Electroweak Symmetry Breaking without a Higgs Boson

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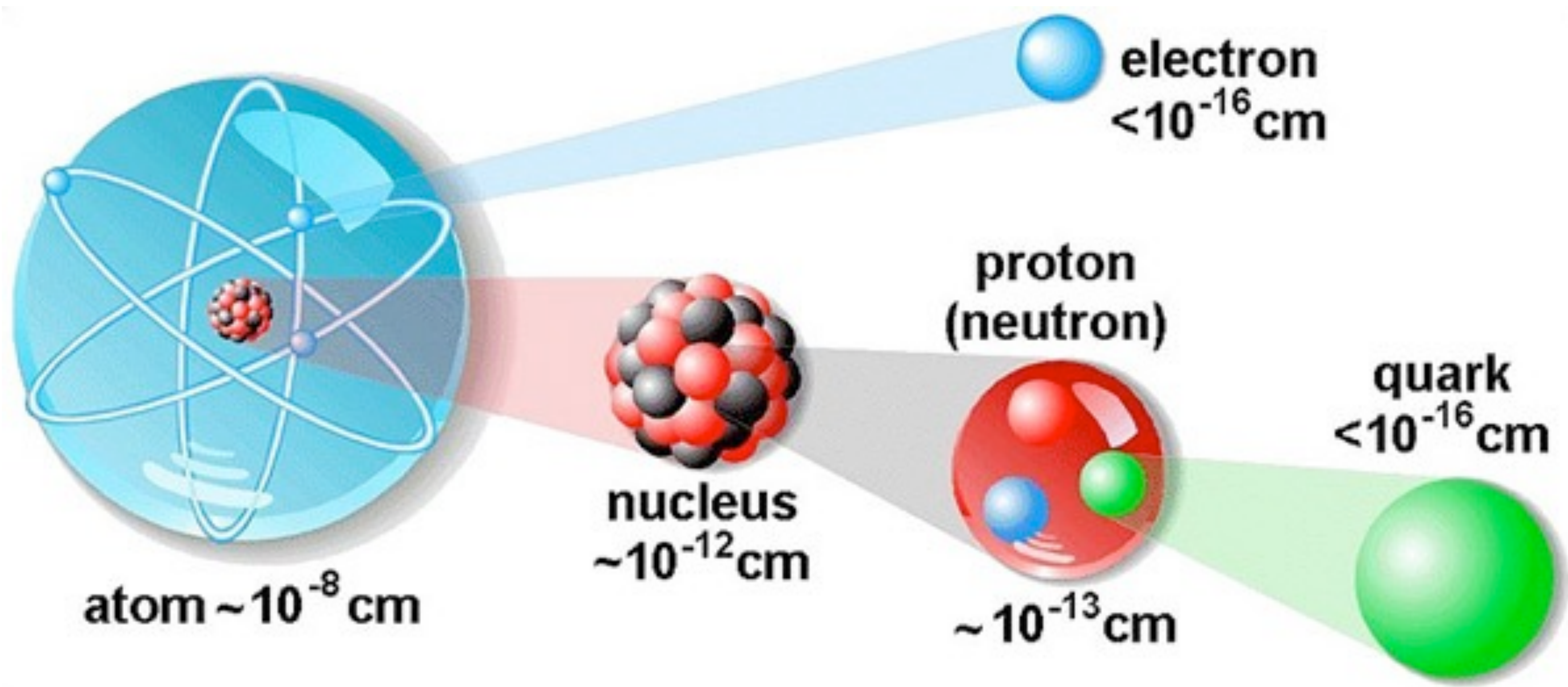
3. Chiral Symmetry Breaking: Technicolor
4. Extra Dimensions: Higgsless Models
5. Conclusions

VIPP July 29, 2010

Introduction:

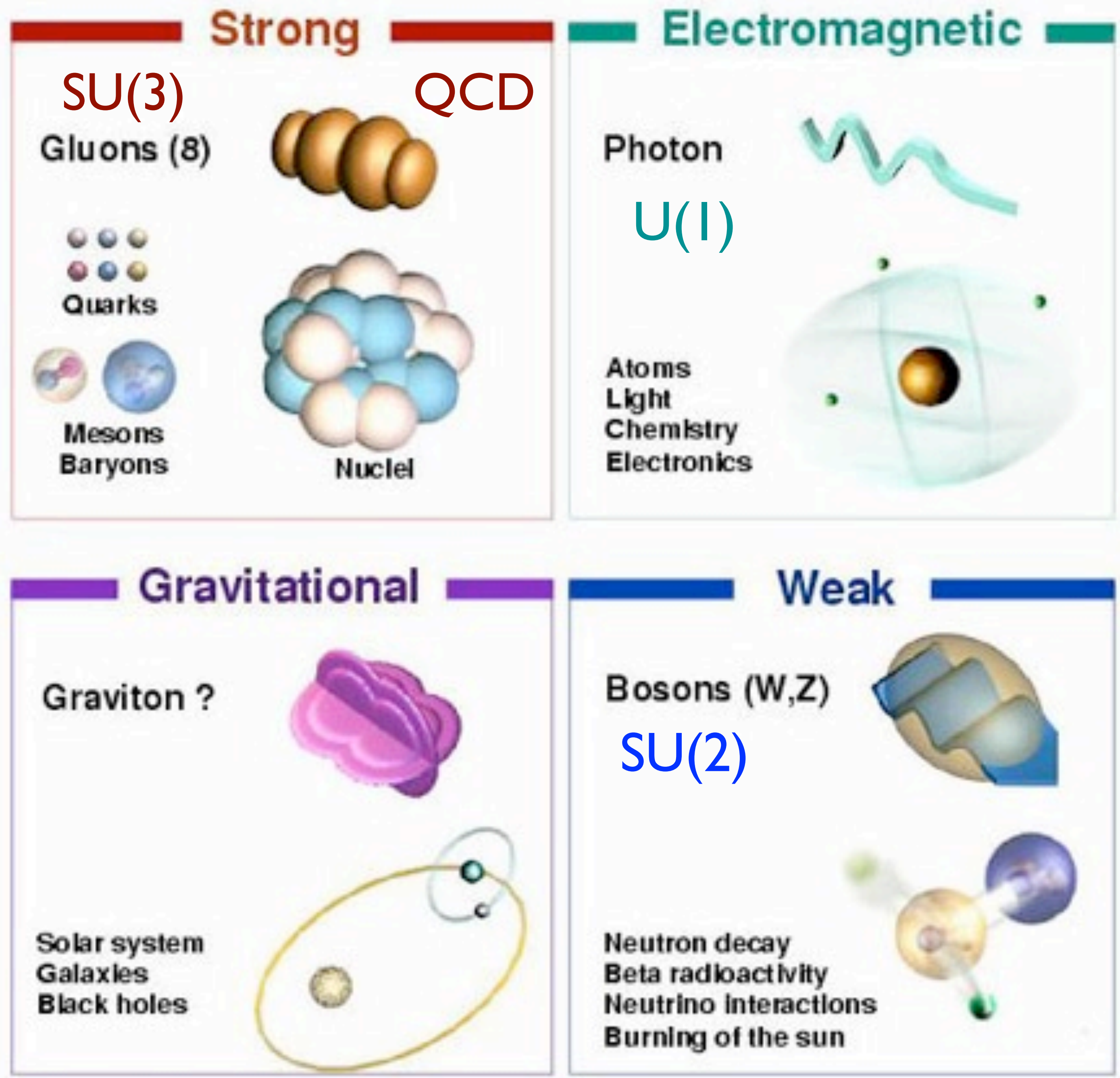
Fundamental Particles and Fundamental questions

Subatomic Structure



ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Force Carriers
(bosons)



The particle drawings are simple artistic representations

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Matter Particles
(fermions)

Each can exist in LH and RH chirality

LH (RH) version is charged (neutral) under weak interactions

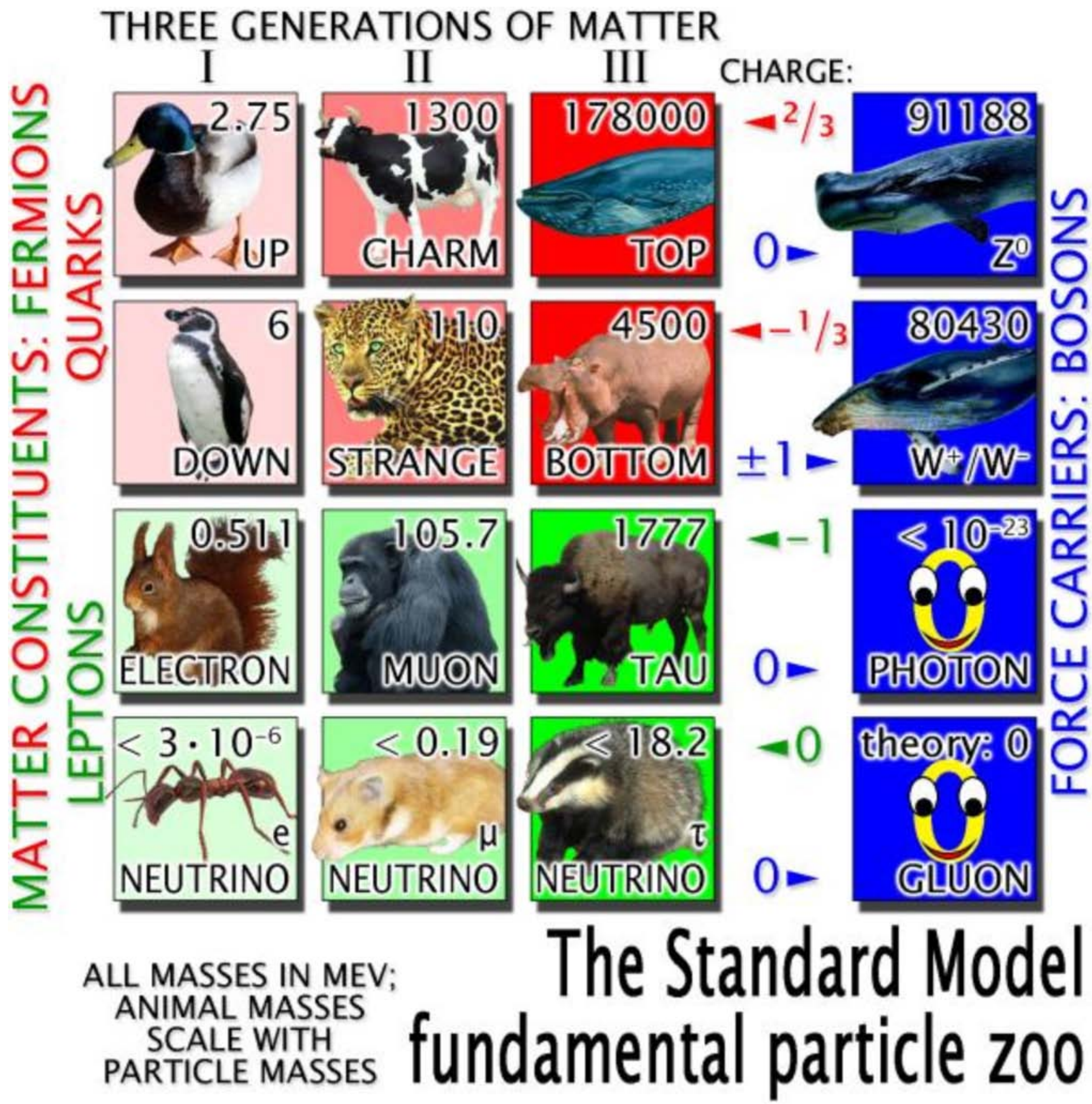
Questions About Broken Symmetries

Flavor:

Why do fermions with the same charge have different masses?

Electroweak:

Why are the W & Z bosons heavy while the photon is massless?



