Stealth SUSY

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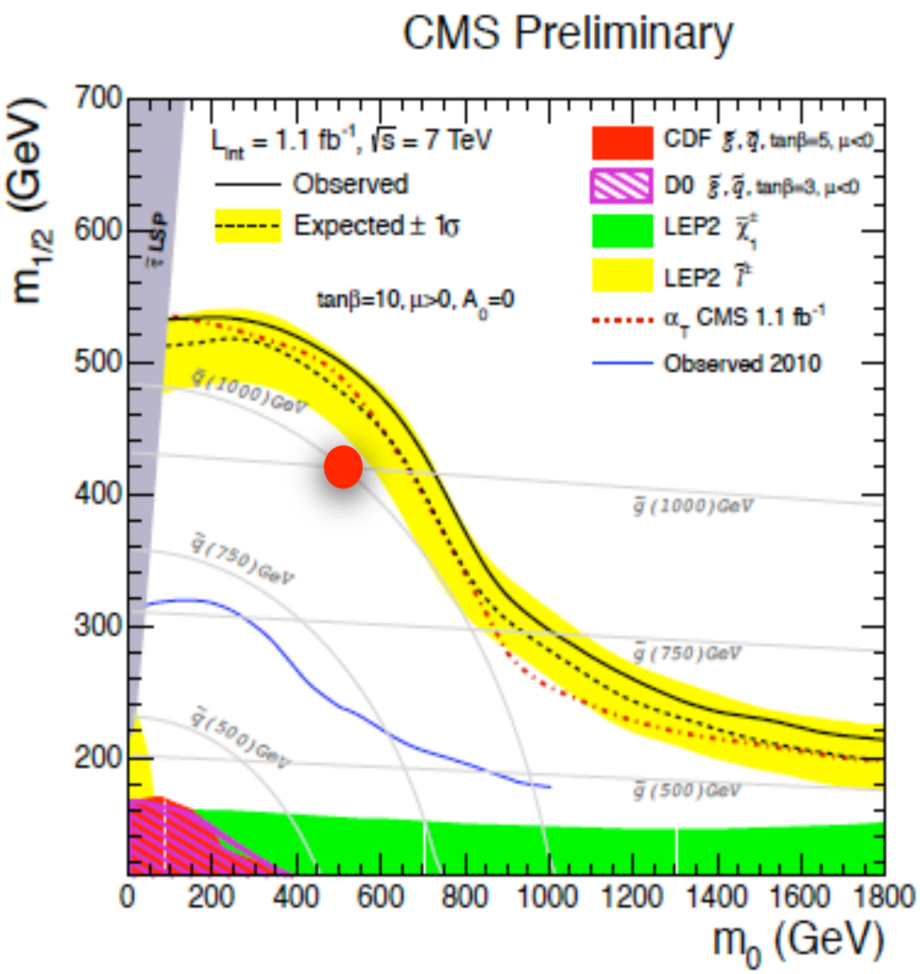
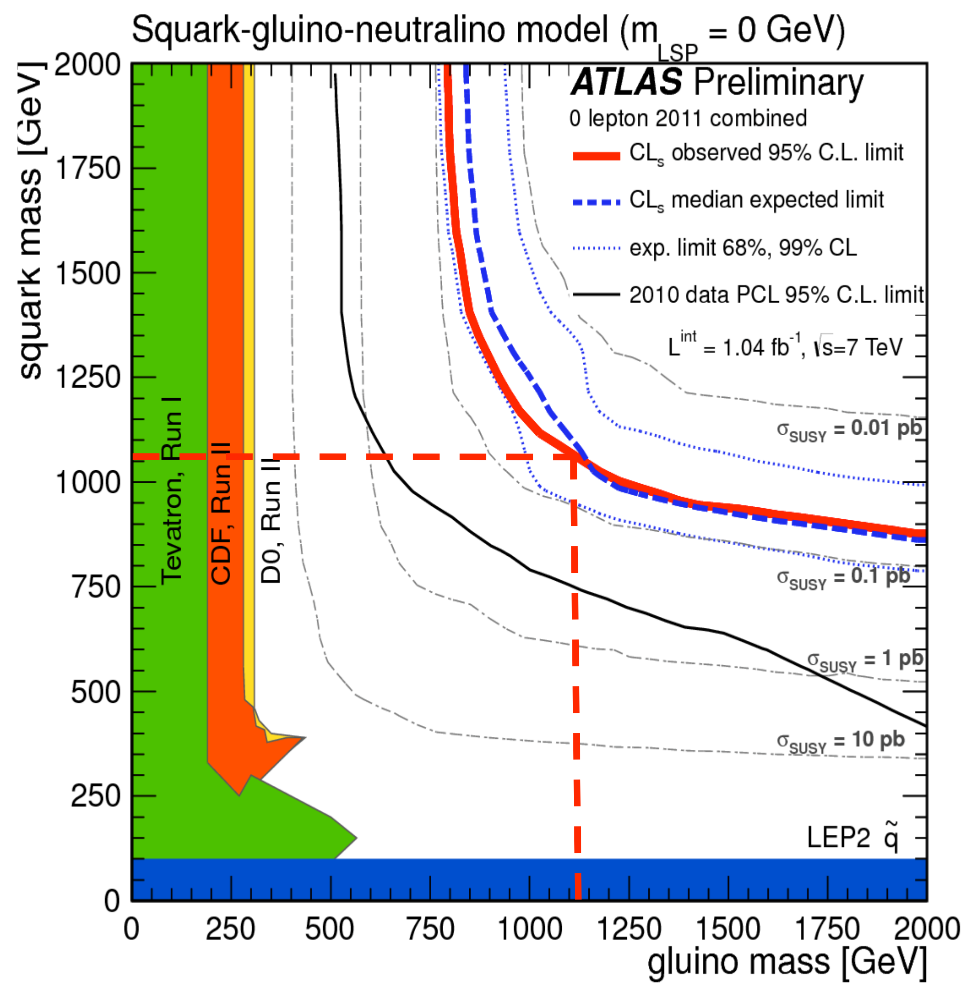
Based on work with Matt Reece and Josh Ruderman
arXiv:1105.5135 [hep-ph], work in progress

- So far Jets+ MET searches at the LHC have already placed strong limits on the colored MSSM superpartners in R-parity conserving scenarios

CMS: HT+missing HT search

ATLAS: MET + m_{eff} search
M_{gluino} > 800 GeV (with decoupled squark)





CMS: HT+missing HT search

Improve sensitivity to high multiplicity final state

	Baseline (H_T >350 GeV) ($\not{H}_T$ >200 GeV)	Medium (H_T >500 GeV) ($\not{H}_T$ >350 GeV)	High H_T (H_T >800 GeV) ($\not{H}_T$ >200 GeV)	High $\not{H}_T$ (H_T >800 GeV) ($\not{H}_T$ >500 GeV)
$Z \to \nu\bar{\nu}$ from γ+jets	$376 \pm 12 \pm 79$	$42.6 \pm 4.4 \pm 8.9$	$24.9 \pm 3.5 \pm 5.2$	$2.4 \pm 1.1 \pm 0.5$
$t\bar{t}$/W $\to$ e, μ+X	$244 \pm 20^{+30}_{-31}$	$12.7 \pm 3.3 \pm 1.5$	$22.5 \pm 6.7^{+3.0}_{-3.1}$	$0.8 \pm 0.8 \pm 0.1$
$t\bar{t}$/W $\to \tau_h$+X	$263 \pm 8 \pm 7$	$17 \pm 2 \pm 0.7$	$18 \pm 2 \pm 0.5$	$0.73 \pm 0.73 \pm 0.04$
QCD	$31 \pm 35^{+17}_{-6}$	$1.3 \pm 1.3^{+0.6}_{-0.4}$	$13.5 \pm 4.1^{+7.3}_{-4.3}$	$0.09 \pm 0.31^{+0.05}_{-0.04}$
Total background	928 ± 103	73.9 ± 11.9	79.4 ± 12.2	4.6 ± 1.5
Observed in data	986	78	70	3

$$H_T^{miss} = \left| - \sum_{p_T > 30\,\mathrm{GeV}} \vec{p_T} \right|$$

ATLAS: MET + m_{eff} search

M_{gluino} > 800 GeV (with decoupled squark)

Signal Region	≥ 2 jets	≥ 3 jets	≥ 4 jets	High mass
E_T^{miss}	> 130	> 130	> 130	> 130
Leading jet p_T	> 130	> 130	> 130	> 130
Second jet p_T	> 40	> 40	> 40	> 80
Third jet p_T	–	> 40	> 40	> 80
Fourth jet p_T	–	–	> 40	> 80
$\Delta\phi(\text{jet}, E_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
E_T^{miss}/m_{eff}	> 0.3	> 0.25	> 0.25	> 0.2
m_{eff} [GeV]	> 1000	> 1000	> 500/1000	> 1100

SUSY variants

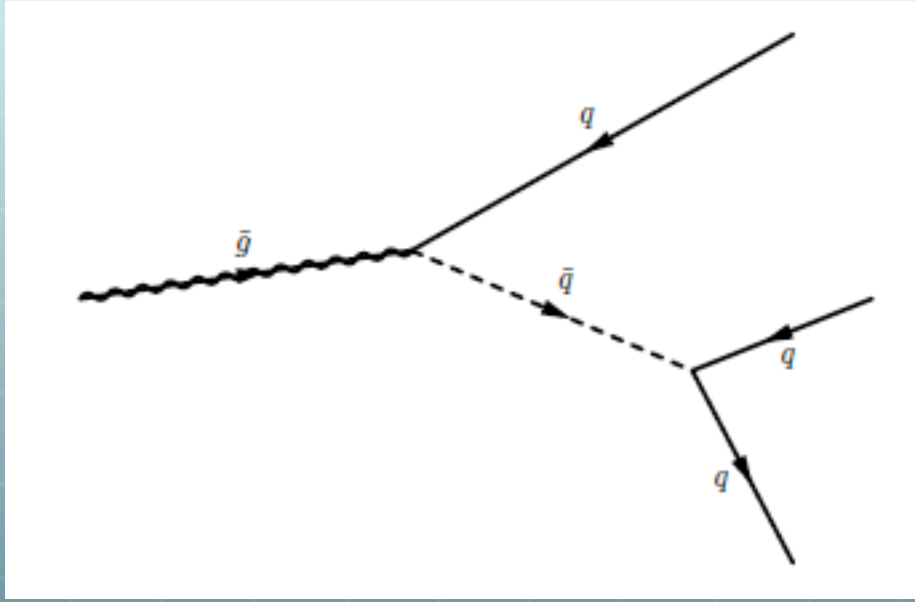
- **The bounds have several known exceptions:**

R-parity violation : e.g., udd

$$\tilde{g} \rightarrow 3q$$

Searches by CDF and CMS

M(gluino)<280 GeV is excluded



- Long cascade decay chain

  Softer jets; less missing energy;

- Squeezed MSSM spectrum Alwall, Le, Lisanti and Wacker; Conley, Gainer, Hewett, Le, Rizzo; LeCompte, Martin

$$m_{\tilde{g}} \sim m_{\tilde{B}}$$

Challenges: jets are softer; Bino momentum cancel when reconstructing MET;

What I will discuss today:

- **One simple and natural exception: SUSY without MET**

  No R-parity violation;

  No artificial tuning: SUSY hides SUSY;

- **An electroweak scale hidden sector with a naturally squeezed spectrum (as a result of an approximate SUSY)**

