Unitarity Bounds and Mass Generation Scale

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Beyond the Standard Model: Mass as a Clue

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Outline

★ Shape of the Standard Model (SM)

★ Scales of Mass Generations: Universal Limits

★ Higgs, Hierarchy Problem & "Little Higgs"

⊛ Beyond 4 Dimensions ?

★ Summary & Outlook

Outline

★ **Shape of the Standard Model (SM)**

- Symmetries, Particles, Mass Spectrum & Exp Data
- Looking beyond: Lesson from Columbus ?
- Looking beyond: Two Essential Clues

★ **Scales of Mass Generations: Universal Limits**

- Scale of Mass Generation & Classic $2 \to 2$ Unitarity Limits
- $2 \to n$ Scattering: Puzzle, Resolution & Surprise
- Scales for Weak Bosons, Quarks/Leptons & Majorana Neutrinos

★ **Higgs, Hierarchy Problem & "Little Higgs"**

- Higgs Mechanism & Hierarchy Problem
- Little Higgs Solves Little Hierarchy
- Unitarity of Little Higgs vs UV Completion

⊛ **Beyond 4 Dimensions ?**

★ **Summary & Outlook**

Shape of the Standard Model

Classical Mechanics

- angular momentum $\gg \hbar$
- speed $\ll c$

Quantum Mechanics

- any angular momentum
- speed $\ll c$

Special Relativity

- angular momentum $\gg \hbar$
- any speed

Quantum field theory

- any angular momentum
- any speed

Standard Model

- local quantum gauge theory
- $SU(3)_C \otimes SU(2)_W \otimes U(1)_Y$
- valid down to $\sim 10^{-16}$ cm

Shape of the Standard Model

Elementary Particles discovered by experiments:

$$\text{leptons}\ \left\{\begin{array}{ccc} \begin{pmatrix}\nu_L^e \\ e_L\end{pmatrix} & \begin{pmatrix}\nu_L^\mu \\ \mu_L\end{pmatrix} & \begin{pmatrix}\nu_L^\tau \\ \tau_L\end{pmatrix} \\ e_R & \mu_R & \tau_R \end{array}\right.$$

$$\text{quarks}\ \left\{\begin{array}{ccc} \begin{pmatrix}u_L \\ d_L\end{pmatrix} & \begin{pmatrix}c_L \\ s_L\end{pmatrix} & \begin{pmatrix}t_L \\ b_L\end{pmatrix} \\ u_R & c_R & t_R \\ d_R & s_R & b_R \end{array}\right.$$

$$\left(\text{spin } \frac{1}{2}\right)$$

$$\underbrace{SU(3)_C}_{\text{8 gluons}} \times SU(2)_W \times U(1)_Y \text{ gauge bosons} \quad \textbf{(spin 1)}$$

$$\text{8 gluons} + W^\pm, Z, \gamma$$

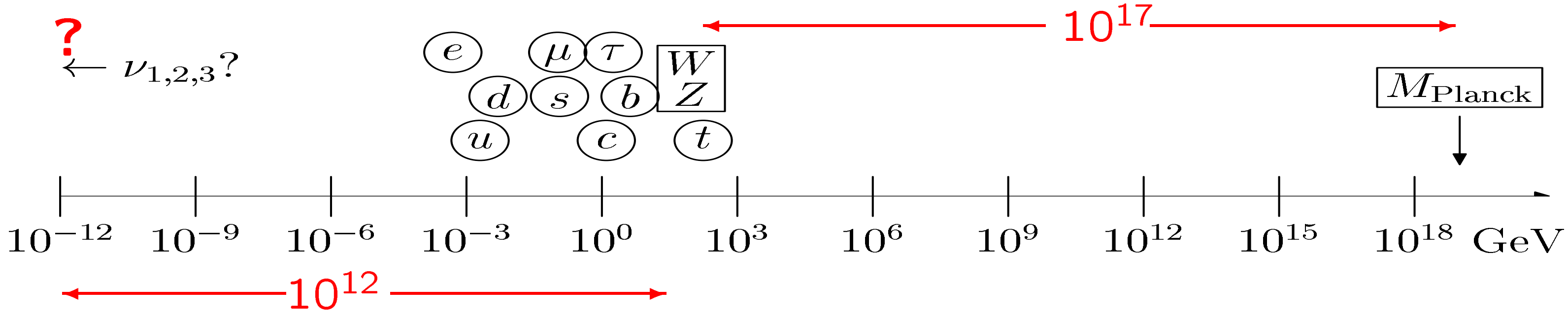
longitudinal $W^\pm$, Z **(spin 0)**

$\oplus$ Higgs H^0 **(spin 0)** $\Rightarrow$ **not yet discovered!**

$\downarrow$

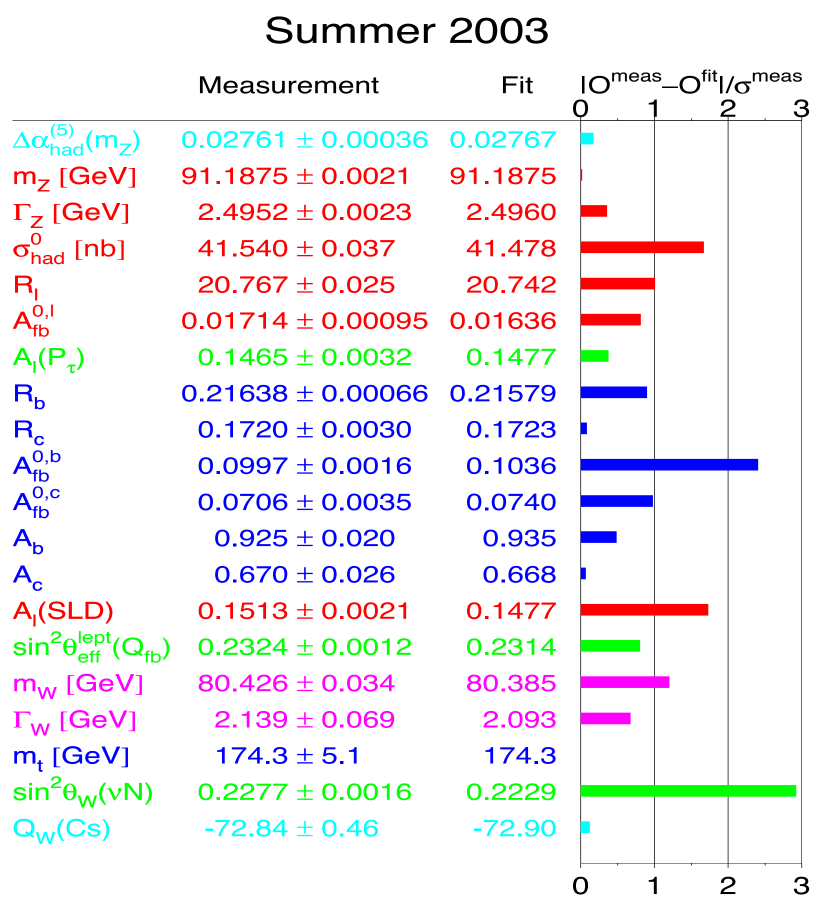
"God Particle" gives masses to W/Z & Quarks/Leptons!

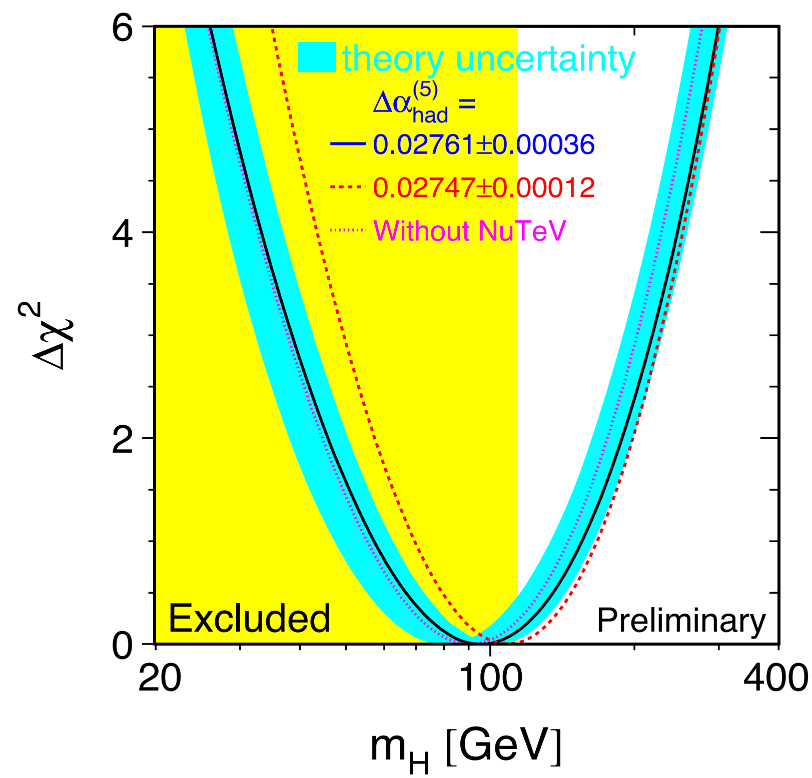
▶ SM Mass Spectrum:



▶ Precision data fit SM well and favor a Light Higgs:

114.4 GeV (direct) $< M_H <$ 219 GeV (precision) **(95% C.L.)**

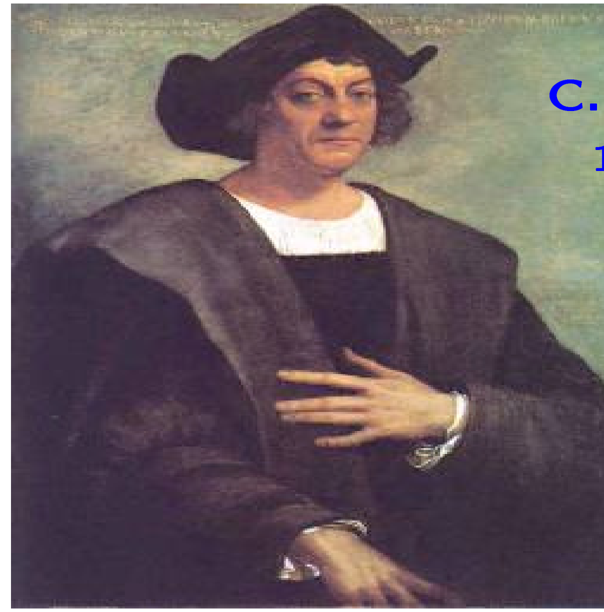




Looking Beyond: Lesson from Columbus ?

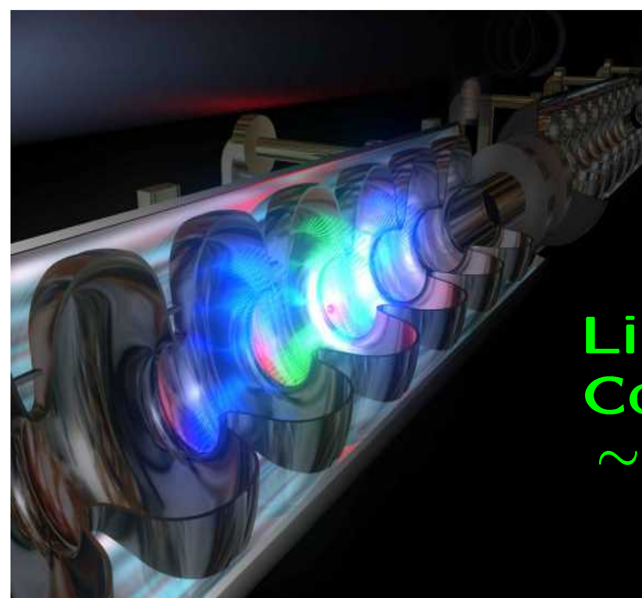
- 1492-1504 A.D.: Columbus carried out heroic experimental probes to prove Pythagoras theory (∼500 B.C.) that the Earth is round (and to search for Mainland China & Gold).....But, he discovered Something Else !!!

Voyage
1492-1504



C. Columbus
1451-1506

CERN
LHC
2007



Linear
Colliders
∼2012

Looking Beyond: Two Essential Clues

★ **Clue-1:**
What's Wrong with just Bare Mass terms for All particles ??

★ **Clue-2:**
What's Wrong with having a Fundamental Higgs Boson ??

Looking Beyond: Two Essential Clues

★ **Clue-1:**

What's Wrong with just Bare Mass terms for All particles ??

▶ Unitarity Violation $\Rightarrow$ Limit on Scale of Mass Generation!

$\Rightarrow$ e.g. $WW \to WW$ Scattering justifies TeV Scale for LHC Energy! .....

★ **Clue-2:**

What's Wrong with having a Fundamental Higgs Boson ??

▶ Hierarchy Problem $\Rightarrow$ Little Higgs, Extra Dim, DSB, SUSY...!

Looking Beyond: Two Essential Clues (1)

★ **Clue-1:**

What's Wrong with just Bare Mass terms for All particles ??

Scales of Mass Generations

Define Scale of Mass Generation

- In Standard Model (SM), Weak Bosons W/Z and all Fermions obtain masses from a Hypothetic Fundamental Higgs H^0. But, the masses can of course be generated by Something Else! Without assuming H^0, all masses must be put in by hand for SM, which can be gauge-invariant only under Nonlinear realization of SM gauge group. $\Rightarrow$ Non-renormalizability! This causes a Unitarity Violation Scale $\Lambda_{\rm U}$ in High Energy Scatterings at which New Physics must enter to restore unitarity!

- Define scale Λ_x for generating a mass m_x to be the Minimal Energy above which the Bare Mass Term for m_x has to be replaced by a Renormalizable Interaction involving New State(s).

- Unitarity Violation Scale $\Lambda_{\rm U}$ provides a Model-Independent Universal Upper Limit on the Scale of Mass-Generation Λ_x (for mass m_x):

$$\boldsymbol{\Lambda_x \leqslant \Lambda_{\rm U}}$$

Nonlinear Realization of SM Gauge Symmetry

▶ Without assuming Higgs H^0, SM gauge symmetry must be nonlinearly realized, and 3 "eaten" Goldstones $\{\pi^a\}$ are formulated by

$U = \exp\left[i\pi^a\tau^a/v\right]$, $\quad (v \simeq 250\text{GeV} \Rightarrow \text{recall:}\ f_\pi^{\text{QCD}} \simeq 92\text{MeV})$

▶ Gauge Boson bare mass terms $M_W^2 W^+W^- + \frac{1}{2}M_Z^2 Z^2$ can be written as dim-2 gauge-invariant operator:

$$\mathcal{L}_{\text{mass}}^V = \frac{v^2}{4}\left|D_\mu U\right|^2,$$

▶ For Dirac Fermions (Quarks/Leptons) $F = (f,\, f')^T$, the bare mass terms $-m_f\overline{f}f - m_{f'}\overline{f'}f'$ can be written as gauge-invariant dim-3 operator:

$$\mathcal{L}_{\text{mass}}^f = -m_f\overline{F_L}U\begin{pmatrix}1\\0\end{pmatrix}f_R - m_{f'}\overline{F_L}U\begin{pmatrix}0\\1\end{pmatrix}f'_R + \text{H.c.}$$

▶ Light Neutrinos can form bare Majorana Mass term $-\frac{1}{2}m_\nu^{ij}\,\nu_{Li}^T\widehat{C}\nu_{Lj} + \text{H.c.}$
$\Rightarrow$ Gauge-invariant form, with $\Phi = U(0, v/\sqrt{2})^T$, $F_{Lj} = L_j$,

$$\mathcal{L}_{\text{mass}}^\nu = -\frac{m_\nu^{ij}}{v^2}L_i^{\alpha T}\widehat{C}L_j^\beta\Phi^{\alpha'}\Phi^{\beta'}\epsilon^{\alpha\alpha'}\epsilon^{\beta\beta'} + \text{H.c.}$$

Classic Limits on Scales of Mass Generations

▶ **Scattering $W_L W_L \to W_L W_L$ on Electroweak Symmetry Breaking Scale:**
(Dicus & Mathur, Phys.Rev.1973; Lee, Quigg, Thacker, Phys.Rev.1977)

$$\Lambda_{\rm U} \;\simeq\; \sqrt{8\pi}\, v \simeq 1.2\,\text{TeV} \quad\Rightarrow\quad \boxed{\textbf{TeV Scale for LHC!!!}}$$

▶ **Scattering $f\bar{f} \to W_L W_L$ on Dirac Fermion Mass Generation:**
(Appelquist & Chanowitz, Phys.Rev.Lett.1987)

$$\Lambda_{\rm U} \;\simeq\; \frac{8\pi\, v^2}{\sqrt{2N_c}\, m_f} \simeq (3.6,\ 2\times 10^5;\ 605,\ 2\times 10^6)\ \text{TeV} \qquad \text{for } f = (t,\, u;\, \tau,\, e)$$

▶ **Scattering $\nu_L \nu_L \to W_L W_L$ on Majorana Neutrino Mass Generation:**
(Willenbrock et al, Phys.Rev.Lett.2001)

$$\Lambda_{\rm U} \;\simeq\; \frac{2\pi\, v^2}{m_\nu} \;\simeq\; 10^{16}\,\text{GeV} \qquad (m_\nu \simeq 0.05\text{eV})$$

$$\Rightarrow \quad \boxed{\textbf{Seesaw/GUT Scale!}}$$

High Energy Scattering: $W_L W_L, f\bar{f} \to nW_L$ $(n \geqslant 2)$

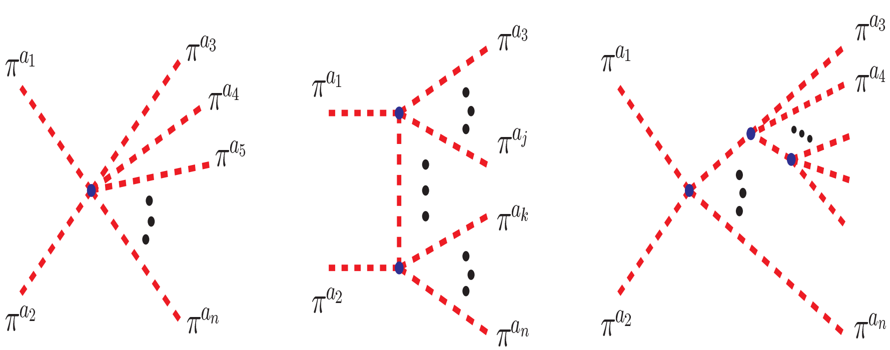
★ **Equivalence Theorem gives,** *(for review, He, et al, hep-ph/9704276)*

$$T\left[W_L^{a_1}, \cdots, W_L^{a_n}; \Phi_{\rm phys}\right] = (-i)^n T\left[\pi^{a_1}, \cdots, \pi^{a_n}; \Phi_{\rm phys}\right] + \mathcal{O}\left(\frac{M_W}{E_j}\right)$$

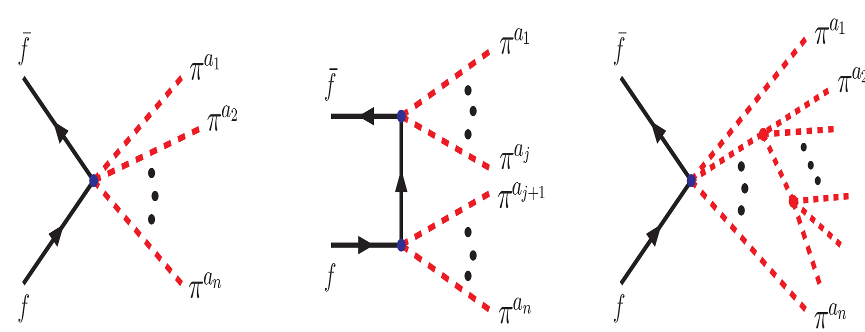
★ **Power Counting of high energy Scattering Amplitudes:**

$$T[f\bar{f}, \nu\nu \to nW_L^a] \simeq T[f\bar{f}, \nu\nu \to n\pi^a] = \mathcal{O}(1)\frac{m_{f,\nu}}{v^n}E\,,$$

$$T[W_L^{a_1}W_L^{a_2} \to nW_L^a] \simeq T[\pi^{a_1}\pi^{a_2} \to n\pi^a] = \mathcal{O}(1)\frac{E^2}{v^n}\,,$$



(a) (b) (c)



$\mathcal{O}(E^1)$ $\mathcal{O}(E^0)$ $\mathcal{O}(E^1)$

(a) (b) (c)

Puzzle: $2 \to n$ Scattering, E-Counting & Unitarity Limit

▶ General $2 \to n$ Unitarity Condition by requiring $SS^\dagger = S^\dagger S = 1$,

$$\sigma[2 \to n] \;<\; \frac{4\pi}{s}$$

▶ **Puzzle**: Energy Power Counting shows: $(s = E^2)$

$$\frac{1}{\mathcal{J}_{\rm in}} \int_{{\rm PS}_n} \sim \; s^{n-3} ,$$

$$\sigma[2 \to n] \;\propto\; \frac{1}{s}\left(\frac{s}{v^2}\right)^{n-2+\delta}\left(\frac{m_f}{v}\right)^{2(2-\delta)} , \qquad (n \geqslant 2),$$

$$\Lambda_{\rm U} \;\sim\; v\left[c_0\left(\frac{v}{m_f}\right)^{2(2-\delta)}\right]^{\frac{1}{2(n-2+\delta)}} \longrightarrow v \, , \qquad (\text{for } n \to \text{large}),$$

Here $\delta = 1$ & 2 for $f\bar{f}/\nu\nu$ & $W_L W_L$ scattering. ▶ No New Scale for m_f ?!

▶ BUT, we have Kinematic Condition:

$$\sqrt{s} \;>\; nM_W \simeq \frac{n}{3}v \, , \qquad \longrightarrow \qquad \Lambda_{\rm U} \;>\; v\,\frac{n}{3} \quad (\uparrow \;\text{with}\; n\,)$$

Resolution and Surprise

★ **Resolution**

Dicus & He, 2003

▶ **Computing Exact Phase Space:** (recall : Fermi's Golden rule in QM $\cdots$)

$$\frac{1}{\mathcal{J}_{\rm in}}\int_{{\rm PS}_n} = \frac{1}{\mathcal{J}_{\rm in}}\int\frac{d^3k_1\cdots d^3k_n}{2E_1\cdots 2E_n}(2\pi)^{4-3n}\,\delta^{(4)}\Big(p_1+p_2-\sum k_j\Big)$$

$$= \frac{s^{n-3}}{2^{4(n-1)}\pi^{2n-3}\,[(n-1)!(n-2)!]}$$

▶ **Improved Estimates: (** $c_0=\mathcal{O}(1)$, $e=2.718\cdots$, $(n!)^{1/n}\to n/e$ **)**

$$\Lambda_{\rm U} \,=\, v\left[c_0\,2^{4n-2}\pi^{2(n-1)}\,[(n-1)!\,(n-2)!]\,\left(\frac{v}{m_f}\right)^{2(2-\delta)}\right]^{\frac{1}{2(n-2+\delta)}}$$

$$\Rightarrow\; v\,\frac{4\pi n}{e} \;>\; v\,\frac{n}{3} \qquad\qquad (\text{for } n\gg 1)$$

▶ **Kinematic Condition** $\Lambda_{\rm U}>v\dfrac{n}{3}$ **is satisfied due to Exact Phase Space!**

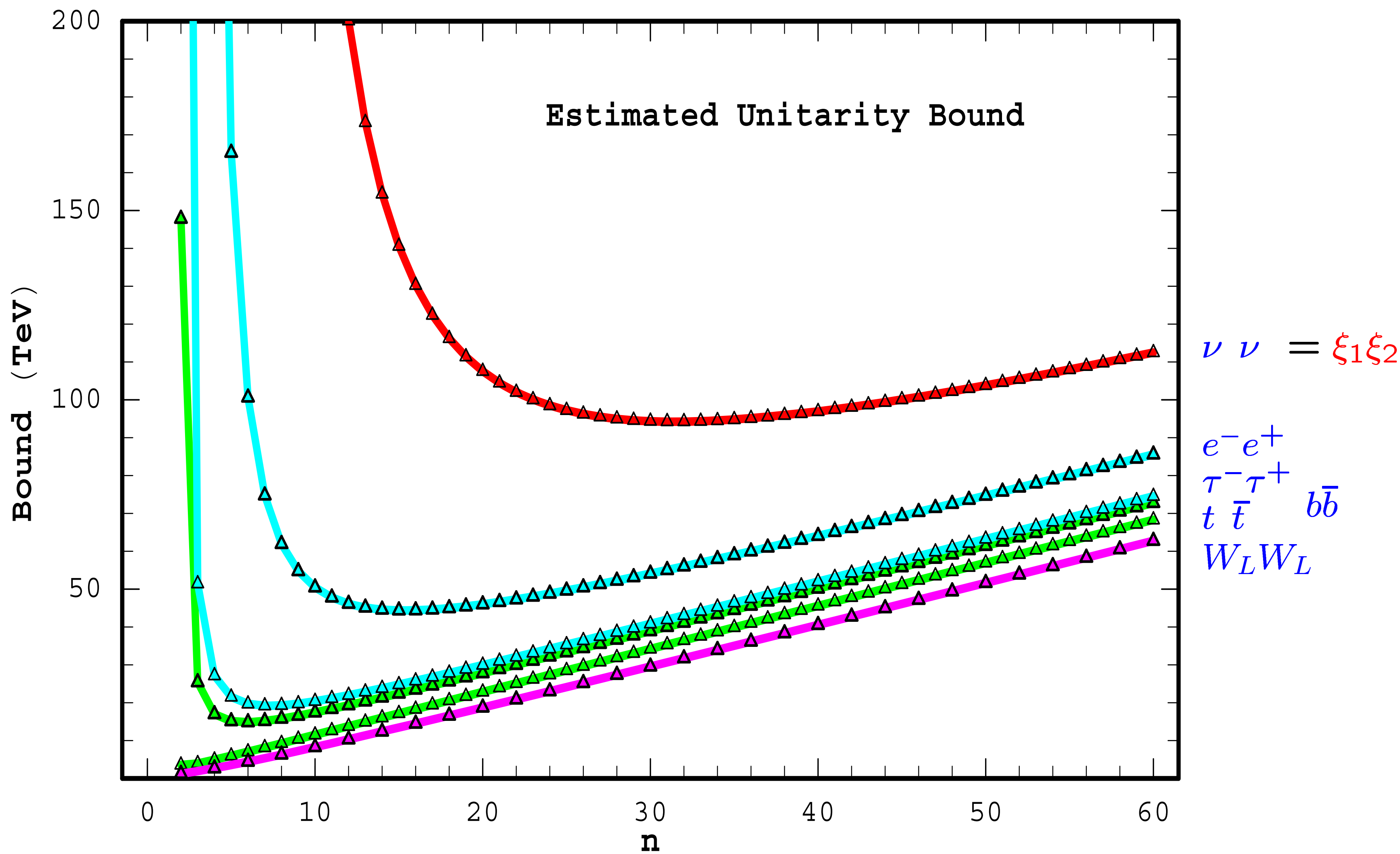
▶ **As** $n\uparrow$**, limit** $\Lambda_{\rm U}$ **exhibits competition between factors** $(\cdots)^{1/2n}$ **and** $(n{-}1)!(n{-}2)!$**.** $\Rightarrow$ **Minimal Bound** $\Lambda_{\rm U}^{\rm min}$ **occurs at a moderate value** $n=n_s$ **.**

Resolution and Surprise

Dicus & He, 2003

★ Surprise

▶ **Improved Estimate of Unitarity Bound Λ_U from $\xi_1\xi_2 \to nW_L^a$.**



Limits on Scales of Fermion Mass Generation

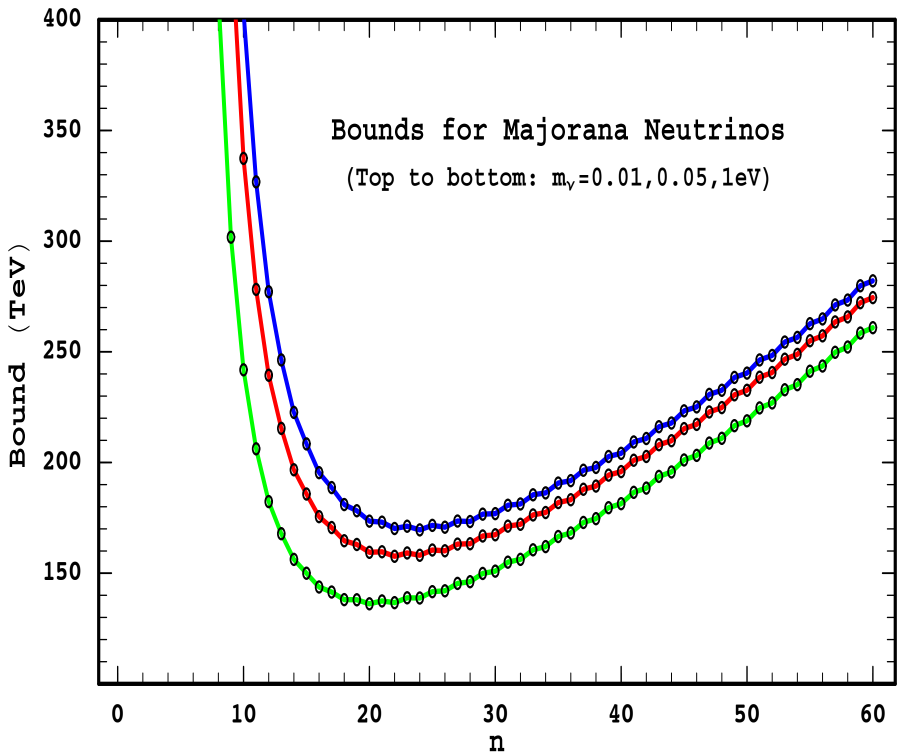
D. A. Dicus, H.-J. He, 2003

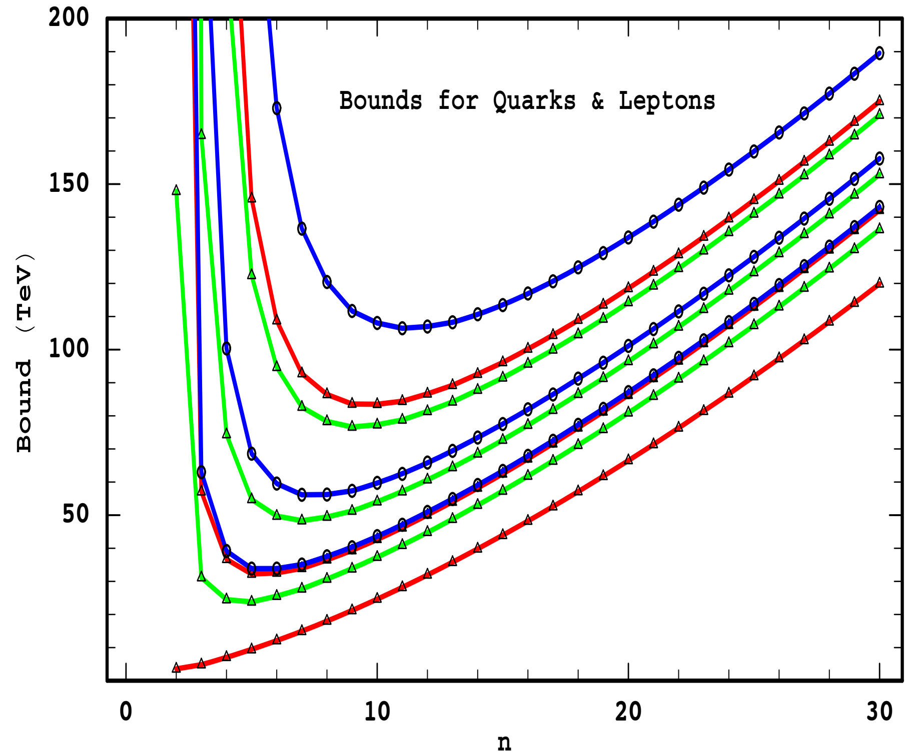
★ Surprise

▶ **Unitarity Bound Λ_U^{new} for Quarks/Leptons (right plot) and Majorana Neutrinos (left plot) from $f\bar{f} \to n\pi^a$.** *[In right plot, curves from bottom to top: $f = t, b, c, \tau, s, \mu, d, u, e$.]*

▶ **Best bounds Λ_U^{min} always occur at $n > 2$ for ALL light quarks/leptons and neutrinos. ⇒ A robust Upper Bound for ALL fermions:**

$$\Lambda_U^{min} \lesssim 170\,\mathrm{TeV}$$





Scales for Mass Generations: Summary

D. A. Dicus, H.-J. He, 2003

▶ **Summary of Classic Unitarity Limits Λ_U^{old} $(n=2)$ vs New Unitarity Limits Λ_U^{new} $(n=n_s)$ for Scattering** $\xi_1\xi_2 \to n\pi^a\,(nW_L^a)$. ($\xi_1\xi_2 = \pi^{a_1}\pi^{a_2}$, or, $f\bar{f}$, and n_s is # of final state π^a's (W_L^a's) corresponding to best limit Λ_U^{new}.)

$\xi_1\xi_2$	$\pi^{a_1}\pi^{a_2}$	$t\bar{t}$	$b\bar{b}$	$c\bar{c}$	$s\bar{s}$	$d\bar{d}$	$u\bar{u}$	$\tau^-\tau^+$	$\mu^-\mu^+$	e^-e^+	$\nu\nu$
Λ_U^{old} (TeV)	1.2	3.6	148	497	4×10^3	10^5	2×10^5	605	10^4	2×10^6	10^{13}
Λ_U^{new} (TeV)	1.2	3.6	25	33	49	77	84	34	56	107	158
n_s	2	2	4	6	8	10	10	6	8	12	22

★ **These limits are Universal & Independent of any detail of the Mechanism of Mass Generation.**

★ **Strong Non-Decoupling of Λ_U^{new} for fermions is essentially due to the Chiral Structure of fermion bare mass term – all left-handed fermions are weak-doublet but right-handed chiral partners are singlet.**

Looking Beyond: Two Essential Clues (2)

★ **Clue-2:**

What's Wrong with having a Fundamental Higgs Boson ??

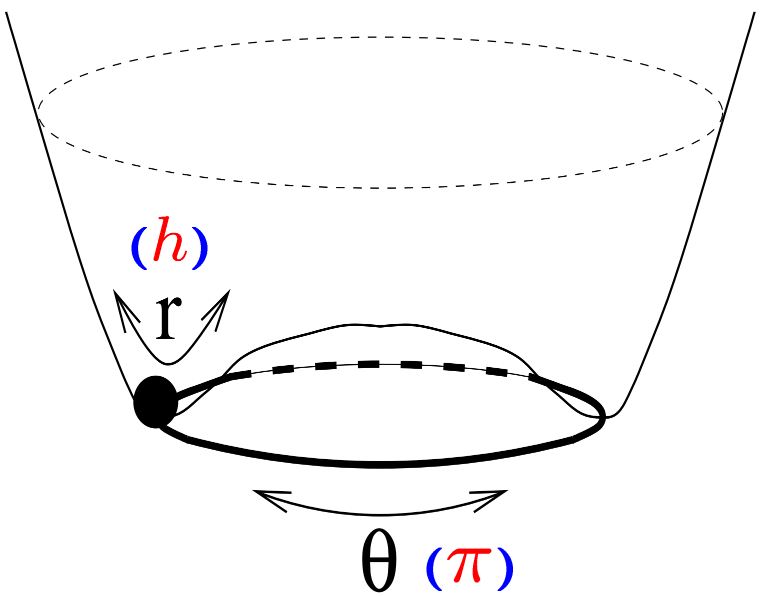
Higgs Mechanism & Higgs Mass in SM

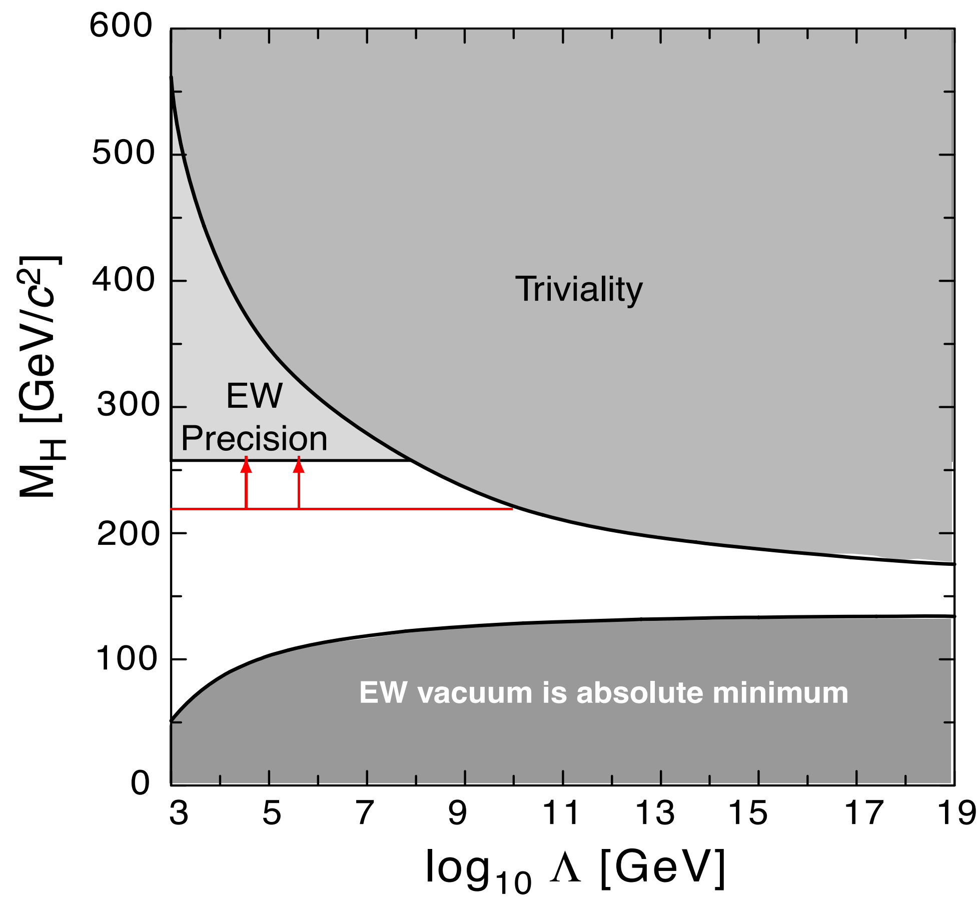
★ **SM Higgs Potential & Theory/Exp Constraints:**

$$V(H) = -\mu^2 H^2 + \lambda H^4, \quad \Longrightarrow \quad \langle H \rangle = \frac{v}{\sqrt{2}} = \sqrt{\mu^2/2\lambda}$$

$M_H = \sqrt{2\lambda}\, v$

$v \simeq 250$ GeV

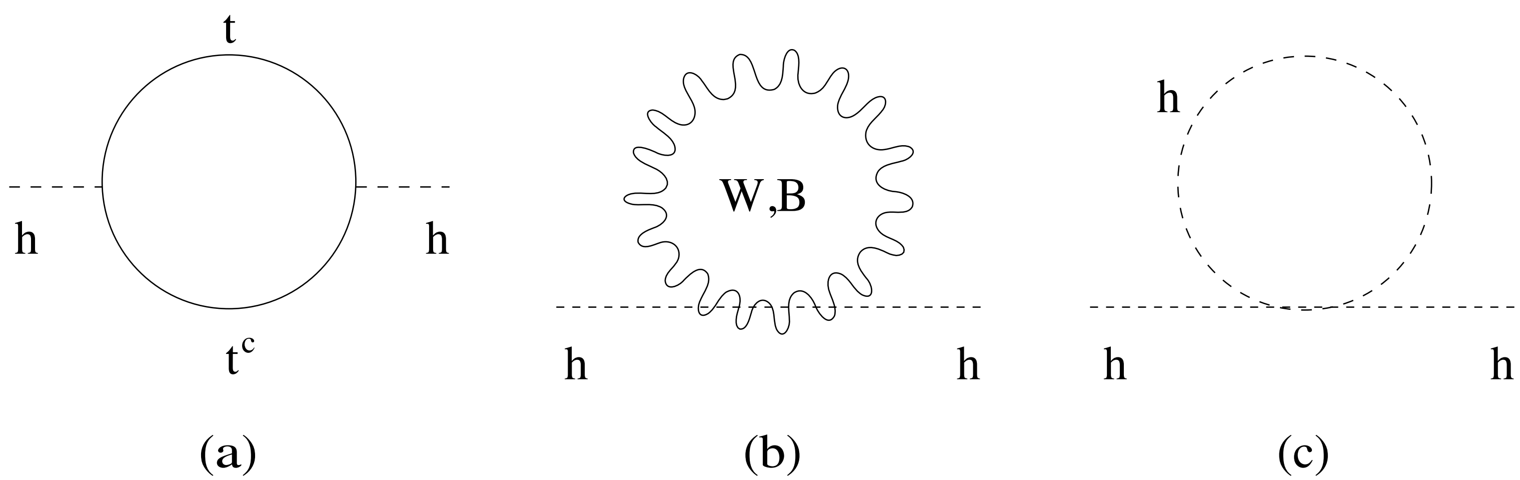




★ **SM with a light Higgs ($M_H \sim 160$ GeV) could be an Effective Theory valid up to Ultraviolet (UV) Cutoff $\Lambda \sim M_{\text{Planck}}$!! ⇒ What's WRONG ??!**

Higgs Mass & Big Hierarchy Problem

▶ **BUT, SM Quantum Corrections are quadratically sensitive to Λ^2:**



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

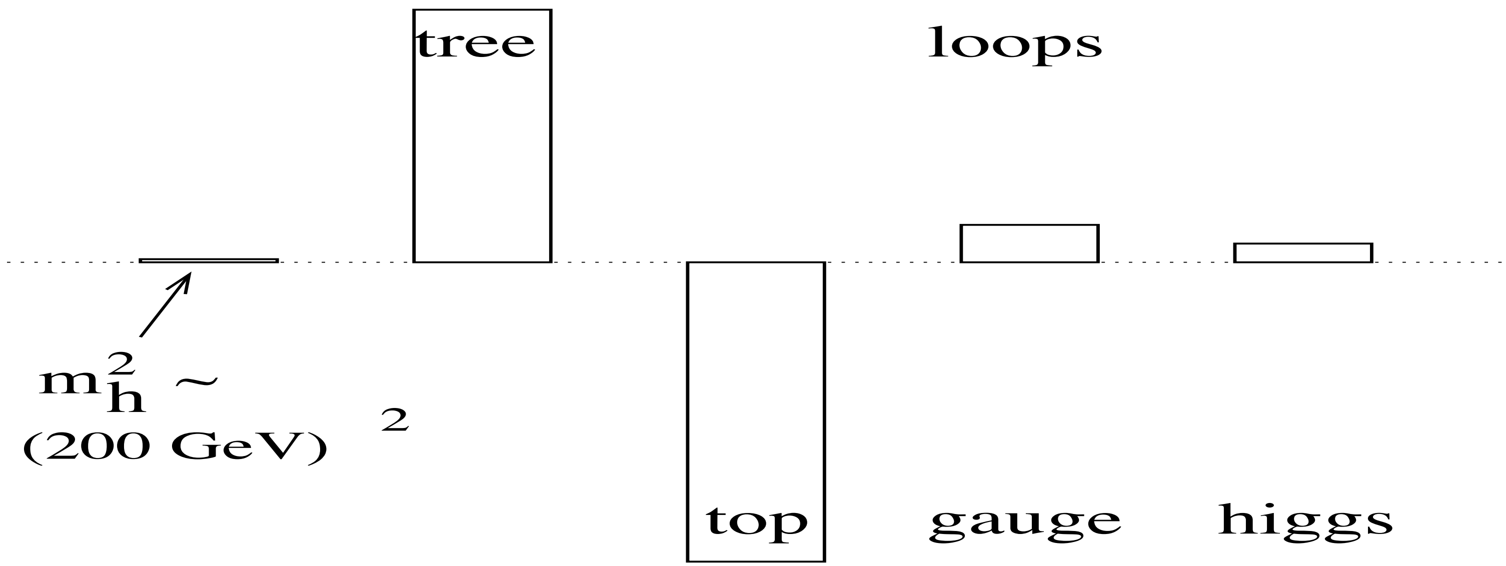
$$(200\,\text{GeV})^2 = M_{H0}^2 + \left[-(2\,\text{TeV})^2 + (700\,\text{GeV})^2 + (500\,\text{GeV})^2\right] \left(\frac{\Lambda}{10\,\text{TeV}}\right)^2$$

▶ **Big Hierarchy Problem:** $(M_{\text{Planck}} \simeq 10^{19}\text{GeV})$

$\Lambda \sim M_{\text{Planck}}$ **would require a fine-tuned cancellation down to** 10^{-30} **!!**

Higgs Mass & Little Hierarchy Problem

$$(200\,\text{GeV})^2 \;=\; M_{H0}^2 \;+\; \left[-(2\,\text{TeV})^2 \;+\; (700\,\text{GeV})^2 \;+\; (500\,\text{GeV})^2\right]\left(\frac{\Lambda}{10\,\text{TeV}}\right)^2$$



▶ Little Hierarchy Problem:

Demanding the **fine-tuning** $\gtrsim 10\%$ in M_H^2 gives

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

$\Rightarrow$ **New Phys** below $\sim$3**TeV** for SM holding up to $\sim$10**TeV** !!!

“Little Higgs” solves “Little Hierarchy”

▶ **“Little Higgs” (LH) opens up a New Avenue for**

Natural Electroweak Symmetry Breaking!

Arkani-Hamed, Cohen, Georgi, hep-ph/0105239

Arkani-Hamed, et al, hep-ph/0206020

Arkani-Hamed, et al, hep-ph/0206021

followed up by $O(100)$ **papers since 2002-2003......** (*cf. Spires*)

▶ **“Little Higgs” is an Effective Theory:**

No Fine-tuning & **Weakly Coupled** **up to** $\sim$10TeV

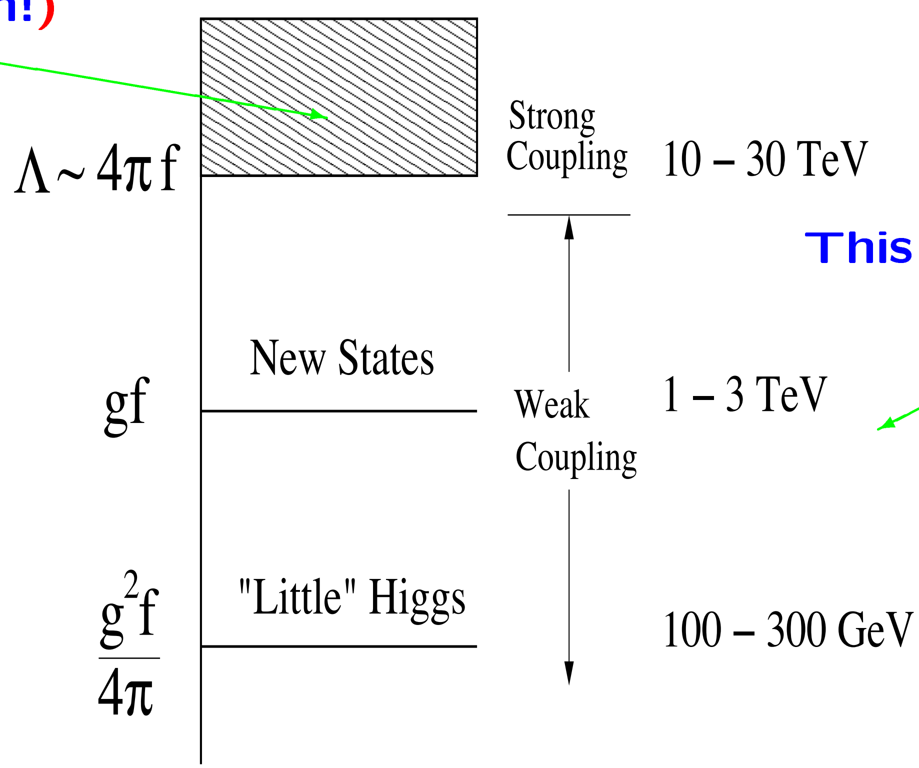
▶ **Today I’ll discuss something new about this direction ...**

"Little Higgs" solves "Little Hierarchy"

- Higgs is a pseudo-Goldstone boson due to Global Symmetry Breaking, $\mathcal{G} \to \mathcal{H}$, at Ultraviolet (UV) Scale $\Lambda \sim 4\pi f$. *(Georgi & Pais, 1974)*
- Higgs is naturally Light as protected by Goldstone theorem; Higgs acquires small mass radiatively. Quadradic Divergence cancelled at 1-Loop by New States with Same Spin: *(Arkani-Hamed, et al, 2001,2002)*

$$W, Z, B \leftrightarrow W', Z', B', \quad t \leftrightarrow t', \quad H \leftrightarrow \chi, \Phi.$$

(UV Completion!)



This perturbative domain reliable ???

Unitarity of Little Higgs vs UV Completion

S. Chang, H.-J. He, hep-ph/0311177

▶ **Unitarity of S-matrix:** $S^\dagger S = 1$, $(S = 1 + iT)$, $\Rightarrow$ $T^\dagger T = 2\,\mathrm{Im}T$

▶ **Partial Wave Expansion:** $T = 16\pi \sum (2j+1) P_j(\cos\theta)\, a_j$

▶ **Unitarity Condition on Partial Wave:** $|\mathrm{Re}\, a_j| < 1/2$

▶ **Coupled Channel Analysis for All Goldstones in each LH model:**

★ **Our observation is that Global Symmetry Breaking of LH Model results in a Large Multiplet of Many Goldstones (including SM H^0). The collective effect of Goldstone Scatterings will much enhance S-matrix via Coupled channels, and thus strengthen Unitarity Limit Λ_{U} to be significantly below naive cutoff scale $\Lambda \sim 4\pi f$, ie, $\boxed{\Lambda_{\mathrm{U}} \ll \Lambda}$.**

▶ **Roughly, Λ_{U} scales like:** *(cf. also GDA, Chivukula et al, 1992, Georgi, 1993)*

$$\sqrt{s} \;<\; \Lambda_{\mathrm{U}} \;\propto\; 4\pi f \frac{O(1)}{\mathcal{N}^{1/4}} < 4\pi f$$

where $\mathcal{N}$ is the number of Goldstones.

Unitarity of Little Higgs vs UV Completion

S. Chang, H.-J. He, hep-ph/0311177

- We found Unitarity Violation Scale $\boxed{\Lambda_{\rm U} \sim (3-4)f} \ll \Lambda \sim 4\pi f \sim 10\,\text{TeV}$.

- $\Lambda_{\rm U}$ is comparable with W' mass $M_{W'}$ $\Rightarrow$ Crucial to do UV completion – additional New States must be included in Multi-TeV range to restore Unitarity! $\Rightarrow$ More New Signals for LHC !!

- New States reflect Little Higgs UV dynamics, and should be included in a way consistent with Λ^2-Cancellation in Higgs Mass at 1-Loop.

- Summary of Unitarity Bounds in various Models. (Note: $\mathcal{N} \gg 1$)

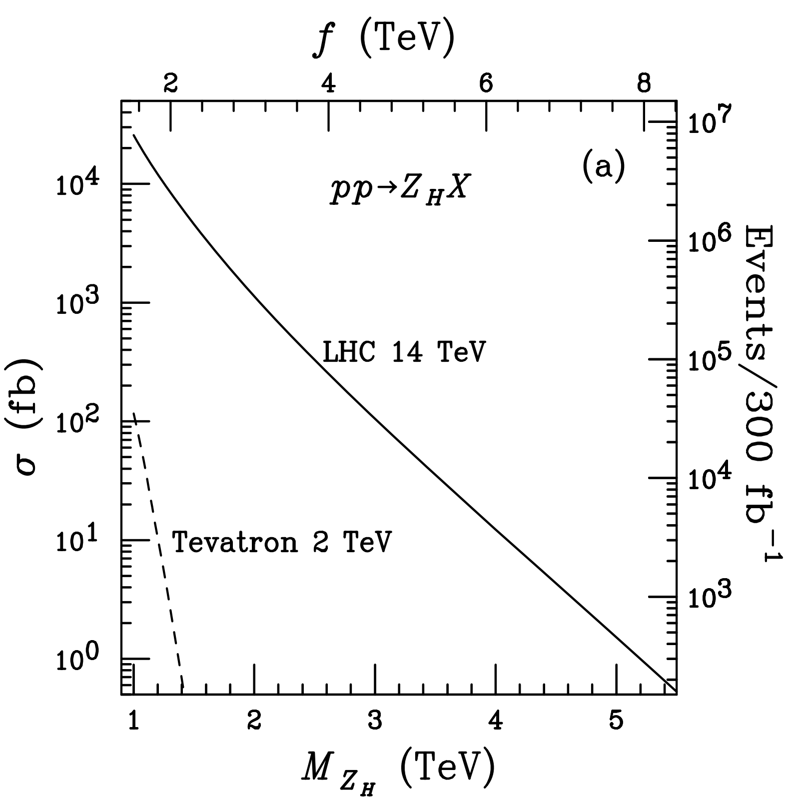
Little Higgs Model	G	H	$\mathcal{N}$	$\Lambda_{\rm U}/f$	$M_{W'}/f$
Minimal Moose	$SU(3)^2$	$SU(3)$	8	2.89	2.29
Littlest Higgs	$SU(5)$	$SO(5)$	14	3.17	1.62
Antisymm Condensate	$SU(6)$	$Sp(6)$	14	3.68	1.62
$SO(5)$ Moose	$SO(5)^2$	$SO(5)$	10	4.09	3.24
$SO(9)$ Littlest Higgs	$SO(9)$	$SO(5)\otimes SO(4)$	20	3.79	2.29

Little Higgs Collider Signals

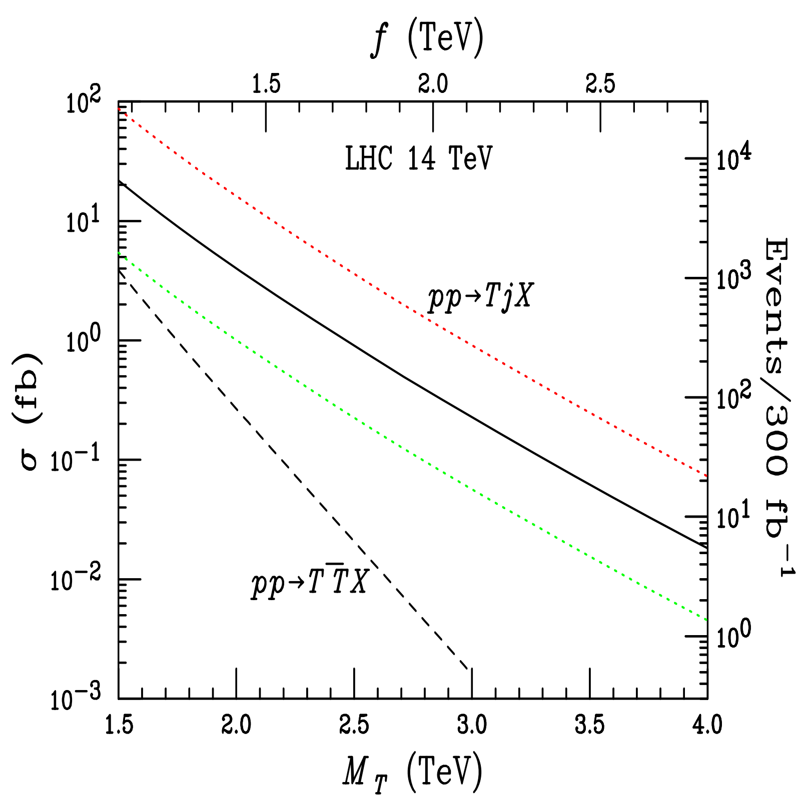
- **Typical Collider Signals of heavy New States in the Littlest Higgs Model $SU(5)/SO(5)$.** *(cf. Han et al, hep-ph/0301040, Peskin et al, hep-ph/0310039,...)*

- **LC can test anomalous ZZH coupling... More studies are upcoming!.....**

Z' Production:



t' Production:



Summary and Outlook ...

★ The Standard Model (SM) is a Local Quantum Gauge Theory, successfully describing the Nature down to $\sim 10^{-16}$ cm.
SM contains 19 free parameters; but 16 are due to our lack of knowledgment about the **Origin of Mass Generations**.

★ With all Bare Masses putting in by hand, SM is plauged with **Unitarity Violation**, which puts Upper Limits on Scale of Mass Generation.

★ By assuming a single fundamental Higgs H^0 for giving masses to ALL particles, SM is then plauged with **Hierarchy Problem**.

★ Unitarity provides Universal Upper Limits on the Scales of Mass Generation for **ALL** SM particles. Our limit $\Lambda_{\rm U}^{\rm new}$ from $2 \to n$ $(n > 2)$ Scatterings revealed strong Non-Decoupling nature:

$$\Lambda_{\rm U}^{\rm new} < (3.6,\, 84,\, 107,\, 170)\ \text{TeV} \qquad (\text{for } f = t,\, u,\, e,\, \nu)$$

$$\Lambda_{\rm U}^{\rm old} < (3.6,\, 2\times 10^5,\, 2\times 10^6,\, 10^{13})\ \text{TeV} \qquad (\text{for } f = t,\, u,\, e,\, \nu)$$

★ "Little Higgs" is an elegant idea, realizing Higgs as a Pseudo-Goldstone boson (—naturally light). It solves a Little Hierarchy Problem, but we showed the UV Completion is crucial and additional **New States** in **Multi-TeV Range** are forced by Unitarity.

Looking back ... The Past ...

▶ During 1492-1504, Columbus carried out heroic EXPERIMENTAL probes to prove Pythagoras Theory (∼500 B.C.) that the Earth is Round (and to search for Mainland China & Gold).....

▶ He had the Correct Theory in mind, but he had not finally proven it before his death.....instead, he discovered Something Else !!!

Voyage
1492-1504

C. Columbus
1451-1506

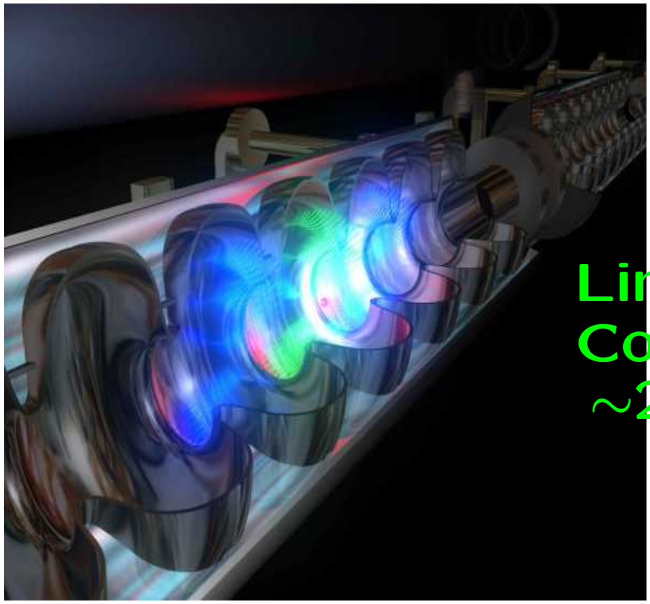
★ Lessons: (1) A Good Theory! (2) Vigorous Experiments!!

(3) **COURAGE** !!!

Outlook ...The Future ...

▶ HEP does have vigorous EXPs upcoming...The Future is bright...

CERN
LHC
2007



Linear
Colliders
∼2012

▶ CERN Large Hadron Collider (LHC) will turn on by 2007. Particle physicists are looking forward to upcoming Original Discoveries.....

▶ Next International Linear Collider (LC) will make Complementary Precision Probes and establish New Physics Beyond the Standard Model!

★ Many more in addition to LHC & LC ..... *cf. my Friday Seminar:*

Structure of Cosmological CP Violation via Neutrino Seesaw