Gauge Higgs Unification Phenomenology in Warped Extra Dimensions

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A. Medina, N. R. Shah and C. Wagner, Phys. Rev. D76:095010, 2007 [arXiv:0706.1281[hep-ph]].
M. Carena, A. Medina, B. Panes, N. R. Shah and C. Wagner, Phys. Rev. D77:076003, 2008 [arXiv:0712.0095[hep-ph]].
M. Carena, A. Medina, N. R. Shah and C. Wagner, Phys. Rev. D79:096010, 2009 [arXiv:0901.0609[hep-ph]].

The Standard Model

- Gauge Symmetries:
  - $SU(3)_C \times SU(2)_W \times U(1)_X$
    - Mass-less gauge bosons: 8 Gluons, $W^{1,2,3}$ & B
- Matter:
  - 3 generations of quarks and leptons.
    - Lepton Weak doublet: $L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}_L \sim (2, 1)_{-1}$
    - Lepton weak singlets: $e_{iL}^c \sim (1, 1)_2$
    - Quark Weak doublet: $Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}_L \sim (2, 3)_{1/3}$
    - Antiquark weak singlets: $u_{iL}^c \sim (1, 3^c)_{-4/3}$

      $d_{iL}^c \sim (1, 3^c)_{2/3}$

No mass terms allowed by gauge symmetries.

The Higgs Mechanism

- In order to generate masses for the charged fermions, one introduces a spinless boson Higgs field which couples the SM singlets and doublets via Yukawa interactions:
  - $H = \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \sim (2, 1^c)_1$
- The Higgs potential leads to the Higgs acquiring a non-zero vacuum expectation value (vev), breaking electroweak symmetry.

  This allows all the SM particles (except neutrinos) to acquire masses.

Dark Matter

- Cosmological observations demand the existence of an unknown, neutral, weakly interacting, non-baryonic particle which makes up approximately 25% of the observed matter density in the universe.
- If the hypothesized dark-matter (DM) consists of this weakly interacting massive particle (WIMP), it would be required to have mass ~ O(1) TeV.

New Physics at the Weak Scale?

- Main Reason:
  - **Understand dynamics behind electroweak symmetry breaking (EWSB).**
- Are there elementary Higgs Bosons?
- Why is the Weak scale so much smaller then the Planck scale?
- Are there new symmetries associated with the dynamics responsible for EWSB?
- Dark Matter?
- Are there new space-like dimensions which will manifest themselves at the weak scale?

Are there Extra Dimensions (ED) ?

- Extra dimensions can help explain the hierarchy between the weak and the Planck scale.
- They can also provide a dark matter candidate.
- Why have we not observed them?
    - A natural possibility is that they are compact.

As a particle moves in the ED, its kinetic energy is converted to an effective mass in our 4D world:

SM particles + tower of new particles:

- Kaluza-Klein (KK) excited states with the same quantum numbers as their SM partners, but larger mass.

Measuring the masses and couplings associated with these particles could tell us the size and number of ED.

Warped Extra Dimensions

- Space is compact, of size ***2L***, with orbifold boundary conditions:
  - (x , y) ⟹ (x , - y).
- Brane at y = 0, UV or Planck Brane
- Brane at y = *L*, IR or TeV Brane
  - Non-factorizable metric: Solution to Einstein's equations in 5D.
  - 5D Planck mass related to M_{PL}

$$M_{Pl}^2 = \frac{(M_{Pl}^{fund.})^3}{2k}(1 - e^{-2kL})$$

$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

$$e^{-kL} << 1$$

- At IR brane, all scales warped down
- Natural scale at the UV brane: *Fundamental Planck scale*
  - All scales of same order with *kL* ~ 30 :
    - Solution to Hierarchy Problem

$$M_{Pl} \approx M_{Pl}^{fund.} \approx k$$

- Higgs field lives on or near the IR brane:

$$v \sim \tilde{k} \equiv k\, e^{-kL} \approx M_{Pl}\, e^{-kL} \sim \text{TeV}$$

Standard Model Particles

The KK mass scale is given by $\tilde{k} = ke^{-kL}$

KK mode expansion:

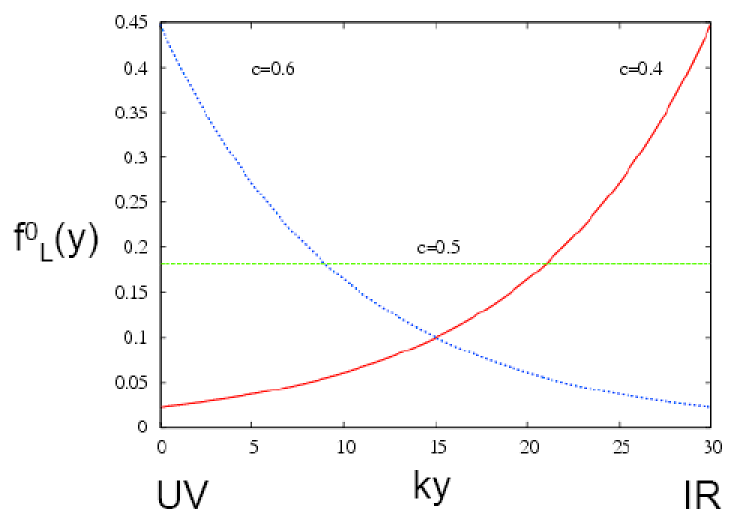
$$\Psi_{L,R}(x,y) = e^{3ky/2}\sum_n \psi^n_{L,R}(x) f^n_{L,R}(y)$$

- SM fermion masses related to their zero mode wave function at the IR brane.
- Localization determined from bulk mass term: $L_m = c_f k\bar{\Psi}\Psi$
- KK wave functions depend on c_f, and are localized towards the IR brane.
- Localization for left-handed fermion:
  - $c_f > 0.5$ UV brane
  - $c_f = 0.5$ Flat
  - $c_f < 0.5$ IR brane

KK mode expansion:

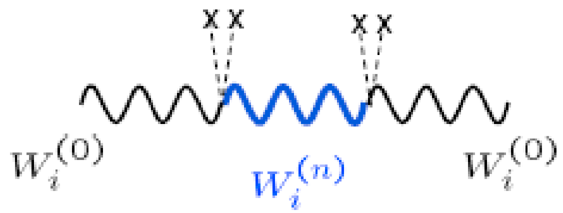
$$A^\lambda(x,y) = \sum_n A^\lambda_n(x) f^n(y)$$

- SM (zero mode) gauge bosons have flat profiles and therefore couple to SM and KK fermions equally.
- KK gauge bosons localized towards IR brane.



Effects of the KK Modes of the Gauge Bosons on the Z Pole Observables.

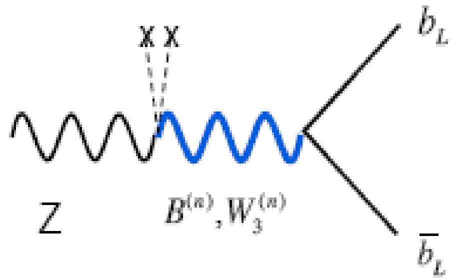
- Large mixing with *Z* and *W* zero modes through *Higgs*
  - Large corrections to the m_Z/m_W ratio (*T* parameter)



$$\Downarrow$$

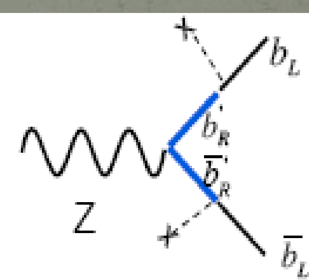
$$M_{KK} \geq 5 - 10 \ \text{TeV}$$

- *Top* and *bottom* zero modes localized close to the IR brane:
  - Large gauge and Yukawa couplings to gauge bosons and fermion KK modes.
  - Large corrections to the $Zb\bar{b}$ coupling



$$\Downarrow$$

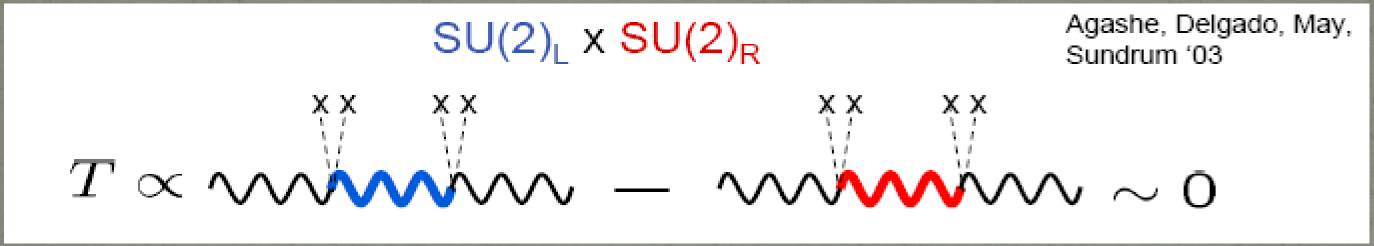
$$M_{KK} \gtrsim 7 - 8 \, \text{TeV}$$



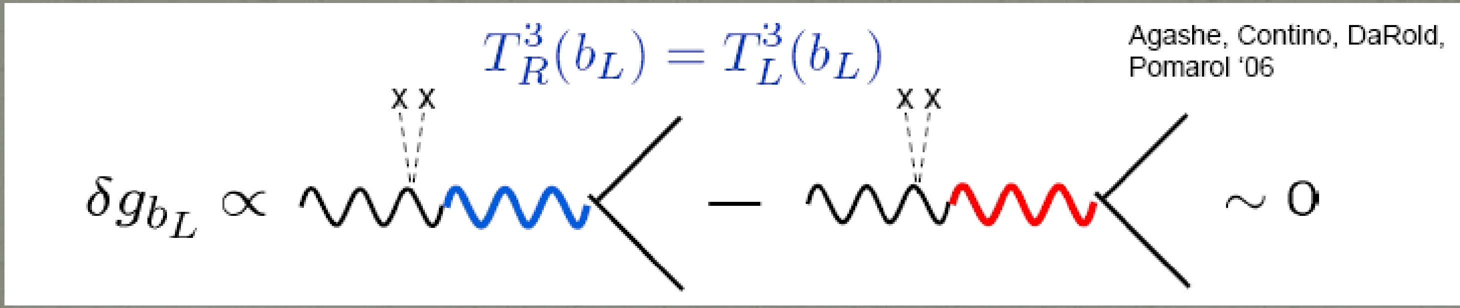
Csaki et al'02; Hewett et al'02, Pomarol et al'02

Phenomenologically Interesting Theory?

- Extend SM bulk gauge symmetry:
  - $SU(2)_R$ (custodial symmetry) is broken in the UV.



- The custodial symmetry together with a discrete L ⟷ R symmetry and a specific bidoublet structure of the fermions under $SU(2)_L$ x $SU(2)_R$:



- Reduces tree level contributions to the *T* parameter and the $Zb\bar{b}$ coupling to allow for lightest KK gauge bosons with $M_{KK} \sim 3$ *TeV*.

Gauge Higgs Unification

Gauge Higgs Unification?

- IDEA: Can we get the *Higgs* from the scalar five dimensional component of the gauge fields?
- PROBLEM: The quantum numbers of the gauge fields discussed so far do not allow for such a possibility.
- Can we extend the gauge symmetry to realize such a possibility?
- New symmetry must be broken on both the branes.
- Scalars acquire zero modes:

  - ***Higgs Boson?***

Outline

- Extend the SM gauge group to SO(5) x $U(1)_X$
- Calculate KK spectrum for the SM particles.
- Calculate one-loop Higgs potential.
- Demonstrate electroweak symmetry breaking.
  - Using known SM gauge boson and quark masses, we obtained a Higgs mass between 115-160 GeV.
  - Localization parameters of the fermions consistent with the ones needed to obtain agreement with electroweak precision observables.

