Production of Supersymmetric Particles at High-Energy Colliders

Tilman Plehn

– Search for the MSSM

– Production of Neutralinos/Charginos

– Stop Mixing

– Production of Stops

– R Parity violating Squarks

– Conclusions and Outlook

Introduction to the MSSM

Supersymmetric extension of Standard Model:

⋆ fermion–boson mapping

→ stable scalar masses $$\frac{\delta m^2}{m^2} \sim g^2 \frac{\tilde{M}^2 - M^2}{\Lambda_{\rm EW}^2} + g^2 \log \frac{\Lambda_{\rm EW}^2}{\Lambda_{\rm P}^2}$$

⋆ unification of gauge couplings

→ prediction of weak mixing angle

⋆ possible extension to supergravity and string models

Particle Content:

		spin	charge	d.o.f.	
light quark	q_L, q_R	1/2	2/3 , −1/3	1+1	
squark	$\tilde{q}_L, \tilde{q}_R$	0	2/3 , −1/3	1+1	5 flavors
top quark	t_L, t_R	1/2	2/3	1+1	
top squark	$\tilde{t}_L, \tilde{t}_R$	0	2/3	1+1	mixing
gluon	G_μ	1	0	$n-2$	→ 2 d.o.f.
gluino	$\tilde{g}$	1/2	0	2	Majorana
gauge bosons	γ, Z	1	0	2+3	
Higgs bosons	h^o, H^o, A^o	0	0	3	
neutralinos	$\tilde{\chi}_i^o$	1/2	0	$4 \cdot 2$	Majorana
gauge bosons	$W^\pm$	1	±1	$2 \cdot 3$	
Higgs bosons	$H^\pm$	0	±1	2	
charginos	$\tilde{\chi}_i^\pm$	1/2	±1	$2 \cdot 4$	Dirac

Supersymmetry Breaking

Mass difference between supersymmetric partners

→ soft SUSY breaking leaves masses stable:

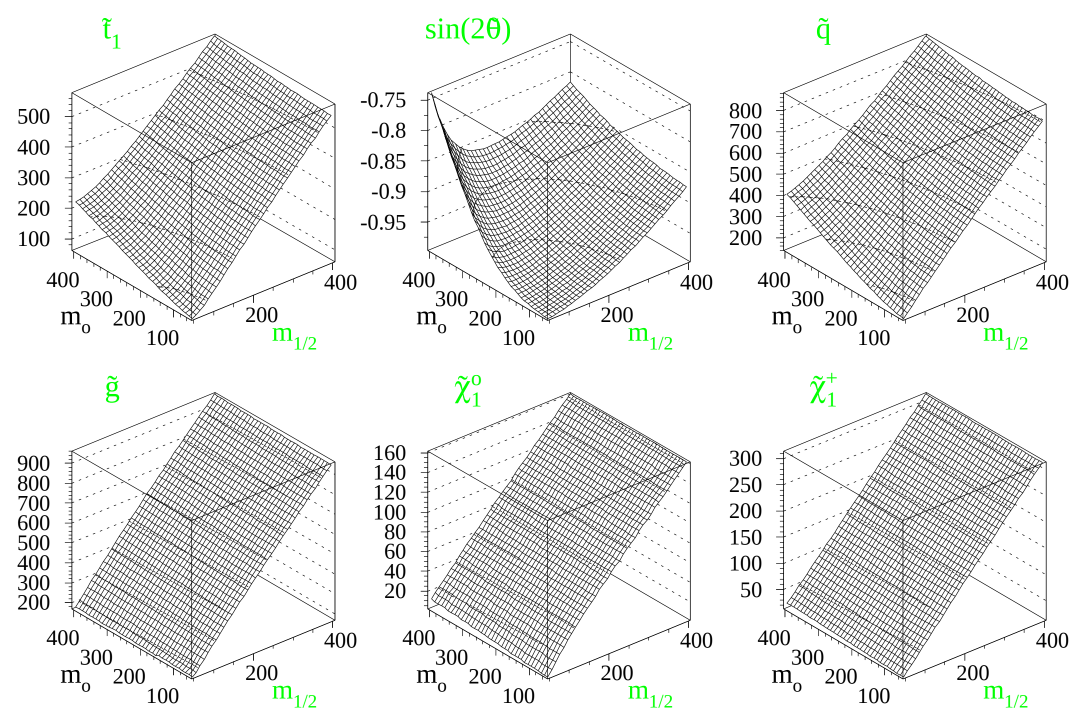
$$\mathcal{L}_{\text{soft}} = -(m_0^2)_{ij} C_i^* C_j - \left[\frac{1}{2}(m_{1/2})_j \lambda_j \lambda_j + \text{h.c.}\right] - \left[\frac{1}{6} A_{ijk} C_i C_j C_k + B\mu H_1 H_2 + \text{h.c.}\right]$$

At a given scale:

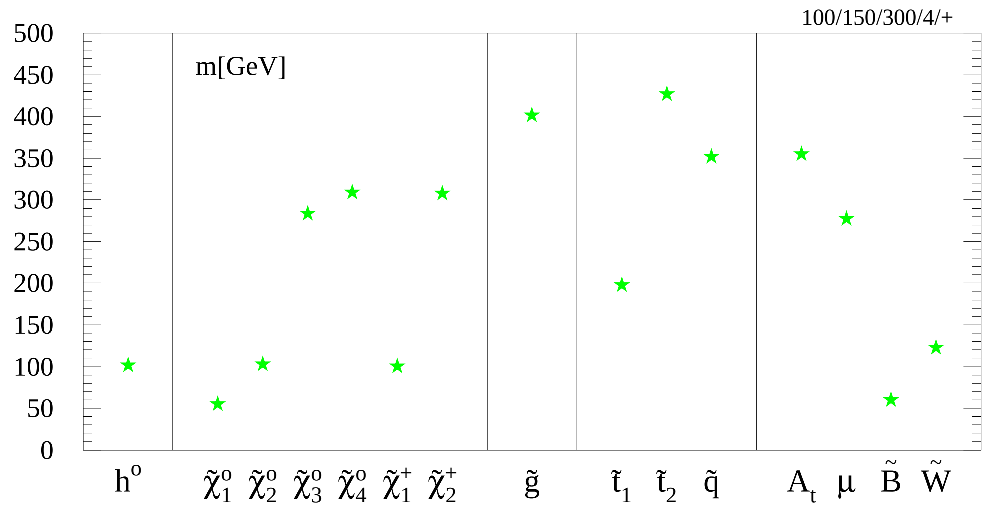
- scalar masses m_0 for squarks and sleptons; chosen real
- gaugino masses $m_{1/2}$
- trilinear couplings A_{ijk}; conserving **R** charge
- complex Higgs mass parameter $B\mu$

Universality at unification scale and ew. symmetry breaking:

→ 4 1/2 free parameters $m_0, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu)$



Mass Spectrum



Typical features:

⋆ light gauginos [$m_{\tilde{B}}, m_{\tilde{W}} \ll |\mu|; m_Z$ inducing mixing]

$$\begin{pmatrix} m_{\tilde{B}} & 0 & -m_Z s_w c_\beta & m_Z s_w s_\beta \\ 0 & m_{\tilde{W}} & m_Z c_w c_\beta & -m_z c_w s_\beta \\ -m_Z s_w c_\beta & m_Z c_w c_\beta & 0 & -\mu \\ m_Z s_w s_\beta & -m_Z c_w s_\beta & -\mu & 0 \end{pmatrix}$$

⋆ heavy gluino [gauge coupling unification]

$$m_{\tilde{B}} \sim 0.4\, m_{1/2}$$
$$m_{\tilde{W}} \sim 0.8\, m_{1/2}$$
$$m_{\tilde{g}} \sim 2.6\, m_{1/2}$$

⋆ light mixing stop [m_t in off-diagonal terms]

$$\begin{pmatrix} m_Q^2 + m_t^2 + \left(\frac{1}{2} - \frac{2}{3}s_w^2\right) m_Z^2 c_{2\beta} & -m_t\left(A_t + \mu \cot\beta\right) \\ -m_t\left(A_t + \mu\cot\beta\right) & m_U^2 + m_t^2 + \frac{2}{3}s_w^2 m_Z^2 c_{2\beta} \end{pmatrix}$$

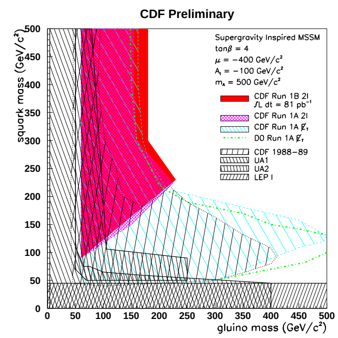
⋆ heavy squark [approximate solution] $\quad m_{\tilde{q}} \gtrsim 0.85 m_{\tilde{g}}$

Tevatron Searches

squarks/gluinos

$$\tilde{q} \longrightarrow \; q\tilde{\chi}_j^0,\; q'\tilde{\chi}_j^+ \quad \longrightarrow \text{jets} + \not{E}_T\; [+\gamma] + \cdots$$

$$\tilde{g} \longrightarrow \; q\bar{q}\tilde{\chi}_j^0,\; q'\bar{q}\tilde{\chi}_j^+ \longrightarrow \text{jets} + \not{E}_T\; [+\gamma] + \cdots$$

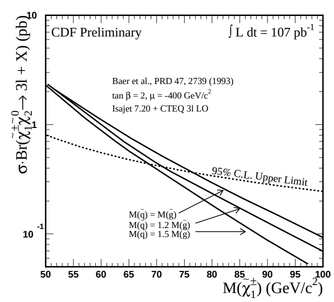


gluinos

$$\tilde{g} \longrightarrow \; q'\bar{q}\tilde{\chi}_j^+ \longrightarrow \text{jets} + \not{E}_T + \ell^\pm + \cdots$$

$\rightarrow$ like-sign leptons

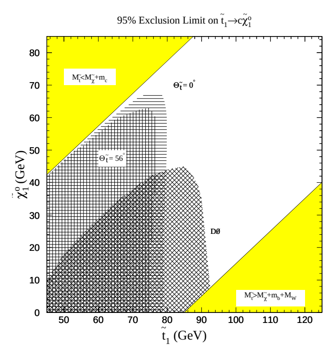
neutralinos/charginos



$$\tilde{\chi}_1^+\; \tilde{\chi}_2^0 \longrightarrow \ell\nu\tilde{\chi}_1^0\; \ell\ell\tilde{\chi}_1^0 \longrightarrow \ell\ell\ell + \not{E}_T + \cdots$$

$\rightarrow$ trileptons

stops



$$\tilde{t}_1 \longrightarrow c\tilde{\chi}_1^0 + \cdots$$

$\rightarrow$ mixing angle in BR

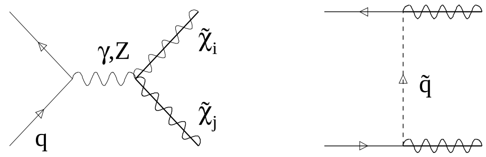
⋆ all limits strongly dependent on cascade decays

complete set of possible decays necessary

supergravity or gauge mediation scenarios only for first guess

Neutralino/Chargino Production

Leading order cross section:



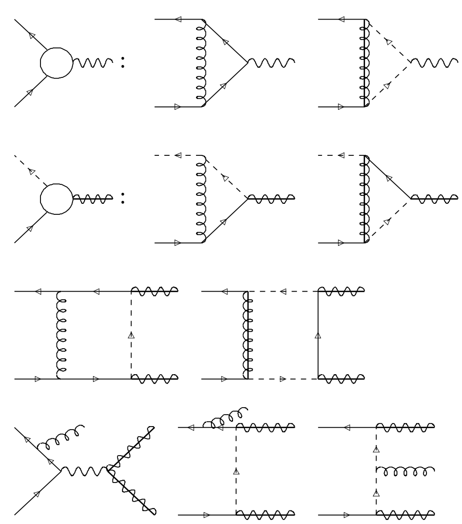
$$\frac{d\hat{\sigma}}{dt}\left(q\bar{q}\to\tilde{\chi}^0_i\tilde{\chi}^0_j\right) = \frac{1}{4N_c}\Bigg[\; 4\,C_{ss}\frac{t_i t_j + u_i u_j \mp 2 s m_i m_j}{(s-m_Z^2)^2} - 8\,C_{st}\frac{t_i t_j \mp s m_i m_j}{(s-m_Z^2)(t-m_{\tilde{q}}^2)} - 8\,C_{st}\frac{u_i u_j \mp s m_i m_j}{(s-m_Z^2)(u-m_{\tilde{q}}^2)} + 4\,C_{tu}\left(\frac{t_i t_j}{(t-m_{\tilde{q}}^2)^2} + \frac{u_i u_j}{(u-m_{\tilde{q}}^2)^2} \mp \frac{2 s m_i m_j}{(t-m_{\tilde{q}}^2)(u-m_{\tilde{q}}^2)}\right)\Bigg]$$

Neutralino production mechanism

– s channel [Drell–Yan like] $Z\tilde{\chi}\tilde{\chi}$ coupling to higgsinos

– t, u channel $q\tilde{q}\tilde{\chi}$ coupling to gauginos

Next-to-leading order cross section:



⋆ Real/virtual SUSY-QCD corrections

→ LO factorization scale dependence
bad measure for theoretical error
→ improvement of error bars

→ $K \equiv \sigma_{\rm NLO}/\sigma_{\rm LO}$
→ improvement of central value

Regularization and Supersymmetry

Dimensional regularization breaks supersymmetry

e.g. non-abelian gauge theory [Jack & Jones]:

$$\delta_S \mathcal{L}[W^a_\mu, \lambda^a, D] \stackrel{n\to 4}{\longrightarrow} 0$$

$\to$ preserved Ward identity contains $\delta_S \mathcal{L}$

$$0 = \langle \int d^n x \, [J^\mu \, \delta_S W_\mu + \bar{j} \, \delta_S \lambda + \bar{j}_D \, \delta_S D + \delta_S \mathcal{L}] \rangle$$

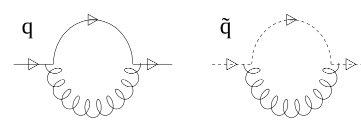
$\to$ Dimensional Regularization can be
rendered consistent with SUSY

Yukawa coupling in supersymmetric limit:

$$Y(qqh) = Y(\tilde{q}\tilde{q}h)\left[1 + \frac{g^2}{16\pi^2}C(r)\right] = Y(q\tilde{q}\tilde{h})\left[1 + \frac{3g^2}{32\pi^2}C(r)\right]$$

different behavior of scalar and fermion masses $Y \equiv mg$

$$m_q = \left[1 + \frac{g^2}{16\pi^2}C(r)\right] m_{\tilde{q}}$$



$$\to g_{\overline{\rm MS}} \equiv g(qqh) = g(\tilde{q}\tilde{q}h) = g(q\tilde{q}\tilde{h})\left[1 + \frac{g^2}{32\pi^2}C(r)\right]$$

- $\star$ difference removed by finite 'renormalization' [Martin & Vaughn]
- $\star$ check by comparison of Green's functions with dimensional reduction

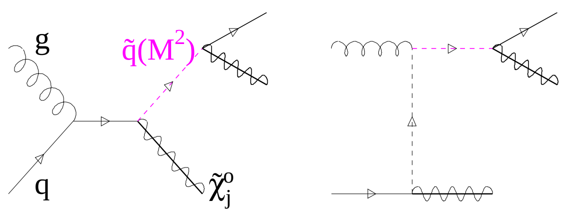
On-Shell Singularities

NLO $\tilde{\chi}\tilde{\chi}$ production includes $\sim G_F^2 \alpha_s$:

$$gq \to \tilde{q}^* \chi_i \to q \chi_j \chi_i \qquad \text{pair production}$$

$$gq \to \tilde{q} \chi_i \cdot \text{BR}(\tilde{q} \to q \chi_j) \qquad \text{associated production}$$

via



(1) Possible inclusion of finite widths:

– double counting of pair and associated production

– breaking of gauge invariance of σ without Γ

– dependence on unknown physical widths

(2) Splitting into on-shell and off-shell squark:

$$\frac{d\sigma}{dM^2} = \sigma\left(gq \to \tilde{q}\chi_i\right) \frac{m_{\tilde{q}}\Gamma_{\tilde{q}}/\pi}{(M^2 - m_{\tilde{q}}^2)^2 + m_{\tilde{q}}^2 \Gamma_{\tilde{q}}^2} \text{BR}\left(\tilde{q} \to q\chi_j\right) + \mathcal{O}\left(\frac{1}{M^2 - m_{\tilde{q}}^2}\right)$$

$$\longrightarrow \sigma\left(gq \to \tilde{q}\chi_i\right) \text{BR}\left(\tilde{q} \to q\chi_j\right) \delta(M^2 - m_{\tilde{q}}^2) + \mathcal{O}\left(\frac{1}{M^2 - m_{\tilde{q}}^2}\right)$$

– cross section in narrow widths approximation

⋆ divergences removed from $\sigma_{\chi\chi}$

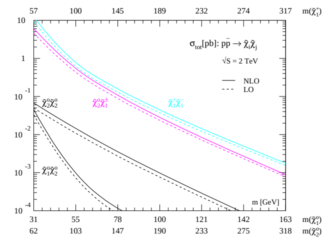
⋆ treatment compatible with experimental Monte-Carlos

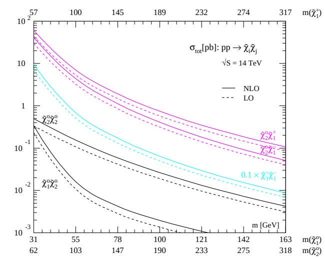
Production Cross Sections

Only $\tilde\chi^0_2\tilde\chi^\pm_1$ and $\tilde\chi^-_1\tilde\chi^+_1$ visible at the Tevatron

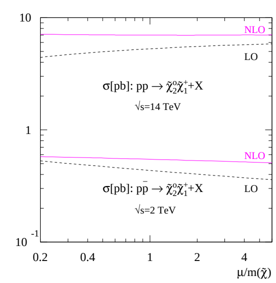
Whole set of processes at the LHC

[higgsino cross sections suppressed]

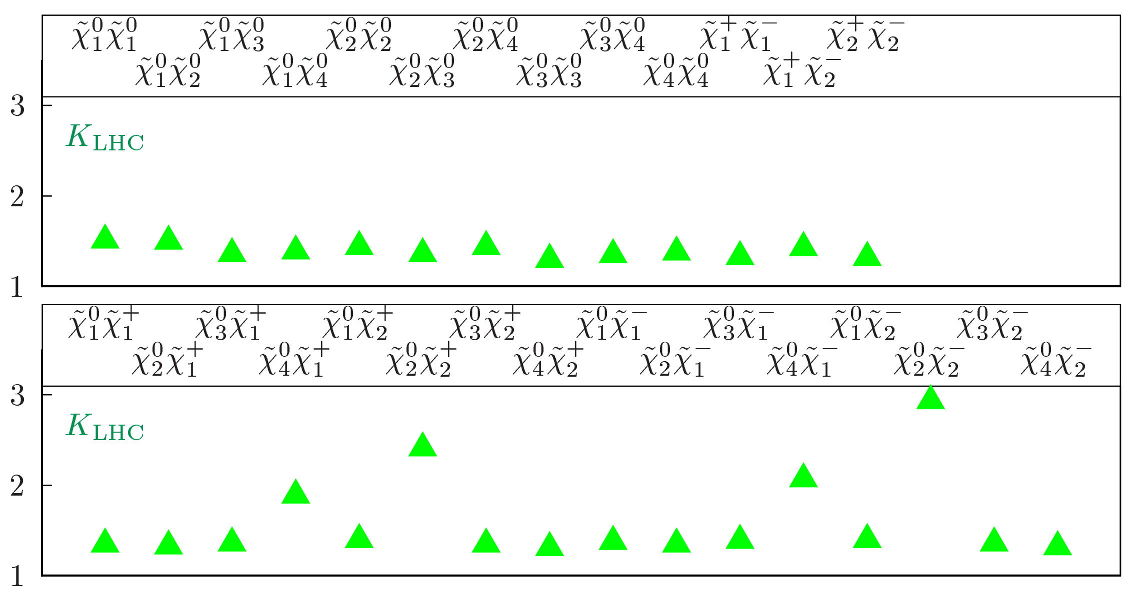




NLO scale dependence good measure
for theoretical uncertainty



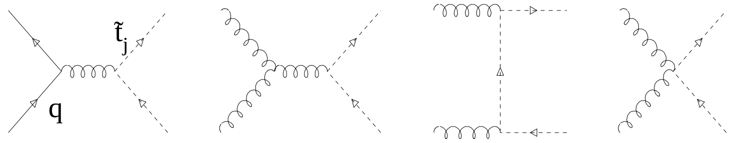
General [mass independent] K factor for all LHC processes,
but huge effects due to destructive interference



