Minimal Walking Technicolor

Dark Matter and Collider Signatures

Mads Toudal Frandsen

University of Oxford

Mini-Workshop on DEWSB models and tools, Southampton, July 7$^{\text{th}}$ 2010

m.frandsen1@physics.ox.ac.uk

Outline

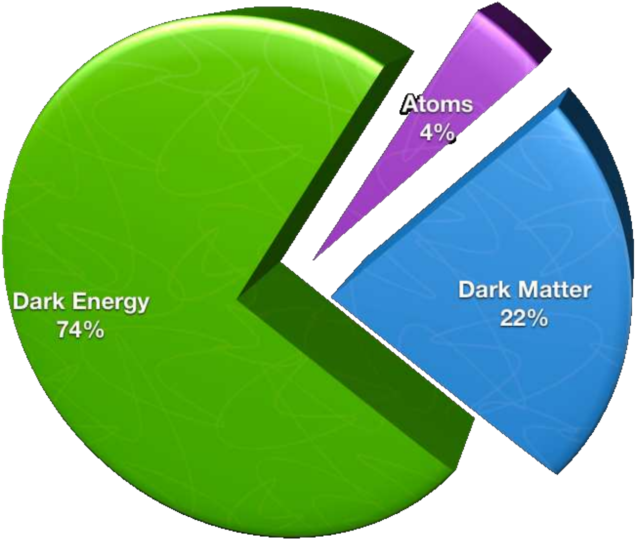
Outline

In collaboration with:

Alexander Belyaev (Southampton U.),
Roshan Foadi (Michigan State U.),
Matti Jarvinen (CP3-Origins),
Alexander Pukhov (Moscow State U.),
Francesco Sannino (CP3-Origins),
Subir Sarkar (Oxford U.)
Alexander Sherstnev (Oxford U.).

A. Belyaev, M.T.F and A. Sherstnev In progress

What is the world made of?



What should the world be made of?

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD}	**Nucleons**	Baryon number	⊗ > 10^{33} yr (dim-6 OK)	'freeze-out' from thermal equilibrium	$\Omega_B \sim 10^{-10}$ cf. observed $\Omega_B \sim 0.05$
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino?	R-parity?	violated?	'freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.3$

For (softly broken) susy we have the 'WIMP miracle':

$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27} \mathrm{cm}^{-3} \mathrm{s}^{-1}}{\langle \sigma v \rangle_{T=T_f}}$$

Why is the abundance of thermal relics **comparable** to that of baryons born non-thermally, with $\Omega_{DM}/\Omega_B \sim 5$?

What should the world be made of?

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD}	**Nucleons**	Baryon number	⊗ > 10^{33} yr (dim-6 OK)	'freeze-out' from thermal equilibrium	$\Omega_B \sim 10^{-10}$ cf. observed $\Omega_B \sim 0.05$
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino? Technibaryon?	R-parity? Technibaryon #	violated? ⊘ ~ 10^{18} yr e^+ excess?!	'freeze-out' from thermal equilibrium Asymmetric (like the observed baryons)	$\Omega_{LSP} \sim 0.3$ $\Omega_{TB} \sim 0.3$
$\Lambda_{DB} \sim 5\,\Lambda_{QCD}$	Dark Baryon?	Dark Baryon #	?	Asymmetric	$\Omega_{DB} \sim 0.3$

Composite vs 'SM-like' Higgs sector

- Natural, $v_{EW} \sim F_\Pi$ dynamical.
- Fine-tuning, triviality etc.

Composite vs 'SM-like' Higgs sector

- Natural, $v_{EW} \sim F_\Pi$ dynamical.
- Known realizations QCD and Superconductivity

- Fine-tuning, triviality etc.
- No known fundamental scalars

Composite vs 'SM-like' Higgs sector

- Natural, $v_{EW} \sim F_{\Pi}$ dynamical.
- Known realizations QCD and Superconductivity
- Naturally stable DM. Ω_{DM}, Ω_B of same origin?

- Fine-tuning, triviality etc.
- No known fundamental scalars
- Hand-made stability.

Composite vs 'SM-like' Higgs sector

- Natural, $v_{EW} \sim F_{\Pi}$ dynamical.
- Known realizations QCD and Superconductivity
- Naturally stable DM. Ω_{DM}, Ω_B of same origin?
- Dynamical flavor sector complicated

- Fine-tuning, triviality etc.
- No known fundamental scalars
- Hand-made stability.
- Flavor sector simply parametrized

Technicolor

EWSB from Technicolor: (Weinberg 78, Susskind 78)

1. In the SM without a Higgs, QCD breaks the EW symmetry:

$$\langle \bar{u}_L u_R + \bar{d}_L d_R \rangle \neq 0 \quad \rightarrow \quad M_W = \frac{g f_\pi}{2} \ .$$

2. Consider a new strongly interacting gauge theory with $F_\Pi = v_{EW} = 246 GeV$.
3. Let the electroweak gauge group be a subgroup of the chiral symmetry group.

Technicolor

EWSB from Technicolor: (Weinberg 78, Susskind 78)

1. In the SM without a Higgs, QCD breaks the EW symmetry:

$$\langle \bar{u}_L u_R + \bar{d}_L d_R \rangle \neq 0 \quad \rightarrow \quad M_W = \frac{g f_\pi}{2} \ .$$

2. Consider a new strongly interacting gauge theory with $F_\Pi = v_{EW} = 246 GeV$.
3. Let the electroweak gauge group be a subgroup of the chiral symmetry group.

Example: Scaled-up QCD !

New Strong Sector

1. The SM gauge group is augmented:

$$G_{SM} \rightarrow SU(3)_{\mathrm{c}} \times SU(2)_{\mathrm{W}} \times U(1)_{\mathrm{Y}} \times G_{\mathrm{TC}} \ .$$

New Strong Sector

1. The SM gauge group is augmented:

$$G_{SM} \rightarrow SU(3)_{\mathrm{c}} \times SU(2)_{\mathrm{W}} \times U(1)_{\mathrm{Y}} \times G_{\mathrm{TC}} \ .$$

2. The Higgs sector of the SM is replaced:

$$\mathcal{L}_{Higgs} \rightarrow -\frac{1}{4} F^{a}_{\mu\nu} F^{a\mu\nu} + i\bar{Q}_{\mathrm{L}} \gamma_{\mu} D^{\mu} Q_{\mathrm{L}} + i\bar{Q}_{\mathrm{R}} \gamma_{\mu} D^{\mu} Q_{\mathrm{R}} + \ldots$$

New Strong Sector

1. The SM gauge group is augmented:

$$G_{SM} \to SU(3)_{\mathrm{c}} \times SU(2)_{\mathrm{W}} \times U(1)_{\mathrm{Y}} \times G_{\mathrm{TC}} \ .$$

2. The Higgs sector of the SM is replaced:

$$\mathcal{L}_{Higgs} \to -\frac{1}{4} F^{a}_{\mu\nu} F^{a\mu\nu} + i \bar{Q}_{\mathrm{L}} \gamma_{\mu} D^{\mu} Q_{\mathrm{L}} + i \bar{Q}_{\mathrm{R}} \gamma_{\mu} D^{\mu} Q_{\mathrm{R}} + \ldots$$

Minimal chiral symmetries: 3 GB's + Custodial + DM.

$$SU_L(2) \times SU_R(2) \times U_{TB}(1) \to SU_V(2) \times U_{TB}(1) \ .$$

Technicolor dark matter

Technocosmology (Nussinov 85)

Lightest Technibaryon as Asymmetric Dark Matter

Technicolor dark matter

Technocosmology (Nussinov 85)

Lightest Technibaryon as Asymmetric Dark Matter

- The LTB abundance:

$$\Omega_{TB}/\Omega_B = m_{TB}/m_B \times n_{TB}/n_B$$

Technicolor dark matter

Technocosmology (Nussinov 85)

Lightest Technibaryon as Asymmetric Dark Matter

- The LTB abundance:

$$\Omega_{TB}/\Omega_B = m_{TB}/m_B \times n_{TB}/n_B$$

- From initial $n_B \sim n_{TB}$:

$$\begin{aligned} \Omega_{TB}/\Omega_B &\sim m_{TB}/m_B \times (m_{TB}/T_{sphaleron})^{3/2} e^{-m_{TB}/T_{sphaleron}} \\ T_{sphaleron} &\sim v_{EW} \ , \end{aligned}$$

(Chivukula and Walker 90; Bahr, Chivukula and Farhi 90; Harvey and Turner 90; Ellis et al 95; Sarkar 95; Gudnason, Kouvaris and Sannino 05)

Technicolor dark matter

Technocosmology (Nussinov 85)

Lightest Technibaryon as Asymmetric Dark Matter

- The LTB abundance:

$$\Omega_{TB}/\Omega_B = m_{TB}/m_B \times n_{TB}/n_B$$

- From initial $n_B \sim n_{TB}$:

$$\Omega_{TB}/\Omega_B \sim m_{TB}/m_B \times (m_{TB}/T_{sphaleron})^{3/2} e^{-m_{TB}/T_{sphaleron}}$$

$$T_{sphaleron} \sim v_{EW} \,, \quad M_{TB} \sim TeV$$

(Chivukula and Walker 90; Bahr, Chivukula and Farhi 90; Harvey and Turner 90; Ellis et al 95; Sarkar 95; Gudnason, Kouvaris and Sannino 05)

Technicolor dark matter

Technocosmology (Nussinov 85)

Lightest Technibaryon as Asymmetric Dark Matter

- The LTB abundance:

$$\Omega_{TB}/\Omega_B = m_{TB}/m_B \times n_{TB}/n_B$$

- From initial $n_B \sim n_{TB}$:

$$\Omega_{TB}/\Omega_B \sim m_{TB}/m_B \times (m_{TB}/T_{sphaleron})^{3/2} e^{-m_{TB}/T_{sphaleron}}$$
$$T_{sphaleron} \sim v_{EW} \ , \quad M_{TB} \sim TeV$$

(Chivukula and Walker 90; Bahr, Chivukula and Farhi 90; Harvey and Turner 90; Ellis et al 95; Sarkar 95; Gudnason, Kouvaris and Sannino 05)

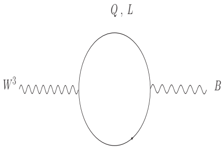
- Or 'Dark Baryon' with $m_{DB} \sim 5 - 10 GeV$?

(D.B.Kaplan 92; An, Chen, Mohapatra and Zhang 09; D.E.Kaplan, Luty and Zurek 09; Fitzpatrick, Zurek and Hooper 10; M.T.F and Sarkar 10)

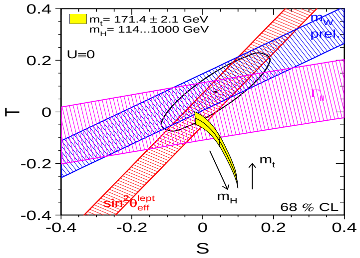
Constraints from LEP

1. A minimal matter content in the TC sector is favored:

$$S \equiv -16\pi \Pi'_{W^3 B}(0) \ , \quad T \equiv \frac{4\pi}{s_W^2 c_W^2 M_Z^2}(\Pi_{W^1 W^1}(0) - \Pi_{W^3 W^3}(0))$$



$$S_{\rm naive} = N_D \frac{d(R_{\rm TC})}{6\pi}$$

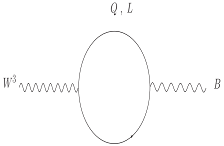


(Kennedy and Lynn 89; Peskin and Takeuchi 90; Altarelli and Barbieri 91)

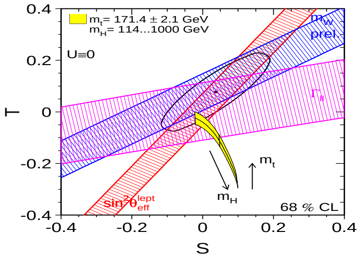
Constraints from LEP

1. A minimal matter content in the TC sector is favored:

$$S \equiv -16\pi\Pi'_{W^3B}(0)\ ,\ \ T \equiv \frac{4\pi}{s_W^2 c_W^2 M_Z^2}(\Pi_{W^1W^1}(0) - \Pi_{W^3W^3}(0))$$



$$S_{\rm naive} = N_D \frac{d(R_{\rm TC})}{6\pi}$$



(Kennedy and Lynn 89; Peskin and Takeuchi 90; Altarelli and Barbieri 91)

2. $S \sim S_{\rm naive}$ in Walking (near-conformal) Technicolor (?)
(Sundrum and Hsu 92; Appelquist and Sannino 98; Harada, Kurachi and Yamawaki 03; Kurachi and Shrock 06; Sannino 10)

Minimal Technicolor Theory Space

Minimal Technicolor: 2 EW charged Dirac Flavors

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \ , \quad U_R^{+1/2} \ , \ D_R^{-1/2} \ ; \quad \lambda^f \ .$$

Minimal Technicolor Theory Space

Minimal Technicolor: 2 EW charged Dirac Flavors

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \ , \quad U_R^{+1/2} \ , \ D_R^{-1/2} \ ; \quad \lambda^f \ .$$

'Orthogonal TC'

'QCD TC'

'Symplectic TC'

Minimal Technicolor Theory Space

Minimal Technicolor: 2 EW charged Dirac Flavors

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \ , \quad U_R^{+1/2} \ , \ D_R^{-1/2} \ ; \quad \lambda^f \ .$$

'Orthogonal TC'

- $\mathcal{R}$ real

'QCD TC'

- $\mathcal{R}$ complex

'Symplectic TC'

- $\mathcal{R}$ pseudo-real

Minimal Technicolor Theory Space

Minimal Technicolor: 2 EW charged Dirac Flavors

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \ , \quad U_R^{+1/2} \ , \ D_R^{-1/2} \ ; \quad \lambda^f \ .$$

'Orthogonal TC'

- $\mathcal{R}$ real
- F of $SO(N)$

'QCD TC'

- $\mathcal{R}$ complex
- F of $SU(N)$

'Symplectic TC'

- $\mathcal{R}$ pseudo-real
- F of $Sp(2N)$

Minimal Technicolor Theory Space

Minimal Technicolor: 2 EW charged Dirac Flavors

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \ , \quad U_R^{+1/2} \ , \ D_R^{-1/2} \ ; \quad \lambda^f \ .$$

'Orthogonal TC'

- $\mathcal{R}$ real
- F of $SO(N)$
- $SU(4)/SO(4)$

'QCD TC'

- $\mathcal{R}$ complex
- F of $SU(N)$
- $SU(2)$

'Symplectic TC'

- $\mathcal{R}$ pseudo-real
- F of $Sp(2N)$
- $SU(4)/Sp(4)$

Minimal Technicolor Theory Space

Minimal Technicolor: 2 EW charged Dirac Flavors

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \ , \quad U_R^{+1/2}\ , \ D_R^{-1/2}\ ; \quad \lambda^f \ .$$

'Orthogonal TC'

- $\mathcal{R}$ real
- F of $SO(N)$
- $SU(4)/SO(4)$
- $3_\Pi \oplus 3 \oplus \bar{3}$

'QCD TC'

- $\mathcal{R}$ complex
- F of $SU(N)$
- $SU(2)$
- 3_Π

'Symplectic TC'

- $\mathcal{R}$ pseudo-real
- F of $Sp(2N)$
- $SU(4)/Sp(4)$
- $3_\Pi \oplus 1 \oplus \bar{1}$

Minimal Technicolor Theory Space

Minimal Technicolor: 2 EW charged Dirac Flavors

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \quad , \quad U_R^{+1/2} \ , \ D_R^{-1/2} \ ; \quad \lambda^f \ .$$

'Orthogonal TC'

- $\mathcal{R}$ real
- F of $SO(N)$
- $SU(4)/SO(4)$
- $3_\Pi \oplus 3 \oplus \bar{3}$

$$\begin{pmatrix} \Pi & T_i \\ T_i^* & \Pi^T \end{pmatrix}$$

'QCD TC'

- $\mathcal{R}$ complex
- F of $SU(N)$
- $SU(2)$
- 3_Π

$$\Pi = \begin{pmatrix} \Pi^0 & \Pi^+ \\ \Pi^- & \Pi^0 \end{pmatrix}$$

'Symplectic TC'

- $\mathcal{R}$ pseudo-real
- F of $Sp(2N)$
- $SU(4)/Sp(4)$
- $3_\Pi \oplus 1 \oplus \bar{1}$

$$\begin{pmatrix} \Pi & T_s \\ T_s^* & \Pi^T \end{pmatrix}$$

Minimal Technicolor Theory Space

Minimal Technicolor: 2 EW charged Dirac Flavors

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \ , \quad U_R^{+1/2} \ , \ D_R^{-1/2} \ ; \quad \lambda^f \ .$$

'Orthogonal TC'

- $\mathcal{R}$ real
- F of $SO(N)$
- $SU(4)/SO(4)$
- $3_\Pi \oplus 3 \oplus \bar{3}$

$$\begin{pmatrix} \Pi & T_i \\ T_i^* & \Pi^T \end{pmatrix}$$

$$T_i = \begin{pmatrix} T^0 & T^+ \\ T^- & T^{0*} \end{pmatrix}$$

'QCD TC'

- $\mathcal{R}$ complex
- F of $SU(N)$
- $SU(2)$
- 3_Π

$$\Pi = \begin{pmatrix} \Pi^0 & \Pi^+ \\ \Pi^- & \Pi^0 \end{pmatrix}$$

'Symplectic TC'

- $\mathcal{R}$ pseudo-real
- F of $Sp(2N)$
- $SU(4)/Sp(4)$
- $3_\Pi \oplus 1 \oplus \bar{1}$

$$\begin{pmatrix} \Pi & T_s \\ T_s^* & \Pi^T \end{pmatrix}$$

$$T_s = \begin{pmatrix} T^0 & 0 \\ 0 & T^{0*} \end{pmatrix}$$

Dark Matter from Minimal Technicolor

TIMP: Complex scalar, charged under the $U(1)_{TB}$ symmetry

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \ , \quad U_R^{+1/2} \ , \ D_R^{-1/2} \ ; \quad \lambda^f \ .$$

Dark Matter from Minimal Technicolor

TIMP: Complex scalar, charged under the $U(1)_{TB}$ symmetry

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \ , \quad U_R^{+1/2} \ , \ D_R^{-1/2} \ ; \quad \lambda^f \ .$$

'iTIMP'

(M.T.F and F.Sannino 09)

'TIMP'

(Bahr, Chivukula and Farhi 90; Nussinov 92)

'TIMP'

(Ryttov and Sannino 08; Foadi, M.T.F and Sannino 09)

Dark Matter from Minimal Technicolor

TIMP: Complex scalar, charged under the $U(1)_{TB}$ symmetry

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \;, \quad U_R^{+1/2} \;, \; D_R^{-1/2} \;; \quad \lambda^f \;.$$

'iTIMP'

- $\mathcal{R}$ real

(M.T.F and F.Sannino 09)

'TIMP'

(Bahr, Chivukula and Farhi 90; Nussinov 92)

'TIMP'

- $\mathcal{R}$ pseudo-real

(Ryttov and Sannino 08; Foadi, M.T.F and Sannino 09)

Dark Matter from Minimal Technicolor

TIMP: Complex scalar, charged under the $U(1)_{TB}$ symmetry

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \ , \quad U_R^{+1/2} \ , \ D_R^{-1/2} \ ; \quad \lambda^f \ .$$

'iTIMP'

- $\mathcal{R}$ real
- $T^0 \sim UD$

(M.T.F and F.Sannino 09)

'TIMP'

(Bahr, Chivukula and Farhi 90; Nussinov 92)

'TIMP'

- $\mathcal{R}$ pseudo-real
- $T^0 \sim UD$

(Ryttov and Sannino 08; Foadi, M.T.F and Sannino 09)

Dark Matter from Minimal Technicolor

TIMP: Complex scalar, charged under the $U(1)_{TB}$ symmetry

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \ , \quad U_R^{+1/2} \ , \ D_R^{-1/2} \ ; \quad \lambda^f \ .$$

'iTIMP'

- $\mathcal{R}$ real
- $T^0 \sim UD$
- Iso-singlet GB

(M.T.F and F.Sannino 09)

'TIMP'

(Bahr, Chivukula and Farhi 90; Nussinov 92)

'TIMP'

- $\mathcal{R}$ pseudo-real
- $T^0 \sim UD$
- SM singlet GB

(Ryttov and Sannino 08; Foadi, M.T.F and Sannino 09)

Dark Matter from Minimal Technicolor

TIMP: Complex scalar, charged under the $U(1)_{TB}$ symmetry

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \ , \quad U_R^{+1/2} \ , \ D_R^{-1/2} \ ; \quad \lambda^f \ .$$

'iTIMP'

- $\mathcal{R}$ real
- $T^0 \sim UD$
- Iso-singlet GB
- $M_{T^0} \sim g\, F_\Pi$

(M.T.F and F.Sannino 09)

'TIMP'

(Bahr, Chivukula and Farhi 90; Nussinov 92)

'TIMP'

- $\mathcal{R}$ pseudo-real
- $T^0 \sim UD$
- SM singlet GB
- $M^2_{T^0} \sim -g^2\, F^2_\Pi$

(Ryttov and Sannino 08; Foadi, M.T.F and Sannino 09)

Dark Matter from Minimal Technicolor

TIMP: Complex scalar, charged under the $U(1)_{TB}$ symmetry

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \ , \quad U_R^{+1/2} \ , \ D_R^{-1/2} \ ; \quad \lambda^f \ .$$

'iTIMP'

- $\mathcal{R}$ real
- $T^0 \sim UD$
- Iso-singlet GB
- $M_{T^0} \sim g\, F_\Pi$

(M.T.F and F.Sannino 09)

'TIMP'

- 4 of $SU(4)$

(Bahr, Chivukula and Farhi 90; Nussinov 92)

'TIMP'

- $\mathcal{R}$ pseudo-real
- $T^0 \sim UD$
- SM singlet GB
- $M^2_{T^0} \sim -g^2\, F^2_\Pi$

(Ryttov and Sannino 08; Foadi, M.T.F and Sannino 09)

Dark Matter from Minimal Technicolor

TIMP: Complex scalar, charged under the $U(1)_{TB}$ symmetry

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \ , \quad U_R^{+1/2} \ , \ D_R^{-1/2} \ ; \quad \lambda^f \ .$$

'iTIMP'

- $\mathcal{R}$ real
- $T^0 \sim UD$
- Iso-singlet GB
- $M_{T^0} \sim g\, F_\Pi$

(M.T.F and F.Sannino 09)

'TIMP'

- 4 of $SU(4)$
- $UDUD$

(Bahr, Chivukula and Farhi 90; Nussinov 92)

'TIMP'

- $\mathcal{R}$ pseudo-real
- $T^0 \sim UD$
- SM singlet GB
- $M_{T^0}^2 \sim -g^2\, F_\Pi^2$

(Ryttov and Sannino 08; Foadi, M.T.F and Sannino 09)

Dark Matter from Minimal Technicolor

TIMP: Complex scalar, charged under the $U(1)_{TB}$ symmetry

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \ , \quad U_R^{+1/2} \ , \ D_R^{-1/2} \ ; \quad \lambda^f \ .$$

'iTIMP'

- $\mathcal{R}$ real
- $T^0 \sim UD$
- Iso-singlet GB
- $M_{T^0} \sim g\,F_\Pi$

(M.T.F and F.Sannino 09)

'TIMP'

- 4 of $SU(4)$
- $UDUD$
- SM singlet

(Bahr, Chivukula and Farhi 90; Nussinov 92)

'TIMP'

- $\mathcal{R}$ pseudo-real
- $T^0 \sim UD$
- SM singlet GB
- $M_{T^0}^2 \sim -g^2\,F_\Pi^2$

(Ryttov and Sannino 08; Foadi, M.T.F and Sannino 09)

Dark Matter from Minimal Technicolor

TIMP: Complex scalar, charged under the $U(1)_{TB}$ symmetry

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \ , \quad U_R^{+1/2} \ , \ D_R^{-1/2} \ ; \quad \lambda^f \ .$$

'iTIMP'

- $\mathcal{R}$ real
- $T^0 \sim UD$
- Iso-singlet GB
- $M_{T^0} \sim g\, F_\Pi$

(M.T.F and F.Sannino 09)

'TIMP'

- 4 of $SU(4)$
- $UDUD$
- SM singlet
- $M_T \sim N_{TC}^{3/2} F_\Pi$

(Bahr, Chivukula and Farhi 90; Nussinov 92)

'TIMP'

- $\mathcal{R}$ pseudo-real
- $T^0 \sim UD$
- SM singlet GB
- $M_{T^0}^2 \sim -g^2\, F_\Pi^2$

(Ryttov and Sannino 08; Foadi, M.T.F and Sannino 09)

Dark Matter from Minimal Technicolor

TIMP: Complex scalar, charged under the $U(1)_{TB}$ symmetry

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \;,\quad U_R^{+1/2}\;,\; D_R^{-1/2}\;;\quad \lambda^f\;.$$

'iTIMP'

- $\mathcal{R}$ real
- $T^0 \sim UD$
- Iso-singlet GB
- $M_{T^0} \sim g\, F_\Pi$

(M.T.F and F.Sannino 09)

'TIMP'

- 4 of $SU(4)$
- $UDUD$
- SM singlet
- $M_T \sim N_{TC}^{3/2} F_\Pi$

(Bahr, Chivukula and Farhi 90; Nussinov 92)

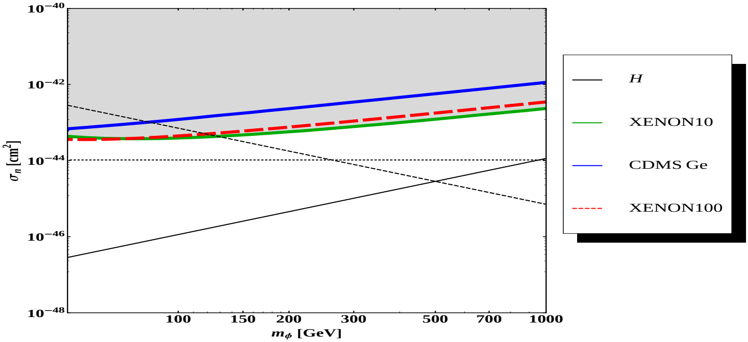
'TIMP'

- $\mathcal{R}$ pseudo-real
- $T^0 \sim UD$
- SM singlet GB
- $M_{T^0}^2 \sim -g^2\, F_\Pi^2$

(Ryttov and Sannino 08; Foadi, M.T.F and Sannino 09)

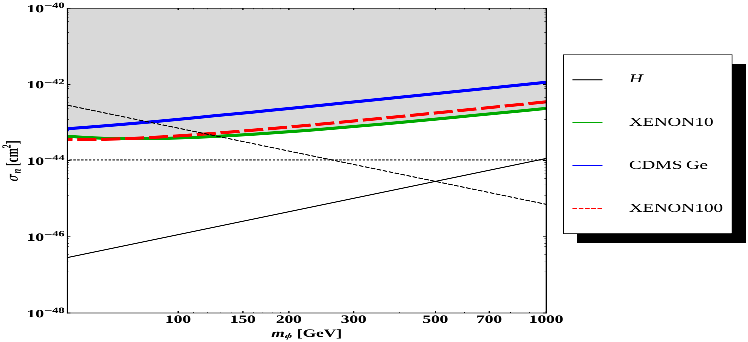
(Other candidates in MWT: Gudnason, Kouvaris and Sannino 05; Kainulainen, Virkajärvi and Tuominen 06, 09, 10; Kouvaris 07; Khlopov and Kouvaris 08)

Direct Detection of iTIMPs



(M.T.F and Sannino 09; Foadi, M.T.F and Sannino 09; Exclusion limits courtesy of C. Mccabe 10)

Direct Detection of iTIMPs

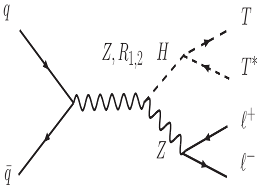


(M.T.F and Sannino 09; Foadi, M.T.F and Sannino 09; Exclusion limits courtesy of C. Mccabe 10)

- Indirect detection of Decaying Dark Matter:
  (Nardi, Sannino and Strumia 09)

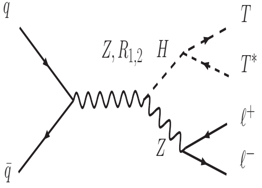
LHC signatures of (i)TIMPs

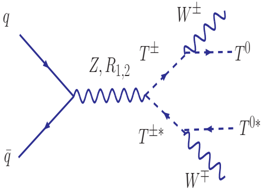
- (i)TIMP Invisible Higgs
  (Foadi, M.T.F and Sannino 08 ; Shrock and Suzuki 88; Godbole, Guchait, Mazumdar, Moretti and Roy 03).



LHC signatures of (i)TIMPs

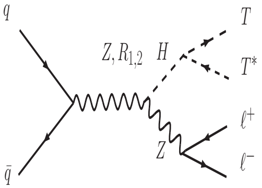
- (i)TIMP Invisible Higgs
  (Foadi, M.T.F and Sannino 08 ; Shrock and Suzuki 88; Godbole, Guchait, Mazumdar, Moretti and Roy 03).
- iTIMP 'Antlers'
  (M.T.F and Sannino 09 ; Han, Kim and Song 09)



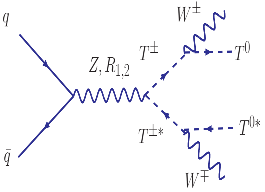


LHC signatures of (i)TIMPs

- (i)TIMP Invisible Higgs
  (Foadi, M.T.F and Sannino 08 ; Shrock and Suzuki 88; Godbole, Guchait, Mazumdar, Moretti and Roy 03).



- iTIMP 'Antlers'
  (M.T.F and Sannino 09 ; Han, Kim and Song 09)



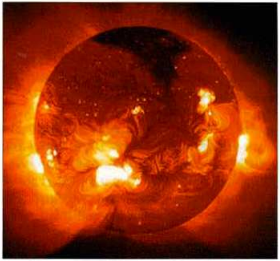
- Note: The same signatures from a new stable heavy lepton!
  (M.T.F, Masina and Sannino 09 ; Antipin, Heikinheimo, Tuominen 09)

Dark Baryons in the sun

PHYSICS WORLD FEBRUARY 2005

Chemical controversy at the solar surface

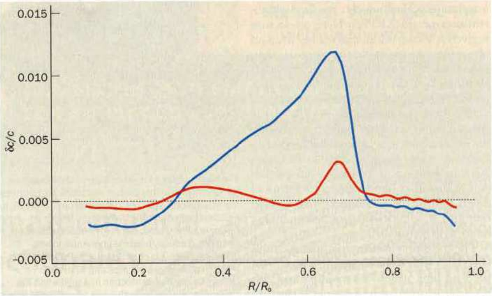
Improved measurements of elemental abundances suggest that something might be wrong with our model of the Sun



An accurate model of the Sun is crucial for our understanding of more-distant stars.

From **John N Bahcall** at the Institute for Advanced Study, Princeton, New Jersey, US

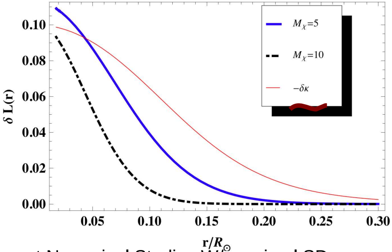
My personal guess is that it may take years before we stumble upon the key to resolving the mystery of why the improved measurements of element abundances cause solar models to disagree with helioseismological measurements while older measurements agree extraordinarily well. However, scientists love a conflict between theory and observation because they are guaranteed to learn something interesting by resolving it.



Solar puzzle – measurements of the speed of sound in the solar interior provide a stringent test of the solar model. This plot shows the fractional difference in the speed of sound (c) between the measured and predicted values as a function of the solar radius ($R_\odot$) (the dashed line represents perfect agreement between theory and observation). When the older heavy-element abundances are used in the model (red)

Dark Baryons in the sun

(M.T.F & Sarkar 10)



	OPA1		OPA2	
	SM	LSM	SM	LSM
$\Delta Y_{\rm ini}$	0.016	0.017	-0.0056	-0.0058
$\delta Z_{\rm ini}$	-0.018	-0.016	0.000	-0.001
$\Delta Y_{\rm b}$	0.014	0.014	-0.0037	-0.0036
$\delta Z_{\rm b}$	-0.018	-0.018	0.0049	0.0047
$\delta R_{\rm b}$	-0.0020	-0.0020	-0.0067	-0.0070
$\delta\Phi_{\rm pp}$	-0.011	-0.010	0.0045	0.0052
$\delta\Phi_{\rm Be}$	0.13	0.13	-0.067	-0.064
$\delta\Phi_{\rm B}$	0.27	0.27	-0.17	-0.17
$\delta\Phi_{\rm N}$	0.14	0.14	-0.10	-0.094
$\delta\Phi_{\rm O}$	0.21	0.22	-0.14	-0.14

Recent Numerical Studies W/ maximal SD cross-section but different numerical/analytical approaches

(Cumberbatch et al 10; Taoso et al 10)

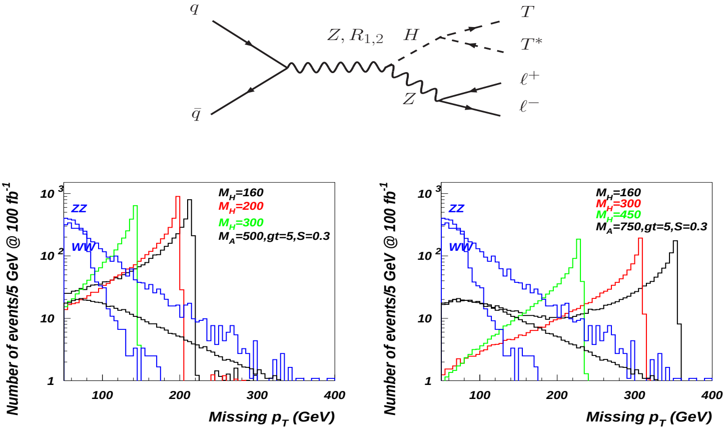
Cumberbatch et al finds smaller variation on Convective Radius, Larger variations on Boron neutrinos

Taoso et al find virtually no effect on Convective Radius and neutrino fluxes

Villante finds 15% opacity variation (as from e.g. ADM) restores agreement with Helioseismology within LSM approach.
Effect on Neutrino fluxes and Helium abundance can constrain/rule out this scenario

(Villante 10)

(i)TIMP missing energy signals (Invisible Higgs)



(Foadi, M.T.F and Sannino 08; Shrock and Suzuki 88; Godbole, Guchait, Mazumdar, Moretti and Roy 03).

Minimal Models of Walking Technicolor

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \quad , \quad U_R^{+1/2} \ , \ D_R^{-1/2} \ ; \quad \lambda^f \ .$$

Minimal Models of Walking Technicolor

MWT model: (Sannino and Tuominen 04)

$G_{TC} = SU(2)$. $\mathcal{R} = Adj$. Leptons.
(Dietrich, Sannino and Tuominen 05)

Minimal Models of Walking Technicolor

MWT model: (Sannino and Tuominen 04)

$G_{TC} = SU(2)$. $\mathcal{R} = Adj$. Leptons.
(Dietrich, Sannino and Tuominen 05)

OMT model

- $G_{TC} = SO(4)$

(M.T.F and F.Sannino 09)

NMWT model

- $G_{TC} = SU(3)$

(Sannino and Tuominen 04)

UMT model

- $G_{TC} = SU(2)$

(Ryttov and Sannino 08)

Minimal Models of Walking Technicolor

MWT model: (Sannino and Tuominen 04)

$G_{TC} = SU(2)$. $\mathcal{R} = Adj$. Leptons.
(Dietrich, Sannino and Tuominen 05)

OMT model

- $G_{TC} = SO(4)$
- $\mathcal{R} = F$

(M.T.F and F.Sannino 09)

NMWT model

- $G_{TC} = SU(3)$
- $\mathcal{R} = 2S$

(Sannino and Tuominen 04)

UMT model

- $G_{TC} = SU(2)$
- $\mathcal{R} = F, Adj$

(Ryttov and Sannino 08)

Minimal Models of Walking Technicolor

MWT model: (Sannino and Tuominen 04)

$G_{TC} = SU(2)$. $\mathcal{R} = Adj$. Leptons.
(Dietrich, Sannino and Tuominen 05)

OMT model

- $G_{TC} = SO(4)$
- $\mathcal{R} = F$
- iTIMP

(M.T.F and F.Sannino 09)

NMWT model

- $G_{TC} = SU(3)$
- $\mathcal{R} = 2S$

(Sannino and Tuominen 04)

UMT model

- $G_{TC} = SU(2)$
- $\mathcal{R} = F, Adj$
- TIMP, $\phi \sim \lambda\lambda$

(Ryttov and Sannino 08)

Minimal Models of Walking Technicolor

MWT model: (Sannino and Tuominen 04)

$G_{TC} = SU(2)$. $\mathcal{R} = Adj$. Leptons.

(Dietrich, Sannino and Tuominen 05)

OMT model

- $G_{TC} = SO(4)$
- $\mathcal{R} = F$
- iTIMP

(M.T.F and F.Sannino 09)

NMWT model

- $G_{TC} = SU(3)$
- $\mathcal{R} = 2S$

(Sannino and Tuominen 04)

UMT model

- $G_{TC} = SU(2)$
- $\mathcal{R} = F, Adj$
- TIMP, $\phi \sim \lambda\lambda$

(Ryttov and Sannino 08)

- Other TC Models (non-minimal/including ETC):
  Farhi and Susskind 79; Eichten and Lane 89; Appelquist and Terning 94; Appelquist, Christensen, Pia and Shrock 04; Lane and Martin 06; Ryttov and Shrock 10

Which gauge theories display walking?

1. Ladder approximation: $\alpha_c = \frac{\pi}{3C_2(\mathrm{R})}$, $\frac{\alpha^*}{4\pi} = -\frac{\beta_0}{\beta_1}$.
   (Appelquist, Lane and Muhanta 88; Cohen and Georgi 89; Sannino and Tuominen 04; Dietrich and Sannino 06; Ryttov and Sannino 07)
2. All-orders beta function conjecture(s)
   (Ryttov and Sannino 08; Antipin and Tuominen 09; Dietrich 09)
3. Dualities
   (Sannino 09)
4. Compactification approach
   (Unsal and Poppitz 09; Ogilvie and Myers 09;)
5. Worldline formalism
   (Armoni 09)
6. Holography (Hong and Yee 06; Alvares, Evans, Gebauer and Weatherill 09)

Phase Diagram - Prelim

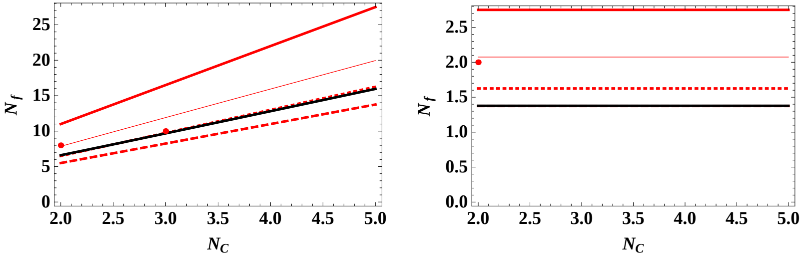


Figure: Conformal windows for SU theories with Dirac fermions in the fundamental (left), adjoint (mid) and two-index symmetric (right) representations. Curves indicate N_f^I (thick upper solid) and N_f^{II} according to SD (thin solid), metric (thick dotted), AO β-function with $\gamma = 2$ (thick dashed) and finally loss of causal analyticity (thick lower solid, black).

(w/ M.Teper and T. Pickup).

Phase Diagram - Prelim

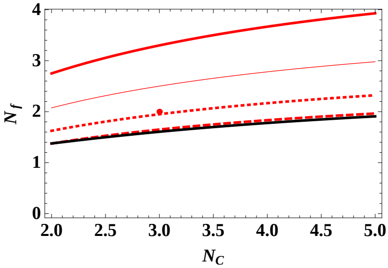


Figure: Conformal windows for SU theories with Dirac fermions in the fundamental (left), adjoint (mid) and two-index symmetric (right) representations. Curves indicate N_f^I (thick upper solid) and N_f^{II} according to SD (thin solid), metric (thick dotted), AO β-function with $\gamma = 2$ (thick dashed) and finally loss of causal analyticity (thick lower solid, black).

(w/ M.Teper and T. Pickup).

EFT for strong dynamics @ LHC

common sector:

$$SU_L(2) \times SU_R(2) \times U_{TB}(1) \to SU_V(2) \times U_{TB}(1) \; .$$

- New states: Lightest (axial)-vector triplets and scalar

$$R_1^{\pm,0}, \;\; R_2^{\pm,0}, \;\; H. \quad \text{TIMPs}$$

- Input parameters and constraints:

$$e, \;\; G_F, \;\; M_Z; \;\; S, \;\; \text{Sum Rules.}$$

- Main free parameters:

$$M_A, \;\; \tilde{g}, \;\; M_H.$$

(Appelquist, Da Silva and Sannino 99; Foadi, M.T.F, Ryttov and Sannino

EFT for strong dynamics @ LHC

common sector:

$$SU_L(2) \times SU_R(2) \times U_{TB}(1) \to SU_V(2) \times U_{TB}(1)\ .$$

- New states: Lightest (axial)-vector triplets and scalar

$$R_1^{\pm,0},\ R_2^{\pm,0},\ H. \quad \text{TIMPs}$$

- Input parameters and constraints:

$$e,\ G_F,\ M_Z;\ S,\ \text{Sum Rules.}$$

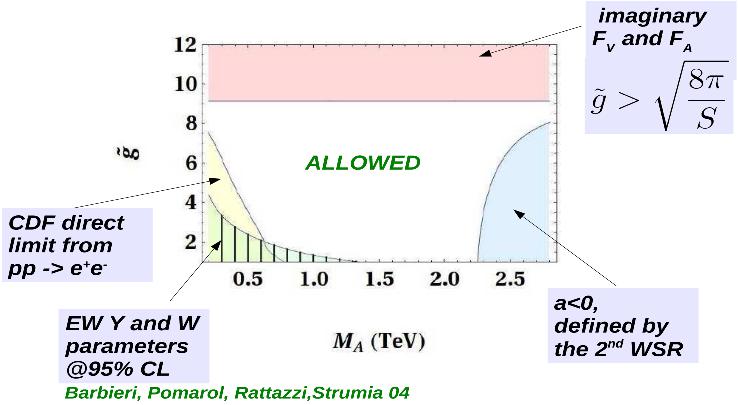
- Main free parameters:

$$M_A,\ \tilde{g},\ M_H.$$

(Appelquist, Da Silva and Sannino 99; Foadi, M.T.F, Ryttov and Sannino

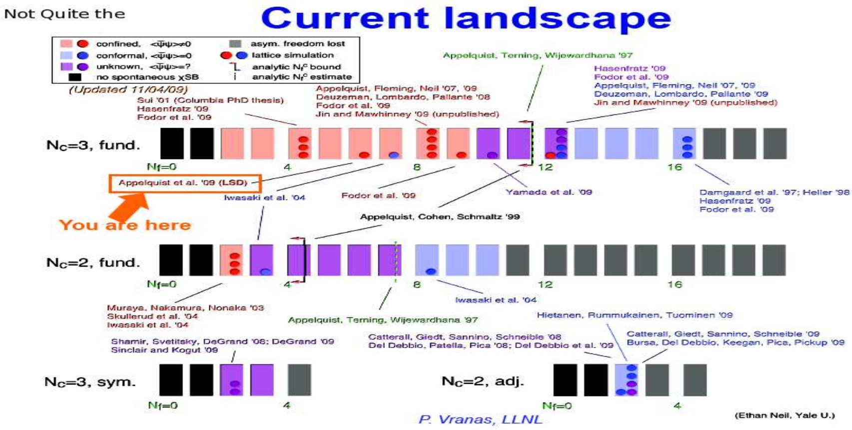
- EFTs for 'BESS' models, '3-site/4-site' models and LSTC (Casalbuoni, Deandrea, De Curtis, Dominici, Gatto, Grazzini 95; He et al 08; Lane and Martin 09)

Parameter space



(Foadi, M.T.F and Sannino 07 ; Belyaev, Foadi, M.T.F, Järvinen, Pukhov, Sannino 08)

Lattice simulations



(Dedicated collaborations: Lattice Strong Dynamics (US) ; Strong BSM (EU))

Mass spectrum, imposing S and WSR1

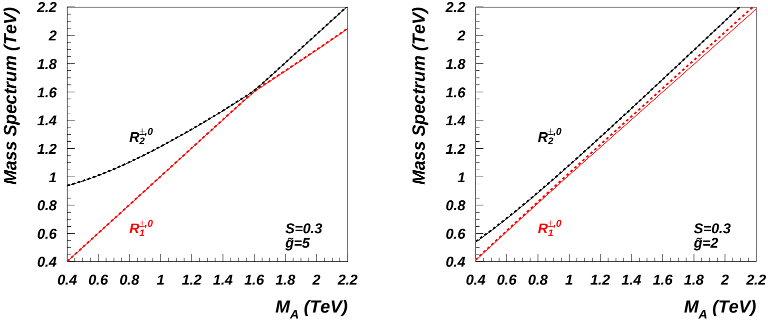
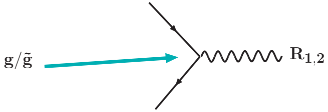


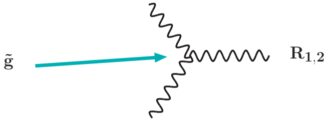
Figure: $R_{1,2}$ spectrum.

(Foadi, M.T.F, Ryttov and Sannion 08)

LHC Phenomenology

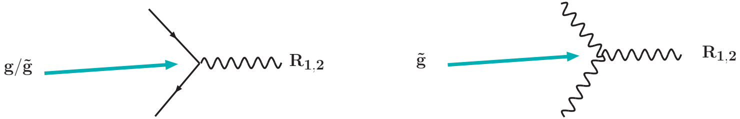
- Basic phenomenology controlled by $\tilde{g}$, M_A, M_H.





LHC Phenomenology

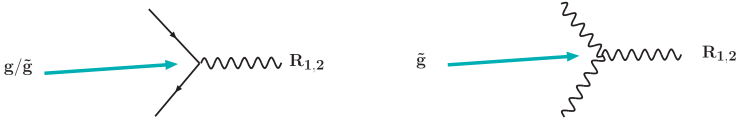
- Basic phenomenology controlled by $\tilde{g}$, M_A, M_H.



- Different decay channels probe R_1, R_2 and H.

LHC Phenomenology

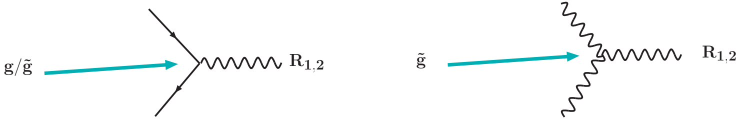
- Basic phenomenology controlled by $\tilde{g}$, M_A, M_H.



- Different decay channels probe R_1, R_2 and H.
  - Di-lepton: $R^0_{1,2} \rightarrow \ell^+\ell^-$. Single top: $R^{\pm}_{1,2} \rightarrow tb$

LHC Phenomenology

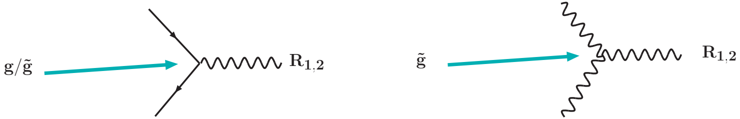
- Basic phenomenology controlled by $\tilde{g}$, M_A, M_H.



- Different decay channels probe R_1, R_2 and H.
  - Di-lepton: $R^0_{1,2} \to \ell^+\ell^-$. Single top: $R^{\pm}_{1,2} \to tb$
  - Di-boson: $R_2 \to ZW/WW$.

LHC Phenomenology

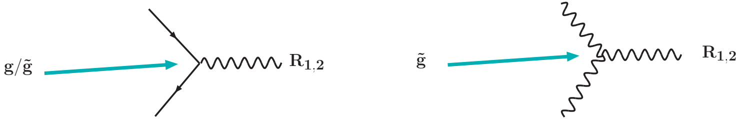
- Basic phenomenology controlled by $\tilde{g}$, M_A, M_H.



- Different decay channels probe R_1, R_2 and H.
  - Di-lepton: $R^0_{1,2} \to \ell^+\ell^-$. Single top: $R^{\pm}_{1,2} \to tb$
  - Di-boson: $R_2 \to ZW/WW$.
  - Higgs-Strahlung: $R_1 \to HZ/HW$.

LHC Phenomenology

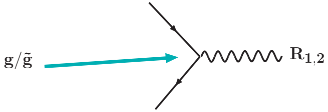
- Basic phenomenology controlled by $\tilde{g}$, M_A, M_H.

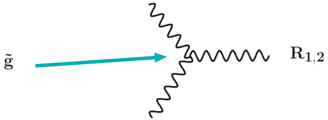


- Different decay channels probe R_1, R_2 and H.
  - Di-lepton: $R^0_{1,2} \to \ell^+\ell^-$. Single top: $R^{\pm}_{1,2} \to tb$
  - Di-boson: $R_2 \to ZW/WW$.
  - Higgs-Strahlung: $R_1 \to HZ/HW$.
  - Higgs-Decays: $H \to ZZ/WW\,(b\bar{b}?)$.

LHC Phenomenology

- Basic phenomenology controlled by $\tilde{g}$, M_A, M_H.

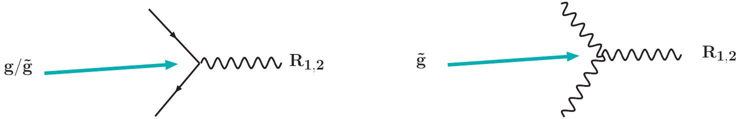




- Different decay channels probe R_1, R_2 and H.
  - Di-lepton: $R^0_{1,2} \to \ell^+\ell^-$. Single top: $R^{\pm}_{1,2} \to tb$
  - Di-boson: $R_2 \to ZW/WW$.
  - Higgs-Strahlung: $R_1 \to HZ/HW$.
  - Higgs-Decays: $H \to ZZ/WW\,(b\bar{b}?)$.
  - boosted tops, W, Z and H

LHC Phenomenology

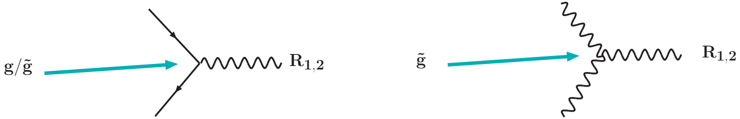
- Basic phenomenology controlled by $\tilde{g}$, M_A, M_H.



- Different decay channels probe R_1, R_2 and H.
    - Di-lepton: $R^0_{1,2} \to \ell^+\ell^-$. Single top: $R^{\pm}_{1,2} \to tb$
    - Di-boson: $R_2 \to ZW/WW$.
    - Higgs-Strahlung: $R_1 \to HZ/HW$.
    - Higgs-Decays: $H \to ZZ/WW\,(b\bar{b}?)$.
    - boosted tops, W, Z and H
- Lattice can (in principle) narrow down parameter space for each model

LHC Phenomenology

- Basic phenomenology controlled by $\tilde{g}$, M_A, M_H.



- Different decay channels probe R_1, R_2 and H.
  - Di-lepton: $R^0_{1,2} \to \ell^+\ell^-$. Single top: $R^\pm_{1,2} \to tb$
  - Di-boson: $R_2 \to ZW/WW$.
  - Higgs-Strahlung: $R_1 \to HZ/HW$.
  - Higgs-Decays: $H \to ZZ/WW\,(b\bar{b}?)$.
  - boosted tops, W, Z and H
- Lattice can (in principle) narrow down parameter space for each model
  - MWT/OMT, NMWT, UMT etc...

Model Implementation

- (N)MWT, UMT and OMT models in:
  - LanHEP (A.Semenov) FeynRules (C.Duhr et al)
  - CalcHEP (A.Pukhov) and CompHEP (E.BOOS et al)
  - LHE output/model files is/will be available for HERWIG/PYTHIA/SHERPA/...

Model Implementation

- (N)MWT, UMT and OMT models in:
  - `LanHEP` (A.Semenov) `FeynRules` (C.Duhr et al)
  - `CalcHEP` (A.Pukhov) and `CompHEP` (E.BOOS et al)
  - LHE output/model files is/will be available for `HERWIG/PYTHIA/SHERPA/...`
  - Dark matter sector in `MicrOMEGAs` (Belanger et al) w/ asymmetry courtesy of A. Pukhov

Model Implementation

- (N)MWT, UMT and OMT models in:
  - LanHEP (A.Semenov) FeynRules (C.Duhr et al)
  - CalcHEP (A.Pukhov) and CompHEP (E.BOOS et al)
  - LHE output/model files is/will be available for HERWIG/PYTHIA/SHERPA/...
  - Dark matter sector in MicrOMEGAs (Belanger et al) w/ asymmetry courtesy of A. Pukhov

- Used ThePEG/HERWIG++ for showering/hadronization (Lönnblad/Bahr et al)
- Used DELPHES for Fast Detector Simulation (Ovyn and Rouby)

Vector BRs

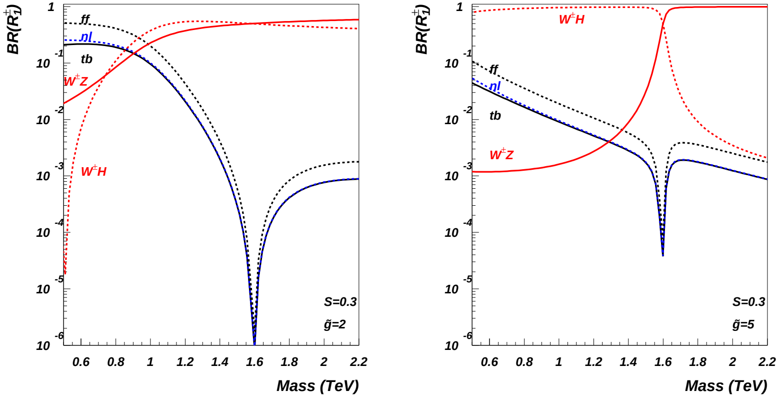


Figure: BR's of R_1.

Vector Production

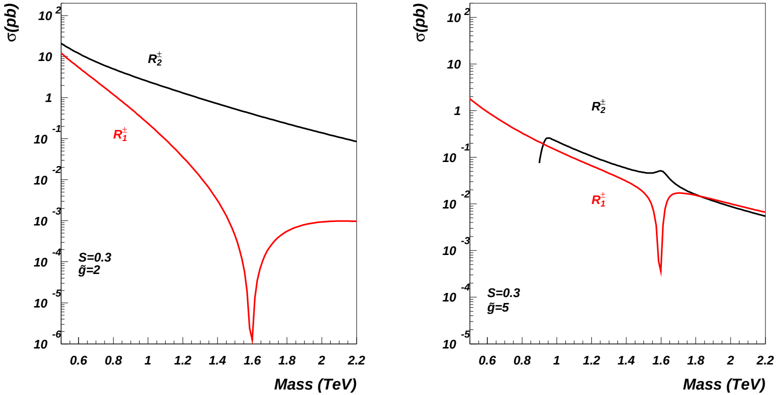


Figure: DY production of $R_{1,2}$.

$\ell^+\ell^-$ signature @ LHC using CalcHEP

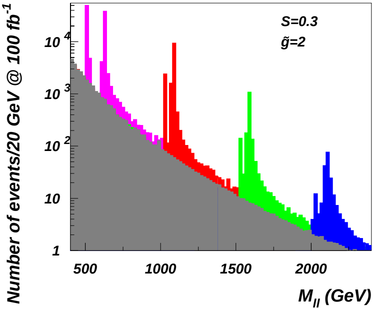


Figure: Dilepton invariant mass distribution $M_{\ell\ell}$ for $pp \to R^0_{1,2} \to \ell^+\ell^-$

(Belyaev, Foadi, M.T.F, Järvinen, Pukhov, Sannino 08)

$\ell^+\ell^-$ signature @ LHC using HERWIG/DELPHES

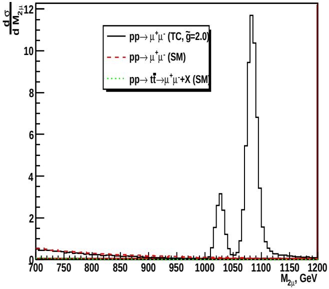


Figure: Dilepton invariant mass distribution $M_{\mu\mu}$ for $pp \to R^0_{1,2} \to \ell^+\ell^-$. $M_A = 1$ TeV, $\tilde{g} = 2$, $S = 0.3$.

Additional Cuts: $M_{\mu\mu} > 500 GeV$ and $R_j = 1$.

(A. Belyaev, M.T.F and A.Sherstnev in preparation)

$\ell^+\ell^-$ signature @ LHC using HERWIG/DELPHES

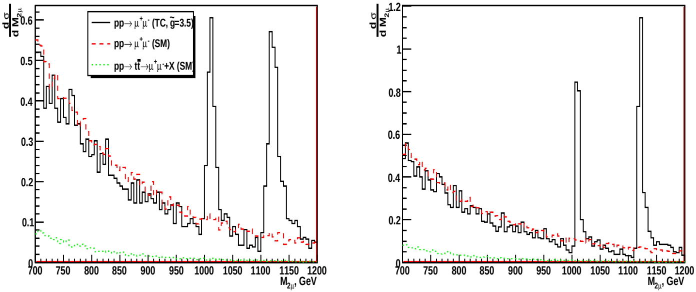
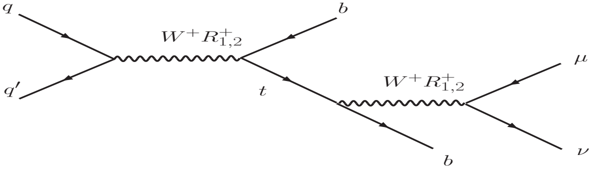


Figure: Dilepton invariant mass distribution $M_{\mu\mu}$ for $pp \to R^0_{1,2} \to \ell^+\ell^-$. $M_A = 1$ TeV, $\tilde{g} = 3.5$, $S = 0.3$.

Additional Cuts: $M_{\mu\mu} > 500 GeV$ and $R_j = 1$.

(A. Belyaev, M.T.F and A.Sherstnev in preparation)

Parton level tb signature @ LHC using CompHEP



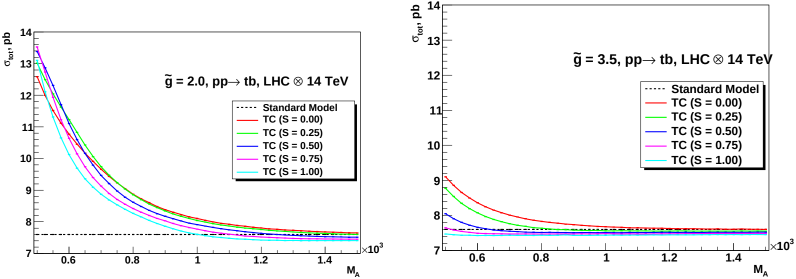


Figure: tb cross-section

Results for *tb*

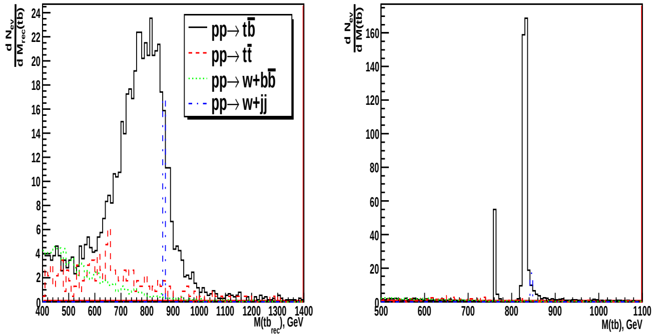
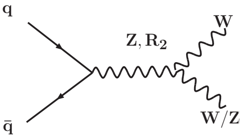
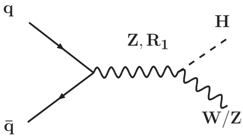
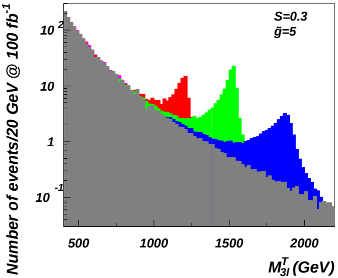


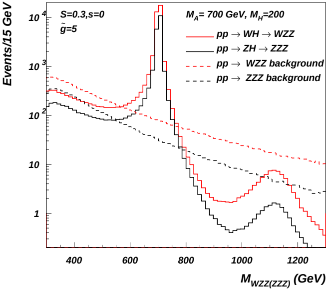
Figure: Reconstructed (left plot) and partonic (right plot) invariant mass of top and b-quarks after final cuts. Distributions normalized to 30 fb^{-1}.

Di-boson vs Higgs-strahlung









(Belyaev, Foadi, M.T.F, Järvinen, Pukhov, Sannino 08)

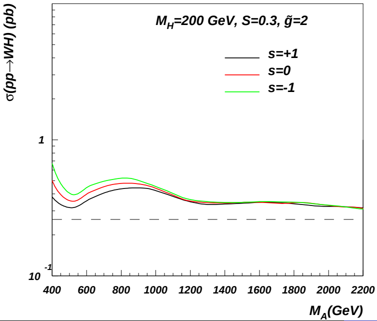
Higgs Strahlung in the SM and TC

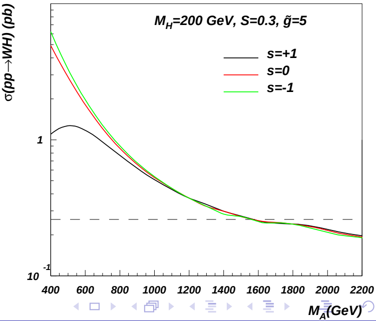
1. Enhanced HZ/HW cross-section from a resonance

Higgs Strahlung in the SM and TC

1. Enhanced HZ/HW cross-section from a resonance
2. $U(1)$ techni-omega, $U(1)$ Z', axial techni-vector (R_1) resonance

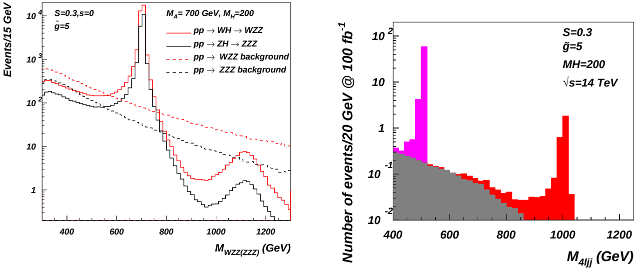
   (Zerwekh 05; Barger, Langacker and Lee 05; Belyaev, Foadi, M.T.F, Järvinen, Pukhov, Sannino 08)





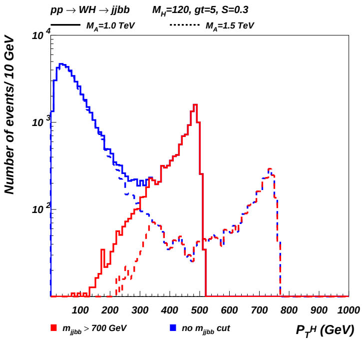
Higgs Strahlung in the SM and TC

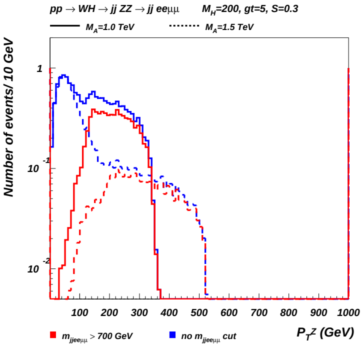
1. Resonance peaks from axial-vector R_1



(Belyaev, Foadi, M.T.F, Järvinen, Pukhov, Sannino 08 ; M.T.F and Sannino 09)

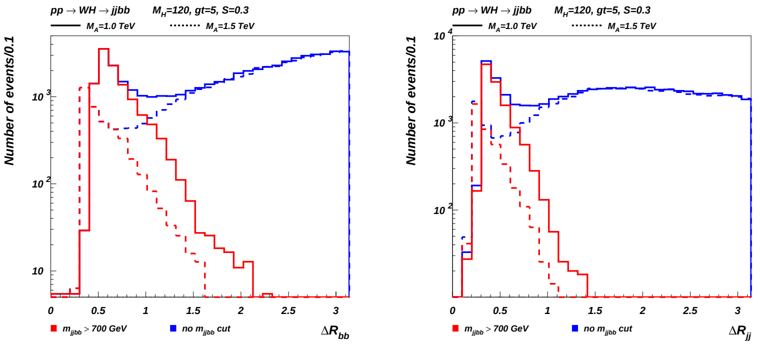
Boosted WH final states: Preliminary analysis





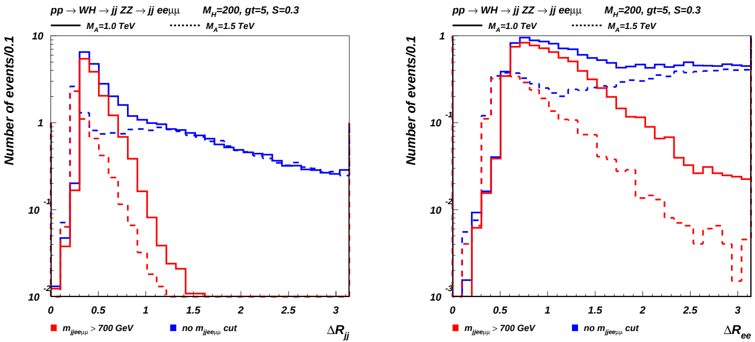
- Large Higgs transverse momenta peaked at $p_T(H) \sim M_{R_1}/2$ (Belyaev, M.T.F and Sherstnev in progress)

Boosted WH final states: Preliminary analysis



- ΔR_{bb} and ΔR_{jj} accordingly small in the $b\bar{b}$ channel: Peaked at $\Delta R_{bb} \sim 4M_H/M_{R_1}, \Delta R_{jj} \sim 4M_Z/M_{R_1}$ (Belyaev, M.T.F and Sherstnev in progress)

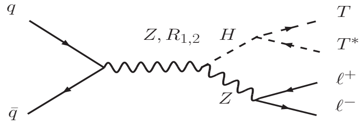
Boosted WH final states: Preliminary analysis

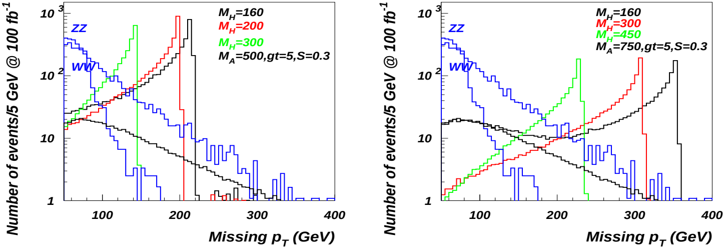


- Boost analysis also relevant when $M_H > 2M_W$ for the W associated with H and for the $Z's$

  (Belyaev, M.T.F and Sherstnev in progress)

(i)TIMP missing energy signals (Invisible Higgs)





(Foadi, M.T.F and Sannino 08; Shrock and Suzuki 88; Godbole, Guchait, Mazumdar, Moretti and Roy 03).

Summary

- Minimal Walking Technicolor models constructed to be viable realizations of DEWSB and DM

Summary

- Minimal Walking Technicolor models constructed to be viable realizations of DEWSB and DM
  - Lattice simulations are vigorously investigating (near)-conformal dynamics

Summary

- Minimal Walking Technicolor models constructed to be viable realizations of DEWSB and DM
  - Lattice simulations are vigorously investigating (near)-conformal dynamics
- MWT Models provide distinctive LHC signatures

Summary

- Minimal Walking Technicolor models constructed to be viable realizations of DEWSB and DM
  - Lattice simulations are vigorously investigating (near)-conformal dynamics
- MWT Models provide distinctive LHC signatures
- General EFT framework for LHC studies

Summary

- Minimal Walking Technicolor models constructed to be viable realizations of DEWSB and DM
  - Lattice simulations are vigorously investigating (near)-conformal dynamics
- MWT Models provide distinctive LHC signatures
- General EFT framework for LHC studies
  - First Fast-Detector analysis in progress.

Summary

- Minimal Walking Technicolor models constructed to be viable realizations of DEWSB and DM
  - Lattice simulations are vigorously investigating (near)-conformal dynamics
- MWT Models provide distinctive LHC signatures
- General EFT framework for LHC studies
  - First Fast-Detector analysis in progress.
- Model implementations/LHE files available for detailed analysis!

Summary

- Minimal Walking Technicolor models constructed to be viable realizations of DEWSB and DM
  - Lattice simulations are vigorously investigating (near)-conformal dynamics
- MWT Models provide distinctive LHC signatures
- General EFT framework for LHC studies
  - First Fast-Detector analysis in progress.
- Model implementations/LHE files available for detailed analysis!
  - `LanHEP` /`FeynRules` and `CalcHEP` /`CompHEP`