SUSY-GUT

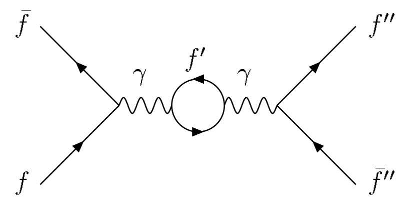
SUSY physically motivated by GUT: stability of the radiative corrections to W, Z, H masses.
Aim: resonstruction of the fundamental SUSY theory at the GUT/PLANCK scale.

MSSM: 124 free parameters $\rightsquigarrow$ constrained by unification at the GUT scale

(a) Unification of the gauge couplings

SM: $SU_3 \times SU_2 \times U_1 \stackrel{GUT}{\rightarrow} SU_5 \quad g_3 \;\; g_2 \;\; g_1 \rightarrow g_5 : \sin^2\theta_W = \frac{3}{8}$ at GUT

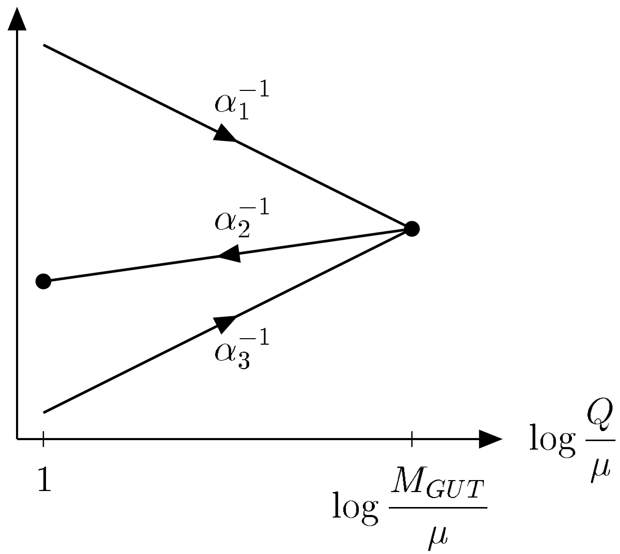
Running couplings:



$$\frac{\partial \alpha_i}{\partial \log \mu^2} = -\frac{b_i}{4\pi}\alpha_i^2 + \mathcal{O}(\alpha_i^3)$$

$$\text{SM:} \quad b_i = \left|\begin{matrix} 0 \\ \frac{22}{3} \\ 11 \end{matrix}\right| - N_G \left|\begin{matrix} \frac{4}{3} \\ \frac{4}{3} \\ \frac{4}{3} \end{matrix}\right| - N_H \left|\begin{matrix} \frac{1}{10} \\ \frac{1}{6} \\ 0 \end{matrix}\right|$$

$$\text{SUSY:} \quad b_i = \left|\begin{matrix} 0 \\ 6 \\ 9 \end{matrix}\right| - N_G \left|\begin{matrix} 2 \\ 2 \\ 2 \end{matrix}\right| - N_H \left|\begin{matrix} \frac{3}{10} \\ \frac{1}{2} \\ 0 \end{matrix}\right|$$



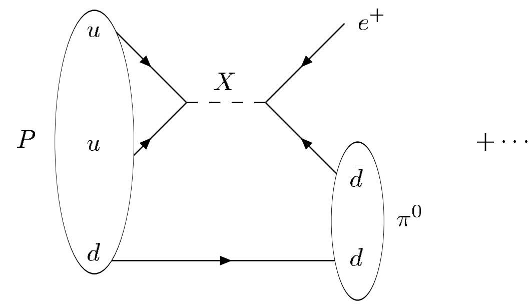
	SM:	0.2100 ± 0.0026
$\underline{\sin^2\theta_W(M_Z^2)}$:	MSSM:	0.2335 ± 0.0017
	exp:	0.2316 ± 0.0002

- SM couplings cannot be unified. SUSY couplings can
- SUSY predictions of $\sin^2\theta_W$ within 2 permille. Independent of details of the $\tilde{M} \sim 1$ TeV spectrum, only sensitive to particle spectrum.

(b) Proton decay:

SM-SU(5): gauge interactions between leptons and quarks:

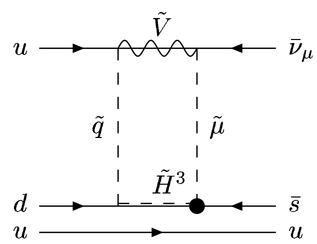
$$\tau(P \to \pi^0 + e^+) \sim \frac{M_X^4}{\alpha_5^2 M_P^5}$$



SM: $M_X \sim 10^{15}$ GeV: $\sim 10^{30}$ a   SUSY: $M_X > 10^{16}$ GeV: $\gtrsim 10^{35}$ a (exp: $> 10^{33}$ a)

However: additional dim 5 contribution

$$\tau(P \to K^+\bar{\nu}_\mu) \sim \left(\frac{16\pi^2}{\lambda^2 g^2}\right)^2 \frac{m_{\tilde{H}^3}^2 \tilde{m}^2}{M_P^5}$$ near experimental limit



(c) Radiative symmetry breaking:

universal sGUT masses (mSUGRA): Gauginos: $M_1, M_2, M_3 = M_{1/2}$

Scalars: $M_H^2 - \mu^2 = m_{\tilde{l}}^2 = m_{\tilde{q}}^2 = M_0^2$

RGE: GUT $\rightarrow$ ELW

$$\frac{\partial}{\partial \log Q} \begin{pmatrix} M_{H_2}^2 \\ m_{\tilde{t}_R}^2 \\ m_{\tilde{t}_L}^2 \end{pmatrix} = \frac{g_t^2}{8\pi^2} \begin{pmatrix} 3 & 3 & 3 \\ 2 & 2 & 2 \\ 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} M_{H_2}^2 \\ m_{\tilde{t}_R}^2 \\ m_{\tilde{t}_L}^2 \end{pmatrix} + \frac{g_t^2 A_t^2}{8\pi^2} \begin{pmatrix} 3 \\ 2 \\ 1 \end{pmatrix}$$

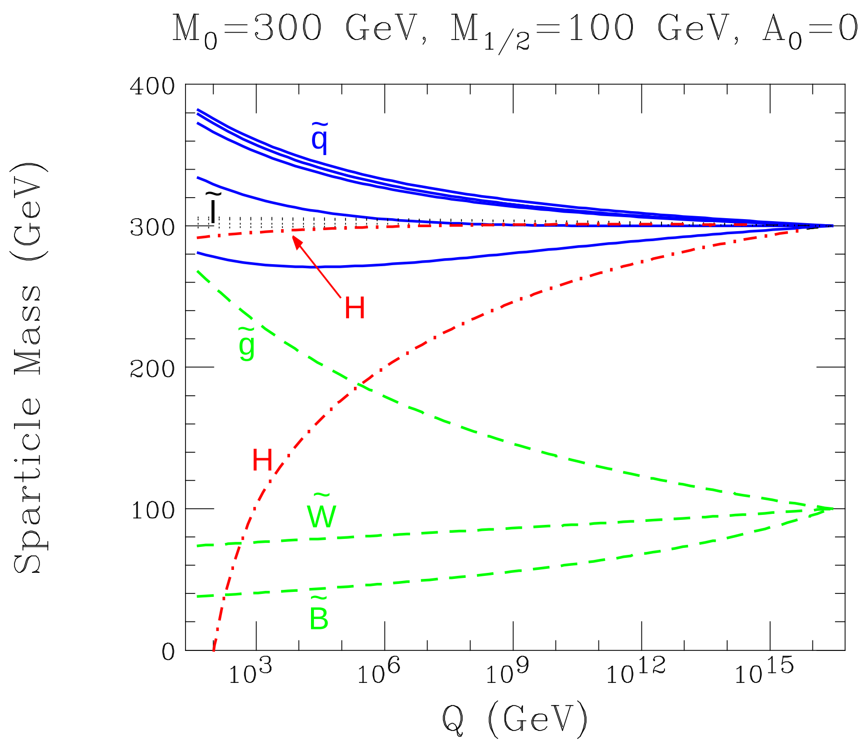
Evolution: $M_{H_2}^2(Q^2) \approx M_0^2 + \mu^2 - \frac{3g_t^2}{8\pi^2}(3M_0^2 + \mu^2) \log \frac{M_{GUT}}{Q}$

Bagger

$M_{H_2}^2(M_Z^2) < 0$ possible for $m_t \sim 100 - 200$ GeV

$\rightarrow$ radiative symmetry breaking

$SU_3 \times SU_2 \times U_1 \rightarrow SU_3 \times U_1^{em}$



SUSY Breaking Mechanisms

Ferrara sum rule: no spontaneous symmetry breaking in eigenworld: $\sum(-1)^{2J}(2J+1)M_J^2 \neq 0$.

Mechanisms:

Mechanisms:	Supergravitation	mSUGRA
	Gauge-mediated SUSY breaking	GMSB
	Anomaly-mediated SUSY breaking	AMSB
	Scherk-Schwarz SUSY breaking	SSSB ...

Minimal SUPERGRAVITATION:

Hidden sector SUSY: $\langle\bar{\lambda}\lambda\rangle \neq 0$	$\rightsquigarrow$ *GRAV.* $\rightsquigarrow$	Eigenworld	$\Rightarrow$ $M_{SUSY\,break} \sim 10^{11}$ GeV

Soft parameters "universal": 5 parameters: $M_0, M_{1/2}, A_0, \tan\beta, \mathrm{sgn}\mu$

Evolution: GUT $\rightarrow$ ELW:

$$\frac{\partial M_i}{\partial \log \mu^2} = -\frac{b_i}{4\pi}\alpha_i M_i$$
$$\frac{\partial \alpha_i}{\partial \log \mu^2} = -\frac{b_i}{4\pi}\alpha_i^2$$
$$\Rightarrow \frac{M_i}{\alpha_i} = \text{const}$$

Gaugino masses run like gauge couplings $\Rightarrow$

$$M_1 = M_2 \tfrac{5}{3} \cdot \tan^2\theta_W \sim \tfrac{1}{2} M_2 \qquad (M_i(M_{GUT}) = M_{1/2})$$
$$\frac{M_3}{M_2} = \frac{\alpha_3}{\alpha_2} \gg 1 \Rightarrow \qquad m_{\tilde{g}} \gg m_{\tilde{\chi}}$$

Reconstruction of the fundamental theory at GUT/Planck scale:

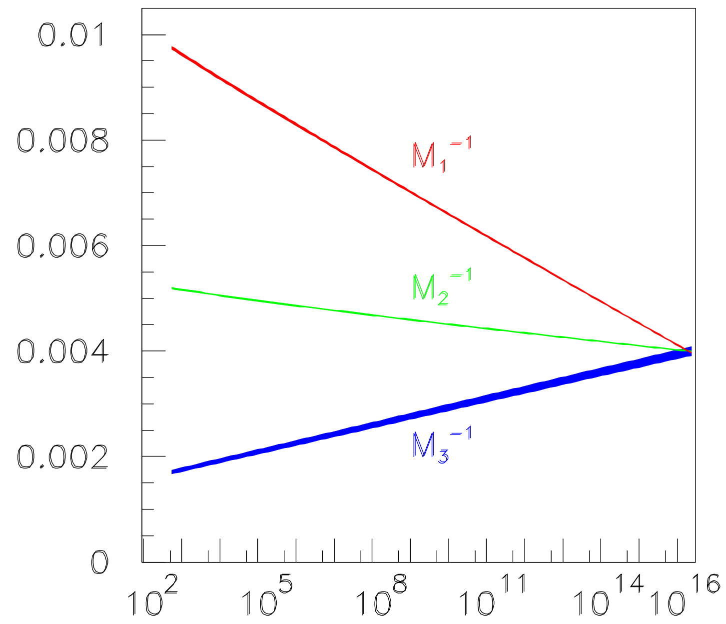
high-precision measurements of low-energy Lagrangian parameters (LHC+ILC)

