

Hunting for Minimal Walking Technicolor using Z' searches at the LHC

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Outline

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3 Phenomenology and LHC Sensitivity

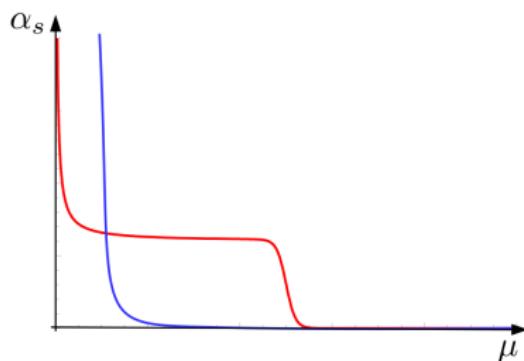
4 Summary

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?
- We are exploring **Walking Technicolor** (WTC) as a dynamical alternative to spontaneous EWSB
- WTC also addresses hierarchy problem and has a consistent Higgs boson-like *composite* particle
- WTC has interesting phenomenology - exploring heavy neutral resonances using **CalcHEP**
- Constraining parameter space to **discover** or **disprove** WTC

WTC Overview

WTC is a strongly interacting theory with interacting bound states of techni-fermions at TeV scale.



Coupling α_S 'walks' between scale of Technicolor, Λ_{TC} up to some Extended TC scale Λ_{ETC} (red)

NMWT has global symmetry $SU(2)_L \times SU(2)_R \times U(1)_Y$.

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} .

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, $\Lambda_{TC} \sim 1\text{TeV}$ dynamically generated
- DSB seen in nature e.g. QCD, superconductivity

Setup of NMWT

NMWT is encoded into the chiral Lagrangian (low energy description)

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

Key constructs in equation 1:

$$C_{L\mu} \equiv A_{L\mu} - \frac{g}{\tilde{g}}\tilde{W}_\mu, \quad C_{R\mu} \equiv A_{R\mu} - \frac{g'}{\tilde{g}}\tilde{B}_\mu, \quad (2)$$

Lagrangian parameters: $m, r_2, r_3, s, \tilde{g}$.

Rephrase parameters in terms of vector-vector and axial-vector masses and decay constants

$$M_V^2 = m^2 + \frac{\tilde{g}^2(s - r_2)v^2}{4}, \quad M_A^2 = m^2 + \frac{\tilde{g}^2(s + r_2)v^2}{4}. \quad (3)$$

Use the Weinberg Sum Rules to connect effective \mathcal{L} to underlying theory

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

where F_V, F_A are vector and axial decay constants.

NMWT defined by 4-D parameter space

$$\boxed{M_A, \quad \tilde{g}, \quad S, \quad s.} \quad (5)$$

Model Implementation

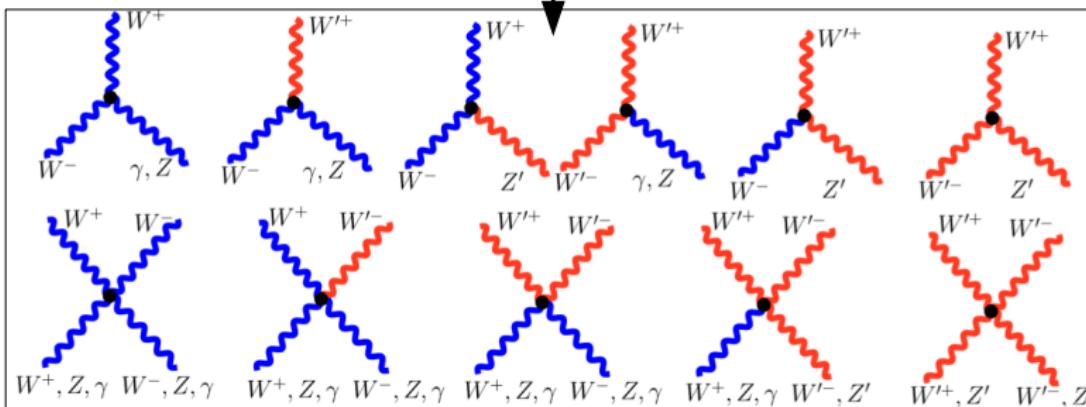
LanHEP

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

```
%%%%%%%%%%%%% 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.|
```

CalcHEP

lhep nmwt_feyn_excluderg.mdl



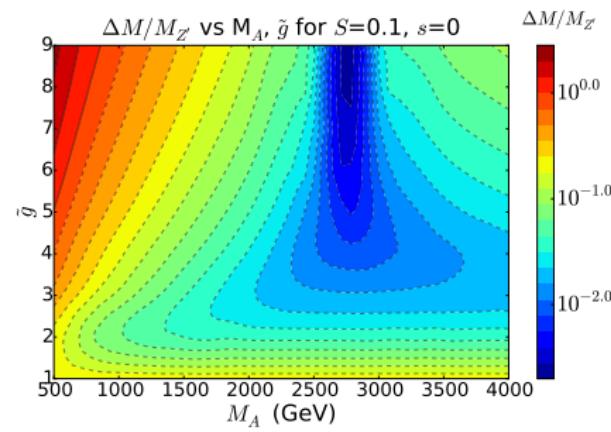
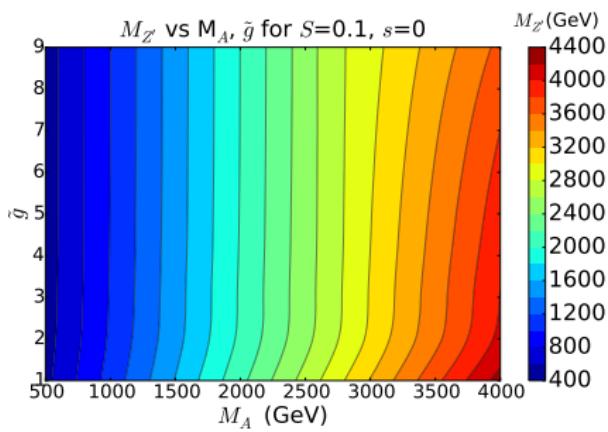
Calculating with CalcHEP

CalcHEP can be utilised through user defined C code - using this method to calculate properties of Z' and Z'' in our NMWT model.

Built in CalcHEP functions can be written in to user scan to collect desired properties

CalcHEP function	Output
<code>assignValW("Parameter name", Param)</code>	Parameter Value
<code>pWidth("Particle name", &branchings)</code>	$\Gamma_{Particle}$
<code>findBr(branchings,"X,Y")</code>	$Br(P \rightarrow X, Y)$
<code>findValW("Constraint name")</code>	Constraint value

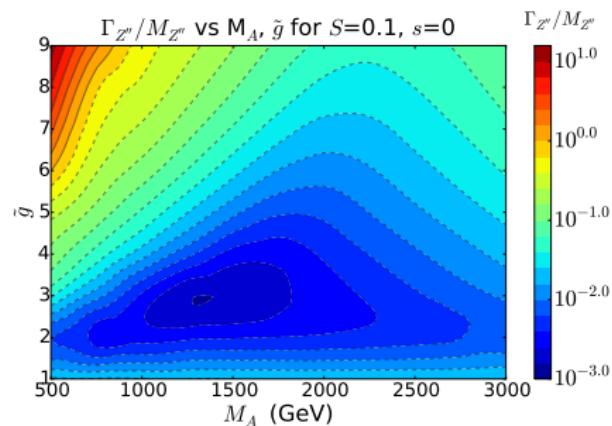
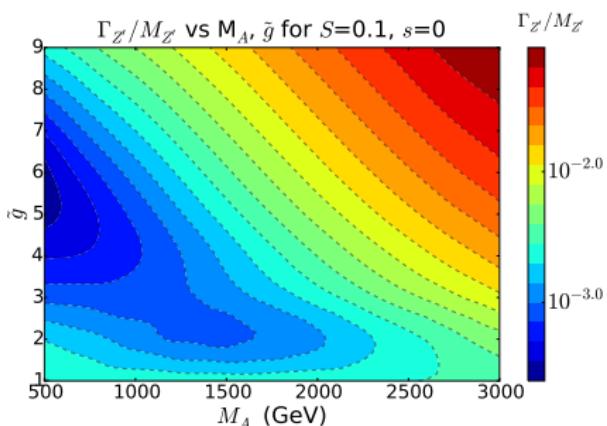
Mass Spectrum



$M_{Z'} \simeq M_A$ (scale of NMWT) for majority of parameter-space.
The Z'' is *always* heavier than the Z' .

Validity of Effective Lagrangian

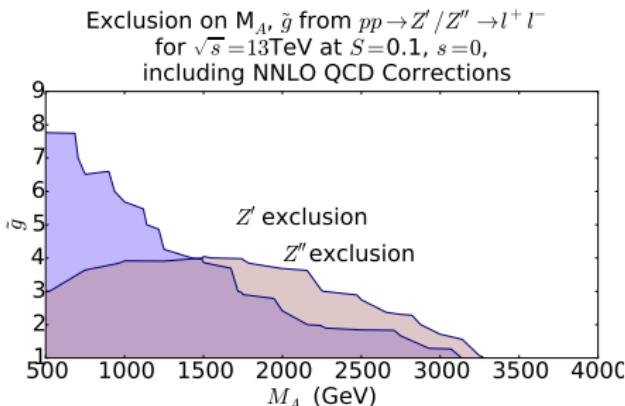
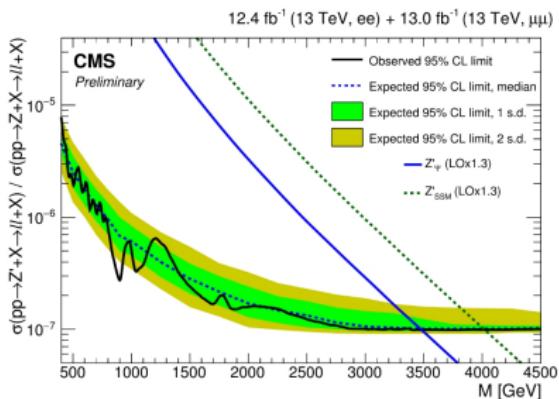
Check Width to Mass ratio for each resonance



Effective Lagrangian describes all of parameter space for Z' , but theory becomes non-perturbative in low M_A , high \tilde{g} for Z'' .

Experimental limit

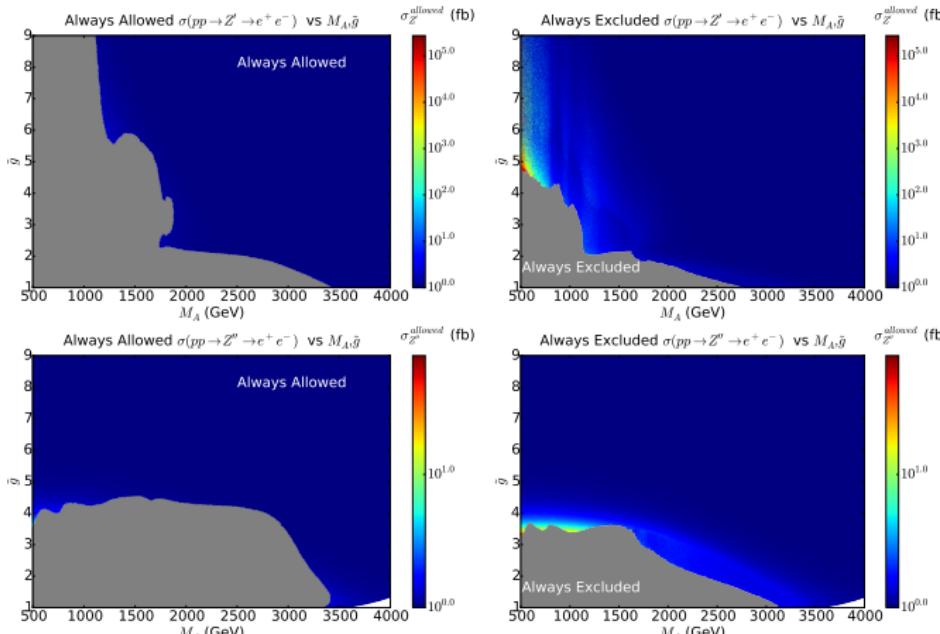
We calculate the theoretical cross section $\sigma(pp \rightarrow Z'/Z'' \rightarrow e^+e^-)$ across the 4-D NMWT parameter space using **IRIDIS4**, through the **HEPMDB** interface.



Exclusion region defined by region where $\sigma^{theory} > \sigma^{exp.}$

AA and AE: $M_A - \tilde{g}$

Using **IRIDIS** we scan $\sim 10M$ points to set up Always Allowed and Always Excluded regions by layering excluded points on top of allowed for AA, and vice versa for AE.



Outlook for WTC

NMW model being tested from a Holography perspective in collaboration with Nick Evans and Marc Scott.

Calculate entire spectrum of possible NMWT models using Holography to predict NMWT parameters.



Project onto our parameter space, can state which possible NMWT theories are excluded.
Results to come soon!

Summary

- NMWT is a well motivated and phenomenologically interesting BSM theory
- We have produced the first combined Z'/Z'' limits on the NMWT parameter space using LHC data
- We have constructed Always Allowed and Always Excluded regions of NMWT space
- Future work: finding limits from all other possible decay channels with aim of "no-lose" theorem exclusions
- Final aim to **discover** or **disprove** NMWT using LHC soon!

Thank you!

Why 'Walking' Technicolor?

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

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

$$\langle\psi\bar{\psi}\rangle_{ETC} = \langle\psi\bar{\psi}\rangle_{TC} \exp \int_{\Lambda_{TC}}^{M_{ETC}} \frac{d\mu}{\mu} \gamma(\mu), \quad (6)$$

If $\alpha(\mu)$ QCD-like (running), anomalous dimension also 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*, anomalous dimension *constant* across these energy scales,

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

Weinberg Sum Rules

- Zeroth WSR

$$S = 4\pi \left[\frac{F_V^2}{M_V^2} - \frac{F_A^2}{M_A^2} \right] \quad (7)$$

- First WSR

$$F_V^2 - F_A^2 = F_\pi^2 \quad (8)$$

- Second WSR

$$F_V^2 M_V^2 - F_A^2 M_A^2 = a \frac{8\pi^2}{d(R)} F_\pi^4 \quad (9)$$

High Luminosity Predictions

Projecting CMS upper limit to higher luminosities we can predict the WTC exclusions that will be found in the future

