Soft-Gluon Resummation For Coloured SUSY Production

Anna Kulesza

RWTH AACHEN

PHYSICS AT THE TERA SCALE Helmholtz Alliance

AK and L. Motyka, Phys. Rev. Lett. 102, 111802 (2009)
AK and L. Motyka, Phys. Rev. D 80 (2009) 095004
W. Beenakker, S. Brensing, M. Krämer, AK, E. Laenen and I. Niessen, JHEP 12 (2009) 041
W. Beenakker, S. Brensing, M. Krämer, AK, E. Laenen and I. Niessen, JHEP 08 (2010) 098
and work in progress

Heavy Particles at the LHC, ETH Zürich, 05.01.2011

Outline

- Motivation
- Theory: NLL resummation for 2→2 processes with coloured and massive particles in the final state
- Predictions for squark and gluino total cross sections at 7 TeV
- Stop-pair production, total cross sections and p_T distributions
- Summary

I. MOTIVATION

Squarks and gluinos at the LHC

MSSM:
minimal content of SUSY particles + R-parity

Hadron colliders:
coloured sparticles most copiously produced

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$$p\,\overset{(-)}{p} \longrightarrow \tilde{t}_k\bar{\tilde{t}}_k,\ \tilde{q}\bar{\tilde{q}},\ \tilde{q}\tilde{q},\ \tilde{q}\tilde{g},\ \tilde{g}\tilde{g}$$

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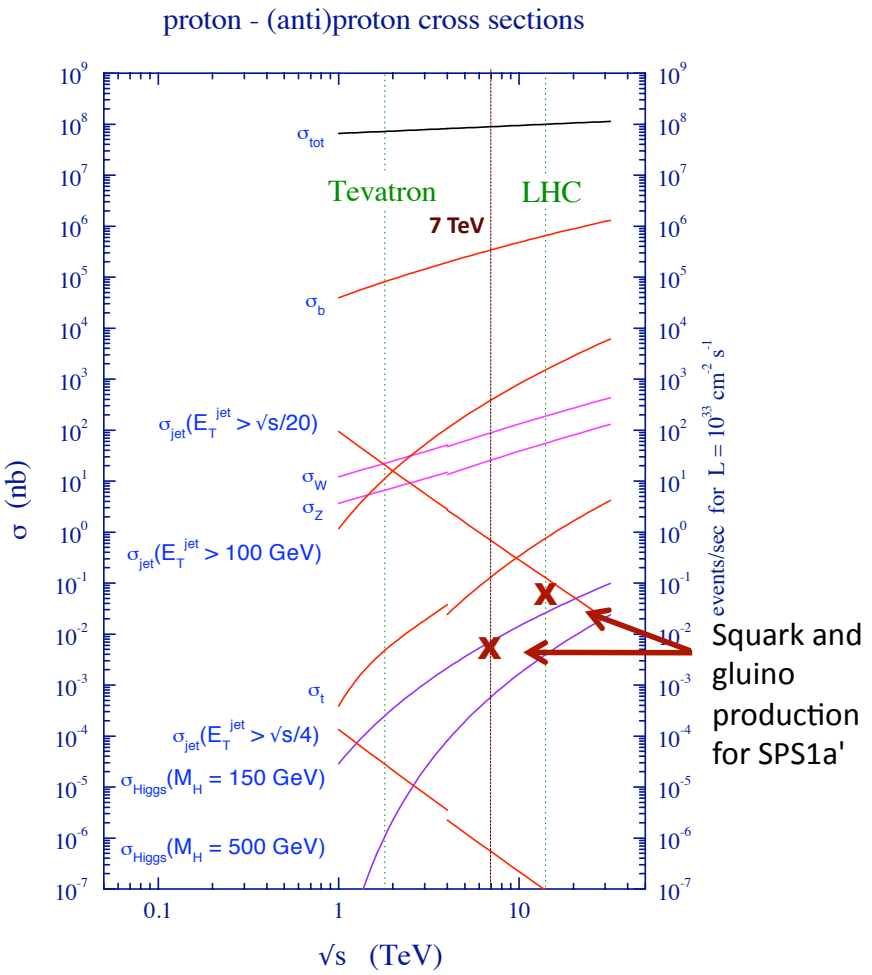
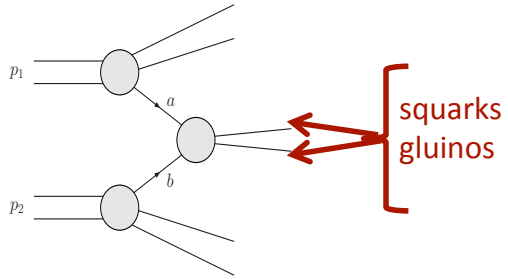
Key discovery processes in SUSY searches

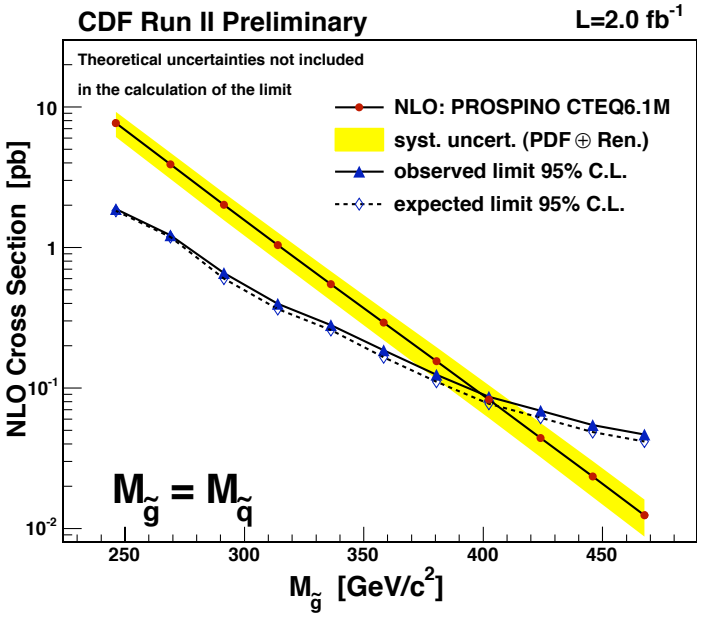


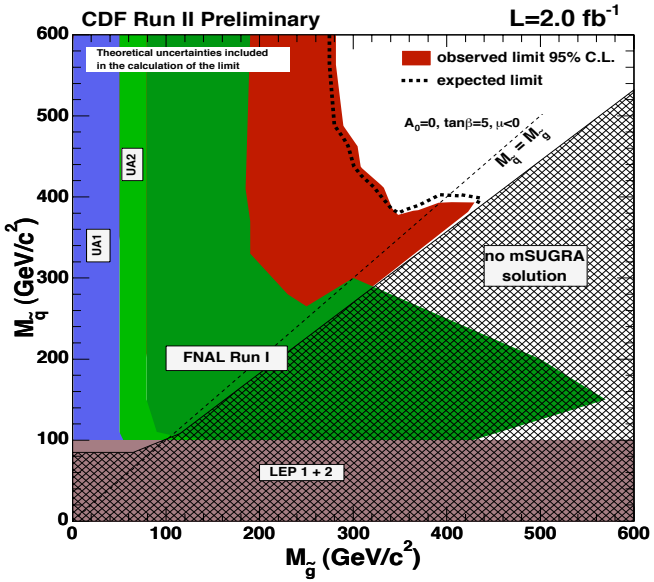
Squark and gluino production for SPS1a'

