

# NNLO corrections to squark - antisquark - production at the LHC

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The Standard Model (SM) has been tested to high precision.

However, many questions are still open:

- solution to hierarchy problem  
( $M_W = o(100 \text{ GeV}) \leftrightarrow M_{\text{Planck}} = o(10^{19} \text{ GeV})$ )
- window to gravity
- dark matter candidate
- CP-phases for baryon asymmetry, baryogenesis
- 19 free parameters in the SM

One solution to some of these questions is Supersymmetry (SUSY).

- symmetry between bosons and fermions
- minimal SUSY extension of SM  $\rightarrow$  MSSM

# Matter fields in the MSSM

Fermionic SM-field $s = \frac{1}{2}$	SUSY partner fields $s = 0$
up-quark $u_{L,a}$ , down-quark $d_{L,a}$	sup $\tilde{u}_{L,a}$ , sdown $\tilde{d}_{L,a}$
up-quark $u_{R,a}$	sup $\tilde{u}_{R,a}$
down-quark $d_{R,a}$	sdown $\tilde{d}_{R,a}$
electron $e_L$ , Neutrino $\nu$	selectron $\tilde{e}_L$ , sneutrino $\tilde{\nu}$
electron $e_R$	selectron $\tilde{e}_R$

$a$  :  $SU(3)$  color index

- in this talk we look at **squarks**

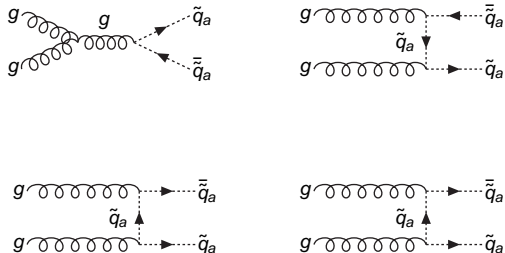
# Squark search at hadron colliders

- energy frontier: Tevatron: 1.96 TeV, LHC: 14 TeV
- present exclusion limits:
  - $m_{\tilde{g}} < 280 \text{ GeV}$ : all squark masses excluded in mSugra scenarios
  - $m_{\tilde{g}} = m_{\tilde{q}}$ :  $m_{\tilde{q}, \tilde{g}} > 392 \text{ GeV}$
  - $m_{\tilde{q}} < 400 \text{ GeV} \Rightarrow m_{\tilde{g}} > 340 \text{ GeV}$
  - Ref: T. Aaltonen *et al.* [CDF Collaboration], arXiv:0811.2512 [hep-ex].
- in mSugra models:  $m_{\tilde{g}} > m_{\tilde{q}}$ ,  
squark masses approximately degenerate, exception: stop mass (not considered here)
- hadronic cross section at hadron collider:

$$\sigma = \sum_{i,j=\text{all partons}} \text{PDF}_i \otimes \text{PDF}_j \otimes \hat{\sigma}_{ij}$$

# The contributing Feynman diagrams for $\hat{\sigma}_{ij}$

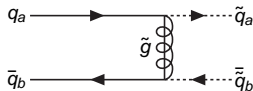
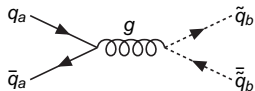
The partonic level



- $gg$  initial state produces squark antisquark pairs of identical flavor

# The contributing Feynman diagrams for $\hat{\sigma}_{ij}$

The partonic level



- $a$  and  $b$  are flavor indices
- $q_a \bar{q}_a$  as initial state allows both diagrams, for the  $s$  channel diagram, initial flavors must be equal, initial and final flavors may be different
- $q_a \bar{q}_b$  with  $a \neq b$  as initial state allows only the  $t$  channel gluino exchange, initial and final flavors are identical

- Full NLO calculation for squark and gluino production has been performed  
(W. Beenakker, R. Hopker, M. Spira and P. M. Zerwas, Nucl. Phys. B **492** (1997) 51  
[arXiv:hep-ph/9610490].)
- separate calculation exists for stop pair production  
(W. Beenakker, M. Krämer, T. Plehn, M. Spira and P. M. Zerwas, Nucl. Phys. B **515** (1998) 3  
[arXiv:hep-ph/9710451].)
- NLO calculation has been implemented in `Prospino`  
(W. Beenakker, R. Hopker and M. Spira, arXiv:hep-ph/9611232.)
- Remember also NLO corrections for heavy quark pair production  
(P. Nason, S. Dawson, and R. K. Ellis, NPB303,(1988), 607)



# The partonic cross section

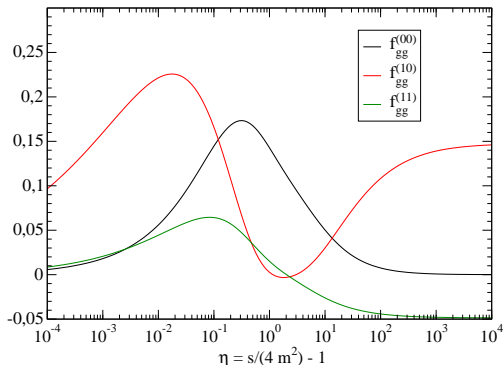
- Partonic cross section can be decomposed as

$$\hat{\sigma} = \frac{\alpha_s^2}{m_q^2} \left[ f_{00} + 4\pi\alpha_s (f_{10} + f_{11} \log(Q^2/m_q^2)) \right. \\ \left. + (4\pi\alpha_s)^2 (f_{20} + f_{21} \log(Q^2/m_q^2) + f_{22} \log^2(Q^2/m_q^2)) + \dots \right]$$

- $f_{00}$  is calculated analytically,  $f_{10}$  numerically using Prospino and then approximated by a fit function  $\rightarrow$  next slide
- scale dependent terms  $f_{11}$ ,  $f_{21}$ , and  $f_{22}$  can be calculated numerically from the previous order using RGEs, then approximated by a fit
- $f_{20}$  calculated by soft gluon resummation

# The partonic cross section

The fit function for  $f_{10}^{gg}$



- first four terms represent the leading logs and the 1st order Coulomb correction  $\Rightarrow$  the fit function is exact in the limit  $\beta \rightarrow 0$

# The partonic cross section

The fit function

$$f_{gg}^{(10)} = \frac{7n_f}{192\pi} \beta \left( \frac{3}{2} \log^2(8\beta^2) - \frac{183}{28} \log(8\beta^2) + \frac{11\pi^2}{336\beta} \right) + h(\beta)$$

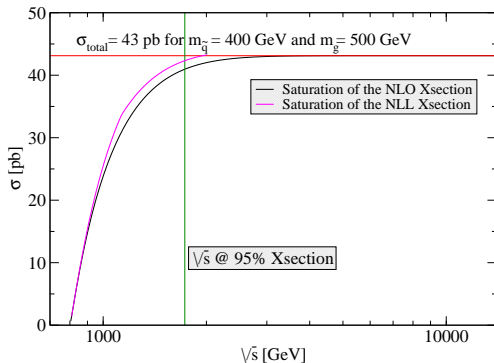
$$\begin{aligned} h(\beta) = & \beta \left[ a_1 + a_2\beta + a_3\beta^2 \log(8\beta^2) + a_4\beta^3 \log(8\beta^2) \right. \\ & + a_5 \frac{1}{\sqrt{1+\eta}} \log^2(1+\eta) + a_6 \frac{1}{\sqrt{1+\eta}} \log(1+\eta) + a_7 \frac{1}{1+\eta} \log\left(\frac{1+\beta}{1-\beta}\right) \\ & + a_8 x \log^2(\eta) + a_9 x \log(\eta) + a_{10} x^2 \log^2(\eta) + a_{11} x^2 \log(\eta) \\ & + a_{12} x^3 \log^2(\eta) + a_{13} x^3 \log(\eta) + a_{14} x^4 \log^2(\eta) + a_{15} x^4 \log(\eta) \\ & \left. + a_{16} x^5 \log^2(\eta) + a_{17} x^5 \log(\eta) \right] \end{aligned}$$

$$\beta = \sqrt{1 - \frac{4m_q^2}{s}}, \quad \eta = \frac{s}{4m_q^2} - 1, \quad x = \frac{\eta}{(1+\eta)^2}$$

# Why NNLO?

- reduce theoretical error of squark pair production cross section
- enlarge mass exclusion limits on squark masses
- need precise input data to "predict" dark matter density
  
- Full NNLO: Very complex calculation
- Particles are produced near kinematical production threshold
- Therefore: Soft gluon resummation (Tool for calculating approximated  $N^k$ LO results)

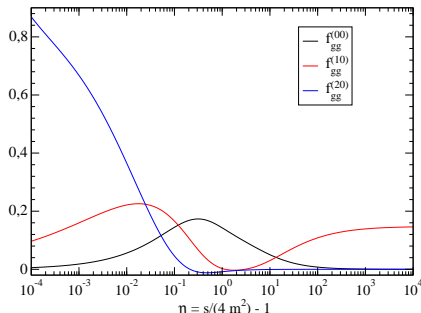
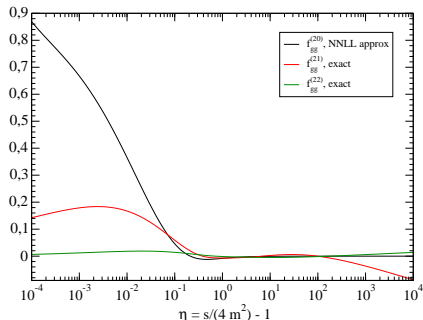
# Why does soft gluon resummation work?



preliminary

- look at which parton energies the total cross section is saturated
- 95% of the total cross section saturated at  $\approx 1700 \text{ GeV}$  cms energy
- NLL curve fits quite well

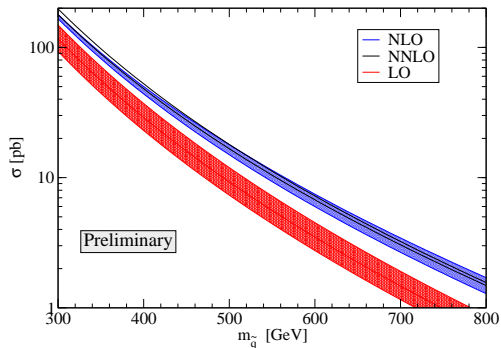
# The NNLO structure function



$$f_{gg}^{(20)} = \frac{f_{gg}^{(00)}}{\pi^4} \left[ \frac{9}{8} \log(\beta^2)^4 + a_3 \log(\beta^2)^3 + (a_2 + b_2/\beta) \log(\beta^2)^2 + (a_1 + b_1/\beta) \log(\beta^2) + \frac{b_0}{\beta} + \frac{b_{-1}}{\beta^2} \right]$$

# Results

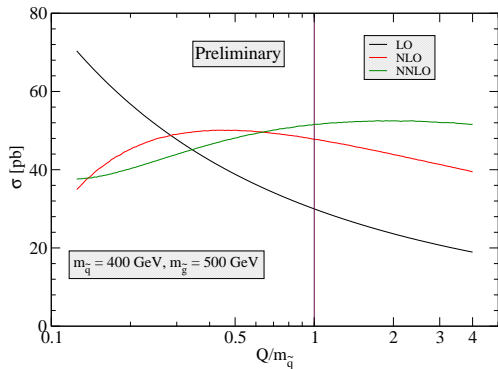
## Total cross section



- NNLO correction are about 5 – 10% of the NLO cross section
- Raising of mass bounds: 100pb 310GeV LO, 340GeV NLO, 345GeV NNLO.

# Results

## Scale dependence



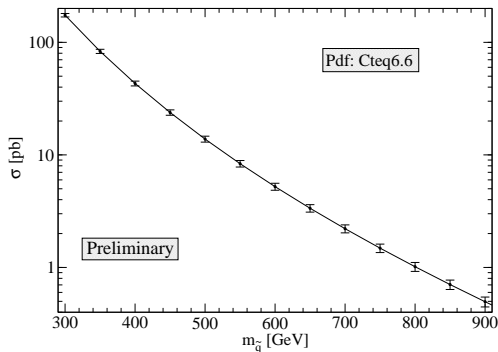
curves become flatter from  
LO  $\rightarrow$  NLO  $\rightarrow$  NNLO



# Results

## Pdf dependence

- What is the error of the total hadronic cross section due to pdf uncertainties?



PDF set: Cteq6.6(1 + 44)  
relative error due to pdf  
uncertainty increases from  
 $\approx 5\%$  at  $m_{\tilde{q}} = 300$  GeV to  
 $\approx 10\%$  at  $m_{\tilde{q}} = 1000$  GeV

- We calculated NNLO corrections for squark pair production at the LHC.
- For the NLO and NNLO structure functions, we calculated fit functions.
- We need NNLO precision for the squark pair production cross section because
  - the scale uncertainty reduces to a small error interval,
  - and the lower mass bounds for squark masses are raised.