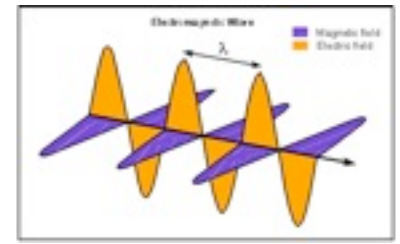
e4.physik.uni-dortmund.de/bin/view/ATLAS/Bildergalerie

The Origin of Mass: Electroweak Symmetry Breaking and the Higgs

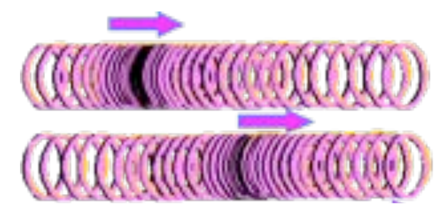
Gauge Boson Masses

Consider the masses of the electroweak gauge bosons:

$M_\gamma = 0$ (2 transverse modes only)



$M_W, M_Z \neq 0$ (2 transverse modes, and 1 longitudinal)



An apparent contradiction exists:

- $W^\pm$ and Z^0 are massive gauge bosons
- mass implies a Lagrangian term $M_W^2 W^\mu W_\mu$

... but such a term is not gauge-invariant

Resolving the contradiction:

The $SU(2)_W$ gauge symmetry is broken at the energies our experiments have probed so far.

Relationship of SU(2) and U(1):

- W bosons are electrically charged (± 1) , implying that the weak & electromagnetic forces are related

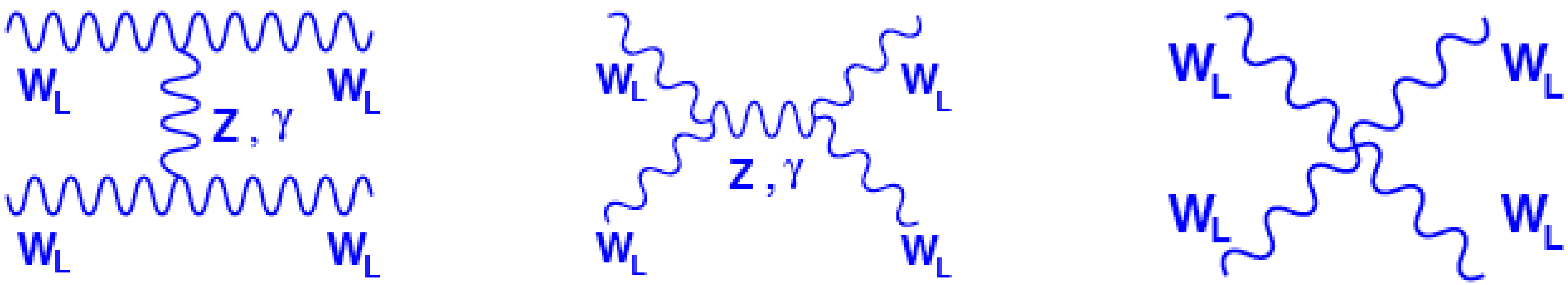
- $U(1)_{EM}$ is the low-energy remnant of a high-energy electroweak gauge symmetry $SU(2)_W \times U(1)_Y$

- how to achieve this symmetry breaking?

Is the symmetry explicitly broken?

i.e., do we just add a W mass term to the Lagrangian?

No: consider high-energy $W_L W_L \longrightarrow W_L W_L$ scattering



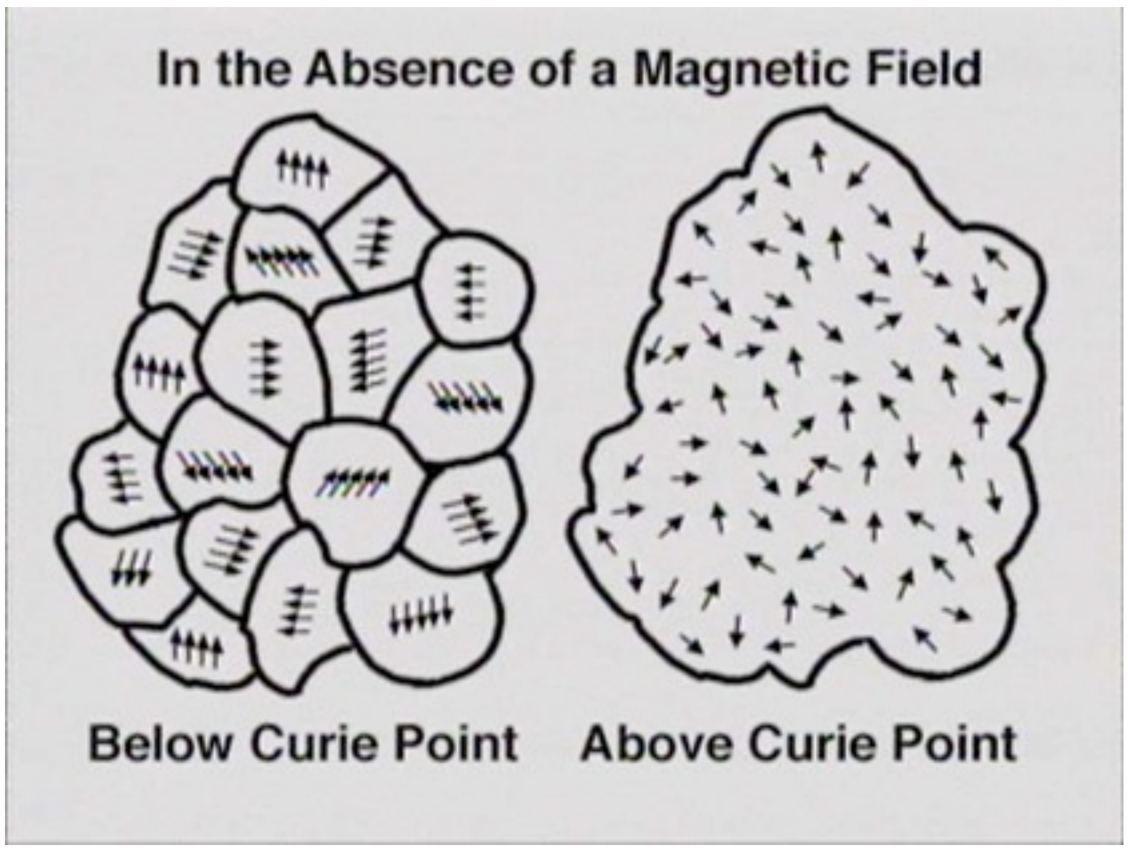
$$\mathcal{A}_{\text{tree level}} \sim \mathrm{E}^2_{\mathrm{c.m.}}/\mathrm{M}^2_{\mathrm{W}}$$

Unitarity would be violated (scattering probability > 100%)
for scattering energies $E_{c.m.}$ ~ 1000 GeV ...
so something is still missing.

Must have spontaneous symmetry breaking!

- Lagrangian is symmetric, but ground state is not
- a familiar example: ferromagnetism

$$\mathcal{H} \sim \boldsymbol{\Sigma}(-\vec{\mathbf{s}}_\mathbf{i} \cdot \vec{\mathbf{s}}_\mathbf{j})$$

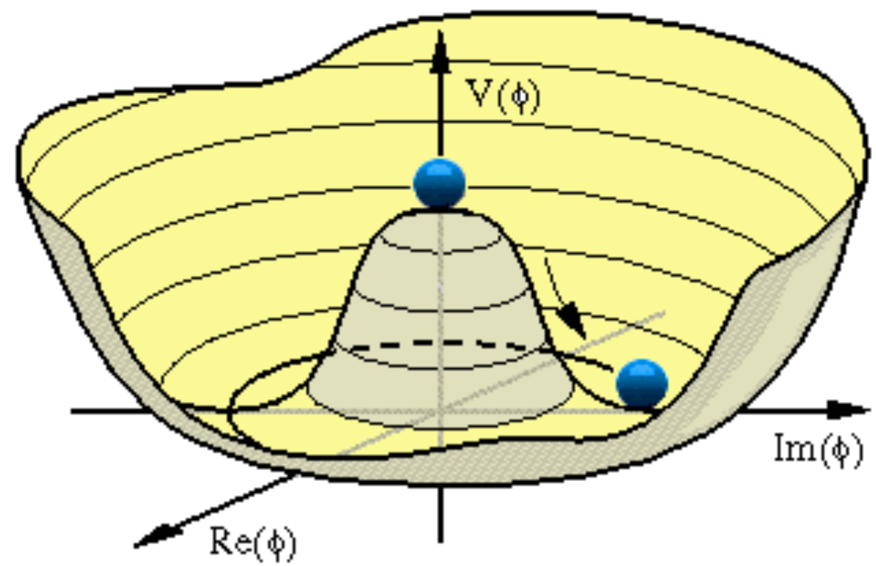


jchemed.chem.wisc.edu/JCESoft/CCA/CCA2/INDEX.HTM

The SM Higgs

A fundamental (not composite) complex weak doublet (4 degrees of freedom) of scalar (spin-0) fields

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$



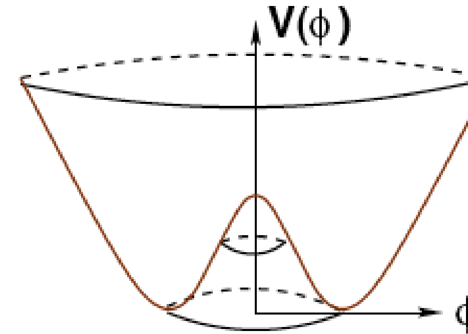
with potential energy function

$$V(\phi) = \lambda \left(\phi^\dagger \phi - \frac{v^2}{2} \right)^2$$

is employed both to break the electroweak symmetry and to generate masses for the fermions in the Standard Model

Nambu-Goldstone bosons provide M_W and M_Z

The potential is minimized away from the origin, so the scalar acquires a non-zero vacuum expectation value:

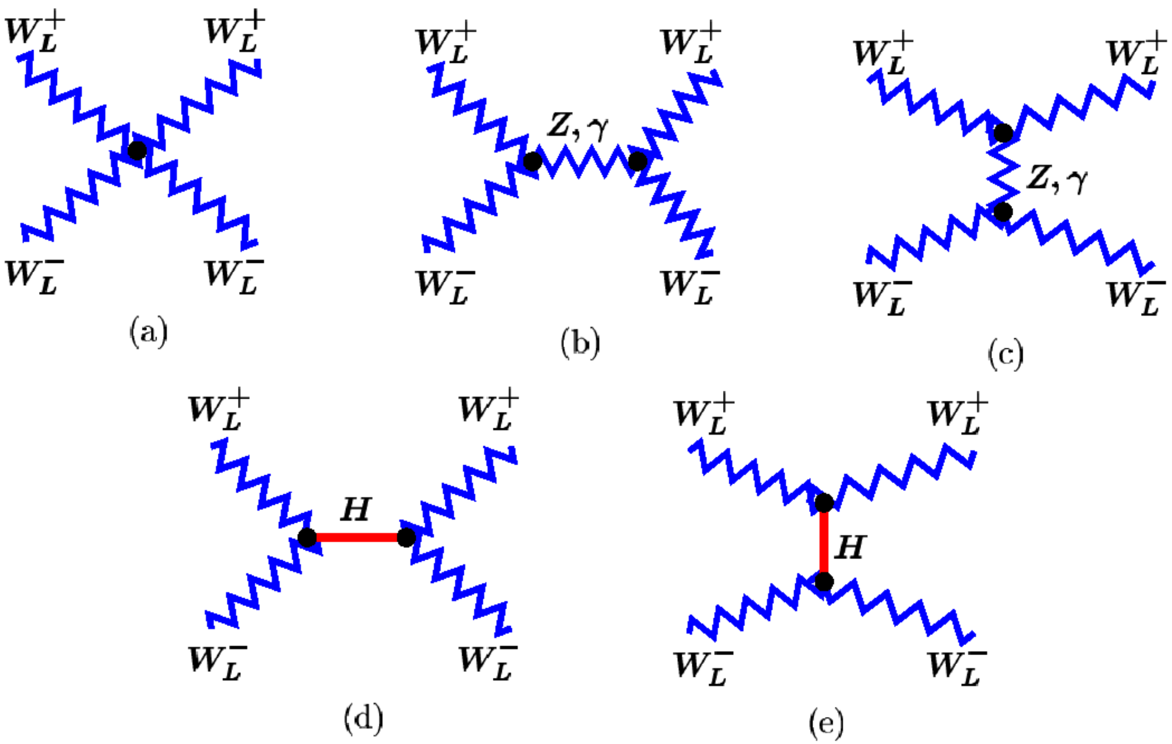


- $\langle\phi\rangle = (0,\ v/\sqrt{2})$ breaks $SU(2)_W \times U(1)_Y \rightarrow U(1)_{EM}$
- breaking this continuous symmetry yields 3 Nambu-Goldstone bosons which become the $W_L^+,\ W_L^-,\ Z_L^0$
- the scalars' kinetic energy term includes $D^\mu\phi^\dagger D_\mu\phi$ which now becomes

$$\frac{1}{4}g^2W^\mu\phi^\dagger W_\mu\phi \rightarrow \frac{1}{8}g^2v^2W^\mu W_\mu \equiv \frac{1}{2}M_W^2W^\mu W_\mu$$

a mass term for the W and Z bosons!

The remaining scalar (H = Higgs Boson) resolves the unitarity problem:



Graphs	$g^2 \frac{E^2}{m_w^2}$
(a)	$+2 - 6\cos\theta$
(b)	$-\cos\theta$
(c)	$-\frac{3}{2} + \frac{15}{2}\cos\theta$
(d + e)	$-\frac{1}{2} - \frac{1}{2}\cos\theta$
Sum including (d+e)	**0**

- $\mathcal{O}(E^0) \Rightarrow$ 4d m_H bound: $m_H < \sqrt{16\pi/3}\, v \simeq 1.0$ TeV
- If no Higgs $\Rightarrow \mathcal{O}(E^2) \Rightarrow E < \sqrt{4\pi}\, v \simeq 0.9$ TeV

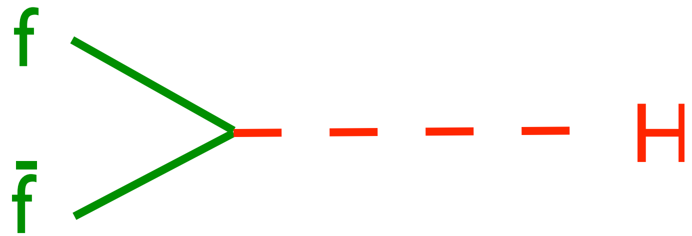
Fermion Masses

The scalar doublet ϕ couples to fermions as $\lambda \bar{f} \phi f$, yielding two effects when the electroweak symmetry breaks

- The fermion coupling to Nambu-Goldstone modes produces masses for the fermions

$$m_f = \lambda \langle \phi \rangle = \lambda v / \sqrt{2}$$

- The coupling of the remaining Higgs Boson (H) to fermions allows the Higgs to be produced by or decay to fermion pairs

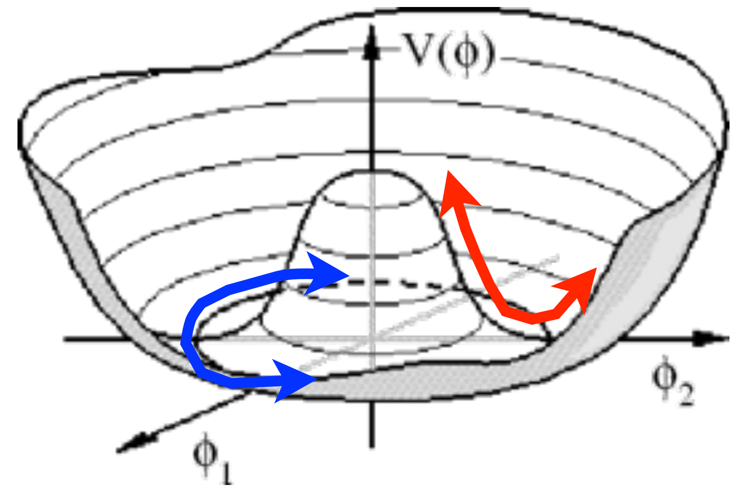


Polar Decomposition

Put ϕ in matrix form by defining $\tilde{\phi} \equiv i\sigma_2\phi^*$

and $\Phi \equiv (\tilde{\phi}, \phi)$ so that $\Phi^\dagger\Phi = \Phi\Phi^\dagger = (\phi^\dagger\phi)\,\mathcal{I}$

A polar decomposition of Φ



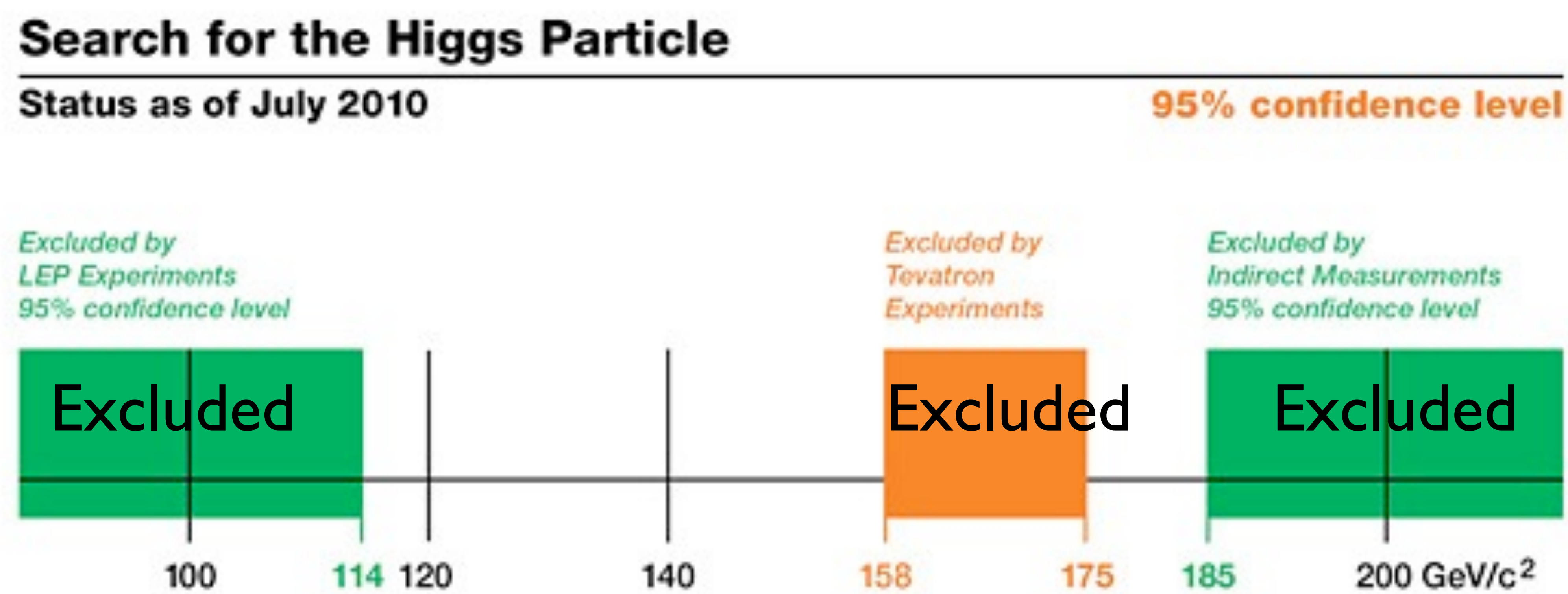
$$\Phi(x) = \frac{1}{\sqrt{2}}\left(H(x) + v\right)\Sigma(x)$$

$$\Sigma(x) = \exp(i\pi^a(x)\sigma^a/v)$$

neatly separates the radial "Higgs boson" from the "pion" modes (Nambu-Goldstone Bosons).

In unitary gauge, $\langle\Sigma\rangle = \mathcal{I}$

Fermilab
press room



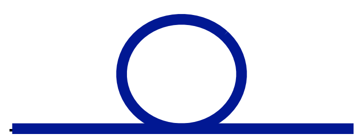
Higgs mass

Problems with the Higgs Model

- No fundamental scalars observed in nature

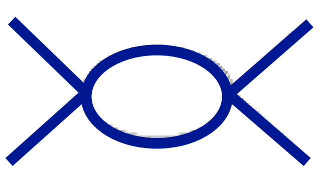
- No explanation of dynamics responsible for Electroweak Symmetry Breaking

- Hierarchy or Naturalness Problem



$$\Rightarrow \; m_H^2 \propto \Lambda^2$$

- Triviality Problem...



$$\Rightarrow \beta = \frac{3\lambda^2}{2\pi^2} > 0 \qquad \lambda(\mu) < \frac{3}{2\pi^2 \log\frac{\Lambda}{\mu}}$$

Interim Conclusions

- The electroweak symmetry is spontaneously broken. The three Nambu-Goldstone bosons of this broken continuous symmetry become the W_L and Z_L states. This process is known as the Higgs Mechanism.

- Additional states must exist in order to unitarize the scattering of the W_L and Z_L bosons. One minimal candidate is the Higgs boson.

- The Standard Model with a Higgs Boson is, at best, a low-energy effective theory valid below a scale Λ characteristic of the underlying physics.

- What lies beyond the Standard Model?

A Fork in the Road...

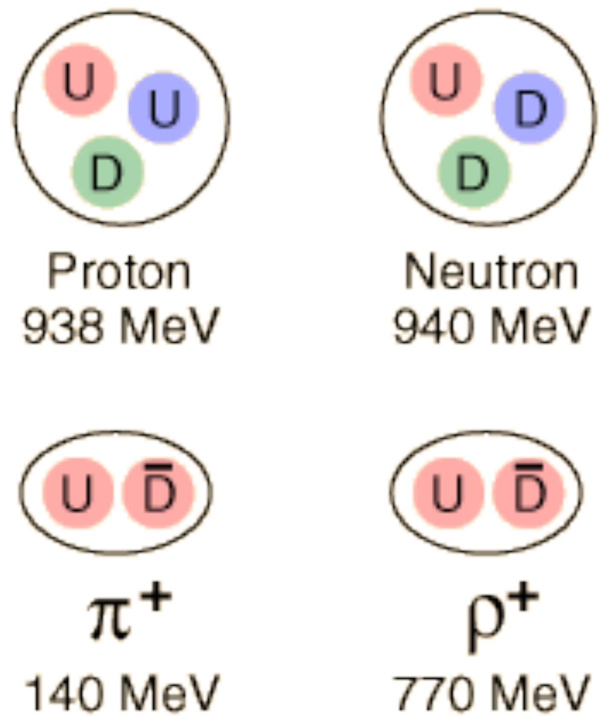
- Make the Higgs Natural: Supersymmetry
- Make the Higgs Composite
  - Little Higgs
  - Twin Higgs
- Eliminate the Higgs
  - Technicolor
  - "Higgsless" Models

"When you come to a fork in the road, take it!"
— Yogi Berra

Chiral Symmetry Breaking: Technicolor

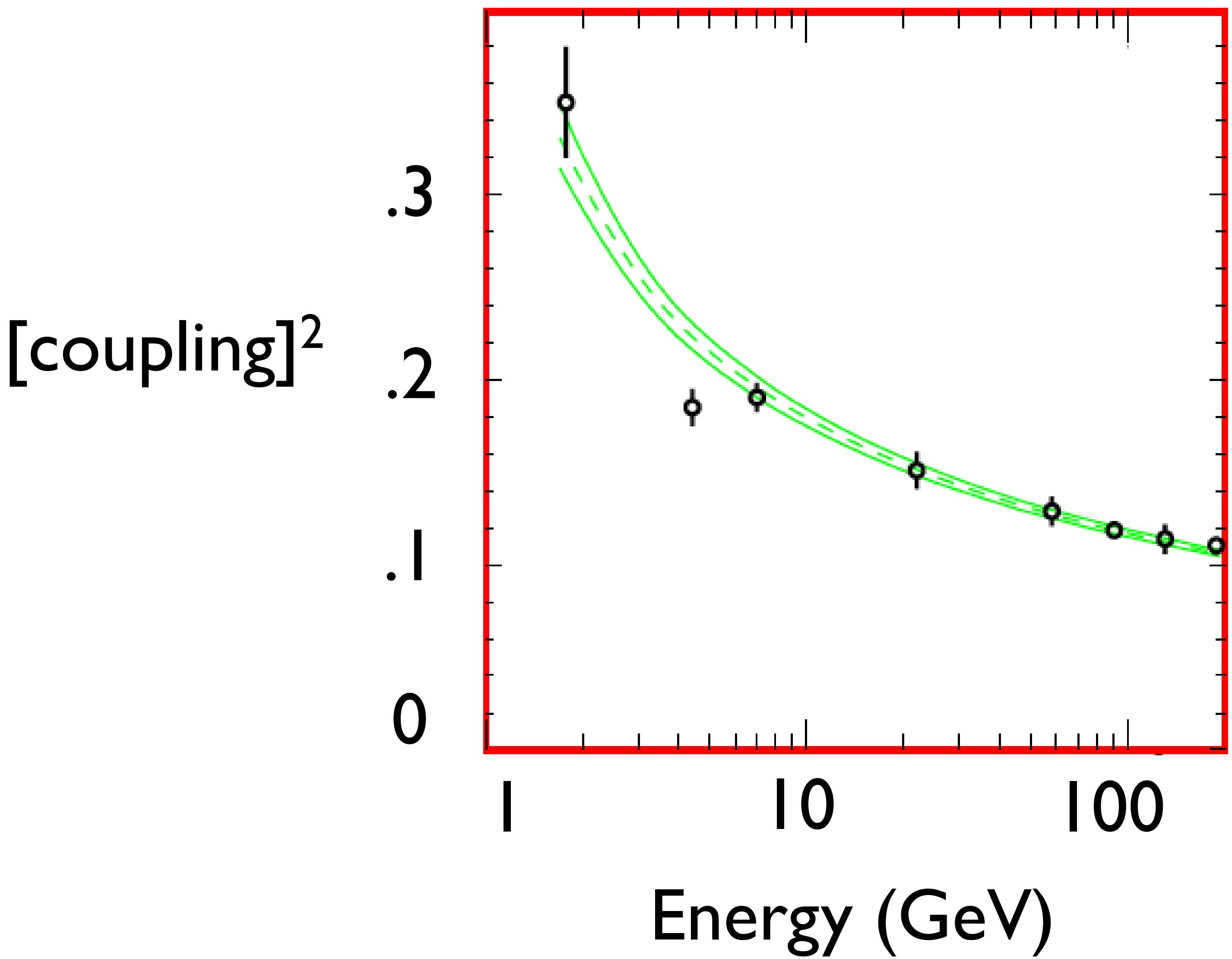
For a new approach to generating mass, we turn to the strong interactions (QCD) for inspiration

Consider the hadrons composed of up and down quarks:



Why is the pion so light?

Recall that the QCD coupling varies with energy scale, becoming strong at energies ~ 1 GeV



The strong-interaction (QCD) Lagrangian for the u and d quarks (neglecting their small masses)

$$\mathcal{L} = i\bar{u}_L \not{D} u_L + i\bar{d}_L \not{D} d_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R$$

displays an $SU(2)_L$ x $SU(2)_R$ global ("chiral") symmetry

When the QCD coupling becomes strong

- $\langle \bar{q}_L q_R \rangle \neq 0$ breaks $SU(2)_L$ x $SU(2)_R$ → $SU(2)_{L+R}$
- pions $(\bar{q}_L q_R)$ are the associated Nambu-Goldstone bosons!

Bonus: from chiral to electroweak symmetry breaking

- u_L, d_L form weak doublet; u_R, d_R are weak singlets
- so $\langle \bar{q}_L q_R \rangle \neq 0$ also breaks electroweak symmetry
- could QCD pions be our composite Higgs bosons?

Not Quite:

- $M_W = .5g\langle\ \rangle = 80$ GeV requires $\langle\ \rangle \sim 250$ GeV
- $\langle \bar{q}_L q_R \rangle$ only supplies ~ 0.1 GeV
- need extra source of EW symmetry breaking

This line of reasoning inspired **Technicolor**

introduce new gauge force with symmetry $SU(N)_{TC}$

- force carriers are technigluons, inspired by QCD gluons
- add techniquarks carrying $SU(N)_{TC}$ charge: i.e., matter particles inspired by QCD quarks
  - e.g. $T_L = (U_L, D_L)$ forms a weak doublet
    U_R, D_R are weak singlets
  - Lagrangian has familiar global (chiral) symmetry $SU(2)_L \times SU(2)_R$

Susskind, Weinberg

If $SU(N)_{TC}$ force is **stronger** than QCD ... then spontaneous symmetry breaking and pion formation will happen at a **higher** energy scale... e.g.

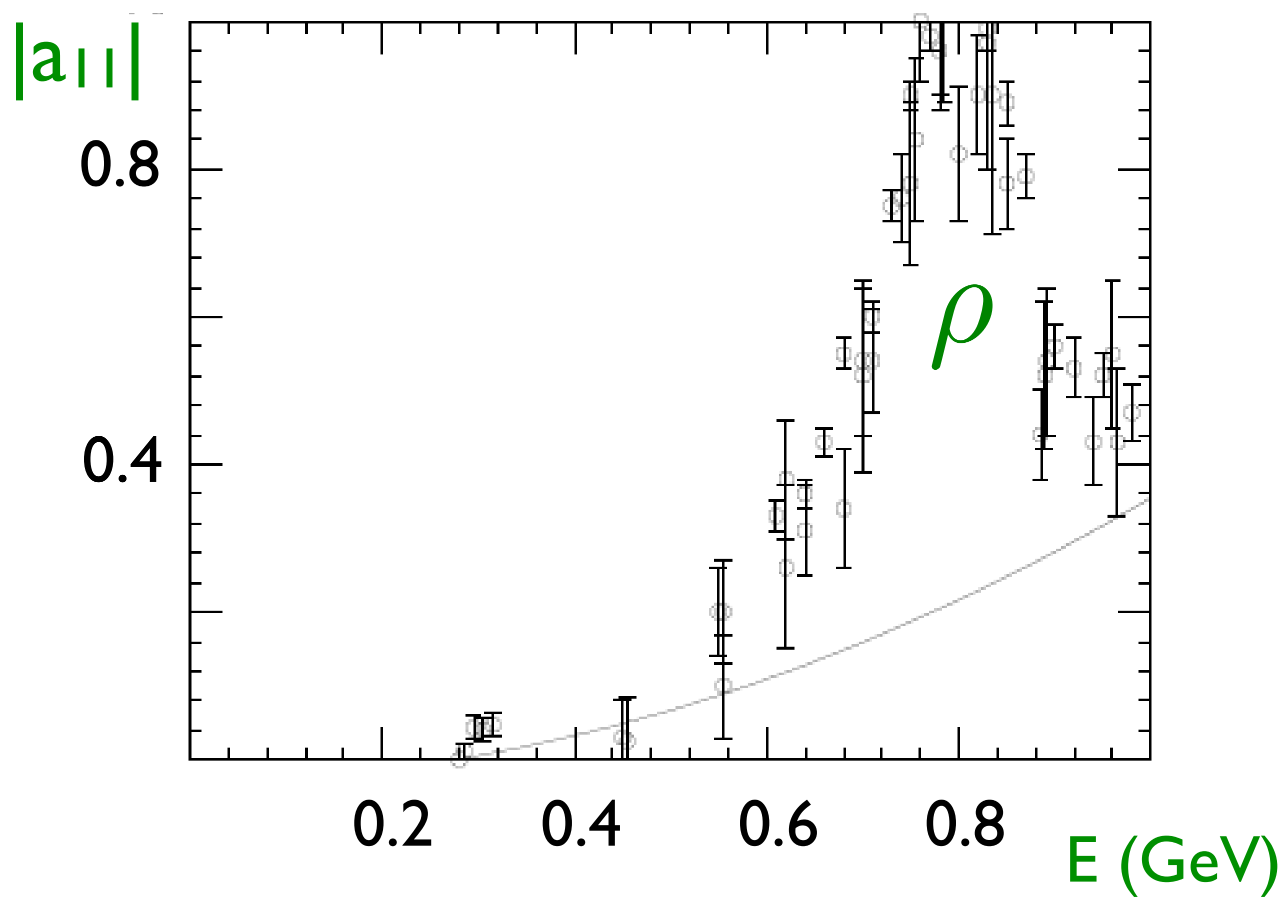
- gauge coupling becomes large at $\Lambda_{TC} \approx \ 1000\,\mathrm{GeV}$
- $\langle T_L T_R \rangle \ \approx \ 250\,\mathrm{GeV}$ breaks electroweak symmetry
- technipions Π_{TC} become the W_L, Z_L
- W and Z boson masses produced by technicolor match the values seen in experiment!

So far, so good... but what about unitarization?

ρ unitarizes $\pi\pi$ scattering in QCD

Data for amplitude of spin-1 isospin-1 $\pi\pi$ scattering

Donoghue, *et. al.*, PRD 38 (1988) 2195

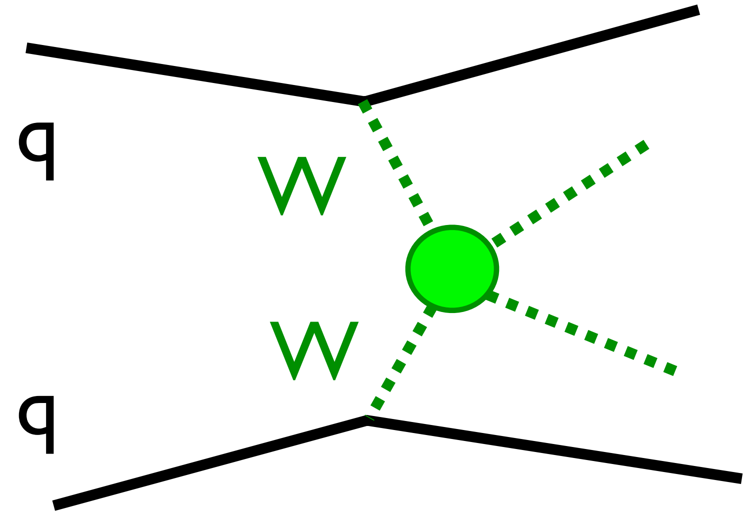


We expect similar behavior in $W_L W_L$ scattering due to the techni-ρ ... which should be ~2500 times heavier

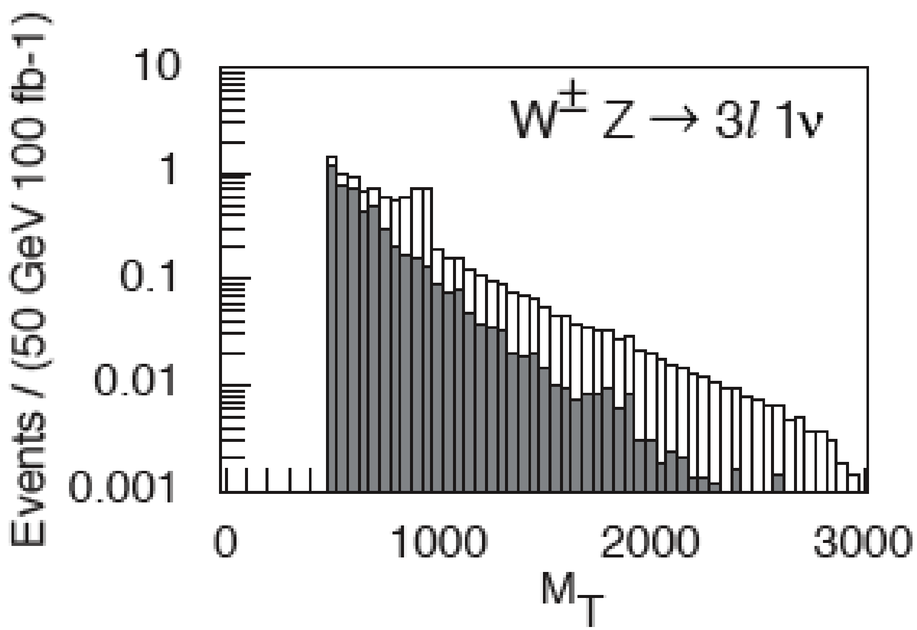
$$M_{\rho_{TC}} \approx 2\,\text{TeV}\sqrt{\frac{3}{N_{TC}}}$$

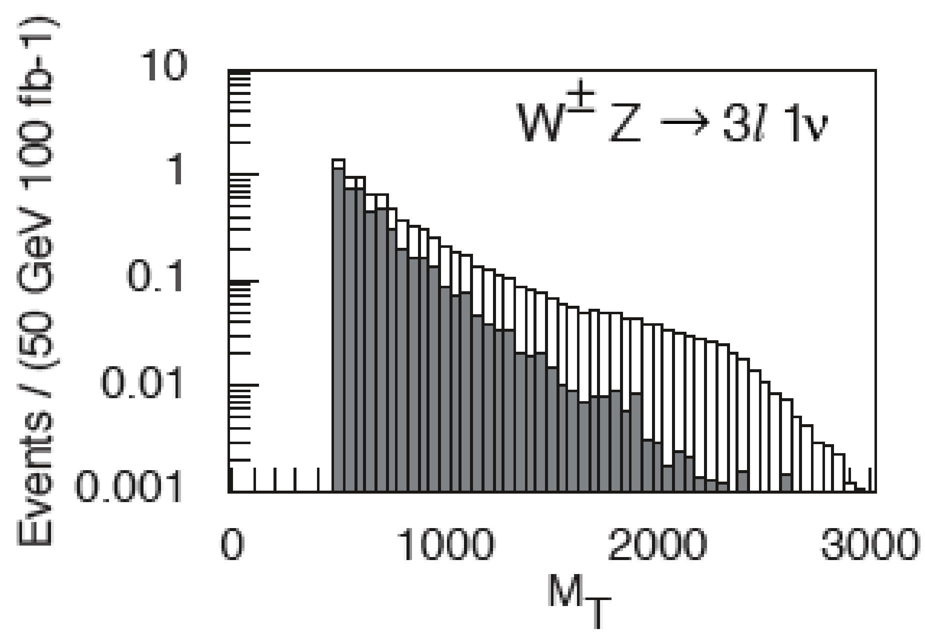
Prediction:

Techni-ρ will unitarize
$W_L W_L$ scattering at LHC



For $M_{\rho_{TC}} = 1.0$ TeV, 2.5 TeV: (simulations only)

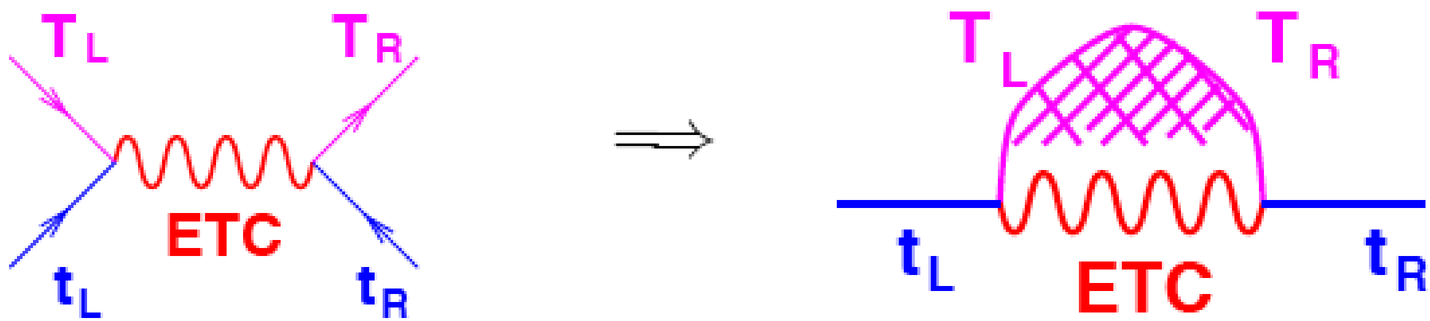




*J. Bagger *et. al.*, hep-ph/9306256, 9504426

Fermion Masses

In extended technicolor* or ETC models, new heavy gauge bosons connect ordinary and techni- fermions. The quarks and leptons acquire mass when technifermions condense. The top quark mass, e.g.



acquires a value $m_t \sim \left(\frac{g_{ETC}}{M_{ETC}}\right)^2 \langle \bar{T}T \rangle$ * (flavor-dependent factor)

Challenge: ETC would cause rare processes that mix quarks of different flavors to happen at enhanced rates excluded by data (e.g. Kaon/anti-Kaon mixing)

*Dimpoulos & Susskind; Eichten & Lane

Precision Electroweak Corrections

General amplitudes for "on-shell" 2-to-2 fermion scattering include deviations from the Standard Model:

$$-\mathcal{A}_{NC} = e^2 \frac{\mathcal{Q}\mathcal{Q}'}{Q^2} + \frac{(I_3 - s^2\mathcal{Q})(I_3' - s^2\mathcal{Q}')}{\left(\frac{s^2c^2}{e^2} - \frac{S}{16\pi}\right) Q^2 + \frac{1}{4\sqrt{2}G_F}(1 - \alpha T)}$$

S : size of electroweak symmetry breaking sector

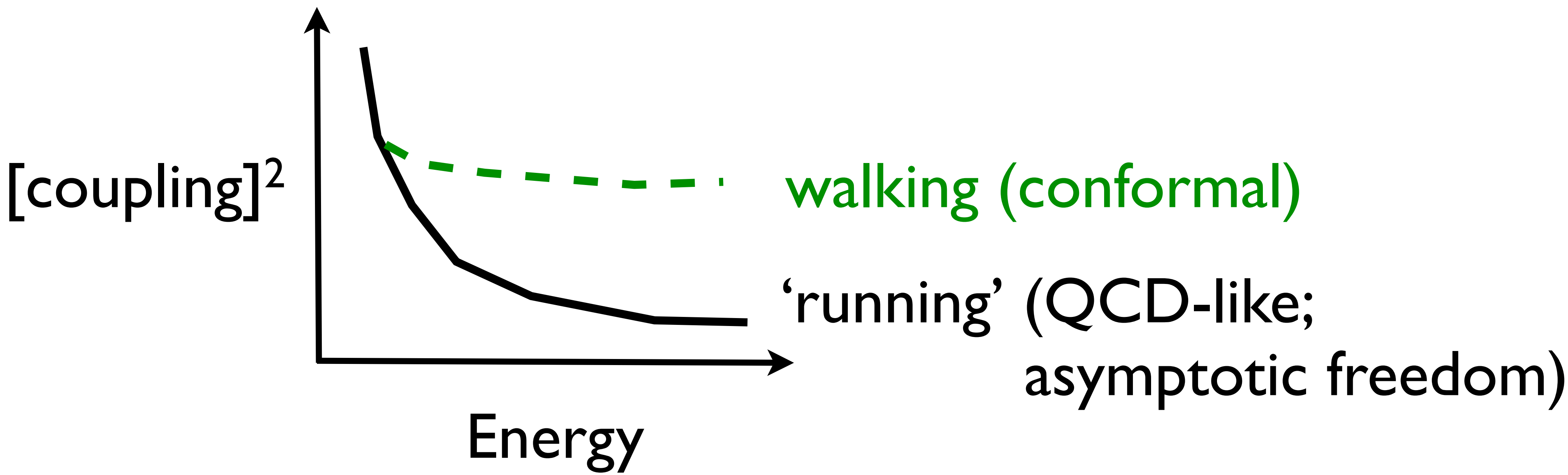
T : tendency of corrections to alter ratio M_W/M_Z

data (e.g. from LEP II, SLC, FNAL) are sensitive to quantum corrections, constraining S, T to be ~.001

QCD-like technicolor models predict larger S, T values

S, T: Peskin & Takeuchi

Walking Technicolor



- Large TC coupling enhances $m_f \sim (\frac{g_{ETC}}{M_{ETC}})^2 \langle \bar{T}T \rangle$
- Pushes flavor symmetry breaking to higher scale (M), so rare process rates agree with data
- Precision electroweak corrections no longer calculable by analogy with QCD ... smaller?

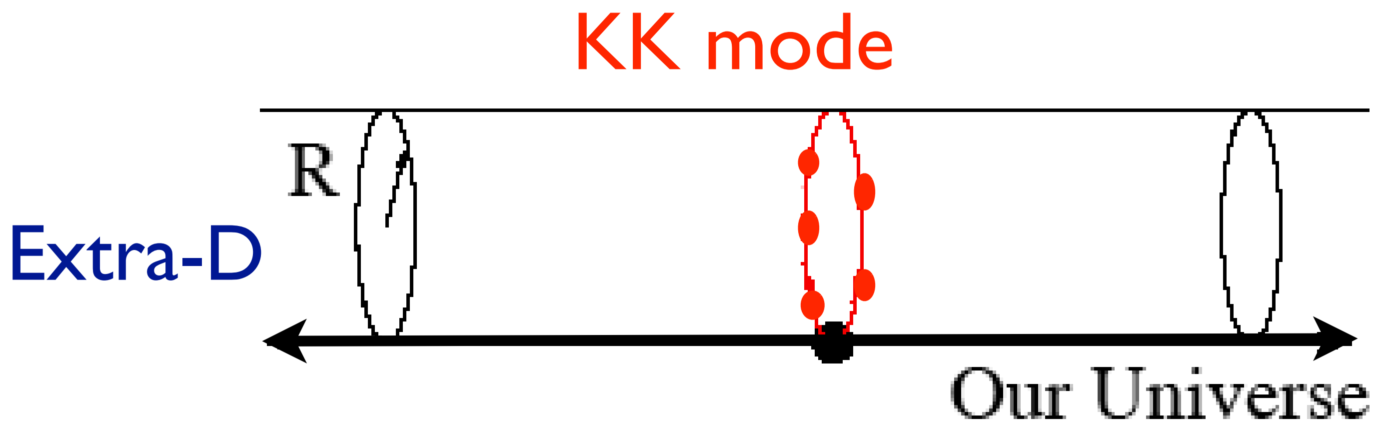
Extra Dimensions:
Higgsless Models

Overview :

Suppose the universe is a 5-D spacetime including a gauge theory subject to appropriate boundary conditions. What we 4-D folk observe is:

- a light set of bosons identified with the photon, W, and Z
- towers of heavy replica gauge bosons (called Kaluza-Klein modes)
- $W_L W_L$ scattering being unitarized through exchange of the KK modes (instead of via Higgs or techni-rho exchange)

Massive Gauge Bosons from Extra-D Theories



Expand 5-D gauge bosons in eigenmodes; e.g. for S^1/Z_2:

$$\hat{A}^a_\mu = \frac{1}{\sqrt{\pi R}}\left[A^{a0}_\mu(x_\nu) + \sqrt{2}\sum_{n=1}^{\infty} A^{an}_\mu(x_\nu)\cos\left(\frac{nx_5}{R}\right)\right]$$

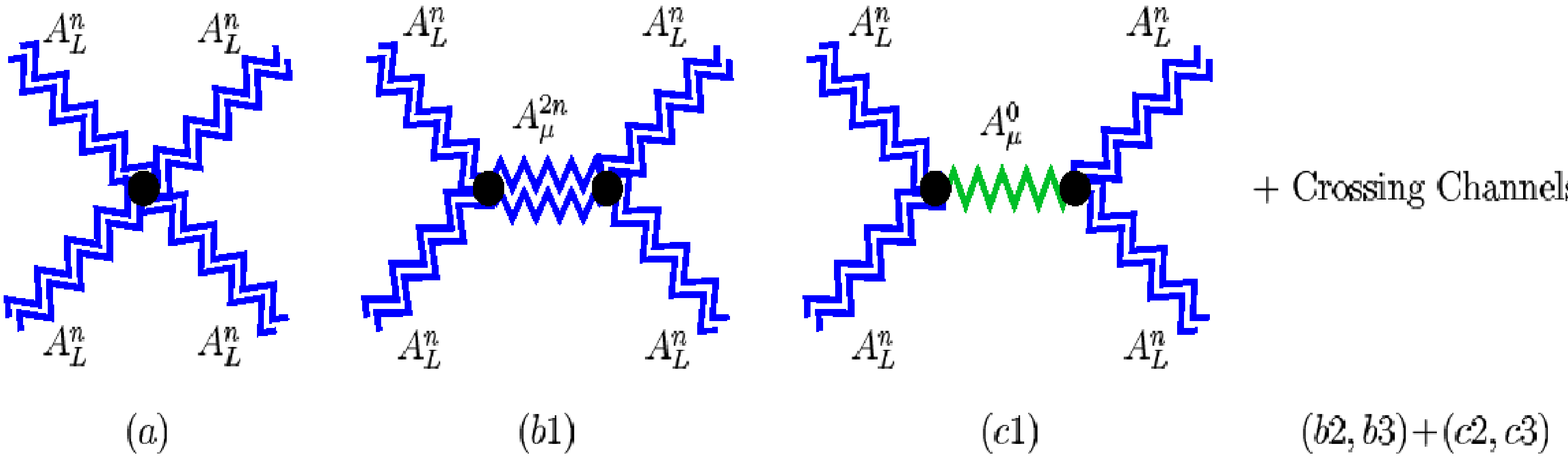
$$\hat{A}^a_5 = \sqrt{\frac{2}{\pi R}}\sum_{n=1}^{\infty} A^{an}_5(x_\nu)\sin\left(\frac{nx_5}{R}\right)$$

4-D gauge kinetic term contains

$$\frac{1}{2}\sum_{n=1}^{\infty}\left[M_n^2(A^{an}_\mu)^2 - 2M_n A^{an}_\mu \partial^\mu A^{an}_5 + (\partial_\mu A^{an}_5)^2\right]$$

i.e., $A^{an}_L \leftrightarrow A^{an}_5$

4-D KK Mode Scattering



Cancellation of bad high-energy behavior through exchange of massive vector particles

graph	$g^2 C^{eab} C^{ecd}$	$g^2 C^{eac} C^{edb}$	$g^2 C^{ead} C^{ebc}$
(a)	$6c(x^4-x^2)$	$\frac{3}{2}(3-2c-c^2)x^4$ $-3(1-c)x^2$	$\frac{-3}{2}(3+2c-c^2)x^4$ $+3(1+c)x^2$
$(b1)$	$-2c(x^4+x^2)$		
$(c1)$	$-4cx^4$		
$(b2,3)$		$\frac{-1}{2}(3-2c+c^2)x^4$ $+3(1-c)x^2$	$\frac{1}{2}(3+2c-c^2)x^4$ $-3(1+c)x^2$
$(c2,3)$		$(-3+2c+c^2)x^4$ $-8cx^2$	$(3+2c-c^2)x^4$ $-8cx^2$
Sum	$-8cx^2$	$-8cx^2$	$-8cx^2 \Rightarrow 0$

RSC, H.J. He, D. Dicus

Recipe for a Higgsless Model:

- Choose "bulk" gauge group, fermion profiles, boundary conditions
- Choose $g(x_5)$
- Choose metric/manifold: $g_{MN}(x_5)$
- Calculate spectrum & eigenfunctions
- Calculate fermion couplings
- Compare to model to data
- Declare model viable or not ....

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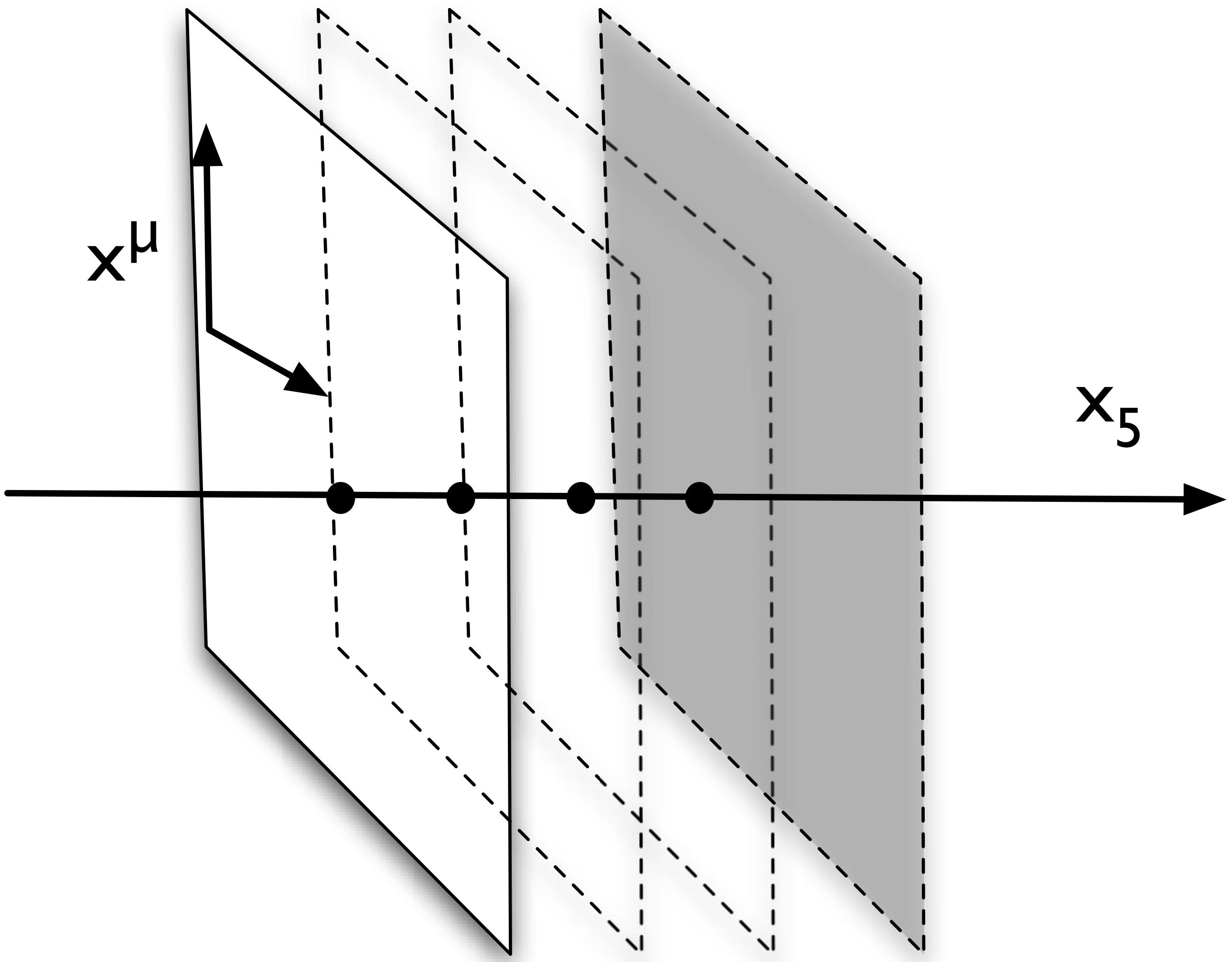
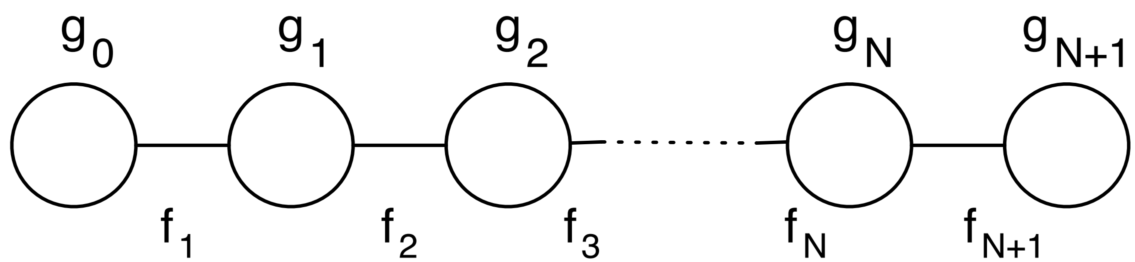
Sisyphus
(Titian, 1548/9)

To break the cycle...
Latticize the Fifth Dimension



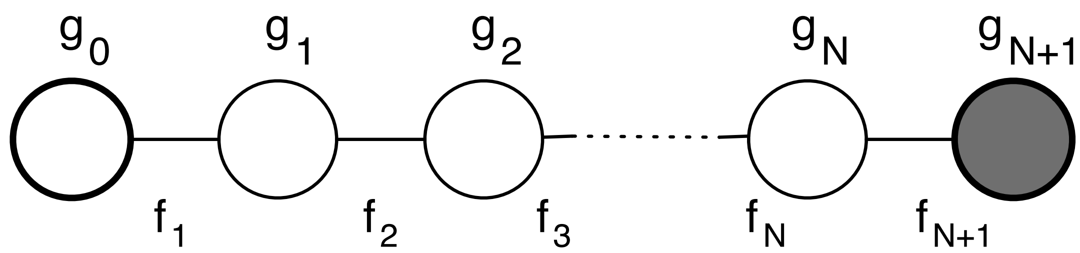
Deconstruction



- Discretize fifth dimension with a 4D gauge group at each site
- Nonlinear sigma model link fields $\Sigma(x) = \exp(i\pi^a(x)\sigma^a/v)$ break adjacent groups to diagonal subgroup
- To include warping: vary f_j
- For spatially dependent coupling: vary g_k
- Continuum Limit: take N $\rightarrow$ infinity

Arkani-Hamed, Georgi, Cohen & Hill, Pokorski, Wang

Brane-Localized Fermions



- consider a generic $SU(2)^{N+1} \times U(1)$ Higgsless model with generic f_j and g_k values

- simplest case: fermions do not propagate in the 5th dimension, but stay on the 4-D "branes" [sites 0 and N+1] at either end

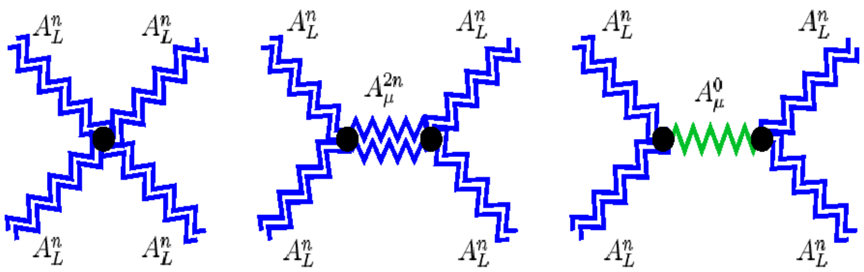
- Many 4-D/5-D theories are limiting cases [e.g. N=0 related to technicolor]; with this technique we can study them all at once!

cf. "BESS" and "HLS"

Foadi, *et. al.* & Chivukula *et. al.*

Conflict of S & Unitarity for Brane-Localized Fermions

Heavy resonances must unitarize WW scattering (since there is no Higgs!)



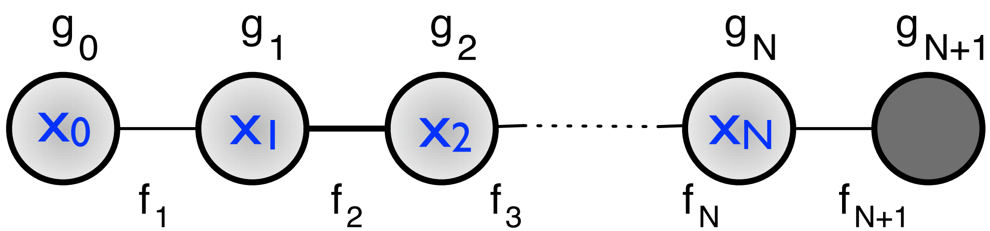
This bounds lightest KK mode mass: $m_{Z_1} < \sqrt{8}\pi v$

... and yields $$\alpha\, S \geq \frac{4 s_Z^2 c_Z^2 M_Z^2}{8\pi v^2} = \frac{\alpha}{2}$$

Too large by a factor of a few!

Independent of warping or gauge couplings chosen...

A New Hope?



Since Higgsless models with localized fermions are not viable, look at:

Delocalized Fermions, .i.e., mixing of "brane" and "bulk" modes

$$\mathcal{L}_f = \vec{J}^\mu_L \cdot \left(\sum_{i=0}^{N} x_i \vec{A}^i_\mu \right) + J^\mu_Y A^{N+1}_\mu$$

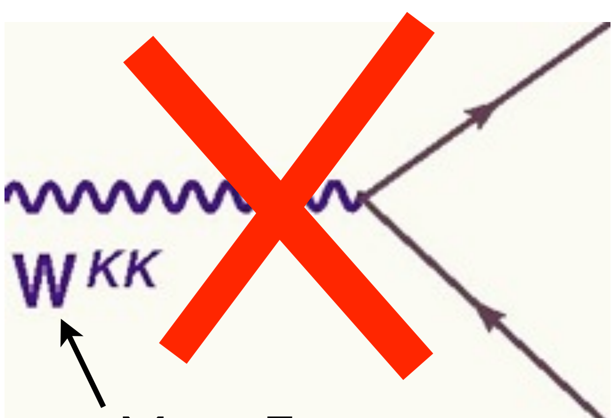
How will this affect precision EW observables?

Ideal Fermion Delocalization

- The light W's wavefunction is orthogonal to wavefunctions of KK modes (charged gauge boson mass-squared matrix is real, symmetric)
- Choose fermion delocalization profile to match W wavefunction profile along the 5th dimension:

$$g_i x_i \propto v_i^W$$

- No (tree-level) fermion couplings to KK modes!



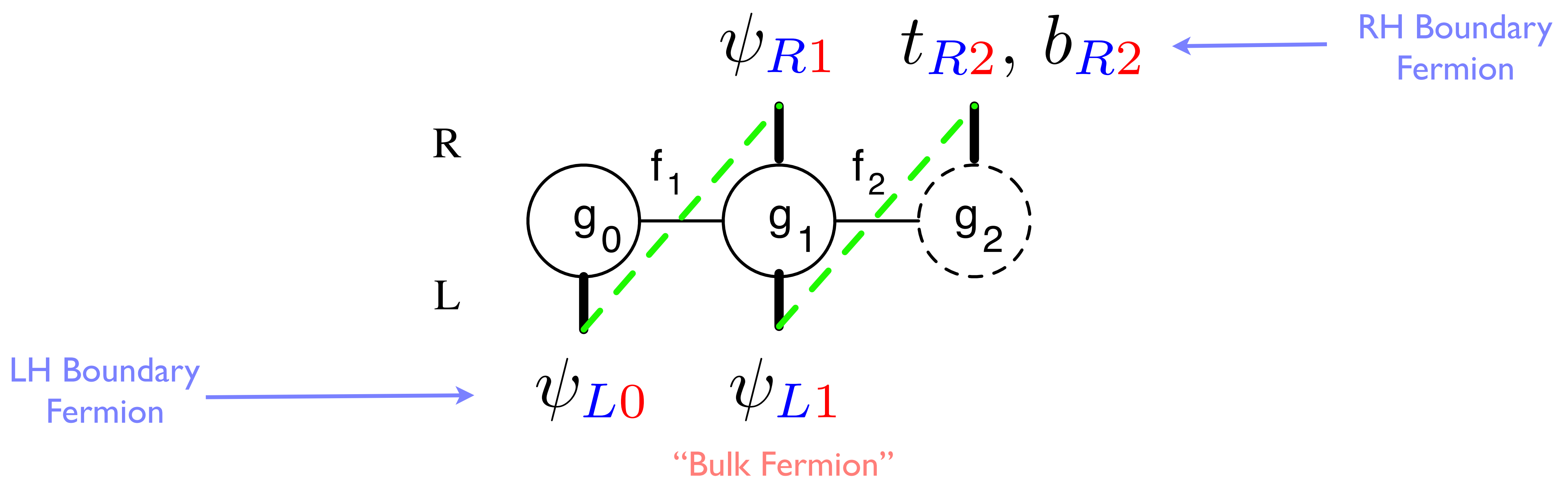
$$\hat{S} = \hat{T} = W = 0$$

$$Y = M_W^2(\Sigma_W - \Sigma_Z)$$

RSC, HJH, MK, MT, EHS hep-ph/0504114

The 3-Site Higgsless Model:

$SU(2) \times SU(2) \times U(1)$ $\quad g_0,\ g_2 \ll g_1$



<u>Gauge boson spectrum</u>: photon, Z, Z', W, W'

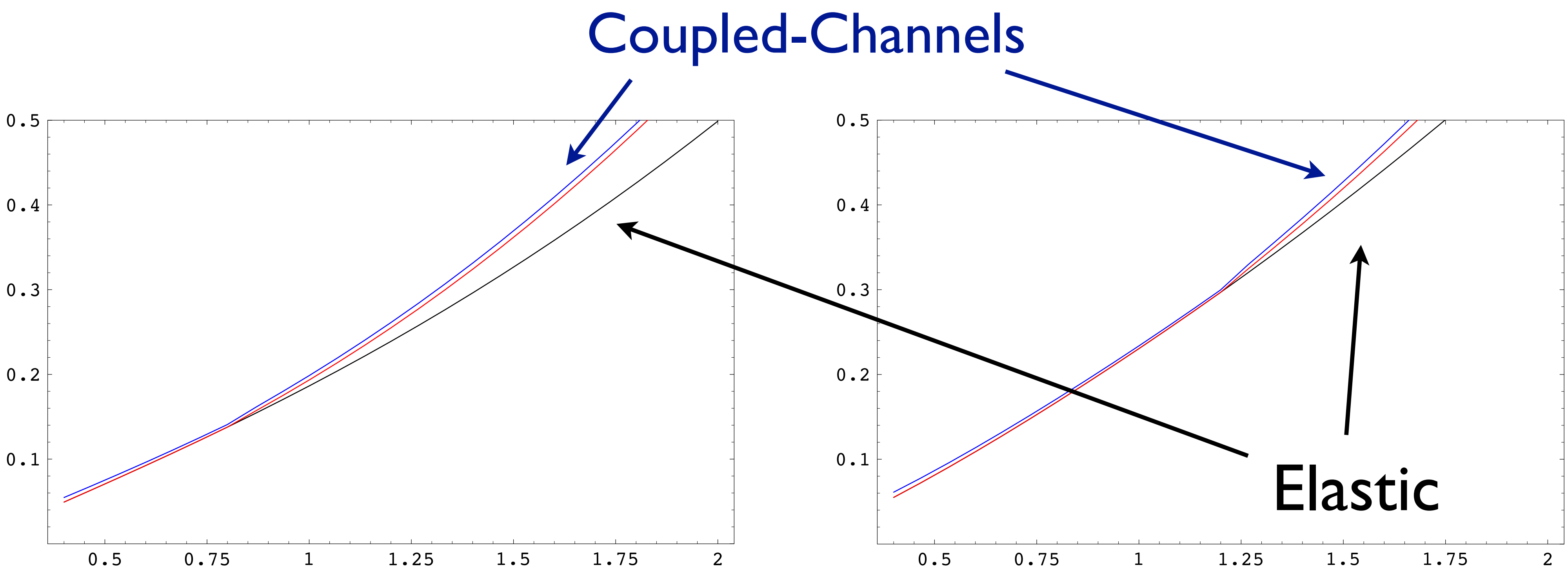
<u>Fermion spectrum</u>: t, T, b, B (ψ is an SU(2) doublet)

and also c, C, s, S, u, U, d, D plus the leptons

Unitarity in the 3-Site Model

$$\mathcal{A}_{I=0}(s,\cos\theta) \; = \; 3A(s,t,u) + A(t,s,u) + A(u,t,s)$$

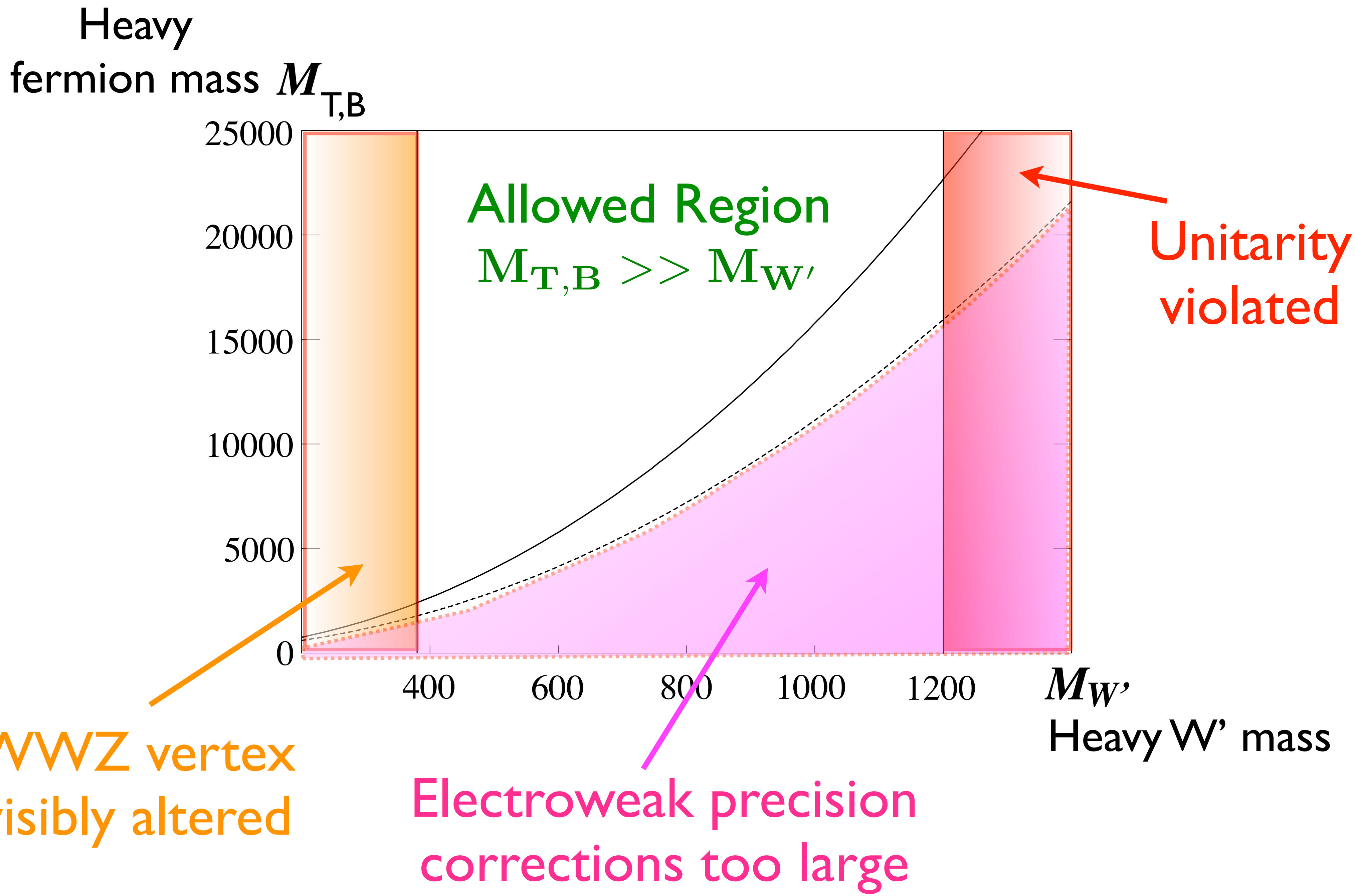
$$\mathcal{A}_{I=J=0}(s) = \frac{1}{64\pi}\int_{-1}^{+1} d\cos\theta \, \mathcal{A}_{I=0}(s,\cos\theta) P_0(\cos\theta)$$



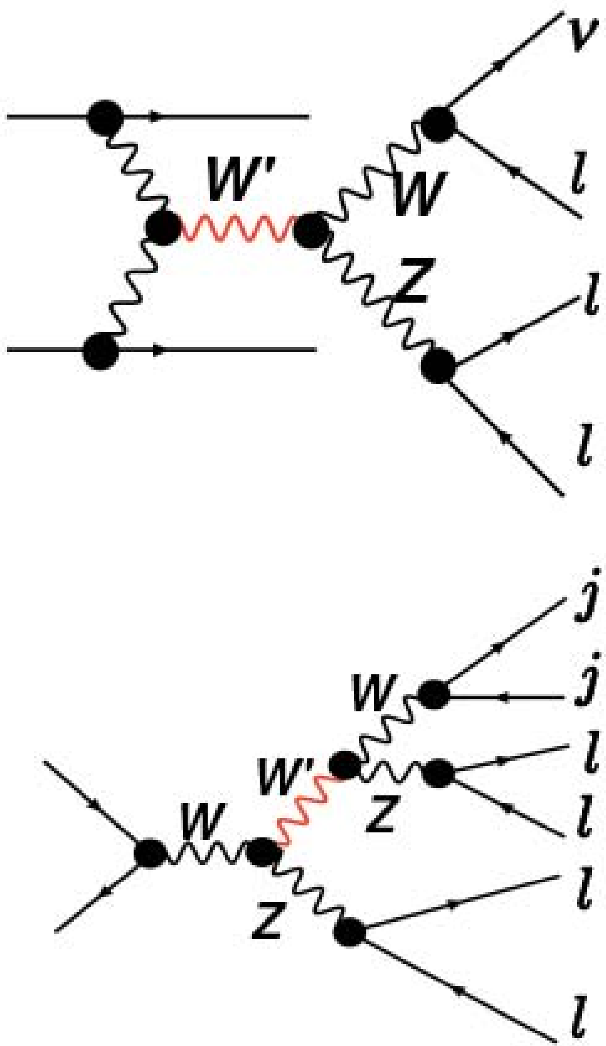
$M_{W'} = 400\,\mathrm{GeV}$ $\qquad$ $M_{W'} = 600\,\mathrm{GeV}$

