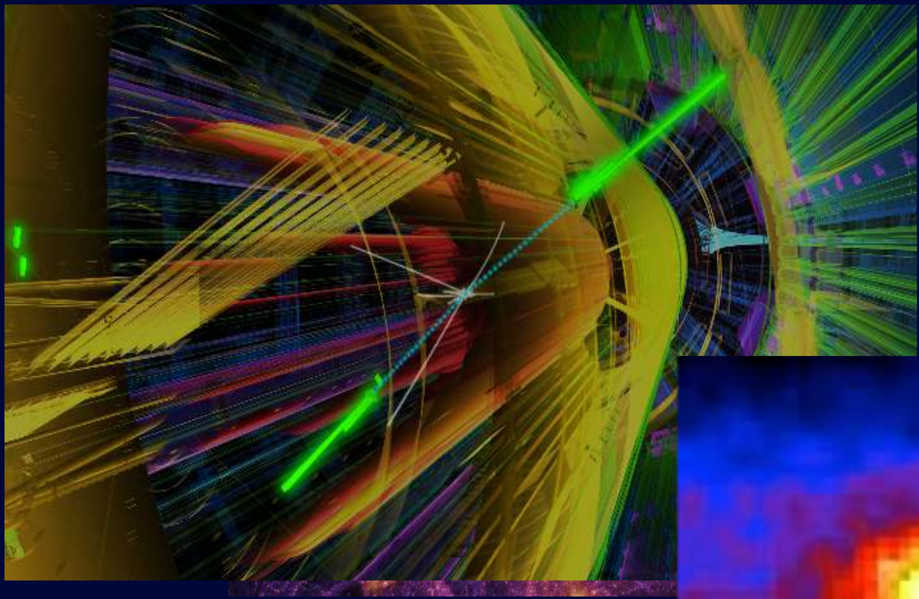
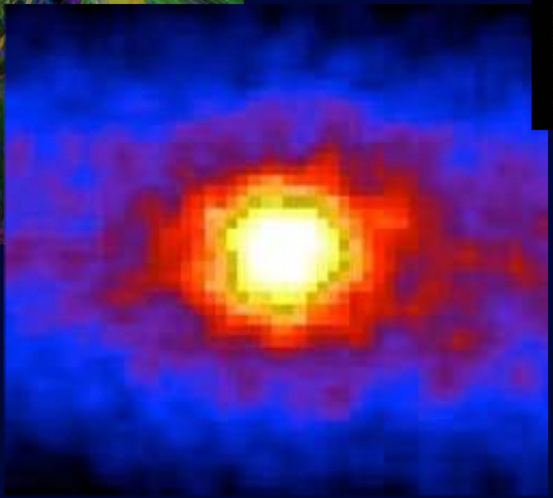
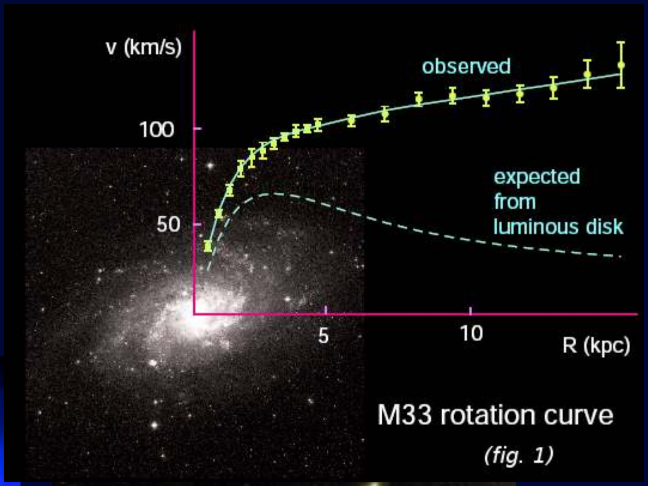
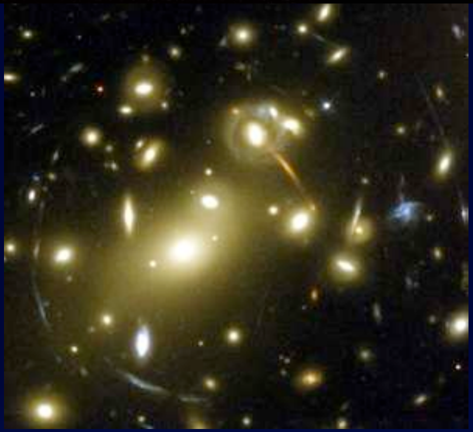
Particle Physics beyond the Higgs









Marcela Carena
Fermilab and U. of Chicago

2015: THE SPACETIME ODYSSEY CONTINUES
Stockholm, June 4, 2015

What changed in Particle Physics in the last quarter of a century?

~ since I became a professional physicists ~

State of the art in 1990

- Excellent agreement with SM predictions at the quantum level
- Value of the weak mixing angle consistent with SUSY GUT prediction : SUSY re-born
- No observation of proton decay put strong constraints on non-SUSY GUT models

Tevatron Run 1 on the way to LEP 2

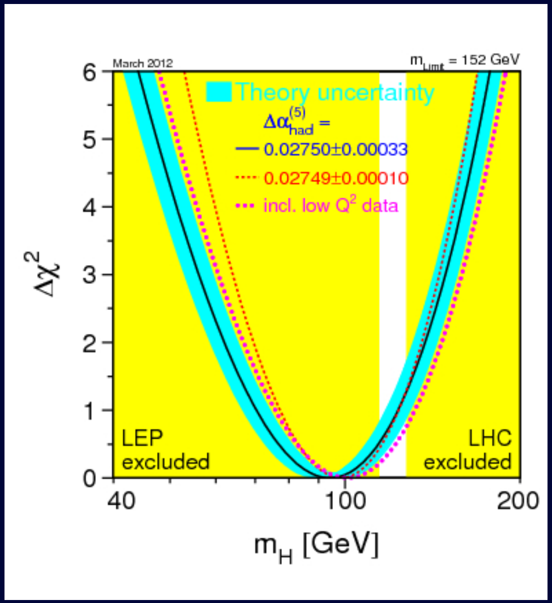
- Precision EW measurements at LEP1 suggested a heavy top quark ($m_t > 130$ GeV)
- **Top quark seen at the Tevatron in 1995**
- Start of precision studies of the Higgs mass while LEP2 started the quest for the Higgs

What changed in Particle Physics in the last quarter of a century? (cont'd)

The LEP 2 Legacy

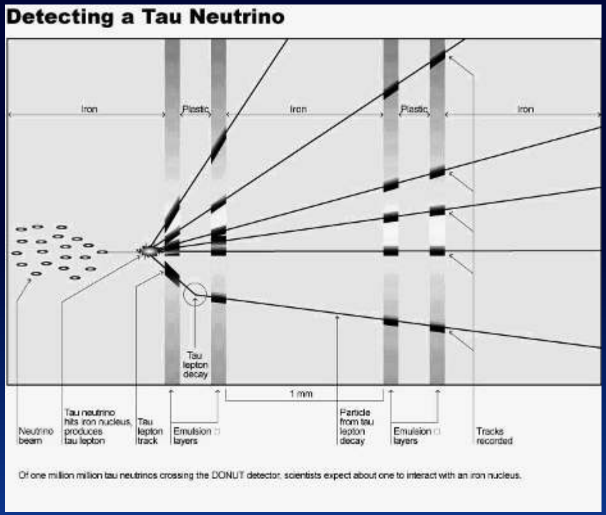
- No Higgs discovery but many valuable measurements
- A decay independent lower bound on the Higgs mass & an upper bound from PEW data

➔ relevant implications for model building: i.e. ruled out SM electroweak baryogenesis



The last of the Neutrinos?

