The Higgs Boson & Beyond*

Tao Han

PITT PACC, Univ. of Pittsburgh

The Christmas Meeting

Dec. 15 - 17, 2014 @ IPPP

* Beyond the SM & beyond the LHC era.

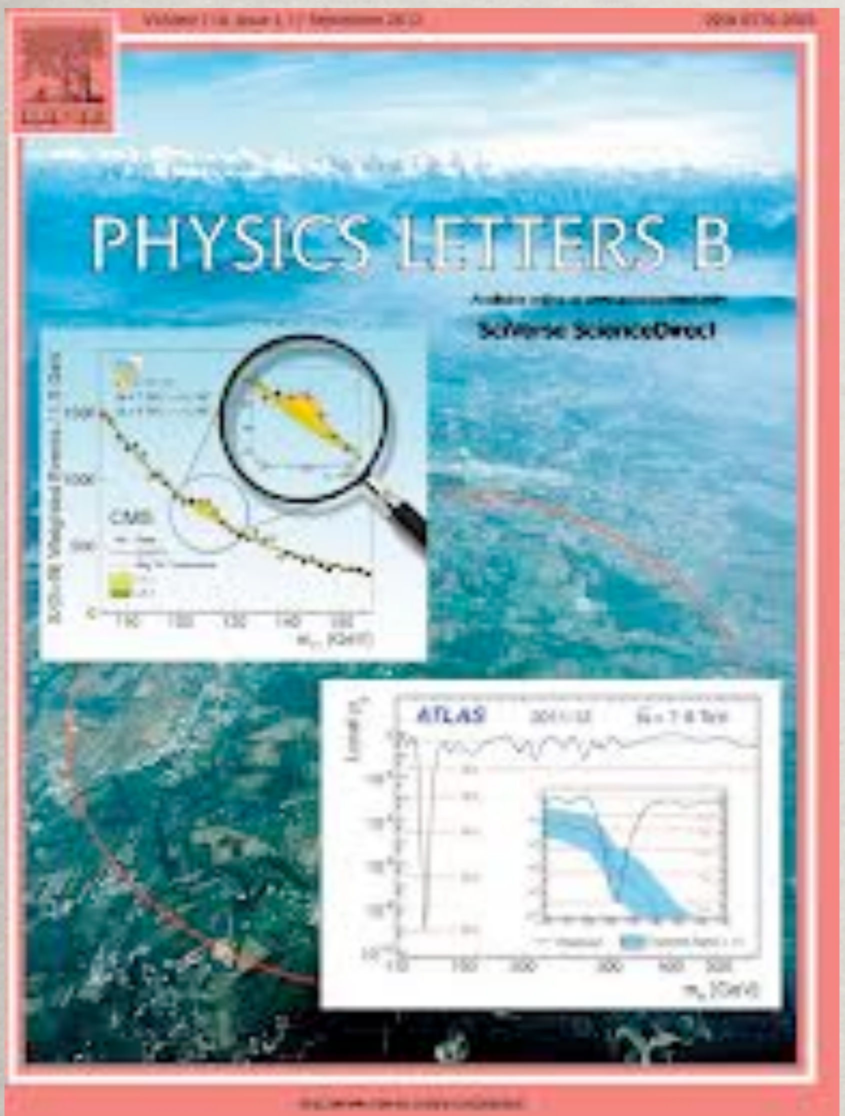


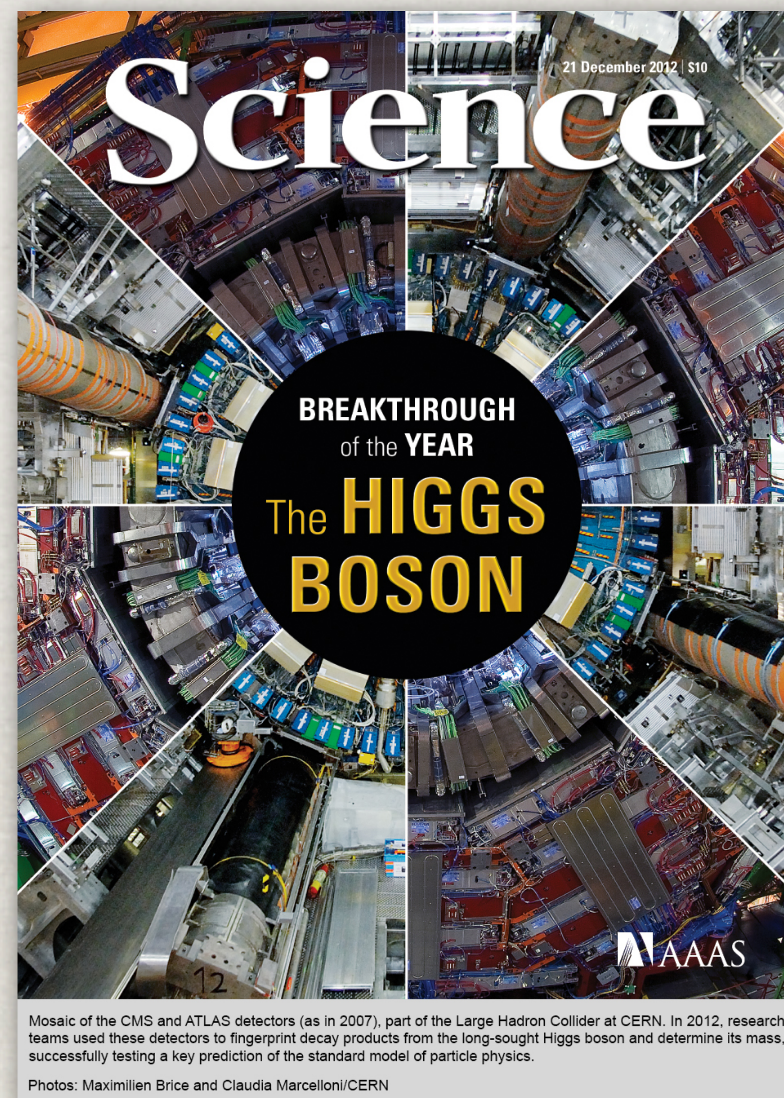

François Englert and Peter W. Higgs

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

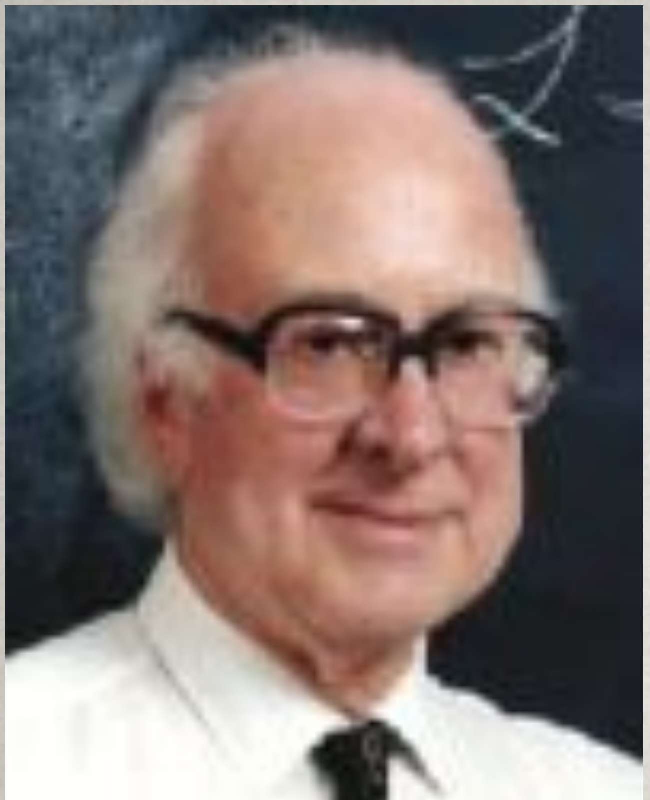
The milestone Discovery:

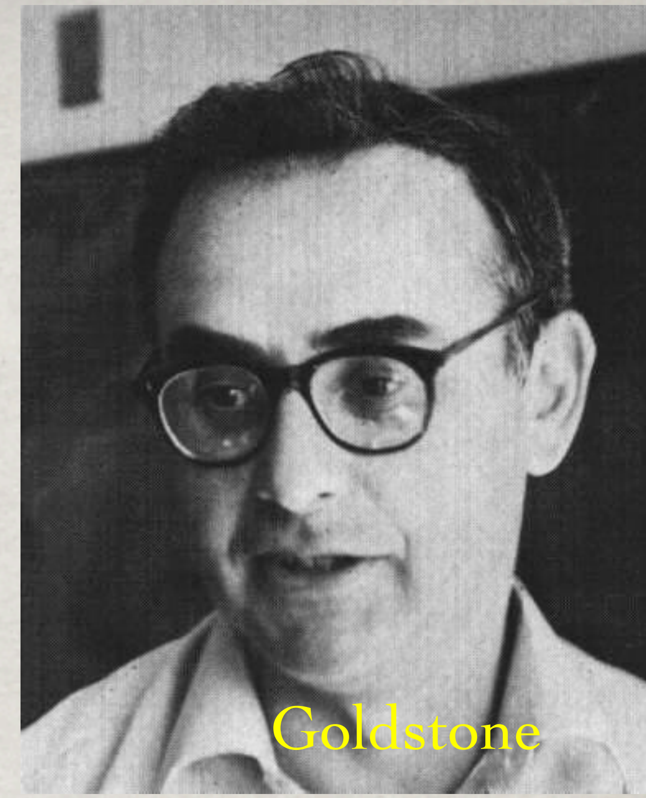
July 4th, 2012: $m_H \approx 126$ GeV
ATLAS: 5.9σ ; CMS: 5.0σ



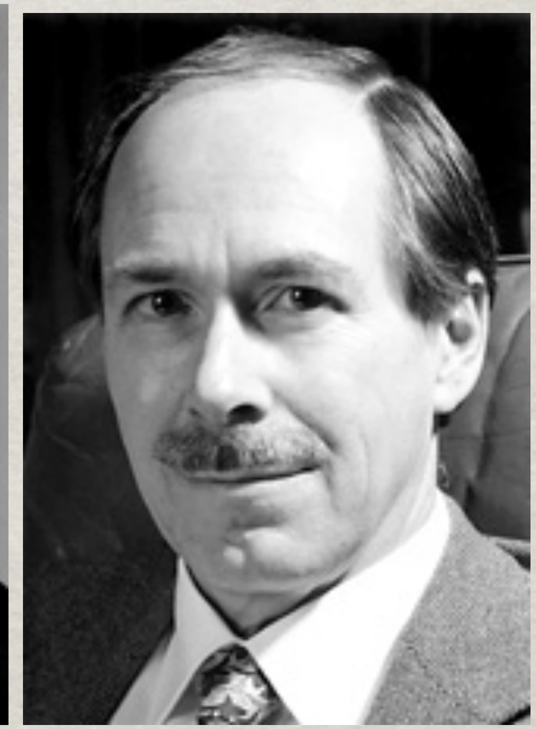


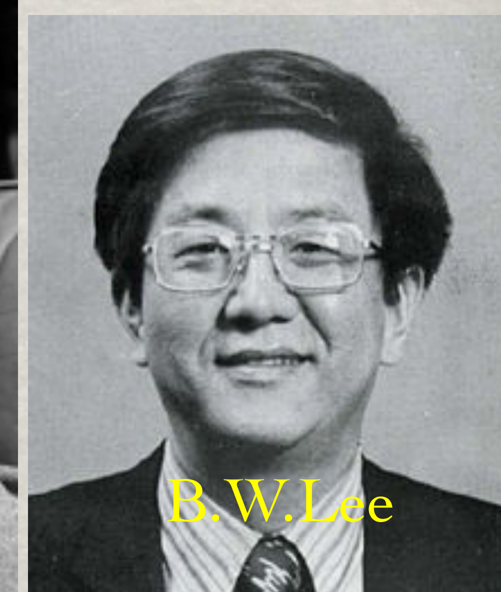
Salute To You All !



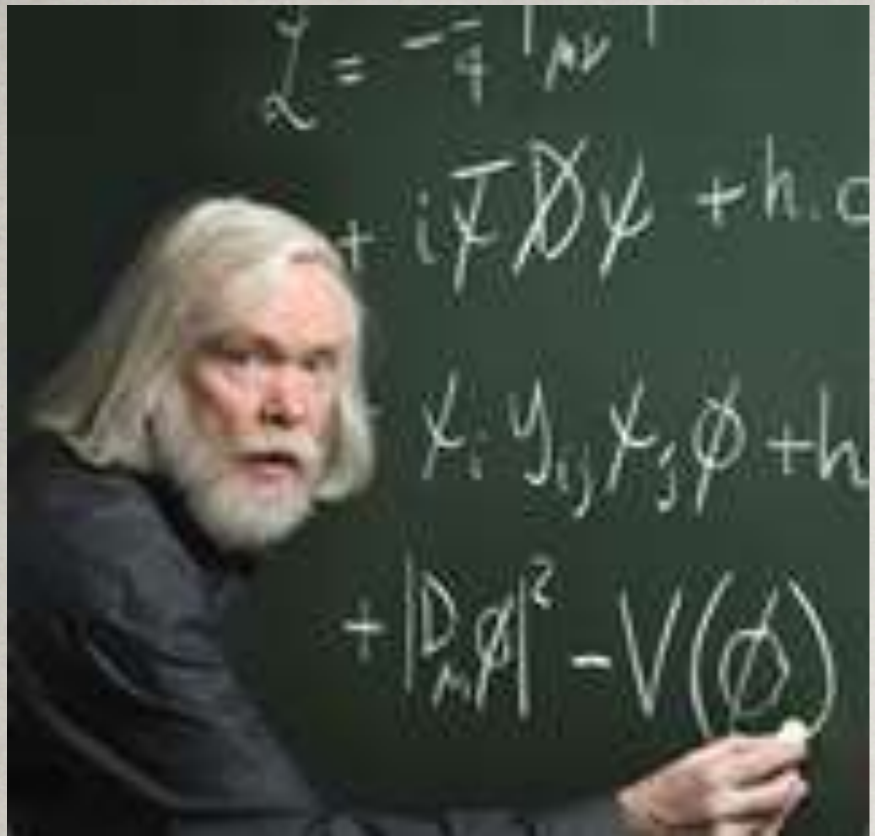


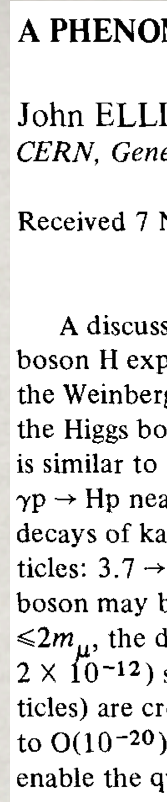
The Higgs mechanism (1964)





The Standard Model (1960-1967, 1972)




A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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

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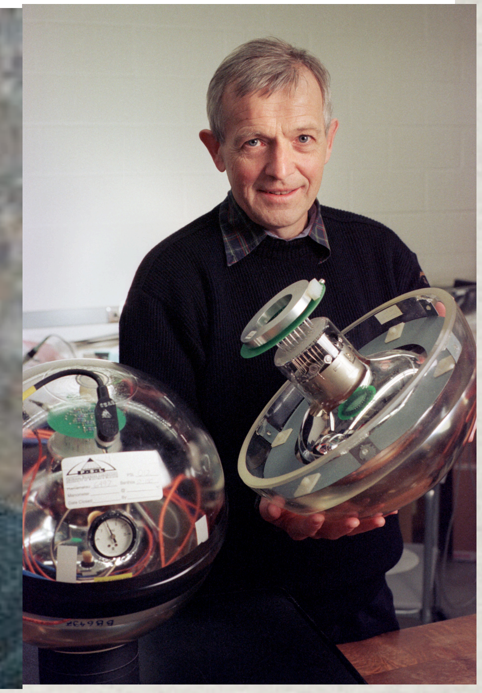
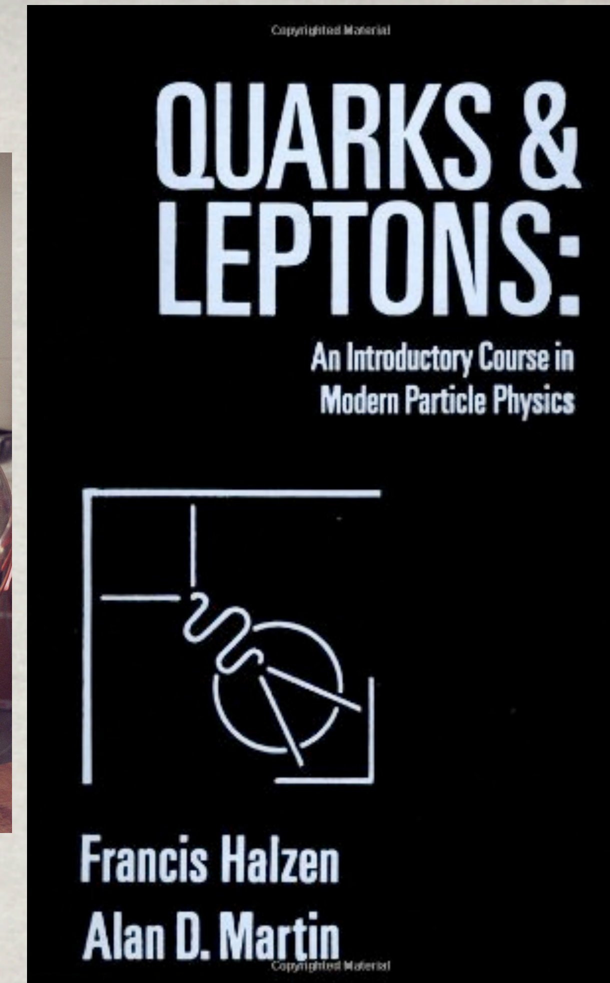
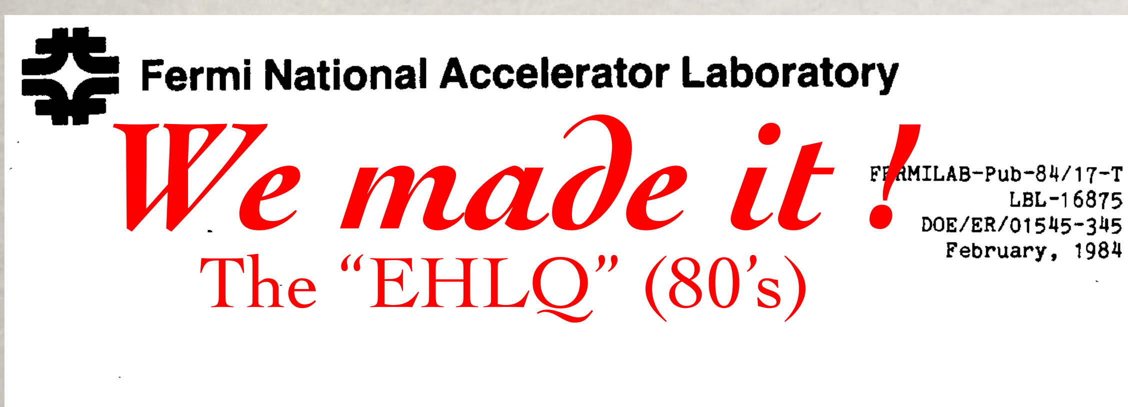




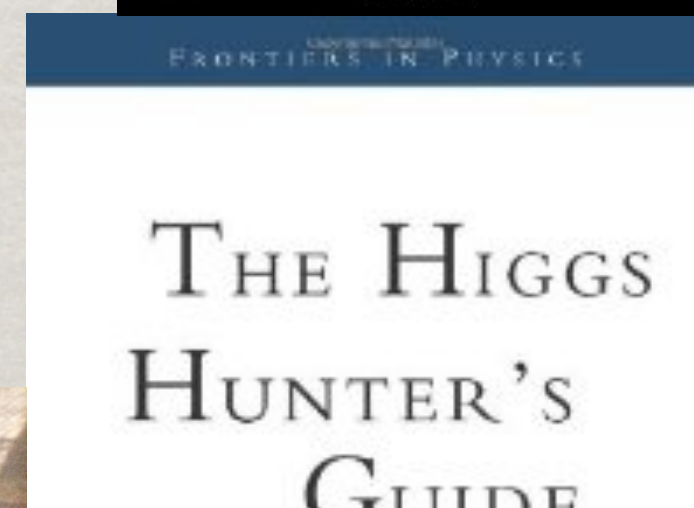
Higgs Phenomenology (70's)

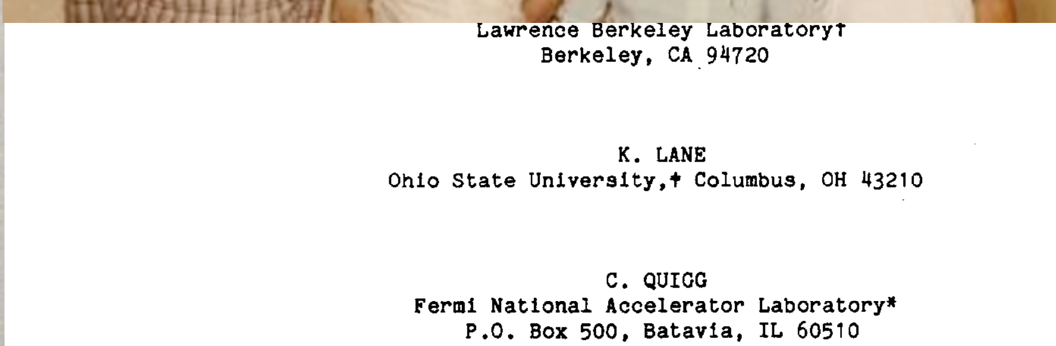

Fermi National Accelerator Laboratory

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

We made it !

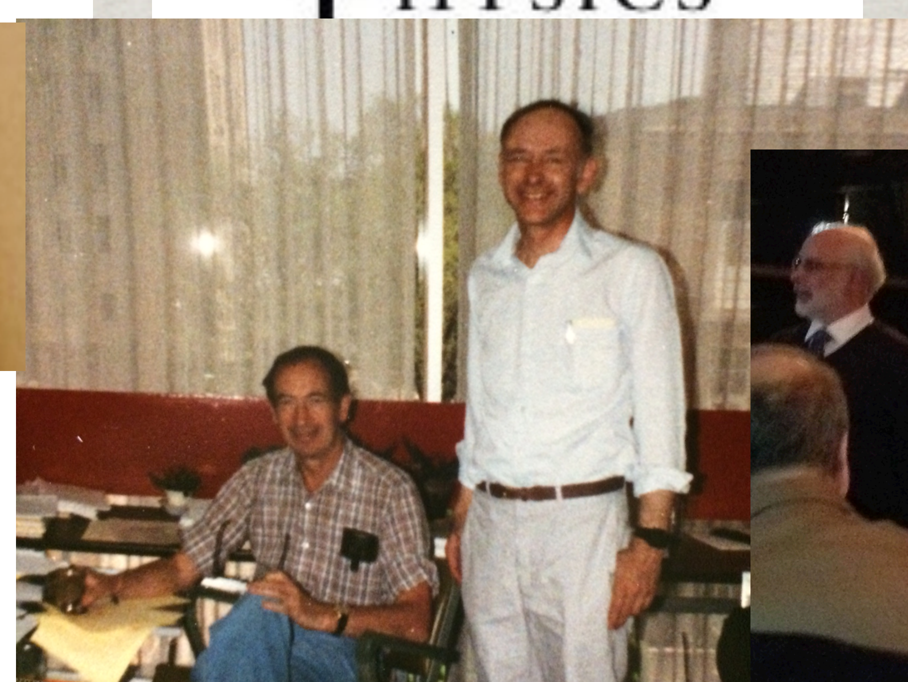
The "EHLQ" (80's)

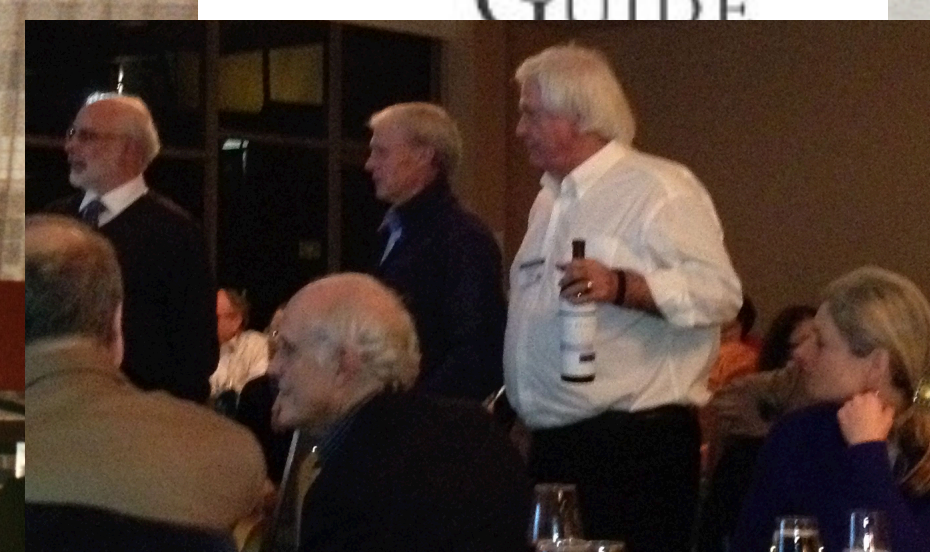



Lawrence Berkeley Laboratory†
Berkeley, CA 94720

K. LANE
Ohio State University,† Columbus, OH 43210

C. QUIGG
Fermi National Accelerator Laboratory*
P.O. Box 500, Batavia, IL 60510





What We Know

1. X → γγ :

- it's neutral, a boson
- can be spin-0
- cannot be spin-1 (Landau-Yang's theorem)
- can be spin-2 unlikely/disfavored

$$\frac{f_s}{\Lambda} H A^{\mu\nu} A_{\mu\nu}$$

$$\frac{f_T}{\Lambda} T_{\mu\mu'} \; g_{\nu\nu'} A^{\mu\nu} A^{\mu'\nu'}$$

2. X → ZZ, W^+W^- :

- Vacuum Q#: EWSB
- CP-odd part of gauge interaction must be small

$$(v+H)^2 \, g^2 V^{\mu} V_{\mu}$$

$$\frac{f_A}{\Lambda} A \, \tilde{V}^{\mu\nu} V_{\mu\nu}$$

H → ZZ, WW crucially important!
(Howard Georgi would not be convinced if only H → γγ seen)

University of Wisconsin - Madison

MAD/PH/397
January 1988

HIGGS BOSON DECAY TO ONE REAL AND ONE VIRTUAL W BOSON

E. W. N. Glover
CERN, Geneva

J. Ohnemus and Scott S. D. Willenbrock
Physics Department, University of Wisconsin, Madison, Wisconsin 53706

ABSTRACT

We study the decay $H \to WW^*$ at future hadron colliders. If the top quark is heavy, $m_t > m_H/2$, the decay $H \to WW^* \to (\ell\bar{\nu})(\bar{\ell}\nu)$ yields an observable signal at the SSC for 140 GeV $\lesssim m_H < 2M_Z$. The cluster transverse mass of the final-state leptons allows a rough estimate of the Higgs-boson mass.

Intermediate-mass Higgs boson at hadron supercolliders

V. Barger, G. Bhattacharya, T. Han,* and B. A. Kniehl
Physics Department, University of Wisconsin, Madison, Wisconsin 53706
(Received 20 August 1990)

We study the inclusive production at future hadron supercolliders of the standard-model Higgs boson in the intermediate-mass region ($M_W \lesssim M_H \lesssim 2M_Z$) and its subsequent decay into two virtual W bosons that decay leptonically. Backgrounds from continuum W pair production and from top-quark pair production with semileptonic decays are investigated. We conclude that the Higgs-boson signal may be observed via the decay $H \to W^* W^* \to (l\bar{\nu}_l)(\bar{l}'\nu_{l'})$ at the Superconducting Super Collider for 145 GeV $< M_H \lesssim 2M_Z$ if $m_t > 150$ GeV. Here W^* denotes an on- or off-shell W boson.

How to find a Higgs Boson with a Mass between 155–180 GeV at the LHC

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[2] Rutherford Laboratory, Chilton, Didcot, OX11 0QX, UK

Abstract

We reconsider the signature of events with two charged leptons and missing energy as a signal for the detection of the Standard Model Higgs boson in the mass region $M(Higgs)$=155–180 GeV. It is shown that a few simple experimental criteria allow to distinguish events originating from the Higgs boson decaying to $H \to W^+W^-$ from the non resonant production of W^+W^-X at the LHC. With this set of cuts, signal to background ratios of about one to one are obtained, allowing a 5–10 σ detection with about 5 fb^{-1} of luminosity. This corresponds to less than one year of running at the initial lower luminosity $\mathcal{L} = 10^{33} cm^{-2}s^{-1}$. This is significantly better than for the hitherto considered Higgs detection mode $H \to Z^0Z^{0*} \to 2\ell^+2\ell^-$, where in this mass range about 100 fb^{-1} of integrated luminosity are required for a 5 σ signal.

