-2 e, $\mu$ 3 e, $\mu$	1-4 b 1 b	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$	139 139	$\tilde{t}_1$ $\tilde{t}_2$		0.86	$m(\tilde{\chi}_1^0) = 360 \text{ GeV}, m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 40 \text{ GeV}$	SUSY-2018-09	
	EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_1^0$ via WZ	3 e, $\mu$ ee, $\mu\mu$	$\geq 1$ jet	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$	139 139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.205	0.64	$m(\tilde{\chi}_1^0) = 0$ $m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	ATLAS-CONF-2020-015 1911.12606
		$\tilde{\chi}_1^\pm\tilde{\chi}_1^0$ via WW	2 e, $\mu$		$E_T^{\text{miss}}$	139	$\tilde{\chi}_1^\pm$	0.42		$m(\tilde{\chi}_1^0) = 0$	1908.08215
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh		0-1 e, $\mu$	2 b/2 $\gamma$	$E_T^{\text{miss}}$	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	Forbidden	0.74	$m(\tilde{\chi}_1^0) = 70 \text{ GeV}$	2004.10894, 1909.09226	
$\tilde{\chi}_1^\pm\tilde{\chi}_1^0$ via $\tilde{\ell}_L/\tilde{\nu}$		2 e, $\mu$		$E_T^{\text{miss}}$	139	$\tilde{\chi}_1^\pm$		1.0	$m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$	1908.08215	
$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$		2 $\tau$		$E_T^{\text{miss}}$	139	$\tilde{\tau}$	[ $\tilde{\tau}_L, \tilde{\tau}_{R,L}$ ]	0.16-0.3 0.12-0.39	$m(\tilde{\chi}_1^0) = 0$	1911.06660	
$\tilde{\ell}_L\tilde{\ell}_L, \tilde{\ell} \rightarrow \tilde{\chi}_1^0$		2 e, $\mu$	0 jets	$E_T^{\text{miss}}$	139	$\tilde{\ell}$		0.7	$m(\tilde{\chi}_1^0) = 0$	1908.08215	
		ee, $\mu\mu$	$\geq 1$ jet	$E_T^{\text{miss}}$	139	$\tilde{\ell}$		0.256	$m(\tilde{\ell}) - m(\tilde{\chi}_1^0) = 10 \text{ GeV}$	1911.12606	
$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$		0 e, $\mu$ 4 e, $\mu$	$\geq 3$ b 0 jets	$E_T^{\text{miss}}$ $E_T^{\text{miss}}$	36.1 139	$\tilde{H}$ $\tilde{H}$		0.13-0.23 0.55	0.29-0.88	$\text{BR}(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 1$ $\text{BR}(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$	1806.04030 ATLAS-CONF-2020-040
Long-lived particles	Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	$E_T^{\text{miss}}$	36.1	$\tilde{\chi}_1^\pm$	0.15	0.46	Pure Wino Pure higgsino	1712.02118 ATL-PHYS-PUB-2017-019	
	Stable $\tilde{g}$ R-hadron	Multiple			36.1	$\tilde{g}$		2.0		1902.01636, 1808.04095	
	Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	Multiple			36.1	$\tilde{g}$	$\tau(\tilde{g}) = 10 \text{ ns}, 0.2 \text{ ns}$	2.05 2.4	$m(\tilde{\chi}_1^0) = 100 \text{ GeV}$	1710.04901, 1808.04095	
RPV	$\tilde{\chi}_1^\pm\tilde{\chi}_1^0/\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow Z\ell\ell$	3 e, $\mu$			139	$\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$	[ $\text{BR}(Z\tau) = 1, \text{BR}(Ze) = 1$ ]	0.625	1.05	Pure Wino	ATLAS-CONF-2020-009
	L $\tilde{\nu}$ $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu$	ee, ee, $\mu\tau$			3.2	$\tilde{\nu}_\tau$		1.9	$\lambda_{311} = 0.11, \lambda_{132/133/233} = 0.07$	1607.08079	
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^0/\tilde{\chi}_2^0 \rightarrow W\tilde{W}/Z\ell\ell\nu\nu$	4 e, $\mu$	0 jets	$E_T^{\text{miss}}$	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	[ $\lambda_{133} \neq 0, \lambda_{124} \neq 0$ ]	0.82	1.33	$m(\tilde{\chi}_1^0) = 100 \text{ GeV}$	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}q$	4-5 large-R jets			36.1 36.1	$\tilde{g}$ $\tilde{g}$	[ $m(\tilde{\chi}_1^0) = 200 \text{ GeV}, 1100 \text{ GeV}$ ] [ $\lambda_{112} = 2e-4, 2e-5$ ]	1.0 1.0	1.3 1.9 2.0	Large $\lambda'_{12}$	1804.03568 ATLAS-CONF-2018-003
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$	Multiple			36.1	$\tilde{t}$	[ $\lambda'_{23t} = 2e-4, 1e-2$ ]	0.55	1.05	$m(\tilde{\chi}_1^0) = 200 \text{ GeV}, \text{bino-like}$	ATLAS-CONF-2018-003
	$\tilde{t}, \tilde{t} \rightarrow b\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow bbs$	$\geq 4$ b			139	$\tilde{t}$	Forbidden	0.95		$m(\tilde{\chi}_1^0) = 500 \text{ GeV}$	ATLAS-CONF-2020-016
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	2 jets + 2 b			36.7	$\tilde{t}_1$	[ $qq, bs$ ]	0.42	0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 e, $\mu$	2 b		36.1	$\tilde{t}_1$		1.0	0.4-1.45	$\text{BR}(\tilde{t}_1 \rightarrow b\ell/bs) > 20\%$ $\text{BR}(\tilde{t}_1 \rightarrow q\mu) = 100\%, \cos\theta = 1$	1710.05544 2003.11956
		1 $\mu$	DV		136	$\tilde{t}_1$	[ $1e-10 < \lambda'_{23t} < 1e-8, 3e-10 < \lambda'_{23t} < 3e-9$ ]	1.0	1.6		

\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models. c.f. refs. for the assumptions made.

10<sup>-1</sup> 1 Mass scale [TeV]



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# (Some) pheno of SUSY particles

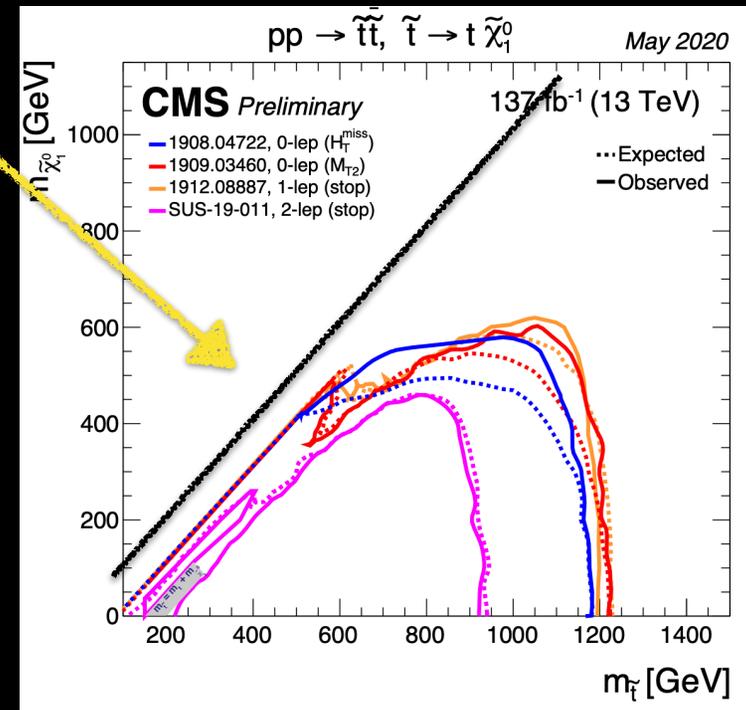
To keep in mind:

There are ways to weaken somewhat these bounds.

For example,

We can reduce the amount of missing energy

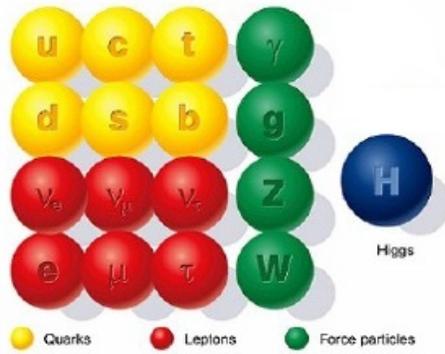
- introducing some (clever) R-parity violating operator;
- using a SUSY dark sector at around the same mass of the SUSY spectrum (stealth SUSY, [Fan et al, 1105.5135](#));
- Squeezing the SUSY spectrum or raising the lightest SUSY mass.



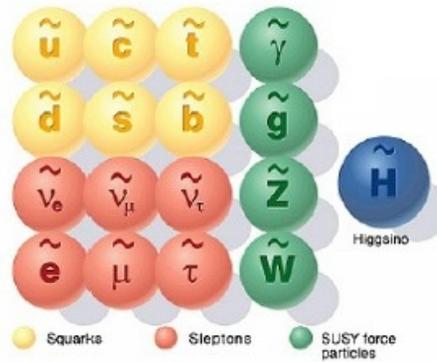
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# SUSY predicts a second Higgs doublet!

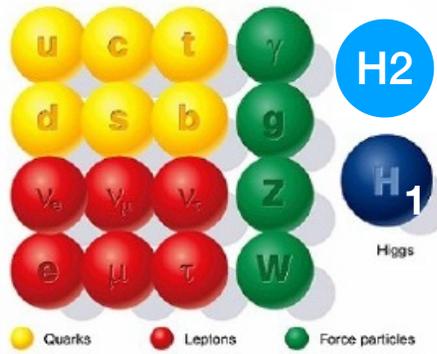


Standard particles

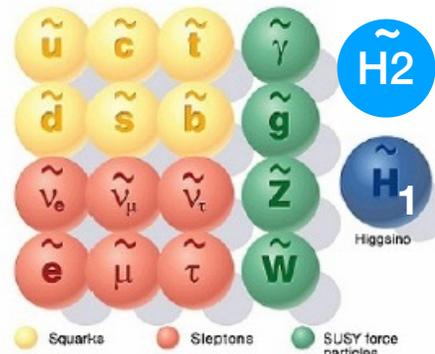


SUSY particles

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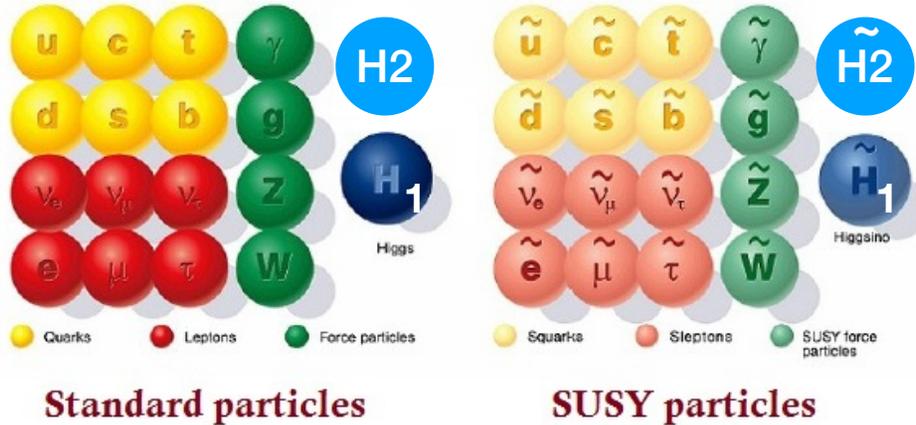
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SUSY particles