REMINDER: TEVATRON SEARCHES

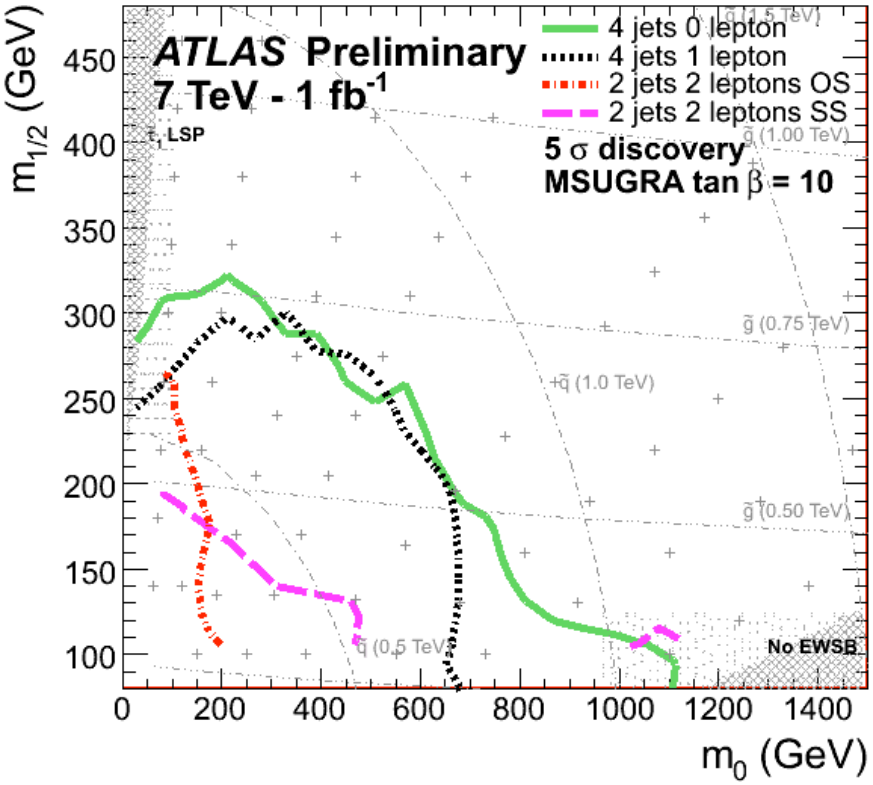


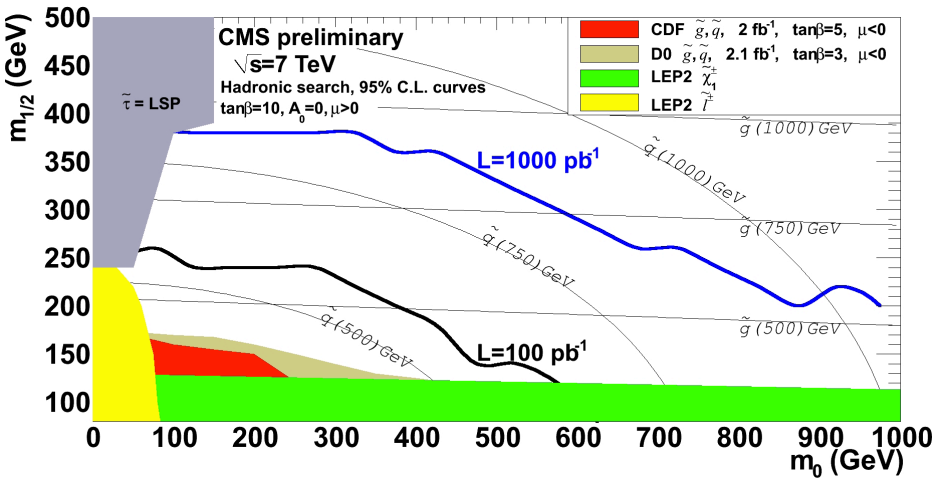
- Inclusive information on total production cross sections
  - crucial for determination of mass limits in case of no discovery





Prospects for 7 TeV LHC





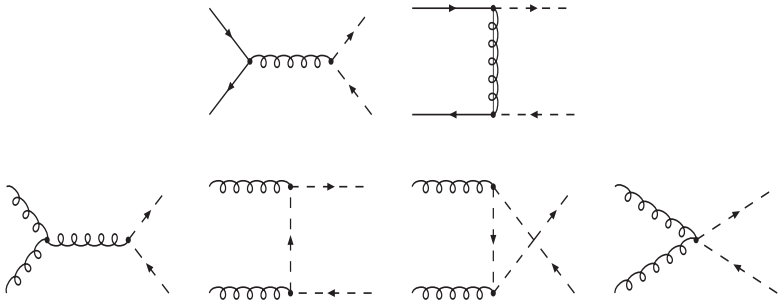
II. THEORETICAL CALCULATIONS

Partonic subprocesses

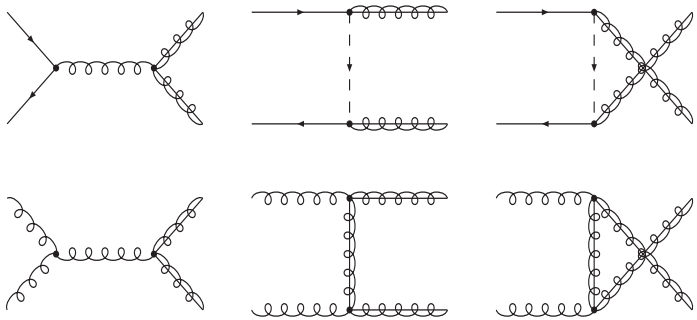
[Kane, Leveille'82][Harrison, Llewellyn Smith'84][Dawson, Eichten, Quigg'85]

Leading Order = $O(\alpha_s^2)$

$\tilde{q}\bar{\tilde{q}}$



$\tilde{g}\tilde{g}$



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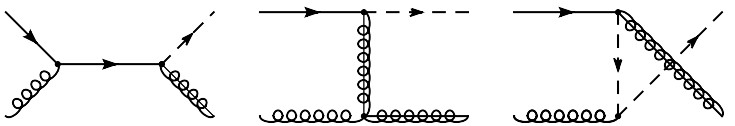

Theoretical Status

Fixed-order corrections to $\mathcal{O}(\alpha_s^2)$ processes

- NLO SUSY-QCD corrections → $\mathcal{O}(\alpha_s^3)$ *[Beenakker, Höpker, Spira, Zerwas'96] [Beenakker, Krämer, Plehn, Spira, Zerwas'97*
  - For squark-antisquark production: dominant NNLO contributions (NNLL-NNLO, Coulomb, scale dependence) → $\mathcal{O}(\alpha_s^4)$ *[Langenfeld, Moch'09]*
- EW corrections → $\mathcal{O}(\alpha_s^2\,\alpha^2)$ *[Hollik, Kollar, Trenkel'07][Hollik, Mirabella'08] [Hollik, Mirabella, Trenkel'08] [Beccaria et al.'08] [Mirabella'09] [Germer, Hollik, Mirabella, Trenkel'10]*

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Tree-level EW effects $\mathcal{O}(\alpha_s\,\alpha)$ 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, Hollik, Mirabella, Trenkel'10]*

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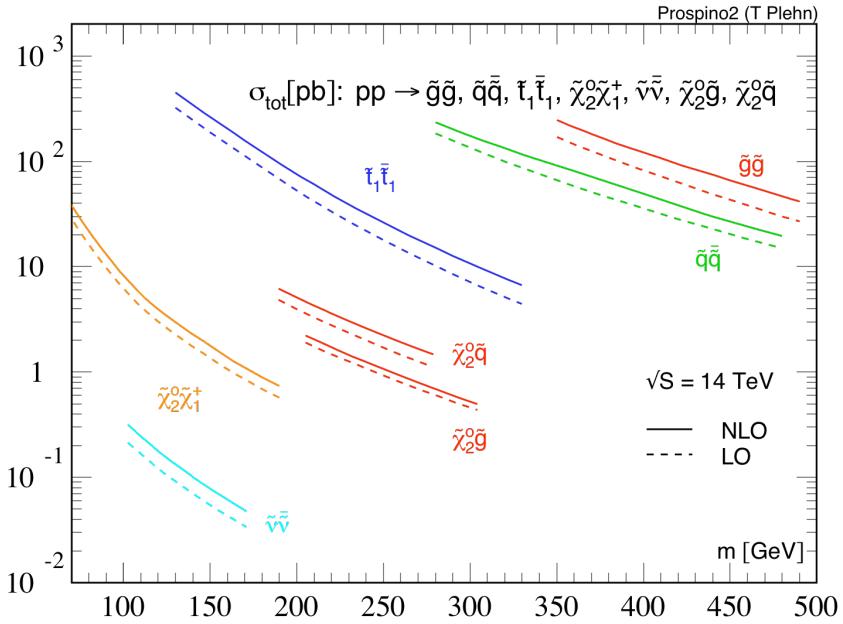
- Bound-state effects in gluino-pair production *[Hagiwara, Yokoya'09]*, gluinonia production and decay *[Kauth, Kühn, Marquard, Steinhauser'09]*

LO vs NLO

[Beenakker, Höpker, Spira, Zerwas'97]