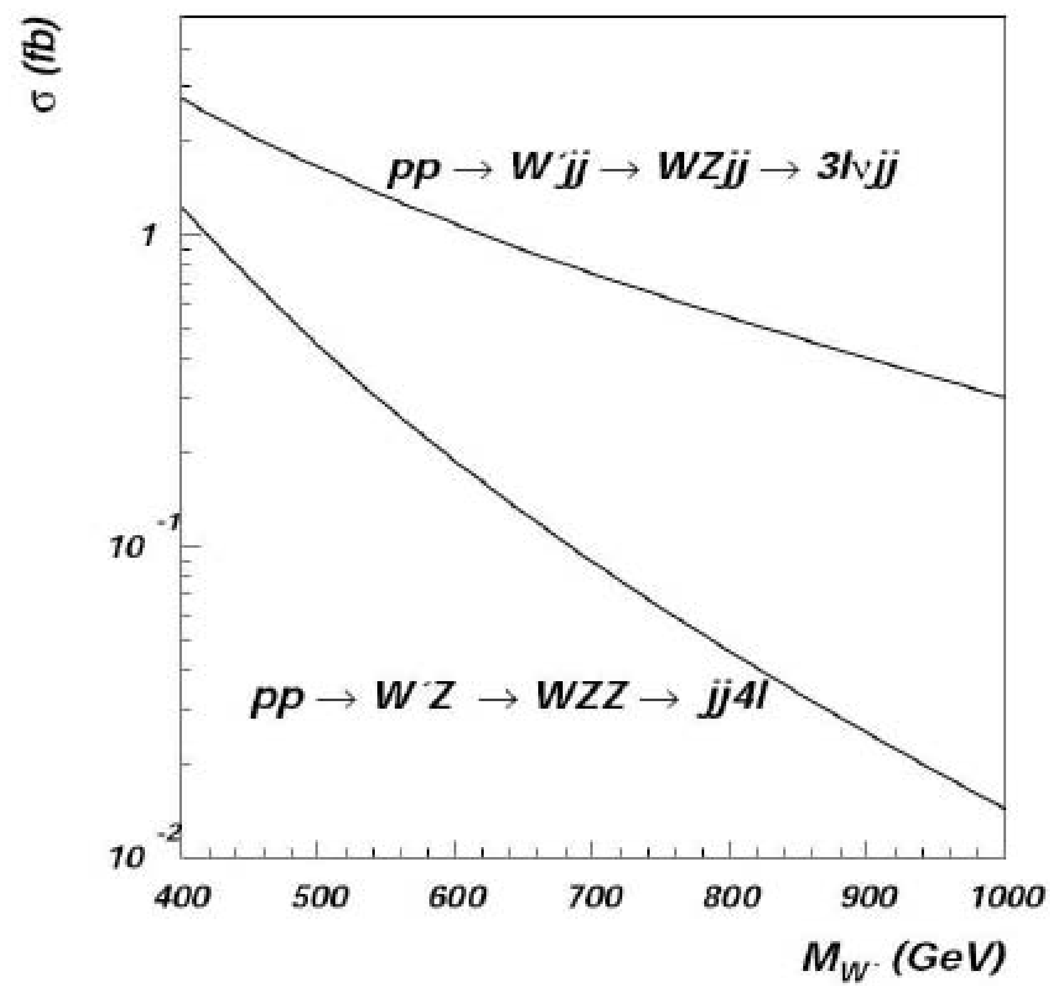
Modest Enhancement of Scale of Unitarity Violation

3-Site Parameter Space

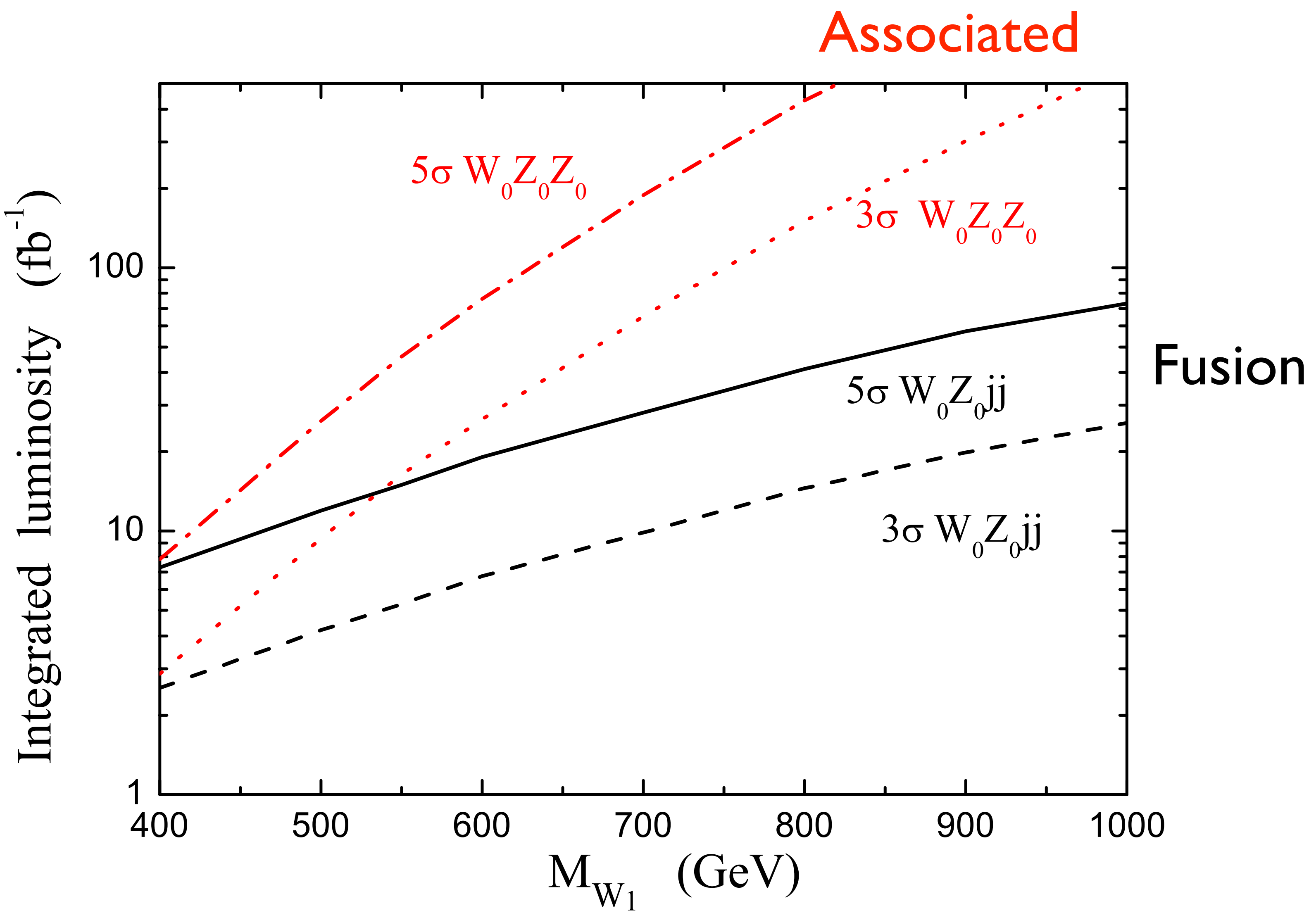


Vector Boson Fusion (WZ → W') and W'Z Associated Production promise large rates and clear signatures





Integrated LHC Luminosity required to discover W' in each channel

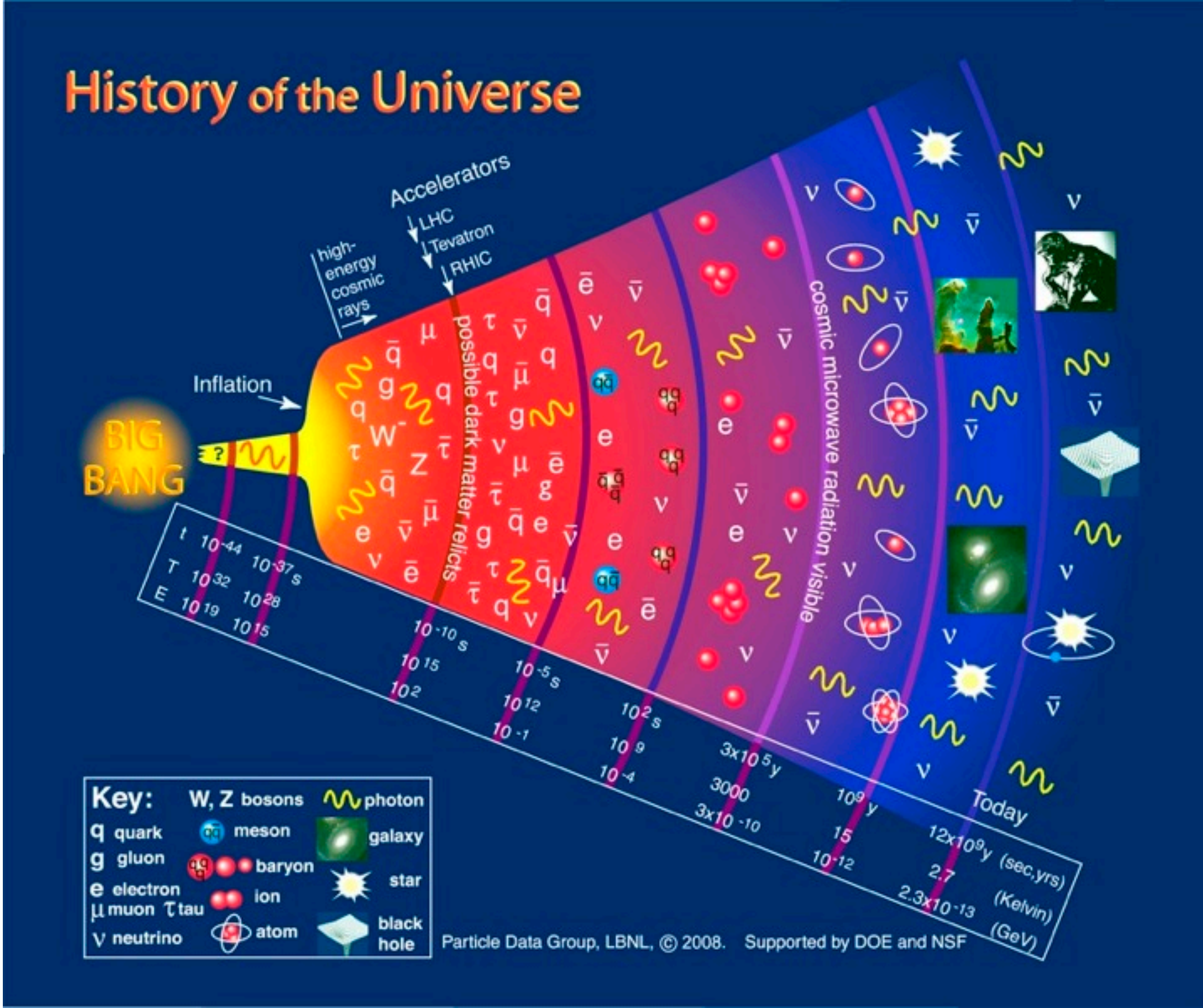


Conclusions

- The Standard Higgs Model is a low-energy effective theory of electroweak symmetry breaking that is valid below a scale characteristic of the underlying physics.

- Intriguing candidates for the underlying physics include:
  - Technicolor
    - composite Nambu-Goldstone bosons
    - techni-rho exchange unitarizes $W_L W_L$ scattering
  - Higgsless models
    - Nambu-Goldstone bosons from extra dimensions
    - KK-mode exchange unitarizes $W_L W_L$ scattering

- Experiments now underway at the Large Hadron Collider (CERN) should be able to tell the difference!


History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
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