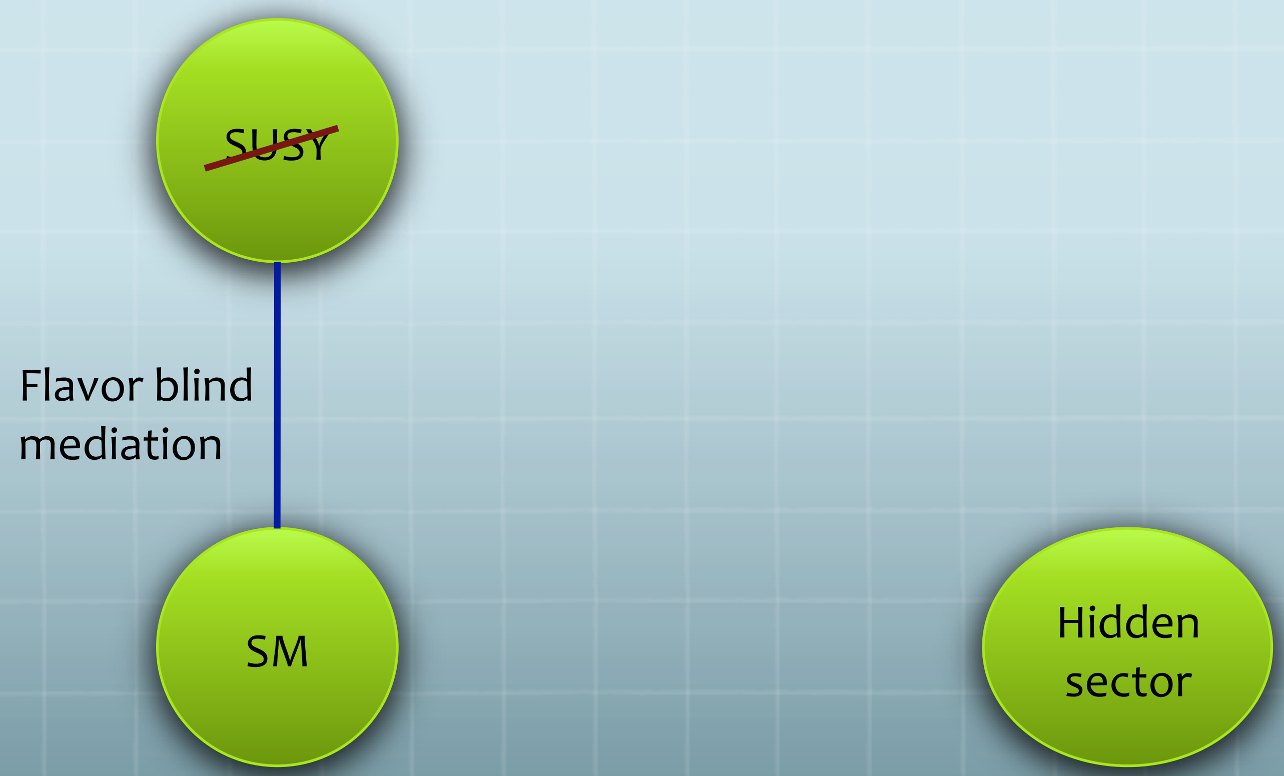
  Different from MSSM with a squeezed spectrum (e.g., gluino mass close to bino mass, which requires tuning)

Outline

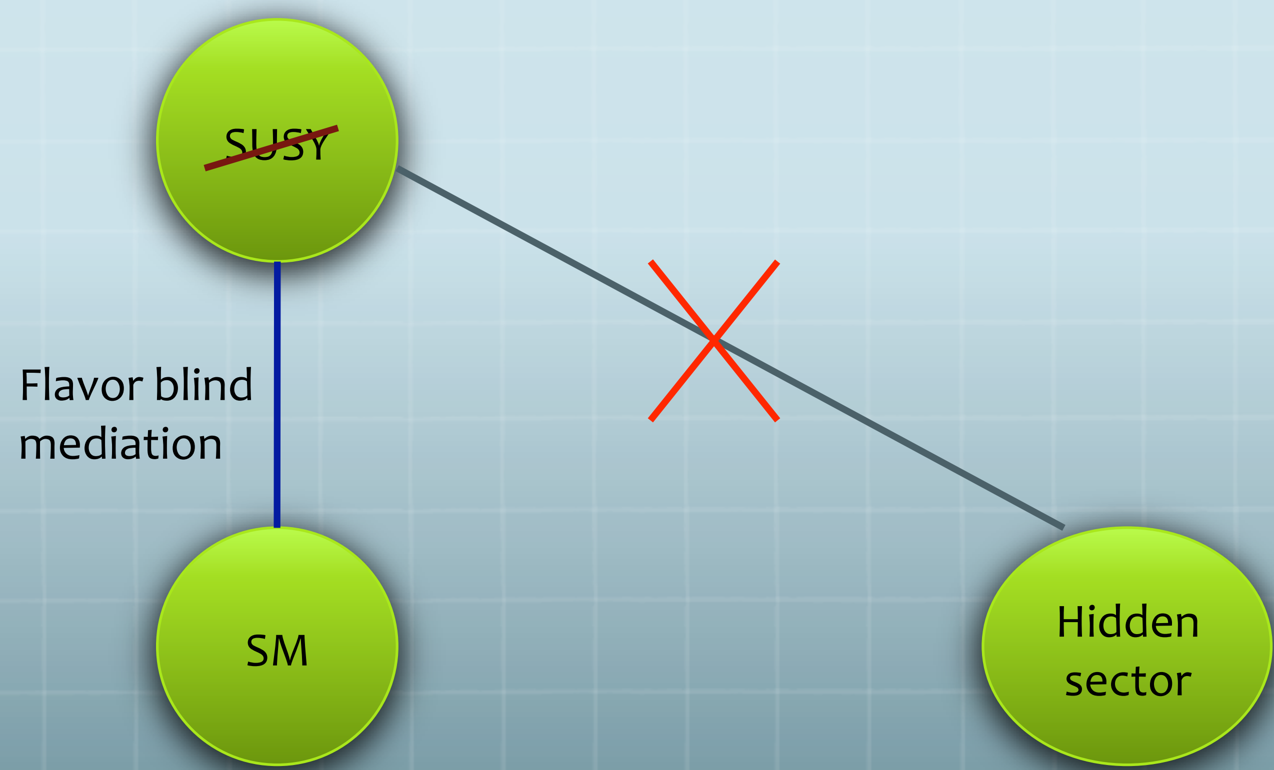
- Basic mechanism
- Simple example models
- Spectrum and collider signals
- Conclusions

Basic Mechanism

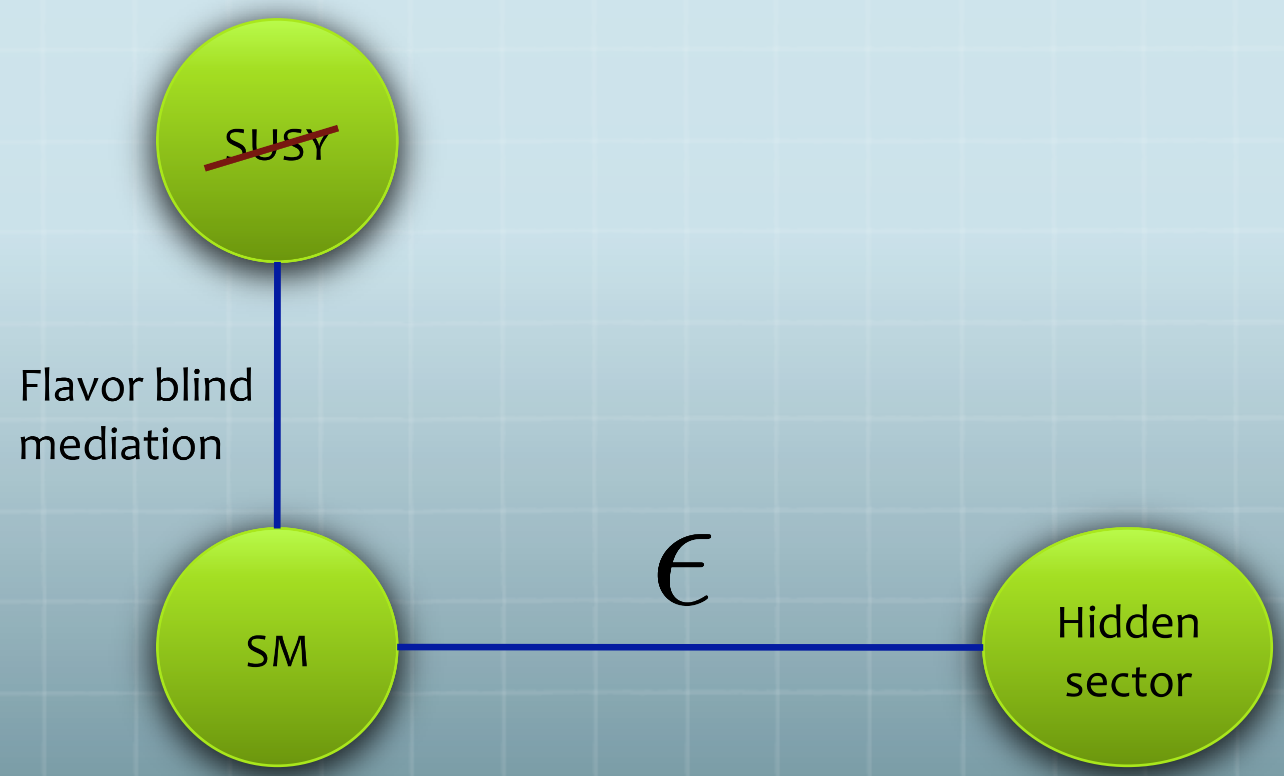
Basic Mechanism



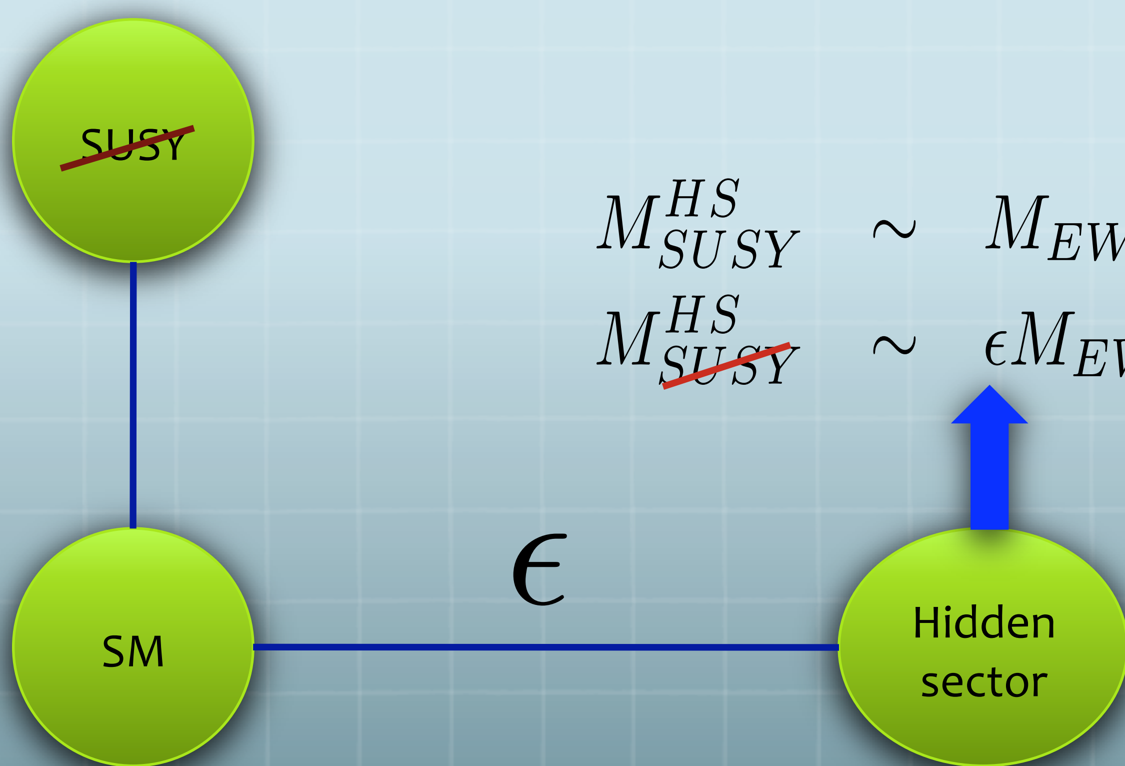
Basic Mechanism



Basic Mechanism



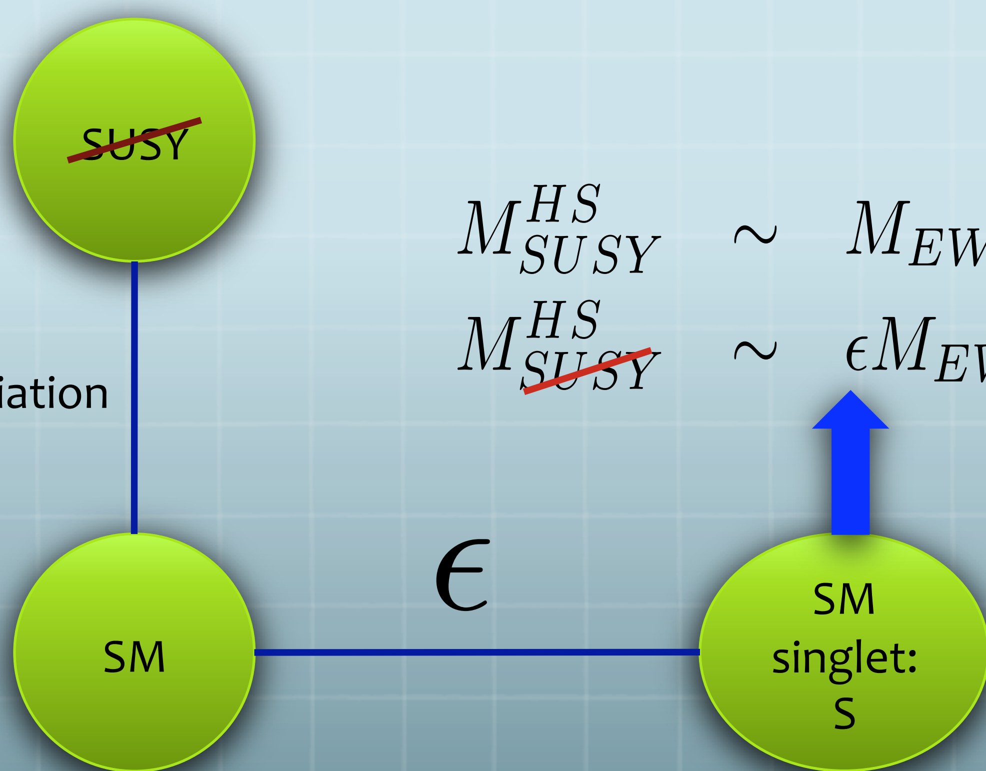
Basic Mechanism



$$M_{SUSY}^{HS} \sim M_{EW}$$

$$M_{\cancel{SUSY}}^{HS} \sim \epsilon M_{EW} \ll M_{SUSY}^{HS}$$

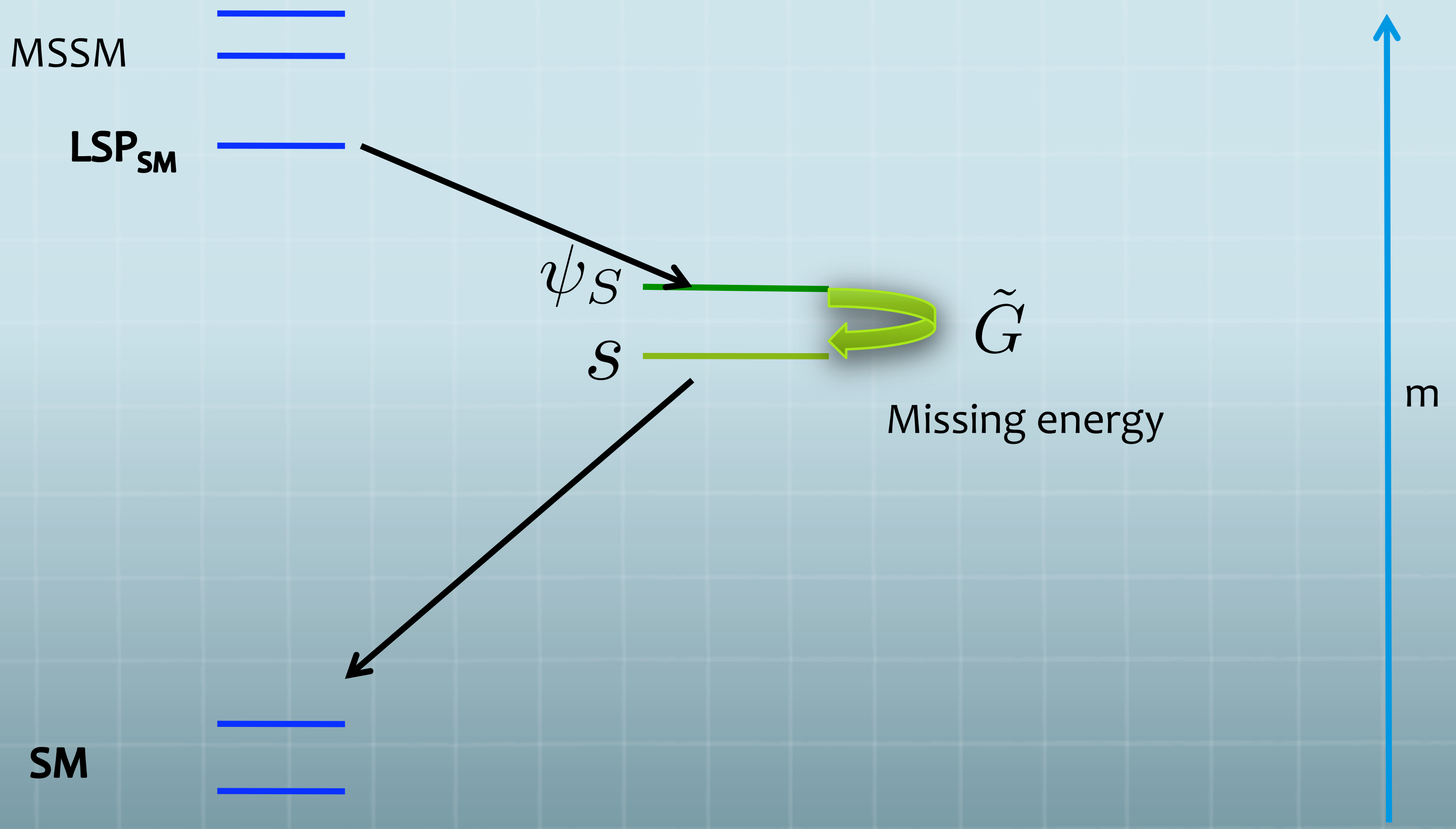
Simplest example:

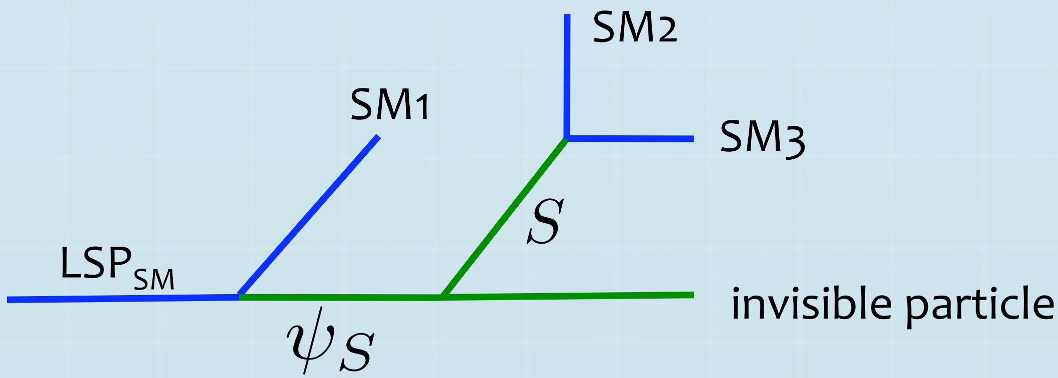


Low-scale gauge mediation w/ a light gravitino

$$M^{HS}_{SUSY} \sim M_{EW}$$
$$M^{HS}_{\cancel{SUSY}} \sim \epsilon M_{EW} \ll M^{HS}_{SUSY}$$

E.g., Low-scale gauge mediation with a singlet S





Fermion mass Scalar mass

$$\delta m \equiv m_{\psi_S} - m_S$$

In the ψ_S rest frame,

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

Controlled by ε

In the lab frame,

$$E_{missing} = \gamma \delta m \approx \frac{m_{LSP_{SM}}}{m_{\tilde{S}}} \delta m$$

$$\boxed{\delta m \to 0, E_{missing} \to 0}$$

Recap: basic requirements for model building

- A nearly supersymmetric hidden sector with SUSY masses at the electroweak scale
- Portals communicating in between our sector and the stealth sector
- A light invisible particle in the hidden sector that carries away the missing momentum

Outline

- Motivation
- Basic mechanism
- **Simple example models**
- Spectrum and collider signals
- Conclusions

An example model

- **Stealth sector: a SM singlet S**
- **Portal:** $Y, \bar{Y} \quad 5 + \bar{5}$ **under SM SU(5)**
- **SUSY breaking:**

  Low-scale gauge mediation: light gravitino
- **Model:**

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

m_S is taken to be 100 GeV

Integrating out ``messengers" Y's,

- **Portal in**

$$\lambda^a \sigma_{\mu\nu} G^{a\mu\nu} \psi_S$$

$$\tilde{g} \longrightarrow g + \psi_S$$
$$\tilde{B} \longrightarrow \gamma + \psi_S$$