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

- Non-universal leptonic couplings unlike the gauge couplings

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

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

   X → $b\bar{b}$ seen (vaguely)

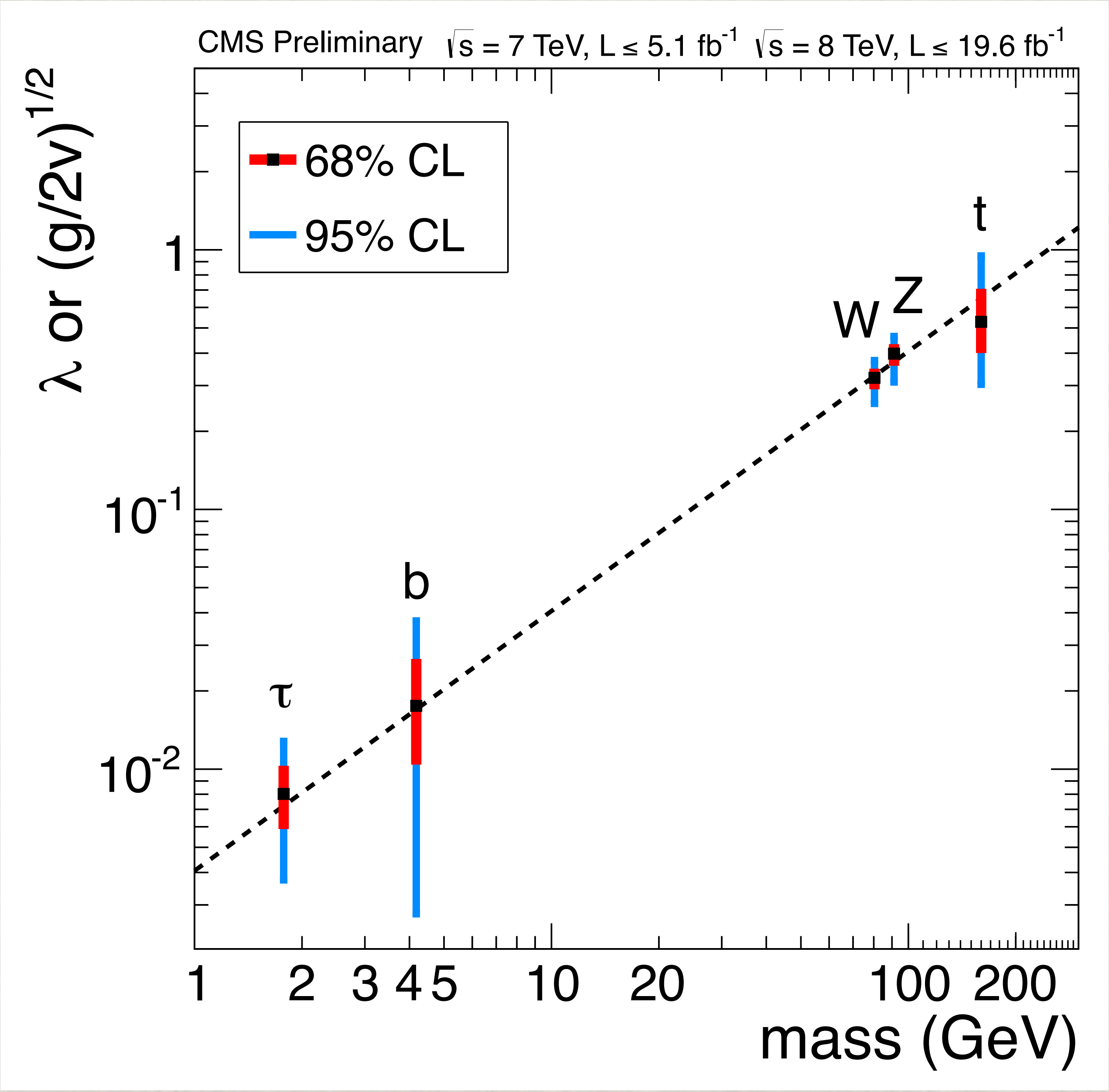
- Non-universal quark couplings

It couples to mass, it is a new class.

It IS a Higgs!

The SM (like) ?

Need further quantitative verification:



If no more than a few% deviations, I'd DEFINE it the SM Higgs!

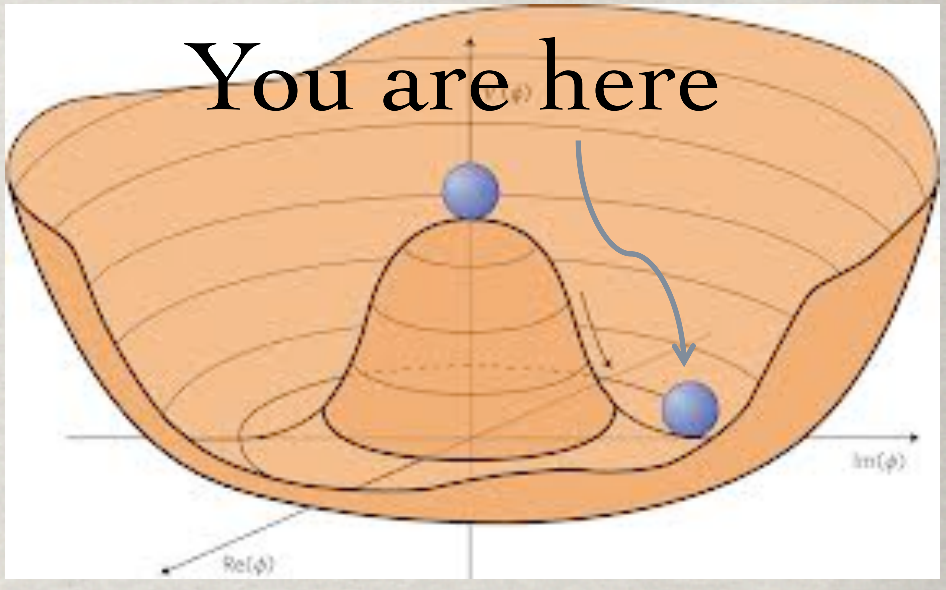
What (else) We Know

$m_H \approx 126$ GeV !

In the SM, the EWSB is parameterized as

$$V(|\Phi|) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

$$\Rightarrow \quad \mu^2 H^2 + \lambda v H^3 + \frac{\lambda}{4}H^4$$



Consequently,

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

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

	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	
				Higgs boson	

Source: AAAS

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 3600 cites each!

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

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:

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

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

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 at collider energies $\lambda \approx 0.13$**
- **In SUSY, it is related to the gauge couplings tree-level: $\lambda = (g_L^2 + g_Y^2)/8 \approx 0.3/4 \leftarrow$ 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.

λ at High energies

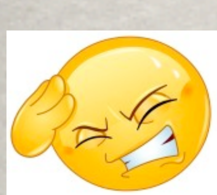
λ is NOT asymptotically free.

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:

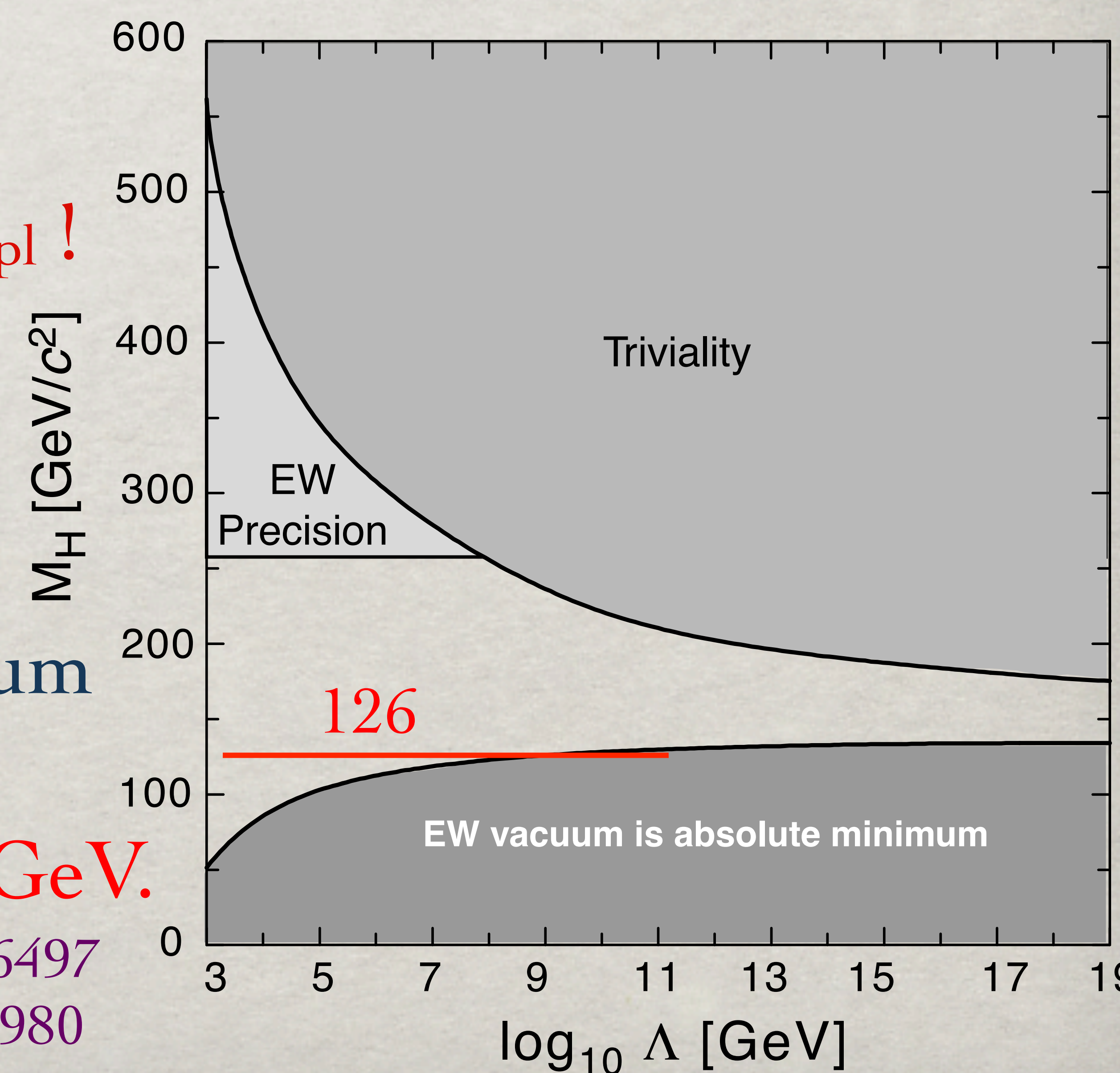
The SM can be a consistent perturbative theory up to M_{pl} ! allowing M_N, M_{GUT}, …

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

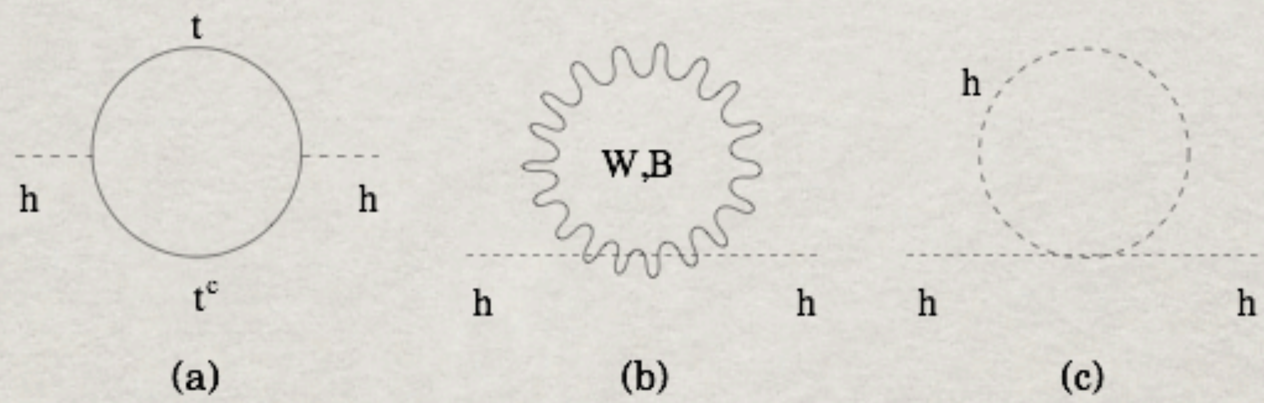


2. $V = -\mu^2|\phi|^2 + \lambda|\phi|^4$

"… 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":



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

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

Cancelation in perspective:

$m_H{}^2$ = 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

= $(125\ \text{GeV})^2$! ?

“Naturalness” in perspective:

Unbelievable!

$4\ mm^2 / 20\ cm^2 \sim 10^{-3}$ fine-tune.

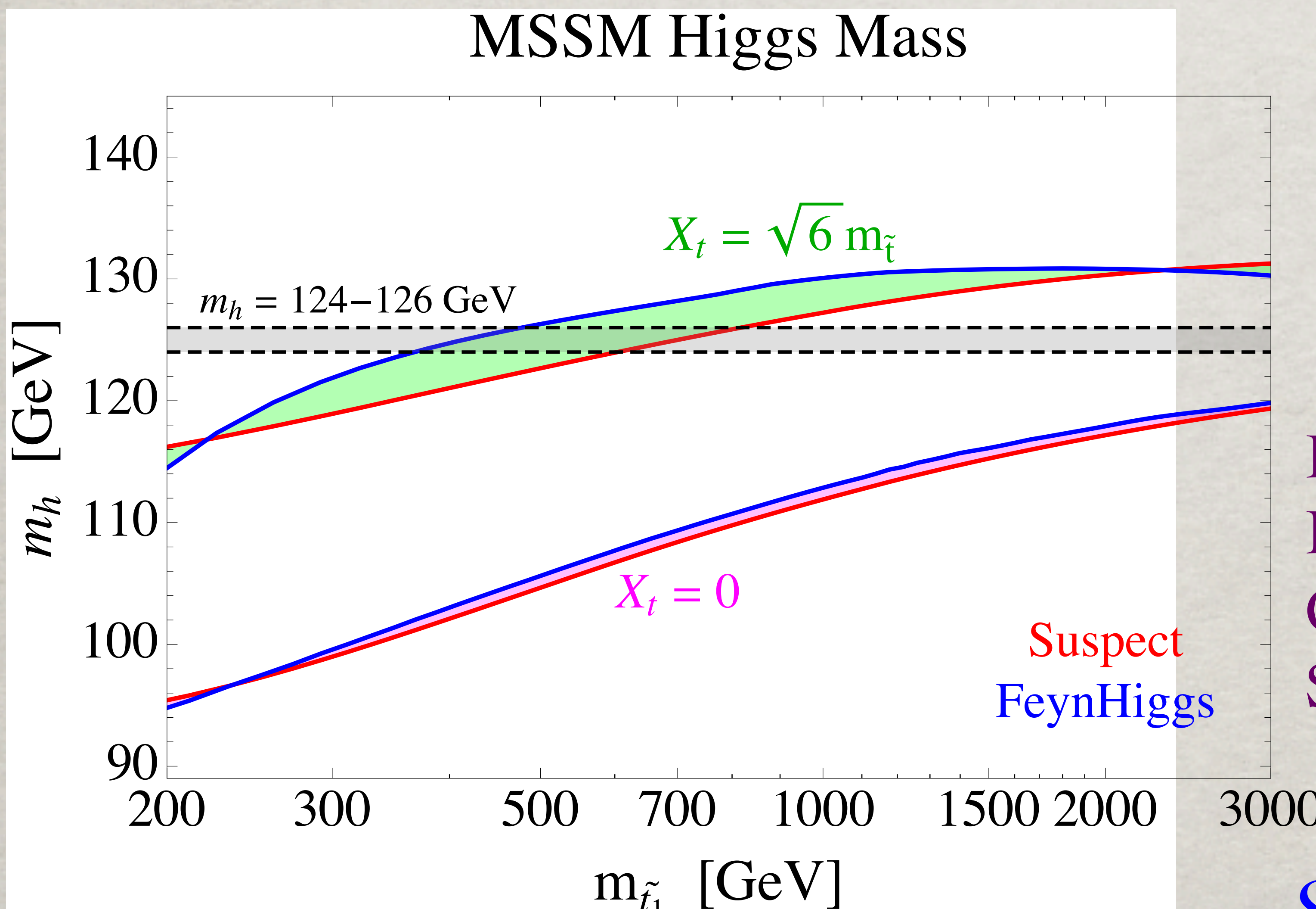
“Naturalness” → TeV scale new physics.

