BEYOND THE STANDARD MODEL

Lecture III

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R-PARITY

- Unlike in the SM, we cannot write down all interactions allowed by gauge symmetries:

$$W = \mu H_u H_d + Y_u Q_L H_u u_R + Y_d Q_L H_d d_R + Y_e L_L H_d e_R$$

$$+\hat{\mu} H_u L_L + \lambda'' u_R d_R d_R + \lambda' Q_L L_L d_R + \lambda L_L L_L e_R$$

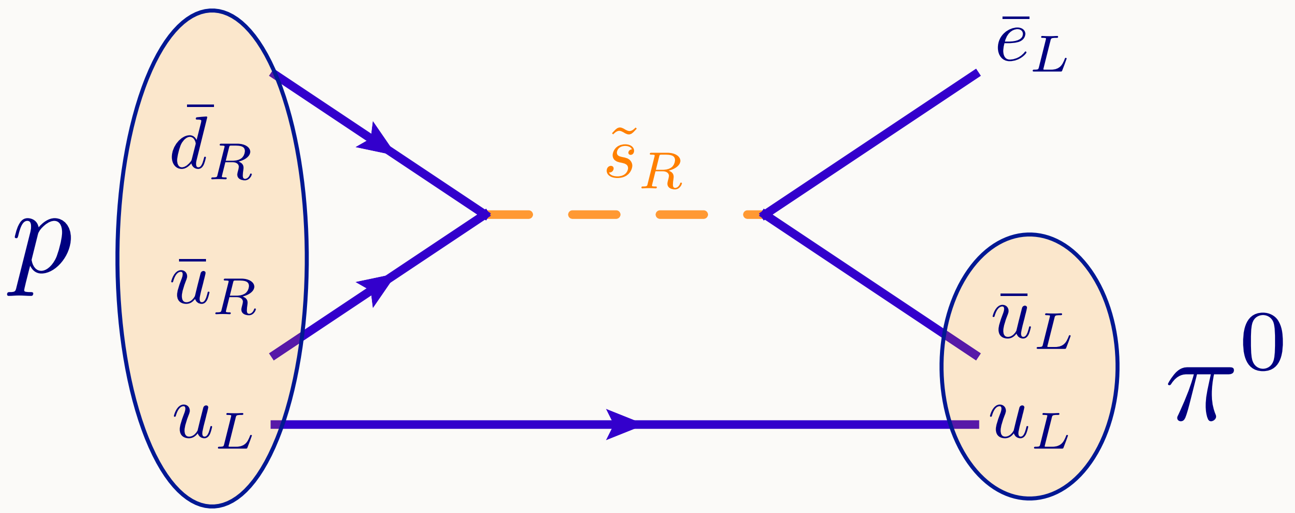
violates B

violates L

- Leads to whole tensors of new B and L-violating couplings:
  - e.g. Yukawas, $\lambda''_{112}(u_R d_R)\tilde{s}_R$, $\lambda'_{112}\tilde{s}_R(e_L u_L)$

R-PARITY

- Catastrophic proton decay:



- *B, L* violating Yukawa couplings must be extremely small:

$$\Gamma \sim \frac{|\lambda''_{112}\lambda'_{112}|^2 m_p^5}{m_{\tilde{s}}^4} < 10^{34} \text{ years}$$

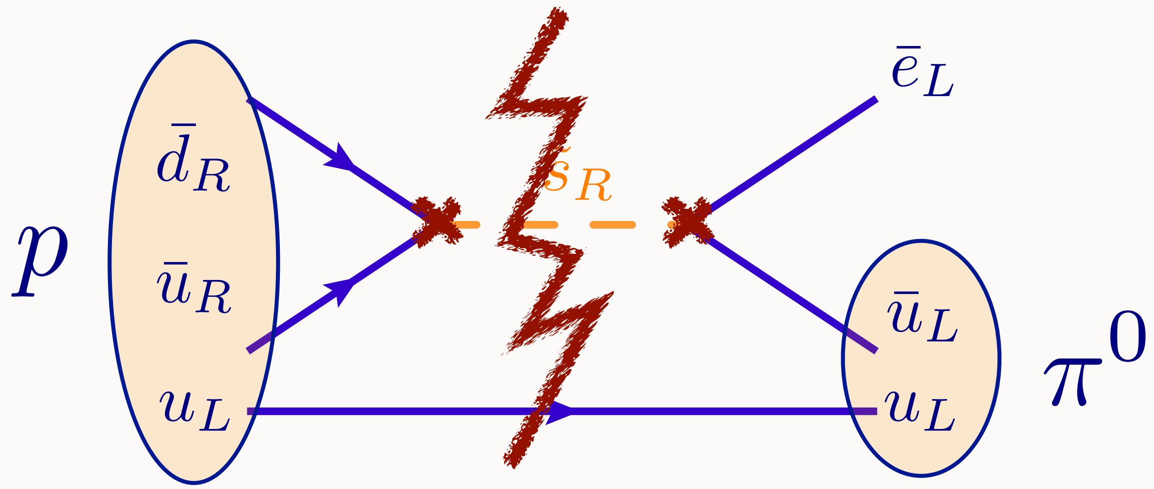
R-PARITY

- Easy solution: impose a new global symmetry:

$$W = \mu H_u H_d + Y_u Q_L H_u u_R + Y_d Q_L H_d d_R + Y_e L_L H_d e_R$$

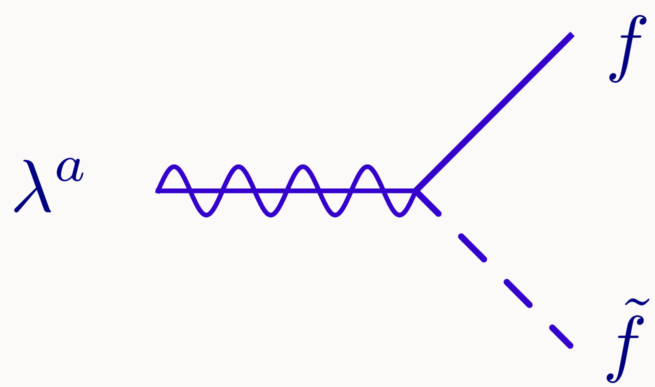
$$+\hat{\mu} H_u L_L + \lambda'' u_R d_R d_R + \lambda' Q_L L_L d_R + \lambda L_L L_L e_R$$

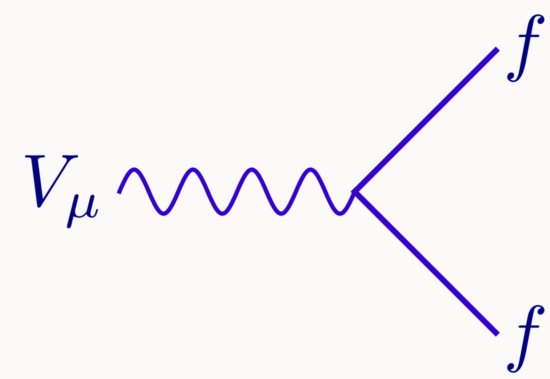
- matter parity: $P_M = (-1)^{3(B-L)}$



R-PARITY

- Gauge interactions:





- define *R*-parity:

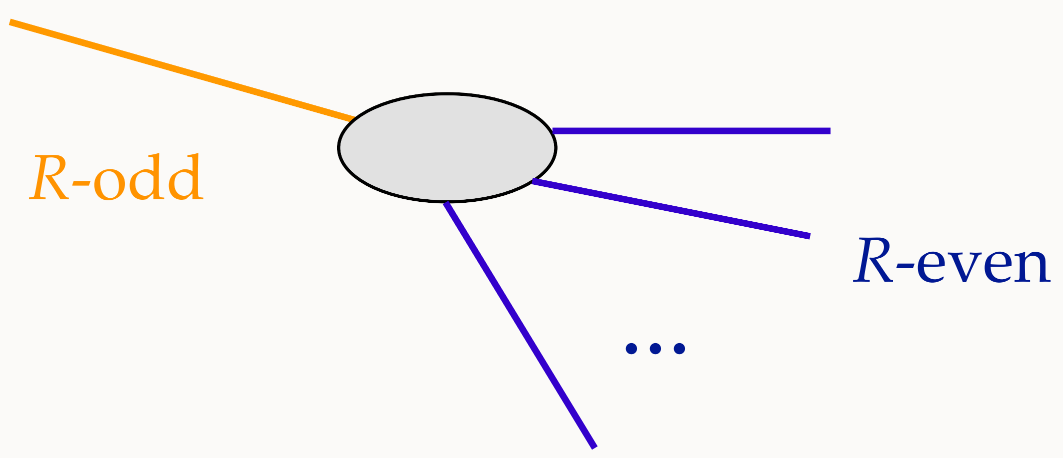
$$P_R = (-1)^{3(B-L)+2s}$$

  - exactly the same! but
    - easier to see consequences
    - natural in SUSY

even	odd
f (spin 1/2)	$\tilde{f}$ (spin 0)
V (spin 1)	$\tilde{V}$ (spin 1/2)
H (spin 0)	$\tilde{H}$ (spin 1/2)

R-PARITY

- Immediate consequence: lightest superpartner is stable



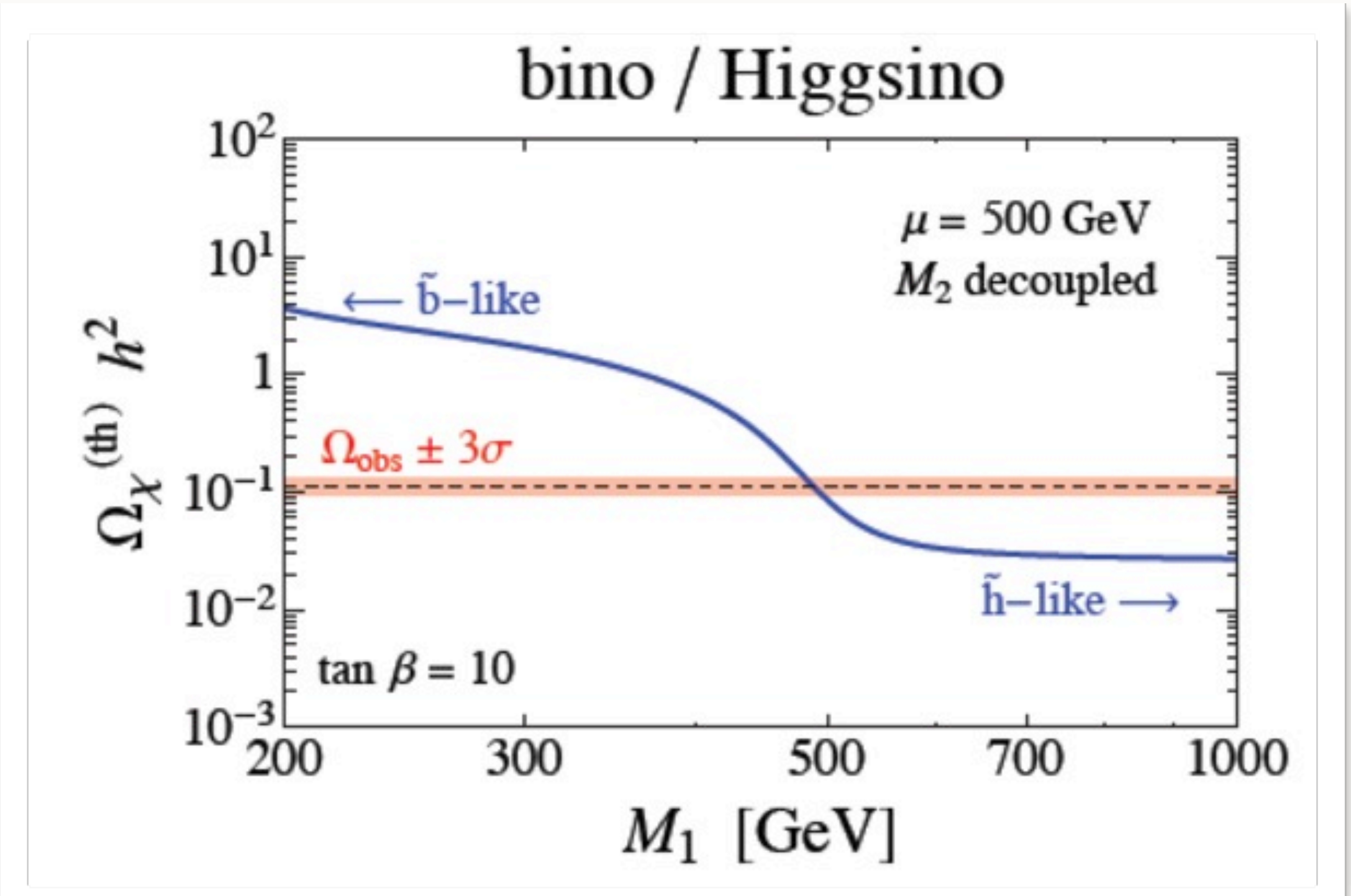
- This significantly restricts the spectrum:
  - lightest superpartner must be neutral
  - and must not over-close the universe

R-PARITY: DARK MATTER

- Lightest Supersymmetric Particle is an attractive DM candidate:
  - electroweak interactions, electroweak scale mass
  - Possible candidates:
    - neutralinos $\tilde{B}, \tilde{W}^3, \tilde{h}_u, \tilde{h}_d$
    - sneutrinos $\tilde{\nu}_L, \tilde{\nu}_R$
  - the devil is in the details...