- Calculate couplings of the KK states and SM particles.
- Study associated collider phenomenology.
  - Mass of the first excited mode of the top quark, t^1, less then half the mass of the first excited state of the gluon , G^1.
  - Collider phenomenology studied showed that the reach at the LHC for the t^1 is extended due to the additional contribution from the G^1 channel.

- Extend the model to include the lepton sector .
- Introduce an additional Z_2 symmetry and additional “odd” fermions.
  - Generated the correct lepton and neutrino masses.
  - Dark matter candidate with a mass as low as 500 GeV.
  - May be probed with scattering experiments with nuclei via Higgs exchange in the near future.

The Model

- SO(5) x $U(1)_X$ → SU(2) x $U(1)_Y$ on UV brane
  via B.C. $SU(2)_L$ x $SU(2)_R$ x $U(1)_X$ on IR brane
- T^i → T_L^a, T_R^a, $T^{\hat{a}}$ $Y/2 = T^{3_R} + Q_X$
- Higgs identified with 4D scalars associated with the broken generators: $H \propto (h^{\hat{1}} + ih^{\hat{2}}, h^{\hat{4}} - ih^{\hat{3}})$
- At one loop, Higgs potential:
  - leads to $< h^{\hat{4}} >= h.$

$$V(h) = \sum_r \pm \frac{N_r}{(4\pi)^2} \int_0^\infty dp p^3 \log[\rho(-p^2)].$$

- Equations of motion for gauge bosons and fermions in presence of vev of *h* mix the different modes and therefore the boundary conditions.

Can use following gauge transformation, which relates the solutions with $h = 0$ to the ones with $h \neq 0$:

$$\Omega(x_5, h) = \exp\left[-iC_h h T^{\hat{4}} \int_0^{x_5} dy\, a^{-2}(y)\right].$$

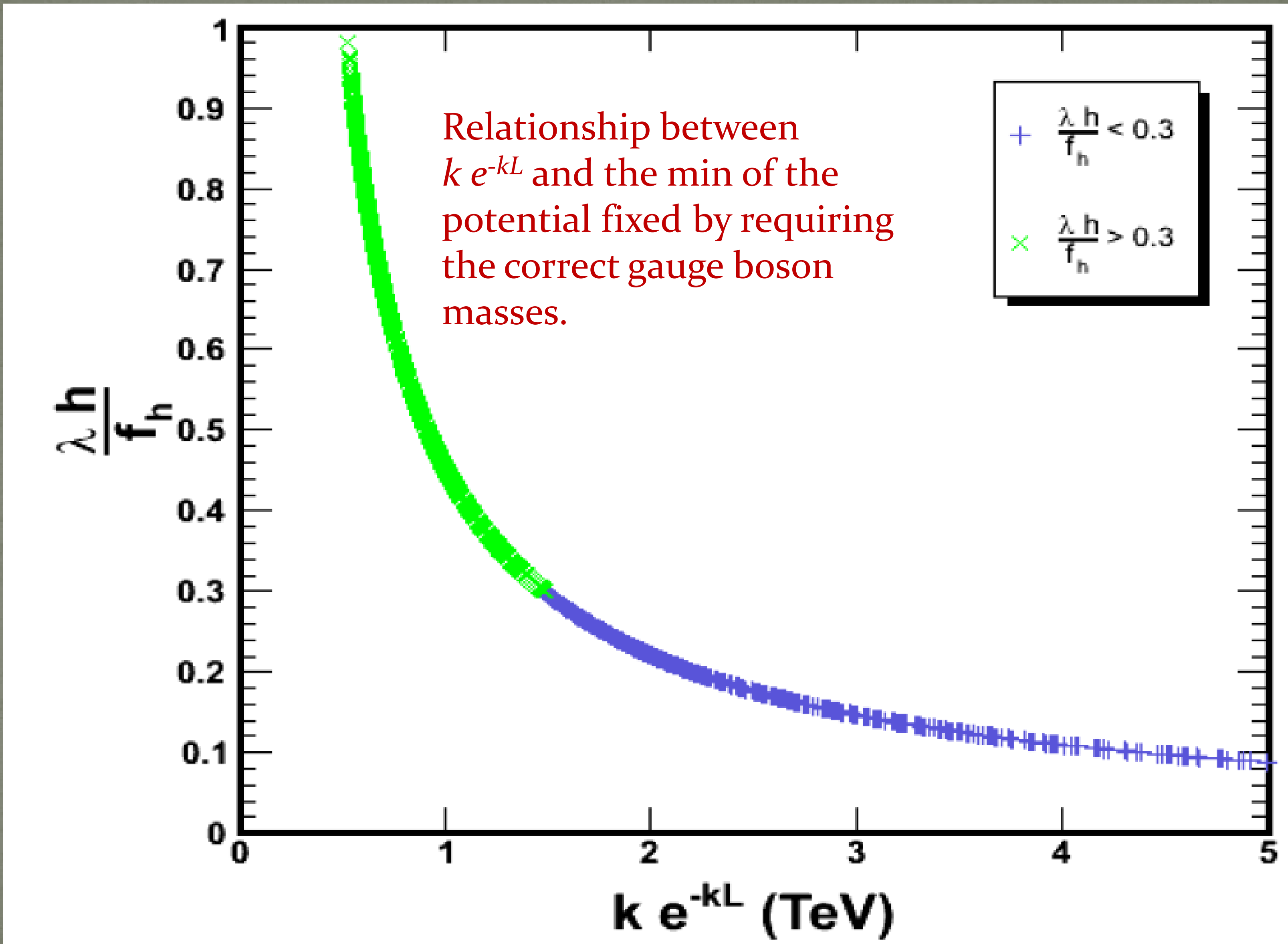
- Solutions to the e.o.m for the gauge bosons and fermions are Bessel functions satisfying either Neumann or Dirichlet B.C.

- Gauge transformation, $\Omega(0,h)$, is 1 at the UV brane.
  - Write solutions for e.o.m consistent with the B.C. at UV brane.
  - Rotate solutions to include the vev of h.
  - Imposing B.C. on IR brane, we arrive at the quantization equations for the gauge and fermion masses, z, given by the zeros of the spectral functions ρ_i.

$$\rho_b(z^2) = 1 + F_b(z^2)\sin^2\left(\frac{\lambda h}{f_h}\right) \qquad \rho_t(z^2) = 1 + F_{t_1}(z^2)\sin^2\left(\frac{\lambda h}{f_h}\right) + F_{t_2}(z^2)\sin^4\left(\frac{\lambda h}{f_h}\right)$$

$$\rho_W(z^2) = 1 + F_W(z^2)\sin^2\left(\frac{\lambda h}{f_h}\right) \qquad \rho_Z(z^2) = 1 + F_Z(z^2)\sin^2\left(\frac{\lambda h}{f_h}\right),$$

  - To reproduce SM like couplings of the Higgs to the SM particles, we will restrict ourselves to $(\lambda h/f_h) < 0.3$.



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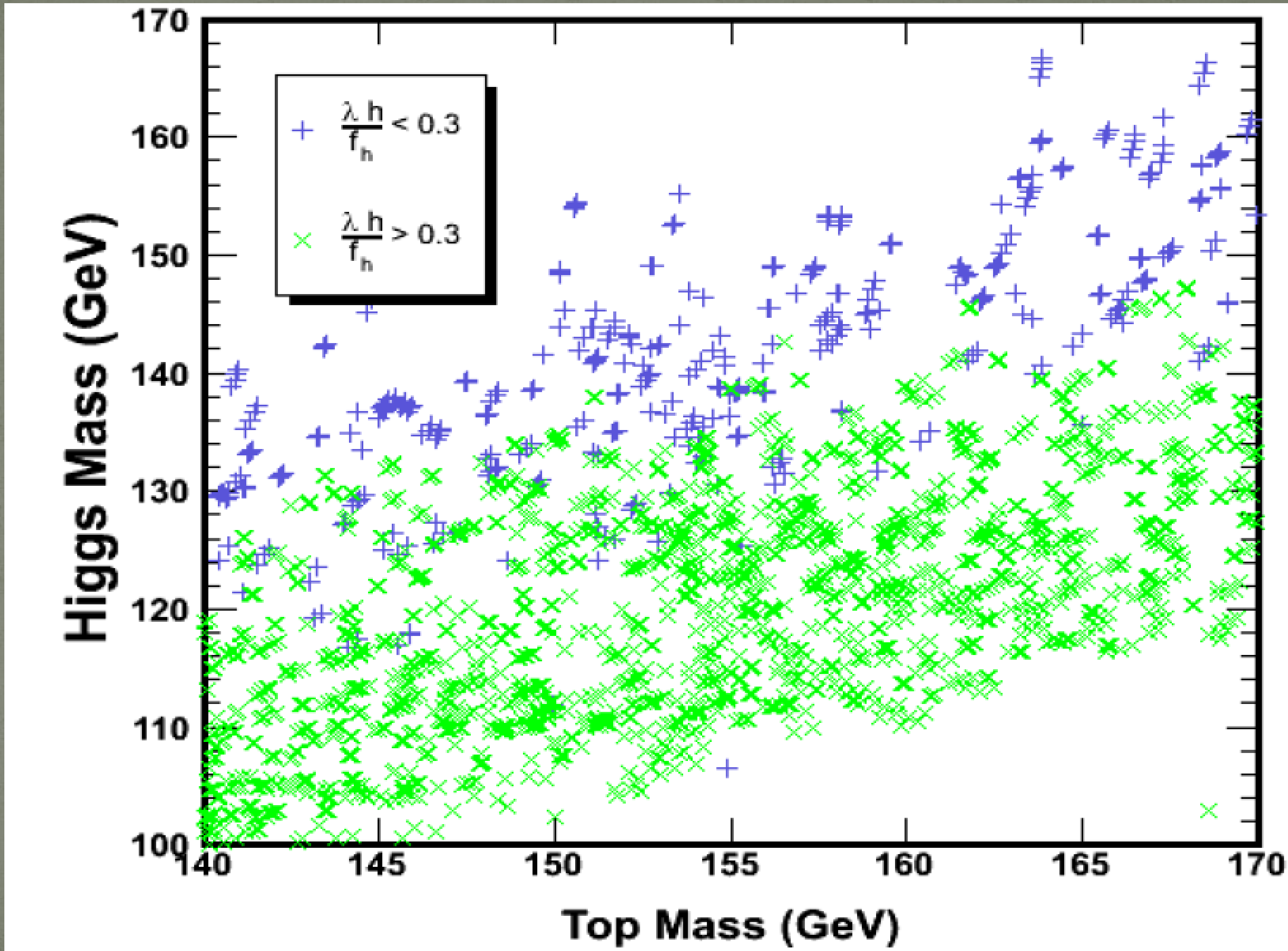

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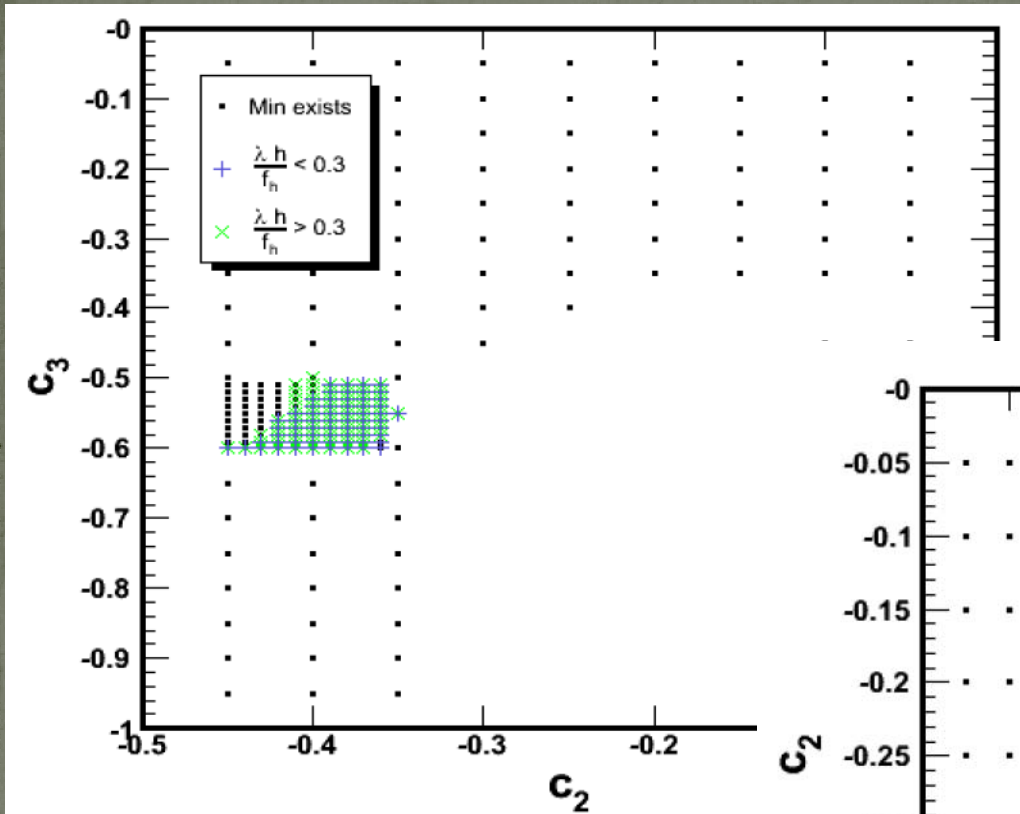
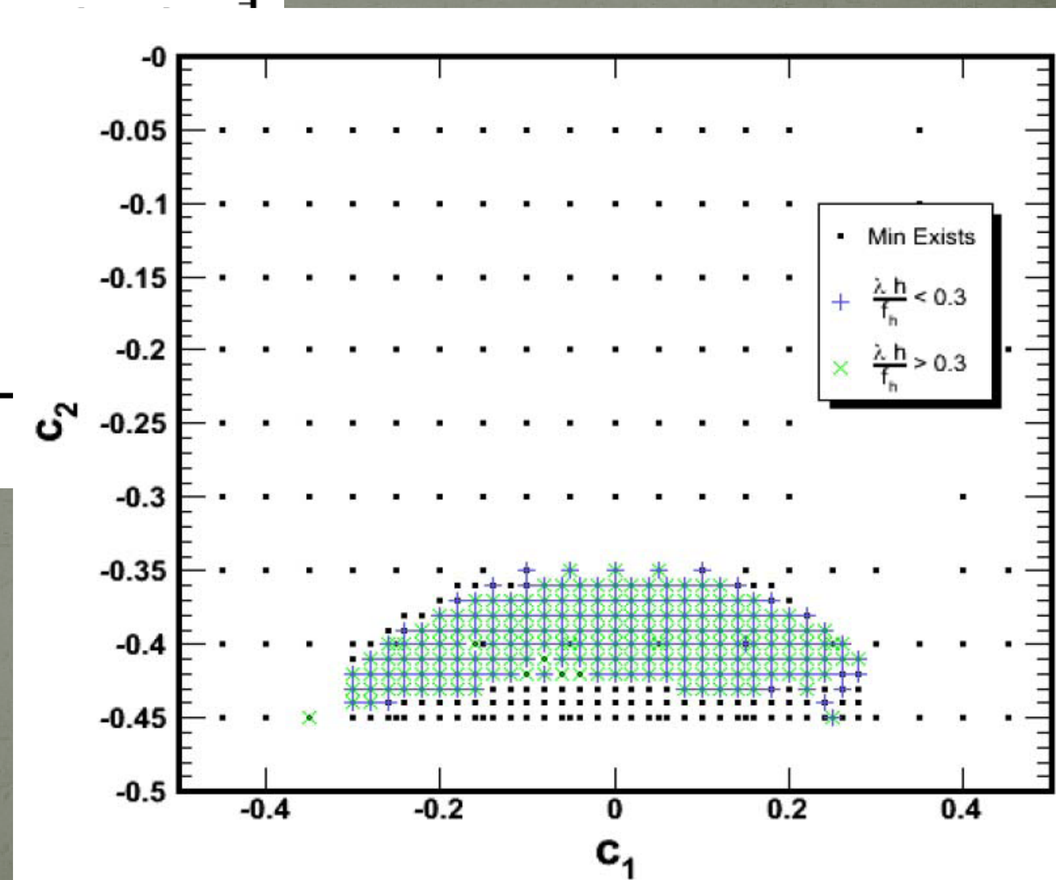
Masses in the phenomenological range only when c_1, c_2 and c_3 in the range allowed by Electro Weak Precision Tests.



Localization parameters:

- c_1: Left handed top and bottom.
- c_2: Right handed top.
- c_3: Right handed bottom.



Similarly, three different localization parameters are required for the leptons and neutrinos.

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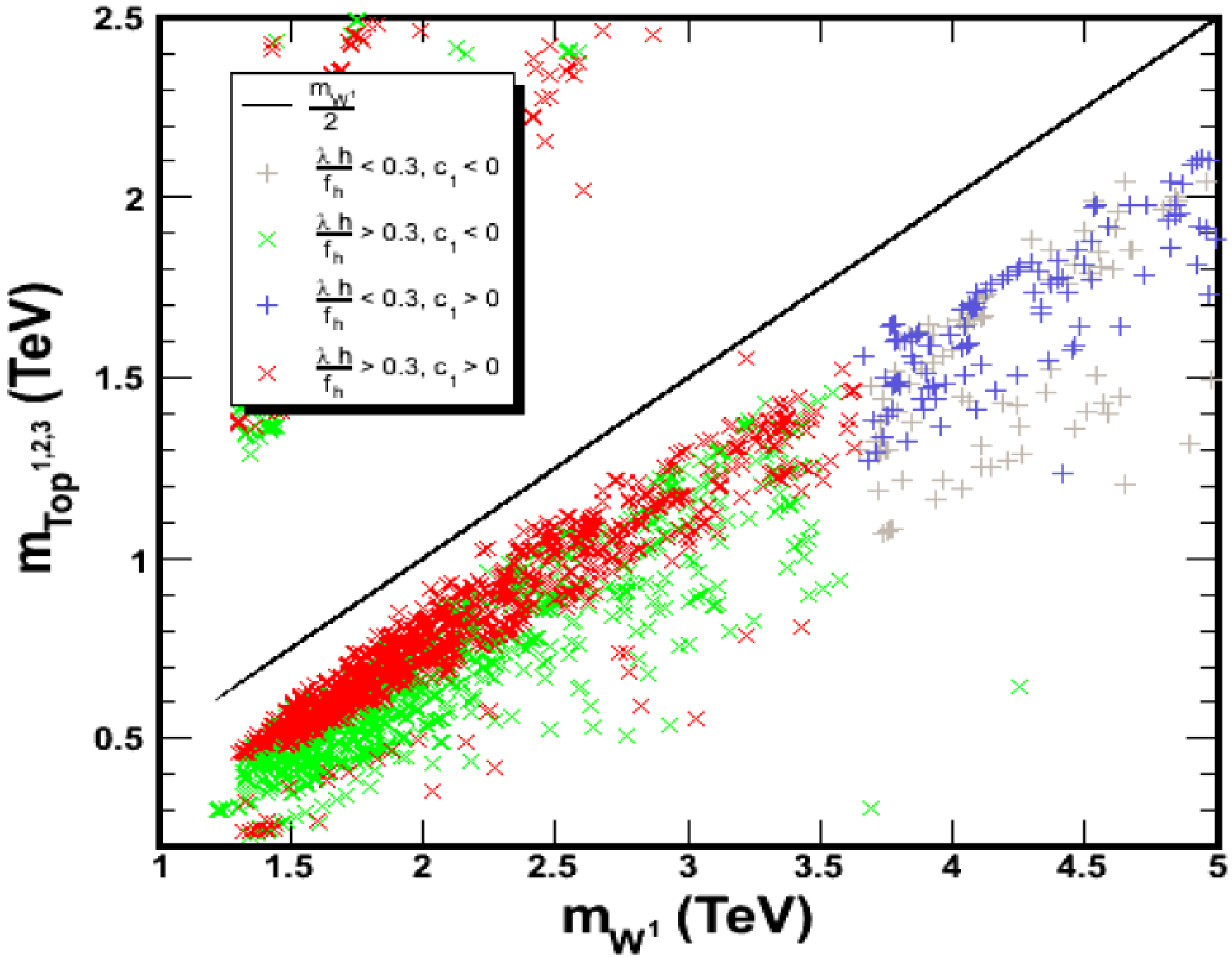
First few KK modes of the *Top* vs. m_{W_1}



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t^1 and G^1 Decays Branching Ratios

- Decays of G^1 into pairs of excited tops, t^1. Improve reach to probe t^1-masses further than direct QCD production.
- Pairs of t^1 decay into either $W^+ b$, $H\,t$ or $Z\,t$.

M. Carena, A. D. Medina, B. Panes, N. R. Shah & C. E. M. Wagner, PRD77:076003, '08

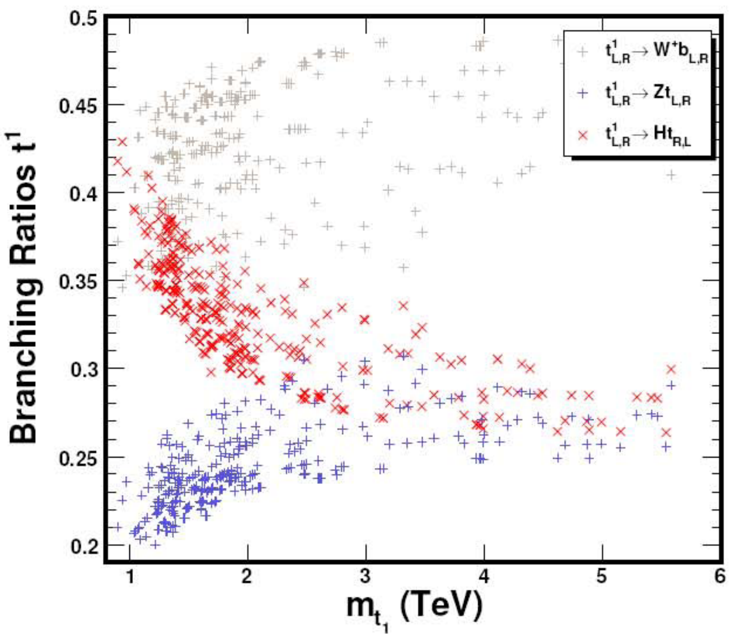


Figure 4: Branching ratios for the decay of t^1 vs m_{t^1} (GeV). Notice that the 2:1:1 relations holds for large m_{t^1}.

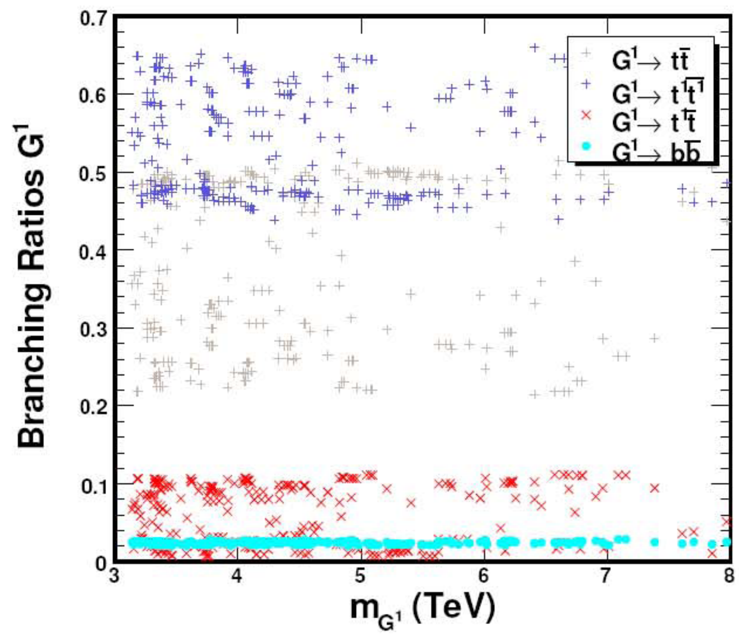


Figure 5: Branching ratios for the decay of G^1 vs m_{G^1} (GeV). Notice that G^1 decays mostly to t^1 pairs.

Collider Phenomenology

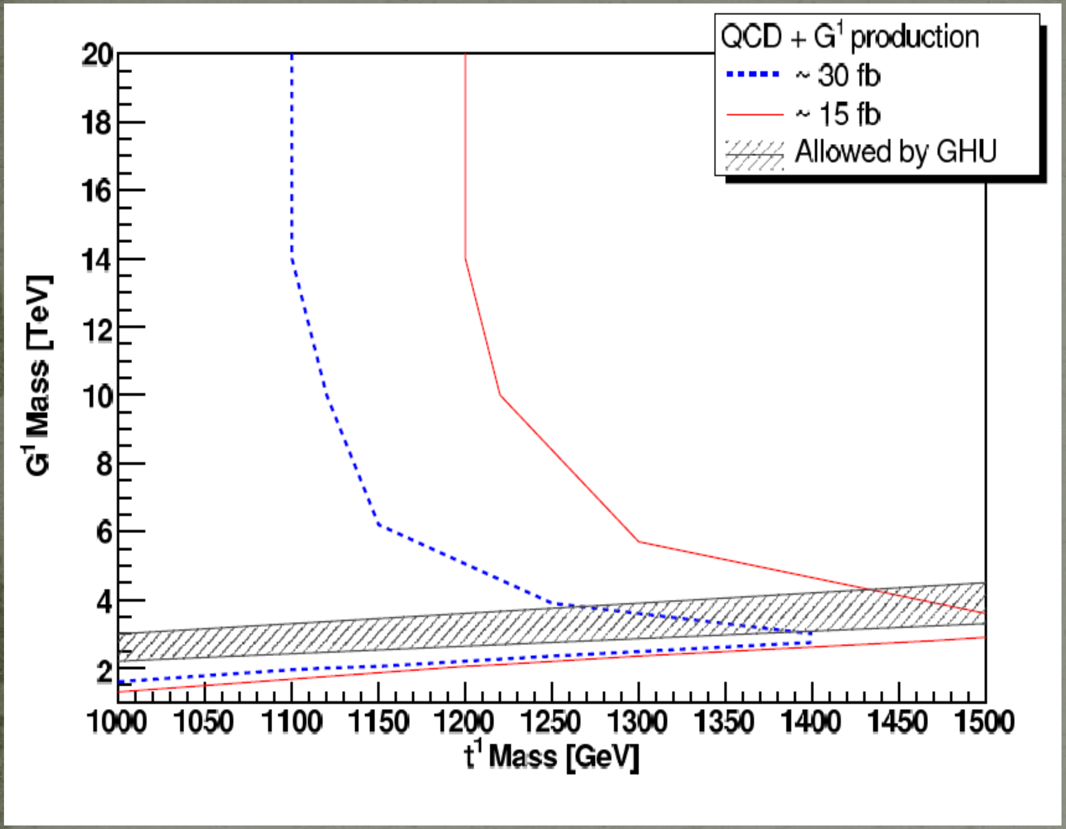
- As shown when we calculated the t^1 branching ratios, ~ 50 % of the time, t^1 decays into $W^+ b$. We shall therefore concentrate on the channel:

$$pp \to (g + G^1) \to t^1\bar{t}^1 \to W^+ b W^- \bar{b} \to l^- \bar{\nu} b \bar{b} jj, \quad (l = e, \mu)$$

- Backgrounds for this signal:
  - Top quark pair production induced by G^1 in addition to QCD (main background)
  - W + jets
  - Z + jets
- Last two backgrounds are reduced to negligible levels by requiring 2 *b*-tags and lepton + MET.

- Madgraph - Madevent package, including the HELAS subroutine was used to generate signal and background. The events are then passed through Pythia and PGS4. Pythia performs the hadronization processes, and includes initial and final state radiation. Finally, PGS4 performs a simulation for the LHC ATLAS detector.

Constant cross-section curves in (m_{G_1}, m_{t_1}) plane to estimate reach at 300 fb^{-1}



Real reach somewhere between blue and red curves.

Grey shaded region is mass spectrum allowed in the GHU model.

QCD alone gives a reach of t^1 mass~1100 GeV with a cross-section of 30 fb.

Including G^1, lines of constant cross-section are plotted on the G^1-t^1 plane.

Left of the blue line, the production cross-section is larger then 30 fb. For cross-sections ~ 30 fb, including G^1 increases the reach for the t^1 mass ~1400GeV.

However, increasing t^1 mass increases efficiency, and our simulation shows that the presence of t^1 can be detected for values of cross-section ~ 15 fb.

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If $c_1 > 0.5$ and $-0.5 < c_3 < c_1$, this reduces to:

$$\left(\frac{z}{\tilde{k}}\right) = M_{L_2} e^{(\frac{1}{2}-c_1)kL} \sin\left[\frac{\lambda h}{f_h}\right] \sqrt{2\,(c_1 - \frac{1}{2})(c_3 + \frac{1}{2})}$$

For $c_1 > 0.5$ and $c_3 > c_1$, instead,

$$\left(\frac{z}{\tilde{k}}\right) = e^{(\frac{1}{2}-c_3)kL} \sin\left[\frac{\lambda h}{f_h}\right] \sqrt{2\,(c_3^2 - \frac{1}{4})}$$

Finally, for the case $c_1 > 0.5$ and $c_3 < -0.5$:

$$\left(\frac{z}{\tilde{k}}\right) = M_{L_2} e^{(1+c_3-c_1)kL} \sin\left[\frac{\lambda h}{f_h}\right] \sqrt{2\,(\frac{1}{2} - c_1)(c_3 + \frac{1}{2})}$$

Lepton Spectrum

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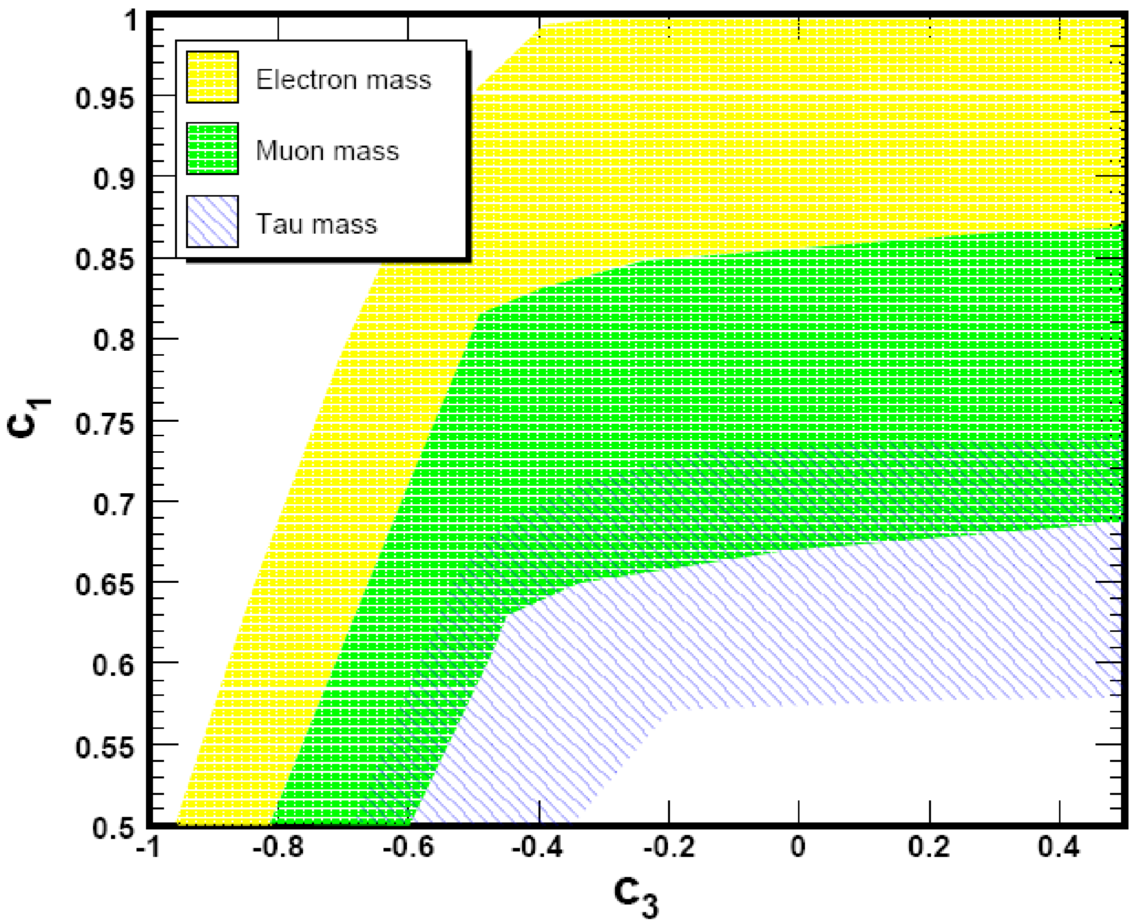
Realistic lepton masses may be generated for 0.5< c_1<0.7.

A common value of c_1 for the three generations is preferred to cancel flavor violating effects.

c_1>0.5 is preferred for agreement with precision electroweak data.

Values of c_1 > 0.75 incompatible with heavy charged lepton masses.



Neutrino Spectrum

- Based on charged lepton spectrum, $c_2<0$ preferred.
- M_{IR} and M_{UV} localized Majorana mass terms for the right handed neutrino.
- Realization of the See-Saw mechanism in warped extra dimensions.

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$c_1 > 0.5$ and $c_2 > 1/(kL)$:

$$\left(\frac{z}{\tilde{k}}\right) = \frac{M_{L_1}^2 (c_1 - \frac{1}{2}) e^{2(\frac{1}{2}-c_1)kL} \sin\left[\frac{\lambda h}{f_h}\right]^2}{M_{IR}}$$

$c_1 > 0.5$ and $c_2 < -1/(kL)$:

$$\left(\frac{z}{\tilde{k}}\right) = \frac{M_{L_1}^2 (c_1 - \frac{1}{2}) e^{2(\frac{1}{2}-c_1+c_2)kL} \sin\left[\frac{\lambda h}{f_h}\right]^2}{M_{UV}}$$

$c_1 > 0.5$ and $c_2 \sim 0$:

$$\left(\frac{z}{\tilde{k}}\right) = \frac{M_{L_1}^2 (c_1 - \frac{1}{2}) e^{2(\frac{1}{2}-c_1)kL} \sin\left[\frac{\lambda h}{f_h}\right]^2}{M_{UV} + M_{IR}}$$

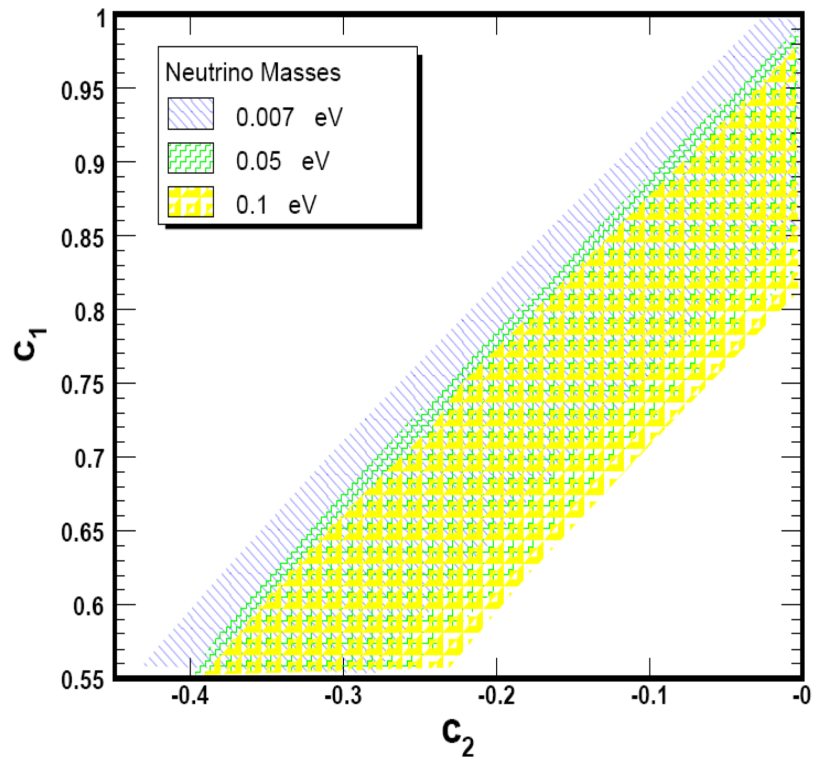


Figure 2: Region of c_1, c_2 parameter space consistent with the neutrino masses of interest: $c_1 > 0.5$ and $-0.5 < c_2 < 0$. The bands correspond to variations of the values of the parameters $\tilde{k}$, M_{L_1} and $M_{UV,IR}$ in the range 1.5 TeV $\lesssim \tilde{k} \lesssim$ 5 TeV, $0.1 \lesssim M_{L_1} \lesssim 1.5$ and $0.5 \lesssim M_{IR,UV} \lesssim 2.5$.

Dark Matter

Z_2 Symmetry :

- Quarks and gauge bosons don't have partner multiplets.
- Identify *c* of odd fermion with right handed neutrino.
- Introduce localized Majorana mass terms, M_{UVo} and M_{IRo}.
- Odd right handed neutrino, N_1, B.C. chosen such that for values of c_2 giving rise to the correct neutrino masses, it is the *Lightest Odd Particle* (LOP).

- LOP mass ~ *1 TeV*
- ***Dark Matter Candidate***

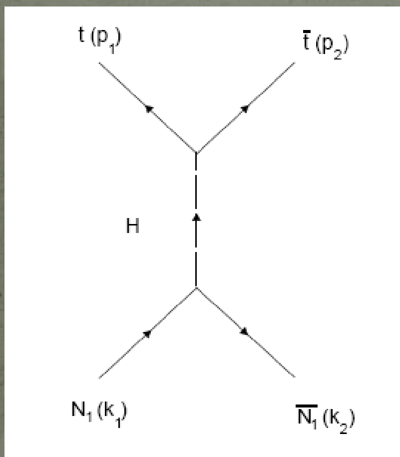
$$\Omega_{DM} = \frac{\gamma s_0 x_F}{\rho_c M_{Pl}(\sigma_0 + 3\sigma_1/x_F)}\sqrt{\frac{45}{\pi g*}},$$

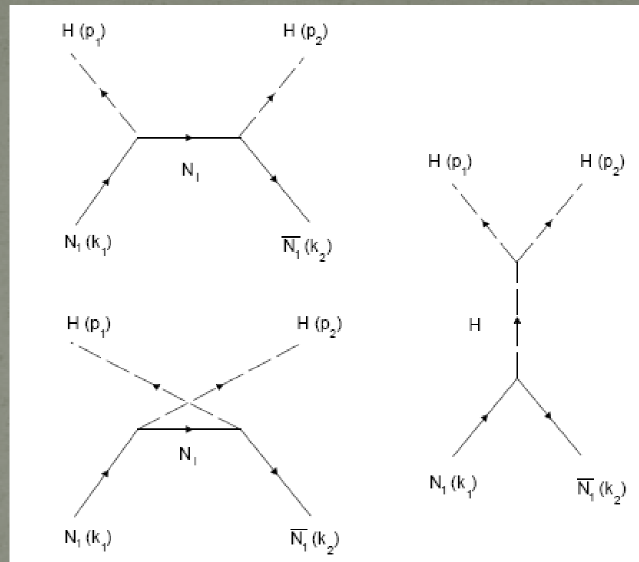
$$< v^2 >_{rel} = \frac{6}{x_F},$$

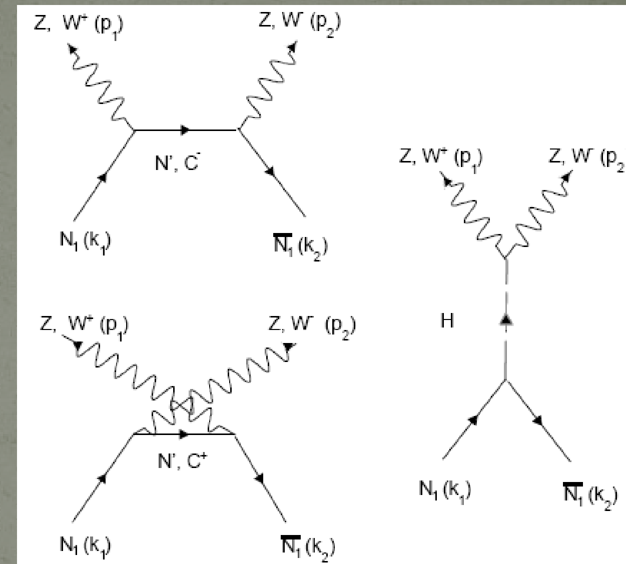
$$x_F = \log\left(c\,(c+2)\sqrt{\frac{90\pi}{x_F g*}}\frac{g_0}{2\pi^3} m_1 M_{Pl} < \sigma v >_T\right)$$

$$< \sigma v >_T = \sigma_0 + \sigma_1 < v^2 > \simeq \sigma_0 + 6\,\sigma_1/x_F$$

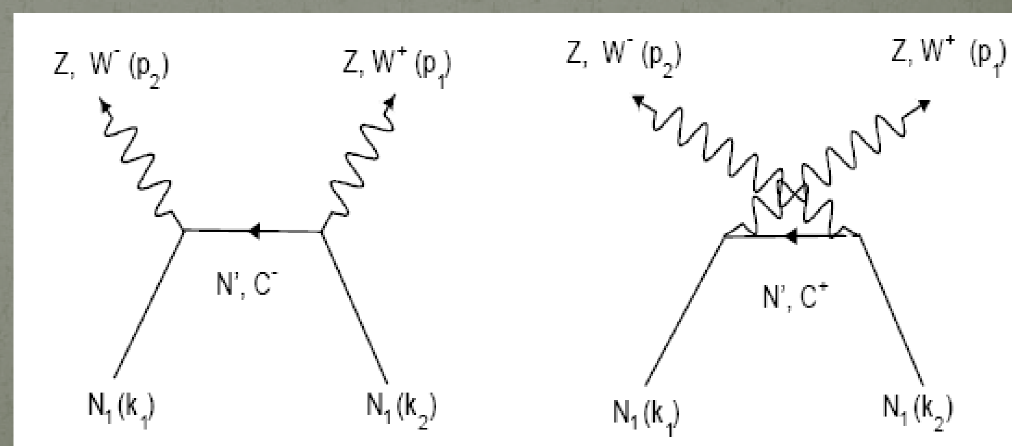
N_1-N_1 Annihilation diagrams







Additional diagrams contributing in the Majorana case:



- Peak of curves corresponds to $m_1 \sim ke^{-kL}$.
- Not possible to generate a consistent DM candidate for larger values of $\tilde{k}$.
- The lower cut-off corresponds to what we call the non-linear regime: □h/f_h<0.3

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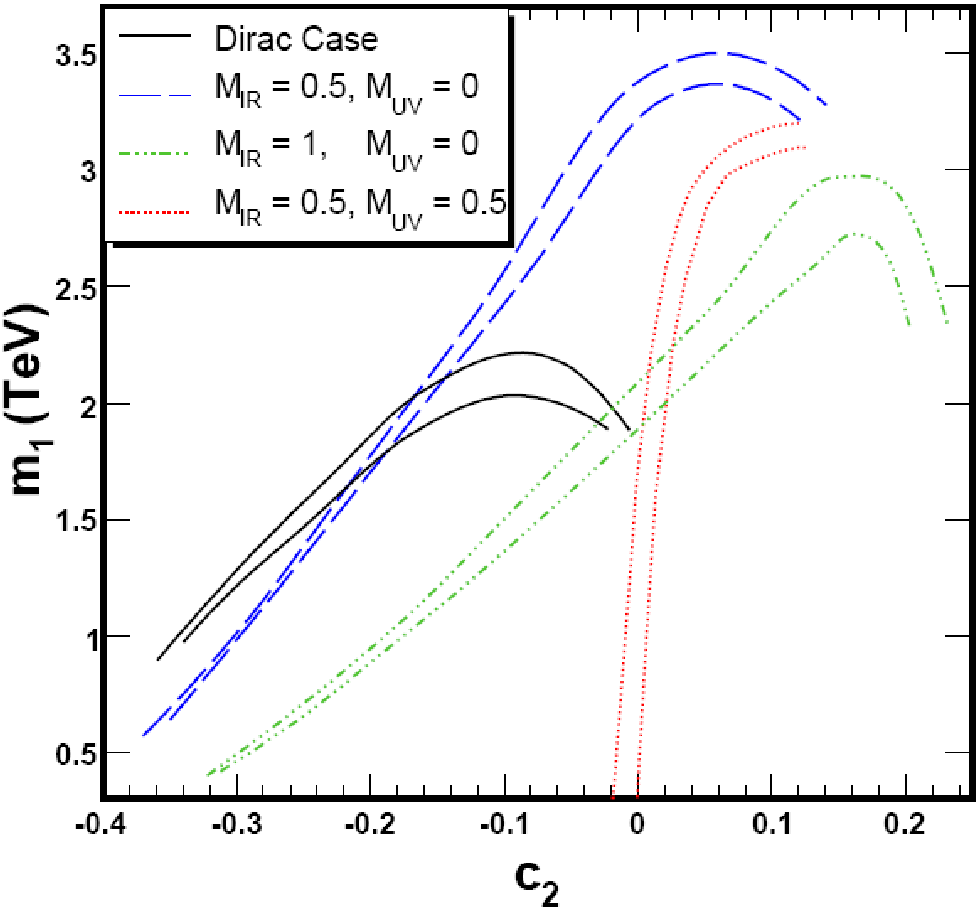


Figure 18: Parametric plot of m_1, the mass of the LOP, versus c_2, the localization parameter of the odd fermions, when $\Omega_{DM} \sim 0.23 \pm 0.1$. The two lines for each value of the Majorana masses are associated with the upper and lower bound on Ω_{DM}.

Direct Dark Matter Detection through Higgs Exchange

- Higgs couplings to the LOP are of the order $\lambda_{11} \simeq 0.3 - 0.7$, with larger couplings associated with larger LOP masses.
- Can induce relatively large cross-section for the scattering of the LOP with nuclei:

$$\Rightarrow \frac{\sigma_{SI}}{A^4} \approx \frac{0.04\ \lambda_{11}^2 m_p^4 g_2^2}{\pi m_W^2 m_H^4}$$

Assuming LOP mass >> nucleus mass.

neutrino-nucleon spin independent cross-section

- For example, with an LOP mass of ~ 700 GeV, Higgs mass ~ 130 GeV and couplings ~ 0.35, the spin independent cross-section is ~ 1.4 x 10^{-43} cm^2.
- The current limit from CDMS is ~ 1.6 x 10^{-43} cm^2, sensitivity should have been ~1.4 x 10^{-43} cm^2.
- Minimal model presented should be probed in the near future by the CDMS and the XENON experiments.

Cross-section Limits

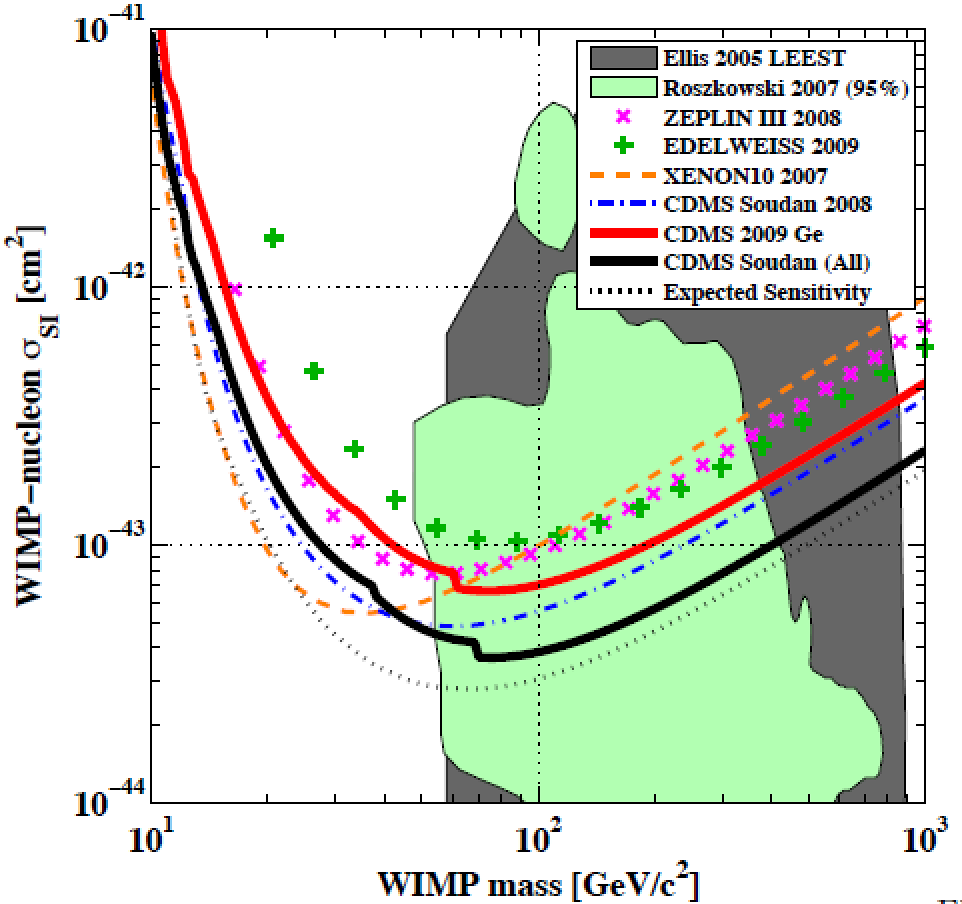
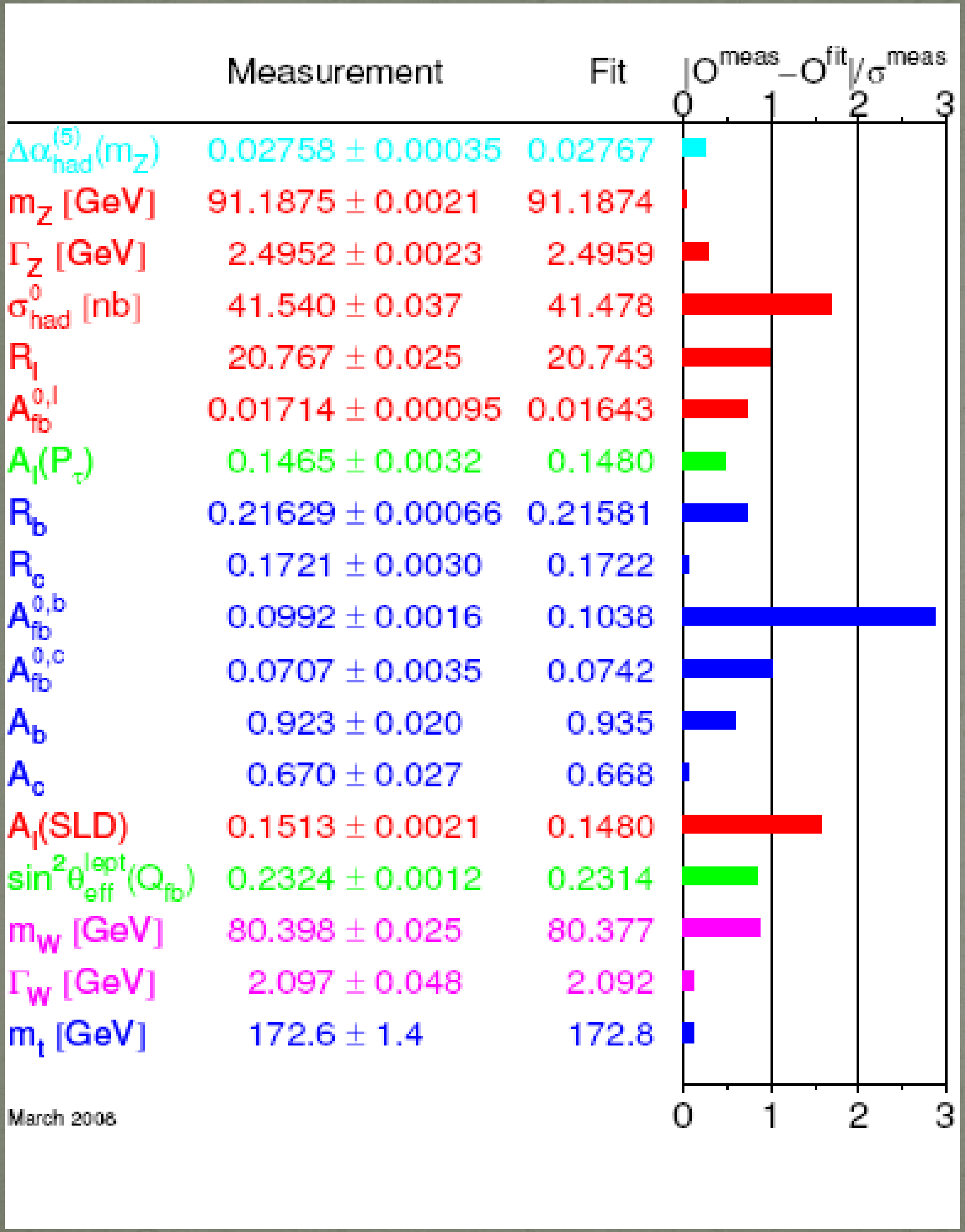


FIG. 4: 90% C.L. upper limits on the WIMP-nucleon spin-independent cross section as a function of WIMP mass. The red (upper) solid line shows the limit obtained from the exposure analyzed in this work. The solid black line shows the combined limit for the full data set recorded at Soudan. The dotted line indicates the expected sensitivity for this exposure based on our estimated background combined with the observed sensitivity of past Soudan data. Prior results from CDMS [11], EDELWEISS II [12], XENON10 [13], and ZEPLIN III [14] are shown for comparison. The shaded regions indicate allowed parameter space calculated from certain Minimal Supersymmetric Models [20, 21] (Color online.)

Conclusions

- We obtained a Higgs Boson, inducing dynamical electroweak symmetry breaking, with mass naturally between *115-160 GeV*.
- Realistic quark and lepton masses may be obtained, with localization parameters consistent with the ones needed to obtain agreement with electroweak precision tests.
- Studied the collider phenomenology of light top KK modes.
- Realistic Neutrino masses were obtained via the See-Saw Mechanism.
- Possibility of a DM candidate with mass ~ *1 TeV*.
- Higgs coupling to the DM candidate should be probed in the near future.

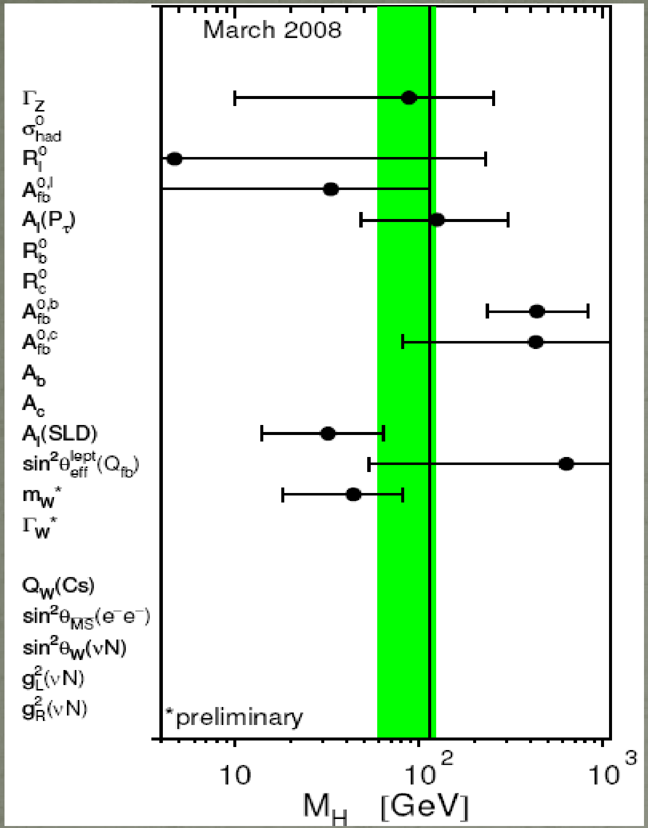
Backup Slides

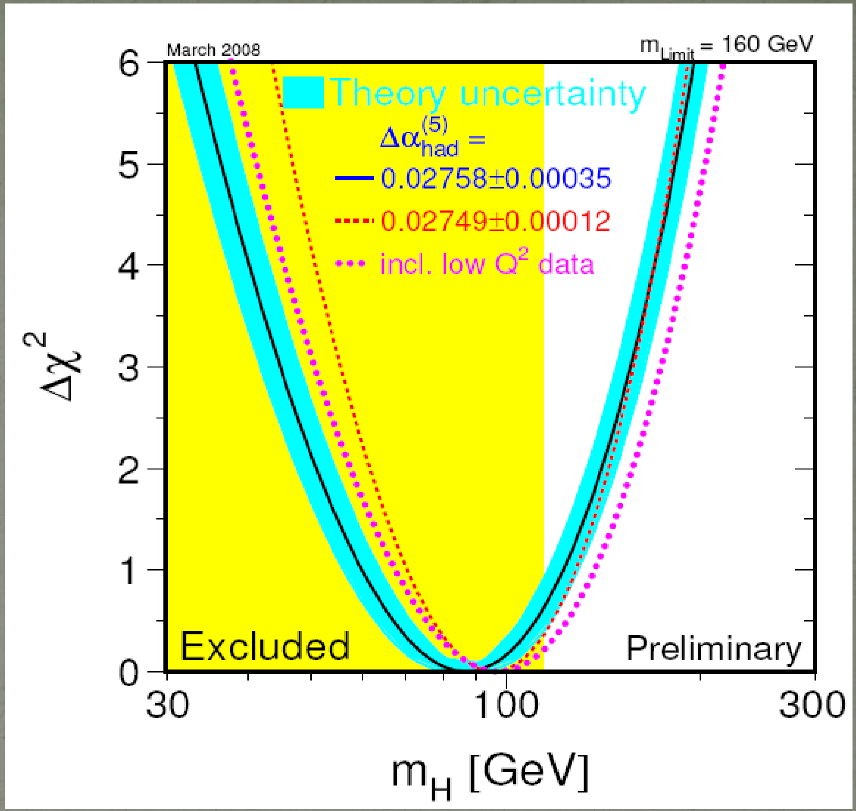


SM agrees with data better then we had hoped.

Discrepancy almost 3 sigma in F-B asymmetry in b production.

LEP Electroweak Working Group, Winter '08





Higgs not observed experimentally.

The vertical green bar denotes overall constraint on M_H derived from the fit to all data.

The vertical black line denotes limit on Higgs mass obtained from the direct search at LEP-2 : $M_H > 114$ GeV.

Precision EW measurements tell us that $M_H < 154$ GeV. This limit increases to 185 GeV when including the LEP-2 direct search limit of 114 GeV.

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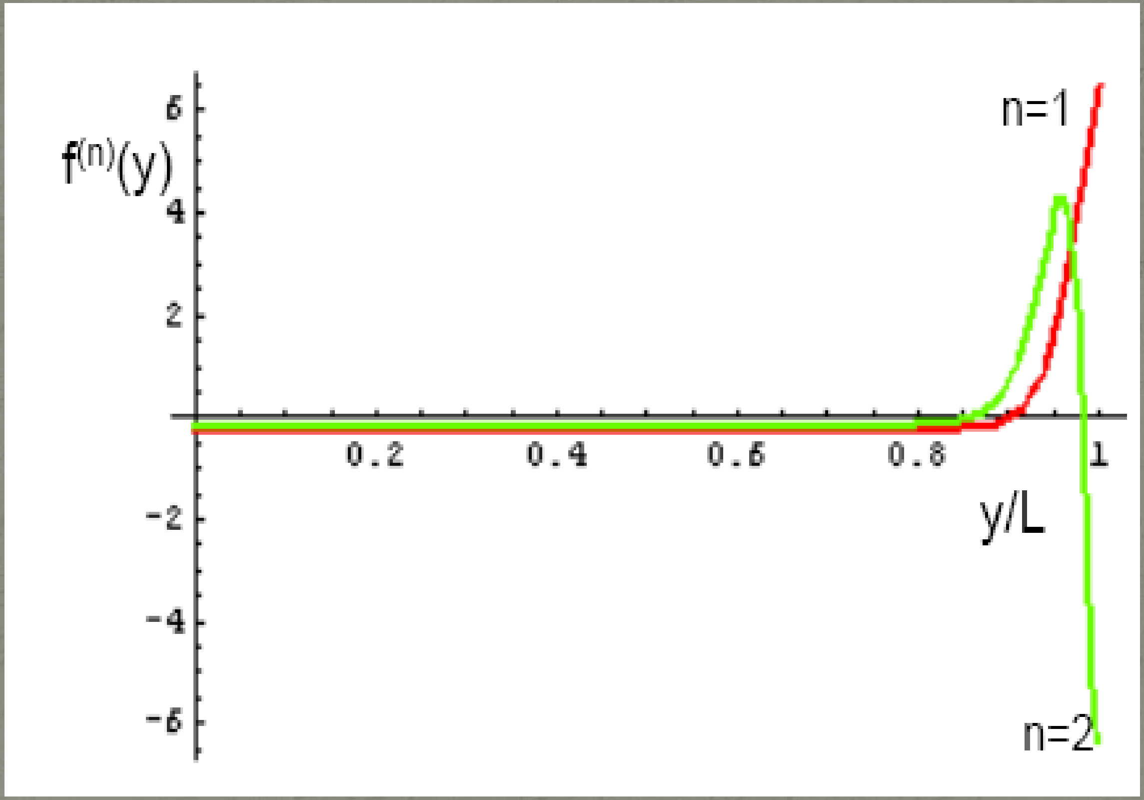
Gauge Boson Profiles



Quark Sector

- t_L and b_L can be written as coming from a $\mathbf{5}_{2/3}$ of SO(5).
- To generate the correct top quark mass without large negative corrections to the T parameter, requires the t_R to be in a separate multiplet from the t_L.
- Additionally the b_R is written in a $\mathbf{10}_{2/3}$ so that the correct bottom Yukawa couplings can be written.
- This then requires 3 vector-like fermion multiplets living in the bulk. Localization parameterized by c_i :

$$\xi^i_{1L} \sim Q^i_{1L} = \begin{pmatrix} \chi^{u_i}_{1L}(-,+)_{5/3} & q^{u_i}_L(+,+)_{2/3} \\ \chi^{d_i}_{1L}(-,+)_{2/3} & q^{d_i}_L(+,+)_{-1/3} \end{pmatrix} \oplus u'^i_L(-,+)_{2/3} \ ,$$

$$\xi^i_{2R} \sim Q^i_{2R} = \begin{pmatrix} \chi^{u_i}_{2R}(-,+)_{5/3} & q'^{u_i}_R(-,+)_{2/3} \\ \chi^{d_i}_{2R}(-,+)_{2/3} & q'^{d_i}_R(-,+)_{-1/3} \end{pmatrix} \oplus u^i_R(+,+)_{2/3} \ ,$$

$SU(2)_L$

$SU(2)_R$

$$\xi^i_{3R} \sim$$

$$T^i_{1R} = \begin{pmatrix} \psi'^i_R(-,+)_{5/3} \\ U'^i_R(-,+)_{2/3} \\ D'^i_R(-,+)_{-1/3} \end{pmatrix} \oplus T^i_{2R} = \begin{pmatrix} \psi''^i_R(-,+)_{5/3} \\ U''^i_R(-,+)_{2/3} \\ D^i_R(+,+)_{-1/3} \end{pmatrix} \oplus Q^i_{3R} = \begin{pmatrix} \chi^{u_i}_{3R}(-,+)_{5/3} & q''^{u_i}_R(-,+)_{2/3} \\ \chi^{d_i}_{3R}(-,+)_{2/3} & q''^{d_i}_R(-,+)_{-1/3} \end{pmatrix}$$

Lepton Sector

- The Lepton sector can be similarly realized,
  - left handed neutrino and electron coming from a **5**$_0$,
  - right handed neutrino arising from another **5**$_0$
  - right handed electron from a **10**$_0$, with the following boundary conditions, and localization parameters c_i :

$\mathrm{SU(2)}_L$ $\mathrm{SU(2)}_R$

$$\xi^i_{1L} \sim L^i_{1L} = \begin{pmatrix} \chi^{e_i}_{1L}(-,+)_1 & l^{n_i}_L(+,+)_0 \\ \chi^{n_i}_{1L}(-,+)_0 & l^{e_i}_L(+,+)_{-1} \end{pmatrix} \oplus N'^i_L(-,+)_0 \,,$$

$$\xi^i_{2R} \sim L^i_{2R} = \begin{pmatrix} \chi^{e_i}_{2R}(-,+)_1 & l'^{n_i}_R(-,+)_0 \\ \chi^{n_i}_{2R}(-,+)_0 & l'^{e_i}_R(-,+)_{-1} \end{pmatrix} \oplus N^i_R(+,+)_0 \,,$$

$$\xi^i_{3R} \sim$$

$$T^i_{1R} = \begin{pmatrix} \psi'^i_R(-,+)_1 \\ N'^i_R(-,+)_0 \\ E'^i_R(-,+)_{-1} \end{pmatrix} \oplus T^i_{2R} = \begin{pmatrix} \psi''^i_R(-,+)_1 \\ N''^i_R(-,+)_0 \\ E^i_R(+,+)_{-1} \end{pmatrix} \oplus L^i_{3R} = \begin{pmatrix} \chi^{e_i}_{3R}(-,+)_1 & l''^{n_i}_R(-,+)_0 \\ \chi^{n_i}_{3R}(-,+)_0 & l''^{e_i}_R(-,+)_{-1} \end{pmatrix}$$

Flavor

- Can demand alignment between the bulk mass parameters and Yukawa couplings to minimize flavor violating effects.

$$
\begin{aligned}
c_3 &= I + a_3 k^2 Y_l^\dagger Y_l \\
c_2 &= I + a_2 k^2 Y_\nu^\dagger Y_\nu \\
c_1 &= I + a_l k^2 Y_l Y_l^\dagger + a_\nu k^2 Y_\nu Y_\nu^\dagger;
\end{aligned}
\longrightarrow
\begin{aligned}
c_3 &= I + a_{32} M_{L_2}^\dagger M_{L_2} \\
c_2 &= I + a_{21} M_{L_1}^\dagger M_{L_1} \\
c_1 &= I + a_{12} M_{L_2} M_{L_2}^\dagger + a_{11} M_{L_1} M_{L_1}^\dagger
\end{aligned}
$$

- A common value of c_1 for the three generations is preferred to cancel flavor violating effects and $c_1 > 0.5$ is preferred for agreement with precision electroweak data.

Dark Matter

- We can further introduce a Z_2 exchange symmetry under which all SM fields are neutral and a new odd partner sector is introduced.
- For simplicity, we will identify the mass parameter of the odd fields with the even SM fields.
  - Identify the lightest odd particle (LOP) multiplet with the second lepton multiplet, containing the right handed neutrino.
  - BC chosen such that the LOP is mainly the neutral singlet for values of the localization parameter that gives rise to the correct neutrino mass via the See-Saw mechanism .

$$\xi^o_R \sim L^o_R = \begin{pmatrix} C^o_R(-,+)_1 & n'^o_R(-,+)_0 \\ n^o_R(-,+)_0 & C'^o_R(-,+)_{-1} \end{pmatrix} \oplus N^o_R(+,-)_0 ,$$

$SU(2)_L$ $SU(2)_R$

The lightest odd particle (LOP) will be absolutely stable:

→ Dark Matter Candidate?

Fermions

- Also allowed boundary mass terms:

$$\mathcal{L}_m = 2\delta(x_5 - L)\left[\bar{u}'_L M_{B_1} u_R + \bar{Q}_{1L} M_{B_2} Q_{3R} + \bar{Q}_{1L} M_{B_3} Q_{2R} + \text{h.c.}\right]$$

$$\mathcal{L}_2 \;=\; -2\delta(x_5 - L)\left[\bar{N}'_L M_{L_1} N_R + \bar{L}_{1L} M_{L_2} L_{3R} + \text{h.c.}\right] - \left[M_{IR}\delta(x_5 - L) - M_{UV}\delta(x_5)\right] N_R N_R$$

  - Similar Majorana mass terms for odd multiplet.
- Same procedure as for the gauge bosons:
  - Quark Spectrum:

$$1 + F_b(m_n^2)\sin^2\left(\frac{\lambda h}{f_h}\right) = 0\,,$$

$$1 + F_{t_1}(m_n^2)\sin^2\left(\frac{\lambda h}{f_h}\right) + F_{t_2}(m_n^2)\sin^4\left(\frac{\lambda h}{f_h}\right) = 0$$

Lepton mass spectrum has a similar structure.