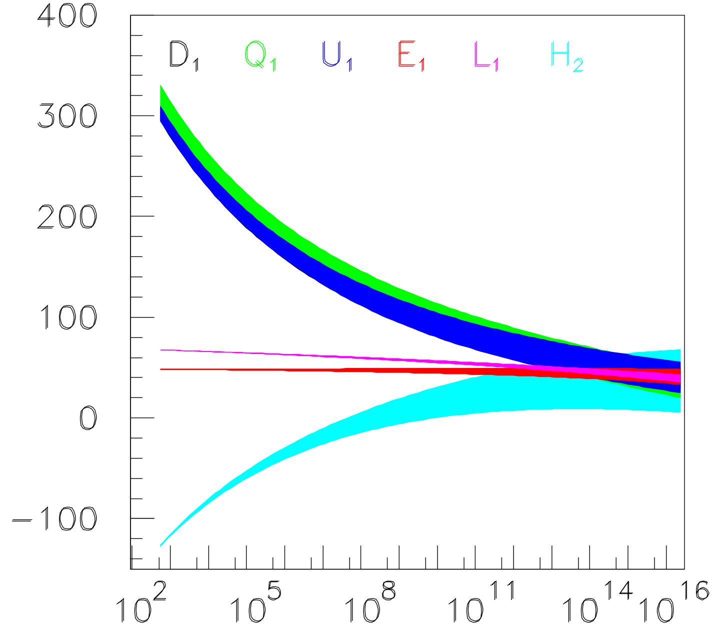
⇒ extrapolate to high scale: - symmetries/universal behaviour?
- impact of high-scale physics?

Evolution: RG equations

Evolution: gaugino and scalar mass parameters

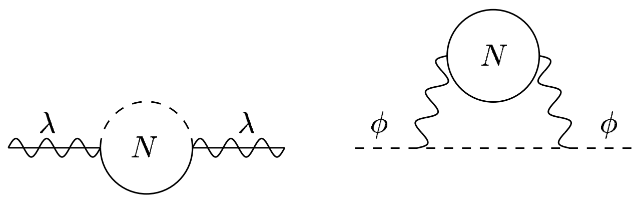
Blair,Porod,Zerwas





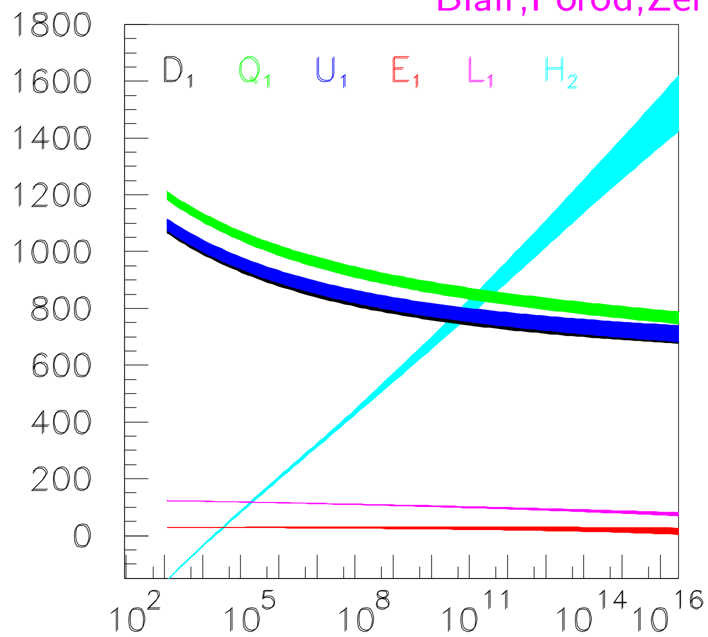
Gauge-mediated SUSY breaking (GMSB):

- flavor-blind SUSY-breaking mediating interactions are ordinary EW and QCD gauge interactions
- MSSM soft terms come from loop diagrams involving messenger particles
- messengers are new chiral supermultiplets coupling to a SUSY breaking VEV (F) and also have $SU(3)_C \times SU(2)_L \times U(1)_Y$ interactions providing the necessary connection to the MSSM



- gaugino masses evolve like in mSUGRA but without unification
- scalar masses significantly different, determined by F, the messenger mass M_{mess} and the number N of messenger fields
- 5 parameters: $F, M_{mess}, N, \tan\beta$, sgn$\mu$
- $m_{\tilde{e}_L} = M_{H_u}$ at $\mu = \sqrt{F} \rightarrow$ exp. reconstr. of $\sqrt{F} = M_{SUSY break}$
- lower limit to M_{mess}, SUSY masses $\Rightarrow \sqrt{F} \gtrsim 10^5$ GeV
- Gravitino is LSP, $m_{\tilde{G}} \sim \frac{<F>}{M_{Planck}} \ll M_{weak}$
- NLSP: (i) N small $\rightarrow$ neutralino
  (ii) N large $\rightarrow$ slepton

Blair,Porod,Zerwas



SUSY Particle Production

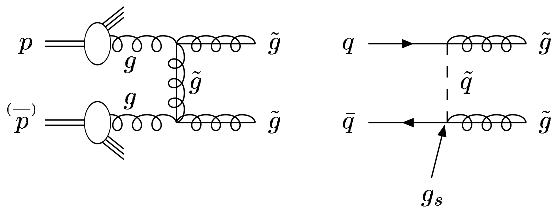
(i) Hadron Collider

Large production cross sections for moderate squark/gluino masses through strong interactions in $pp/p\bar{p}$ collisions

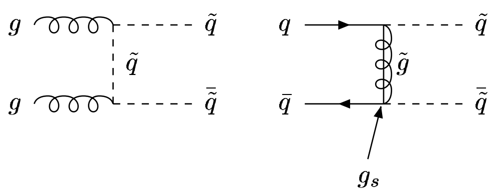
3 classes of SUSY pair production processes:

(i) Strongly interacting particle pairs

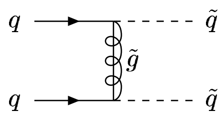
$p\overset{(-)}{p} \longrightarrow \tilde{g}\tilde{g}$



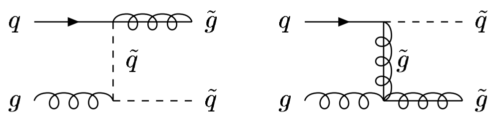
$p\overset{(-)}{p} \longrightarrow \tilde{q}\bar{\tilde{q}}$



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



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



$$\sigma_{gg} = \int_{\tau_0}^1 dx_1 \int_{\tau_0/x_1}^1 dx_2 \, g(x_1, \mu_F^2) g(x_2, \mu_F^2) \, \hat{\sigma}_{gg}(\hat{s} = x_1 x_2 s)$$

with $\tau_0 = 4m^2/s$ $[m = (m_1 + m_2)/2]$ and

$$\hat{\sigma}_{gg}(\hat{s} = x_1 x_2 s) = \alpha_s^2(\mu_R) f_0(\hat{s} = x_1 x_2 s)$$

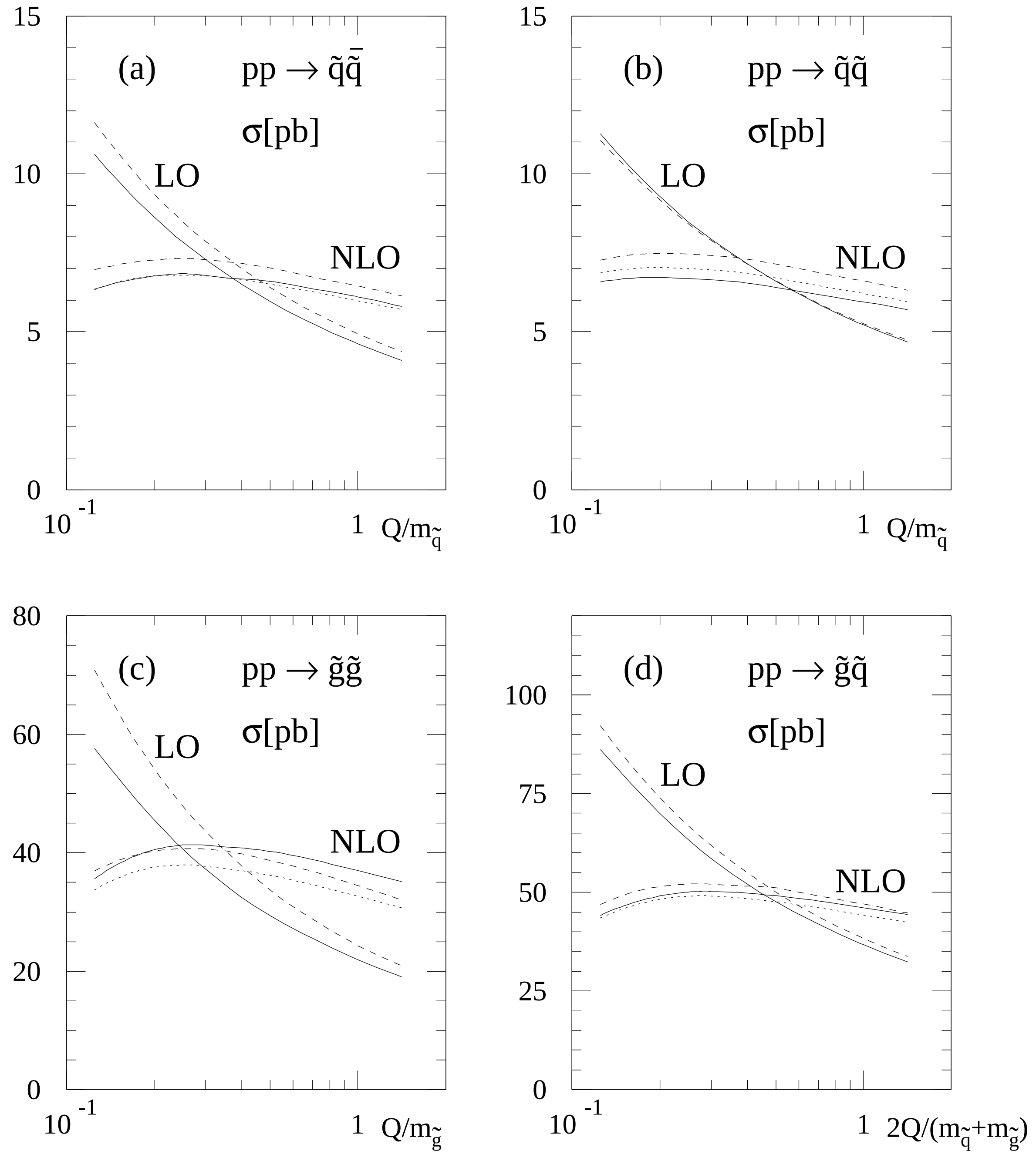
- leading order: large theoretical uncertainties (due to undefined renormalization scale μ_R, factorisation scale μ_F)
- natural scale: $\mu_R = \mu_F = m$; scale variation $\rightarrow$ estimate of theoretical uncertainties with respect to scale choice (large logarithms in higher order):

$$\begin{aligned} \alpha_s(Q^2) &= \frac{\alpha_s(\mu^2)}{1 + \frac{33-2N_F}{12} \frac{\alpha_s(\mu^2)}{\pi} \log \frac{Q^2}{\mu^2}} \\ &= \alpha_s(\mu^2) \left[1 - \frac{33-2N_F}{12} \frac{\alpha_s}{\pi} \log \frac{Q^2}{\mu^2} + \mathcal{O}(\alpha_s^2) \right] \end{aligned}$$

[parton densities in analogy]

$$\tfrac{1}{2} m < \mu_R = \mu_F < 2m : \delta\sigma \sim \pm 50\ \%$$

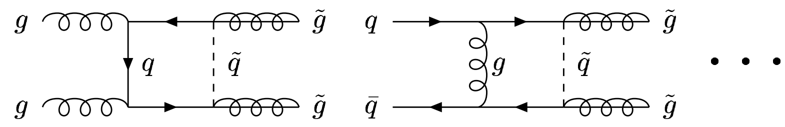
LHC



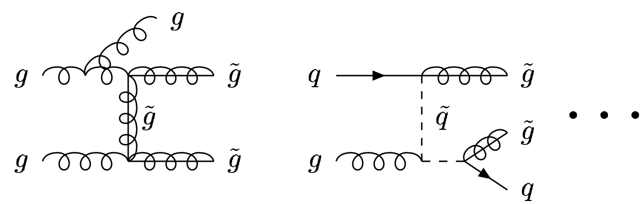
Beenakker, Höpker, Spira, Zerwas

Effect reduced through SUSY QCD corrections:

- virtual 1-loop contributions



- real contributions through gluon radiation/crossing



$$\hat{\sigma}_{gg} = \alpha_s^2(\mu_R)\left\{f_0 + f_0 \frac{33-3N_F}{6}\frac{\alpha_s}{\pi}\log\frac{\mu_R^2}{m^2} + \frac{\alpha_s}{\pi}f_1\right\}$$
$$= \alpha_s^2(m^2)\left\{f_0 + \frac{\alpha_s}{\pi}f_1 + \mathcal{O}(\alpha_s^2)\right\}$$

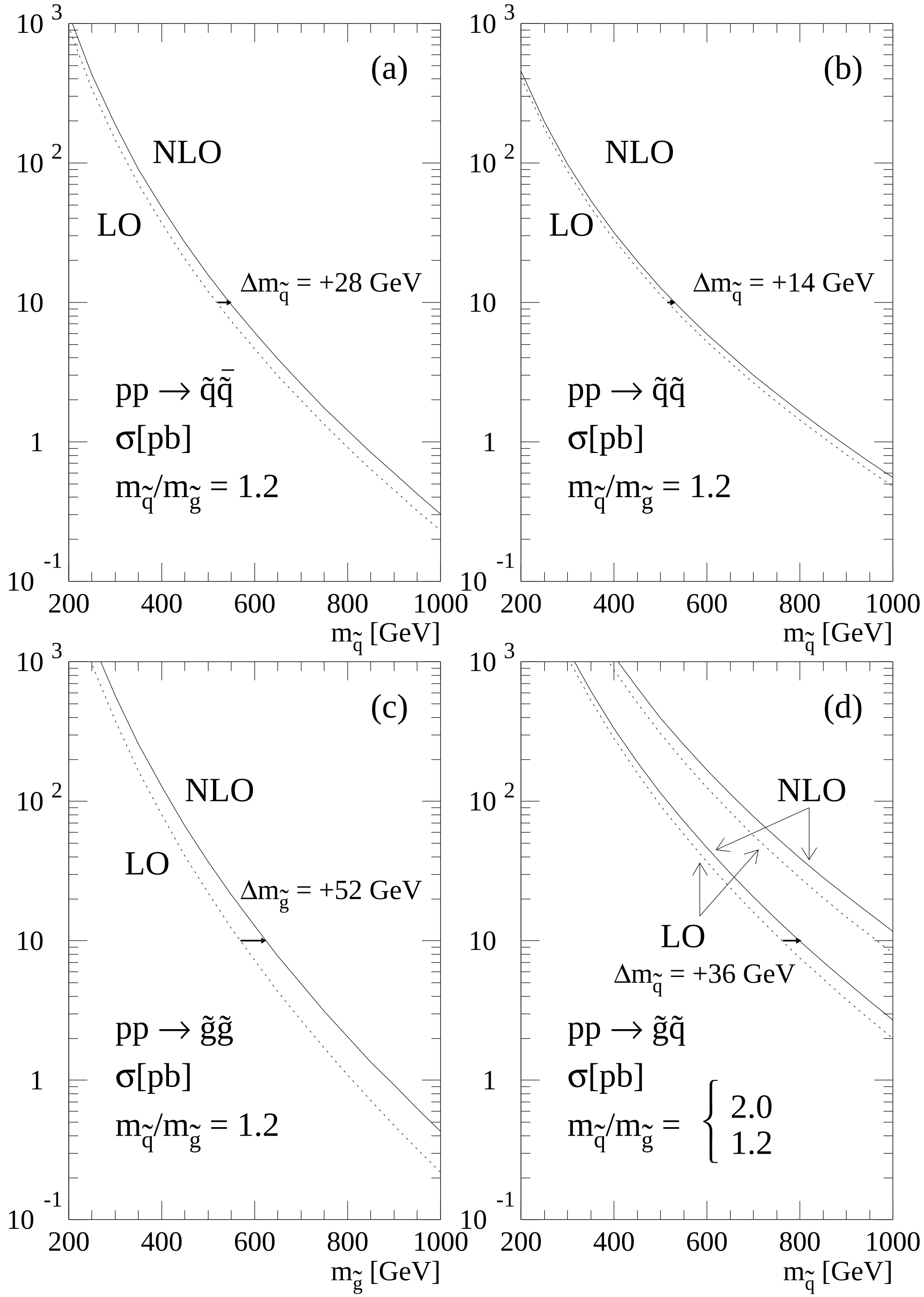
[parton densities in analogy]

$$\tfrac{1}{2}m < \mu_R = \mu_F < 2m : \delta\sigma \sim \pm 10\ \%$$

⇒ NLO corrections provide reliable predictions of cross sections at hadron colliders

central scale: $K = \frac{\sigma_{NLO}}{\sigma_{LO}} \sim 1.1 - 2.0$

LHC



Beenakker,Höpker,Spira,Zerwas

Implications for exp. searches:

(i) Renorm./factor. scale dep. reduced by $\sim 2.5 - 4 \rightsquigarrow$ stable theor. predictions for σ

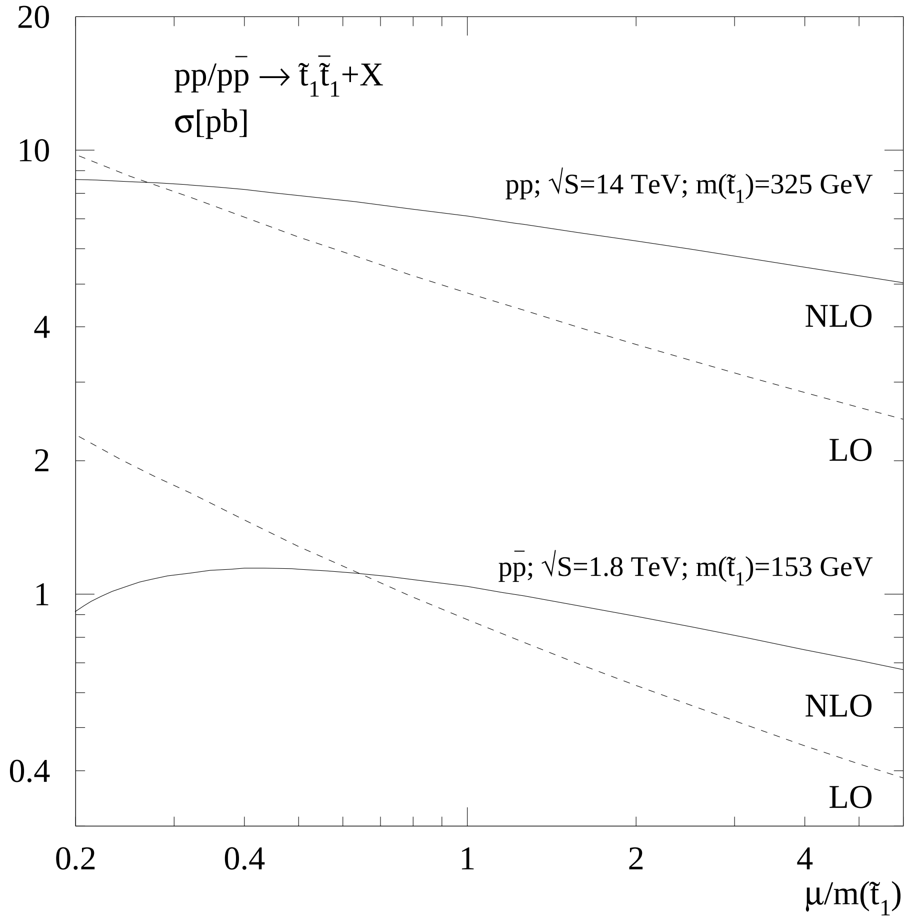
(ii) NLO corrs. large & positive $\rightsquigarrow$ to be included in analyses ($\longrightarrow$ masses)

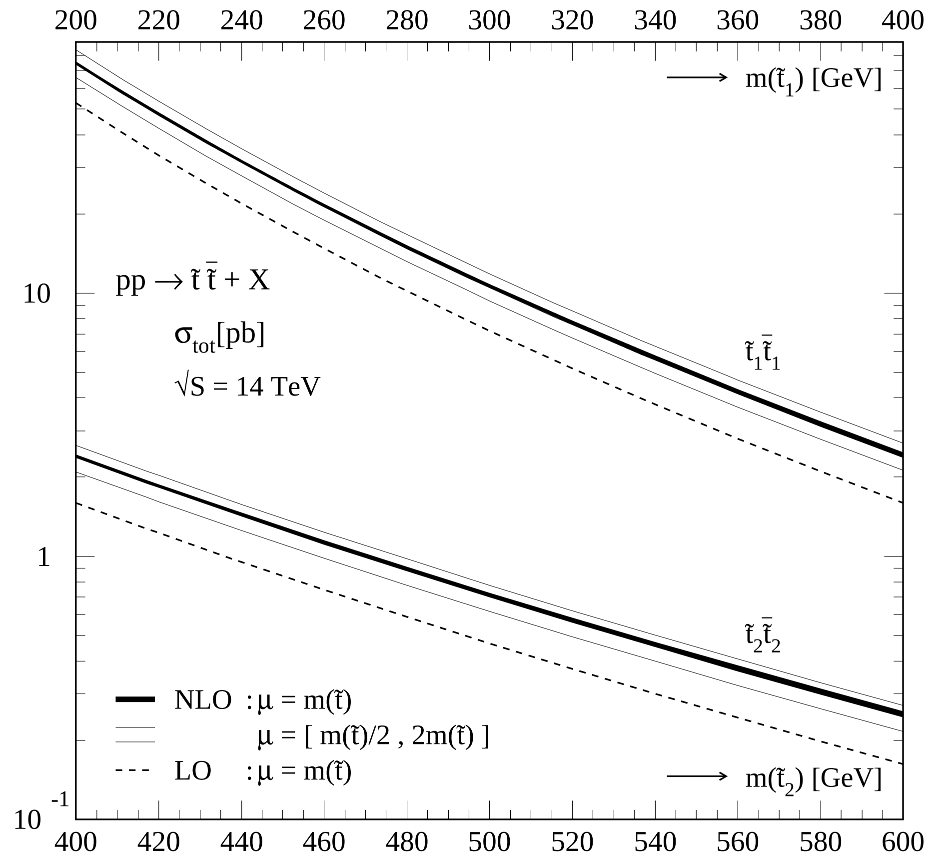
(iii) p_T and y distributions hardly affected by NLO

(iv) NLO $\rightsquigarrow$ raise of Tev lower $\tilde{q}, \tilde{g}$ mass bounds by +10–30 GeV

Stop-antistop pairs

Beenakker,Krämer,Plehn,Spira,Zerwas





Classical signatures (R-parity conserving SUSY, i.e. pair production/LSP stable):

- gluino > squark:

$$\tilde{q} \rightarrow q\tilde{\chi}_1^0 = q + E_T^{miss}$$

$$\tilde{g} \rightarrow q\tilde{q} \rightarrow qq\tilde{\chi}_1^0 = qq + E_T^{miss}$$

- squark > gluino:

$$\tilde{g} \rightarrow q\tilde{q}_{virt} \rightarrow qq\tilde{\chi}_1^0 = qqE_T^{miss}$$

$$\tilde{q} \rightarrow q\tilde{g} \rightarrow qqq\tilde{\chi}_1^0 = qqq + E_T^{miss}$$

$$pp \rightarrow n\ jets + E_T^{miss}$$

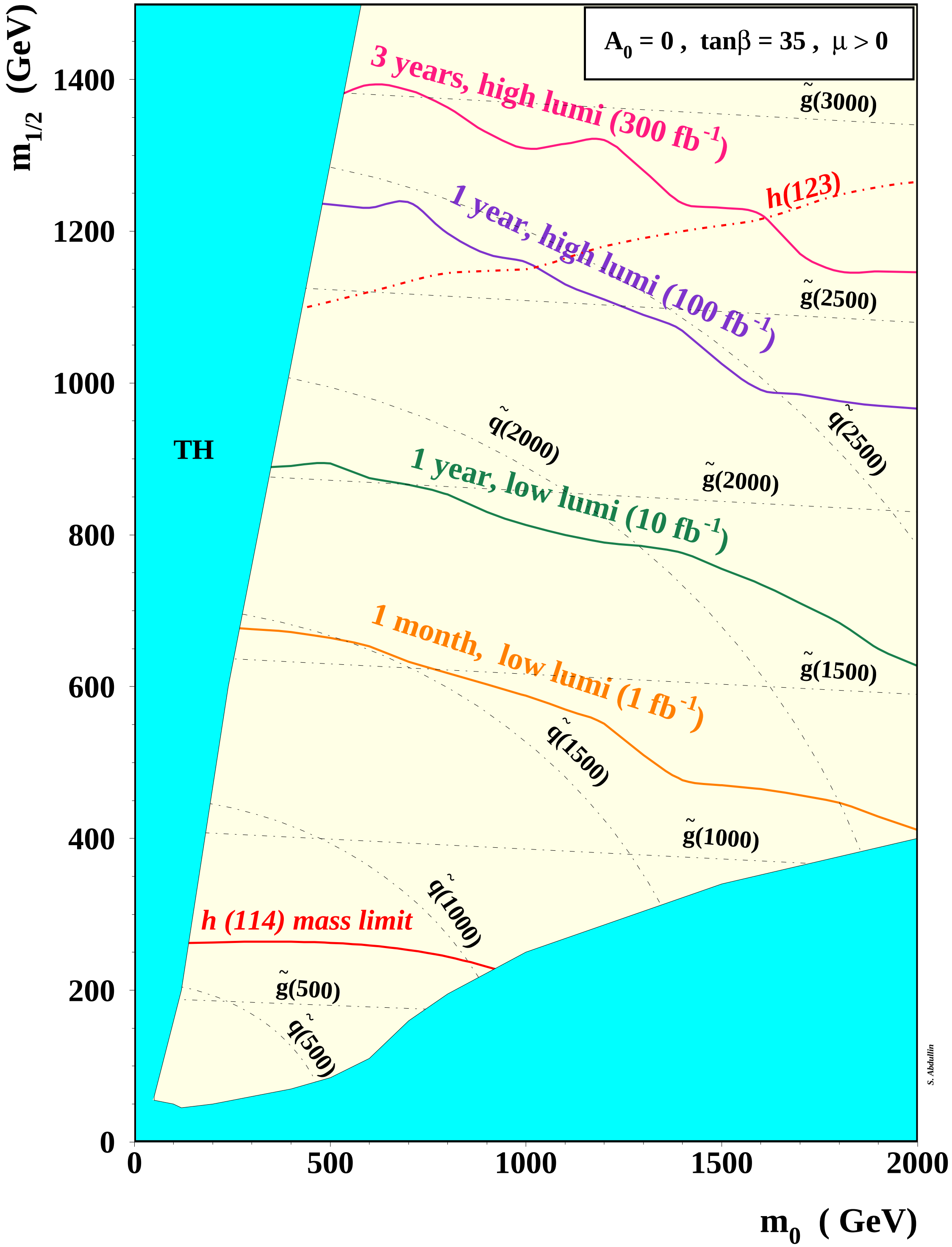
Discovery range:

Tevatron	$\lesssim$	500 GeV
LHC	$\lesssim$	2.5...3 TeV

Mass reach of the LHC

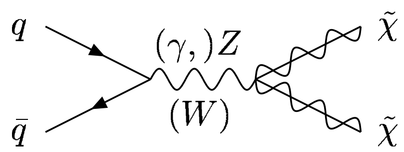
$M_{\tilde{q},\tilde{g}} \leq 2.5$ to 3 GeV

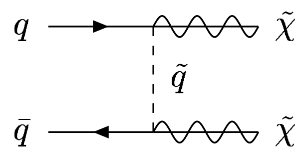
Signature: $E_T^{\text{miss}} +$ jets



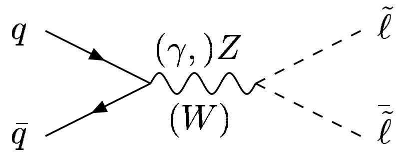
(ii) Weakly interacting particle pairs

$$p \overset{(-)}{p} \to \tilde{\chi}\tilde{\chi}$$





$$p \overset{(-)}{p} \to \tilde{l}\bar{\tilde{l}}$$



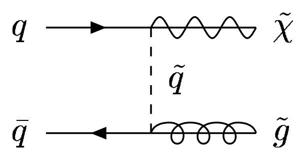
Signatures

$$\tilde{l} \quad \to \quad l\tilde{\chi}_1^0 \; : \qquad pp \to l^+l^- + E_T^{miss}$$

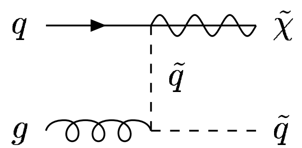
$$\tilde{\chi}_2^0 \quad \to \quad l^+l^-\tilde{\chi}_1^0 \quad \text{etc.} \; : \quad pp \to l^+l^+l^-l^- + E_T^{miss} \quad \text{etc.}$$

(iii) Associated production

$$p \overset{(-)}{p} \to \tilde{g}\tilde{\chi}$$



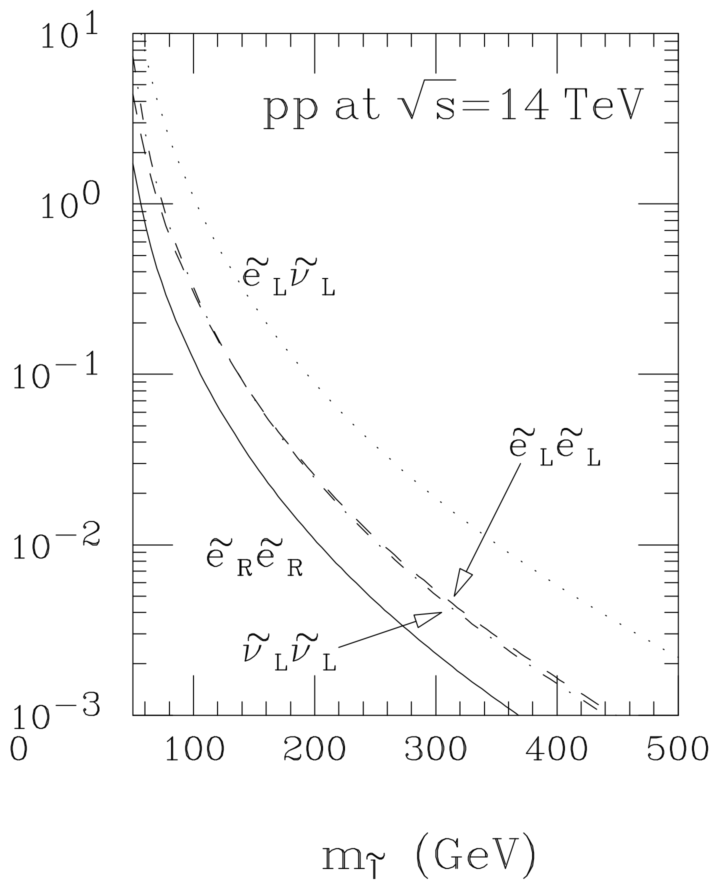
$$p \overset{(-)}{p} \to \tilde{q}\tilde{\chi}$$



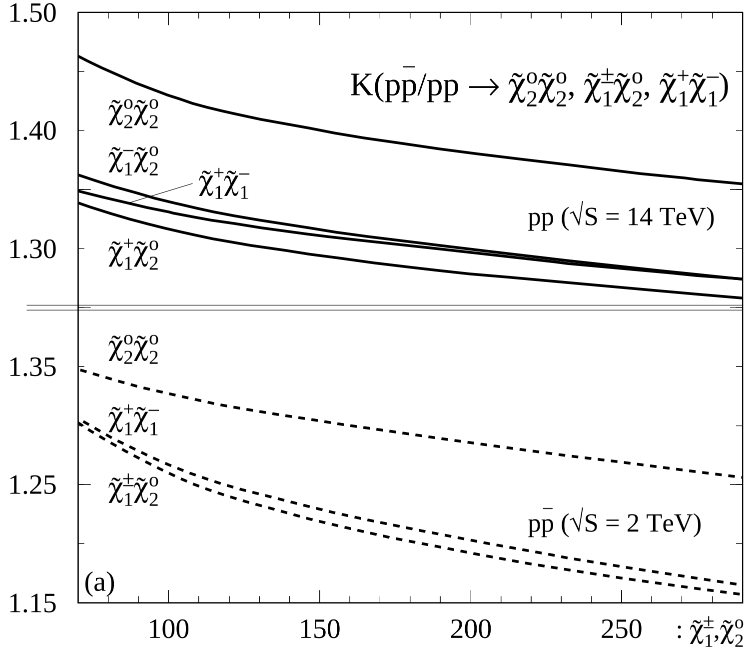
Slepton pair production at NLO

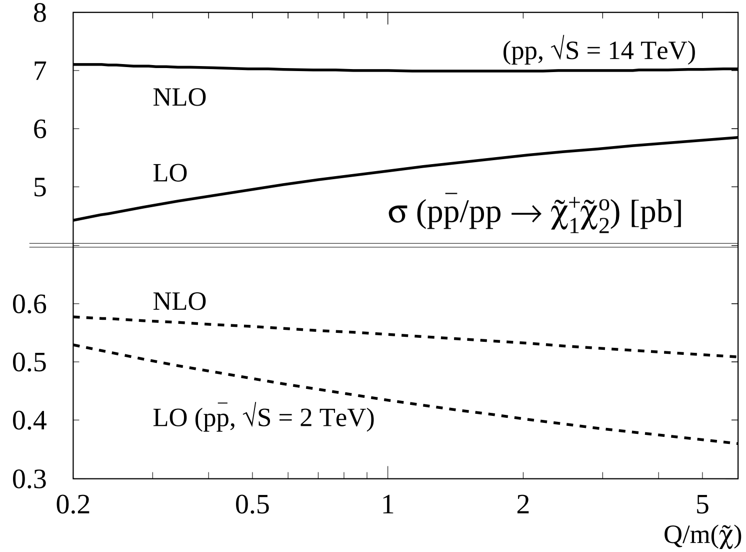
- Drell-Yan processes mediated by Z^* or W^*
- With QCD corrections at LHC $\sigma_{NLO} \sim (1.25 - 1.35)\sigma_{LO}$
- Cross section is small < 1 fb at $m_{\tilde{l}} \approx 500$ GeV

