LHC lights the way: the Higgs & Beyond

IPA 2013, WIPAC, May 14, 2013

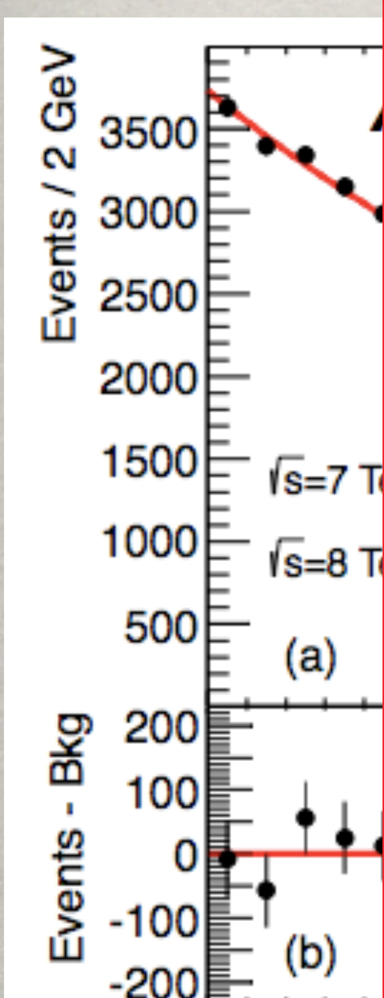
Tao Han, Univ. of Pittsburgh

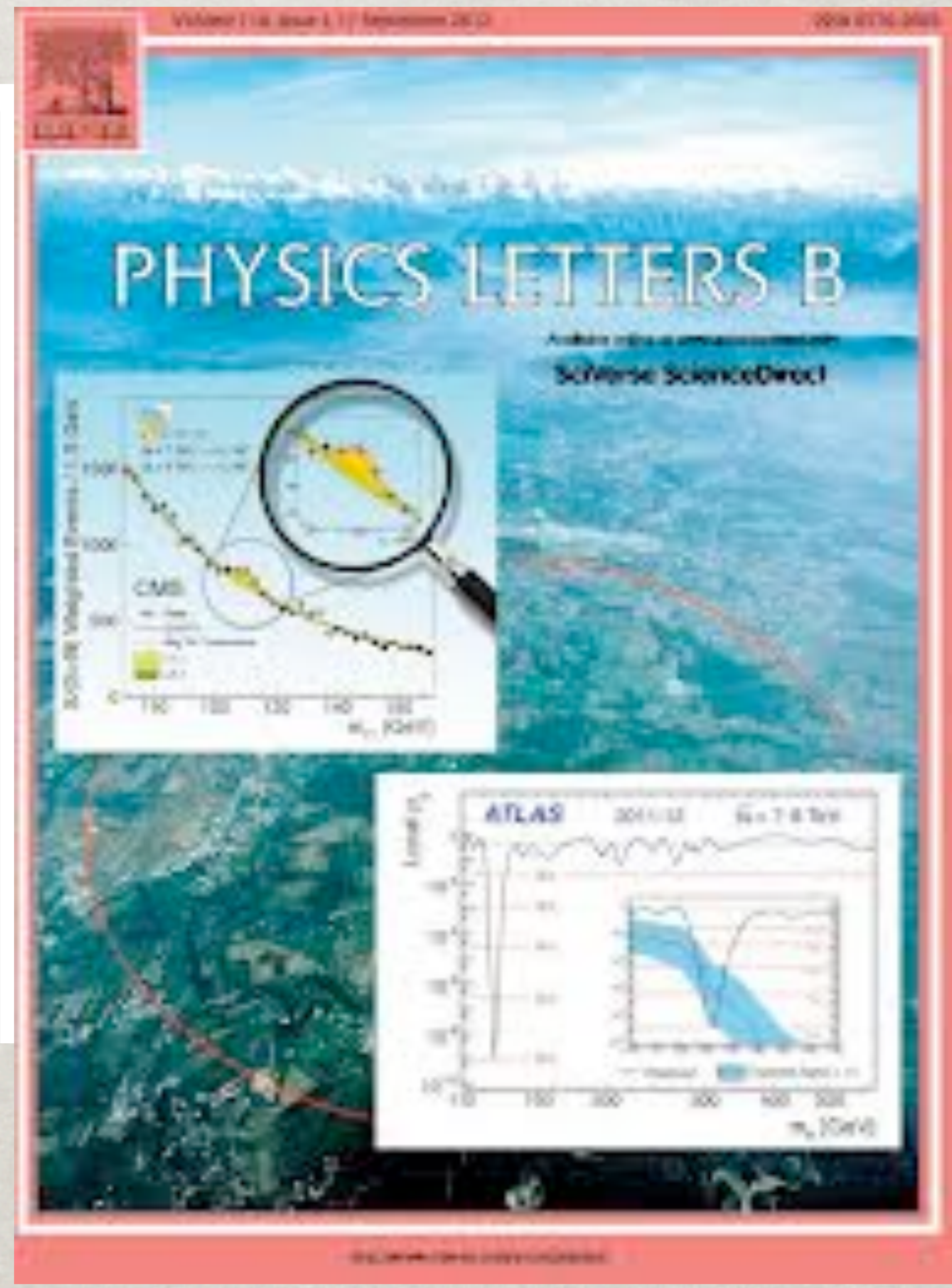
PITTPACC

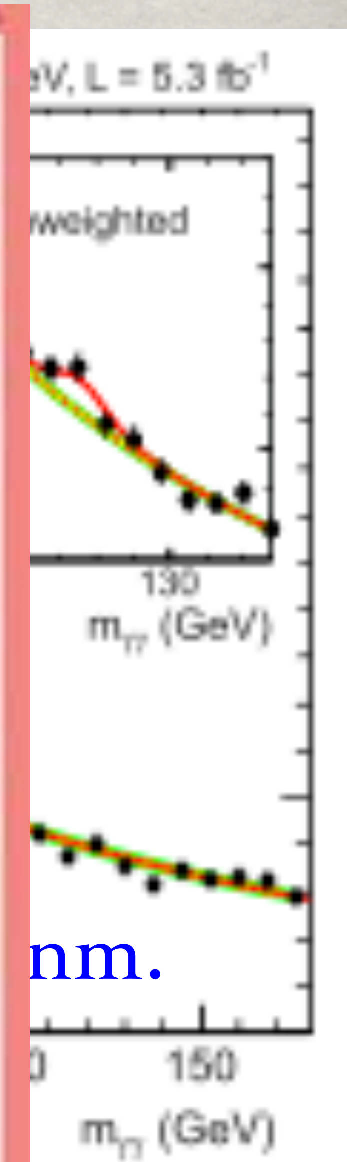
PITTSBURGH PARTICLE PHYSICS ASTROPHYSICS COSMOLOGY CENTER

Announcement on the 4th of July, 2012:

A neutral boson decay to two photons







The com

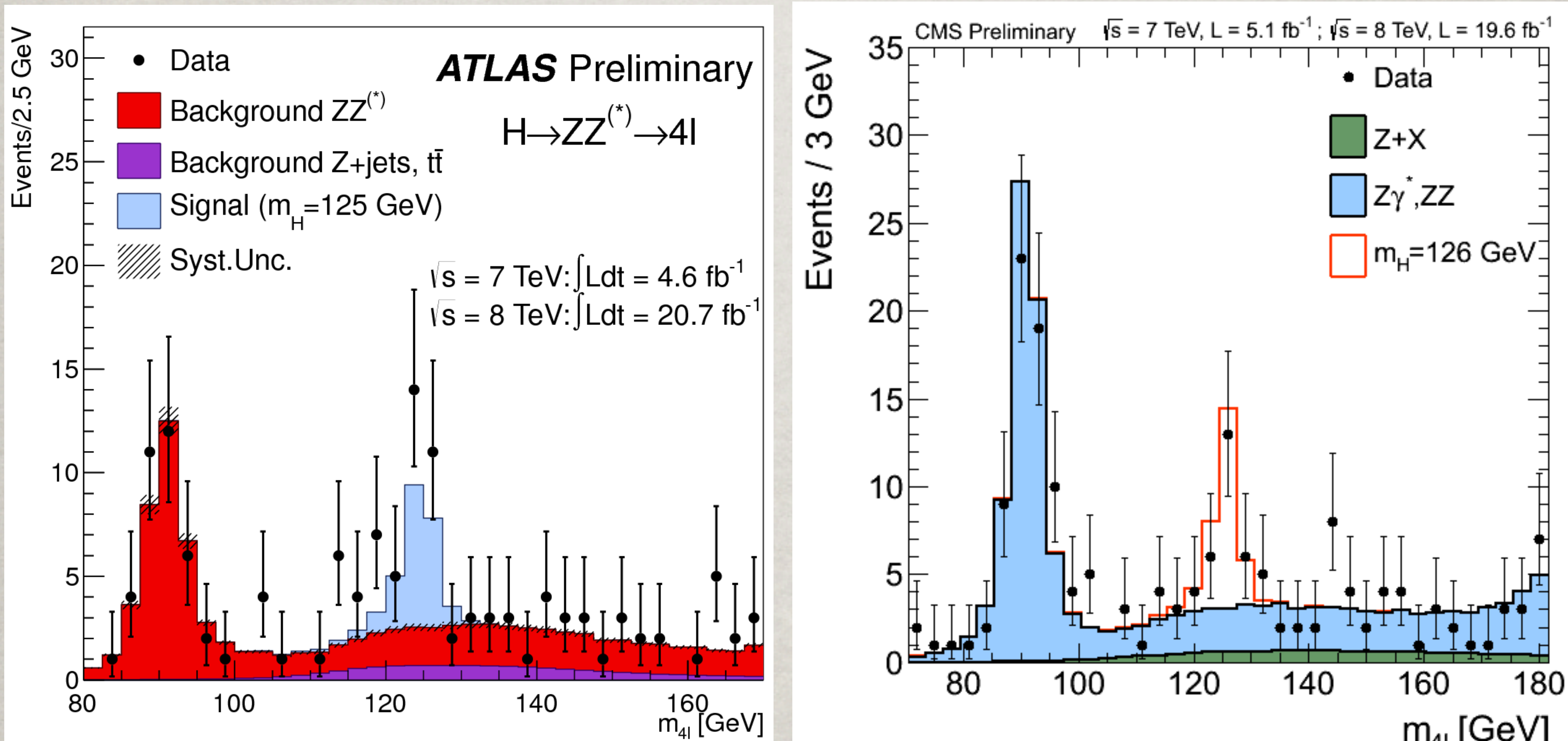
nm.

Phys. Lett. B716, 1 (2012)

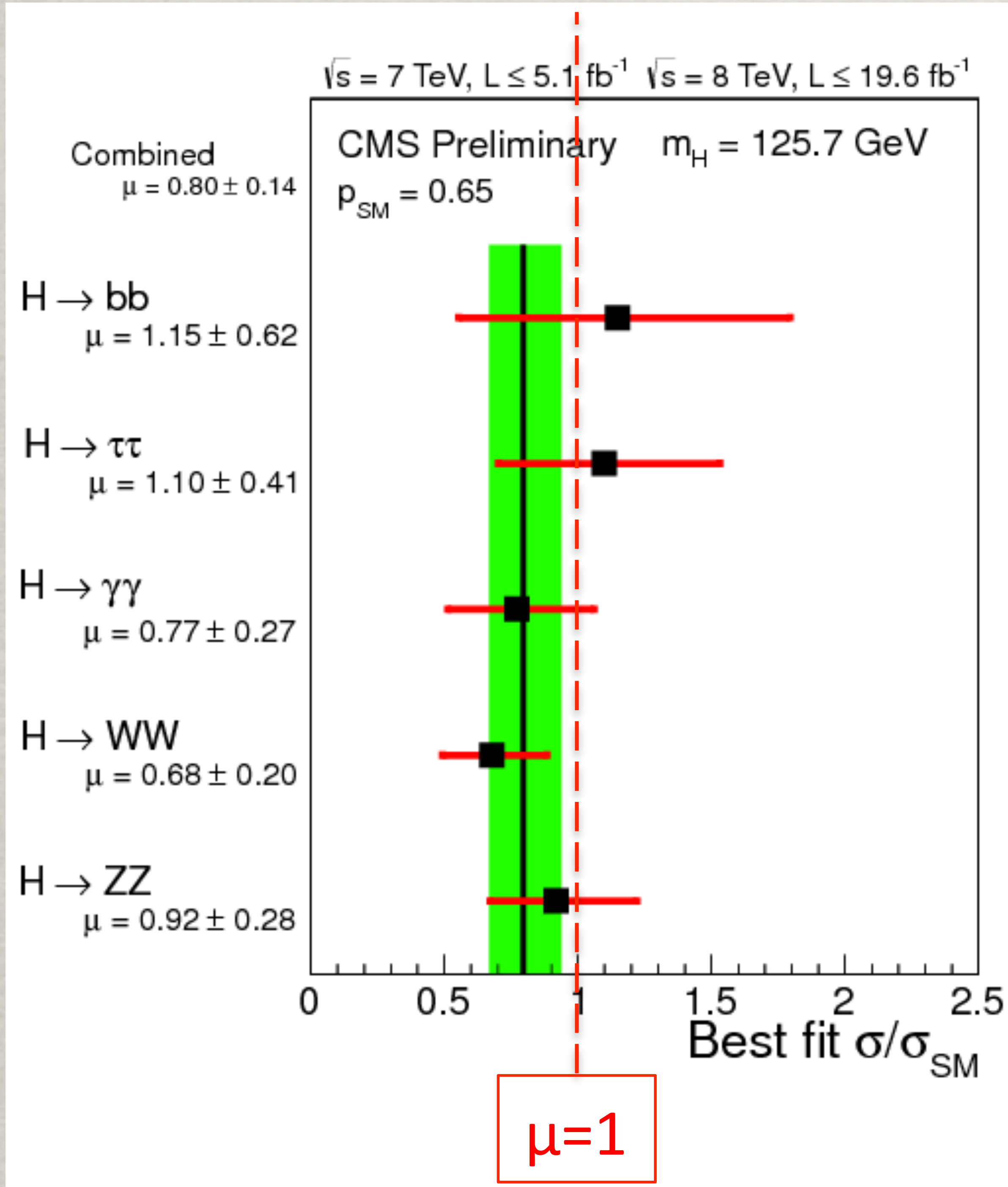
Phys. Lett. B716, 30 (2012)

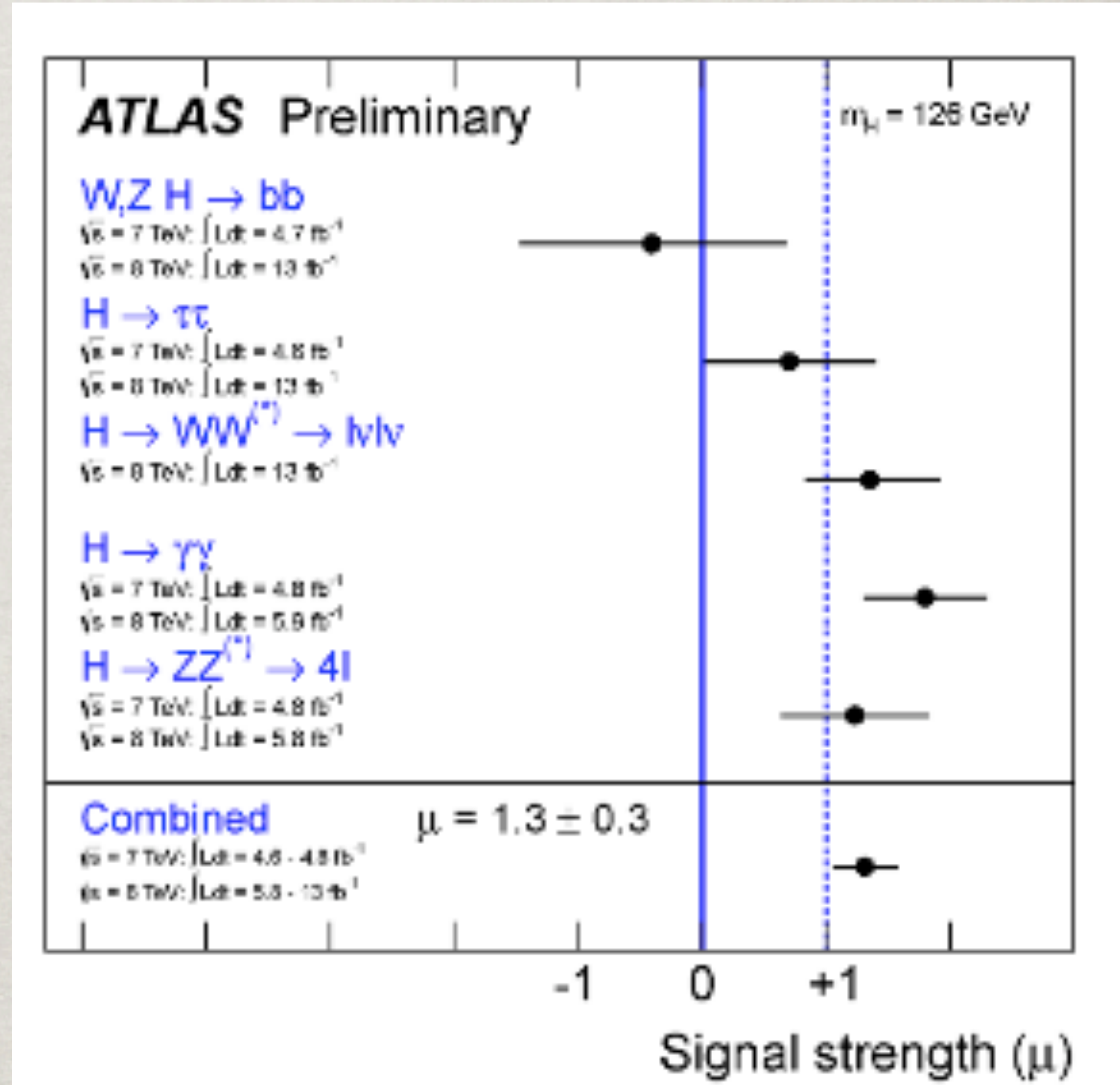
2013 Moriond Update:

The "Gold plated" channel:



Five channels:





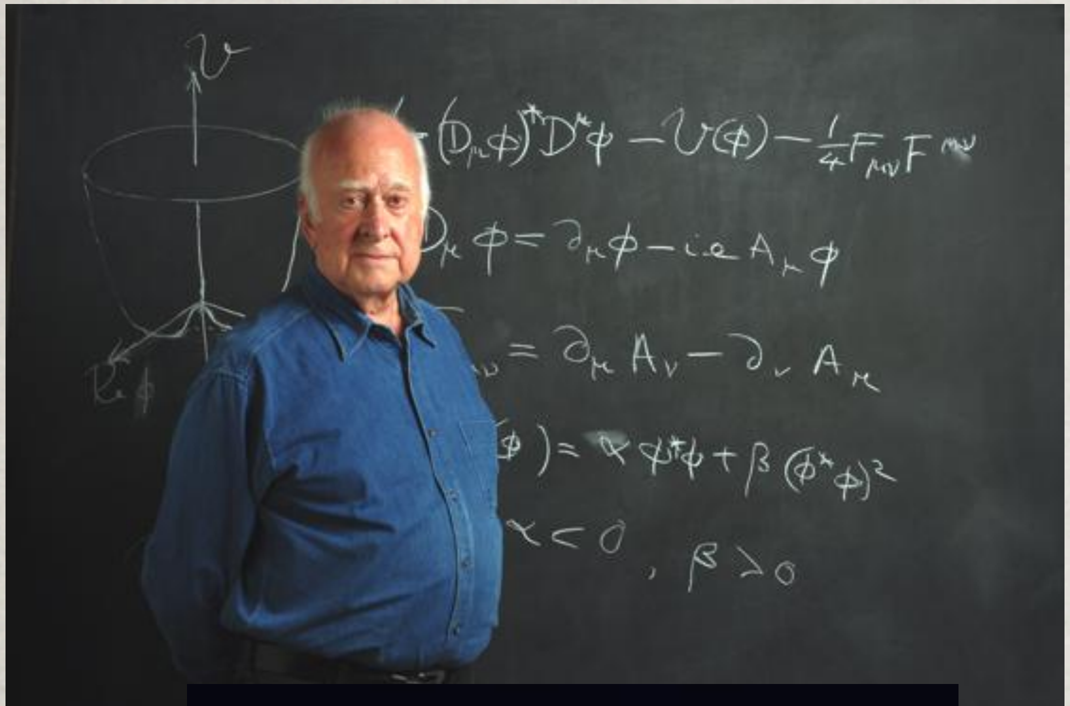
CMS/ATLAS Signal significance: **ZZ(4l): 6.7/6.6σ; γγ: 3.2/7.4σ; WW: 3.9/3.8σ; bb+ττ: 3.4σ**

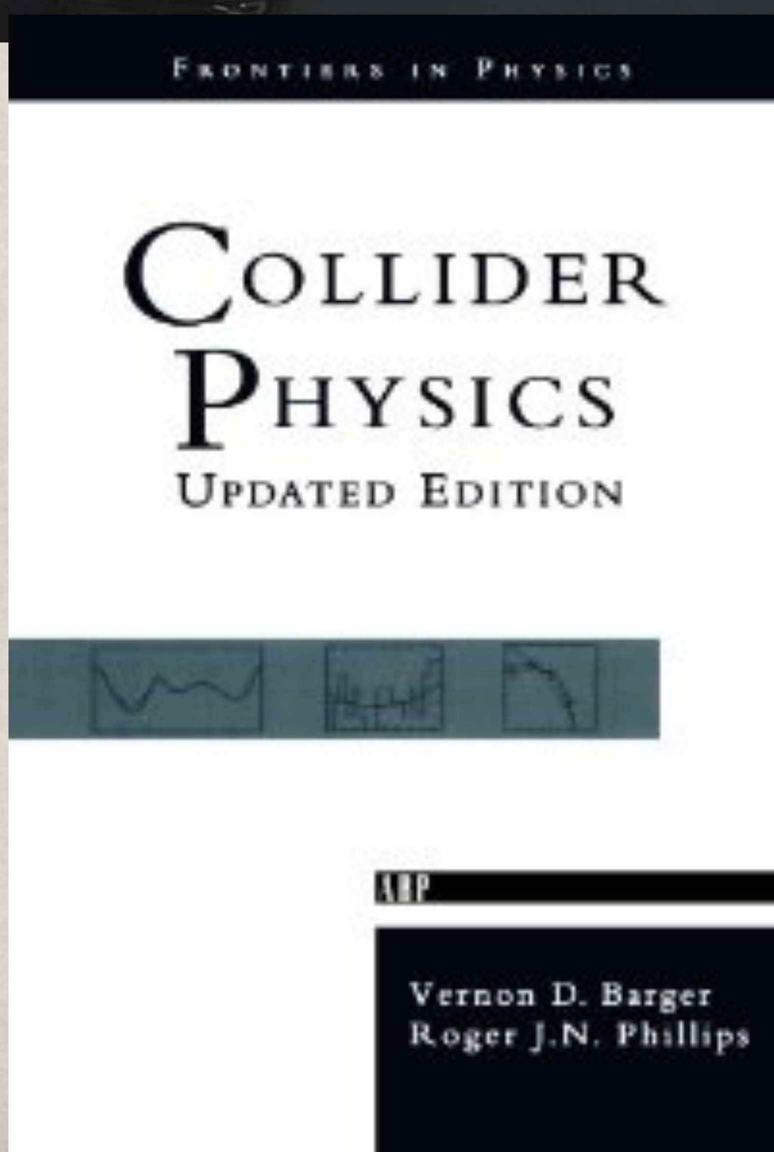
What IS it?

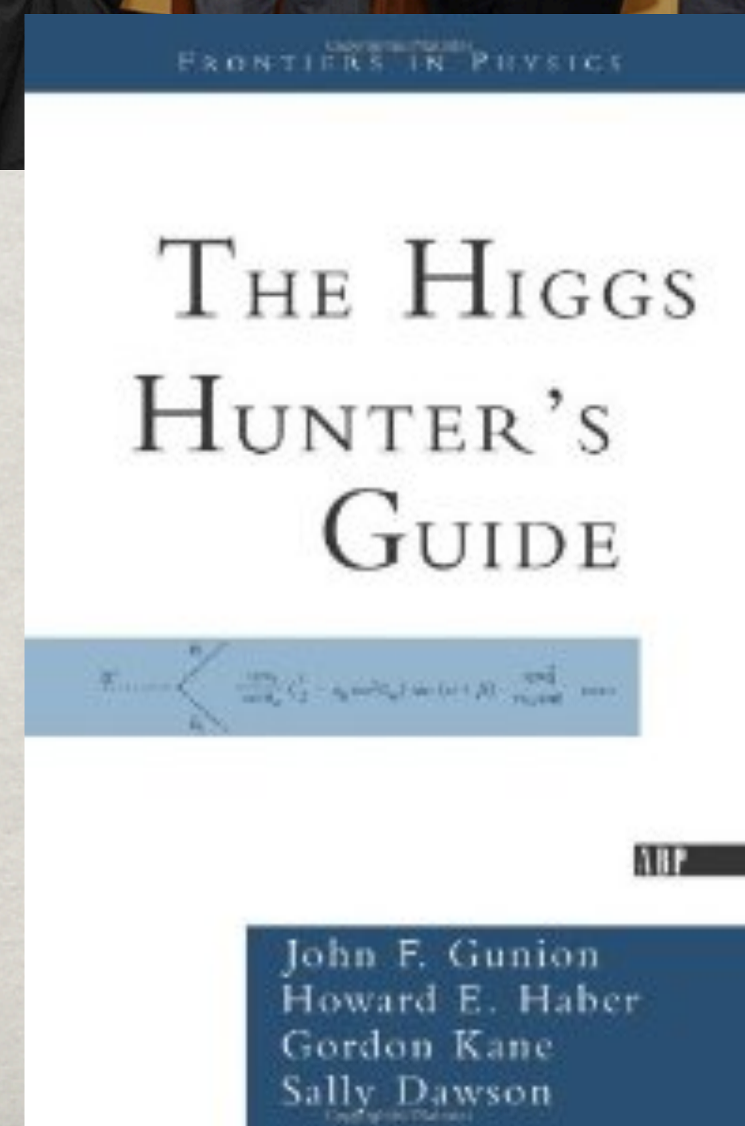
1. X → $\gamma\gamma$:
   - its neutral; can be spin-0
   - cannot be spoin-1 (Yang's theorem)
   - can be spin-2, but unlikely/disfavored
2. X → ZZ, W^+W^- seen.
   - the source for EWSB (vacuum excit.)
3. X not to $\mu^+\mu^-$, e^+e^-, but $\tau^+\tau^-$ seen.
   - non universal leptonic coupling (gauge)
4. Xtt needed to match, X → bb seen.
   - non universal quark coupling

Higgs signal beyond any reasonable and unreasonable doubt

50 year's work by numerous theorists

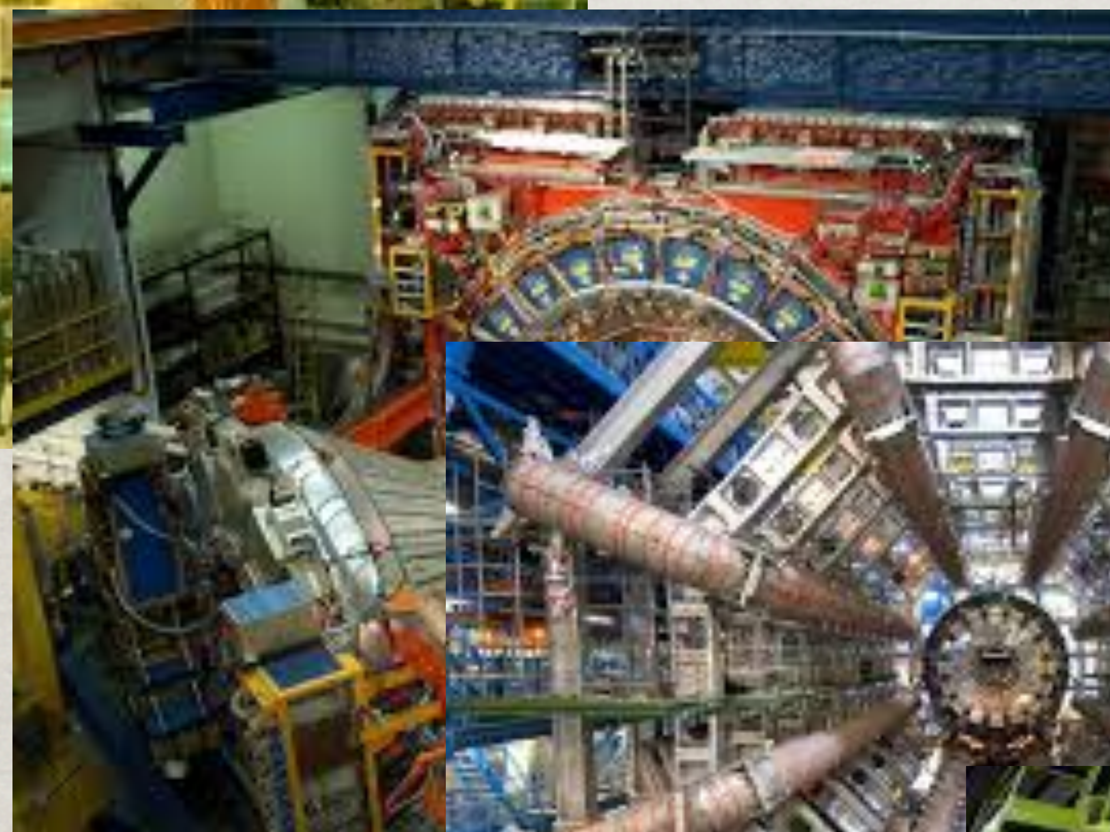




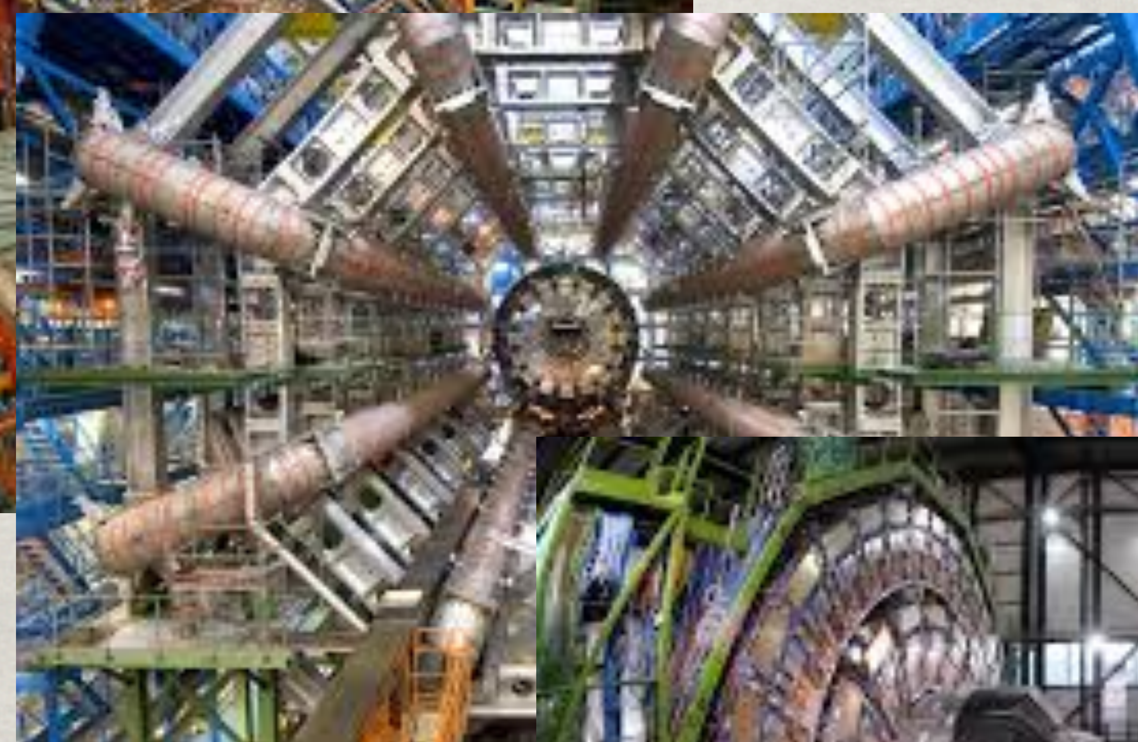


25 year's work by thousands experimenters

CDF@Tevatron



ALEPH@LEP



ATLAS

CMS

The Higgs hunt …

This is truly a monumental triumph!
We have reached a deeper understanding of nature!

Rest of the talk:
Under the Higgs lamp post

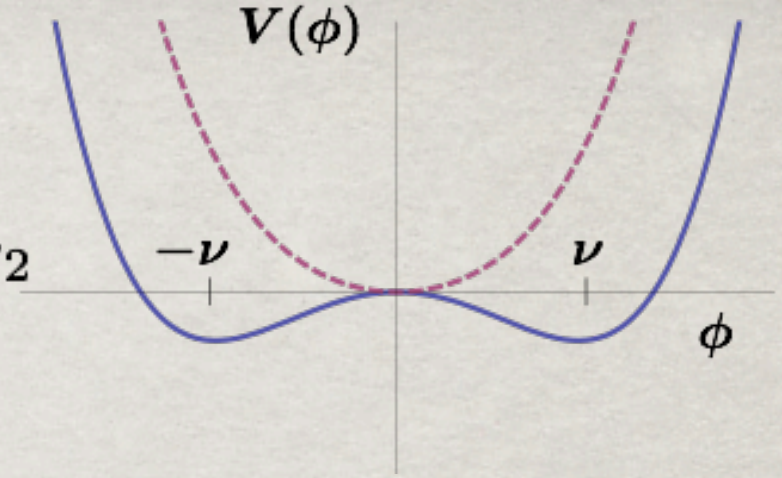
The discovery has given us tremendous confidence for our understanding of Nature:

β-decay → $W^{\pm}/Z$ → Higgs boson!

The discovery has sharpened more profound questions …

$$V(\phi) = +\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2.$$

$M_H^2 = -2\mu^2 = 2\lambda v^2$ $\nu = (-\mu^2/\lambda)^{1/2}$



Quest 1: λ, a new force?

$$V(\phi) = -\frac{\mu^4}{4\lambda} - \mu^2 H^2 + \lambda\nu H^3 + \frac{\lambda}{4} H^4.$$

λ is NOT governed by gauge interactions.

The (rather) light, weakly coupled boson:

$M_H \approx 126$ GeV → $\lambda \approx 1/8$!

At the verge of uncovering a deeper theory?

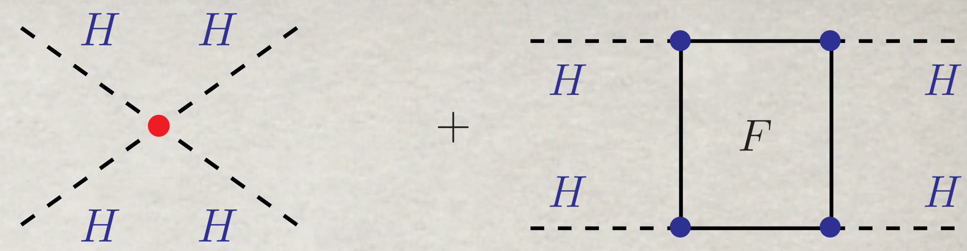
- λ determined by gauge couplings?

  In SUSY, $\lambda = (g_1^2 + g_2^2)/8$

- or dynamically generated by a new strong force?

