The Higgs Boson & Beyond

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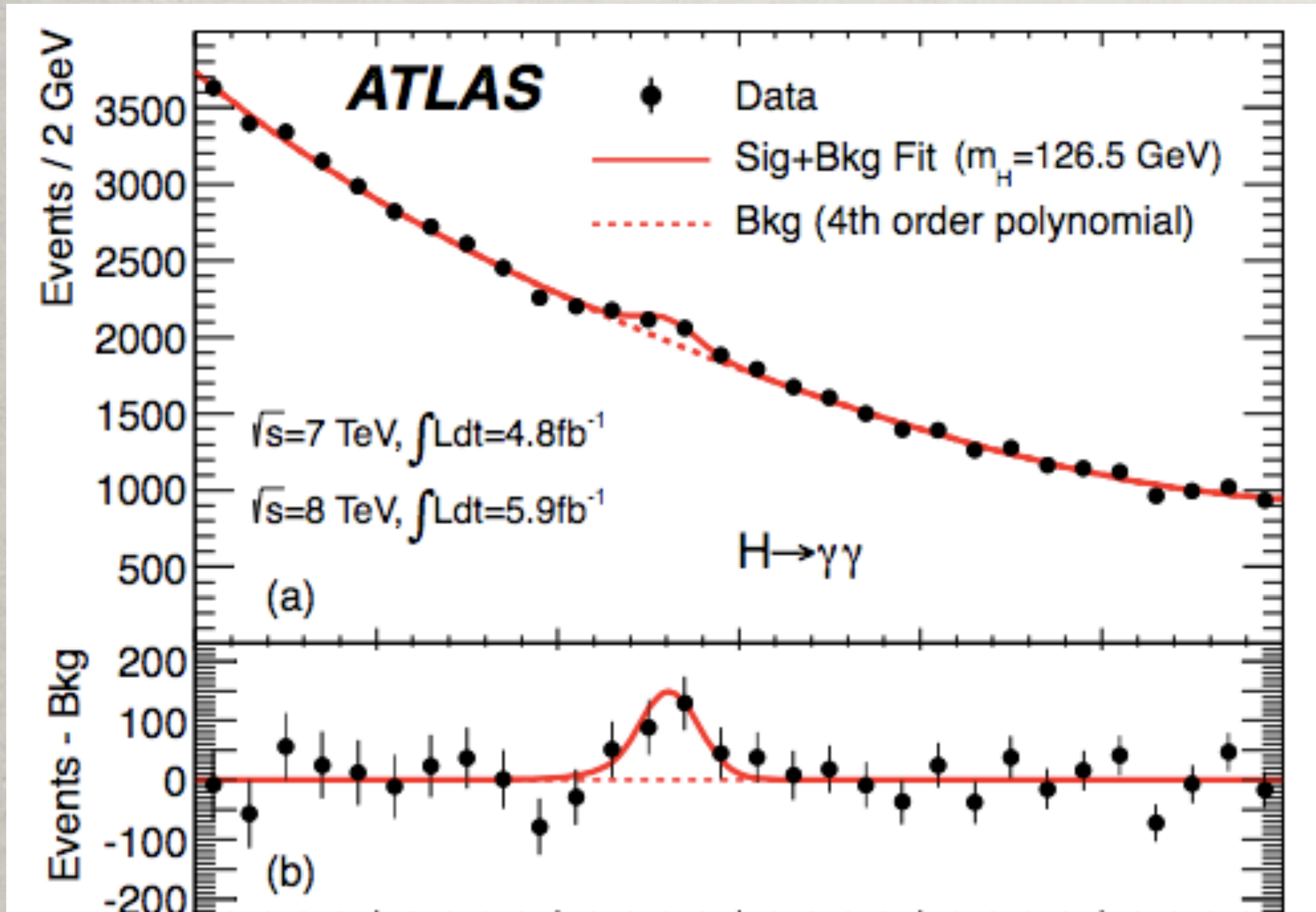
National Taiwan University, Dec. 8, 2015

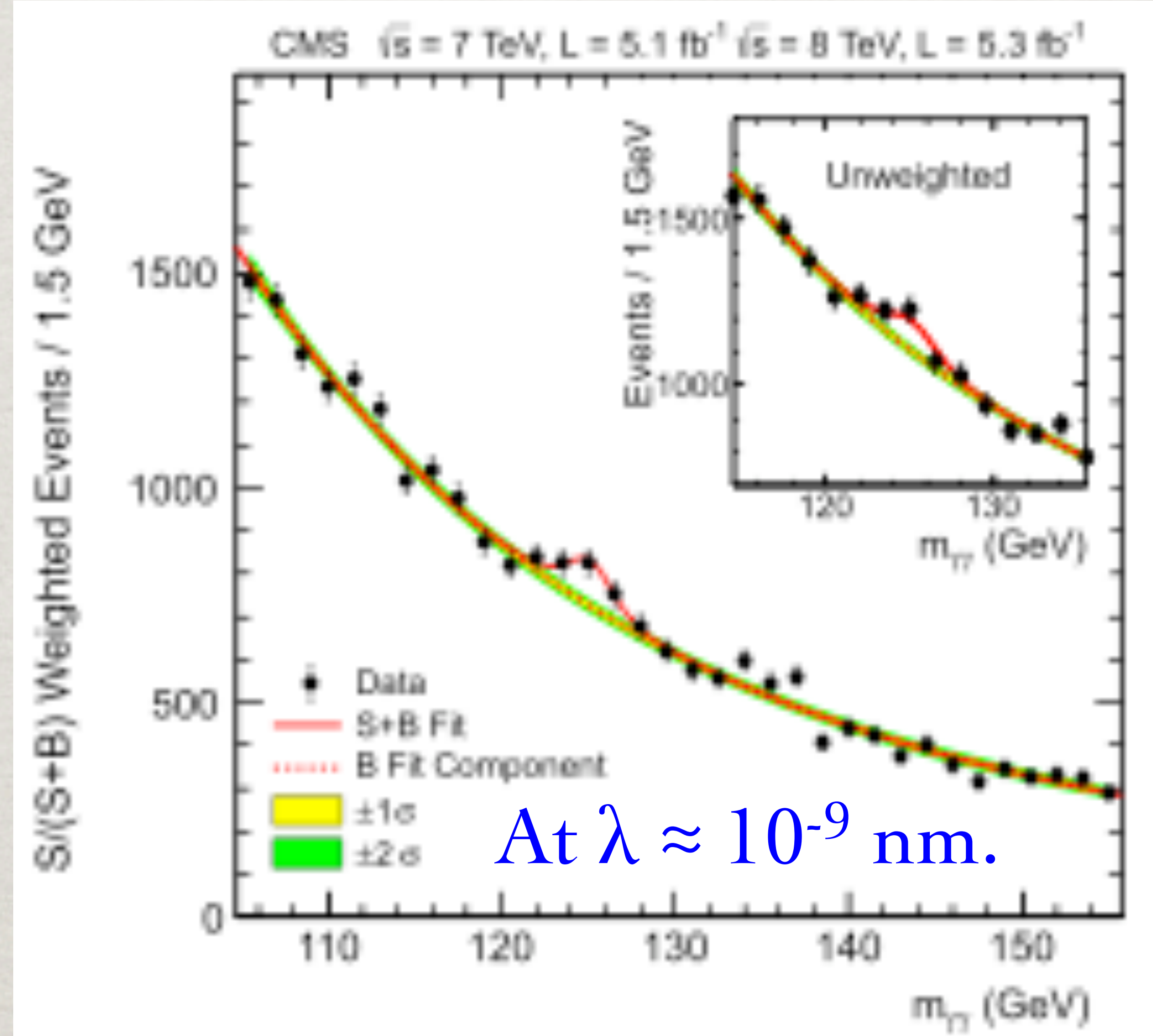
François Englert and Peter W. Higgs

"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 DISCOVERY: July 4th, 2012:

A neutral boson decay to two photons





At $\lambda \approx 10^{-9}$ nm.

The combined signal significance:

ATLAS: 5.9σ

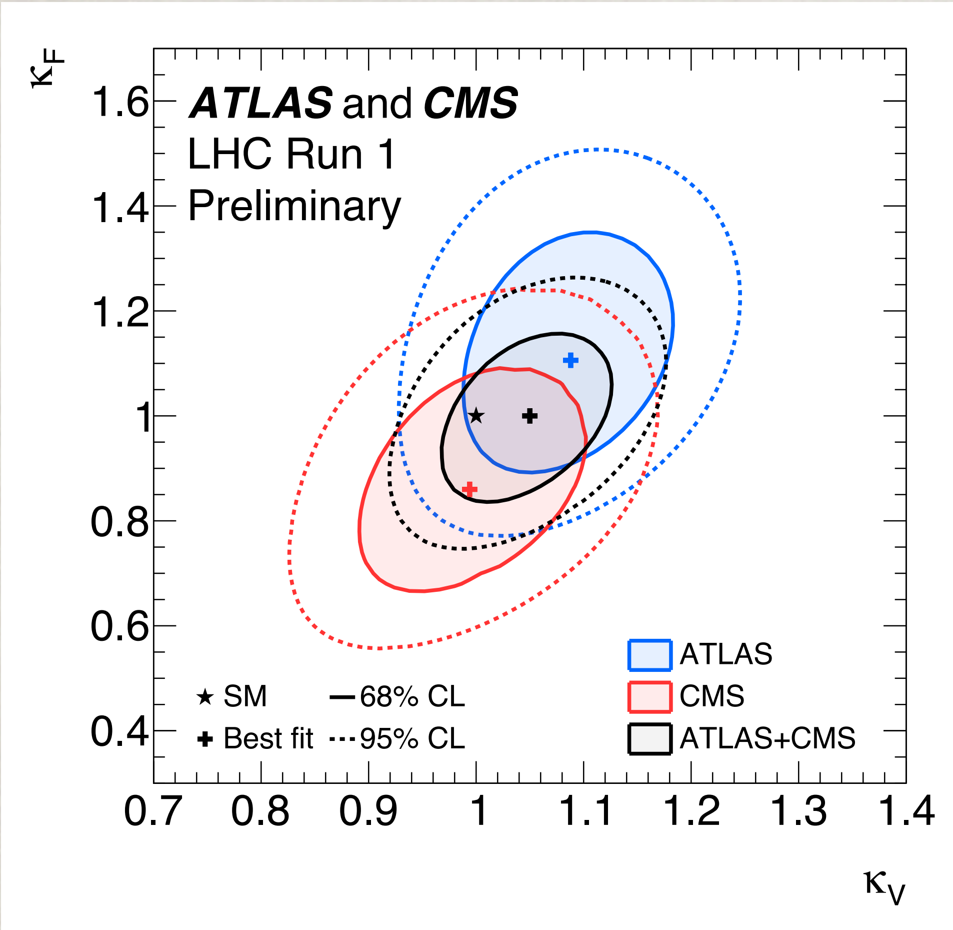
CMS: 5.0σ

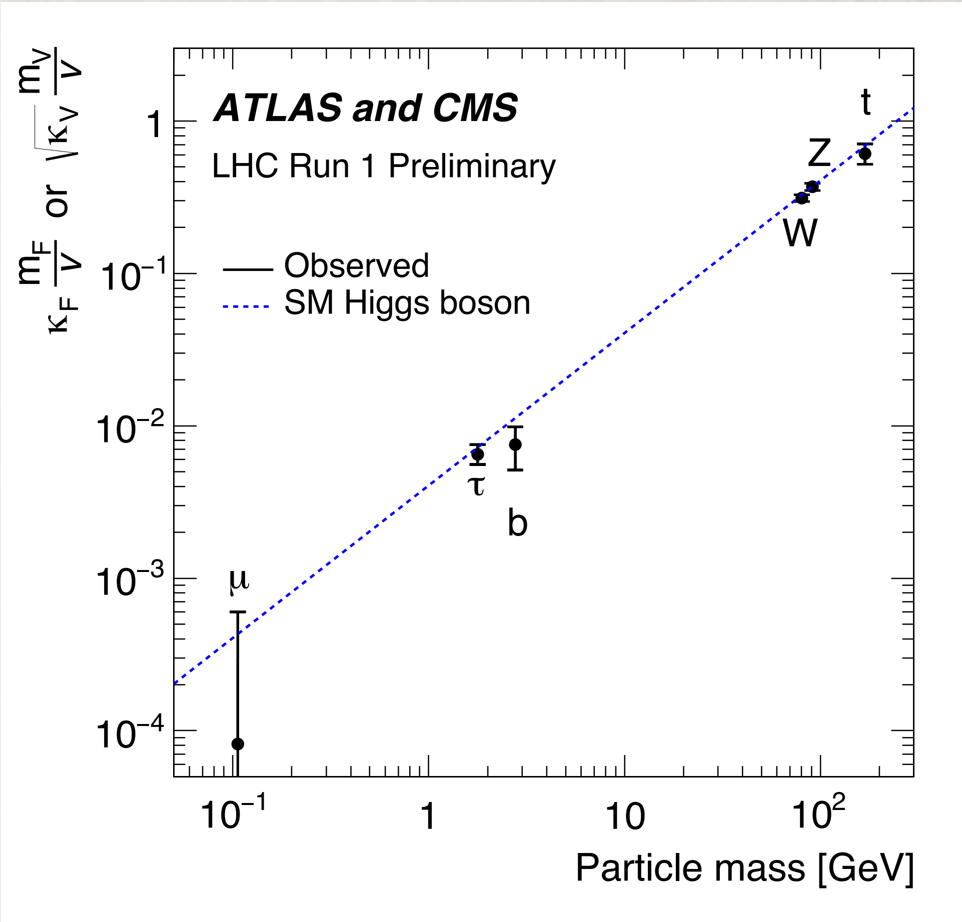
Phys. Lett. B716, 1 (2012)

Phys. Lett. B716, 30 (2012)

Summer 2015 update:

5σ for both fermion coupling h → ττ
& bosonic coupling WW→h





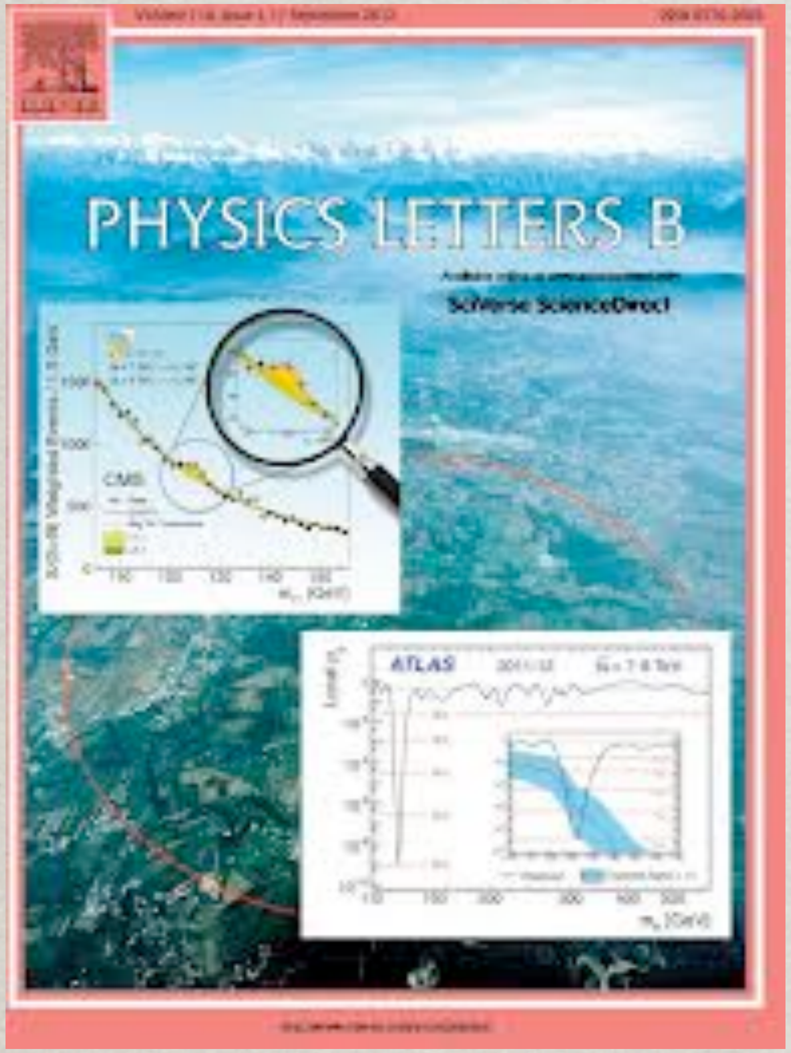
- it's neutral, a boson

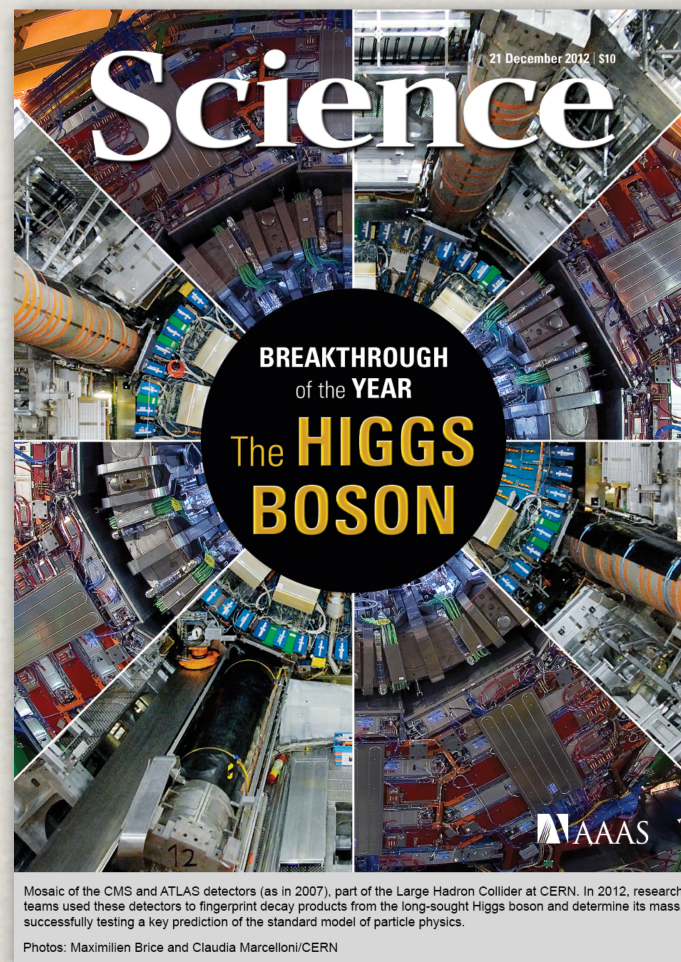
- it's spin-0, parity-even

- it couples to mass, non-universally

All indications point to the SM Higgs !

A milestone discovery:
It is a brand new class!





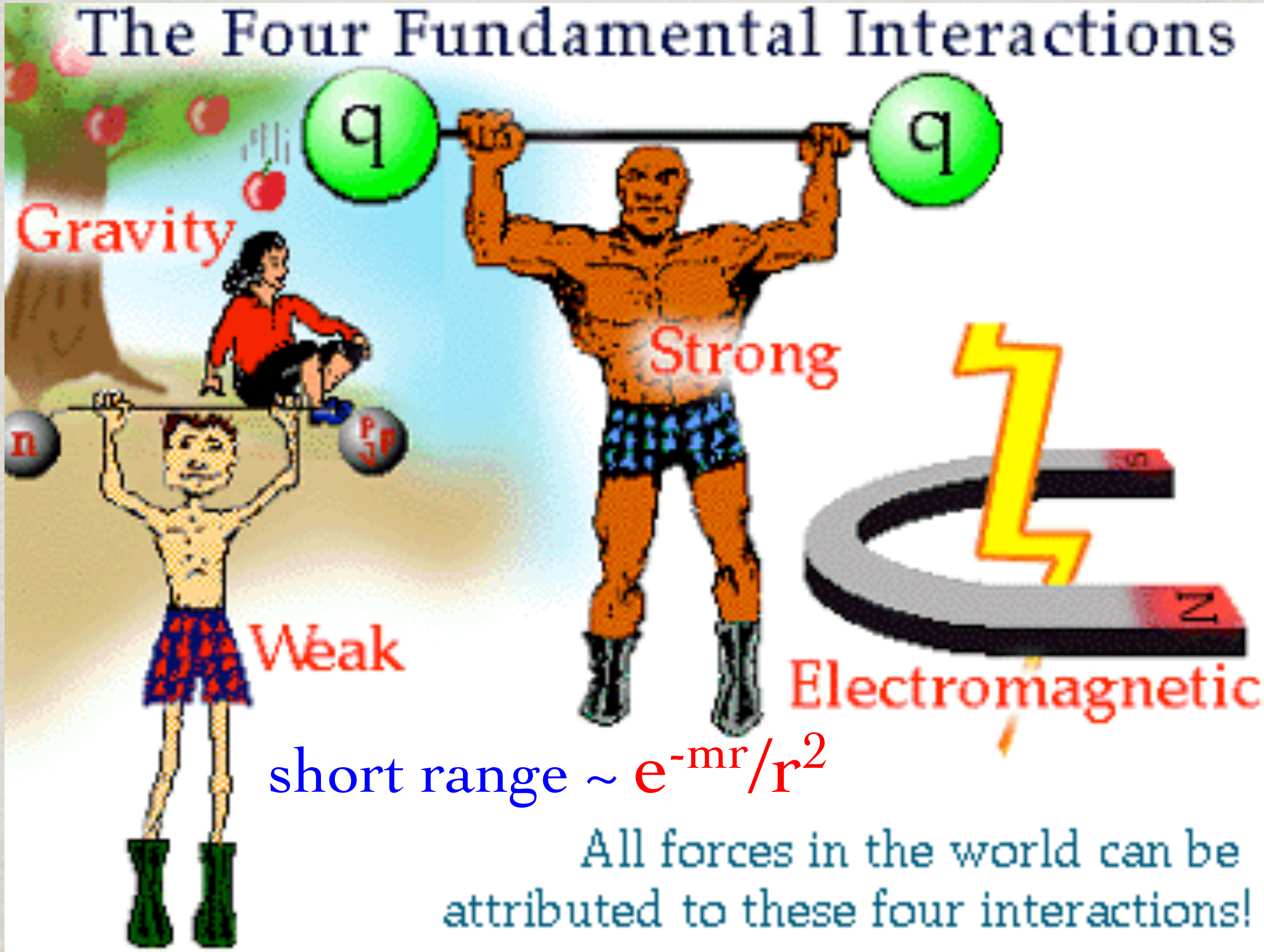
50 years theoretical work …

25 years experimental work …

Congratulations to our CMS colleagues in Taiwan !

The Nature of Forces:

long range
$\sim (G_N\, m_1 m_2)/r^2$



long range
$\sim (\alpha\, e_1 e_2)/r^2$

short range $\sim e^{-mr}/r^2$

All known physics

$$W = \int_{k<\Lambda} [\mathcal{D}g \ldots] \exp\left\{ \frac{i}{\hbar} \int d^4x \sqrt{-g} \left[\frac{1}{16\pi G} R - \frac{1}{4} F^2 + \bar{\psi} i \not{D} \psi - \lambda \phi \bar{\psi} \psi + |D\phi|^2 - V(\phi) \right] \right\}$$

amplitude | current understanding | quantum mechanics | spacetime | gravity | strong & electroweak | matter | Higgs

E&M: Most Successful in Theory & Practice!

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - m_e)\psi$$

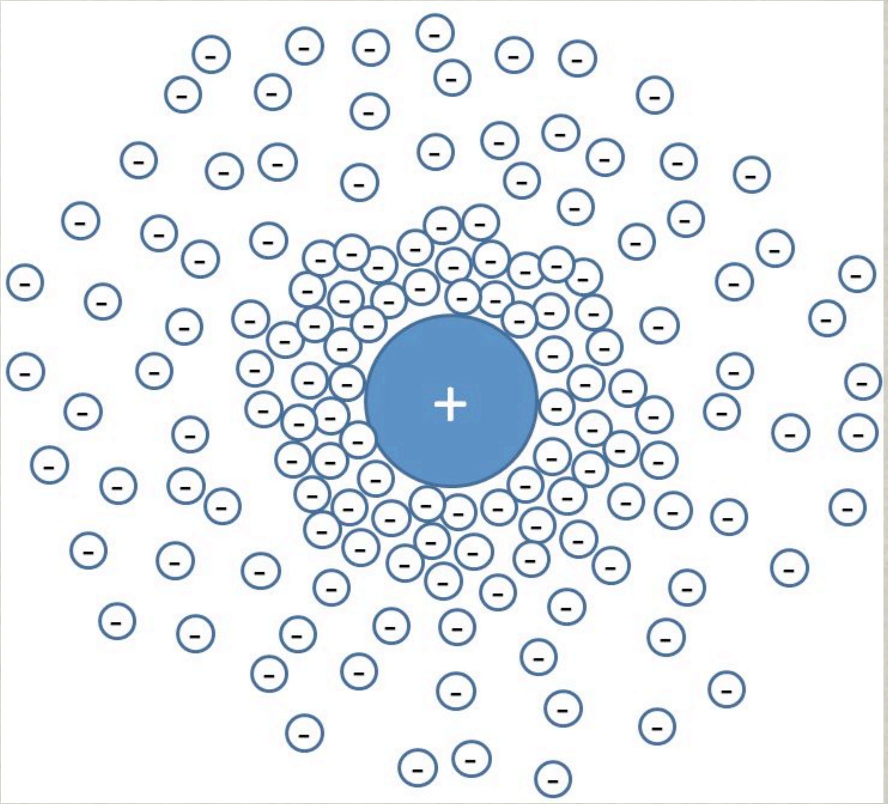
$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu, \; D_\mu = \partial_\mu + ieA_\mu$$

- At low energies → Maxwell's theory; vector-like coupling by a $U_{em}(1)$ gauge symmetry
- At high energies → Quantum-mechanical, renormalizable, most accurate (in science!): a part of trillion

$$a_e^{theo} = 0.001159652181643(763)$$
$$a_e^{exp} = 0.00115965218073(28)$$

- QED becomes strongly interacting asymptotically (screening effects)

$$\alpha(Q^2) = \frac{\alpha(Q_0^2)}{1 - \frac{\alpha(Q_0^2)}{3\pi}\ln(Q^2/Q_0^2)}$$



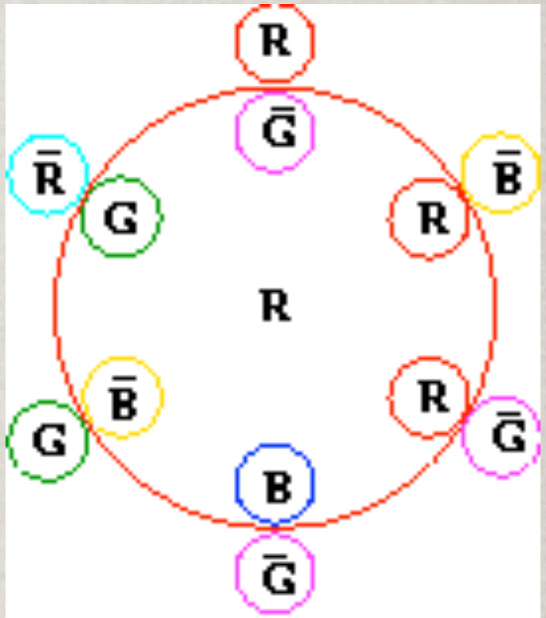
At ultra-violet (UV) → theory is invalid.

The strong force: $SU_c(3)$ Quantum Chromo-Dynamics
Successful Theory, Challenging in Practice!

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \sum_f^{n_f} \bar{q}_f (i\gamma^\mu \partial_\mu - g_s \gamma^\mu A_\mu - m_f) q_f$$

$$F_{\mu\nu} = \partial\mu A_\nu - \partial\mu A_\nu + i g_s [A_\mu, A_\nu]$$

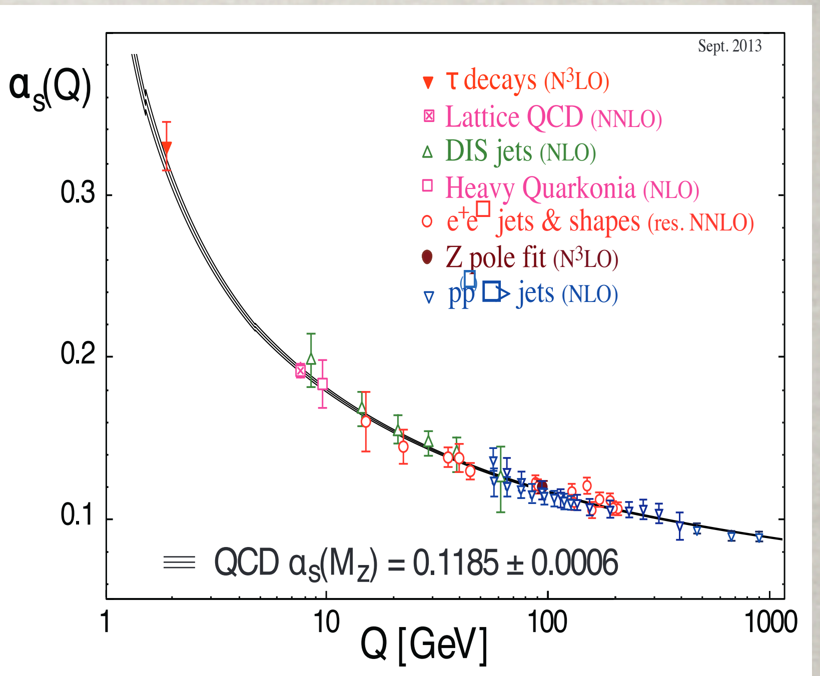
$$A^\mu(x) = \sum_1^8 A(x)^\mu_a \, T^a, \qquad [T^a, T^b] = i f_{abc} T^c.$$



- At short distances/high energies → asymptotically free (anti-screening effects)

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\ln(Q^2/\Lambda^2)}$$

Highly predictable at high energies:
Crucial for HEP, early Universe …



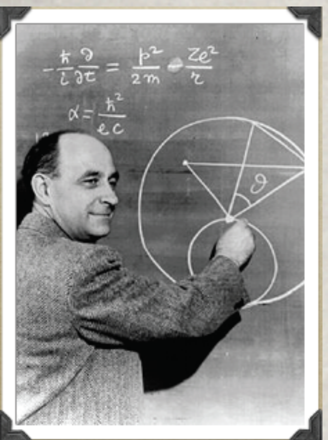
- At long distances/low energies > 10^{-13}cm

→ Strongly interacting: quarks condensate (π^0, $\pi^\pm$…) & (colorless) hadrons (p^+, n) formed.

Short range force by a dynamical mass: $e^{-m_\pi r}/r^2$

The Weak force: Quark & Lepton Flavor Transitions

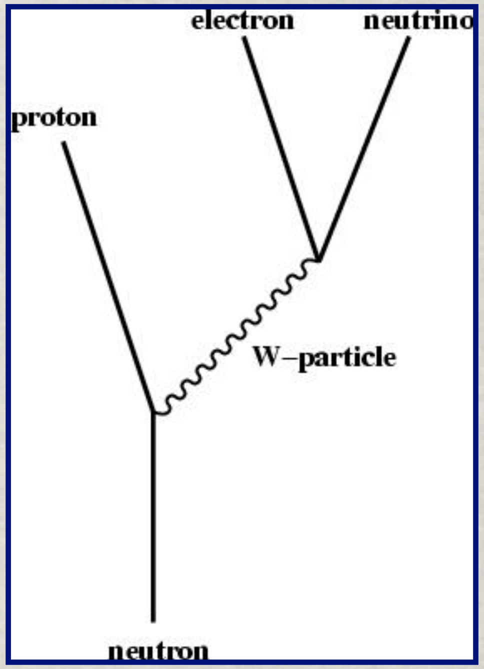
Beta decay $n \rightarrow p^+ e^- \nu$ ➔ Charged current interaction: $W^\pm$



Inspired by EM current-current interactions, Fermi proposed (1934)

$$\mathcal{L}_{weak} = -\frac{G_F}{\sqrt{2}} J^\mu(p^+ n) J_\mu(e^- \nu)$$

$$\text{force range} \sim \sqrt{G_F} \sim M_W^{-1} \sim 10^{-18}\text{m}$$



Weak interaction based on SU(2) x U(1): (Glashow, '63)

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

$$W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu - g\epsilon_{ijk} W^j_\mu W^k_\nu$$

$$-\frac{g}{2\sqrt{2}} \sum_i \overline{\Psi}_i \gamma^\mu (1-\gamma^5)(T^+ W^+_\mu + T^- W^-_\mu) \Psi_i$$

$$-e \sum_i q_i \overline{\psi}_i \gamma^\mu \psi_i A_\mu$$

$$-\frac{g}{2\cos\theta_W} \sum_i \overline{\psi}_i \gamma^\mu (g^i_V - g^i_A \gamma^5) \psi_i Z_\mu \, .$$

However,

The local gauge symmetry prevents gauge bosons masses!

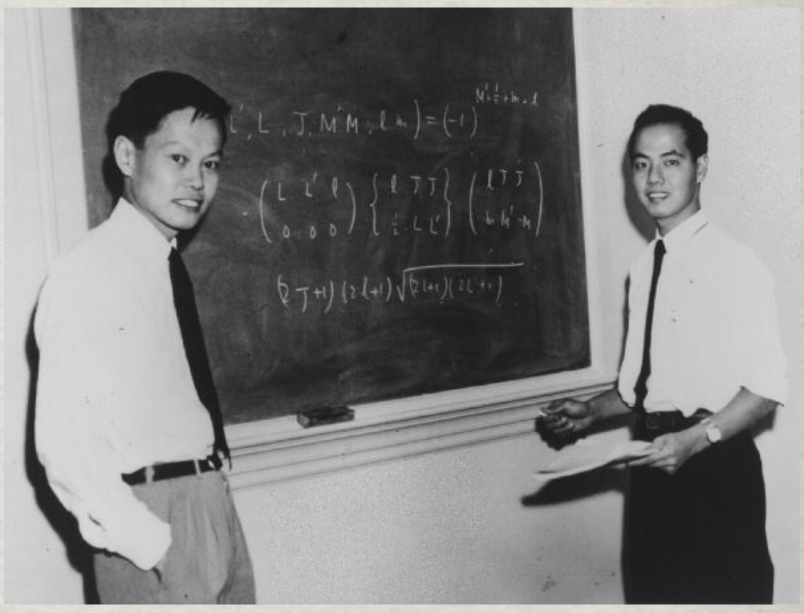
$$\frac{1}{2} M_A^2 A_\mu A^\mu \rightarrow \frac{1}{2} M_A^2 (A_\mu - \frac{1}{e}\partial_\mu \alpha)(A^\mu - \frac{1}{e}\partial^\mu \alpha) \neq \frac{1}{2} M_A^2 A_\mu A^\mu$$

Pauli's rejection to the Yang-Mills theory.

The Weak force: Quark & Lepton Flavor Transitions

Even worse:

``The Left- and right-chiral electrons carry different Weak charges" (Lee & Yang)



- Simple structure and particle contents:

Leptons:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L, \quad e_R,\ \mu_R,\ \tau_R, \quad (\nu_R' s\ ?)$$

Quarks:

$$\begin{pmatrix} u \\ d \end{pmatrix}_L, \quad \begin{pmatrix} c \\ s \end{pmatrix}_L, \quad \begin{pmatrix} t \\ b \end{pmatrix}_L, \quad u_R,\ d_R,\ c_R,\ s_R,\ t_R,\ b_R$$

Fermion masses also forbidden by gauge symmetry!

$$-m_e \bar{e} e = -m_e \bar{e}\left(\frac{1}{2}(1-\gamma_5) + \frac{1}{2}(1+\gamma_5)\right) e = -m_e(\bar{e}_R e_L + \bar{e}_L e_R)$$

Electroweak gauge theory → massless!

The Spontaneous Symmetry Breaking

" The Lagrangian of the system may display an symmetry, but the ground state does not respect the same symmetry."

Known Example: Ferromagnetism

Domains Before Magnetization

Domains After Magnetization

Above a critical temperature, the system is symmetric, magnetic dipoles randomly oriented. Below a critical temperature, the ground state is a completely ordered configuration in which all dipoles are ordered in some arbitrary direction

$SO(3) \rightarrow SO(2)$

Low temperature super-conductivity is another example!

The concept of SSB: profound, common.

The Nambu-Goldstone Theorem

"If a continuous symmetry of the system is spontaneously broken, then there will appear a massless degree of freedom, called the Nambu-Goldstone boson."

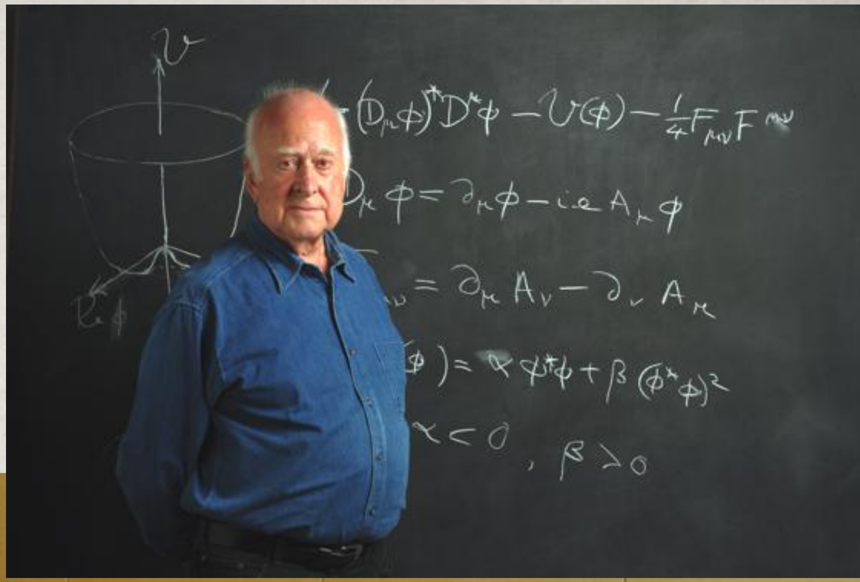
Except the photon, no massless boson (a long-range force carrier) has been seen in Nature!

(Recall Pauli's criticism)

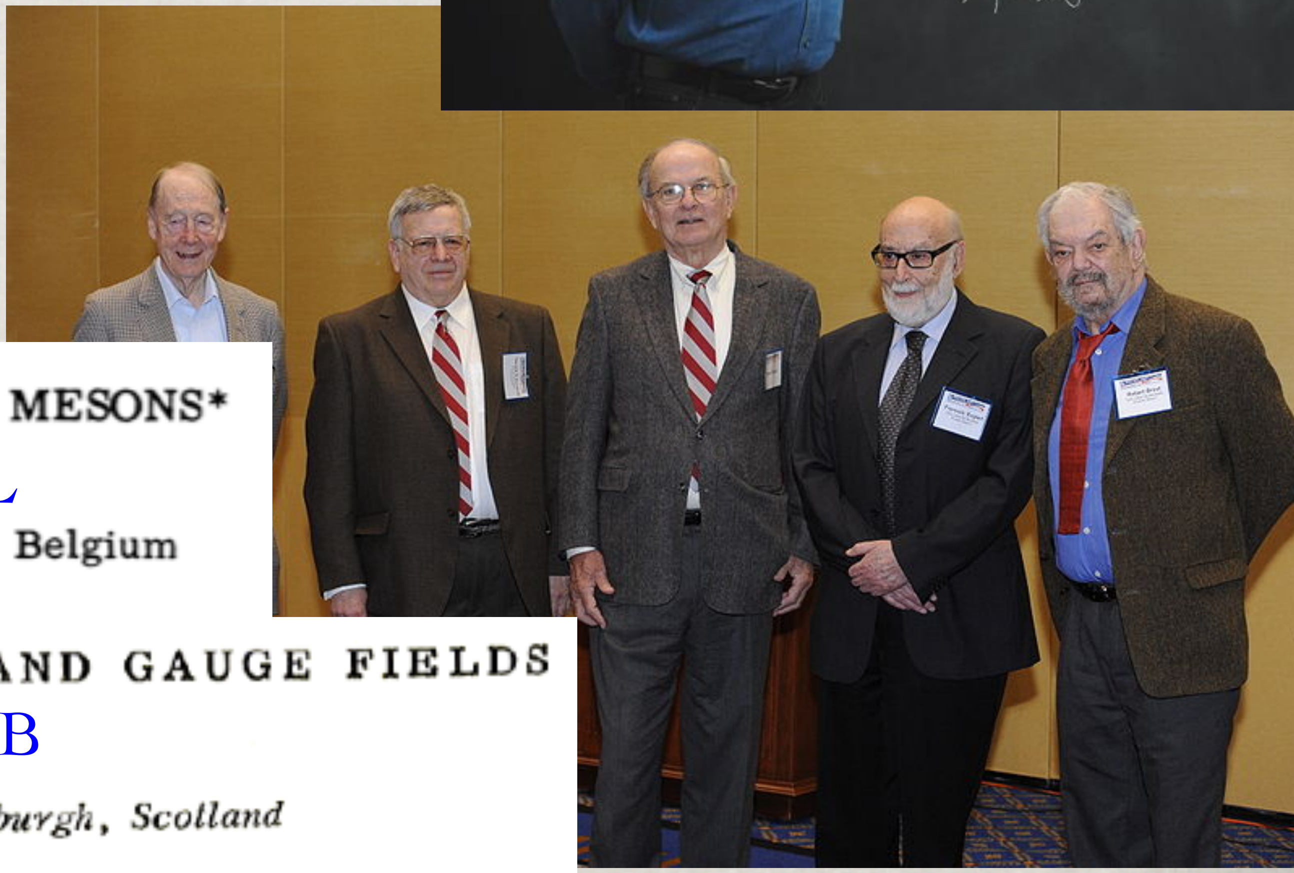
The Spontaneous Symmetry Breaking:
Brilliant idea & common phenomena, confronts the Nambu-Goldstone theorem!

-- A show stopper ?

The Higgs Mechanism: The Magic in 1964



"If a LOCAL gauge symmetry is spontaneously broken, then the gauge boson acquires a mass by absorbing the Goldstone mode."



BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

PRL

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

PLB

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

PRL

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble PRL
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

An illustrative (original) Model:¶

$$\mathcal{L} = |\mathcal{D}^\mu \phi|^2 - \mu^2 |\phi|^2 - |\lambda| (\phi^* \phi)^2 - \tfrac{1}{4} F_{\mu\nu} F^{\mu\nu},$$

where

$$\phi = \frac{\phi_1 + i\phi_2}{\sqrt{2}}$$

is a complex scalar field[4] and as usual

$$\mathcal{D}_\mu \equiv \partial_\mu + iqA_\mu$$

and

$$F_{\mu\nu} \equiv \partial_\nu A_\mu - \partial_\mu A_\nu .$$

The Lagrangian (5.3.1) is invariant under U(1) rotations

$$\phi \to \phi' = e^{i\theta} \phi$$

and under the local gauge transformations

$$\phi(x) \to \phi'(x) = e^{iq\alpha(x)} \phi(x),$$
$$A_\mu(x) \to A'_\mu(x) = A_\mu(x) - \partial_\mu \alpha(x).$$

¶ C. Quigg, Gauge Theories of the Strong ...

An illustrative (original) Model:¶

After the EWSB, parameterized in terms of

$$\langle \phi \rangle_0 = v/\sqrt{2}, \qquad \phi = e^{i\zeta/v}(v+\eta)/\sqrt{2} \approx (v+\eta+i\zeta)/\sqrt{2}.$$

Then the Lagrangian appropriate for the study of small oscillations is

$$\mathscr{L}_{\text{so}} = \tfrac{1}{2}[(\partial_\mu \eta)(\partial^\mu \eta) + 2\mu^2\eta^2] + \tfrac{1}{2}[(\partial_\mu \zeta)(\partial^\mu \zeta)] - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + qvA_\mu(\partial^\mu \zeta) + \frac{q^2v^2}{2}A_\mu A^\mu + \cdots$$

The gauge field acquires a mass, mixes with the Goldstone boson.

Upon diagonalization: $$\frac{q^2v^2}{2}\left(A_\mu + \frac{1}{qv}\partial_\mu \zeta\right)\left(A^\mu + \frac{1}{qv}\partial^\mu \zeta\right),$$

a form that pleads for the gauge transformation

$$A_\mu \to A'_\mu = A_\mu + \frac{1}{qv}\partial^\mu \zeta,$$

which corresponds to the phase rotation on the scalar field

$$\phi \to \phi' = e^{-i\zeta(x)/v}\phi(x) = (v+\eta)/\sqrt{2}.$$

the resultant Lagrangian is then:

$$\mathscr{L}_{\text{so}} = \tfrac{1}{2}[(\partial_\mu \eta)(\partial^\mu \eta) + 2\mu^2\eta^2] - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{q^2v^2}{2}A'_\mu A'^\mu$$

- an η-field, with $(\text{mass})^2 = -2\mu^2 > 0$; the Higgs boson!
- a massive vector field A'_μ, with mass $= qv$
- no ζ-field.

- By virtue of a gauge choice - the unitary gauge, the ζ-field disappears in the spectrum: a massless photon "swallowed" the massless NG boson!

Degrees of freedom count:

Before EWSB: After:

2 (scalar)+2 (gauge pol.); 1 (scalar)+3 (gauge pol.)

- Two problems provide cure for each other!

massless gauge boson + massless NG boson

→ massive gauge boson + no NG boson

This is truly remarkable!

A Few Observations

A. 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 –
UV completion / renormalizibility .

B. λ: a "New Force"

The Higgs potential: $V = -\mu^2 |\phi|^2 + \lambda |\phi|^4$

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

- **In the SM, λ is a free parameter, now measured:**

  $\lambda = m_H^2 / 2v^2 \approx 0.13$

Is it fundamental or induced?

- **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.

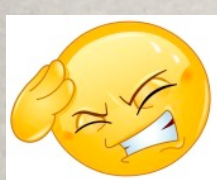
(due to the loop suppression by design)

Already possess challenge to BSM theories.

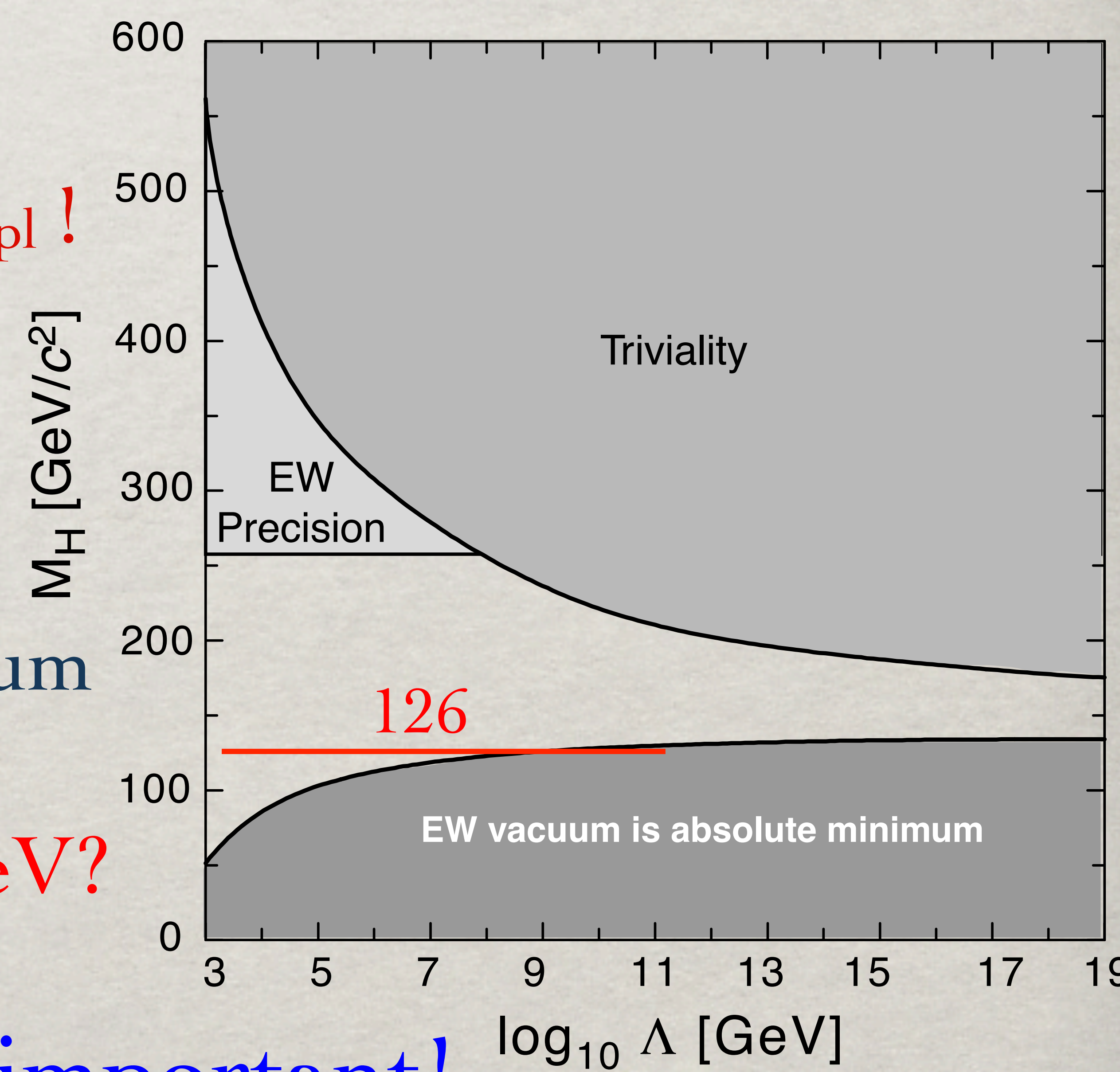
At higher energies, λ is NOT asymptotically free.
It blows up at a high-energy scale (the Landau pole),
unless it starts from small (or zero → triviality).

For m_H = 126 GeV, rather light:

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



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



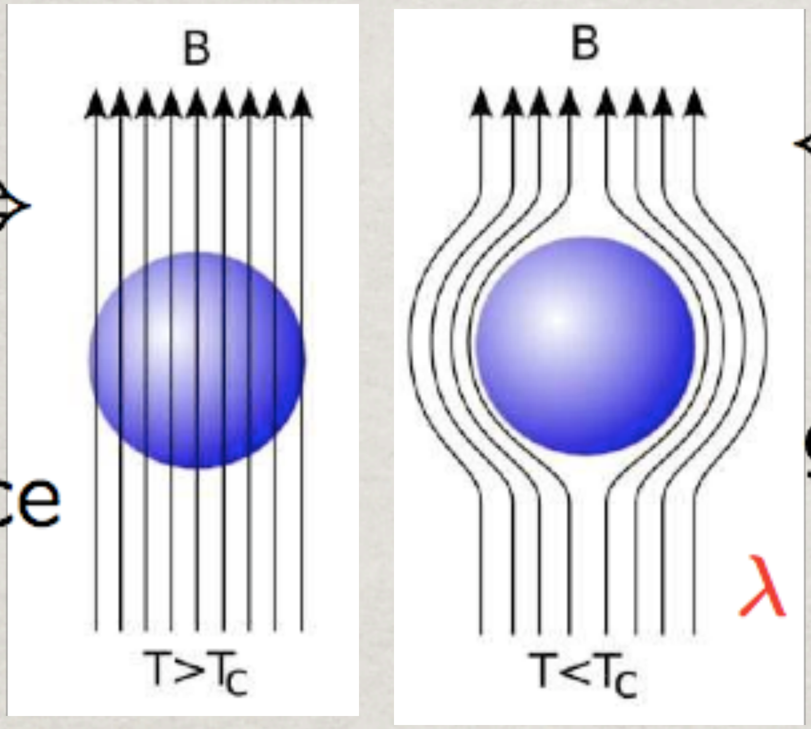
The new coupling λ very important!

C. Electroweak Super-Conductivity

Normal phase⇒

$E^2 = p^2c^2$

Long-range force



⇐Superconducting phase

$E^2 = p^2c^2 + m^2c^4$

gap leads to $\sim exp(-r/\lambda)$

$\lambda \sim m^{-1}$ penetration depth

In "conventional" electro-magnetic superconductivity:

$m_\gamma \sim m_e/1000$, $T_c^{em} \sim \mathcal{O}(\text{few } K)$. BCS theory.

In "electro-weak superconductivity":

$m_w \sim G_F^{-\frac{1}{2}} \sim 100$ GeV, $T_c^w \sim 10^{15} K!$

The Higgs potential is of the Landau-Ginsburgh form, but it represents a new fundamental interaction.

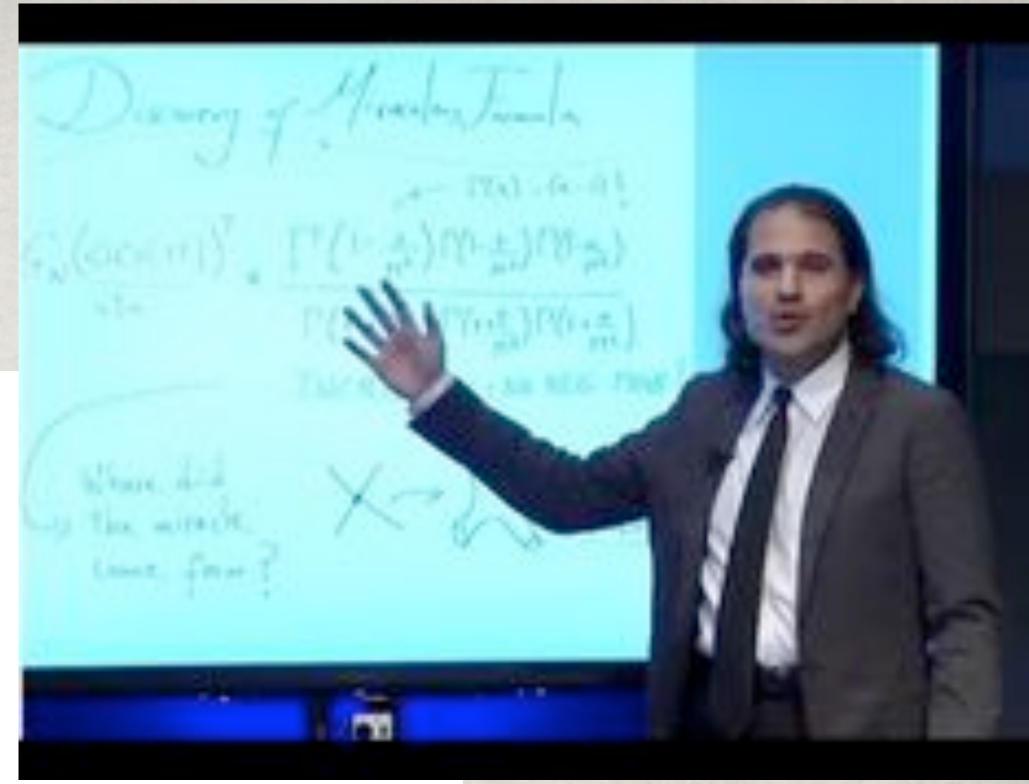
"... most of the grand underlying principles have been firmly established. An eminent physicist remarked that the future truths of physical science are to be looked for in the sixth place of decimals. "

--- Albert Michelson (1894)

Michelson–Morley experiments (1887):
"the moving-off point for the theoretical aspects of the second scientific revolution"

Will History repeat itself (soon)?

Nima Arkani-Hamed
(Director of CFHEP, Beijing)



The central questions today are not details — but structural: origin of spacetime, UV/IR connection, standard model → real theory

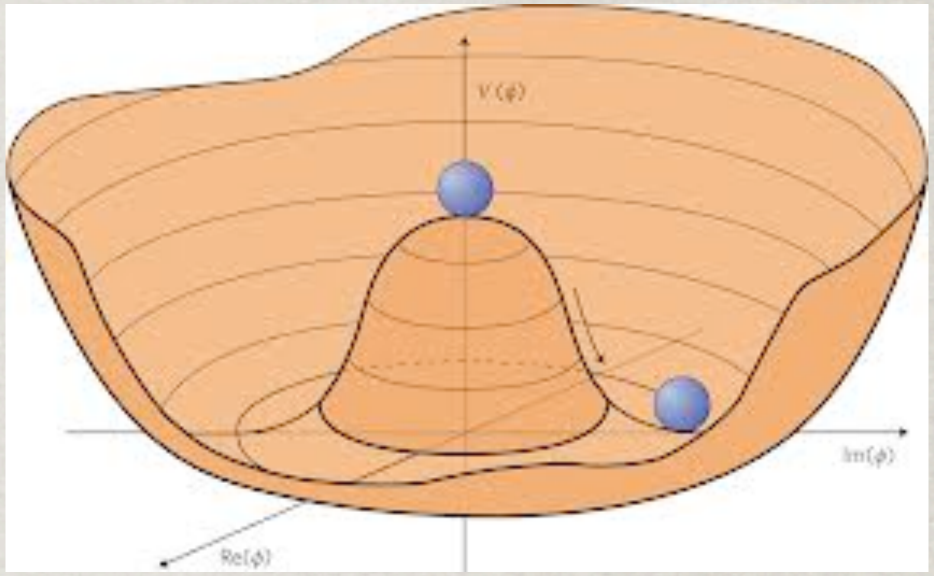
New Era:
Under the Higgs lamp post

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 …."

Question 1: The Nature of EWSB ?

In the SM:



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

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

Fully determined at the weak scale:

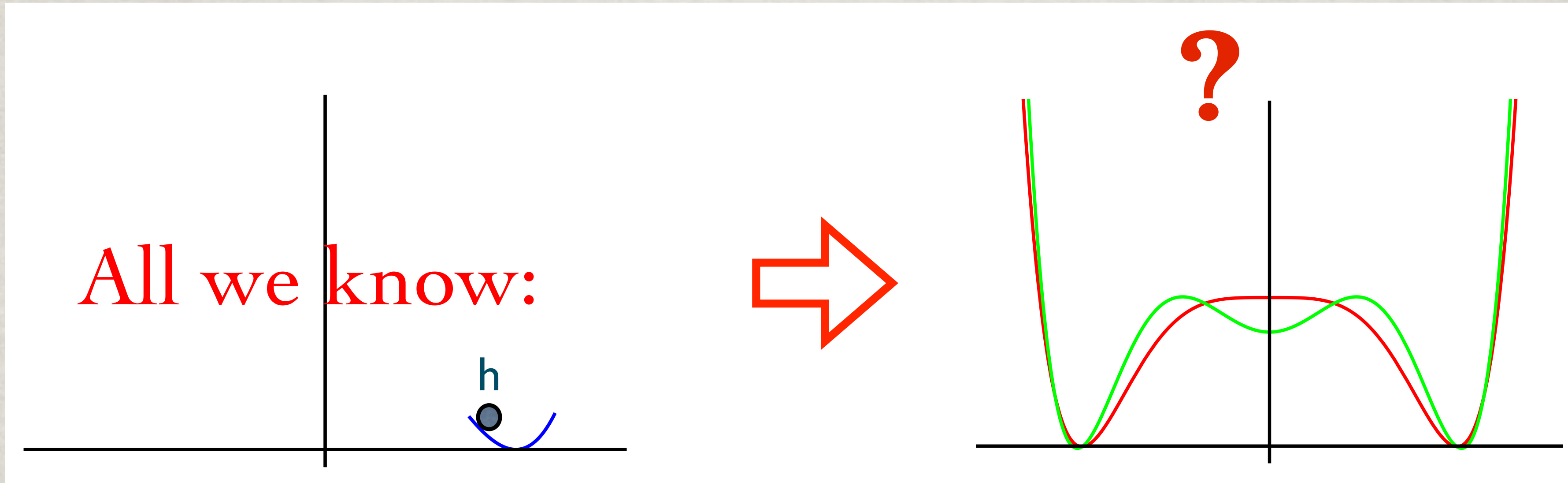
$v = (\sqrt{2}G_F)^{-1/2} \approx 246$ GeV $\quad m_H \approx 126$ GeV

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

It is a weakly coupled new force,
underwent a 2$^{\text{nd}}$ order phase transition.

Is there anything else?

Question 1: The Nature of EWSB ?



With new physics near the EW scale:

$$V(h) \to m_h^2(h^\dagger h) + \frac{1}{2}\lambda(h^\dagger h)^2 + \frac{1}{3!\Lambda^2}(h^\dagger h)^3 \quad \to \lambda_{hhh} = (7/3)\lambda_{hhh}^{SM}$$

$$\to \frac{1}{2}\lambda(h^\dagger h)^2 \log\left[\frac{(h^\dagger h)}{m^2}\right] \quad \to \lambda_{hhh} = (5/3)\lambda_{hhh}^{SM}$$

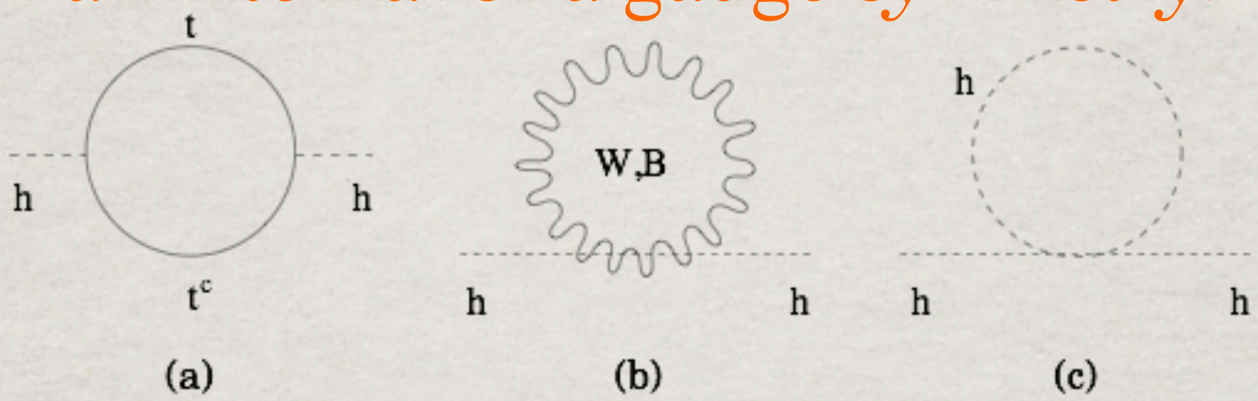
$\lambda(h^+h)^2$ term could be made "-":

leading to EW phase transition strong 1st order!

→ O(1) deviation on λ_{hhh}

Question 2: The "Naturalness"

"… 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



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

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

The Higgs mass fine-tune:

$\delta m_H / m_H \sim 1\% \, (1 \text{ TeV}/\Lambda)^2$

Natural: O(1 TeV) new physics, associated with ttH.
Unknown: Deep UV-IR correlations?
Agnostic: Multiverse/anthropic?

“Naturalness” in perspective:

Unbelievable!

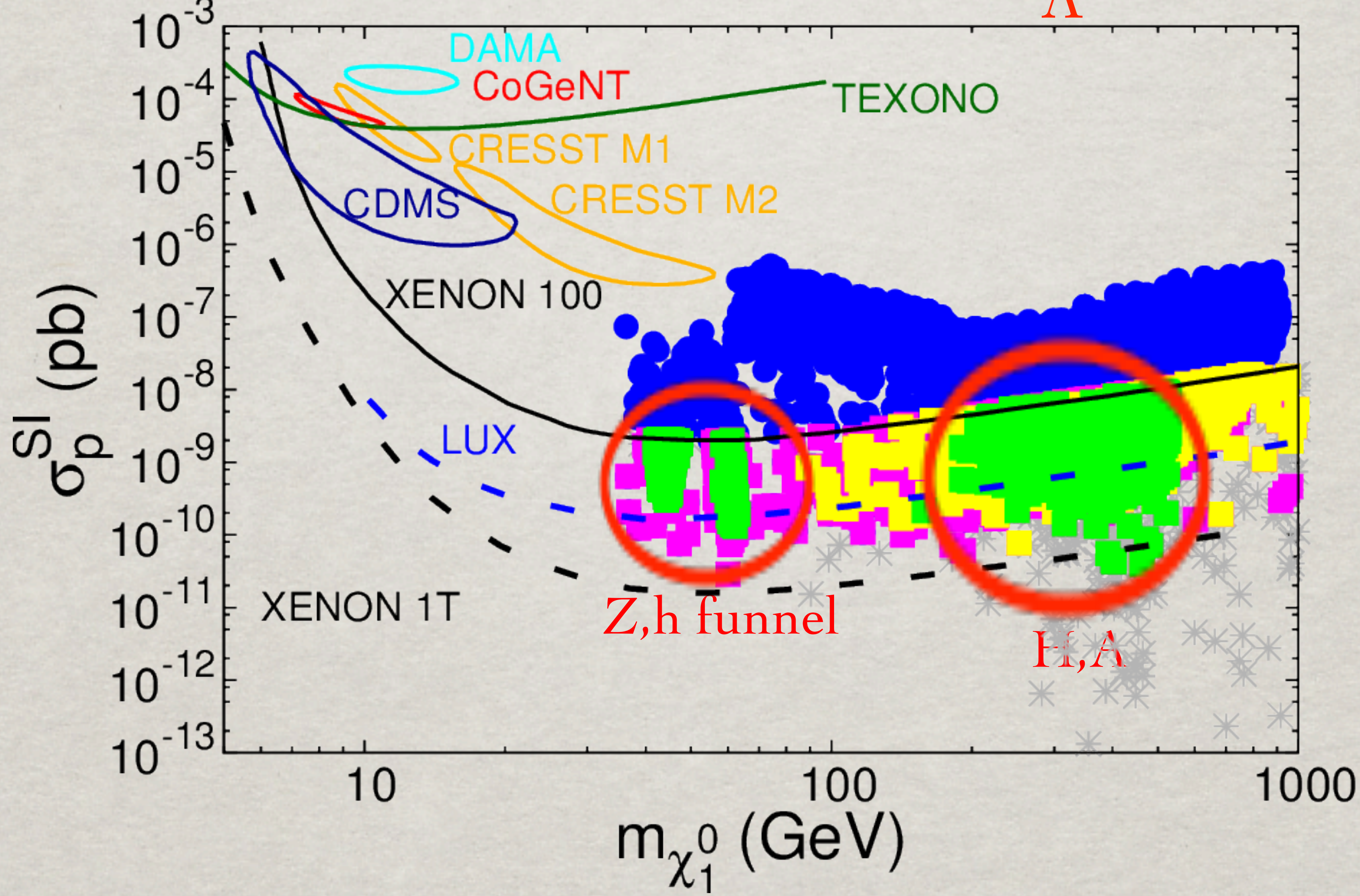
$4\ \mathrm{mm}^2 / 20\ \mathrm{cm}^2 \sim 10^{-3}$ fine-tune.

“Naturalness” → TeV scale new physics.

Question 3: The Dark Sector

The un-protected operator may reveal secret

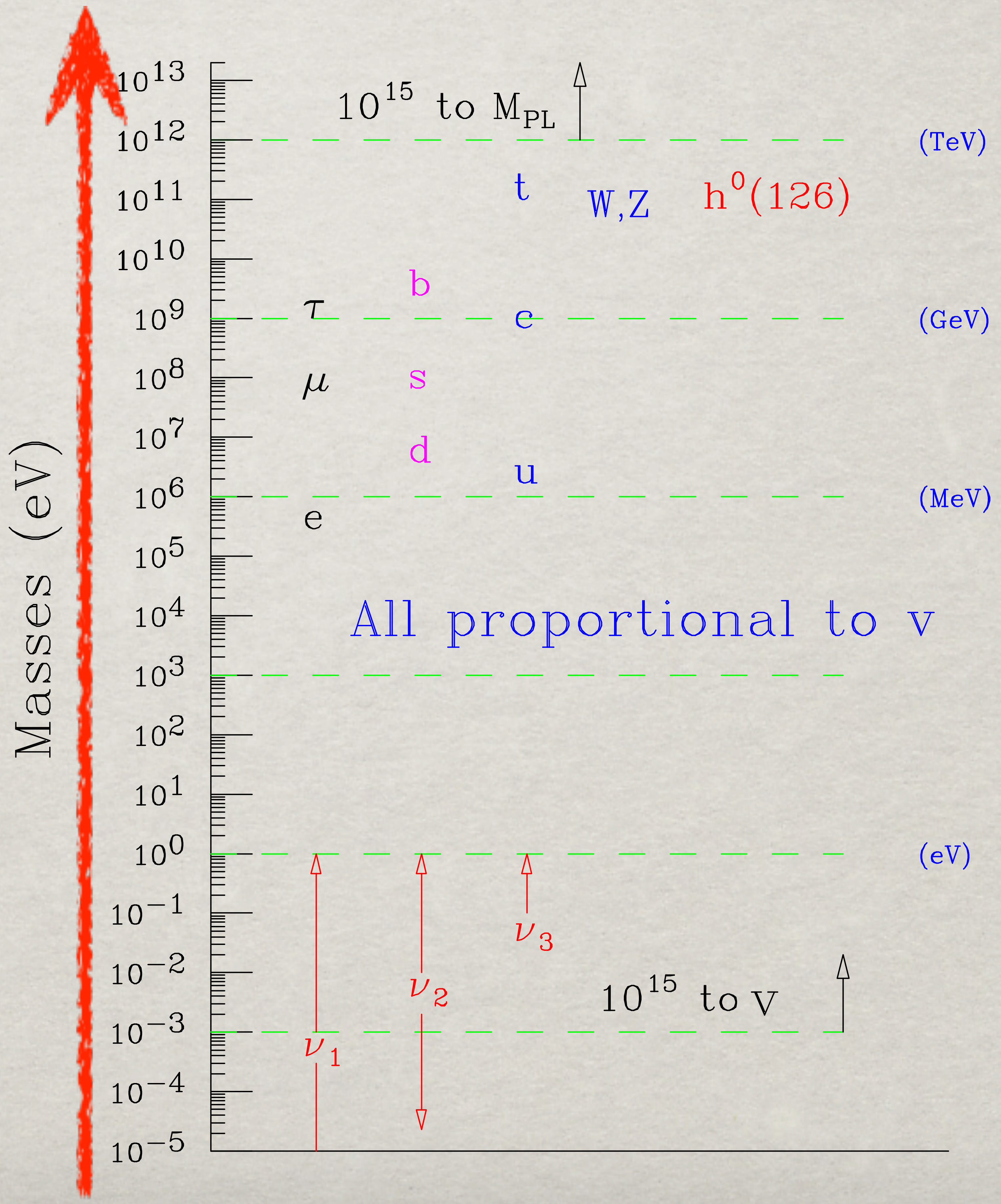
Higgs portal: $k_s H^\dagger H \; S^* S, \quad \frac{k_\chi}{\Lambda} H^\dagger H \; \bar{\chi}\chi.$



Question 4: The "Flavor Puzzle"

- Particle mass hierarchy
- Patterns of quark, neutrino mixings
- New CP-violation sources?

Higgs Yukawa couplings as the pivot!



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) $N_R{}^i$

$H \to NN, \ N \to H\nu, \ldots$

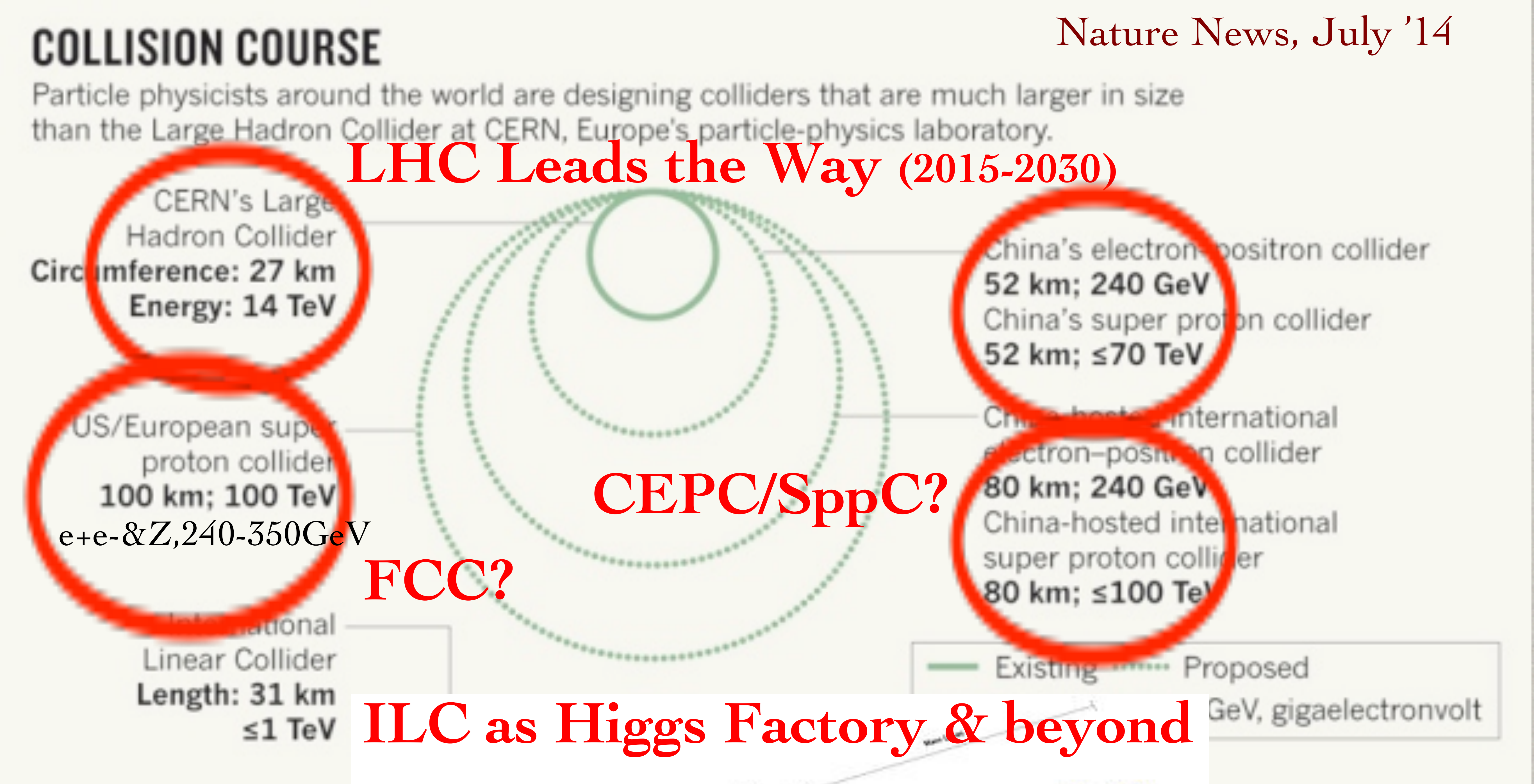
Type II seesaw: $M = M_{H++}$, a Higgs triplet Φ_3

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

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

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

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



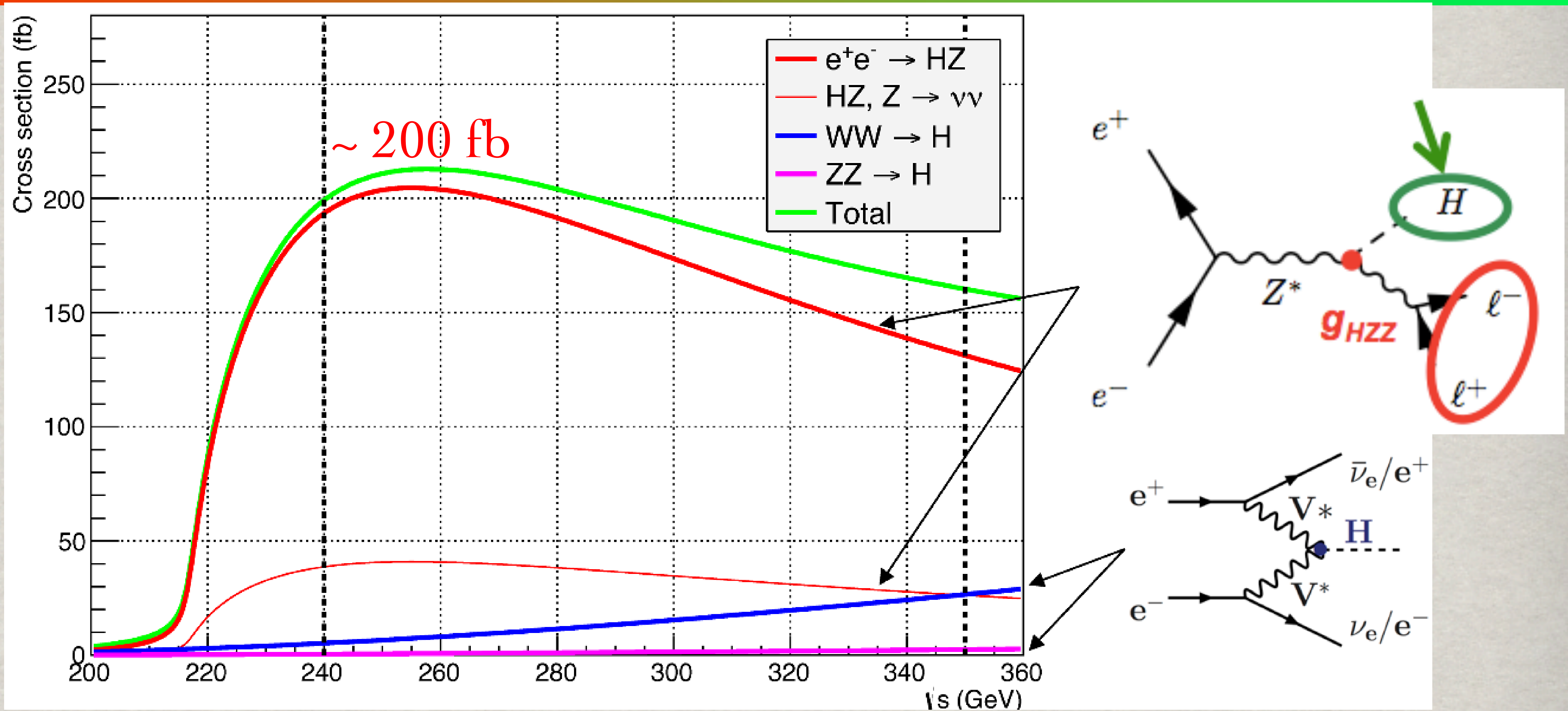
ILC as Higgs Factory & beyond

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

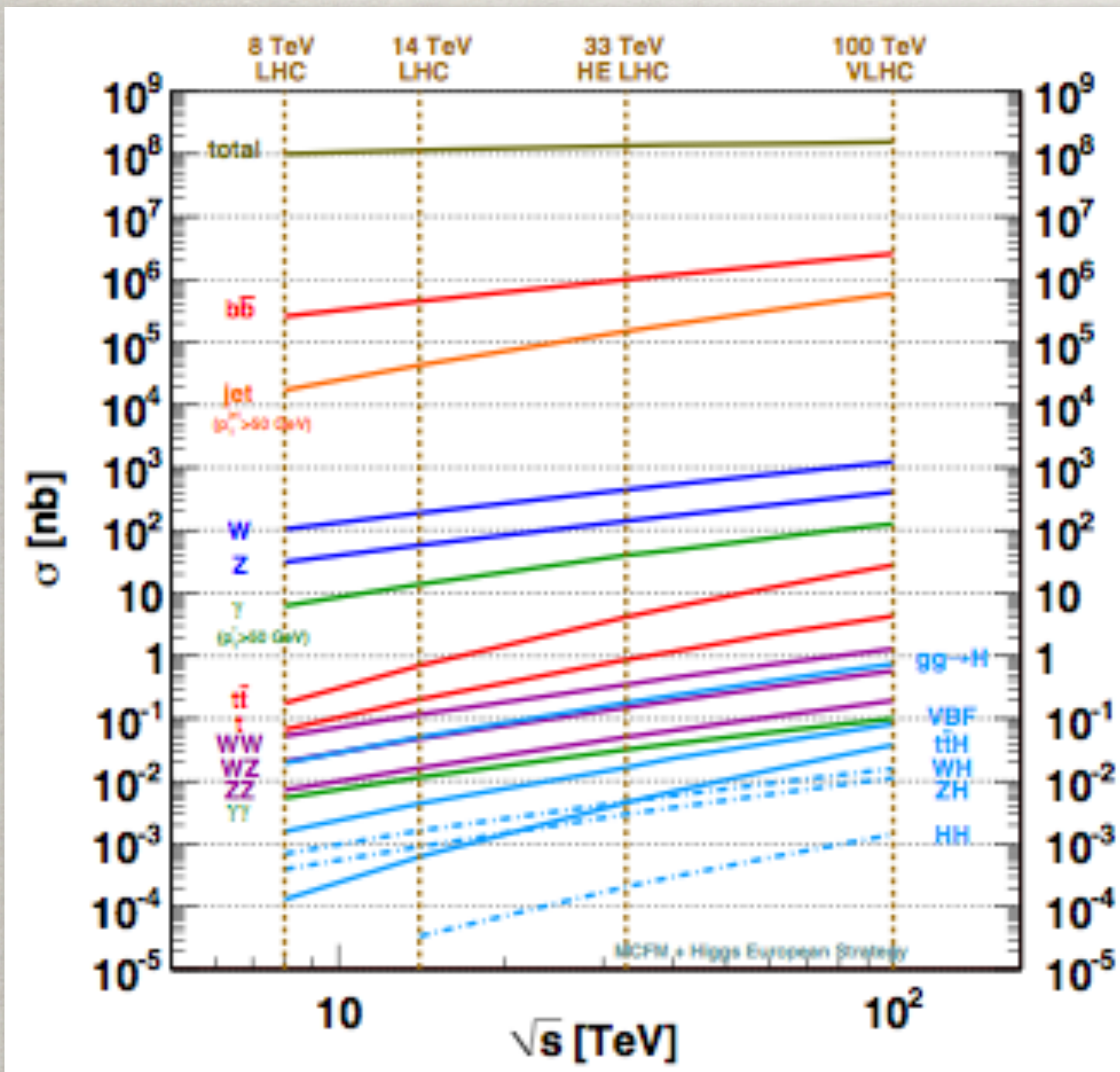
  $\Gamma_H \sim 6\%$, $\Delta m_H \sim 30$ MeV

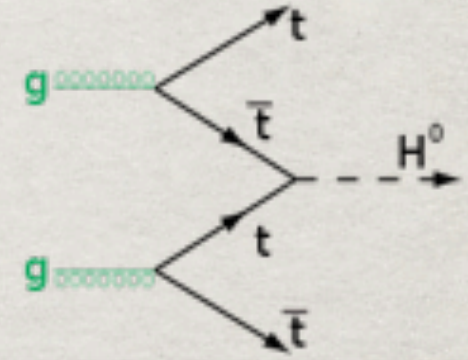
  (HL-LHC: assume SM, $\Gamma_H \sim 5\text{-}8\%$, $\Delta m_H \sim 50$ MeV)

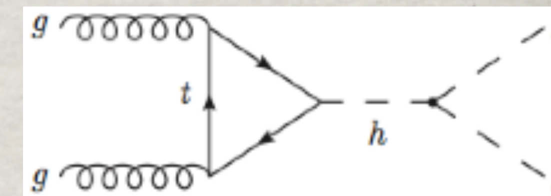
- TLEP 10^6 Higgs: $\Gamma_H \sim 1\%$, $\Delta m_H \sim 5$ MeV.

  TLEP Report: 1308.6176

The Next Energy Frontier: 100 TeV Hadron Collider







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%

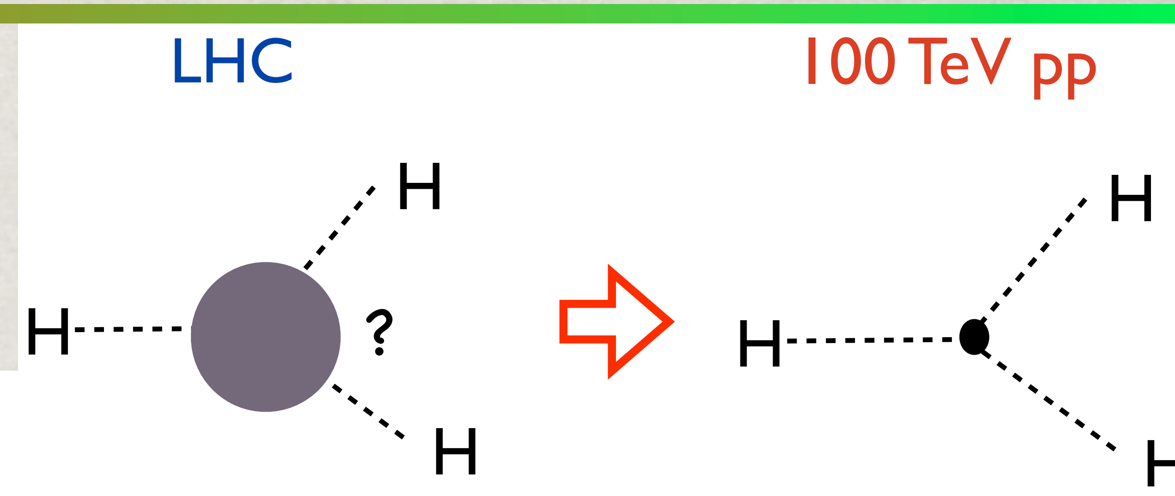
Snowmass QCD Working Group: 1310.5189

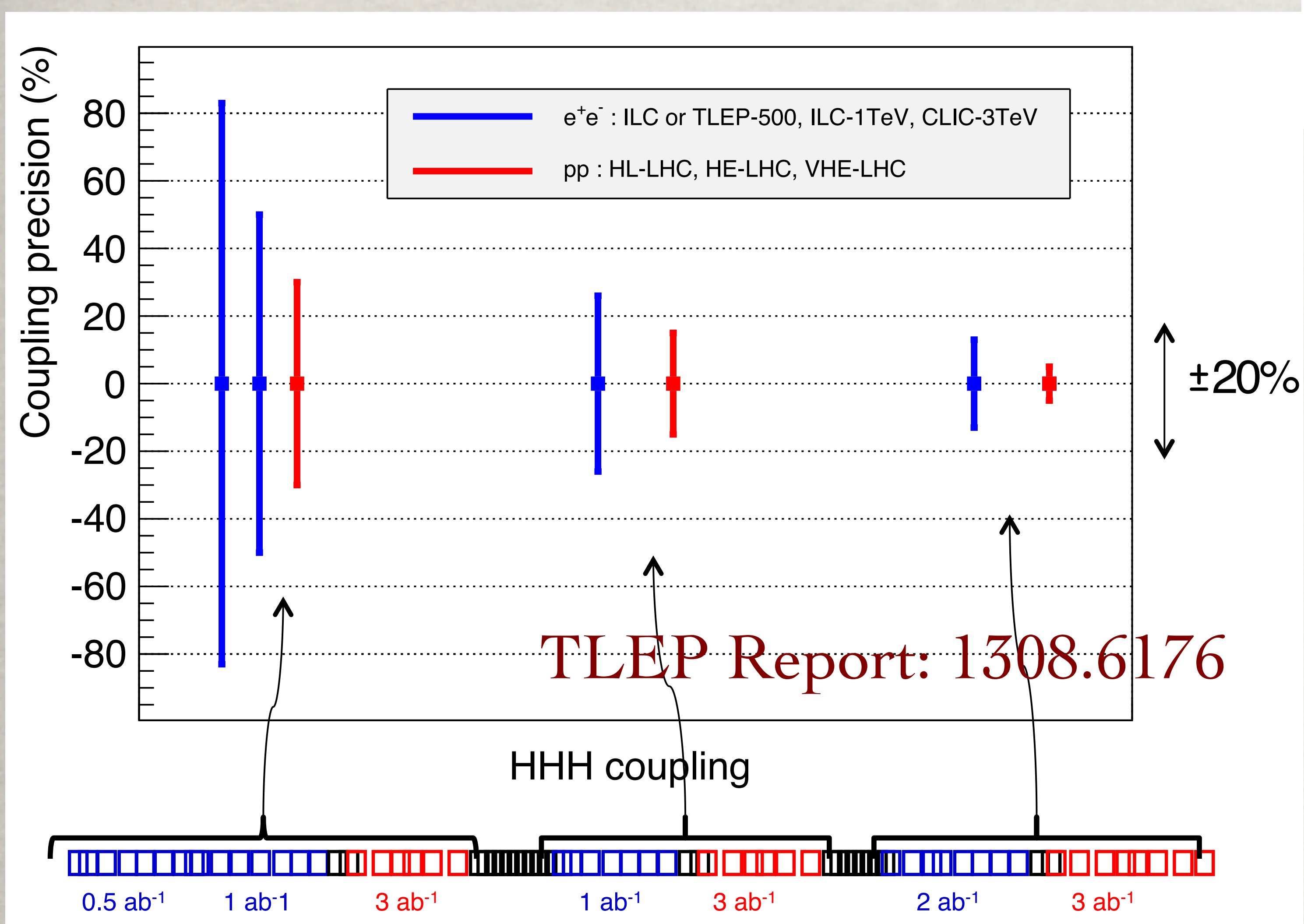
Arkani-Hamed, TH, Mangano, LT Wang, 1511.06495

Higgs Self-couplings:

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

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



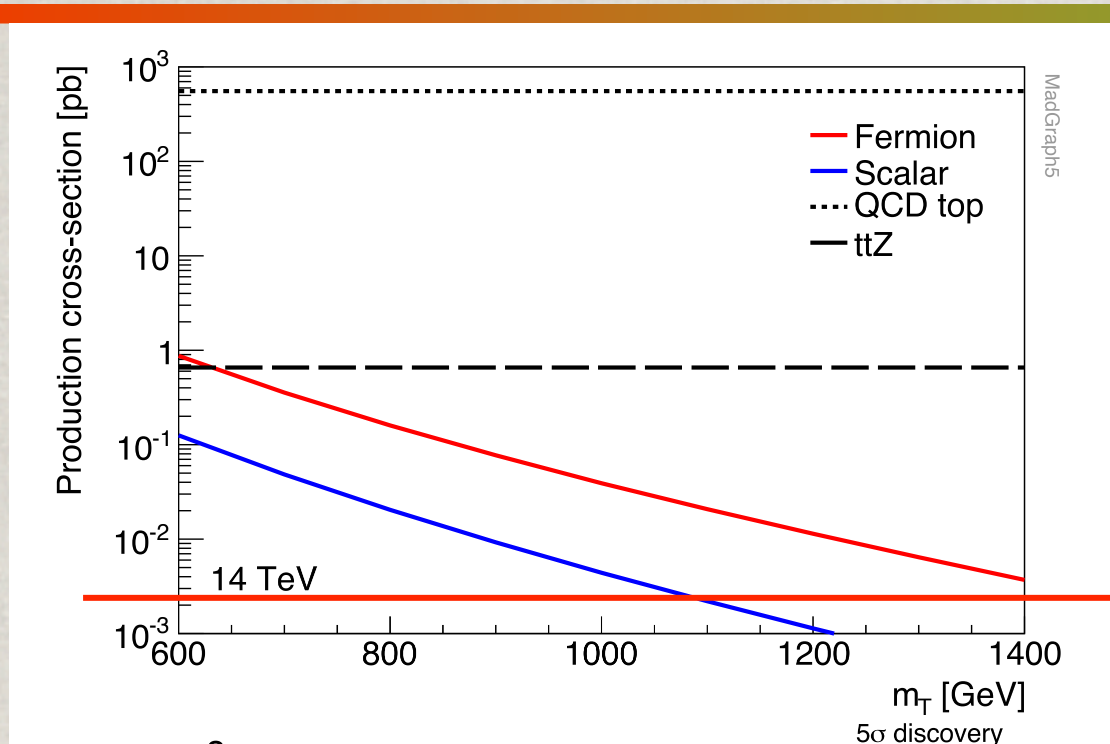


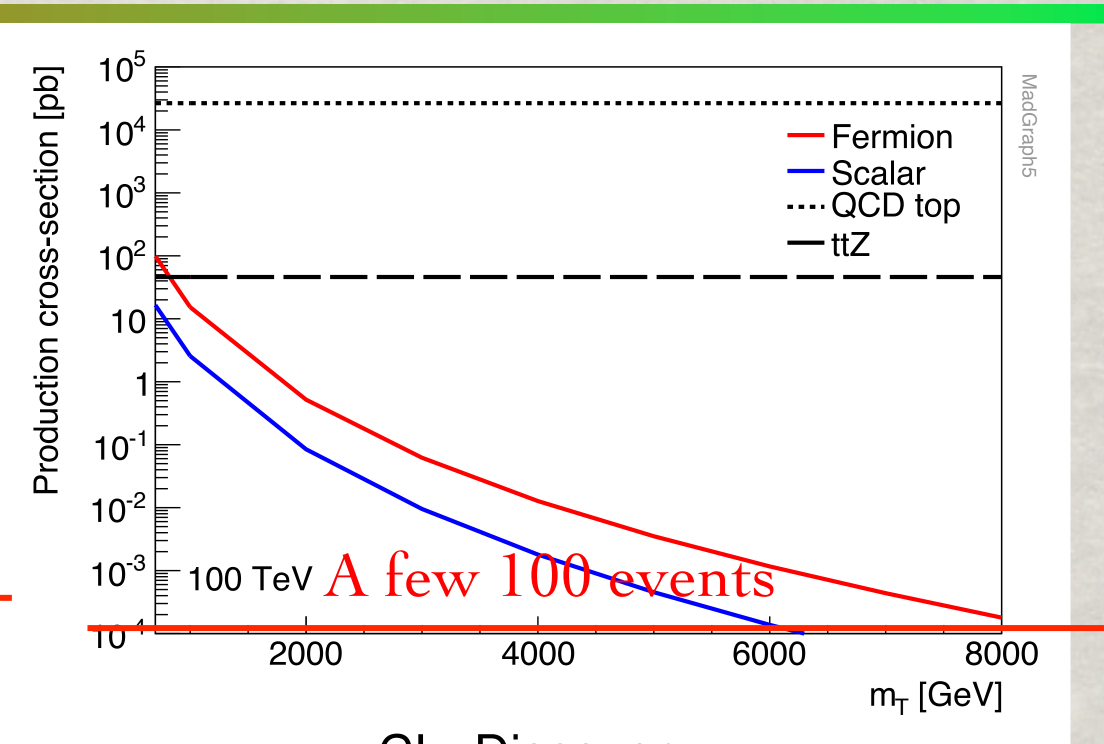
Triple coupling sensitivity:
Test the shape of the Higgs potential, and the fate of the EW-phase transition!

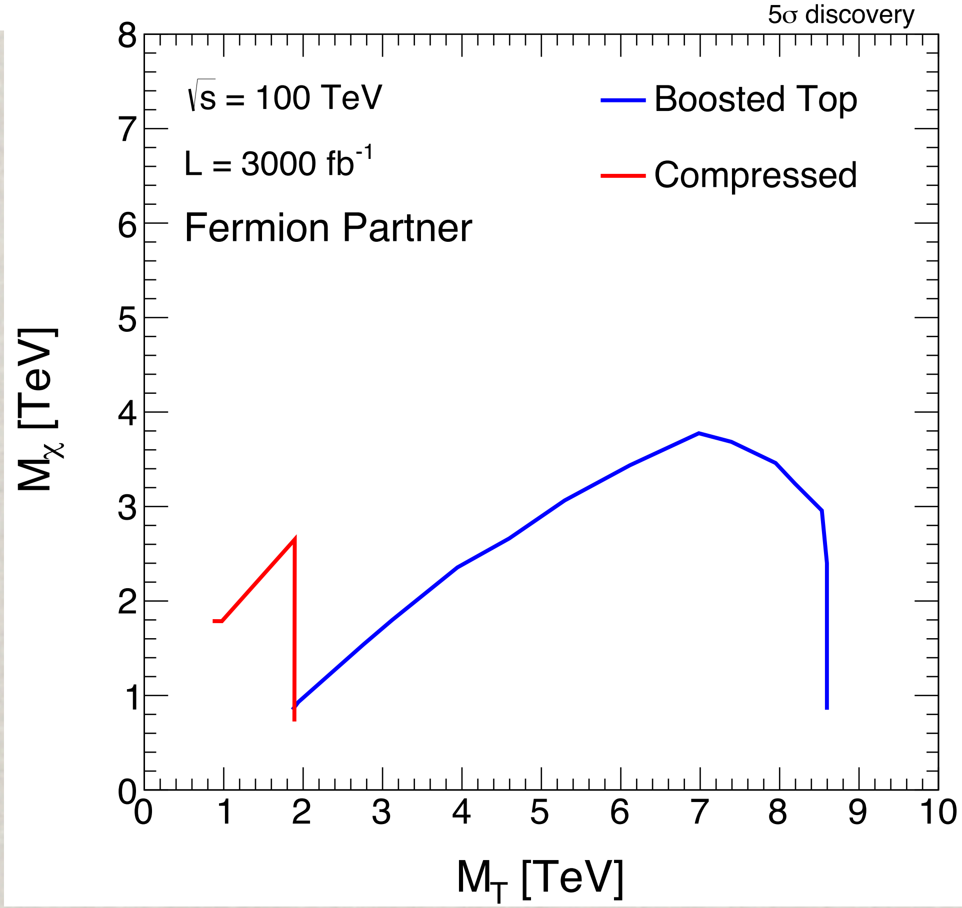
Snowmass 1310.8361

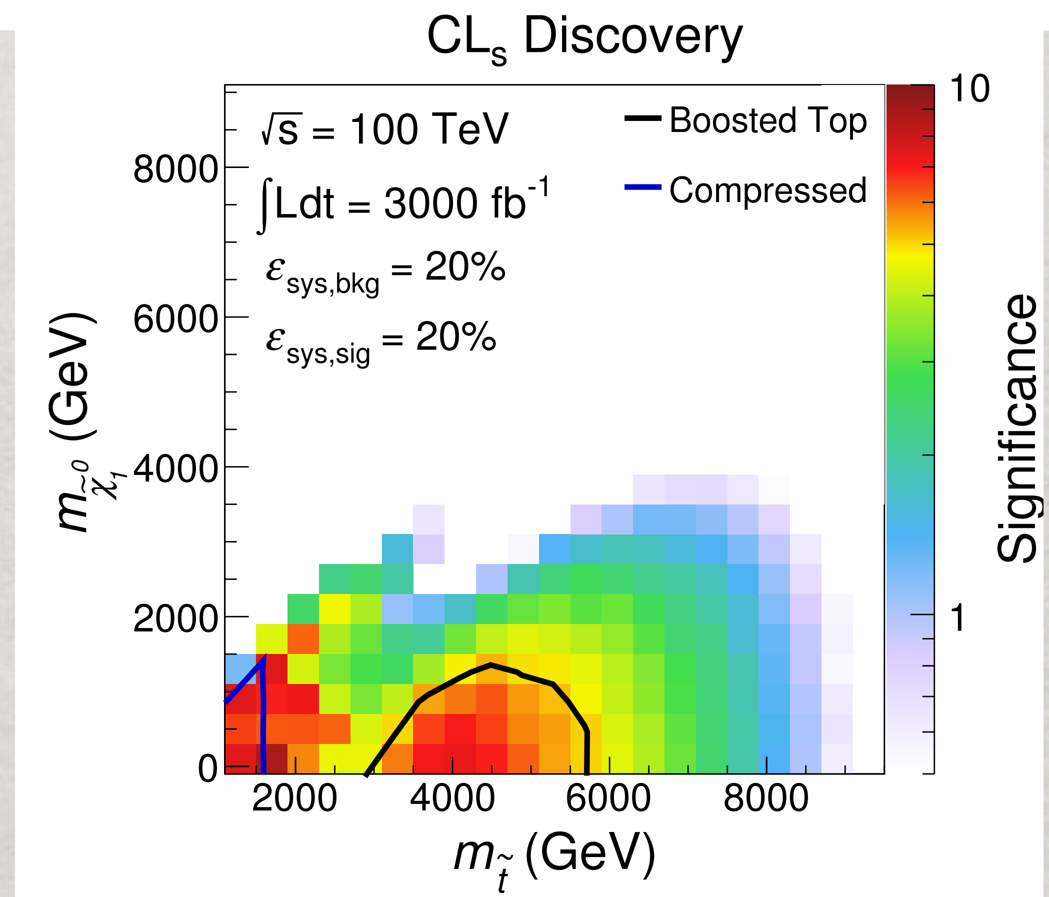
	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	500	$1600^\ddagger$	500+1000	$1600+2500^\ddagger$	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%

Pushing the "Naturalness" limit





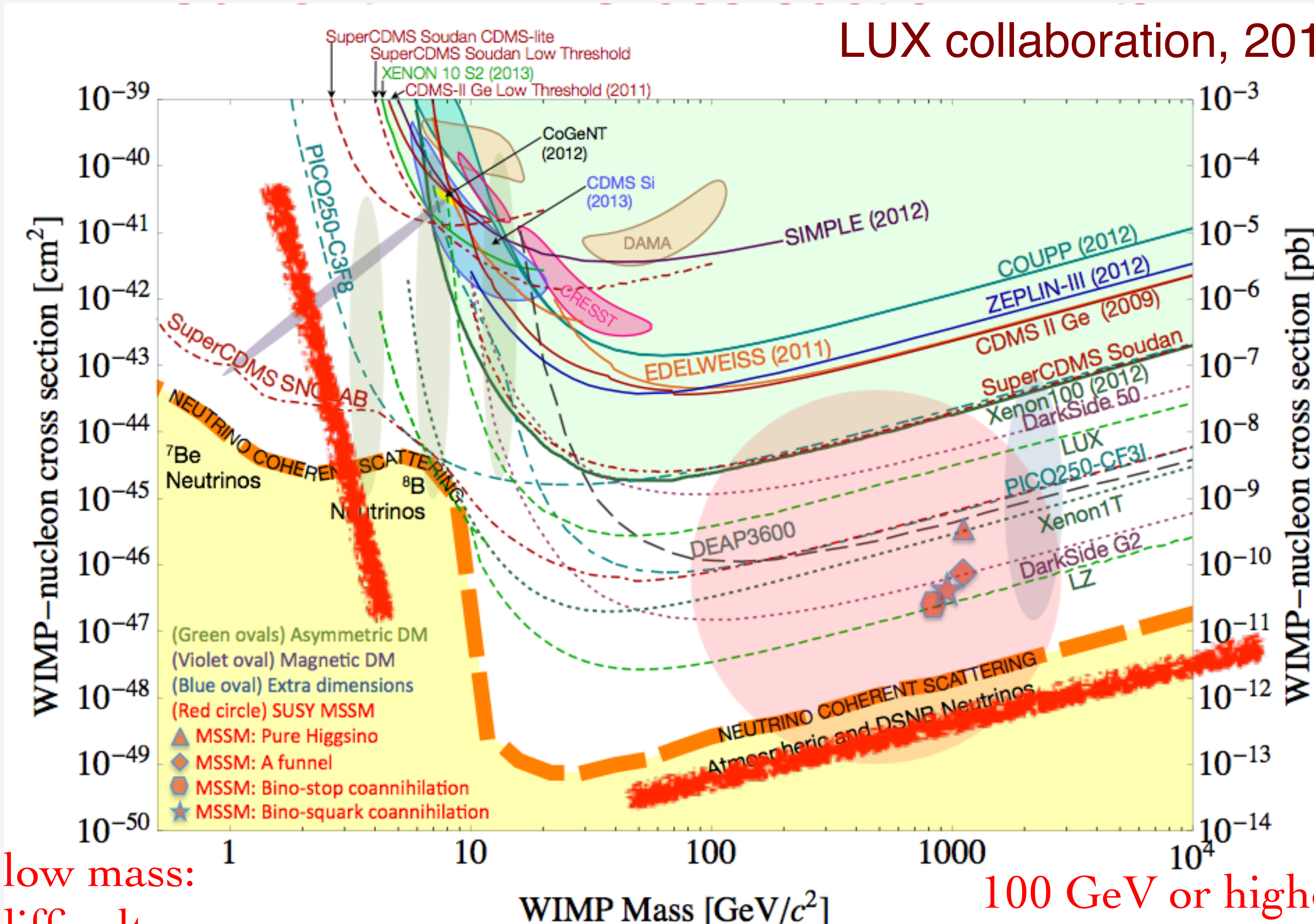




The Higgs mass fine-tune: $\delta m_H/m_H \sim 1\% \, (1 \text{ TeV}/\Lambda)^2$

Thus, $m_{stop} > 8$ TeV → 10^{-4} fine-tune!

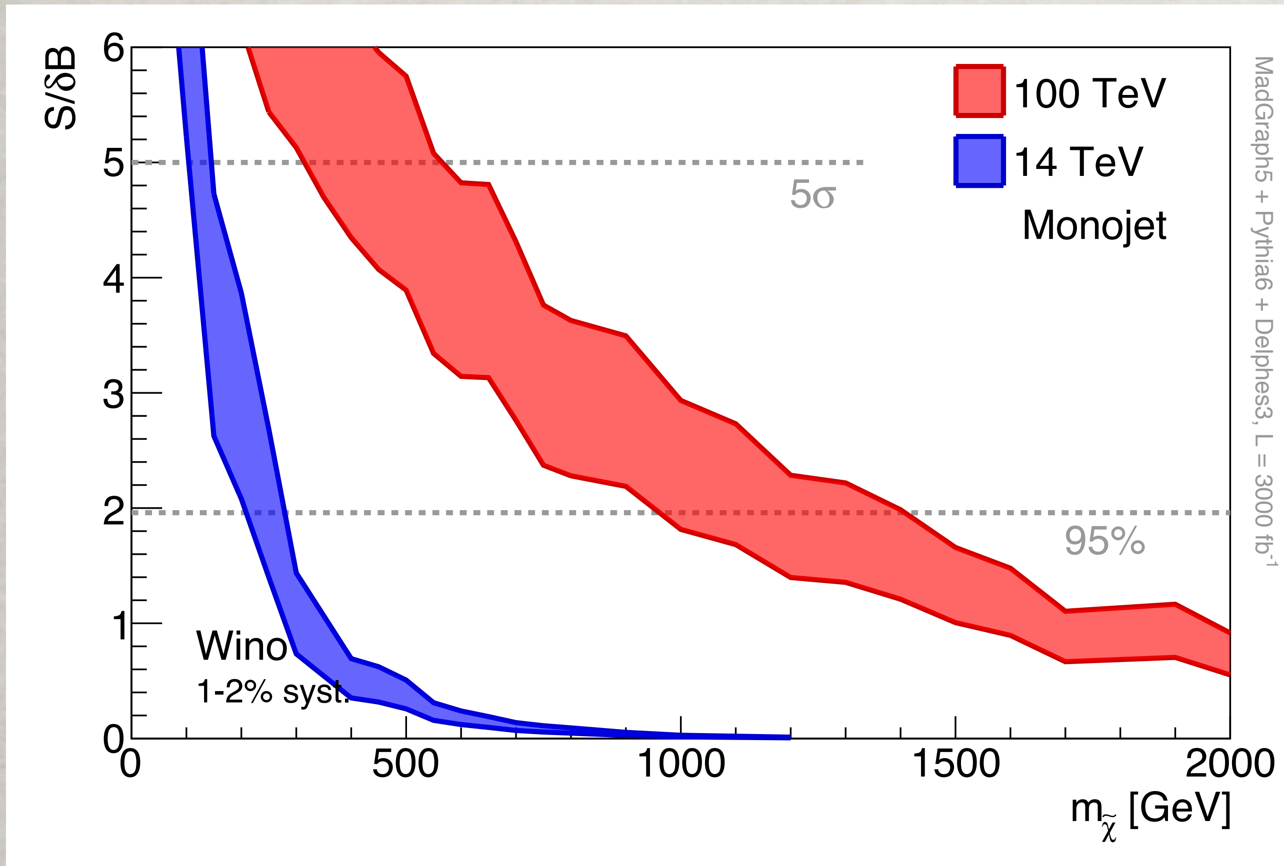
DM Searches

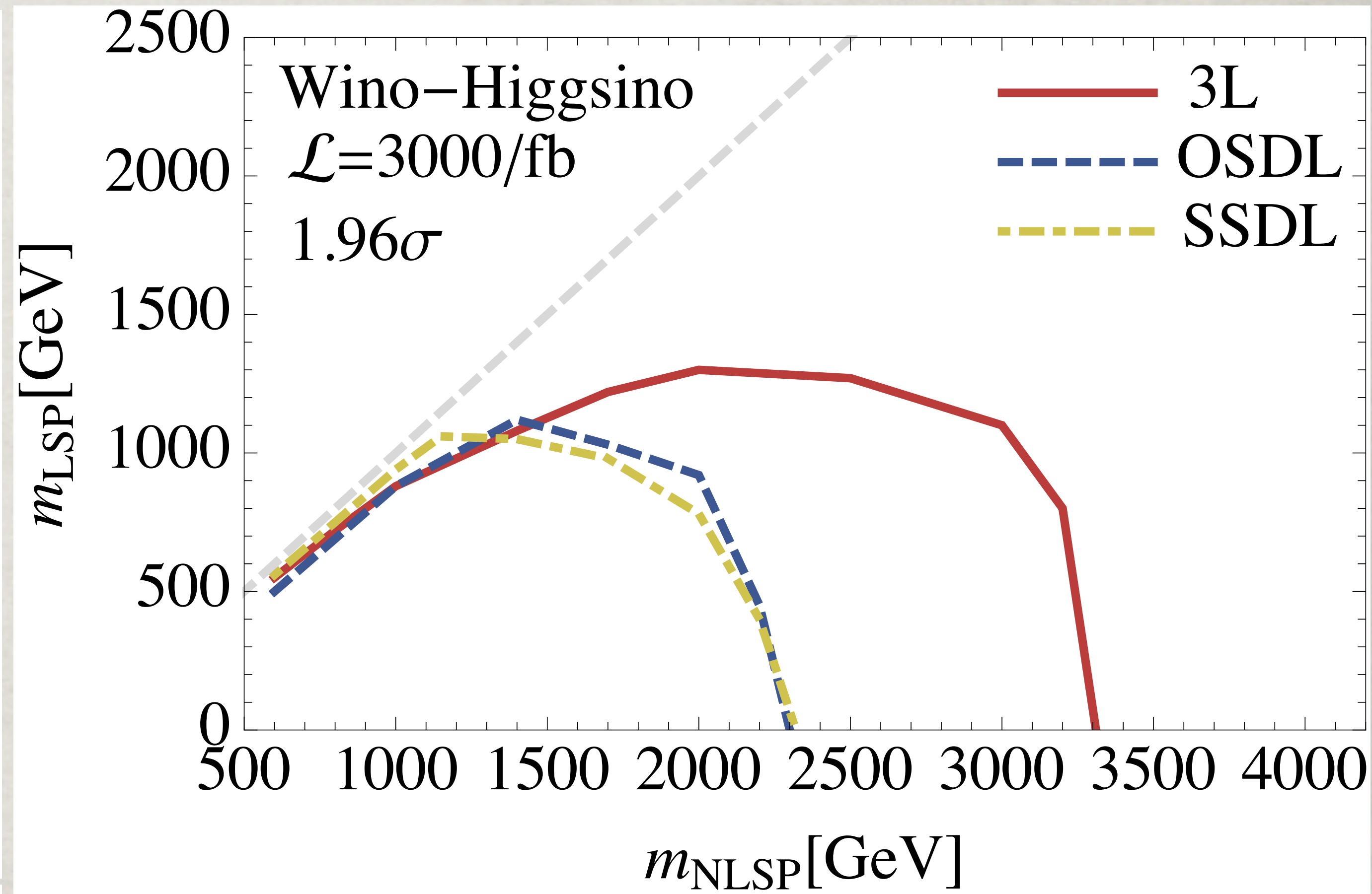


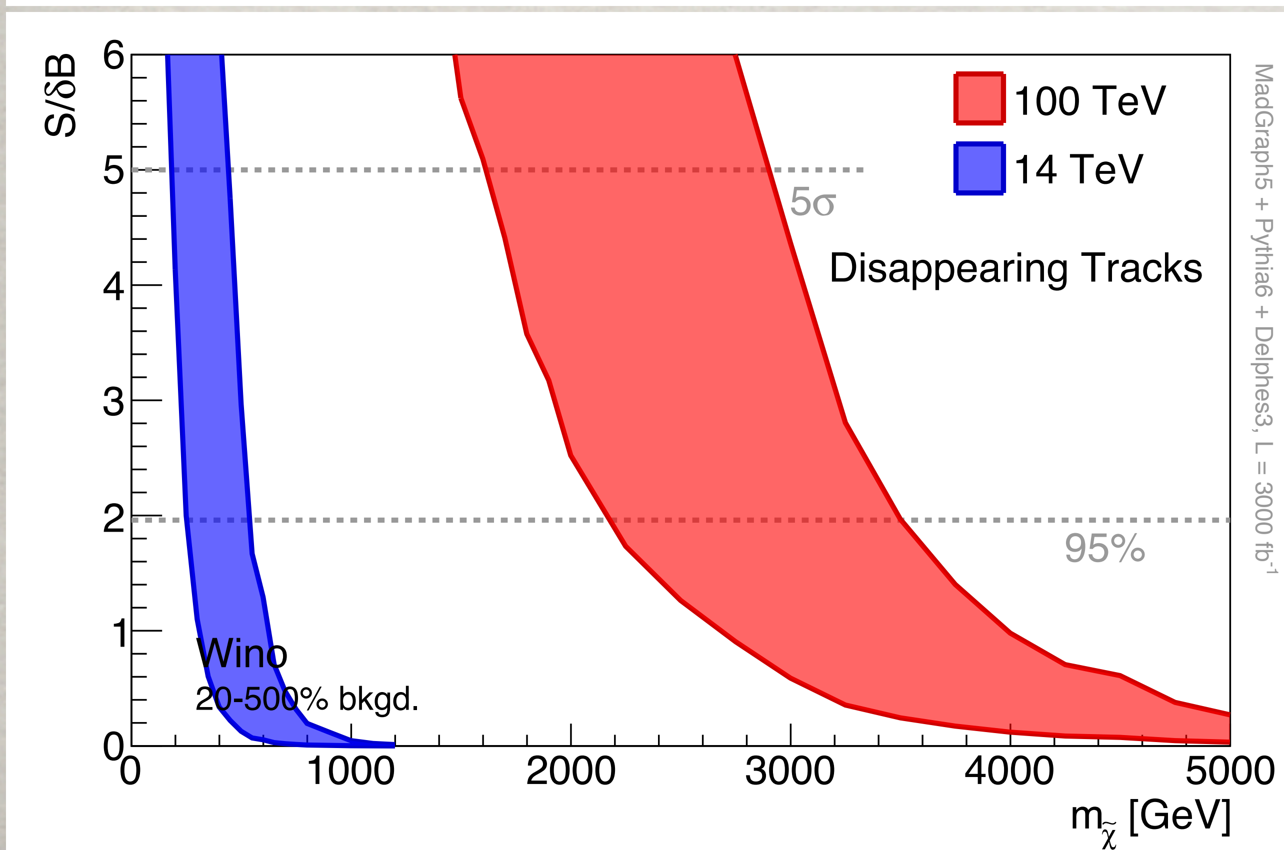
GeV low mass:
DD difficult;
Collider complementary

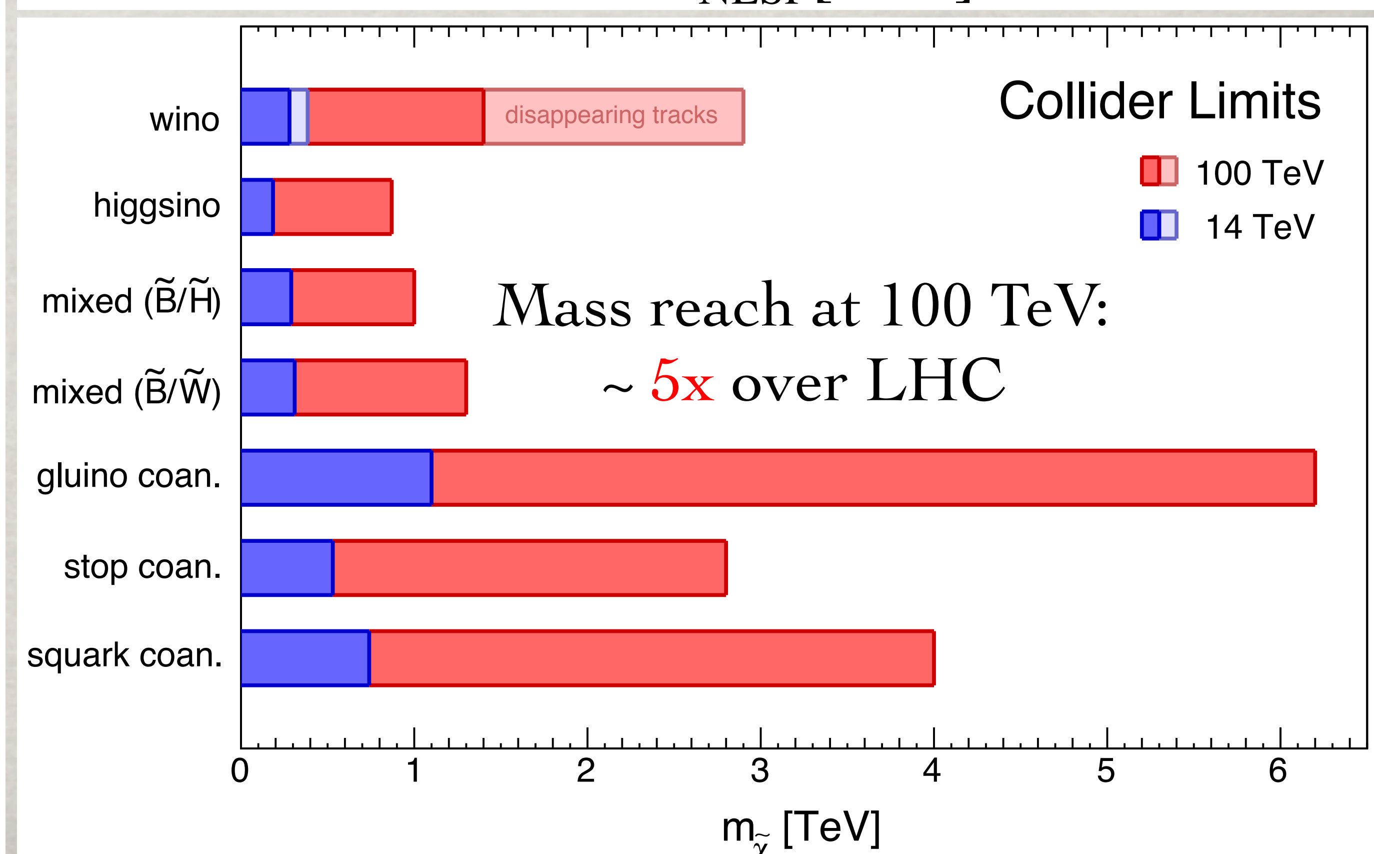
100 GeV or higher mass:
DD + ID + HE Collider

WIMP DM: $M_{\mathrm{DM}} < 1.8\ \mathrm{TeV}\left(\frac{g_{\mathrm{eff}}^2}{0.3}\right)$



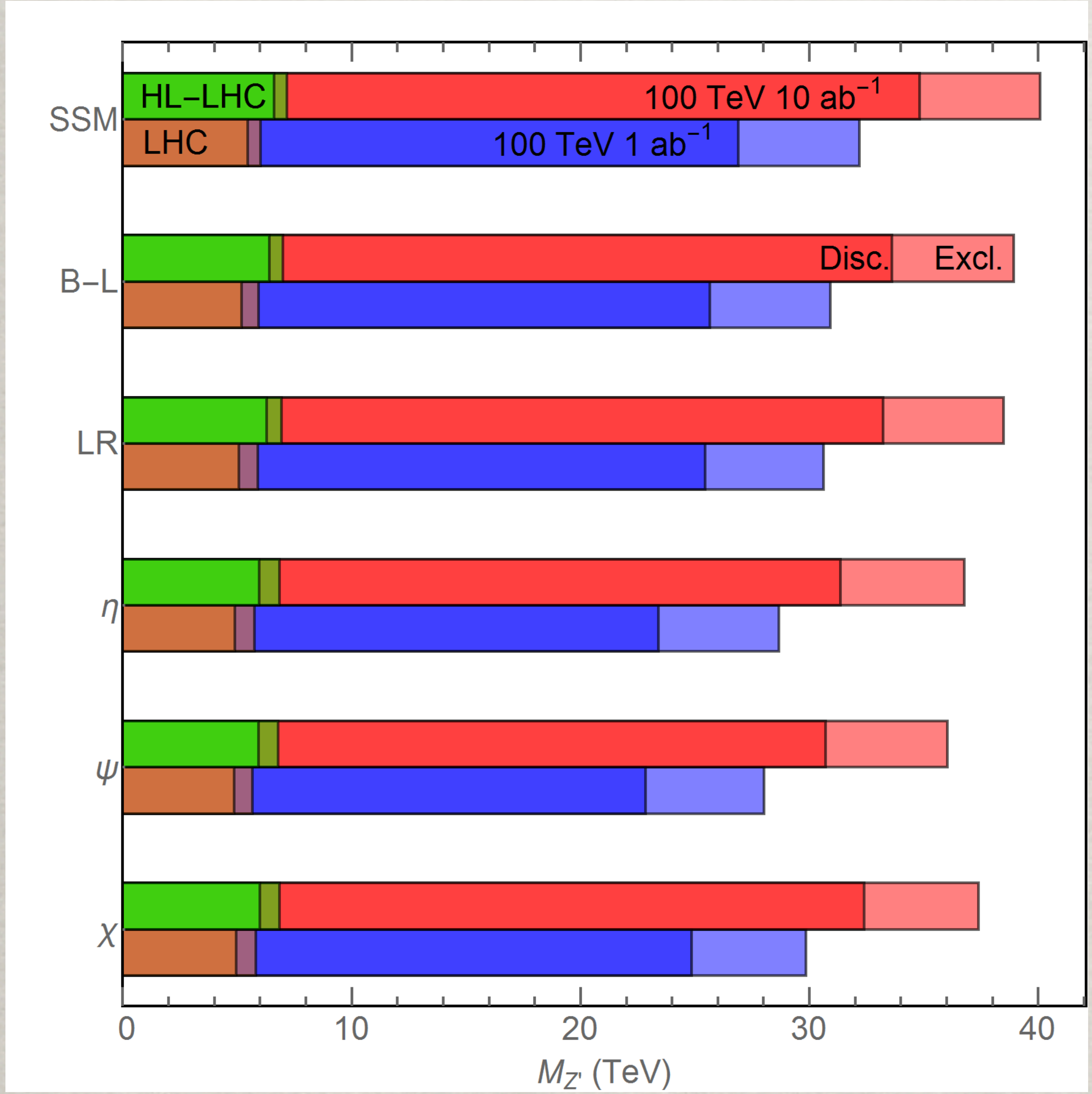






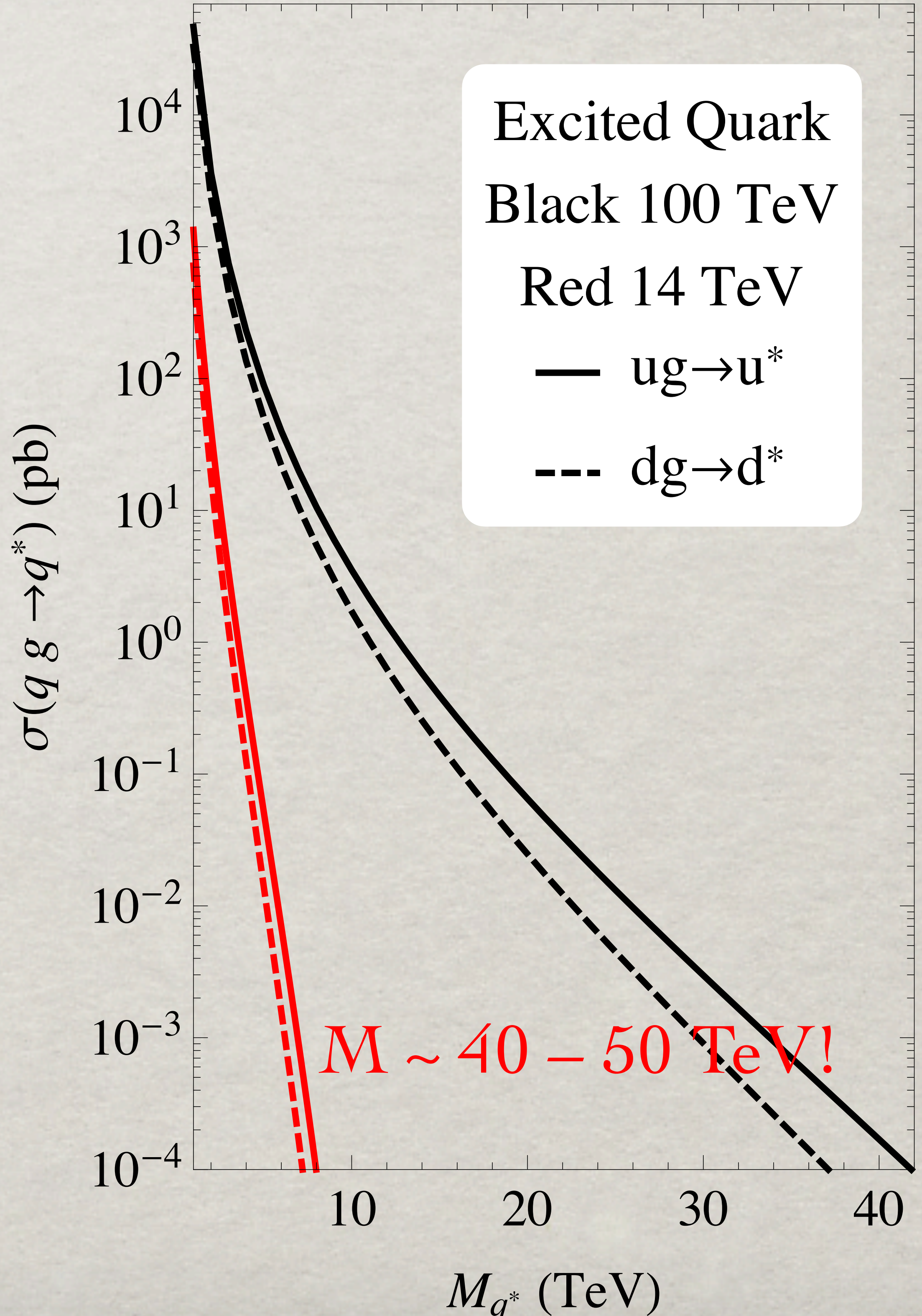
New Particle Searches

Electroweak Resonances: Z',W'

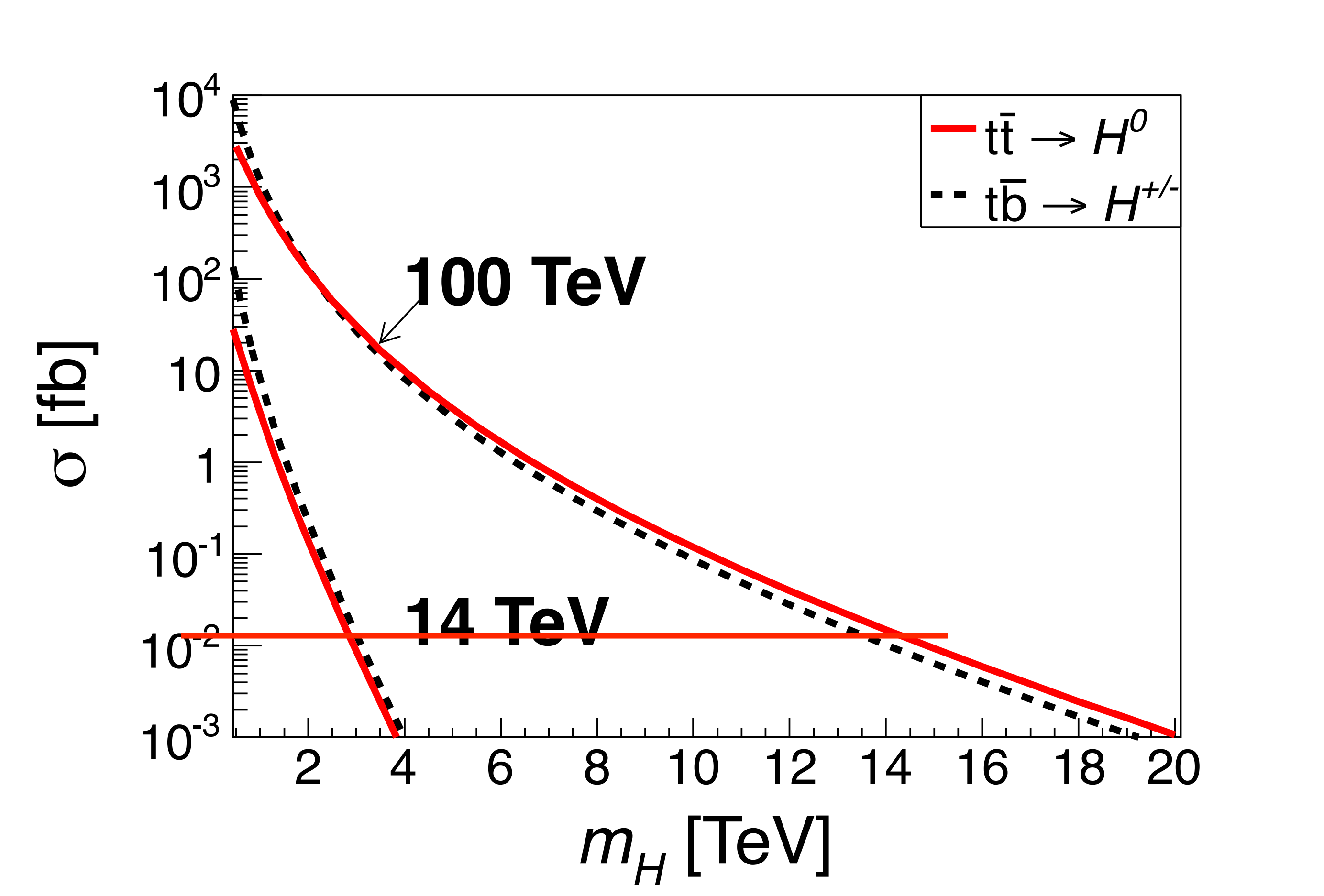


~ 6x over LHC

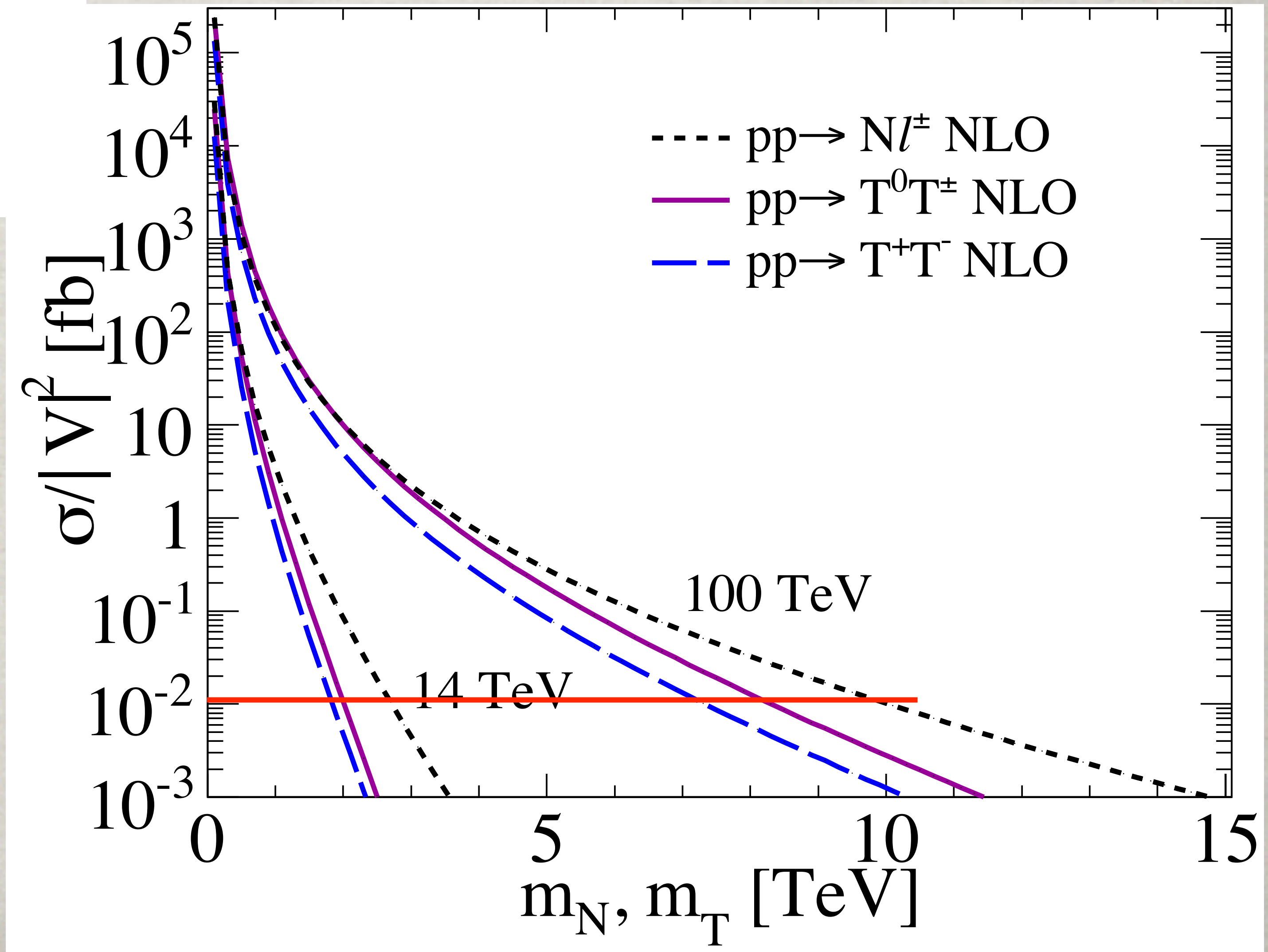
Colored Resonances:



Heavy Higgs bosons: *H^0, $H^\pm$*



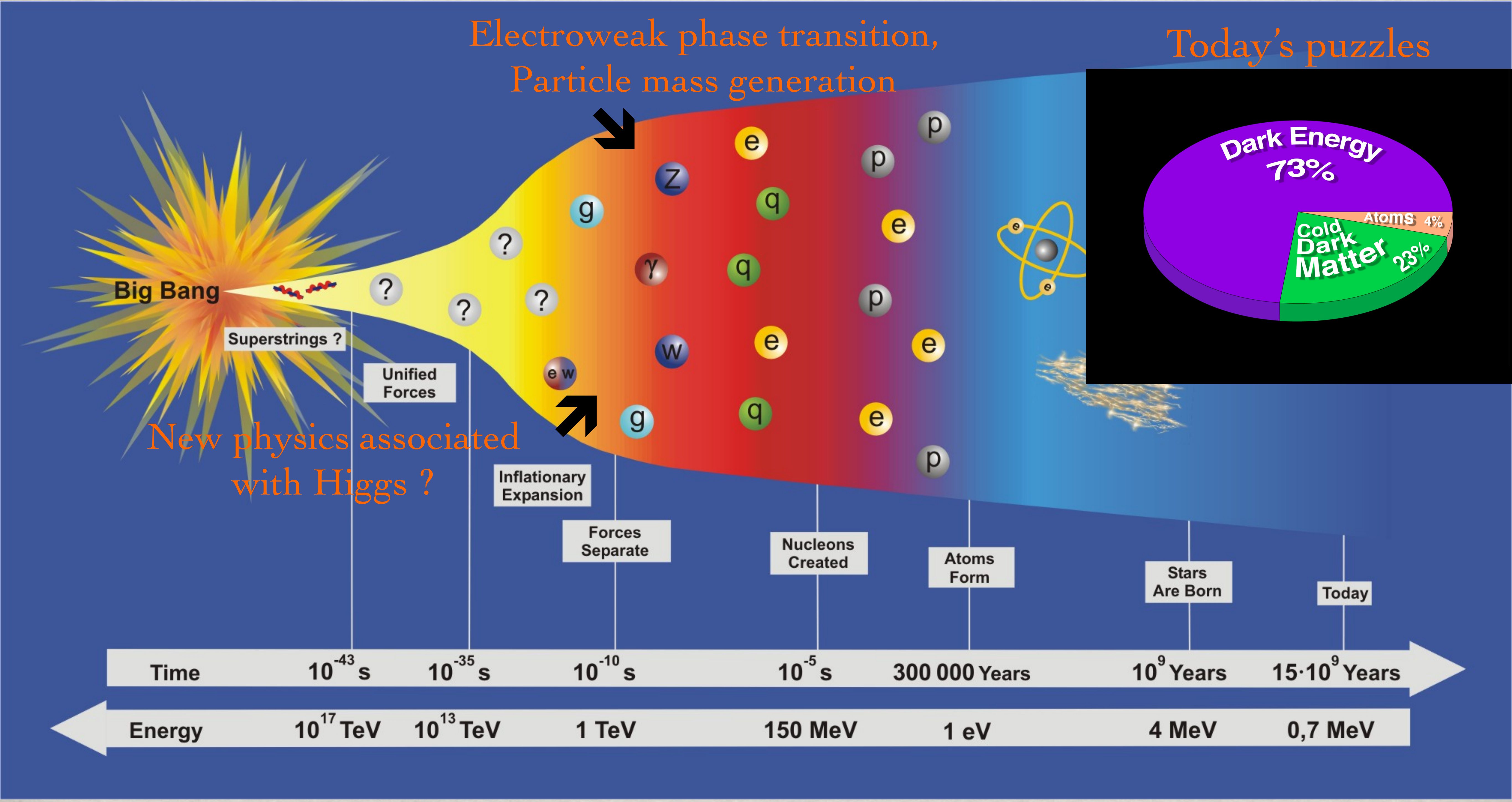
New (vector-like) leptons



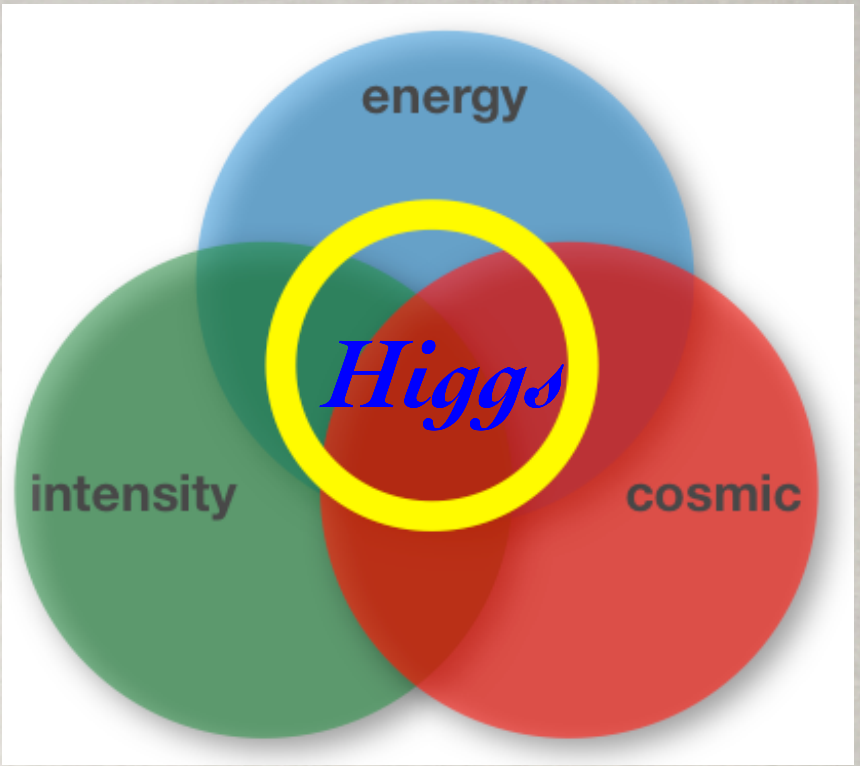
Mass reach at 100 TeV:

~ 5x over LHC

A Grand Picture:



Summary:



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

"Naturally speaking":

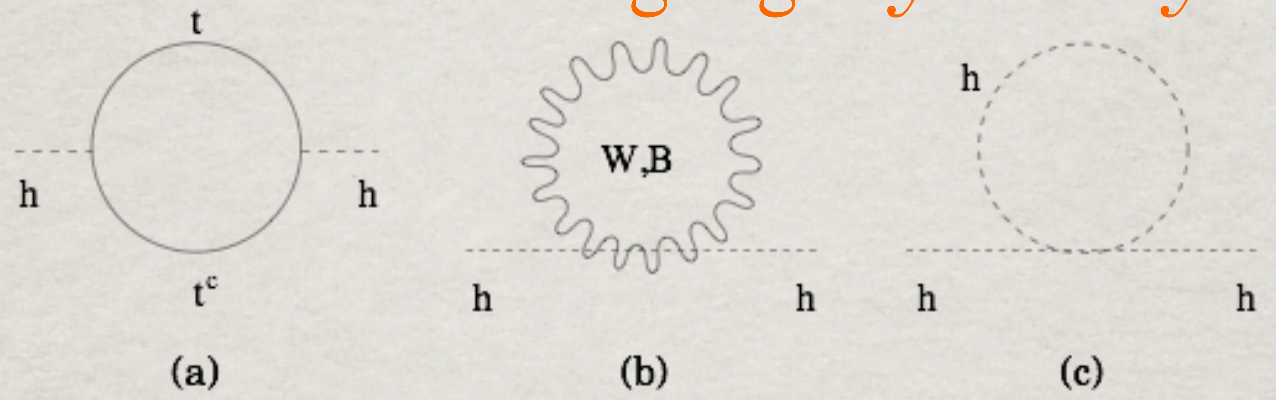
It should not be a lonely solitary particle.

- Precision Higgs physics:
  LHC lights the way: g~10%; λ_{HHH} ~ 50%; $Br_{inv.}$~ 20%
  Higgs factory/SppC: g~1%; λ_{HHH} < 10%; $Br_{inv.}$ ~ 2%; Γ_{tot} < 6%
- CEPC/SppC New physics reach:
  6x LHC reach: 10 – 30 TeV → fine-tune < 10^{-4}
  WIPM DM mass ~ 1 – 5 TeV

An exciting journey ahead!

Question 2: The "Naturalness"

"… 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



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

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

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

Natural: O(1 TeV) new physics, associated with ttH.

Unknown: Deep UV-IR correlations?

Agnostic: Multiverse/anthropic?