Baer et al., hep-ph/9712315: Cross section in [pb]



Gaugino Pairs

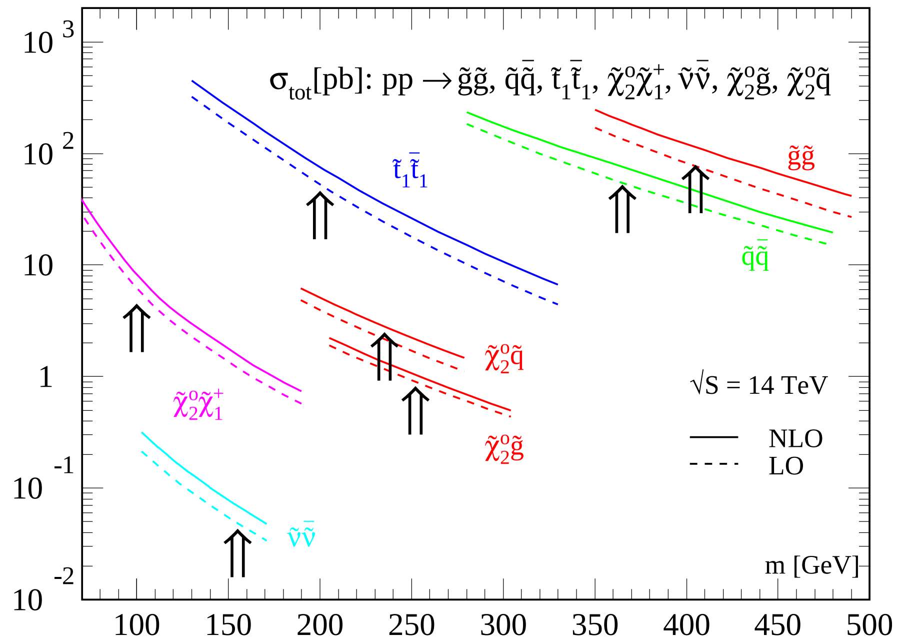


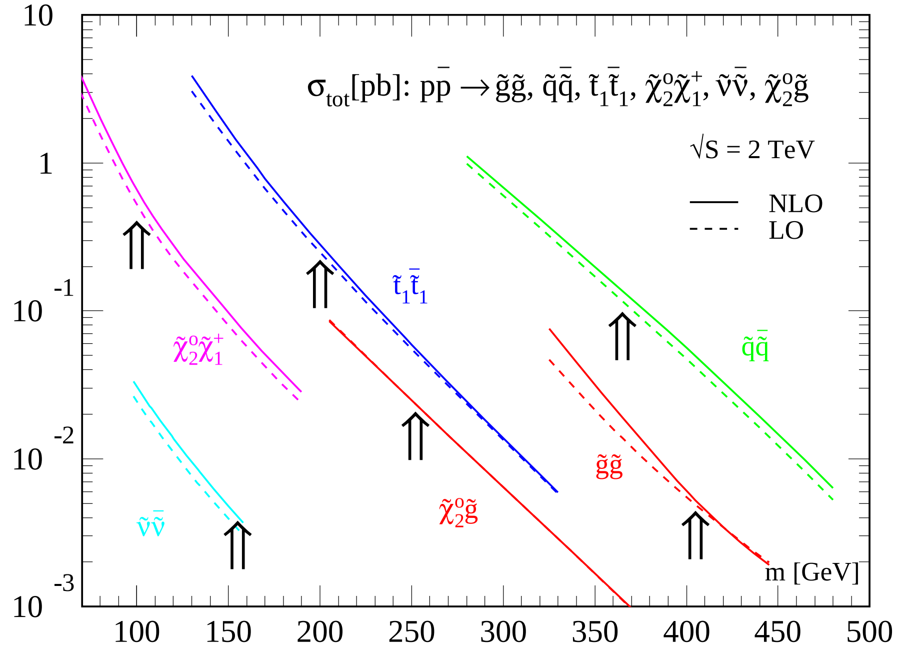


Beenakker, Klasen, Krämer, Plehn, Spira, Zerwas

Prospino

Beenakker, Krämer, Plehn, Spira, Zerwas





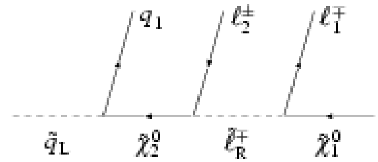
Cascade decays

gluino/squark decays = rich source for non-colored (supersymmetric) particles

Mass determination: kinematic endpoint technique

Contruct lepton/quark upper/lower endpoints and relate them to the masses in the decay chain

E.g.: $\tilde{q} \to \tilde{\chi}_2^0 q \to \tilde{l}^{\pm} l^{\mp} q \to \tilde{\chi}_1^0 l^+ l^- q = j + l^+ + l^- + E_T^{miss}$



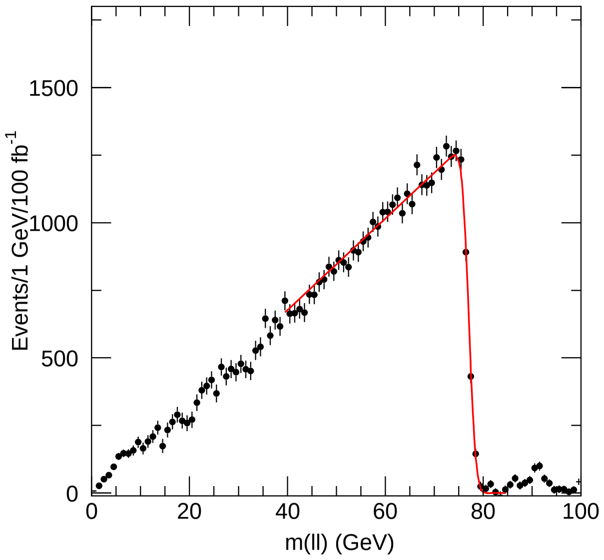
4 unknown masses: $M_{\tilde{q}}, M_{\tilde{\chi}_2^0}, M_{\tilde{l}}, M_{\tilde{\chi}_1^0}$

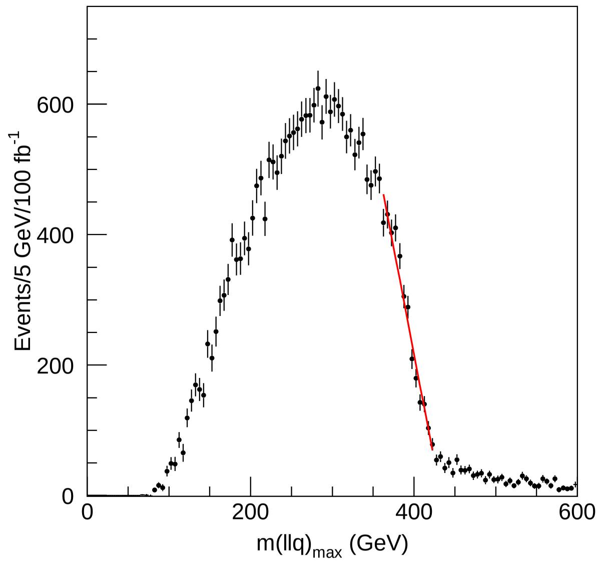
4 endpoints: $M(ll)^{max}, M(l_1 q)^{max}, M(l_2 q)^{max}, M(llq)^{max}$

$\Rightarrow$ all masses can be determined

$$\max M^2(ll) = M^2_{\tilde{\chi}_2^0}\left[1 - \frac{M^2_{\tilde{l}}}{M^2_{\tilde{\chi}_2^0}}\right]\left[1 - \frac{M^2_{\tilde{\chi}_1^0}}{M^2_{\tilde{l}}}\right]$$

$$\max M^2(llq) = M^2_{\tilde{q}}\left[1 - \frac{M^2_{\tilde{\chi}_2^0}}{M^2_{\tilde{q}}}\right]\left[1 - \frac{M^2_{\tilde{\chi}_1^0}}{M^2_{\tilde{\chi}_2^0}}\right]$$





Spin:

particle chain in SUSY equivalent to UED

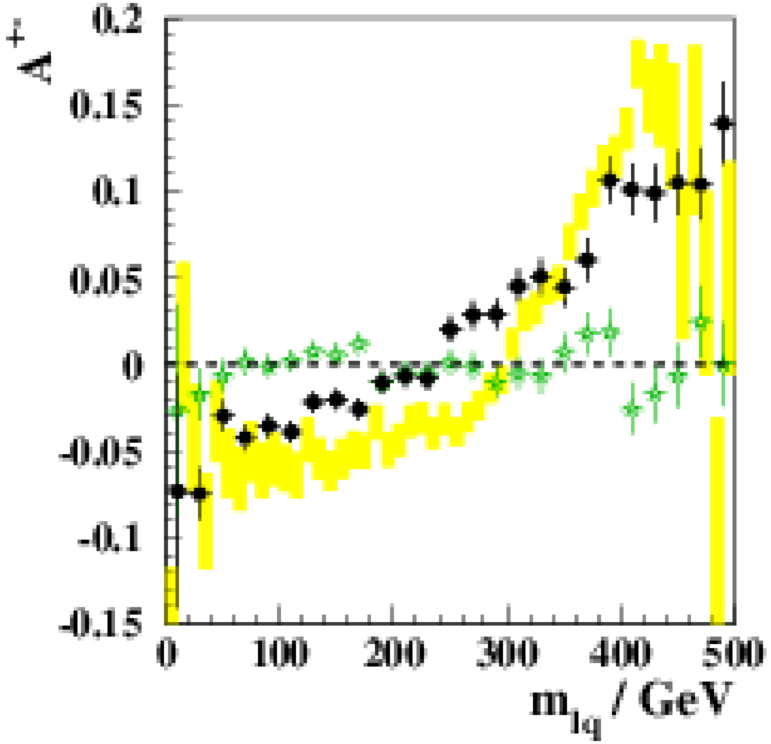
SUSY: $\tilde{q}_L \to q + \tilde{\chi}_2^0 \to q + (\tilde{l}l) \to q + ll + \tilde{\chi}_1^0$

UED: $q_1 \to q + Z_1 \to q + (l_1 l) \to q + ll + \gamma_1$

distinction by spin: $\sim$ angular distributions / invariant masses

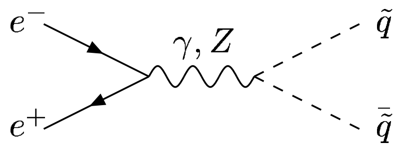
charge asymmetry in $[ql^+]$ vs $[ql^-]$:

difficult analysis $\to$ A.J.Barr, hep-ph/0405052.



