Beyond the SM at a Hadron Collider

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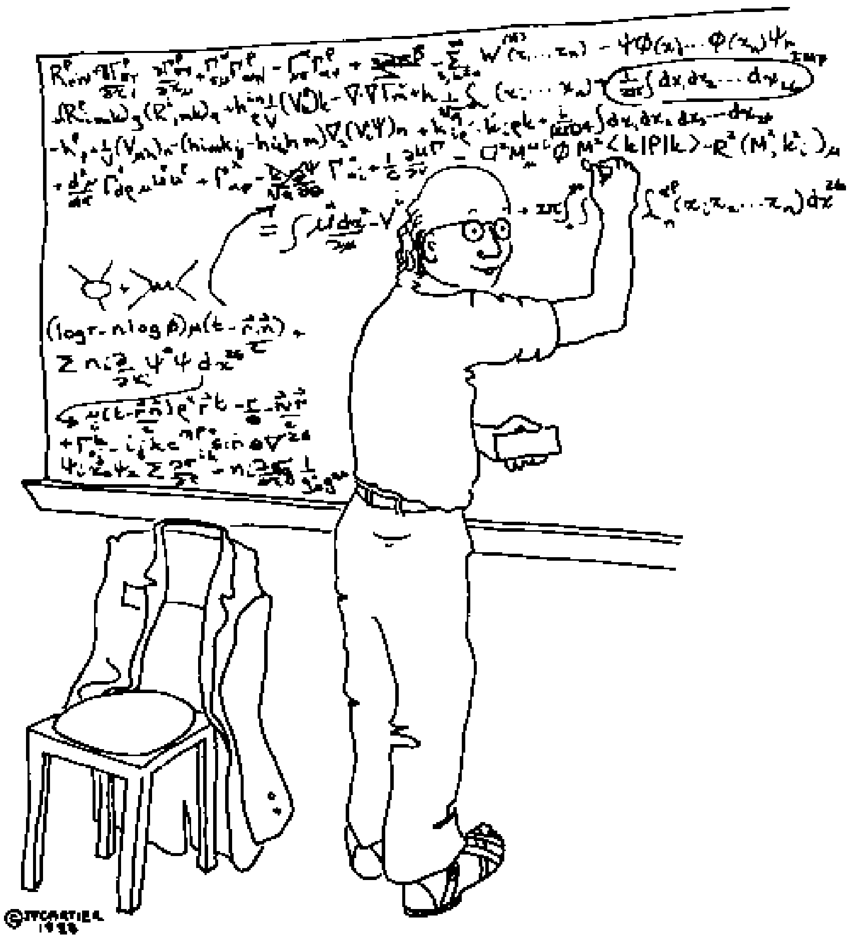
Maria Laach School, 2004

Lecture 4

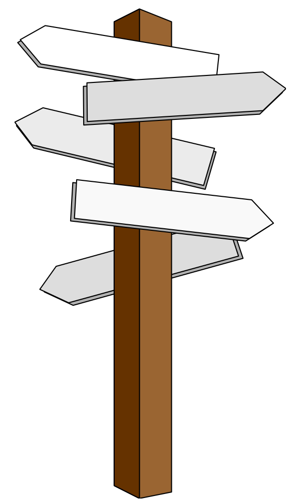
- Why go beyond the SM?
- What is unitarity telling us?
- The SM as an effective low energy theory
- Specific examples
  - SUSY (See Peskin's lectures)
  - Strongly interacting WW interactions
  - Little Higgs
  - Extra dimensions
  - Technicolor

How do we know where to go?



"At this point we notice that this equation is beautifully simplified if we assume that space–time has 92 dimensions."

Precision measurements versus direct observation of new particles



Much easier if we see new particles

SM is incomplete

- ***No mechanism for neutrino mass in SM***
  - ***Dirac Neutrino mass term has form:***

$$L = -\frac{m_f}{v}\left(\bar{f}_L f_R + \bar{f}_R f_L\right)h$$

No ν_R in SM

- Simplest Majorana neutrino mass term (dimension 5): $\frac{C}{\Lambda} hLhL \approx \frac{Cv^2}{\Lambda} (\bar{\nu}_L)^c \nu_L$
  - Majorana mass term violates lepton number

- Suppose $m_\nu < 1$ eV: $\Lambda = C\frac{2v^2}{m_\nu} \geq C(10^{14}\ GeV)$

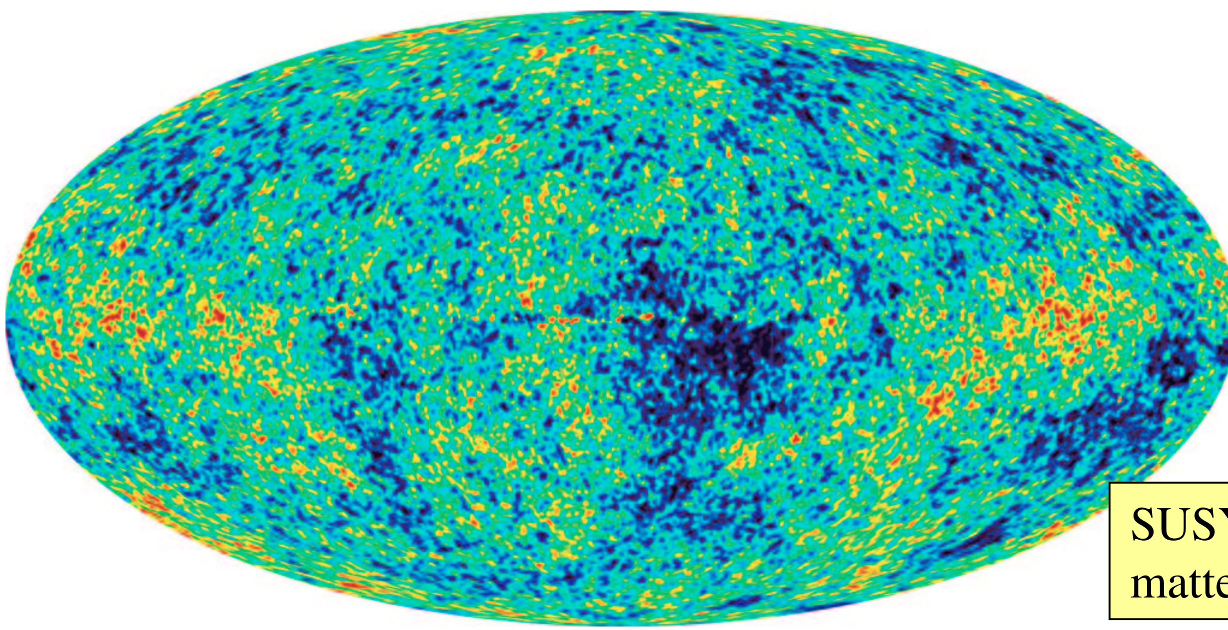
The smaller the fermion masses, the larger the new physics scale is!

