LHC and Dark Matter signatures of improved naturalness

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This talk is based on a paper in preparation with

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Overview

- Motivation
- The model
- Electroweak precision tests
- Dark matter constraints and predictions
- LHC phenomenology

Two problems

- Hierarchy problem:
  The Standard Model is fine tuned
  - the Higgs mass is quadratically divergent and one expects a correction ~ Planck mass

Theoretical lore: there should be some new physics to stabilize the hierarchy and it should be seen at LHC

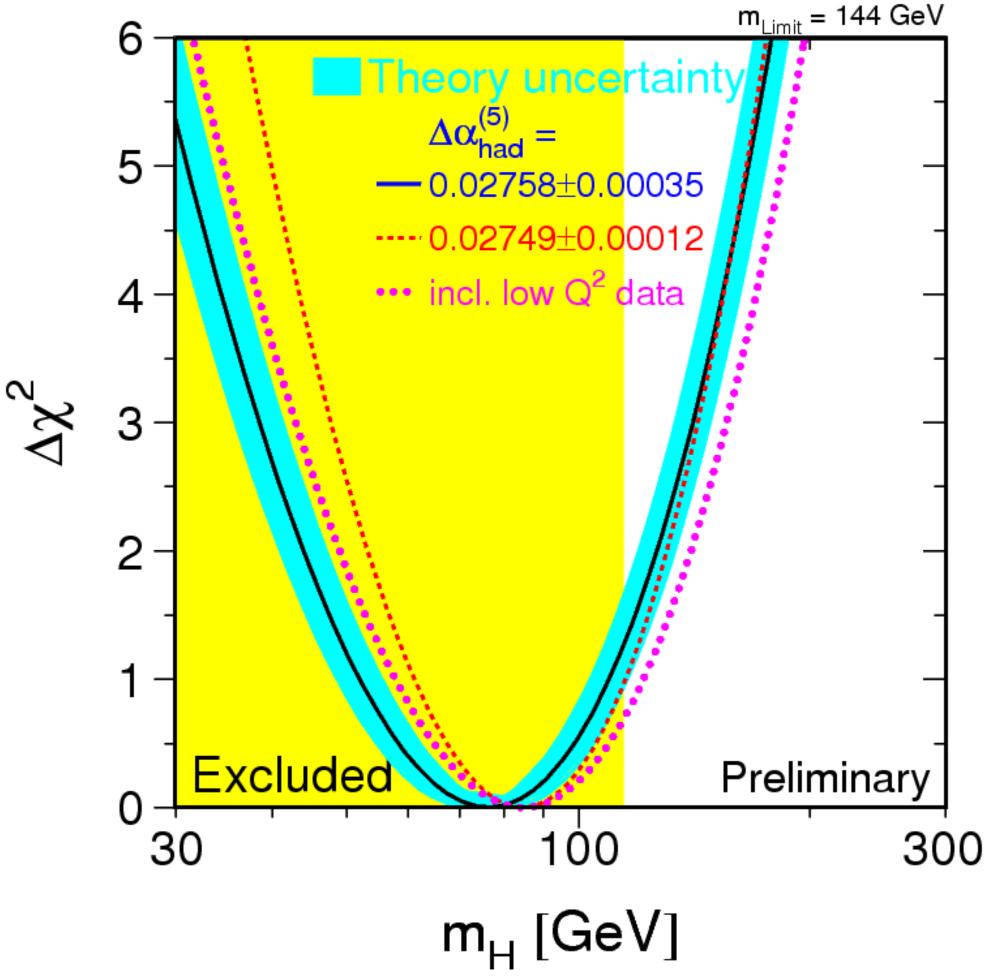
- Dark matter problem:
  There appears to be a lot of dark matter

Dark matter = WIMPs?

Questions...

- At what energy scale should the new physics appear?
- Are we sure new physics will be seen?
- Can we produce dark matter at LHC?
- Your question here...

What is the Higgs mass?



- LEP direct searches:
  m_H > 114 GeV
- EW precision fits:
  m_H < 144 GeV *(95% CL)*
  m_H < 182 GeV *(w/ search)*
  $m_H = 76^{+33}_{-24}$ GeV

Mass range is constrained in the Standard Model

The SM as an effective theory

- Higher dimension operators suppressed by scale Λ

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \dots$$

- This is a way to parameterize our ignorance and look for effects of new physics at the scale Λ

- In general, bounds from LEP imply Λ > a few TeV

Example dimension 6 operator

- An example of a possible operator is

$$\mathcal{O}_H = \left|H^\dagger D_\mu H\right|^2, \qquad \mathcal{L}_H = \frac{c_H}{\Lambda^2}\left|H^\dagger D_\mu H\right|^2$$

- Affects gauge boson vacuum polarizations (T or ρ parameter)

- LEP 95% CL for c_H=-1: $\Lambda > 4.6$ TeV at m_H=115
  $\Lambda > 3.4$ TeV at m_H=300
  $\Lambda > 2.8$ TeV at m_H=800

Quadratic divergence in m_H

- The 1-loop correction to the Higgs mass is

$$\begin{aligned}\delta m_H^2 =& \frac{3m_t^2}{4\pi^2 v^2}\Lambda_t^2 - \frac{3m_h^2}{16\pi^2 v^2}\Lambda_h^2 - \frac{6m_W^2+3m_Z^2}{16\pi^2 v^2}\Lambda_g^2 \\ \equiv& \alpha_t\Lambda_t^2 + \alpha_h\Lambda_h^2 + \alpha_g\Lambda_g^2\end{aligned}$$

- How do we quantify fine-tuning?

Quadratic divergence in m_H

- $$\delta m_H^2 = \frac{3m_t^2}{4\pi^2 v^2}\Lambda_t^2 - \frac{3m_h^2}{16\pi^2 v^2}\Lambda_h^2 - \frac{6m_W^2+3m_Z^2}{16\pi^2 v^2}\Lambda_g^2$$
  $$\equiv \alpha_t\Lambda_t^2 + \alpha_h\Lambda_h^2 + \alpha_g\Lambda_g^2$$

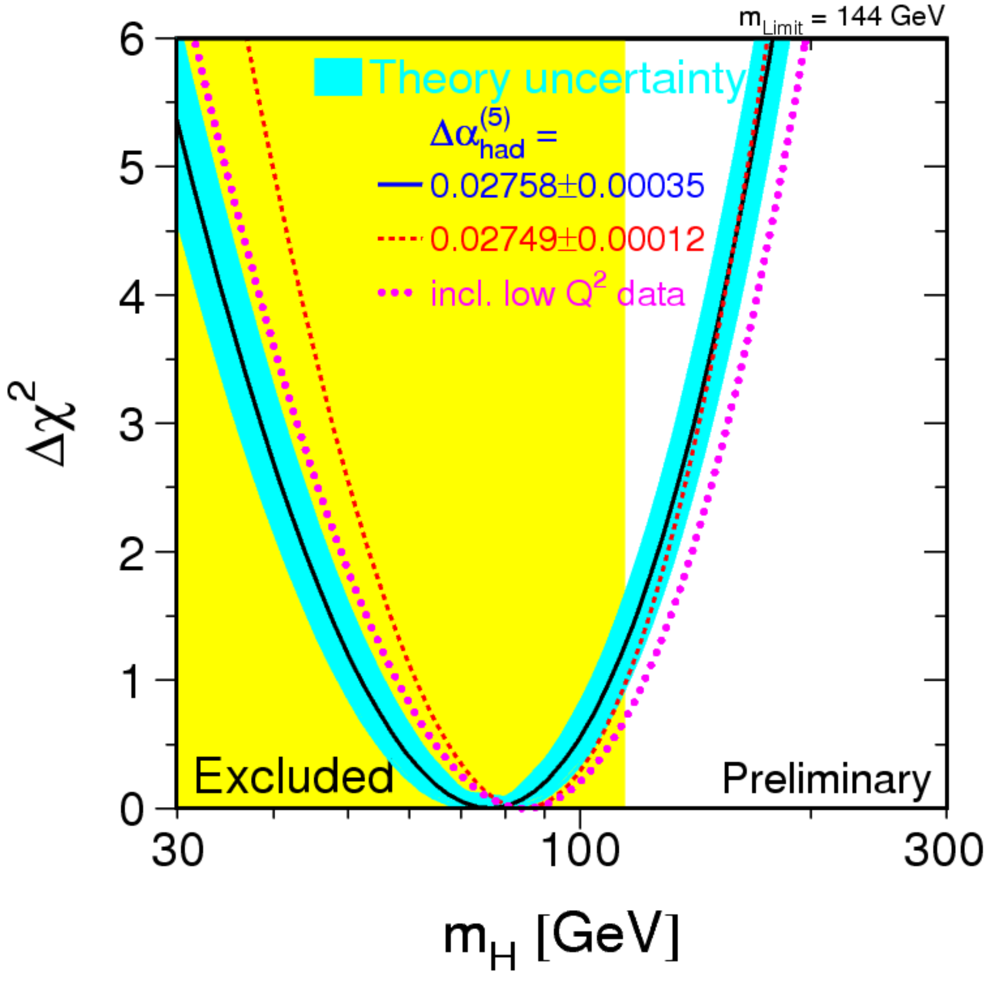
- Define the amount of *fine-tuning* as the sensitivity to the cutoff scale:

  $$D_i(m_H) = \left|\frac{\partial \log m_H^2}{\partial \log \Lambda_i^2}\right| = \frac{|\alpha_i|\Lambda_i^2}{m_H^2}$$

  If $D > 1$ the parameter is fine-tuned to one part in D

- **D = 1 gives Λ_t~3.7 m_H** ($\Lambda_g > \Lambda_t$ and Λ_h~1.3 TeV)

The LEP paradox



- Higgs mass bounds: without fine-tuning the cut-off scale is roughly
  Λ < 600-700 GeV
- But LEP constraints on new physics say
  Λ > several TeV
- This is known as the **LEP paradox** or **little hierarchy problem**

(Barbieri & Strumia)

What we want to do

- “Solve” LEP paradox
- Provide an explanation for Dark Matter
- Fulfill all experimental constraints

- ...in the minimal possible way

Solving the LEP paradox

“Improved naturalness models”: *

- Simple idea: if the Higgs is heavy, the cutoff scale of the SM increases – since $\mathbf{\Lambda_t \sim 3.7\, m_H}$
- But a heavy Higgs is not allowed by electroweak tests!

- Cutoff is large – maybe new physics will *not* be seen at LHC ?

* *Barbieri, Hall & Rychkov; Barbieri, Hall, Nomura & Rychkov*

Electroweak precision tests

- *Oblique parameters* *S*,*T*,*U* take into account a limited set of observables: corrections to gauge boson vacuum polarizations *(Peskin and Takeuchi, 1990)*

- For us *T* is the most important: $\alpha_{em} \Delta T = \Delta\rho$

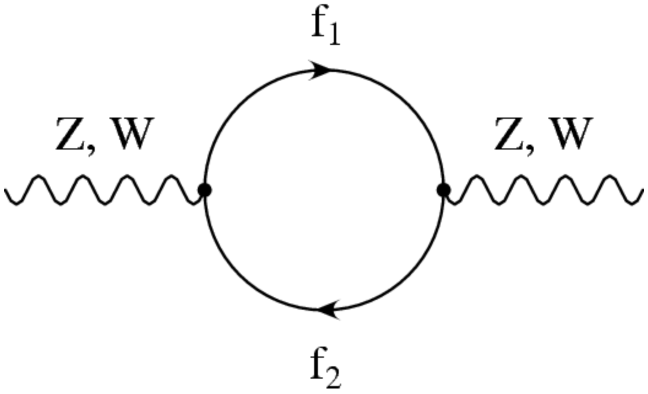
  where ρ is the ratio of gauge boson masses:

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1 \text{ (at tree level)}$$

$$\alpha_{\text{em}} \Delta T = \frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(0)}{m_Z^2}.$$

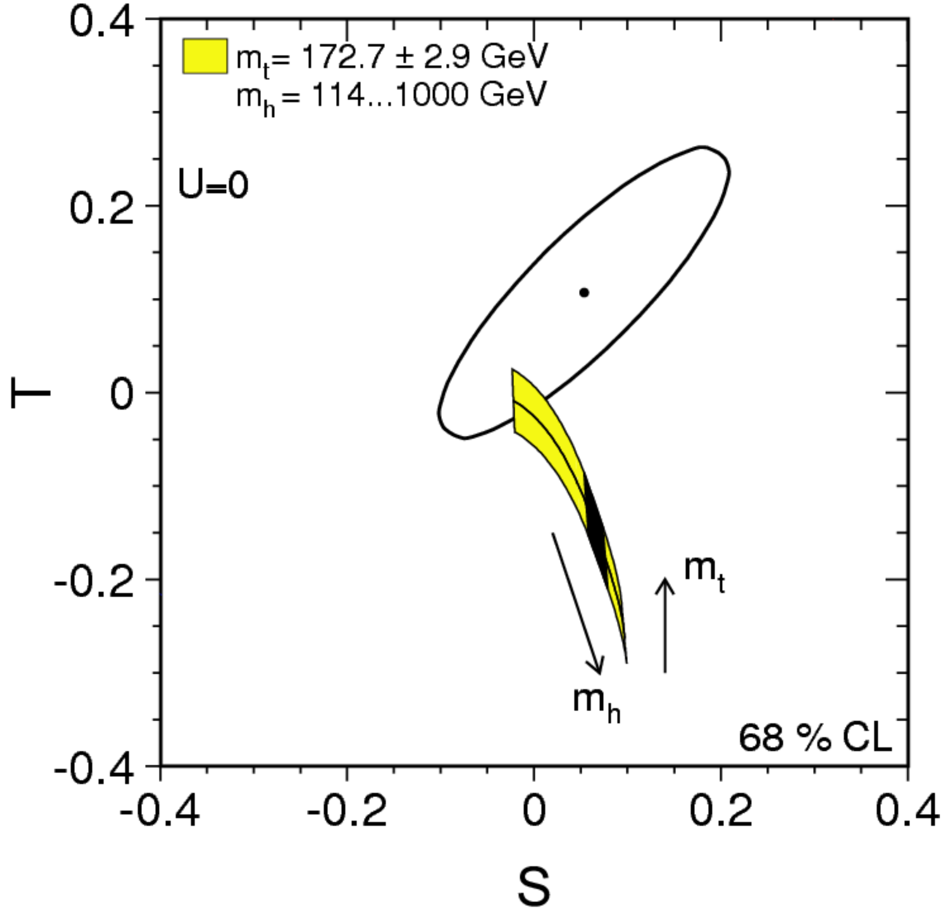
T parameter

- The *S*,*T*,*U* parameters are defined to be zero in the Standard Model at some reference parameter values
- Fermions contribute to e.g. *T* through loops:



- This gives a contribution in $m_t >> m_b$ limit $$\Delta T \sim \frac{3m_t^2}{16\pi s_W^2 c_W^2 m_Z^2}$$
- We will get similar contributions when adding fermions

Heavy Higgs and EWPT



- When the Higgs mass is increased *T* decreases and we go outside the allowed ellipse
- But fermion loop contributions increase *T* *(top loops ~ m_t^2)*
- If we add new fermions, we may get back in the ellipse!

M_H=500 GeV requires Δ*T ~ 0.15—0.35*

Adding fermions

So we want to add more fermions to the Standard Model

- Strong indirect constraints on additional generations
- Anomalies must cancel

Solution:

- Vectorlike fermions
- *Add two SU(2) doublets and one singlet*

Adding only doublets would not give right DM abundance and would not contribute to T (no mass splitting)

Vectorlike fermions

- *Vectorlike* fermions come in pairs with opposite charges under the gauge group(s)

- Gauge invariant mass terms

- Anomalies cancel automatically

Our model

- Introduce the SU(2) doublets *L*, *L*^{c} and the singlet *N*:

$$L = \begin{pmatrix} \nu \\ E \end{pmatrix}, \quad L^c = \begin{pmatrix} E^c \\ \nu^c \end{pmatrix}$$

- Allowed terms in Lagrangian *(with Z$_2$ symmetry):*

$$\mathcal{L} \supset -\lambda L\tilde{H}N - \lambda' L^c H N + M_L L L^c + \frac{1}{2} M_N N^2 + h.c.$$

- After Higgs gets vev: $(v = \langle H \rangle = 174\ \mathrm{GeV})$

$$(\lambda v)\nu N + (\lambda' v)\nu^c N + M_L(\nu\nu^c - EE^c) + \frac{1}{2} M_N N^2 + \mathrm{h.c.}$$

[Same Lagrangian as Mahbubani & Senatore, 2005]

Our model

- There are three neutrino states—the gauge eigenstate 2-component spinors are (N, ν, ν^c):

$$(\lambda v)\nu N + (\lambda' v)\nu^c N + M_L(\nu\nu^c - EE^c) + \frac{1}{2}M_N N^2 + \text{h.c.}$$

- Mass matrix for (N, ν, ν^c):

$$\begin{pmatrix} M_N & \lambda v & \lambda' v \\ \lambda v & 0 & M_L \\ \lambda' v & M_L & 0 \end{pmatrix}$$

where we assume no complex phases

Particle content

- Three neutrino states

$$(\lambda v)\nu N + (\lambda' v)\nu^c N + M_L(\nu\nu^c - EE^c) + \frac{1}{2}M_N N^2 + \mathrm{h.c.}$$

- Without Yukawas: One Dirac neutrino from (ν, ν^c) and one Majorana from *N*
- These mix to form three "pseudo"-Majorana mass eigenstates (ν_1, ν_2, ν_3)
- There are two charged lepton spinors—these combine into one Dirac particle

$$\psi_E = \begin{pmatrix} E \\ \bar{E}^c \end{pmatrix}$$

Interactions

Interaction Lagrangian in terms of four-component spinors:

$$\begin{aligned}
\mathcal{L}_{\rm int} = & \frac{g}{2c_W}\bar{\psi}_{\nu_i}\gamma^\mu\gamma_5 V_{ij}\psi_{\nu_j}\, Z_\mu \\
& + \frac{g}{c_W}\bar{\psi}_E\gamma^\mu\psi_E(T^3 - s_W^2 Q)\, Z_\mu \\
& + eQ\,\bar{\psi}_E\gamma^\mu\psi_E A_\mu \\
& + \frac{g}{\sqrt{2}}\bar{\psi}_{\nu_i}\gamma^\mu\left(g_V^i - g_A^i\gamma_5\right)\psi_E\, W_\mu^+ + h.c. \\
& + U_{ij}\,\bar{\psi}_{\nu_i}\psi_{\nu_j} h
\end{aligned}$$

where $U_{ij}, V_{ij}, g^i_{V,A}$ are couplings for the neutrinos

Parameters and bounds

There are four new parameters in our model:

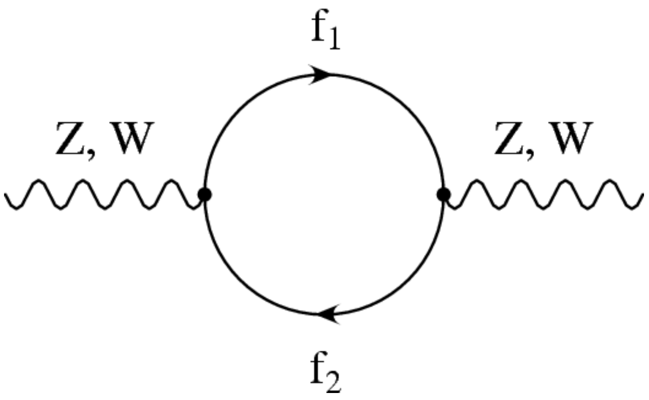
- Mass of the lepton doublets L and L^c
- Mass of the singlet lepton N
- Yukawa couplings λ, λ' of L and L^c

These are constrained by experiment:

- EWPT and desired value of ΔT
- Dark matter abundance and direct search limits
- Particles have not been seen at LEP & Tevatron

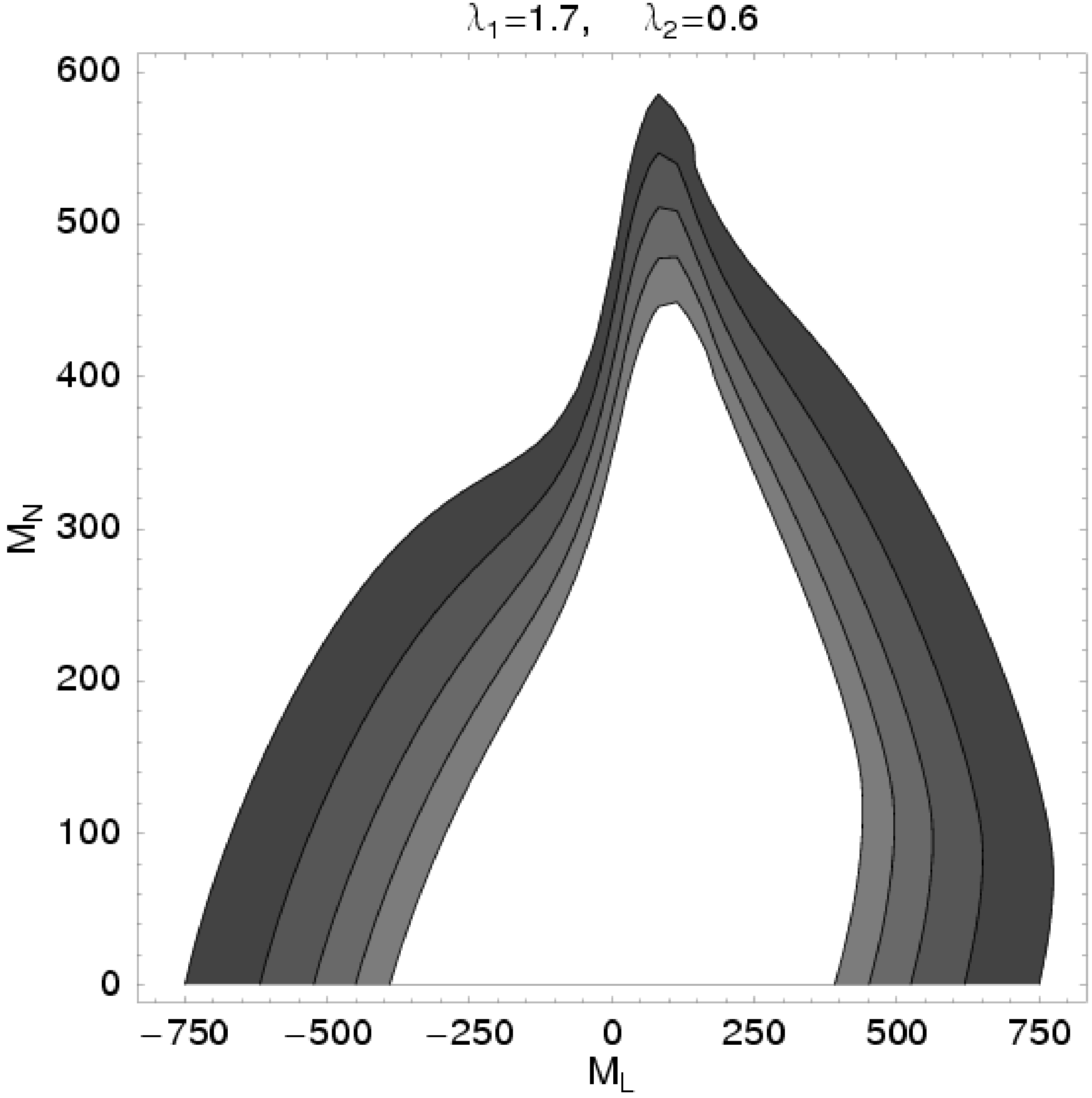
T parameter

- We have the contributions of the form



- For *ZZ* the fermions are $\nu_i\nu_j$ and for *WW* they are $E\nu_i$
- Calculate these in dimensional regularization
- We find quite large regions of parameter space fulfilling ΔT ~ 0.15—0.35

T parameter—example region



Gray regions are allowed — here λ_1=1.7, λ_2=0.6

Dark matter

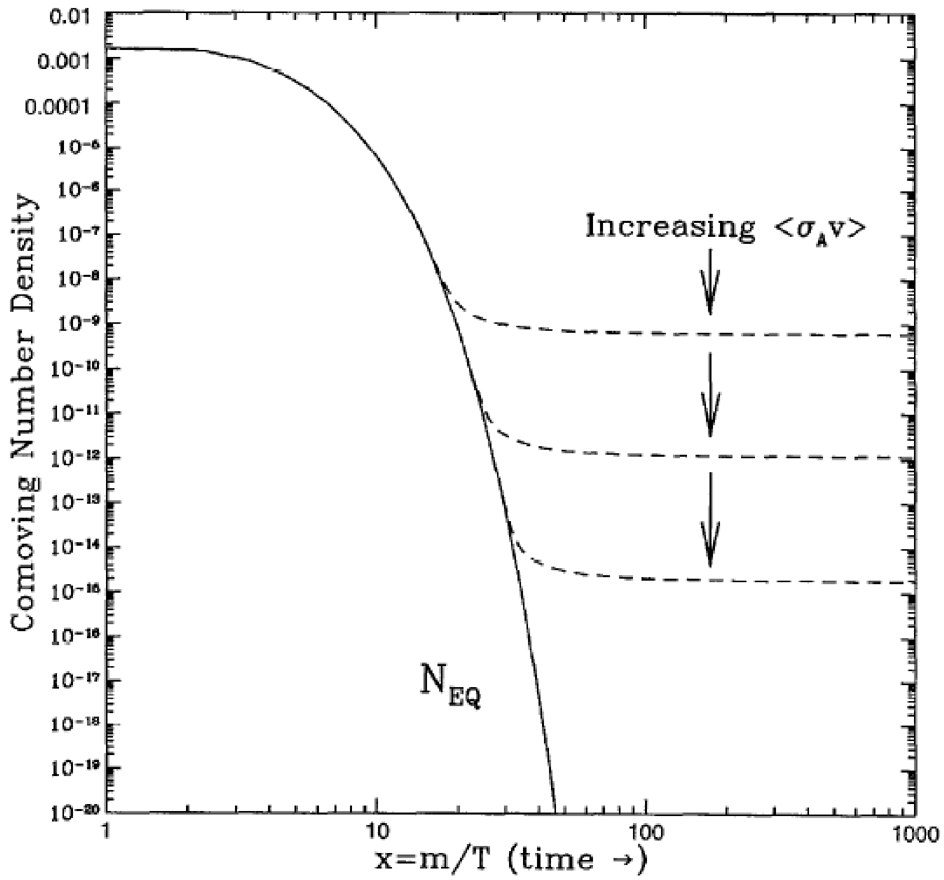
- The lightest neutrino in our model is stable and is therefore a good WIMP dark matter candidate

- There are regions of parameter space where the WIMP mass is in the range 50—200 GeV and where ΔT has the right size

- Does this lead to viable dark matter—compatible with the measured abundance and direct searches?

- WMAP + others: $\Omega h^2 = 0.111 \pm 0.006$

Dark matter abundance



- *Assumption:* WIMP was in *thermal equilibrium* in the early universe through

$$\nu\nu \leftrightarrow X\bar{X}$$

- It *froze out* when the temperature was too low to keep interaction rate > expansion rate
- To find the rate and abundance we must solve the *Boltzmann eq.*

Basic ingredient: thermal averaged annihilation xsec <σv>

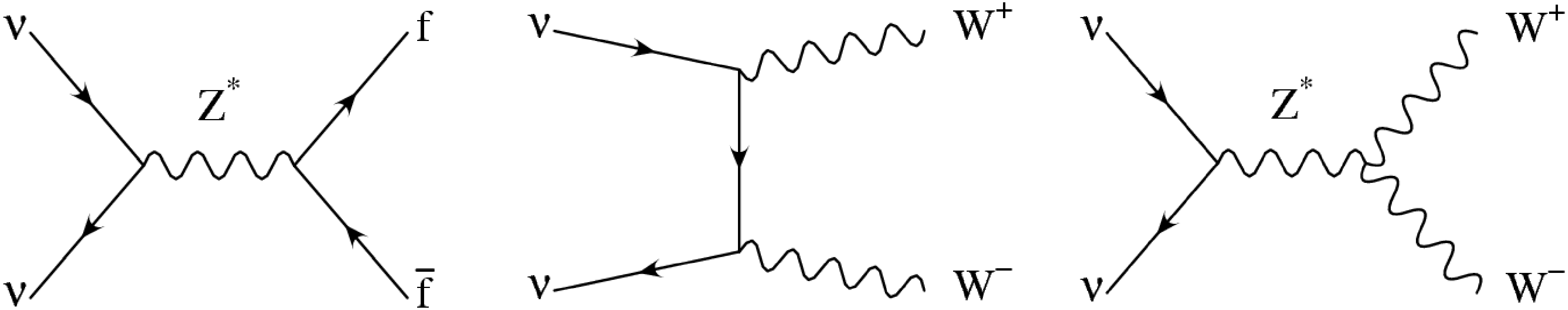
Dark matter abundance

- Obtaining the approximate CDM abundance Ω for a WIMP is a fairly standard task *(see e.g. Kolb & Turner)*
- Compute the annihilation cross sections $\nu\nu \to X\bar{X}$
- Take nonrelativistic limit—expand in *v*: $\sigma v = a + b v^2$
- Thermal average of this enters the Boltzmann eq.
- Approximate standard solution gives (with $x_F = m/T_F$)

$$\Omega_{\nu_{\rm DM}} h^2 \approx \frac{1.07 \times 10^9 \mathrm{GeV}^{-1}}{M_{\rm Pl}} \frac{x_F}{\sqrt{g_*}} \frac{1}{a + 3b/x_F}$$

Dark matter annihilation

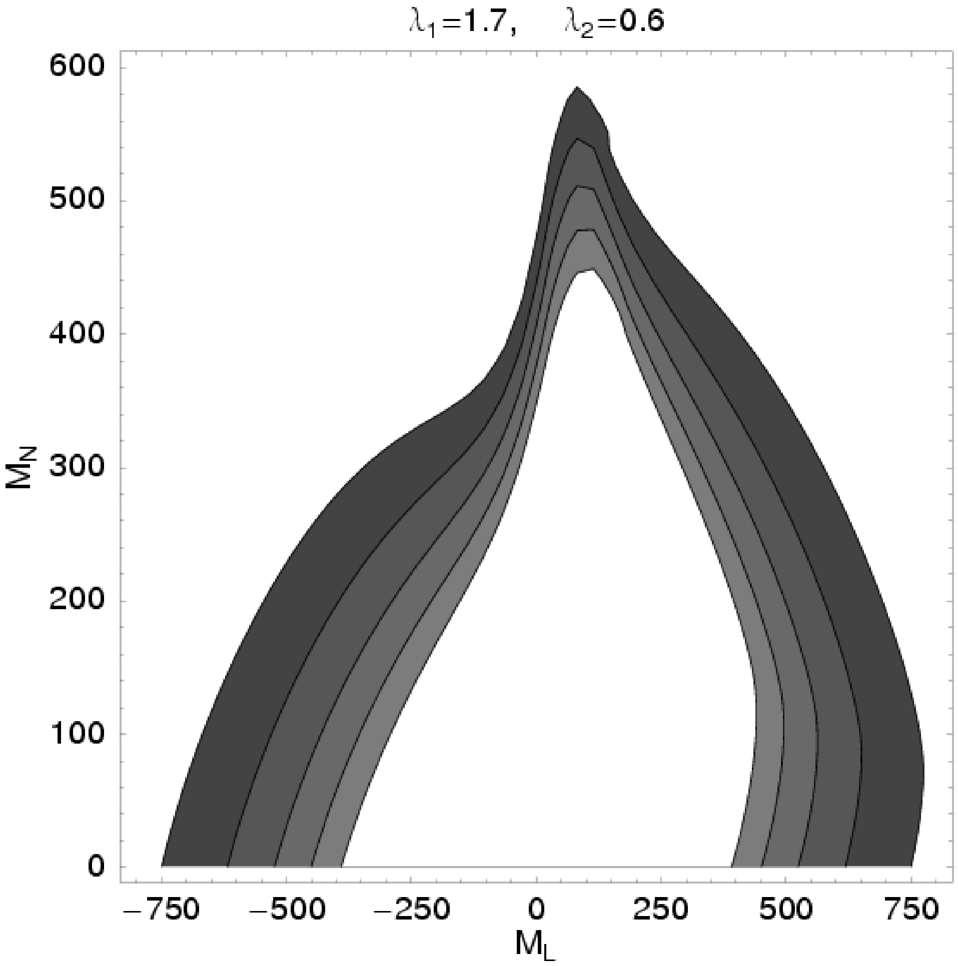
- We have the following annihilation channels plus *ZZ* (neglecting Higgs exchange):

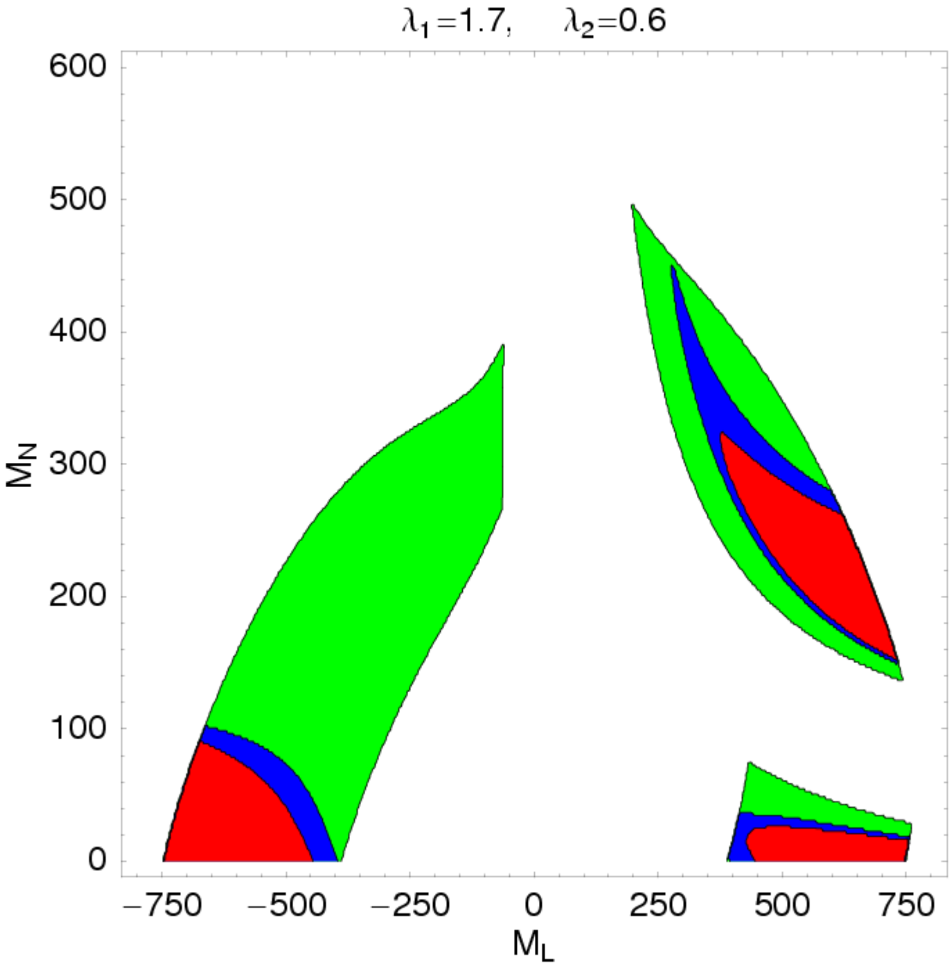


- We have computed these cross sections and applied the method from the previous slide.

- *We have also used the MicrOmegas program: good agreement with analytic calc*

Dark Matter example region





T-parameter sets upper bound on masses

Direct detection of dark matter

- Dark matter WIMPs are distributed throughout the galaxy
- Earth is moving with $\langle v \rangle$ = 220 km/s = $10^{-3}c$
- There should be collisions between nuclei on earth and WIMPS
- Experiments search for such (elastic) collisions by detecting recoils of nuclei

(CDMS, NAIAD, XENON, ZEPLIN, DAMA, EDELWEISS, ...)

Direct detection of dark matter

- Experiments have put bounds on spin-independent and spin-dependent WIMP—nucleus cross sections
- They unfold this to give WIMP-nucleon limits

For us:

- Spin dependent: *Z* exchange with partons in nucleons
- Spin independent: Higgs exchange (*Z* negligible)

- Compute WIMP—quark elastic scattering for $v \ll c$
- Average over quarks in nucleon

Spin independent scattering

- The Higgs couples to the quarks through

$$\mathcal{L} = f_q \, \bar{\nu}\nu \, \bar{q}q$$

- Nucleus cross section is (*f*$_p$ and *f*$_n$ are obtained from *f*$_q$)

$$\sigma^A = \frac{4\mu_A^2}{\pi} \left[Z f_p + (A - Z) f_n \right]^2$$

- The cross section on nucleons is approximately

$$\sigma^p = \sigma^A \frac{\mu_p^2}{\mu_A^2} \frac{1}{A^2} = \frac{4\mu_A^2}{\pi} f_p^2 .$$

- The relation is not so simple for spin dependent scattering...

Elastic cross sections

- Spin dependent:

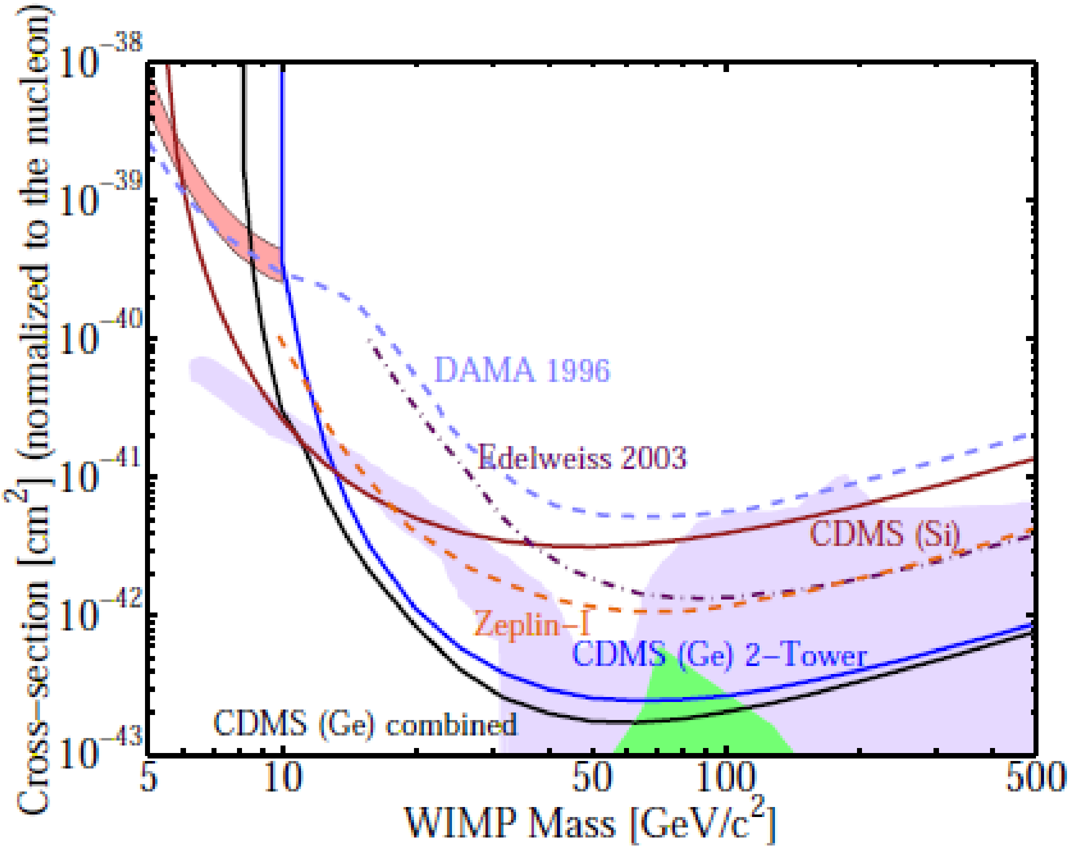
$$\sigma^{p,n} = \frac{24 G_F^2 C_\chi^2}{\pi} \left[\frac{m_{p,n} m_\chi}{m_{p,n} + m_\chi} \right]^2 \left[\sum_{q=u,d,s} T^{3(q)} \Delta q^{(p,n)} \right]^2$$

$$\sigma^p \simeq 1.77 \times 10^{-37} \, C_\chi^2 \ \mathrm{cm}^2$$
$$\sigma^n \simeq 1.10 \times 10^{-38} \, C_\chi^2 \ \mathrm{cm}^2$$

- Spin independent:

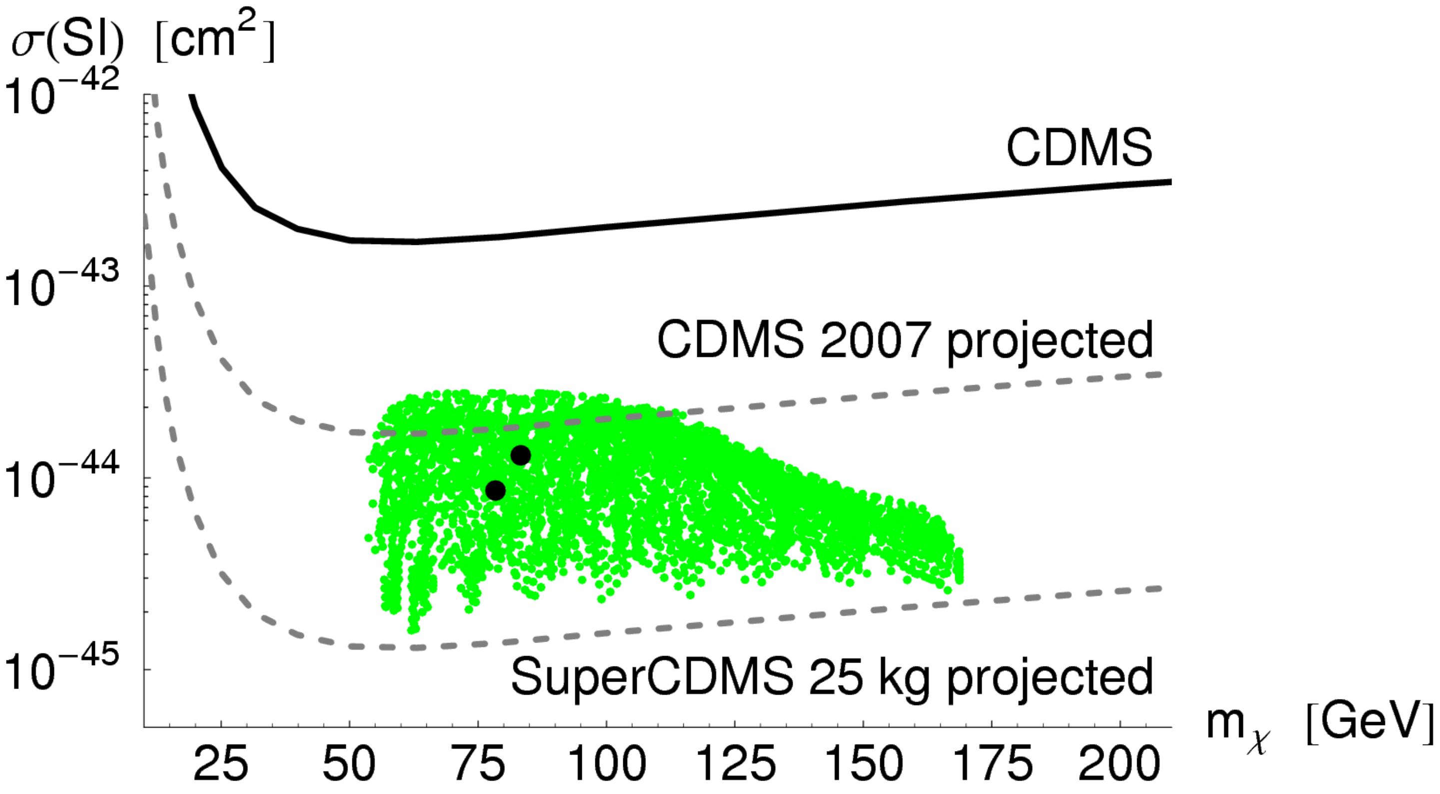
$$\sigma^p \simeq 9.37 \times 10^{-45} \, U_{11}^2 \left(\frac{500 \ \mathrm{GeV}}{m_H} \right)^4 \ \mathrm{cm}^2$$

Limits: CDMS spin-independent



Shaded lower regions are various MSSM scenarios, shaded upper left corner is DAMA

Spin-independent & our model

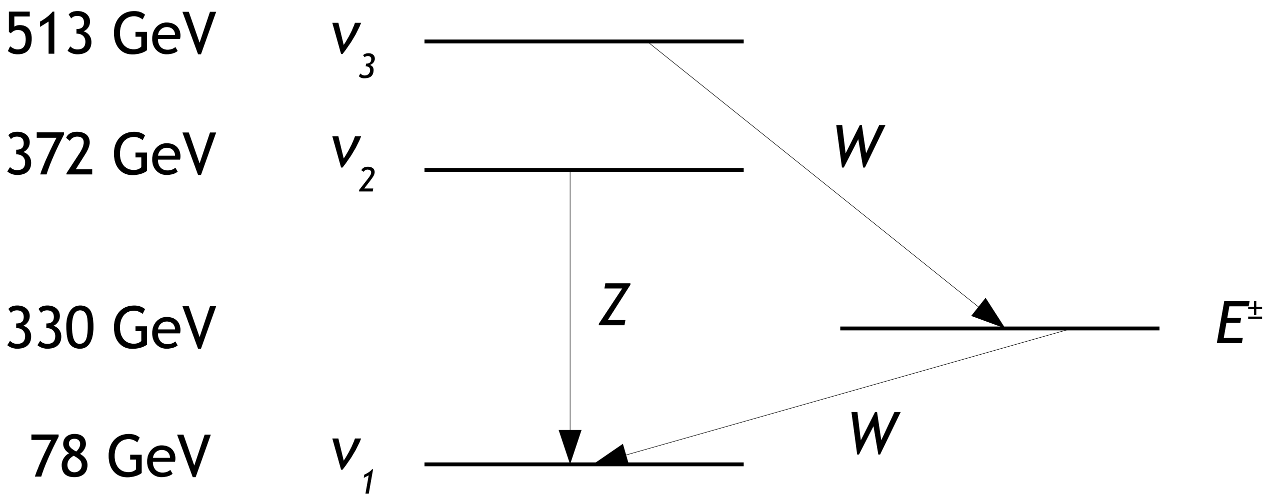


Green: parameter points allowed by DM and *T*
Lines: CDMS present and projected 2007 bounds

LHC

How would our model be discovered at LHC?

- Neutrinos $\nu_{2,3}$ decay to lightest ν_1
- Stable lightest neutrino leads to missing energy
- Sample mass spectrum with decays:



513 GeV ν_3

372 GeV ν_2

330 GeV $E^{\pm}$

78 GeV ν_1

W

Z

W

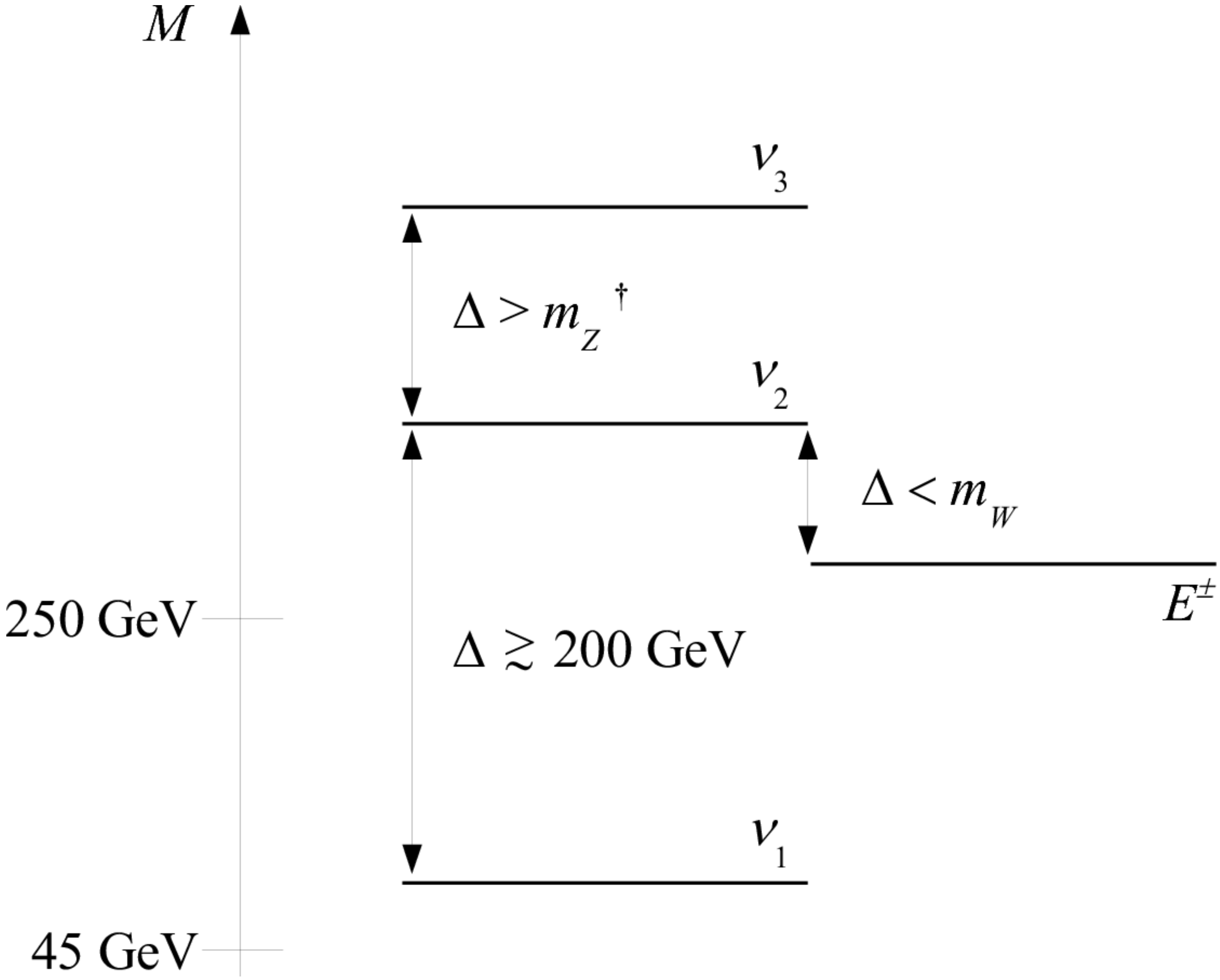
M_D=330 GeV

M_D=220 GeV

λ=1.5

λ'=0.3

General features



LHC phenomenology

- We have implemented the model in the parton level calculators and Monte Carlos CalcHep and MadGraph/MadEvent

- We interface these with the Monte Carlo PYTHIA to decay, parton shower, hadronize

- We pass the result through PGS *(Pretty Good Simulation)* for fast detector simulation

- Overall conclusion: Since we only have weak production, LHC will be challenging

LHC production

- Production of $E^{\pm} \nu_i$ through a W
  - σ ~ 10's—100's of fb
  - $E^{\pm}$ decays to $W^{\pm} \nu_1$
  - $E^{\pm} \nu_1$: missing energy and one lepton
  - Additional W or Z for ν_2 or ν_3 — e.g. trilepton signal!
- Production of two $\nu_{1,2,3}$ with decays
  - $\nu_1 \nu_1$ from H: invisible Higgs width — up to 20 GeV
- Production of $E^{+} E^{-}$ —gives two W and missing energy

Example: one lepton

- pp → $E\,\nu_1 \to W\,\nu_1\,\nu_1$

- Missing energy and one lepton, plus jets

- Backgrounds are pp → tt, WZ, Drell-Yan W
  - Drell-Yan can be completely cut out
  - WZ can be reduced to acceptable
  - tt is too large

- There are not enough kinematical variables to cut on

Example: two leptons

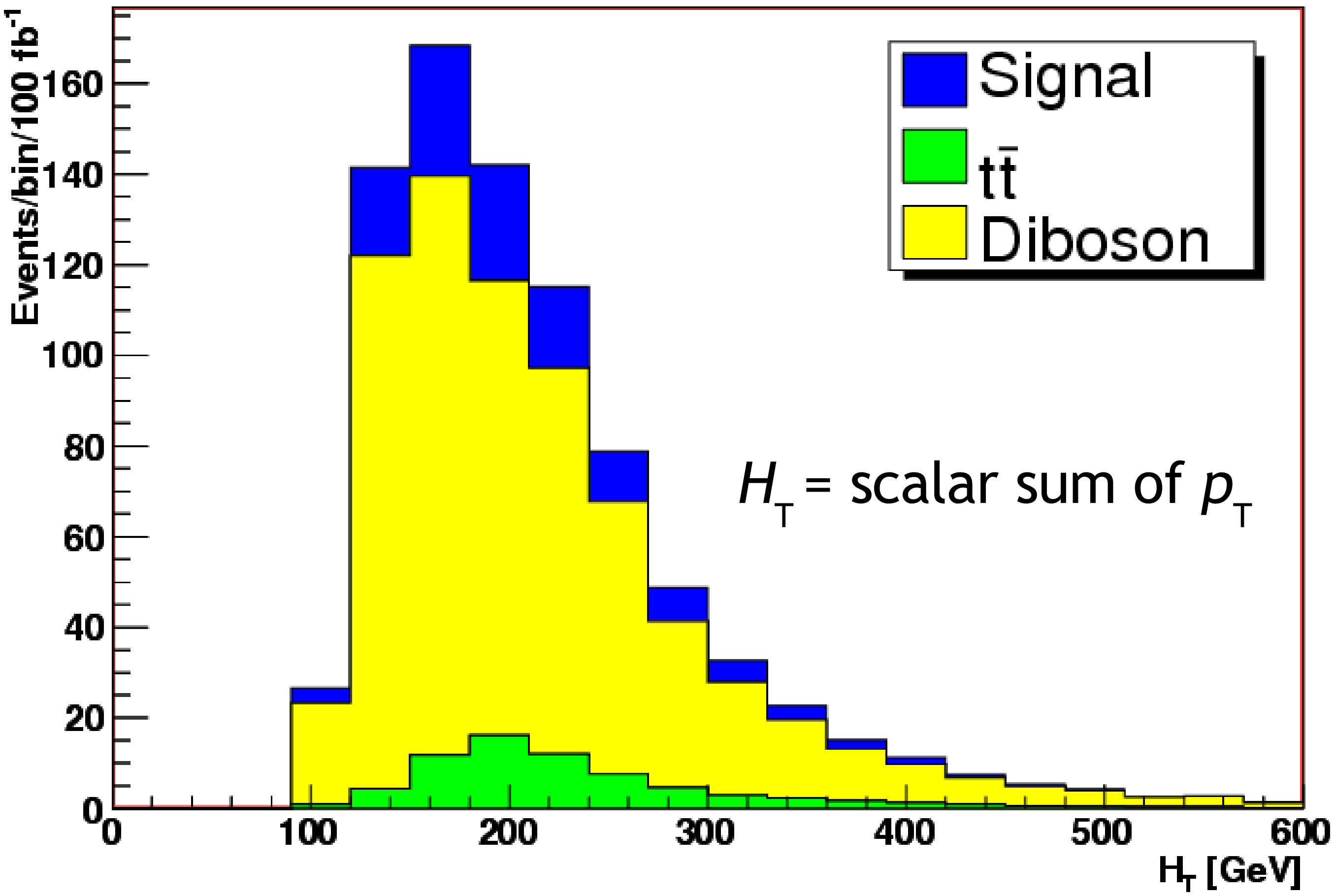
- pp → $v_1 v_2 \to Z\, v_1 v_1$

- Missing energy and two leptons

- Main backgrounds: tt, WZ, ...

- Let's look at one particular point in parameter space

Two lepton signal

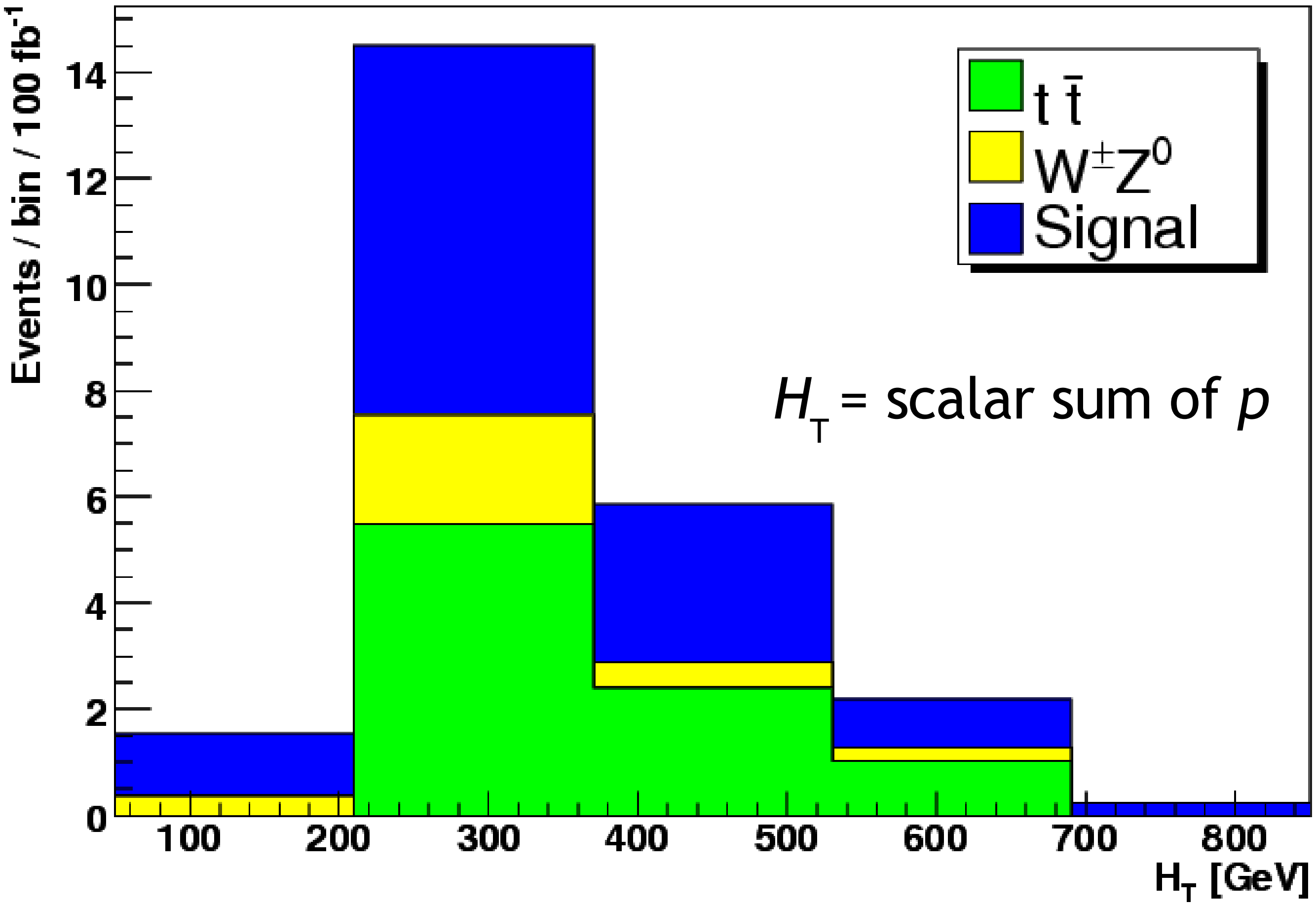


Significance $S/\sqrt{B}$ = 4.8 @ 100 fb^{-1} (8 @ 300 fb^{-1})

Example: trileptons

- pp $\rightarrow$ $E\, v_2 \rightarrow W\, Z\, v_1\, v_1$
- Missing energy and three leptons
- Main backgrounds: tt, WZ, Drell-Yan, ...
- Standard signal for SUSY chargino-neutralino prod, but they have off-shell Z and we have on-shell Z

Three lepton signal



Significance $S/\sqrt{B}$ = 3.5 @ 100 fb^{-1} (6 @ 300 fb^{-1})

LHC conclusion

- It will be hard to pin down this model at LHC:
  - Only weak production mechanisms:
    - swamped by QCD
  - On-shell W,Z in decays:
    - Large SM backgrounds

- Maybe what will be seen will be very confusing:
  - a very heavy Higgs, and nothing else to start with
  - then excess in some channels after a few years
  - and maybe direct dark matter detection

LHC conundrum

- Hard to pin down at LHC
- Dark matter detection *may* occur *before* LHC sees anything!
- “Inert Model”: same story
- Colored particles above cutoff: heavy

Conclusions

- The LEP paradox poses an interesting question about the scale of new physics
- ...and what if Higgs is heavy?
- We have proposed a model that solves the LEP paradox by postponing new physics to a higher scale
- It predicts dark matter in the right amount
- It would hopefully be seen at LHC