in the light of future hadron colliders

Theory Overview
The Role of Future Hadron Colliders
The Need for Going Beyond SM
The Standard Model as It Is

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in the light of future hadron colliders

Theory Overview
The Standard Model as a Low-Energy Effective Theory

\[ SU(3) \]

QCD as the theory of strong interactions:

\[ SY^O_3(3) \] QCD as the theory of strong interactions

as a low-energy effective theory

The Standard Model
EW theory and precision measurements:

Summer 2003

\[ S_{\nu} \otimes (1) (2) \]

\[ \eta \]
EW vacuum is absolute minimum

Triviality

Log_{10} \Lambda [\text{GeV}]

M_{H} [\text{GeV}/c^2]

Fig. from C. Quigg.
SM with a light H could be an effective theory to a $M_H \sim \Lambda \sim M_{Pl}$.

renormalizability...

non-trivial interactions;

a stable vacuum;

EW vacuum is absolute minimum.

fig. from C. Quigg.
The Need For Going Beyond SM
Due to quantum corrections, the Higgs mass is quadratically sensitive to the cut-off scale: $V_2 \sim V_2^2$. 

The Large Hierarchy: $\frac{g_W^d}{M_W} - \frac{g_W}{M_W}$
Due to quantum corrections, the Higgs mass is quadratically sensitive to the cutoff scale: $V \sim (\Lambda)^2$.

If requiring less than 90% cancellation, $\Lambda \gtrsim \sqrt{3} \text{ TeV}$.

If $\Lambda \approx M_{\text{pl}}$, it would need a 10-30-level cancellation!

$M_W - \sqrt{\Lambda} \sim (\Lambda)^2$.

The Large Hierarchy:
On the one hand, the "naturalness" argument prefers $\Lambda_{\text{new}} \sim \sim 4\pi v$.

On the other hand, EW precision data indicate "decoupling" behavior $\Lambda_{\text{EW}} \sim 2 - 10 \text{ TeV}$.

* $\Lambda_{\text{flavor}} \sim 70 - 100 \text{ TeV}$.

$\Lambda_{\text{FCNC}}$ (e.g. $K^0 - \bar{K}^0$ mixing etc.) constraints set $\Lambda_{\text{flavor}} \sim 70 - 100 \text{ TeV}$.

* EW precision data indicate "decoupling" behavior $\Lambda_{\text{EW}} \sim 2 - 10 \text{ TeV}$.

(based on generic strong dynamics, or generic MSSM $^\dagger$

$\Lambda_{\text{EW}} \sim 4\pi v$.

(based on generic strong dynamics, or generic MSSM $^\dagger$


† Chivukula, Evans, Simmons.

‡ Bagger, Feng, Polonsky, Zhang.

The little Hierarchy: $4\pi v - \Lambda_{\text{new}}$.
The Little Hierarchy: $4\pi v - V_{\text{new}}$

On the one hand, the "naturalness" argument prefers $\Lambda_{\text{ew}} < \sim 4\pi v$.

On the other hand, $\Lambda_{\text{ew}} > \sim 2 - 10 \text{ TeV}$.

- $V_{\text{ew}} > \sim 70 - 100 \text{ TeV}$ (based on generic strong dynamics, or generic MSSM).
- $\Lambda_{\text{EW precision}} > \sim 2 - 10 \text{ TeV}$ (based on generic dim-6 operators).
- $\Lambda_{\text{FCNC}} (K^0 - \bar{K}^0)$ mixing etc.) constraints set $\Lambda_{\text{flavor}} > \sim 70 - 100 \text{ TeV}$.
- $\Lambda_{\text{EW precision data indicate 'decoupling' behavior}}$.
- $\Lambda_{\text{EW}} > \sim 4 \pi v$.

**Implies** special structure or symmetry.

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Barbieri, Feng, Polonsky, Zhang.
Chivukula, Evans, Simmons.

---
It implies a large scale, even we take $m_{\nu} \lesssim 10^{-6}$. 

Taking $m_{\nu} \lesssim 1 \text{ eV}$, we get:

\begin{align*}
\text{The simplest (Majorana) neutrino mass term} = L^c (\frac{\nu}{\sqrt{2}}) H \nu \sim \sqrt{2} m_{\nu} \sim 10^{14} \text{ GeV}.
\end{align*}

Yet another Hierarchy: all way down to $m_{\nu}$.
The smaller the fermion masses are, the larger the new physics scale is.

\[ \nu \sim 10^{-6} \text{eV}. \]

It implies a large scale, even we take

\[ \eta \lesssim \frac{\eta}{2} \eta \sim V \iff \text{Taking } m \nu \sim 1 \text{eV,} \]

\[ T^\nu \left( T_\nu \right) \frac{V}{\eta} \eta \sim \frac{V}{\eta} \eta \sim \frac{V}{\eta} \eta \]

The simplest (Majorana) neutrino mass term

yet another hierarchy: all way down to \( m^\nu \)
Theoretical issues to understand:

- Vastly different mass scales:
  - EW gauge symmetry breaking;
  - Charged fermion masses;
  - Vastly different mass scales;

- Nontrivial fermion structure:
  - Three fermion generations;
  - Nearly (maximal) neutrino mixing;

- Unified description:
  - Yukawa couplings;
  - Gauge interactions;

- CP violation:
  - Quark small mixing; neutrino (nearly) maximal mixing;
Theoretical issues to understand:

- Vastly different mass scales: EW gauge symmetry breaking; charged fermion masses; neutrino masses.
- Nontrivial fermion structure: three fermion generations; CP violation.
- Nontrivial Yukawa couplings; gauge interactions; mass relations.
- Gravitational and cosmology connections: inflation; dark matter; dark energy; gravity and Planck scale physics; cosmology connections: (see M. Turner).

...
We are entering a "data-rich" era:
We are entering a “data-rich” era.

Electroweak precision constraints;
We are entering a "data-rich" era.

Electroweak precision constraints:

- \( \mu - e \) ...
- Electron/neutron EDMs;
-Muon \( g - 2 \);
- ...
We are entering a “data-rich” era:

Neutrino masses and mixing;

Muon $g - 2$, $\mu \rightarrow e\gamma$...

Electroweak precision constraints;

Neutron/electron EDMs;
We are entering a "data-rich" era:

Electroweak precision constraints; 
muon $\mu \rightarrow e \gamma$ ...

Neutrino masses and mixing;

$K/B$ rare decays and CP violation: $B \rightarrow X_{s} \phi, J/\psi K_{S}, \mu / K_{S}$;

Electroweak precision constraints;

We are entering a "data-rich" era:
We are entering a "data-rich" era:

Neutrino mass and mixing:
• $\mu \rightarrow e\gamma$

Electroweak precision constraints:
• $K/\bar{B}$ rare decays and CP violation: $B \rightarrow X_s \gamma$, $J/\psi \phi/K^0_{S,S}$, $\mu K^0_S$

Nucleon stability:
We are entering a „data-rich“ era.

Dark matter constraint on stable particles (\text{MLSP});

Nucleon stability;

K/B rare decays and CP violation: B \rightarrow X_s \gamma, J/\psi K_S, \eta K_S, \phi K_S, \nu \mu K_S;

Neutrino masses and mixing;

Muon g − 2: \mu \rightarrow e\gamma; neutron/electron EDMs;

Electroweak precision constraints;
We are entering a “data-rich” era:

- Cosmology constraints on $m_{r}$ and dark energy ($\Omega$).
- Dark matter constraint on stable particles (WSP).
- Nucleon stability.
- $K/B$ rare decays and CP violation: $B \to X^{s}\phi, \phi/K_{S}, J/\psi, \eta, \eta'$.
- Neutrino masses and mixing.
-Muon $g-2$: $\mu \to e\gamma$; neutron/electron EDMs.

Electroweak precision constraints:

Electroweak precision constraints:...
We are entering a “data-rich” era:

**Electroweak precision constraints:**
- \( \mu g - 2 \)
- \( \mu \rightarrow e\gamma \)

**Neutrinomasses and mixing:**
- Neutrino masses and mixing:
  -Muon 9 – 2; \( \nu_e \rightarrow \nu_x \)

**Cosmology constraints on \( m_\nu \) and dark energy:**
- Dark matter constraint on stable particles (WIMP)

**Baryon stability:**
- K/B rare decays and CP violation: \( B \leftrightarrow X_s , J/\psi K^0, \phi, K^0 S, mu S, \mu R \)

**Neutrino studies:**
- Higgs studies, comprehensive new particle searches...
- LHC: Higgs sector, top sector, new particle searches...
- Tevatron: EW, top sector, Higgs (?), new particle searches...

