Soft gluon resummation for squark and gluino hadroproduction

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PHYSICS AT THE TERA SCALE
Helmholtz Alliance

AK and L. Motyka, Phys. Rev. Let. **102**, 111802 (2009)

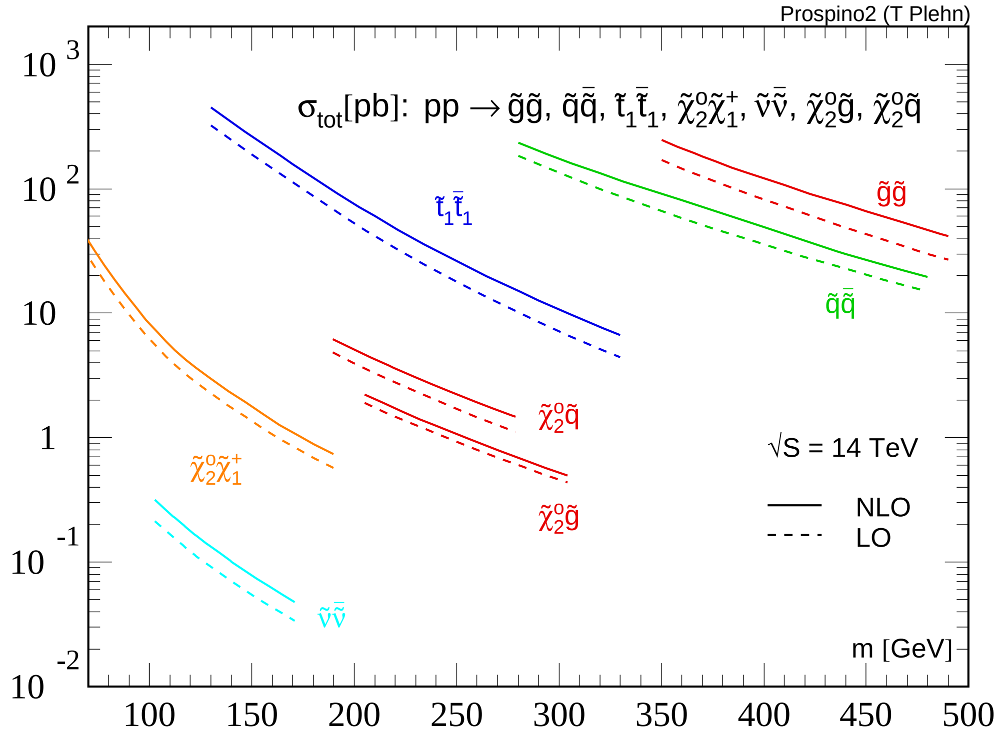
AK and L. Motyka, arXiv:0905.4749 [hep-ph], to appear in Phys. Rev. D

W. Beenakker, S. Brensing, M. Krämer, AK, E. Laenen and I. Niessen, arXiv:0909.4418 [hep-ph]

Theory Workshop, DESY Hamburg, 29 September - 2 October 2009

SUSY particle pair-production at the LHC

- MSSM: minimal content of SUSY particles + $R-$parity conservation
- At the LHC dominant sparticle production channels involve squarks ($\tilde{q}$) and gluinos ($\tilde{g}$) in the final state ($\tilde{q}\bar{\tilde{q}}$, $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$, $\tilde{g}\tilde{g}$ pairs)

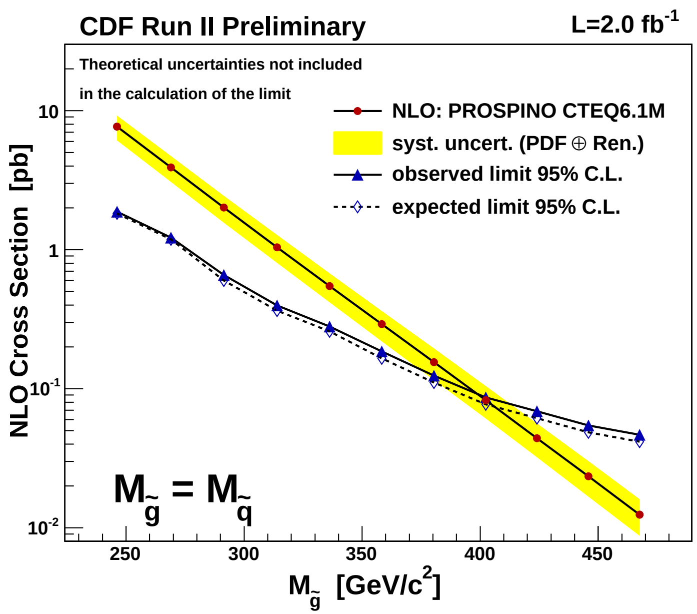


[Plehn, Prospino2]

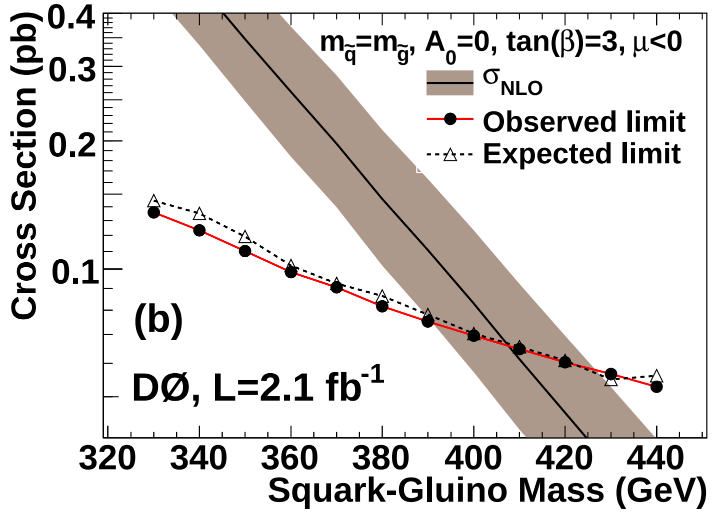
- Production cross sections large ⇒ “easy” SUSY discovery

Total cross sections

- Total cross sections: crucial for exclusion limits / useful for mass determination in case of discovery



$(A_0 = 0, sgn(\mu) = -1, \tan\beta = 5)$



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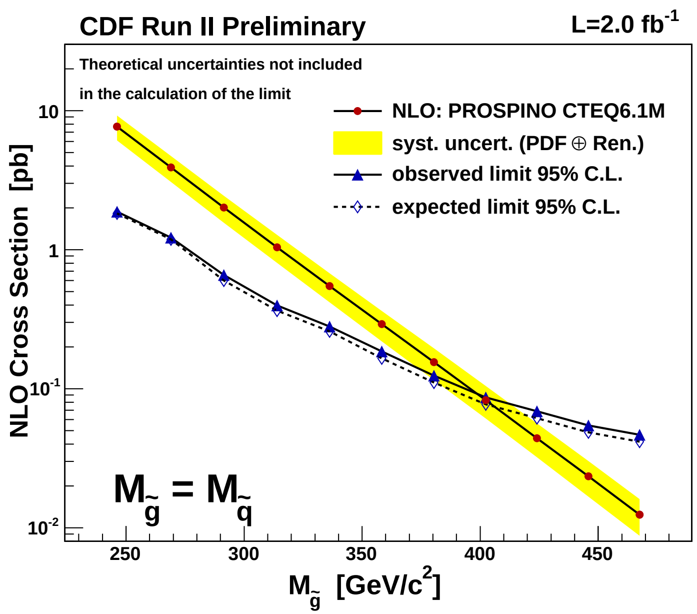

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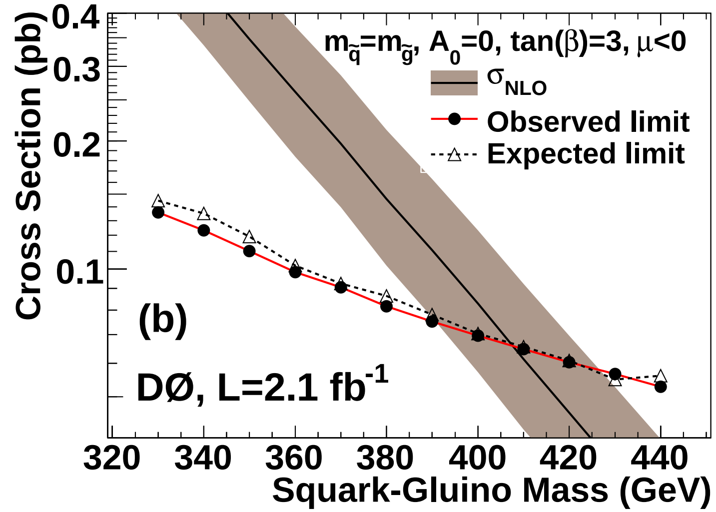

- Important to know total cross sections with high precision

Theoretical status

- Leading order = $\mathcal{O}(\alpha_s^2)$ [*Kane, Leveille'82*][*Harrison, Llewellyn Smith'84*][*Dawson, Eichten, Quigg'85*]
- Higher-order corrections to $\mathcal{O}(\alpha_s^2)$ processes
  - NLO SUSY-QCD corrections $\longrightarrow \mathcal{O}(\alpha_s^3)$ [*Beenakker, Höpker, Spira, Zerwas'96*]
  - This talk: NLL threshold resummed corrections
  - For $\tilde{q}\bar{\tilde{q}}$ production:
    - dominant NNLO contributions (NNLL-NNLO, Coulomb, scale dependence) $\longrightarrow \mathcal{O}(\alpha_s^4)$ [*Langenfeld, Moch'09*]
    - resummation of Coulomb and threshold corrections [*Beneke, Falgari, Schwinn'09*]
  - EW corrections $\longrightarrow \mathcal{O}(\alpha_s^2\alpha)$ [*Hollik, Kollar, Trenkel'07*][*Hollik, Mirabella'08*][*Hollik, Mirabella, Trenkel'08*][*Beccaria et al.'08*][*Mirabella'09*][*Germer et al.'09*]

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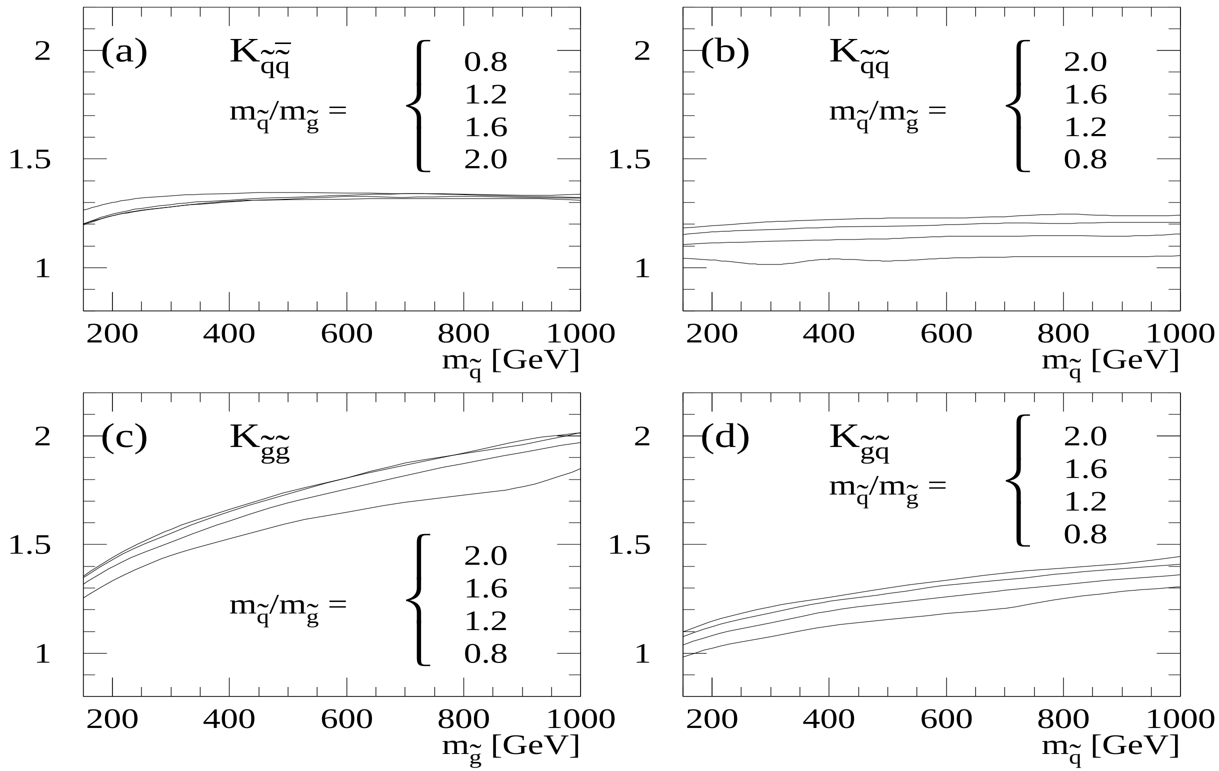
- Tree-level EW effects of $\mathcal{O}(\alpha\alpha_s)$ and $\mathcal{O}(\alpha^2)$
  - QCD-EW interference and photon-induced contributions, tree-level EW [Bornhauser et al.'07] [Alan, Cankocak, Demir'07][Hollik, Kollar, Trenkel'07][Hollik, Mirabella'08][Hollik, Mirabella, Trenkel'08][Bozzi, Fuks, Klasen'05][Germer et al.'09]

Coloured sparticle production at NLO (SUSY-QCD)

[*Beenakker, Höpker, Spira, Zerwas'96*]

$$K_{ij} = \sigma_{ij}^{\rm NLO}/\sigma_{ij}^{\rm LO}$$



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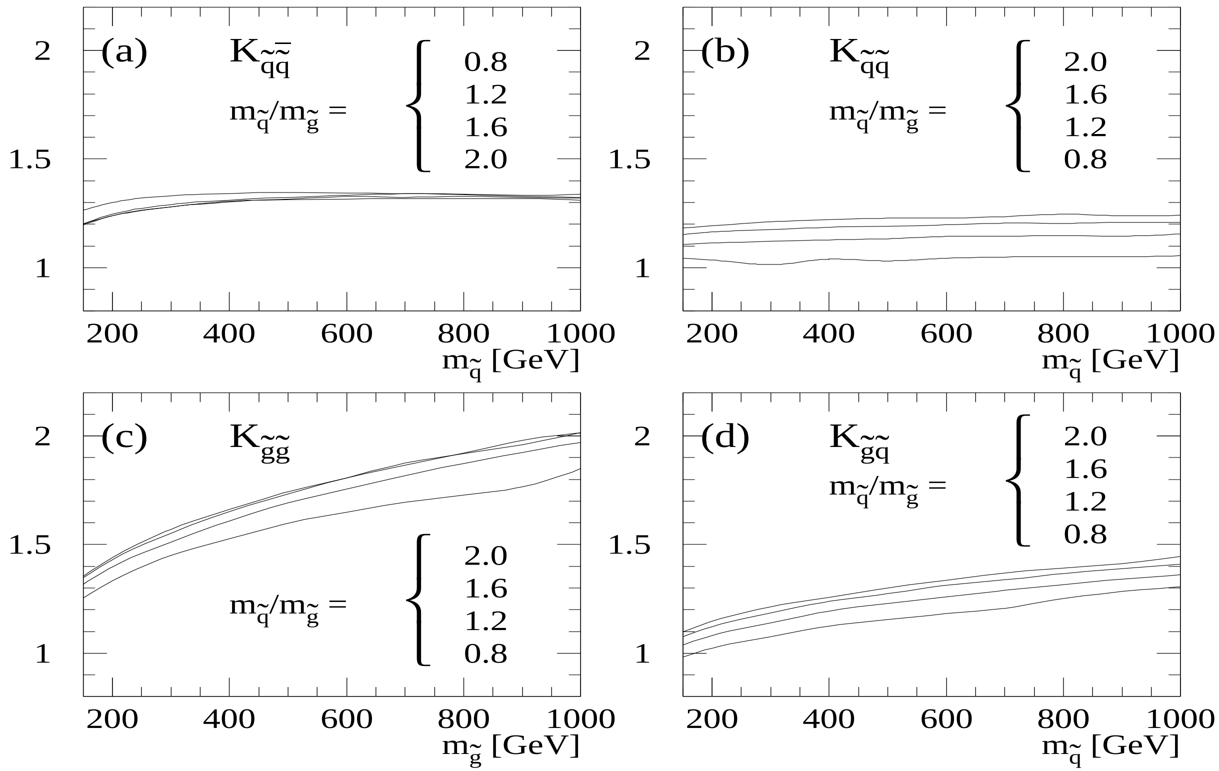

$\Rightarrow$ Significant NLO SUSY-QCD corrections (can be $\sim 100\%$!)

Note: assume all squarks ($\tilde{q}_L$,$\tilde{q}_R$) mass degenerate; no final state stops $\Rightarrow$

[*Beenakker, Krämer, Plehn, Spira, Zerwas'98*]

Higher-order soft gluon effects

- Large masses of squarks and gluons
  $\Rightarrow$ often production close to threshold $\hat{s} \sim 4m^2$ ($m = \frac{m_{\tilde{q}}+m_{\tilde{g}}}{2}$ for $\tilde{q}\tilde{g}$ production)
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- At n-th order in $\alpha_{\rm s}$ (wrt. LO) soft gluon contributions of the form

$$\alpha_{\rm s}^n \log^m(\beta^2),\ m \leq 2n \qquad\qquad \beta^2 = 1 - \frac{4m^2}{\hat{s}}$$

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    $\rightarrow$ expect large contributions from soft gluon radiation

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In the limit of $\beta \to 0$ convergence of fixed-order expansion spoiled

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$$+ \alpha_s \Big(c_{12} \log^2 (\beta^2) + c_{11} \log (\beta^2) + c_{10} \Big) \quad \longleftarrow \text{NLO}$$

$$+ \alpha_s^2 \Big(c_{24} \log^4 (\beta^2) + c_{23} \log^3 (\beta^2) + c_{22} \log^2 (\beta^2) + \ldots \Big) \quad \longleftarrow \text{NNLO}$$

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$$LL \qquad NLL \qquad NNLL \qquad \ldots \qquad\qquad L = \log(\ldots)$$

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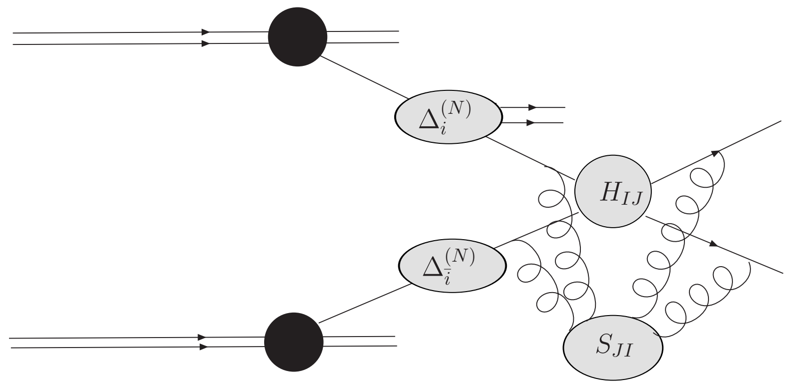
- Threshold corrections exponentiate in the space of Mellin moments taken wrt. $z \equiv \frac{4m^2}{\hat{s}} = 1 - \beta^2$ [Sterman'87][Catani,Trentadue'89]

$$f^{(N)} = \int_0^1 dz\, z^{N-1} f(z) \qquad \Rightarrow \qquad \log(\beta^2) = \log(1-z) \longleftrightarrow \log(N)$$

Resummation for $2 \rightarrow 2$ with colour and masses

$2 \longrightarrow 2$ with colour flow [Kidonakis, Sterman'96-97][Kidonakis, Oderda, Sterman'98][Bonciani et al.'03]



$$\hat{\sigma}^{(\mathrm{res},N)}_{ij\to kl} = \underbrace{H^{(N)}_{ij\to kl,IJ}}_{\text{hard function}} \times \underbrace{\Delta_i^{(N)}\Delta_j^{(N)}}_{\text{soft-collinear radiation}} \times \underbrace{S^{(N)}_{ij\to kl,JI}}_{\text{soft wide-angle emission}}$$

hard function: process-dependent

soft-collinear radiation: universal factors; KNOWN; exponential factor

soft wide-angle emission: process-dependent; exponential factor

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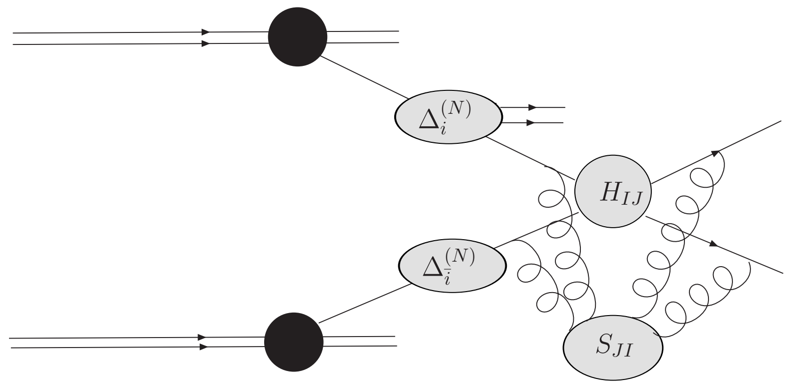

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- The soft function S given by a solution of renormalization group equation

$$\left(\mu\frac{\partial}{\partial\mu} + \beta(g)\frac{\partial}{\partial g}\right) S^{(N)}_{JI} = -\Gamma^{\dagger}_{JK} S^{(N)}_{KI} - S^{(N)}_{JL}\Gamma_{LI}$$

$\longrightarrow$ soft anomalous dimension matrices Γ to be calculated

Anomalous dimensions

- Need 1-loop anomalous dimension matrices in order to resum up to NLL
  - massless $2 \to n$ QCD processes [*Kidonakis, Oderda, Sterman'98*][*Bonciani et al.'03*][*Mert Aybat, Dixon, Sterman'06*]
  - massive case: heavy quark $Q\bar{Q}$ production [*Kidonakis, Sterman'96*][*Bonciani et al.'98*]
- Calculation of 1-loop soft anomalous dimension matrices Γ_{IJ} for $2 \to 2$ processes with nontrivial colour structure and massive particles in the final state

$$
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\tilde{q}\bar{\tilde{q}} & \mathbf{3} \otimes \bar{\mathbf{3}} & = & \mathbf{1} \oplus \mathbf{8} \\
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- Threshold limit $\hat{s} \to 4m^2$
  - Γ_{IJ} matrices calculated in the s-channel colour basis become diagonal
  - Up to NLL, in the threshold limit the resummed partonic cross section becomes

$$\tilde{\sigma}^{(\mathrm{res},N)}_{ij\to kl} = \sum_I \tilde{\sigma}^{(0,N)}_{ij\to kl,I}\, \Delta_i^{(N)}\, \Delta_j^{(N)}\, \Delta^{(\mathrm{soft},N)}_{ij\to kl,I}$$

$$\Delta^{(\mathrm{soft},N)}_{ij\to kl,I} = \exp\left[\int_\mu^{Q/N} \frac{dq}{q}\, \frac{\alpha_s(q)}{\pi}\, D_{ij\to kl,I}\right], \quad D_{ij\to kl,I} = \lim_{\beta\to 0} \frac{\pi}{\alpha_s}\, 2\,\mathrm{Re}\,(\bar{\Gamma}_{II})$$

Resummation-improved NLL+NLO total cross section

NLL resummed expression has to be matched with the full NLO result

$$\sigma^{(\mathrm{match})}_{h_1 h_2 \to kl}(\rho, m^2, \{\mu^2\}) = \sum_{i,j=q,\bar{q},g} \int_{C_{\mathrm{M}P}-i\infty}^{C_{\mathrm{M}P}+i\infty} \frac{dN}{2\pi i}\, \rho^{-N}\, f^{(N+1)}_{i/h_1}(\mu_F^2)\, f^{(N+1)}_{j/h_2}(\mu_F^2)$$

$$\times \left[\hat{\sigma}^{(\mathrm{res},N)}_{ij\to kl}(m^2, \{\mu^2\}) - \hat{\sigma}^{(\mathrm{res},N)}_{ij\to kl}(m^2, \{\mu^2\}) \Big|_{\mathrm{NLO}} \right]$$

$$+ \quad \sigma^{\mathrm{NLO}}_{h_1 h_2 \to kl}(\rho, m^2, \{\mu^2\}),$$

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- Inverse Mellin transform evaluated using a contour in the complex N space according to 'Minimal Prescription' [Catani, Mangano, Nason Trentadue'96]
- NLO cross sections evaluated with publicly available code PROSPINO

[Beenakker, Hoepker, Krämer, Plehn, Spira, Zerwas]

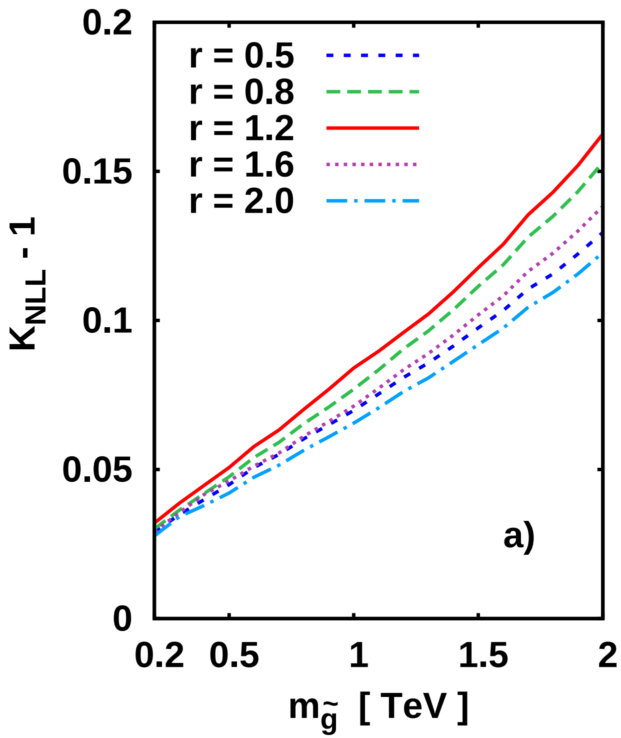
[Plehn, http://www.ph.ed.ac.uk/ tplehn/prospino/]

The NLL K-factors at the LHC

[*AK, Motyka'08*]

$$\mathrm{K}^{\mathrm{NLL}} - 1 = \frac{\sigma^{\mathrm{match}} - \sigma^{\mathrm{NLO}}}{\sigma^{\mathrm{NLO}}}$$

$pp \longrightarrow \tilde{g}\tilde{g}$



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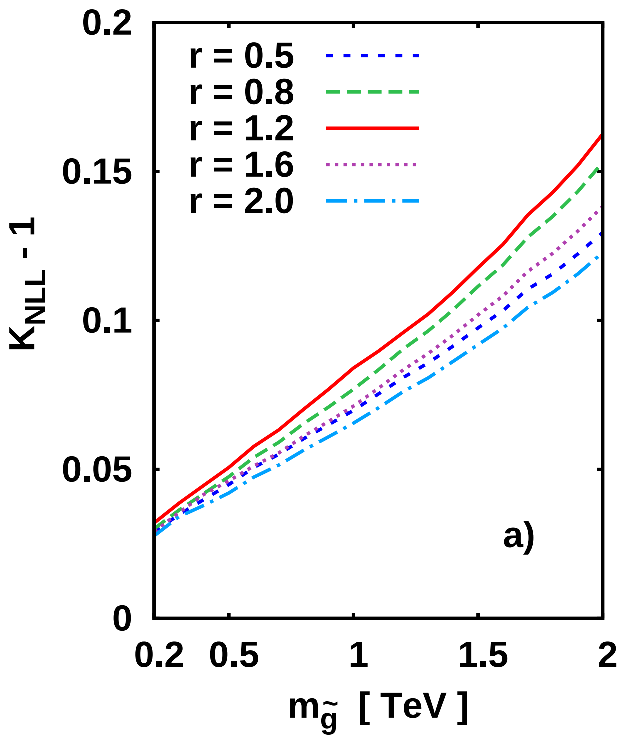

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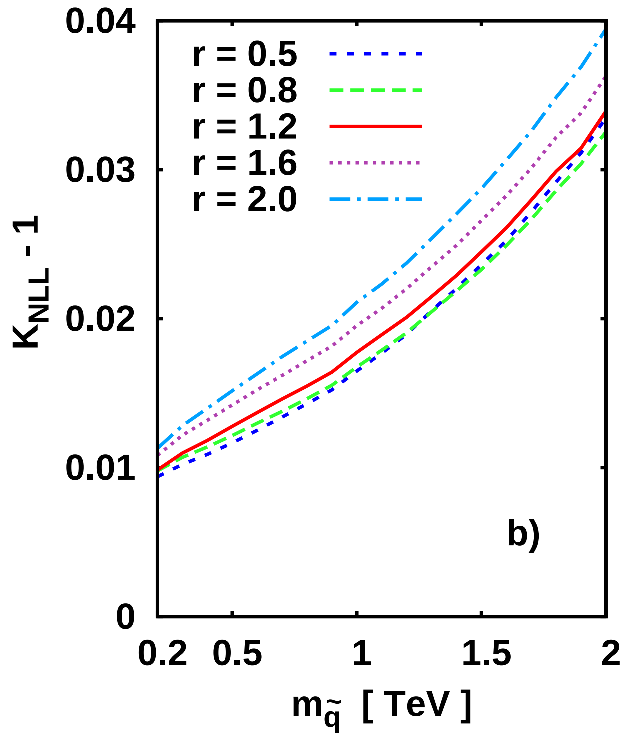

$r = \frac{m_{\tilde{g}}}{m_{\tilde{q}}}$, $\mu_F = \mu_R = m$, CTEQ6M pdfs

The NLL K-factors at the LHC cntd.

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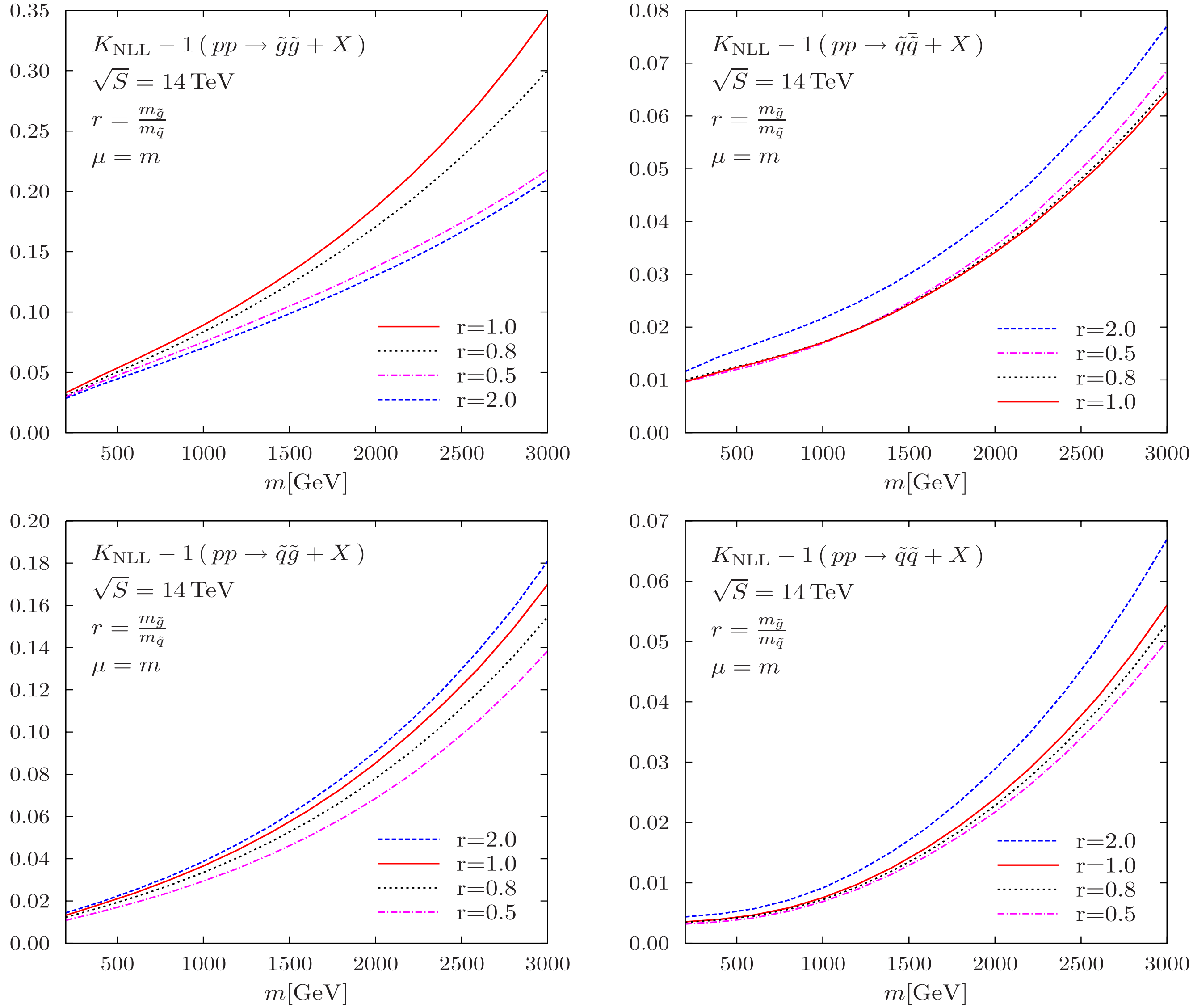

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The NLL K-factors at the Tevatron

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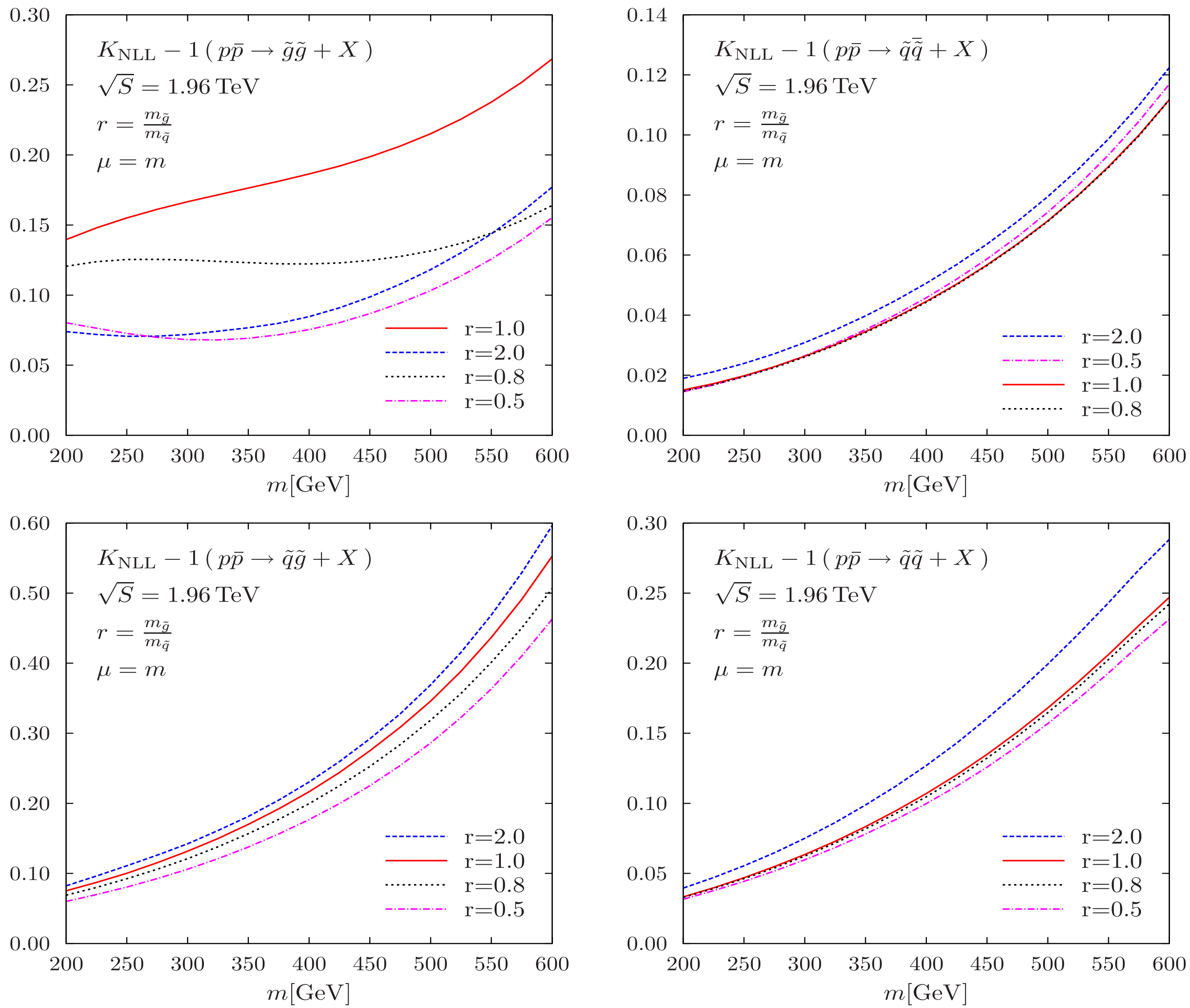

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Squark and gluino production at hadron colliders

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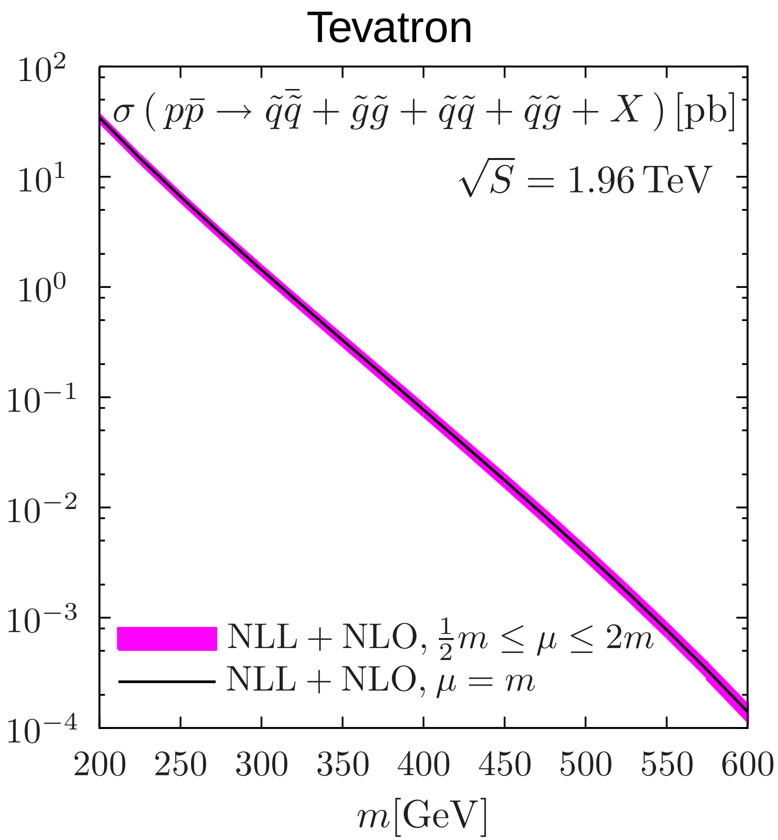

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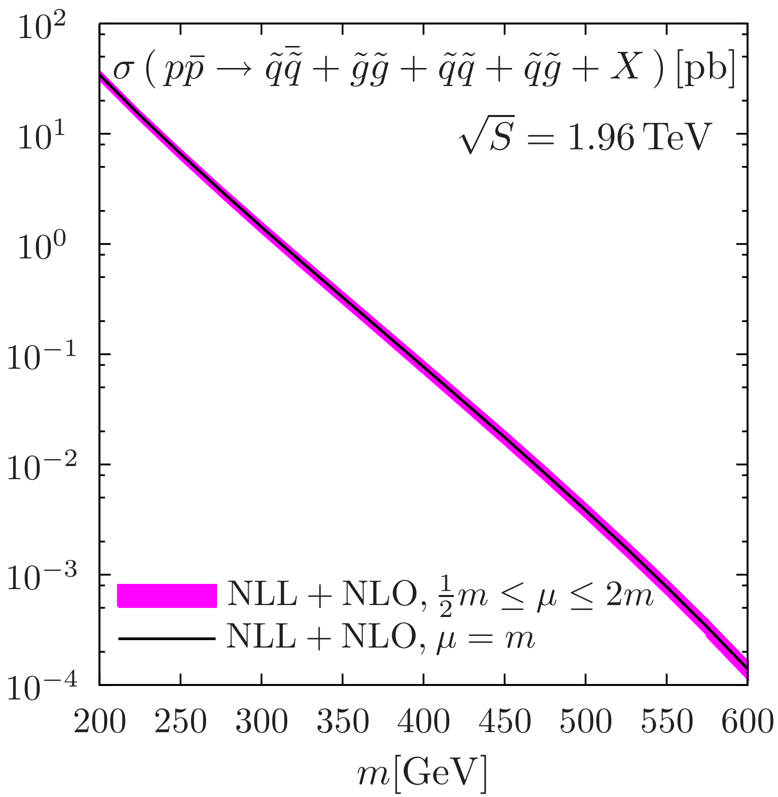
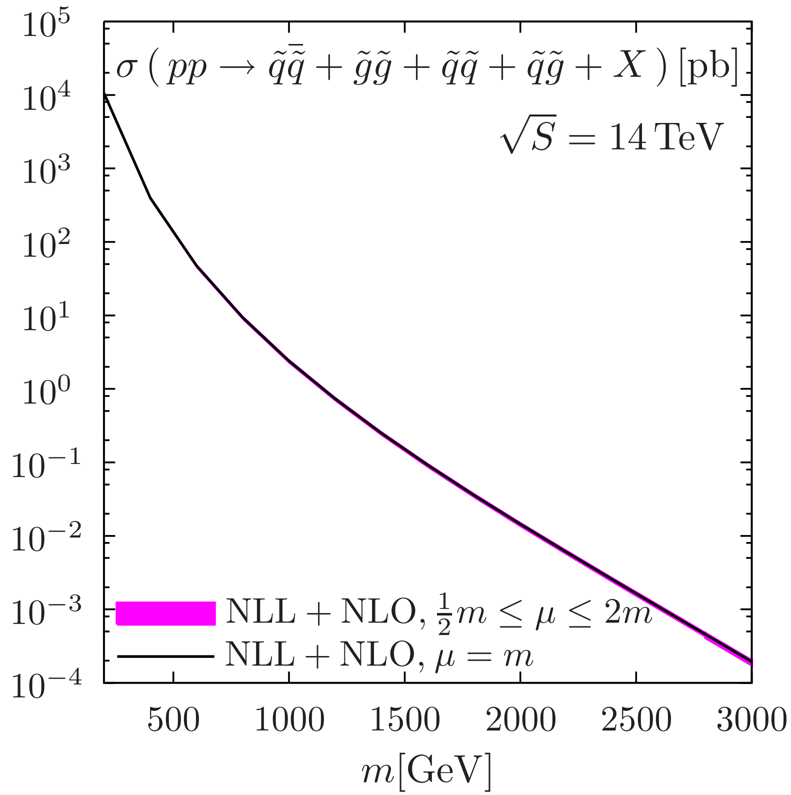


LHC

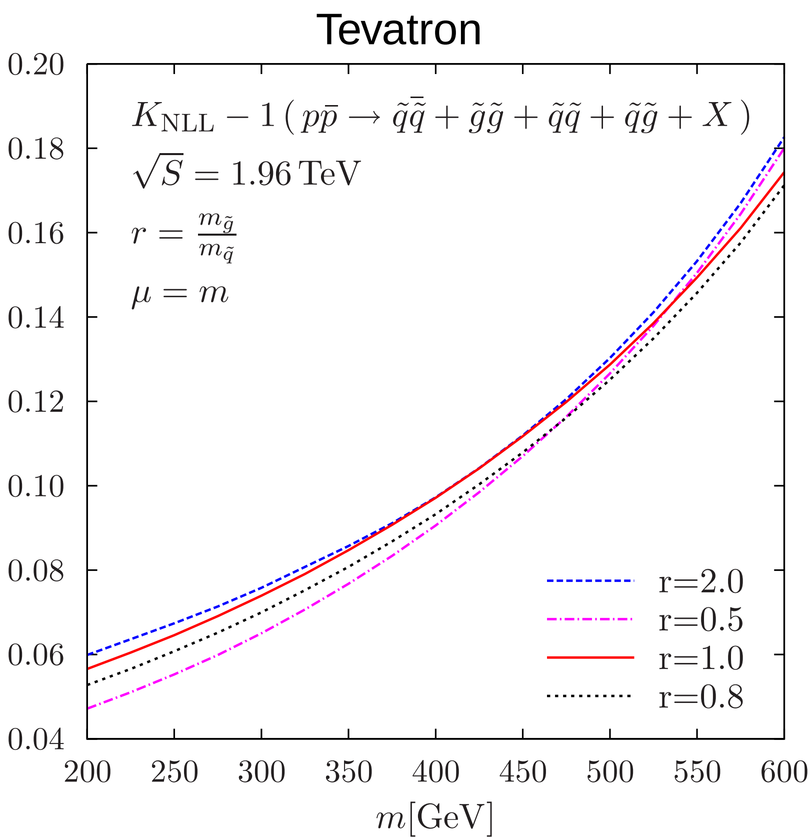


$m_{\tilde{q}} = m_{\tilde{g}}$, MSTW2008

NLL K-factor for $\tilde{q}$ and $\tilde{g}$ production at hadron colliders

[*Beenakker, Brensing, Krämer, AK, Laenen, Niessen'09*]

- Total cross section for production of $\tilde{q}$ and $\tilde{g}$ through all four processes
  $\Rightarrow$ different processes provide different weight to the combined NLL correction



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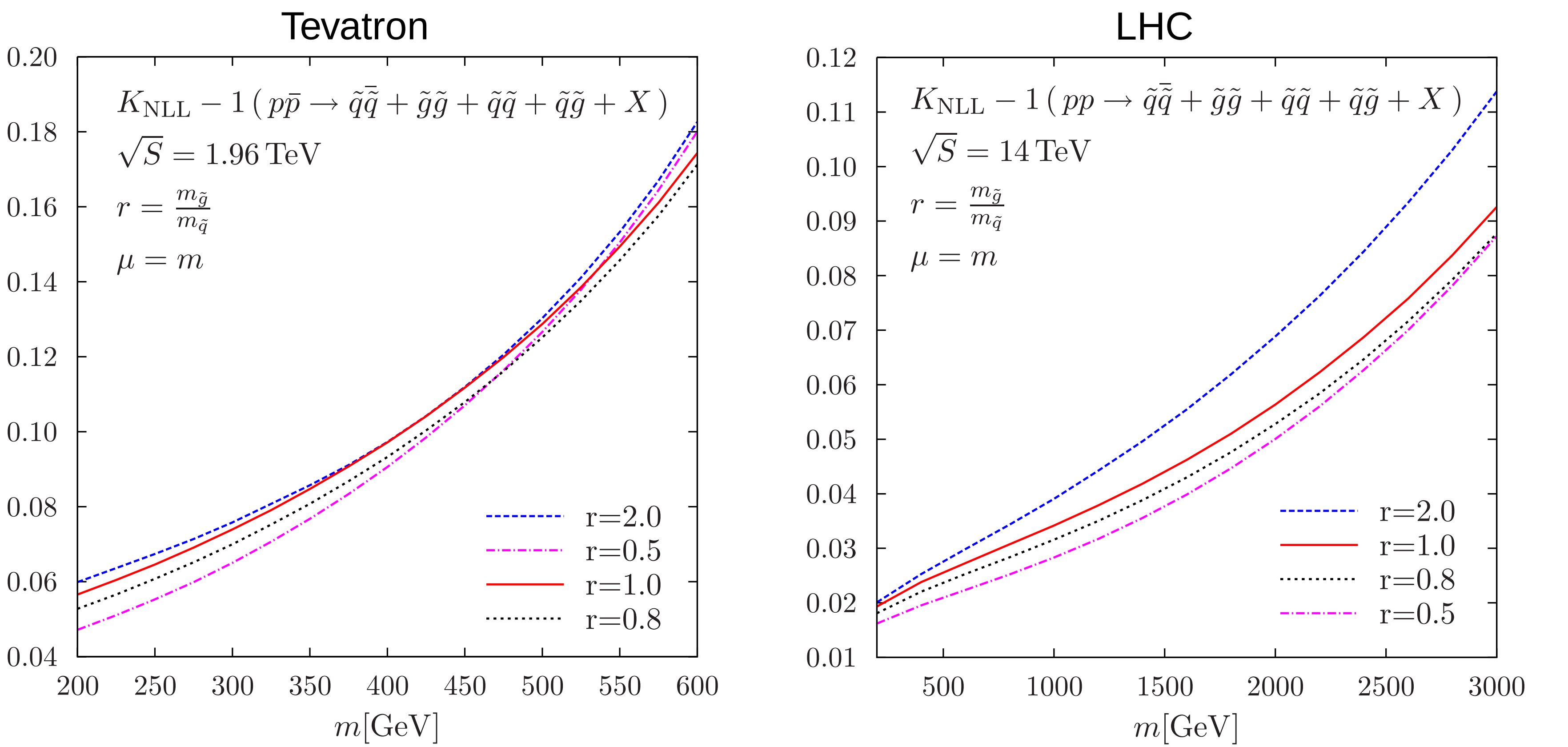

MSTW2008

Scale dependence for $\tilde{q}$ and $\tilde{g}$ hadroproduction

[*AK, Motyka'08-'09*] [*Beenakker, Brensing, Krämer, AK, Laenen, Niessen'09*]

- Reduction of scale dependence observed individually for each process
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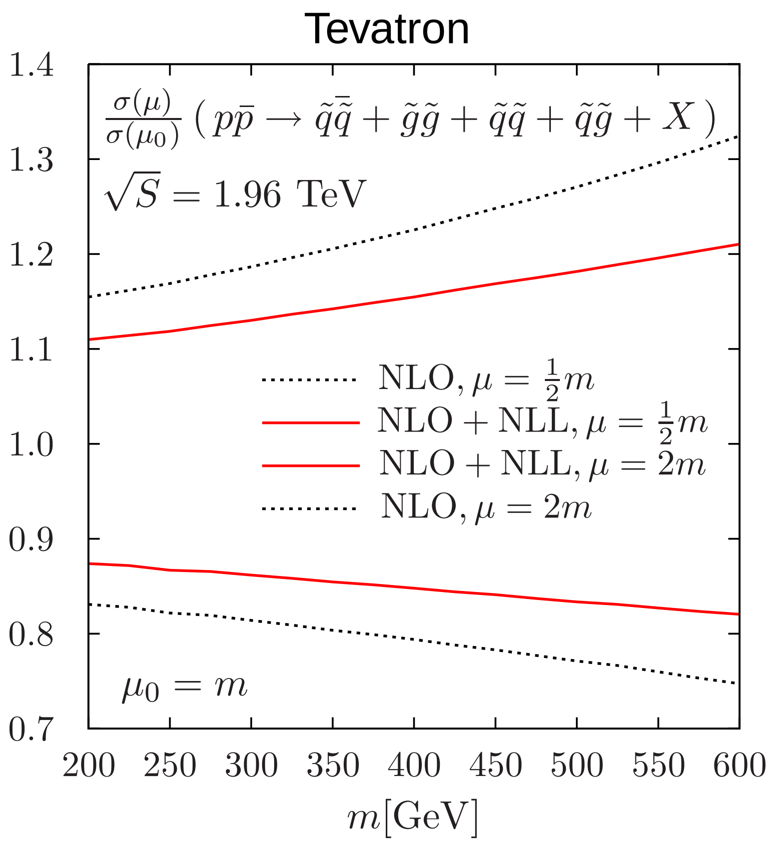

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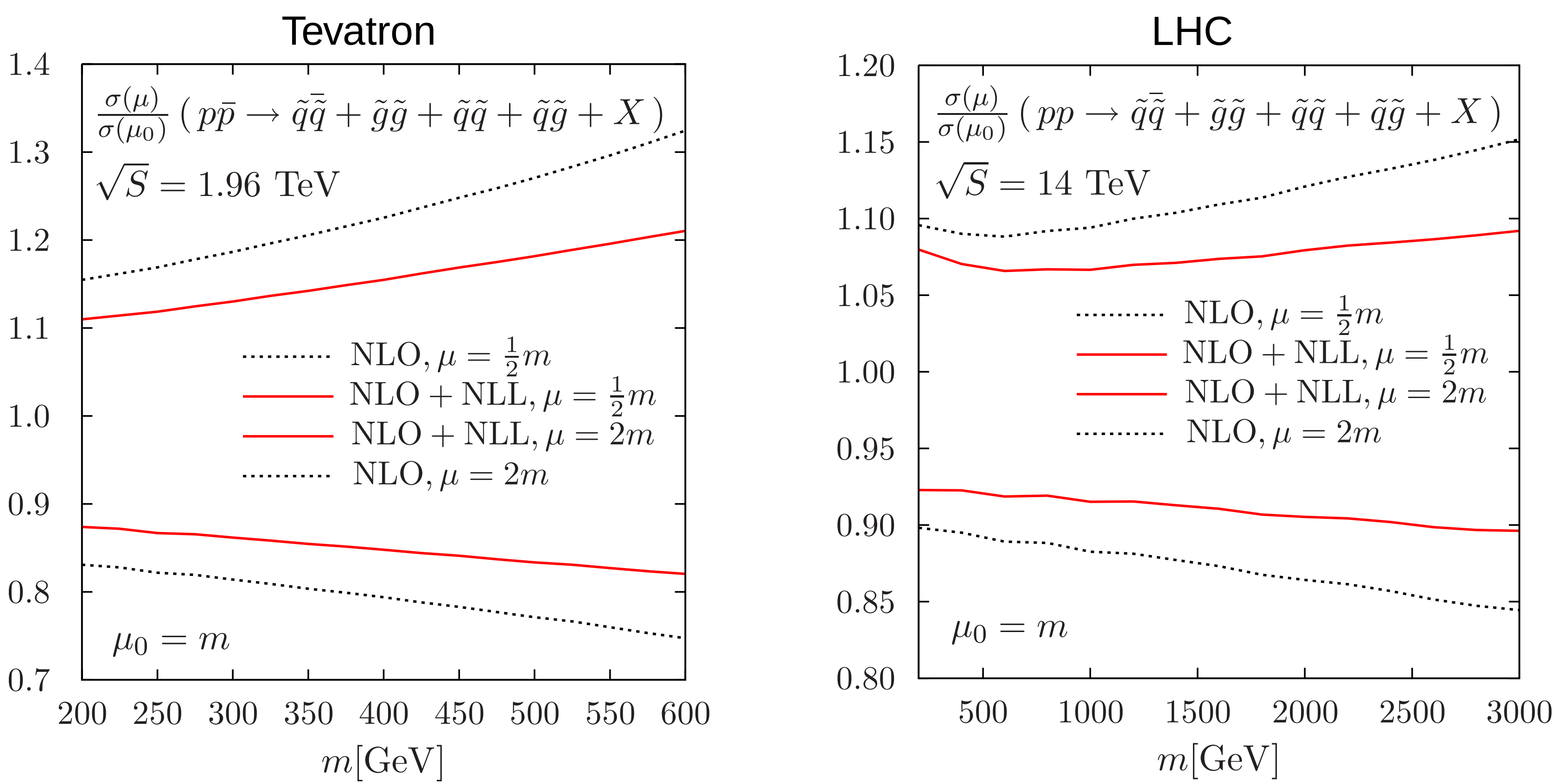

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- NLL resummed (matched with NLO) predictions for total cross sections: corrections due to soft gluon emissions above NLO

Summary

- If SUSY realized in Nature, $\tilde{q}$ and $\tilde{g}$ production processes will be among the most dominant mechanisms of sparticle production at the LHC
- NLL resummed (matched with NLO) predictions for total cross sections: corrections due to soft gluon emissions above NLO
- One-loop anomalous dimensions for $\tilde{q}\bar{\tilde{q}}$, $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$ and $\tilde{g}\tilde{g}$ production processes available

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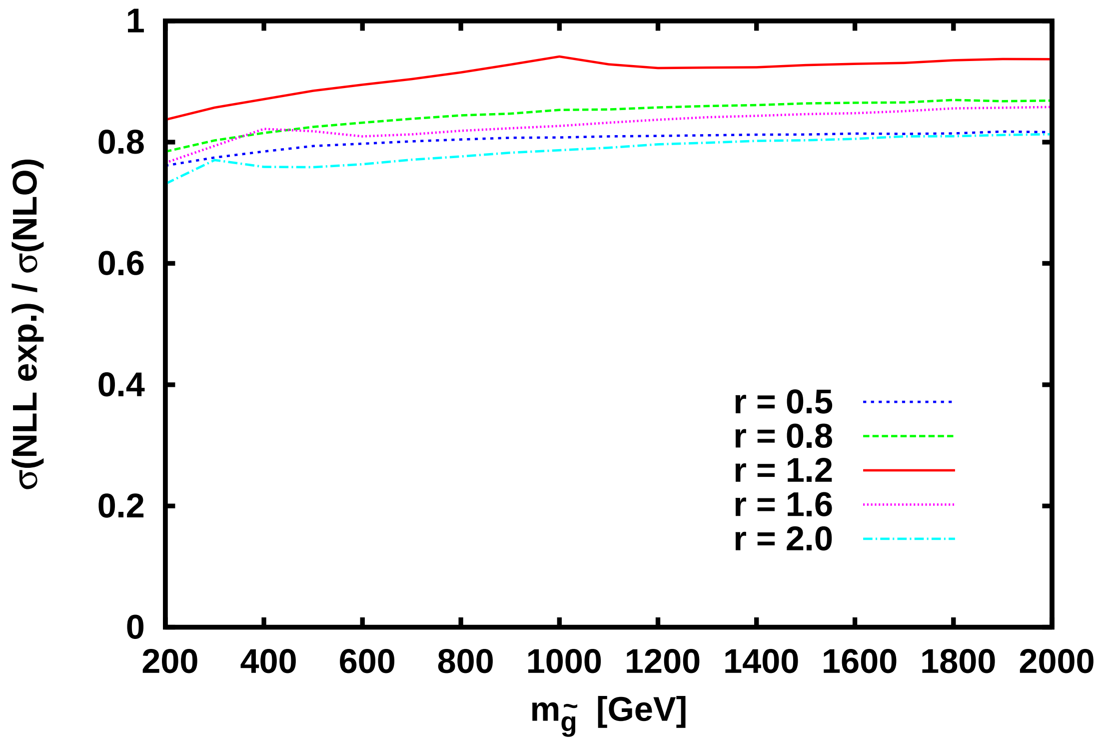
- One-loop anomalous dimensions for $\tilde{q}\bar{\tilde{q}}, \tilde{q}\tilde{q}, \tilde{q}\tilde{g}$ and $\tilde{g}\tilde{g}$ production processes available
- Corrections due to NLL resummation highest for processes with gluons in the initial state and gluinos in the final state.
  - $\sim 15\%$ correction for $m_{\tilde{g}} \sim 2\,\mathrm{TeV}$ for $\tilde{g}\tilde{g}$ production at the LHC
  - $\sim 40\%$ correction for at $0.5(m_{\tilde{q}} + m_{\tilde{g}}) \sim 500\,\mathrm{GeV}$ for $\tilde{q}\tilde{g}$ production at the Tevatron
- Significant reduction of the theoretical error due to scale variation

Extra slides

Importance of the NLL terms

[*AK, Motyka'09*]

Expanded NLL-resummed cross section up to $\mathcal{O}(\alpha_s^3)$ vs. NLO



$pp \longrightarrow \tilde{g}\tilde{g}$ at the LHC

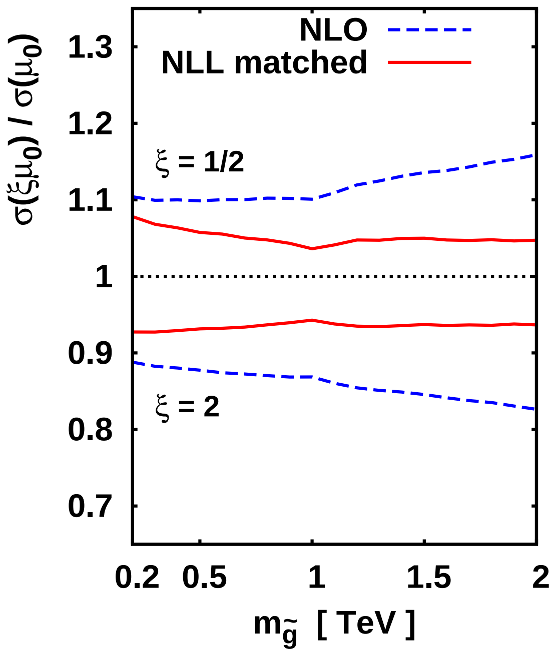
$r = \frac{m_{\tilde{g}}}{m_{\tilde{q}}}$ ($\mu_F = \mu_R = m_{\tilde{g}}$, CTEQ6M)

The scale dependence

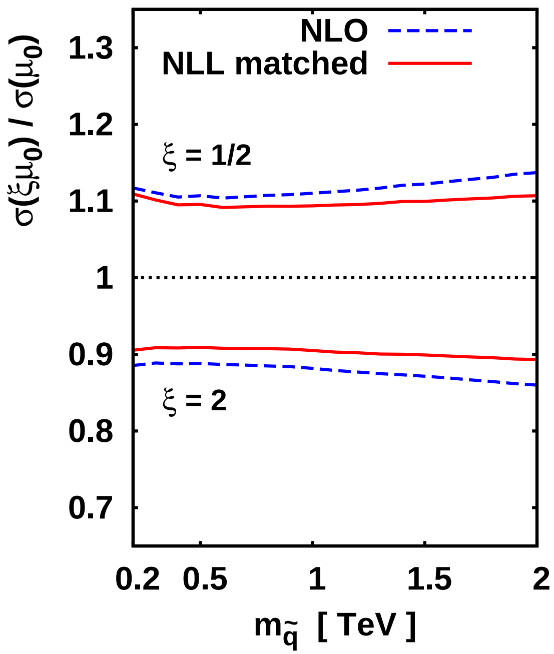
$$\frac{\sigma^{\rm NLO}(\mu = \xi m_{\tilde q})}{\sigma^{\rm NLO}(\mu = m_{\tilde q})} \text{ vs. } \frac{\sigma^{\rm (match)}(\mu = \xi m_{\tilde q})}{\sigma^{\rm (match)}(\mu = m_{\tilde q})}$$

[*AK, Motyka'08*]

$pp \to \tilde g \tilde g$



$pp \to \tilde q \bar{\tilde q}$



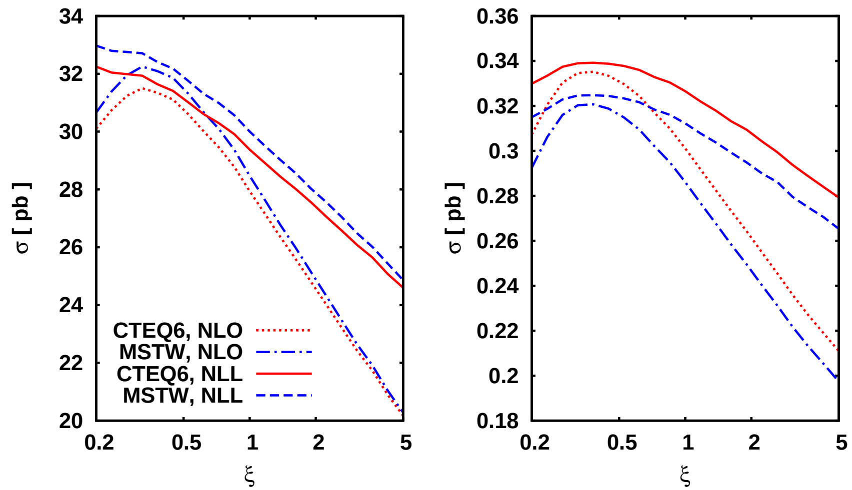
$r = \frac{m_{\tilde g}}{m_{\tilde q}} = 1.2$, $\mu_F = \mu_R$, CTEQ6M pdfs

The scale dependence

[*AK, Motyka'09*]

$$\xi = \mu/m,\, \mu = \mu_F = \mu_R,\, r = \frac{m_{\tilde{g}}}{m_{\tilde{q}}} = 1.2$$

$$pp \to \tilde{g}\tilde{g}$$



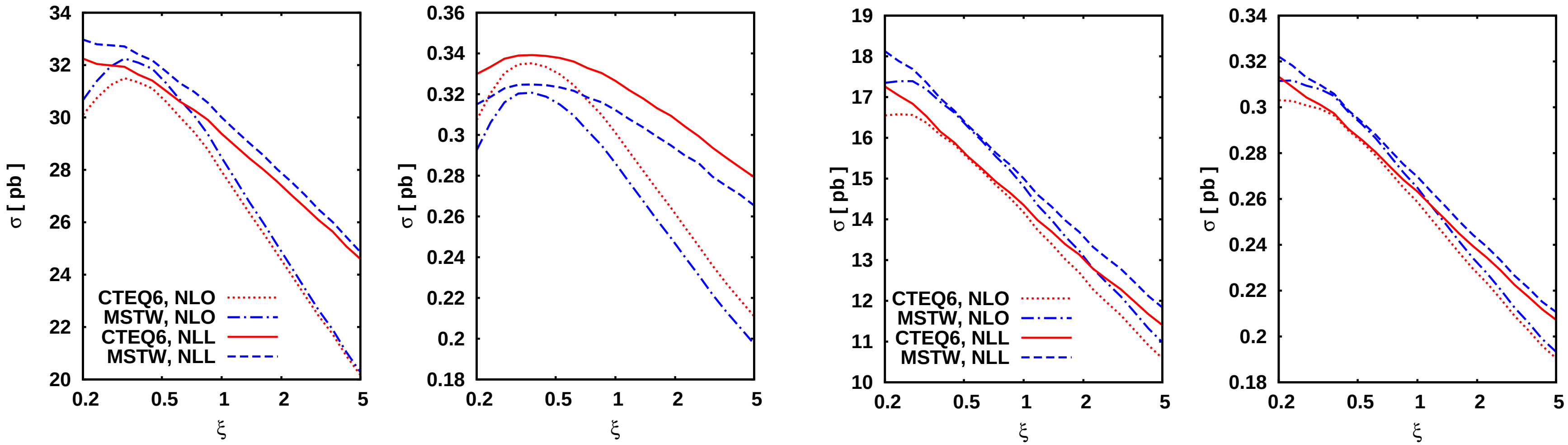
$m_{\tilde{g}} = 500$ GeV $\qquad$ $m_{\tilde{g}} = 1$ TeV

The scale dependence

[*AK, Motyka'09*]

$$\xi = \mu/m,\ \mu = \mu_F = \mu_R,\ r = \frac{m_{\tilde{g}}}{m_{\tilde{q}}} = 1.2$$

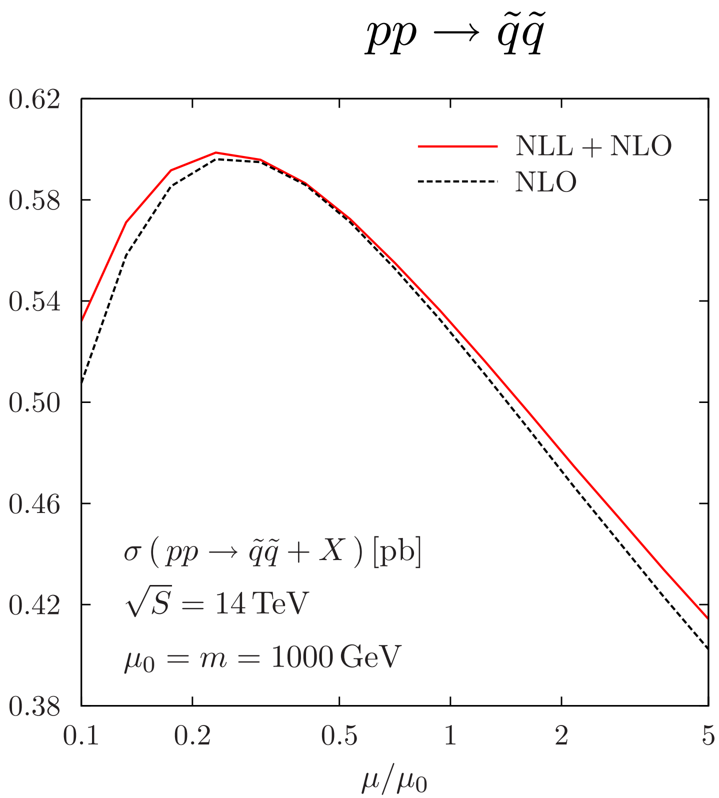
$pp \longrightarrow \tilde{g}\tilde{g}$ $\qquad\qquad$ $pp \longrightarrow \tilde{q}\bar{\tilde{q}}$

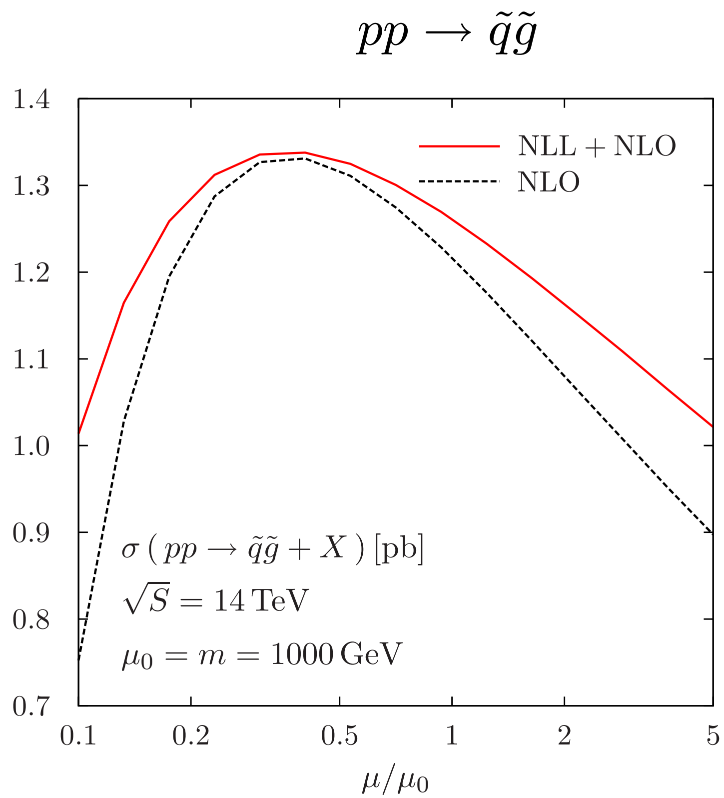


$m_{\tilde{g}} = 500$ GeV $\quad$ $m_{\tilde{g}} = 1$ TeV $\quad$ $m_{\tilde{q}} = 500$ GeV $\quad$ $m_{\tilde{q}} = 1$ TeV

The scale dependence cntd.

[*Beenakker, Brensing, Krämer, AK, Laenen, Niessen'09*]

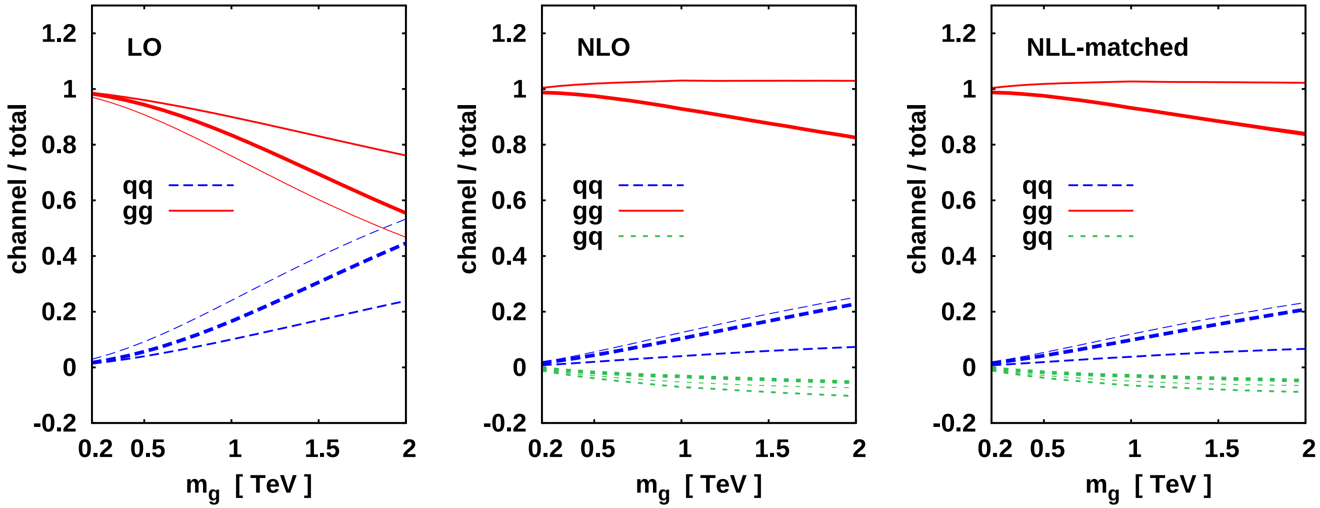




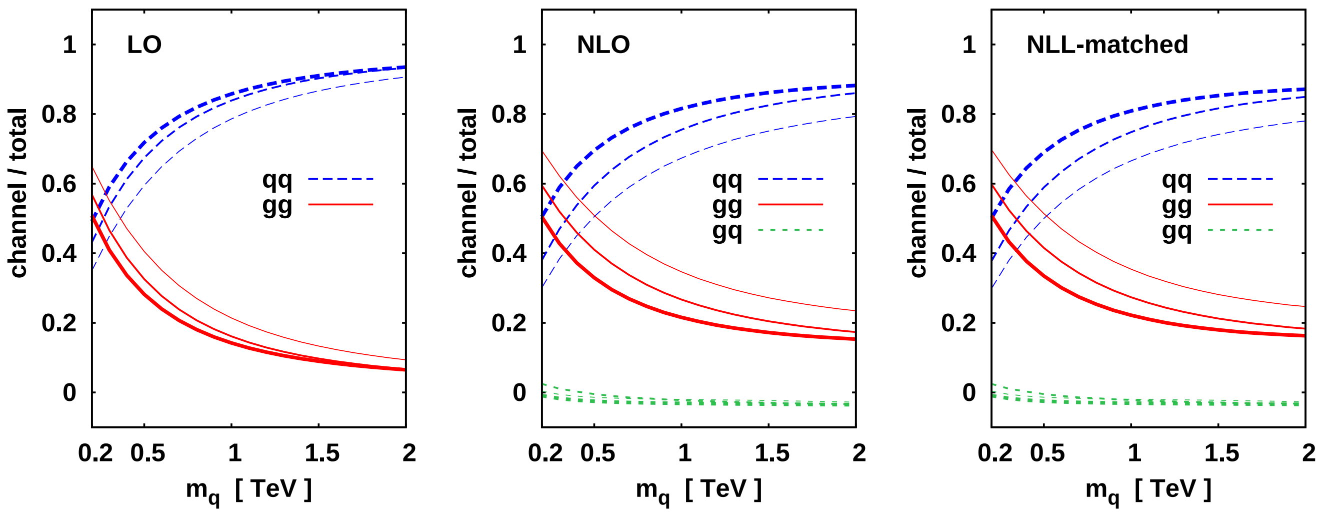
Squark and gluino production at the LHC

$pp \longrightarrow \tilde{g}\tilde{g}$:

[*AK, L. Motyka, in prep.*]



$pp \longrightarrow \tilde{q}\bar{\tilde{q}}$:



(thick line: $m_{\tilde{g}}/m_{\tilde{q}} = 0.5$, medium: $m_{\tilde{g}}/m_{\tilde{q}} = 1.2$, thin: $m_{\tilde{g}}/m_{\tilde{q}} = 2$)

Coulomb corrections

Leading Coulomb corrections

$$\alpha_s^n/\beta^n \qquad \text{wrt. LO}$$

can also be resummed [Fadin, Khoze, Sjöstrand' 90] [Catani, Mangano, Nason, Trentadue'96]

$$\hat{\sigma}^{\text{Coul}}_{ij\to kl} = \sum_I \hat{\sigma}^{\text{LO}}_{ij\to kl,\, I} \, \frac{X_{ij\to kl,\, I}}{1-\exp(-X_{ij\to kl,\, I})}$$

$$X_{ij\to kl,\, I} = \pi\alpha_s C_{ij\to kl,\, I}\,/\beta$$

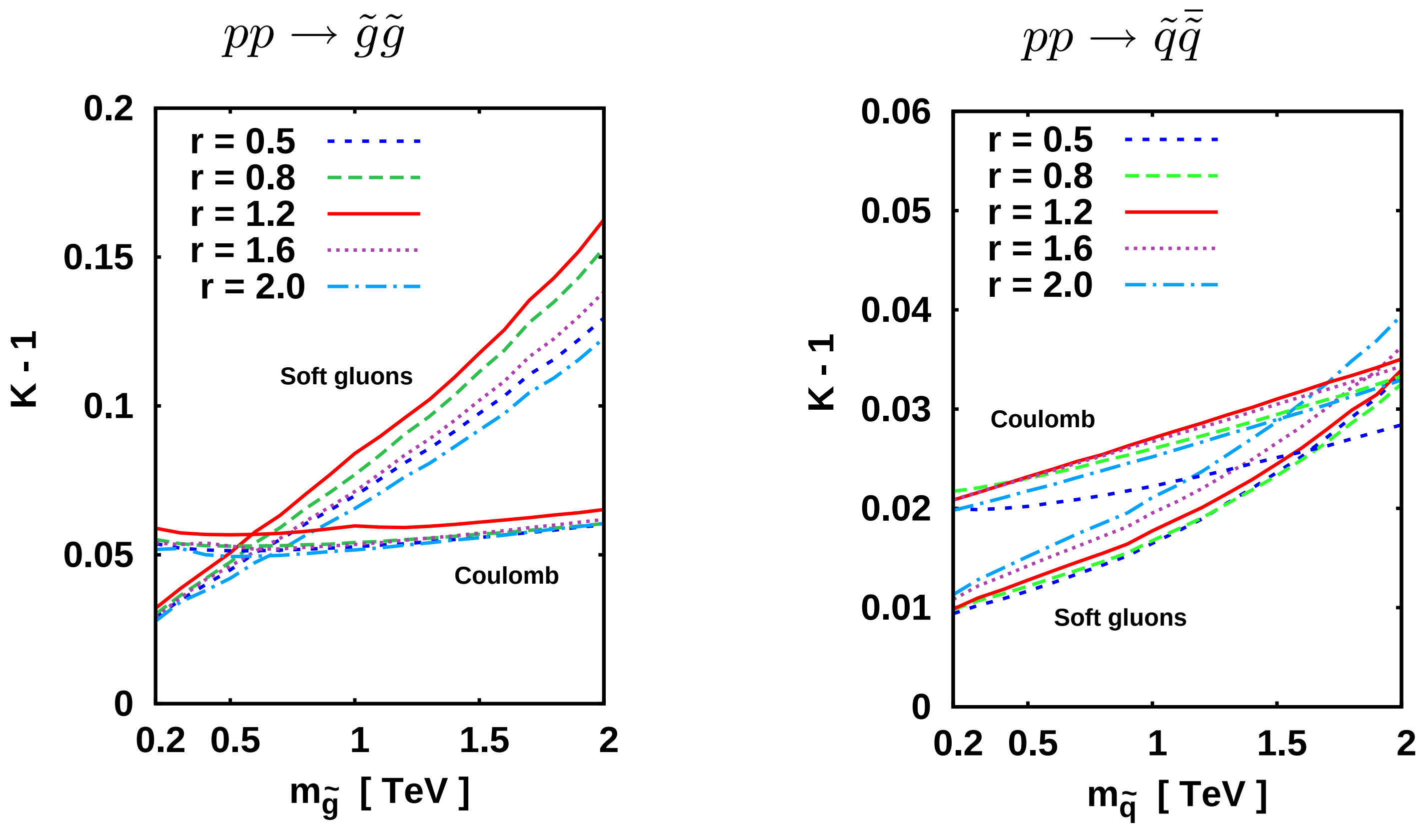
$C_{ij\to kl,\, I}$ are appropriate colour factors

Define the "Coulomb K-factor" as

$$K^{\text{Coul}}_{ij\to kl} = \frac{\hat{\sigma}^{\text{Coul}}_{ij\to kl} - \hat{\sigma}^{\text{Coul}}_{ij\to kl}|_{\text{NLO}}}{\sigma^{\text{NLO}}_{ij\to kl}}$$

Threshold effects for $\tilde{g}\tilde{g}$ and $\tilde{q}\bar{\tilde{q}}$ production at the LHC

[AK, L. Motyka'09]

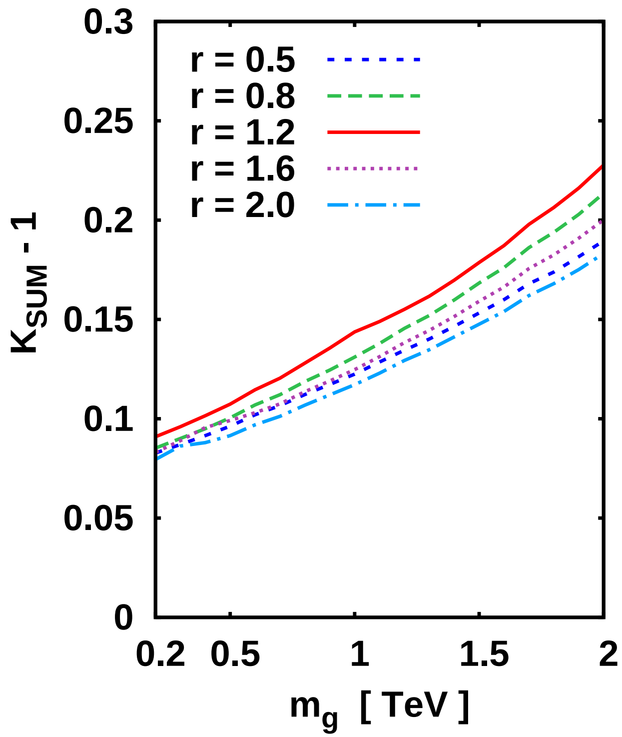


Threshold effects for $\tilde{g}\tilde{g}$ and $\tilde{q}\bar{\tilde{q}}$ production at the LHC

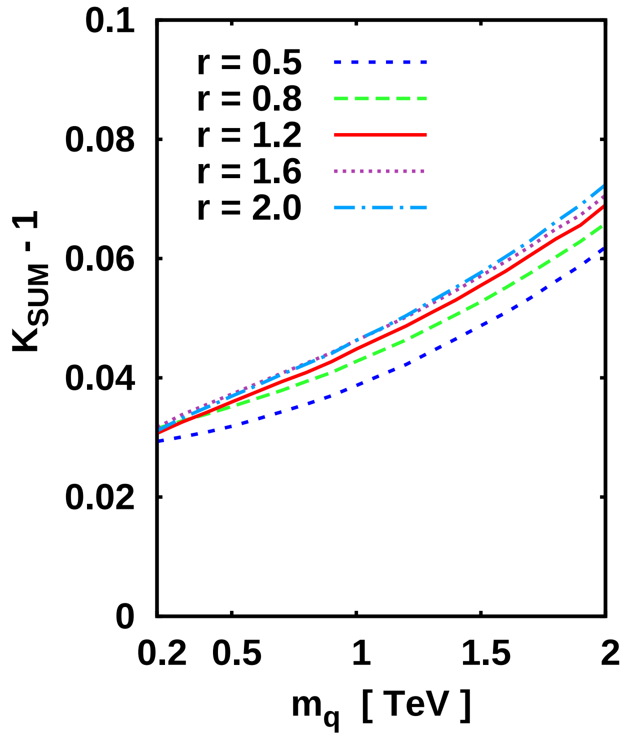
[*AK, Motyka'09*]

Soft + Coulomb corrections

$pp \rightarrow \tilde{g}\tilde{g}$



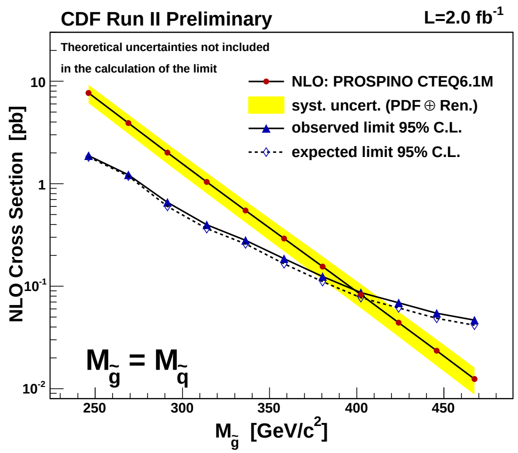
$pp \rightarrow \tilde{q}\bar{\tilde{q}}$



Limits on squark and gluino masses from the Tevatron

[*Beenakker, Brensing, Krämer, AK, Laenen, Niessen*]

Impact on limits on squark and gluino masses under investigation



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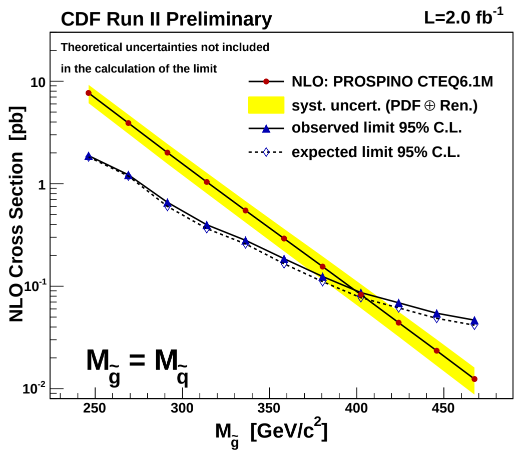

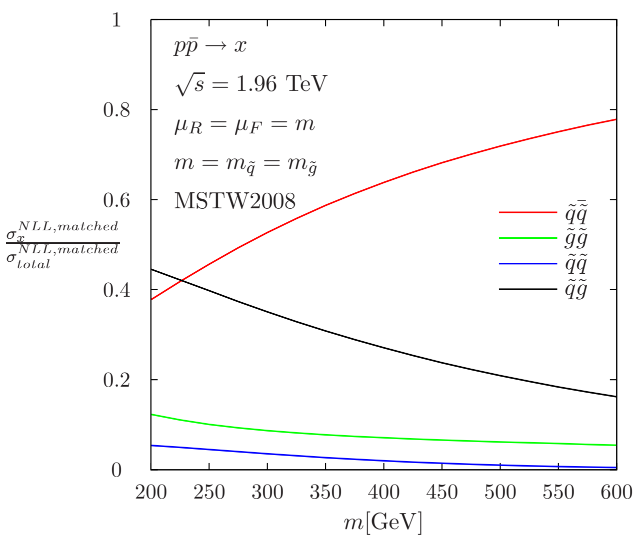

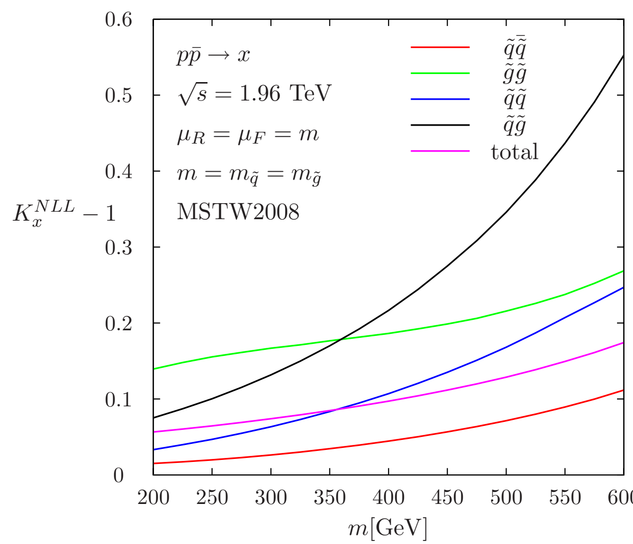

[PRELIMINARY]