LHC Exotica II
Overview of Alternative Signatures

Technicolor, Higgsless, Little Higgs, Composite Higgs, Twin Higgs, Fat Higgs. . . oh, my!

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Boston University

6 April 2009

Outline

Electroweak theory and spontaneous electroweak symmetry breaking

- Electromagnetism and the weak force unified in *electroweak* gauge theory.
- Exact electroweak gauge invariance (“symmetry”) forbids gauge boson masses. ∴ observation of massive $W^{\pm}$ and Z means electroweak symmetry must be (spontaneously) broken.

$$SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$$

- Electroweak symmetry breaking (EWSB) allows $W^{\pm}$ and Z to become massive.
- Recall massless vector bosons only have two degrees of freedom (transverse polarizations), while massive vector bosons have a third (longitudinal).
- Where do these extra degrees of freedom come from?

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Standard Model Higgs mechanism

- (As Phil discussed a few weeks ago. . .)
- In the standard model (SM), a complex $SU(2)$ doublet

$$\Phi = \begin{pmatrix} \phi_1 + i\phi_2 \\ v + h + i\phi_3 \end{pmatrix}$$

  is introduced by hand, with a potential

$$V(\Phi) \sim \lambda \left(\Phi^\dagger \Phi - v^2\right)^2$$

  engineered to produce spontaneous symmetry breaking.
- $\phi_1 \pm i\phi_2$ “eaten” by $W^\pm$, ϕ_3 by Z, providing masses $m_W, m_Z \sim v$.
- h remains as physical “Higgs” boson with mass $m_h \sim \sqrt{\lambda} v$.
  v is fixed, λ and hence m_h are not.
- Added bonus: electroweak symmetry also forbids fermion masses.
  The humble doublet above provides those as well, $m_f \sim \lambda_f v$.
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Problems with SM Higgs mechanism

- Unfortunately, the standard model Higgs mechanism is not satisfactory.
- Gives no dynamical explanation of electroweak symmetry breaking – explicitly added to SM by hand.
- Sensitive to highest momentum scale at which theory is applicable: un-“natural” fine-tuning required to maintain hierarchy.
- Theory is “trivial”: new physics has to appear at scale Λ or else coupling λ vanishes:

$$\lambda(\mu) \simeq \frac{\lambda(\Lambda)}{1 + (24/16\pi^2)\lambda(\Lambda)\log(\Lambda/\mu)}.$$

- Gives no insight into flavor physics (patterns of fermion masses). (As Adam mentioned a few weeks ago. . .)

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Dynamical electroweak symmetry breaking (DEWSB)

- Are there any possible alternatives to the standard model Higgs mechanism?
- Consider the best-known examples of spontaneous symmetry breaking:

1. Superconductivity.
    - Originally modelled (by Ginzburg and Landau) using a complex scalar field.
    - Dynamically explained (by Bardeen, Cooper and Schrieffer) through the formation of electron condensate (Cooper pairs) $\langle ee \rangle$.
2. (Approximate) chiral symmetry breaking in quantum chromo-dynamics (QCD).
    - Originally modelled (by Gell-Mann and Lévy) using scalar fields (σ model).
    - Dynamically explained (by Nambu and Jona-Lasinio) through the formation of quark condensate $\langle \overline{q} q \rangle$.
    - (Fun fact: QCD condensate $\langle \overline{q} q \rangle$ breaks electroweak symmetry, generating $m_W = m_Z \cos\theta_W \simeq 34$ MeV.)

- Dynamics naturally explains scale of symmetry breaking – no hierarchy problem.

Speculate:

3. Electroweak symmetry breaking.
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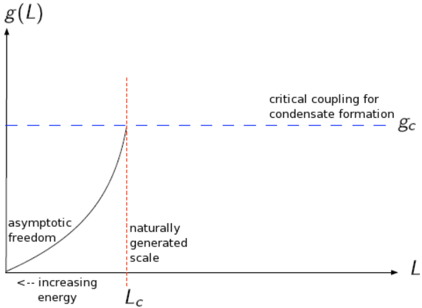

Cartoon of running coupling in QCD.

- Asymptotic freedom means coupling vanishes at high energies (short distances).
- As energy decreases, coupling becomes strong enough to form condensate at some dynamically-generated scale.

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Technicolor as scaled-up QCD

- Such dynamical breaking of electroweak symmetry is technicolor (TC).[1,2,3,4]
- Originally modelled on chiral symmetry breaking in QCD.[5,6,7] Introduce new, unbroken, asymptotically free, nonabelian gauge interaction that becomes strong around the weak scale.
- Electroweak symmetry is broken by condensates $\left\langle \overline{T} T \right\rangle \equiv 4\pi F_T^3 \neq 0$, giving $m_W = m_Z \cos\theta_W \propto F_T$.
- Since TC is unbroken, only technicolor-singlet states (technihadrons and SM particles) are observable. Three lightest technipions identified as $W_L^\pm$ and Z_L.
- Strong interactions $\Longrightarrow$ perturbation theory inapplicable, analytic calculations difficult, generally intractable.
- However, can use QCD as an "analog computer" for technicolor to obtain approximate results.

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Extended technicolor (ETC)

- Recall that the standard model (SM) Higgs mechanism also provides fermion masses. We need to do that dynamically as well.
- “Extend” technicolor to fill the gap.[8]
- Add even more strong interactions, at an even higher scale, these involving both SM- and techni-fermions. Then SM fermion masses also proportional to technifermion condensate (to leading order),

$$m_f \propto \left\langle \overline{T}T \right\rangle / M_{ETC}^2 \sim m_W^3 / M_{ETC}^2$$

- Unlike TC, ETC gauge theory is broken (to TC+SM).
- Exact mechanism of symmetry breaking is (very hard) open problem.
- Successful model will dynamically explain observed pattern of fermion masses (the “flavor problem”), as well as CKM matrix elements and CP violation.

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Extended technicolor challenges

- Frequently asked question: Wasn't ETC ruled out a decade or two ago?
- While it wasn't, technicolor-as-scaled-up-QCD *does* face serious difficulties.
- ETC interactions produce flavor changing neutral current (FCNC) operators.
- Strong constraints from experiment (e.g. K_L-K_S mass difference, K-$\overline{K}$ mixing) require large $M_{ETC} \gtrsim 10^3$ TeV, producing tension with fermion masses $m_f \sim m_W^3 / M_{ETC}^2 \sim 1$ MeV.
- "Scaled-up QCD" calculations for precision electroweak observables ("S parameter", "T parameter")[9] in tension with experiment – at least 2.5σ disagreement.
- Heavy top quark problematic – too close to electroweak scale.

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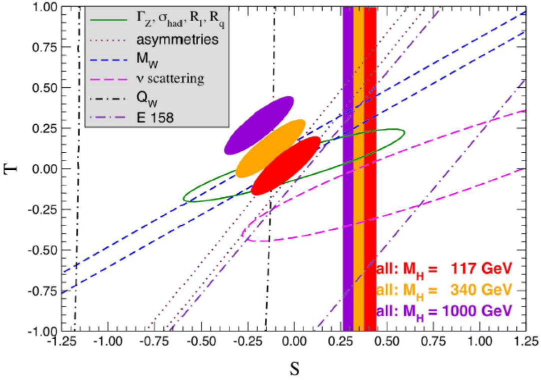

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- T measures weak-isospin violating effects.

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(Partial) solution: “walking” technicolor (WTC)

For those too young to remember the early ’80s,
nothing can fully evoke the horror
of hearing the phrase “walking technicolour” again.
(Jacques Distler, 12 December 2003)

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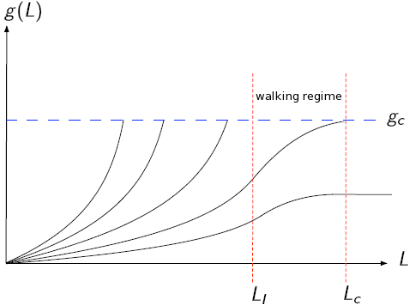
- "Walking" behavior can solve some of these problems.[10,11,12,13]
- In walking technicolor (WTC) the TC coupling (interaction strength) changes slowly between electroweak scale and ETC scale – instead of "running", it "walks".
- In technical terms, small β function $\beta \approx 0$ or large anomalous dimension $\gamma \sim 1$.



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The Trouble with WTC

- Now that we can't use QCD as an "analog computer" for technicolor, very tough to make any solid predictions.
- Can try to extract (qualitative) information from extra-dimensional dualities (AdS/CFT, etc. – very active field, about which more below).
- Lattice gauge theory is quantitative, non-perturbative, first-principles approach.[14] However, very computationally intensive.
- Lattice Strong Dynamics (LSD) Collaboration conducting non-perturbative studies of (non-QCD) strongly-interacting gauge theories.[15]

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[14] Fleming, PoS LATTICE2008:021 (2008) 0812.2035.

[15] http://www.yale.edu/LSD

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- Lattice gauge theory is quantitative, non-perturbative, first-principles approach.[14] However, very computationally intensive.
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[14] Fleming, PoS LATTICE2008:021 (2008) 0812.2035.

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Managing the top mass

- Top quark mass m_t is too big to be explained by basic ETC, even helped by walking.
- There are various possible fixes, typically involving generation-dependent strong dynamics:
  - Tumbling – different ETC scales for each SM generation. Hard to engineer “naturally”.
  - Topcolor – replace TC condensate with top quark condensate, which breaks electroweak symmetry and produces large m_t… unfortunately too large, $m_t \gtrsim 600$ GeV.[16]
  - Top seesaw – like topcolor, except top quark coupled with heavy (several TeV) fermion that can evade constraints.
  - Topcolor-assisted technicolor (TC2) – topcolor takes care of large m_t, WTC does the rest.[17]
  - Strong/Conformal ETC – even larger anomalous dimension $\gamma \sim 1.5$ to 2.[18, 19]

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- Topcolor-assisted technicolor (TC2) is most commonly used technicolor model.
- Topcolor and technicolor each solve difficulties faced by the other: topcolor pushes up m_t, but it doesn't need to go as high because WTC takes care of EWSB.
- Breaking topcolor to ordinary color produces additional resonances, including massive gauge bosons (color-octet "colorons" V_8 and color-singlet Z') and color-octet technimesons (ρ_{T8}, π_{T8}).
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Low-scale technicolor (LSTC)

- (Still topcolor-assisted.)
- A promising way to get walking behavior is to have a large number N_f of technifermions (reduces leading order of β function).
- A helpful side effect of large N_f is that the scale of technicolor is reduced by

$$F_T \simeq \left(\sqrt{\frac{2}{N_f}}\right) 250 \text{ GeV} \lesssim 100 \text{ GeV}.$$

- So walking can reduce the masses of certain resonances, improving prospects for collider discovery.
- Such low-scale technicolor (LSTC) can also arise from having technimatter in multiple representations of the TC group, with widely separated scales.[17,18]
- May be required by topcolor breaking and SM fermions' masses and mixings.[19,20]

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The technicolor straw man model (TCSM)

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- Try to get simplest, least-cluttered spectrum, considering in isolation lowest-lying color-singlet bound states (π_T, ρ_T, a_T, ω_T) of lightest technifermion doublet.[22]
- The Typical TCSM parameters:
  - $N_{TC} = 4$ (so technicolor is $SU(4)$ gauge theory).
  - $N_f = 18$ (compare with 24 in the SM – count each color).
  - $M_{\rho_T} = M_{\omega_T}$ and $M_{a_T} \simeq 1.1 M_{\rho_T}$.
  - ρ_T and a_T pairs have comparable couplings to the appropriate currents (inspired by HTC, helps reduce contributions to S).
- Used for most collider studies (only TC model implemented in `PYTHIA`).[23]

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Extra-dimensional approaches

- As mentioned above, can try to extract qualitative information from extra-dimensional “dualities”.
- These relate strongly-interacting four-dimensional gauge theories to weakly-interacting five-dimensional gravity theories.
- Simplest and best-known example is AdS/CFT, but need to go beyond simple AdS to model (viable) technicolor.
- The observables we get from these dualities are the masses and couplings of the resonances (bound states).
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- Two conceptual pictures: the fifth dimension is physically present (higgsless models) or is just a mathematical trick (holographic technicolor).

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Higgsless models

- In higgsless models, we live on a 4d "brane" in a 5d universe.
- Boundary conditions on branes break electroweak symmetry (in the proper way) and provide particle masses without a Higgs.
- Original model had a "flat" extra dimension.[24] When that didn't work, a warp factor was added à la Randall-Sundrum.[25]
- Main observable signatures are Kaluza-Klein (KK) modes W' and Z', which Cory talked about last week.
- Lower limit on W', Z' masses around 400 GeV, from experiment.[26,27,28]
- Upper limit on W', Z' masses around 1.2 TeV, from unitarity.
- Next KK modes should be around $M_{W_3} \sim M_{Z_3} \sim 1.9$ TeV, again from unitarity.

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Holographic technicolor

- Mathematically, holographic technicolor (HTC) is nearly identical to higgsless model described above.
- Main difference is conceptual: 5d language simply used to describe 4d scenarios.[29], [30]
- Allows more flexibility: different fields can “feel” different 5d “geometry”.
- Goal is simple parameterization(s) of (walking) technicolor with few variables (à la mSUGRA) that can be set in various ways to sample particular models.
- Can look for much the same signatures as higgsless models, W', Z', W_3, Z_3.
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Little Higgs

- In little Higgs models, the Higgs is a pseudo-Nambu-Goldstone boson (PNGB) of a spontaneously broken approximate global symmetry.[31] Weakly-coupled, non-supersymmetric theory.
- Idea introduced long ago,[32,33] only recently built into viable models in context of extra dimensions.[34]
- Familiar example of such PNGBs is Gell-Mann's "eightfold way": $SU(3)_L \times SU(3)_R \to SU(3)_V$ chiral symmetry breaking produces the PNGB octet

$$\pi^0, \pi^\pm, K^0, \overline{K}^0, K^\pm, \eta$$

- Popular little Higgs models:
  - The Minimal Moose: $[SU(3)_L \times SU(3)_R \to SU(3)_V]^4$, producing four PNGB octets (32 PNGBs total).
  - The littlest Higgs: $SU(5) \to SO(5)$, producing 14 PNGBs.
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Little Higgs complications

- Need to ensure that symmetries are broken in the right ways (“collectively”) to cancel quadratic divergences, while still giving uneaten PNGBs large enough masses around the TeV scale.
- Enlarge electroweak gauge symmetry, and break it back down to $SU(2) \times U(1)$.
    - Minimal Moose: $SU(3) \times SU(2) \times U(1)$ subgroup of global $SU(3)^8$.
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- Add new fermions (“top partners”) transforming under enlarged gauge symmetries to cancel fermionic contributions to quadratic divergences.
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Little Higgs as effective theory

- You might be wondering how these new symmetries are broken.
- Much like electroweak symmetry breaking, we need new scalars or new strong dynamics at higher scale.
- If the former, need to do it all over again at even higher scale, etc.
- Little Higgs theories are effective theories valid up to cutoff $\Lambda \sim (4\pi)^2 \, m_W \sim 5$ to 10 TeV.[35]
- Not the end of the story: (more) new physics required.

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[35] Limited range of applicability justified by invoking the "little hierarchy problem", tension between the natural scales for new physics that seem to be required by unitarity and Higgs mass (on one hand) and precision electroweak constraints (on the other).

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- Different little Higgs models predict varying spectra of new particles.
- However, all predict at least one top partner, generically with mass $\lesssim 1$ TeV.[36]
- Top partner pair produced, with cascade decay like supersymmetry.

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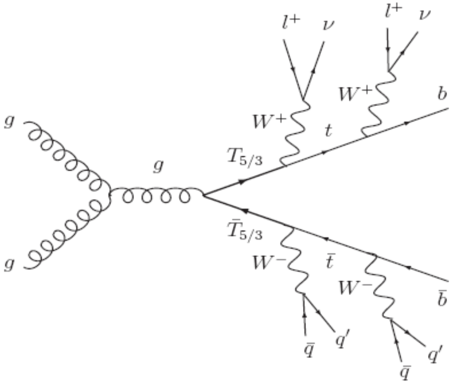

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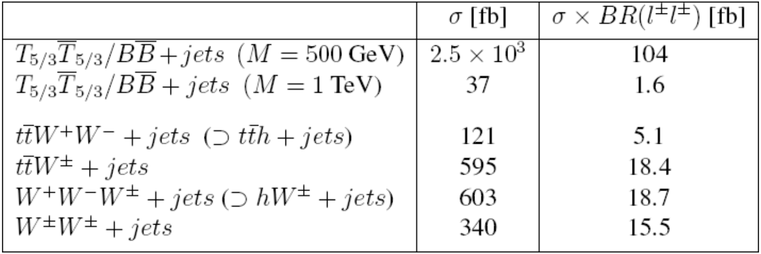
[36] Bose, Contino, Narain and Servant, in Brooijmans et al., 0802.3715.

Little Higgs prospects at the LHC

- Require same-sign leptons to suppress $t\bar{t}$ backgrounds.
- Leading order cross section of signal vs. backgrounds varies strongly depending on top partner mass.[37]



	σ [fb]	$\sigma \times BR(l^\pm l^\pm)$ [fb]
$T_{5/3}\overline{T}_{5/3}/B\overline{B} + jets\ \ (M = 500\ \mathrm{GeV})$	2.5×10^3	104
$T_{5/3}\overline{T}_{5/3}/B\overline{B} + jets\ \ (M = 1\ \mathrm{TeV})$	37	1.6
$t\bar{t}W^+W^- + jets\ \ (\supset t\bar{t}h + jets)$	121	5.1
$t\bar{t}W^\pm + jets$	595	18.4
$W^+W^-W^\pm + jets\ (\supset hW^\pm + jets)$	603	18.7
$W^\pm W^\pm + jets$	340	15.5

- Les Houches study claims discovery of 500 GeV top partners from this process could require only 60 to 250 pb^{-1} at 14 TeV (if both $T_{5/3}$ and B are present).[38]

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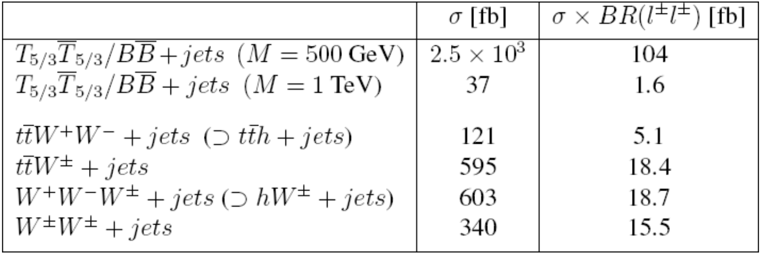

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Twin Higgs

- Twin Higgs models adapt the little Higgs approach, simplifying collective symmetry breaking by introducing a discrete Z_2 symmetry in the UV.
- In the original $SU(4) \to SU(3)$ (7 PNGBs) model, this symmetry connected the entire SM with a “twin” or “mirror” SM.[39]
- A consequence is that all new physics only shows up as missing energy at colliders. Not ideal for LHC.
- Alternative: Z_2 symmetry connects left-handed and right-handed sectors of an expanded SM, with symmetry breaking $O(8) \times O(8) \to O(7) \times O(7)$ (or $U(4) \times U(4) \to U(3) \times U(3)$) (14 PNGBs).[40]
- Such “left-right twin Higgs” (LRTH) models have top partners (and more) like little Higgs models, allowing more feasible collider studies.[41,42]
- Les Houches study claims entire interesting LRTH parameter region will be probed to 3σ with 30 fb^{-1} of integrated luminosity.
- Like little Higgs, twin Higgs models are effective theories that require additional new physics around 5 to 10 TeV.

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[39] Chacko, Goh and Harnik, PRL 96:231802 (2006) hep-ph/0506256.

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Composite Higgs

- Recalling the QCD meson octet, we now know that these are all composites of more fundamental, strongly-interacting constituents.
- Same could be true of the PNGBs in little Higgs theories. Treating them as composites of strongly-interacting constituents can provide the “UV completion” of the models above the 5 to 10 TeV scale.[43,44,45,46,47]
- Unfortunately, this brings us back to strong interactions (but not TC).
- As before, can look for extra-dimensional dualities.[48,49]
- Recent work using this approach seems to be focusing on composite descriptions of the top and top partners (in 5d language, they are the lightest KK modes).[50]
- Or can just focus on low-energy phenomenology, which is described well by little Higgs models.

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Fat Higgs

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- Allows larger Higgs mass (around 250 to 400 GeV) and superpartner masses, solving (N)MSSM “little hierarchy problem”.
- Initial model lost natural gauge coupling unification. Can be restored in a “slimmer” model that returns to elementary Higgs fields but keeps the N scalar composite.[52]
- Now upper bound on Higgs mass is 350 GeV.
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Generic features of technicolor searches

- Since technicolor involves new strong dynamics, will not see individual technifermions.
- Look for bound states, analogous to the π, ρ, ω of QCD.
- Technivector resonances (ρ_T, a_T, ω_T) expected to be relatively narrow.

$$\begin{aligned} 1\text{ GeV} &\lesssim \Gamma(\rho_T) \lesssim 5\text{ GeV} \\ 0.1\text{ GeV} &\lesssim \Gamma(\omega_T) \lesssim 0.5\text{ GeV} \\ &\ \Gamma(a_T) \lesssim 0.5\text{ GeV} \end{aligned}$$

  ($\Gamma/M \sim 10^{-4}$ to 10^{-2})
- Walking increases technipion masses, closing off all-π_T decays and limiting the phase space of decays with one π_T.
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TC at the Tevatron

- Main TCSM discovery channel at the Tevatron is $\rho_T \to W^\pm \pi_T \to \ell^\pm \nu_\ell bj$.
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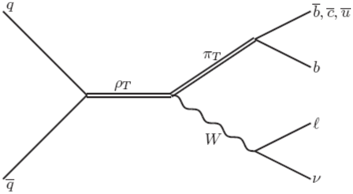

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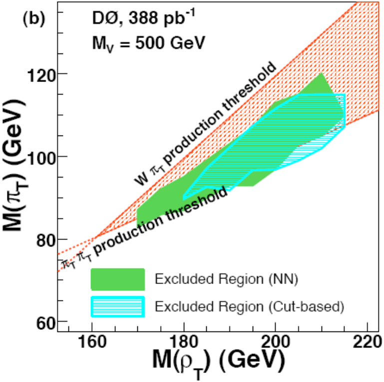

- Electrons only, results somewhat different than expected.

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[53] DØ, PRL 98:221801 (2007) hep-ex/0612013.

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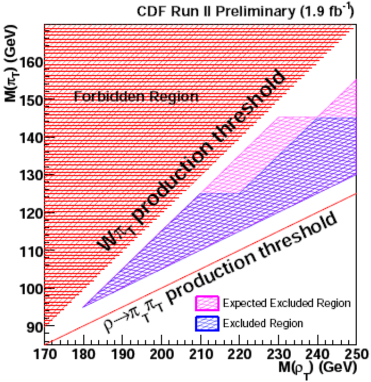

- Five times as much data, almost identical limits!

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[53] CDF, Public Note 9302 (2008).

[54] Nagai, Masubuchi, Kim and Yao, 0808.0226 (2008).

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- Theorists expect Tevatron run II to probe up to $M_{\rho_T} \simeq 400$ GeV.[57]
- More recently suggested $M_{\rho_T} \lesssim 250$ GeV, $M_{\pi_T} \lesssim 150$ GeV accessible with data collected as of mid-2008.[58]

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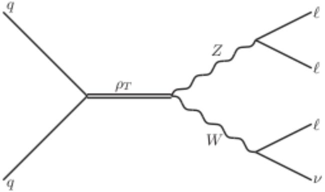
[57] Lane, PRD 60:075007 (1999) hep-ph/9903369.
[58] Eichten and Lane, PLB 669:235 (2008) 0706.2339.

LHC discovery channels

- Some preliminary TCSM studies performed by CMS,[59,60] ATLAS,[61,62] and Les Houches working group.[63]
- At the LHC the $\rho_T \to W^{\pm}\pi_T$ channel will be swamped by $t\bar{t}$ and $W+$ heavy flavor backgrounds.
- Best discovery channels are diboson decays of vector resonances, with leptons in the final state: clean signals and low backgrounds.

$$\rho_T \to WZ \to 3\ell + \nu \qquad a_T \to \gamma W \to \ell\nu\gamma \qquad \omega_T \to \gamma Z \to \ell\ell\gamma$$



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[59] Bose, CMS CR 2008-4.

[60] Kreuzer, CMS CR 2006-42.

[61] Azuelos, Ferland, Lane and Martin, ATL-PHYS-CONF-2008-3.

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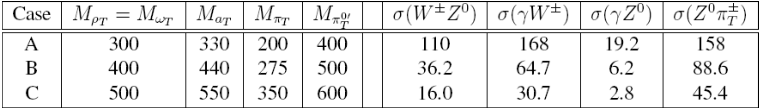
- Cross section estimates



Case	$M_{\rho_T} = M_{\omega_T}$	M_{a_T}	M_{π_T}	$M_{\pi^{0\prime}_T}$		$\sigma(W^{\pm}Z^0)$	$\sigma(\gamma W^{\pm})$	$\sigma(\gamma Z^0)$	$\sigma(Z^0\pi_T^{\pm})$
A	300	330	200	400		110	168	19.2	158
B	400	440	275	500		36.2	64.7	6.2	88.6
C	500	550	350	600		16.0	30.7	2.8	45.4

Signal cross sections in fb, including W, Z branching ratios to e, μ.

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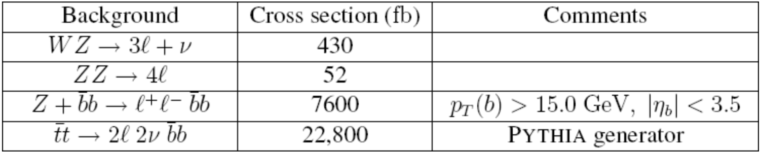
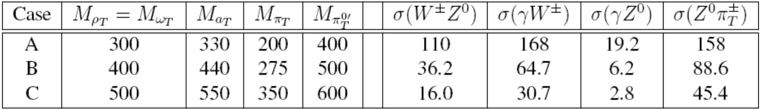


Background	Cross section (fb)	Comments
$WZ \to 3\ell + \nu$	430	
$ZZ \to 4\ell$	52	
$Z + \bar{b}b \to \ell^+\ell^- \bar{b}b$	7600	$p_T(b) > 15.0$ GeV, $\lvert\eta_b\rvert < 3.5$
$\bar{t}t \to 2\ell\ 2\nu\ \bar{b}b$	22,800	PYTHIA generator

ALPGENv13 except for $t\bar{t}$; $\ell = e, \mu$.

- Compare with



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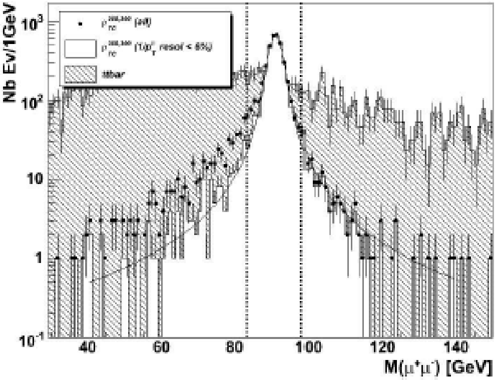
- Kill $t\bar{t}$ background by requiring $\left|M(\ell^+\ell^-) - m_Z\right| \lesssim 7.5$ GeV.



- Figure simulates 5 fb^{-1} of integrated luminosity.

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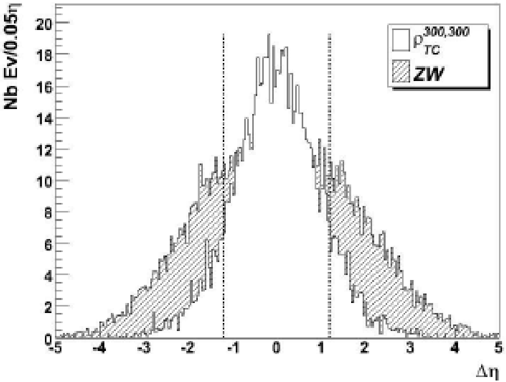
- Kill WZ background by considering difference in W and Z rapidities,

$$|\Delta\left[\eta(Z) - \eta(W)\right]| \leq 1.2.$$



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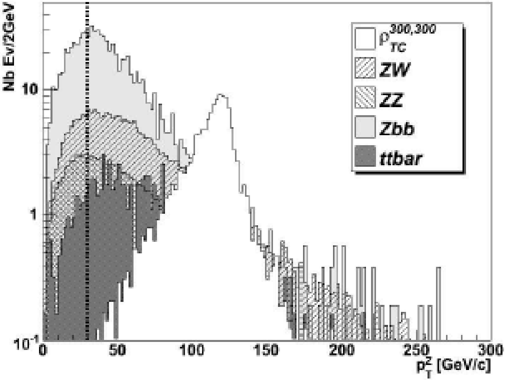
- Reduce all backgrounds further with cuts on $p_T(W)$, $p_T(Z)$, and $\not{E}_T$.
- However, keep cuts modest so that sidebars remain around signal peak.



The inverse problem

- Should we see some signal, how do we decide it’s actually technicolor?

Angular distributions

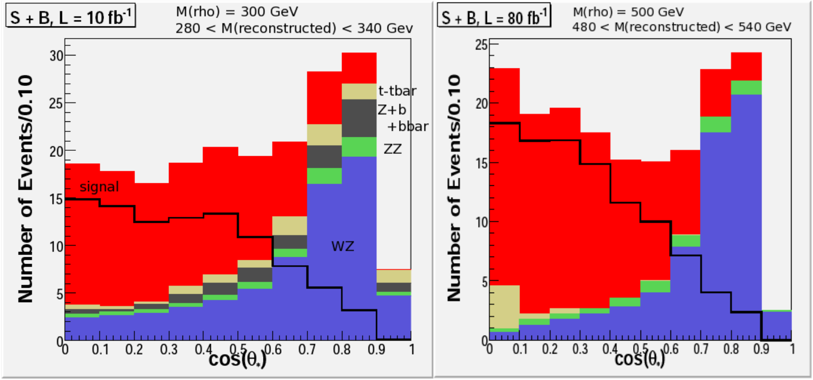
- Should we see some signal, how do we decide it's actually technicolor?
- Distinctive angular distributions in technivector rest frame.

$$\frac{d\sigma\left(\overline{q}q \to \rho_T^\pm \to W_L^\pm Z_L^0\right)}{d\cos\theta} \propto \sin^2\theta \qquad \frac{d\sigma\left(\overline{q}q \to \rho_T^\pm \to \pi_T^\pm Z_L^0\right)}{d\cos\theta} \propto \sin^2\theta$$

$$\frac{d\sigma\left(\overline{q}q \to a_T^\pm \to \gamma W_L^\pm\right)}{d\cos\theta} \propto 1 + \cos^2\theta \qquad \frac{d\sigma\left(\overline{q}q \to \omega_T \to \gamma Z_L^0\right)}{d\cos\theta} \propto 1 + \cos^2\theta.$$

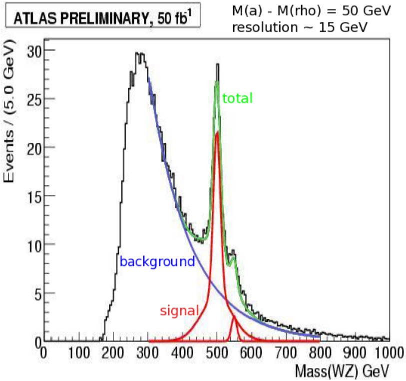
Angular distributions

- Should we see some signal, how do we decide it's actually technicolor?
- Distinctive angular distributions in technivector rest frame.
- Subtract backgrounds from sidebands (e.g. $220 \lesssim M_{WZ} \lesssim 280$ GeV and $340 \lesssim M_{WZ} \lesssim 400$ GeV).



Resonance patterns

- Patterns of masses and widths also provides evidence of new strong interactions.
- E.g. a_T also contributes to WZ channel, but much less than ρ_T.
- With enough data (at least 10 fb^{-1}) and large enough $\Delta m = m_{a_T} - m_{\rho_T}$, can see both resonances in same final state.



Technipions

- Conclusive proof would be direct observation of technipions (apart from $W_L^\pm$ and Z_L) in addition to vector resonances.
- Most promising channel is

$$\rho_T^\pm, a_T^\pm \to Z^0 \pi_T^\pm \to \ell^+\ell^- bj.$$

- Backgrounds ($t\bar{t}$ and Z+jets) not as bad as for $W^\pm \pi_T$ channel since no $\not{E}_T$ helps kill $t\bar{t}$ background.
- Need higher p_T cuts on jets as well, 80 to 150 GeV depending on π_T mass.[64]
- Again see both ρ_T and a_T resonances in final state (with enough integrated luminosity).

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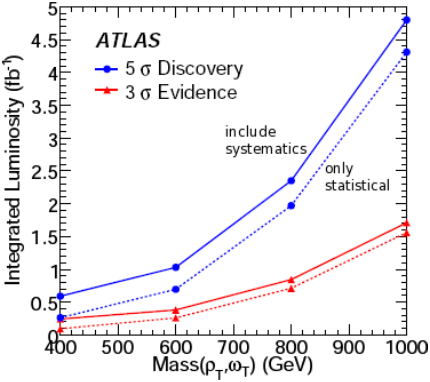
Prospects for LHC discovery

- Les Houches study claims TCSM ρ_T, a_T, ω_T generally observable up to 600 GeV with $\mathcal{O}$(1-10) fb^{-1}.[65] Would need $\mathcal{O}$(10-100) fb^{-1} to check angular distributions.
- ATLAS search for $\omega_T \to \mu^+\mu^-$ (like a Z') also provides promising results at even higher masses.[66]



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[65] Azuelos, Black, Bose, Ferland, Gershtein, Lane and Martin, in Brooijmans et al., 0802.3715.

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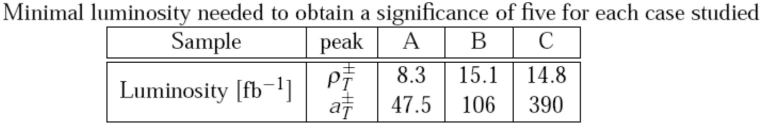
- Decays involving technipions generally harder:



Minimal luminosity needed to obtain a significance of five for each case studied

Sample	peak	A	B	C
Luminosity [fb^{-1}]	$\rho_T^\pm$	8.3	15.1	14.8
	$a_T^\pm$	47.5	106	390

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Only scratching the surface!

- All studies so far rather preliminary.
- Typically only consider a few sets of parameters for straw man model.
- Additional promising modes not yet considered:

$$a_T^0 \to \ell^+\ell^- \qquad \rho_T^0, \omega_T \to \gamma\pi_T^0 \to \gamma b\bar{b}$$

- Many analyses still need to include detector effects, pileup, fakes, systematics.
- Lots more to be done, and opportunities at BU to do it.

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Backup slides

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β function and anomalous dimension.

- Nonabelian gauge theory with n_f approximately massless fermions transforming in the representation r of the gauge group.

$$\begin{aligned}\beta(\alpha) &\equiv \frac{\mu}{2}\frac{\partial\alpha}{\partial\mu} \\ &= -\left(\frac{11}{3}C_2(Adj) - \frac{4}{3}n_f C(r)\right)\frac{\alpha_s^2}{4\pi} - \left(\frac{51}{3}C_2(Adj) - \frac{38}{3}n_f C(r)\right)\frac{\alpha_s^3}{8\pi^2} - \cdots \\ \gamma(\alpha) &\equiv \frac{\mu}{2Z}\frac{\partial Z}{\partial\mu} \overset{\text{SDE}}{\approx} 1 - \sqrt{1 - \frac{3\alpha C_2(F)}{\pi}}\end{aligned}$$

- β and γ depend on the coupling α, which depends on the scale μ.
- For $SU(N)$, $C(F) = 1/2$, $C_2(Adj) = N_C$, and $C_2(F) = (N^2 - 1)/(2N)$, where F is the fundamental representation and Adj is the adjoint.
- Z is the renormalization factor for the operator under consideration $\left(\left\langle \overline{T}T\right\rangle\right)$.
- "SDE" stands for "Schwinger-Dyson equation", nonperturbative approximation for $\gamma \leq 1$.

Backup slides

$\left\langle \overline{T}T \right\rangle$ renormalization group equation

- $\left\langle \overline{T}T \right\rangle\Big|_{ETC} = \left\langle \overline{T}T \right\rangle\Big|_{TC} \exp\left(\int_{\Lambda_{TC}}^{M_{ETC}} \frac{d\mu}{\mu}\gamma(\alpha(\mu))\right).$
- If $\gamma(\alpha(\mu)) \approx \gamma$ is roughly constant from the TC scale to the ETC scale, integrate to get

$$\left\langle \overline{T}T \right\rangle\Big|_{ETC} = \left\langle \overline{T}T \right\rangle\Big|_{TC} \exp\left[\gamma \log\left(\frac{M_{ETC}}{\Lambda_{TC}}\right)\right] = \left\langle \overline{T}T \right\rangle\Big|_{TC} \left(\frac{M_{ETC}}{\Lambda_{TC}}\right)^{\gamma}.$$

- QCD: $\gamma \sim \mathcal{O}(\alpha) \ll 1$, so $\left\langle \overline{T}T \right\rangle\Big|_{ETC} \approx \left\langle \overline{T}T \right\rangle\Big|_{TC}$.
- Walking TC: $\gamma \sim 1$ (upper limit of Schwinger-Dyson equation approximation).
- Strong/conformal TC: $\gamma \sim 1.5$ to 2 (actual upper limit from unitarity).

Backup slides

Symmetry breaking patterns for standard model, technicolor, topcolor, topcolor-assisted technicolor, and a particular ETC model (“hypercolor”).

- SM: $SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(3)_C \times U(1)_{em}$.
- TC: $SU(N_{TC}) \times SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(N_{TC}) \times SU(3)_C \times U(1)_{em}$.
- Topcolor: $SU(3)_1 \times U(1)_{Y1} \times SU(3)_2 \times U(1)_{Y2} \times SU(2)_L \to SU(3)_C \times U(1)_{em}$.
- TC2: $SU(N_{TC}) \times SU(3)_1 \times U(1)_{Y1} \times SU(3)_2 \times U(1)_{Y2} \times SU(2)_L \to SU(N_{TC}) \times SU(3)_C \times U(1)_{em}$.
- ETC/HC (two possible sequences):

$$\begin{aligned}
&SU(5)_{ETC} \times SU(2)_{HC} \times SU(3)_C \times SU(2)_L \times U(1)_Y \\
&\qquad \to SU(4)_{ETC} \times SU(2)_{HC} \times SU(3)_C \times SU(2)_L \times U(1)_Y \\
&\qquad \to SU(3)_{ETC} \times SU(2)_{HC} \times SU(3)_C \times SU(2)_L \times U(1)_Y \\
&\qquad \to SU(2)_{TC} \times SU(2)_{HC} \times SU(3)_C \times U(1)_{em} \\
&SU(5)_{ETC} \times SU(2)_{HC} \times SU(3)_C \times SU(2)_L \times U(1)_Y \\
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&\qquad \to SU(2)_{TC} \times SU(2)_{HC} \times SU(3)_C \times SU(2)_L \times U(1)_Y \\
&\qquad \to SU(2)_{TC} \times U(1)_{HC} \times SU(3)_C \times U(1)_{em}
\end{aligned}$$

Backup slides

Seesaw mass generation mechanism

- In seesaw schemes, we have mass terms (in the flavor basis) like

$$\begin{pmatrix} \bar{t}_L & \overline{T}_L \end{pmatrix} \begin{pmatrix} 0 & \mu \\ m & M \end{pmatrix} \begin{pmatrix} t_R \\ T_R \end{pmatrix},$$

  where $m, \mu \ll M$.

- To move to the mass basis, we have to diagonalize

$$\mathcal{M}^\dagger \mathcal{M} = \begin{pmatrix} 0 & m \\ \mu & M \end{pmatrix} \begin{pmatrix} 0 & \mu \\ m & M \end{pmatrix} = \begin{pmatrix} m^2 & mM \\ mM & \mu^2 + M^2 \end{pmatrix}$$

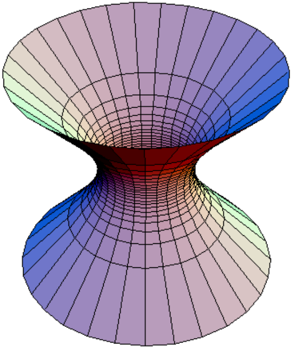
- The eigenvalues are the squared masses

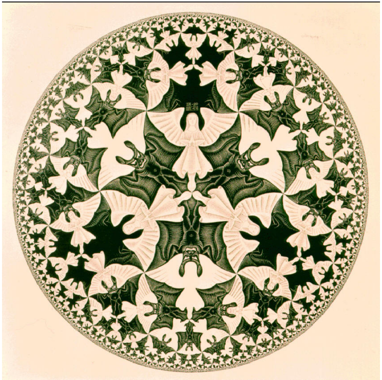
$$m_T^2 = \frac{1}{2}\left[m^2 + \mu^2 + M^2 + \sqrt{\left(m^2 + \mu^2 + M^2\right)^2 - 4m^2\mu^2}\right] \approx m^2 + \mu^2 + M^2$$
$$m_t^2 = \frac{1}{2}\left[m^2 + \mu^2 + M^2 - \sqrt{\left(m^2 + \mu^2 + M^2\right)^2 - 4m^2\mu^2}\right] \approx \frac{m^2\mu^2}{m^2 + \mu^2 + M^2}.$$

- With $m, \mu \ll M$, we naturally have $m_t \ll m_T$.
- Moreover, the larger $m_T \sim M$ is, the smaller $m_t \sim 1/M$ is. Hence "seesaw".

Backup slides

Visualizing AdS (constant negative curvature – hyperboloids)





Backup slides

Dimensional deconstruction

- Perhaps surprisingly, little Higgs models can also be related to extra dimensions, through a scheme known as “dimensional deconstruction”.
- Here the fifth dimension not continuous, but rather a discrete lattice, with as few as three lattice sites (the “Three Site Model”).
- Can also have higgsless models with discrete extra dimension, with at few as three lattice sites (the “Minimal Higgsless Model”).[67,68]
- In deconstructed little Higgs models, fifth dimension is not physical. Each lattice site identified with some of the symmetry groups.
- In simplest case each site has the same groups, just like domain wall lattice gauge theory.
- Also possible to have different groups on different lattice sites.
- Ken’s not a fan.[69]

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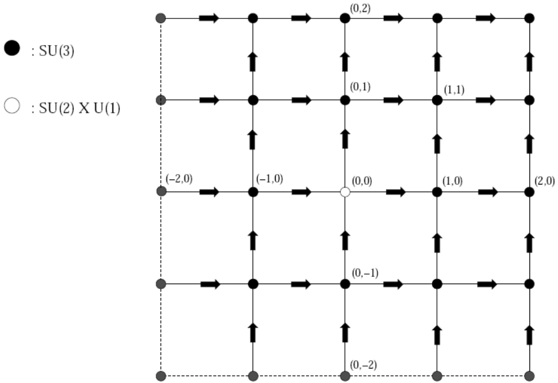
[67] He et al., PRD 78:031701 (2008) 0708.2588.

[68] Belyaev, 0711.1919.

[69] Lane, PRD 65:115001 (2002) hep-ph/0202093.

Backup slides

Sample Moose diagram (two discrete extra dimensions, toroidally compactified)[70]



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[70] Arkani-Hamed, Cohen, Gregoire and Wacker, JHEP 0208:020 (2002) hep-ph/0202089.