Higgs Couplings & new Physics

KITP, Dec. 17, 2012

Tao Han

HEPAP Question:

“What couplings should be measured and to what precision?”

To uncover new physics

1. **How badly (likely) we need BSM new physics?**

2. **Direct search for Higgs' companions.**
3. **Indirect searches under the *Higgs lamp post.***

Currently Indications from the LHC:

1. No light companions observed (yet):

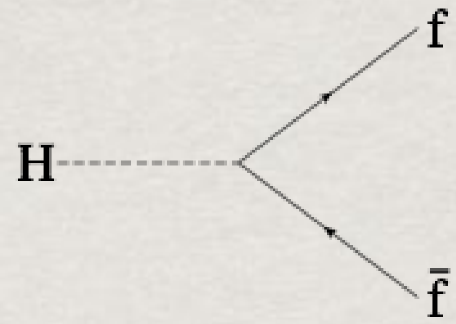
$$\tilde{t},\ \tilde{g}, \ldots \quad \tilde{H}^{\pm,0},\ \tilde{W}^{\pm,0} \ldots$$

2. $M_H = 126$ GeV needs large SUSY split, so the stop seems to be heavy.

Not-So Natural Higgs Sector

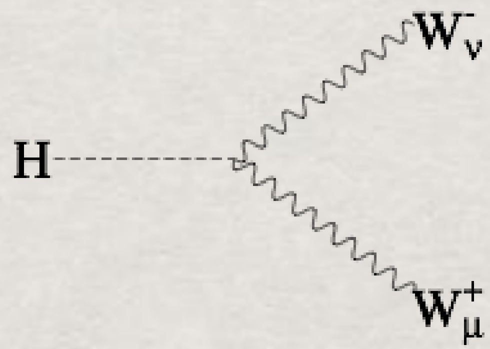
If they are not directly observed at the LHC, the probe to the high scale new physics associated with the EWSB relies on detecting the deviations from the SM-like Higgs couplings.

Yukawa coupling:

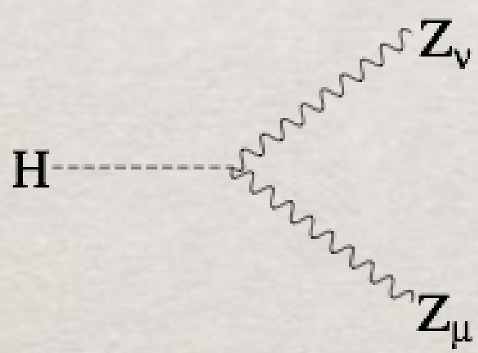


$$-i\frac{m_f}{v}\left(1+\Delta_f\right)$$

EWSB
(more Higgs
bosons)

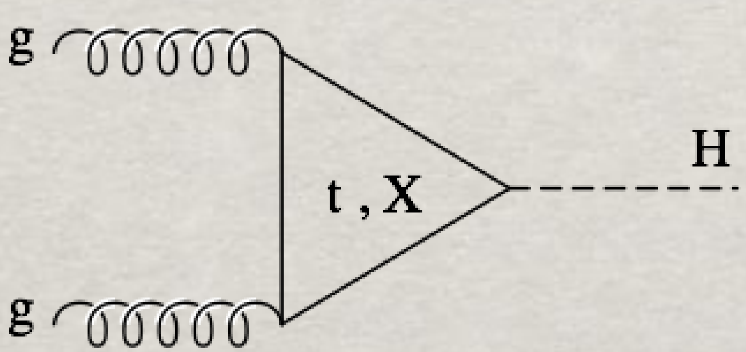


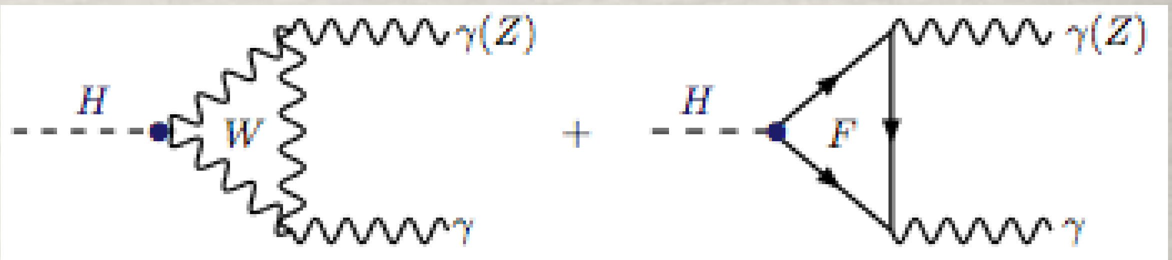
$$ig\,m_W\,(1+\Delta_W)g_{\mu\nu}$$



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

Color/charge
particles in
loops:



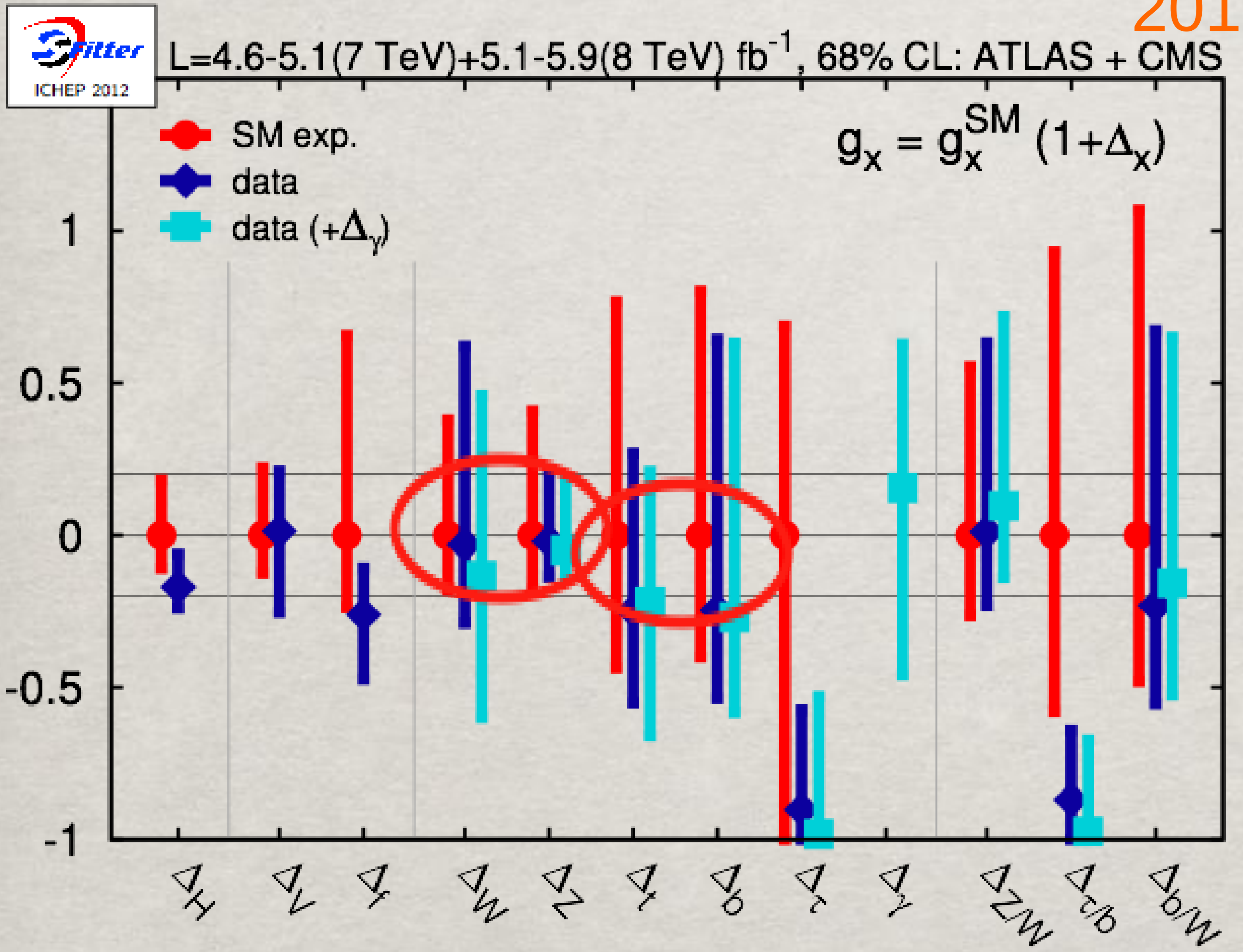


Current accuracies:

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: $\chi^2/\text{d.o.f.} = 27.7/49$

Integrating out the heavy states at the scale M ≈ 1 TeV,

we expect the tree-level corrections:

$$\Delta_i \equiv \frac{g_i}{g_{SM}} - 1 \sim \mathcal{O}(v^2/M^2)$$

≈ a few %

We illustrate the possible effects

in a few specific models.

For each model, we aim at the mass scale M

which is not easily accessible by

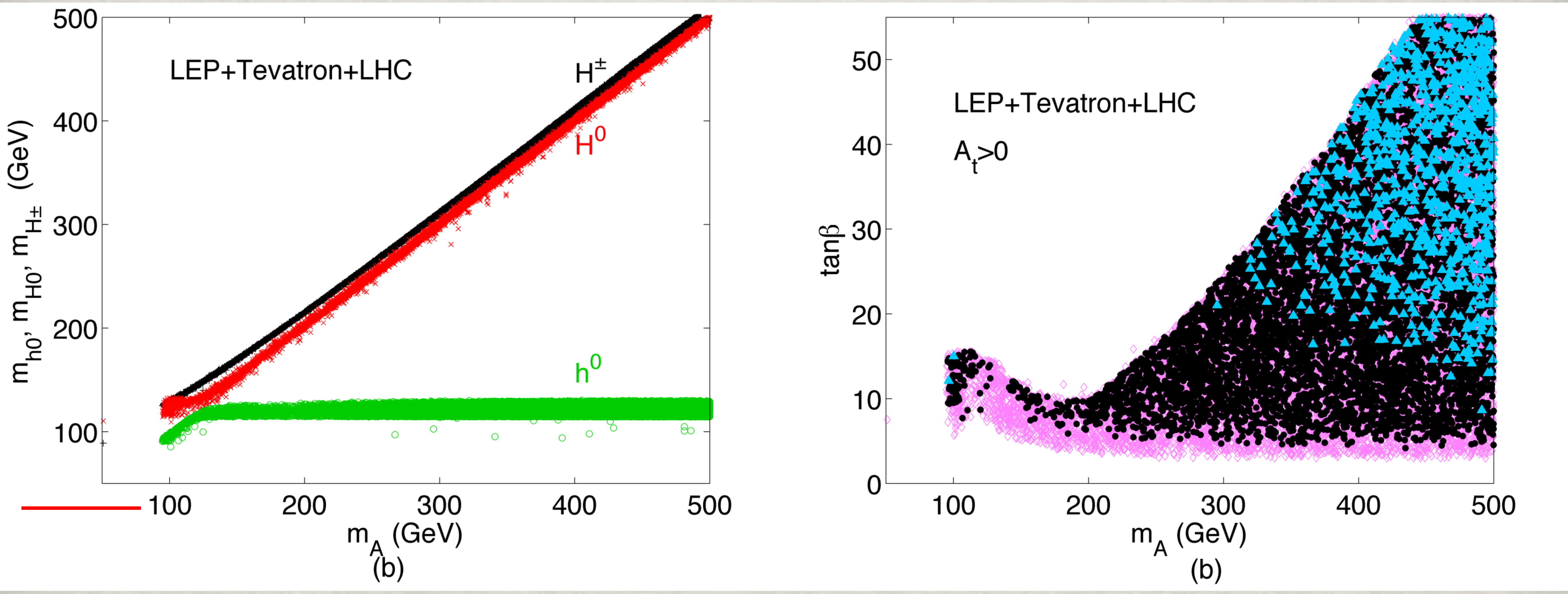
14 TeV LHC with 300 fb^{-1}.

Example 1: Extended Higgs Sector:

MSSM: Two Higgs-Doublet Model

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

Current LHC bounds:



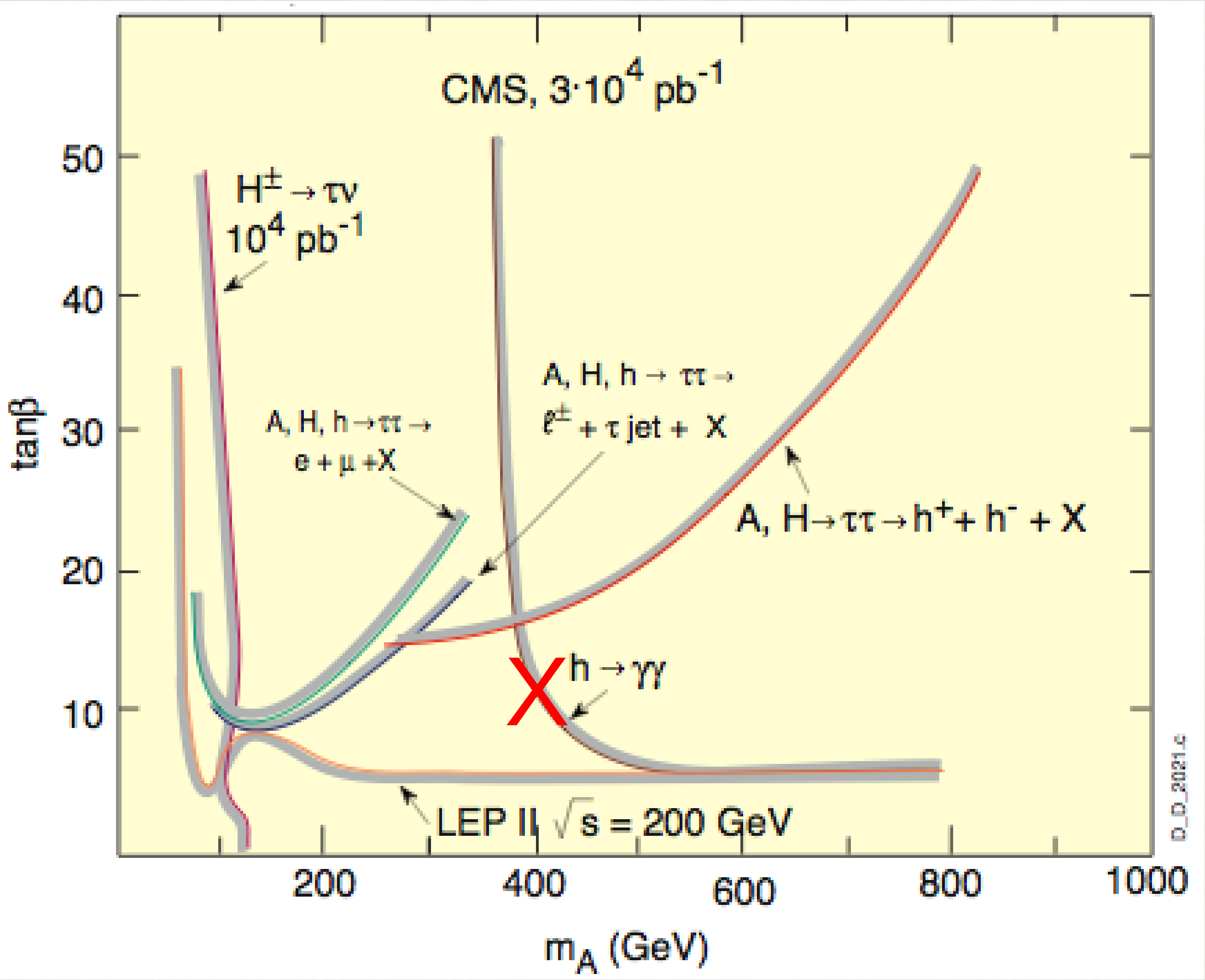
TH, Su, Christensen, arXiv:1203.3207

The decoupling limit in MSSM: H. Haber, hep-ph/9501320.

$$\Delta_{VVH} \sim \mathcal{O}(M_Z^4/M_A^4), \quad \Delta_{ffH} \sim \mathcal{O}(M_Z^2/M_A^2).$$

(Similar decoupling limit also exists in 2HDM)

A^0, H^0, $H^\pm$ may be out of LHC detection:

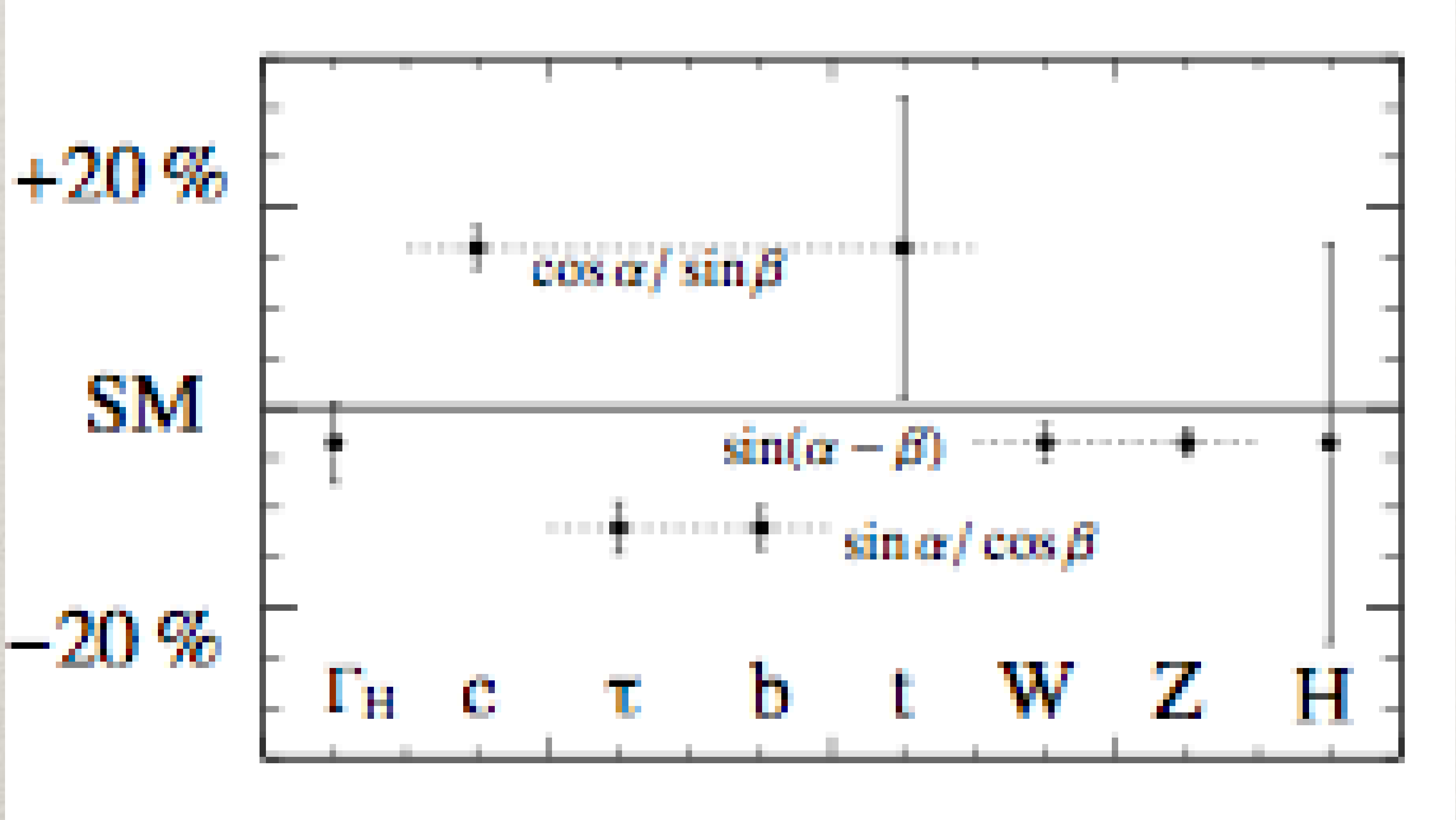


Corrections in the MSSM decoupling limit:

Carena, Haber et al., 2002

Δ_{hVV}	Δ_{htt}	$\Delta_{hbb,h\tau\tau}$
$\frac{-2M_Z^4}{m_A^4 \tan^2\beta}$	$\frac{-2M_Z^2}{m_A^2 \tan^2\beta}$	$\frac{2M_Z^2}{m_A^2}$
$-5\cdot 10^{-5}(\frac{10}{\tan^2\beta})^2(\frac{400\ \mathrm{GeV}}{m_A})^4$	$-10^{-3}(\frac{10}{\tan^2\beta})^2(\frac{400\ \mathrm{GeV}}{m_A})^2$	$10\%(\frac{400\ \mathrm{GeV}}{m_A})^2$

Corrections in the 2HDM decoupling limits:



J.Brau et al., arXiv:1210.0202

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 $\tilde{t}$	$1.4\%(\frac{1\ \text{TeV}}{m_{\tilde{t}}})^2$	$-0.4\%(\frac{1\text{TeV}}{m_{\tilde{t}}})^2$
Little Higgs T	$-10\%(\frac{1\ \text{TeV}}{M_T})^2$	$-6\%(\frac{1\text{TeV}}{M_T})^2$

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.
The Higgs boson couplings may receive corrections from the other heavy states $\Delta_i \sim \mathcal{O}(v^2/f^2)$

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

	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.

SILH: similar corrections to above,
for $\Delta_{h\gamma\gamma}, \Delta_{gg} \sim 6\%\ (\frac{1\ \mathrm{TeV}}{\Lambda})^2.$

Guidice, Grojean, Pomarol, Rattazzi; 2007; Ian Low, Rattazzi, 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.

Not So Natural Higgs Sector

Example 5. Higgs self-coupling:

$$\mathcal{L}' = \sum_i^2 \frac{f_i}{\Lambda^2}\mathcal{O}_i, \quad \mathcal{O}_1 = \frac{1}{2}\partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi) \quad \text{and} \quad \mathcal{O}_2 = -\frac{1}{3}(\Phi^\dagger\Phi)^3,$$

$$\mathcal{L}_{H^3} = -\frac{m_H^2}{2v}\left((1 - \frac{a_1}{2} + \frac{2a_2}{3}\frac{v^2}{m_H^2})H^3 - \frac{2a_1 H\partial_\mu H\partial^\mu H}{m_H^2}\right)$$

$$\mathcal{L}_{H^4} = -\frac{m_H^2}{8v^2}\left((1 - a_1 + \frac{4a_2 v^2}{m_H^2})H^4 - \frac{4a_1 H^2\partial_\mu H\partial^\mu H}{m_H^2}\right)$$

$$a_i = f_i\,\frac{v^2}{\Lambda^2}$$

$$f_i \sim O(1 - 4\pi).$$

Barger, TH, Langacker, Zerwas, 2003.

$$\Delta_2 \approx 0.06 f_2(\frac{1\ \text{TeV}}{\Lambda})^2, \quad \Delta_1 \approx 0.03 f_1(\frac{1\ \text{TeV}}{\Lambda})^2 + O(\frac{E^2}{m_h^2}).$$

$$\mathcal{L}_M = (M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2}M_Z^2 Z_\mu Z^\mu)\left((1 - \frac{a_1}{2})\frac{2H}{v} + (1 - a_1)\frac{H^2}{v^2}\right)$$

$$V(\eta_H) = \frac{1}{2}m_H^2\,\eta_H^2 + \lambda\, v\,\eta_H^3 + \frac{1}{4}\tilde{\lambda}\,\eta_H^4,$$

Baur, Plehn, Rainwater, 2003

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 $H \to$ invisible.

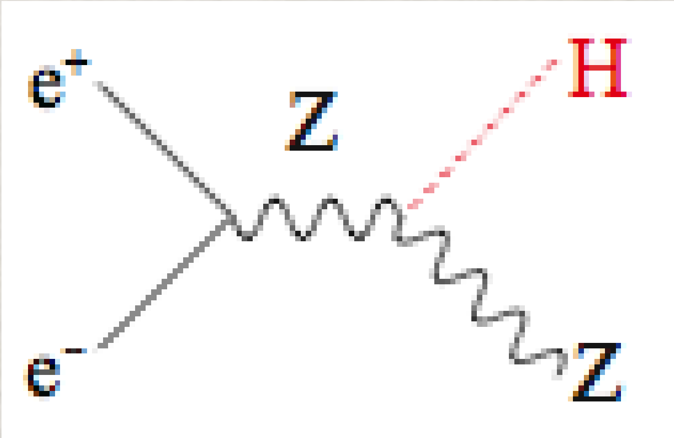
3. Determine Γ_{tot} to 10%.

A Word of Expectations

1. LHC:

- $\sigma_{obs} \propto g_{in}^2 \frac{\Gamma_{final}}{\Gamma_{tot}}$ measured at 10% level.
- σ_{obs}/σ_{SM} $Br(h \to \bar{N}N,\ \chi\chi,\ ...)$ 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 Standard Higgs Sector

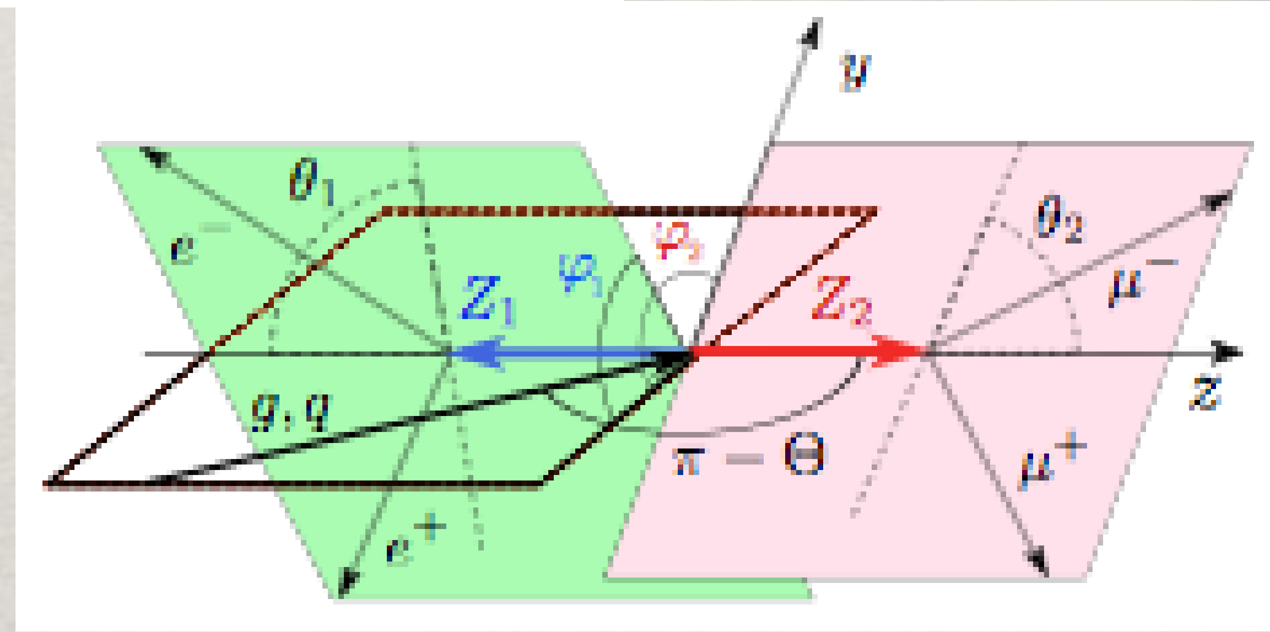
Precision measurements may be
(surprisingly) rewarding !

Most general $V^{\mu}V^{\nu}H$ coupling:

$$
\begin{aligned}
T^{\mu\nu} \; = \; & a_1\, g^{\mu\nu} + \\
& a_2\, \left(q_1 \cdot q_2\, g^{\mu\nu} - q_1^{\nu} q_2^{\mu}\right) + \\
& a_3\, \varepsilon^{\mu\nu\rho\sigma}\, q_{1\rho} q_{2\sigma}
\end{aligned}
$$

The $a_i = a_i(q_1, q_2)$ are scalar form factors

$$H \to ZZ^* \to \mu^+\mu^-\; e^+e^-$$



Test Higgs spin-parity property,
search for CP violation
(may not be larger than 10^{-3}).

De Rujula, Lykken, Spiropulu et al., 2010.

Not-So "Standard" Higgs Sector

Most general $Hf\bar{f}$ coupling:

$$H\bar{t}(a + ib\gamma_5)t$$

$$gg,\ q\bar{q} \to t\bar{t}H,\ \text{with } H \to b\bar{b},\ \tau\bar{\tau},\ \gamma\gamma$$

Gunion and He, 1996.

It will be very challenging
to study the $H\bar{t}t$ coupling at the LHC:
20%?

Not-So "Standard" Higgs Sector

FCNC decays? $H \to \mu^{\pm}\ \tau^{\mp}$

TH, Marfatia, hep-ph/0008141.

Maybe sizeable:

- maximal ν_μ-ν_τ mixing
- large coupling

$$\kappa_{\mu\tau}\frac{\sqrt{m_\mu m_\tau}}{v}$$

$$\frac{Br(\mu\tau)}{Br(\tau\tau)} = 2\kappa_{\mu\tau}\frac{m_\mu}{m_\tau}$$

A recent study:

Harnik, Kopp, Jupan, arXiv:1209.1397.

$$H \to \ell_i^+\ \ell_j^-$$

Summary:

“Naturally speaking”:

- H should not be a lonely particle; has an “interactive friend circle”: $t,\ W^{\pm},\ Z$
  and partners $\tilde{t},\ \tilde{W}^{\pm},\ \tilde{Z},\ \tilde{H}^{\pm,0}$
- If we do not see them at the LHC, they may reveal their existence from Higgs coupling deviations from the SM values at a few percentage level.

HEPAP Question:

“What couplings should be measured and to what precision?”

Discussion Notes

1.

2.

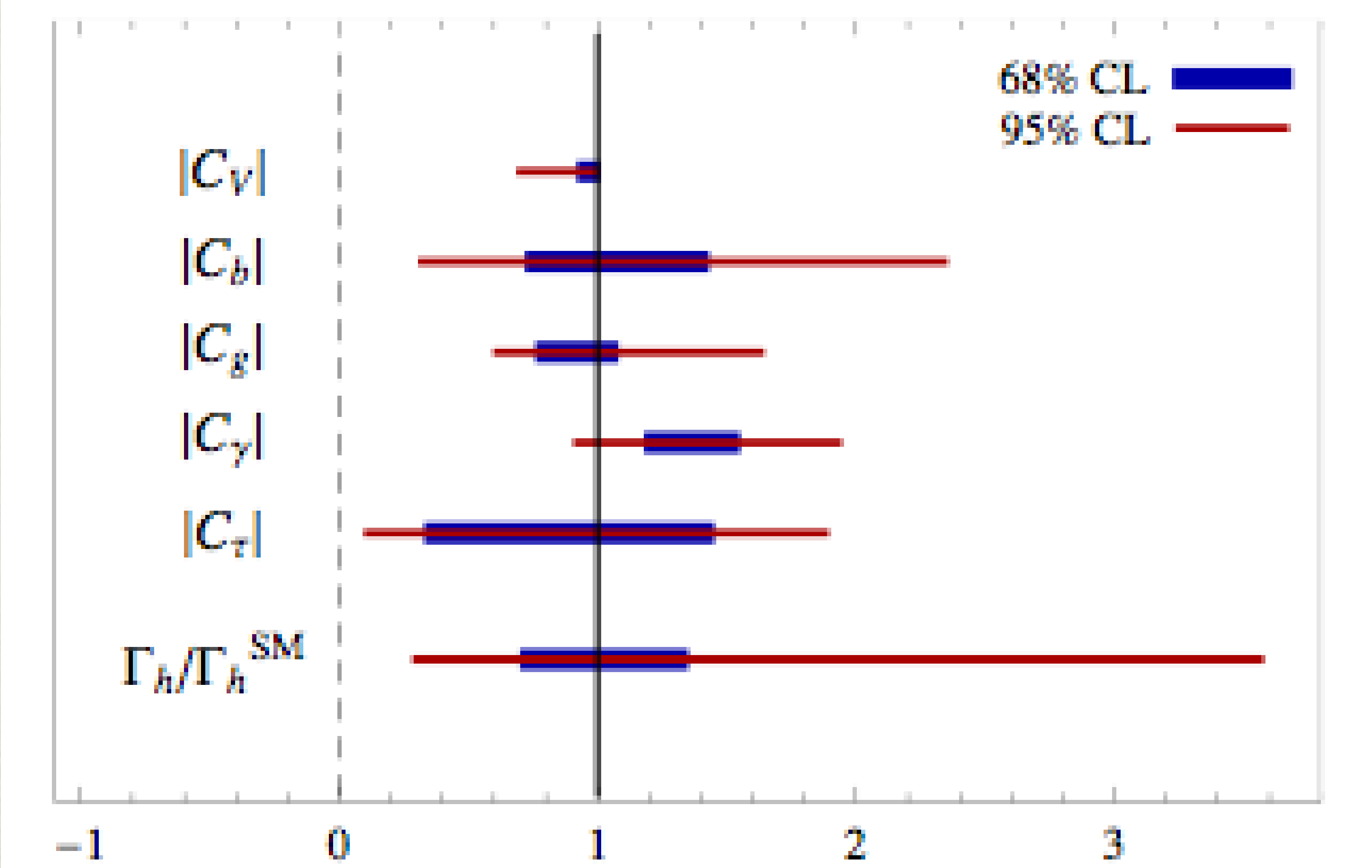
3.

4.

Backup slides

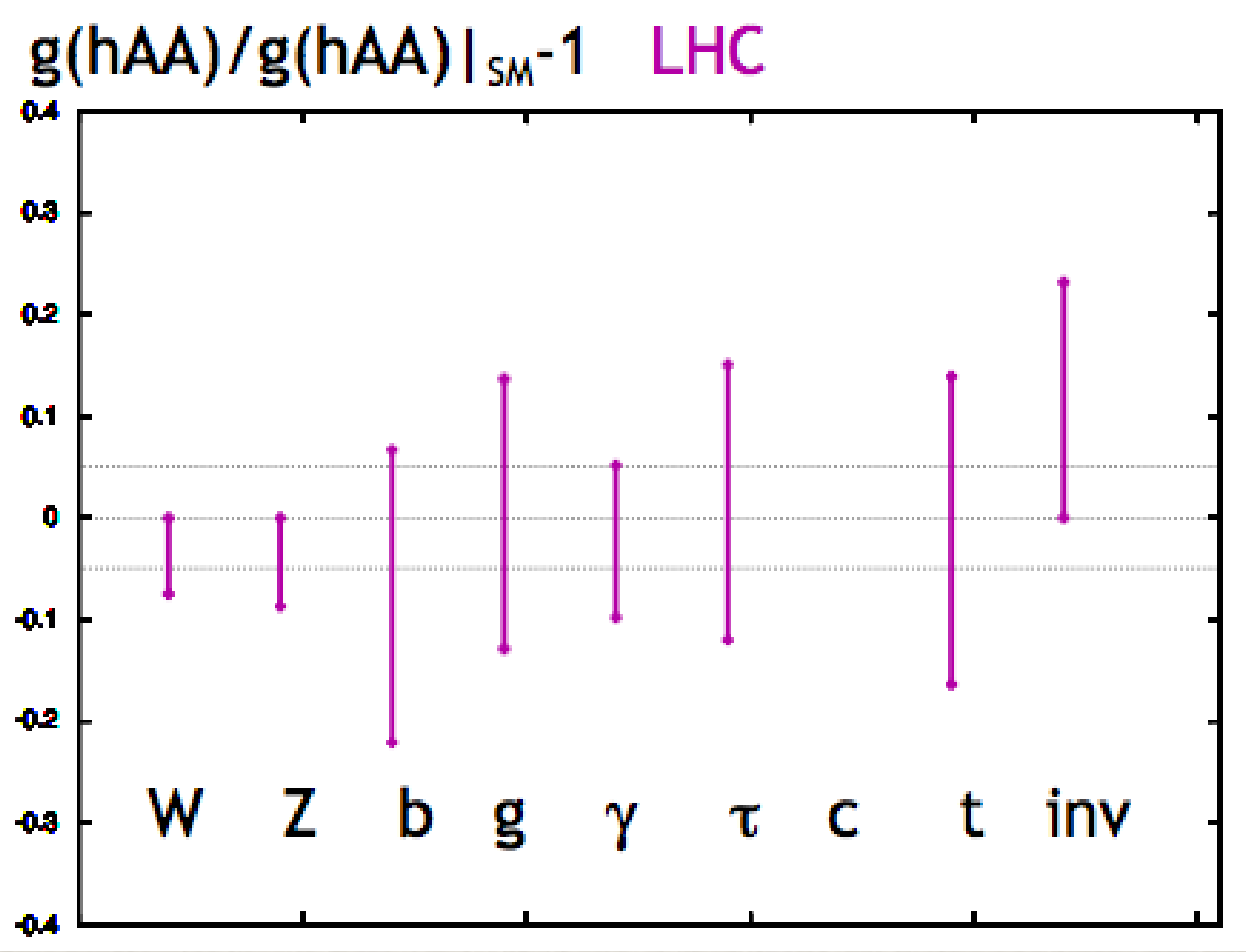
couplings & total width

Assuming $\Gamma_{W,Z} < (\Gamma_{W,Z})^{SM}$, one can derive bounds on Γ_{tot} based on the LHC data



Dobrescu & Lykken, arXiv:1210.3342.

Future LHC sensitivities:



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

Peskin, arXiv:1207.2516; arXiv:1208.5152.

SFitter analysis of Higgs couplings at LHC

- Parameterize deviations from SM couplings

$$g_i = g_i^{\rm SM}\ (1 + \Delta_i)$$

- Five free parameters $i = W, Z, t, b, \tau$ plus generation universality
- Loop-induced couplings change from modifying contributing tree-level couplings
- Δ_H: common parameter modifying all (tree-level) couplings
- Assume no add. contribution to total width

- Background expectations, exp. errors, etc. from published analyses
- cross-checked with exclusion and signal-strength plots

List of input channels for 2011 data

ATLAS		CMS	
$\gamma\gamma$		$\gamma\gamma$	
$ZZ \to 4\ell$		$\gamma\gamma$	di-jet
WW	0-jet	$ZZ \to 4\ell$	
WW	1-jet	WW	0-jet
WW	2-jet	WW	1-jet
$\tau\tau$	0-jet	WW	2-jet
$\tau\tau$	1-jet	$\tau\tau$	0/1-jet
$\tau\tau$	VBF	$\tau\tau$	Boosted
$\tau\tau$	VH	$\tau\tau$	VBF
$b\bar{b}$	WH	$b\bar{b}$	WH
$b\bar{b}$	$Z(\to \ell\bar{\ell})H$	$b\bar{b}$	$Z(\to \ell\bar{\ell})H$
$b\bar{b}$	$Z(\to \nu\bar{\nu})H$	$b\bar{b}$	$Z(\to \nu\bar{\nu})H$

plus inclusion of 2012 data (ICHEP)

LHC @ high L

	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
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 $\Delta h\bar{b}b$ 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

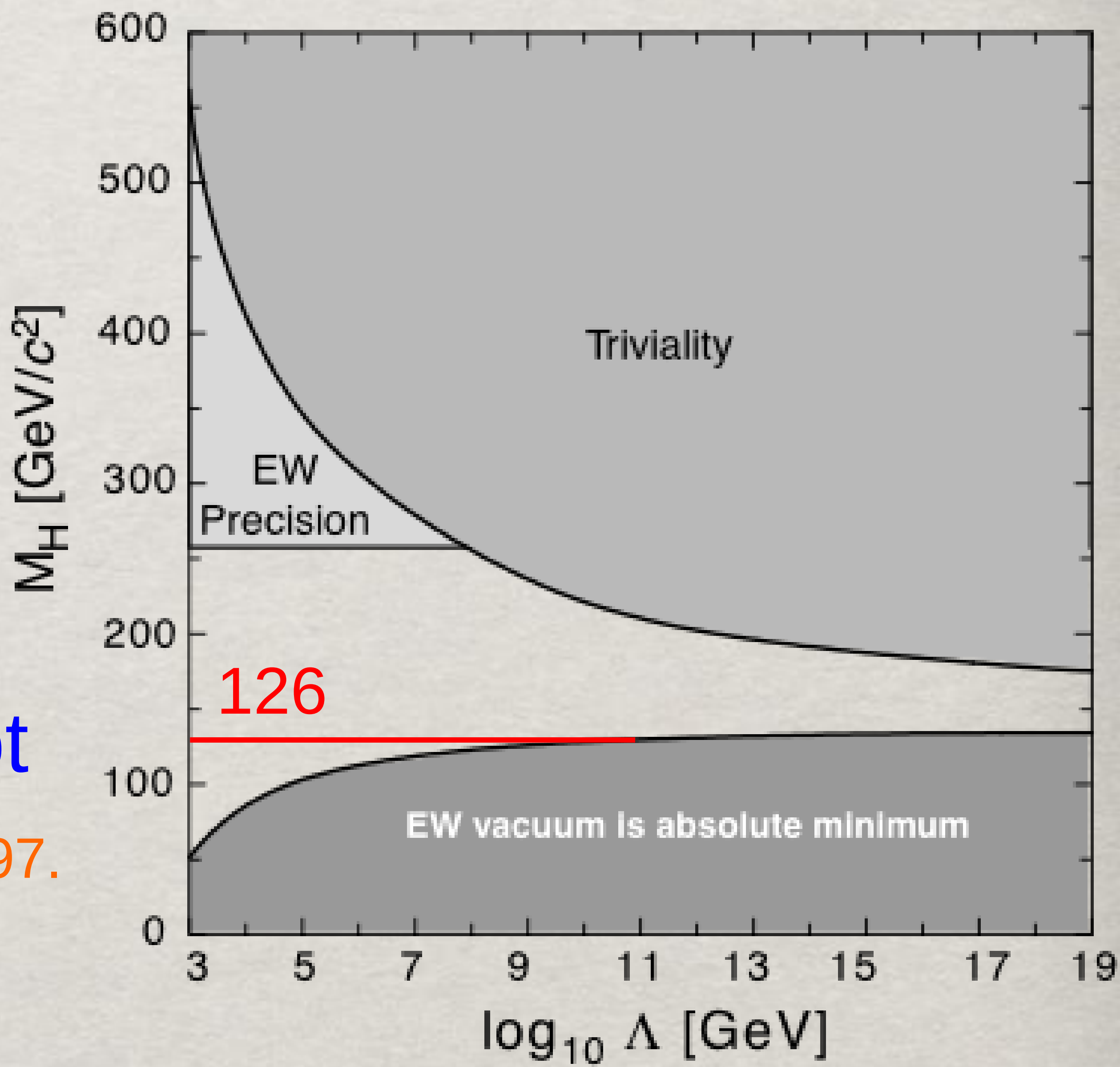
λ at High energies

(1) The Triviality Bound

For M_H = 126 GeV, the SM Higgs boson is light enough,

→ The SM can be a consistent perturbative theory up to M_p

Bezrukov et al., arXiv:1205.2893.



(2) Vacuum Stability:

E ~ $10^{7\text{-}8}$ GeV

A meta-stable vacuum should not be a concern.

Degrassi et al., arXiv:1205.6497.

No pressing need for BSM new physics?

“Large Hierarchy problem”

(fine-tune/naturalness)

→ TeV scale new physics.

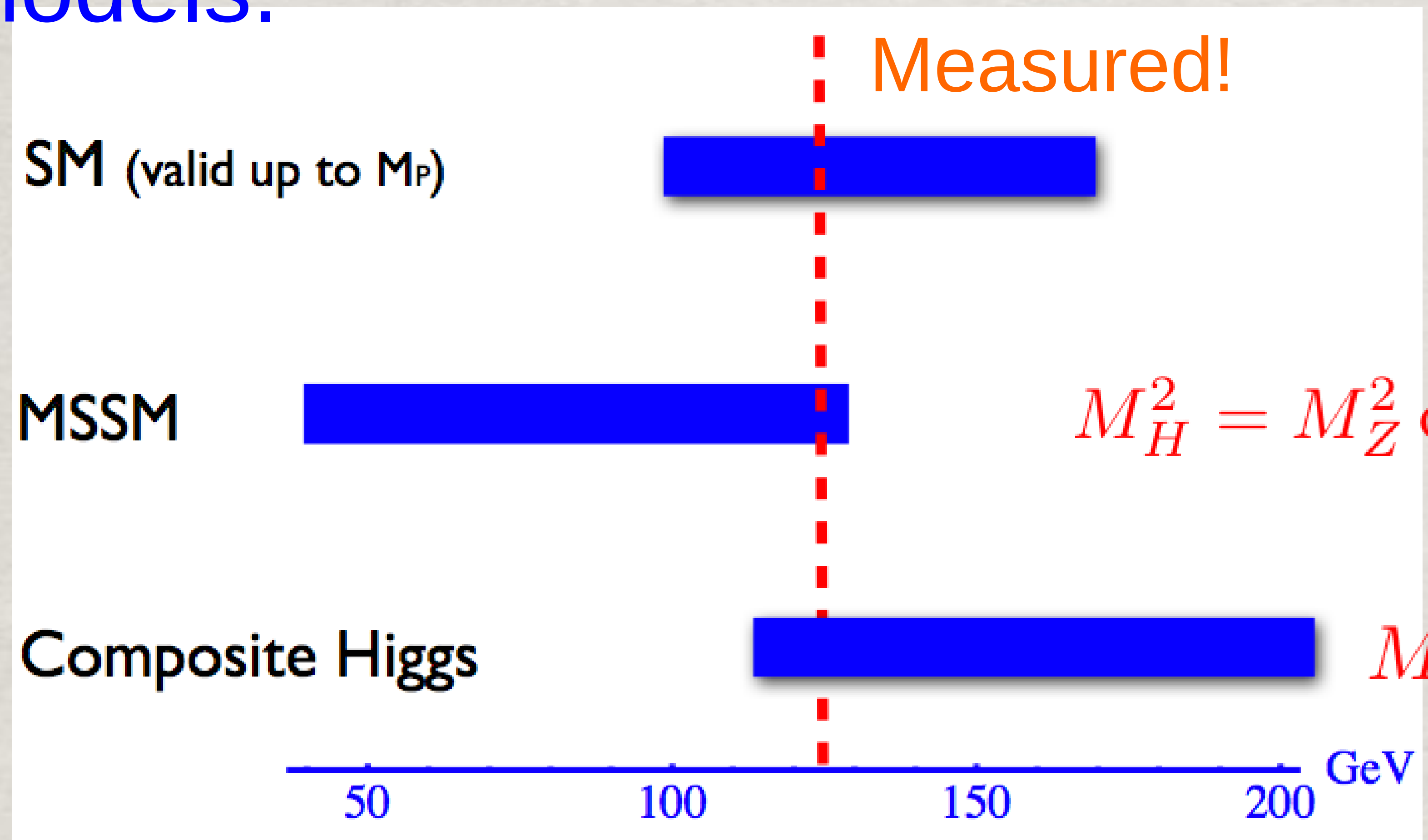
90% fine-tune → $\Lambda_t < 3$ TeV, $\Lambda_W < 9$ TeV

Pressing need for BSM 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.



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

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

Pomarol, ICHEP'12

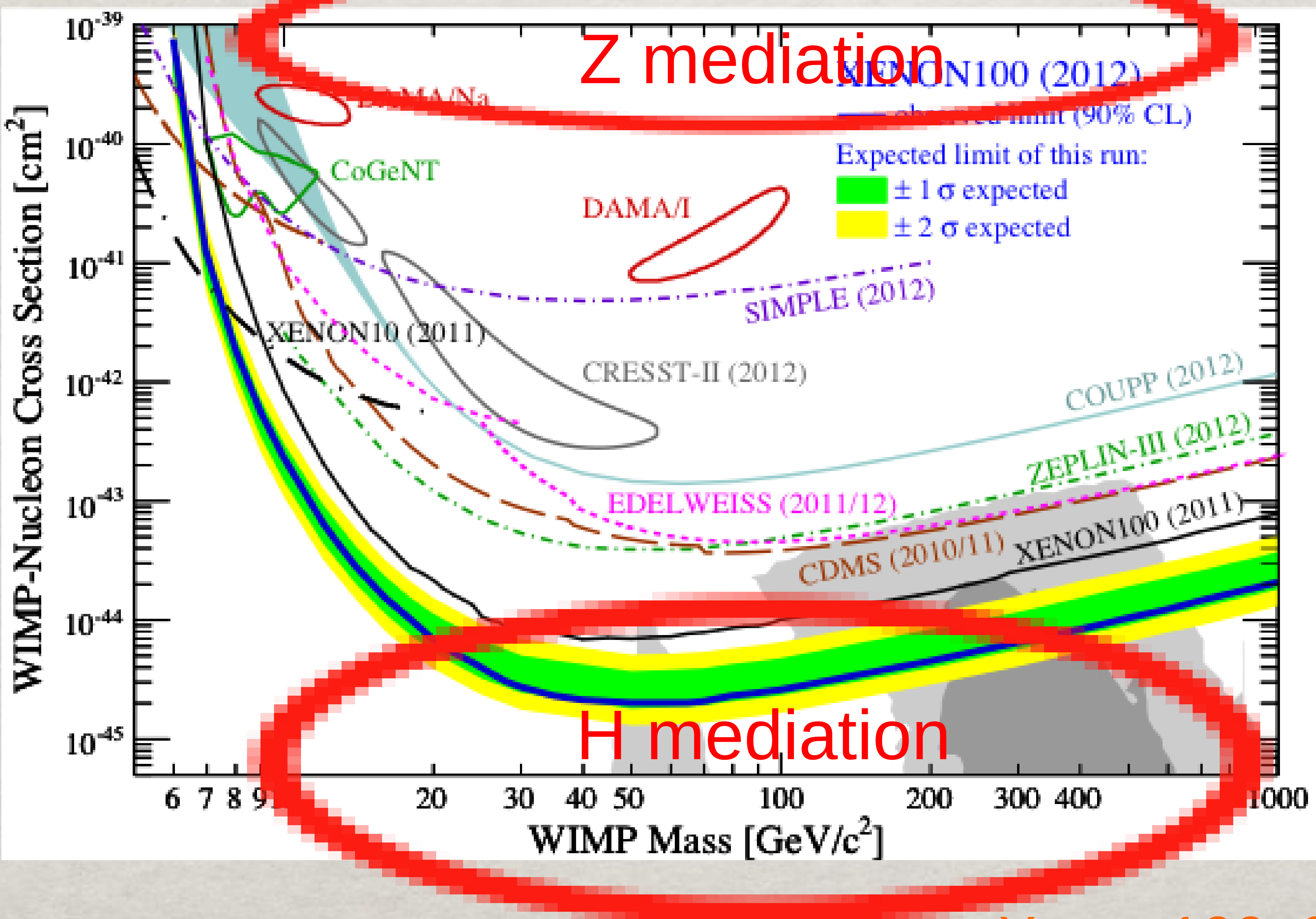
Both suffer from some degree of fine-tune (already).

For a given model, there is different degree of "Little Hierarchy problem"

– flavor scale, EW scale

Other hints ?

Direct searches on WIMP dark matter:



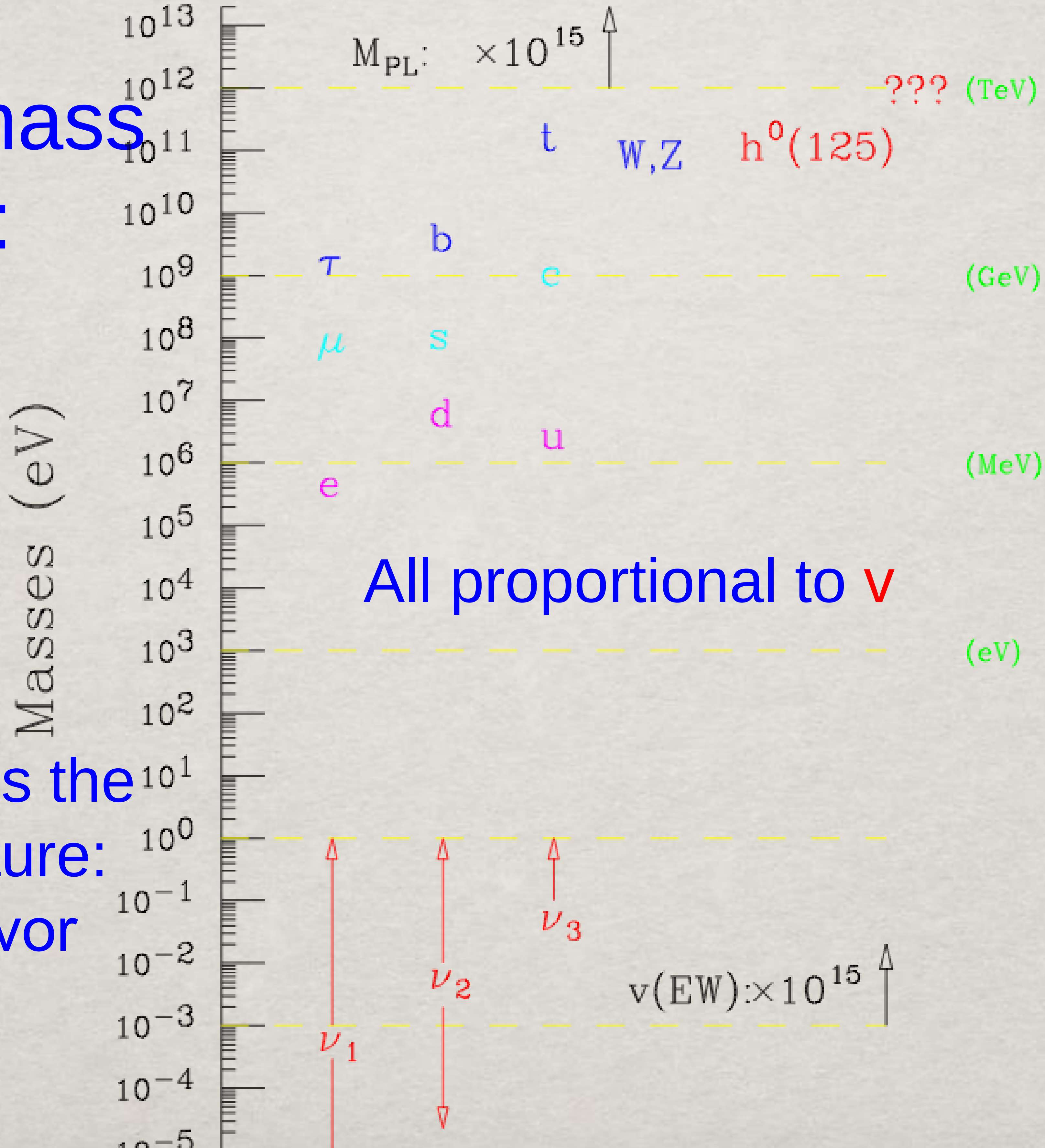
$\kappa_s H^\dagger H S^* S$

$\frac{\kappa_\chi}{\Lambda} H^\dagger H \ \bar{\chi}\chi$

Xenon100, 2012

“Most troublesome”: flavor physics

Particle mass hierarchy:



All proportional to v

What controls the mixing structure: “Minimal Flavor Violation”?

Higgs as the pivot

(a). Neutrino mass generation:

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

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

λ, a new force?

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

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

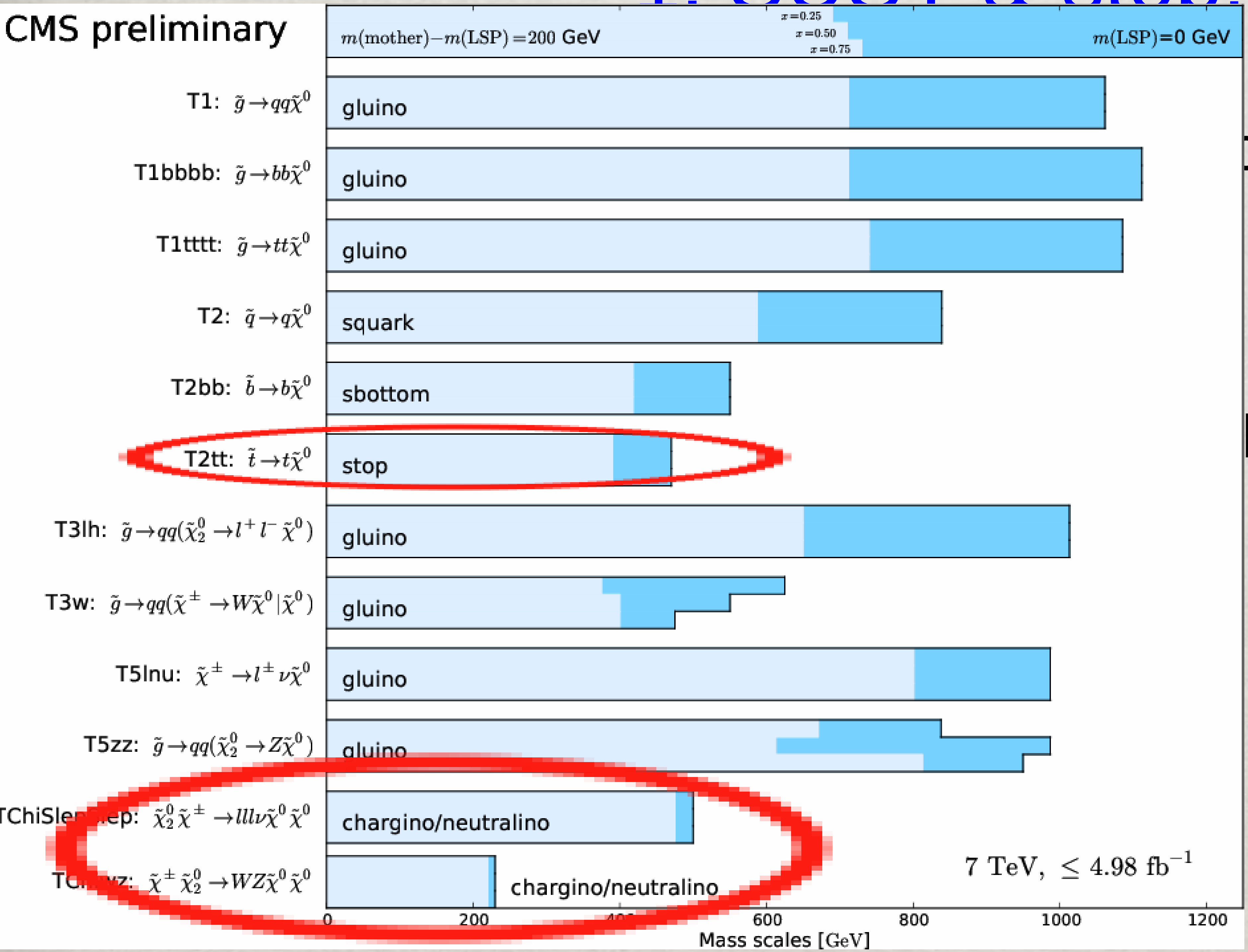
- or dynamically generated by a new strong force?

Hints for BSM new physics, or wishful thinking?

A Natural Higgs Sector at LHC

Searches are on going …

1. SUSY & stop:



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. T' in the Little Higgs Model

$$q\bar{q},\ gg \rightarrow T\bar{T} \rightarrow t\bar{t}\ A^0A^0X \rightarrow bj_1j_2\ \bar{b}\ \ell^-\bar{\nu}\ A^0A^0\ X + c.c.$$

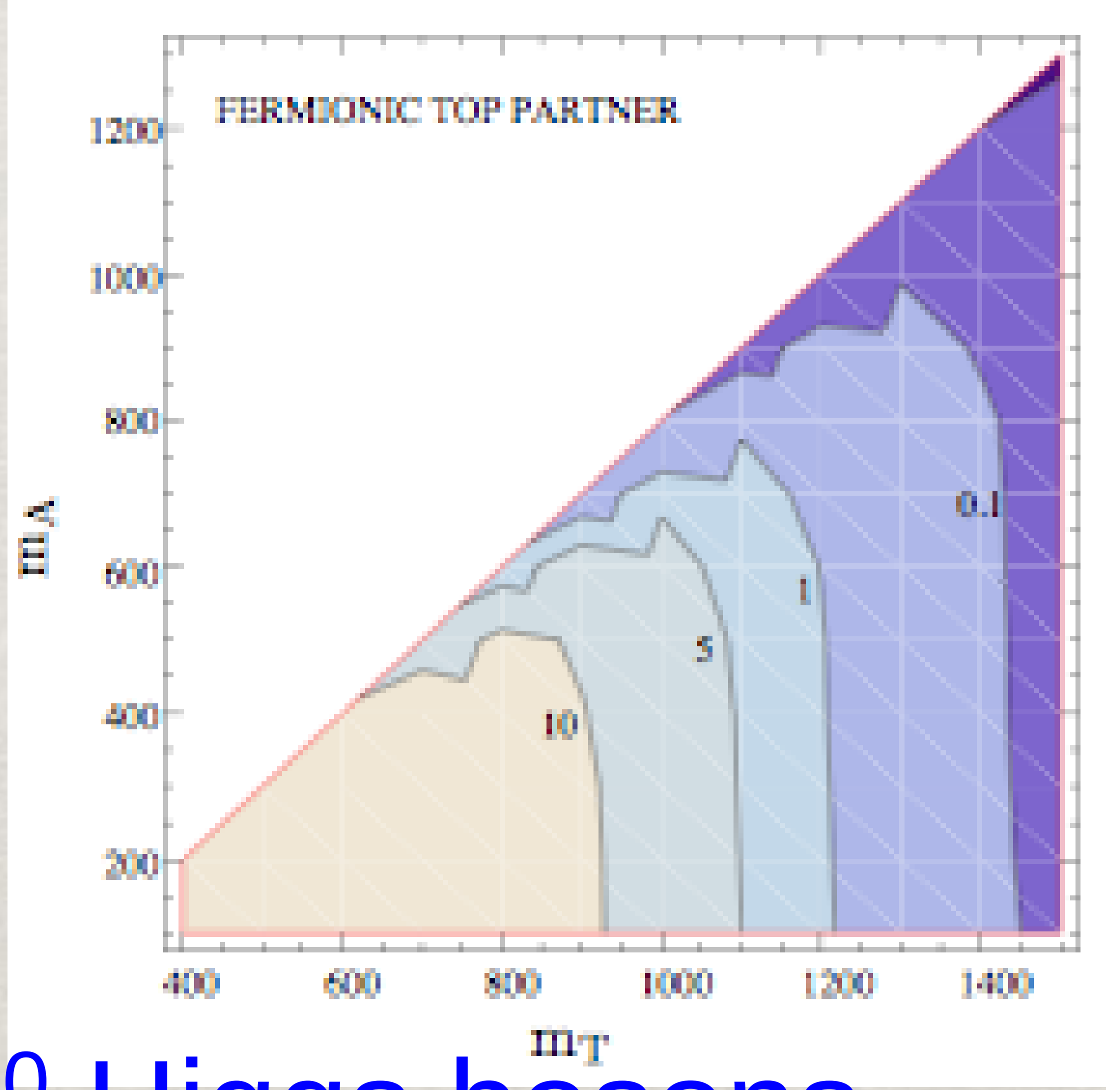
The current ATLAS limit: M_T > 480 GeV, for M_A < 100 GeV.