The "Little hierarchy":

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

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

→ Need large $\tan\beta$; 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
S. Heinemeyer et al., 2012-2014

See Sheinemeyre's talk …

The "Little hierarchy":

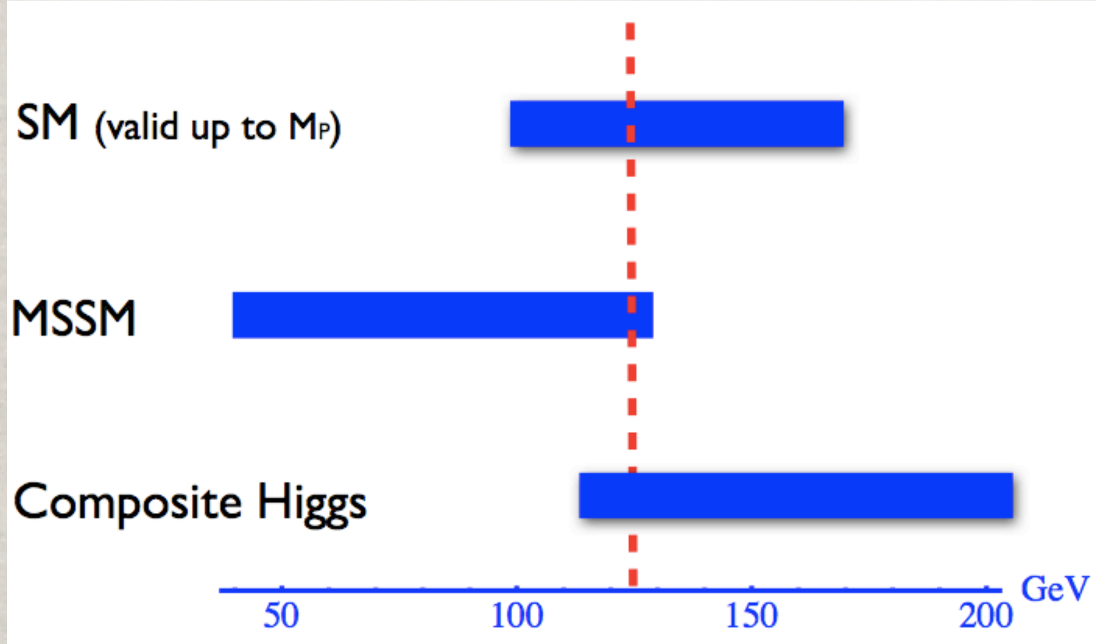
- **In composite/strong dynamics:**
  (dual of extra dimension theory)

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 .



Pomarol, ICHEP'12

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

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

What We Wish to Know in the LHC Era

1. A "natural" EW theory?

- "Natural SUSY":

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

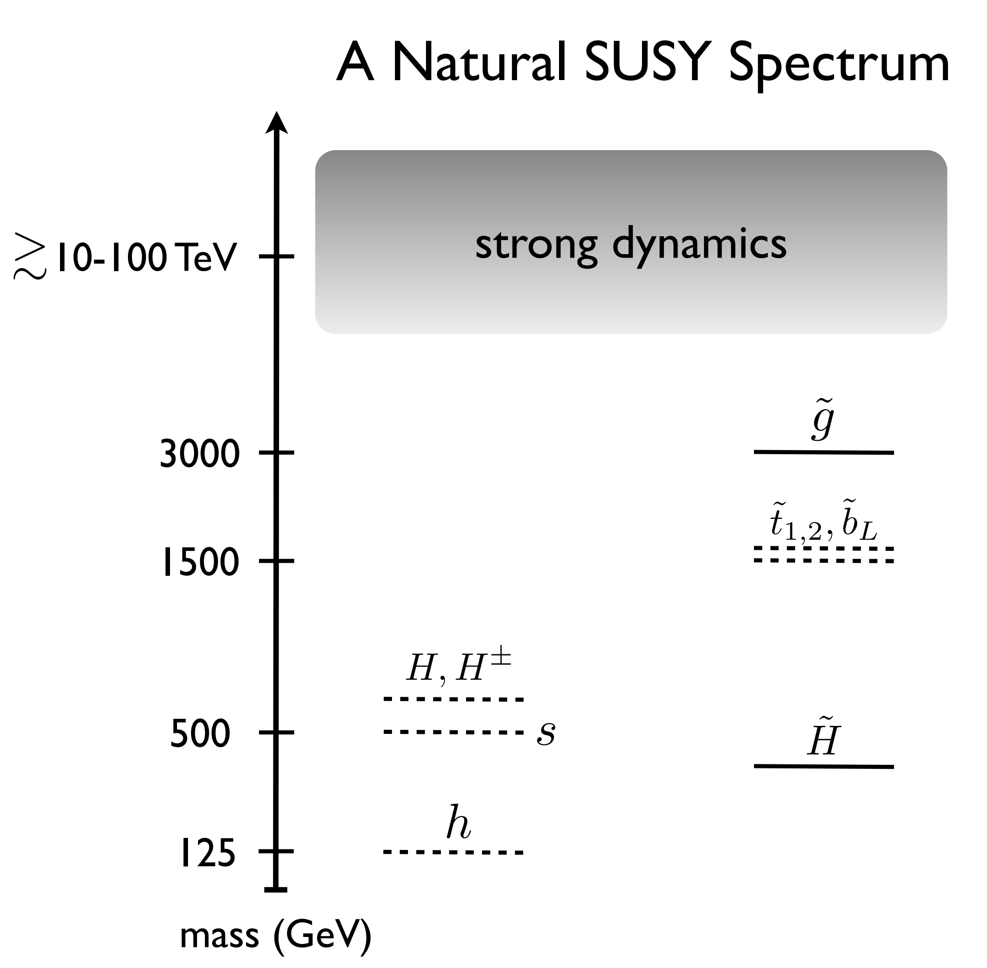
Relevant to the Higgs and the "Most Wanted":

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

Current LHC bounds:

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

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



- "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 …
  neutrino mass connection via Type II seesaw.

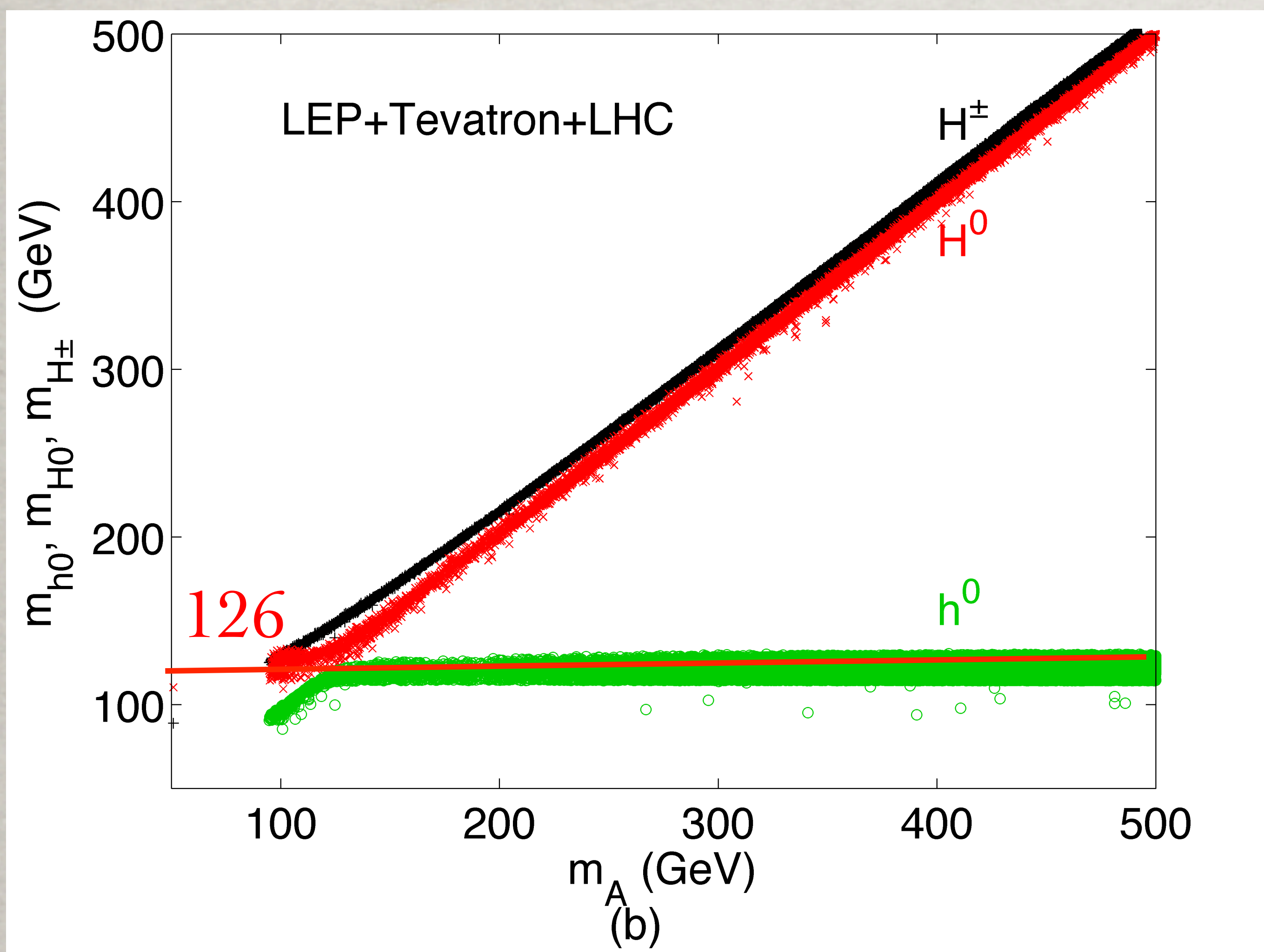
Example: MSSM Two Higgs-Doublet Model after the discovery:

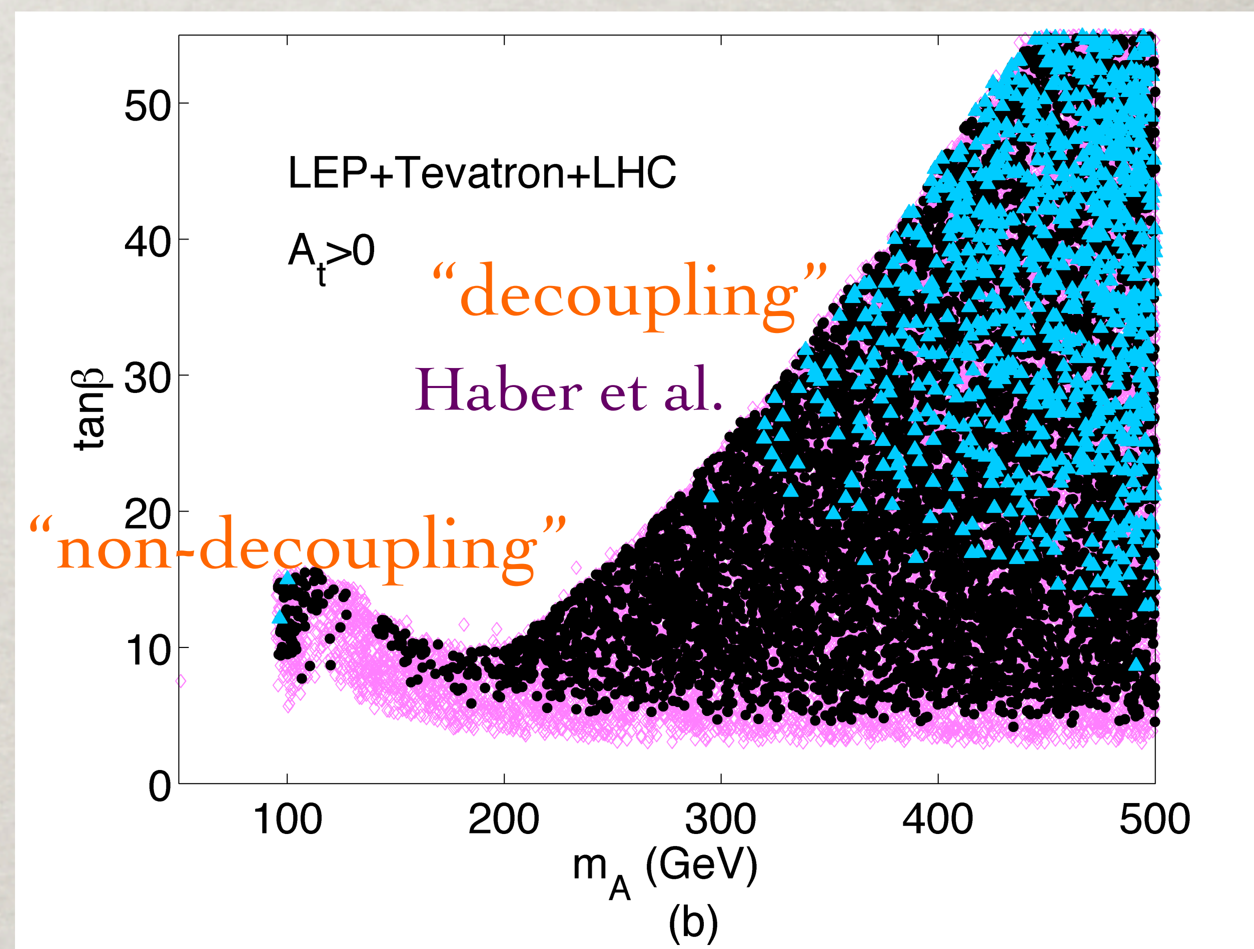
Arbey et al., 2011, 2012
Baer et al., 2012
Heinemeyer et al., 2012
Carena 2012, 2013, … …

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:

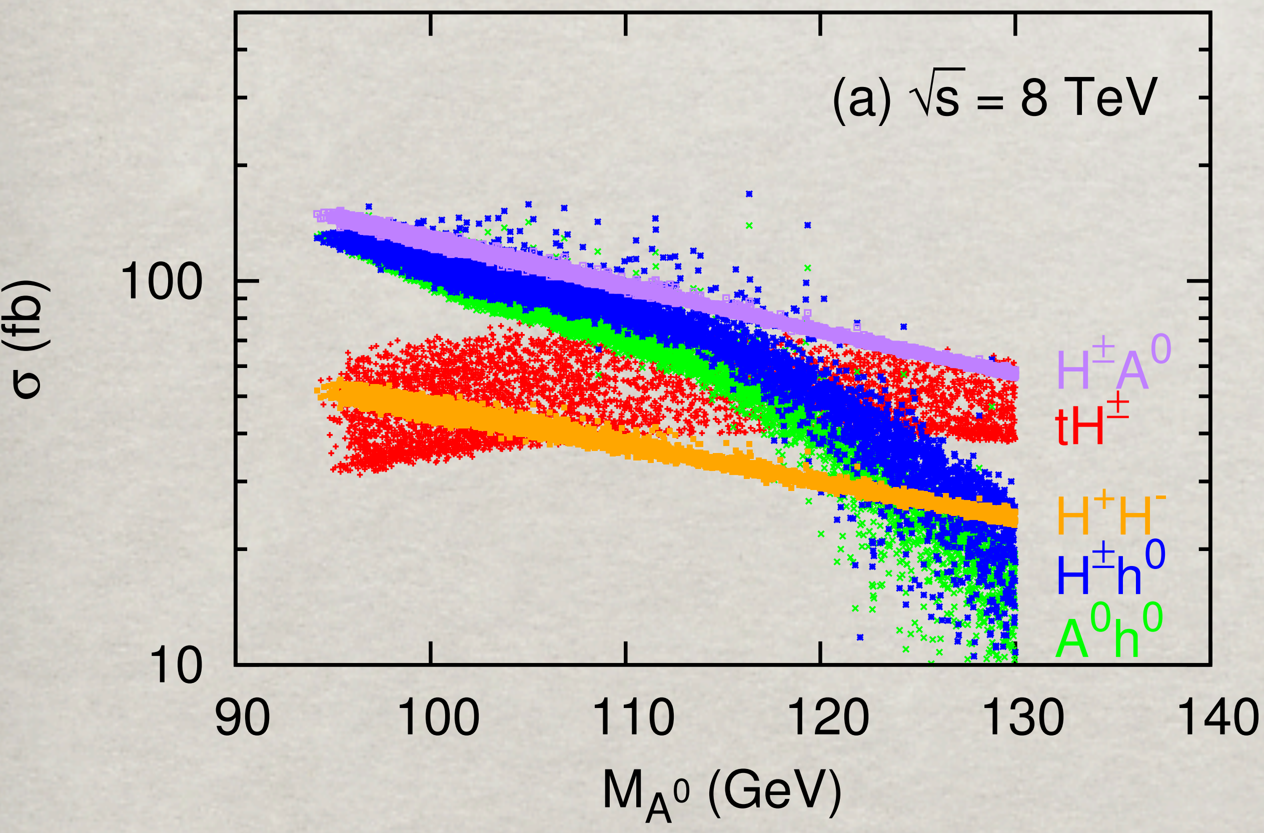
Search for heavy H^0, A^0, $H^\pm$ will continue.

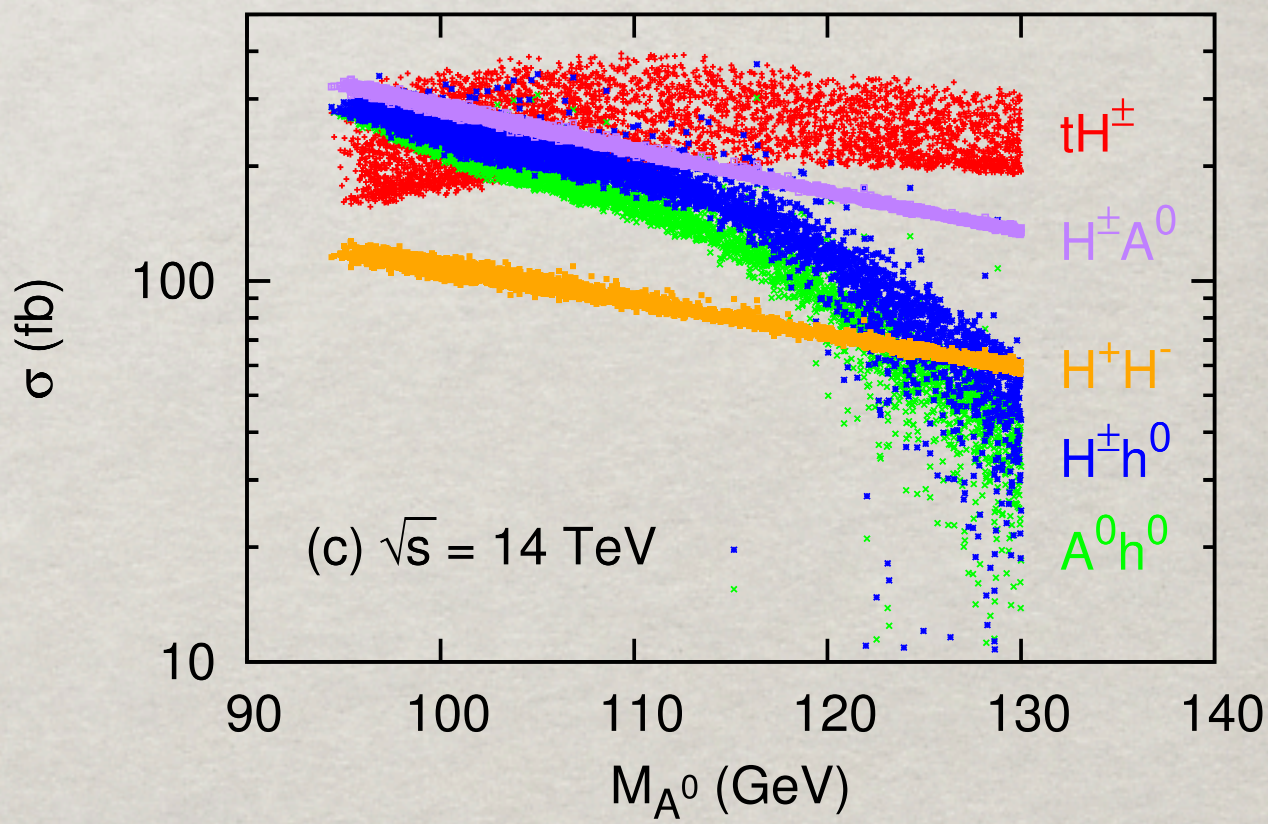
Non-Decoupling Sector: immediate relevance!

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

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

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





TH, Li, Christensen, arXiv:1206.5816

3. The Higgs portals to Cosmos?

(a). Dark Matter

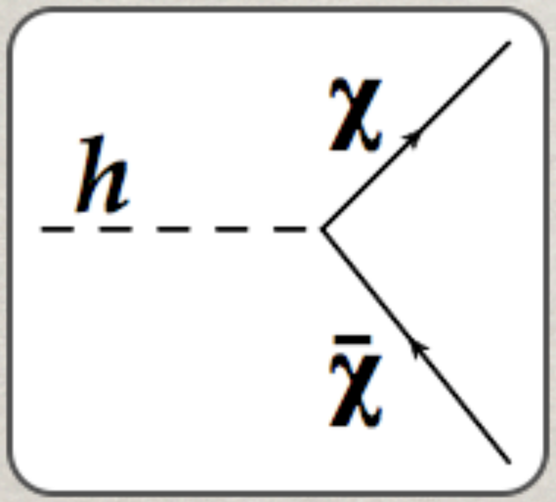
$H^\dagger H$ is the only bi-linear SM gauge singlet.

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

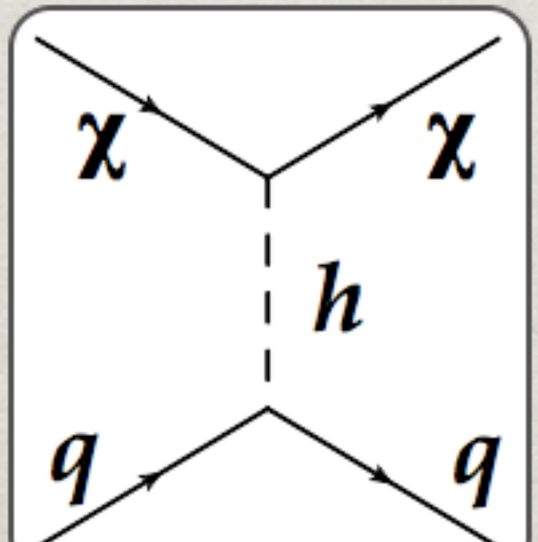
Good: May readily serve as a portal to the dark sector:

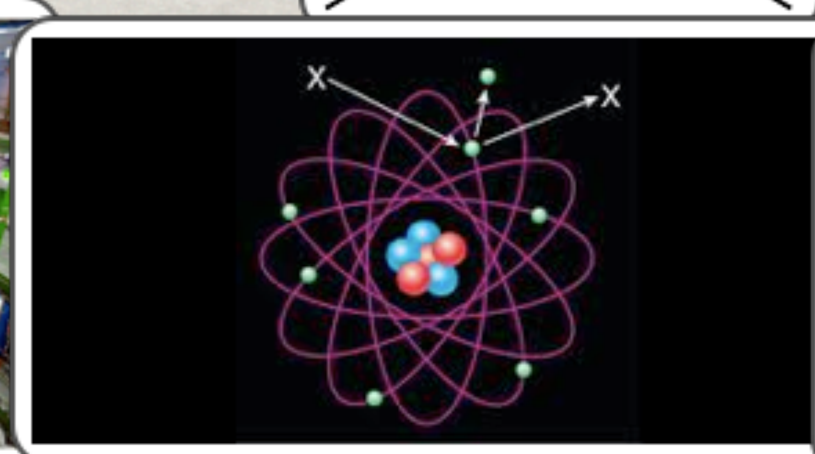
$$k_s H^\dagger H\ S^* S, \qquad \frac{k_\chi}{\Lambda} H^\dagger H\ \bar\chi\chi.$$

Missing energy at LHC

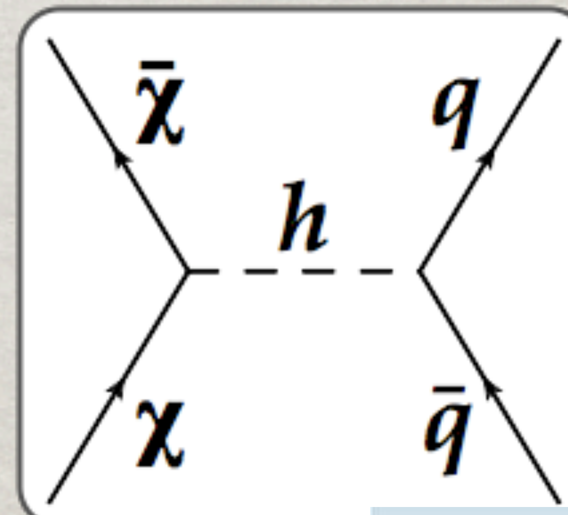


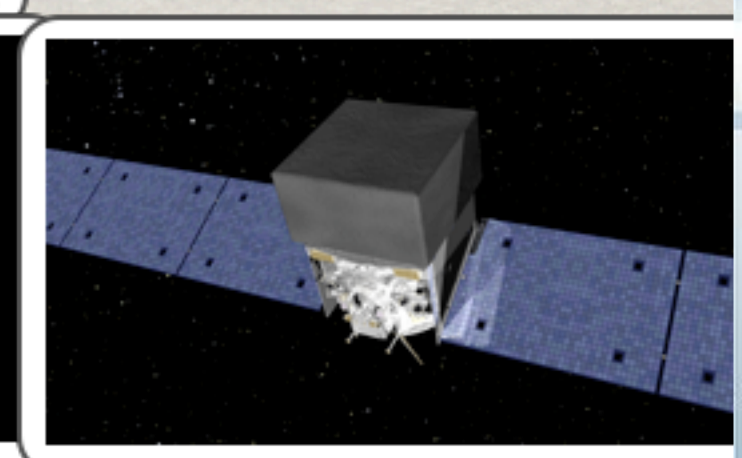
Direct detection

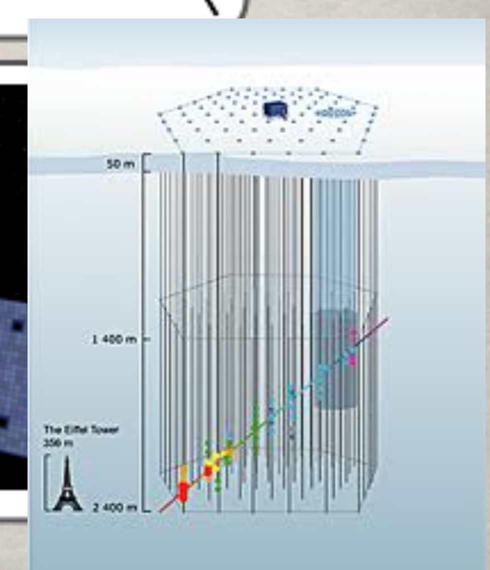




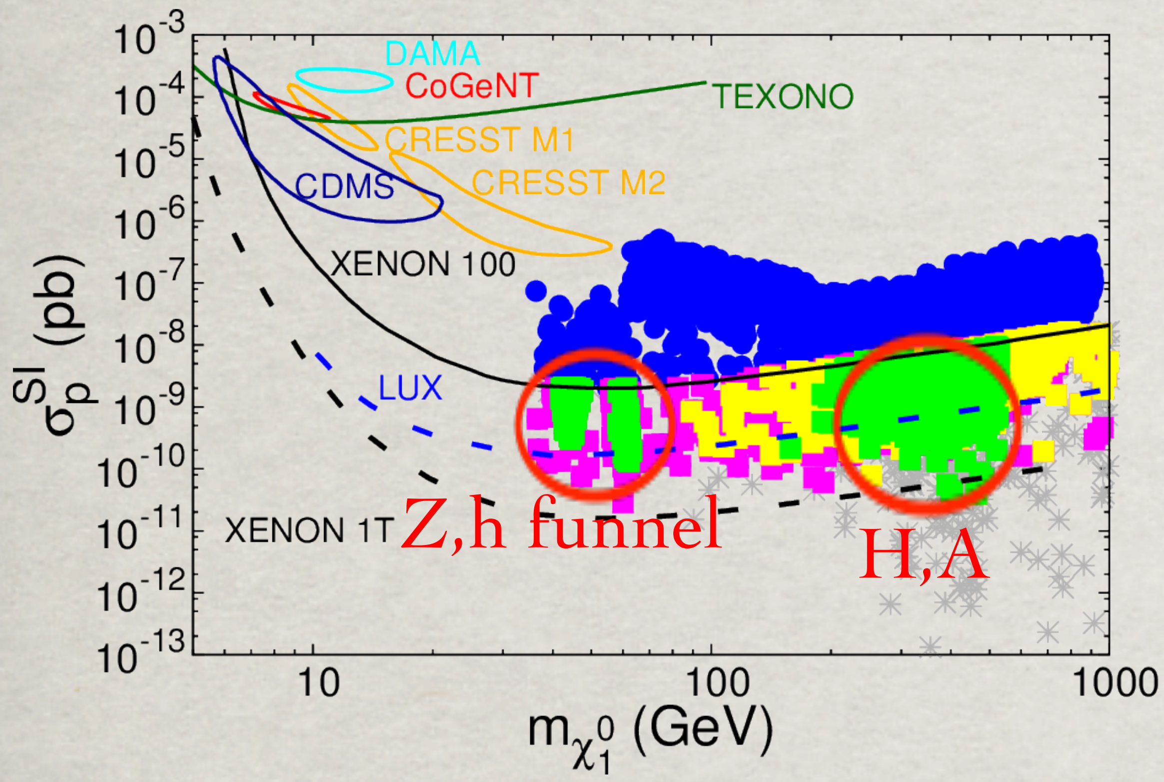
Indirect detection



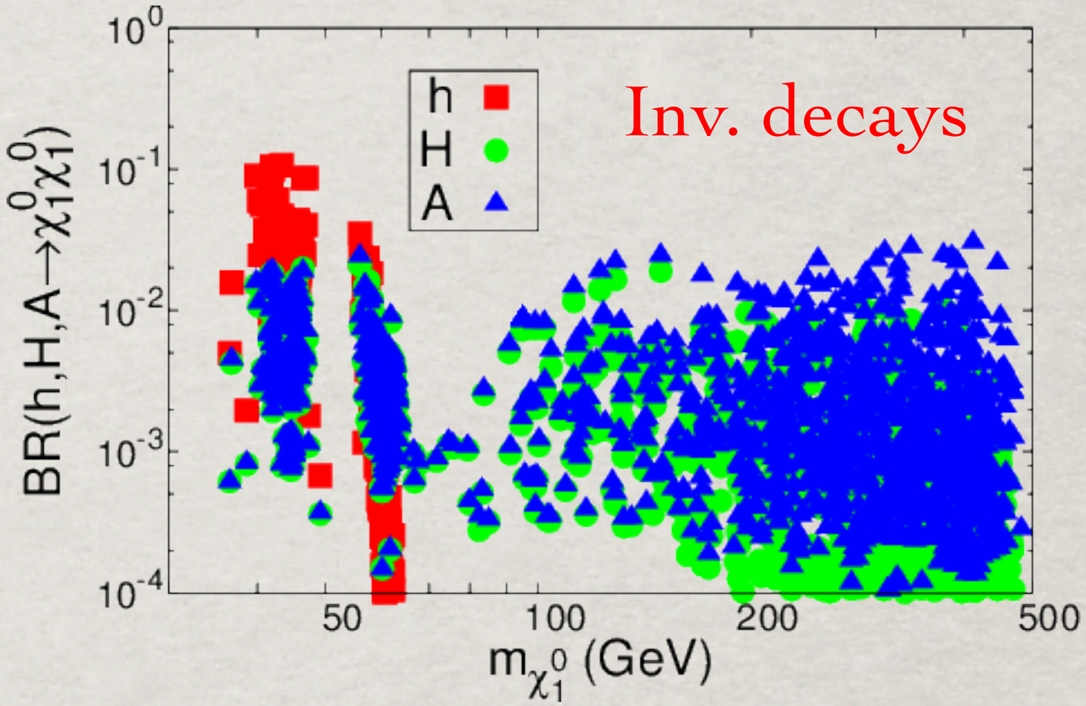


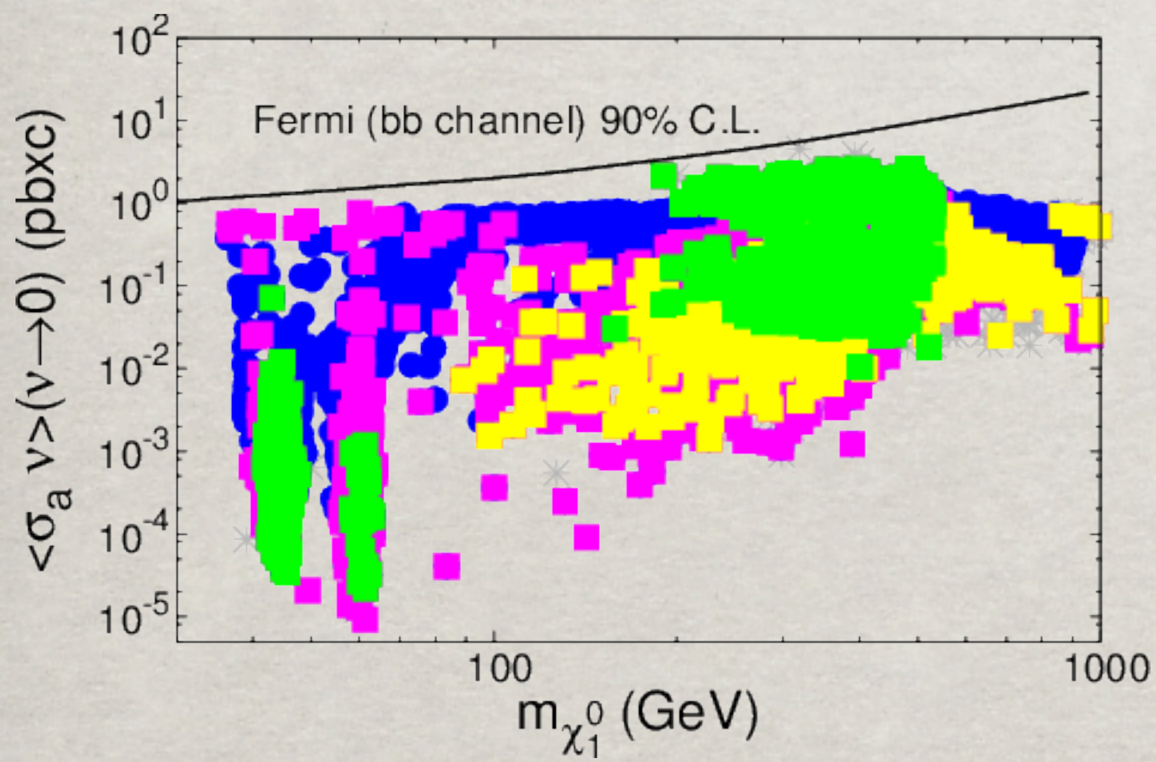


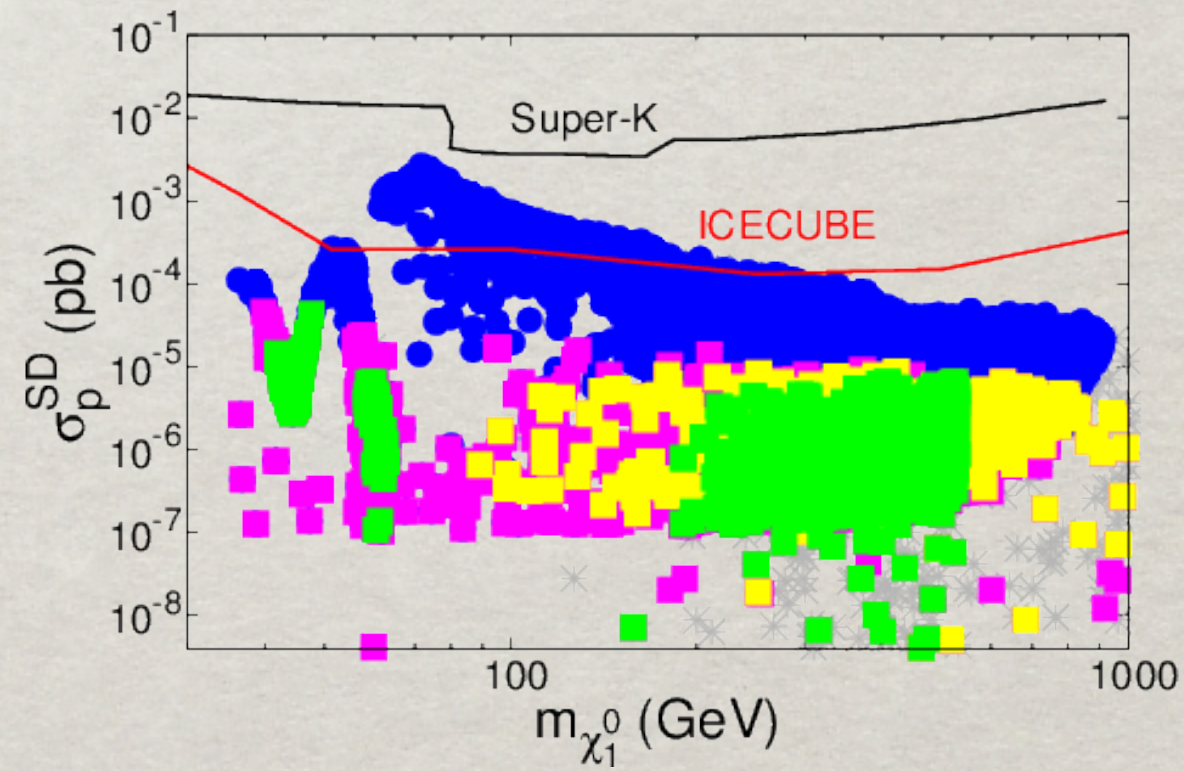
SUSY Higgs funnel soon covered by direct searches:



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.

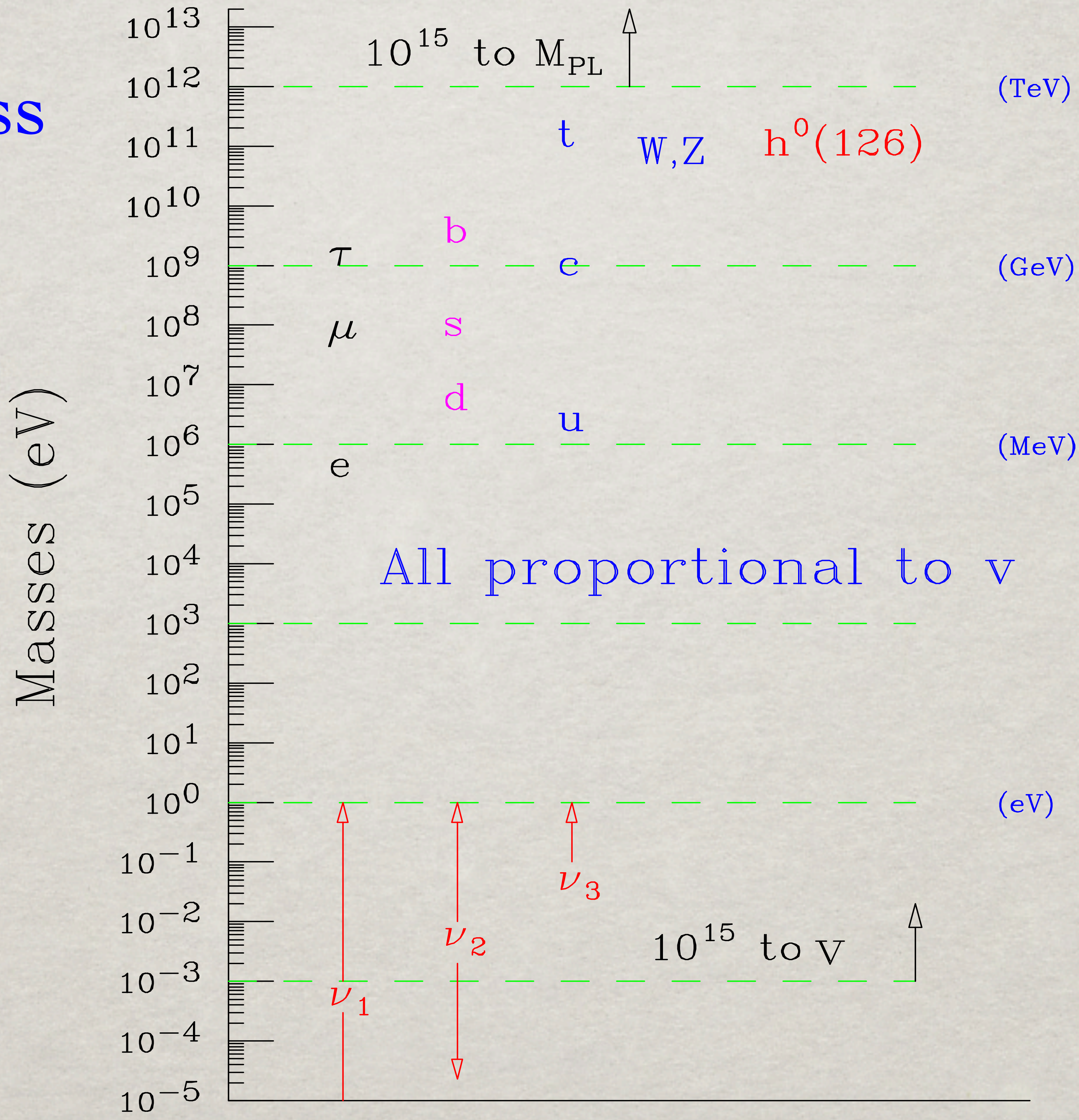
(c). Higgs as an inflaton?
(d). Higgs field & Dark Energy?

Bezrukov, 2008;
Nakayama, 2011.

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

4. Flavor & Masses

Particle mass hierarchy:

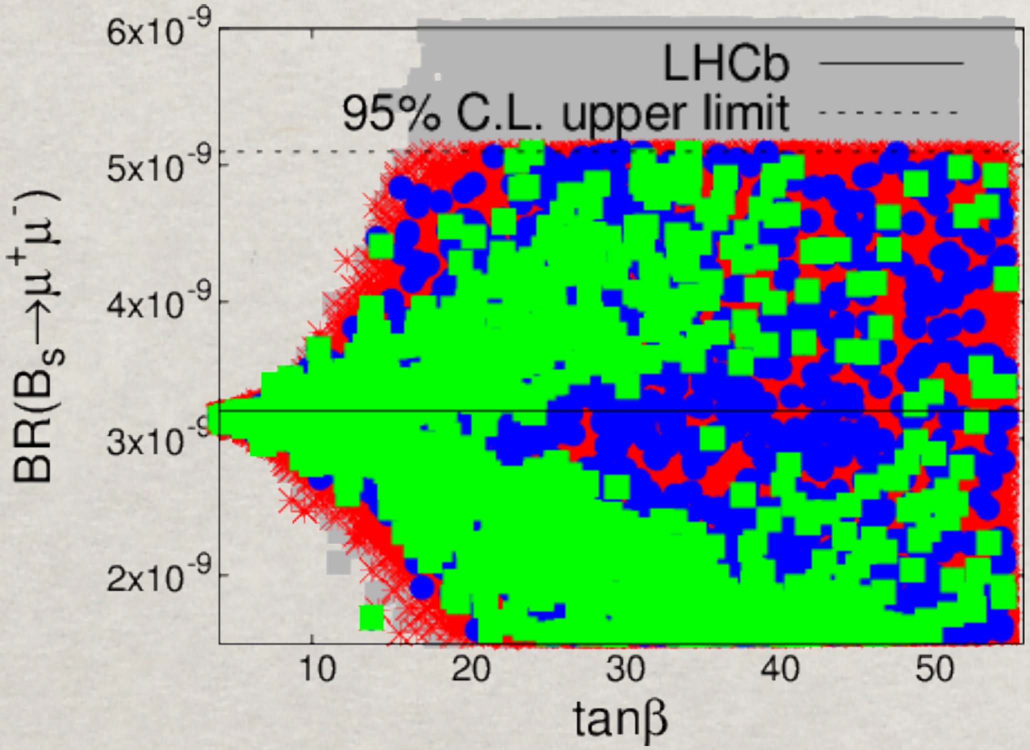


The fermion mass/mixing is a much^n bigger puzzle!

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) ~ $\tan^6\beta \,/\, M_A^4$



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

Most recent LHCb+CMS:
arXiv:1411.4413

$$\mathcal{B}(B_s^0 \quad \mu^+\mu^-) = 2.8\,^{+0.7}_{-0.6} \times 10^{-9} \text{ and}$$
$$\mathcal{B}(B^0 \quad \mu^+\mu^-) = 3.9\,^{+1.6}_{-1.4} \times 10^{-10},$$

$$\mathcal{S}_{\rm SM}^{B_s^0} = 0.76\,^{+0.20}_{-0.18} \text{ and } \mathcal{S}_{\rm SM}^{B^0} = 3.7\,^{+1.6}_{-1.4}.$$

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": $m_\nu \sim \kappa \frac{\langle H^0 \rangle^2}{M}$

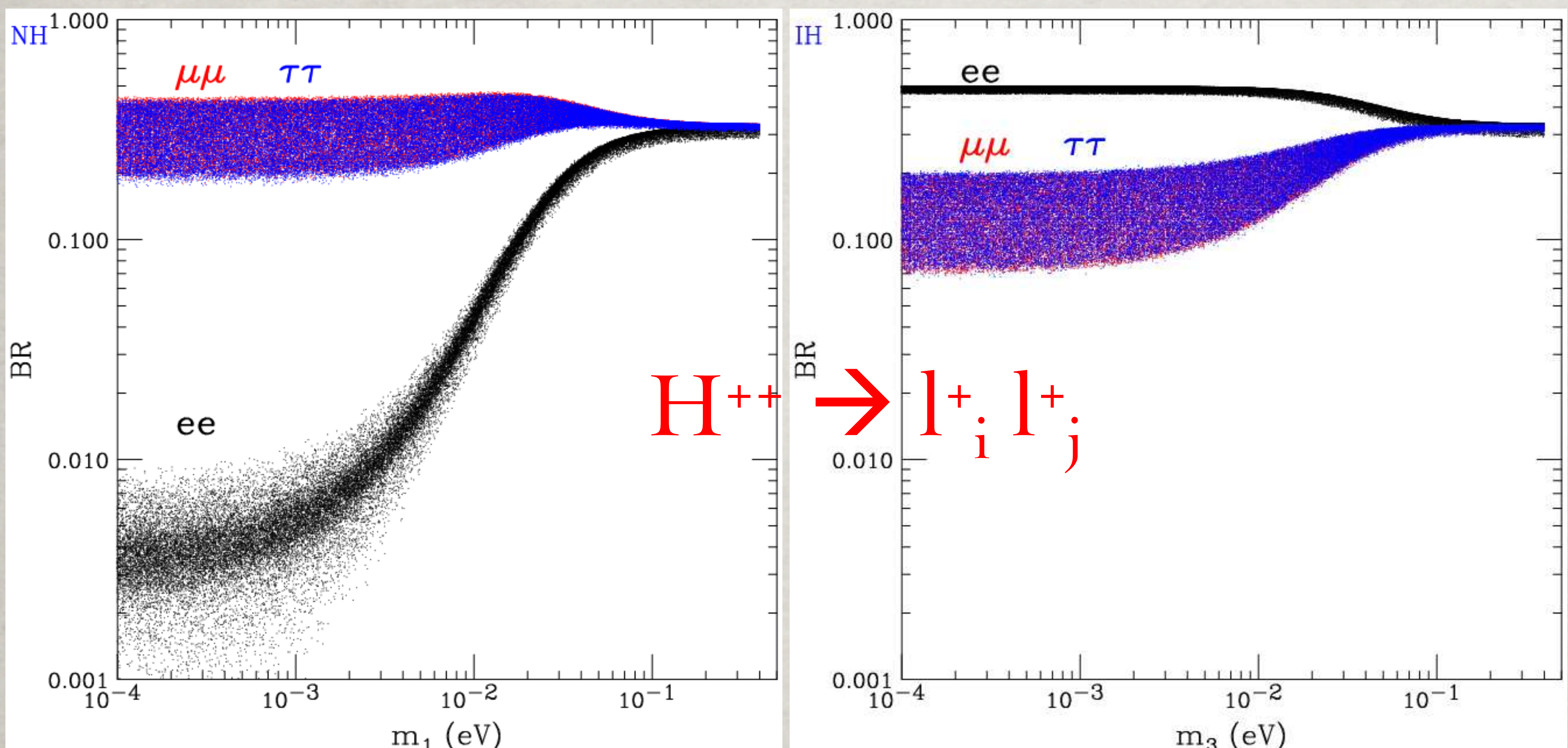
Type I seesaw: $M = M_N$, right-handed (sterile) N_R^i

$H \to NN$, $N \to H\nu$, …

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

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.

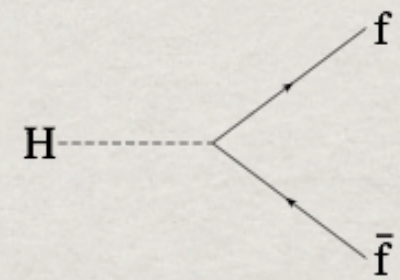
Watch out: $H^0 \to \mu\tau$ $(l^+_i\, l^-_j)$ for BSM flavor physics!

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

5. Couplings & Width

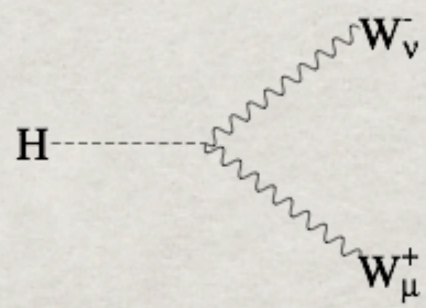
Higgs boson couplings encode its properties:

Yukawa coupling

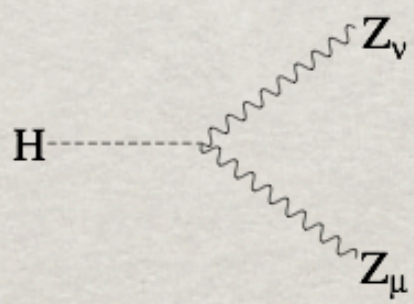


$$-i\frac{m_f}{v}\left(1+\Delta_f\right)$$

EWSB

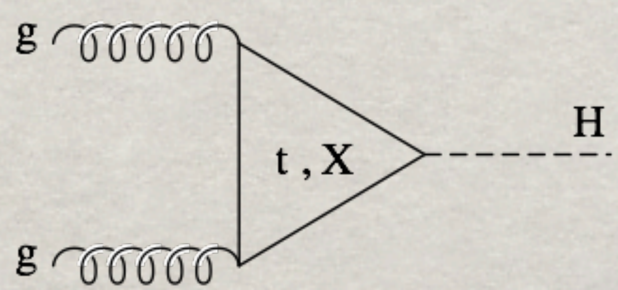


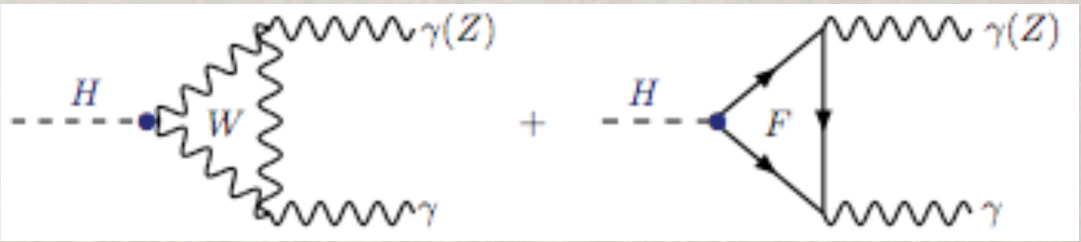
$$ig\, m_W\,(1+\Delta_W)g_{\mu\nu}$$



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

Color/charged particles in loops:





Precision Higgs Physics

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 Higgs coupling g_i at the scale M:

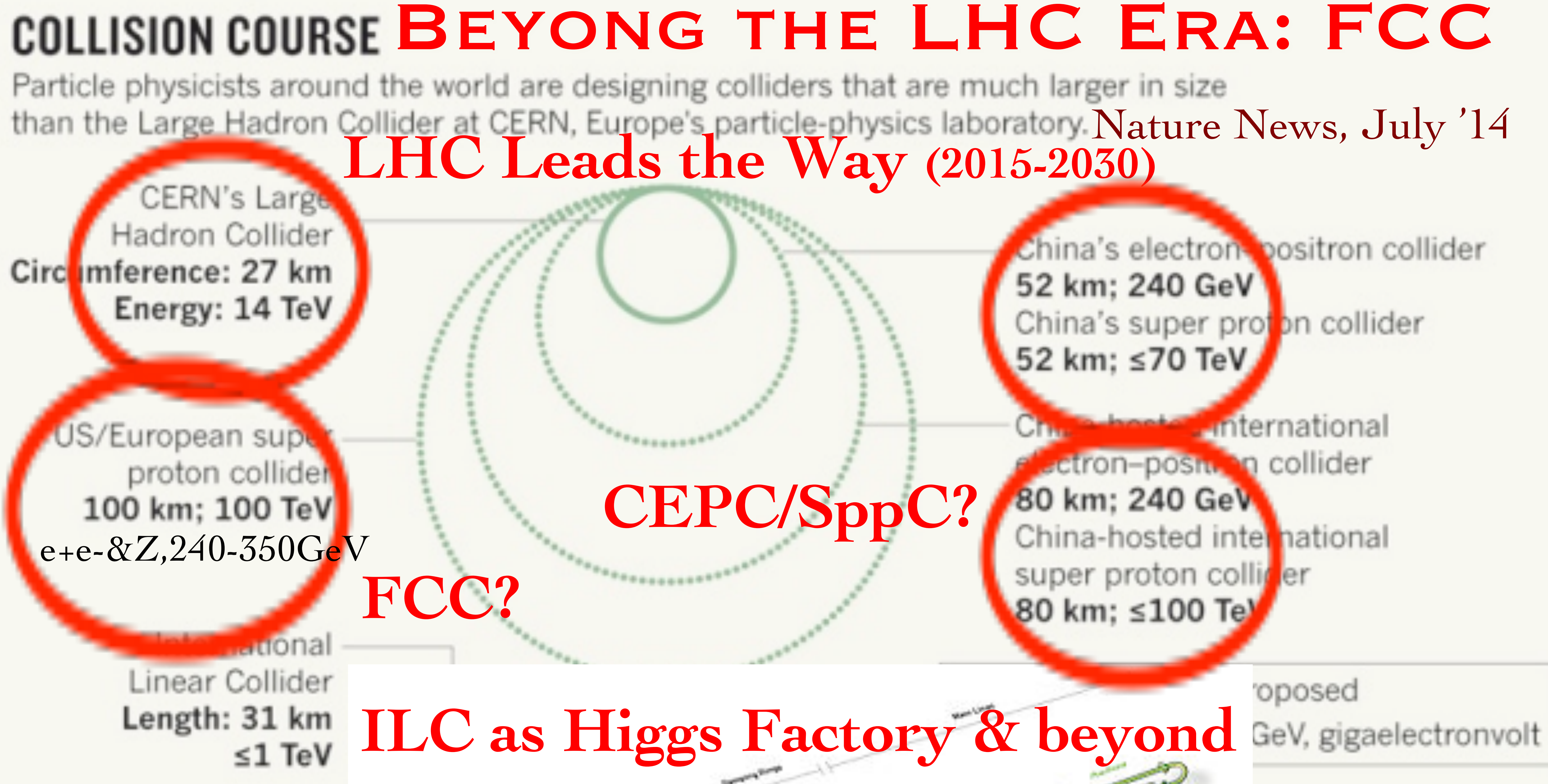
$$\Delta_i \equiv \frac{g_i}{g_{SM}} - 1 \sim \mathcal{O}(v^2/M^2) \approx \underline{\text{a few \% for } M \approx 1 \text{ TeV}}$$

If not observed, I'd DEFINE it THE SM Higgs!

Higgs coupling deviations:

Δ:	VVH	bbH,ττH	ggH,γγH	HHH
Composite	(3-9)%	$(1\ \text{TeV}/f)^2$	(tree-level)	100%
H^0, A^0		6% $(500\ \text{GeV}/M_A)^2$		
T'			-10% $(1\ \text{TeV}/M_T)^2$ (loop)	
LHC 14 TeV, $3ab^{-1}$:	8%	15%	few%	50%

Beyong the LHC Era: FCC



Nature News, July '14

LHC Leads the Way (2015-2030)

e+e-&Z,240-350GeV

FCC?

CEPC/SppC?

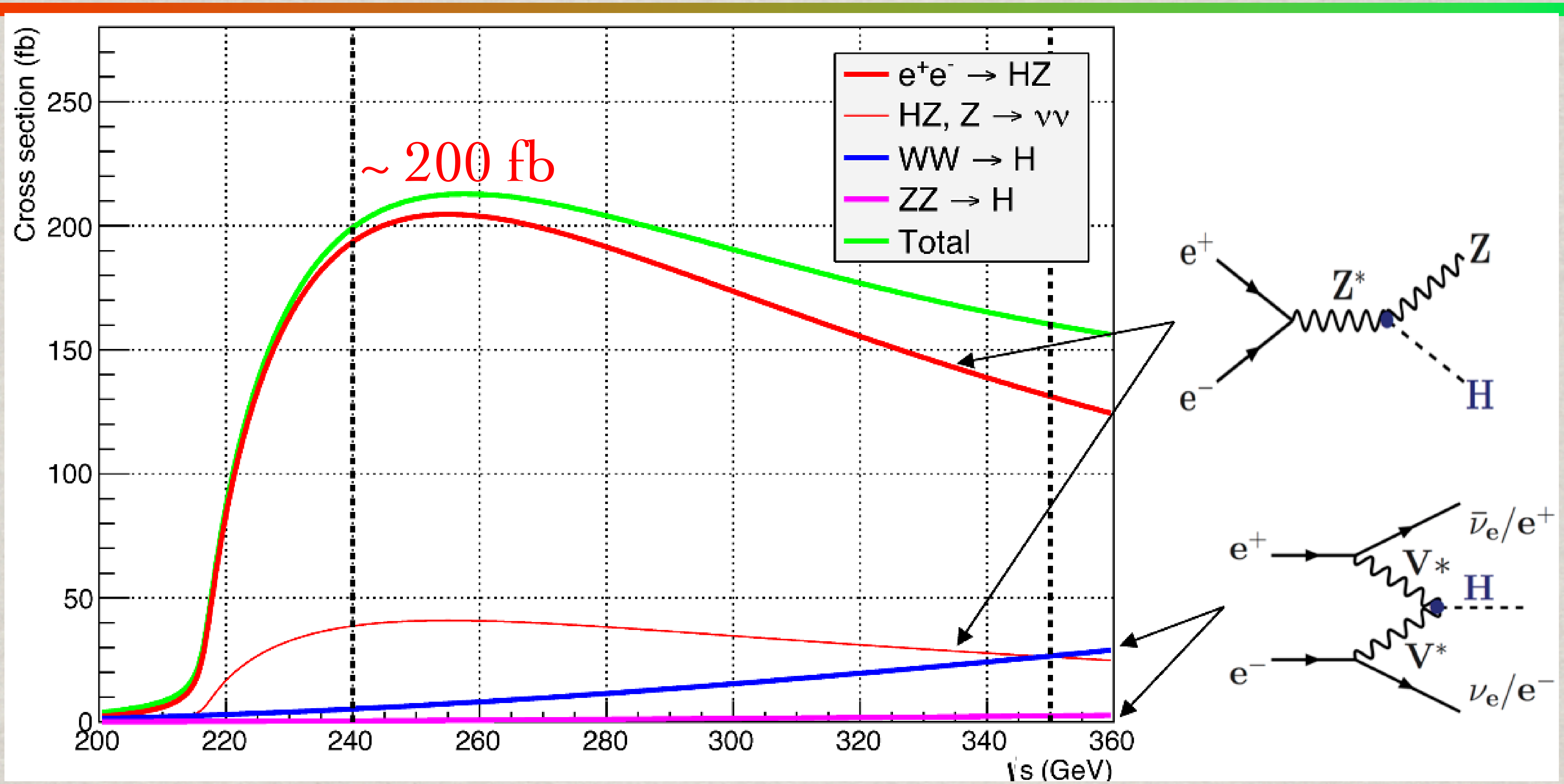
ILC as Higgs Factory & beyond

Table 1-1. *Proposed running periods and integrated luminosities at each of the center-of-mass energies for each facility.*

Snowmass 1310.8361

Facility	HL-LHC	ILC	ILC(LumiUp)	CLIC	TLEP (4 IPs)	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14,000	250/500/1000	250/500/1000	350/1400/3000	240/350	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600	3000	3000
dt (10^7s)	6	3+3+3	(ILC 3+3+3) + 3+3+3	3.1+4+3.3	5+5	6	6

Higgs-Factory: Mega (10^6) Higgs Physics



ILC: E_{cm} = 250 (500) GeV, 250 (500) fb^{-1}

- Model-independent measurement: ILC Report: 1308.6176

$\Gamma_H \sim 6\%$, $\Delta m_H \sim 30$ MeV

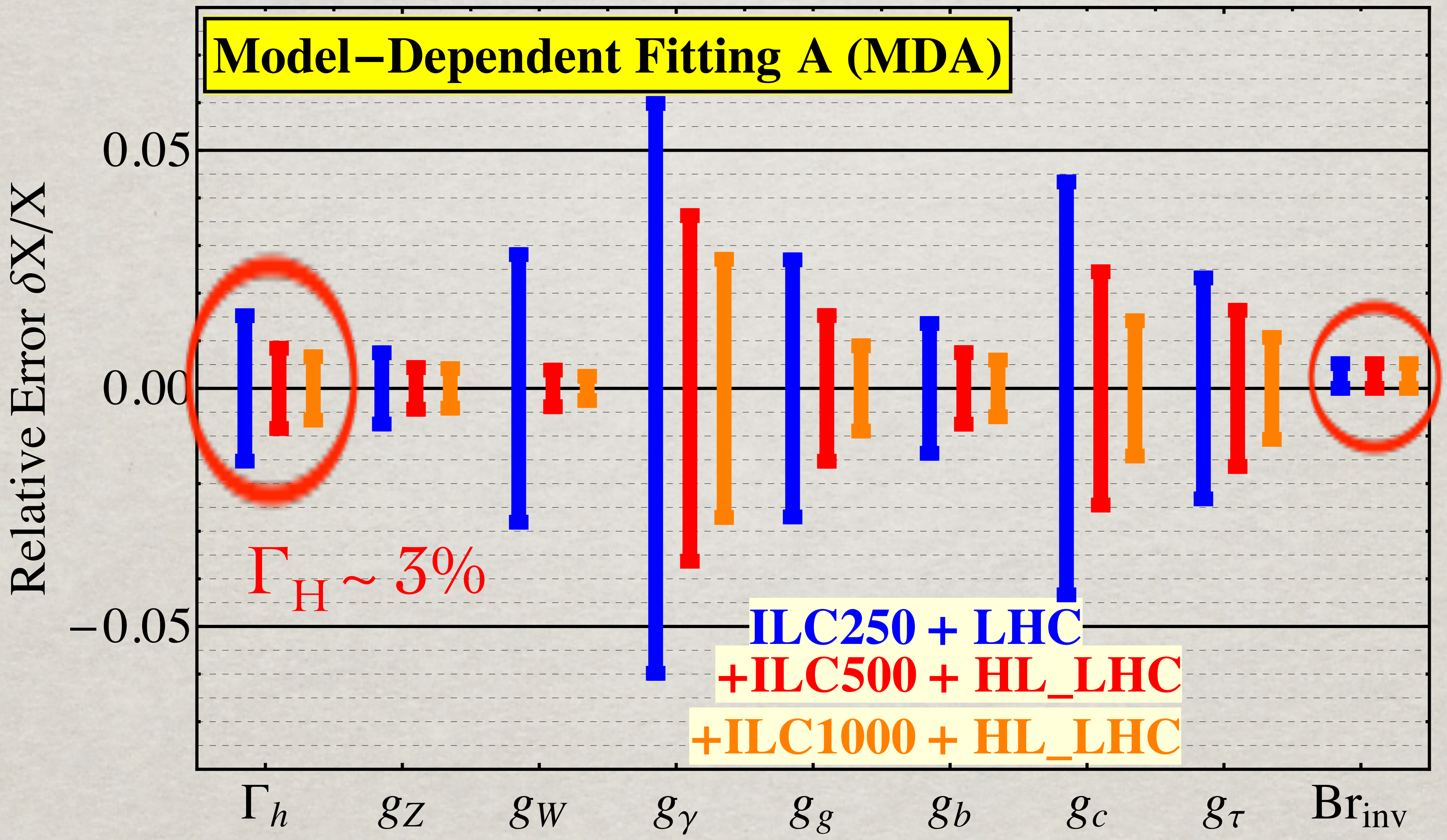
(HL-LHC: assume SM, $\Gamma_H \sim$ 5-8%, $\Delta m_H \sim 50$ MeV)

- TLEP 10^6 Higgs@10x4 L: $\Gamma_H \sim 1\%$, $\Delta m_H \sim 5$ MeV.

TLEP Report: 1308.6176

Higgs Total Width & Invisibale BR:

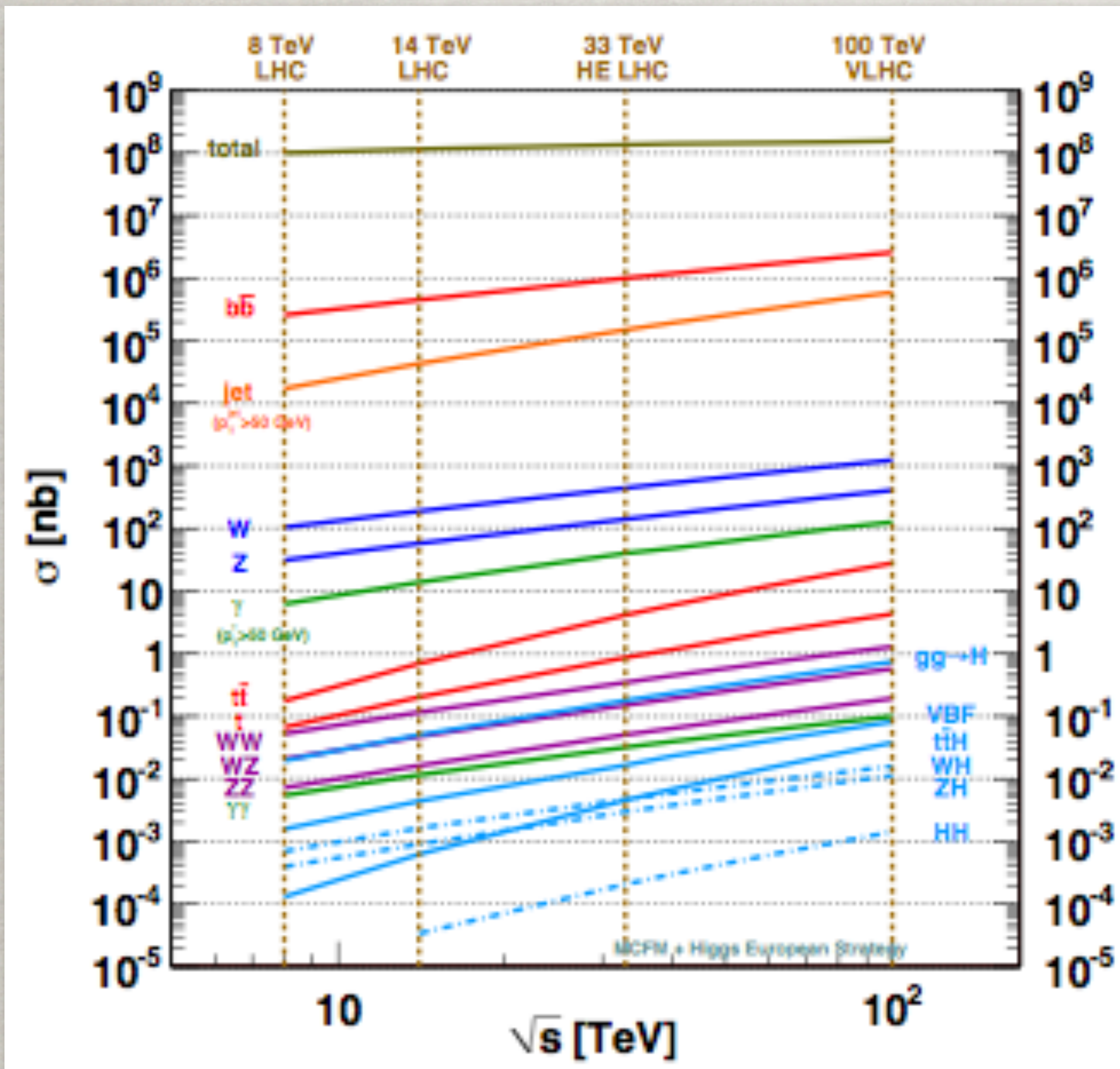
TH, Z.Liu, J.Sayre, arXiv:1311.7155



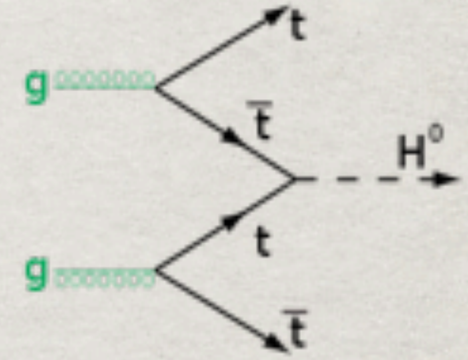
$BR_{inv} < 1\%$

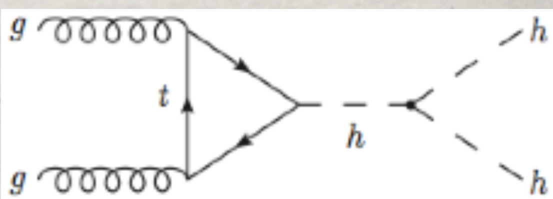
Also see, Peskin, arXiv:1312.4974
including ILC luminosity upgrade.

Higgs Production @ SPPC



Snowmass QCD Working Group: 1310.5189





Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10^3

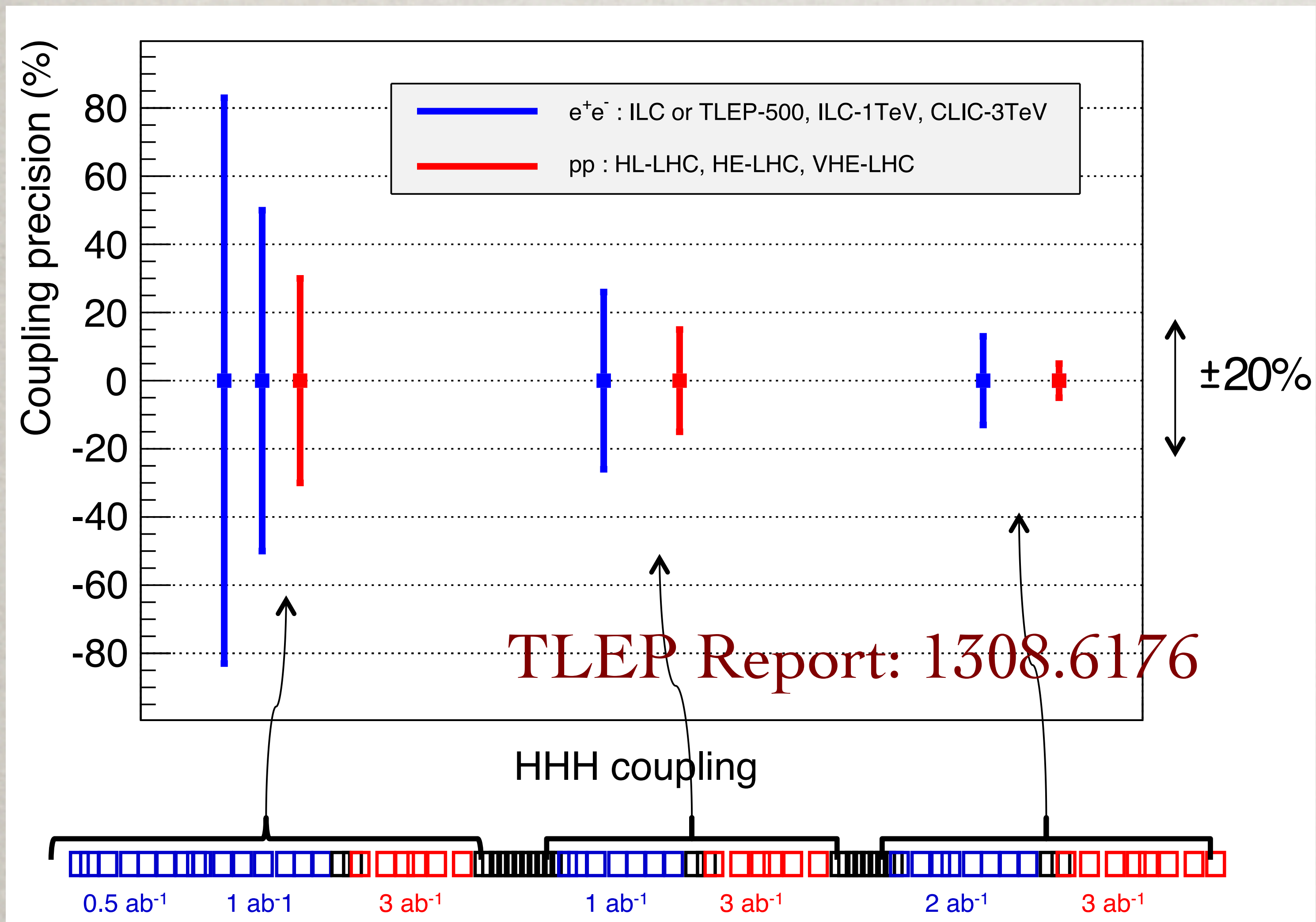
λ_t : 1%

λ : 8%

Higgs Self-couplings:

$$\mathcal{L} = -\frac{1}{2}m_H^2 H^2 - \frac{g_{HHH}}{3!}H^3 - \frac{g_{HHHH}}{4!}H^4$$

$$g_{HHH} = 6\ \ v = \frac{3m_H^2}{v}, \qquad g_{HHHH} = 6\ \ = \frac{3m_H^2}{v^2}.$$



TLEP Report: 1308.6176

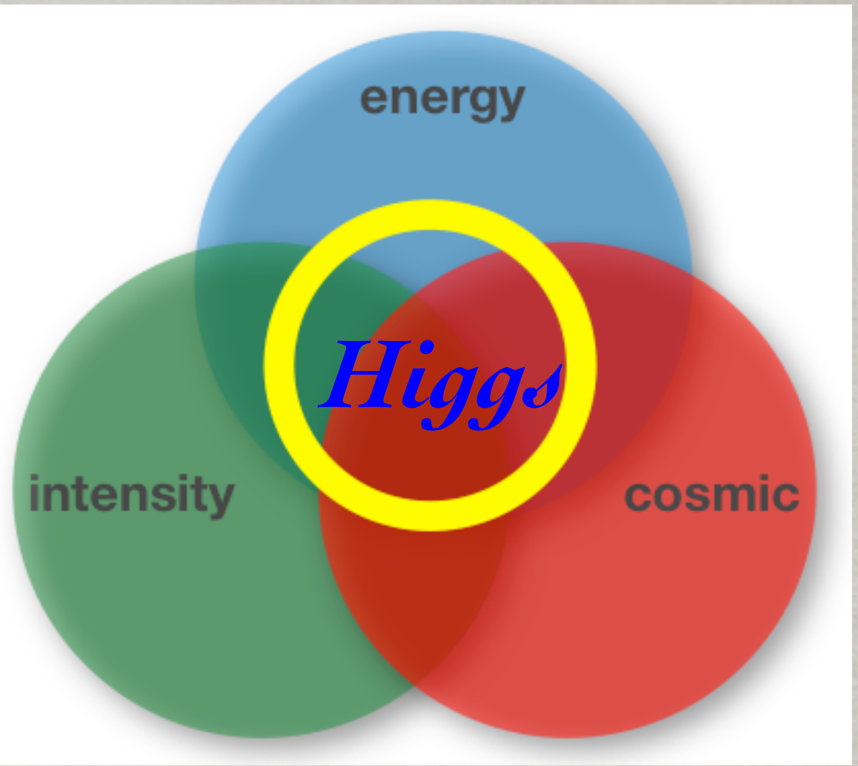
Triple coupling sensitivity:

Test the shape of the Higgs potential, and perhaps the fate of the EW-phase transition!

Snowmass 1310.8361

	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	HE-LHC	VLHC
$\bar{s}$ (GeV)	14000	500	500	500/1000	500/1000	33,000	100,000
$\mathcal{L}dt$ (fb^{-1})	3000/expt	500	1600‡	500+1000	1600+2500‡	3000	3000
	50%	83%	46%	21%	13%	20%	8%

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

- Precision Higgs physics:

  LHC lights the way: g~10%; λ_{HHH} ~ 50%; $Br_{inv.}$~ 20%

  Higgs factory/FCC: g~1%; λ_{HHH} < 10%; $Br_{inv.}$ ~ 2%; Γ_{tot} < 6%

An exciting journey ahead!

Merry Christmas and a Happy New Year