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SUSY-particle production at Hadron Colliders

Michael Krämer

(RWTH Aachen)

- Basics of SUSY particle production at hadron colliders
- The calculation of SUSY-QCD corrections

Work done in collaboration with W. Beenakker, R. Höpker, M. Klasen, T. Plehn, M. Spira, P.M. Zerwas

Introduction: Why Supersymmetrie?

- There are many good reasons to study supersymmetric field theories and TeV-scale SUSY at colliders:

  – SUSY is the unique extension of the Lorentz-symmetry

  – SUSY provides a solution to the hierarchy problem

  – SUSY allows for gauge coupling unification

  – SUSY provides a dark matter candidate

  – SUSY can generate EWSB dynamically

  – . . .

The Minimal Supersymmetric Standard Model

- The MSSM particle spectrum

Gauge Bosons $S = 1$ gluon, $W^{\pm}, Z, \gamma$	Gauginos $S = 1/2$ gluino, $\widetilde{W}, \tilde{Z}, \tilde{\gamma}$
Fermions $S = 1/2$ $\begin{pmatrix} u_L \\ d_L \end{pmatrix} \begin{pmatrix} \nu^e_L \\ e_L \end{pmatrix}$ u_R, d_R, e_R	Sfermions $S = 0$ $\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix} \begin{pmatrix} \tilde{\nu}^e_L \\ \tilde{e}_L \end{pmatrix}$ $\tilde{u}_R, \tilde{d}_R, \tilde{e}_R$
Higgs $\begin{pmatrix} H^0_2 \\ H^-_2 \end{pmatrix} \begin{pmatrix} H^+_1 \\ H^0_1 \end{pmatrix}$	Higgsinos $\begin{pmatrix} \widetilde{H}^0_2 \\ \widetilde{H}^-_2 \end{pmatrix} \begin{pmatrix} \widetilde{H}^+_1 \\ \widetilde{H}^0_1 \end{pmatrix}$

SUSY particle production at hadron colliders

SUSY particle production at hadron colliders

- In the MSSM one imposes a symmetry to avoid proton decay

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

$\longrightarrow$ SUSY particles produced pairwise

$\longrightarrow$ lightest SUSY particle stable (dark matter candidate)

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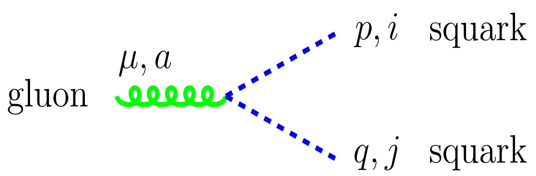
- The interactions of MSSM particles are determined by gauge symmetry and SUSY

example:



$$= -i\, g_s\, (T_a)_{ij} (p+q)^{\mu}$$

$\longrightarrow$ no new coupling!

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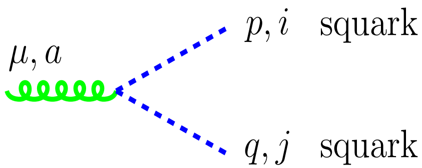
  example: gluon 

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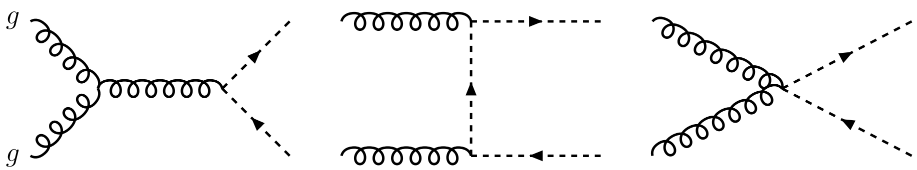
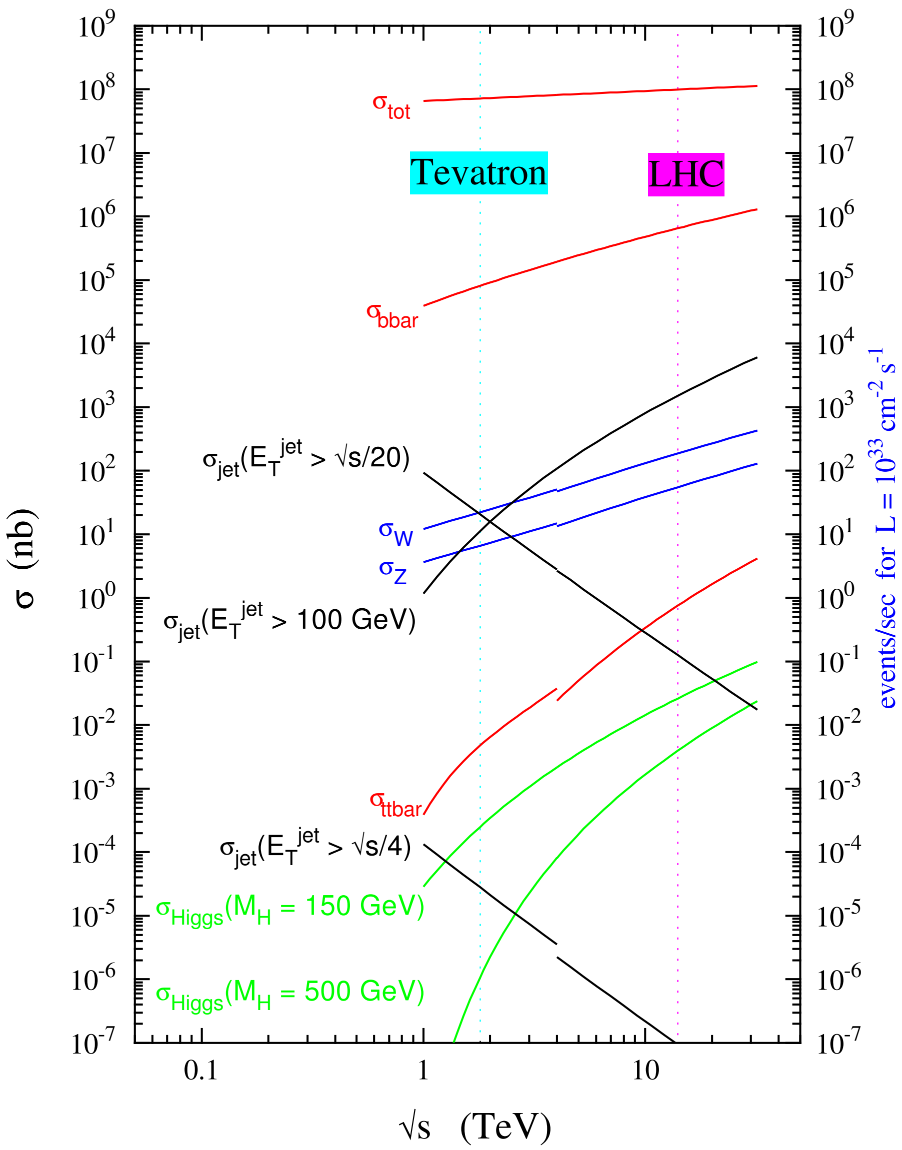
- SUSY particles should be produced copiously at hadron colliders through QCD processes, e.g.



Squark and gluino cross section at the LHC



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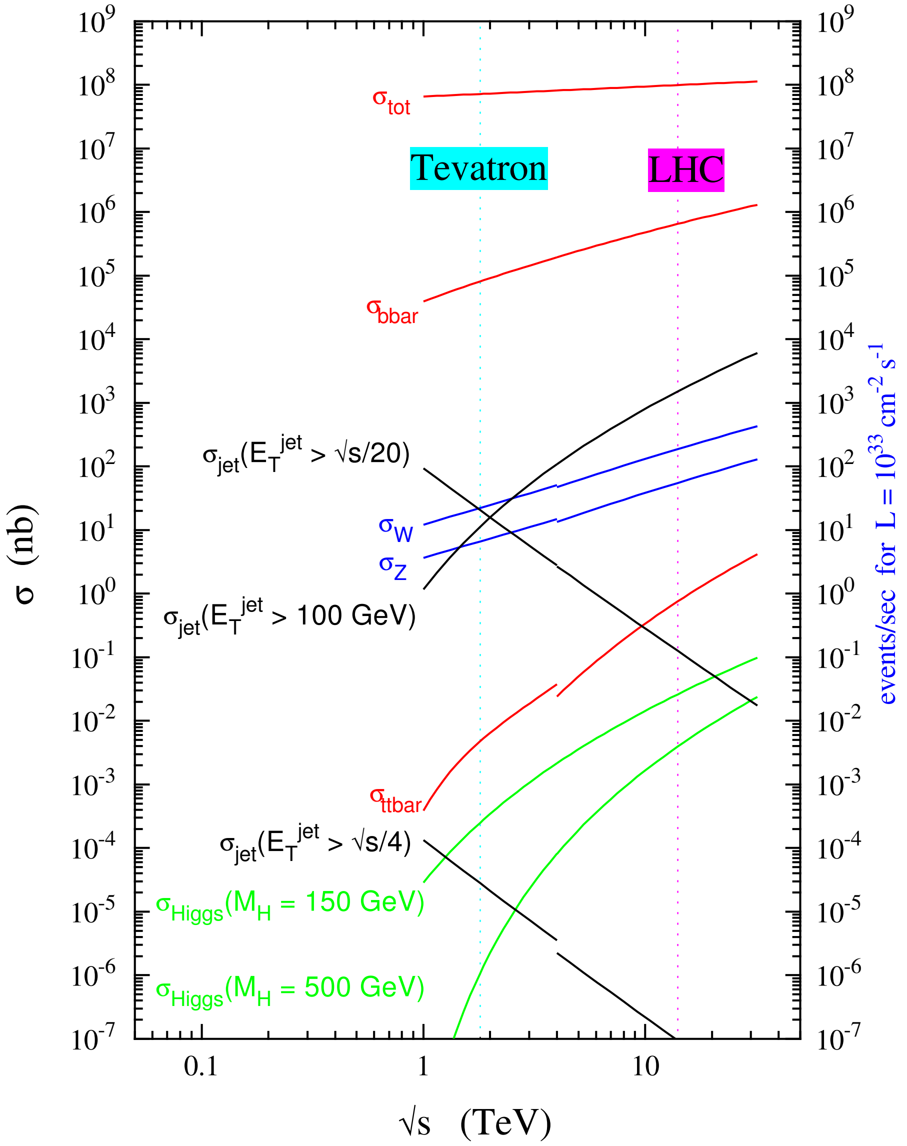


$\longrightarrow$ SUSY signal:

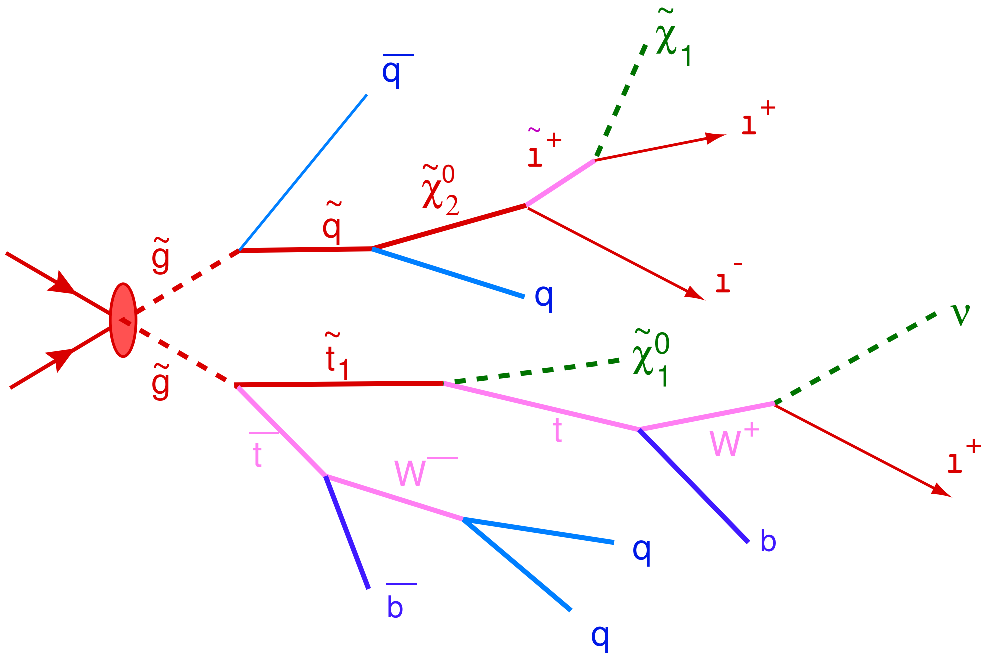
$\sigma(\tilde{q}\tilde{q} + \tilde{g}\tilde{g} + \tilde{g}\tilde{q}) \approx 2$ nb $\quad (M_{\tilde{q},\tilde{g}} \approx 300$ GeV)

$\hookrightarrow \approx 10^8$ squarks & gluinos/year ($\int\mathcal{L} = 30$ fb^{-1})

SUSY searches at hadron colliders

- Distinctive signature due to cascade decays:

  multiple jets (and/or leptons) with large amount of missing energy



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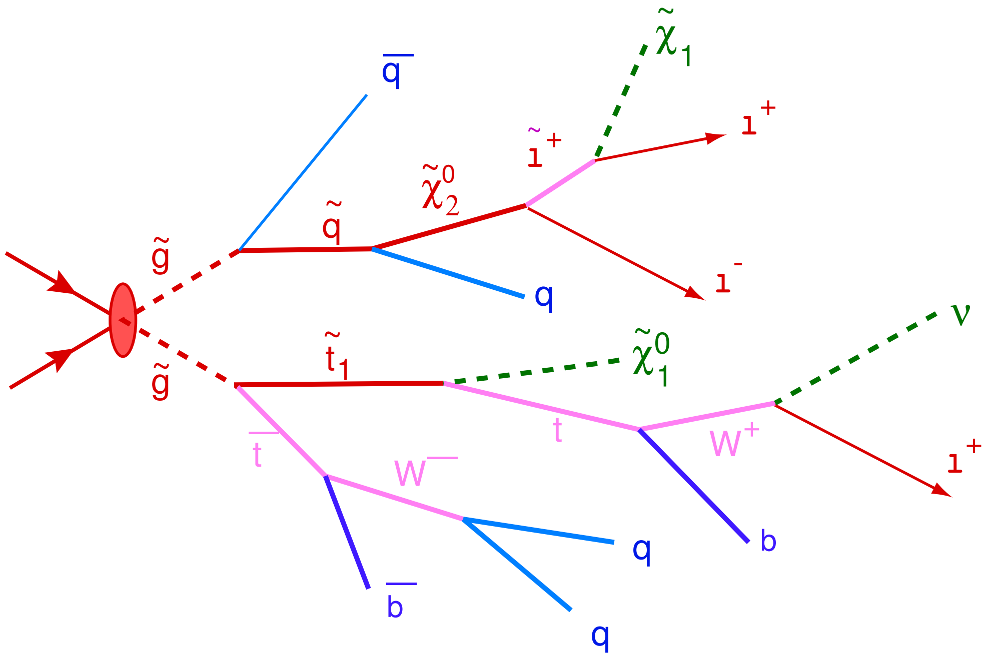
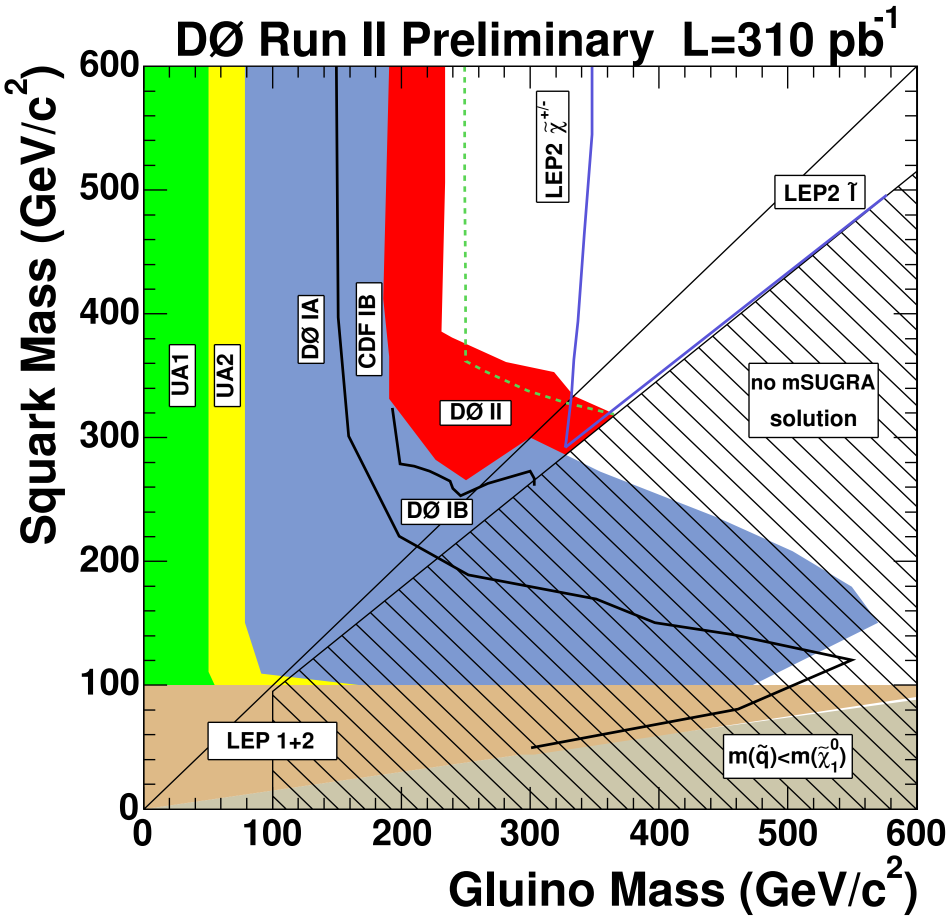


$\longrightarrow$ LHC discovery reach for squarks and gluinos: $M_{\tilde{q},\tilde{g}} \lesssim 2.5$ TeV

Current limits on sparticle masses



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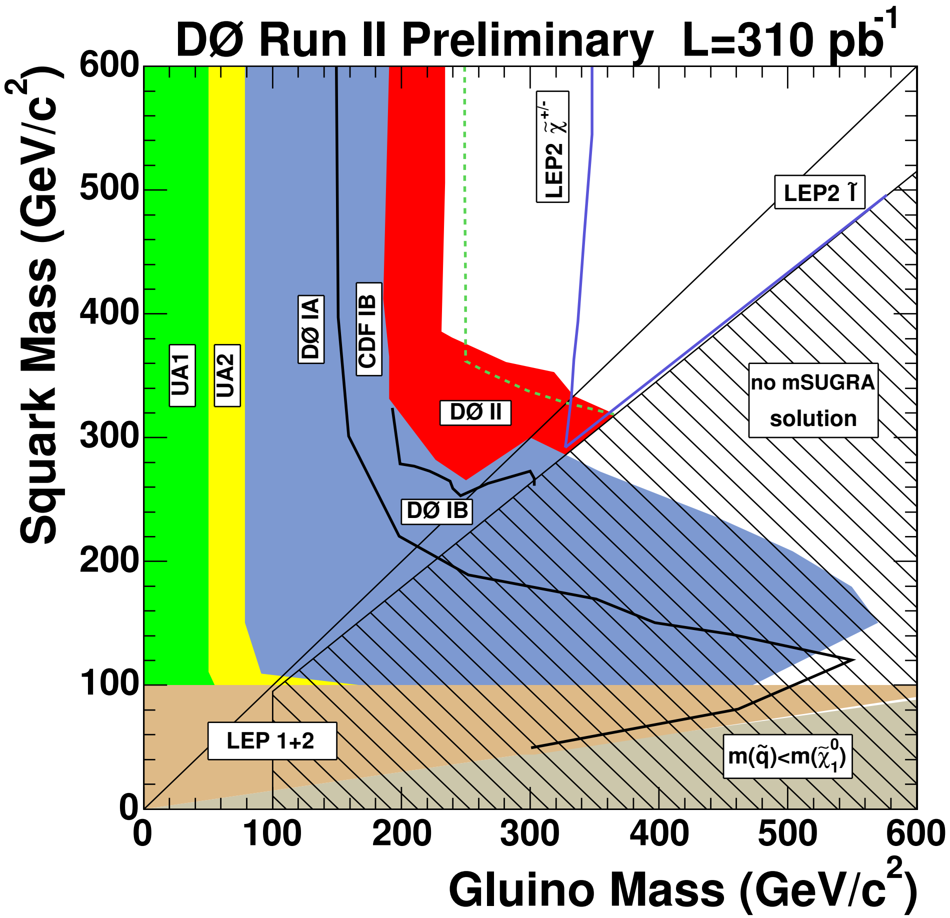


- mass limits (roughly)

$M_{\tilde{g}} \gtrsim$ 200 GeV

$M_{\tilde{q}} \approx M_{\text{gluino}} \gtrsim$ 300 GeV

$M_{\tilde{t}_1} \gtrsim$ 100 GeV

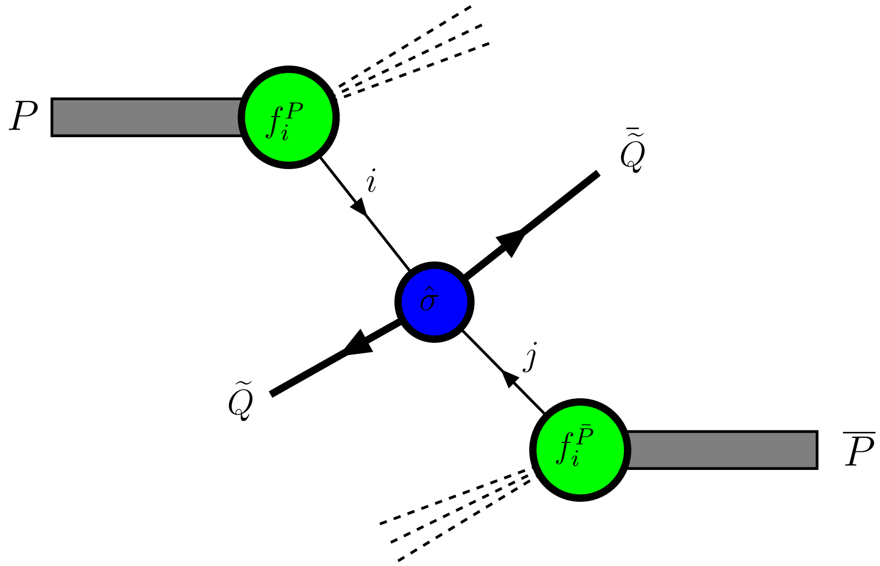
$M_{\tilde{\chi}_1^0} \gtrsim$ 50 GeV

$M_{\tilde{\chi}_1^\pm} \gtrsim$ 100 GeV

$M_{\text{sleptons}} \gtrsim$ 100 GeV

MSSM particle production at hadron colliders

- production dynamics



$$\sigma(pp/p\bar{p} \to \tilde{q}\bar{\tilde{q}}) \;=\; \int \mathrm{d}x_1 f_i^P(x_1,\mu) \int \mathrm{d}x_2 f_j^P(x_2,\mu)\; \sigma(ij \to \tilde{q}\bar{\tilde{q}})$$
$$+\mathcal{O}(\Lambda/M_{\tilde{q}})$$

$\longrightarrow$ effective energy for (s)particle production $\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} < \sqrt{s}$

MSSM particle production at hadron colliders

- Scale dependence

$$\sigma = \int dx_1 f_i^P(x_1, \mu_F) \int dx_2 f_j^P(x_2, \mu_F) \times \sum_n \alpha_s^n(\mu_R)\, C_n(\mu_R, \mu_F)$$

finite order in perturbation theory

$\longrightarrow$ artificial μ-dependence:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\ln\mu_{\mathrm{R}}^2} = \sum_{n=0}^{N} \alpha_s^n(\mu_R)\, C_n(\mu_R, \mu_F) = \mathcal{O}(\alpha_s(\mu_R)^{N+1})$$

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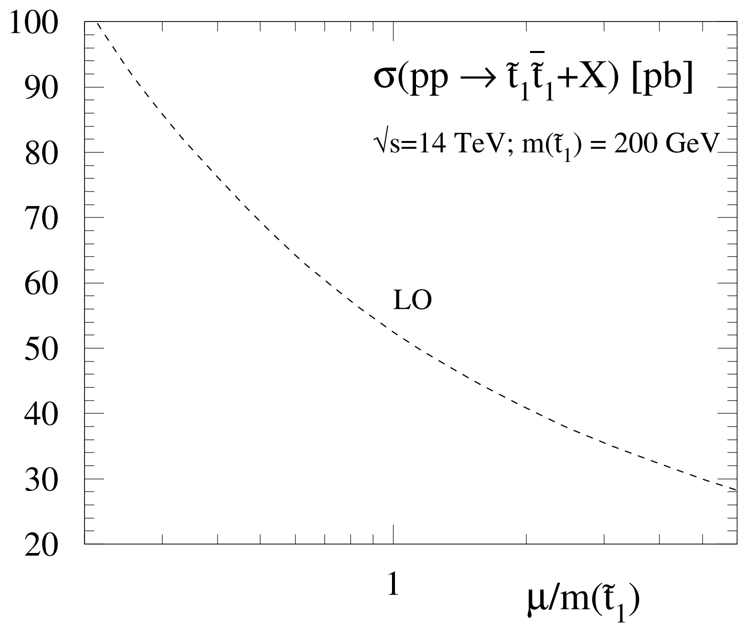
Example: Stop-pair production at leading order



$\rightarrow$ theoretical uncertainty $\gtrsim \pm 100\%$ at LO

$\Rightarrow$ must include NLO corrections

MSSM particle production at hadron colliders

MSSM sparticle pair production

- squarks & gluinos $pp/p\bar{p} \longrightarrow \widetilde{q}\bar{\widetilde{q}}, \widetilde{g}\widetilde{g}, \widetilde{q}\widetilde{g}$
- stops $pp/p\bar{p} \longrightarrow \widetilde{t}\bar{\widetilde{t}}$
- gauginos $pp/p\bar{p} \longrightarrow \widetilde{\chi}^0\widetilde{\chi}^0, \widetilde{\chi}^\pm\widetilde{\chi}^0, \widetilde{\chi}^+\widetilde{\chi}^-$
- sleptons $pp/p\bar{p} \longrightarrow \widetilde{l}\widetilde{l}$
- associated production $pp/p\bar{p} \longrightarrow \widetilde{q}\widetilde{\chi}, \widetilde{g}\widetilde{\chi}$

Top-squark production

- $\widetilde{t}_L, \widetilde{t}_R$ mix to form mass states $\widetilde{t}_1, \widetilde{t}_2 \longrightarrow$ potentially small $\widetilde{t}_1$ mass

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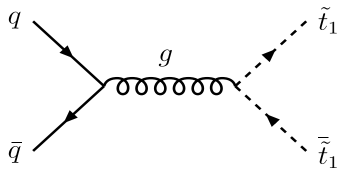
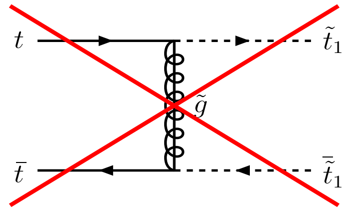
- LO parton reations

$$q + \bar{q} \rightarrow \widetilde{t}_i + \bar{\widetilde{t}}_i \quad (i = 1, 2)$$





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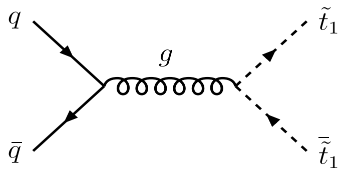

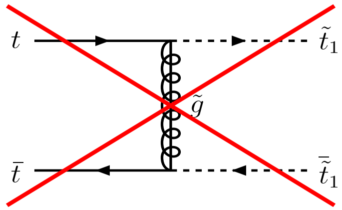

$$\hat{\sigma}_{\rm LO}[q\bar{q}] = \frac{\alpha_s^2 \pi}{s} \frac{2}{27} \beta^3 \quad (\beta^2 = 1 - 4m^2/s)$$

$\Big($ c.f. top production: $\hat{\sigma}_{\rm LO}[q\bar{q}] \approx \frac{\alpha_s^2\pi}{s}\frac{12}{27}\beta$
$\rightarrow \sigma^{\rm top}/\sigma^{\rm stop} \sim 10$ at the Tevatron $\Big)$

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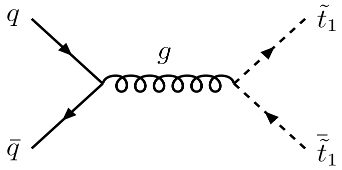

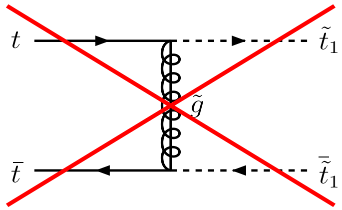

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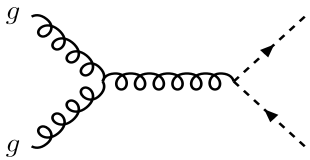
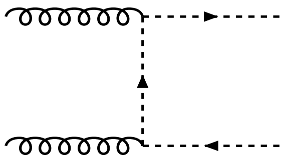
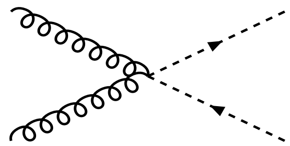
$$g + \bar{g} \to \widetilde{t}_i + \bar{\widetilde{t}}_i \quad (i = 1, 2)$$



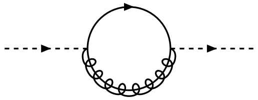


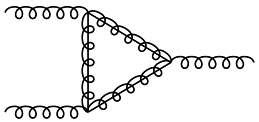


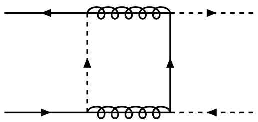
$$\hat{\sigma}_{\mathrm{LO}}[gg] = \frac{\alpha_s^2 \pi}{s} \left[\beta \left(\frac{5}{48} + \frac{31m^2}{24s} \right) + \left(\frac{2m^2}{3s} + \frac{m^4}{6s^2} \right) \log \frac{1-\beta}{1+\beta} \right]$$

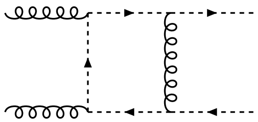
$\Rightarrow$ no MSSM parameter dependence

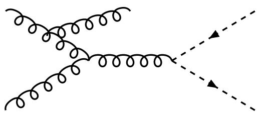
SUSY-QCD corrections

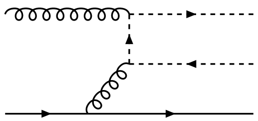
self energies:  $+ \cdots$

vertex corrections:  $+ \cdots$

box diagrams:  $+ \cdots$

 $+ \cdots$

gluon emission:  $+ \cdots$

gluon-quark scattering:  $+ \cdots$

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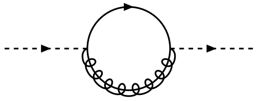
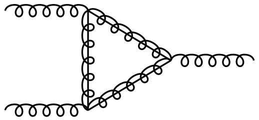
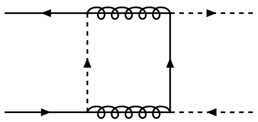
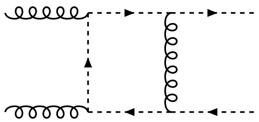
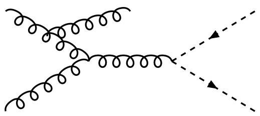
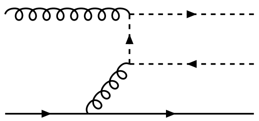
self energies:  $+\ \cdots$

vertex corrections:  $+\ \cdots$

box diagrams:  $+\ \cdots$

 $+\ \cdots$

gluon emission:  $+\ \cdots$

gluon-quark scattering:  $+\ \cdots$

- NLO cross section depends on

  squark & gluino masses

  stop mixing angle

  $\longrightarrow$ dependence numerically small

SUSY-QCD corrections

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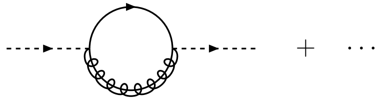

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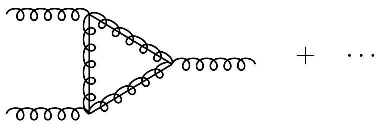

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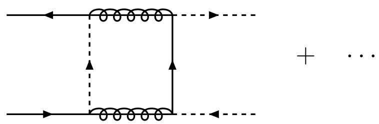

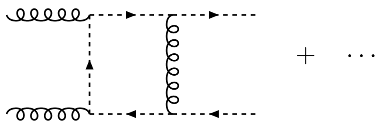

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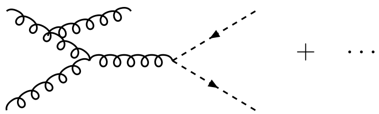

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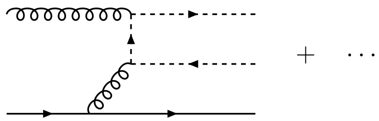

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- NLO cross section near threshold $\beta \ll 1$:

$$\sigma_{q\bar{q}} \approx \frac{\alpha_s^2(\mu^2)}{m^2}\frac{\pi}{54}\beta^3 \times \left(1 + 4\pi\alpha_s(\mu^2)\left\{-\frac{1}{48\beta} + \frac{2}{3\pi^2}\ln^2(8\beta^2) - \frac{107}{36\pi^2}\ln(8\beta^2) - \frac{2}{3\pi^2}\ln(8\beta^2)\ln\left(\frac{\mu^2}{m^2}\right)\right\}\right)$$

$$\sigma_{gg} \approx \frac{\alpha_s^2(\mu^2)}{m^2}\frac{7\pi}{384}\beta \times \left(1 + 4\pi\alpha_s(\mu^2)\left\{\frac{11}{336\beta} + \frac{3}{2\pi^2}\ln^2(8\beta^2) - \frac{183}{28\pi^2}\ln(8\beta^2) - \frac{2}{3\pi^2}\ln(8\beta^2)\ln\left(\frac{\mu^2}{m^2}\right)\right\}\right)$$

$\longrightarrow$ large NLO corrections in gg channel

SUSY-QCD corrections: results

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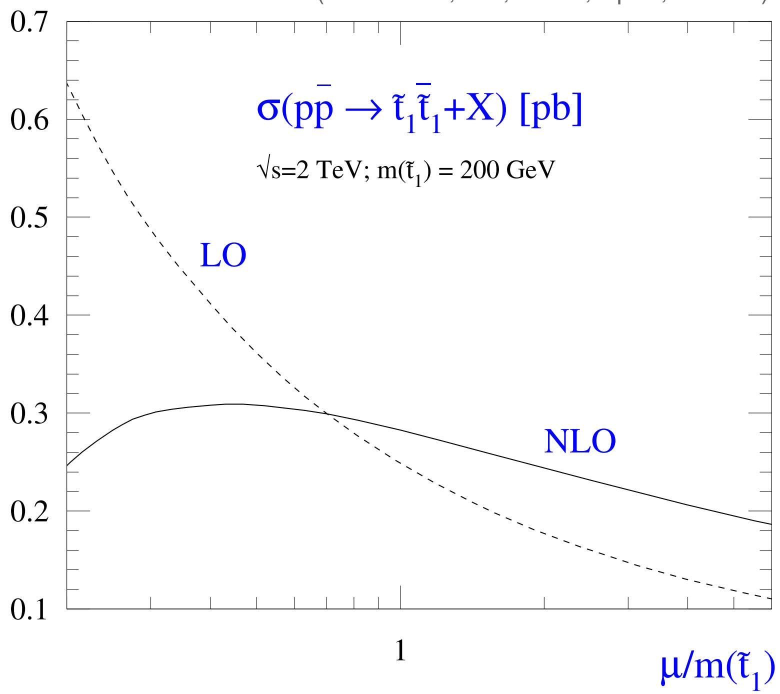
- reduced scale dependence $\lesssim 15\%$

(Beenakker, MK, Plehn, Spira, Zerwas)



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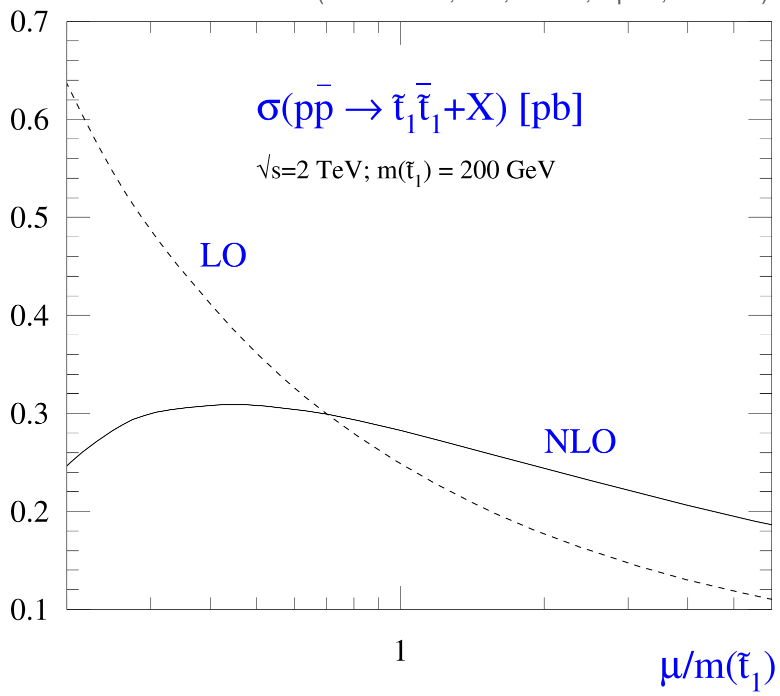
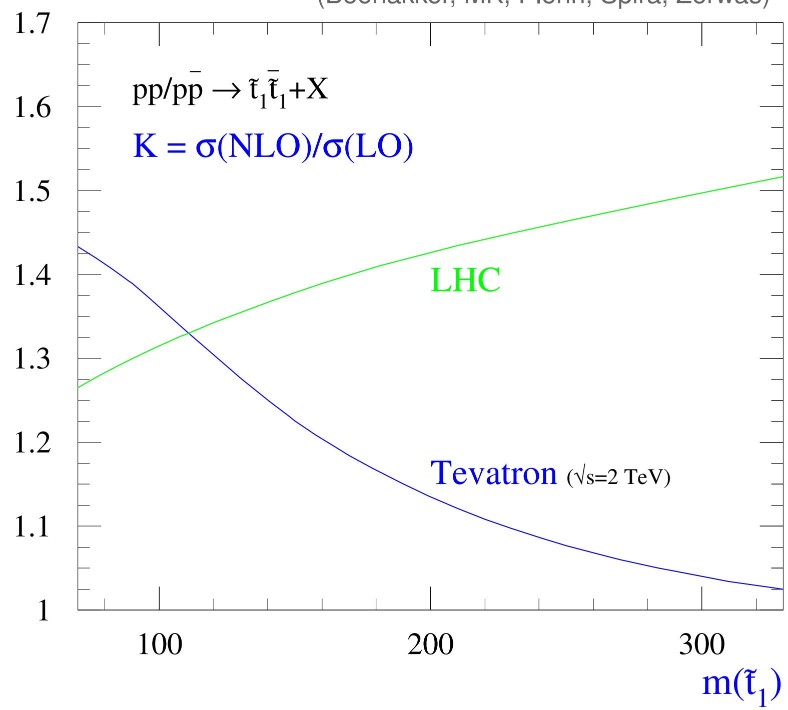


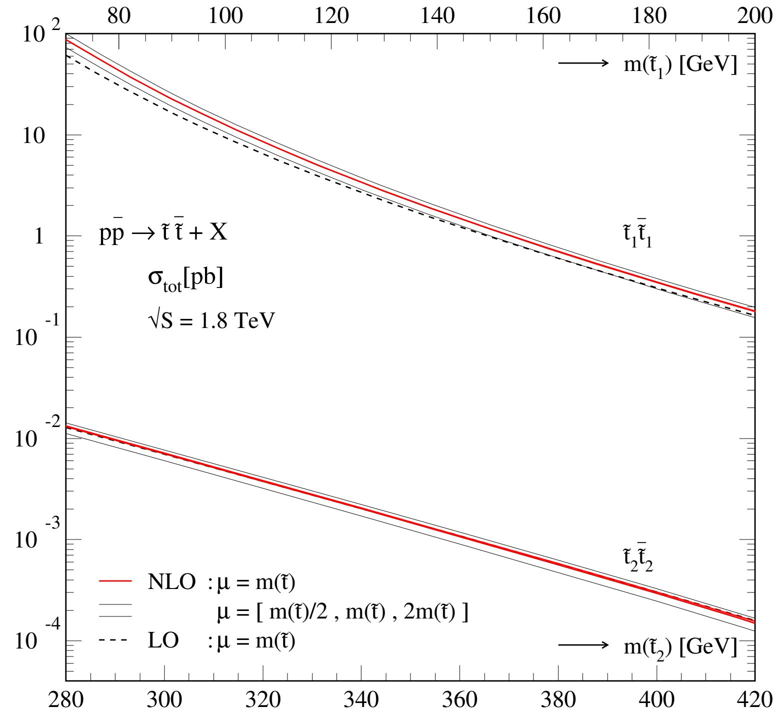
- K-faktor $K = \sigma(\mathrm{NLO})/\sigma(\mathrm{LO}) \sim 1 - 1.5$

(Beenakker, MK, Plehn, Spira, Zerwas)

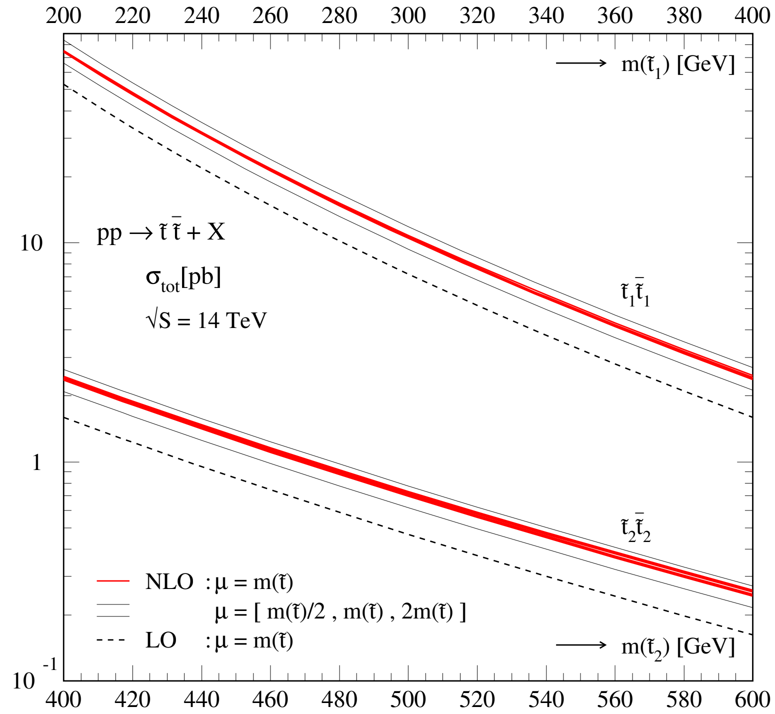


Top-squark production: NLO cross sections

- Tevatron



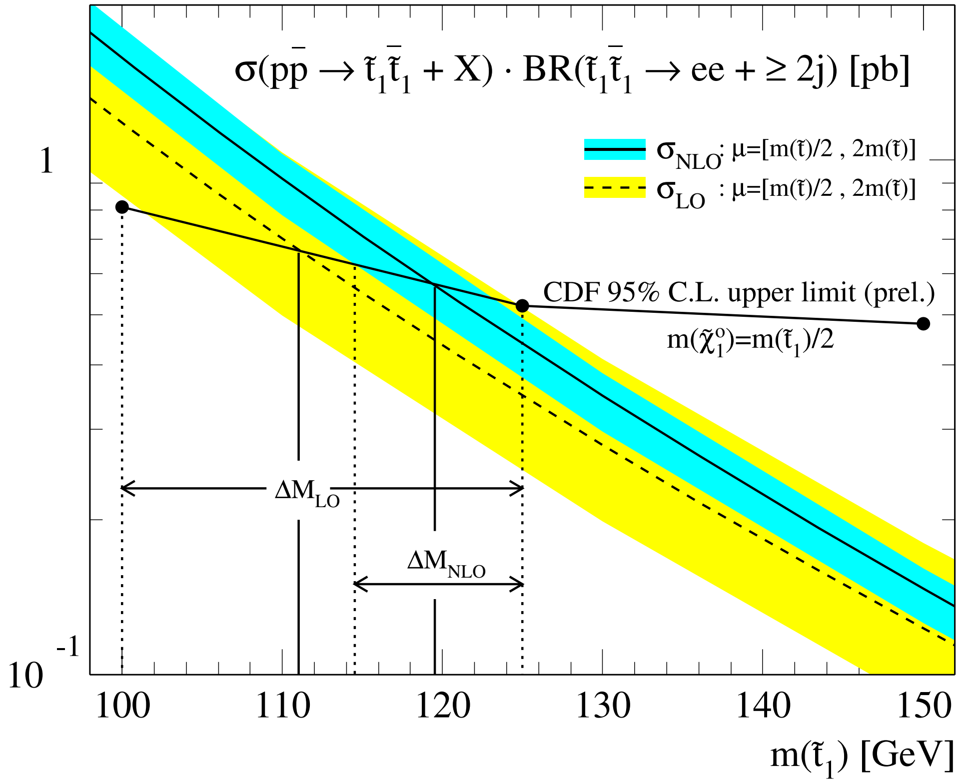
- LHC



$\longrightarrow$ small dependence on SUSY-Parameters

Top-squark searches

- Top-squark search in $e^{\pm}e^{\pm} + \geq 2j$ final startes (CDF, Phys. Rev. Lett. 83 (1999))



$$\Rightarrow M_{\tilde{t}_1} > \begin{cases} 110 \pm 15 \text{ GeV} & \text{LO} \\ 120 \pm 5 \text{ GeV} & \text{NLO} \end{cases}$$

Current project: associated $pp/p\bar{p} \longrightarrow \tilde{q}\widetilde{\chi}, \tilde{g}\widetilde{\chi}$ production

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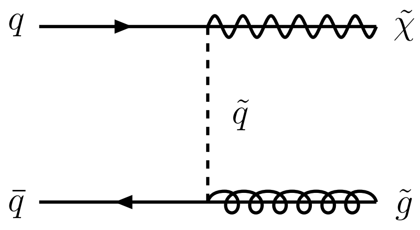

Beenakker, MK, Plehn, Spira, Zerwas; Berger, Klasen, Tait

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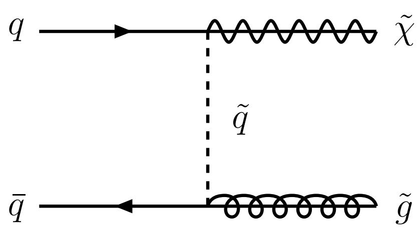

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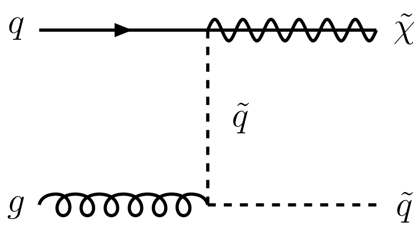
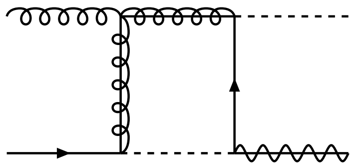
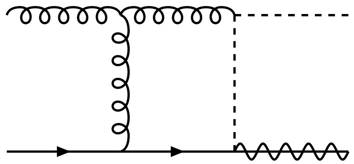


LO scale uncertainty $\mathcal{O}(100\%) \Rightarrow$ need NLO calculation

SUSY-QCD corrections



$+ \quad \cdots$



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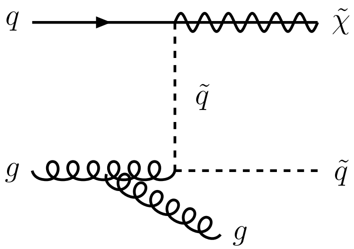

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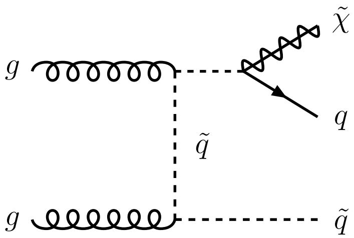

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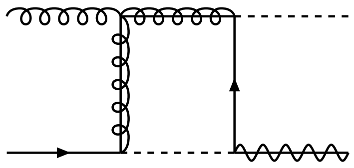

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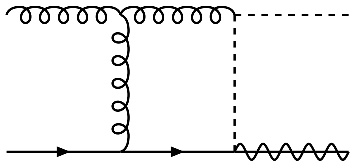

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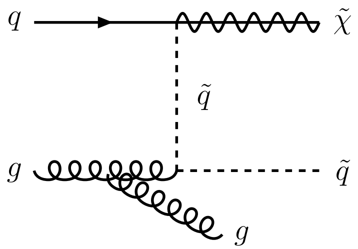

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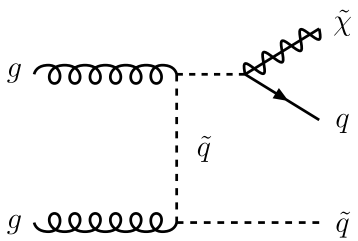


$+ \cdots$

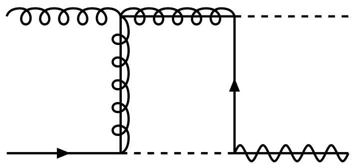
- SUSY breaking in dimensional regularization

  $\tilde{g}, \tilde{\chi}$: 2 d.o.f.

  g, γ, Z: $(n-2)$ d.o.f.

  $\longrightarrow$ restauration through finite counter terms

SUSY-QCD corrections



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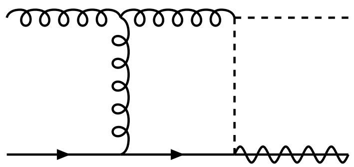

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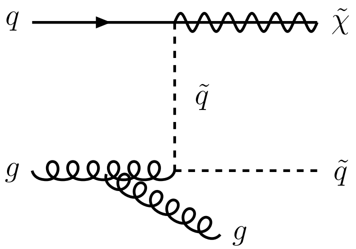

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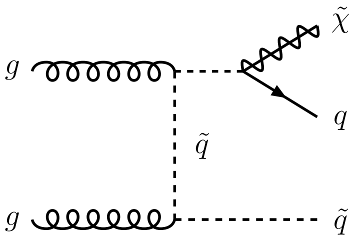


$+ \cdots$

- double counting: $gg \to \tilde{q}\bar{\tilde{q}} \to \tilde{q}\tilde{\chi}\bar{q}$ (if $m_{\tilde{q}} > m_{\tilde{\chi}}$)

$$\frac{d\sigma_{\rm res}}{dM^2} = \sigma(gg \to \tilde{q}\bar{\tilde{q}}) \frac{m_{\tilde{q}}\Gamma_{\tilde{q}}/\pi}{(M^2 - m_{\tilde{q}}^2)^2 + m_{\tilde{q}}^2\Gamma_{\tilde{q}}^2} BR(\bar{\tilde{q}} \to \chi\bar{q})$$

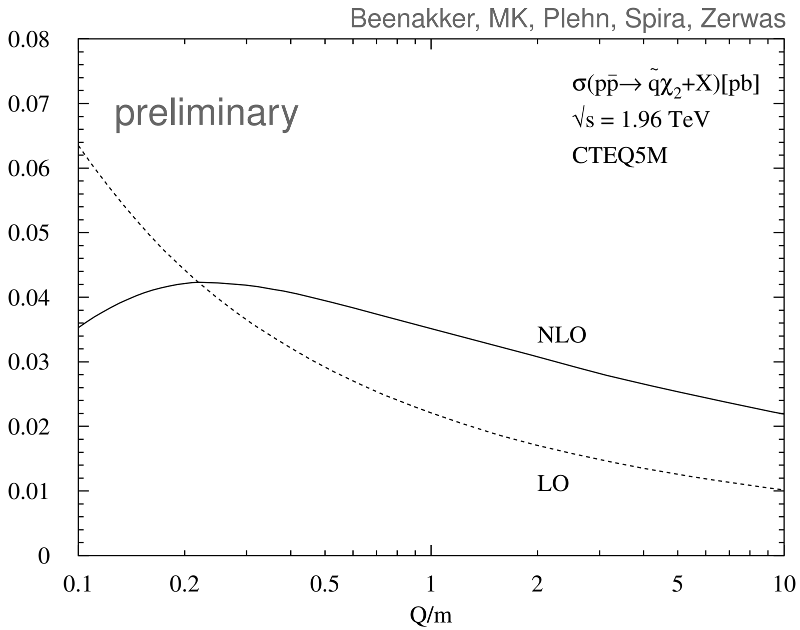
$$\longrightarrow \sigma(gg \to \tilde{q}\bar{\tilde{q}}) BR(\bar{\tilde{q}} \to \chi\bar{q}) \delta(M^2 - m_{\tilde{q}}^2)$$

$\longrightarrow$ resonance contributions to be subtracted

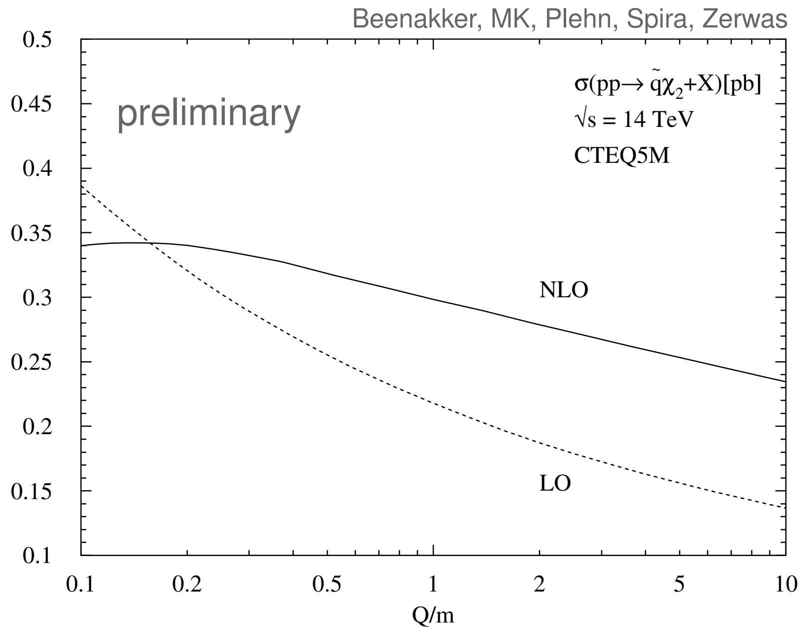
SUSY-QCD corrections: preliminary results

- reduced scale dependence

Tevatron



LHC



Summary

- NLO SUSY-QCD corrections for MSSM particle production at hadron colliders

$\longrightarrow$ public code PROSPINO (Beenakker, MK, Plehn, Spira, Zerwas)

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