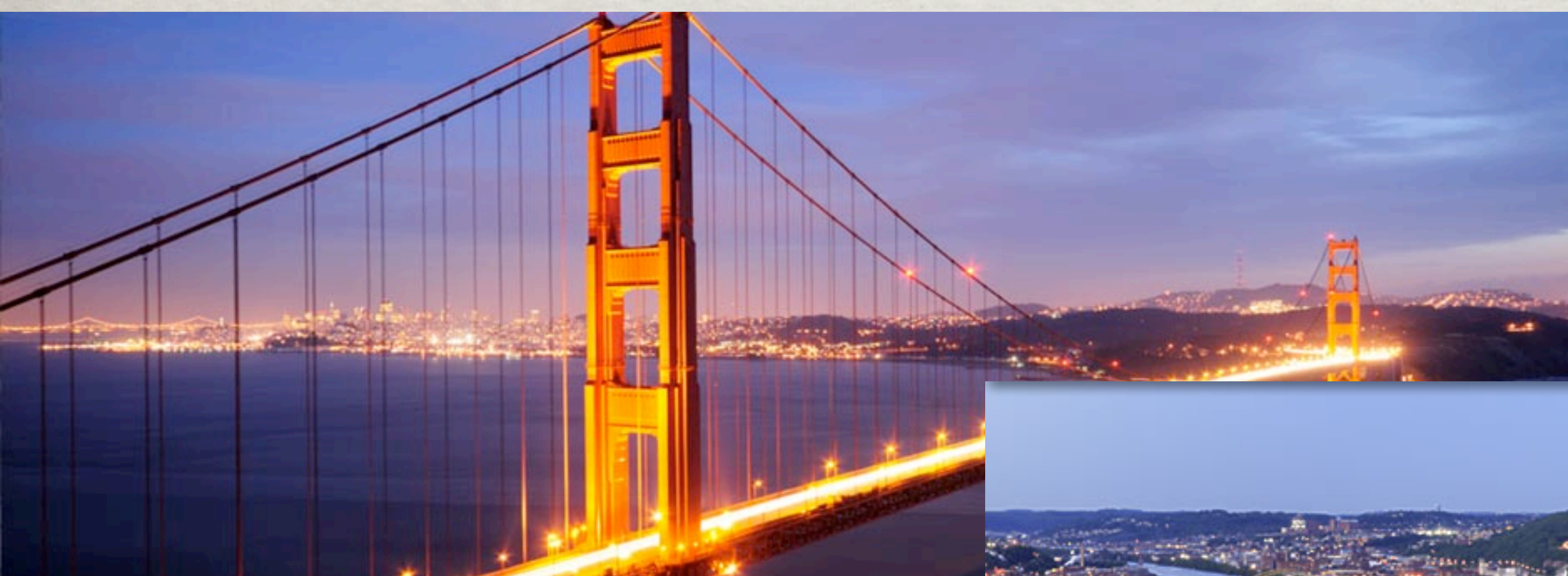
The Higgs Boson & Beyond

--- In light of the Discovery

Tao Han, Univ. of Pittsburgh

LP 2013, SLAC, San Francisco

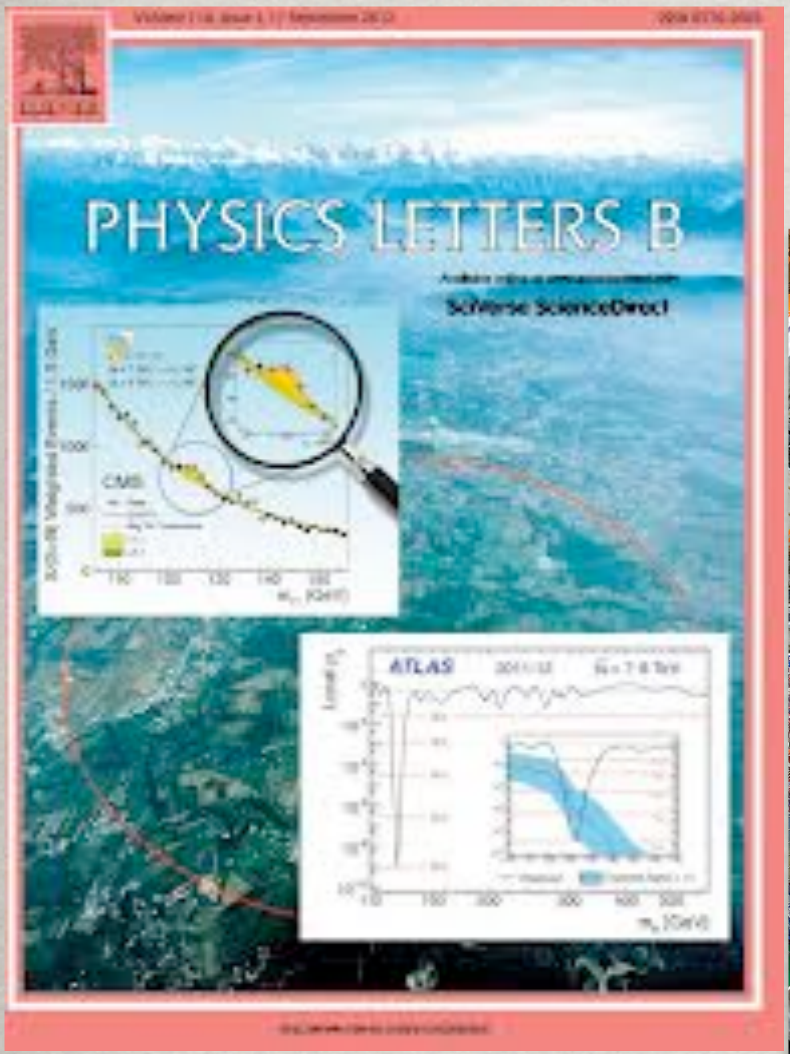
June 24, 2013

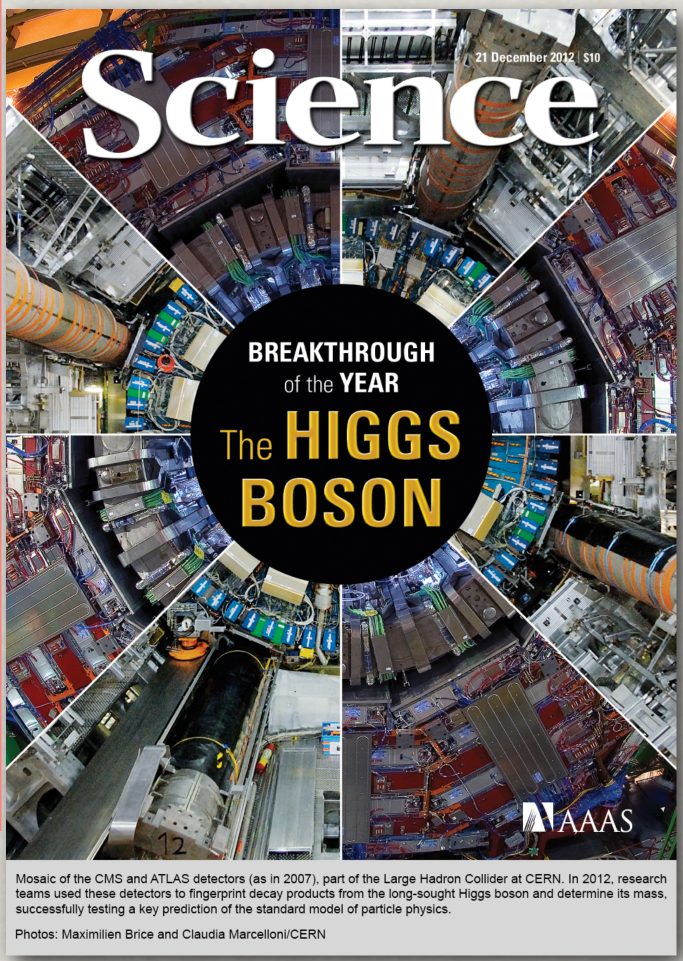


The milestone Discovery:

July 4^{th}, 2012:

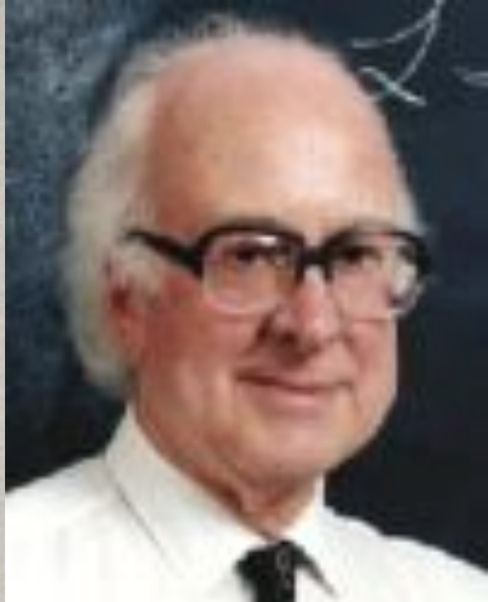
$m_H \approx 126$ GeV
ATLAS: 5.9σ ; CMS: 5.0σ

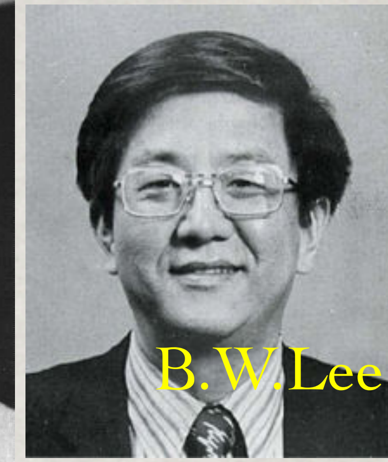


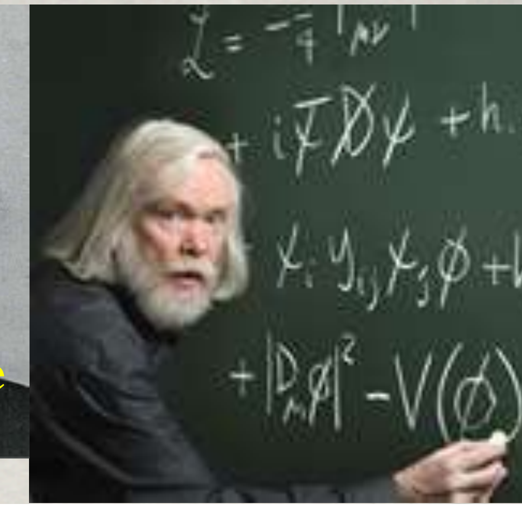


Salute To You All !

Higgs Phenomenology (70's)







The Higgs mechanism (1964)

The SM (1960-1967)

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as ...

The "EHLQ" (80's)

Fermi National Accelerator Laboratory

FERMILAB-Pub-84/17-T
LBL-16875
DOE/ER/01545-345
February, 1984

Supercollider Physics

E. EICHTEN
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...rkeley, CA 94720

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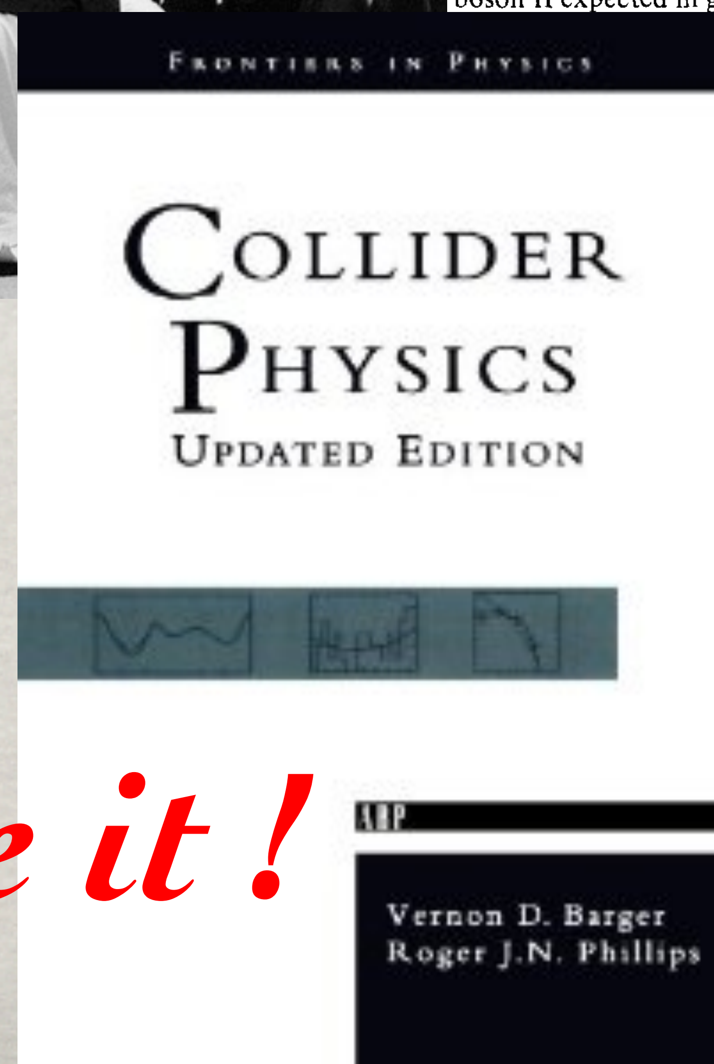
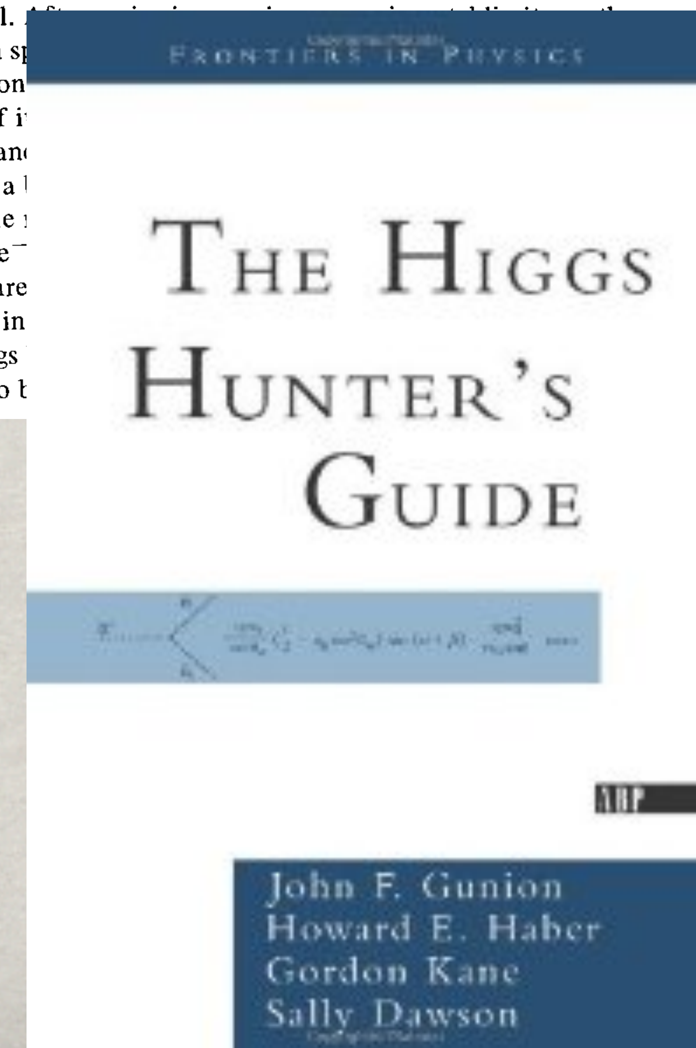




We made it !

