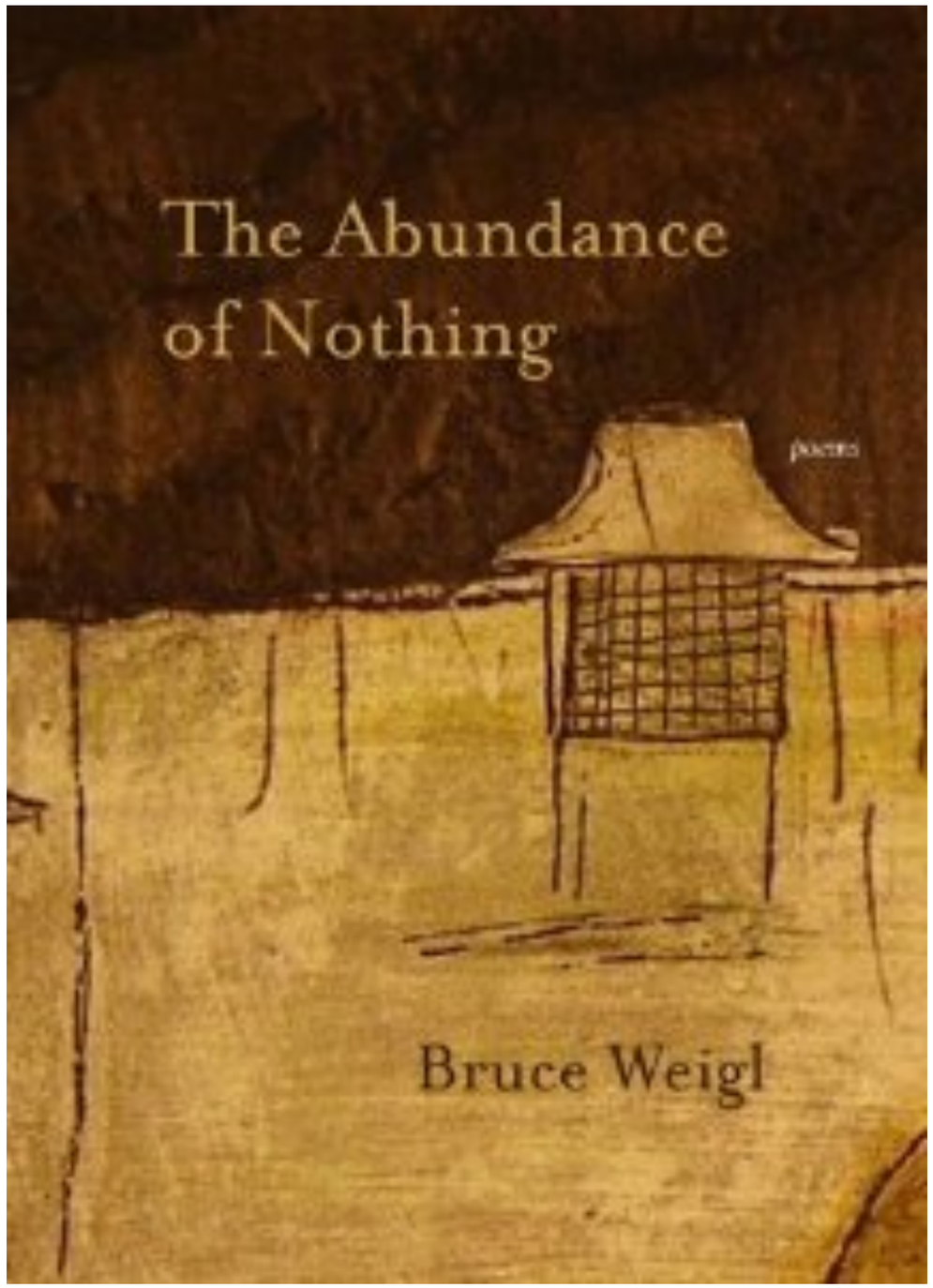


Savas Dimopoulos
Stanford University

States of BSM Theorists after LHC 8

States of BSM Theorists after LHC 8

- The Orthodox:
  Stick with Naturalness no matter the cost (model complexity)

States of BSM Theorists after LHC 8

- The Orthodox:
  Stick with Naturalness no matter the cost (model complexity)

- The Ultra-orthodox:
  Stick with ?MSSM no matter the cost (tuning, model complexity)

States of BSM Theorists after LHC 8

- The Orthodox:
  Stick with Naturalness no matter the cost (model complexity)

- The Ultra-orthodox:
  Stick with ?MSSM no matter the cost (tuning, model complexity)

- The Heretics:
  Abandon Naturalness and Move to the Landscape
  (10^{500} Universes!)

The History of Heresy

"the whole evolutionary process, both cosmic and organic, is one, and ... the universe in its very essence is biocentric"

L. J. Henderson

The History of Heresy

"the whole evolutionary process, both cosmic and organic, is one, and ... the universe in its very essence is biocentric"

L. J. Henderson, 1913

The History of Heresy

"the whole evolutionary process, both cosmic and organic, is one, and ... the universe in its very essence is biocentric"

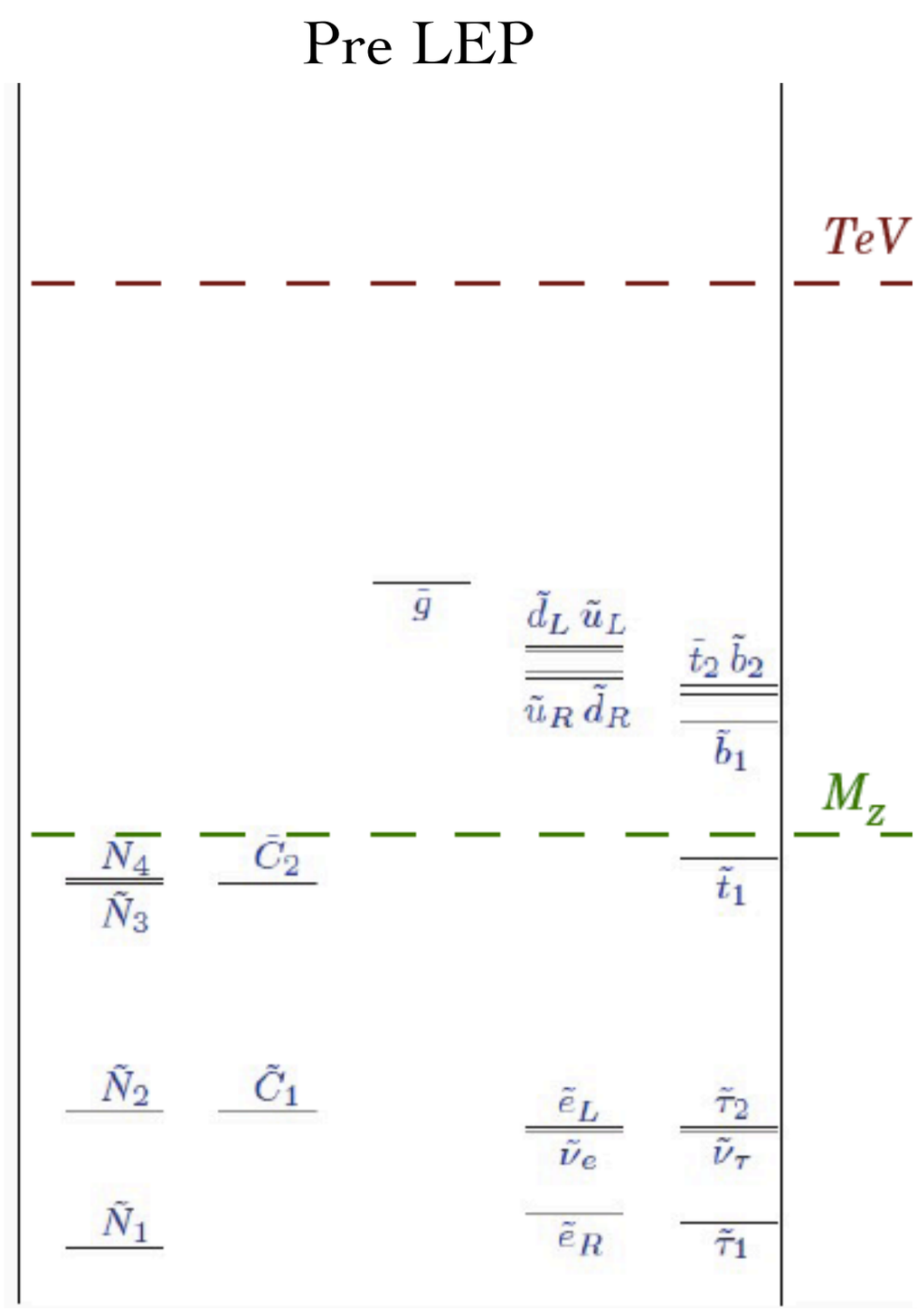
L. J. Henderson, 1913

Fear of Premature Application

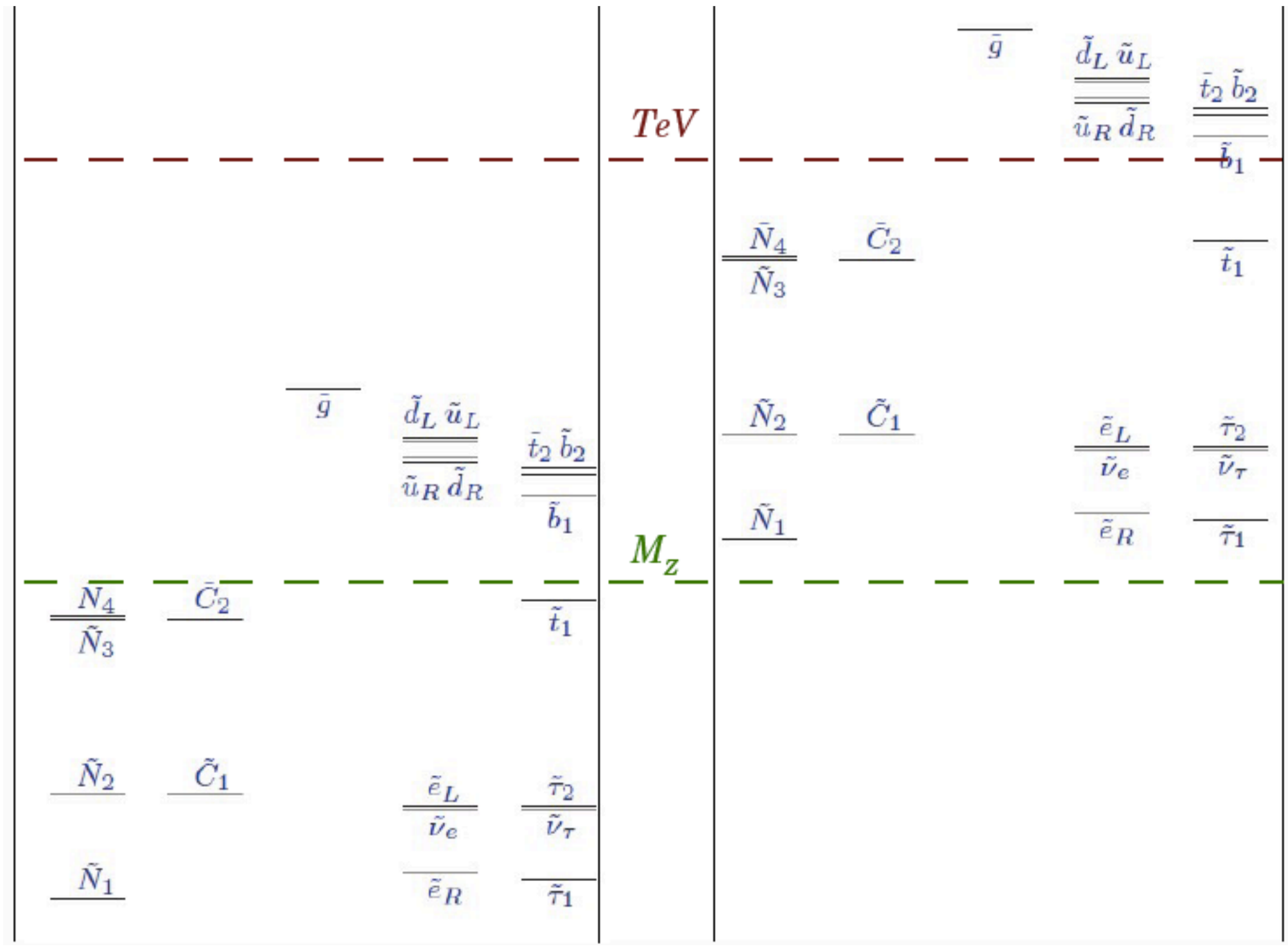
Outline

- Natural Theories
- Split Supersymmetry
- Refining Naturalness?

The Hard Facts

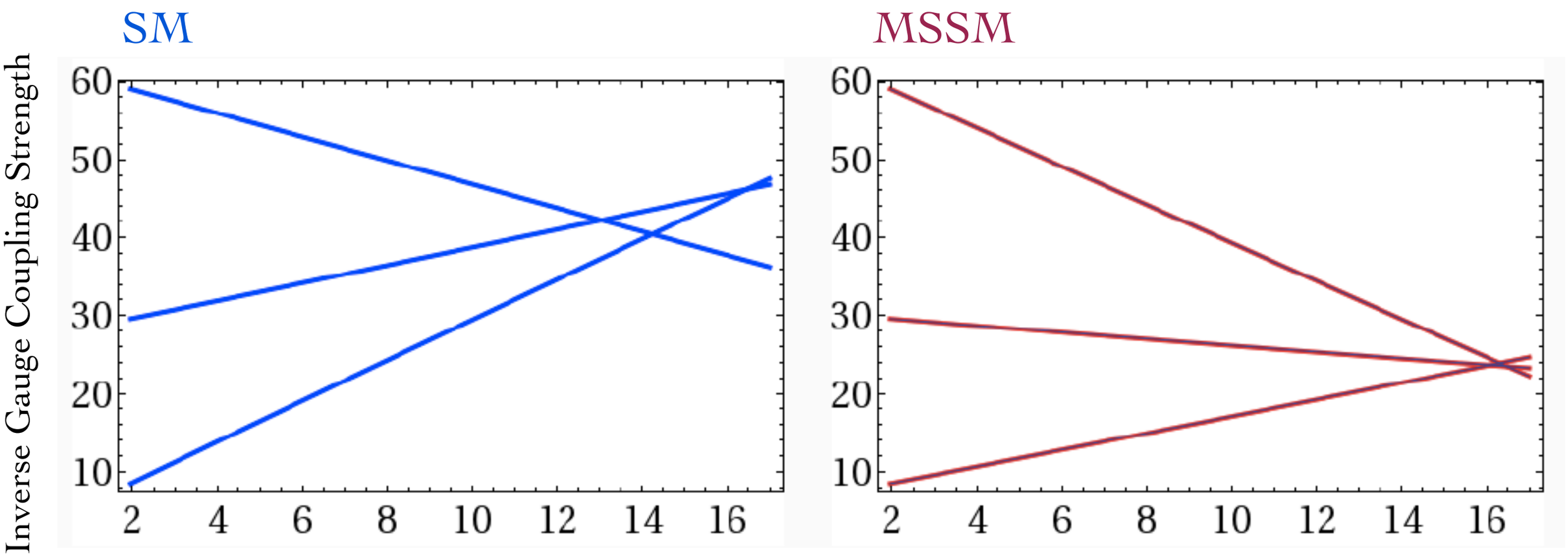


The Hard Facts



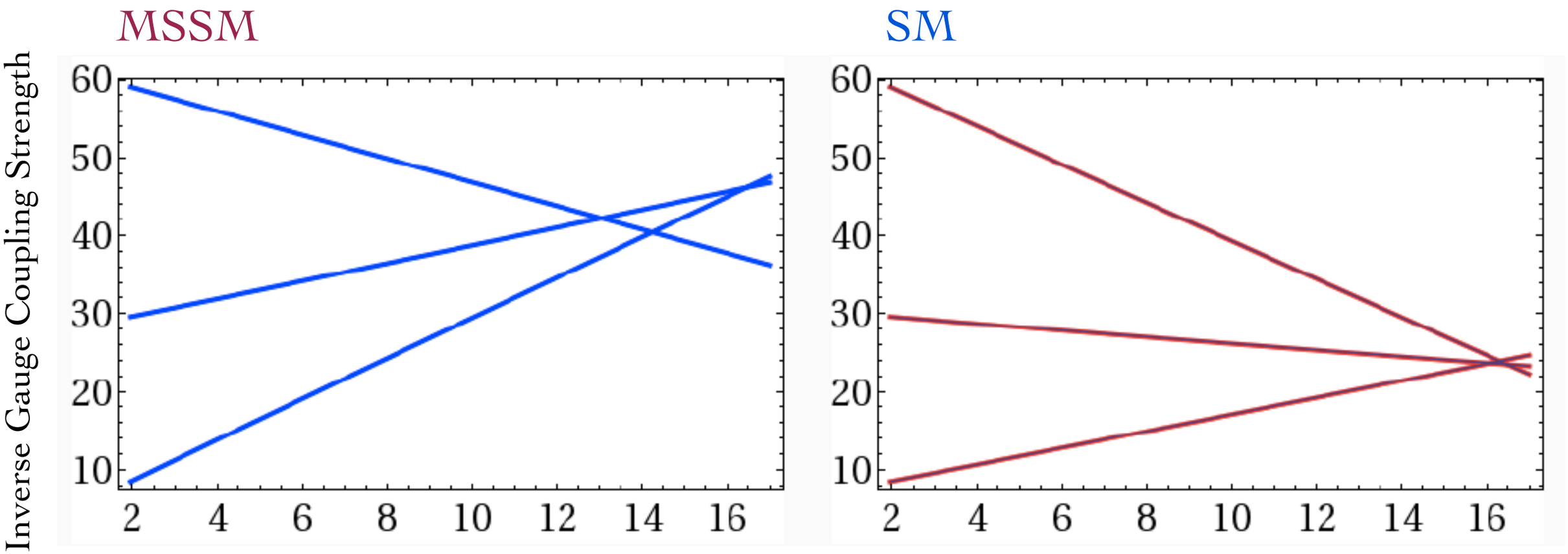
The connection with the hierarchy problem is diminished

Why Supersymmetry?



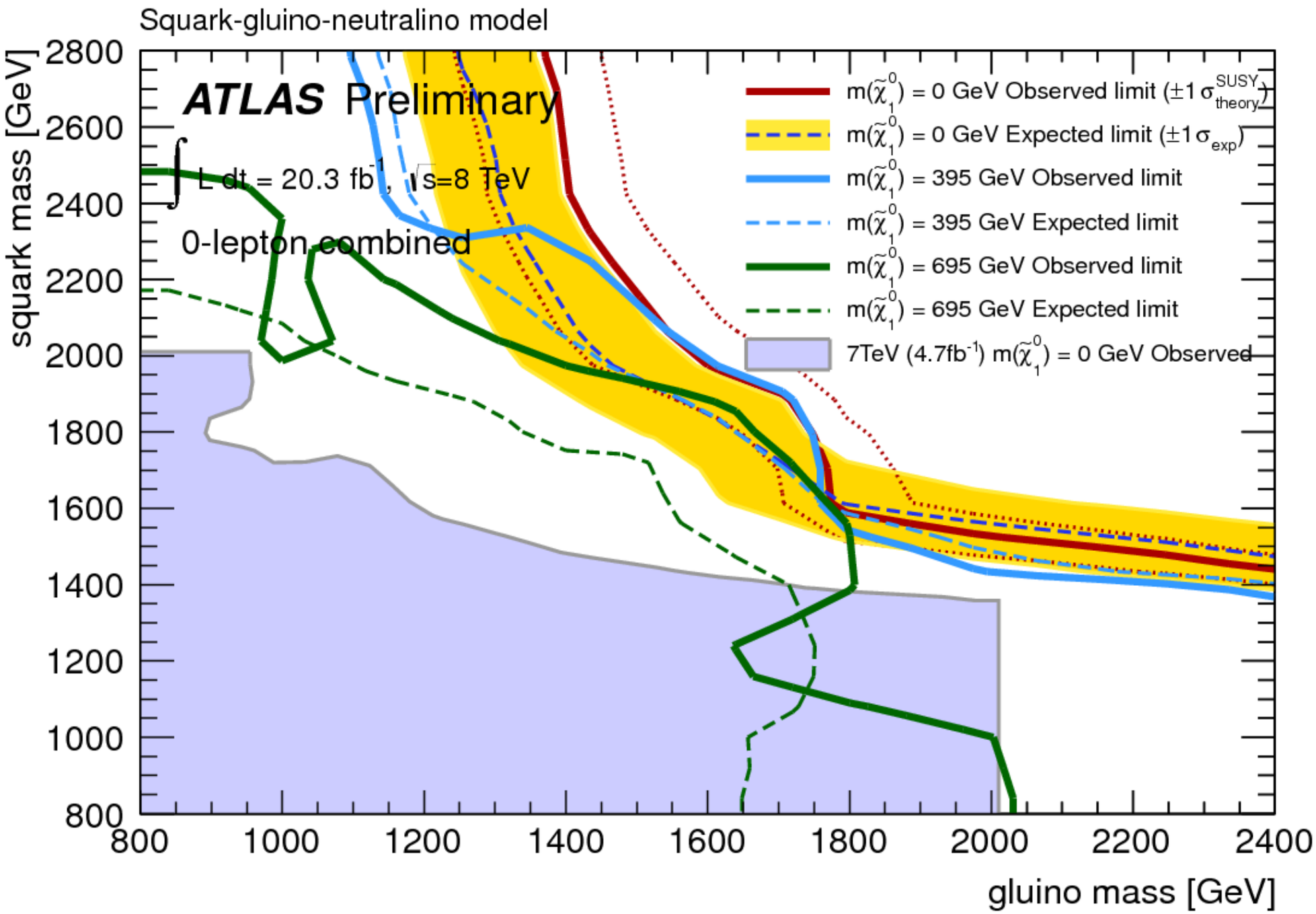
Gauge Coupling running at two loops

Why Supersymmetry?



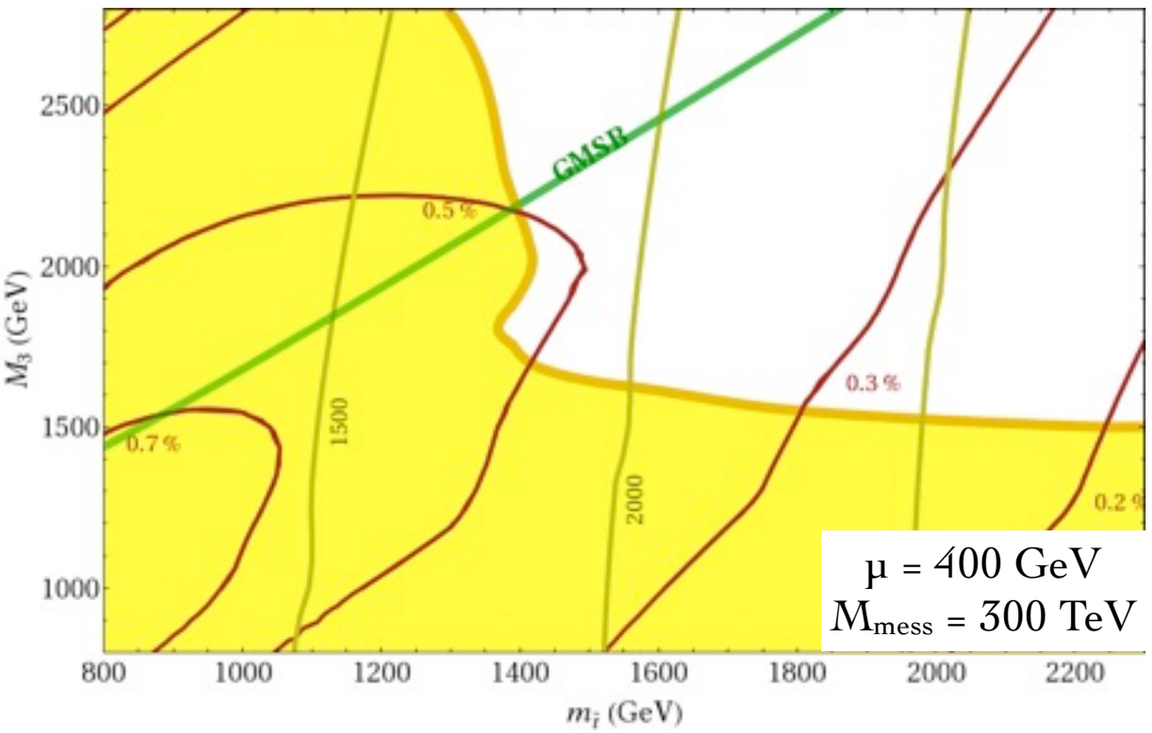
Gauge Coupling running at two loops

The Missing Superpartner Problem



The Status of Naturalness in SUSY

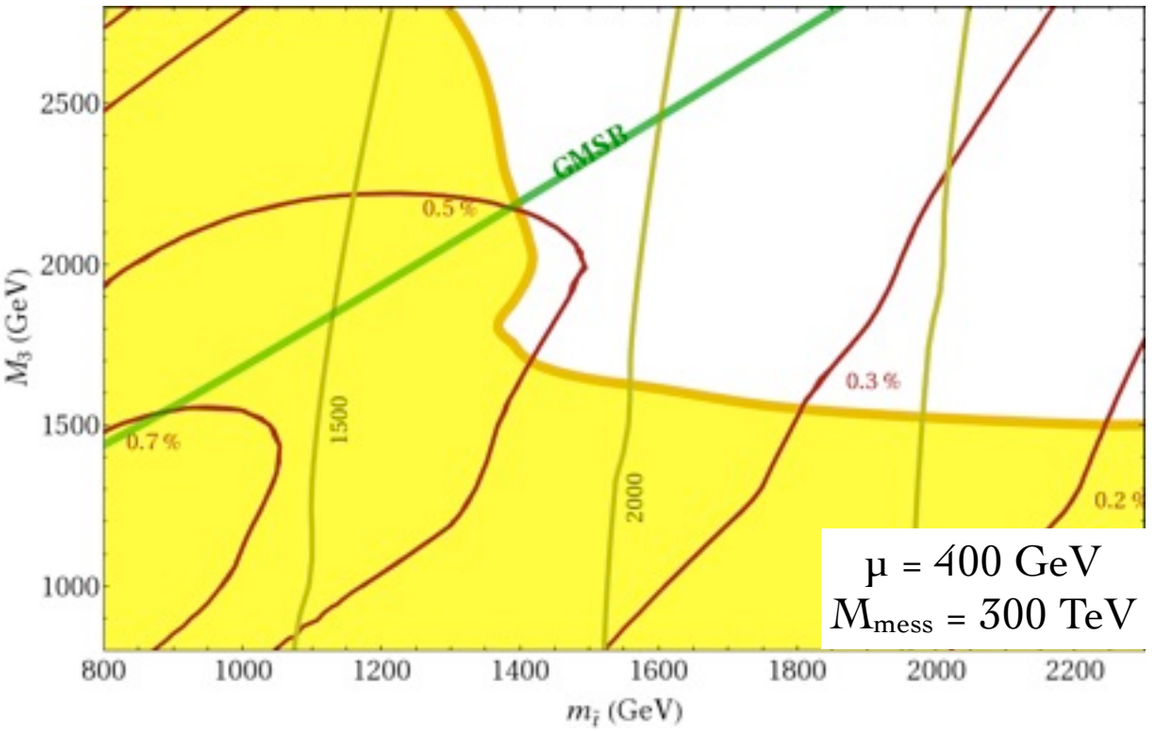
MSSM with A-terms



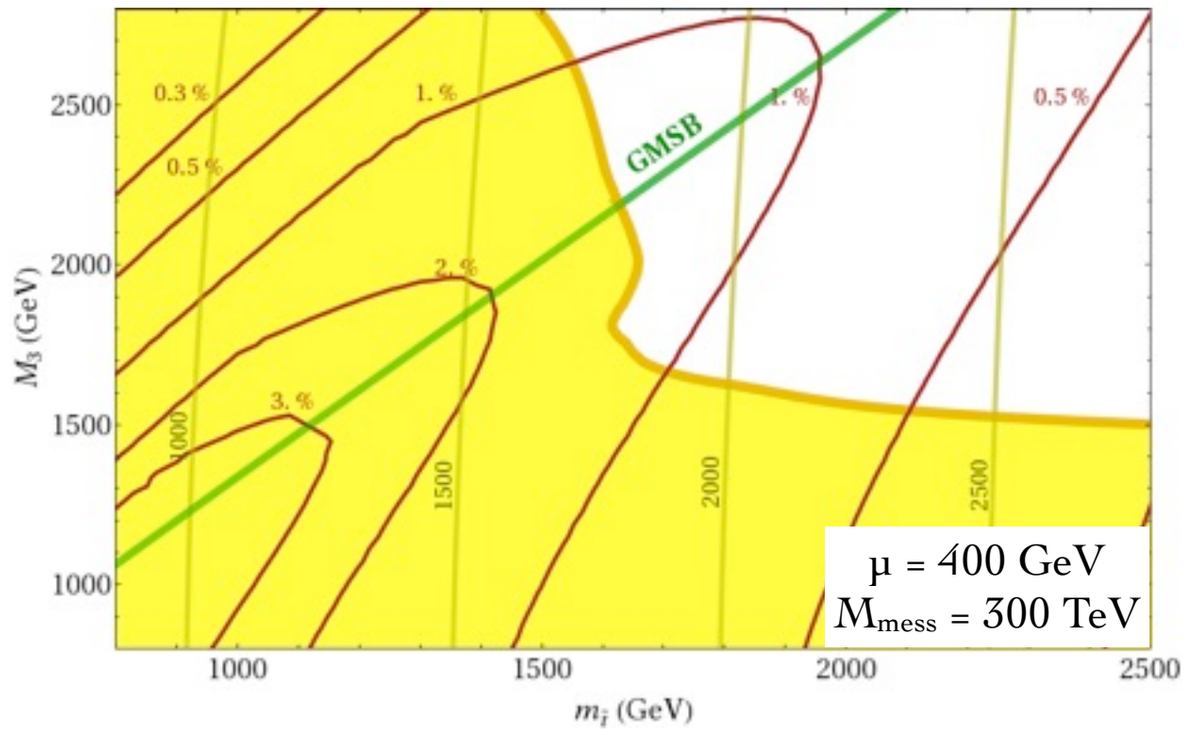
- In the MSSM: Tuning dominated by the Higgs Mass

The Status of Naturalness in SUSY

MSSM with A-terms



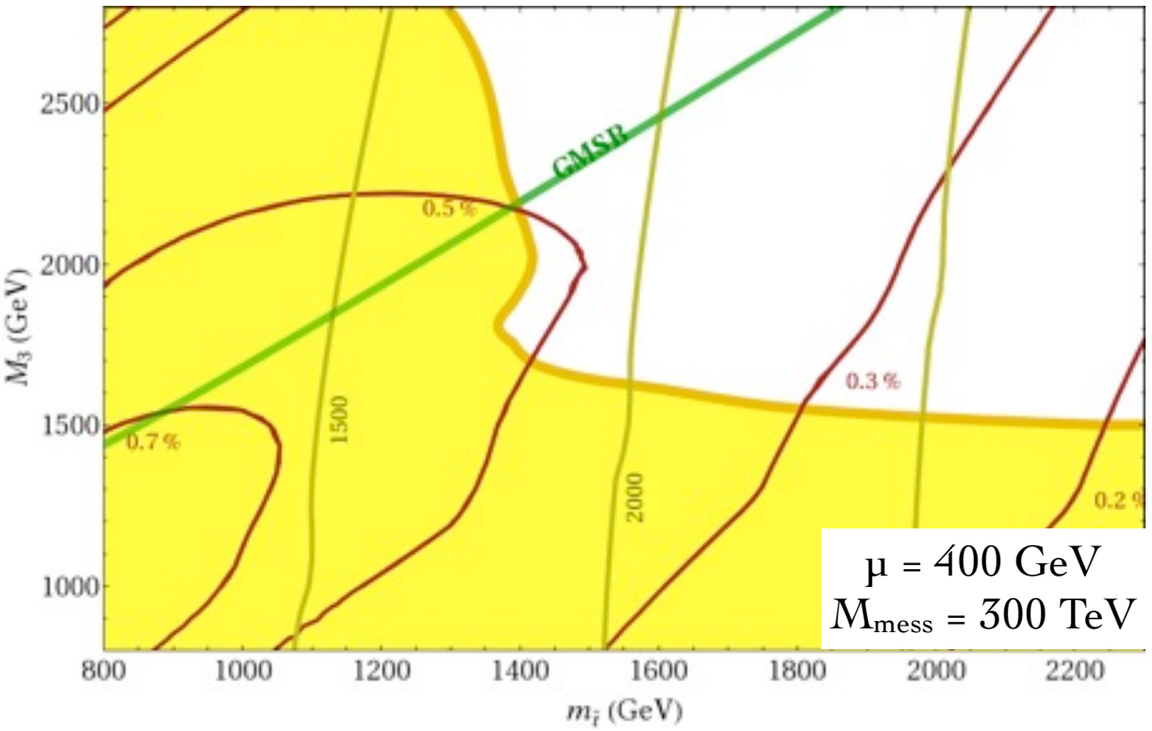
NMSSM
or any model that "fixes" the Higgs mass



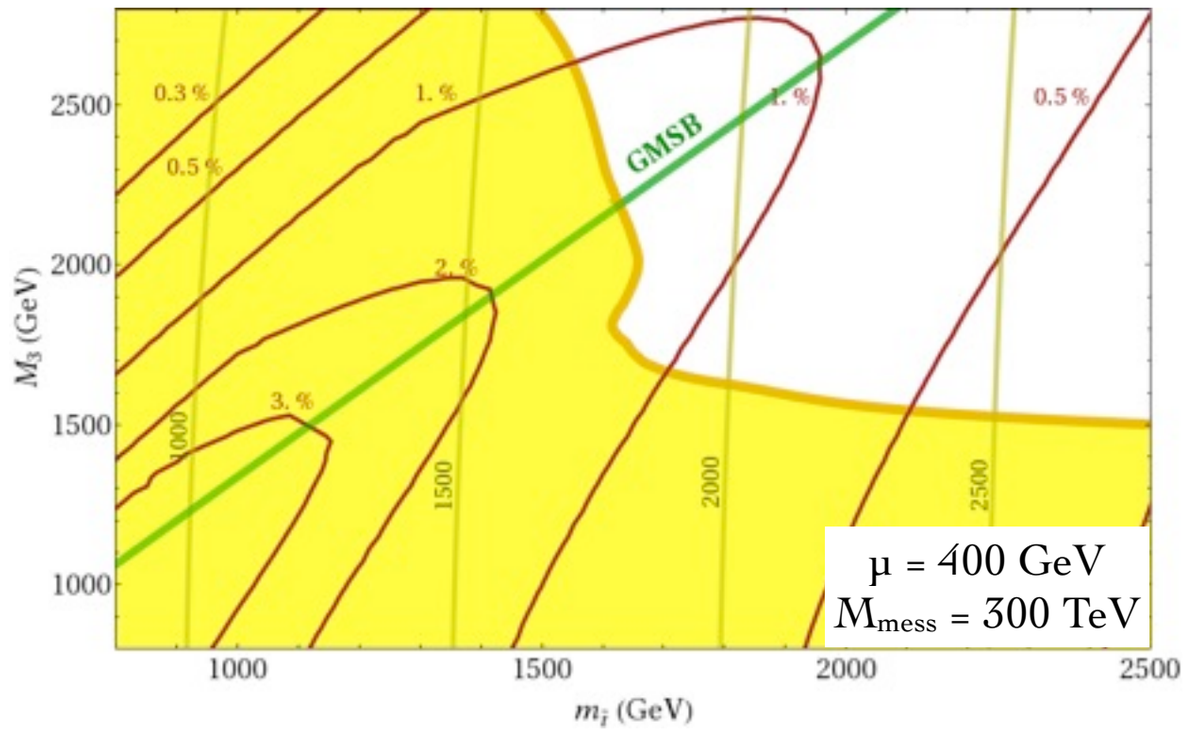
- In the MSSM: Tuning dominated by the Higgs Mass
- In any model that fixes the Higgs mass: Tuning dominated by LHC bounds

The Status of Naturalness in SUSY

MSSM with A-terms

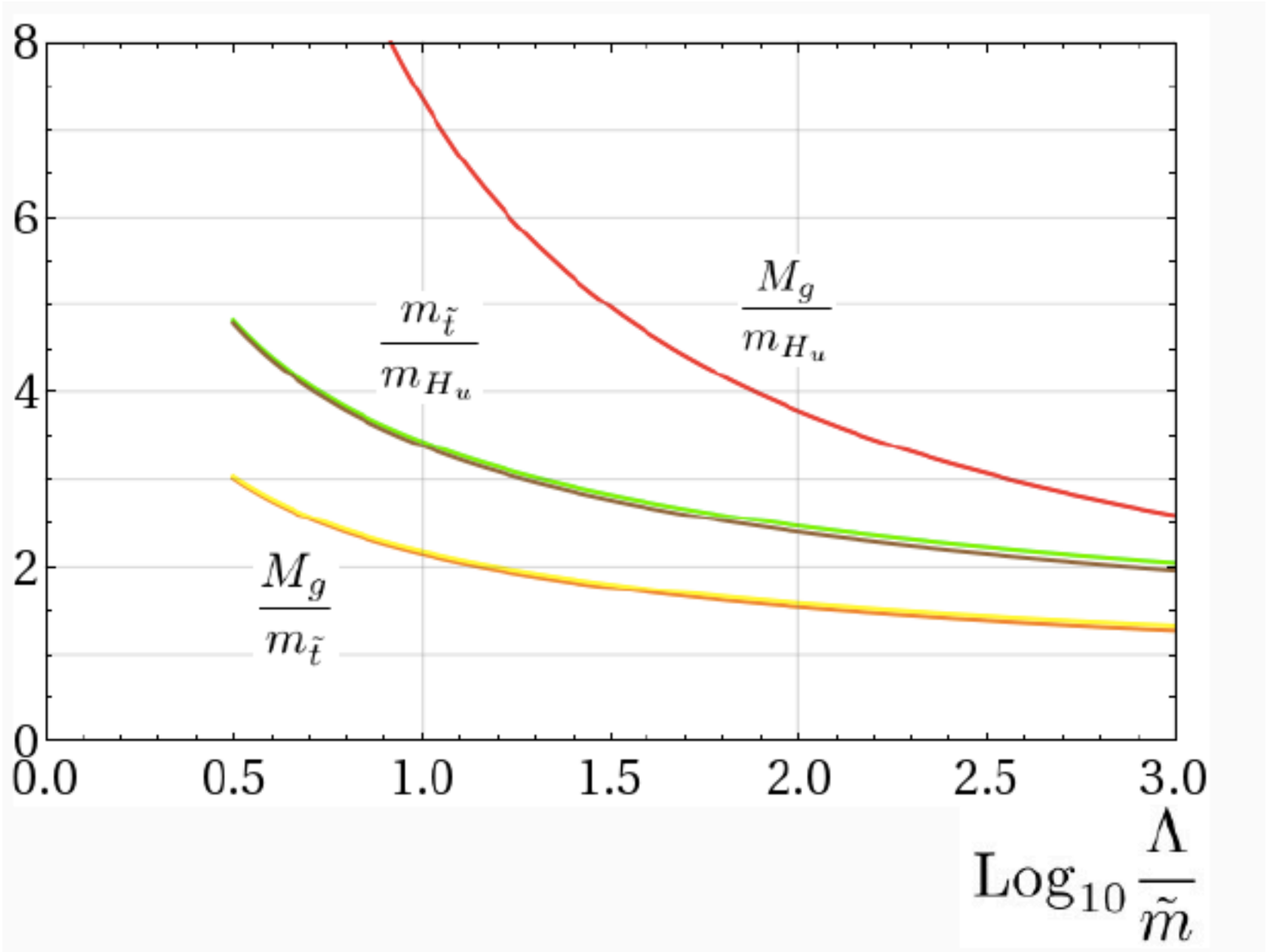


NMSSM
or any model that "fixes" the Higgs mass



- In the MSSM: Tuning dominated by the Higgs Mass
- In any model that fixes the Higgs mass: Tuning dominated by LHC bounds
- LHC pushes the bounds on Naturalness
- Natural SUSY and RPV: Gluino bounds above a TeV imply significant tuning (see talk by M. Baryakhtar)

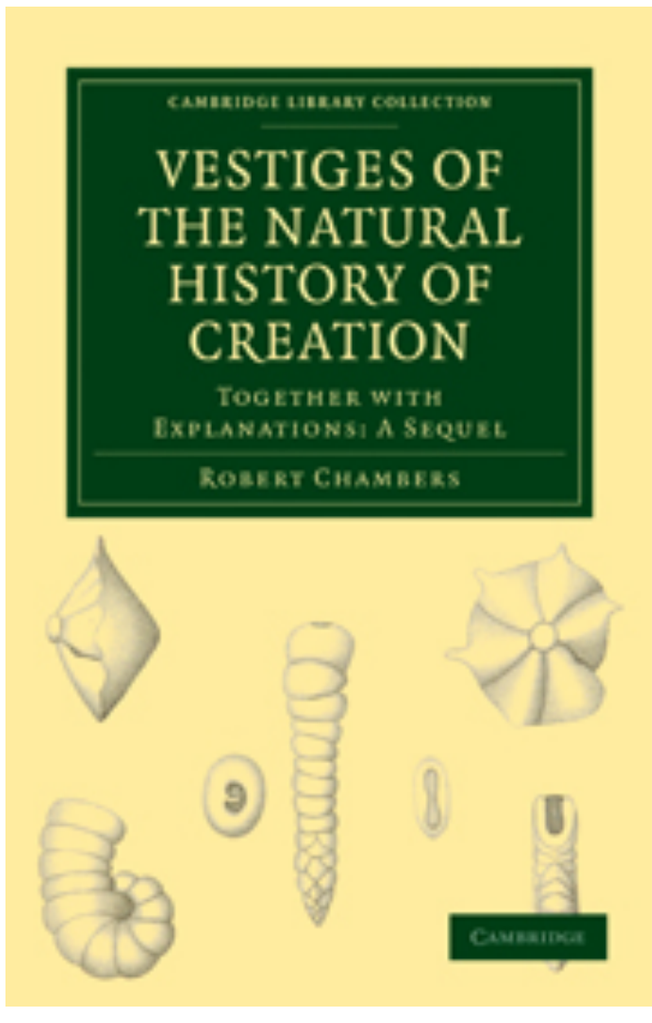
The Gluino Sucks



Gluino Bounds constrain all Low Energy Supersymmetry scenarios

Dirac gluino models also have problems

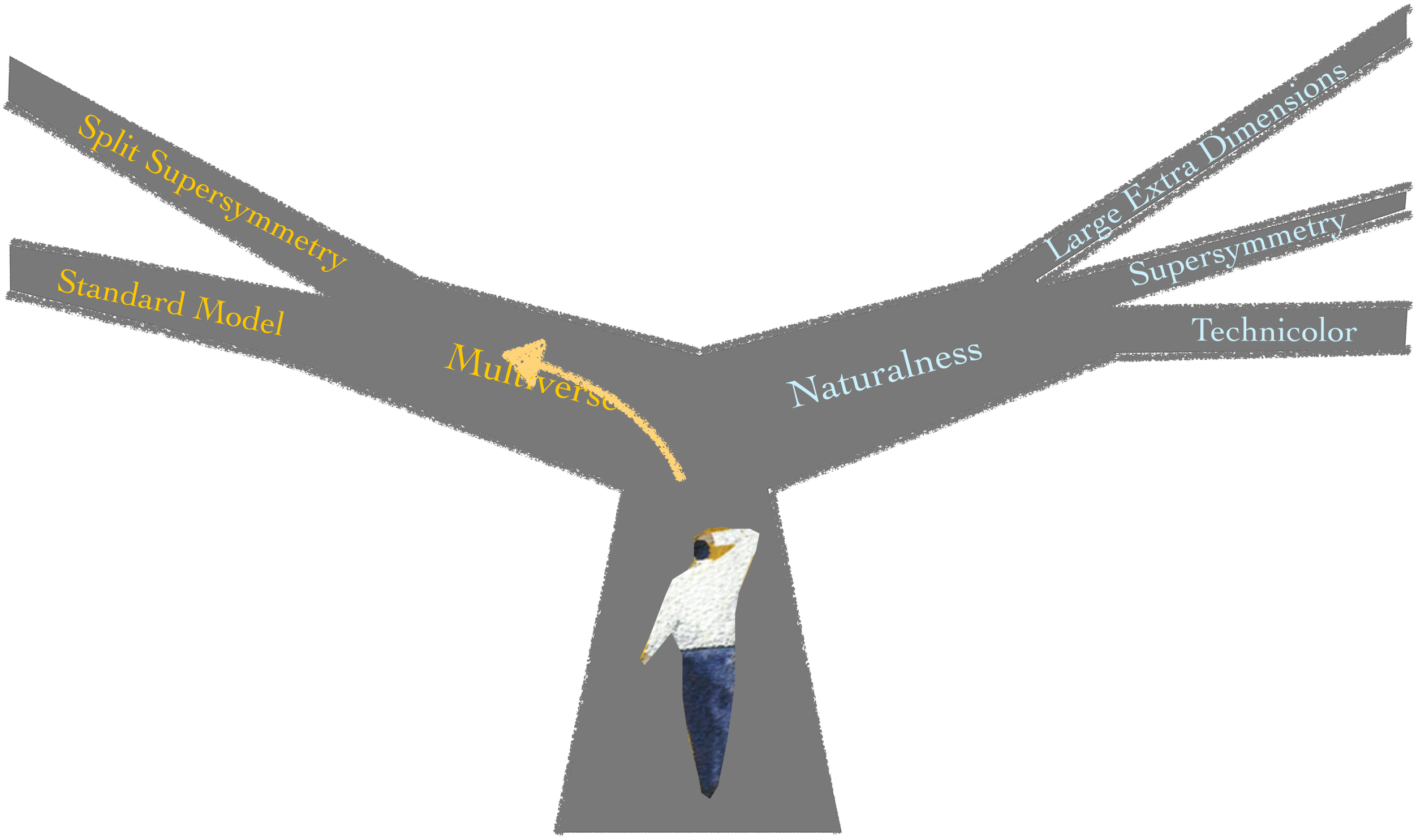
Last Vestiges of Naturalness?



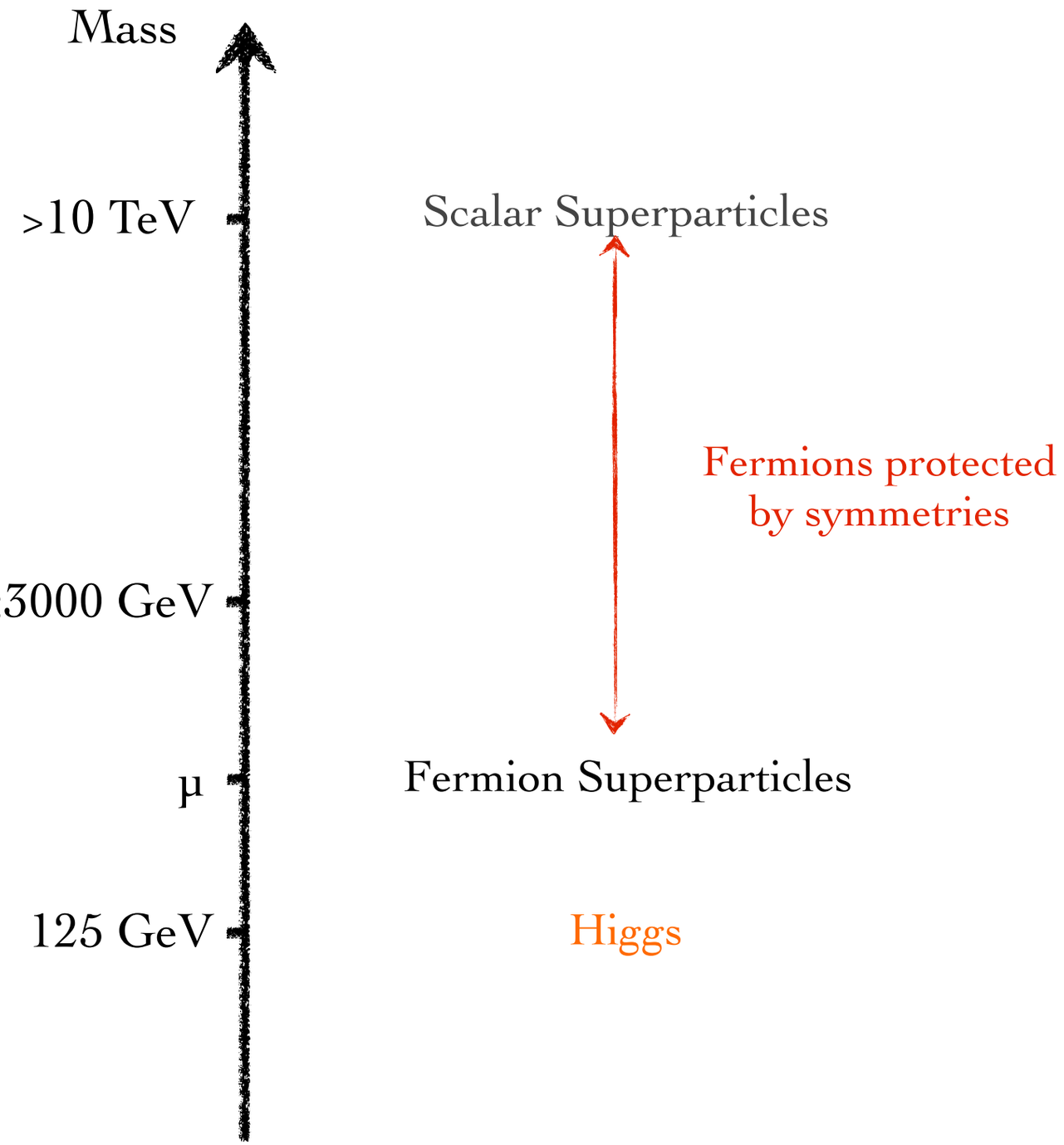
- Natural SUSY
- Hide and Seek models
- R-Parity breaking: B violation
- Dirac Gauginos

(see talks by M.Baryakhtar, P. Sarashwat)

At the Crossroads



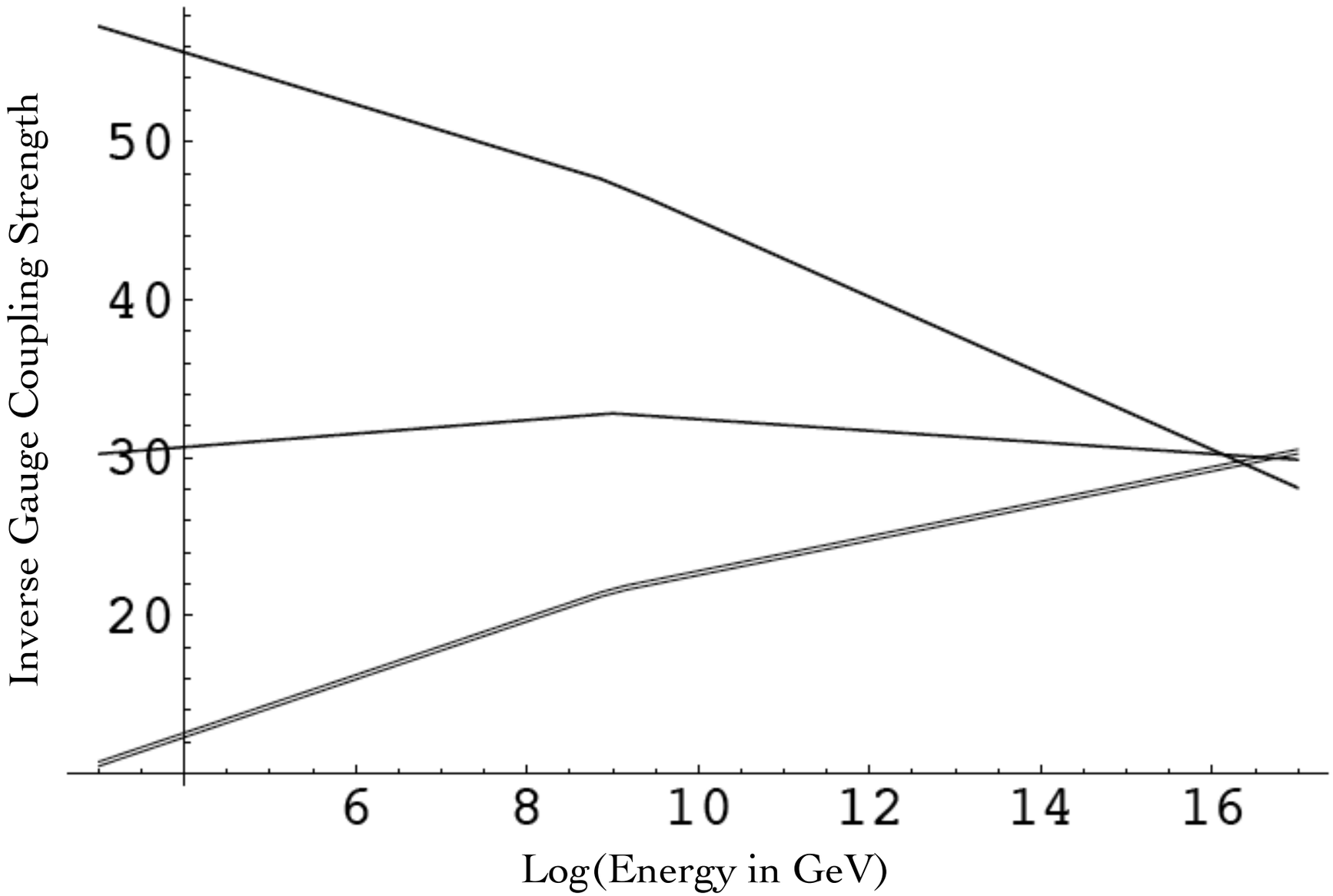
Split Supersymmetry



- Preserves successes of Dark Matter and gauge coupling unification

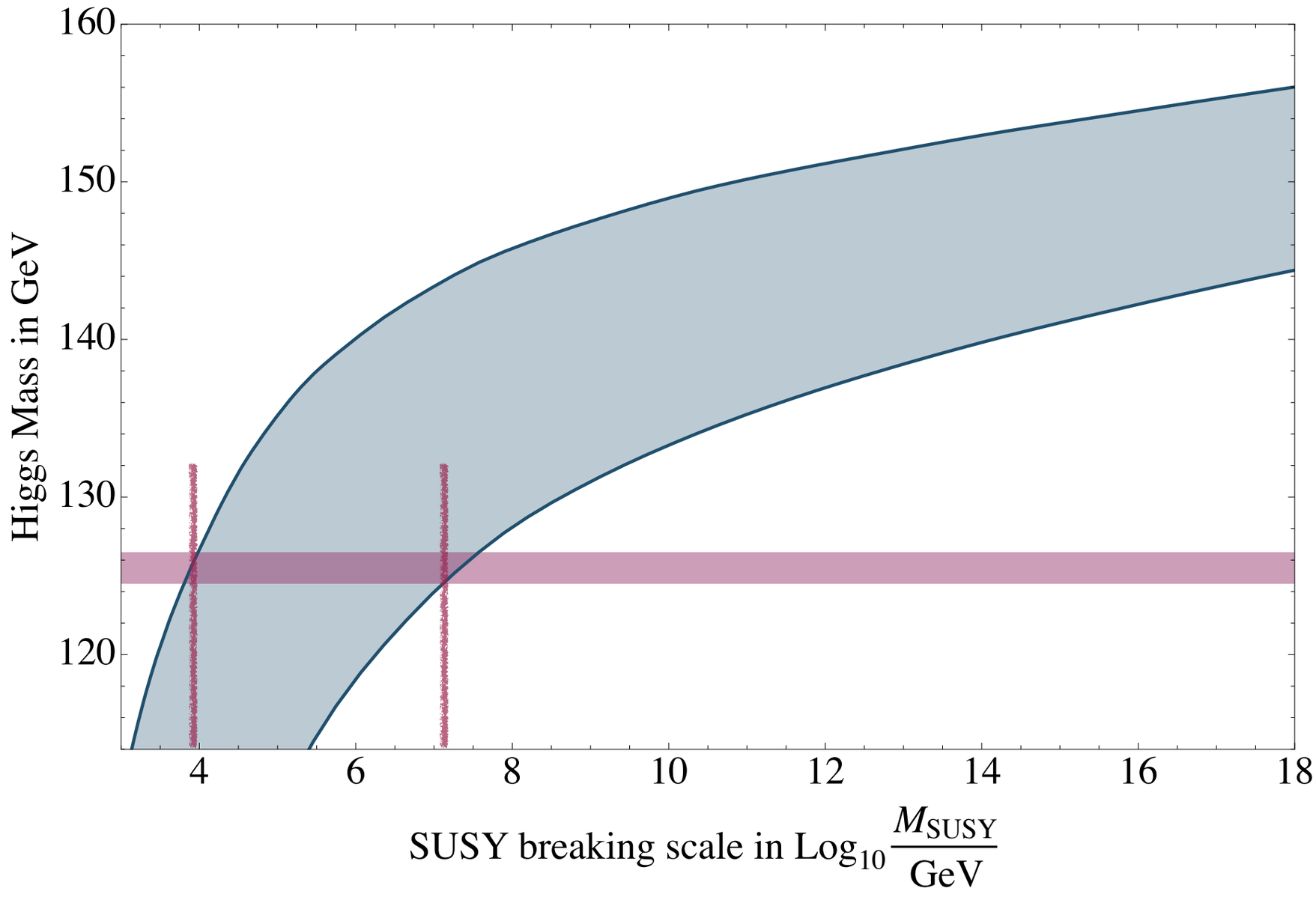
- Atomic Principle: One tuned light higgs

Unification in Split Supersymmetry



Works as well as ordinary Supersymmetry

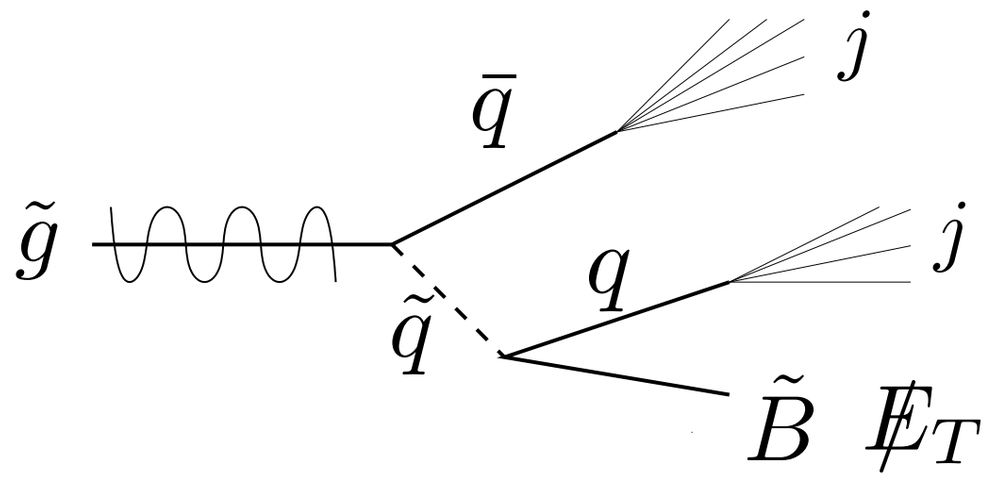
125 GeV Higgs in Split Supersymmetry



- Favors scalars between 10-10^4 TeV: Mini-Split
- One- or two-loop separation from the gauginos

Long-lived Gluinos

Gluino decay through the heavy scalars



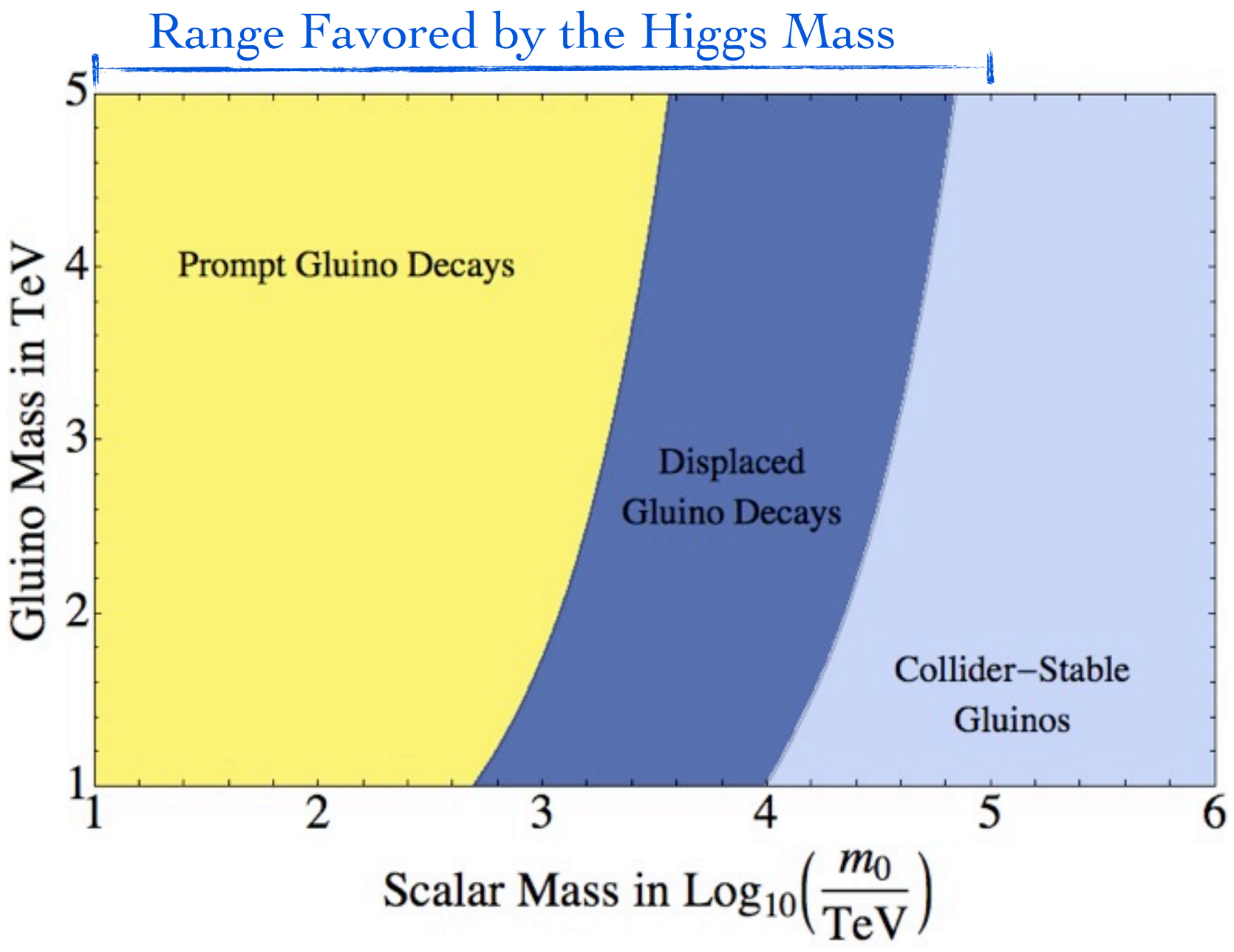
Signature:

2 jets and missing energy

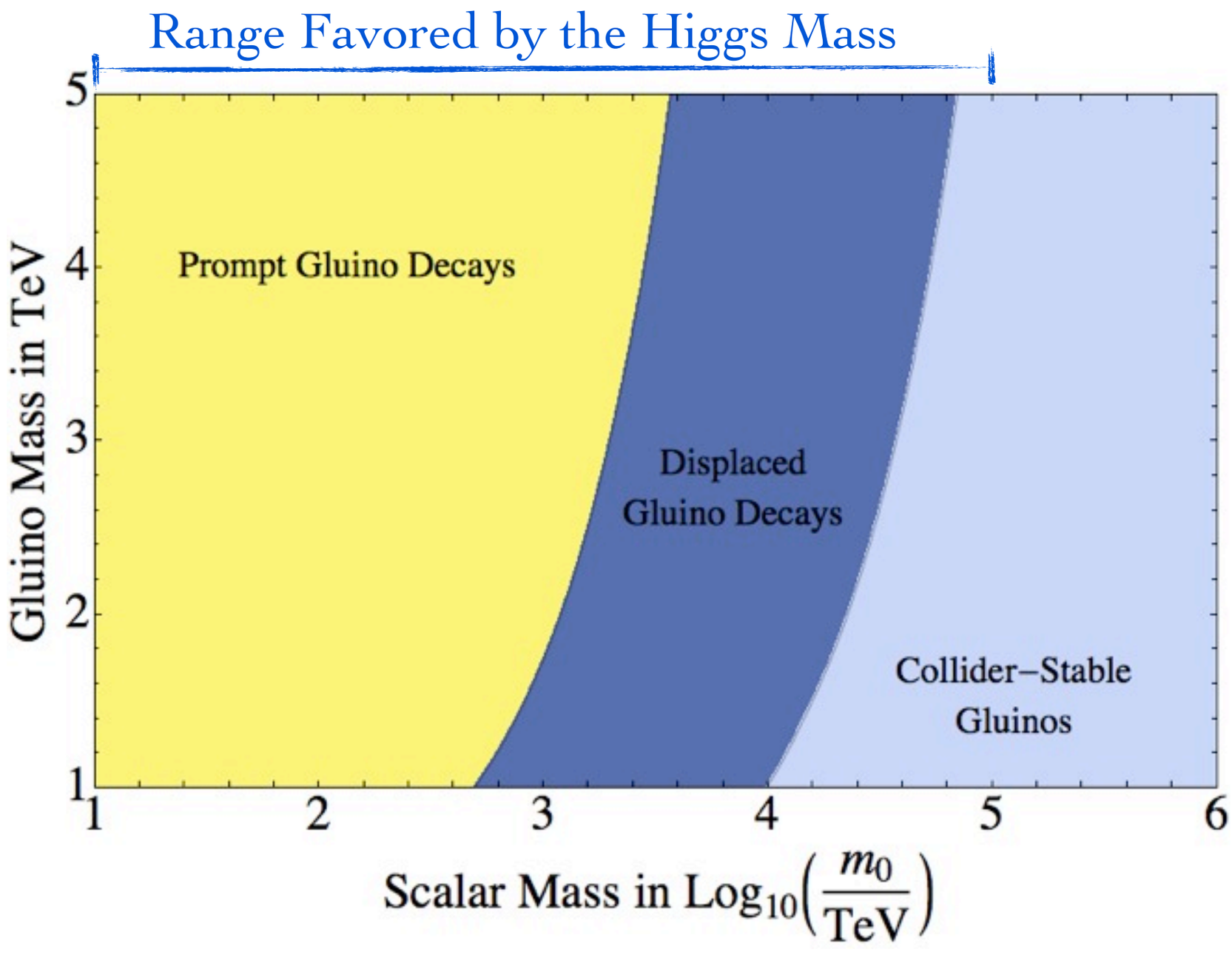
Lifetime:

$$c\tau_{\tilde{g}} \simeq 3 \times 10^{-2}\ \mathrm{m} \left(\frac{1\ \mathrm{TeV}}{m_{\tilde{g}}}\right)^5 \left(\frac{M_{\mathrm{Susy}}}{10^4\ \mathrm{TeV}}\right)^4$$

Long-lived Gluinos at the LHC



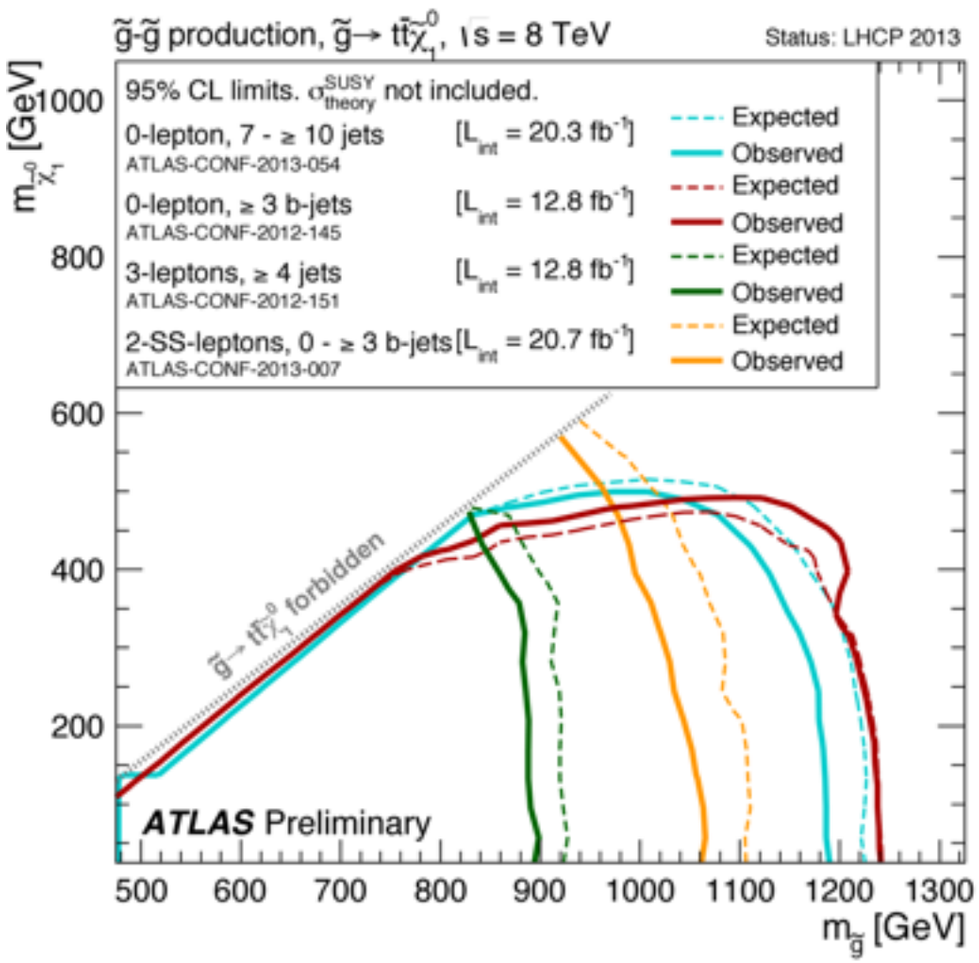
Long-lived Gluinos at the LHC



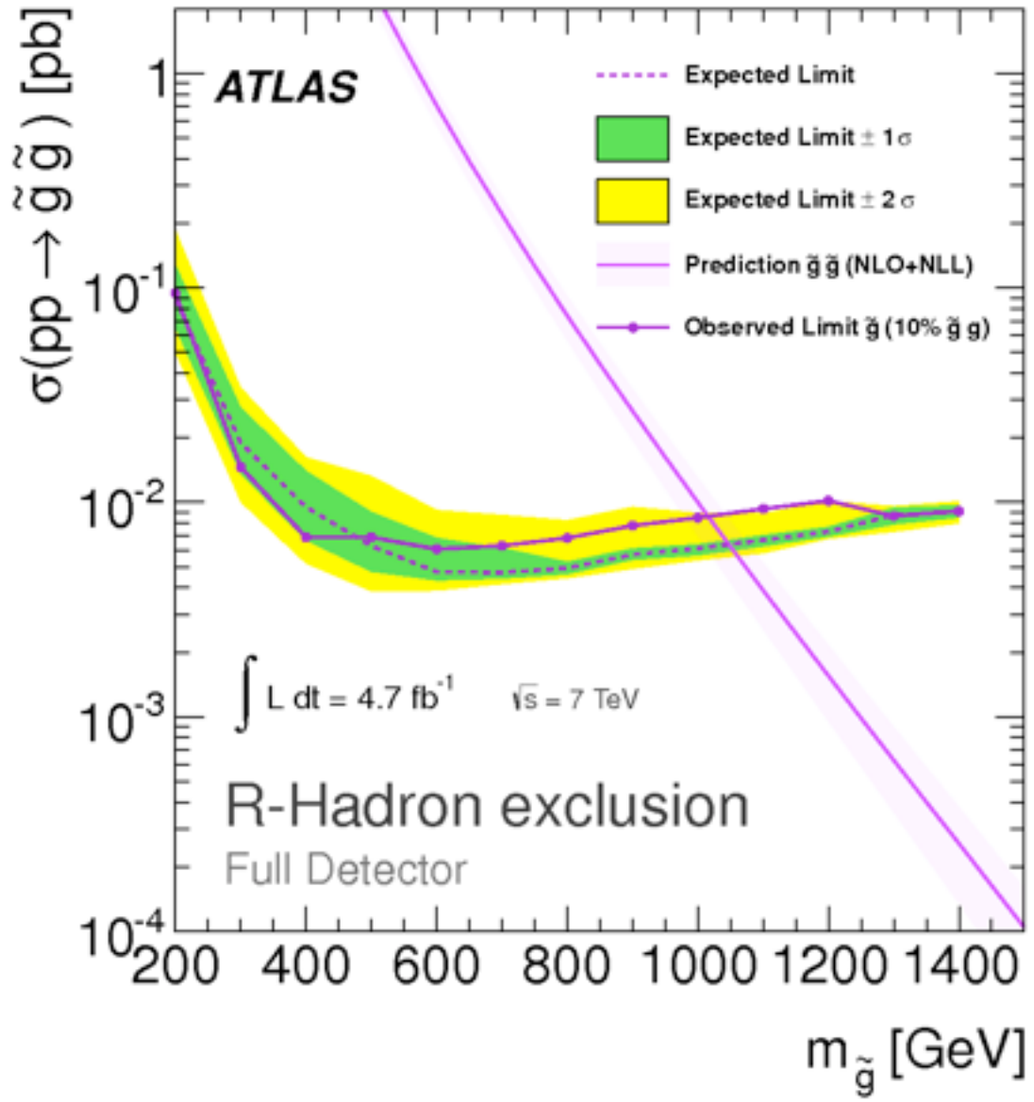
Stops as the lightest sparticle:

Tops and bottoms in the final state of the decay

Gluino Bounds from the LHC



For prompt or
slightly displaced gluinos



For collider "stable" gluinos

M_{gluino} > 1 TeV for split gluino

Small window for 10 cm - 1 m lifetimes?

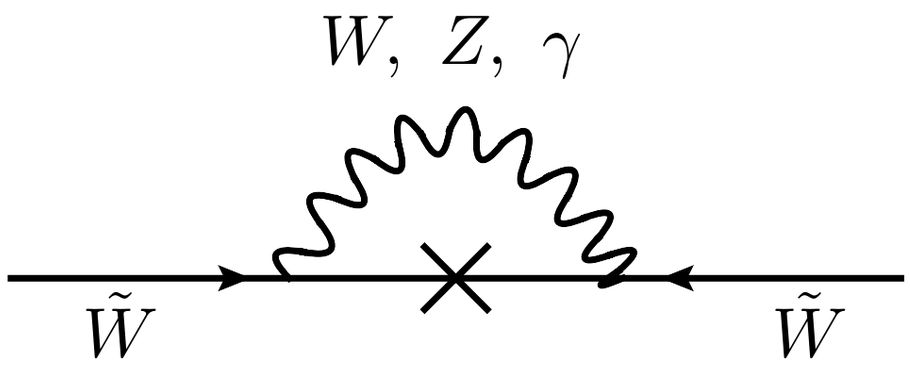
Split Signatures beyond the Gluino: Electroweakinos and Higgsinos

- Light Winos
  - Displaced Winos at the LHC

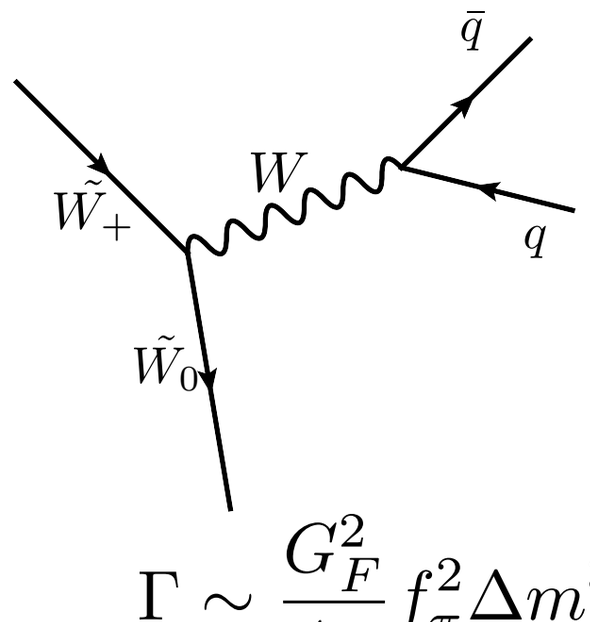
- Light Higgsinos
  - Displaced Higgsinos at the LHC

- Both Winos and Higgsinos light
  - Electroweakino and Higgsino Yukawa Coupling Unification

Wino LSP with Heavy Higgsinos



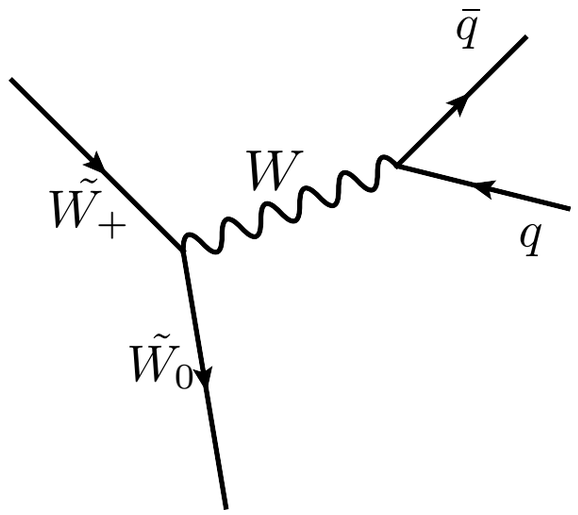
$$\Delta m \sim \frac{\alpha}{4\pi} M_Z \approx 155 - 175 \text{ MeV}$$



$$\Gamma \sim \frac{G_F^2}{4\pi} f_\pi^2 \Delta m^3$$

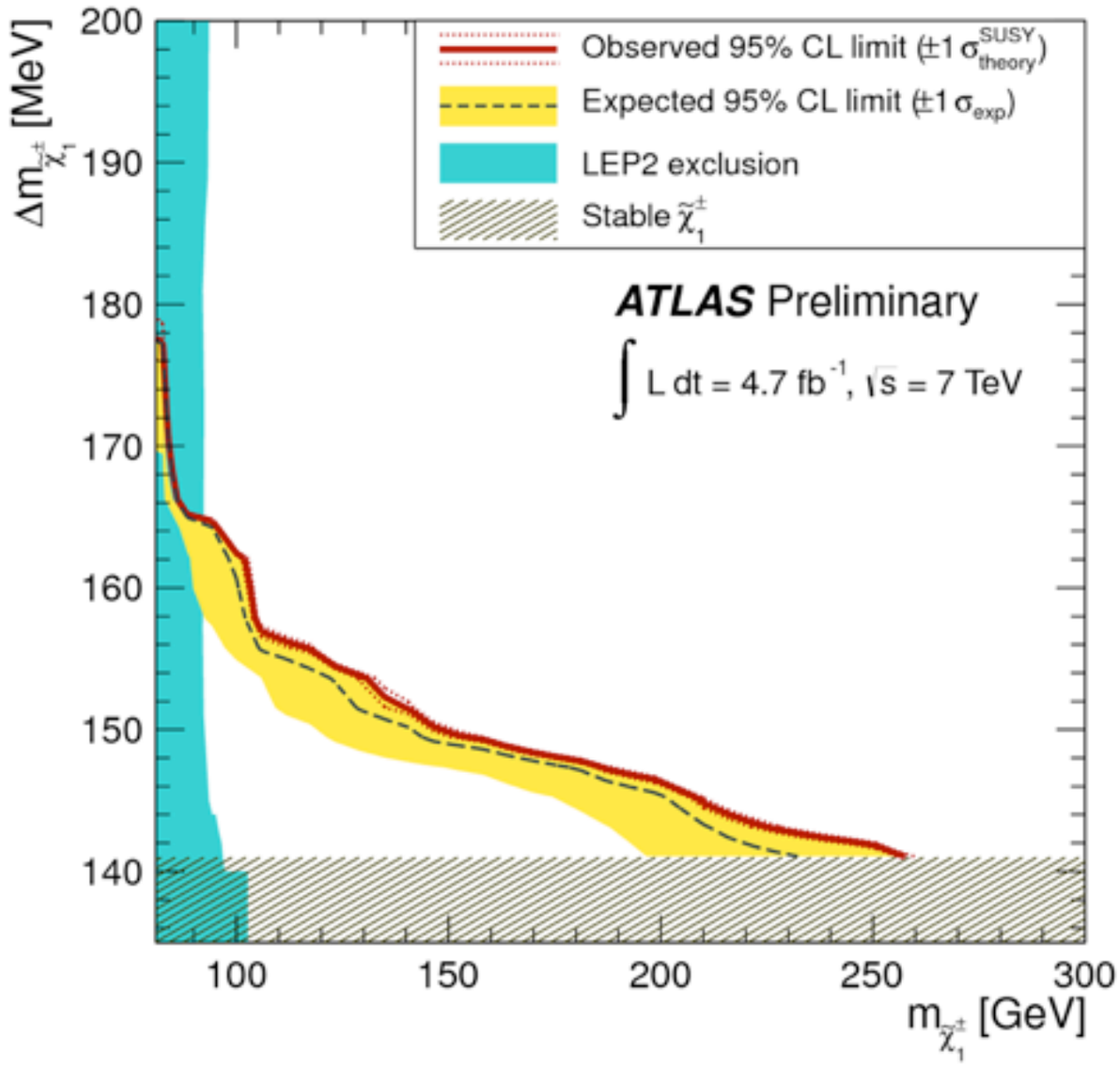
- Charged wino heavier than Neutral Wino
- cm size tracks with soft pions

Wino LSP with Heavy Higgsinos



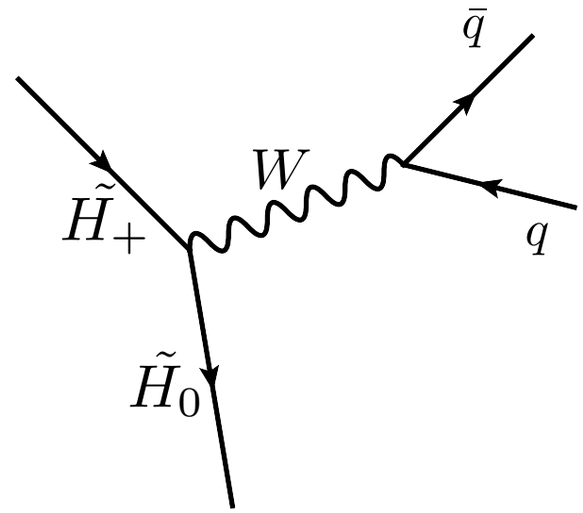
$\Delta m \approx 155 - 175$ MeV

- ISR mono-jets
- Charged track length of order cm



Higgsino LSP:
The Minimal Model for Unification

- Only light Higgsinos in the Spectrum



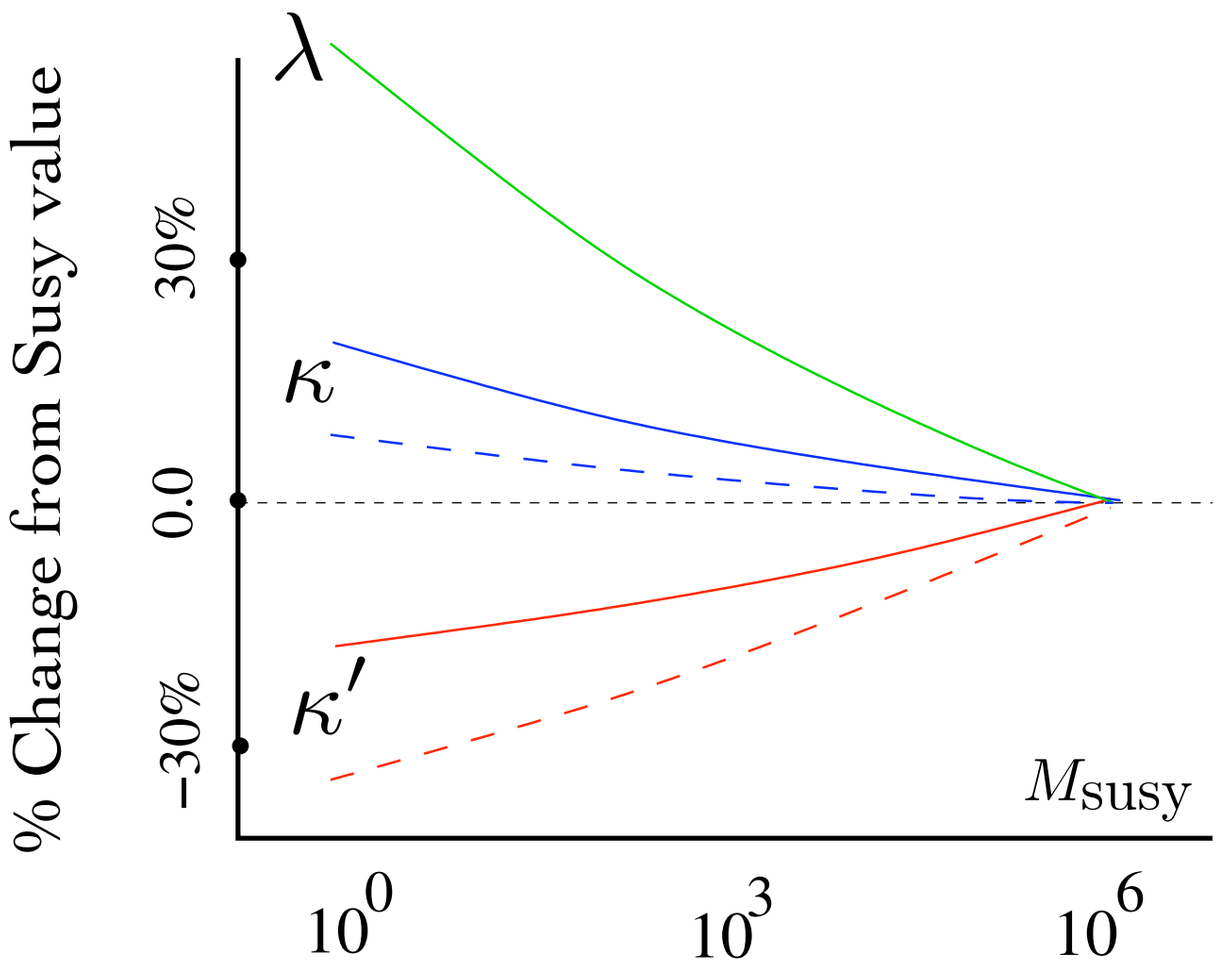
- Mass splitting ~355 MeV

- Soft pions with sub-cm charged tracks

- No LHC bounds
  - No working search strategy yet

Electroweakinos and Higgsinos at the LHC

Gaugino and Higgsino Yukawa Coupling Unification

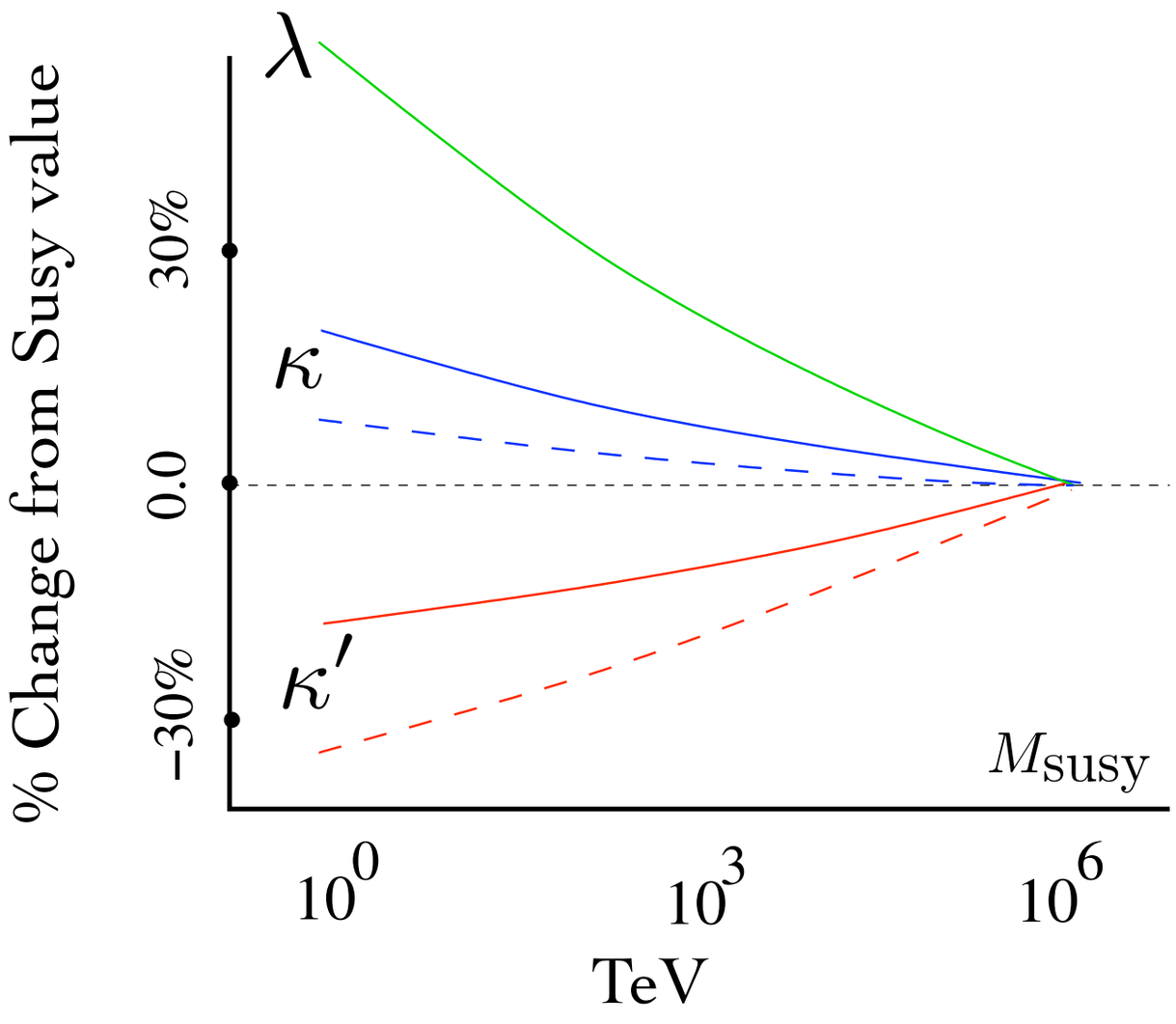


$\kappa_u H \widetilde{H}_u \widetilde{W} + \kappa_d H^\dagger \widetilde{H}_d \widetilde{W}$ $\quad$ $\kappa'_u H \widetilde{H}_u \widetilde{B} + \kappa'_d H^\dagger \widetilde{H}_d \widetilde{B}$

λ: Higgs Quartic

Electroweakinos and Higgsinos at the LHC

Gaugino and Higgsino Yukawa Coupling Unification



Combined with gluino lifetime measurement establishes supersymmetric origin of new particles

Mini-Split Phenomenology

- Displaced Gluinos at the LHC

- Displaced Winos and Higgsinos at the LHC

- Yukawa Coupling Unification

Model Ranking

Model	Grade
MSSM	D–
NMSSM	D
Natural SUSY	C
R-parity breaking	B
Colorless Top Partners	B
Split SUSY	A

Is there a third road?

Physical Naturalness

Bardeen, Foot, Shaposhnikov, Strumia, Dubovsky

- Quadratic contributions to the Higgs mass only from heavy particles

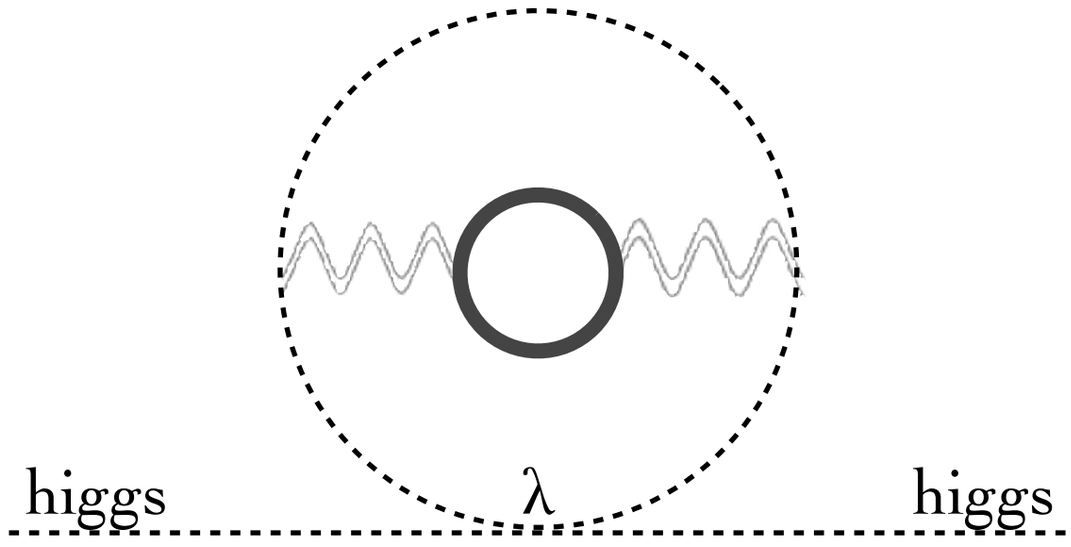
- Gravity can be UV completed with no new particles and does not affect the Higgs mass

Consequences of Physical Naturalness

- All BSM states carrying SM gauge quantum number still below a few TeV -- no high scale GUT (non-SUSY)

- Yukawa coupled particles can be heavier, ex. $M_{\nu R} < 10^7$ GeV

- Gravitationally coupled particles less than 10^{12} GeV



Challenges

- Do all physics with these constraints:

  Charge quantization, SO_{10} families, Dark Matter, Neutrino masses, Baryogenesis, Inflation, Flavor, $\sin^2\theta_w$...

AND

- Avoid ALL Landau Poles

Experimental Signatures

- Many states at or close to the TeV scale

- Unique signatures: eg: SM + TeV scalars

- No need for new states to be colored

Model Building Physical Naturalness

w/ Arvanitaki, Dubovsky, Strumia, Villadoro

- Need to expand gauge group at the TeV (SU(4)xSU(2)xSU(2), $SU(3)^3$ ...)

- Add states to avoid Higgs quartic Landau pole

- And do all the rest of physics...

Model Building Physical Naturalness

w/ Arvanitaki, Dubovsky, Strumia, Villadoro

- Need to expand gauge group at the TeV (SU(4)xSU(2)xSU(2), $SU(3)^3$ ...)

- Add states to avoid Higgs quartic Landau pole

- And do all the rest of physics...

Obliterated by the usual suspect: FCNC

Since Naturalness seems violated, Why expect something at LHC-14?

Why is tuning of 1 per 1000 acceptable but 1 per 10000 unacceptable?

Since Naturalness seems violated, Why expect something at LHC-14?

Why is tuning of 1 per 1000 acceptable but 1 per 10000 unacceptable?

The Bruce Lee Principle:

Since Naturalness seems violated, Why expect something at LHC-14?

Why is tuning of 1 per 1000 acceptable but 1 per 10000 unacceptable?

The Bruce Lee Principle: