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ICTP 40th Anniversary

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"VII School on Non-Accelerator Astroparticle Physics"

26 July - 6 August 2004

Standard Model and Beyond - III

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Minimal Supersymmetric Standard Model (MSSM)

$q_{L,R}$ $\ell_{L,R}$ ν	$\tilde{q}_{L,R}$ $\tilde{\ell}_{L,R}$ $\tilde{\nu}$	
g	$\tilde{g}$	
$W^\pm, Z^0, \gamma$	$\tilde{W}^\pm, \tilde{Z}^0, \tilde{\gamma}$	charginos $\tilde{\chi}_i^\pm, i=1,2$
$H^\pm, h^0, A^0, H^0$	$\tilde{H}^\pm, \tilde{H}_1^0, \tilde{H}_2^0$	$\tilde{\chi}_i^0, i=1...4$ neutralinc

Parameters:

$M, M', \mu, \tan\beta = \frac{v_2}{v_1}$ $\qquad m_W^2 = \frac{1}{2}g^2(v_1^2+v_2^2)$

$m_{\tilde{q}_{L,R}}, m_{\tilde{\ell}_{L,R}}, m_{\tilde{\nu}}, m_0$

m_A, A ...., m_t, m_b

Unification relations: $m_{\tilde{g}} = \frac{\alpha_s}{\alpha_2} \cdot M \approx 3M$

$$M' = 5/3 \tan^2\theta_W \cdot M \approx \frac{M}{2}$$

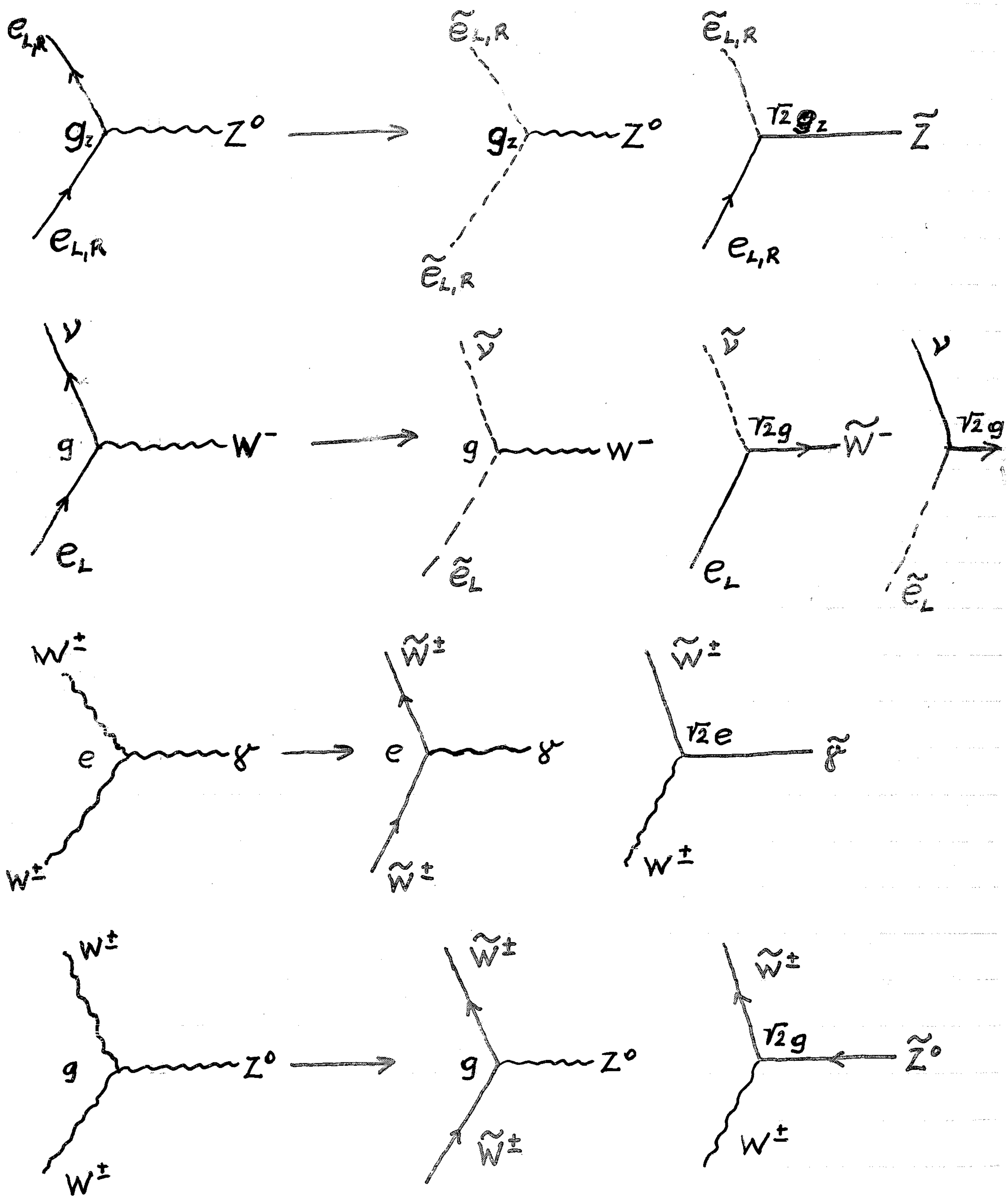
$$m^2_{\tilde{f}_{L,R}} = m_f^2 + m_{soft}(\tilde{f}) \pm m_D^2(f)$$

$$m^2_{soft}(\tilde{f}) = m_0^2 + C(\tilde{f}) . M^2$$

$$m_D^2(\tilde{f}) = m_Z^2 \cos 2\beta \left(T_{3L}^f - Q_f \cdot \sin^2\theta_W\right)$$

R-parity conserved, $\tilde{\chi}_1^0$ assumed LSP

Further constraints: RGE & boundary conditions (GUT

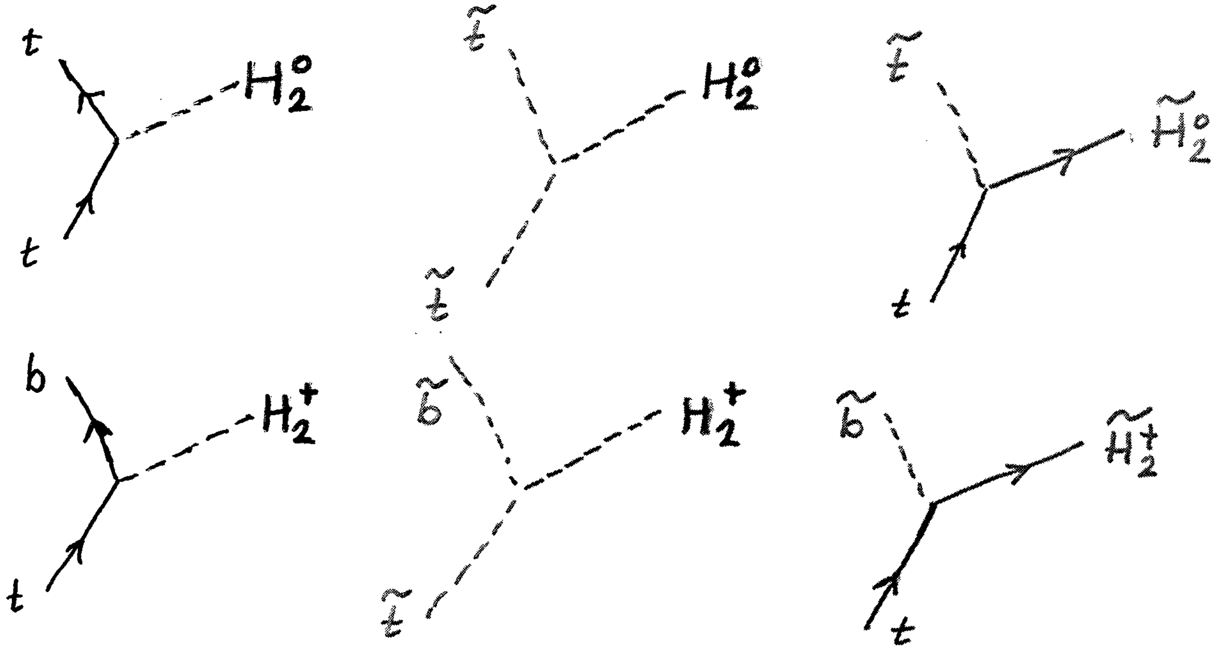


+ 4-Boson couplings

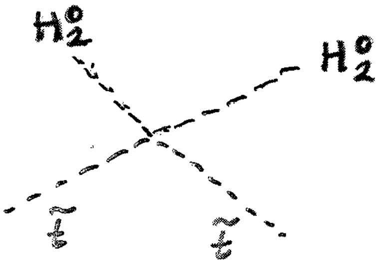
Gauge interactions

Yukawa Interactions

from Superpotential



Via $V(A, A^+)$:



etc

Theoretical "merits" of **SUSY**:

- SUSY algebra is only non-trivial extension of space-time symmetry in relativistic quantum field theory
- Local SUSY ⇒ supergravity
  (hope for a finite theory of quantum gravity)
- Superstrings ⊕ fermions
  ⟹ SUSY below M_{Planck}
- Non-renormalization theorems

From these follow the specific motivations for weak-scale SUSY

Supersymmetric extension of Standard Model.

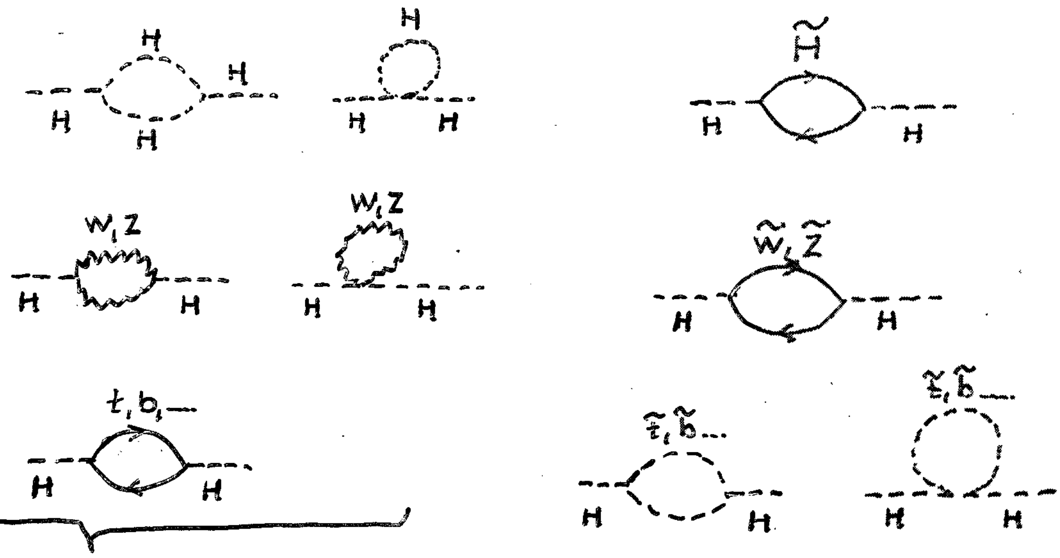
Eliminates quadratic divergencies of scalar Higgs field.

Mass of an <u>elementary</u> scalar field would "naturally" be $\mathcal{O}(M_{GUT}) \div \mathcal{O}(M_{Planck})$.

SUSY is the **best** way we know that render $M_{Higgs} \lesssim 1\,\text{TeV}$, maybe even $M_{Higgs} \approx M_{weak}$ (in 4-dim space-time)

In SUSY GUT:

$\Delta M^2_{Higgs} \approx$



$\mathcal{O}(M^2_{GUT}) \div \mathcal{O}(M^2_{Planck})$

$\propto \ln M^2_{GUT} \; [\mathcal{O}((10^2\,GeV)^2) \div \mathcal{O}((10^3\,GeV)^2)]$

SUSY $\Rightarrow$ Cancellation of quadratic divergence

Large m_{top} ($\gtrsim 60$ GeV) $\Rightarrow M^2_{Higgs} < 0$ for one of the Higgs states

Radiative breaking of $SU(2) \times U(1)$ is a derived consequence of SUSY breaking

Experimental hint: gauge coupling unification

Extra bonus: good candidate for cold dark matte

(lightest SUSY particle **LSP** is stable if R_P is conserved)

New ~~CP~~ complex couplings

SUSY can solve hierarchy problem and can stabilize Higgs mass

If Nature is SUSY at weak scale, LHC, [Tevatron (upgraded)] will detect SUSY (and Higgs) particles

At LHC: SUSY parameter determination only within specific models will be possible.

At an e^+e^- Linear Collider with $\sqrt{s} = 500$ GeV – 1.5 TeV detection of SUSY particles and precision determination of the parameters will be possible.

Charginos, neutralinos, 3rd generation sfermions may be light.

$\tilde{\chi}^0_1$ Lightest Supersymmetric Particle LSP ⇒ dark matter

Higgs Sector in MSSM

$$H_1^i = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \qquad H_2^i = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$$

Spont. EW Sym. Breaking

$$\Downarrow$$

$\underbrace{h^0, H^0}$	A^0 (G^0)	$H^\pm$ $(G^\pm)$
mixing angle α	$\downarrow$ m_Z	$\downarrow$ m_W
CP: even	odd	

At tree level two free parameters:

$$m_A, \; \tan\beta = \frac{v_2}{v_1}$$

We take m_A independent of m_0 etc, not restricted by m SUGRA

1-loop rad. corr. in Higgs sector are important, $\left(\Delta m_{h^0}^2 \approx \frac{m_t^4}{m_W^2}\right)$

J. Ellis-Ridolfi-Zwirner, Dabelstein, Pokorski et al. .....

$m_{h^0} \lesssim 140$ GeV

LEP: $m_{h^0} \gtrsim 91.5$ GeV
m [illegible] > 91 [illegible]

Higgs Sector:

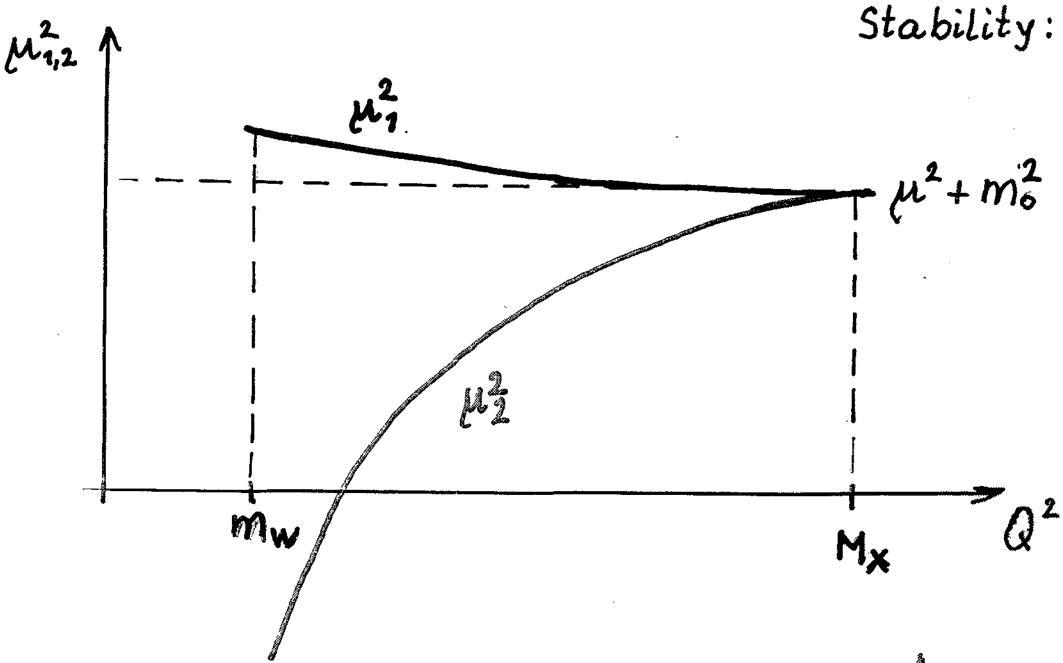
$$V_H = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 + B\mu m_0 \, (H_1 H_2 + h.c) + \frac{g^2}{8\cos^2\theta_W}\left(|H_2|^2 - |H_1|^2\right)^2$$

At scale M_X: $\mu_1^2 = \mu_2^2 = \mu^2 + m_0^2$

SU(2)×U(1) breaking:

$\mu_1^2 \cdot \mu_2^2 < B^2 \mu^2 m_0^2$

Stability: $\mu_1^2 + \mu_2^2 \geq 2|B\mu m_0$



$\tan\beta = \frac{v_2}{v_1}$

Works if $m_t \gtrsim 60$ GeV

Top quark loop:

Minimum of V_H at $\langle H_{1,2}^0 \rangle = \frac{1}{\sqrt{2}} v_{1,2}$

$m_W^2 = \frac{1}{2} g^2 (v_1^2 + v_2^2$

$$m_{H\pm}^2 = m_W^2 + m_{H3}^2$$

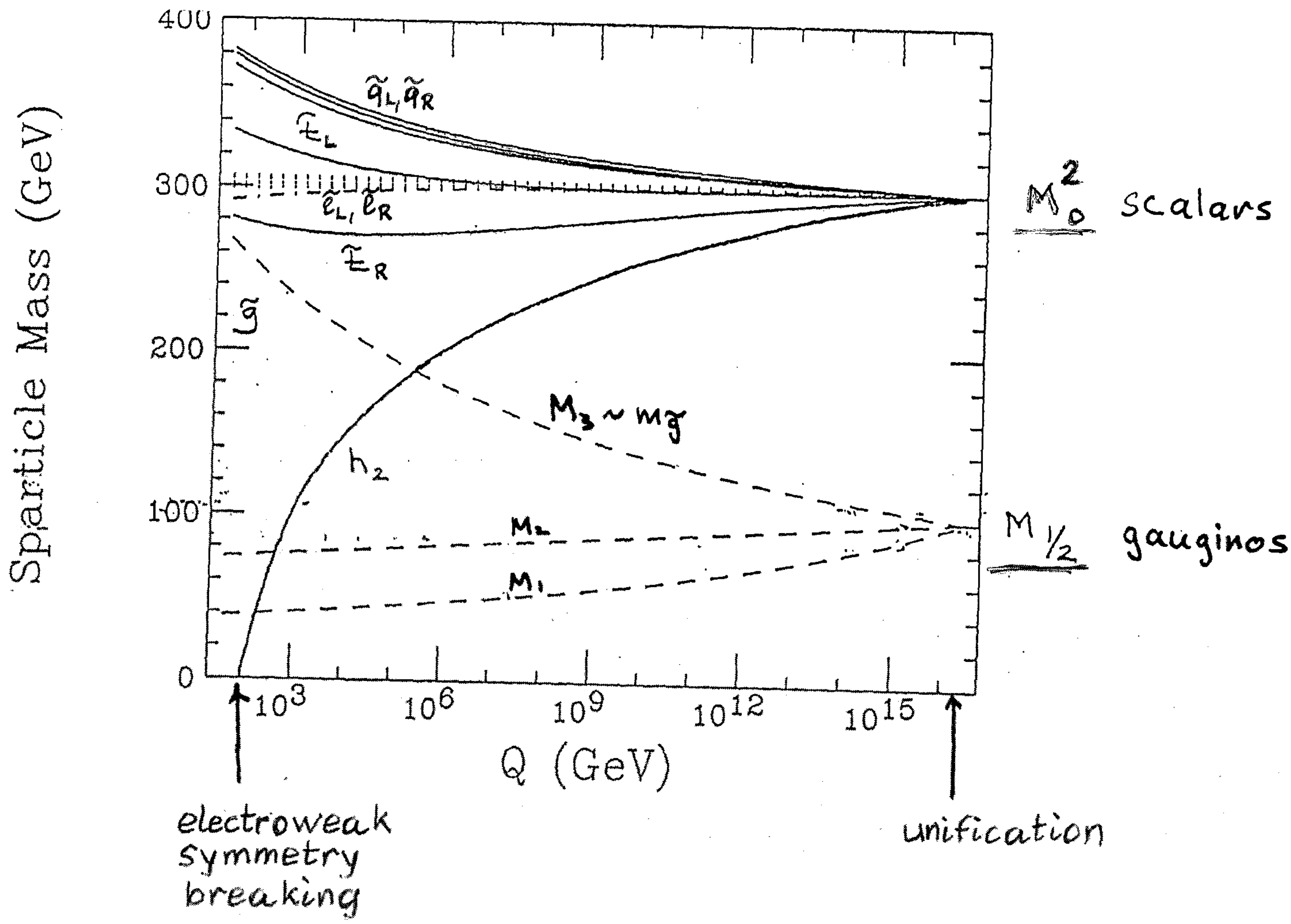
$$m_{H1\,(H2)}^2 = \frac{1}{2}\left[m_{H3}^2 + m_Z^2 \overset{+}{\underset{(-)}{}} \sqrt{(m_{H3}^2 + m_Z^2)^2 - 4 m_Z^2 m_{H3}^2 \cos^2 2\beta}\right]$$

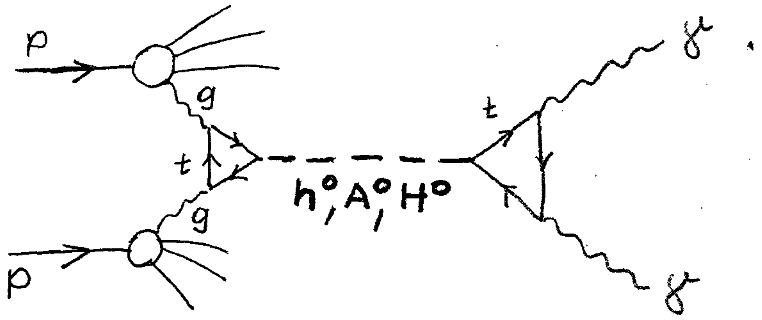
$$\tan\beta = v_2 / v_1$$

$$|m_{H\pm}| \geq m_W \;, \quad |m_{H1}| \geq m_Z \;, \quad |m_{H2}| \leq m_Z |\cos 2\beta|$$

Bagger et al.:

Evolution of "soft" SUSY masses





$p + p \rightarrow h^0 + X$
$\quad \hookrightarrow \gamma + \gamma$

Specific mechanism for Higgs producti
in hadronic reactions

(hatched) not covered by LHC or LEP

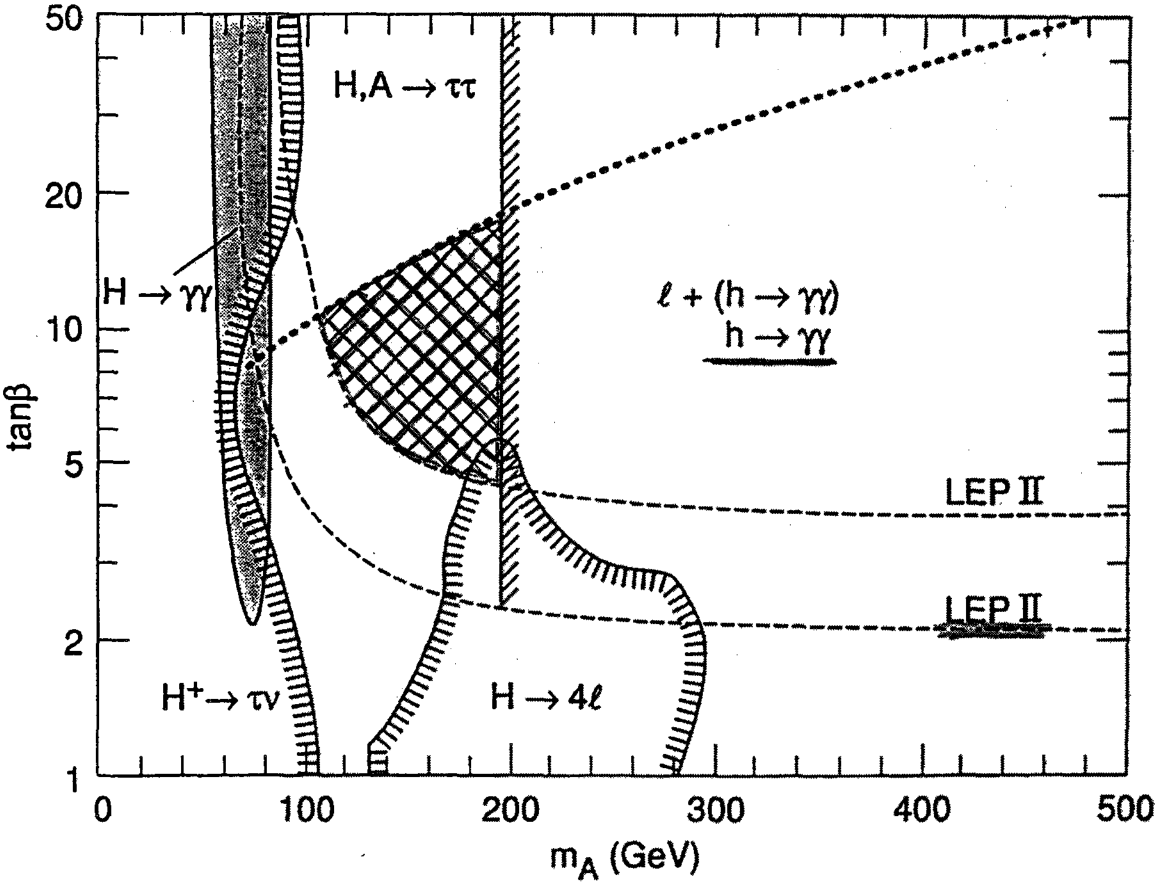
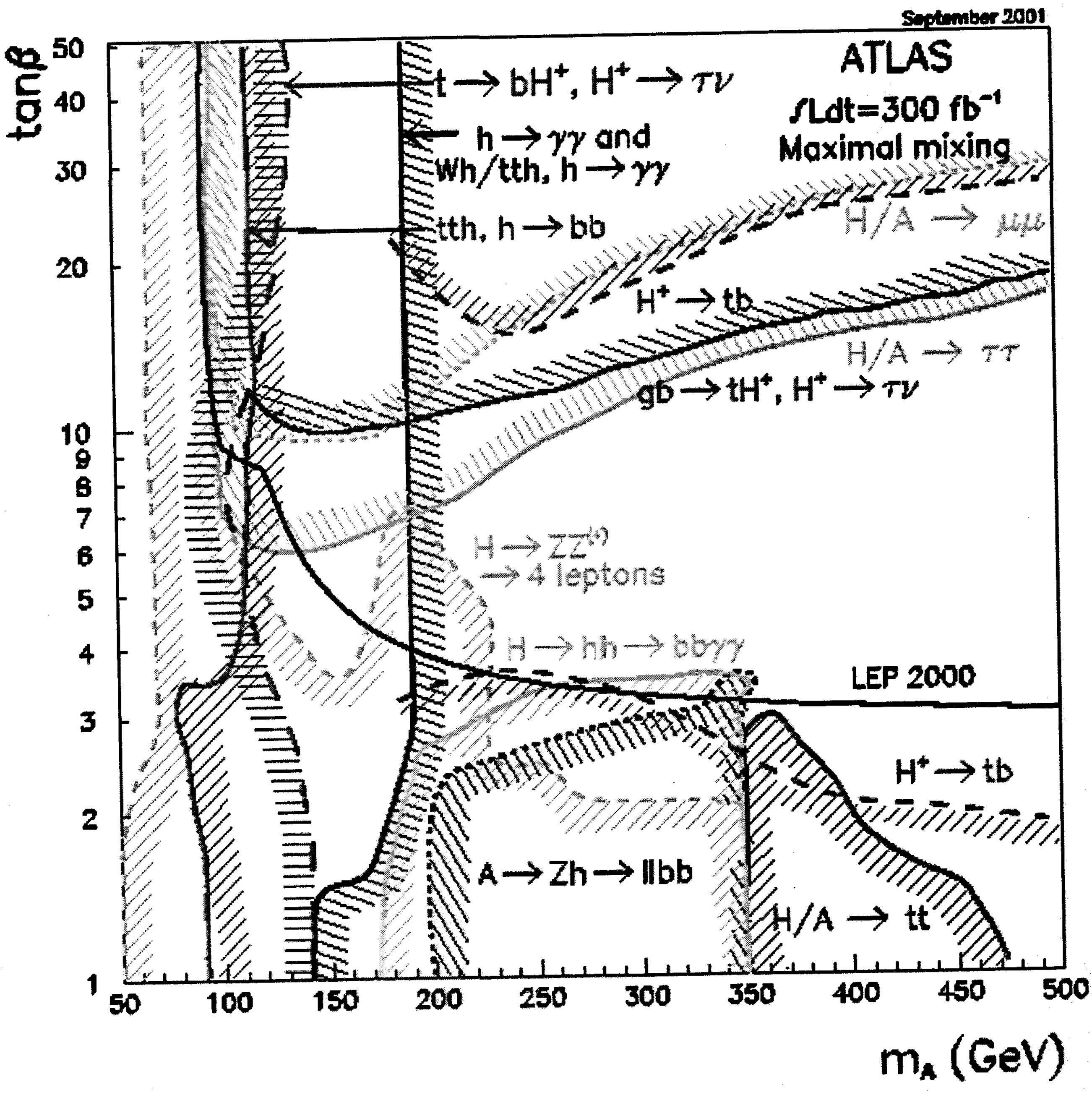


Fig. 30

MSSM HIGGS Production at LHC

ATLAS, CMS, Kunszt-Zwirner

MSSM Higgs Search at LHC



In MSSM: 5 Higgs states.

Neutral { h, H scalar, CP-even; A pseudoscalar, CP-odd

Basic principle of **MSSM** particle searches:

$R_p = (-1)^{3B+L+2S}$ conserved

SUSY particles produced in pairs
Lightest SUSY particle is stable and only weakly interacting (like neutrino)

A SUSY particle decays into LSP and known particles (maybe in cascades)

Signal for SUSY: Events with missing energy-momentum carried by the invisible LSP.

Machines:

e^+e^-: LEP, SLC, e^+e^-LC (NLC, JLC, CLIC, TESLA)

pp: Tevatron p-$\bar{p}$, LHC, Eloisatron, VLHC

e-p: HERA, LEP/LHC

$\mu^+\mu^-$?

Strategy:

Look for **excess of events** for characteristic final states (compared to SM prediction)

SUSY at hadron colliders

p-$\bar{p}$: Tevatron, $\sqrt{s} \approx 2$ TeV (CERN S$p\bar{p}$S)

p-p: LHC, $\sqrt{s} \approx 14$ TeV (Eloisatron ?)
(VLHC ?)

$pp \to \tilde{g}\tilde{g} + X$, $pp \to \tilde{q}\overset{(-)}{\tilde{q}} + X$, $pp \to \tilde{g}\tilde{q} + X$
have largest cross sections of all SUSY particles — Barnett et al., Baer et al.

Gluino $\tilde{g}$, squarks $\tilde{q}$, decay into charginos $\tilde{\chi}_i^\pm$ and neutralinos $\tilde{\chi}_i^0$, until $\tilde{\chi}_1^0$ (LSP) is reached

A.B. et al

– Also associated production with $\tilde{\chi}_i^\pm$, $\tilde{\chi}_i^0$ is possible:

$$pp \to \tilde{g}\tilde{\chi}_i^\pm + X,\ \tilde{g}\tilde{\chi}_i^0 + X,\ \tilde{q}\tilde{\chi}_i^\pm + X,\ \tilde{q}\tilde{\chi}_i^0 + X$$

(H. Baer et al.)

– Drell-Yan production:

$$pp \to \tilde{\chi}^\pm \tilde{\chi}_i^0 + X,\ \tilde{\chi}_i^+ \tilde{\chi}_j^- + X,\ \tilde{\chi}_i^0 \tilde{\chi}_j^0 + X$$

$$pp \to \tilde{\ell}^+ \tilde{\ell}^- + X \ldots\ldots$$

Barbieri et al.
Baer et al.

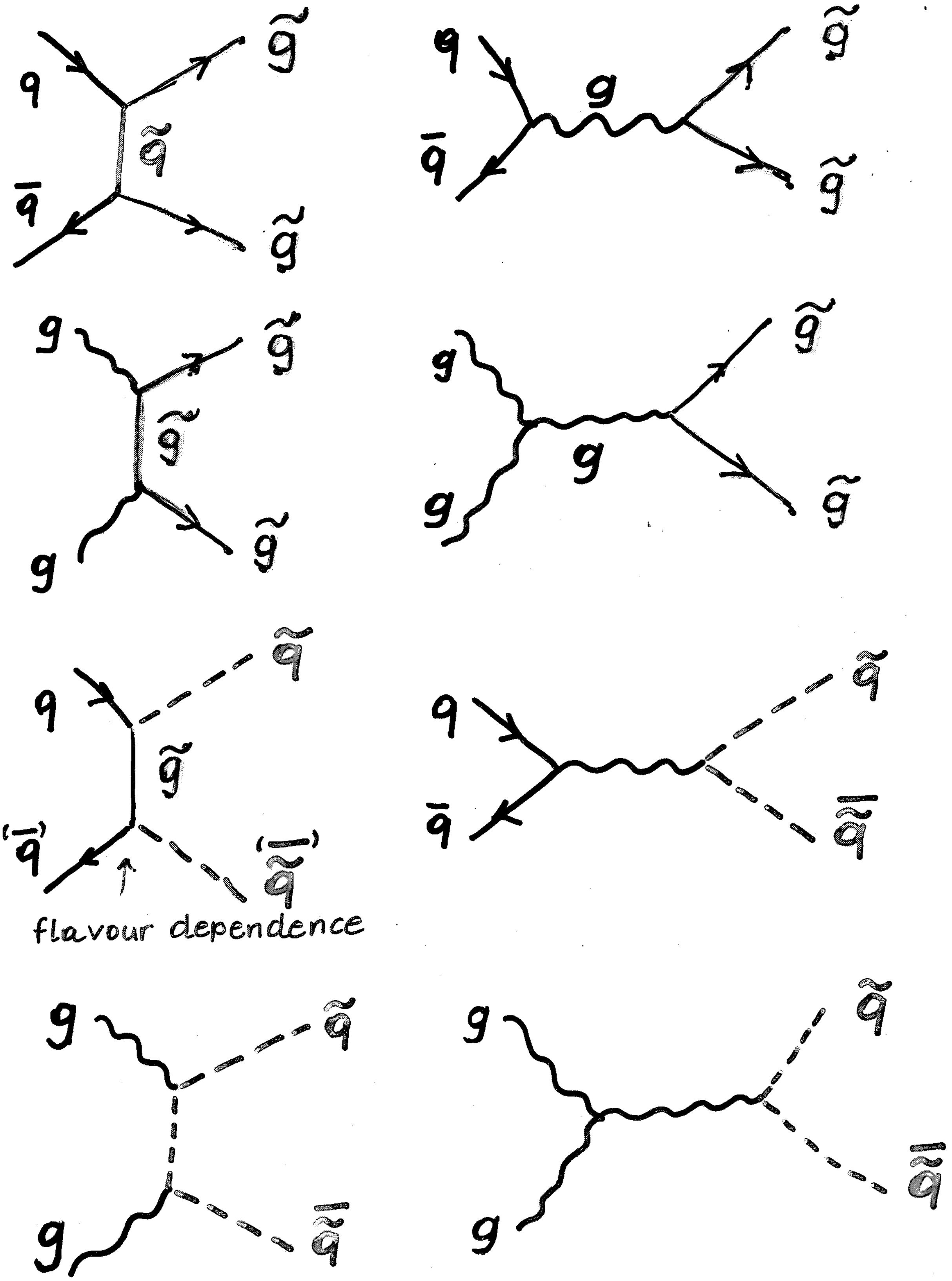
May be detectable at LHC if $m \lesssim 200$ GeV, large $t\bar{t}$ background

$$p+p \longrightarrow \tilde{g} + \tilde{g} + X$$

$$p+p \longrightarrow \tilde{q} + \overset{(-)}{\tilde{q}} + X$$

LHC $\sqrt{s}=14\,TeV$

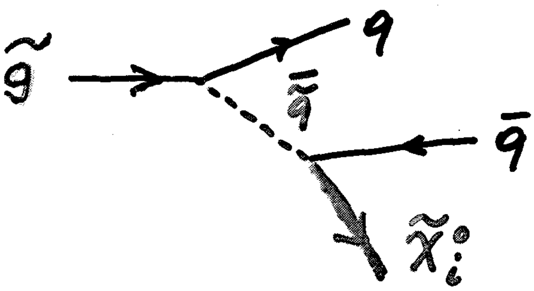
TEVATRON $\sqrt{s}=1.8\,TeV$

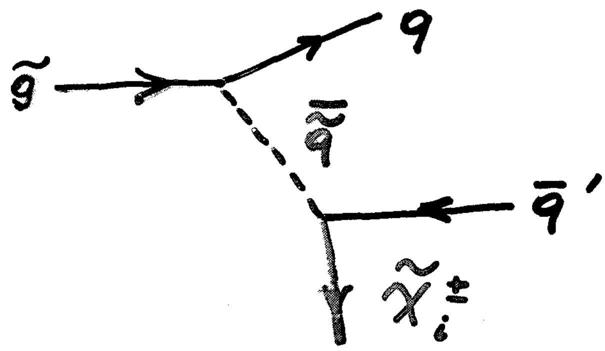


Decays:

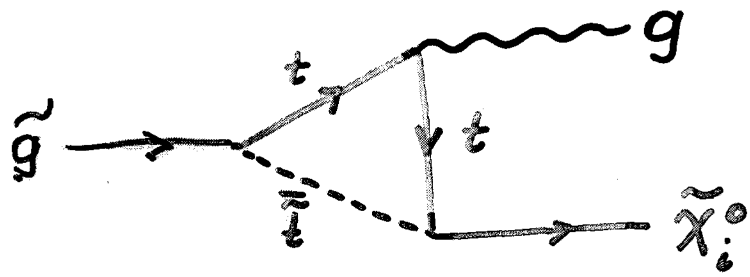
$\tilde{g} \rightarrow q + \bar{q} + \tilde{\chi}_i^0 \,, \quad t + \bar{t} + \tilde{\chi}_i^0$ if $\underline{M_{\tilde{q}} > m_{\tilde{g}}}$

$q + \bar{q}' + \tilde{\chi}_i^{\pm} \,, \quad t + \bar{b} + \tilde{\chi}_i^- \,, \quad \bar{t} + b + \tilde{\chi}_i^+$





$\tilde{g} \rightarrow g + \tilde{\chi}_i^0$



if $\underline{m_{\tilde{g}} > M_{\tilde{q}}}$:

$\tilde{q}_{L,R} \rightarrow q + \tilde{\chi}_i^0$

$\tilde{u}_L \rightarrow d + \tilde{\chi}_i^+$

$\tilde{d}_L \rightarrow u + \tilde{\chi}_i^-$

$\tilde{t}_{L,R} \rightarrow t + \tilde{\chi}_i^0$

$\tilde{t}_R \rightarrow b + \tilde{\chi}_i^+$

$\tilde{b}_L \rightarrow t + \tilde{\chi}_i^-$

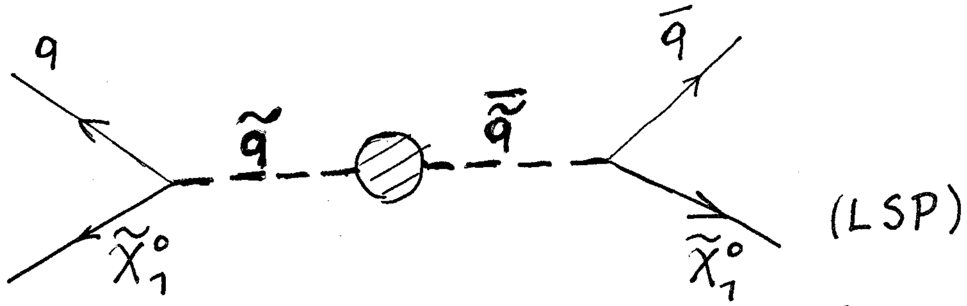
} $\tilde{t}_L$-$\tilde{t}_R$ mixing, $\tilde{b}_L$-$\tilde{b}_R$ mixing, $\tilde{t}_1, \tilde{b}_1$ may be much lighter

Cascades

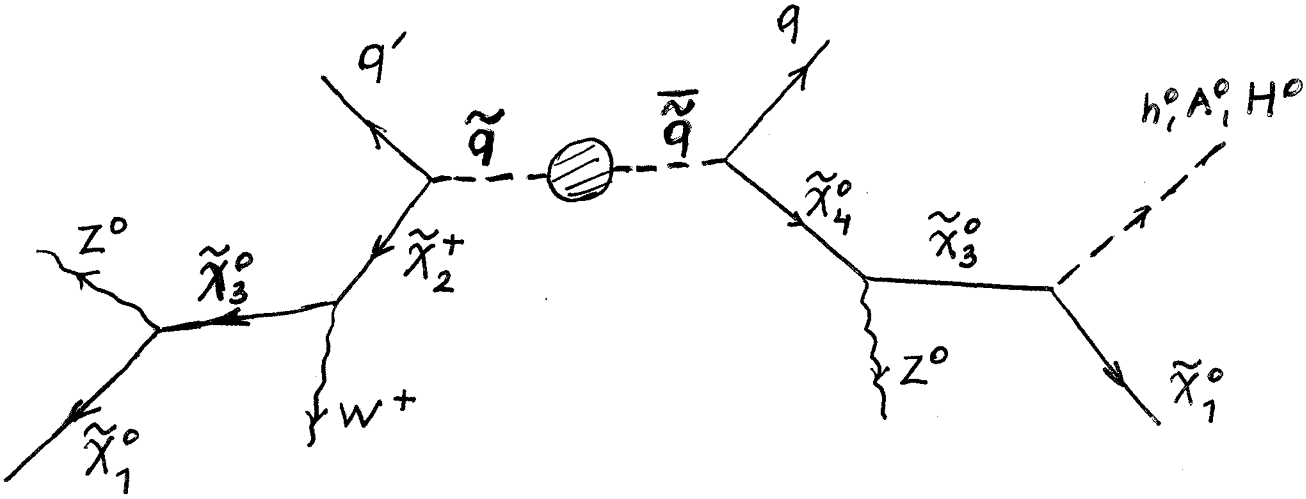
A.B., W. Majerotto, B. Mößlacher, N. Oshimo, S. Stippel

Also: H. Baer et al., R. Barbieri et al.
R.M. Barnett et al.

Signatures of $\tilde{q}\bar{\tilde{q}}$ pairs:



2 jets, large $p_{T\,miss}$

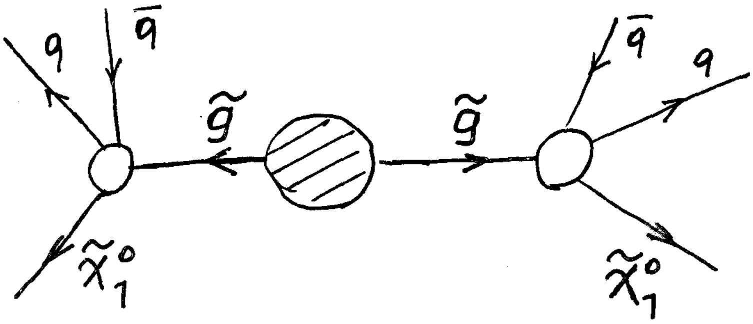


jets, $W^{\pm}$'s, Z^0's, Higgses, reduced $p_{T\,miss}$

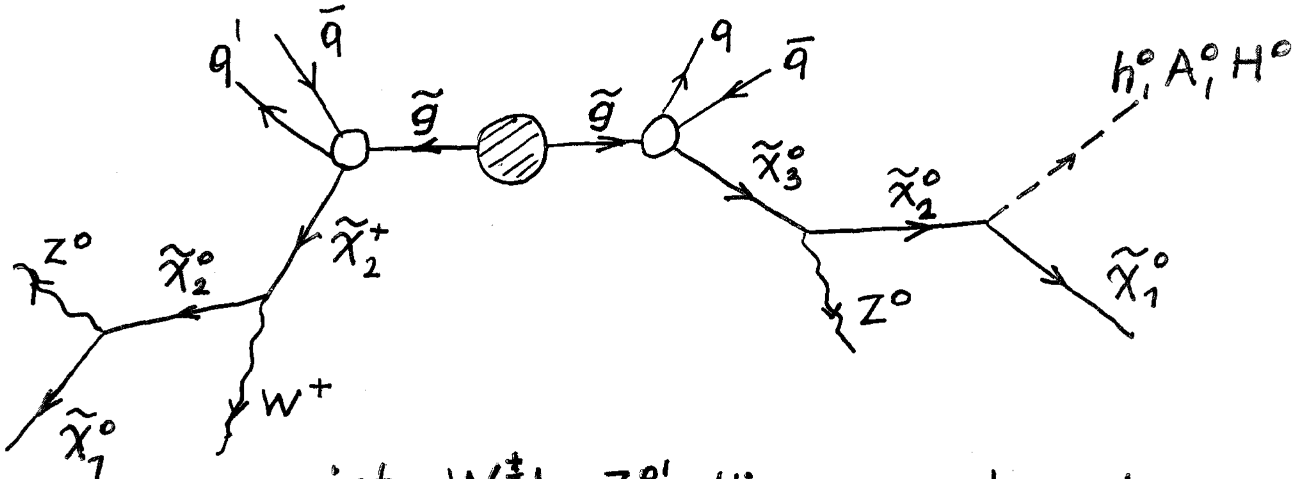
↓ ↓

Leptons (isolated)

Signatures of $\tilde{g}\tilde{g}$ pairs:



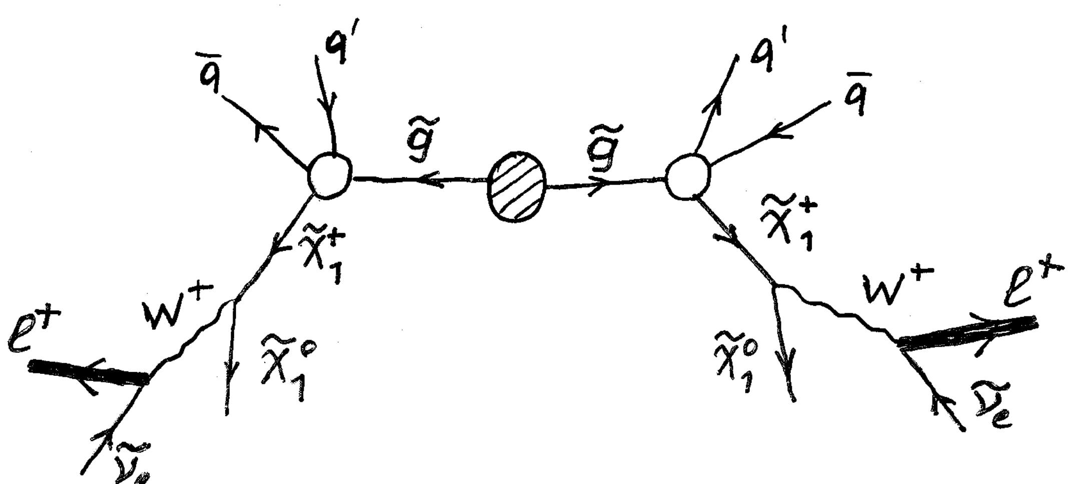
4jets, large $p_{T\,miss}$



jets, $W^{\pm}$'s, Z^{0}'s, Higgses, reduced $p_{T\,miss}$

↓ ↓

leptons (isolated)



same-sign dileptons ($\tilde{g}$ Majorana)

Possible TEVATRON Upgrades

Run "1B": Peak luminosity $\approx 2 \times 10^{31}\,cm^{-2}s^{-1}$

18 months $\Rightarrow$ $100\,pb^{-1}$

Main Injector: $\mathcal{L} \approx 10^{32}\,cm^{-2}s^{-1}$, Run "II": $2\,fb^{-1}$

CDF, DØ: proposed upgrades carried out

Ideas how to bridge time between LEP and LHC:

? TeV*: $\mathcal{L} \approx 2 \times 10^{32}\,cm^{-2}s^{-1}$

"Run II - stretch" $\Rightarrow$ $10\,fb^{-1}$?

? Incremental CDF and DØ upgrades?

? TeV33: $\mathcal{L} \approx 10^{33}\,cm^{-2}s^{-1}$ $\Rightarrow$ $25\,fb^{-1} \div 100\,fb^{-1}$?

? CDF, DØ ?

SUSY mass reach expected:

$\int \mathcal{L} = 2\,fb^{-1}$: $m_{\tilde{g}/\tilde{q}} \lesssim 350\,GeV$, $m_{\tilde{t}} \lesssim 150\,GeV$, $m_{\tilde{\chi}^{\pm}} \lesssim 210\,GeV$

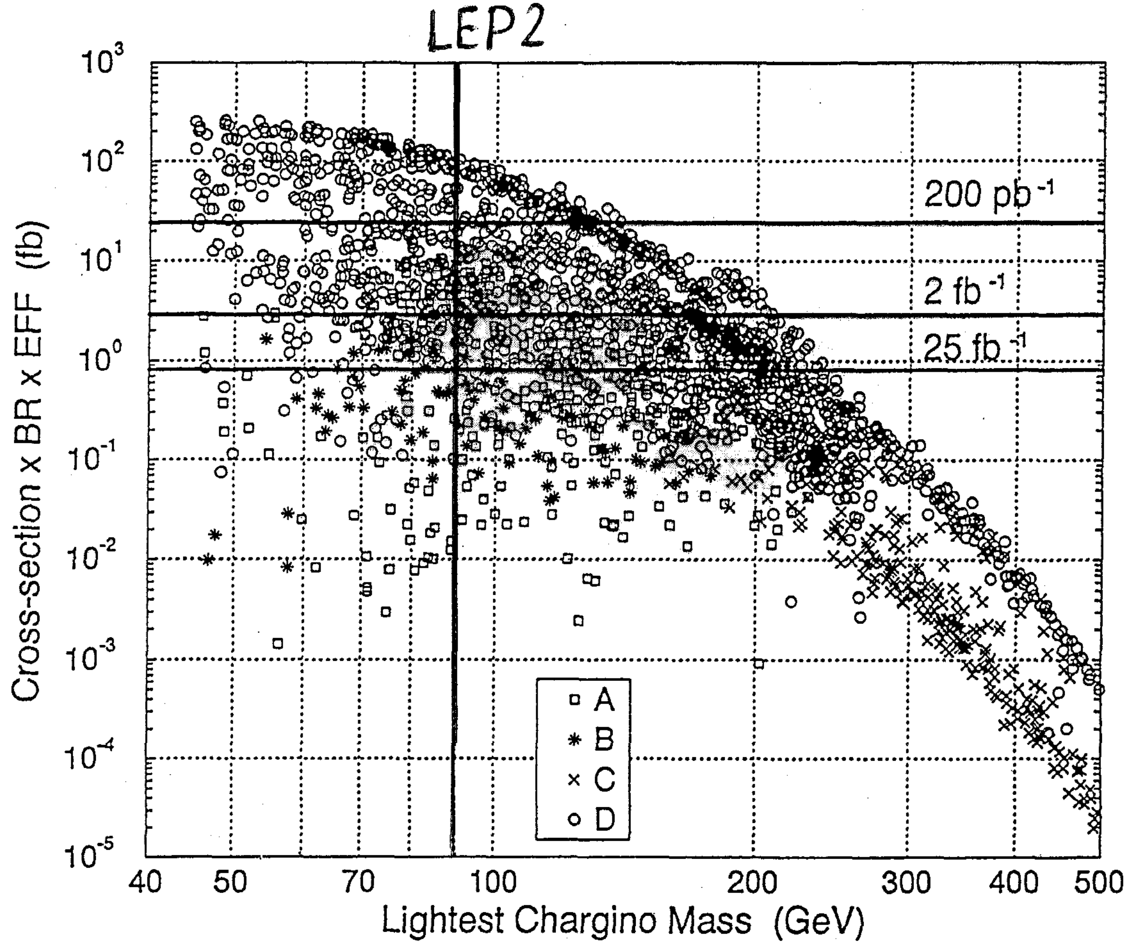
$\int \mathcal{L} = 25\,fb^{-1}$: $m_{\tilde{g}/\tilde{q}} \lesssim 400\,GeV$, $m_{\tilde{t}} \lesssim 180\,GeV$, $m_{\tilde{\chi}^{\pm}} \lesssim 250\,GeV$

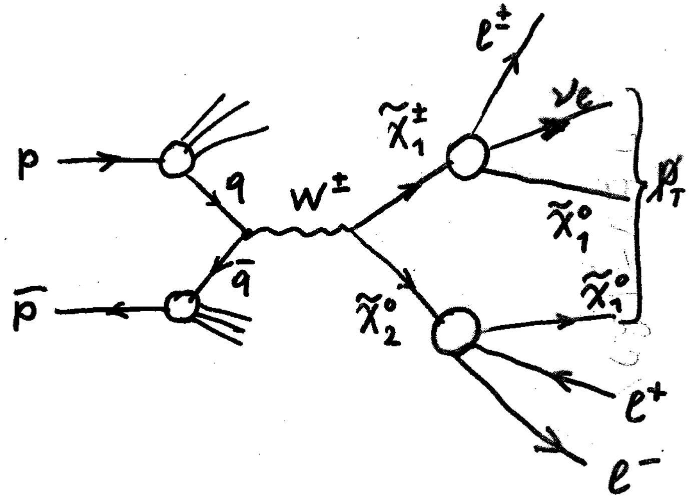
$p\bar{p} \to \tilde{\chi}_1^{\pm} \tilde{\chi}_2^{0} X \to \ell^{\pm} \ell^{+} \ell^{-} + \not{p}_T$

TEVATRON

TeV*, TeV33

$\sqrt{s} = 2\ \text{TeV}$





tev 2000 Study Group

□ A: $BR(\tilde{\chi}_2^0 \to \text{invisible}) > 90\%$

* B: large destructive interference in leptonic decays

× C: $BR(\tilde{\chi}_2^0 \to h^0 \tilde{\chi}_1^0) > 50\%$

Production X sections in pp:

([illegible] Snowmass)

LHC, $\sqrt{s} = 14$ TeV, $\int \mathcal{L} dt \approx 10^5 \, pb^{-1}$

$pp \to \tilde{g} + \tilde{g} + X$:

$m_{\tilde{g}} = 500$ GeV: $\sigma \approx 50$ pb $\sim 5 \times 10^6$ ev/y

$m_{\tilde{g}} = 1$ TeV: $\sigma \approx 1$ pb $\sim 10^5$ ev/y

$pp \to \tilde{q} + \bar{\tilde{q}} + X$:

$M_{\tilde{q}} = 500$ GeV: $\sigma \approx 15$ pb $\sim 10^6$ ev/y

$M_{\tilde{q}} = 1$ TeV: $\sigma \approx 0.4$ pb $\sim 4 \times 10^4$ ev/y

summed over flavours

Eloisatron, $\sqrt{s} = 200$ TeV, $\int \mathcal{L} dt \approx 10^5 \, pb^{-1}$

$pp \to \tilde{g} + \tilde{g} + X$:

$m_{\tilde{g}} = 1$ TeV: $\sigma \approx 900$ pb $\sim 9 \times 10^7$ ev/y

$pp \to \tilde{q} + \bar{\tilde{q}} + X$:

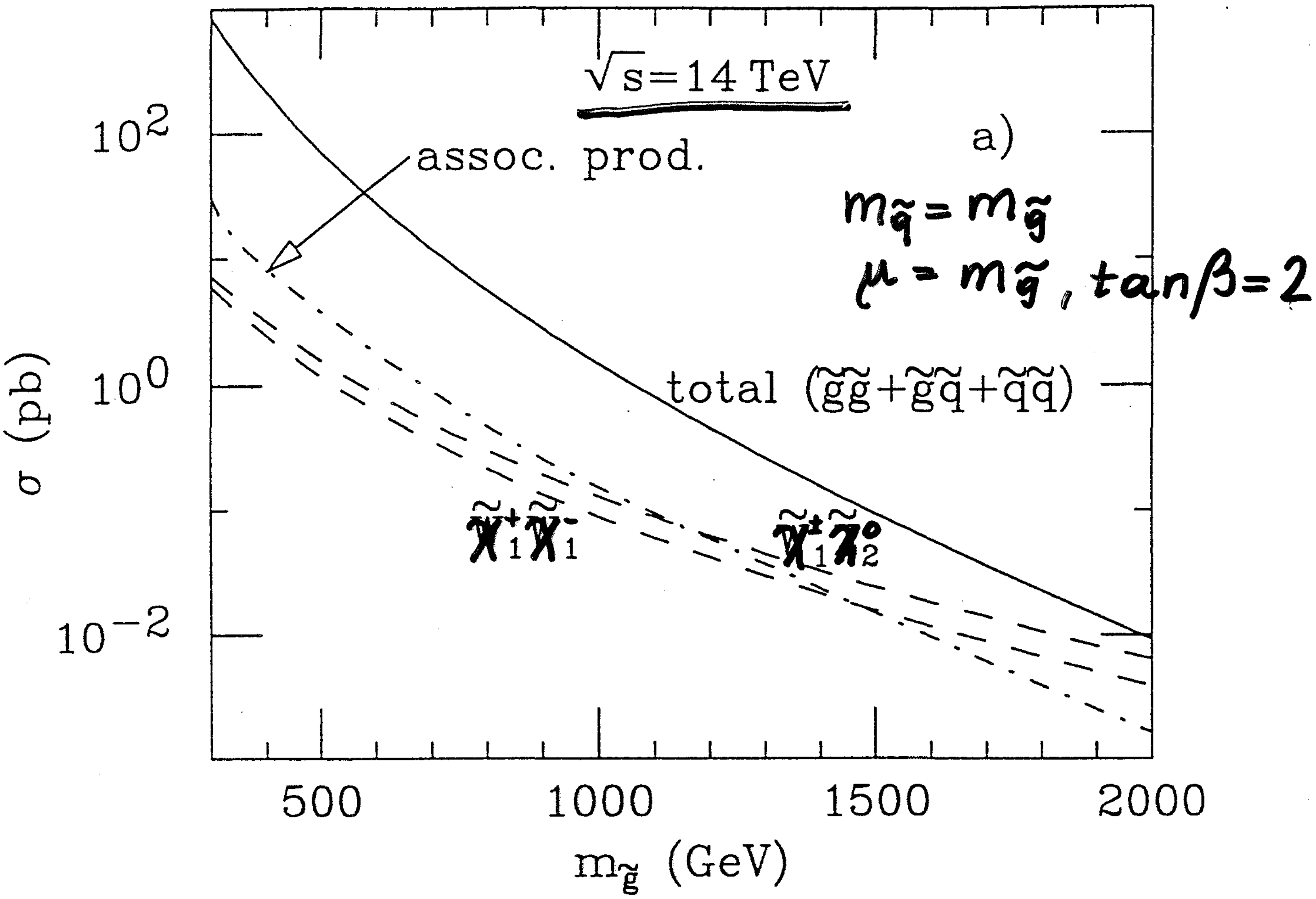
$M_{\tilde{q}} = 1$ TeV: $\sigma \approx 200$ pb $\sim 2 \times 10^7$ ev/y

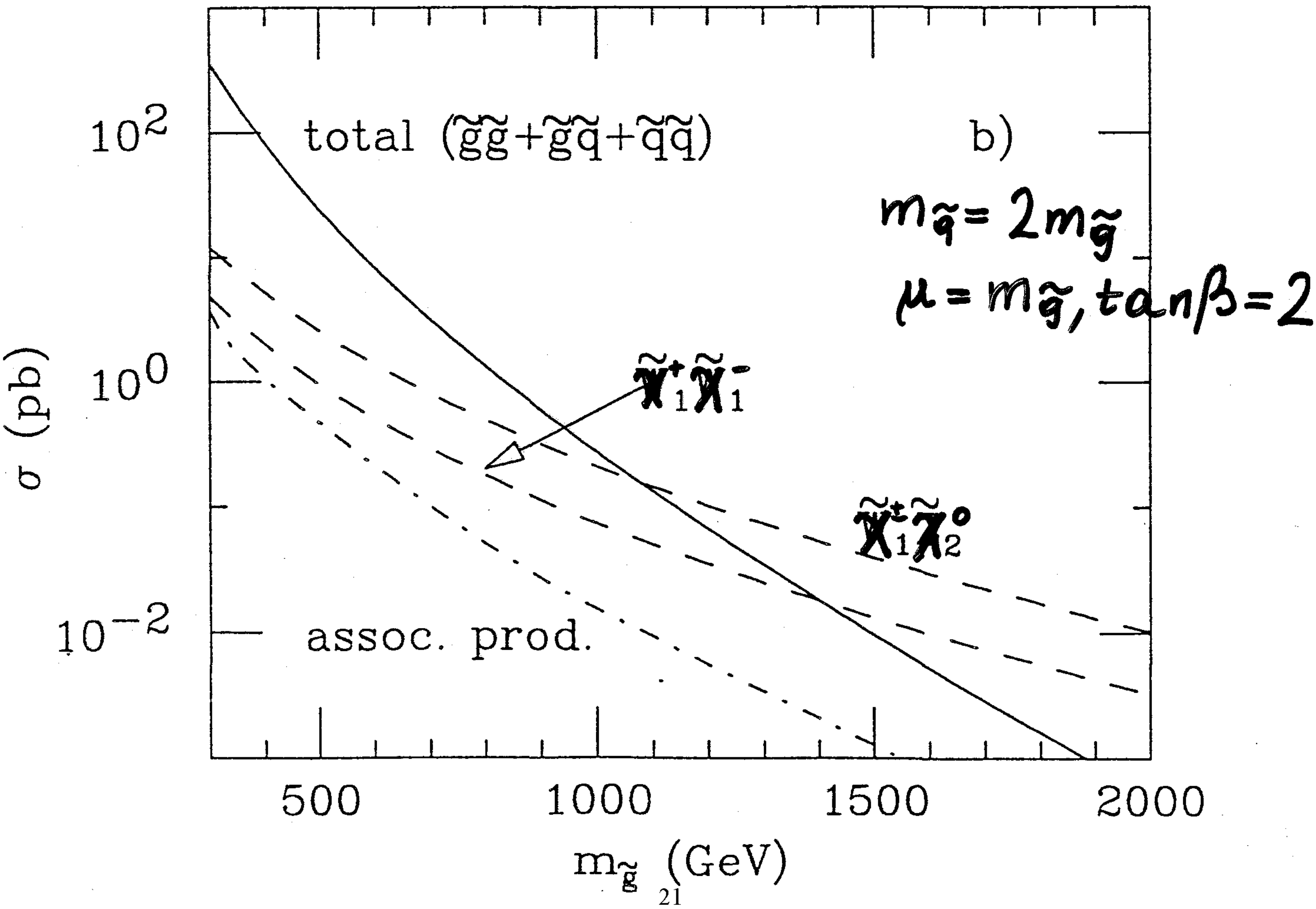
In addition: $pp \to \tilde{g} + \tilde{q} + X$, $pp \to \tilde{q}\tilde{q} X$

Results depend on details, like $\frac{m_{\tilde{g}}}{M_{\tilde{q}}}$, nucleon structure functions etc

Strong dependence on s and $m_{\tilde{q}, \tilde{g}}$

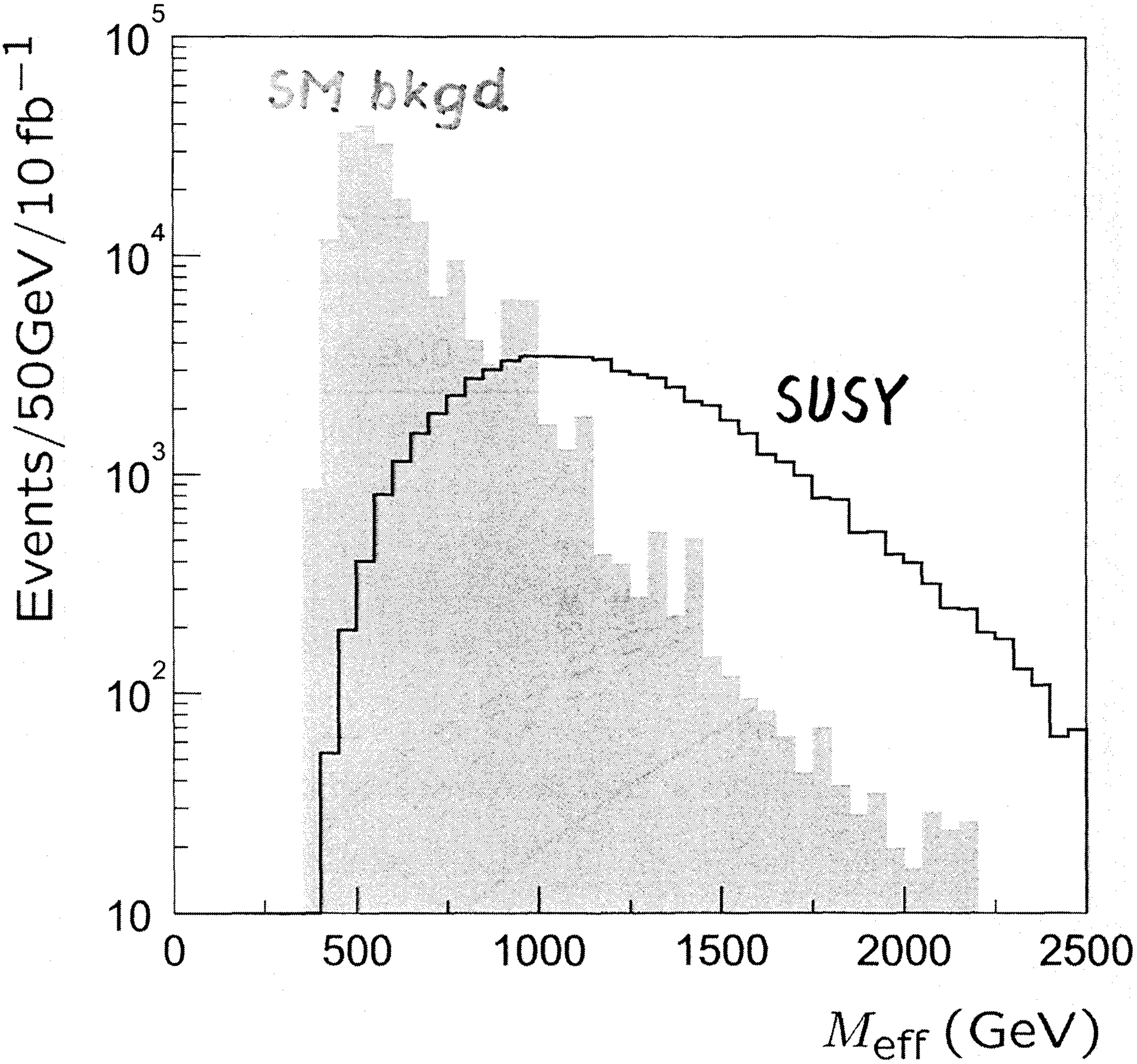
SUSY production LHC





M_{eff} : first indication for SUSY in events with jets + E_{miss}

$$M_{eff} = E_{T miss} + \sum_j E_{T j}$$



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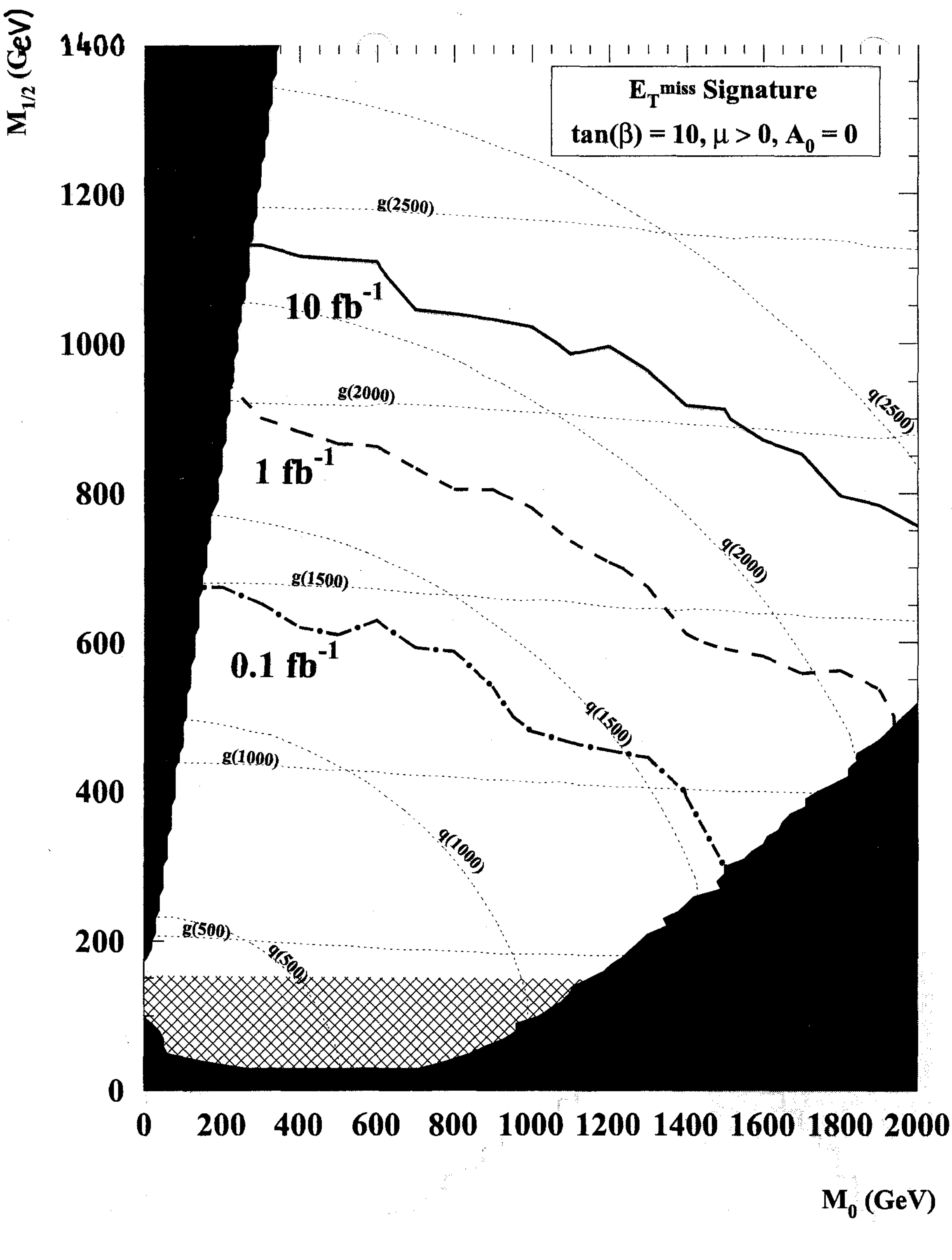
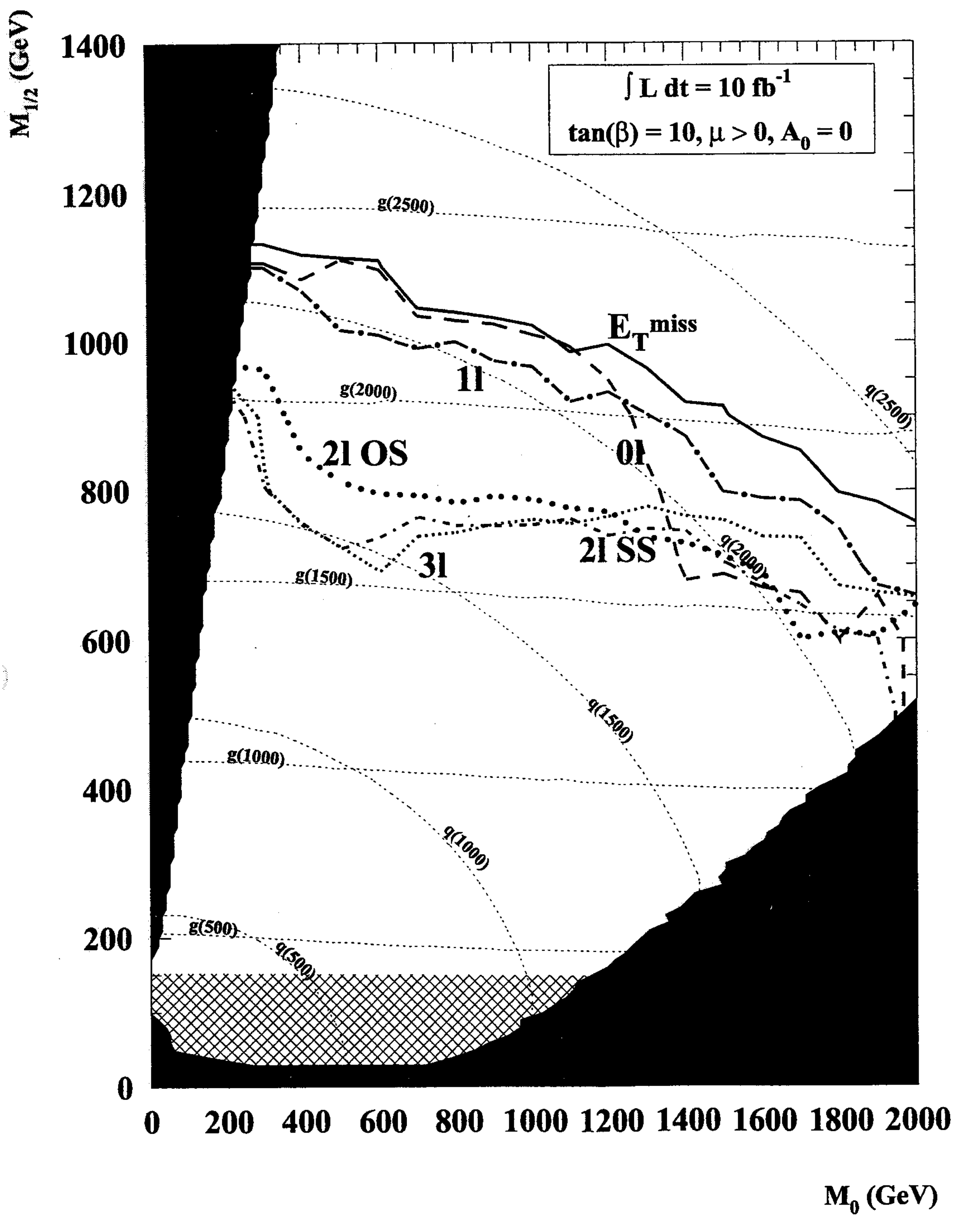
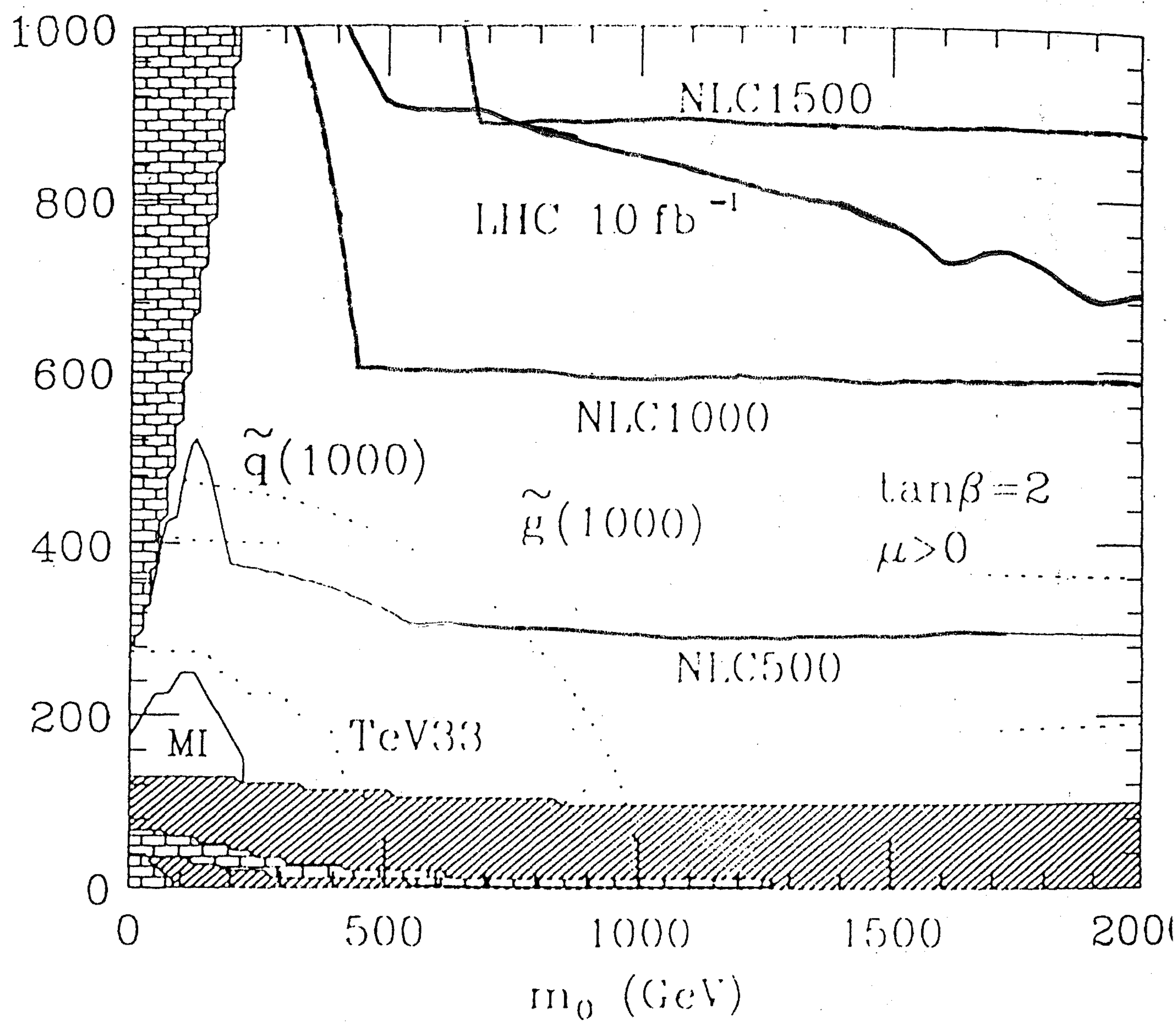


E_T^{miss} Signature
tan(β) = 10, μ > 0, A_0 = 0
$M_{1/2}$ (GeV)
M_0 (GeV)
10 fb^{-1}
1 fb^{-1}
0.1 fb^{-1}
g(2500)
g(2000)
g(1500)
g(1000)
g(500)
q(2500)
q(2000)
q(1500)
q(1000)
q(500)
0
200
400
600
800
1000
1200
1400
1600
1800
2000



∫ L dt = 10 fb^-1
tan(β) = 10, μ > 0, A_0 = 0
E_T^miss
1l
0l
2l OS
2l SS
3l
g(2500)
g(2000)
g(1500)
g(1000)
g(500)
q(2500)
q(2000)
q(1500)
q(1000)
q(500)
M_1/2 (GeV)
M_0 (GeV)
0
200
400
600
800
1000
1200
1400
1600
1800
2000


1000
800
600
400
200
0
0
500
1000
1500
2000
m_0 (GeV)
NLC1500
LHC 10 fb^{-1}
NLC1000
$\tilde{q}(1000)$
$\tilde{g}(1000)$
$\tan\beta=2$
$\mu>0$
NLC500
MI
TeV33

SUSY in e^+e^- collisions

LEP, LC

$e^+e^- \longrightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0, \tilde{\chi}_1^0 \tilde{\chi}_2^0, \tilde{\chi}_1^0 \tilde{\chi}_3^0, \tilde{\chi}_2^0 \tilde{\chi}_2^0 \ldots$

$e^+e^- \longrightarrow \tilde{\chi}_i^+ \tilde{\chi}_j^-$

$e^+e^- \longrightarrow \tilde{e}_{L,R}^+ \tilde{e}_{L,R}^-, \tilde{\mu}_{L,R}^+ \tilde{\mu}_{L,R}^-, \tilde{\tau}_i^+ \tilde{\tau}_j^-, \tilde{\nu}\bar{\tilde{\nu}}, \tilde{q}_{L,R}\bar{\tilde{q}}_{L,R} \ldots$

$\tilde{\chi}_1^0$ not seen (lightest SUSY particle)

Characteristic signatures from SUSY particle decays:

$\tilde{\chi}^\pm \longrightarrow \ell^\pm + \overset{(-)}{\nu} + \tilde{\chi}_1^0$
$\longrightarrow q + \bar{q}' + \tilde{\chi}_1^0$

$\tilde{\ell}_R \rightarrow \ell + \tilde{\chi}_1^0$
$\tilde{\ell}_L \rightarrow \ell + \tilde{\chi}_1^0, \nu_L + \tilde{\chi}_1^\pm$

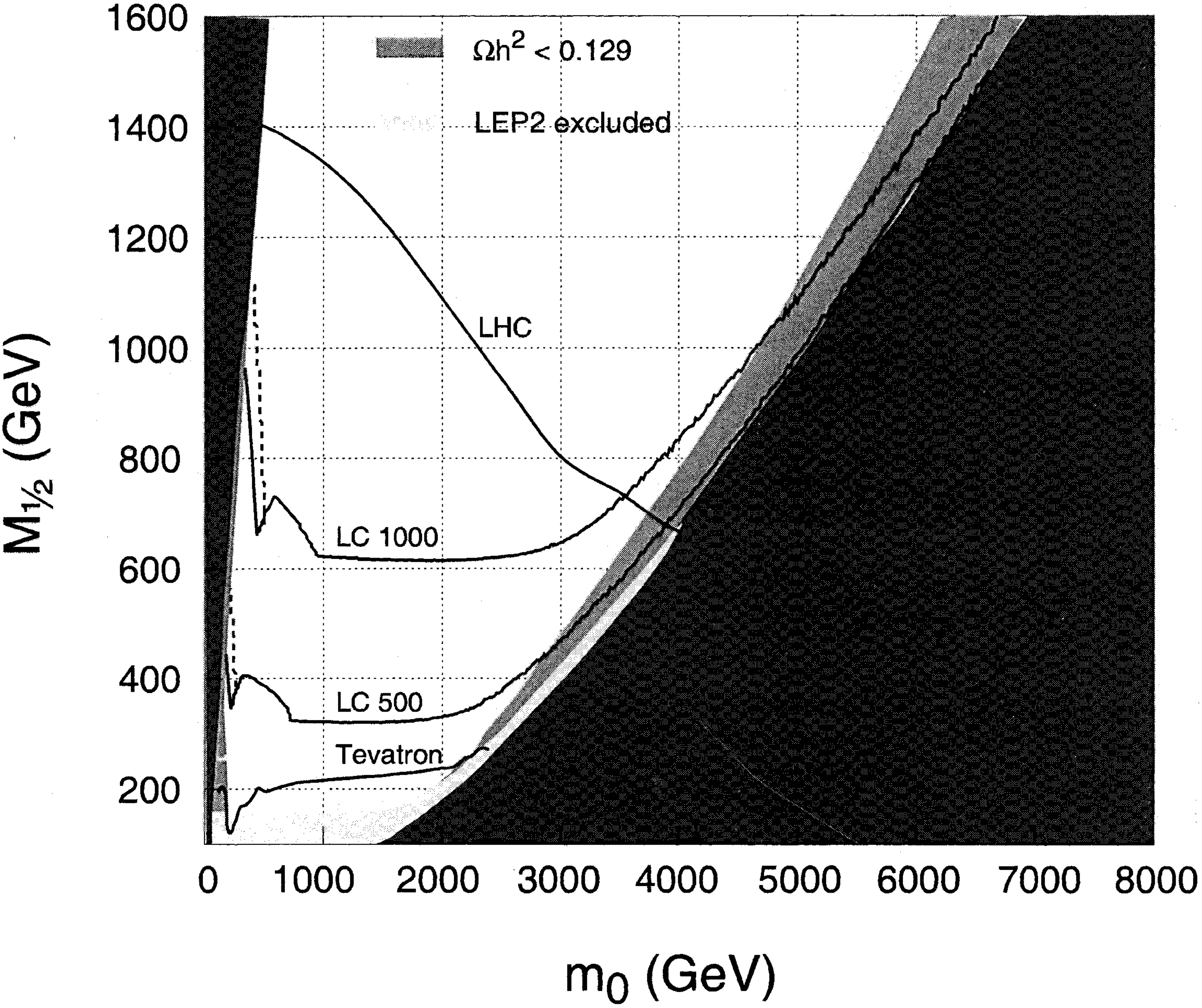
$\tilde{\chi}_i^0 \longrightarrow \ell^+ + \ell^- + \tilde{\chi}_1^0$ $\quad i = 2,3,4$
$\longrightarrow q + \bar{q} + \tilde{\chi}_1^0$
$\longrightarrow \nu + \bar{\nu} + \tilde{\chi}_1^0$
$\longrightarrow \gamma + \tilde{\chi}_1^0$
$\longrightarrow h\,(A) + \tilde{\chi}_1^0$

Barbieri et al.
J. Ellis et al.
K. Hidaka et al.
A.B. et al.
Chen et al. (Phys. Rep)

Canditates for lightest visible SUSY particle (LVSP)
$\tilde{\chi}_1^\pm, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_1, \tilde{t}_1, \tilde{b}_1, [\tilde{\chi}_2^0]$

$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \longrightarrow \ell^+ + \ell^- + \tilde{\chi}_1^0 + \tilde{\chi}_1^0$ two-sided events
$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0 \longrightarrow \ell^+\ell^- + \tilde{\chi}_1^0 + \tilde{\chi}_1^0$ one-sided events

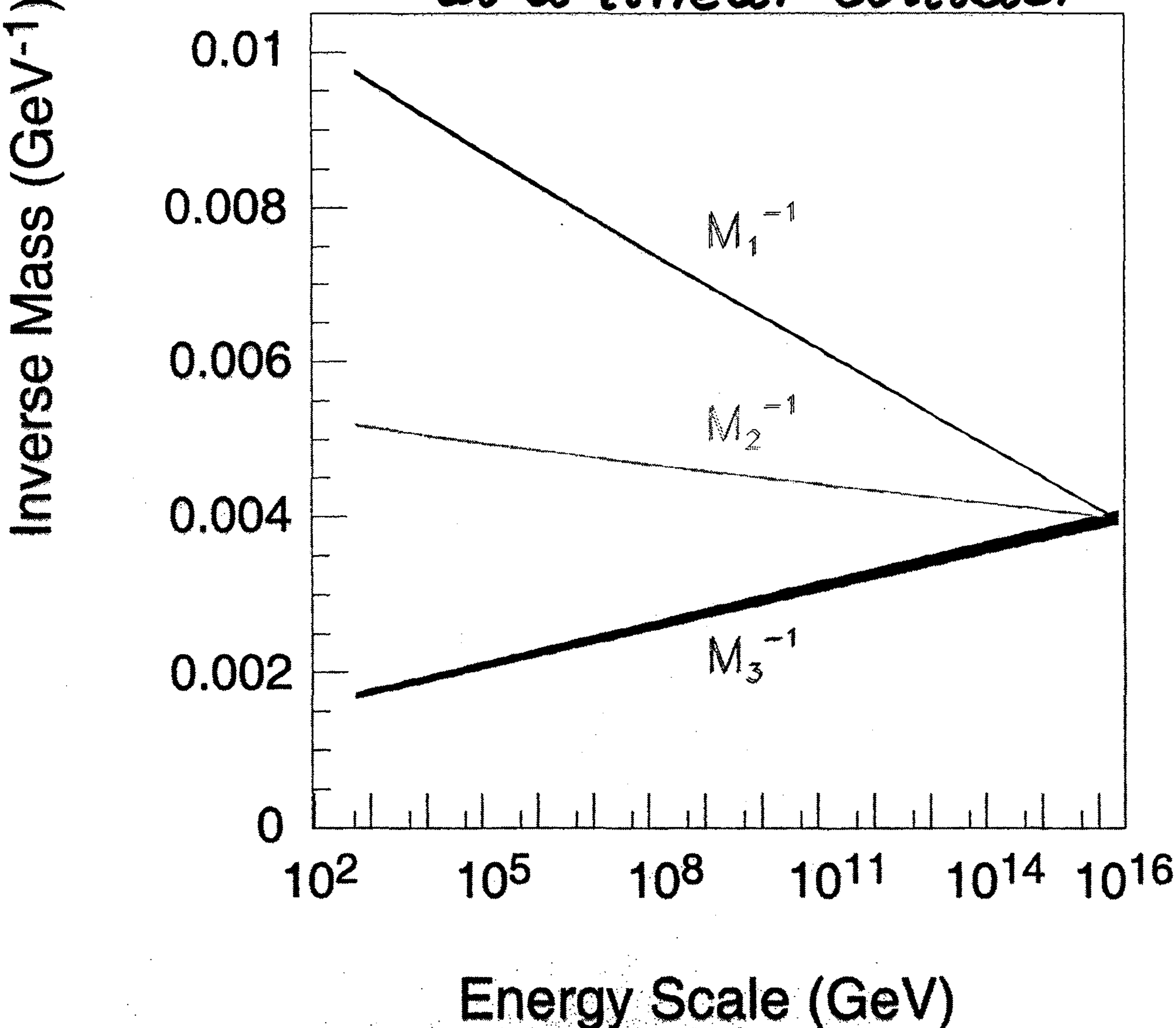
Canonical signature for SUSY: Missing $E, \vec{p}$



1600
1400
1200
1000
800
600
400
200
0
1000
2000
3000
4000
5000
6000
7000
8000
$M_{1/2}$ (GeV)
m_0 (GeV)
$\Omega h^2 < 0.129$
LEP2 excluded
LHC
LC 1000
LC 500
Tevatron

HO-PA 225
PVC FREI

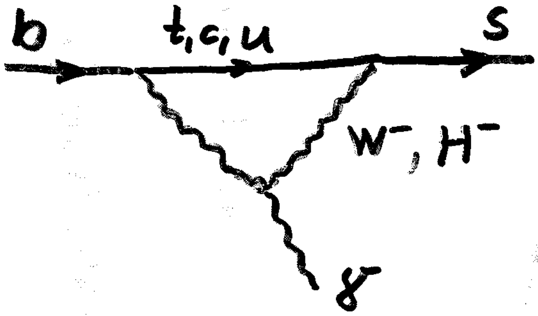
Test of gaugino masses unification at a linear collider



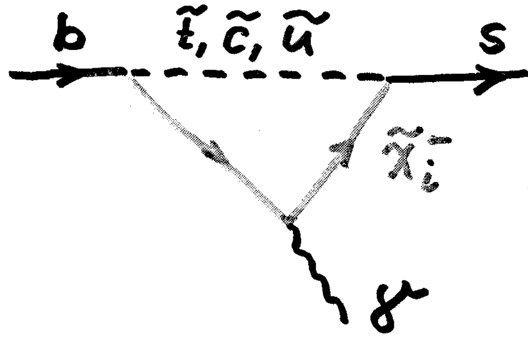
Indirect SUSY Searches

Contributions of virtual SUSY particle to precisely measured observables

- $b \to s + \gamma$: measured in $B \to K^* \gamma$ etc.



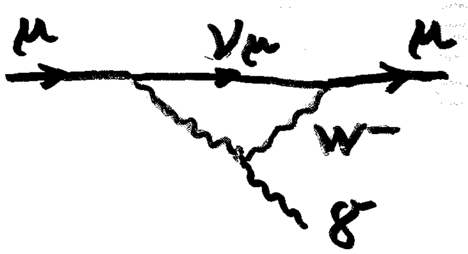
$+ \cdots$



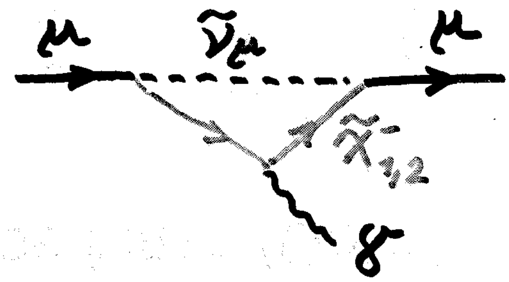
$+ \cdots$

$$2 \times 10^{-4} < BR(b \to s\gamma) < 4.5 \times 10^{-4}$$

- g-2 of muon: recently measured BNL



$+ \cdots$

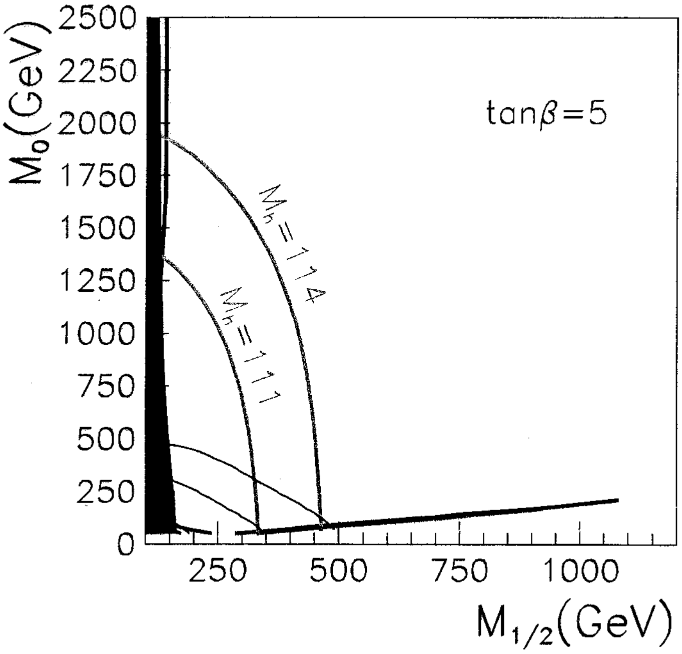


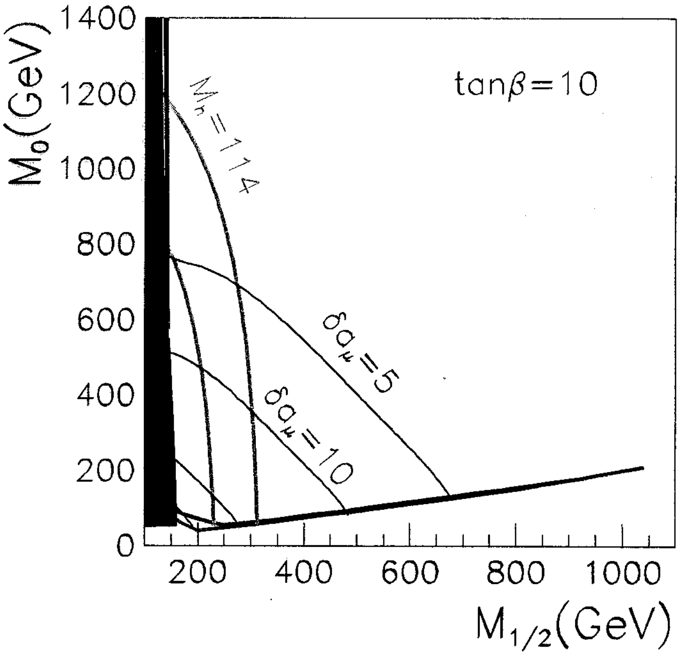
$+ \cdots$

$$a_\mu(\text{exp}) = 116592037(78) \times 10^{-11}$$
$$a_\mu(\text{SM}) = 116591883(49) \times 10^{-11}$$

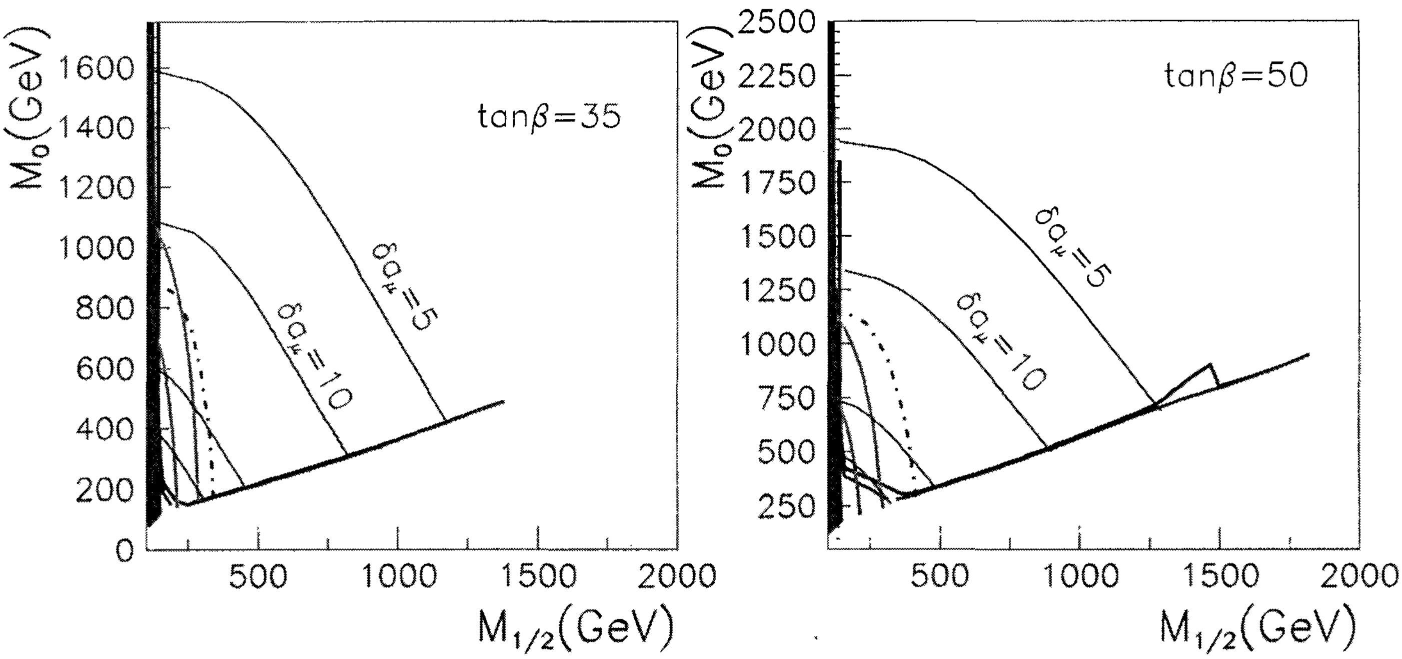
- Electric Dipole Moment of e and n
  $|d_e| < 4.0 \times 10^{-27}$ e cm

Constraints from relic $\tilde{\chi}_1^0$ density [WMAP] on mSUGRA parameters





Constraints from relic $\tilde{\chi}_1^0$ density [WMAP] on mSUGRA parameters



Extra Dimensions

ADD Model

prototype example

N. Arkadi-Hamed, S. Dimopoulos, G.R. Dvali (1998)

Gravity acts in $4+\delta$ dimensional "bulk"

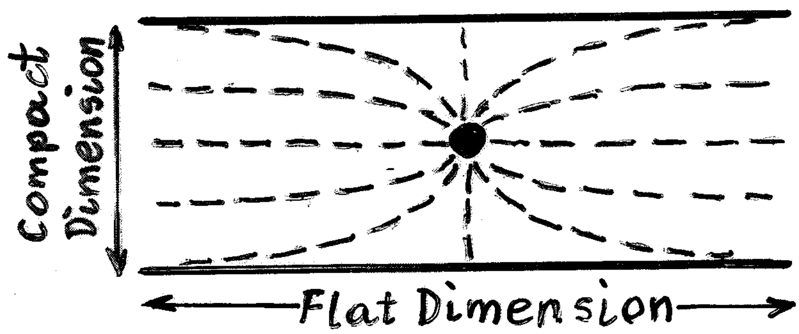
$\delta = 1, 2, 3, \ldots$ extra dimensions, compactified with a Radius R

SM fields restricted to 4-dim. brane

Newton's law

$$V(r) = \frac{1}{M_{Pl}^2}\frac{m_1 m_2}{r} \Longrightarrow \frac{1}{M_D^{2+\delta}}\frac{m_1 m_2}{r^{1+\delta}}$$

$$V(r) \xrightarrow[r \gg R]{} \frac{1}{M_D^{2+\delta}}\frac{m_1 m_2}{R^\delta r}$$



In 4-dim space-time: Planck mass $M_{Pl} = 1.2 \cdot 10^{19}$ GeV

In $4+\delta$ dim.: Planck mass $M_D^{2+\delta} \propto \frac{M_{Pl}^2}{R^\delta}$

Take $R \gg M_{Pl}^{-1}$, adjust R, δ that $M_D \approx \mathcal{O}(1\,\text{TeV})$

$\Rightarrow$ no hierarchy problem

More precisely: $R^\delta = \frac{1}{2\sqrt{\pi}\, M_D^\delta}\left(\frac{M_{Pl}}{M_D}\right)^2$

Take $M_D = 1\,\text{TeV} \Rightarrow R = \begin{cases} 8\times 10^{12}\,\text{m} & \delta = 1 \\ 0.7\,\text{mm} & \delta = 2 \\ 3\,\text{nm} & \delta = 3 \\ 6\times 10^{-12}\,\text{m} & \delta = 4 \end{cases}$

We could have $M_D \approx 1\,\text{TeV}$ for $\delta \gtrsim 2$.

Expect deviations from Newton's law for small r. For $r \lesssim 1\,\text{mm}$ experimentally not tested.

Gravity is strong force in $4+\delta$ dimensions, on the brane its effect is diluted by the volume of the bulk.

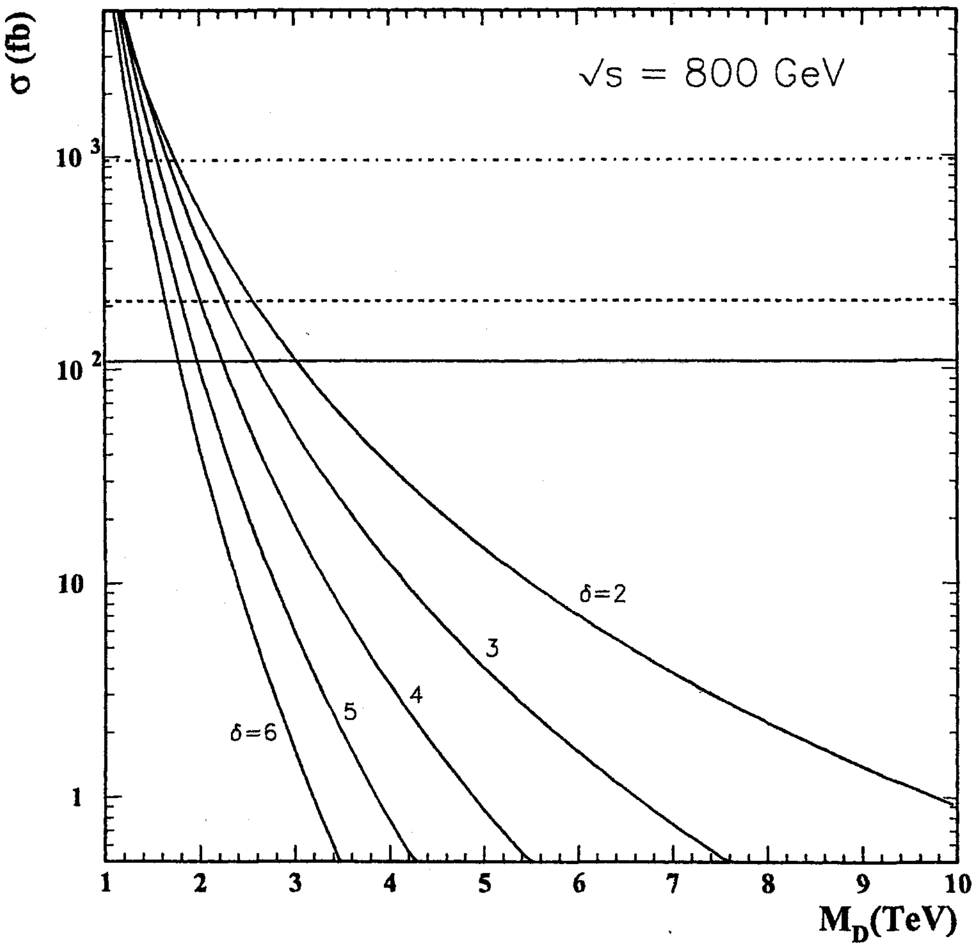
Compactification ⇒ Kaluza-Klein modes of graviton may be excited in the bulk.

Other models:

Universal extra dimensions (UED):
Gravity and SM fields in the bulk
↳ have also KK states

Randall-Sundrum (RS) model:
5-dim AdS with two branes and scalar field (→ radion) in bulk.
SM fields on "TeV brane", gravity on "Planck brane".
Strength of gravity on TeV brane reduced by "warp factor" $e^{-\pi k R}$

"Large" extra dimensions — Arkadi-Hamed et al., Antonidis et al....



M_D reach:

$M_D \lesssim 7.9$ TeV for $\delta = 2$

$M_D \lesssim 5.6$ TeV for $\delta = 3$

$M_D \lesssim 4.2$ TeV for $\delta = 4$

equivalent to LHC

$M_D \lesssim 3.4$ TeV for $\delta = 5$

$M_D \lesssim 2.9$ TeV for $\delta = 6$

no result from LHC for $\delta = 5, 6$

Figure 4.2.1: *Total cross sections for* $e^+e^- \to \gamma G$ *at* $\sqrt{s} = 800$ *GeV as a function of the scale* M_D *for different numbers* δ *of extra dimensions. These signal cross-sections take into account 80% electron and 60% positron polarisation [14]. The three horizontal lines indicate the background cross-sections from* $e^+e^- \to \nu\bar{\nu}\gamma$ *for both beams polarised (solid), only electron beam polarisation (dashed) and no polarisation (dot-dashed). Signal cross-sections are reduced by a factor of 1.48 for the latter two scenarios.*

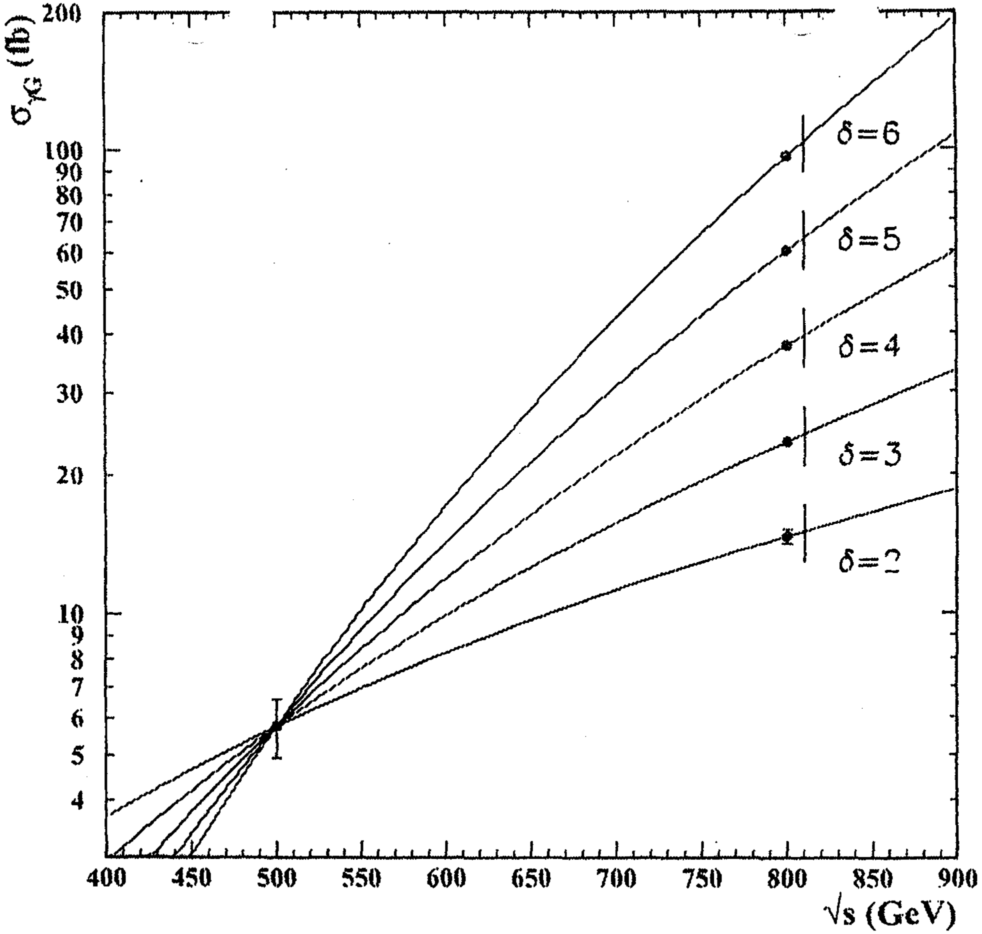


Figure 4.2.2: *Determining δ from anomalous single photon cross-section measurements at $\sqrt{s} = 500$ GeV and 800 GeV. The sensitivity shown corresponds to integrated luminosities of 500fb^{-1} at $\sqrt{s} = 500$ GeV and 1 ab^{-1} at $\sqrt{s} = 800$ GeV with 80% electron and 60% positron polarisation with a cross-section at 500 GeV equivalent to $M_D = 5$ TeV if $\delta = 2$. The points with error bars show the measurements one could expect. The smooth curves show the cross-section dependence on $\sqrt{s}$ for the central value of the 500 GeV cross-section measurement under the hypotheses of δ = 2,3,4,5 and 6. The vertical lines adjacent to the 800 GeV measurements indicate the range that would be consistent within $\pm 1\sigma$ with the 500 GeV measurement.*

Randall-Sundrum model

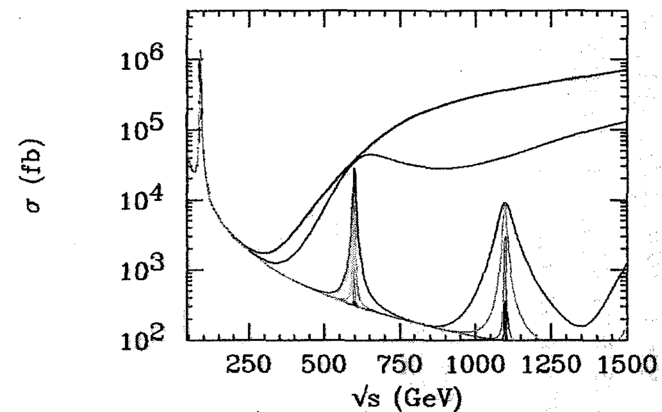


Figure 4.2.5: *The cross section for $e^+e^- \to \mu^+\mu^-$ including the exchange of a KK tower of gravitons with $m_1 = 600$ GeV. From top to bottom the curves correspond to $k/\overline{M}_{Pl} =$ 1.0, 0.7, 0.5, 0.3, 0.2 and 0.1.*

AdS_5 with 2 branes:

SM on one brane, gravity on the other one.

"Strength" of gravity on SM brane reduced by $\exp\{-2kr_c\}$

curvature ↗ ↖ compactification

2 parameters determine phenomenology

$\Rightarrow \frac{k}{\overline{M}_{Pl}}$ and m_1 (1st KK excitation of graviton)

Two classes of signatures:

(i) Emission of real gravitons plus KK modes

(ii) Modification of SM reactions by exchange of virtual graviton plus KK modes

Searches at LEP, Tevatron, LHC, Linear Collider.

M_D reach at Linear Collider:

M_D = 10 TeV, 6.9 TeV, 5.1 TeV, 4 TeV
for δ = 2, 3, 4, 5

$e^+e^- \longrightarrow \gamma + G_n$

↳ graviton plus KK states, not seen in detector $\Rightarrow E_{miss}$

Detailed analyses of angular distributions to distinguish E_{miss} signature from SUSY

Final remark

There are good prospects that we will find interesting new results in

Accelerator Particle Physics

and

Non-Accelerator Astroparticle Physics