Technicolor and
Lattice Gauge Theory

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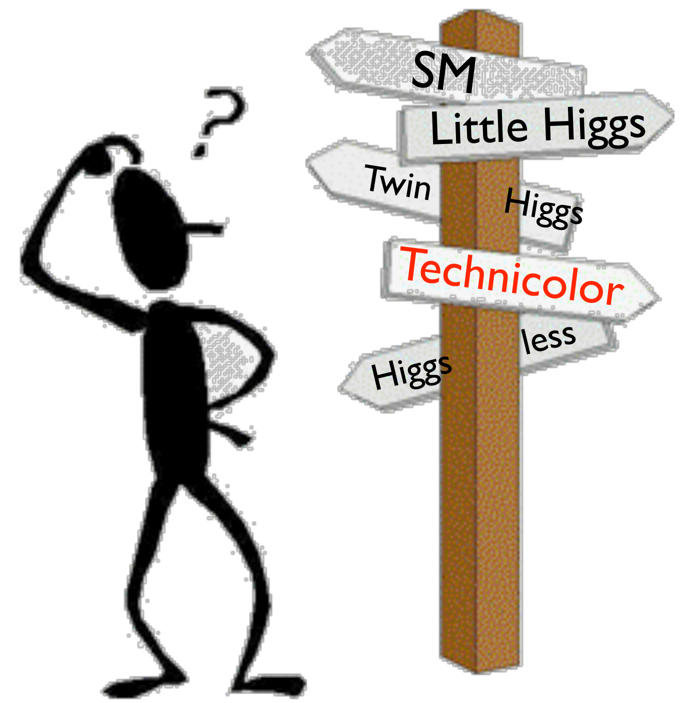


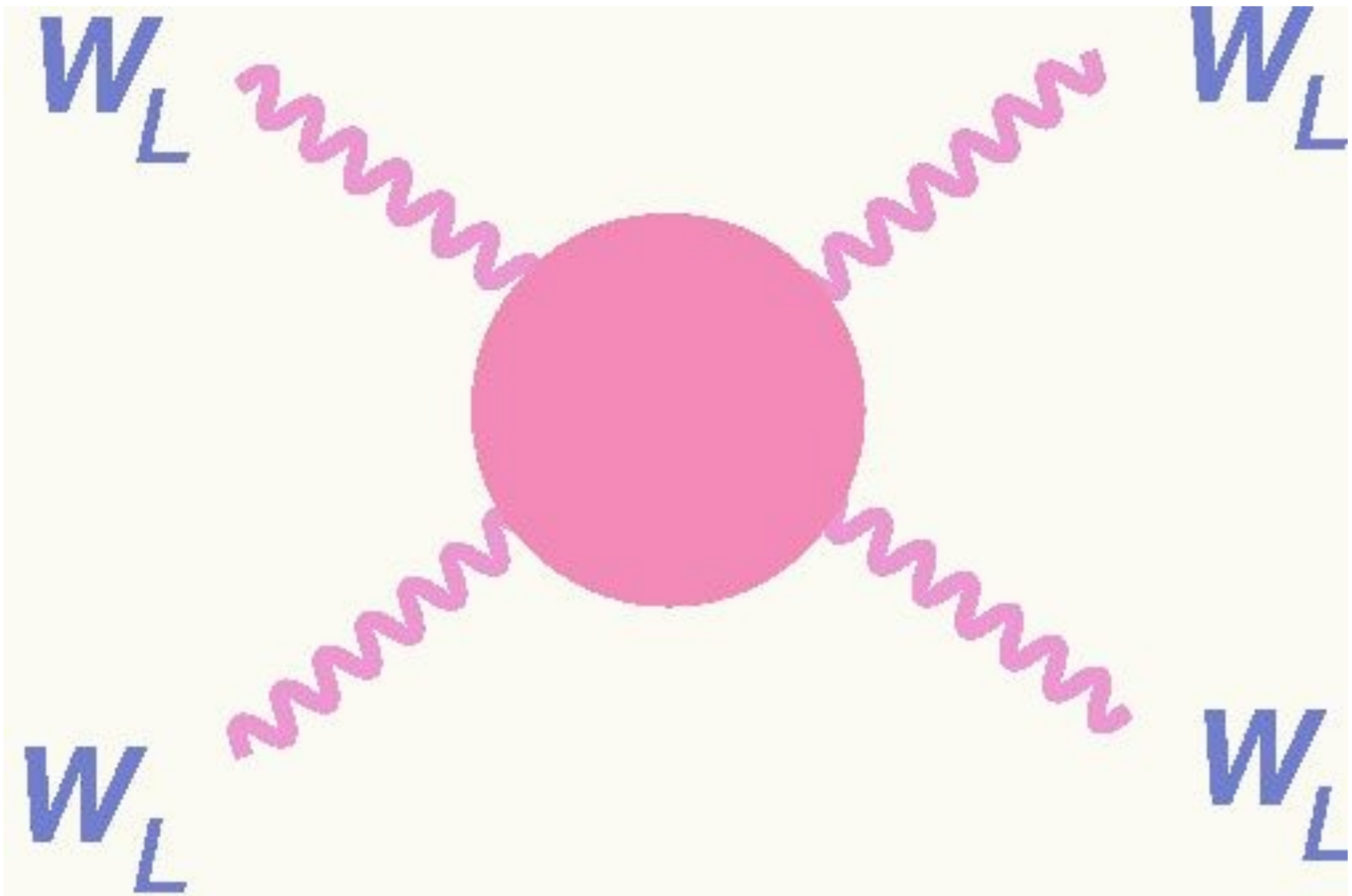
EWSB?

Lattice 2010
June 14 - 19 Villasimius, Sardinia, Italy

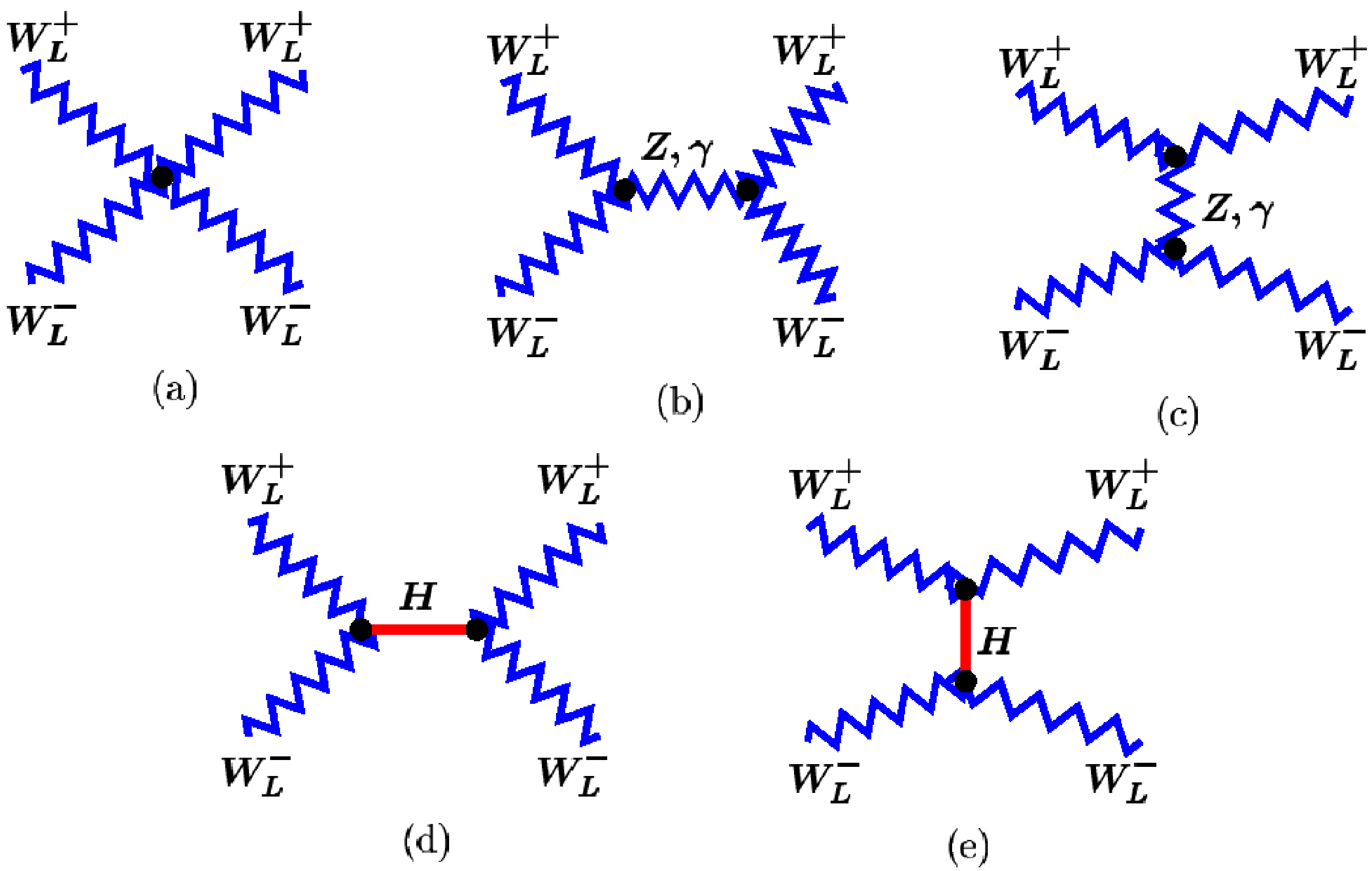
The XXVIII International Symposium on Lattice Field Theory

Why Worry About EWSB?

Loss of Unitarity in



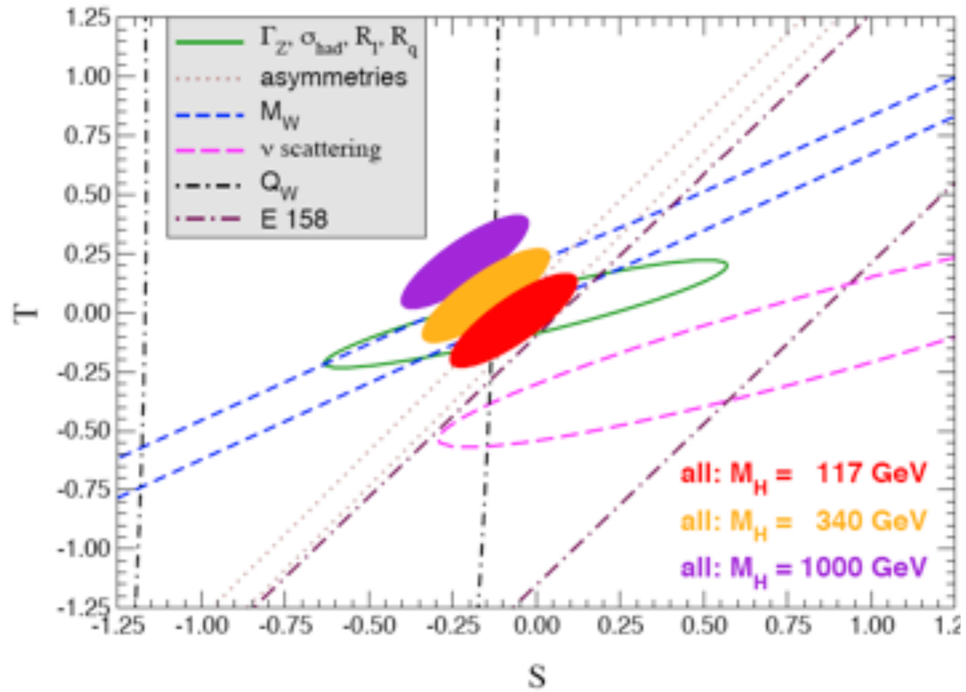
SU(2) x U(1) @ E^2

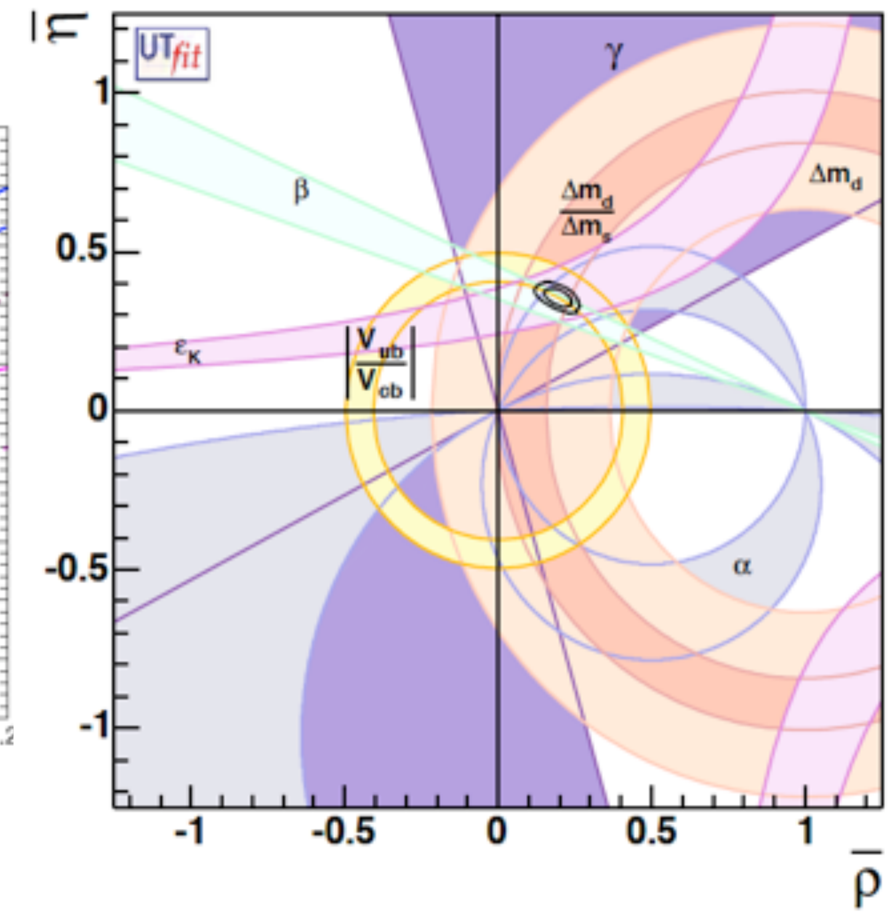


Graphs	$g^2 \frac{E^2}{m_w^2}$
(a)	$+2 - 6\cos\theta$
(b)	$-\cos\theta$
(c)	$-\frac{3}{2} + \frac{15}{2}\cos\theta$
(d + e)	$-\frac{1}{2} - \frac{1}{2}\cos\theta$
Sum including (d+e)	**0**

- ▶ $\mathcal{O}(E^0) \Rightarrow$ 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

So what do we know about EW/SB?





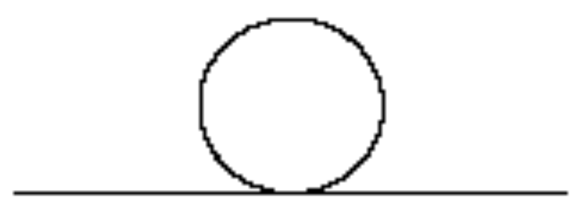
Gauge Interactions: Flavor Universal!

$SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$ symmetry: $F_Z \approx F_W \approx 246$ GeV

SM "works" to O(few x 10^{-3})

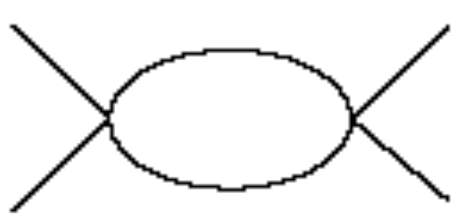
Problems with a fundamental Higgs Boson

- No fundamental scalars observed in nature!
- No explanation of Electroweak Symmetry Breaking
- Hierarchy and Naturalness Problem



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

- Triviality Problem ...

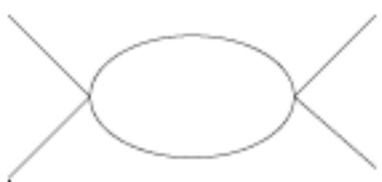


$$\Rightarrow \beta = \frac{3\lambda^2}{2\pi^2} > 0 \quad .$$

Lattice Contribution to EWSB

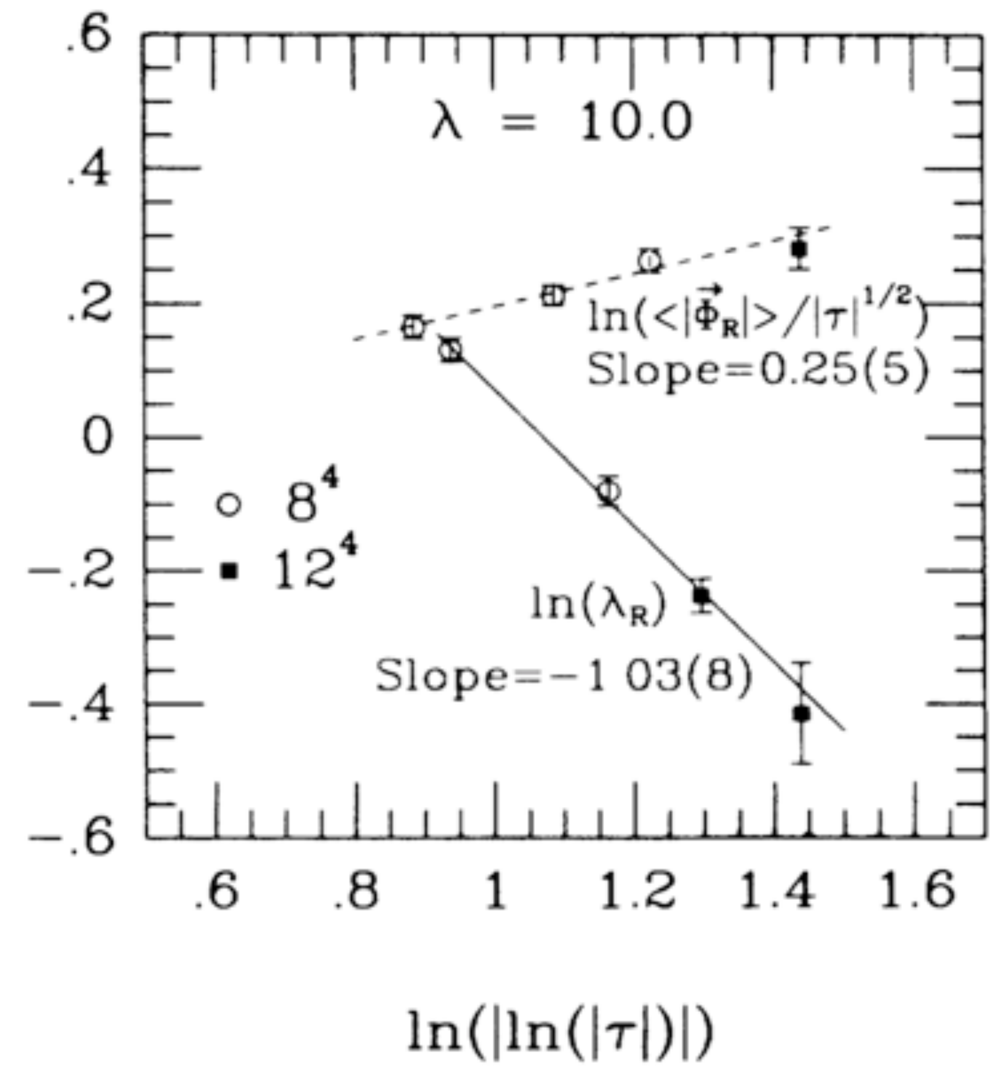
Higgs Lagrangian: $$\frac{1}{2}\mathrm{Tr}\left(D^\mu \Phi D_\mu \Phi^\dagger\right) + \frac{\lambda}{4}\left(\mathrm{Tr}\left(\Phi\Phi^\dagger\right) - v^2\right)^2$$

Triviality Problem . . .



$$\Rightarrow \beta = \frac{3\lambda^2}{2\pi^2} > 0$$

$$\lambda(\mu) < \frac{3}{2\pi^2 \log \frac{\Lambda}{\mu}} \quad .$$



Kuti, et. al. PRL 61 (1988) 678

Dashen & Neuberger PRL 50 (1983) 1897

A Fork in the Road...

- Make the Higgs Natural: Supersymmetry
- Make the Higgs Composite
  - Little Higgs
  - Twin Higgs
- <u>Eliminate the Higgs</u>
  - Technicolor
  - "Higgsless" Models

<u>All involve strong dynamics!</u>

"Theory Space": H. Murayama

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

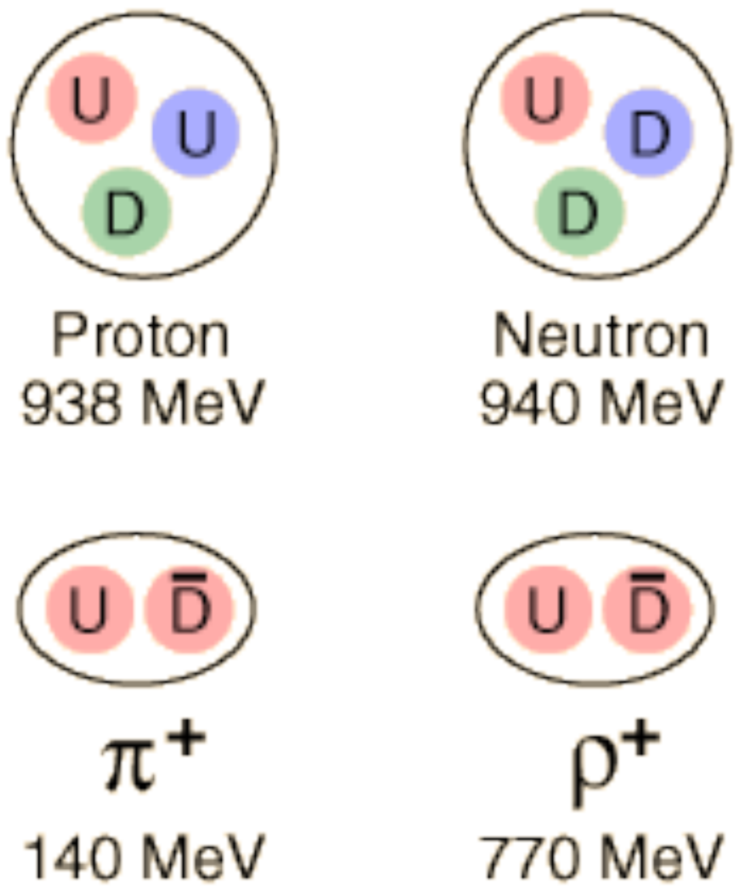
Eliminate the Higgs...

Technicolor: Higgsless since 1976!

Eliminate Scalars: Electroweak gauge symmetry broken by the nonzero expectation value of a fermion bilinear, driven by new strong interactions.

Understanding of strongly-interacting gauge theories is extremely limited $\Rightarrow$ theories constructed by analogy!

From QCD:



<u>Why is the pion so light?</u>

Just right for EWSB!

When the QCD coupling becomes strong

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

This line of reasoning inspired **Technicolor:**

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

force carriers are **techni**gluons, inspired by QCD gluons

add **techni**quarks carrying $SU(N)_{TC}$ charge:

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

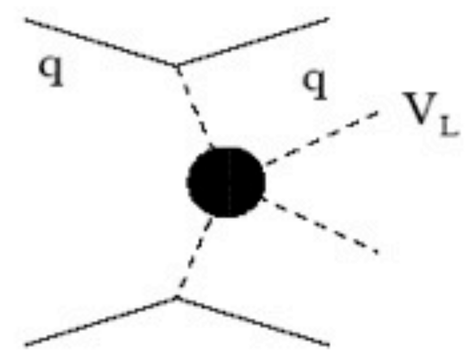
If $SU(N)_{TC}$ force were stronger than QCD ... then spontaneous symmetry breaking and pion formation would happen at a higher energy scale... e.g.

- gauge coupling becomes large at $\Lambda_{TC} \approx 1000\,\mathrm{GeV}$
- $\langle T_L T_R \rangle \approx$ -(1 TeV)^3 breaks electroweak symmetry
- `**techni**pions' Π_{TC} become the W_L, Z_L
- W and Z boson masses are the size seen in experiment!

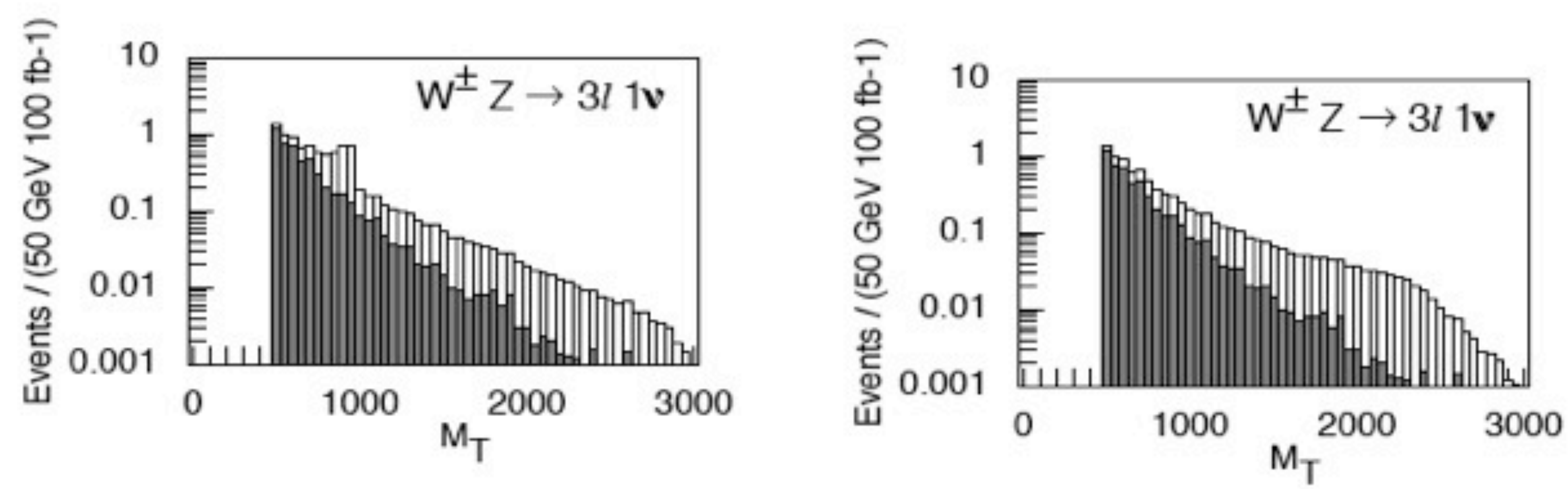
$f_\pi \to v$
$N_c \to N_{TC}$
fundamental $\to$?

Classic TC @ LHC:

Gauge-Boson Scattering:

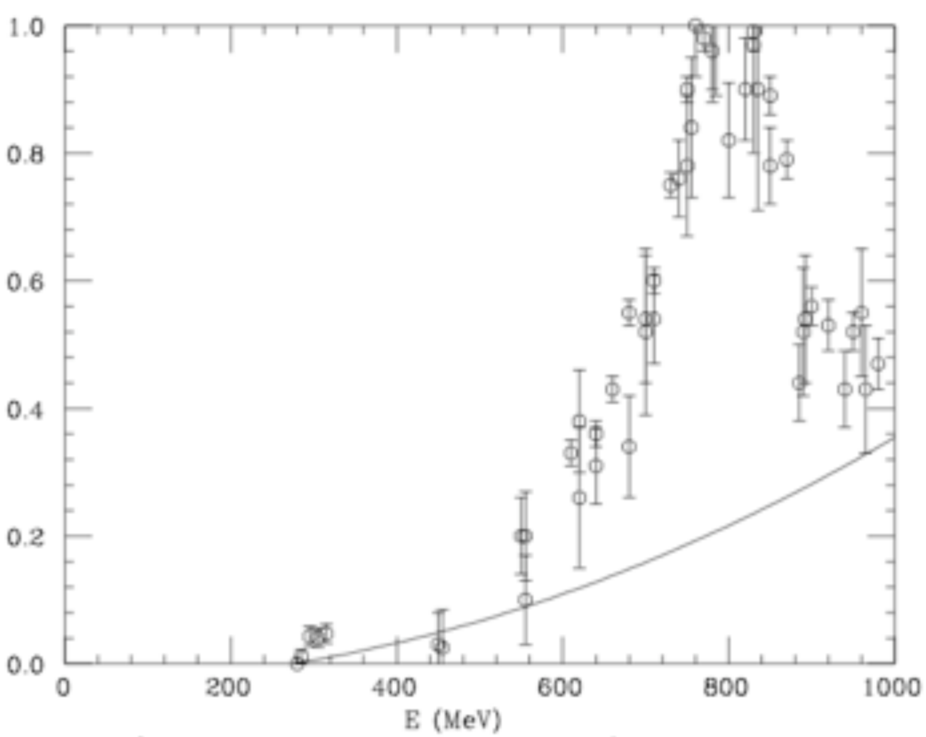


For $M_{\rho_{TC}} = 1.0$ TeV, 2.5 TeV:



NB: unlike Higgs!!

I=J=1 ππ scattering

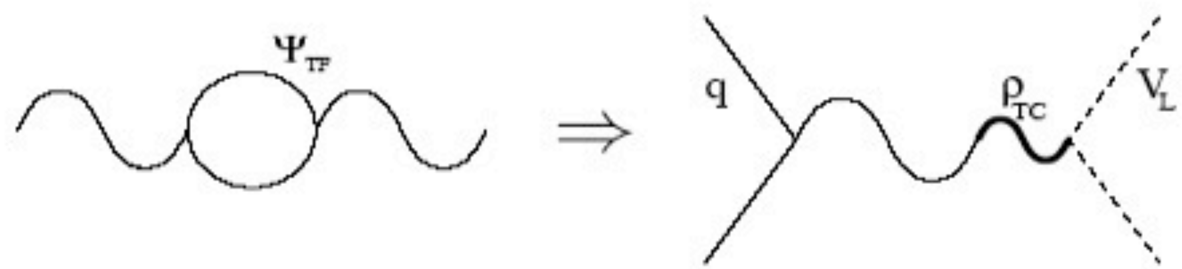


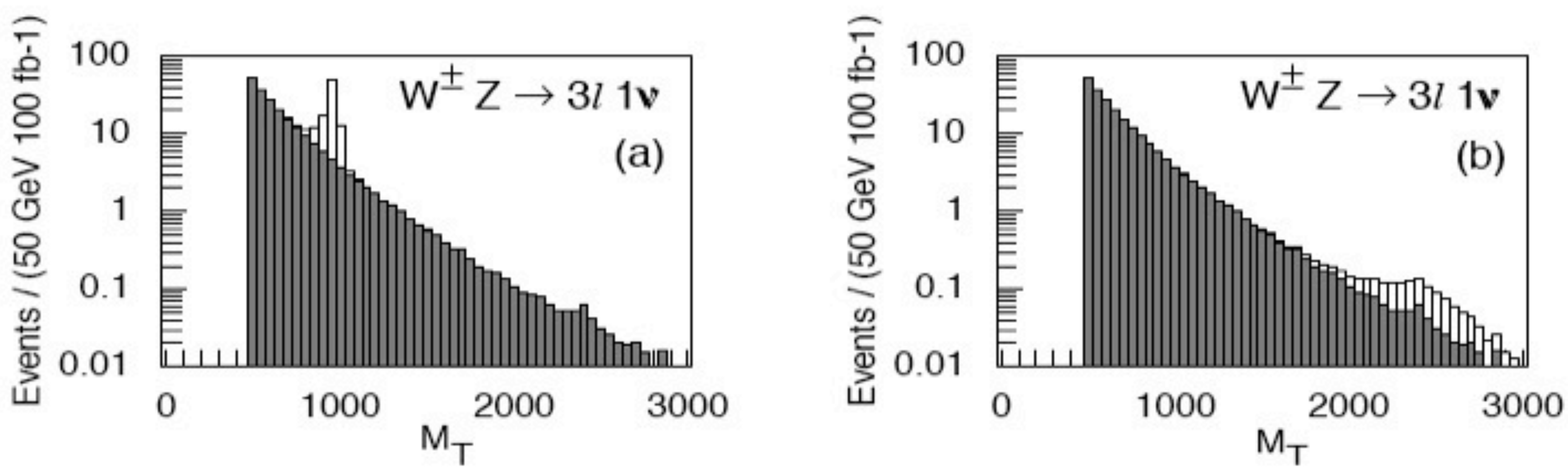
leptonic cuts	jet cuts
$\lvert y(\ell)\rvert < 2.5$	$E(j_{tag}) > 0.8$ TeV
$p_T(\ell) > 40$ GeV	$3.0 < \lvert y(j_{tag})\rvert < 5.0$
$p_T^{\text{miss}} > 50$ GeV	$p_T(j_{tag}) > 40$ GeV
$p_T(Z) > \frac{1}{4} M_T$	$p_T(j_{veto}) > 60$ GeV
$M_T > 500$ GeV	$\lvert y(j_{veto})\rvert < 3.0$

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

Classic TC @ LHC:

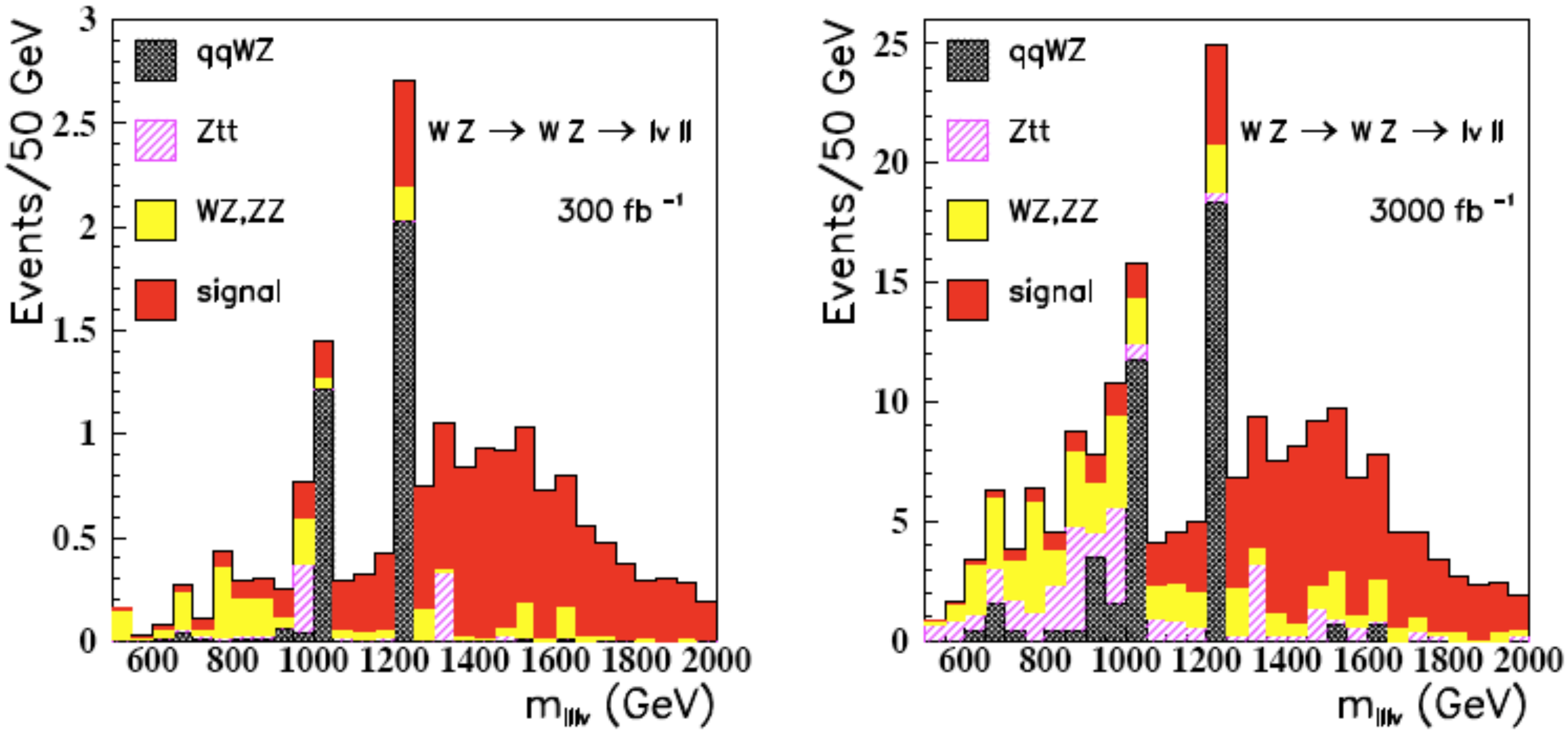
Gauge-Boson — Vector Meson Mixing:





*M. Golden, *et. al.*, hep-ph/9511206

WZ Scattering at SLHC



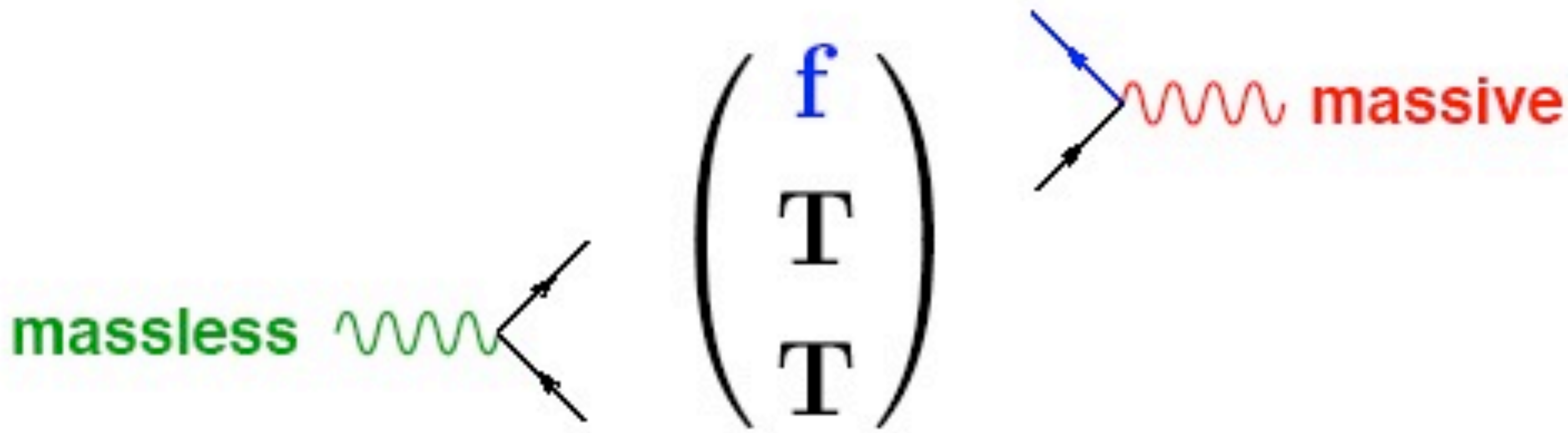
$$p_T(\ell_1) > 150 \text{ GeV}, \quad p_T(\ell_2) > 100 \text{ GeV}, \quad p_T(\ell_3) > 50 \text{ GeV}$$
$$|m(\ell_1\ell_2) - m_Z| < 10 \text{ GeV}$$
$$E_T^{miss} > 75 \text{ GeV}$$

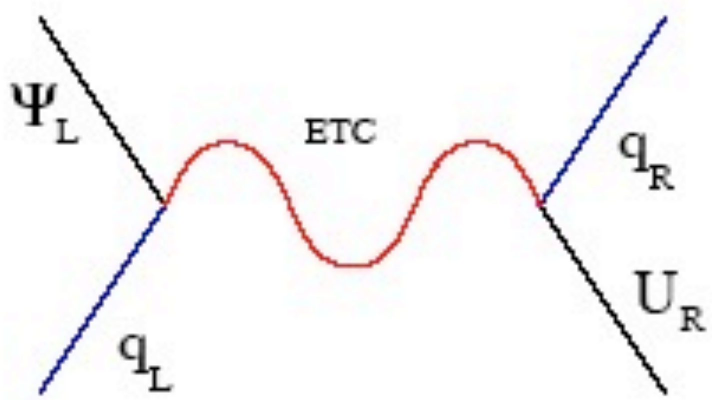
+ forward jets

F. Gianotti, et. al., hep-ph/0204087

Fermion Masses & ETC Interactions

Extended Technicolor Interactions — Connect chiral-symmetries of TFs to quarks & leptons.





$$\Rightarrow \frac{g_{ETC}^2}{M_{ETC}^2}(\overline{\Psi}_L U_R)(\overline{q}_R q_L)$$

$$m_q \approx \frac{g_{ETC}^2}{M_{ETC}^2}\langle \overline{U} U\rangle_{ETC}$$

$$\langle \overline{U}U \rangle_{ETC} = \langle \overline{U}U \rangle_{TC} \exp\left(\int_{\Lambda_{TC}}^{M_{ETC}} \frac{d\mu}{\mu} \gamma_m(\mu) \right)$$

For QCD-like TC ("precociously" asymptotically free), γ_m is small over this range:

Voodoo QCD*!

$$\langle \overline{U}U \rangle_{ETC} \approx \langle \overline{U}U \rangle_{TC} \approx 4\pi F_{TC}^3$$

$$\frac{M_{ETC}}{g_{ETC}} \approx 40\,\mathrm{TeV} \left(\frac{F_{TC}}{250\,\mathrm{GeV}} \right)^{\frac{3}{2}} \left(\frac{100\,\mathrm{MeV}}{m_q} \right)^{\frac{1}{2}}$$

*Bjorken

"Toy" ETC Model

A "Toy" Model : $SU(N_{ETC})$

$N_{ETC} = N_{TC} + N_F$

$$
\begin{array}{ll}
Q_L = (N_{ETC}, 3, 2)_{1/6} & L_L = (N_{ETC}, 1, 2)_{-1/2} \\
U_R = (N_{ETC}, 3, 1)_{2/3} & E_R = (N_{ETC}, 1, 1)_{-1} \\
D_R = (N_{ETC}, 3, 1)_{-1/3} & N_R = (N_{ETC}, 1, 1)_0
\end{array}
$$

$$
\begin{array}{ccc}
 & SU(N_{TC}+3) & \\
\Lambda_1 & \downarrow & m_1 \approx \frac{4\pi F^3}{\Lambda_1^2} \\
 & SU(N_{TC}+2) & \\
\Lambda_2 & \downarrow & m_2 \approx \frac{4\pi F^3}{\Lambda_2^2} \\
 & SU(N_{TC}+1) & \\
\Lambda_3 & \downarrow & m_3 \approx \frac{4\pi F^3}{\Lambda_3^2} \\
 & SU(N_{TC}) &
\end{array}
$$

$$[G_{ETC}, SU(3)_C] = [G_{ETC}, SU(2)_W] = 0$$

"One-Family": $SU(8)_L \times SU(8)_R \to SU(8)_V$

Results in three isospin-symmetric families of degenerate quarks and leptons, $m_1 < m_2 < m_3$.

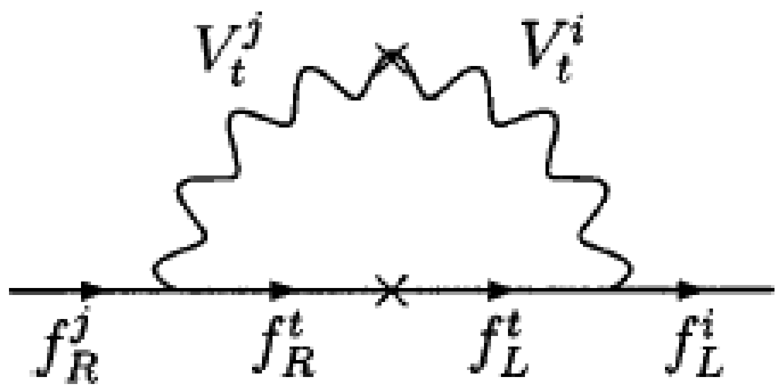
Shortcomings of this toy model:

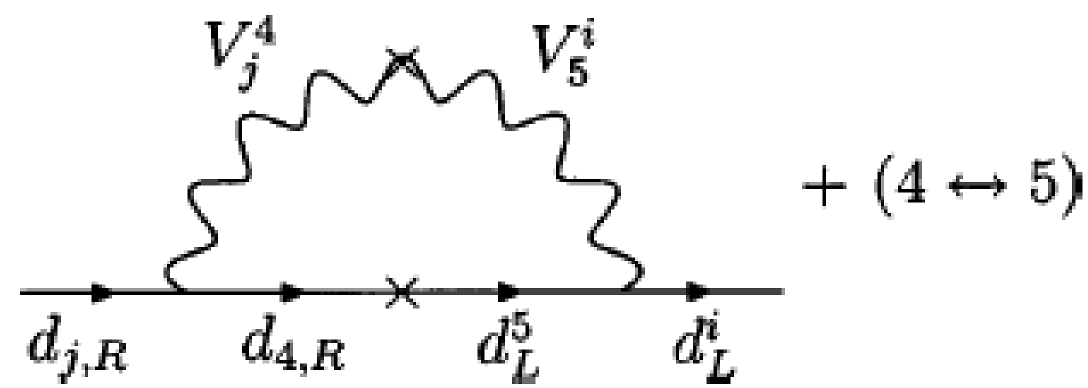
- What breaks ETC?
- Need a separate scale for each family.
- All quark (& lepton) mixing angles zero.
- $T_3 = \pm\frac{1}{2}$ fermions have equal masses.
  u_R & d_R must be in different representations of ETC.
- RH-technineutrinos $\Rightarrow$ RH-ν's, $m_\nu \neq 0$.

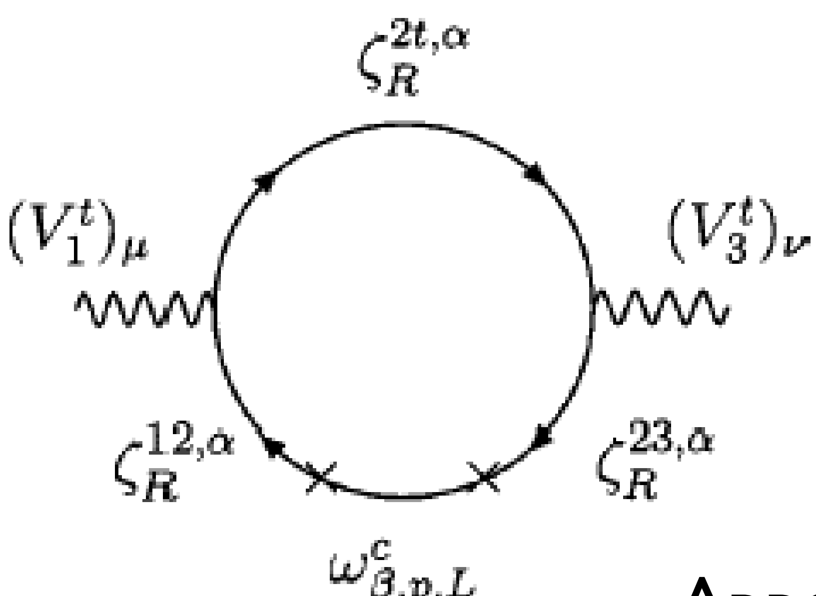
Mixing $\Rightarrow$

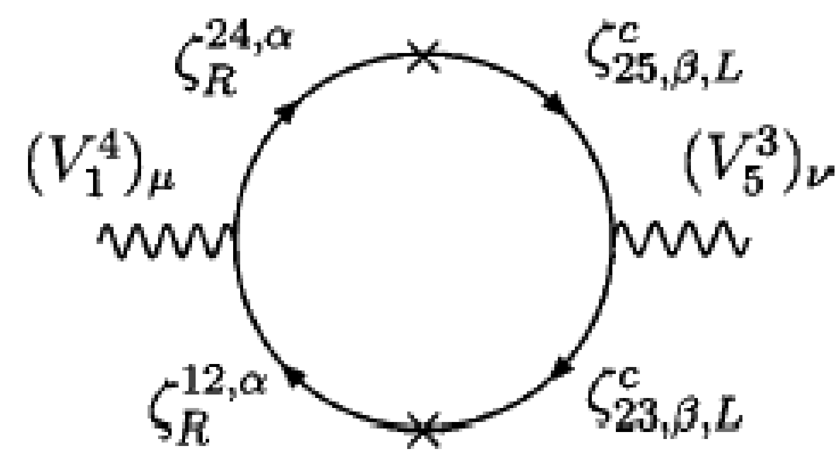
Nontrivial flavor structure!

ETC & Fermion Mixing?









Appelquist, Shrock, Piai
hep-ph/0308061 and references therein
Can include some GIM-like suppression?

Goal:

Can we construct a TC theory *into which* a theory of flavor can safely* be inserted?

*Assuming *no* GIM-like FCNC suppression

FCNCs and Walking Technicolor

Quark mixing implies transitions between different generations: $q \to \Psi \to q'$. ETC algebra:

$$[\bar{q}\gamma\Psi, \bar{\Psi}\gamma q'] \supset \bar{q}\gamma q' \,.$$

$|\Delta S| = 2$ interactions:

$$\mathcal{L}_{|\Delta S|=2} = \frac{1}{\Lambda^2} \; (\bar{s}\Gamma^{\mu} d) \; (\bar{s}\Gamma'_{\mu} d) + \text{h.c.}$$

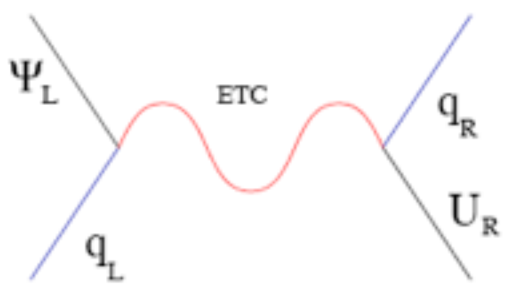
Bounds on FCNCs

Bound on operator coefficient (GeV^{-2})	Implied lower limit on ETC scale (10^3 TeV)
$-9.6 \times 10^{-13} < \Re(C_K^1) < 9.6 \times 10^{-13}$	1.0 $K^0 - \bar{K}^0$
$\lvert C_D^1 \rvert < 7.2 \times 10^{-13}$	1.5 (!) $D^0 - \bar{D}^0$
$\lvert C_{B_d}^1 \rvert < 2.3 \times 10^{-11}$	0.21 $B_d^0 - \bar{B}_d^0$
$\lvert C_{B_s}^1 \rvert < 1.1 \times 10^{-9}$	0.03 $B_s^0 - \bar{B}_s^0$
$-4.4 \times 10^{-15} < \Im(C_K^1) < 2.8 \times 10^{-15}$	10

UFit Collaboration: JHEP 0803, 049 (2008)

"Walking Technicolor"

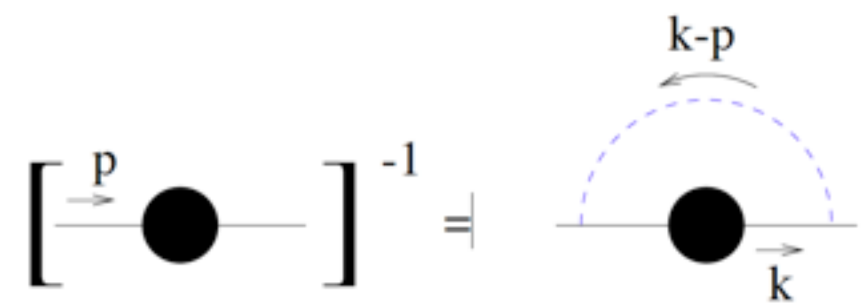
Extended Technicolor Interactions — Connect chiral-symmetries of TFs to quarks & leptons.



$$\Rightarrow \quad \frac{1}{\Lambda^2}\,(\overline{\Psi}_L U_R)(\overline{q}_R q_L)$$

If β_{TC}~0, we expect γ_m~1, enhancing fermion masses.

$$m_q \approx \frac{1}{\Lambda^2}\,\langle \overline{U}U\rangle_{ETC}$$



$$\langle \overline{U}U\rangle_{ETC} = \langle \overline{U}U\rangle_{TC} \exp\left(\int_{\Lambda_{TC}}^{M_{ETC}} \frac{d\mu}{\mu}\gamma_m(\mu)\right)$$

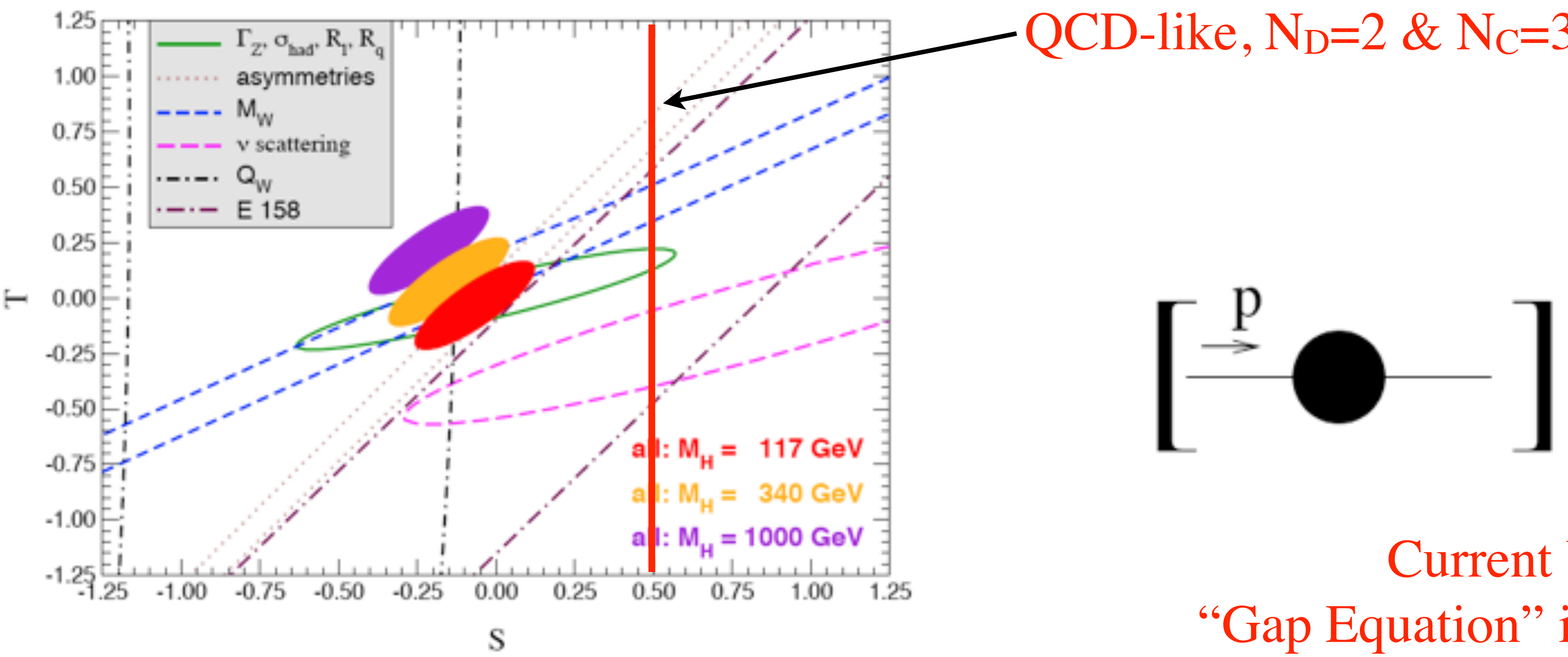
Voodoo QCD!

A realistic (E)TC model will not be like QCD!

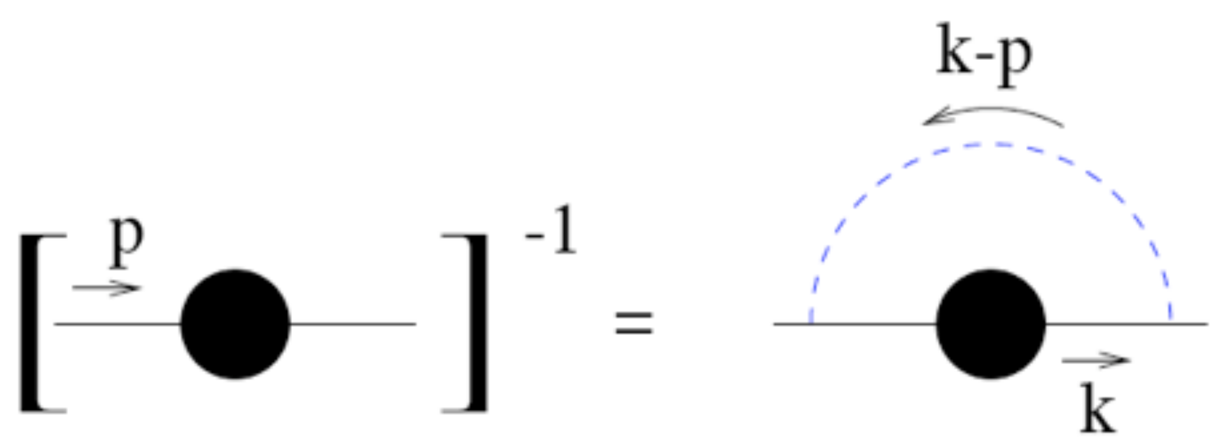
Holdom, Yamawaki et. al., Appelquist and Wijewardana

Does $\gamma_m = 1$ in a walking theory?

- Chiral symmetry breaking in an approximately conformal theory
- Large anomalous dimension of $\bar{\psi}_L \psi_R$
- Can we calculate α*S*?
- What is the spectrum? PNGB masses?



PDG2006: Erler and Langacker



Current Understanding from
"Gap Equation" in "Rainbow Approximation"

A Model Builder's Dream:

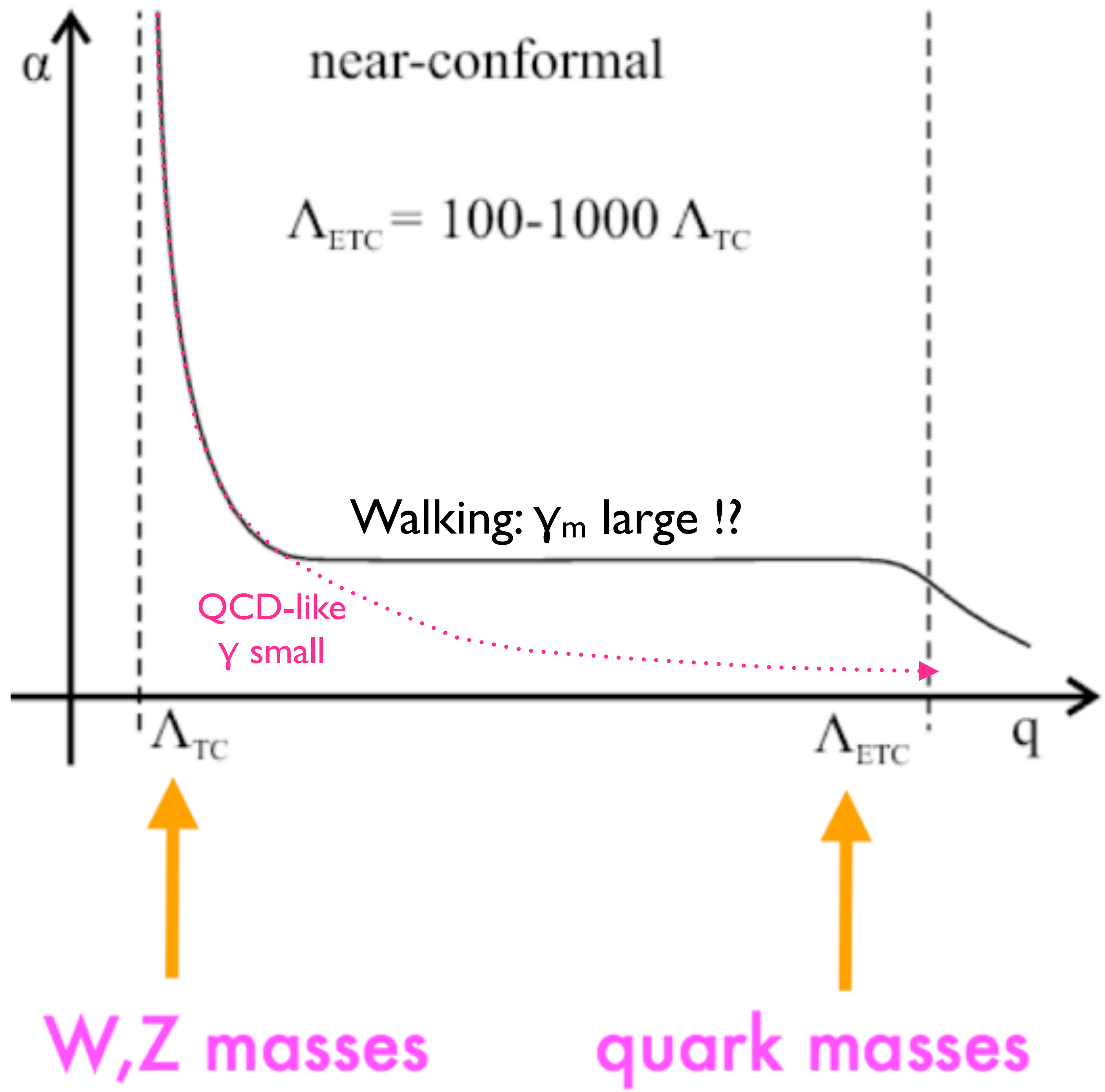


Figure: K. Holland XQCD 2008

Quark Masses from ETC Operators†

Region of interest for charm and strange!

"Gauge-NJL" Models, top?

γ_m	0	0.25	0.5	0.75	1.0	1.25	1.5	1.75	2.0
m_q^{NDA}	0.2 MeV	0.8 MeV	3.5 MeV	15 MeV	63 MeV	260 MeV	1.1 GeV	4.7 GeV	20 GeV
m_q^{DA}	1 MeV	5.6 MeV	32 MeV	180 MeV	1 GeV	5.6 GeV	32 GeV	180 GeV	1 TeV

current lattice studies*

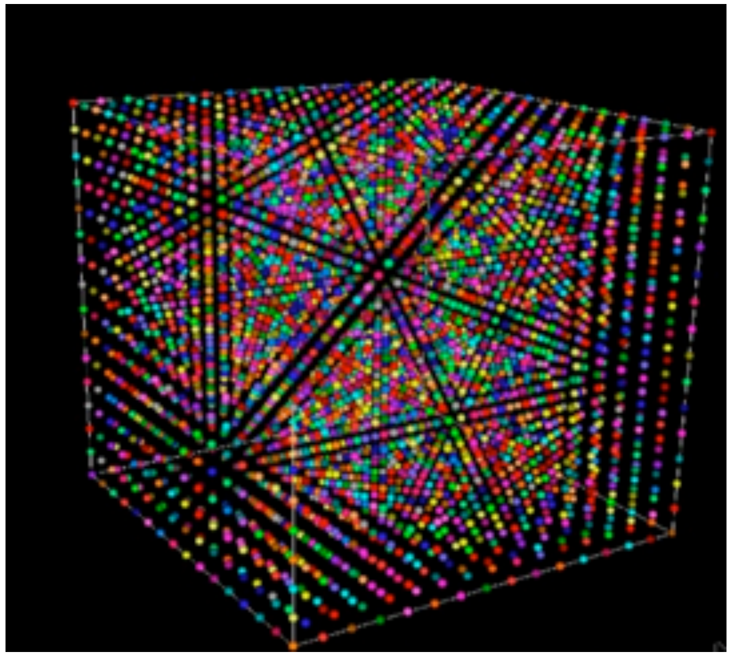
$$\Lambda_{ETC} \simeq 10^3 \text{ TeV}$$

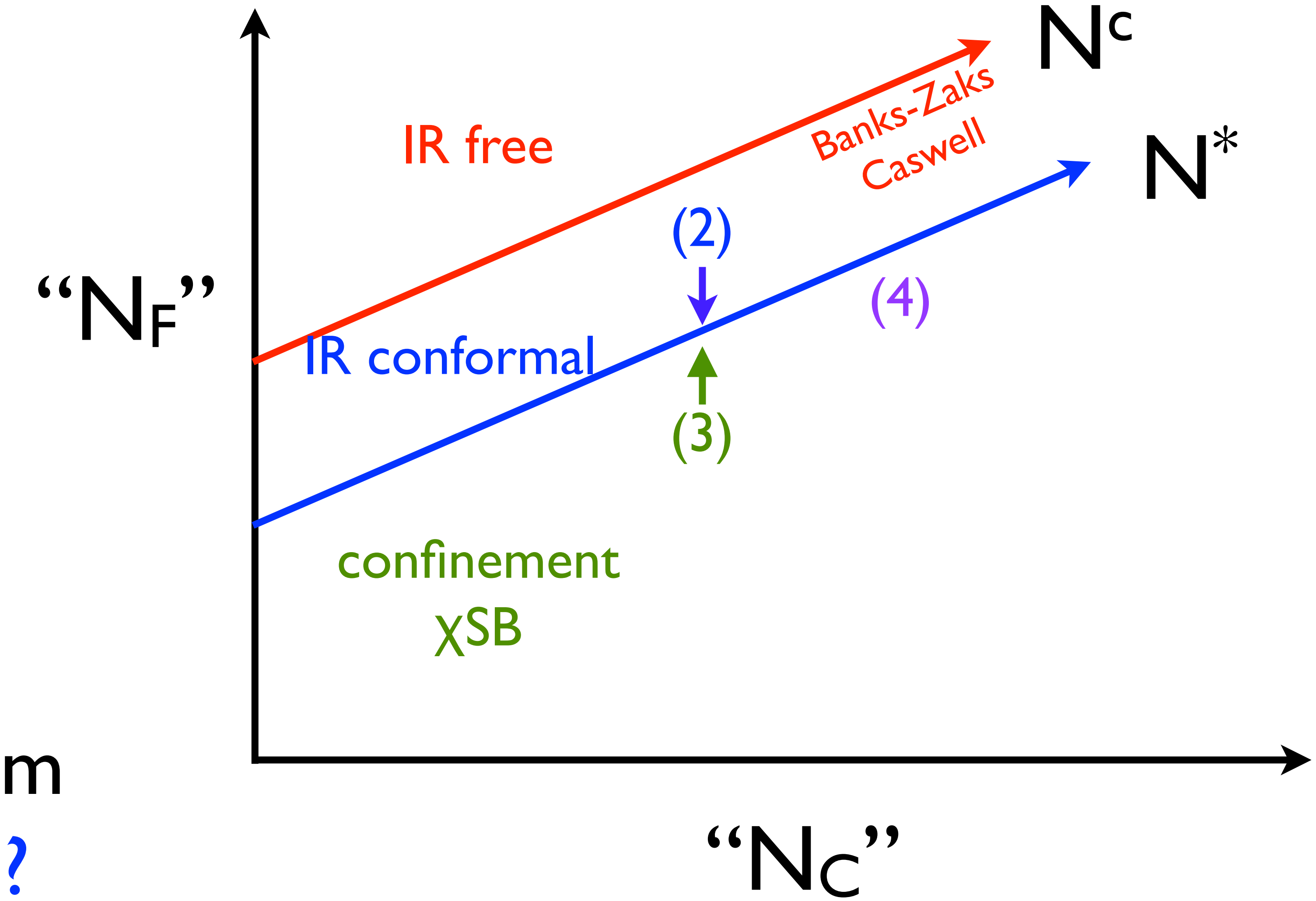
†Assuming *no* GIM-like FCNC suppression

RSC and E. Simmons: arXiv 1005.5727 [hep-lat]

*See talk by Del Debbio

Lattice TC Questions





(1) Establish Phase Diagram

(2) What is γ_m? Near 1? 2?

(3) What is S? The spectrum?

  (1)Is there a 0^{++} (pseudo-dilaton, Higgs-like)state?

(4) Other marginal/relevant operators?

  (1)Strong-ETC and "Gauge-NJL" model

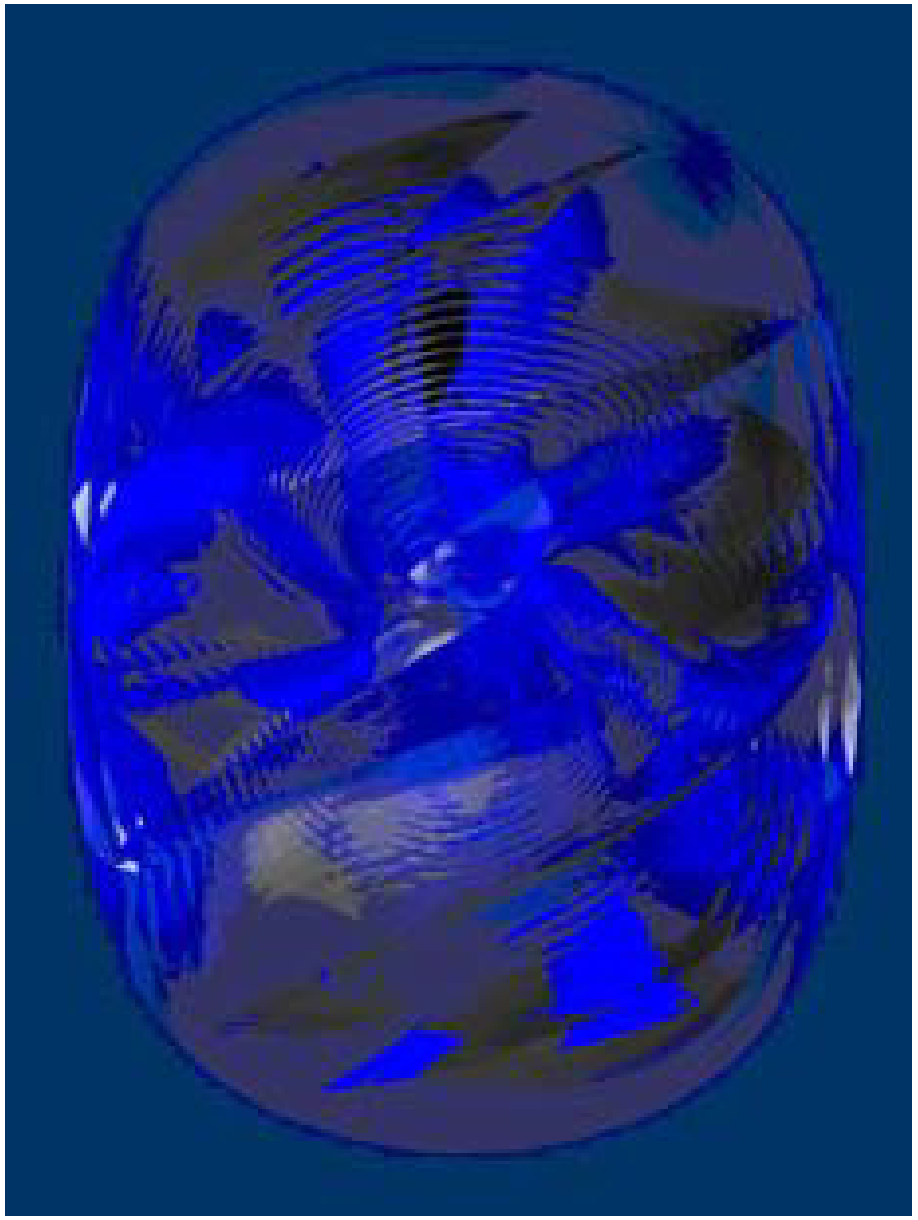
Conclusions:
EWSB Theory Summary

Theory	WW Scattering	Hierarchy Problem	"Calculable" @ LHC?	Precision EW	Λ_{UV}
Fundamental Higgs	I=J=0	YES!	✔	✔	1 TeV - M_{GUT}
SUSY	I=J=0	No	✔	✔	M_{GUT}?
Composite Higgs	I=J=0	No	✔	f > 5 TeV	50 TeV
Higgsless	I=J=1	No	✔	Ideal fermions	10 TeV
Technicolor	I=J=1	No	??	Non-QCD	few TeV

Help needed in <u>all</u> theories!

This talk

One thing we didn't talk about: TOP



Top interacting with Higgs Boson
Prof. Jan-Henrik Andersen,
University of Michigan

Thanks to...

- Elizabeth Simmons
- Tom Appelquist, Simon Catterall, Tom DeGrand, Luigi Del Debbio, Ken Lane, Francesco Sannino, Bob Shrock, Ben Svetitsky, Rohana Wijewhardana
- All the participants in the “Strong Dynamics Beyond the Standard Model” workshop at the Aspen Center for Physics, this summer.