May 24, 2019

Colloquium @ USTC, Hefei

質量不簡單
淺談希格斯物理

Cheng-Wei Chiang (蔣正偉)
National Taiwan University

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Subtle is generating mass — The Higgs physics

Cheng-Wei Chiang (蔣正偉)
National Taiwan University

Plan of Talk

- Mass
- Standard explanation
- Higgs boson
- Neutrino and exotic Higgs bosons
- Summary

God particle

Holy Grail in particle physics

Origin of mass

Symmetry breaking

Secret of Universe

Hope to explain them all...

Disclaimers

- Do not be surprised if you do not understand some technical parts of my talk, and do not feel too great if you do!
  ➠ about a topic of Nobel prize level

- Will use HEP natural unit: $\hbar = c = 1$.
  ex. $m_p = 940\ \mathrm{MeV}/c^2$ ➠ $940\ \mathrm{MeV} \sim 1\ \mathrm{GeV}$

$E = mc^2$

$$1\,\mathrm{GeV} \simeq 1.6 \times 10^{-10}\,\mathrm{Joules} \simeq 1.78 \times 10^{-24}\,\mathrm{g}$$

- How did the Universe start?
- How does the Universe evolve to the current state?
- How will the Universe end?

Rephrased Questions

- What are the fundamental compositions of matter in the Universe?
- How do they interact with one another?

- Then we will know how structures (dust, stars, galaxies, clusters, etc) are formed, at least in principle.
- Really?

- Massless particles always hurtle at the speed of light.
  ➠ no structure possibly formed
  ➠ no civilization!

Additional Requirement

- Fundamental particles must have mass of inertia so that they can slow down to congregate.
- Luckily, almost all elementary particles have mass.
- "Why" do particles have mass?

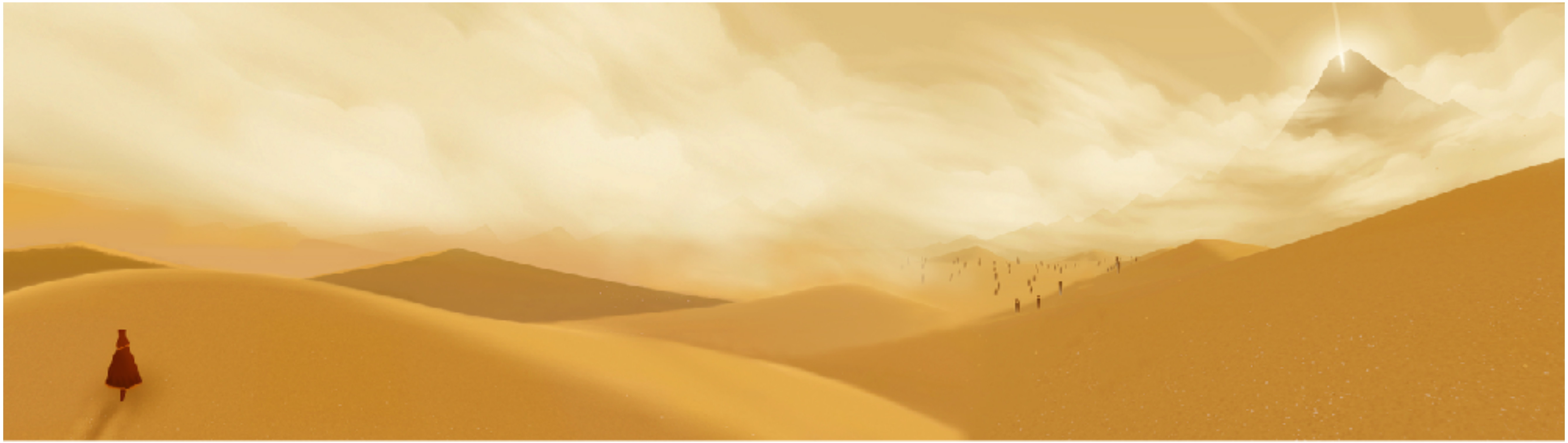
  ➠ a philosophical/religious question for now
- "How" do elementary particles get their mass?
- Put in by hand?
- No! This will violate a sacred principle, gauge invariance, of Nature.

- Let's see how subtle it needs to be to give mass to particles.

Cheng-Wei Chiang (NTU)

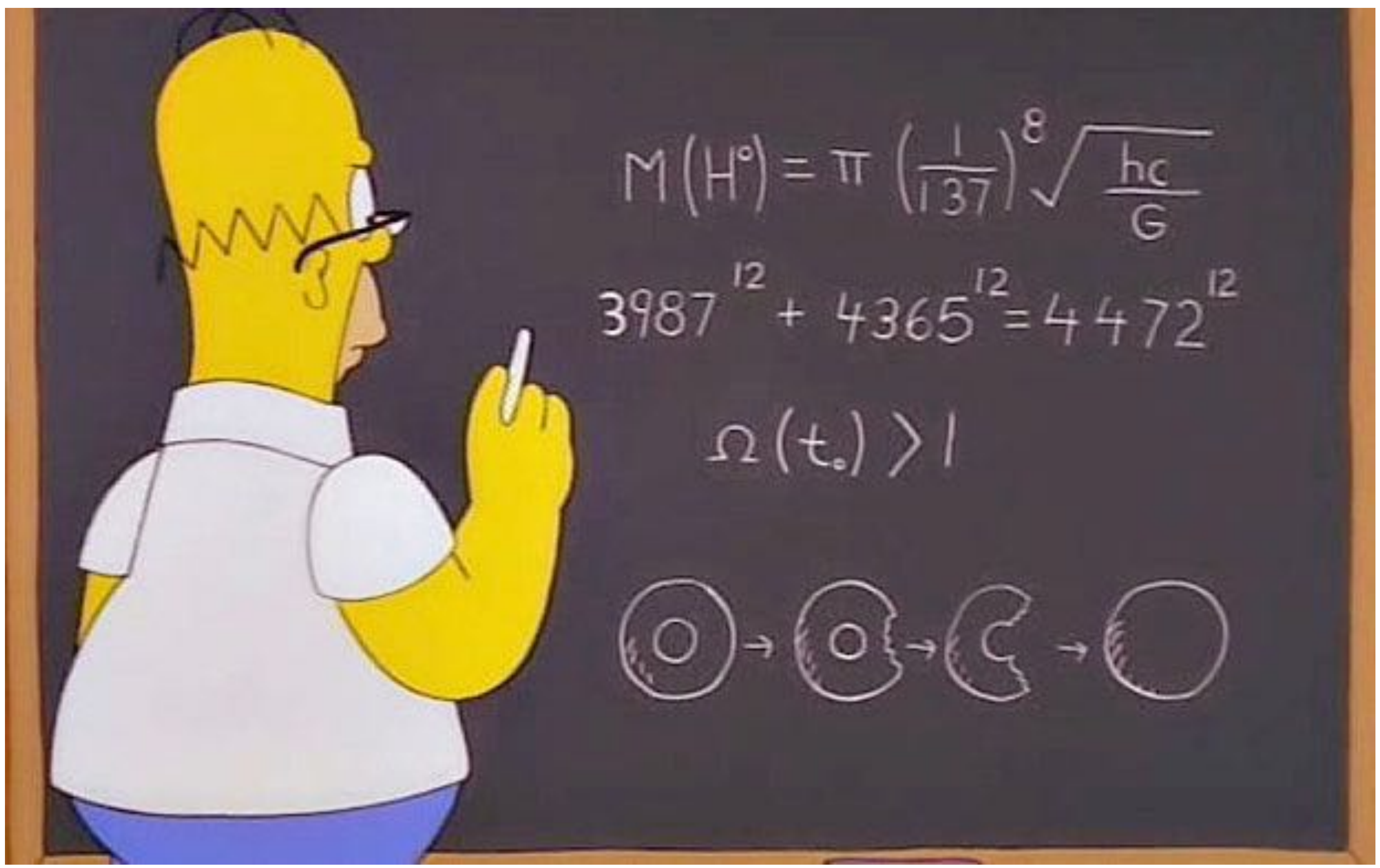
The Story Goes Like This…

- A scheme about origin of elementary particle mass was proposed in 1964, and predicted a new particle.
- A long scientific expedition of searching for this mysterious particle set off and continued ever since then…
- Theory does not predict where (what mass) to look for this particle.



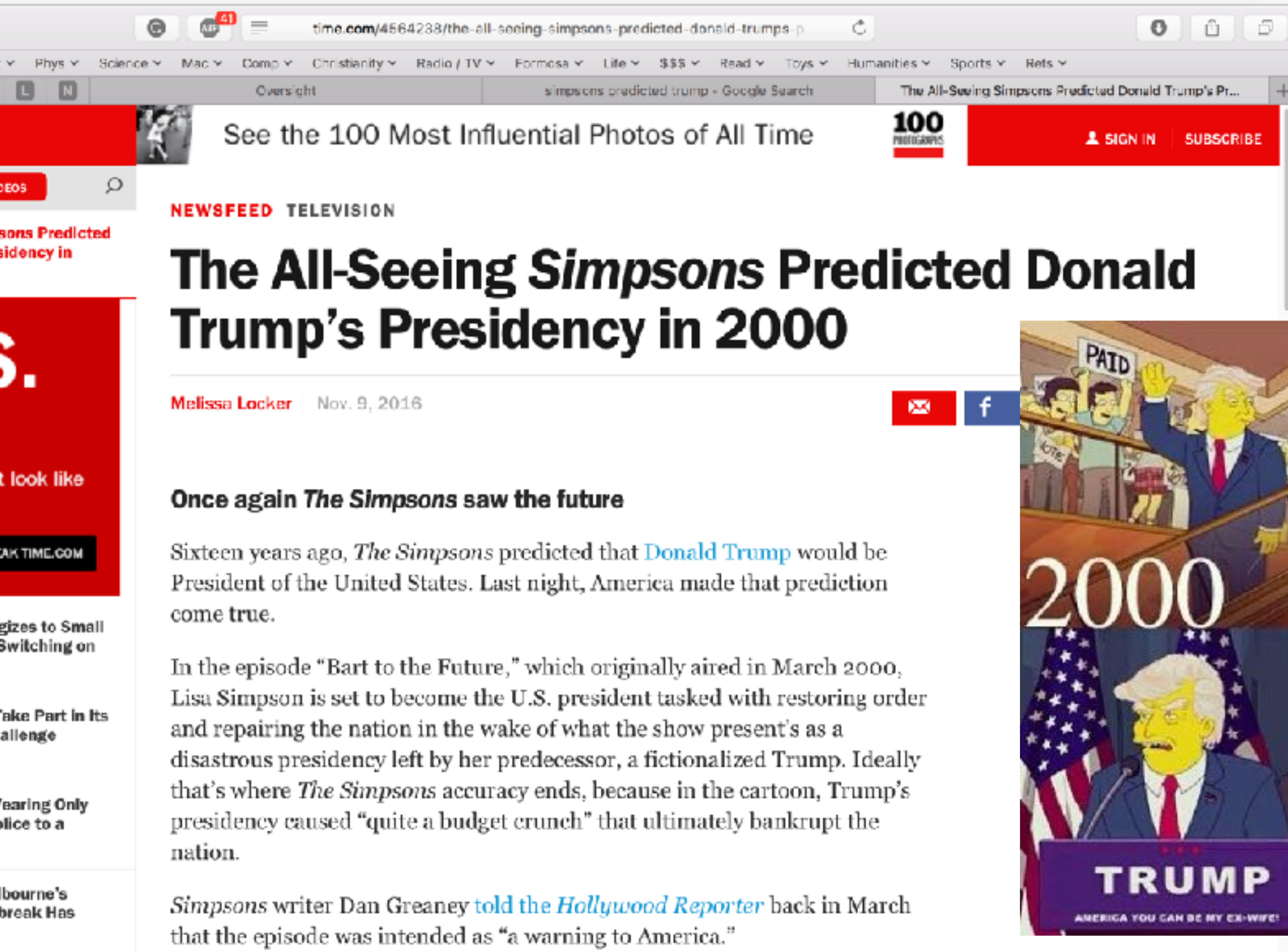
Simpson's Prediction

- According to a science writer, Homer Simpson predicted the mass of the Higgs boson in a 1998 episode of The Simpsons.



Simpson's Prediction

- Simpson also predicted who the US president would be.


time.com/4564238/the-all-seeing-simpsons-predicted-donald-trumps-p

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The All-Seeing *Simpsons* Predicted Donald Trump's Presidency in 2000

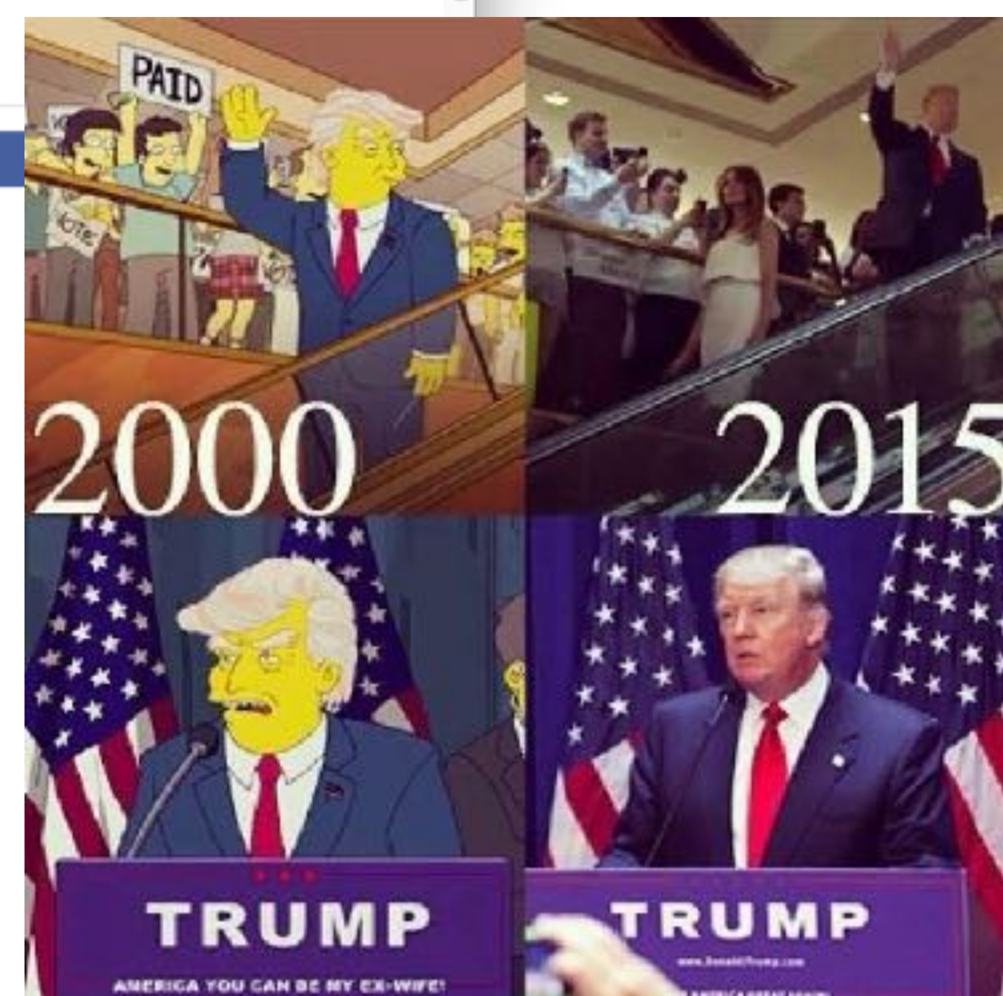
Melissa Locker | Nov. 9, 2016

Once again *The Simpsons* saw the future

Sixteen years ago, *The Simpsons* predicted that Donald Trump would be President of the United States. Last night, America made that prediction come true.

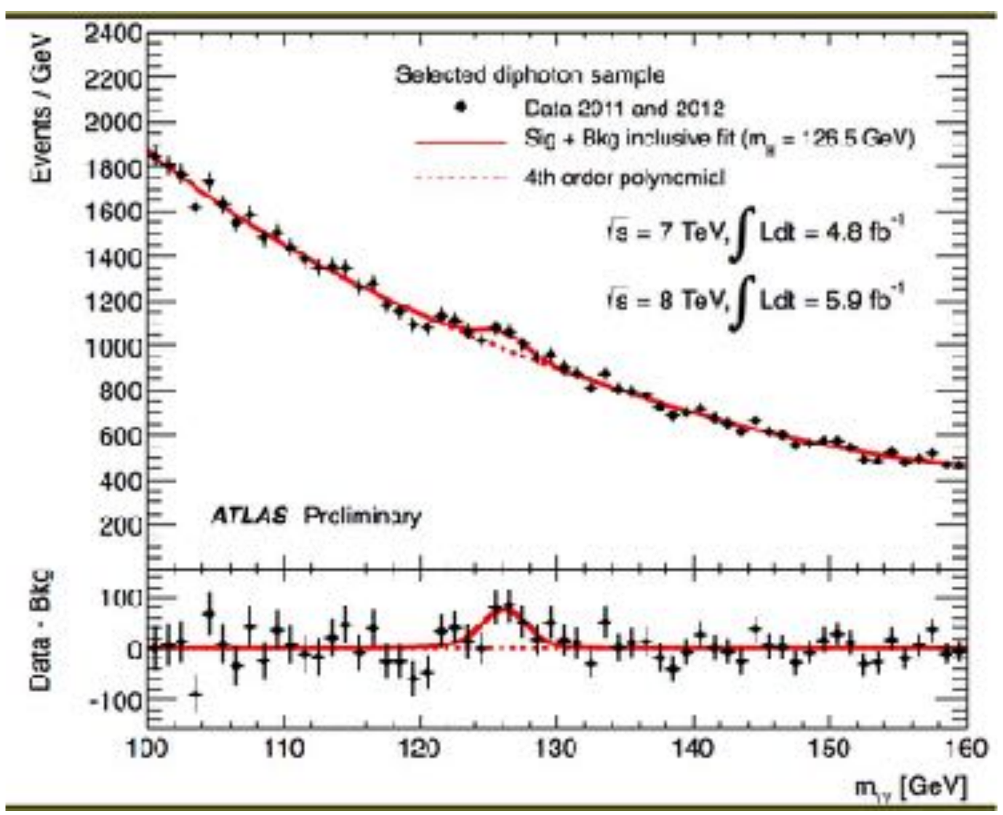
In the episode "Bart to the Future," which originally aired in March 2000, Lisa Simpson is set to become the U.S. president tasked with restoring order and repairing the nation in the wake of what the show present's as a disastrous presidency left by her predecessor, a fictionalized Trump. Ideally that's where *The Simpsons* accuracy ends, because in the cartoon, Trump's presidency caused "quite a budget crunch" that ultimately bankrupt the nation.

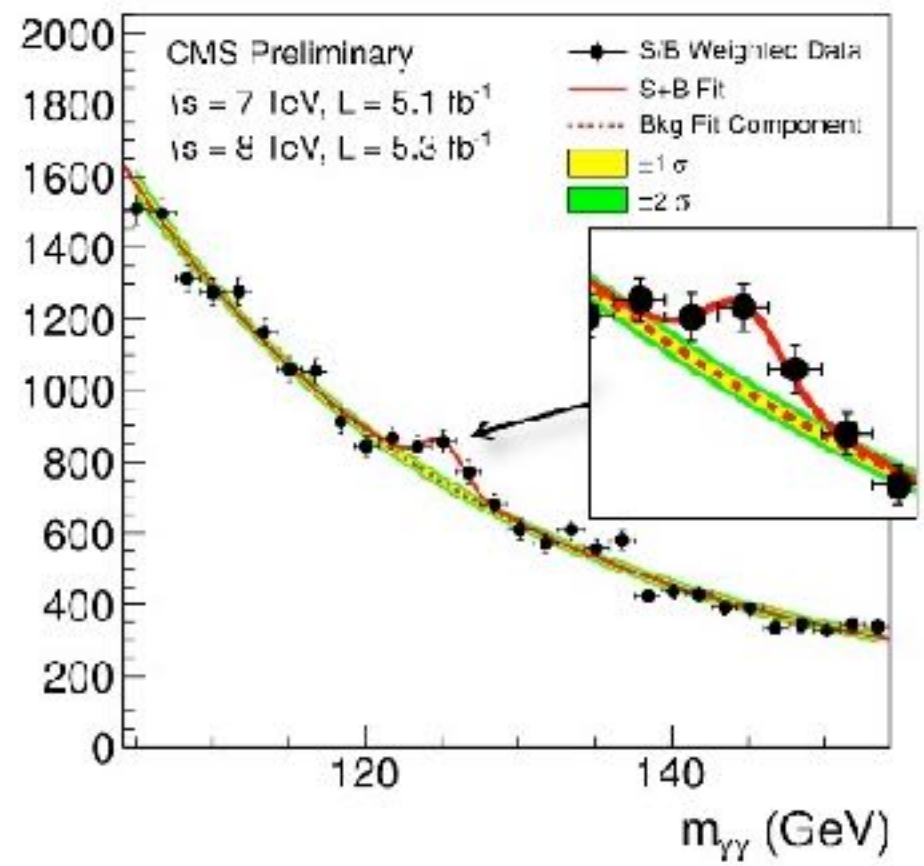
Simpsons writer Dan Greaney told the *Hollywood Reporter* back in March that the episode was intended as "a warning to America."



The Story Goes Like This...

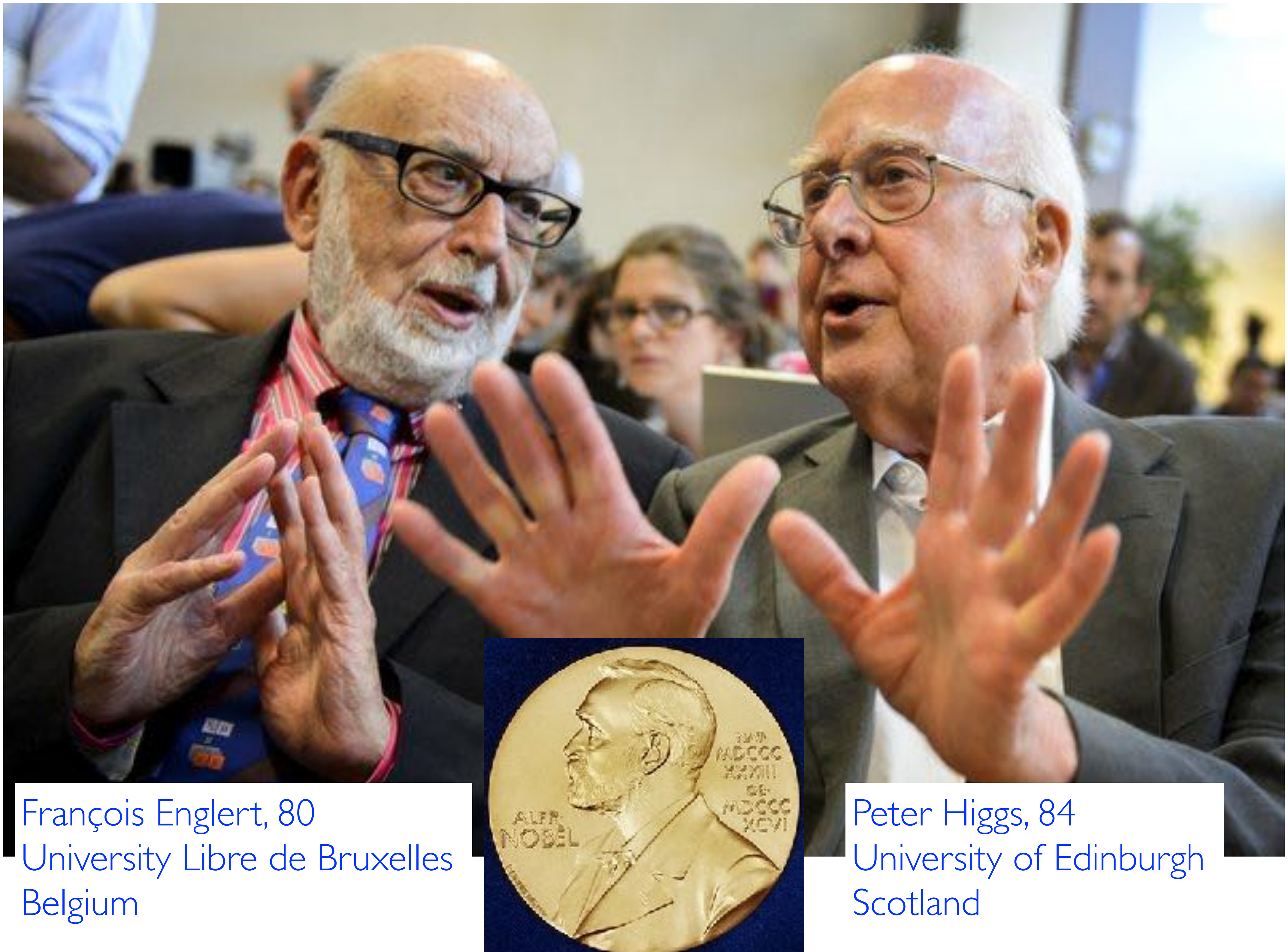
- On a breezy summer day in 2012, CERN experimentalists announced the discovery of a Higgs-like particle by showing the following plots:





- It was later confirmed as a SM-like Higgs boson in 2013 after examining more data and cross checks.

Nobel Laureates of 2013



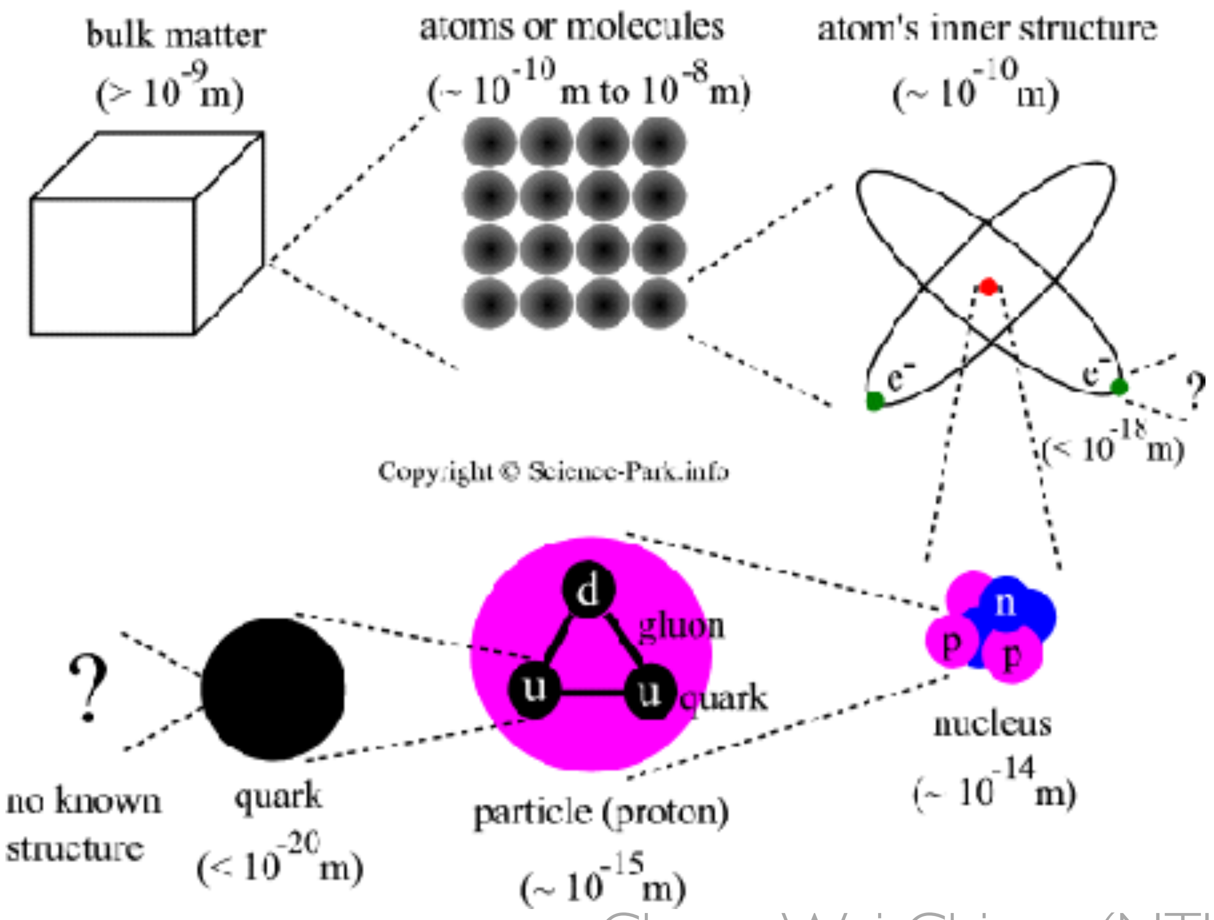
François Englert, 80
University Libre de Bruxelles
Belgium

Peter Higgs, 84
University of Edinburgh
Scotland

ORIGIN OF MASS

What Is Mass?

- Mass is an intrinsic property of matter, and is additive from its smallest constituents.
  ➠ sum rule of mass
- Ordinary matter is made of atoms.
- Atoms are made of protons, neutrons, and electrons.
- Most (> 99.95%) of the mass of an atoms comes from the nucleons located inside the tiny nucleus.



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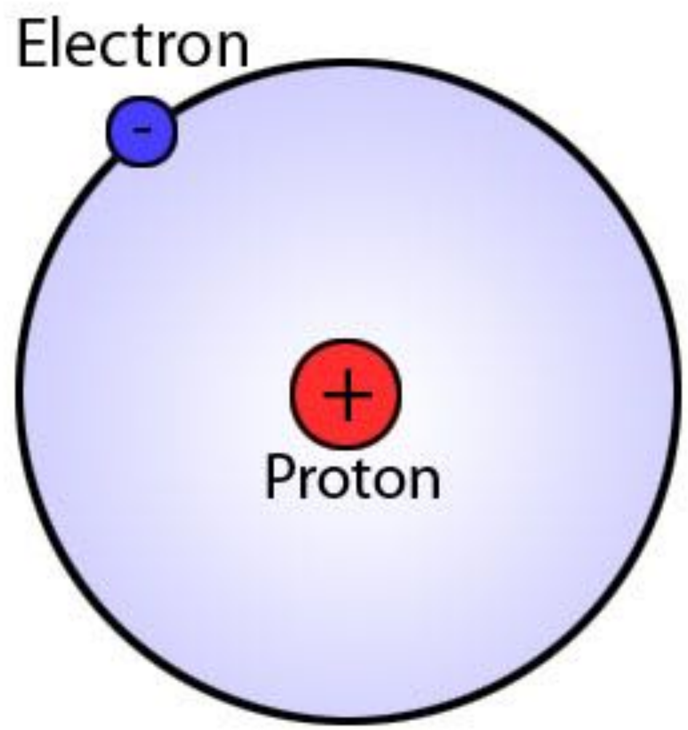
Hydrogen

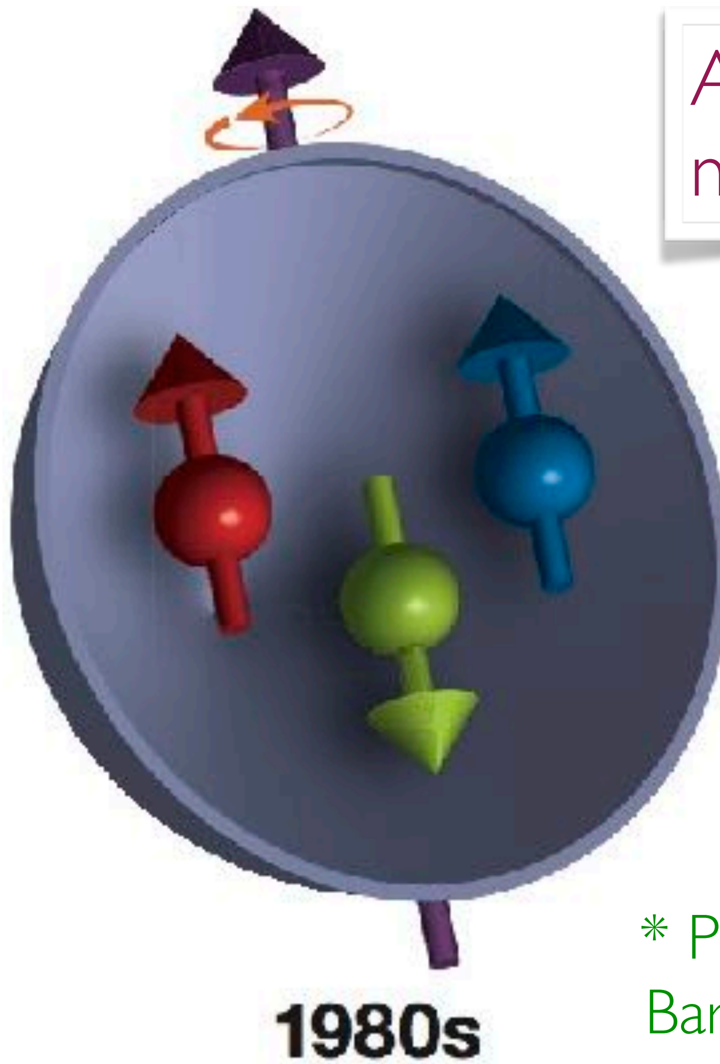
- Hydrogen atom is a composite particle with a radius about 0.0529 nm.



$$m_H = m_p + m_e$$

Proton / Neutron

- Proton (likewise neutron) is a composite particle with a charge radius about 0.877 fm.



A naive picture ~30 yrs ago
more static

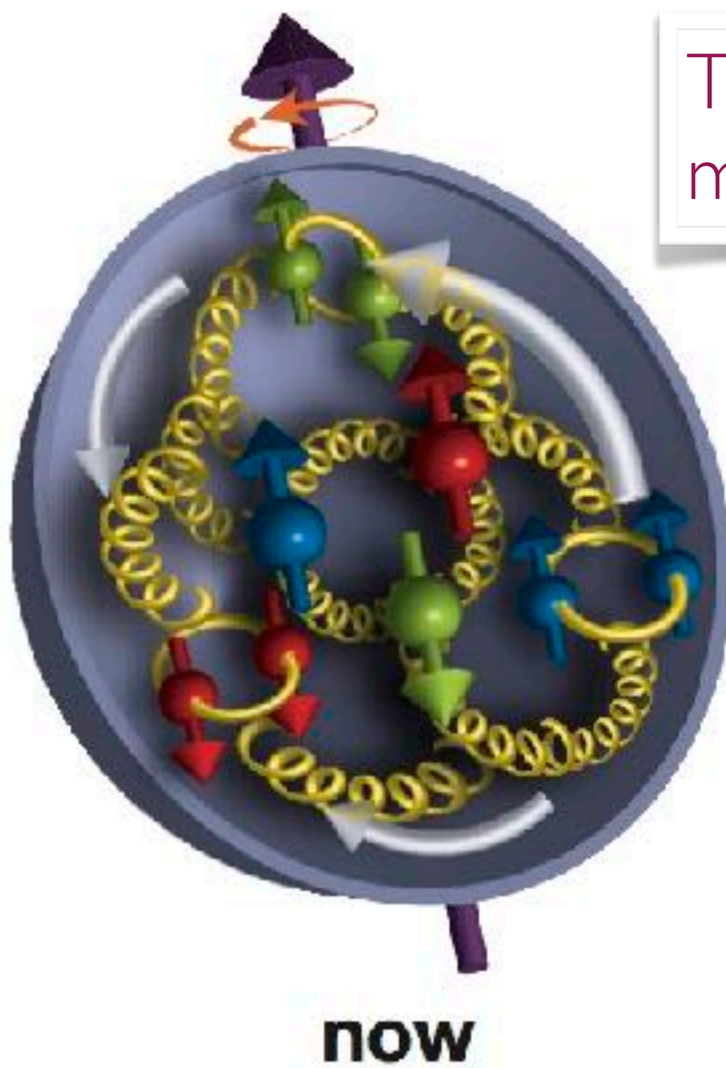
* Proton size anomaly
Barger, CWC, Keung, Marfatia PRL 2011

$$\underbrace{m_p}_{940\ \mathrm{MeV}} \gg 2\underbrace{m_u}_{2.5\ \mathrm{MeV}} + \underbrace{m_d}_{5\ \mathrm{MeV}}$$

Proton / Neutron

- Most mass (~ 99%) inside nucleons actually comes from gluon interactions, instead of the constituent quarks.

The modern picture now more dynamical



$$m_p = 2m_u + m_d + \text{gluon interaction energy}$$

Origin of Mass

- Most mass of ordinary matter in Universe comes from potential energy of strong interactions, not elementary particles.
  ➠ ~ 99% mass explained

- Even though tiny, what is the origin of mass for elementary particles?
- How do these supposedly massless particles (due to the gauge principle) become massive?

Symmetry Rules

- "Symmetry dictates interactions."
  — C.N. Yang

- Fundamental interactions in Nature are governed by local symmetries (gauge field theories):
  - electromagnetic interaction (first unification, late 1800s)
    ➠ U(1) gauge symmetry (unbroken!)
    ➠ guarantees electric charge conservation
  - electro-weak interaction (second unification, ~1970)
    ➠ $SU(2)_L \times U(1)_Y$ gauge symmetry (broken!)
    ➠ at a deeper level, Nature has such a symmetry

Massive Gauge Boson

- Gauge invariance forbids gauge bosons to obtain mass.
- Take a U(1) gauge theory (e.g., EM) as an example,

$$\mathcal{L} \ni \frac{1}{2} m_A^2 A_\mu A^\mu$$

is NOT invariant under the gauge transformation:

$$A^\mu(x) \to A^\mu(x) + \partial^\mu \Lambda(x) \quad \text{or} \quad \begin{cases} V \to V + \partial_t \Lambda \\ \mathbf{A} \to \mathbf{A} - \nabla \Lambda \end{cases}$$

- The gauge boson (e.g., photon) should be massless, transversely-polarized and long-range interactions.
- How do we consistently give masses to weak force mediators (known to mediate a short-range interaction)?

ELECTROWEAK SYMMETRY BREAKING

A Simplified Version

- The mechanism involves a complex scalar field with a global U(1) symmetry (or SO(2) in components), a two-dimensional rotation symmetry in an internal space:

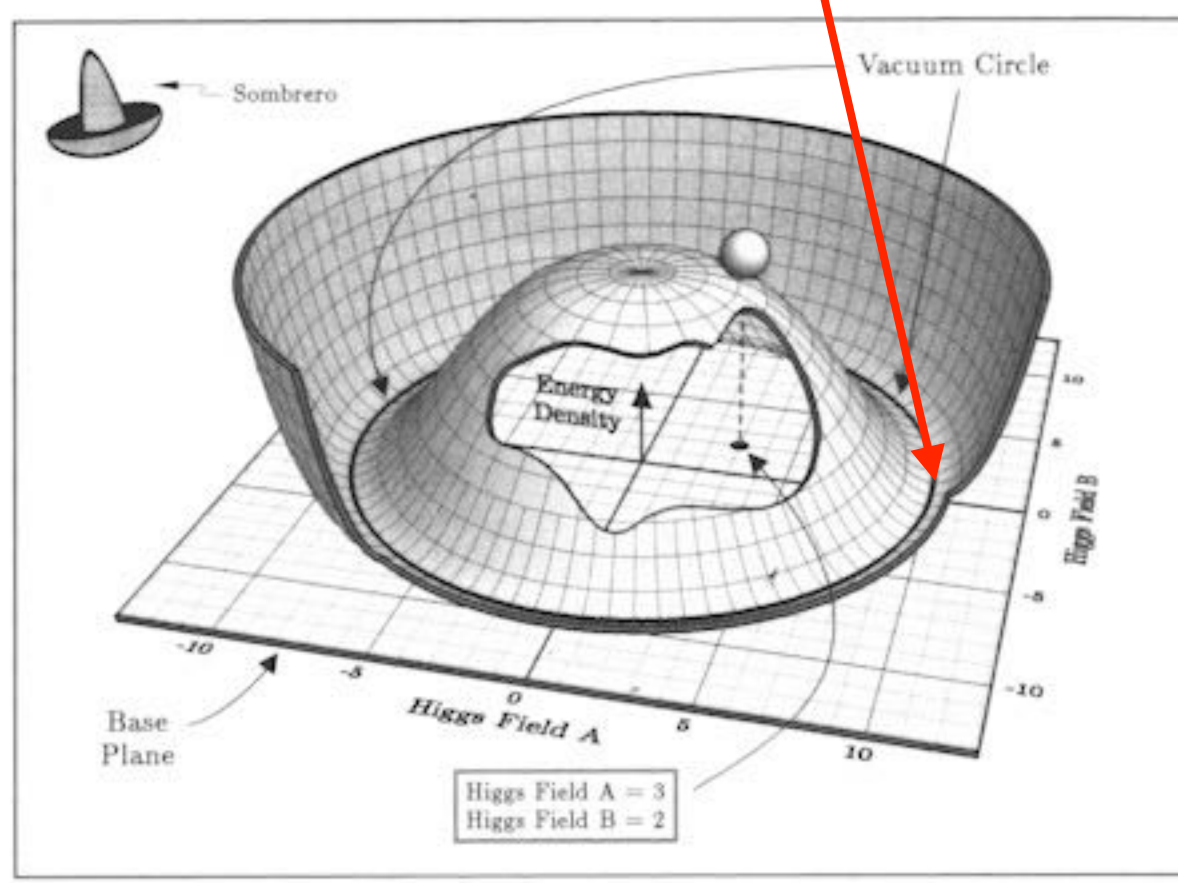
$$\mathcal{L}_\phi = \partial_\mu \phi^* \partial^\mu \phi - V(\phi^* \phi) \qquad \phi \to e^{-i\alpha(x)} \phi$$

Mexican-hat or wine-bottle potential

$$V = -\mu^2 |\phi|^2 + \frac{\lambda}{4} |\phi|^4 \qquad (\mu^2, \lambda > 0) \qquad |\phi|^2 = 2\mu^2/\lambda \equiv v^2$$

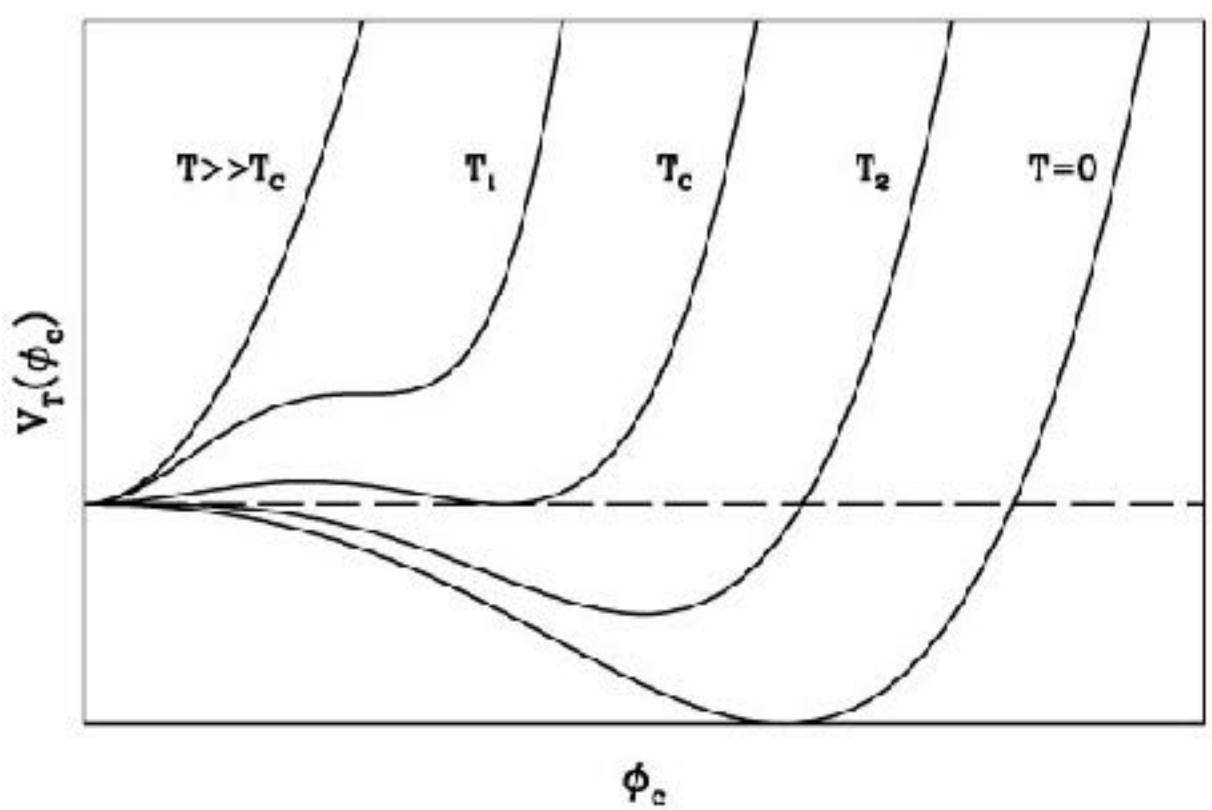
v ~ O(200 GeV) at T = 0.

