Walking Technicolor in light of Z' searches at the LHC

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NExT

Motivation for Technicolor

- Standard Model has many issues; hierarchy problem, no Dark Matter candidate, etc.
- Higgs discovery at LHC leaves many open questions - Which Higgs? Fundamental or Composite? Higgs mechanism realised?
- **Walking Technicolor** (WTC) offers dynamical alternative to spontaneous EWSB
- WTC also addresses hierarchy problem and has a consistent Higgs boson-like *composite* particle

Standard Model vs Technicolor

SM

- Simple, concise lagrangian
- No FCNC issues or tension with EW precision data
- Established and well tested model, agrees with current observation
- Fine-tuning and naturalness problem in 1-loop Higgs mass corrections
- No example of fundamental scalar

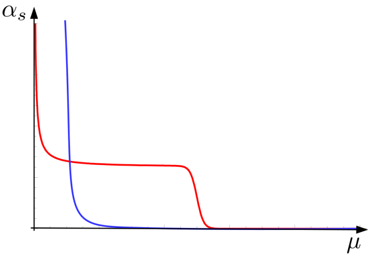
TC

- Complicated eff. lagrangian
- Constraints from FCNC require *walking*, possible EW precision data tension
- TC/Higgs interactions mediated by unknown ETC sector, no viable ETC model
- No fine-tuning, $\Lambda_{TC} \sim 1$TeV dynamically generated
- DSB seen in nature e.g. QCD, superconductivity

Why 'Walking' Technicolor?

To give mass to SM fermions, need new gauge bosons at *Extended Technicolor* scale Λ_{ETC}.

Chiral condensate $\langle\psi\bar{\psi}\rangle$ evaluated at TC scale, but runs to ETC scale.



- Running no light scalar mode (Higgs)
- Walking motivates light Higgs from natural energy scale Λ_{TC}
- Walking enhances $\langle\psi\bar{\psi}\rangle$, suppressing FCNC's
- Running gives too large S, ruled out by EWPD
- Walking reduced S, motivated by EWPD

Particle Spectrum of NMWT

NMWT has simplest global (chiral) symmetry,

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_Y .$$

with chiral symmetry breaking pattern

$$2_L \otimes 2_R \otimes 1_Y \to 3_{V/A} + 1_V .$$

Two new neutral resonances analogous to ρ and a mesons in QCD.

Gauge sector particle spectrum is then:

- SM gauge bosons γ, Z, $W^\pm$
- Composite Higgs as lightest scalar mode, analagous to σ meson in QCD
- New vector and axial triplets, physical particles are $Z', W'^\pm$ and $Z'', W''^\pm$

Setup of NMWT

NMWT is encoded into the low energy effective Lagrangian

$$\mathcal{L}_{boson} = -\frac{1}{2}\mathrm{Tr}\left[\tilde{W}_{\mu\nu}\tilde{W}^{\mu\nu}\right] - \frac{1}{4}\tilde{B}_{\mu\nu}\tilde{B}^{\mu\nu} - \frac{1}{2}\mathrm{Tr}[F_{L\mu\nu}F_L^{\mu\nu} + F_{R\mu\nu}F_R^{\mu\nu}]$$
$$+ m^2\mathrm{Tr}[C_{L\mu}^2 + C_{R\mu}^2] + \frac{1}{2}\mathrm{Tr}[D_\mu M D^\mu M^\dagger] - \tilde{g}^2 r_2 \mathrm{Tr}[C_{L\mu} M C_R^\mu M^\dagger]$$
$$- \frac{i\tilde{g} r_3}{4}\mathrm{Tr}[C_{L\mu}(M D^\mu M^\dagger - D^\mu M M^\dagger) + C_{R\mu}(M^\dagger D^\mu M - D^\mu M^\dagger M)]$$
$$+ \frac{\tilde{g}^2 s}{4}\mathrm{Tr}[C_{L\mu}^2 + C_{R\mu}^2]\mathrm{Tr}[M M^\dagger] + \frac{\mu^2}{2}\mathrm{Tr}[M M^\dagger] - \frac{\lambda}{4}\mathrm{Tr}[M M^\dagger]^2$$

L/R fields are combination of TC and SM fields,

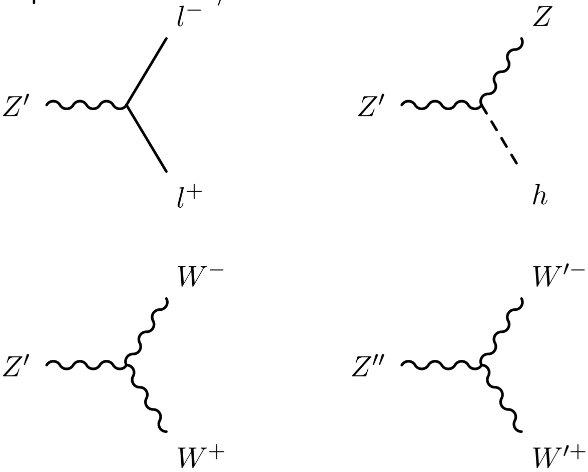
$$C_{L\mu} \equiv A_{L\mu} - \frac{g}{\tilde{g}}\tilde{W}_\mu, \qquad C_{R\mu} \equiv A_{R\mu} - \frac{g'}{\tilde{g}}\tilde{B}_\mu,$$

Note: Coupling between TC and EW sector is $1/\tilde{g}$

Belyaev *et al* 0809.0793

Important Interactions of Z', Z''

Sample of Z'/Z'' decay modes, potential to constrain NMWT parameter space from LHC/collider searches.



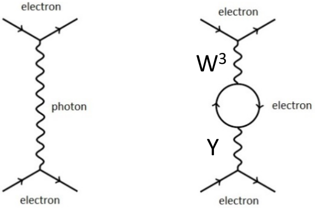
NMWT Parameter Space

Connect effective $\mathcal{L}$ to underlying theory using vector/axial-vector masses and decay constants

$$M_V^2 = m^2 + \frac{\tilde{g}^2(s - r_2)v^2}{4}, \qquad M_A^2 = m^2 + \frac{\tilde{g}^2(s + r_2)v^2}{4},$$

and Weinberg Sum Rules (WSR)

$$S = 4\pi \left[\frac{F_V^2}{M_V^2} - \frac{F_A^2}{M_A^2} \right].$$



NMWT defined by 4-D parameter space

$$\boxed{M_A, \qquad \tilde{g}, \qquad S, \qquad s.}$$

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Model Implementation

LanHEP

$$\mathcal{L}_{kin} = -\frac{1}{2}\mathrm{Tr}\left[\tilde{W}_{\mu\nu}\tilde{W}^{\mu\nu}\right] - \frac{1}{4}\tilde{B}_{\mu\nu}\tilde{B}^{\mu\nu} - \frac{1}{2}\mathrm{Tr}\left[F_{L\mu\nu}F_L^{\mu\nu} + F_{R\mu\nu}F_R^{\mu\nu}\right]$$

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%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Gauge and Vector Kinetic plus Self Interaction Terms %%%%%%%%%%%%

lterm -F**2/4  where  F = deriv^mu*B1^nu-deriv^nu*B1^mu.

lterm -F**2/4  where  F = deriv^mu*WW1^nu^a-deriv^nu*WW1^mu^a -g2*eps^a^b^c*WW1^mu^b*WW1^nu^c.

lterm -F**2/4  where  F = deriv^mu*AL1^nu^a-deriv^nu*AL1^mu^a -g0*eps^a^b^c*AL1^mu^b*AL1^nu^c.

lterm -F**2/4  where  F = deriv^mu*AR1^nu^a-deriv^nu*AR1^mu^a -g0*eps^a^b^c*AR1^mu^b*AR1^nu^c.
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lterm -F**2/4  where  F = deriv^mu*AR1^nu^a-deriv^nu*AR1^mu^a -g0*eps^a^b^c*AR1^mu^b*AR1^nu^c.
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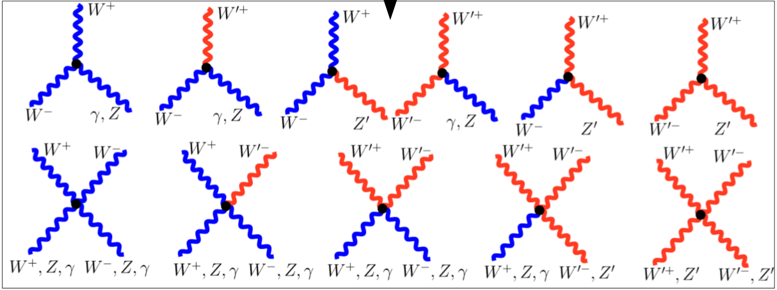
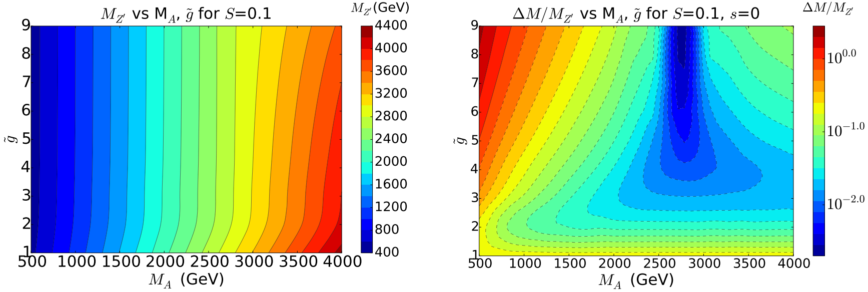
lhep nmwt_feyn_excluderg.mdl

CalcHEP



Mass Spectrum

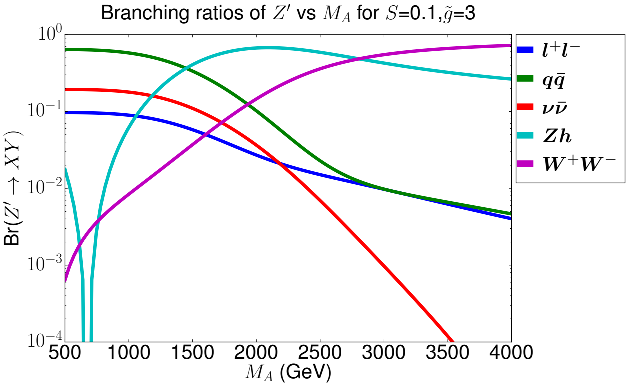


$Z'(Z'')$ switches to mostly vector(axial-vector) resonance at the mass inversion

$$M_{inv}^2 = \left(1 + \frac{g_1^2 + g_2^2}{\tilde{g}^2}\right) \frac{4\pi}{S} F_\pi^2. \qquad (1)$$

Z' Branching Ratios: $\tilde{g} = 3$

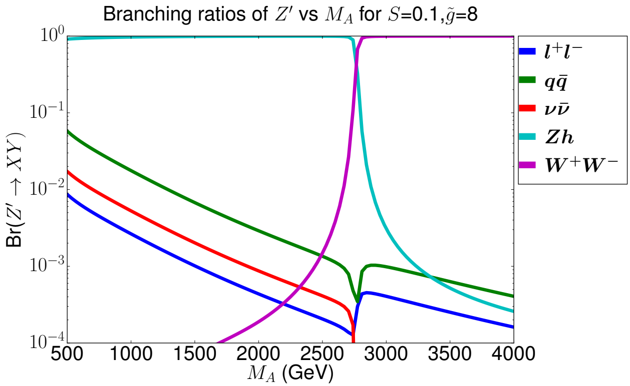
Z' Branching fractions for all all channels in large coupling regime



At low M_A dilepton/quark branching is SM-like, at high M_A di-boson channel dominant.

Z' Branching Ratios: $\tilde{g} = 8$

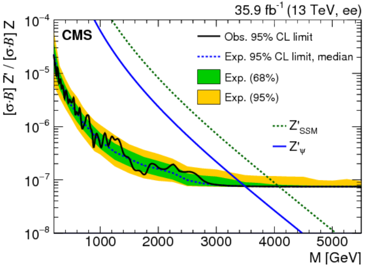
Z' Branching fractions for all all channels in small coupling regime



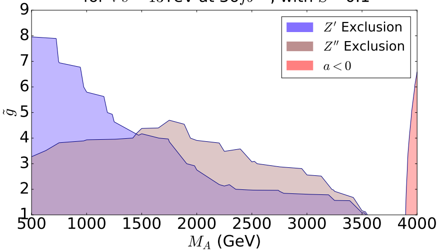
Dilepton channel suppressed at all M_A due to high $\tilde{g}$, Zh dominant when $M_A < M_{inv}$, W^+W^- dominant when $M_A > M_{inv}$.

CMS Drell-Yan dilepton limit on NMWT

We calculate $\sigma^{NNLO}(pp \to Z'/Z'' \to l^+l^+)$ by applying NNLO K-factors to LO σ_{theory} from CalcHEP.



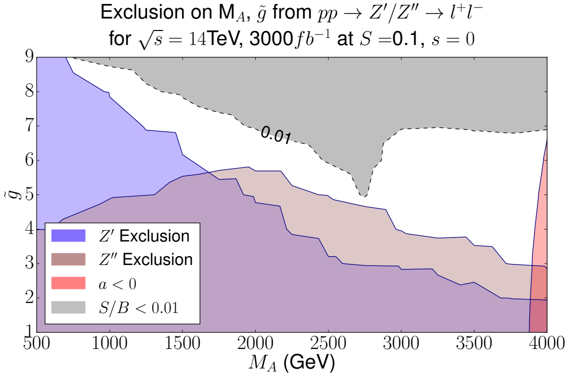
Exclusion on M_A, $\tilde{g}$ from $pp \to Z'/Z'' \to l^+l^-$
for $\sqrt{s} = 13$TeV at 36fb^{-1}, with $S = 0.1$



Exclusion region defined by region where $\sigma^{NNLO}_{theory} > \sigma^{exp}$, Z' and Z'' exclude complementary regions of the NMWT parameter space.

Outlook for WTC at HLLHC: $\sqrt{s} = 14\text{TeV}, 3000\text{fb}^{-1}$

Projected limits on WTC from dilepton channel at the proposed end-point of HLLHC



Dilepton channel limited by S/B ratio, need to extend search to complementary channels.

Conclusions and Outlook

Potential to **disprove** or **discover** Technicolor

- Made first steps by exploring scope of limits from DY dilepton channel
- Working with Holography group to predict the full spectrum of viable WTC models (see Nick Evan's talk)

In progress

- Combining exclusions from complimentary VV and Vh channels for Z'/Z''
- Exclusions from *charged* vector mesons (W'/W'') from VV/Vh channels

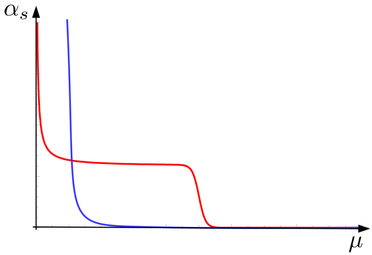
Thank you!

Why 'Walking' Technicolor?

To give mass to SM fermions, need new gauge bosons at *Extended Technicolor* scale Λ_{ETC}.

$\langle\psi\bar{\psi}\rangle$ evaluated at TC scale, but runs to ETC scale

$$\langle\psi\bar{\psi}\rangle_{ETC} = \langle\psi\bar{\psi}\rangle_{TC} \exp \int_{\Lambda_{TC}}^{\Lambda_{ETC}} \frac{d\mu}{\mu}\gamma(\mu), \qquad (2)$$



If $\alpha(\mu)$ running

$$\langle\psi\bar{\psi}\rangle_{ETC} = \langle\psi\bar{\psi}\rangle_{TC} \ln \left(\frac{\Lambda_{ETC}}{\Lambda_{TC}}\right)^{\gamma}$$

If $\alpha(\mu)$ *walking*

$$\langle\psi\bar{\psi}\rangle_{ETC} = \langle\psi\bar{\psi}\rangle_{TC} \left(\frac{\Lambda_{ETC}}{\Lambda_{TC}}\right)^{\gamma}$$

Weinberg Sum Rules

- Zeroth WSR

$$S = 4\pi \left[\frac{F_V^2}{M_V^2} - \frac{F_A^2}{M_A^2} \right] \tag{3}$$

- First WSR

$$F_V^2 - F_A^2 = F_\pi^2 \tag{4}$$

- Second WSR

$$F_V^2 M_V^2 - F_A^2 M_A^2 = a \frac{8\pi^2}{d(R)} F_\pi^4 \tag{5}$$

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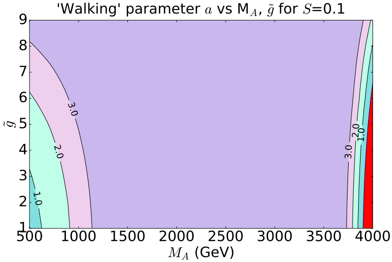
Theoretical constraints

We can constrain the parameter space by considering deviations from 2nd WSR

$$a\frac{8\pi^2}{d(R)}F_\pi^4 = F_V^2 M_V^2 - F_A^2 M_A^2, \quad (6)$$

Require $a > 0$ for walking dynamics



Particle Spectrum

Theory with simplest global symmetry is NMWT, which adds $SU(2)_R$ group to SM. Global (chiral) symmetry is

$$SU(2)_L \times SU(2)_R \times U(1)_Y . \quad (7)$$

Chiral symmetry breaking pattern:

$$2_L \otimes 2_R \otimes 1_Y \to 3_{V/A} + 1_V , \quad (8)$$

We have **two gauge triplets** in TC sector under *hidden local symmetry* in the EFT. Physical particles are $Z', W'^{\pm}$ and $Z'', W''^{\pm}$.

Gauge Mixing Matrix

Matrix of gauge field mixing can be set up directly from $\mathcal{L}_{boson}$

$$\mathcal{M}_N^2 = \begin{pmatrix} \frac{g_1^2}{\tilde{g}^2} M_V^2 & 0 & \frac{g_1}{\sqrt{2}\tilde{g}} M_A^2 \chi & -\frac{g_1}{\sqrt{2}\tilde{g}} M_V^2 \\ 0 & \frac{g_2^2}{\tilde{g}^2} M_V^2 & -\frac{g_2}{\sqrt{2}\tilde{g}} M_A^2 \chi & -\frac{g_2}{\sqrt{2}\tilde{g}} M_V^2 \\ \frac{g_1}{\sqrt{2}\tilde{g}} M_A^2 \chi & -\frac{g_2}{\sqrt{2}\tilde{g}} M_A^2 \chi & M_A^2 & 0 \\ -\frac{g_1}{\sqrt{2}\tilde{g}} M_V^2 & -\frac{g_2}{\sqrt{2}\tilde{g}} M_V^2 & 0 & M_V^2 \end{pmatrix} . \quad (9)$$

Analytic masses

We diagonalise $\mathcal{M}_N^2$ perturbatively order by order in $\tilde{g}^{-1}$,

$$\mathcal{N}^\dagger \mathcal{M}_N^2 \mathcal{N} = \mathcal{D}, \tag{10}$$

where diagonal elements of $\mathcal{D}$ are square masses.

To 2nd order,

$$M_{Z'}^2 = M_A^2 \left(1 + \frac{g_1^2 + g_2^2}{\tilde{g}^2}\chi^2\right) \tag{11}$$

$$M_{Z''}^2 = M_A^2 \left(1 + \frac{g_1^2 + g_2^2}{2\tilde{g}^2}\right)\left(\chi^2 + \frac{\tilde{g}^2 F_\pi^2}{2M_A^2}\right), \tag{12}$$