Progress on (Minimal) Walking Technicolor

(M)WT on Calchep

Roshan Foadi

CERN, March 10$^{\text{th}}$ 2008

In collaboration with:

Alexander Belyaev

Mads T. Frandsen

Matti O. Järvinen

Francesco Sannino

Technicolor

1. Strongly coupled gauge theory, with a spontaneously broken and electroweak gauged chiral symmetry. (Weinberg 79; Susskind 79)

Technicolor

1. Strongly coupled gauge theory, with a spontaneously broken and electroweak gauged chiral symmetry. (Weinberg 79; Susskind 79)
2. Already observed in Nature: QCD !

Technicolor

1. Strongly coupled gauge theory, with a spontaneously broken and electroweak gauged chiral symmetry. (Weinberg 79; Susskind 79)
2. Already observed in Nature: QCD !
3. No hierarchy problem: theory natural all the way up to the unification scale.

Technicolor

1. Strongly coupled gauge theory, with a spontaneously broken and electroweak gauged chiral symmetry. (Weinberg 79; Susskind 79)
2. Already observed in Nature: QCD !
3. No hierarchy problem: theory natural all the way up to the unification scale.
4. Problem: no fermion masses. Extended Technicolor (ETC) needed at some higher scale. (Lane and Eichten 80)

Technicolor

1. Strongly coupled gauge theory, with a spontaneously broken and electroweak gauged chiral symmetry. (Weinberg 79; Susskind 79)
2. Already observed in Nature: QCD !
3. No hierarchy problem: theory natural all the way up to the unification scale.
4. Problem: no fermion masses. Extended Technicolor (ETC) needed at some higher scale. (Lane and Eichten 80)
   - ETC typically leads to flavor changing neutral currents (FCNC).

Technicolor

1. Strongly coupled gauge theory, with a spontaneously broken and electroweak gauged chiral symmetry. (Weinberg 79; Susskind 79)
2. Already observed in Nature: QCD !
3. No hierarchy problem: theory natural all the way up to the unification scale.
4. Problem: no fermion masses. Extended Technicolor (ETC) needed at some higher scale. (Lane and Eichten 80)
    - ETC typically leads to flavor changing neutral currents (FCNC).
    - Tension between fermion masses and FCNC in QCD-like Technicolor.

Walking Technicolor

1. Near conformal theory between $E > \Lambda_{\mathrm{TC}}$ and $E < \Lambda_{\mathrm{ETC}}$. (Holdom 81)

Walking Technicolor

1. Near conformal theory between $E > \Lambda_{\text{TC}}$ and $E < \Lambda_{\text{ETC}}$. (Holdom 81)
2. Enhancement of SM fermion masses and suppression of FCNC. (Appelquist, Karabali and Wijewardhana 86; Yamawaki, Bando, and Matumoto 86)

Walking Technicolor

1. Near conformal theory between $E > \Lambda_{\rm TC}$ and $E < \Lambda_{\rm ETC}$. (Holdom 81)
2. Enhancement of SM fermion masses and suppression of FCNC. (Appelquist, Karabali and Wijewardhana 86; Yamawaki, Bando, and Matumoto 86)
3. Better behavior of the S parameter relative to a running theory. (Appelquist and Sannino 98)

Walking Technicolor

1. Near conformal theory between $E > \Lambda_{\rm TC}$ and $E < \Lambda_{\rm ETC}$. (Holdom 81)
2. Enhancement of SM fermion masses and suppression of FCNC. (Appelquist, Karabali and Wijewardhana 86; Yamawaki, Bando, and Matumoto 86)
3. Better behavior of the S parameter relative to a running theory. (Appelquist and Sannino 98)
4. Problem: Walking dynamics with fermions in the fundamental representation is only achieved for a large number of flavors. → **Large contribution to the S parameter**.