- NLO SUSY QCD



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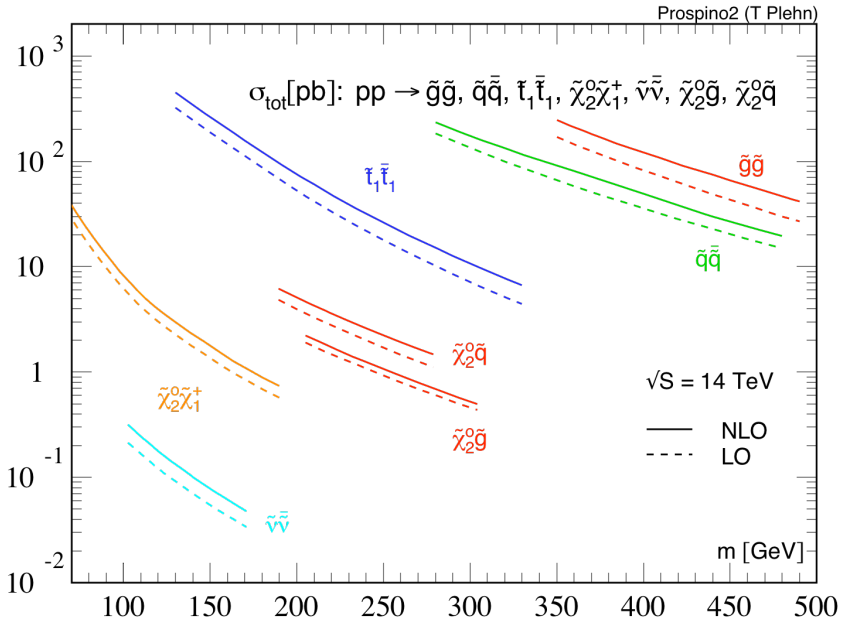
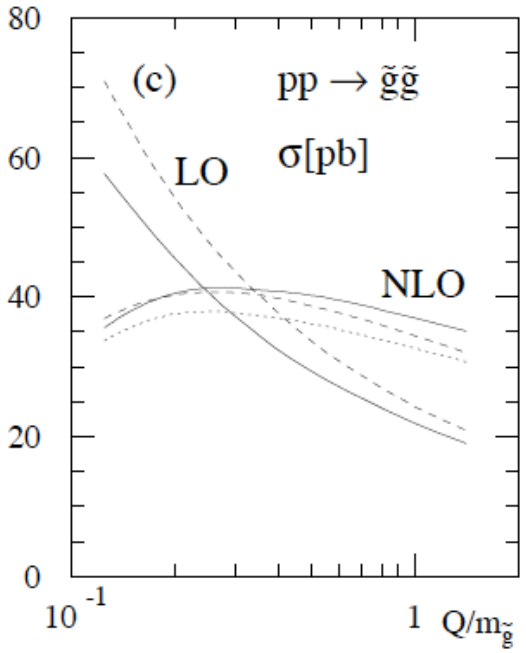


[Beenakker, Höpker, Spira, Zerwas'97]

- LO results for total cross sections suffer from enormous scale dependence



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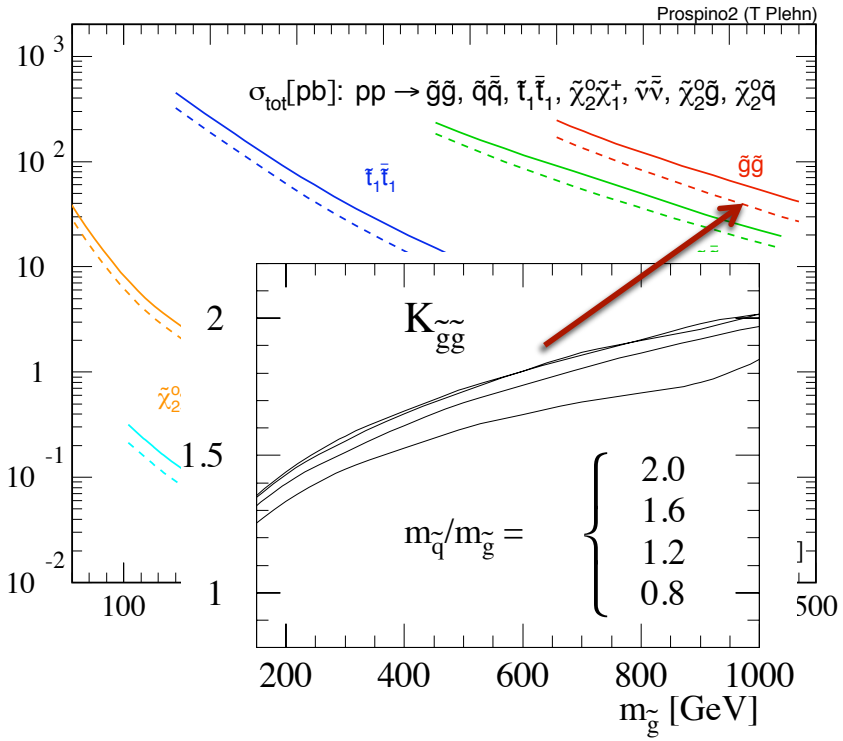

$$K_{\tilde{g}\tilde{g}} = \frac{\sigma^{\mathrm{NLO}}}{\sigma^{\mathrm{LO}}}$$

100% correction!

[Beenakker, Hopker, Spira, Zerwas'97]

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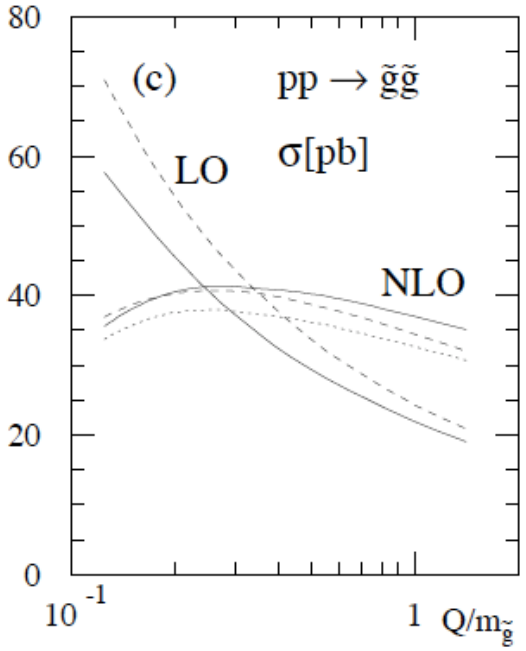

At Threshold

- Large masses of SUSY particles ⇒ production close to threshold $\hat{s} \sim 4m^2$
- General structure of the NLO correction in the threshold limit $\beta \to 0, \quad \beta^2 = 1 - 4m^2/\hat{s}$

$$\Delta\hat{\sigma}_i^{\mathrm{NLO}} \sim \alpha_s \, \hat{\sigma}_i^{\mathrm{LO}} \left\{ A^{(i)} \log^2(\beta^2) + B^{(i)} \log(\beta^2) + C^{(i)} \frac{1}{\beta} + D^{(i)} \right\}$$

Soft/collinear gluon emission

Coulomb gluons

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→ LO Coulomb corrections $(\alpha_s/\beta)^n$ resummed for $\tilde{q}\bar{\tilde{q}}$ and $\tilde{g}\tilde{g}$ *[Kulesza, Motyka'09]*

→ Boundstate corrections for $\tilde{g}\tilde{g}$ *[Hagiwara, Yokoya'09]*

Resummation of soft and Coulomb corrections together *[Beneke, Schwinn, Falgari'09]*, applied to $\tilde{q}\bar{\tilde{q}}$ *[Beneke, Schwinn, Falgari'10]*

SOFT GLUON RESUMMATION

Systematic reorganization of perturbative series, for threshold logs performed in the space of Mellin moments

[Sterman'87][Catani, Trentadue'89]

$$\sigma^{(N)}_{h_1h_2\to kl}(\{m^2\}) = \int_0^1 d\rho\, \rho^{N-1}\, \sigma_{h_1h_2\to kl}(\rho,\{m^2\}) = \sum_{i,j} f^{(N+1)}_{i/h_1}(\mu^2) f^{(N+1)}_{j/h_2}(\mu^2) \hat{\sigma}^{(N)}_{ij}(\{m^2\},\mu^2)$$

$$\rho = 4m^2/S$$

with

$$\hat{\sigma}^{(N)}_{ij\to kl}(\{m^2\},\mu^2) = \int_0^1 d\hat{\rho}\, \hat{\rho}^{N-1}\, \hat{\sigma}_{ij\to kl}(\hat{\rho},\{m^2\},\mu^2)$$

$$\hat{\rho} = \frac{4m^2}{\hat{s}} = 1-\beta^2 \qquad \log(1-\hat{\rho}) = \log(\beta^2) \longleftrightarrow \log(N) \equiv L$$

$$\hat{\sigma}^{(N)} \sim \mathcal{C}(\alpha_s) \exp\left[L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \dots\right]$$

sums up LL: $\alpha_s^n \log^{n+1}(N)$ NLL: $\alpha_s^n \log^n(N)$

Resummation for 2→2 Processes with colour and mass in the final state

- Threshold limit: NLL resummed partonic cross section *[Kidonakis, Sterman'96-97] [Bonciani, Catani, Mangano, Nason'98]*

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

N-moments of LO

Soft-collinear radiation from incoming partons, universal, known

Soft, wide-angle emission, process dependent

$$\Delta^{(\mathrm{soft},N)}_{ij\to kl,I} = \exp\left[\int_\mu^{Q/N} \frac{dq}{q}\,\frac{\alpha_\mathrm{s}(q)}{\pi}\, D^{(1)}_{ij\to kl,I}\right], \qquad D^{(1)}_{ij\to kl,I} = \lim_{\beta\to 0}\frac{\pi}{\alpha_\mathrm{s}}\, 2\,\mathrm{Re}\left(\bar{\Gamma}_{II}\right)$$

Soft anomalous dimension matrix

- Condition: choice of orthogonal basis in colour space for which Γ_{IJ} is diagonal in the threshod limit, here s-channel basis *[AK, Motyka' 09]* . In general possible to construct such basis in which Γ_{IJ} diagonal to all orders *[Beneke, Falgari, Schwinn'09]*