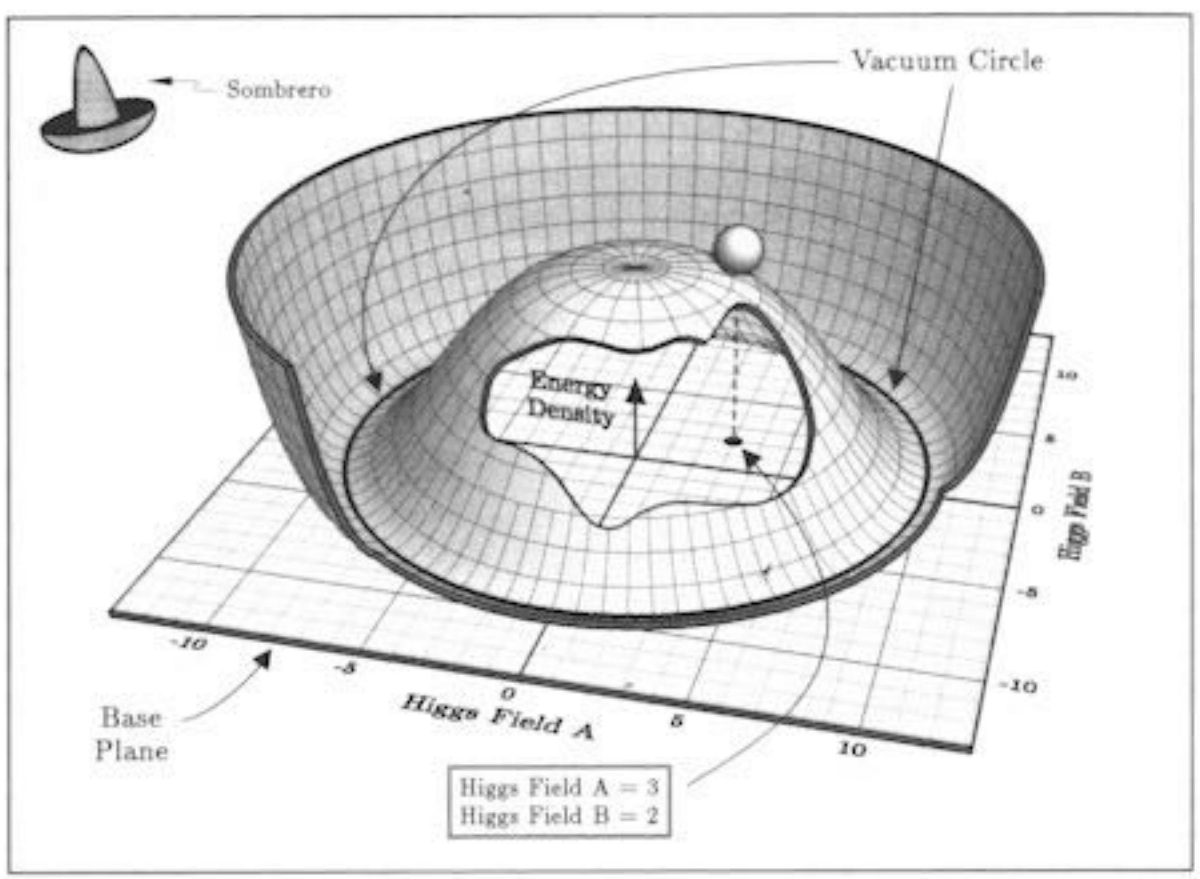
- The process of turning on the VEV is triggered by an unstable symmetry origin.



Electroweak Phase Transition

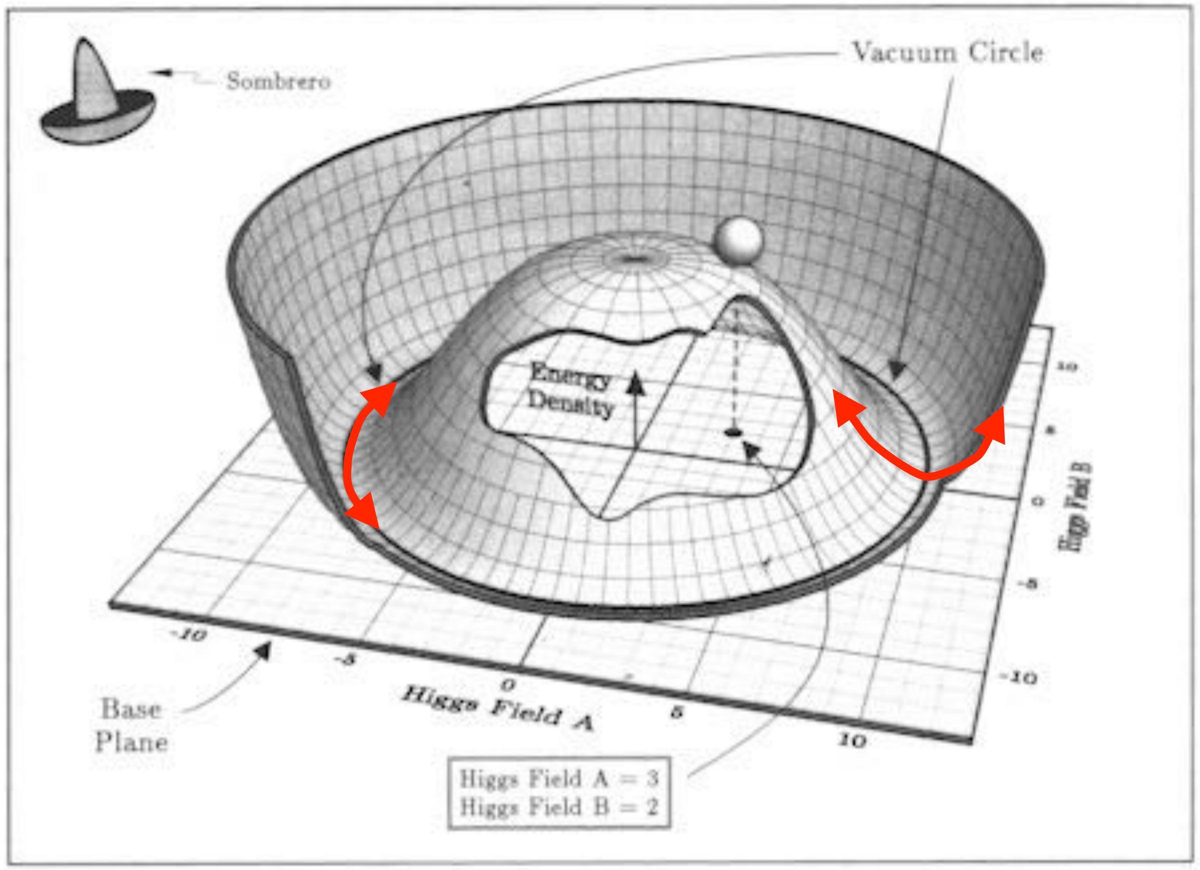
- As the Universe cools down, the Higgs field throughout the Universe undergoes a phase transition, from the unstable symmetry phase to a more stable but symmetry-broken phase, like water going from vapor phase to liquid phase.
- Particles are then traveling in Higgs "ocean" rather than Higgs "atmosphere," thus acquiring their masses.





The Higgs Boson

- After the symmetry breaking, we still have two dof's:
  - one in the radial direction with mass $m^2 = 2\lambda v^2$;
  - the other in the azimuthal direction with zero mass!
- Zero-mass mode is the Nambu-Goldstone (NG) boson, to become longitudinal modes of the gauge boson.
  ➠ 3 polarization components
  ➠ massive gauge bosons
- In general, there would be one NG boson for each broken symmetry of the theory.



BEH or Higgs Mechanism

Higgs 1964; Englert and Brout 1964; Guralnik, Hagen and Kibble 1964 (**not just Higgs!**)

- When the scalar field is coupled to a gauge field, endowing a vacuum expectation value (VEV) to the scalar field makes the gauge boson massive:

$$\mathcal{L} \ni |D_\mu \phi|^2 \qquad \text{where } D_\mu = \partial_\mu - igQA_\mu$$

$$\ni -g^2 v^2 A_\mu A^\mu$$

m_A^2, squared mass of A_μ

- Gauge symmetry is not ‘broken’, but simply ‘hidden’.
- This is the so-called BEH or Higgs mechanism.

Electroweak Unification

Glashow 1961; Weinberg 1967; Salam 1968

- Employ the BEH mechanism to break the $SU(2)_L \times U(1)_Y$ symmetry down to the $U(1)_{EM}$ symmetry.
  ➠ Standard Model of particle physics

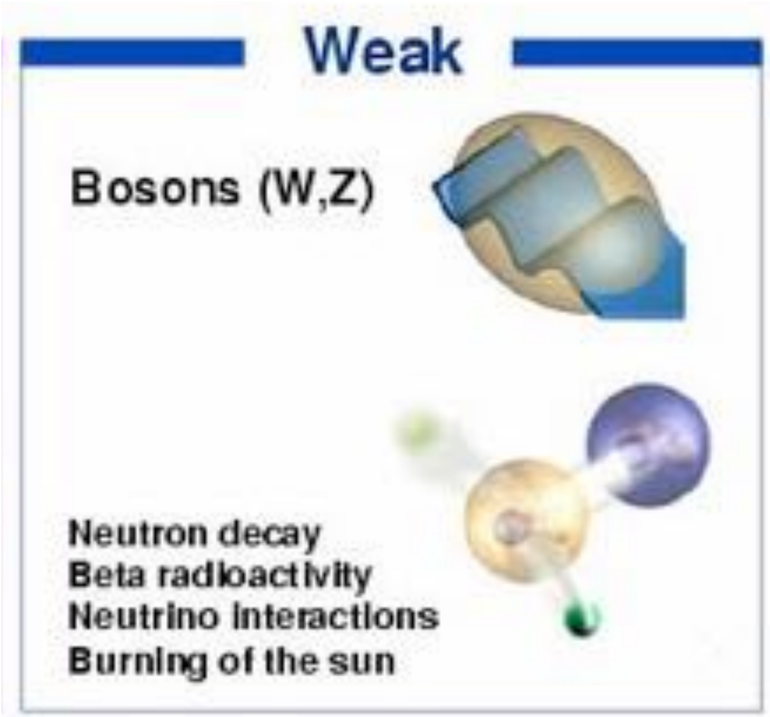
"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"

1979 Nobel Prize in Physics


Sheldon Lee Glashow

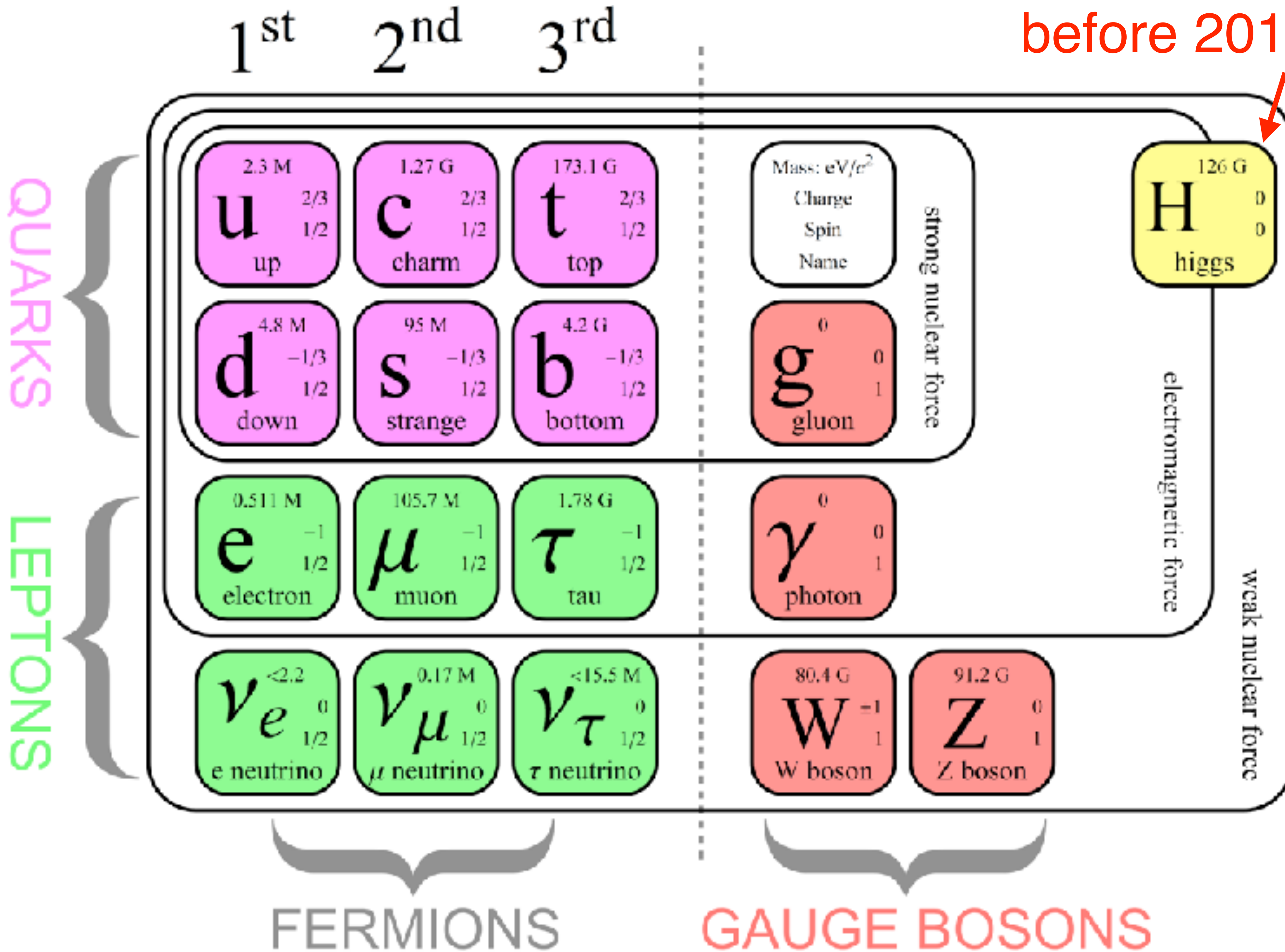

Abdus Salam


Steven Weinberg



Standard Model

last piece yet seen
before 2012 summer



spin-0

spin-1/2 spin-1

Cheng-Wei Chiang (NTU)

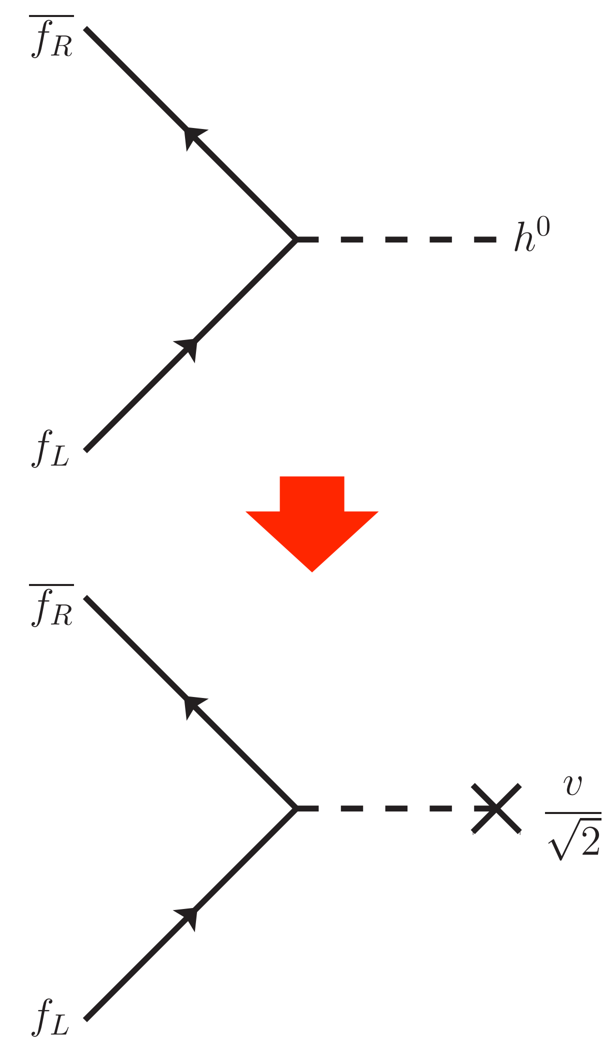
Fermion Masses

- In the SM, an economic/necessary* way of giving mass to charged fermions is through the so-called Yukawa interactions:

$$\mathcal{L}_Y \ni -y_f \left(\overline{f_L} \cdot \Phi\right) f_R + \text{h.c.}$$

$$SU(2)_L \qquad \mathbf{2} \quad \mathbf{2} \quad \mathbf{1}$$

$$\to -\underbrace{y_f \langle \Phi \rangle}_{m_f} \overline{f_L}\, f_R$$

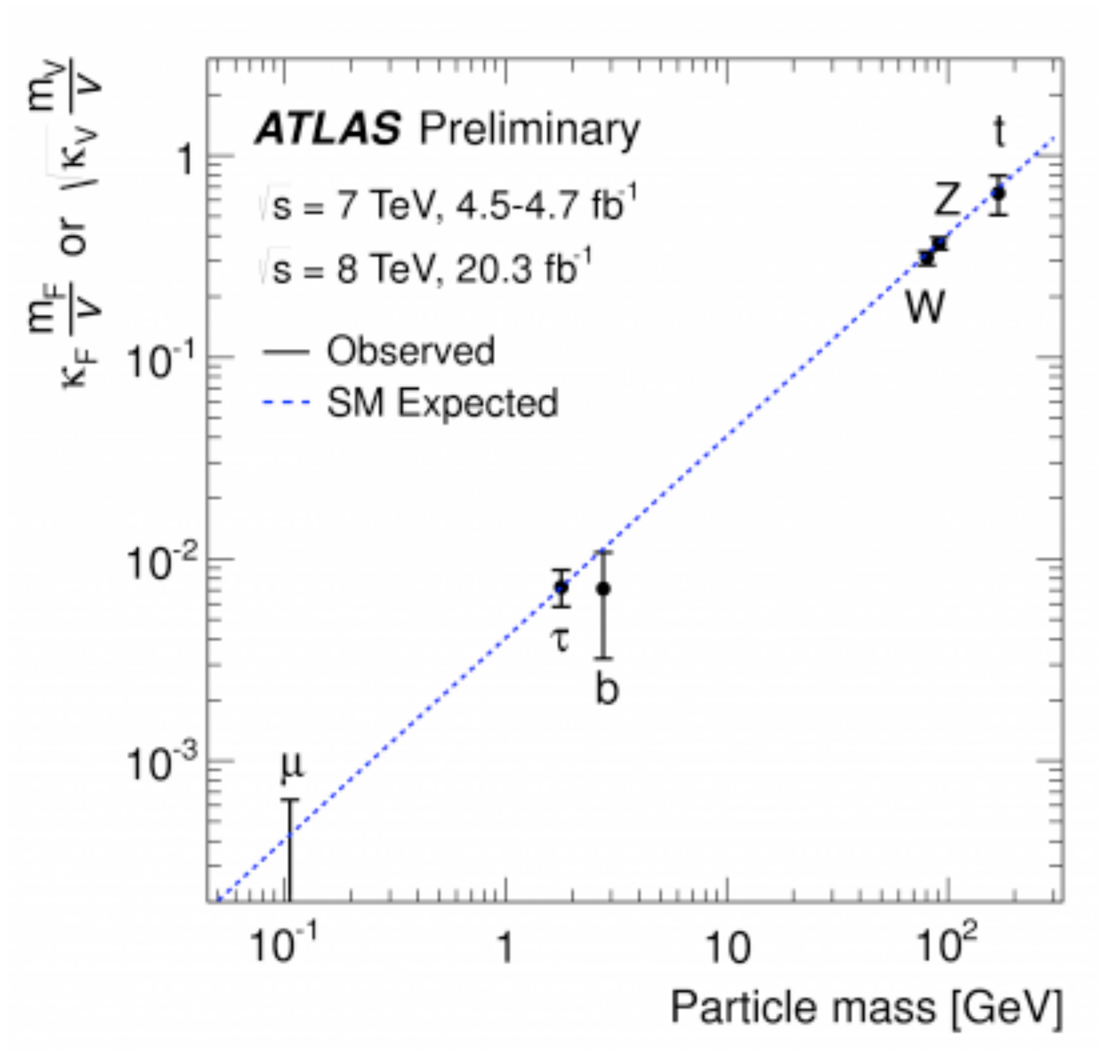


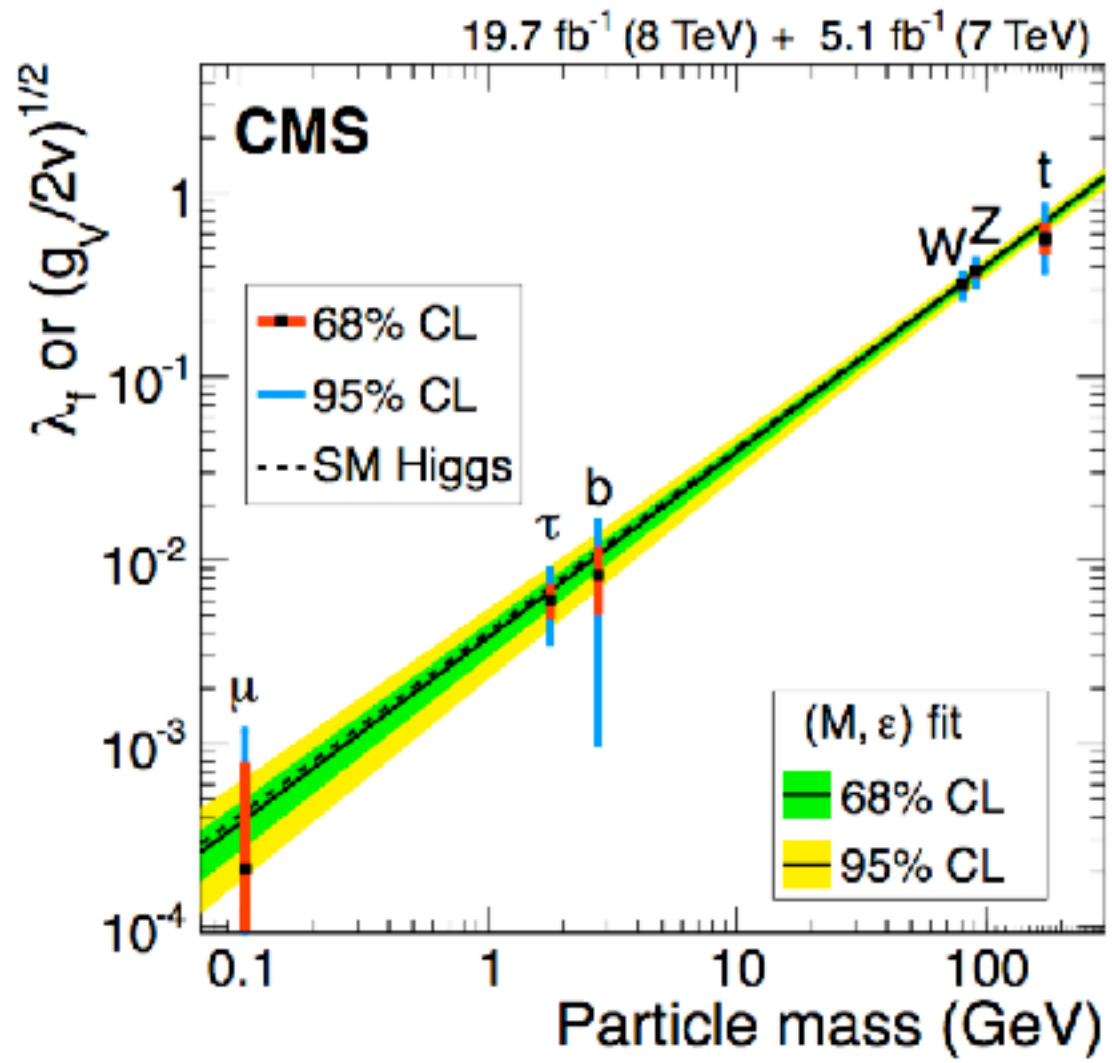
- The fermion masses are thus also proportional to the VEV of the Higgs field.
  ➠ killing two birds with one stone!

* Weinberg's view on effective theory: all terms allowed by gauge symmetry should be included in Lagrangian.

Higgs Couplings to Particles

- It is important to verify the linear relation of SM particle couplings to the Higgs boson – a unique feature of SM.



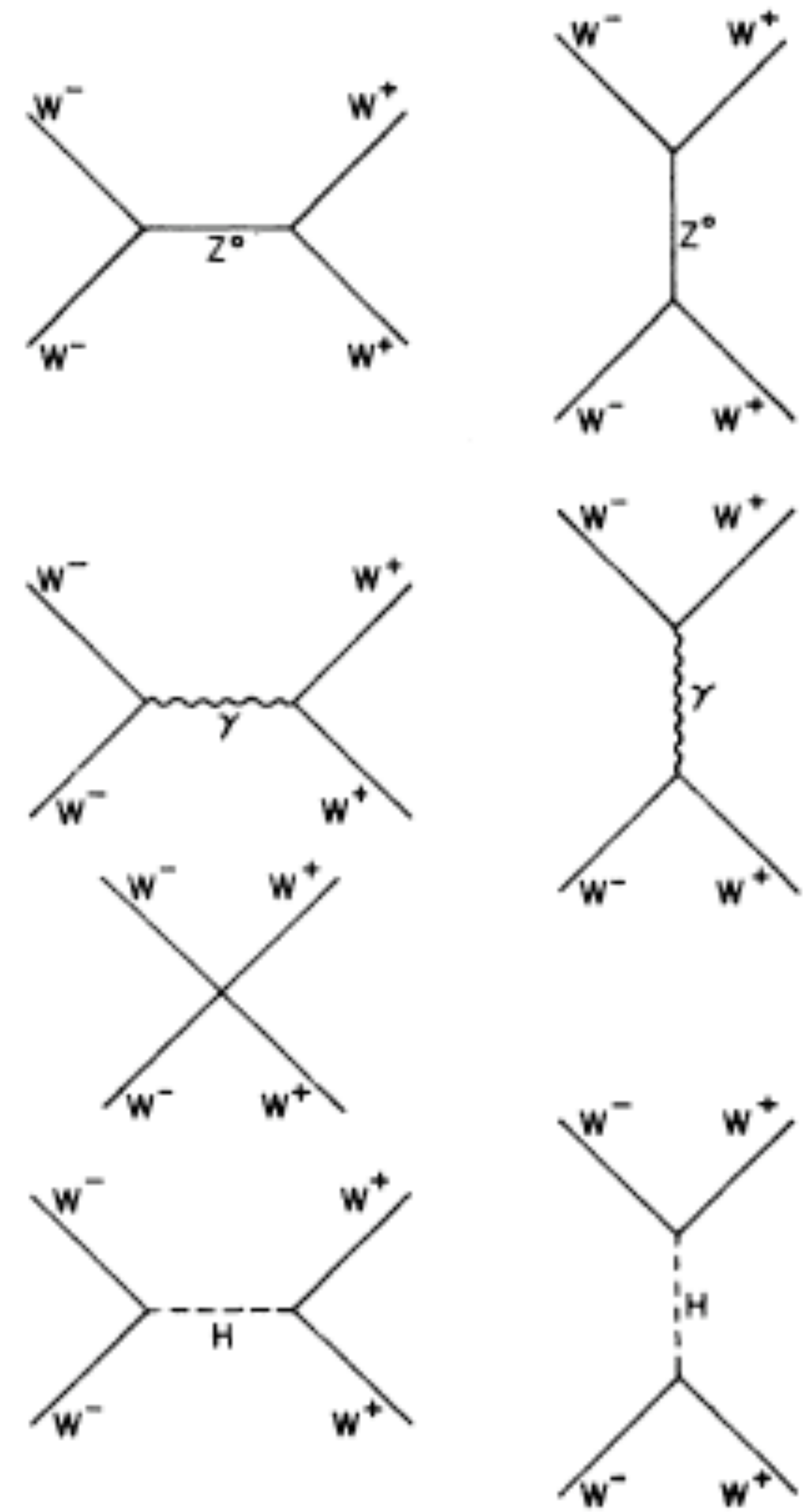


- So far, the particle is very much standard model-like.

$W_L W_L \rightarrow W_L W_L$

Lee, Quigg, Thacker 1977

- Remember that the longitudinal components have the origin from the Higgs sector.
- Consider this process in the SM in the $s \gg m_h^2, M_W^2$ limit.
- Tree-level Feynman diagrams in the unitarity gauge:
  - 1 four-point interaction;
  - Z and γ in s and t channels; and
  - Higgs boson in s and t channels.
- Other $V_L V_L \rightarrow V_L V_L$ scatterings have similar structures.



$W_L W_L \to W_L W_L$

- Individual amplitudes of gauge diagrams are functions of scattering energy, angle, and particle masses:

$$i\mathcal{M}_4 = i\frac{g^2}{4M_W^4}\left[s^2 + 4st + t^2 - 4M_W^2(s+t) - \frac{8M_W^2}{s}ut\right]$$

$$i\mathcal{M}_t^{\gamma+Z} = -i\frac{g^2}{4M_W^4}\left[(s-u)t - 3M_W^2(s-u) + \frac{8M_W^2}{s}u^2\right]$$

$$i\mathcal{M}_s^{\gamma+Z} = -i\frac{g^2}{4M_W^4}\left[s(t-u) - 3M_W^2(t-u)\right]$$

  where s,t,u ~ E^2 .

  ➠ Individual diagrams grow like $(E/M_W)^4$!

- The sum of them nicely cancel with each other to remove such a divergence.

$W_L W_L \to W_L W_L$

- However, there is still an O((E/M$_W$)^2) divergence in the sum, which needs a sufficiently light Higgs boson to cure:

$$i\mathcal{M}^{\text{gauge}} = -i\frac{g^2}{4M_W^2}u + \mathcal{O}\left((E/M_W)^0\right) \;, \quad \sim \left(\frac{E}{M_W}\right)^2$$

$$i\mathcal{M}^{\text{Higgs}} = -i\frac{g^2}{4M_W^2}\left[\frac{(s-2M_W^2)^2}{s-m_h^2} + \frac{(t-2M_W^2)^2}{t-m_h^2}\right]$$

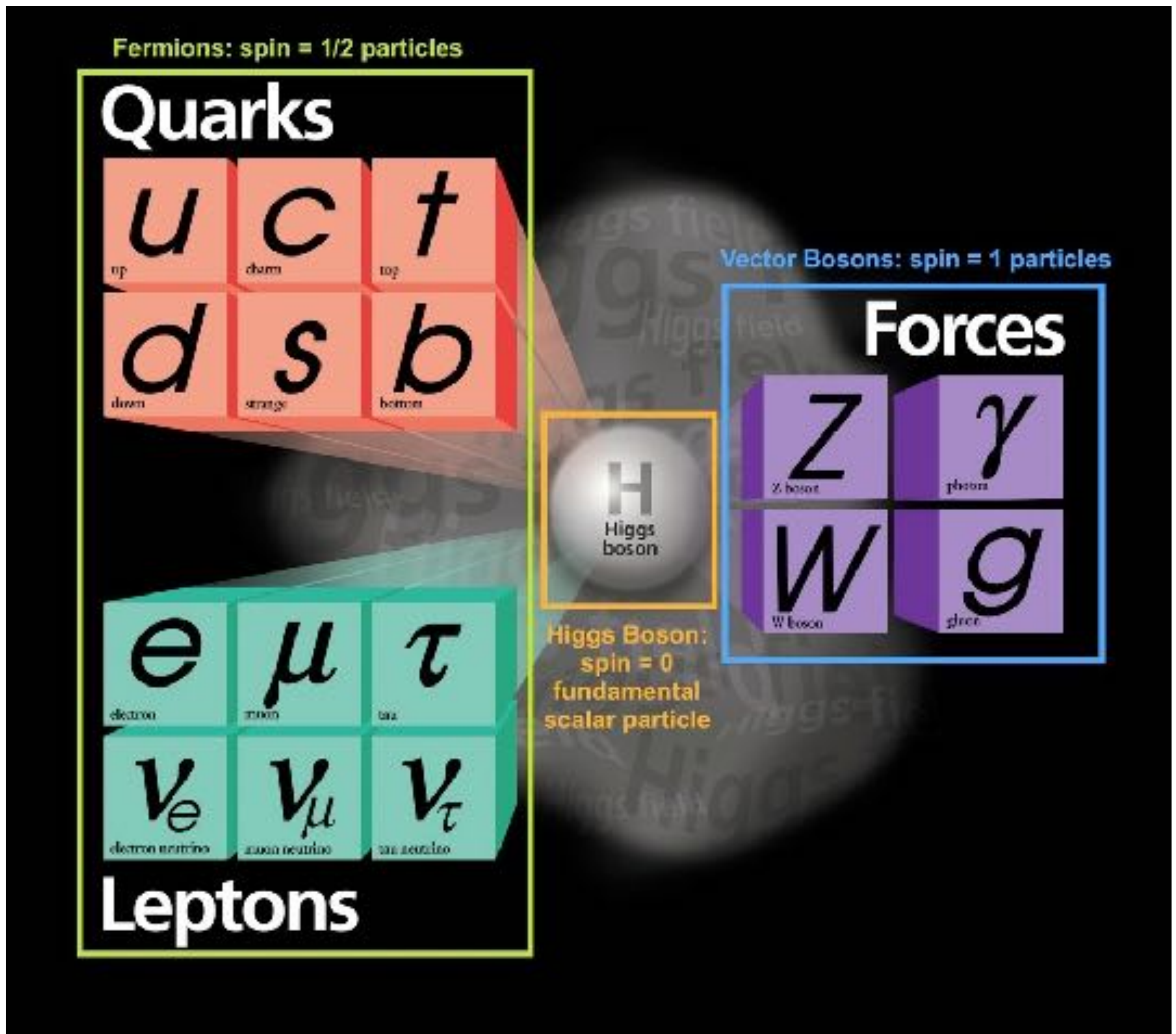
$$\simeq i\frac{g^2}{4M_W^2}u + \mathcal{O}\left((E/M_W)^0\right) \;.$$

$$\Rightarrow \text{ complete } (E/M_W)^2 \text{ cancellation}$$

- Success of SM is seen to rely on nice relations among gauge bosons couplings (due to gauge structure) and a suitable Higgs boson (depending on EWSB structure).

The Holy Grail

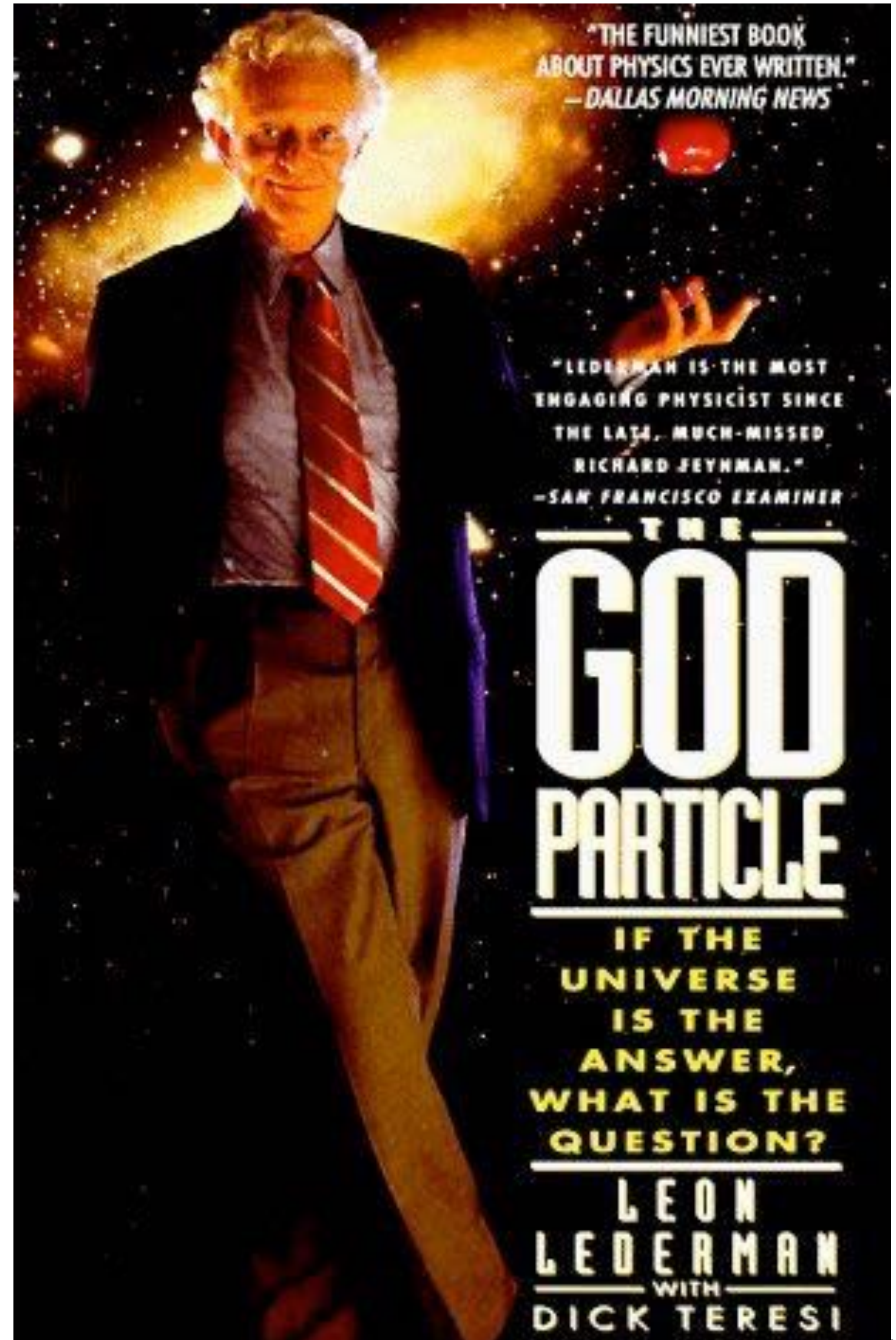
- The Higgs boson holds the secret to the origin of mass for elementary particles.



GOD PARTICLE OR GODDAMN PARTICLE?

The God Particle

- *The God Particle: If the Universe Is the Answer, What is the Question?* is a 1993 popular science book by Nobel laureate Leon M. Lederman and science writer Dick Teresi.
- Official reason: the particle is "so central to the state of physics today, so crucial to our final understanding of the structure of matter, yet so elusive."



The God Particle

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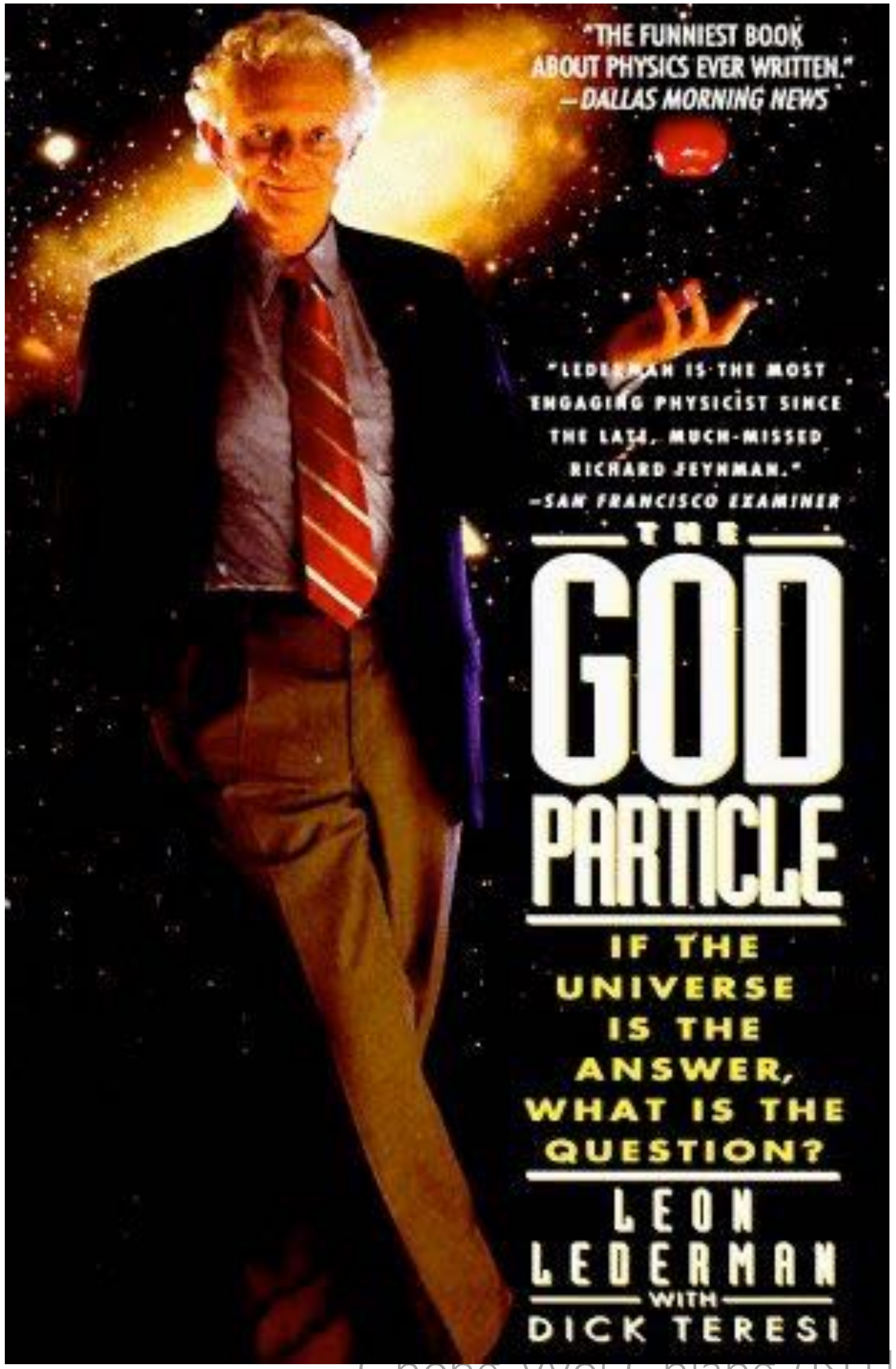
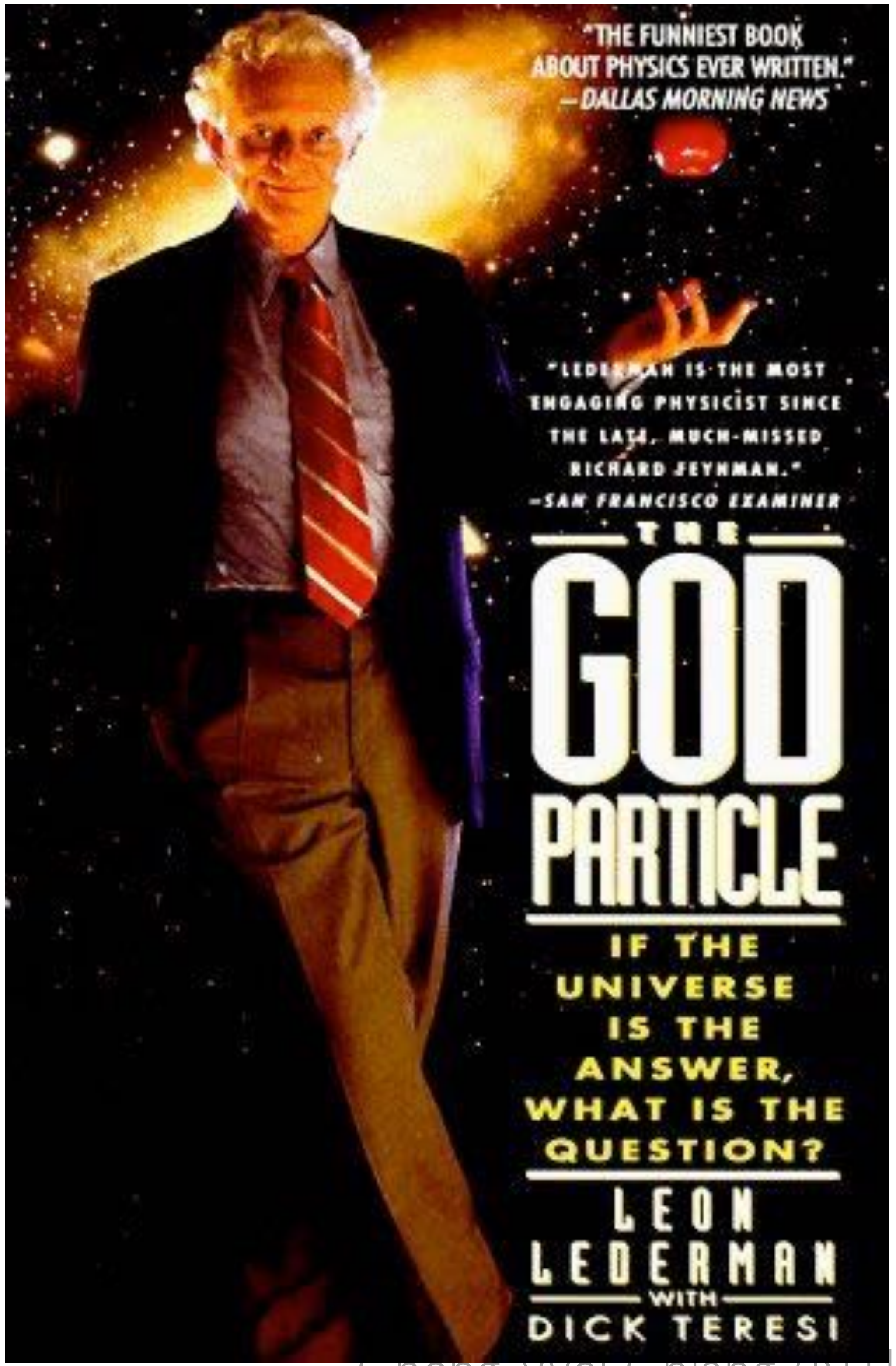
- Second reason: "I was planning to call my book 'The Higgs Particle', but the editor said that no one had ever heard of Higgs."