(Minimal) Walking Technicolor

1. **Fermions in higher dimensional representations** screen more than fermions in the fundamental representation: small number of flavors required to achieve walking dynamics. → **Small** S. (Sannino and Tuominen 05)

(Minimal) Walking Technicolor

1. **Fermions in higher dimensional representations** screen more than fermions in the fundamental representation: small number of flavors required to achieve walking dynamics. $\rightarrow$ **Small** S. (Sannino and Tuominen 05)
2. Additional negative contributions to S from other sectors (e.g. leptons). (R.F., Frandsen, Ryttov, and Sannino 07)

(Minimal) Walking Technicolor

1. **Fermions in higher dimensional representations** screen more than fermions in the fundamental representation: small number of flavors required to achieve walking dynamics. → **Small** S. (Sannino and Tuominen 05)
2. Additional negative contributions to S from other sectors (e.g. leptons). (R.F., Frandsen, Ryttov, and Sannino 07)
3. Examples:

(Minimal) Walking Technicolor

1. **Fermions in higher dimensional representations** screen more than fermions in the fundamental representation: small number of flavors required to achieve walking dynamics. → **Small** S. (Sannino and Tuominen 05)
2. Additional negative contributions to S from other sectors (e.g. leptons). (R.F., Frandsen, Ryttov, and Sannino 07)
3. Examples:
   - $N_c = 2,\ N_f = 2$ in the adjoint → Minimal Walking Technicolor (MWT)

(Minimal) Walking Technicolor

1. **Fermions in higher dimensional representations** screen more than fermions in the fundamental representation: small number of flavors required to achieve walking dynamics. → **Small** S. (Sannino and Tuominen 05)
2. Additional negative contributions to S from other sectors (e.g. leptons). (R.F., Frandsen, Ryttov, and Sannino 07)
3. Examples:
   - $N_c = 2,\ N_f = 2$ in the adjoint → Minimal Walking Technicolor (MWT)
   - $N_c = 3,\ N_f = 2$ in the two index symmetric → Next to Minimal Walking Technicolor (NMWT)

(Minimal) Walking Technicolor

1. Tests of the walking dynamics are underway in lattice simulations. (Catteral and Sannino 07; Del Debbio, Frandsen, Panagopoulos, and Sannino 08)

New Physics

- $\mathcal{L}_{\text{newphysics}} = -\frac{1}{4} F^{a}_{\mu\nu} F^{a\mu\nu} + i\bar{Q}_{\text{L}} \gamma_{\mu} D^{\mu} Q_{\text{L}} + i\bar{Q}_{\text{R}} \gamma_{\mu} D^{\mu} Q_{\text{R}}$

New Physics

- $\mathcal{L}_{\text{newphysics}} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + i\bar{Q}_{\text{L}} \gamma_\mu D^\mu Q_{\text{L}} + i\bar{Q}_{\text{R}} \gamma_\mu D^\mu Q_{\text{R}}$
  - Plus possible lepton doublets or matter in the adjoint.

New Physics

- $\mathcal{L}_{\rm newphysics} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{Q}_{\rm L}\gamma_\mu D^\mu Q_{\rm L} + i\bar{Q}_{\rm R}\gamma_\mu D^\mu Q_{\rm R}$
    - Plus possible lepton doublets or matter in the adjoint.
    - Plus ETC interactions.

Effective Theory

1. At small momenta the interaction is confining.

Effective Theory

1. At small momenta the interaction is confining.
2. The chiral symmetry is spontaneously broken.

Effective Theory

1. At small momenta the interaction is confining.
2. The chiral symmetry is spontaneously broken.
   - $SU(4) \rightarrow SO(4)$ for MWT
   - $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$ for NMWT

Effective Theory

1. At small momenta the interaction is confining.
2. The chiral symmetry is spontaneously broken.
   - SU(4) $\rightarrow$ SO(4) for MWT
   - $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$ for NMWT
3. Effective theory:
   - spin-0 and spin-1 objects filling out representations of the chiral symmetry group.
   - Higgs sector with a broken phase.

Effective Theory

1. Codify the walking behavior and the minimality of the theory (small S) in the effective Lagrangian.

Effective Theory

1. Codify the walking behavior and the minimality of the theory (small S) in the effective Lagrangian.
2. This can be achieved by using the Weinberg Sum Rules (WSRs). (R.F., Frandsen, Ryttov, and Sannino 07)

Effective Theory

1. Codify the walking behavior and the minimality of the theory (small S) in the effective Lagrangian.
2. This can be achieved by using the Weinberg Sum Rules (WSRs). (R.F., Frandsen, Ryttov, and Sannino 07)
   - Model the spin-1 spectrum with a vector and an axial resonances and a close-to-continuum spectrum in the near conformal region.