- **Portal out**

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

$$s \longrightarrow gg$$

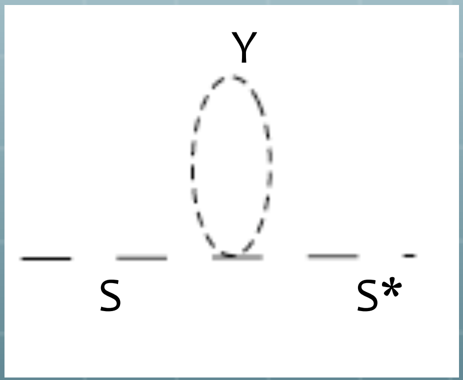
Mass splitting

- **Model:**

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

- **Soft mass of S is generated at one-loop**

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



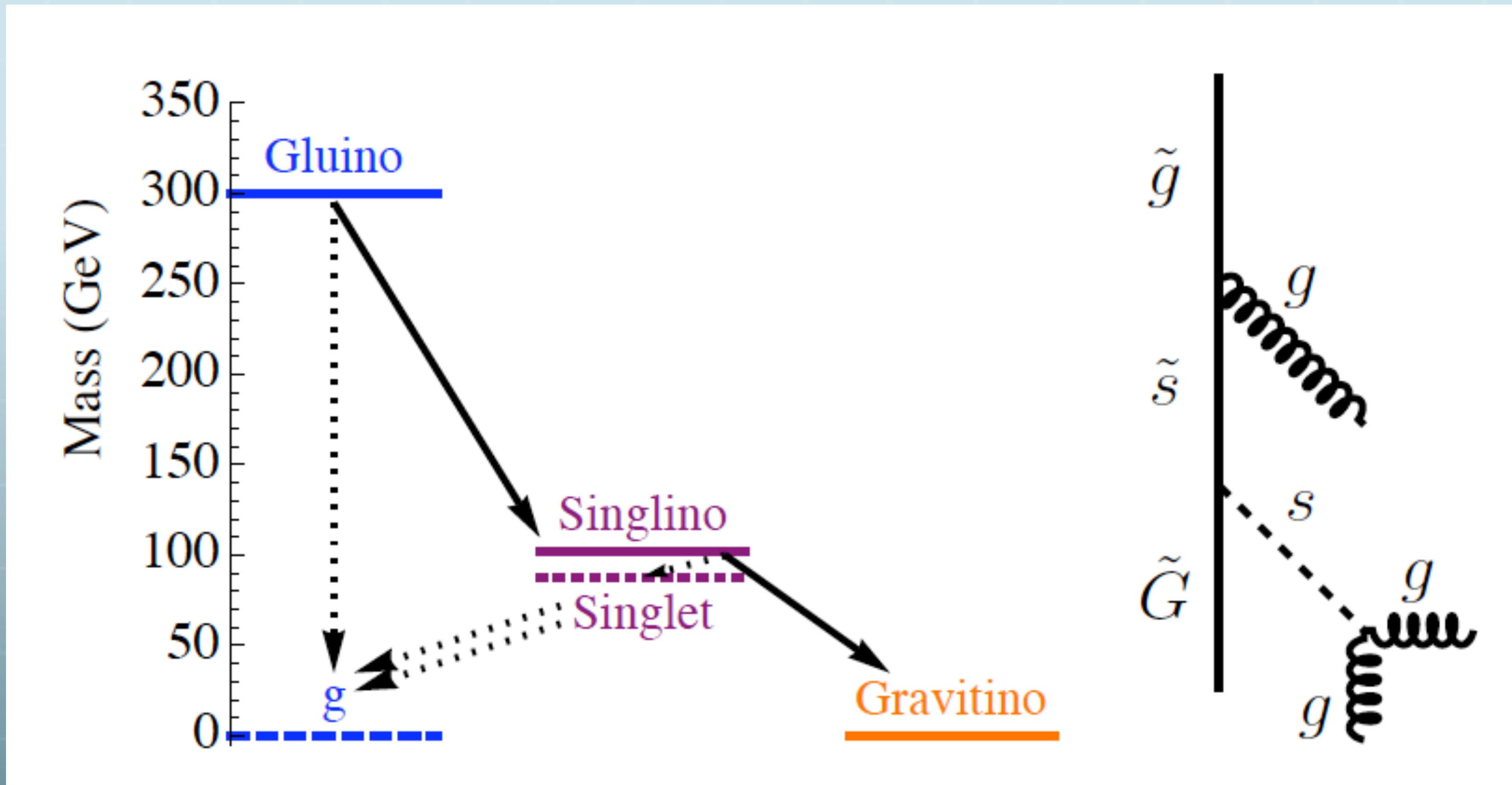
Assuming both m_D, m_L are positive

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

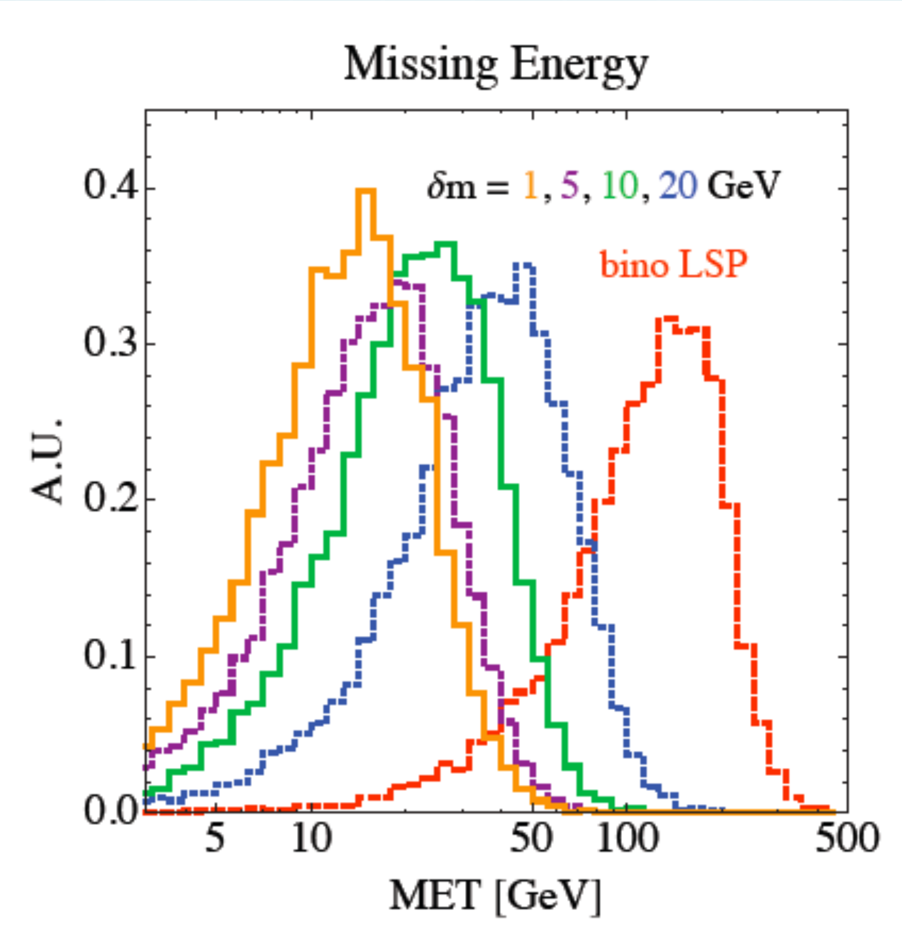
$SY\bar{Y}$	
$m = 100$ GeV	$m_{\tilde{s}} = 100$ GeV
$\lambda = 0.2$	$m_{s,a} = 91$ GeV
$m_Y = 1000$ GeV	$\Gamma_{s,a} = 2 \times 10^{-7}$ GeV
$\tilde{m}_D = 300$ GeV $\quad \tilde{m}_L = 200$ GeV	$\mathrm{Br}_{s,a \to \gamma\gamma} = 4 \times 10^{-3}$
$M_{\mathrm{mess}} = 100$ TeV	

$$\lambda \lesssim 0.1 - 0.2 \quad \delta m \lesssim 10 GeV$$

Spectrum and decay chain

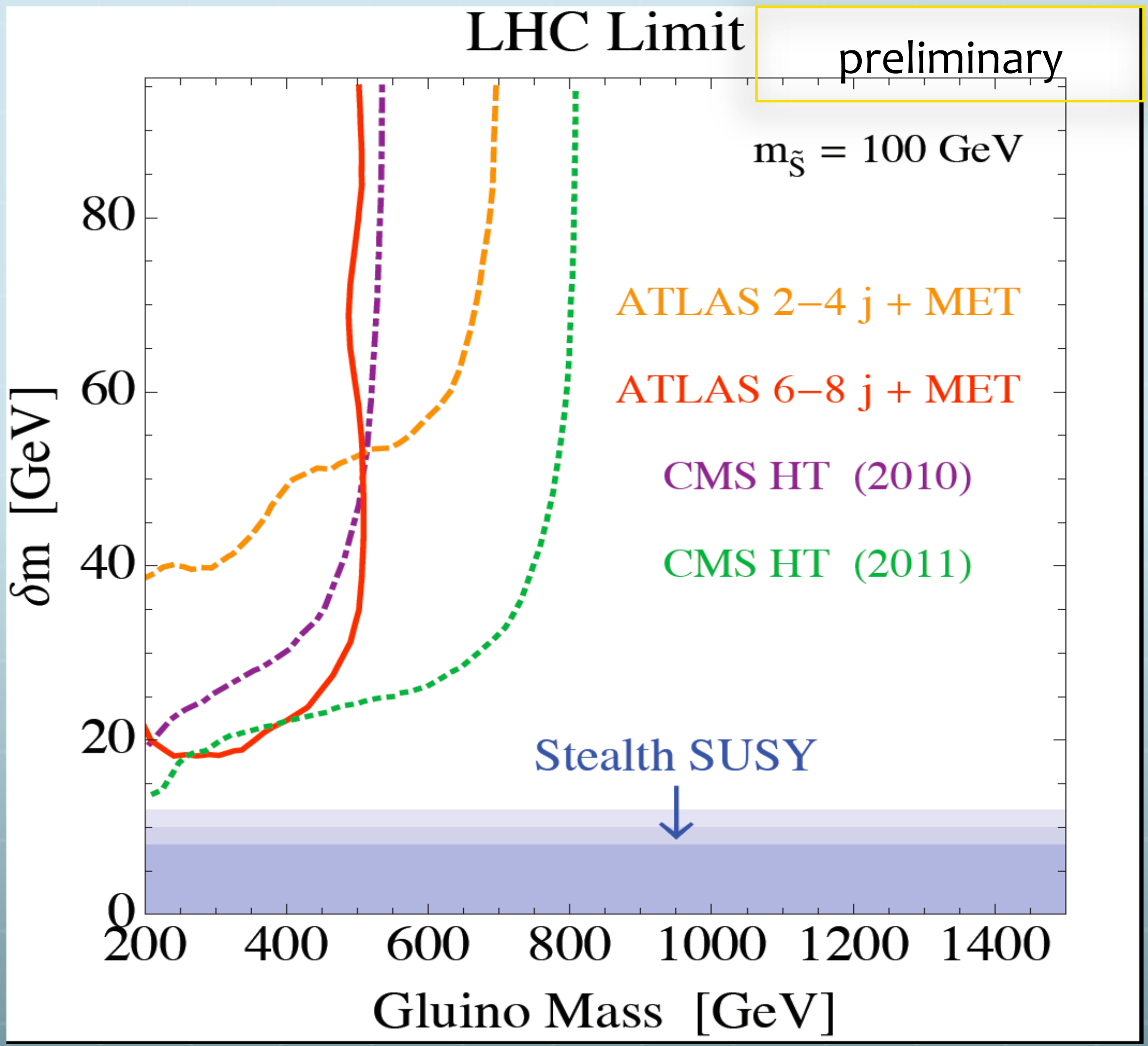


Missing energy spectrum



LHC searches always cut hard on missing E_T,

E.g., Missing E_T> 130 GeV (trigger requirement), ATLAS missing E_T + m_{eff} search



Bottom line:

current limits do not apply to stealth SUSY with mass splitting smaller than 10 GeV !

- **A very similar model**

Stealth sector: S

Portal: MSSM Higgses: Hu, Hd

SUSY breaking: Low-scale gauge mediation w/ a light gravitino

Model:

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

After SUSY breaking and EWSB, $\delta m \sim \lambda\kappa\mu v^2/m^2$

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	$N_{\tilde{s}(\tilde{B},\tilde{W}^0)} = (0.0063, -0.0058)$

Scalar S mixes with higgses;

Singlino S mixes with higgisino

$$\begin{tikzcd} \tilde{B} \arrow[r] \arrow[dr] & \tilde{S} \arrow[r] & S + \tilde{G} \arrow[d] \\ & h & b + \bar{b} \end{tikzcd}$$

- So far we consider models in which the symmetry S is charged under is broken by small couplings to the portals.
- There is another possibility:

S is charged under a symmetry of the *MSSM* , for instance,

Baryon number !

Example 3: Sudd

- **Stealth sector: S**
- **Portals:**

$$W \supset \frac{1}{\Lambda}\lambda_{ijk} u_i d_j d_k S$$

Now scalar S is the R-odd particle!

Could be generated by integrating out heavy fields, e.g.:

$$M D\bar{D} + d\bar{D}S + udD$$

Decay in: $\tilde{t} \to bsS$

$$\tilde{B}, \tilde{g} \to u_i d_j d_k S$$

Decay out: $\tilde{S} \to u_i d_j d_k$

$$\Gamma(\tilde{B} \to uddS) \sim \frac{\alpha^2 \lambda^2}{(4\pi)^3 \Lambda^2 m_{\tilde{q}}^4} m_{\tilde{B}}^7$$

$$\sim 0.02\,\mathrm{cm} \left(\frac{300\,\mathrm{GeV}}{m_{\tilde{B}}}\right)^7 \left(\frac{\Lambda}{100\,\mathrm{TeV}}\right)^2 \left(\frac{m_{\tilde{q}}}{1\,\mathrm{TeV}}\right)^4 \frac{1}{\lambda^2}$$

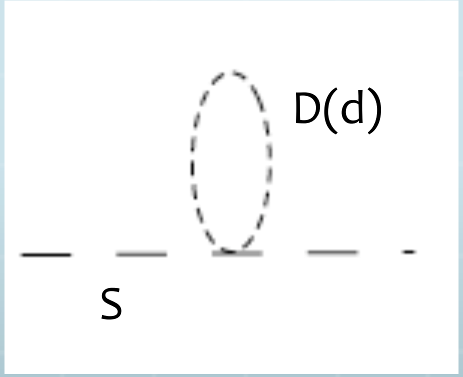
$$\Gamma(\tilde{S} \to udd) \sim \frac{\alpha_s^2 \lambda^2}{(4\pi)^5 \Lambda^2 m_{\tilde{g}}^2} m_{\tilde{S}}^5$$

$$\sim 24\,\mu\mathrm{m} \left(\frac{200\,\mathrm{GeV}}{m_{\tilde{S}}}\right)^5 \left(\frac{\Lambda}{100\,\mathrm{TeV}}\right)^2 \left(\frac{1\,\mathrm{TeV}}{m_{\tilde{g}}}\right)^2 \frac{1}{\lambda^2}$$

For Λ/λ < 1000 TeV, the decay would be displaced slightly, but is still in range where MET remains small

For low-scale gauge mediation w/ light gravitino

Scalar S has to obtain a positive soft mass,



$$M D\bar{D} + d\bar{D}S + udD$$

$$m^2_{\bar{D}} + m^2_d < 0 \longrightarrow m^2_S > 0$$

Not possible in minimal gauge mediation,
But possible in general gauge mediation (with non-zero D term)
Which only constrains sum of soft masses

$$S \to \tilde{S} + \tilde{G}$$

- **So far focus on low-scale gauge mediation,**
- **Could a stealth sector exist in the high-scale mediation schemes with a heavy gravitino, e.g., $m_{3/2} > 100$ GeV**
- **Stealth sector has to be sequestered from the SUSY breaking sector**
- **Two other problems …**

- **Decay inside the stealth sector:**

$$\mathrm{R-odd} \rightarrow \mathrm{R-even}+?$$

For high-scale mediations w/ heavy gravitino, add a light N

e.g:

$$W = \frac{uddS}{\Lambda} + m_S S S_2 + \lambda S^2 N$$

N has charge -2 under $U(1)_B$, m N^2 is forbidden;
N is naturally light

Other candidate : light axino

- **A more serious problem: stealth μ/μB problem**

$$W \supset \mu S^2$$

$$\supset \mu\phi S^2$$

$$V \supset \mu m_{3/2} S^2$$

Conformal compensator $\phi = 1 + \theta^2 m_{3/2}$

$$\delta m = \mu - \sqrt{\mu^2 - \mu B} \approx \frac{B}{2}$$

$$\delta m < 10\,\mathrm{GeV} \longrightarrow B \sim m_{3/2} < 20\,\mathrm{GeV}$$

However, if the μ term arises from some dynamically generated VEVs X S^2 and X obtains a VEV dynamically, e.g., through SQCD

$$W = X\bar{Q}Q - X^3$$

Or other solutions analogous to the B solution in anomaly mediation
e.g: Pomarol and Rattazzi,…

- **More possibilities**

  Z' model: One additional U(1) both our sector and stealth sector is charged under and the U(1) is spontaneously broken in the stealth sector;

  Vector-like confinement sector: strongly coupled SQCD sector with SM gauge group as the flavor symmetry of the matter fields.

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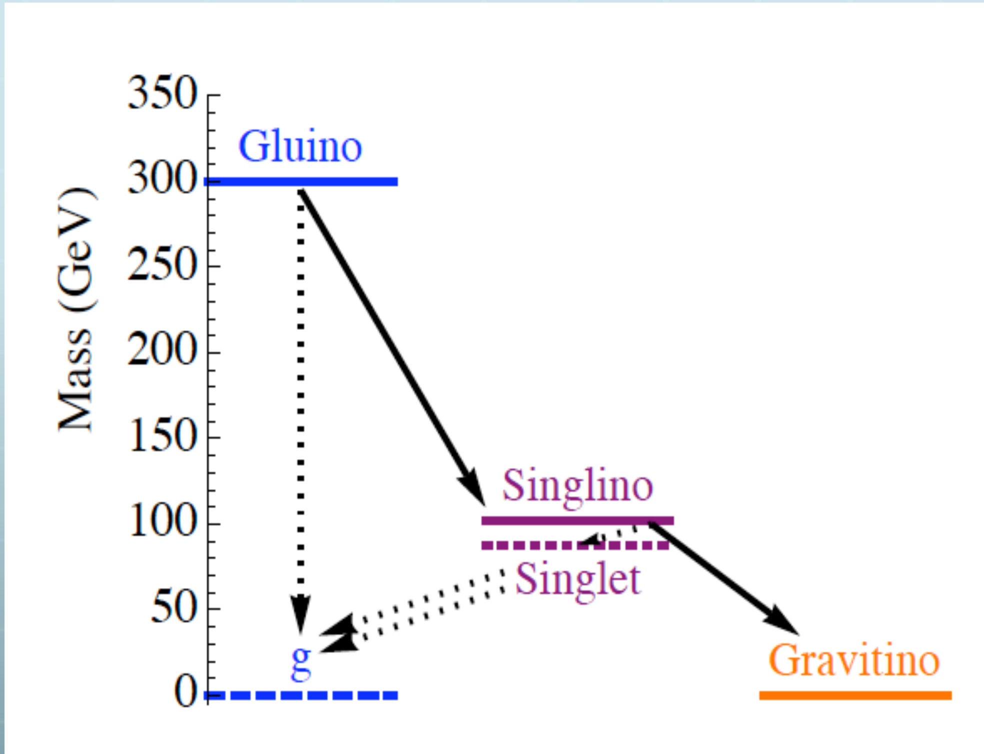
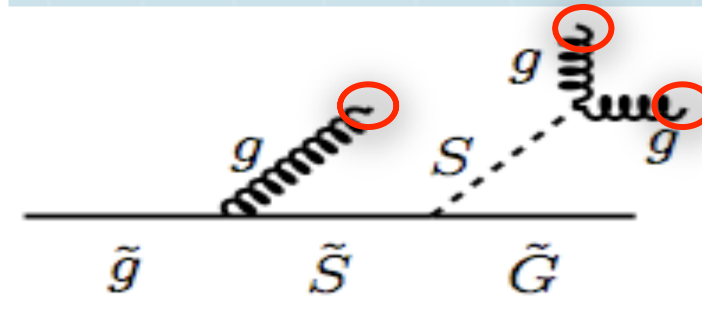
- Basic mechanism
- Simple example models
- **Spectrum and collider signals**
- Conclusions

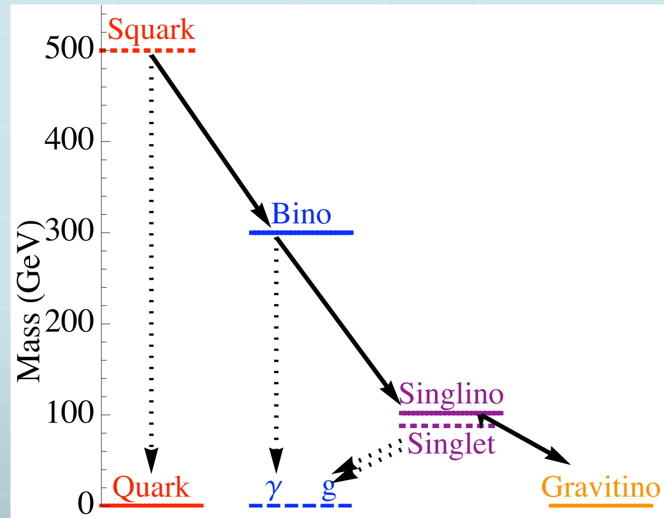
False resonance of jets

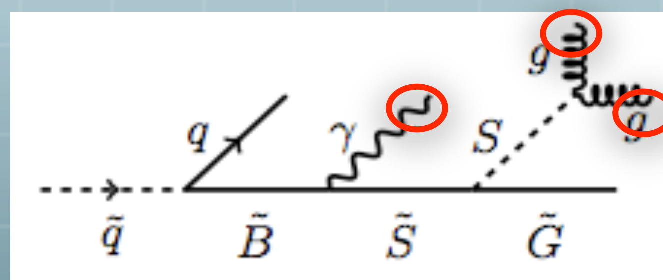




Search at CDF and CMS on resonance of 3 jets, motivated by $\tilde{g} \longrightarrow 3q$ also applies here!

False resonance of photon+jets

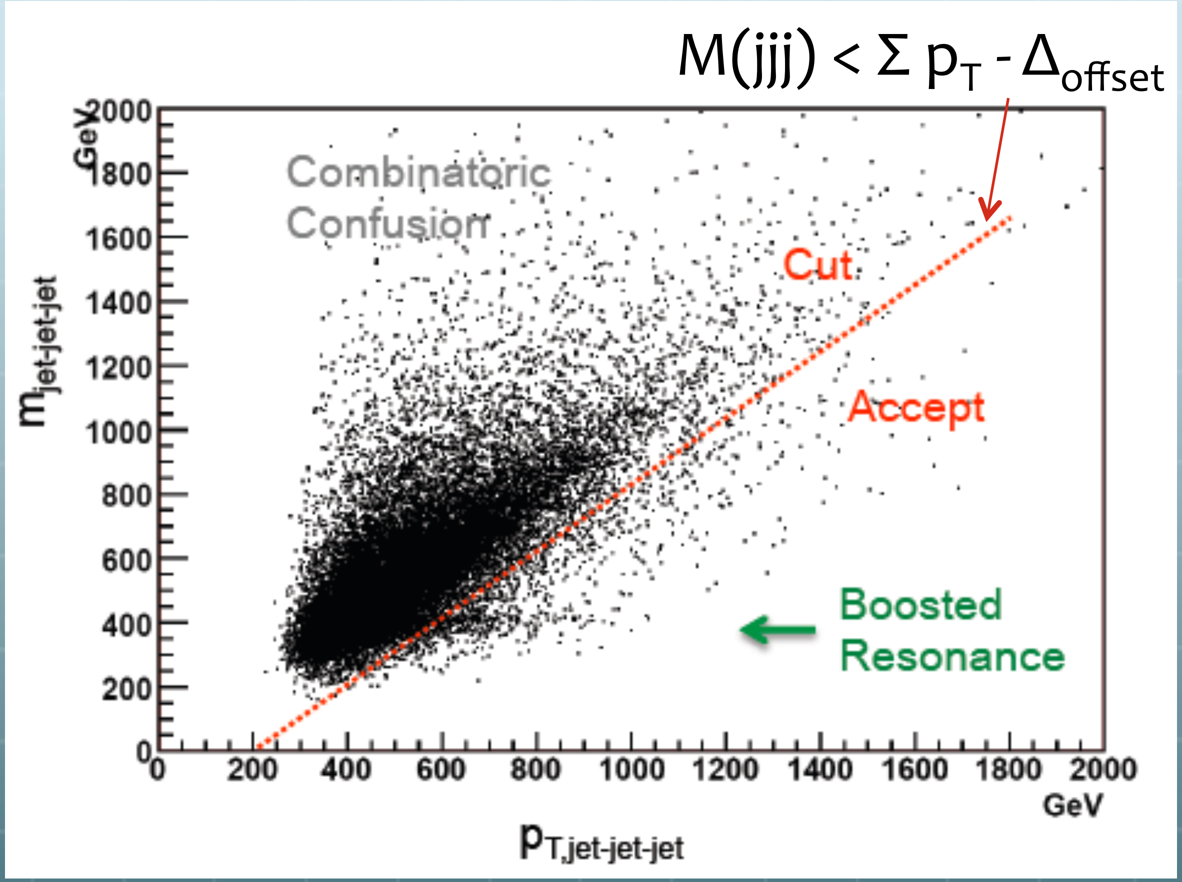




Main challenge: combinatorics

Method: "jet ensemble correlation" R. Essig Ph. D thesis

E.g: for three-jet resonance

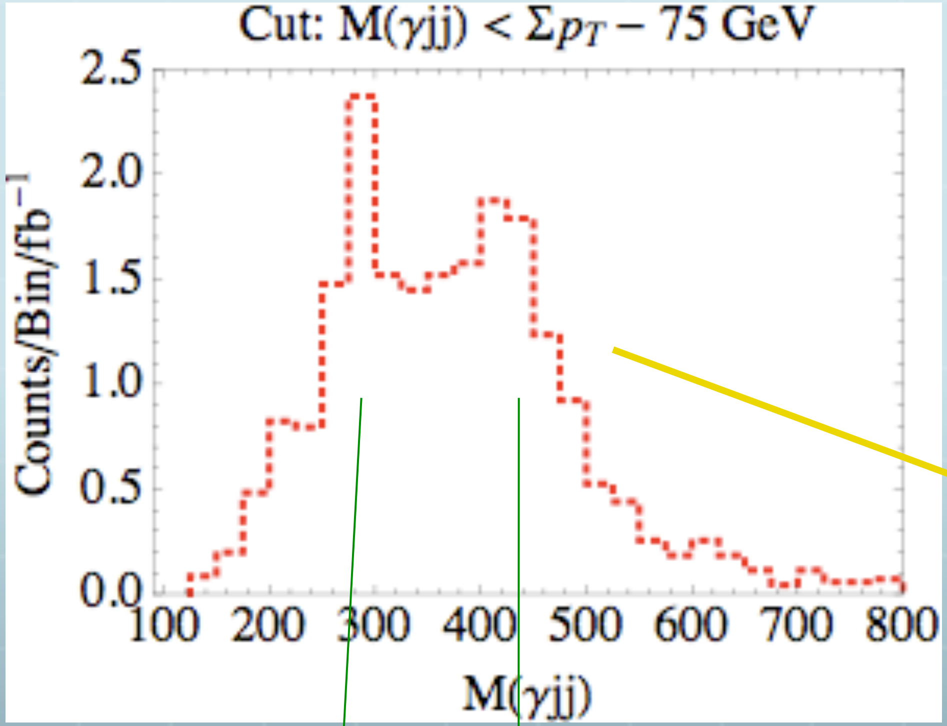


- **Cuts: (photon + jets)**

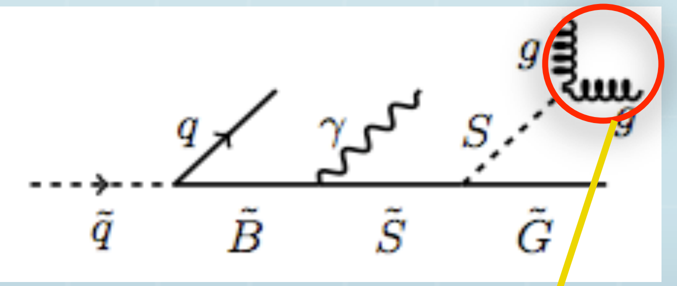
Photon: $E_T^\gamma > 120\,\mathrm{GeV} \quad |\eta| < 1.44$

At least two jets: $E_T > 45\,\mathrm{GeV} \quad \sum_{jets} E_T > 200\,\mathrm{GeV}$

Diagonal cut: $\mathrm{M}(\gamma jj) < \sum_{\gamma jj} p_T - 75\,\mathrm{GeV}$

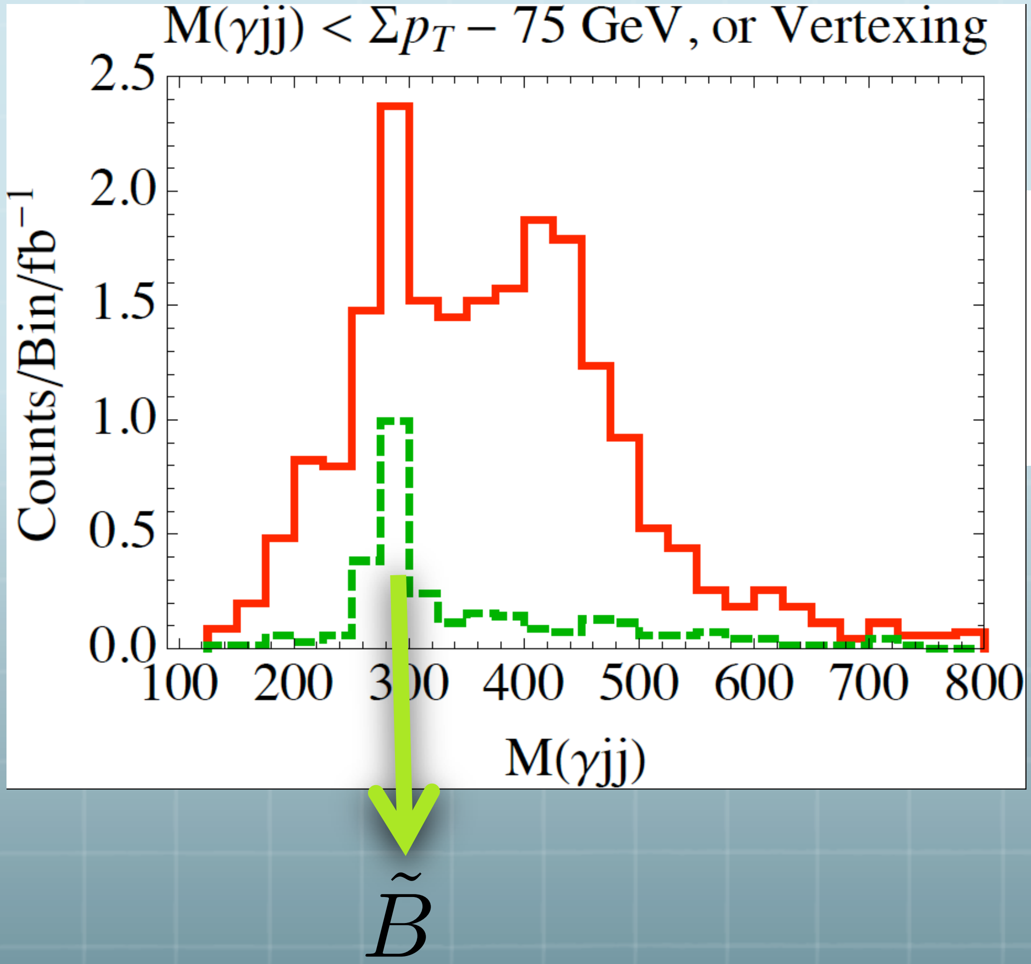


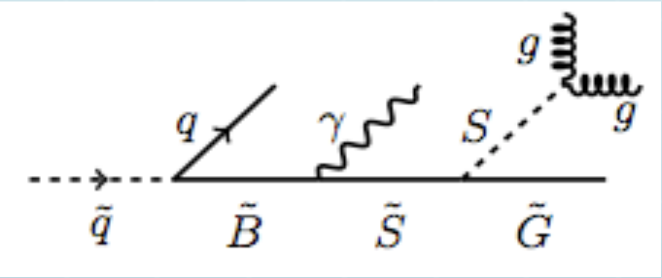
$\tilde{B}$ $\tilde{q}$



Two jets collimated into one "singlet jet"!

Substructure could help!





Vertexing: Require two jets from the same vertex.

More searching strategies (model dependent)

- **Displaced vertex:** $\tilde{s} \longrightarrow s + \tilde{G}$

Decay length ranging from mm to several cm;

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

E.g.:

$$\sqrt{F} = 100\,\mathrm{TeV}, \quad m_{\tilde{S}} = 100\,\mathrm{GeV}, \quad m_S = 90\,\mathrm{GeV}$$

$$c\tau = 8\,cm$$

More searching strategies (continue)

- **High multiplicity (of b jets) : Model dependent**

$$\begin{tikzcd} \tilde{g} \arrow[r] \arrow[dr] & \tilde{b} \arrow[r] \arrow[dr] & \tilde{B} \arrow[r] \arrow[dr] & \tilde{s} \arrow[r] & s + \tilde{G} \arrow[d] \\ & b & b & h \arrow[d] & b + \bar{b} \\ & & & b + \bar{b} & \end{tikzcd}$$

In model where S mixes with SM Higgs: SH_uH_d

Smoking gun for SUSY? -- Spin paradox

SHuHd

$$
\begin{tikzcd}
\tilde{b} \arrow[r] \arrow[dd] & \tilde{S} \arrow[r] \arrow[d] & \tilde{G} \\
& S \arrow[d] & \\
b & b+\bar{b} &
\end{tikzcd}
$$

Production cross section scalar

(Visible) final states: 3 b-jets fermion

Conclusion

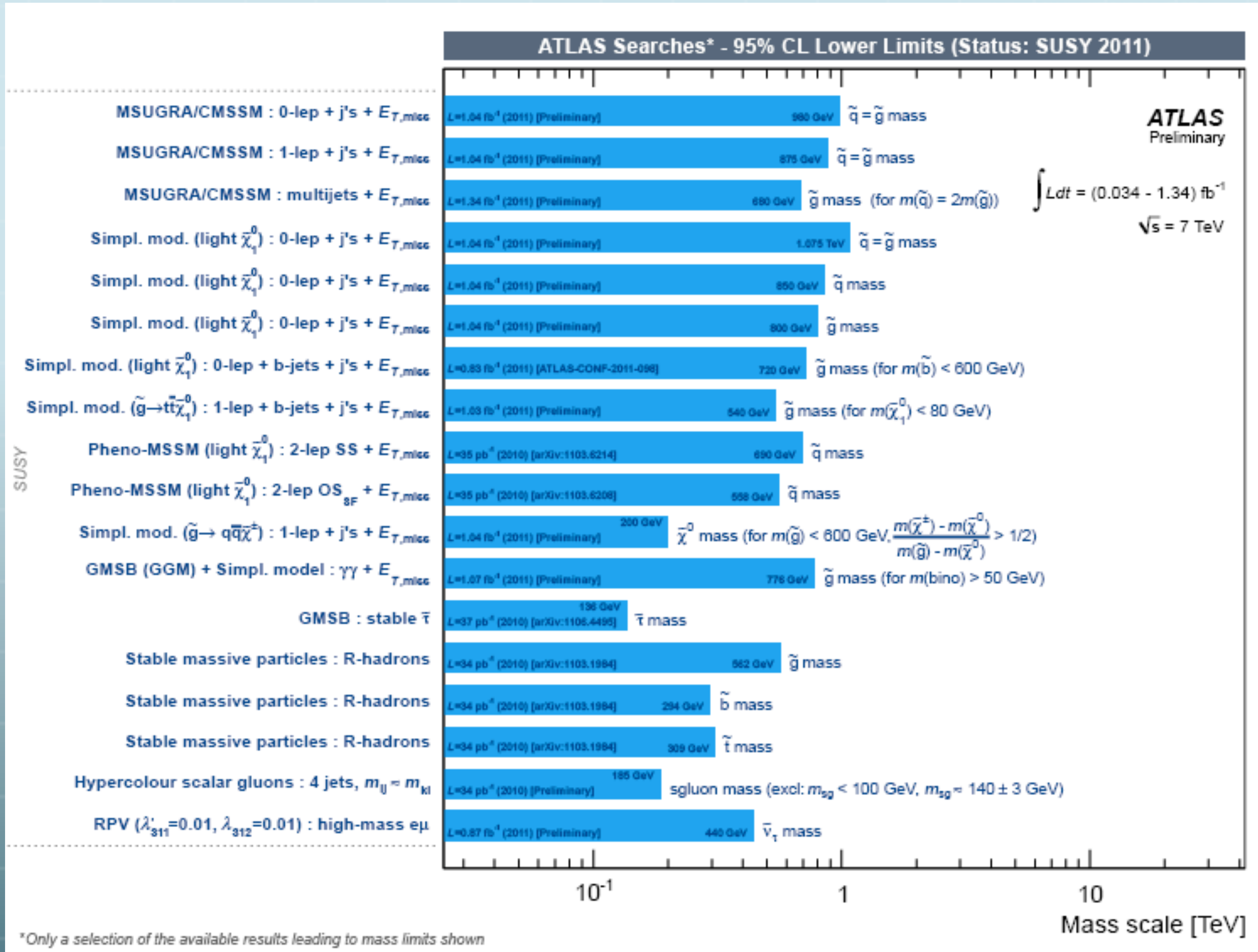
- We present a broad class of natural supersymmetric models that preserve R-parity but lack missing energy signatures.

- The main feature is the presence of nearly degenerate fermion-boson pairs at the electroweak scale due to an approximate supersymmetry.

  Even MSSM may have a form of stealth supersymmetry, if the right handed stop and top have nearly degenerate masses.

- It opens up more possibilities for model building and searching strategies at the LHC.

Thank you!



