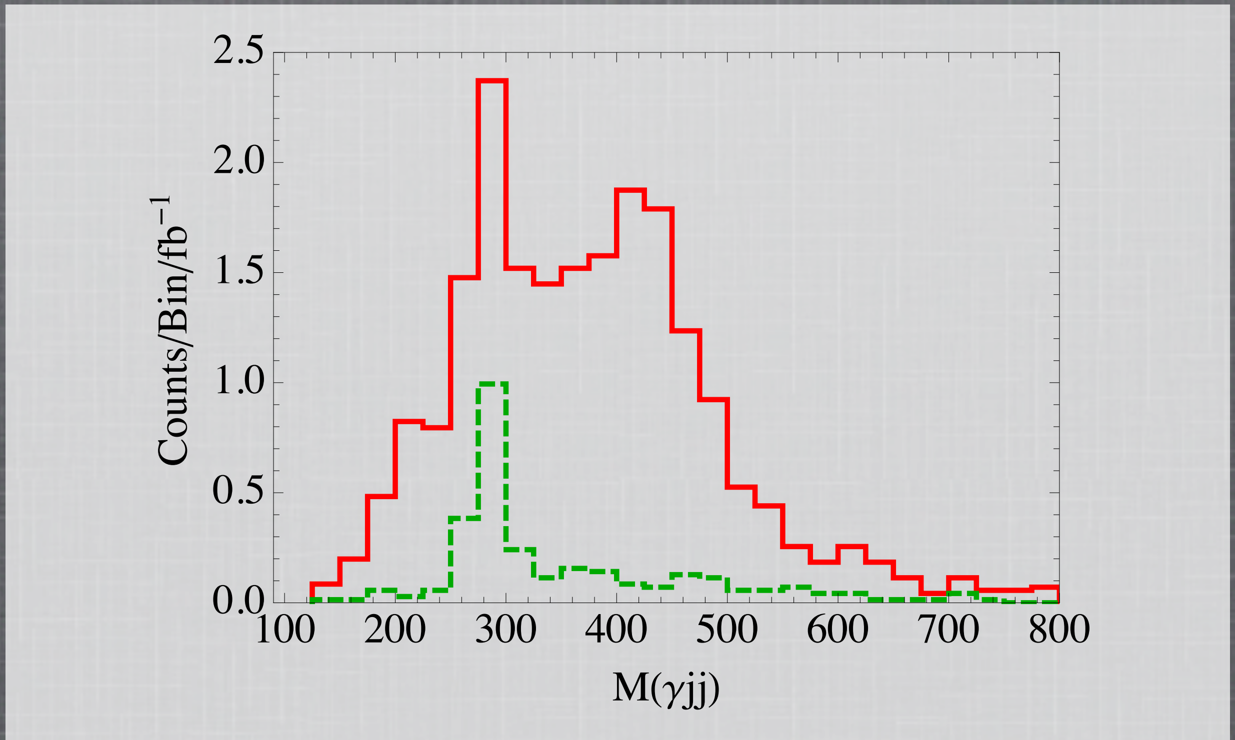
STEALTH SUPERSYMMETRY

Matt Reece, Harvard University

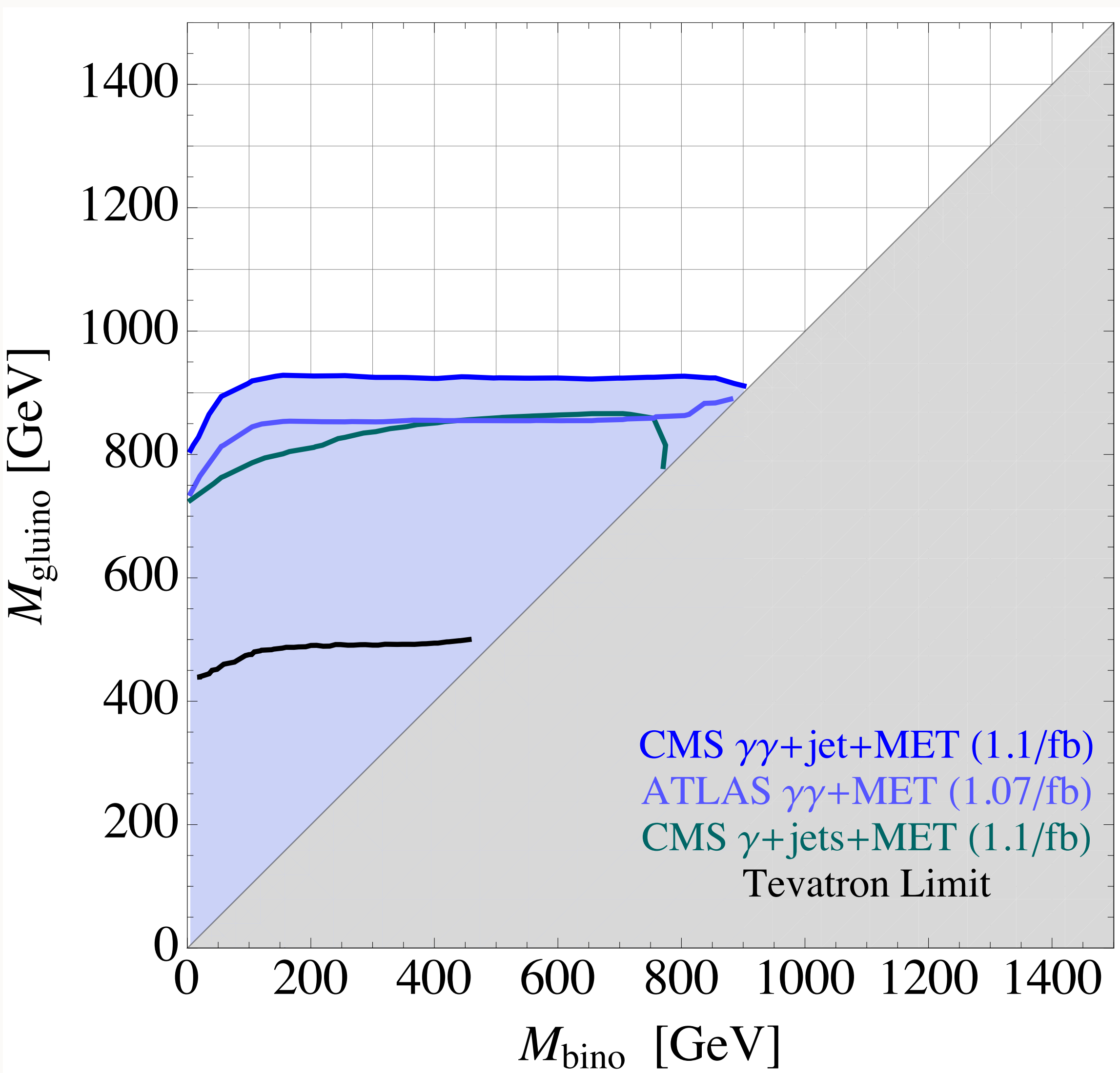


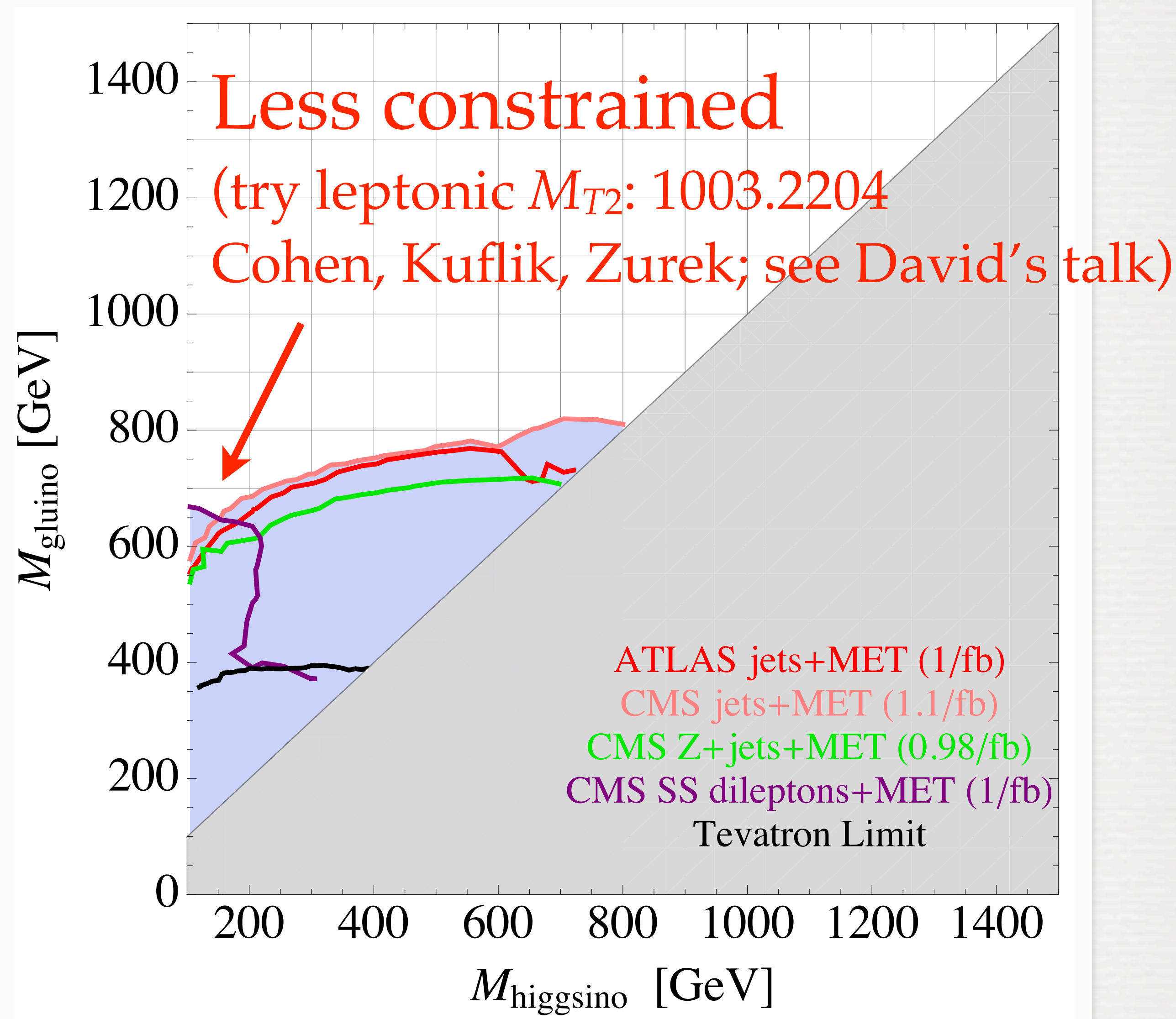
with JiJi Fan and Josh Ruderman: 1105.5135 and "A Stealth Supersymmetry Sampler," to appear soon