Soft anomalous dimensions

- Need 1-loop anomalous dimension matrices in order to resum up to NLL
  - massless 2→n QCD processes [*Kidonakis, Oderda, Sterman'98] [Bonciani et al.'03][Mert Aybat, Dixon, Sterman'06]*
  - massive case: heavy quark pair-production *[Kidonakis, Sterman'96][Bonciani et al.'98]*

- Calculation of 1-loop soft anomalous dimension matrices Γ_{ij} for 2→2 processes with nontrivial colour structure and massive particles in the final state

$$
\begin{array}{llll}
\tilde{q}\bar{\tilde{q}} & \mathbf{3}\otimes\bar{\mathbf{3}} & = & \mathbf{1}\oplus\mathbf{8} \\
\tilde{q}\tilde{q} & \mathbf{3}\otimes\mathbf{3} & = & \bar{\mathbf{3}}\oplus\mathbf{6} \\
\tilde{q}\tilde{g} & \mathbf{3}\otimes\mathbf{8} & = & \mathbf{3}\oplus\bar{\mathbf{6}}\oplus\mathbf{15} \\
\tilde{g}\tilde{g} & \mathbf{8}\otimes\mathbf{8} & = & \mathbf{1}\oplus\mathbf{8}\oplus\mathbf{8}\oplus\mathbf{10}\oplus\bar{\mathbf{10}}\oplus\mathbf{27}
\end{array}
$$

same colour structure as in top-antitop production ✓

- Full set of $D^{(1)}$ coefficients for squark and gluino production processes
  - $D^{(1)}$ correspond to values of the quadratic Casimir operators for the SU(3) representations for the outgoing state ➔ soft gluon radiation only "feels" the total colour charge of the heavy-particle pair produced at threshold

RESUMMATION-IMPROVED NLL+NLO TOTAL CROSS SECTION

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

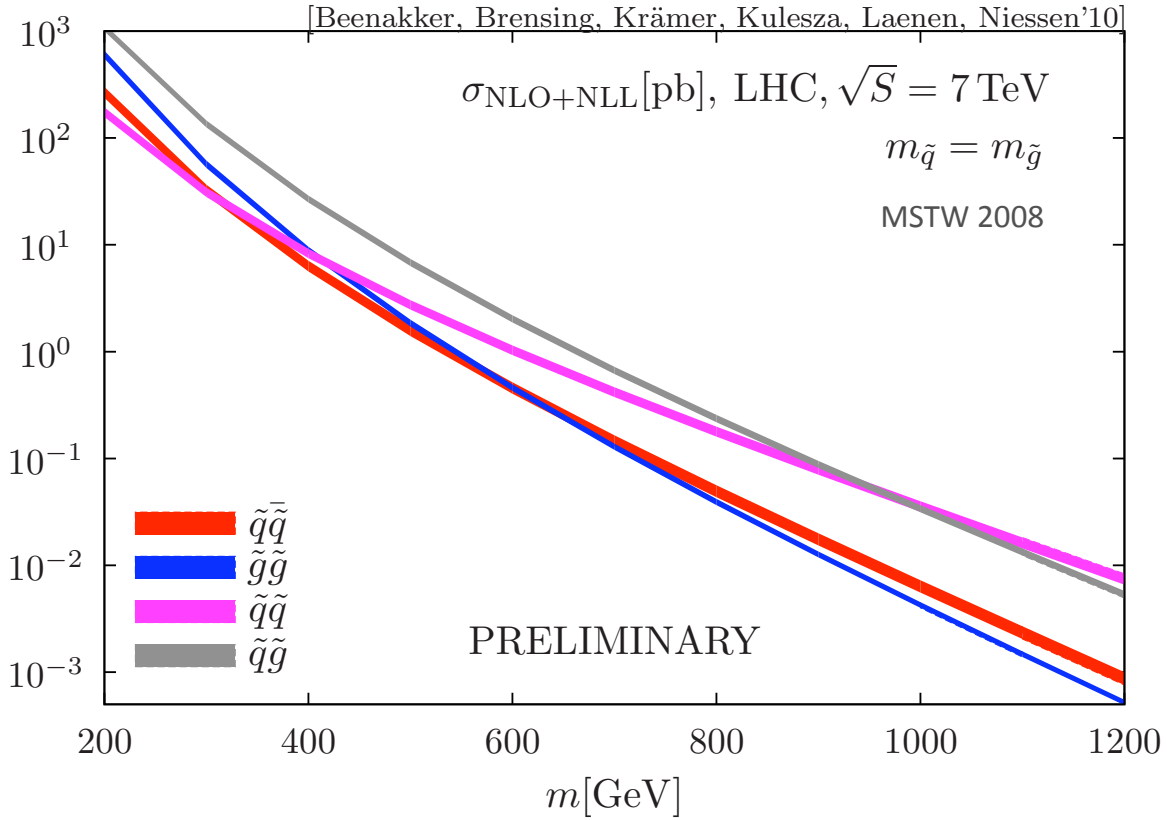
$$\sigma^{(\mathrm{match})}_{h_1 h_2 \to kl}(\rho, \{m^2\}, \mu^2) = \sum_{i,j=q,\bar{q},g} \int_{C_{MP}-i\infty}^{C_{MP}+i\infty} \frac{dN}{2\pi i}\, \rho^{-N}\, f^{(N+1)}_{i/h_1}(\mu^2)\, f^{(N+1)}_{j/h_2}(\mu^2)$$
$$\times \left[\hat{\sigma}^{(\mathrm{res},N)}_{ij\to kl}(\{m^2\}, \mu^2) - \hat{\sigma}^{(\mathrm{res},N)}_{ij\to kl}(\{m^2\}, \mu^2)\Big|_{NLO} \right]$$
$$+ \sigma^{\mathrm{NLO}}_{h_1 h_2 \to kl}(\rho, \{m^2\}, \mu^2)\,,$$

- 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] [http://people.web.psi.ch/spira/prospino/] [http://www.thphys.uni-heildelberg.de/plehn/prospino/]*

III. RESULTS FOR 7 TEV

TOTAL NLL+NLO PRODUCTION RATES

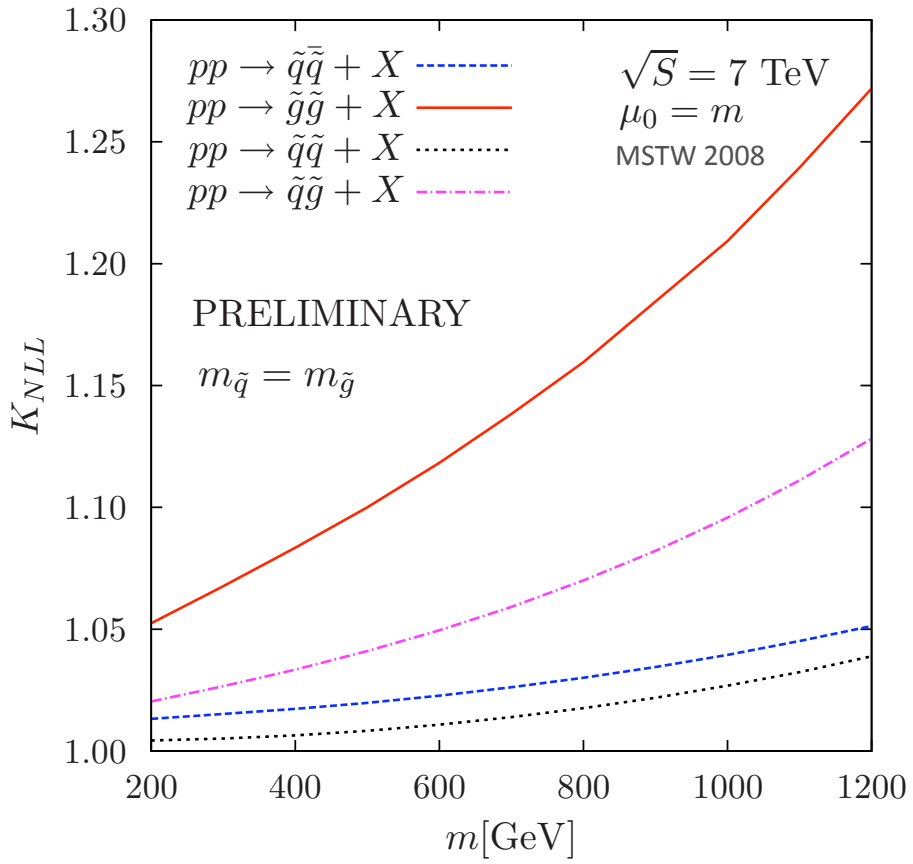


Squark-gluino channel dominates for moderate masses

Width of the bands: theory error due to scale variation $0.5 < \mu/m < 2$

NLL Corrections

[Beenakker, Brensing, Krämer, Kulesza, Laenen, Niessen'10]