R-PARITY: DARK MATTER

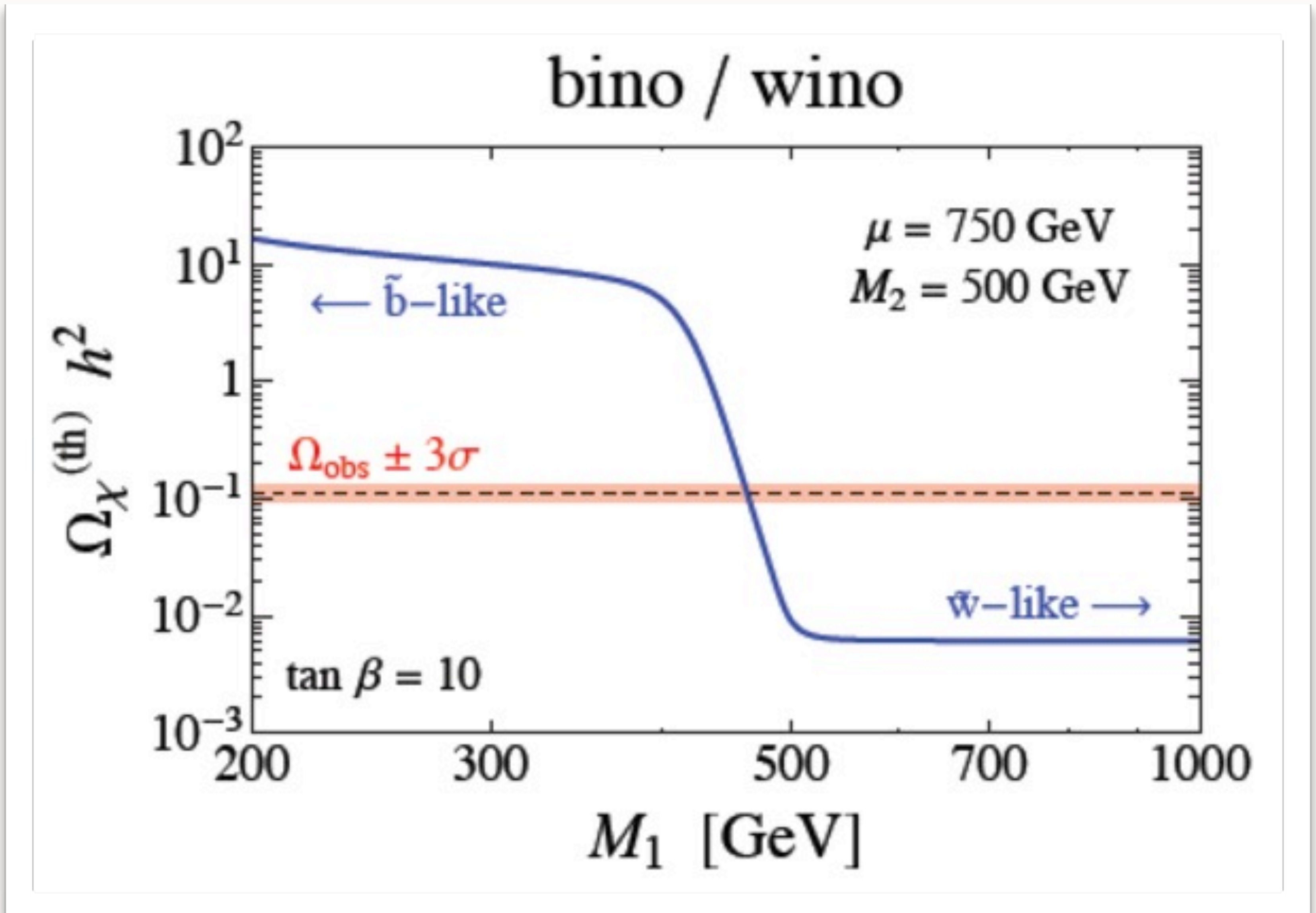
- Relic abundance delicate function of spectrum:



[Hall, Pinner, Ruderman]

R-PARITY: DARK MATTER

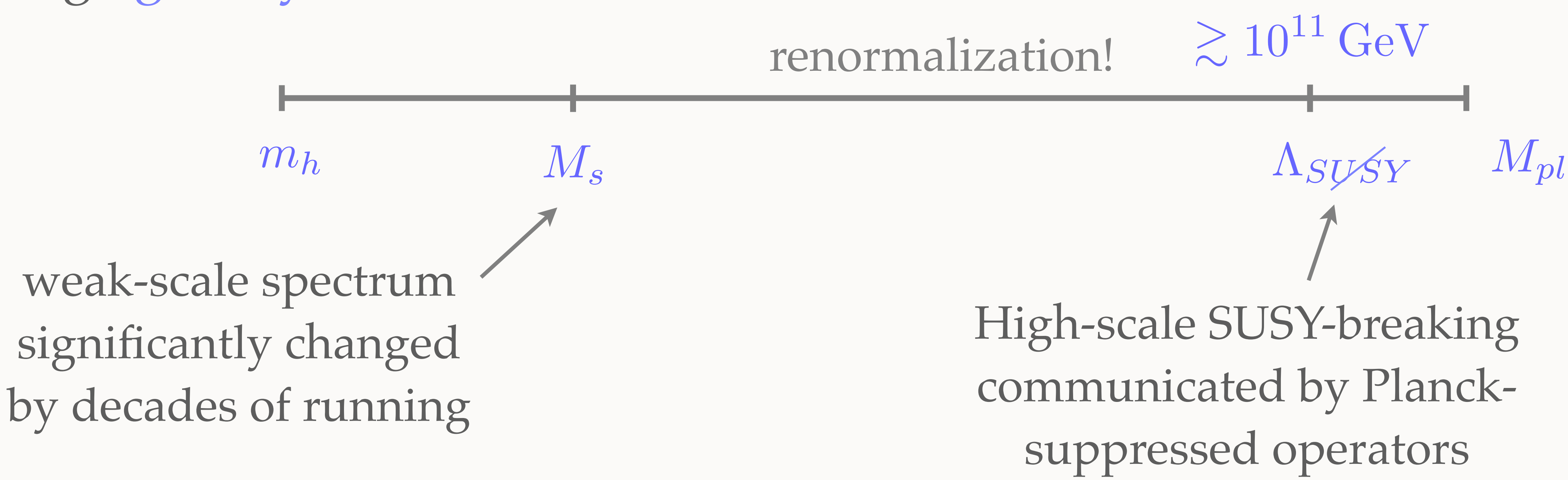
- Relic abundance delicate function of spectrum:



[Hall, Pinner, Ruderman]

MSSM SPECTRA

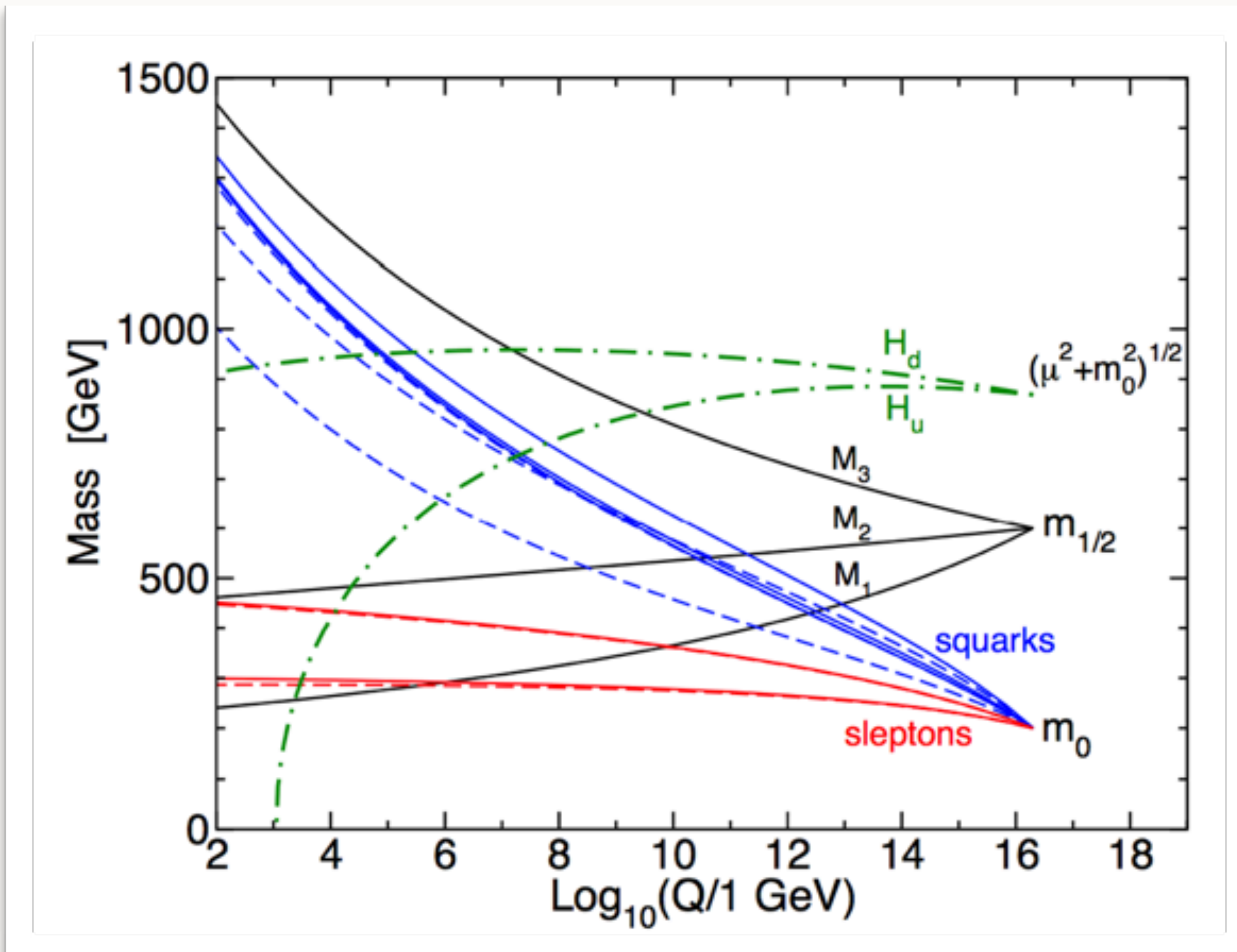
- High-scale SUSY breaking
  - e.g.: gravity-mediated



  - gravitino mass: $m_{3/2} = \frac{\Lambda^2_{SUSY}}{M_{Pl}}$ sets scale for soft masses

MSSM SPECTRA

- Effects of RG evolution:



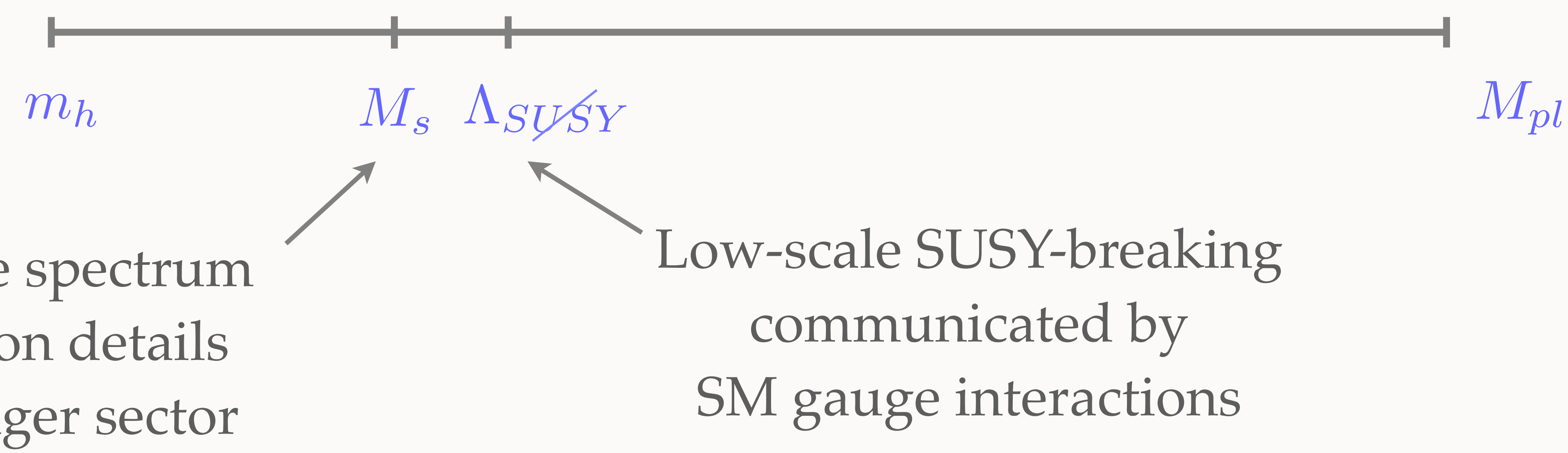
[Martin]

MSSM SPECTRA

- Simplest gravity-mediated model: mSUGRA
  - 100 parameters $\rightarrow$ 5
  - useful toy model! But highly simplified
- Biggest issue: flavor
  - Gravitational interactions don't care about flavor $\Longrightarrow$ anarchic flavor structure
  - Straightforward mediation requires sfermions $m \gtrsim 100\ \mathrm{TeV}$
  - (Maybe this is our universe? Sacrifice naturalness....)

MSSM SPECTRA

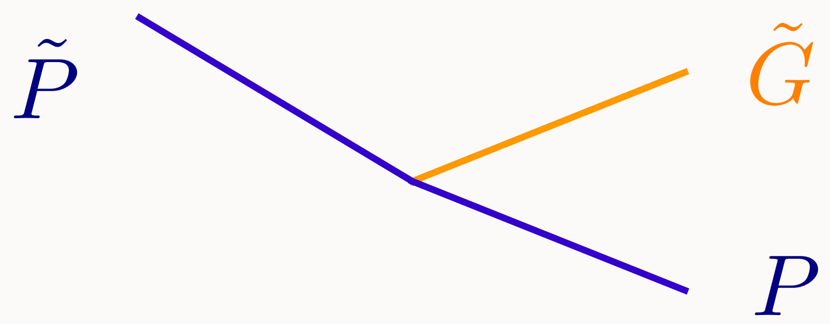
- Low-scale SUSY breaking
  - e.g.: gauge-mediated $\gtrsim 10\,\text{TeV}$



  - gravitino mass: $m_{3/2} = \dfrac{\Lambda^2_{SUSY}}{M_{Pl}}$
  - soft masses: $m_{soft} \sim \dfrac{\alpha}{4\pi}\Lambda_{SUSY}$

MSSM SPECTRA

- Gravitino is the LSP
  - Cosmology very different - no more neutralino dark matter
  - Now charged superpartners can be the NLSP:



  - Decay of NLSP to gravitino can be prompt or displaced
- Big plus: neatly solves flavor problem

MSSM SPECTRA

- But...
  - adding charged mediators can make it tricky to maintain gauge unification
  - new cosmological problems with non-thermally produced stable gravitinos
  - Biggest disadvantage: hard to accommodate $m_h = 125$ GeV

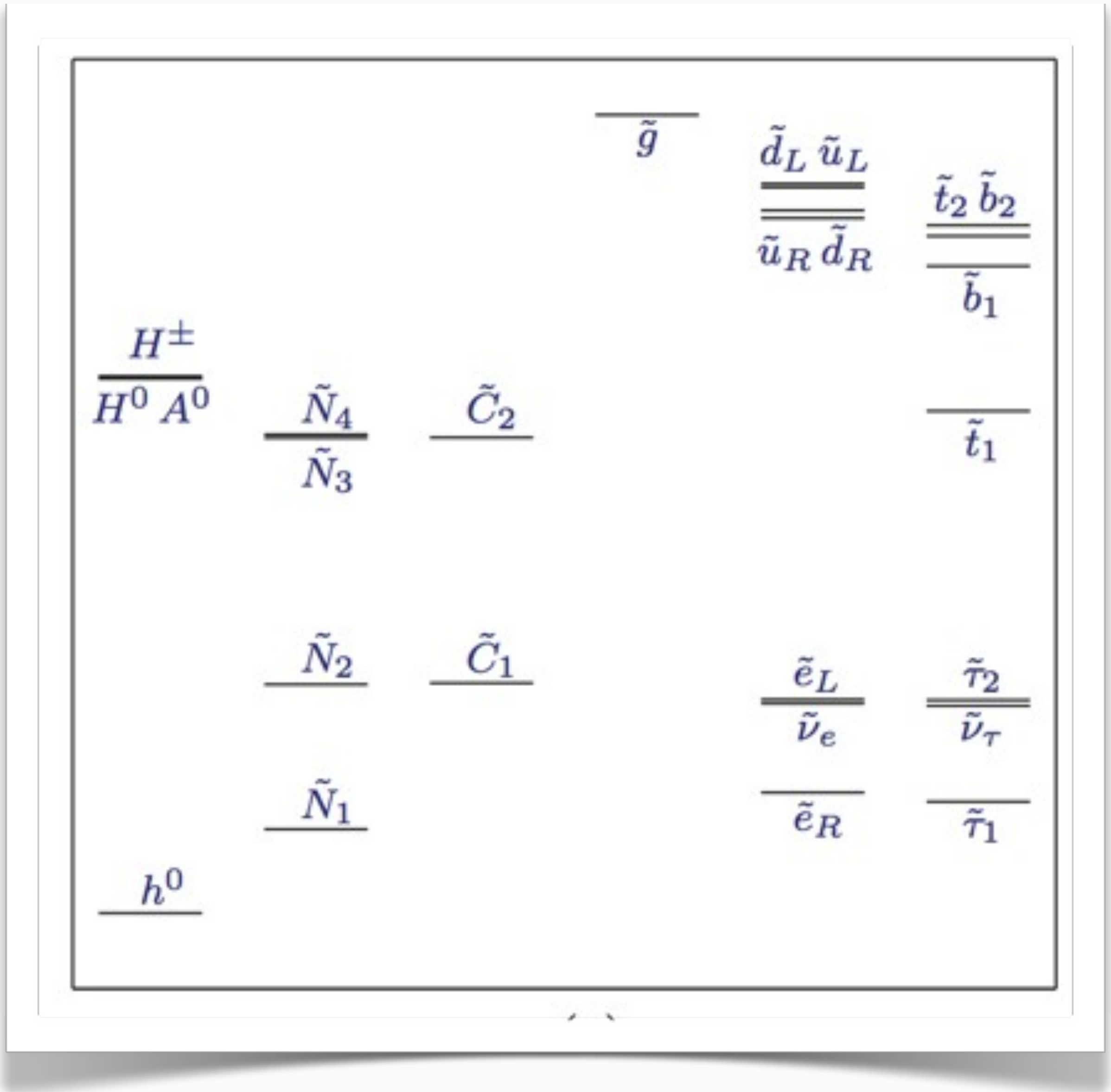
MSSM SPECTRA

- Have never yet developed a completely convincing top-down model of SUSY-breaking

- Since experimental signatures extremely sensitive to detailed spectrum, important to consider bottom-up approaches and make sure bases are covered

MSSM SPECTRA

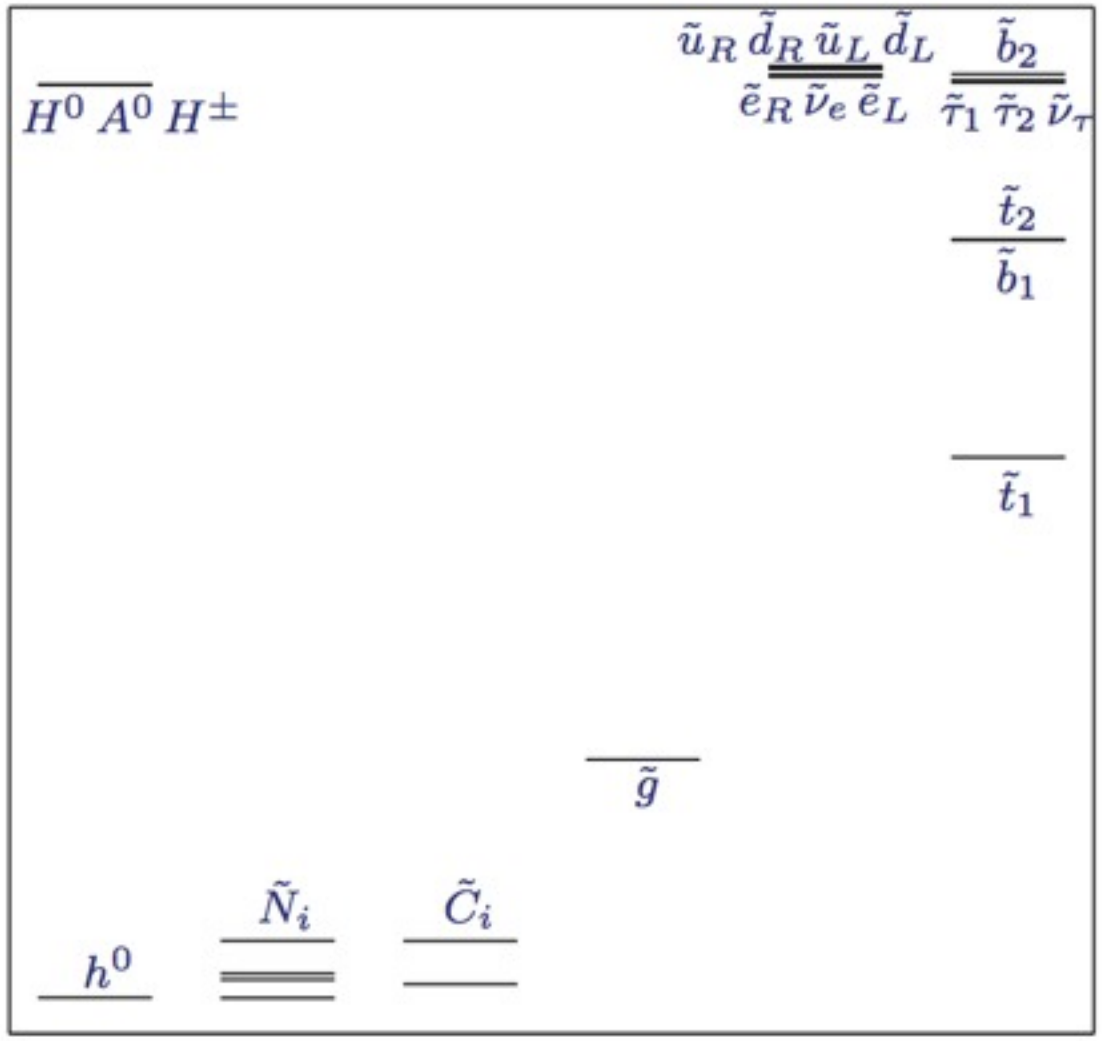
- Example gravity-mediated spectrum



[Martin]

MSSM SPECTRA

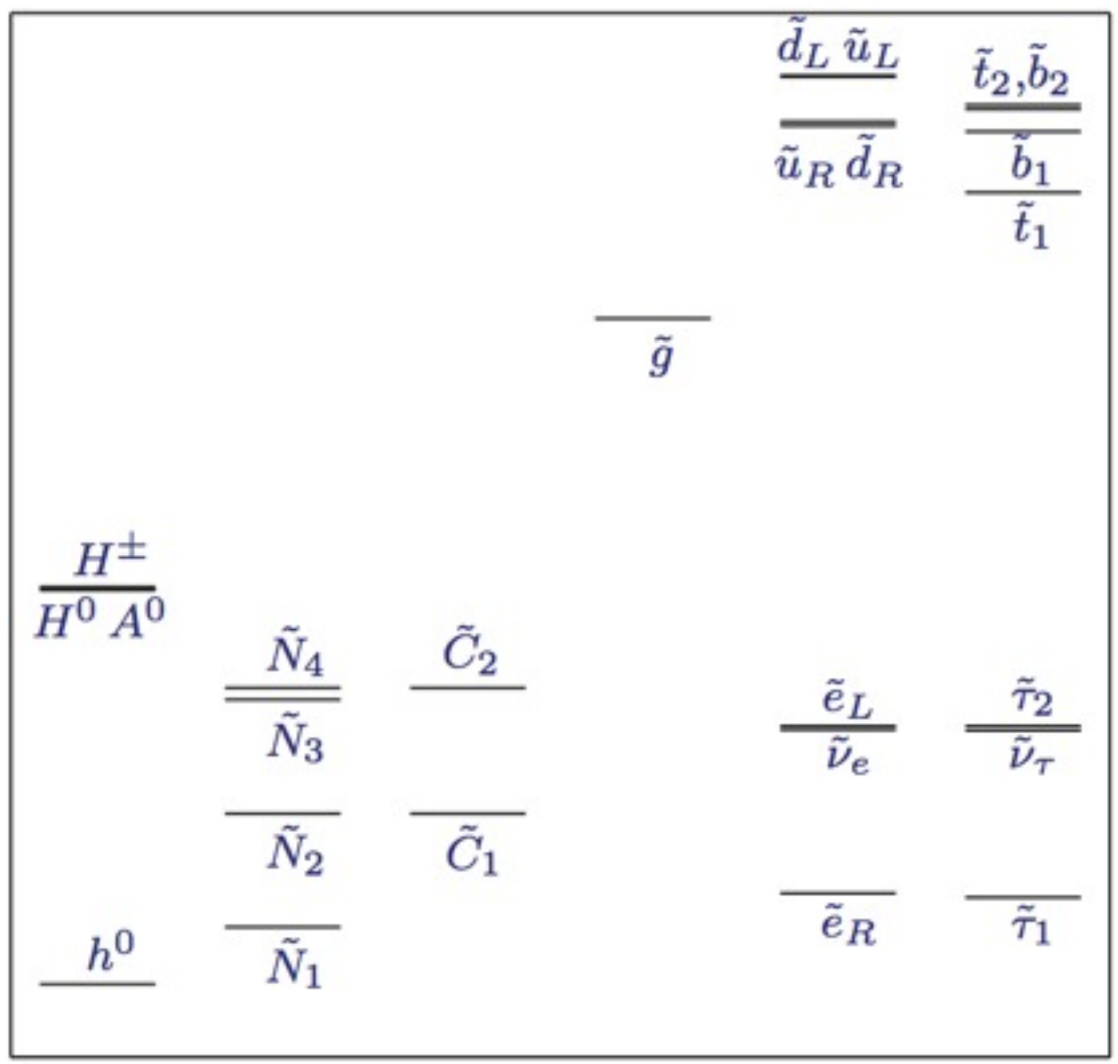
- Example gravity-mediated spectrum



[Martin]

MSSM SPECTRA

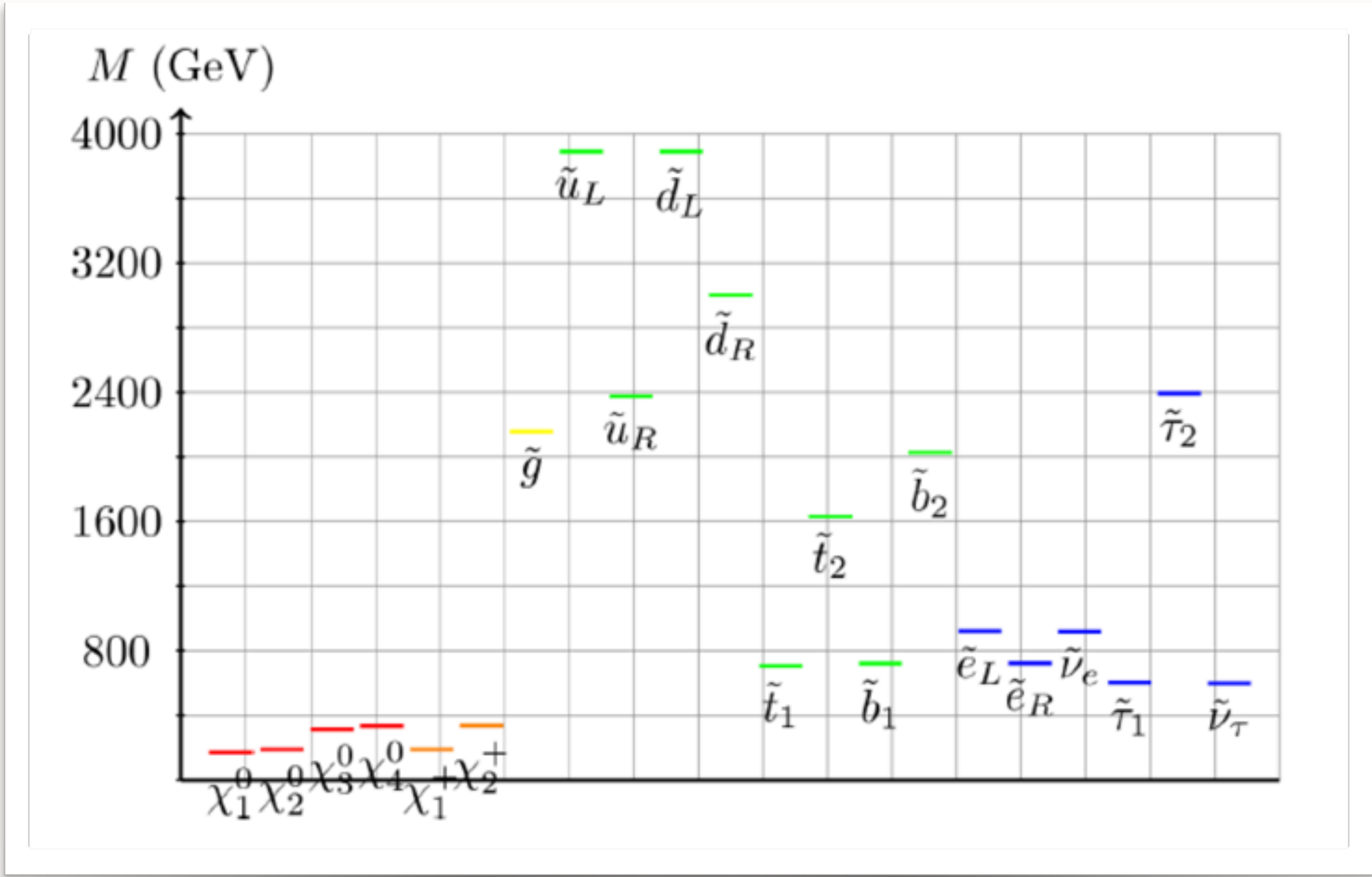
- Example gauge-mediated spectrum



[Martin]

MSSM SPECTRA

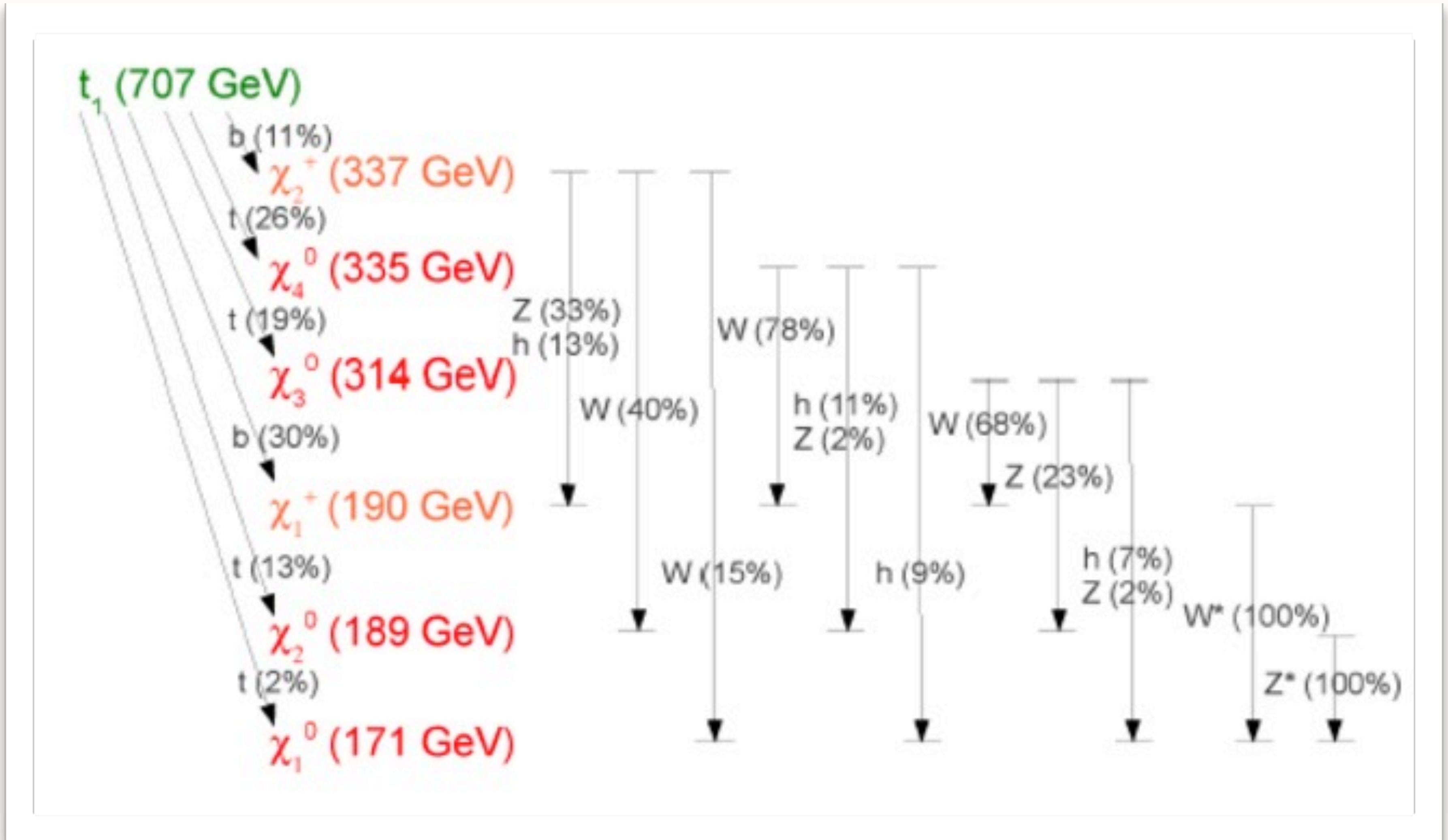
- Example bottom-up spectrum



[Cahill-Rowley, Hewett, Ismail, Rizzo]

MSSM SPECTRA

- Rich spectrum means complicated decays:



[Cahill-Rowley, Hewett, Ismail, Rizzo: 1407.4130]

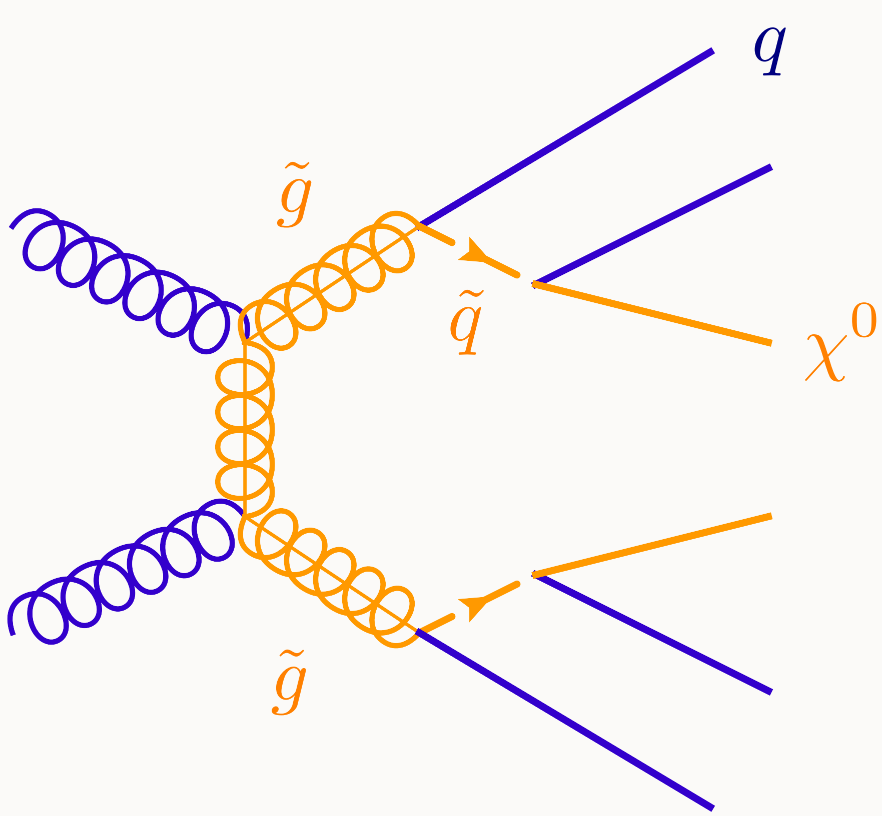
SUSY SEARCHES

- Given enormous complexity and variability of signals, how should we design SUSY searches at colliders?