λ at high energies:

For small λ, the Top-Yukawa dominates:



$$32\pi^2\frac{d\lambda}{dt} = -24y_t^4 \qquad \lambda(\Lambda) = \lambda(v) - \frac{3}{4\pi^2}y_t^4\log\left(\frac{\Lambda^2}{v^2}\right)$$

To have a stable vacuum,

$$\lambda(\Lambda) > 0 \quad \longrightarrow \quad M_H^2 > \frac{3v^2}{2\pi^2}y_t^4\log\left(\frac{\Lambda^2}{v^2}\right)$$

$$\Lambda_C \sim 10^3 \text{ GeV} \quad \Rightarrow \quad M_H \gtrsim 70 \text{ GeV}$$

$$\Lambda_C \sim 10^{16} \text{ GeV} \quad \Rightarrow \quad M_H \gtrsim 130 \text{ GeV}$$

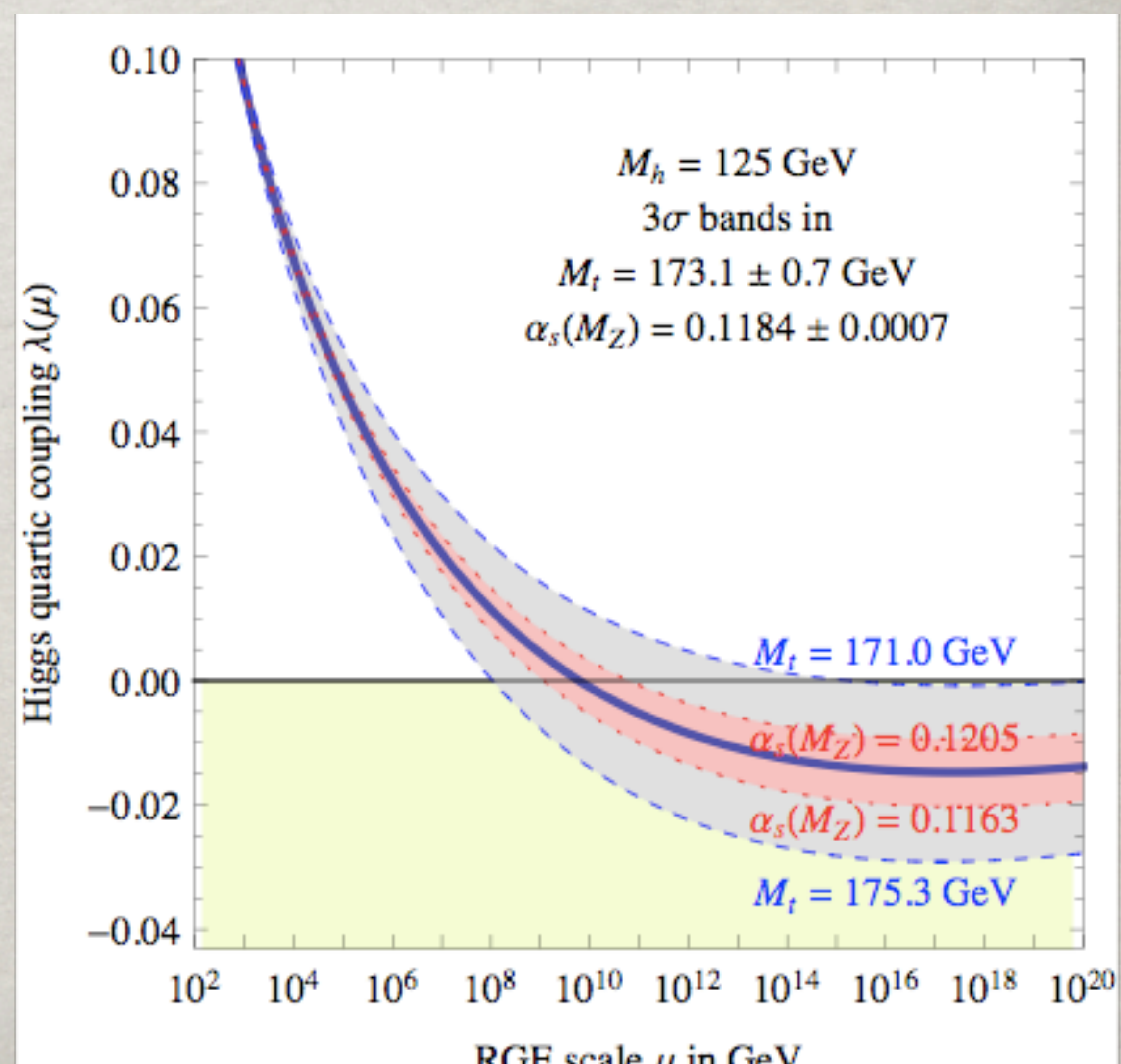
Much renewed interest, updates:$

$ G. Degrassi et al., arXiv:1205.6497.

For M_H = 125 GeV,

then $\Lambda(m_t=175) < 10^7$ GeV.

A metastable Universe?



Quest 2:
μ^2: The Higgs mass

$$V(\phi) = +\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2. \quad M_H^2 = -2\mu^2 = 2\lambda v^2$$

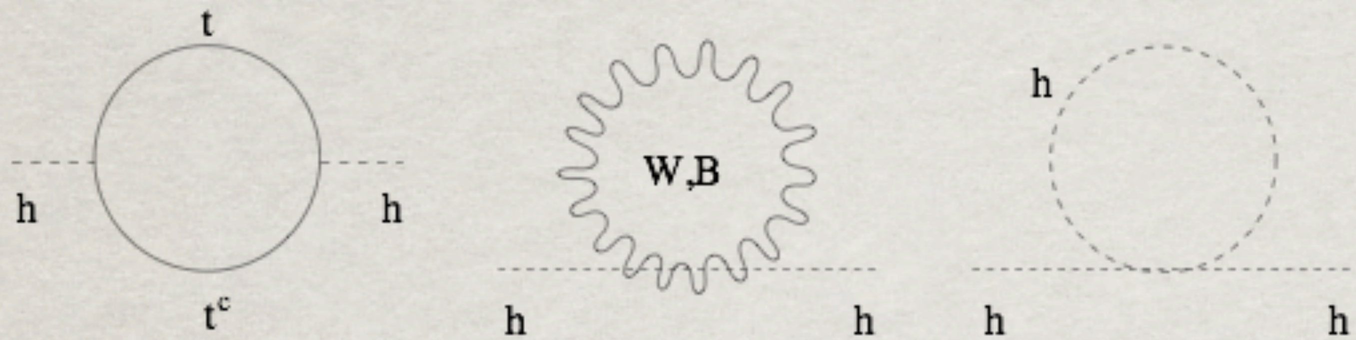
"It is interesting to note that there are no weakly coupled scalar particles in nature; scalar particles are the only kind of free particles whose mass term does not break either an internal or a gauge symmetry." -- Ken Wilson, 1970

No symmetry to protect M_H in the SM.

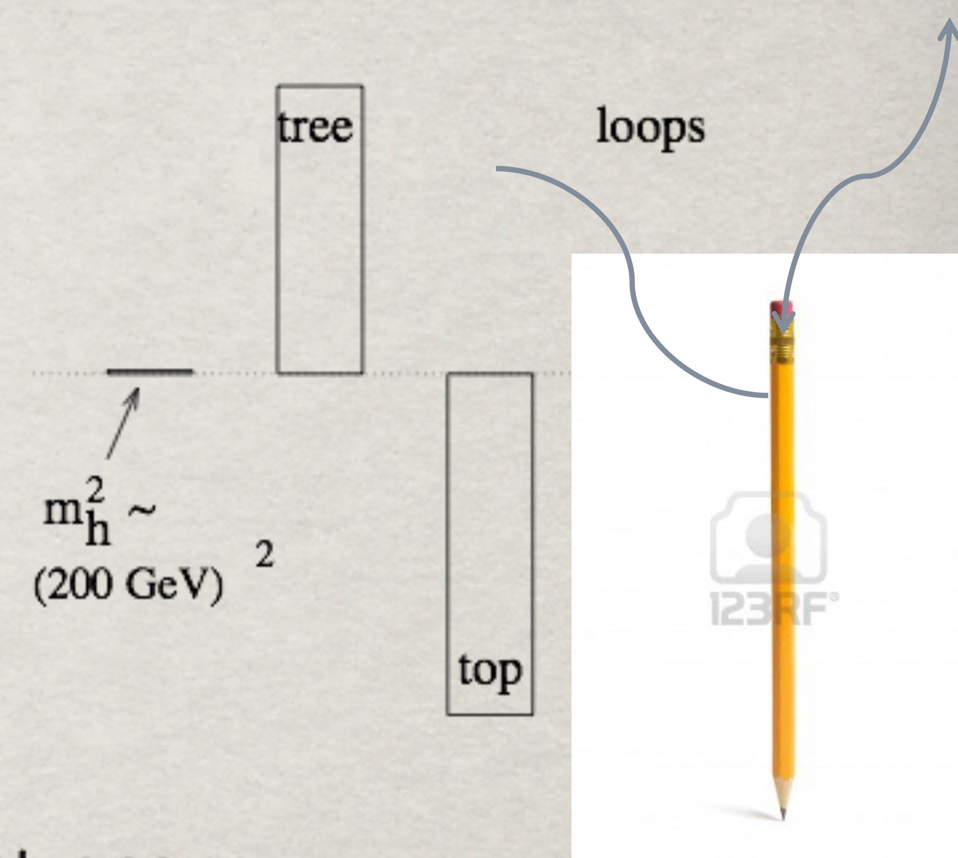
→ it is unstable against quantum corrections.

Unnatural:
Fine-tuned to
0.05 mm/0.5 cm ~ 10^{-2}

Quantum corrections to the Higgs mass:



(a) (b) (c)



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

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

$$(200\ \text{GeV})^2 = m_{H0}^2 + \left[-(2\ \text{TeV})^2 + (700\ \text{GeV})^2 + (500\ \text{GeV})^2\right] \left(\frac{\Lambda_{t,W,H}}{10\ \text{TeV}}\right)^2$$

If believing $\Lambda \to M_{PL}$, then the cancellation IS ... !!! ???

"Naturalness requirement": less than 90% cancellation on m_H^2

$$\Lambda_t \lesssim 3\ \text{TeV} \quad \Lambda_W \lesssim 9\ \text{TeV} \quad \Lambda_H \lesssim 12\ \text{TeV}$$

• SUSY:
Symmetry between different spin-states (opposite statistics)

$$\Delta m_H^2 \sim (M_{SUSY}^2 - M_{SM}^2)\, \frac{\lambda_f^2}{16\pi^2} \ln\left(\frac{\Lambda}{M_{SUSY}}\right).$$

Weak scale SUSY is natural if $M_{SUSY} \sim \mathcal{O}(1\ \text{TeV})$.

Relevant states to Higgs: $\tilde{t}\ (\tilde{g}),\ \tilde{W}^{\pm},\ \tilde{Z},\ \tilde{H}^{\pm,0}$

• Composite Higgs (or dual of extra dimension theory):
The Higgs boson as a pseudo-Goldstone boson
(from a larger global symmetry breaking)

- The Little Higgs idea – Strongly interacting dynamics:
  An alternative way to keep H light (naturally).
  Again, predicting new states:

Arkani-Hamed, Cohen, Katz, Nelson, 2002.

$$W^{\pm}, Z, B \leftrightarrow W_H^{\pm}, Z_H, B_H; \quad t \leftrightarrow T; \quad H \leftrightarrow \Phi.$$

(cancellation among same spin states!)

A light Higgs implies new physics near 1 TeV!

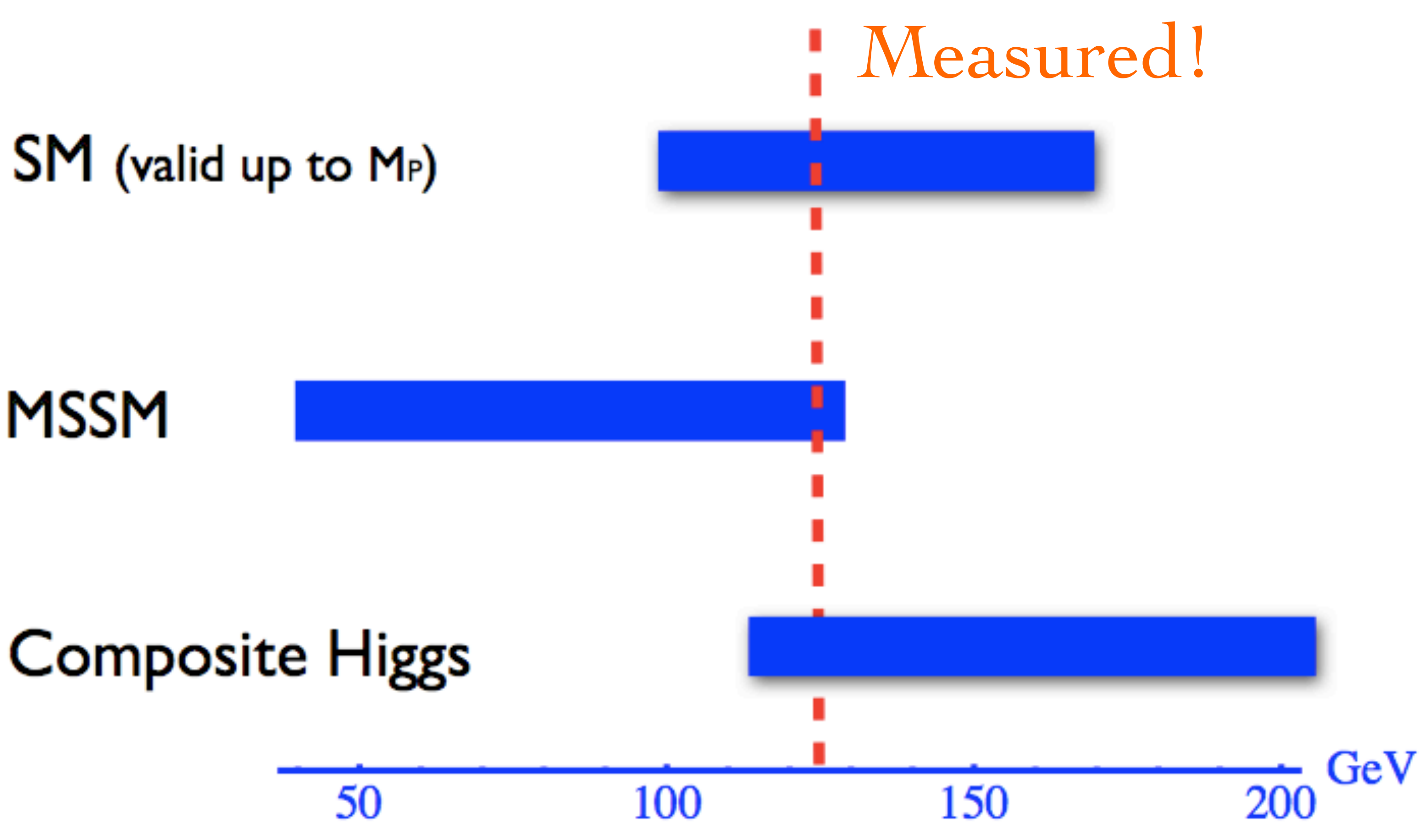
“Naturalness” argument strongly suggests the existence of TeV scale new physics.

If you give up this belief, you are subscribing the “anthropic principle”.*

* A physicist talking about the anthropic principle runs the same risk as a cleric talking about pornography: no matter how much you say you are against it, some people will think you are a little too interested. -- Steven Weinberg

The fact that M_H = 126 GeV
has already provides non-trivial test to some models.

In a given theory with additional symmetries, one may be able
- to calculate (in a weakly coupled theory – SUSY)
- to (g)estimate (in a strongly coupled theory – composite)



$$M_H^2 = M_Z^2 \cos^2 2\beta + \Delta_{SUSY}^2$$

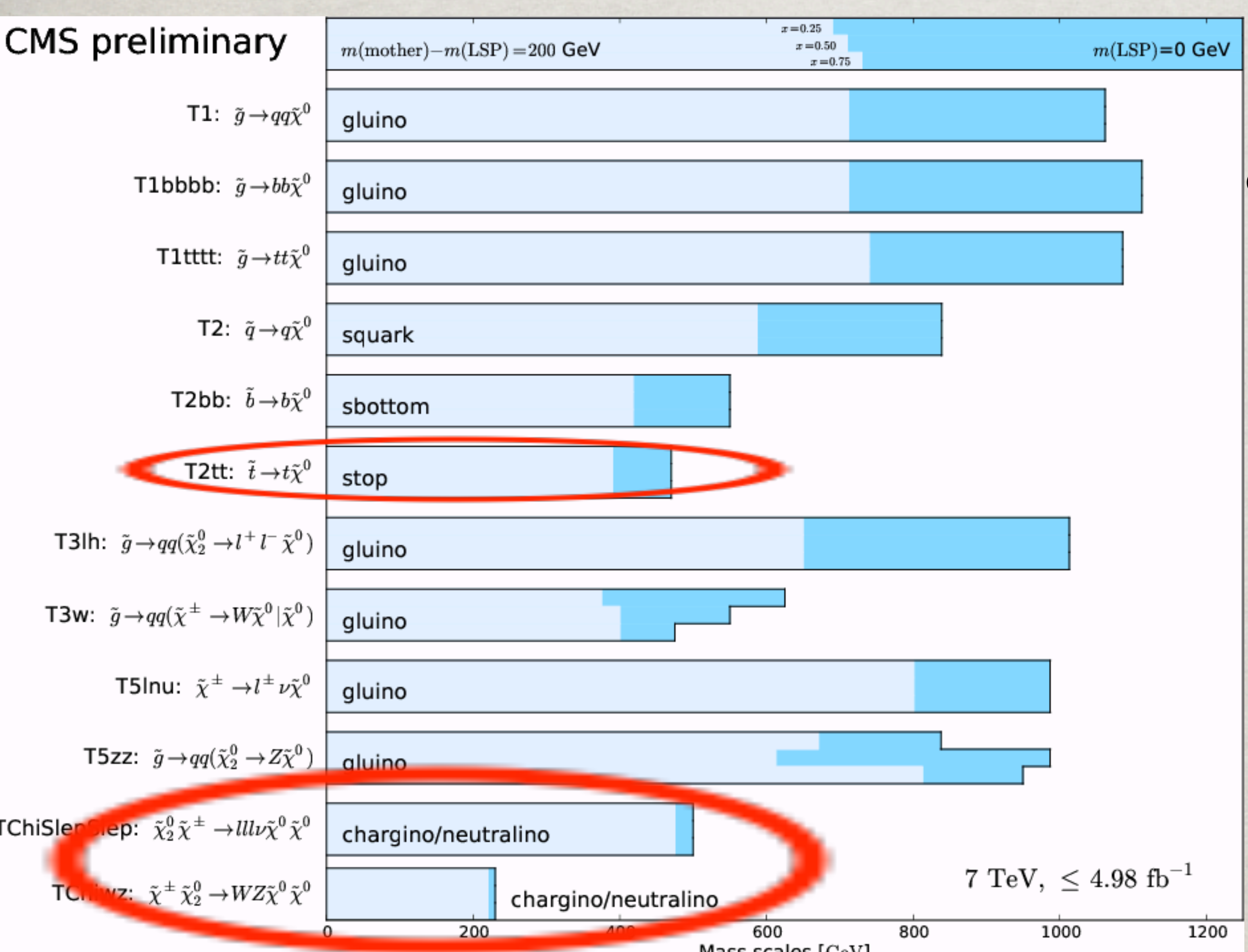
$$M_H^2 \approx \frac{3}{\pi} \frac{m_t^2 M_T^2}{f^2}$$

Pomarol, ICHEP'12

Both suffer from some degree of fine-tune (already).

A Natural Higgs Sector at LHC

1. Supersymmetry:



Current bounds on the “most wanted” are still loose.

LHC will push stop to the extreme.

LHC may be limited to cover gauginos and Higgsinos.

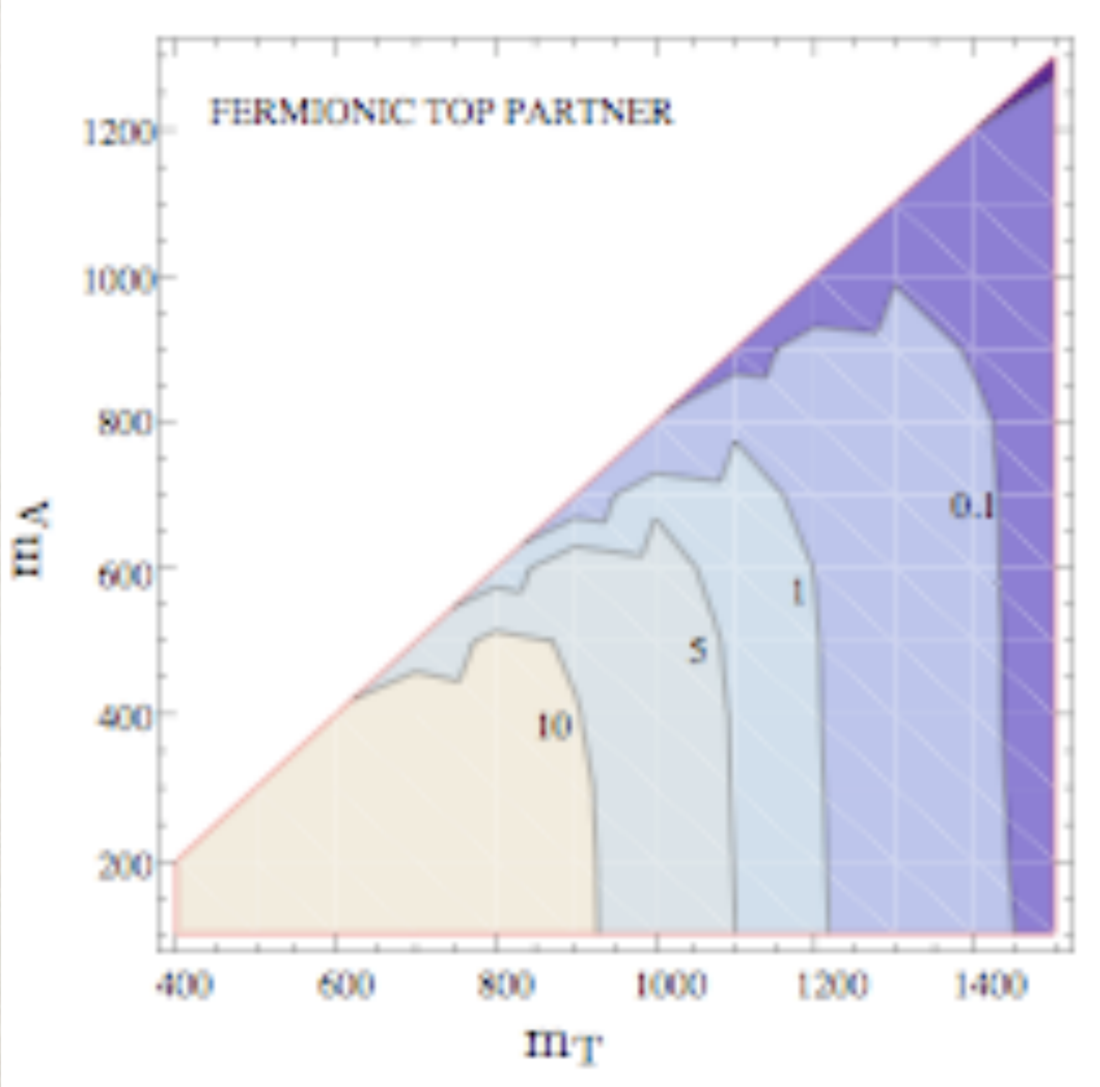
2. Composite Higgs:
e.g. T' in the Little Higgs Model

$$q\bar{q},\ gg \rightarrow T\bar{T} \rightarrow t\bar{t}\ A^0 A^0 X \rightarrow b j_1 j_2\ \bar{b}\ \ell^- \bar{\nu}\ A^0 A^0\ X + c.c.$$

The current ATLAS limit: $M_T > 480$ GeV, for $M_A < 100$ GeV.

Future projection:
At 14 TeV, 100 fb^{-1}:

reaching to
$M_T \sim 1.1$ TeV at 5σ



TH, Mahbubani, Walker, Wang, 2008.

3. Light $H^\pm$, A^0, H^0 Higgs bosons.
4. Electroweak gauginos/Higgsinos.

Quest 3:
Fermion mass and flavors

(a). Neutrino mass generation:

The Higgs may be the pivot for "seesaw" :

$$m_\nu \sim \frac{\langle H^0 \rangle^2}{M_N}$$

The Higgs may serve as a probe to heavy neutrino sector.

Watch out H → N N !

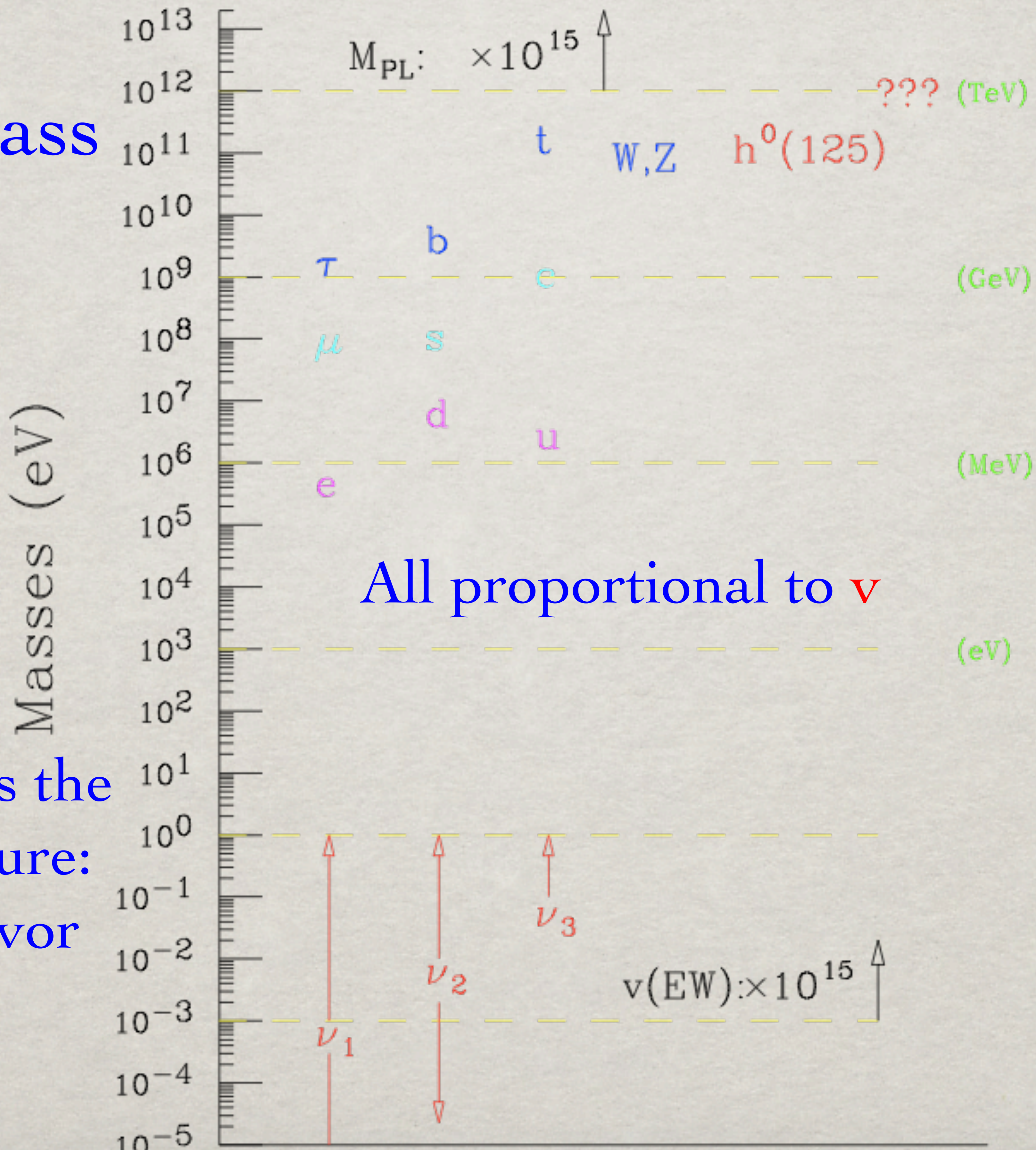
The seesaw gangs, 1977-1980.

In an extended Higgs sector (doubly charged Higgs in a triplet model), there may be predicted correlations between neutrino oscillation and LHC signatures.

Fileviez-Perez et al., 2008

(b). Fermion masses & flavor physics

Particle mass hierarchy:



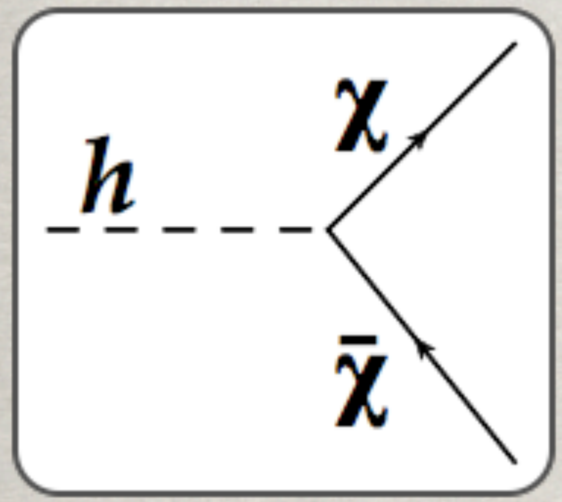
All proportional to v

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

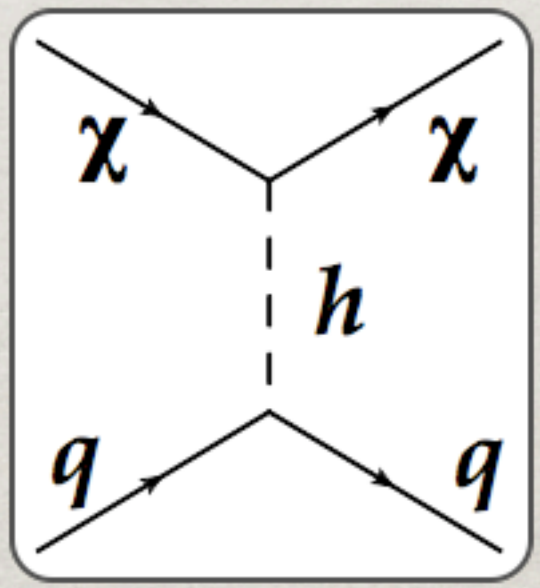
Quest 4:
The Higgs portals to Cosmos?
(a). Dark Matter

The Higgs boson may serve as a portal to the dark sector.

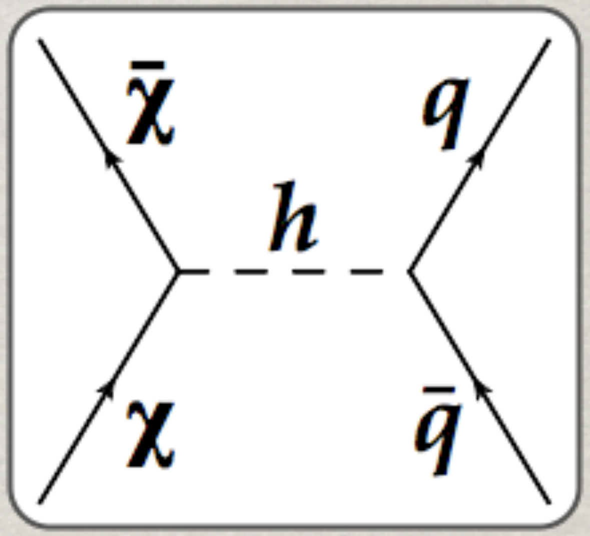
Missing energy at LHC

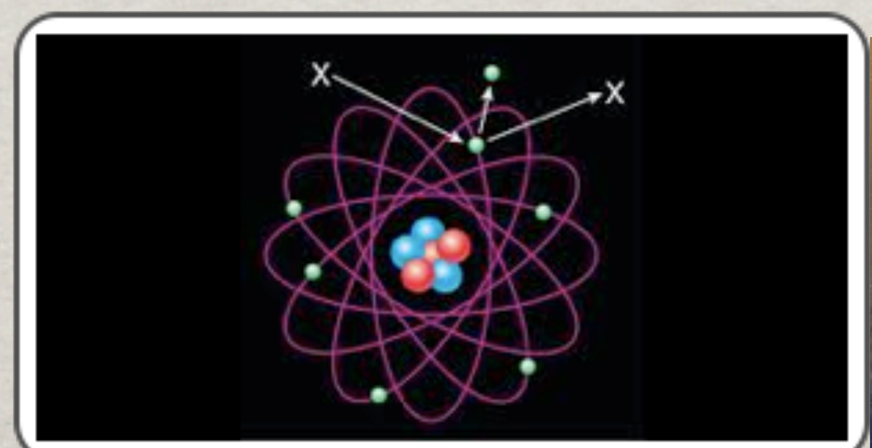


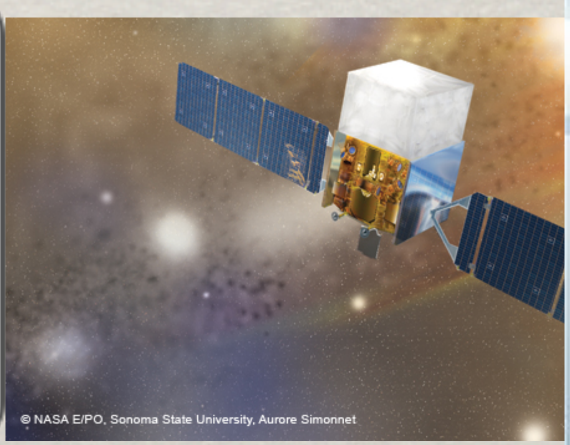
Direct detection

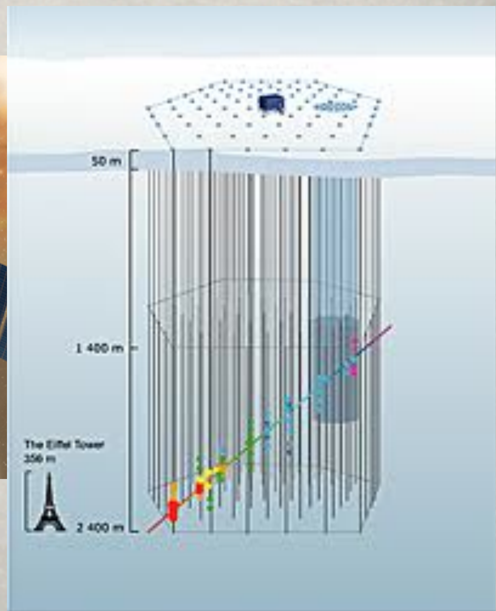


Indirect detection



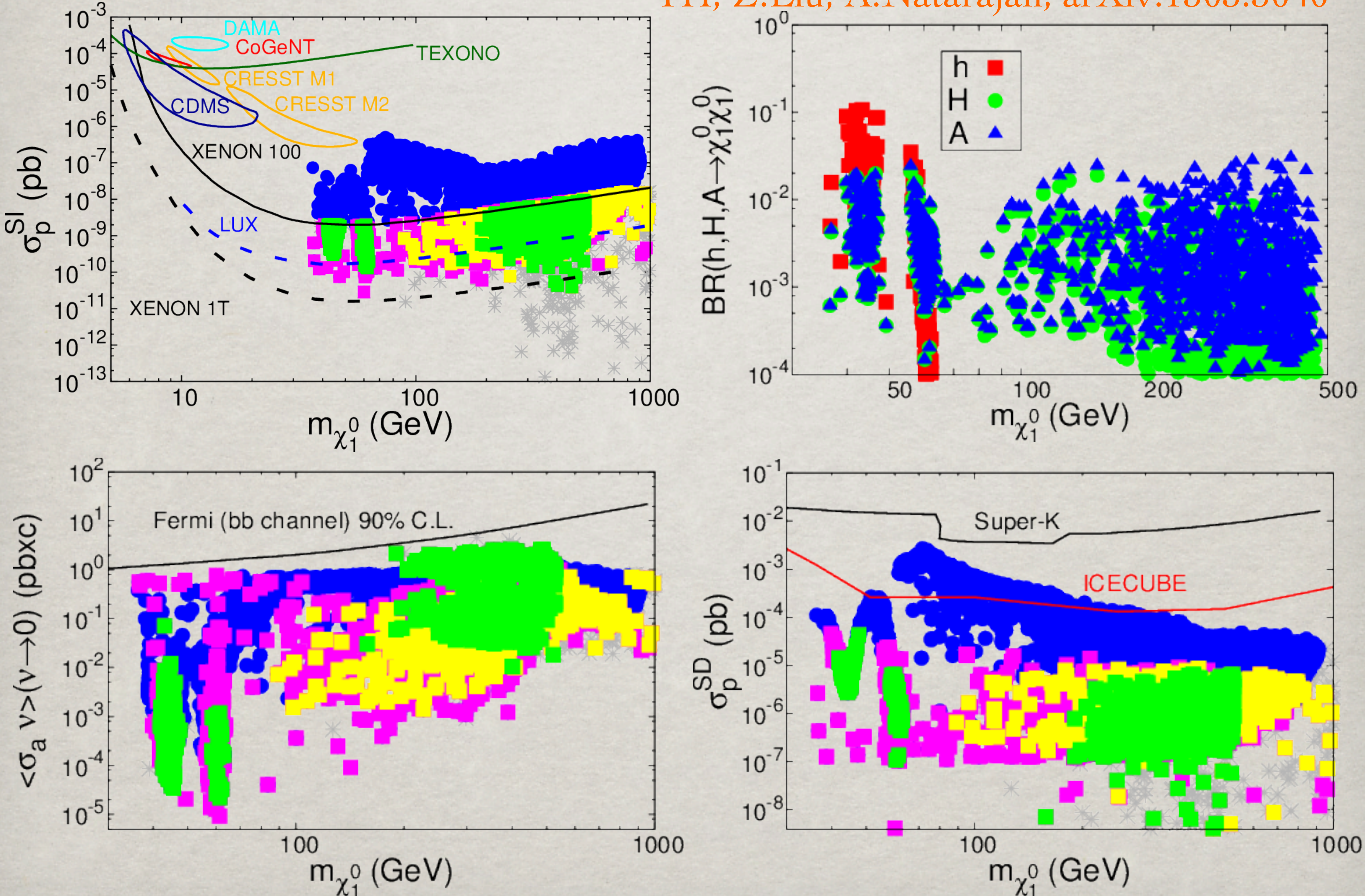






SUSY DM+Higgs in close scrutiny:

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



Other potential consequences

(b). Baryon – anti-baryon Asymmetry

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

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

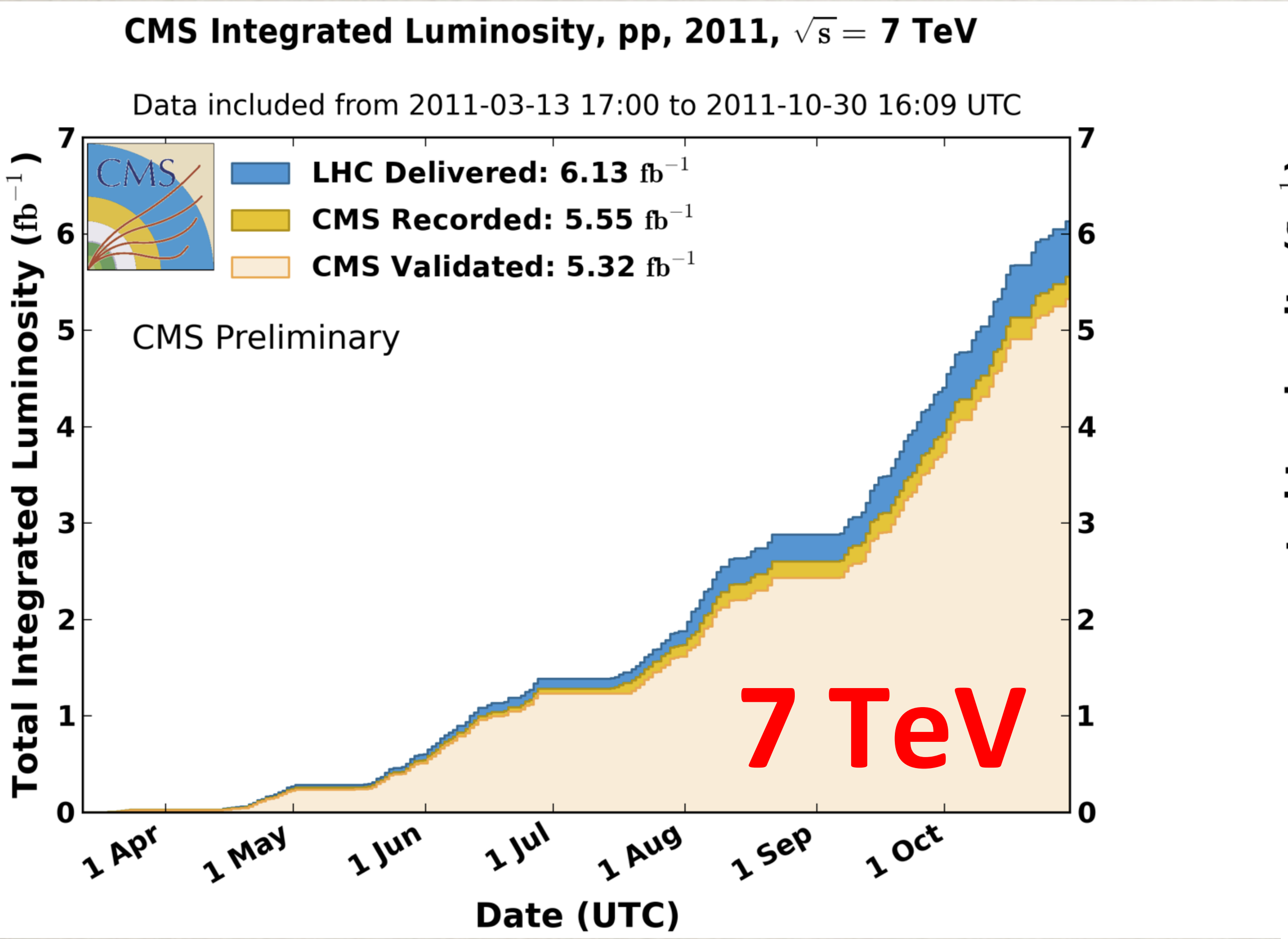
(c). Higgs as an inflaton?
(d). Higgs field & Dark Energy?

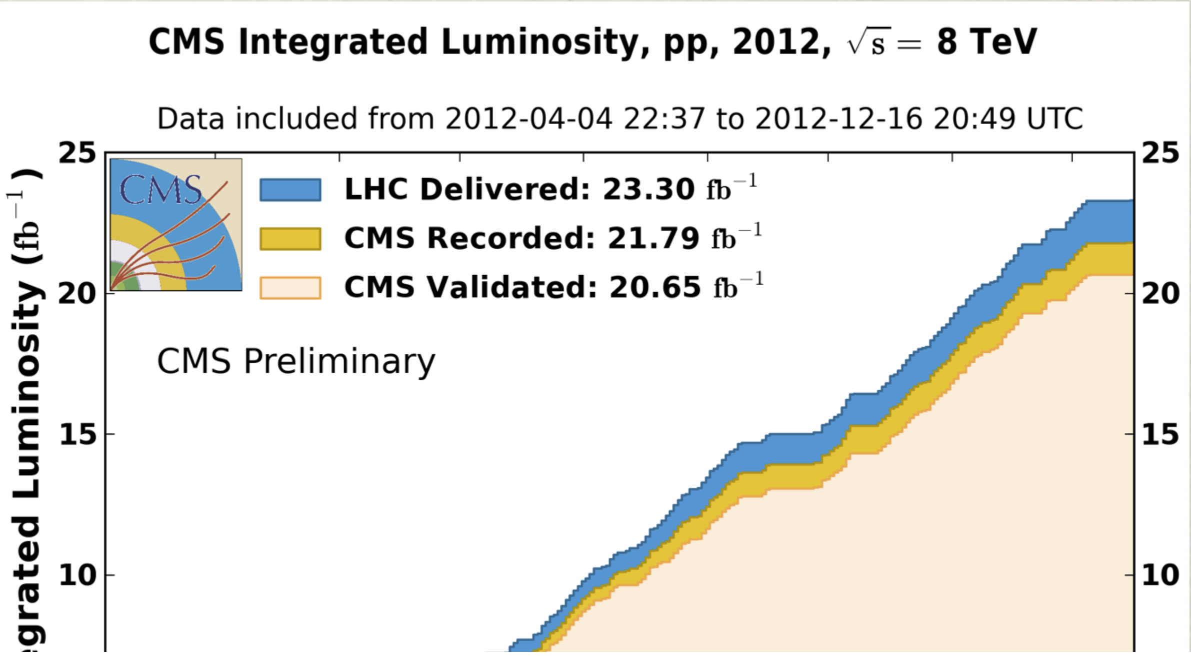
Bezrukov, 2008;
Nakayama, 2011.

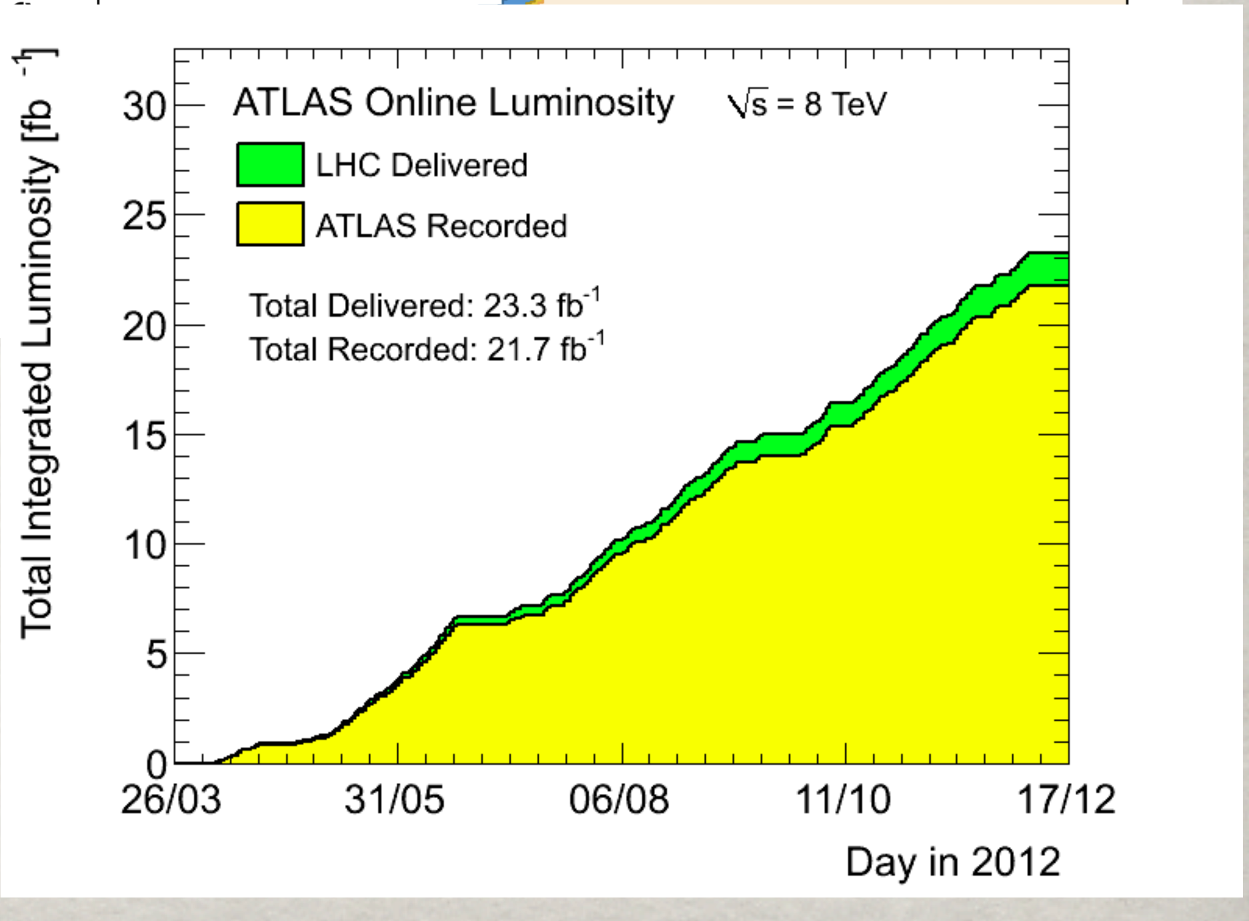
The existence of a fundamental scalar encourages the consideration of scalar fields in cosmological applications.

The discovery of the Higgs-like boson is merely a beginning of a long, exciting journey!

LHC miracles: Accelerator and detectors outstanding performances:

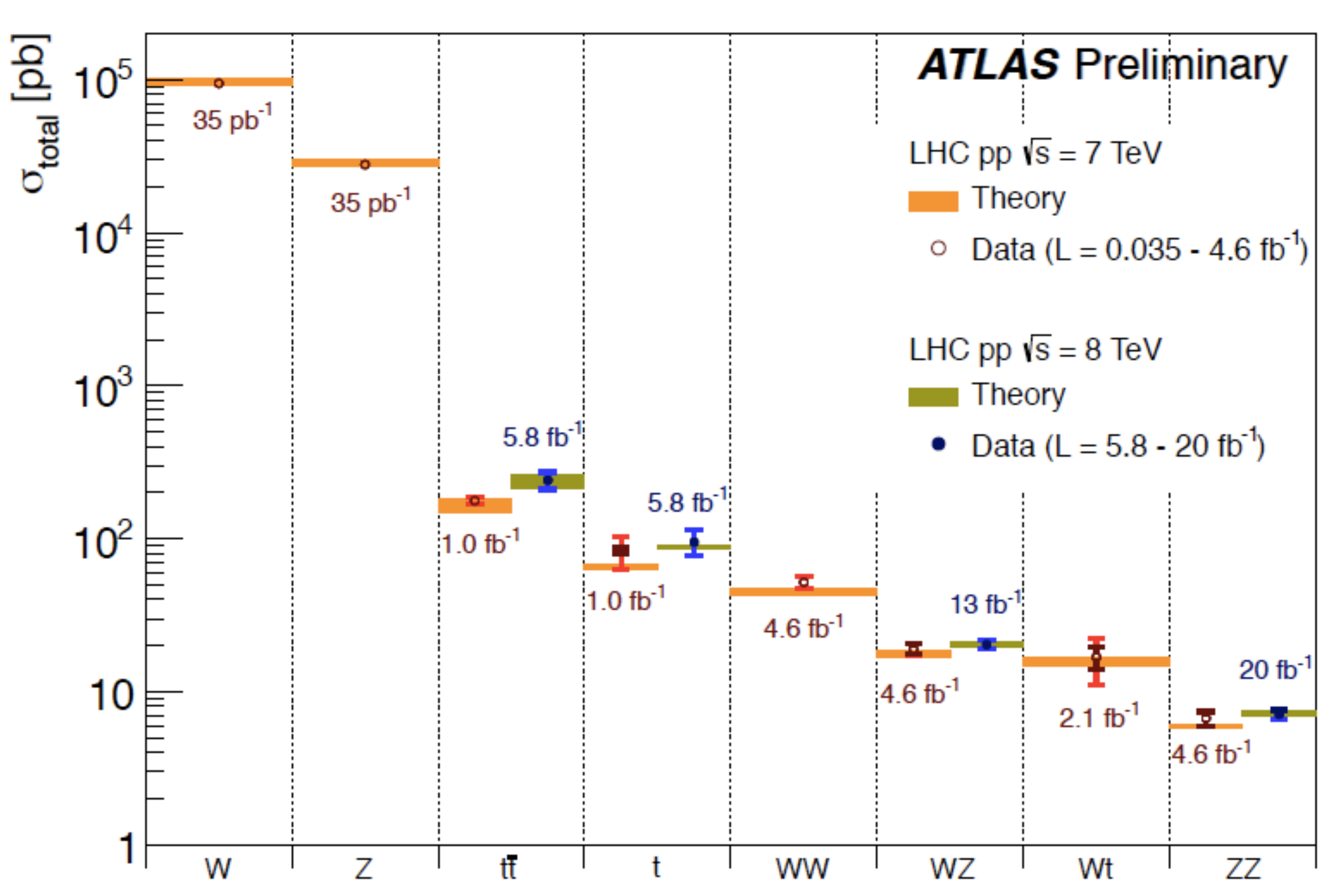


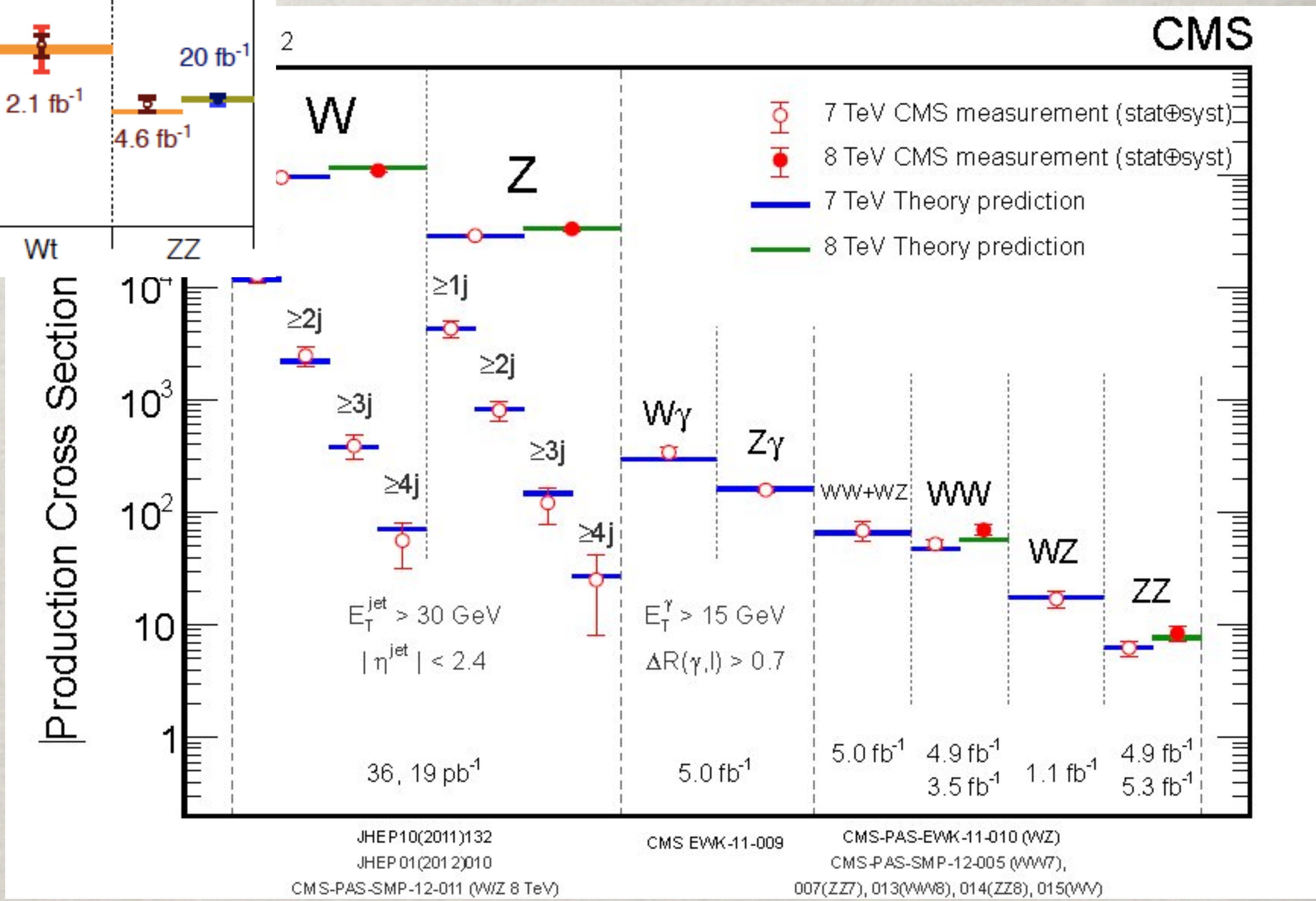




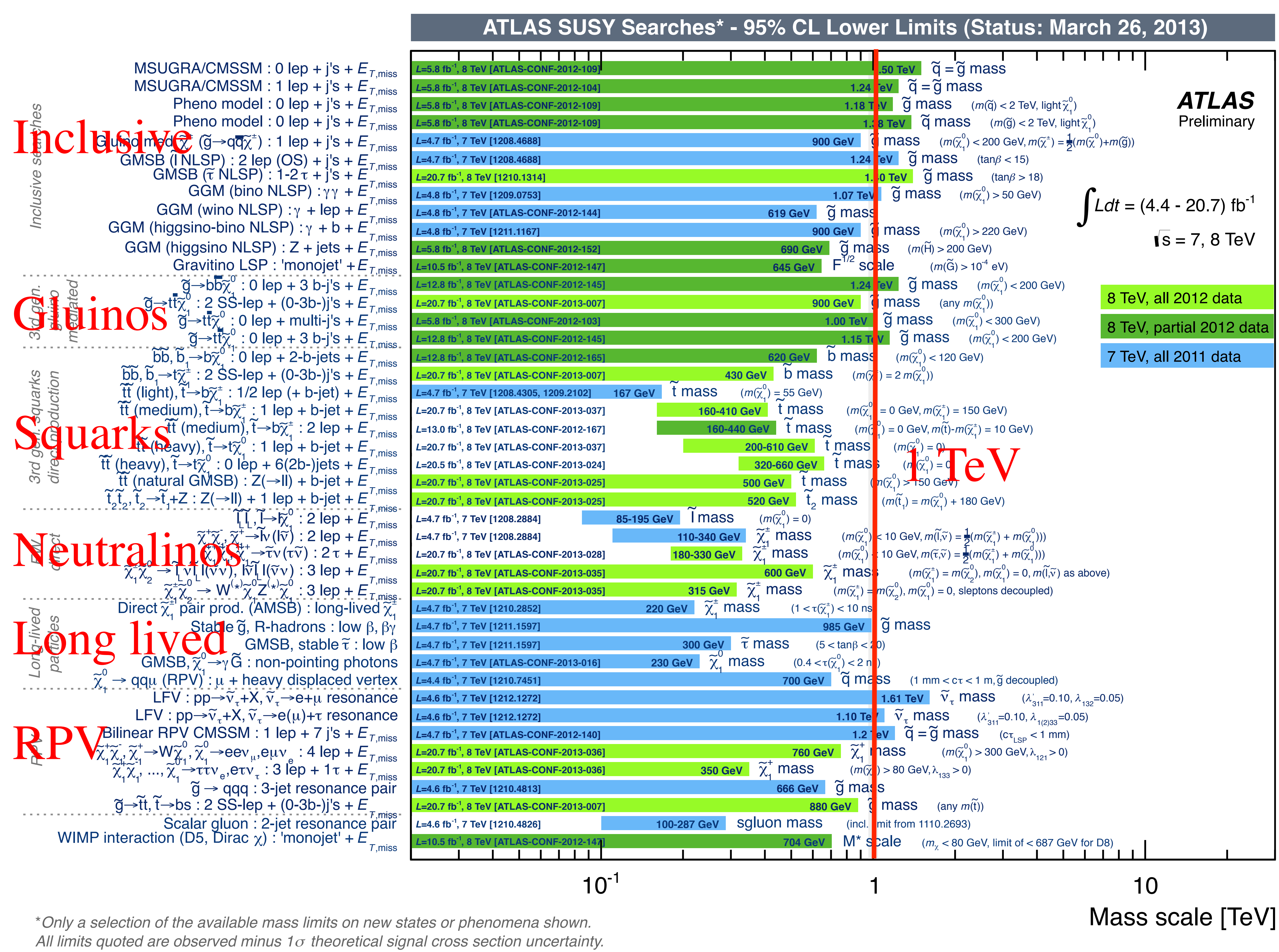
Each detector has reached the CDF/D0 sum.

SM well studied at the Tera scale:



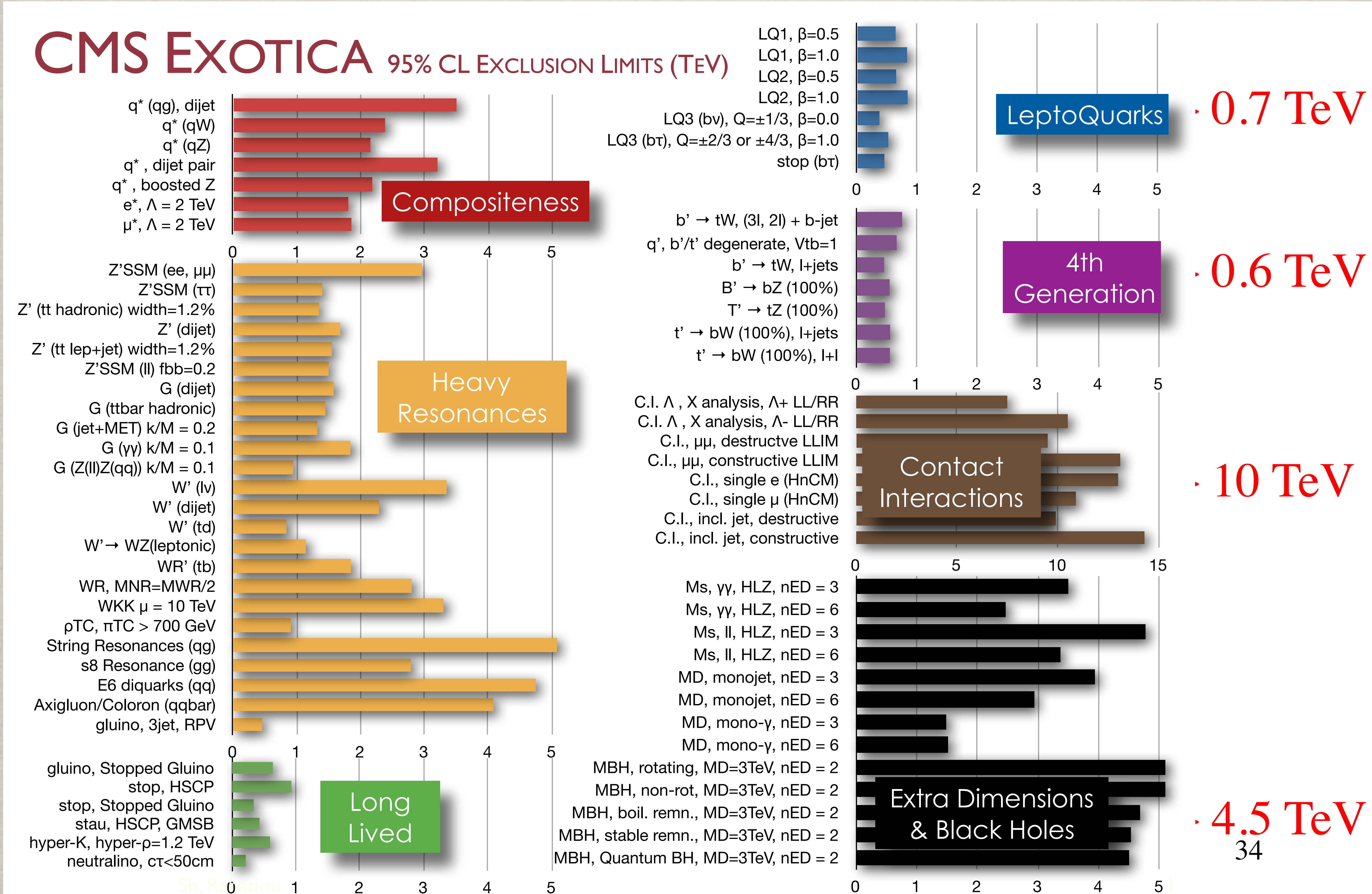


No SUSY (yet)



ATLAS SUSY Searches* - 95% CL Lower Limits (Status: March 26, 2013)
ATLAS
Preliminary
$\int L dt = (4.4 - 20.7)\ fb^{-1}$
$\sqrt{s}$ = 7, 8 TeV
8 TeV, all 2012 data
8 TeV, partial 2012 data
7 TeV, all 2011 data
Inclusive
Gluinos
Squarks
Neutralinos
Long lived
RPV
1 TeV
Inclusive searches
3rd gen. squarks direct production
Long-lived particles
10^{-1}
1
10
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Nothing “exotic” (either)



LHC upgrades

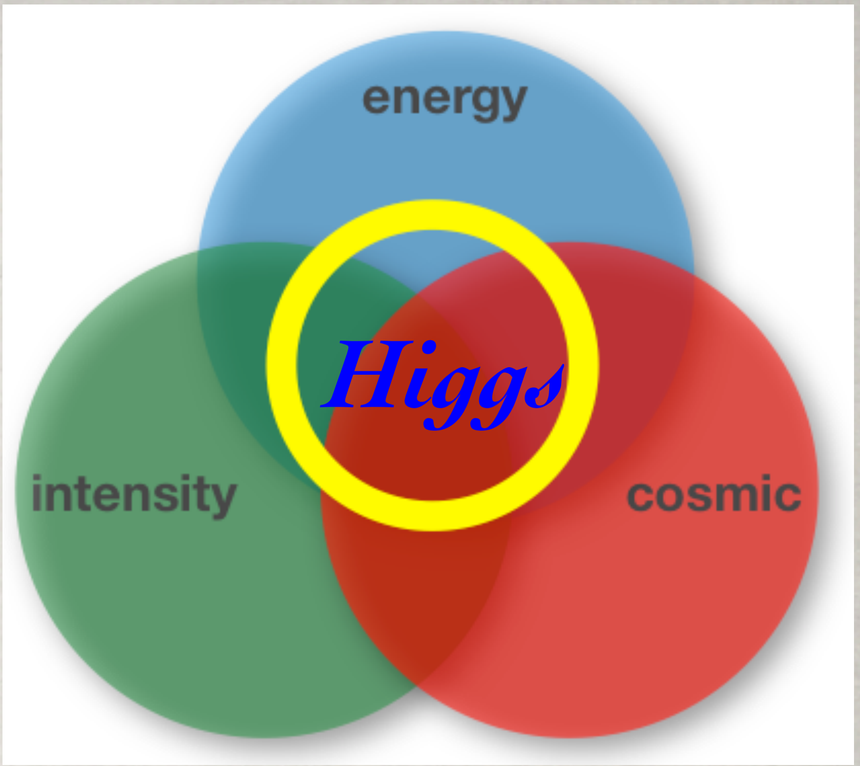
LHC will restart in 2014, till 2017(?):
~ 13 TeV with expectation of 100-300 fb^{-1} .

HL LHC's ultimate goal, till 202x:
~ 14 TeV with expectation of 3000 fb^{-1} .
→ So the curent 7/8 TeV data is only 1% of total!

In the mean time:
ILC (250 GeV-1 TeV), Higgs Factory(?)

Summary:

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



"Naturally speaking":

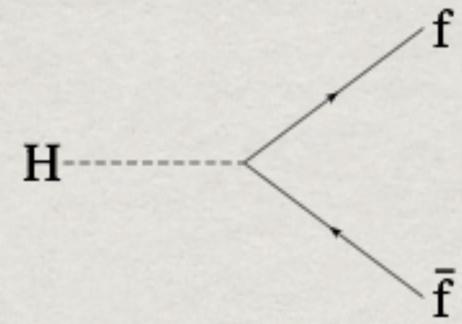
- It should not be a lonely particle; has an "interactive friend circle": $t,\ W^{\pm},\ Z$ and partners $\tilde{t},\ \tilde{W}^{\pm},\ \tilde{Z},\ \tilde{H}^{\pm,0}\ldots$
- LHC lights the way for the searches.
- Higgs factory may reveal their existence from Higgs coupling measurements.

An exciting journey ahead of us!

Backup slides

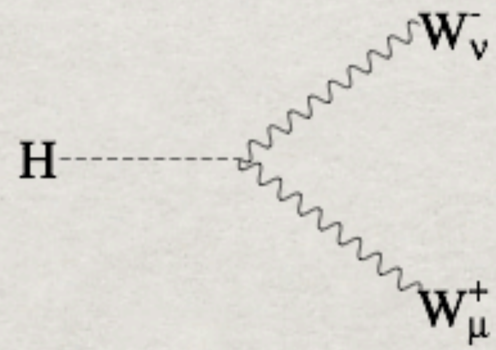
Measuring Higgs Couplings

Yukawa coupling:

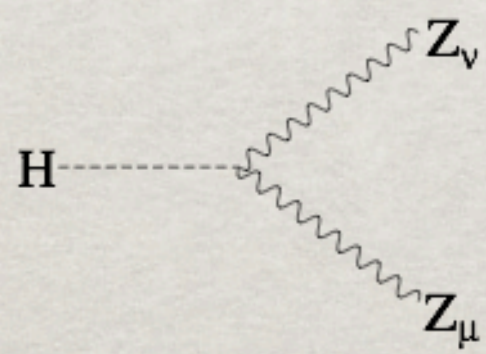


$$-i\frac{m_f}{v}\left(1+\Delta_f\right)$$

EWSB
(more Higgs bosons)

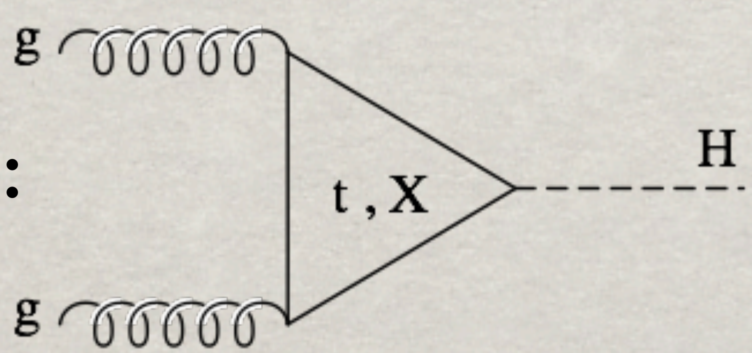


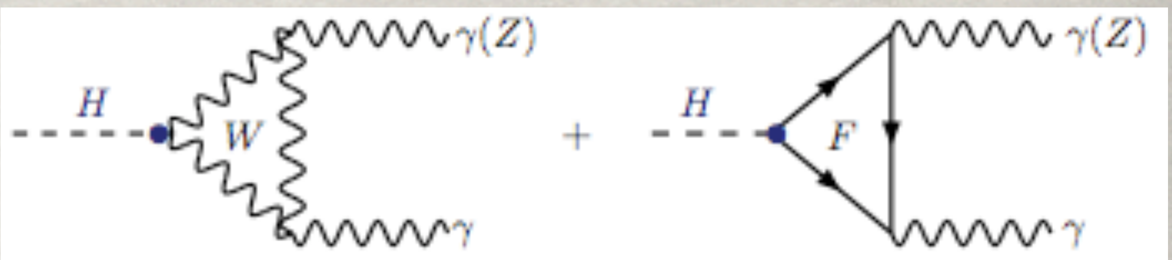
$$ig\, m_W\, (1+\Delta_W) g_{\mu\nu}$$



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

Color/charge
particles in loops:

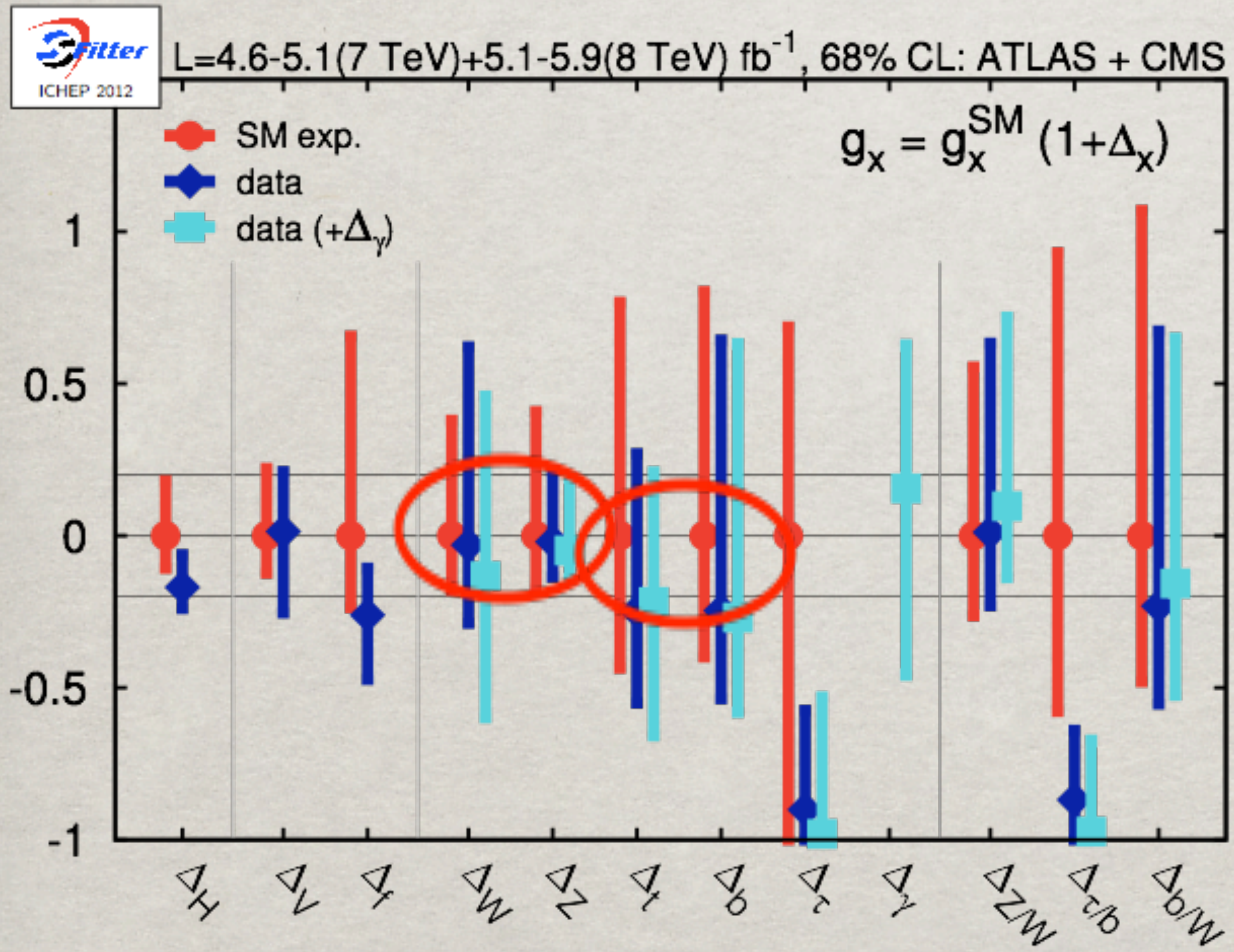




Current accuracies:

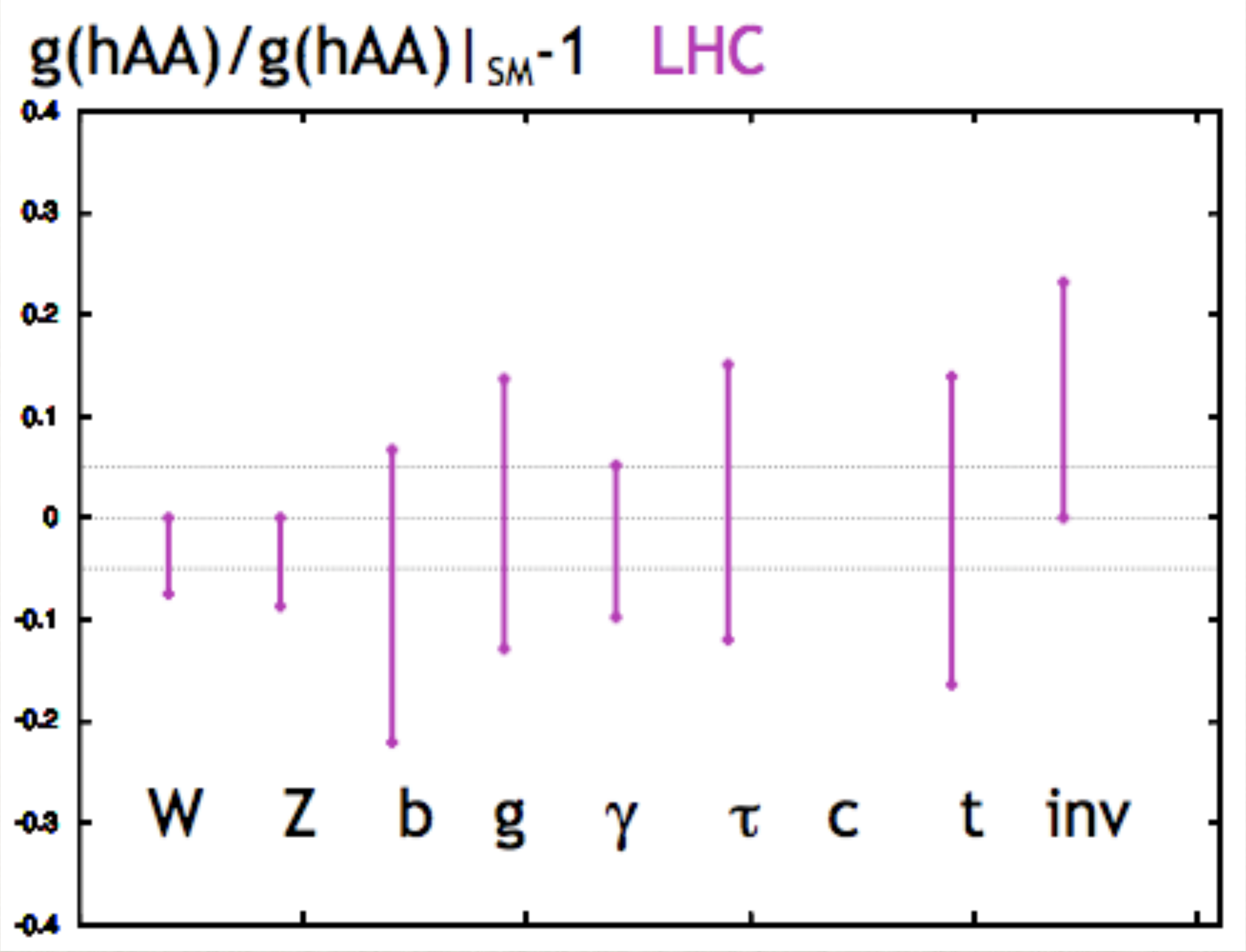
Central values and errors on couplings

Assuming SM: SFitter: T. Plehn et al., 2012.



- SM provides good overall description
- Two parameter fit with $\Delta_V \equiv \Delta_W = \Delta_Z$ and $\Delta_f \equiv \Delta_b = \Delta_\tau = \Delta_t$ gives improvement to $\chi^2/\text{d.o.f.} = 29.0/52$
- Five parameter fit does not give further improvement: $\chi^2/\text{d.o.f.} = 27.7/49$

Future LHC sensitivities:



14 TeV LHC with 300 fb^{-1}.

Peskin, arXiv:1207.2516; arXiv:1208.5152.

LHC/ILC Comparison:

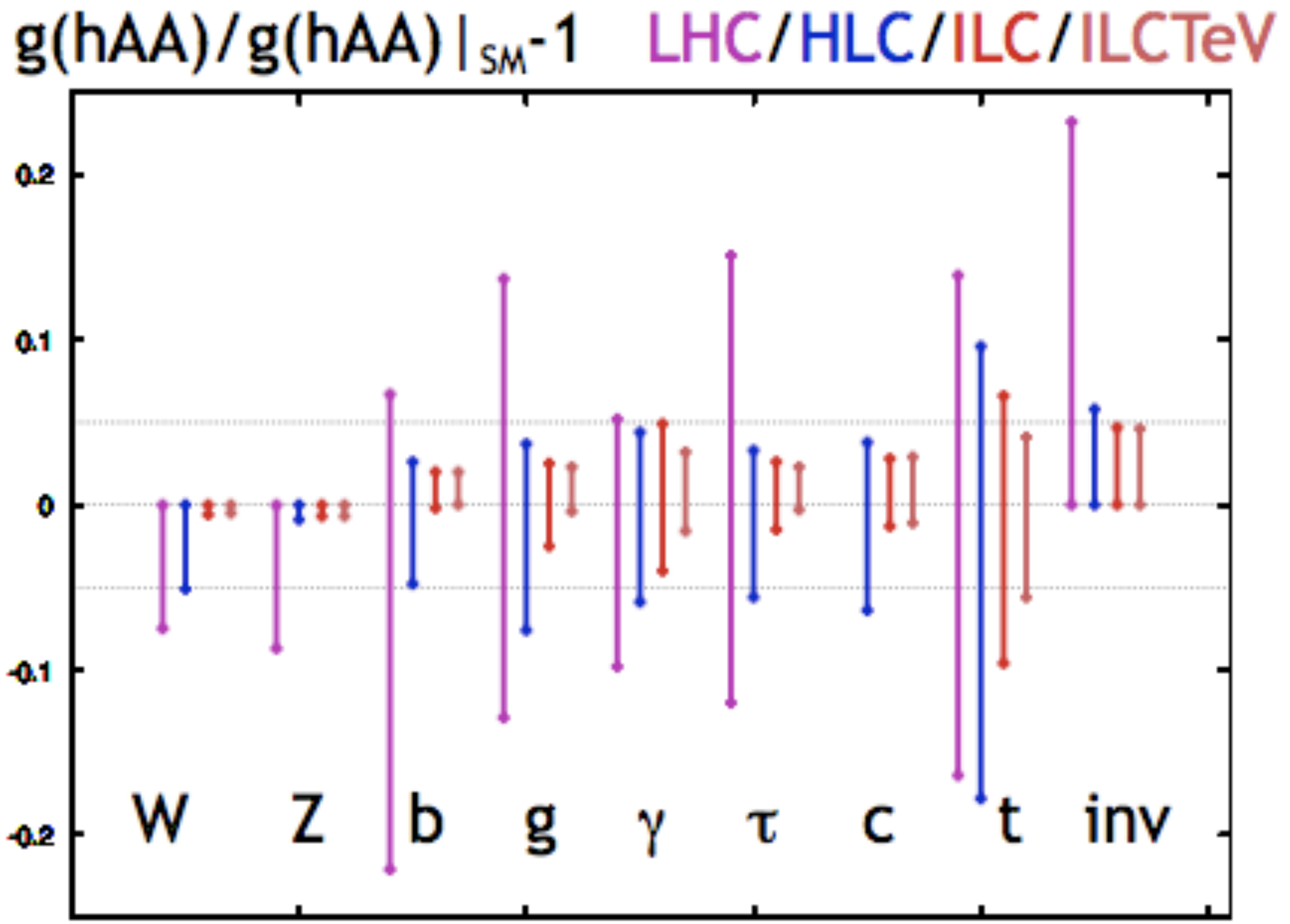


Figure 20: Estimate of the sensitivity of the ILC experiments to Higgs boson couplings in a model-independent analysis. The four sets of errors for each Higgs coupling represent the results for LHC, the threshold ILC Higgs program at 250 GeV, the full ILC program up to 500 GeV, and the extension of the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

Peskin, arXiv:1207.2516

What we need to achieve …

To go beyond the LHC direct search,

1. Precision Higgs physics at a few %:
   Δ_{VVH} for composite dynamics;
   $\Delta_{bbH,\ \tau\tau H}$ for decoupling H^0, A^0;
   $\Delta_{ggH,\ \gamma\gamma H}$ for color/charge loops.

2. Reach 10% for H → invisible.

3. Determine Γ_{tot} to 10%.

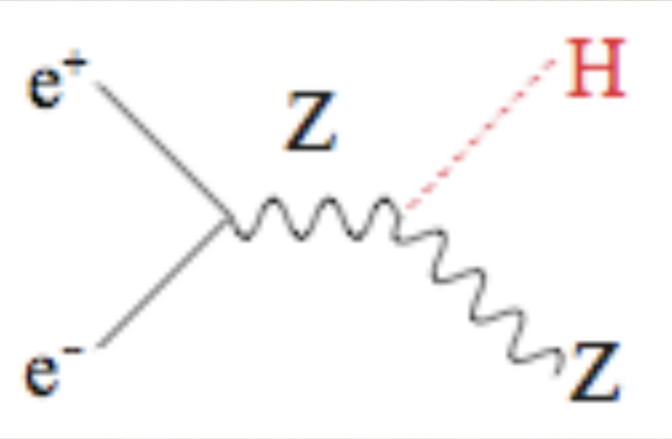
A Word of Expectations

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.

Not-So Natural Higgs Sector

Example 2: Top quark partner

The top quark partners are most wanted to cancel the quadratic sensitivity to the quantum corrections of M_H.

	Δ_{hgg}	$\Delta_{h\gamma\gamma}$
SUSY $\tilde{t}$	$1.4\%(\frac{1\ \mathrm{TeV}}{m_{\tilde{t}}})^2$	$-0.4\%(\frac{1\mathrm{TeV}}{m_{\tilde{t}}})^2$
Little Higgs T	$-10\%(\frac{1\ \mathrm{TeV}}{M_T})^2$	$-6\%(\frac{1\mathrm{TeV}}{M_T})^2$

Peskin, arXiv:1208.5152;
TH, Logan, McElrath, Wang, 2004

Not-So Natural Higgs Sector

Example 3. Composite Higgs

The Higgs boson as a pseudo-Goldstone boson,
so that it is much lighter than the dynamical scale f ~ TeV.

The Higgs boson couplings may receive corrections from the other heavy states

Contino, Nomura, Pomarol, 2003;
Agashe, Contino, Pomarol, 2005.

$$\Delta_i \sim \mathcal{O}(v^2/f^2)$$

	Δ_{hVV}	Δ_{hff}
Minimal Composite Higgs	$-3\%(\frac{1\ \mathrm{TeV}}{f})^2$	$-(3-9)\%(\frac{1\ \mathrm{TeV}}{f})^2$

Espinosa, Grojean, Muhlleitner; 2010;
Gupta, Rzehak, Wells, arXiv:1206.3560.

Not-So Natural Higgs Sector

Example 4. Missing MSSM at LHC

For an illustration:

Peskin et al., 2012, to appear.

$M_A = 1 \text{ TeV}, \ \tan\beta = 5, \ m_{\tilde{t}} = 900 \text{ GeV} :$

MSSM	Δ_{hVV}	$\Delta_{hbb,\ h\tau\tau}$
Tree-level	10^{-4}	3%
	Δ_{hgg}	$\Delta_{h\gamma\gamma}$
Loop induced	-2.7%	0.2%

Carena, Heinemeyer, Wagner, Weiglein, 1999;
Carena, Haber, Logan, Mrenna, 2002.

SUSY is a weakly coupled theory,
thus with modest corrections.

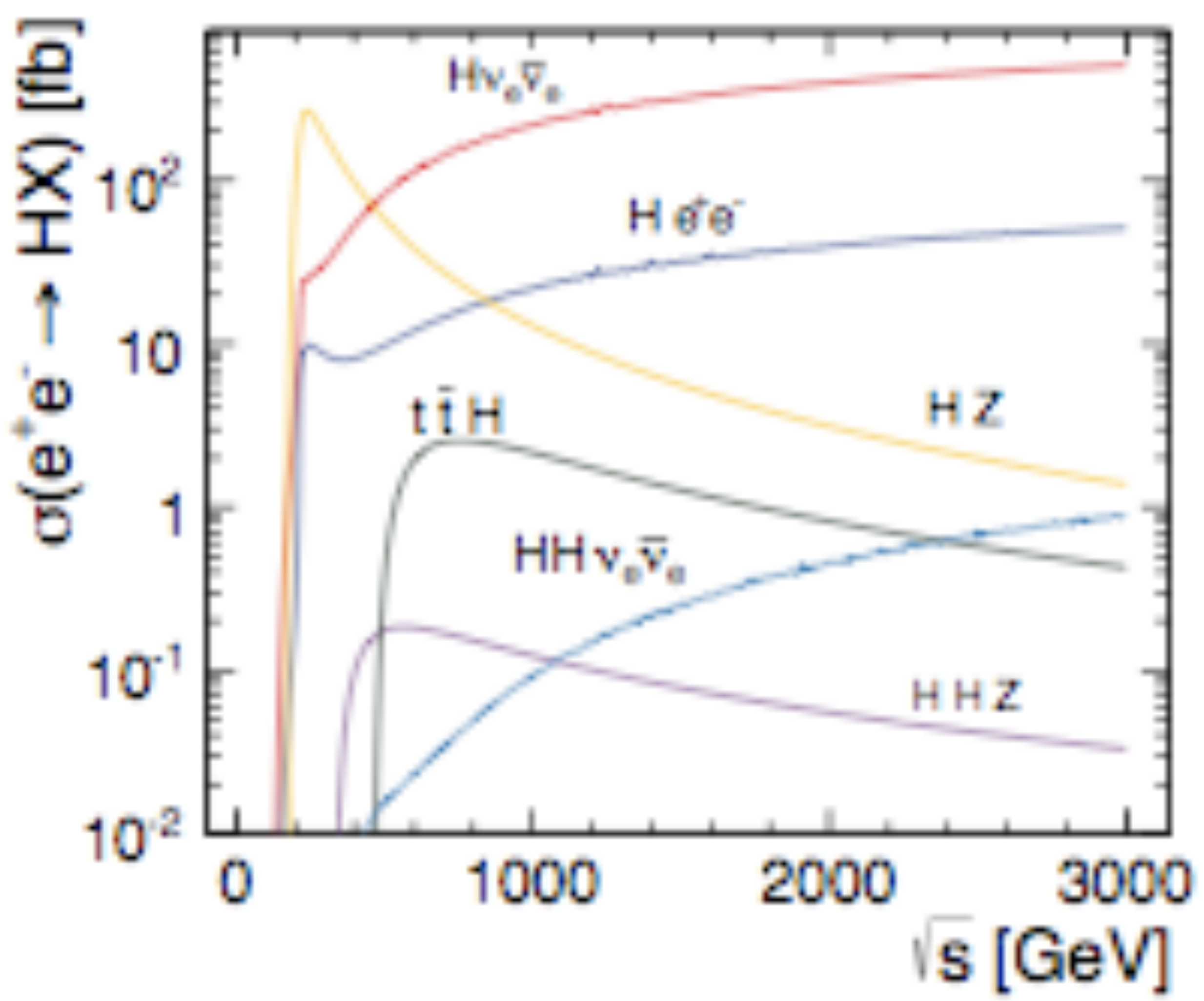
LHC @ HIGH L

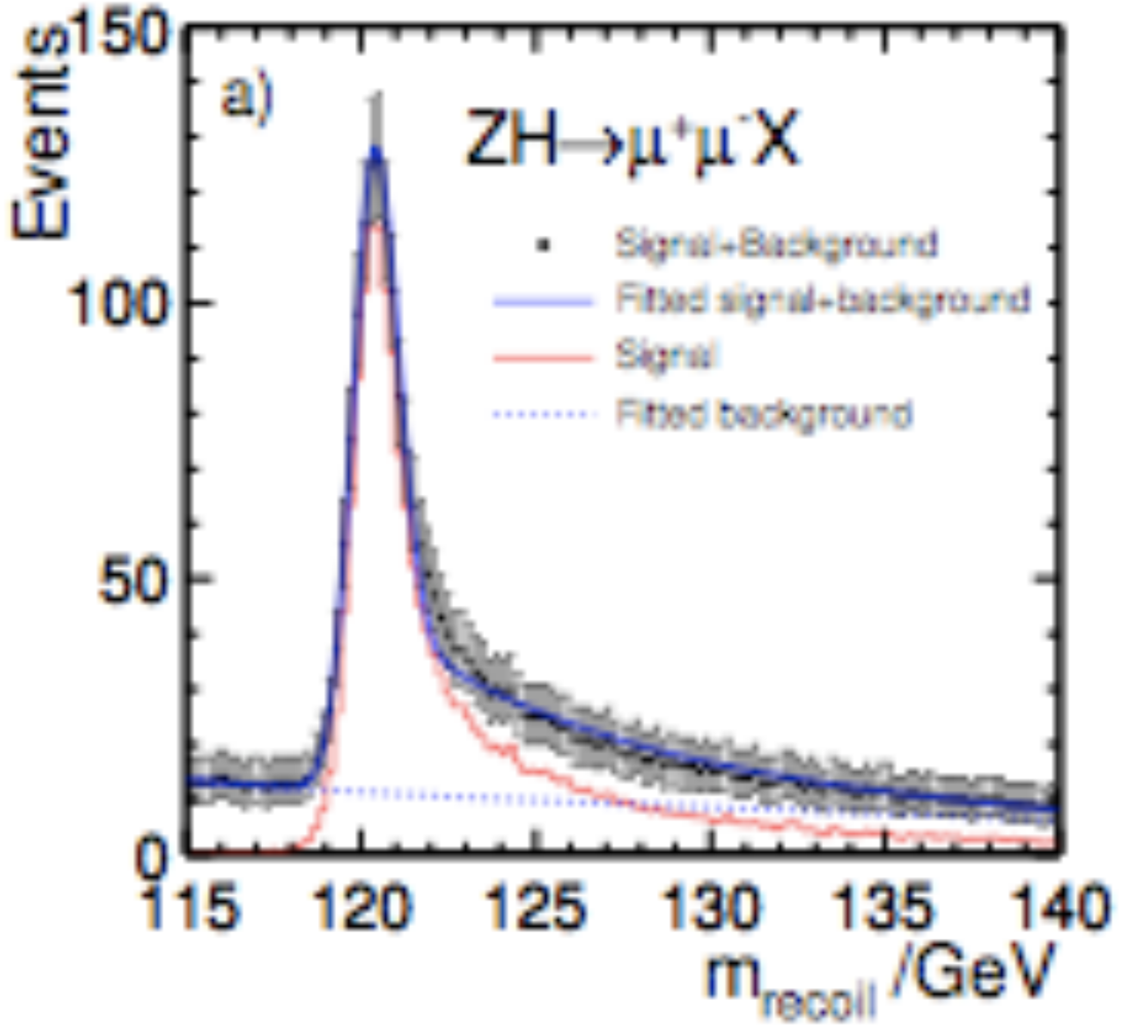
	ΔhVV	$\Delta ht\bar{t}$	$\Delta hb\bar{b}$
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	$< 1\%$	3%	$10\%^{a}$, $100\%^{b}$
LHC 14 TeV, 3 ab^{-1}	8%	10%	15%

TABLE I: Summary of the physics-based targets for Higgs boson couplings to vector bosons, top quarks, and bottom quarks. The target is based on scenarios where no other exotic electroweak symmetry breaking state (e.g., new Higgs bosons or ρ particle) is found at the LHC except one: the ~ 125 GeV SM-like Higgs boson. For the $\Delta hb\bar{b}$ values of supersymmetry, superscript a refers to the case of high $\tan\beta > 20$ and no superpartners are found at the LHC, and superscript b refers to all other cases, with the maximum 100% value reached for the special case of $\tan\beta \simeq 5$. The last row reports anticipated 1σ LHC sensitivities at 14 TeV with 3 ab^{-1} of accumulated luminosity [5].

Gupta, Rzehak, Wells, arXiv:1206.3560

ILC Higgs





F. Simon, arXiv:1211.7242.

Example 1: Extended Higgs Sector:

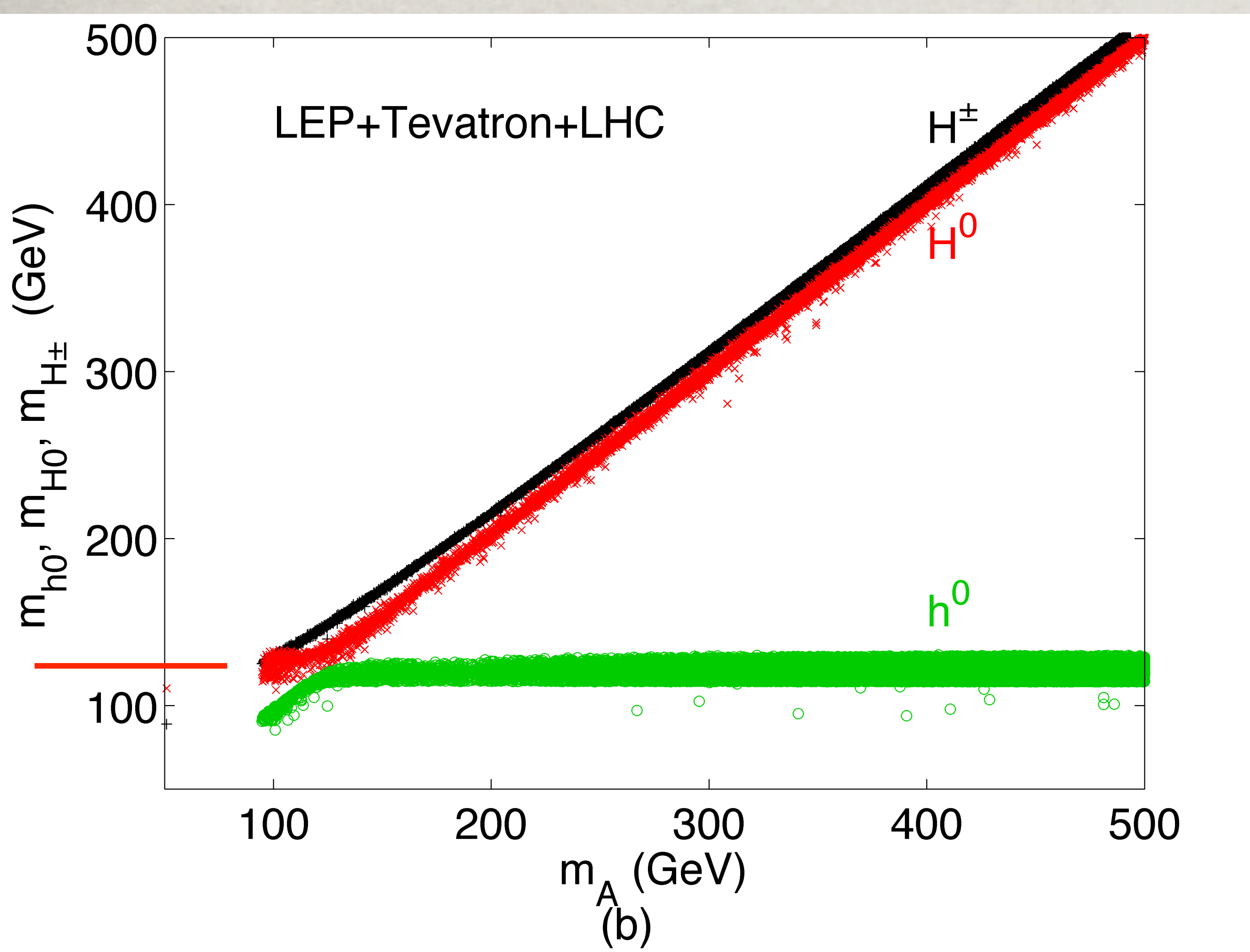
MSSM: Two Higgs-Doublet Model

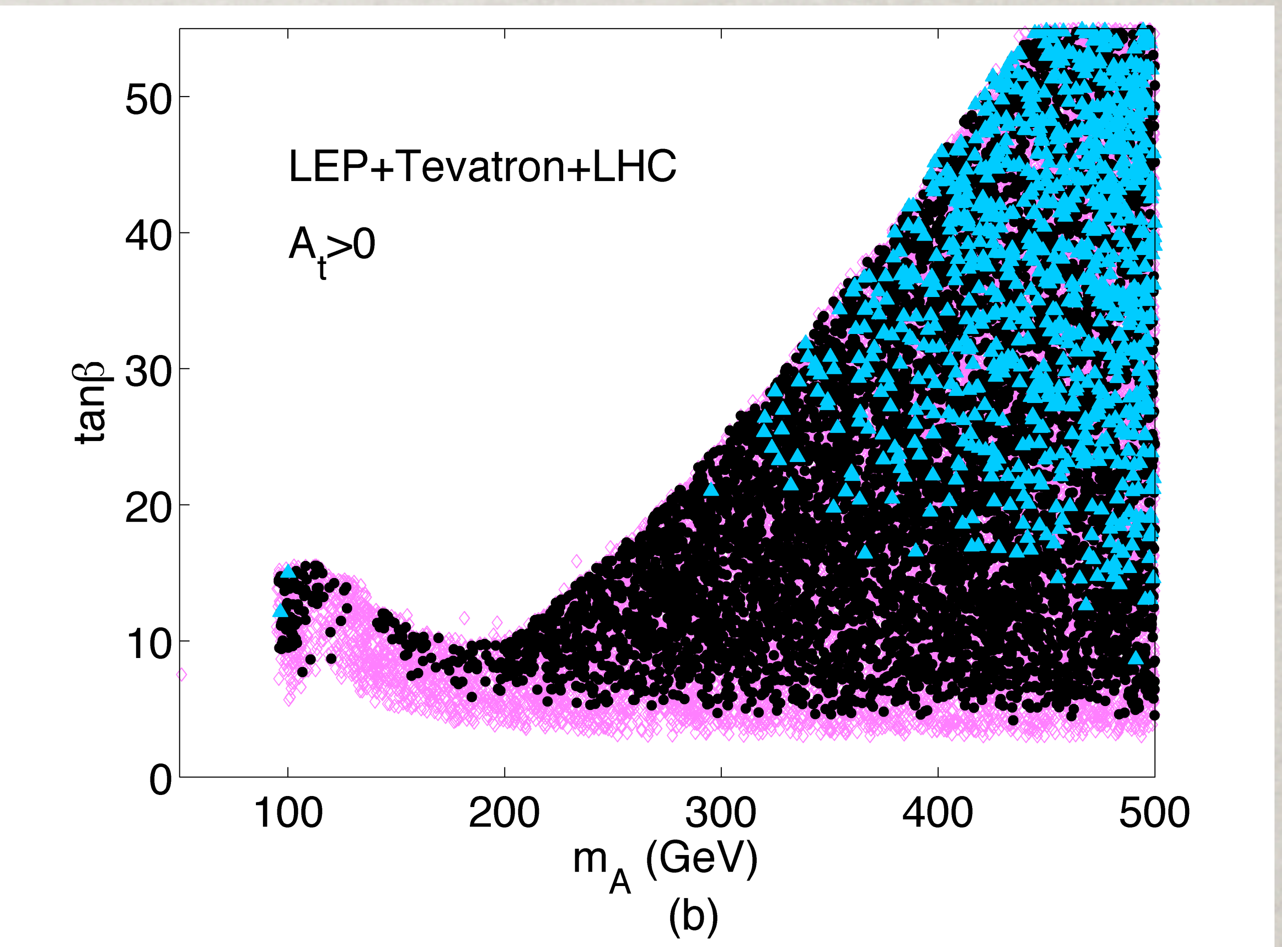
3 Goldstone bosons, 5 Higgs bosons:

$$h^0,\ H^0,\ A^0,\ H^\pm$$

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

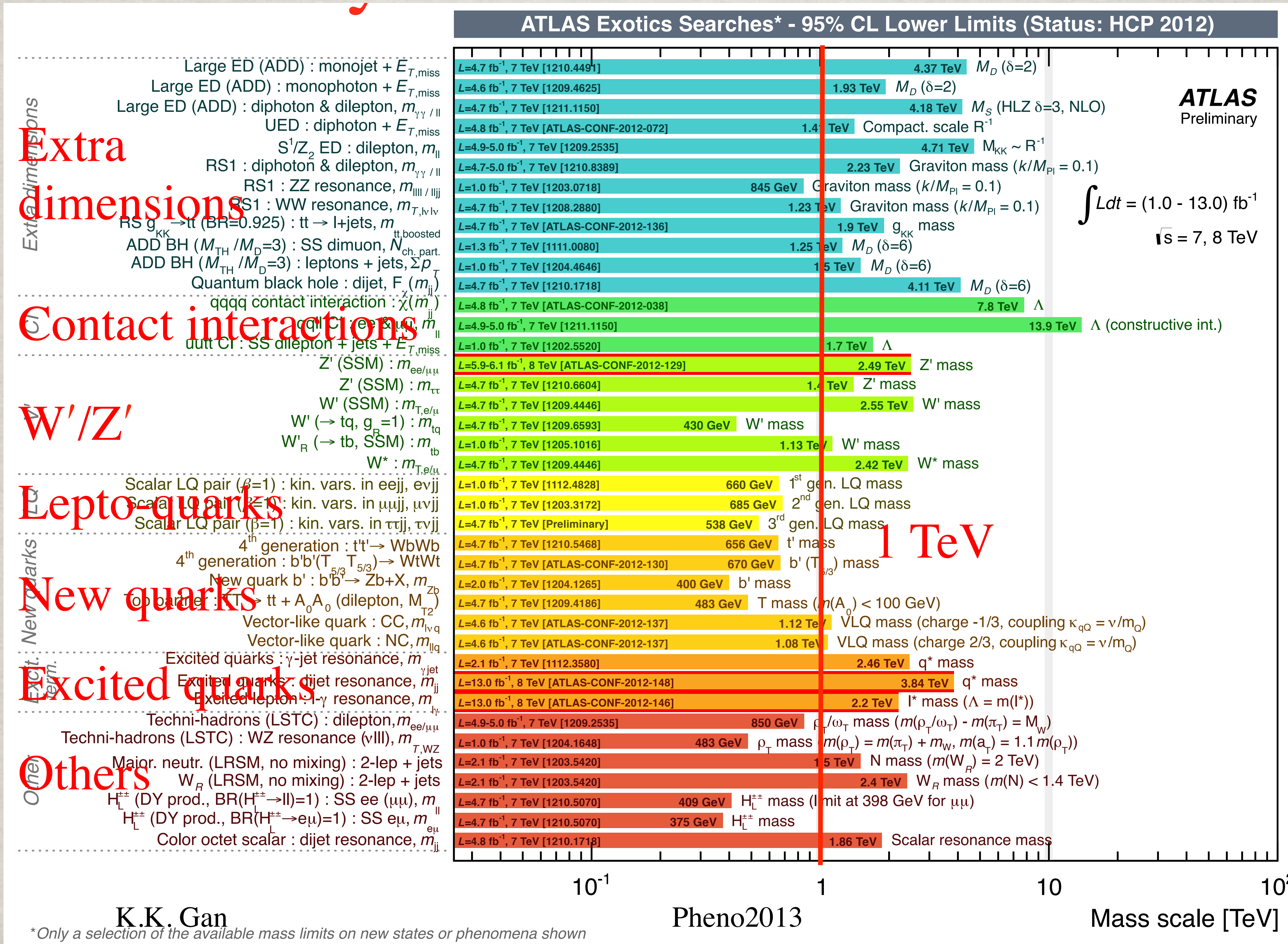
Current LHC bounds:





.2 TH, Su, Christensen, arXiv:1203.3207

SM well studied at the highest energies:



K.K. Gan

Pheno2013

1. **LHC Lights the way for new physics searches.**

2. **Under the *Higgs lamp post.***