Natural Scalar Dark Matter from an Unnatural Higgs

Aaron Pierce

atpierce@umich.edu

University of Michigan

$hep - ph/0703056$

with Jesse Thaler (Berkeley)

Natural Theories?

Two Motivations for Beyond the Standard Model physics at the TeV scale

- Hierarchy Problem/ Electroweak Symmetry Breaking

$$\Delta m_h^2 = \frac{3y_{top}^2}{8\pi^2}\Lambda^2$$

Natural Theories?

Two Motivations for Beyond the Standard Model physics at the TeV scale

- Thermal Relic Abundance of Dark Matter

$$\langle \sigma v \rangle = 0.1 \text{ pb} = \alpha / m^2 \Rightarrow m \approx 100 \text{ GeV}$$

caveat: Axions/non-thermal

Cosmological Constant

- $\Lambda \sim (\text{meV})^4$.
- This represents a 10^{120} fine-tuning (cosmological constant problem)
- Do we really understand fine-tuning?

Cosmological Constant

- $\Lambda \sim (\mathrm{meV})^4$.
- This represents a 10^{120} fine-tuning (cosmological constant problem)
- Do we really understand fine-tuning?

Can we go beyond weak Scale SUSY/Technicolor/Little Higgs/Warped Extra Dimensions?

Cosmological Constant

- $\Lambda \sim (\mathrm{meV})^4$.
- This represents a 10^{120} fine-tuning (cosmological constant problem)
- Do we really understand fine-tuning?

Can we go beyond weak Scale SUSY/Technicolor/Little Higgs/Warped Extra Dimensions?

Are there new structures at the TeV Scale?

Outline

- What is the minimum needed for Dark Matter?
- Relating the Higgs and the Dark Matter
- Current Bounds
- Collider Consequences

Simple Weak Scale Dark Matter

$$\mathcal{L} = \mathcal{L}_{SM} + m_N^2 N^2 + \lambda_n N^2 |H|^2$$

The gauge-singlet N field can annihilate via Higgs bosons and reproduce the correct relic abundance (Burgess *et al*; McDonald; Davoudiasl, *et al*).

Simple Weak Scale Dark Matter

$$\mathcal{L} = \mathcal{L}_{SM} + m_N^2 N^2 + \lambda_n N^2 |H|^2$$

The gauge-singlet N field can annihilate via Higgs bosons and reproduce the correct relic abundance (Burgess *et al*; McDonald; Davoudiasl, *et al*).

Potential Issues:

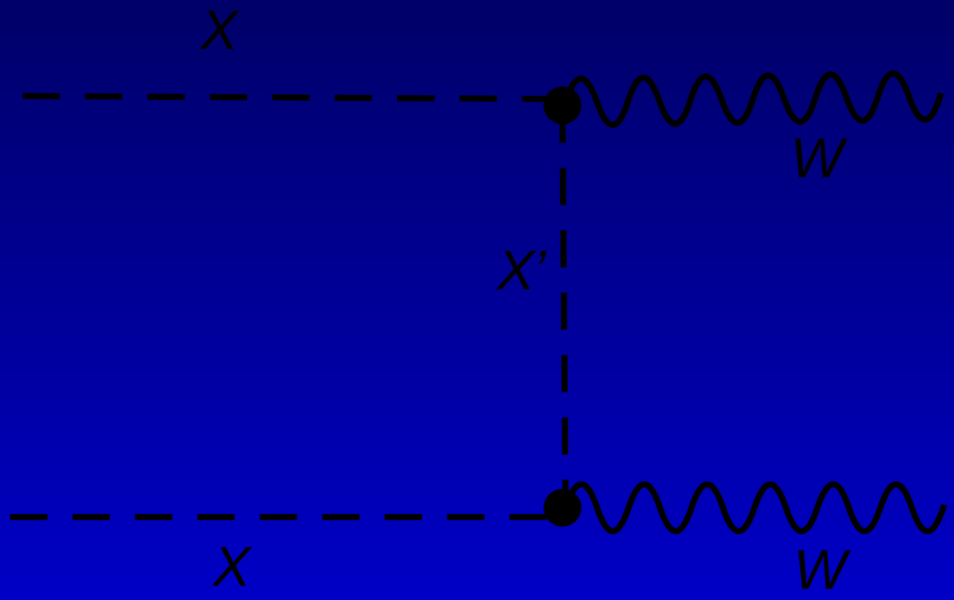
- Must fine tune both m_H and m_N.
- No collider phenomenology (possible invisible Higgs decays)

