Lecture 3

Collider Phenomenology

on

Supersymmetry

Outline

1. Motivations.
2. A few supersymmetry breaking scenarios, associated phenomena and current experiment limits.
3. Connection with Cosmology (next lecture).

Motivations for Supersymmetry

- Provide an elegant solution to hierarchy problem
- Gauge coupling unification
- Dynamical electroweak symmetry breaking
- Provide a natural dark matter candidate

Gauge Hierarchy Problem

Two known scales in particle physics:

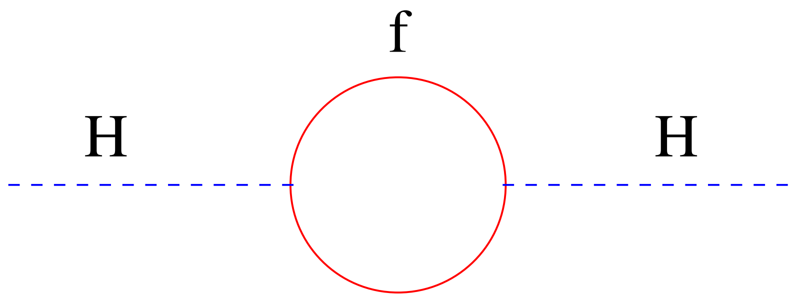
- Weak scale $M_{\rm W} \sim 100$ GeV,
- Planck scale $M_{\rm Pl} \sim 10^{19}$ GeV.

$$\frac{M_{\rm Pl}}{M_{\rm W}} \sim 10^{17}$$

A very large disturbing sensitivity to the Higgs potential.

Mass Protection

- Fermion mass protected by chiral symmetry.
- Gauge boson mass protected by gauge symmetry.
- Scalar boson mass ??

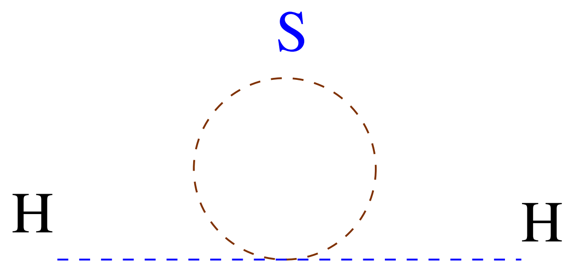


$$\Delta M_H^2 = \frac{|\lambda_f|^2}{16\pi^2}\left[-2\Lambda_{UV}^2 + 6m_f^2 \ln\left(\frac{\Lambda_{UV}}{m_f}\right) + ...\right]$$

Two choices:

1. Make Λ_{UV} not too large, where some new physics appears.
2. Find some cancellation mechanism to remove Λ_{UV}^2 divergence

Suppose there exists a new scalar



$$\Delta M_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{UV}^2 - 2m_S^2 \ln\left(\frac{\Lambda_{UV}}{m_S}\right) + \ldots\right]$$

The leading term in Λ_{UV} will cancel if

$$\lambda_S = |\lambda_f|^2 \quad \text{and if there are 2 such scalars}$$

Such systematic cancellation requires a new symmetry

$\Rightarrow$ Supersymmetry.

$$Q|\text{boson}\rangle = |\text{fermion}\rangle \quad Q|\text{fermion}\rangle = |\text{boson}\rangle$$

Cancellation OK if SUSY partner mass splitting $\sim M_W$

Minimal Supersymmetric Standard model (MSSM)

Standard Model		Supersymmetrize	
$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\Longleftrightarrow$	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$	squarks
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\Longleftrightarrow$	$\begin{pmatrix} \tilde{\nu}_L \\ \tilde{l}_L \end{pmatrix}$	sleptons
$u^c, \ d^c, \ e^c$	$\Longleftrightarrow$	$\tilde{u}^c, \ \tilde{d}^c, \ \tilde{e}^c$	
$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$	$\Longleftrightarrow$	$\begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}$	higgsinos
$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$	$\Longleftrightarrow$	$\begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{pmatrix}$	
g	$\Longleftrightarrow$	$\tilde{g}$	gluino
$W^\pm, \ W^0$	$\Longleftrightarrow$	$\tilde{W}^\pm, \ \tilde{W}^0$	winos
B	$\Longleftrightarrow$	$\tilde{B}$	bino

• Neutral higgsinos, winos, and bino mix to form mass eigenstates:

$$\tilde{H}_u^0,\ \tilde{H}_d^0,\ \tilde{W}^0,\ \tilde{B}\ \Longrightarrow \text{neutralinos}\ \ \tilde{\chi}_1^0,\ \tilde{\chi}_2^0,\ \tilde{\chi}_3^0,\ \tilde{\chi}_4^0$$

• Charged higgsinos and winos mix to form mass eigenstates:

$$\tilde{H}_u^+,\ \tilde{H}_d^-,\ \tilde{W}^\pm,\ \Longrightarrow \text{charginos}\ \ \tilde{\chi}_1^\pm,\ \tilde{\chi}_2^\pm$$

• The left-handed squark and right-handed squark mix to form mass eigenstates, especially the stop, sbottom, and stau

$$\text{e.g.}\quad \tilde{b}_L,\ \tilde{b}_R \Longrightarrow \tilde{b}_1,\ \tilde{b}_2$$

Soft supersymmetry breaking

$$\mathcal{L} = \mathcal{L}_{susy}$$

- Based on the underlying gauge symmetries and supersymmetry.
- So far supersymmetry is not broken. SM particles and SUSY partners are both massless.
- Gluon, W, Z bosons are massless and so are the gluino, wino, bino before SUSY breaking.

Soft supersymmetry breaking

$$\mathcal{L} = \mathcal{L}_{susy} + \mathcal{L}_{\rm soft-susy-break}$$

- Based on the underlying gauge symmetries and supersymmetry.
- So far supersymmetry is not broken. SM particles and SUSY partners are both massless. It is broken by $\mathcal{L}_{\rm soft-susy-break}$.
- Gluon, W, Z bosons are massless and so are the gluino, wino, bino before SUSY breaking.

Soft supersymmetry breaking

$$\mathcal{L} = \mathcal{L}_{susy} + \mathcal{L}_{\rm soft-susy-break}$$

- Based on the underlying gauge symmetries and supersymmetry.
- So far supersymmetry is not broken. SM particles and SUSY partners are both massless. It is broken by $\mathcal{L}_{\rm soft-susy-break}$.
- Gluon, W, Z bosons are massless and so are the gluino, wino, bino before SUSY breaking.

$$\mathcal{L}_{\rm soft} = -\frac{1}{2}(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B}) + c.c. \quad \text{gaugino mass}$$

give masses to the gluino, wino, bino. Thus, break SUSY.

Soft supersymmetry breaking

$$\mathcal{L} = \mathcal{L}_{susy} + \mathcal{L}_{\text{soft}-\text{susy}-\text{break}}$$

- Based on the underlying gauge symmetries and supersymmetry.
- So far supersymmetry is not broken. SM particles and SUSY partners are both massless. It is broken by $\mathcal{L}_{\text{soft}-\text{susy}-\text{break}}$.
- Gluon, W, Z bosons are massless and so are the gluino, wino, bino before SUSY breaking.

$$\mathcal{L}_{\text{soft}} = -\frac{1}{2}(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B}) + c.c. \quad \text{gaugino mass}$$

give masses to the gluino, wino, bino. Thus, break SUSY.

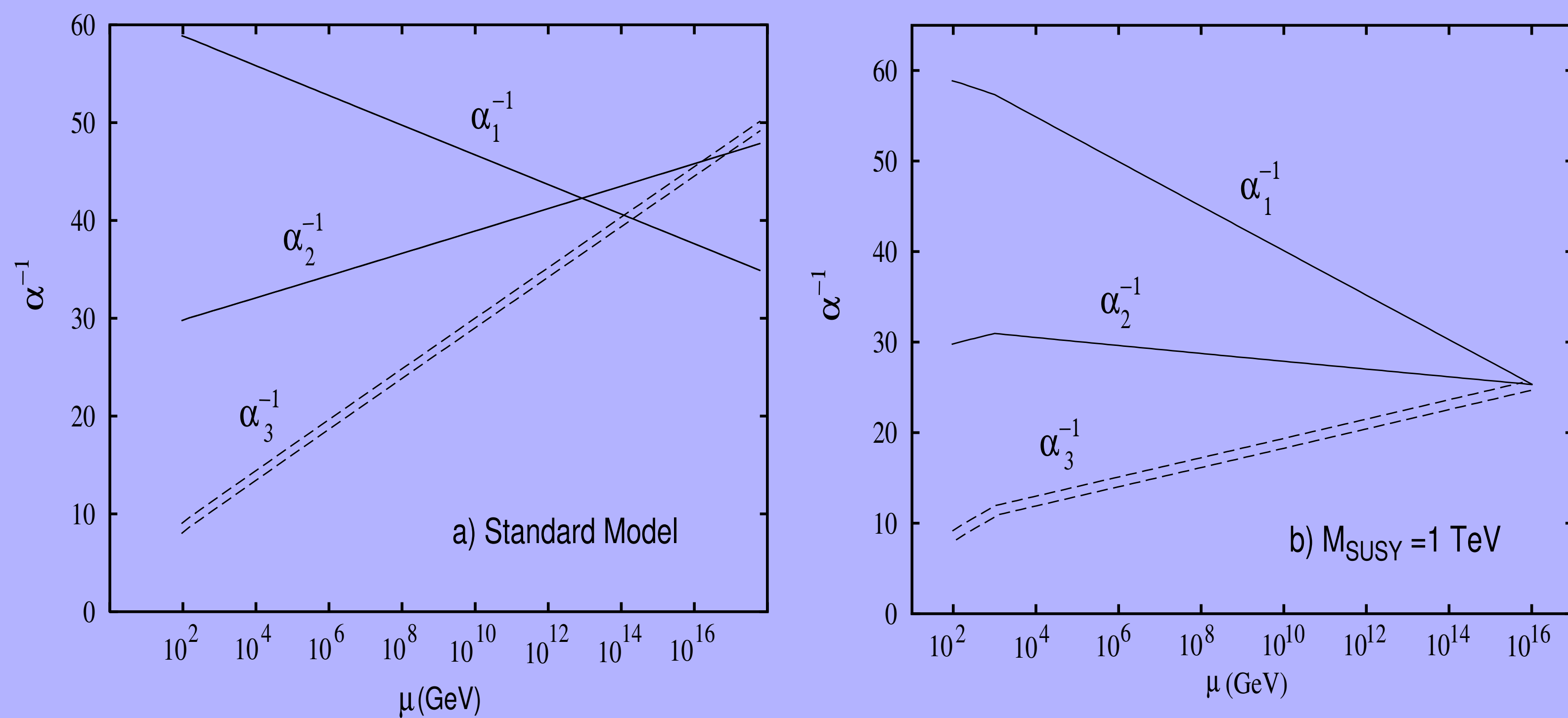
- Similarly,

$$\mathcal{L}_{\text{soft}} = -\tilde{Q}^\dagger M_Q^2 \tilde{Q} - \tilde{L}^\dagger M_L^2 \tilde{L} - \ldots \quad \text{scalar mass}$$

give masses to the scalar quarks and scalar leptons.

Gauge Coupling Unification

$$\frac{dg_i}{dt} = \frac{g_i}{16\pi^2}\left[b_i g_i^2 + \frac{1}{16\pi^2}\left(\sum_{j=1}^{3} b_{ij} g_i^2 g_j^2 - \sum_{j=1}^{3} a_{ij} g_i^2 \lambda_j^2\right)\right]$$



Ellis, Kelly, Nanopoulos; Amaldi, de Hoer, Furstenau; Langacker, Luo (1991).

Dynamical Electroweak Symmetry Breaking

(Chamseddine, Arnowitt and Nath; Gaume, Polchinski, and Wise; Ellis, Nanopoulos, Tamvakis (1982–1983))

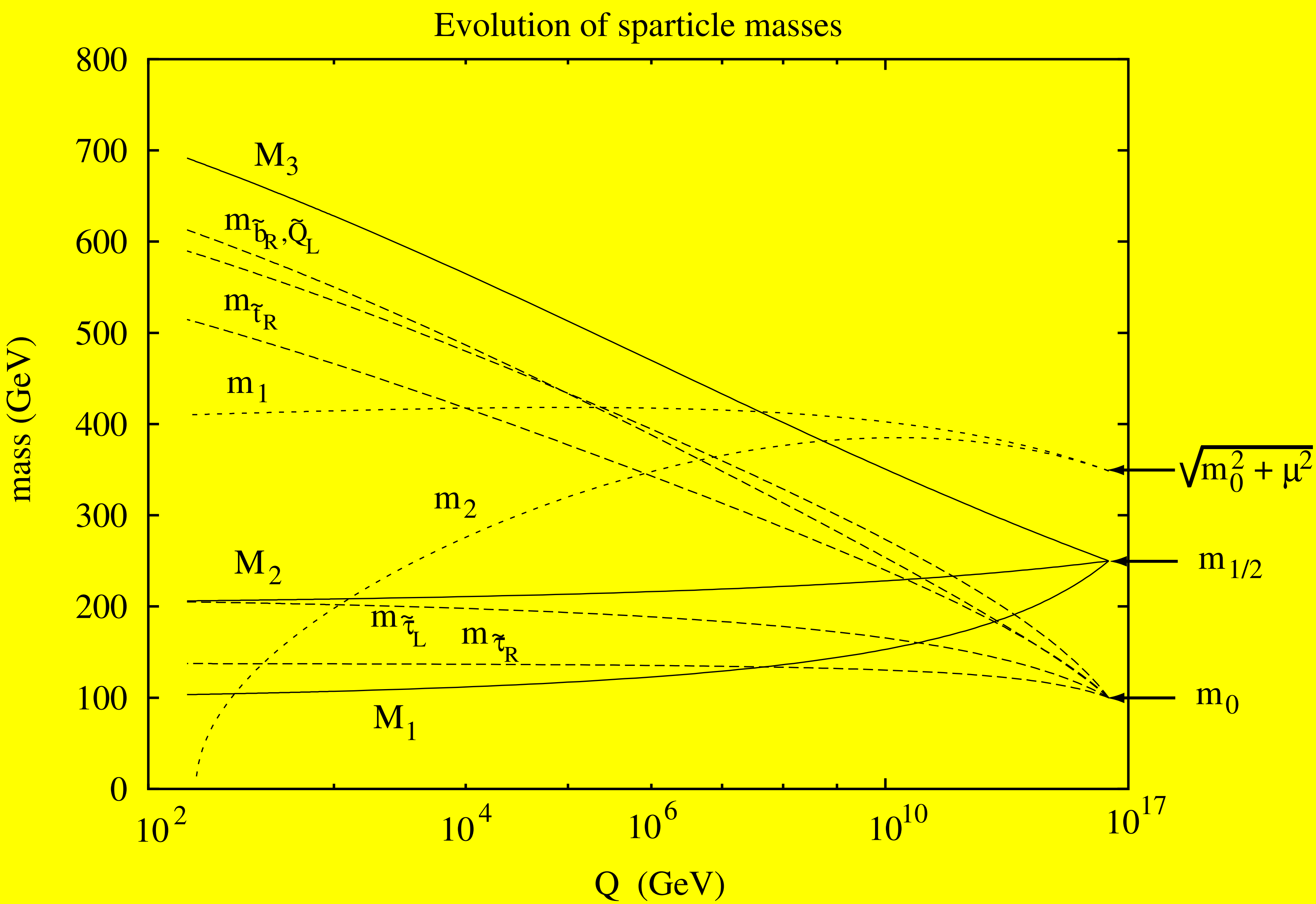
The Higgs potential

$$\begin{aligned} V_H &= (M_{H_u}^2 + \mu^2)|H_u|^2 + (M_{H_d}^2 + \mu^2)|H_d|^2 + B(\epsilon_{ij} H_d^i H_u^j + h.c.) \\ &+ \frac{1}{8}(g^2 + g'^2)\left[|H_u|^2 - |H_d|^2\right]^2 + \frac{1}{2} g^2 |H_d^{i*} H_u^i|^2 \end{aligned}$$

EWSB occurs when one of the $(M_{H_u}^2 + \mu^2), (M_{H_d}^2 + \mu^2)$ becomes negative.

$M_{H_u}^2$ can run to a negative value by the top Yukawa coupling.

$$\frac{dM_{H_u}^2}{dt} = \frac{1}{8\pi^2}\left(-\frac{3}{5} g_1^2 M_1^2 - 3 g_2^2 M_2^2 + 3\lambda_t^2 (M_{Q_L}^2 + M_{t_R}^2 + M_{H_u}^2 + A_t^2)\right)$$


Evolution of sparticle masses
mass (GeV)
800
700
600
500
400
300
200
100
0
10^2
10^4
10^6
10^{10}
10^{17}
Q (GeV)
M_3
$m_{\tilde{b}_R,\tilde{Q}_L}$
$m_{\tilde{\tau}_R}$
m_1
m_2
M_2
$m_{\tilde{\tau}_L}$
$m_{\tilde{\tau}_R}$
M_1
$\sqrt{m_0^2+\mu^2}$
$m_{1/2}$
m_0

The lightest SUSY particle (LSP)

is a **Dark Matter** candidate.

Imposing the R-parity conservation

- $R = 1$ for the SM particles
- $R = -1$ for SUSY particles

SUSY particles must be pair produced. E.g.

$$p\, p \;\rightarrow\; q\, \bar{q}\, \tilde{g}\, \tilde{g}$$

The LSP is stable:

$$\tilde{\chi}_1^0 \not\rightarrow \text{SM particles}$$

LSP remains since freeze-out in the early universe

Some problems of SUSY

- Too many soft parameters, more than 100.
- μ problem
- Proton decay operators
- Too many sources for FCNC and CP violation

No SUSY Particles (NSP) Found So Far

Various SUSY scenarios

and

Associated Phenomenology

Gravity mediated SUSY breaking

Arnowitt, Chamseddine, Nath

SUSY breaking theory origin is in the hidden sector, and the SUSY breaking effect is transmitted by a mediation sector.

Historically, the most popular one is the gravity. Gravitation, suppressed by $M_{\rm Pl}$ couples the hidden sector to the visible. By dimension:

$$M_{\rm soft} \sim \frac{\langle F \rangle}{M_{\rm Pl}}$$

Naturalness requires $M_{\rm soft} \sim O(0.1-1)$ TeV, implying

$$\sqrt{\langle F \rangle} \sim 10^{11-12}\ {\rm GeV}$$

Gravitino mass is $\sim F/M_{\rm Pl}$.

Supergravity Lagrangian

The hidden sector fields couple to the visible sector via gravity interactions. In the effective Lagrangian, it contains nonrenormalizable terms:

$$\begin{aligned}\mathcal{L}_{\rm sugra} &= -\frac{F_X}{M_{\rm Pl}} \sum \frac{1}{2} f_a \lambda^a \lambda^a + c.c. - \frac{F_X F_X^*}{M_{\rm Pl}^2} k^i_j \phi_i \phi^{*j} \\ & \quad -\frac{F_X}{M_{\rm Pl}} \left(\frac{\alpha^{ijk}}{6} \phi_i \phi_j \phi_k + \frac{\beta^{ij}}{2} \phi_i \phi_j \right) + c.c.\end{aligned}$$

where F_X is the auxillary field of a chiral superfield X in the hidden sector.

When F_X develops a VEV, SUSY is broken in the hidden sector and thus communicates to the visible sector. It develops

- gaugino masses: $M_a = f_a \langle F_X \rangle / M_{\rm Pl}$
- sfermion masses: $(M^2)^i_j = k^i_j \langle F_X \rangle^2 / M^2_{\rm Pl}$
- Trilinear terms: $A^{ijk} = \alpha^{ijk} \langle F_X \rangle / M_{\rm Pl}$
- B term: $B_{ij} = \beta^{ij} \langle F_X \rangle / M_{\rm Pl}$

It is not obvious they are flavor-blind.

Minimal Supergravity (mSUGRA)

Arnowitt, Chamseddine, Nath

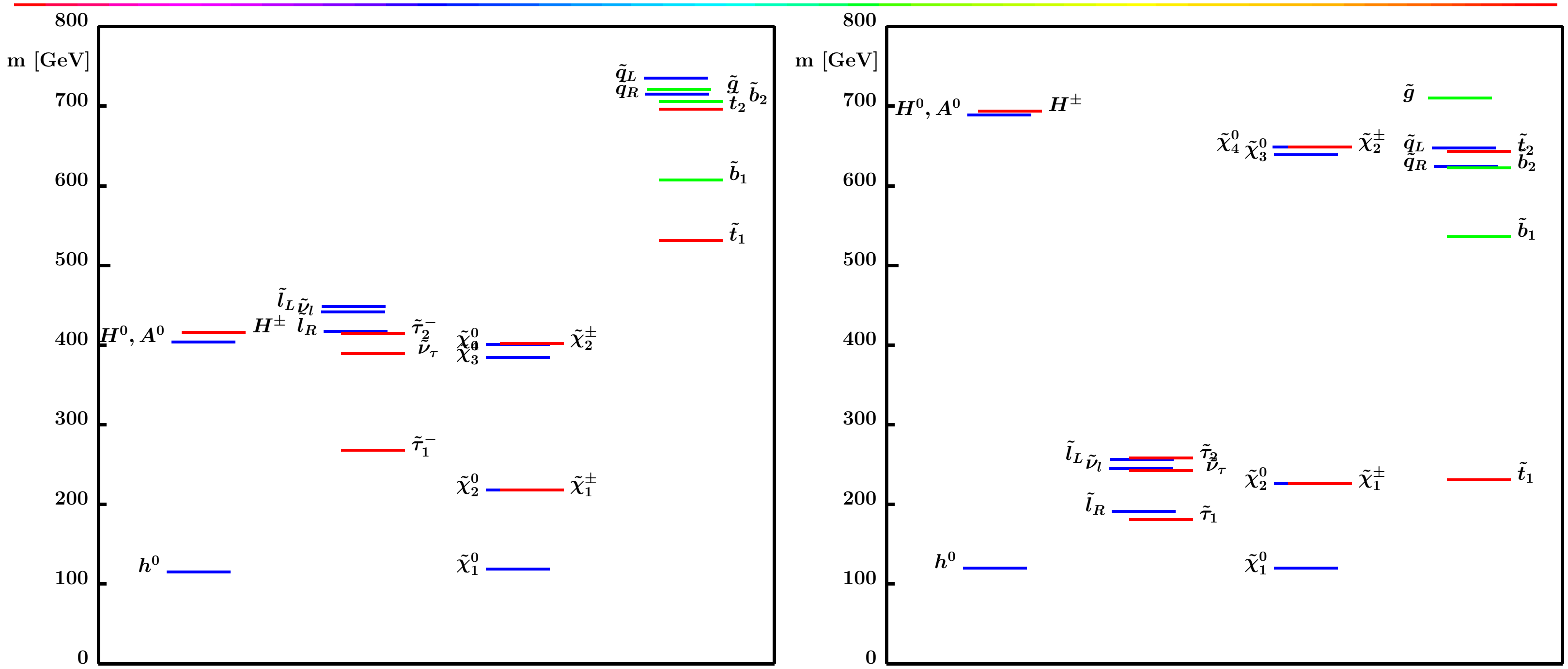
One solution to flavor problem is to adopt universal boundary conditions.
The soft parameters are defined by 5 parameters only:

$$
\begin{aligned}
M_0 &: \quad \text{universal scalar mass} \\
M_{1/2} &: \quad \text{universal gaugino mass} \\
A_0 &: \quad \text{universal } A \text{ term} \\
\tan\beta \equiv v_u/v_d &: \quad \text{ratio of VEV of the Higgs fields} \\
\text{sign}(\mu) &: \quad \text{sign of the } \mu \text{ parameter}
\end{aligned}
$$

The LSP is usually the lightest neutralino (the combination of bino, neutral wino and higgsinos). It is the dark matter candidate.

Only 5 parameters $\Rightarrow$ very predictive. But somehow quite restrictive now by the WMAP data. Relaxing the universality can relieve the suitable parameter space.

mSUGRA Spectrum



SPS 4 SPS 5

SPS4: mSUGRA: $m_0 = 400$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 0$, $\tan\beta = 50$, $\mu > 0$.

SPS5: mSUGRA: $m_0 = 150$ GeV, $m_{1/2} = 300$ GeV, $A_0 = -1000$, $\tan\beta = 5$, $\mu > 0$.

Collider Phenomenology of SUGRA

The neutral LSP will not leave any tracks in the detector, ie, it gives to missing energies.

Smoking gun signatures:

1. Multi-leptons plus $\not{E}_T$

$$pp \to \widetilde{\chi}_1^+ \widetilde{\chi}_1^- \to \ell^+ \ell^- \nu \bar{\nu} \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$$

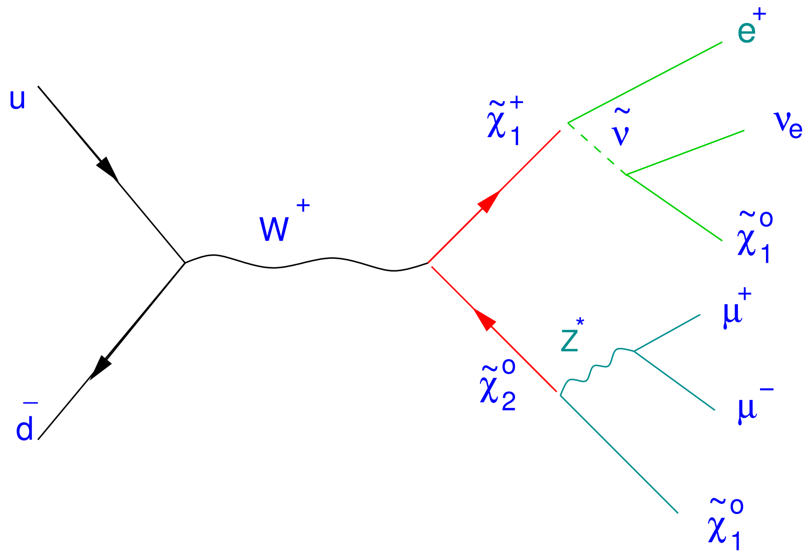
$$pp \to \widetilde{\chi}_1^\pm \widetilde{\chi}_2^0 \to \ell^\pm \ell^+ \ell^- \nu \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$$

2. Multi-lepton multi-jets plus $\not{E}_T$

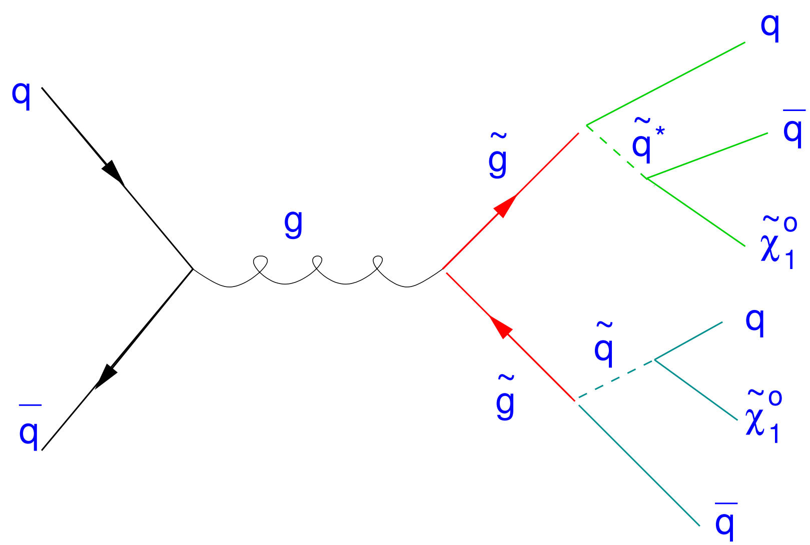
$$pp \to \tilde{g}\tilde{g},\ \tilde{q}\tilde{q}^*,\ \tilde{g}\tilde{q}$$

   Gluino is majorana that can decay into leptons of either charges $\Rightarrow$ same-sign dilepton + $\not{E}_T$ signal.

3. Gluino can decay into $b\tilde{b}_1^* \to b\bar{b}\widetilde{\chi}_1^0 \Rightarrow 4b+ \not{E}_T$ signal.



Tri-lepton + $\not{E}_T$ signal



Multi-jet + $\not{E}_T$

CDF search for gluino decays $\tilde{g} \to \tilde{b}\, b$

In the gluino pair production

$$p\bar{p} \to \tilde{g}\tilde{g} \to (\tilde{b}^* b/\tilde{b}\bar{b})\ (\tilde{b}^* b/\tilde{b}\bar{b}) \to 4b + 2\widetilde{\chi}_1^0$$

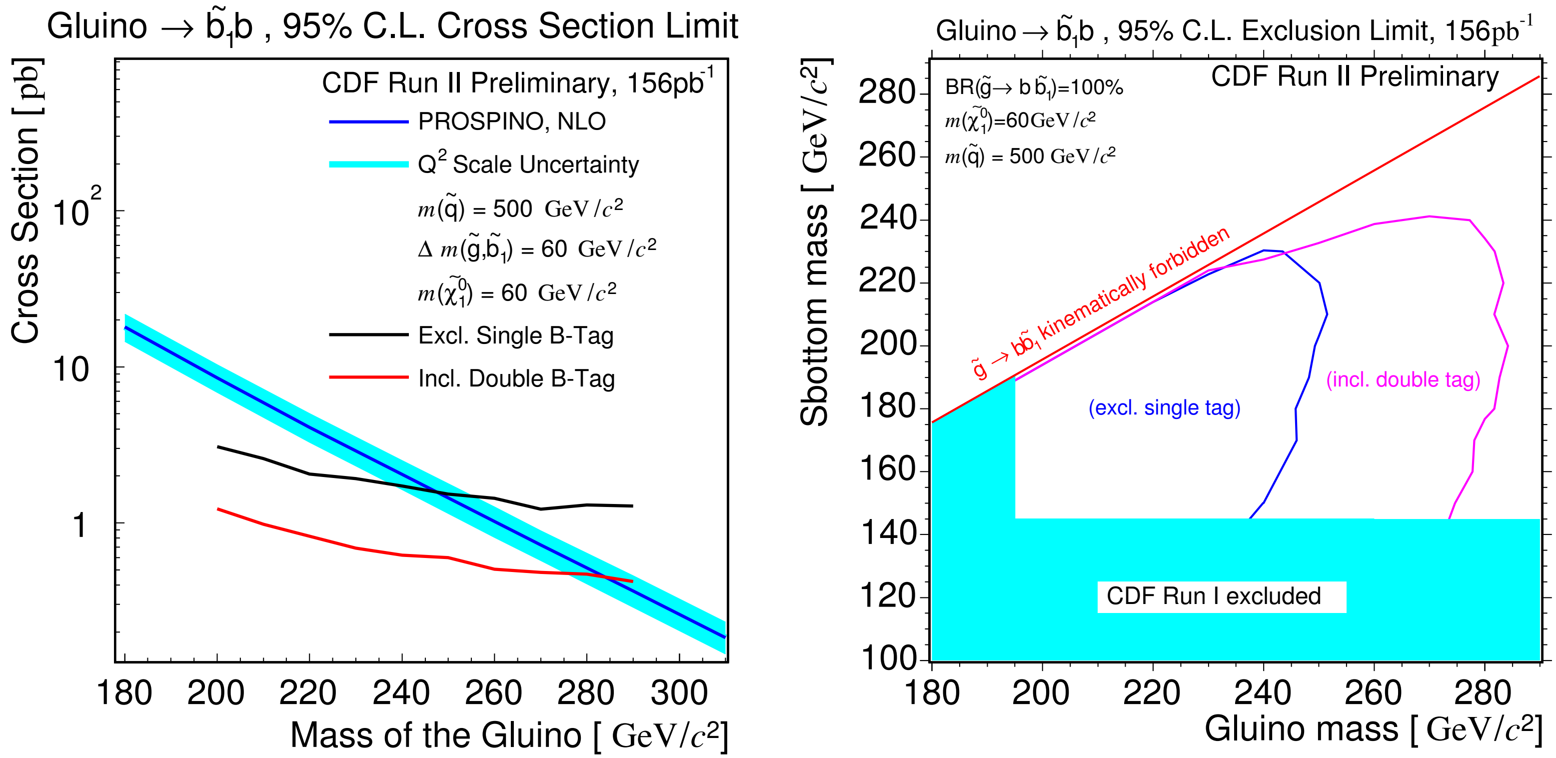
The signal is defined by a $\not{E}_T > 80$ GeV plus b tags.

Process	Exclusive Single B-Tag	Inclusive Double B-Tag
EWK	$5.66 \pm 0.76(stat) \pm 1.72(sys)$	$0.61 \pm 0.21(stat) \pm 0.19(sys)$
TOP	$6.18 \pm 0.12(stat) \pm 1.42(sys)$	$1.84 \pm 0.06(stat) \pm 0.46(sys)$
QCD	$4.57 \pm 1.64(stat) \pm 0.57(sys)$	$0.18 \pm 0.08(stat) \pm 0.05(sys)$
Total Predicted	$16.41 \pm 1.81(stat) \pm 3.15(sys)$	$2.63 \pm 0.23(stat) \pm 0.66(sys)$
Observed	21	4

Table 24: Number of expected and observed events in signal region.

Thus, no evidence for gluino pair production with squential decay into sbottom-bottom is observed.

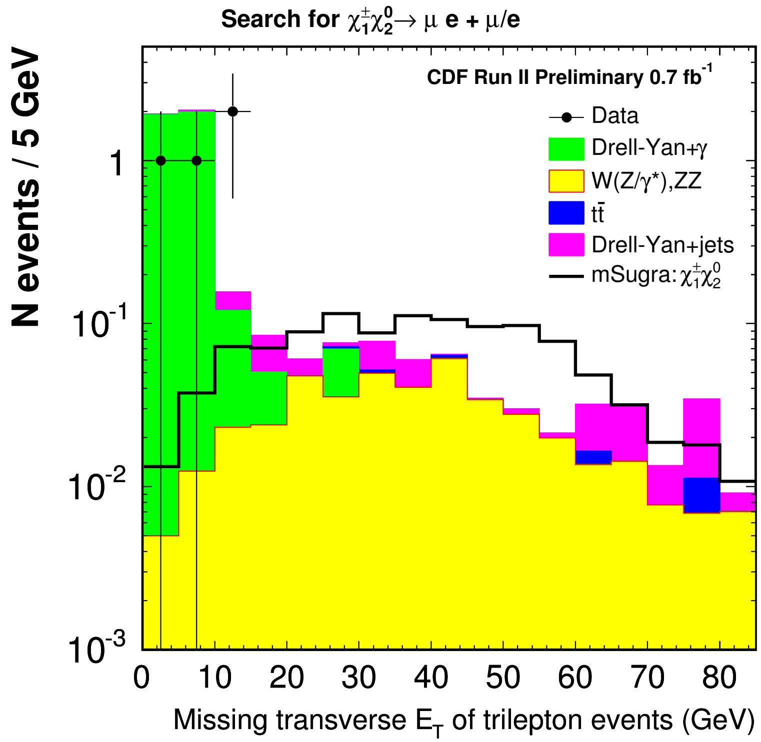
Gluino-sbottom 95% exclusion



CDF Tri-lepton search for chargino-neutralino production

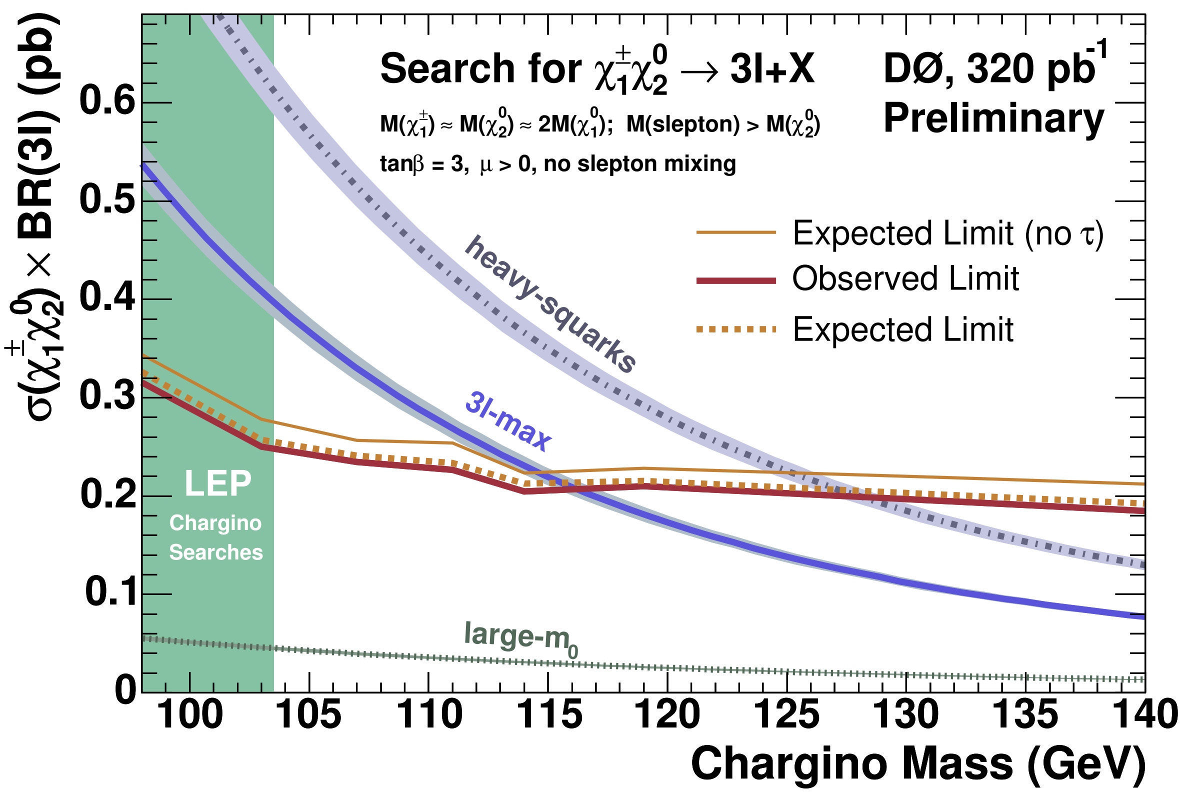
Tri-lepton signal comes from the associated chargino-neutralino production

$$p\bar{p} \to \widetilde{\chi}_1^{\pm} \widetilde{\chi}_2^0 \to \ell^+ \ell^- \ell \nu \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$$



With $\mathcal{L} = 745$ pb^{-1} the $\mu + \ell\ell$ final state only found one event, consistent with the SM background of 0.64 event.

DØ Tri-lepton search for chargino-neutralino production (325 pb^{-1})



Heavy squarks: no negative interference in the production. 3ℓ-max: leptonic BR is enhanced maximally for $m_{\tilde{\ell}} \gtrsim m_{\tilde{\chi}_2^0}$. Large m_0: gives small leptonic BR.

LEP 2 limits

At LEP2 $e^- e^+$ collider, it can produce many sparticle pairs:

$$e^- e^+ \to \tilde{\ell}^+ \tilde{\ell}^-, \; \widetilde{\chi}_1^+ \widetilde{\chi}_1^-, \; \widetilde{\chi}_1^0 \widetilde{\chi}_2^0, \; \widetilde{\chi}_2^0 \widetilde{\chi}_2^0, \; \tilde{q} \tilde{q}^*$$

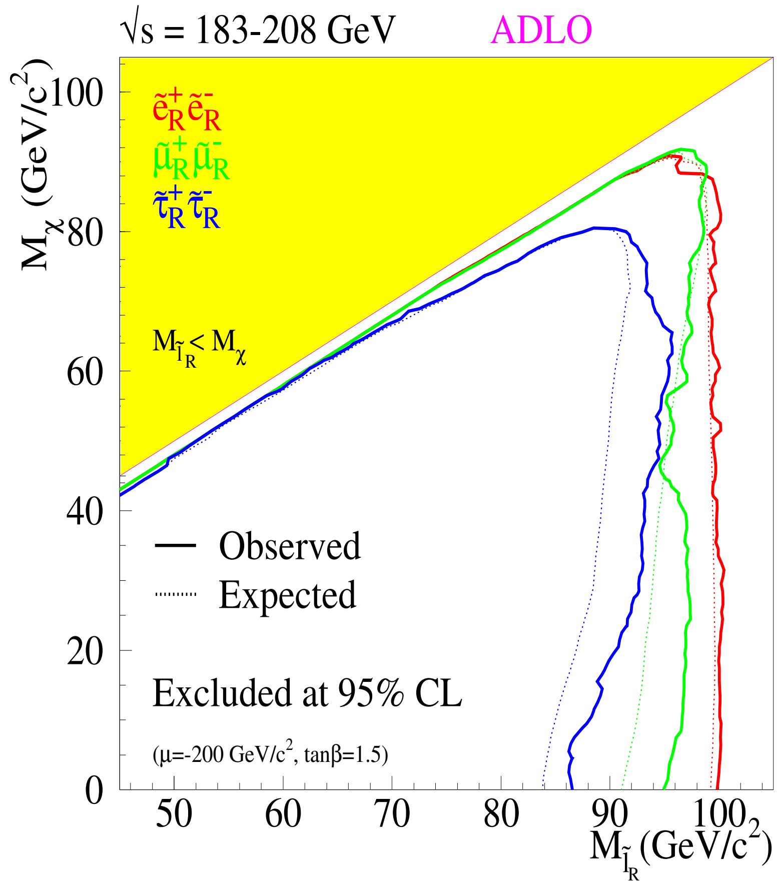
There are limits on slepton masses, chargino masses, as they can readily produced at LEP if they exist. The exclusion is almost up to half of the $\sqrt{s}$ if the mass difference from the LSP is large enough.

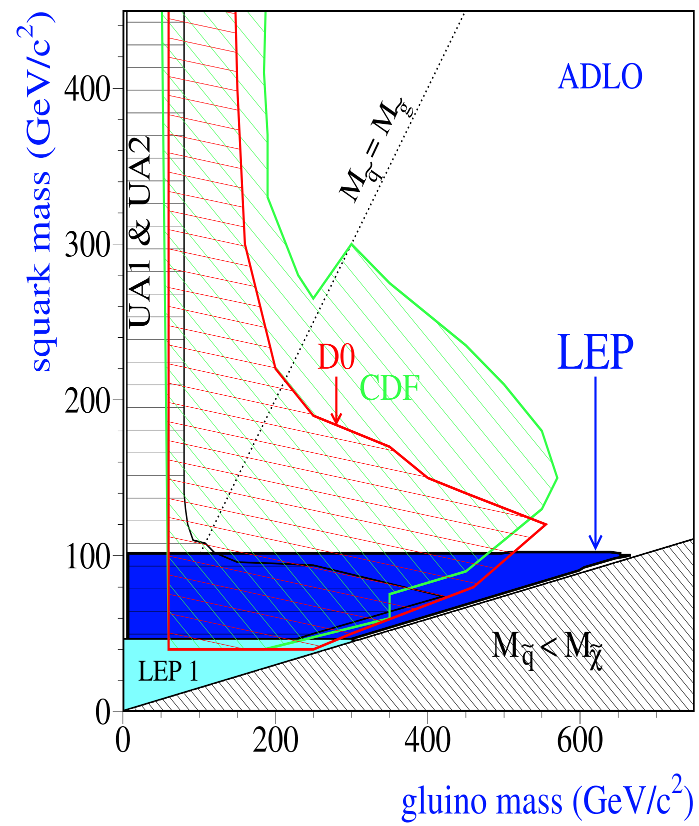
Another constraint comes from SM Higgs mass bound:

$$m_h > 114.4 \text{ GeV}$$

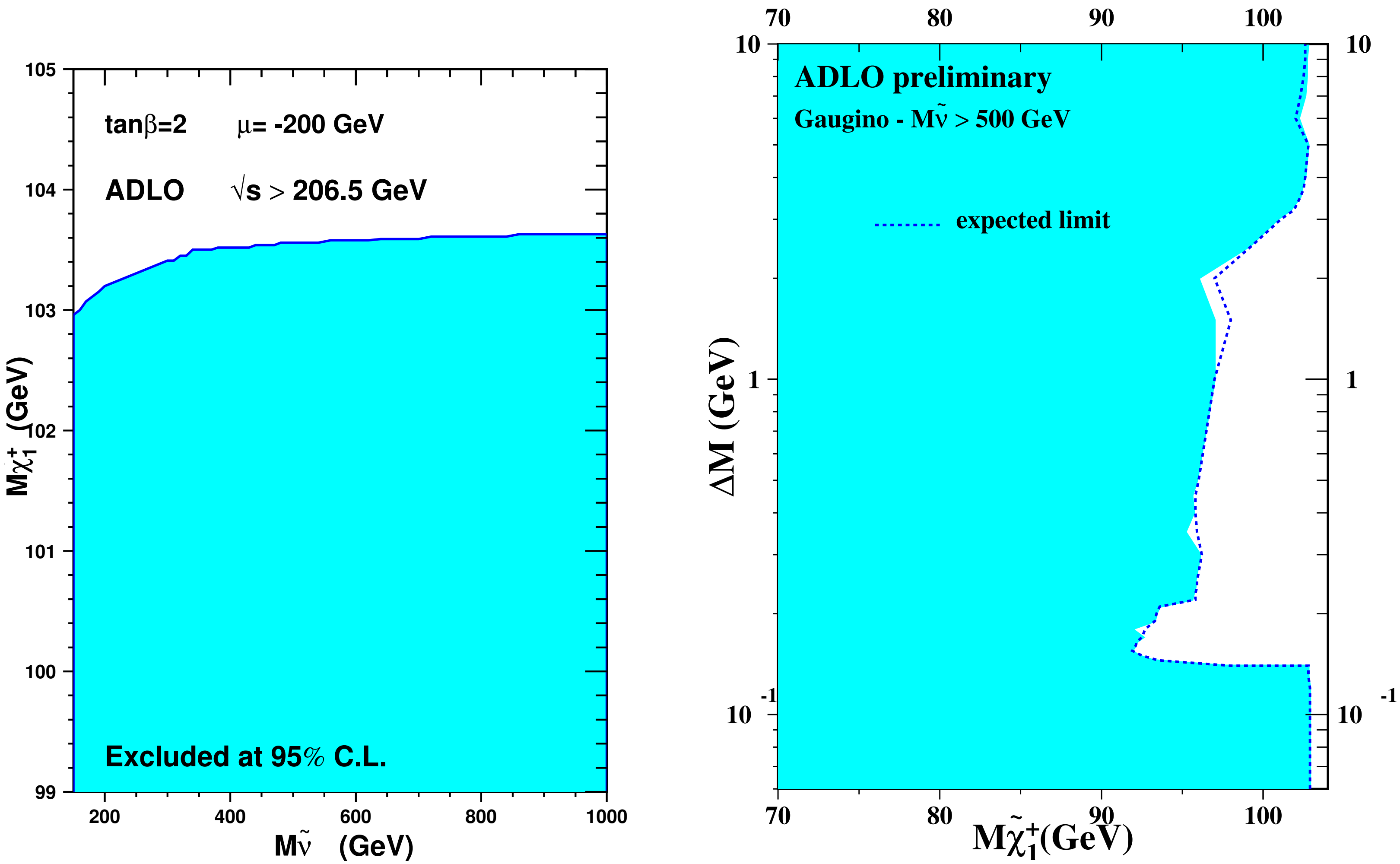
Most of the SUSY parameter space yields a SM-like Higgs boson, therefore the Higgs mass bound is applicable.

LEP2 slepton and squark mass limits





LEP2 chargino mass limits



Gauge mediated SUSY breaking

Dine, Nelson, Shirman; Dimopoulos, Dine, Raby, Thomas

This is a very simple idea to use the gauge interactions to communicate the SUSY breaking from the hidden sector to the visible sector. It is flavor-blind. It could just be the $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetry.

Typical soft masses are of order

$$M_{\rm soft} \sim \frac{\alpha}{4\pi} \frac{\langle F_X \rangle}{M_{\rm mess}}$$

where F_X is the auxillary field of a chiral superfield in the hidden sector, $M_{\rm mess}$ is the mass scale of the messenger sector.

Both $\langle F_X \rangle$ and $M_{\rm mess}$ can be as low as 10 TeV.

The gravition mass $M_{3/2} \sim \langle F_X \rangle / M_{\rm Pl} \ll M_{\rm soft}$ can be as low as sub-eV.

A minimal GMSB model

Suppose the messenger sector contains q, q^c, ℓ, ℓ^c that transform under $SU(3) \times SU(2)_L \times U(1)_Y$ as

$$q \sim (\mathbf{3}, \mathbf{1}, -1/3), \quad q^c \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/3), \quad \ell \sim (\mathbf{1}, \mathbf{2}, 1/2), \quad \ell^c \sim (\mathbf{1}, \mathbf{2}, -1/2)$$

which contain the fermionic and scalar parts. They couple to a gauge singlet chiral superfield of the hidden sector

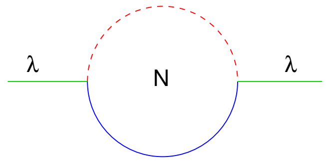
$$W_{\rm mess} = y_2 S \ell \ell^c + y_3 S q q^c$$

Suppose F_S develops a VEV by some dynamical SUSY breaking mechanisms, and we assume the scalar part of S develops a VEV too: $\langle S \rangle$.

The effect of SUSY breaking is then transmitted to the messenger sector:

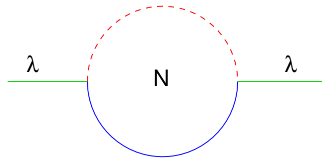
$$\begin{array}{lcll} \ell, \ell^c & : & M^2_{\rm ferm} = |y_2 \langle S \rangle|^2, & M^2_{\rm scal} = |y_2 \langle S \rangle|^2 \pm |y_2 \langle F_S \rangle| \\ q, q^c & : & M^2_{\rm ferm} = |y_3 \langle S \rangle|^2, & M^2_{\rm scal} = |y_3 \langle S \rangle|^2 \pm |y_3 \langle F_S \rangle| \end{array}$$

The SUSY breaking is then transmitted to MSSM gauginos via 1 loop diagram:



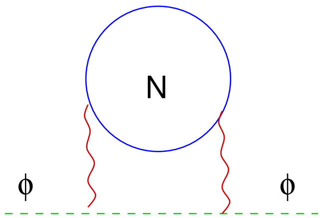
$$M_a(M_{\text{mess}}) = \frac{\alpha_a}{4\pi}\Lambda \quad \text{where} \quad \Lambda = \frac{\langle F_S \rangle}{\langle S \rangle}$$

The SUSY breaking is then transmitted to MSSM gauginos via 1 loop diagram:



$$M_a(M_{\rm mess}) = \frac{\alpha_a}{4\pi}\Lambda \;\; \text{where} \;\; \Lambda = \frac{\langle F_S \rangle}{\langle S \rangle}$$

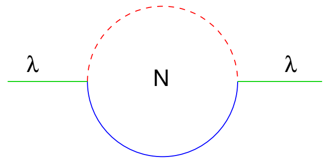
MSSM scalars receive mass from 2 loop diagrams:



$$M_i^2(M_{\rm mess}) = 2\Lambda^2 \left[\left(\frac{\alpha_3}{4\pi}\right)^2 C_3^i + \left(\frac{\alpha_2}{4\pi}\right)^2 C_2^i + \frac{3}{5}\left(\frac{\alpha_1}{4\pi}\right)^2 C_1^i \right]$$

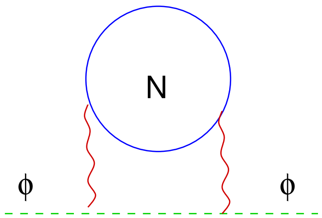
where $C_{3,2,1} = 0$ for gauge singlets, and otherwise $C_{3,2,1} = 4/3, 3/4, (Y/2)^2$ for fundamental representation of $SU(3)$, $SU(2)_L$, $U(1)_Y$, respectively.

The SUSY breaking is then transmitted to MSSM gauginos via 1 loop diagram:



$$M_a(M_{\rm mess}) = \frac{\alpha_a}{4\pi}\Lambda \quad \text{where} \quad \Lambda = \frac{\langle F_S \rangle}{\langle S \rangle}$$

MSSM scalars receive mass from 2 loop diagrams:



$$M_i^2(M_{\rm mess}) = 2\Lambda^2 \left[\left(\frac{\alpha_3}{4\pi}\right)^2 C_3^i + \left(\frac{\alpha_2}{4\pi}\right)^2 C_2^i + \frac{3}{5}\left(\frac{\alpha_1}{4\pi}\right)^2 C_1^i \right]$$

where $C_{3,2,1} = 0$ for gauge singlets, and otherwise $C_{3,2,1} = 4/3, 3/4, (Y/2)^2$ for fundamental representation of $SU(3)$, $SU(2)_L$, $U(1)_Y$, respectively. The minimal messenger sector can be generalized to N copies, then

$$\begin{aligned} M_a(M_{\rm mess}) &= N\,\frac{\alpha_a}{4\pi}\Lambda \\ M_i^2(M_{\rm mess}) &= 2N\,\Lambda^2 \left[\left(\frac{\alpha_3}{4\pi}\right)^2 C_3^i + \left(\frac{\alpha_2}{4\pi}\right)^2 C_2^i + \frac{3}{5}\left(\frac{\alpha_1}{4\pi}\right)^2 C_1^i \right] \end{aligned}$$

Phenomenology

- Trilinear terms are further suppressed by $\alpha_a/4\pi$ relative to gaugino mass.

Phenomenology

- Trilinear terms are further suppressed by $\alpha_a/4\pi$ relative to gaugino mass.
- The LSP is always the gravitino (sub-eV).

Phenomenology

- Trilinear terms are further suppressed by $\alpha_a/4\pi$ relative to gaugino mass.
- The LSP is always the gravitino (sub-eV).
- Gaugino and scalars have comparable mass

$$M_a, M_i \sim \frac{\alpha_a}{4\pi}\Lambda$$

Phenomenology

- Trilinear terms are further suppressed by $\alpha_a/4\pi$ relative to gaugino mass.
- The LSP is always the gravitino (sub-eV).
- Gaugino and scalars have comparable mass

$$M_a\,,\, M_i \sim \frac{\alpha_a}{4\pi}\Lambda$$

- Note that the gaugino mass increases as N, but scalar mass increases as $\sqrt{N}$. For $N=1$ bino is the NLSP while for $N\geq 2$ the stau is the NLSP.

Phenomenology

- Trilinear terms are further suppressed by $\alpha_a/4\pi$ relative to gaugino mass.
- The LSP is always the gravitino (sub-eV).
- Gaugino and scalars have comparable mass

$$M_a\,,\,M_i \sim \frac{\alpha_a}{4\pi}\Lambda$$

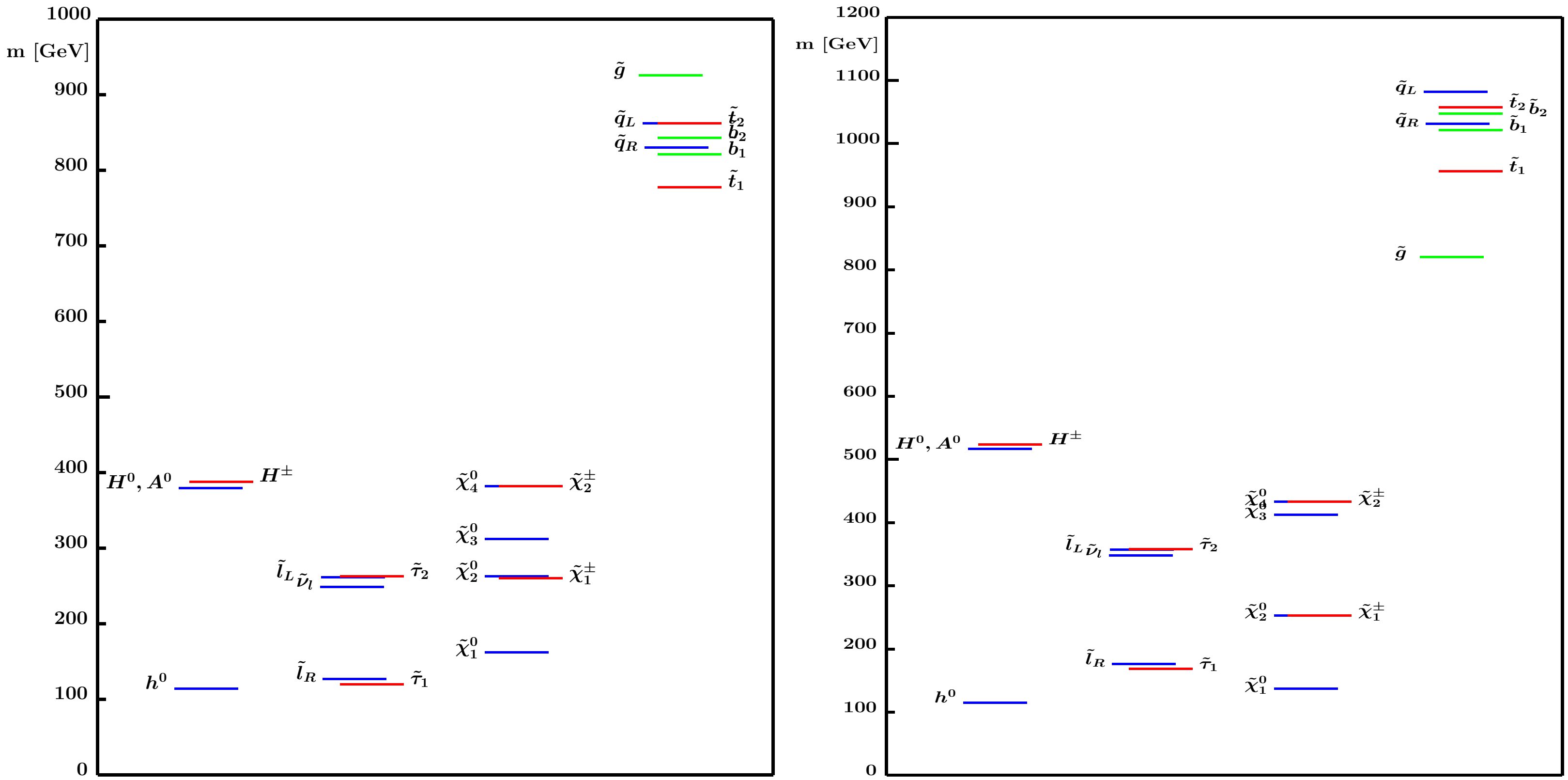
- Note that the gaugino mass increases as N, but scalar mass increases as $\sqrt{N}$. For $N=1$ bino is the NLSP while for $N \geq 2$ the stau is the NLSP.
- Collider signature depends on which is the NLSP:

$$\widetilde{\chi}^0_1 \to \widetilde{G} + (\gamma, Z, h)\,, \qquad \tilde{\tau} \to \widetilde{G} + \tau$$

One is the multi-photon while another is multi-tau-lepton in the final state.
Typical decay length if the NLSP is

$$L \simeq (10 \text{ km})\,\langle \beta\gamma \rangle \left(\frac{\sqrt{F}}{10^7\,\text{GeV}} \right)^4 \left(\frac{100\,\text{GeV}}{M_{\text{NLSP}}} \right)^5$$

Typical GMSB spectrum

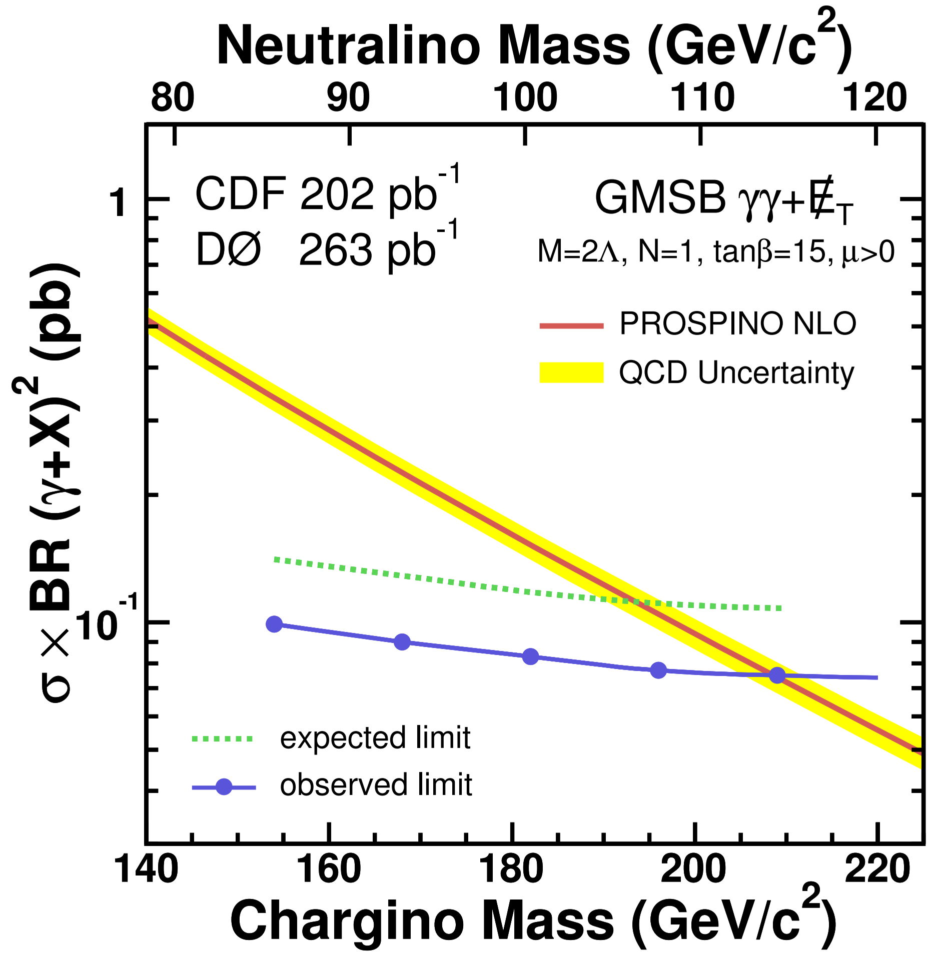


SPS 7 SPS 8

SPS7: GMSB with $\tilde{\tau}$ NLSP: $\Lambda = 40$ TeV, $M_{\rm mess} = 80$ TeV, $N = 3$, $\tan\beta = 15$, $\mu > 0$.

SPS8: GMSB with $\widetilde{\chi}_1^0$ NLSP: $\Lambda = 100$ TeV, $M_{\rm mess} = 200$ TeV, $N = 1$, $\tan\beta = 15$, $\mu > 0$.

Combined CDF and DØ limit on GMSB diphoton plus $\not\!\!E_T$ events



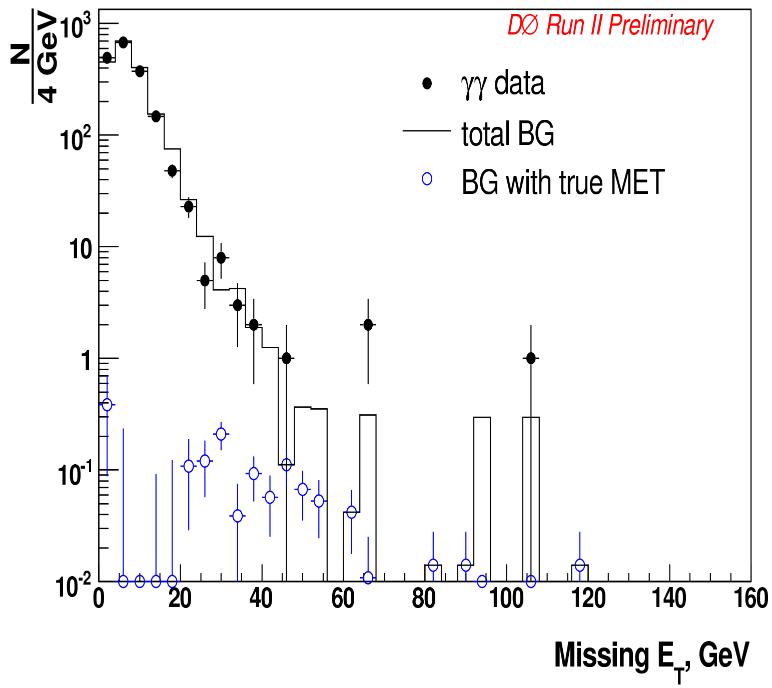
DØ Search for GMSB diphoton plus $\not\!\!E_T$ events

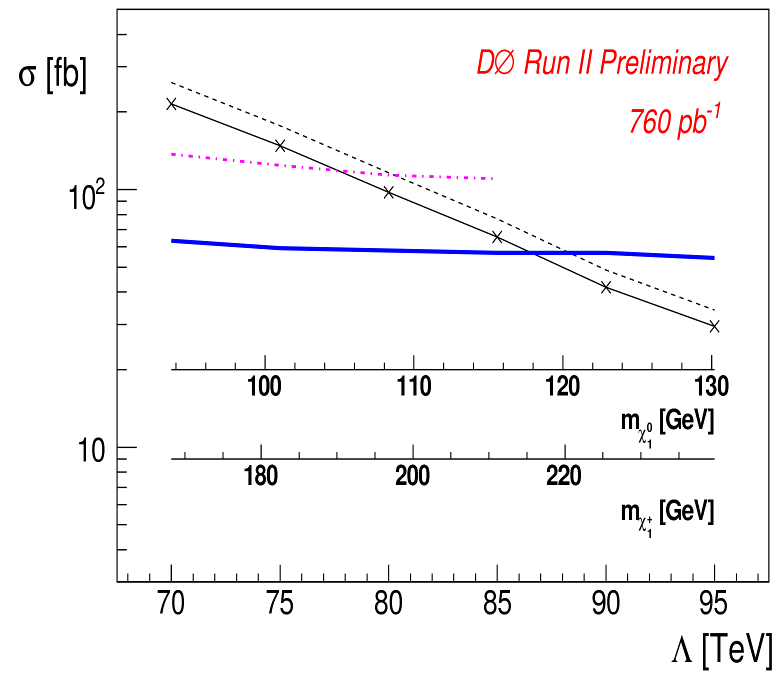
Using 760 pb^{-1} data, search for events with 2γ

$$E_T > 25 \text{ GeV} \;\; \text{and} \;\; |\eta| < 1.1 \qquad \not\!\!E_T > 45 \text{ GeV}$$

4 events with an estimated background of 2.1 ± 0.7 events.

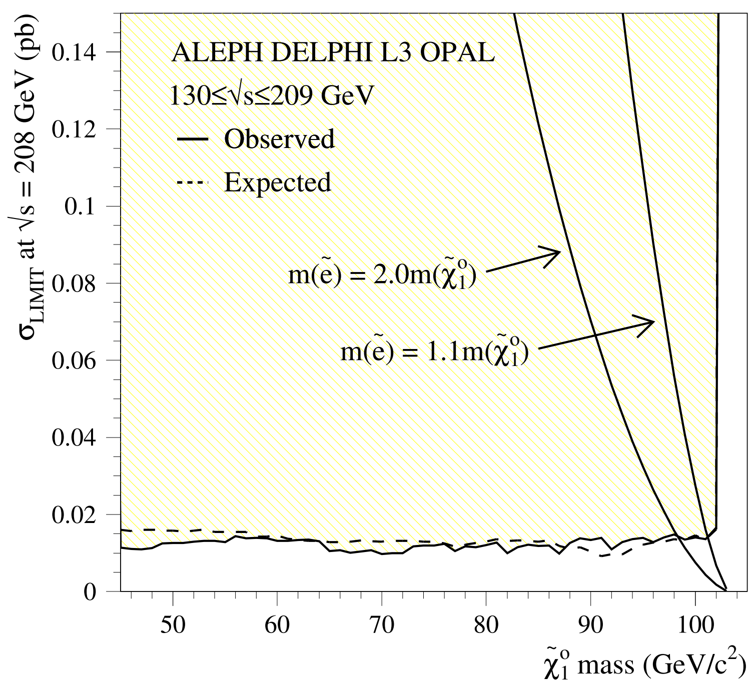
DØ GMSB limit using 760 pb^{-1}

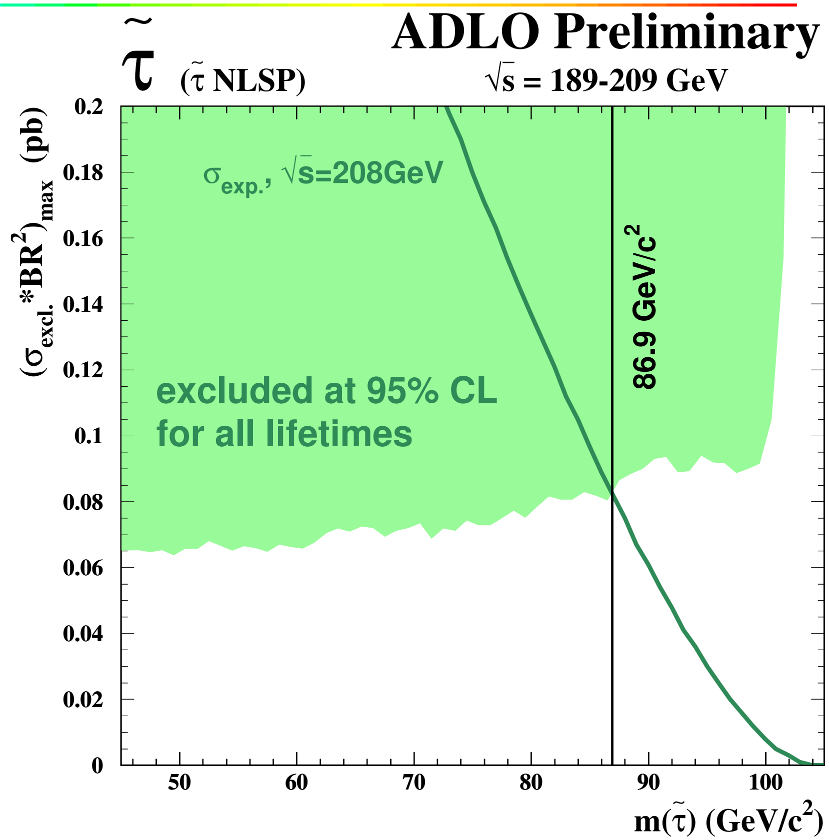




Expected limit on chargino mass > 215 GeV.

LEP2 GMSB limits





Search using acoplanar diphoton plus $\not{E}_T$, and di-taus plus $\not{E}_T$.

Anomaly mediated SUSY breaking

Randall, Sundrum; Giudice, Luty, Murayama, Rattazzi

In 4D, gravity mediation between hidden and visible sectors is always present. In extra dimensions, one can separate the two sectors geometrically. The hidden and visible sectors on separate branes. Only the gravity in the bulk communicate in between. Almost all SUSY breaking effects are suppressed.

The conformal anomaly generates loop-suppressed soft SUSY breaking. These contributions are always present. Gauginos and scalars acquire

$$M_a = \frac{\beta_a}{g_a}\, m_{3/2}\,, \qquad (M^2)_i^j = -\frac{1}{2}\frac{d\gamma_i^j}{d(\ln Q)} m_{3/2}^2$$

where $m_{3/2}$ is the gravitino mass, $\beta_a = -b_a g_a^3$, and $b_a = (-33/5, -1, 3)$, and γ_i^j are anomalous dimensions.

The slepton masses are tachyonic.

Phenomenology

- Need some means to give positive slepton mass squared.

Phenomenology

- Need some means to give positive slepton mass squared.
- The most special feature of the model is the gaugino mass pattern. Wino is the lightest particle.

Phenomenology

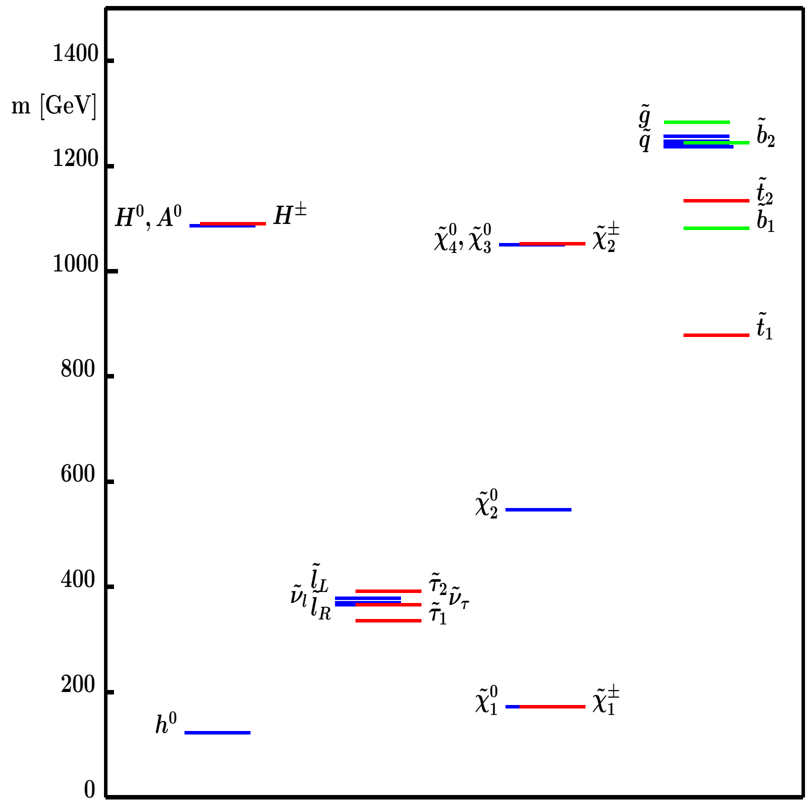
- Need some means to give positive slepton mass squared.
- The most special feature of the model is the gaugino mass pattern. Wino is the lightest particle.
- Note that the gravitino mass $m_{3/2}$ needs to be in $O(100)$ TeV in order to give acceptable gaugino masses.

Phenomenology

- Need some means to give positive slepton mass squared.
- The most special feature of the model is the gaugino mass pattern. Wino is the lightest particle.
- Note that the gravitino mass $m_{3/2}$ needs to be in $O(100)$ TeV in order to give acceptable gaugino masses.
- In this wino-LSP scenario, the charged wino forming the lightest chargino is very close in mass to the LSP:

$$\widetilde{\chi}_1^+ \rightarrow \widetilde{\chi}_1^0 + (\pi^+ \ \text{or} \ \ell^+ \nu)$$

Typical AMSB spectrum



SPS 9

SPS9: AMSB : $m_0 = 450$ GeV, $m_{3/2} = 60$ TeV, $\tan\beta = 10$, $\mu > 0$.

Chargino Decay and detection in wino-LSP scenario

The decay of $\widetilde{\chi}_1^+ \to \widetilde{\chi}_1^0 W^{+*}$ depends critically on $\Delta M \equiv M_{\widetilde{\chi}_1^+} - M_{\widetilde{\chi}_1^0}$.

- $\Delta M < m_\pi$:
The only available modes are $e^+\nu_e$ and $\mu^+\nu_\mu$. The chargino will travel 1 m or so before decay, so appears as heavily charged tracks. Background free.

- $m_\pi < \Delta M < 1$ GeV:
The most difficult region that depends on how many layers of silicon that the chargino can travel before decays, and the momentum resolution to tell the non-pointing pion.

- $1 - 2$ GeV $\lesssim \Delta M$:
The decay is prompt. If ΔM is large enough to have energetic leptons and jets, it is easy for detection. If the decay products are too soft, have to rely on other methods. E.g.

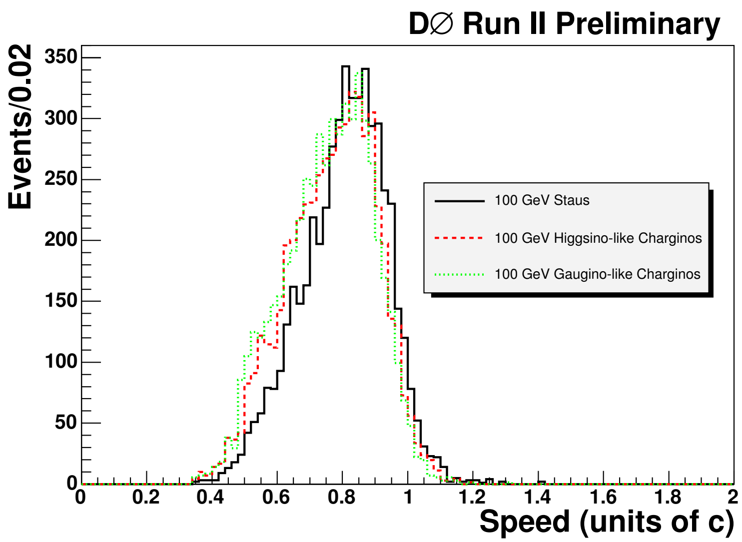
$$e^+e^- \to \widetilde{\chi}_1^+ \widetilde{\chi}_1^- \gamma$$

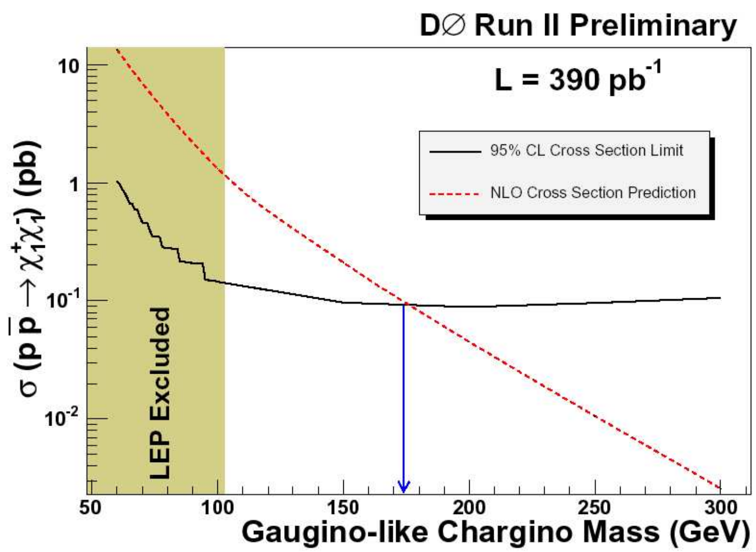
Chen, Gunion, Drees.

- $\Delta M >$ a few GeV:
charged lepton and jets are detectable.

DØ search for metastable charginos

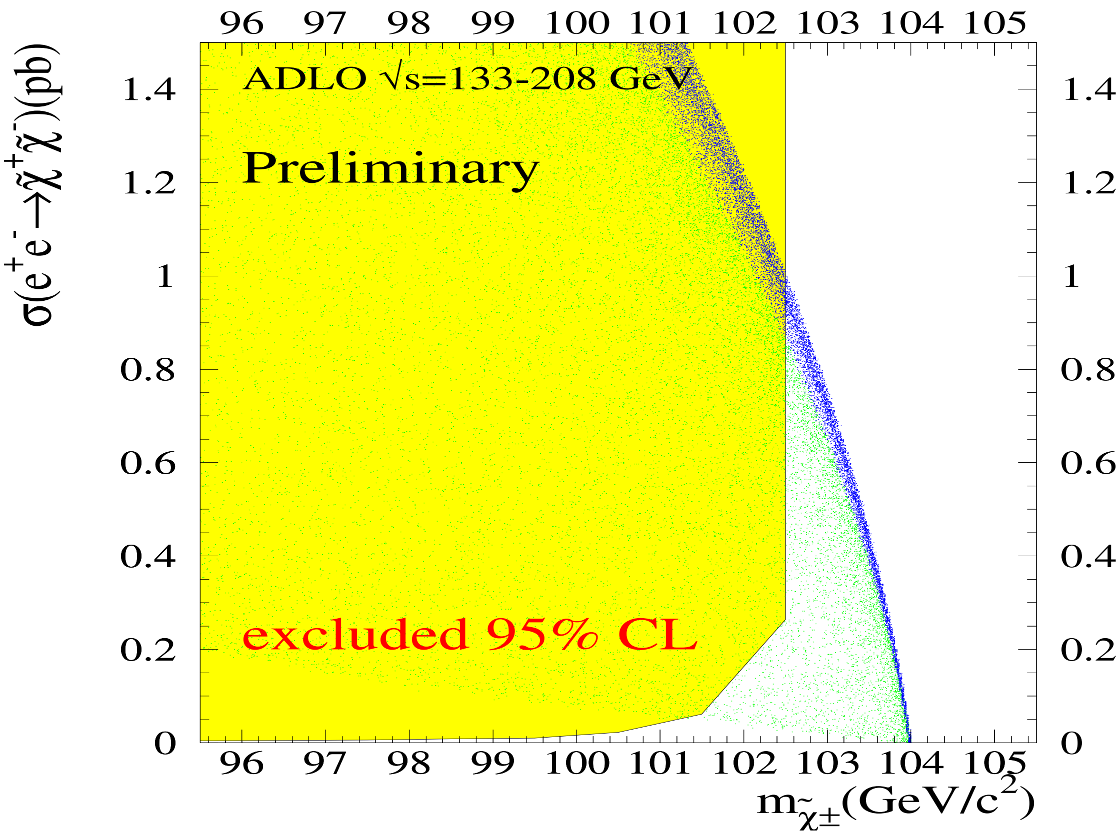
Signatures for stable charged tracks, reconstructed as “muons”, but with speed and mass inconsistent with beam-produced muons.





If $m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0} < m_\pi$, chargino may have a long decay.

LEP2 limits on stable charginos



Split Supersymmetry

(Arkani, Dimopoulos 2004)

The magic word: Landscape!!

In the vast number of vacua, there is a good chance to find some with high SUSY breaking scales.

In reality, Why Not!! These scenarios are not impossible

- All scalars are super heavy, except for a light SM-like Higgs boson

$$\tilde{m} \sim 10^{9-16}\ \text{GeV}$$

- Gauginos and Higgsinos are $O(\text{TeV})$.

Split Supersymmetry

Properties:

- Gauge coupling unification
- Light SM-like Higgs boson
- Super heavy scalars $\Rightarrow$ safe FCNC, CP-violation, EDM, but there is still one possible source
- Relatively light gauginos, Higgsinos, μ parameter

$\Rightarrow$ Dark Matter

- Stable gluino, gluinonium signature

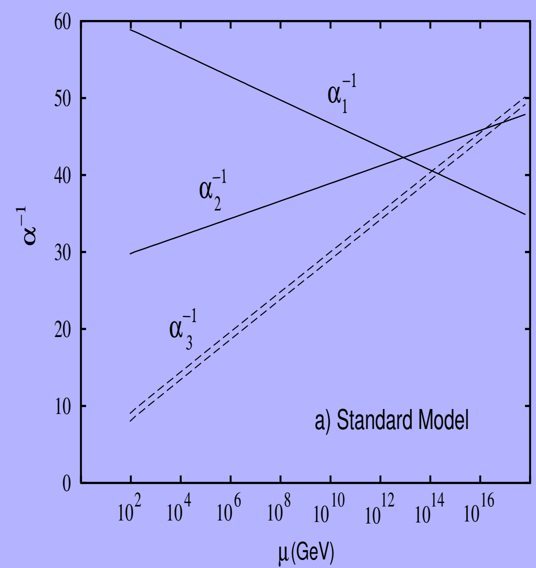
Gauge Coupling Unification

$$\frac{1}{\alpha_i(M_X^2)} = \frac{1}{\alpha_i(M_Z^2)} - \frac{\beta_i}{4\pi} \ln\left(\frac{M_X^2}{M_Z^2}\right)$$

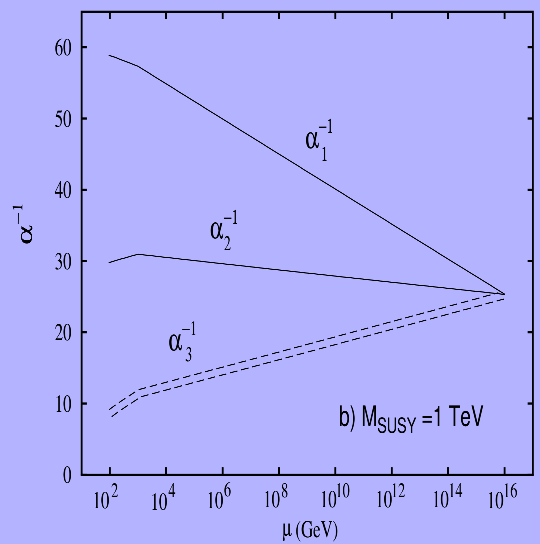
$$\begin{aligned}
SM : (\beta) &= \begin{pmatrix} 0 \\ -\frac{22}{3} \\ -11 \end{pmatrix} + \begin{pmatrix} \frac{4}{3} \\ \frac{4}{3} \\ \frac{4}{3} \end{pmatrix} F + \begin{pmatrix} \frac{1}{10} \\ \frac{1}{6} \\ 0 \end{pmatrix} N_H \\
SUSY : (\beta)_{\rm SUSY} &= \begin{pmatrix} 0 \\ -6 \\ -9 \end{pmatrix} + \begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix} F + \begin{pmatrix} \frac{3}{10} \\ \frac{1}{2} \\ 0 \end{pmatrix} N_H \\
Split - SUSY : (\beta)_{\rm split}|_{<\tilde{m}} &= \begin{pmatrix} 0 \\ -6 \\ -9 \end{pmatrix} + \begin{pmatrix} \frac{4}{3} \\ \frac{4}{3} \\ \frac{4}{3} \end{pmatrix} F + \begin{pmatrix} \frac{5}{10} \\ \frac{5}{6} \\ 0 \end{pmatrix}
\end{aligned}$$

Gauge Coupling Unification

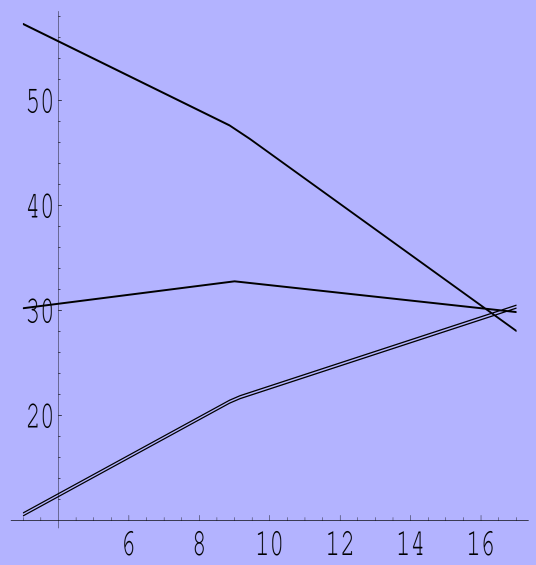
SM



Weak Scale SUSY



Split SUSY



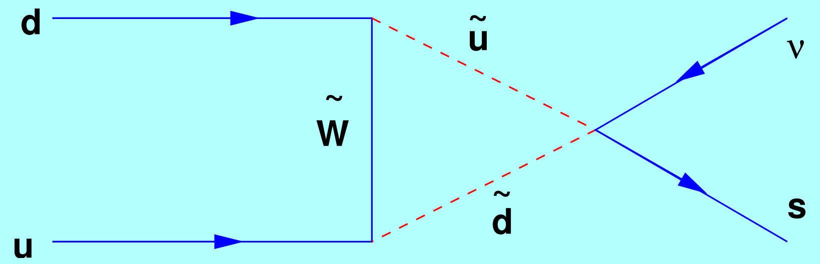
Ellis, Kelly, Nanopoulos (1991); Arkani, Dimopoulos 2004

Proton decay

Consider split SUSY with SU(5) unification.

- Dim-5 operator is highly suppressed

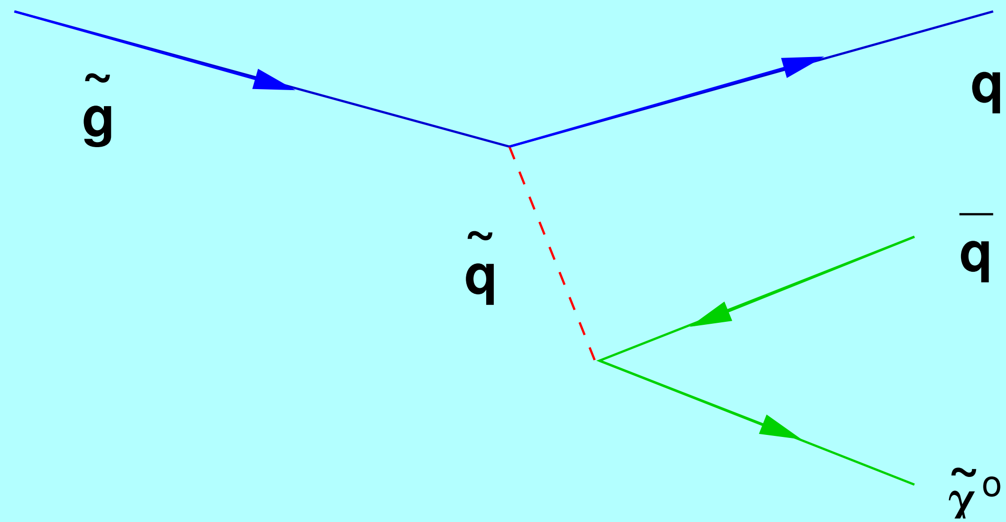
$$\mathcal{O}_5 \sim \frac{QQ\widetilde{Q}\widetilde{Q}}{M_{\rm Pl}}$$



- Dim-6 operators: $p \to e^+ \pi^0$ with exchanges of $M_{X,Y}$ bosons. Proton decay rate depends on M_{GUT} and α_{GUT}. Additional matter in complete SU(5) added to the intermediate scale will increase α_{GUT}.

Gluino Signature

Decay of gluino has to go through a squark:



$$\tilde{m} \sim 10^{9-16}\ \mathrm{GeV} \Rightarrow \tau_{\tilde{g}} \gtrsim 10^{-2} - 10^{14}\mathrm{s}$$

Gluino is stable within particle detectors.

Stable gluino-hadron

- Hadronize into a massive stable particle.
- Electrically either neutral or charged, depending on the mass spectrum.
- The heavy neutral particle will go through the detector unnoticed, very small energy loss.
- Charged particles also undergo ionization energy loss, via which it can be detected. It happens in central vertex detector and also in muon chamber.

(Kilian et al., Hewett et al., KC and Keung)

Experimentally, the massive stable charged particle will produce a track in the central tracking and/or silicon vertex system, where dE/dx and p can be measured.

$$\beta\,\gamma = \frac{p}{E}\,\frac{E}{M} = \frac{p}{M} \lesssim 0.85$$

The particle is required to penetrate to the outer muon chamber.

$$0.25 - 0.5 \lesssim \beta\,\gamma$$

c.f. CDF Coll. used a criteria: $0.26 - 0.5 \lesssim \beta\gamma \lesssim 0.86$, but it is for a particle of mass of $50 - 500$ GeV only.

Cross sections at the LHC.

$\sigma_{1\mathrm{MCP}}$, $\sigma_{2\mathrm{MCP}}$ denote requiring the detection of 1, 2 massive stable charged particles (MCP) in the final state.

$m_{\tilde g}$ (TeV)	$\sigma_{1\mathrm{MCP}}$ (fb) $P = 0.5$	$\sigma_{2\mathrm{MCP}}$ $P = 0.5$	$\sigma_{\geq 1\mathrm{MCP}}$ $P = 0.5$	$\sigma_{\geq 1\mathrm{MCP}}$ $P = 0.1$	$\sigma_{\geq 1\mathrm{MCP}}$ $P = 0.01$
0.5	4050	620	4670	1040	105
1.0	67	13	80	18	1.9
1.5	3.7	0.91	4.6	1.1	0.11
2.0	0.3	0.09	0.39	0.09	0.0096

$P \equiv$ probability that $\tilde g$ fragments into charged R-hadron

Problems with R-hadron detection

- The probability that $\tilde{g} \to$ charged hadrons depends crucially on the bound state spectrum.
- The detected cross section depends strongly on P:

$$\sigma(m_{\tilde{g}} = 1.5\mathrm{TeV}) = 4.6 - 0.11\,\mathrm{fb} \quad \mathrm{for}\, P = 0.5 - 0.01$$

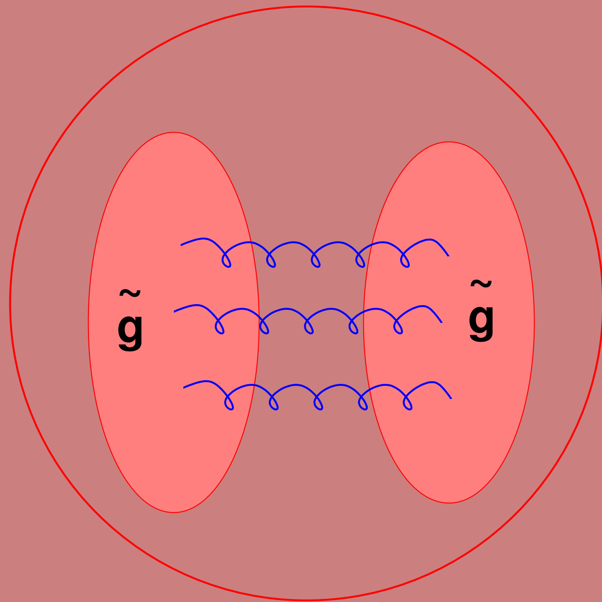
- More complications occur when frequent swapping between neutral and charged R-hadron states. E.g.,

$$(\tilde{g}u\bar{d}) \longleftrightarrow (\tilde{g}d\bar{d})$$

- Need an unambiguous signature.

Gluinonium

Gluinos are stable, exchange gluons to form a bound state.



$$\begin{aligned} \text{Color} &: \quad \mathbf{8} \otimes \mathbf{8} = \mathbf{1} + \mathbf{8}_S + \mathbf{8}_A + \mathbf{10} + \overline{\mathbf{10}} + \mathbf{27} \\ \text{S-wave, Spin} &: \quad {}^1S_0(\text{antisymmetric}),\ {}^3S_1(\text{symmetric}) \end{aligned}$$

Possible configurations: ${}^1S_0(\mathbf{1})$, ${}^1S_0(\mathbf{8}_S)$, and ${}^3S_1(\mathbf{8}_A)$

Production of Gluinonium

Replace the spinor combination $u(P/2)\bar{v}(P/2)$ by

$$
\begin{aligned}
{}^1S_0(\mathbf{1}) &: \quad u(P/2)\bar{v}(P/2) \longrightarrow \frac{1}{\sqrt{2}} \frac{R_1(0)}{2\sqrt{4\pi M}} \; \frac{1}{\sqrt{8}} \delta^{ab} \, \gamma^5 \, (\not{P} + M) \\
{}^1S_0(\mathbf{8}_S) &: \quad u(P/2)\bar{v}(P/2) \longrightarrow \frac{1}{\sqrt{2}} \frac{R_8(0)}{2\sqrt{4\pi M}} \; \sqrt{\frac{3}{5}} d^{hab} \, \gamma^5 \, (\not{P} + M) \\
{}^3S_1(\mathbf{8}_A) &: \quad u(P/2)\bar{v}(P/2) \longrightarrow \frac{1}{\sqrt{2}} \frac{R_8(0)}{2\sqrt{4\pi M}} \; \frac{1}{\sqrt{3}} f^{hab} \;\; \not{\epsilon}(P) \, (\not{P} + M)
\end{aligned}
$$

Color factors:

$$
\begin{aligned}
\mathbf{1} &: \quad \frac{1}{\sqrt{8}} \delta^{ab} \\
\mathbf{8}_S &: \quad \sqrt{\frac{3}{5}} d^{hab} \\
\mathbf{8}_A &: \quad \frac{1}{\sqrt{3}} f^{hab}
\end{aligned}
$$

Production of Gluinonium ...

The values of the color octet and singlet wave functions at the origin are given by the coulombic potential between the gluinos, with one-gluon approximation

$$
\begin{aligned}
|R_8(0)|^2 &= \frac{27\alpha_s^3(M)M^3}{128} \\
|R_1(0)|^2 &= \frac{27\alpha_s^3(M)M^3}{16}
\end{aligned}
$$

There is an additional factor of $1/\sqrt{2}$ because of the identical gluinos in the wave function of the gluinonium.

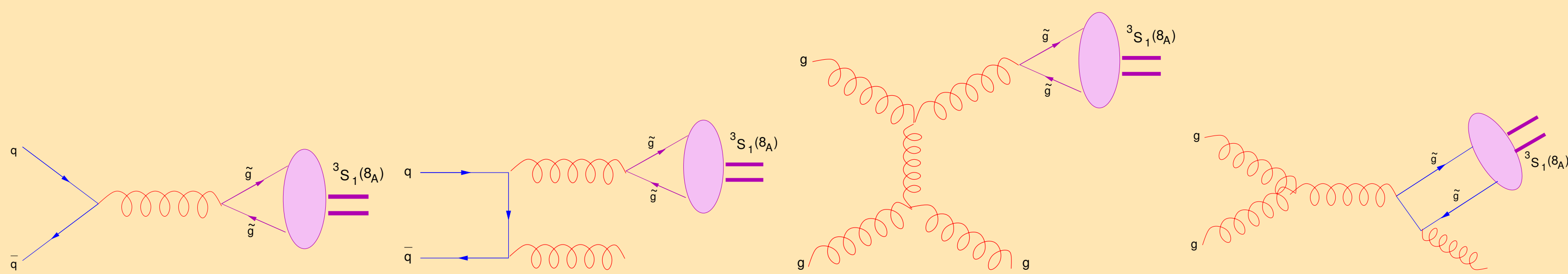
Hadronic Production of Gluinonium ${}^3S_1(\mathbf{8}_A)$

The lowest order process for ${}^3S_1(\mathbf{8}_A)$

$$q\bar{q} \rightarrow^3 S_1(\mathbf{8}_A)$$

The next order include

$$\begin{aligned} q\bar{q} &\rightarrow {}^3S_1(\mathbf{8}_A) + g \\ qg &\rightarrow {}^3S_1(\mathbf{8}_A) + q \\ gg &\rightarrow {}^3S_1(\mathbf{8}_A) + g \end{aligned}$$



Hadronic Production of Gluinonium $^3S_1(\mathbf{8}_A)$ ...

$$\hat\sigma = \frac{16\pi^2\alpha_s^2}{3}\,\frac{|R_8(0)|^2}{M^4}\,\delta(\sqrt{\hat s} - M)\ .$$

After folding with the parton distribution functions:

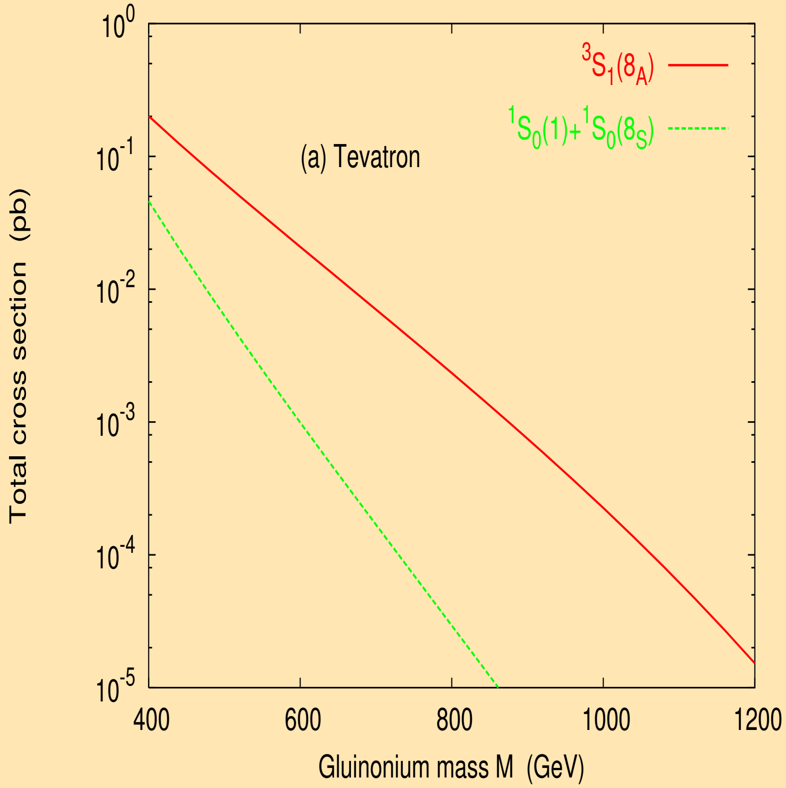
$$\sigma = \frac{32\pi^2\alpha_s^2}{3s}\,\frac{|R_8(0)|^2}{M^3}\,\int f_{q/p}(x) f_{\bar q/p}(M^2/sx)\frac{dx}{x}\ ,$$

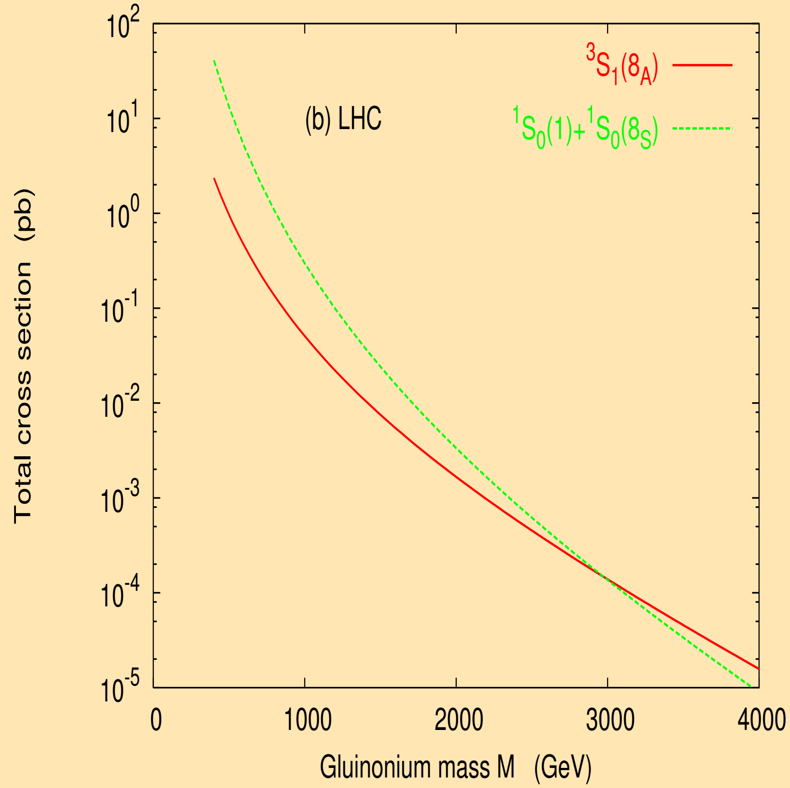
Decay width into $u\bar u$, $d\bar d$, $s\bar s$, $c\bar c$, $b\bar b$, $t\bar t$:

$$\Gamma\left({}^3S_1(\mathbf{8}_A)\right) = \sum_{Q=u,d,s,c,b,t} \alpha_s^2\,\frac{|R_8(0)|^2}{M^4}\,(M^2 + 2m_Q^2)\,\sqrt{1 - 4m_Q^2/M^2}$$

Each mode $\sim \frac{1}{6}$ for heavy gluinonium.

Hadronic Production of Gluinonium ...





Detection & Background analysis

$$
\begin{aligned}
{}^1S_0(\mathbf{1},\mathbf{8}_S) &\rightarrow gg \\
{}^3S_1(\mathbf{8}_A) &\rightarrow q\bar{q}
\end{aligned}
$$

buried under huge QCD background.

$$
{}^3S_1(\mathbf{8}_A) \rightarrow t\bar{t},\ b\bar{b}
$$

have the potential feasibility for observation.

Irreducible background comes from QCD $t\bar{t}$ or $b\bar{b}$

Detection & Background analysis ...

- Gluinonium annihilates into t and $\bar{t}$ with a large p_T

$$p_T \sim O(M_{\tilde{g}})$$

We impose

$$\begin{aligned} p_T(t),\ p_T(\bar{t}) &> \frac{3}{4} m_{\tilde{g}} \quad \text{for } M \geq 1 \text{ TeV} \\ p_T(t),\ p_T(\bar{t}) &> 100 \text{ GeV} \quad \text{for } M < 1 \text{ TeV} \end{aligned}$$

- Invariant mass $M_{t\bar{t}}$ forms a peak right at gluinonium mass, width determined by experimental resolution.

$$\delta E/E = 50\%/\sqrt{E}$$

We can then calculate the SM background right under the peak.

Detection & Background analysis ...

Cross sections at the LHC for the gluinonium signal into $t\bar{t}$ with mass M and the continuum $t\bar{t}$ background between $M - 50$ GeV and $M + 50$ GeV.

$M = 2m_{\tilde{g}}$ (TeV)	$\sigma({}^3S_1(\mathbf{8}_A))$ (fb)	$t\bar{t}$ bkgd (fb) (fb)	$S/\sqrt{B}$ for $L = 100$ fb^{-1}
0.5	120	83000	4.2
0.75	28	19000	2.0
1	4.9	1150	1.4
1.5	0.78	97	0.79
2.0	0.17	14	0.45
3.0	0.014	0.67	0.17

Including $b\bar{b}$ would increase $S/\sqrt{B}$ by $\sqrt{2}$.

DØ search for stopped Gluinos

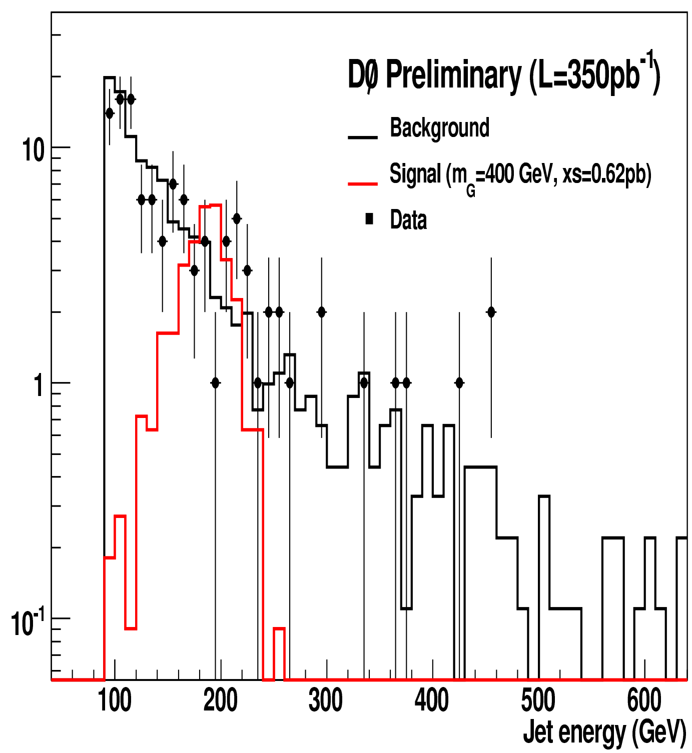
The long-lived gluino can hadronize into charged R-hadron. It may lose all its K.E. by ionization and stopped inside the detector. Then after a "while" it decays into a gluon and LSP. The signaure is a jet plus $\not{E}_T$.

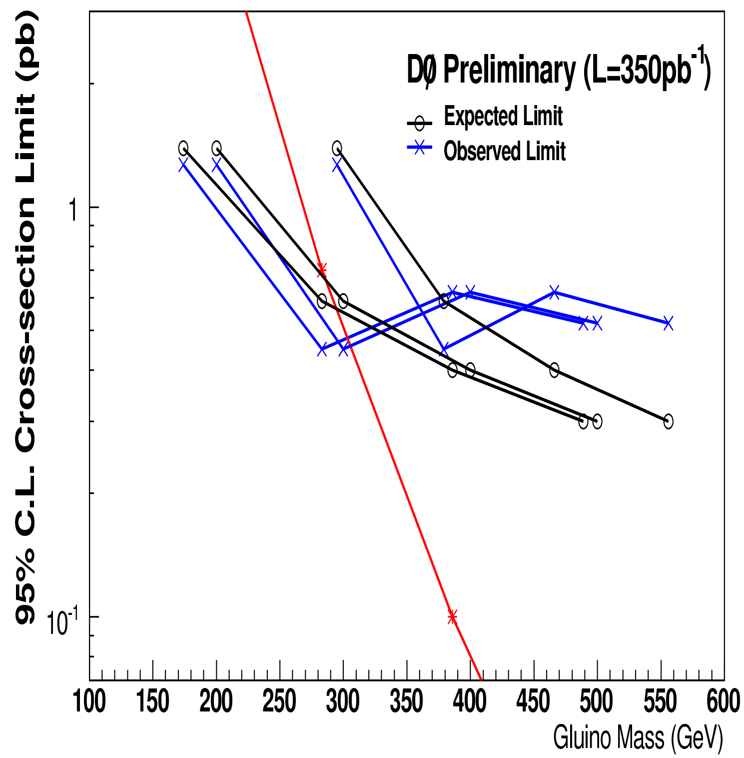
Backgrounds:

- Cosmic muons that fake the signal by initiating a high-energy shower within the detector (identified by a muon in or out of the muon system).
- Beam-halo muons are those traveling parallel to the beam, very narrow in ϕ.

A gluino-induced shower would be wide and contain no muon.

DØ results for stopped gluinos





A simulated signal of $m_{\tilde g} = 400$ GeV. 95% C.L. upper limits on $\sigma(\tilde g) \times B(\tilde g \to j + \not\!\!E_T)$ for 3 LSP masses of 50, 90, 200 GeV.

Neutralinos and Charginos

(KC and J. Song, hep-ph/0507113)

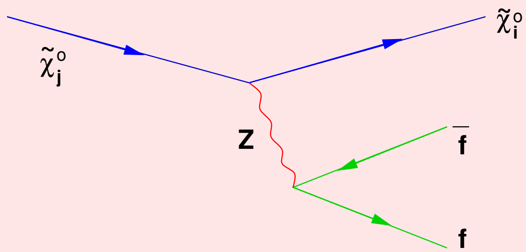
- Production and decay via intermediate $\tilde{f}$ disappear.
- Direct production via Drell-Yan-like processes (γ, Z^*, W^*).
- Neutralino decays via

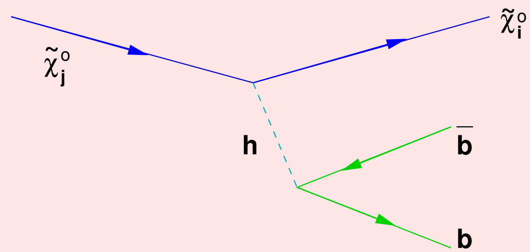
$$\begin{array}{ccl} \widetilde{\chi}_j^0 & \to & \widetilde{\chi}_i^0 Z^* \to \widetilde{\chi}_i^0 f\bar{f} \\ \widetilde{\chi}_j^0 & \to & \widetilde{\chi}_i^{\pm} W^* \to \widetilde{\chi}_i^0 f\bar{f}' \\ \widetilde{\chi}_j^0 & \to & \widetilde{\chi}_i^0 h^* \to \widetilde{\chi}_i^0 b\bar{b} \\ \widetilde{\chi}_j^0 & \xrightarrow{\widetilde{\chi}^+ W^- loop} & \tilde{\chi}_i^0 \gamma \end{array}$$

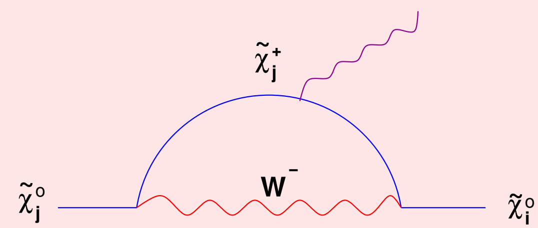
- Chargino decays via

$$\tilde{\chi}_j^+ \to \tilde{\chi}_i^0 W^* \to \tilde{\chi}_i^0 f\bar{f}'$$

Decays of Neutralinos







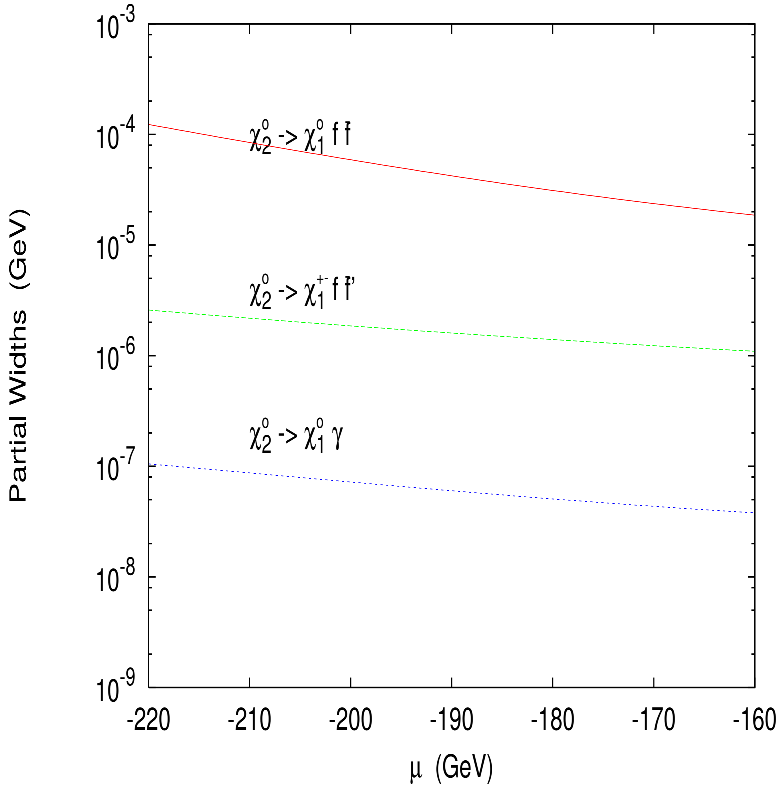
Aim: to enhance the $\tilde{\chi}^0_j \to \tilde{\chi}^0_i + \gamma$ by suppressing the $Z - \tilde{\chi}^0_j - \tilde{\chi}^0_i$ couplings:

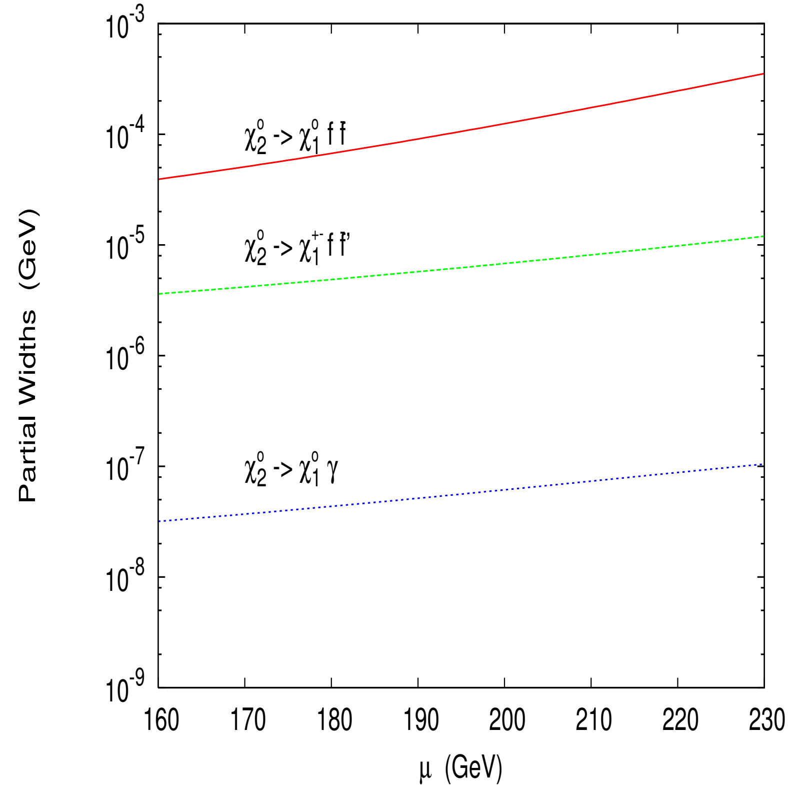
$$O''^L_{ij} = -O''^R_{ij} = \frac{1}{2}(N_{i4}N^*_{j4} - N_{i3}N^*_{j3})$$

It is possible but needs fine tuned relation between μ and M_1. Specifically, need

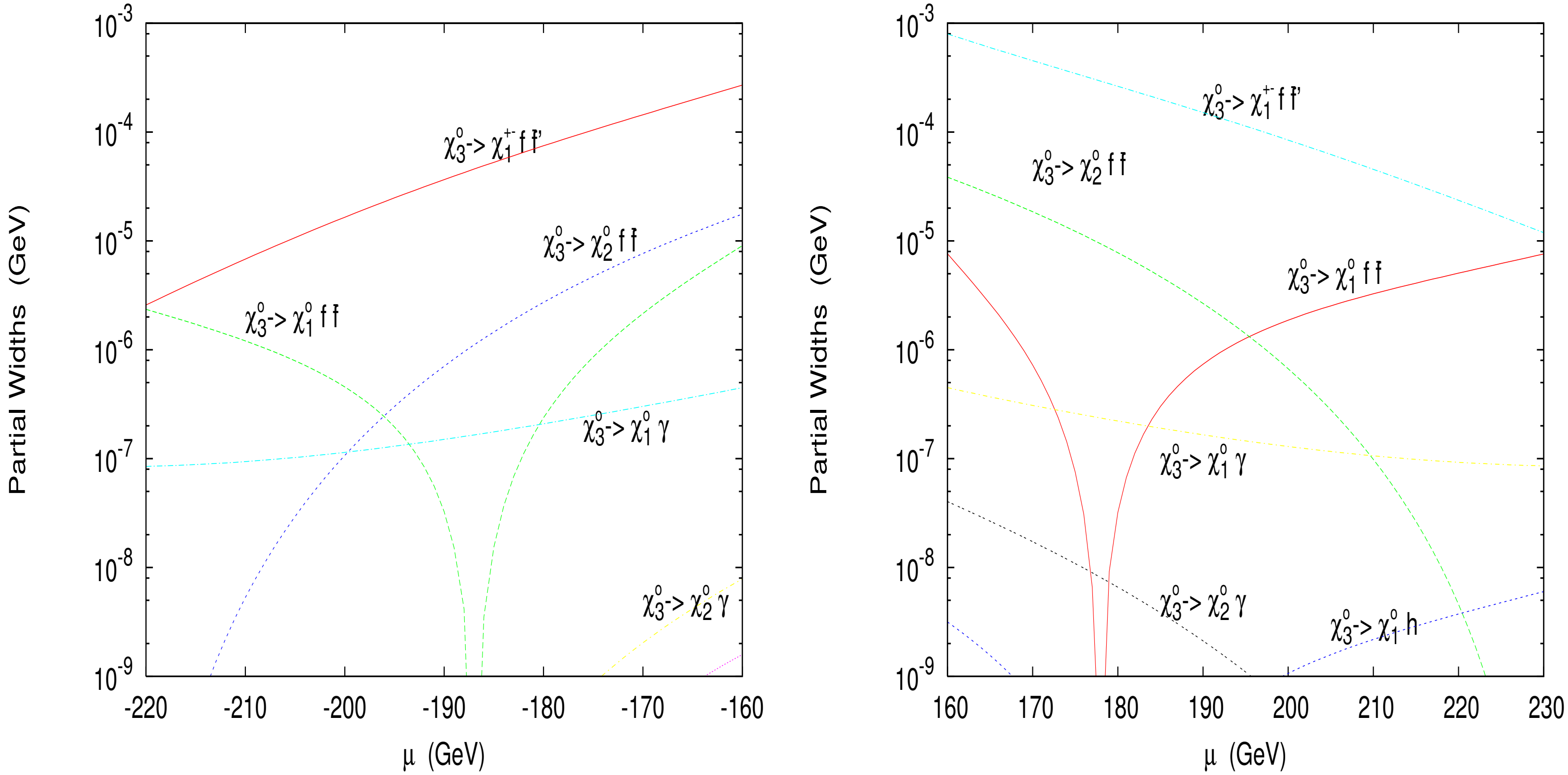
$$M_1 \sim |\mu|$$

Potentially, observe mono-photon plus missing energy signature at hadron colliders.

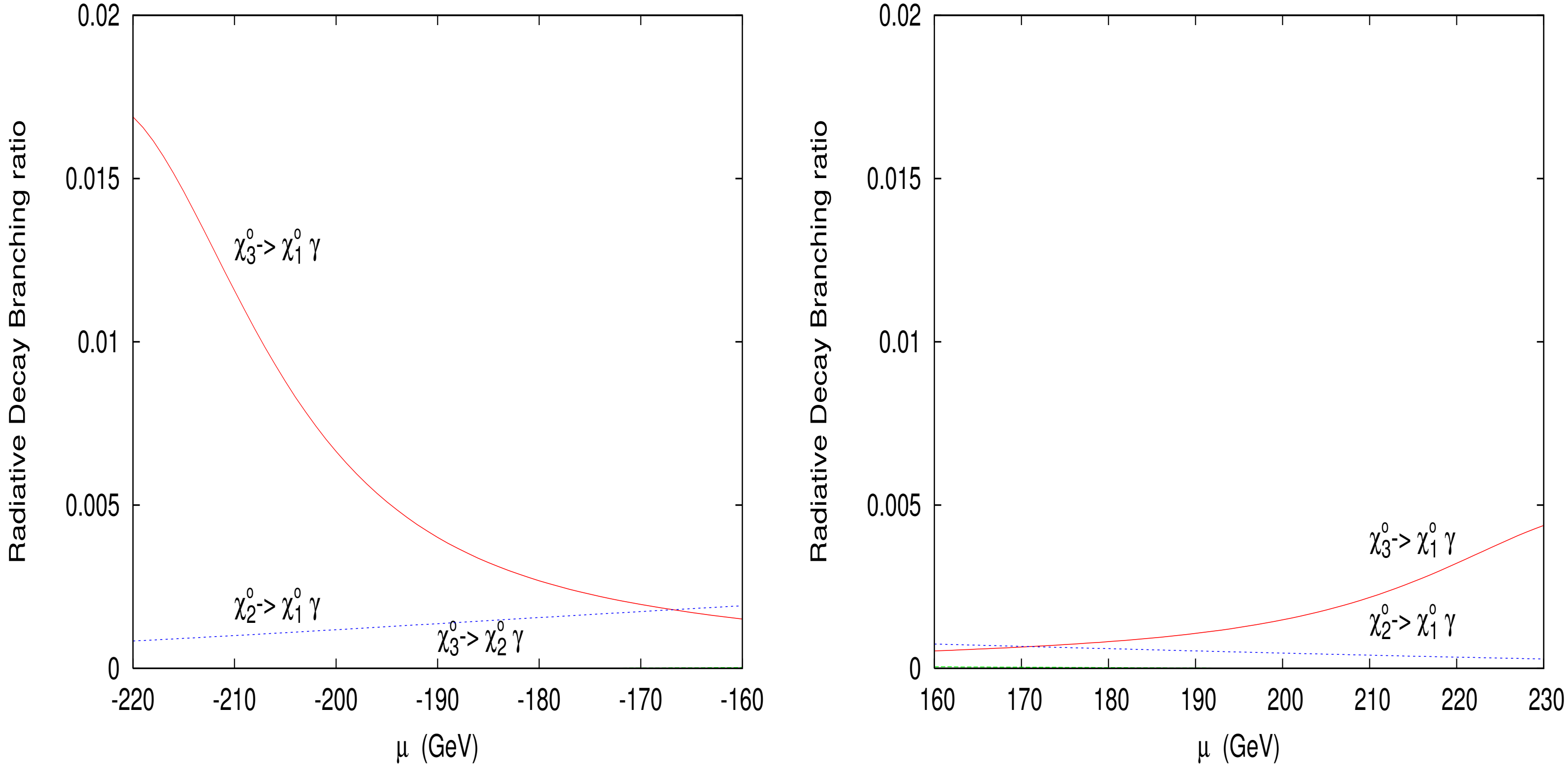




$\widetilde{\chi}_2^0$ decay widths, $M_1 = 200$ GeV



$\widetilde{\chi}^0_3$ decay widths, $M_1 = 200$ GeV

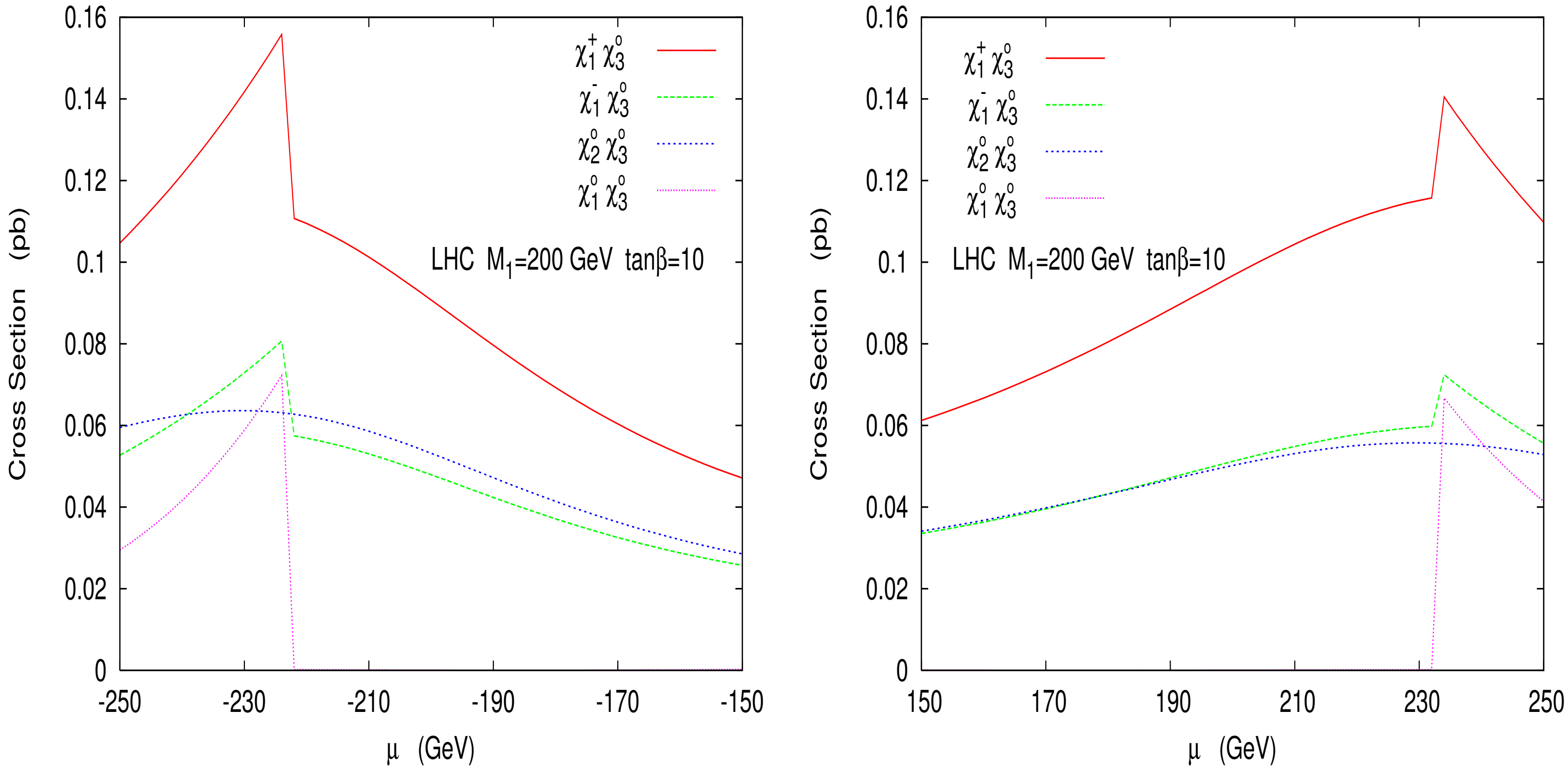


$\widetilde{\chi}^0_{3,2}$ radiative decay branching ratios

Production of Neutralinos and Charginos

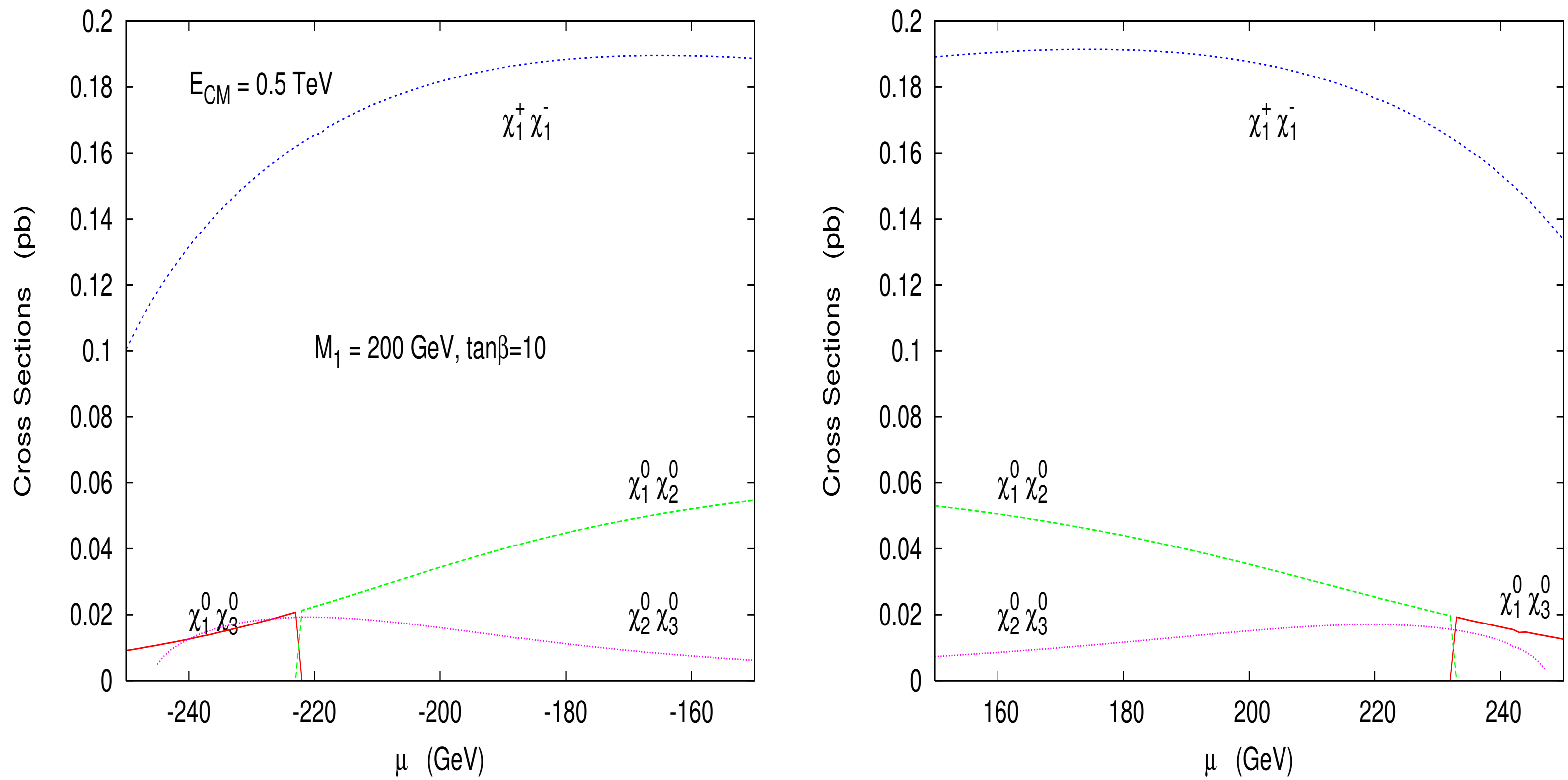
$$
\begin{aligned}
q+\overline{q} &\xrightarrow{Z^*} \widetilde{\chi}_i^0 + \widetilde{\chi}_j^0 \\
q+\overline{q} &\xrightarrow{\gamma, Z^*} \widetilde{\chi}_i^- + \widetilde{\chi}_j^+ \\
q+\overline{q}' &\xrightarrow{W^*} \widetilde{\chi}_i^\pm + \widetilde{\chi}_j^0 \\
e^- e^+ &\xrightarrow{\gamma, Z^*} \widetilde{\chi}_i^+ + \widetilde{\chi}_j^- \\
e^- e^+ &\xrightarrow{Z^*} \widetilde{\chi}_i^0 + \widetilde{\chi}_j^0
\end{aligned}
$$

(Zhu; Kilian et al.; KC and Song)



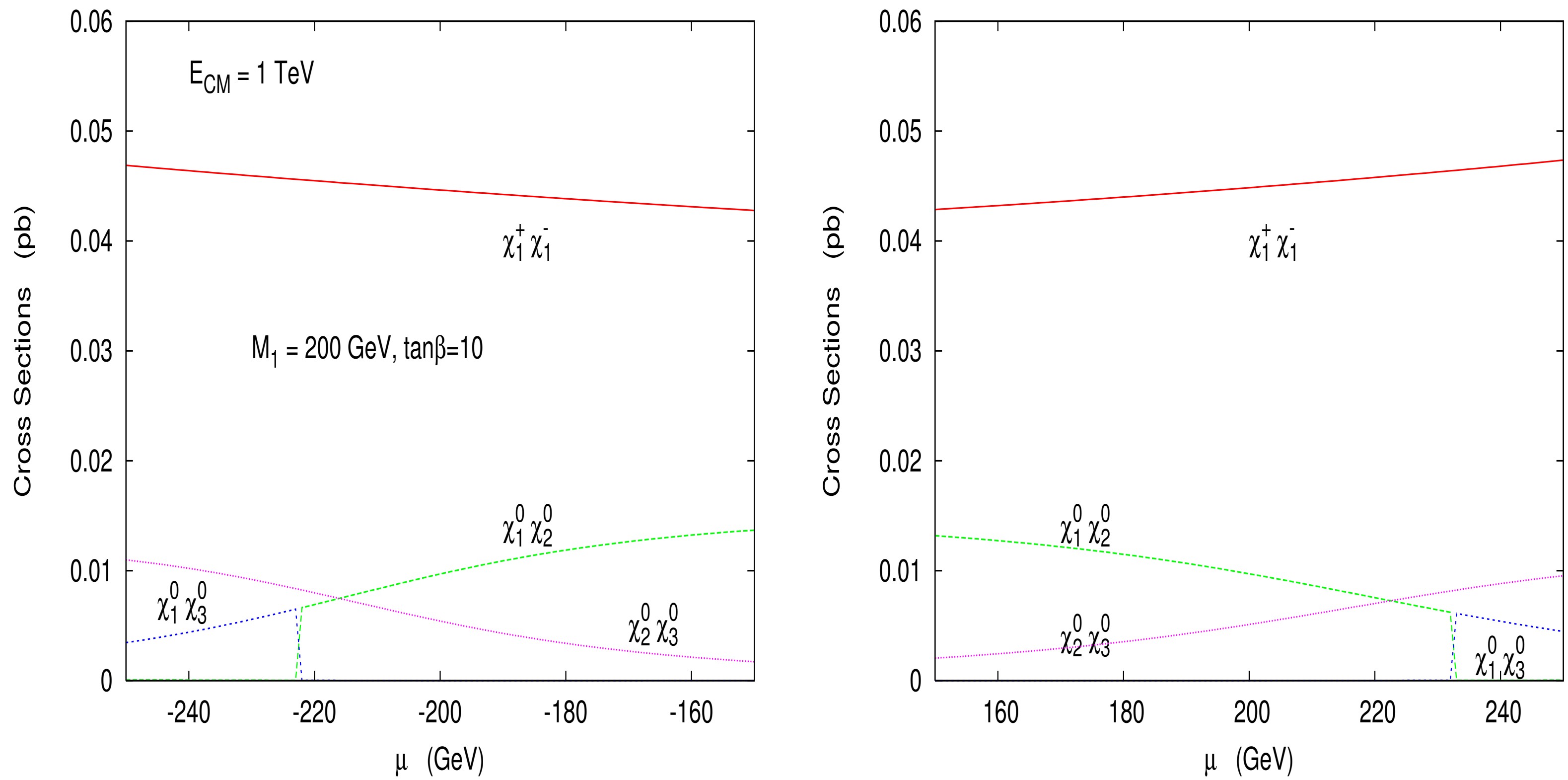
$\widetilde{\chi}_3^0$ production, $M_1 = 200$ GeV

Production at 0.5 TeV e^+e^- ILC



$$M_1 = 200 \text{ GeV}, \; M_2 = 400 \text{ GeV}, \; \tan\beta = 10$$

Production at 1 TeV e^+e^- ILC



$$M_1 = 200 \text{ GeV},\ M_2 = 400 \text{ GeV},\ \tan\beta = 10$$

Topics that cannot be covered in this lecture but equally interesting

- Mixed Moduli-anomaly SUSY breaking (Choi, hep-ph/0511162).
- Gaugino mediated SUSY breaking (Kaplan et al. hep-ph/9911293, Chacko et al. hep-ph/9911323).
- SUSY breaking by 5d boundary conditions (Scherk-Schwarz SUSY breaking).
- Gluino LSP scenarios (Baer et al. hep-ph/9806361).
- Next-to-minimal supersymmetric model (NMSSM).