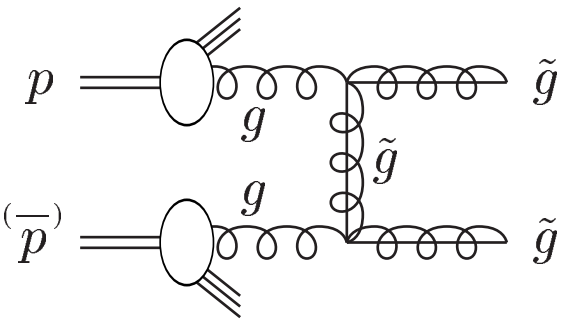
§6. SUSY Phenomenology

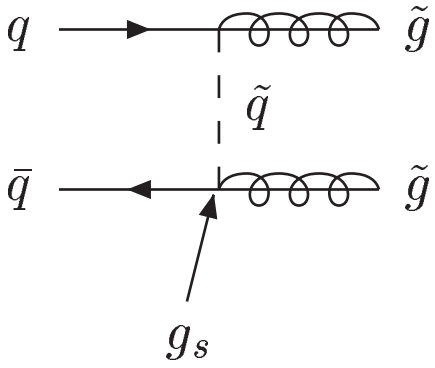
I Hadron Colliders

3 classes of SUSY production processes:

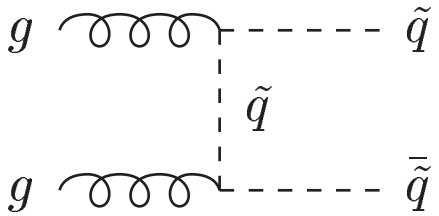
(i) strongly interacting particle pairs:

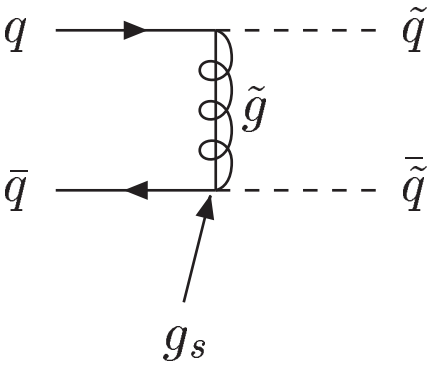
$p\overset{(-)}{p} \to \tilde{g}\tilde{g}$



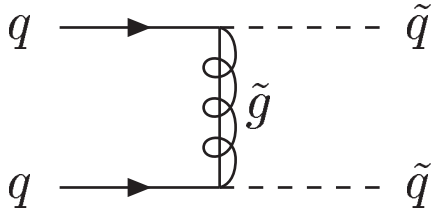


$p\overset{(-)}{p} \to \tilde{q}\bar{\tilde{q}}$

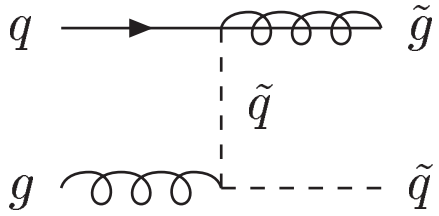


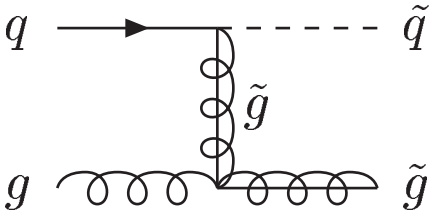


$p\overset{(-)}{p} \to \tilde{q}\tilde{q}$



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





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

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 [renormalization scale μ_R, factorization scale μ_F undetermined]

• natural scale: $\mu_R = \mu_F = m$.

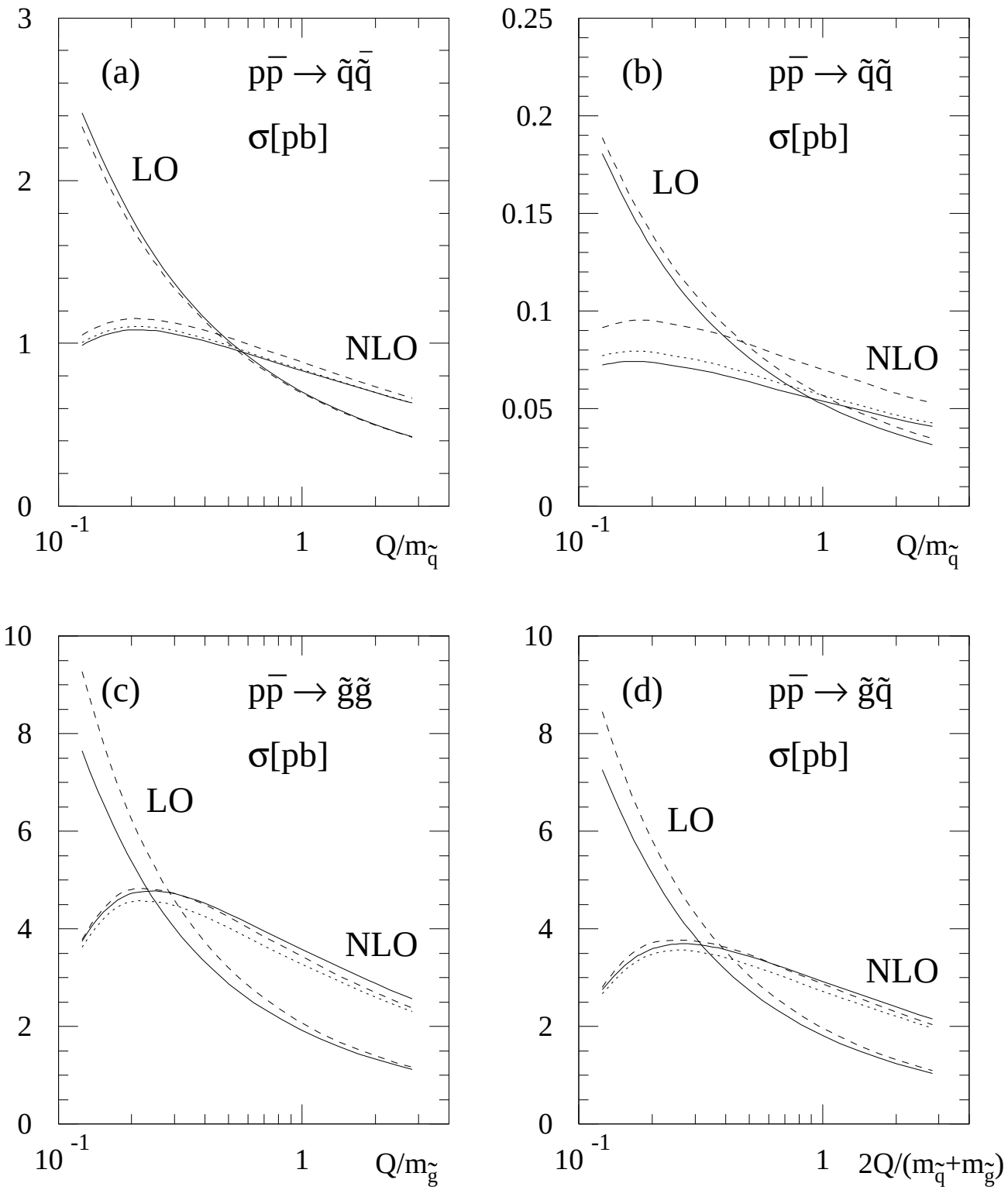
scale variation $\rightarrow$ estimate of uncertainties w.r.t. scale choice [large logarithms in HO]:

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

[analogous for parton densities $\leftarrow$ DGLAP equations]

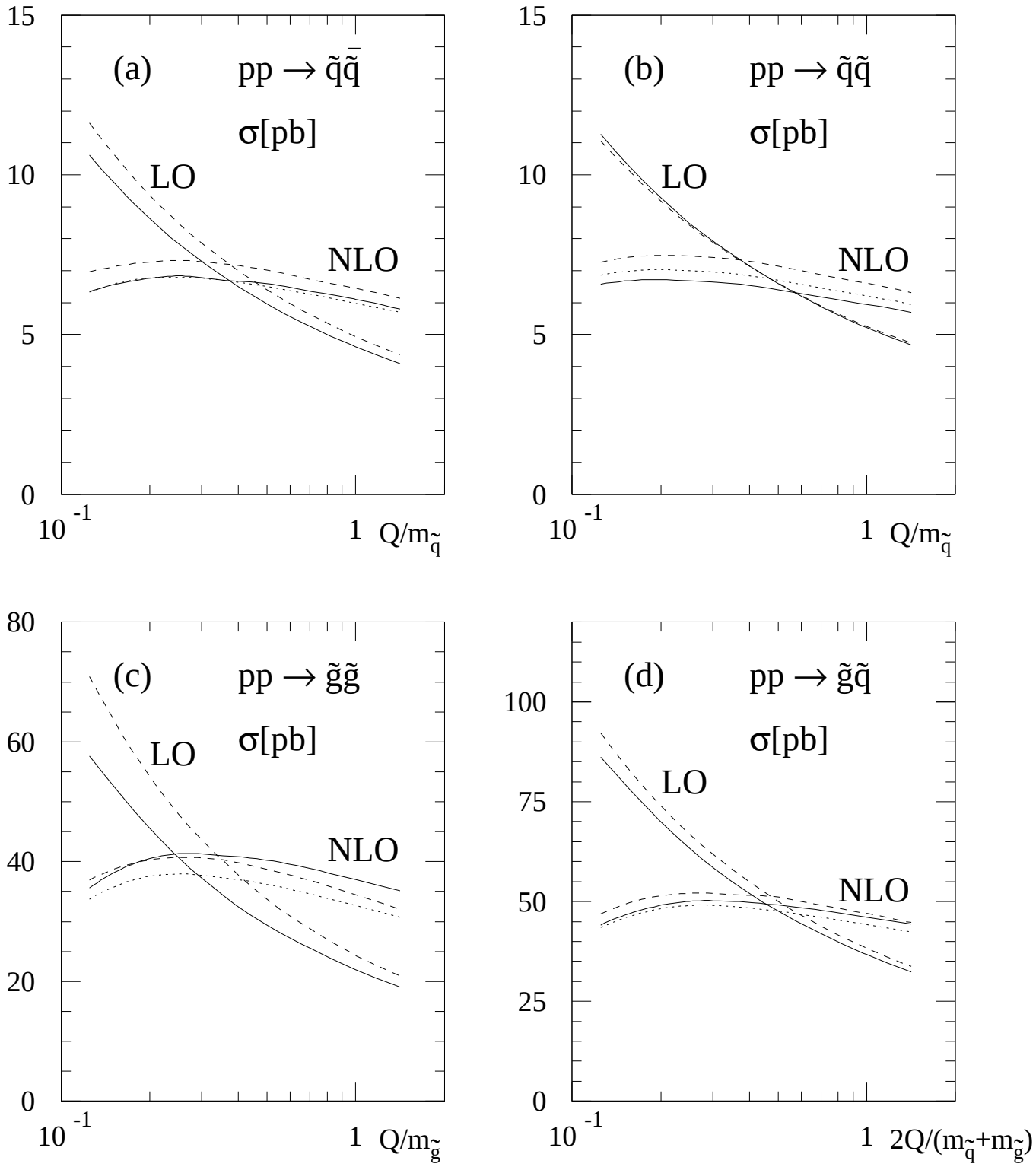
$\frac{1}{2} m < \mu_R = \mu_F < 2m$: $\delta\sigma \sim \pm 50\%$

Tevatron



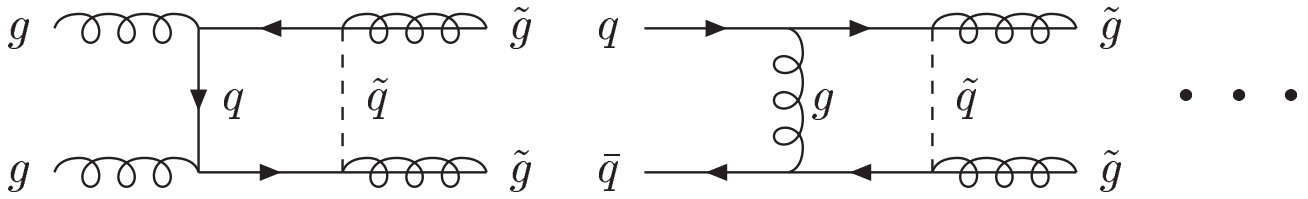
Beenakker, Höpker, S., Zerwas

LHC

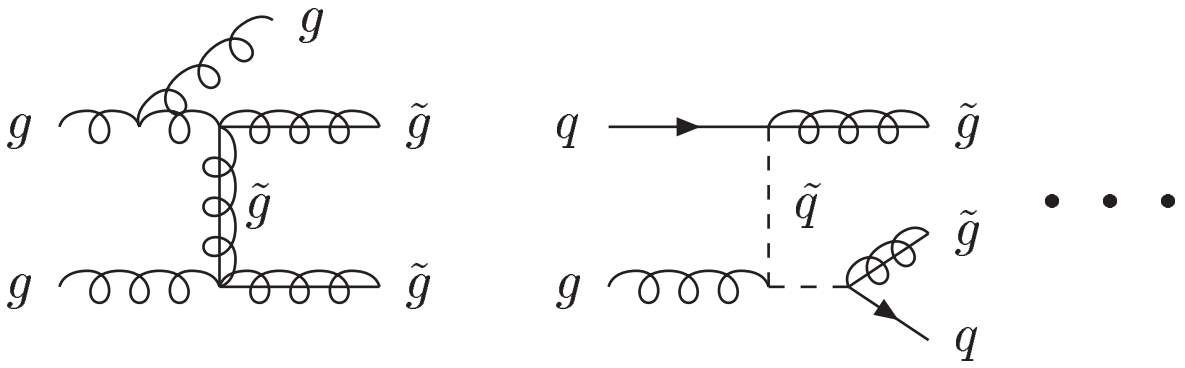


Beenakker, Höpker, S., Zerwas

effect reduced by SUSY–QCD corrections:
— virtual 1–loop contributions



— real contributions due to gluon radiation/crossing



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

$$= \alpha_s^2(m^2)\left\{f_0 + \frac{\alpha_s}{\pi}f_1 + \mathcal{O}(\alpha_s^2)\right\}$$

[analogous for parton densities]

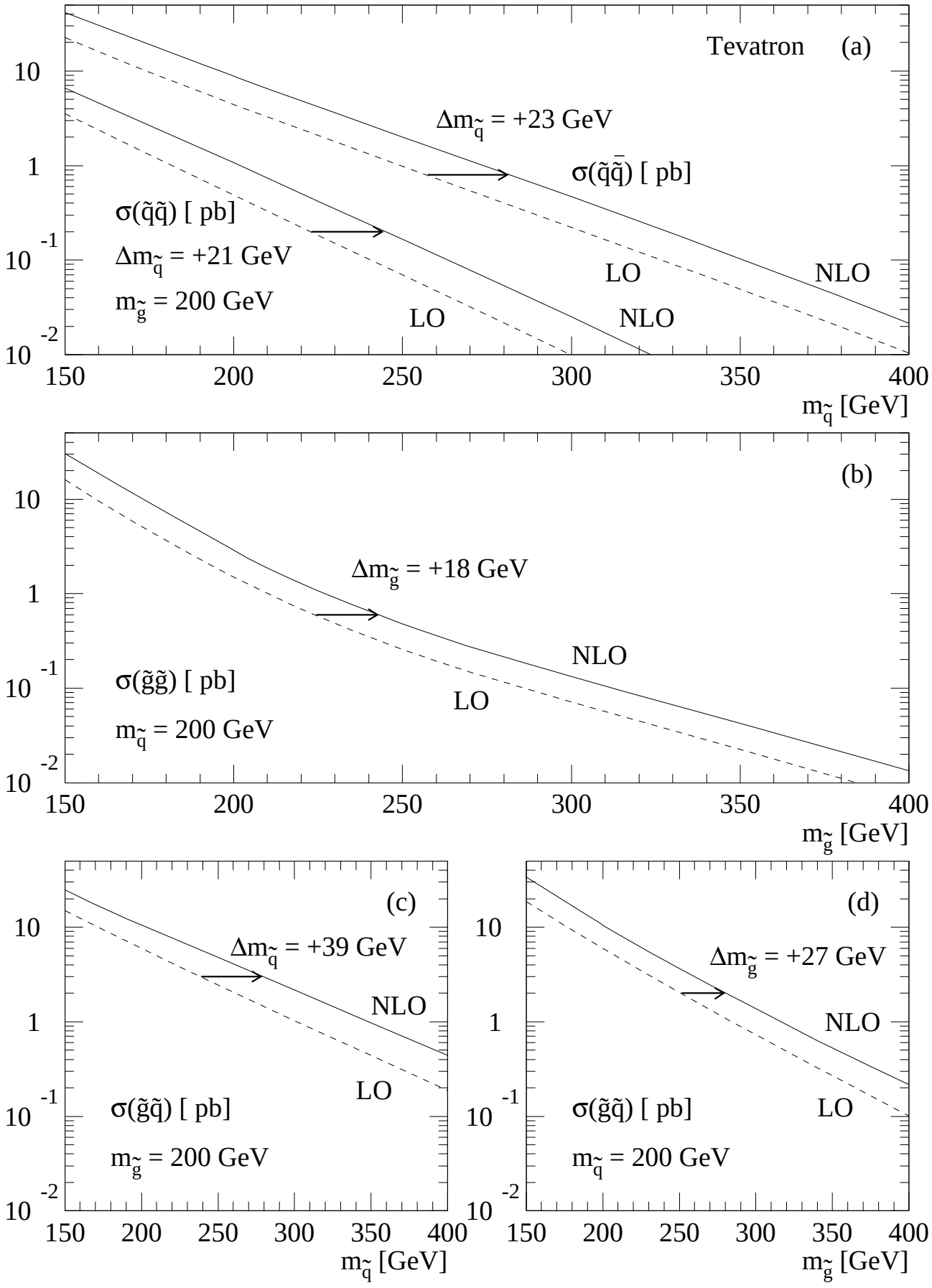
$\frac{1}{2}m < \mu_R = \mu_F < 2m$: $\delta\sigma \sim \pm 10\%$

$\Rightarrow$ NLO corrections yield reliable predictions for cross sections at hadron colliders

moderate increase by soft-gluon effects beyond NLO

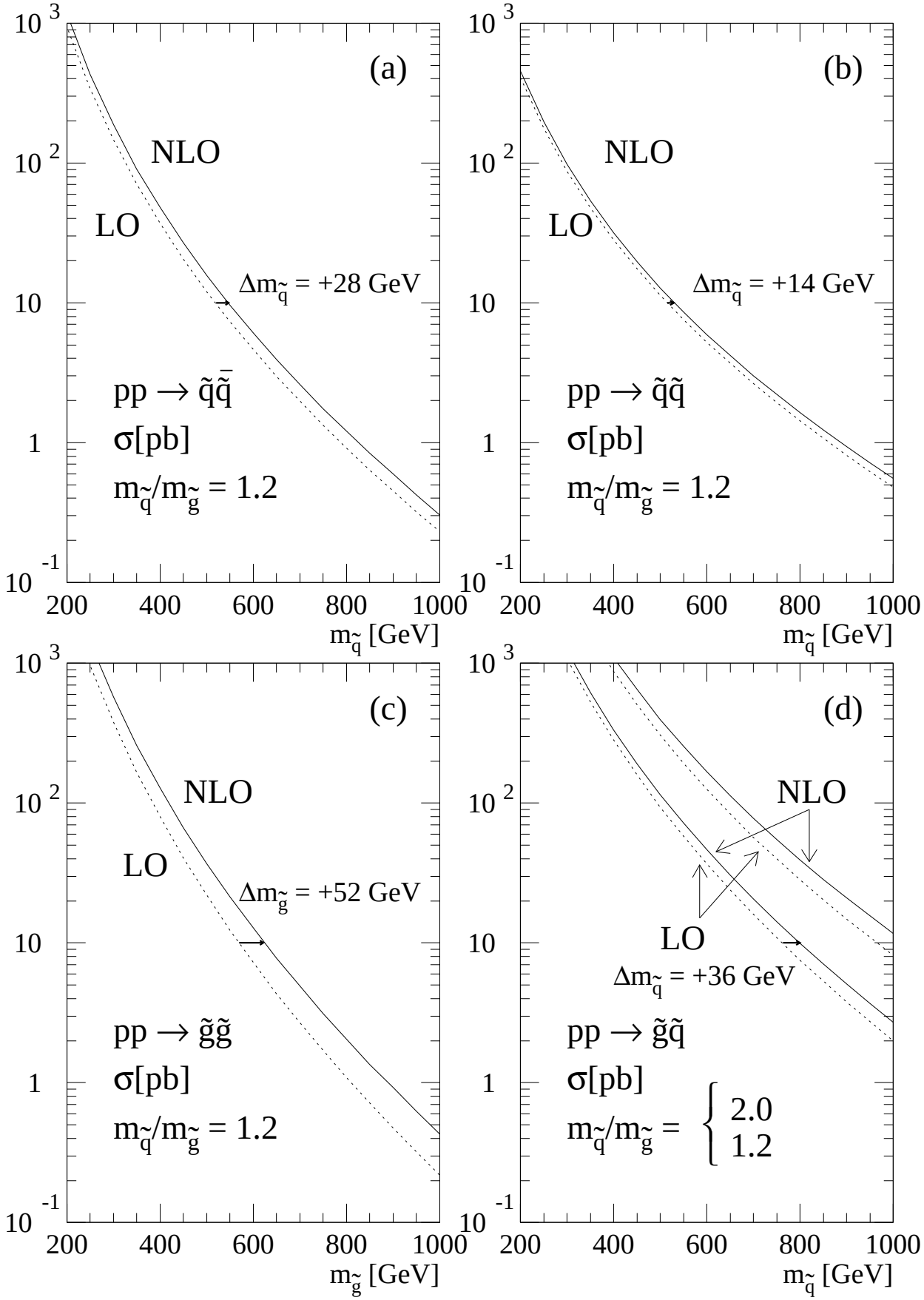
central scale: $K = \sigma_{NLO}/\sigma_{LO} \sim 1.1 - 2.0$

Tevatron

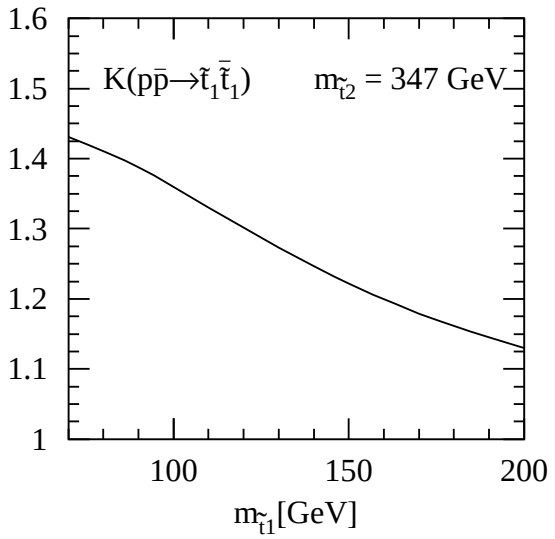


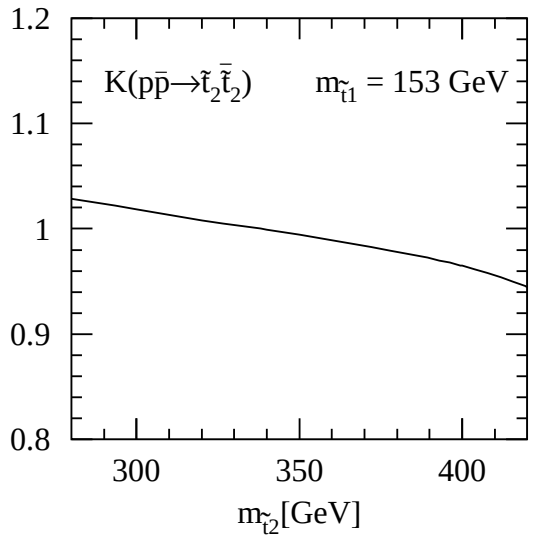
Beenakker, Höpker, S., Zerwas

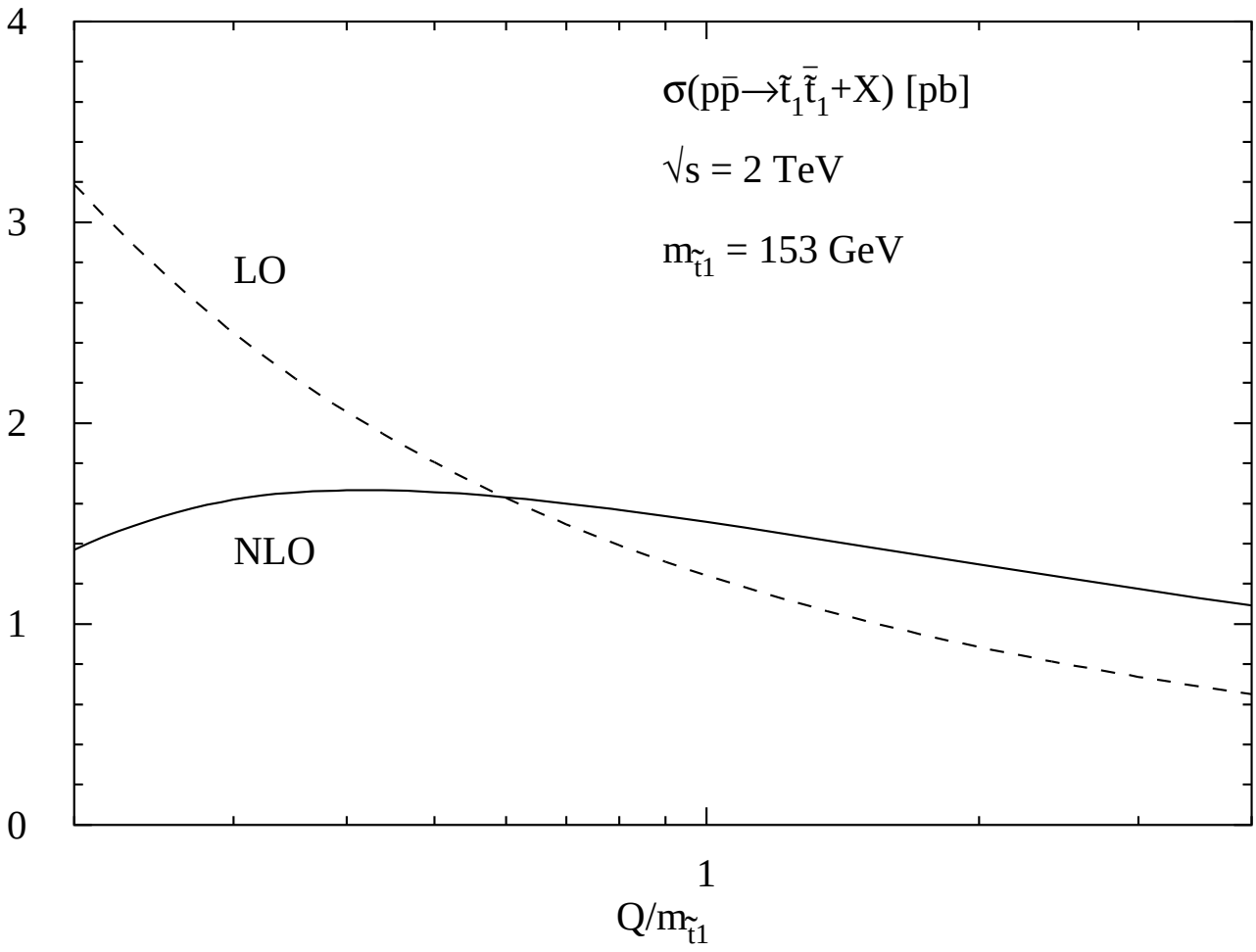
LHC



Beenakker, Höpker, S., Zerwas



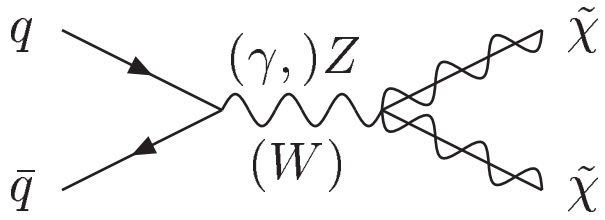


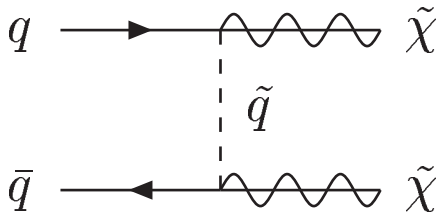


Beenakker, Krämer, Plehn, S., Zerwas

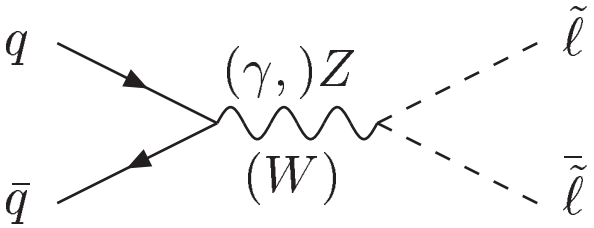
- weakly interacting particle pairs:

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



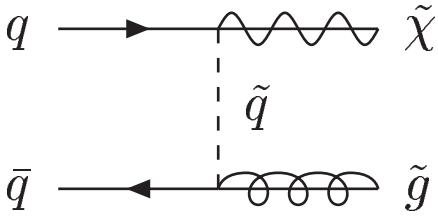


$p\overset{(-)}{p} \to \tilde{\ell}\bar{\tilde{\ell}}$

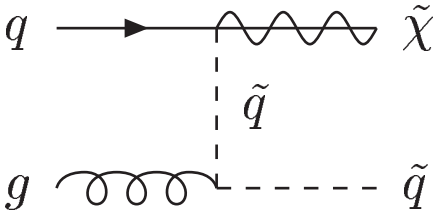


- associated production:

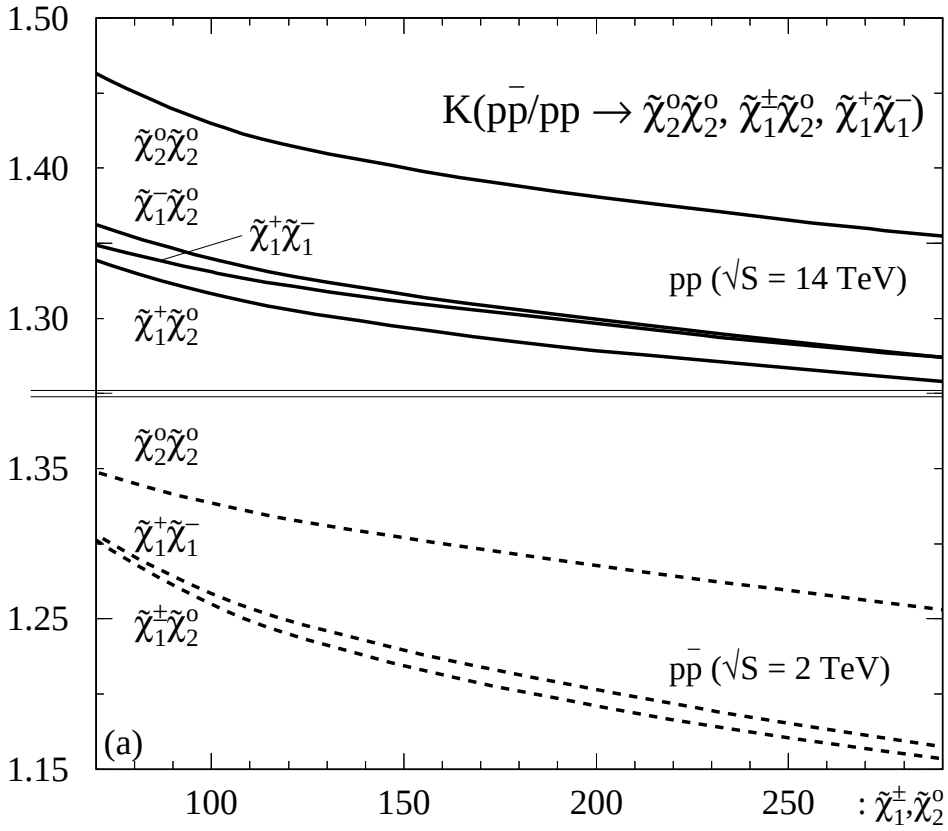
$p\overset{(-)}{p} \to \tilde{g}\tilde{\chi}$

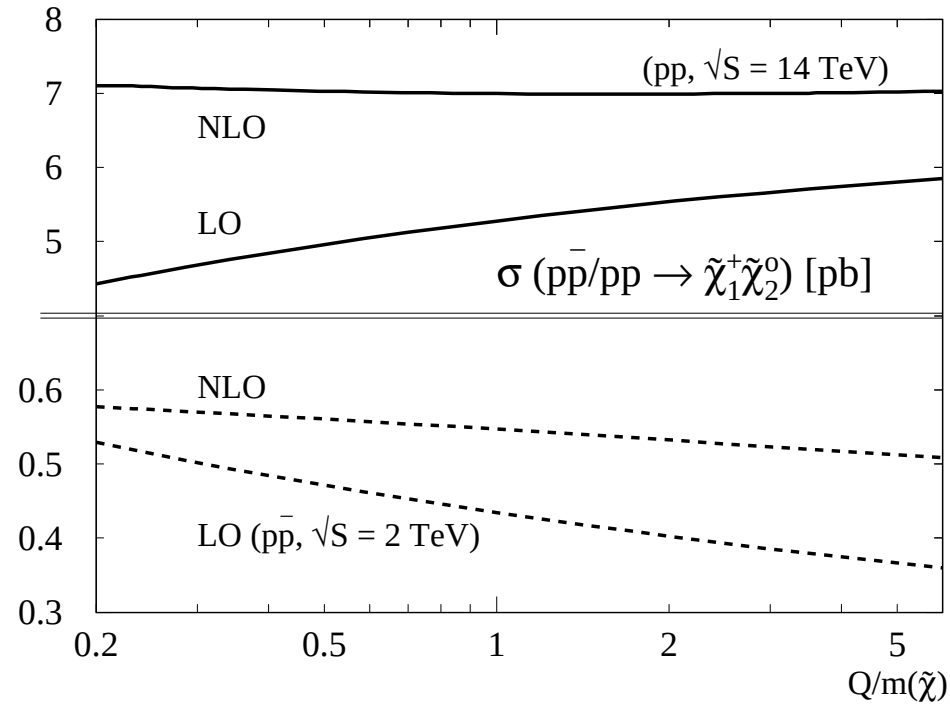


$p\overset{(-)}{p} \to \tilde{q}\tilde{\chi}$



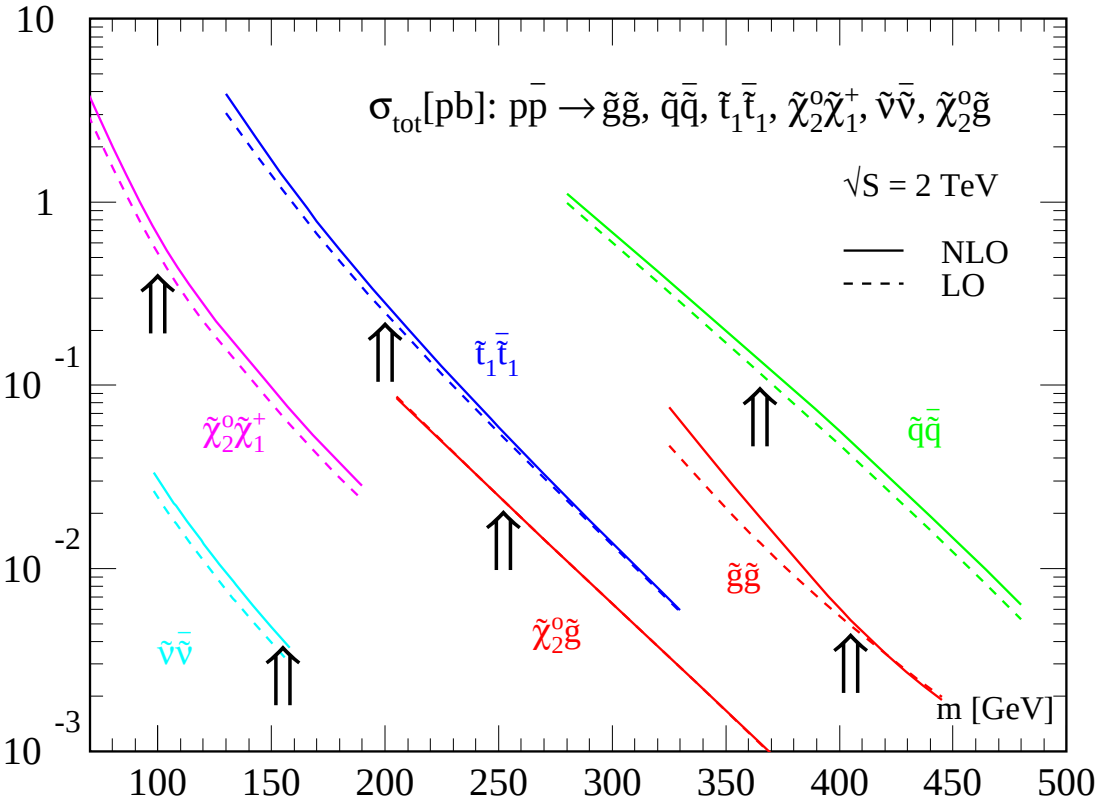
Gaugino Pairs

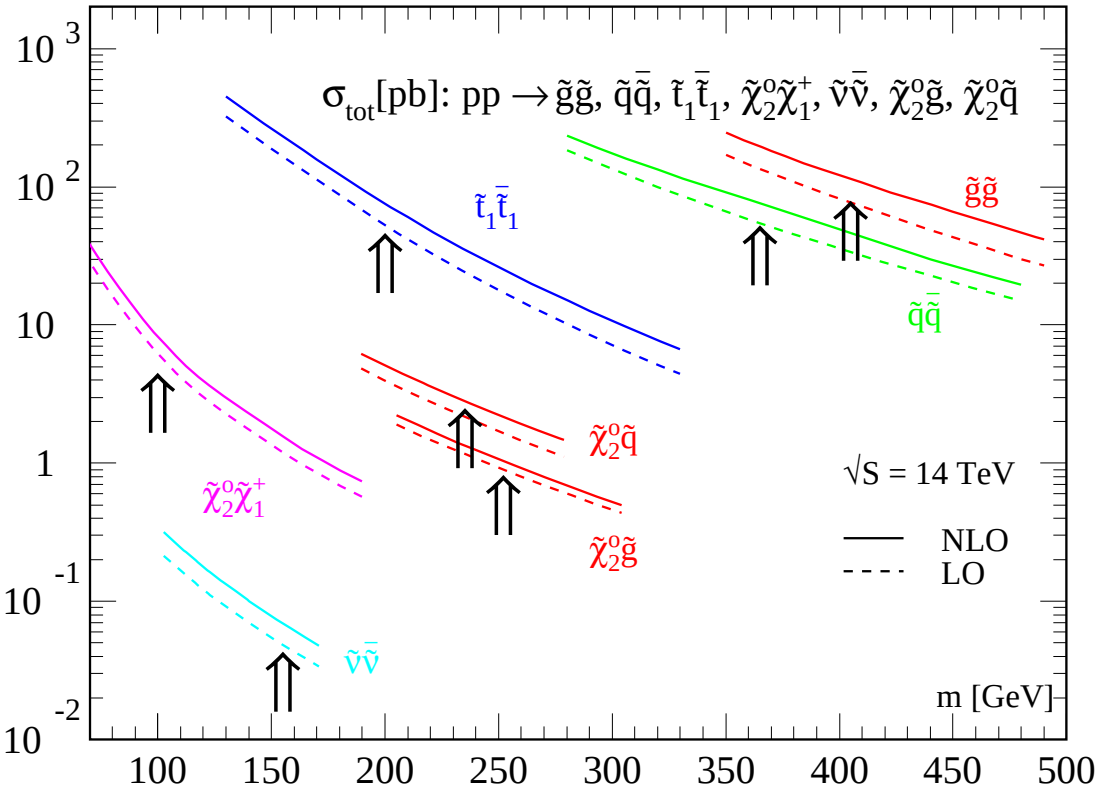




Beenakker, Klasen, Krämer, Plehn, S., Zerwas

PROSPINO

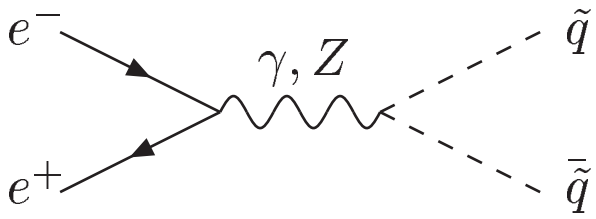




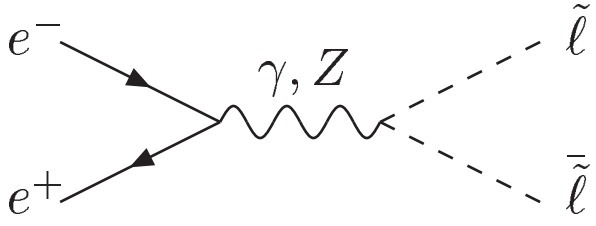
Beenakker, Krämer, Plehn, S., Zerwas

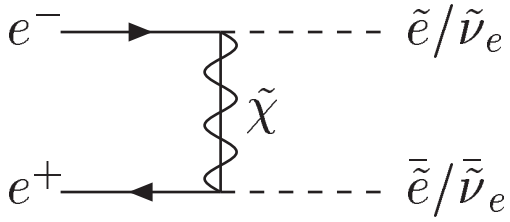
II e^+e^- Colliders

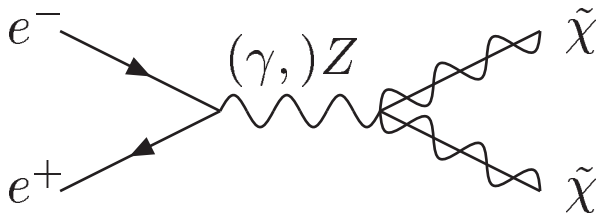
2 classes of SUSY particle production processes:
(i) strongly interacting particle pairs:

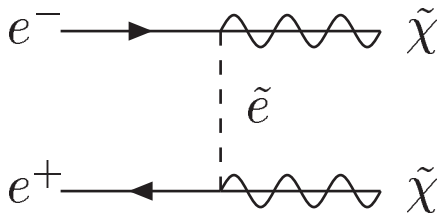


(ii) weakly interacting particle pairs:



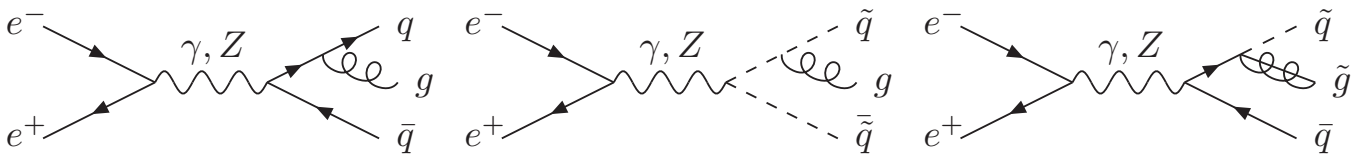






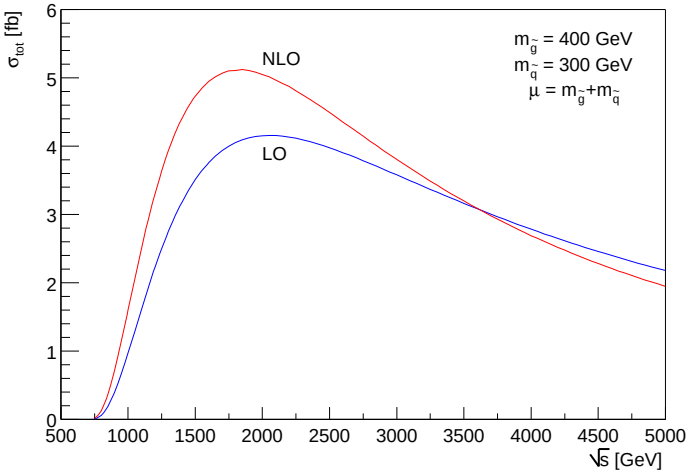
- dominant NLO corrections known

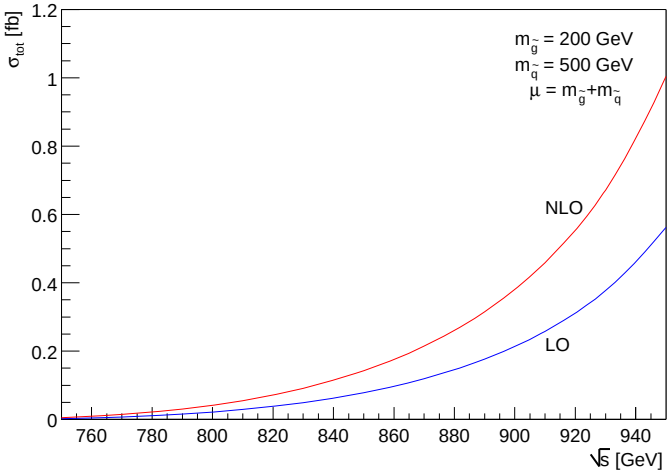
$e^+e^- \to q\bar{q}g, \tilde{q}\bar{\tilde{q}}g, \tilde{q}\bar{q}\tilde{g}$

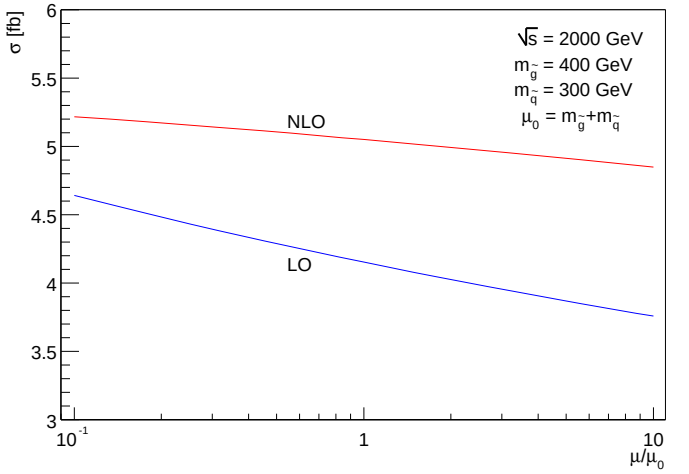


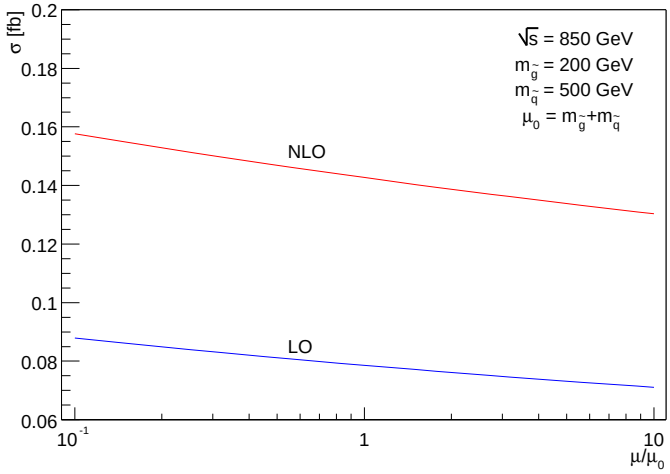
- possibility to test coupling equality ← NLO required!

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









Brandenburg, Maniatis, Weber, Zerwas

Programs:

(i) (S)PYTHIA: event generator for SM processes of all kinds with extensions for SUSY; LO results with ISR and FSR as well as hadronization effects; very famous among experimentalists

(ii) (S)Herwig: event generator for SM processes of all kinds with extensions for SUSY; similar to PYTHIA

(iii) ISAJET: event generator for SUSY processes of all kinds; LO results with ISR and FSR as well as hadronization effects; very famous among SUSY experimentalists

(iv) POWHEG/MC@NLO: event generator for some SUSY processes; NLO results with ISR and FSR as well as hadronization effects (link to PYTHIA/Herwig)

(v) ISASUSY, SOFTSUSY, SPHENO, SUSPECT: mSUGRA/GMSB/AMSB evolution programs; differences become smaller (implementation of more and more precise results in all programs)

•
•
•

pMSSM:

(i) R-parity conserved

(ii) soft parameters are real [$\rightarrow$ CKM complex]

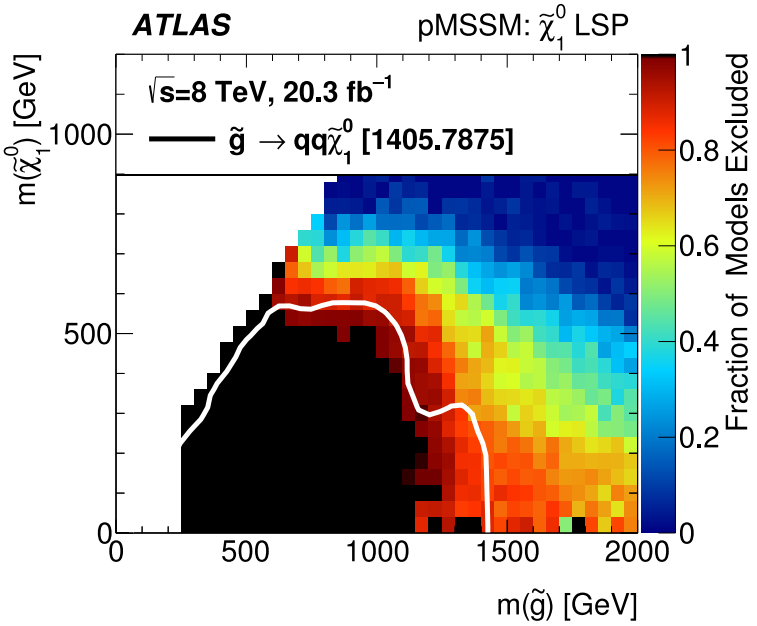
(iii) Minimal flavour violation at electroweak scale

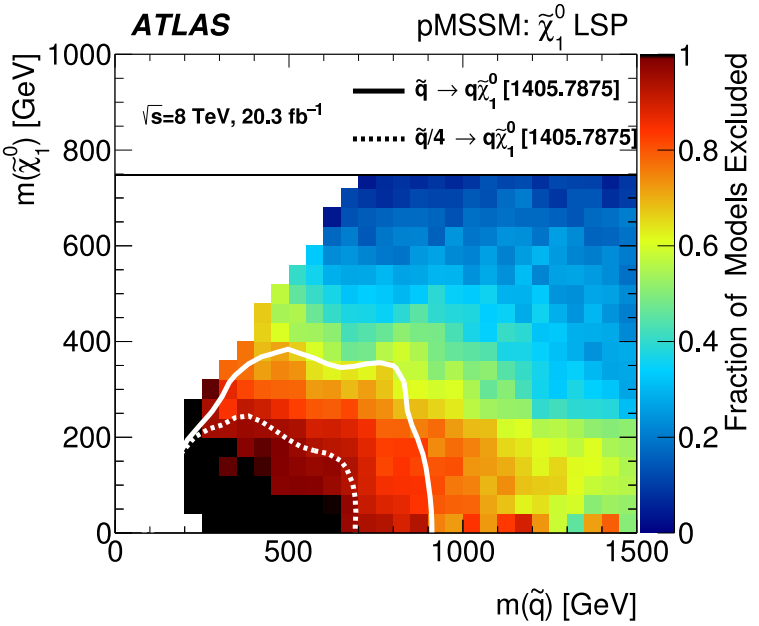
(iv) first 2 generations of squarks/sleptons with same quantum numbers

(v) LSP is $\tilde{\chi}_1^0$

$\Rightarrow$ 19 SUSY-parameters: $m_{\tilde{L}_1}$, $m_{\tilde{e}_1}$, $m_{\tilde{L}_3}$, $m_{\tilde{e}_3}$, $m_{\tilde{Q}_1}$, $m_{\tilde{u}_1}$, $m_{\tilde{d}_1}$, $m_{\tilde{Q}_3}$, $m_{\tilde{u}_3}$, $m_{\tilde{d}_3}$, $M_{1,2,3}$, μ, $A_{t,b,\tau}$, M_A, tgβ

- $pp \rightarrow \tilde{g}\tilde{g}, \tilde{q}\tilde{g}, \tilde{\chi}\tilde{g}$

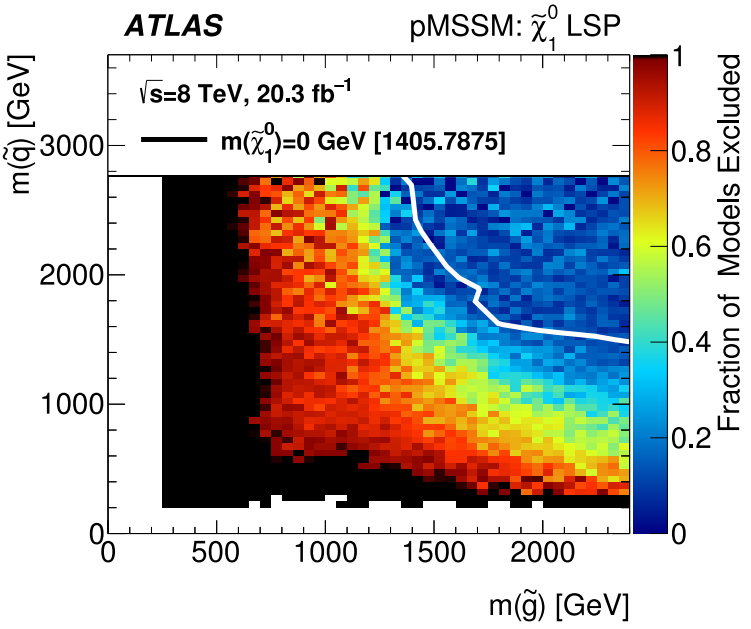


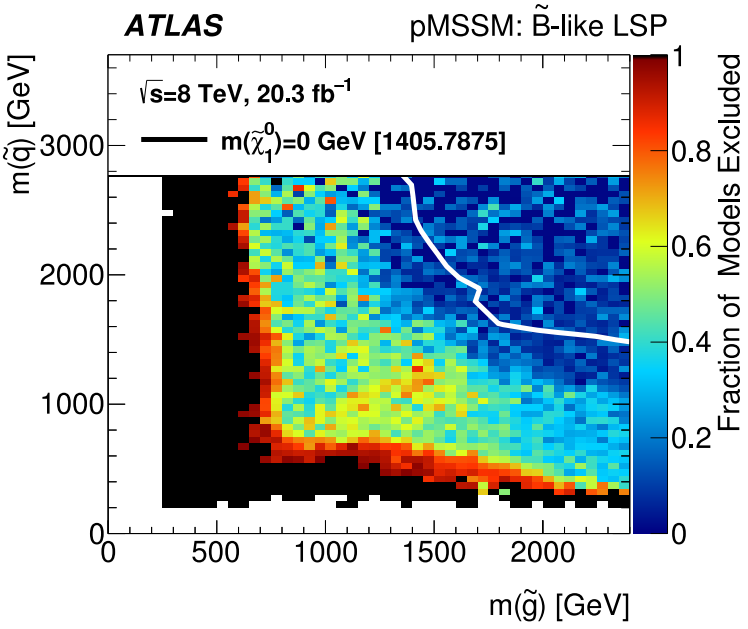


simplified model: squarks decoupled

$\Rightarrow \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$

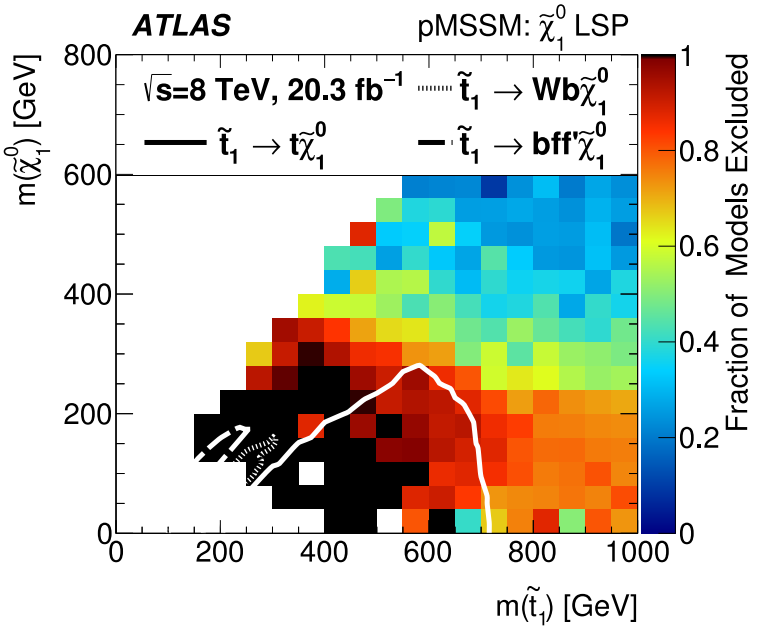
- $\tilde{q} - \tilde{g}$ plane

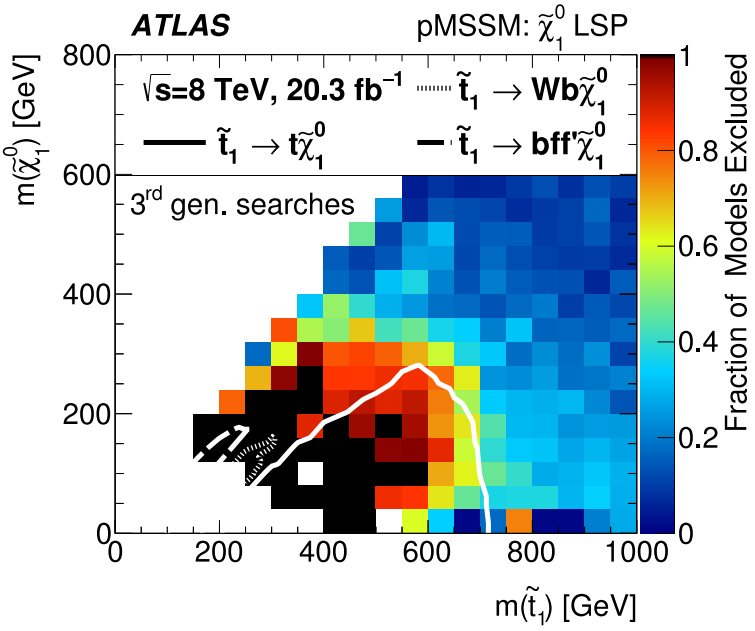




simplified model: LSP massless

- stop searches





simplified model: $pp \to \tilde{t}_1\bar{\tilde{t}}_1$ with $BR(\tilde{t}_1 \to t\chi_1^0) = 1$

§7. R Parity Violation

H. Dreiner, hep–ph/9707435

- superpotential:

$$\begin{aligned}
\mathcal{L}_W &= -\sum_i \left|\frac{\partial W}{\partial \phi_i}\right|^2 - \frac{1}{2}\sum_{ij} \overline{\psi_{iL}{}^c} \frac{\partial^2 W}{\partial \phi_i \partial \phi_j} \psi_{jL} + h.c. \\
W &= W_R + W_{\not R} \\
W_{\not R} &= \lambda_{ijk} \tilde{L}_i \tilde{L}_j \tilde{E}^c_k + \lambda'_{ijk} \tilde{L}_i \tilde{Q}_j \tilde{D}^c_k + \lambda''_{ijk} \tilde{U}^c_i \tilde{D}^c_j \tilde{D}^c_k
\end{aligned}$$

(i, j, k: generation indices)

- $SU(2)_L$ invariance: $\lambda_{ijk} = -\lambda_{jik}$

- $SU(3)_c$ invariance: $\lambda''_{ijk} = -\lambda''_{ikj}$

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

- Lagrange density of 1. term:

$$\mathcal{L}_{LLE} = \lambda_{ijk}\left[\tilde{\nu}^i_L \bar{e}^k_R e^j_L + \tilde{e}^j_L \bar{e}^k_R \nu^i_L + \bar{\tilde{e}}^k_R \overline{\nu^{ic}_L} e^j_L - (i \leftrightarrow j)\right] + h.c.$$

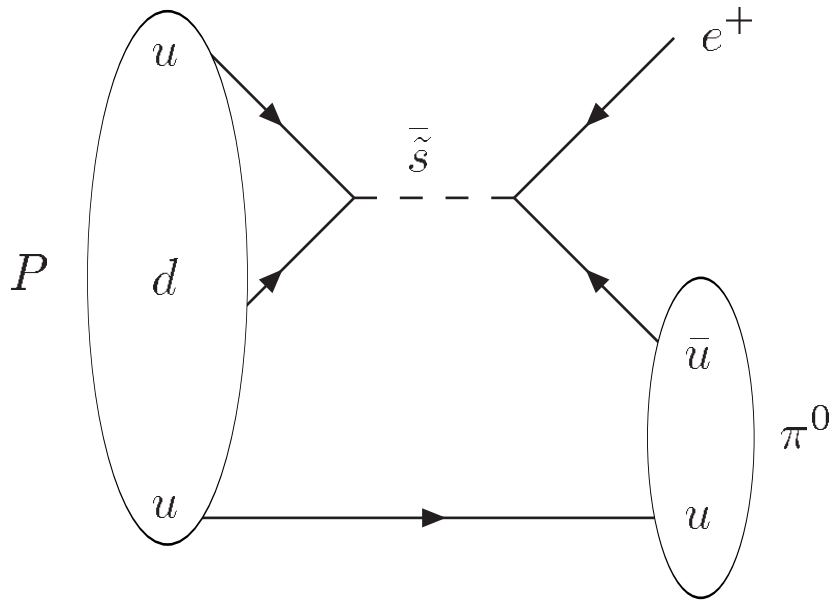
$\Rightarrow$ $\lambda_{ijk}, \lambda'_{ijk}$ lepton number violating
λ''_{ijk} baryon number violating

- R parity:

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

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

- proton decay:



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

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

$\rightarrow$ symmetries:

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

(ii) matter parity:

$$\begin{aligned} (\tilde{L}_i, \tilde{E}_i^c, \tilde{Q}_i, \tilde{U}_i^c, \tilde{D}_i^c) &\rightarrow -(\tilde{L}_i, \tilde{E}_i^c, \tilde{Q}_i, \tilde{U}_i^c, \tilde{D}_i^c) \\ (H_1, H_2) &\rightarrow (H_1, H_2) \end{aligned}$$

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

(iii) baryon parity:

$$\begin{aligned} (\tilde{Q}_i, \tilde{U}_i^c, \tilde{D}_i^c) &\rightarrow -(\tilde{Q}_i, \tilde{U}_i^c, \tilde{D}_i^c) \\ (\tilde{L}_i, \tilde{E}_i^c, H_1, H_2) &\rightarrow (\tilde{L}_i, \tilde{E}_i^c, H_1, H_2) \end{aligned}$$

$\Rightarrow \lambda''_{ijk} = 0$

(iv) lepton parity:

$$\begin{aligned} (\tilde{L}_i, \tilde{E}_i^c) &\rightarrow -(\tilde{L}_i, \tilde{E}_i^c) \\ (\tilde{Q}_i, \tilde{U}_i^c, \tilde{D}_i^c, H_1, H_2) &\rightarrow (\tilde{Q}_i, \tilde{U}_i^c, \tilde{D}_i^c, H_1, H_2) \end{aligned}$$

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

$M_p < M_{LSP} \Rightarrow$ 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 $\tilde{m}$:

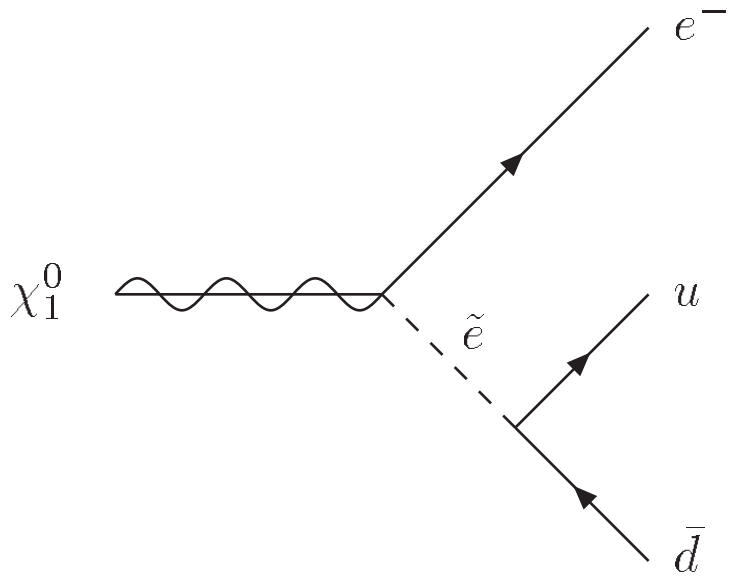
λ_{ijk}	$m_{\tilde{e}_{Rk}}/100GeV$	λ'_{111}	$(m_{\tilde{q}}/100GeV)^2(m_{\tilde{g}}/1TeV)^{1/2}$
λ'_{11k} , λ'_{21k}	$m_{\tilde{d}_{Rk}}/100GeV$	λ'_{1j1}	$m_{\tilde{q}_{Lj}}/100GeV$
λ_{133} , λ'_{1jj}	$(m_{\tilde{\tau},\tilde{d}_j}/100GeV)^{1/2}$	λ'_{123}	$(m_{\tilde{b}_R}/100GeV)^{1/2}$
λ'_{231}	$m_{\tilde{\nu}_{\tau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



$$\Gamma_{\tilde{\gamma}} = \frac{3\alpha\lambda'^2_{111}}{128\pi^2}\,\frac{M^5_{\tilde{\gamma}}}{\tilde{m}_e^4} \qquad (\tilde{\gamma} = \tilde{\chi}_1^0 \text{ LSP})$$

decay in detector: $c\gamma\tau \lesssim 1m$

$$\Rightarrow \lambda'_{111} > 1.4 \times 10^{-6}\sqrt{\gamma}\left(\frac{\tilde{m}_e}{200\text{ GeV}}\right)^2 \sqrt{\frac{100\text{ GeV}}{M_{\tilde{\gamma}}}}^5$$

$\Rightarrow$ no natural candidate for dark matter

(iii) LSP $\in (\tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \tilde{g}, \tilde{q}, \tilde{t}, \tilde{\ell}, \tilde{\nu})$
need not be charge and color neutral [$\leftarrow$ cosmology]

(iv) production of single SUSY particles:

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

• collider phenomenology:

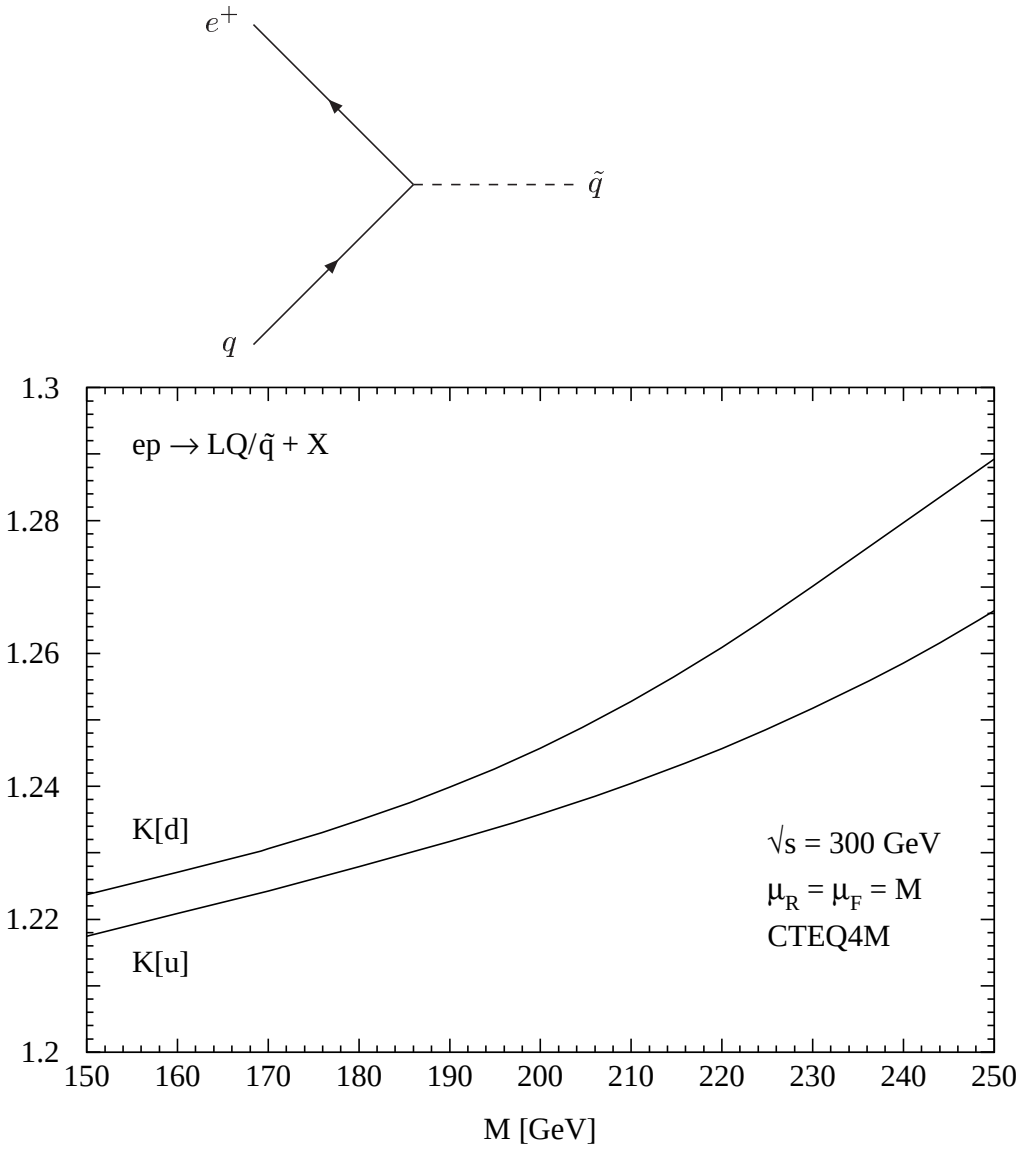
pair production: $\tilde{m} \lesssim \dfrac{\sqrt{s}}{2} \Rightarrow$ kinematical limitation

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

Ex.: resonant squark production at HERA

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

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



Plehn, Spiesberger, S., Zerwas
Kunszt, Stirling

gaugino decays:

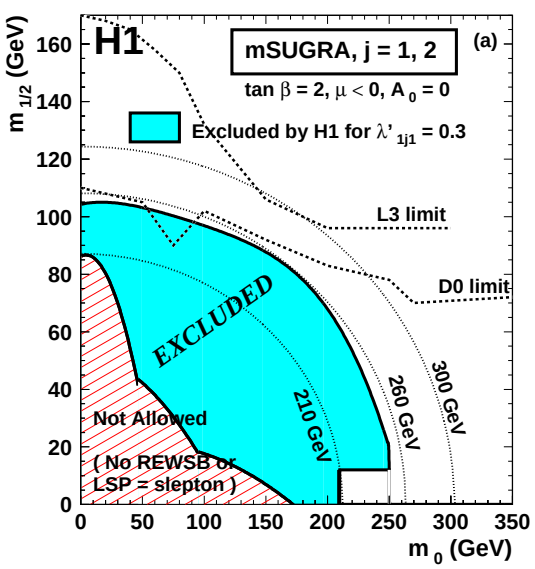
$$\tilde{\chi}_1^0 \rightarrow (e^{\pm}, \nu) + 2\ jets$$
$$\tilde{\chi}_1^+ \rightarrow (e^+, \nu) + 2\ jets$$

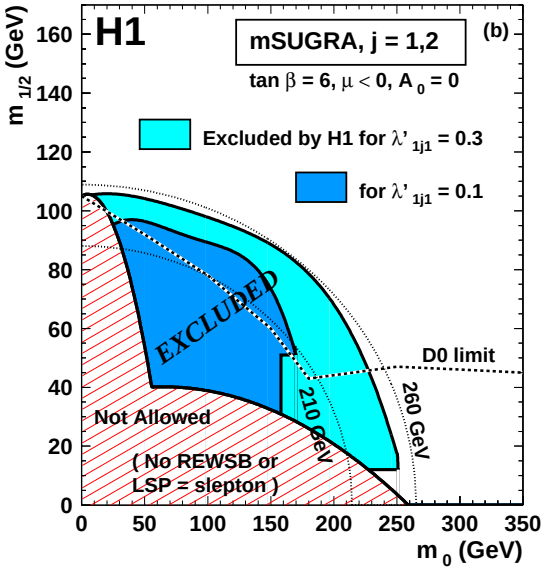
RPV: Limits from H1

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 (m_o, $m_{1/2}$)–plane





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

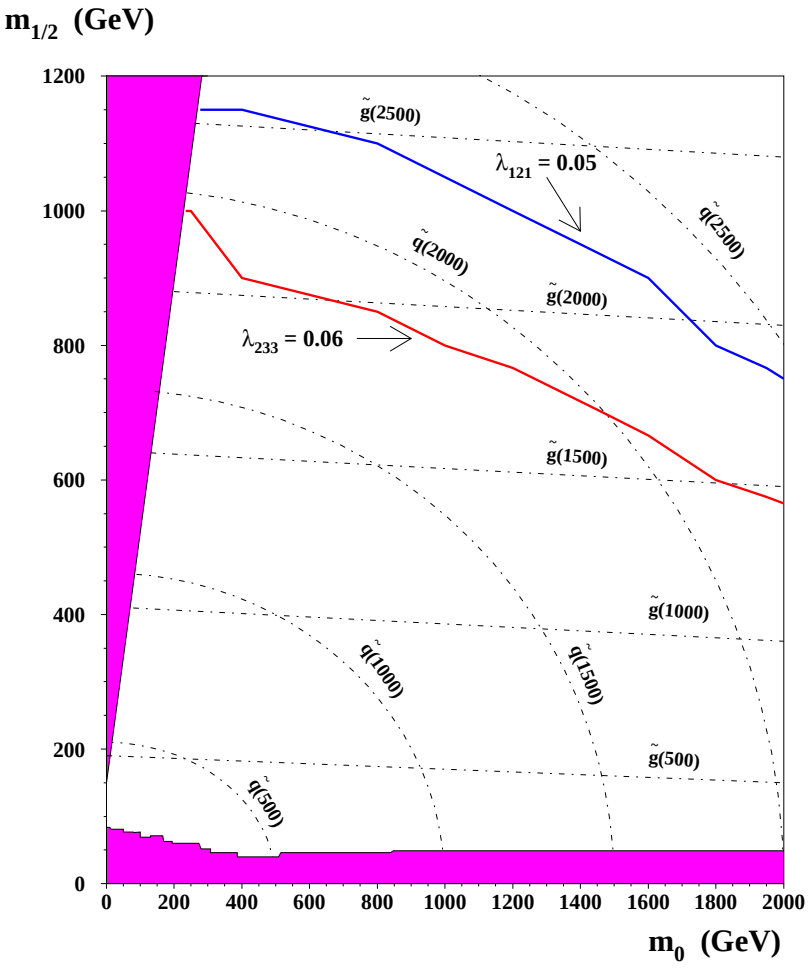
REWSB .. Radiative ElectroWeak Symmetry Breaking

Remark: LEP and Tevatron bounds do not depend on the value of the Yukava coupling

Similar results from ZEUS

RPV: Reach at LHC

CMS reach for 10fb^{-1}



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

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

$\Longrightarrow$ Reach compatible to R_P conserving mSUGRA scenario