Simple Weak Scale Dark Matter

A n-plet charged under SU(2) with a $X \to -X$ symmetry.
Gauge interactions allow for annihilation.
(see Strumia, Cirelli, Fornengo, Tamburini)

Simple Weak Scale Dark Matter

A n-plet charged under SU(2) with a $X \rightarrow -X$ symmetry.
Gauge interactions allow for annihilation.
(see Strumia, Cirelli, Fornengo, Tamburini)



Simple Weak Scale Dark Matter

A n-plet charged under SU(2) with a $X \rightarrow -X$ symmetry.
Gauge interactions allow for annihilation.
(see Strumia, Cirelli, Fornengo, Tamburini)

Potential Issues:

- Must fine tune both m_X and m_N (scalars).
- Correct relic abundance often recovered for very high (multi-TeV) masses.
- Direct Detection Bounds can be stringent for non-zero hypercharge
- Collider Phenomenology?

Simple Weak Scale Dark Matter

A n-plet charged under SU(2) with a $X \rightarrow -X$ symmetry.
Gauge interactions allow for annihilation.
(see Strumia, Cirelli, Fornengo, Tamburini)

Potential Issues:

- Must fine tune both m_X and m_N (scalars).
- Correct relic abundance often recovered for very high (multi-TeV) masses.
- Direct Detection Bounds can be stringent for non-zero hypercharge
- Collider Phenomenology?

Moral: Need additional structure to get light colored particles.

An Example: Split SUSY

- No attempt to solve the gauge hierarchy problem.
- New structure (SUSY) + Dark Matter leads to weak scale gauginos.
- Exciting collider phenomenology: e.g. stopping gluinos

Natural Dark Matter, Unnatural Higgs

Suppose Higgs boson is fine-tuned to be light.

Q: Could this tuning ensure light Dark Matter?

Natural Dark Matter, Unnatural Higgs

Suppose Higgs boson is fine-tuned to be light.

Q: Could this tuning ensure light Dark Matter?

A: Yes, if there is additional structure that relates the Higgs and the Dark Matter

Natural Dark Matter, Unnatural Higgs

Suppose Higgs boson is fine-tuned to be light.

Q: Could this tuning ensure light Dark Matter?

A: Yes, if there is additional structure that relates the Higgs and the Dark Matter

Idea: allow a single fine-tuning (for atomic principle/structure principle considerations? environmental considerations take you “halfway”)

New Structure

Put Higgs and Dark Matter together in a global multiplet.

$$h \leftrightarrow \phi.$$

Enforce stability of ϕ:

$$\phi \leftrightarrow -\phi.$$

Scalar potential:

$$V(h,\phi) = m^2\left(|h|^2 + |\phi|^2\right) + \lambda_1\left(|h|^4 + |\phi|^4\right) + \lambda_3 |h|^2|\phi|^2$$
$$+\lambda_4 |h\phi^\dagger|^2 + \lambda_5\,\mathrm{Re}\left(h^\dagger\phi h^\dagger\phi\right).$$

Coupling to Fermions

Up sector couplings:

$$\mathcal{L}_{\text{Yukawa}} = \lambda_u \left(q h u^c \right)$$

Coupling to Fermions

Up sector couplings:

$$\mathcal{L}_{\text{Yukawa}} = \lambda_u \left(q h u^c + Q \phi u^c + q \phi U^c + Q h U^c \right) .$$

Equality of the h and ϕ couplings are enforced by our symmetry.

