General Gauge Mediation at the Tevatron and LHC

David Shih
Rutgers University

Meade, Seiberg & DS: **0801.3278**
Buican, Meade, Seiberg & DS: **0812.3668**
Meade, Reece & DS: **0911.4130, 1006.4575**
Ruderman & DS: **1009.1665**

also work in progress with
Josh Ruderman, Scott Thomas, Michael Park, Yue Zhao,
Mariangela Lisanti & Tracy Slatyer...

Real World Supersymmetry

- Low energy supersymmetry is a compelling candidate for physics beyond the Standard Model.
- The simplest scenario is the Minimal Supersymmetric Standard Model (MSSM). Among its virtues are:
  - Solution to the gauge hierarchy problem
  - Gauge coupling unification
  - Dark matter candidates
  - Calculable framework
  - Distinctive phenomenology

Soft SUSY Breaking

- Superpartners have not been observed, so SUSY must be spontaneously broken.
- In the MSSM, this breaking occurs through explicit soft (dimensional) terms.
- Naturalness puts the scale of soft terms at the TeV scale -- should observe the superpartners at the LHC!

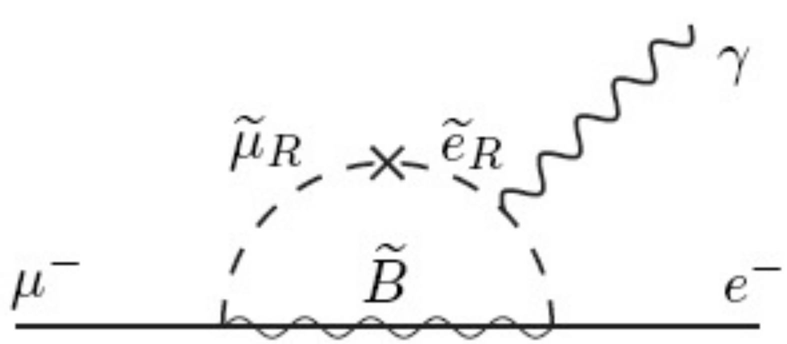
$$\mathcal{L}_{soft} = -\frac{1}{2}\sum_{i=1}^{3} M_i \lambda_i \lambda_i - \sum_{\tilde{f}=\tilde{Q},\tilde{u},\tilde{d},\tilde{L},\tilde{e}} \tilde{f}^\dagger m^2_{\tilde{f}} \tilde{f} + (Higgs)$$

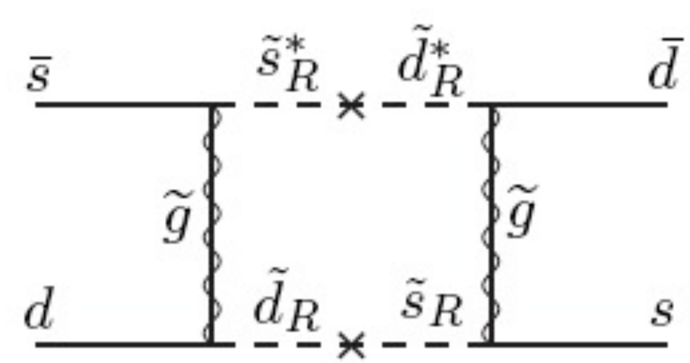
complex gaugino masses

3x3 Hermitian squark and slepton masses

SUSY Flavor Problem

- The soft Lagrangian of the MSSM contains 100+ new parameters. A generic point in this parameter space is ruled out by stringent experimental constraints:
  - Precision tests of flavor-violation
  - Precision tests of CP violation
  - Non-observation of superpartners





Gauge Mediation

- Gauge mediation provides an attractive solution to the MSSM flavor problem.
- In gauge mediation, MSSM soft terms generated only via SM gauge interactions. Guarantees flavor-diagonal soft masses!
- Many models of gauge mediation have been constructed over the past 20 years. Most have been some variant of minimal gauge mediation.

Minimal gauge mediation

(Dine, Nelson, Nir, Shirman, …)

Minimal gauge mediation

(Dine, Nelson, Nir, Shirman, ...)

- X is a singlet spurion for hidden sector SUSY-breaking.

$$\langle X \rangle = M + \theta^2 F$$

Minimal gauge mediation

(Dine, Nelson, Nir, Shirman, …)

- X is a singlet spurion for hidden sector SUSY-breaking.

$$\langle X \rangle = M + \theta^2 F$$

- ϕ are messengers in real representations of G_{SM} (e.g. $\mathbf{5} \oplus \bar{\mathbf{5}}$)

Minimal gauge mediation

(Dine, Nelson, Nir, Shirman, …)

- X is a singlet spurion for hidden sector SUSY-breaking.

$$\langle X \rangle = M + \theta^2 F$$

- ϕ are messengers in real representations of G_{SM} (e.g. $\mathbf{5} \oplus \bar{\mathbf{5}}$)

- Through their coupling to X:

$$\mathcal{L} = \lambda \int d^2\theta \, X \phi^2 + c.c.$$

Minimal gauge mediation

(Dine, Nelson, Nir, Shirman, …)

- X is a singlet spurion for hidden sector SUSY-breaking.

$$\langle X \rangle = M + \theta^2 F$$

- ϕ are messengers in real representations of G_{SM} (e.g. $\mathbf{5} \oplus \bar{\mathbf{5}}$)
- Through their coupling to X:

$$\mathcal{L} = \lambda \int d^2\theta \, X \phi^2 + c.c.$$

- they receive tree-level SUSY-breaking mass splittings:

Minimal gauge mediation

(Dine, Nelson, Nir, Shirman, ...)

- X is a singlet spurion for hidden sector SUSY-breaking.

$$\langle X \rangle = M + \theta^2 F$$

- ϕ are messengers in real representations of G_{SM} (e.g. $\mathbf{5} \oplus \bar{\mathbf{5}}$)
- Through their coupling to X:

$$\mathcal{L} = \lambda \int d^2\theta \, X \phi^2 + c.c.$$

- they receive tree-level SUSY-breaking mass splittings:

$$M_{\psi_\phi} = \begin{pmatrix} M & 0 \\ 0 & M \end{pmatrix}, \qquad M_\phi^2 = \begin{pmatrix} M^2 & F \\ F & M^2 \end{pmatrix}$$

Minimal gauge mediation

(Dine, Nelson, Nir, Shirman, …)

- X is a singlet spurion for hidden sector SUSY-breaking.

$$\langle X \rangle = M + \theta^2 F$$

- ϕ are messengers in real representations of G_{SM} (e.g. $\mathbf{5} \oplus \bar{\mathbf{5}}$)
- Through their coupling to X:

$$\mathcal{L} = \lambda \int d^2\theta \, X \phi^2 + c.c.$$

- they receive tree-level SUSY-breaking mass splittings:

$$M_{\psi_\phi} = \begin{pmatrix} M & 0 \\ 0 & M \end{pmatrix}, \qquad M_\phi^2 = \begin{pmatrix} M^2 & F \\ F & M^2 \end{pmatrix}$$

- Loops of the messengers and SM gauge fields communicate SUSY-breaking to the MSSM.

MGM Soft Masses

$$M_{r=1,2,3} \sim \frac{\alpha_r}{4\pi}\frac{F}{M}$$

$$m_{\tilde{q}}^2 \sim \left(\frac{\alpha_3}{4\pi}\right)^2 \left(\frac{F}{M}\right)^2$$

$$m_{\tilde{\ell}}^2 \sim \left(\frac{\alpha_{1,2}}{4\pi}\right)^2 \left(\frac{F}{M}\right)^2$$

MGM Soft Masses

- In MGM, all the soft masses are determined by a single scale, F/M.

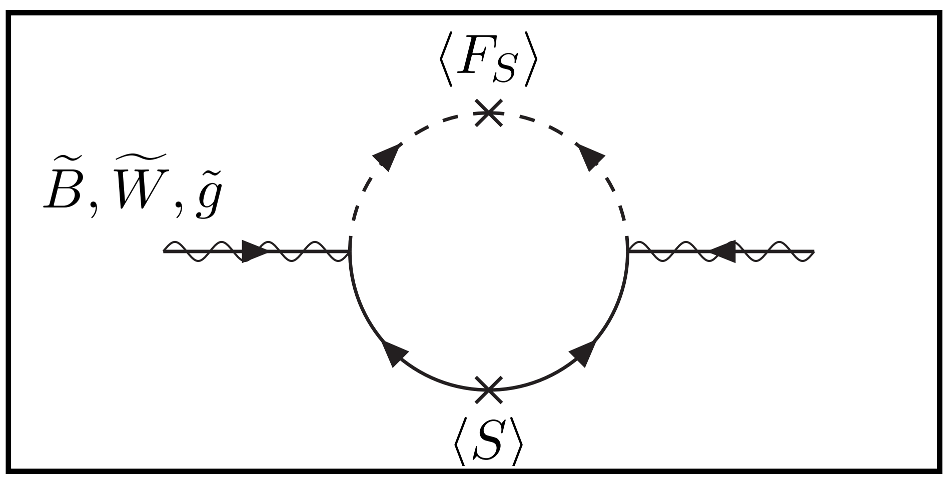
$$M_{r=1,2,3} \sim \frac{\alpha_r}{4\pi}\frac{F}{M}$$

$$m_{\tilde{q}}^2 \sim \left(\frac{\alpha_3}{4\pi}\right)^2\left(\frac{F}{M}\right)^2$$

$$m_{\tilde{\ell}}^2 \sim \left(\frac{\alpha_{1,2}}{4\pi}\right)^2\left(\frac{F}{M}\right)^2$$

MGM Soft Masses

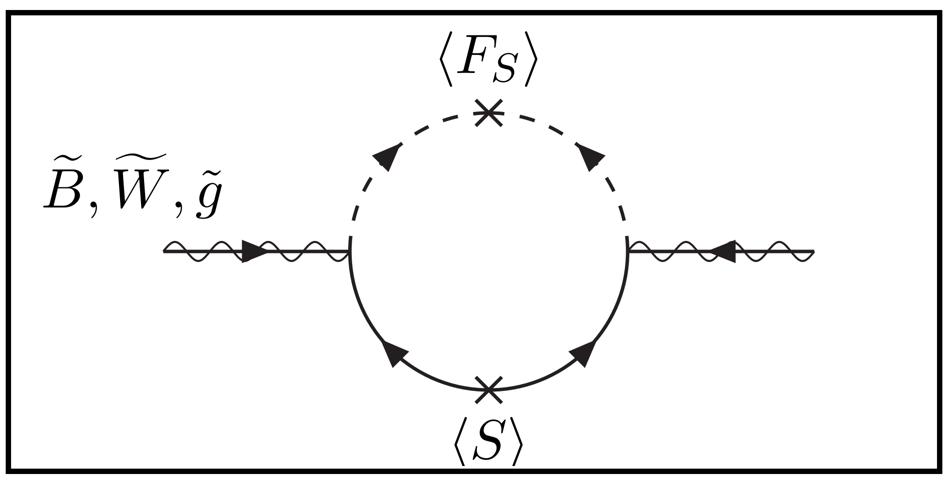
- In MGM, all the soft masses are determined by a single scale, F/M.
- 1-loop gaugino masses:



$$M_{r=1,2,3} = \frac{\alpha_r}{4\pi} \frac{F}{M}$$

MGM Soft Masses

- In MGM, all the soft masses are determined by a single scale, F/M.
- 1-loop gaugino masses:



$$M_{r=1,2,3} = \frac{\alpha_r}{4\pi}\frac{F}{M}$$

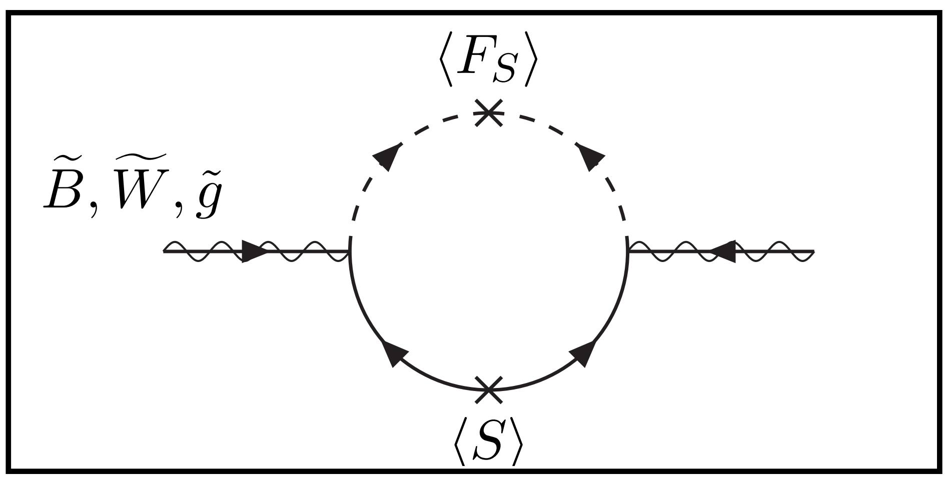
"gaugino unification"

$$m_{\tilde{q}}^2 \sim \left(\frac{\alpha_3}{4\pi}\right)^2 \left(\frac{F}{M}\right)^2$$

$$m_{\tilde{\ell}}^2 \sim \left(\frac{\alpha_{1,2}}{4\pi}\right)^2 \left(\frac{F}{M}\right)^2$$

MGM Soft Masses

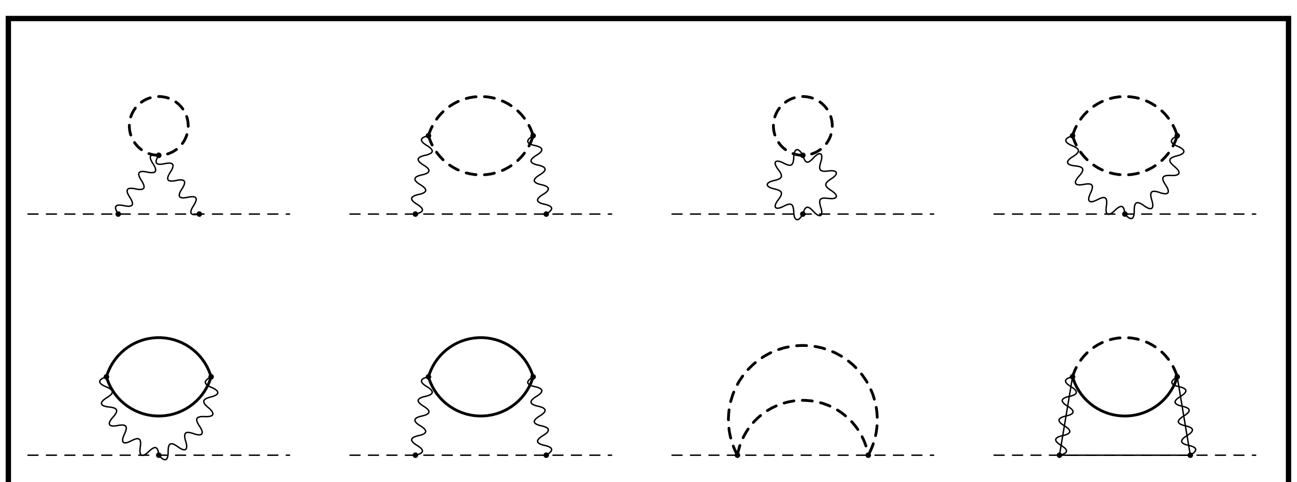
- In MGM, all the soft masses are determined by a single scale, F/M.
- 1-loop gaugino masses:



$$M_{r=1,2,3} = \frac{\alpha_r}{4\pi}\frac{F}{M}$$

"gaugino unification"

- 2-loop sfermion mass-squareds:



$$m^2_{\tilde{q}} \sim \left(\frac{\alpha_3}{4\pi}\right)^2 \left(\frac{F}{M}\right)^2$$

$$m^2_{\tilde{\ell}} \sim \left(\frac{\alpha_{1,2}}{4\pi}\right)^2 \left(\frac{F}{M}\right)^2$$

MGM Bias

- The focus on MGM and MGM-like models has led to a biased picture of the phenomenology of gauge mediation.
- This bias has had pronounced effects on the experimental searches for gauge mediation.
- Recently, gauge mediation was reformulated in a general, model-independent way.
- This provides a useful framework for the study of general signatures of gauge mediation.

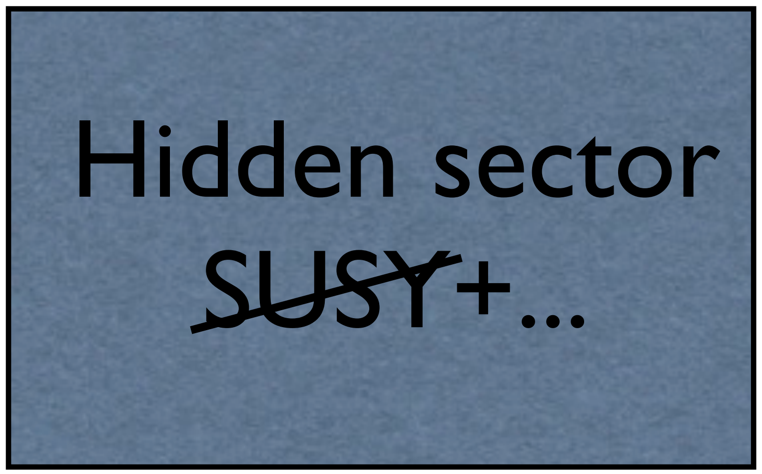
General Gauge Mediation

General Gauge Mediation

(Meade, Seiberg, DS)

General Gauge Mediation

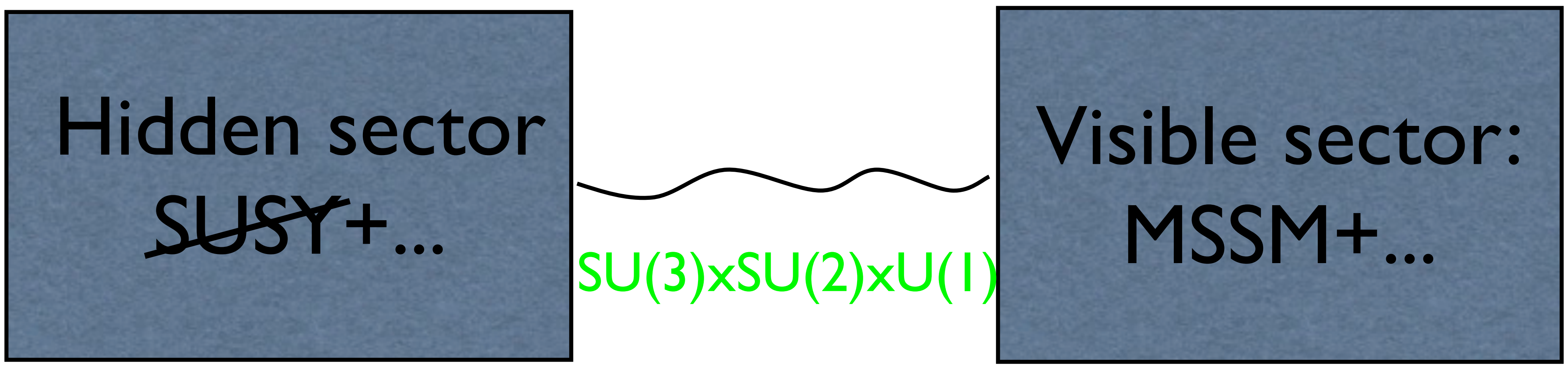
(Meade, Seiberg, DS)



- Hidden sector:
  - spontaneously breaks SUSY at a scale M

General Gauge Mediation

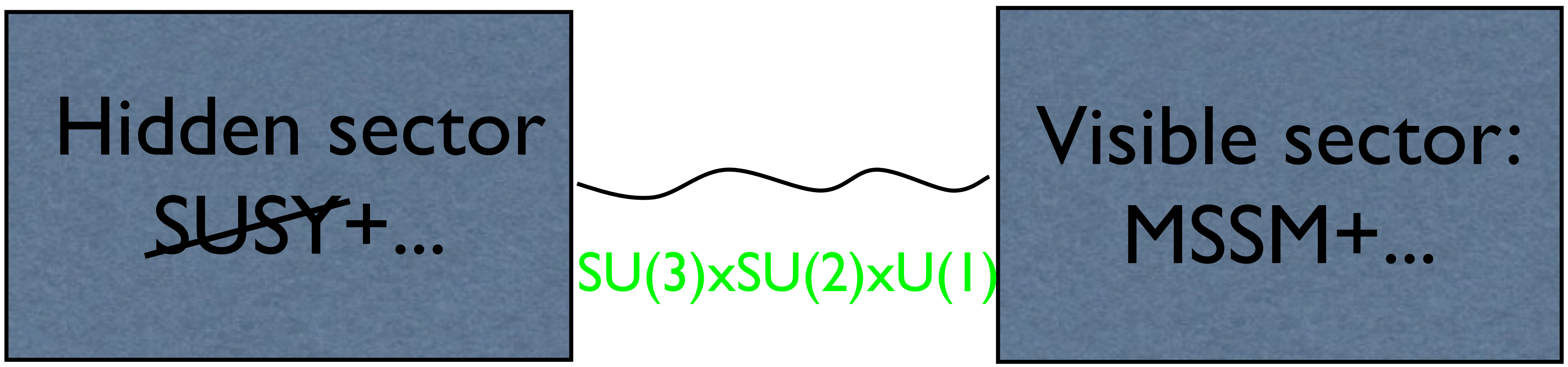
(Meade, Seiberg, DS)



- Hidden sector:
  - spontaneously breaks SUSY at a scale M
  - has a weakly-gauged global symmetry G containing SU(3)xSU(2)xU(1)

General Gauge Mediation

(Meade, Seiberg, DS)



- Hidden sector:
  - spontaneously breaks SUSY at a scale M
  - has a weakly-gauged global symmetry G containing SU(3)xSU(2)xU(1)
  - includes messengers, if present

General Gauge Mediation

(Meade, Seiberg, DS)

Hidden sector
~~SUSY~~+...

Visible sector:
MSSM+...

- Hidden sector:
  - spontaneously breaks SUSY at a scale M
  - has a weakly-gauged global symmetry G containing SU(3)xSU(2)xU(1)
  - includes messengers, if present
- Theory decouples into separate hidden and visible sectors in g->0 limit.

General Gauge Mediation

(Meade, Seiberg, DS)

Hidden sector
~~SUSY~~+...

Visible sector:
MSSM+...

- Hidden sector:
  - spontaneously breaks SUSY at a scale M
  - has a weakly-gauged global symmetry G containing SU(3)xSU(2)xU(1)
  - includes messengers, if present
- Theory decouples into separate hidden and visible sectors in g->0 limit.
- Work exactly in the hidden sector but to leading order in g.

Current Supermultiplet

- All the information we need about the hidden sector is encoded in the currents of G and their correlation functions.
- The current belongs to a supermultiplet:

$$j_\mu \to (J,\, j_\alpha,\, \bar{j}_{\dot{\alpha}},\, j_\mu)$$

- In superspace, the SUSY generalization of current conservation is

$$D^2 \mathcal{J} = 0$$

$$\mathcal{J} = J + i\theta j - i\bar{\theta}\bar{j} - \bar{\theta}\sigma^\mu \theta j_\mu + \ldots$$

Current Supermultiplet

- All the information we need about the hidden sector is encoded in the currents of G and their correlation functions.
- The current belongs to a supermultiplet:

$$j_\mu \to (J,\, j_\alpha,\, \bar{j}_{\dot\alpha},\, j_\mu)$$

(Assume G=U(1) for simplicity)

- In superspace, the SUSY generalization of current conservation is

$$D^2\mathcal{J} = 0$$

$$\mathcal{J} = J + i\theta j - i\bar{\theta}\bar{j} - \bar{\theta}\sigma^\mu\theta j_\mu + \ldots$$

Current two-point functions

- By current conservation and Lorentz invariance, the nonzero two-point functions are:

$$\left.\begin{aligned}\langle J(x)J(0)\rangle &\to C_0(x)\\ \langle j_\alpha(x)\bar{j}_{\dot\alpha}(0)\rangle &\to C_{1/2}(x)\\ \langle j_\mu(x)j_\nu(0)\rangle &\to C_1(x)\end{aligned}\right\}\ \text{Real}$$

$$\langle j_\alpha(x)j_\beta(0)\rangle \to B(x) \qquad \text{Complex}$$

- If SUSY is unbroken, can show:

$$C_0 = C_{1/2} = C_1, \qquad B = 0$$

Coupling to visible sector

Coupling to visible sector

- Weakly gauge G:

$$\begin{aligned}\mathcal{L}_{int} &= g\int d^4\theta \mathcal{J}\mathcal{V} + \mathcal{O}(g^2)\\ &= g(JD + \lambda^\alpha j_\alpha + \bar{\lambda}_{\dot{\alpha}}\bar{j}^{\dot{\alpha}} + j^\mu V_\mu) + \mathcal{O}(g^2)\end{aligned}$$

Coupling to visible sector

- Weakly gauge G:

$$\begin{aligned}\mathcal{L}_{int} &= g\int d^4\theta \mathcal{J}\mathcal{V} + \mathcal{O}(g^2) \\ &= g(JD + \lambda^\alpha j_\alpha + \bar{\lambda}_{\dot{\alpha}}\bar{j}^{\dot{\alpha}} + j^\mu V_\mu) + \mathcal{O}(g^2)\end{aligned}$$

- Integrate out hidden sector exactly. Effective theory for the gauge supermultiplet:

$$\begin{aligned}\delta\mathcal{L}_{eff} &= \frac{1}{2}g^2\tilde{C}_0(p^2)D^2 + g^2\tilde{C}_{1/2}(p^2)i\lambda\sigma^\mu\partial_\mu\bar{\lambda} + \frac{1}{4}g^2\tilde{C}_1(p^2)F_{\mu\nu}F^{\mu\nu} \\ &\quad -\frac{1}{2}g^2(M\tilde{B}_{1/2}(p^2)\lambda\lambda + c.c.)\end{aligned}$$

Coupling to visible sector

- Weakly gauge G:

$$\begin{aligned}\mathcal{L}_{int} &= g\int d^4\theta \mathcal{J}\mathcal{V} + \mathcal{O}(g^2) \\ &= g(JD + \lambda^\alpha j_\alpha + \bar{\lambda}_{\dot{\alpha}}\bar{j}^{\dot{\alpha}} + j^\mu V_\mu) + \mathcal{O}(g^2)\end{aligned}$$

- Integrate out hidden sector exactly. Effective theory for the gauge supermultiplet:

$$\begin{aligned}\delta\mathcal{L}_{eff} &= \frac{1}{2}g^2\tilde{C}_0(p^2)D^2 + g^2\tilde{C}_{1/2}(p^2)i\lambda\sigma^\mu\partial_\mu\bar{\lambda} + \frac{1}{4}g^2\tilde{C}_1(p^2)F_{\mu\nu}F^{\mu\nu} \\ &\quad -\frac{1}{2}g^2(M\tilde{B}_{1/2}(p^2)\lambda\lambda + c.c.)\end{aligned}$$

- Soft terms can be written in terms of the current-current correlators.

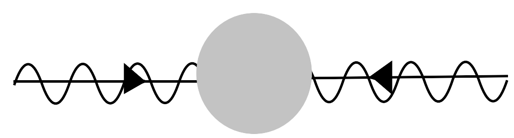
Coupling to visible sector

Coupling to visible sector

$$\delta\mathcal{L}_{eff} = \frac{1}{2}g^2\tilde{C}_0(p^2)D^2 + g^2\tilde{C}_{1/2}(p^2)i\lambda\sigma^\mu\partial_\mu\bar{\lambda} + \frac{1}{4}g^2\tilde{C}_1(p^2)F_{\mu\nu}F^{\mu\nu}$$
$$-\frac{1}{2}g^2(M\tilde{B}_{1/2}(p^2)\lambda\lambda + c.c.)$$

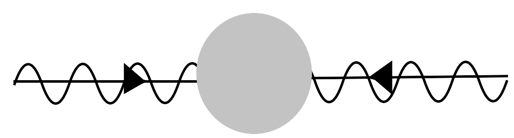
Coupling to visible sector

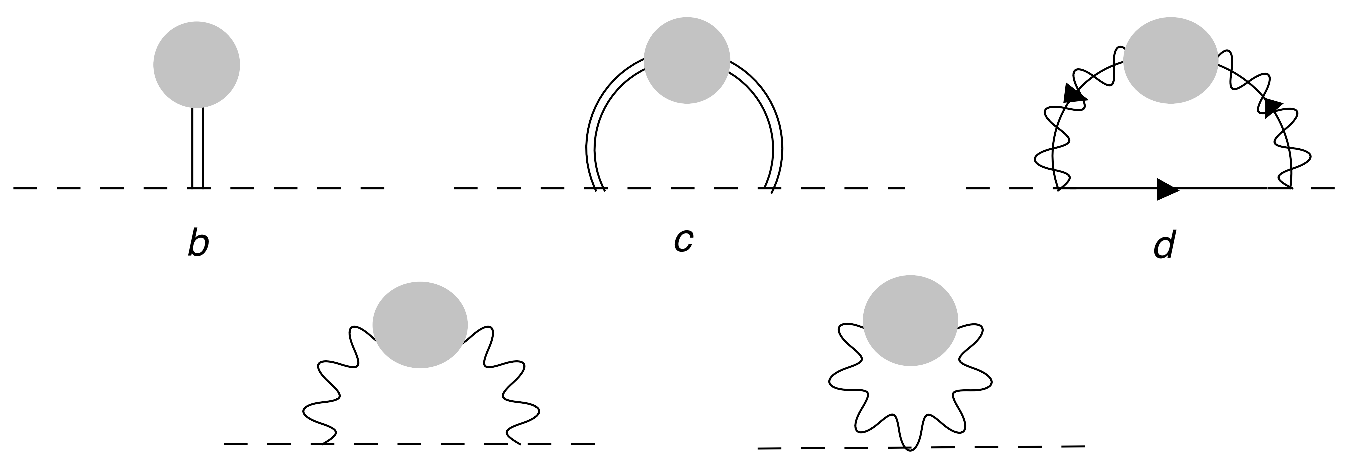
$$\delta\mathcal{L}_{eff} = \frac{1}{2}g^2\tilde{C}_0(p^2)D^2 + g^2\tilde{C}_{1/2}(p^2)i\lambda\sigma^\mu\partial_\mu\bar{\lambda} + \frac{1}{4}g^2\tilde{C}_1(p^2)F_{\mu\nu}F^{\mu\nu}$$
$$-\frac{1}{2}g^2(M\tilde{B}_{1/2}(p^2)\lambda\lambda + c.c.)$$

- Gaugino mass:  $M_\lambda = g^2 M\tilde{B}_{1/2}(0)$

Coupling to visible sector

$$\delta\mathcal{L}_{eff} = \frac{1}{2}g^2\tilde{C}_0(p^2)D^2 + g^2\tilde{C}_{1/2}(p^2)i\lambda\sigma^\mu\partial_\mu\bar{\lambda} + \frac{1}{4}g^2\tilde{C}_1(p^2)F_{\mu\nu}F^{\mu\nu}$$
$$-\frac{1}{2}g^2(M\tilde{B}_{1/2}(p^2)\lambda\lambda + c.c.)$$

- Gaugino mass:  $M_\lambda = g^2 M\tilde{B}_{1/2}(0)$

- Sfermion mass: 

$$m^2_{\tilde{f}} = g^4 A$$

$$A = -\int \frac{d^4p}{(2\pi)^4}\frac{1}{p^2}\Big(3C_1(p^2/M^2) - 4C_{1/2}(p^2/M^2) + C_0(p^2/M^2)\Big)$$

Generalizing to SU(3)xSU(2)xU(1)

- Trivial to generalize from U(1) to SU(3)xSU(2)xU(1).
- Each gauge group factor comes with its own current supermultiplet.
- Gaugino and sfermion masses are given by the same formulas as before, convolved with group theory factors:

$$M_{\lambda_r} = g_r^2 M B_r \quad (r = 1, 2, 3)$$

$$m_{\tilde{f}}^2 = \sum_{r=1}^{3} C_{\tilde{f}}^r g_r^4 A_r$$

Generalizing to SU(3)xSU(2)xU(1)

- Trivial to generalize from U(1) to SU(3)xSU(2)xU(1).
- Each gauge group factor comes with its own current supermultiplet.
- Gaugino and sfermion masses are given by the same formulas as before, convolved with group theory factors:

$$M_{\lambda_r} = g_r^2 M B_r \quad (r = 1, 2, 3)$$

$$m_{\tilde{f}}^2 = \sum_{r=1}^{3} C_{\tilde{f}}^r g_r^4 A_r$$

Quadratic Casimirs:

$$C^3_{Q,u,d} = \frac{4}{3}, \quad C^3_{L,e} = 0$$

$$C^2_{Q,L} = \frac{3}{4}, \quad C^2_{u,d,e} = 0$$

$$C^1_{\tilde{f}} = \frac{3}{5} Y_{\tilde{f}}^2$$

Sum Rules

$$m^2_{\tilde{f}} = \sum_{r=1}^{3} C^r_{\tilde{f}} g^4_r A_r$$

Sum Rules

$$m_{\tilde{f}}^2 = \sum_{r=1}^{3} C_{\tilde{f}}^r g_r^4 A_r$$

- Five MSSM sfermion masses f=Q,U,D,L,E are given in terms of 3 parameters $A_{1,2,3}$. So there must be 2 relations.

Sum Rules

$$m_{\tilde{f}}^2 = \sum_{r=1}^{3} C_{\tilde{f}}^r g_r^4 A_r$$

- Five MSSM sfermion masses f=Q,U,D,L,E are given in terms of 3 parameters $A_{1,2,3}$. So there must be 2 relations.
- These take the form:

$$\mathrm{Tr}\, Y m^2 = m_Q^2 - 2m_U^2 + m_D^2 - m_L^2 + m_E^2 = 0$$
$$\mathrm{Tr}\, (B-L) m^2 = 2m_Q^2 - m_U^2 - m_D^2 - 2m_L^2 + m_E^2 = 0$$

Sum Rules

$$m_{\tilde{f}}^2 = \sum_{r=1}^{3} C_{\tilde{f}}^r g_r^4 A_r$$

- Five MSSM sfermion masses f=Q,U,D,L,E are given in terms of 3 parameters $A_{1,2,3}$. So there must be 2 relations.
- These take the form:

$$\mathrm{Tr}\, Y m^2 = m_Q^2 - 2m_U^2 + m_D^2 - m_L^2 + m_E^2 = 0$$
$$\mathrm{Tr}\, (B-L) m^2 = 2m_Q^2 - m_U^2 - m_D^2 - 2m_L^2 + m_E^2 = 0$$

- Sum rules true at the scale M. (Small) corrections from RG and EWSB.

Sum Rules

$$m_{\tilde{f}}^2 = \sum_{r=1}^{3} C_{\tilde{f}}^r g_r^4 A_r$$

- Five MSSM sfermion masses f=Q,U,D,L,E are given in terms of 3 parameters $A_{1,2,3}$. So there must be 2 relations.

- These take the form:

$$\mathrm{Tr}\, Y m^2 = m_Q^2 - 2m_U^2 + m_D^2 - m_L^2 + m_E^2 = 0$$
$$\mathrm{Tr}\, (B-L) m^2 = 2m_Q^2 - m_U^2 - m_D^2 - 2m_L^2 + m_E^2 = 0$$

- Sum rules true at the scale M. (Small) corrections from RG and EWSB.

- These relations were known before in specific models (Martin & Ramond; Faraggi et al; Kawamura et al; Martin; Dimopoulos et al). Here we learn that they are completely general.

Parameter space

Parameter space

- The GGM parameter space consists of 9 real parameters:

$$A_{1,2,3}, \quad |B_{1,2,3}|, \quad \arg(B_{1,2,3})$$

Parameter space

- The GGM parameter space consists of 9 real parameters:

$$A_{1,2,3}, \quad |B_{1,2,3}|, \quad \arg(B_{1,2,3})$$

- Comments:

Parameter space

- The GGM parameter space consists of 9 real parameters:

$$A_{1,2,3}, \quad |B_{1,2,3}|, \quad \arg(B_{1,2,3})$$

- Comments:
  - SUSY CP problem in general

Parameter space

- The GGM parameter space consists of 9 real parameters:

$$A_{1,2,3}, \quad |B_{1,2,3}|, \quad \arg(B_{1,2,3})$$

- Comments:
    - SUSY CP problem in general
    - Gauge coupling unification not tied to gaugino unification

Parameter space

- The GGM parameter space consists of 9 real parameters:

$$A_{1,2,3}, \quad |B_{1,2,3}|, \quad \arg(B_{1,2,3})$$

- Comments:
  - SUSY CP problem in general
  - Gauge coupling unification not tied to gaugino unification
  - Parameter space much larger than minimal gauge mediation

Parameter space

- The GGM parameter space consists of 9 real parameters:

$$A_{1,2,3}, \quad |B_{1,2,3}|, \quad \arg(B_{1,2,3})$$

- Comments:
  - SUSY CP problem in general
  - Gauge coupling unification not tied to gaugino unification
  - Parameter space much larger than minimal gauge mediation
  - “Existence proof model” was constructed which covers the entire parameter space (Buican, Meade, Seiberg, DS).

Parameter space

- The GGM parameter space consists of 9 real parameters:

$$A_{1,2,3}, \quad |B_{1,2,3}|, \quad \arg(B_{1,2,3})$$

- Comments:
  - SUSY CP problem in general
  - Gauge coupling unification not tied to gaugino unification
  - Parameter space much larger than minimal gauge mediation
  - "Existence proof model" was constructed which covers the entire parameter space (Buican, Meade, Seiberg, DS).
  - The entire parameter space is physical! Should use it to study the general phenomenology of gauge mediation!

Phenomenology of GGM

Gauge Mediation

Gauge Mediation

- The phenomenology of gauge mediation is distinctive: gravitino is the lightest superpartner (LSP).

$$m_{\tilde{G}} = \frac{F}{M_{pl}} \ll m_{weak}$$

Gauge Mediation

- The phenomenology of gauge mediation is distinctive: gravitino is the lightest superpartner (LSP).

$$m_{\tilde{G}} = \frac{F}{M_{pl}} \ll m_{weak}$$

- Lightest MSSM sparticle becomes the next-to-lightest superpartner (NLSP). It decays to the gravitino plus its SM superpartner.

$$\tilde{X}_{NLSP} \to \tilde{G} + X, \quad \tau_{NLSP} \sim \frac{F^2}{m_{NLSP}^5}$$

Gauge Mediation

- The phenomenology of gauge mediation is distinctive: gravitino is the lightest superpartner (LSP).

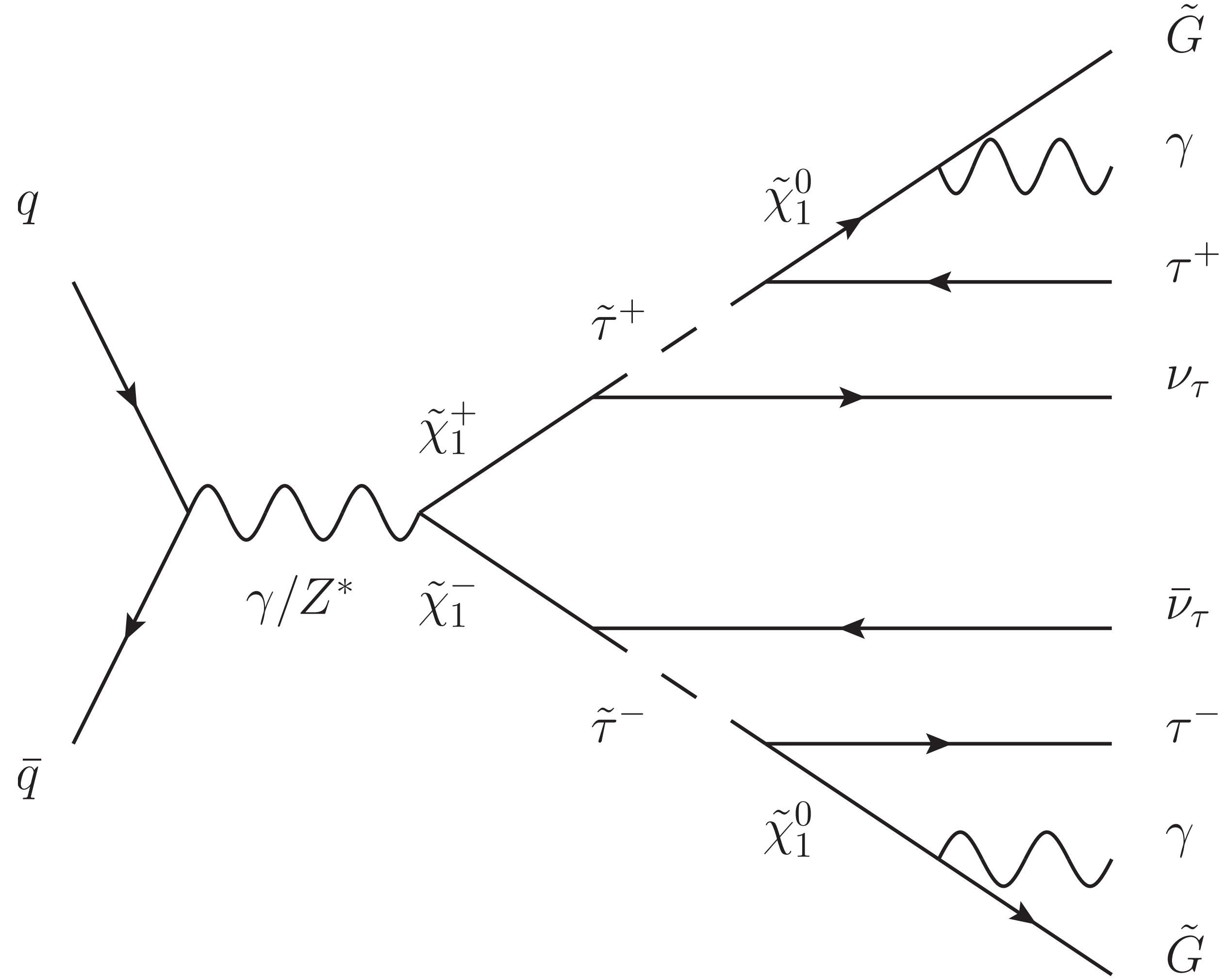
$$m_{\tilde{G}} = \frac{F}{M_{pl}} \ll m_{weak}$$

- Lightest MSSM sparticle becomes the next-to-lightest superpartner (NLSP). It decays to the gravitino plus its SM superpartner.

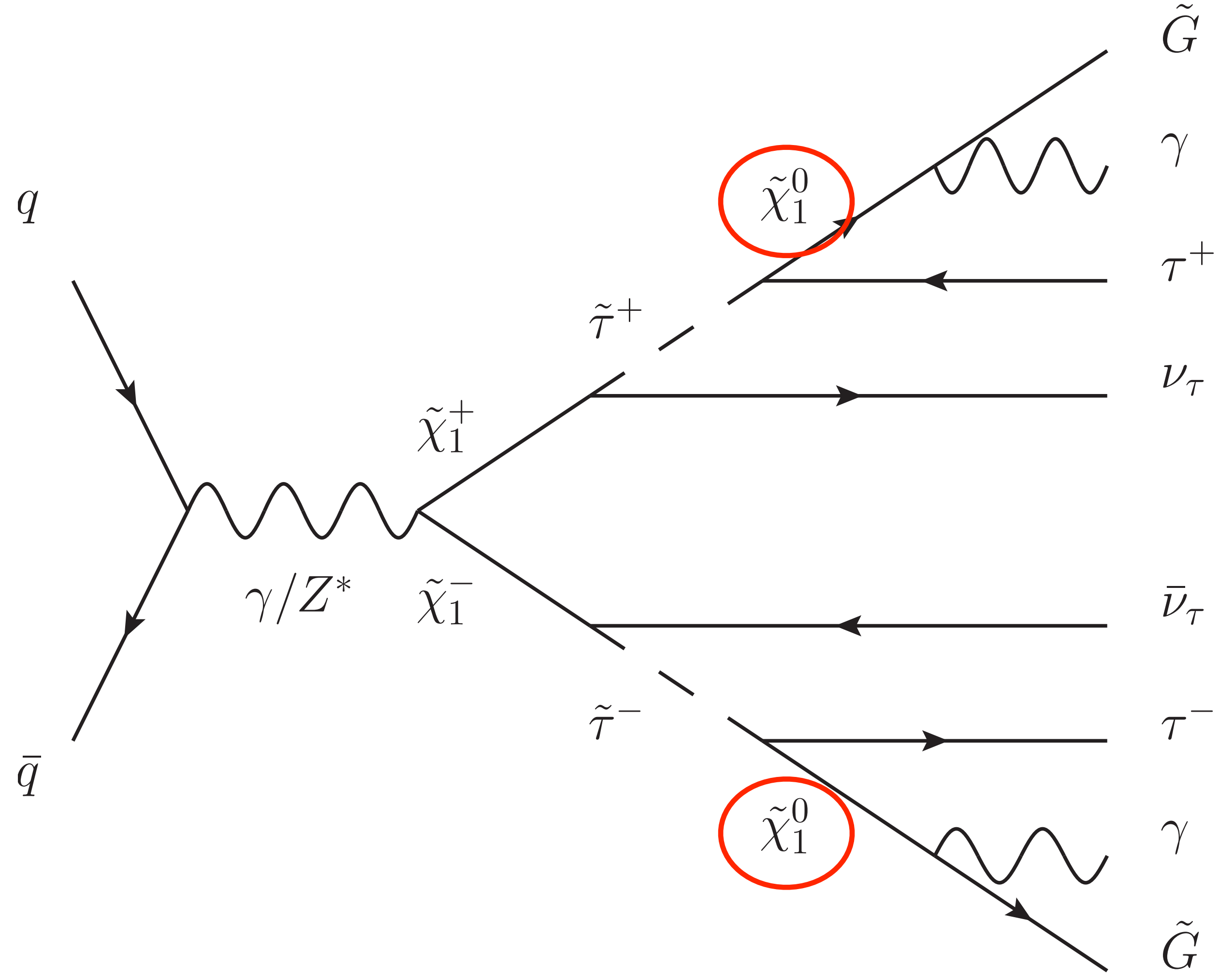
$$\tilde{X}_{NLSP} \to \tilde{G} + X, \quad \tau_{NLSP} \sim \frac{F^2}{m_{NLSP}^5}$$

- Decays can be prompt or delayed. We will focus on prompt case. This corresponds to low-scale SUSY breaking.

Gauge Mediation

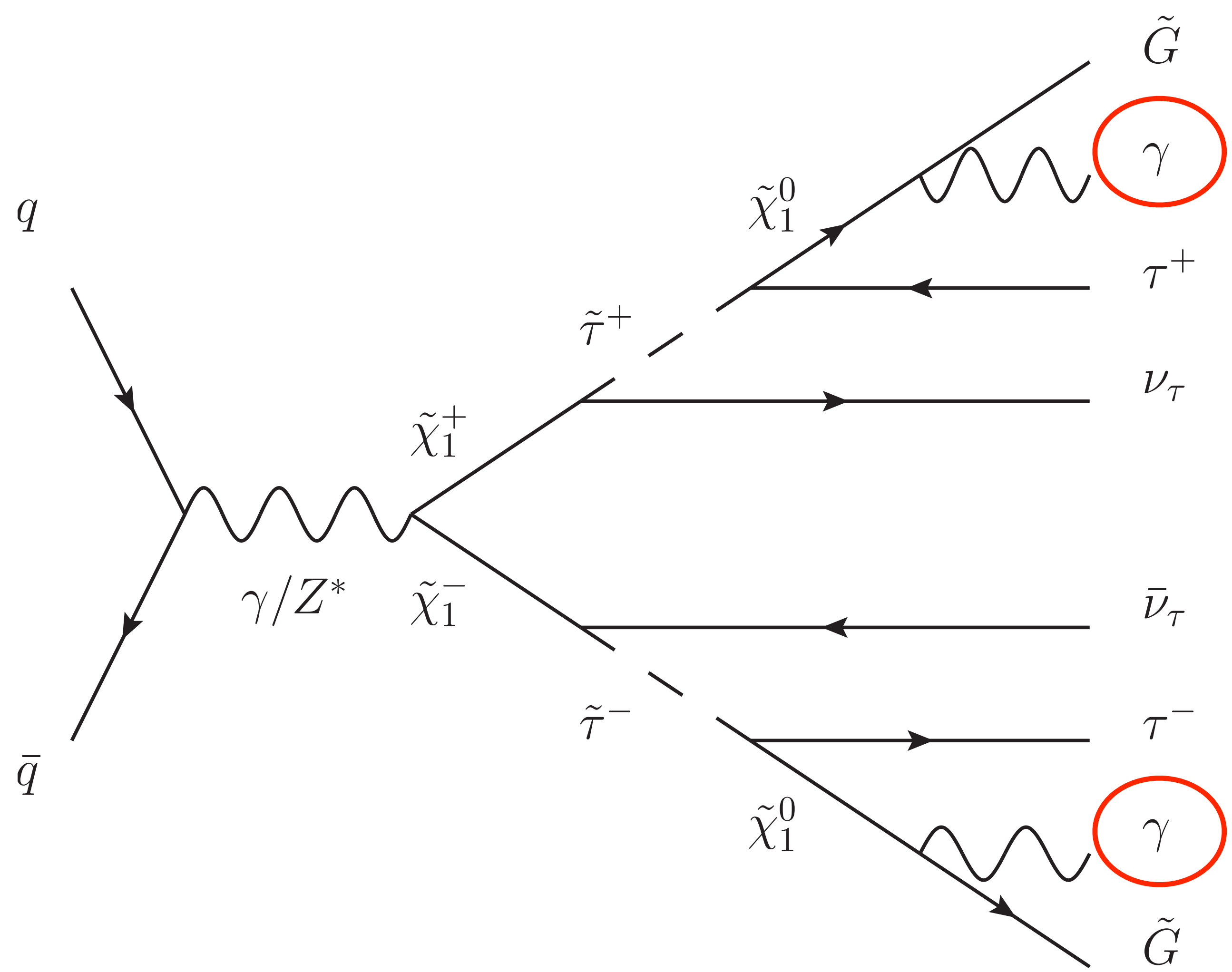


Gauge Mediation



- All SUSY cascade decays pass through the NLSP.

Gauge Mediation

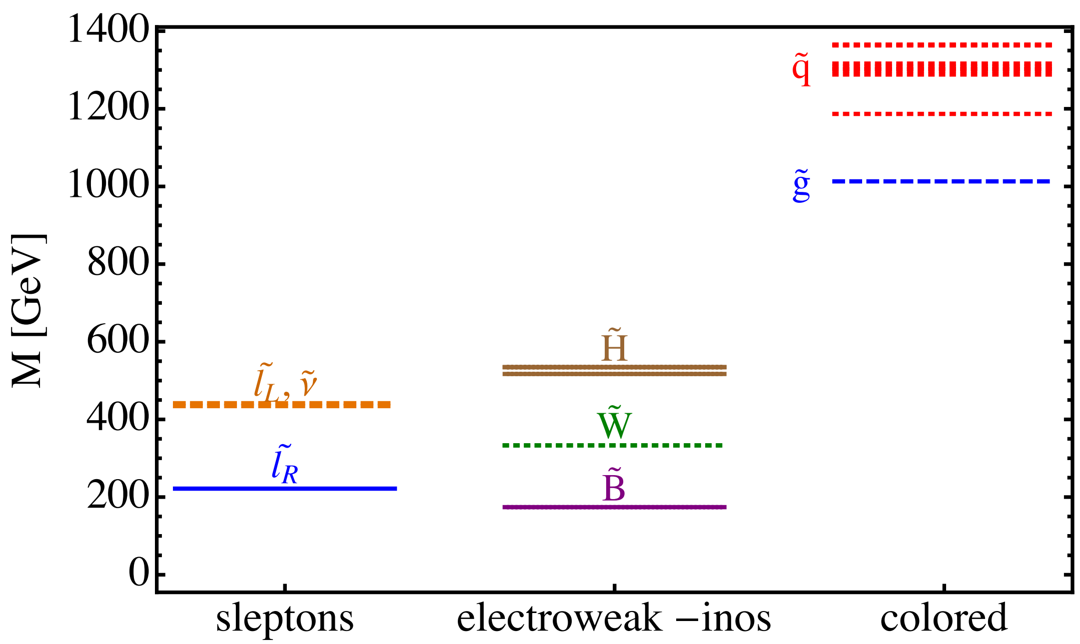


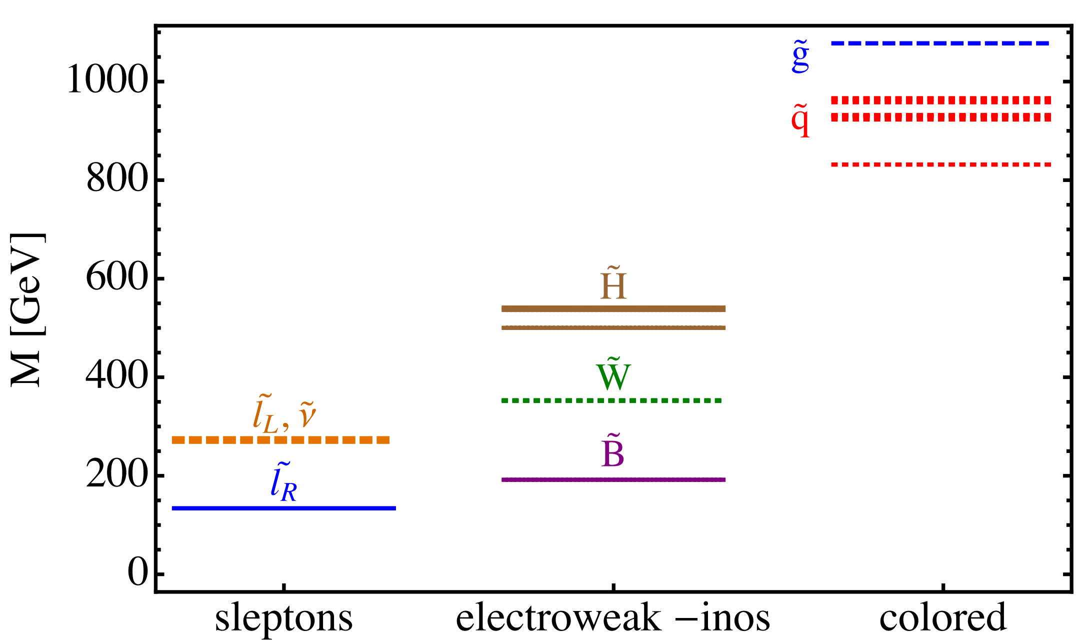
- All SUSY cascade decays pass through the NLSP.
- So all events contain high pT objects determined by the NLSP type, plus missing energy.

Minimal Gauge Mediation

$$M_{1,2,3} = \frac{\alpha_{1,2,3}}{4\pi} \frac{F}{M}, \qquad m^2_{\tilde{q}} \sim \left(\frac{\alpha_3}{4\pi} \frac{F}{M} \right)^2, \qquad m^2_{\tilde{\ell}} \sim \left(\frac{\alpha_{1,2}}{4\pi} \frac{F}{M} \right)^2$$

- In the early days of GMSB, the collider signatures of "Minimal Gauge Mediation" were extensively studied.

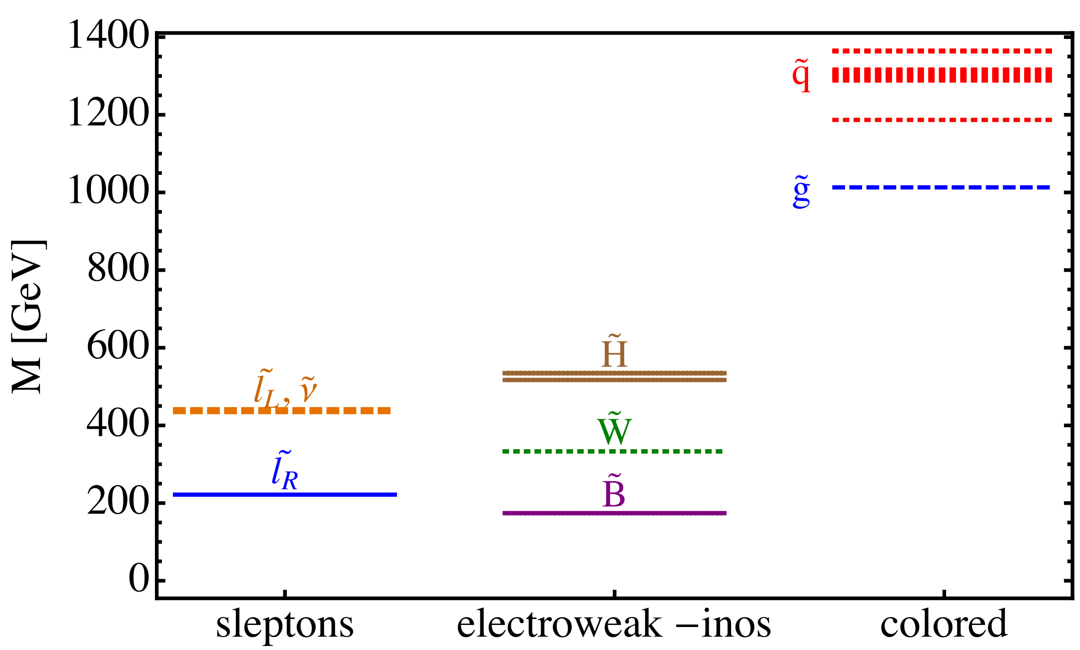


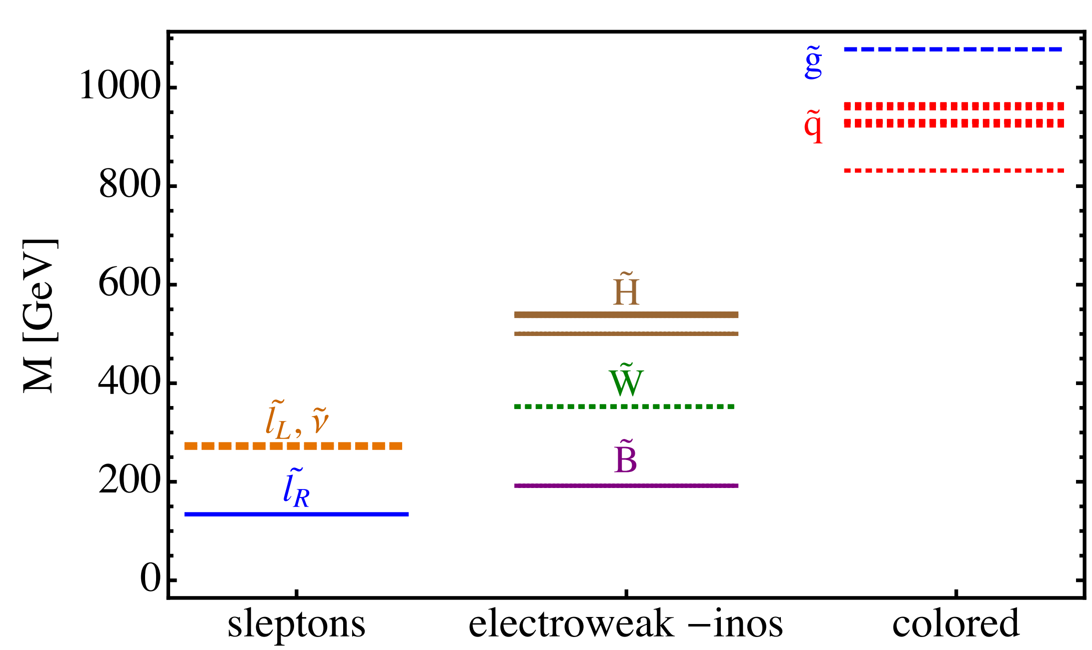


Minimal Gauge Mediation

$$M_{1,2,3} = \frac{\alpha_{1,2,3}}{4\pi}\frac{F}{M}, \qquad m_{\tilde{q}}^2 \sim \left(\frac{\alpha_3}{4\pi}\frac{F}{M}\right)^2, \qquad m_{\tilde{\ell}}^2 \sim \left(\frac{\alpha_{1,2}}{4\pi}\frac{F}{M}\right)^2$$

- In the early days of GMSB, the collider signatures of "Minimal Gauge Mediation" were extensively studied.



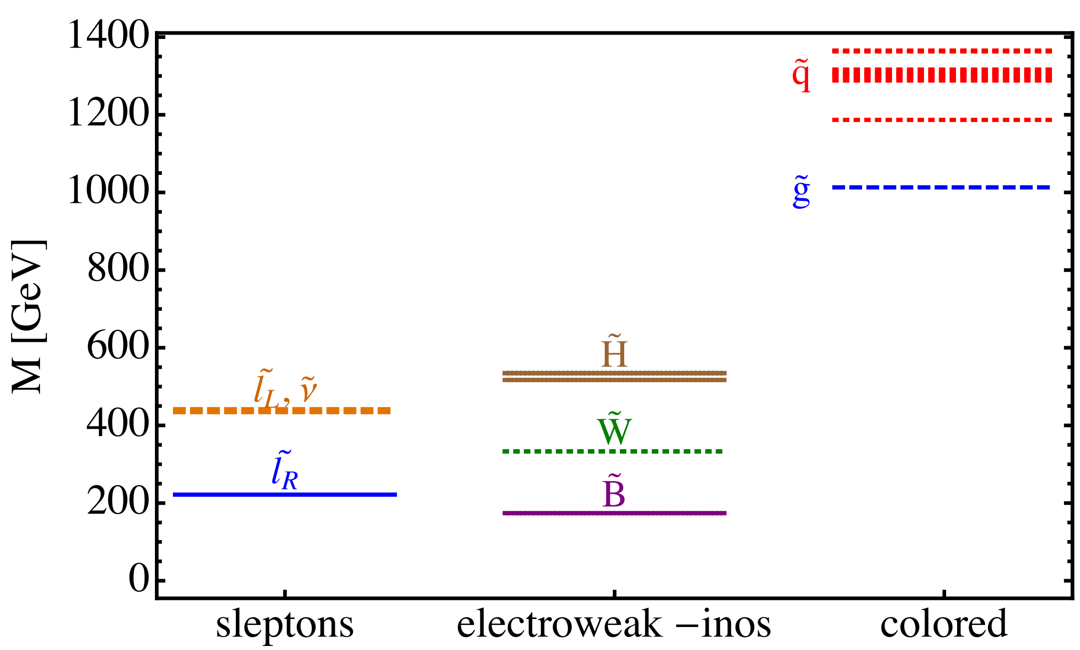


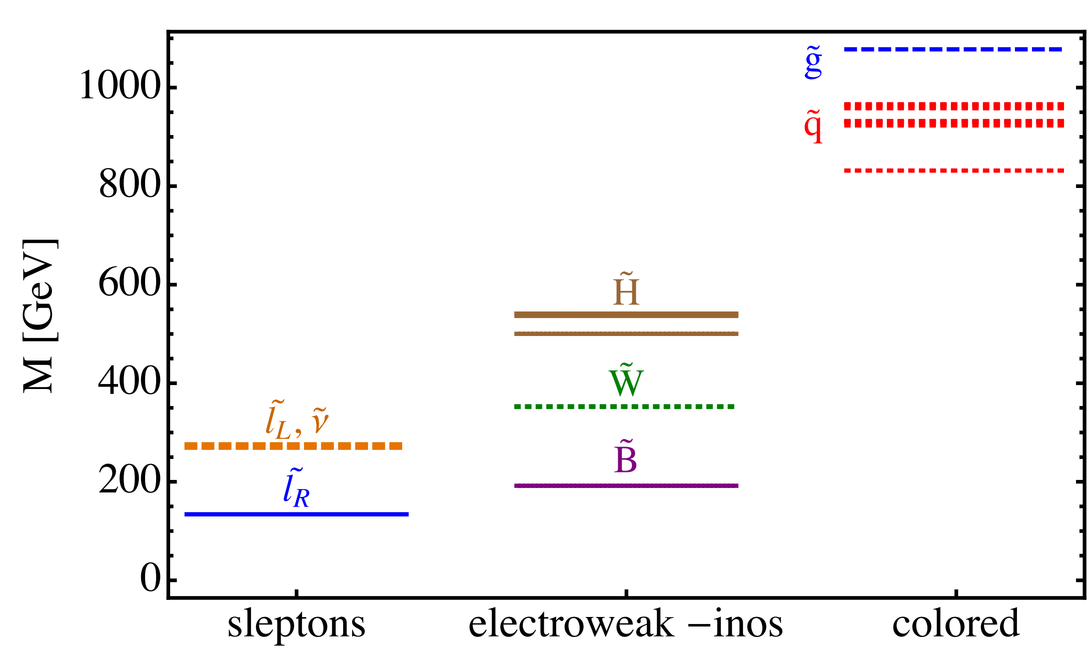
bino or slepton (co-)NLSP

Minimal Gauge Mediation

$$M_{1,2,3} = \frac{\alpha_{1,2,3}}{4\pi}\frac{F}{M}, \qquad m_{\tilde{q}}^2 \sim \left(\frac{\alpha_3}{4\pi}\frac{F}{M}\right)^2, \qquad m_{\tilde{\ell}}^2 \sim \left(\frac{\alpha_{1,2}}{4\pi}\frac{F}{M}\right)^2$$

- In the early days of GMSB, the collider signatures of "Minimal Gauge Mediation" were extensively studied.



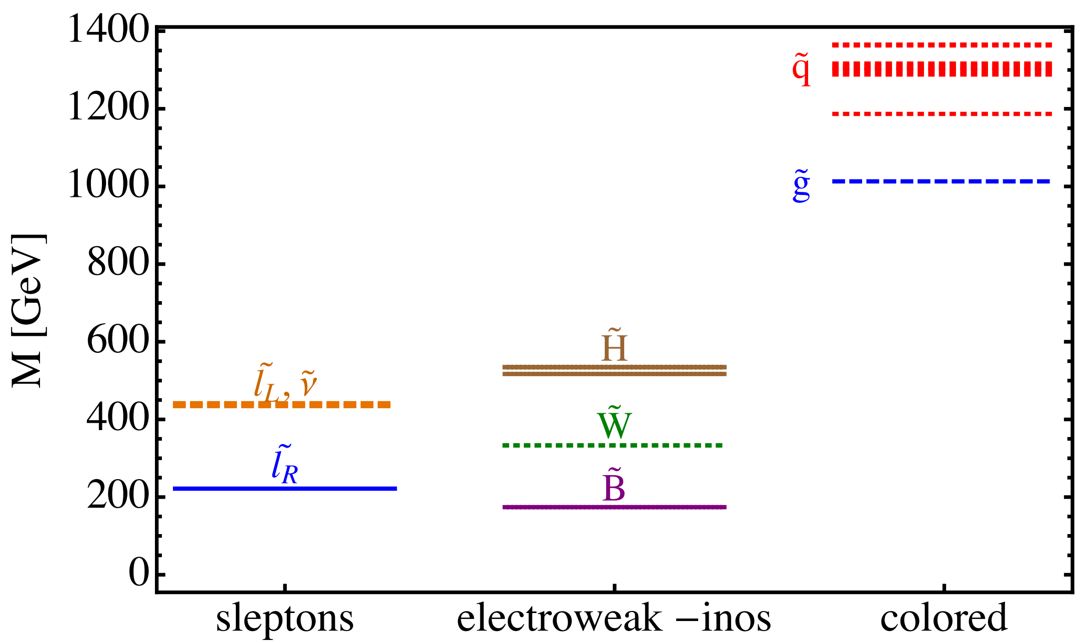


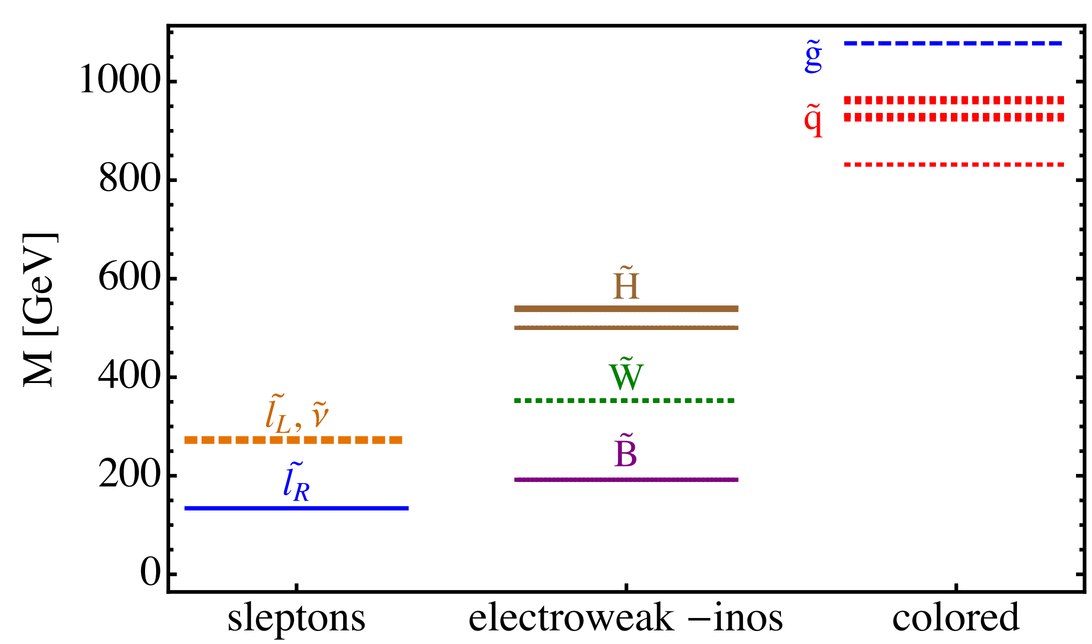
bino or slepton (co-)NLSP heavy squarks and gluinos

Minimal Gauge Mediation

$$M_{1,2,3} = \frac{\alpha_{1,2,3}}{4\pi}\frac{F}{M}, \qquad m_{\tilde{q}}^2 \sim \left(\frac{\alpha_3}{4\pi}\frac{F}{M}\right)^2, \qquad m_{\tilde{\ell}}^2 \sim \left(\frac{\alpha_{1,2}}{4\pi}\frac{F}{M}\right)^2$$

- In the early days of GMSB, the collider signatures of "Minimal Gauge Mediation" were extensively studied.





bino or slepton (co-)NLSP   heavy squarks and gluinos   M1: M2: M3 ~ 1: 2 : 7

Beyond MGM?

Beyond MGM?

- Additionally, a variety of different signatures beyond MGM were catalogued and studied by many authors.

Beyond MGM?

- Additionally, a variety of different signatures beyond MGM were catalogued and studied by many authors.
- However, experimental searches for GMSB have focused almost entirely on MGM signatures and parameter space.

Beyond MGM?

- Additionally, a variety of different signatures beyond MGM were catalogued and studied by many authors.
- However, experimental searches for GMSB have focused almost entirely on MGM signatures and parameter space.
    - diphoton+MET (bino NLSP)

Beyond MGM?

- Additionally, a variety of different signatures beyond MGM were catalogued and studied by many authors.
- However, experimental searches for GMSB have focused almost entirely on MGM signatures and parameter space.
  - diphoton+MET (bino NLSP)
  - displaced photons+MET (bino NLSP)

Beyond MGM?

- Additionally, a variety of different signatures beyond MGM were catalogued and studied by many authors.
- However, experimental searches for GMSB have focused almost entirely on MGM signatures and parameter space.
    - diphoton+MET (bino NLSP)
    - displaced photons+MET (bino NLSP)
    - long-lived stau NLSP

Beyond MGM?

- Additionally, a variety of different signatures beyond MGM were catalogued and studied by many authors.
- However, experimental searches for GMSB have focused almost entirely on MGM signatures and parameter space.
  - diphoton+MET (bino NLSP)
  - displaced photons+MET (bino NLSP)
  - long-lived stau NLSP
  - OS dilepton+MET (slepton NLSP; LEP only)

Beyond MGM?

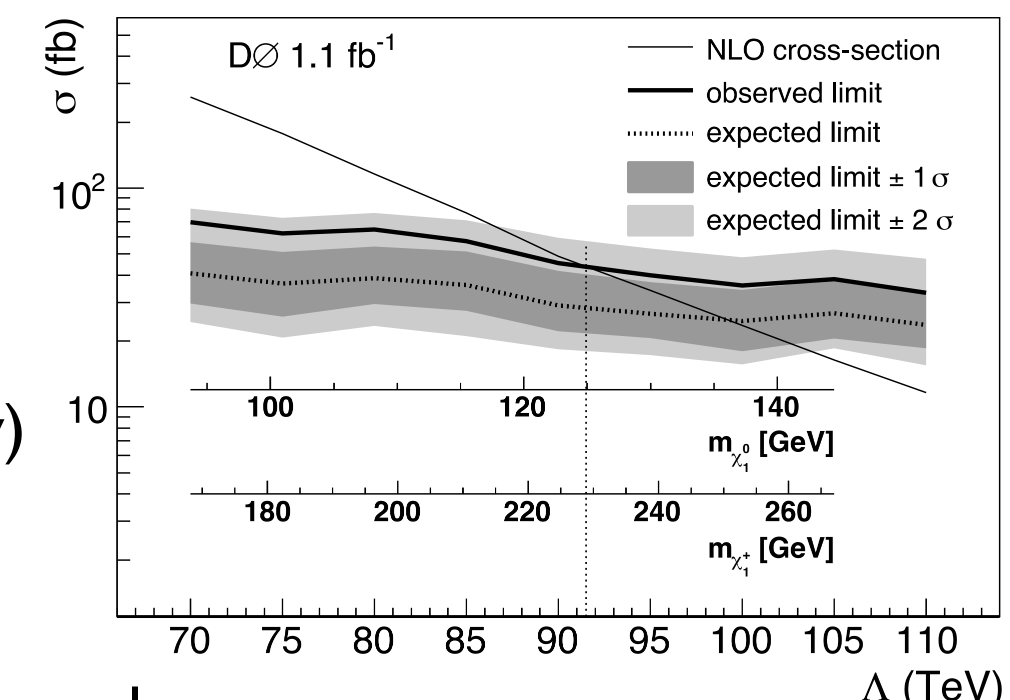
- Additionally, a variety of different signatures beyond MGM were catalogued and studied by many authors.
- However, experimental searches for GMSB have focused almost entirely on MGM signatures and parameter space.
    - diphoton+MET (bino NLSP)
    - displaced photons+MET (bino NLSP)
    - long-lived stau NLSP
    - OS dilepton+MET (slepton NLSP; LEP only)
    - ....

Beyond MGM?

- Additionally, a variety of different signatures beyond MGM were catalogued and studied by many authors.
- However, experimental searches for GMSB have focused almost entirely on MGM signatures and parameter space.
    - diphoton+MET (bino NLSP)
    - displaced photons+MET (bino NLSP)
    - long-lived stau NLSP
    - OS dilepton+MET (slepton NLSP; LEP only)
    - ....
    - Heavy squarks & gluinos => EW production only...

Beyond MGM?

- Additionally, a variety of different signatures beyond MGM were catalogued and studied by many authors.
- However, experimental searches for GMSB have focused almost entirely on MGM signatures and parameter space.
    - diphoton+MET (bino NLSP)
    - displaced photons+MET (bino NLSP)
    - long-lived stau NLSP
    - OS dilepton+MET (slepton NLSP; LEP only)
    - ....
    - Heavy squarks & gluinos => EW production only...



NLSPs in GGM

NLSPs in GGM

- In GGM parameter space, the NLSP can be nearly anything:

NLSPs in GGM

- In GGM parameter space, the NLSP can be nearly anything:
    - general neutralino NLSP (more than just bino!)

NLSPs in GGM

- In GGM parameter space, the NLSP can be nearly anything:
  - general neutralino NLSP (more than just bino!)
  - right-handed slepton NLSP

NLSPs in GGM

- In GGM parameter space, the NLSP can be nearly anything:
  - general neutralino NLSP (more than just bino!)
  - right-handed slepton NLSP
  - sneutrino NLSP

NLSPs in GGM

- In GGM parameter space, the NLSP can be nearly anything:
  - general neutralino NLSP (more than just bino!)
  - right-handed slepton NLSP
  - sneutrino NLSP
  - gluino NLSP

NLSPs in GGM

- In GGM parameter space, the NLSP can be nearly anything:
  - general neutralino NLSP (more than just bino!)
  - right-handed slepton NLSP
  - sneutrino NLSP
  - gluino NLSP
  - squark NLSP

NLSPs in GGM

- In GGM parameter space, the NLSP can be nearly anything:
  - general neutralino NLSP (more than just bino!)
  - right-handed slepton NLSP
  - sneutrino NLSP
  - gluino NLSP
  - squark NLSP
- Squarks and gluinos can be light, and can have significant production cross sections at Tevatron and LHC.

NLSPs in GGM

- In GGM parameter space, the NLSP can be nearly anything:
  - general neutralino NLSP (more than just bino!)
  - right-handed slepton NLSP
  - sneutrino NLSP
  - gluino NLSP
  - squark NLSP
- Squarks and gluinos can be light, and can have significant production cross sections at Tevatron and LHC.
- Phenomenological possibilities go far beyond MGM!

GGM Zoology

GGM Zoology

- Huge space, bewildering zoo of possibilities. What to do?

GGM Zoology

- Huge space, bewildering zoo of possibilities. What to do?
- Goals:

GGM Zoology

- Huge space, bewildering zoo of possibilities. What to do?
- Goals:
    - Categorize minimal inclusive signatures for early LHC discovery. Not necessary to include every particle from every possible decay chain.

GGM Zoology

- Huge space, bewildering zoo of possibilities. What to do?
- Goals:
  - Categorize minimal inclusive signatures for early LHC discovery. Not necessary to include every particle from every possible decay chain.

    ➡ Inclusive signatures primarily controlled by NLSP type

GGM Zoology

- Huge space, bewildering zoo of possibilities. What to do?
- Goals:
  - Categorize minimal inclusive signatures for early LHC discovery. Not necessary to include every particle from every possible decay chain.
    - ➡ Inclusive signatures primarily controlled by NLSP type
    - ➡ Include minimal particle content for production and signature

GGM Zoology

- Huge space, bewildering zoo of possibilities. What to do?
- Goals:
  - Categorize minimal inclusive signatures for early LHC discovery. Not necessary to include every particle from every possible decay chain.
    - ➡ Inclusive signatures primarily controlled by NLSP type
    - ➡ Include minimal particle content for production and signature
  - Provide simple benchmark spaces to experimentalists for search optimization and limit-setting. These should be carefully chosen to be as comprehensive and bias-free as possible.

GGM Zoology

- Huge space, bewildering zoo of possibilities. What to do?
- Goals:
  - Categorize minimal inclusive signatures for early LHC discovery. Not necessary to include every particle from every possible decay chain.
    - ➡ Inclusive signatures primarily controlled by NLSP type
    - ➡ Include minimal particle content for production and signature
  - Provide simple benchmark spaces to experimentalists for search optimization and limit-setting. These should be carefully chosen to be as comprehensive and bias-free as possible.
    - ➡ Formulate benchmark spaces in terms of physical masses

GGM Zoology

- Huge space, bewildering zoo of possibilities. What to do?
- Goals:
  - Categorize minimal inclusive signatures for early LHC discovery. Not necessary to include every particle from every possible decay chain.
    - ➡ Inclusive signatures primarily controlled by NLSP type
    - ➡ Include minimal particle content for production and signature
  - Provide simple benchmark spaces to experimentalists for search optimization and limit-setting. These should be carefully chosen to be as comprehensive and bias-free as possible.
    - ➡ Formulate benchmark spaces in terms of physical masses
  - Understand existing constraints and potential reach in these parameter spaces to help guide future searches.

Minimal Parameter Spaces

- Our approach: simple 2D spaces, parametrized by NLSP mass and production mode mass.
- At LHC, focus on colored production (gluinos for simplicity).
- Characterize kinematical features (squeezing) that affect signal acceptance.
- More complicated spectra will contain these minimal parameter spaces. Well suited for inclusive searches.

Minimal Parameter Spaces

$m_{colored}$

$\vdots$

m_{NLSP}

- Our approach: simple 2D spaces, parametrized by NLSP mass and production mode mass.
- At LHC, focus on colored production (gluinos for simplicity).
- Characterize kinematical features (squeezing) that affect signal acceptance.
- More complicated spectra will contain these minimal parameter spaces. Well suited for inclusive searches.

Examples

General Neutralino NLSPs

General Neutralino NLSPs

- In the MSSM, superpartners of the photon, Z and Higgses consist of four neutralinos and two charginos

$$(\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0) \qquad (\chi_1^\pm, \chi_2^\pm)$$

General Neutralino NLSPs

- In the MSSM, superpartners of the photon, Z and Higgses consist of four neutralinos and two charginos

$$(\chi_1^0,\,\chi_2^0,\,\chi_3^0,\,\chi_4^0) \qquad\qquad (\chi_1^\pm,\,\chi_2^\pm)$$

- General neutralino NLSPs have three possible decays:

$$\chi_1^0 \to (\gamma,\,Z,\,h) + \tilde{G}$$

General Neutralino NLSPs

- In the MSSM, superpartners of the photon, Z and Higgses consist of four neutralinos and two charginos

$$(\chi_1^0,\, \chi_2^0,\, \chi_3^0,\, \chi_4^0) \qquad (\chi_1^\pm,\, \chi_2^\pm)$$

- General neutralino NLSPs have three possible decays:

$$\chi_1^0 \to (\gamma,\, Z,\, h) + \tilde{G}$$

- Focus on simplifying gauge eigenstate limits:
  - Bino NLSP
  - Wino NLSP
  - Higgsino NLSP

Example #1: Bino NLSP

Example #1: Bino NLSP

- This is the classic MGM signature. Here we will revisit it in the model-independent fashion advocated above.

Example #1: Bino NLSP

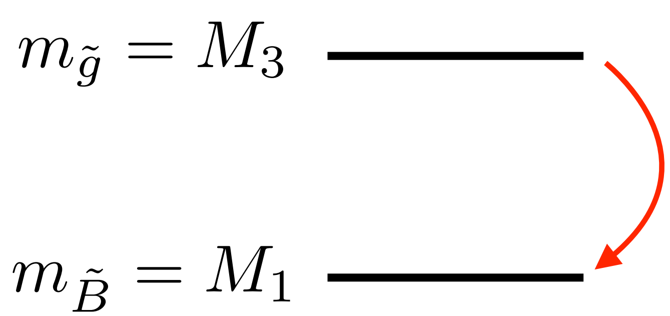
- This is the classic MGM signature. Here we will revisit it in the model-independent fashion advocated above.
- Minimal LHC spectrum for bino NLSP:

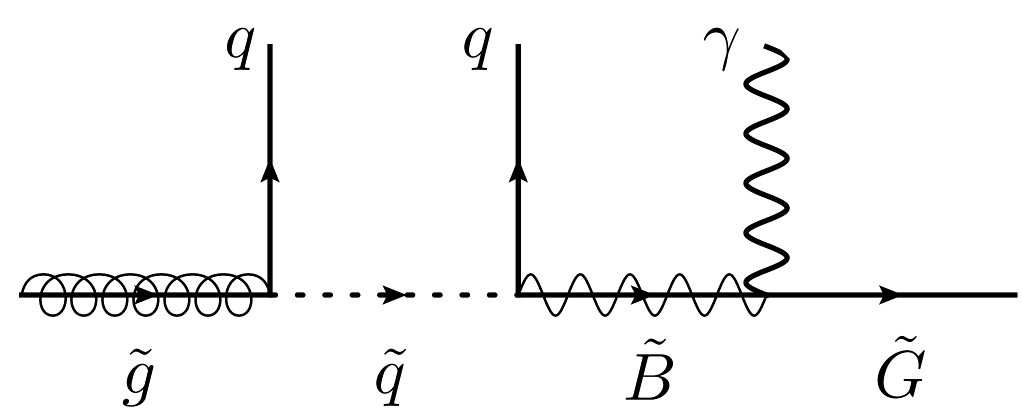
$m_{\tilde{g}} = M_3$

$m_{\tilde{B}} = M_1$

Example #1: Bino NLSP

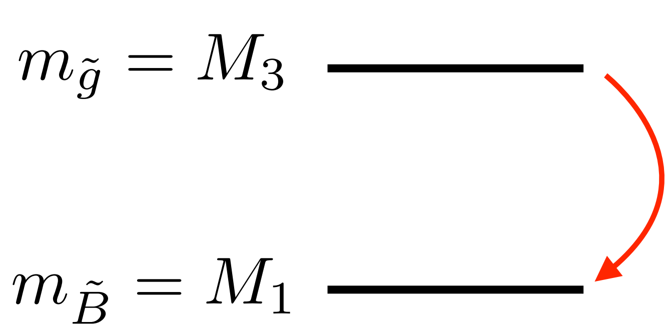
- This is the classic MGM signature. Here we will revisit it in the model-independent fashion advocated above.
- Minimal LHC spectrum for bino NLSP:

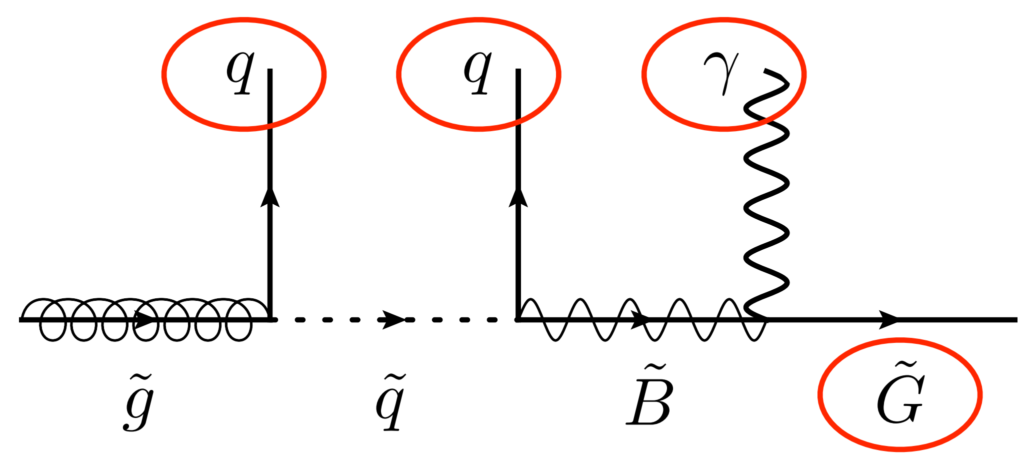




Example #1: Bino NLSP

- This is the classic MGM signature. Here we will revisit it in the model-independent fashion advocated above.
- Minimal LHC spectrum for bino NLSP:

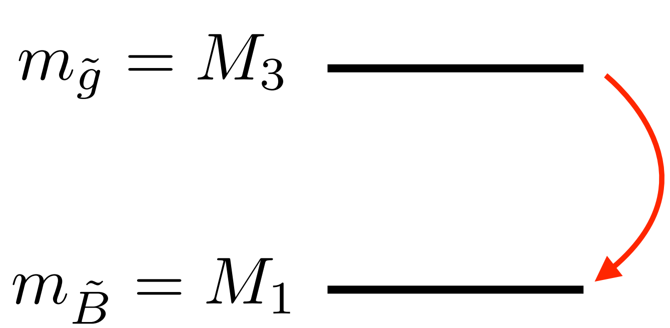


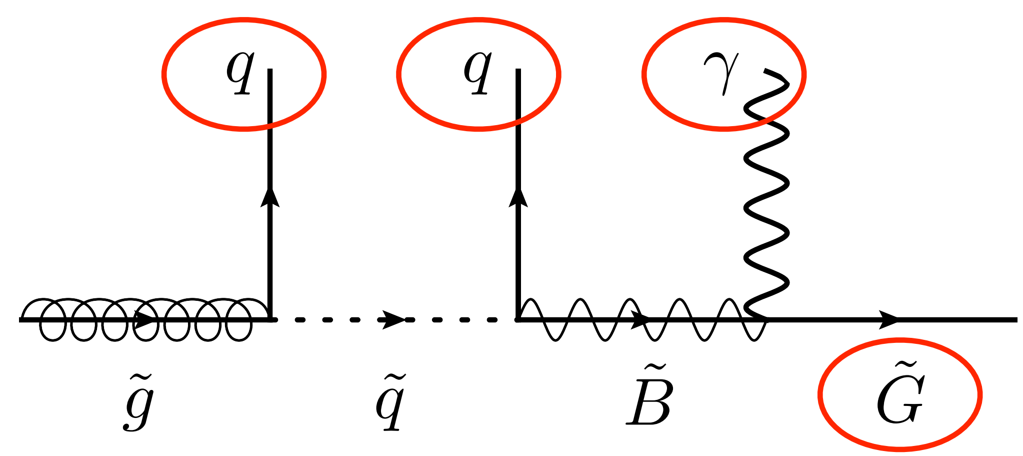


- Signature: $\gamma\gamma + \mathrm{jets} + \mathrm{MET}$

Example #1: Bino NLSP

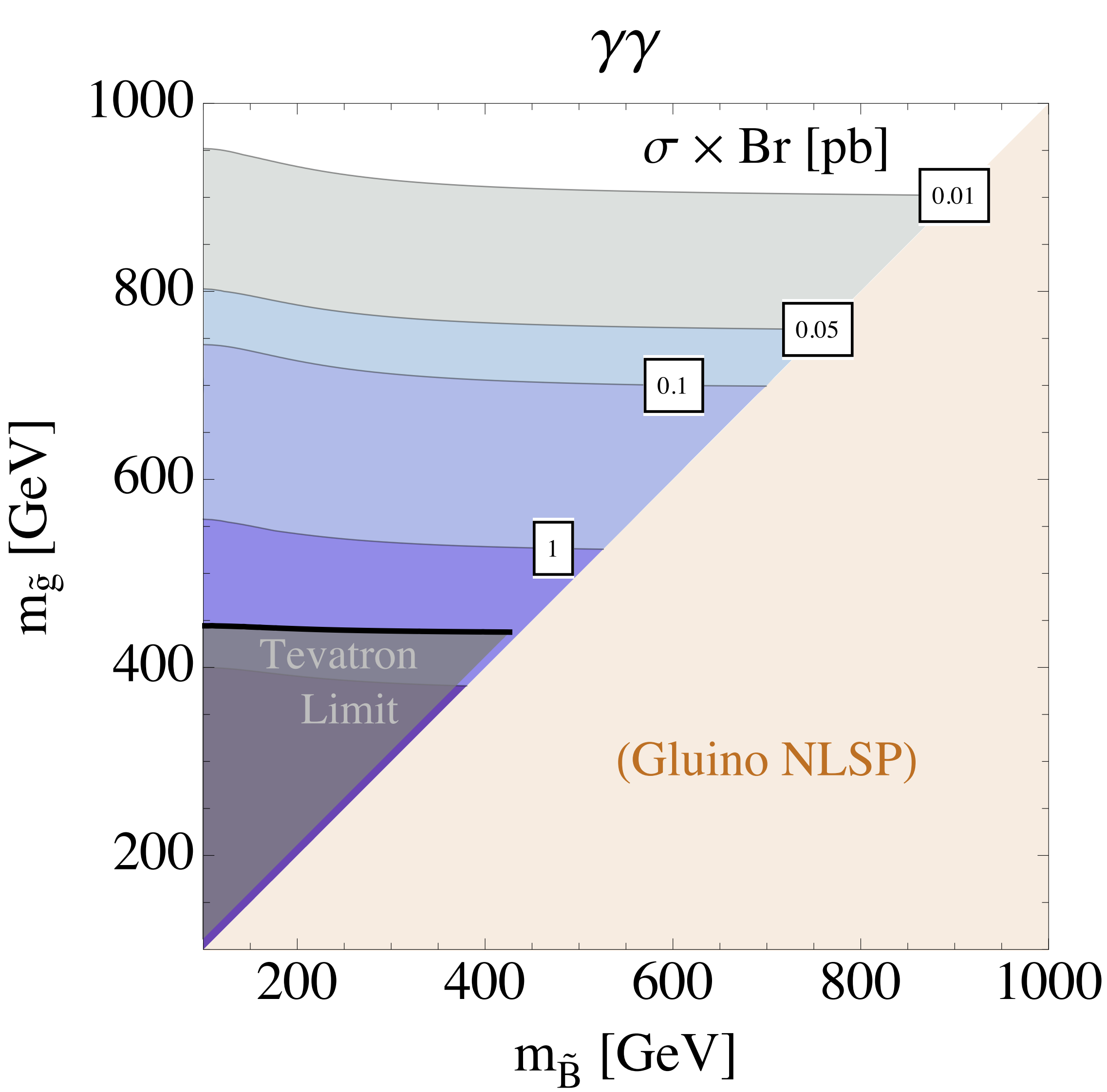
- This is the classic MGM signature. Here we will revisit it in the model-independent fashion advocated above.
- Minimal LHC spectrum for bino NLSP:

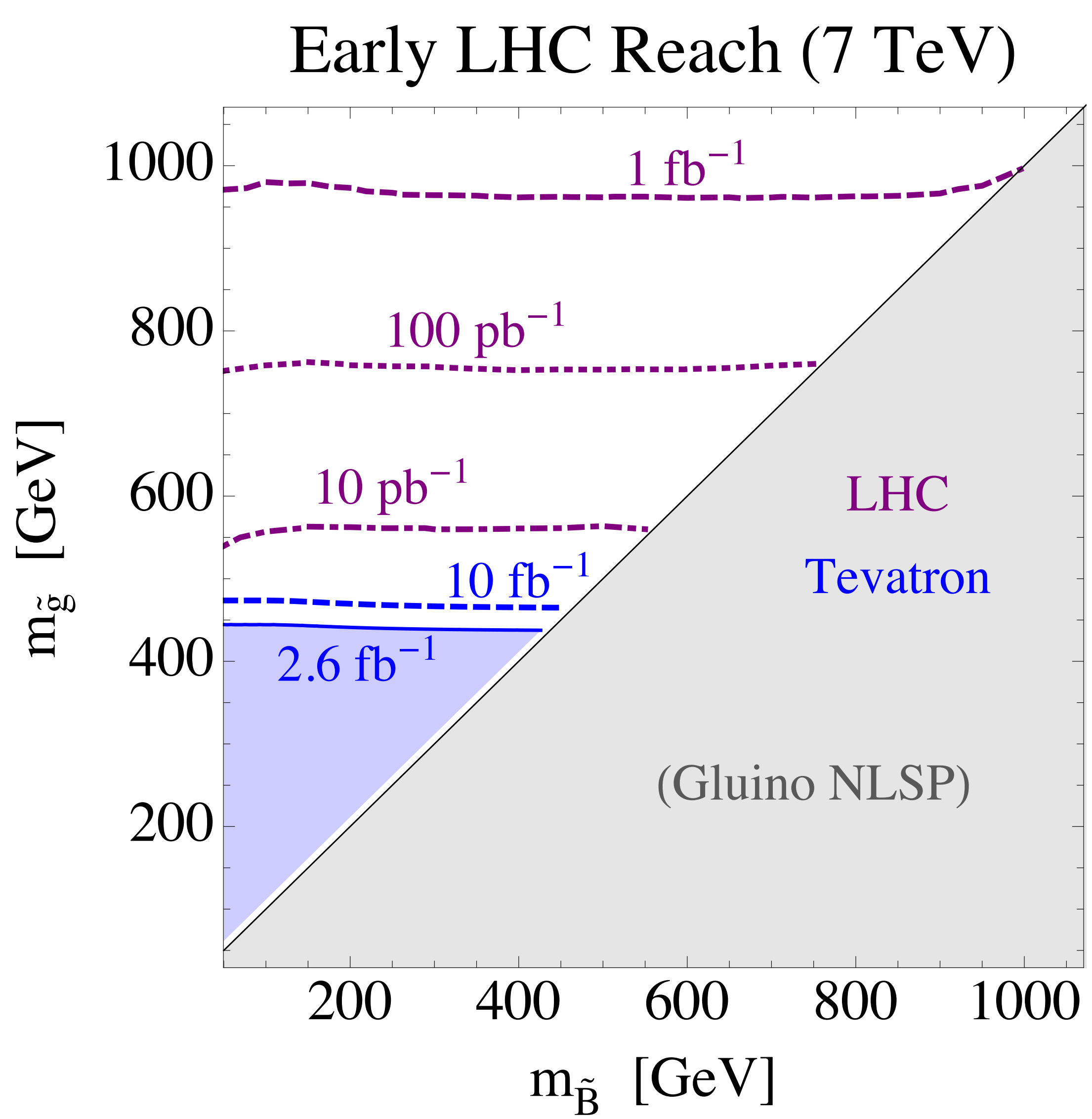




- Signature: $\gamma\gamma + \mathrm{jets} + \mathrm{MET}$
- CDF and D0 have searched for diphotons+MET. Their null results set a lower limit on the gluino mass.

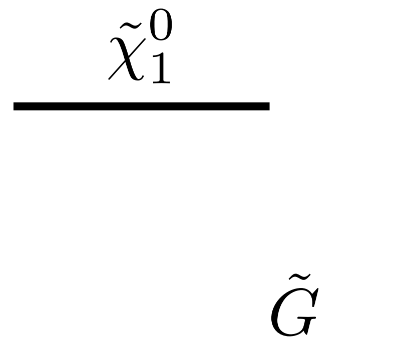
Example #1: Bino NLSP



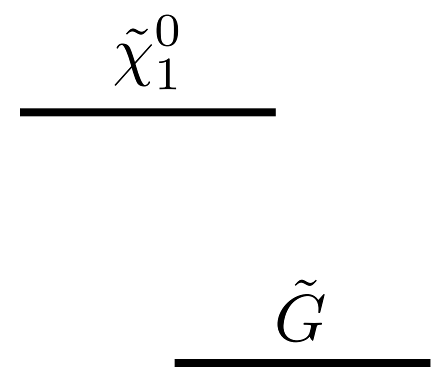


Tevatron surpassed after less than 10/pb !

Example #2: Wino co-NLSP

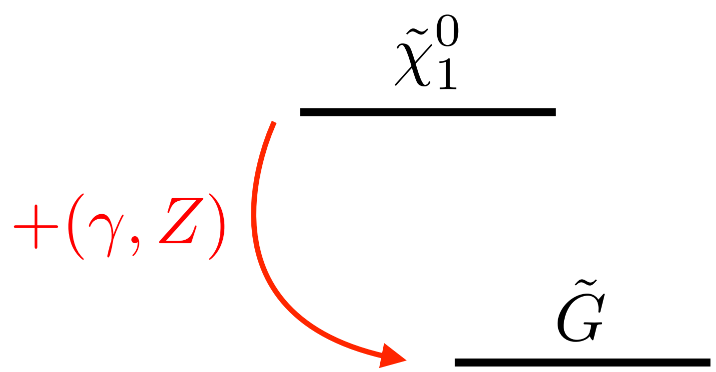


Example #2: Wino co-NLSP



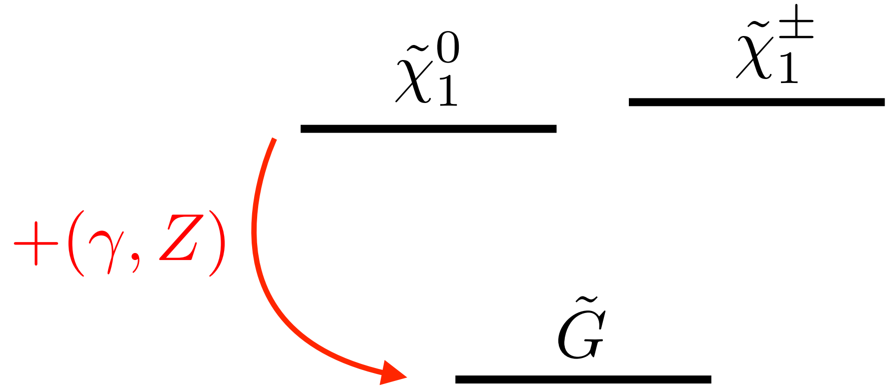
- In this limit, superpartners of the W and Z are lightest.

Example #2: Wino co-NLSP



- In this limit, superpartners of the W and Z are lightest.
- Wino neutralino decays to photons and Z.

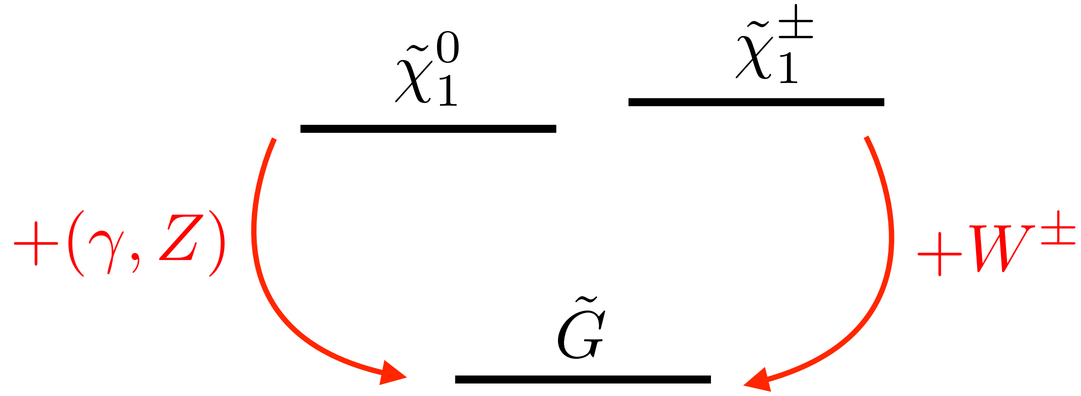
Example #2: Wino co-NLSP



- In this limit, superpartners of the W and Z are lightest.
- Wino neutralino decays to photons and Z.
- Due to accidental cancellations, wino chargino and neutralino are extremely degenerate.

$$|m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}| \sim \frac{m_Z^4}{\mu^3} \ll \mathrm{GeV}$$

Example #2: Wino co-NLSP



- In this limit, superpartners of the W and Z are lightest.
- Wino neutralino decays to photons and Z.
- Due to accidental cancellations, wino chargino and neutralino are extremely degenerate.

$$|m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}| \sim \frac{m_Z^4}{\mu^3} \ll \mathrm{GeV}$$

- Winos are co-NLSPs! Novel, unexplored phenomenology!

Example #2: Wino co-NLSP

Example #2: Wino co-NLSP

- Minimal LHC spectrum for wino co-NLSPs:

$$m_{\tilde{g}} = M_3$$

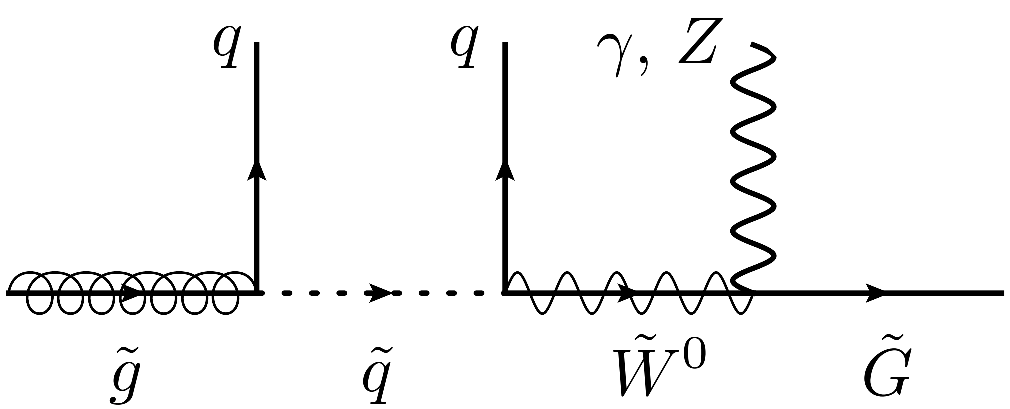
$$m_{\tilde{W}^0} = m_{\tilde{W}^\pm} = M_2$$

Example #2: Wino co-NLSP

- Minimal LHC spectrum for wino co-NLSPs:

$$m_{\tilde{g}} = M_3$$

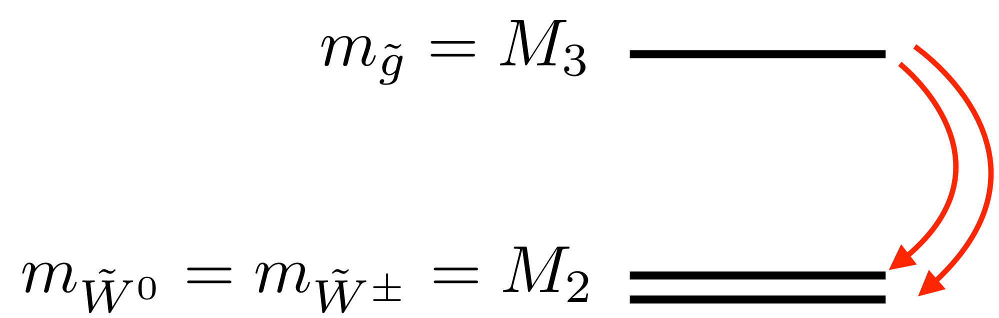
$$m_{\tilde{W}^0} = m_{\tilde{W}^\pm} = M_2$$

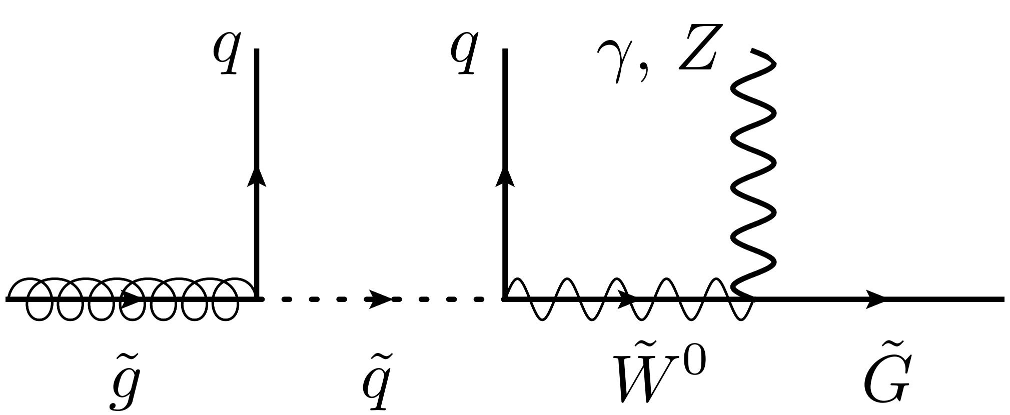


$$\mathrm{Br}(\tilde{g} \to \tilde{W}^0 + \mathrm{jets}) \approx 40\%$$

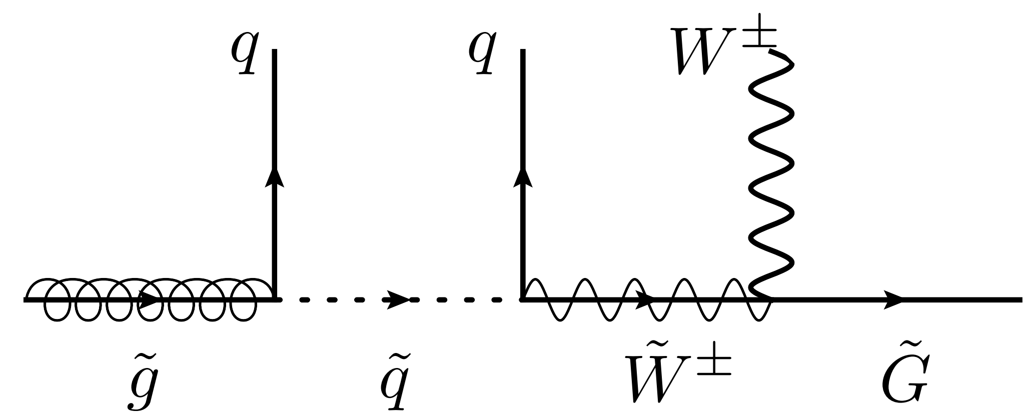
Example #2: Wino co-NLSP

- Minimal LHC spectrum for wino co-NLSPs:





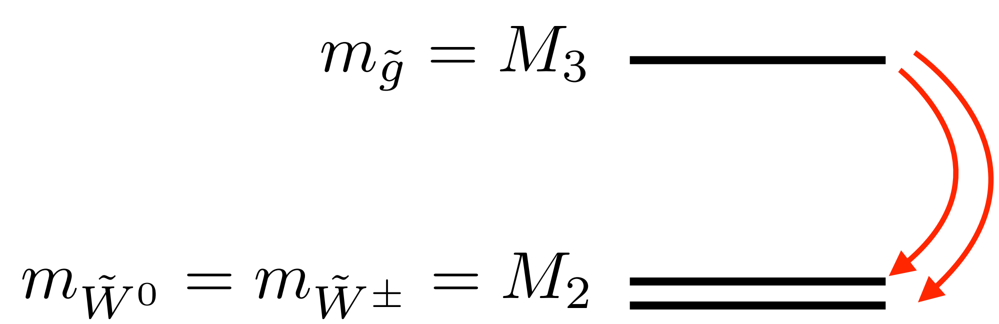
$\mathrm{Br}(\tilde{g} \to \tilde{W}^0 + \mathrm{jets}) \approx 40\%$

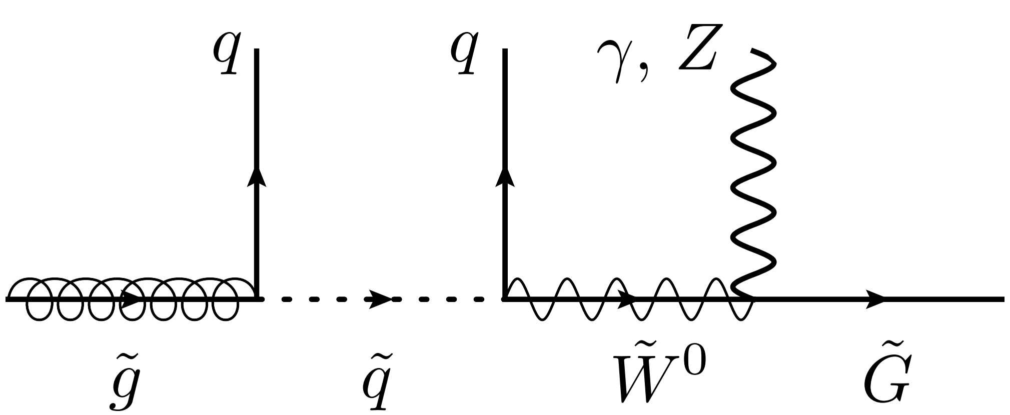


$\mathrm{Br}(\tilde{g} \to \tilde{W}^\pm + \mathrm{jets}) \approx 60\%$

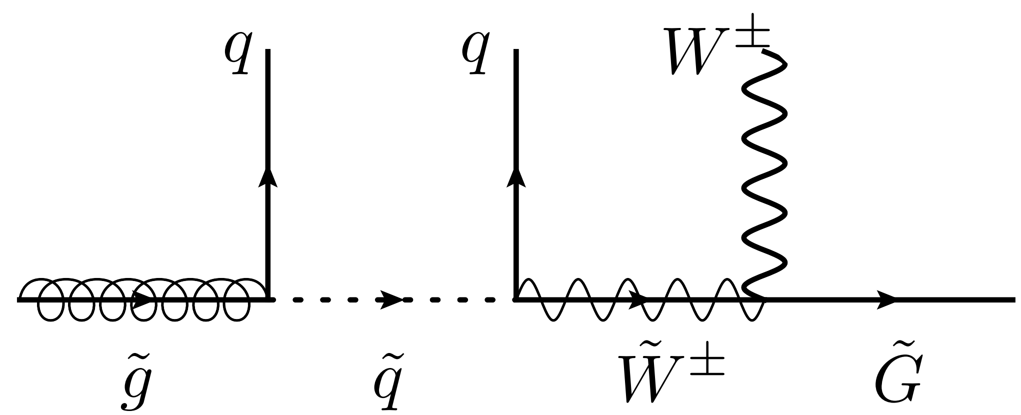
Example #2: Wino co-NLSP

- Minimal LHC spectrum for wino co-NLSPs:





$\mathrm{Br}(\tilde{g} \to \tilde{W}^0 + \mathrm{jets}) \approx 40\%$

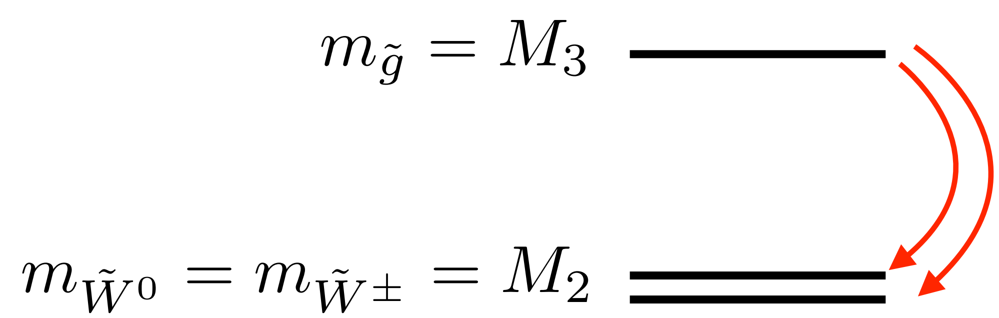


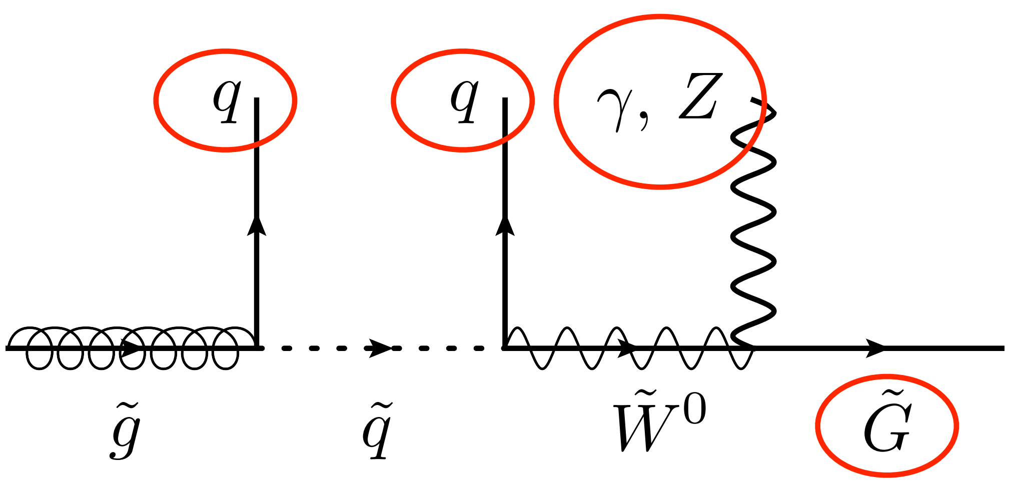
$\mathrm{Br}(\tilde{g} \to \tilde{W}^\pm + \mathrm{jets}) \approx 60\%$

- Signatures:

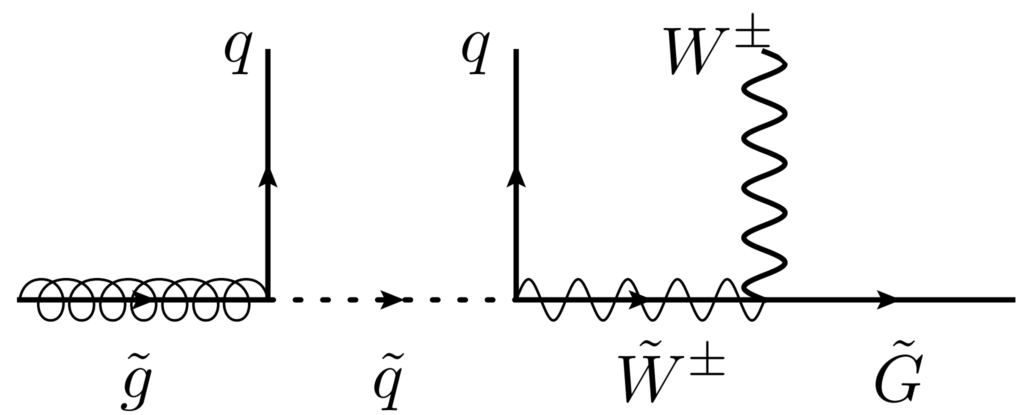
Example #2: Wino co-NLSP

- Minimal LHC spectrum for wino co-NLSPs:





$\mathrm{Br}(\tilde{g} \to \tilde{W}^0 + \mathrm{jets}) \approx 40\%$

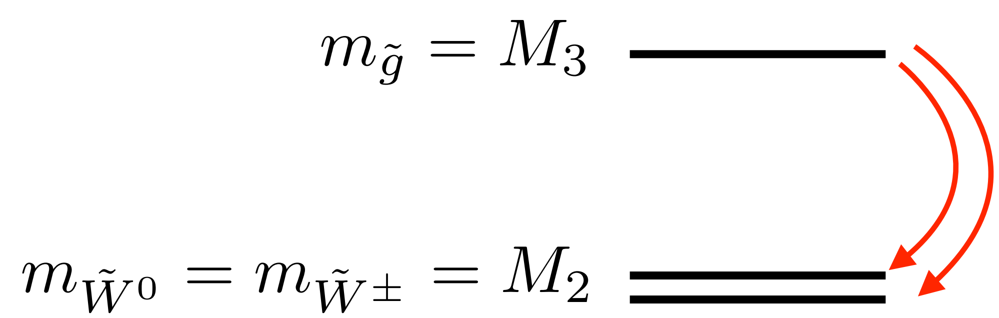


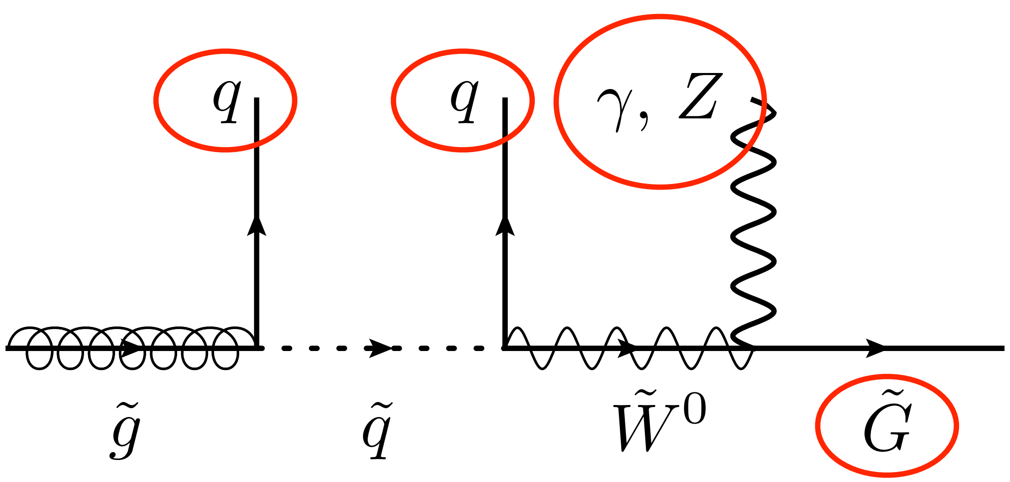
$\mathrm{Br}(\tilde{g} \to \tilde{W}^\pm + \mathrm{jets}) \approx 60\%$

- Signatures: $\gamma\gamma + \mathrm{jets} + \mathrm{MET}$

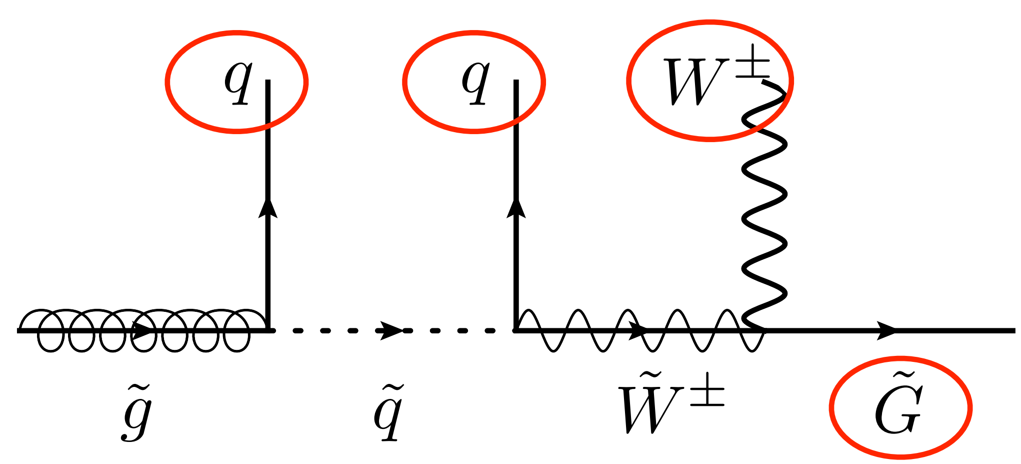
Example #2: Wino co-NLSP

- Minimal LHC spectrum for wino co-NLSPs:





$\mathrm{Br}(\tilde{g} \to \tilde{W}^0 + \mathrm{jets}) \approx 40\%$



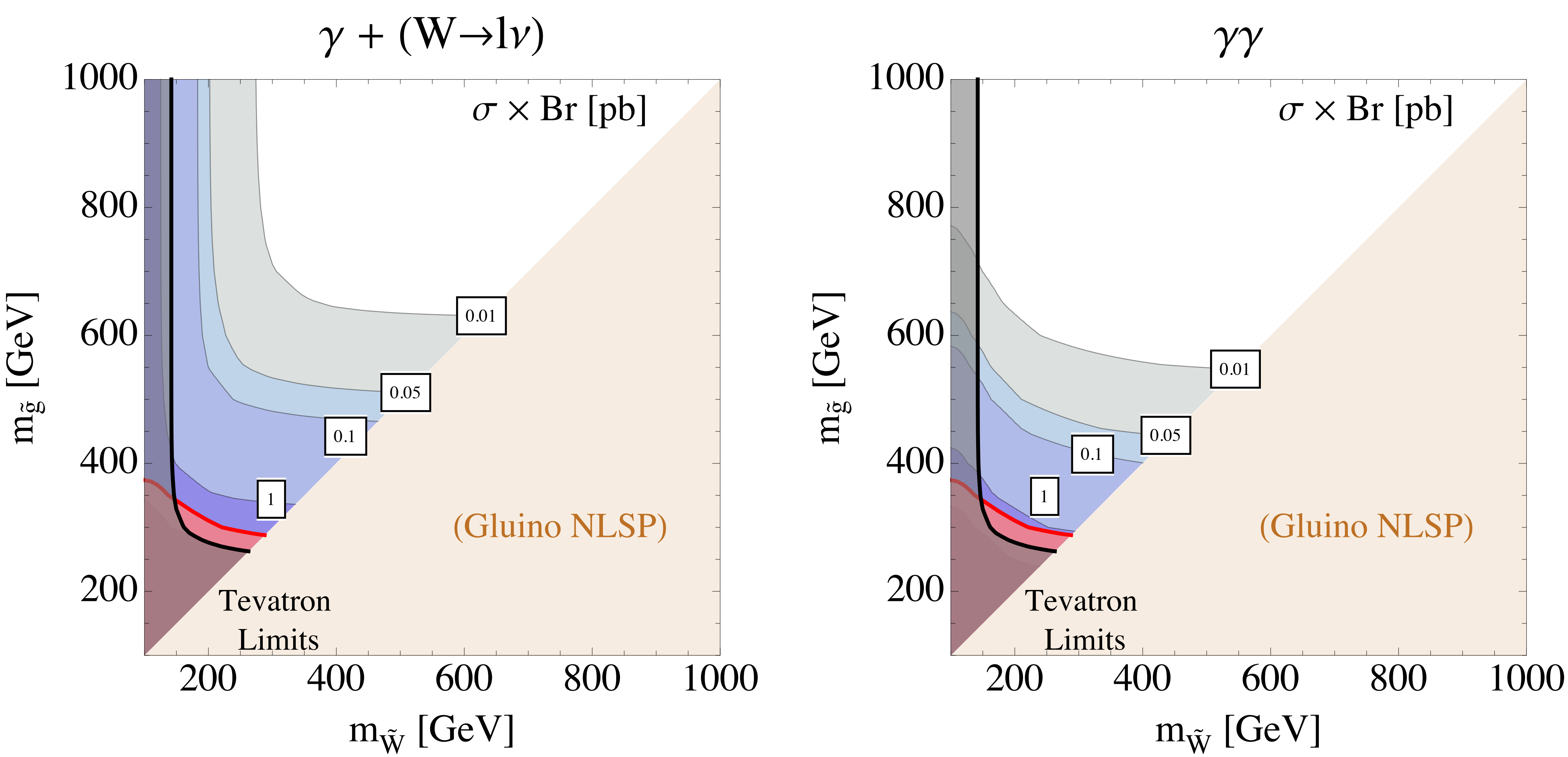
$\mathrm{Br}(\tilde{g} \to \tilde{W}^\pm + \mathrm{jets}) \approx 60\%$

- **Signatures:** $\gamma\gamma + \mathrm{jets} + \mathrm{MET}$

  $W(\ell\nu)\gamma + \mathrm{jets} + \mathrm{MET}$

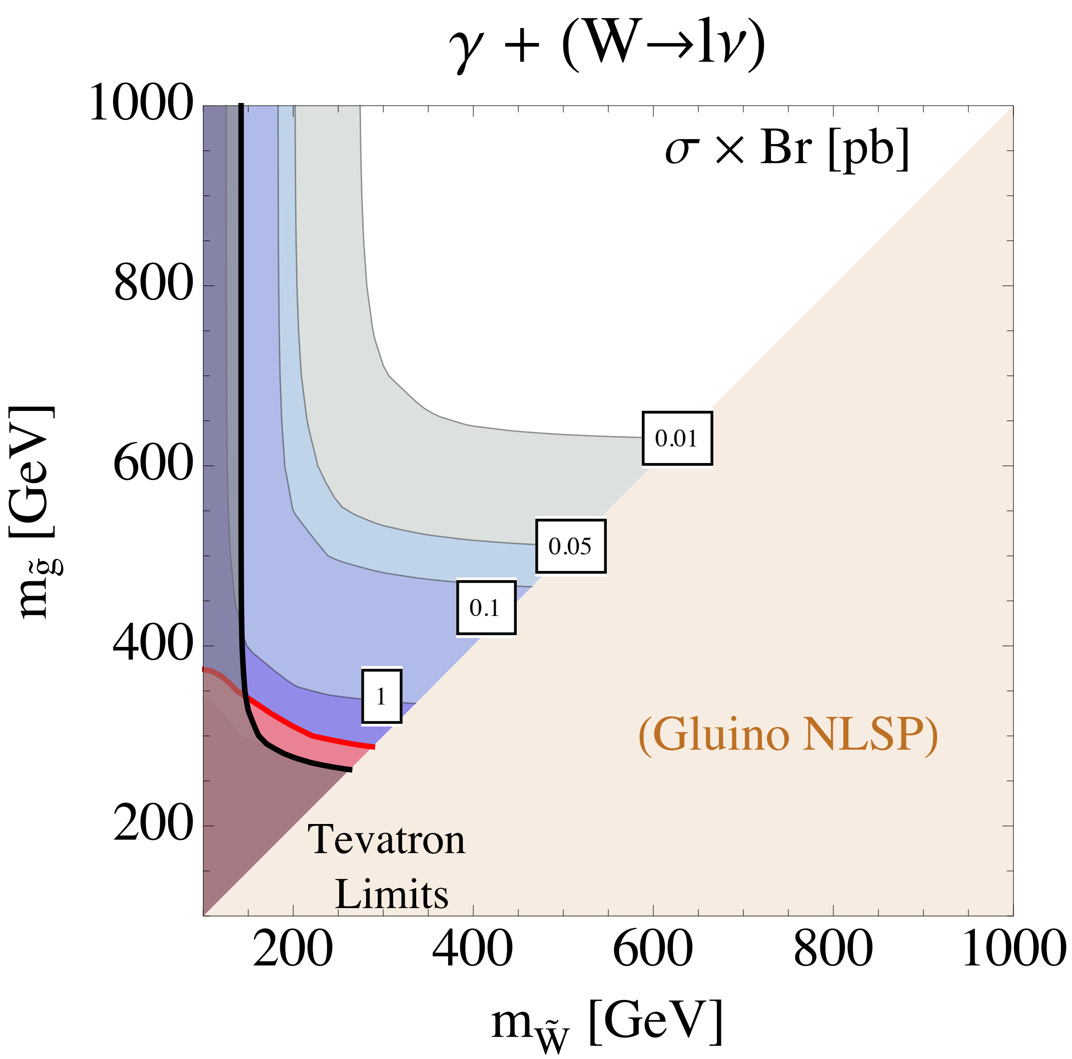
Example #2: Wino co-NLSP

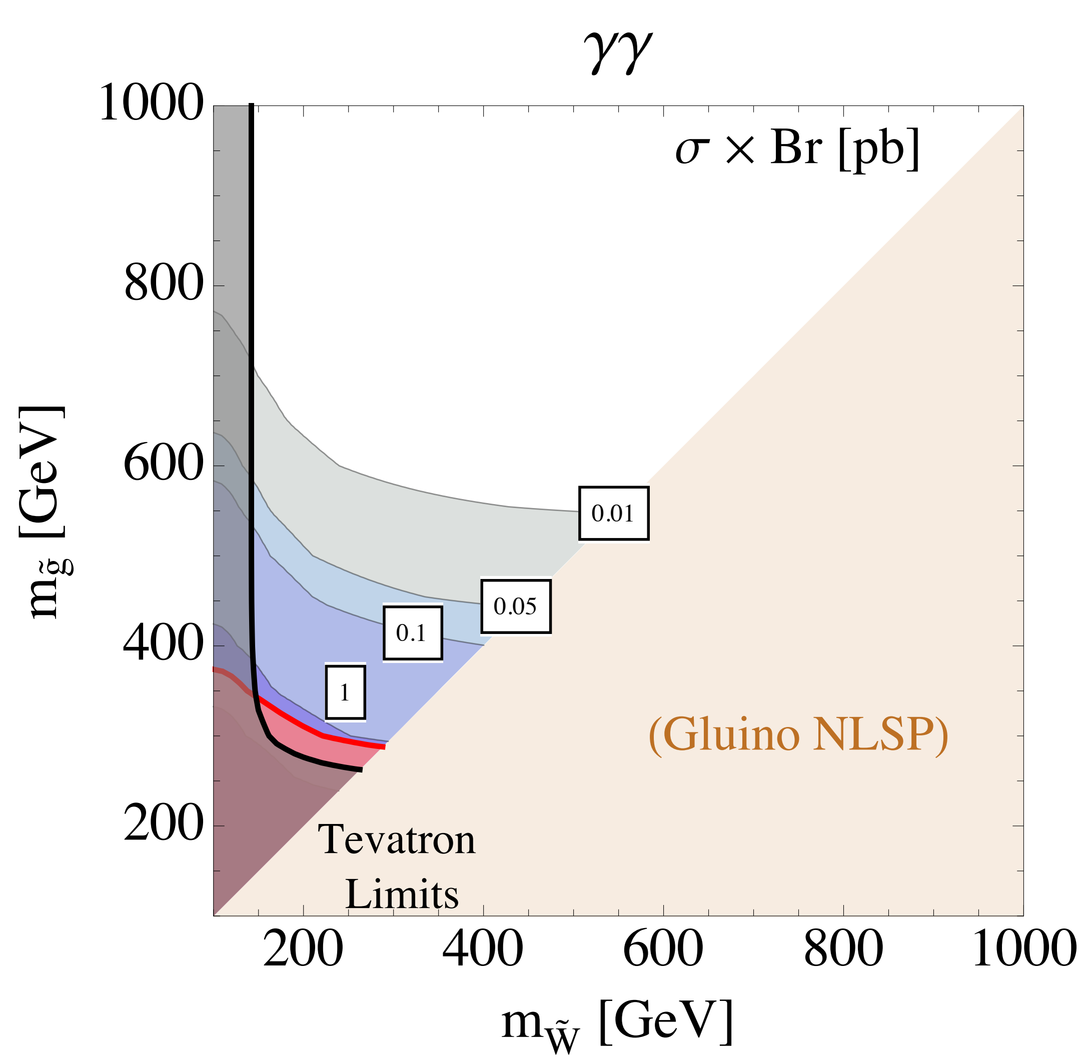
- Tevatron constraints from $\gamma\gamma$+MET. Also, a CDF search for $\ell + \gamma$ +MET. Latter was not optimized for GMSB, but (crude) optimization can be inferred from their paper.



Example #2: Wino co-NLSP

- Tevatron constraints from $\gamma\gamma$+MET. Also, a CDF search for $\ell + \gamma$ +MET. Latter was not optimized for GMSB, but (crude) optimization can be inferred from their paper.





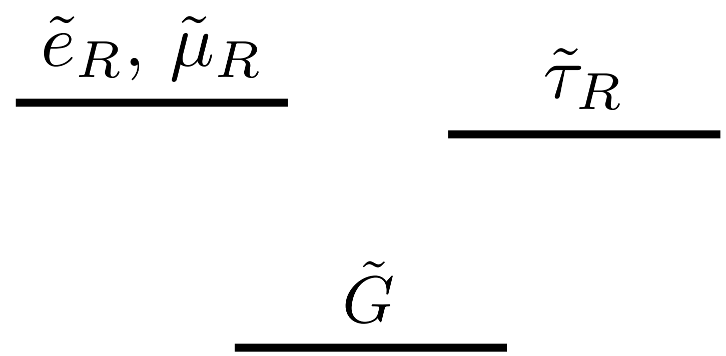
Reach depends on backgrounds.
Work in progress...

Example #3: Slepton co-NLSPs

$\tilde{e}_R,\, \tilde{\mu}_R$ $\tilde{\tau}_R$

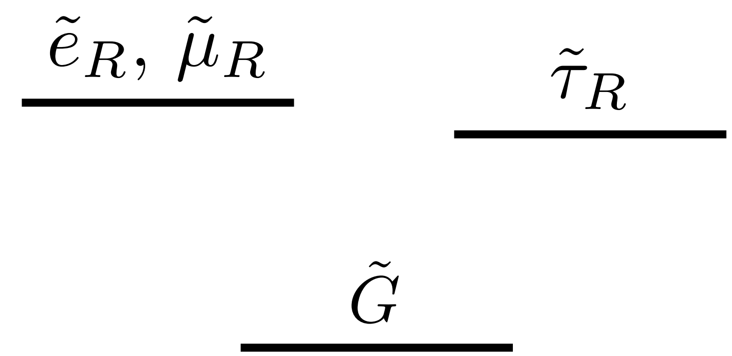
$\tilde{G}$

Example #3: Slepton co-NLSPs



- Another interesting case is where the right-handed sleptons are the NLSPs.

Example #3: Slepton co-NLSPs



- Another interesting case is where the right-handed sleptons are the NLSPs.
- In GMSB, right-handed sleptons are flavor degenerate at the messenger scale. Third generation always becomes lighter due to RG running and left-right mixing.

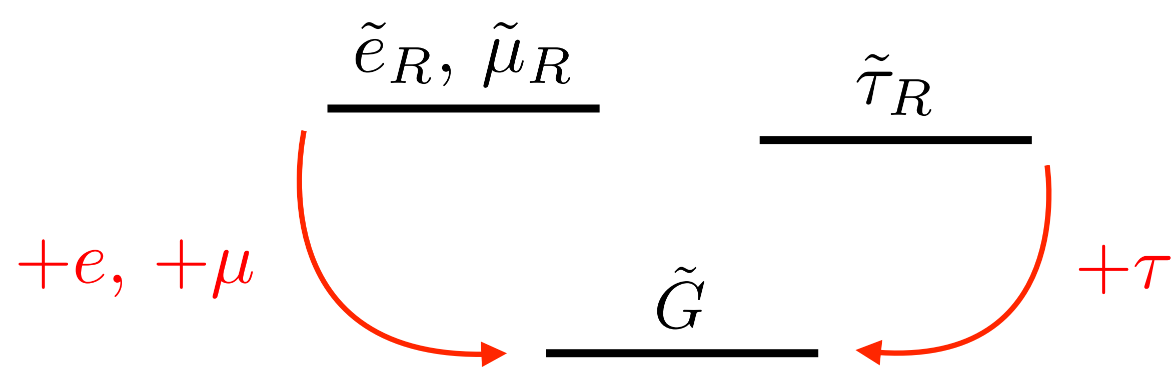
Example #3: Slepton co-NLSPs

$\tilde{e}_R,\ \tilde{\mu}_R$ $\qquad$ $\tilde{\tau}_R$

$\tilde{G}$

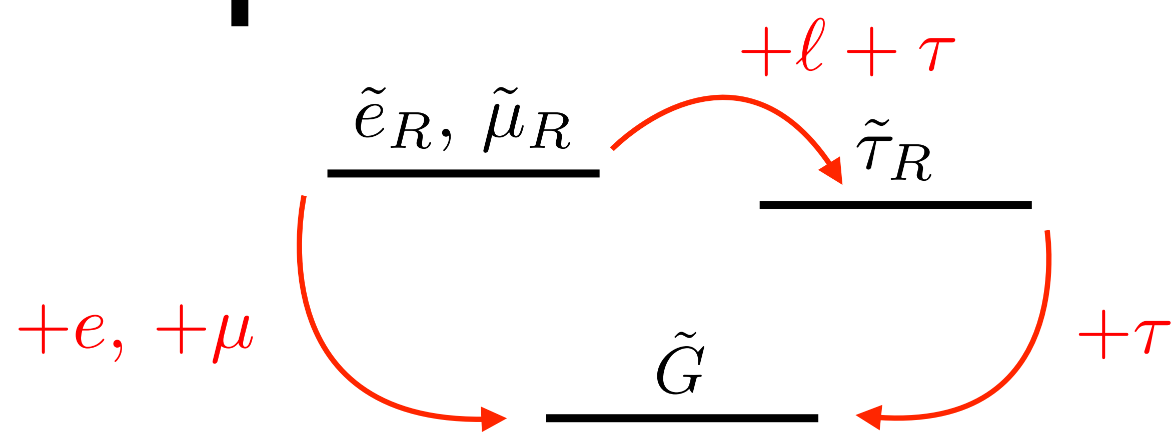
- Another interesting case is where the right-handed sleptons are the NLSPs.
- In GMSB, right-handed sleptons are flavor degenerate at the messenger scale. Third generation always becomes lighter due to RG running and left-right mixing.
- Two cases:

Example #3: Slepton co-NLSPs



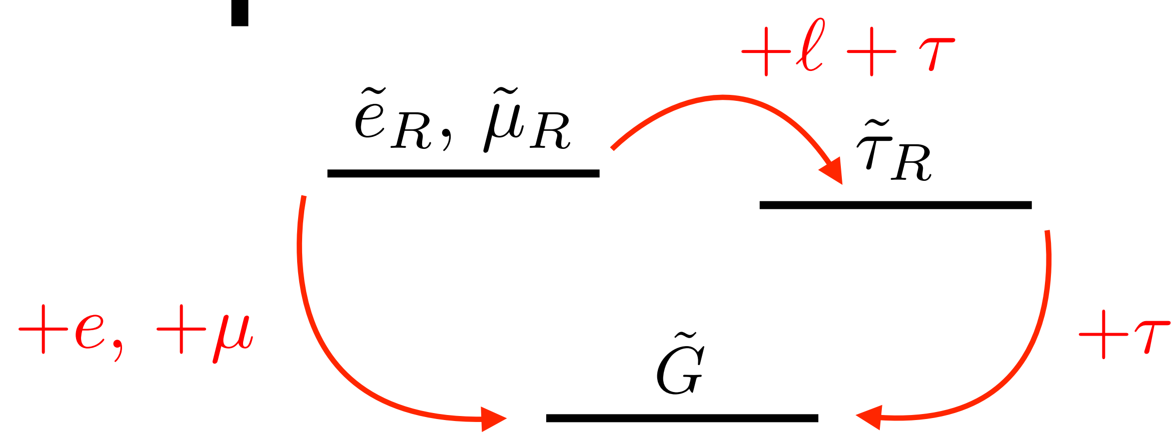
- Another interesting case is where the right-handed sleptons are the NLSPs.
- In GMSB, right-handed sleptons are flavor degenerate at the messenger scale. Third generation always becomes lighter due to RG running and left-right mixing.
- Two cases:
  - slepton co-NLSP

Example #3: Slepton co-NLSPs



- Another interesting case is where the right-handed sleptons are the NLSPs.
- In GMSB, right-handed sleptons are flavor degenerate at the messenger scale. Third generation always becomes lighter due to RG running and left-right mixing.
- Two cases:
  - slepton co-NLSP
  - stau NLSP

Example #3: Slepton co-NLSPs



- Another interesting case is where the right-handed sleptons are the NLSPs.

- In GMSB, right-handed sleptons are flavor degenerate at the messenger scale. Third generation always becomes lighter due to RG running and left-right mixing.

- Two cases:
  - slepton co-NLSP
  - stau NLSP

Cleaner experimental signatures

Example #3:
Slepton co-NLSPs

Example #3:
Slepton co-NLSPs

- Slepton co-NLSPs are generic in GGM (i.e. fine-tuning not required).

Example #3: Slepton co-NLSPs

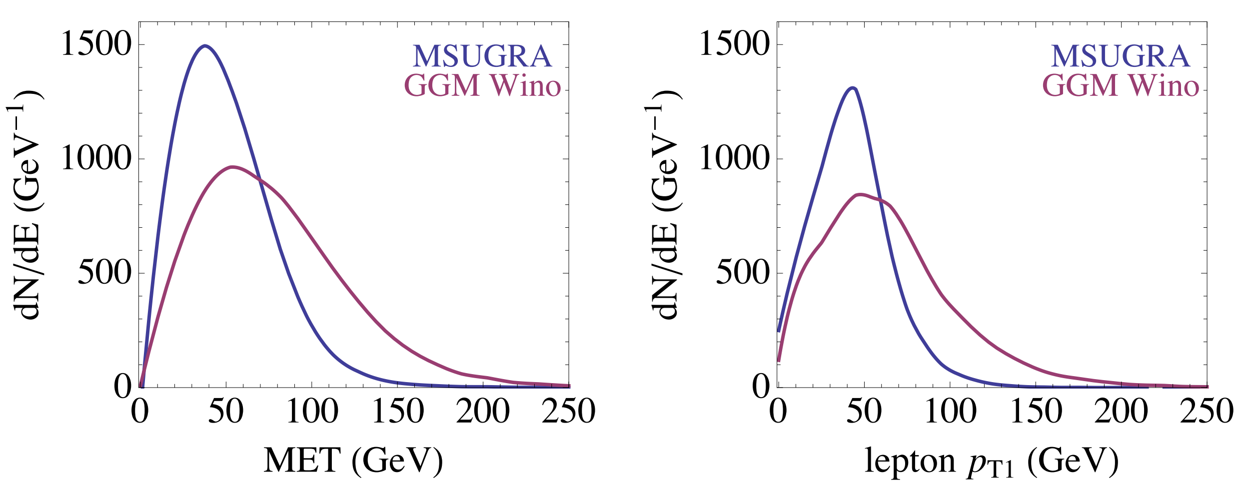
- Slepton co-NLSPs are generic in GGM (i.e. fine-tuning not required).
    - E.g. they occur in MGM for $N_{mess} \geq 3,\ \tan\beta \lesssim 10$

Example #3: Slepton co-NLSPs

- Slepton co-NLSPs are generic in GGM (i.e. fine-tuning not required).
    - E.g. they occur in MGM for $N_{mess} \geq 3, \ \tan\beta \lesssim 10$
- This scenario gives rise to multilepton signatures. These are especially nice final states for hadron colliders.

Example #3: Slepton co-NLSPs

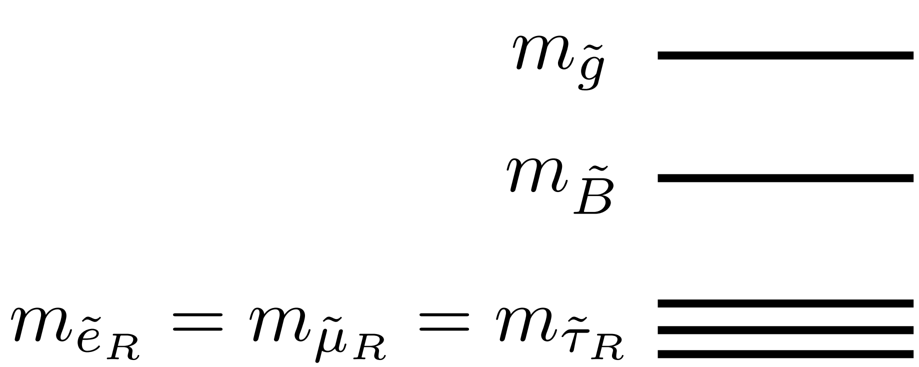
- Slepton co-NLSPs are generic in GGM (i.e. fine-tuning not required).
    - E.g. they occur in MGM for $N_{mess} \geq 3, \ \tan\beta \lesssim 10$
- This scenario gives rise to multilepton signatures. These are especially nice final states for hadron colliders.
- These signatures have traditionally been studied only in context of mSUGRA. Kinematics for gauge mediation are totally different.



Example #3:
Slepton co-NLSPs

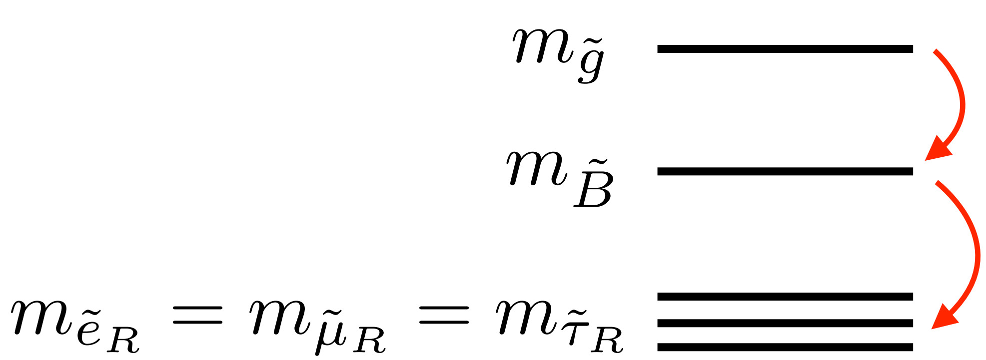
Example #3: Slepton co-NLSPs

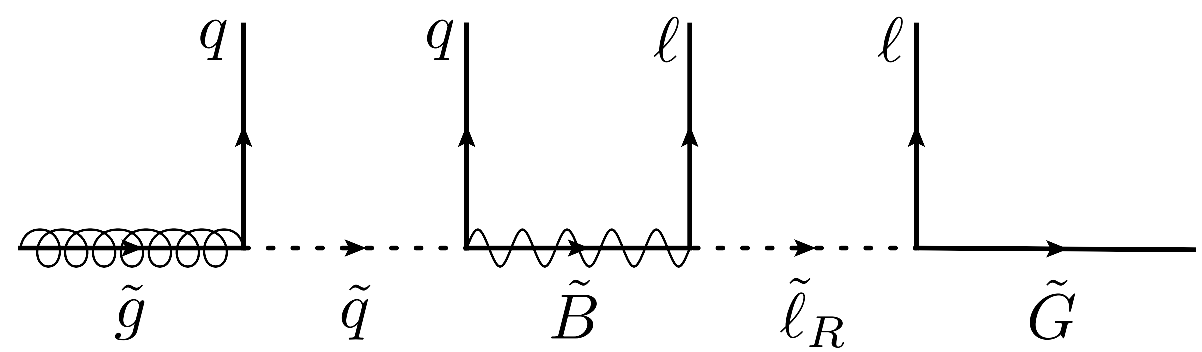
- Minimal LHC spectrum for slepton co-NLSP:



Example #3: Slepton co-NLSPs

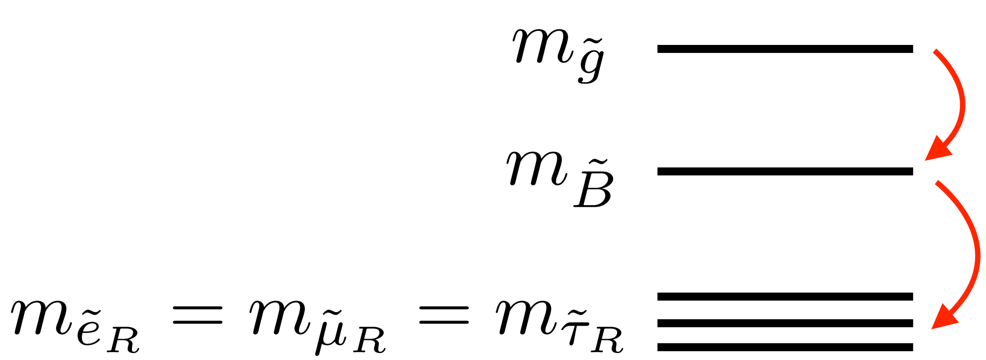
- Minimal LHC spectrum for slepton co-NLSP:

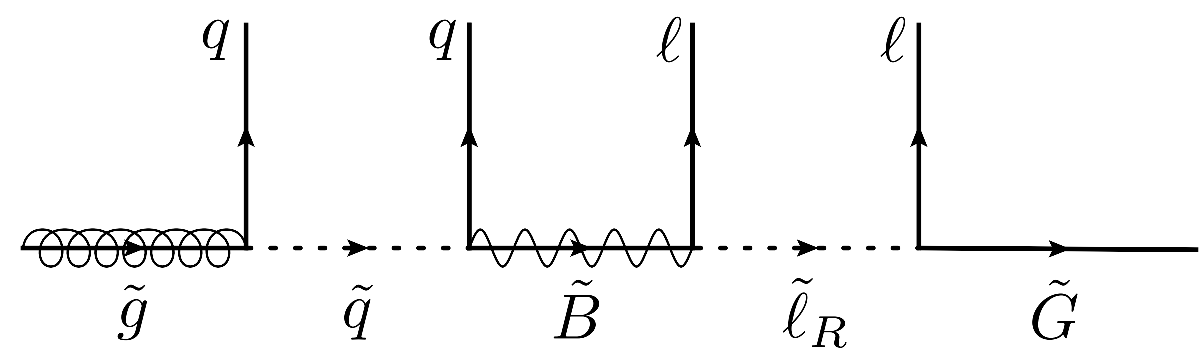




Example #3: Slepton co-NLSPs

- Minimal LHC spectrum for slepton co-NLSP:

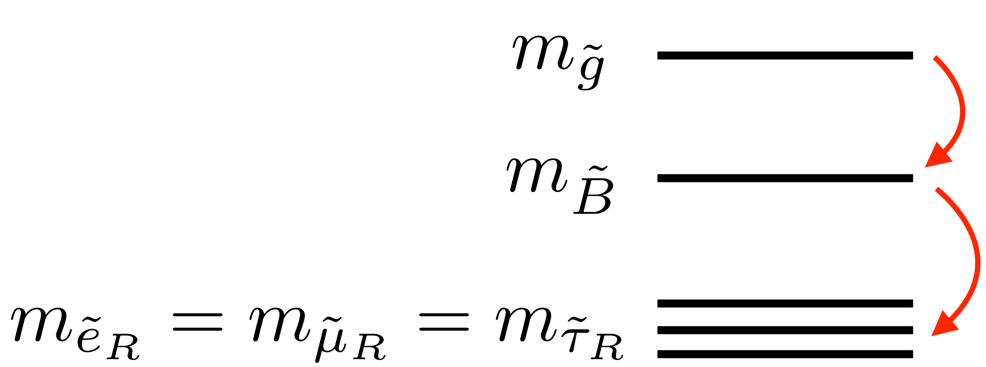


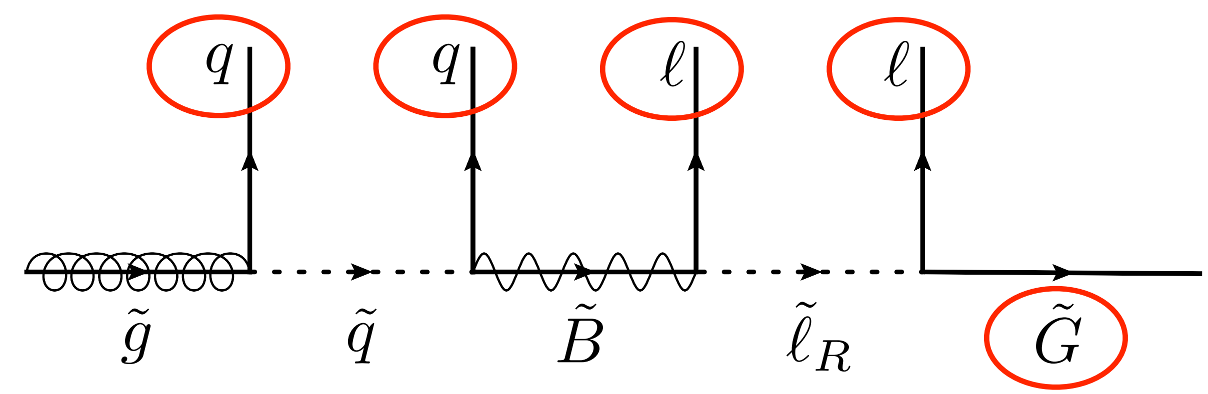


- Intermediate bino included for convenience -- otherwise gluino decays are 4-body.

Example #3: Slepton co-NLSPs

- Minimal LHC spectrum for slepton co-NLSP:

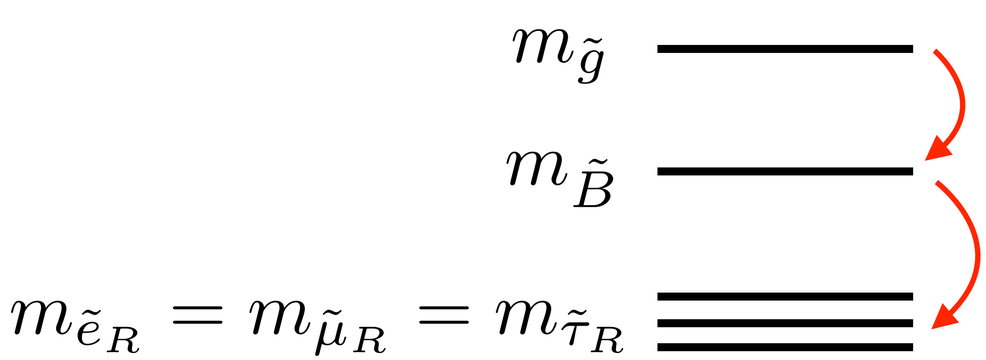


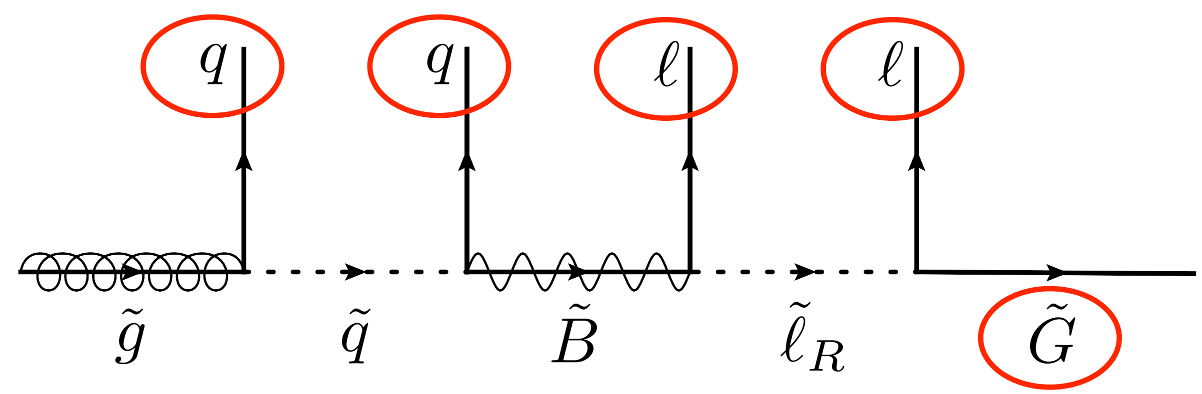


- Intermediate bino included for convenience -- otherwise gluino decays are 4-body.
- Signatures: up to 4 leptons + jets + MET

Example #3:
Slepton co-NLSPs

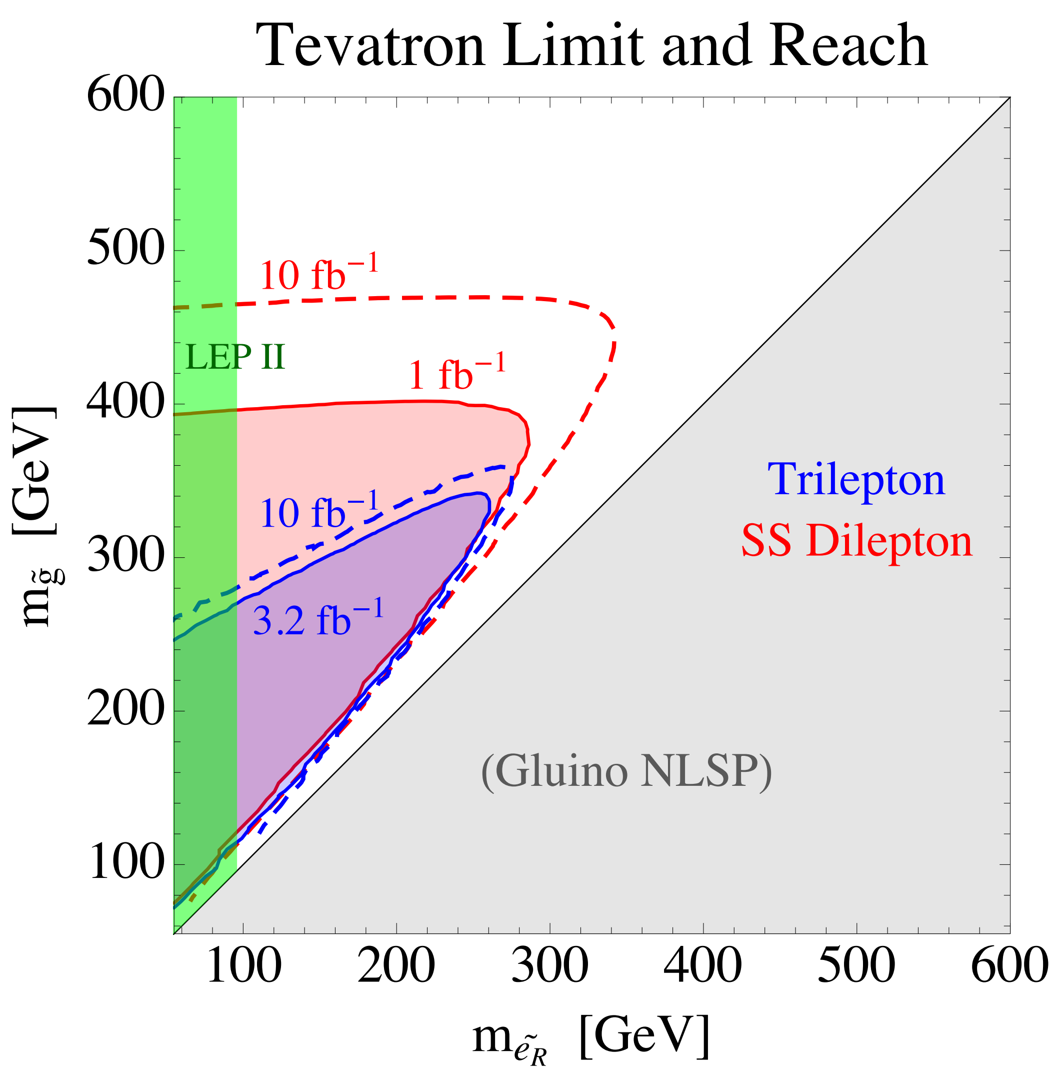
- Minimal LHC spectrum for slepton co-NLSP:

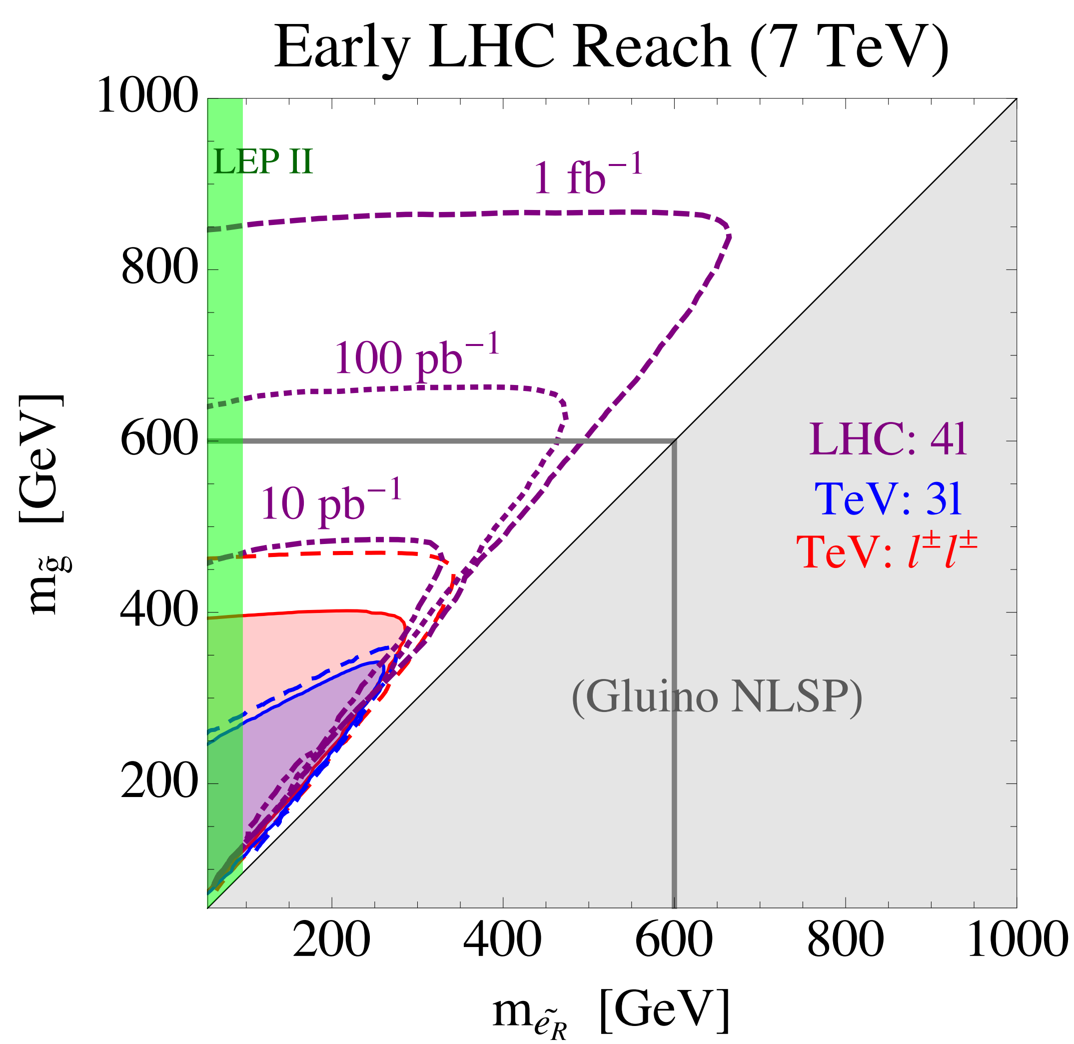




- Intermediate bino included for convenience -- otherwise gluino decays are 4-body.
- Signatures: up to 4 leptons + jets + MET
- Tevatron constraints from: trileptons+MET and SS dileptons +MET.

Example #3: Slepton co-NLSPs





Here we fix

$$m_{\tilde{B}} = \frac{1}{2}(m_{\tilde{g}} + m_{\tilde{l}_R})$$

Conclusions

- We are in the process of formulating minimal parameter spaces for each NLSP type in GGM.
- These will characterize all the relevant signatures for early discovery of GMSB.
- These can serve as minimally-biased, model-independent benchmarks for early LHC searches. We hope that experimentalists will find them useful.
- If we are to discover or rule out GMSB at the LHC, we must move beyond MGM!
- Early LHC has excellent reach for colored production; should surpass Tevatron with only ~10-100/pb!