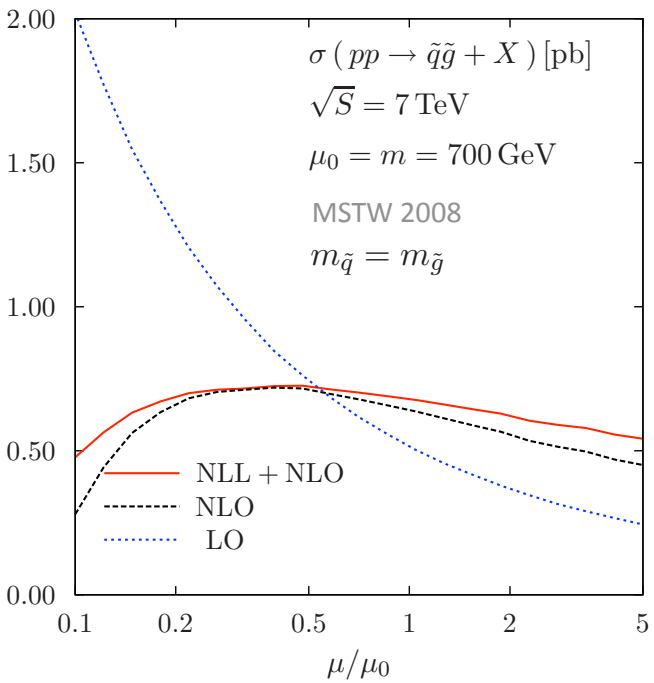


$$K_{\mathrm{NLL}} = \frac{\sigma^{\mathrm{resummed,NLL}}}{\sigma^{\mathrm{NLO}}}$$

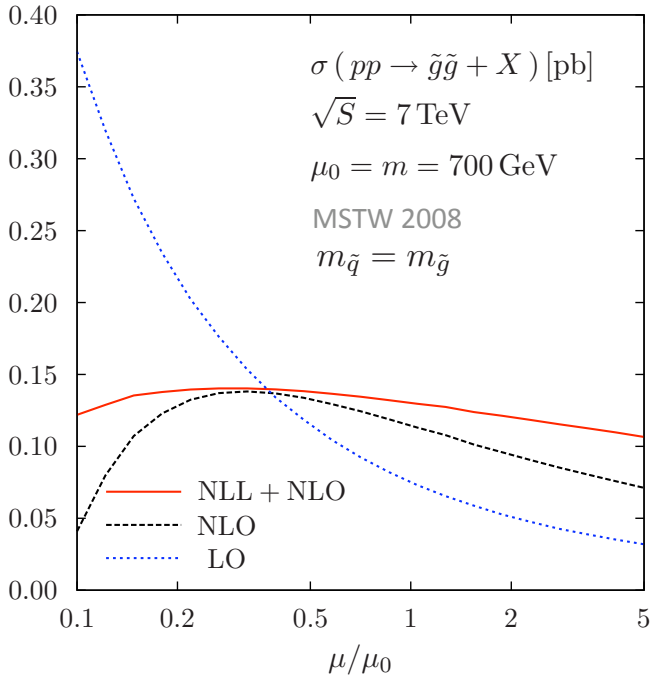
- Soft-gluon resummation enhances the cross sections
- Highest corrections for the gluino-pair production: 20% correction to the NLO results for m_{gl}= 1 TeV
- For the squark-gluino channel, NLL correction reaches 10% at m_{sq}= m_{gl}= 1 TeV

Scale variation

- Squark-gluino production



- Gluino-pair production

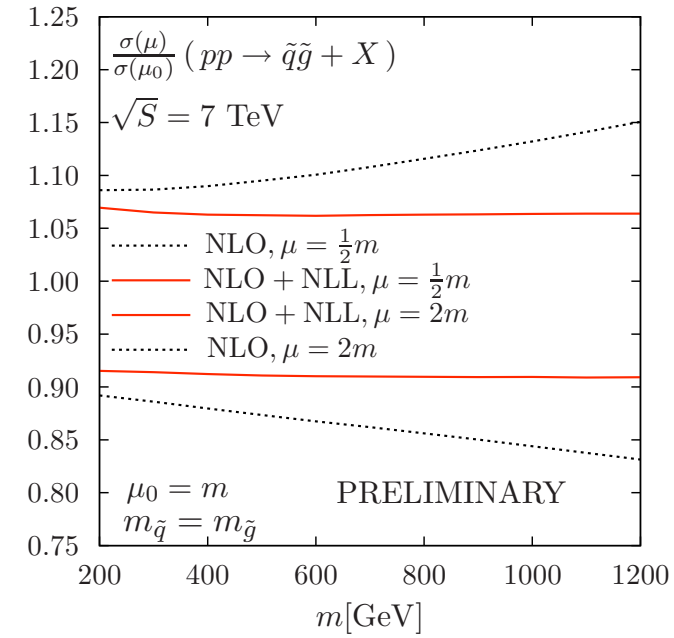


Significant reduction of the scale dependence for NLL+NLO compared to NLO, especially for gluino-pair production

Scale variation ctnd.

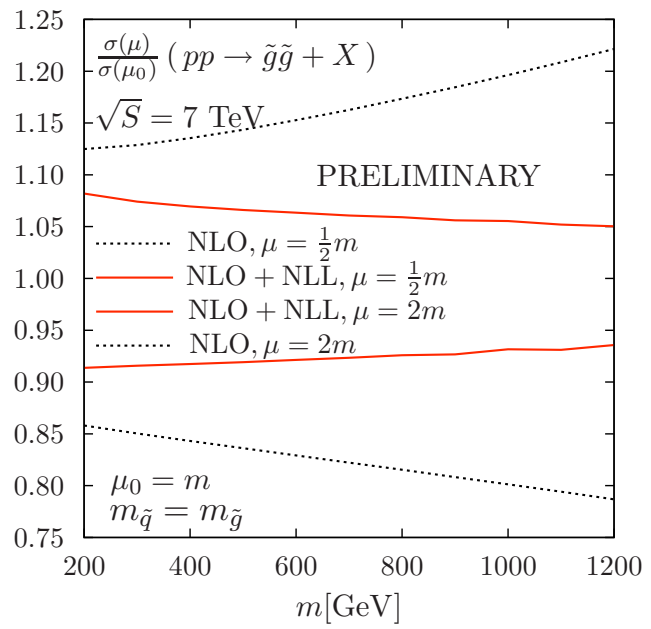
- Squark-gluino production

[Beenakker, Brensing, Krämer, Kulesza, Laenen, Niessen'10]



- Gluino-pair production

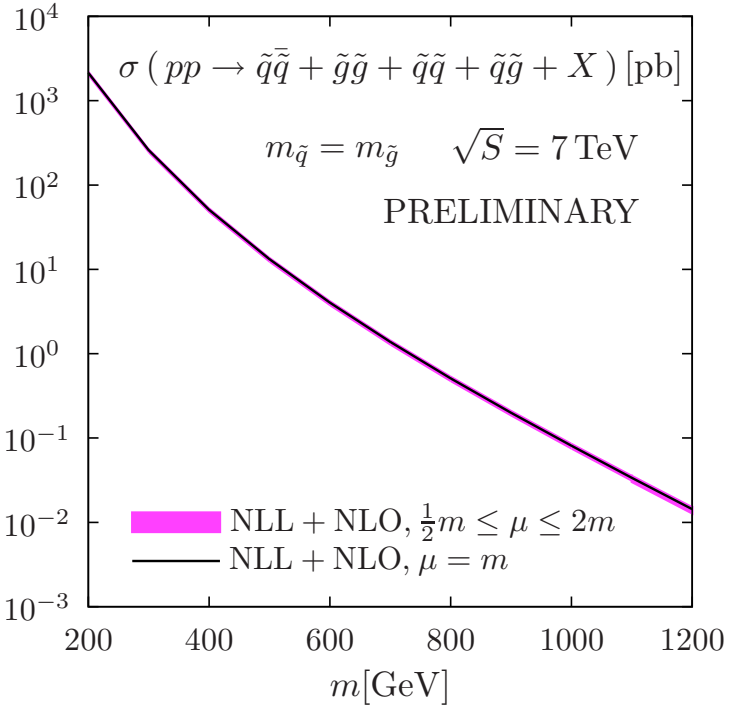
[Beenakker, Brensing, Krämer, Kulesza, Laenen, Niessen'10]

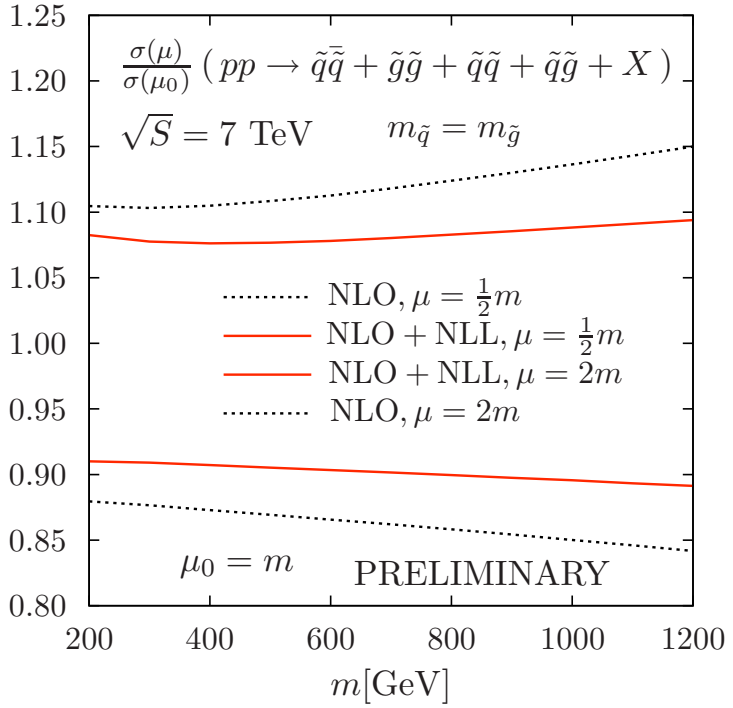


Theory error due to scale variation below 10% for NLL+NLO
down by a factor of 2 (squark-gluino) or a factor of 4 (gluino-pair) for masses > 1 TeV

NLL @ 7 TeV

[Beenakker, Brensing, Krämer, Kulesza, Laenen, Niessen'10]

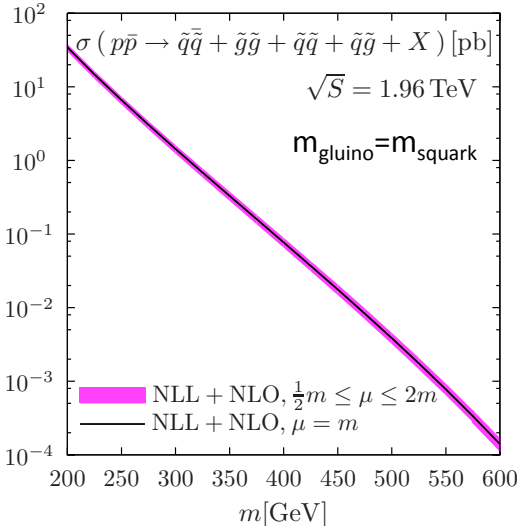


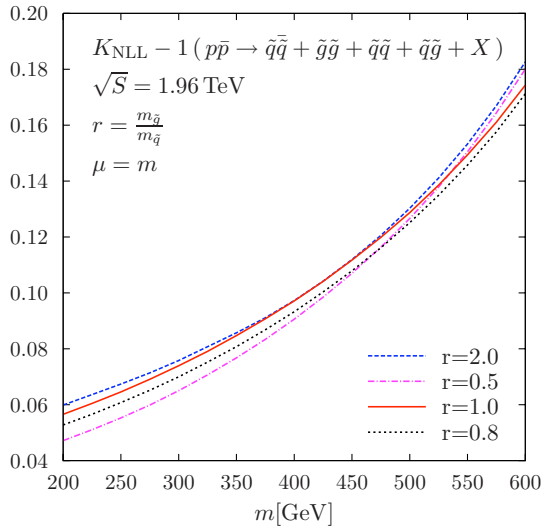


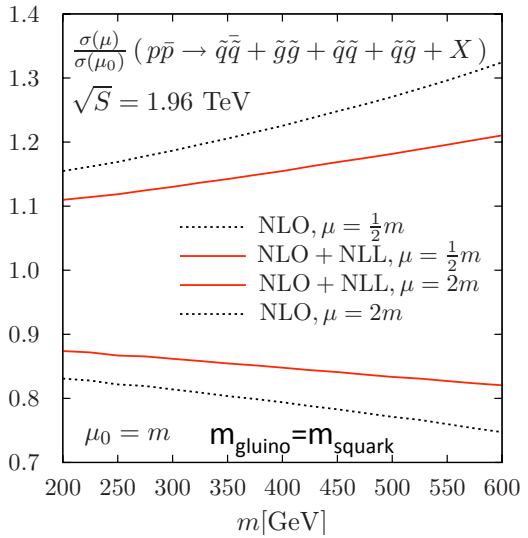
Most precise predictions for squark and gluino production rates currently available

NLL at Tevatron

- NLL resummed results also available for all four processes of squark and gluino production at the Tevatron *[Beenakker, Brensing, Krämer, A.K., Laenen, Niessen'09]*







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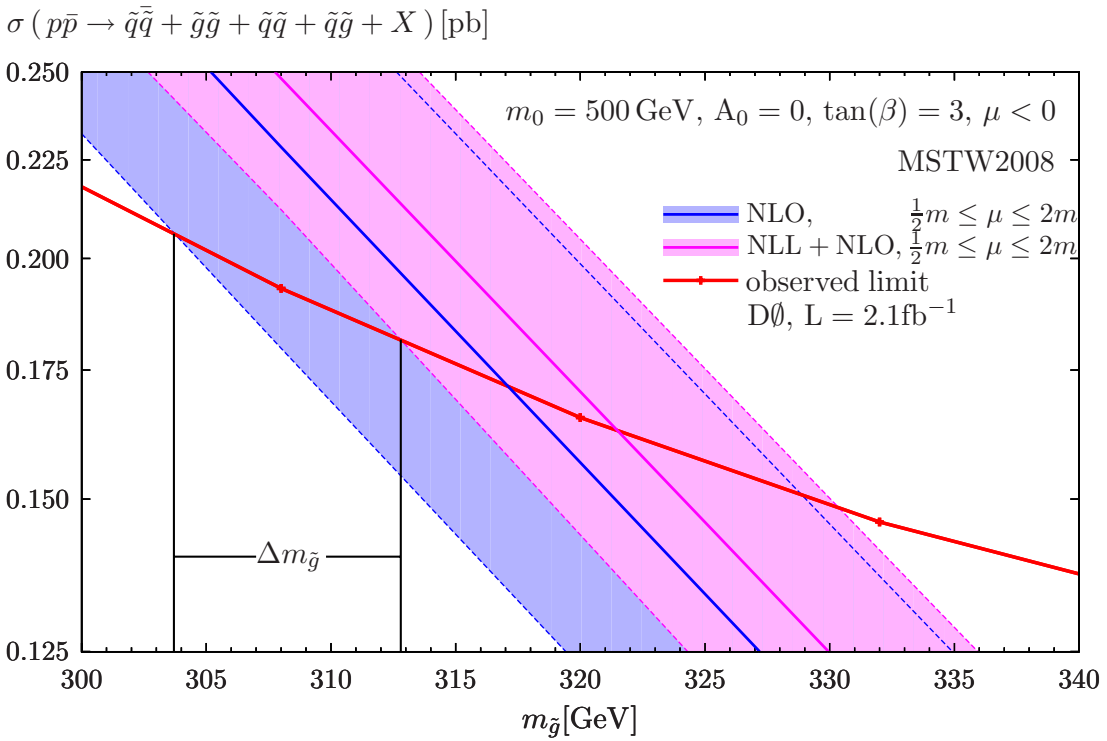
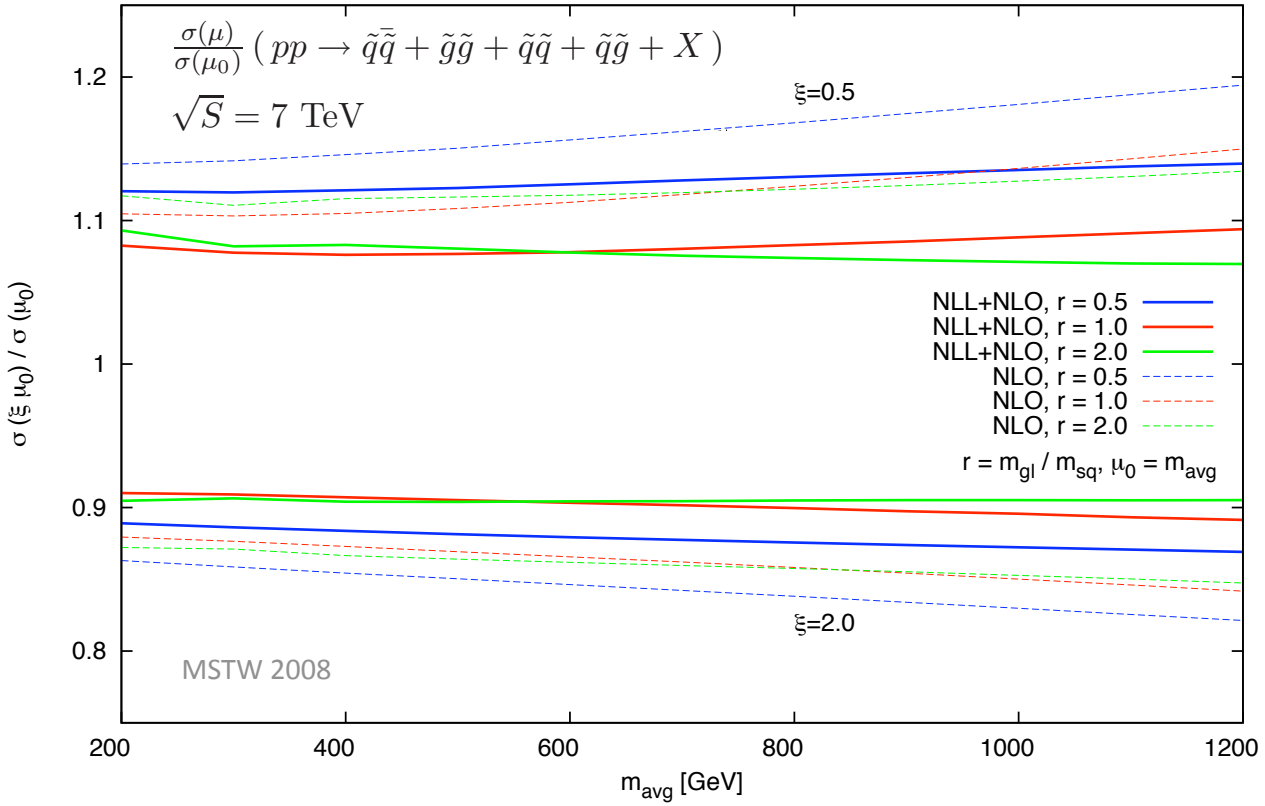
TEVATRON MASS LIMITS REVISITED

[Beenakker, Brensing, Krämer, A.K., Laenen, Niessen, in preparation]



- Reduced theory error due to scale variation
- Shift of the central value and the error band

Mass-ratio dependence



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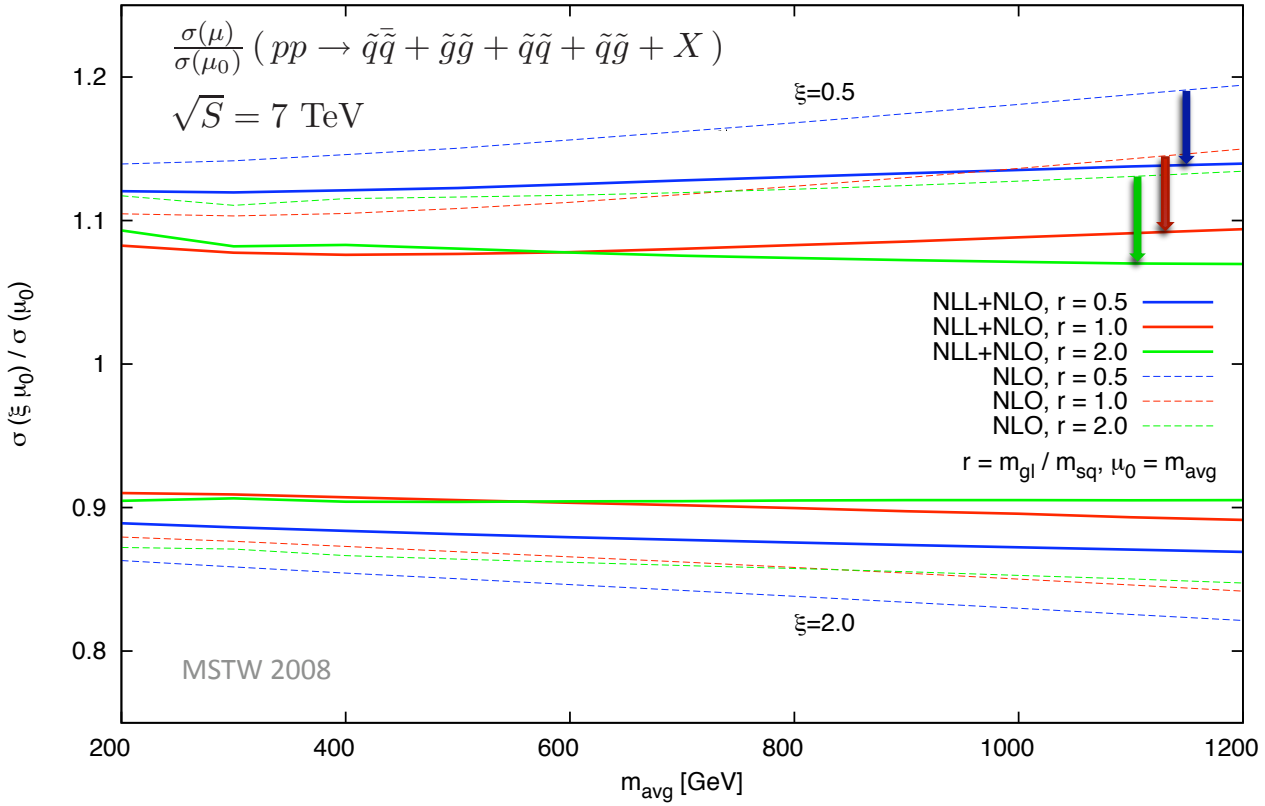
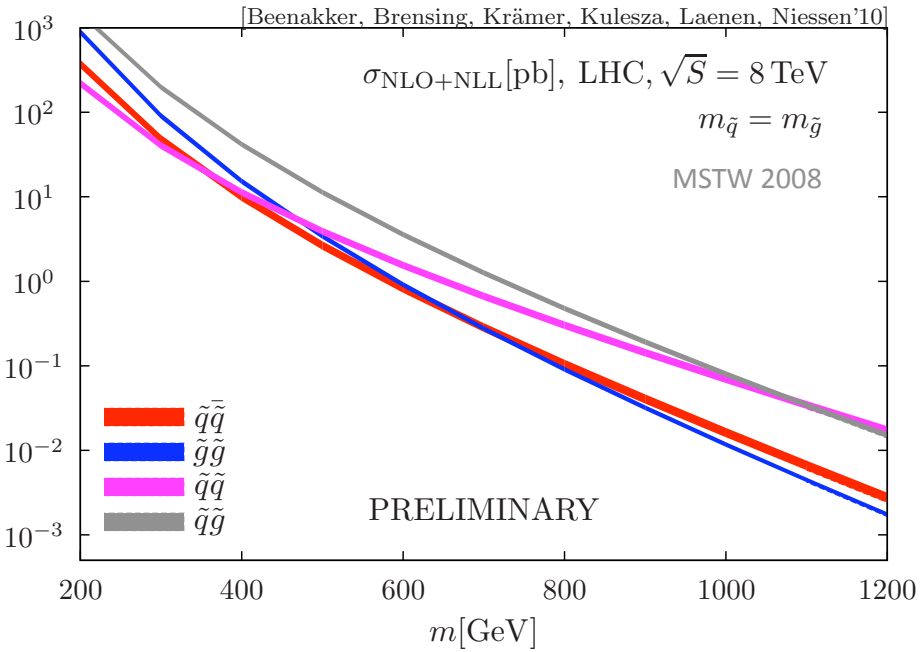


Similar reduction in the theory error due to introducing NLL corrections for various values of $r=m_{gluino}/m_{squark}$

LHC@ 8 TeV



(only theory error due to scale variation shown)

Process	$\sigma_{\mathrm{NLL+NLO}}$ (8 TeV) / $\sigma_{\mathrm{NLL+NLO}}$ (7 TeV) m = 500 GeV
$p\,p \to \tilde{q}\tilde{g}$	1.7
$p\,p \to \tilde{q}\tilde{q}$	1.4
$p\,p \to \tilde{q}\bar{\tilde{q}}$	1.7
$p\,p \to \tilde{g}\tilde{g}$	1.8

IV. STOPS

Stops

- Scalar SUSY-partners of left- and right-handed fermions mix: weak interaction eigenstates $\tilde{f}_L, \tilde{f}_R$ mix into mass eigenstates $\tilde{f}_1, \tilde{f}_2$
- The off-diagonal terms in the mixing matrix are proportional to fermion mass, m_f

Strongest mixing in the 3rd generation, in particular in the stop sector

- Stop likely to be the lightest squark

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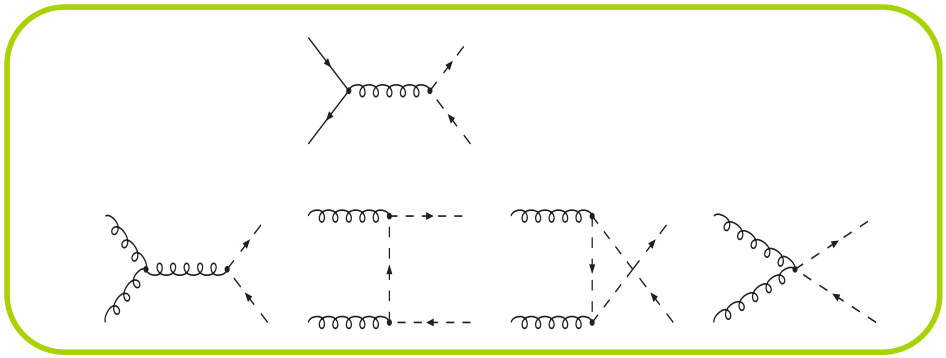
Stop-antistop



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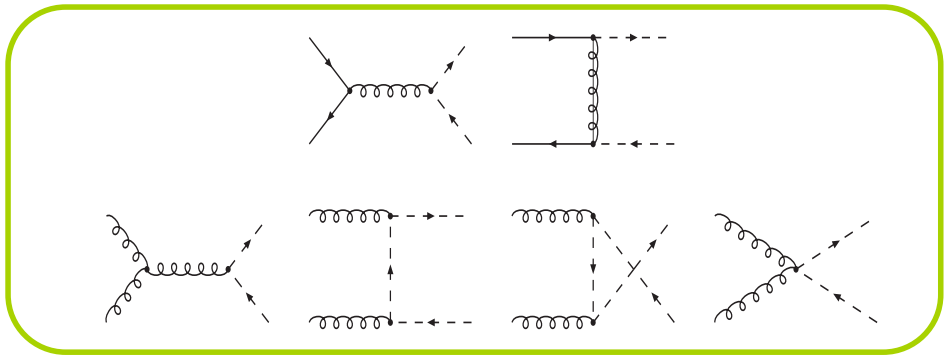
Squark-antisquark



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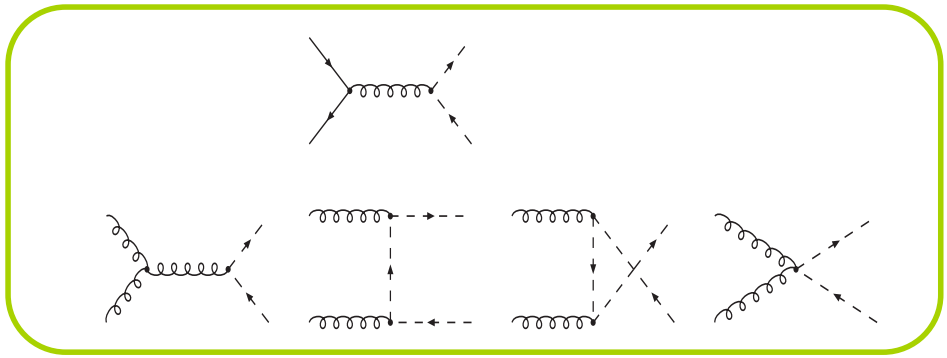


- Only diagonal i.e. $\tilde{t}_1\bar{\tilde{t}}_1$, $\tilde{t}_2\bar{\tilde{t}}_2$ pairs produced
- LO cross section depends only on the stop mass
- Note: for sbottom-pair $\tilde{b}_k\bar{\tilde{b}}_k$ production LO $b\bar{b}$ contribution negligible

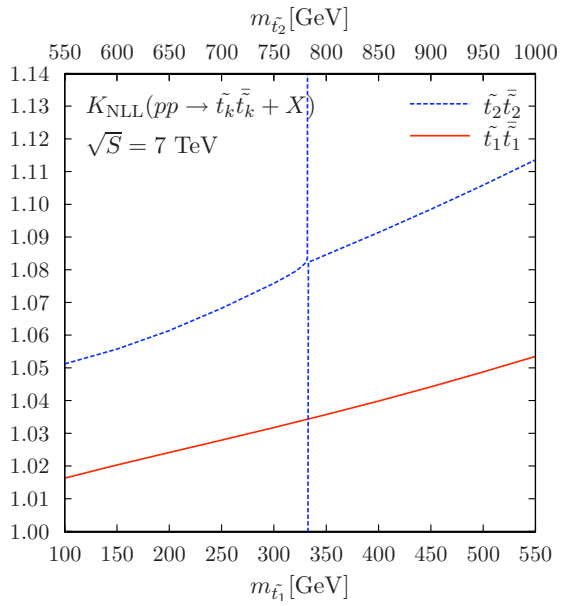
Stop Resummation

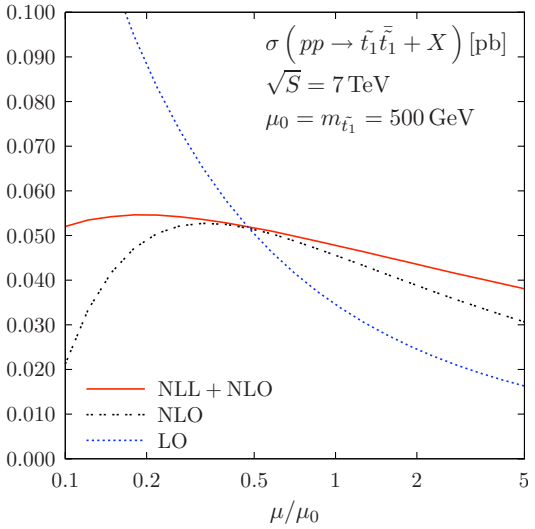
Status: NLO SUSY-QCD *[Beenakker, Krämer, Plehn, Spira, Zerwas'97]*

NNLO dominant contributions *[Langefeld'10]*

Here: NLL+NLO *[Beenakker, Brensing, Krämer, A.K., Laenen, Niessen'10]*

$$K_{\rm NLL} = \frac{\sigma^{\rm resummed,NLL}}{\sigma^{\rm NLO}}$$

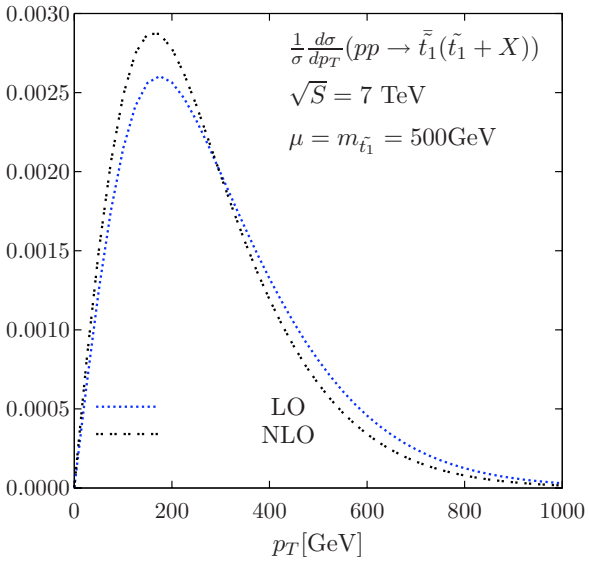


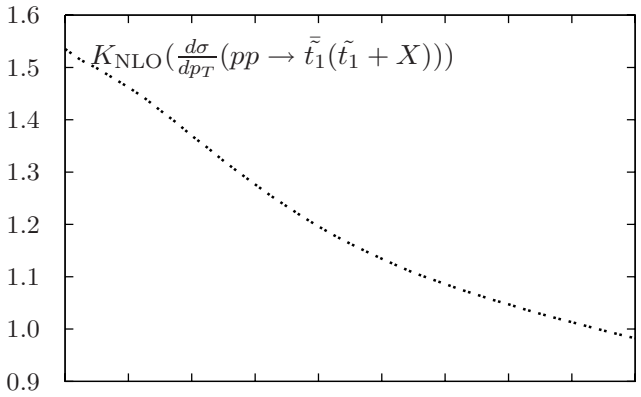


Reduction of the scale dependence for NLO+NLL predictions, compared with NLO

STOP p_T DISTRIBUTION

[Beenakker, Höpker, Spira, Zerwas'97]
[Beenakker, Brensing, Krämer, A.K., Laenen, Niessen'10]





K-factors for transverse momentum distributions are not constant and depend on p_T!

Resummation for p_T distributions

- Transverse momentum distributions contain logarithmic terms which become large in the threshold limit

$$\frac{d\sigma}{dp_T} \sim \frac{d\sigma^{(0)}}{dp_T} \sum_n \alpha_s^n \sum_{k=0}^{2n-1} C_{nk} \log^{k+1}(\beta)\,, \qquad \beta = \sqrt{1 - \frac{4m_T^2}{\hat{s}}} \qquad m_T = \sqrt{m^2 + p_T^2}$$

- Same structure of the threshold resummed cross section in the Mellin moment space (moments taken wrt. $4m_T^2/S$) , soft anomalous dimension a function of p_T.

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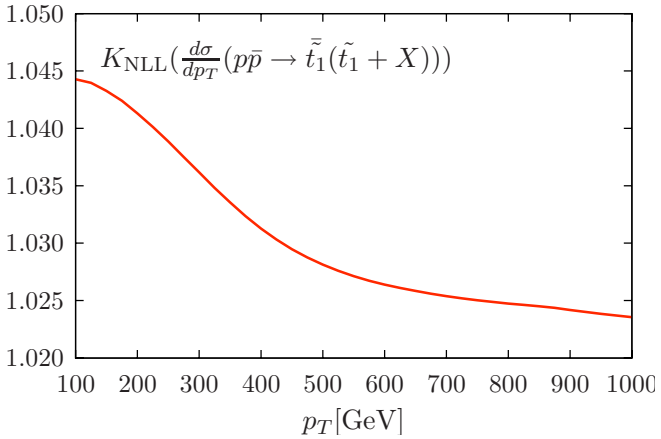

[Beenakker, Brensing, Krämer, A.K., Laenen, Niessen'10]

Summary

- Processes involving squarks and gluinos are the most relevant SUSY production channels at the LHC
- Results for the threshold-resummed total cross section at NLL+NLO available for all four processes of squark and gluino production, as well as stop-pair production
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CMS search for long-lived gluinos
arXiv 1011.5861