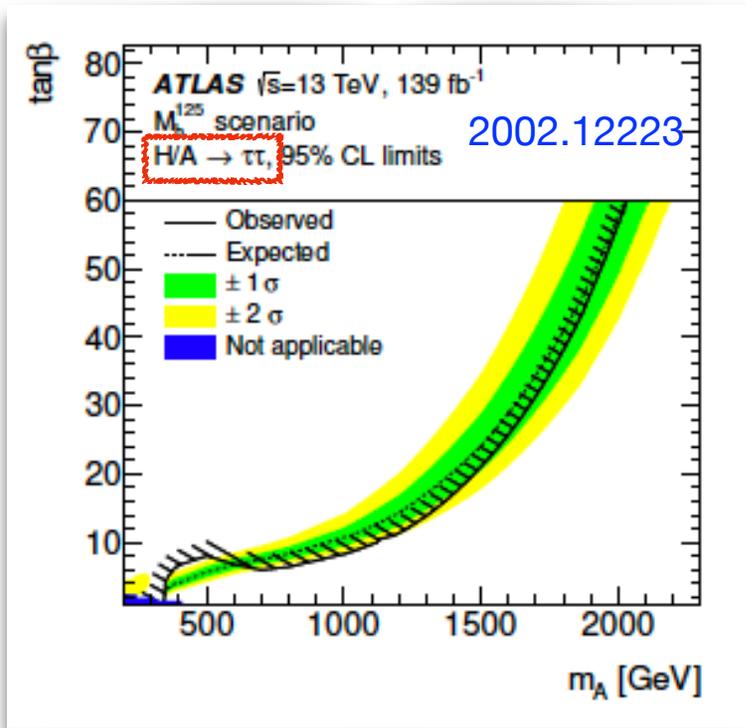
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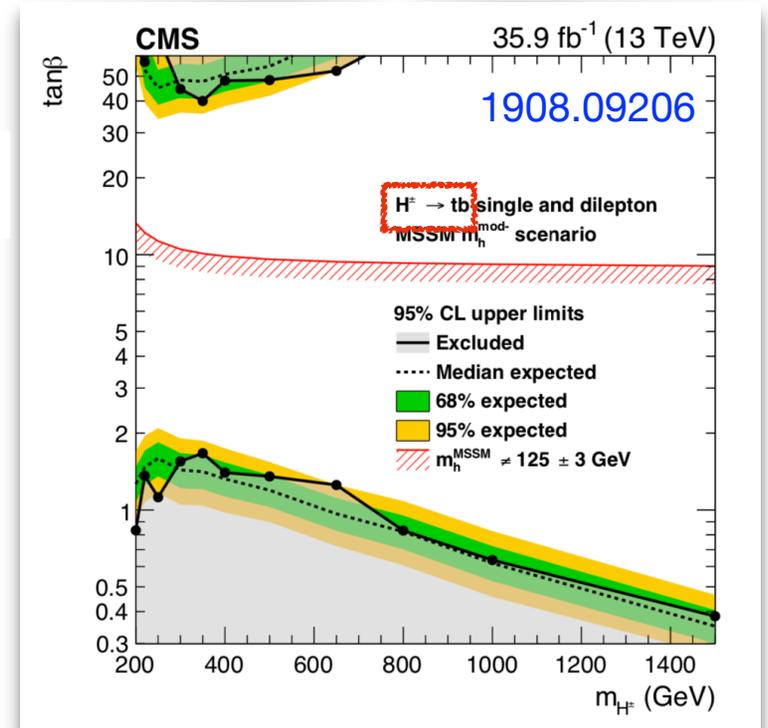


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Several searches for new Higgs bosons at the LHC

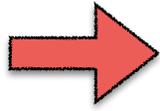


$$\tan \beta \equiv \frac{v_2}{v_1}$$



# Beyond direct searches: The Higgs precision program

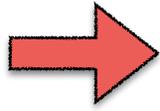
After the Higgs discovery, we have learned that the 125 GeV Higgs boson has SM-like properties



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

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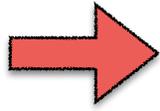
At the LHC, we measure **Higgs rates**:

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

$$\sigma(pp \rightarrow h \rightarrow \gamma\gamma)_{\text{exp}} = \sigma(pp \rightarrow h)_{\text{theory}} \times \text{BR}(h \rightarrow \gamma\gamma)_{\text{theory}}$$

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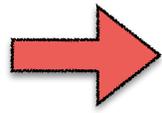
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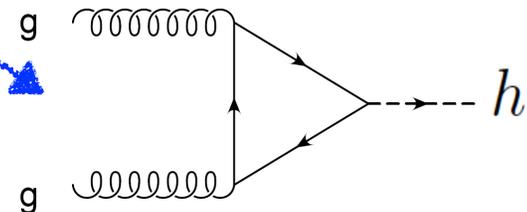
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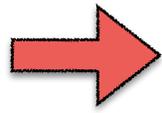
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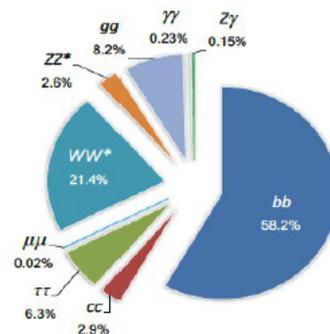
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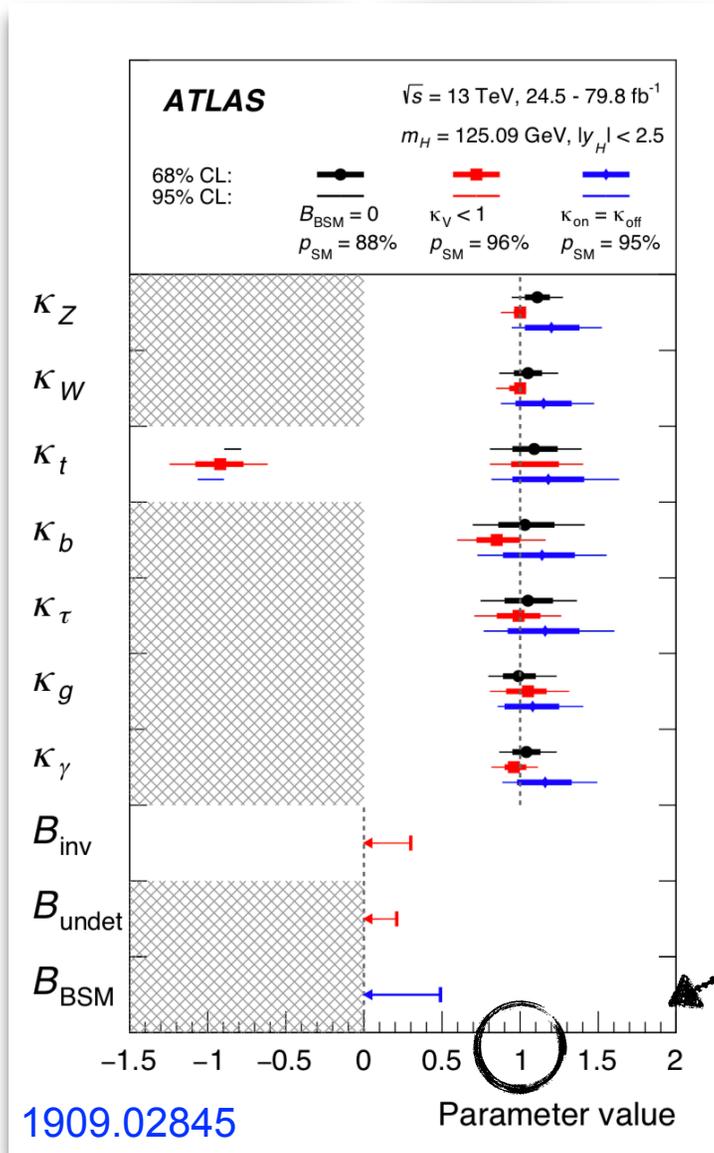


We need to make some assumption.

e.g.  $\Gamma_{\text{theory}}^{\text{tot}} = \Gamma_{\text{SM}}^{\text{tot}}(\kappa_i)$

# Status & prospects for the Higgs measurements

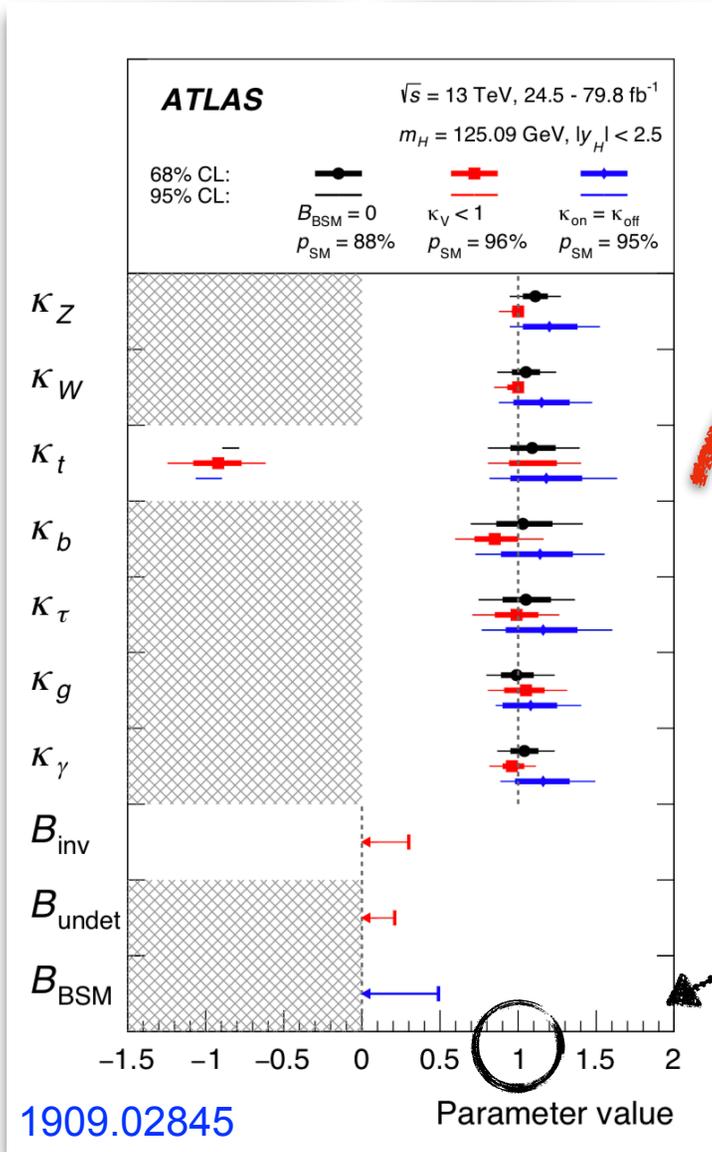
## The “kappa framework”



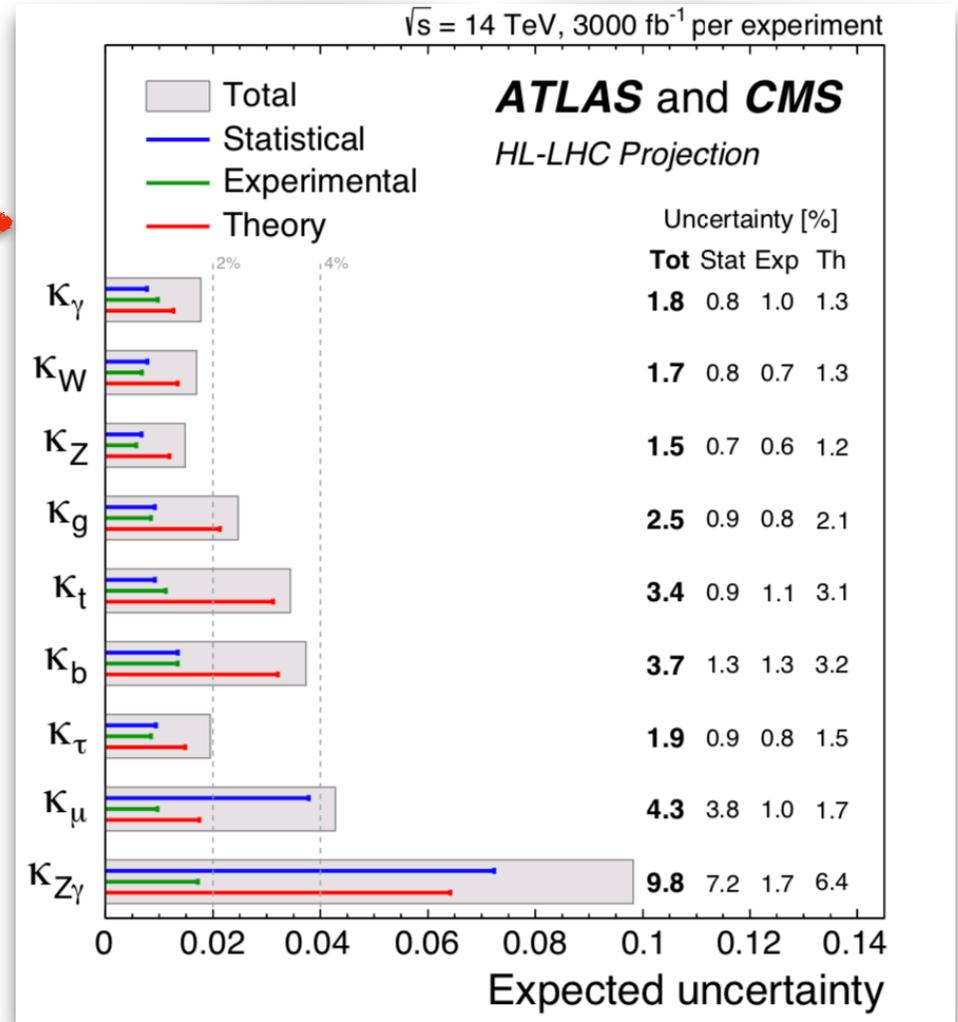
SM prediction

# Status & prospects for the Higgs measurements

## The “kappa framework”



Cepeda, SG, Kado, Ilten, Riva et al., 1902.00134



SM prediction

# Implications on the heavy 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

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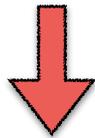
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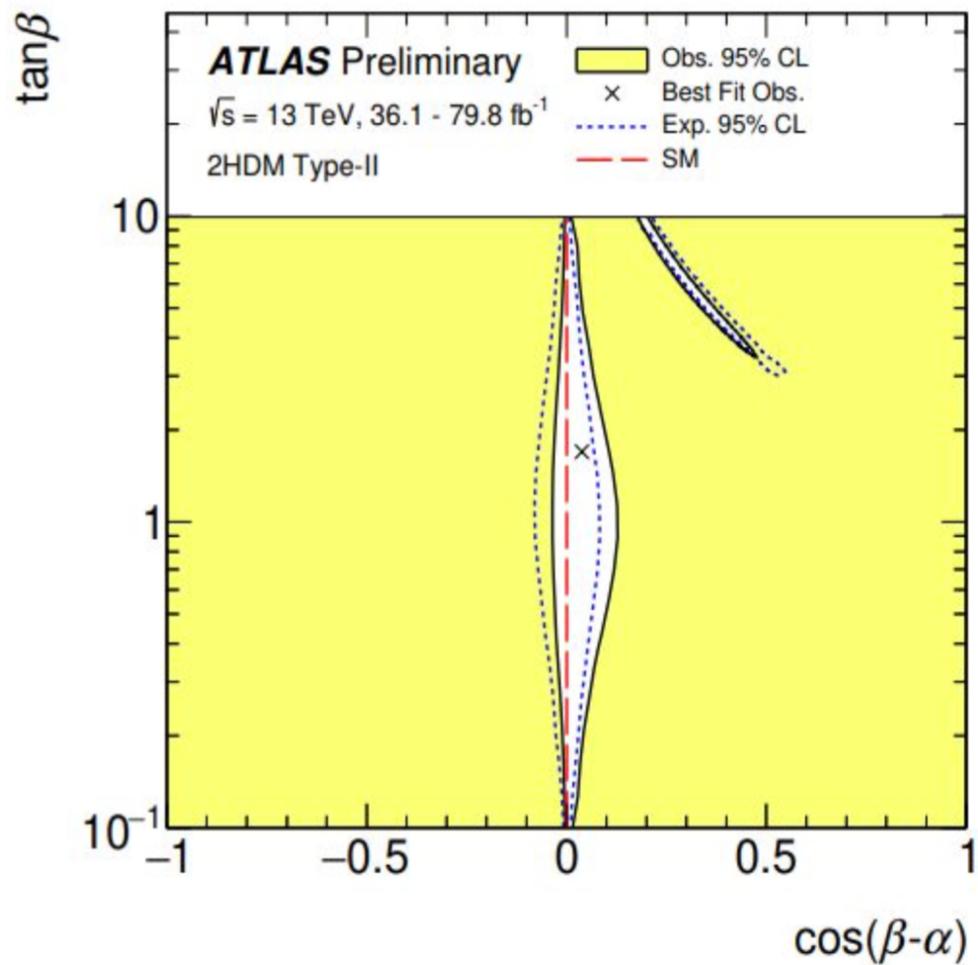


Generically, we have an upper bound on the value of  $|\alpha|$  with  $\alpha = \beta - \pi/2 + \chi$

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# Bound on the mixing angle

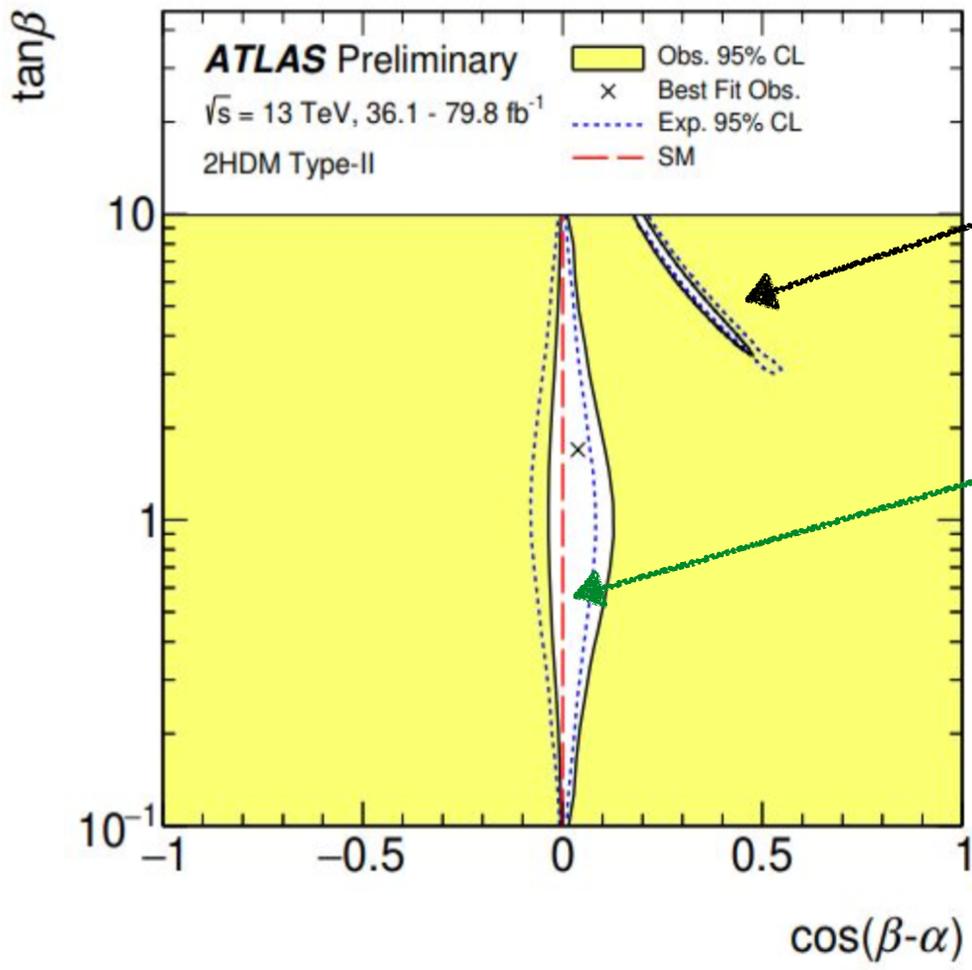
Putting all measurements together...



1909.02845

# Bound on the mixing angle

Putting all measurements together...



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)

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

1909.02845

# What do we learn on the new H bosons?

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

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

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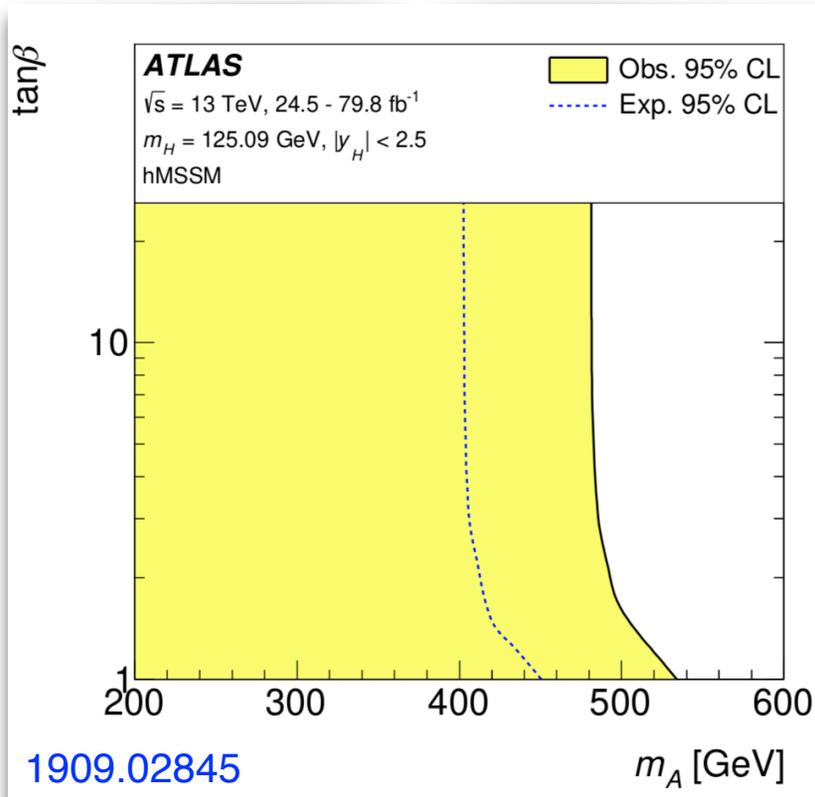
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 & we learn about  
 new Higgs bosons  
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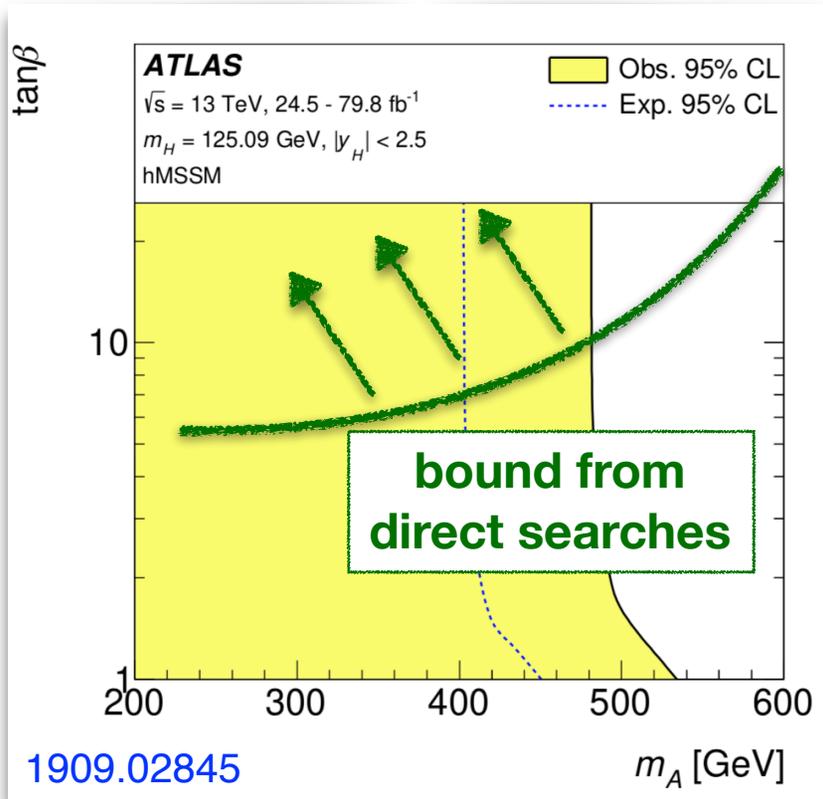
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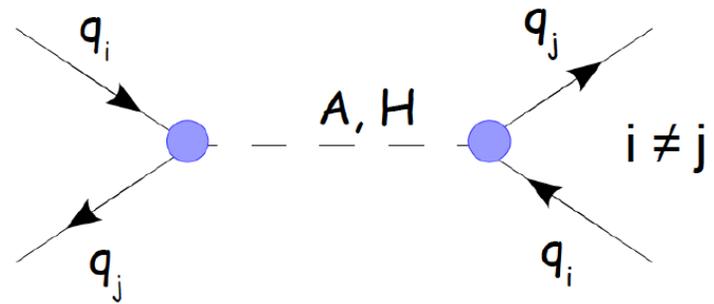
# Heavy Higgs impact on flavor physics

\* In all generality, we can write

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

( $H_1, H_2$  with hypercharge  $\pm 1/2$ )

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!**



# Heavy Higgs impact on flavor physics

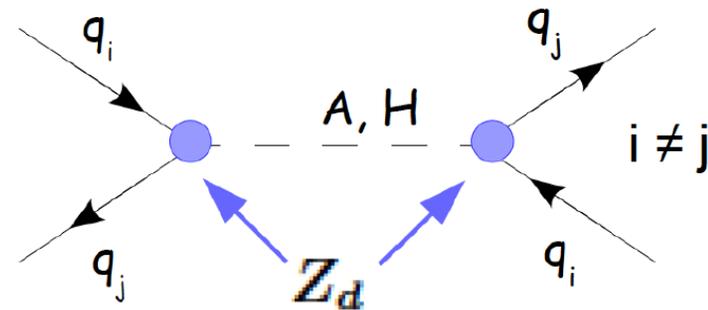
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\* **How to see this?**

Step 1: go to the “Higgs basis”

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

$$\tan \beta \equiv \frac{v_2}{v_1} \quad \begin{cases} \langle \Phi_v^\dagger \Phi_v \rangle = v^2/2, \\ \langle \Phi_H^\dagger \Phi_H \rangle = 0 \end{cases}$$

Step 2: write the Lagrangian in this basis

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

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!

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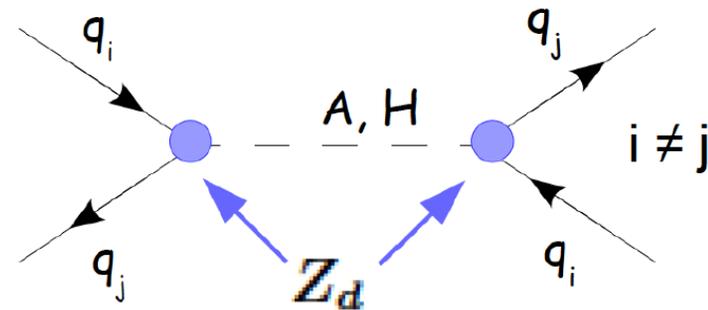
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**Flavor changing neutral currents  
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\* Result: 2HDMs with a generic flavor structure have

**Very stringent bounds from low energy flavor measurements!**

e.g. the H, A Higgs bosons should have a mass  $\geq \mathbf{O(10^4 \text{ TeV})}$ ,  
to agree with measurements of Kaon mixings

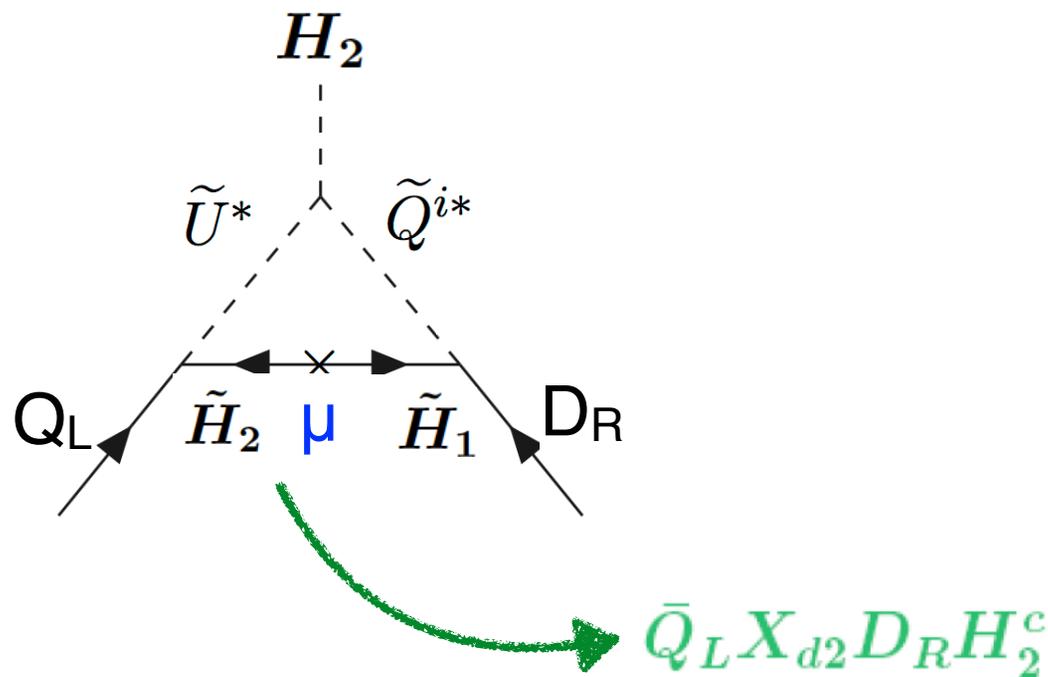
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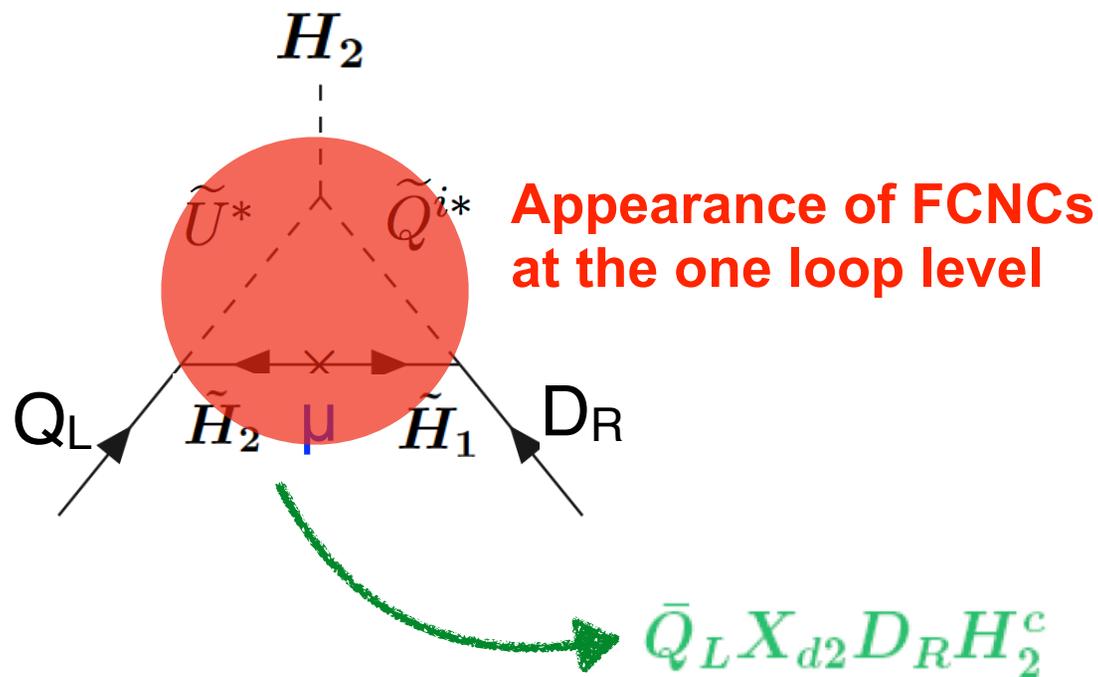
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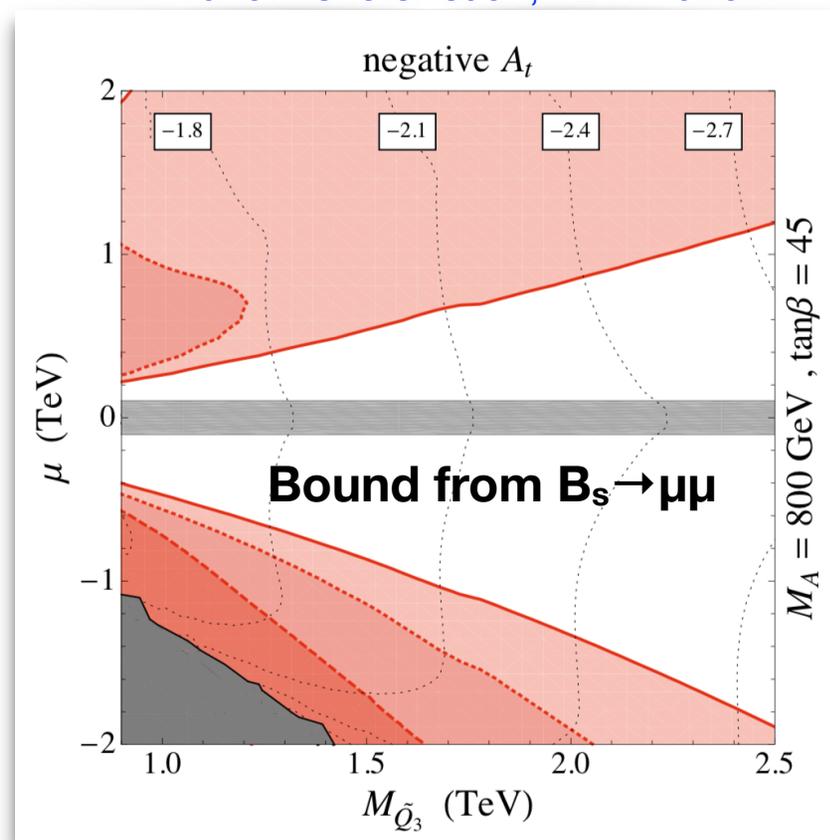
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Altmannshofer et al., 1211.1976



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# Twin Higgs models & the hierarchy problem

$$\mathbf{SM}_A \times \mathbf{SM}_B \times \mathbf{Z}_2$$

Global symmetry of the scalar potential (e.g. SU(4))

→ The SM Higgs is a (massless) Nambu-Goldstone boson

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} \quad \begin{array}{l} \sim \text{SM Higgs doublet} \\ \text{Twin Higgs doublet} \end{array}$$

$$V(H) = -m^2 H^\dagger H + \lambda (H^\dagger H)^2$$

# Twin Higgs models & the hierarchy problem

$$\boxed{SM_A \times SM_B \times Z_2}$$

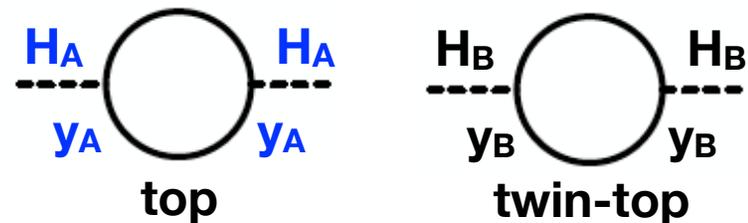
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Loop corrections to the Higgs mass:  $\frac{3}{8\pi^2} \Lambda^2 (y_A^2 H_A^\dagger H_A + y_B^2 H_B^\dagger H_B)$



$$\boxed{Z_2 \Rightarrow y_A = y_B}$$

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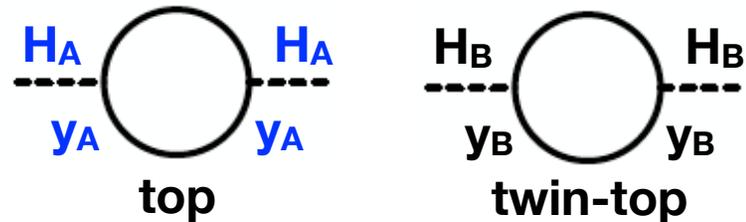
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$$\mathbf{Z}_2 \Rightarrow y_A = y_B$$

SU(4) and Z<sub>2</sub> are (softly) broken:

$$v_A \neq v_B$$

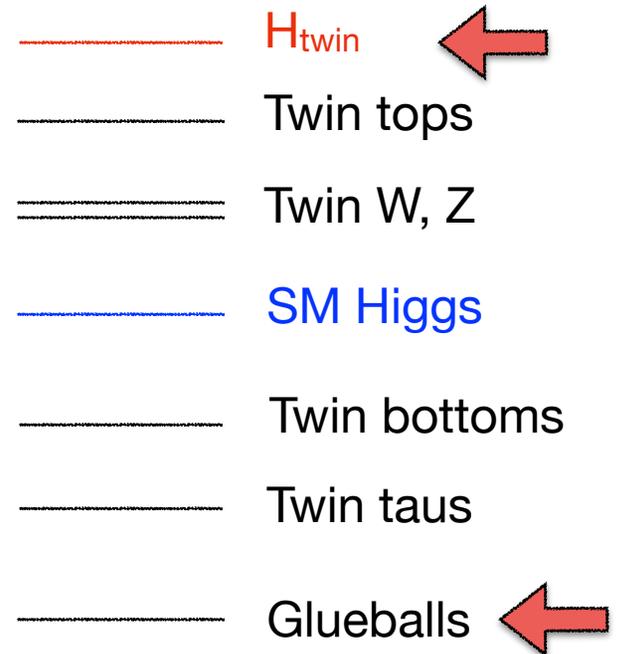
$$(f^2 \equiv v_A^2 + v_B^2 \gg 246 \text{ GeV})$$

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# Phenomenology of the twin Higgs

**A typical spectrum:**



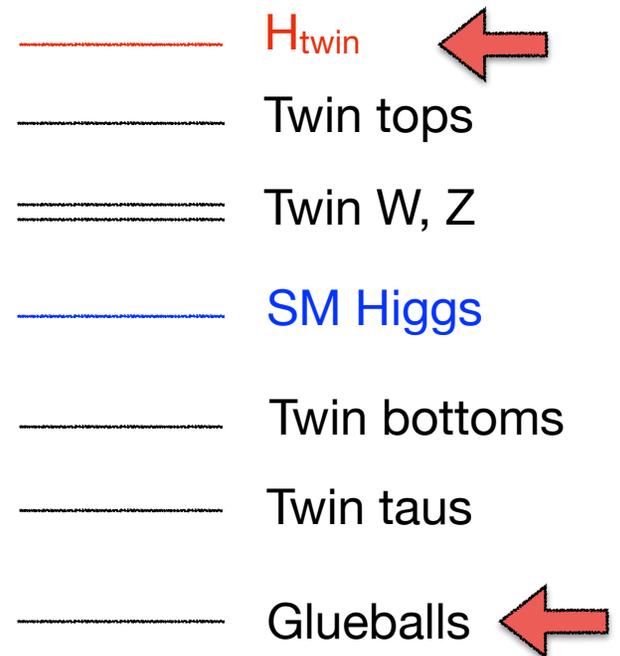
# Phenomenology of the twin Higgs

## 1. Production of the twin Higgs

The twin Higgs will mix with the 125 GeV Higgs with a mixing angle  $\sim v^2/f^2$

Because of this mixing, it can be produced as a SM Higgs boson (reduced rates!)

### A typical spectrum:



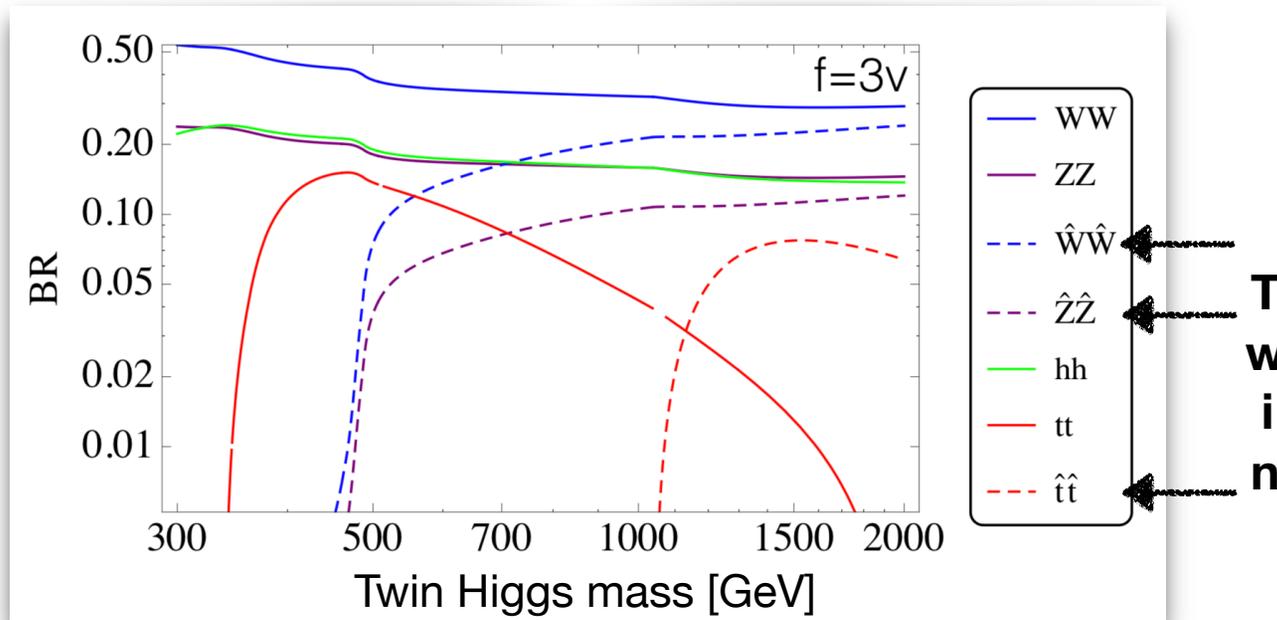
# Phenomenology of the twin Higgs

## 1. Production of the twin Higgs

The twin Higgs will mix with the 125 GeV Higgs with a mixing angle  $\sim v^2/f^2$

Because of this mixing, it can be produced as a SM Higgs boson (reduced rates!)

## 2. Decay of the twin Higgs



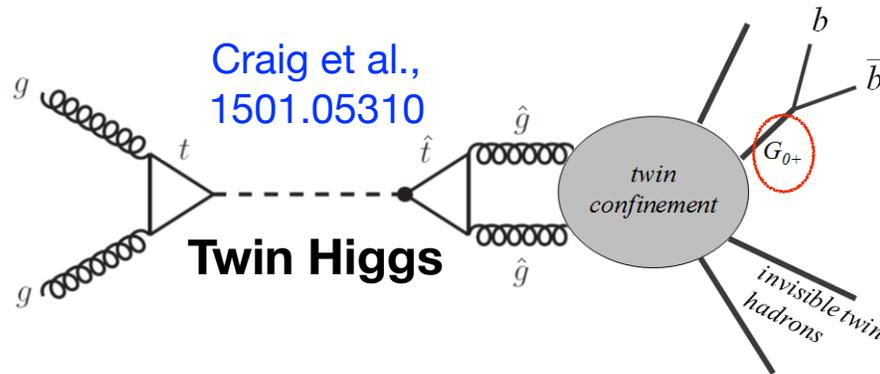
N.Craig

### A typical spectrum:



**Twin particles** undertake cascade decays  
to (typically) long lived glue-balls

# Long-lived signatures from twin Higgs decays

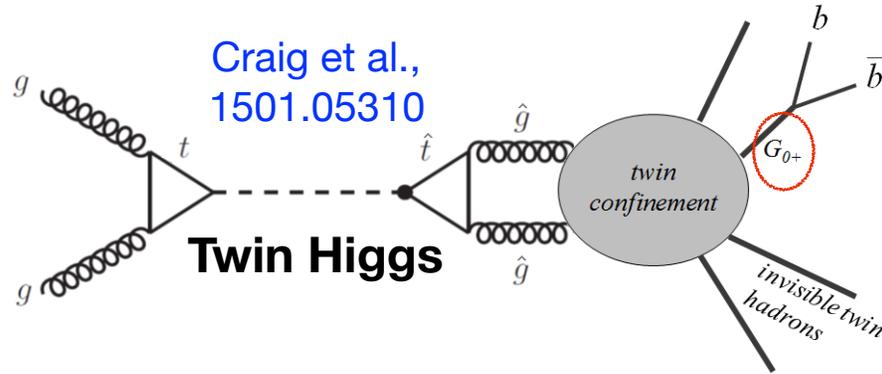


Glue-ball.

$O^{++}$  mixes with the 125 GeV Higgs and decays typically displaced.

**Signature:  $H_T \rightarrow \geq 2$  displaced**

# Long-lived signatures from twin Higgs decays

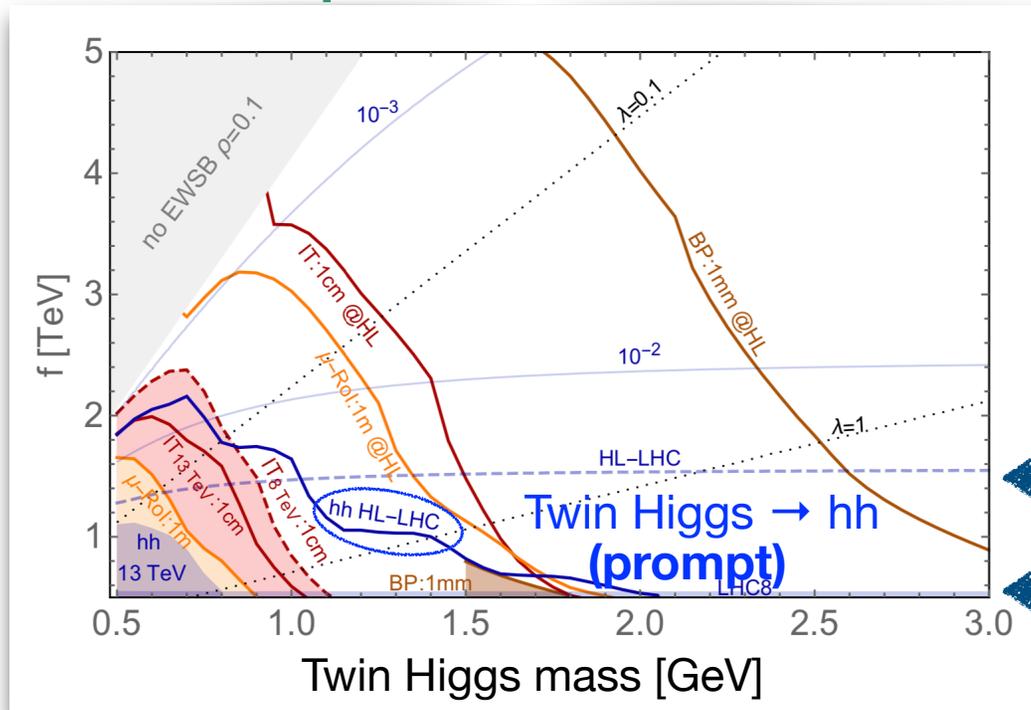


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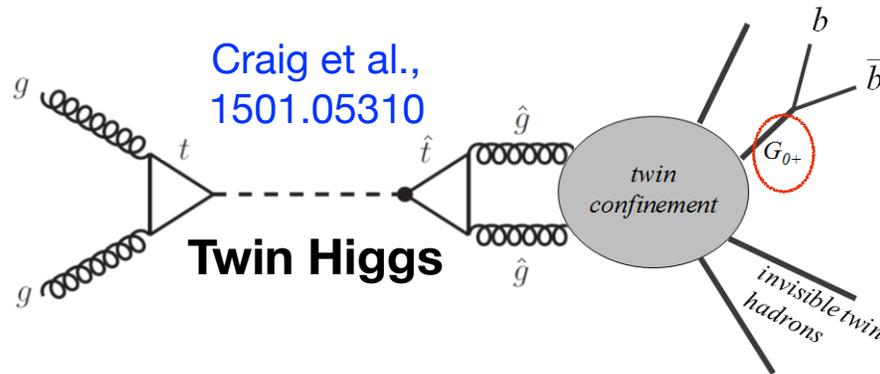
## Prospects for the HL-LHC



125 GeV Higgs coupling measurements

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

# Long-lived signatures from twin Higgs decays

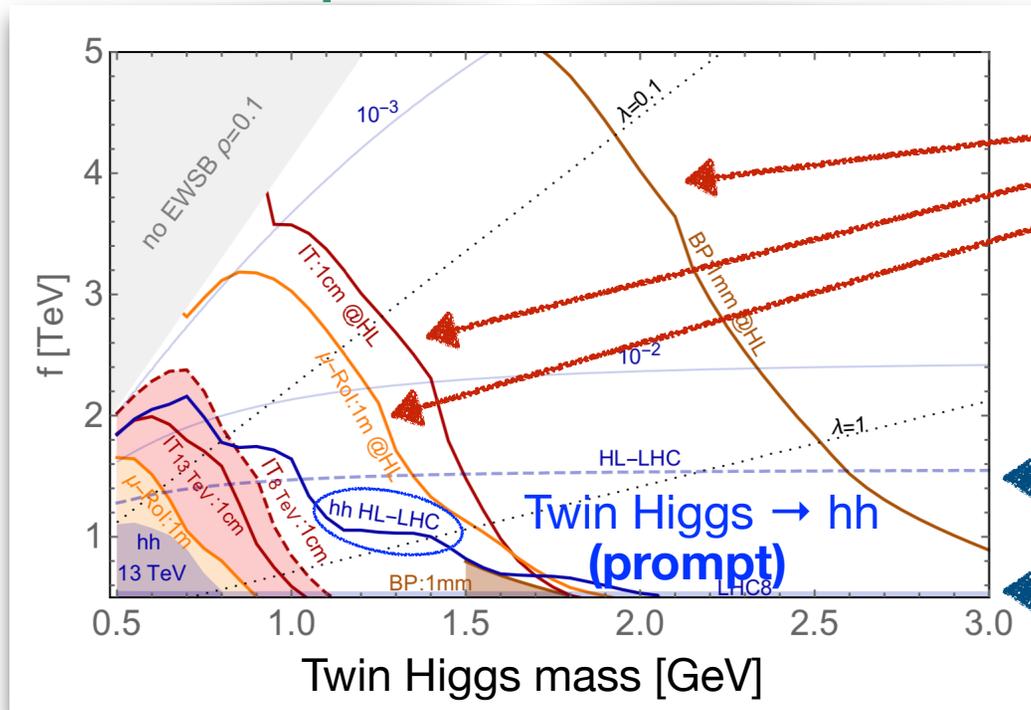


**Glue-ball.**

$O^{++}$  mixes with the 125 GeV Higgs and decays typically displaced.

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## Prospects for the HL-LHC



**Twin Higgs  $\rightarrow$  glue-balls: (long lived)**

CMS inner tracker analysis;  
CMS beam pipe analysis;  
ATLAS muon spectrometer analysis

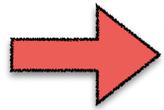
The relative strength depends on other parameters of the theory

125 GeV Higgs coupling measurements

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

# Effects on the 125 GeV Higgs pheno

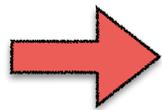
The 125 GeV Higgs will mix with the twin Higgs with a mixing angle  $\sim v^2/f^2$



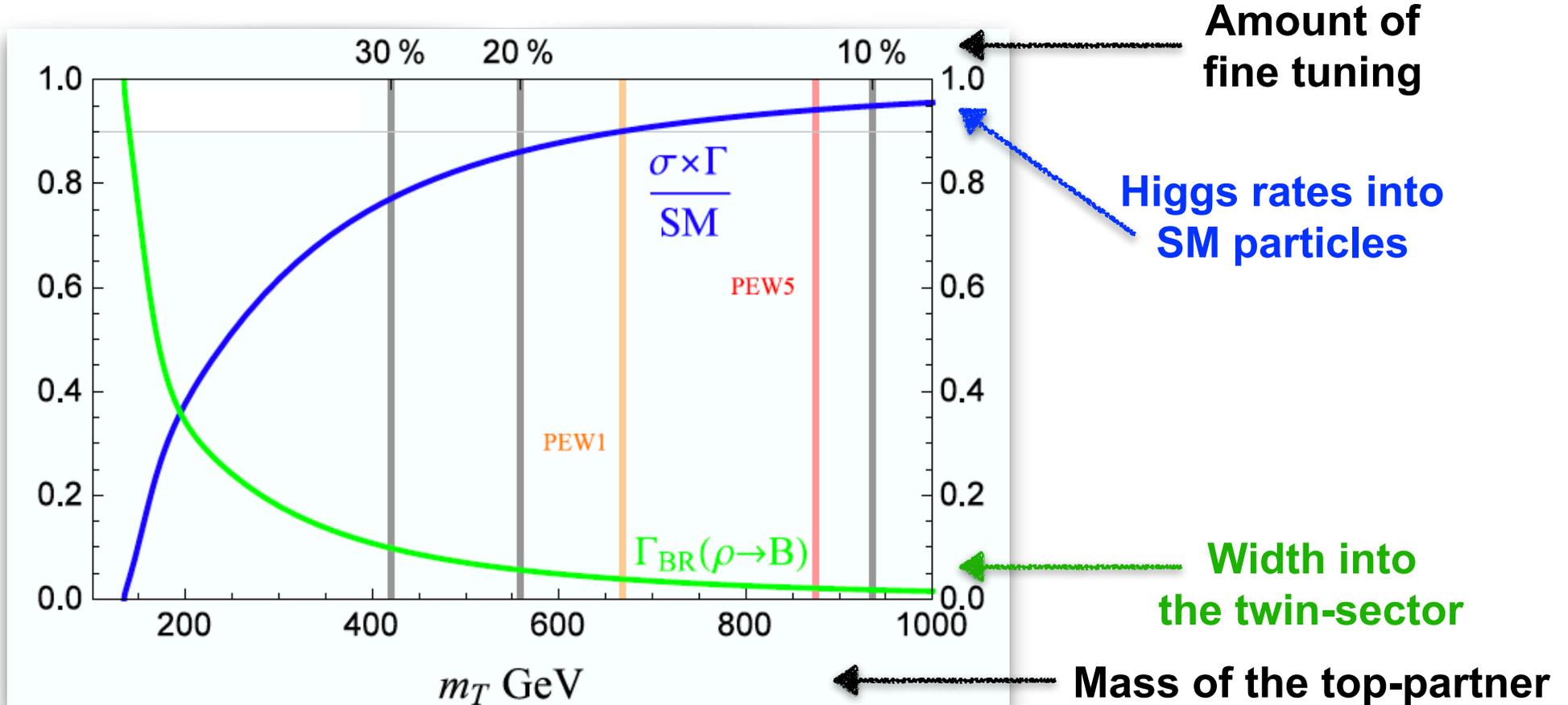
- \* The Higgs couplings to the SM particles will be reduced
- \* The Higgs will decay to light twin states (invisible Higgs width)

# Effects on the 125 GeV Higgs pheno

The 125 GeV Higgs will mix with the twin Higgs with a mixing angle  $\sim v^2/f^2$



- \* The Higgs couplings to the SM particles will be reduced
- \* The Higgs will decay to light twin states (invisible Higgs width)



Burdman et al, 1411.3310

# Outlook: What have we learned?

**The Standard Model is a remarkable theory**  
**however**  
**it does not answer several fundamental questions**

## **Supersymmetry**

**Hierarchy problem:**  
**Scalar partners of the SM fermions**  
**Direct searches (sparticles + Higgses)**  
**Interplay with precision measurements (Higgs & flavor)**

## **Twin Higgs**

**Hierarchy problem:**  
**Global symmetry between the SM and the twin sectors**  
**Direct searches of the twin Higgs (displaced signatures!)**  
**Interplay with precision measurements (Higgs)**

# T-parameter and custodial symmetry (1)

\* Why is the T parameter interesting?

hep-ph/0410370

\* Let us define the symmetry  $SU(2)_L \times SU(2)_R$   an additional  $SU(2)$

 The usual gauge symmetry

\* Let us write the SM Lagrangian in terms of  $SU(2)_L \times SU(2)_R$  invariant objects

✓ The Higgs is now in a bi-doublet representation:

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \tilde{\phi} & \phi \end{pmatrix} \quad \text{with} \quad \phi = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad \tilde{\phi} \equiv \epsilon\phi^* = \begin{pmatrix} \phi^{0*} \\ -\phi^- \end{pmatrix}$$

✓ The Higgs Lagrangian is given by

$$\Phi \rightarrow e^{i\omega_L^i \sigma_i / 2} \Phi e^{i\omega_R^j \sigma_j / 2}$$

$$\mathcal{L}_{Higgs} = \text{Tr} D^\mu \Phi^\dagger D_\mu \Phi - \mu^2 \text{Tr} [\Phi^\dagger \Phi] + \lambda \text{Tr} [\Phi^\dagger \Phi]^2$$

✓ Electroweak symmetry breaking

$$\langle \Phi \rangle = \frac{1}{2} \begin{pmatrix} v & 0 \\ 0 & v \end{pmatrix} \quad SU(2)_L \times SU(2)_R \rightarrow SU(2)_D \text{ (custodial symmetry)}$$

✓ We can demonstrate that the hypercharge interaction and the Yukawa couplings break the custodial symmetry

# T-parameter and custodial symmetry (2)

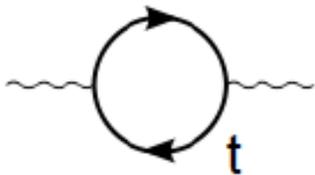
- \* Why is the T parameter interesting?
- \* Going back to our definition of the T parameter:

$$\mathcal{L}_{vac-pol} = -\frac{1}{2}W_\mu^3\Pi_{33}(q^2)W_\mu^3 - \frac{1}{2}B_\mu\Pi_{00}(q^2)B_\mu - W_\mu^3\Pi_{30}(q^2)B_\mu - W_\mu^+\Pi_{WW}(q^2)W_\mu^-$$

$$\hat{T} \equiv \frac{\Pi_{33}(0) - \Pi_{WW}(0)}{m_W^2} = \rho - 1$$

$W_\mu^i$  ( $i = 1, 2, 3$ )  
 is triplet of  $SU(2)_L$ ,  
 singlet of  $SU(2)_R$   
 triplet of  $SU(2)_D$

- \* In any theory with custodial symmetry, the T parameter is = 0
- \* In the SM, the top Yukawa is strongly breaking the custodial symmetry



$$\hat{T} \sim \frac{3G_F m_t^2}{8\sqrt{2}\pi^2} + \dots$$

# Heavy Higgs boson couplings

A bound on  $x$  gives also information about the heavy Higgs couplings with fermions (Note: everything is at the tree-level!)

125 GeV Higgs

Heavy scalar

Heavy pseudo-scalar

$y_{2\text{HDM}}/y_{\text{SM}}$	Type-II $K$	Alignment limit:
$hVV$	$s_{\beta-\alpha}$	1
$hQu$	$s_{\beta-\alpha} + c_{\beta-\alpha}/t_\beta$	1
$hQd$	$s_{\beta-\alpha} - t_\beta c_{\beta-\alpha}$	1
$hLe$	$s_{\beta-\alpha} - t_\beta c_{\beta-\alpha}$	1
$HVV$	$c_{\beta-\alpha}$	0
$HQu$	$c_{\beta-\alpha} - s_{\beta-\alpha}/t_\beta$	$1/t_\beta$
$HQd$	$c_{\beta-\alpha} + t_\beta s_{\beta-\alpha}$	$t_\beta$
$HLe$	$c_{\beta-\alpha} + t_\beta s_{\beta-\alpha}$	$t_\beta$
$AVV$	0	0
$AQu$	$1/t_\beta$	$1/t_\beta$
$AQd$	$t_\beta$	$t_\beta$
$ALe$	$t_\beta$	$t_\beta$

Note the flavor universality!

$$y_{Q^i} = K \times m_{Q^i}/v$$

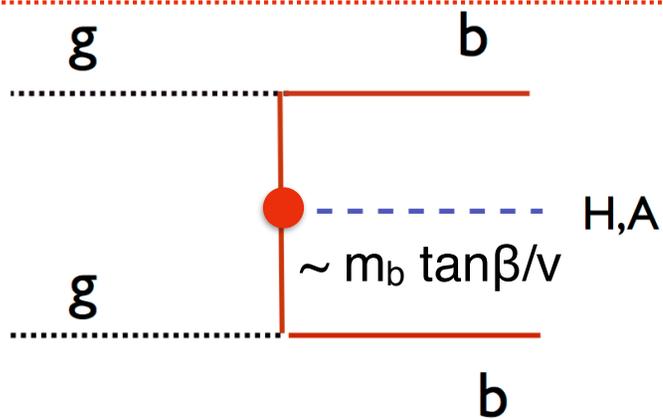
independent on  $i$

The pheno of the additional Higgs is determined by  $\beta$  and their mass

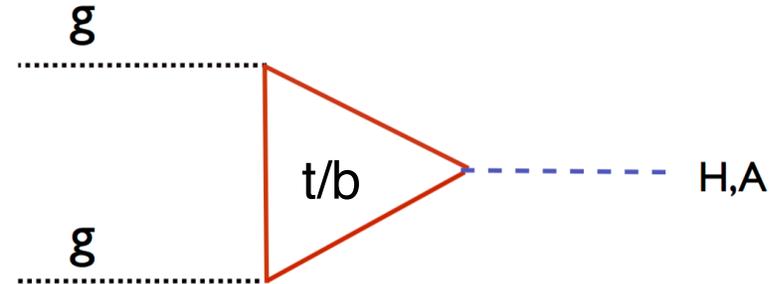
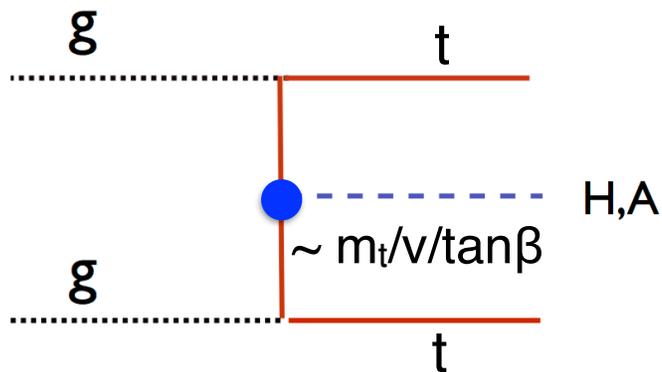
# How to produce these H bosons at the LHC?

\* Neutral Higgs bosons (H,A)

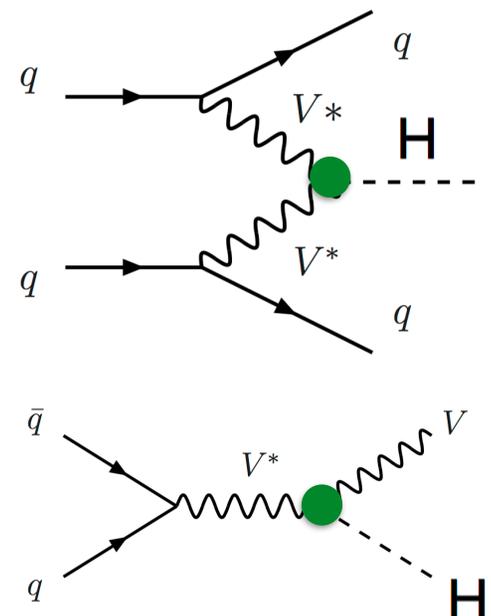
Dominant  
at **large  $\tan\beta$** :



Dominant  
at **small  $\tan\beta$** :



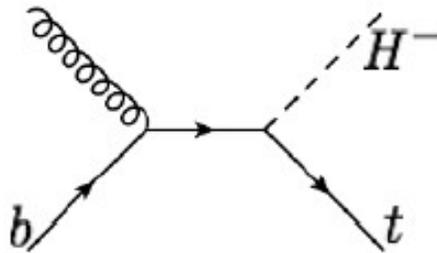
Suppressed in  
the alignment limit:



# How to produce these H bosons at the LHC?

## \* Charged Higgs bosons ( $H^\pm$ )

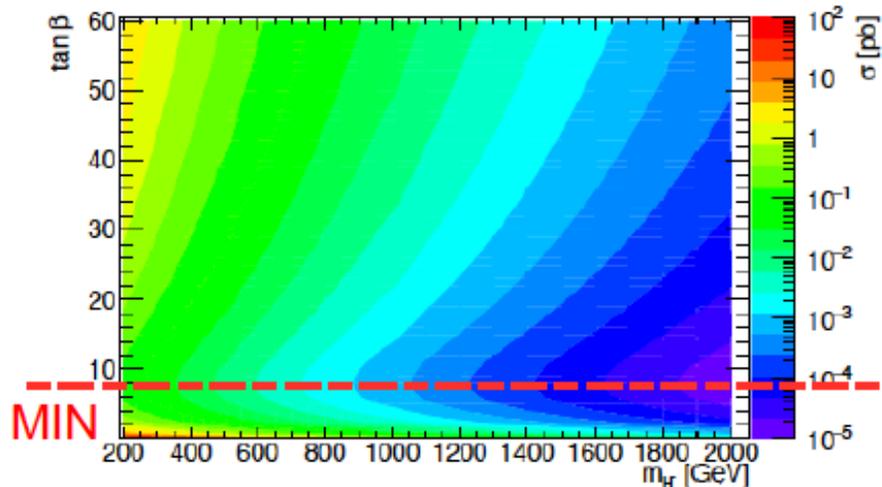
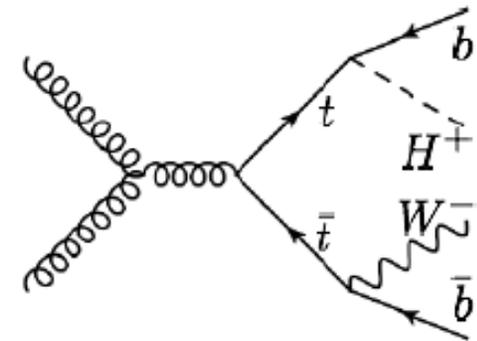
Above the top mass:



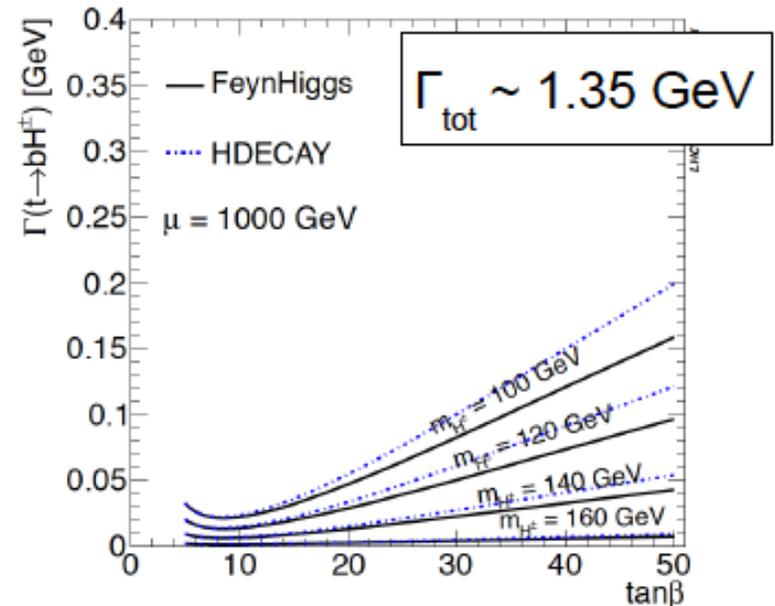
$$H^\pm b_R t_L \sim m_b \tan\beta / v$$

$$H^\pm t_R b_L \sim m_t / \tan\beta / v$$

Below the top mass:



From the LHCHSWG YR4, 1610.07922



From the LHCHSWG YR2, 1201.3084

# What are the signatures?

Craig et al., 1305.2424

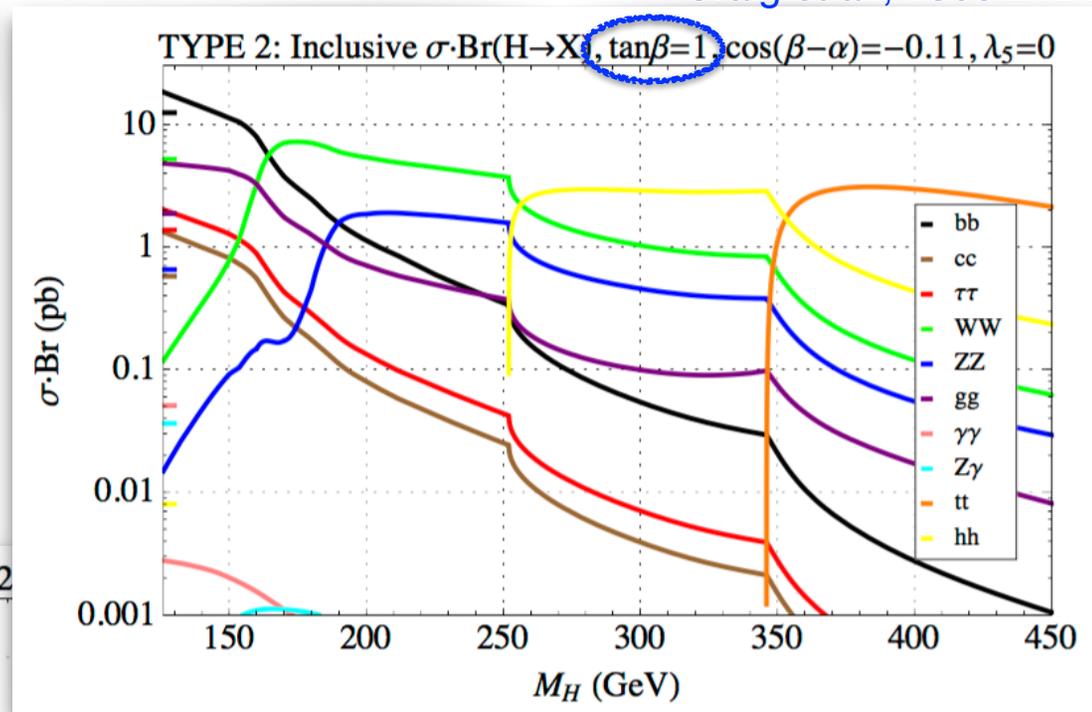
\* Neutral Higgs bosons

Large  $\tan\beta$ :

enhanced couplings with  $bb$ ,  $\tau\tau$

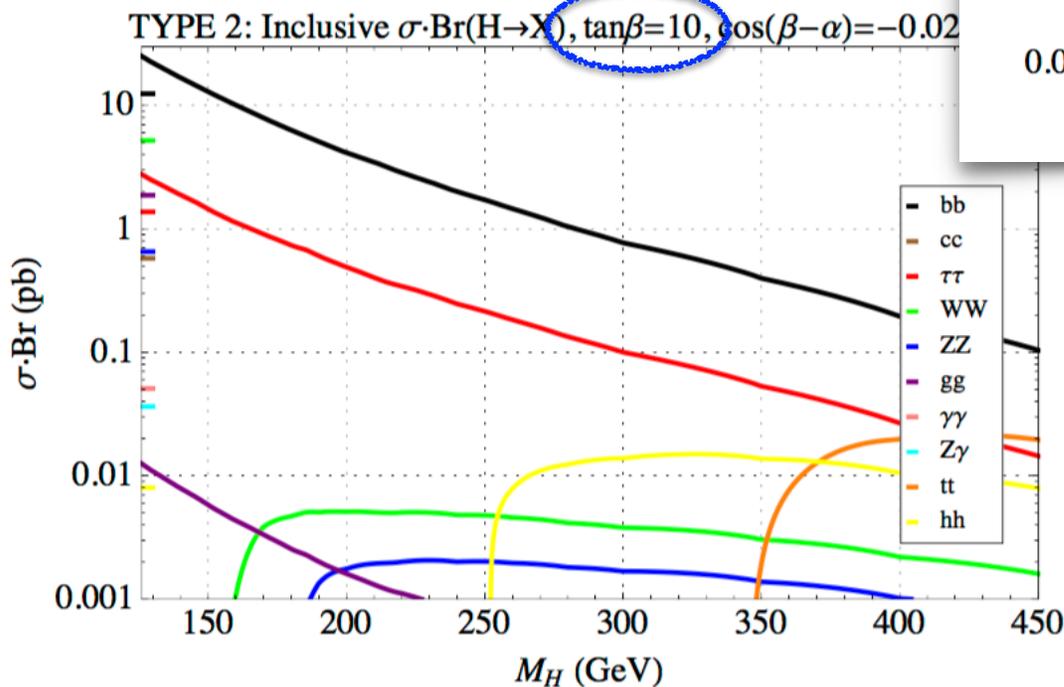
Alignment limit:

suppressed couplings with  $hh$ ,  $WW$ ,  $ZZ$



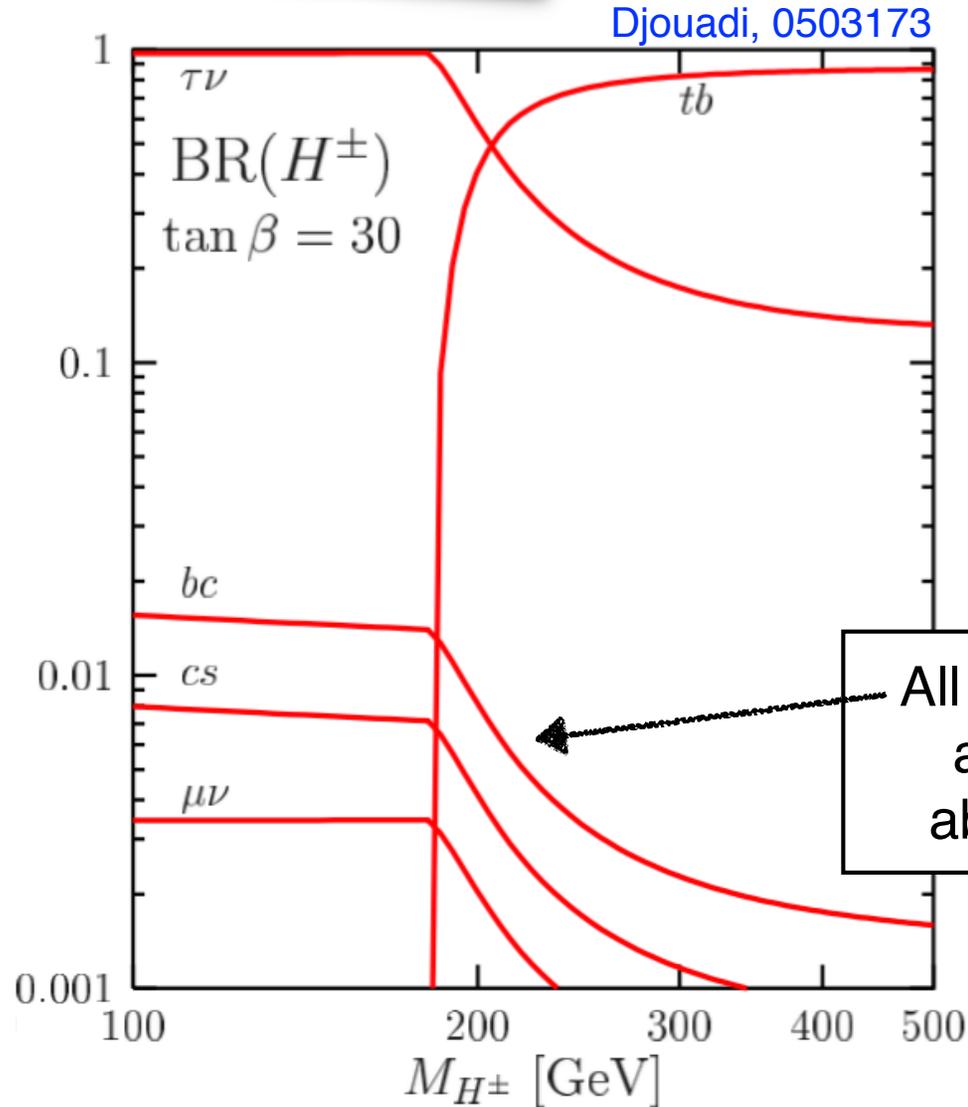
Small  $\tan\beta$ :

enhanced couplings with  $tt$



# What are the signatures?

## \* Charged Higgs bosons



All the other decay modes are pretty suppressed above the top threshold