Stop Production

Leading order cross section:

$$q\bar{q}/gg \to \tilde{t}_1\bar{\tilde{t}}_1 \quad \tilde{t}_2\bar{\tilde{t}}_2 \quad [\tilde{t}_1\bar{\tilde{t}}_2 \quad \bar{\tilde{t}}_1\tilde{t}_2]$$



$$\hat{\sigma}_{LO}[q\bar{q} \to \tilde{t}_j\bar{\tilde{t}}_j] = \frac{\alpha_s^2\pi}{s}\,\frac{2}{27}\,\beta^3$$

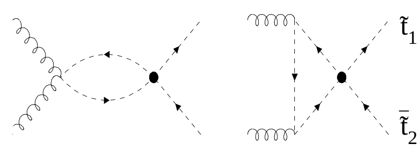
$$\hat{\sigma}_{LO}[gg \to \tilde{t}_j\bar{\tilde{t}}_j] = \frac{\alpha_s^2\pi}{s}\left\{\beta\left(\frac{5}{48}+\frac{31m_{\tilde{t}_j}^2}{24s}\right)+\left(\frac{2m_{\tilde{t}_j}^2}{3s}+\frac{m_{\tilde{t}_j}^4}{6s^2}\right)\log\left(\frac{1-\beta}{1+\beta}\right)\right\}$$

– diagonal cross section function of final state mass

– factor $1/(2n_f)$ compared to light-flavor squarks

– t, u channel gluino exchange missing compared to light-flavor squarks

– non-diagonal production via one loop amplitude; calculated for decoupled gluinos $\to$ suppressed



$$\hat{\sigma}_{\infty} = \frac{\alpha_s^4\beta\sin^2(4\tilde{\theta})}{256\pi s}\,\frac{37}{54}\left|m_{\tilde{t}_1}^2 C_0(s;m_{\tilde{t}_1}) - (\tilde{t}_1 \to \tilde{t}_2)\right|^2$$

Next-to-leading order cross section

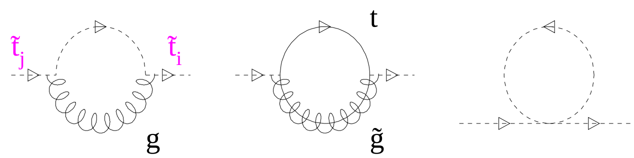
⋆ LO cross section strongly dependent on renormalization/factorization scale
$\to$ large theoretical uncertainty

⋆ NLO dependence on additional mixing and mass parameters?

MSSM Stop Mixing

LO stop mass matrix diagonalized by $\tilde{\theta}_0$

NLO contribution $\Sigma_{ij} = \Sigma_{ji}$:



Mixing absorbed into wave function renormalization:

$$\begin{aligned}
\tilde{t}_{1,2} &= Z^{-1/2}\ \ \tilde{t}^0_{1,2} \\
&= Z_{\rm D}^{-1/2}\ \mathcal{R}(-\delta\tilde{\theta})\ \left[\mathcal{R}(\tilde{\theta}_0)\ \ \tilde{t}^0_{R,L}\right] \qquad \text{with } \Sigma = \Sigma^T\ [CP] \\
&= Z_{\rm D}^{-1/2}\ \mathcal{R}(\tilde{\theta}_0 - \delta\tilde{\theta})\ \ \tilde{t}^0_{R,L}
\end{aligned}$$

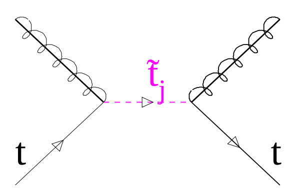
written as propagator diagonalization:

$$D^{-1}_{\rm ren}(Q^2) \sim Z_{\rm D}^{-1/2}\ \mathcal{R}(\tilde{\theta}_0 - \delta\tilde{\theta})^{-1} \left[Q^2\ 1 - \mathcal{M}_{LR} - \text{Re}\ \Sigma(Q^2)\right] \mathcal{R}(\tilde{\theta}_0 - \delta\tilde{\theta})\ Z_{\rm D}^{-1/2T}$$

$$\rightarrow \quad \delta\tilde{\theta}(Q^2) = -\text{Re}\ \Sigma_{12}(Q^2)/(m^2_{\tilde{t}_1} - m^2_{\tilde{t}_2})$$

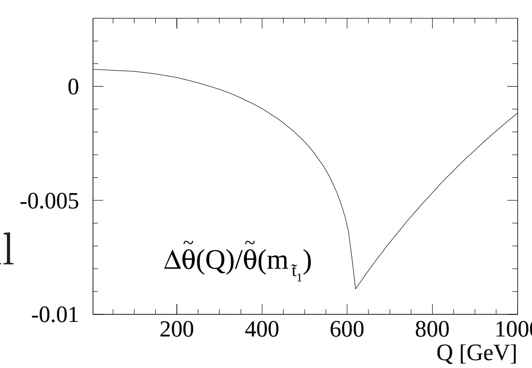
$$\rightarrow \quad \tilde{\theta}(Q'^2) - \tilde{\theta}(Q^2) \propto \frac{\cos(2\tilde{\theta})}{m^2_{\tilde{t}_2} - m^2_{\tilde{t}_1}} \text{Re}\ \left[B(Q'^2, m_{\tilde{g}}, m_t) - B(Q^2, m_{\tilde{g}}, m_t)\right]$$

Virtual stop state $\rightarrow$ complex continuation



Running mixing angle:

- ⋆ symmetry $\tilde{t}_1 \leftrightarrow \tilde{t}_2$ restored
- ⋆ possible measurements in decays
- ⋆ numerical difference between schemes small
  Bartl et al., Djouadi et al.



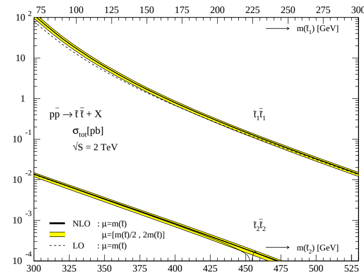
Production Cross Section

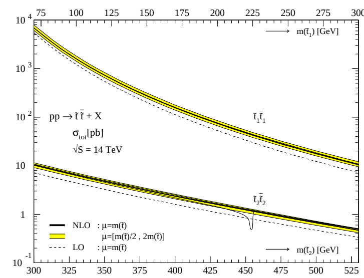
NLO cross section almost independent of additional parameters

→ $\tilde{t}_1$ and $\tilde{t}_2$ the same

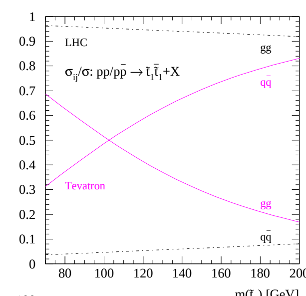
→ no dependence on SUSY scenario

[however: cascade decays]



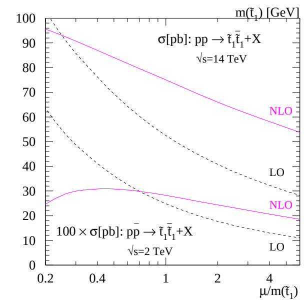


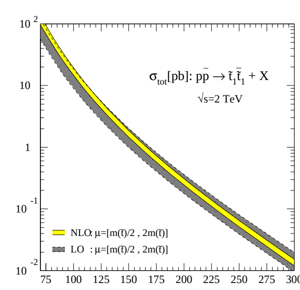
Tevatron K factor strongly mass dependent due to fraction of incoming quarks/gluons



Scale dependence strongly reduced in NLO

→ improvement of mass bounds not only for $K > 1$



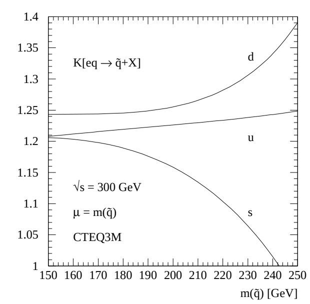


Addendum: R Parity violating Squarks

Soft SUSY breaking → three-scalar interaction
→ leptoquark-like superfield couplings $\lambda' \cdot LQ\overline{D}$
→ $\mathbf{R} = (-1)^{3B+L+2S}$ conservation

Broken **R** parity:

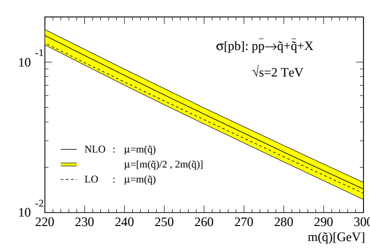
$$eq \to \tilde{q} \qquad \text{HERA production}$$
$$q\bar{q}/gg \to \tilde{q}\bar{\tilde{q}} \qquad \text{Tevatron production}$$



– soft breaking coupling parameter λ' free [running]

– SU(3) gauge couplings fixed as for stop

→ QCD corrections to HERA process
and Tevatron cross section fixed



Combined analysis of BR($\tilde{q} \to eq$):

$m_{\tilde{q}} = 200$ GeV	$e^+d \to \tilde{c}$	$e^+d \to \tilde{t}$	$e^+s \to \tilde{t}$
HERA: $\lambda'\sqrt{\text{BR}}$	$\sim 0.017 \cdots 0.025$	$\sim 0.025 \cdots 0.033$	$\sim 0.15 \cdots 0.25$
APV: λ'	$\lambda' \lesssim 0.055$	$\lambda' \lesssim 0.055$	
LEP: λ'			$\lambda' \lesssim 0.6$
	BR $\gtrsim 0.2 \cdots 0.4$	BR $\gtrsim 0.2 \cdots 0.4$	BR $\gtrsim 0.05 \cdots 0.2$
Tevatron: BR	BR $\lesssim 0.5 \cdots 0.7$ → heavy gauginos	BR $\lesssim 0.5 \cdots 0.7$ → heavy gauginos	BR $\lesssim 0.5 \cdots 0.7$

Conclusions and Outlook

Processes in next-to-leading order SUSY QCD:

- Stop cross sections at hadron colliders
- Neutralino/Chargino cross sections at hadron colliders

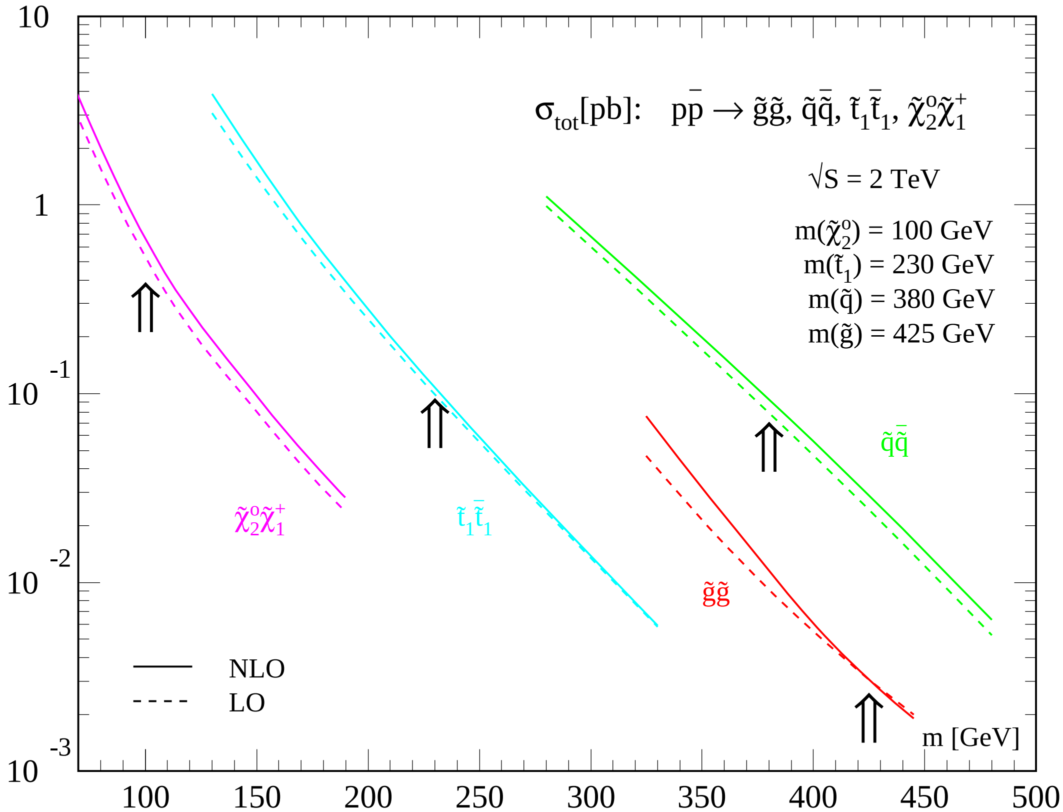
Results:

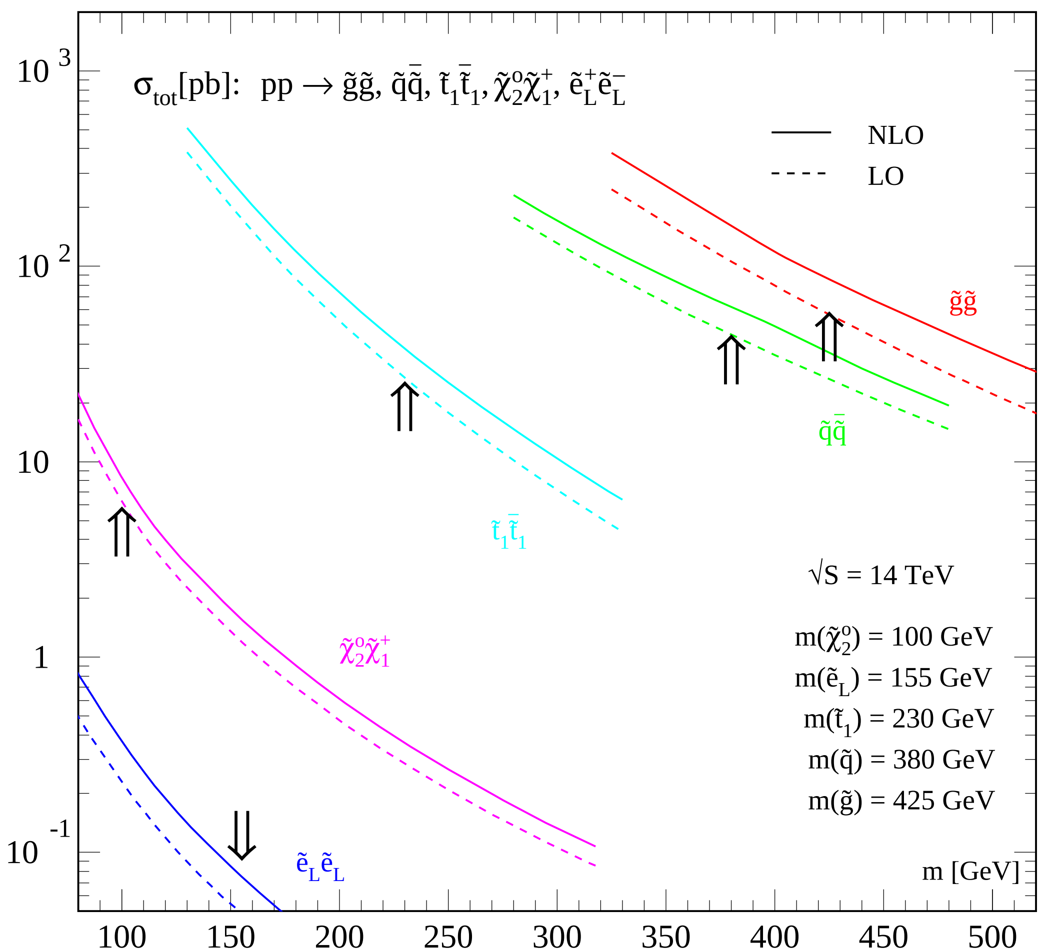
- ⋆ QCD corrections to stop cross sections between −10% and +50%
- ⋆ QCD corrections to neutralino/chargino cross sections around +30% [up to interference effects]
- ⋆ Scale dependence small in NLO

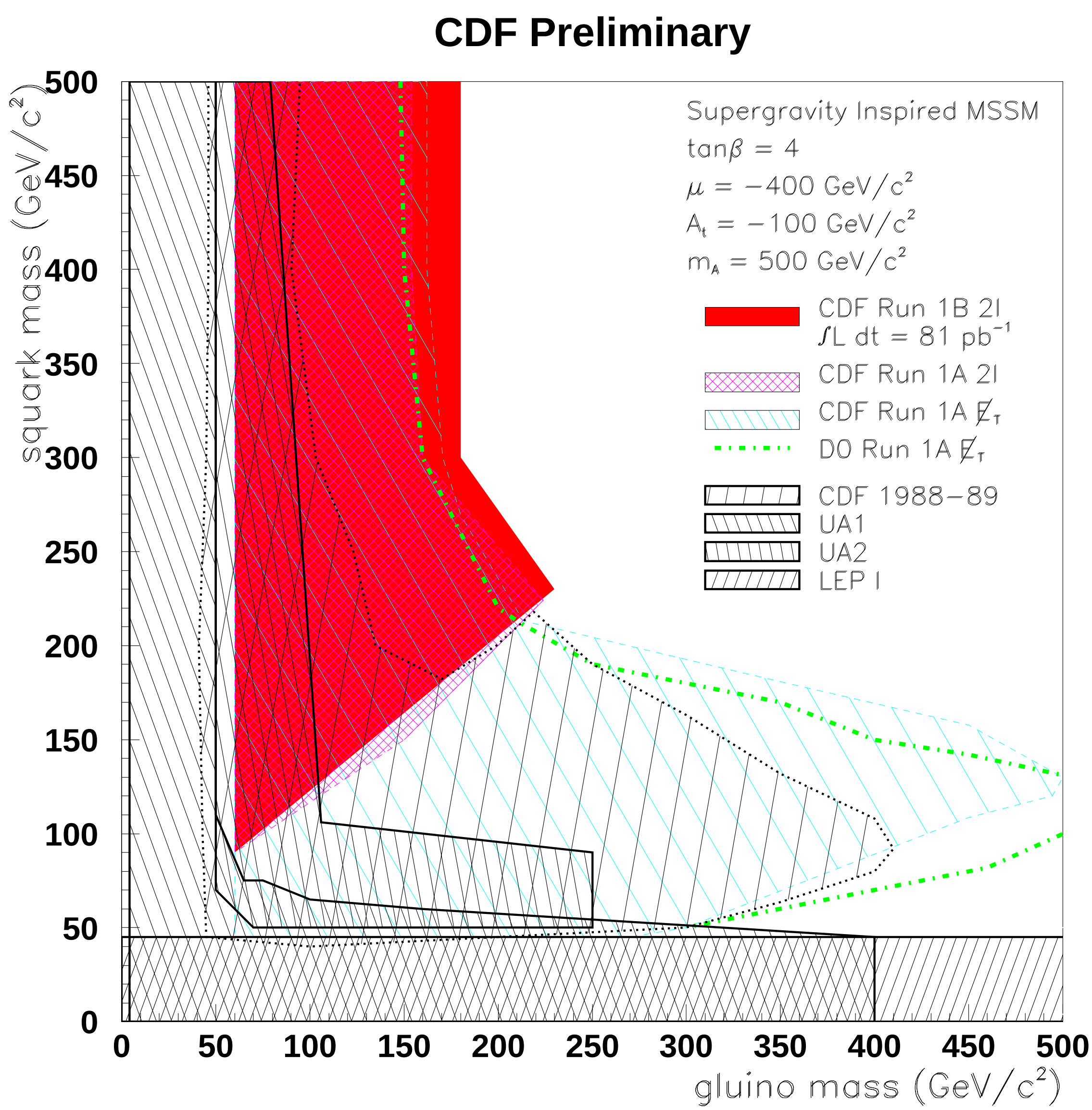
Conclusions & Outlook:

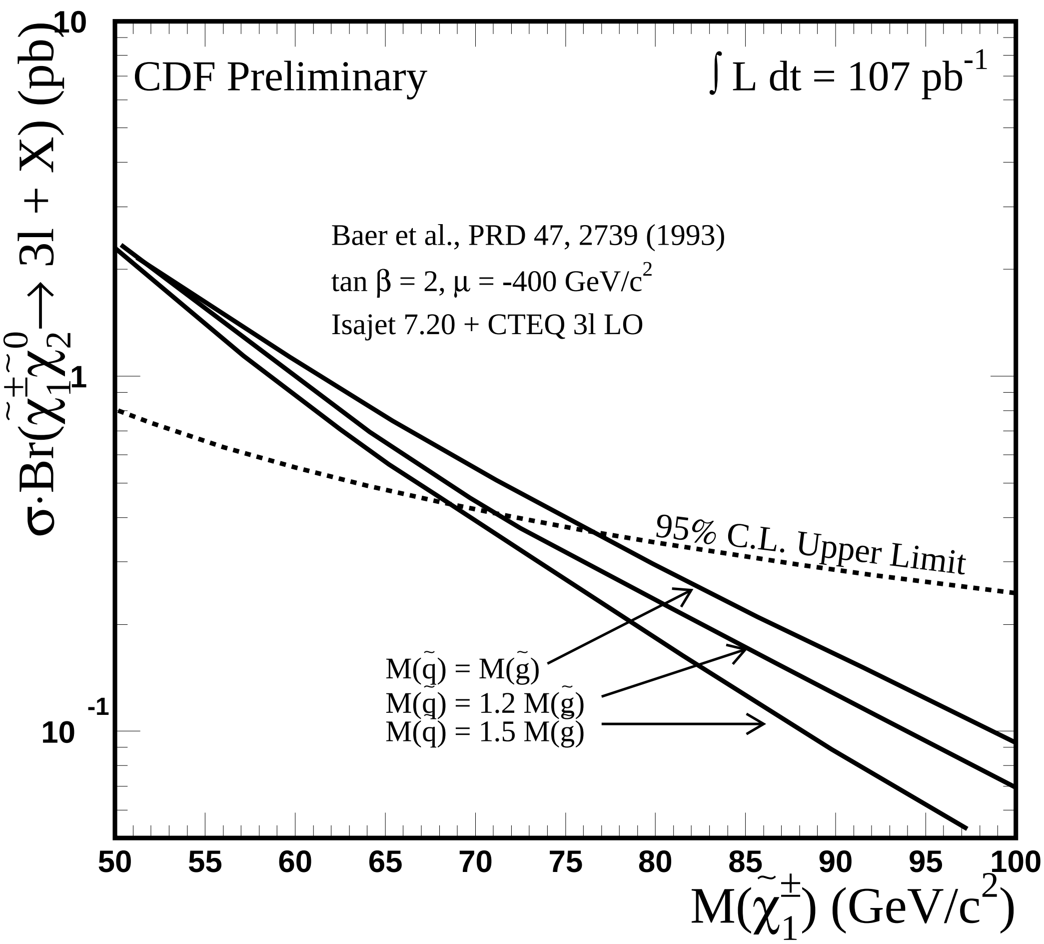
- ⋆ NLO stop cross sections only mildly dependent on mixing angle and internal masses
- ⋆ Corrections to neutralino/chargino cross section non-negligiable and dependent on scenario

$\Longrightarrow$ NLO analyses at upgraded Tevatron and LHC


σ_tot[pb]: pp̄ → g̃g̃, q̃q̄̃, t̃₁t̄̃₁, χ̃⁰₂χ̃⁺₁
√S = 2 TeV
m(χ̃⁰₂) = 100 GeV
m(t̃₁) = 230 GeV
m(q̃) = 380 GeV
m(g̃) = 425 GeV
NLO
LO
m [GeV]

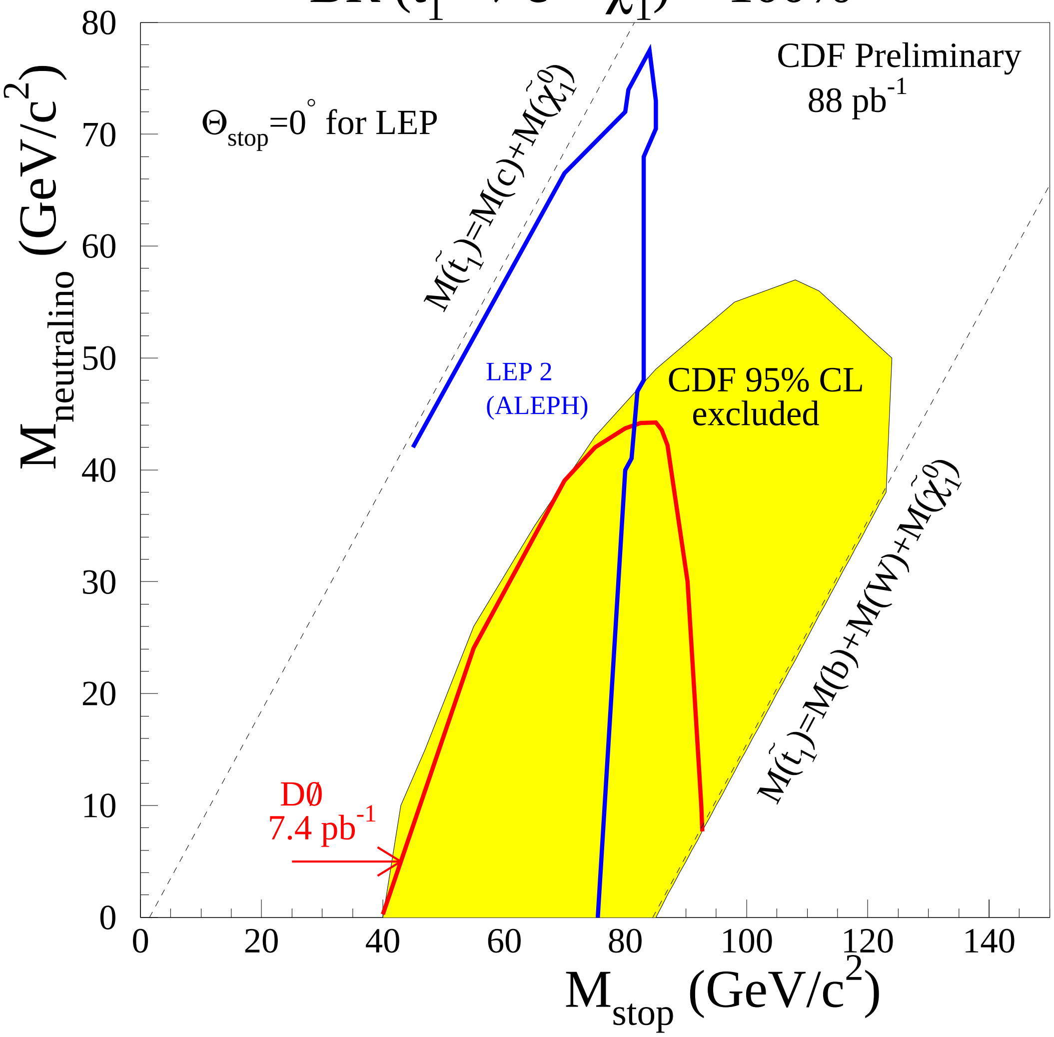

σ_tot[pb]: pp → g̃g̃, q̃q̄̃, t̃₁t̄̃₁, χ̃⁰₂χ̃⁺₁, ẽ⁺_Lẽ⁻_L
NLO
LO
√S = 14 TeV
m(χ̃⁰₂) = 100 GeV
m(ẽ_L) = 155 GeV
m(t̃₁) = 230 GeV
m(q̃) = 380 GeV
m(g̃) = 425 GeV
m [GeV]

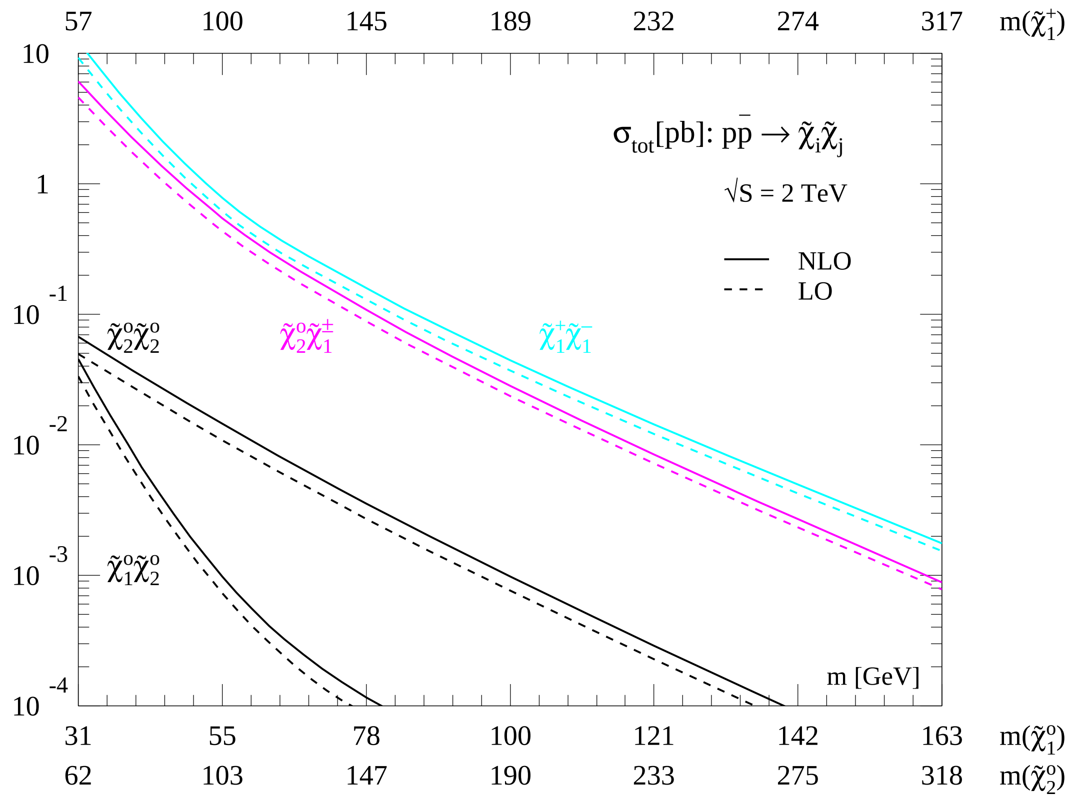

CDF Preliminary
Supergravity Inspired MSSM
tanβ = 4
μ = −400 GeV/c²
A_t = −100 GeV/c²
m_A = 500 GeV/c²
CDF Run 1B 2l
∫L dt = 81 pb⁻¹
CDF Run 1A 2l
CDF Run 1A E̸_T
D0 Run 1A E̸_T
CDF 1988−89
UA1
UA2
LEP I
squark mass (GeV/c²)
gluino mass (GeV/c²)
0
50
100
150
200
250
300
350
400
450
500


CDF Preliminary
$\int L\,dt = 107\ pb^{-1}$
Baer et al., PRD 47, 2739 (1993)
tan β = 2, μ = -400 GeV/c^2
Isajet 7.20 + CTEQ 3l LO
95% C.L. Upper Limit
$M(\tilde{q}) = M(\tilde{g})$
$M(\tilde{q}) = 1.2\ M(\tilde{g})$
$M(\tilde{q}) = 1.5\ M(\tilde{g})$
$\sigma \cdot Br(\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow 3l + X)$ (pb)
$M(\tilde{\chi}_1^{\pm})$ (GeV/c^2)
10
1
10^{-1}
50
55
60
65
70
75
80
85
90
95
100

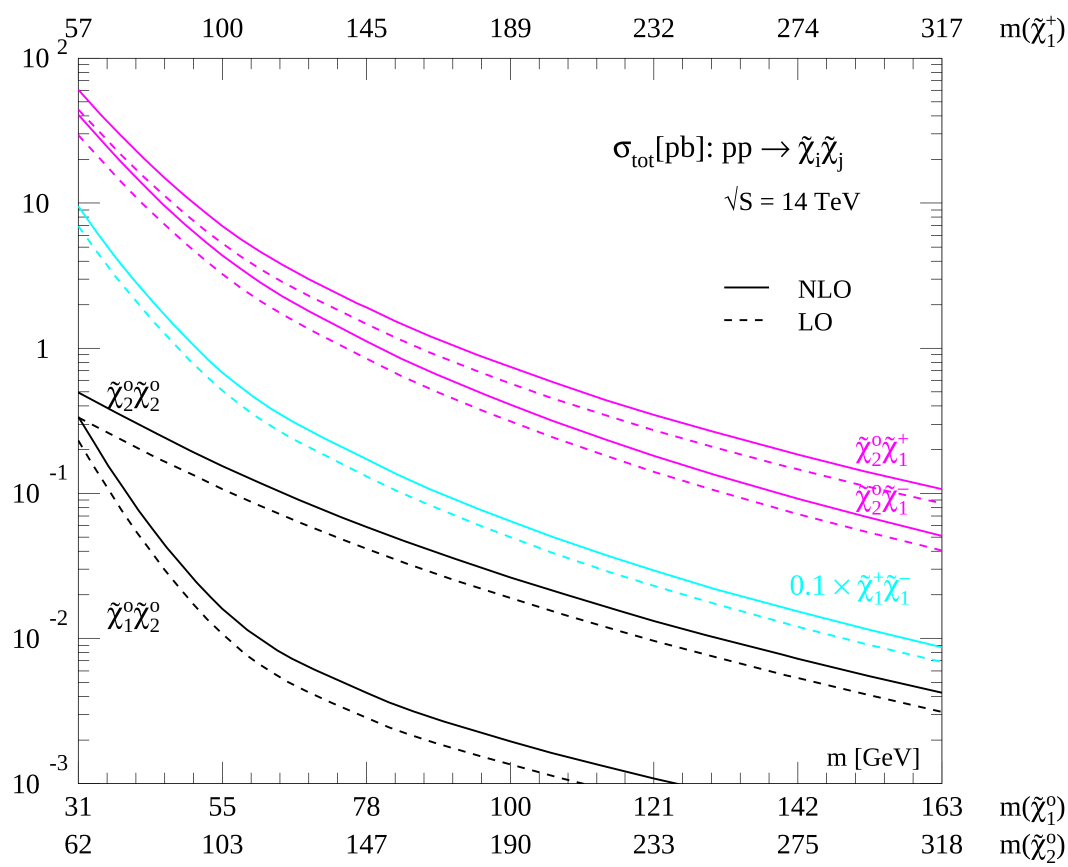
Search for Scalar Top

BR $(\tilde{t}_1 \rightarrow c + \tilde{\chi}_1^0) = 100\%$

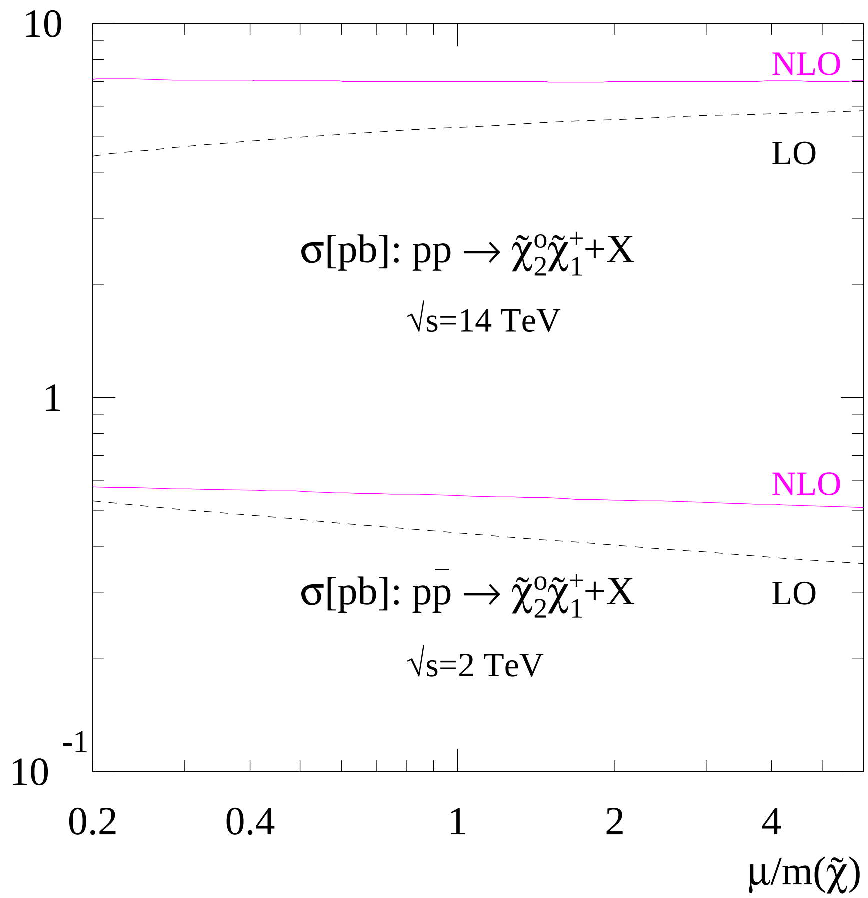




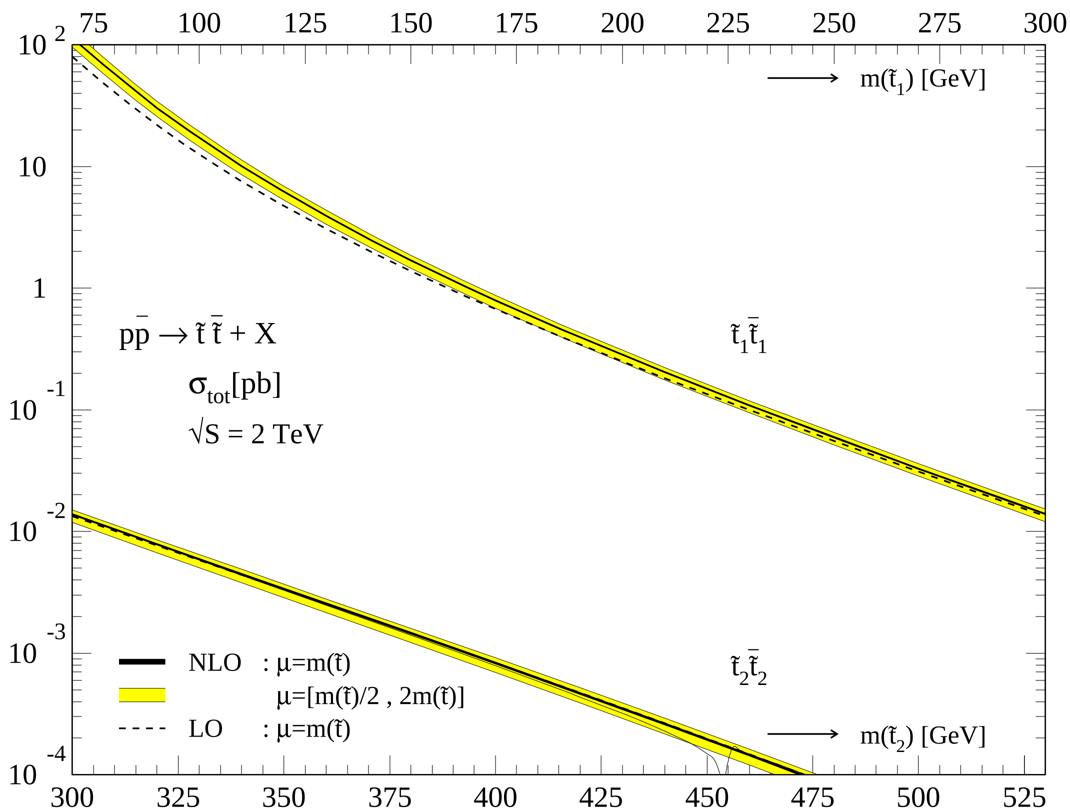
σ_{tot}[pb]: $p\bar{p} \to \tilde{\chi}_i\tilde{\chi}_j$
$\sqrt{S}$ = 2 TeV
NLO
LO
$\tilde{\chi}^o_2\tilde{\chi}^o_2$
$\tilde{\chi}^o_2\tilde{\chi}^\pm_1$
$\tilde{\chi}^+_1\tilde{\chi}^-_1$
$\tilde{\chi}^o_1\tilde{\chi}^o_2$
m [GeV]
$m(\tilde{\chi}^+_1)$
$m(\tilde{\chi}^o_1)$
$m(\tilde{\chi}^o_2)$



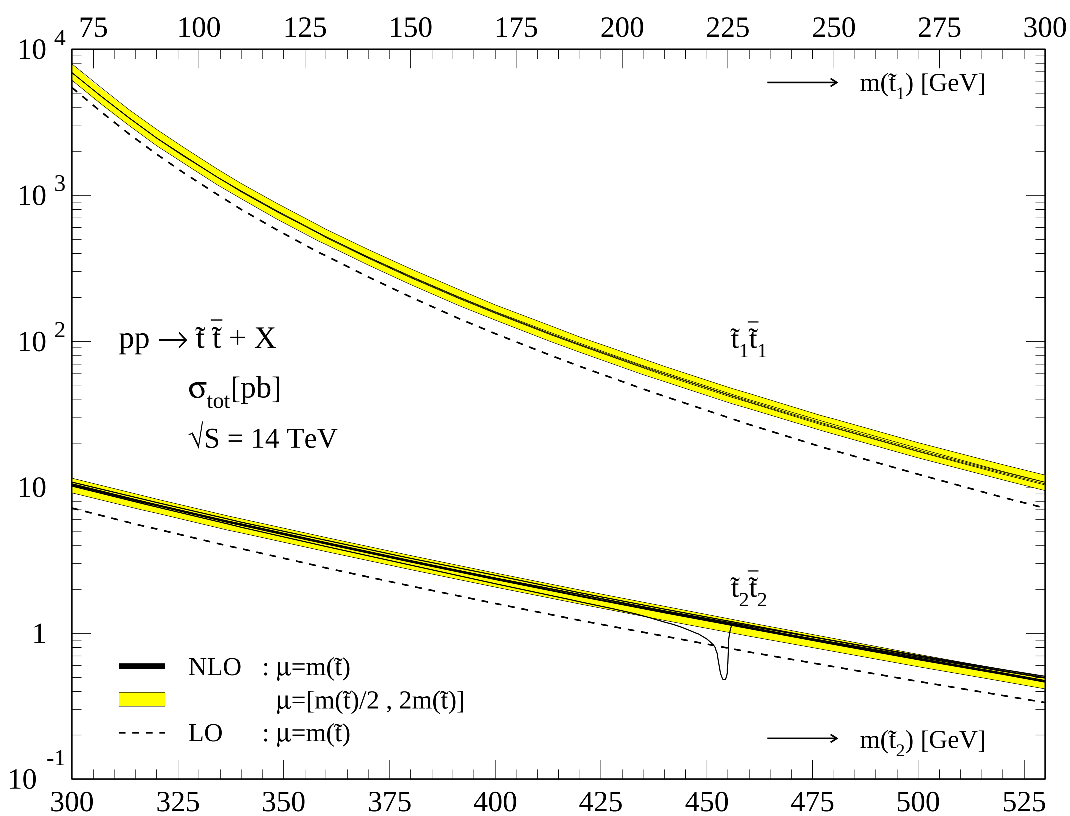
σ_{tot}[pb]: $pp \to \tilde{\chi}_i\tilde{\chi}_j$
$\sqrt{S}$ = 14 TeV
NLO
LO
$\tilde{\chi}^o_2\tilde{\chi}^o_2$
$\tilde{\chi}^o_2\tilde{\chi}^+_1$
$\tilde{\chi}^o_2\tilde{\chi}^-_1$
$0.1 \times \tilde{\chi}^+_1\tilde{\chi}^-_1$
$\tilde{\chi}^o_1\tilde{\chi}^o_2$
m [GeV]
$m(\tilde{\chi}^+_1)$
$m(\tilde{\chi}^o_1)$
$m(\tilde{\chi}^o_2)$



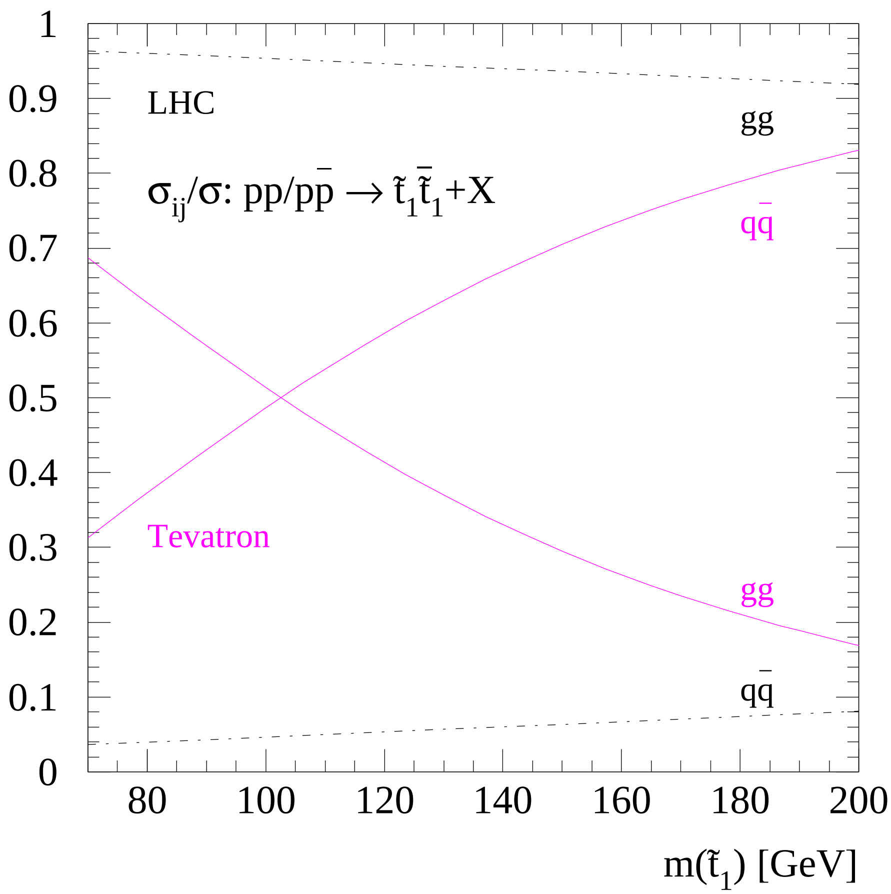
10
1
10^-1
NLO
LO
σ[pb]: pp → χ̃₂⁰χ̃₁⁺+X
√s=14 TeV
NLO
LO
σ[pb]: pp̄ → χ̃₂⁰χ̃₁⁺+X
√s=2 TeV
0.2
0.4
1
2
4
μ/m(χ̃)



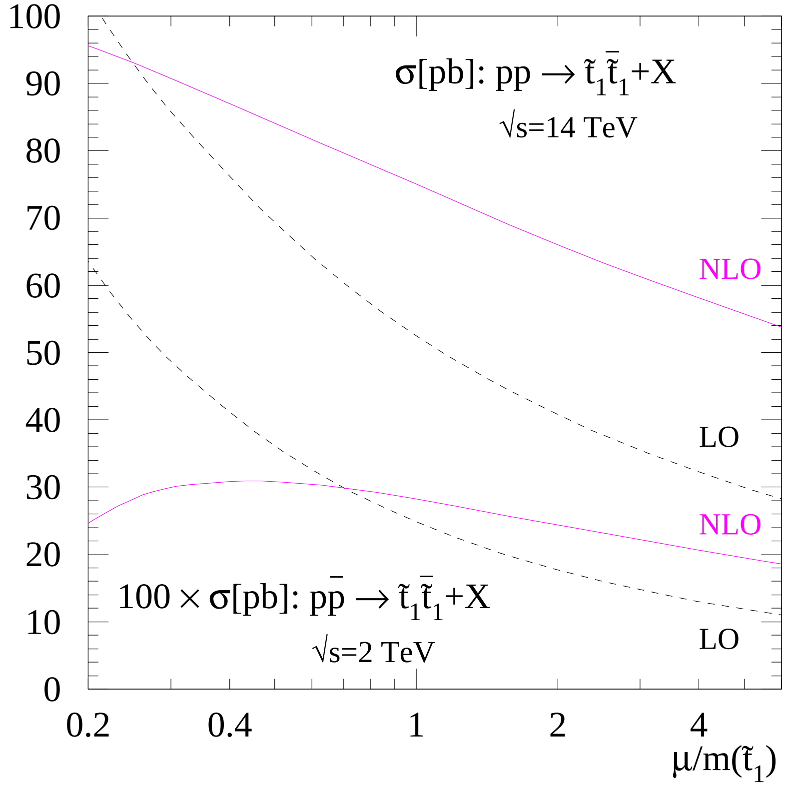
$p\bar{p} \to \tilde{t}\,\bar{\tilde{t}} + X$
σ_{tot}[pb]
$\sqrt{S}$ = 2 TeV
$m(\tilde{t}_1)$ [GeV]
$m(\tilde{t}_2)$ [GeV]
$\tilde{t}_1\bar{\tilde{t}}_1$
$\tilde{t}_2\bar{\tilde{t}}_2$
NLO : $\mu=m(\tilde{t})$
$\mu=[m(\tilde{t})/2 , 2m(\tilde{t})]$
LO : $\mu=m(\tilde{t})$



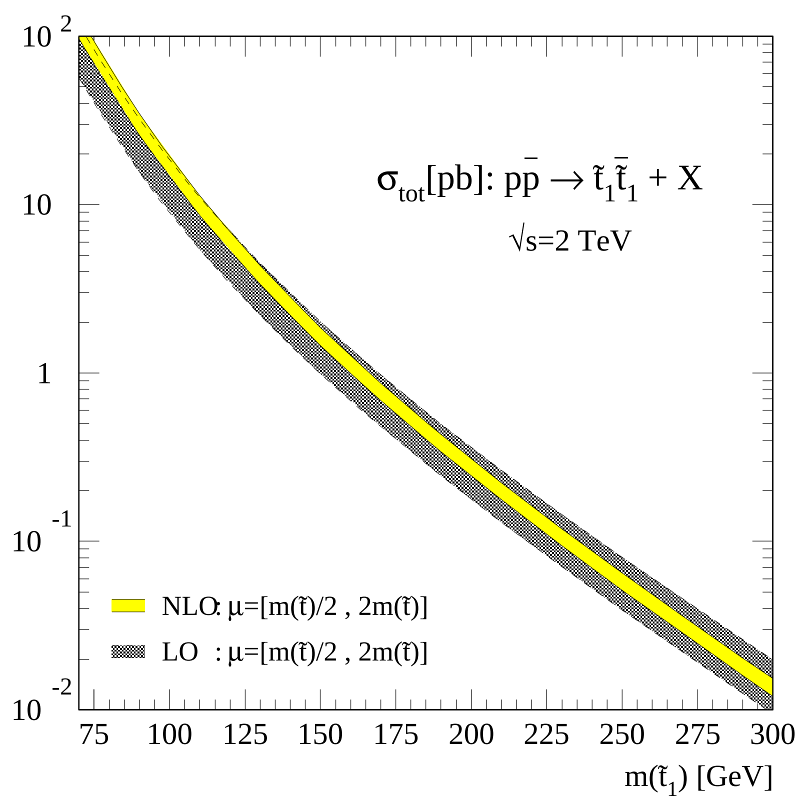
$pp \to \tilde{t}\,\bar{\tilde{t}} + X$
σ_{tot}[pb]
$\sqrt{S}$ = 14 TeV
$m(\tilde{t}_1)$ [GeV]
$m(\tilde{t}_2)$ [GeV]
$\tilde{t}_1\bar{\tilde{t}}_1$
$\tilde{t}_2\bar{\tilde{t}}_2$
NLO : $\mu=m(\tilde{t})$
$\mu=[m(\tilde{t})/2 , 2m(\tilde{t})]$
LO : $\mu=m(\tilde{t})$



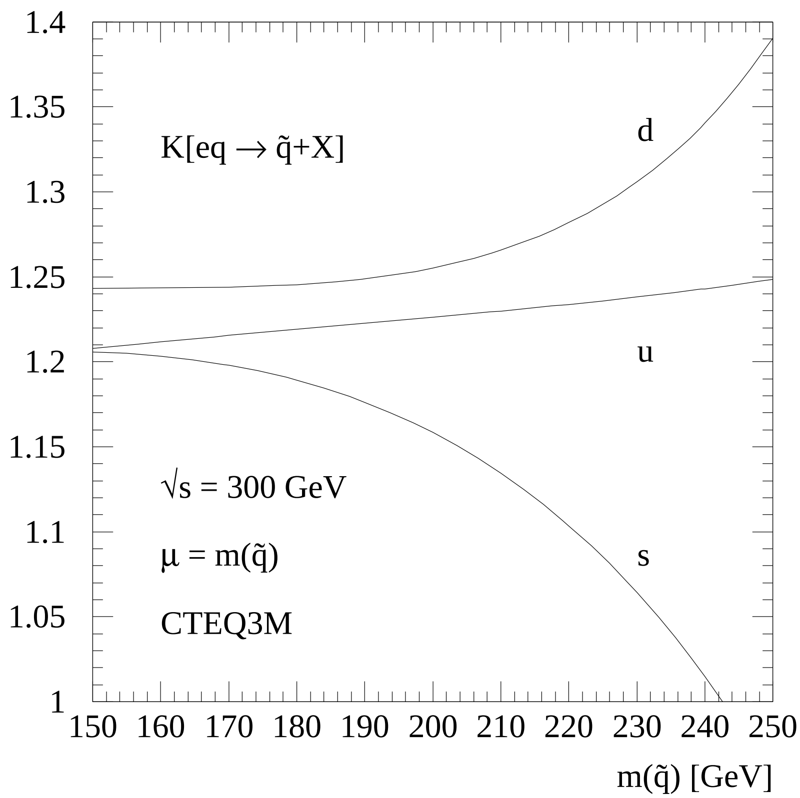
LHC
σ_{ij}/σ: pp/p$\bar{p}$ $\rightarrow \tilde{t}_1\bar{\tilde{t}}_1$+X
gg
$q\bar{q}$
Tevatron
gg
$q\bar{q}$
m($\tilde{t}_1$) [GeV]



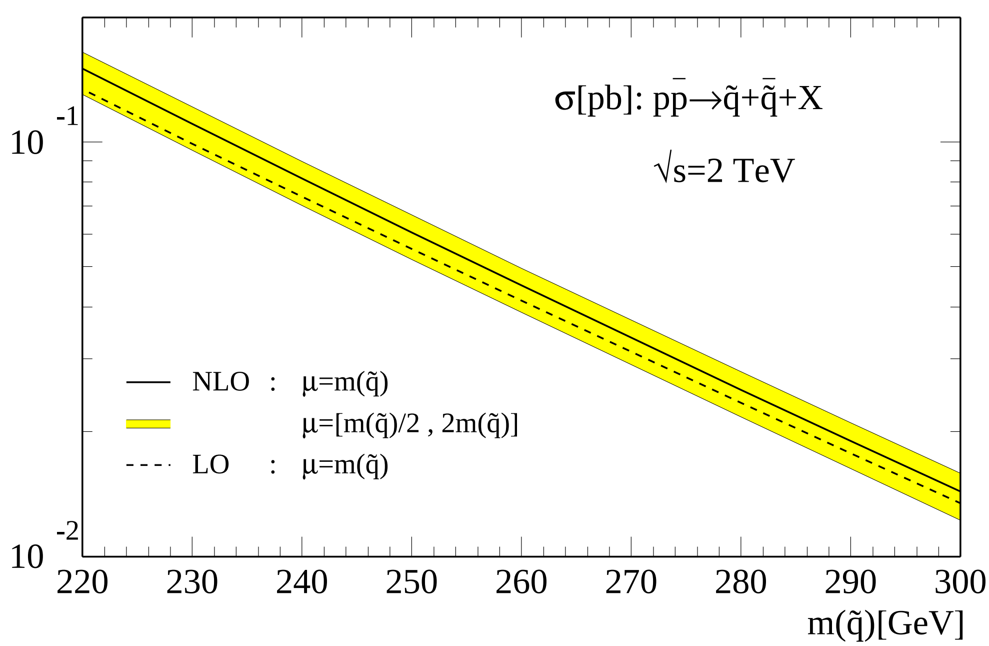
σ[pb]: pp → t̃₁t̃̄₁+X
√s=14 TeV
NLO
LO
NLO
100 × σ[pb]: pp̄ → t̃₁t̃̄₁+X
√s=2 TeV
LO
μ/m(t̃₁)



σ_tot[pb]: pp̄ → t̃₁t̃̄₁ + X
√s=2 TeV
NLO: μ=[m(t̃)/2 , 2m(t̃)]
LO : μ=[m(t̃)/2 , 2m(t̃)]
m(t̃₁) [GeV]



K[eq → q̃+X]
d
u
s
√s = 300 GeV
μ = m(q̃)
CTEQ3M
1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
150 160 170 180 190 200 210 220 230 240 250
m(q̃) [GeV]



σ[pb]: pp̄→q̃+q̃̄+X
√s=2 TeV
NLO : μ=m(q̃)
μ=[m(q̃)/2 , 2m(q̃)]
LO : μ=m(q̃)
10^-1
10^-2
220 230 240 250 260 270 280 290 300
m(q̃)[GeV]