NEXT-TO-LEADING ORDER SUSY SEARCHES AT THE TEVATRON

Tilman Plehn

Madison

– Introduction into MSSM and NLO Searches

– Discovery Channels: Squarks, Stops, Trileptons

– Associate Production: Squarks, Gluinos with Gauginos

– Exotic Channels: R Parity Violation

– Conclusions and Outlook

W. Beenakker, M. Krämer, TP, M. Spira, P.M. Zerwas, Nucl. Phys. B515 (1998) 3

W. Beenakker, M. Klasen, M. Krämer, TP, M. Spira, P.M. Zerwas, Phys. Rev. Lett. 83 (1999) 3780

W. Beenakker, M. Krämer, TP, M. Spira, P.M. Zerwas, in preparation and in preparation^2

TP, Phys. Lett. B488 (2000) 359

A. Alves, O.J.P. Éboli, TP, in preparation

Particles in the MSSM

Supersymmetric extension of Standard Model

- ⋆ fermion–boson mapping $\rightarrow$ stable scalar masses
- ⋆ unification of gauge couplings $\rightarrow$ prediction of weak mixing angle
- ⋆ possible extension to supergravity and string models

Particle Content of the MSSM

		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	$n-2$	$\rightarrow$ 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

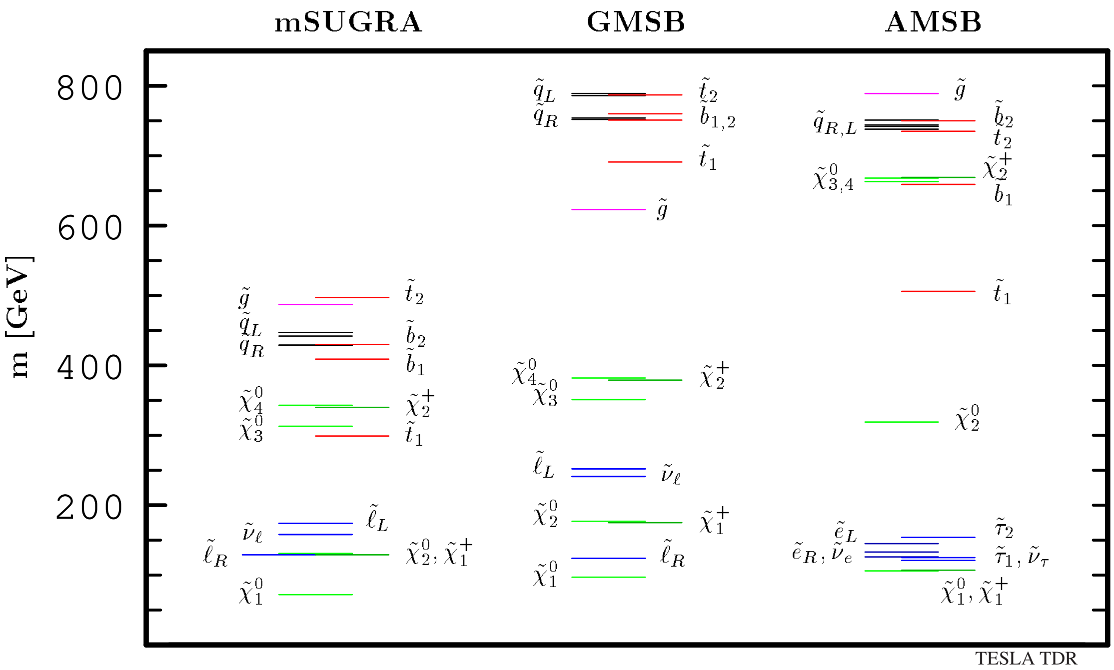
- ⋆ experimentally shown
- ⋆ mSUGRA unified scenario: free $m_0, m_{1/2}, A_0, \tan\beta, \mathrm{sign}(\mu)$

SUPERSYMMETRY SPECTRA

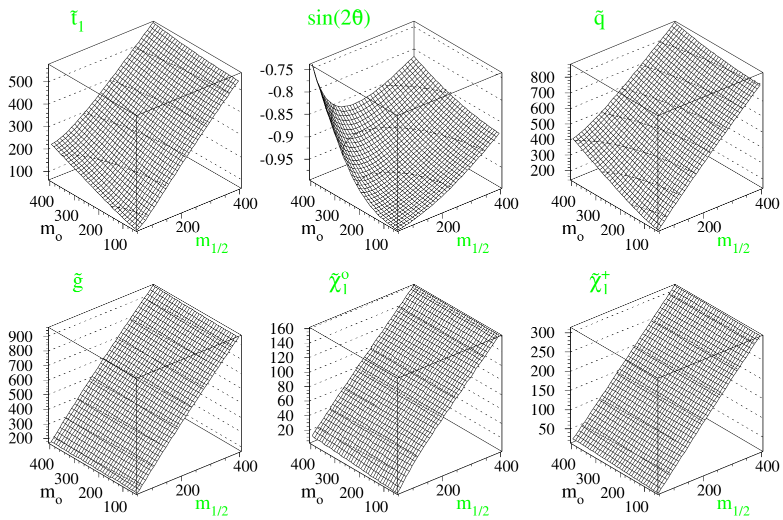
Supersymmetry Breaking Scenarios

- ⋆ mSUGRA (used throughout the talk) → maximal GUT unification
- ⋆ gauge mediation, anomaly mediation, gaugino mediation,...

  [(815) 753-6467]

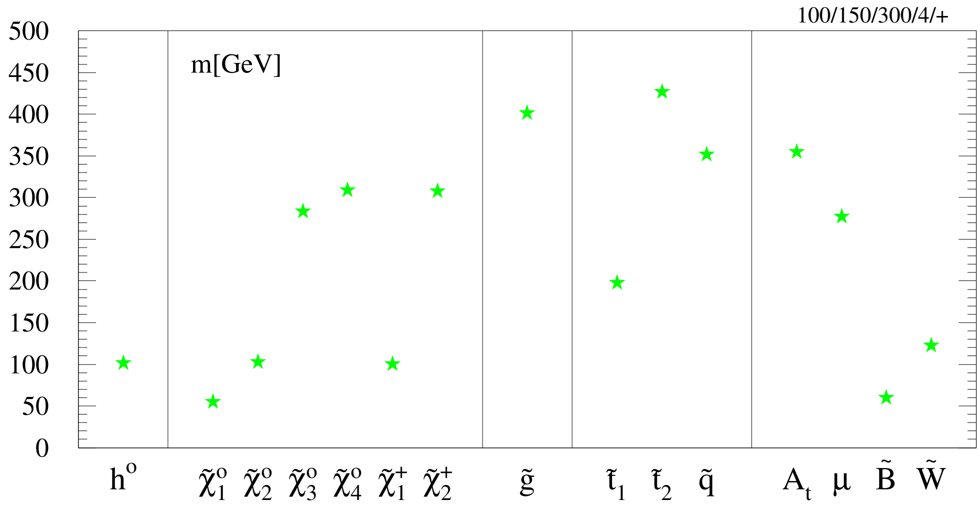


Some more parameters for mSUGRA



MSSM FEATURES

What is mSUGRA and what MSSM?



MSSM Features

- heavy squarks/gluinos (renormalization group running)

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

- light gauginos ($m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^+}$ or $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^+}$ purely MSSM)

$$\begin{pmatrix} m_{\tilde{B}} & 0 & -m_Z s_w c_\beta & m_Z s_w s_\beta \\ 0 & m_{\tilde{W}} & m_Z c_w c_\beta & -m_z c_w s_\beta \\ -m_Z s_w c_\beta & m_Z c_w c_\beta & 0 & -\mu \\ m_Z s_w s_\beta & -m_Z c_w s_\beta & -\mu & 0 \end{pmatrix} \begin{pmatrix} m_{\tilde{W}} & \sqrt{2} m_W s_\beta \\ \sqrt{2} m_W c_\beta & -\mu \end{pmatrix}$$

- light sleptons
- lightest particle: $\tilde{\chi}_1^0, \tilde{\nu}$
- large stop mass splitting (m_t in stop matrix, MSSM feature)

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

- clustering of gaugino and higgsino masses ($M_{1,2}$ vs $|\mu|$, again MSSM feature)

HIGHER ORDER CROSS SECTIONS

Typical SUSY Signatures assuming R Parity

– avoids leptoquarks, proton decay, APV, FCNC,...

– stable lightest SUSY partner $\rightarrow$ LSP dark matter [Ellis, Falk, Olive,...]

– pair production of SUSY partners [Dawson, Eichten, Quigg; Bartl, Majerotto;...]

– two invisible LSPs at the end of the cascade

– no mass reconstruction, not even transverse mass

Requirements on Cross Section Predictions

– extract mass limits from cross section limits
exception: mass difference from lepton endpoint spectra [Hinchliffe]

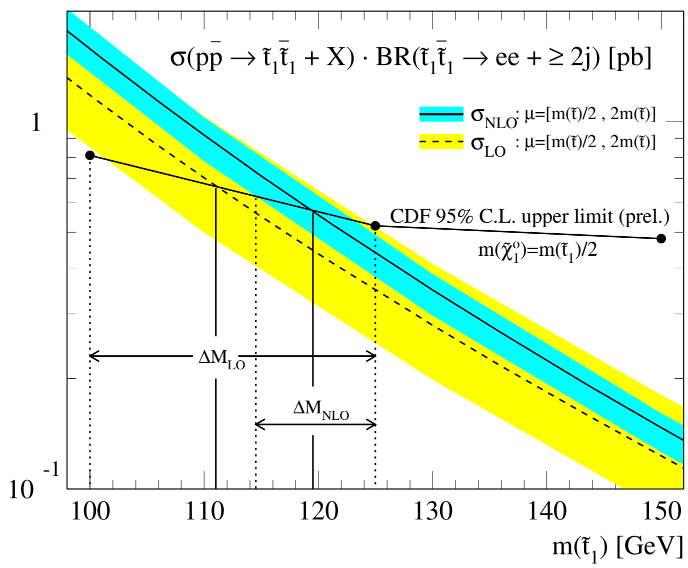
– <u>but:</u> many cross sections $\sigma \propto \alpha_S^2$, gluon incoming states [similar to top production]

$\Rightarrow$ want to know the value of the cross section $\rightarrow K = \sigma_{\rm NLO}/\sigma_{\rm LO}$

$\Rightarrow$ want to know the uncertainty $\rightarrow \sigma(Q_R), \sigma(Q_F)$ good measure for what range?

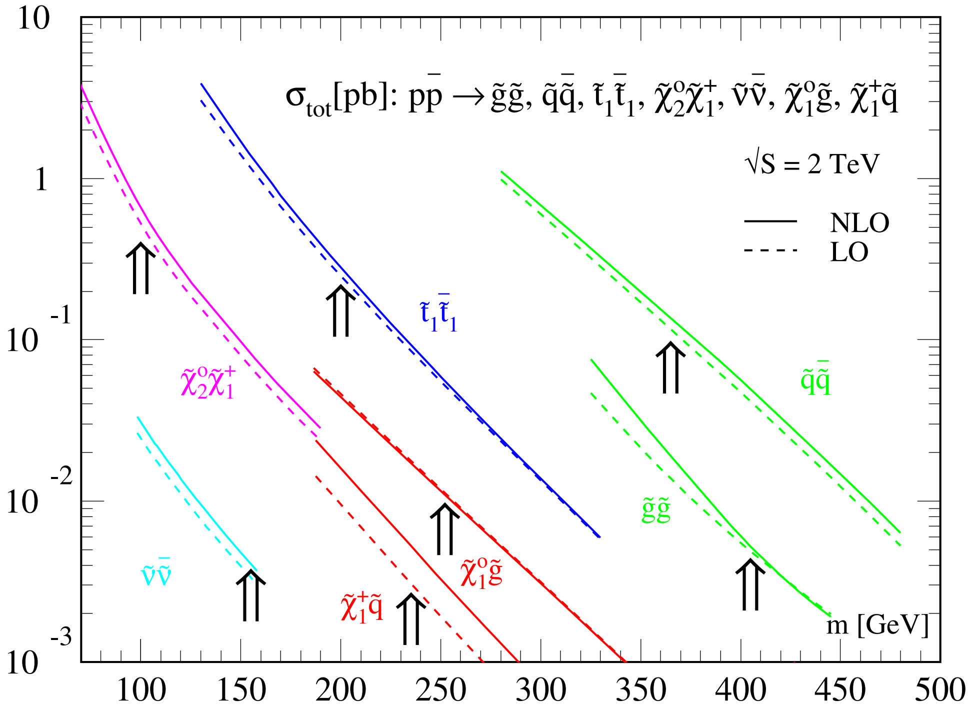
$\Rightarrow$ check if K factor describes cross section after cuts [$y, p_{\rm T}$ distributions]

$\Rightarrow$ compute the complete SUSY-QCD corrections to production cross sections
actual MSSM scenario with decays picked by user



PROSPINO PROPAGANDA

MSSM Production Cross Sections in Run2



(1) Discovery Channels: $\tilde{t}_1\tilde{t}_1^*, \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{\chi}_1^\pm\tilde{\chi}_2^0$

– used in Run1 already, maybe different decay scenarios for Run2

– generically large cross sections $\gtrsim$ 100 fb

(2) Associated Production: $\tilde{q}\tilde{\chi}, \tilde{g}\tilde{\chi}$

– no analyses available from Run1

– possible at Run2 and LHC

(3) 'Exotic' Channels: $\tilde{t}_1, \tilde{t}_1\ell$

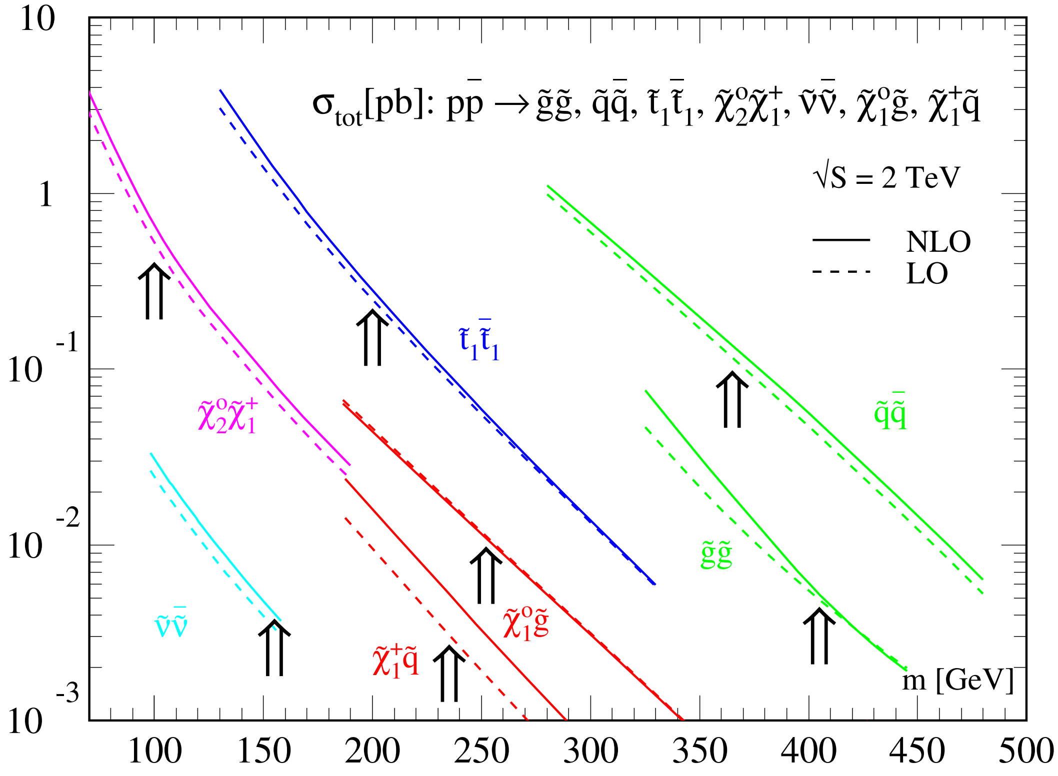
– require R parity violation

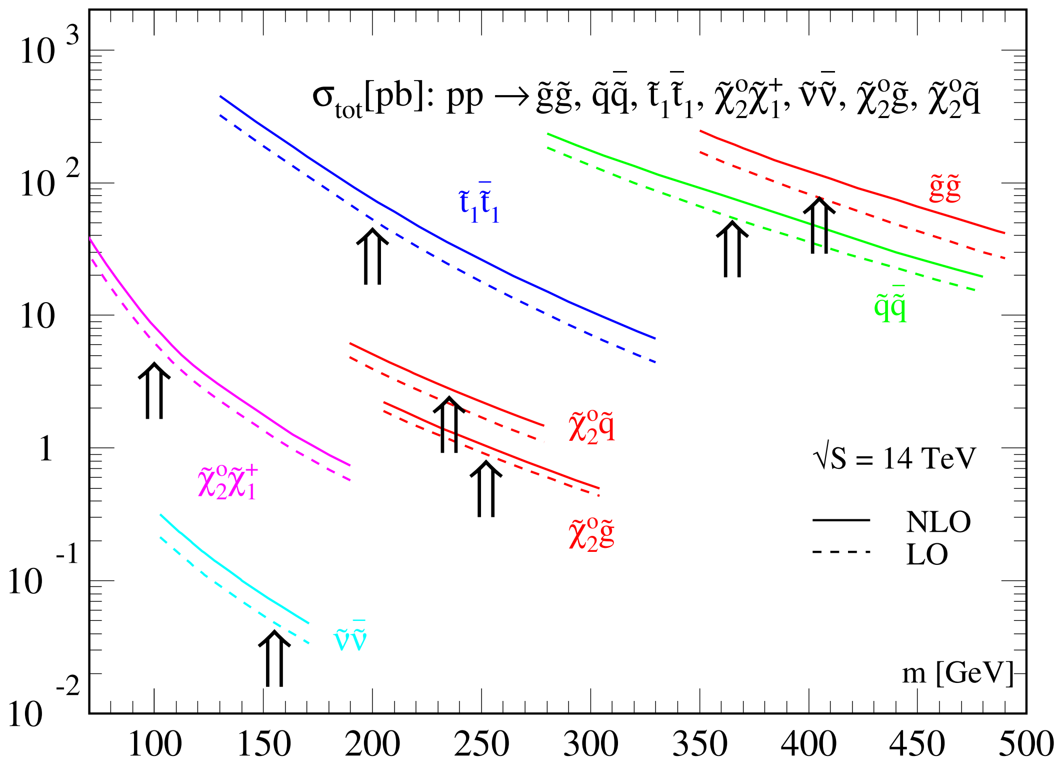
– rare signal events

$\rightarrow$ only non-Tevatron SUSY limit: charginos/sleptons at LEP

$\rightarrow$ email further suggestions to: `prospino@pheno.physics.wisc.edu`

TEVATRON VS LHC

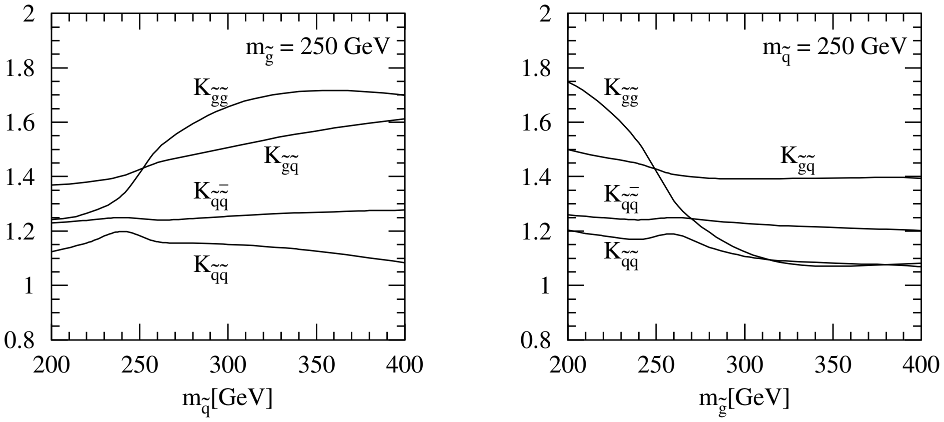




Discovery Channel 1: Squarks & Gluinos

Production Mechanism in NLO

- three production channels: $\tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{g}\tilde{q}$
- for pair production the respective other particles in t channel
  $\Rightarrow$ experimental analysis in $m_{\tilde{g}} - m_{\tilde{q}}$ plane (mSUGRA for LSP mass)
- K factor large for gluinos [Beenakker, Höpker, Spira, Zerwas]
  $\Rightarrow$ improved mass reach $\delta m \gtrsim 20 \cdots 40$ GeV
- scale dependence reduced to $\mathcal{O}(15\%)$ for $Q = m/2 \cdots 2m$
- normalized $y, p_{\rm T}$ distributions stable

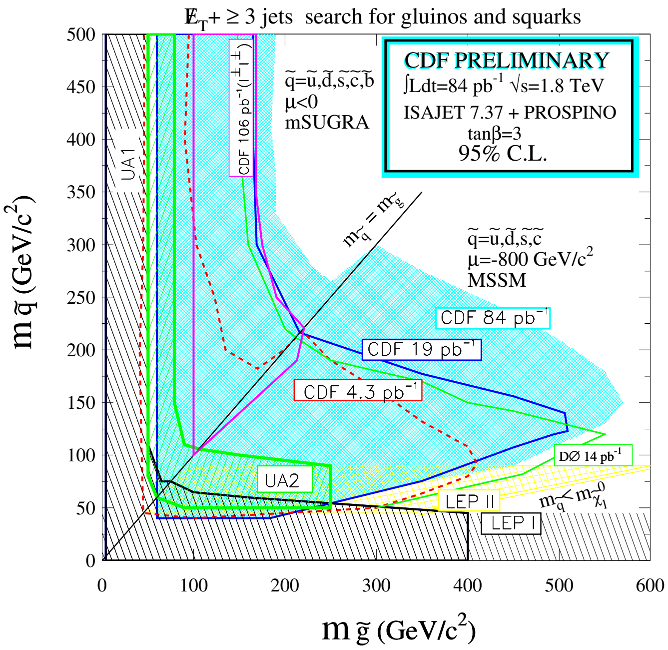


Decay Channels

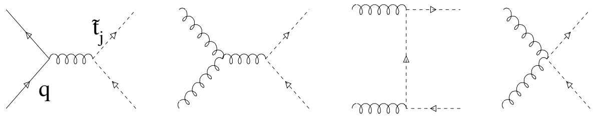
$$\tilde{q} \longrightarrow q\tilde{\chi}^0_j,\ q'\tilde{\chi}^+_j \longrightarrow 1 \text{ jet} + \not{E}_T + \cdots$$

$$\tilde{g} \longrightarrow q\bar{q}\tilde{\chi}^0_j \longrightarrow 2 \text{ jets} + \not{E}_T$$

$$\tilde{g} \longrightarrow q'\bar{q}\tilde{\chi}^+_j \longrightarrow 2 \text{ jets} + \ell + \not{E}_T$$



DISCOVERY CHANNEL 2: STOPS



Production Cross Section

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

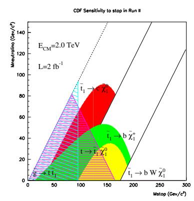
$$\hat{\sigma}_{LO}[gg \to \tilde{t}_j \tilde{t}_j^*] = \frac{\alpha_s^2 \pi}{s} \left\{ \beta \left(\frac{5}{48} + \frac{31 m_{\tilde{t}_j}^2}{24 s} \right) + \left(\frac{2 m_{\tilde{t}_j}^2}{3 s} + \frac{m_{\tilde{t}_j}^4}{6 s^2} \right) \log \left(\frac{1-\beta}{1+\beta} \right) \right\}$$

– diagonal cross section function of final state mass (unlike light-flavor squarks)

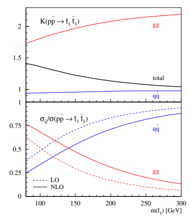
– suppression factor $1/(2n_f)$ compared to light-flavor squarks, but smaller stop mass

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

– whole zoo of decay channels [NLO: Höpker, TP, Zerwas]
  $\Rightarrow$ dependence on LSP mass, chargino mass, stop mixing angle
  $\Rightarrow$ multiple analyses beyond Run1 [Demina, Lykken, Matchev, Nomerotski]



NLO results



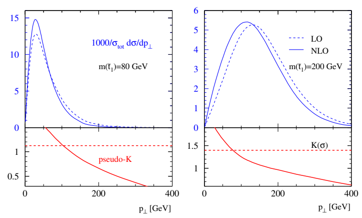
⋆ $K \gtrsim 1$ for the Tevatron (mass dependent)

⋆ improved mass bounds from reduced scale dependence: $\mathcal{O}(20\%)$

⋆ dependence of NLO result on SUSY parameters negligible

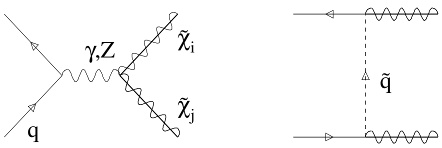
⋆ p_{T} distribution softer in NLO

⋆ uncertainty from parton densities? [Giele, Keller, Kosover]



Phenomenological Addendum:
– QCD interactions blind for mixing angle
$\rightarrow$ determination of mixing angle together with neutralino/chargino mixing

Discovery Channel 3: Trileptons



Production of Neutralino/Chargino Pairs

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

Tevatron Analyses

⋆ trileptons from $p\bar{p}\to\tilde{\chi}_2^0\tilde{\chi}_1^\pm\to(\ell\ell\not{E}_T)(\ell\not{E}_T)$

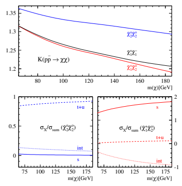
→ no signal if intermediate W, Z on-shell [Matchev, Pierce; Barger, Kao; Baer, Tata,..].

→ no coverage for large scalar masses [Martin, Wells; TP, Rainwater, not to be published]

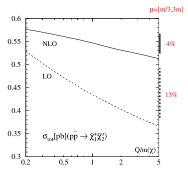
⋆ $p\bar{p}\to\tilde{\chi}_1^+\tilde{\chi}_1^-$ large, but hardly detectable [TP, Rainwater, not to be published either]

⋆ wait for neutralinos and charginos in cascade decays?

NLO cross sections

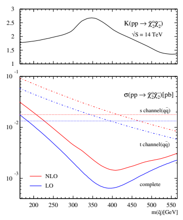


⋆ K factor Drell–Yan like for $\tilde{\chi}_2^0\tilde{\chi}_2^0, \tilde{\chi}_1^-\tilde{\chi}_1^+, \tilde{\chi}_2^0\tilde{\chi}_1^\pm$ production



⋆ scale dependence $\lesssim\pm 4\%$ in NLO,
<u>not</u> a measure for theoretical uncertainty

⋆ phase space subtraction, flexible to produce distributions



⋆ K factor might reflect LO cancellations

Associated Channel 1: Squark–Gaugino

Associated Production vs Trileptons

– trade larger (α_S) coupling for heavier (squark) mass

– cross section tens of fb

$\Rightarrow$ not useful at Run1 luminosities

$\Rightarrow$ some hundred events at Run2

– unexpected signatures, no analysis available

(1) $p\bar{p} \to \tilde{q}\tilde{\chi}_1^0$: monojet plus $\not{E}_T$

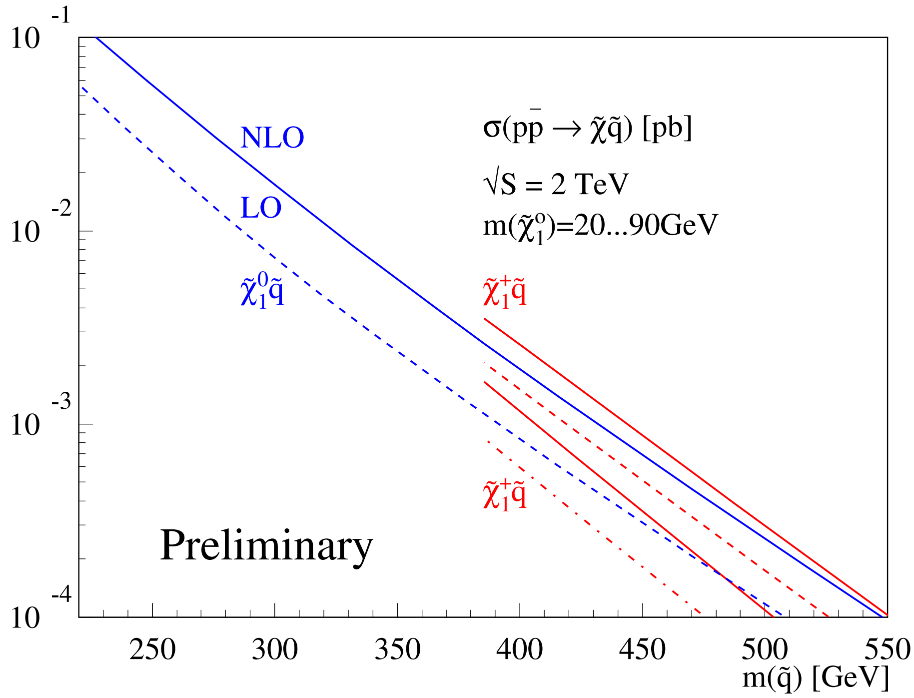
(2) $p\bar{p} \to \tilde{q}\tilde{\chi}_1^\pm$: jet–lepton plus $\not{E}_T$

$\rightarrow$ monojet signature particularly interesting for

(1) light LSP (no serious constraints on LSP mass)

(2) light squark (Run1 limit $\sim$ 120 GeV)

$\rightarrow$ signal–background analysis needed



ASSOCIATED CHANNEL 2: GLUINO–NEUTRALINO

Associated Gluino Production

– trade larger (α_S) coupling for gluino mass [Berger, Klasen, Tait]

– again cross section several tens of fb
$\Rightarrow$ several hundred events at Run2

– (1) $p\bar{p} \to \tilde{g}\tilde{\chi}_1^0 \to 2$ jets $+ \not{E}_T$: severe misbalance in event
(2) $p\bar{p} \to \tilde{g}\tilde{\chi}_2^0 \to ?? + \ell\ell\not{E}_T$: mixed signature, safe trigger

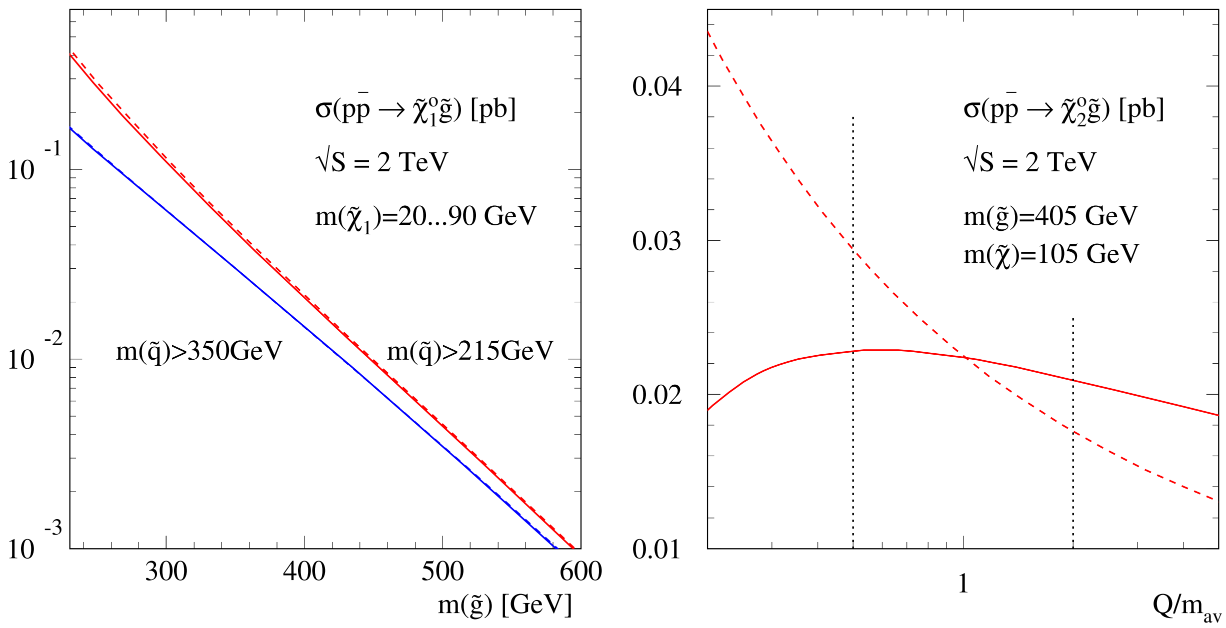
– what if your gluino wants to have a mass of 11 GeV
and there is no data to contradict that? [Berger...]

$\to$ never be sure you have all your channels together!

NLO prediction

– K factor close to unity

– scale variation $\lesssim 10\% \to$ underestimate of theoretical uncertainty?



Exotic Channel 1: Single Stops

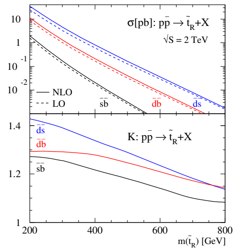
Single Stop Production:

– only allowed through R parity violation

$\rightarrow$ third generation coupling alone less constrained [Slavich]

$\rightarrow$ $\sigma\left(\bar{d}\bar{s} \rightarrow \tilde{t}_1\right) \propto |\lambda''_{312}|^2 \ \sin^2\theta_t / m^2_{\tilde{t}_1}$ [Berger, Harris, Sullivan]
leading to strong constraints in the $m_{\tilde{t}_1} - \lambda''$ plane

NLO analysis:



– K factors moderate, corrections positive

– scale dependence reduced (cancellations between Q_F and Q_R in LO)

– possible cut on transverse momenta: $p\bar{p}/pp \rightarrow \tilde{t}$+jet

$\rightarrow$ soft and collinear divergences no longer cancelled

$\rightarrow$ cross section divergent for small transverse momentum

$$\frac{1}{\sigma_0}\frac{d\sigma^{\rm asym}}{dp_T dy} = K_{qq}\frac{\alpha_s}{\pi}\frac{1}{Sp_T}\left[C_F\left(2\log\frac{m^2}{p_T^2}-4\right)f_{\bar{q}}(x_1^0)f_{\bar{q}}(x_2^0) + \sum_{i=\bar{q},g}(f_i \circ P_{\bar{q}\leftarrow i})(x_1^0)f_{\bar{q}}(x_2^0)\right]$$

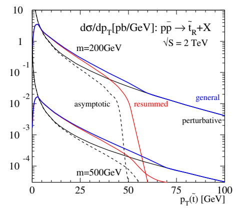
$\rightarrow$ leading logarithms can be resummed [Sterman, Collins, Soper,...]

$$\frac{1}{\sigma_0}\frac{d\sigma^{\rm resum}}{dp_T dy} = K_{qq}\frac{2p_T}{S}\int_0^\infty db\frac{b}{2}J_0(bp_T)W(b)$$

$$W(b) = \exp\left[-\int_{b_0^2/b^2}^{m^2}\frac{dq^2}{q^2}\frac{\alpha_s(q^2)C_F}{2\pi}\left(2\log\frac{m^2}{p_T^2}-4\right)\right] f_{\bar{q}}(x_1^0)f_{\bar{q}}(x_2^0)$$

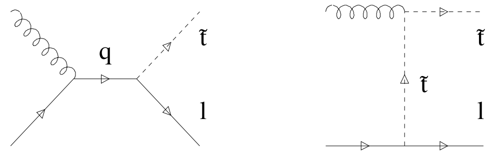
$\rightarrow$ matching procedure yields general formula

$$\frac{d\sigma^{\rm general}}{dp_T dy} = \frac{d\sigma^{\rm pert}}{dp_T dy} + \frac{1}{1+\left(p_T/p_T^{\rm match}\right)^4}\left[\frac{d\sigma^{\rm resum}}{dp_T dy} - \frac{d\sigma^{\rm asym}}{dp_T dy}\right]$$



Exotic Channel 2 : Stop Lepton Associated

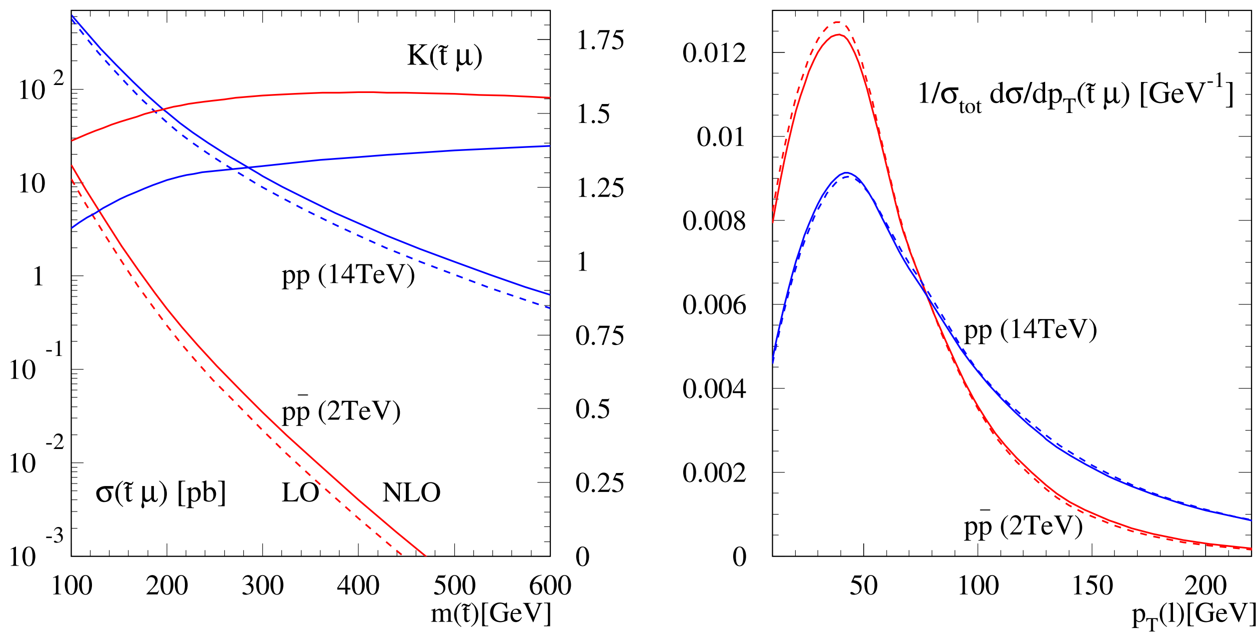
R parity violating coupling λ':



- interesting for neutrino mass generation
- constrained by APV, rare decays, etc

$\rightarrow$ second and third generation λ' weakly constrained

$\rightarrow$ all combinations probed in $\tilde{q}\ell$ associated production [Éboli et al.]



Running of $\lambda'(Q^2)$:

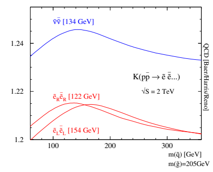
$$\lambda^2(Q^2) = \lambda^2(M^2)\left[1+\frac{\alpha_s}{\pi}\log\frac{Q^2}{M^2}\right]^{-1} \quad \text{for LQ effective theory}$$

$$\lambda^2(Q^2) = \lambda^2(M^2) \quad \text{including gluinos}$$

OUTLOOK

Current Status of SUSY-NLO Program at Hadron Colliders:

- squark/gluino production (used in Run1 analyses)
- stop pair production (used in Run1 analyses)
- neutralino/chargino production (completely exclusive)
- slepton pair production (not likely at Tevatron) [Baer, Harris, Reno]



- prelim. associated neutralino/chargino and gluino
- prelim. associated neutralino/chargino and squark
- R parity violating single stop production
- prelim. associated lepton and R parity violating stop

$\Longrightarrow$ NLO analyses at Run2 and LHC possible for SUSY signals

$\Longrightarrow$ ALL WE NEED NOW IS DATA!

REGULARIZATION AND SUPERSYMMETRY

Dimensional Regularization breaks supersymmetry

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

$$\delta_S \mathcal{L}[W_\mu^a, \lambda^a, D] \xrightarrow{n \to 4} 0$$

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

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

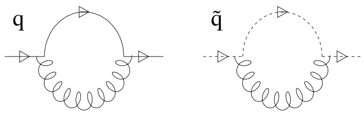
$\rightarrow$ Dimensional Regularization can be
rendered consistent with SUSY

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 $Y \equiv mg$

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



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

- $\star$ difference removed by finite ‘renormalization’

  [Martin, Vaughn; Kraus, Stöckinger]

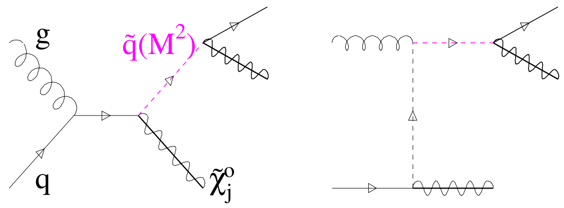
- $\star$ check by comparison of Green’s functions with Dim. Reduction

On-Shell Singularities

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

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

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:

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

- cross section in narrow widths approximation

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

⋆ treatment compatible with experimental Monte-Carlos

⋆ major source of computational difficulties

STOP MIXING

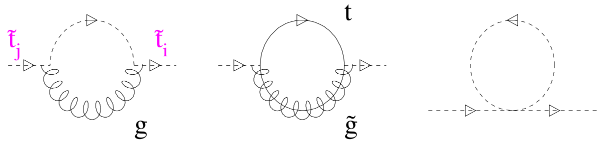
LO stop mass matrix diagonalized by $\tilde{\theta}_0$

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

$$\mathcal{M}_{12} = \mathcal{R}(\tilde{\theta}_0)\mathcal{M}_{\rm LR}\mathcal{R}(\tilde{\theta}_0)^{-1}$$

NLO contribution $\mathcal{M}_{12} \to \mathcal{M}_{12} + \Sigma(Q^2)$

- ⋆ non-diagonal stop and gluino contribution Σ
- ⋆ only gluonic self energy remains diagonal
- ⋆ dependent on momentum transfer $\Sigma(Q^2)$
- ⋆ CP conserved / real coupling parameters $\to \Sigma = \Sigma^T$
  $\to$ not valid e.g. for Majorana neutrinos and CP violation



Mixing absorbed into wave function renormalization

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

written as real orthogonal propagator diagonalization

$$\begin{aligned} D^{-1}_{\rm ren}(Q^2) &\sim \left[Q^2\ 1 - \mathcal{M}_{12} - \text{Re}\ \Sigma(Q^2)\right]_{\rm ren} \\ &= Z_{\rm D}^{-1/2}\ \mathcal{R}(\tilde{\theta}_0 - \delta\tilde{\theta})^{-1}\left[Q^2\ 1 - \mathcal{M}_{LR} - \text{Re}\ \Sigma(Q^2)\right]\mathcal{R}(\tilde{\theta}_0 - \delta\tilde{\theta})\ Z_{\rm D}^{-1/2T} \end{aligned}$$

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

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

Running Mixing Angle

$$\tilde{\theta}({Q_1}^2) - \tilde{\theta}(Q_2^2) = \frac{C_F \alpha_s m_{\tilde{g}} m_t \cos(2\tilde{\theta})}{\pi(m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)} \text{ Re } \left[B(Q_2^2, m_{\tilde{g}}, m_t) - B(Q_1^2, m_{\tilde{g}}, m_t) \right]$$

Running mixing angle [c.f. Diaz et al.]

⋆ generalized on-shell renormalization scheme

⋆ Symmetry of the Lagrangean restored in observables

$$\begin{aligned} m_{\tilde{t}_1} &\leftrightarrow m_{\tilde{t}_2} \\ \sin(2\tilde{\theta}) &\leftrightarrow -\sin(2\tilde{\theta}) \\ \cos(2\tilde{\theta}) &\leftrightarrow -\cos(2\tilde{\theta}) \end{aligned}$$

⋆ related counter terms $\displaystyle \frac{\delta s_{2\tilde{\theta}}}{s_{2\tilde{\theta}}} = -\frac{\delta(m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2)}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2} + \frac{\delta m_t}{m_t} + \frac{\delta(A_t + \mu \cot\beta)}{A_t + \mu \cot\beta}$

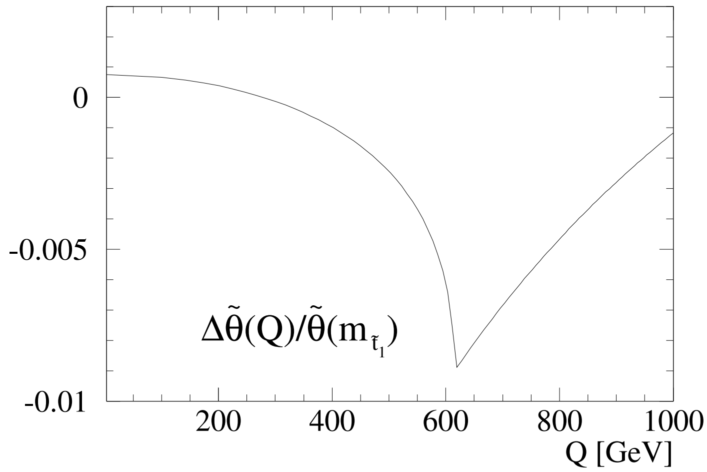
⋆ possible measurements in decays

⋆ numerical effect small

[Kraml et al., Djouadi et al.]

⋆ not valid for weak corrections

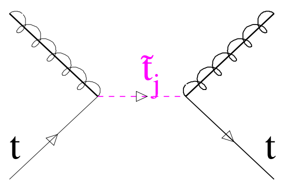
[Yamada]



Virtual stop state, effective mixing angle

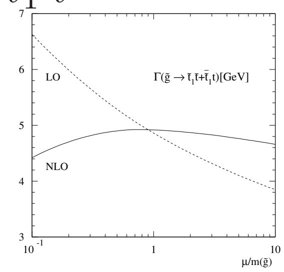
$$\tilde{\theta}_{\text{eff}}(p^2) = \tilde{\theta}_0 - \frac{1}{2} \arctan \left[\frac{2\Sigma_{12}(p^2)}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2 + \Sigma_{22}(p^2) - \Sigma_{11}(p^2)} \right]$$

$$\xrightarrow{\text{NLO}} \tilde{\theta}(p^2) + \frac{\text{Im}\, \Sigma_{12}(p^2)}{m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2}$$



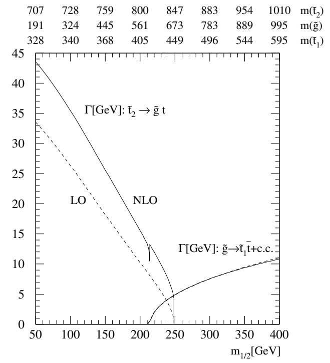
Stop Decays

Decays involving the strong coupling $\quad \tilde{t}_2 \to t\,\tilde{g}, \quad \tilde{g} \to \tilde{t}_1\,\bar{t}$



$$\Gamma(\tilde{t}_{1,2} \to t\,\tilde{g}) = \frac{2\alpha_s\lambda}{3m^3_{\tilde{t}_{1,2}}}\left[m^2_{\tilde{t}_{1,2}} - m_t^2 - m_{\tilde{g}}^2 \pm 2m_t m_{\tilde{g}} \sin(2\tilde{\theta})\right]$$

$$\Gamma(\tilde{g} \to \bar{t}\,\tilde{t}_{1,2}) = -\frac{\alpha_s\lambda}{8m^3_{\tilde{g}}}\left[m^2_{\tilde{t}_{1,2}} - m_t^2 - m_{\tilde{g}}^2 \pm 2m_t m_{\tilde{g}} \sin(2\tilde{\theta})\right]$$

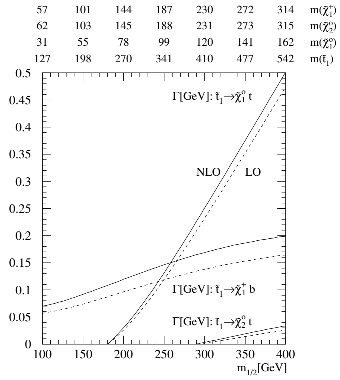


SUSY-QCD corrections

- ⋆ scale dependence strongly reduced
- ⋆ different K factors for stop/gluino decay
- ⋆ no additional parameter dependence

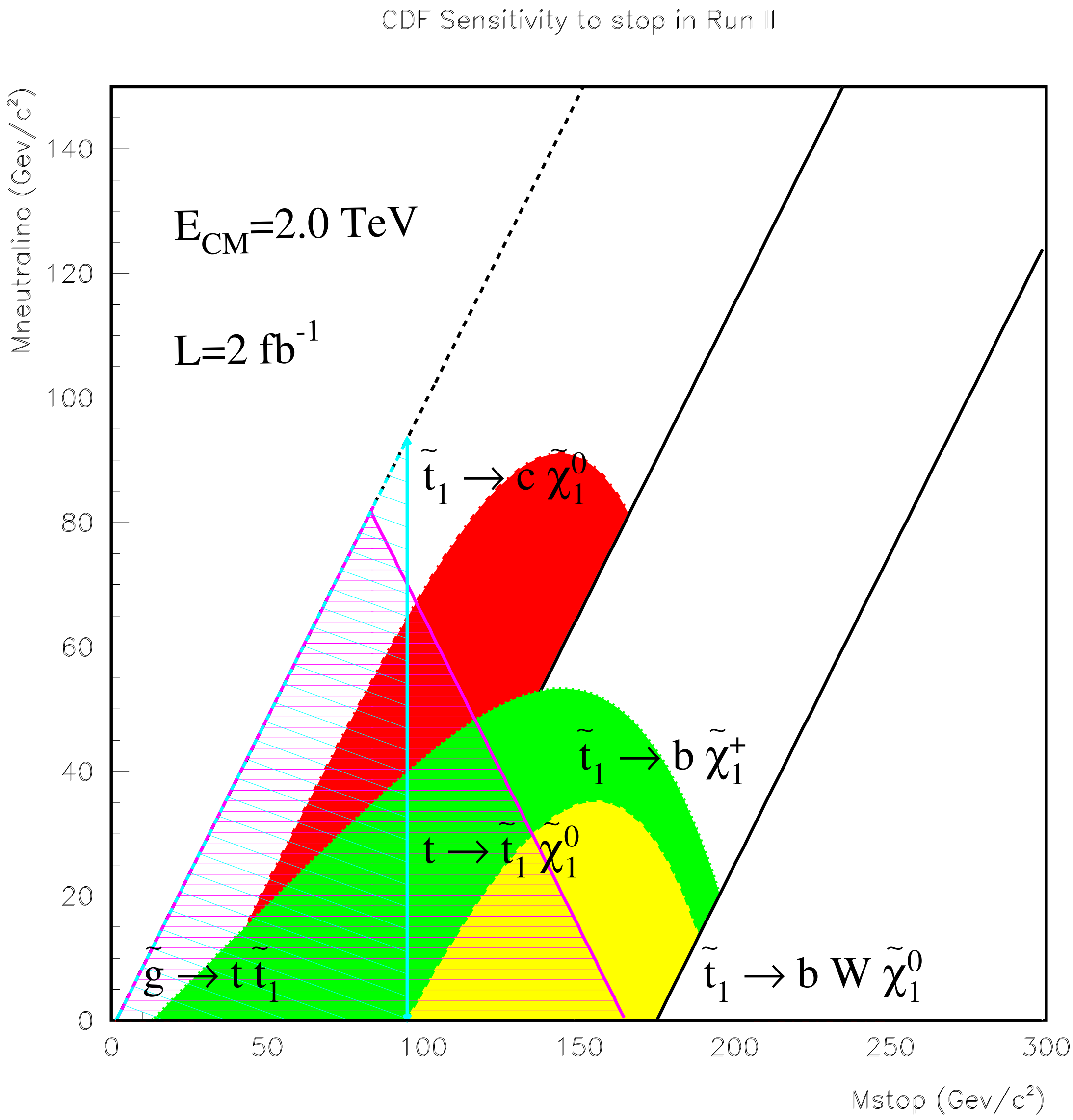
Decays involving the weak coupling $\quad \tilde{t}_1 \to t\,\tilde{\chi}^0_j, \quad \tilde{t}_1 \to b\,\tilde{\chi}^+_j$

$$\Gamma(\tilde{t}_{1,2} \to t\,\tilde{\chi}^0_j) = \frac{\alpha_s\lambda}{2m^3_{\tilde{t}_{1,2}}}\left[(a_L^{(j)\,2} + a_R^{(j)\,2})(m^2_{\tilde{t}_{1,2}} - m_t^2 - m^2_{\tilde{\chi}_j}) \pm 4m_t m_{\tilde{\chi}_j} a_L^{(j)} a_R^{(j)}\right]$$

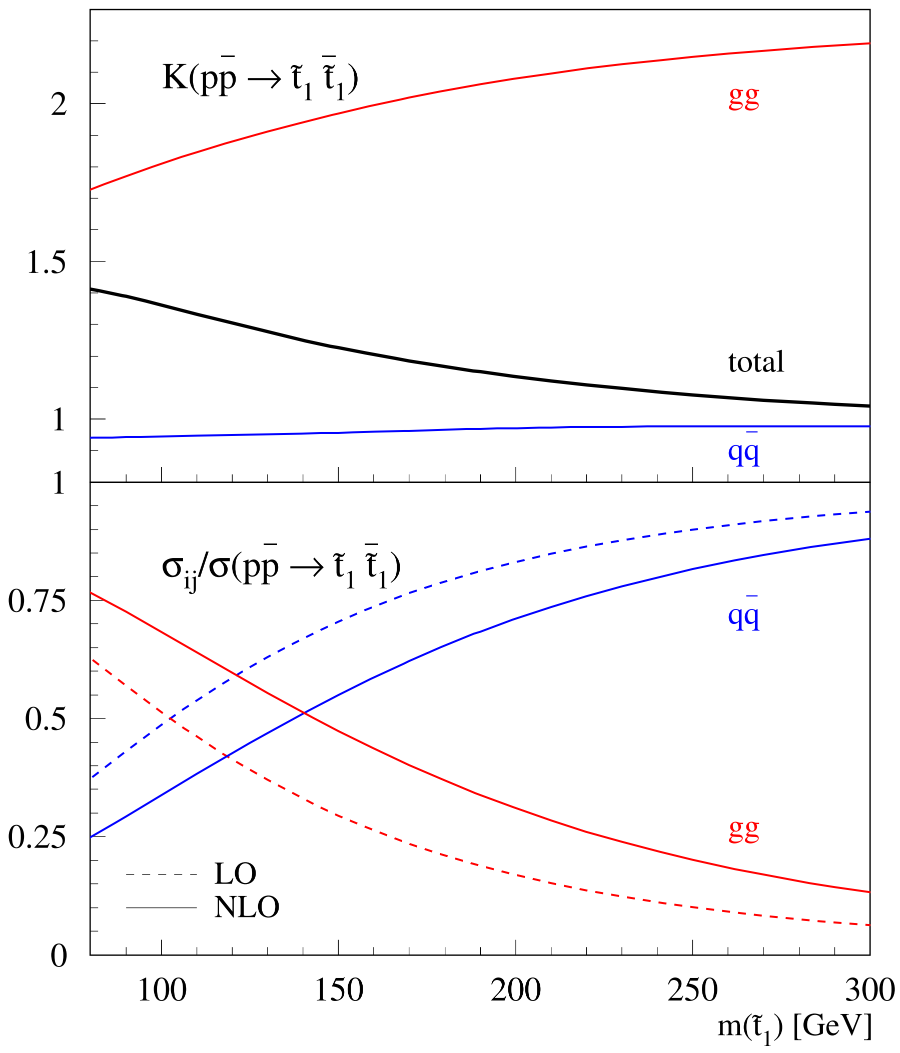


SUSY-QCD corrections

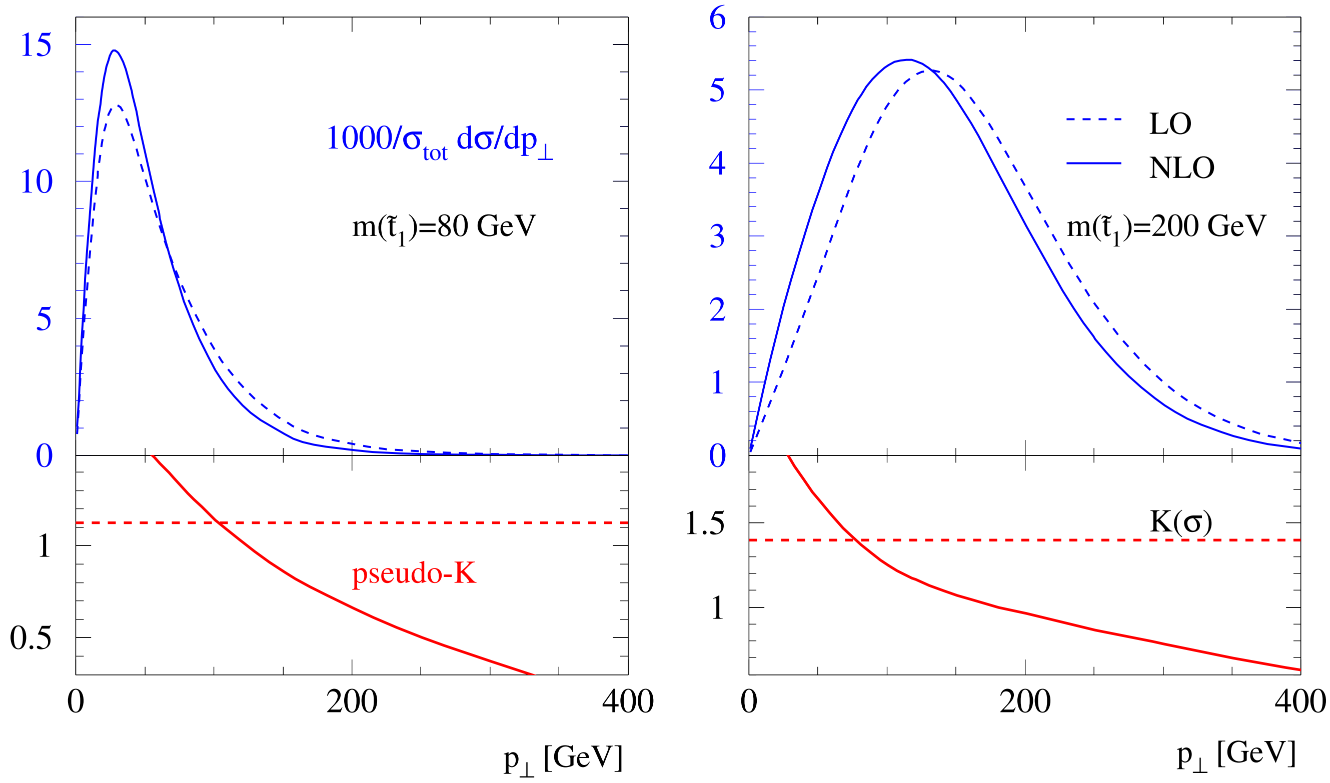
- ⋆ theoretical uncertainty reduced
- ⋆ sizable corrections to partial widths
- ⋆ small effect on branching ratios



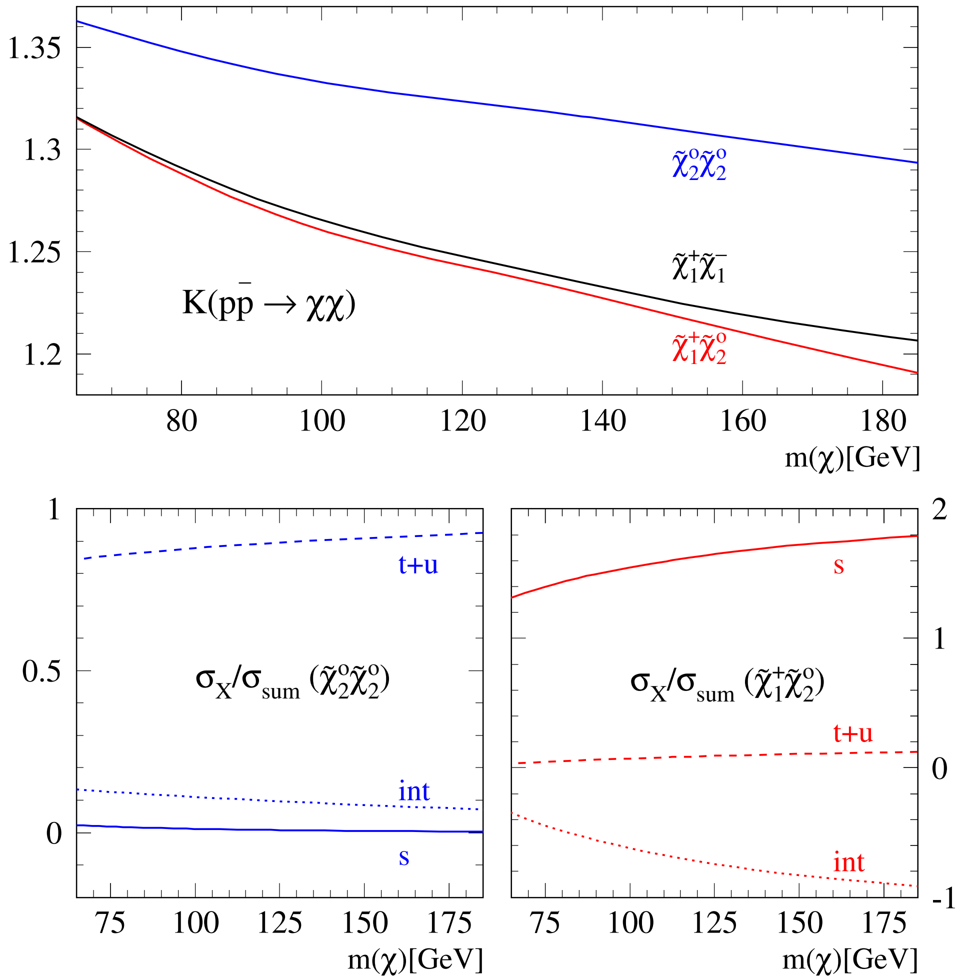
CDF Sensitivity to stop in Run II
E_{CM}=2.0 TeV
L=2 fb^{-1}
$\tilde{t}_1 \rightarrow c\,\tilde{\chi}_1^0$
$\tilde{t}_1 \rightarrow b\,\tilde{\chi}_1^+$
$t \rightarrow \tilde{t}_1\,\tilde{\chi}_1^0$
$\tilde{g} \rightarrow t\,\tilde{t}_1$
$\tilde{t}_1 \rightarrow b\,W\,\tilde{\chi}_1^0$
Mneutralino (Gev/c^2)
Mstop (Gev/c^2)
0
20
40
60
80
100
120
140
0
50
100
150
200
250
300



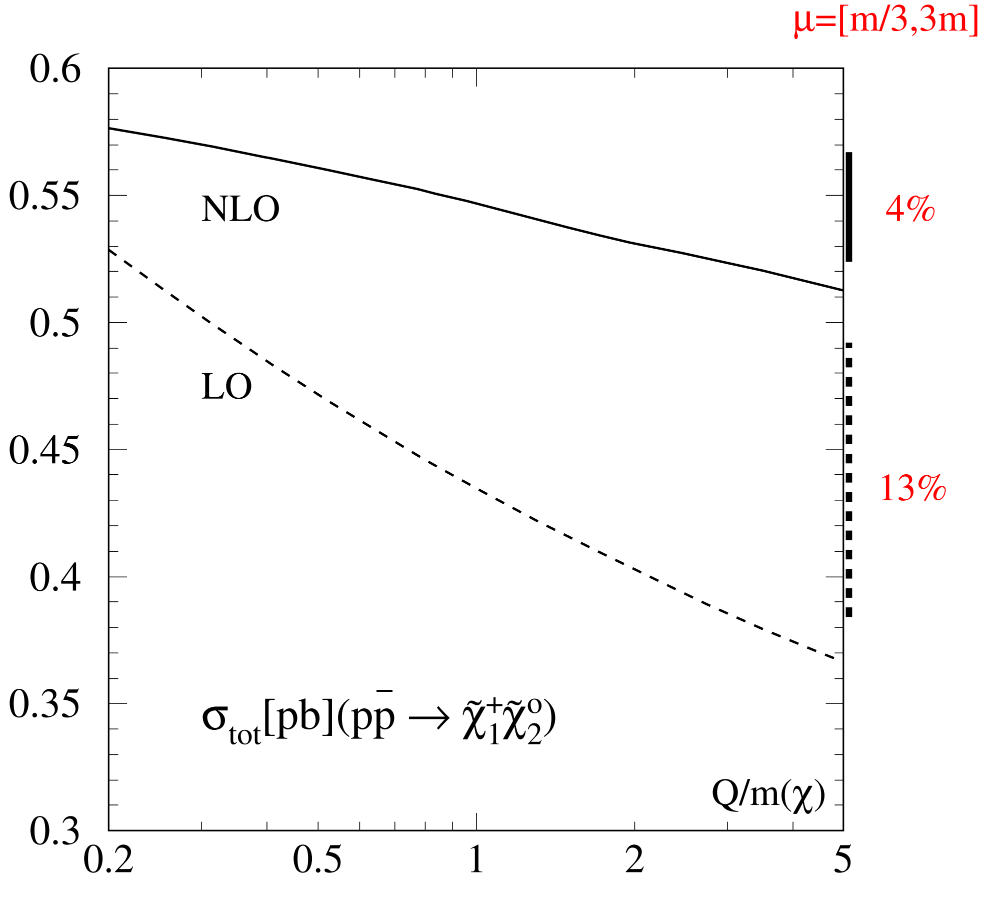
$K(p\bar{p} \to \tilde{t}_1 \bar{\tilde{t}}_1)$
gg
total
$q\bar{q}$
$\sigma_{ij}/\sigma(p\bar{p} \to \tilde{t}_1 \bar{\tilde{t}}_1)$
$q\bar{q}$
gg
LO
NLO
2
1.5
1
1
0.75
0.5
0.25
0
100
150
200
250
300
$m(\tilde{t}_1)$ [GeV]



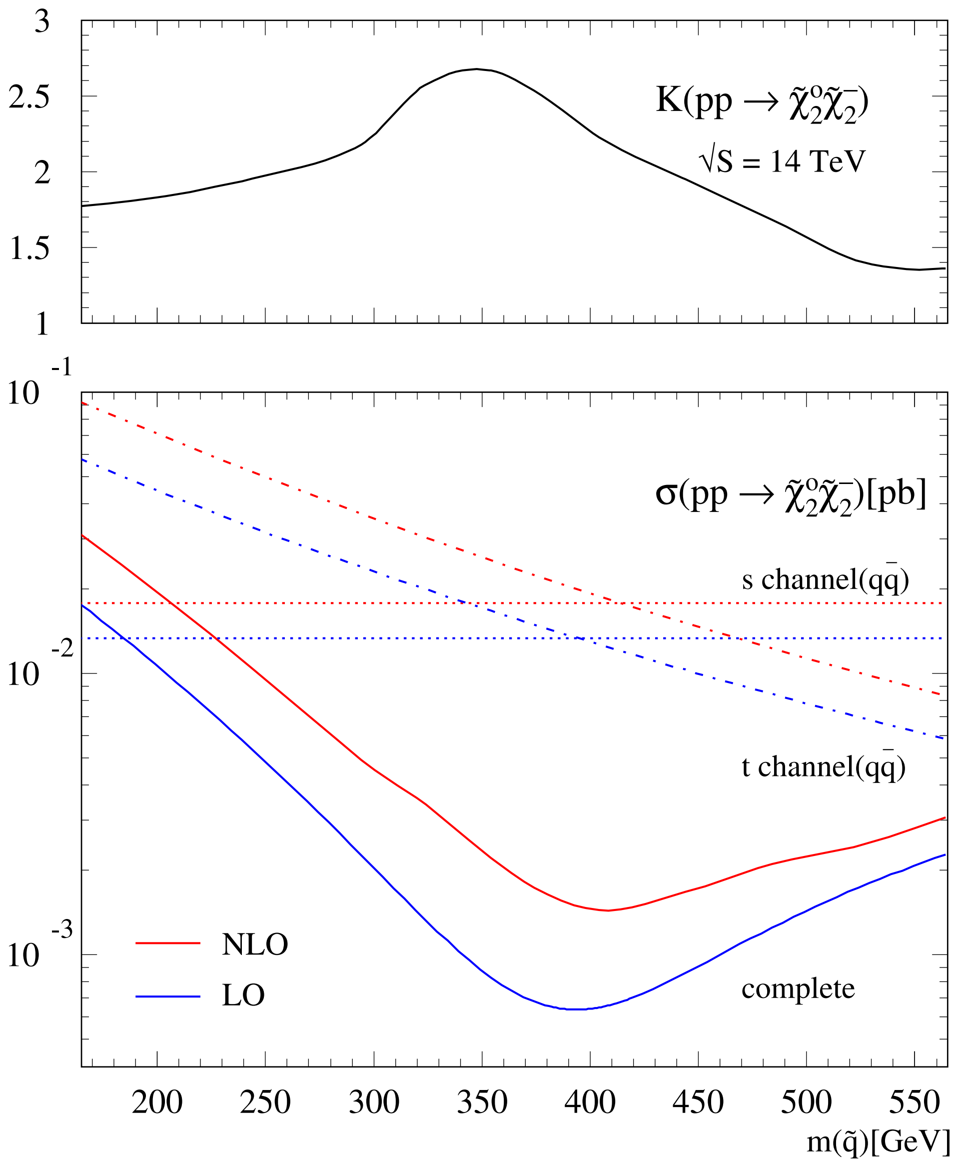
15
10
5
0
1000/σ_{tot} dσ/d$p_\perp$
m($\tilde{t}_1$)=80 GeV
1
0.5
pseudo-K
0
200
400
$p_\perp$ [GeV]
6
5
4
3
2
1
0
LO
NLO
m($\tilde{t}_1$)=200 GeV
1.5
1
K(σ)
0
200
400
$p_\perp$ [GeV]



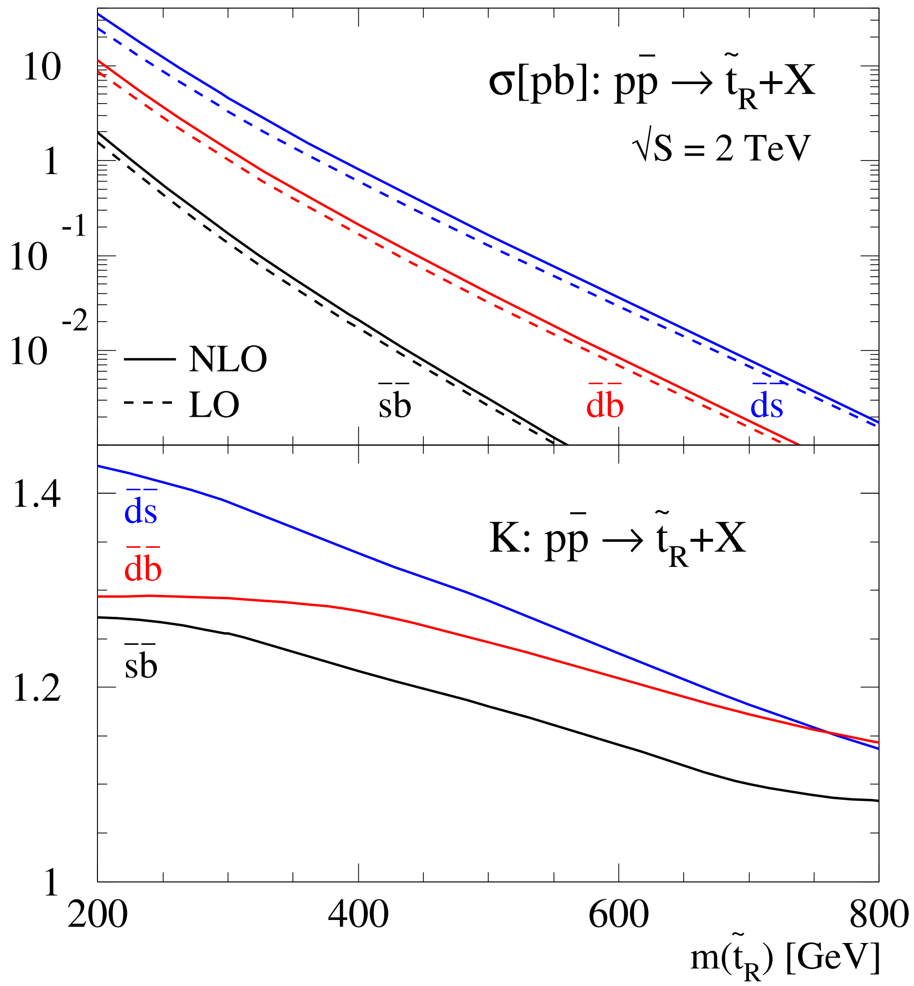
1.35
1.3
1.25
1.2
$\tilde{\chi}^o_2\tilde{\chi}^o_2$
$\tilde{\chi}^+_1\tilde{\chi}^-_1$
$K(p\bar{p} \to \chi\chi)$
$\tilde{\chi}^+_1\tilde{\chi}^o_2$
80
100
120
140
160
180
m(χ)[GeV]
1
0.5
0
t+u
σ_X/σ_{sum} $(\tilde{\chi}^o_2\tilde{\chi}^o_2)$
int
s
75
100
125
150
175
m(χ)[GeV]
2
1
0
-1
s
σ_X/σ_{sum} $(\tilde{\chi}^+_1\tilde{\chi}^o_2)$
t+u
int
75
100
125
150
175
m(χ)[GeV]



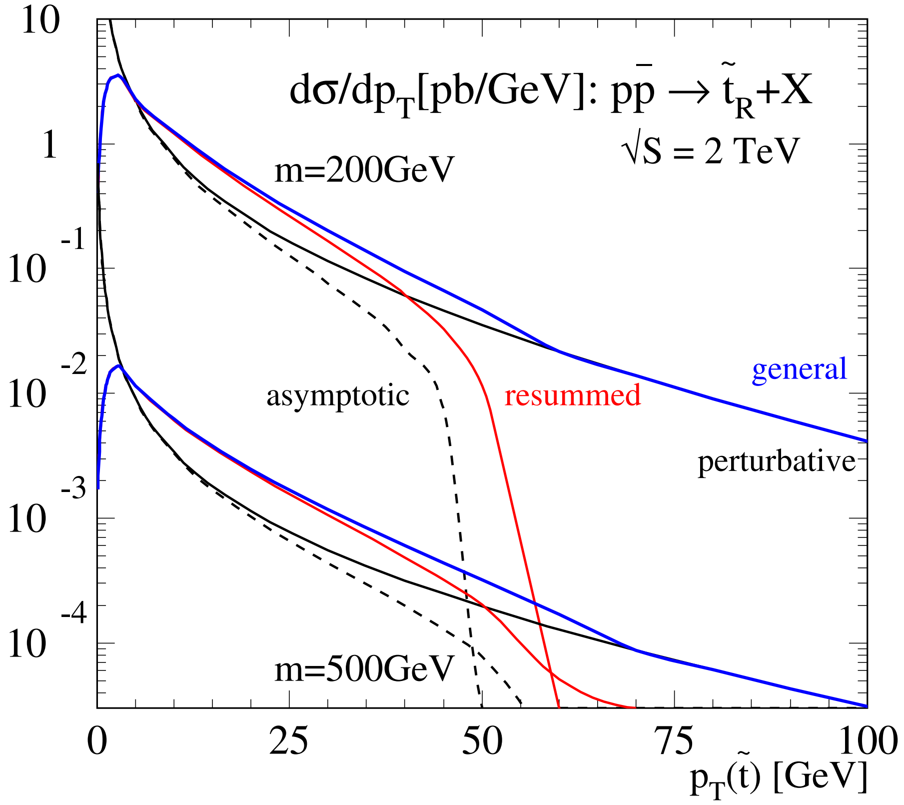
μ=[m/3,3m]
0.6
0.55
0.5
0.45
0.4
0.35
0.3
NLO
LO
4%
13%
$\sigma_{tot}[pb](p\bar{p} \to \tilde{\chi}_1^+\tilde{\chi}_2^o)$
Q/m(χ)
0.2
0.5
1
2
5



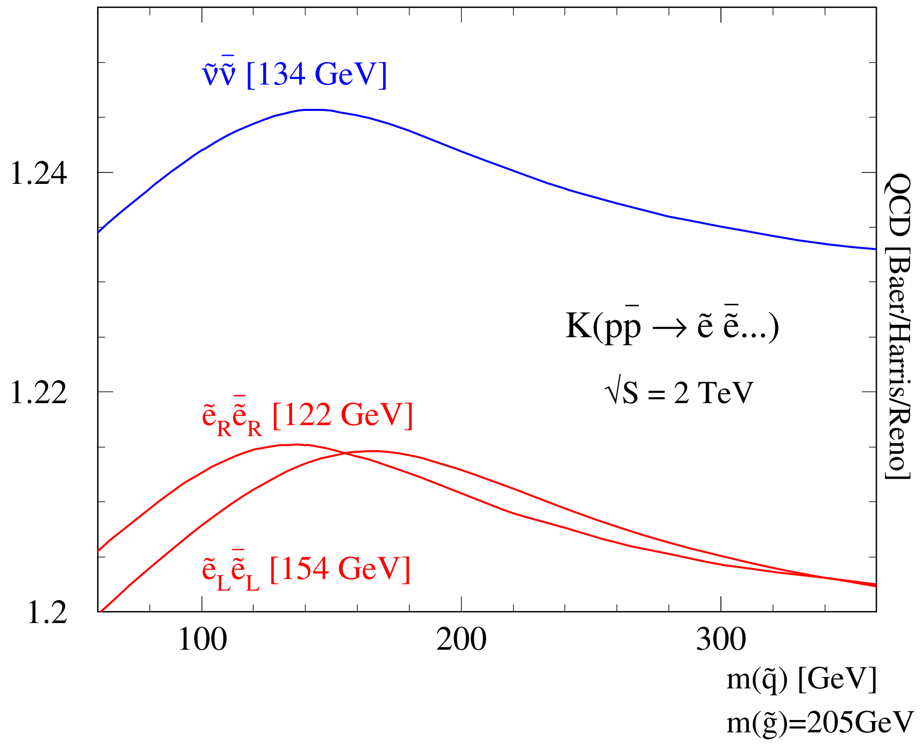
K(pp → $\tilde{\chi}_2^o\tilde{\chi}_2^-$)
√S = 14 TeV
σ(pp → $\tilde{\chi}_2^o\tilde{\chi}_2^-$)[pb]
s channel(q$\bar{q}$)
t channel(q$\bar{q}$)
NLO
LO
complete
m($\tilde{q}$)[GeV]



σ[pb]: $p\bar{p} \to \tilde{t}_R+X$
$\sqrt{S}$ = 2 TeV
NLO
LO
$\bar{s}\bar{b}$
$\bar{d}\bar{b}$
$\bar{d}\bar{s}$
10
1
10^{-1}
10^{-2}
K: $p\bar{p} \to \tilde{t}_R+X$
1.4
1.2
1
200
400
600
800
$m(\tilde{t}_R)$ [GeV]



$d\sigma/dp_T$[pb/GeV]: $p\bar{p} \rightarrow \tilde{t}_R$+X
$\sqrt{S}$ = 2 TeV
m=200GeV
m=500GeV
asymptotic
resummed
general
perturbative
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
25
50
75
100
$p_T(\tilde{t})$ [GeV]



$\tilde{\nu}\bar{\tilde{\nu}}$ [134 GeV]
$\tilde{e}_R\bar{\tilde{e}}_R$ [122 GeV]
$\tilde{e}_L\bar{\tilde{e}}_L$ [154 GeV]
$K(p\bar{p} \rightarrow \tilde{e}\,\bar{\tilde{e}}...)$
$\sqrt{S}$ = 2 TeV
QCD [Baer/Harris/Reno]
1.24
1.22
1.2
100
200
300
$m(\tilde{q})$ [GeV]
$m(\tilde{g})$=205GeV