Signatures of Naturalness

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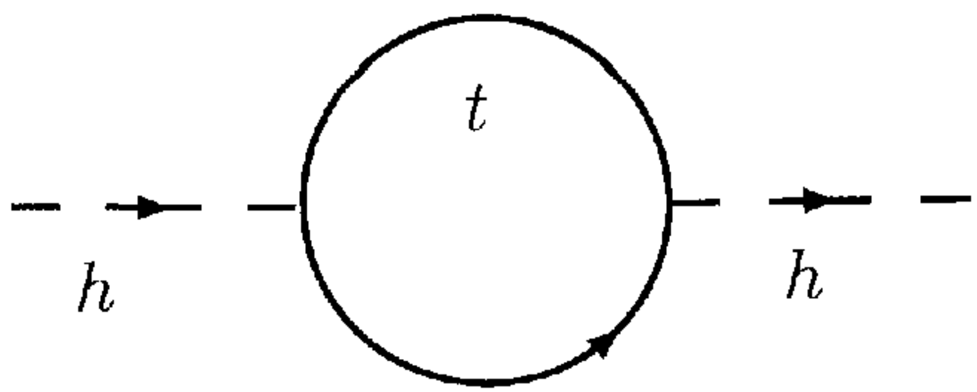
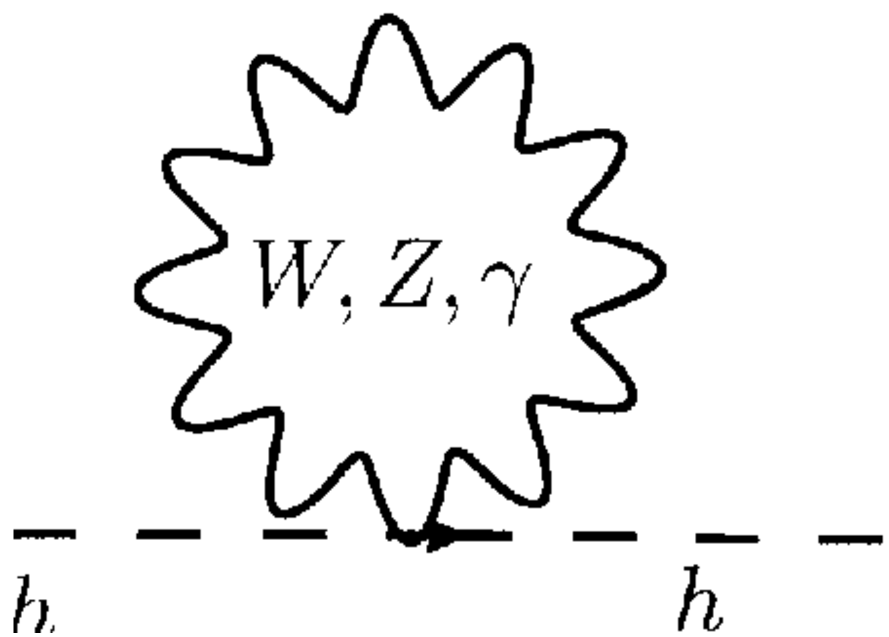
Outline

- Motivation
  - Model Independent approach to Naturalness
- Minimal Naturalness at current experiments
- Indirect evidence of naturalness : top divergence
  - Little Higgs Theories
  - SUSY theories

Quadratic Divergences





- Masses of scalars sensitive to the cutoff scale
- Mass splitting between charged and neutral pions well explained by an EM quadratic divergence
- Without fine tuning bare mass and quantum corrections, expect scalars to have masses of order the cutoff.
- Higgs at 125 GeV so cutoff/new physics around the corner
- So why haven't we seen it?

What are we looking for?

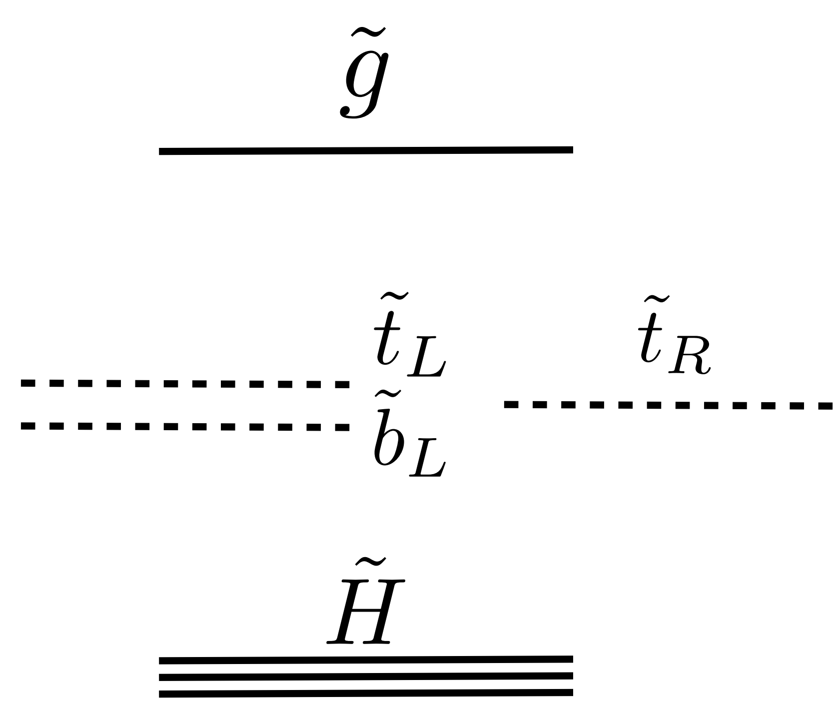
- Supersymmetry
- Little Higgs
- Extra Dimensions/CFTs
- Fourth Generation
- Leptoquarks
- ...

What are we looking for?

- **Supersymmetry**
- **Little Higgs**
- **Extra Dimensions/CFTs**
- Fourth Generation
- Leptoquarks
- ...

Simplified Models

- Supersymmetry
  - Light Stops - Cancels the top quadratic divergence to the Higgs mass
  - Light Higgsinos - Z mass not Higgs Mass
  - Light Gluinos - So that the Stops are not too light



taken from 1110.6926

Simplified Models

- Little Higgs/Extra Dimensions/CFTs
  - Light fermionic top partners
  - single or pair produced
  - 3 different decay channels

$$\mathcal{L} \supset THQ_3$$

Signals

- The signals are due to the additional structure of the solutions!
- Stops solve naturalness with $\mathcal{L} \supset \phi_t \phi_t^\dagger H H^\dagger$
  - but decay via $\mathcal{L} \supset \phi_t \tilde{H} t$
- Fermionic partners use $\mathcal{L} \supset T T^c H H^\dagger$
  - but decay via $\mathcal{L} \supset T H Q_3$

Question

- If all of these signatures are not related to Higgs naturalness, then what are the model independent signatures of a Natural Higgs?

- Leads to Minimal Naturalness.

Minimal Naturalness

- Minimal Naturalness
  - Add a new particle to the SM
  - Impose that it cancels a quadratic divergence
  - No additional interactions
- All signatures are directly tied to the cancelation of quadratic divergences
  - Signatures of the model vanish in the limit that the new particle does not contribute to the Higgs quadratic divergence

Minimal Naturalness

- Model Independent Naturalness
  - Naturalness requires cancelation of quadratic divergences
  - The UV symmetry can add any number of additional interactions
  - A true model independent approach would consider all models where quadratic divergences are canceled with every possible additional interaction
  - A more tractable approach: consider all these additional terms vanishing

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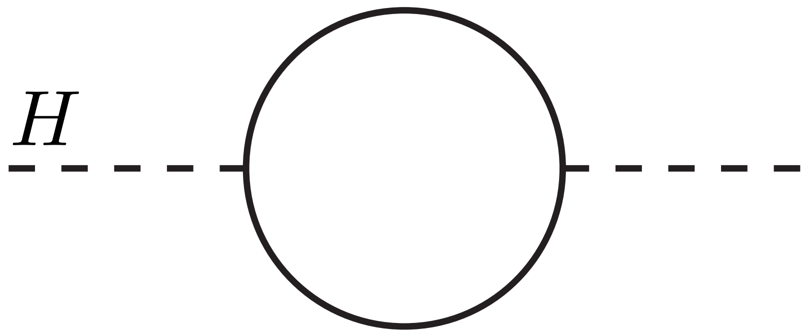
Minimal Naturalness

- Yukawa terms $\mathcal{L} \supset \lambda H \bar{\psi}_1 \psi_2$



- Quartic terms $\mathcal{L} = \lambda H H^\dagger \Phi \Phi^\dagger$

Yukawa Interactions

$$\mathcal{L} \supset \lambda H \bar{\psi}_1 \psi_2$$

- Either ψ_1 or ψ_2 is charged under SU(2)
  - Pair or associated production via gauge bosons
- Decays through W/Z/H

Yukawa Interactions

$$\mathcal{L} \supset \lambda H \bar{\psi}_1 \psi_2$$

- Case 1: Both are new particles
  - Electroweakino phenomenology
  - They might be in different representations than electroweakinos.
  - Decays that end in MET/R-hadrons/CHAMPs with different sized production cross sections

Yukawa Interactions

$$\mathcal{L} \supset \lambda H \bar{\psi}_1 \psi_2$$

- Case 2: ψ_2 is a SM particle
  - ψ_1 must have the same quantum numbers as a SM field
  - A 4th generation model whose interactions cancel a quadratic divergence
  - Single production through yukawa interaction and pair production via gauge interactions

Quartic Interactions

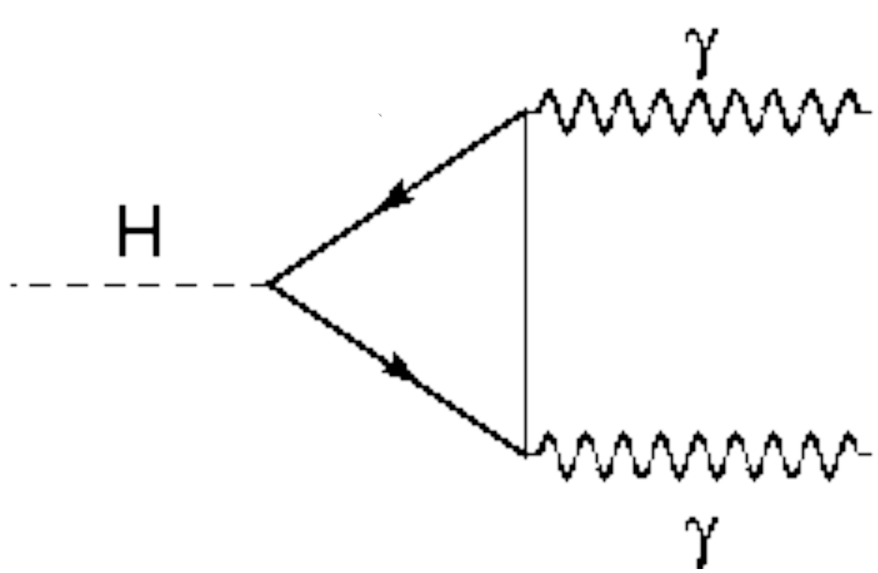
$$\mathcal{L} \supset \lambda\psi^\dagger\psi H H^\dagger$$
$$= \lambda\psi^\dagger\psi\frac{h^2}{2} + \lambda v\psi^\dagger\psi h + \lambda\frac{v^2}{2}\psi^\dagger\psi$$

- Case 1: $m_\psi < \frac{m_h}{2}$
  - New decays of the Higgs. Charged and Colored ψ ruled out by experiments so only invisible decays of the Higgs
  - If top/gauge quadratic divergences are canceled, decay width orders of magnitude larger than the decay width into bottoms
  - Other quadratic divergences yield decay widths too small to be observed

Quartic Interactions

$$\mathcal{L} \supset \lambda\psi^\dagger\psi H H^\dagger$$
$$= \lambda\psi^\dagger\psi\frac{h^2}{2} + \lambda v\psi^\dagger\psi h + \lambda\frac{v^2}{2}\psi^\dagger\psi$$

- Case 2: ψ has SM charge
  - Modified couplings to the gauge bosons at 1-loop



Quartic Interactions

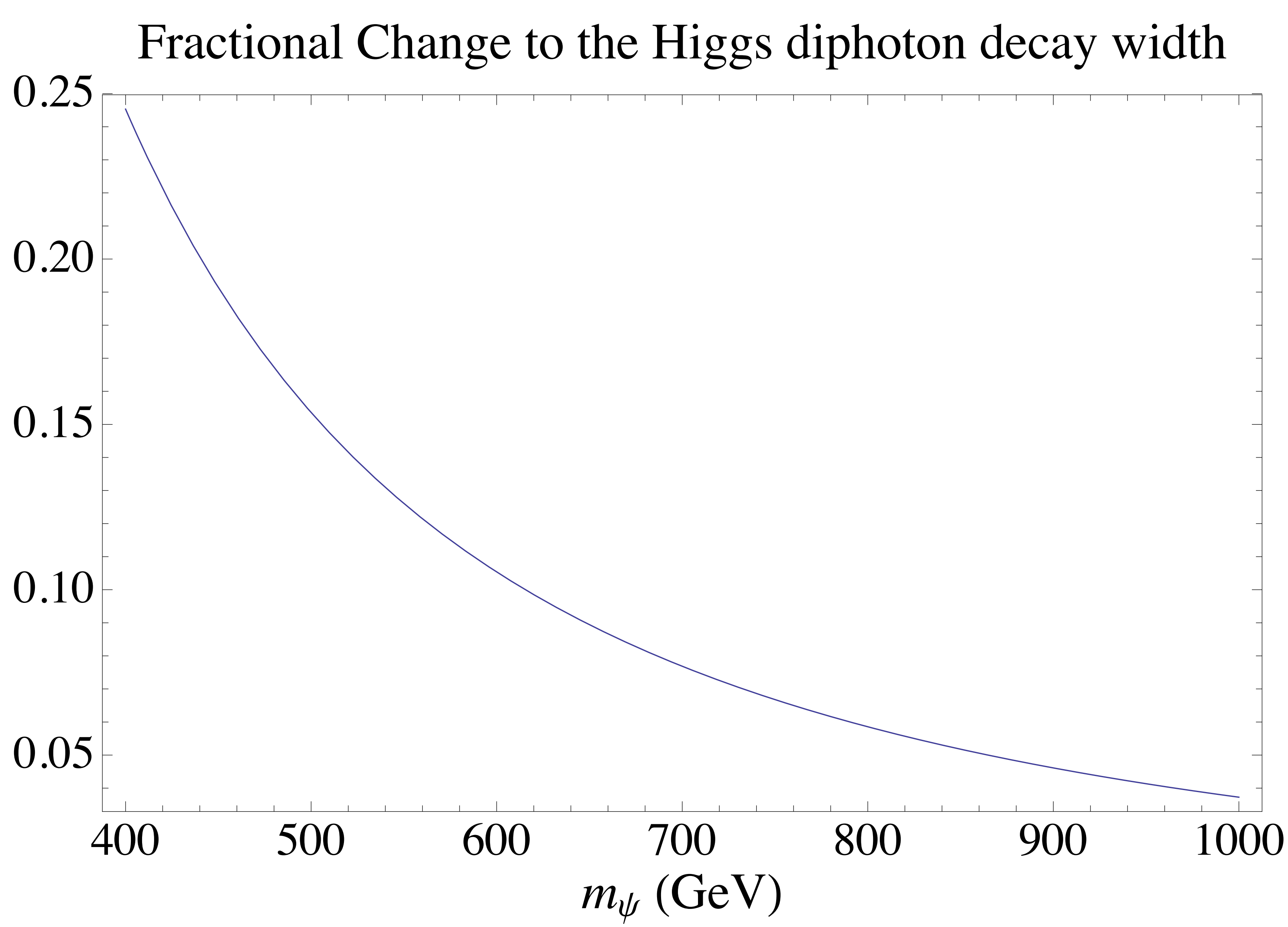
- Case 2: ψ has SM charge
  - e.g. a singlet fermion with electric charge 1 canceling the top divergence

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\rm SM}} = \left| 1 - \frac{1}{6.49} Q^2 \frac{4}{3} \left(\frac{\log m_\psi}{\log v} \right) \left(1 + \frac{7 m_h^2}{120 m_\psi^2} \right) \right|^2$$

  - Mass term from $\mathcal{L} \supset -m\psi^\dagger\psi + \frac{3y_t^2}{2m}\psi^\dagger\psi H H^\dagger$

Quartic Interactions

- Case 2: ψ has SM charge



Quartic Interactions

$$\begin{aligned}\mathcal{L} &= \lambda H H^\dagger \Phi \Phi^\dagger \\ &= \lambda v v_\Phi h \phi + \frac{\lambda}{2} v_\Phi \phi h h + \frac{\lambda}{2} v \phi \phi h + \ldots\end{aligned}$$

- Case 3: $\langle \Phi \rangle \neq 0$
  - If Φ has the quantum numbers of a Higgs, then this is a two higgs doublet model satisfying the Veltman conditions
  - Mass mixing with the Higgs!

$$\begin{pmatrix} h_m \\ \phi_m \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ \phi \end{pmatrix}$$

  - This suppresses all of the Higgs couplings by the same amount

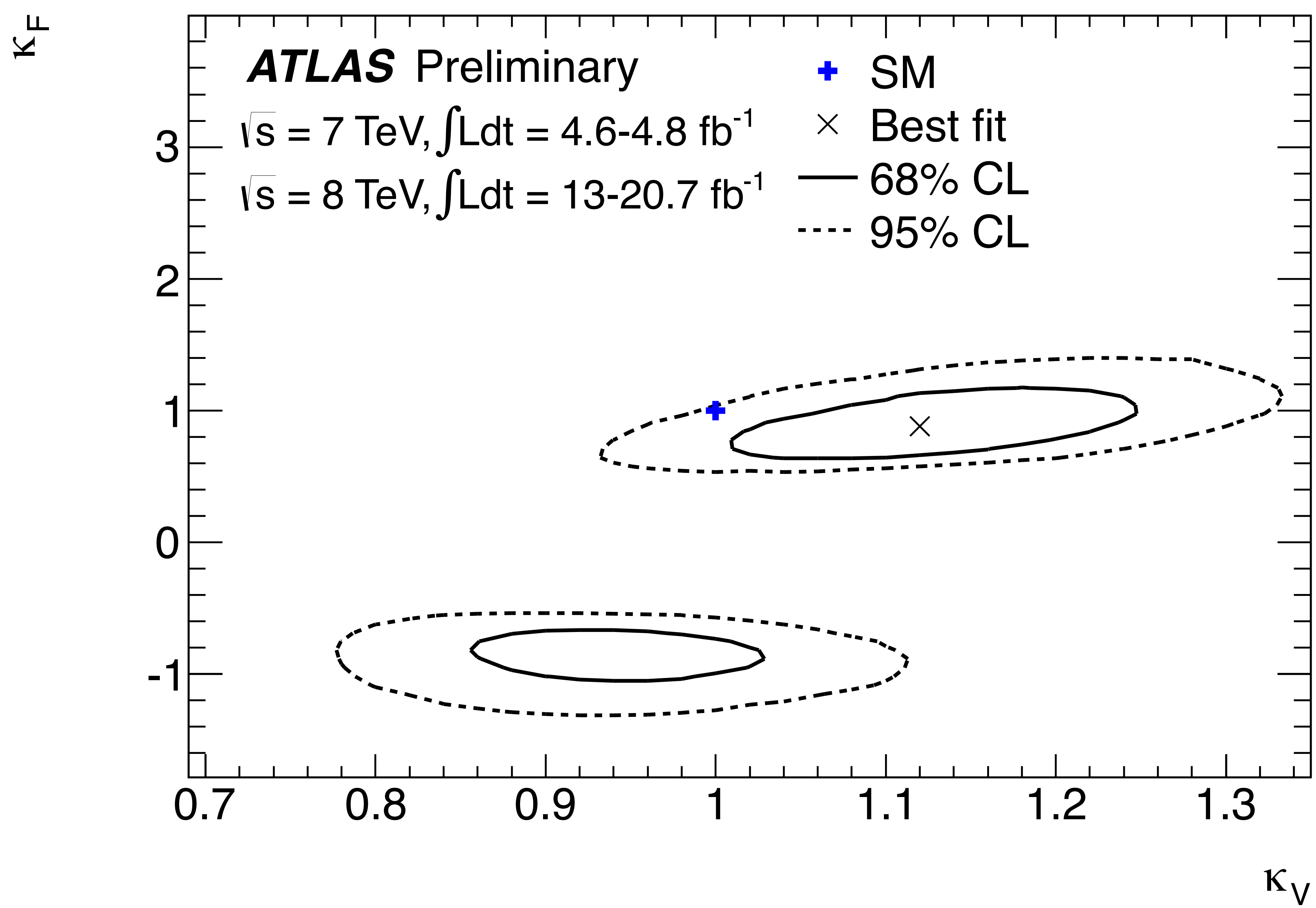
Quartic Interactions

$$\begin{aligned}\mathcal{L} &= \lambda H H^\dagger \Phi \Phi^\dagger \\ &= \lambda v v_\Phi h \phi + \frac{\lambda}{2} v_\Phi \phi h h + \frac{\lambda}{2} v \phi \phi h + \ldots\end{aligned}$$

- Case 3: $\langle \Phi \rangle \neq 0$
  - Current ATLAS bounds place $\cos\alpha \geq 0.93$
  - ATLAS-CONF-2013-034

Quartic Interactions

- Case 3: $\langle \Phi \rangle \neq 0$



Quartic Interactions

$$\mathcal{L} = \lambda H H^\dagger \Phi \Phi^\dagger$$
$$= \lambda v v_\Phi h \phi + \frac{\lambda}{2} v_\Phi \phi h h + \frac{\lambda}{2} v \phi \phi h + \ldots$$

- Case 3: $\langle \Phi \rangle \neq 0$
  - Two decay channels from the quartic interaction
  - Mixing with the Higgs is important for $m_\Phi < 2m_h$
    - New SM-Higgs like particle with suppressed couplings
  - Second term important for $m_\Phi > 2m_h$
    - New scalar that decays to WW/ZZ/hh with a ratio of 2:1:1 in the large mass limit from the Goldstone boson equivalence theorem

Quartic Interactions

$$\begin{aligned}\mathcal{L} &= \lambda H H^\dagger \Phi\Phi^\dagger \\ &= \lambda v v_\Phi h\phi + \frac{\lambda}{2} v_\Phi \phi h h + \frac{\lambda}{2} v \phi\phi h + \ldots\end{aligned}$$

- Case 3: $\langle \Phi \rangle \neq 0$
  - Precision Higgs physics gives bounds of $\sin^2\alpha \leq 14\%$.
  - Bounds on Heavy Higgses are generally not competitive with current precision Higgs physics

Quartic Interactions

$$\mathcal{L} \supset \lambda\psi^\dagger\psi H H^\dagger$$
$$= \lambda\psi^\dagger\psi\frac{h^2}{2} + \lambda v\psi^\dagger\psi h + \lambda\frac{v^2}{2}\psi^\dagger\psi$$

- Case 4: ψ is dark matter
  - Direct detection

$$\sigma_{p,n,SI} = \frac{a}{\pi}\frac{m_p^2}{(m_\psi + m_p)^2}\frac{9y_t^4 m_p^2}{m_h^4}f^2$$
$$f = \frac{6}{27} + \frac{21}{27}(f_{Tu} + f_{Td} + f_{Ts})$$

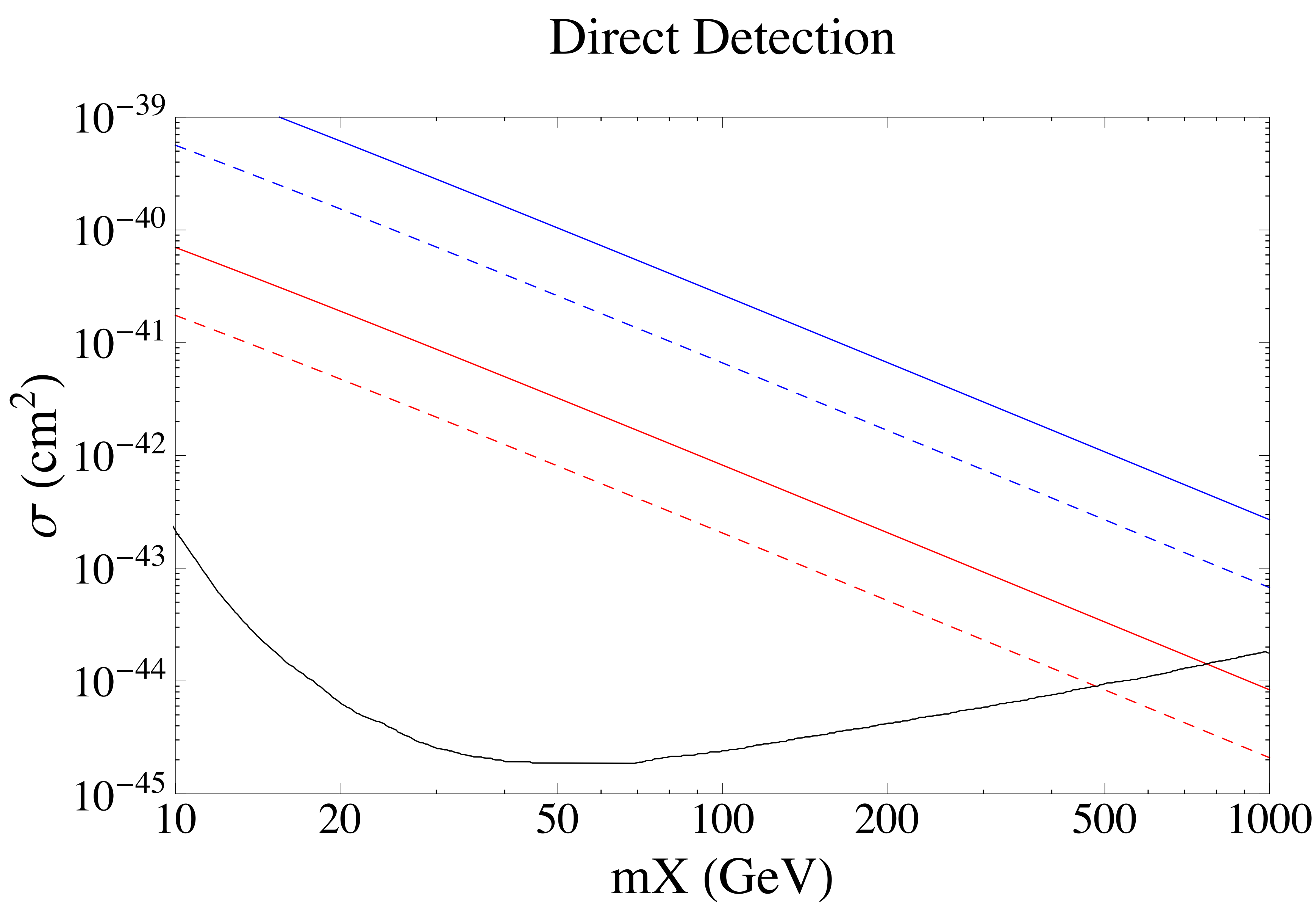
a=4 for a real scalar

a=1 for a complex scalar or majorana fermion

a=1/4 for a dirac fermion

Quartic Interactions

- Case 4: Dark matter



Blue = Top divergence canceled

Red = Gauge divergence canceled

Solid = Complex scalar

Dashed = Dirac fermion

Quartic Interactions

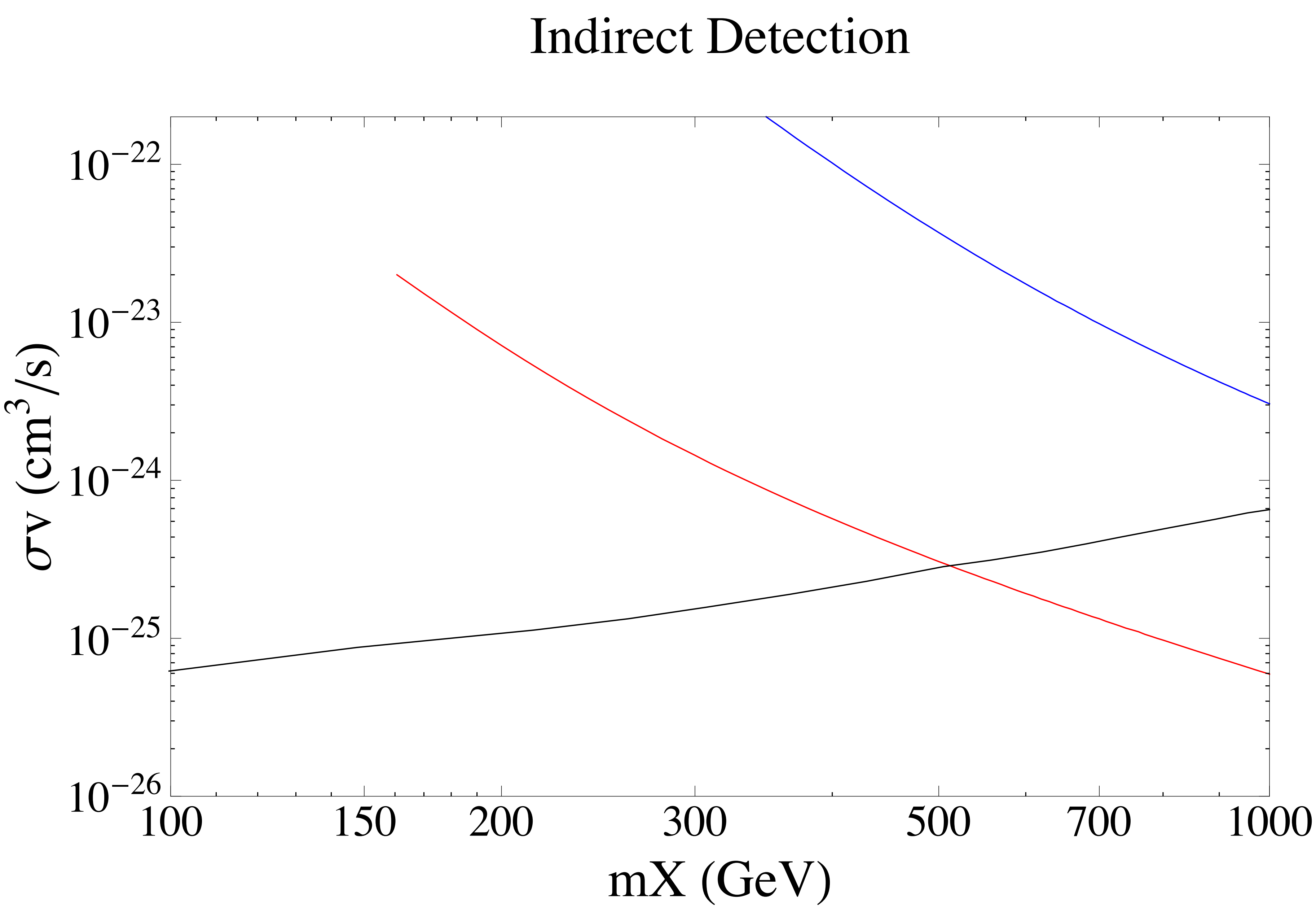
$$\mathcal{L} \supset \lambda\psi^\dagger\psi H H^\dagger$$
$$= \lambda\psi^\dagger\psi\frac{h^2}{2} + \lambda v\psi^\dagger\psi h + \lambda\frac{v^2}{2}\psi^\dagger\psi$$

- Case 4: ψ is dark matter
  - Indirect detection
  - Cross sections in the large mass, small velocity limit

$$\langle\sigma_{\text{fermion}} v\rangle_{v=0} = 0$$
$$\langle\sigma_{\text{scalar}} v\rangle_{v=0} = \frac{9y_t^4}{16\pi m_\psi^2}$$

Quartic Interactions

- Case 4: Dark matter



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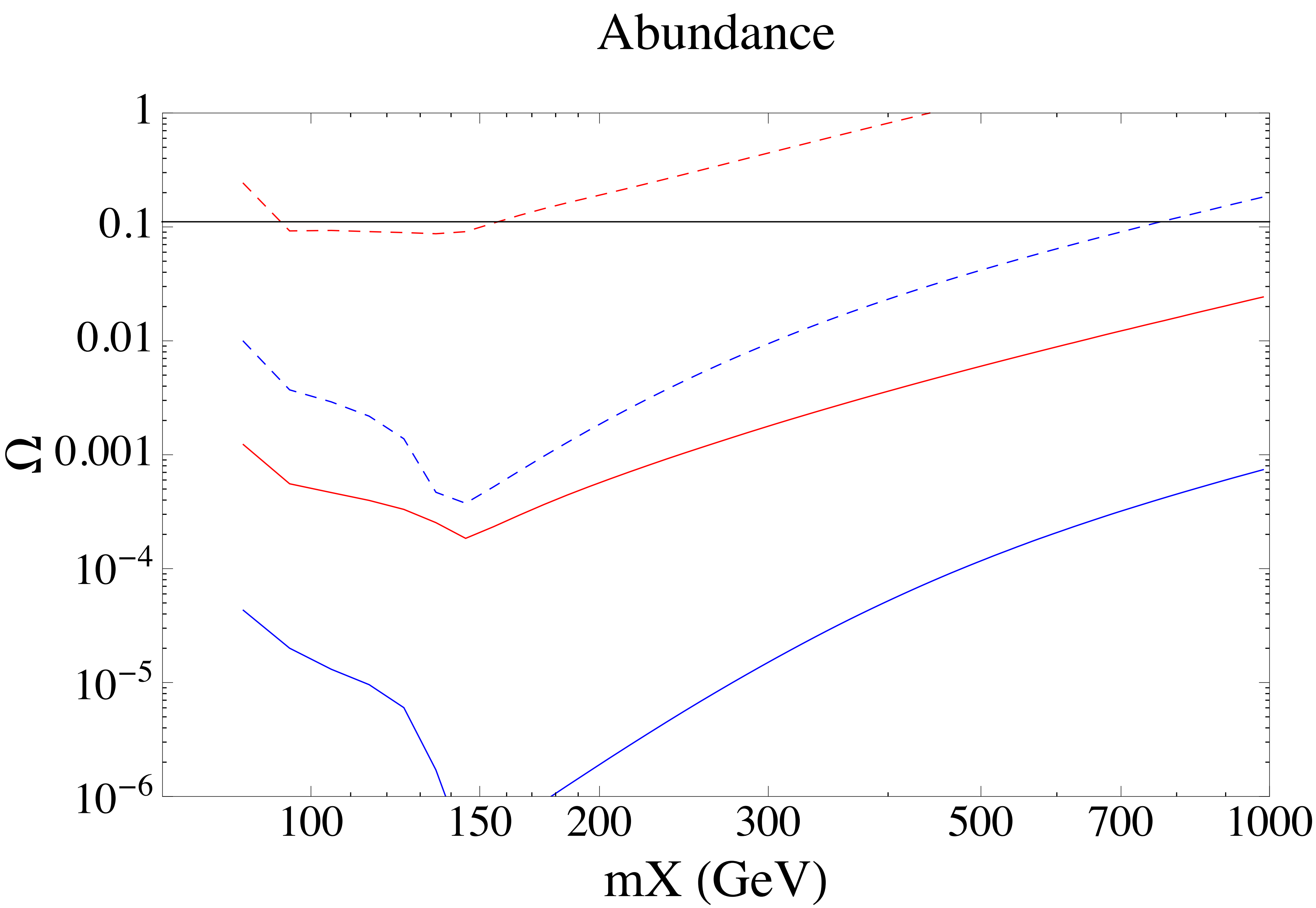
Quartic Interactions

- Case 4: Dark matter



Blue = Top divergence canceled

Red = Gauge divergence canceled

Solid = Complex scalar

Dashed = Dirac fermion

Minimal Naturalness Summary

- Yukawa terms
  - 4th generation and electroweakino like signals
- Quartic terms
  - New Higgs decays if ψ is light enough
  - Modified decays to gauge bosons if ψ is charged under the SM
  - Suppressed Higgs couplings and either a SM-like heavy higgs or a scalar that decays to pairs of Ws/Zs/hs
  - Direct and Indirect detection signals if ψ is dark matter
    - A measurable correlation if ψ is a scalar

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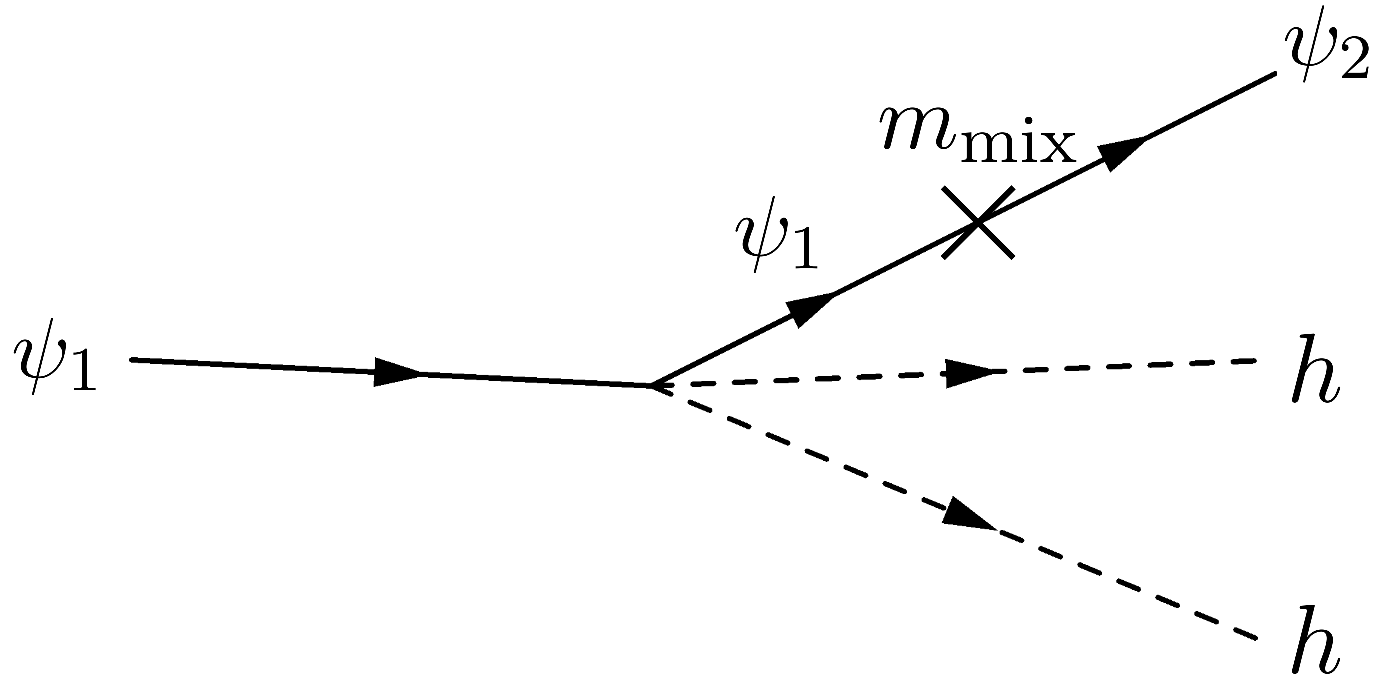
Mass Mixing

- Is there some other way to tie the quartic interaction with a decay channel without assuming a symmetry?
- Adding a generic term in the Lagrangian will generate their own signatures

Mass Mixing

- Mass mixing is unique in that it allows the quartic to become a decay channel



Decays via a Higgs

- Obviously not direct evidence as the term could have been in the Lagrangian from the start
- Unique low energy assumption for generating an observable signature at the LHC!
- Decays through the Higgs but NOT gauge bosons.
- Cascades through the Higgs and only the Higgs inform us about quartics responsible for naturalness!

Decays via a Higgs

- This simplified model can be reached as a limit of Little Higgs models
- Assume a single vector like new particle canceling the top quadratic divergence.

$$\mathcal{L} = f\lambda_1\psi_1 t_R^c + f\lambda_2\psi_1\psi_1^c - \lambda_1 Q_3 H t_R^c + \frac{\lambda_1}{2f} H H^\dagger t_R^c \psi_1$$

Decays via a Higgs

- Go to mass basis in the small v limit

$$\begin{aligned}\mathcal{L}_{\text{mixing}} &= m_U U U^c + \lambda_U^i U^c H Q_i + \lambda_{SM}^{ij} u_i^c H Q_j \\ &+ \frac{\lambda_{UU}}{m_U} U^c U H H^\dagger + \frac{\lambda_{Uu}^i}{m_U} u_i^c U H H^\dagger\end{aligned}$$

- In Little Higgs models, the quartics are related by a rotation angle.
- In the past, λ_U^i was assumed to dominate the phenomenology
- At the level of 2 body decays, only true if $\lambda_U^i > \lambda_{Uu}^i \frac{v}{m_U}$

Decays via a Higgs

- Quartic dominating decays
  - λ_U^i related to flavor physics. Typical assumptions of Little Higgs and Fourth generation models are a flavor texture that makes these terms small so that FCNC are not an issue. Assume that making them small also makes them irrelevant for phenomenology.
  - If there are no ad hoc cancelations λ_U^i is of similar size to the SM particle being mixed with while λ_{Uu}^i is of similar size to the quadratic divergence being canceled. Mixing with light partners while canceling top quadratic divergences yields phenomenology based off of the quartic.

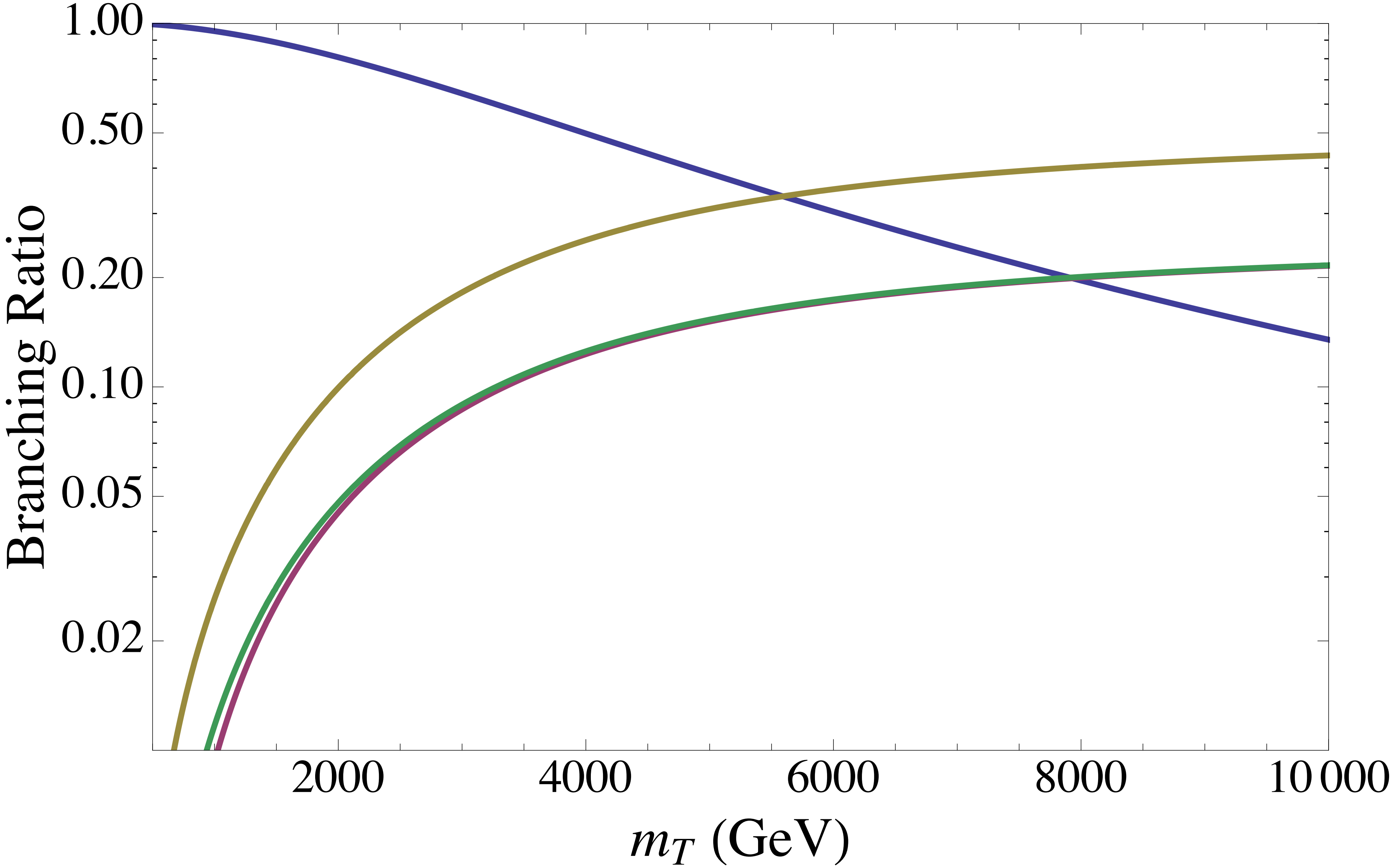
Phenomenology of Quartic

$$\frac{\lambda^i_{Uu}}{m_U} u^c_i U H H^\dagger$$

- Quartic gives four decay channels

$$\begin{aligned} U &\rightarrow u_i + h \\ U &\rightarrow u_i + h + h \\ U &\rightarrow u_i + Z + Z \\ U &\rightarrow u_i + W^+ + W^- \end{aligned}$$

Phenomenology of Quartic



Blue = a single Higgs

Yellow = a pair of Ws

Green = a pair of Zs

Red = a pair of Higgses

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SUSY Quartics

- Current collider signatures of SUSY are independent of the cancelation of the top quadratic divergence.
- SUSY relates top yukawa to various quartics

$$W = y_t Q_3 H_u t^c - y_b Q_3 H_d b^c$$

SUSY Quartics

- Only fermionic symmetries can relate yukawas to scalar quartics
  - Measure any scalar quartic to test supersymmetry
- Focus has been on

$$\mathcal{L} \supset \tilde{t}\tilde{t}^\dagger H_u H_u^\dagger = \frac{v}{\sqrt{2}} h \tilde{t}\tilde{t}^\dagger + \cdots$$

  - Not LHC observable

SUSY Quartics

- Any LHC observable quartics?

$$
\begin{aligned}
F_Q &= y_t H_u \tilde{t}_R + y_b H_d \tilde{b}_R \\
\mathcal{L} &\supset y_t y_b^* H_u \tilde{t}_R H_d^\dagger \tilde{b}_R^\dagger + h.c. = v y_t y_b^* H^- \tilde{t}_R \tilde{b}_R^\dagger + \cdots
\end{aligned}
$$

- Mediates decays between right handed stop and sbottoms!

SUSY Quartics

$$\mathcal{L} \quad \supset \quad y_t y_b^* H_u \tilde{t}_R H_d^\dagger \tilde{b}_R^\dagger + h.c.$$

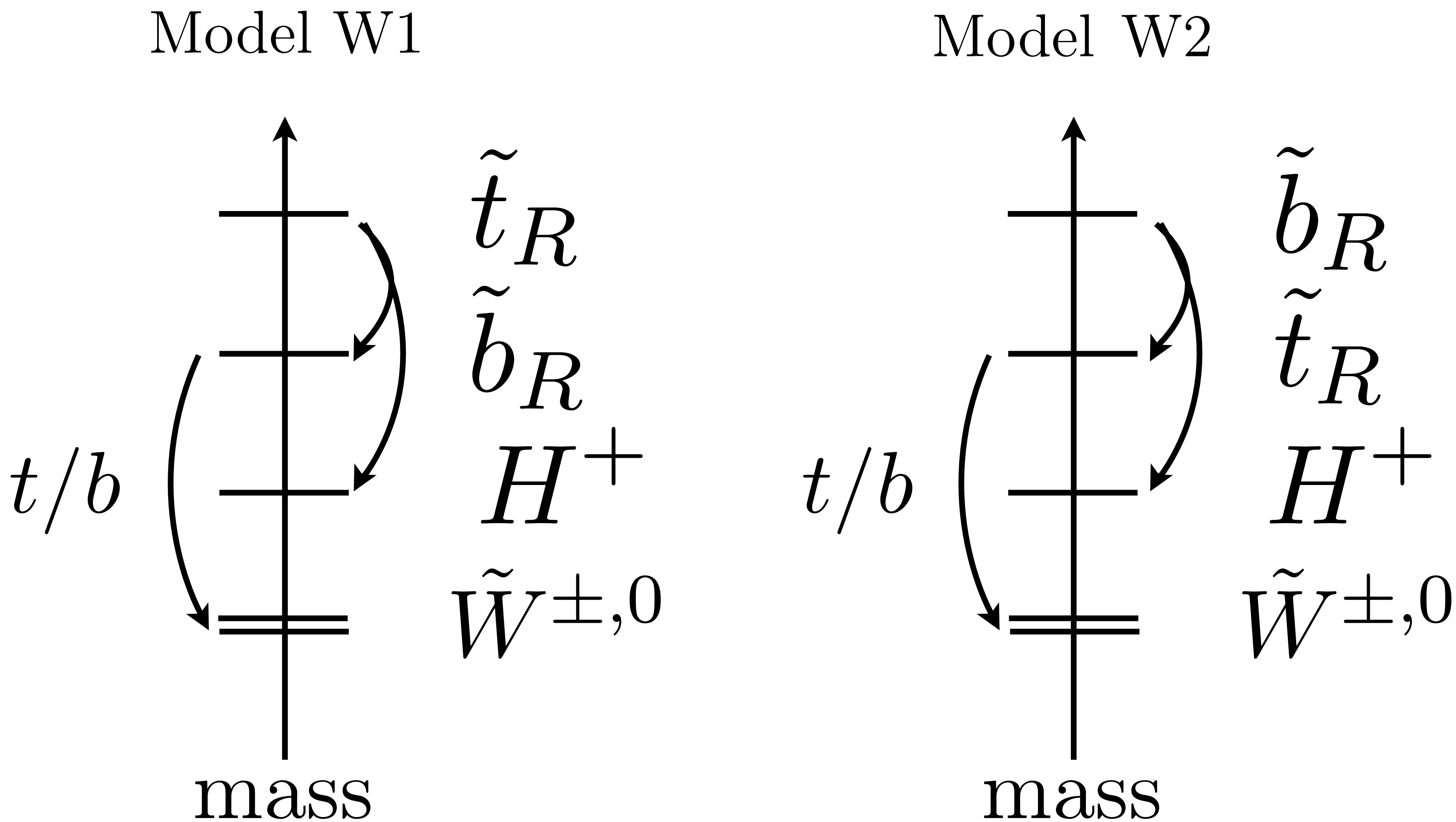
- No tree level term in the MSSM, soft or not that allows for a right handed stop to decay to a right handed sbottom decay!
- Unlike the well studied quartic, demonstrating the existence of this operator or measuring its value is doable at the LHC
    - Just observe the decay

Easy Simplified Models

- Light right handed stop, sbottom and LSP
- Naturalness requires light stops
  - Many models of natural SUSY have NLSP stops/sbottoms
  - Left handed stops tend to be heavier due to RG effects of the gaugino
  - In fact making the 3rd generation squarks not tachyonic can be a strong constraint
- Also provides an interesting way to study the charged Higgs

Easy Simplified Models

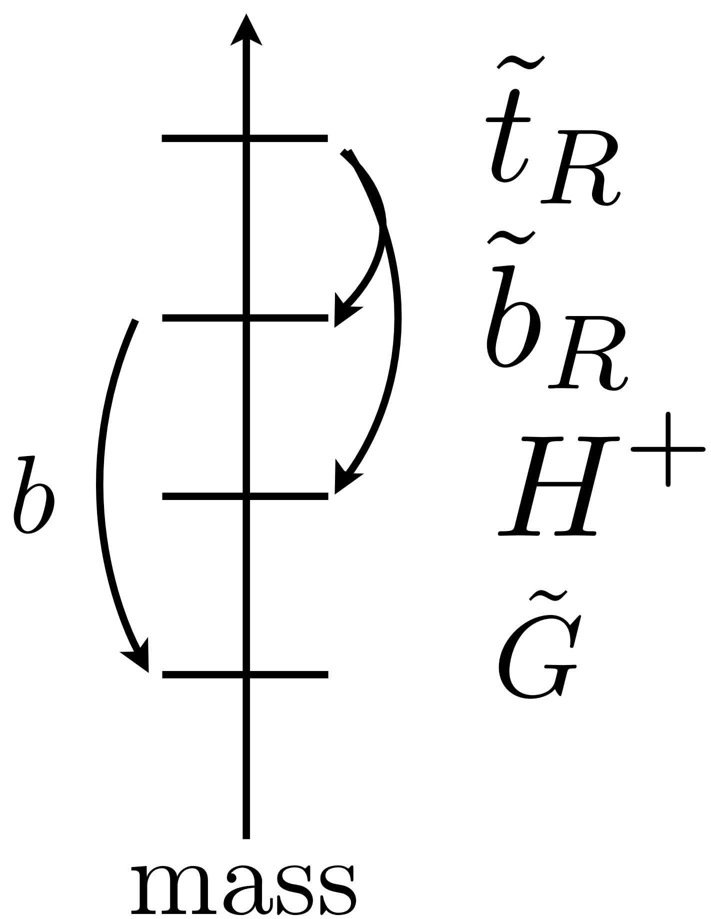
Wino LSP



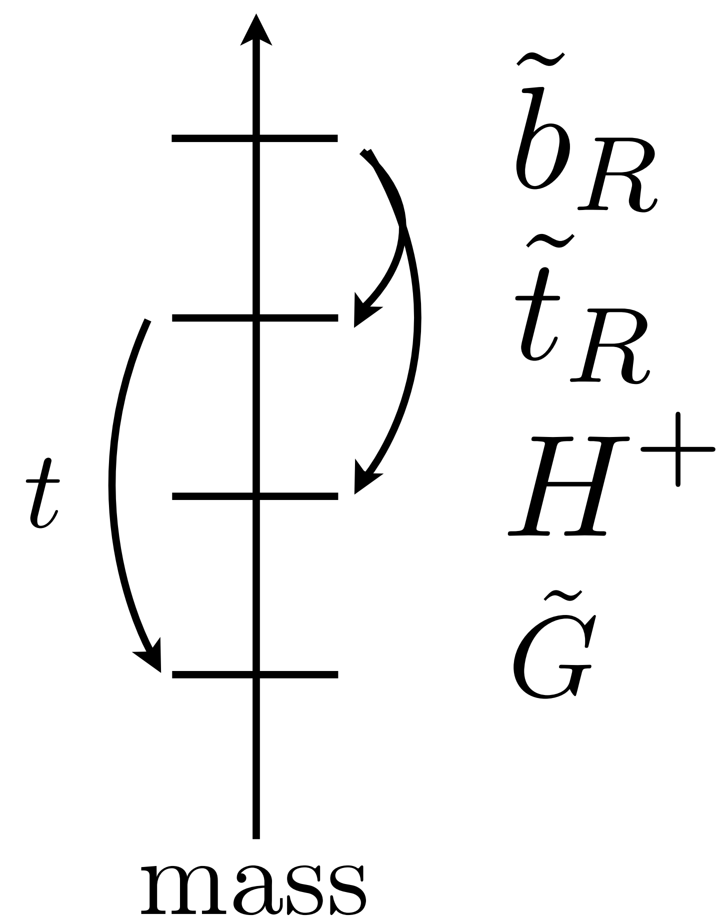
Easy Simplified Models

Gravitino LSP

Model G1



Model G2



Easy Simplified Models

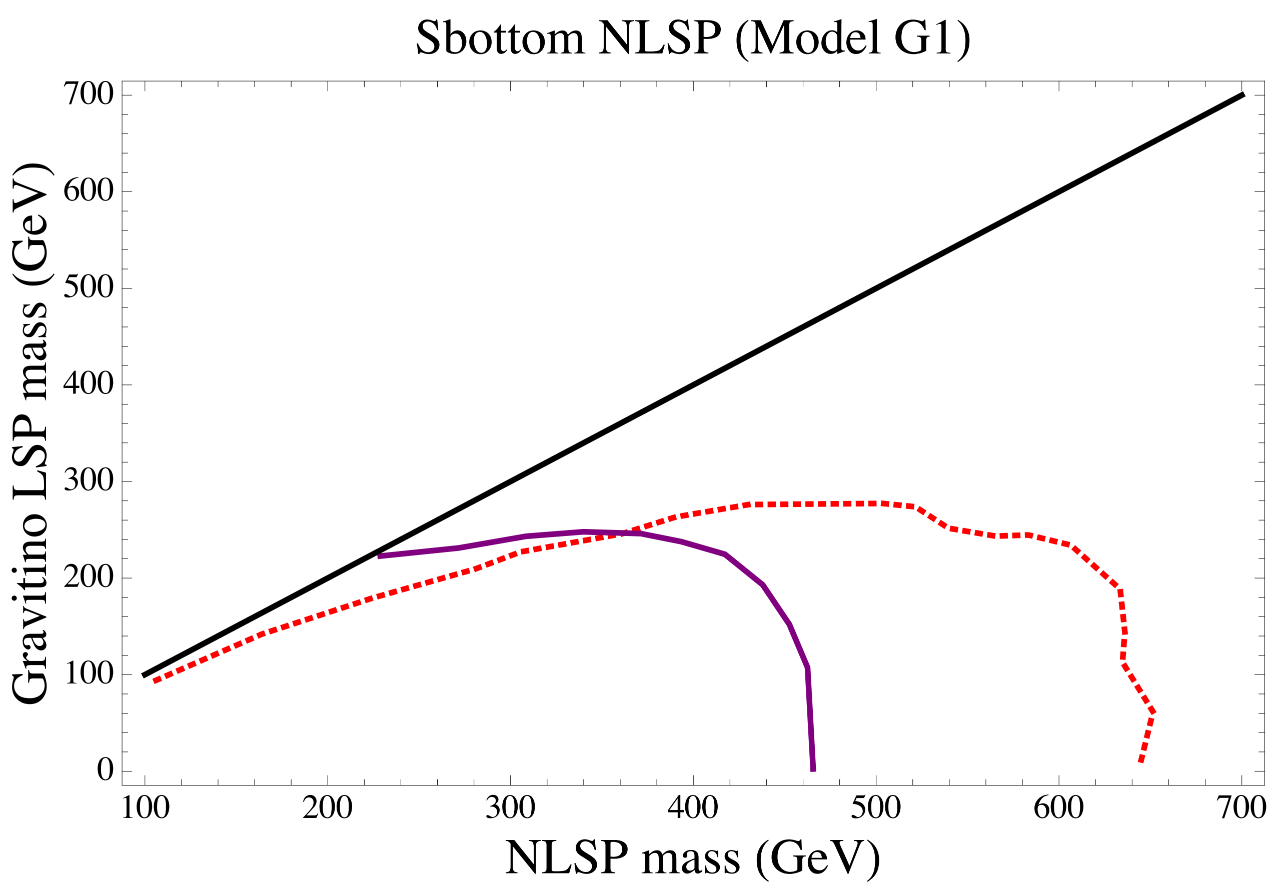
- For some regions of parameter space current searches have good sensitivity
  - If the charged Higgs is heavy, it decays into 3rd gen. quarks
- Signal has 2-4 tops and 2-4 bottoms for which searches already exist
- Assume $m_{H^+} = 300 GeV \quad m_H = m_L + 350\,\mathrm{GeV}$

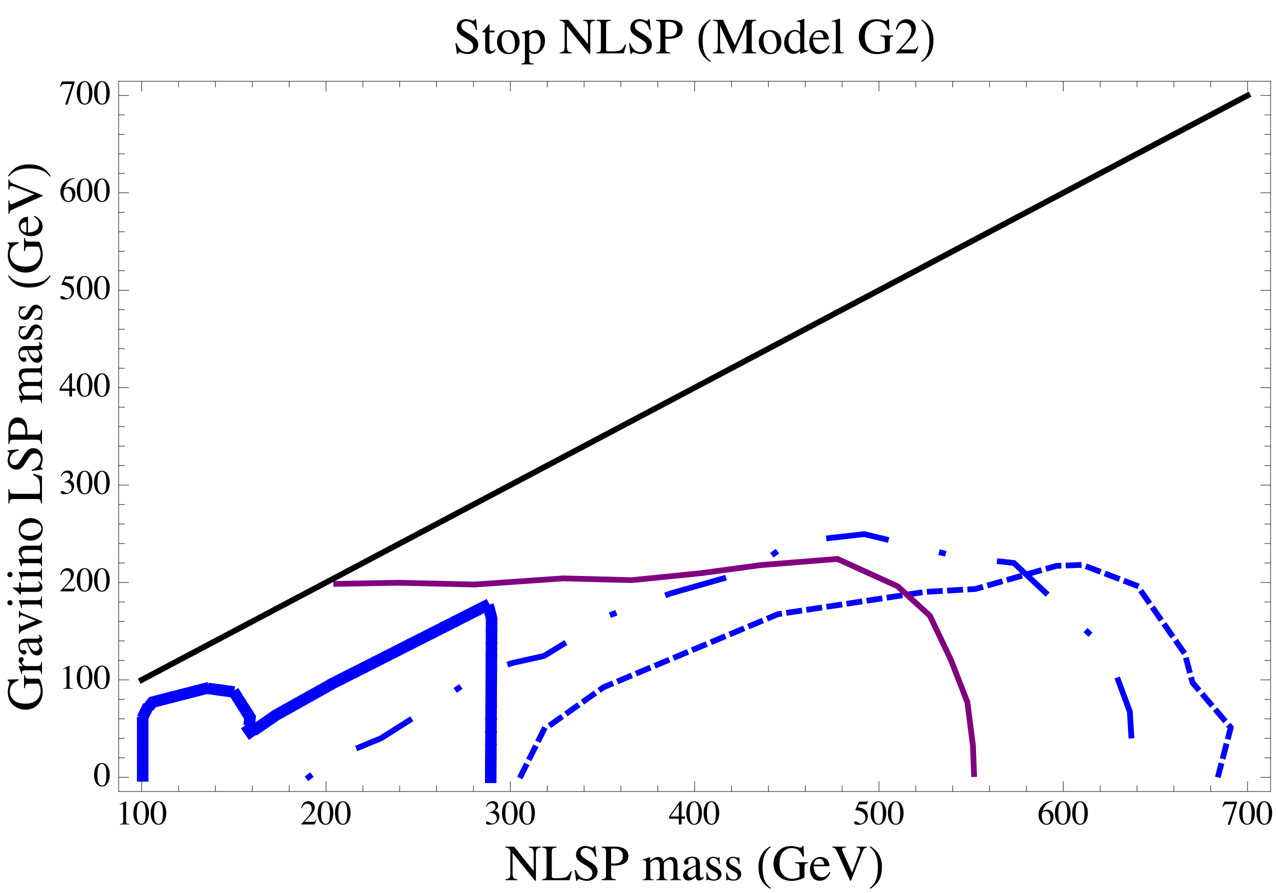
Easy Simplified Models

Purple : many tops/bottom ATLAS search applied Simplified Models

Red : direct sbottom production bounds

Blue : direct stop production bounds





Conclusion

- Should approach naturalness in a model independent manner
  - 4th generation and electroweakino like signals
  - Precision Higgs measurements
  - Extra Higgs-like scalars
  - Direct and Indirect detection signals for dark matter
    - A measurable correlation for scalars

Conclusion

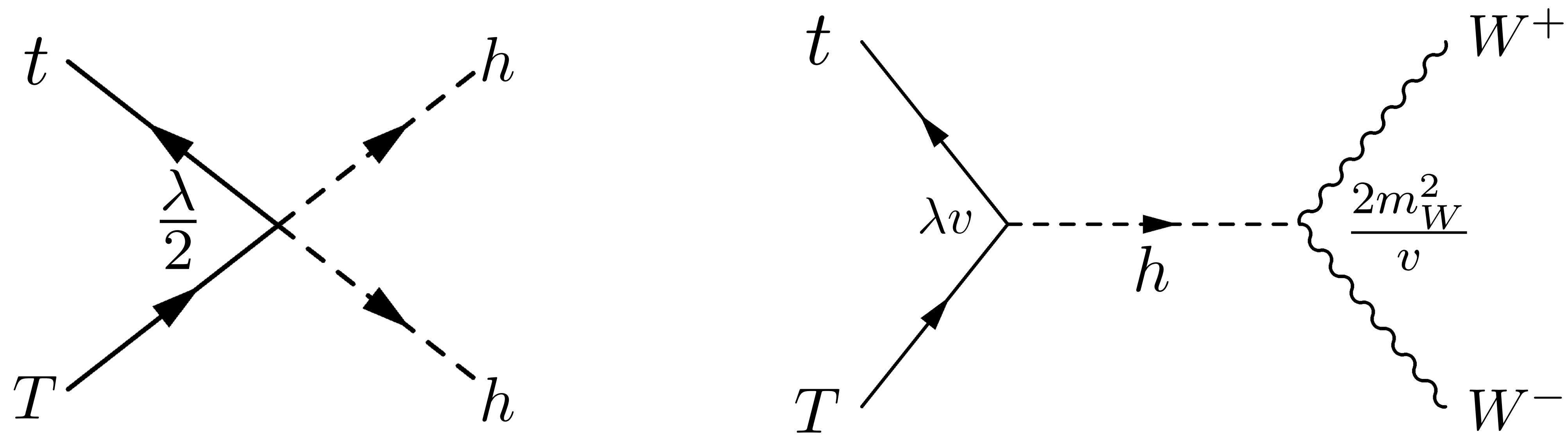
- Decays involving only scalars are important
  - Mass mixing the quartic results in an observable decay that involves only the Higgs - seen in Little Higgs models
  - Decays involving charged higgses and not W bosons : evidence that the stop sector is supersymmetric

Goldstone Equivalence Theorem

$$\mathcal{L} \supset -m_T T T^c + \lambda H H^\dagger T u_3^c$$

In the large mass limit, the decay to two W/Z should be described by this term

Goldstone Equivalence Theorem



$$|M(T\to thh)|^2 \sim \frac{\lambda^2}{2} p_{T,\mu} p_t^{\mu}$$

$$|M(T\to tW^+W^-)|^2 \sim 4\lambda^2 m_W^4 p_{T,\mu} p_t^{\mu} \frac{1}{((p_T-p_t)^2-m_h^2)^2} \frac{(p_{W^+}\cdot p_{W^-})^2}{m_W^4}$$

Little Higgs Model

- Toy Little Higgs model describing SU(3) breaking down to SU(2)

$$\Sigma = \exp\left(\frac{i}{f}\begin{pmatrix} 0 & H \\ H^\dagger & 0 \end{pmatrix}\right)\begin{pmatrix} 0 \\ f \end{pmatrix}$$

- Collective symmetry breaking dictates that the Lagrangian is

$$\mathcal{L} \supset \lambda_1 u_3^c \Sigma \chi + \lambda_2 f u'^c u'$$

- Lowest order terms are

$$\mathcal{L} \supset f(\lambda_1 u_3^3 + \lambda_2 u'^c)u' - \lambda_1 u_3^c H Q_3 + \frac{\lambda_1}{2f} H H^\dagger u_3^c u'$$

Little Higgs Model

- Diagonalize in the small v limit

$$\mathcal{L} \supset \frac{\lambda_1 \lambda_2}{\sqrt{\lambda_1^2+\lambda_2^2}} t_3^c H Q_3 + \frac{\lambda_1^2}{\sqrt{\lambda_1^2+\lambda_2^2}} T^c H Q_3 + \frac{\lambda_1^2}{2m_T} H H^\dagger T^c T + \frac{\lambda_1 \lambda_2}{2m_T} H H^\dagger t_3^c T$$

- Comparing the two and three body decays give

$$\frac{\lambda_2}{\lambda_1} \frac{\sqrt{\lambda_1^2+\lambda_2^2} v}{2m_T} = \frac{\lambda_2^2 v}{2y m_T}$$