Walking in Monte-Carlo

Mads Toudal Frandsen

University of Oxford

MC4BSM, April 15$^{\text{th}}$ 2010

m.frandsen1@physics.ox.ac.uk

Outline

Work 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.).

Bright and Dark connection?

- $v_{weak} \simeq 246\text{GeV}$

Bright and Dark connection?

- $v_{weak} \simeq 246\text{GeV}$
- $\langle \sigma_{ann} v_{rel} \rangle \sim \frac{\alpha_W^2}{1\,TeV^2}$

Bright and Dark connection?

- $v_{weak} \simeq 246\text{GeV}$
- $\langle \sigma_{ann} v_{rel} \rangle \sim \frac{\alpha_W^2}{1\,TeV^2}$

$$\Omega_{DM}/\Omega_B \sim 5$$

Bright and Dark connection?

- $v_{weak} \simeq 246\text{GeV}$
- $\langle \sigma_{ann} v_{rel} \rangle \sim \frac{\alpha_W^2}{1\,TeV^2}$

$$\Omega_{DM}/\Omega_B \sim 5$$

- The baryonic mass is due to strong interactions, not the Higgs!

Bright and Dark connection?

- $v_{weak} \simeq 246\text{GeV}$
- $\langle \sigma_{ann} v_{rel} \rangle \sim \frac{\alpha_W^2}{1\,TeV^2}$

$$\Omega_{DM}/\Omega_B \sim 5$$

- The baryonic mass is due to strong interactions, not the Higgs!
- The baryonic relic density is due to an asymmetry not a thermal relic density!

Bright and Dark connection?

- $v_{weak} \simeq 246\text{GeV}$
- $\langle \sigma_{ann} v_{rel} \rangle \sim \frac{\alpha_W^2}{1\,TeV^2}$

$$\Omega_{DM}/\Omega_B \sim 5$$

- The baryonic mass is due to strong interactions, not the Higgs!
- The baryonic relic density is due to an asymmetry not a thermal relic density!

A dynamical origin of mass ?

Technicolor (Weinberg 78, Susskind 78)

1. The SM gauge group is augmented:

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

Technicolor (Weinberg 78, Susskind 78)

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:

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

Technicolor (Weinberg 78, Susskind 78)

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:

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

3. The techniquark condensate breaks EW symmetry:

$$\langle \bar{U}_L U_R + \bar{D}_L D_R \rangle \neq 0 \quad \rightarrow \quad M_W = \frac{g F_{\Pi}}{2} \ .$$

Technicolor (Weinberg 78, Susskind 78)

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:

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

3. The techniquark condensate breaks EW symmetry:

$$\langle \bar{U}_L U_R + \bar{D}_L D_R \rangle \neq 0 \quad \rightarrow \quad M_W = \frac{g F_{\Pi}}{2} \ .$$

Minimal chiral symmetries $\rightarrow$ 3 GB's + custodial + relic.

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

Technicolor dark matter

Technocosmology (Nussinov 85)

Lightest Technibaryon as asymmetric DM

Technicolor dark matter

Technocosmology (Nussinov 85)

Lightest Technibaryon as asymmetric DM

- Ω_{TB} related to asymmetries.

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

(Nussinov 85; Chivukula and Walker 90; Bahr, Chivukula and Farhi 90; Harvey and Turner 90; Sarkar 95)

Technicolor dark matter

Technocosmology (Nussinov 85)

Lightest Technibaryon as asymmetric DM

- Ω_{TB} related to asymmetries.

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

(Nussinov 85; Chivukula and Walker 90; Bahr, Chivukula and Farhi 90; Harvey and Turner 90; Sarkar 95)

Techni-Interacting Massive Particles

TIMPs from extended chiral symmetries

(Gudnason, Kouvaris and Sannino 05; Sannino and Ryttov 08; Foadi, M.T.F and Sannino 08; M.T.F and Sannino 09)

Extended Chiral symmetries and (i)TIMPs

(M.T.F and Sannino 09)

- Minimal TC matter content in representation $\mathcal{R}$ of G_{TC}

$$Q_L = \begin{pmatrix} U_L^{+1/2} \\ D_L^{-1/2} \end{pmatrix} , \quad U_R^{+1/2} , \; D_R^{-1/2} . \tag{1}$$

Extended Chiral symmetries and (i)TIMPs

(M.T.F and Sannino 09)

- Minimal TC matter content in representation $\mathcal{R}$ of G_{TC}

$$Q_L = \begin{pmatrix} U_L^{+1/2} \\ D_L^{-1/2} \end{pmatrix}, \quad U_R^{+1/2}, \; D_R^{-1/2} . \tag{1}$$

- If $\mathcal{R}$ is real: $SU(4) \rightarrow SO(4)$. 3+6 GB's.

Extended Chiral symmetries and (i)TIMPs

(M.T.F and Sannino 09)

- Minimal TC matter content in representation $\mathcal{R}$ of G_{TC}

$$Q_L = \begin{pmatrix} U_L^{+1/2} \\ D_L^{-1/2} \end{pmatrix}, \quad U_R^{+1/2}, \; D_R^{-1/2}. \tag{1}$$

- If $\mathcal{R}$ is real: $SU(4) \rightarrow SO(4)$. 3+6 GB's.
- If $\mathcal{R}$ is pseudo-real: $SU(4) \rightarrow Sp(4)$. 3+2 GB's.

Extended Chiral symmetries and (i)TIMPs

(M.T.F and Sannino 09)

- Minimal TC matter content in representation $\mathcal{R}$ of G_{TC}

$$Q_L = \begin{pmatrix} U_L^{+1/2} \\ D_L^{-1/2} \end{pmatrix}, \quad U_R^{+1/2}, \; D_R^{-1/2} . \tag{1}$$

- If $\mathcal{R}$ is real: $SU(4) \rightarrow SO(4)$. 3+6 GB's.
- If $\mathcal{R}$ is pseudo-real: $SU(4) \rightarrow Sp(4)$. 3+2 GB's.
- The (i)TIMP is $T^0 \sim U_L D_L$.

Extended Technicolor and fermion masses

1. Four fermion operators:

$$\alpha\frac{\bar{Q}Q\bar{Q}Q}{\Lambda^2_{ETC}}+\beta\frac{\bar{Q}Q\bar{\psi}\psi}{\Lambda^2_{ETC}}+\gamma\frac{\bar{\psi}\psi\bar{\psi}\psi}{\Lambda^2_{ETC}}+\ldots$$

2. Fermion masses:

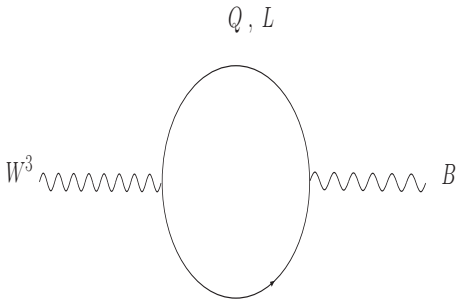
$$M_\psi\sim\frac{\langle\bar{Q}Q\rangle_{ETC}}{\Lambda^2_{ETC}}\sim d(R_{TC})\frac{\Lambda^{3-\gamma}\Lambda^{\gamma}_{ETC}}{\Lambda^2_{ETC}}$$

(Holdom 81, 85; Yamawaki, Bando and Matumoto 86; Appelquist, Karabali and Wijewardhana 86)

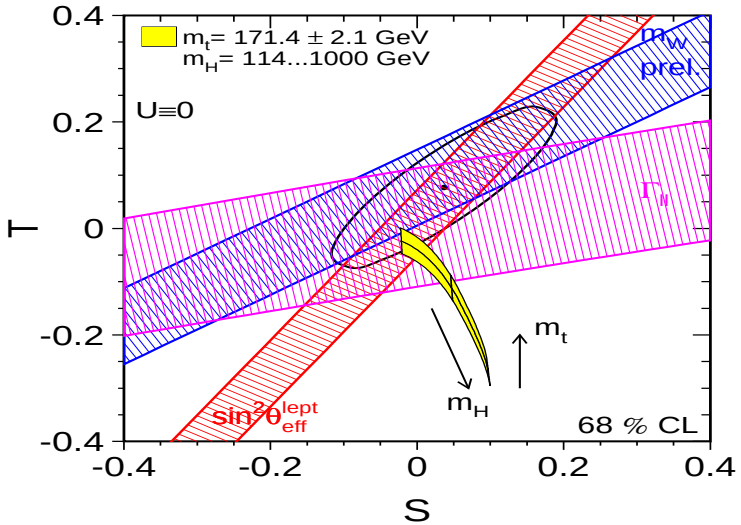
Constraints from LEP

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

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

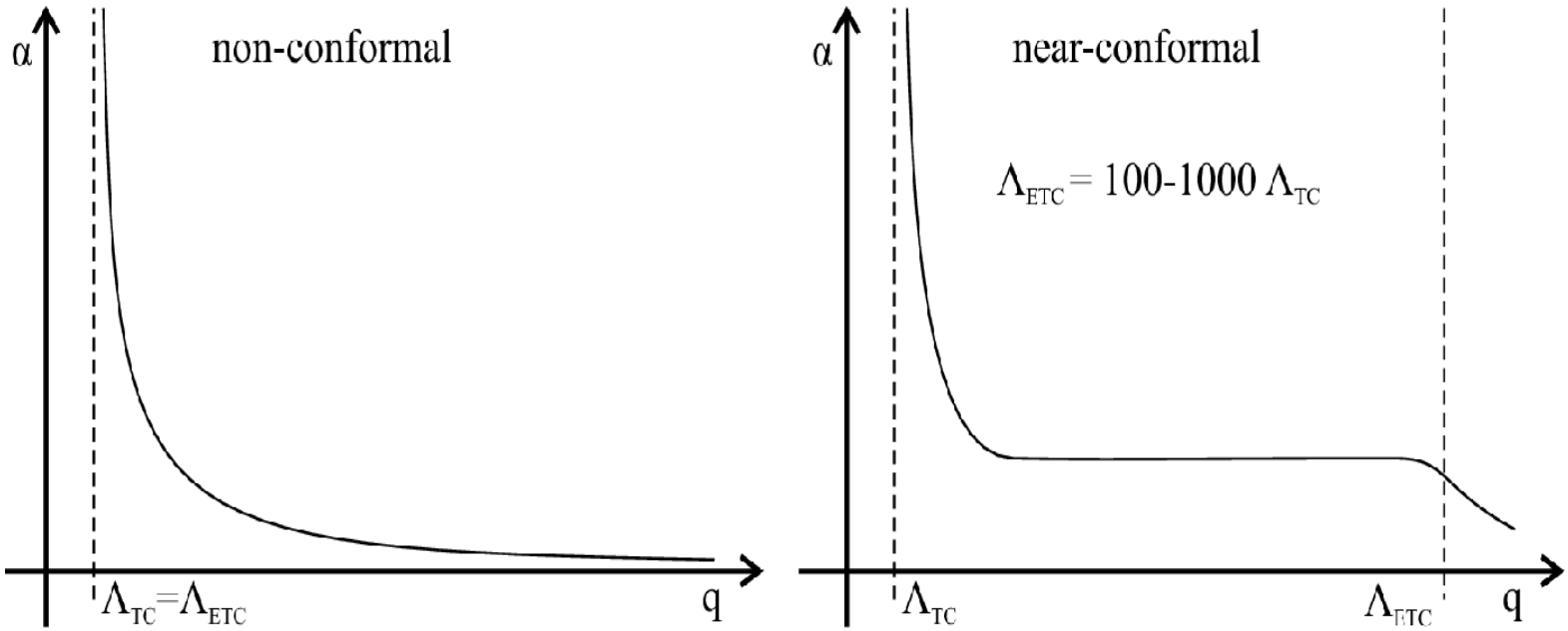


$$S_{\text{naive}} = N_D \frac{d(R_{\text{TC}})}{6\pi}$$

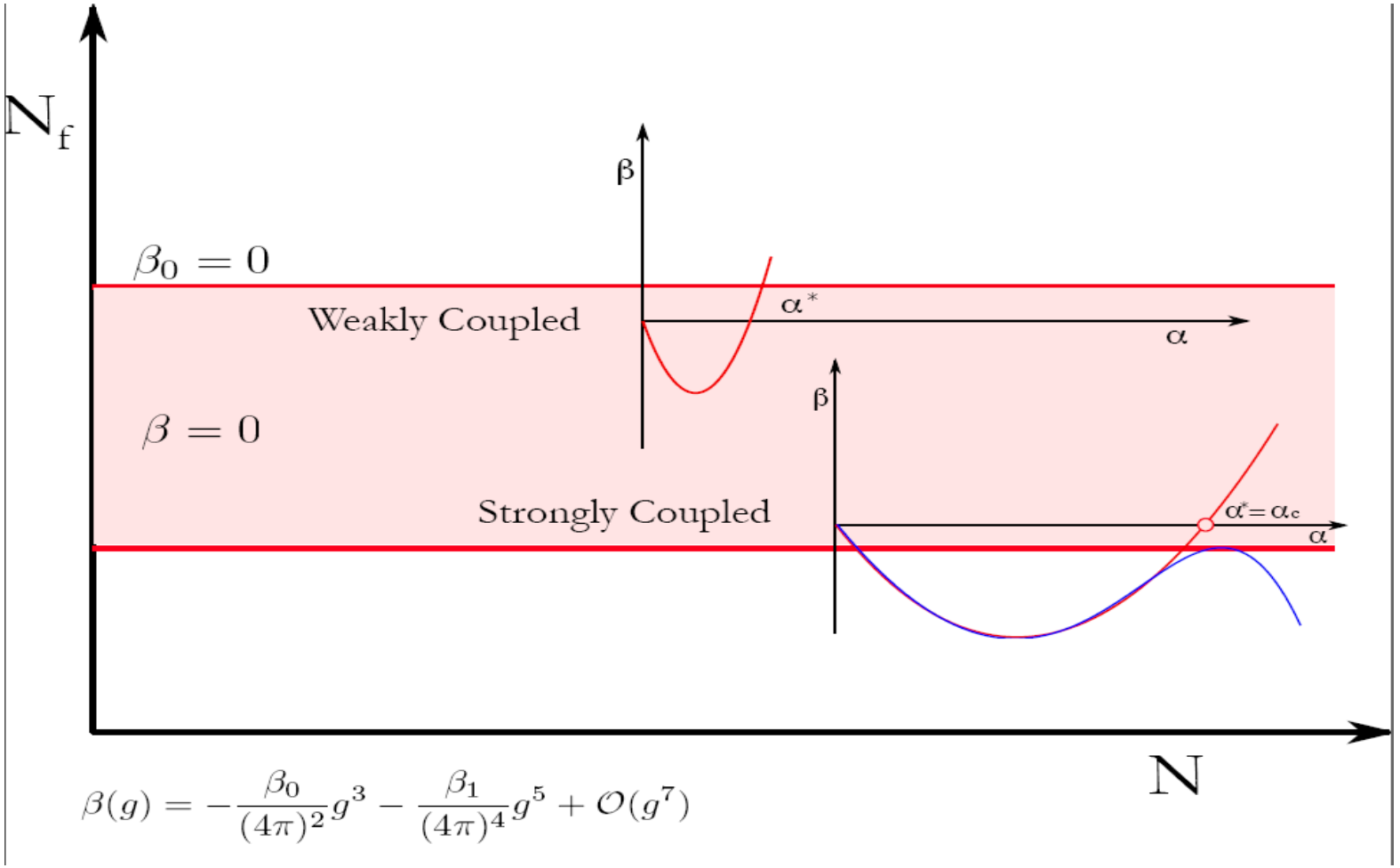


(Kennedy and Lynn 89; Peskin and Takeuchi 90; Altarelli and Barbieri 91)

Walking Technicolor



Which gauge theories display walking?



(Sannino, cp3-origins 09)

Minimal models of Walking Technicolor

MWT model: (Sannino and Tuominen 05)

$SU(2)_{TC}$ gauge group. 2 Dirac Flavors in the adjoint rep. of $SU(2)_{TC}$. Additional lepton family: $(N\ E)_L^T$, $(N_R,\ E_R)$.

Minimal models of Walking Technicolor

MWT model: (Sannino and Tuominen 05)

$SU(2)_{TC}$ gauge group. 2 Dirac Flavors in the adjoint rep. of $SU(2)_{TC}$. Additional lepton family: $(N\ E)_L^T$, $(N_R,\ E_R)$.

UMT model: (Ryttov and Sannino 08)

$SU(2)_{TC}$ gauge group. 2 Dirac flavors in the fundamental, 2 Weyl flavors in the adjoint rep. of $SU(2)_{TC}$. TIMP.

Minimal models of Walking Technicolor

MWT model: (Sannino and Tuominen 05)

$SU(2)_{TC}$ gauge group. 2 Dirac Flavors in the adjoint rep. of $SU(2)_{TC}$. Additional lepton family: $(N\ E)_L^T$, $(N_R,\ E_R)$.

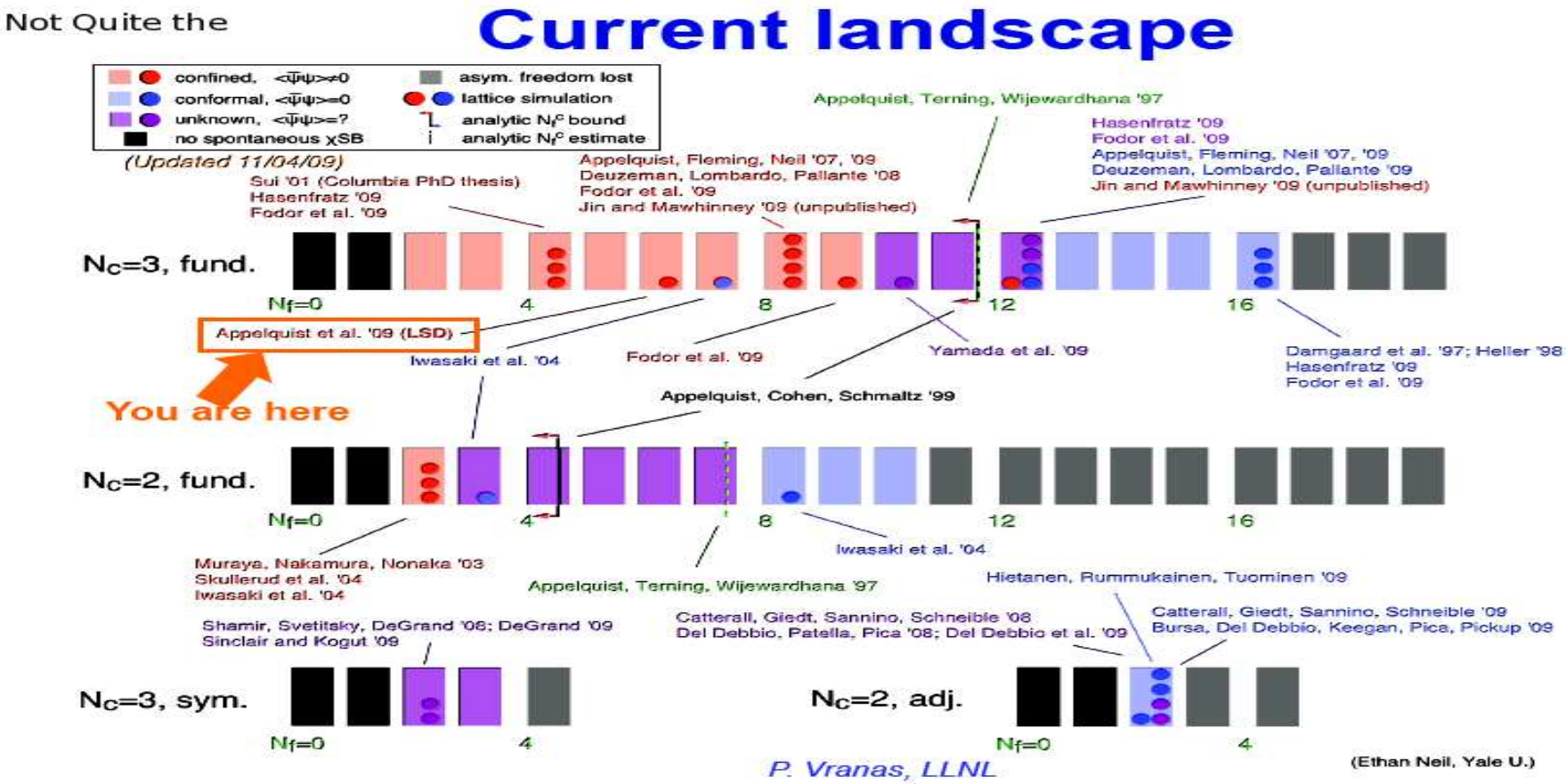
UMT model: (Ryttov and Sannino 08)

$SU(2)_{TC}$ gauge group. 2 Dirac flavors in the fundamental, 2 Weyl flavors in the adjoint rep. of $SU(2)_{TC}$. TIMP.

OMT model: (M.T.F and Sannino 09)

$SO(4)_{TC}$ gauge group. 2 Dirac flavors in the vector rep. of $SO(4)_{TC}$. iTIMP.

Lattice efforts



EFT for MWT models @ LHC

common sector:

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

1. New states:

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

2. Input parameters and constraints:

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

3. Important free parameters:

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

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

Collider signatures for MWT

- Phenomenology controlled by $g/\tilde{g}$ and masses.

Collider signatures for MWT

- Phenomenology controlled by $g/\tilde{g}$ and masses.
- Different channels probe R_1, R_2 and H independently

Collider signatures for MWT

- Phenomenology controlled by $g/\tilde{g}$ and masses.
- Different channels probe R_1, R_2 and H independently
- Production

Collider signatures for MWT

- Phenomenology controlled by $g/\tilde{g}$ and masses.
- Different channels probe R_1, R_2 and H independently
- Production
  - $pp \longrightarrow R_{1,2}^{0\pm}$

Collider signatures for MWT

- Phenomenology controlled by $g/\tilde{g}$ and masses.
- Different channels probe R_1, R_2 and H independently
- Production
  - $pp \longrightarrow R_{1,2}^{0\pm}$
  - $pp \longrightarrow R_{1,2}^{0\pm}/H\ jj$

Collider signatures for MWT

- Phenomenology controlled by $g/\tilde{g}$ and masses.
- Different channels probe R_1, R_2 and H independently
- Production
  - $pp \longrightarrow R_{1,2}^{0\pm}$
  - $pp \longrightarrow R_{1,2}^{0\pm}/H\ jj$

Collider signatures for MWT

- Phenomenology controlled by $g/\tilde{g}$ and masses.
- Different channels probe R_1, R_2 and H independently
- Production
  - $pp \longrightarrow R_{1,2}^{0\pm}$
  - $pp \longrightarrow R_{1,2}^{0\pm}/H\ jj$
- Decays

Collider signatures for MWT

- Phenomenology controlled by $g/\tilde{g}$ and masses.
- Different channels probe R_1, R_2 and H independently
- Production
  - $pp \to R^{0\pm}_{1,2}$
  - $pp \to R^{0\pm}_{1,2}/H\ jj$
- Decays
  - $R^{0}_{1,2} \to \ell^+\ell^-$

Collider signatures for MWT

- Phenomenology controlled by $g/\tilde{g}$ and masses.
- Different channels probe R_1, R_2 and H independently
- Production
  - $pp \longrightarrow R^{0\pm}_{1,2}$
  - $pp \longrightarrow R^{0\pm}_{1,2}/H\ jj$
- Decays
  - $R^{0}_{1,2} \longrightarrow \ell^+\ell^-$
  - $R^{\pm}_{1,2} \longrightarrow tb$

Collider signatures for MWT

- Phenomenology controlled by $g/\tilde{g}$ and masses.
- Different channels probe R_1, R_2 and H independently
- Production
  - $pp \to R^{0\pm}_{1,2}$
  - $pp \to R^{0\pm}_{1,2}/H\ jj$
- Decays
  - $R^{0}_{1,2} \to \ell^+\ell^-$
  - $R^{\pm}_{1,2} \to tb$
  - $R^{\pm}_{1,2} \to ZW^{\pm}$

Collider signatures for MWT

- Phenomenology controlled by $g/\tilde{g}$ and masses.
- Different channels probe R_1, R_2 and H independently
- Production
  - $pp \to R^{0\pm}_{1,2}$
  - $pp \to R^{0\pm}_{1,2}/H\ jj$
- Decays
  - $R^0_{1,2} \to \ell^+\ell^-$
  - $R^\pm_{1,2} \to tb$
  - $R^\pm_{1,2} \to ZW^\pm$
  - $R_{1,2} \to HZ \to ZWW$

Implementation status

- Lagrangians of (N)MWT, UMT and OMT models in LanHEP.

Implementation status

- Lagrangians of (N)MWT, UMT and OMT models in LanHEP.

Implementation status

- Lagrangians of (N)MWT, UMT and OMT models in LanHEP.

Implementation status

- Lagrangians of (N)MWT, UMT and OMT models in LanHEP.
  - CalcHEP/CompHEP

Implementation status

- Lagrangians of (N)MWT, UMT and OMT models in LanHEP.
  - CalcHEP/CompHEP
  - HERWIG/PYTHIA

Implementation status

- Lagrangians of (N)MWT, UMT and OMT models in LanHEP.
  - CalcHEP/CompHEP
  - HERWIG/PYTHIA
  - DELPHES/GEANT

Implementation status

- Lagrangians of (N)MWT, UMT and OMT models in LanHEP.
  - CalcHEP/CompHEP
  - HERWIG/PYTHIA
  - DELPHES/GEANT
- FeynRules (In progress)

Implementation status

- Lagrangians of (N)MWT, UMT and OMT models in LanHEP.
  - CalcHEP/CompHEP
  - HERWIG/PYTHIA
  - DELPHES/GEANT
- FeynRules (In progress)
  - ...

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

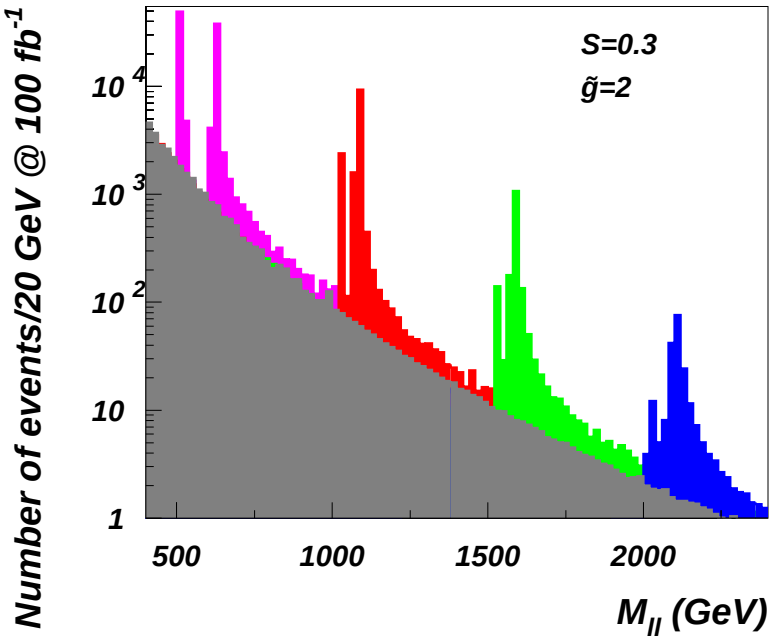


Figure: Dilepton invariant mass distribution $M_{\ell\ell}$ for $pp \longrightarrow R^0_{1,2} \longrightarrow \ell^+\ell^-$

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

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

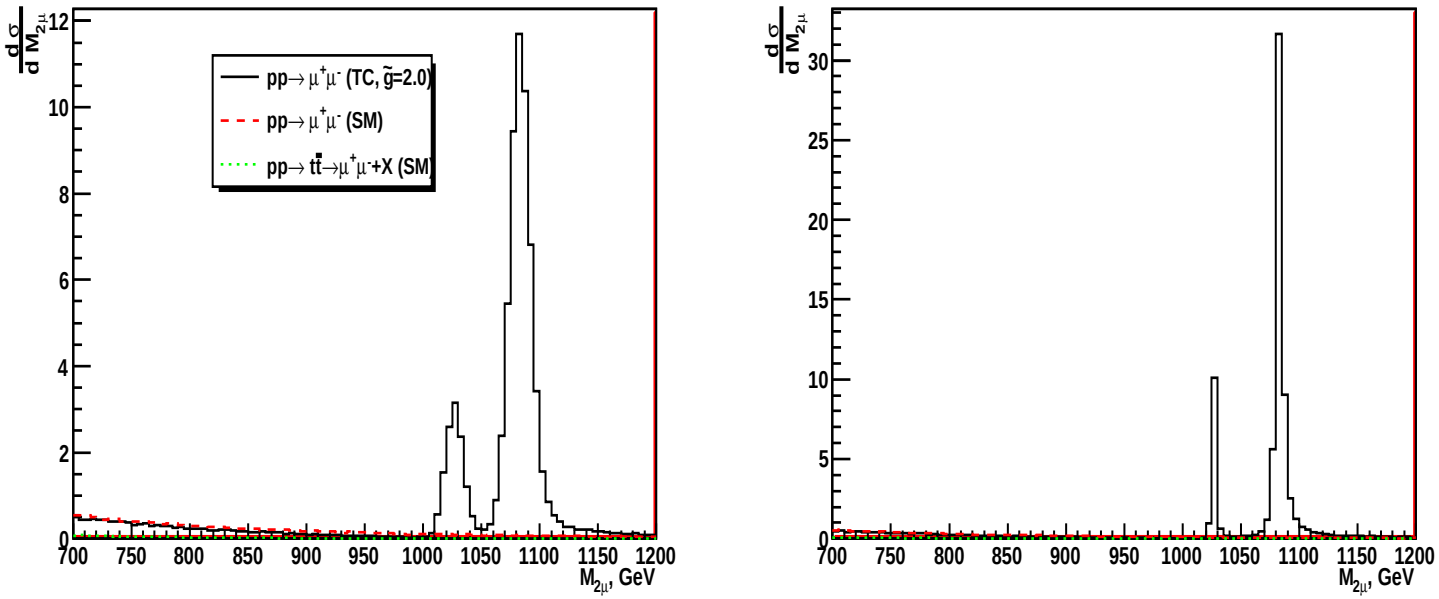


Figure: Dilepton invariant mass distribution $M_{\mu\mu}$ for $pp \to R^0_{1,2} \to \ell^+\ell^-$. $M_A = 1$ TeV, $\tilde{g} = 2$, $S = 0.3$.

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

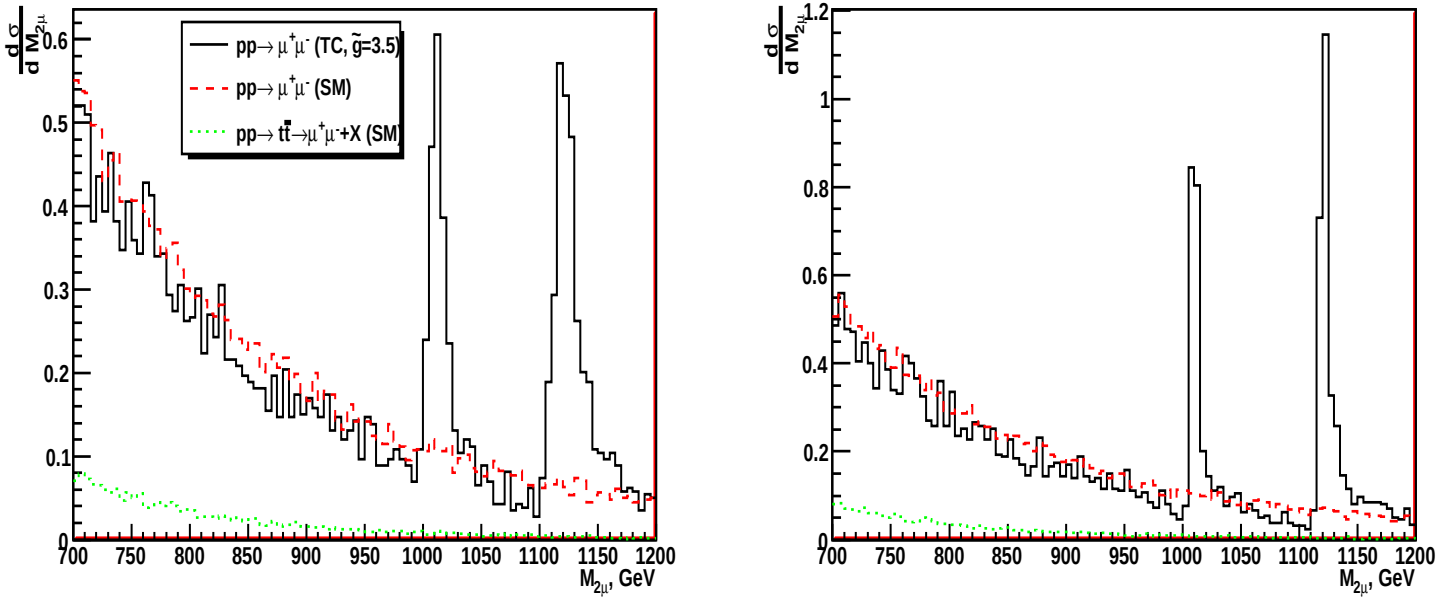


Figure: Dilepton invariant mass distribution $M_{\mu\mu}$ for $pp \to R^0_{1,2} \to \ell^+\ell^-$. $M_A = 1$ TeV, $\tilde{g} = 3.5$, $S = 0.3$.

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

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

tb signature @ LHC using CompHEP

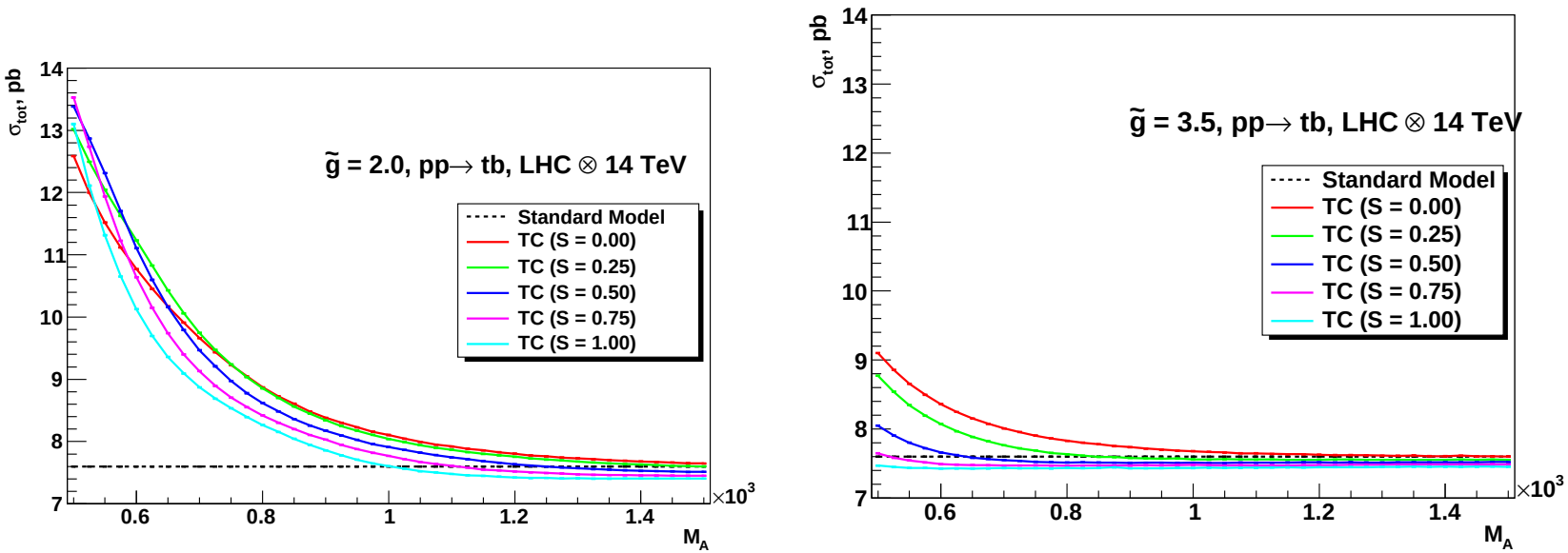


Figure: tb cross-section

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

$3\ell + \not{E}_T$ signature

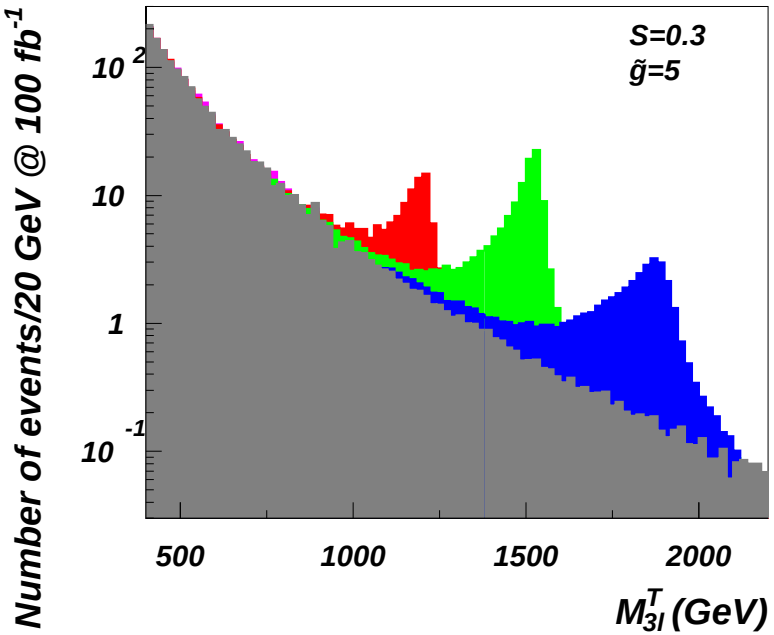
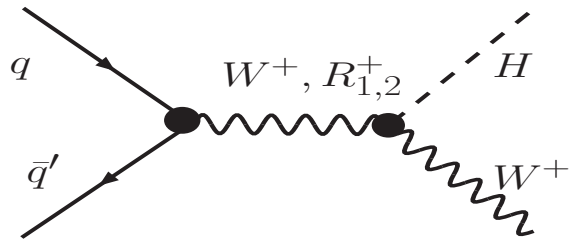
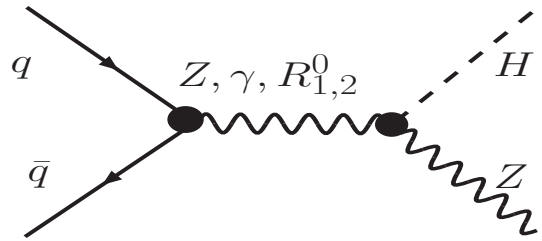


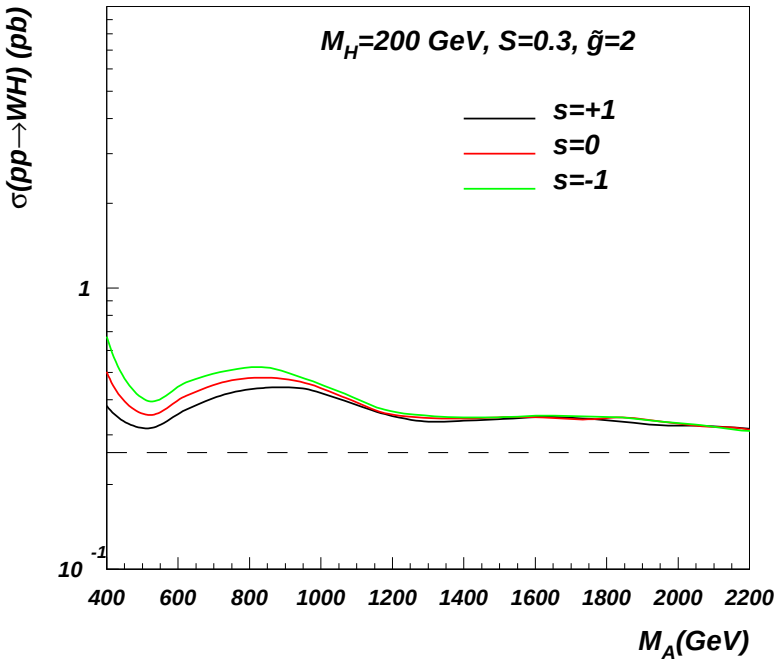
Figure: $M_{3\ell}^T$ mass distribution for $pp \to R_{1,2}^{\pm} \to ZW^{\pm} \to 3\ell\nu$

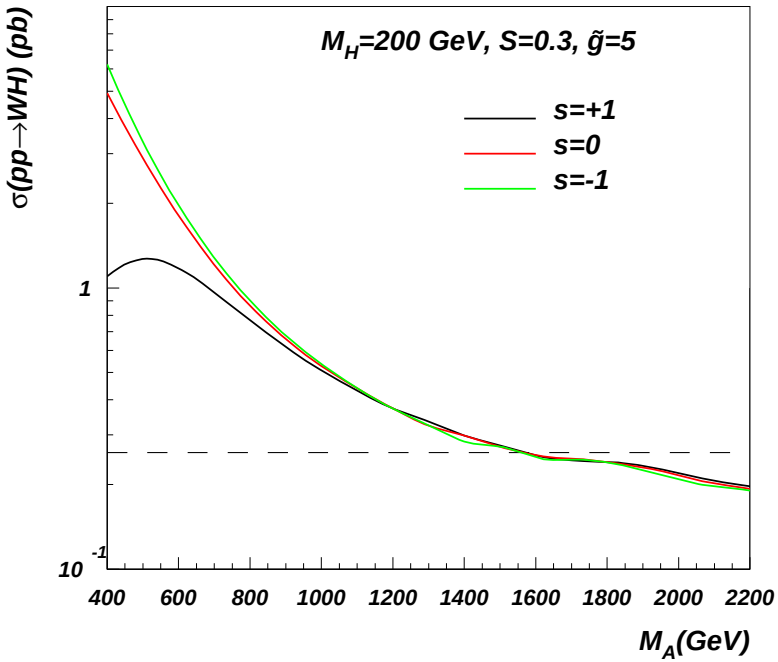
(Belyaev, Foadi, M.T.F, Järvinen, Pukhov, Sannino 08)

associate higgs production: $pp \longrightarrow R_{1,2} \longrightarrow HV$



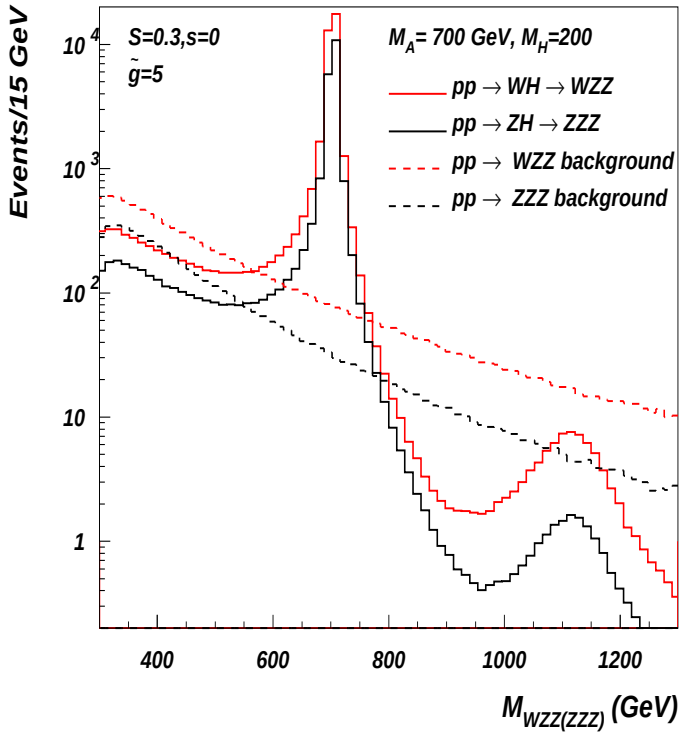


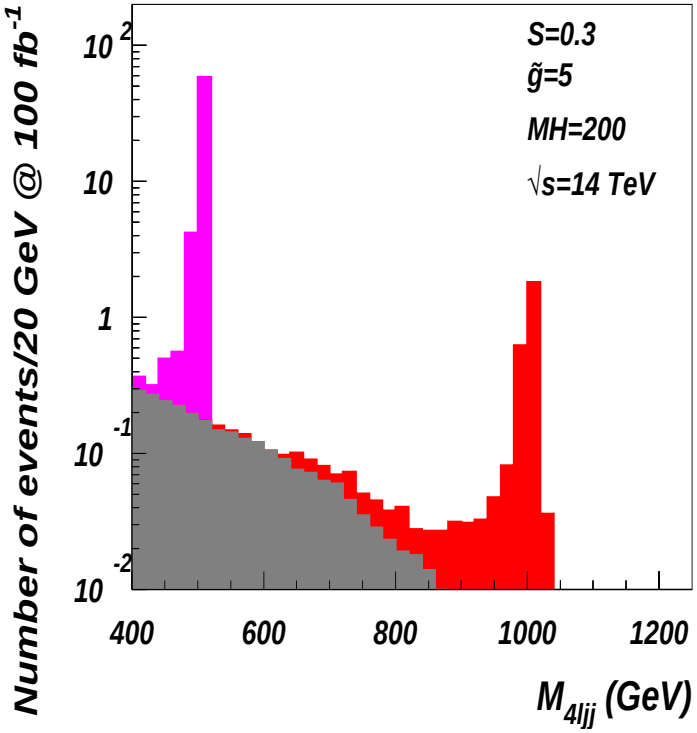




(Zerwekh 05; Belyaev, Foadi, M.T.F, Järvinen, Pukhov, Sannino 08)

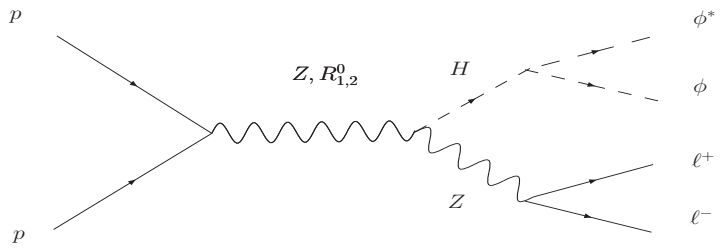
$4\ell jj$ signature:

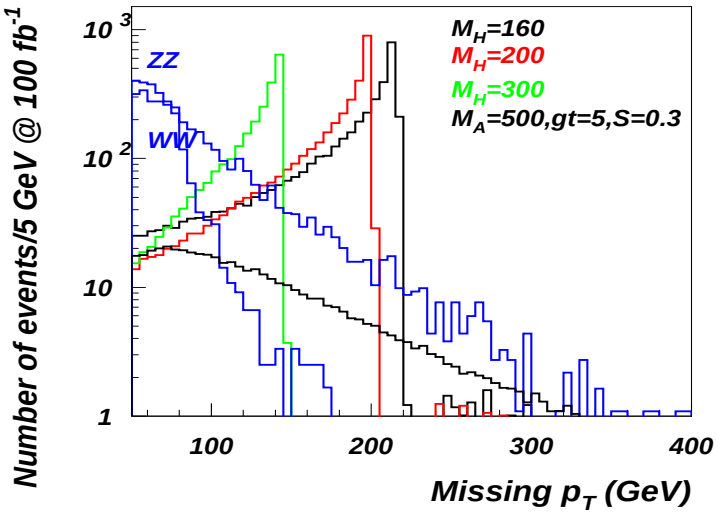


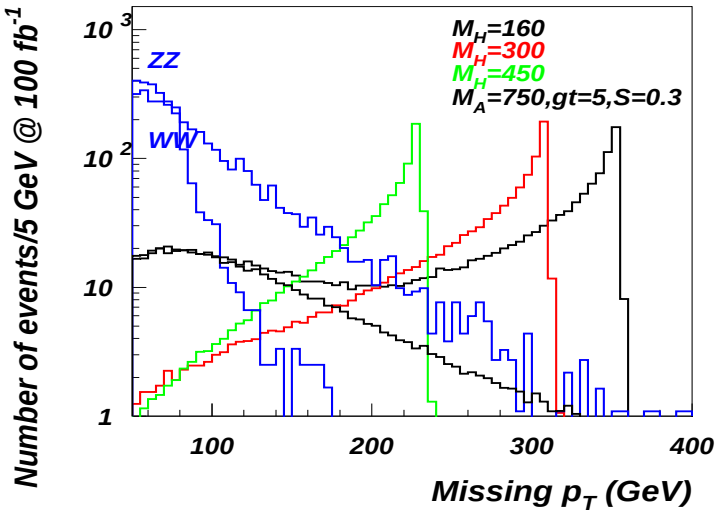


(Zerwekh 05; Belyaev, Foadi, M.T.F, Järvinen, Pukhov, Sannino 08)

(i)TIMP missing energy signals







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

Summary

- MWT models provide viable dynamical models of EWSB and natural Dark Matter.

Summary

- MWT models provide viable dynamical models of EWSB and natural Dark Matter.
- MWTs with (i)TIMPs provide in addition (light) viable dark matter.

Summary

- MWT models provide viable dynamical models of EWSB and natural Dark Matter.
- MWTs with (i)TIMPs provide in addition (light) viable dark matter.
- Compilation of MWT signals for LHC/LCs in progress:

Summary

- MWT models provide viable dynamical models of EWSB and natural Dark Matter.
- MWTs with (i)TIMPs provide in addition (light) viable dark matter.
- Compilation of MWT signals for LHC/LCs in progress:
  - LanHEP/FeynRules implementations completed/in progress.