What We Know

1. X → γγ :

- it's neutral, a boson
- can be spin-0 $\frac{f_s}{\Lambda} H A^{\mu\nu} A_{\mu\nu}$
- cannot be spin-1 (Landau-Yang's theorem)
- can be spin-2 $\frac{f_T}{\Lambda} T_{\mu\mu'} g_{\nu\nu'} A^{\mu\nu} A^{\mu'\nu'}$
  unlikely/disfavored

2. X → ZZ, W^+W^- :

- Vacuum Q#: EWSB $(v+H)^2 g^2 V^\mu V_\mu$
- CP-odd part must be small $\frac{f_A}{\Lambda} A \tilde{V}^{\mu\nu} V_{\mu\nu}$

3. X not to $\mu^+\mu^-$, e^+e^-, but $\tau^+\tau^-$ seen (vaguely)

- Non-universal leptonic couplings unlike the gauge couplings

$$(1 + H/v)\, m_f \bar{\psi}_f \psi_f$$

4. X$t\bar{t}$ needed for gluon fusion

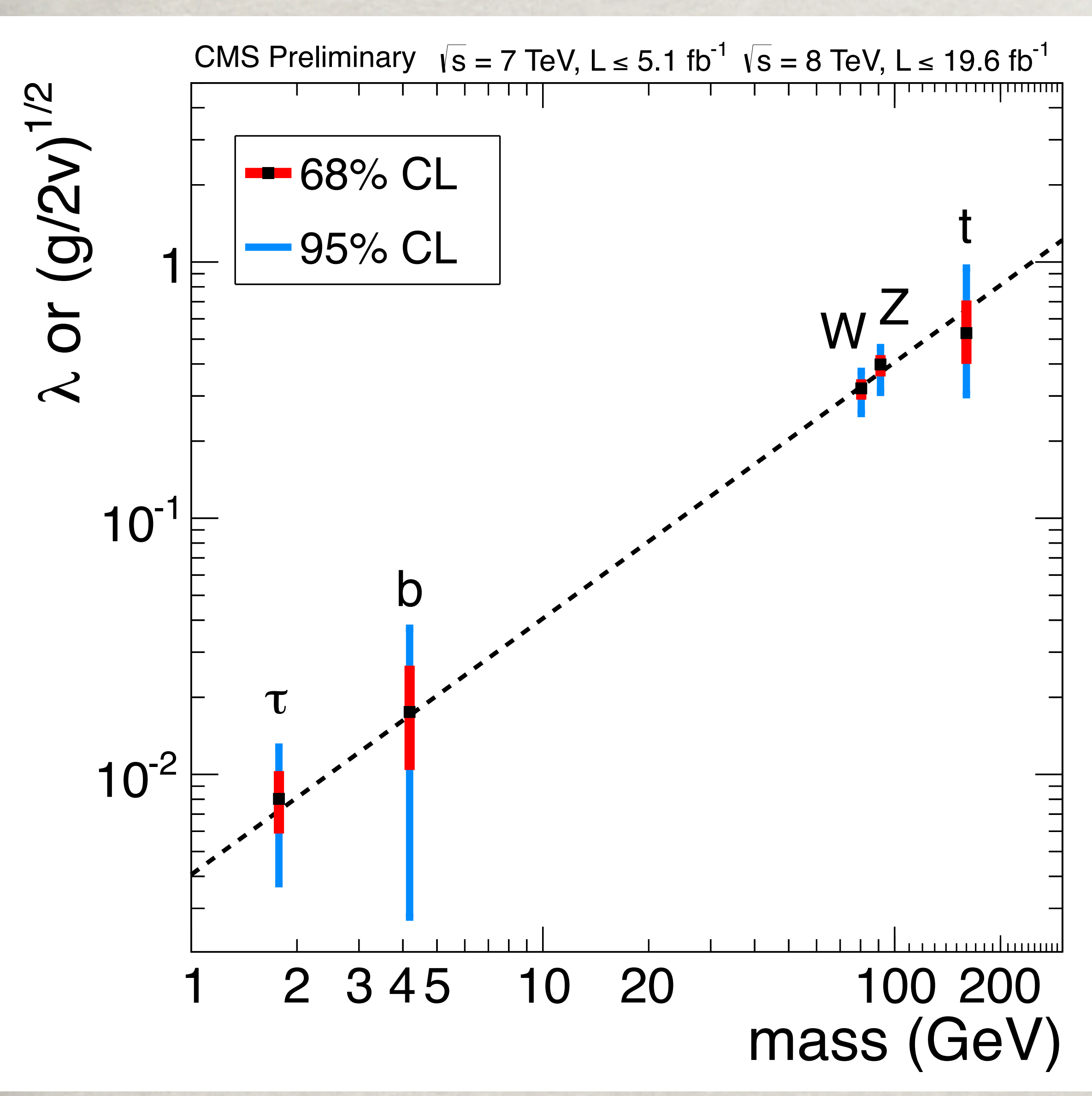
X → $b\bar{b}$ seen (vaguely)

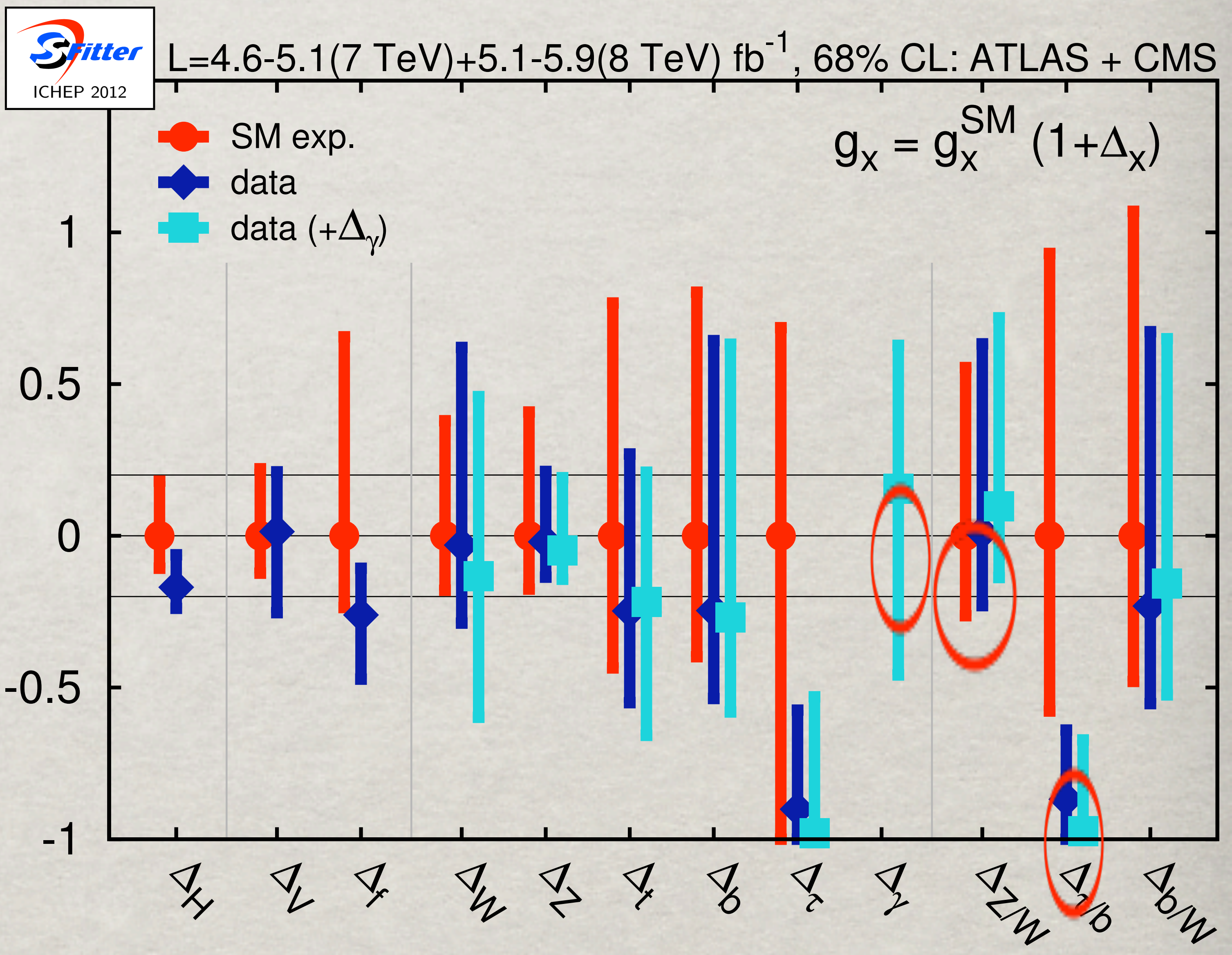
- Non-universal quark couplings

It couples to mass, it IS a Higgs!

The SM (like) ?

Need further quantitative verification:





SFitter: T. Plehn et al., 2012

See talks by

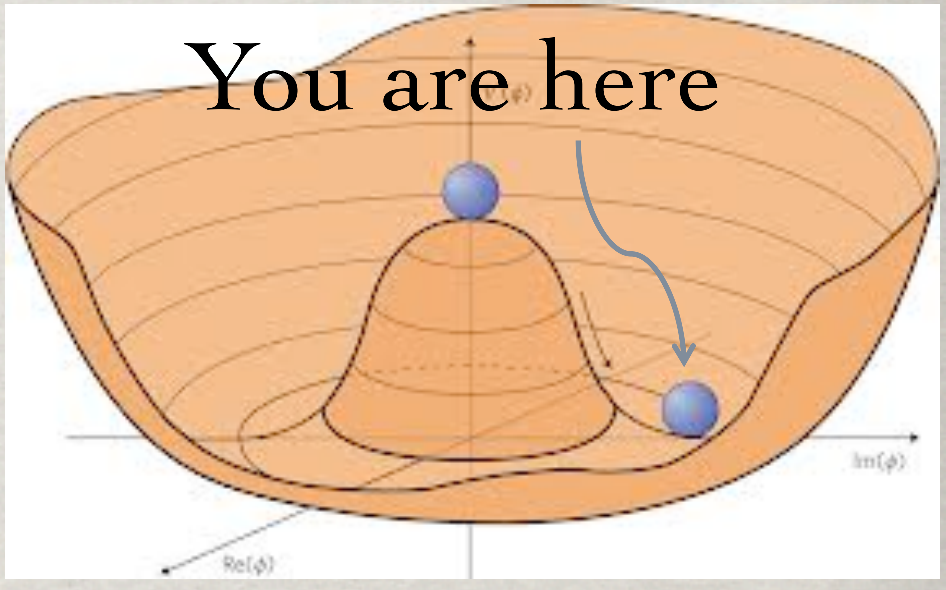
Karl Jakobs, A. de Roeck

What (else) We Know

$m_H \approx 126$ GeV !