SUSY AT COLLIDERS

- *R*-parity: produce superparticles in pairs

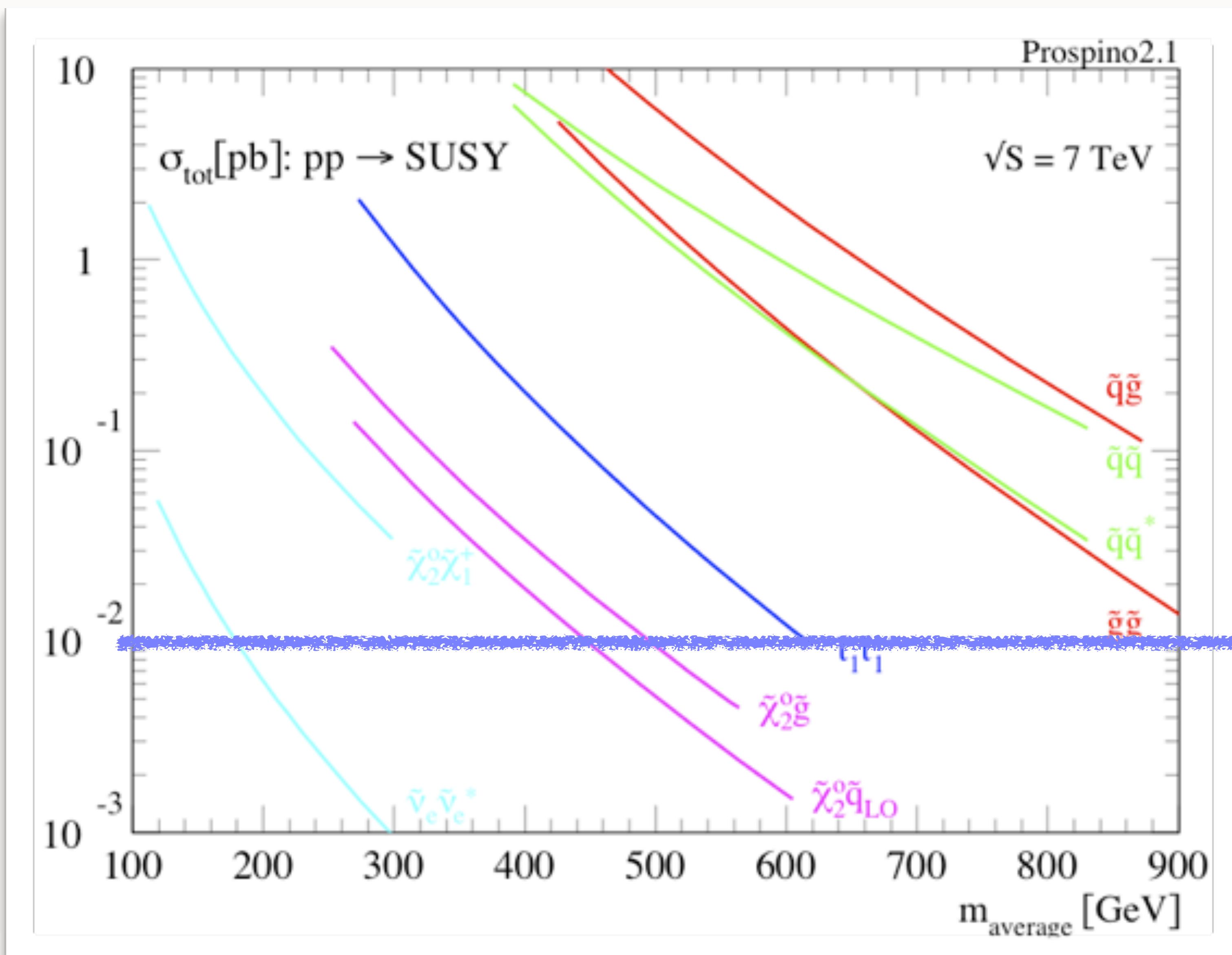
gluino pair production



- superparticles cascade down to pairs of (N)LSPs: generic missing energy

SUSY AT COLLIDERS

- Superpartner production cross-sections

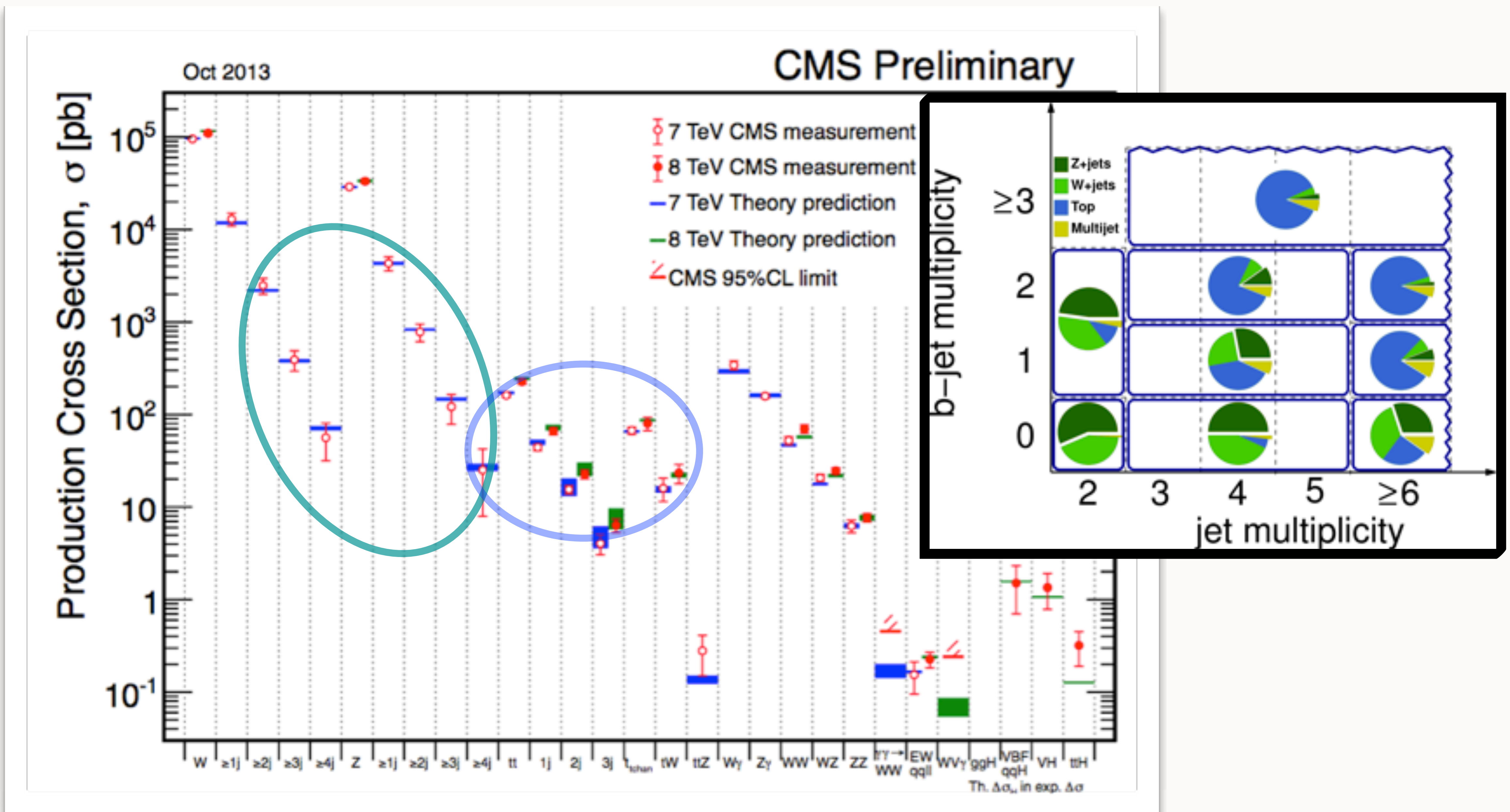


colored states dominate production

~10 events in 1 fb^{-1}

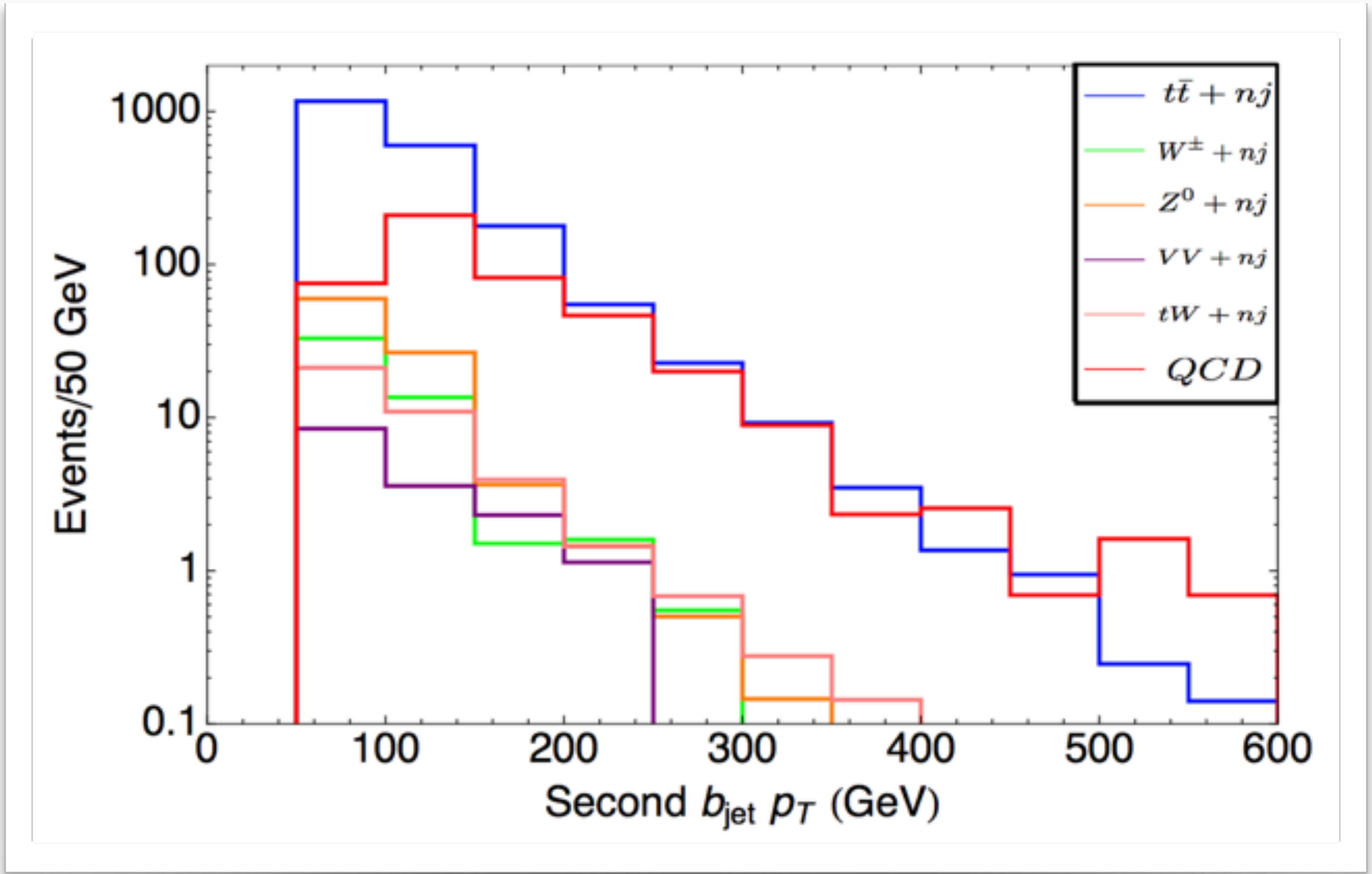
SUSY AT COLLIDERS

- SM background cross-sections are much larger overall



SUSY AT COLLIDERS

- ...but fall off rapidly with just about any kinematic variable that has dimensions of mass:



[Essig, Izaguirre, Kaplan, Wacker]

SUSY AT COLLIDERS

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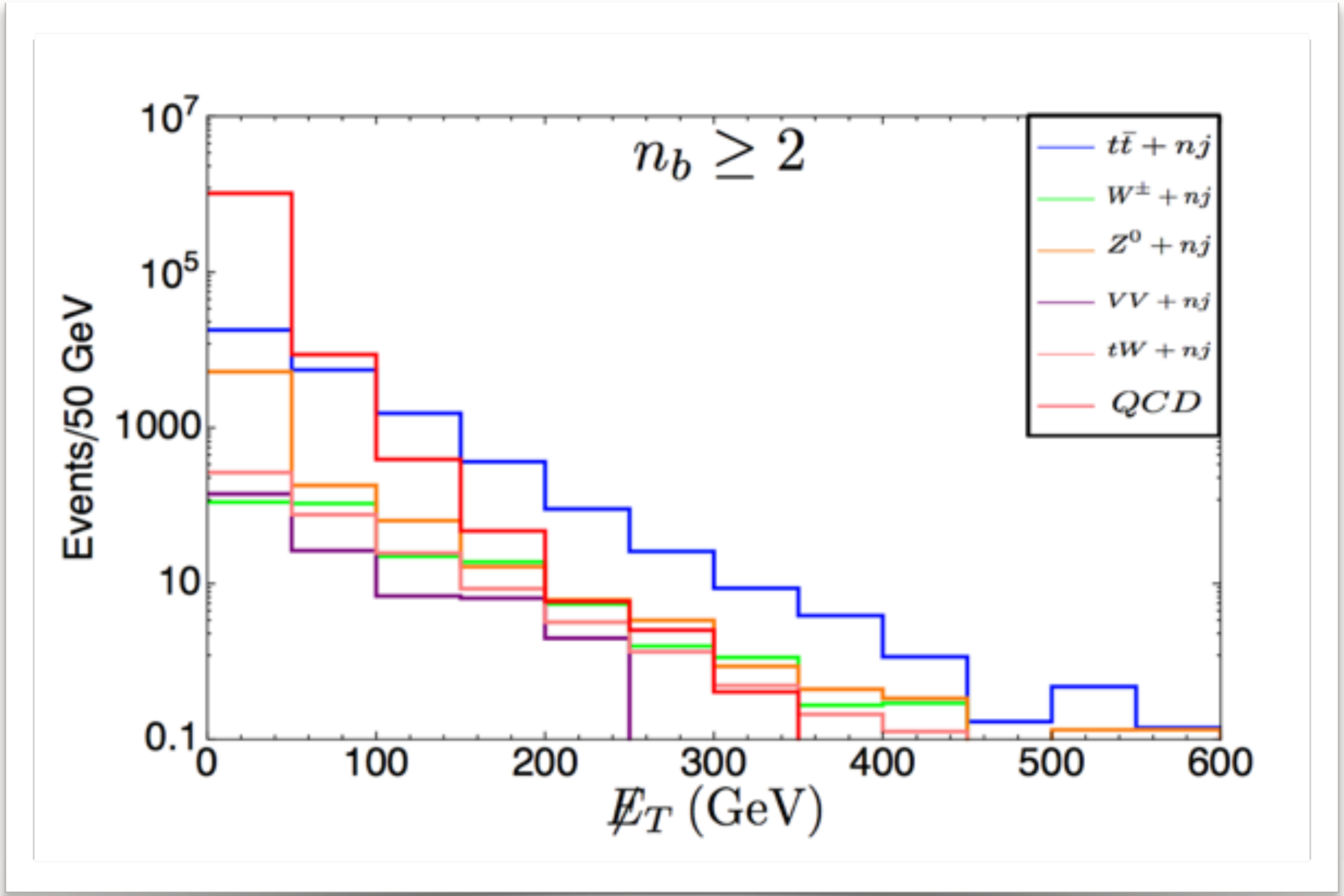
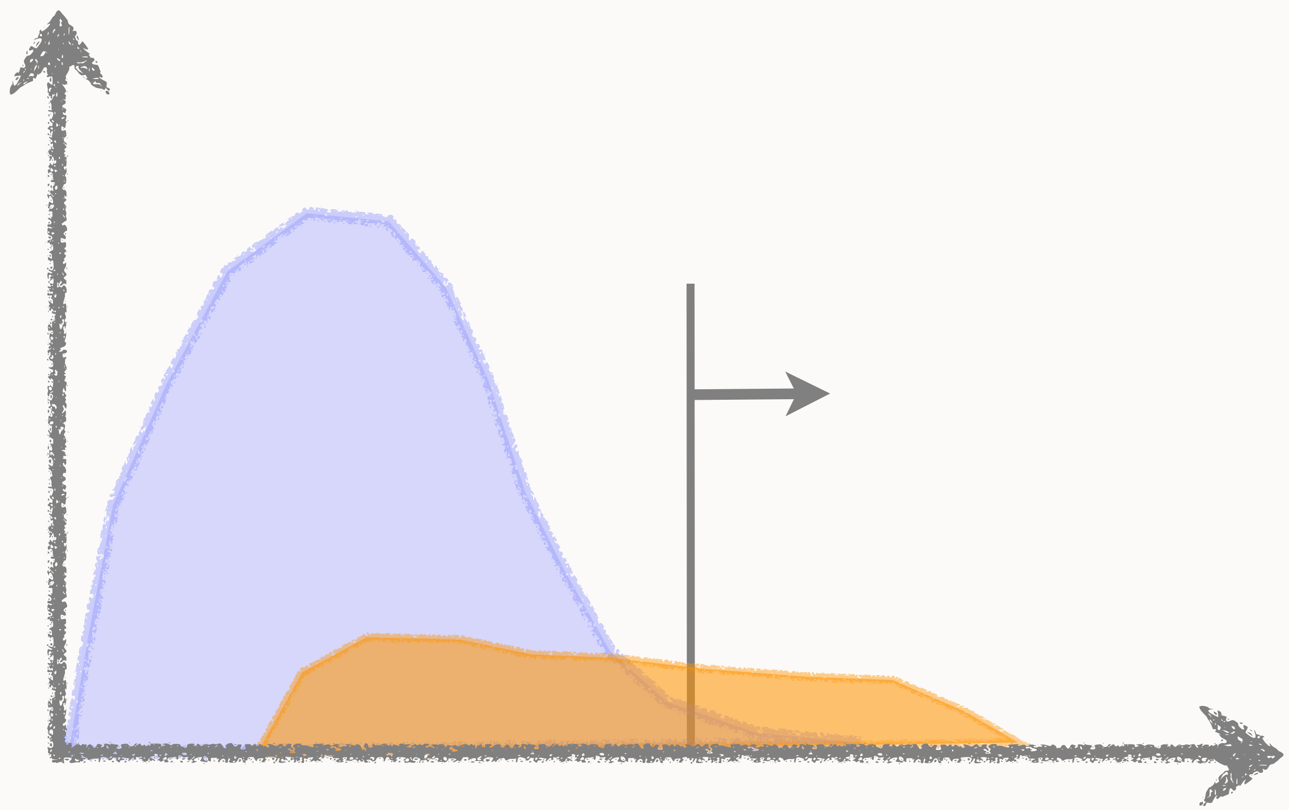


[Essig, Izaguirre, Kaplan, Wacker]

SUSY SEARCHES

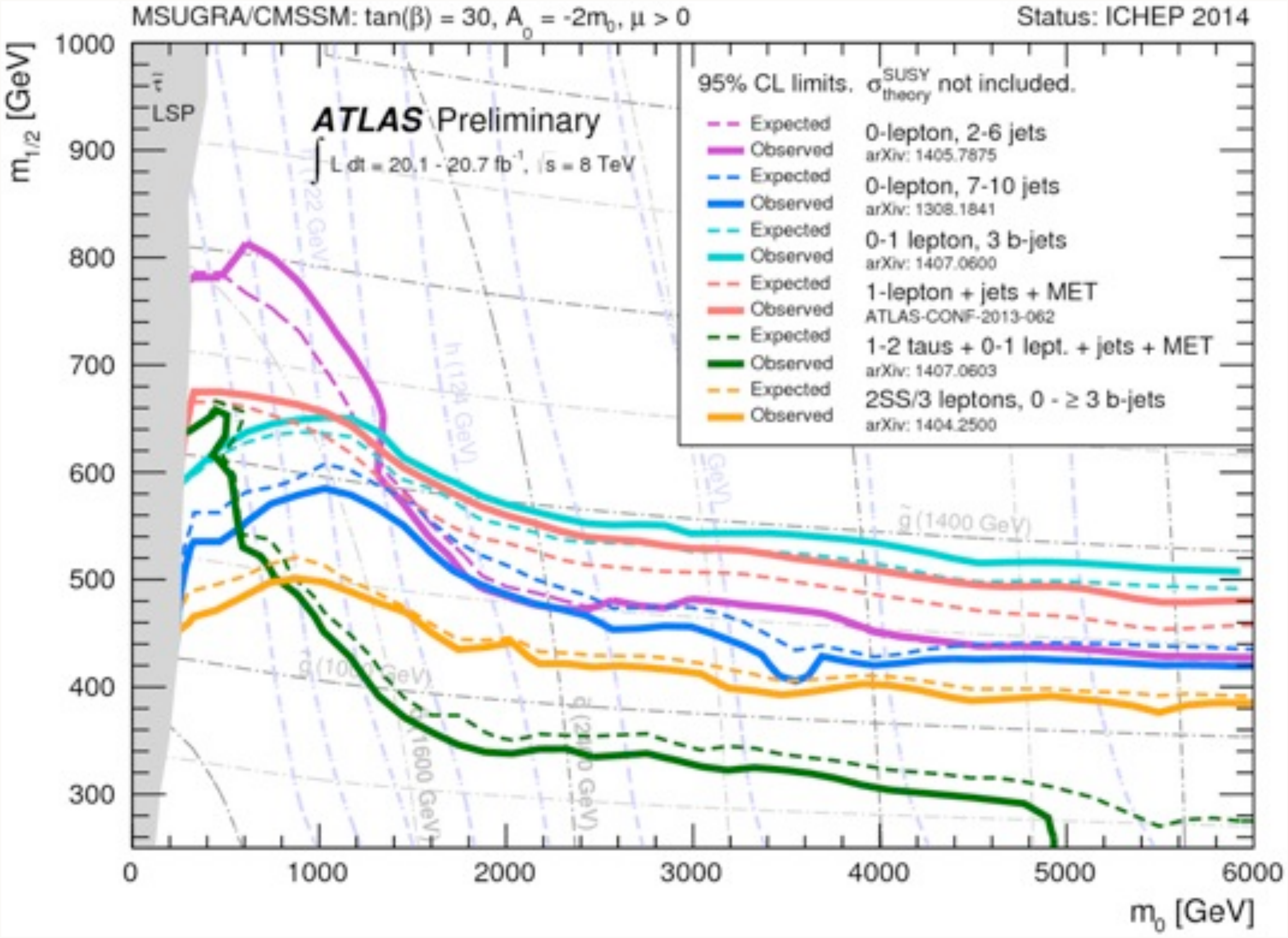
- Essential discovery strategy:



- demand certain numbers of objects (jets, *b*-jets, MET, leptons...)
- determine a suitable kinematic variable or two
- count events in the energetic tail

SUSY SEARCHES

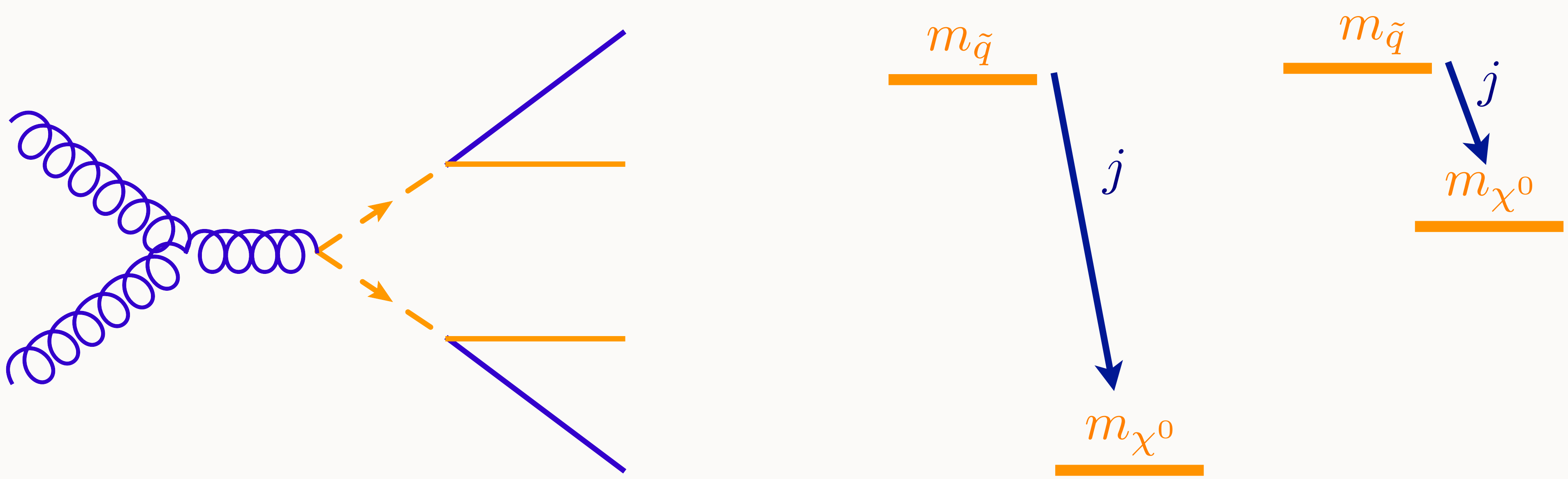
- Efficiently parameterize search for whole model at once?



- not transparent; not flexible

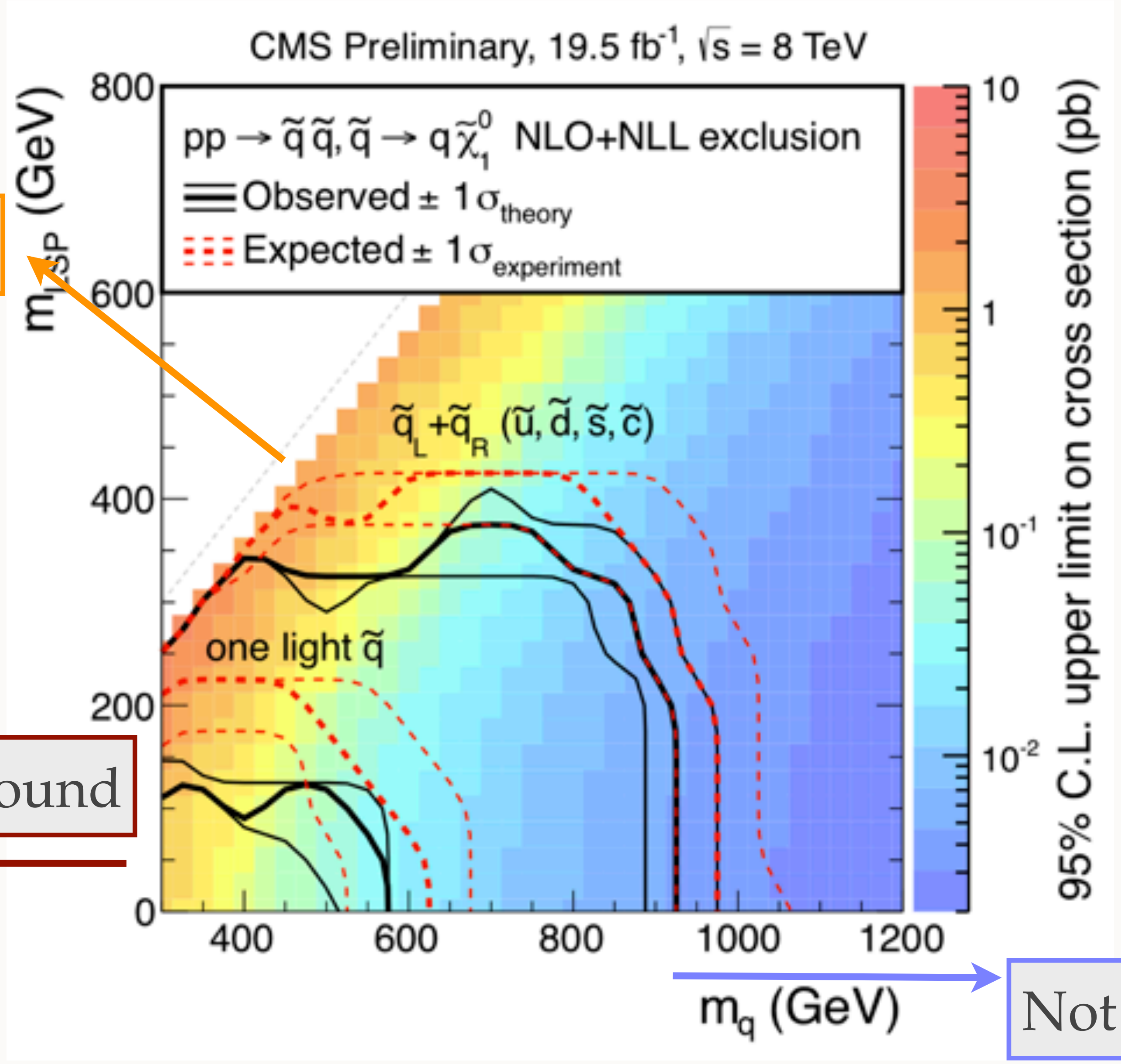
SUSY SEARCHES

- Design search regions that balance:
  - high signal efficiency, i.e., are well-targeted to the model
  - flexibility, i.e., also have reach for the model next door
- Useful to focus on a few particles at a time:



SUSY SEARCHES

- Results for specific production and decay chain:



Not enough MET

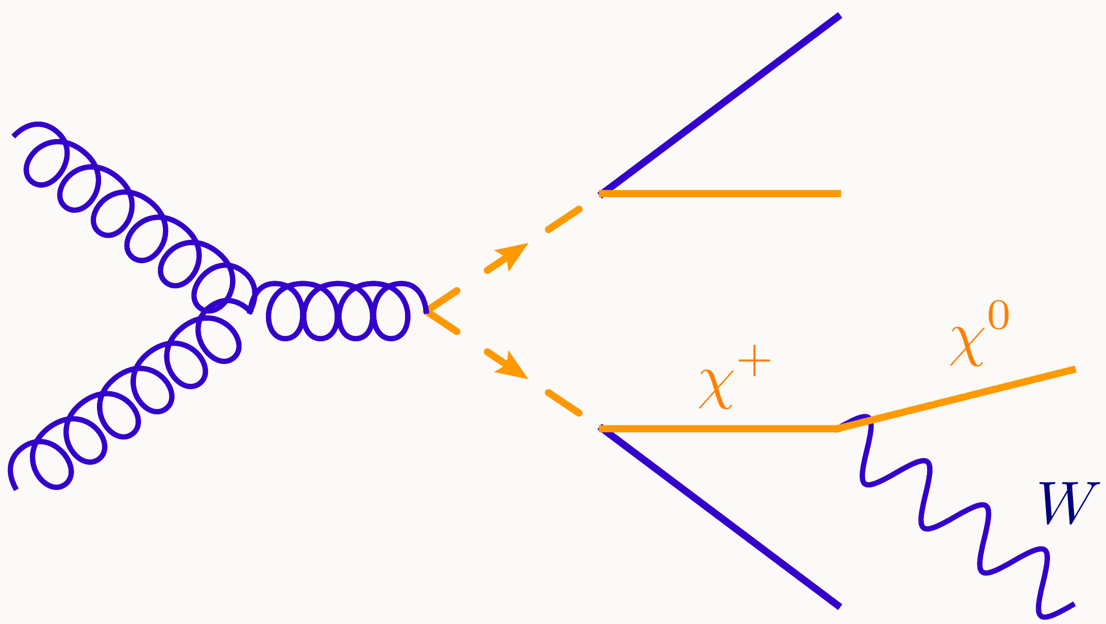
Too much background

Not enough signal events

Big difference:
8 squarks
vs
1 squark

SUSY SEARCHES

- Often a model will predict additional processes:



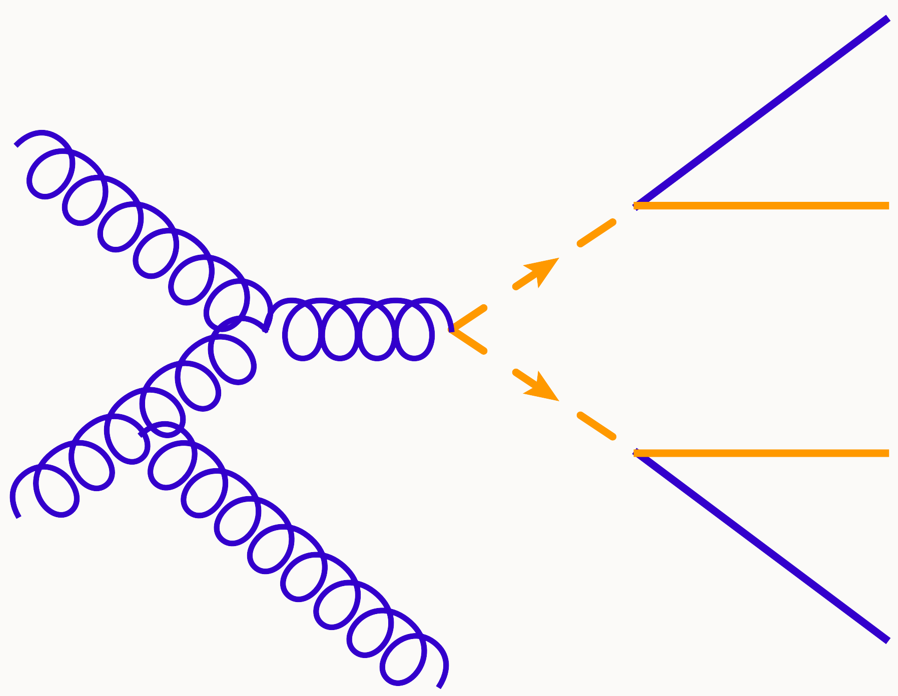
- Different search: jets + MET + lepton
- define enough search regions to cover almost all production, decay modes; kinematics
- and remember that a typical MSSM signal will have finite branching ratios for any specific search topology

SUSY SEARCHES

- Search reach is maximized for:
  - high, but not too high, mass
  - large cross-section: many colored degrees of freedom
  - lots of MET
- Much remaining space for SUSY signals (and BSM signals in general!) where these conditions break down

SQUEEZED SUSY

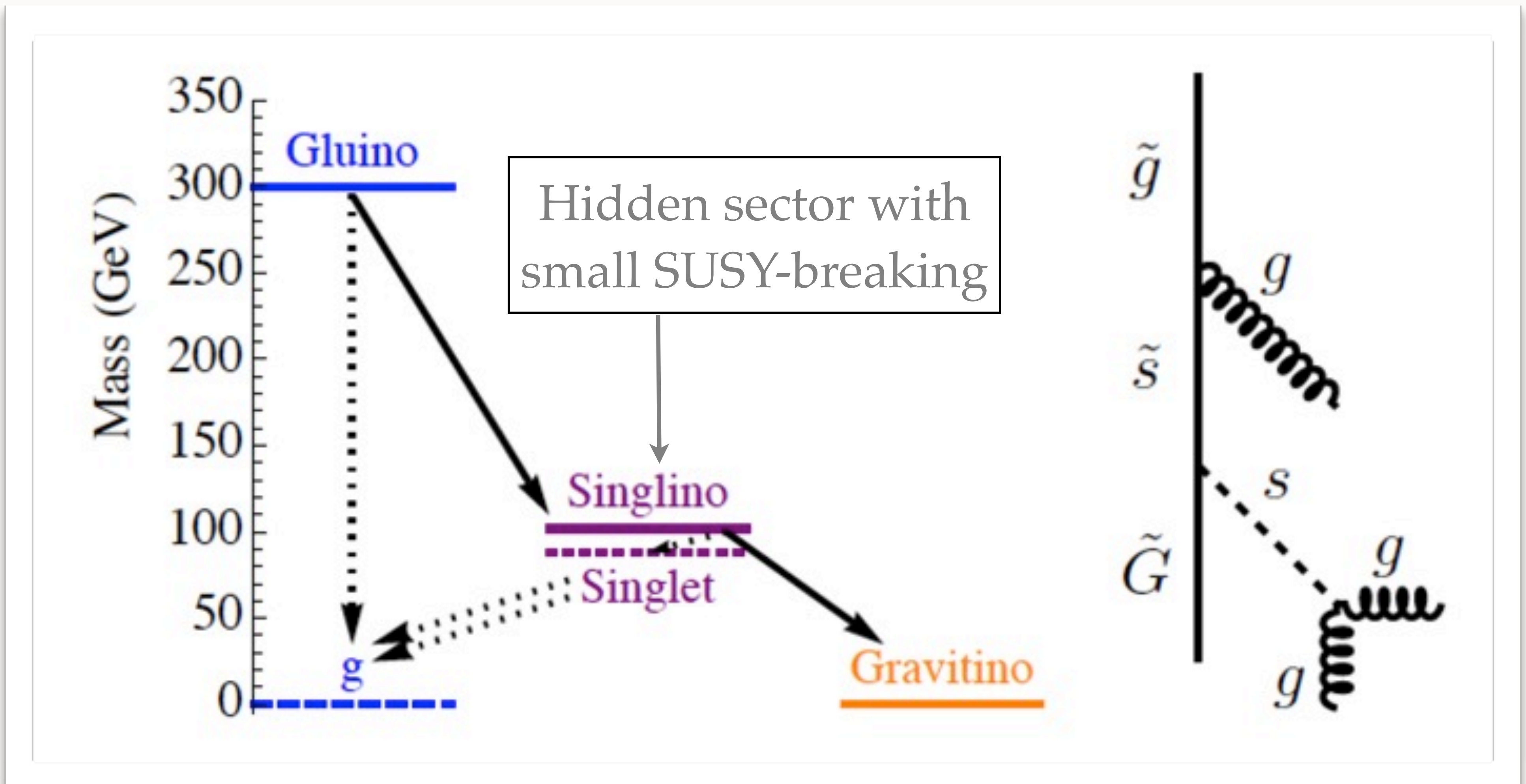
- Maybe SUSY spectrum is very compressed?



  - Need hard ISR jet: reduces rate by $\mathcal{O}(\alpha_s) \sim 0.1$

STEALTH SUSY

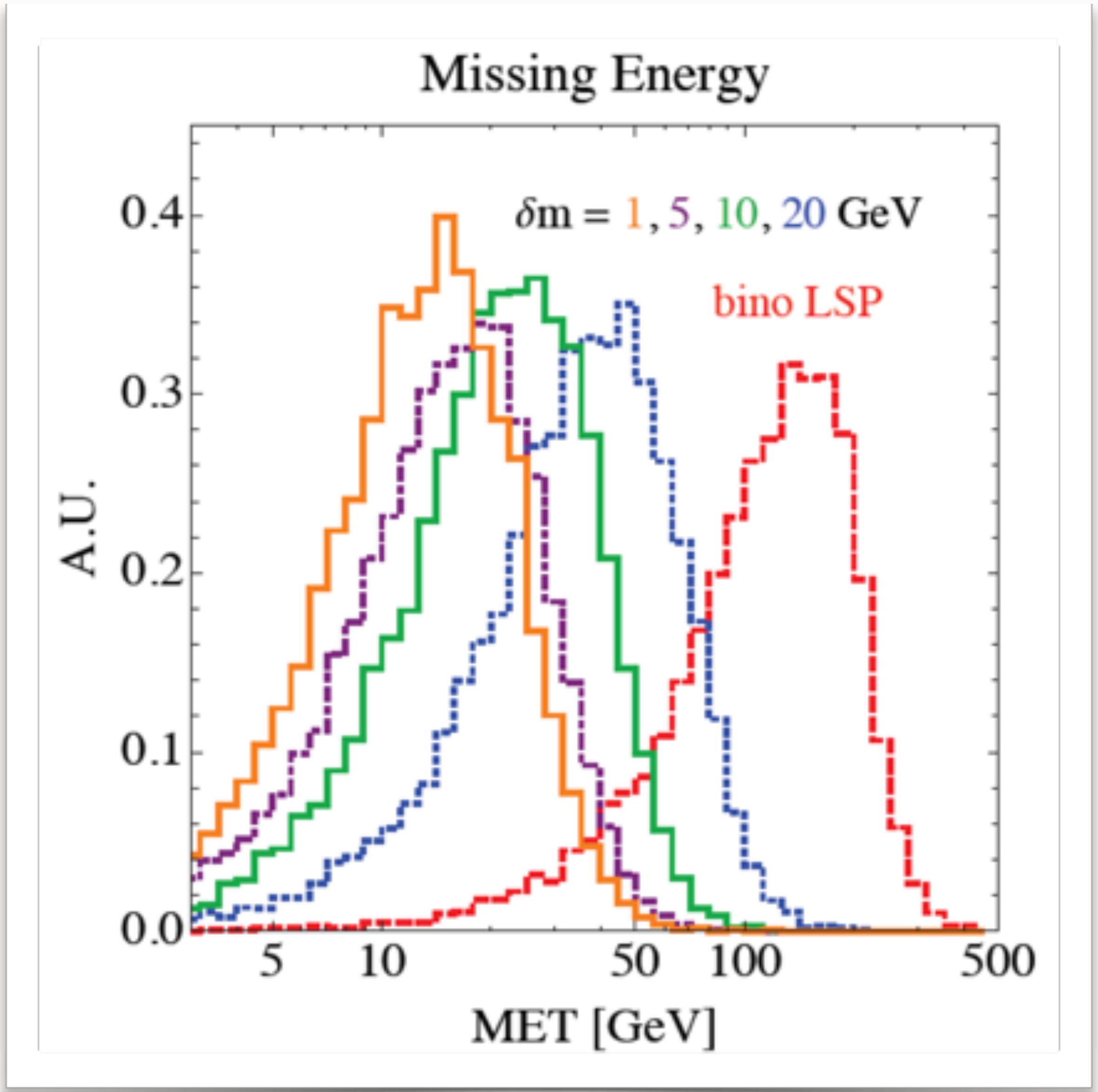
- Can also hide SUSY by sticking a small mass splitting on the end of the cascade decay:



[Fan, Reece, Ruderman]

STEALTH SUSY

- Trading MET for high jet multiplicities

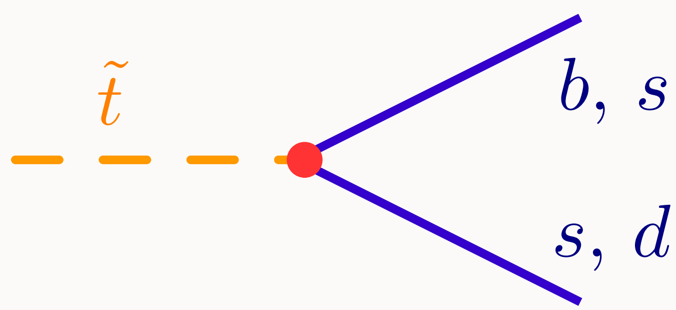


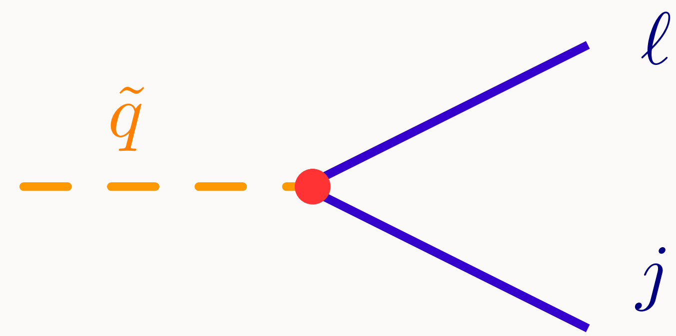
- Experimental handles:
  - resonances
  - possibly: high-multiplicity *b*-jets
  - possibly: displaced vertices
- Hidden sectors signatures: more tomorrow

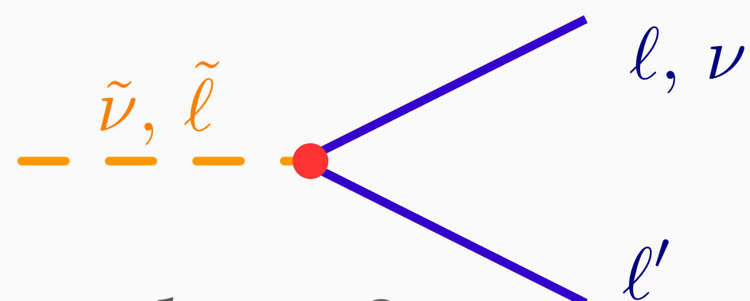
[Fan, Reece, Ruderman]

RPV SUSY

- Can eliminate MET signal with just the MSSM: allow *R*-parity violating couplings







- But what about proton decay?
  - switch on only *B*-violating or only *L*-violating couplings

RPV SUSY

- Still expect pair production to dominate: $\lambda_{RPV} \ll g, g_s$

squark is lightest neutralino/chargino is lightest

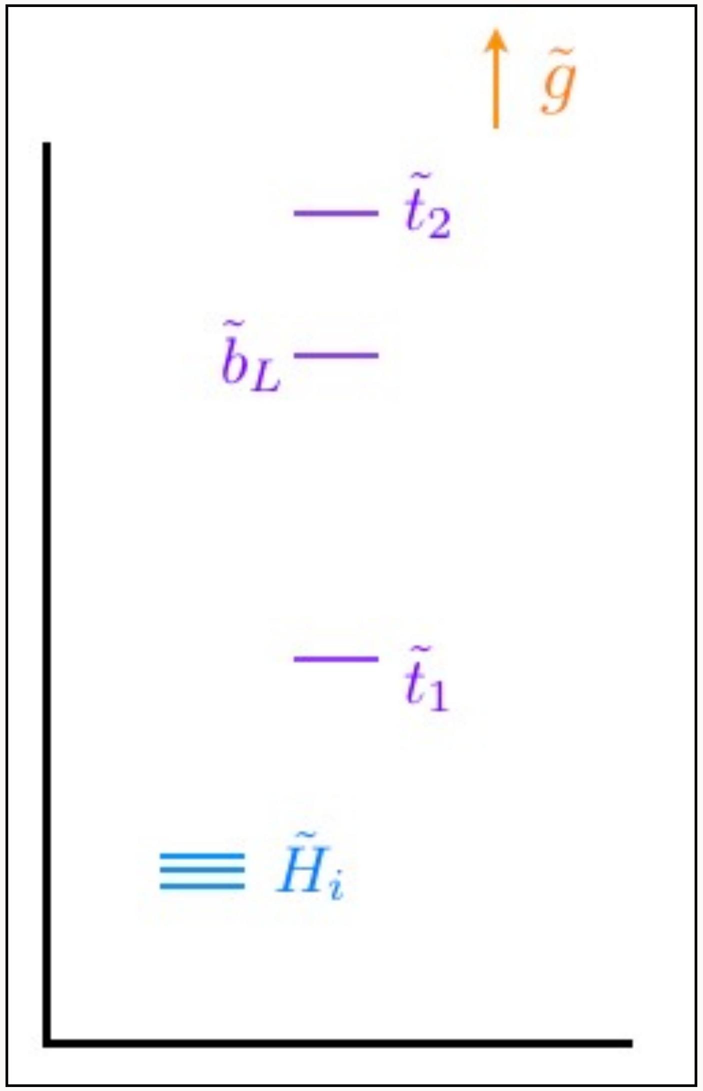
- Signatures have variable number of jets (and/or leptons, tops), 2 or 3 object resonances, possibly displaced vertices

RPV SUSY

- Cosmologically these models look very different:
  - Lose dark matter candidate
  - Gain baryogenesis mechanism
- Search reach highly dependent on spectrum, type, flavor structure of RPV coupling
  - leptonic RPV: excellent (e.g.: gluinos excluded up to kinematic limit)
  - all-hadronic: much harder (e.g.: $\tilde{g} \to jjj$ excluded up to ~650 GeV)

NATURAL SUSY

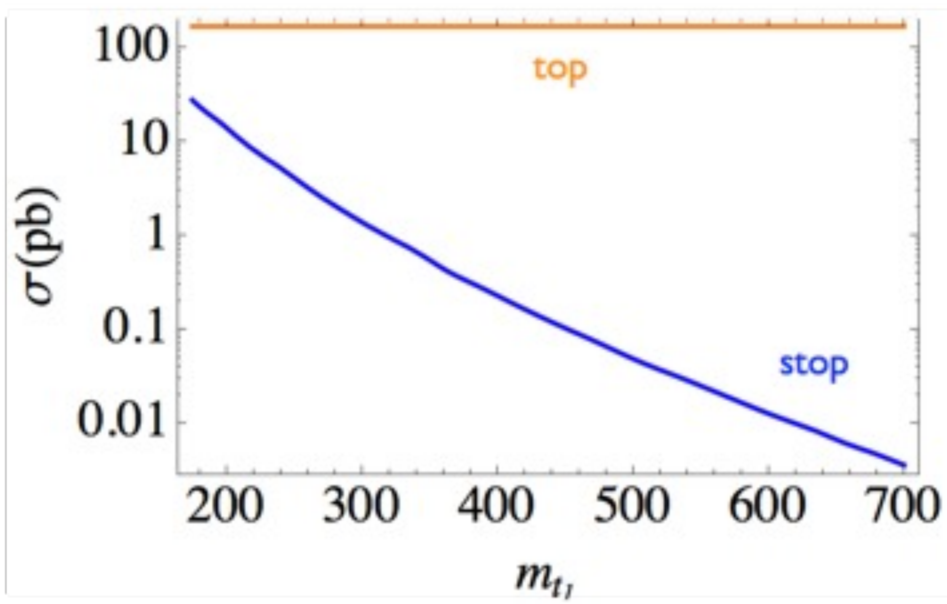
- Maybe we don’t have the whole zoo of MSSM states near the weak scale

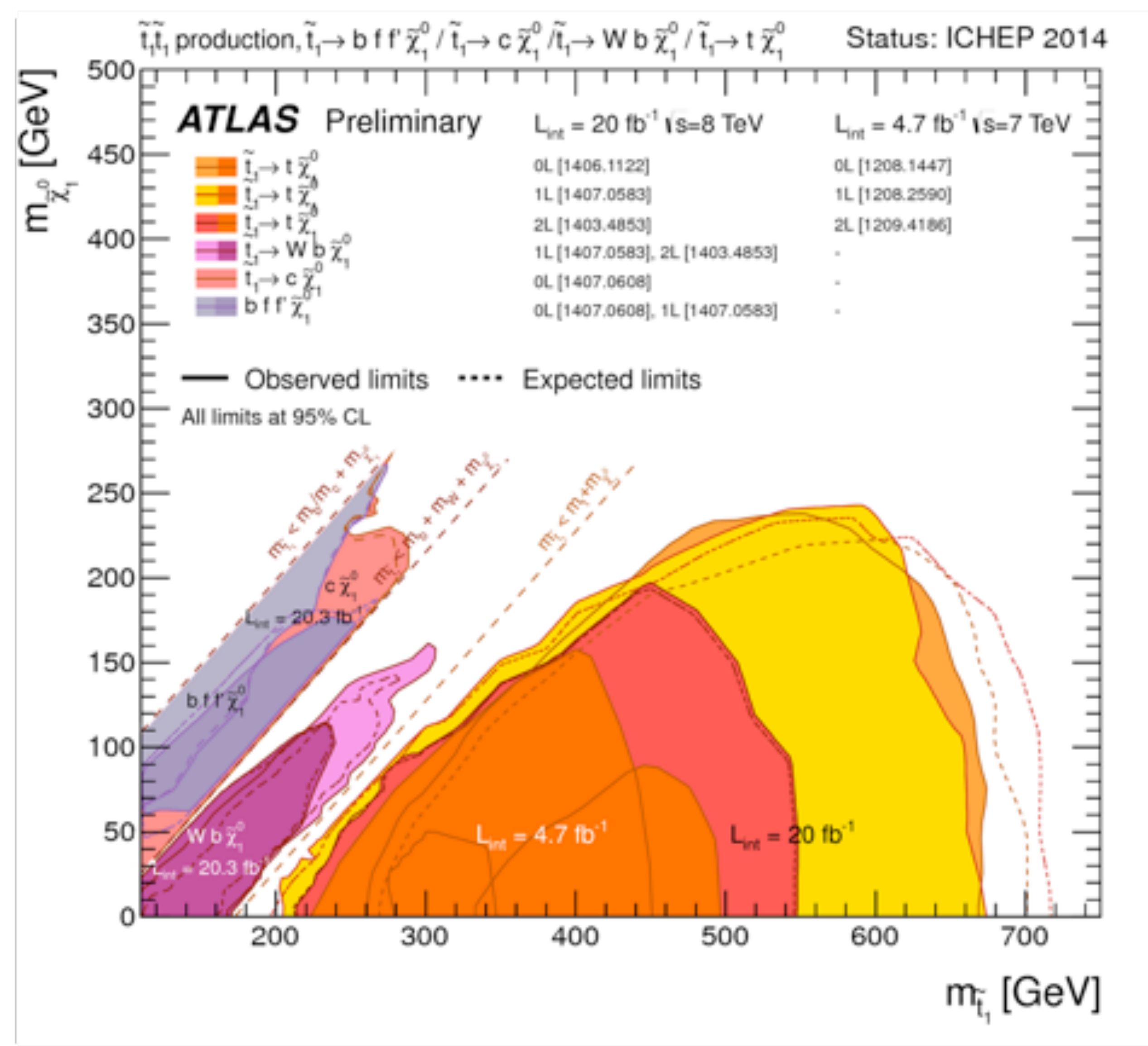


- Maybe just the states most immediately important for addressing the hierarchy problem:
  - higgsinos - mass related to m_h at tree level
  - stops - most important quantum correction
  - gluinos - stops have their own hierarchy problem!

NATURAL SUSY

- Probing direct stop production is tougher



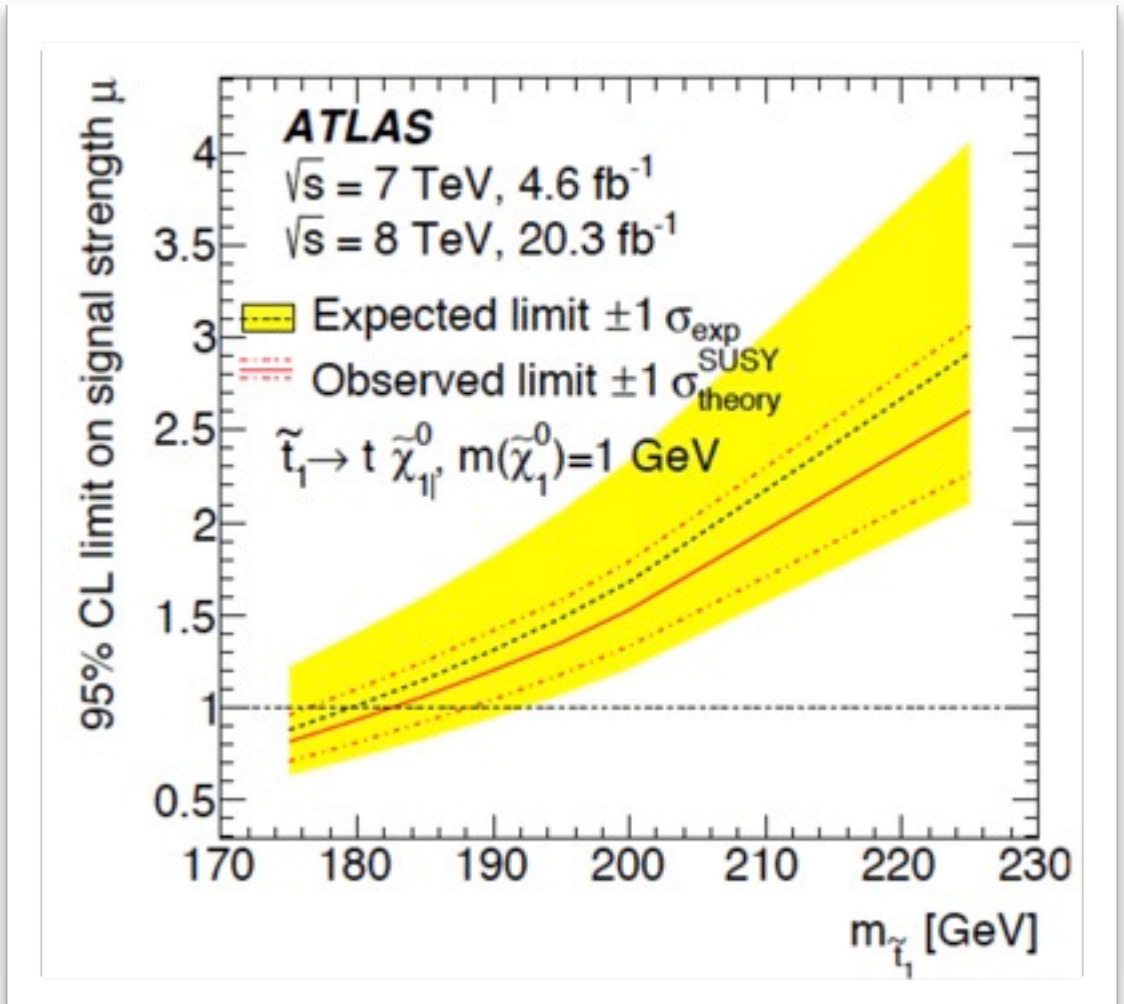


Compressed spectra are hard!

Light stops are hard!

NATURAL SUSY

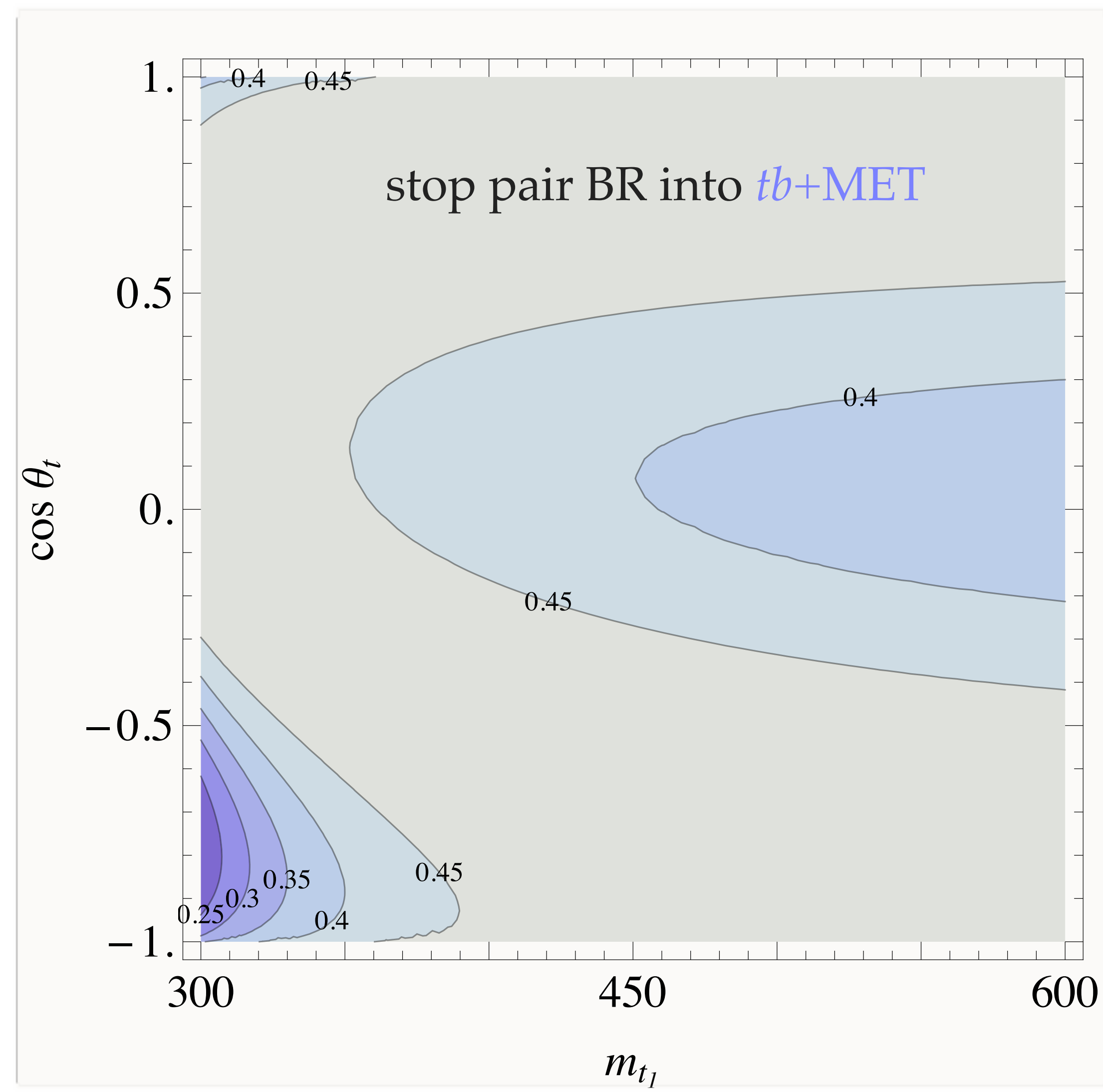
- Light stops have very few kinematic handles to separate from enormous, similar top background



- extreme case: look for rate deviation in top production
  - further precision studies: spin correlations, ...
- Stops in a sparse spectrum: well-defined target, can design precisely targeted searches

NATURAL SUSY

- Even in stripped-down particle content of natural SUSY, many lurking assumptions
  - RPV?
  - Nature and mass of LSP
  - handedness of stop
  - non-unit branching fractions
  - Important, complex target for LHC Run II



[Graesser, JS]

ELECTROWEAK SUSY

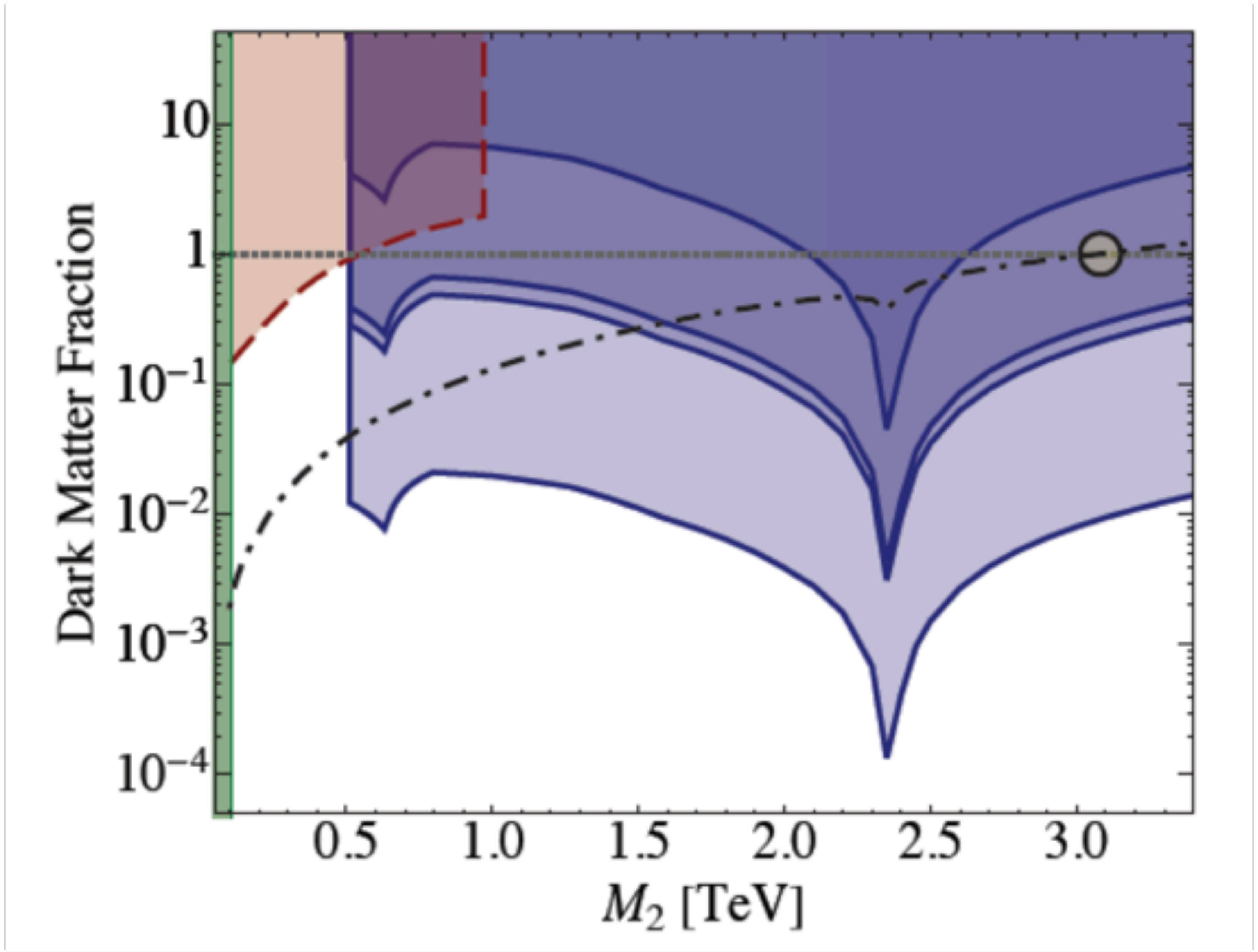
- Neutralinos and charginos:
  - keep unification and dark matter (give up a bit on naturalness)
  - pure Higgsino thermal DM: $m \sim$ TeV
  - pure wino thermal DM: $m \sim 3$ TeV
  - pure bino thermal DM: impossible
  - thermal but subdominant? non-thermal? "well-tempered"?
  - New electroweak states of interest independently of SUSY

ELECTROWEAK SUSY

- Interesting interplay with astrophysical searches

Fermi

LHC



HESS
line search

[Cohen, Lisanti, Pierce, Slatyer]

ELECTROWEAK SUSY