Summary

- MWT models provide viable dynamical models of EWSB and natural Dark Matter.
- MWTs with (i)TIMPs provide in addition (light) viable dark matter.
- Compilation of MWT signals for LHC/LCs in progress:
  - LanHEP/FeynRules implementations completed/in progress.
  - CalcHEP/CompHEP implementations completed.

Summary

- MWT models provide viable dynamical models of EWSB and natural Dark Matter.
- MWTs with (i)TIMPs provide in addition (light) viable dark matter.
- Compilation of MWT signals for LHC/LCs in progress:
  - LanHEP/FeynRules implementations completed/in progress.
  - CalcHEP/CompHEP implementations completed.
  - Detector level simulations in progress

Summary

- MWT models provide viable dynamical models of EWSB and natural Dark Matter.
- MWTs with (i)TIMPs provide in addition (light) viable dark matter.
- Compilation of MWT signals for LHC/LCs in progress:
  - LanHEP/FeynRules implementations completed/in progress.
  - CalcHEP/CompHEP implementations completed.
  - Detector level simulations in progress
- Much more to be done

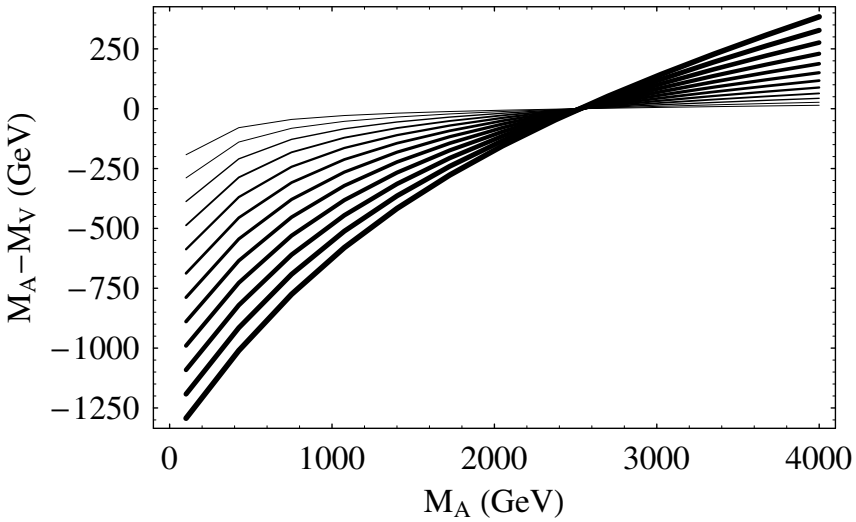
Summary

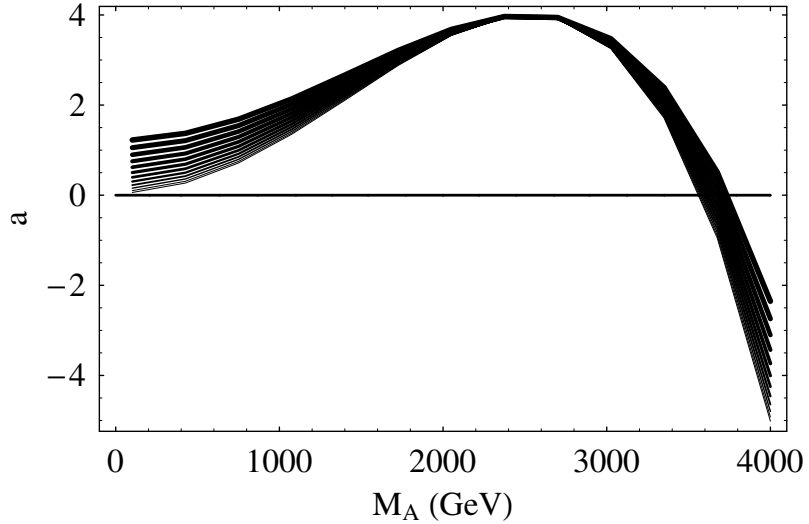
- MWT models provide viable dynamical models of EWSB and natural Dark Matter.
- MWTs with (i)TIMPs provide in addition (light) viable dark matter.
- Compilation of MWT signals for LHC/LCs in progress:
  - LanHEP/FeynRules implementations completed/in progress.
  - CalcHEP/CompHEP implementations completed.
  - Detector level simulations in progress
- Much more to be done
  - Lattice input.

Summary

- MWT models provide viable dynamical models of EWSB and natural Dark Matter.
- MWTs with (i)TIMPs provide in addition (light) viable dark matter.
- Compilation of MWT signals for LHC/LCs in progress:
  - LanHEP/FeynRules implementations completed/in progress.
  - CalcHEP/CompHEP implementations completed.
  - Detector level simulations in progress
- Much more to be done
  - Lattice input.
  - **EXPERIMENTAL ANALYSIS**

vector-axial spectrum



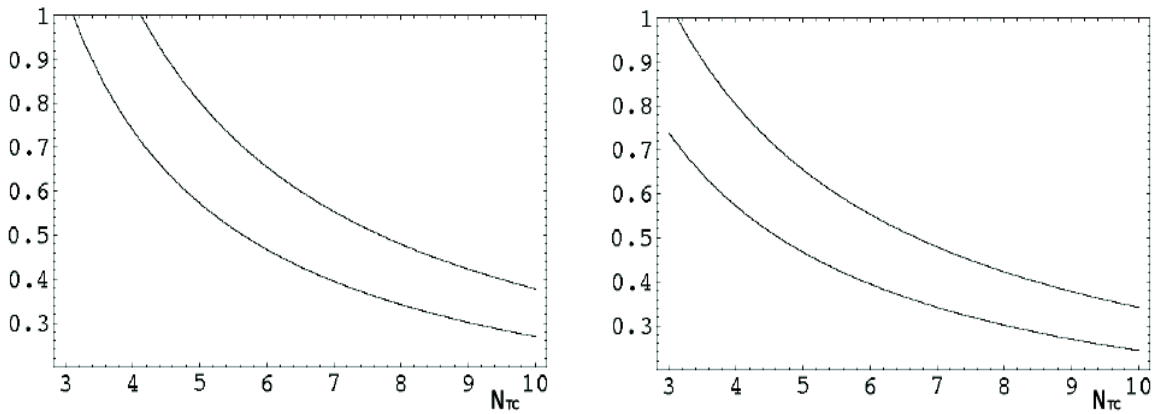


- $M_V - M_A$ is a function of $\tilde{g}$ and M_A after imposing a fixed S.
- Inversion point sensitive to S
- a monitors walking

(Foadi, M.T.F, Ryttov, and Sannino 07)

LCH @ LHC ?

1. The QCD σ is lighter than the QCD ρ meson.
2. Large-N_{TC} scaling suggest the same in two-index representation theories, 2AS vs 2S:



3. Near-conformal phase transition can further reduce the σ_{TC} wrt F_Π

(Hong, Hsu and Sannino 04; Dietrich, Sannino and Tuominen 05; Sannino 08; Kurachi and Shrock 06; Doff, Natale and Rodrigues da Silva 08)