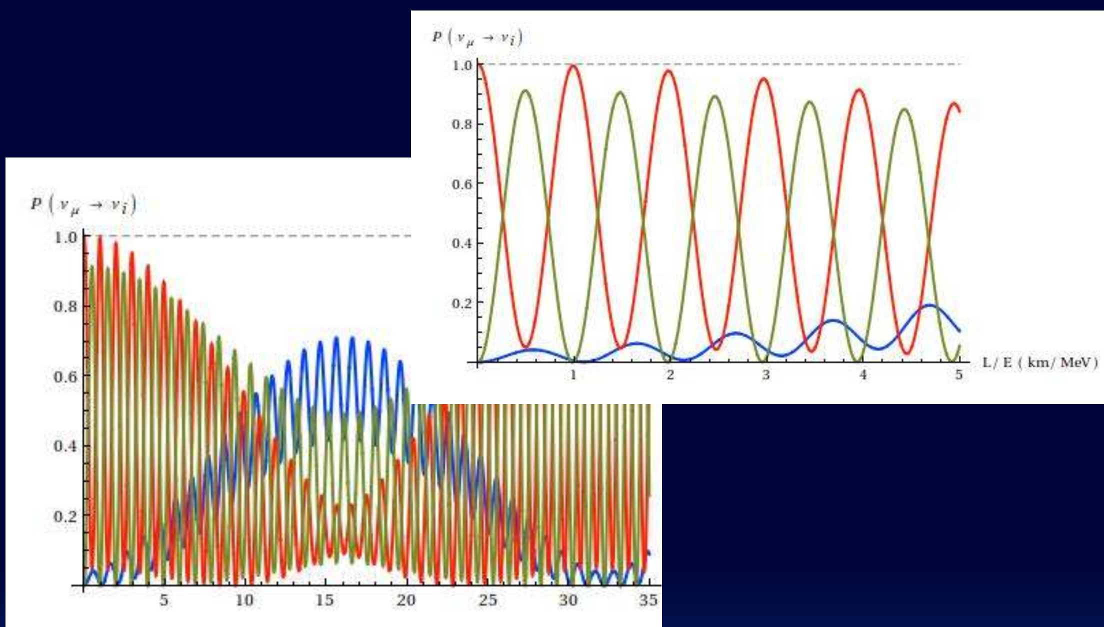
- 2000: the tau neutrino was observed at Fermilab

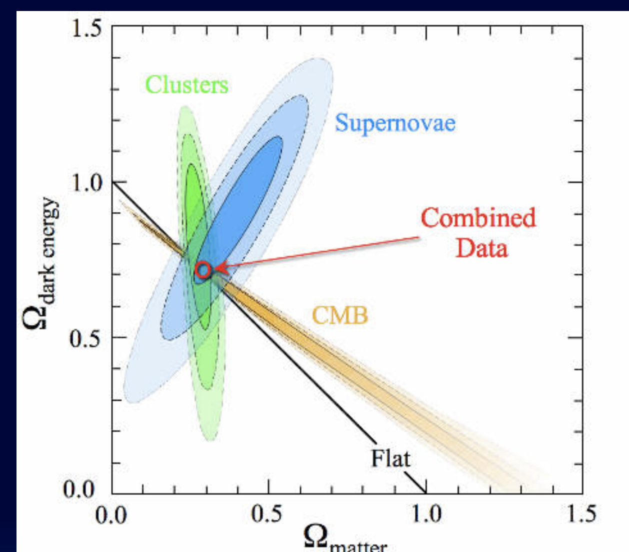


Particle physics in the 21st century

Many things happened at the turn of the Century, at the end of the LEP years

- Neutrino Oscillations led to convincing evidence of neutrino masses
- CMB studies led to conclusive evidence of Dark Matter
- Supernova and CMB studies led to evidence of Dark Energy

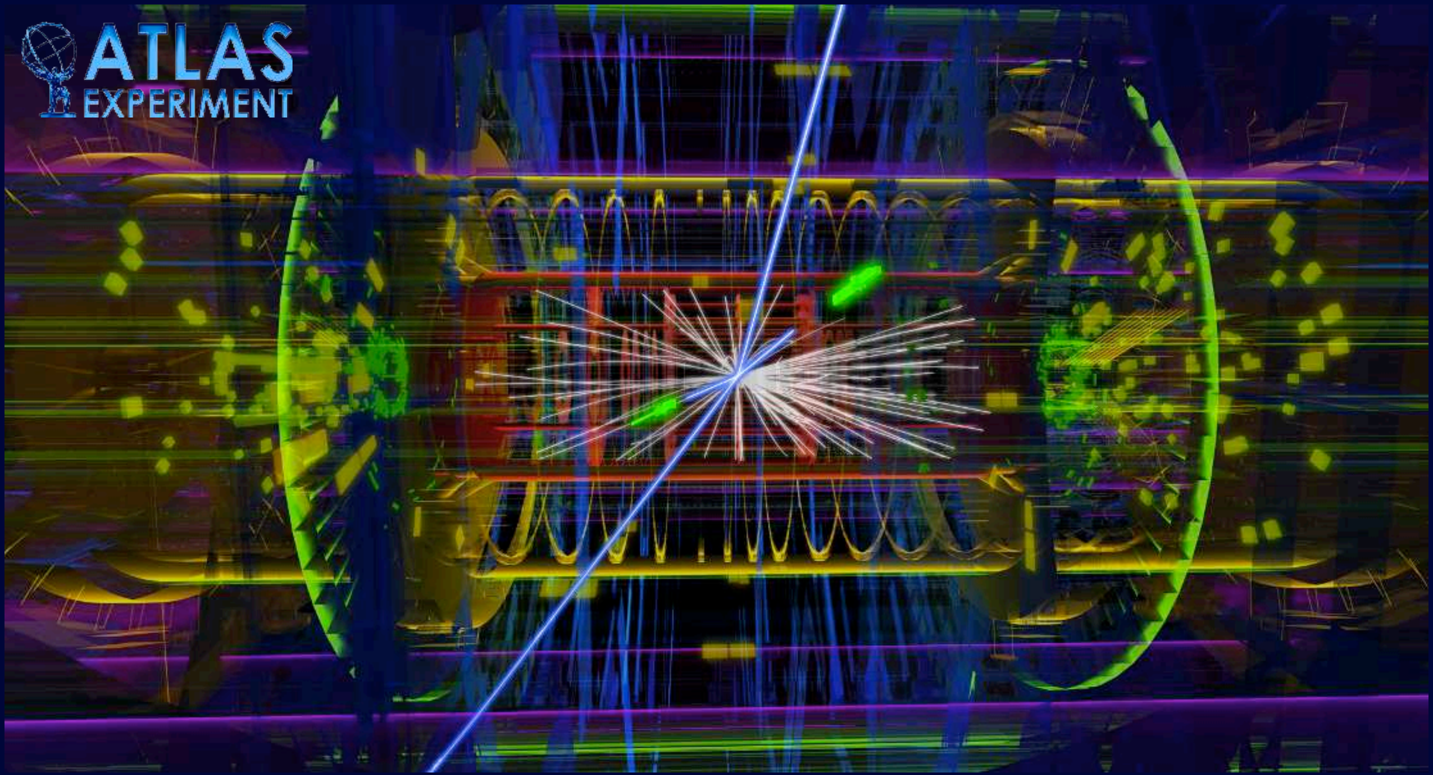




The Higgs was not yet there

The Tevatron and the LHC started the race for it.

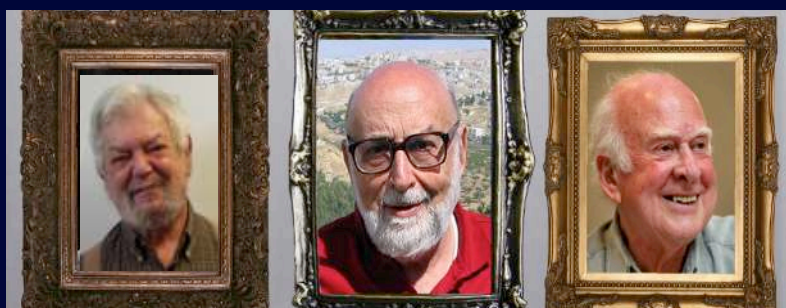
Fireworks on 4th July 2012



- Discovery of a new type of particle
- Discovery of a new type of force
- Start of a new era for particle physics and cosmology

The Brout-Englert-Higgs + Guralnik-Hagen-Kibble Mechanism & the Higgs Boson (1964)

A fundamental scalar field with self-interactions
can cause spontaneous symmetry breaking in the vacuum,
respecting the sophisticated choreography of gauge symmetries,
and can give gauge bosons mass



One particle left in
the spectrum

The fermions also get mass from a new type of interactions (Yukawa int.) with the scalar field

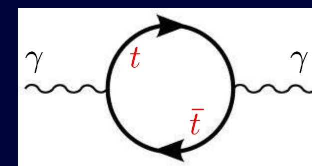
Weinberg-Salam: The electroweak SM (1967)

Higgs explains: My first paper was rejected because it was not relevant for phenomenology

Quantum Fluctuations produce the Higgs at the LHC

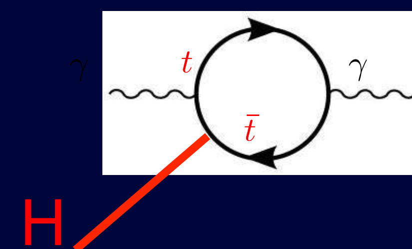
"Nothingness" is the most exciting medium in the cosmos!

