

# Soft-gluon resummation for squark and gluino hadroproduction

Silja Brening

Institut für Theoretische Physik E, RWTH Aachen

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in collaboration with W. Beenakker, SB, M. Krämer, A. Kulesza, E. Laenen, I. Niessen  
[arXiv:0909.4481v1 [hep-ph]] and work in preparation

## 1 Introduction

## 2 Soft-gluon resummation

- Introduction
- Threshold resummation for coloured particles
- Numerical results for squark and gluino pair-production processes
- Stop pair-production

## 3 Summary

## 1 Introduction

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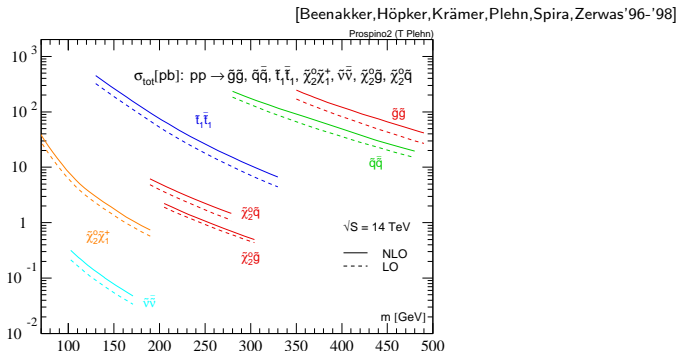
## 3 Summary

# Introduction

## SUSY particle production at hadron colliders

Framework: MSSM with R-parity conservation

LHC:



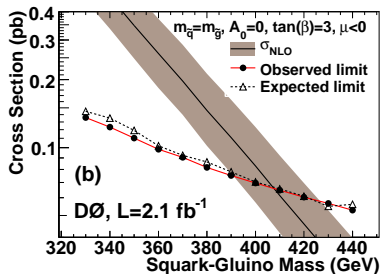
- dominated by processes involving coloured particles in the final state:  $\tilde{q}\tilde{q}, \tilde{q}\tilde{q}, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$  and  $\tilde{t}_1\tilde{t}_1$   
Note: Assume all squarks  $\tilde{q} = (\tilde{q}_L, \tilde{q}_R)$  with  $\tilde{q} \neq \tilde{t}$  mass degenerate
- total cross sections are used to determine the masses in case of discovery

# Introduction

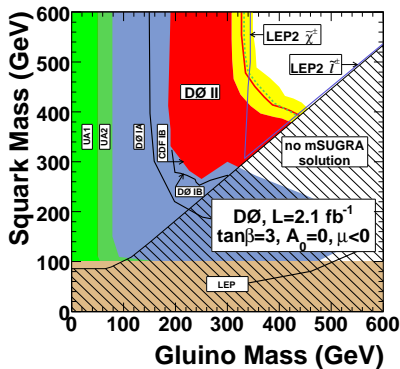
## SUSY particle production at hadron colliders

- total cross sections are used to derive exclusion limits

### Tevatron:



[DØ, PL B660, 449, '08]



⇒ precise theoretical predictions are needed

# Introduction

## Squark and gluino production at hadron colliders

- NLO SUSY-QCD corrections [Beenakker et al.'96][Beenakker et al.'97]
- NLL-resummed corrections ( $\tilde{q}\tilde{q}^*$ ,  $\tilde{g}\tilde{g}$ ) [Kulesza, Motyka '08,'09]
- combined (soft-gluon & Coulomb) NLL-resummed corrections ( $\tilde{q}\tilde{q}^*$ ) [Beneke, Falgari, Schwinn '09]
- dominant NNLO-N<sup>2</sup>LL contributions ( $\tilde{q}\tilde{q}^*$ ) [Langenfeld, Moch '09]
  
- NLO EW corrections [Beccaria et al. '07,'08][Hollik, Kollar, Trenkel '07][Hollik, Mirabella '08][Hollik, Mirabella, Trenkel '08][Mirabella '09][Germer et al. '09]
- LO EW and QCD-EW interference [Bozzi, Fuks, Klasen '05][Alan, Cankocak, Demir '07][Bornhauser et al '07][Hollik, Kollar, Trenkel '07][Hollik, Mirabella '08][Hollik, Mirabella, Trenkel '08][Germer et al. '09]
  
- bound state effects in  $\tilde{g}\tilde{g}$ -production (NLO QCD potential) [Hagiwara, Yokoya '09]
- gluinonia production and decay (NLO QCD) and energy levels (NNLO QCD potential) [Kauth et al. '09]

- large positive corrections  $K_{\text{NLO}} = \frac{\sigma_{\text{NLO}}}{\sigma_{\text{LO}}} \sim 1.0 - 1.9$   
depending on process and on  $m_q, m_g$
  - significant part can be attributed to threshold region  $\hat{s} \sim 4m^2$
  - threshold behaviour of NLO partonic cross section:  
 $\beta = \sqrt{1 - \hat{\rho}} \rightarrow 0$  with  $\hat{\rho} = \frac{4m^2}{\hat{s}}$   
$$\hat{\sigma}^{\text{NLO}} \propto \hat{\sigma}^{\text{LO}} \left\{ \frac{\alpha_s}{\pi} \left( a \log^2(\beta^2) + b \log(\beta^2) + c \log(\beta^2) \log\left(\frac{\mu^2}{m^2}\right) + d \frac{1}{\beta} \right) \right\}$$
    - logarithmic terms  $\log^i \beta^2 (i = 1, 2)$  result from soft-gluon emission and become large at threshold
    - $1/\beta$ -term: Coulomb corrections
- can be taken into account to all orders in perturbation theory by means of threshold resummation

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# Soft-gluon resummation

## Introduction

schematic perturbative expansion ( $L = \log(\beta^2)$ )

$$\begin{aligned}d\sigma &= 1 \\ &+ \alpha_s(L^2 + L + 1) \\ &+ \alpha_s^2(L^4 + L^3 + L^2 + L + 1) \\ &\vdots \\ &+ \alpha_s^n(\underbrace{L^{2n}}_{\text{LL}} + \underbrace{L^{2n-1}}_{\text{NLL}} + \dots)\end{aligned}$$

→ even for small  $\alpha_s$  convergent behaviour spoiled

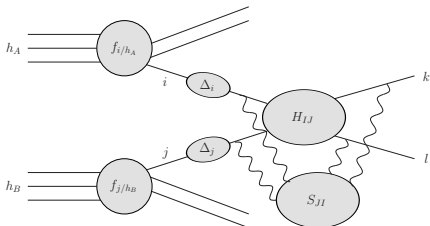
**Resummation=organisation of large logs in perturbative expansions**

$$\sigma^{\text{res}} = \sigma^{\text{LO}} \underbrace{C(\alpha_s)}_{\text{constants}} \exp\left(\underbrace{Lg_1(\alpha_s L)}_{\text{LL}} + \underbrace{g_2(\alpha_s L)}_{\text{NLL}} + \dots\right) + \text{suppressed terms}$$

- summation of these logs to all orders

# Threshold resummation for coloured particles

[Contopanagos, Kidonakis, Laenen, Oderda, Sterman '96-'98; Bonciani, Catani, Mangano, Nason '98]



schematically:

$$\hat{\sigma} = \Delta_i \Delta_j \otimes S \otimes H \xrightarrow{\text{Mellin transf.}} \hat{\sigma}_N = \underbrace{\Delta_i \Delta_j}_{\text{universal}} \overbrace{\sum_{IJ} H_{IJ} S_{JI}}^{\text{process-dependent}}$$

$$\hat{\sigma}_{ij \rightarrow kl, N}^{\text{res}} = \underbrace{\Delta_{N+1}^i \Delta_{N+1}^j}_{\text{soft-collinear (universal)}} \sum_I \hat{\sigma}_{ij \rightarrow kl, l, N}^{\text{LO}} \underbrace{\Delta_{ij \rightarrow kl, l, N+1}^S}_{\text{soft non-collinear (process-dependent)}}$$

$l$ : different colour channels

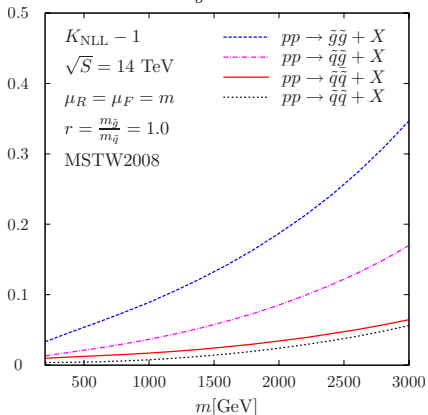
$$\sigma_{h_A h_B \rightarrow kl, N}^{\text{res}} = \sum_{i,j} f_{i/h_A}^{(N+1)} f_{j/h_B}^{(N+1)} \hat{\sigma}_{ij \rightarrow kl, N}^{\text{res}}$$

→ Calculation of  $\sigma^{\text{res}}$  up to NLL accuracy & matching with NLO:  $\sigma_{\text{NLL+NLO}}$

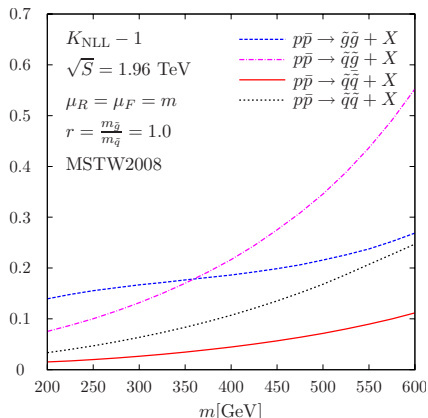
# Numerical results

for all possible squark and gluino pair-production processes

$$K_{\text{NLL}} = \frac{\sigma^{\text{NLL+NLO}}}{\sigma^{\text{NLO}}}$$



[Beenakker, SB, Krämer, Kulesza, Laenen, Niessen '09]



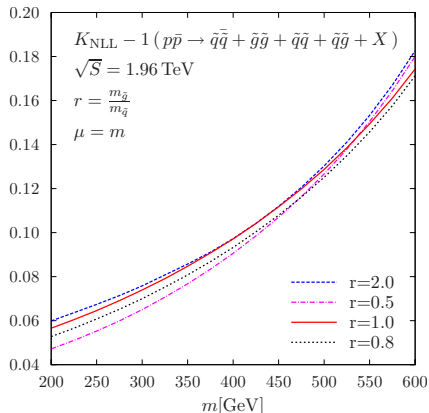
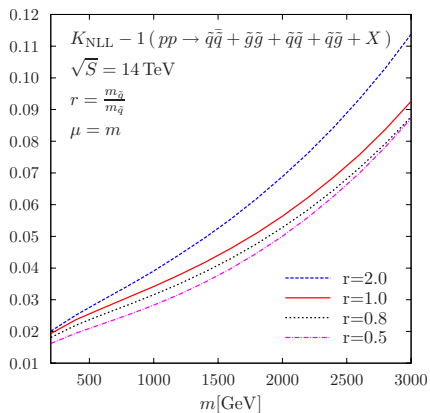
- calculated numerical results for various mass ratios:  $r=0.5..2.0$ , here shown for  $r=1.0$
- large effects for processes involving large colour charge, i.e. initial state gluons and final state gluinos

# Numerical results

for inclusive squark and gluino production

$K_{\text{NLL}}$  for  $p\bar{p}/pp \rightarrow \tilde{q}\tilde{q} + \tilde{q}\tilde{q} + \tilde{q}\tilde{g} + \tilde{g}\tilde{g} + X$

[Beenakker, SB, Krämer, Kulesza, Laenen, Niessen '09]



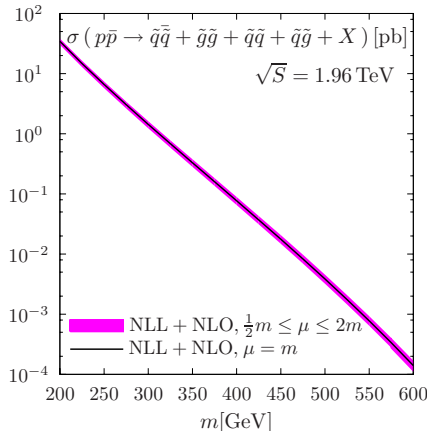
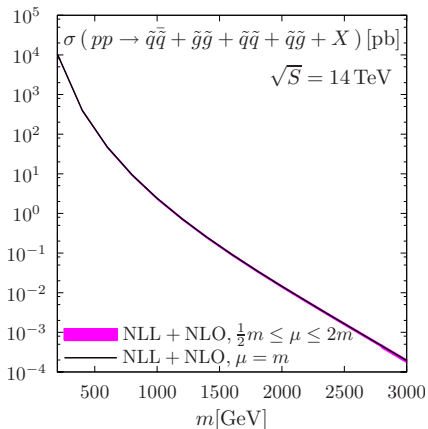
- distance from threshold on average larger at LHC than at Tevatron for shown particle masses ( $\rho_{\text{LHC}}(3\text{TeV}) \sim \rho_{\text{Tevatron}}(420\text{GeV})$ )  
 $\Rightarrow$  corrections smaller at LHC for particle masses below 3 TeV

# Numerical results

for inclusive squark and gluino production

[Beenakker, SB, Krämer, Kulesza, Laenen, Niessen '09]

NLL-resummed cross sections matched with NLO



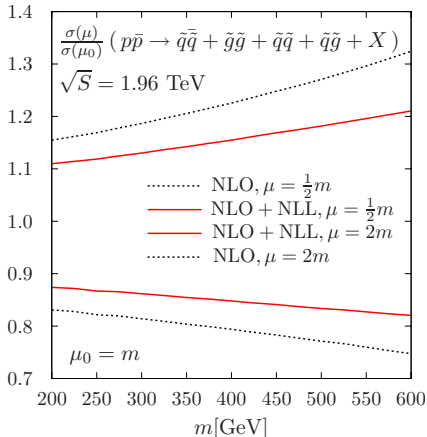
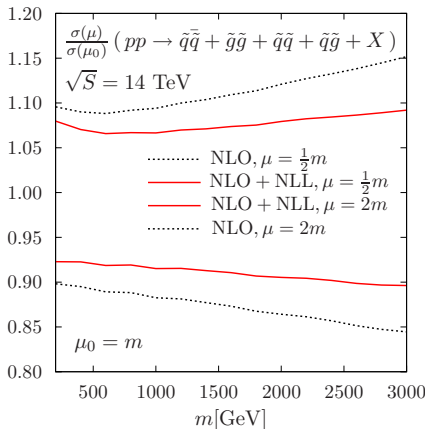
- most accurate theoretical predictions currently available

# Numerical results

for inclusive squark and gluino production

[Beenakker, SB, Krämer, Kulesza, Laenen, Niessen '09]

Scale dependence of NLL+NLO and NLO cross section for  $r=1.0$



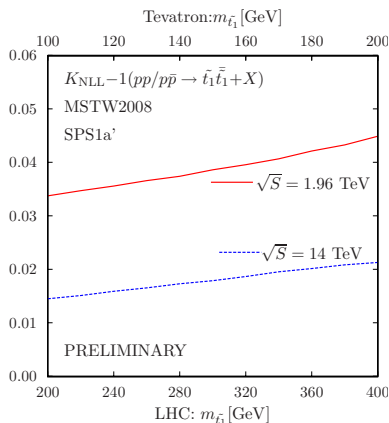
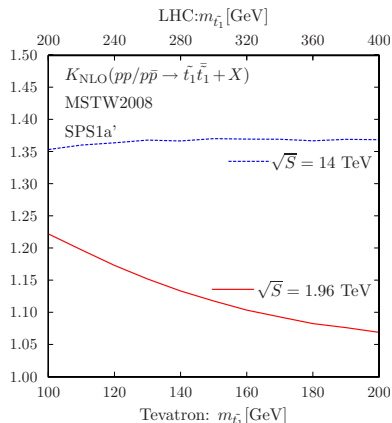
- significant reduction of theoretical uncertainty due to scale variation
- reduced scale sensitivity for each single process  $p\bar{p}/pp \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g} + X$

# Stop pair-production

- $\tilde{t} = (\tilde{t}_L, \tilde{t}_R)$  mix to form mass eigenstates  $\tilde{t}_1, \tilde{t}_2 \rightarrow$  potentially small  $m_{\tilde{t}_1}$
- $m_{\tilde{t}_1}$  crucial parameter in the electroweak baryogenesis mechanism ( $m_{\tilde{t}_1} \lesssim m_t$ )
- current limits  $m_{\tilde{t}_1} > 95.7 \text{ GeV}$  ( $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0, m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} > 10 \text{ GeV}$ ) [PDG, PL B667,1 '09]

[Beenakker et al., '97]PROSPINO

[Beenakker, SB, Krämer, Kulesza, Laenen, Niessen, in prep.]



SPS1a':  $m_{\tilde{t}_1} = 363 \text{ GeV}, m_{\tilde{t}_2} = 582 \text{ GeV}, m_{\tilde{q}} = 546 \text{ GeV}, m_{\tilde{g}} = 605 \text{ GeV}, \sin(2\Theta) = 0.926$

- MSSM parameter dependence enters only via matching with NLO (numerically small)

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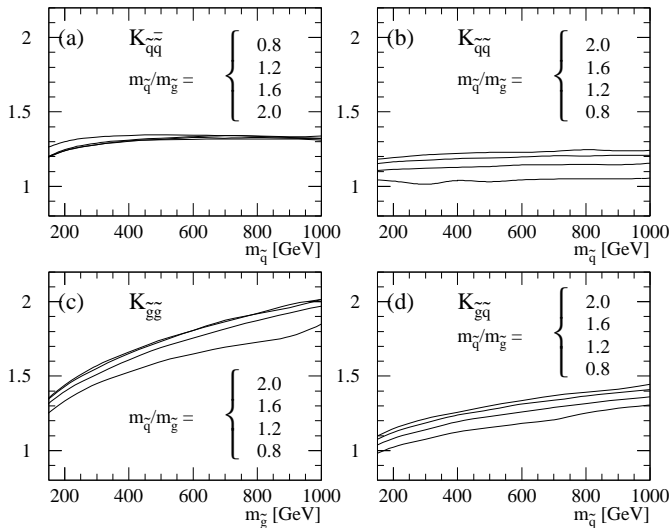


- Squark and gluino production are the most dominant channels for sparticle production at the LHC
  - NLL+NLO matched predictions for total cross sections for all possible squark and gluino pair-production processes at the Tevatron and the LHC
    - significant enhancement of NLO cross section predictions
    - most pronounced for processes involving large colour charge: gluons in the initial state and gluinos in the final state
    - $\sim 40\%$  at the Tevatron for  $\tilde{q}\tilde{g}$  and  $m=500$  GeV
    - $\sim 35\%$  at the LHC for  $\tilde{g}\tilde{g}$  and  $m=3$  TeV
    - significant reduction of the theoretical error due to scale variation
- should be used to interpret current and future searches for SUSY at the Tevatron and the LHC

# Numerical results

NLO SUSY-QCD calculation

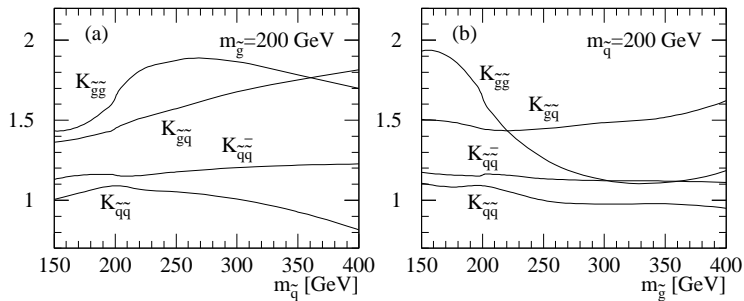
[Beenakker et al. '06]



# Numerical results

NLO SUSY-QCD calculation

[Beenakker et al. '06]



# Matching with NLO

- matching of NLL-resummed with NLO

$$\begin{aligned}\sigma_{h_A h_B \rightarrow kl}^{\text{NLL+NLO}}(\rho, m^2, \mu_F^2, \mu_R^2) &= \overbrace{\sum_{i,j} \int_{C-i\infty}^{C+i\infty} \frac{dN}{2\pi i} \rho^{-N} f_{i/h_A}^{(N+1)}(\mu_F^2) f_{j/h_B}^{(N+1)}(\mu_F^2)}^{\text{inv. Mellin transf.}} \\ &\times \left[ \hat{\sigma}_{ij \rightarrow kl, N}^{\text{res}}(m^2, \mu_F^2, \mu_R^2) - \hat{\sigma}_{ij \rightarrow kl, N}^{\text{res}}(m^2, \mu_F^2, \mu_R^2) \Big|_{(\text{NLO})} \right] \\ &+ \sigma_{h_A h_B \rightarrow kl}^{\text{NLO}}(\rho, m^2, \mu_F^2, \mu_R^2)\end{aligned}$$

with  $\rho = \frac{4m^2}{s}$

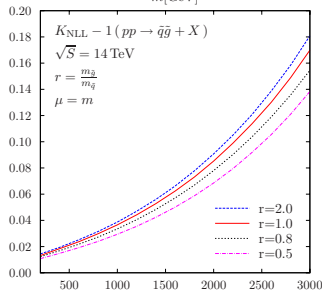
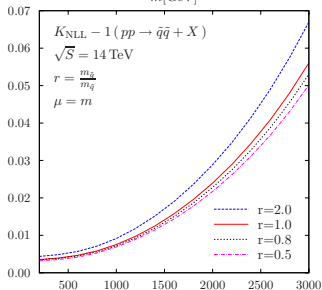
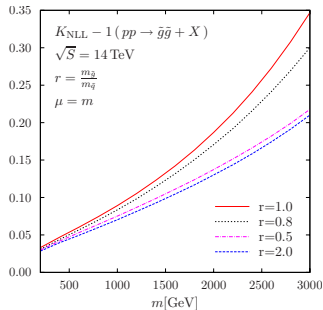
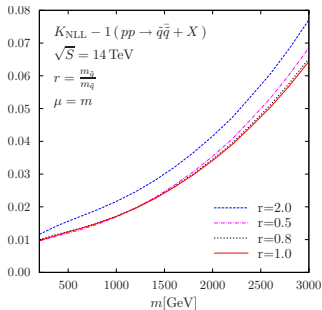
- NLO cross section calculated with PROSPINO

[Beenakker, Höpker, Krämer, Plehn, Spira, Zerwas, '96-'98]

# Numerical results

 $K_{\text{NLL}}$ 

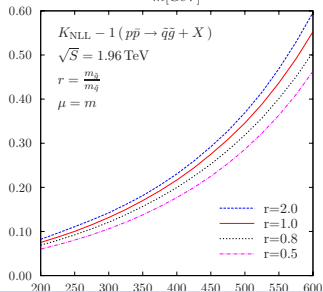
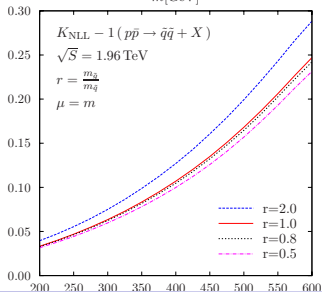
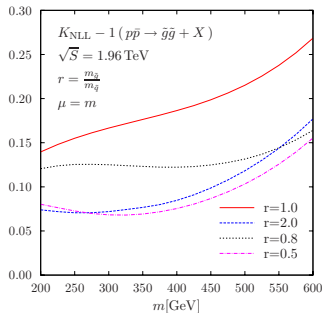
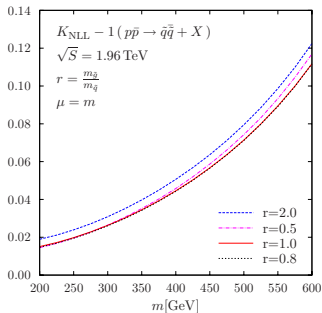
[Beenakker, SB, Krämer, Kulesza, Laenen, Niessen '09]



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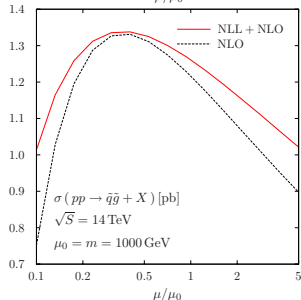
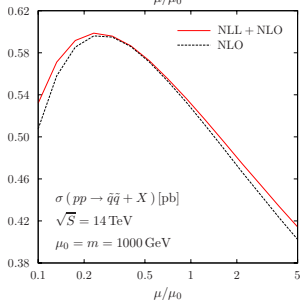
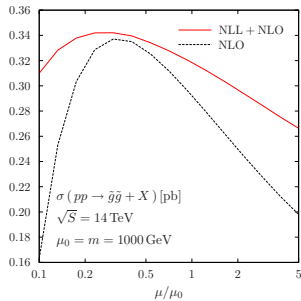
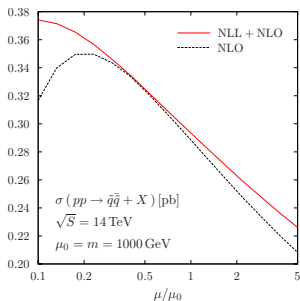
[Beenakker, SB, Krämer, Kulesza, Laenen, Niessen '09]



# Numerical results

## Scale variation

[Beenakker, SB, Krämer, Kulesza, Laenen, Niessen '09]



# Numerical results

## Scale variation

[Beenakker, SB, Krämer, Kulesza, Laenen, Niessen '09]

