# Collider Phenomenology of Minimal Walking Technicolor

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**Template for Minimal Walking Technicolor**

LanHEP/CalcHEP project in collaboration with:

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... to appear soon

# Technicolor Phenomenology Road Map

1. Identify Benchmark Walking Technicolor theories:
   Not ruled out by Electroweak Precision Measurements
2. Construct Effective Lagrangians:
   Using the symmetries of the underlying Lagrangian.
3. Constrain Parameter Space of the Effective Lagrangian from the Underlying Dynamics:
   Using Weinberg sum rules and electroweak precision measurements.
4. Implement Effective Lagrangian in MC Generators and Study the LHC Phenomenology.
5. Perform Lattice Simulations of Benchmark Theories:
   Determine the spectrum and LEC's of the underlying theory.

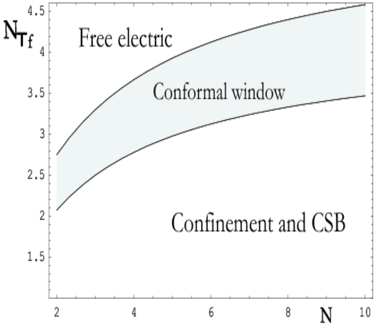
# Related Phenomenology of Strong Interactions

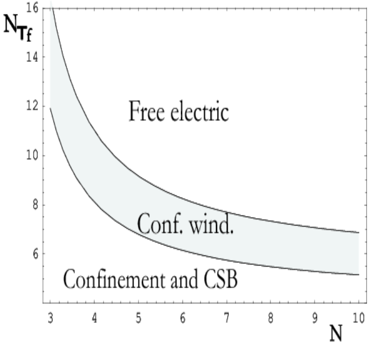
1. Technicolor Straw Man Model(Lane 99; Lane, Mrenna 02 )
2. Degenerate BESS Model (Casalbuoni, De Andrea, De Curtis, Dominici, Gatto, Grazzini 95).
3. Holographic Technicolor models (Hirn, Sanz 06; Hirn, Martin, Sanz 08).
4. Higssless models (Birkedal, Matchev, Perelstein 04; He et al 07).

# Benchmark Walking Technicolor Models

1. $\mathcal{L}_{\mathsf{newphysics}} = -\frac{1}{4} F^{a}_{\mu\nu} F^{a\mu\nu} + i\bar{Q}_{\mathsf{L}} \gamma_\mu D^\mu Q_{\mathsf{L}} + i\bar{Q}_{\mathsf{R}} \gamma_\mu D^\mu Q_{\mathsf{R}}$
2. Minimal Walking Technicolor (MWT) (Sannino and Tuominen 05)
   - $SU(2)_{TC}$ gauge group. 2 Flavors in the adjoint rep. of $SU(2)_{TC}$.
3. Next to Minimal Walking Technicolor (NMWT) (Sannino and Tuominen 05)
   - $SU(3)_{TC}$ gauge group. 2 Flavors in the 2-index symmetric rep. of $SU(3)_{TC}$.

# Phase Diagram




**2-index symmetric and fundamental reps. of $SU(N)$ (Dietrich, Sannino and Tuominen 05).**

# Effective Theories and Constraints

1. Effective theory of the MWT (Foadi, M.T.F, Ryttov, and Sannino 07)
   - Parameter space constraints from LEP and unitarity (Dietrich, Sannino and Tuominen 05; Foadi, M.T.F and Sannino 07; Foadi and Sannino 08)
2. Effective theory of the NMWT (M. Jarvinens talk this workshop )

# NMWT Model Particle Content

1. Particles:
   - A composite Higgs boson.
   - Spin-1 vector and an axial-vector resonances.
   - Eaten pions.
   - This is a complete list in NMWT. Additional bound states in MWT due to the larger chiral symmetry and a new lepton doublet due to Witten anomaly.
2. Input parameters are $M_H$, $M_{\mathsf{A}}$, $\tilde{g}$, $\gamma$, $s$
   - $S$ is taken fixed from underlying theory.
   - $M_V, r_2, r_3$ fixed using also Weinberg Sum Rules.
   - $r_1$ extra parameter in the MWT model.