Photon propagates in Quantum Vacuum

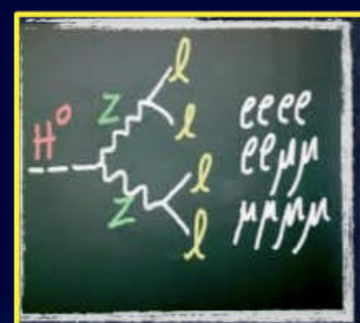


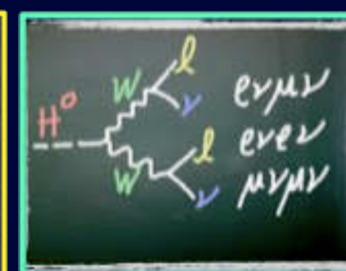
Quantum fluctuations create and annihilate "virtual particles" in the vacuum

Higgs decays into 2 Photons

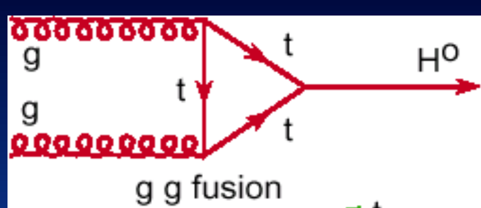


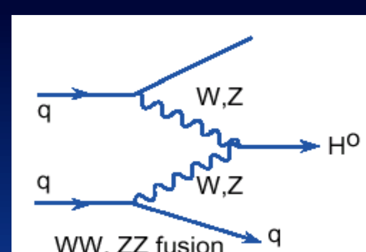
Higgs decay into 4 leptons via virtual Z/W bosons



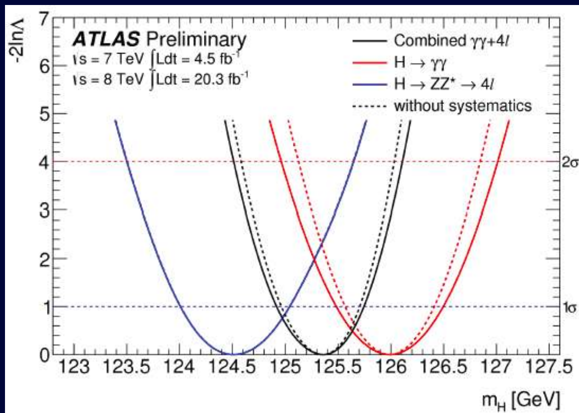


Also main production channels
involve virtual particles





No doubt that a Higgs boson has been discovered

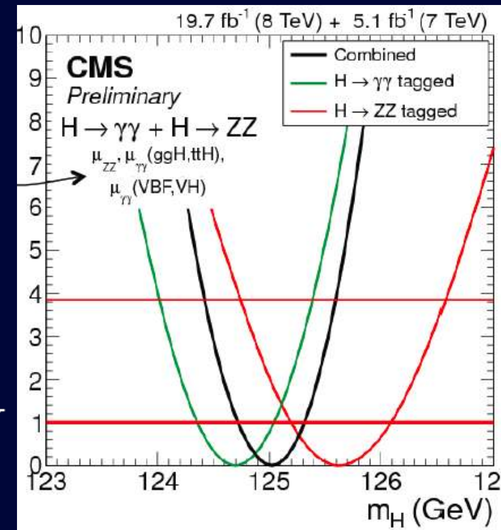


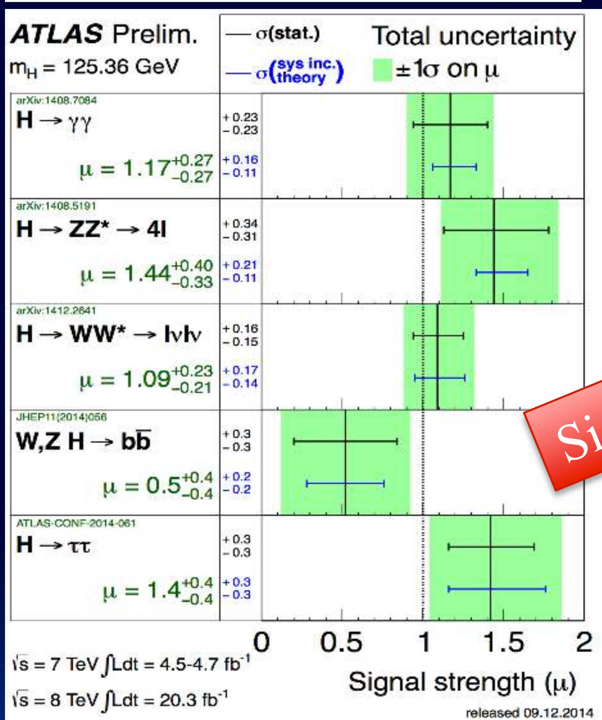
ATLAS:

$$m_H = [125.36 \pm 0.41] \mathrm{GeV}$$

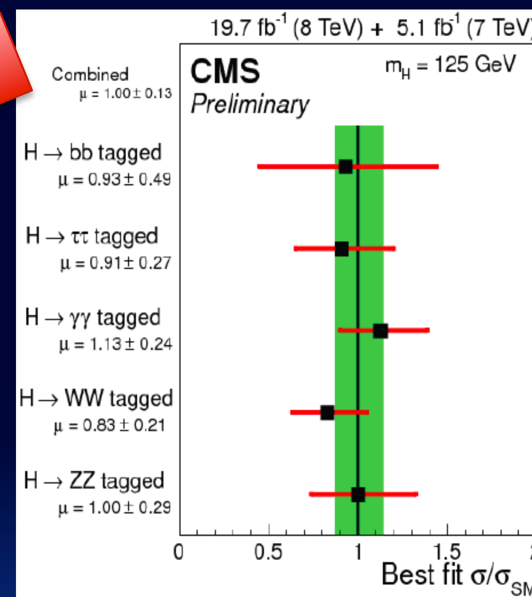
CMS:

$$m_H = [125.03 \pm 0.30] \mathrm{GeV}$$





Signal compatible with SM Higgs



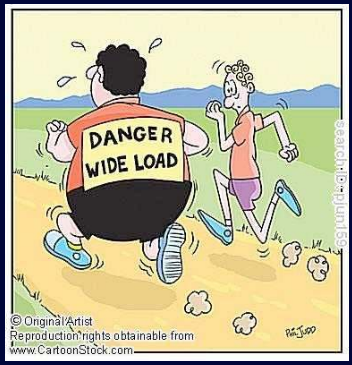
$$\sigma/\sigma_{\mathrm{SM}} = 1.00 \pm 0.13 \left[\pm 0.09(\mathrm{stat.})^{+0.08}_{-0.07}(\mathrm{theo.}) \pm 0.07(\mathrm{syst.})\right]$$

Are we Done? Not really, much to explain yet

Dark Matter, Baryogenesis, Dynamical Origin of Fermion Masses, Mixings, CP Violation, Tiny Neutrino Masses, ….

None of the above demands NP at the electroweak scale, but…

The Higgs is special : it is a scalar



Although the SM with the Higgs is a consistent theory, light scalars like the Higgs cannot survive in the presence of heavy states at GUT/String/Planck scales

Also, many other open questions:

Do forces unify? Is the proton (ordinary matter) stable ? Are neutrinos their own antiparticle? Are there more generations of matter? What about Dark Energy ?

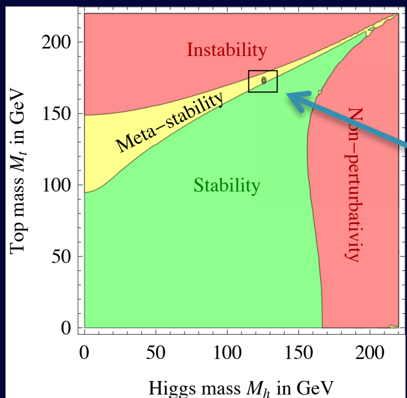
And some interesting electroweak scale anomalies !