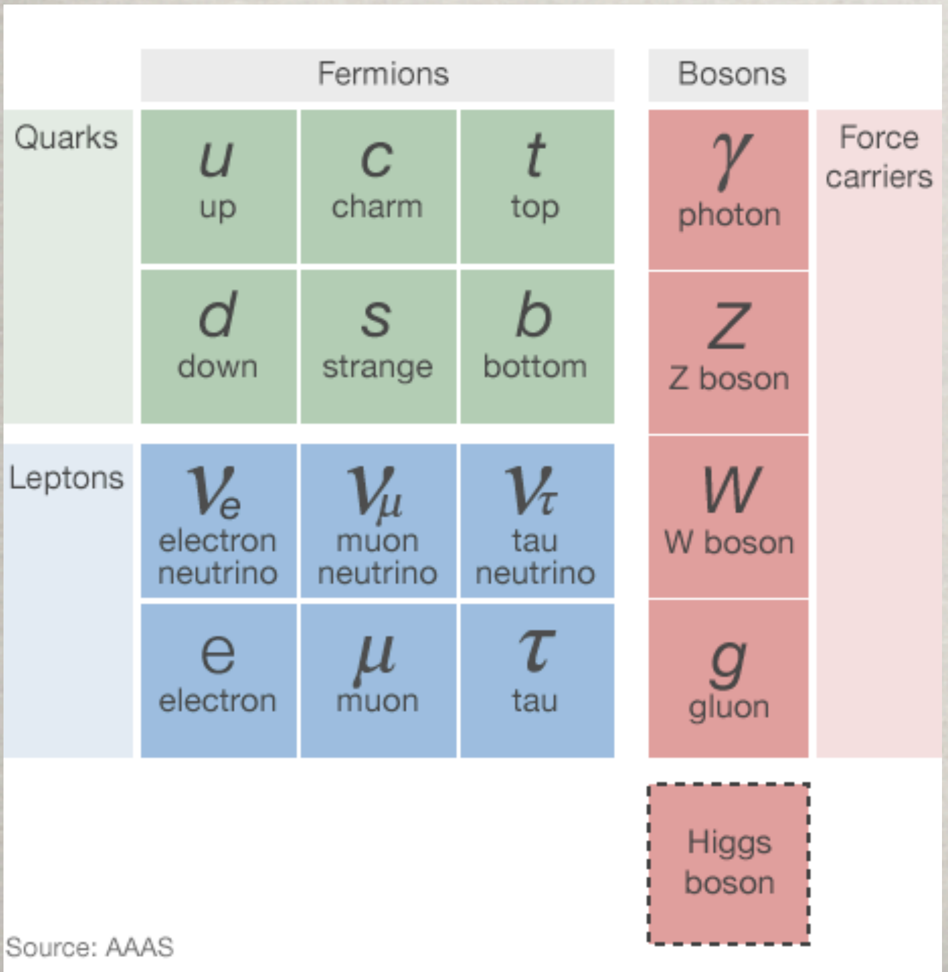
In the SM, the EWSB is parameterized as

$$V(|\Phi|) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$
$$\Rightarrow \mu^2 H^2 + \lambda v H^3 + \frac{\lambda}{4}H^4$$



Consequently,

$$m_H^2 = 2\mu^2 = 2\lambda v^2 \quad \Rightarrow \quad \mu \approx 89 \text{ GeV}, \quad \lambda \approx \frac{1}{8}.$$



$$v = (\sqrt{2}G_F)^{-1/2} \approx 246 \text{ GeV}$$

Completion of the SM:
A perturbative, renormalizable theory, valid up to a scale of

TeV ? …, M_{Pl} ?

New Era: Under the Higgs lamp post

The "Observation" papers: now 1350 cites each!

Vast scope of topics, from interpretations, explorations in & beyond the SM; applications in astronomy, cosmology, CC; strings/branes, to "Philosophical Perspectives …."

Apologies for not being able to properly reflect the efforts!

A Reminder

The Higgs mechanism ≠ a Higgs boson !

From theoretical point of view,
3 Nambu-Goldstone bosons were all we need!
A non-linear realization of the gauge symmetry:

$$U = \exp\{i\omega^i \tau^i / v\}, \quad D_\mu U = \partial_\mu U + i g W_\mu^i \frac{\tau^i}{2} U - i g' U B_\mu \frac{\tau^3}{2}$$

$$\mathcal{L} = \frac{v^2}{2}[D^\mu U^\dagger D_\mu U] \to \frac{v^2}{4}(\sum_i g^2 W_i^2 + g'^2 B^2)$$

The theory is valid to a unitarity bound ~ 2 TeV

The existence of a light, weakly coupled Higgs boson carries important message for our understanding & theoretical formulation in & beyond the SM.

What It tells us

1. $V = -\mu^2 |\phi|^2 + \lambda |\phi|^4$

It represents a weakly coupled
new force (a fifth force):

- **In the SM, λ is a free parameter, now measured $\lambda \approx 0.13$**

- **In SUSY, it is related to the gauge couplings tree-level: $\lambda = (g_L^2 + g_Y^2)/8 \approx 0.3/4$ ← a bit too small**

- **In composite/strong dynamics, harder to make λ big enough. (due to the loop suppression by design)**

Already possess challenge to BSM theories:

Too heavy to be light; too light to be heavy!

λ at High energies

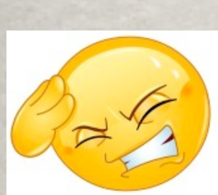
λ is NOT asymptotically free.

It blows up at a high-energy scale (the Landau pole), unless it starts from small (or zero → triviality).

For M_H = 126 GeV, rather light:

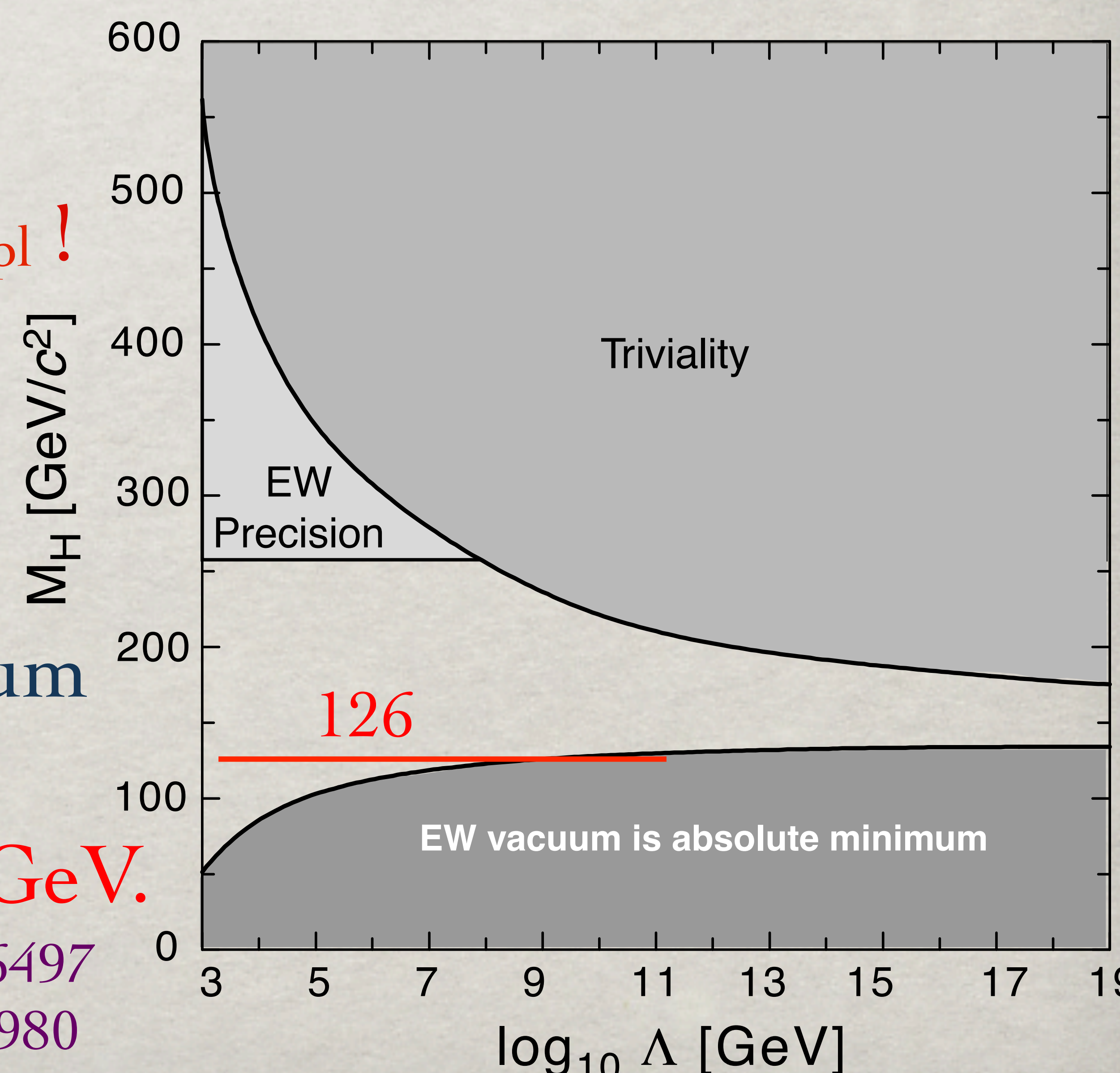
The SM can be a consistent perturbative theory up to M_{pl} ! allowing M_N, M_{GUT}, …

Bezrukov et al., arXiv:1205.2893.



Top-Yukawa drags the vacuum meta-stable, or new physics below $10^{7\text{-}11}$ GeV.

Degrassi et al., arXiv:1205.6497
Djouadi et al., arXiv:1207.0980

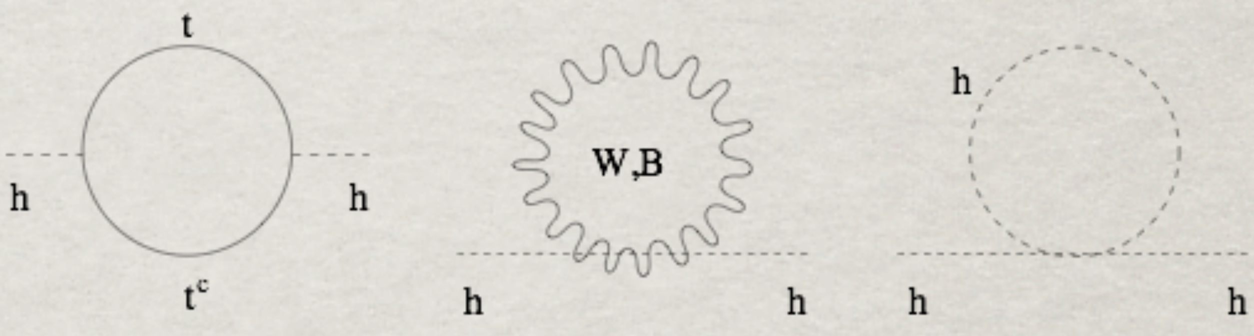


2. $V = -\mu^2|\phi|^2 + \lambda|\phi|^4$

"… scalar particles are the only kind of free particles whose mass term does not break either an internal or a gauge symmetry." Ken Wilson, 1970

the only dimensional parameter allowed by SM symmetry.

The "large hierarchy":



(a) (b) (c)

$$m_H^2 = m_{H0}^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2 + \frac{1}{16\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

If $\Lambda^2 \gg m_H^2$, then unnaturally large cancellations must occur.

Michael Dine's cancelation:

m_H^2 = 36,127,890,984,789,307,394,520,932,878,928,933,023

−36,127,890,984,789,307,394,520,932,878,928,917,398

= (125 GeV)^2 ! ?

10^{-3} fine-tune

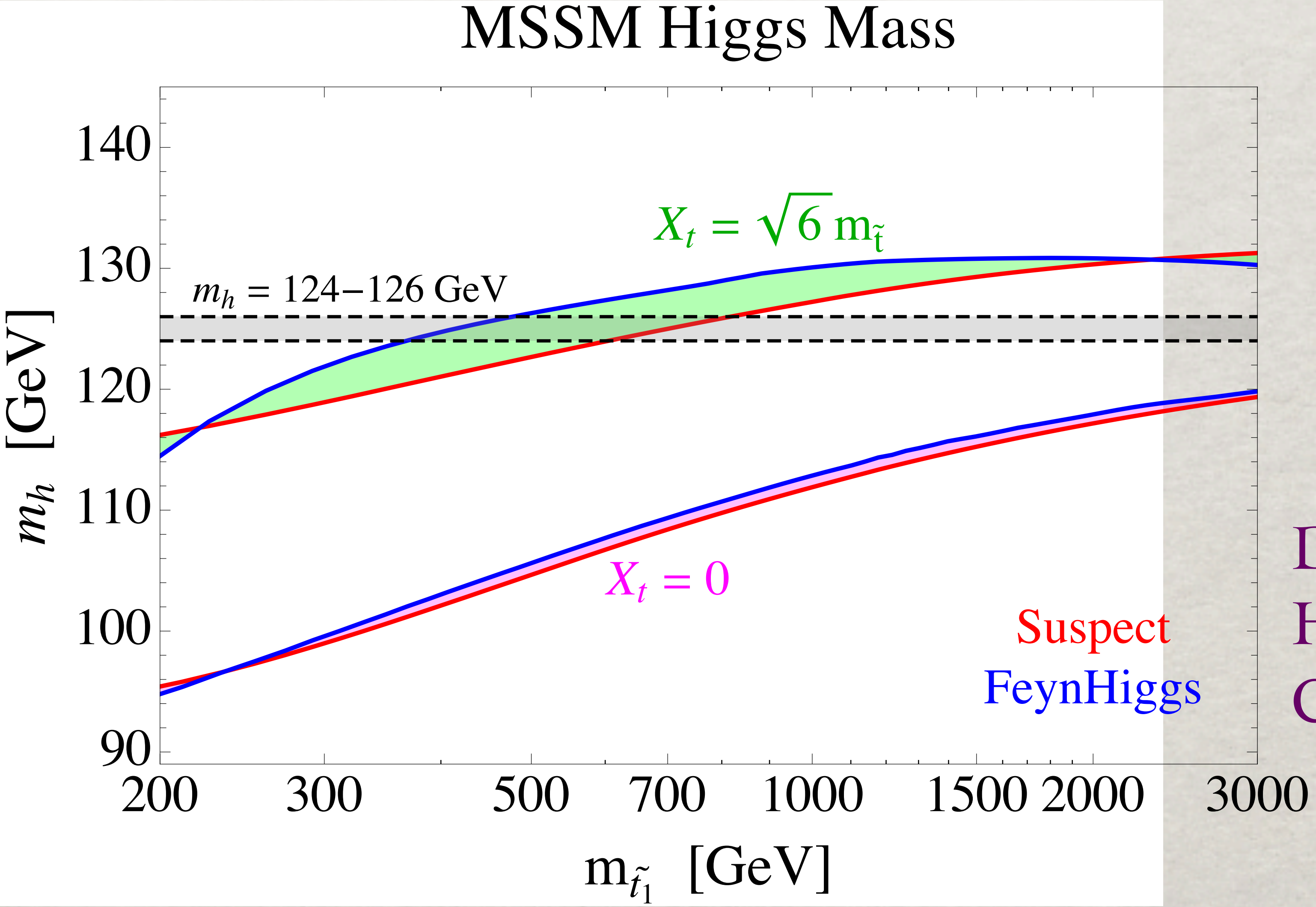
"Naturalness" → TeV scale new physics.

The "Little hierarchy":

- **In SUSY,** $m_H^2 \approx M_Z^2 \cos^2 2\beta + \Delta m^2_{SUSY}$

  Tree-level $<(80\text{ GeV})^2$ + loop-level: $>(45\text{ GeV})^2$

→ Need large tanβ; m_{stop} & mixing $X_t >> m_t$



Barbieri, Giudice, 1988
Kitano et al, 2005
Giudice, 2007
Feng, 2013

Draper, Shih, Meade, Reece, 2011
Hall, Pinner, Ruderman, 2012
Carena et al., 2012, 2013

The "Little hierarchy":

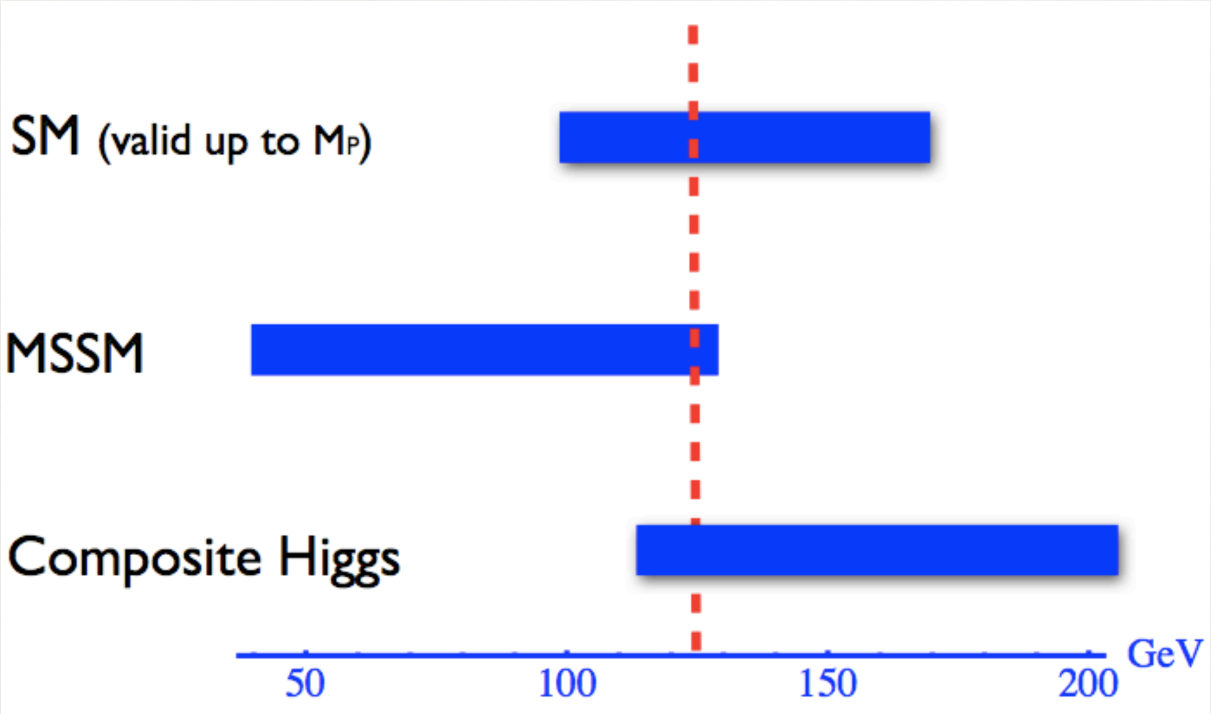
- **In composite/strong dynamics:**
  (dual of extra dimension theory)

The Higgs boson as a pseudo-Goldstone boson:

$$m_H^2 \sim \frac{f^2}{(4\pi)^2} \sim \frac{m_t^2 M_T^2}{f^2}.$$

Akani-Hamed et al., 2002
Contino, Nomura, Pomarol, 2003
Agashe, Contino, Pomeral, 2005
Csaki, Hubitz, 2012

→ "naturally light": Need low scale f, M_T .



Both SUSY/Compositeness suffer from some degree of "fine-tune": < 1% .

See talk by M. Nojiri

Pomarol, ICHEP'12

What We Wish to Know

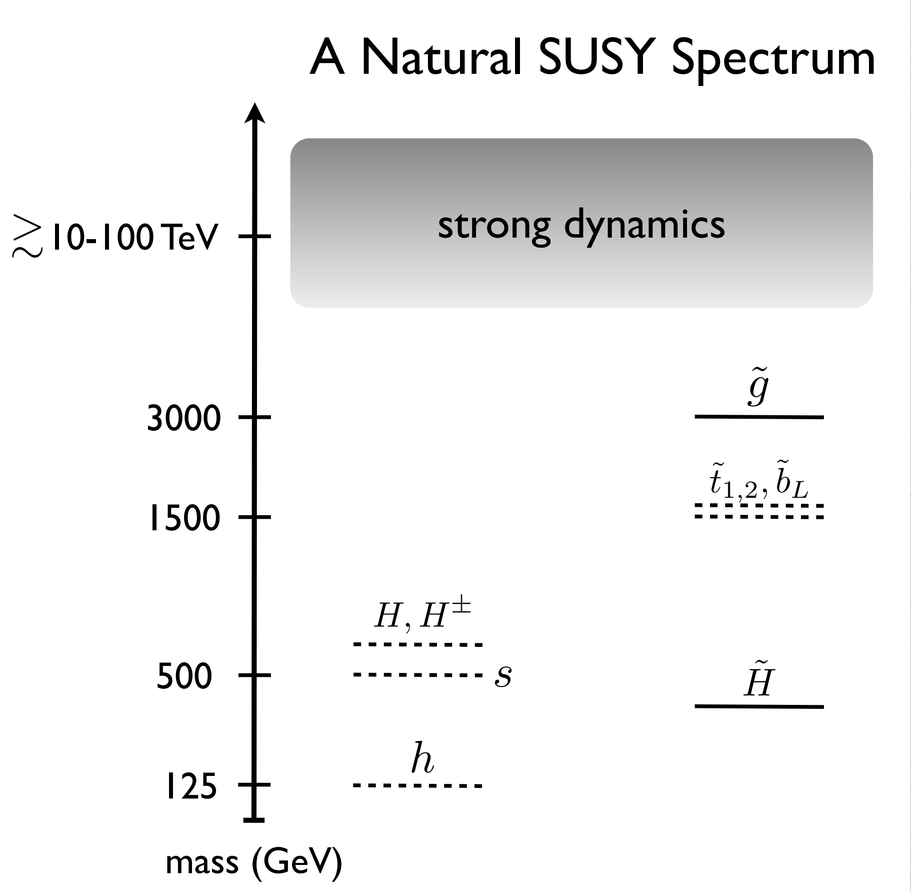
1. A "natural" EW theory ?

- "Natural SUSY":

Cohen, Kaplan, Nelson, 1996
Hall, Pinner, Ruderman, 2012
Baer, Barger, Huang, Tata, 2012

Relevant to the Higgs and the "Most Wanted":

$\tilde{H}^{0,\pm}, \ \tilde{t}, \ \tilde{b}, \ (\tilde{g}); \ S, \ \tilde{S}...$



Current LHC bounds:

$m_{\tilde{t}} > 200 - 680$ GeV,

See talk by A. Hoecker

$m_{\tilde{\chi}^{\pm}} > 100 - 600$ GeV (depending on m_{χ^0})

- "Compositeness": the T', current ATLAS limit:

$M_T > 480$ GeV, for $M_A < 100$ GeV.

2. Extended Higgs sector?

The Higgs boson should have not only relatives:

$\tilde{t},\ \tilde{b},\ \tilde{H}^{\pm,0};\ \ T',$

But also siblings: $H_i^0,\ A_j^0,\ H^{\pm},\ H^{\pm\pm}, \ldots.$

Haber, 2012
Branco, Ferreira, Rebelo,
Sher, Silva, arXiv:1106.0034;
Coleppa, Kling, Su, arXiv:1305.0002.

- Two Higgs Doublet Model (2HDM):
  rich phenomenology, Type II SUSY option …

Ellwanger, Gunion et al., 2012
S. King et al., 2012
R. Barbieri et al., 2013, ……

- Plus a singlet:
  NMSSM, solve the μ-problem, relax fine-tune, light DM…

- Triplet Model:
  m_ν , L-R symmetric theories, Little Higgs …

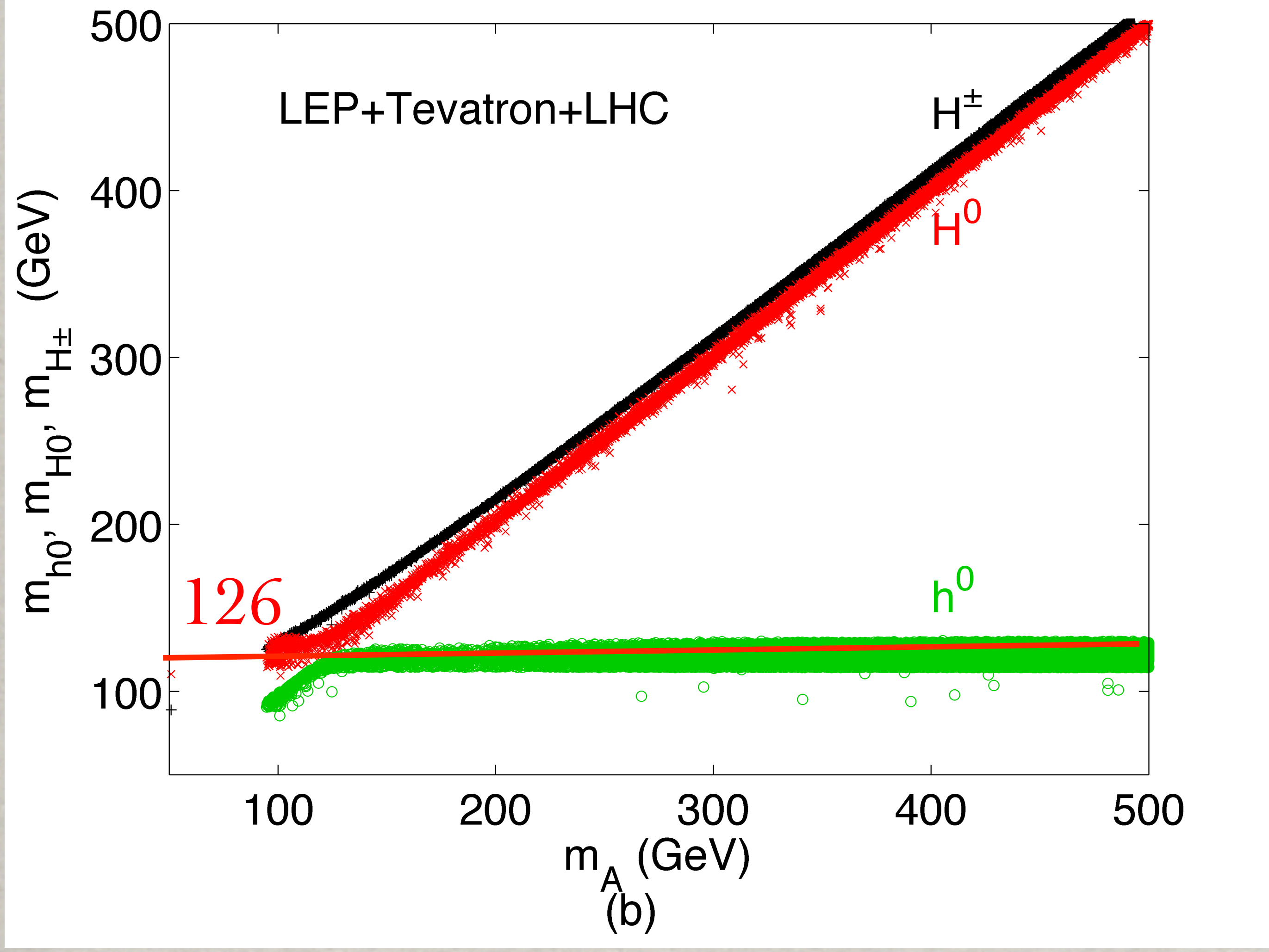
Example: MSSM Two Higgs-Doublet Model after the discovery:

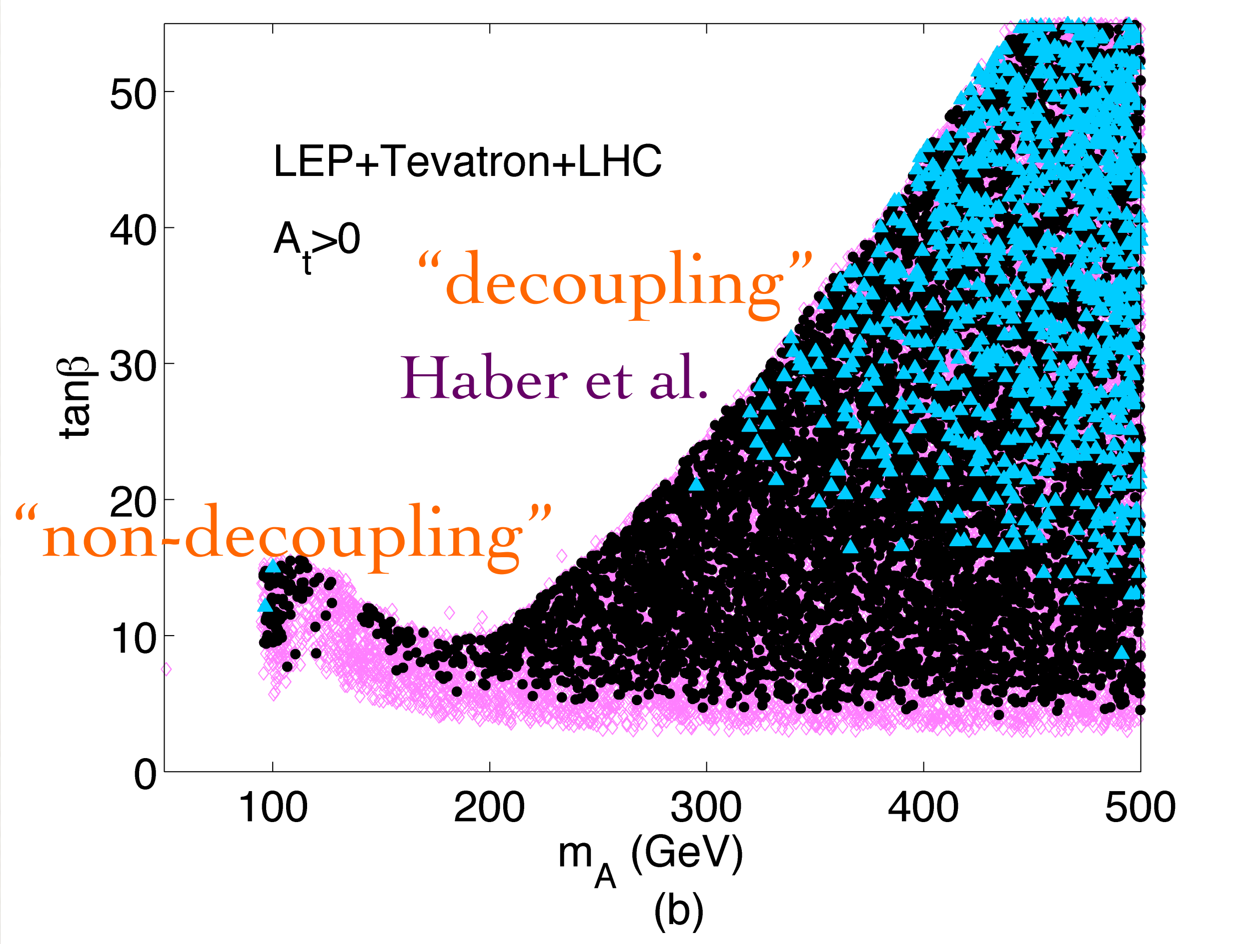
Arbey et al., 2011, 2012
Baer et al., 2012
Heinemeyer et al., 2012
Carena 2012, 2013, … …

5 Higgs bosons: $h^0,\ H^0,\ A^0,\ H^\pm$

Tree-level masses given by $M_A,\ \tan\beta$

Collider bounds:





TH, Su, Christensen, arXiv:1203.3207

Decoupling Sector M_A > 300 GeV:

Search for heavy H^0, A^0, $H^\pm$ will continue.

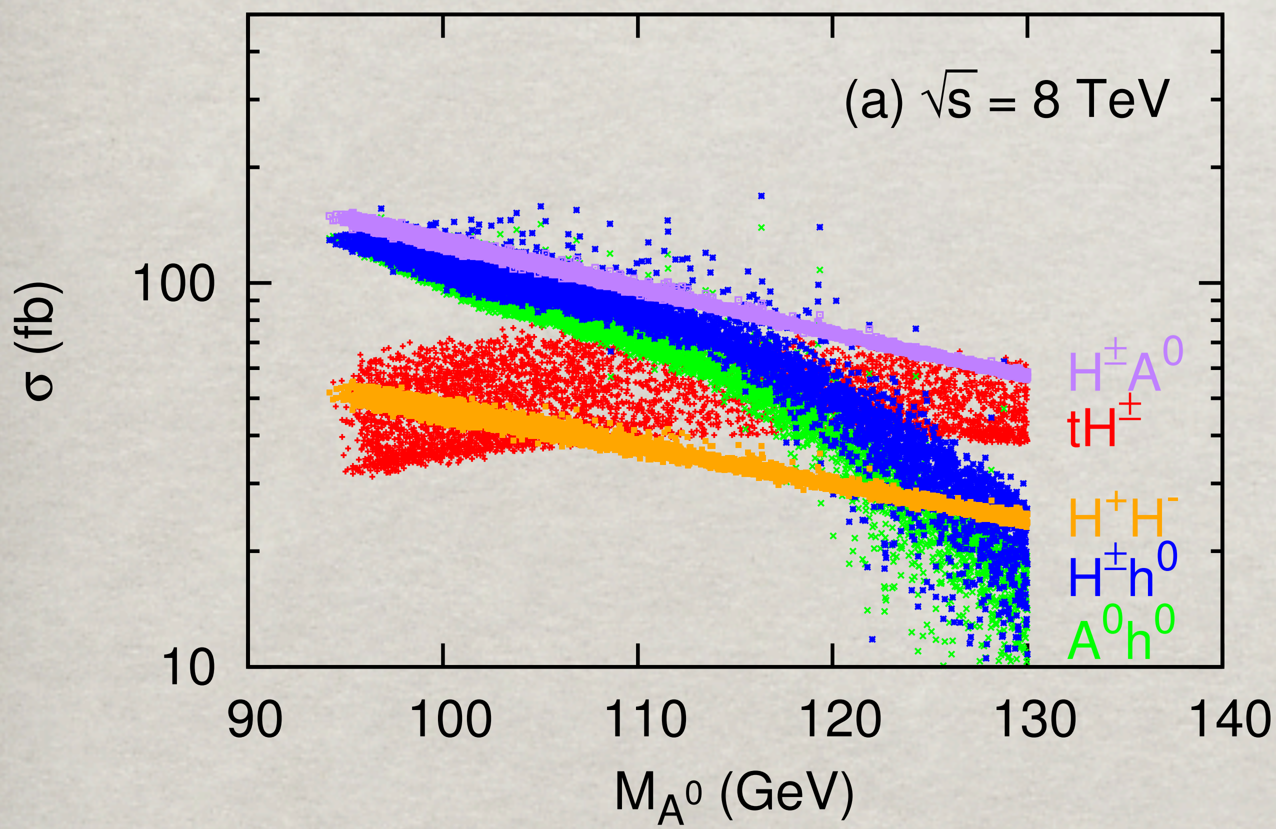
See talk by M.A. Owen

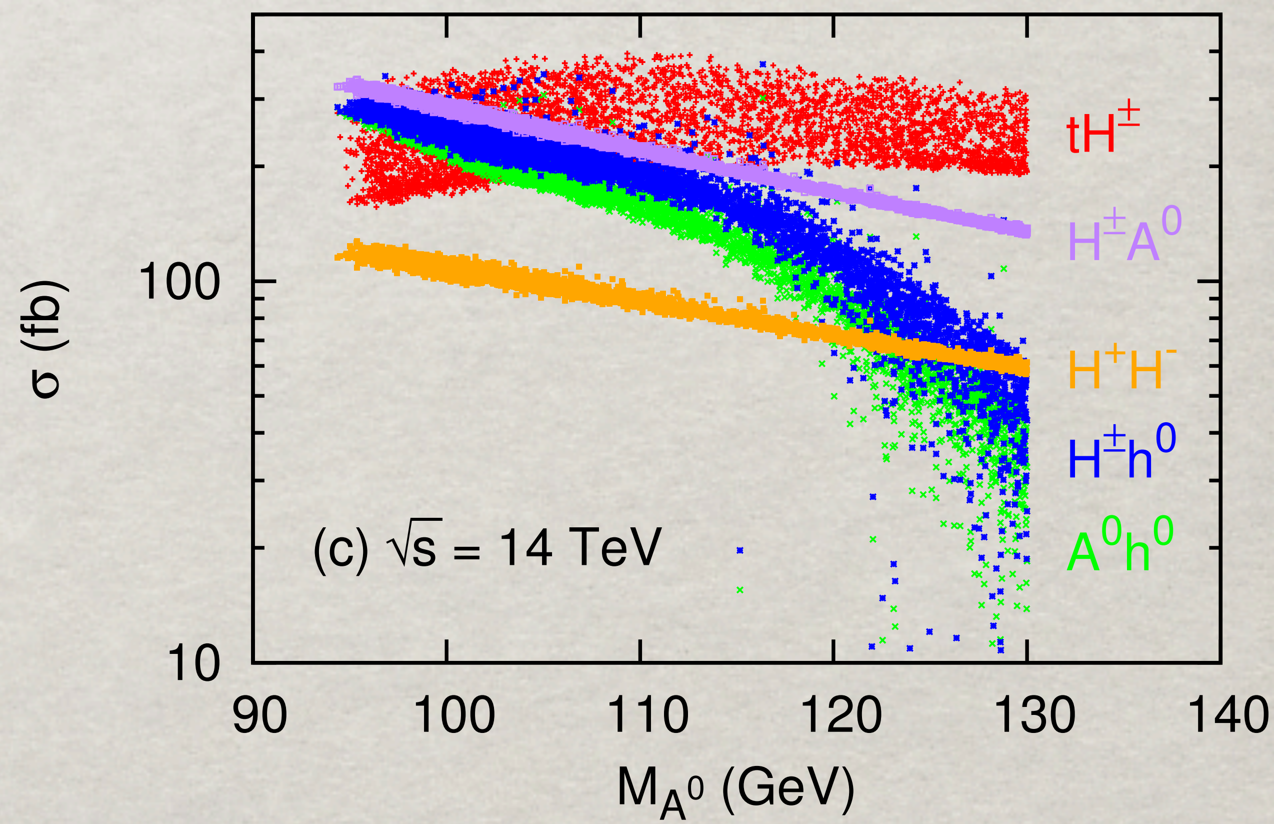
Non-Decoupling Sector: immediate relevance!

Typically: m_h, $M_A \sim M_Z$; while M_{H0}, $M_{H^\pm} \sim 125$ GeV

Model-independent: pp → $H^\pm A^0$, H^+H^- rate sizeable

Model-dependent: pp → $H^\pm h$, Ah comparable





TH, Li, Christensen, arXiv:1206.5816

3. The Higgs portals to Cosmos?

(a). Dark Matter

$H^\dagger H$ is the only bi-linear SM gauge singlet.

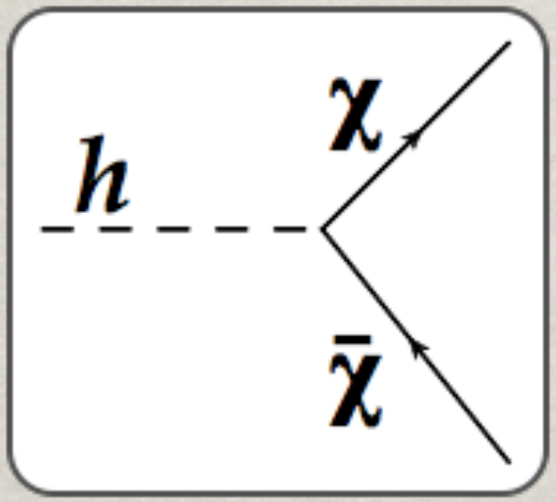
Bad: May lead to hierarchy problem with high-scale physics;

Good: May readily serve as a portal to the dark sector:

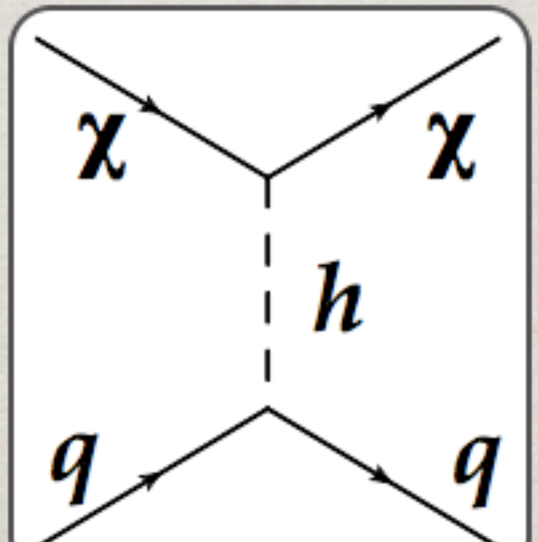
$$k_s H^\dagger H\ S^* S, \qquad \frac{k_\chi}{\Lambda} H^\dagger H\ \bar{\chi}\chi.$$

See talks by K. Zurek, T. Tait

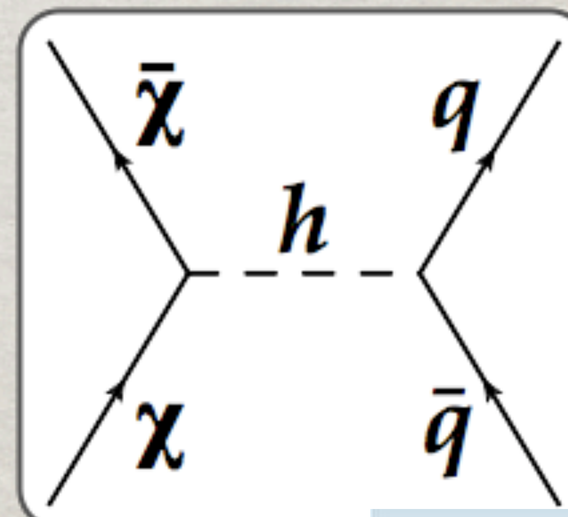
Missing energy at LHC

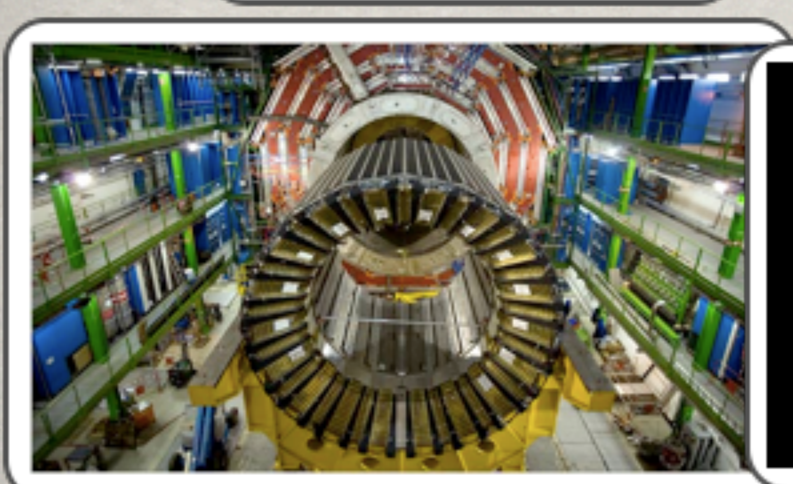


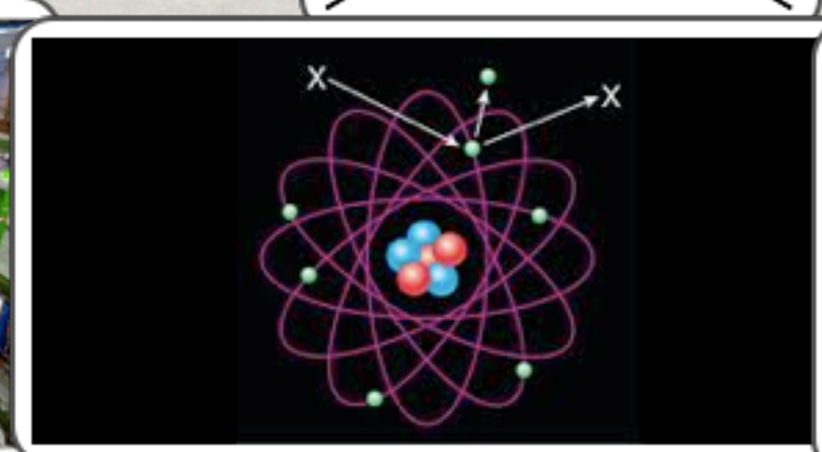
Direct detection

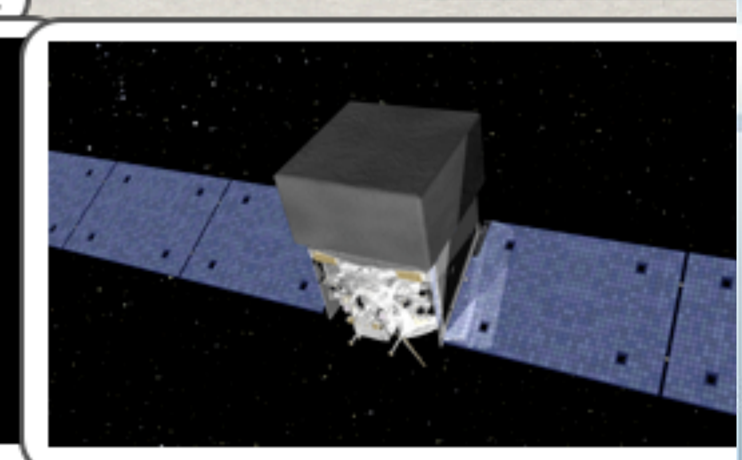


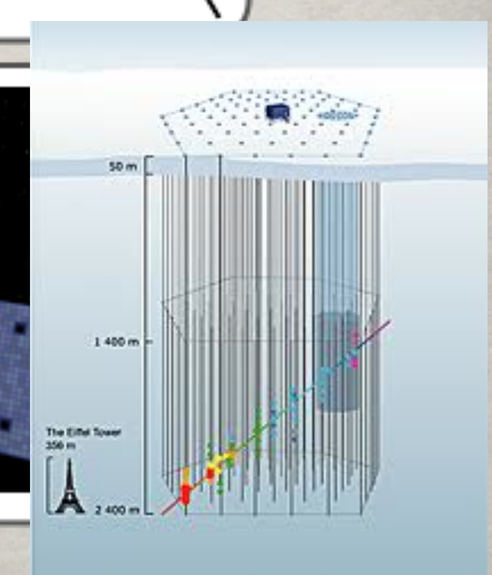
Indirect detection



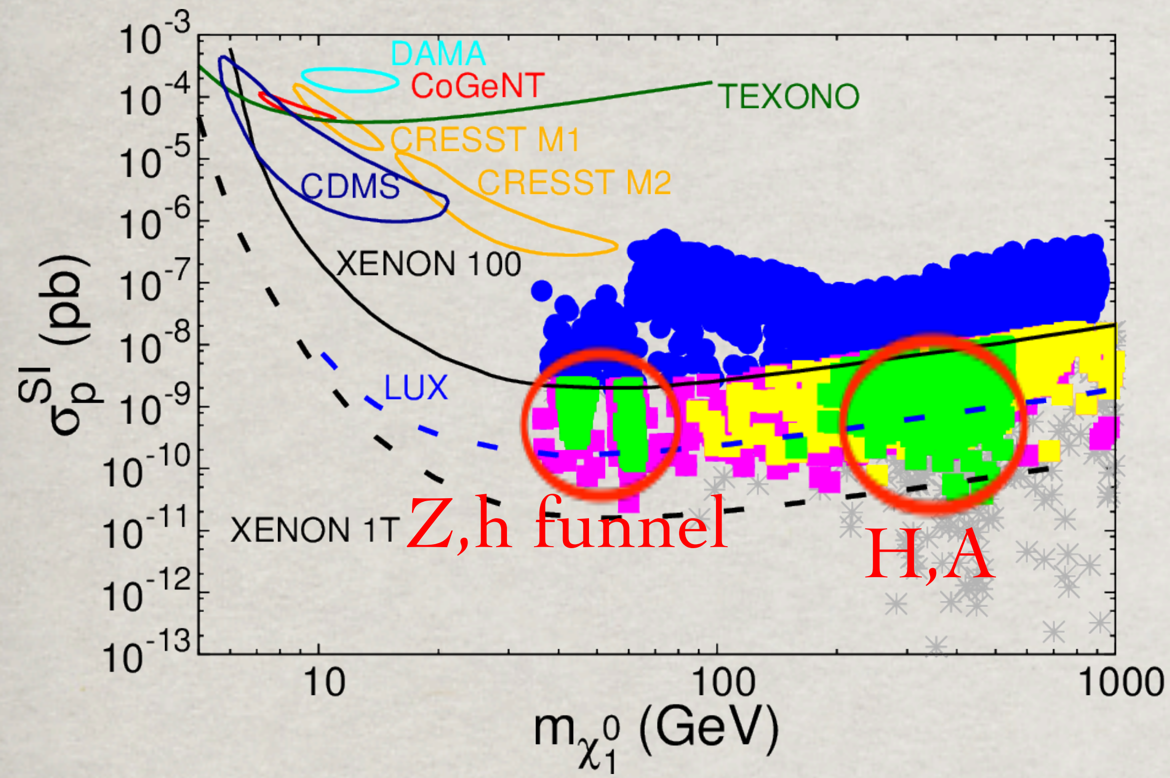




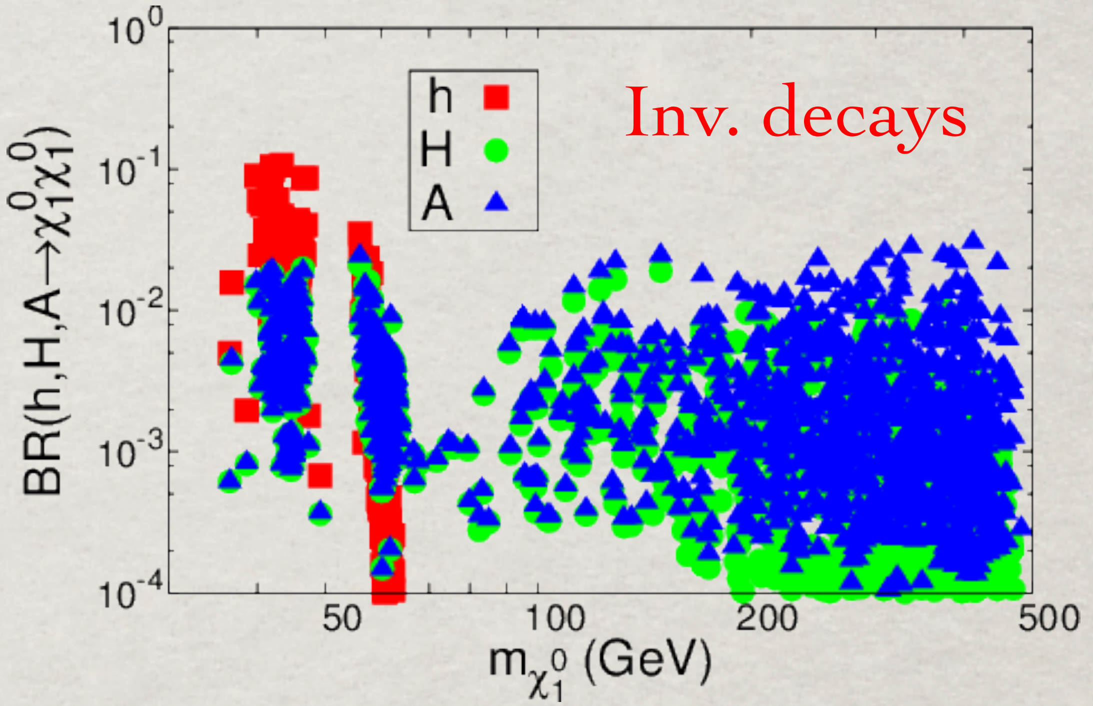


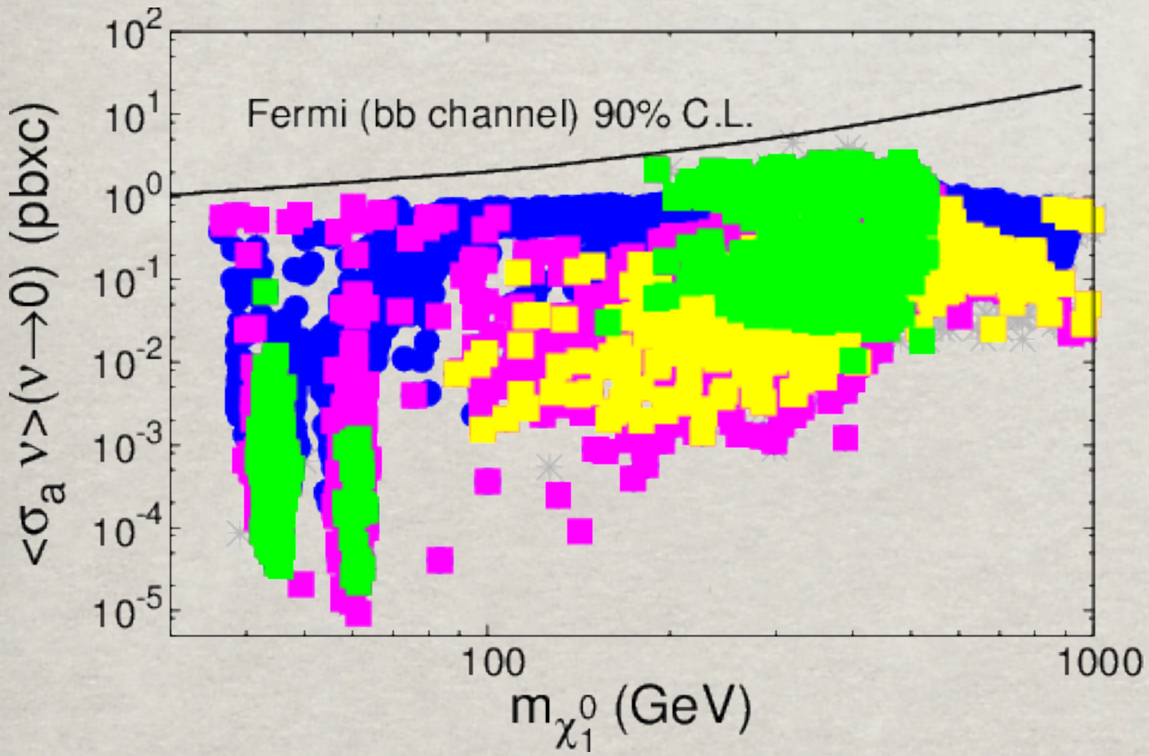


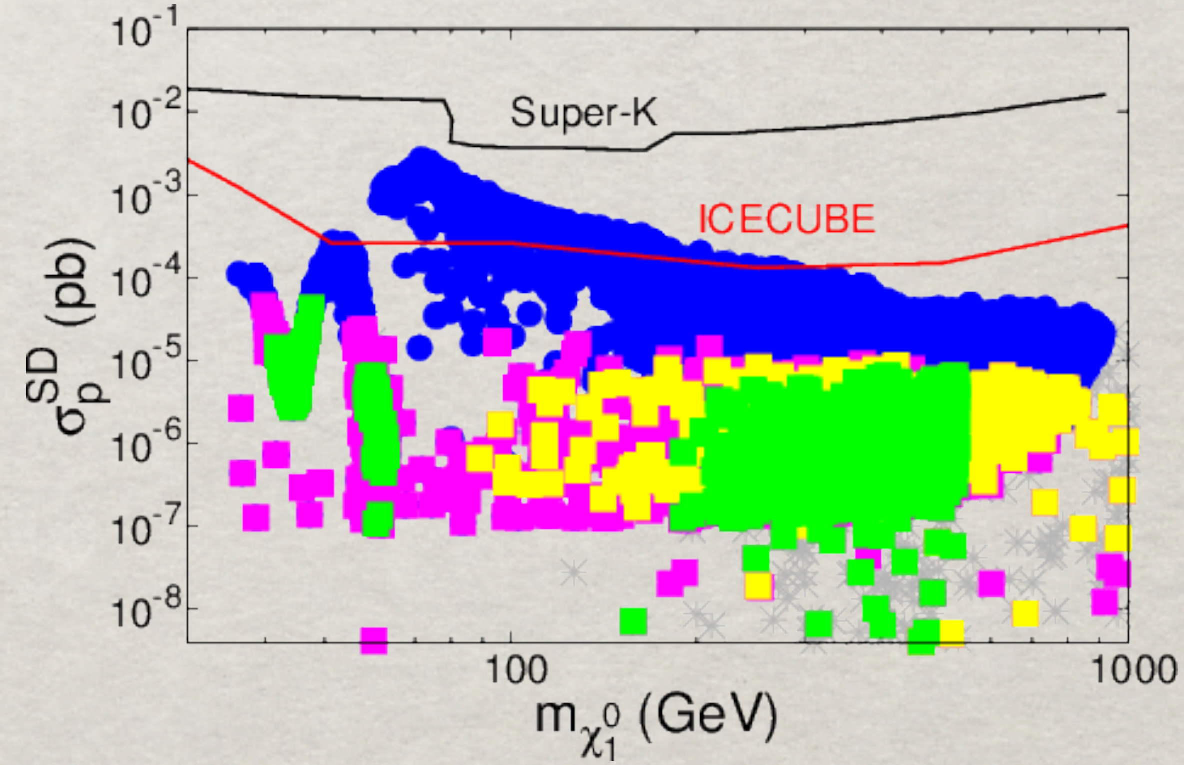
SUSY Higgs funnel soon covered by direct searches:



TH, Z.Liu, A.Natarajan, arXiv:1303.3040







Cahill-Rowley, Rizzo, Hewett et al. arXiv:1305.6921
Fowlie, Roszkowsky et al., arXiv:1306.1567

Other potential consequences

(b). Baryon – anti-baryon Asymmetry

For M_H = 126 GeV,
EW baryogenesis needs light sparticles:
$m_{stop} \approx 150$ GeV,
plus a light neutralino, singlets …

Carena et al., 2011;
Chung et al., 2011.