**Other complementary experiments:**
- non-colliders...
- LC: more on top sector, precision Higgs and light new particles...

Yet more to come:

**Dark matter constraint on stable particles (WIMP):**

**Electroweak precision constraints:**
- We are entering a “data-rich” era.
Only if the "soft-SUSY breaking"

\[ M_W - M_W \]

weak scale SUSY stabilizes the hierarchy.

A natural cancellation mechanism:

\[ \left( \frac{\lambda_{\text{SUSY}}}{\lambda_{\text{SUSY}}} \right) \ln \left( \frac{M_W}{f_X} \right) (M_W - \lambda_{\text{SUSY}}) \sim \frac{H_w}{z} \nabla \]

Our "theory bank"
Our theory bank

\(\Delta m^2_H \sim (M^2_{\text{SUSY}} - M^2_{\text{SM}}) \lambda^2 f_{16}^2 \pi^2 \ln \left(\frac{\Lambda}{M_{\text{SUSY}}}\right)\).

Weak scale SUSY stabilizes the hierarchy \(M_W - M_{\text{Pl}}\) only if the "soft-SUSY breaking"\( \rho^d W - M_W \) weak scale SUSY destabilizes the hierarchy

\[
\frac{\lambda_{\text{SUSY}} W}{v} \log \frac{\mu}{1 \text{ GeV}} \frac{1}{f} = \frac{\rho W - \lambda_{\text{SUSY}} W}{f} \sim H_{\text{w}} \Delta
\]

A natural cancellation mechanism:

(4) Weak-scale Supersymmetry:

Our "theory bank"
M.SUSY scenario: $m_0$, $m_{1/2}$, $A$, $\tan \beta$, and $\text{sign}(\mu)$

Merely (124?) unknown parameters, and most part of the para-space is inconsistent with observations.

What about M.SUSY?
The Little Hierarchy persists:

\[ m_{\tilde{t}} \gtrsim \text{several TeV}, \text{or } m_{\tilde{q}} \gtrsim 4 \text{ TeV}. \]

• Inverted hierarchy: \[ m_{\tilde{q}} \gtrsim \text{several TeV}, m_{\tilde{t}} \gtrsim 4 \text{ TeV}. \]

• "Focus point" scenario: \[ f \text{ insensitive to } m_0, \text{ so that } m_{\tilde{l}}, m_{\tilde{q}} \gtrsim \text{several TeV}. \]

• Heavy \( m_0 \), so that \( \mu \) keeps the naturalness.

• New scale \( F \approx 5 - 20 \text{ TeV}, \text{ so that } m_{\tilde{t}} \gtrsim \text{several TeV}. \]

• "More minimal MSSM":

 Arkani-Hamed, Schmaltz, TH, Kribs, McElrath.

Feng, Matchev, Moroi
Bagger, Feng, Polonsky, Zhang

Cohen, Kaplan, Nelson.

References:

*Arkani-Hamed, Schmaltz, TH, Kribs, McElrath.
†Bagger, Feng, Polonsky, Zhang
‡Feng, Matchev, Moroi

"Inverted hierarchy" persists:

"Focus point" scenario:

\[ m_0 > 4000 \text{ GeV}, \quad m_{1/2} > 1400 \text{ GeV}, \quad \tan \beta \gtrsim 45. \]

LHC may NOT guarantee a SUSY discovery.

\[ 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1 \quad 1.2 \quad 1.4 \quad 1.6 \quad 1.8 \quad 2 \]

\[ 0.5 \quad 1 \quad 1.5 \quad 2 \quad 2.5 \quad 3 \quad 3.5 \quad 4 \quad 4.5 \quad 5 \quad 5.5 \]

LHC, ET

\[ \text{m}_{\text{SUGRA}}: \tan \beta = 45, A_0 = 0, \mu < 0 \]

LEP2

\[ \text{no REWSB} \]

\[ m_\nu \text{ LEP2 limit} \]

\[ a_{\mu} \times 10^{10} \]

\[ \times 10^{10} \]

\[ \text{Br}(b \rightarrow s \gamma) \times 10^4 \]

\[ \text{Br}(B_s \rightarrow \mu^+ + \mu^-) \times 10^8 \]

\[ 0.094 < \Omega h^2 < 0.129 \]

\[ f_{\sigma}(Z'_{\text{p}}) \times 10^{11} \text{ pb} \]

\[ 100 \quad 10 \quad 1 \quad 0.1 \quad 0.01 \quad 0.001 \]

\[ \text{Stage 3} \]
There is the messenger sector to explore: $m_{\text{eff}}(\mathcal{O}) \sim \Phi W$. Squarks and gluinos are typically heavier.

