What we need to know about Top and why

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Inspirational Message
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Major milestones in particle physics

1970s particle zoo understood:
u, d, s bound states

1974 charm discovered

1975 $\tau^{\pm}$ discovered - 3^{rd} generation lepton

1978 bottom discovered - 3^{rd} gen. quark;
up-type partner (top) hypothesized

1979 gluon discovered:
$SU(3)$ of QCD becomes rock-solid

1983 $W^{\pm}, Z$ discovered:
strong belief in $SU(2)_L$ established

1990 LEP data supports 3 neutrinos (gen.'s)

1995 top quark candidate discovered

1990s LEP $e^+e^- \to W^+W^-$ confirmation of
$SU(2)_L$ gauge theory

2000 ν_τ discovered (*yawn*)

→ Reinforces Standard Model gauge theory of all forces except gravity:

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

(strong, weak, EM)

Matter particles we see in nature:

$$\binom{u}{d}_L \; u_R \; d_R \qquad \binom{\nu_e}{e}_L \; e_R$$
$$\binom{c}{s}_L \; c_R \; s_R \qquad \binom{\nu_\mu}{\mu}_L \; \mu_R$$
$$\binom{t}{b}_L \; t_R \; b_R \qquad \binom{\nu_\tau}{\tau}_L \; \tau_R$$

Note that we *have* to have 3 generations to have CP violation!

Top candidate is abnormally heavy, but otherwise looks like SM top quark:

- $\sigma_{t\bar{t}}$ is right size for QCD production
- BR($t \rightarrow W^+ b$)$\sim$1 is expected weak decay

▶ $Q = +\frac{2}{3}$ or $-\frac{4}{3}$, but not determined

Q_t meas'mt at LHC - no surprises excpected

So why study top in more detail?

1. top is background to NP @ LHC

   model it well!

2. top is SM-like, but not well-measured

   $g_{\gamma tt}$, g_{Ztt} , g_{Wtb} , V_{tb} not known!

3. top can be a window to NP

   2HDMs, SUSY, Little Higgs, Topcolor, flavor, ...

1,2,3 are related, but different aspects

Modeling top

- corrections to $\sigma_{t\bar{t}}$:
  NLO+NLL+[NNLO+NNLL] $\sim +40\%$,
  but uncertainty $\sim 5-20\%$! (exp. $< 10\%$)
  $\longrightarrow$ need full NNLO+NNLL
- $\sigma_{t\bar{t}+jets}$: add'tl hard partons
  dominant bkg to Higgs, other searches
  Pythia/Herwig give wrong (low) rates!
  LO matrix elements IR unsafe -
  simple matching possible, not rigorous
  also: $t \longrightarrow Wbj$ needs proper matching
- off-shell top production:
  difficult, crucial issue at LHC for
  $H \longrightarrow W^+W^- \longrightarrow \ell^+\ell^- + X$
- $t\bar{t}$ spin correlations:
  $\frac{1}{\sigma}\frac{d^2\sigma}{d(\cos\theta_i)d(\cos\theta_{\bar{i}})} = \frac{1}{4}(1 - C\alpha_i\alpha_{\bar{i}}\cos\theta_i\cos\theta_{\bar{i}})$
  C_{NLO} important, depends on spin basis

$\longrightarrow$ theor. unc. $>$ exp. unc. in all cases!

(similar issues for single-top production)

Top properties - SM?

$\longrightarrow$ $\sigma_{t\bar{t}}$ suggests $g_{gtt} = g_s$ (t is color triplet)

QCD anom. coups tough at Tev2, LHC

$\longrightarrow$ $g_{\gamma tt}$, g_{Ztt} essentially unprobed

must measure $t\bar{t}Z$,$t\bar{t}\gamma$ rates

$\longrightarrow$ g_{Wtb} roughly limited from BR($t \to Wb$)$\sim$1

and lack of single-top so far

CLEO $b \to s\gamma$ data more constraining

$\longrightarrow$ Γ_t (lifetime): involves g_{Wtb} and V_{tb}

only indirectly at Tev/LHC (and tough)

directly via threshold fit at LC!

$\longrightarrow$ Yukawa coupling: $Y_t \approx 1$?

direct meas'mt via $t\bar{t}H$ production

confirm spont. sym. breaking gen.'s m_f

$\longrightarrow$ $t\bar{t}$ spin correlation:

$S = \frac{1}{2}$, τ_t too short to hadronize, $|V_{tb}| > 0.03$

$\longrightarrow$ charge (Q_t) ($Q_t = -4/3$ is exotic, not likely)

need LHC to confirm w/ $t\bar{t}\gamma$ production

or lucky $t \to b\ell\nu$ events @ Tev2 w/ Q_b

Type II 2HDMs (incl. SUSY)

$\longrightarrow$ driven by parameters M_A and $\tan\beta$, ratio of up/down vevs v_2, v_1

(small or large $\tan\beta$ preferred, ~ 3 or ~ 30)

Five physical states:

- h, H CP-even, typically one is SM-like
  mixing of states parameterized by α
- A CP-odd, typically degenerate w/ H
- $H^{\pm}$ typically degenerate w/ H, A

$t \longrightarrow H^+ b$ non-trivial if kinem. allowed

$t\bar{t}\phi$ ($\phi = h, H, A$) production possible,
unless ϕ heavy

$$g_{tth} \propto \frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \frac{1}{\tan\beta}\cos(\beta-\alpha)$$

$$g_{ttH} \propto \frac{\sin\alpha}{\sin\beta} = \cos(\beta-\alpha) - \frac{1}{\tan\beta}\sin(\beta-\alpha)$$

$$g_{ttA} \propto \cot\beta$$

(may be difficult to observe...)

SUSY decays of top

In addition to $t \to H^+ b$, top can decay to SUSY pairs ($\mathcal{R}$-parity conserving) or SUSY/SM mixed pairs ($\mathcal{R}$-parity violating).

→ $\mathcal{R}$-parity conserved: SUSY pairs only

$t \to \tilde{t}\tilde{g}$ $\quad \mathcal{O}(1)$

$t \to \tilde{b}\chi_1^+$ $\quad \mathcal{O}(1)$

$t \to \tilde{t}\chi_1^0$ $\quad \mathcal{O}(1)$

where kinematically accessible

(light $\tilde{t}, \tilde{b}$ perhaps not so likely)

→ $\mathcal{R}$-parity violated: tree-level

$e.g.\ t \to \tilde{\tau} b \to \tau b \tilde{\chi}_1^0$

→ $\mathcal{R}$-parity violated: 1-loop

$t \to c\tilde{\nu}$ $\quad BR \sim 10^{-3}$

→ loop-induced FCNC decays

$t \to cg$ $\quad BR \sim 10^{-3}$

$t \to c\gamma$ $\quad BR \sim 10^{-5}$

$t \to cZ$ $\quad BR \sim 10^{-4}$

$t \to ch$ $\quad BR \sim 10^{-4}$

Little Higgs models

Motivation:

precision data constrains new flavor physics to $f \sim 10$ TeV: Little Heirarchy

solve the SM Higgs sector Big Heirarchy problem by postponing it to f

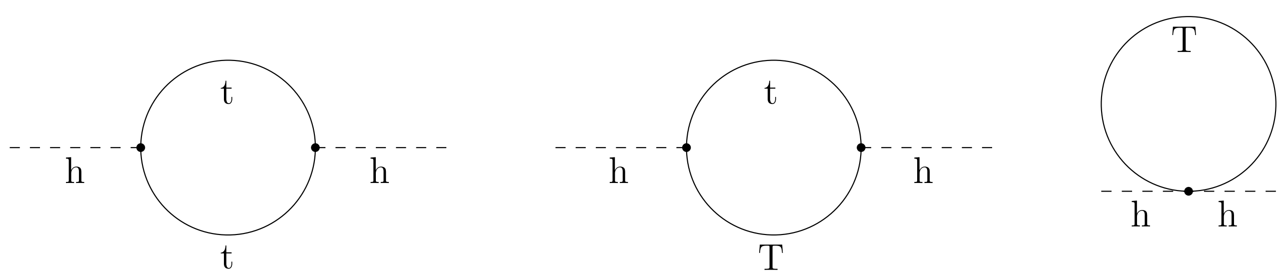
Basic idea: some large gauge group broken down at scale $f \sim 1 - 10$ TeV to SM

minimal new content:

$$h, \pi, \pi', \pi^{\pm}, \pi^{\pm\pm}, T, Z', W'^{\pm}$$

next to minimal is 2HDM: add $H, A, H^{\pm}$

(elaborate) new gauge structure cancels quadratic divergence *to one-loop order* – new physics cutoff @ $f \sim 10$ TeV scale



Little Higgs phenomenology

Begin with $SU(5)$ Yukawa Lagrangian:

$$\mathcal{L}_Y = -\lambda_1 f\, \bar{t}_R \,\mathrm{Tr}[\Xi^*(iT_2^2)\Xi^* \hat{\chi}_L] - \lambda_2 f\, \bar{T}_L T_R + h.c.$$

where $\hat{\chi}_L$ is 5x5 matrix containing t_L,b_L,T_L

t and T mixtures of chiral t_3 & vector-like $\tilde{t}$:

$$\sin_L = s_L \simeq \frac{\lambda_1}{\lambda_2}\frac{m_t}{m_T}$$

T too heavy? Check SM top observables:

1. CKM not unitary:

   $V_{tb} = c_L\, V_{tb}^{SM} \qquad V_{Tb} = s_L\, V_{Tb}^{SM}$

2. modified FFV couplings:

$W^\mu\, \bar{t}_L b_L$	$\frac{ig}{\sqrt{2}}[1 - (\frac{v^2}{f^2})\frac{1}{2}(x_L^2 + c^2(c^2 - s^2))]\gamma^\mu V_{tb}^{SM}$
$W^\mu\, \bar{T}_L b_L$	$\frac{g}{\sqrt{2}}(\frac{v}{f})x_L\, \gamma^\mu V_{tb}^{SM}$
$\gamma\bar{t}t$	eQ_t (unaffected)
$\gamma\bar{T}t$	0
$\gamma\bar{T}T$	0
$Z\bar{t}t$	really complicated...

3. modified Yukawa couplings as well

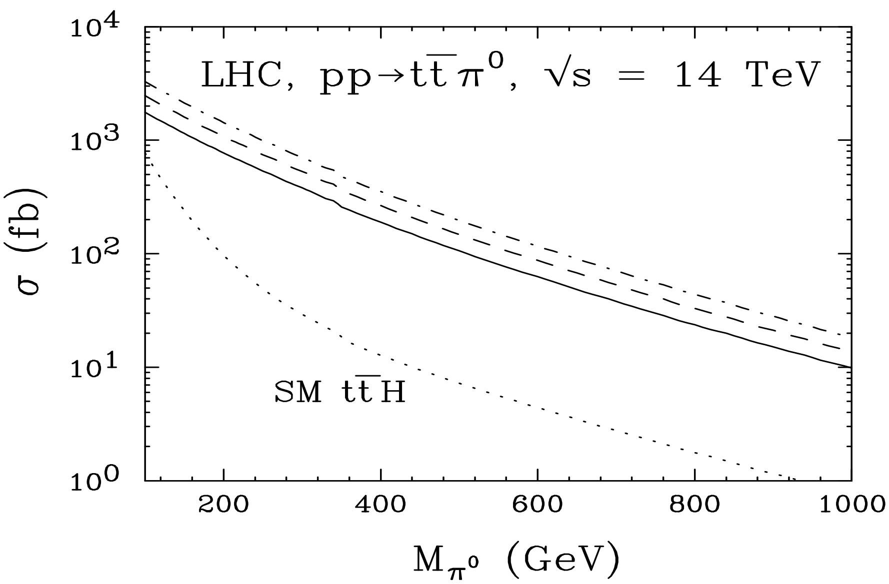
Viable strong dynamics model: **Topcolor**

$\rightarrowtail$ $\mathbf{3^{rd}}$ generation is special:

$SU(3)_h \otimes SU(3)_l \otimes U(1)_h \otimes U(1)_l \otimes SU(2)_L$

Breaks down to SM + extra $U(1)$ (find Z'!)

Eff. 2HDM: H_{TC2}, H_{ETC} + "top-pion" triplet



top decays $t \longrightarrow \pi^+ b$ also possible

Expect to see rare FCNC top decays:

$$t \longrightarrow c\gamma, cZ, cg$$

Expect FCNC single-top production:

$$pp \longrightarrow t\bar{c}, tg, \text{ etc.}$$

$Zt\bar{t}$ coupling non-SM due to Z, Z' mixing

Summary

- EW data/theory require t, partner of b
- We believe this $m = 175$ GeV object to be SM top, but it is not fully verified!
- LHC/FLC must verify charge, spin, top-gauge couplings, CKM V_{tb}, ...
- In general, any new physics has some observable effect on top:
  $\longrightarrow$ rare decays
  $\longrightarrow$ FCNC production
  $\longrightarrow$ altered couplings to Z, W, γ, g
  $\longrightarrow$ richer Yukawa structure
- Even if no new physics directly in top, must understand SM top *far* better, as a bkg to new physics