Odd spectrum:

$$\dot{\tilde{S}}_{-M_2}\left(\dot{\tilde{S}}_{M_2} - M_{IR_o}\tilde{S}_{M_2} - e^{2c_2kL}M_{UV_o}\left(\tilde{S}_{-M_2} - M_{IR_o}\dot{\tilde{S}}_{-M_2}\right)\right) + \sin\left[\frac{\lambda h}{f_h}\right]^2 = 0$$

Majorana mass terms split Dirac states into two Majorana states.

t^1 production cross-section through QCD alone and through QCD+G^1 for $M_{G^1} = 4$ TeV.

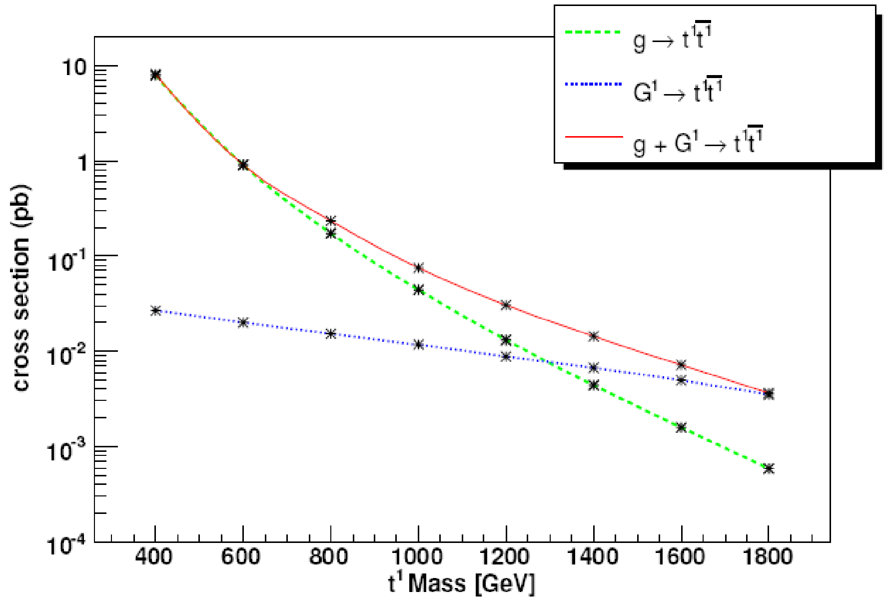


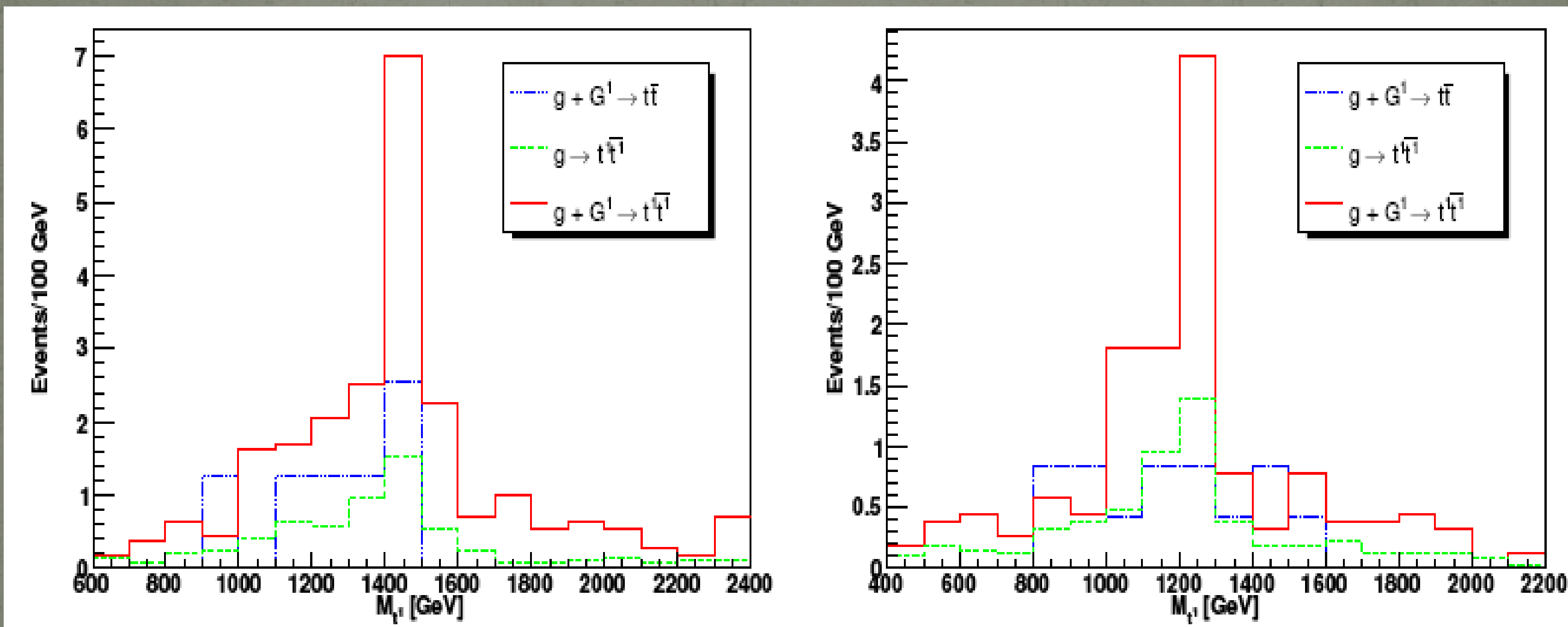
Figure 5: Cross section for $M_{G^1} = 4.0$ TeV with couplings $g_{G^1\bar{t}^1{}_L t^1_L} = -5.8$ and $g_{G^1\bar{t}^1{}_R t^1_R} = -3.1$.

Notice that for $m_{t^1} \sim 1.5$ TeV, G^1 induced production contributes significantly to the t^1 production cross section.

M. Carena, A. D. Medina, B. Panes, N. R. Shah & C. E. M. Wagner, PRD77:076003, '08

- W-mass reconstructed using two methods:
  - W $\to$ 2 jets. Works well for t^1 masses less than 1 TeV. ΔR=0.4.
  - W $\to$ 1 jet. Works well for t^1 masses larger than 1 TeV. Increases signal and decreases background. ΔR=0.6.
- Reconstructed t^1 invariant mass distribution, choosing b with largest ΔR w.r.t W:

m_{t1}~1.47 TeV, m_{G1}~3.9 TeV m_{t1}~ 1.25 TeV, m_{G1}~3.4 TeV



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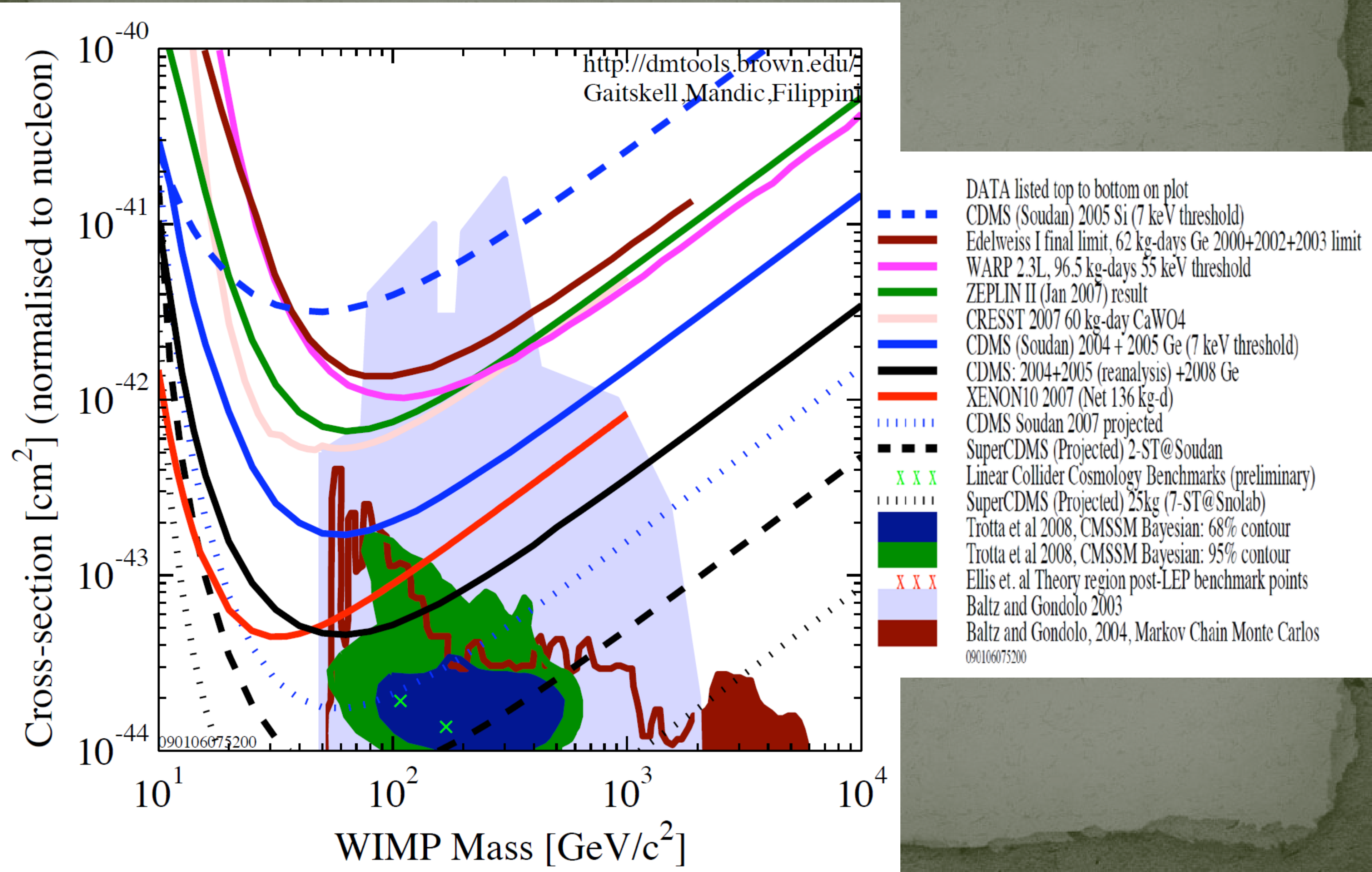
We estimate statistical significance as $S/(S+B)^{1/2}$.
Presence of these particles may be found already at 100 fb^{-1} for Point 1 (60 fb^{-1} point 2) (3-sigma) and discovery at 300 fb^{-1} for point 1 (200 $fb^{-1}$for point 2) (5-sigma).

Cross-section Limits (Pre-2009)



Cross-section Limits

90% C.L. WIMP exclusion limits from CoGeNT: green shaded patches denote the phase space favoring the DAMA/LIBRA annual modulation (the dashed contour includes ion channeling). Their exact position has been subject to revisions. The violet band is the region supporting the two CDMS candidate events. The scatter plot and the blue hatched region represent some hallamrk supersymmetric models and their uncertainties, respectively. For WIMP masses in the interval 7- 11 GeV/cm² a best fit to CoGeNT data does not favor a background-only model. The region encircled by a solid red line contains the 90% confidence interval in WIMP Coupling for those instances. The relevance of XENON10 constraints in this low-mass region has been questioned.