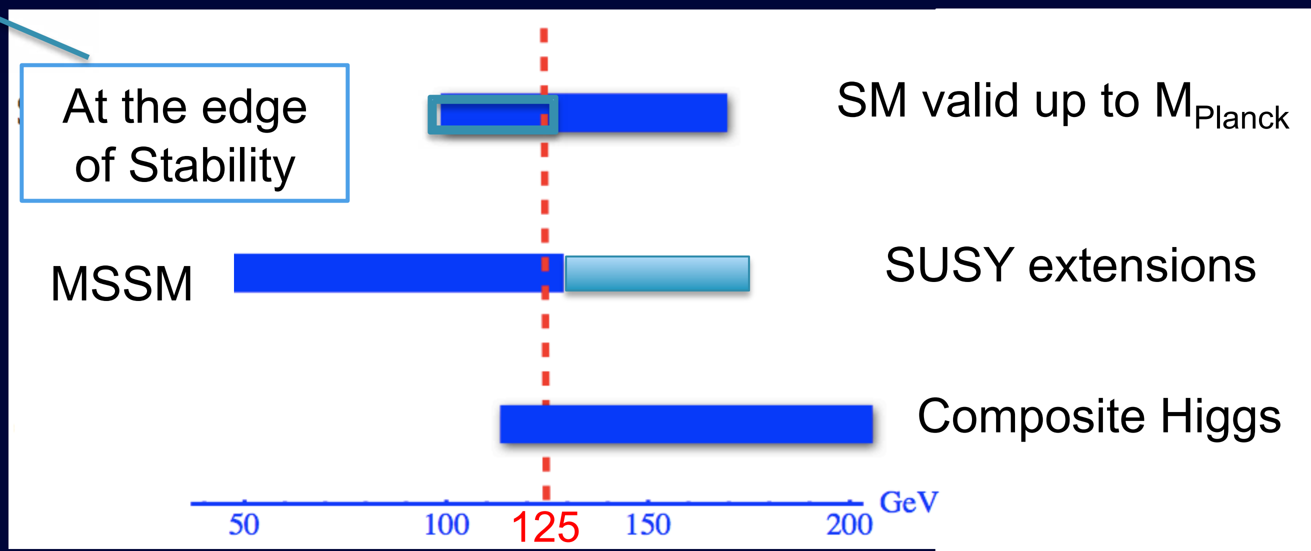
Signals which are two to three standard deviations away from the expected SM predictions

e.g. Anomalous magnetic moment of the muon, Higgs decay to $\tau\mu$, Excess in Dibosons, Anomalous events in same flavor, opposite sign leptons, …

Look under the lamp-post:

What type of Higgs have we seen?





125 GeV is suspiciously light for a composite Higgs boson

but it is suspiciously heavy for minimal SUSY

Additional option: Higgs as part of an extended sector (e.g. 2HDM) to explain flavor from the electroweak scale

Composite Higgs Models

The Higgs does not exist above a certain scale, at which the new strong dynamics takes place

➔ dynamical origin of EWSB

New strong resonance masses constrained by Precision Electroweak data and direct searches

Higgs ➔ scalar resonance much lighter that other ones

Supersymmetry: a fermion-boson symmetry

The Higgs remains elementary but its mass is protected by SUSY ➔ $\delta m^2 = 0$

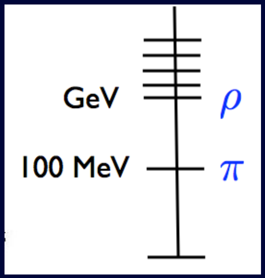
Flavor from the electroweak scale

Flavor hierarchies arise from a Froggatt-Nielsen mechanism with

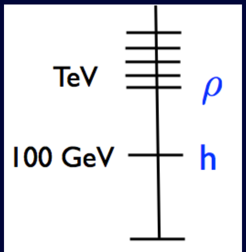
two Higgs doublets jointly acting as a flavon

All options imply changes in the Higgs phenomenology and beyond

Composite Higgs Models
The Higgs as a pseudo Nambu-Goldstone Boson (pNGB)



Inspired by pions in QCD



QCD with 2 flavors: global symmetry $SU(2)_L \times SU(2)_R / SU(2)_V$.

π^{+-} π^0 are Goldstones associated to spontaneous breaking

$g, g' \to 0 \quad \& \quad m_q \to 0$

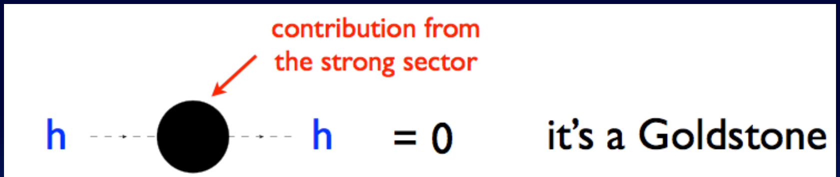
$\Rightarrow m_\pi = 0$

$m_q \neq 0 \Rightarrow m_\pi^2 \simeq m_q B_0$

$e \neq 0 \Rightarrow \delta m_{\pi^\pm}^2 \simeq \frac{e^2}{16\pi^2} \Lambda_{QCD}^2$

Higgs is light because is the pNGB
-- a kind of pion – of a new strong sector

Mass protected by the global symmetries



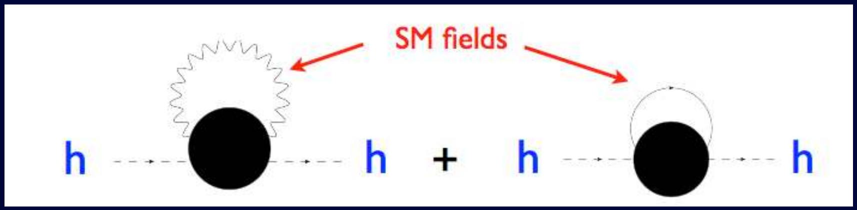
A tantalizing alternative to the strong dynamics realization of EWSB

Georgi,Kaplan'84

Higgs as a PNGB

Light Higgs since its mass arises from one loop

Mass generated at one loop: explicit breaking of global symmetry due to SM couplings



Dynamical EWSB: large set of vacua, some of them break $SU(2)_L \times U(1)_Y$

The Higgs potential depends on the chosen global symmetry
AND
on the fermion embedding in the representations of the symmetry group

Higgs mass challenging to compute due to strong dynamics behavior

$$m_H^2 \propto m_t^2 M_T^2 / f^2$$

Marzoca, Serone, Shu'12, Pomarol, Riva '12

New Heavy Resonances being sought for at the LHC

Minimal Composite Higgs models phenomenology

-- All About Symmetries --

Choosing the global symmetry [SO(5)] broken to a smaller symmetry group [SO(4)]
-- at an intermediate scale f larger than the electroweak scale -- such that:
the Higgs can be a pNBG, the SM gauge group remains unbroken until the EW scale
and there is a custodial symmetry that protects the model from radiative corrections

Higgs couplings to W/Z determined by the gauge groups involved

SO(5) → SO(4)

Giudice, Grojean, Pomarol Rattazzi'07;
Montull, Riva, Salvioni, Torre'13; M.C., Da Rold, Ponton'14

Generic features:

Suppression of all partial decay widths
Suppression of all production modes
Enhancement/Suppression of BR's dep. on the effect of the total width suppression