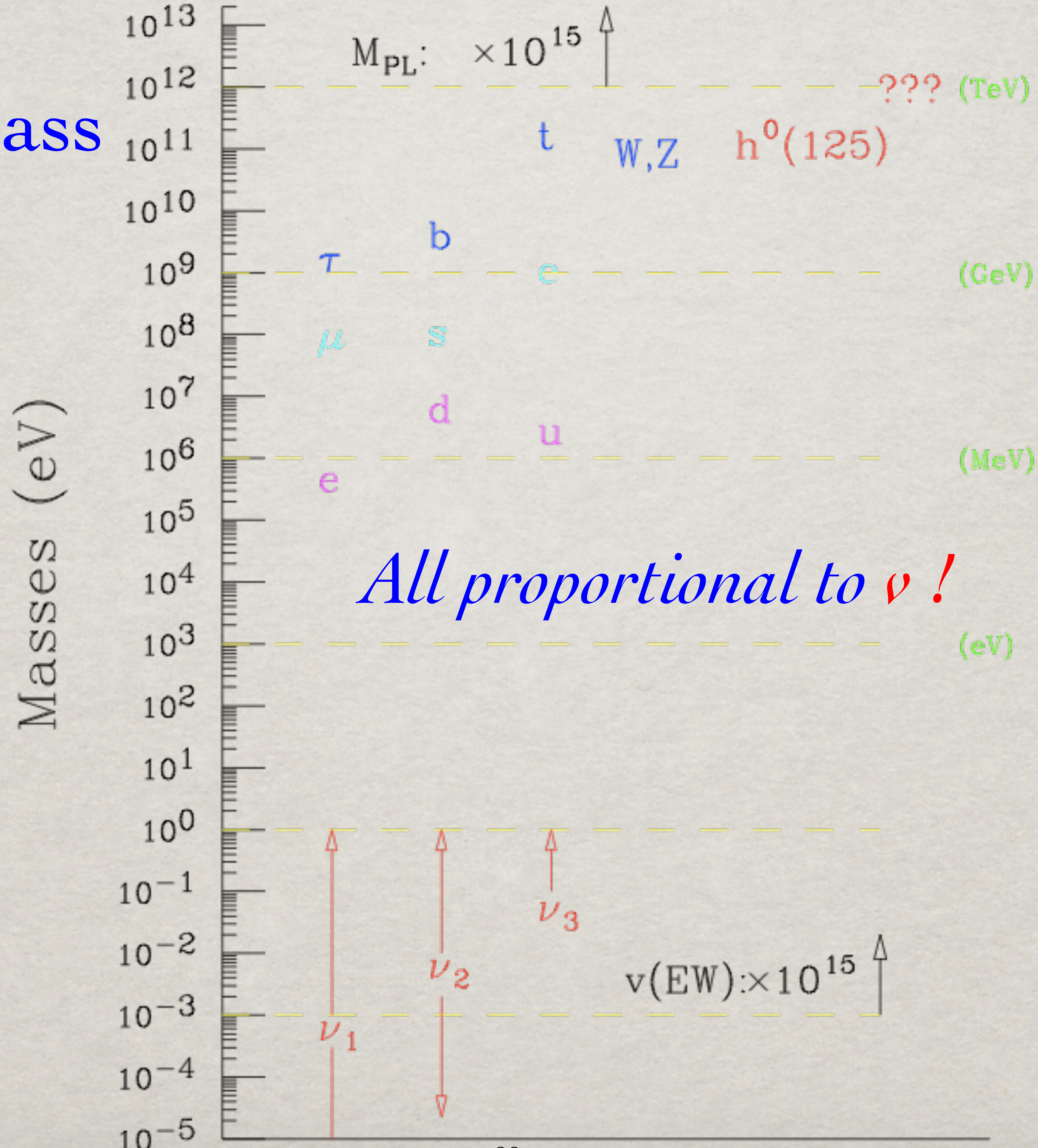
(c). Higgs as an inflaton?
(d). Higgs field & Dark Energy?

Bezrukov, 2008;
Nakayama, 2011.

The existence of a fundamental scalar encourages the consideration of scalar fields in cosmological applications.

4. Flavor & ν Masses

Particle mass hierarchy:



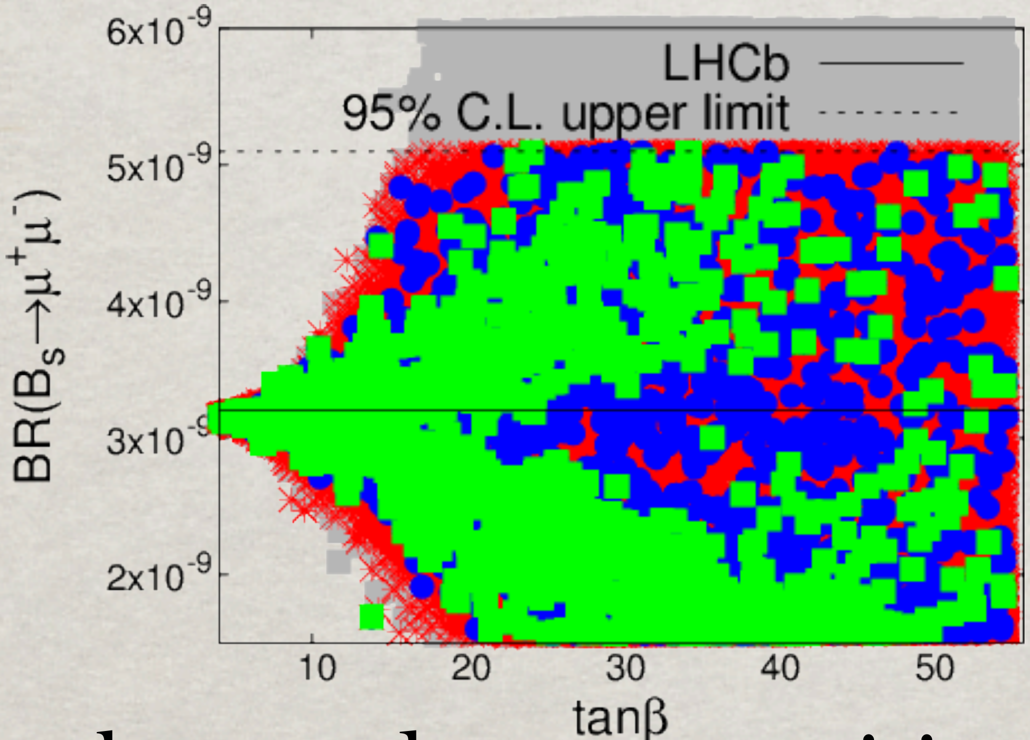
All proportional to v !

The fermion mass/mixing is a much^{n} bigger puzzle!

What controls the mixing structure:
"Minimal Flavor Violation" for BSM?

The b rare decays are pushing the limits:

$b \to s\gamma$, $B_s \to \mu^+\mu^-$ BR(Bs) ~ $\tan^6\beta / M^4_A$



TH, Liu, arXiv:1303.3040
Carena et al., arXiv:1305.5761.

See talk by Jernej Kamenik

Top-quark rare decays sensitive to BSM Higgs physics:

$t \to b\,H^{\pm}$, $b\,H\,W^{\pm *}$, $c\,H$, …

Eilam, Hewett, Soni, 1991; Mele et al., 1998;
Atwood, Soni, 1997, 2001; W.S. Hou et al., arXiv:1304.8037
…

The Higgs as pivot for "seesaw": $m_\nu \sim \kappa \frac{\langle H^0 \rangle^2}{M}$

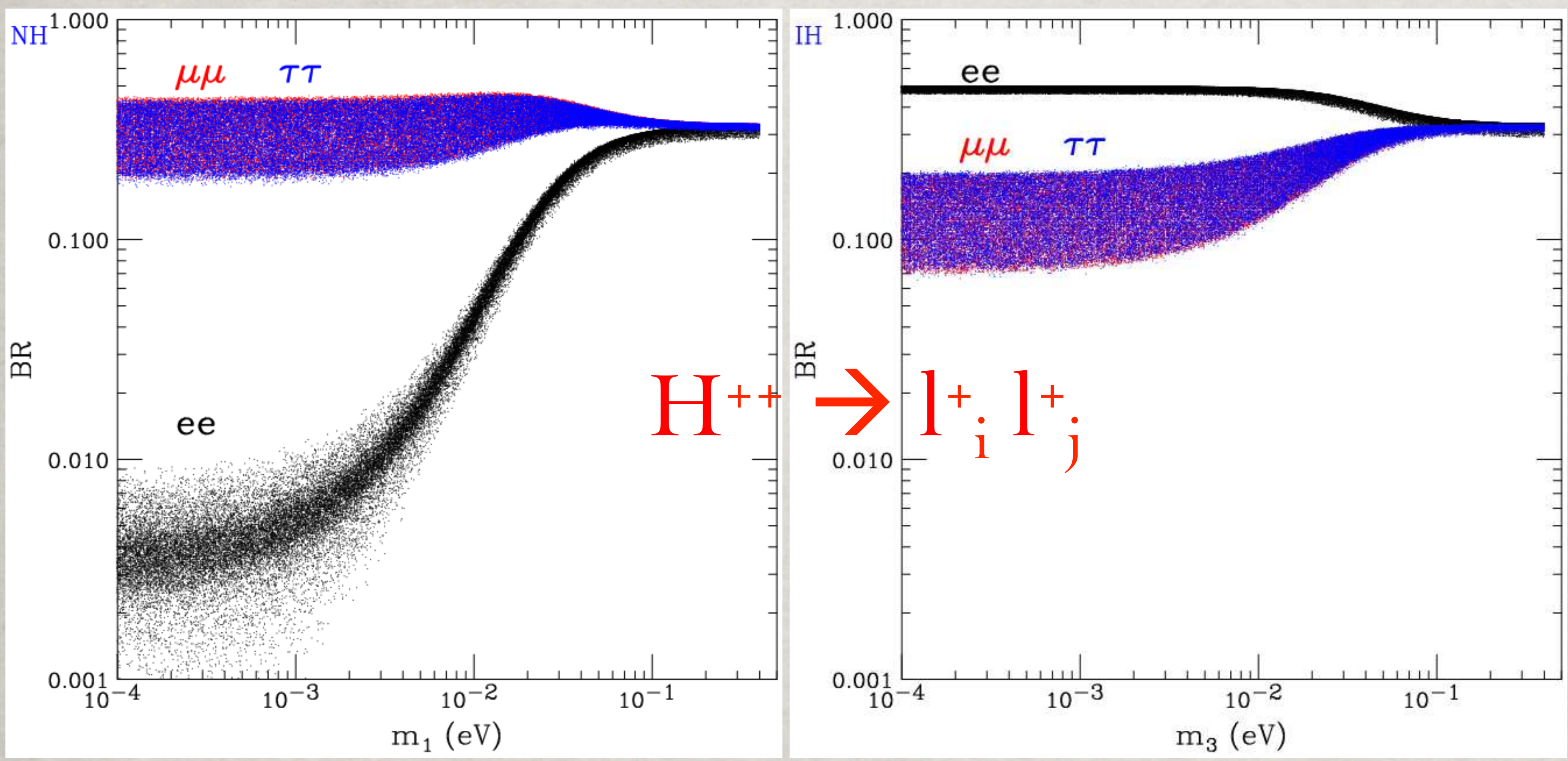
Type I seesaw: $M = M_N$, right-handed (sterile) $N_R{}^i$

$H \to NN$, $N \to H\nu$, …

Yanagida; Ramond et al.; Mohapatra …

Type II seesaw: $M = M_{H++}$, a Higgs triplet Φ_3 $H^{++} \to l^+_i\, l^+_j$

Mohapatra, Senjanovic, …



$H^{++} \to l^+_i\, l^+_j$

Fileviez-Perez et al., 2008.
Chaudhuri, Grimus, Mukhopadyaya, arXiv:1305.5761
Chun et al., arXiv:1305.0329

See talk by Silvia Pascoli

Type III seesaw: $M = M_T$, a fermionic triplet T_3:

$T^+ \to H\, l^+_i$, $T^0 \to W^\pm\, l$

Senjanovic et al., arXiv:0904.2309.

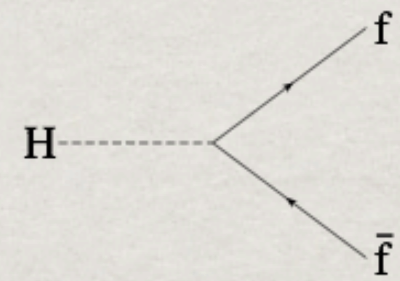
Watch out: $H^0 \to \mu\tau$ $(l^+_i\, l^-_j)$ for BSM flavor physics!