Coupling to Fermions

Up sector couplings:

$$\mathcal{L}_{\rm Yukawa} = \lambda_u \left(q h u^c + Q \phi u^c + q \phi U^c + Q h U^c \right) .$$

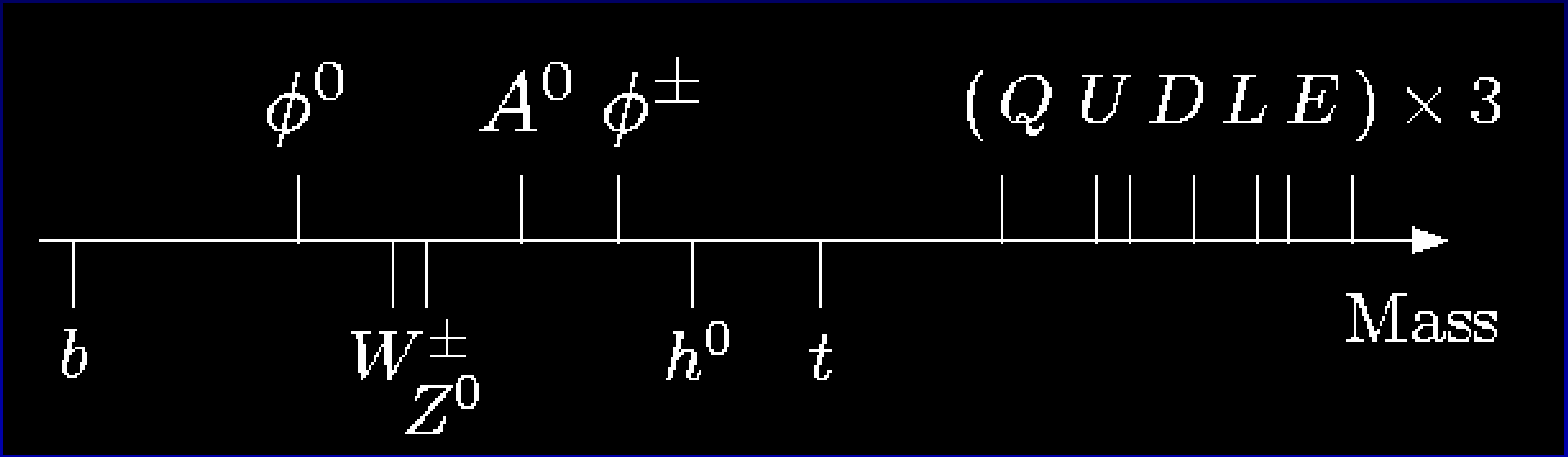
Equality of the h and ϕ couplings are enforced by our symmetry.

Soft breaking of the exchange symmetry:

$$\mathcal{L}_{\rm soft} = m_Q Q Q^c + m_U U U^c$$

Typical Spectrum

$$m^2_{A^0} = m^2_{\phi^0} - \lambda_5 v^2, \qquad m^2_{\phi^\pm} = m^2_{\phi^0} - \frac{v^2}{2}(\lambda_4 + \lambda_5)$$



$$V(h,\phi) = m^2\left(|h|^2 + |\phi|^2\right) + \lambda_1\left(|h|^4 + |\phi|^4\right) + \lambda_3|h|^2|\phi|^2$$
$$+\lambda_4|h\phi^\dagger|^2 + \lambda_5\,\mathrm{Re}\left(h^\dagger\phi h^\dagger\phi\right).$$

Fine Tuning

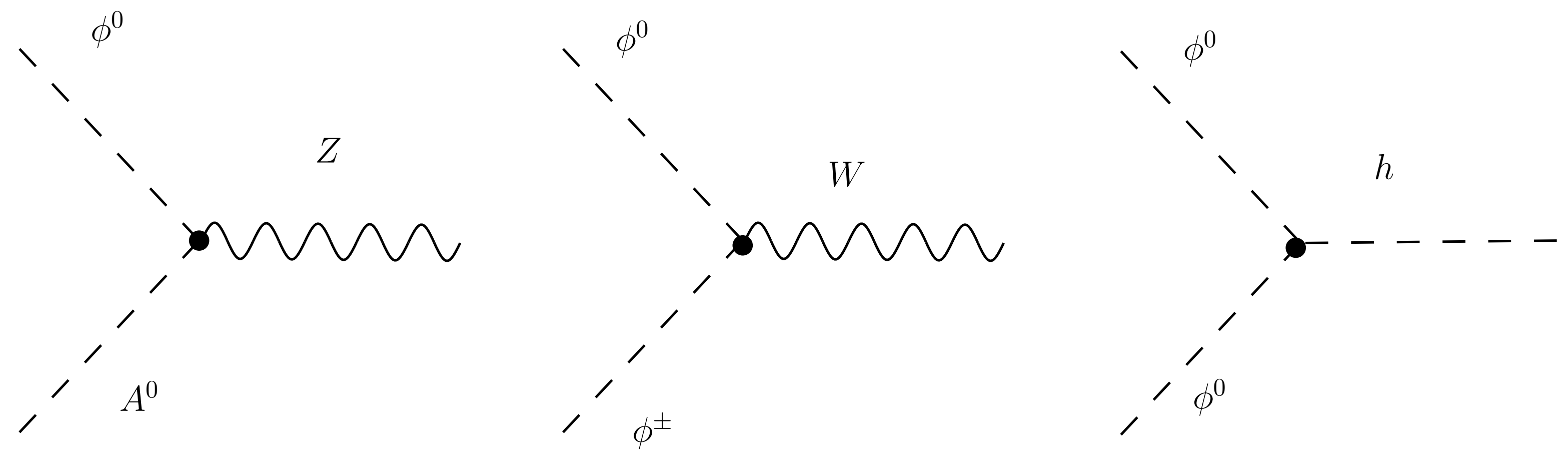
The scalar $(mass)^2$ parameters are fine–tuned, but the difference is one-loop finite!
Where are the top partners?

$$m_\phi^2 - m_h^2 = +\frac{3\lambda_{\rm top}^2}{8\pi^2}\frac{m_Q^2 m_U^2}{m_Q^2 - m_U^2}\log\left(\frac{m_Q^2}{m_U^2}\right)$$

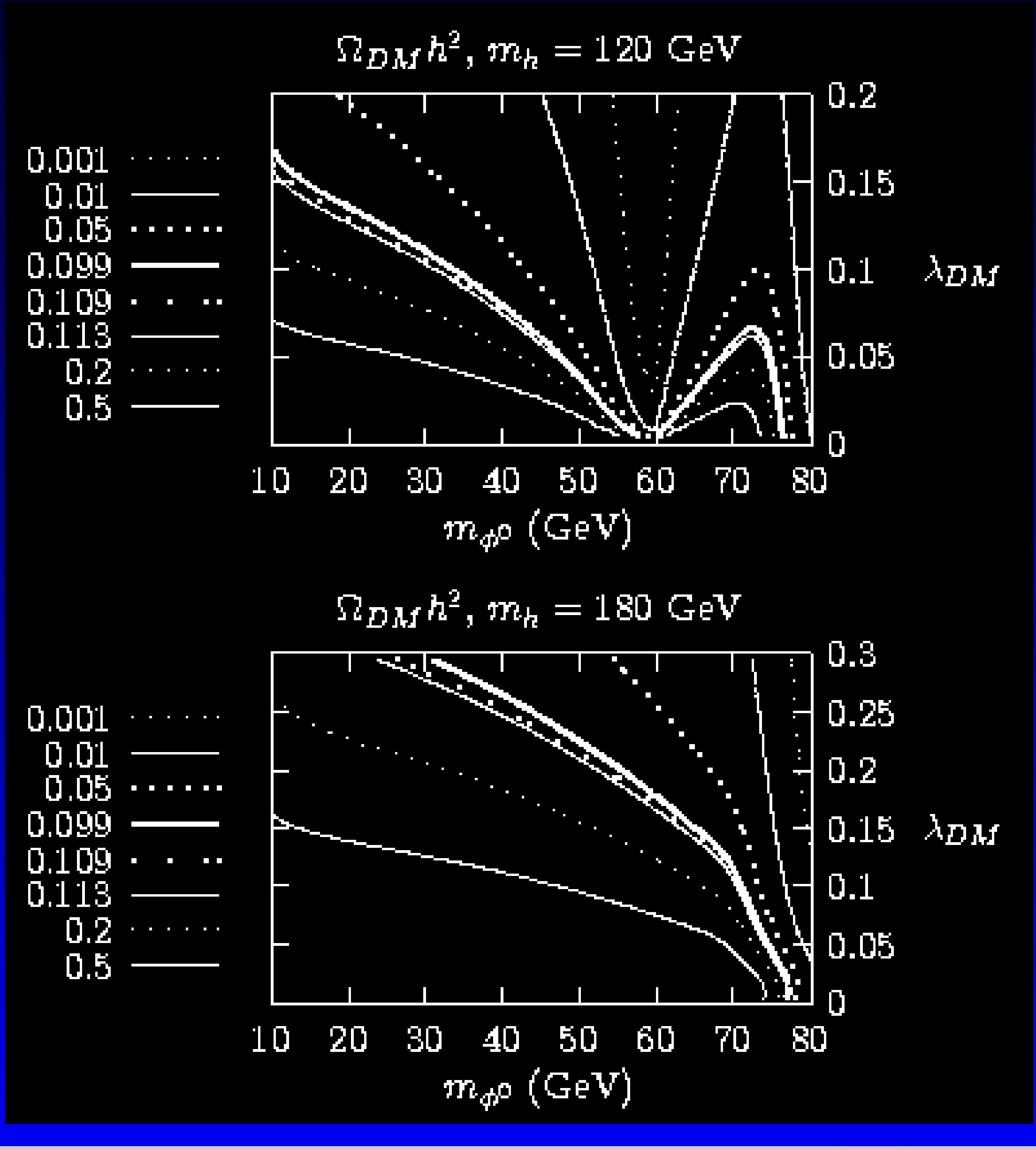
$$m_T \approx 620\ {\rm GeV}\left(\frac{m_h}{120\ {\rm GeV}}\right).$$

Annihilation of Dark Matter

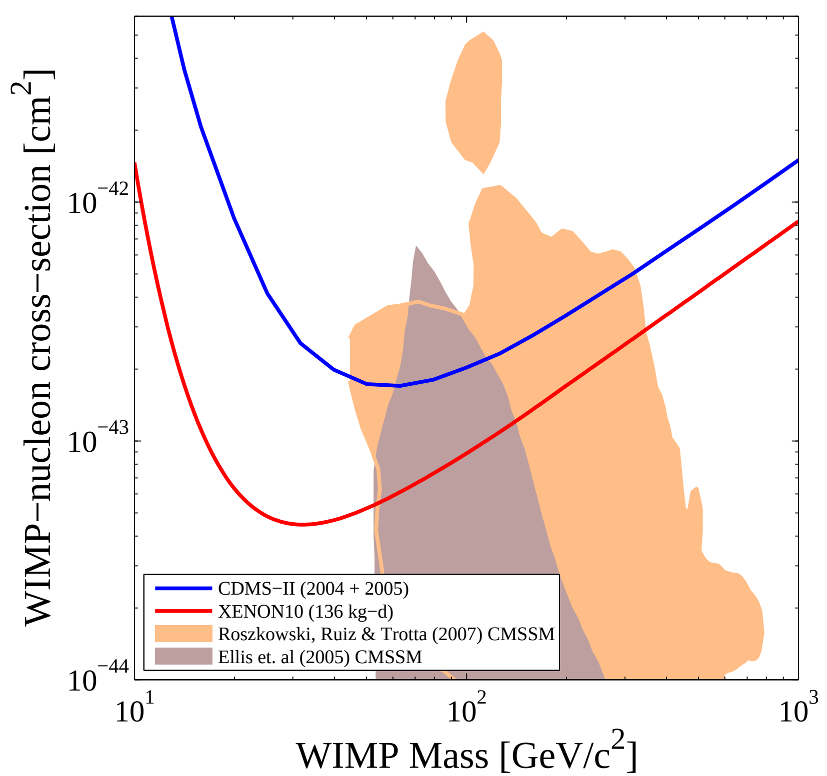
Annihilation is similar to the “inert doublet” model. L. Lopez Honorez et al. (hep-ph/0612275), Barbieri, et al. (hep-ph/0603188).



Relic Abundance



Direct Detection



arXiv:0706.0039 [astro-ph] (Xenon Collaboration)

Direct Detection

- Current bound from XENON-10 (136 kg-day) for $m_{WIMP} \approx 40$ GeV is $\sigma_{Xp} \approx 5 \times 10^{-8}$pb

$$\sigma_{Xp} \approx 4 \times 10^{-8}\text{pb} \left(\frac{\lambda_{DM}}{0.075}\right)^2 \left(\frac{40\text{GeV}}{m_\phi}\right)^2 \left(\frac{120\text{GeV}}{m_h}\right)^4$$

- Current experiments starting to probe this model (especially for low Higgs mass)!

Precision Electroweak

There are contributions from both the extra (inert) doublet, and from the top partners.

- Double contributions small for parameters typical of correct DM abundance
- Strongest constraint from the T is from T.

$$\alpha T \simeq \frac{7 G_F}{80\sqrt{2}\pi^2}\frac{m_{\text{top}}^4}{M^2}$$

$$M > 360 \text{ GeV}$$

LEP Searches

As discussed also in Barbieri, et al. (hep-ph/0603188):

$$e^+e^- \to \phi^\pm\phi^\pm, \phi^0 A^0$$

Might have even occurred at LEP.
Bounds imply

- $m_{\phi^\pm} > 70$ GeV
- $(m_\phi + m_A) > 130$ GeV

These constraints place (mild) limits on the Higgs–Phi couplings.

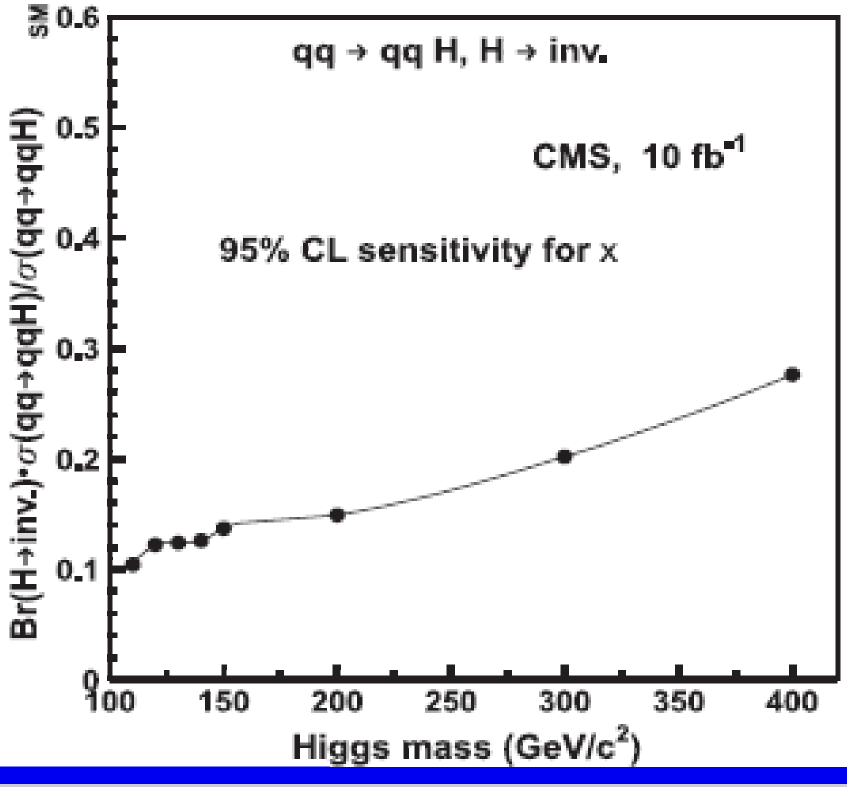
LHC Phenomenology

- Potential Modification of the Higgs properties
- Invisible Decays:

$$\Gamma_{\text{invisible}} = \frac{v^2}{32\pi m_h}\lambda_{DM}^2 \left(1 - \frac{4m_\phi^2}{m_h^2}\right)^{1/2} .$$

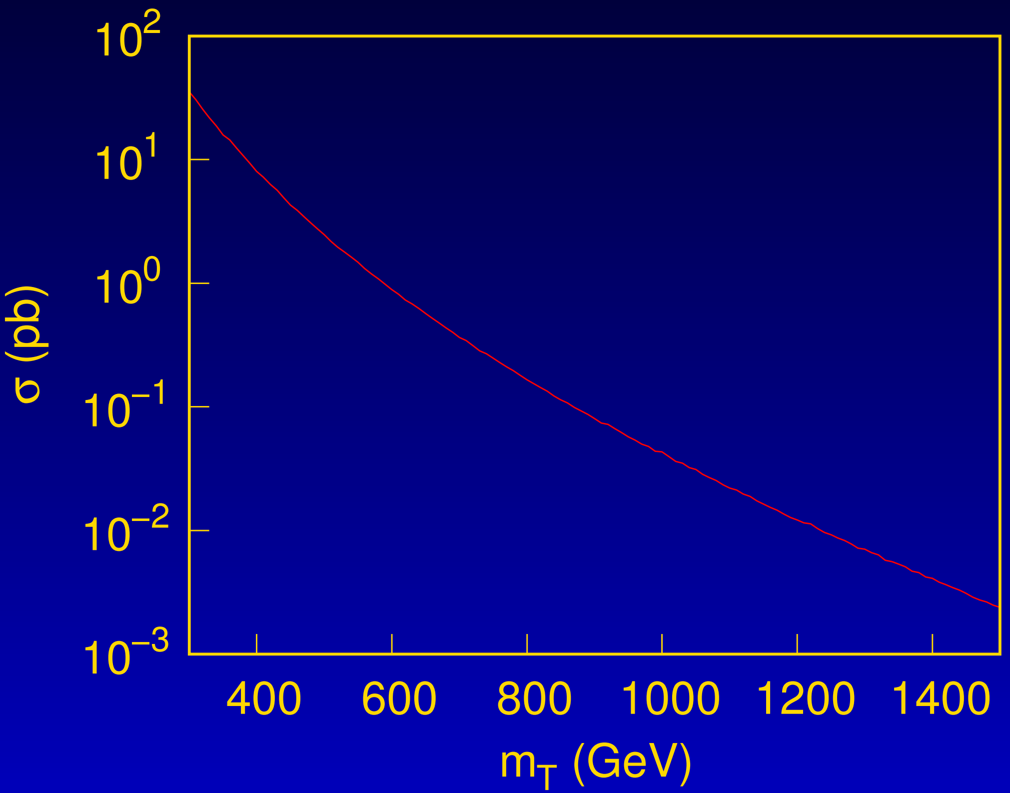
If $m_h > 2M_W$, invisible decays are likely $\sim 20\%$ of the branching ratio. Otherwise may dominate.

Invisible Higgs at the LHC



LHC Phenomenology

- Production of the Top Partners



- $gg \to TT \to tt\phi^0\phi^0$, $gg \to TT \to tb\phi^\pm\phi^0$
- For a 600 GeV top partner, production is $\sim$ 1pb.
- Looks qualitatively like a $\tilde{t}$ (or KK top).

Conclusions

Our understanding of fine-tuning is obviously incomplete.

Absent a need to solve the hierarchy problem, why see anything at the LHC?

What measurements would convince us that we really have a natural theory?