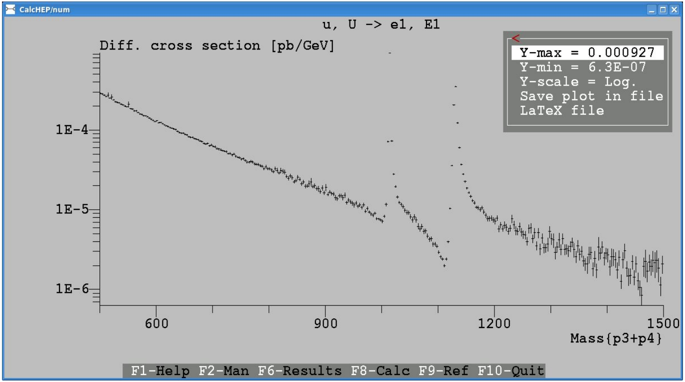
# NMWT Model Effective Lagrangian

$$
\begin{aligned}
\mathcal{L}_{\mathsf{H}} &= \frac{1}{2}\mathsf{Tr}\left[D_\mu M (D^\mu M)^\dagger\right] - \mathcal{V}(\mathcal{M}) \\
\mathcal{L}_{\mathsf{kin}} &= -\frac{1}{2}\mathsf{Tr}\left[\widetilde{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \\
&- \frac{1}{2}\mathsf{Tr}\left[F_{\mathsf{L}\mu\nu}F_{\mathsf{L}}^{\mu\nu} + F_{\mathsf{R}\mu\nu}F_{\mathsf{R}}^{\mu\nu}\right] \\
\mathcal{L}_{\mathsf{MN}} &= -\frac{r_3}{4}\ \mathsf{Tr}\left[(D_\mu N_{\mathsf{L}})^\dagger N_{\mathsf{L}}\left(M(D^\mu M)^\dagger - D^\mu M M^\dagger\right)\right] + \ldots \\
\mathcal{L}_\gamma &= -\frac{2\gamma}{v^2}\ \mathsf{Tr}\left[N_{\mathsf{L}}^\dagger F_{\mathsf{L}\mu\nu} N_{\mathsf{L}} M N_{\mathsf{R}} F_{\mathsf{R}}^{\mu\nu} N_{\mathsf{R}}^\dagger M^\dagger\right]\ . \qquad (1)
\end{aligned}
$$

# LanHEP/CalcHEP Implementation of (N)MWT Models

1. LanHEP (A.Semenov ) allows automatic generation of Feynman rules from 'paper' Lagrangian. Checks for:
   - Hermiticity
   - BRST invariance
   - Electromagnetic charge conservation
   - Conversion to Sherpa format (Ferland and Krauss)
2. CalcHEP (A.Pukhov ) allows immediate model implementation using LanHEP and a user friendly graphical interface
   - Interface to MicroOmegas (G.Belanger et al)
   - Interface to Pythia (Belyaev et al 01)

# Mass bumps in DY process for NMWT



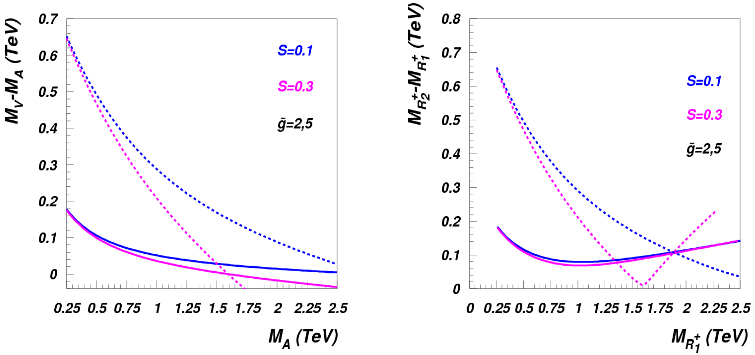
# Implementation Cross Checks

1. Check decoupling limit: large vector masses and $S = 0$.
2. Check degenerate BESS limit:
   $M_V = M_A, r_1 = r_2 = r_3 = s = 0$ (Casalbuoni, De Andrea, De Curtis, Dominici, Gatto, Grazzini 95).
3. Compare decay widths with analytical computations.
4. Compare unitary gauge and 't Hooft-Feynman gauge implementations.

# Signatures of the (N)MWT models

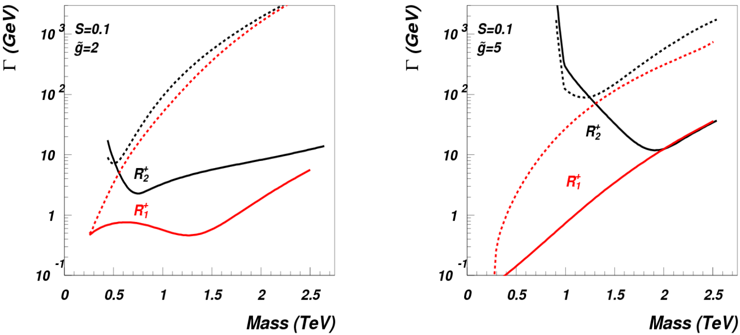
1. New physics of composite heavy vectors
    - Drell-Yan production of heavy vector bosons
    - Vector Boson Fusion production of heavy vectors
    - Associate production of heavy vectors
2. Composite Higgs signals
    - Associate Higgs Production (Zerwekh 05 )
    - Higgs $\rightarrow \gamma\gamma$ (Belyaev, Blum, Chivukula and Simmons 05 )
    - Vector Boson Fusion production of Higgs
3. Further signatures of MWT model
    - DM candidates (Gudnason, Kouvaris and Sannino 05; Kainulainen, Tuominen, Virkajarvi 06; Kouvaris 07; Kouvaris, Khlopov 08 )
    - New lepton family - Additional contribution to S
    - Extra scalars

# Vector Axial-Vector Mass Splitting



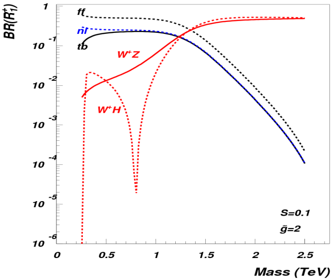

**Within the LHC reach, $M_V > M_A$ for small values of $S$.**

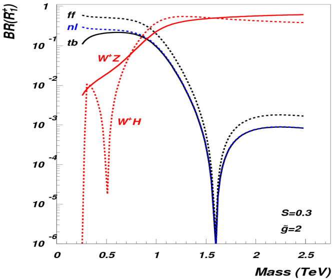
# Vector and Axial-Vector Decay Widths




1. **The vector can be much wider than the axial:** $R_2^0 \to R_1^+ R_1^-$.
2. **This changes when $\gamma$ is different from zero.**

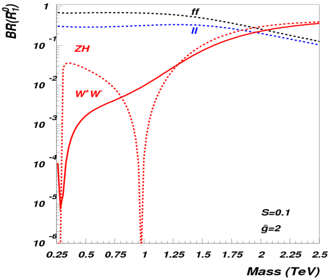
# $R_1^+$ Resonance Branching Ratios



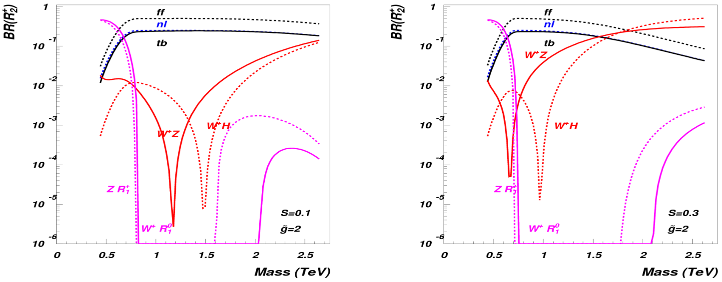

1. **BR to $WH$ dip: Due to small $S$ (minimality).**
2. **BR to fermions dip: No mixing at mass inversion (Compare w/ D-BESS).**

# $R_1^0$ Resonance Branching Ratios



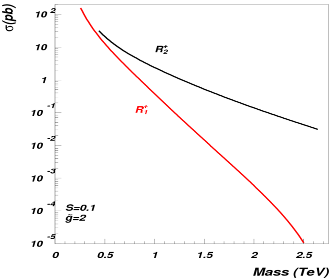

1. **No dip in BR to fermions: $R_1^0$ Mixing w/ photon (Compare w/ D-BESS).**

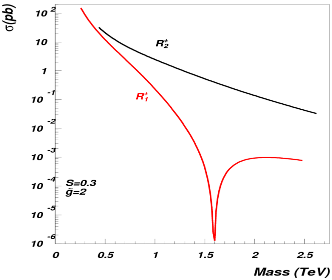
# $R_2^+$ Resonance Branching Ratios




1. **BR to $WZ$ dip: Consequence of small $S$ (minimality).**
2. **BR to fermions no dip: No decoupling at mass inversion.**

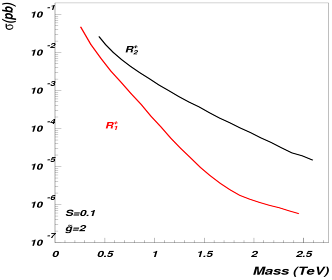
# Drell-Yan production of the charged resonances

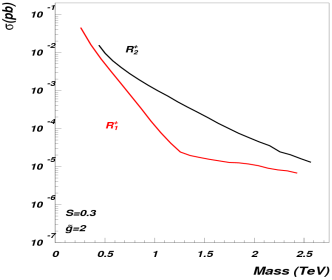



1. **Characteristic dip in $R_1^+$ production.**
2. **CS $O(100)$ above Higgsless (3-site) models .**

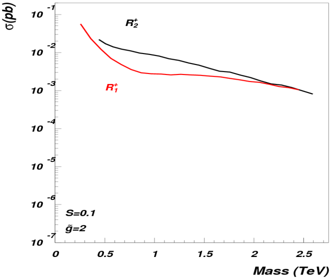
# VBF production of the charged resonances



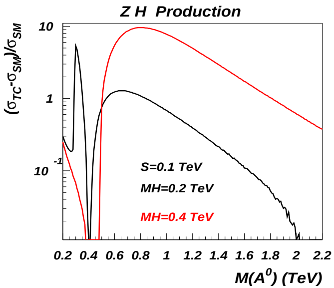

1. **Cuts applied (Birkedal, Matchev, Perelstein 04; He et al 07).**
2. **CS $O(10)$ below Higgsless (3-site) models. Compare to D-BESS.**

# VBF production of the charged resonances




1. **Turning on the $\gamma$ parameter: CS comparable to 3-site model at large masses.**

# Associate Higgs Production




1. Notice the vanishing for finite values of the axial mass: consequence of small $S$.
2. Early analysis in a simpler Technicolor model. (Zerwekh 05 )

# Lattice Simulations

1. MWT and NMWT provide new avenues for lattice BSM physics
   - Dynamical fermions are crucial, but only at a low number of flavors.
2. Identify the (near-by) fixed point and the Walking behavior.
3. determine the mass spectrum and the parameters of the effective lagrangian
4. Work is underway (Catteral and Sannino 07; Del Debbio, M.T.F, Panagopoulos, and Sannino 08; Del debbio, Patella and Pica 08 )

# Summary

1. (N)MWT models are viable and natural candidates for EWSB.
2. The LHC phenomenology is rich, including several Dark Matter candidates
3. The LHC signatures and discovery potential should be investigated
   - NMWT model has been (MWT is being) implemented in LanHEP/CalcHEP in different gauges.
   - MWT model is being implemented into Sherpa, more to follow...
   - The first phenomenology to appear very soon!
4. Lattice simulations are starting to provide information on the spectrum of the models