Status of Supersymmetry

GMSB LIMITS

with Y. Kats, P. Meade, D. Shih, 1110.6444



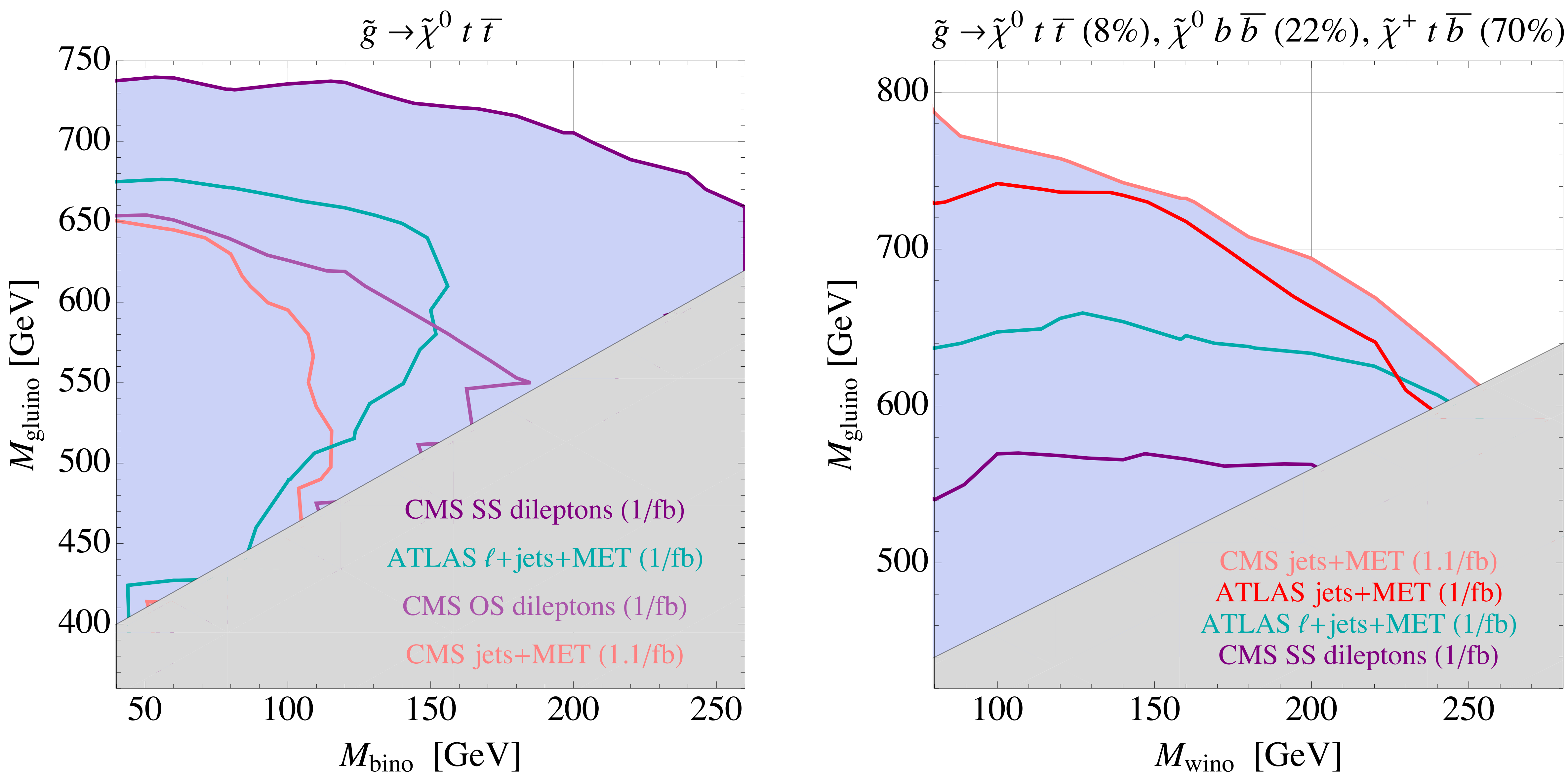


bino NLSP $\tilde{B} \to \gamma\tilde{G}$

higgsino NLSP $\tilde{h} \to Z\tilde{G}$

MORE LIMITS

Gluino through off-shell stops & sbottoms



Scenarios A and C of 1101.1963, Kane, Kuflik, Lu, Wang

MY VIEWPOINT

- Flavor remains the *most* important constraint on standard *R*-parity preserving SUSY
- Cosmological problems (moduli/gravitino/axino) can also be severe (but more UV-dependent)
- In light of those, whether the gluino is at 700 GeV or 1 TeV doesn't seem like a big deal
- Still, it's interesting to think about scenarios that allow *much* weaker direct constraints

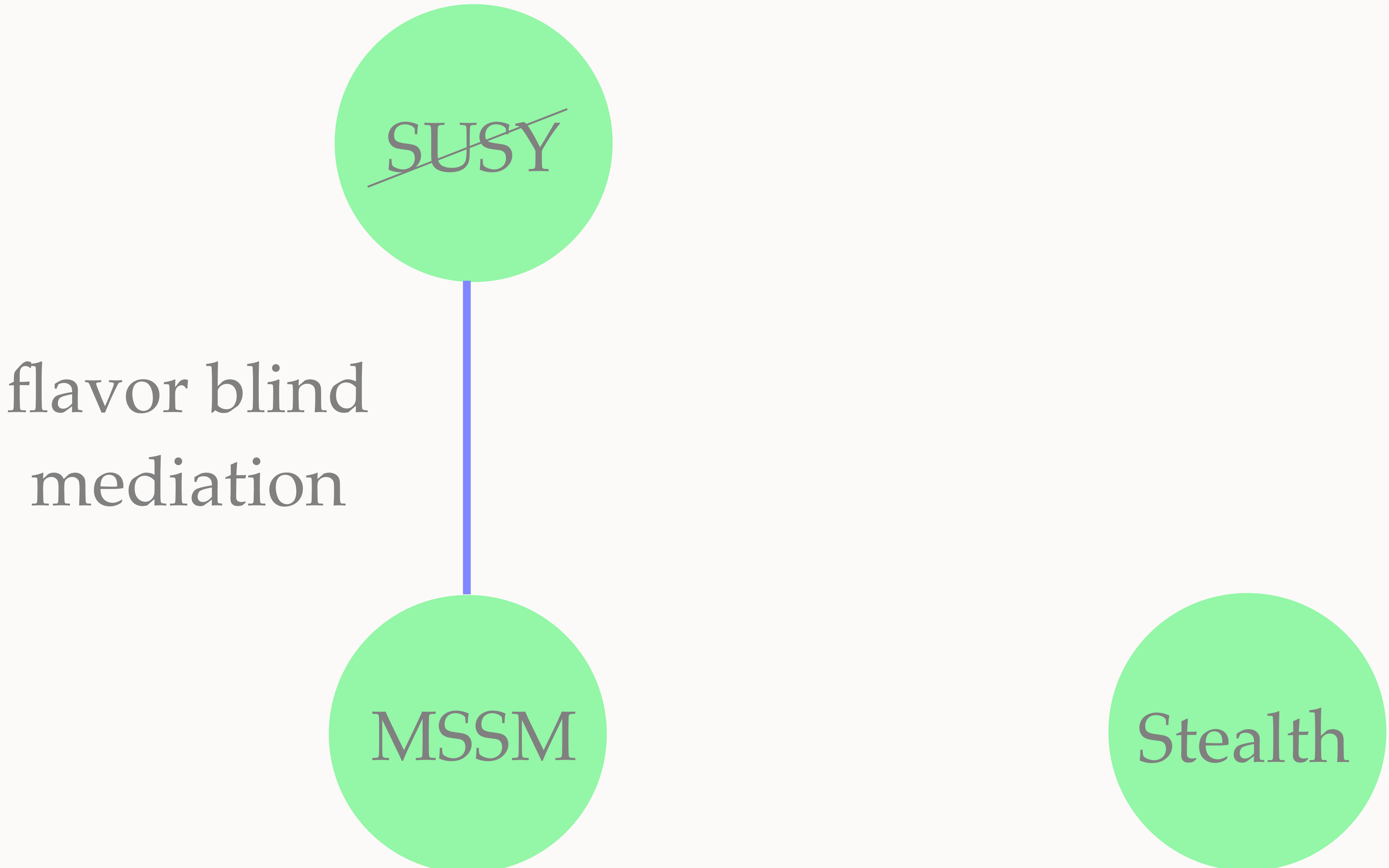
SUPPRESSING MET

- Several known scenarios allow for smaller-than-usual missing E_T. They are:
- R-parity Violation
- Long decay chains / hidden valleys
- Squeezed spectrum
- However, there is a previously unexplored option: ***R-parity preserving SUSY with naturally low missing E_T, a.k.a. "stealth supersymmetry."***