The God Particle

- *The God Particle: If the Universe Is the Answer, What is the Question?* is a 1993 popular science book by Nobel laureate Leon M. Lederman and science writer Dick Teresi.
- Third reason: "the publisher wouldn't let us call it the Goddamn Particle, though that might be a more appropriate title, given its villainous nature and the expense it is causing."



Pandora's Box

- Almost all current particle physics problems are rooted in the Higgs field! ➠ The stone hits a beehive!

$$\mathcal{L}_{\text{Higgs}} = |D_\mu \phi|^2 - V_0 + \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2 - \sum_{ij} y_{ij} \overline{\psi}_{iL} \psi_{jR} \phi + \text{h.c.}$$

massive weak gauge bosons

tiny vacuum energy
$V_{obs} \sim (2\times10^{-3}\ \text{eV})^4$

origin of the negative coefficient unclear; quadratic divergence in Higgs mass correction

possible instability of the potential at high energies

source of flavor problems: mass hierarchy, CP violation, etc

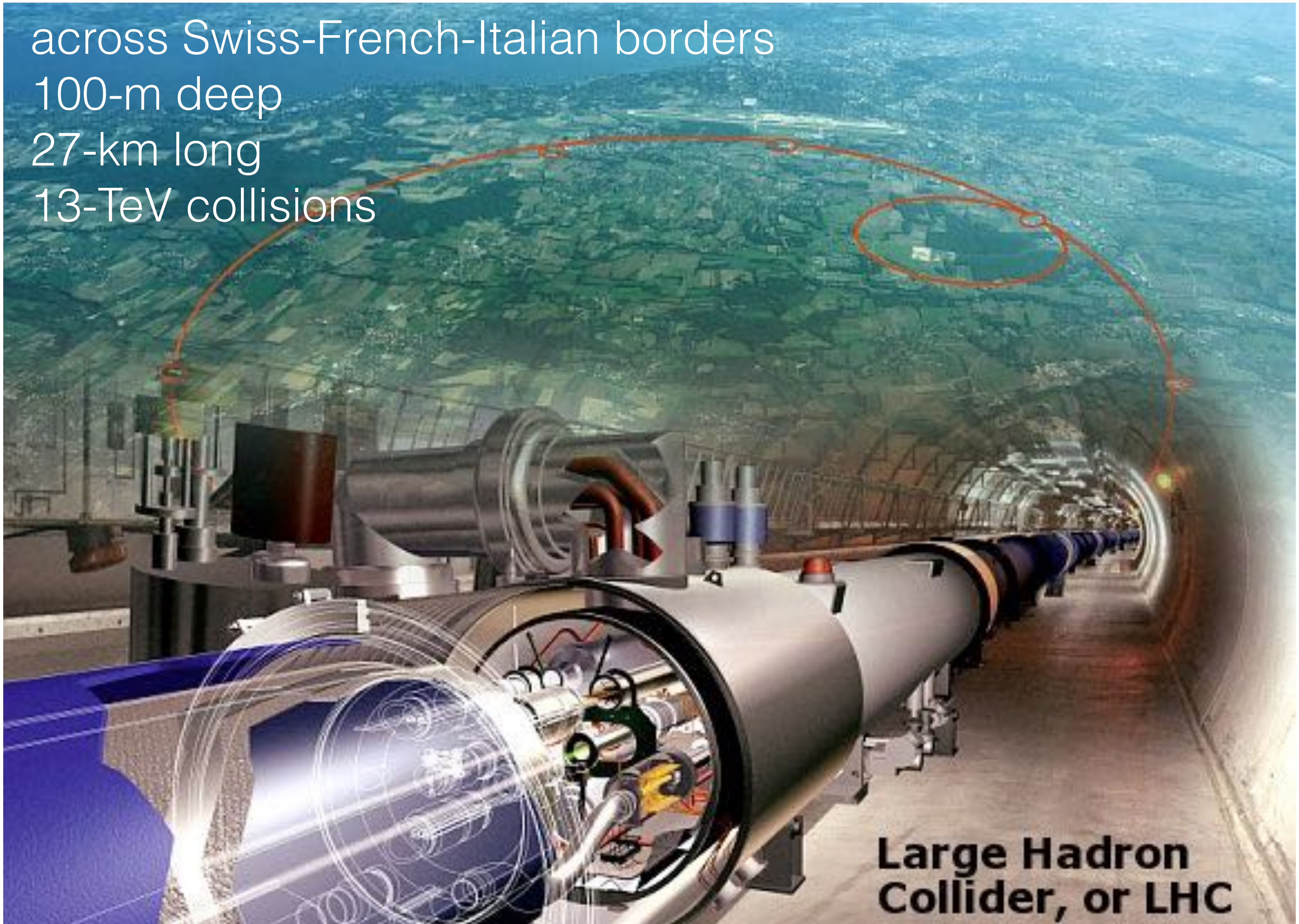
(NTU)

Why is it Elusive?

- Discovery of the Higgs boson is thus very essential:
  - ➠ completes the spectrum of SM
  - ➠ answers origin of elementary particle mass
  - ➠ justifies previously mentioned problems
  - ➠ possibly points us to physics beyond SM
- It has been searched for almost half a century!
- Why is it so elusive?

- How can we produce the Higgs boson?
  - ➠ how many per unit time we can create at colliders
- How does it decay?
  - ➠ which modes we should use for detection

Large Hadron Collider



My Talk @ PSROC 2006

Purposes of the LHC

[Quoted from LHC website]

- With the LHC the aim is to continue to push our understanding of the fundamental structure of the universe. The results from the LHC might shed light on:
  - Dark energy
  - Dark matter
  - Extra dimensions
  - Higgs
  - Supersymmetry

- A broader notion is that we want to learn and study any sort of possible new physics from LHC experiments.

My Talk @ PSROC 2006

Possible Outcomes of LHC Exp'ts

- Expect possibly chaotic data from LHC during its commission and first-year runs.
- Afterwards, be prepared to face the following possibilities:
  - The SM Higgs boson is found, but nothing else;
  - Nothing new is found;
  - Many new particles are discovered.
- The first case may be acceptable by the public, but for experts it means that conventional particle physics is dead.
- The second case will be embarrassing, but it is somewhat theoretically interesting.
- The last case is the best; but are we ready to study them?

My Talk @ PSROC 2006

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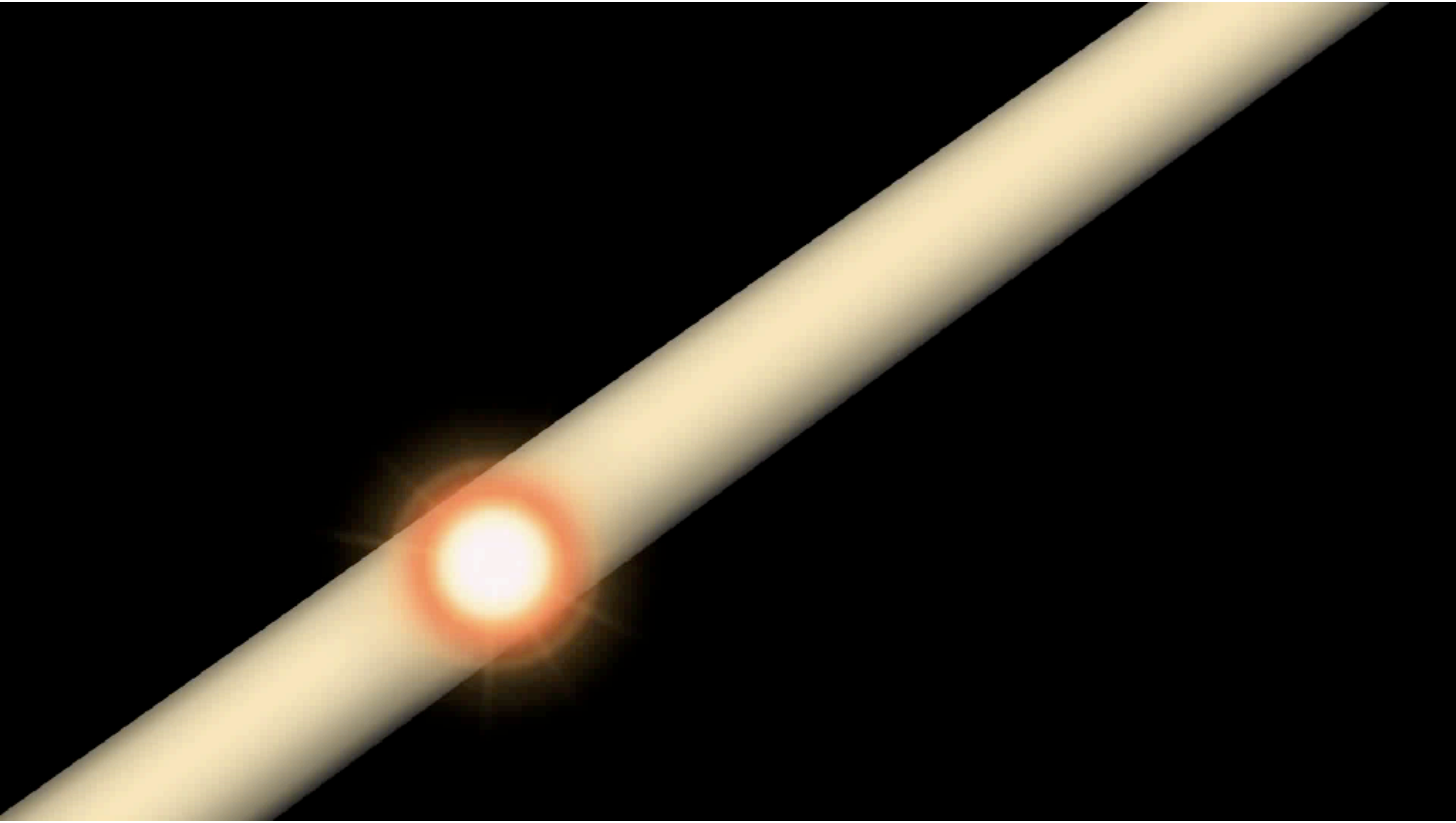
Worst scenario for us

What We Need is Time

- It took us about half a century to discover the Higgs boson predicted by Higgs et al.
- It took us a whole century to detect gravitational waves from black hole and neutron star mergers predicted by Einstein's theory.
- It took us decades to finally see the photo of a black hole in M87 one month ago.

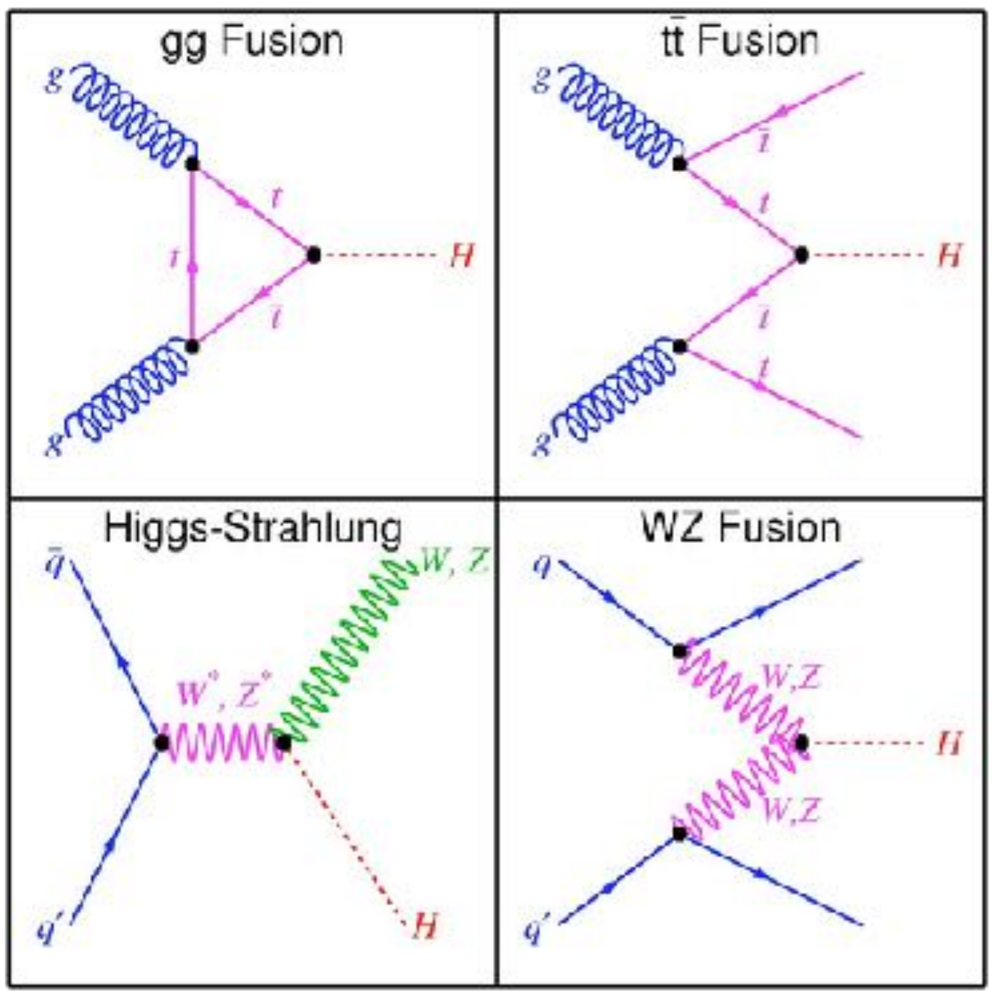
- Important physics results are worth waiting. It often takes time to verify a good theory.

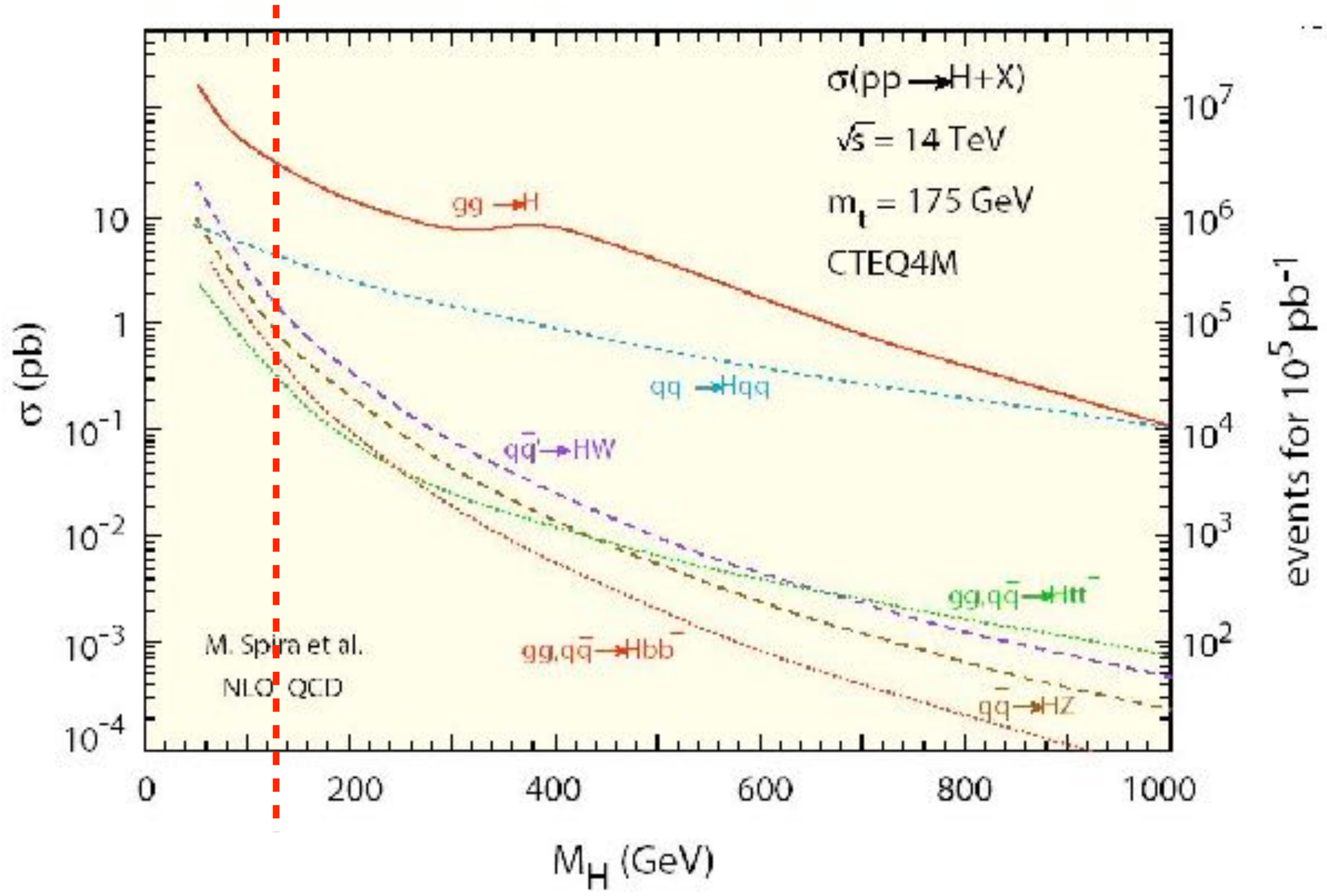
Large Hadron Collider



Major Higgs Production

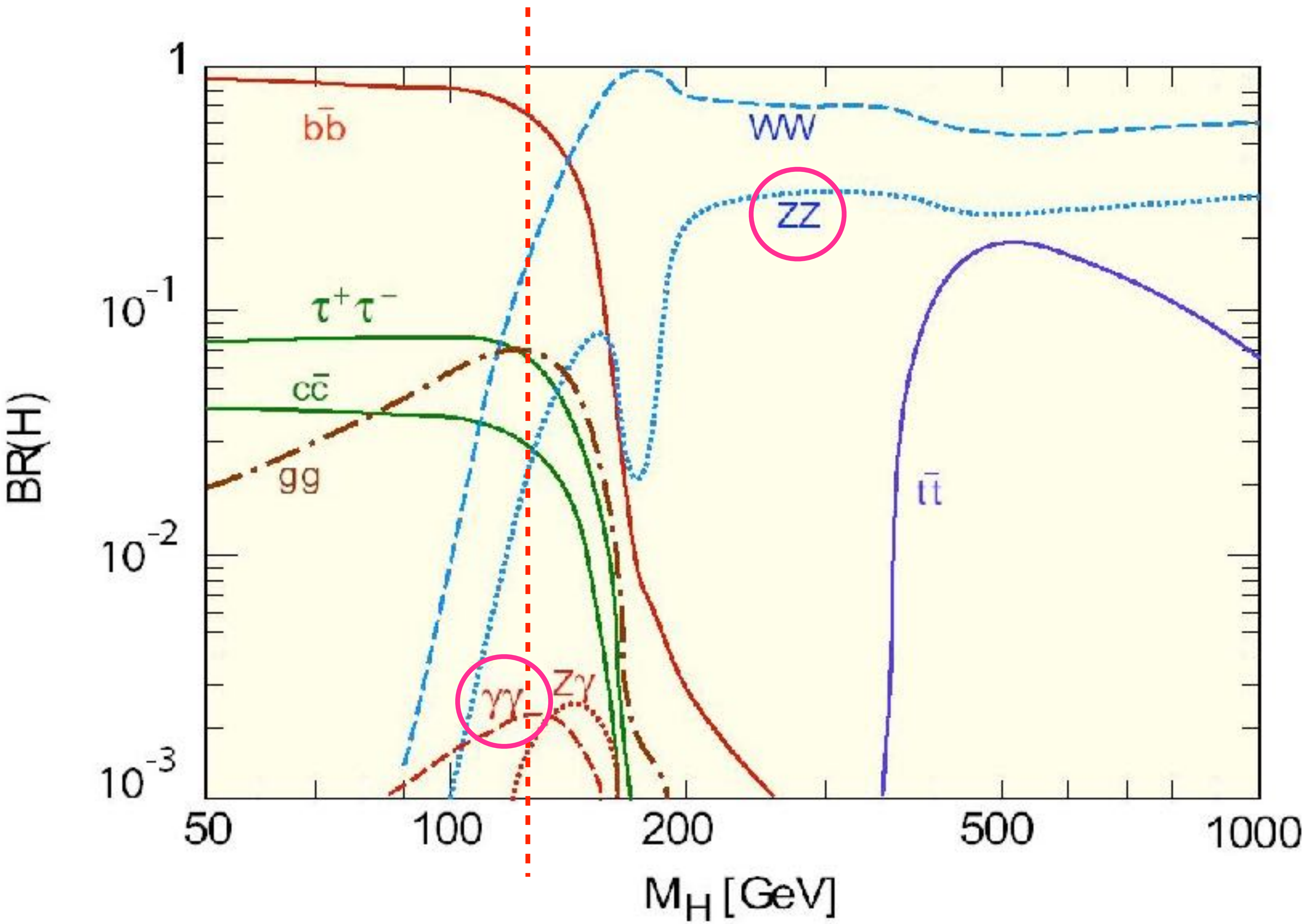
- Hard processes:



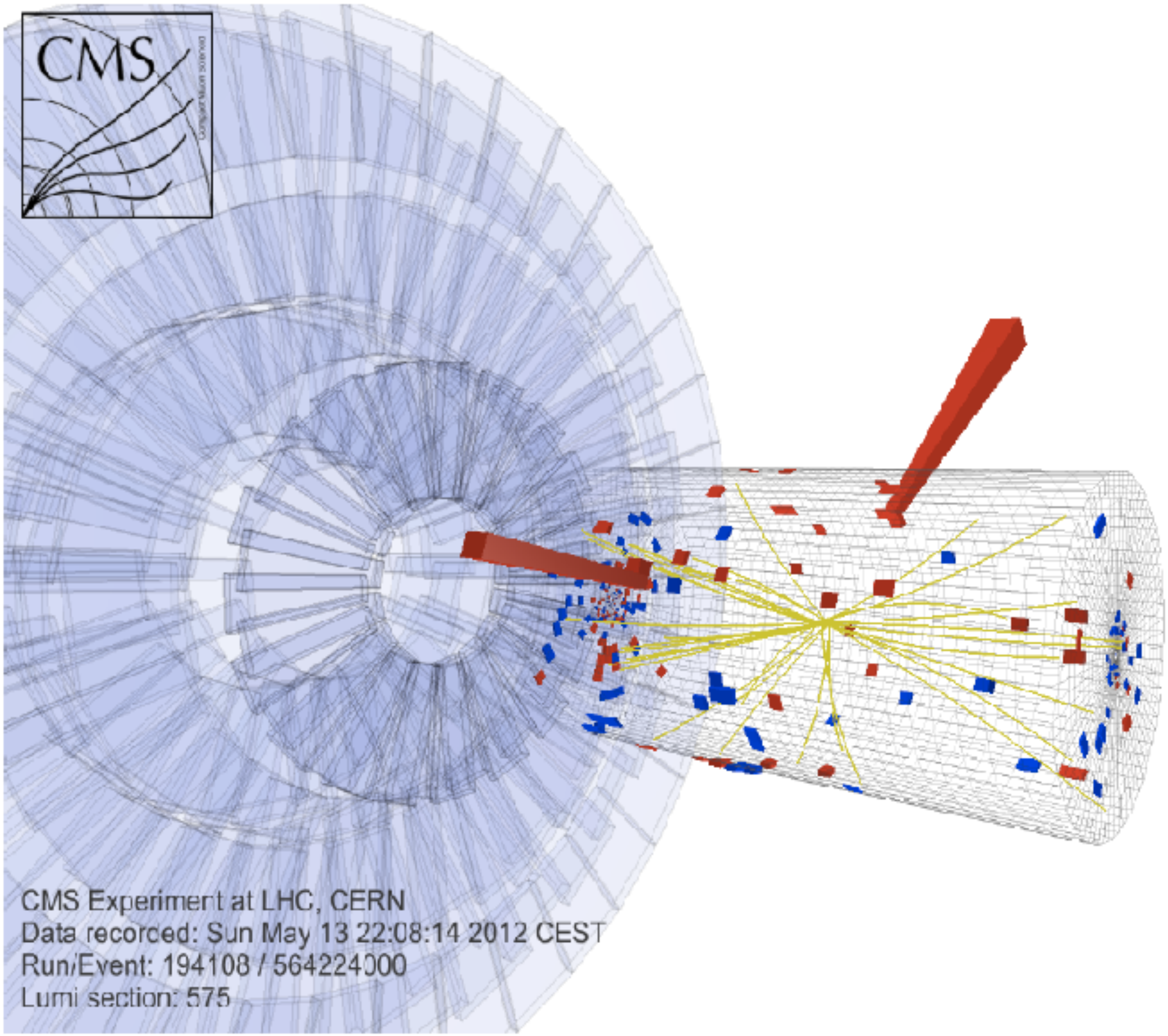


$$1 \text{ pb} = 10^{-36} \text{ cm}^2 = 10^{-10} \text{ fm}^2$$

Higgs BR's in SM



A Higgs To Diphoton Event



Event parameters:

$M_{\gamma\gamma}$ = 125.9 GeV

$p_T^{\gamma 1}$ = 89.8 GeV

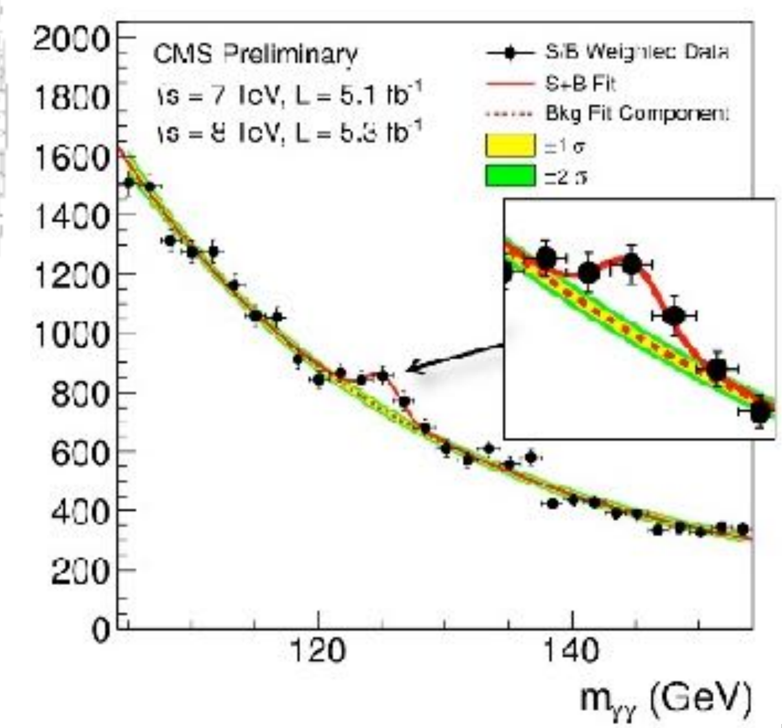
$p_T^{\gamma 2}$ = 46.5 GeV

$\eta_{\gamma 1}$ = 0.06

$\eta_{\gamma 2}$ = -0.81

σ_M/M =0.89%

$p_T^{\gamma\gamma}$ =78.4 GeV



Frantic Collisions

- At design luminosity of LHC, there are ~ 20 interactions every time beams cross. Beams will cross about 40 million times/sec at final configuration.
  ➠ about a billion interactions/sec (a billion frames/sec!), of which only about 10 SM Higgs bosons are produced

Where's Waldo?

After the Discovery

- Is this the Standard Model Higgs boson? (SM-like now)
- How does it interact with other SM particles exactly?
- How does it undergo electroweak phase transition?
- Does it have cousins (beyond the SM)?
- Will it open a door to new physics that is more transparent only at a higher energy scale?

EXTENDED HIGGS SECTOR

"*All models are wrong, but some are useful.*"
— George E.P. Box

An Extended Higgs Sector

- The SM Higgs sector offers an elegant and minimal framework that successfully induces EWSB.
  ➟ giving mass to massive particles, except for neutrinos

- Other than usual symmetries, no guiding principles in constructing the scalar sector:
  ➟ representations of scalar bosons
  ➟ numbers of scalar bosons
  ➟ extra symmetries (continuous/discrete)
  ➟ required by new physics
  (neutrino mass, DM, EWBG, SUSY, etc)

cf. 3 generations of fermions and 3 gauge interactions

Neutrino Mass

- Neutrino mass is an interesting topic on its own.
- Within SM and without right-handed (RH) neutrino fields, left-handed (LH) neutrinos have to be massless
  ➡ in conflict with data — neutrinos have sub-eV mass
- Possible solutions:
  - ❖Neutrinos have RH components at low energy and Dirac mass, as other fermions
    ➡ still within SM

$$\mathcal{L}_Y \ni -y_f \left(\overline{f_L} \cdot \Phi\right) f_R + \text{h.c.}$$

$$SU(2)_L \qquad \mathbf{2} \quad \mathbf{2} \quad \mathbf{1}$$

  - ❖Neutrinos have no RH components at low energy and Majorana mass due to the so-called seesaw mechanism
    ➡ beyond SM; three types; involving new particles
    ➡ a paradigm in particle physics nowadays

Type-I Seesaw Mechanism

Minkowski 1977; Gell-Mann, Ramond, Slansky 1979;
Yanagida 1979; Glashow 1980; Mohapatra, Senjanovic 1980

- Suppose neutrino mass matrix is in the form

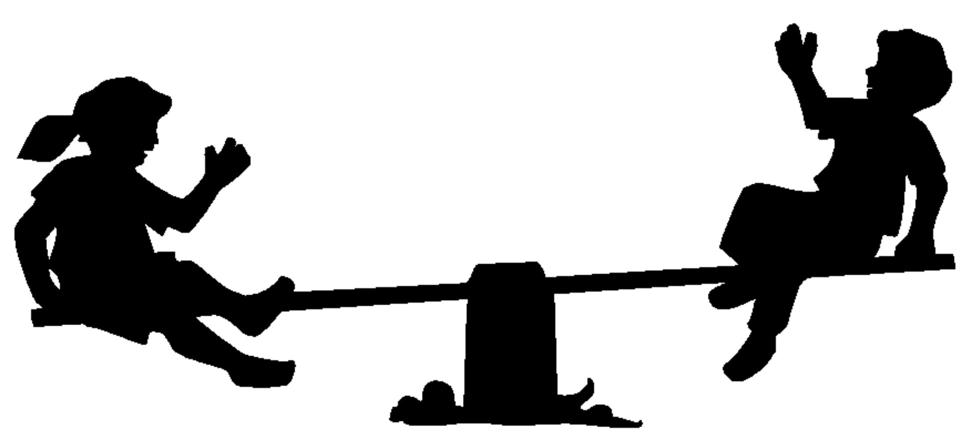
$$\mathcal{L} \supset -\frac{1}{2} (\nu_L^c \quad \nu_R) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}$$

  for all generations.

- If $M_R \gg m_D$, the eigenmasses are

$$m_\nu \simeq -m_D M_R^{-1} m_D^T \qquad m_N \simeq M_R$$

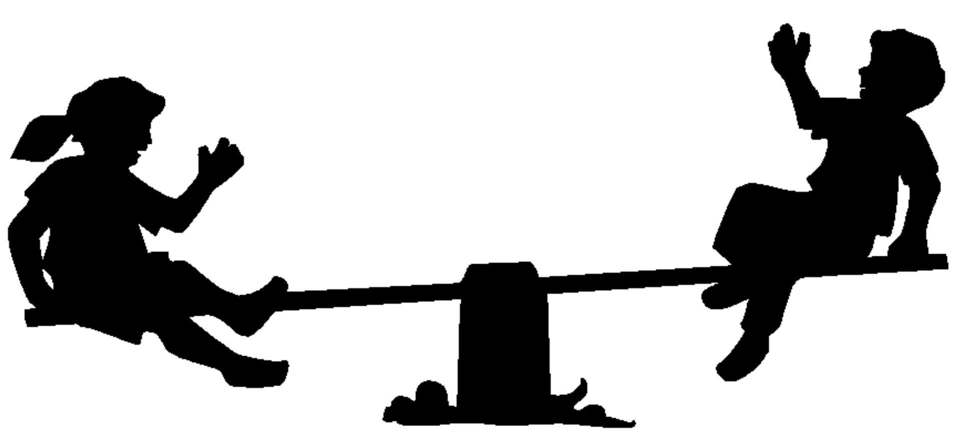
  which can be naturally light.



Type-II Seesaw Mechanism

- RH neutrinos carry no SM quantum numbers, and thus do not have much effect on the visible sector except through the above-mentioned mass terms.

- We explore another viable and possibly more interesting path: introducing another Higgs field of the weak iso-triplet representation.
  ➠ give neutrino Majorana mass
  ➠ new Higgs phenomenology



Georgi-Machacek Model

- The Higgs sector includes SM doublet field ϕ(2,1/2) and triplet fields χ(3,1) and ξ(3,0)

Georgi, Machacek 1985
Chanowitz, Golden 1985

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^{+} \\ \phi^{-} & \phi^{0} \end{pmatrix}, \qquad \Delta = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ \chi^{-} & \xi^{0} & \chi^{+} \\ \chi^{--} & \xi^{-} & \chi^{0} \end{pmatrix}$$

$SU(2)_L$

$SU(2)_R$

Georgi-Machacek Model

- The Higgs sector includes SM doublet field ϕ(2,1/2) and triplet fields χ(3,1) and ξ(3,0)

Georgi, Machacek 1985
Chanowitz, Golden 1985

$$\Phi = \begin{pmatrix} v_\phi & \phi^+ \\ \phi^- & v_\phi \end{pmatrix}, \qquad \Delta = \begin{pmatrix} v_\Delta & \xi^+ & \chi^{++} \\ \chi^- & v_\Delta & \chi^+ \\ \chi^{--} & \xi^- & v_\Delta \end{pmatrix}$$

- Take $v_\chi = v_\xi \equiv v_\Delta$ (aligned VEV*).

➟ $SU(2)_L \times SU(2)_R \to$ custodial $SU(2)_V$

➟ $\rho = 1$ at tree level

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1.00039 \pm 0.00019$$

PDG 2018

*Such a symmetry is broken by radiative effects. But ρ = 1 can be restored by renormalization.

CWC, Kuo, Yagyu PLB 2017, PRD 2018

Yukawa Terms and Neutrino Mass

- Yukawa interactions between Δ and LH leptons:

$$-\, h_{ij}\psi_{iL}^{T} C i\sigma_2\, \Delta\, \psi_{jL} + \text{h.c.}$$

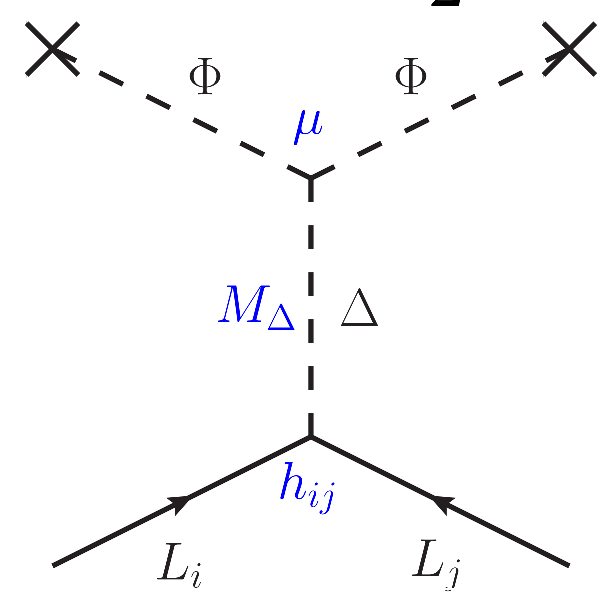
$$SU(2)_L \qquad \mathbf{2} \qquad \mathbf{3} \quad \mathbf{2}$$

- Triplet VEV is triggered/induced by EWSB through a term of the form $\mu_1 \Phi^\dagger \Phi \Delta$:

$$\langle \delta^0 \rangle = \frac{v_\Delta}{\sqrt{2}} \quad \text{and} \quad v_\Delta = \frac{\mu_1 v_0^2}{\sqrt{2} m_2^2}$$

- Majorana neutrino mass matrix

$$M_\nu = \sqrt{2} h v_\Delta = h \frac{\mu_1 v_0^2}{m_2^2}$$



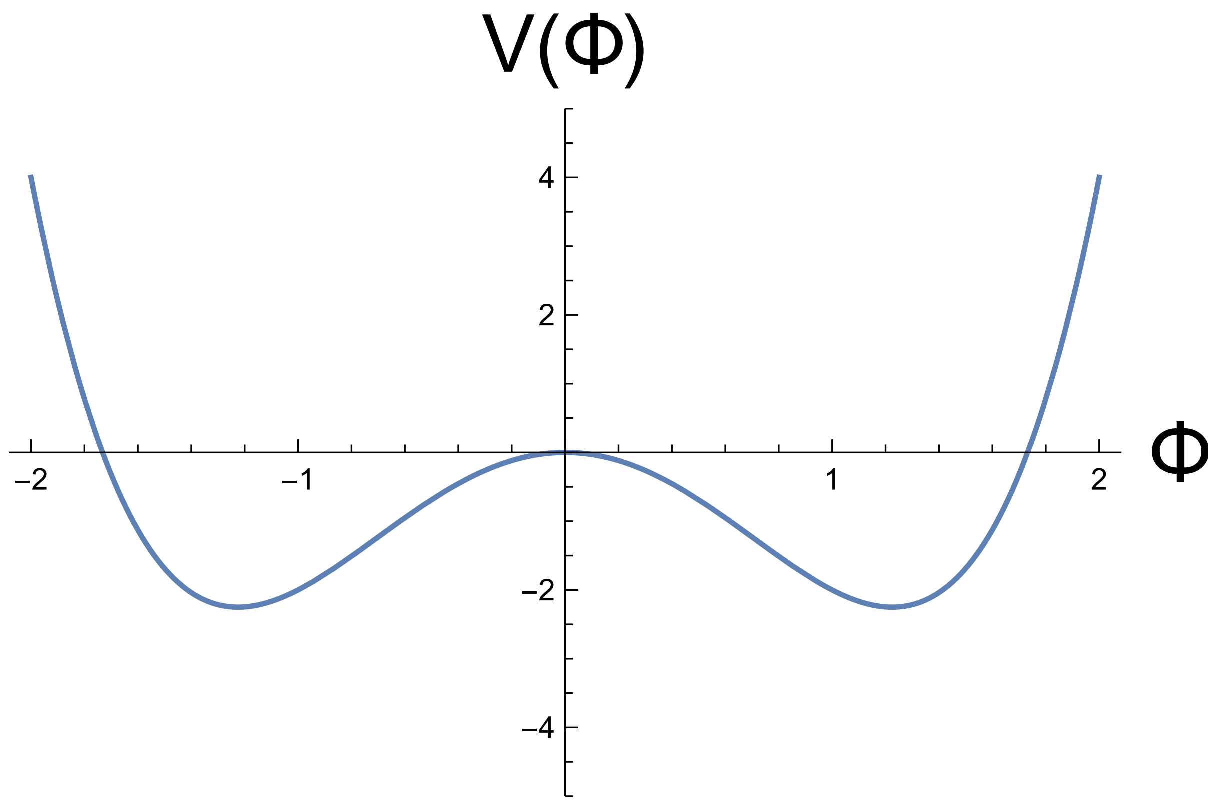
Type-II seesaw

$M_\Delta = m_2$; $\mu = \mu_1$

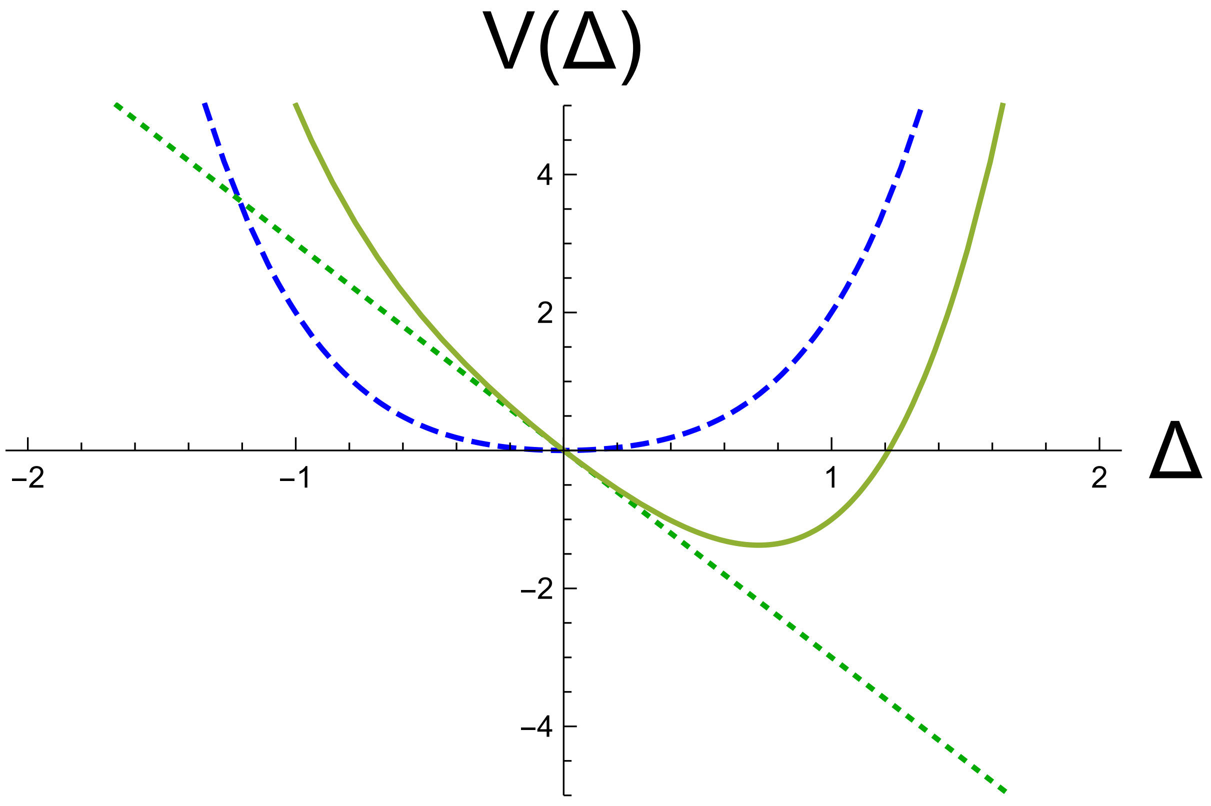
- v_Δ is an important order parameter of model.

Symmetry Breaking Types

- Two types of symmetry breaking involved here:

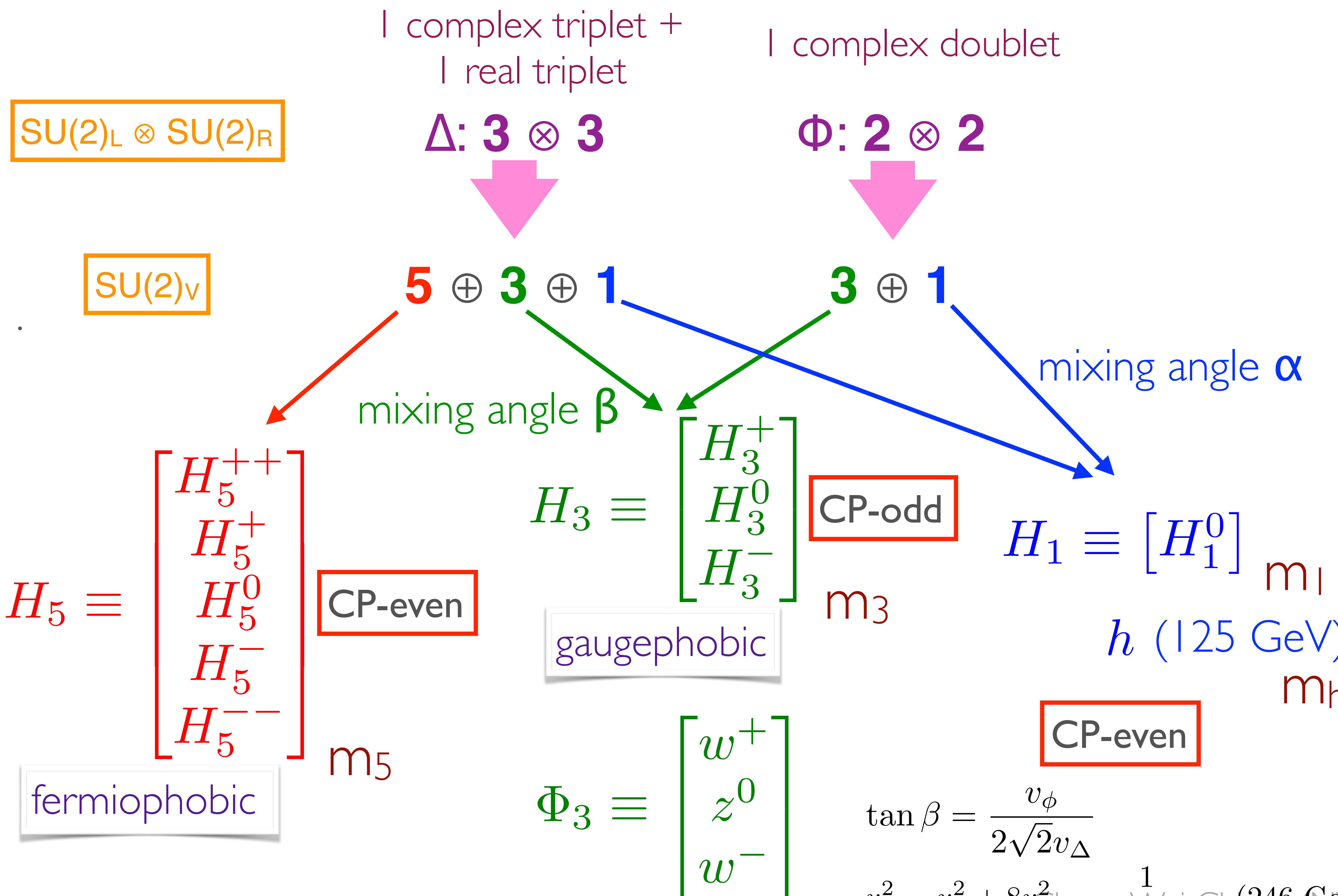


spontaneous symmetry breaking



induced symmetry breaking

Higgs Spectrum



$$\tan\beta = \frac{v_\phi}{2\sqrt{2}v_\Delta}$$

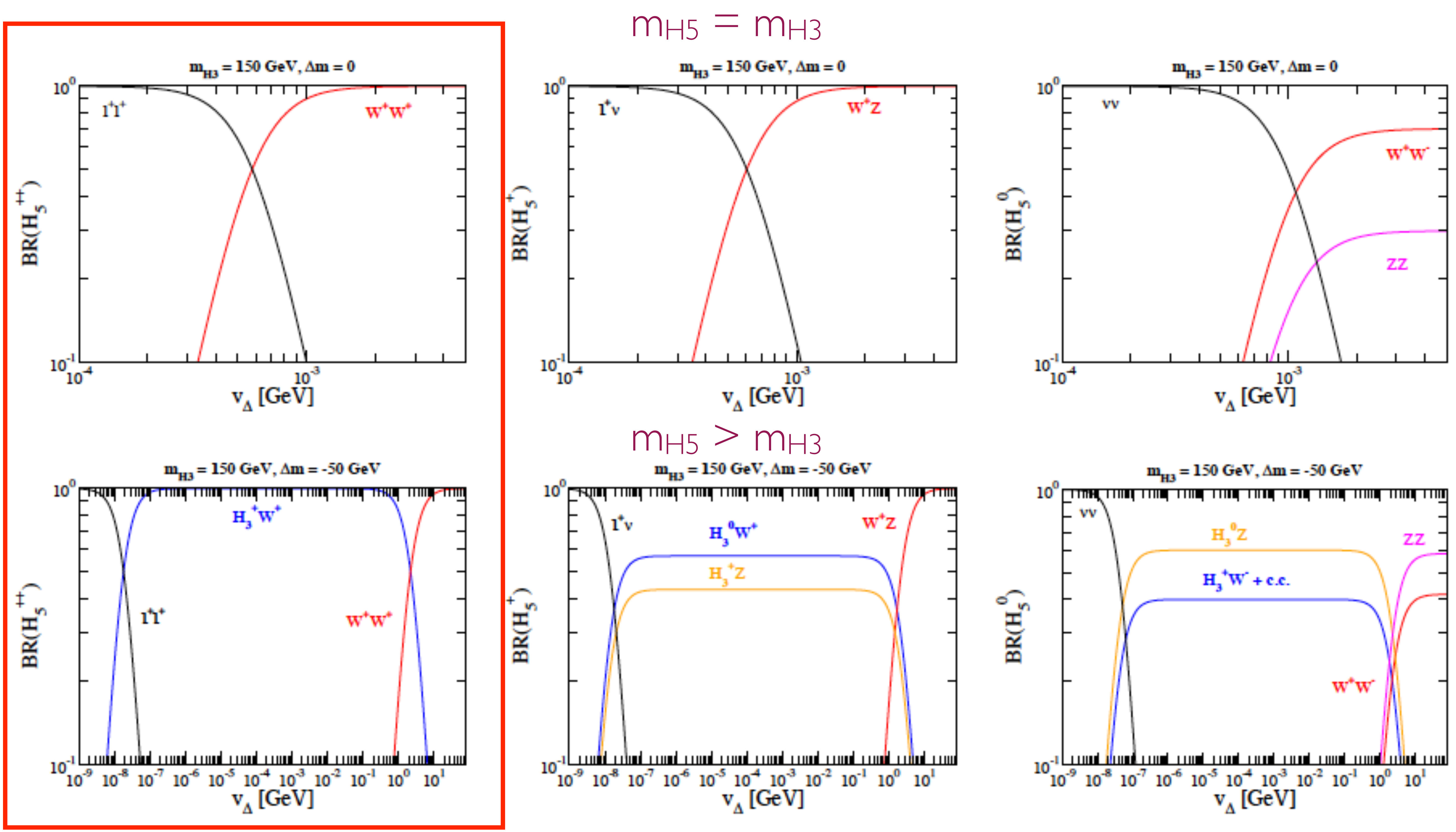
$$v^2 = v_\phi^2 + 8v_\Delta^2 = \frac{1}{\sqrt{2}G_F} = (246\ \text{GeV})^2$$

Features of GM Model

- A renormalizable model
- Provides Majorana masses to neutrinos
- Predicts existence of doubly charged Higgs bosons
- Predicts lepton number [or even flavor] violating processes
- Allows large triplet VEV, ~ O(GeV), by custodial symmetry
- Allows stronger/weaker hWW/hZZ couplings than SM
- Has a tree-level $H_5^{\pm}W^{\mp}Z$ vertex through mixing and proportional to v_Δ
- Links between LHC collider physics and neutrino physics

DECAYS OF H_5 BOSONS

doubly-charged | singly-charged | neutral



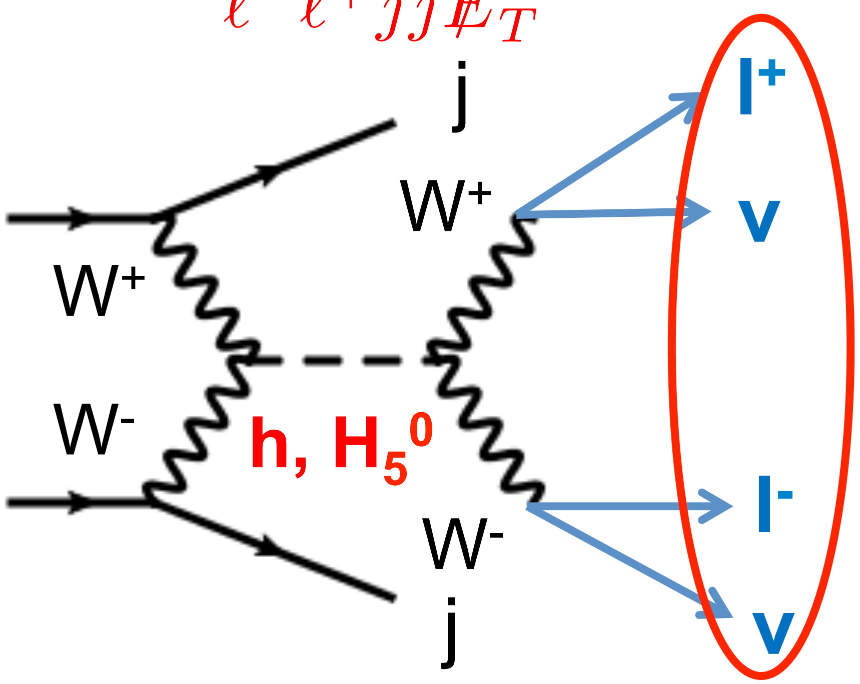
v_Δ is an important order parameter of the model.

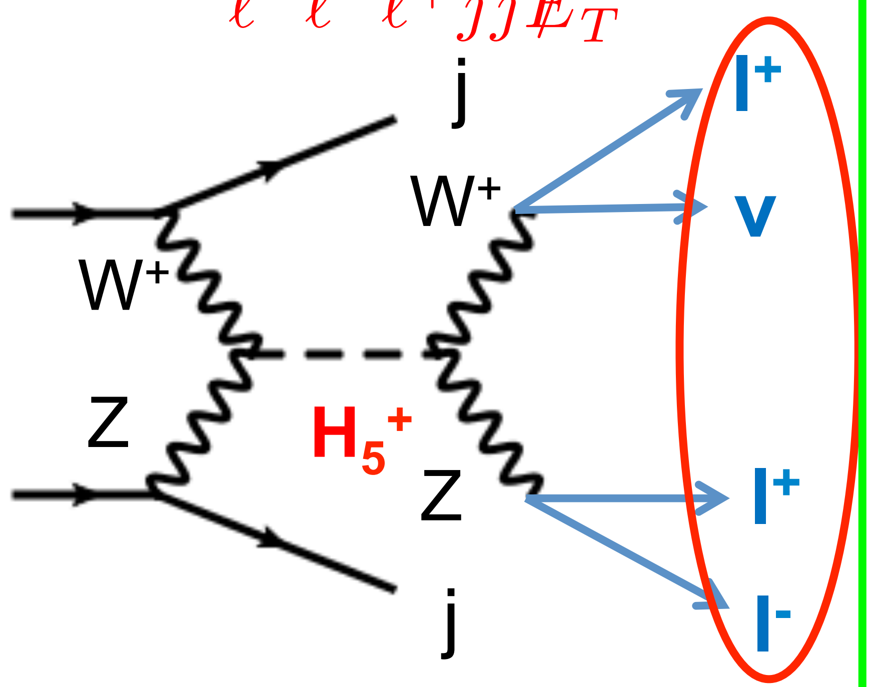
Collider Signatures

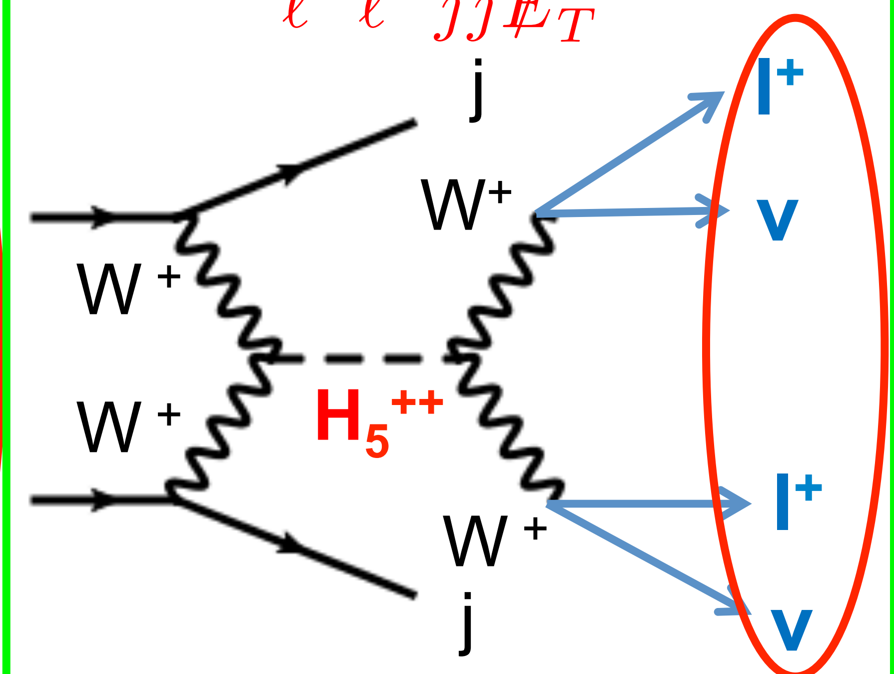
κ_V = 1.3 with (θ_H, α) = (40°,55°) and $M_{H5} = M_{H3} = M_{H1}$ = 300 GeV ➠ no mass hierarchy

CWC, Kuo, Yagyu JHEP 2013

neutral	singly-charged	doubly-charged
$\ell^\pm \ell^\mp jj \not{E}_T$	$\ell^\pm \ell^\pm \ell^\mp jj \not{E}_T$	$\ell^\pm \ell^\pm jj \not{E}_T$

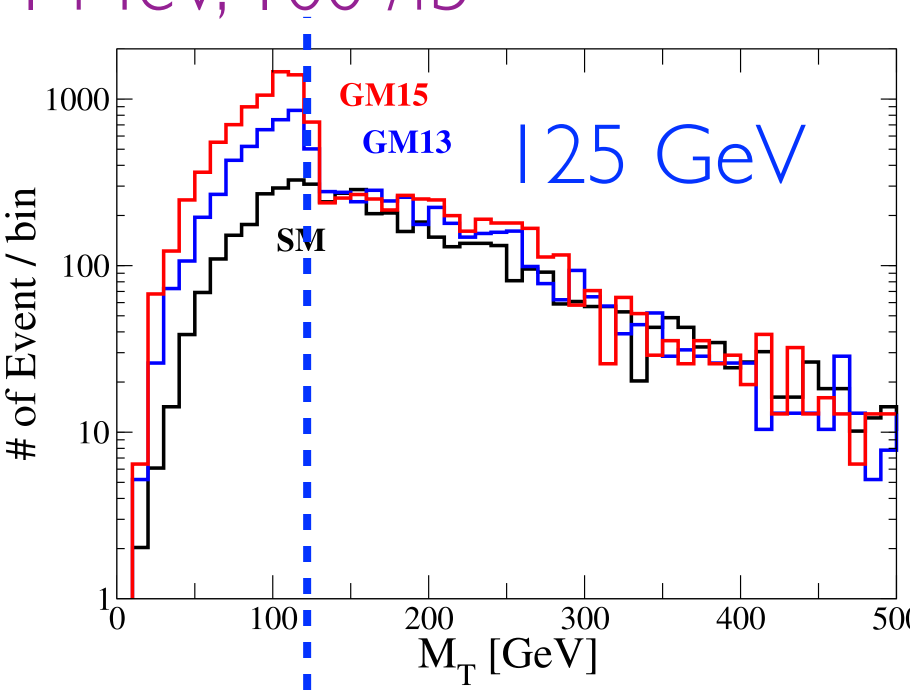


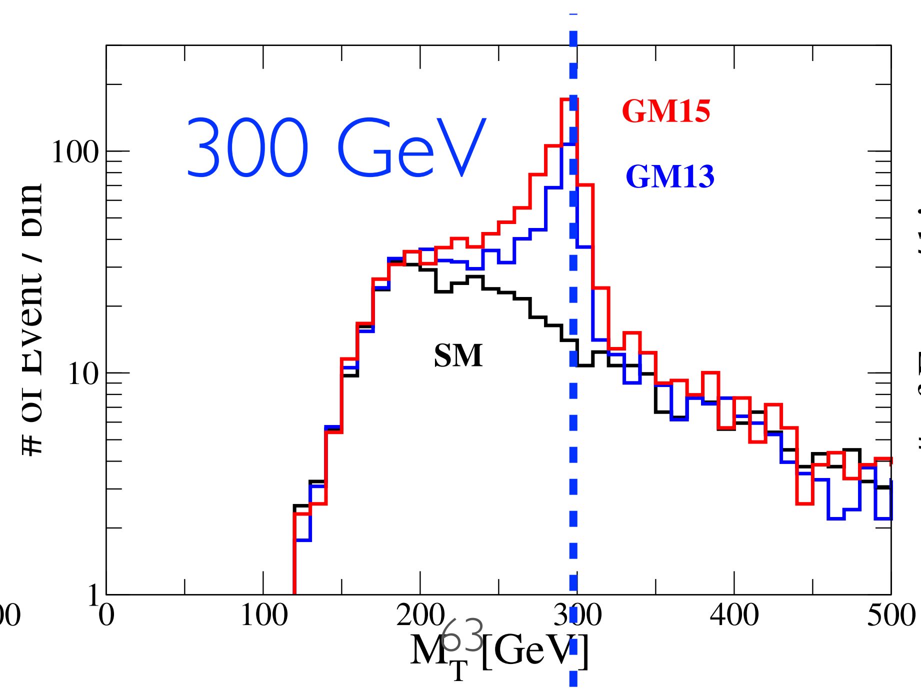


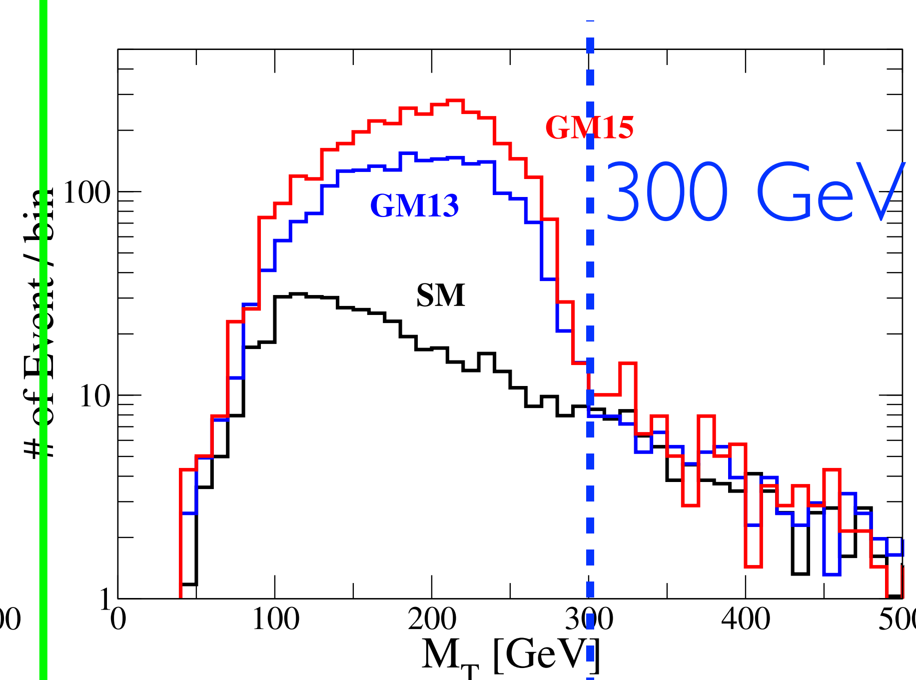


14 TeV, 100 /fb

easier to determine $H_5^{\pm\pm}$ mass than the other two







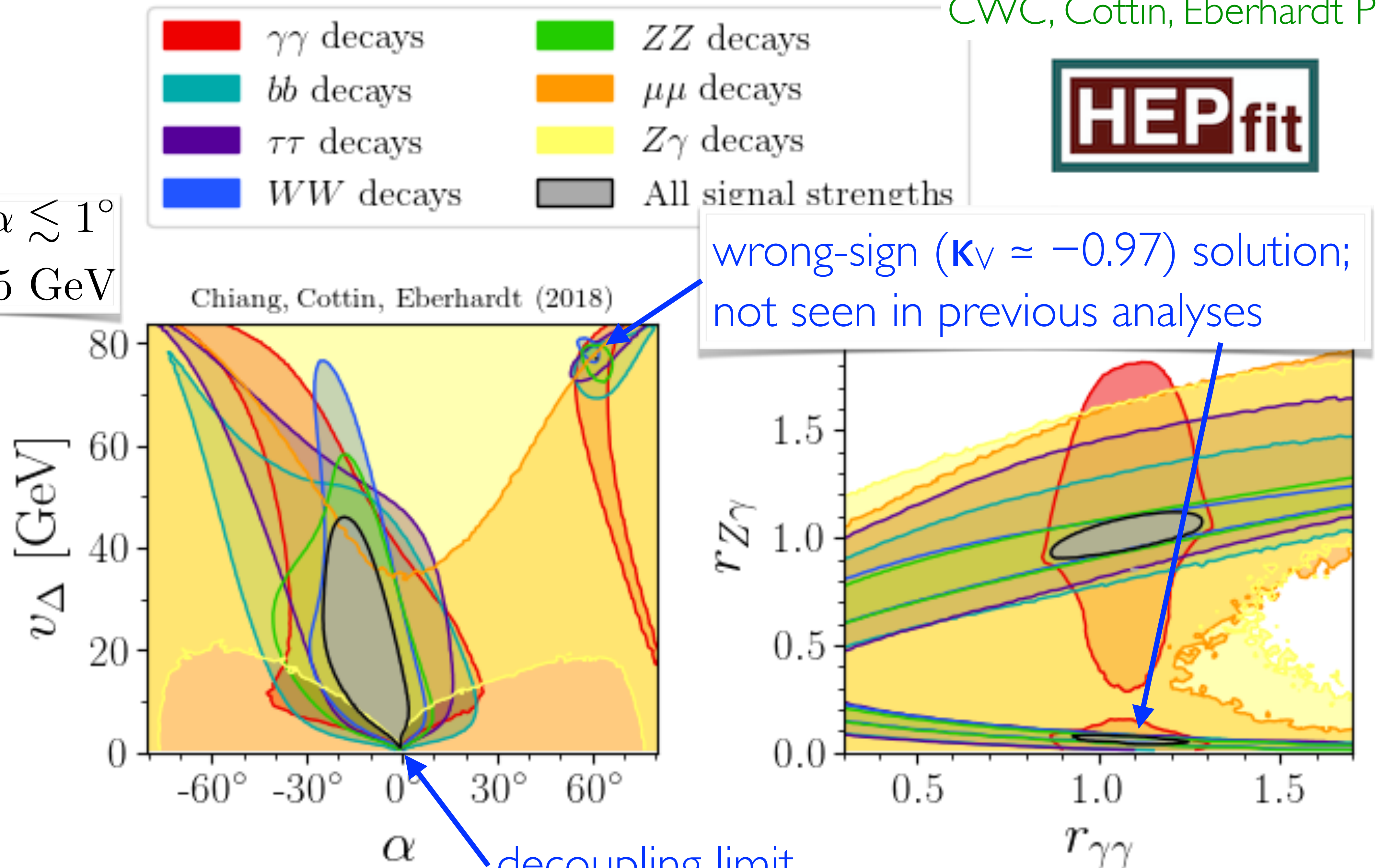
Recent Global Fit Results

- Fit based on Higgs signal strengths after ICHEP 2018, all colored regions with 95% probability.

CWC, Cottin, Eberhardt PRD 2018

HEPfit

$$-30^\circ \lesssim \alpha \lesssim 1^\circ$$
$$v_\Delta \lesssim 45 \text{ GeV}$$

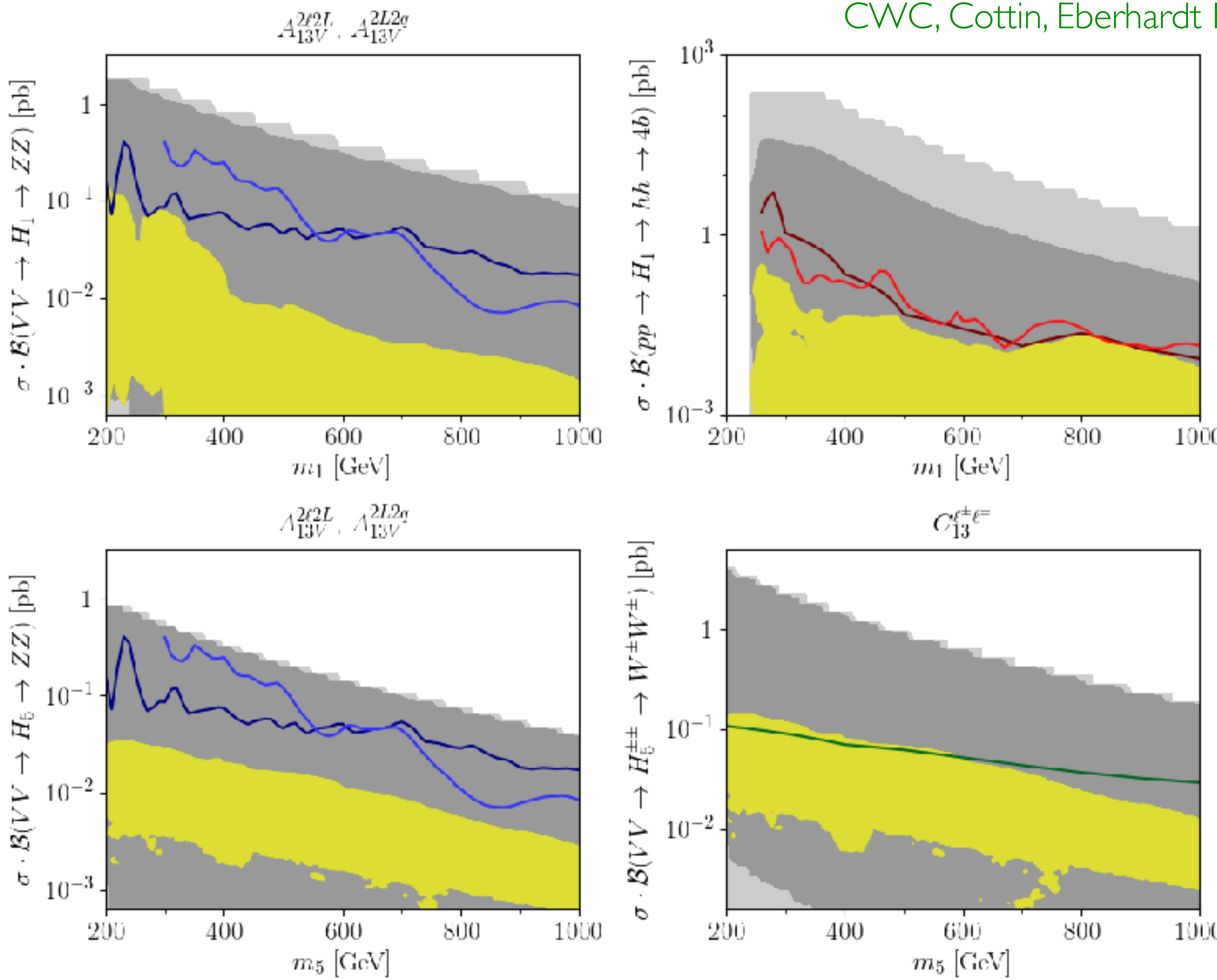


wrong-sign ($\kappa_V \simeq -0.97$) solution; not seen in previous analyses

decoupling limit

Promising Processes

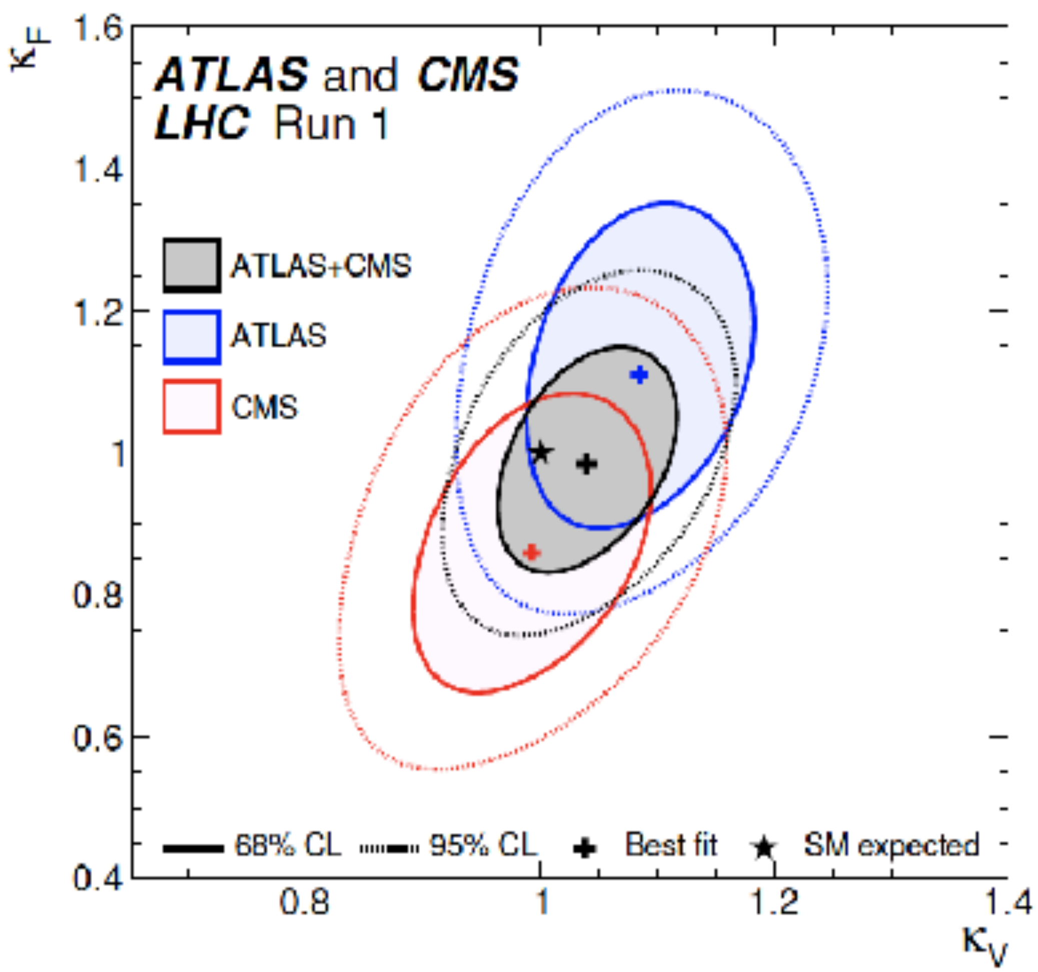
CWC, Cottin, Eberhardt PRD 2018

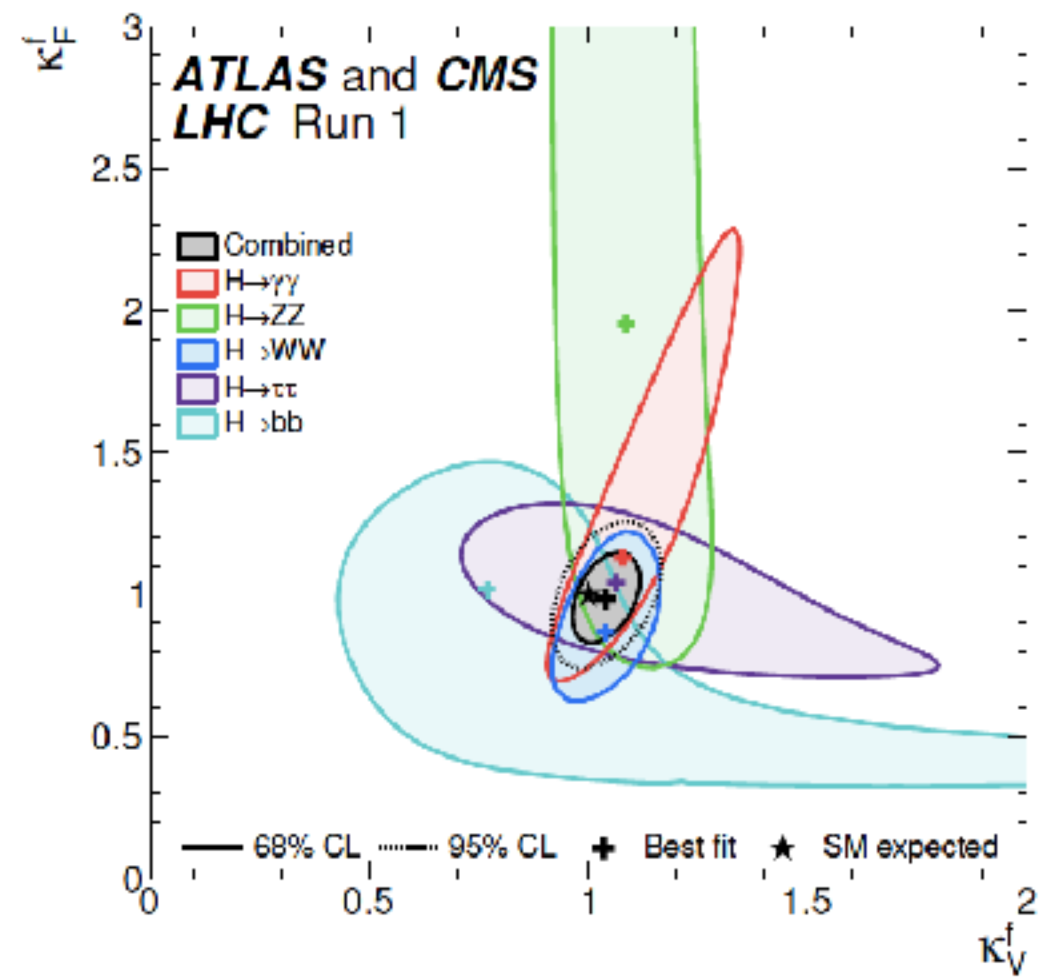


Higgs Physics Program

- Global fits of Higgs couplings (assuming universal scaling factors $\kappa_{F,V}$) from LHC Run-I
  ➠ quite consistent with SM

$$\kappa_F = \frac{g_{\varphi FF}}{g_{hFF}^{\text{SM}}} \,, \quad \kappa_V = \frac{g_{\varphi VV}}{g_{hVV}^{\text{SM}}}$$

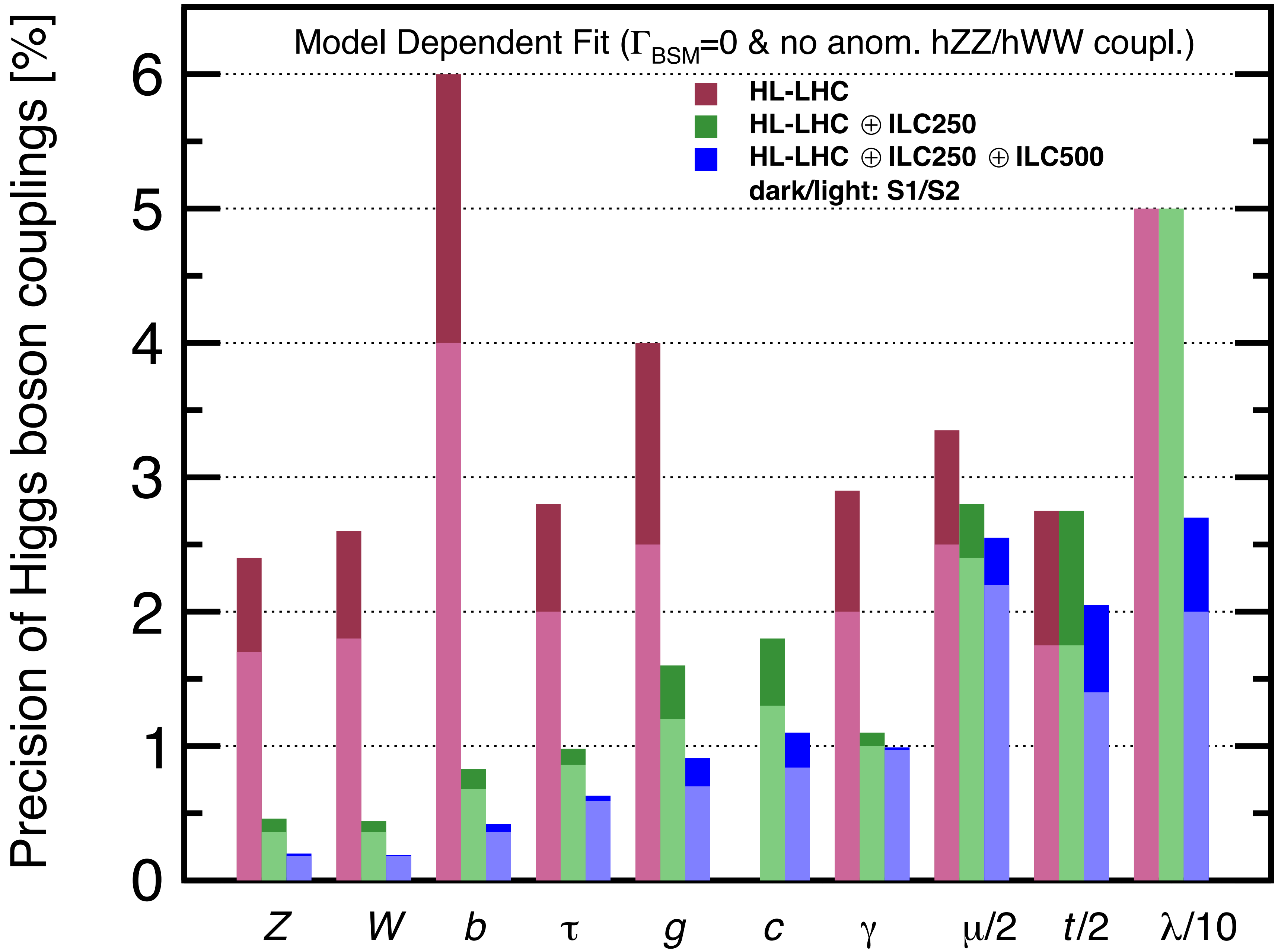




circa 2016 summer

Expected Coupling Precision

- All Higgs couplings will be determined by HL-LHC + ILC to O(1%) or sub-percent level (particularly hVV couplings).



Aihara et al 2019

κ_V in Simple Models

Model	Higgs	$\kappa_V = g_{HVV}/g_{h_{\rm SM}VV}$	κ_W/κ_Z
rHSM	h	$\cos\alpha$	1
2HDM	h	$\sin(\beta-\alpha)$	1
	H	$\cos(\beta-\alpha)$	1
GM	h	$\sin\beta\cos\alpha - \sqrt{\frac{8}{3}}\cos\beta\sin\alpha$	1
	H_1^0	$\sin\beta\sin\alpha + \sqrt{\frac{8}{3}}\cos\beta\cos\alpha$	1
	H_3^0	0	—
	H_5^0	$\kappa_W = -\frac{\cos\beta}{\sqrt{3}}$ and $\kappa_Z = \frac{2\cos\beta}{\sqrt{3}}$	$-1/2$

SM-like Higgs

≤ 1

κ's all normalized to corresponding SM values

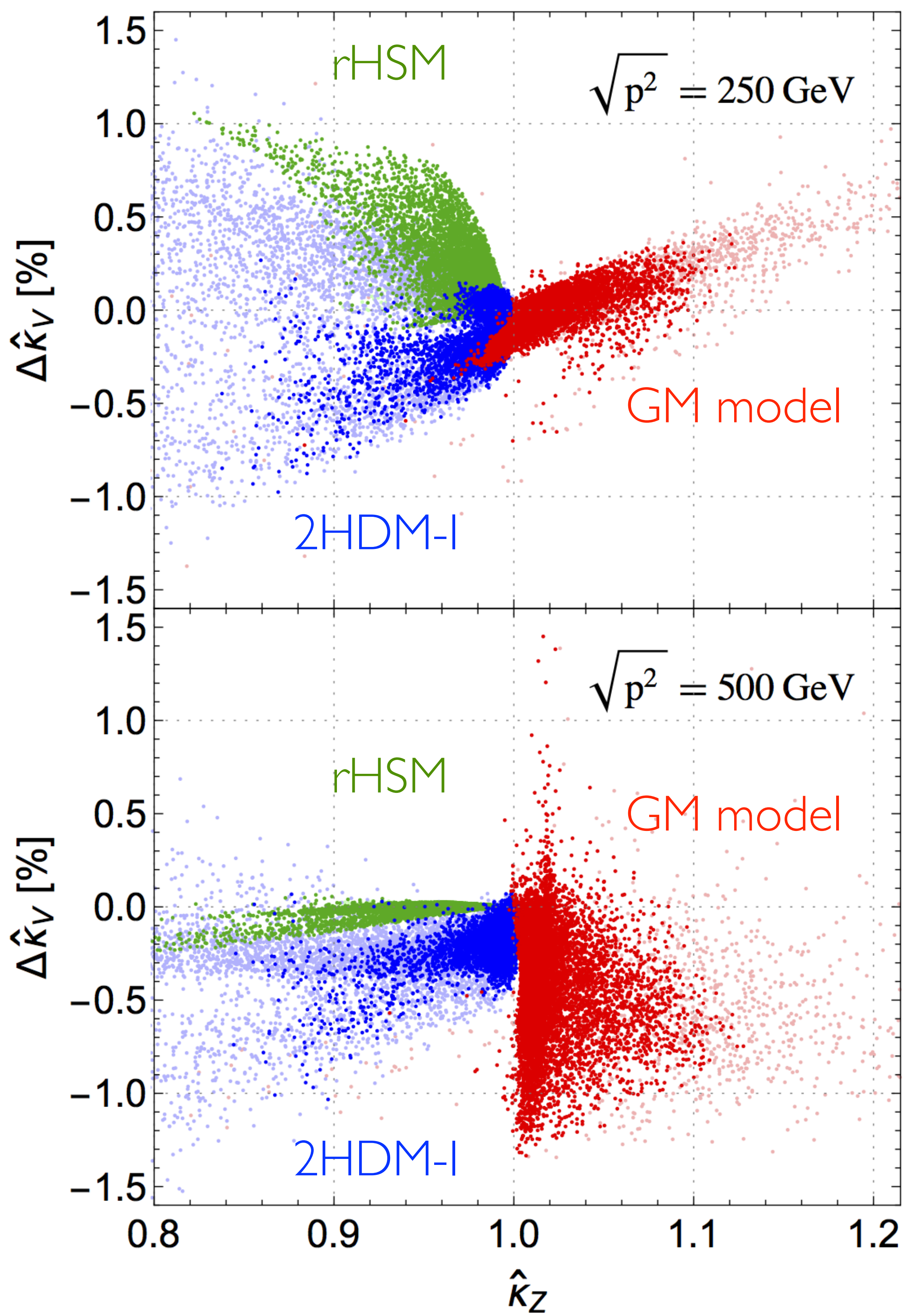
$$\text{2HDM}: \tan\beta = \frac{v_u}{v_d} \quad \text{and} \quad \text{GM}: \tan\beta = \frac{v_\phi}{2\sqrt{2}v_\Delta}$$

1-Loop Results

$\Delta\hat{\kappa}_V \equiv \hat{\kappa}_W - \hat{\kappa}_Z$

- Lighter dots satisfy theoretical constraints (unitarity, stability, perturbativity, and oblique parameters [S and T]).
- Darker dots further satisfy Higgs signal strengths from LHC Run-I (20 channels).
- Other types of 2HDM are expected to have a similar result as 2HDM-I.
- It is possible to discriminate among the rHSM, 2HDMs and GM model.
- $\Delta\kappa_V \sim O(1\%)$ and may be observable.

CWC, Kuo, and Yagyu PLB 2017



Recent Run-II Data

Parameter	ATLAS	CMS	Average
κ_W	1.07 ± 0.10	$1.12^{+0.13}_{-0.19}$	1.08 ± 0.08
κ_Z	1.07 ± 0.10	0.99 ± 0.11	1.03 ± 0.07

ATLAS-CONF-2018-31 (13 TeV, 80/fb)
CMS-PAS-HIG-17-031 (13 TeV, 36/fb)

- Concentrate on the central values.
- κ_W and/or κ_Z may be greater than 1.
- κ_W and κ_Z may be different. (~10% from CMS alone)
- What kind of (minimally extended) Higgs sector features these properties?
- What future data of κ_W and κ_Z can be?
- Maybe need a more exotic Higgs sector?

CWC, Yagyu PLB 2018
CWC, He, Li JHEP 2018

Summary

- The discovery of Higgs boson and verification of its interactions with other particles prove that our Standard Model of particle physics is basically correct.
- Breakdown of electroweak symmetry is induced by the vacuum expectation value of the Higgs field and gives rise to mass for elementary particles (except for neutrinos).
- Ongoing LHC experiments keep probing physics at the TeV scale and give us more insight into the nature of EWSB.
  ➠ new Higgs particles (for neutrino mass) and interactions?
- Georgi-Machacek model extends the SM with a custodial Higgs triplet field and leads to interesting collider phenomenology.
- History has taught us that every time we look deeper into things, we discover more dazzling beauty and amazement.
  ➠ let's keep learning how subtle Nature is!

- Hopefully by now, you have a rough idea about where your mass comes from...

Thank You!