Higgs couplings to SM fermions depend on fermion embedding

With Notation $MCHM_{Q\text{-}U\text{-}D}$

5, 10,
5-5-10, 5-10-10, 10-5-10
14-14-10, 14-1-10

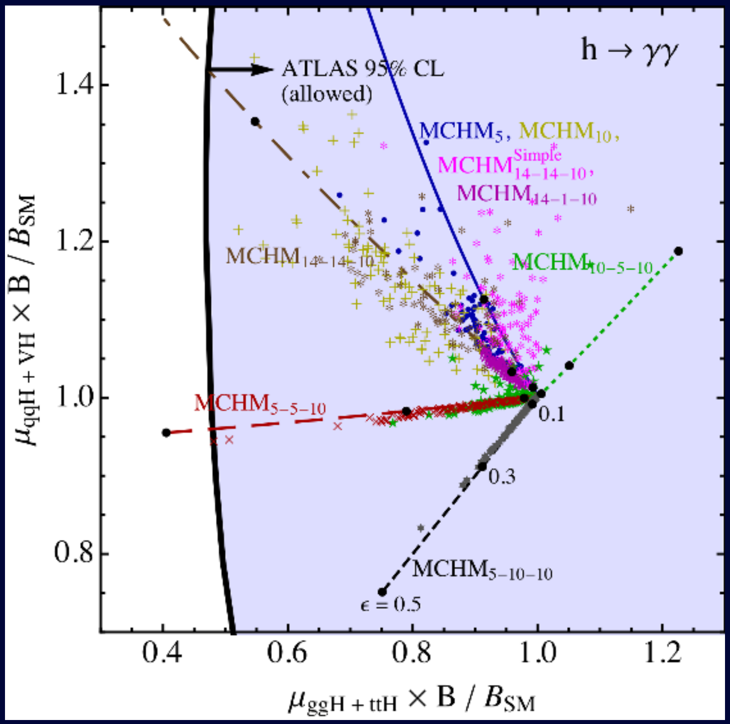
Representations of SO(5)

Driven by the idea that heavy SM fermions are a mixture of elementary and composite states

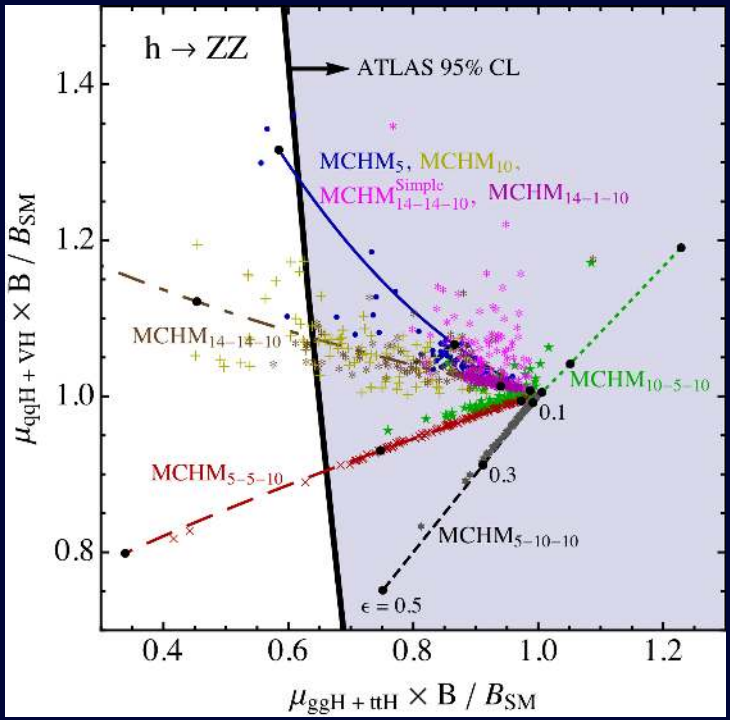
Falkowski'07;Azatov et al '11
Montull et al'13; MC, Da Rold, Ponton'14

Minimal Composite Higgs models confronting data

h to di-photons



h to ZZ



M.C., Da Rold, Ponton'14

After EWSB: $\varepsilon = v_{SM}/f$ and precision data demands f > 500 GeV

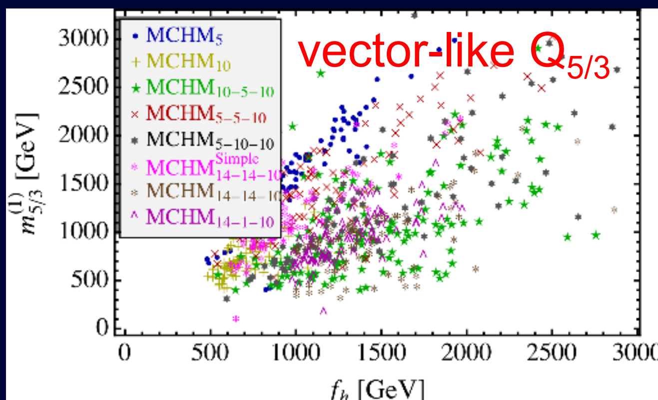
More data on Higgs observables will distinguish between different realizations in the fermionic sector, providing information on the nature of the UV dynamics

Other global symmetry patterns allow for additional Higgs Bosons in the spectrum

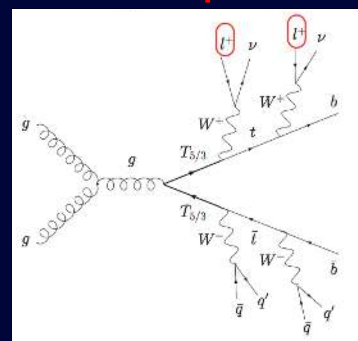
Composite pNGB Higgs Models predict light Fermions

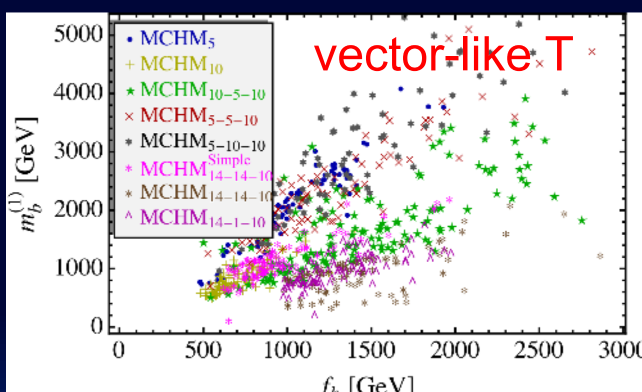
Pair production, single production, or exotic Higgs production of vector-like fermions

[masses in the TeV range and possibly with exotic charges: Q = 2/3,−1/3, 5/3,8/3,−4/3]



SS di-leptons





M.C., Da Rold, Ponton'14

Large variety of signatures, many with energetic leptons

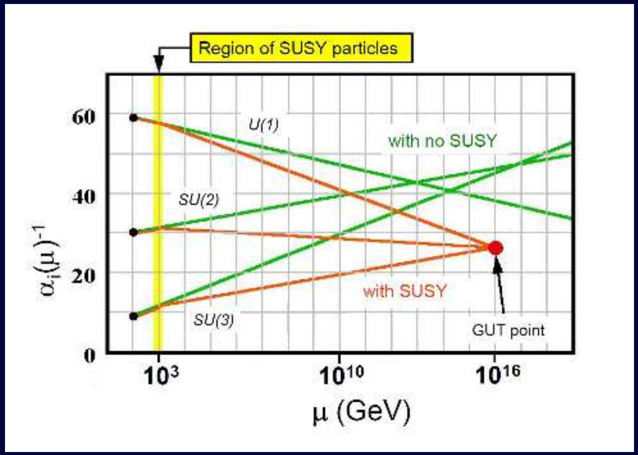
LHC exclusion for M_f < 800 GeV]

SUSY has great credentials

- **Allows a hierarchy between the electroweak scale and the Planck/unification scales**

- **Generates EWSB automatically from corrections to the Higgs potential**

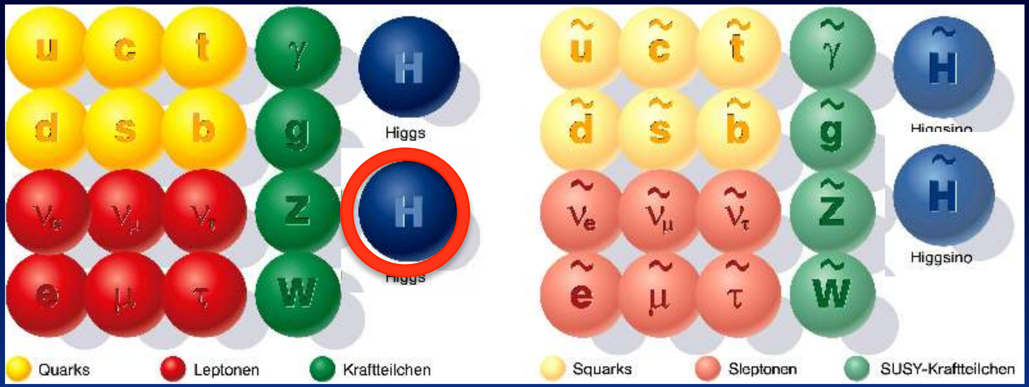
- Allows gauge coupling unification at ~10^{16} GeV



- Provides a good dark matter candidate:

- Allows the possibility of electroweak baryogenesis

- String friendly



Extended Higgs sector

SUSY and Naturalness

- Higgs mass parameter protected by the fermion-boson symmetry: $\delta \mathbf{m}^2 = 0$

In practice, no SUSY particles seen yet ➔ SUSY broken in nature:

$$\delta \mathbf{m}^2 \propto \mathbf{M}^2_{\mathbf{SUSY}}$$

If $M_{SUSY} \sim M_{weak}$ ⟶ Natural SUSY

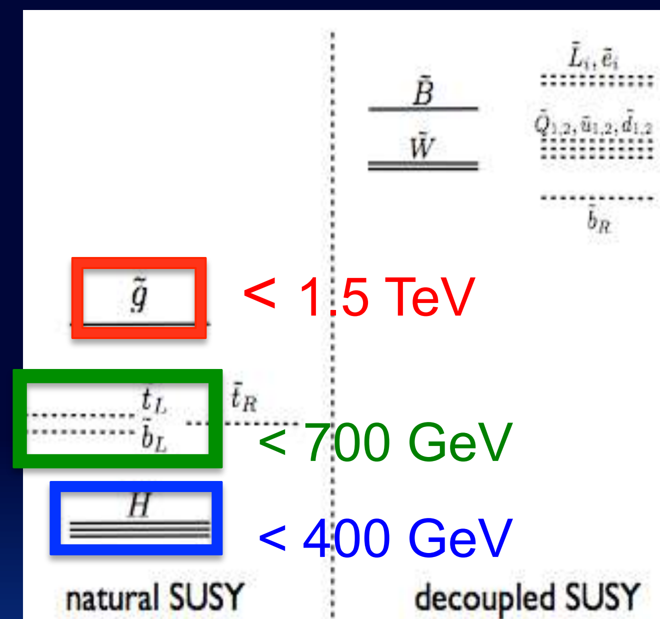
If $M_{SUSY} \ll M_{GUT}$ ⟶ big hierarchy problem solved

Where are the superpartners?

- **Not all SUSY particles play a role in the Higgs Naturalness issue**

Higgsinos, stops (sbottoms) and gluinos are special

- So why didn't we discover any SUSY particle already at LEP, Tevatron, or LHC8?



Papucci, Rudermann, Weiler '11

SUSY Weltschmerz*?

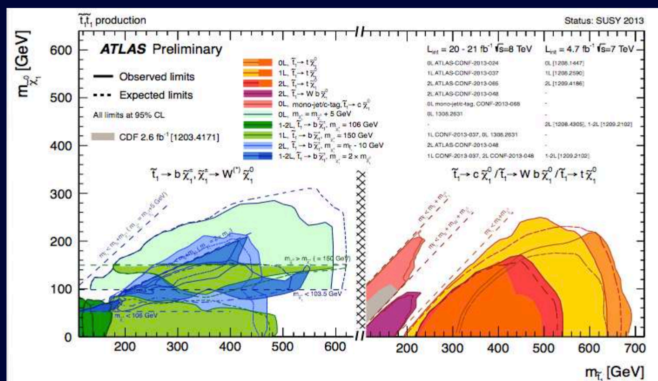
ATLAS/CMS are aggressively pursuing the signatures of “naturalness”.

Specific SUSY models: MSUGRA/CMSSM,GMSB, AMSB, RPV, mini-split SUSY, …

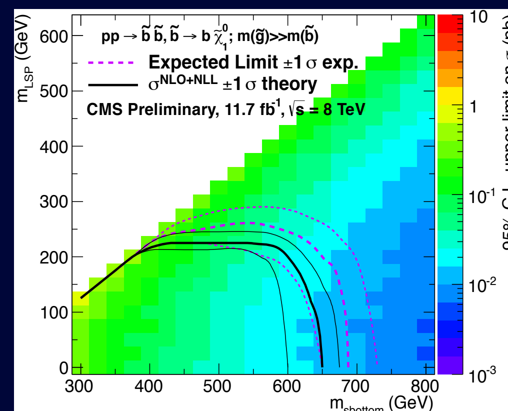
and Simplified Models

prompt decays, long lived/detector-stable particles, displaced vertices, disappearing tracks

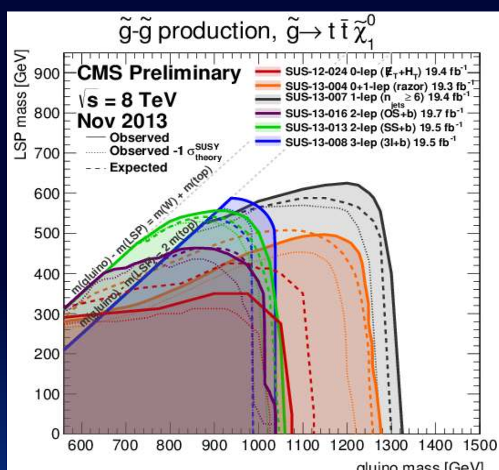
stops



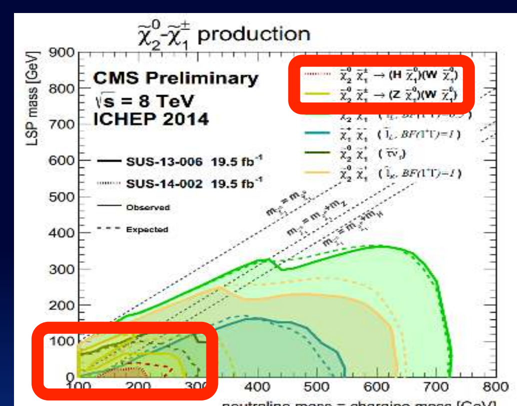
sbottoms



gluinos



Higgsinos



**The feeling experienced by someone who understands that physical reality can never satisfy the demands of the mind*

Is SUSY hiding?

It is possible to have SUSY models with super-partners well within LHC8 kinematic reach, but with ***degraded*** missing energy signatures or event activity

- Compressed spectra: e.g. stop mass ~ charm mass + LSP mass

M.C., Freitas, Wagner '08

- Stealth SUSY: long decay chains soften the spectrum of observed particles from SUSY decays
- The LSP is not the dark matter, but decays

ATLAS/CMS closing the gaps

Still many opportunities for non-minimal "Natural" SUSY models, not yet badly threaten by LHC:

- address flavor as part of the SUSY breaking mechanism

connect lightness of 3rd generation sfermions to heaviness of 3rd generation fermions

- alleviate the tension of a Higgs mass that needs sizeable radiative corrections from stop contributions, by raising its tree level value

additional SM singlets or triplets or models with enhanced weak gauge symmetries

What does a 125 GeV Higgs implies in SUSY?

SUSY also predicts *at least* four kinds of Higgs bosons, differing in their masses and other properties

Minimal SUSY : 2 CP-even Higgs: h and H with mixing angle α

1 CP-odd Higgs A and 1 charged Higgs H^{+-}

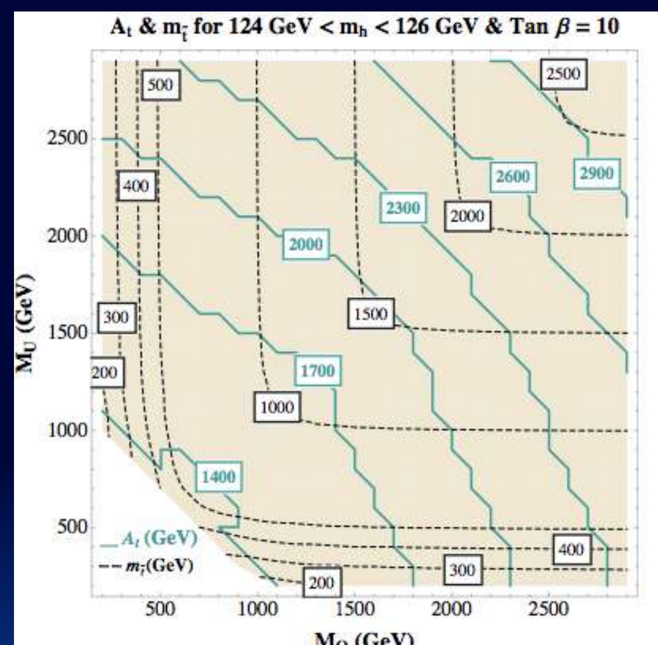
$\tan\beta = v_2/v_1$

$v = \sqrt{(v_1^2 + v_2^2)}$

h may be the SM Higgs with $m_h \sim 125$ GeV

$$m_h^2 = \underbrace{M_Z^2 \cos^2 2\beta}_{< (91\ \text{GeV})^2} + \Delta m_h^2$$

Important radiative corrections with strong dependence on top/stop sector



M. C., Gori, Shah, Wagner '11

MSSM

large stop mixing or large stop masses (> 5 TeV)

One stop can be light and the other heavy

or

in the case of similar stop soft masses both stops should be > 500 GeV

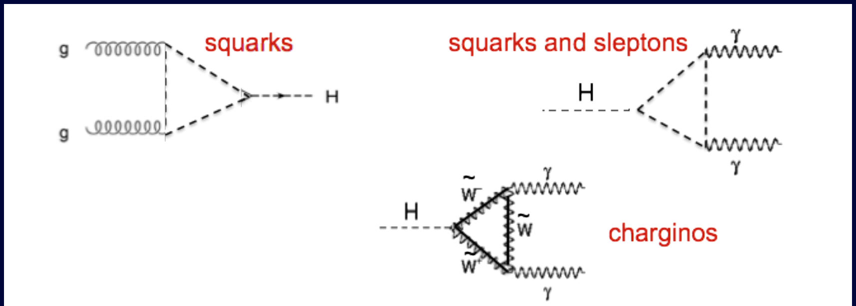
Arbey, Battaglia, Djouadi, Mahmoudi, Quevillon; Draper Meade, Reece, Shih Heinemeyer, Stal, Weiglein'11; Ellwanger'11; Shirman et al.

The new era of precision Higgs Physics

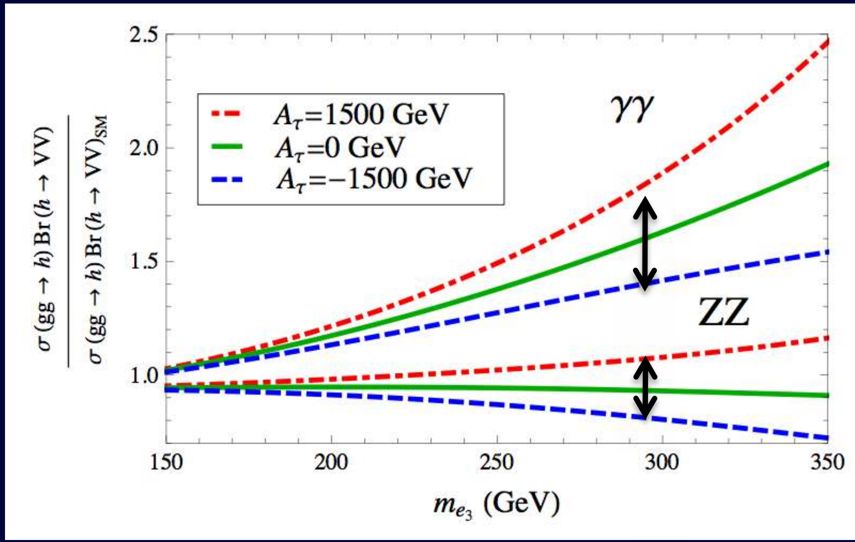
There could be one or more "large" ~10% deviations in Higgs couplings versus the SM, detectable at LHC or HL-LHC running

ILC, CEPC, 100 TeV HC?

- New light charged or colored particles in loop-induced processes



- Modification of tree level couplings due to Higgs mixing effects



M.C., Gori, Shah, Liantao Wang, Wagner'12

- Through vertex corrections to Higgs-fermion couplings:

  This destroys SM relation BR(h → bb)/BR(h → ττ) ~ m_b^2/m_τ^2

- Decays to new or invisible particles

Very SUSY model dependent

The new era of precision Higgs Physics (cont'd)

All other 3 Higgs bosons may be heavy ~ TeV range ~ (Decoupling)
Or as light as a few hundred GeV (Alignment)

Additional Higgs Bosons Searches:
A/H → ττ (shaded)
Vs Precision Higgs Physics:
h → WW/ZZ (dashed lines)

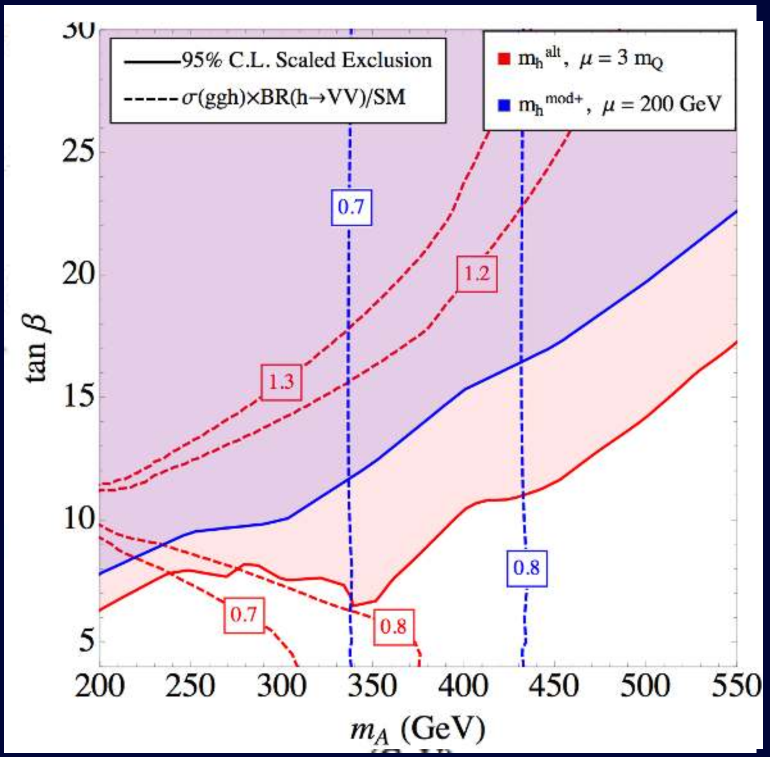
Complementarity crucial to probe
SUSY Higgs sector

Correlations between deviations
may reveal underlying physics

A

At low tanβ: important to look for
H → WW+ ZZ, hh, tt ; A → Zh, tt

tanβ



M.C., Haber, Low, Shah, Wagner'14

m_A [GeV]

Similar effects in Extensions of the MSSM

~ Add new degrees of freedom that contribute at tree level to m_h ~

e.g. additional SM singlets or triplets or models with enhanced weak gauge symmetries

Two Higgs Doublet models and a Theory of Flavor

- The Froggatt Nielsen mechanism: Effective Yukawa coupling

$$\mathcal{L}_{\rm Yuk} = y_t \bar{Q}_L \tilde{H} t_R + y_b \left(\frac{S}{\Lambda}\right)^{n_b} \bar{Q}_L H\, b_R + \cdots$$

• New scalar singlet S obtains a vev: <S> =f

• Quarks & scalars are charged under a global $U(1)_F$ flavor symmetry

$$m_t = y_t \frac{v}{\sqrt{2}} \qquad m_b = y_b \frac{v}{\sqrt{2}} \left(\frac{f}{\Lambda}\right)^{n_b}$$

• Lighter quarks, more S insertions

$$y_{\rm eff} = \epsilon^n y \qquad \epsilon = f/\Lambda$$

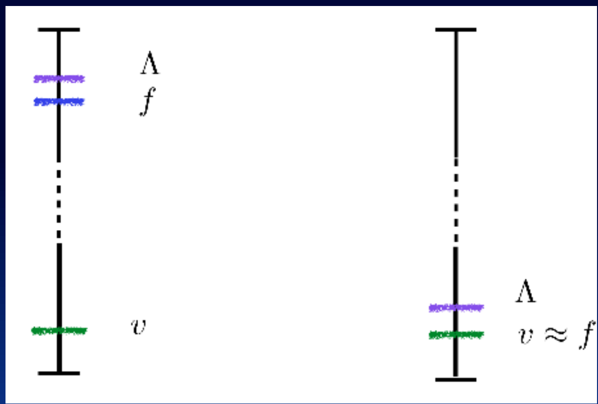
Issue: Scales undetermined

- How to define the scales? Can the Higgs play the role of the Flavon?