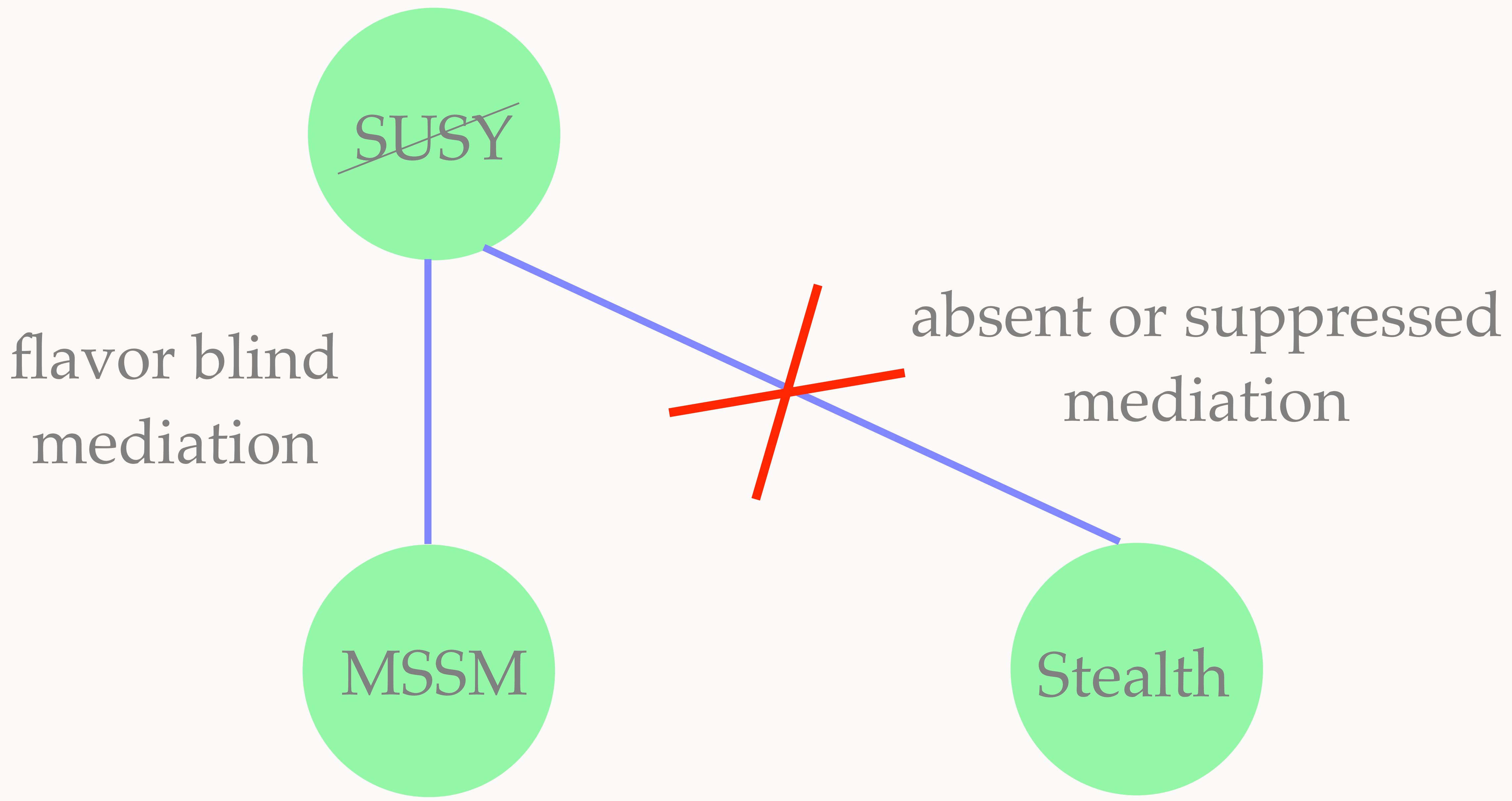
The Stealth Mechanism

BASIC MECHANISM

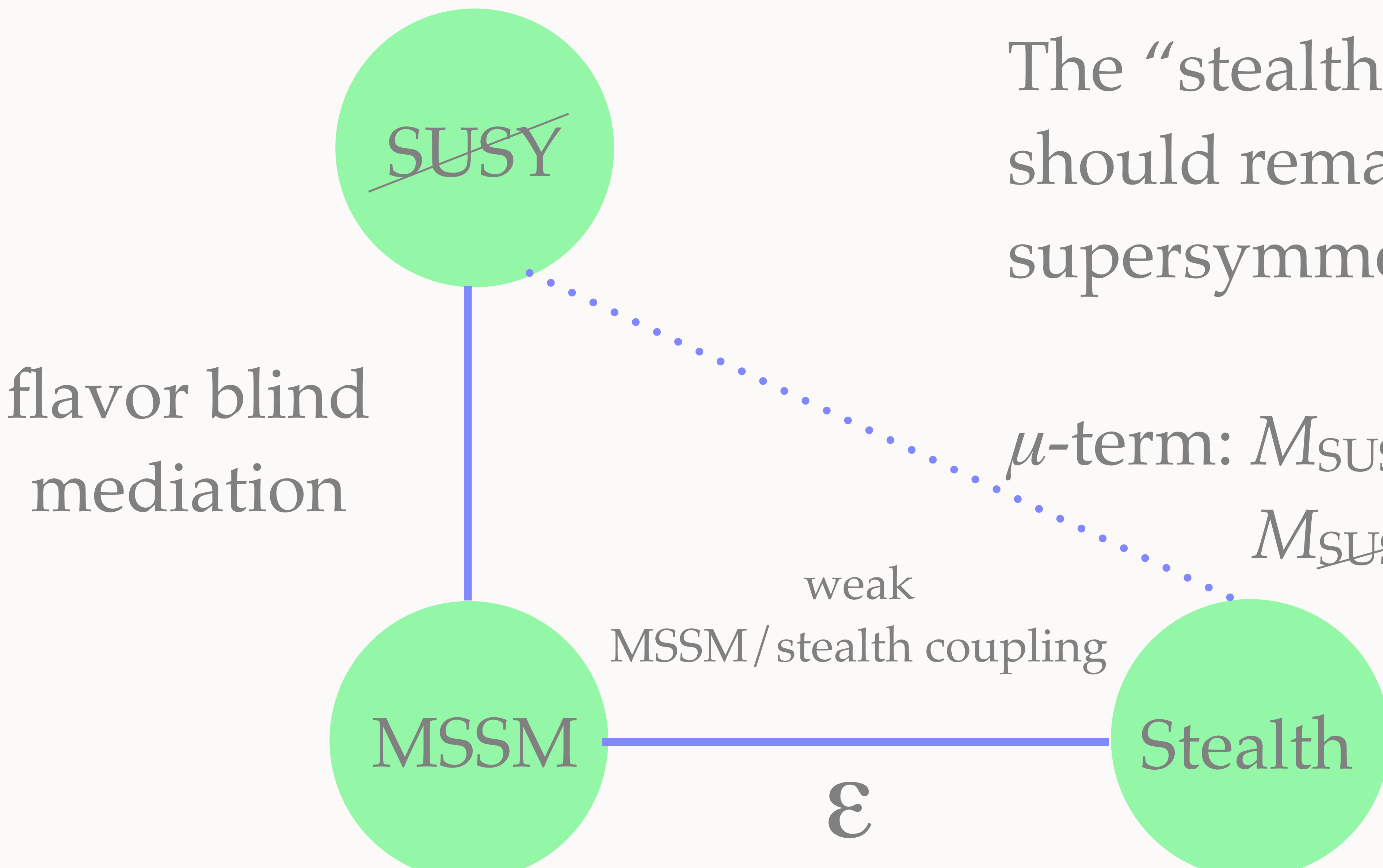
BASIC MECHANISM



BASIC MECHANISM



BASIC MECHANISM

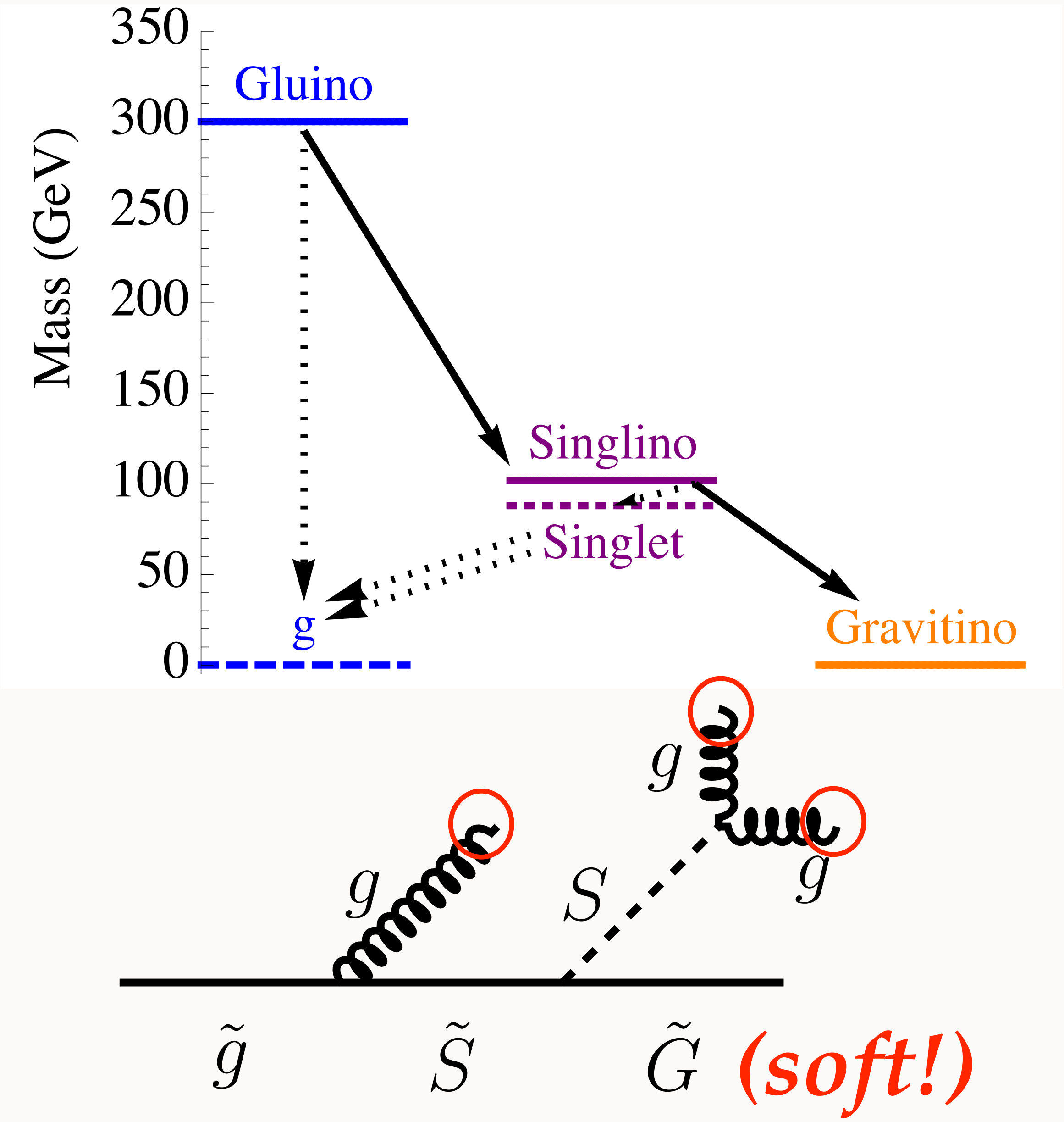


The "stealth" sector should remain nearly supersymmetric

μ-term: $M_{\text{SUSY}} \sim M_{\text{EWK}}$,
$M_{\cancel{\text{SUSY}}} \sim \varepsilon\, M_{\text{EWK}}$

WHAT IS "STEALTH SUSY"?

- A nearly-supersymmetric hidden sector (small δm)
- Preserves R-parity: lightest visible sector R-odd particle ("LVSP") is *forced* to decay to a stealth particle
- R-even stealth particles decay back to SM states

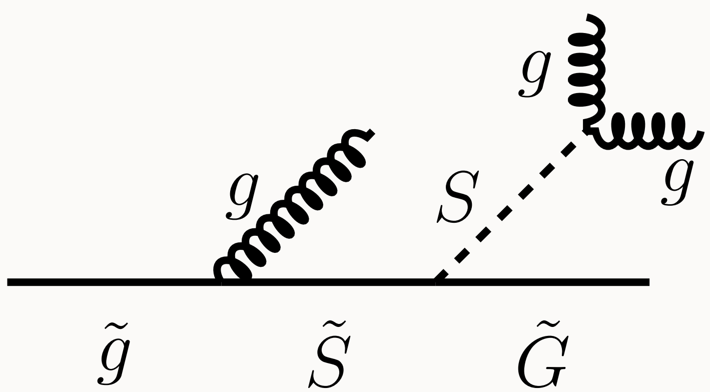


THE STEALTH MECHANISM

- If the LVSP is *forced* to decay into a stealth particle, and the stealth particle is *forced* to decay to its superpartner, which decays to visible SM states, the small mass splitting ensures that only a soft *R*-odd particle escapes.
- The simplest option is the gravitino.
- Its missing E_T is suppressed:

$$MET \approx (\delta m_{stealth}/m_{stealth}) m_{SUSY}$$

MET SUPPRESSION



- In the $\tilde{S}$ rest frame, we have:

$$E_{\text{missing}} = \frac{m_{\tilde{S}}^2 - m_S^2}{2m_{\tilde{S}}} \approx \delta m$$

- Boosting to the lab frame:

$$E_{\text{missing}} = \gamma \delta m \sim \frac{m_{MSSM}}{m_{\tilde{S}}} \delta m$$

- Main lesson:

$$\delta m \to 0 \Rightarrow E_{\text{missing}} \to 0$$

PORTALS

- Many SM operators could mediate the decay to the stealth sector. For instance,

  SH_uH_d (final states with *b*-jets),
  SYY' (vectorlike matter),
  Z' models, ...

- An interesting option is for S to carry a charge. If it carries lepton number, decays involve neutrinos and are less stealthy. But: could carry baryon number,

  $Sudd$ (note: S scalar is R-odd)

An Example

VECTORLIKE PORTAL

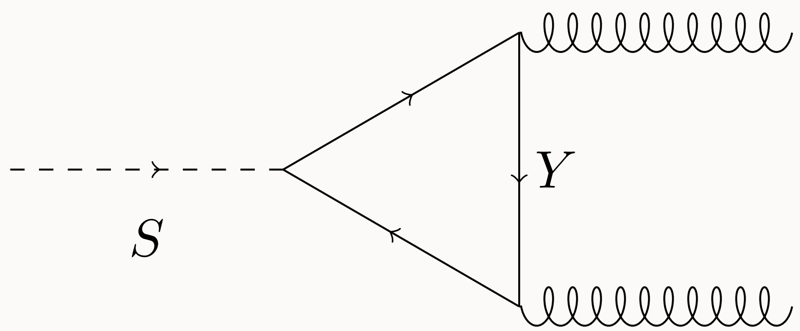
- Introduce fields Y ($\mathbf{5}$ of $SU(5)$), $\bar{Y}$ ($\bar{\mathbf{5}}$ of $SU(5)$)
- Superpotential:

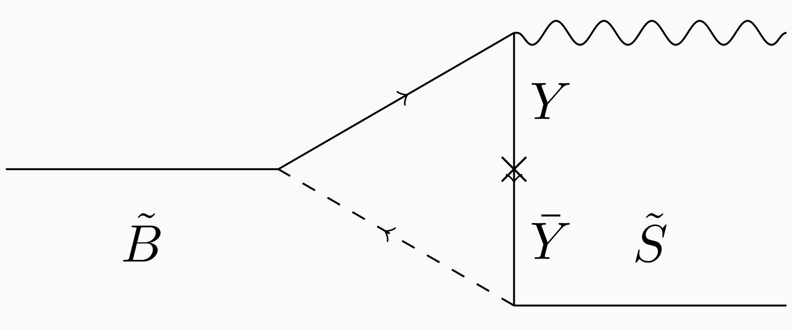
$$W = \lambda S Y \bar{Y} + m_S S^2 + m_Y Y \bar{Y}$$

- Assume: $m_S \sim 100$ GeV (below the superpartner spectrum), $m_Y \sim 1$ TeV or somewhat higher
- Y should *not* couple directly to SUSY breaking (not a messenger in GMSB)

DECAYS TO AND FROM S

- The S fermion is R-parity odd, and the LVSP can decay to it.
- Decay goes through a loop of Y's.





$$sG^a_{\mu\nu}G^{a\mu\nu}$$

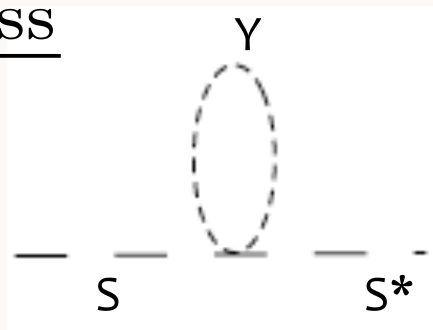
$$\lambda^a\sigma_{\mu\nu}G^{a\mu\nu}\tilde{s}$$

GAUGE MEDIATION

- First, assume a light gravitino and GMSB.
- The fields $Y, \bar{Y}$ feel SUSY breaking through gauge mediation: get same (positive) soft mass^2 as *D, L*.
- Then the Yukawa coupling to *S* generates a negative *S* soft mass^2, leading to an *S* scalar lighter than the fermion:

$$\tilde{m}_s^2 \approx -\frac{|\lambda|^2}{(4\pi)^2}\left(6\tilde{m}_D^2 + 4\tilde{m}_L^2\right)\log\frac{M_{\rm mess}^2}{m_Y^2}$$

- Also a tadpole



TADPOLE ISSUES

- *S* is a singlet under all symmetries (m_Y breaks any charge it could have), so gets a tadpole:

$$V_{soft} \supset -\frac{\lambda m_Y}{(4\pi)^2}\left(6\tilde{m}_D^2 + 4\tilde{m}_L^2\right)\log\frac{M_{\text{mess}}^2}{m_Y^2}s$$

- This induces a VEV proportional to the soft mass²:

$$\langle S\rangle \sim \frac{m_Y}{\lambda}\frac{\tilde{m}_s^2}{m_S^2}$$

- Shifts the *Y* masses, but as long as trilinear κS^3 is small ($\kappa \sim 10^{-2}$), the stealth mechanism is safe.

- Small λ is also an option.

SAMPLE SPECTRUM

$SY\bar{Y}$	
$m = 100$ GeV $\lambda = 0.2$ $m_Y = 1000$ GeV $\tilde{m}_D = 300$ GeV $\quad \tilde{m}_L = 200$ GeV $M_{\rm mess} = 100$ TeV	$m_{\tilde{s}} = 100$ GeV $m_{s,a} = 91$ GeV $\Gamma_{s,a} = 2 \times 10^{-7}$ GeV $\text{Br}_{s,a \to \gamma\gamma} = 4 \times 10^{-3}$

Obtain a “stealthy” splitting (10 GeV) with a reasonable coupling (0.2).

S decays overwhelmingly to gluons.

Collider Phenomenology

DECAYS TO GRAVITINO

- Lifetimes of decays to gravitinos are always somewhat long. *Displaced vertex signatures.*

$$\Gamma_{\tilde{X}} = \frac{m_{\tilde{X}}^5}{16\pi F^2}\left(1 - \frac{m_X^2}{m_{\tilde{X}}^2}\right)^4 \approx \frac{m_{\tilde{X}}\,(\delta m)^4}{\pi F^2}$$

$$c\tau = 6\ \text{cm}\ \left(\frac{\sqrt{F}}{100\ \text{TeV}}\right)^4 \left(\frac{10\ \text{GeV}}{\delta m}\right)^4 \frac{100\ \text{GeV}}{m_{\tilde{X}}}$$

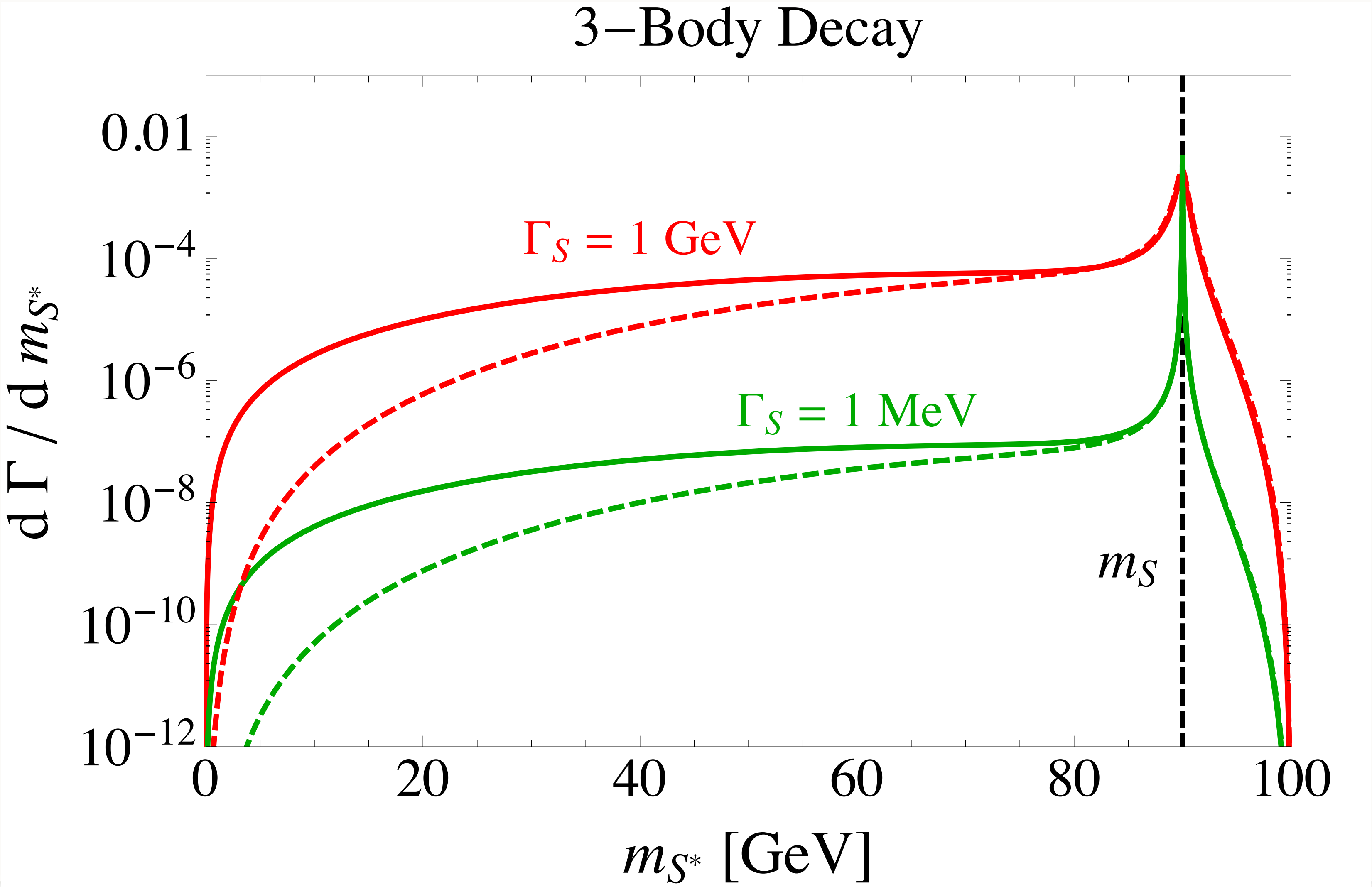
- The phase-space dependence is because the goldstino couples to SUSY breaking (hence splittings): on-shell,

$$-\frac{1}{F}\bar{\psi}_L \gamma^\mu \gamma^\nu \partial_\nu \phi \partial_\mu \tilde{G} \to \frac{1}{F}\left(m_\psi^2 - m_\phi^2\right)\bar{\psi}_L \phi \tilde{G}$$

- Creates a risk that 3-body beats 2-body

DECAYS TO GRAVITINO

- Condition for 2-body dominant: $\Gamma_X \ll 192\pi \frac{(\delta m)^4}{m_{\tilde{X}}^3}$



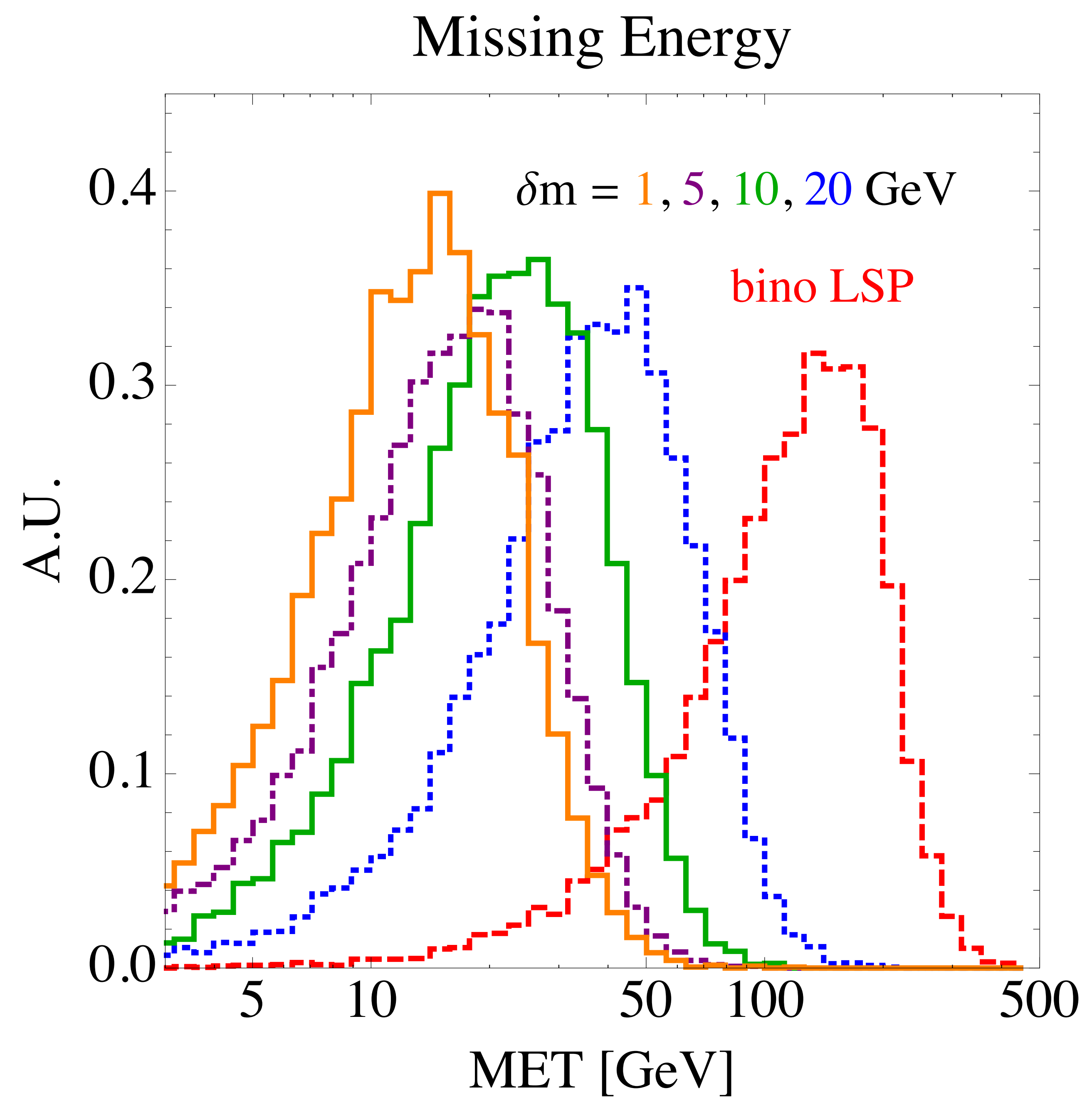
MISSING E_T: SQUASHED

Comparison:

300 GeV gluinos decaying to a 100 GeV bino,

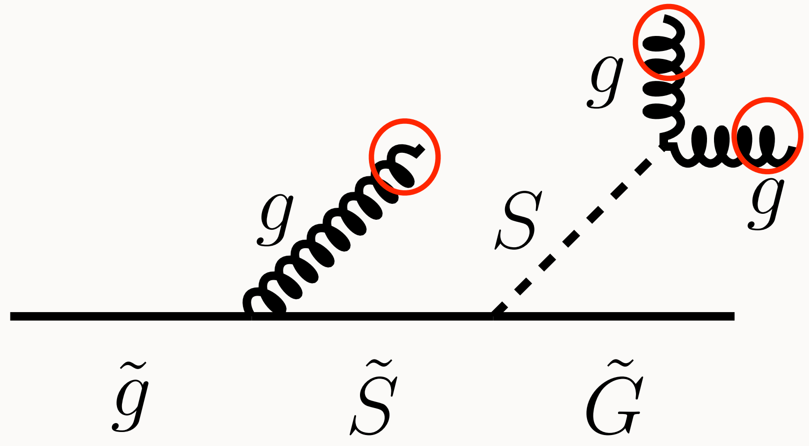
versus

Gluinos decaying to singlino (to 2 jets and soft gravitino)

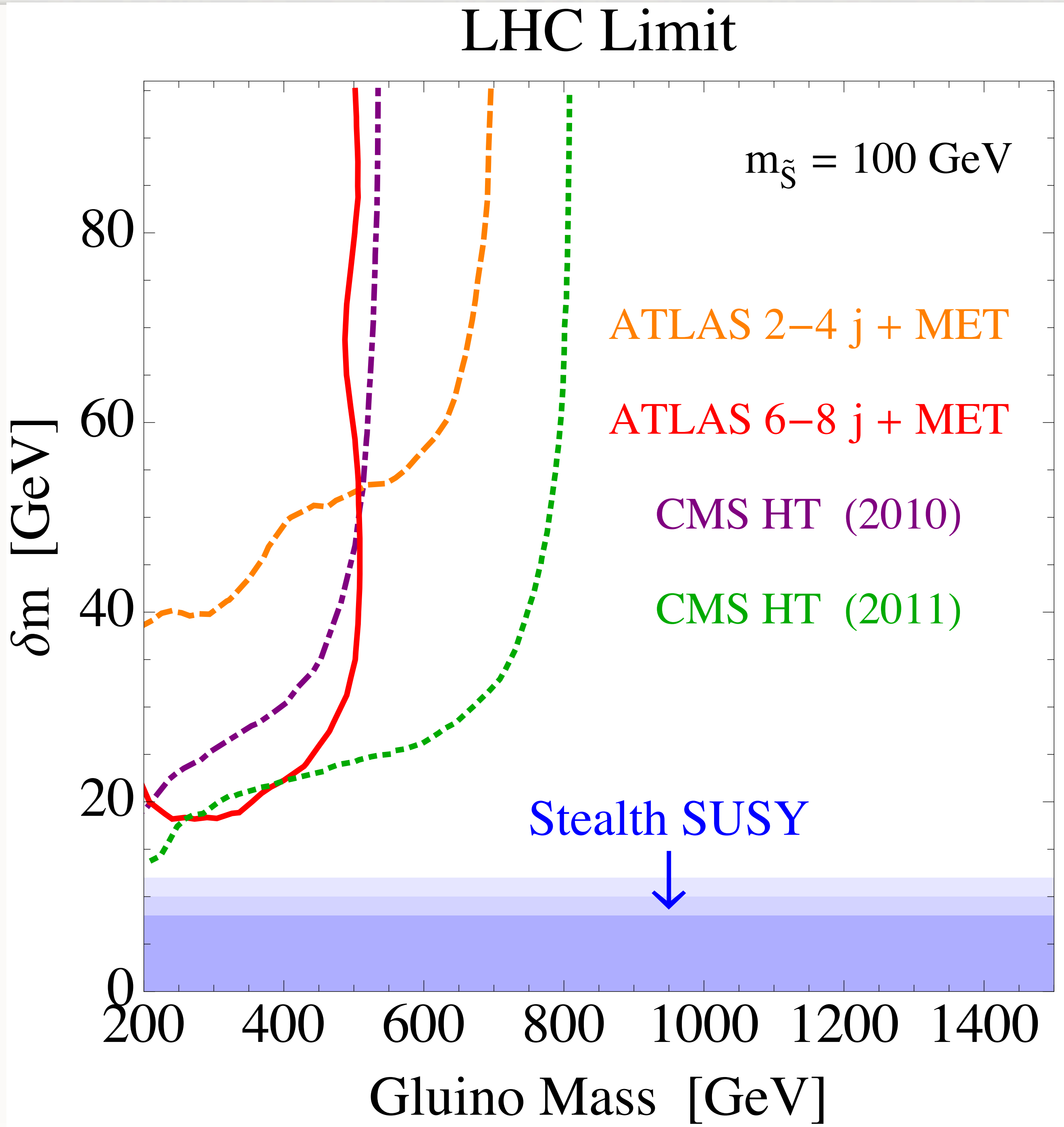


COLLIDER BOUNDS

- Gluino LVSP
- 6-jet Final States
- Low missing E_T



- *False resonances*

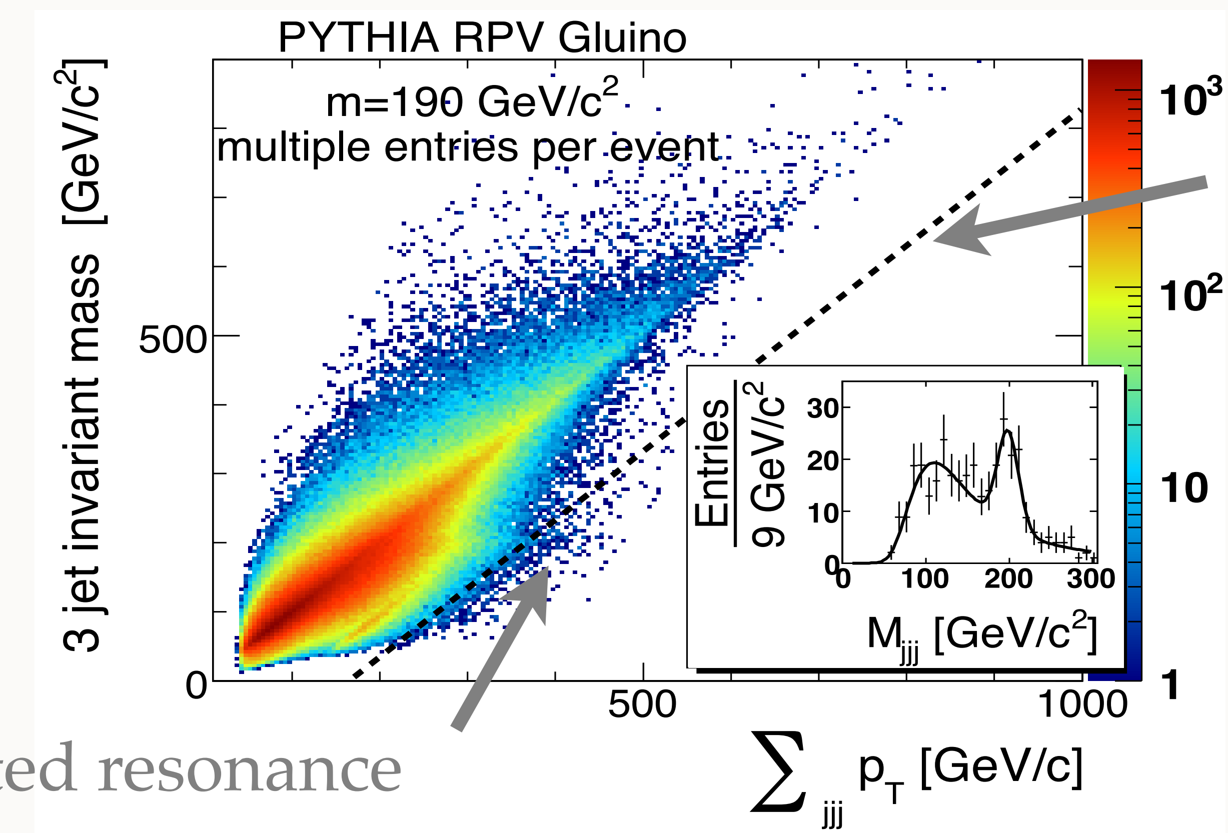


HADRONIC RESONANCES

- How to find new physics in final states with multiple jets? Large backgrounds, combinatoric problems.
- One approach studied for RPV gluinos is to use substructure (Butterworth, Ellis, Raklev, & Salam; Raklev, Salam, & Wacker)
- A simple cut-based approach has been tried...

RUTGERS RPV SEARCH

- Nice idea originally in Rouven Essig's thesis.



cut: $\Sigma p_T > M_{jjj} + \Delta$

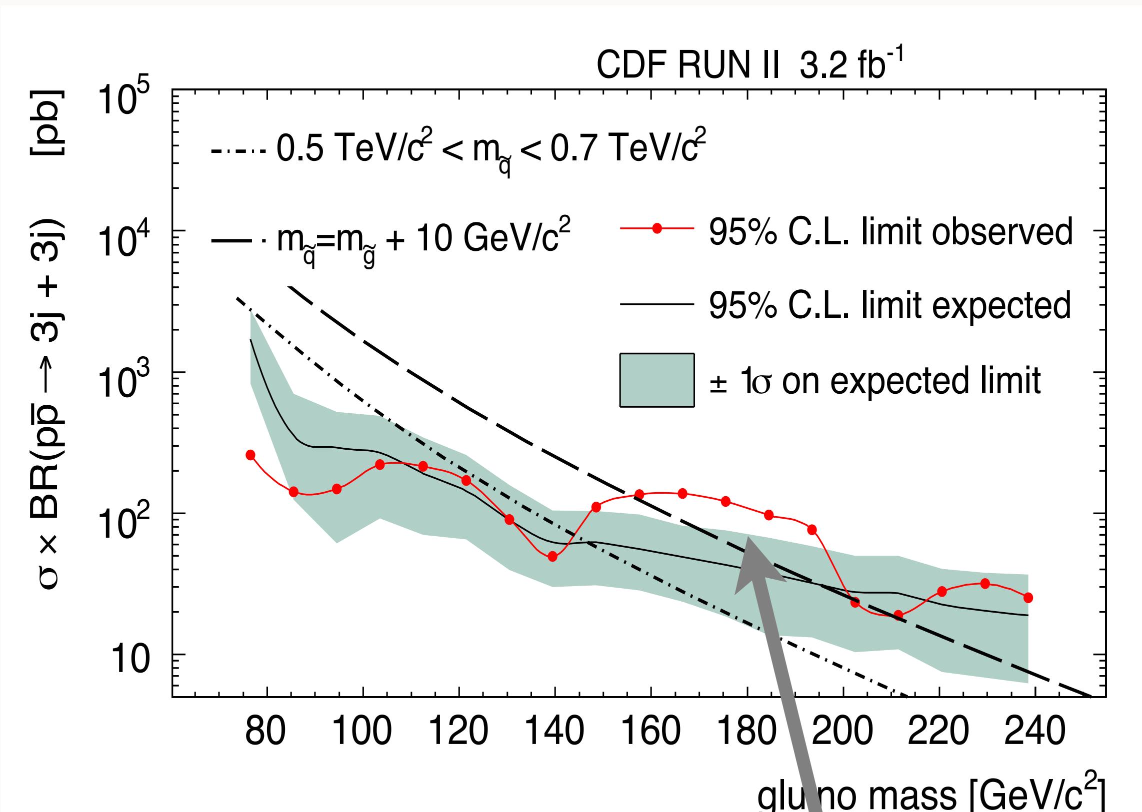
boosted resonance

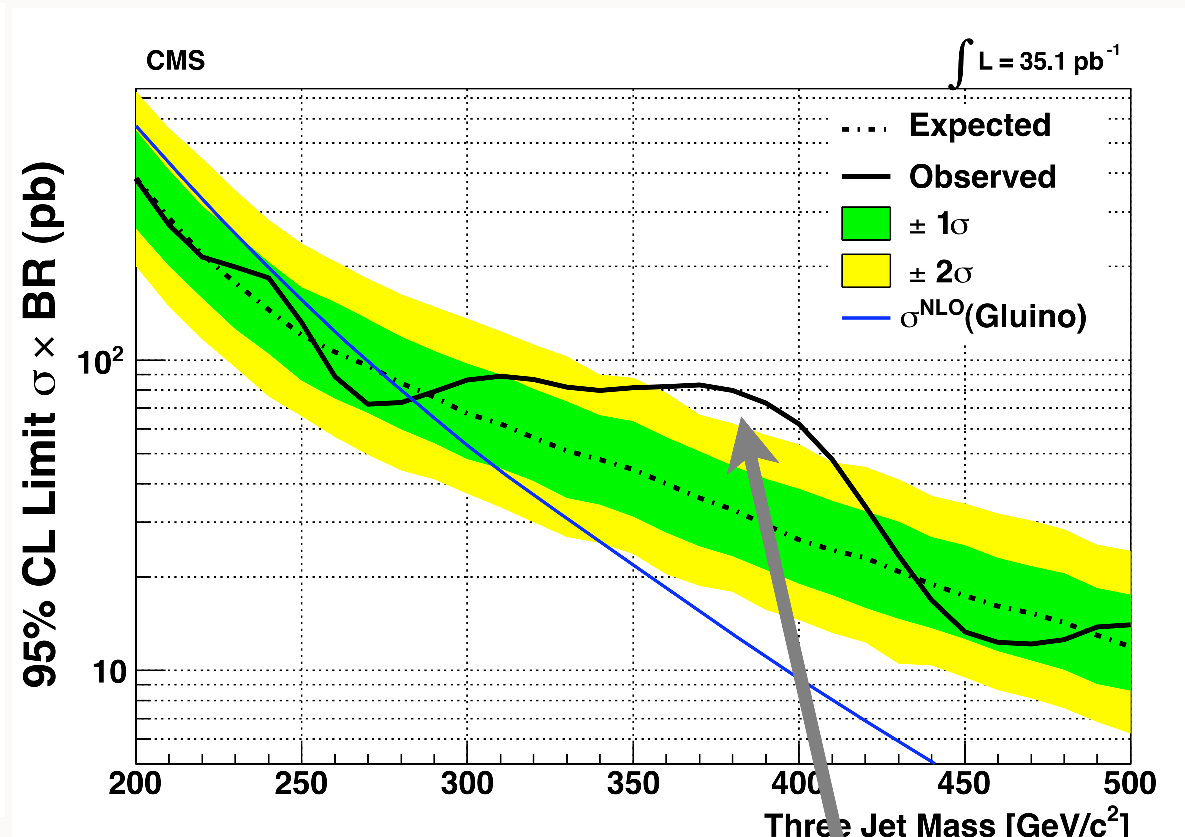
figure from 1105.2815

- CDF, CMS rule out most gluino → 3j signals below 380 GeV.

CDF AND CMS 3J RESONANCE LIMITS

the least-chased ambulances in particle physics?





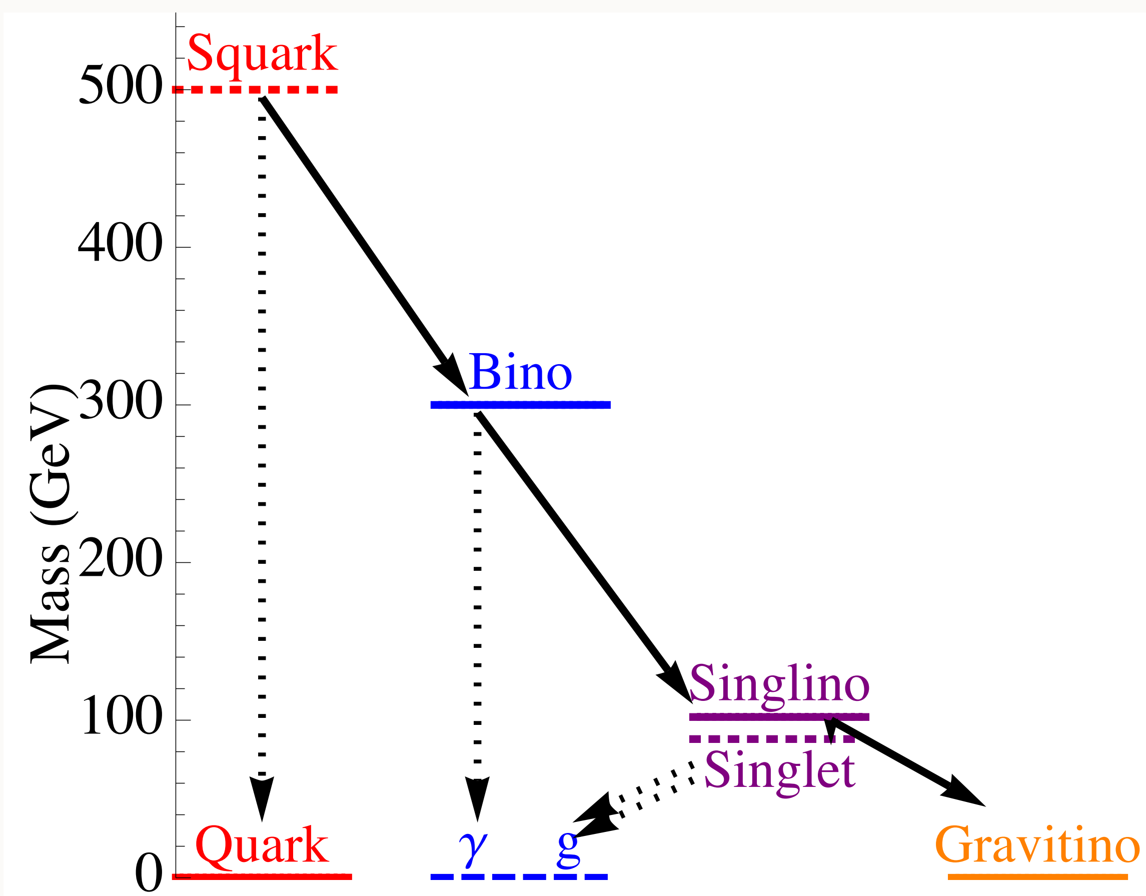
CDF: extra tops

CMS: excess near 380 GeV

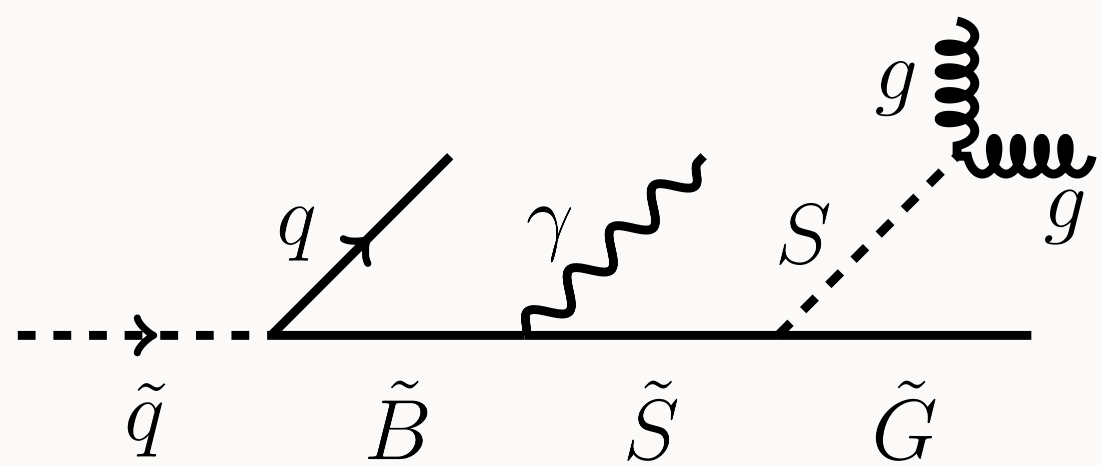
NEW SIGNATURES

- Let's consider the case with a bino NLSP, e.g. produced through squark decays:

$$\tilde{q} \to q(\tilde{B} \to \gamma(\tilde{s} \to \tilde{G}(s \to gg)))$$



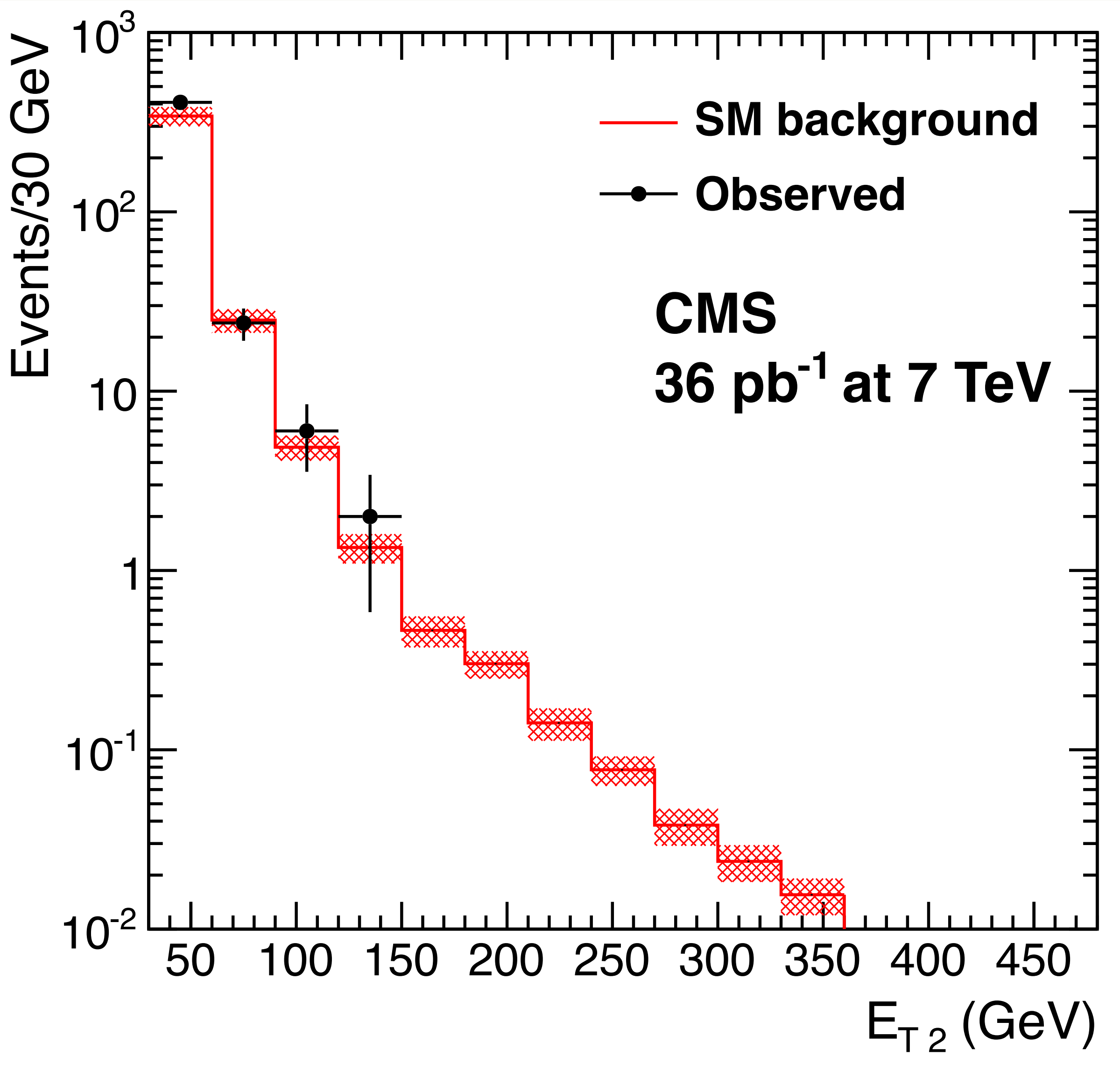
new signal:
γ-jet-jet "resonance"



PHOTON+JETS CUTS

Two photons: $E_T(\gamma) > 120\ \text{GeV}, \quad |\eta(\gamma)| < 1.44$

$\geq\ 2$ jets with $E_T(j) > 45\ \text{GeV}, \quad \sum_{jets} E_T(j) > 200\ \text{GeV}$



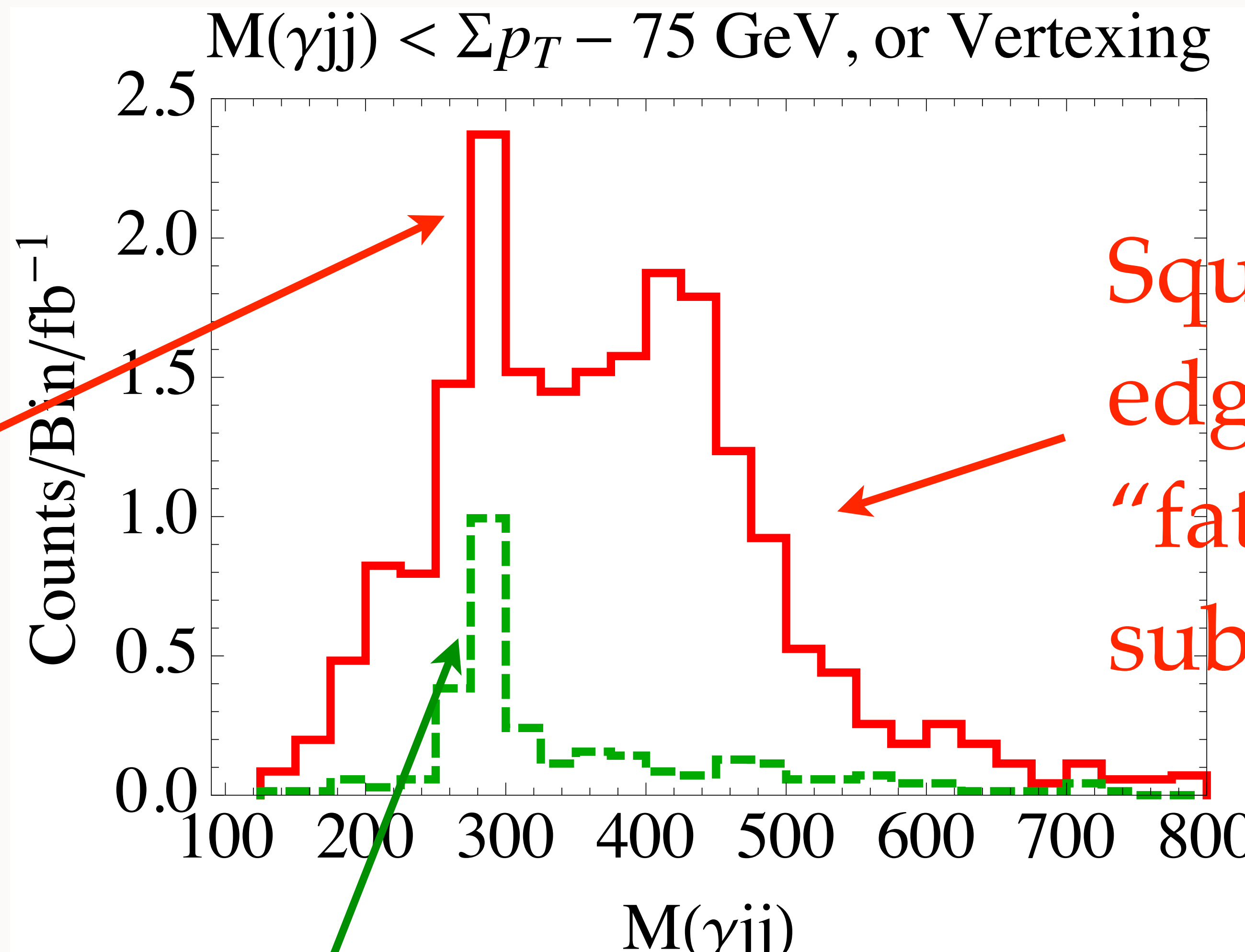
reduces background below signal: compare to CMS, 1103.4279

$$\sum_{\gamma,j,j} p_T > M(\gamma j j) + 75\ \text{GeV}$$

beats combinatorics

MASS SPECTRUM

After these cuts, see interesting structure in the mass spectrum:



Bino mass peak

Squark mass edge: S is one "fat jet" with substructure...

If the displaced vertex of the $S \to gg$ decay can be tagged, isolate the bino peak.

Further Examples

THE HIGGS PORTAL

- Another model:

$$W = \frac{m}{2}S^2 + \frac{\kappa}{3}S^3 + \lambda S H_u H_d + \mu H_u H_d$$

- This time, have tree-level mixing. Need small λ.

SH_uH_d	
$m = 80$ GeV	$m_a = 90$ GeV $\quad m_s = 103$ GeV
$\mu = 300$ GeV	$m_h = 125$ GeV
$\lambda = -0.02 \quad \kappa = 0.5$	$\sigma_{sZ} = 0.22\,\sigma_{hZ}$
$\tan\beta = 10 \quad m_A = 700$ GeV	$\Gamma_a = 6 \times 10^{-8}$ GeV
$M_1 = 200$ GeV	$m_{\tilde{s}} = 100$ GeV
$M_2 = 300$ GeV	$N_{\tilde{s}(\tilde{H}_u,\tilde{H}_d)} = (-0.014, 0.0059)$
$M = -2$ TeV	$N_{\tilde{s}(\tilde{B},\tilde{W}^0)} = (0.0063, -0.0058)$

- Similar signals, but *S* decays to *b*-jets.

THE BARYON PORTAL

- Let's consider the *Sudd* model as another example.
- Sometimes called the "neutron portal," but recall the down-type flavors are antisymmetrized; more of a Λ-baryon portal.
- For prompt decays we need the scale suppressing the operator not to be too high. Complete as:

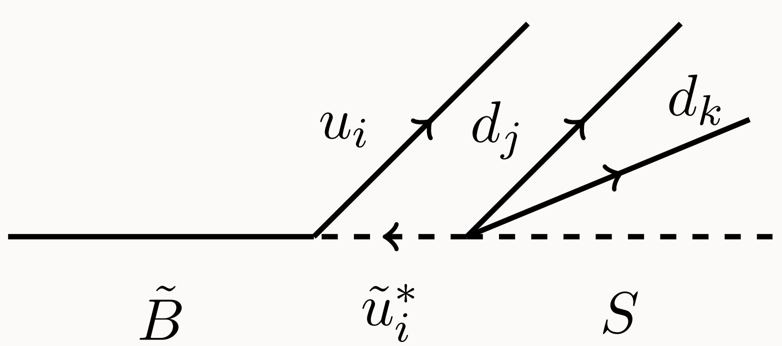
$$W_U \supset a_{jk} U d_j d_k + M U \bar{U} + a_i \bar{U} u_i S + m S \bar{S}$$

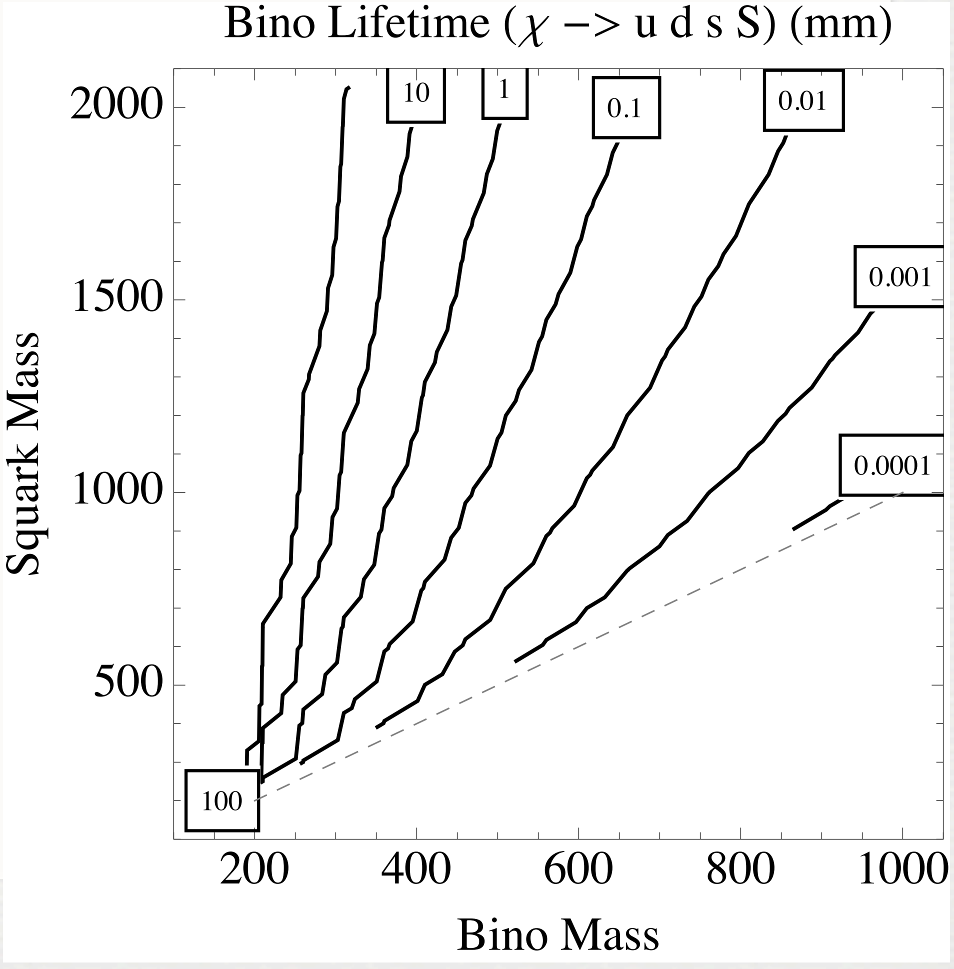
or

$$W_D \supset b_{jk} D u_j d_k + M D \bar{D} + b_i \bar{D} d_i S + m S \bar{S}.$$

DECAYING INTO THE STEALTH SECTOR

- If the LVSP is a squark, the operator *Sudd* mediates a decay to the (*R*-odd) scalar *S* and two jets.
- If the LVSP is a bino, need a more complicated decay:

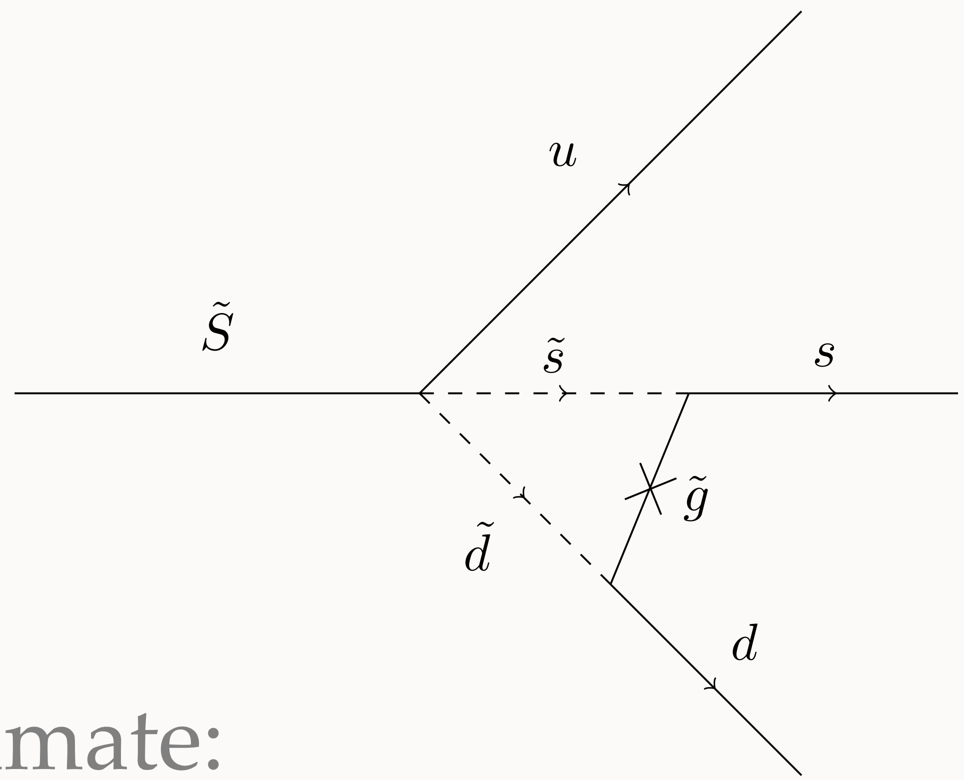




Lifetimes at M = 100 TeV, singlet at 100 GeV, $\lambda_{uds} = 1$.

DECAYING OUT OF THE STEALTH SECTOR

- Similarly, the *Sudd* operator allows a decay of the fermionic (*R*-even) *S* to three jets, through a loop:



- Lifetime estimate:

$$c\tau \sim 1\ \text{cm} \left(\frac{100\ \text{GeV}}{m_{\tilde{S}}}\right)^5 \left(\frac{M}{100\ \text{TeV}}\right)^2 \left(\frac{m_{\tilde{g},\tilde{q}}}{1\ \text{TeV}}\right)^2 \frac{1}{\lambda^2_{uds}}$$

SUSY BREAKING

- For the *Sudd* model we want the *S* scalar heavier than its fermionic partner for stealth phenomenology.
- A "General Gauge Mediation" analysis shows that this can be accommodated in the model UV-completed by $D, \bar{D}$ provided there is an effective hypercharge FI term.
- What about high-scale breaking?

GRAVITY MEDIATION

- For high-scale breaking, one approach to stealth is to replace the gravitino in our decays by the fermionic partner of a Goldstone boson.
- We won't UV-complete this, but just assume an effective theory with Kähler potential:

$$K \supset f^2 \left(A + A^\dagger\right)^2 + c\left(A + A^\dagger\right) S^\dagger S$$

- f is well above the scale of soft masses. Generically, Goldstone fermions get mass ~ $m_{3/2}$, so we need sequestering

THE *B*-TERM PROBLEM

- Consider high scale breaking, with $m_{3/2} > 1$ TeV and some form of gravity mediation in the visible sector.
- Then the stealth sector has a problem directly analogous to the $\mu/B\mu$ problem of AMSB.
- $\int d^2\theta\ \phi m_S SS' \rightarrow m_{3/2} m SS'$ soft mass, i.e. $B \approx m\, m_{3/2}$
  (or, from $(D_iW)(WD_iK)$ and $-3|W|^2$ terms in SUGRA potential)
- For a small splitting we need $B << m^2$.
- Sequestering is not enough (as in AMSB).

GENERATING STEALTH MASSES

- For the stealth mechanism to work, we need supersymmetric masses of order 100 GeV. For low scale, can retrofit.
- High-scale: replace $m_S S S'$ with $X S S'$, where $\langle X \rangle \neq 0$, to avoid B-term. Can dynamically generate $\langle X \rangle$ with a gauge theory, even as an R-breaking VEV not associated with SUSY breaking (Dine & Kehayias)
- Roughly: $X_{ij} Q_i Q'_j$ + Tr X^3, then ADS superpotential

ANOMALY MEDIATION

- Simplest: sequester the MSSM *and* the stealth sector
- Anomaly mediation generates SUSY breaking in all sectors ⇒ *SUSY-breaking proportional to the couplings*
- The stealth mechanism is protected just by being slightly more weakly coupled

EXAMPLE

- Rather than an axino, consider a new light field *N* carrying baryon number in the *Sudd* model with $U, \bar{U}$

$$W \supset a\bar{U}uS + m_S S\bar{S} + yS^2N$$

- ($m_S = \langle X \rangle$, but assume that's a SUSY threshold)
- $U, \bar{U}$ are a non-SUSY threshold: evaluate AMSB formulas above that scale. AMSB result is $\propto \dot{\gamma}_S$ and depends on Yukawas and strong interaction.

EXAMPLE

- The AMSB calculation gives the result:

$$\tilde{m}_S^2 = \frac{1}{2}\left|m_{3/2}\right|^2 \frac{d}{dt}\gamma_S = \frac{\left|m_{3/2}\right|^2}{(16\pi^2)^2}\left(6\left|y\right|^4 + 15\left|a\right|^4 - 16\left(g_3^2 + \frac{g'^2}{3}\right)\left|a\right|^2 + 12\left|y\right|^2\left|a\right|^2\right)$$

- For $m_{3/2} = 100$ TeV, supersymmetric mass of S at $m_S = 100$ GeV, $y = 0.24$ and $a = 0.03$, the S scalar is 12 GeV heavier than the S fermion.

- Consistent stealth phenomenology just requires slightly small couplings and/or mild cancellations.

- *Sudd* model also has some RPV-like flavor bounds, but can easily be safe ($M_{U \text{ or } D} \approx 10$ TeV).

Final Remarks

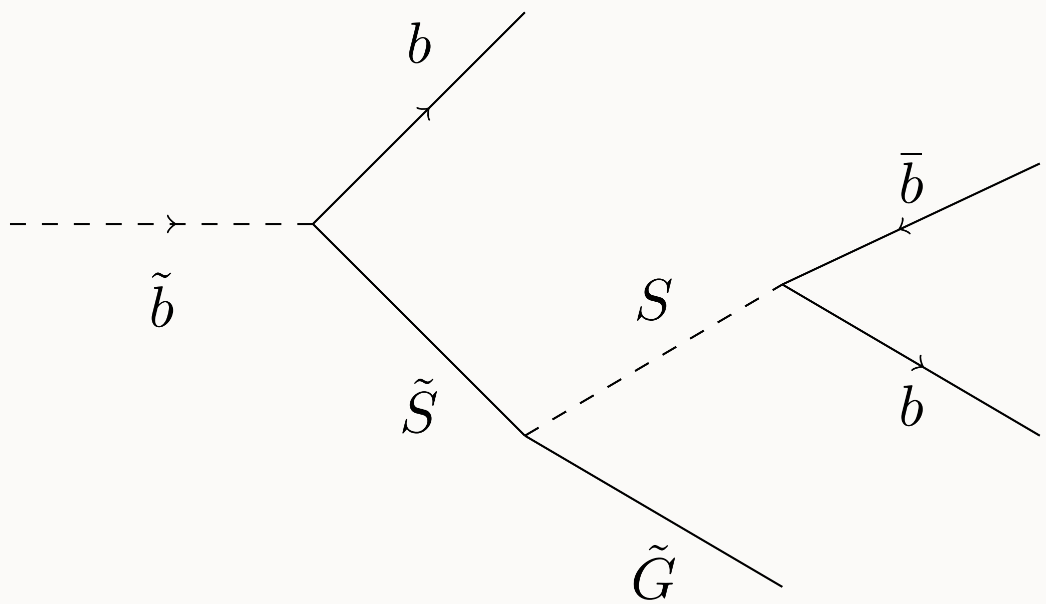
DIAGNOSING STEALTH

- If we see resonant final states, can we know it's stealth?
- ***Nearly degenerate bosons and fermions should be a smoking gun for supersymmetry.***
- Stealth may be a form of "hidden" SUSY, but if we find it, SUSY reveals its structure.

SPIN PARADOX

- One example of how stealth might be found:

  SH_uH_d model, sbottom LVSP: count *b*-tags to confirm



- Fermion (3b) “resonance” with cross section of *scalar*.
- Prototype for more interesting collider phenomenology.

CONCLUSIONS

- Stealth supersymmetry provides natural models with *R*-parity that do not have missing energy signals.
- The simplest realization has decays to gravitino and displaced vertex signatures.
- High-scale breaking is slightly trickier to build models for (*B*-term problem), but also possible.
- Many models, with many different possible signatures. Message: ***Look for resonant new physics. It could be SUSY!***