Effective Theory

1. Codify the walking behavior and the minimality of the theory (small S) in the effective Lagrangian.
2. This can be achieved by using the Weinberg Sum Rules (WSRs). (R.F., Frandsen, Ryttov, and Sannino 07)
   - Model the spin-1 spectrum with a vector and an axial resonances and a close-to-continuum spectrum in the near conformal region.
   - Use some trustable approximation to compute the contribution of the near conformal region to the vacuum polarization amplitudes. (Appelquist and Sannino 98)

WSRs

1. First WSR: no important contributions from the near conformal region.
   - $F_V^2 - F_A^2 = F_\pi^2$

WSRs

1. First WSR: no important contributions from the near conformal region.
   - $F_{\rm V}^2 - F_{\rm A}^2 = F_\pi^2$
2. Second WSR: important contributions from the near conformal region.
   - $F_{\rm V}^2 M_{\rm V}^2 - F_{\rm A}^2 M_{\rm A}^2 = a \frac{8\pi^2}{d({\rm R})} F_\pi^4, \quad a \in \mathcal{O}(1)$

WSRs

1. First WSR: no important contributions from the near conformal region.
   - $F_{\mathrm{V}}^2 - F_{\mathrm{A}}^2 = F_\pi^2$
2. Second WSR: important contributions from the near conformal region.
   - $F_{\mathrm{V}}^2 M_{\mathrm{V}}^2 - F_{\mathrm{A}}^2 M_{\mathrm{A}}^2 = a \frac{8\pi^2}{d(\mathrm{R})} F_\pi^4, \quad a \in \mathcal{O}(1)$
3. S parameter, or "zeroth WSR": important contributions from the near conformal region.
   - $S = 4\pi^2 F_\pi^2 \left[\frac{1}{M_{\mathrm{V}}^2} + \frac{1}{M_{\mathrm{A}}^2} - a \frac{8\pi^2 F_\pi^2}{d(\mathrm{R}) M_{\mathrm{V}}^2 M_{\mathrm{A}}^2} \right]$

Model Content

1. Strongly coupled sector with a walking dynamics.

Model Content

1. Strongly coupled sector with a walking dynamics.
2. A relatively small S parameter.

Model Content

1. Strongly coupled sector with a walking dynamics.
2. A relatively small S parameter.
    - T is identically zero due to custodial symmetry. With mass splitting of the new leptons we can easily be within 1σ in the (S, T) plane.

Model Content

1. Strongly coupled sector with a walking dynamics.
2. A relatively small S parameter.
   - T is identically zero due to custodial symmetry. With mass splitting of the new leptons we can easily be within 1σ in the (S, T) plane.
3. Particles:

Model Content

1. Strongly coupled sector with a walking dynamics.
2. A relatively small S parameter.
   - T is identically zero due to custodial symmetry. With mass splitting of the new leptons we can easily be within 1σ in the (S, T) plane.
3. Particles:
   - A Higgs boson.

Model Content

1. Strongly coupled sector with a walking dynamics.
2. A relatively small S parameter.
   - T is identically zero due to custodial symmetry. With mass splitting of the new leptons we can easily be within 1σ in the (S, T) plane.
3. Particles:
   - A Higgs boson.
   - Spin-1 vector and an axial resonances.

Model Content

1. Strongly coupled sector with a walking dynamics.
2. A relatively small S parameter.
   - T is identically zero due to custodial symmetry. With mass splitting of the new leptons we can easily be within 1σ in the (S, T) plane.
3. Particles:
   - A Higgs boson.
   - Spin-1 vector and an axial resonances.
   - Eaten pions.

Model Content

1. Strongly coupled sector with a walking dynamics.
2. A relatively small S parameter.
   - T is identically zero due to custodial symmetry. With mass splitting of the new leptons we can easily be within 1σ in the (S,T) plane.
3. Particles:
   - A Higgs boson.
   - Spin-1 vector and an axial resonances.
   - Eaten pions.
   - This is a complete description in NMWT (except for the leptons). More bound states in MWT, due to the larger chiral symmetry.

Model Content

1. **All these objects are strongly coupled !**

Model Content

1. **All these objects are strongly coupled !**
2. Important signatures for:
   - $pp \to R^0 \to WW$
   - $pp \to R^+ \to WZ$
   - $pp \to A^0 \to ZH$
   - $pp \to A^+ \to WH$

Model Content

1. **All these objects are strongly coupled !**
2. Important signatures for:
   - $pp \to R^0 \to WW$
   - $pp \to R^+ \to WZ$
   - $pp \to A^0 \to ZH$
   - $pp \to A^+ \to WH$
3. Important signatures from vector boson fusion as well.

Implementation into LanHEP and CalcHEP

1. Write the Lagrangian with the resonances as gauge fields.
(Bando, Kugo, Uehara, Yamawaki, and Yanagida 85)

Implementation into LanHEP and CalcHEP

1. Write the Lagrangian with the resonances as gauge fields. (Bando, Kugo, Uehara, Yamawaki, and Yanagida 85)
2. Impose WSRs to reduce input parameters. After this, main input parameters are $M_{\rm A}$, $\tilde{g}$, and S (or $M_{\rm A}$, $M_{\rm V}$, and S)

Implementation into LanHEP and CalcHEP

1. Write the Lagrangian with the resonances as gauge fields. (Bando, Kugo, Uehara, Yamawaki, and Yanagida 85)
2. Impose WSRs to reduce input parameters. After this, main input parameters are $M_{\rm A}$, $\tilde{g}$, and S (or $M_{\rm A}$, $M_{\rm V}$, and S)
3. Test the model:

Implementation into LanHEP and CalcHEP

1. Write the Lagrangian with the resonances as gauge fields. (Bando, Kugo, Uehara, Yamawaki, and Yanagida 85)
2. Impose WSRs to reduce input parameters. After this, main input parameters are $M_{\rm A}$, $\tilde{g}$, and S (or $M_{\rm A}$, $M_{\rm V}$, and S)
3. Test the model:
   - Check the decoupling limit (large vector masses and $S = 0$).

Implementation into LanHEP and CalcHEP

1. Write the Lagrangian with the resonances as gauge fields. (Bando, Kugo, Uehara, Yamawaki, and Yanagida 85)
2. Impose WSRs to reduce input parameters. After this, main input parameters are $M_{\rm A}$, $\tilde{g}$, and S (or $M_{\rm A}$, $M_{\rm V}$, and S)
3. Test the model:
   - Check the decoupling limit (large vector masses and $S = 0$).
   - Check the degenerate BESS limit. (Casalbuoni, De Andrea, De Curtis, Dominici, Gatto, Grazzini 95).

Implementation into LanHEP and CalcHEP

1. Write the Lagrangian with the resonances as gauge fields. (Bando, Kugo, Uehara, Yamawaki, and Yanagida 85)
2. Impose WSRs to reduce input parameters. After this, main input parameters are $M_{\rm A}$, $\tilde{g}$, and S (or $M_{\rm A}$, $M_{\rm V}$, and S)
3. Test the model:
   - Check the decoupling limit (large vector masses and $S = 0$).
   - Check the degenerate BESS limit. (Casalbuoni, De Andrea, De Curtis, Dominici, Gatto, Grazzini 95).
   - Compare obtained results with some analytical computations. (Partially done.....)

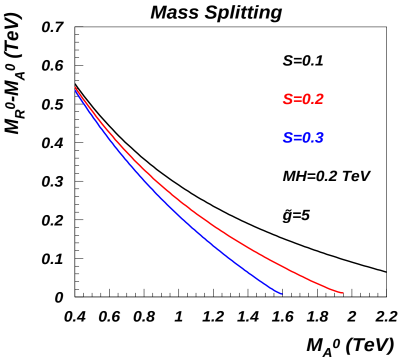
Implementation into LanHEP and CalcHEP

1. Write the Lagrangian with the resonances as gauge fields. (Bando, Kugo, Uehara, Yamawaki, and Yanagida 85)
2. Impose WSRs to reduce input parameters. After this, main input parameters are $M_{\rm A}$, $\tilde{g}$, and S (or $M_{\rm A}$, $M_{\rm V}$, and S)
3. Test the model:
   - Check the decoupling limit (large vector masses and $S = 0$).
   - Check the degenerate BESS limit. (Casalbuoni, De Andrea, De Curtis, Dominici, Gatto, Grazzini 95).
   - Compare obtained results with some analytical computations. (Partially done.....)
   - Compare unitary gauge and 't Hooft-Feynman gauge implementations. (Still to do !)

CAUTION: WORK IN PROGRESS !

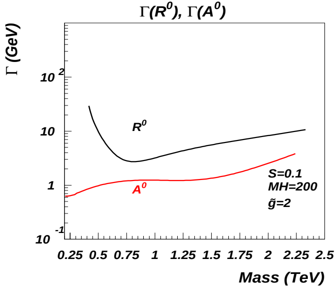
At the early stages.....