Future projection:

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

reaching to

M_T ~ 1.1 TeV at 5σ

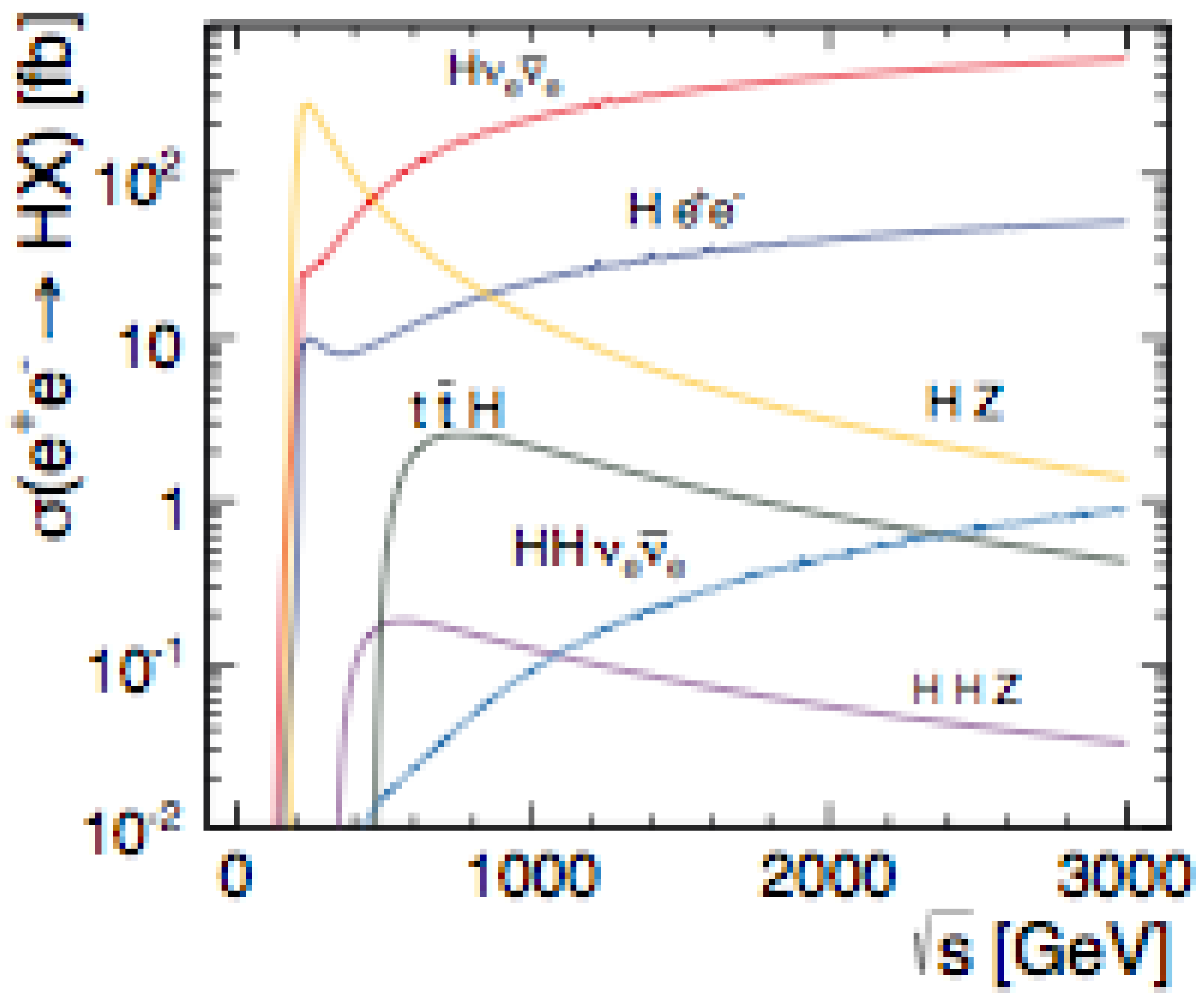


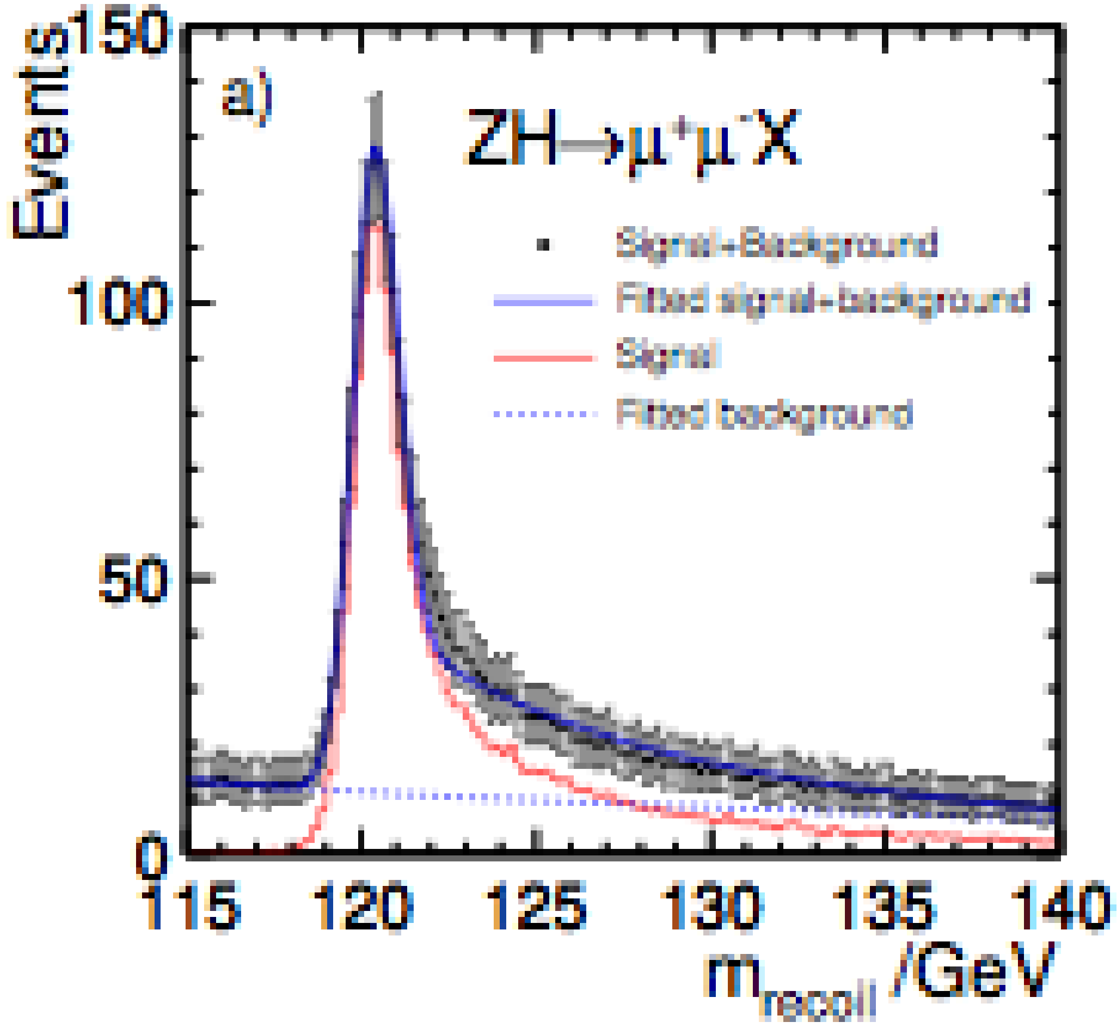
TH, Mahbubani, Walker, Wang, 2008.

3. Light $H^\pm$, A^0, H^0 Higgs bosons.

4. Electroweak gauginos/Higgsinos.

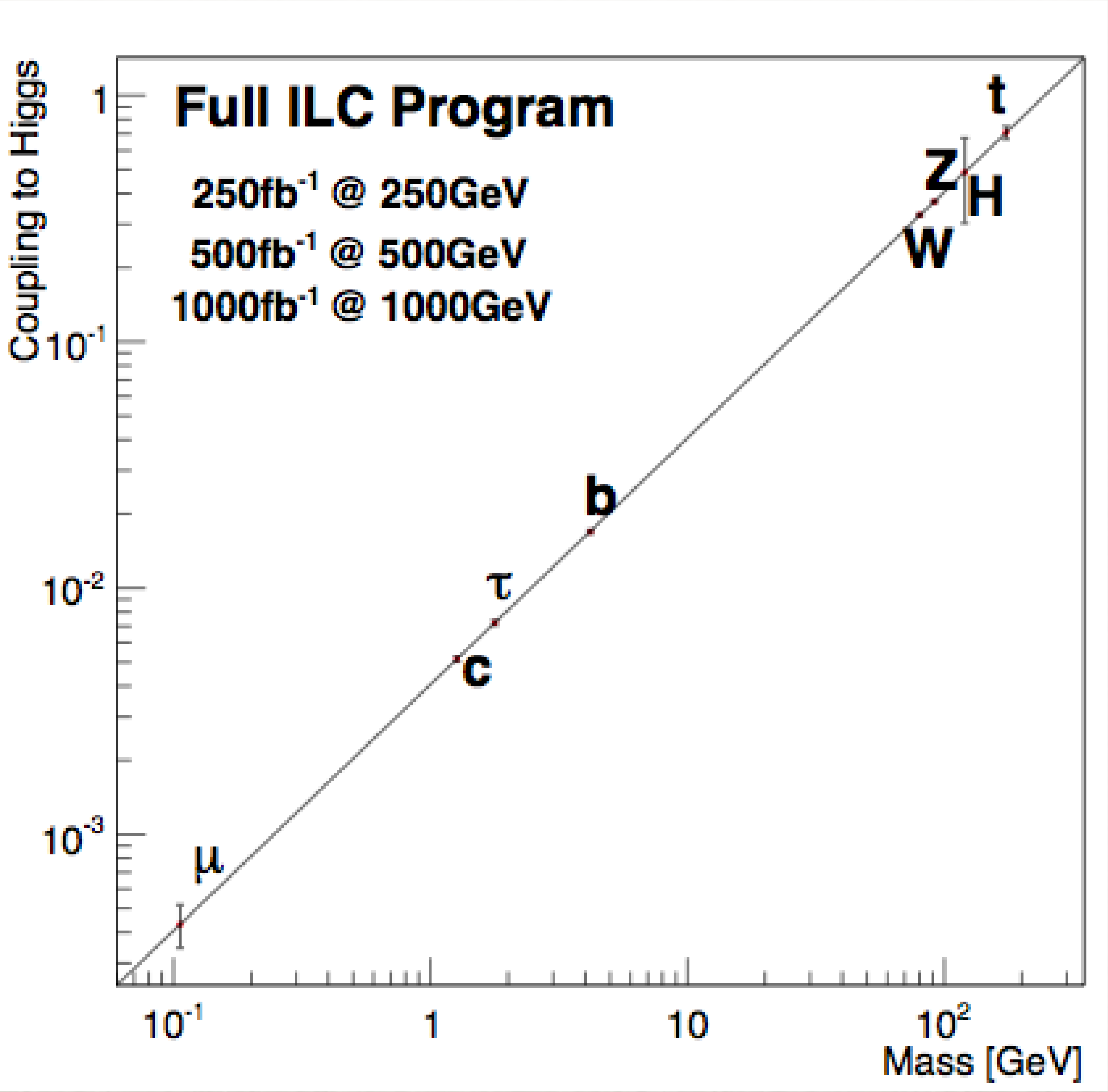
ILC Higgs





F. Simon, arXiv:1211.7242.

Couplings



J.Brau et al., arXiv:1210.0202

$$\Gamma_H = \Gamma(H \to WW^*) / Br(H \to WW^*)$$ @ 5%

LHC/ILC Comparison:

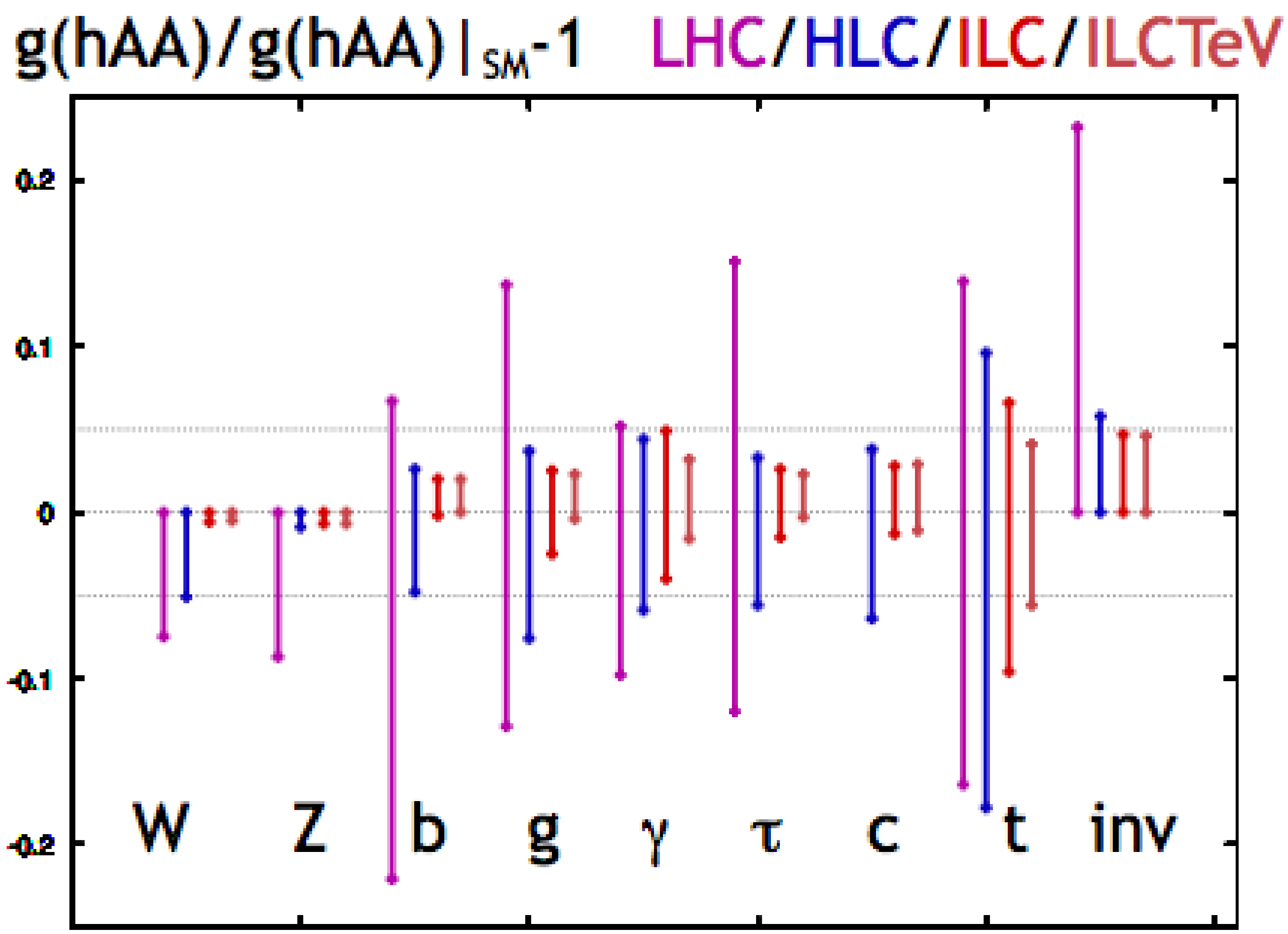
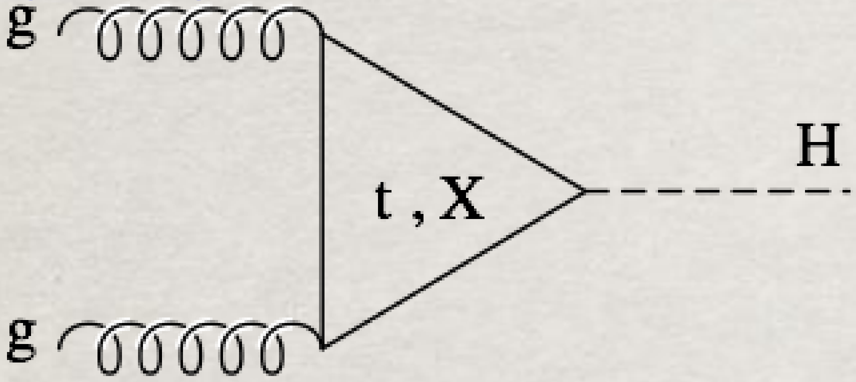