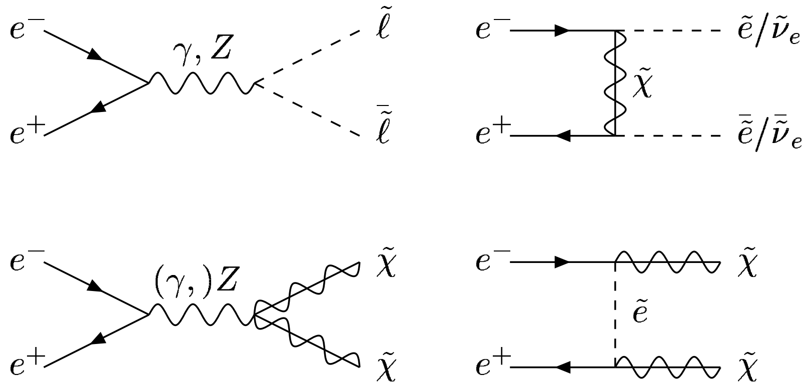
(ii) e^+e^- Collider 2 classes of SUSY particle pair production processes:

(i) Strongly interacting particle pairs



NLO QCD & SUSY-QCD corrections known, $\mathcal{O}$(several 10%)

(ii) Weakly interacting particle pairs



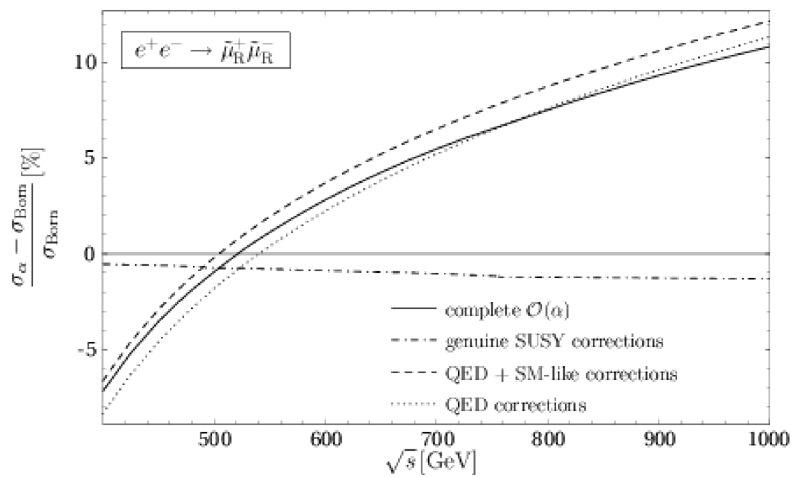
1-loop analysis

[Freitas,Manteuffel,Zerwas]:

dominating QED, but $\Rightarrow$

genuine SUSY $\sim$ few percent

experimentally relevant

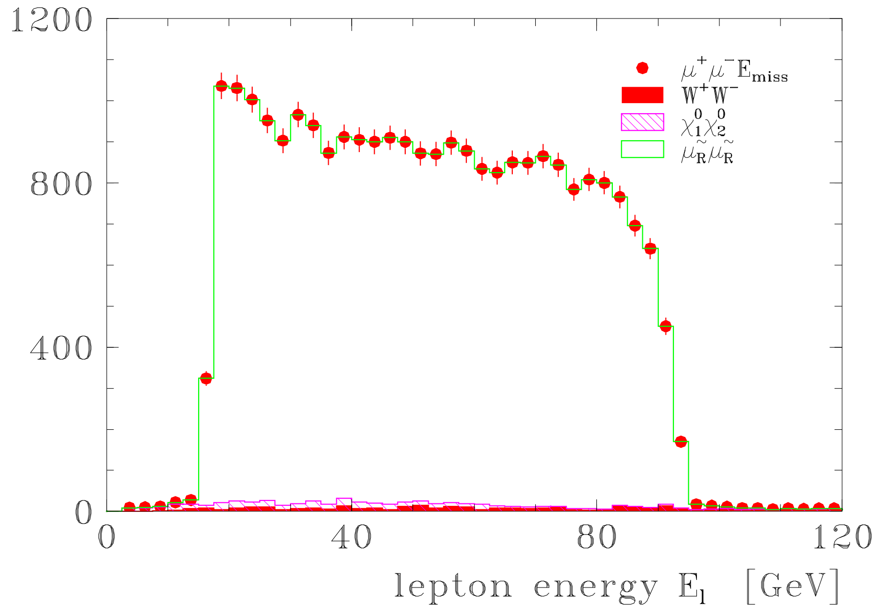


Masses at the ILC:

- Edge effects: $\tilde{\mu}_R \to \mu\tilde{\chi}_1^0$

$$m_{\tilde{l}} = \sqrt{s}[E_+E_-]^{\frac{1}{2}}/(E_+ + E_-)$$
$$m_{\tilde{\chi}_1^0} = m_{\tilde{l}}[1 - 2(E_+ + E_-)/\sqrt{s}]^{\frac{1}{2}}$$

precision on $\tilde{\chi}_1^0$ improved by $\sim 10^2$



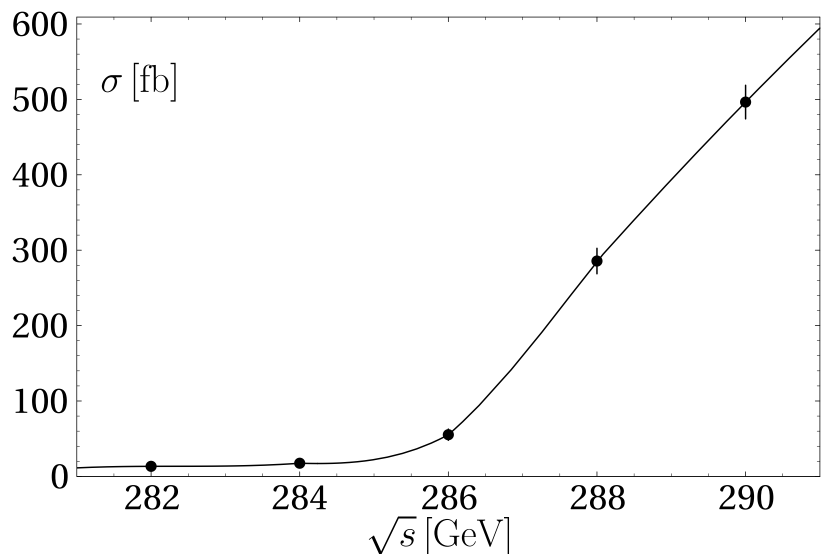
- Threshold excitations:

$$e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^- + E_{miss}$$

P-wave: slow $\beta^3 \sim [s - 4m_{\tilde{\mu}}^2]^{\frac{3}{2}}$ rise

$$e^-e^- \to \tilde{e}_R^-\tilde{e}_R^- \to e^-e^- + E_{miss}$$

S-wave: fast $\beta \sim [s - 4m_{\tilde{e}}^2]^{\frac{1}{2}}$ rise



- voids filled: LHC and LC complementarity
- accuracy increased by 1 to 2 orders of magnitude: $\Delta\tilde{m} \sim 50$ MeV ~ 0.2 per mille
- coherent [LHC⊕LC] analysis superior to incoherent sum of individual analyses

Summary:

LHC+ILC

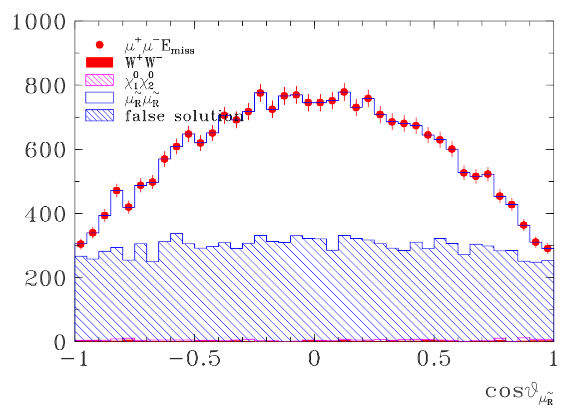
Coherent LHC+ILC analyses complete and increase resolution of SUSY picture significantly

	Mass, ideal	"LHC"	"ILC"	"LHC+ILC"
$\tilde{\chi}_1^\pm$	179.7		0.55	0.55
$\tilde{\chi}_2^\pm$	382.3	–	3.0	3.0
$\tilde{\chi}_1^0$	97.2	4.8	0.05	0.05
$\tilde{\chi}_2^0$	180.7	4.7	1.2	0.08
$\tilde{e}_R$	143.9	4.8	0.05	0.05
$\tilde{e}_L$	207.1	5.0	0.2	0.2
$\tilde{\nu}_e$	191.3	–	1.2	1.2
$\tilde{\mu}_R$	143.9	4.8	0.2	0.2
$\tilde{\tau}_1$	134.8	5-8	0.3	0.3
$\tilde{\tau}_2$	210.7	–	1.1	1.1
$\tilde{q}_L$	570.6	8.7	–	4.9
$\tilde{t}_1$	399.5		2.0	2.0
$\tilde{t}_2$	586.3		–	
$\tilde{g}$	604.0	8.0	–	6.5
h^0	110.8	0.25	0.05	0.05
A^0	399.4		1.5	1.5

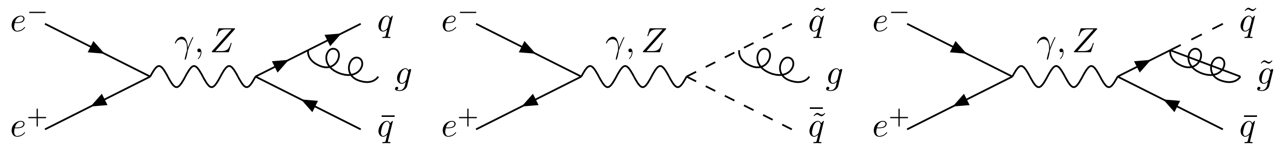
Spin at the ILC:

$$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^- \to \mu^+\mu^- + \tilde{\chi}_1^0\tilde{\chi}_1^0$$

production axis can be reconstructed up to 2-fold ambiguity



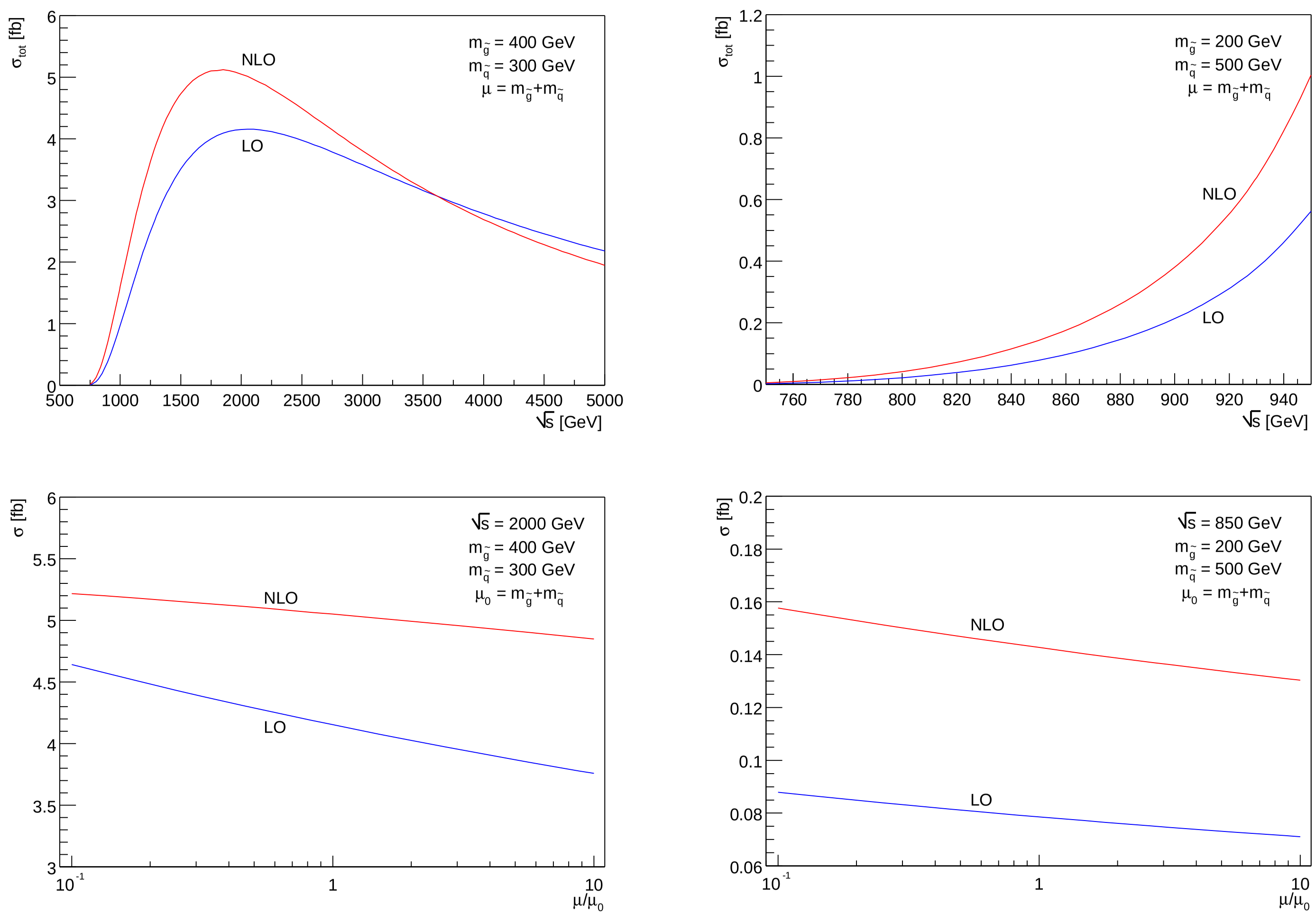
$e^+e^- \to q\bar{q}g, \tilde{q}\bar{\tilde{q}}g, \tilde{q}\bar{q}\tilde{g}$



Possibility to test equality of couplings, needs NLO!

$e^+e^- \to \tilde{q}\bar{q}\tilde{g}$

Brandenburg, Maniatis, Weber, Zerwas



R-$\mathcal{P}$arity $\mathcal{V}$iolation

- **Superpotential**

$$\begin{aligned} \mathcal{L}_W &= -\sum_i \left|\frac{\partial W}{\partial \phi_i}\right|^2 - \frac{1}{2}\sum_{ij} \overline{\psi^c_{iL}} \frac{\partial^2 W}{\partial\phi_i \partial\phi_j} \psi_{jL} + h.c. \\ W &= W_R + W_{\not R} \\ W_{\not R} &= \sum_{i,j=1}^{2} \sum_{r,s,t=1}^{3} \epsilon_{ij} [\lambda_{rst} \hat{L}_{ir} \hat{L}_{js} \hat{E}^c_t + \lambda'_{rst} \hat{L}_{ir} \hat{Q}_{js} \hat{D}^c_t] + \lambda''_{rst} \hat{U}^c_r \hat{D}^c_s \hat{D}^c_t \end{aligned}$$

(r, s, t : generation indices)

- ***SU*(2)$_L$-invariance:** $\lambda_{rst} = -\lambda_{srt}$

- ***SU*(3)$_C$-invariance:** $\lambda''_{rst} = -\lambda''_{rts}$

$\Rightarrow$ 9+27+9= 45 new couplings

- **Lagrangian of the 1st term:**

$$\mathcal{L}_{LLE} = \lambda_{rst}[\tilde{\nu}^r_L \bar{e}^t_R e^s_L + \tilde{e}^s_L \bar{e}^t_R \nu^r_L + \bar{\tilde{e}}^t_R \overline{\nu^{rc}_L} e^s_L - (r \leftrightarrow s)] + h.c.$$

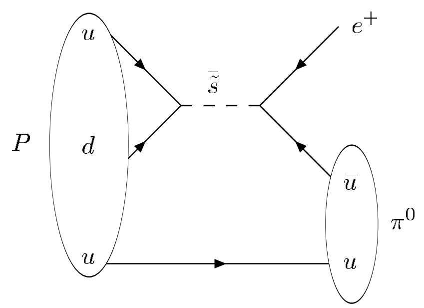
$\Rightarrow$ $\lambda_{rst}, \lambda'_{rst}$ lepton number violating

λ''_{rst} baryon number violating

- **R-Parity**

$$R = (-1)^{3B+L+2S} = \begin{cases} +1 & \text{SM particle} \\ -1 & \text{SUSY partner} \end{cases}$$

$\Rightarrow W_{\not R}$ violates R-parity.



$$\Gamma(p \to e^+\pi^0) \sim \frac{(\lambda'_{11k}\lambda''_{11k})^2}{\tilde{m}_k^4} M_p^5$$

$$\begin{aligned} \tau(p \to e^+\pi^0) &> 1.6 \times 10^{33} a \\ &\Rightarrow \lambda'_{11k}\lambda''_{11k} \lesssim \frac{1}{2} \times 10^{-27} \left(\frac{\tilde{m}_k}{100\ \text{GeV}}\right)^2 \\ &\Rightarrow \lambda'_{11k}\lambda''_{11k} \sim 0 \end{aligned}$$

- **Symmetries**

(i) R-Parity $\Rightarrow W_{\not R} = 0$

(ii) Matter-Parity

$$\begin{aligned}(\hat{L}_r, \hat{E}^c_r, \hat{Q}_r, \hat{U}^c_r, \hat{D}^c_r) &\rightarrow -(\hat{L}_r, \hat{E}^c_r, \hat{Q}_r, \hat{U}^c_r, \hat{D}^c_r) \\ (H_1, H_2) &\rightarrow (H_1, H_2)\end{aligned}$$

$\Rightarrow W_{\not R} = 0$

(iii) Baryon-Parity

$$\begin{aligned}(\hat{Q}_r, \hat{U}^c_r, \hat{D}^c_r) &\rightarrow -(\hat{Q}_r, \hat{U}^c_r, \hat{D}^c_r) \\ (\hat{L}_r, \hat{E}^c_r, H_1, H_2) &\rightarrow (\hat{L}_r, \hat{E}^c_r, H_1, H_2)\end{aligned}$$

$\Rightarrow \lambda^{''}_{rst} = 0$

(iv) Lepton-Parity

$$\begin{aligned}(\hat{L}_r, \hat{E}^c_r) &\rightarrow -(\hat{L}_r, \hat{E}^c_r) \\ (\hat{Q}_r, \hat{U}^c_r, \hat{D}^c_r, H_1, H_2) &\rightarrow (\hat{Q}_r, \hat{U}^c_r, \hat{D}^c_r, H_1, H_2) \qquad (1)\end{aligned}$$

$\Rightarrow \lambda_{rst} = \lambda'_{rst} = 0$

$M_p < M_{LSP} \Rightarrow$ proton stable

RPV: low energy limits

H.Dreiner, Perspectives on Supersymmetry,
ed. G.Kane, World Scientific, Singapore (hep-ph/9707435)

Bounds on RPV Yukawa couplings, assuming $\tilde{m} = 100GeV$:

ijk	λ_{ijk}	ijk	λ'_{ijk}	ijk	λ'_{ijk}	ijk	λ'_{ijk}	ijk	λ''_{ijk}
121	0.05^a	111	0.001^d	211	0.09^h	311	0.16^k	112	$10^{-6,l}$
122	0.05^a	112	0.02^a	212	0.09^h	312	0.16^k	113	$10^{-5,m}$
123	0.05^a	113	0.02^a	213	0.09^h	313	0.16^k	123	1.25^n
131	0.06^b	121	0.035^e	221	0.18^i	321	0.20^f	212	1.25^n
132	0.06^b	122	0.06^c	222	0.18^i	322	0.20^f	213	1.25^n
133	0.004^c	123	0.20^f	223	0.18^i	323	0.20^f	223	1.25^n
231	0.06^b	131	0.035^e	231	0.22^j	331	0.26^g	312	0.43^g
232	0.06^b	132	0.33^g	232	0.39^g	332	0.26^g	313	0.43^g
233	0.06^b	133	0.002^c	233	0.39^g	333	0.26^g	323	0.43^g

Dependence of the bounds on $\tilde{m}$:

λ_{ijk}	$m_{\tilde{e}_{Rk}}/100GeV$	λ'_{111}	$(m_{\tilde{q}}/100GeV)^2(m_{\tilde{g}}/1TeV)^{1/2}$
λ'_{11k} , λ'_{21k}	$m_{\tilde{d}_{Rk}}/100GeV$	λ'_{1j1}	$m_{\tilde{q}_{Lj}}/100GeV$
λ_{133} , λ'_{1jj}	$(m_{\tilde{\tau},\tilde{d}_j}/100GeV)^{1/2}$	λ'_{123}	$(m_{\tilde{b}_R}/100GeV)^{1/2}$
λ'_{231}	$m_{\tilde{\nu}_{\tau L}}/100GeV$	λ'_{32k}	$(m_{\tilde{d}_{Rk}}/100GeV)^{1/2}$

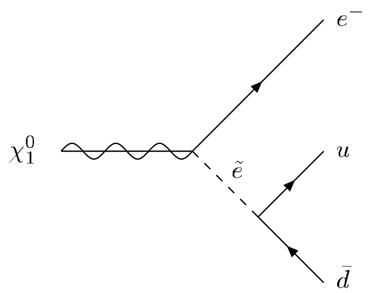
Experimental inputs :

- (a) : charged current universality
- (b) : $\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$
- (c) : bound on ν_e mass
- (d) : neutrinoless double-beta decay
- (e) : atomic parity violation
- (f) : $D^0 - \bar{D}^0$ mixing
- (g) : $R_l = \Gamma_{had}(Z)/\Gamma_l(Z)$
- (h) : $\Gamma(\pi \to e\bar{\nu})/\Gamma(\pi \to \mu\bar{\nu})$
- (i) : $B(D^+ \to \bar{K}^{*0}\mu^+\nu_\mu)/B(D^+ \to \bar{K}^{*0}e^+\nu_e)$
- (j) : ν_μ deep inelastic scattering
- (k) : $B(\tau \to \pi\nu_\tau)$
- (l) : heavy nucleon decay
- (m) : $n - \bar{n}$ oscillations
- (n) : Yukawas remain within unitarity bound up to GUT scale

- **Phenomenological consequences of $\not{R}$**

(i) L- or B-Violation

(ii) LSP not stable:



$$\Gamma_{\tilde{\gamma}} = \frac{3\alpha\lambda'^2_{121}}{128\pi^2}\frac{M_{\tilde{\gamma}}^5}{\tilde{m}_e^4} \qquad (\tilde{\gamma} = \tilde{\chi}_1^0 \text{ LSP})$$

Decay within detector: $c\gamma\tau \lesssim 1m$

$$\Rightarrow \lambda'_{121} > 1.4 \times 10^{-6}\sqrt{\gamma}\left(\frac{\tilde{m}_e}{200 \text{ GeV}}\right)^2 \sqrt{\frac{100 \text{ GeV}}{M_{\tilde{\gamma}}}}^5$$

$\Rightarrow$ no natural candidate for Dark Matter

(iii) LSP $\in (\tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \tilde{g}, \tilde{q}, \tilde{t}, \tilde{l}, \tilde{\nu})$

need not be charge- and color neutral ($\leftarrow$ cosmology)

(iv) Production of single SUSY particles:

$$
\begin{array}{llll}
e^+e^- \rightarrow \tilde{\nu}_{Lj} & (\hat{L}_1\hat{L}_j\hat{E}^c_1) & \text{LEP} \\
e^-u_j \rightarrow \tilde{d}_{Rk} & (\hat{L}_1\hat{Q}_j\hat{D}^c_k) & \text{HERA} \\
e^-\bar{d}_k \rightarrow \bar{\tilde{u}}_{Lj} & (\hat{L}_1\hat{Q}_j\hat{D}^c_k) & \text{HERA} \\
\bar{u}_j d_k \rightarrow \tilde{e}^-_{Li} & (\hat{L}_i\hat{Q}_j\hat{D}^c_k) & \text{Tevatron,LHC} \\
d_j\bar{d}_k \rightarrow \bar{\tilde{\nu}}_{Li} & (\hat{L}_i\hat{Q}_j\hat{D}^c_k) & \text{Tevatron,LHC} \\
\bar{u}_i\bar{d}_j \rightarrow \tilde{d}_{Rk} & (\hat{U}_i\hat{D}^c_j\hat{D}^c_k) & \text{Tevatron,LHC} \\
d_j d_k \rightarrow \bar{\tilde{u}}_{Ri} & (\hat{U}^c_i\hat{D}^c_j\hat{D}^c_k) & \text{Tevatron,LHC}
\end{array}
$$

- **Collider phenomenology:**

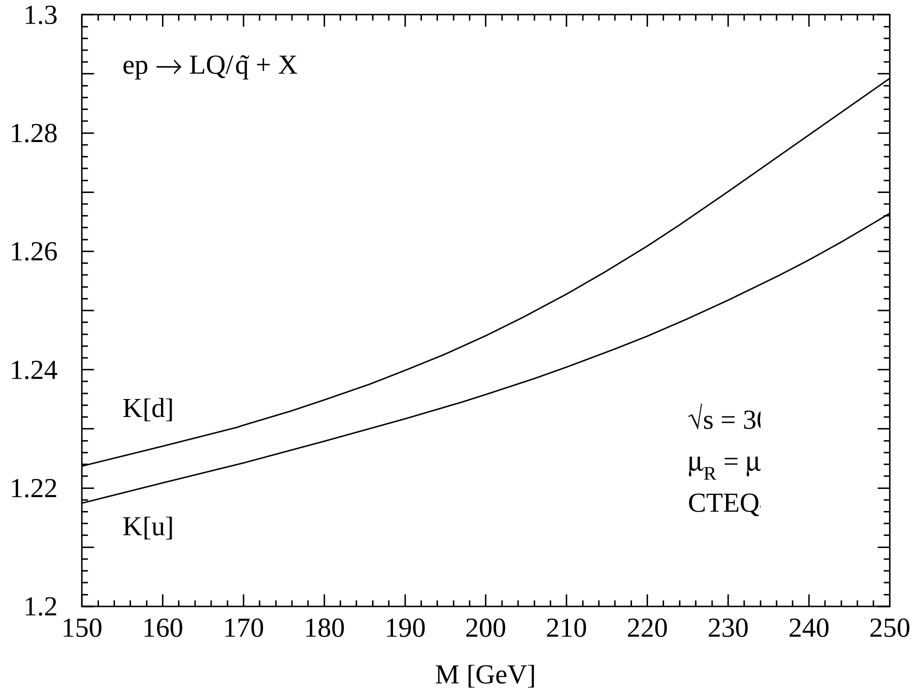
  Pair production: $\tilde{m} \lesssim \frac{\sqrt{s}}{2} \Rightarrow$ cinematical limitation

  Single production: small coupling $\lambda, \lambda', \lambda''$, but $\tilde{m} \lesssim \sqrt{s}$

Example: Resonant squark production at HERA

$$e^+ d_k \quad \to \quad \tilde{u}_j \to (e^+ d_k, \tilde{\chi}_1^0 u_j, \tilde{\chi}_1^+ d_j)$$
$$e^+ \bar{u}_j \quad \to \quad \tilde{d}_k \to (e^+ \bar{u}_j, \bar{\nu}_e \bar{d}_j, \tilde{\chi}_1^0 \bar{d}_k)$$

[QCD $\sim +20 - 30\%$]



Plehn et al
Kunszt,Stirling

Gaugino decays:

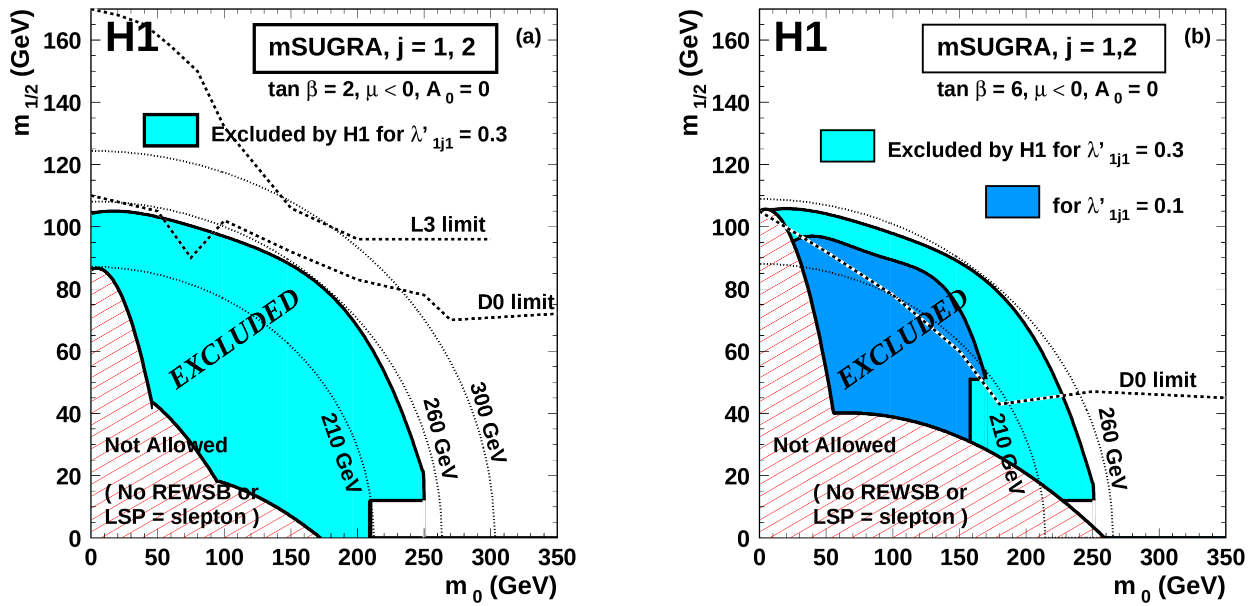
$$\tilde{\chi}_1^0 \to (e^\pm, \nu) + 2 \text{ jets}$$
$$\tilde{\chi}_1^+ \to (e^+, \nu) + 2 \text{ jets}$$

- **Limits from H1**

  Constraints in the mSUGRA model

  Assuming a fixed value for RPV couplings λ'_{1j1}

  $\longrightarrow$ searches can be expressed in terms of mSUGRA parameters, e.g. in the $(m_0, m_{1/2})$ plane



Dotted lines: isolines for $\tilde{u}_L^j$ masses

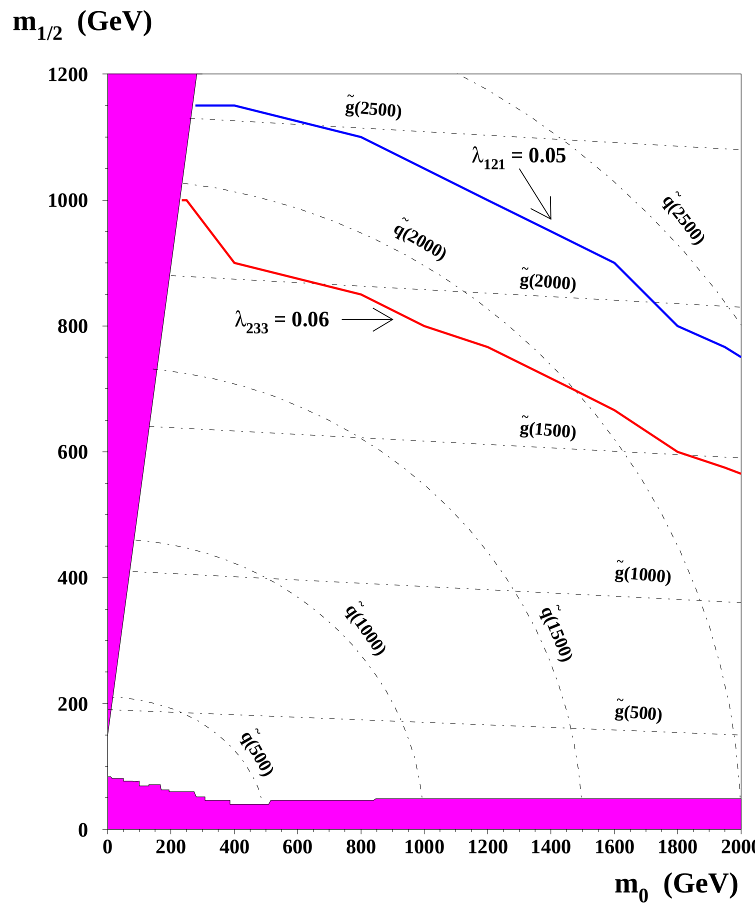
REWSB .. Radiative Electroweak Symmetry Breaking

Remarks: LEP and Tevatron bounds do not depend on the value of the Yukawa coupling

Similar results from ZEUS

- **RPV: Reach at the LHC**

  CMS reach for 10 fb^{-1}



$\lambda_{121} = 0.05$: squark mass reach ~ 2.2 TeV, gluino mass reach ~ 1.8 TeV

$\lambda_{233} = 0.06$: squark mass reach ~ 1.7 TeV, gluino mass reach ~ 1.5 TeV

$\Rightarrow$ Reach compatible to R_P conserving mSUGRA scenario