SM is incomplete

- 23% of universe is cold dark matter:

$\Omega_{CDM}h^2 = .1126\,^{+.0161}_{-.0181}$

No dark matter candidate in SM

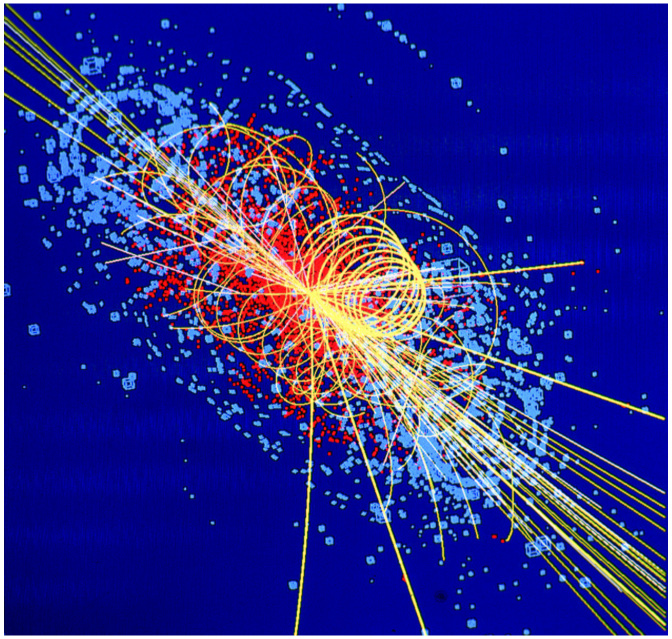


SUSY has dark matter candidate

SM is incomplete

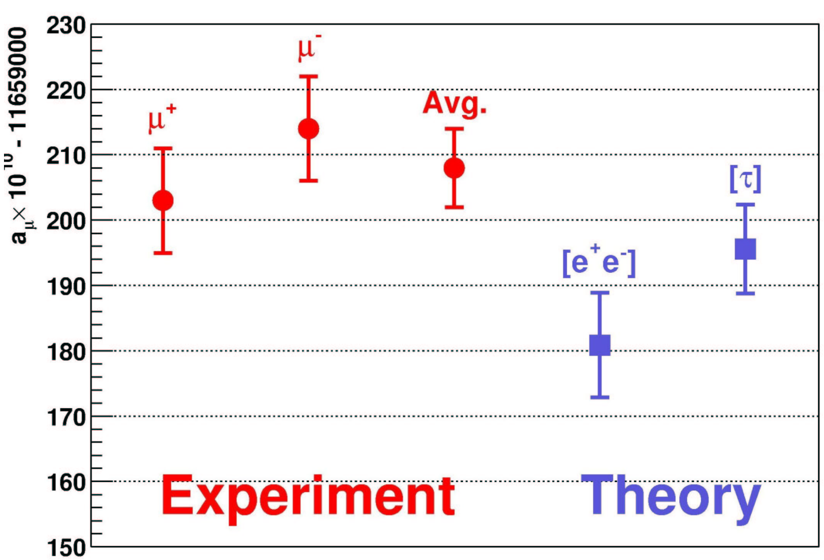
- We haven't found the Higgs boson
  - Even when we find it, we won't understand why $M_W << Mpl$
  - We won't understand why fermion masses have the values they do…..Why is $M_t >> M_b$? Why are neutrino masses so small?
  - We won't understand why there are 3 generations
  - Corrections to Higgs mass quadratically sensitive to higher mass scales

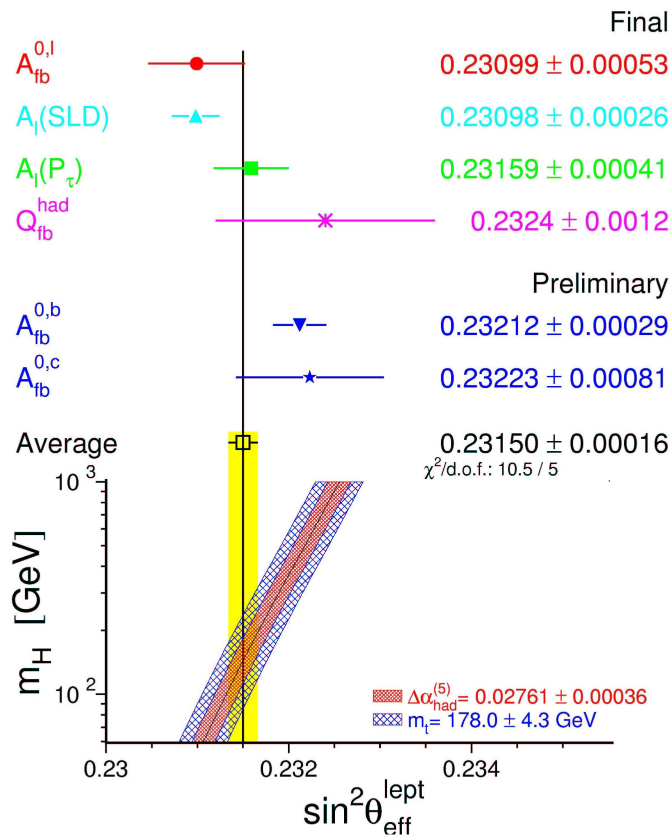
Higgs at LHC



The SM isn't perfect

$(g\text{-}2)_\mu$





Possibilities at the LHC

- We find a light Higgs with SM couplings and nothing else
  - How to answer our questions?
- We find a light Higgs, but it doesn't look SM like
  - Most models (SUSY, Little Higgs, etc) have other new particles
- We don't find a Higgs (or any other new particles)
  - How can we reconcile precision measurements?
  - This is the hardest case

SM with $M_h \to \infty$

Example $h \to W^+W^-$

$\Gamma(h \to W^+W^-)$ grows with M_h^3

- From $D_\mu \varphi^+ D_\mu \varphi$:

$$\frac{1}{2}\left(\frac{g^2}{2}W_\mu^+ W^{-\mu}(v+h)^2 + \frac{g^2}{4\cos^2\theta_W}Z_\mu Z^\mu (v+h)^2\right)$$

- $h \to W^+W^-$ has the matrix element: $A(h \to W^+W^-) = \frac{g^2 v}{2}\varepsilon_+^* \varepsilon_-^*$
- Polarization sum:

$$\sum \varepsilon_{+\mu}^* \varepsilon_{+\nu}^* = -g_{\mu\nu} + \frac{p_\mu^+ p_\nu^+}{M_W^2}$$

- Matrix element squared:

$$\left|A(h \to W^+W^-)\right|^2 = \frac{g^2}{4M_W^2}\left(1 - 4\frac{M_W^2}{M_h^2} + 12\frac{M_W^2}{M_h^2}\right)$$

$$\Gamma(h \to W^+W^-) = \frac{1}{2M_h^2}|A|^2 \frac{\beta_W}{8\pi}$$

$$\approx \frac{M_h^3}{8\pi}\frac{G_F}{\sqrt{2}}$$

Leading piece is longitudinal W's

SM and Goldstone Bosons

- Rewrite SM Higgs doublet in terms of Goldstone bosons, $\omega_i = \omega^\pm, z$ (which become longitudinal components of W,Z)

$$\Phi = \frac{1}{\sqrt{2}} e^{i\omega_i \sigma_i / v} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

- Scalar potential give interactions of Higgs-Goldstone bosons

$$V = \frac{M_h^2}{2v} h\left(h^2 + z^2 + 2\omega^+\omega^+\right) + \frac{M_h^2}{8v^2}\left(h^2 + z^2 + 2\omega^+\omega^+\right)^2$$

- Compute $h \to \omega^+\omega^-$

$$\Gamma(h \to \omega^+\omega^-) = \frac{M_h^3}{8\pi} \frac{G_F}{\sqrt{2}}$$

Amplitudes which grow with M_h connected to Goldstone Bosons and EWSB

General result: Electroweak equivalence theorem

$$A(V_L^1 \ldots . V_L^n \to V_L^1 \ldots . V_L^{n'}) = (i)^n (-i)^{n'} A(\omega_1 \ldots . \omega_n \to \omega_1 \ldots . \omega_{n'}) + O\left(\frac{M_V}{E}\right)$$

Unitarity

- Strongly constrains SM and new physics models
- Consider 2→2 elastic scattering

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}|A|^2$$

- Partial wave decomposition

$$A = 16\pi \sum_{l=0}^{\infty} (2l+1) P_l(\cos\theta) a_l$$

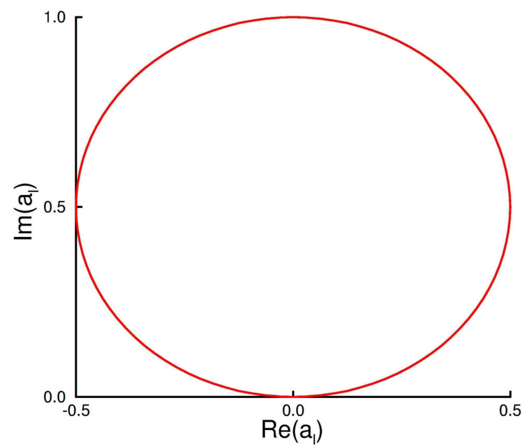
- a_l are the spin l partial waves
- $P_l(\cos\theta)$ are Legendre polynomials $\int_{-1}^{1} dx P_l(x) P_{l'}(x) = \frac{2\delta_{l,l'}}{2l+1}$

$$\sigma = \frac{8\pi}{s} \sum_{l=0}^{\infty} (2l+1) \sum_{l'=0}^{\infty} (2l'+1) a_l a_{l'}^* \int_{-1}^{1} d\cos\theta P_l(\cos\theta) P_{l'}(\cos\theta)$$
$$= \frac{16\pi}{s} \sum_{l=0}^{\infty} (2l+1)^2 |a_l|^2$$

Unitarity, continued

- Optical theorem:
- Unitarity requirement
  - Partial waves sit on Argand diagram $|a_l|^2 < \frac{1}{2}$
- Idea: Use unitarity to limit theory
- Interesting channels are $W_L^+W_L^-$, Z_LZ_L, hZ_L,hh
  - We have already seen that these grow with M_h

$$\sigma = \frac{1}{s}\mathrm{Im}[A(\theta=0)] = \frac{16\pi}{s}\sum_{l=0}^{\infty}(2l+1)|a_l|^2$$



Unitarity, continued

- If unitarity bound is respected:
  - Weak interactions weak at all energy and perturbation theory valid
- If unitarity bound is violated:
  - Perturbation theory breaks down and weak interactions become strong

New EW physics at the TEV scale

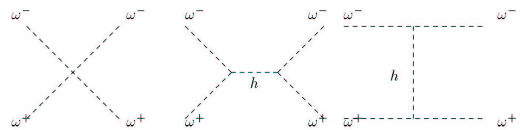
How do we know this is TeV Scale?

Unitarity, New Physics, and WW Scattering

$W_L W_L$ scattering amplitudes can be found from Goldstone Boson scattering up to corrections $O(v^2/s)$

- $\omega^+\omega^- \to \omega^+\omega^-$

$$iA(\omega^+\omega^- \to \omega^+\omega^-) = \left(\frac{-iM_h^2}{v}\right)^2 \frac{i}{s-M_h^2} + \left(\frac{-iM_h^2}{v}\right)^2 \frac{i}{t-M_h^2} - \frac{2iM_h^2}{v^2}$$
$$= \frac{-iM_h^2}{v^2}\left(\frac{s}{s-M_h^2} + \frac{t}{t-M_h^2}\right)$$



- Two interesting limits:
  - $s >> M_h^2$ $\quad A(\omega^+\omega^- \to \omega^+\omega^-) = -2M_h^2/v^2$
  - $s << M_h^2$ $\quad A(\omega^+\omega^- \to \omega^+\omega^-) = -u/v^2$
- Compute J=0 partial wave:
  - $s >> M_h^2$ $\quad \left|a_0(\omega^+\omega^- \to \omega^+\omega^-)\right| \to \frac{M_h^2}{8\pi v^2}$
  - $s << M_h^2$ $\quad \left|a_0(\omega^+\omega^- \to \omega^+\omega^-)\right| \to \frac{s}{32\pi v^2}$

Interpreting J=0 Partial Waves

- Require perturbative unitarity, $a_0 < 1/2$
  - If we remove the Higgs from the theory, $M_h^2 >> s$, then

$$a_0 < \frac{1}{2} \quad \Rightarrow \quad s < 4v\sqrt{\pi} \approx 1.8 TeV$$

  - Origin of statement: ***"There must be new physics at the TeV scale"***
  - On the other hand, if $s >> M_h^2$, perturbative unitarity requires:

$$M_h < 2v\sqrt{\pi} \approx 900\ GeV$$

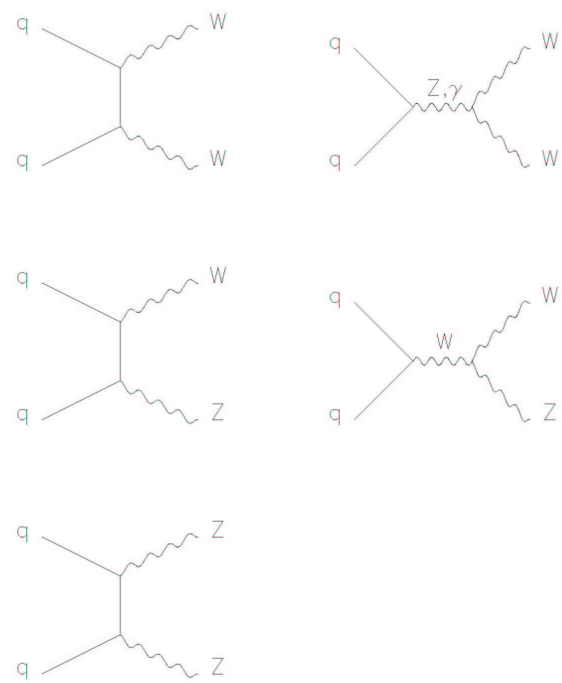
  - Similar upper bounds on M_h from lattice gauge theory

No lose theorem: Either we find a light Higgs or we find new physics at the TeV scale *

* Clever theorists can of course evade this bound

Gauge Boson Pair Production sensitive to New Physics

- W^+W^-, $W^\pm\gamma$, etc, production sensitive to new physics
- Expect effects which grow with energy
  - $A_t \sim (\ldots)(s/v^2)+O(1)$
  - $A_s \sim -(\ldots)(s/v^2)+O(1)$
  - $\sigma_{TOT} \sim O(1)$
- Interesting angular correlations: eg, $W^\pm\gamma$, has radiation zero at LO



Remember $e^+e^- \rightarrow W^+W^-$

Non-SM 3 gauge boson couplings spoil unitarity cancellation

Consider Non-SM W^+W^-V Couplings

- Most general gauge and Lorentz invariant couplings with C and P separately conserved

$$\frac{L_{VWV}}{-ig_V} = g_1^V (W^+_{\mu\nu} W^{-\mu} V^\nu - W^+_\mu V_\nu W^{-\mu\nu}) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}$$

- Where V=Z,γ
  - λ_V higher order in derivative expansion (often ignored)
  - SM: $\kappa_\gamma=\kappa_Z=g_1^Z=g_1^\gamma=1$, $\lambda_V=0$
  - EM gauge invariance requires$\Delta g_1^\gamma=0$
- Often assume $SU(2)_c$ and neglect higher dimension operators
  - $g_1^Z= \kappa_Z + \tan^2\theta_W \Delta\kappa_\gamma$
  - $\lambda_V= \lambda_\gamma$

A model of BSM will specify these anomalous couplings

What size effects can we hope to see?

- NLO corrections to W^+W^- known
- Can hope to see small BSM effects
  - At the Tevatron: $p\bar{p} \to W^+W^- \to e^+e^- p_T^{miss}$

$p_T^e > 20 GeV$

$|\eta_e| < 2.5, |\eta_e| < 2.5,$

$p_T^{miss} > 20 GeV$

$p_T(jet) > 20 GeV$

Theory →

$$\sigma_{LO} = 62\, fb$$
$$\sigma_{NLO} = 82\, fb$$

- With Non-SM couplings:

$\Delta g_1^Z = .5, \lambda_Z = \lambda_\gamma = .1, \Delta\kappa_Z = \Delta\kappa_\gamma = .3$

$$\sigma_{LO} = 83\, fb$$
$$\sigma_{NLO} = 107\, fb$$

Tevatron sensitive to new physics!

Three Gauge Boson Couplings

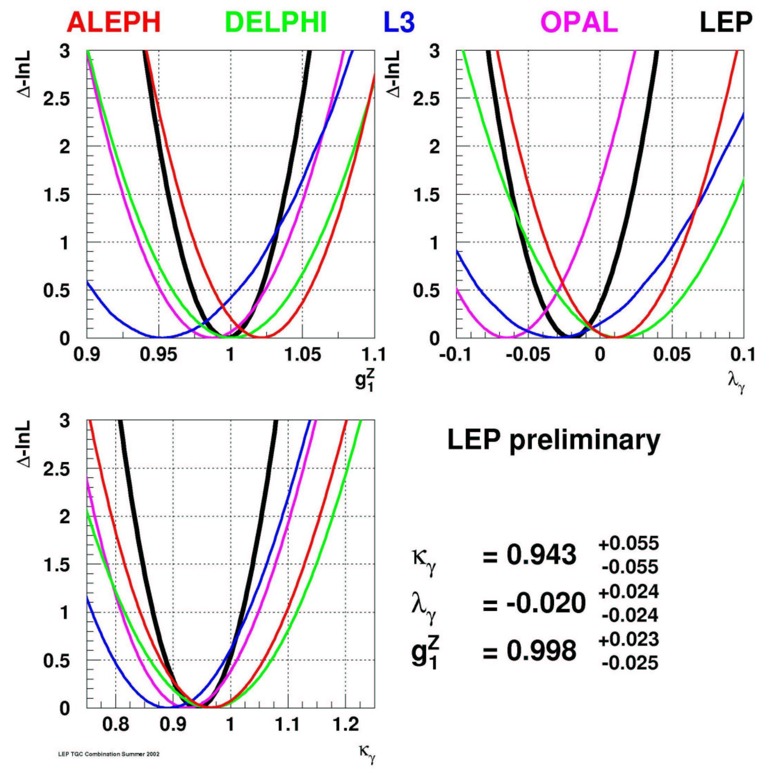
D0 Run I 95% CL limits
from WW/WZ →μνjj

95% C.L. Limits	$\Lambda_{FF} = 1.5$ TeV
$\lambda_\gamma = \lambda_Z \ (\Delta\kappa_\gamma = \Delta\kappa_Z = 0)$	-0.45, 0.46
$\Delta\kappa_\gamma = \Delta\kappa_Z \ (\lambda_\gamma = \lambda_Z = 0)$	-0.62, 0.78
λ_γ(HISZ) $(\Delta\kappa_\gamma = 0)$	-0.44, 0.46
$\Delta\kappa_\gamma$(HISZ) $(\lambda_\gamma = 0)$	-0.75, 0.99

Limits aren't yet in interesting range!

D0, hep-ex/9903038

From LEPII



LEP EWWG

WW scattering at LHC

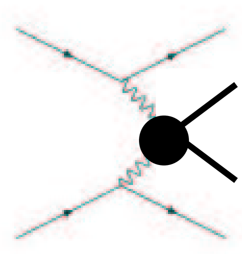
- Four gauge boson interactions sensitive to unitarity violating physics (Vector boson fusion)
- Look for W^+W^-, ZZ, Zγ, Wγ pair production in vector boson fusion
- Remove the Higgs boson from the theory

$$\Sigma = e^{i\omega_i\sigma_i/v} \qquad D_\mu\Sigma = \partial_\mu\Sigma + ig\frac{\sigma_i}{2}W_\mu^i\Sigma - ig'\Sigma\frac{\sigma_3}{2}B_\mu$$

- Effective SU(2) x U(1) low energy theory containing gauge bosons and Goldstone Bosons

$$L = \frac{v^2}{4}Tr\left(D_\mu\Sigma D^\mu\Sigma^+\right)$$

- This is SU(2) x $U(1)_{SM}$ with $M_h \rightarrow \infty$
  - Reproduces gauge boson masses and interactions
  - Violates unitarity
- Consistent expansion in powers of s/v^2



V=W,Z,γ

WW Scattering without a Higgs

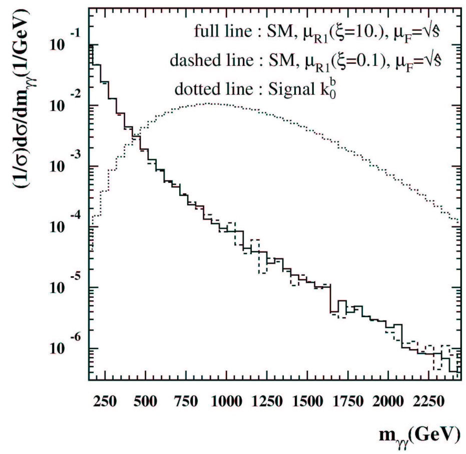
- Add terms of $O(s^2/v^4)$ to effective L

$$L = \ldots + L_1\left(Tr\left(D_\mu \Sigma D^\mu \Sigma^+\right)\right)^2 + L_2\left(Tr\left(D_\mu \Sigma D^\nu \Sigma^+\right)\right)^2 + \ldots.$$

  - This Lagrangian violates unitarity
  - n derivative vertex $\approx E^n/\Lambda^{n-4}$
- This is counting experiment (no resonance)
  - Example: Search for anomalous WW$\gamma\gamma$ vertex through gauge boson fusion

Hard!

LHC



Normalized to show difference in shape of signal and background

Eboli et al, hep-ph/0310141

But don't precision measurements require a light Higgs?

- Higgs mass limits from precision measurements assume SM
  - Loop effects calculated assuming SM is valid at all energy scales
  - Suppose the SM is effective low energy theory valid to scale Λ

$$L = L_{SM} + \sum \frac{c_i}{\Lambda^2} O_i^6 + \ldots..$$

  - Include all operators allowed by SU(3) x SU(2) x U(1) gauge symmetry (and assume a light Higgs)
  - Leading operators which are important for Higgs and EW physics:

$$\frac{c_1}{\Lambda^2}\left\{\left[D_\mu, D_\nu\right]\phi\right\}^+\left[D^\mu, D^\nu\right]\phi + \frac{c_2}{\Lambda^2}\left(\varphi^+ \overleftrightarrow{D}^\mu \phi\right)\left(\varphi^+ \overleftrightarrow{D}_\mu \phi\right)$$

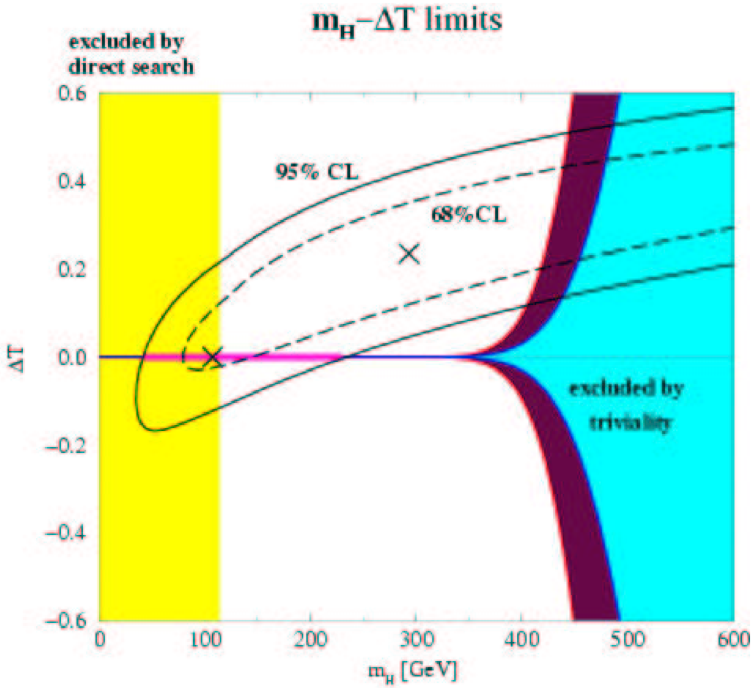
  - Include effects of new operators in fits

$$\delta\rho = \alpha\Delta T = \frac{2c_2 v^2}{\Lambda^2}$$

Higgs can be heavy with new physics

- $M_h \approx$ 450-500 GeV allowed with large isospin violation, ΔT

Constructing actual models with this feature is hard



•Chivukula, Holbling, hep-ph/0110214

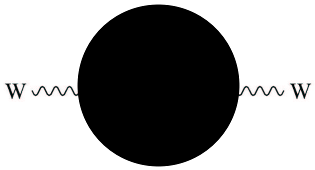
New Physics Restricted by S,T, U

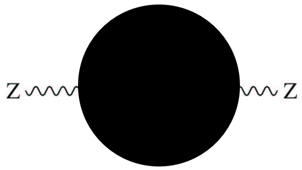
- Suppose new physics contains heavy ($M \gg M_Z$) particles

–Assume new particles contribute to Z and W self energies, but don't couple directly to ordinary fermions

–Effects can be described by 3 parameters (S,T,U)

–S,T,U defined to be O(1)





In a specific model, we can calculate S,T,U

$$\alpha T = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2} = \delta\rho$$

$$\frac{\alpha}{4\sin^2\theta_W \cos^2\theta_W} S = \frac{\Pi_{ZZ}(M_Z^2)}{M_Z^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2} - \left(\frac{\cos^2\theta_W - \sin^2\theta_W}{\cos^2\theta_W \sin^2\theta_W}\right)\frac{\Pi_{Z\gamma}(0)}{M_Z^2} - \frac{\Pi_{\gamma\gamma}(M_Z^2)}{M_Z^2}$$

$$\frac{\alpha}{4\sin^2\theta_W}(S+U) = \frac{\Pi_{WW}(M_W^2)}{M_W^2} - \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\cos\theta_W}{\sin\theta_W}\frac{\Pi_{Z\gamma}(M_Z^2)}{M_Z^2} - \frac{\Pi_{\gamma\gamma}(M_Z^2)}{M_Z^2}$$

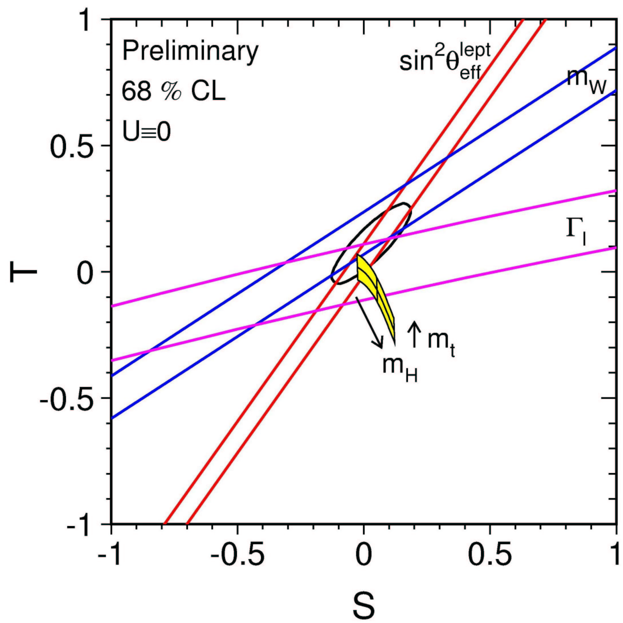
Peskin & Takeuchi, PRD46 (1992) 381

What if no light Higgs?

- Excluded by EW fits?
  - Need mechanism with positive ΔT
  - ΔT is isospin violating
- Must confront unitarity violation

Heavy degenerate 4th generation:
$\Delta S = 2/(3\pi), \quad \Delta T = 0$

Non-degenerate 4th generation:
$\Delta T = N_c G_F \Delta m^2 / (8\sqrt{2}\pi^2) > 0$



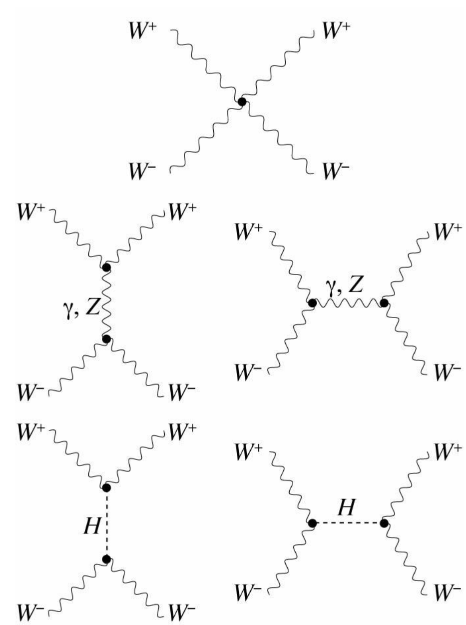
LEP EWWG 2004

Models without Higgs have difficulties with Unitarity

- Without Higgs, *W*-boson scattering grows with energy

  $A \sim G_F s$

  – Violates unitarity at 1.8TeV
- SM Higgs has just the right couplings to restore unitarity
- Extra D models have infinite tower of Kaluza-Klein states
- Need cancellations both in s and s^2 contributions to amplitudes
- Arrange couplings to make this happen

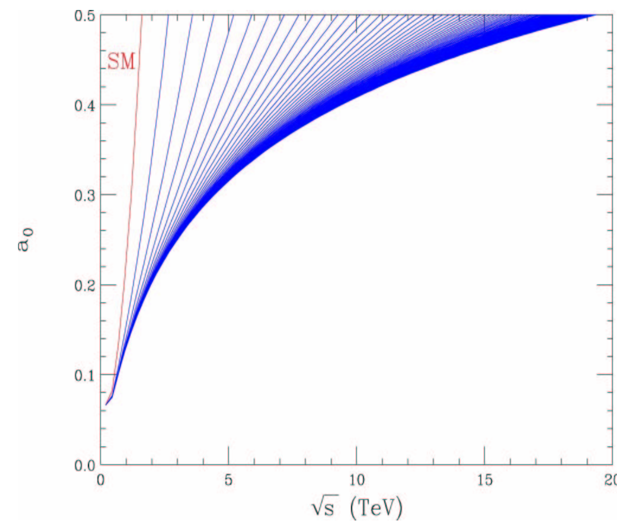


Look for heavy gauge bosons

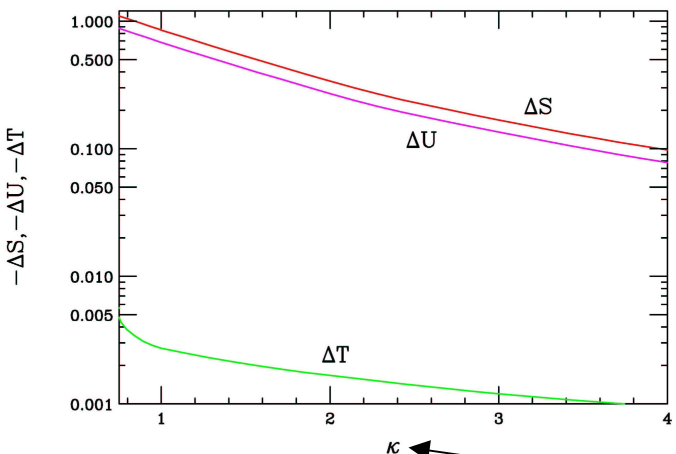
Higgsless phenomenology

- Tower of KK vector bosons
  - Can be produced at LHC, e^+e^-
  - *WW* scattering becomes strong
- Tension between:
  - Unitarity wants light KK
  - precision EW wants heavy KK

J=0 partial wave for WW scattering



Foadi, Gopalakrishna, Schmidt, hep-ph/0312324



Davoudiasl, Hewett, Lillie, Rizzo, hep-ph/0312193

Heavier κ⟶heavier KK gauge bosons

EW data limit new physics at TEV Scale

- Try to add new physics involving fermions with dimension 6 operators

$$L \approx \sum \frac{c_i}{\Lambda^2} O_i$$

- Precision measurements already limit $\Lambda > 5\text{-}10$ TeV

$\bar{e}\gamma_\mu e \bar{l}\gamma^\mu l$	$\Lambda >$ 4.5 – 6 TeV
$\bar{e}\gamma_\mu \gamma_5 e \bar{b}\gamma^\mu \gamma_5 b$	$\Lambda >$ 3 – 4 TeV
$(H^+ \tau^a H) W_{\mu\upsilon} B^{\mu\upsilon}$	$\Lambda >$ 10 TeV

- Flavor violating couplings even more tightly constrained

"Little Hierarchy Problem"

Hard to get new physics at the TeV Scale

Much Activity in EW Scale Model Building

- Remove Higgs completely
  - Dynamical symmetry breaking
  - Higgsless models in extra D
- Lower cut-off scale
  - Large extra dimensions
- Force cancellations of quadratic contributions to Higgs mass
  - SUSY
  - Little Higgs
  - Make Higgs component of gauge field in extra D

Much more satisying to have a model than just an effective theory!

Ultimate answer will come from data!

Strong limits from precision measurements

Symmetries maintain cancellations at higher order!

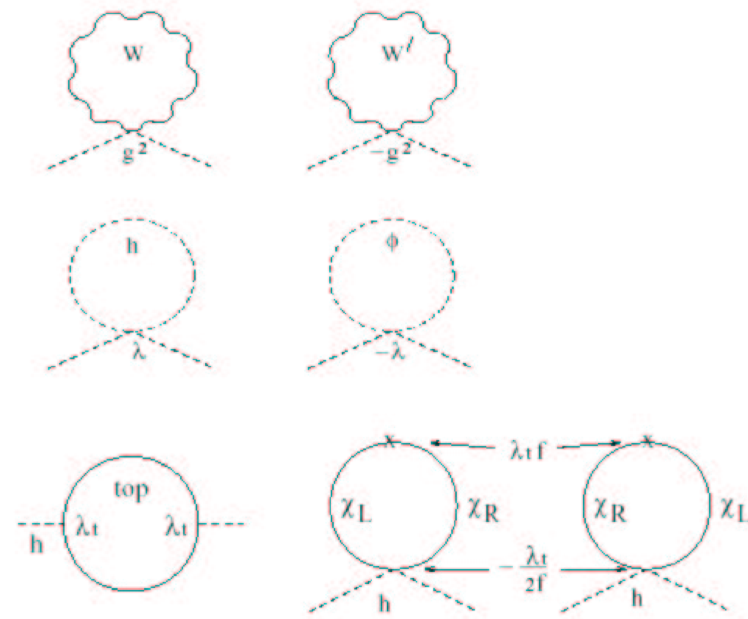
Little Higgs Models

New particles at scale f ~ Λ cancel SM quadratic divergences

Cancellation from same spin particles

Need symmetry to enforce cancellation

- Heavy W_H,Z_H,A_H cancel gauge loops
- Scalar triplet cancels Higgs loop
- Vector-like charge 2/3 quark cancels top loop



Arkani-Hamed, Cohen, Katz, Nelson, hep-ph/0206021

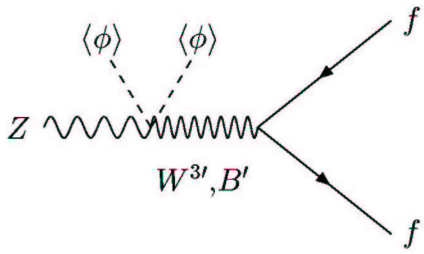
More on little Higgs

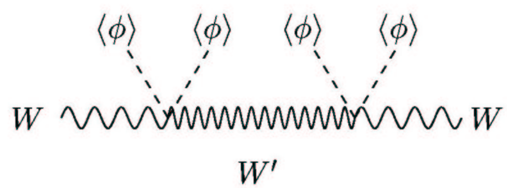
- Global Symmetry, G (SU(5))
  - Broken to subgroup H (SO(5)) at scale $4\pi f$
- Higgs is Goldstone Boson of broken symmetry
  - Effective theory below symmetry breaking scale
- Gauged subgroups of G ($[SU(2)xU(1)]^2$) contain SM
- Higgs gets mass at 2 loops (naturally light)

•Freedom to arrange couplings of 1^{st} 2 generations of fermions (their quadratic divergences small)

- Heavy W's, Z's, γ's
- Heavy top
- Extended Higgs sector

Little Higgs & Precision EW

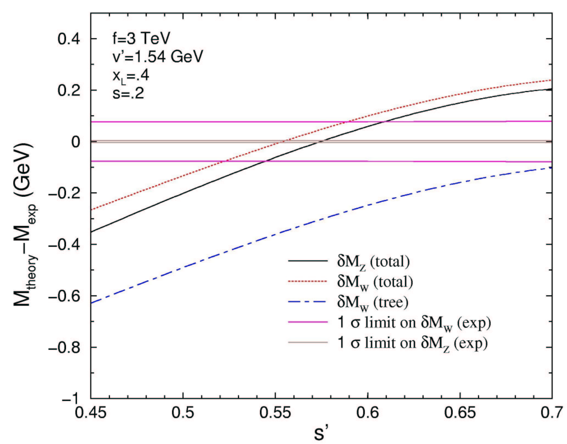




- Mixing of heavy-light gauge bosons leads to problems with precision measurements

$$\frac{\delta\Gamma_Z}{\Gamma_Z} \approx 1 + (\ldots)\frac{v^2}{f^2}$$

$$\frac{\delta M_W^{\ 2}}{M_W^{\ 2}} \approx 1 + (\ldots)\frac{v^2}{f^2}$$

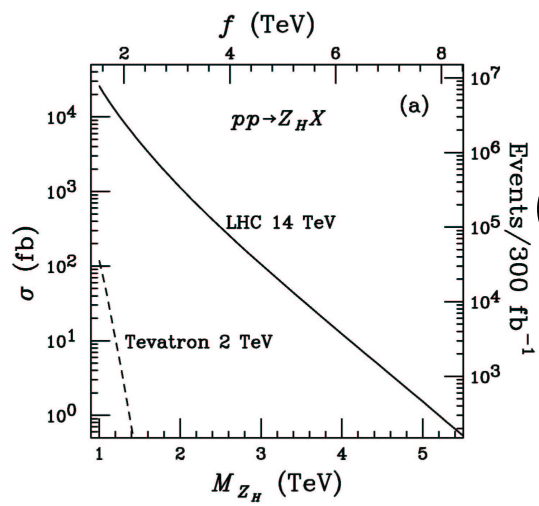


- Many models
- Triplets cause problems with ρ parameter unless VEV small
- Typically, $f \geq 3-4\,TeV$

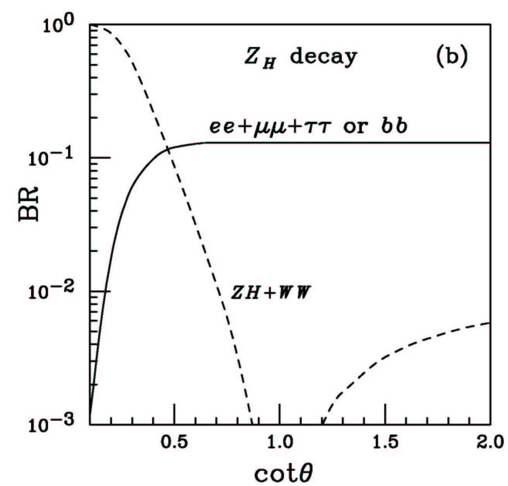
Chen& Dawson, hep-ph/0311032

New Phenomenology in Little Higgs Models

- Drell-Yan production of Z_H
  - EW precision limits prefer cot θ≈.2 (Heavy-light gauge mixing parameter)
  - BRs very different from SM
  - $M_{Z_H}^2 \approx M_Z^2 f^2/v^2$
- Look for heavy tops
- Look for non-SM 3 gauge boson vertices



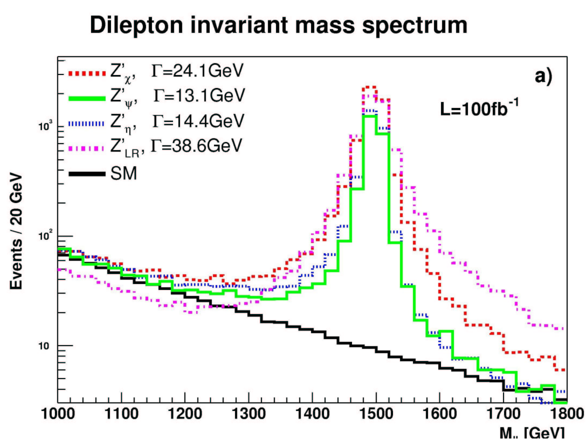
Scale down by $\cot^2\theta \approx .04$

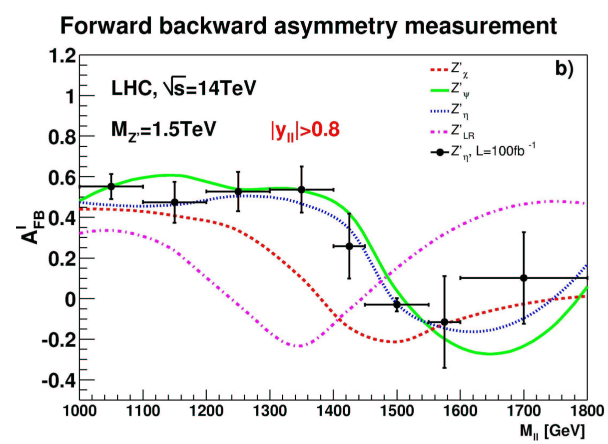


Han,Logan,McElrath, Wang, hep-ph/0301040

Distinguish models at LHC

- Distinction of "usual models" to $M_{Z'} < 2\text{-}2.5$ TeV
- Measure mass at LHC through mass bumps
  - Z' couplings through asymmetry





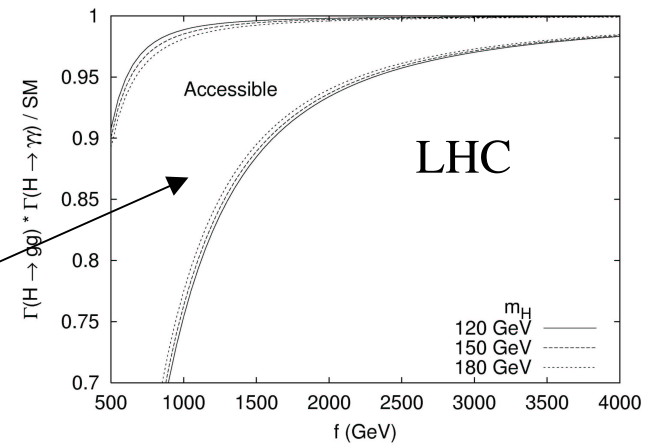
Dittmar, Djouadi, Nicollerat, hep-ph/0307020

Higgs production & decay in Little Higgs Models

•Growing realization that EWSB isn't just Higgs discovery, but requires finding spectrum of new particles!

- Rate could be reduced by ≈25%
- Have to see new particles
  - Z_H, W_H, γ_H

$gg \rightarrow h \rightarrow \gamma\gamma$



This is theoretically allowed region

Han, Logan, McElrath, Wang, hep-ph/0302188

Technicolor

- Think about QCD with M_u=M_d=0

$$L=\overline{\psi}_L D\psi_L+\overline{\psi}_R D\psi_R \qquad \psi=\begin{pmatrix} u \\ d \end{pmatrix}$$

- QCD has an $SU(2)_L$ x $SU(2)_R$ chiral symmetry

$$\psi_L \to \psi_L e^{i\vec{\tau}\vec{\theta}_L}$$
$$\psi_R \to \psi_R e^{i\vec{\tau}\vec{\theta}_R}$$

- At an energy scale, Λ_{QCD}, fermion condensates form

$$\langle \overline{\psi}_L^i \psi_R^j \rangle \approx \delta_{ij}\Lambda_{QCD}^3$$ ***Breaks the chiral symmetry***

- $SU(2)_L$ x $SU(2)_R \to SU(2)_V$
  - 3 Goldstone bosons: one for each broken generator (pions)
  - The pions would be massless if M_u=M_d=0

Technicolor, 2

- Copy QCD
- $SU(N_{TC})$ gauge theory
  - TechniColor fermions, Q=U,D
- EWSB by technifermion condensate at Λ_{TC}
  - $v \sim \langle \overline{Q}_L Q_R \rangle^{1/3}$
- Predicts new resonances at the TeV scale
  - π_T, η_T, ρ_T, ω_T
- Simplest version doesn't work
  - Radiative corrections too big
    - $S=N_{TC}/4$: experimental limit $S \sim -0.07 \pm 0.11$
  - No fermion masses

Extended Technicolor

- G_{ETC} gauge theory with ETC fermions to generate fermion masses $M_f \approx \Lambda_{TC}^3 / \Lambda_{ETC}^2$
- Integrate out ETC gauge bosons at scale Λ_{ETC}
- Fermion flavor physics at the TeV scale
- Big Problem:
  - FCNCs require $\Lambda_{ETC} > 10^3$ TeV
  - $M_q \approx 1$ Gev requires $\Lambda_{ETC} < 30\,(\Lambda_{TC}/ 1\ \text{TeV})$
    - Can't be QCD like

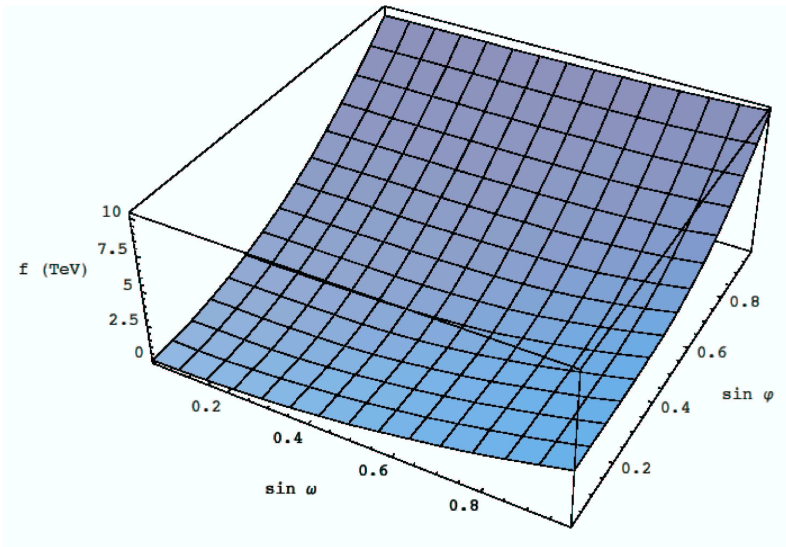
Hard to construct explicit models

- Models are complicated
- Tend to have replicated weak gauge structure
  - SU(2) x SU(2)
    - non-commuting extended TC
    - topflavor
    - ununified SM
  - U(1) x U(1)
    - topcolor-assisted TC
    - topflavor-seesaw
- General analysis of limits from precision measurements
  - Fermion charge assignments have major effect

None of these models give better fits to EW precision data than SM

SUSY can give better fit than SM

95% cl bound on new physics scale



–Topcolor, NCETC, UUM

new physics scale bounded≈ 10 TeV…..Extra gauge bosons too heavy to be observed at LHC

–Topflavor bounds ≈ few TeV

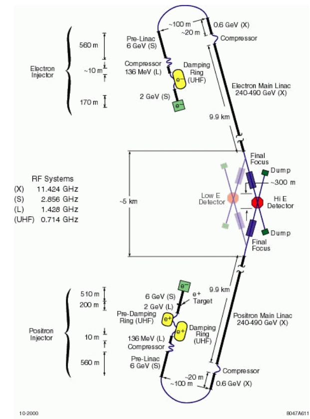
Chivukula, He, Howard, Simmons, hep-ph/0307209

General Themes

- SM works well
  - Lots of unanswered questions though
- Hard to construct models which work as well as SM
  - Tension between unitarity (wants new physics at TeV scale) and precision measurements (likes SM)
  - Supersymmetry is the exception

Only the data can tell us the answers!

Science Timeline



Tevatron	LHC	LHC Upgrade	LC
2004	2007	2012	2015?

This is the decade of the hadron colliders!