Gauge mediation scenario: $H$, $W$, $N$, $\tan \beta$, and $\mathcal{O}$. 

$\mathcal{O} \sim$ few $- 100$ TeV.
... In TC, EWSB by techni-fermion condensation:

In TC, EWSB by techni-fermion condensation:

Technicolor/Extended Technicolor (see K. Lane)

(2). Dynamical approach/Little Higgs:

•
The little hierarchy persists! New strong dynamics with multi scales? 

\[ \frac{V_t^{ETC}}{V_{\chi}^{ETC}} < \frac{1}{100 \text{ MeV}}. \]

And large \( m_q \) and \( \Lambda_{ETC} < 10^3 \text{ TeV} \), \( \Lambda_{ETC}^2 > 100 \text{ MeV} \). 

Small FCNC: \( \sim 0 \) \( \langle \bar{Q}_L Q_R \rangle \) \( \sim \frac{1}{3} \).

It is phenomenologically difficult for generating 

When generalizing to ETC to incorporate fermion masses,

\[ \begin{align*}
\langle \bar{Q}_L Q_R \rangle & \sim 0 \\
\text{In TC, EWSB by techni-fermion condensation:} \\
\text{Technicolor/Extended Technicolor: (see K. Lane)}
\end{align*} \]

(B) Dynamical approach/little Higgs:
Topcolor special:

\[ m_t \approx \frac{v}{\sqrt{2}} = 174 \text{ GeV}. \]

"Topcolor/Top-seesaw": Introducing an additional fermion pair \( \chi \), with a heavy state \( \chi \), and a SM \( t \) leads to a SM \( t \) and a heavy Higgs \( H \) with 

\[ m_H \sim 1 \text{ TeV}. \]

(2) Topcolor seesaw:

\[ \left( \bar{\chi}^R_t \chi^L, \bar{\chi}^R_b \chi^L \right) \Rightarrow \text{EWSB and a heavy Higgs} \]

\[ \sim 4 \text{ TeV}. \]

(1) Topcolor generates the condensation

\[ \sim H \]

Introducing an additional fermion pair \( \chi \), \( \chi \):

\[ \text{Top quark special?} \]
Introducing an additional fermion pair $X_L^T X_R^T$;

(1) topcolor generates the condensation $H \sim (X_R^T X_L^T)$

(2) topseesaw leads to a SM $t'$ and a heavy Higgs $H_{\text{ew}} \sim 1 \text{ TeV}$

$\langle \bar{\chi}_L t_L, \bar{\chi}_L b_L \rangle \Rightarrow$ EWSB and a heavy Higgs $m_H \approx 1 \text{ TeV}$

Top quark special? $m_t \approx \sqrt{\frac{v^2}{2}} = 174 \text{ GeV}$

$\chi_L \approx \chi_R \approx 4 \text{ TeV}$
New symmetries introduced to cancel the (1-loop) quadratic divergence.

Little Higgs: as a pseudo Nambu-Goldstone boson (see G. Kribs)
With the help of extra-dimensions, gravity/string theories resolve the large hierarchy. By the help of extra-dimensions, low-scale gravity/string theories resolve the large hierarchy.

New states predicted: KK, stringy, and winding modes depending on the geometry of the extra-dim.

\[ M^2_n \sim n^2 k R^2, n^2 M^2 S, n^2 w R^2 M^4 S. \]

\[ (S_W H^m u, S_W s u, \frac{H}{f_u} \sim \frac{u}{f} W \]

With the help of extra-dimensions, low-scale gravity/string theories resolve the large hierarchy:

\[ M_{n+2} \sim M_2^{S/n} / R^n \rightarrow O(1 \text{TeV}) \]

New states predicted: KK, stringy, and winding modes.

TeV-scale Black Holes: For a black hole of mass \( M_{BH} \), its size is

\[ r_{bh} = \sqrt{\frac{\frac{1}{8\Gamma(\frac{n}{2}+2)}}{\frac{2}{n+2} \left(\frac{2}{n+2}\right)}} \]

\[ \frac{M_{BH}}{M_{pl}^4} \] in 4d

Gravitational/strong gravitational theories resolve the large hierarchy.

Extra-dimensions: (see G. Guidice, T. Rizzo, S. Nandi)
With the help of extra-dimensions, low-scale gravity/string theories resolve the large hierarchy: $M_n^{n+2} \approx \frac{m_{W_H}}{M^{n+1}} \rightarrow \mathcal{O}(1 \text{ TeV})$.

New states predicted: KK, stringy, and winding modes (depending on the geometry of the extra-dim.)

$\frac{S}{4} W^2 H^{m_2 u} W^2 H^{s u} \frac{S}{2} W^2 \frac{H}{2} u \sim \frac{u W}{S}$

Gravitivity/string theories resolve the large hierarchy with the help of extra-dimensions, low-scale (see G. Guidice, T. Rizzo, S. Nandi).
SUSYGUTS with extra-dimensions

- Hall, Nomura, Smith.

- dotted: $321$ gaugino KK modes; thin solid: $XY$ and $321$ KK gauge.
- thick solid: MSSM gauginos; dot-dashed: $XY$ gauginos;
- dashed (bottom up): $[\tilde{e},\tilde{\mu},\tilde{\tau}]$, $[\tilde{\nu}_e,\tilde{\nu}_\mu,\tilde{\nu}_\tau]$ and $[\tilde{u},\tilde{c},\tilde{t}]$ nearly degenerate.

SU(5) GUTS with extra-dimensions
Fermion masses and mixing remain the most challenging task!

(D). The flavor sector:
The flavor sector: Fermion masses and mixing remain the most challenging task.

(D). The flavor sector:

$\mathcal{SM}$: 20+ free parameters of $g$, $\tau$, $\nu$.
The flavor sector:

- Fermion masses and mixing remain the most challenging task

**SM**: 20+ free parameters of $q$, $\ell$, $\nu$

Ansatzs/textures for mass/mixing relations
• Attempts in ETC/Walking TC/Topcolor assisted TC/Top-seesaw...

• Ansatz/textures for mass/mixing relations

• SM: $20^+ \text{ free parameters of } q, \ell, \nu$

Fermion masses and mixing remain the most challenging task!

(D) The flavor sector:
The flavor sector: Fermion masses and mixing remain the most challenging task.

\[ \text{Froggatt-NielSEN's mechanism (family symmetry e.g., SMG}_3^3 \]

\[ \text{SM: 20+ free parameters of } q, g, \lambda \]

Attempts in ETC/Wajking TC/Topcolor assisted TC/Top-seesaw...

Attempts/textures for mass/mixing relations

\( \text{The flavor sector:} \)
The flavor sector:

Fermion masses and mixing remain the most challenging task

(D). The flavor sector:

\begin{itemize}
  \item Fermion mass relations
  \item Froggatt-Nielson's mechanism (family symmetry e.g. (SMG)\textsuperscript{3})
  \item Ansätze/textures for mass/mixing relations
  \item Attempts in ETC/Walkirkig TC/Topcolor assisted TC/Top-seesaw
  \item SO(5): \( y_b = y_t = y_\tau \)
  \item SM: \( 20 + \) free parameters of \( q, \ell, \nu \)
\end{itemize}
The flavor sector:

Fermion masses and mixing remain the most challenging task.

\( \text{(D). The Flavor Sector:} \)

- SM: 20+ free parameters of \( q, \bar{q} \), \( \nu, \bar{\nu} \)

- Ansatz/textures for mass/mixing relations

- Froggatt-Nielsen's mechanism (family symmetry e.g. (SM(3))

- Attempts in ETC/Walking TC/Topcolor assisted TC/Top-seesaw

- See-saw mechanism for \( m_\nu \approx \frac{m_D^2}{M_\text{IR}} \)

- \( \phi = \phi = \phi : SO(10) \) (E.g. \( SU(5): y_b = y_\tau = y_t \))

- SMY GUT's relations,
The flavor sector:

- Fermion masses and mixing remain the most challenging task.

SM: $20 + \text{free parameters of } g, \xi, \lambda$

SO(10) : $\text{SUSY GUTS relations,}$

- Froggatt-Nielsen’s mechanism (family symmetry e.g. $\text{SMG}_3$)

- Ansatz/textures for mass/mixing relations

- Fermion separation in extra-dimensions

- See-saw mechanism for $m_\nu \approx \frac{m_D}{M_R}$

- Attempts in ETC/Walkking TC/Topcolor assisted TC/Top-seesaw
The flavor sector: Fermion masses and mixing remain the most challenging task!

