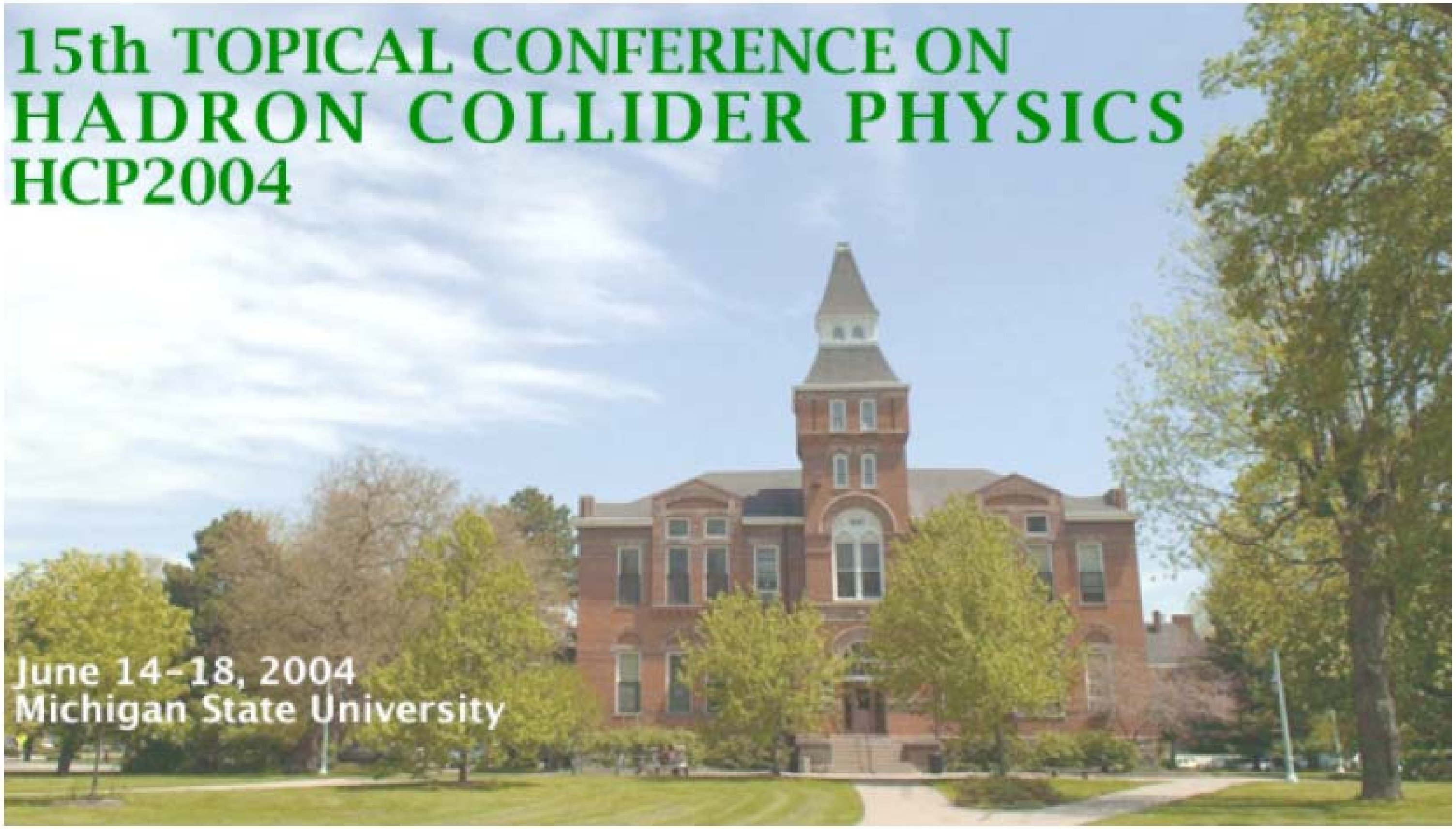


Another Outlook

In 10 years the written laws of physics will be different than they are now.

What is the biggest unsolved problem in physics?

"I do not like this question... Galileo was surrounded by great professors of theology, Aristotelian philosophy, and so forth, who addressed all the 'greatest' questions about the nature of the universe, the meaning of life, and so on, in long treatises. But Galileo made a more lasting contribution by studying and figuring out precisely how balls roll down inclined planes."

Frank Wilczek, in Physics World, Dec. 1999

Sarcophilis harrisii
(Tasman devil)

“The devil is in the details.”

How Will It Emerge?

- The energy frontier
- The quark flavor frontier
- The neutrino frontier
- The theory frontier
- The cosmic frontier

The Energy Frontier

Local Gauge Invariance on a Wallet Card

$$\Psi(x,t) \longrightarrow e^{i\theta(x,t)}\Psi'(x,t)$$ Local

$$D_\mu\psi(x,t) \longrightarrow e^{i\theta(x,t)}D'_\mu\psi'(x,t)$$

$$D_\mu = \partial_\mu - ieA_\mu(x,t)$$

$$A_\mu(x,t) \longrightarrow A_\mu(x,t)' + \frac{1}{e}\partial_\mu\theta$$

$$F_{\mu\nu} = \frac{i}{e}[D_\mu, D_\nu] = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + (D_\mu\Psi)^\dagger D^\mu\Psi - M^2\Psi^\dagger\Psi$$

$$\mathcal{L}(\Psi, A_\mu) = \mathcal{L}(\Psi', {A_\mu}')$$ Gauge Invariance

Can the Photon Have a Mass?

$$\mathcal{L} = -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \tfrac{1}{2}m^2 A_\mu A^\mu$$

$$A_\mu(x,t) \longrightarrow A_\mu(x,t)' + \tfrac{1}{e}\partial_\mu\theta$$

$$\mathcal{L} \to -\tfrac{1}{4}F'_{\mu\nu}F^{\mu\nu\prime} + \tfrac{1}{2}m^2(A'_\mu + \tfrac{1}{e}\partial_\mu\theta)^2 \quad \text{NO!!!}$$

$$\mathcal{L} = -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \tfrac{1}{2}m^2 A_\mu A^\mu + \tfrac{1}{2}(\partial_\mu\phi)^2 - mA_\mu\partial^\mu\phi$$

$$\mathcal{L} = -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \tfrac{1}{2}m^2(A_\mu - \tfrac{1}{m}\partial_\mu\phi)^2$$

$$\mathcal{L} \to -\tfrac{1}{4}F'_{\mu\nu}F^{\mu\nu\prime} + \tfrac{1}{2}m^2(A'_\mu - \tfrac{1}{m}\partial_\mu\phi')^2$$

$$\phi \longrightarrow \phi' + \tfrac{m}{e}\theta \qquad \text{OK!!!}$$

London's Theory of Superconductivity

$$\mathcal{L} = -\tfrac{1}{2m_e}[(-i\vec{\nabla} - \tfrac{e}{c}\vec{A})\psi]^\dagger(-i\vec{\nabla} - \tfrac{e}{c}\vec{A})\psi + \ldots$$

"rigid wavefunction" $\leftrightarrow$ energy "gap" $\leftrightarrow$

$$\psi \sim \psi_0 e^{i\phi(\vec{x},t)} \qquad |\psi_0|^2 = n_e$$

$$\mathcal{L} \to -\tfrac{1}{2m_e}(\vec{\nabla}\phi - \tfrac{e}{c}\vec{A})|\psi_0|^2$$

gauge invariant: $\vec{A} \to \vec{A}' + \tfrac{c}{e}\vec{\nabla}\theta, \quad \phi \to \phi' + \theta$

photon mass: $m^2 = \frac{e^2 n_e}{m_e c}$ 2× too small!!!

BCS Theory: $\psi \to \psi(x)\psi(y)$ Cooper Pair

The Devil is inWeak Scale Superconductivity

The Devil May Soon Appear

- CDF & D-Zero have excellent chances at catching the devil!
- Intriguing new hints of "something"
  - (Edward Teller, "If only you knew what I know!")
- Possible dramatic results within 1 fb^{-1}

The Energy Frontier will move to CERN in 4 years

The VLHC will become imperative in less than 10 years!

Candidate Operating Principles come from theories with extra dimensions.

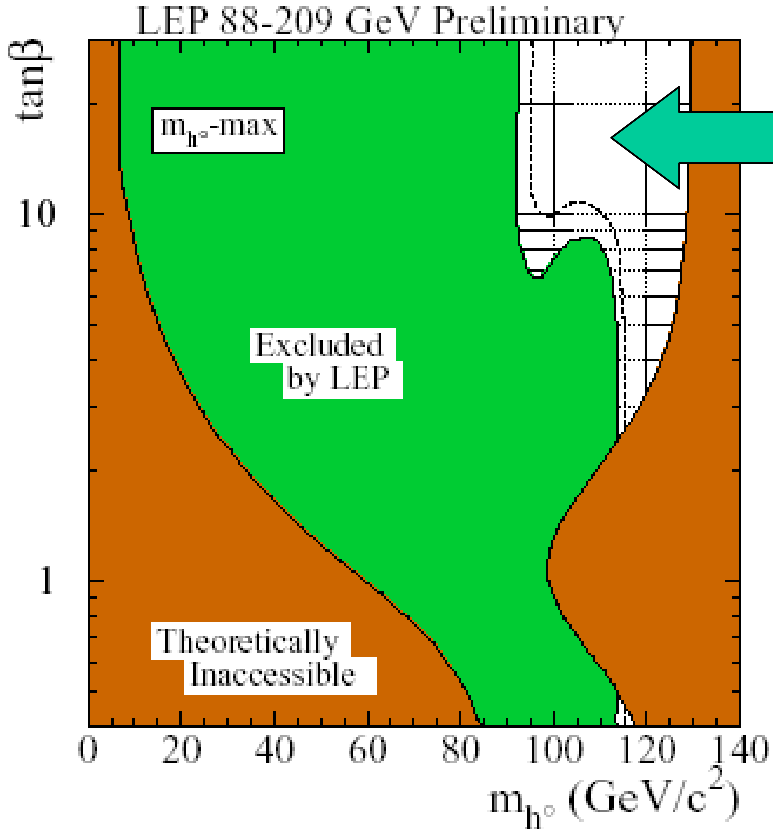
- Conventional extension of Lorentz Group.
- New "rotations" and "translations."
- Broken Lorentz Invariance by compactification: *Kaluzsa-Klein modes.*
- High energy Theory: Superstring Theory?
- Extra dimensions can be associated with the electroweak scale, e.g., ~ 1 TeV, rather than M_{Planck} ?

  (D. Jackson, ca 1972; Antoniadis 1991, Lykken 1996, ...)

e

Trouble with SUSY?

The MSSM is being squeezed:



Fine Tuning < 10% precision

What we mean by weak scale SUSY:

- Must provide a *custodial symmetry* for the "weak scale" via SUSY.
- Must have *unification* in a simple and compelling way (consistent with String).
- Must **not be** "*fine-tuned*." (This is supposed to be *the* fundamental theory!)

$$-m_H{}^2 H^* H + \frac{\lambda}{2}(H^* H)^2$$

Fixed = 175 GeV

$$\mathrm{v}_{weak} = m_H / \sqrt{\lambda}$$

Increased by experimental limit

forced to increase

Compute Higgs mass from Quartic coupling:

$$m_H{}^2 \approx M_Z{}^2 + \frac{3}{8\pi^2 \mathrm{v}_{weak}{}^2} m_{top}{}^4 \ln(m_{\tilde{t}}{}^2 / m_{top}{}^2)$$

Tree approximation, large tan β

Top-stop loop

(2) Top-stop loop

Compute Higgs mass
From bare Higgs mass:

$$m_H{}^2 \approx -\mu^2 f(\ldots) + \frac{3}{8\pi^2}(m_{\tilde{t}}{}^2 - m_t{}^2)$$

(1) Tree approximation

Must arrange a cancellation between (1) and (2)

Fine tuning < 10%

How to fix it?

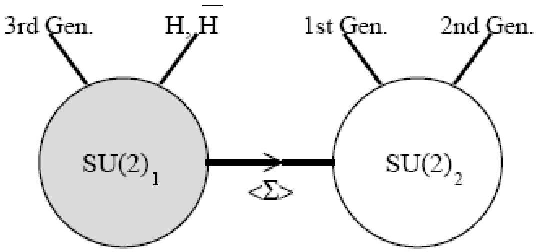
Batra,Delgado,Kaplan,Tait

JHEP **0402**, 043 (2004) and *hep-ph/0404251*

NMSSM: Modify the tree relationship: $m_h \leq |\cos 2\beta| m_Z$

(1) Replace μ-term by gauge singlet

(2) Topflavor gauge structure is now $SU(2)_1 \times SU(2)_2 \times U(1)_Y$



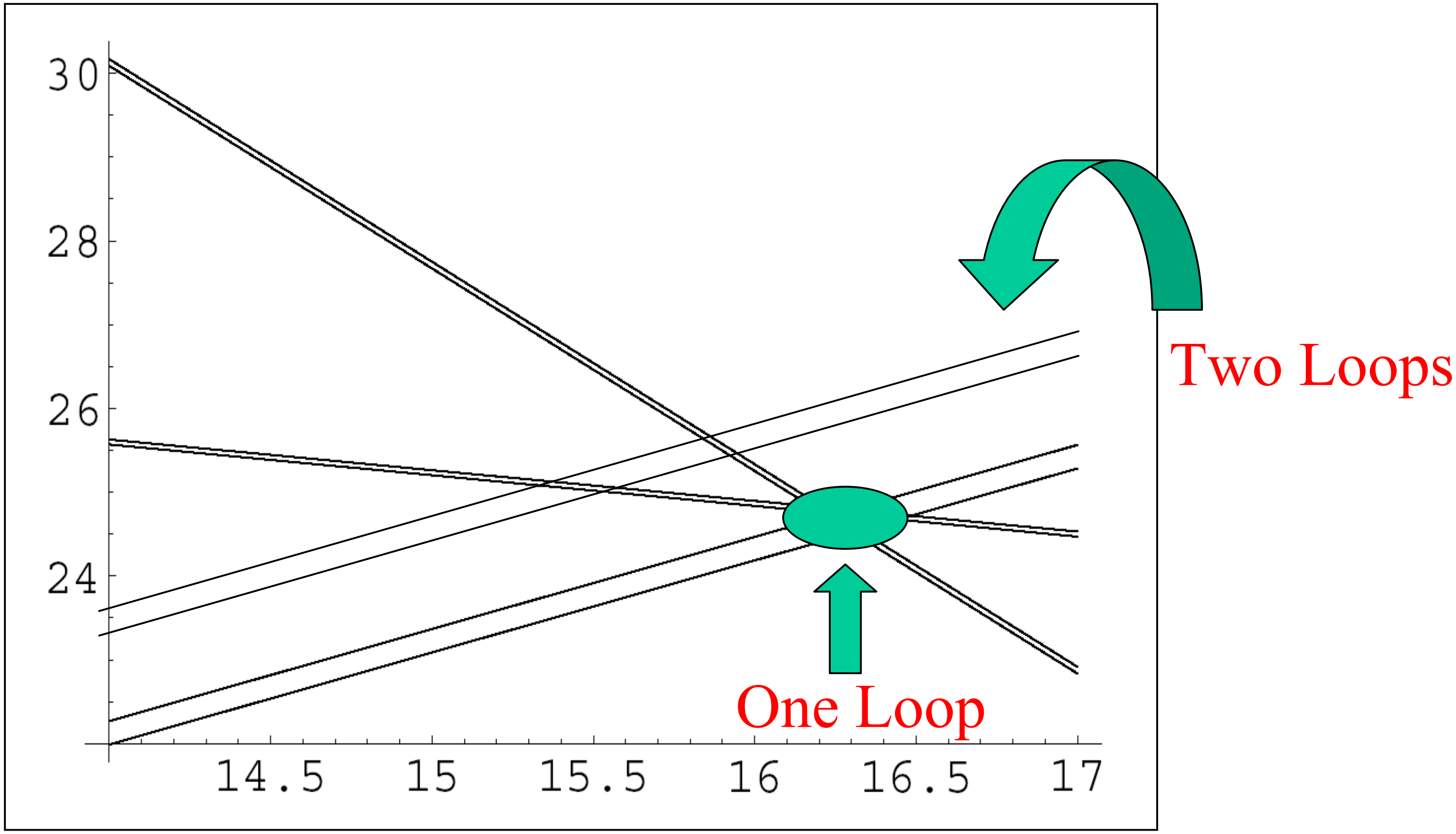
$$m_{h^o}^2 \quad < \quad \frac{1}{2}\left(g^2\Delta + g_Y^2\right) v^2 \cos^2 2\beta$$

$$\Delta = \frac{1 + \frac{2m^2}{u^2}\frac{1}{g_2^2}}{1 + \frac{2m^2}{u^2}\frac{1}{g_1^2+g_2^2}} \quad \text{and} \quad \frac{1}{g^2} = \frac{1}{g_1^2} + \frac{1}{g_2^2}$$

Solutions
Create tension with
Unification!

Does SUSY Unify?

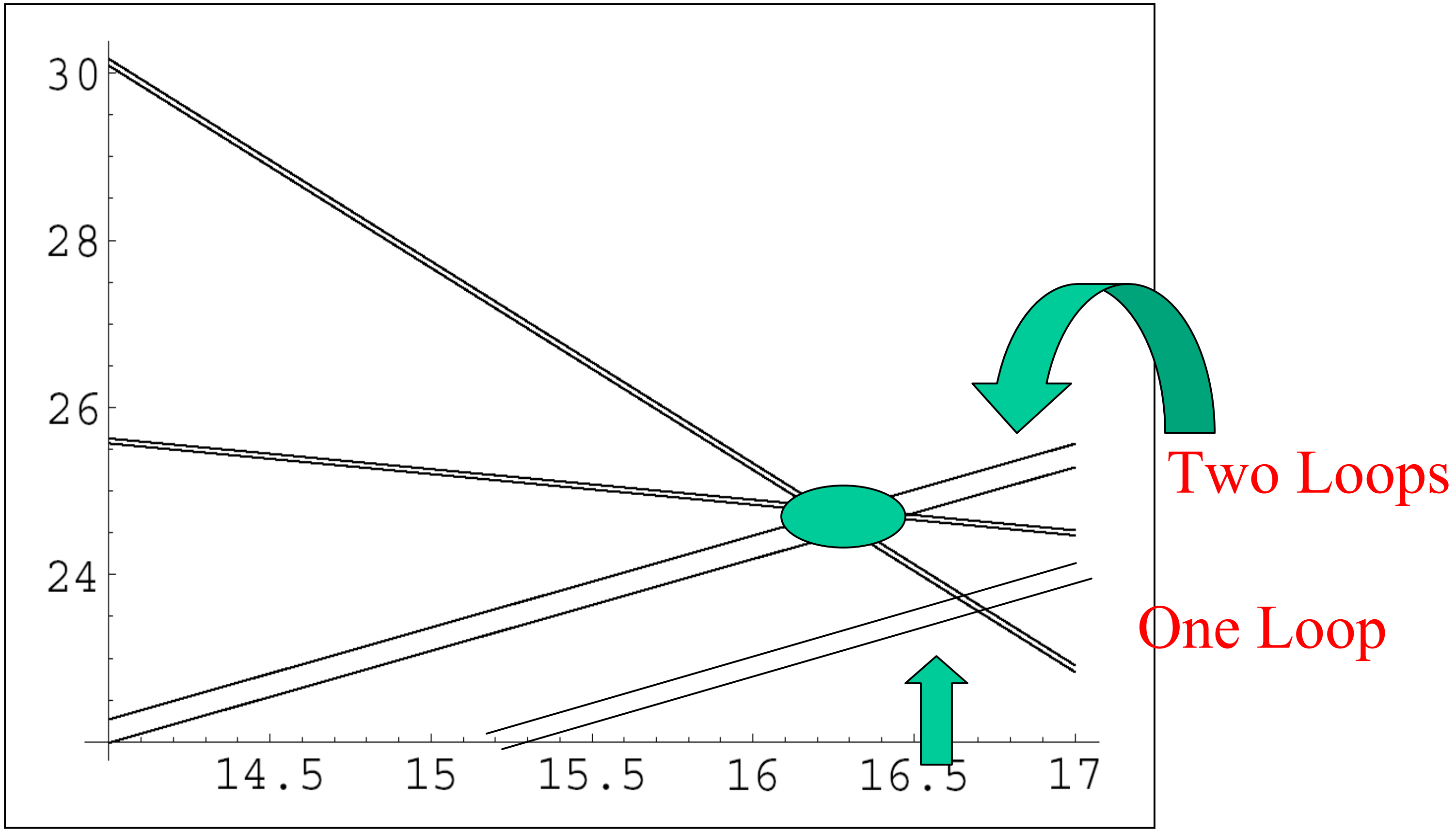
S. Raby PDG



4% discrepancy = 3 sigma discrepancy predicting $\alpha(M_Z)$

Make SUSY Unify!

Dimopoulos
Arkani-Hamed



Raise m_{stop} to 10^{10} GeV; invoke “anthropic principle.”

Perhaps something else:

Solutions pull away from SU(5) perturbative unification and toward a strongly interacting theory

Non-SUSY solutions to EWSB exist and are natural.

New Strong Dynamics?

Deconstruction, Little Higgs, Higgless Models…

The Role of Scale Symmetry?

- We live in 1+3 dimensions
- The big cosmological constant conundrum
- The Higgs Boson mass scale
- How QCD solves the problem of hierarchy
- New Strong Dynamics?

$$\partial_\mu S^\mu = T_\mu{}^\mu = \Lambda_{\cos mo\log ical} + \frac{\beta(g)}{2g} Tr(G_{\mu\nu} G^{\mu\nu}) + m_H{}^2 H^* H + \ldots$$

?

$$\approx 0$$

?

The Role of Extra Dimensions?

- We live in large 1+3 dimensions
- Other dimensions violate scale invariance
- Is it normal geometry?
- Deconstruction and Abstraction
- Renormalization Group as a Symmetry Principle?

Why not Extra Time Dimensions?

Requires a complete reinterpretation of dynamics:

- e.g., Nambu dynamics!
- Classical Hamiltonian dynamics must be reformulated!
- Consider variable $q(t_1, t_2, ..., t_d)$
- d time coordinates $\longrightarrow$ d canonical conjugates $p_1, p_2, ..., p_d$
- d Hamiltonians $H_1, H_2, ...H_d$

Generalized Hamilton Equations:

$$\frac{\partial \mathcal{X}}{\partial \tau} = \frac{\partial (\mathcal{X}, H_1, H_2, ...H_d)}{\partial (q, p_1, p_2, ..., p_d)}$$

Generalized Quantum Mechanics:

$$i\hbar \frac{\partial \mathcal{O}}{\partial \tau} = (\Lambda)^{-(d-1)}[\mathcal{O}, H_1, H_2, ...H_d]$$

Can Theory solve the cosmological constant problem? Reduces back to ordinary quantum mechanics when $H_2, H_3...H_d$ have large energy gap. Only one time variable: worldline proper time!

A Gedanken Experiment:

An experimentalist discovers a 0.5 TeV,
$J = 1$, $I = 0$, Degenerate Color= **8** particle
("coloron"), produced at the Tevatron.
How do we describe this with a Lagrangian?

Sufficient Solution, i.e., "Hidden Local Symmetry of Vector Mesons." (Bando, Kugo, Yamawaki, et.al.)

- QCD: $SU(3)_1$ $-\frac{1}{4}(G^a_{\mu\nu}G^{a\mu\nu})$ $\longrightarrow$ ○
- Coloron: $SU(3)_2$ $-\frac{1}{4}(F^a_{\mu\nu}F^{a\mu\nu})$ $\longrightarrow$ ○

  (spin-1 $\times$ Lorentz Invariance $\times$ Quantum Mechanics $\rightarrow$

  A_0 cannot propagate $\rightarrow$ Gauge invariance.)

- Must give mass to the coloron $\longrightarrow$ Need Φ a $(\bar{3}_1, 3_2)$ under $SU(3)_1 \times SU(3)_2$.

$$\langle 0|\Phi|0\rangle = \begin{pmatrix} v & 0 & 0 \\ 0 & v & 0 \\ 0 & 0 & v \end{pmatrix}$$

○ $-\ \Phi\ -$ ○

Result of $SU(3) \times SU(3)$, Φ (Topcolor):

Analogue of an Ethane Molecule:

- QCD gluon (zero-mode): $\rightarrow \bigcirc - \bigcirc \rightarrow$

  $G = \frac{1}{\sqrt{2}}[A_1 + A_2]$ $\qquad M_G = 0$

- Coloron: $\rightarrow \bigcirc - \bigcirc \leftarrow$

  $H = \frac{1}{\sqrt{2}}[A_1 - A_2]$ $\qquad M_H = gv$

- QCD coupling constant:

$$\frac{1}{g_{QCD}^2} = \frac{1}{g_1^2} + \frac{1}{g_2^2}$$

  If $g = g_1 = g_2$ then $g^2 = 2g_{QCD}^2$!

- Phenomenology: $G \rightarrow VV$, $GG \rightarrow VV$, but no $G \rightarrow GV$, etc.

Experimentalists discover a second 1.0 TeV, $J = 1$, $I = 0$, coloron:

Expanded effective Lagrangian:

- $SU(3)_1 \times SU(3)_2 \times SU(3)_3$
- 2 Higgs Fields:
  Φ_1: $(\bar{3}_1, 3_2)$; Φ_2: $(\bar{3}_2, 3_3)$;
- Unambiguous Structure:
  "Propane" ○ – ○ – ○
- QCD coupling: $g^2 = 3g_{QCD}^2$
- Spectrum:
  gluon (zero-mode) + 2 Colorons

$G = \frac{1}{\sqrt{3}}[A_1 + A_2 + A_3]$ ○ → ○ → ○ →

$H_1 = \frac{1}{\sqrt{2}}[A_1 - A_3]$: ○ → ○ ← ○

$H_2 = \frac{1}{\sqrt{6}}[A_1 - 2A_2 + A_3]$: ○ → ○ ←—→ ○

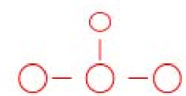
Experimentalists discover third 1.5 TeV, $J = 1$, $I = 0$, coloron:

Again, expand Effective Lagrangian:

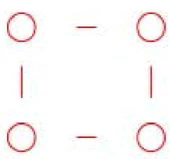
- QCD: $SU(3)_1 \times SU(3)_2 \times SU(3)_3 \times SU(3)_4$; g_L
- 3 Higgs: Φ_1, Φ_2, Φ_3; v.
- $g_L^2 = 4g_{QCD}^2$; gluon + 3 heavy H's.
- Equivalent to Geometrical Configurations and Normal Modes of Butane Isomers:

  Aliphatic Butane: ○ – ○ – ○ – ○

  Methylpropane:



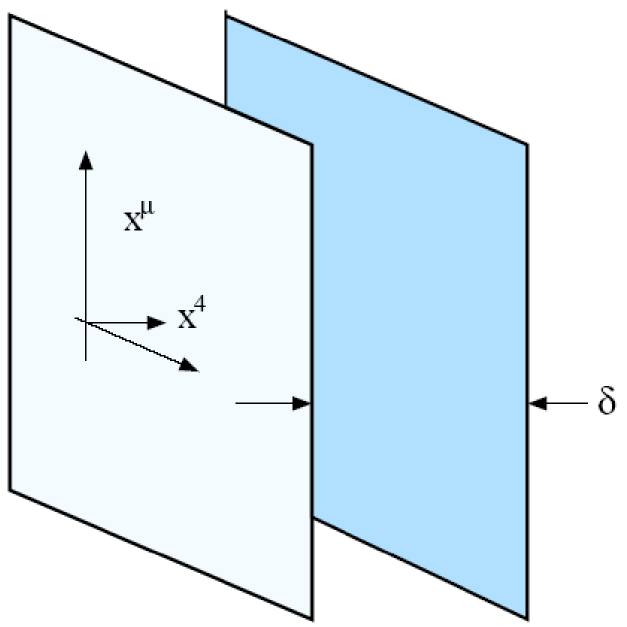
  Cyclobutane:



(requires 4 Higgses)

What is the organizing principle here?

A Geometrical Extra Dimension



Fields Propagate in the Extra Dimensions

Compactification Boundary Conditions:

- Periodic:

All basis functions periodic under $x^4 \to x^4 + \delta$

- Orbifold:

Divide basis functions into even F_+ and odd F_- under $x^4 \to 2\delta - x^4$

E.g., vector field A_μ: A^μ even; A^4 odd.

Assign $A^\mu \sim F_+$; $A^4 \sim F_-$.

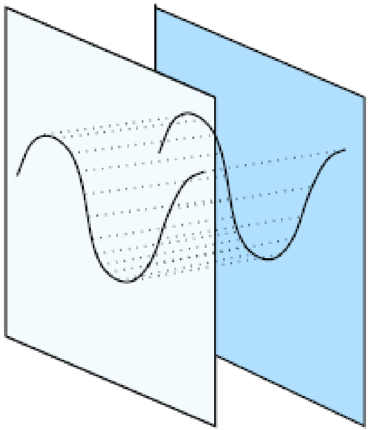
Kaluza-Klein Modes

Zero-mode (Gluon):

Vanishing $p^4 \to M_g = 0$

Orbifold: No A^4 zero mode, only A^μ.

Periodic: Both A_μ and A^4 zero-modes.



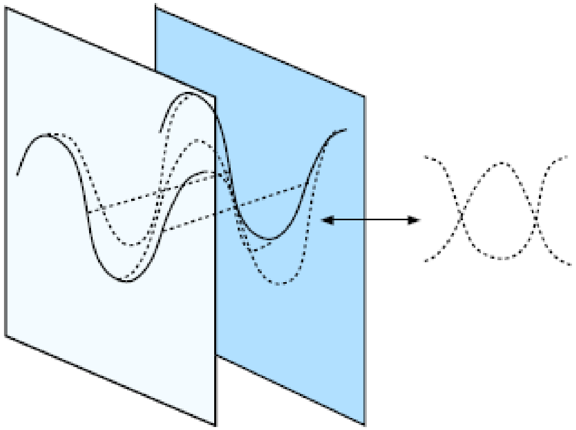
First KK Mode (Gluon):

Has mass:

$\partial_B \partial^B A = (\partial_\mu \partial^\mu + M^2) A$

$M = p^4 = 2\pi/\delta$:

A^4 is "eaten"
becomes longitudinal mode.

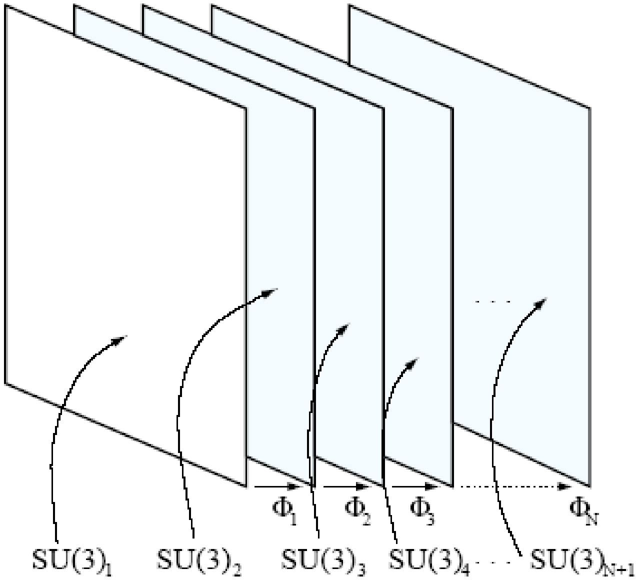


An Organizing Principle for $3+1$

Kaluza-Klein spectrum of an extra dimension of unknown geometry and topology.

Describe it in $3+1$ Dimensions:

Aliphatic case → Effective Lagrangian of a Transverse Wilsonian Lattice of an Extra Dimension.



Continuum $SU(3)_n$ on nth "brane."

Latticization
or
"Deconstruction"

CTH, Pokorski, Wang;
Arkani-Hamed, Georgi, Cohen

A Yang-Mills gauge theory in compact extra dimensions at low energy is indistinguishable from a $3+1$ theory with *replicant* gauge groups.

e.g., QCD $\rightarrow SU(3) \times SU(3) \times SU(3)$...

The Standard Model $\rightarrow [SU(3) \times SU(2) \times U(1)]^N$

Generic "Aliphatic" $(SU(3)^N, \Phi^{N-1})$ model $\longrightarrow$

Yang-Mills Lagrangian in $1+3$ dimensions for N copies of QCD:

$$\mathcal{L}_{QCD} = -\sum_{j=1}^{N} \frac{1}{2} \operatorname{Tr} F_{\mu\nu j} F_j^{\mu\nu} + \sum_{j=1}^{M} D_\mu \Phi_j^\dagger D^\mu \Phi_j$$

N gauge groups $SU(3)_j$ with common g_L

$M = N - 1$ $\Phi_j \longleftrightarrow$ Orbifold

$M = N$ $\Phi_j \longleftrightarrow$ Periodic

The Kaluza-Klein Spectrum

Φ_j get VEV's: $\langle 0|\Phi_j|0\rangle = vI_3$

(Can use potentials; all unwanted modes heavy)

Thus:

$$\Phi_j \rightarrow vI_3 \exp(i\phi_i^a \lambda^a / 2v)$$

ϕ_i^a KK-modes are eaten.
ϕ_i^a zero-mode iff periodic compactification.

Φ_j kinetic terms $\rightarrow$ gauge field mass matrix:

$$\sum_{j=1}^{N} \frac{1}{2} g_L^2 v^2 (A^a_{(j-1)\mu} - A^a_{j\mu})^2$$

Mass term has the structure of a nearest neighbor coupled oscillators (e.g. phonons in crystal).

Diagonalize Mass Matrix:

$$M_n = \sqrt{2} gv \sin\left[\frac{n\pi}{2N}\right] \qquad n = 0, 1, 2, ...N-1$$

For small n this system fakes a "KK tower:"

$$M_n \approx \frac{gv\pi n}{\sqrt{2}N} \qquad n << N$$

$n = 0 \longrightarrow M_0 = 0$, the gluon "zero-mode."

Match to geometry:

$$\frac{gv}{\sqrt{2}N} = \frac{1}{R}.$$

R is "radius" of extra dimension.

Spectrum of KK modes reveals the geometry/topology of the "extra dimensions."

Extra Geometrical Dimensions swapped for a field theory, lose their absolute meaning.

Fermions

Free fermion Dirac action:

$$\int d^5x\ \bar{\Psi}(i\gamma_\mu\partial^\mu - \gamma^5\partial_5 - M)\Psi$$

Latticize: $\Psi(x^\mu, x^4) \to \Psi_n(x^\mu)$

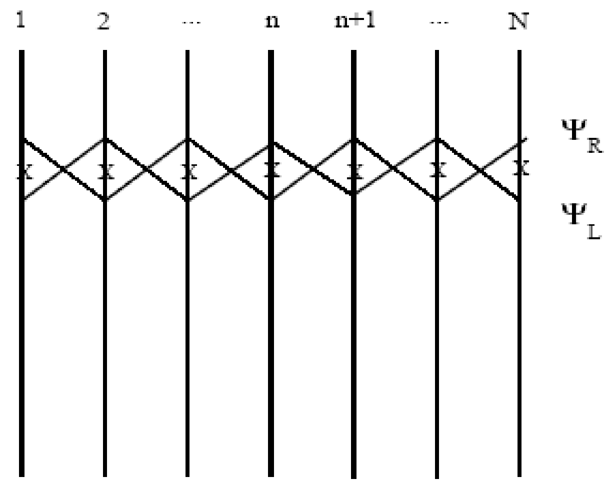
$$\sum_{n=1}^{N}\left(\bar{\Psi}_n i\gamma_\mu\partial^\mu\Psi_n - M\bar{\Psi}_n\Psi_n - v\bar{\Psi}_n\gamma^5\Psi_{n+1} + h.c.\right)$$

Use Chiral Projections:

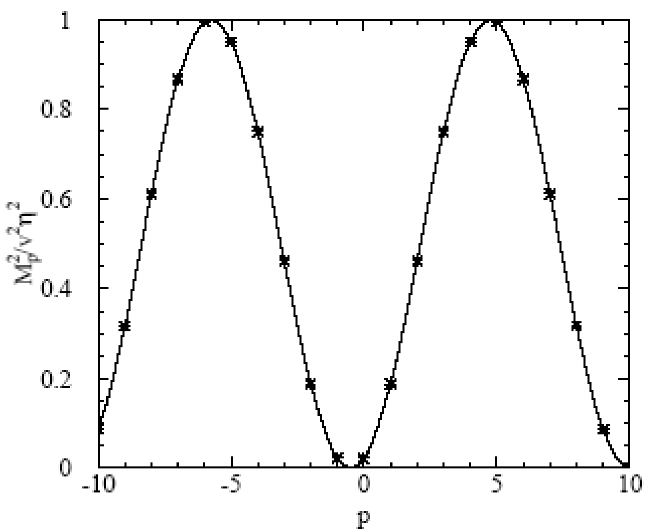
$$\Psi_L = \frac{1-\gamma^5}{2}\Psi \qquad \Psi_R = \frac{1+\gamma^5}{2}\Psi$$

Lattice Hopping terms $\longrightarrow$

$$M(\overline{\Psi}_{Ln}\Psi_{Rn} + h.c.) + v\overline{\Psi}_{Ln}\gamma^5\Psi_{Rn+1} - v\overline{\Psi}_{Rn}\gamma^5\Psi_{Ln+1}$$



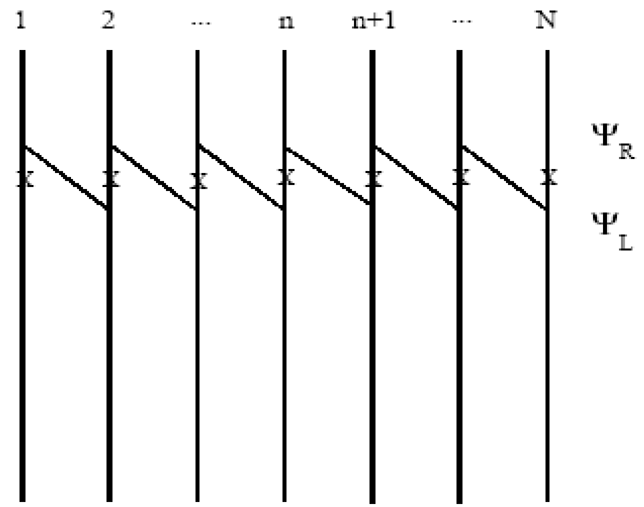
Describes a Mass Matrix in $3+1$ Dimensions of N Dirac Fermions coupled to N Gauge Fields!

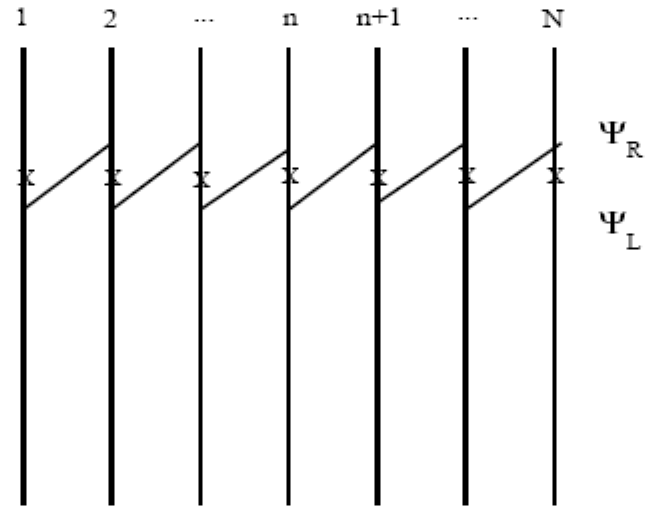


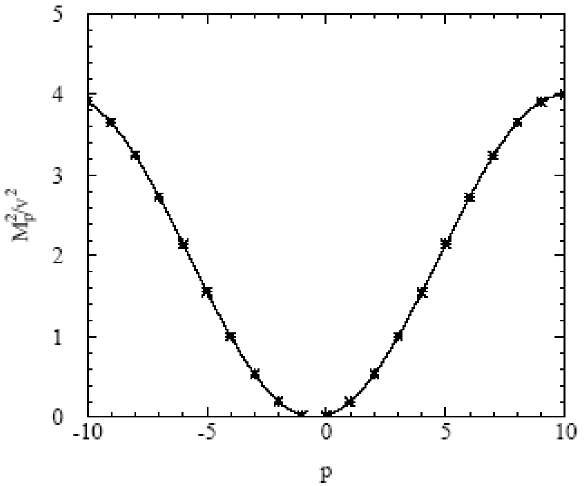
Fermion Doubling Problem

Fermion Doubling Problem → Add Wilson Term:

$$\int d^5x\, \bar{\Psi}(\partial_5^2)\Psi \;\sim\; v\overline{\Psi}_n(\Psi_{n+1} + \Psi_{n-1} - 2\Psi_n)$$





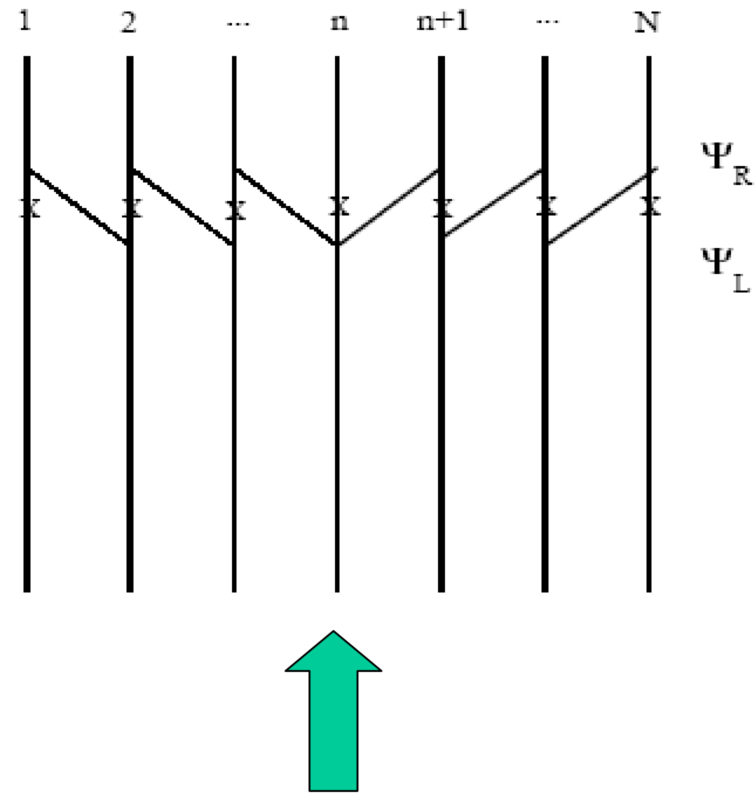


Chiral Fermions are Lattice Dislocations

Chiral fermions are localizable in fifth dimension by domain walls.

(Jackiw, Rebbi; Kaplan)

The chiral zero mode is a dislocation in the lattice:



Gauge coupling strength g_n of $SU(3)_n$ on the n-th brane can be supercritical!

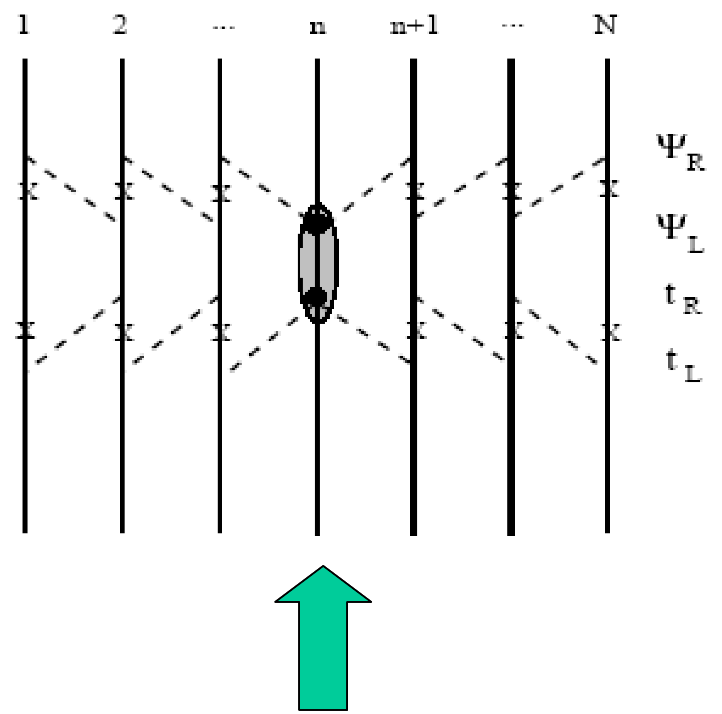
Composite Higgs

Introduce two flavors of fermions:

$$\Psi = \begin{pmatrix} t \\ b \end{pmatrix}_L , \quad t \sim t_R$$

All chiral zero-modes on brane n with strong couplin[g]

Top Quark Condensation via Topcolor:

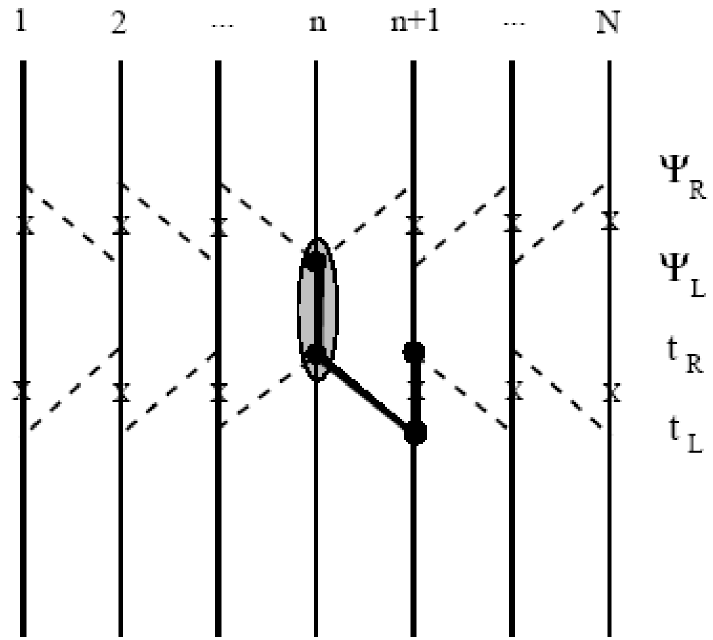


Higgs is composite: $H \sim \begin{pmatrix} \bar{t}_L t_R \\ \bar{b}_L t_R \end{pmatrix}$

Top Quark Seesaw Model

Some links to nearest neighbors may not be completely decoupled.
Background field renormalization.

Mixing with heavy KK fermions occurs in addition to the chiral dynamics on brane n.



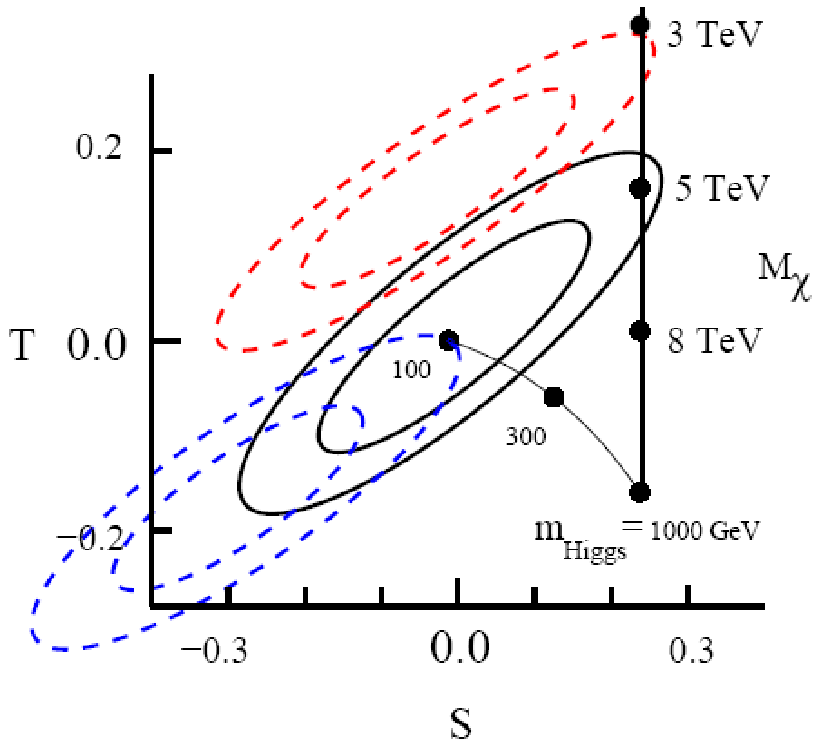
Top Seesaw model is prime example of new organizing principle leading to completely different paradigm for the Higgs mechansm!

Mass matrix for $t-\chi$ system is,

$$-\left(\overline{t_L}\ \ \overline{\chi_L}\right)\begin{pmatrix} 0 & \mu \approx 600\ GeV \\ m \approx 1\ TeV & M \approx 4\ TeV \end{pmatrix}\begin{pmatrix} t_R \\ \chi_R \end{pmatrix} + \text{h.c}$$

Diagonalized:

$$m_t \approx \frac{\mu m}{M}$$
$$m_\chi \approx M$$



68% and 95% C.L. S-T contours, superimposing the Standard Model curve for Higgs mass varying from 100 GeV up to 1000 GeV. Pre-1999 ellipse. 2001: Ignore b-quark FBA).

1998: Top Seesaw DOA (outside of the S-T ellipse by $\sim 4\sigma$. (Chivukula, Dobrescu, Georgi, Hill)

1999: S-T error ellipse shifts along major axis toward upper right (predicted by the theory!).

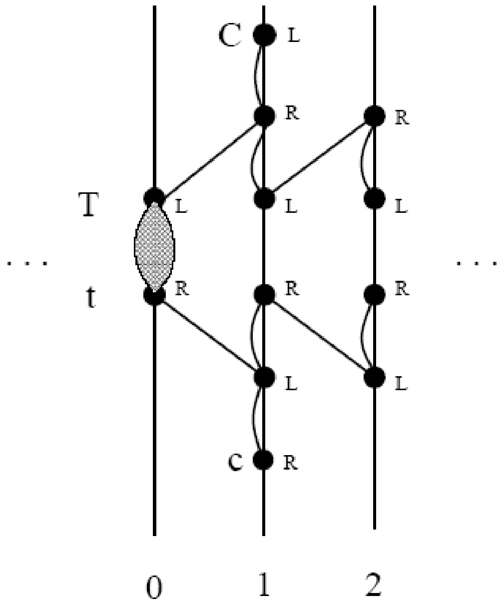
2001: Inconsistencies in data; keep only leptons → Top Seesaw consistent and SM ruled out at $\sim 2\sigma$!!!

Theory consistent for natural values of its parameters at the 2σ level (He, CTH, Tait)

The measured error ellipse is determination of heavy seesaw partner mass; obtain roughly: $M_\chi \sim 4 \pm 1$ TeV.

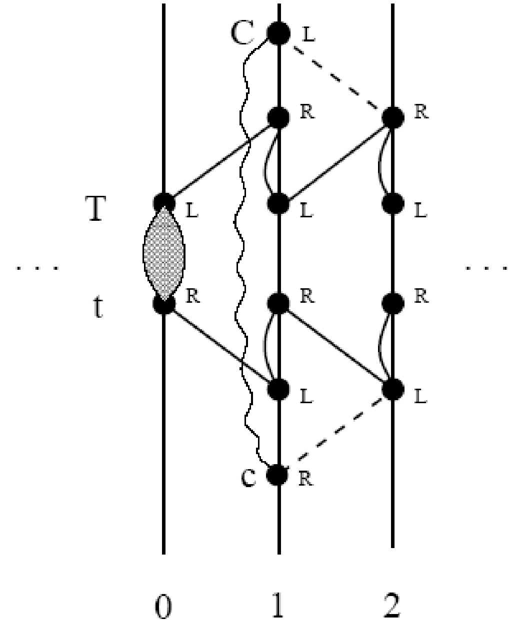
High precision electroweak measurements probing mass of heavy new particle, the χ quark, significantly above the electroweak mass scale!

Blueprints for a Flavor Theory?

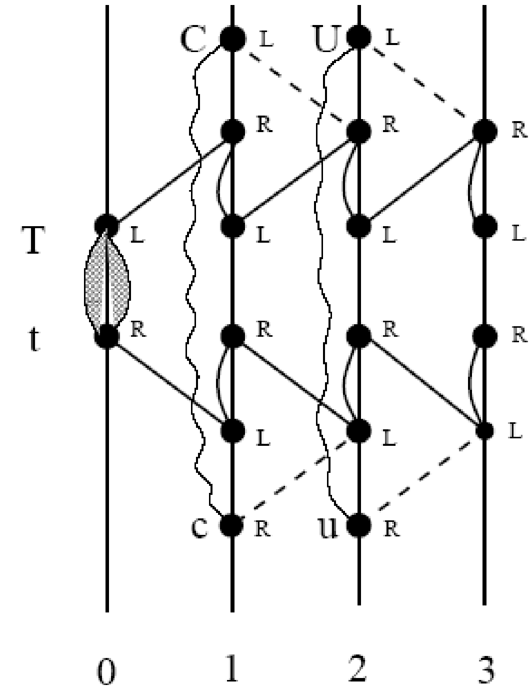


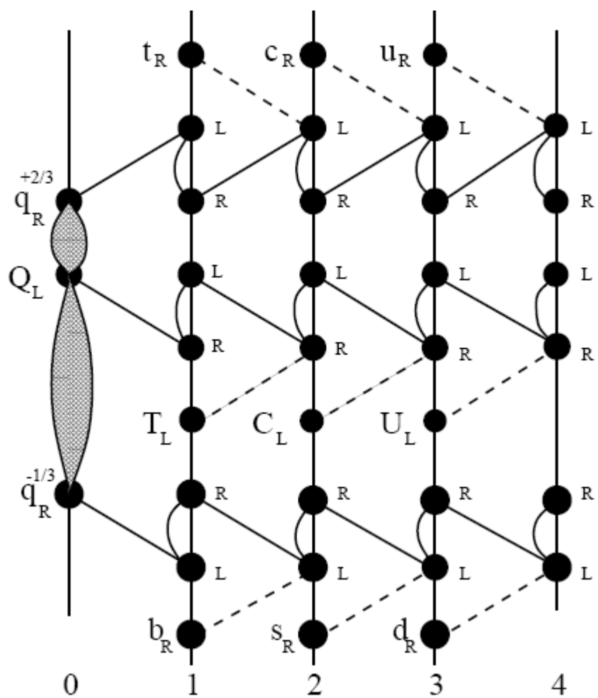
Three brane approximation incorporating charm, where $C = (c, s)_L$ is a doublet zero-mode, and $c = c_R$ is a singlet zero mode, both trapped on brane 1 (we assume the vectorlike partners of C and c are decoupled). Dirac flavor mixing between $\bar{C}_L \psi_{R1}$ and $\bar{c}_R t_{L1}$ can be rotated away by redefinition of ψ_{R1} and t_{L1}. Cheng, CTH, Wang

The flavor mixing (dashed lines) between $\bar{C}_L \prod(\Phi/v)\psi_{R12}$ and $\bar{c}_R \prod(\Phi/v) t_{L2}$ cannot be rotated away by redefinitions of ψ_{R2} and t_{L2} without generating effective kinetic term mixing which leads to non-zero-mode flavor changing gluon vertices (in the broken phase where $\Phi \to v$; this mixing is actually a higher dimension operator). The charm quark mass is thus generated when radiative corrections are included (wavy line).



The extension to include the up quark in a 4-brane model with radiatively generated mass and mixing.





The fourth generation condensate generating the up and down type quark masses.

Deconstruction as a Principle?

- Higgsless Models — Chivukula, Simmons, He, Kurachi, Tanabashi
- Little Higgs — Arkani-Hamed, Cohen, Georgi
- Fractal Extra Dimensions:
  - finite QFT's? — Hill
- Theory of Majoronic Dark Energy and Neutrino Dark Matter

Hill, Ross, Schramm, Fry, Frieman, Stebbins, Waga, Kolb;

Inspiration?!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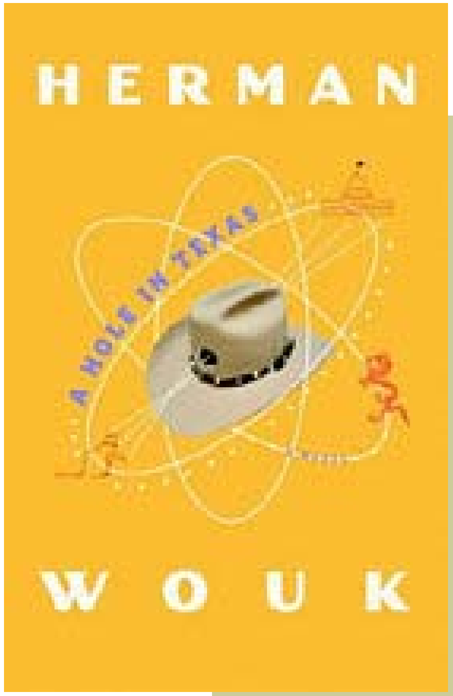

Love, Politics and Subatomic Particles

Reviewed by Linda Richards

In reviewing *A Hole In Texas,* it seems significant to note that Herman Wouk's first novel, *Aurora Dawn,* was published in 1947: 56 years ago. Also significant: he was 32 years old at the time. Wouk received the Pulitzer Prize for *The Caine Mutiny,* which was published in 1951. As I write this, Wouk is just days shy of his 89th birthday. (He was born on May 27th, 1915.)