Figure 20: Estimate of the sensitivity of the ILC experiments to Higgs boson couplings in a model-independent analysis. The four sets of errors for each Higgs coupling represent the results for LHC, the threshold ILC Higgs program at 250 GeV, the full ILC program up to 500 GeV, and the extension of the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

Peskin, arXiv:1207.2516

2. Signal Characteristics:

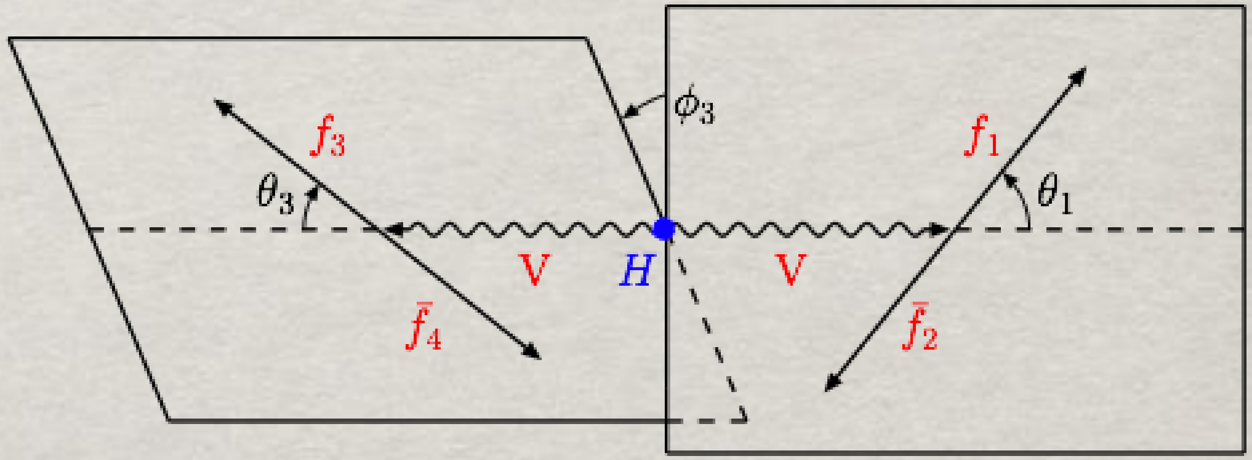
(a). Gluon fusion: The leading production channel



σ(125 GeV@ 8 TeV) ≈ 20 pb
σ(125 GeV@14 TeV) ≈ 40 pb

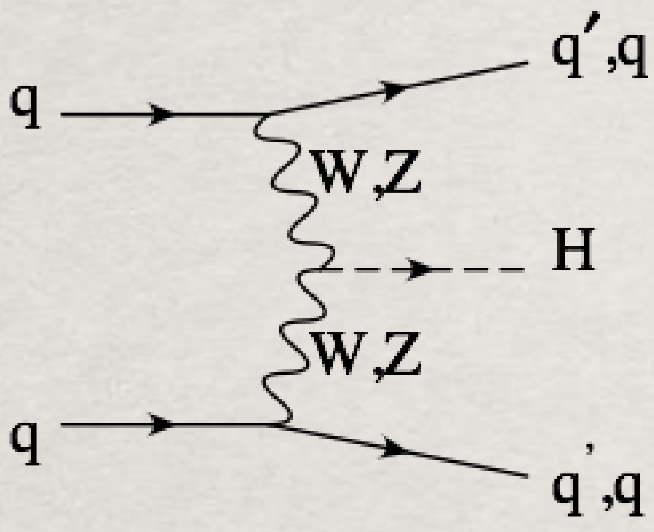
- Need clean decay modes: γγ, WW, ZZ
- Effects from radiative corrections very large!§
- Sensitive to new colored particles in the loop:

gg -> H sensitive to new colored states: Q
H -> γγ sensitive to new charged states: Q, L
H -> ZZ -> 4 leptons
best to study the Higgs
CP properties:



§ L. Reina, TASI lectures, 2011.

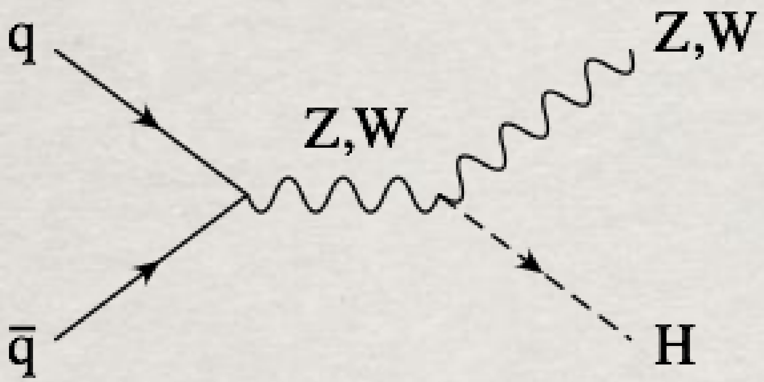
(b). The Vector Boson Fusion:



σ(14 TeV) ≈ 4 pb

- Need clean decay modes: ττ, WW, ZZ, γγ
- Effects from radiative corrections very small!
  -> color singlet exchange, low jet activities.
- Sensitive to HWW, HZZ couplings
- Good for H -> ττ, γγ
- A bit lower rate, but unique kinematics

(c). VH Associate production:

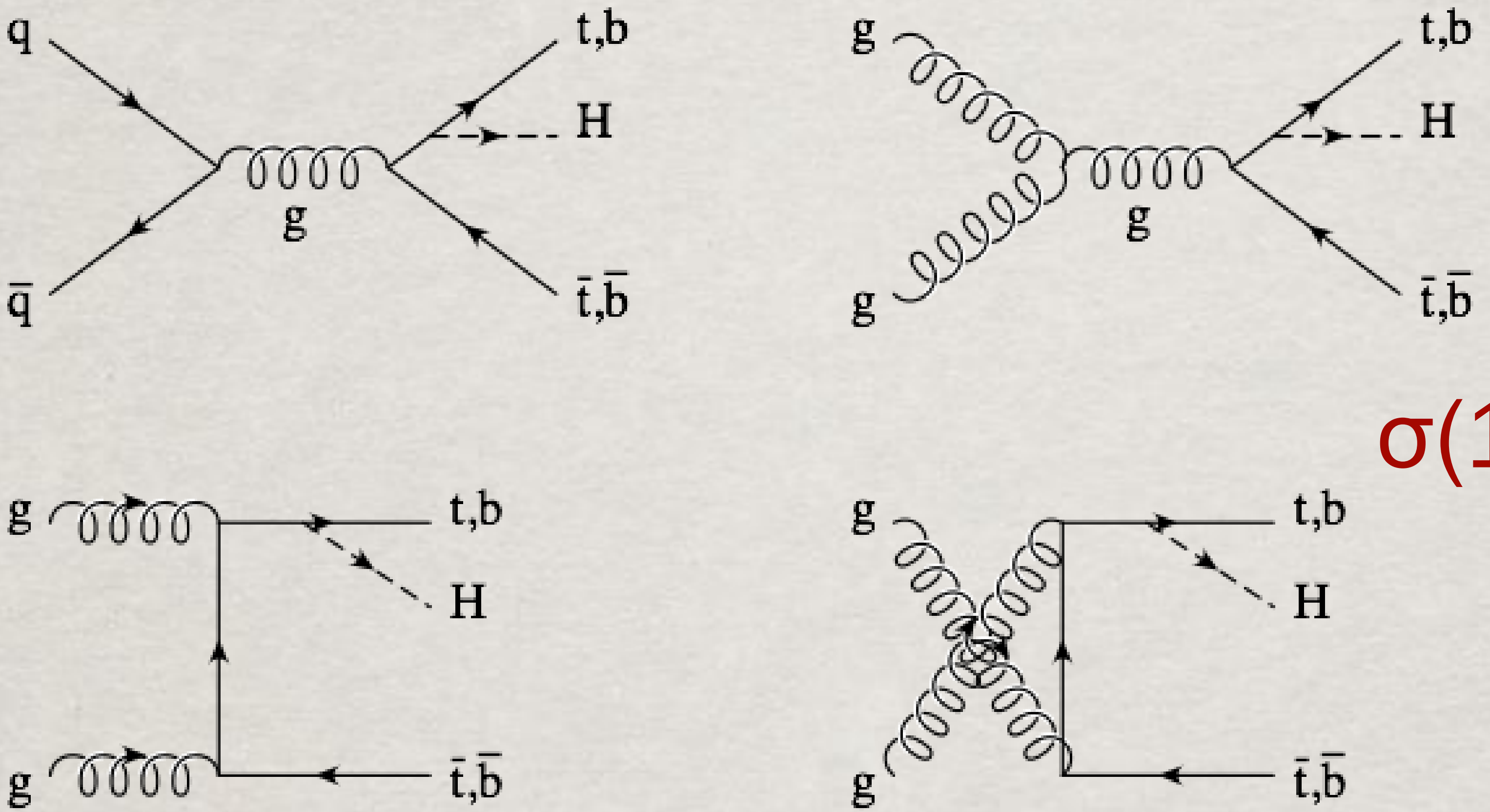


σ(14 TeV) ≈ 2.2 pb

- W/Z leptonic decays serve as good trigger.
- Effects from radiative corrections very modest.
- Sensitive to HWW, HZZ couplings
- Do not need clean decay modes: chance for b bbar !

  Boosted Higgs helps for the signal ID!

(d). Top quark pair associate production:



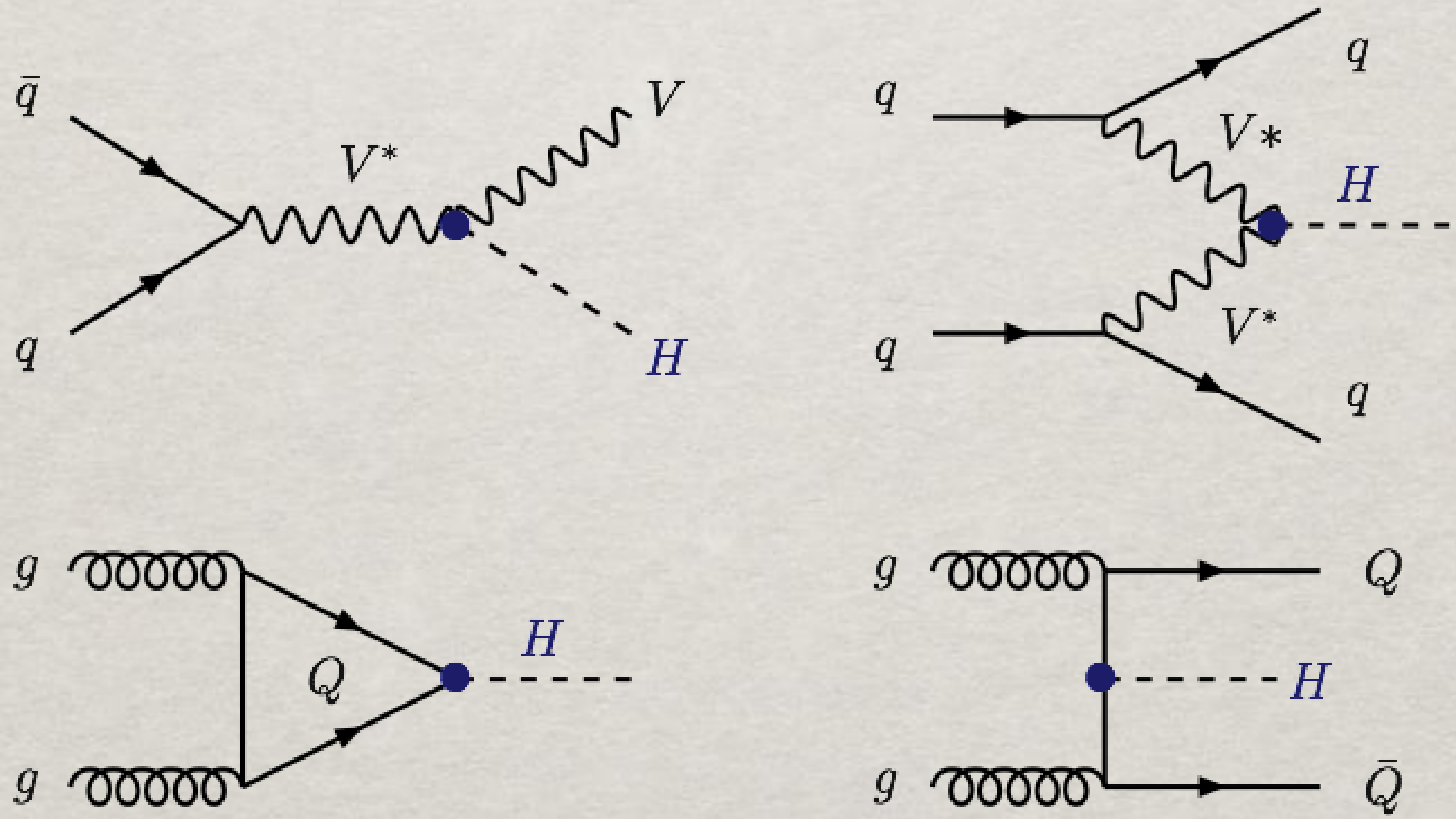
σ(14 TeV) ≈ 0.6 pb

- Top leptonic decays serve as good trigger.
- Effects from radiative corrections can be large.
- Directly sensitive to Htt coupling
- Do not need clean decay modes: chance for b bbar !
- Combinatorics of the 4 b's are difficult to handle...

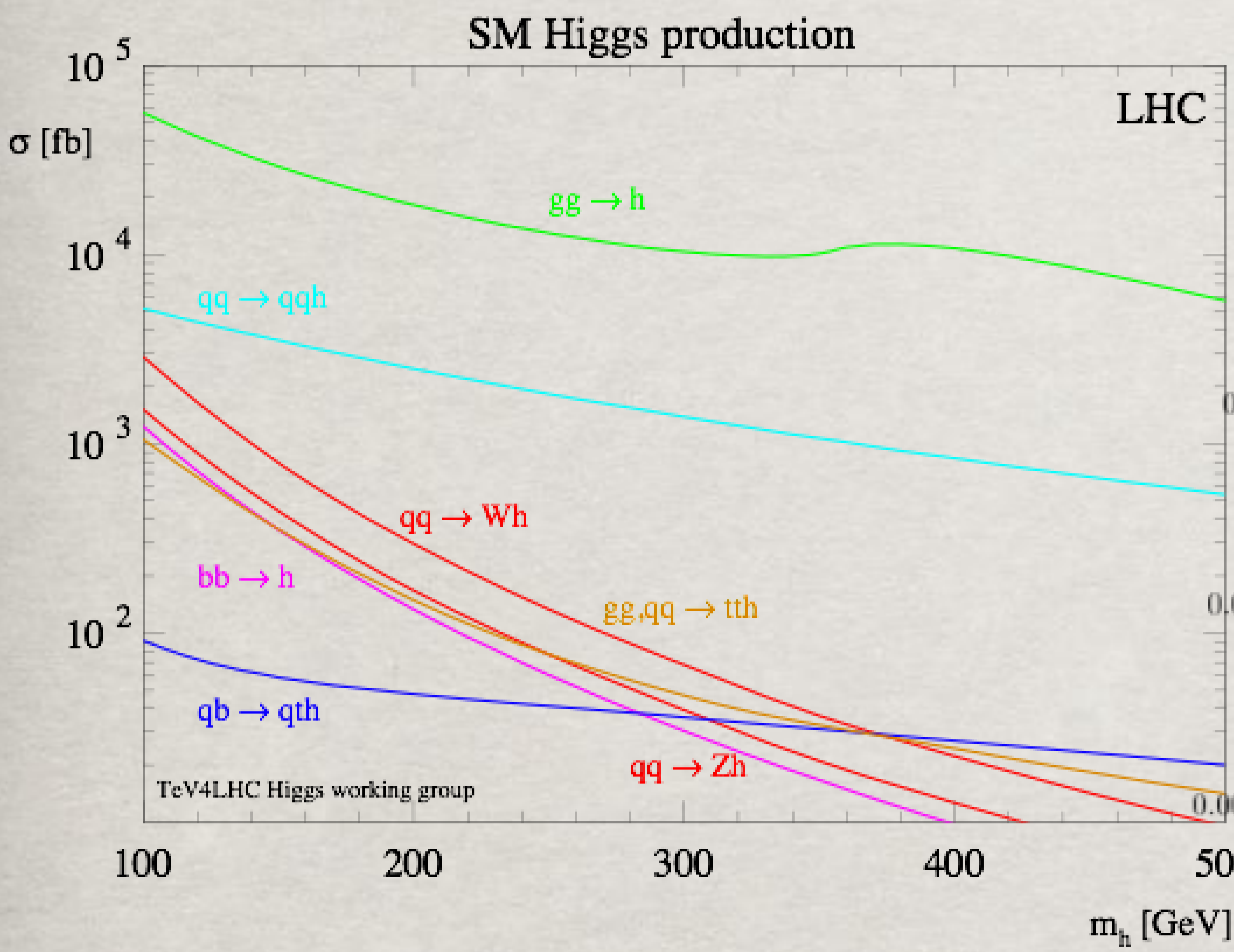
4. Higgs Boson Production at LHC

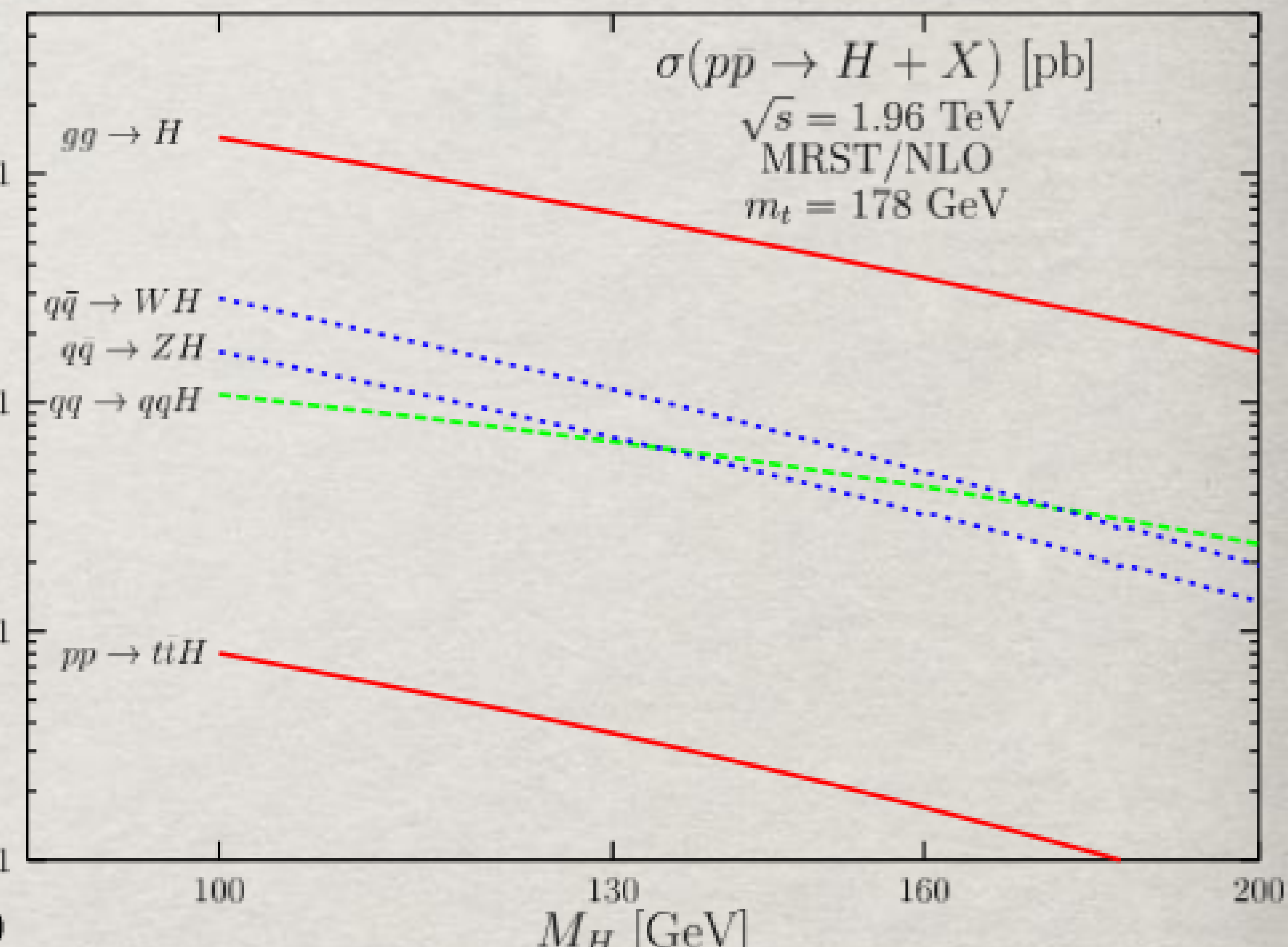
Recall that the Higgs couples preferably to heavier particles.

$$
\begin{aligned}
\text{associated production with } W/Z: &\quad q\bar{q} \longrightarrow V + H \\
\text{vector boson fusion}: &\quad qq \longrightarrow V^*V^* \longrightarrow qq + H \\
\text{gluon} - \text{gluon fusion}: &\quad gg \longrightarrow H \\
\text{associated production with heavy quarks}: &\quad gg, q\bar{q} \longrightarrow Q\bar{Q} + H
\end{aligned}
$$



Production cross sections at hadron colliders:

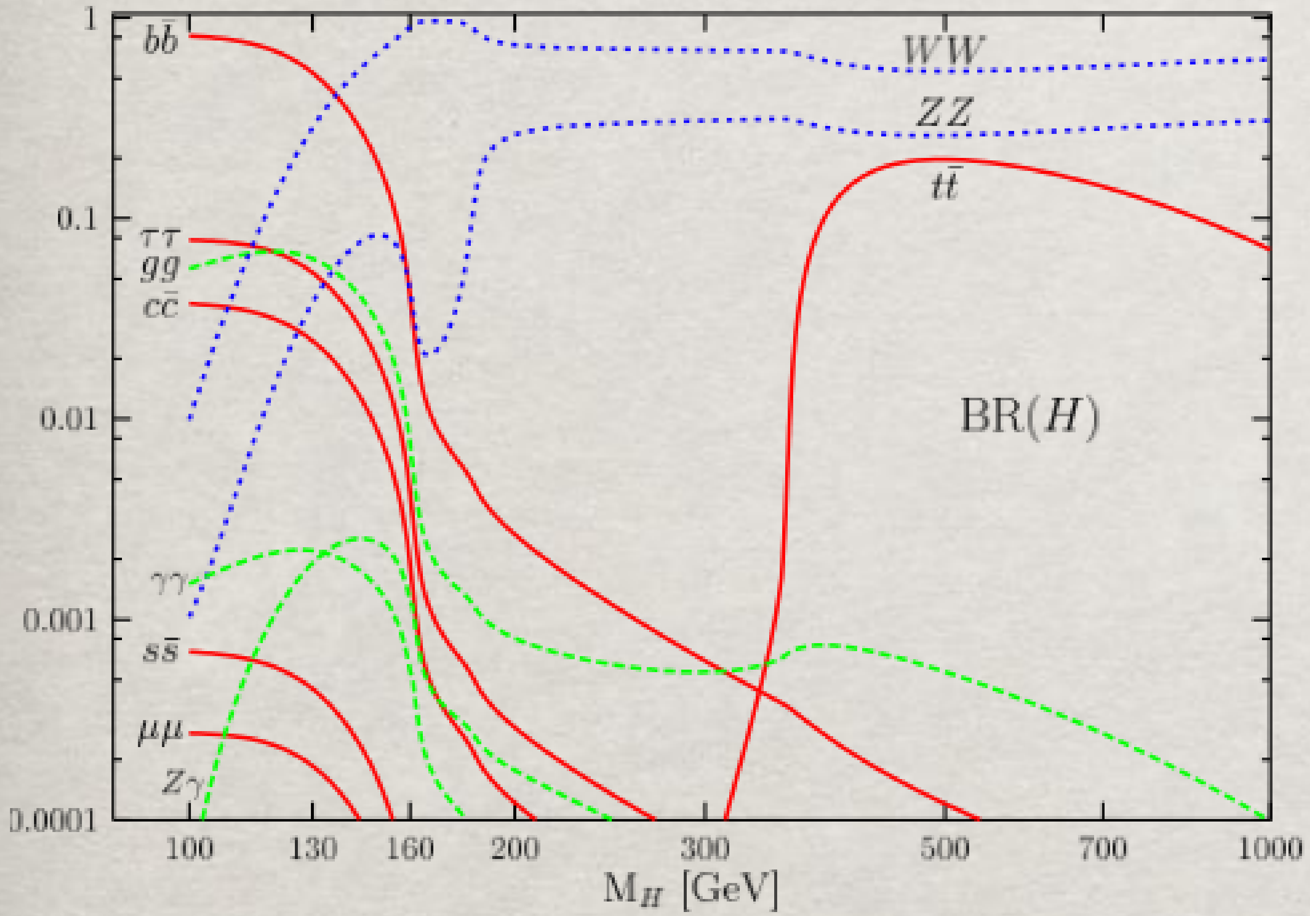


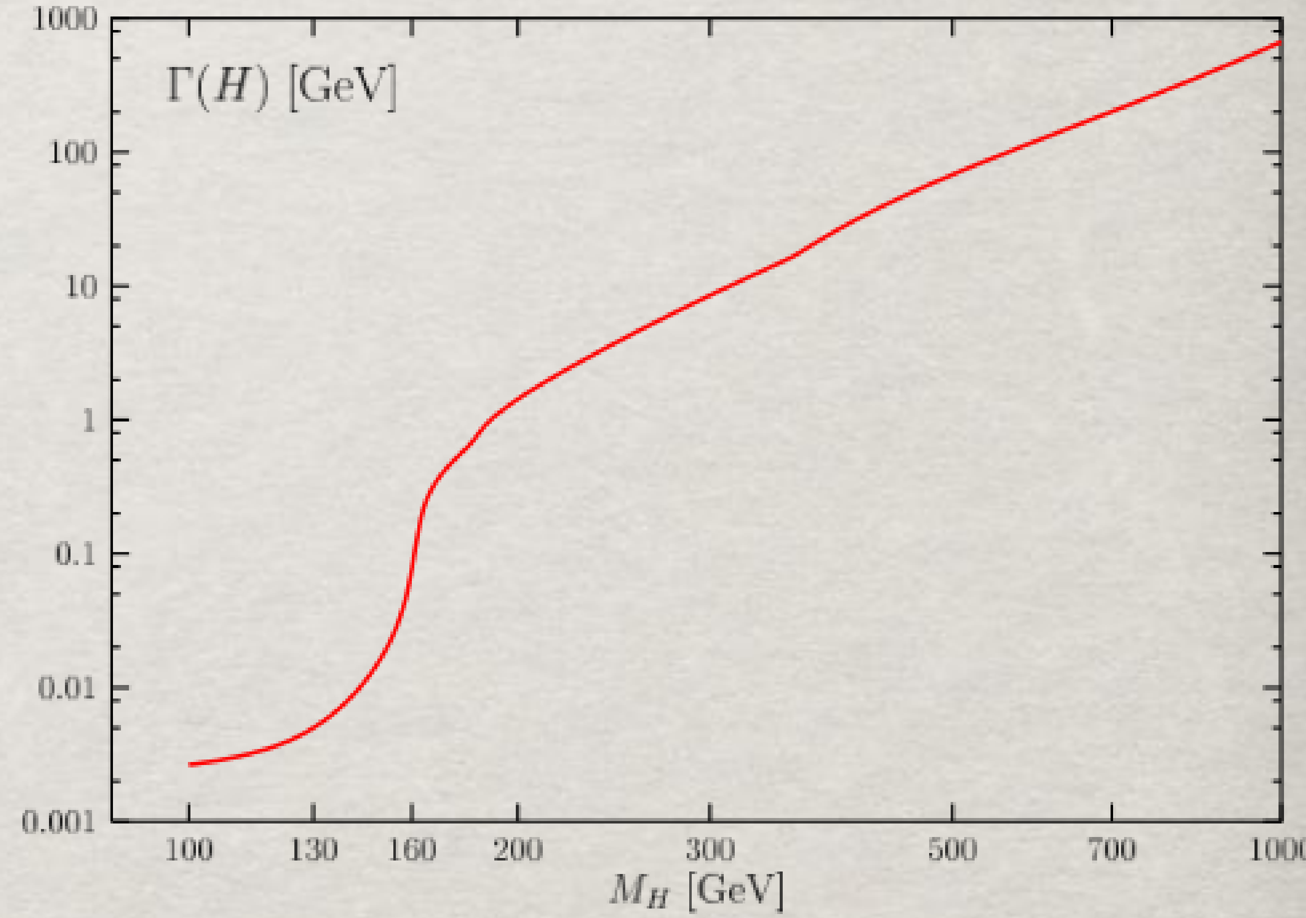


Exercise 9: List three leading processes for SM Higgs pair production and comment on their relative sizes.

§ L. Reina, TASI lectures, 2011.
A. Djouadi, hep-ph/0503172.

As the results for a SM Higgs: The branching fractions and total width





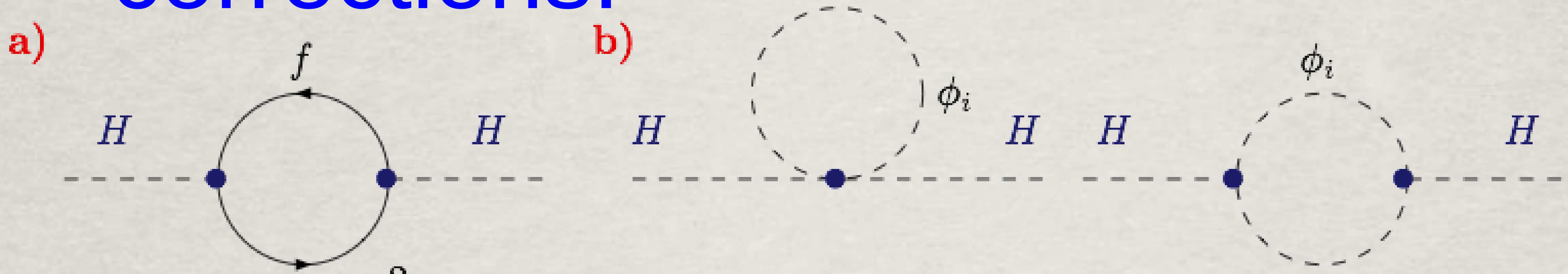
For m_H = 125 GeV, Γ(total) ≈ 4 MeV

BR(bb) ≈ 60% | BR(ττ) ≈ 8%

BR(WW) ≈ 21% | BR(ZZ) ≈ 2%

BR(gg) ≈ 9% | BR(γγ) ≈ 0.22%

Thus the Higgs mass corrections:



$$\Delta M_H^2 = \frac{\lambda_f^2 N_f}{4\pi^2}\left[(m_f^2 - m_S^2)\log\left(\frac{\Lambda}{m_S}\right) + 3m_f^2\log\left(\frac{m_S}{m_f}\right)\right].$$

* In SUSY limit, the correction vanishes.
* In soft SUSY breaking case, $m_S \sim O(1\ \text{TeV})$.

- predict TeV scale new physics:
  light Higgs bosons, SUSY partners...
- imply a (possible) grand desert in $M_{SUSY} - M_{GUT}$, and unification
- radiative EWSB:

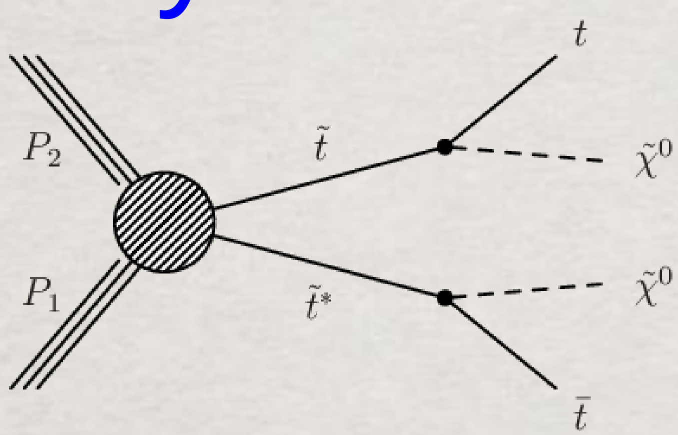
$$M_Z^2/2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2.$$

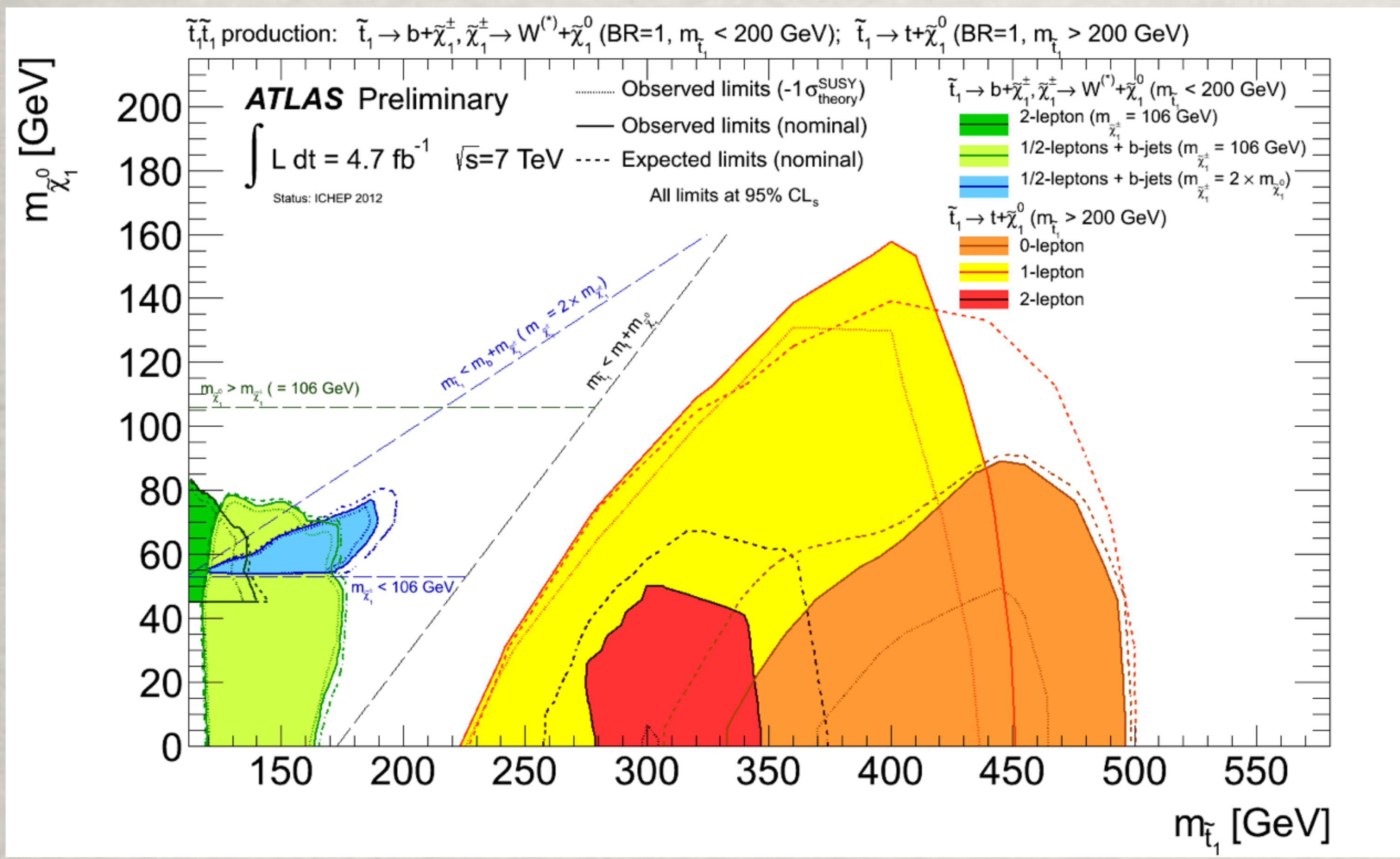
- SUSY dark matter with R-parity conservation

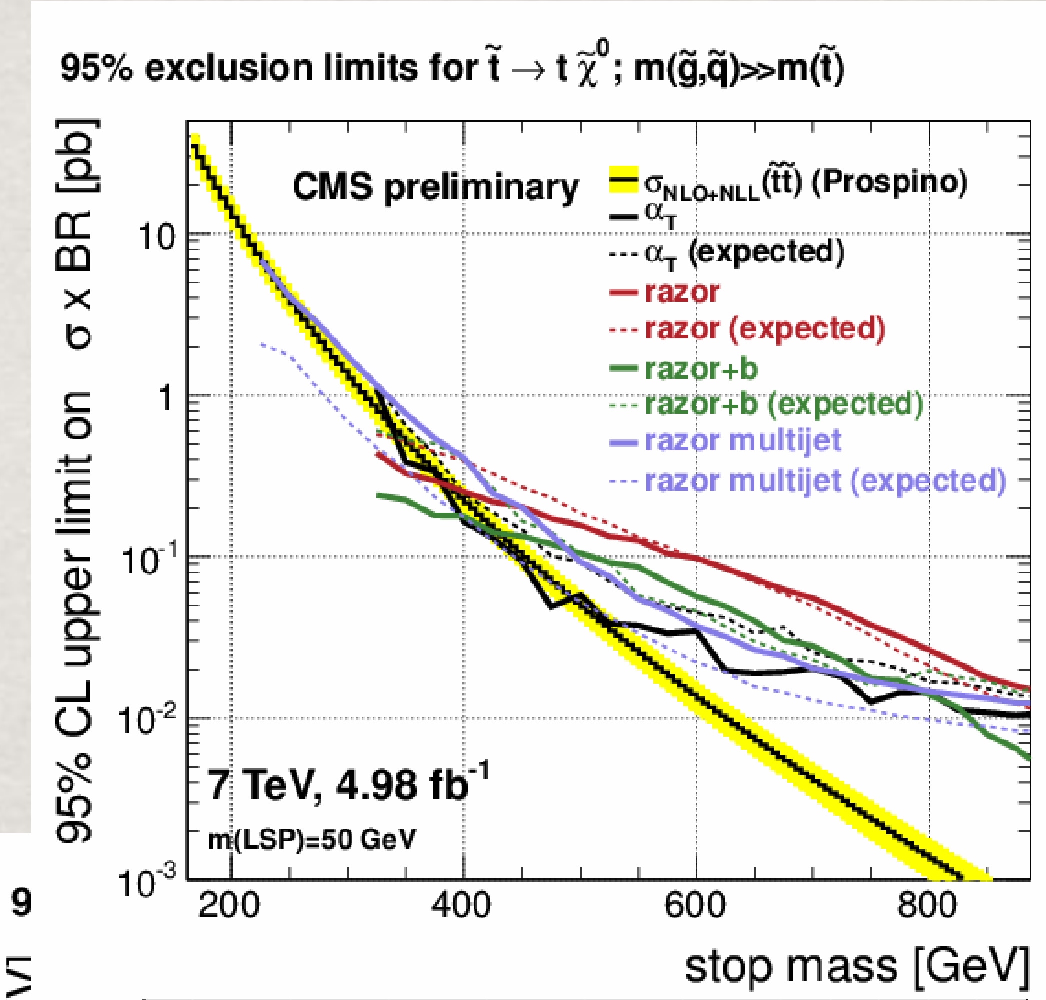
A Natural Higgs Sector

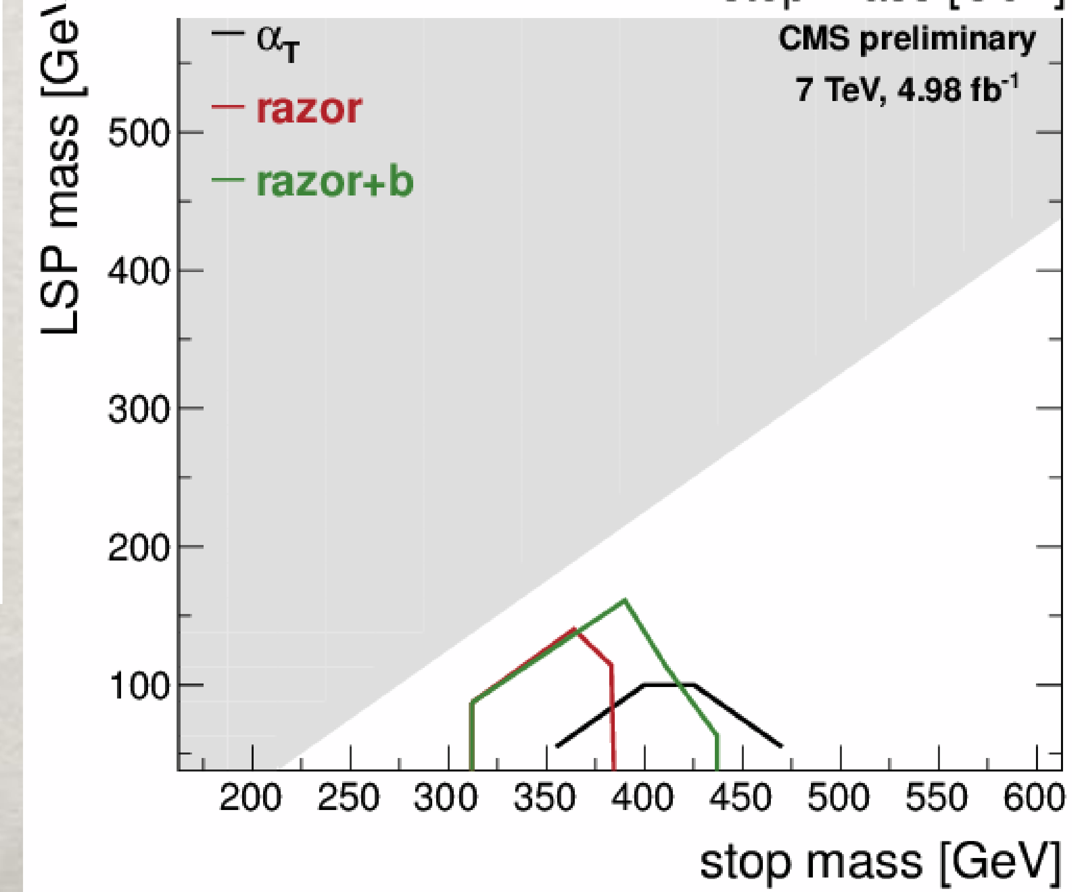
1. Supersymmetry:

Top-partner: the most wanted!









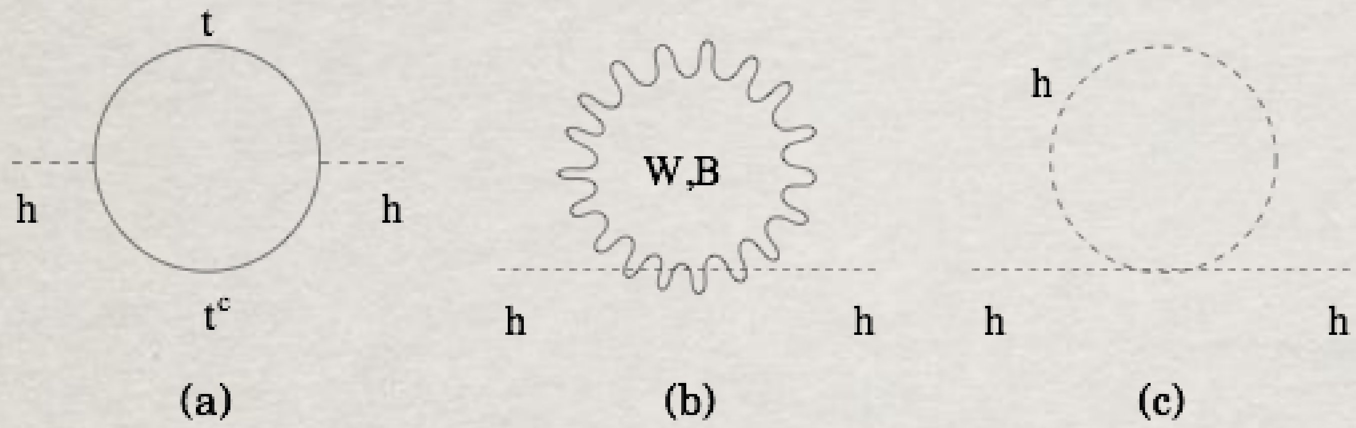
The current bounds still loose.

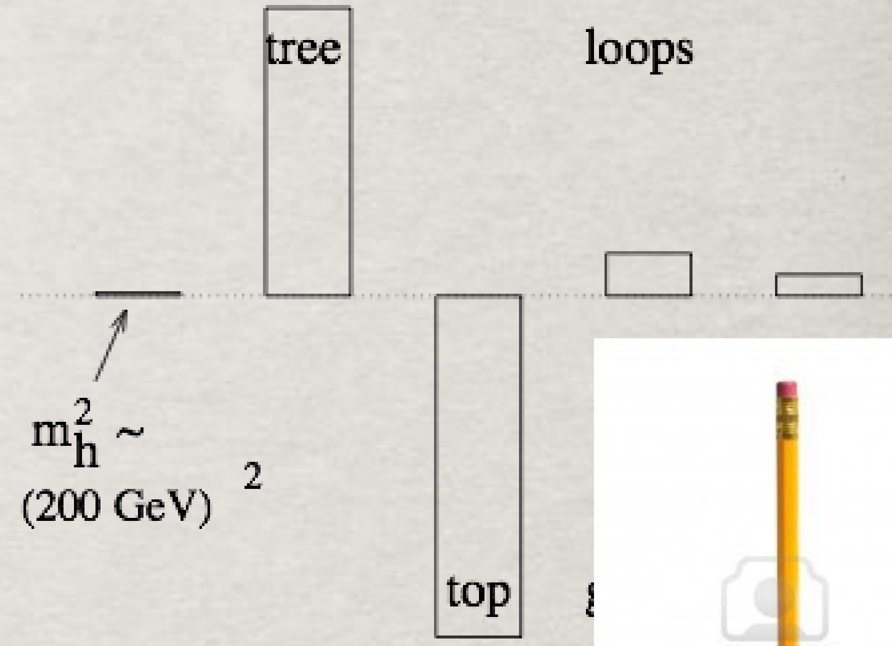
Fitting the SM Higgs @ μ-Collider

$\Gamma_h = 4.21$ MeV	L_{step} (fb^{-1})	$\delta\Gamma_h$ (MeV)	δB	$\delta m_h (MeV)$
Case A	0.005	1.5	13%	0.51
$R = 0.01\%$	0.025	0.85	6.1%	0.32
	0.2	0.34	2.2%	0.13
Case B	0.01	0.61	8.3%	0.40
$R = 0.003\%$	0.05	0.30	3.8%	0.13
	0.2	0.17	2.0%	0.10

TABLE II: Fitting accuracies for one standard deviation range of $\delta\Gamma_h$, δB and δm_h of the SM Higgs with the scanning scheme as specified in Eq. (7) for three representative luminosities per step.

Quantum corrections to the Higgs mass:





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

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

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

• 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:

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

(cancellation among same spin states!)

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

In either case, needs new symmetry and new partners