Babu ‘03, Giudice-Lebedev ‘08

$$y_b \left(\frac{S}{\Lambda}\right)^{n_b} \bar{Q}_L H\, b_R \to y_b \left(\frac{H^\dagger H}{\Lambda^2}\right)^{n_b} \bar{Q}_L H\, b_R$$

$$\epsilon = v^2/2\Lambda^2 \equiv m_b/m_t \to \Lambda \approx (5-6)v$$



Two Main Problems

- **The flavon is a flavor singlet**
- **The Higgs coupling to Bottom quarks is too large**

$$g_{hbb} \propto 3\, m_b/v$$

Two Higgs Doublet models and a Theory of Flavor (cont'd)

- Type II 2HDM with different flavor charges for H_u and H_d

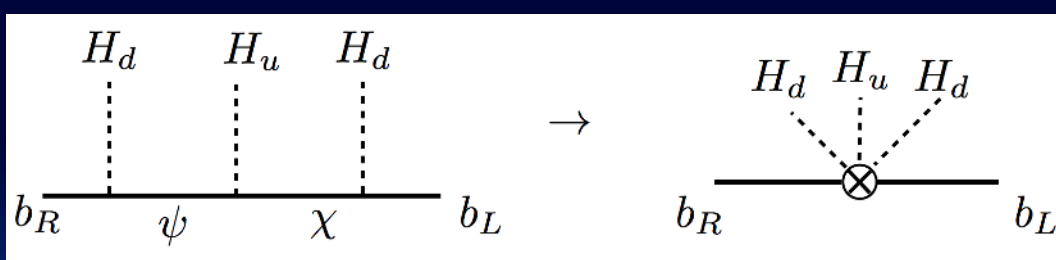
$$y_b \left(\frac{S}{\Lambda}\right)^{n_b} \bar{Q}_L H\, b_R \to y_b \left(\frac{H_u H_d}{\Lambda^2}\right)^{n_b} \bar{Q}_L H_d\, b_R$$

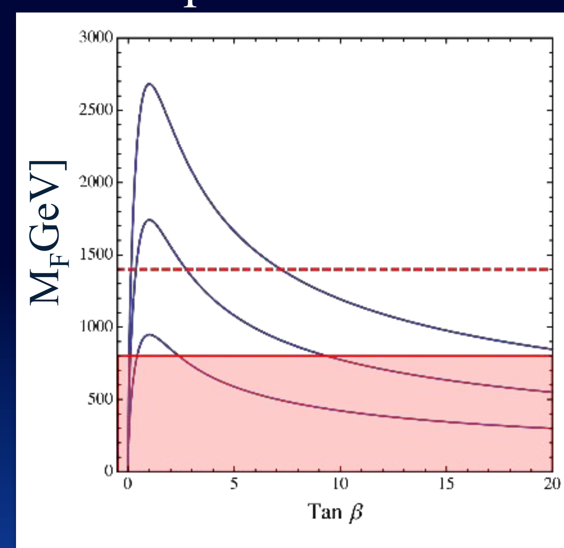
Bauer, MC, Gemmler '15

With effective Yukawa coupling suppression factor

$$\epsilon = \mathbf{v_u v_d/2\Lambda^2 \equiv m_b/m_t \to \Lambda \approx (5-6)v} \left(\frac{\tan\beta}{1+\tan^2\beta}\right)^{1/2}$$

The value of $\Lambda \sim 4$ v ~ 1TeV (maximizes for tan β = 1)
and can be slightly larger depending on the specific UV completion





Flavor from the Electroweak Scale

- Flavor Structure by fixing flavor charges

$$m_t \approx \frac{v_u}{\sqrt{2}}, \quad \frac{m_b}{m_t} \approx \frac{m_c}{m_t} \approx \varepsilon^1, \quad \frac{m_s}{m_t} \approx \varepsilon^2, \quad \frac{m_d}{m_t} \approx \frac{m_u}{m_t} \approx \varepsilon^3$$

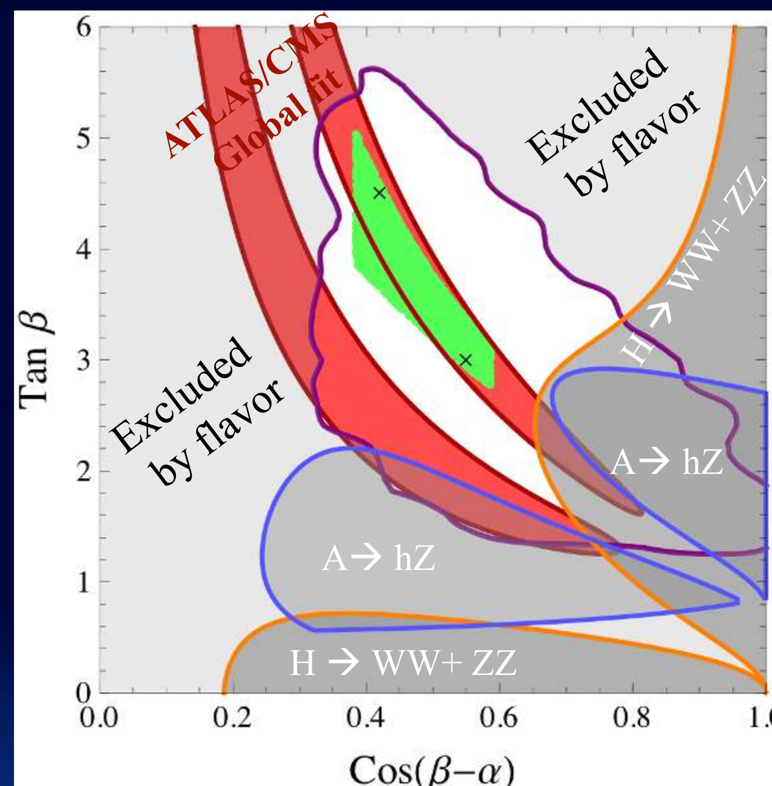
$$(V_{\rm CKM})_{12} \approx \varepsilon^0, \qquad (V_{\rm CKM})_{13} \approx (V_{\rm CKM})_{23} \approx \varepsilon^1$$

- Higgs couplings to gauge bosons and top quark as in 2HDM
- Light quark coupling to Higgs special!

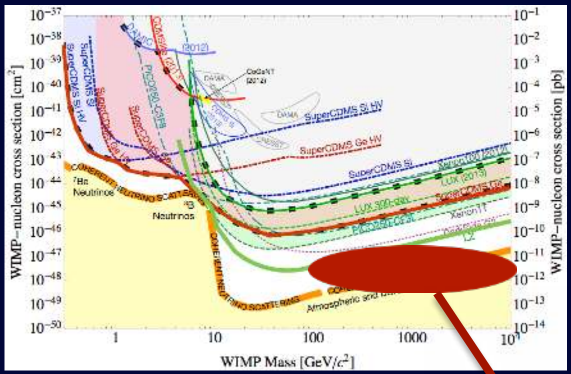
~ in particular Higgs-bottom coupling ~

A predictive model with new Physics at LHC reach (shaded green)

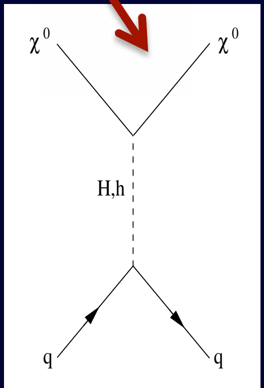
- Interplay of flavor phyiscs with precision Higgs global fit {ATLAS/CMS)
- Great possibilities for direct collider searches for additional Higgs bosons
- New particles in the few TeV range



We are exploring the Higgs connections



- In there a Higgs portal to dark matter and/or other dark sectors?



- Is Baryogenesis generated at the EWSB scale?
- How does the Higgs talk to neutrinos ?
- What are the implications of the Higgs sector for flavor?
- Is the Higgs a portal to new particles and new energy scales?
- Is the Higgs related to inflation or dark energy?
- What is the dynamical origin of the electroweak scale?

Revolutionary advances
in our understanding of the Universe
are driven by
powerful ideas and powerful instruments

Higgs Mechanism ⟷ LHC

What's Next?

The existence of Dark Matter and the Matter-Antimatter Imbalance implies new physics which may be accessible to experiment in this decade

The Higgs boson may play a key role in understanding both mysteries of matter and even connecting with neutrinos