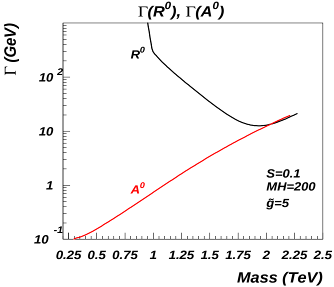
Vector-Axial Mass Splitting



Within the LHC reach, $M_{\rm V} > M_{\rm A}$ for small values of S.

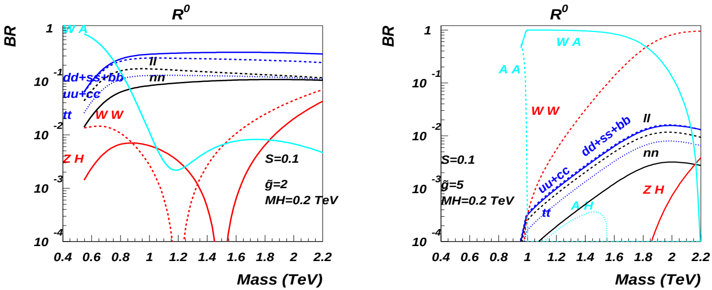
Vector and Axial Decay Widths





1. **The vector can be much wider than the axial because of the decay $R^0 \to A^+A^-$.**
2. **If $M_{R^0} < 2M_{A^0}$, both vector and axial are very narrow.**

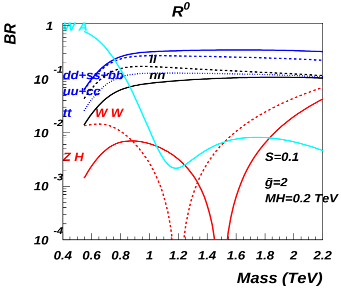
Vector Resonance Branching Ratios

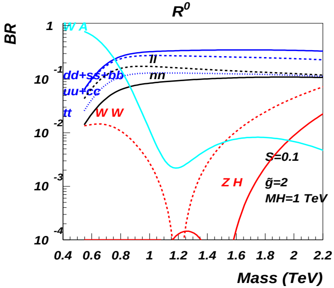


1. **The BR in WW drops to zero and rises: consequence of small S (minimality of the theory).**
2. **For large $\tilde{g}$ BR to fermions drops.**

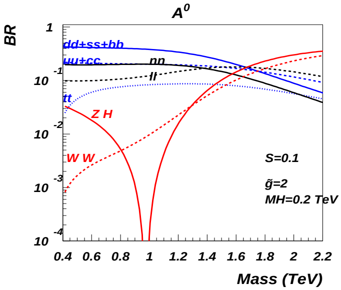
Vector Resonance Branching Ratios

Compare BRs for different Higgs masses.

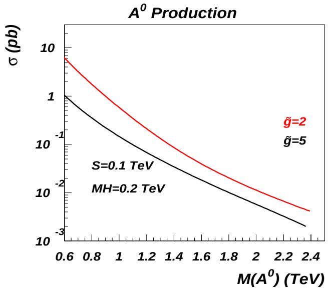




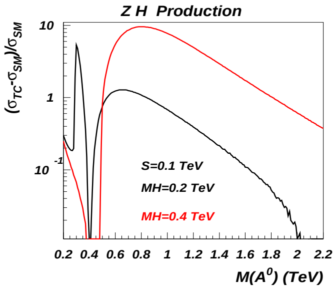
Axial Resonance Branching Ratios



Vector and Axial Direct Production



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)

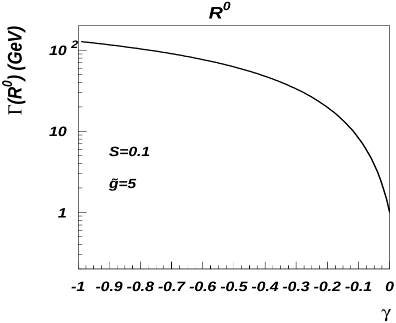
Narrow Widths ?

1. In technicolor models the vector resonances are typically narrow. In (M)WT, if $M_{R^0} < 2M_{A^0}$, both vector and axial are very narrow.
2. However, there is a term in the Lagrangian which mixes left and right field strength tensors......(Kaymacalan and Schechter 85)

$$\mathcal{L} \supset -\frac{2\gamma}{v^2}\mathrm{Tr}\left[F_{L\mu\nu} M F_R^{\mu\nu} M^\dagger\right]$$

$$\Gamma_{\rm V} \propto \left(-\frac{\gamma}{1-\gamma} + \frac{1+\gamma}{1-\gamma}\frac{\tilde{g}^2 S}{16\pi}\right)^2$$

Narrow Widths ?



$$M_{\rm A} = 1\ {\rm TeV}, \quad S = 0.1, \quad \tilde{g} = 5$$

$\mathcal{O}(10^2)$ **enhancement of the vector width !**

Conclusions

- (Minimal) Walking Technicolor is an ordinary 4D gauge theory.

Conclusions

- (Minimal) Walking Technicolor is an ordinary 4D gauge theory.
- It satisfies the electroweak constraints.

Conclusions

- (Minimal) Walking Technicolor is an ordinary 4D gauge theory.
- It satisfies the electroweak constraints.
- It does not give rise to FCNC.

Conclusions

- (Minimal) Walking Technicolor is an ordinary 4D gauge theory.
- It satisfies the electroweak constraints.
- It does not give rise to FCNC.
- It can be extended to include more models, like split technicolor or partially gauged technicolor. (Dietrich and Sannino 05)

Conclusions

- (Minimal) Walking Technicolor is an ordinary 4D gauge theory.
- It satisfies the electroweak constraints.
- It does not give rise to FCNC.
- It can be extended to include more models, like split technicolor or partially gauged technicolor. (Dietrich and Sannino 05)
- It can be written as an effective field theory with vector and axial resonances and a Higgs (NMWT), plus other resonances in models with a large chiral symmetry group (MWT).

Conclusions

- New leptons can always be added in the spectrum (needed in MWT), as well as matter in the adjoint.

Conclusions

- New leptons can always be added in the spectrum (needed in MWT), as well as matter in the adjoint.
- Dark matter candidates were discussed in previous works. (Gudnason, Kouvaris, and Sannino 06; Kainulainen, Tuominen, and Virkajarvi 06)

Conclusions

- New leptons can always be added in the spectrum (needed in MWT), as well as matter in the adjoint.
- Dark matter candidates were discussed in previous works. (Gudnason, Kouvaris, and Sannino 06; Kainulainen, Tuominen, and Virkajarvi 06)
- Important phenomenological signatures are:
  - Axial resonance lighter than the vector if within the LHC reach.

Conclusions

- New leptons can always be added in the spectrum (needed in MWT), as well as matter in the adjoint.
- Dark matter candidates were discussed in previous works. (Gudnason, Kouvaris, and Sannino 06; Kainulainen, Tuominen, and Virkajarvi 06)
- Important phenomenological signatures are:
  - Axial resonance lighter than the vector if within the LHC reach.
  - Vanishing BRs for R^0 and A^0 into WW and ZH at finite mass. (Consequence of small S.)

Conclusions

- New leptons can always be added in the spectrum (needed in MWT), as well as matter in the adjoint.
- Dark matter candidates were discussed in previous works. (Gudnason, Kouvaris, and Sannino 06; Kainulainen, Tuominen, and Virkajarvi 06)
- Important phenomenological signatures are:
  - Axial resonance lighter than the vector if within the LHC reach.
  - Vanishing BRs for R^0 and A^0 into WW and ZH at finite mass. (Consequence of small S.)
  - Enhancement in the associate Higgs production with Z.

Conclusions

- Additional expected signatures are:
  - Enhancement in $pp \to WZ$, with a clean trileptonic signature.

Conclusions

- Additional expected signatures are:
  - Enhancement in $pp \to WZ$, with a clean trileptonic signature.
  - If $\tilde{g}$ is large, production by vector boson fusion becomes dominant over direct production.

Conclusions

- For these reasons and more (M)WT should be considered as a **benchmark for Technicolor** theories.

Conclusions

- For these reasons and more (M)WT should be considered as a **benchmark for Technicolor** theories.
- Investigations with SHERPA are in progress. (Frank Kraus, Jonathan Ferland)

Conclusions

- For these reasons and more (M)WT should be considered as a **benchmark for Technicolor** theories.
- Investigations with SHERPA are in progress. (Frank Kraus, Jonathan Ferland)
- ETC theories for higher dimensional representation should be investigated. (See for ex. Christensen and Shrock 05.)