ATLAS Searches* - 95% CL Lower Limits (Status: SUSY 2011)
ATLAS
Preliminary
∫Ldt = (0.034 - 1.34) fb⁻¹
√s = 7 TeV
SUSY
MSUGRA/CMSSM : 0-lep + j's + E_T,miss
q̃ = g̃ mass
MSUGRA/CMSSM : 1-lep + j's + E_T,miss
q̃ = g̃ mass
MSUGRA/CMSSM : multijets + E_T,miss
g̃ mass (for m(q̃) = 2m(g̃))
Simpl. mod. (light χ̃₁⁰) : 0-lep + j's + E_T,miss
q̃ = g̃ mass
Simpl. mod. (light χ̃₁⁰) : 0-lep + j's + E_T,miss
q̃ mass
Simpl. mod. (light χ̃₁⁰) : 0-lep + j's + E_T,miss
g̃ mass
Simpl. mod. (light χ̃₁⁰) : 0-lep + b-jets + j's + E_T,miss
g̃ mass (for m(b̃) < 600 GeV)
Simpl. mod. (g̃→tt̄χ̃₁⁰) : 1-lep + b-jets + j's + E_T,miss
g̃ mass (for m(χ̃₁⁰) < 80 GeV)
Pheno-MSSM (light χ̃₁⁰) : 2-lep SS + E_T,miss
q̃ mass
Pheno-MSSM (light χ̃₁⁰) : 2-lep OS_SF + E_T,miss
q̃ mass
Simpl. mod. (g̃→ qq̄χ̃±) : 1-lep + j's + E_T,miss
χ̃⁰ mass (for m(g̃) < 600 GeV, (m(χ̃±) - m(χ̃⁰))/(m(g̃) - m(χ̃⁰)) > 1/2)
GMSB (GGM) + Simpl. model : γγ + E_T,miss
g̃ mass (for m(bino) > 50 GeV)
GMSB : stable τ̃
τ̃ mass
Stable massive particles : R-hadrons
g̃ mass
Stable massive particles : R-hadrons
b̃ mass
Stable massive particles : R-hadrons
t̃ mass
Hypercolour scalar gluons : 4 jets, m_ij ≈ m_kl
sgluon mass (excl: m_sg < 100 GeV, m_sg ≈ 140 ± 3 GeV)
RPV (λ'₃₁₁=0.01, λ₃₁₂=0.01) : high-mass eμ
ν̃_τ mass
10⁻¹
1
10
Mass scale [TeV]
*Only a selection of the available results leading to mass limits shown

Atlas 6-8 jet search

Signal region	7j55	8j55	6j80	7j80
Jet p_T	$> 55\,\mathrm{GeV}$		$> 80\,\mathrm{GeV}$	
Jet $\lvert\eta\rvert$	< 2.8			
ΔR_{jj}	> 0.6 for any pair of jets			
Number of jets	≥ 7	≥ 8	≥ 6	≥ 7
$E_T^{miss}/\sqrt{H_T}$	$> 3.5\ \mathrm{GeV}^{1/2}$			

Trigger plateau

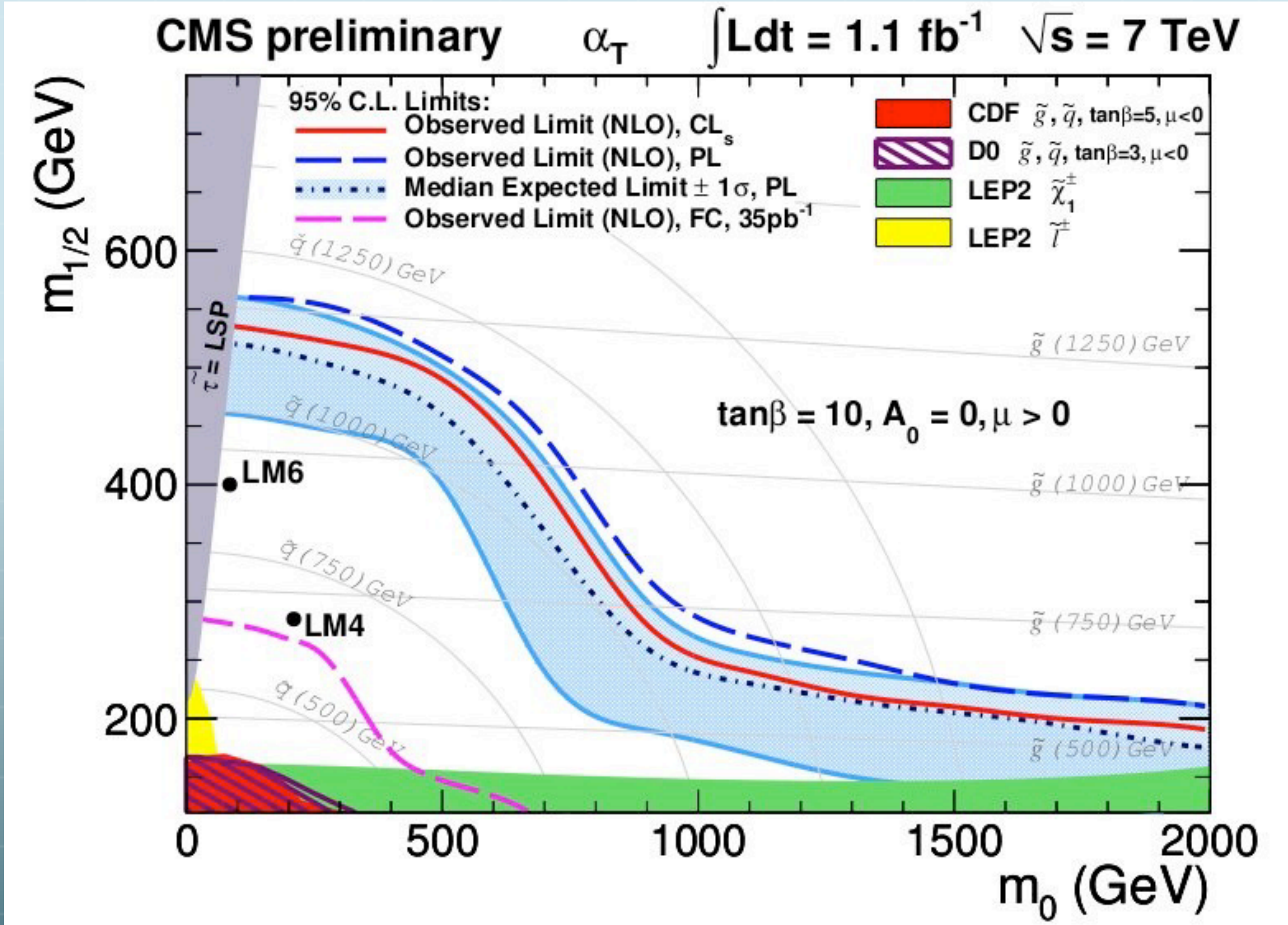
SR definition

BG reduction and control

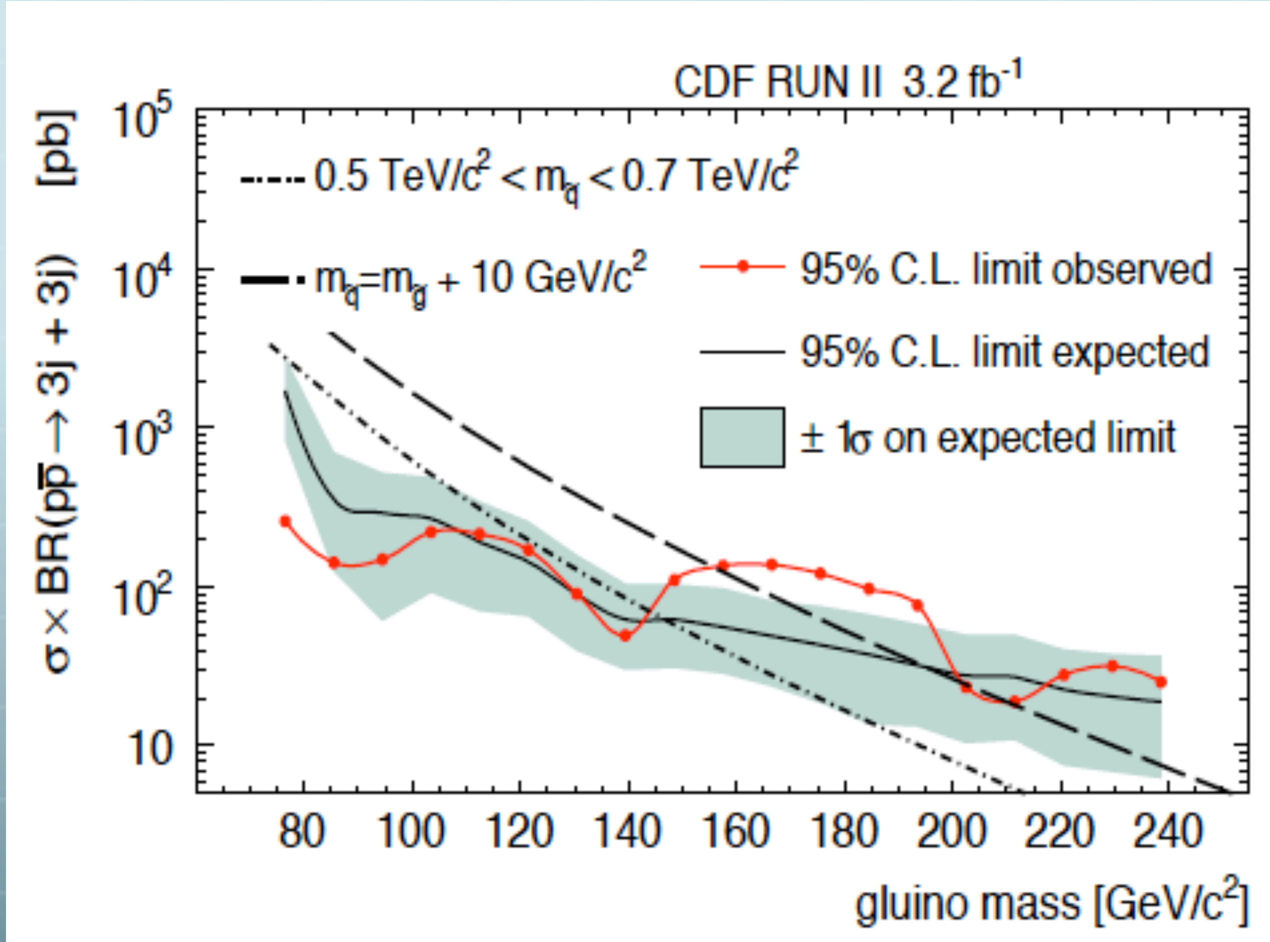
$$\int L\,dt = 1.34\ \mathrm{fb}^{-1}$$

$$H_T = \sum_{\mathrm{Jets}} p_T$$

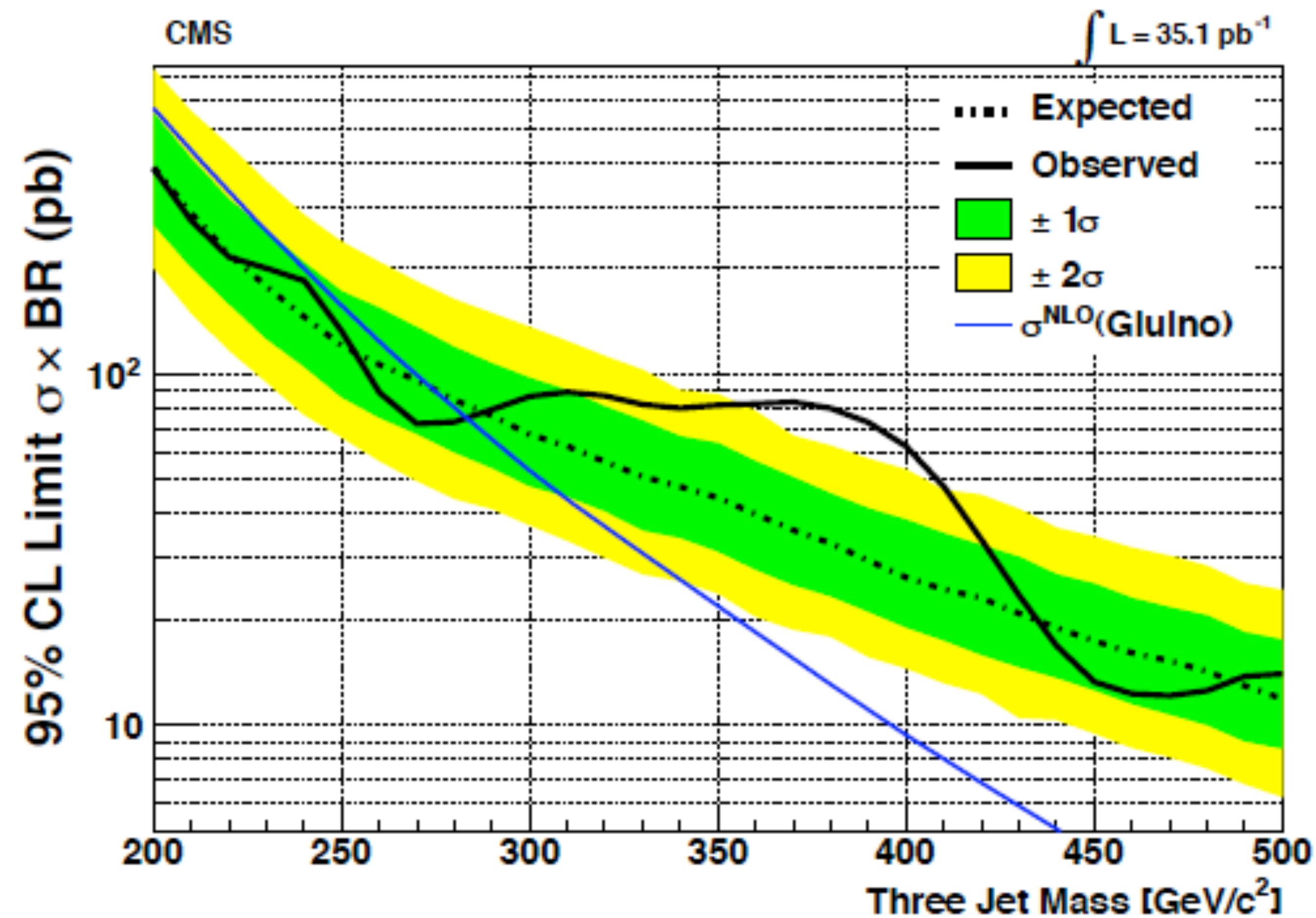
$(p_T > 40\ \mathrm{GeV}, |\eta| < 2.8)$

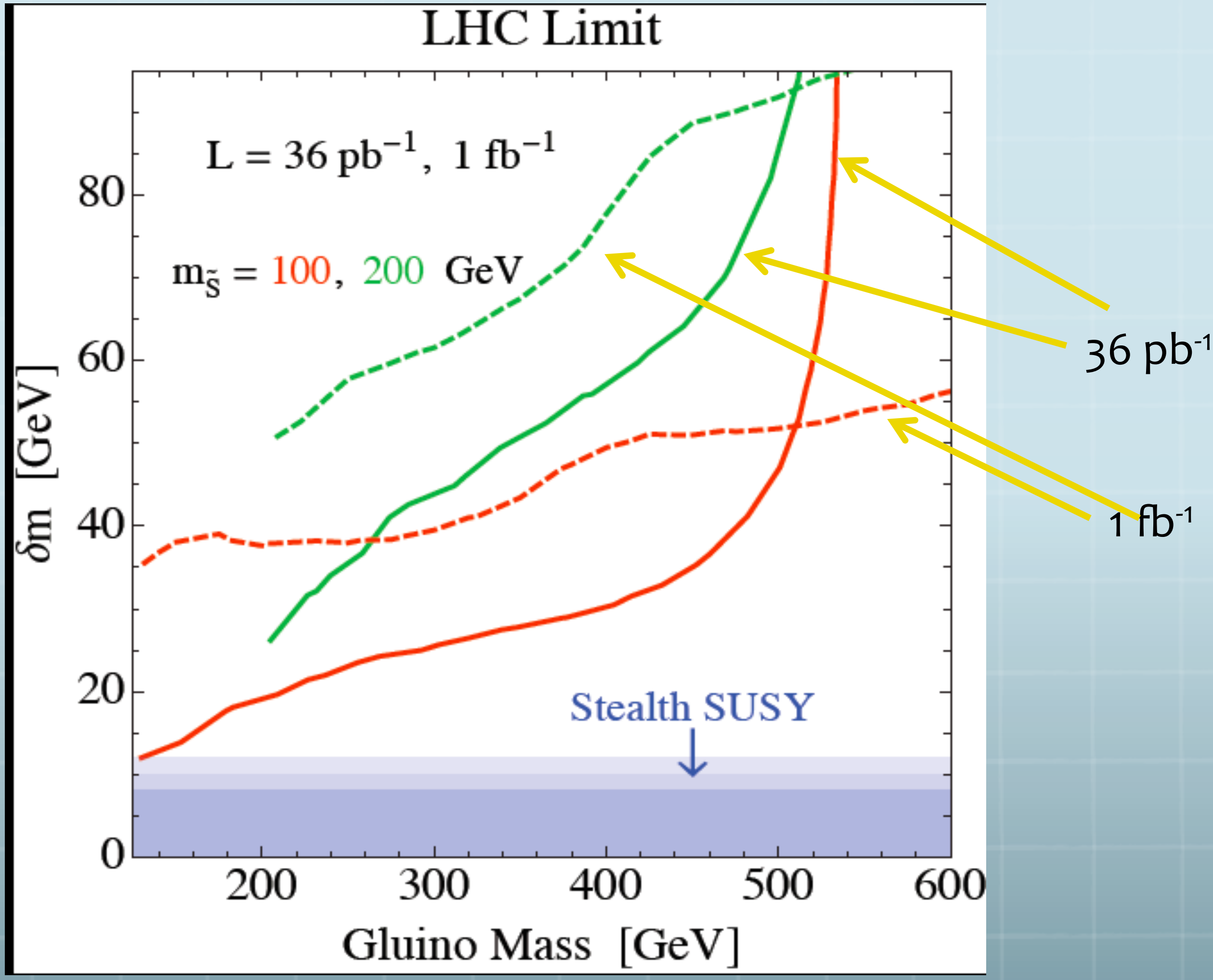


CMS preliminary
α_T
$\int L dt = 1.1\ fb^{-1}$ $\sqrt{s} = 7$ TeV
95% C.L. Limits:
Observed Limit (NLO), CL_s
Observed Limit (NLO), PL
Median Expected Limit $\pm$ 1σ, PL
Observed Limit (NLO), FC, $35pb^{-1}$
CDF $\tilde{g}, \tilde{q}$, tanβ=5, μ<0
D0 $\tilde{g}, \tilde{q}$, tanβ=3, μ<0
LEP2 $\tilde{\chi}^{\pm}_1$
LEP2 $\tilde{l}^{\pm}$
$\tilde{\tau}$ = LSP
$\tilde{q}$ (1250) GeV
$\tilde{q}$ (1000) GeV
$\tilde{q}$ (750) GeV
$\tilde{q}$ (500) GeV
$\tilde{g}$ (1250) GeV
$\tilde{g}$ (1000) GeV
$\tilde{g}$ (750) GeV
$\tilde{g}$ (500) GeV
tanβ = 10, A_0 = 0, μ > 0
LM6
LM4
$m_{1/2}$ (GeV)
m_0 (GeV)
0
500
1000
1500
2000
200
400
600



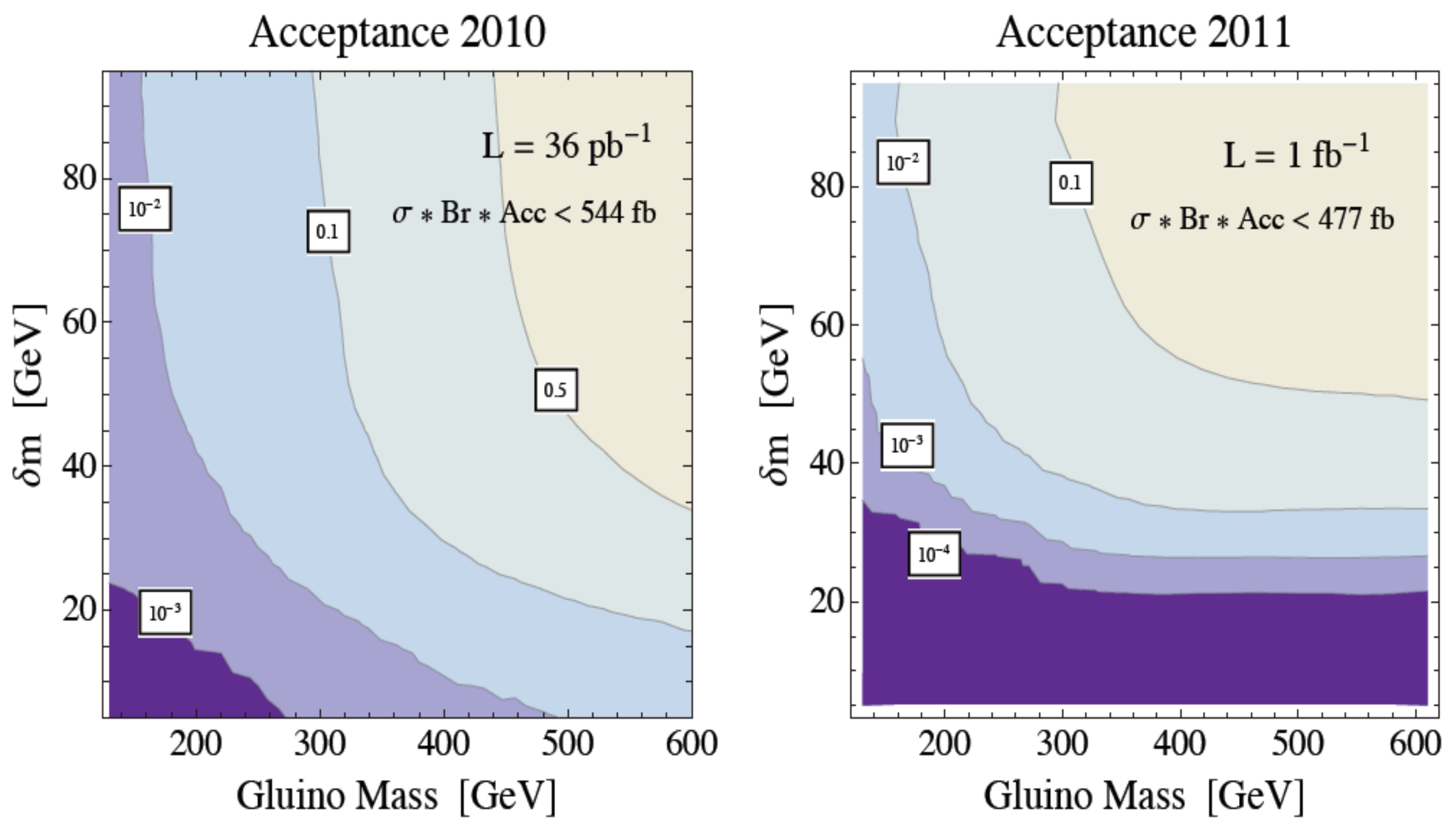
CDF RUN II 3.2 fb^{-1}
0.5 TeV/c^2 < $m_{\tilde{q}}$ < 0.7 TeV/c^2
$m_{\tilde{q}}$=$m_{\tilde{g}}$ + 10 GeV/c^2
95% C.L. limit observed
95% C.L. limit expected
± 1σ on expected limit
σ × BR($p\bar{p}$ → 3j + 3j) [pb]
10^5
10^4
10^3
10^2
10
80
100
120
140
160
180
200
220
240
gluino mass [GeV/c^2]


CMS
∫ L = 35.1 pb⁻¹
Expected
Observed
± 1σ
± 2σ
σ^NLO(Gluino)
95% CL Limit σ × BR (pb)
10²
10
200
250
300
350
400
450
500
Three Jet Mass [GeV/c²]



Bottom line:

current limits do not apply to stealth SUSY with mass splitting smaller than 10 GeV !



Acceptance 2010
L = 36 pb^{-1}
σ * Br * Acc < 544 fb
10^{-2}
0.1
0.5
10^{-3}
δm [GeV]
Gluino Mass [GeV]
Acceptance 2011
L = 1 fb^{-1}
σ * Br * Acc < 477 fb
10^{-2}
0.1
10^{-3}
10^{-4}
δm [GeV]
Gluino Mass [GeV]

Aside: Things not to do:

tadpole and high-scale mediation

A tadpole of the singlet S is often generated at one-loop if S is not charged under any symmetry;

Tadpole is small in gauge mediation and do not change the calculation of the S soft mass.

However, this will kill attempts to embed SYYbar and SHuHd models into high-scale mediation scenario.

E.g.: $$SY\bar{Y} + m_Y Y\bar{Y} + mS^2 + S^2 N$$

A tadpole will give both S, N a VEV. N fermion will become massive and due to S,N mixing, $\psi_S \rightarrow \psi_N$ N which will bring back MET.