TH, Marfatia, PRL (2001)
Harnik, Kopp, Zupan, 2013

5. Couplings & Width

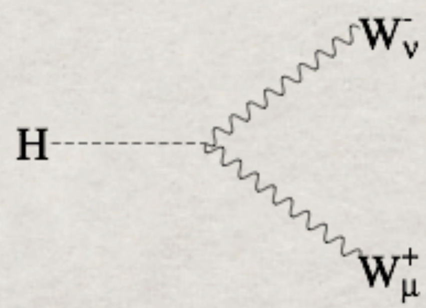
Higgs boson couplings encode its properties:

Yukawa coupling

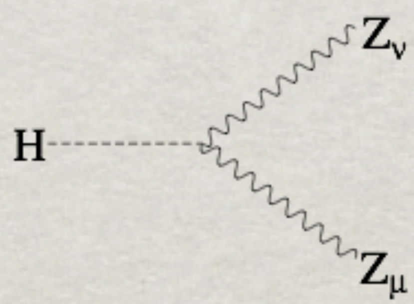


$-i\frac{m_f}{v}\left(1+\Delta_f\right)$

EWSB

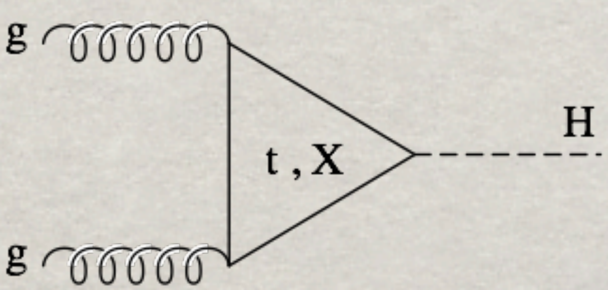


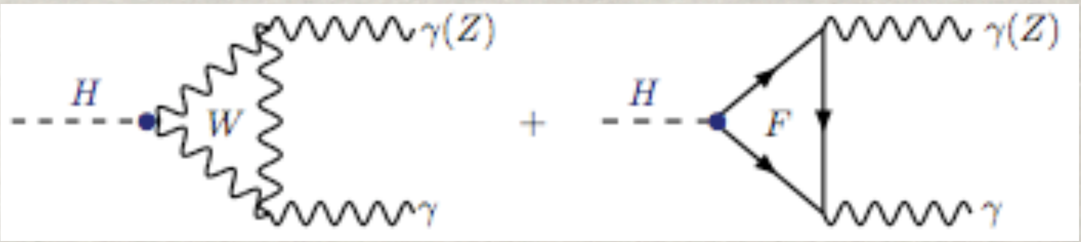
$ig\, m_W\,(1+\Delta_W)g_{\mu\nu}$



$i\,g\,\frac{1}{\cos\theta_W}\,m_Z\,(1+\Delta_Z)g_{\mu\nu}$

Color/charged particles in loops:





In a pessimistic scenario, the LHC does not see a new particle associated with the Higgs sector, then the effects of a heavy state on g_i at the scale M:

$$\Delta_i \equiv \frac{g_i}{g_{SM}} - 1 \sim \mathcal{O}(v^2/M^2) \approx \text{a few \% for } M \approx 1 \text{ TeV}$$

Higgs coupling deviations:

Δ:	VVH	$b\bar{b}H+\tau\bar{\tau}H$	ggH,γγH
Composite	(3-9)% (1 TeV/f)^2		
H^0, A^0		6% (500 GeV/M_A)^2	
T'			-10% (1 TeV/M_T)^2

Agashe et al.; Haber, Carena; TH, Logan, Wang

Dedicated programs to update the fitting analyses:

Plehn, Rauch, Zerwas et al., SFitter;
Hewett, Rizzo, et al., pMSSM;
Strumia, Raidal et al., arXiv:1303.3570;
Gunion, Ellwanger, Kraml et al., … **ATLAS, CMS.**

Future Measurements:

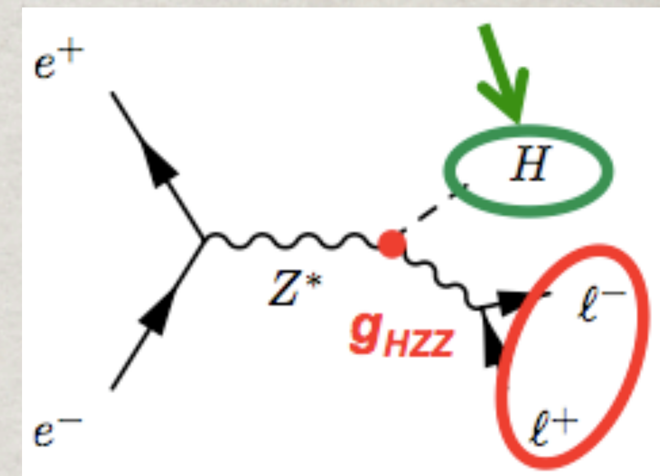
(from Roy Aleksan)

With M_H all parameters of SM are known!
What do we need to measure now?

	LHC(300)	LHC (3000)	ILC (250+350+500)	TLEP (240+350)	Comment
Δm_H (MeV)	~100	~50	~30	~7	Overkill for now
$\Delta\Gamma_H/\Gamma_H$ ($\Delta\Gamma_{inv}$)			5.5(1.2)%	1.1(0.3)%	
H spin	✓	✓	✓	✓	
Δm_W (MeV)	~10	~10	~6	<1	Theo. limits
Δm_t (MeV)	800-1000	500-800	20	15	~100 from theo.
$\Delta g_{HVV}/g_{HVV}$	2.7-5.7%*	1-2.7%*	1-5%	0.2-1.7%	
$\Delta g_{Hff}/g_{Hff}$	5.1-6.9%*	2- 2.7%*	2-2.5%	0.2-0.7%	
$\Delta g_{Htt}/g_{Htt}$	8.7%*	3.9%*	~15%	~30%	
$\Delta g_{HHH}/g_{HHH}$	--	~30%	15-20%**	--	Insufficient ?

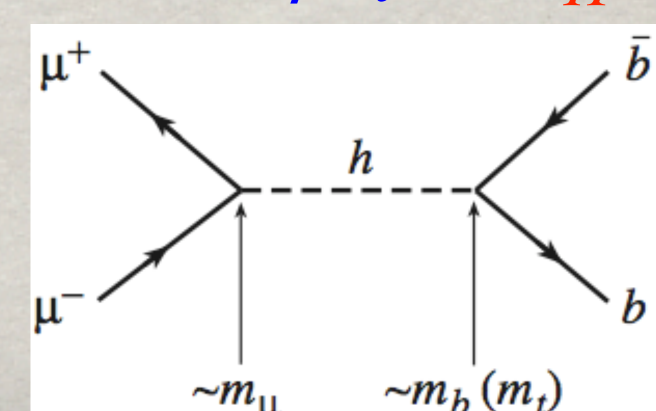
*Assuming systemaical errors scales as statistical and theoretical errors divided by 2 compared to now

**Sensibility with 2ab^{-1} at 500 GeV (TESLA TDR) and needs to be comfirmed by on-going more detailed studies



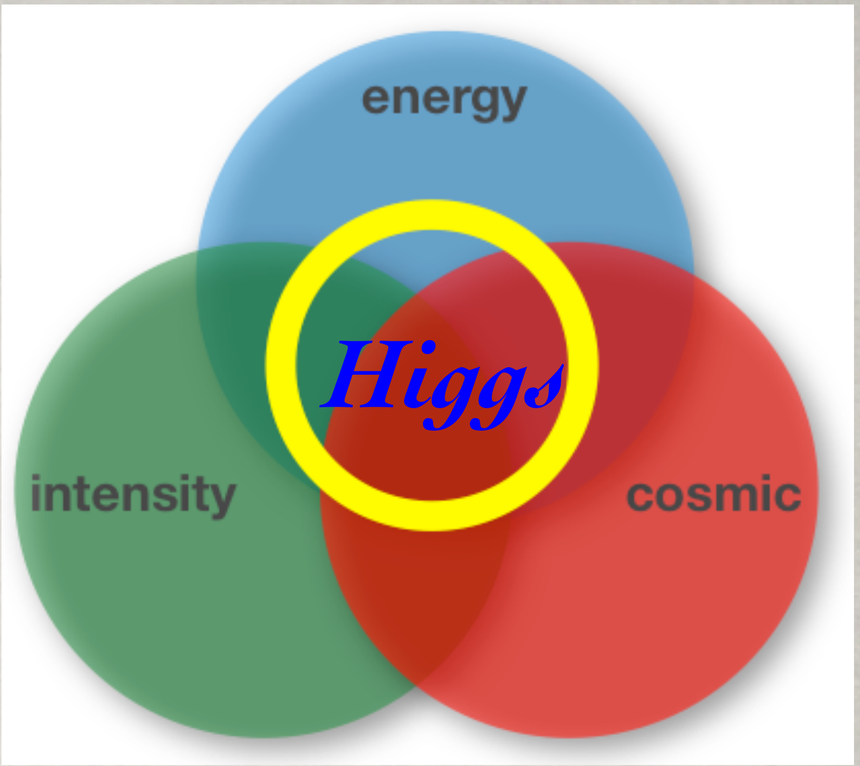
e^+e^- Higgs factory: model-independent

$\mu^+\mu^-$ Higgs factory: Model-independentpe line-shape for Γ_H



LHC results need assumptions: SM-like, no-missing mode, etc.

Summary:



- The Higgs boson is a new class, at a pivotal point of energy, intensity, cosmic frontiers.

"Naturally speaking":

- It should not be a lonely solitary particle; has an "interactive friend circle": $t,\ W^{\pm},\ Z$

"relatives": $\tilde{H}^{0,\pm},\ \tilde{t},\ \tilde{b},\ (\tilde{g});\ S,\ \tilde{S}...$

"siblings": $H^0,\ A^0,\ H^{\pm},\ H^{\pm\pm},\ S...$

- LHC lights the way for the searches.
- Higgs factory may reveal their properties from Higgs coupling measurements at 1%-level.

An exciting journey ahead!

LHC/ILC Comparison:

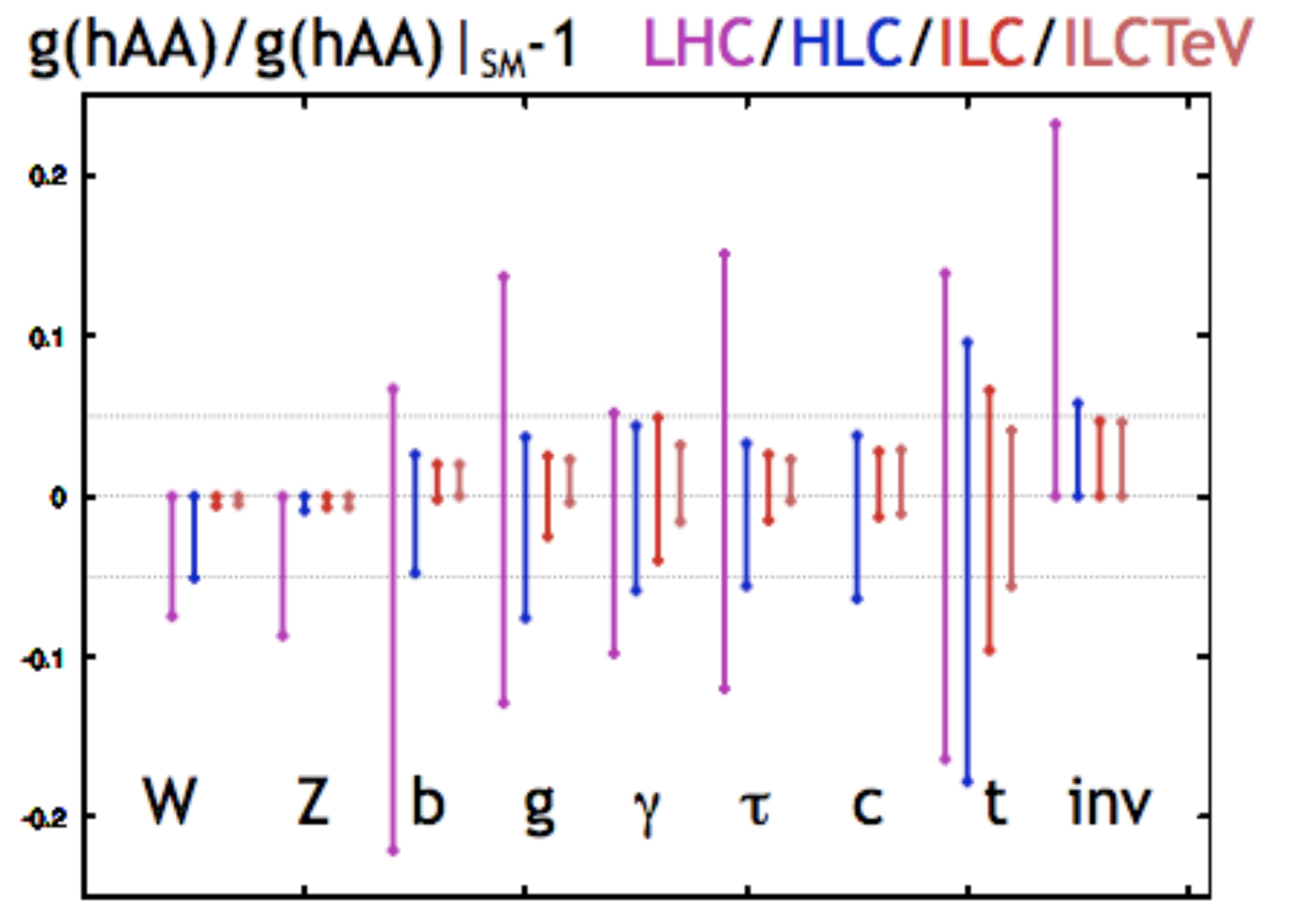


Figure 20: Estimate of the sensitivity of the ILC experiments to Higgs boson couplings in a model-independent analysis. The four sets of errors for each Higgs coupling represent the results for LHC, the threshold ILC Higgs program at 250 GeV, the full ILC program up to 500 GeV, and the extension of the ILC program to 1 TeV. The methodology leading to this figure is explained in [45].

Peskin: arXiv:1207.2516, arXiv:1208.5152.

1. LHC: $\sigma_{obs} \propto g_{in}^2 \frac{\Gamma_{final}}{\Gamma_{tot}}$

- σ_{obs}/σ_{SM} measured at <10% level.
- $Br(h \to \bar{N}N,\ \chi\chi,\ ...)$ sensitive to <20% level.
- No model-independent measure for $\Gamma_i,\ \Gamma_{tot}$

2. e^+e^- Higgs factory:

- model-independent for g_{ZZh} at 1.5% level
- Extraction for $\Gamma_{tot} \equiv \Gamma_{ZZ}/BR_{ZZ}$

3. $\mu^+\mu^-$ Higgs factory:

- Direct measurement of Γ_{tot} by scanning.