- SM: 20+ free parameters of \( g, \lambda, \nu \)
- See-saw mechanism for \( m_\nu \approx m_D^2/M_R \)
- Froggatt-Nielsen’s mechanism (family symmetry e.g. (SMG)\(^3\))
- SUSY GUTs relations, e.g. \( SU(5): y_b = y_\tau \); \( SO(10): y_t = y_b = y_\tau \)
- Ansatz/textures for mass/mixing relations
- Attempts in ETC/Walking TC/Topcolor assisted TC/Top-seesaw...

Fermion separation in extra-dimensions
- Calculations in heterotic orbifold/intersecting D-branes
Further experiments for more hints.

- Calculations in heterotic orbifold/intersecting D-branes
- Fermion separation in extra-dimensions
- See-saw mechanism for $m_\nu \approx m_\nu^H / M_R$
  - $y_t = y_\tau, y_t = y_\tau, SU(5)$
  - $y_b = y_\tau, SU(5) \cap SO(10)$
- Froggatt-Nielsen's mechanism (family symmetry e.g. $\text{SM(G)}_3$)
- SUSY GUTS relations
- Attempts in ETC/WMIRing T/C/Topcolor assisted T/C/Top-seesaw
- Ansatz/textures for mass/mixing relations
  - SM: 20 free parameters of $\nu_i$
- Fermion masses and mixing remain the most challenging task!
For any scenario beyond SM, VLHC will contribute:

\[ \text{Multi-TeV Squarks} \]

\[ n \frac{p}{q} : \text{FCNC} \]

\[ \text{SUSY needs VLHC} \]

\[ \text{Multi-TeV Squarks} \]

\[ n \frac{p}{q} : \text{FCNC} \]
SUSY Breaking Messengers: $\Phi \sim O(\text{few} - 100 \text{TeV})$.

If the messenger number is conserved, then the Lightest Messenger Particle (LMP) is stable, leading to

$\Phi' \rightarrow \Phi^0 \rightarrow e + \mu, \tau, \gamma + \bar{\nu}, \bar{\tau}, \bar{\nu}, \bar{\tau}$, etc.

Interesting signal; large SM backgrounds...

If $\Phi, \bar{\Phi}$ couple to SM multiplets (fermions...), then

$\Phi^0 \rightarrow e + \bar{\mu}, \bar{\tau}, \bar{\nu}, \bar{\tau}, \bar{\nu}$, etc.

Almost like RP violating interactions (almost like $R_p$ violating interactions)

Which would lead to spectacular new experimental signatures!

$\Phi^0 \rightarrow e + \mu, \tau, \gamma + \bar{\nu}, \bar{\tau}, \bar{\nu}$, etc.

If the messenger number is conserved, then the lightest messenger particle

Almost like $R_p$ violating interactions

Which would lead to spectacular new experimental signatures!
Strong dynamics needs VLHC:

\[ \chi_R, \chi_L \rightarrow t\bar{t}, h, bW... \]

\[ \text{with good signatures.} \]

\[ m_\chi = 1 \text{ TeV} \]

\[ m_\chi = 3 \text{ TeV} \]

\[ m_\chi = 5 \text{ TeV} \]

\[ M_Z = 1 \text{ TeV} \]

\[ M_W = 10 \text{ TeV} \]

\[ \sigma (\chi \chi) \rightarrow (fb) \]

\[ \Rightarrow \]

\[ \chi_R, T' \rightarrow \chi_L, W^{\pm} \]
Little Higgs: the "top-partner" $T$ with $\mathcal{L} \leftarrow W, Z, t\bar{t}, bW, th$ with good signatures.

(b) Little Higgs: the "top-partner" $T$
The production rate is comparable or higher than $pp \rightarrow \bar{t}t$.
At high energies, e.g.,

\[ \text{two very mass jets!} \]
Strongly-interacting Electroweak Sector: If no SUSY found at the LHC, W+W→W+W scattering must reveal new dynamics

\[ \Lambda_{\text{EW}} \approx \sqrt{8/\pi} v \approx 1.2 \text{ TeV} \]

\[ \sqrt{s} \approx 2 \text{ TeV} \Rightarrow \sqrt{s} \gg 4 \text{ TeV} \Rightarrow 2 \text{ TeV} < M_{\text{W+W}} \]

If no SUSY found at the LHC, scattering must reveal new dynamics.
Contact Interactions: Compositeness?

Heavy bosons and quark/lepton sub-structure lead to 4-fermion contact interactions:

\[
\frac{V}{Z}^4
\]

The best channel at hadron colliders is the DY process:

\[
X + \bar{n} + n + e + e \leftrightarrow Z \leftrightarrow dd
\]

The sensitivity to the "composite scale \( \Lambda \)" goes like:

\[
s^2 \Lambda^4
\]
4-fermion contact interactions lead to 4-fermion contact interactions: Compositeness? Contact Interactions: Compositeness?

Contact Interactions: Compositeness?

The best channel at hadron colliders is the DY process:

The sensitivity to the "composite scale \( \Lambda \)" goes like

\[
X + n + n/ e + e \leftarrow Z \leftarrow pp
\]

Heavy bosons and quark/lepton substructure lead to 4-fermion contact interactions:

\[
\frac{V}{\Lambda^4}
\]

So that \( \text{Tevatron} \leftarrow \text{LHC} \leftarrow \text{VLHC} \):

\[
\frac{4}{\Lambda^4} (1.8 \text{ TeV}) \sim \frac{4}{\Lambda^4} (3 \text{ TeV}) \sim \frac{4}{\Lambda^4} (14 \text{ TeV}) \sim \frac{4}{\Lambda^4} (25 \text{ TeV}) \sim \frac{4}{\Lambda^4} (100 \text{ TeV}) \sim \frac{4}{\Lambda^4} (170 \text{ TeV})
\]

\( 170 \text{ TeV} \Rightarrow 10^{-18} \text{ cm} \) would cover the "little hierarchy".
Deep into extra-dimensions at VLHC:

(a) Large extra-dim ADD & warped extra-dim RS:

Left: ADD with \( M^* = 20, 25, 30, 35 \text{ TeV} \);
Right: RS with \( M_{KK} = 16 \text{ TeV} \).

* T. Rizzo
Low-scale string resonances:

\[ p p \rightarrow S \n \rightarrow l^+ l^- \]

String state masses

\[ M^{\text{state}}(\text{GeV}) = \sqrt{n} M_S = \sqrt{n} \text{15 TeV}. \]

\[ \mu^\Lambda = \frac{1}{\mu^\Lambda} \]

\[ X - l + l \leftarrow X \mathcal{L}_u S \leftarrow d d \]

(b) Low-scale string resonances:

*TH, P. Burikham
Black Hole Production at the 200 TeV VLHC

At $\sqrt{s} = 200$ TeV, $\sigma(M_B < 25 \text{ TeV}) = 3 \text{ pb}$.

Greg Landsberg
• Bread & butter SM physics

• Rare processes like $\gamma \rightarrow \mu^+\mu^-$ (D. Rainwater)

• Total cross section as expected $dd$

• $10-100$ times more $W/Z, WW, \bar{t}...$

• \(\times 10^2 \)
More Higgses: $pp \rightarrow Vhh$; $WW \rightarrow hh$ (see D. Rainwater) and a very heavy "Higgs" ($1\ TeV$)
Any hope to probe the Majorana mass?
Any hope to probe the Majorana mass?
Multi-W production via Sphalerons (see A. Ringwald)

Electroweak instantons/sphalerons induce $B + \tau \bar{\tau}$ violating transitions

Multijet production via $H, W, M$ (see A. Ringwald)

Enhanced for $M_W < s \sqrt{\alpha} \leq 16\pi s$.

With total cross section

\[ \sigma \left( pp \to nW^+nW^- \right) \sim (10^{10}) \text{ pb} \]

\[ \frac{s}{16\pi} \geq \frac{M_W}{s} \sqrt{\alpha} \Rightarrow M_W \sim (10^{10}) \text{ pb} \]
Top Reasons For The VLHC.
Top Reasons For VLHC:

• There are unanswered questions left after the LHC/LC.

  (In any scenarios, pretty much!)
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Top Reasons For The VLHC:

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• While the LHC is to study the "Large Hierarchy,"

• VLHC is to explore the "Little Hierarchy."

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Top Reasons For The VLHC:
Go for the energy frontier!

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Top Reasons for the VLHC: