Small Numbers and Large Machines

Savas Dimopoulos
Stanford University

The Origin of Small Numbers

Small Numbers and Coincidences

Naturalness - Dynamics

Problem	Solution
Hydrogen Binding Energy	$E_b = \frac{1}{2}\frac{e^4}{(4\pi)^2} m_e$
Deuteron Binding Energy	$E_b \approx \frac{1}{2}\frac{1}{(4\pi)^2}\frac{m_N}{2}$
Nuclear Binding Energy	
π^+ - π^o mass difference	Symmetry/Dynamics
$K - \bar{K}$ mixing	Flavor Symmetry
QCD scale	Dimensional Transmutation
Electron Mass	Chiral Symmetry

Small Numbers and Coincidences

Something else…

Problem	Solution
Earth-Sun Distance	Environmental Selection 10^{22} suns
Cosmological Constant	Environmental Selection? 10^{500} universes!
7 eV line of ^{229}Th nucleus	“Look-elsewhere” effect
Solar Eclipse	Plain Luck!

Small Numbers and Coincidences

What about the Electroweak Scale?

The hierarchy Problem

Split Supersymmetry

Standard Model

Multiverse

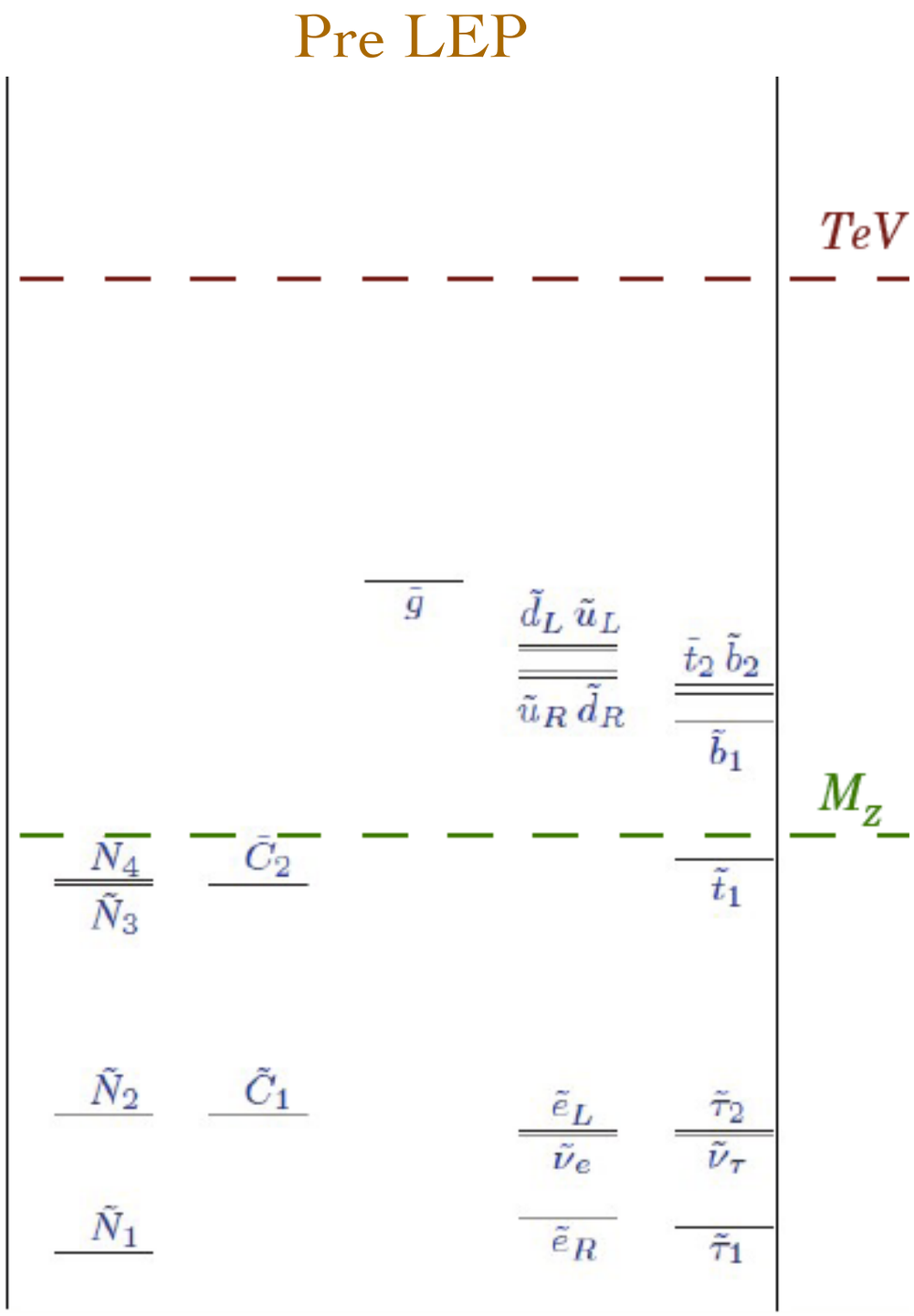
Naturalness

Large Extra Dimensions

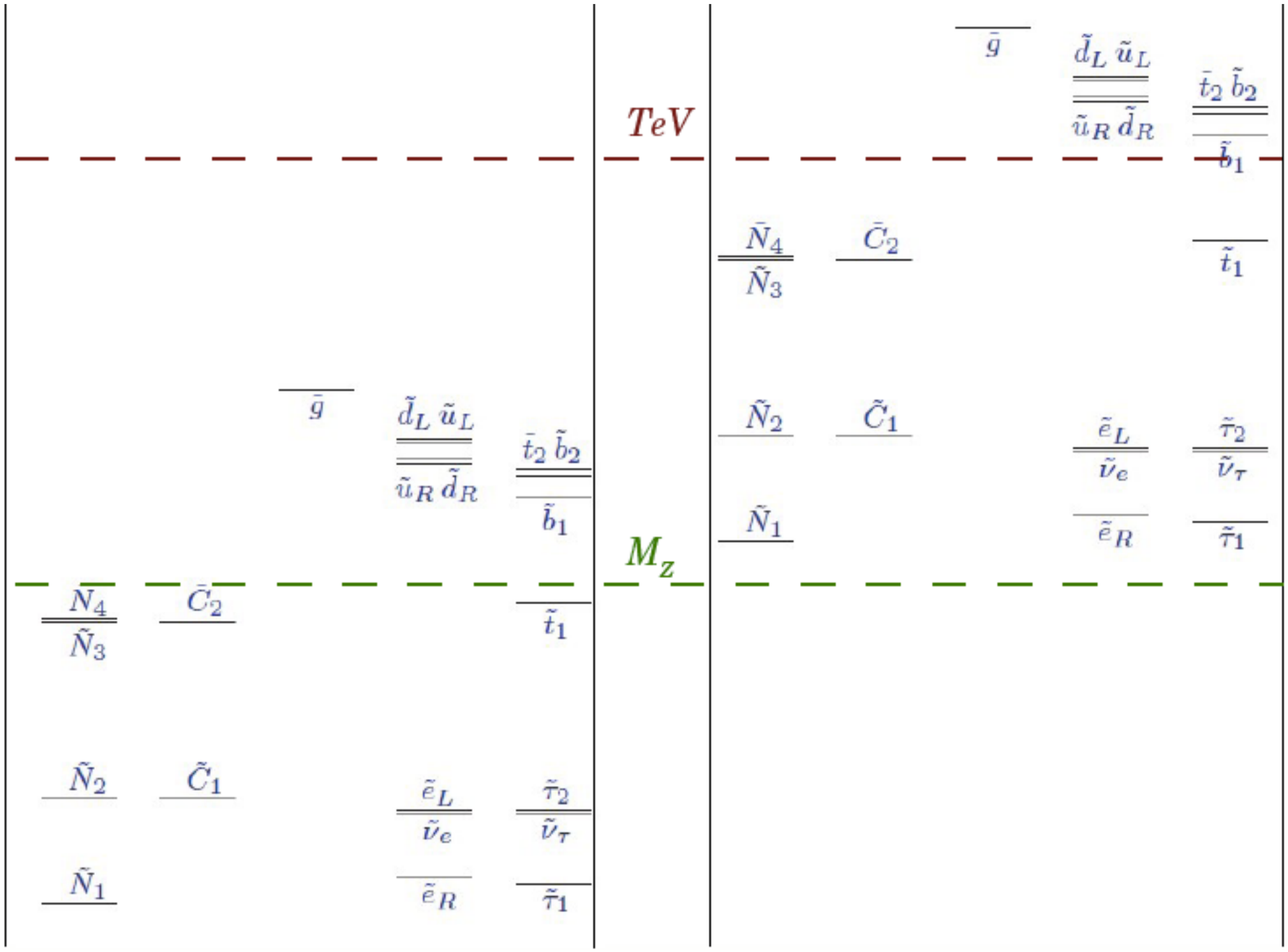
Supersymmetry

Technicolor

The Hard Facts

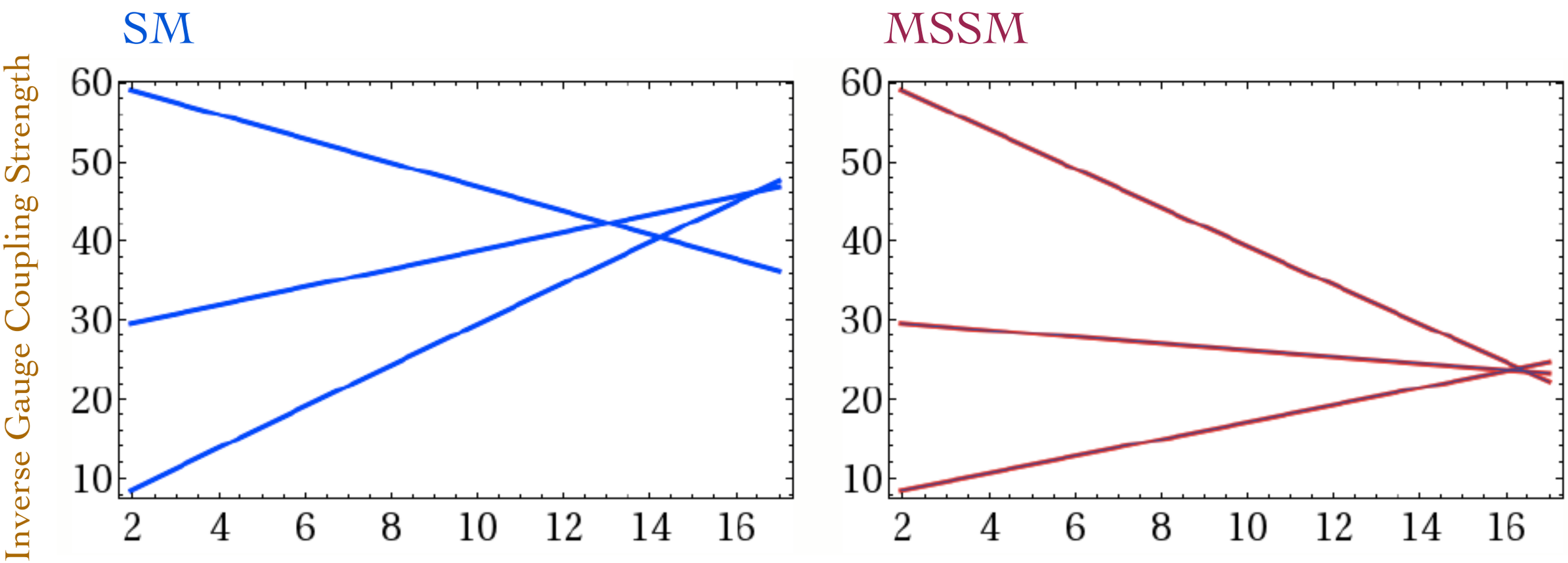


The Hard Facts



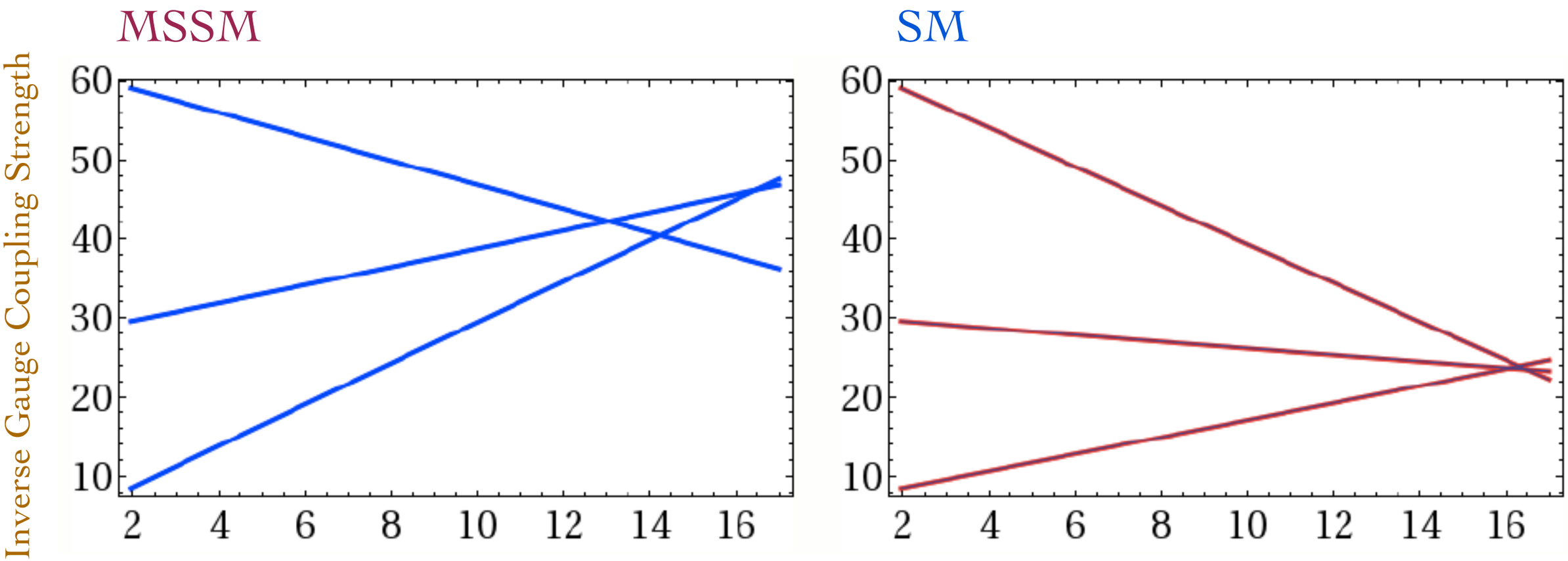
The connection with the hierarchy problem is diminished

Why Supersymmetry?



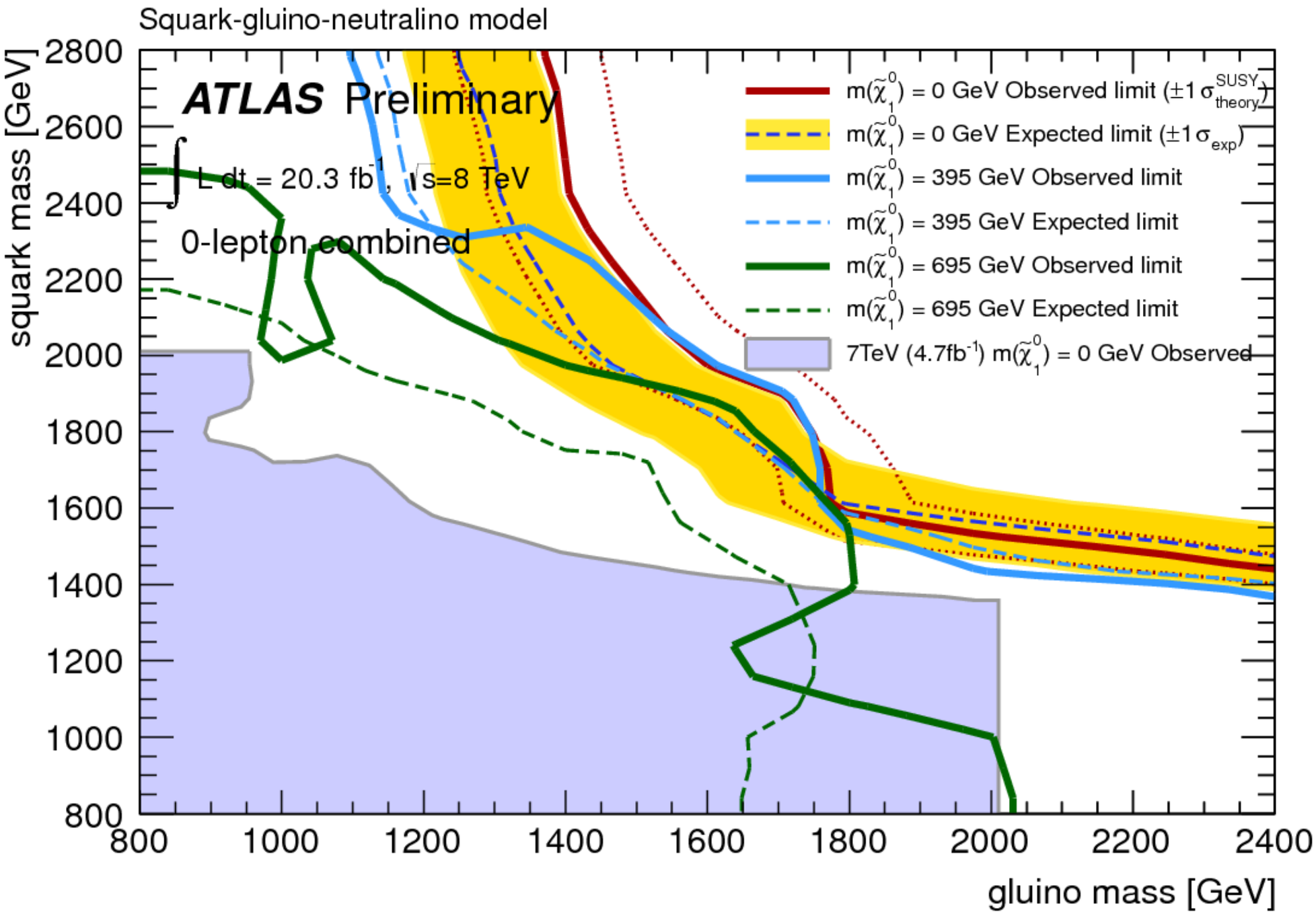
Gauge Coupling running at two loops

Why Supersymmetry?

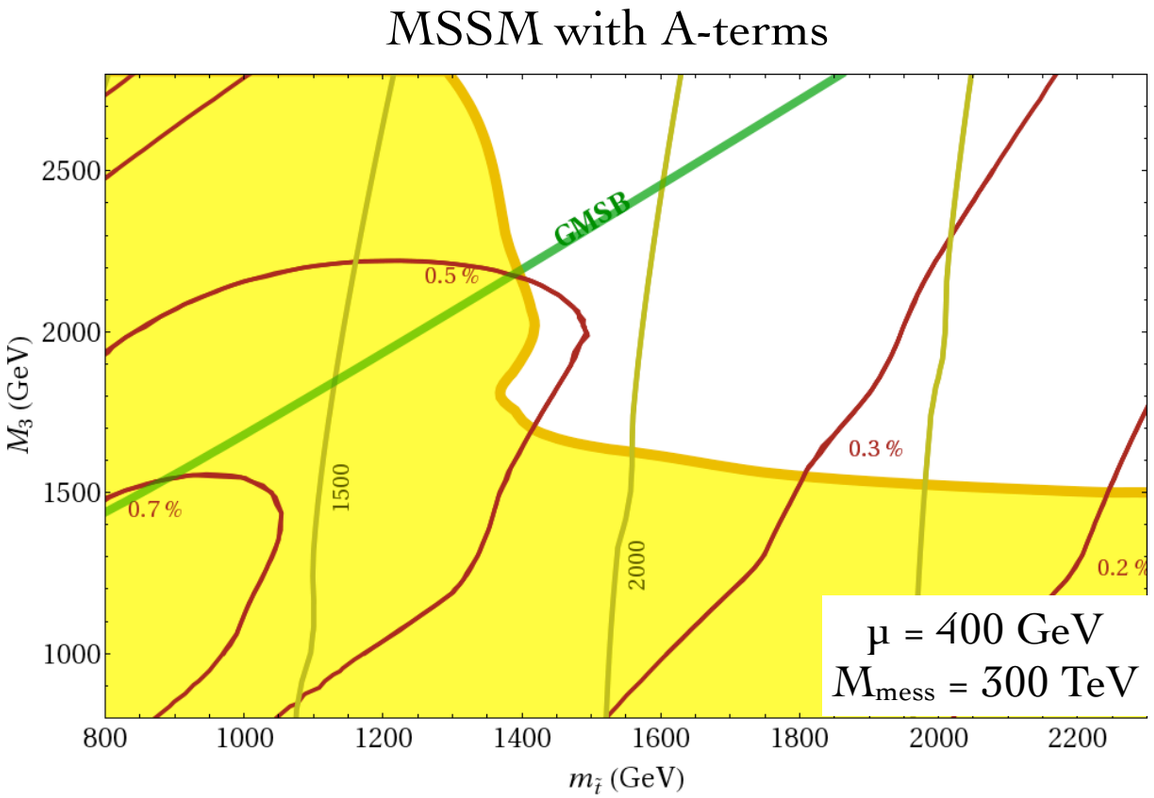


Gauge Coupling running at two loops

The Missing Superpartner Problem



The Status of Naturalness in SUSY

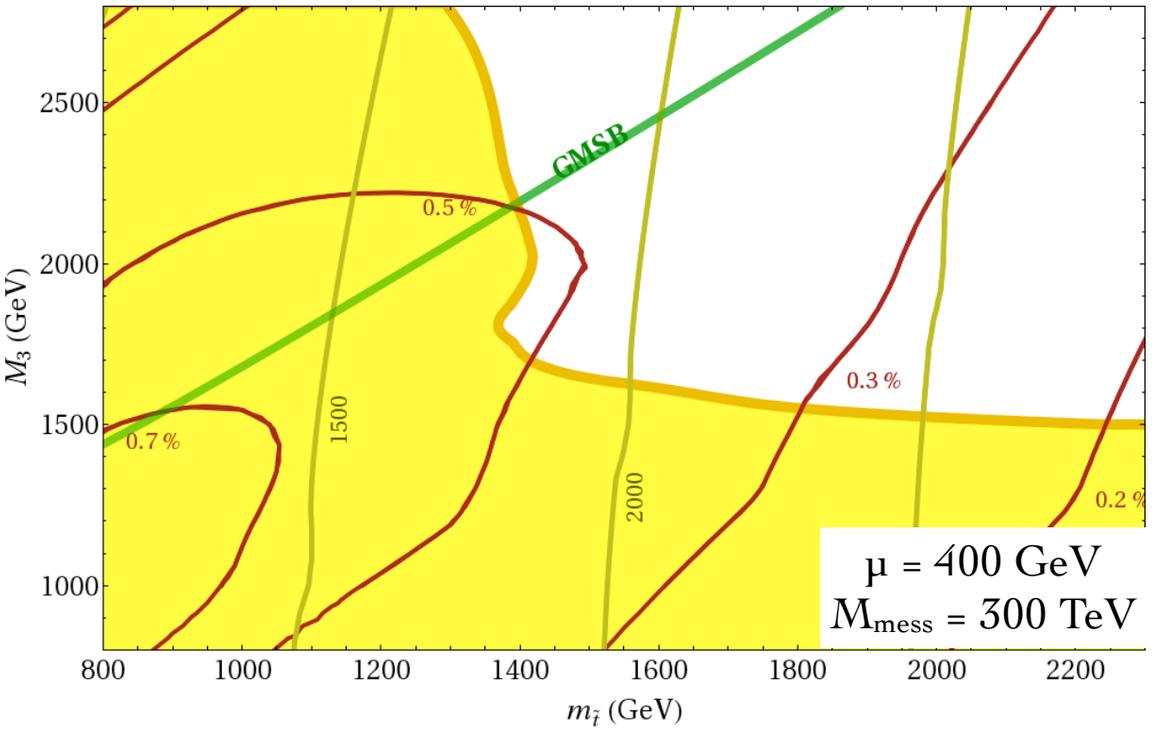


Arvanitaki et. al. (2013)

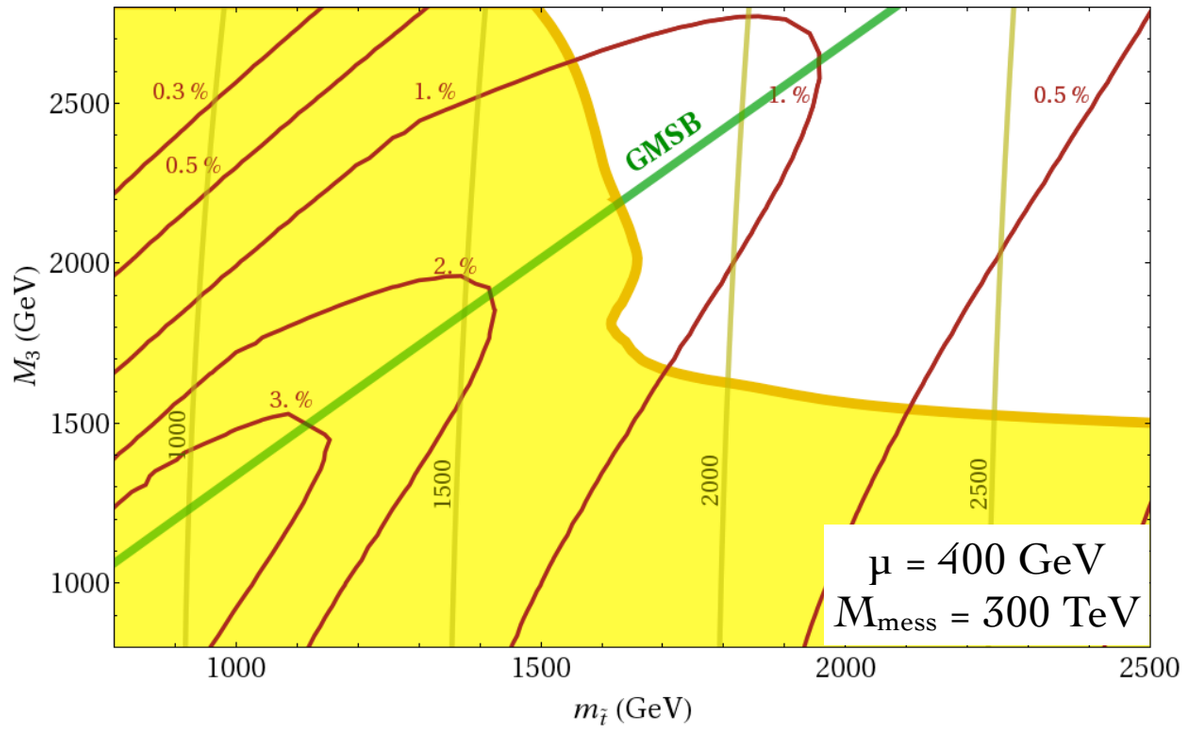
- In the MSSM: Tuning dominated by the Higgs Mass

The Status of Naturalness in SUSY

MSSM with A-terms



NMSSM
or any model that "fixes" the Higgs mass



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- In the MSSM: Tuning dominated by the Higgs Mass
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The Status of Naturalness in SUSY

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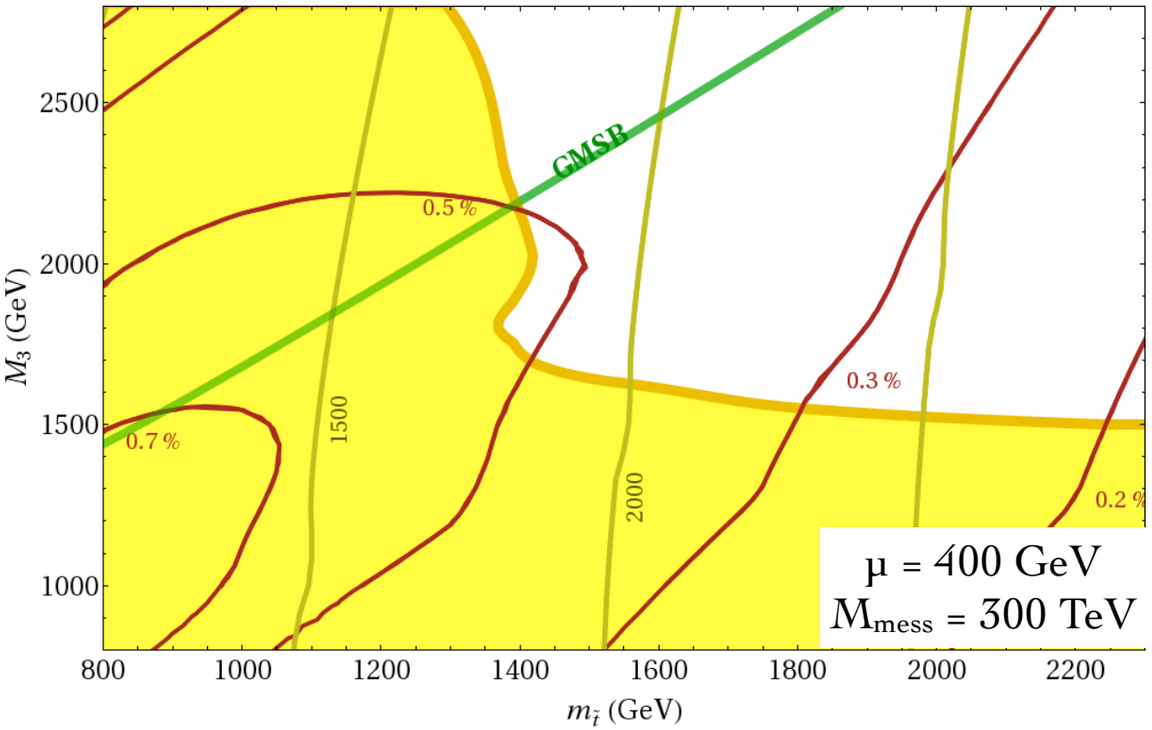

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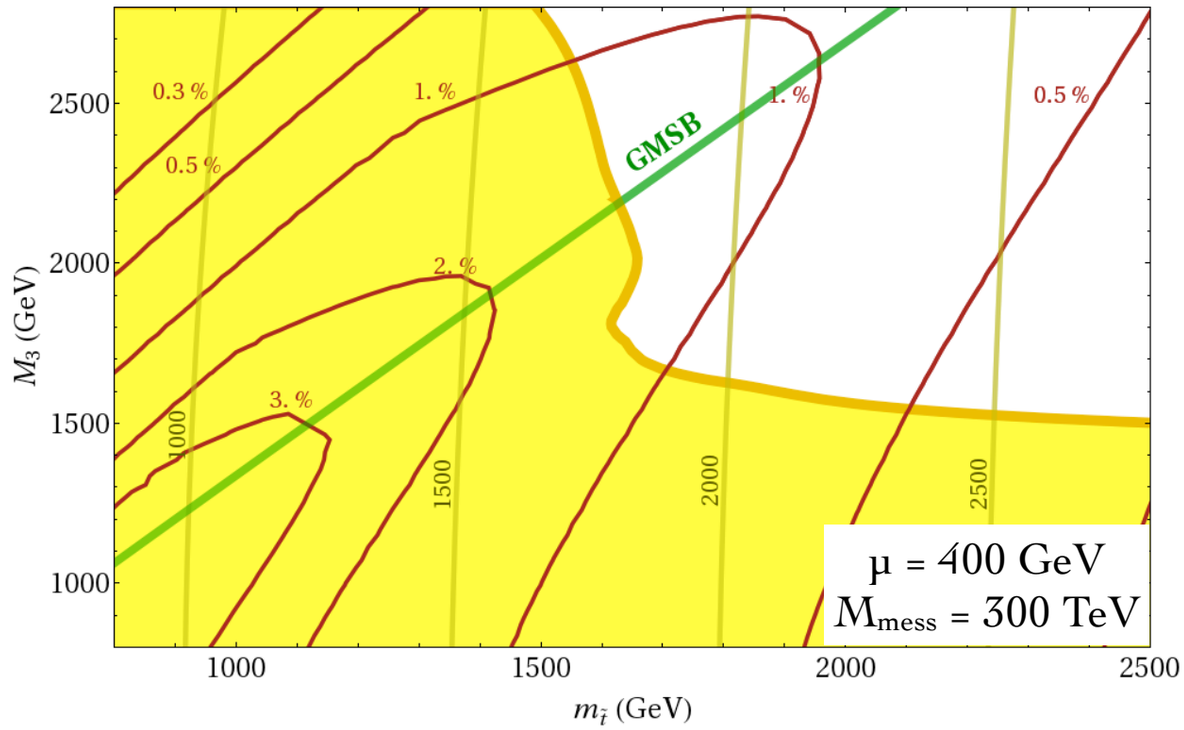
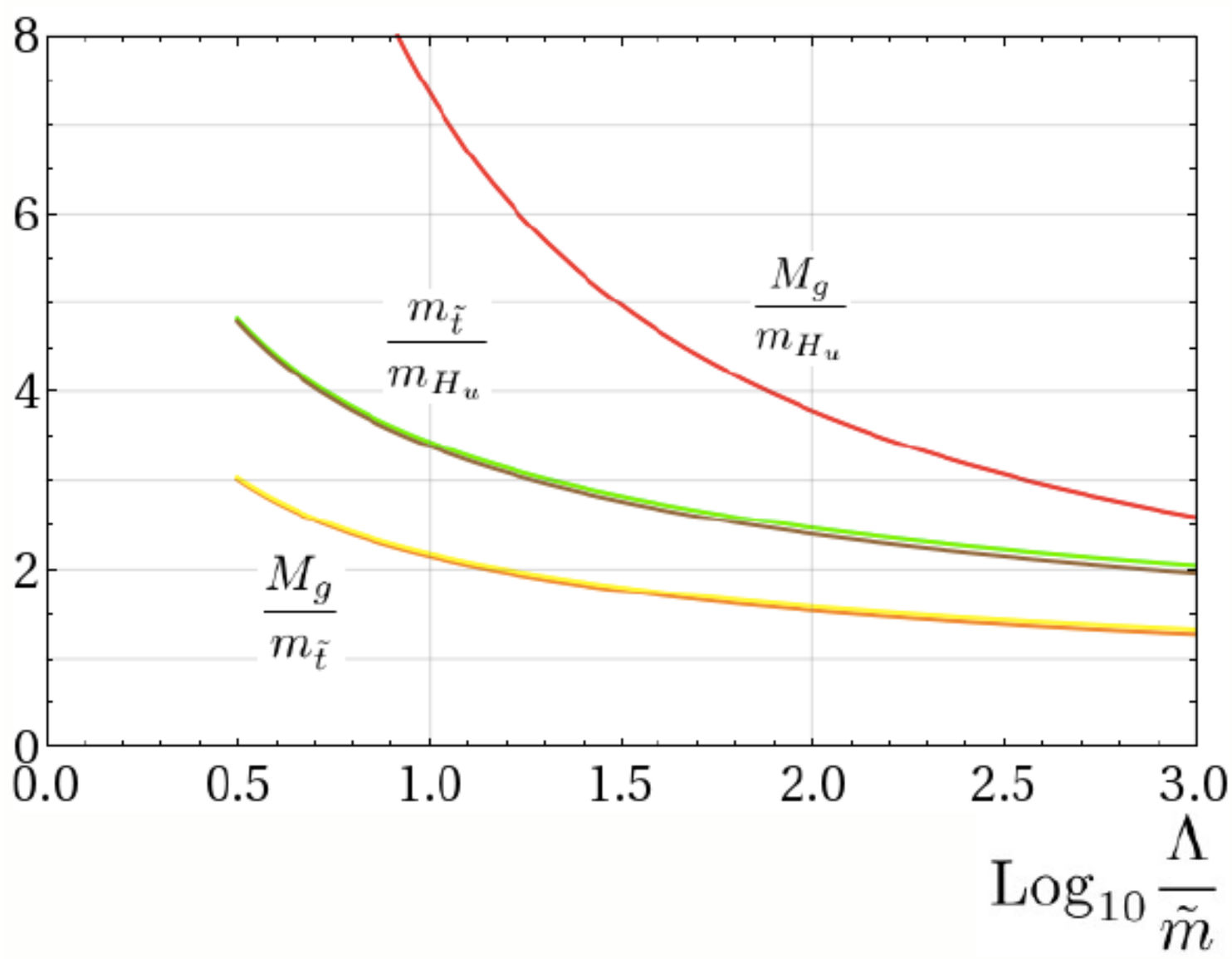


Arvanitaki et. al. (2013)

- 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

The Gluino Sucks

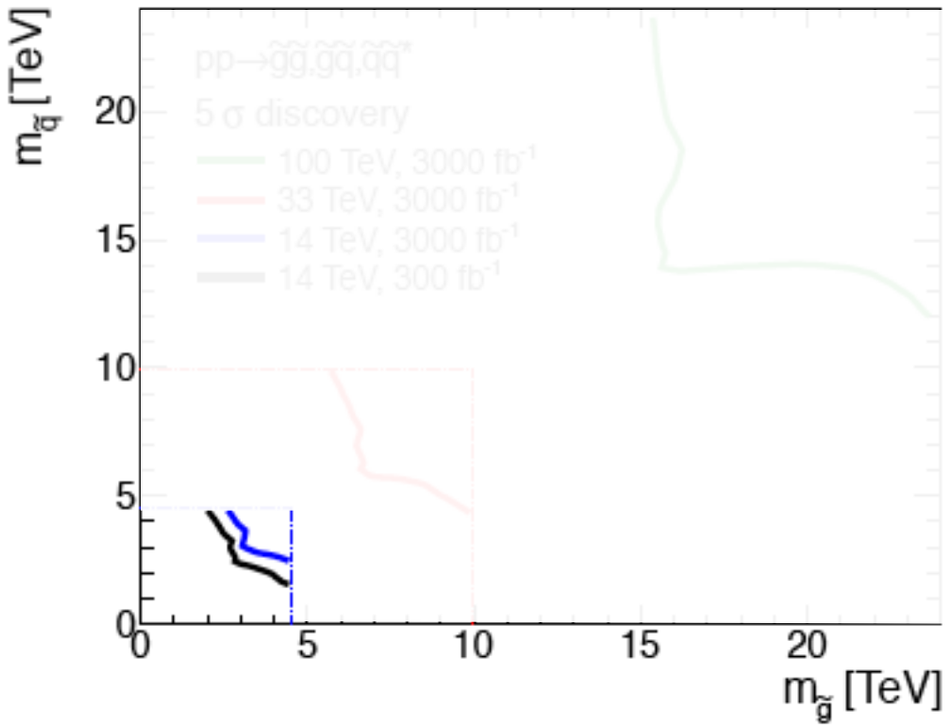


Gluino Bounds constrain all Low Energy Supersymmetry scenarios

Reach of 100 TeV

Squark-Gluino Reach

Discovery



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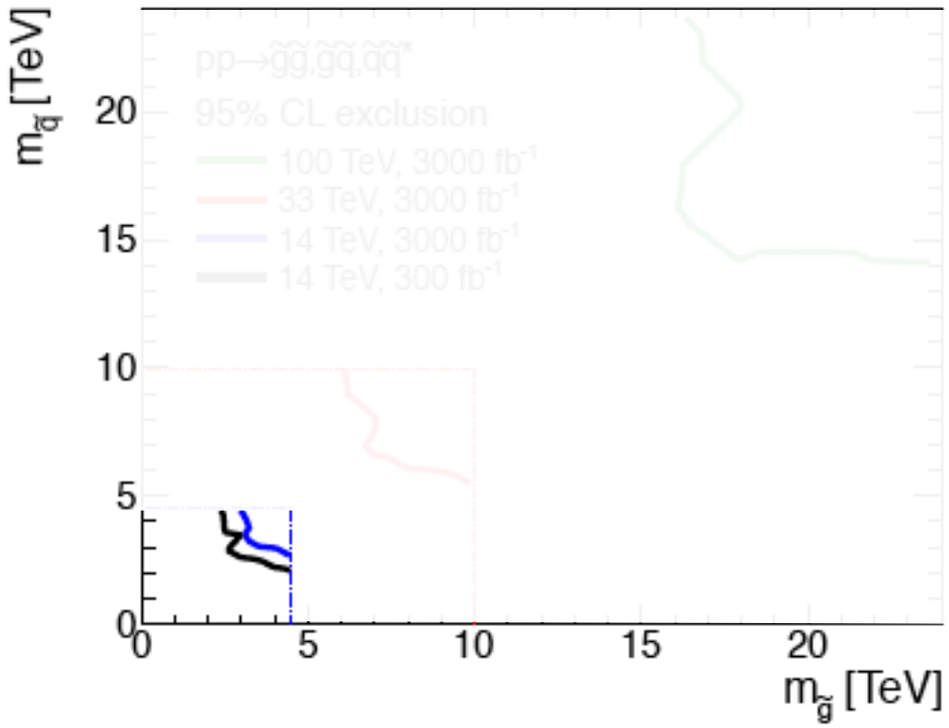

Cohen et. al. (2013)

LHC 14: Probing theories worse than 1% tuned

Reach of 100 TeV

Squark-Gluino Reach

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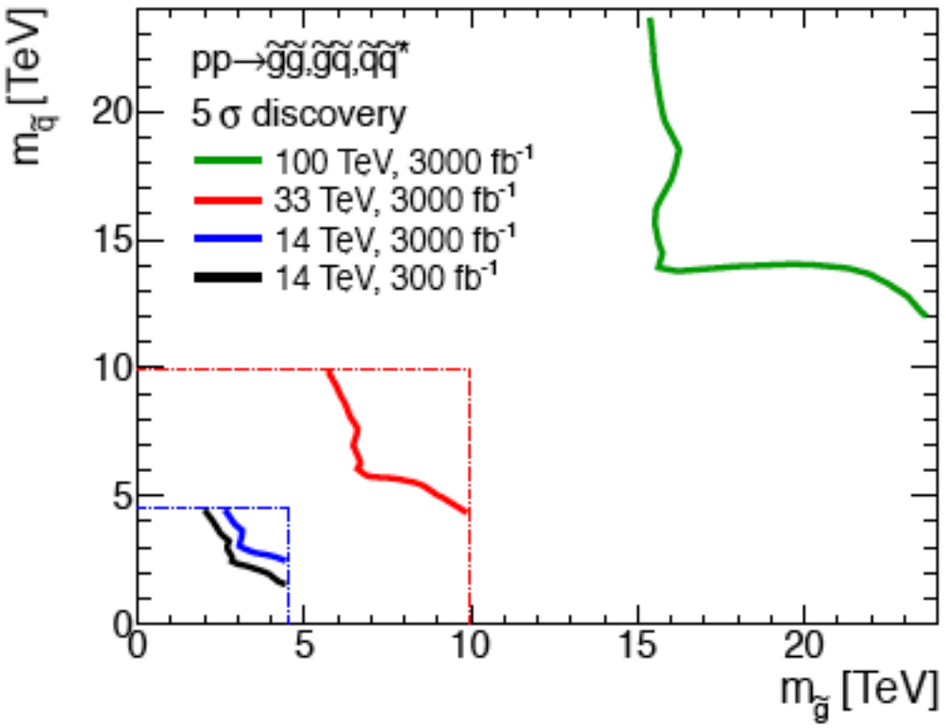

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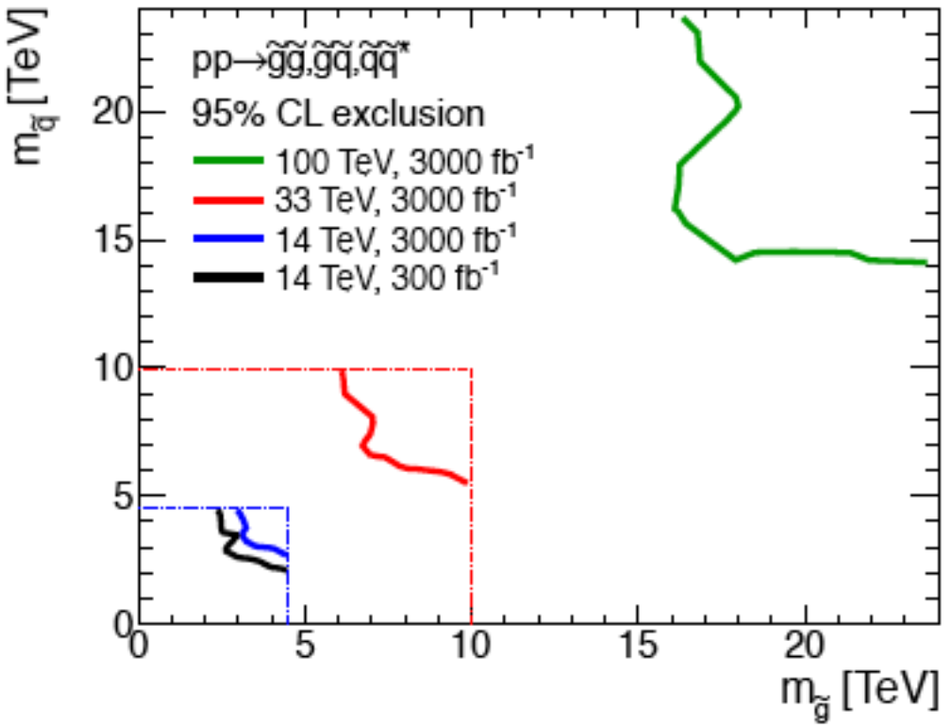

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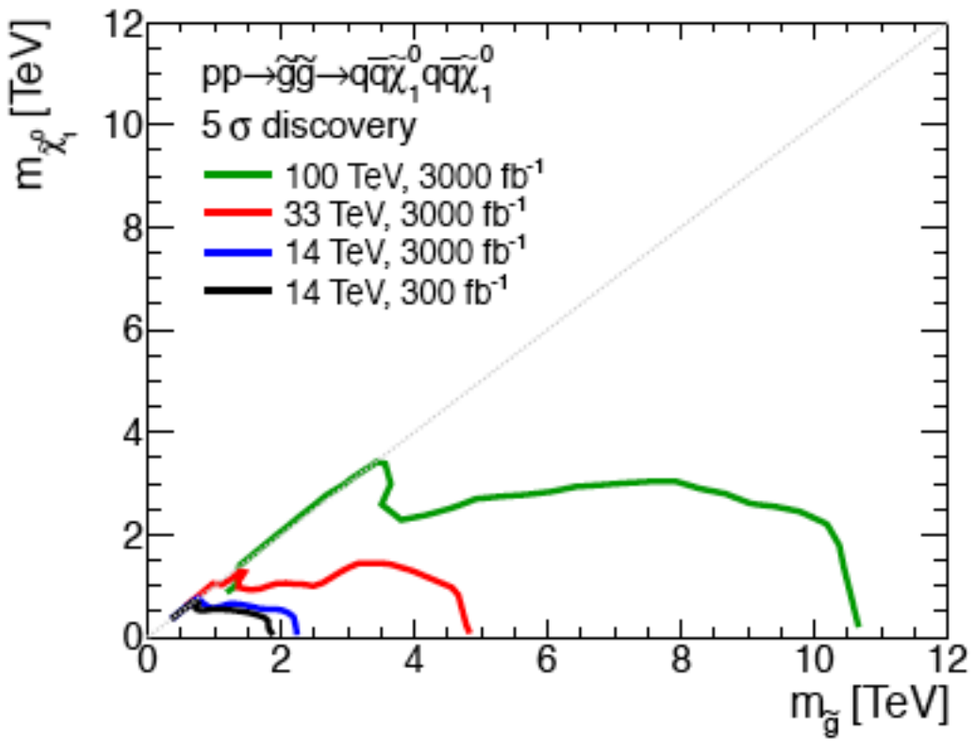
100 TeV Collider: Probes Naturalness at the 0.01% level

Reach of 100 TeV

Gluino Reach

Discovery



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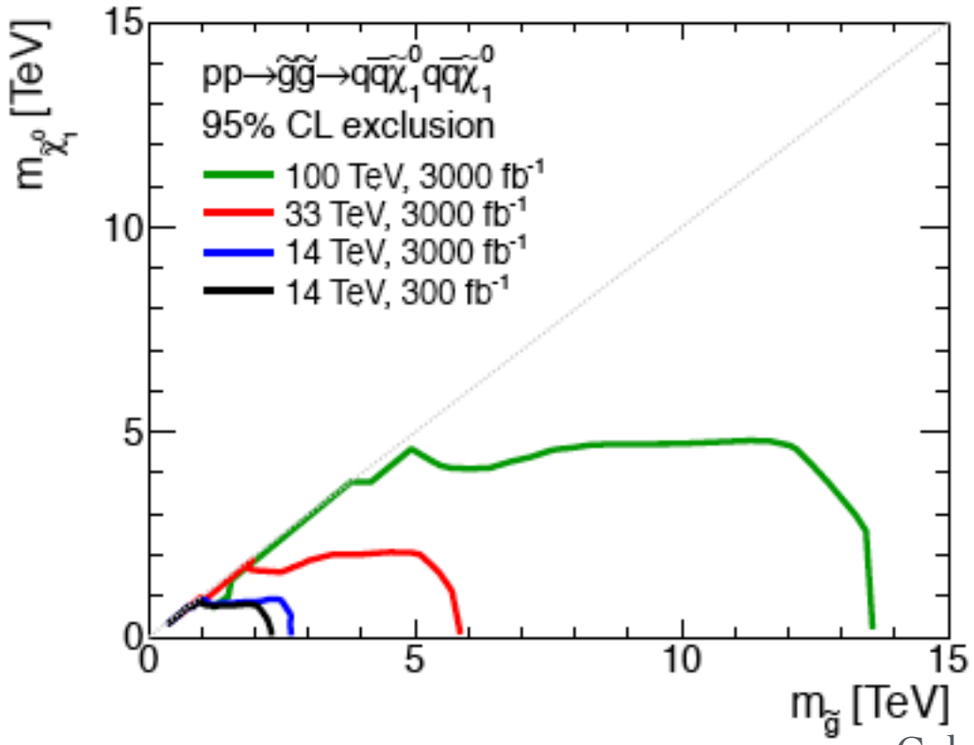

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LHC 14: Probing theories worse than 1% tuned

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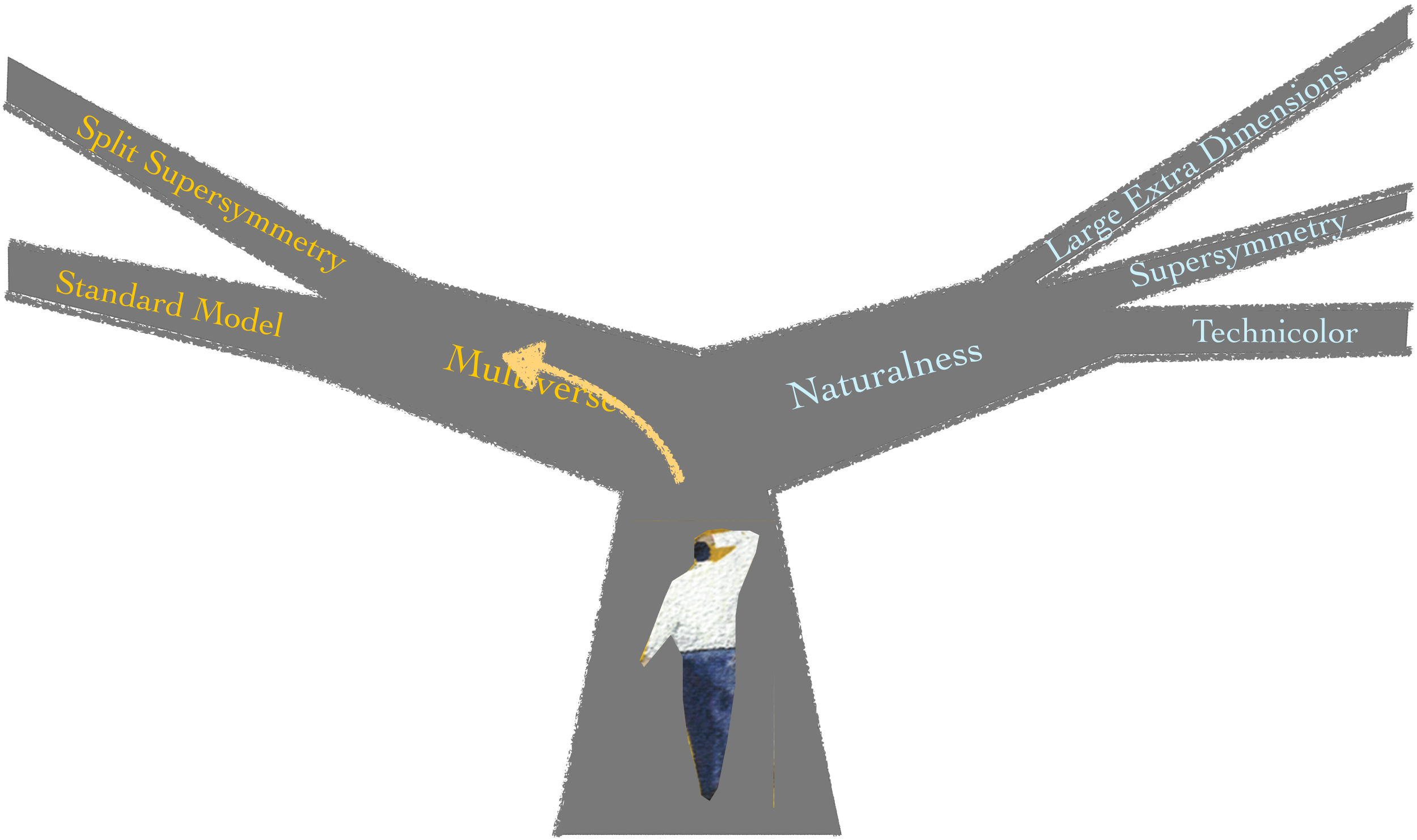
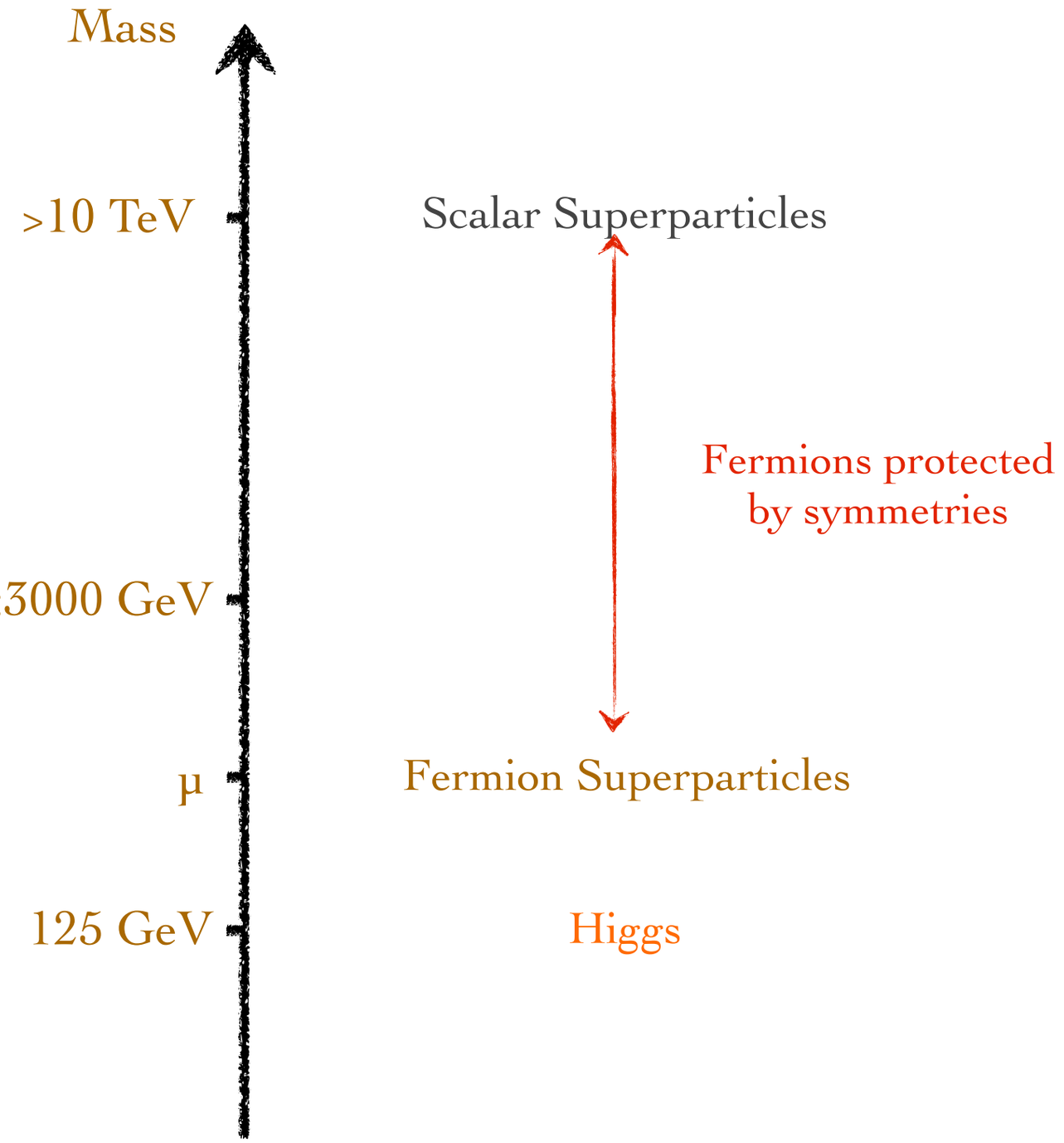
At the Crossroads



Split Supersymmetry

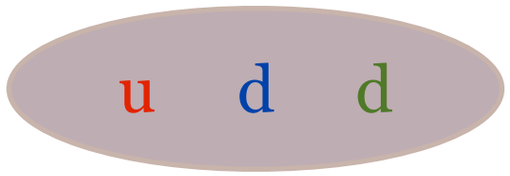


- Preserves successes of Dark Matter and gauge coupling unification

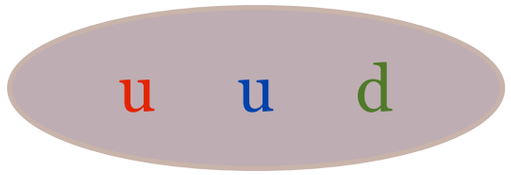
- Atomic Principle: One tuned light higgs

What if we now vary the weak scale?

Neutron

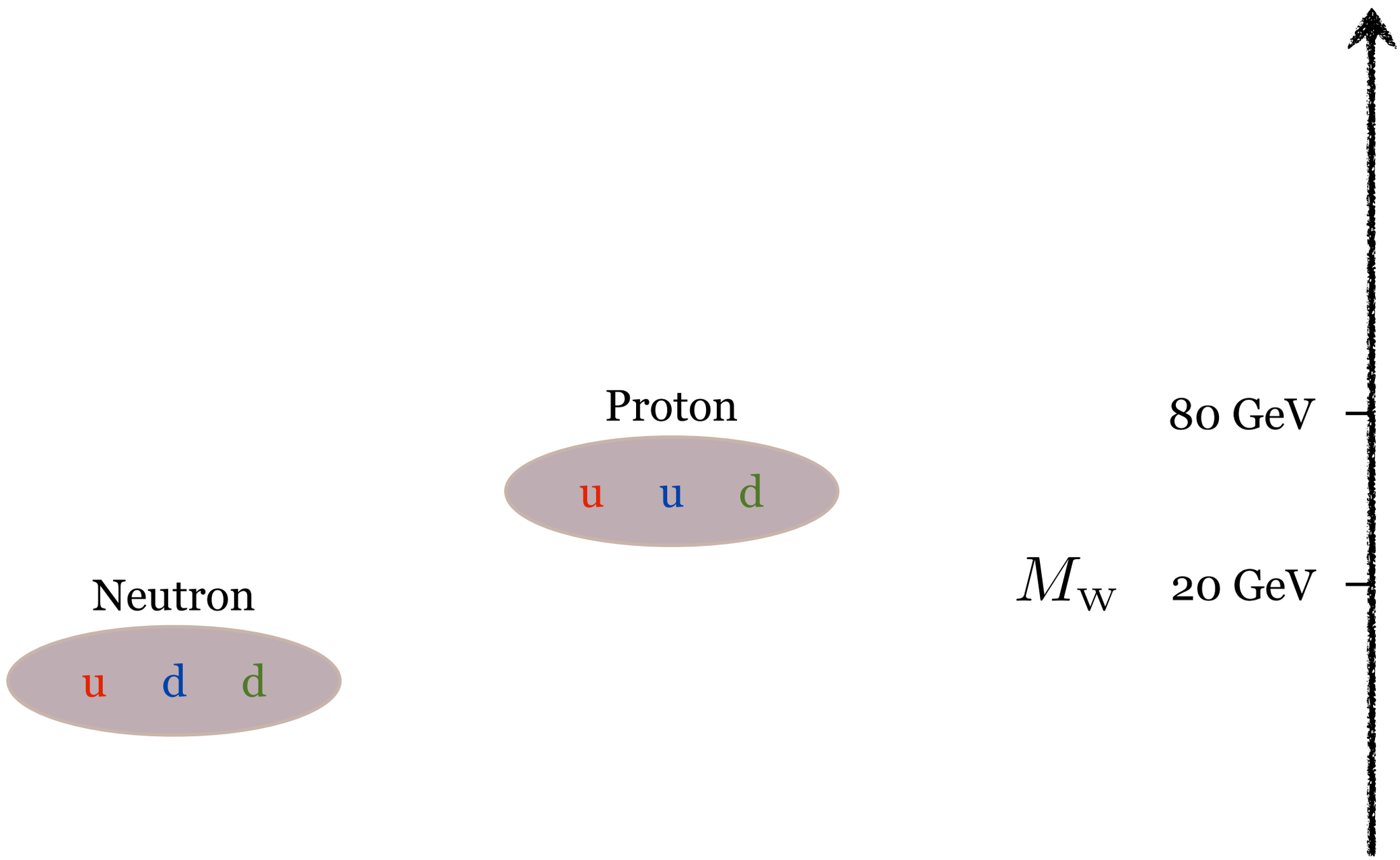


Proton



M_{W} 80 GeV

What if we now vary the weak scale?

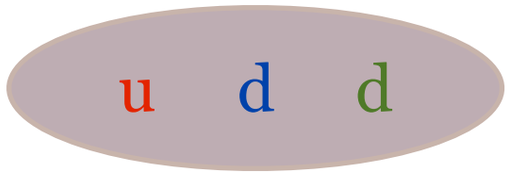


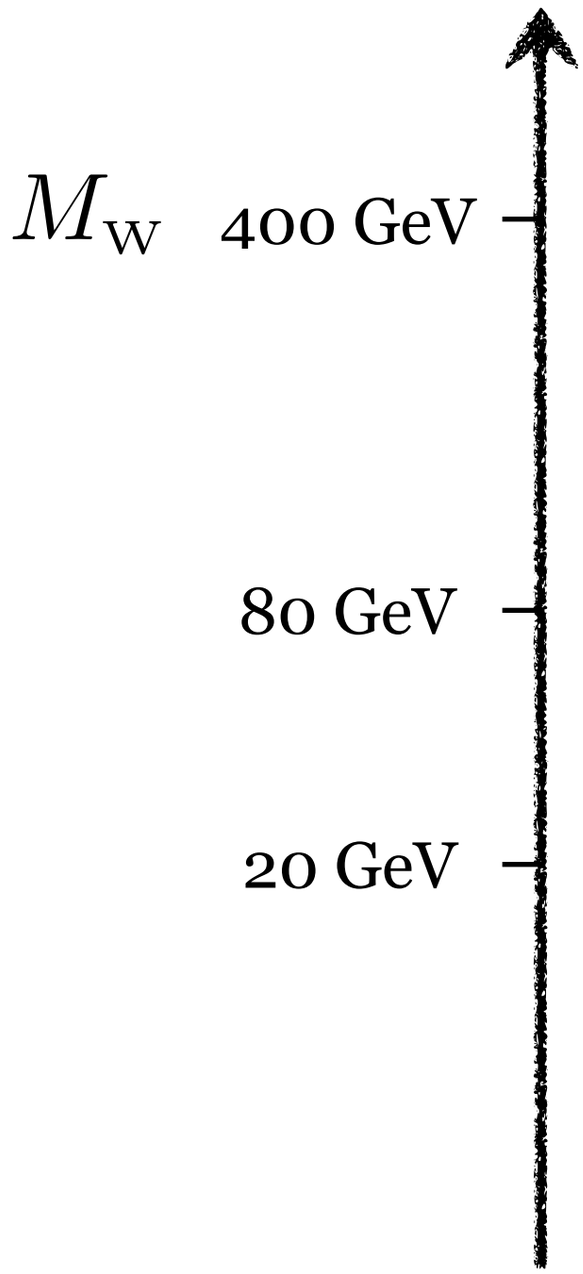
Protons decay to neutrons inside nuclei:

No Hydrogen

What if we now vary the weak scale?

Neutron





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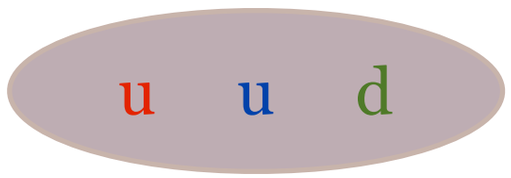
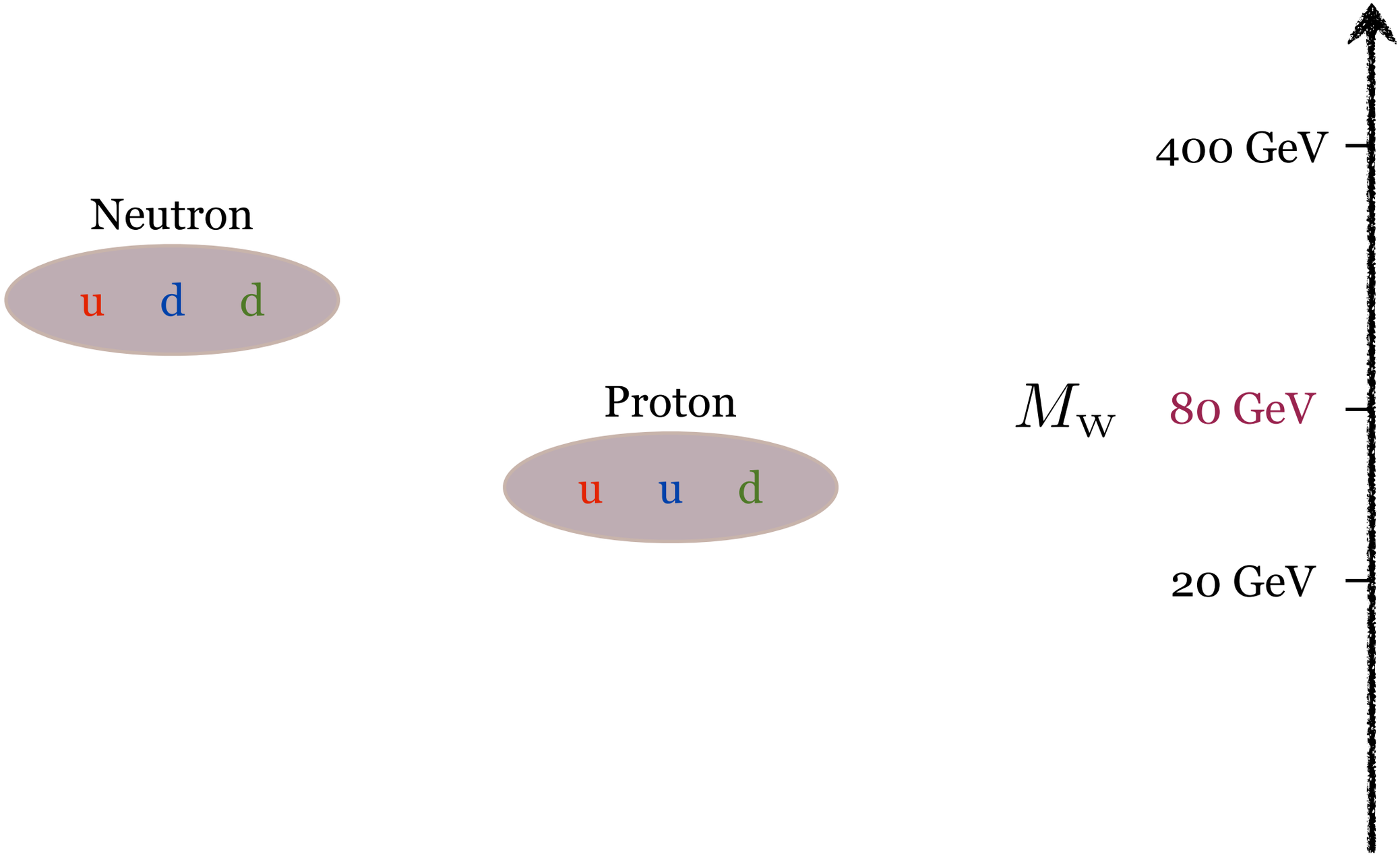


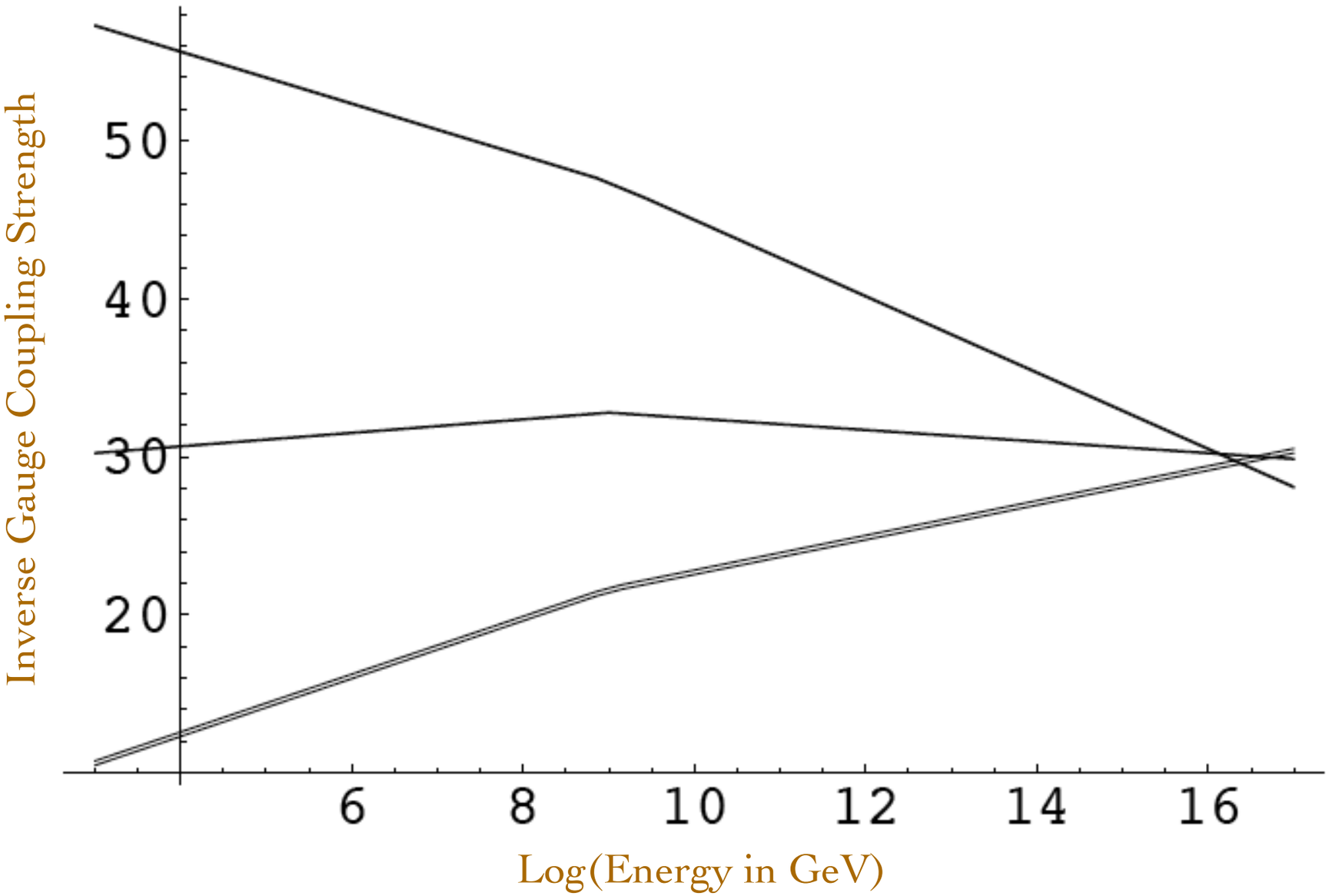
Neutrons decay inside nuclei:
Only Hydrogen

What if we now vary the weak scale?



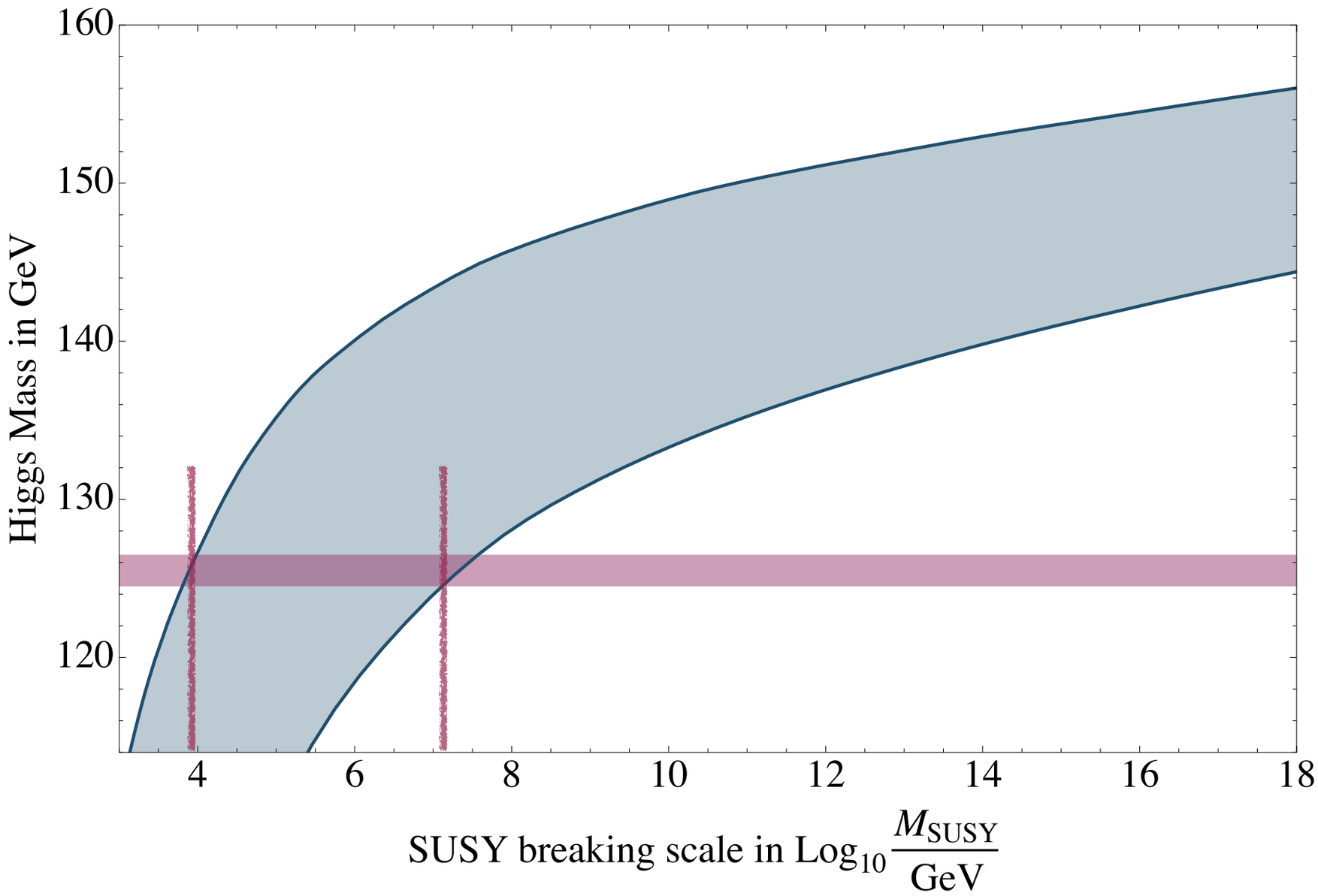
The weak scale at ~100 GeV is essential for the existence of atoms:
'Atomic principle'

Unification in Split Supersymmetry



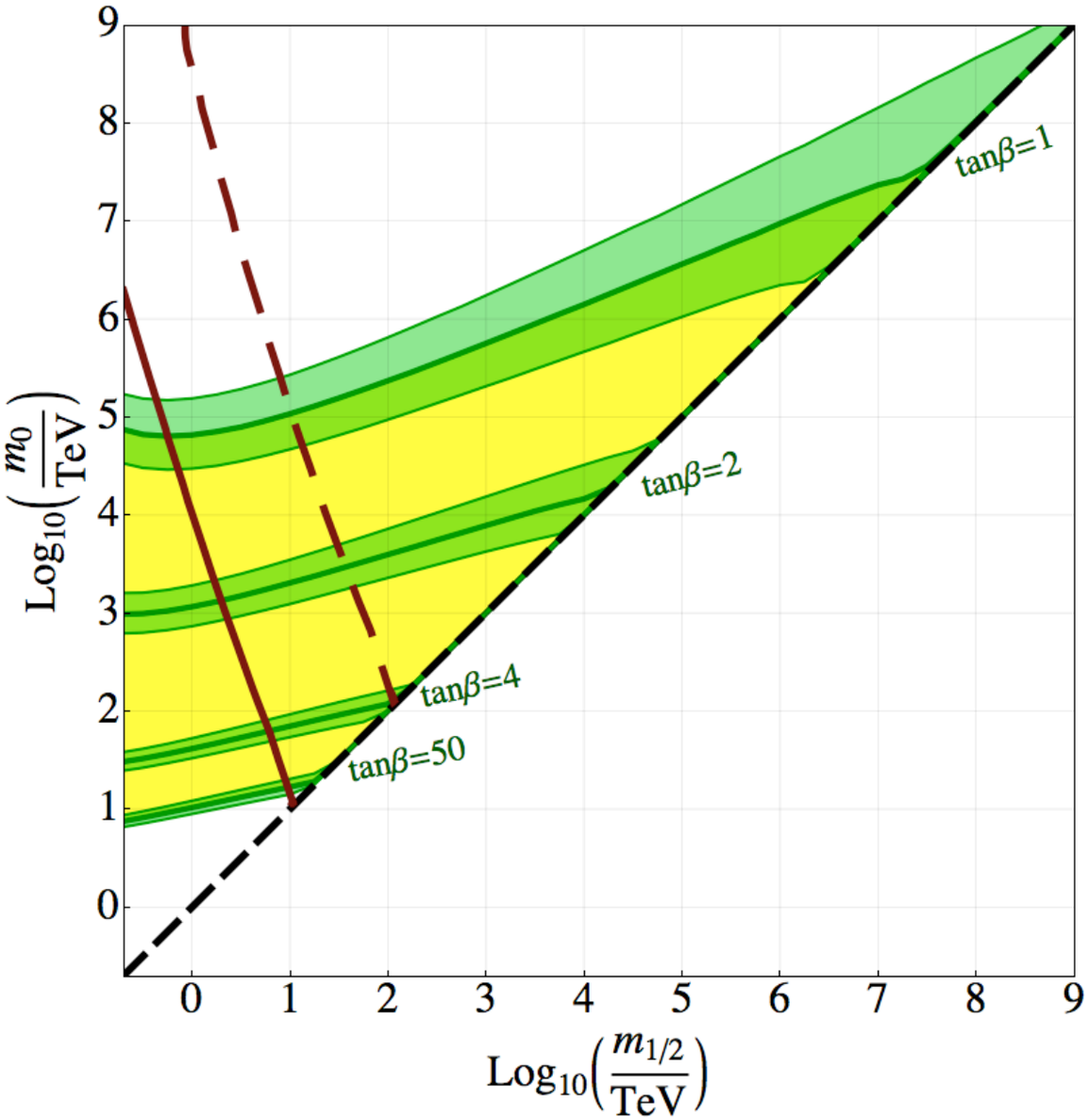
Works as well as ordinary Supersymmetry

125 GeV Higgs in Split Supersymmetry



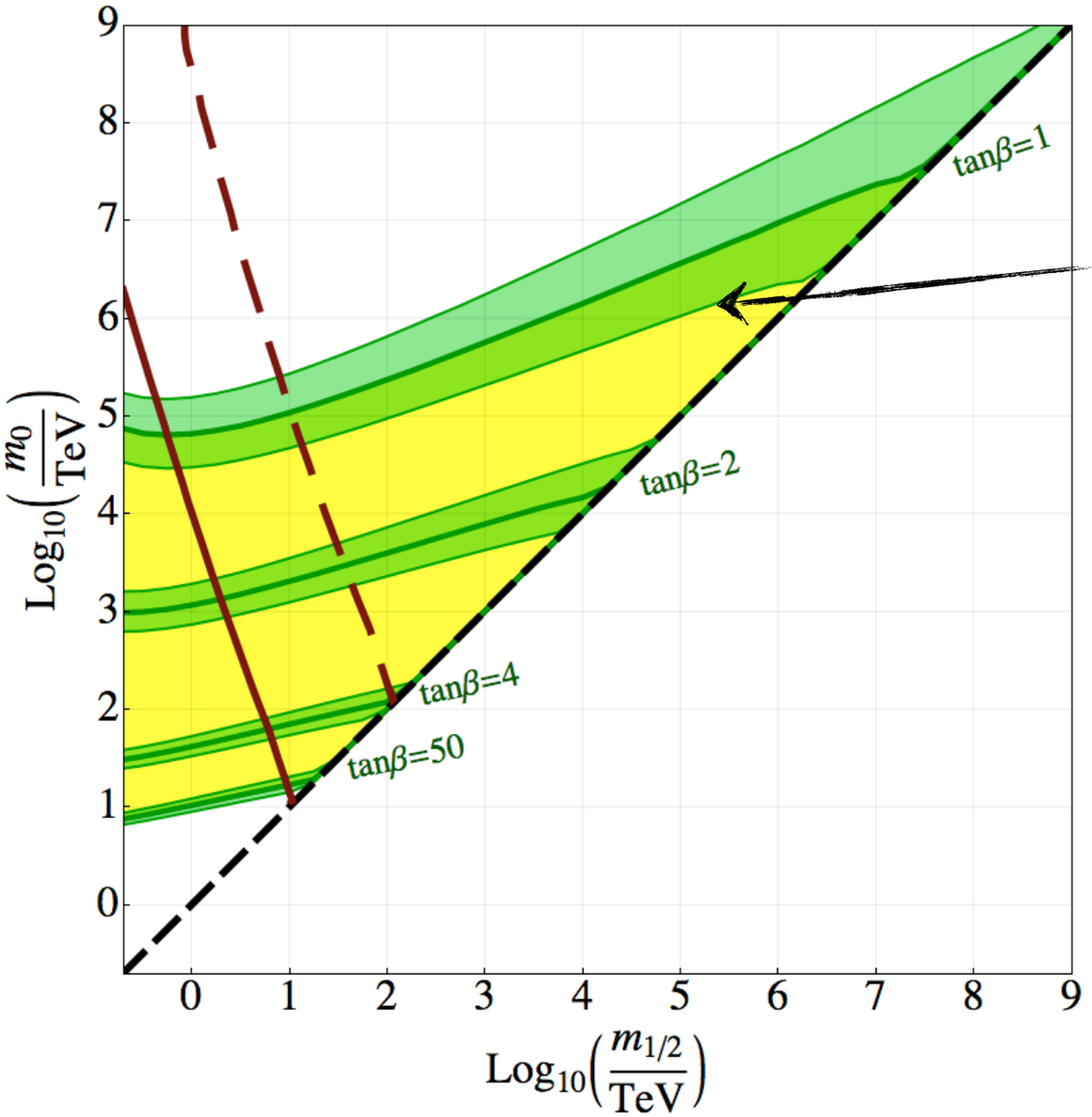
- Favors scalars between 10-10^4 TeV: Mini-Split

The 125 GeV Higgs and Unification in Mini-Split



w/ Arvanitaki, Craig, Villadoro

The 125 GeV Higgs and Unification in Mini-Split

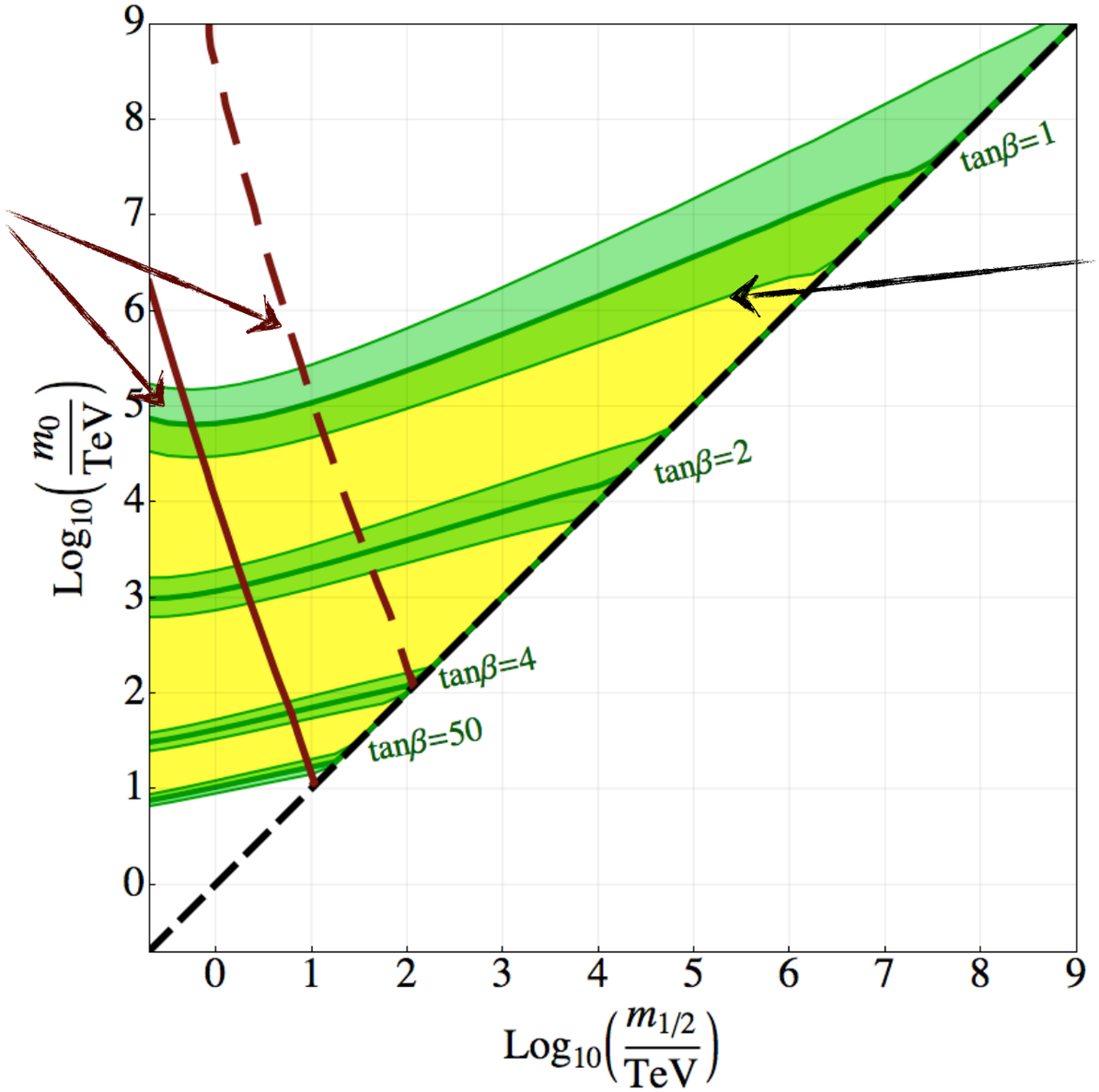


Parameter space for 125 GeV Higgs

w/ Arvanitaki, Craig, Villadoro

The 125 GeV Higgs and Unification in Mini-Split

1σ and 2σ contours for unification



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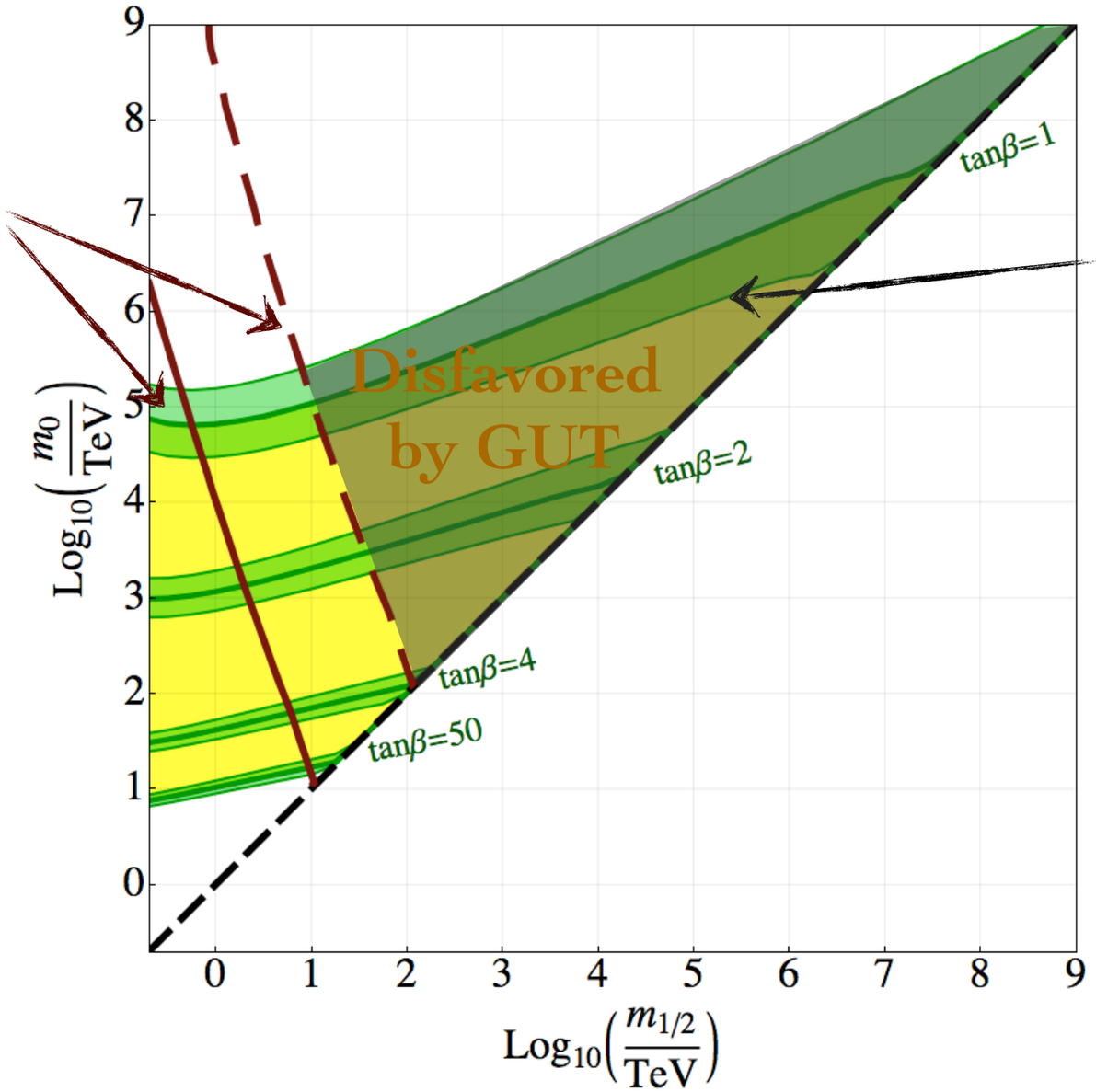


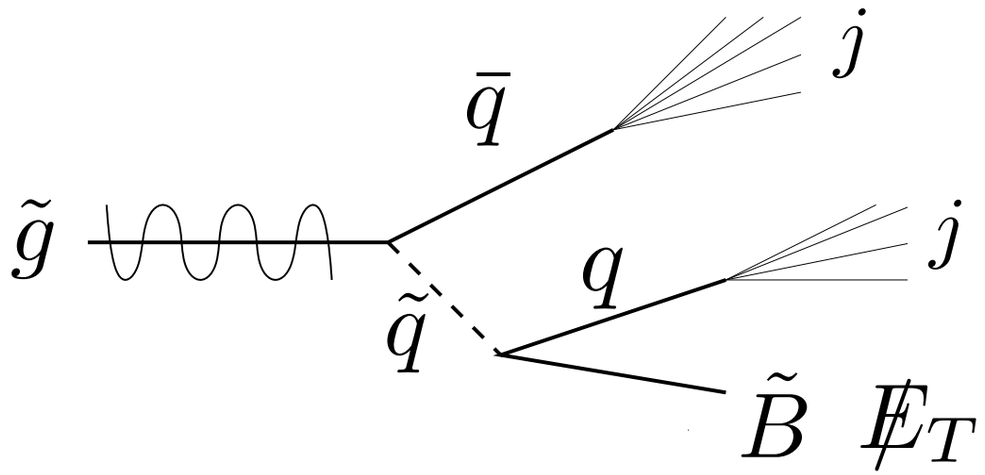
Parameter space for 125 GeV Higgs

w/ Arvanitaki, Craig, Villadoro

- Higgsinos have to be lighter than 100 TeV for Unification
- Scalars below 100 TeV when tanβ > few
- Unification: Further motivates 100 TeV collider

Long-lived Gluinos

Gluino decay through the heavy scalars

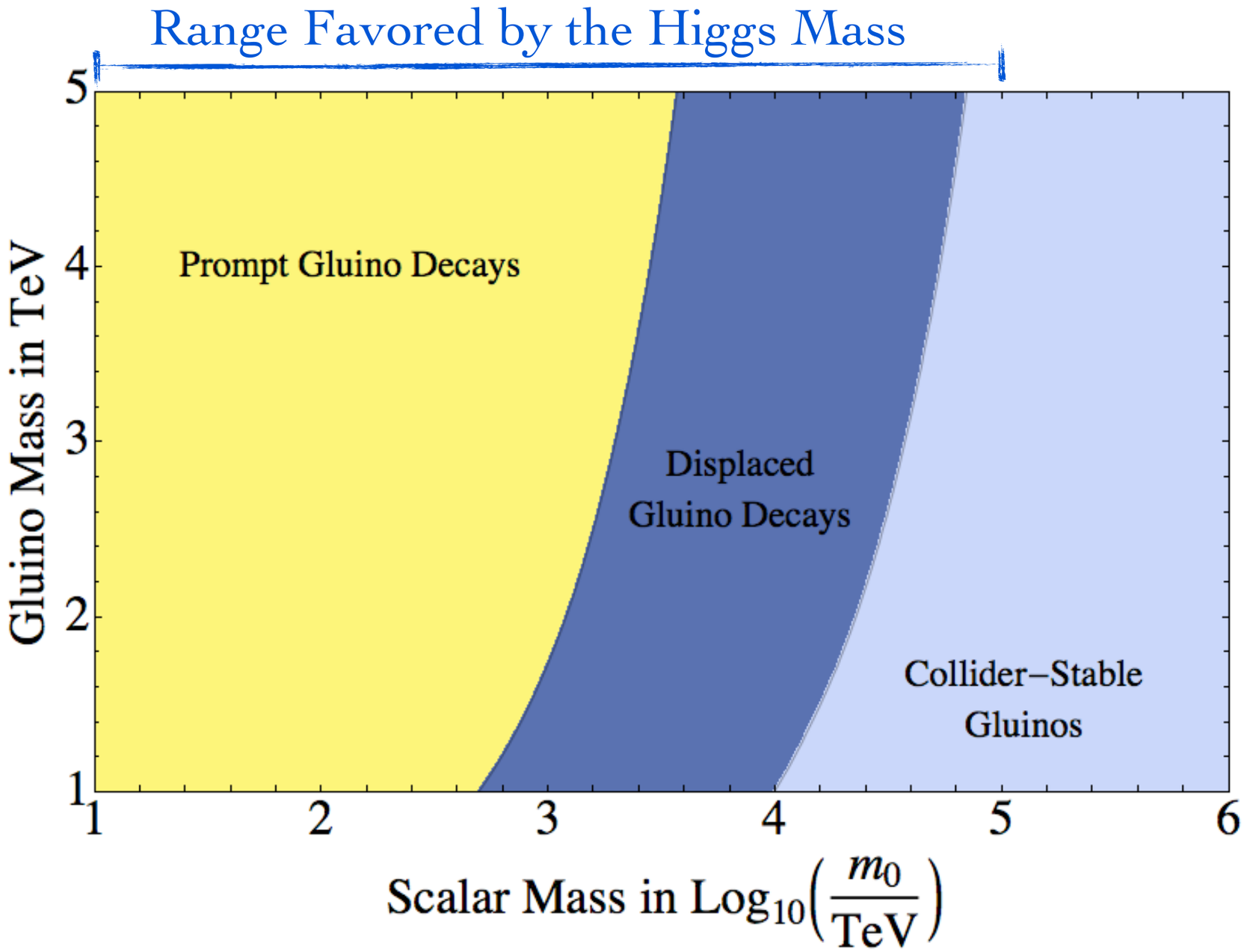


Signature:
2 jets and missing energy

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



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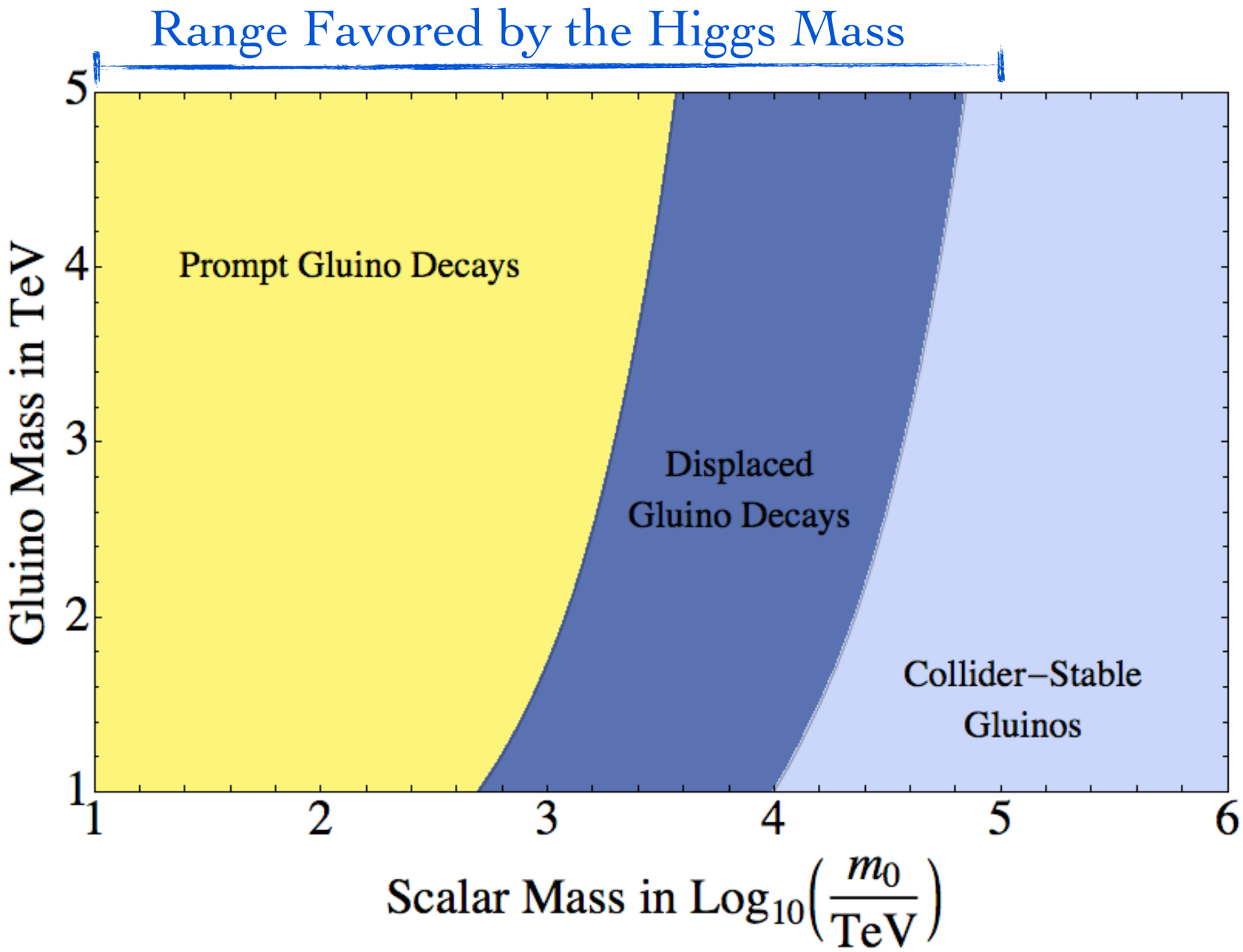
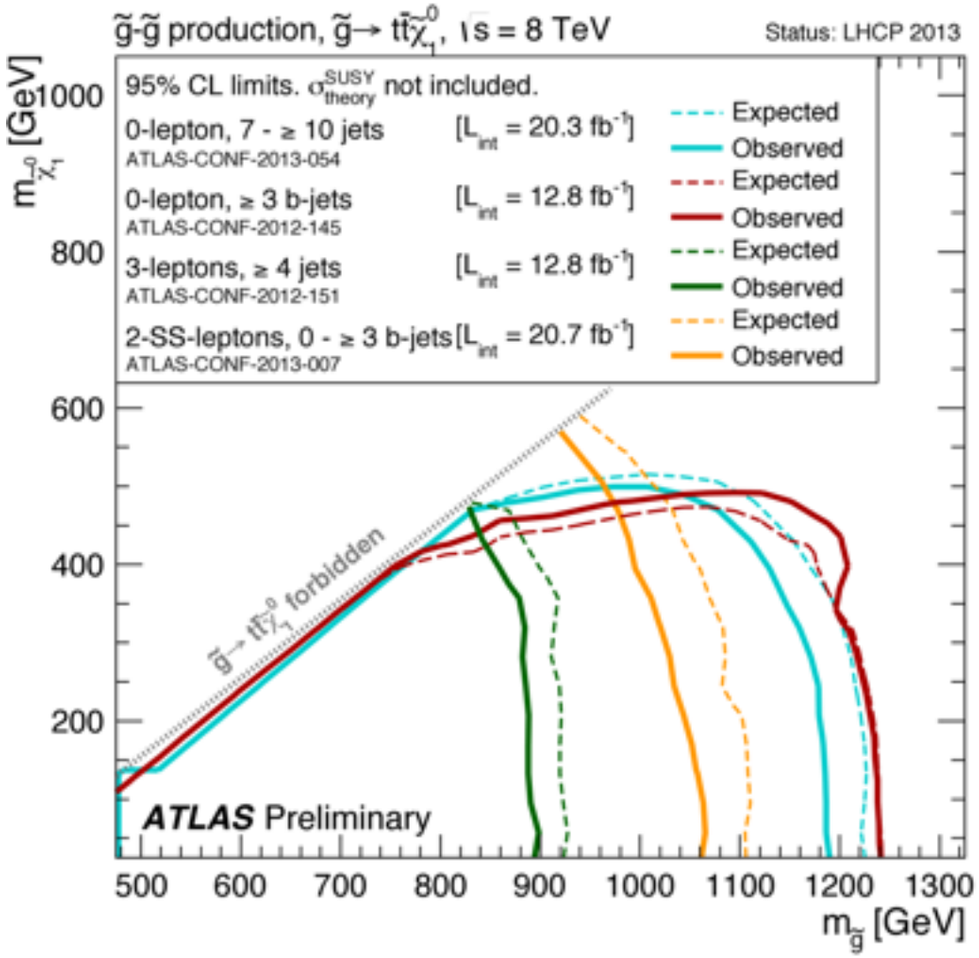
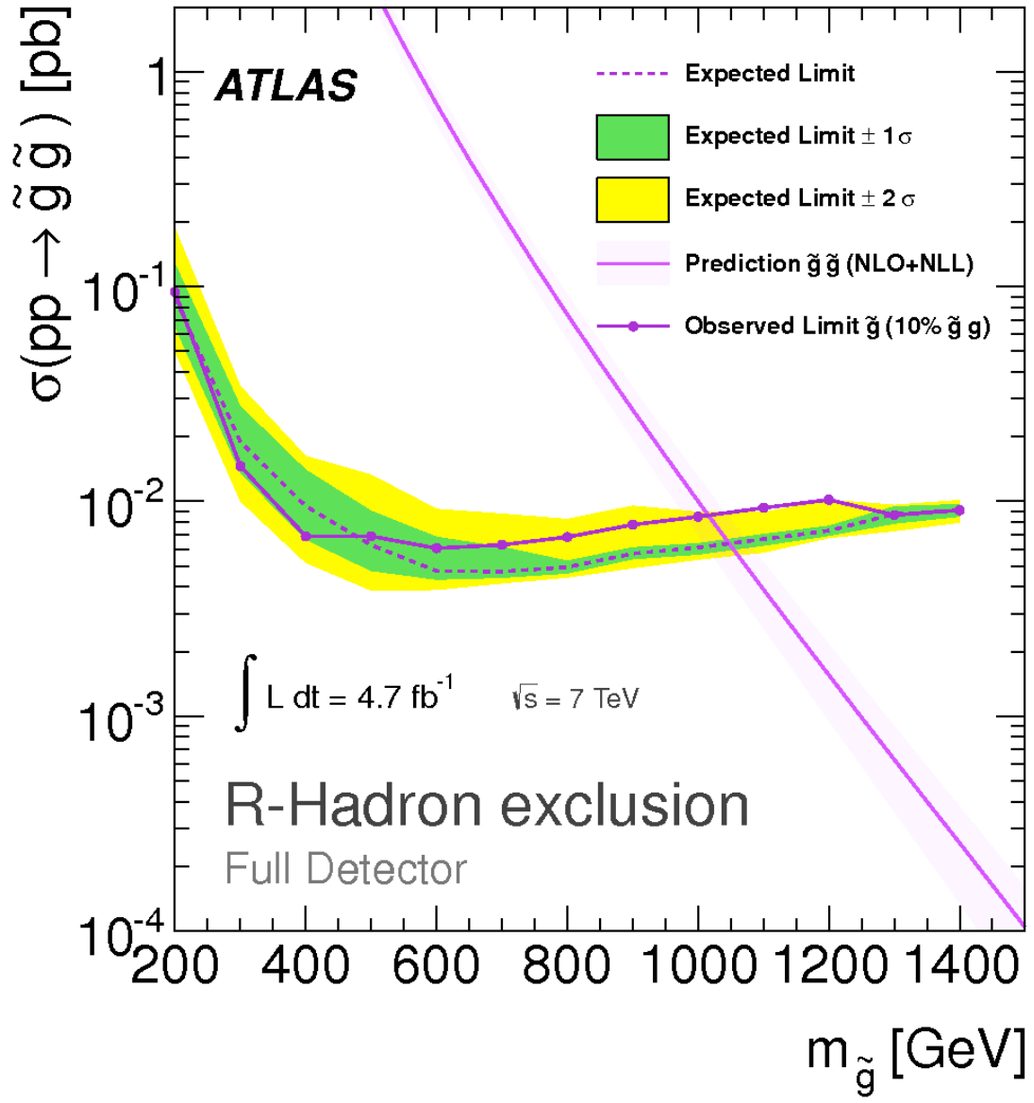


Stops as the lightest scalar sparticle:
Tops and bottoms in the final state of the decay

Gluino Bounds from the LHC



For prompt or
slightly displaced gluinos



For collider "stable" gluinos

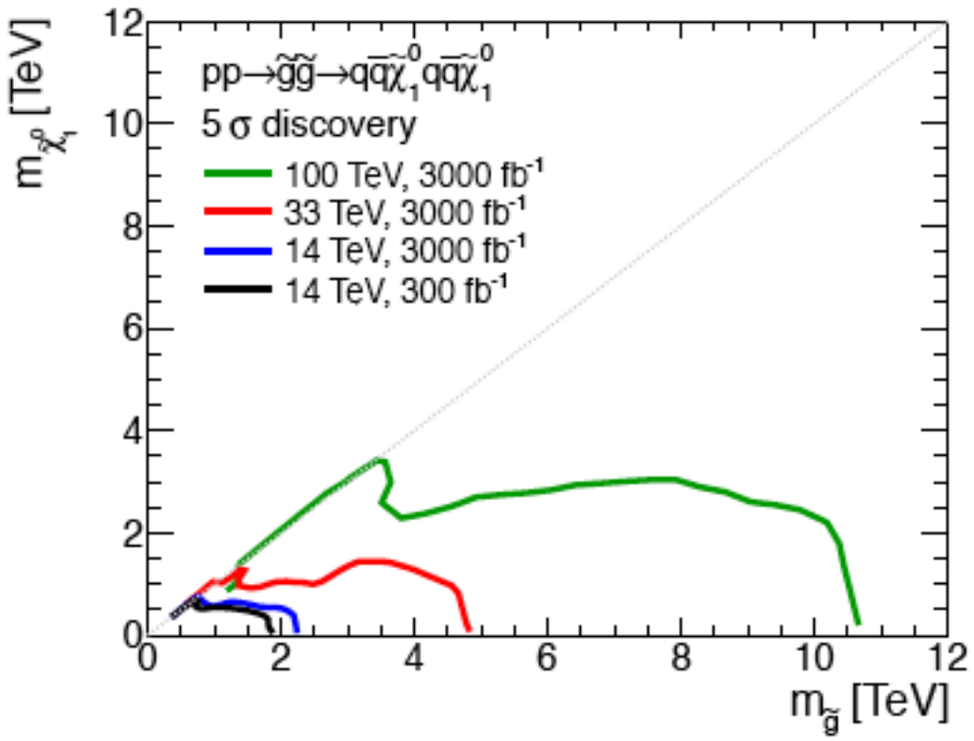
M_{gluino} > 1 TeV for split gluino

Small window for 10 cm - 1 m lifetimes?

Gluino Reach with 100 TeV

Cohen et. al. (2013)

Discovery



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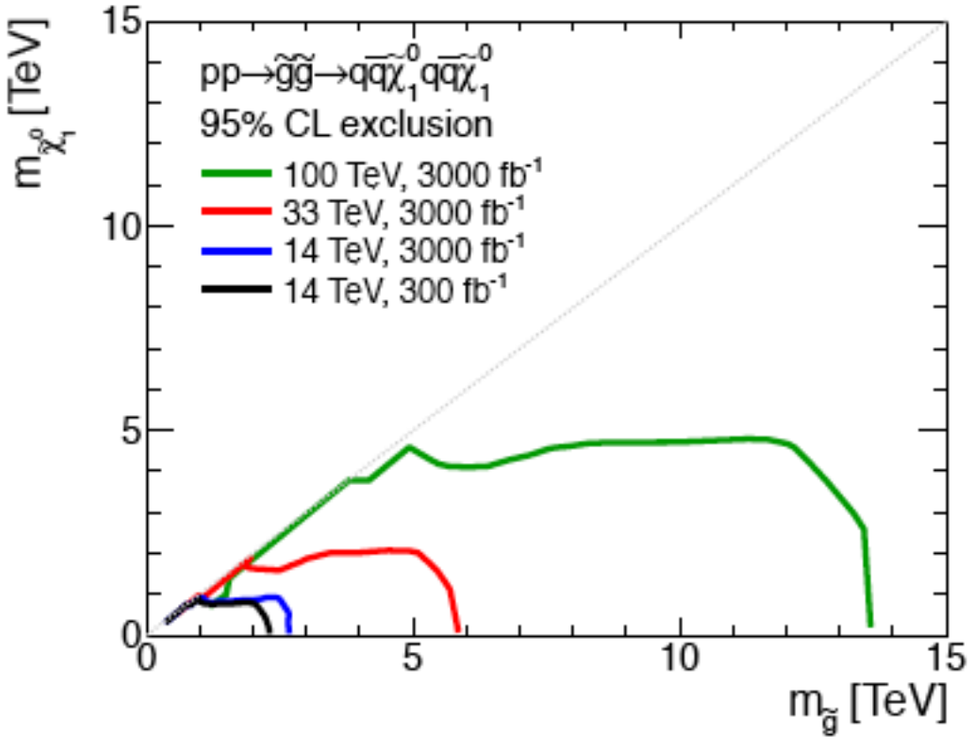
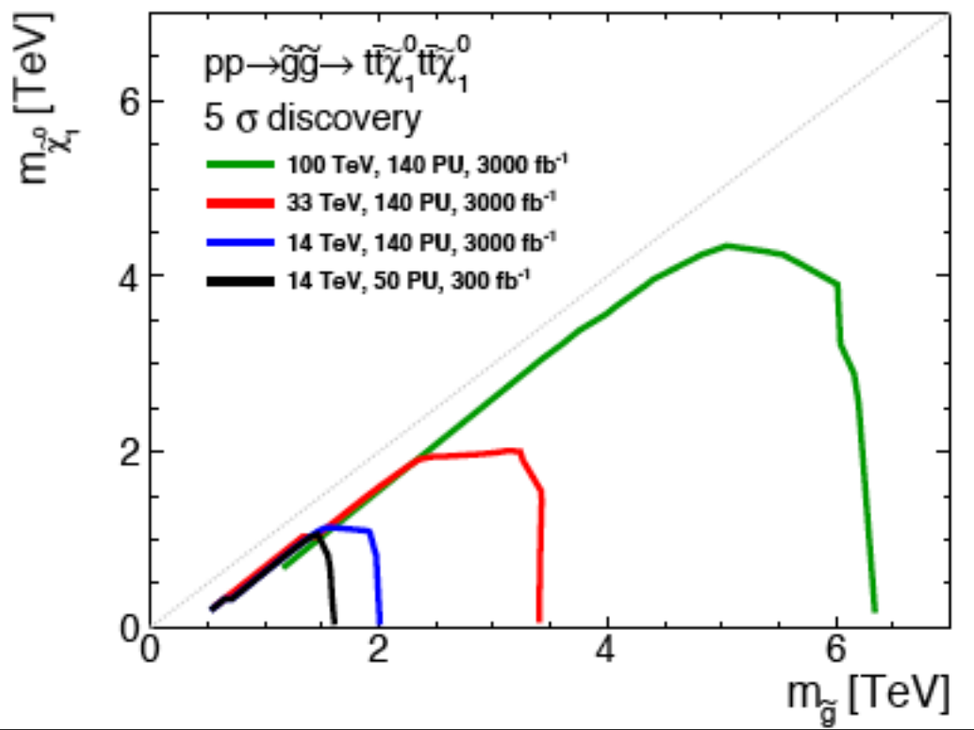
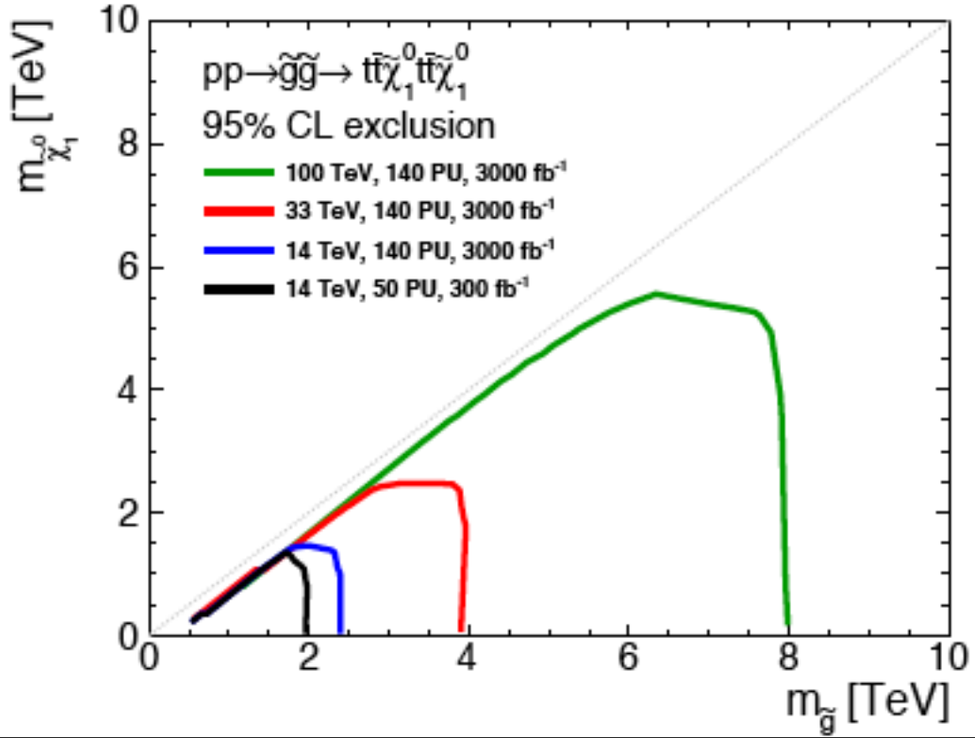






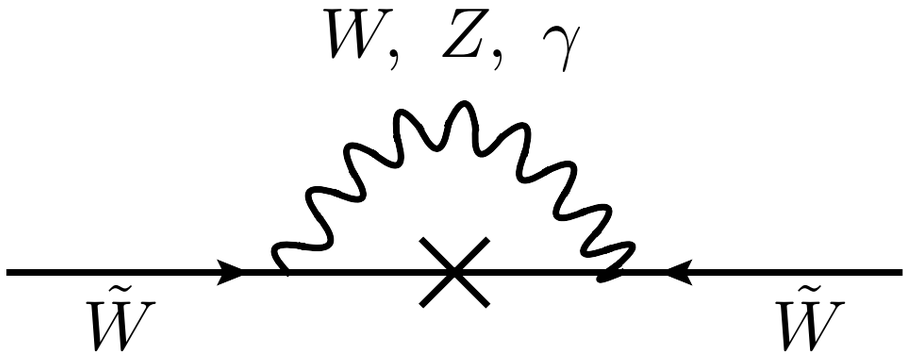
Split Signatures beyond the Gluino: Electroweakinos and Higgsinos

- Light Winos
  - Minimal Dark Matter Candidate $M_{DM} \sim 2.5$ TeV
  - Displaced Wino decays

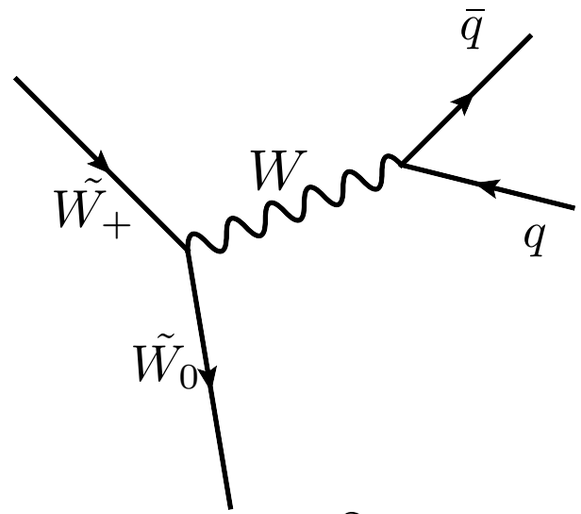
- Light Higgsinos
  - Minimal Dark Matter Candidate $M_{DM} \sim 1$ TeV
  - Displaced Higgsino decays

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

Wino LSP with Heavy Higgsinos



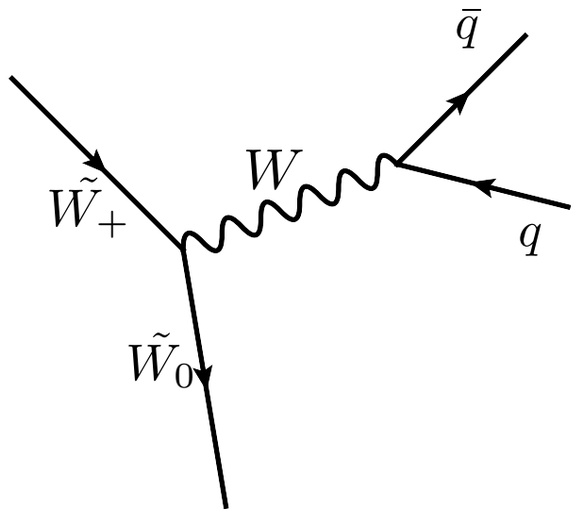
$$\Delta m \sim \frac{\alpha}{4\pi} M_Z \approx 155 - 175 \text{ MeV}$$



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

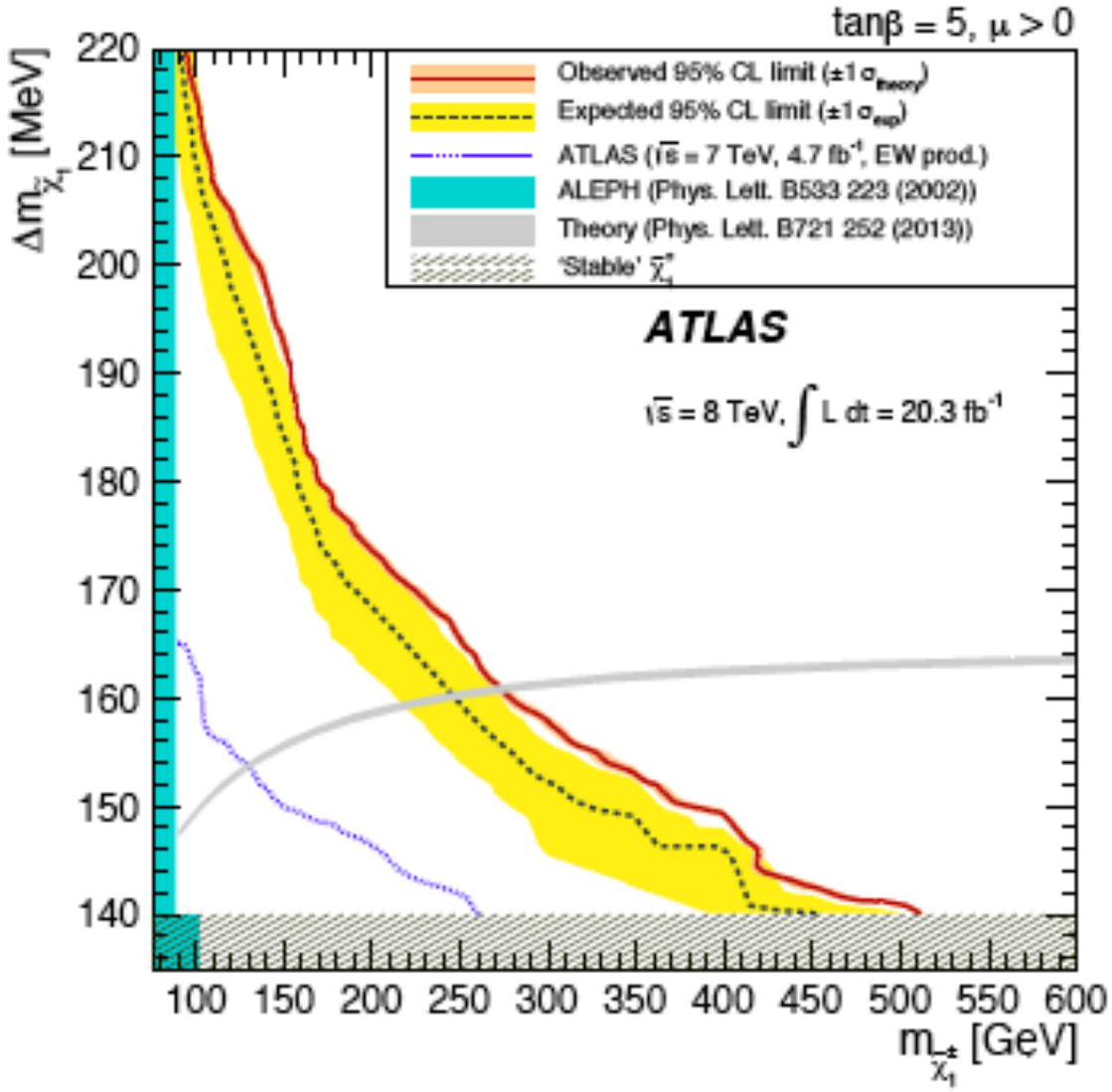
- Charged wino heavier than Neutral Wino
- cm size tracks with soft pions

Wino LSP with Heavy Higgsinos

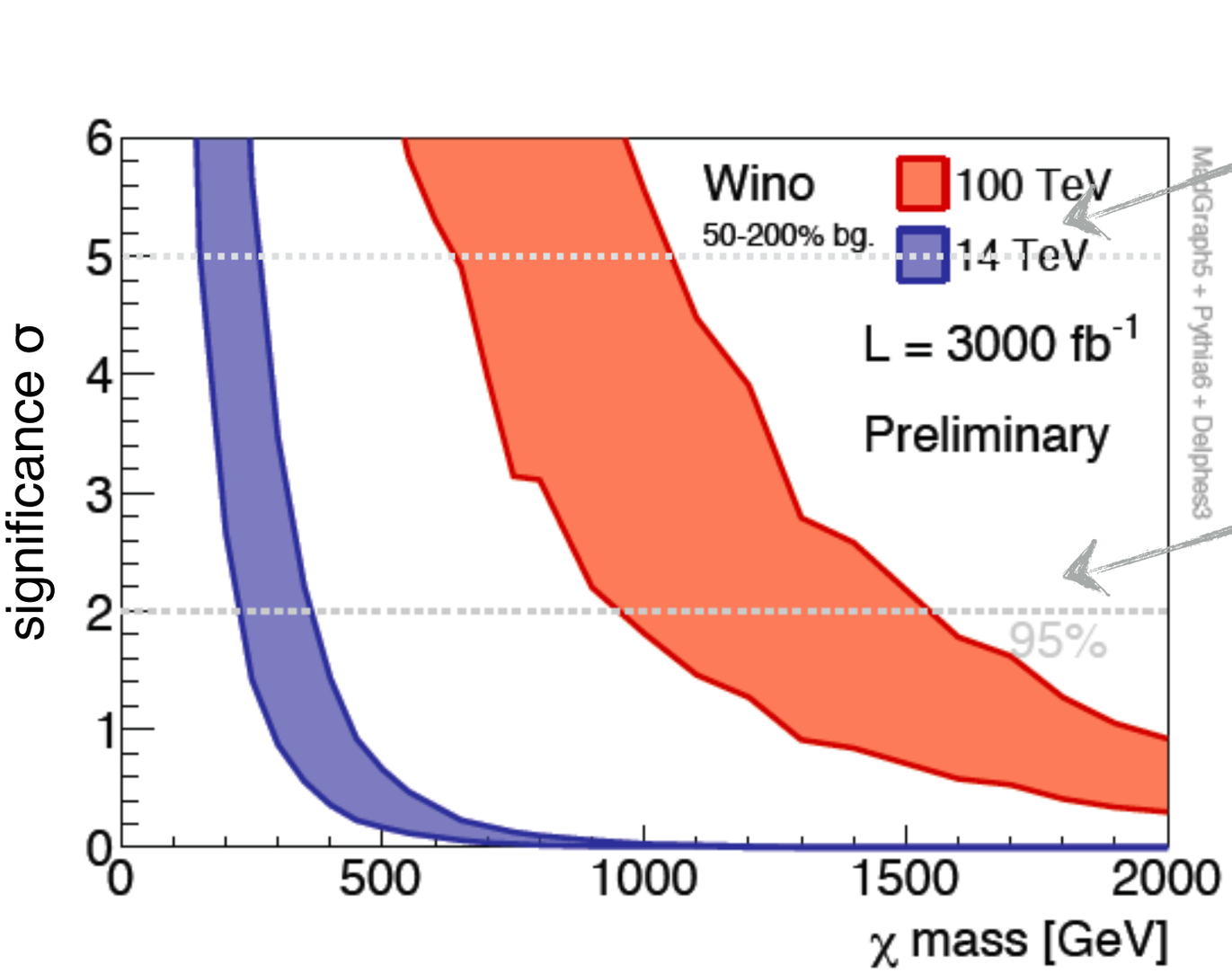


$\Delta m \approx 155 - 175$ MeV

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



Wino reach at 100 TeV

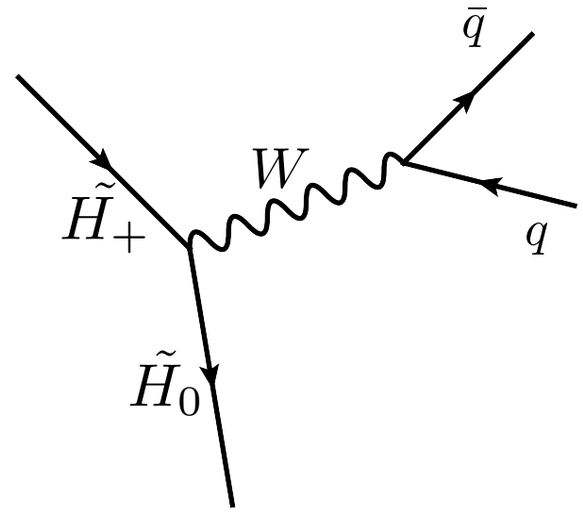


Talk given by Lian-Tao Wang

Factor of few gain compared to the LHC

Higgsino LSP:
The Minimal Model for Unification

- Only light Higgsinos in the Spectrum

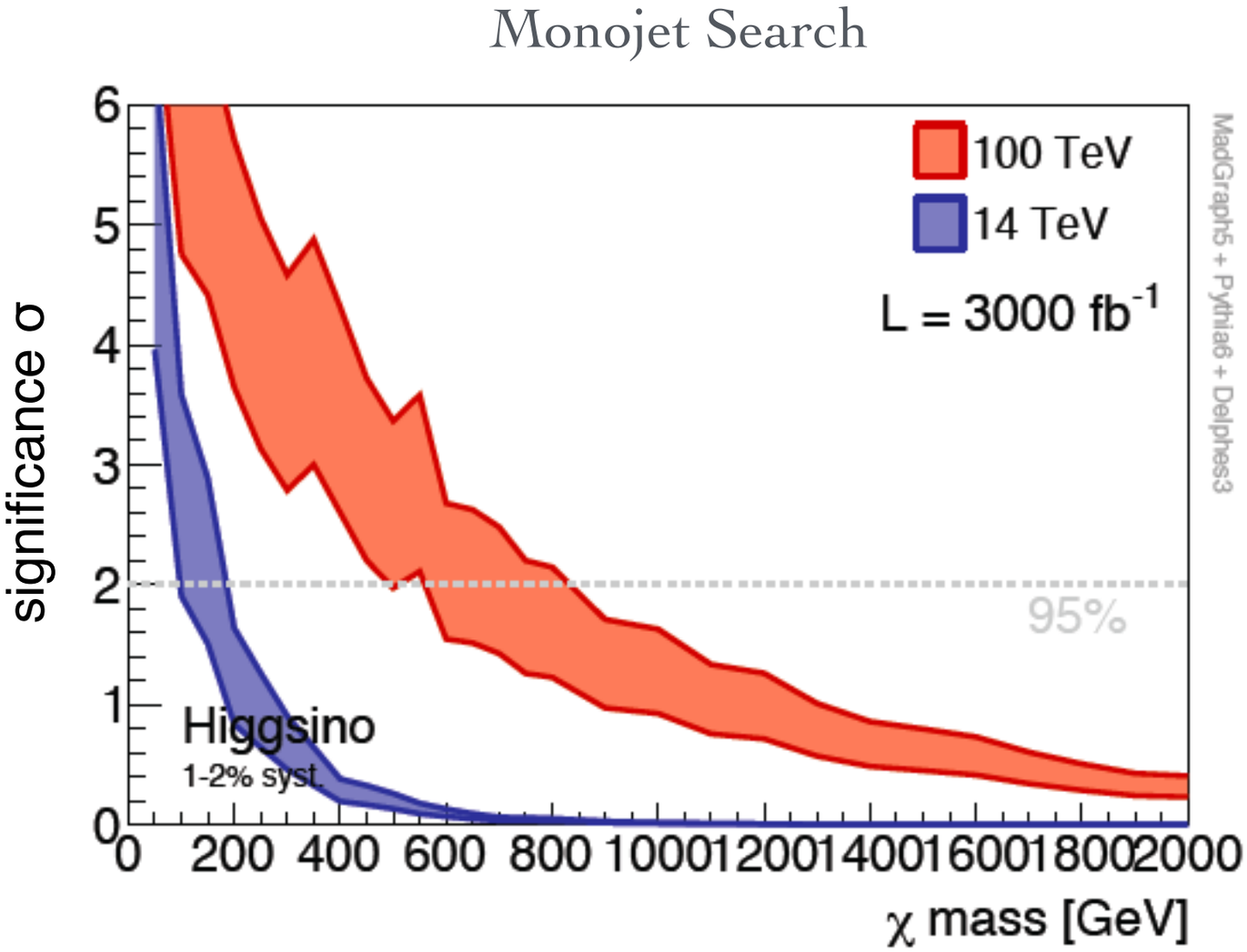


- Mass splitting ~355 MeV

- Soft pions with sub-cm charged tracks

- No LHC bounds
  - No working search strategy yet

Higgsino reach at 100 TeV



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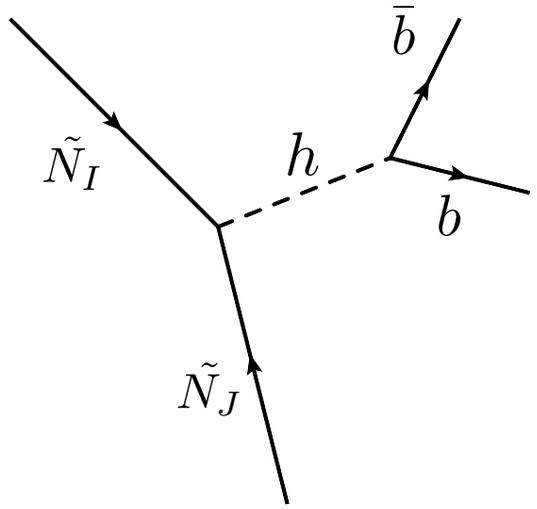
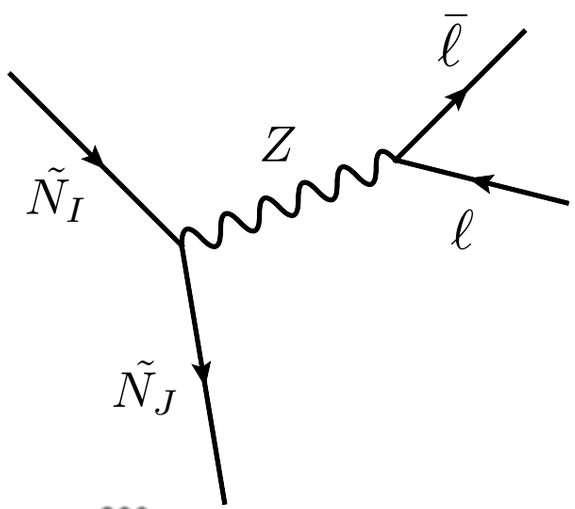
Factor of few gain compared to the LHC

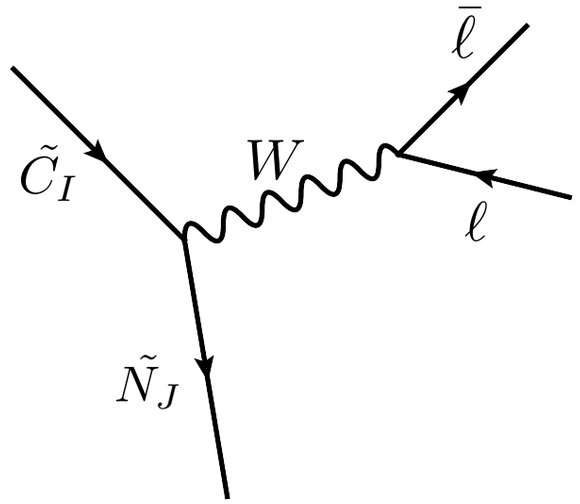
Electroweakinos and Higgsinos at the LHC

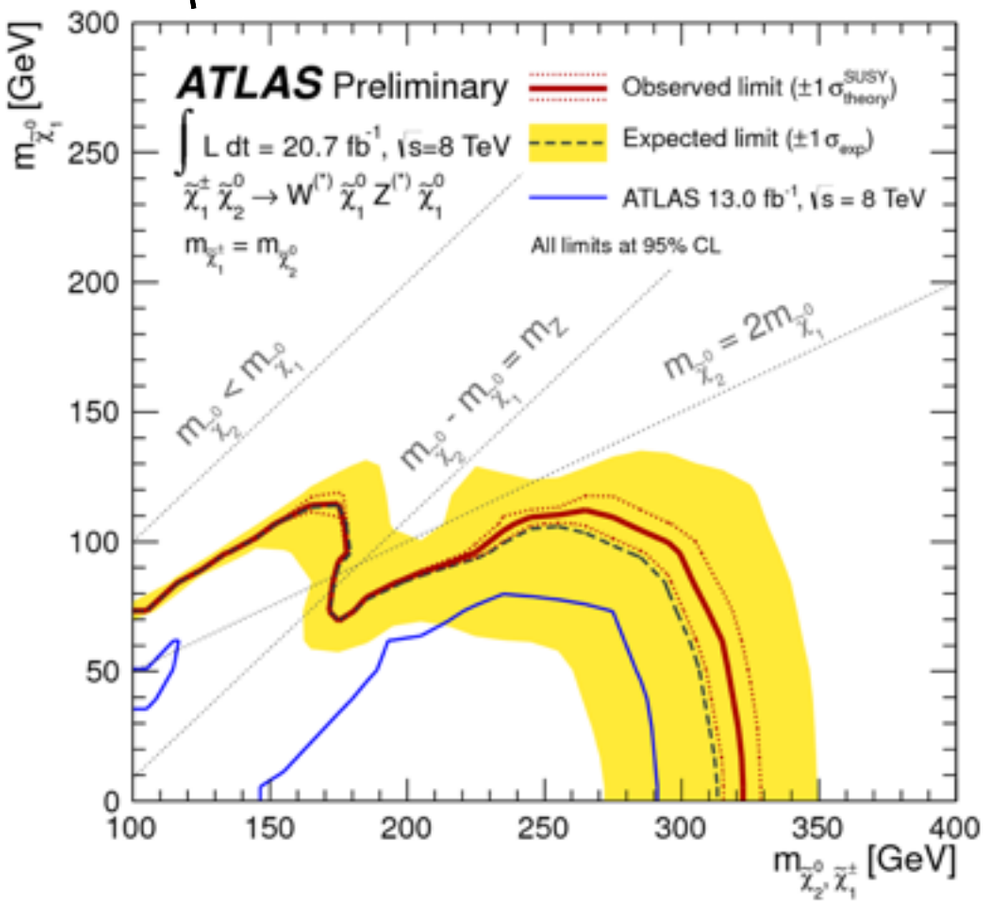
Neutralino decays





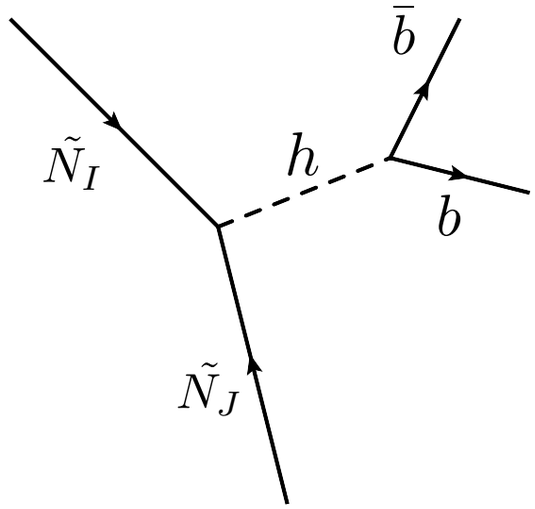
Chargino decays

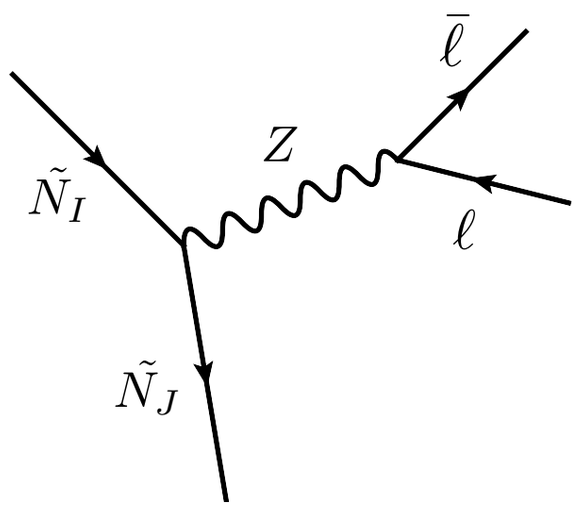




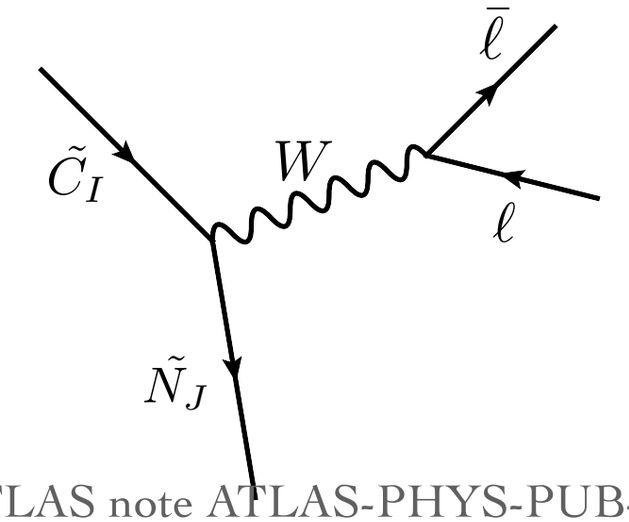
Electroweakinos and Higgsinos at the LHC

Neutralino decays

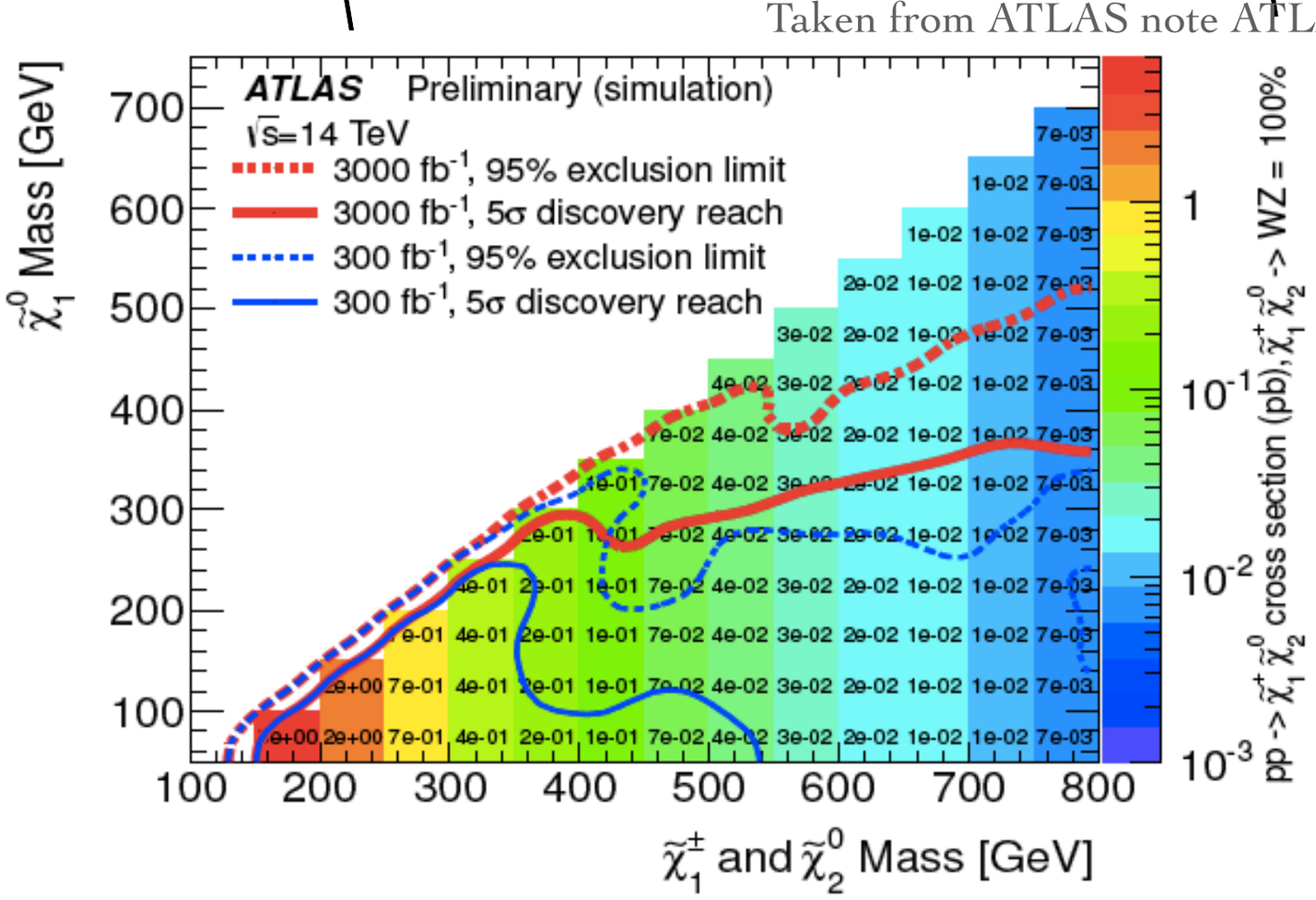




Chargino decays

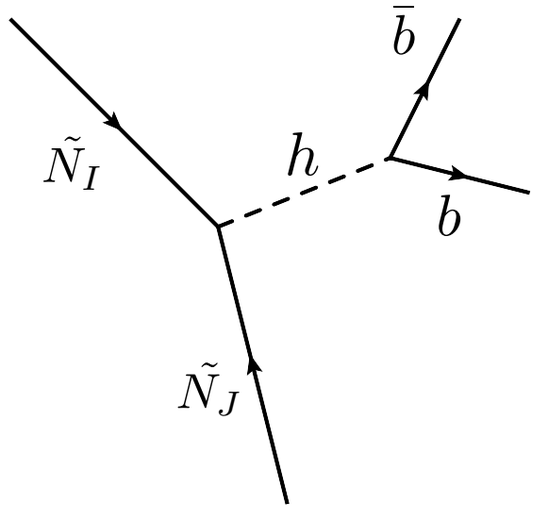


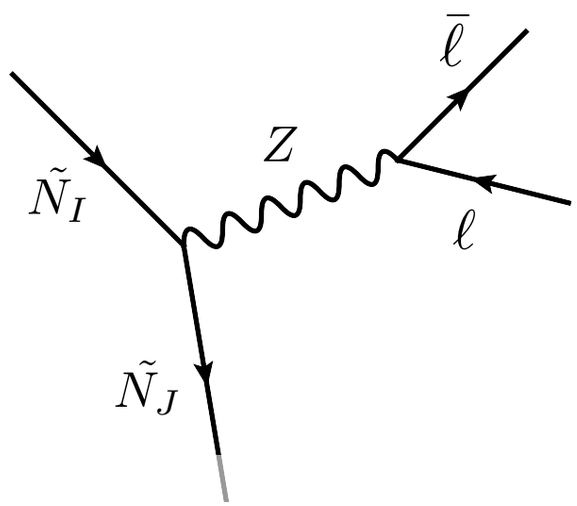
Taken from ATLAS note ATLAS-PHYS-PUB-2013-002



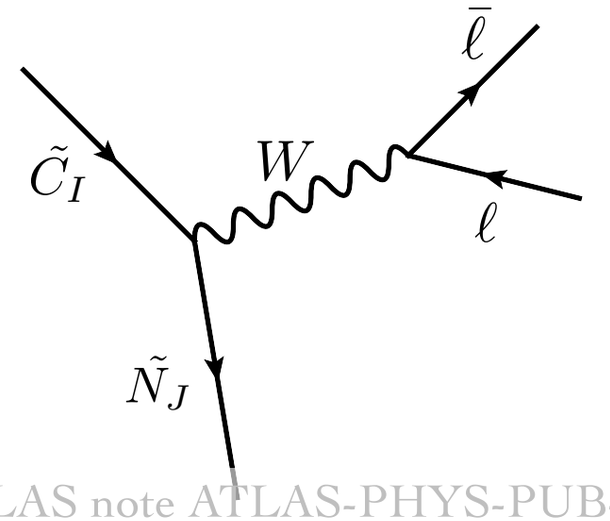
Electroweakinos and Higgsinos at the LHC

Neutralino decays

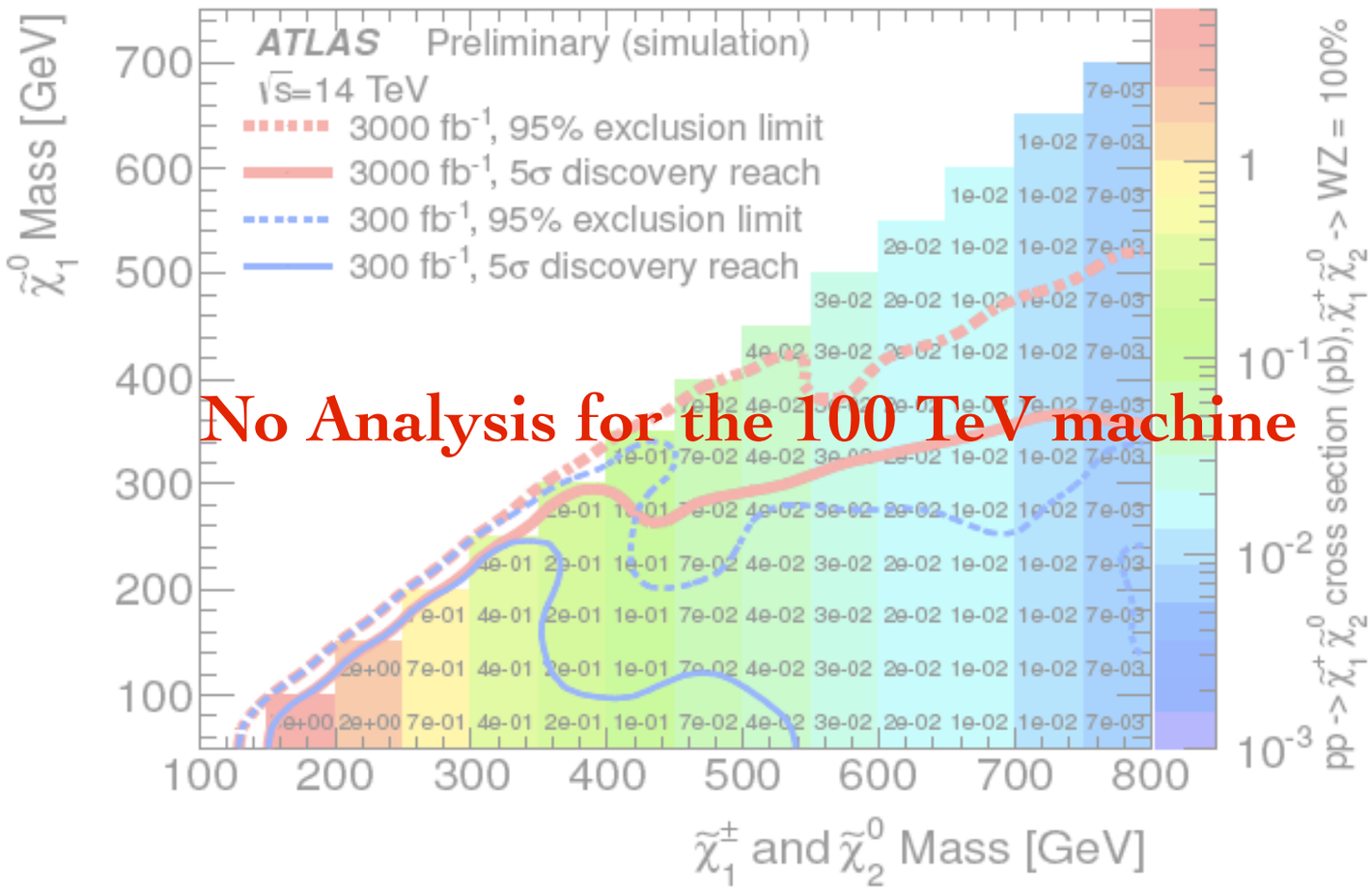




Chargino decays



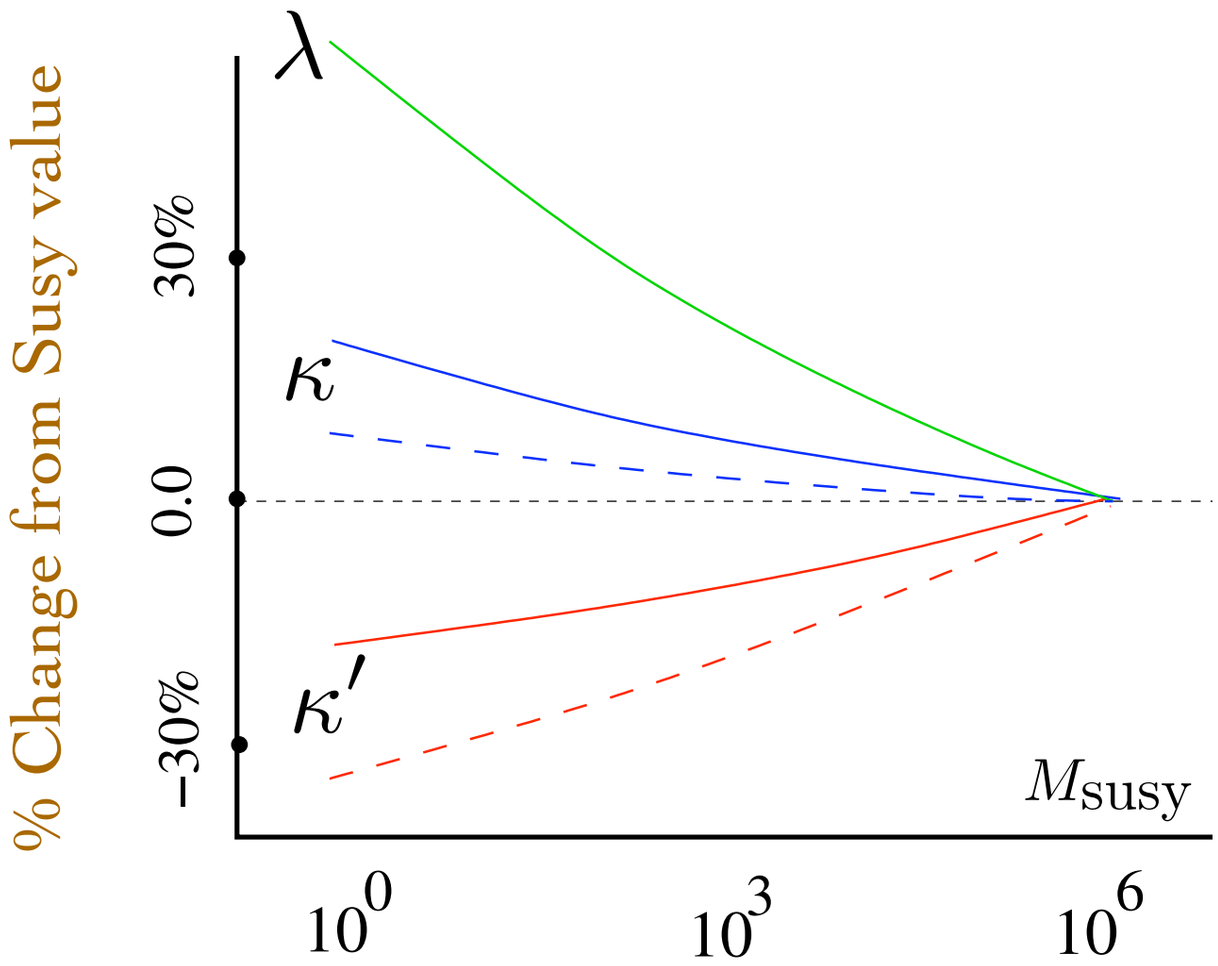
Taken from ATLAS note ATLAS-PHYS-PUB-2013-002



No Analysis for the 100 TeV machine

Electroweakinos and Higgsinos at the LHC

Gaugino and Higgsino Yukawa Coupling Unification

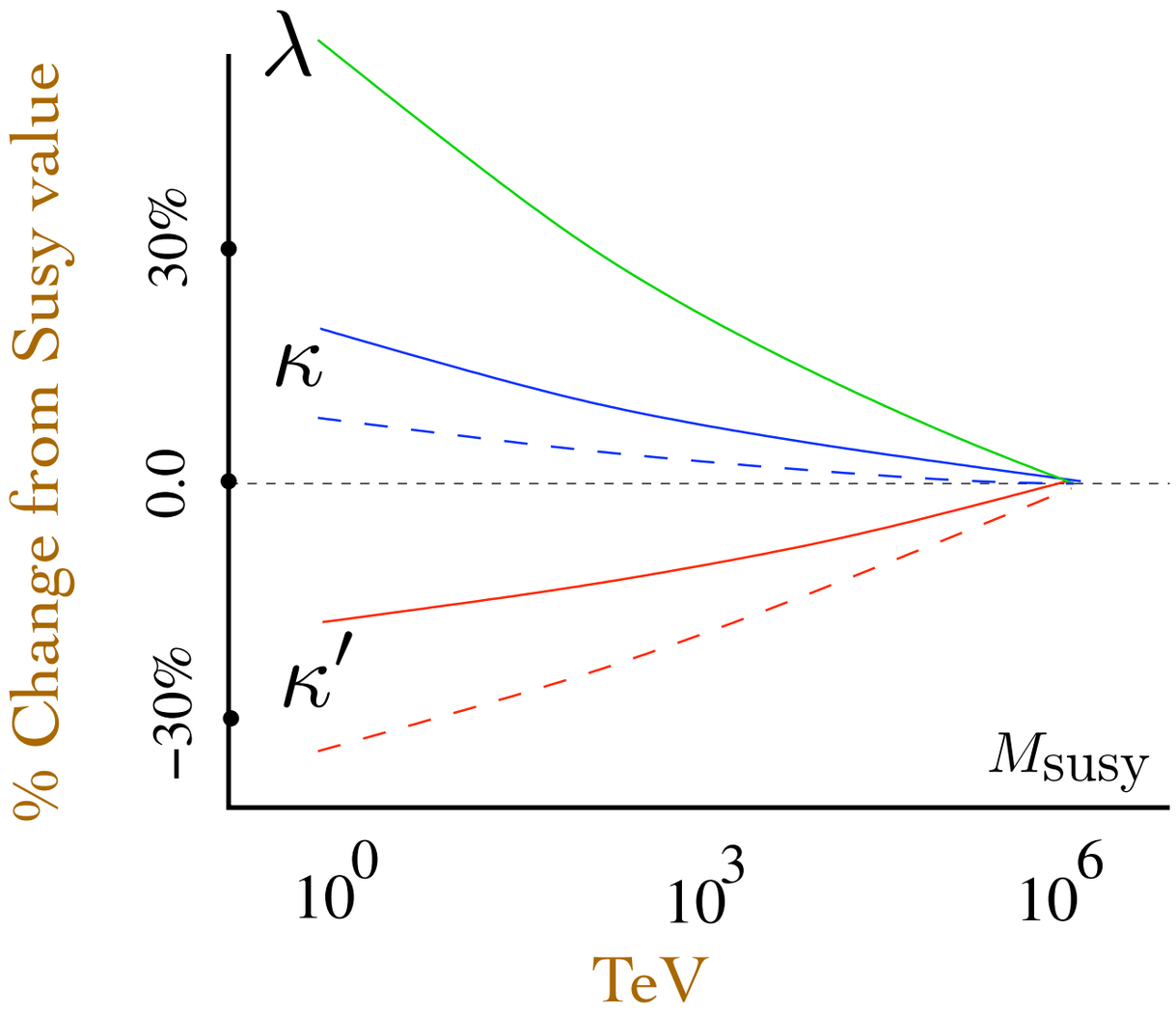


$$\kappa_u H \widetilde{H}_u \widetilde{W} + \kappa_d H^\dagger \widetilde{H}_d \widetilde{W} \qquad \kappa'_u H \widetilde{H}_u \widetilde{B} + \kappa'_d H^\dagger \widetilde{H}_d \widetilde{B}$$

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

- Displaced Winos and Higgsinos

- Yukawa Coupling Unification

Model Ranking

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

The Mystery of Naturalness

Sherlock: '[I draw your attention] to the curious incident of the dog in the night-time.'

Inspector: 'The dog did nothing in the night-time.'

Sherlock: 'That was the curious incident.'

Sherlock Holmes

-Silver Blaze

The Mystery of Naturalness

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"Data! Data! Data!" he cried impatiently. "I can't make bricks without clay."

Sherlock Holmes

-The Adventure of the Copper Beeches