Squark and Gluino Production at the LHC

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
W. Beenakker, S. Brensing, M. Krämer, AK, E. Laenen, L.Motyka and I. Niessen, arXiv:1105.1110
and work in progress

Loopfest X, Northwestern University, 12-14.05.2011

Outline

- Motivation
- Theoretical status
  - NLL resummation for squark and gluino production
- Predictions for total cross sections at 7 TeV
- Summary

I. MOTIVATION

Squarks and Gluinos at Hadron Colliders

MSSM:
minimal content of SUSY particles + R-parity

Hadron colliders:
coloured sparticles most copiously produced

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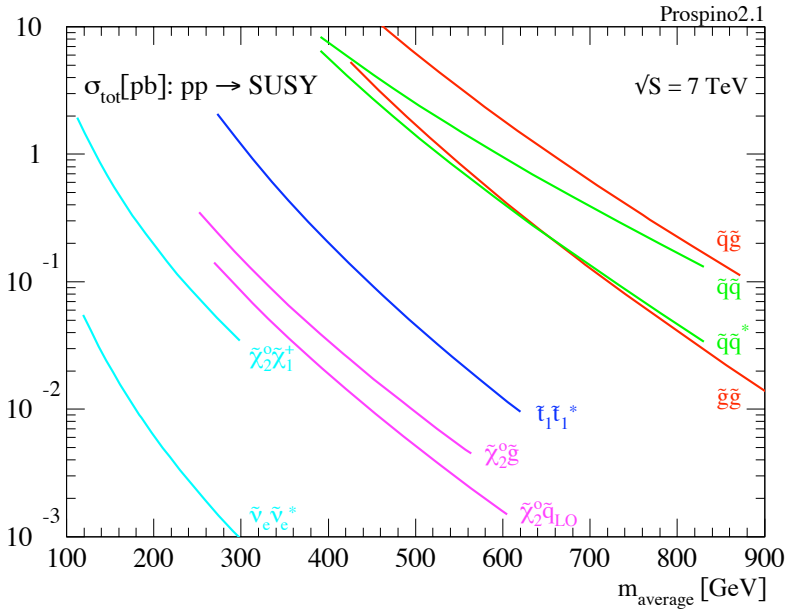
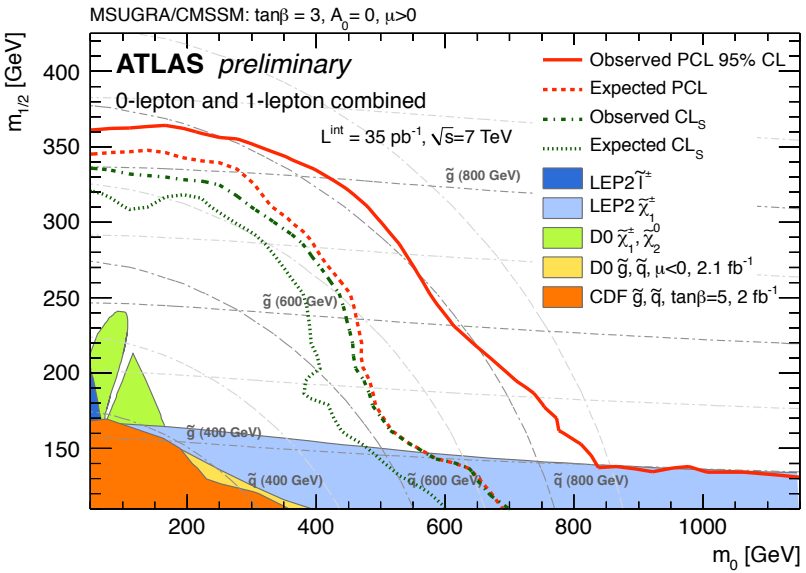
Key discovery processes in SUSY searches

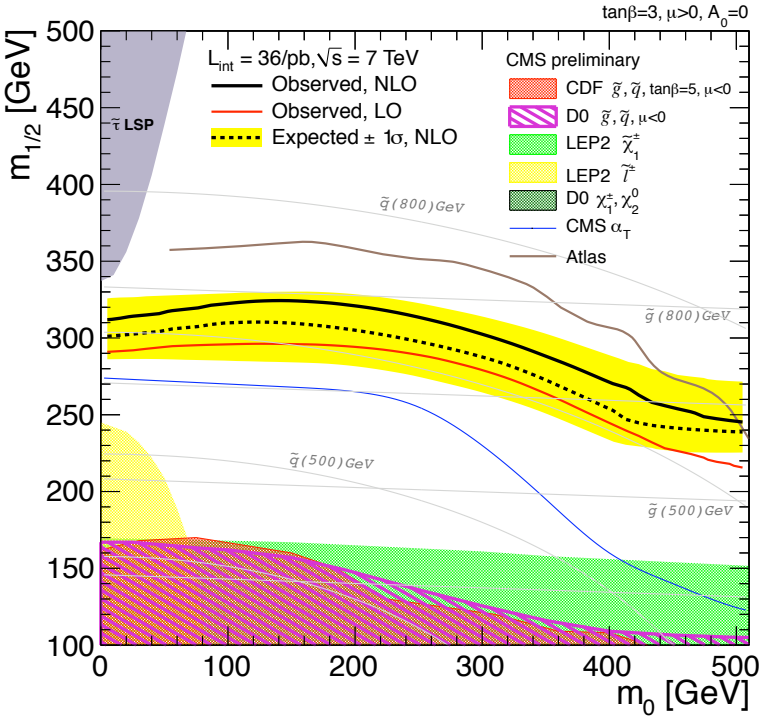


LHC Searches

[ATLAS-CONF-2011-064]

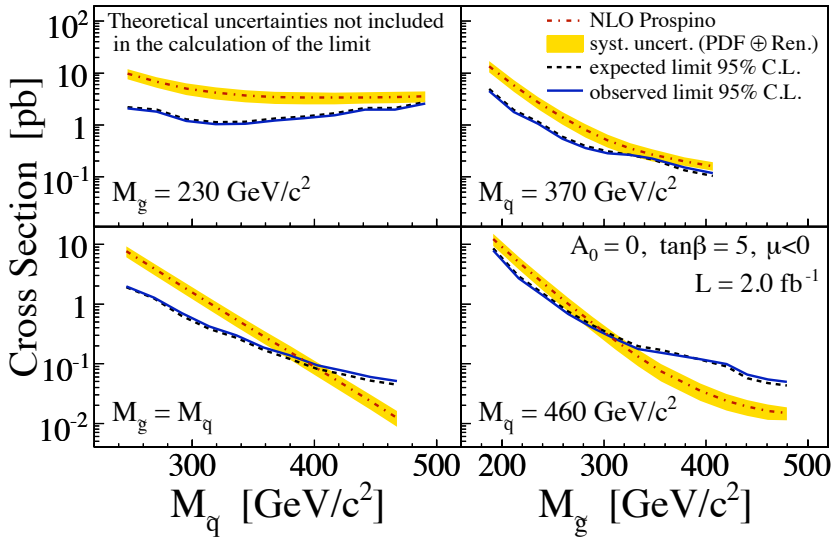


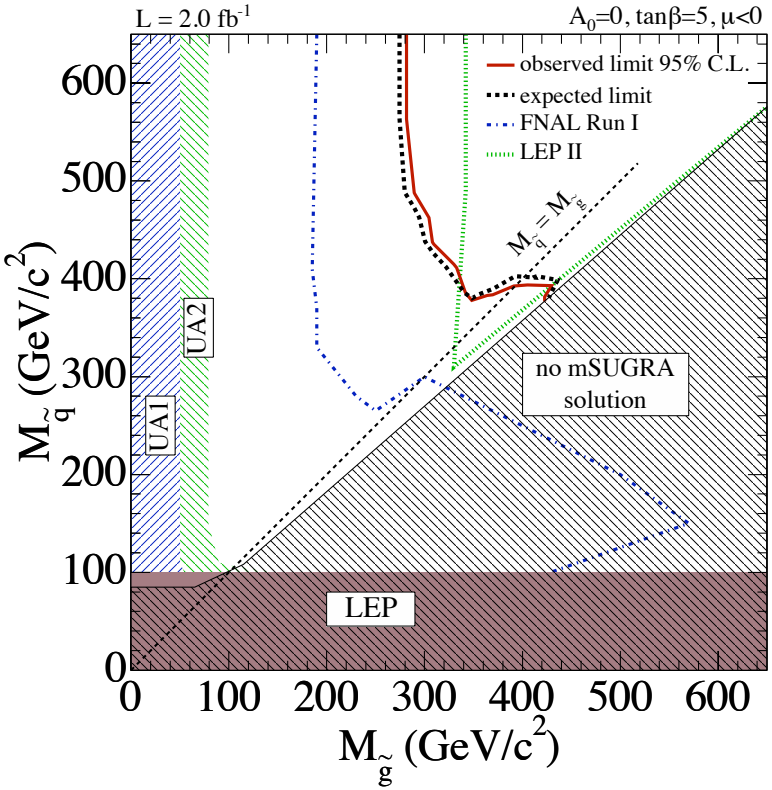
[CMS-PAS-SUS-10-005]



REMINDER: TEVATRON SEARCHES

[CDF, Phys. Rev. Lett. 102, 121801 (2009)]





Information on total production cross sections for squarks and gluinos crucial for determination of mass limits in case of no discovery

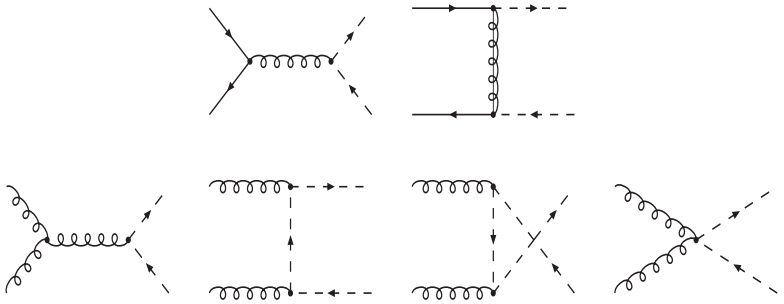
II. THEORETICAL CALCULATIONS

Partonic subprocesses

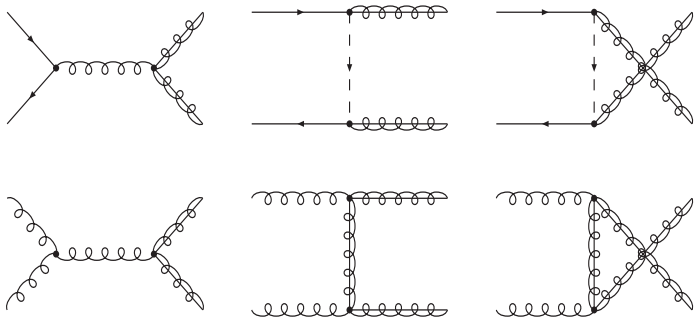
[Kane, Leveille'82][Harrison, Llewellyn Smith'84][Dawson, Eichten, Quigg'85]

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

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



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



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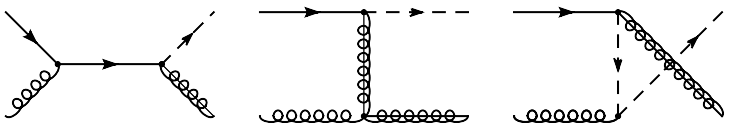

Theoretical Status: Fixed Order

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 and stop-antistop production: dominant NNLO contributions (NNLL-NNLO, Coulomb, scale dependence) → $\mathcal{O}(\alpha_s^4)$ *[Langenfeld, Moch'09] [Langenfeld'10]*
- 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]] [Germer, Hollik, Mirabella'11]*

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Tree-level EW effects $\mathcal{O}(\alpha_s\,\alpha)$ and $\mathcal{O}(\alpha^2)$

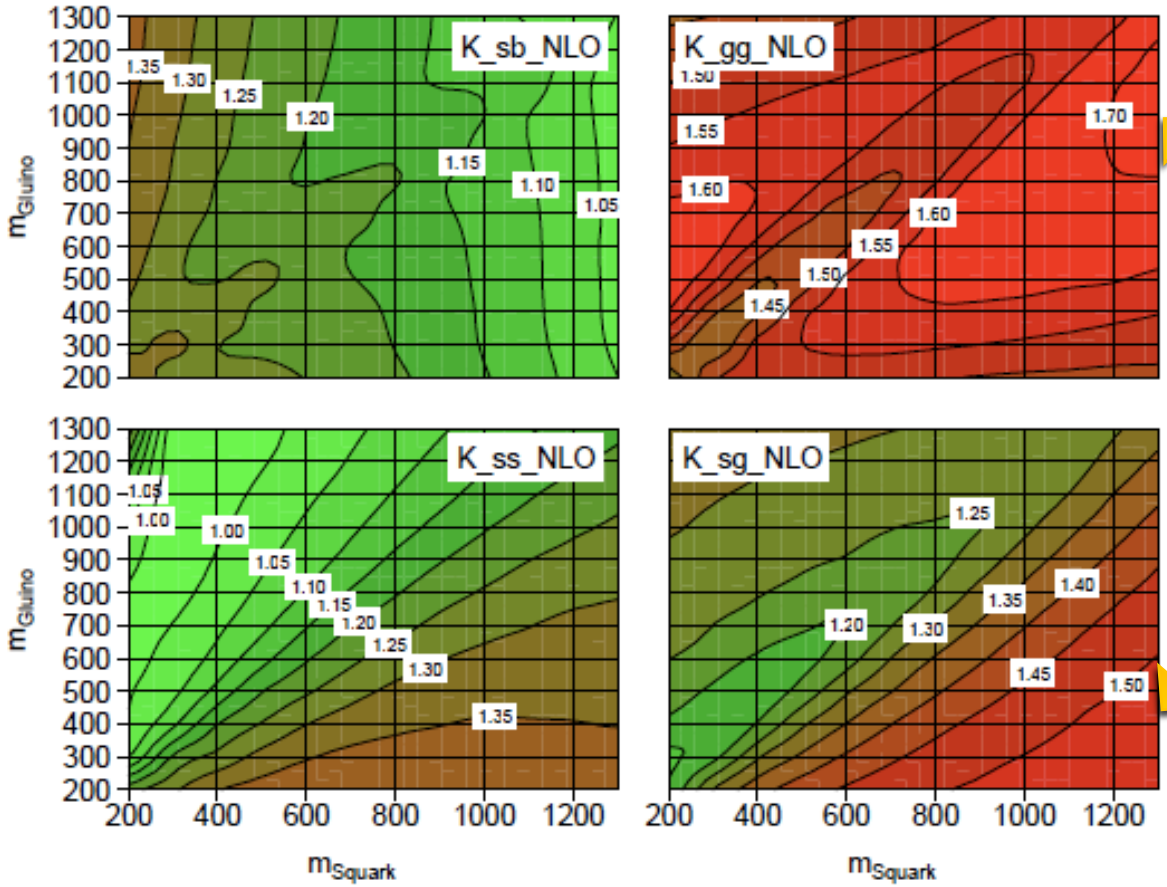
- QCD-EW interference and photon-induced contributions, tree-level EW *[Bornhauser et al.'07][Alan, Cankocak, Demir'07] [Hollik, Kollar, Trenkel'07][Hollik, Mirabella'08] [Hollik, Mirabella, Trenkel'08] [Bozzi, Fuks, Klasen'05] [Germer, Hollik, Mirabella, Trenkel'10] [Germer, Hollik, Mirabella'11]*

→ W. Hollik's talk

LO vs NLO

NLO SUSY QCD K-factors, LHC @ 7 TeV

[Beenakker, Höpker, Spira, Zerwas'97]



Large NLO K-factors, in particular for gluino-pair and squark-gluino production

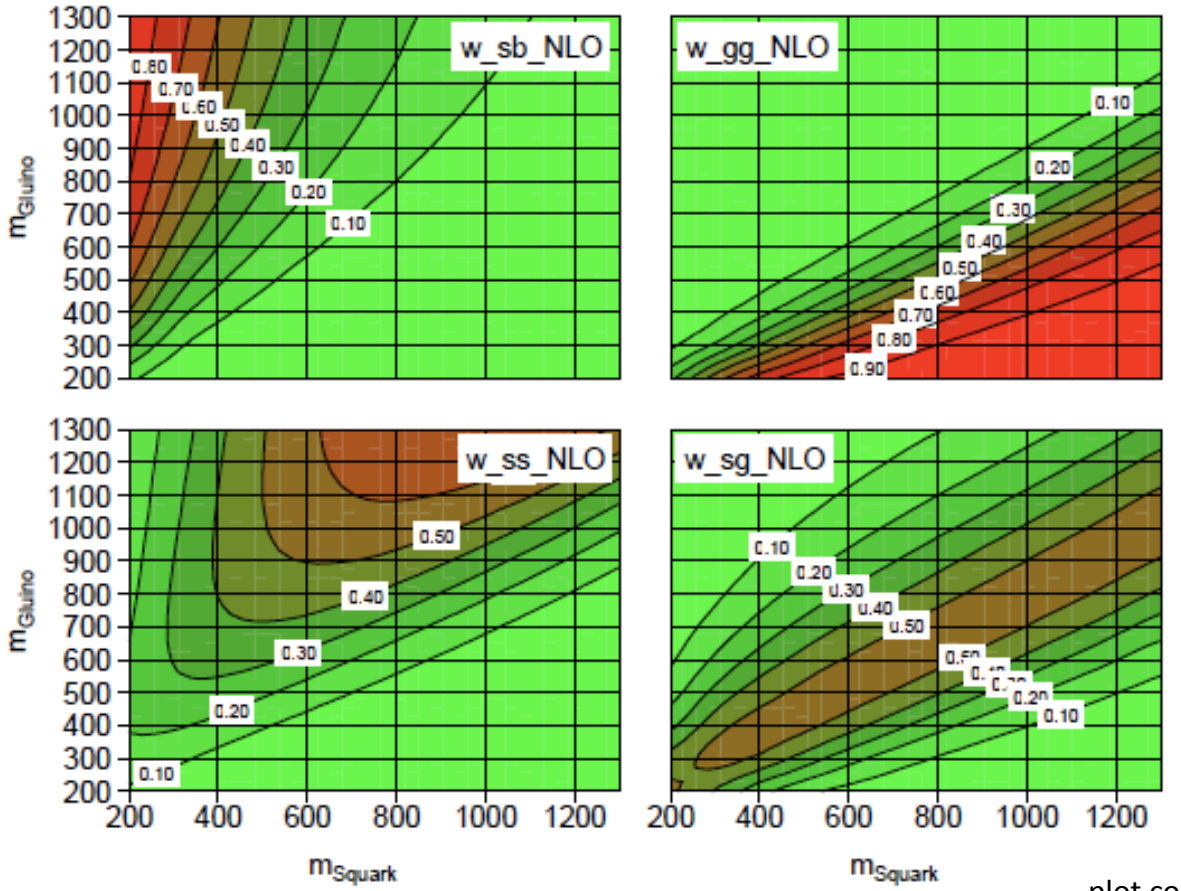
SUSY-QCD: only m_{squark} and m_{gluino} dependence

plot courtesy of S. Brensing

NLO

NLO SUSY QCD, LHC @ 7 TeV

[Beenakker, Höpker, Spira, Zerwas'97]



Importance of a process depends on relation between squark and gluino masses

Relative weights

$$w\_x\_NLO = \frac{\sigma(x)}{\sum_y \sigma(y)}$$

plot courtesy of S. Brensing

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]*

→ Bound-state effects and Coulomb corrections for $\tilde{g}\tilde{g}$ *[Hagiwara, Yokoya'09] [Kauth, Kühn, Marquard, Steinhauser'10]*

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

→ Ch. Schwinn's talk

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

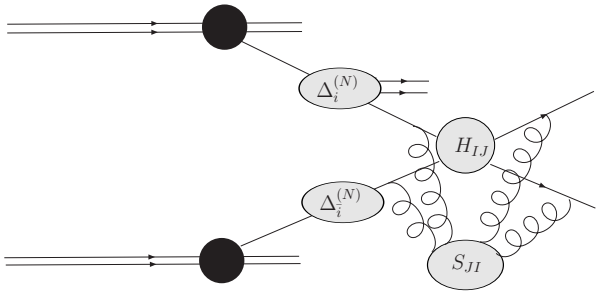
$$\hat{\sigma}^{(N)}_{ij\to kl}(\{m^2\},\mu^2) = \int_0^1 d\hat{\rho}\, \hat{\rho}^{N-1}\, \hat{\sigma}_{ij\to kl}(\hat{\rho},\{m^2\},\mu^2)$$

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

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

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

Threshold Resummation For Squarks And Gluinos



- All-order factorization of soft and collinear emission

  Schematically, in *N* space

$$\sigma \sim H(\text{off} - \text{shell}) \times \Delta_i(\text{col}) \times \Delta_j(\text{col}) \times S_{ij}(\text{soft})$$

- Exponentiation from solving RGEs

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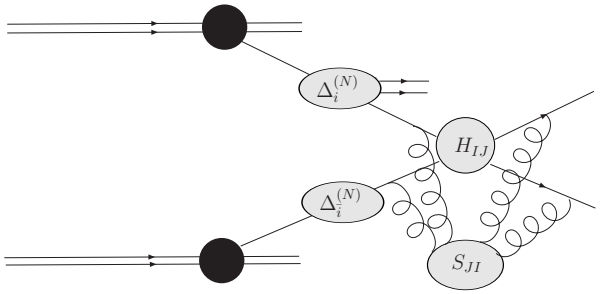

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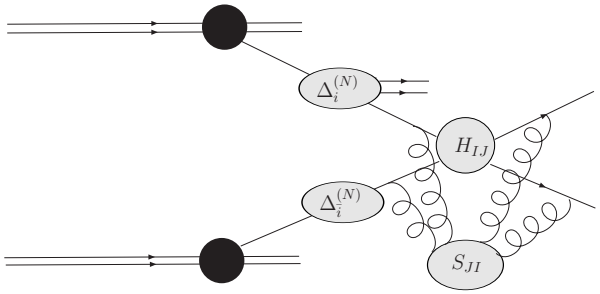
$$\begin{array}{llll} \tilde{q}\bar{\tilde{q}} & \mathbf{3} \otimes \bar{\mathbf{3}} & = & \mathbf{1} \oplus \mathbf{8} \\ \tilde{q}\tilde{q} & \mathbf{3} \otimes \mathbf{3} & = & \bar{\mathbf{3}} \oplus \mathbf{6} \\ \tilde{q}\tilde{g} & \mathbf{3} \otimes \mathbf{8} & = & \mathbf{3} \oplus \bar{\mathbf{6}}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

Threshold Resummation For Squarks And Gluinos



- All-order factorization of soft and collinear emission

$$\sigma_{ij\to kl}^{(N)} = \underbrace{H_{ij\to kl,IJ}^{(N)}}_{\text{hard function}} \times \underbrace{\Delta_i^{(N)}\Delta_j^{(N)}}_{\text{soft- collinear radiation}} \times \underbrace{S_{ij\to kl,JI}}_{\text{soft wide-angle emission}}$$

universal factors; KNOWN

process-dependent

- Exponentiation from solving RGEs

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  - *H, S* are matrices in colour space

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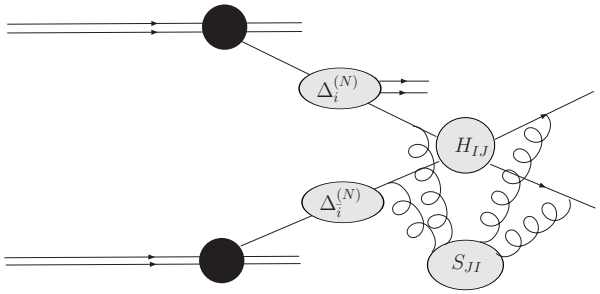

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universal factors; KNOWN — process-dependent

- Exponentiation from solving RGEs

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

- Complication: colour structure
  - *H, S* are matrices in colour space

Need to know soft anomalous dimension matrix Γ_{IJ}

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]*

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

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 threshold 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]*
  - (By now, anomalous dimensions known at 2 loops for massless *[Mert Aybat, Dixon, Sterman'06]* and massive case *[Mitov, Sterman, Sung'09-'10][Ferroglia, Neubert, Pecjak, Yang'09] [Beneke, Falgari, Schwinn'09], [Czakon, Mitov, Sterman'09] [Kidonakis'10]* and higher *[Becher, Neubert'09] [Gardi, Magnea'09] [Dixon,Gardi, Magnea'09]*)

Soft anomalous dimensions

- Need 1-loop anomalous dimension matrices in order to resum up to NLL
- Γ_{ij} for 2→2 processes with nontrivial colour structure and massive particles in the final state ⇒ full set of $D^{(1)}$ coefficients for squark and gluino production processes

$$
\begin{aligned}
D^{(1)}_{q\bar{q}\to\bar{q}\bar{q},\,I} &= \{0,-3\} && I=\{\mathbf{1},\mathbf{8}\}\\
D^{(1)}_{gg\to\bar{q}\bar{q},\,I} &= \{0,-3\} && I=\{\mathbf{1},\mathbf{8}\}\\
D^{(1)}_{q\bar{q}\to g\bar{g},\,I} &= \{0,-3,-3\} && I=\{\mathbf{1},\mathbf{8_S},\mathbf{8_A}\}\\
D^{(1)}_{gg\to g\bar{g},\,I} &= \{0,-3,-3,-6,-8\} && I=\{\mathbf{1},\mathbf{8_S},\mathbf{8_A},\mathbf{10}\oplus\overline{\mathbf{10}},\mathbf{27}\}\\
D^{(1)}_{qq\to\bar{q}\bar{q},\,I} &= \{-4/3,-10/3\} && I=\{\bar{\mathbf{3}},\mathbf{6}\}\\
D^{(1)}_{qg\to\bar{q}g,\,I} &= \{-4/3,-10/3,-16/3\} && I=\{\mathbf{3},\bar{\mathbf{6}},\mathbf{15}\}
\end{aligned}
$$

- $D^{(1)}$ 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/]*

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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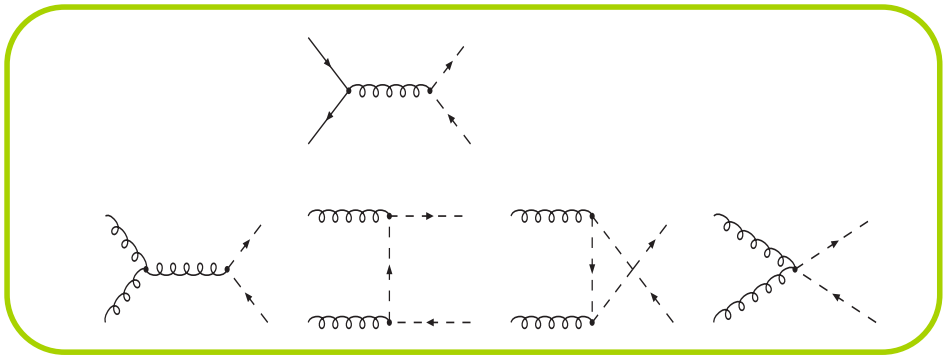
- At leading order

Stop-antistop



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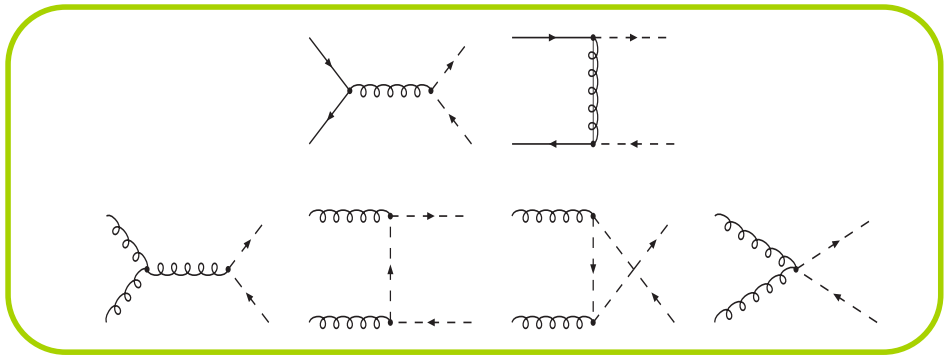
Squark-antisquark



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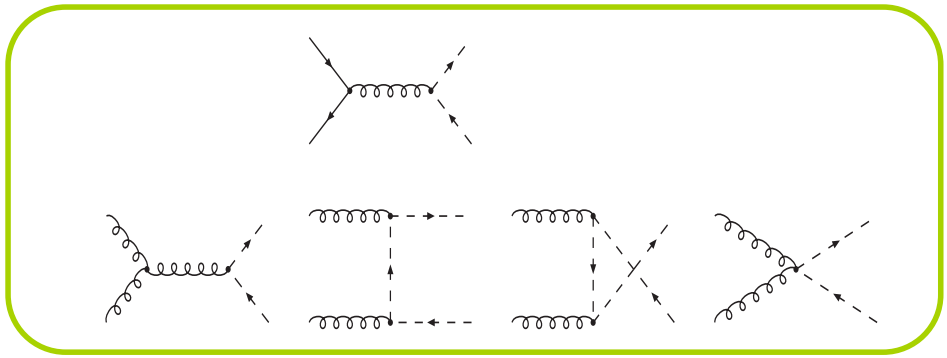
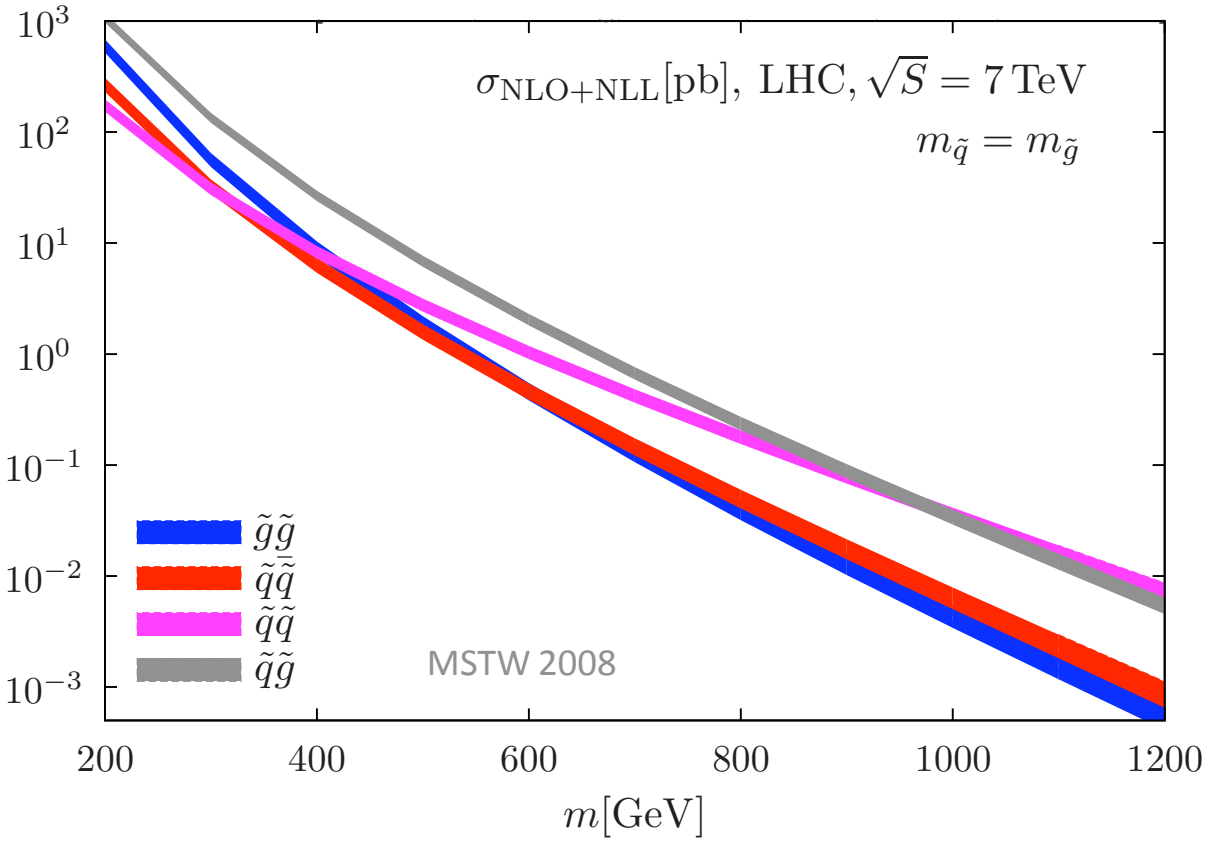


- Only diagonal i.e. $\tilde{t}_1\bar{\tilde{t}}_1$, $\tilde{t}_2\bar{\tilde{t}}_2$ pairs produced
- LO cross section depends only on the stop mass
- Note: for sbottom-pair $\tilde{b}_k\bar{\tilde{b}}_k$ production LO $b\bar{b}$ contribution negligible

III. RESULTS FOR 7 TEV

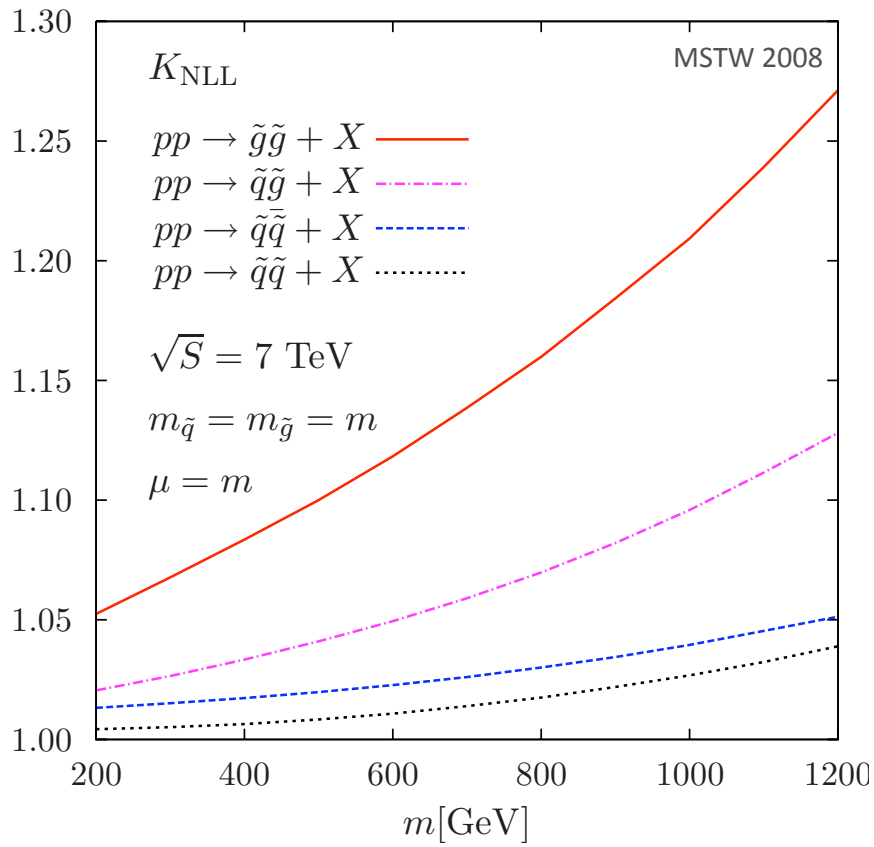
TOTAL NLL+NLO PRODUCTION RATES



Width of the bands: theory error due to scale variation $0.5 < \mu/m < 2$,
68% C.L. pdf error and α_s error

NLL Corrections

[W. Beenakker, S. Brensing, M. Krämer, AK, E. Laenen, L.Motyka and I. Niessen, arXiv:1105.1110]



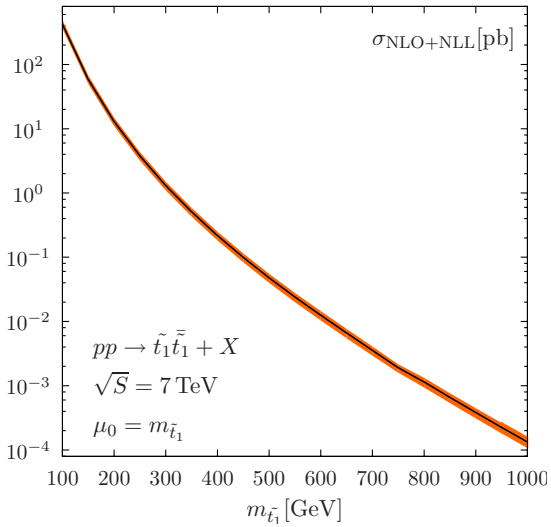
$$K_{\rm NLL} = \frac{\sigma^{\rm resummed,NLL}}{\sigma^{\rm NLO}}$$

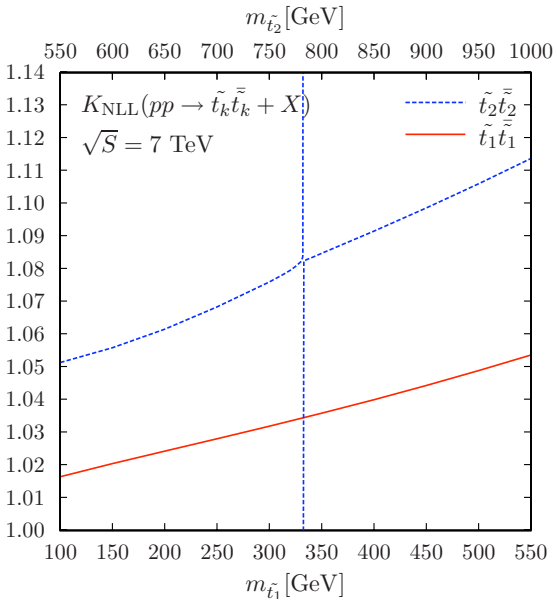
- Soft-gluon resummation enhances the cross sections
- Highest corrections for the gluino-pair production: 20% correction to the NLO results for m_{gl}= 1 TeV
- For the squark-gluino channel, NLL correction reaches 10% at m_{sq}= m_{gl}= 1 TeV

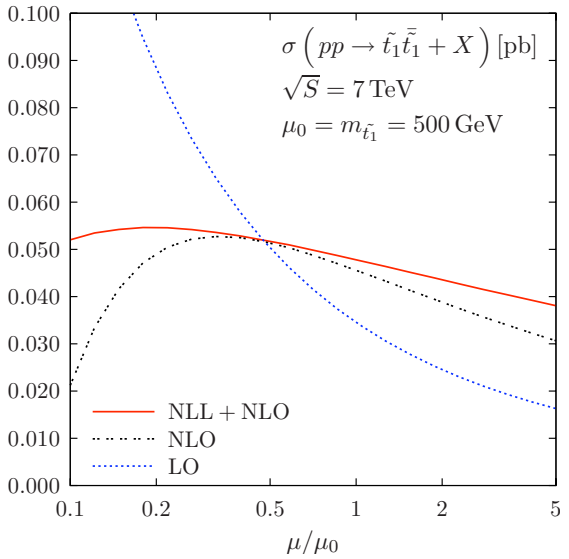
Stop Resummation

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]*





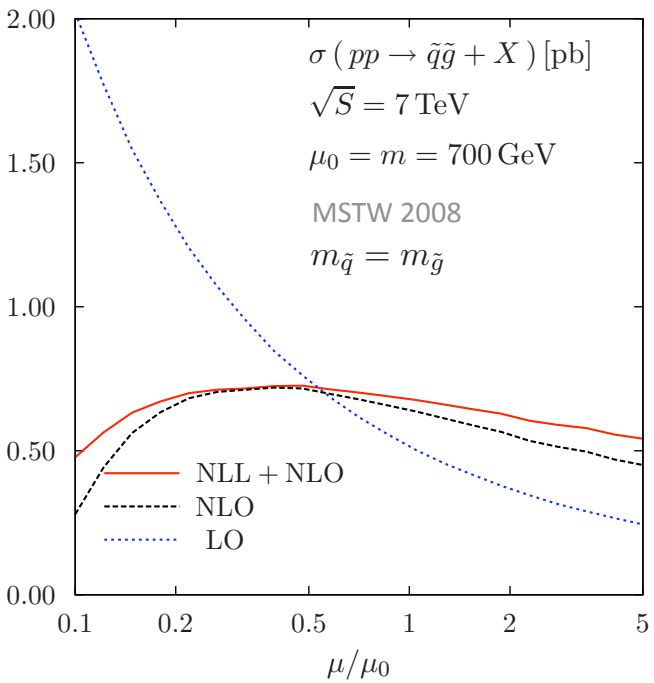


Reduction of the scale dependence for NLO+NLL predictions, compared with NLO

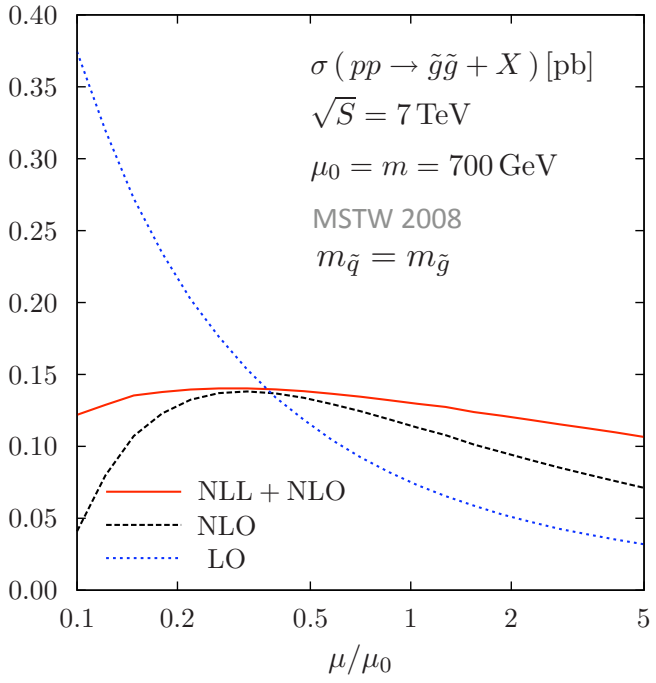
Scale variation

[W. Beenakker, S. Brensing, M. Krämer, AK, E. Laenen, L.Motyka and I. Niessen, arXiv:1105.1110]

- Squark-gluino production



- Gluino-pair production

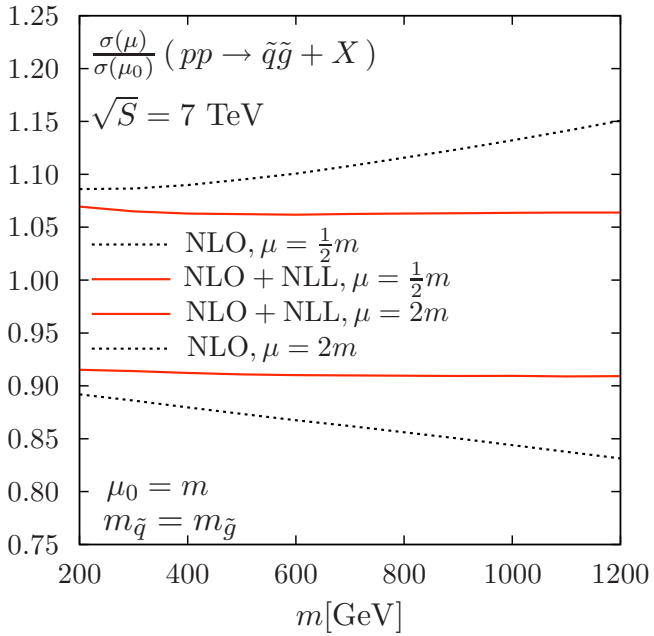


Significant reduction of the scale dependence for NLL+NLO compared to NLO, especially for gluino-pair production

Scale variation ctnd.

[W. Beenakker, S. Brensing, M. Krämer, AK, E. Laenen, L.Motyka and I. Niessen, arXiv:1105.1110]

- Squark-gluino production



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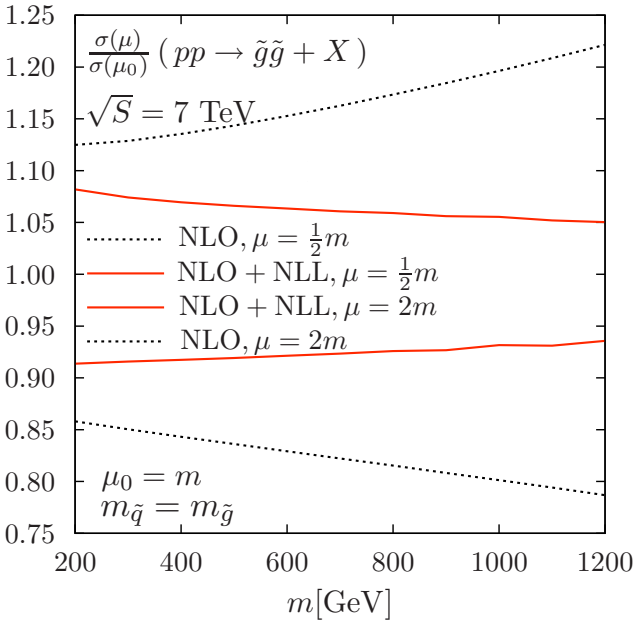
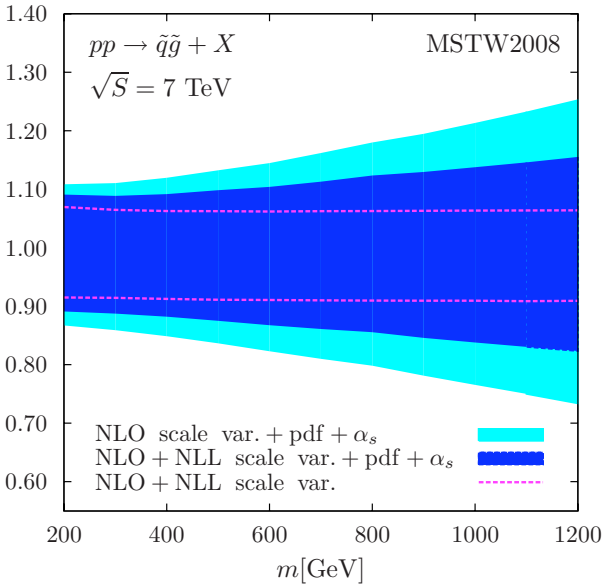


Theory error due to scale variation below 10% for NLL+NLO
down by a factor of 2 (squark-gluino) or a factor of 4 (gluino-pair) for masses > 1 TeV

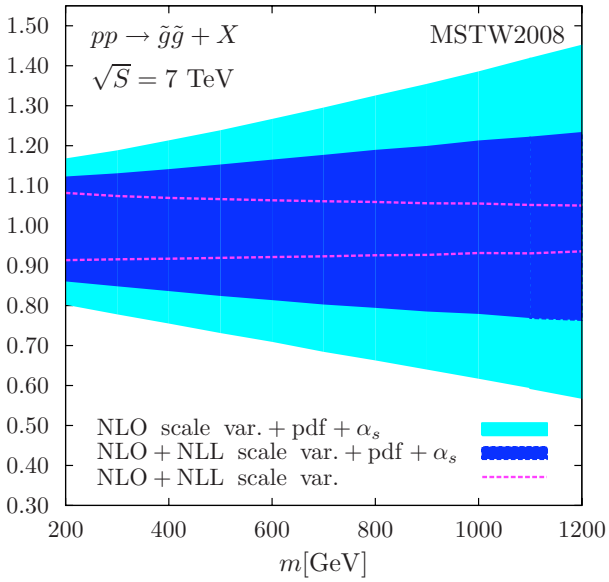
Theory Error

[W. Beenakker, S. Brensing, M. Krämer, AK, E. Laenen, L.Motyka and I. Niessen, arXiv:1105.1110]

- Squark-gluino production

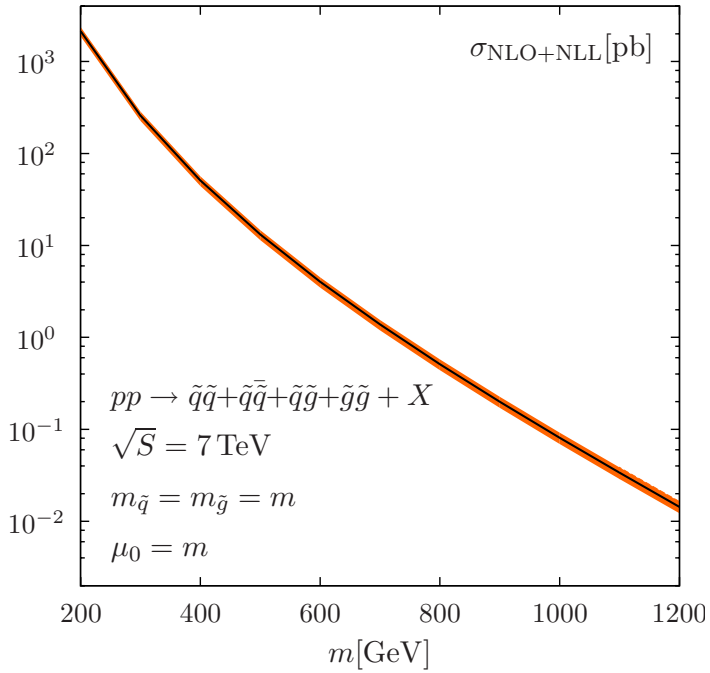


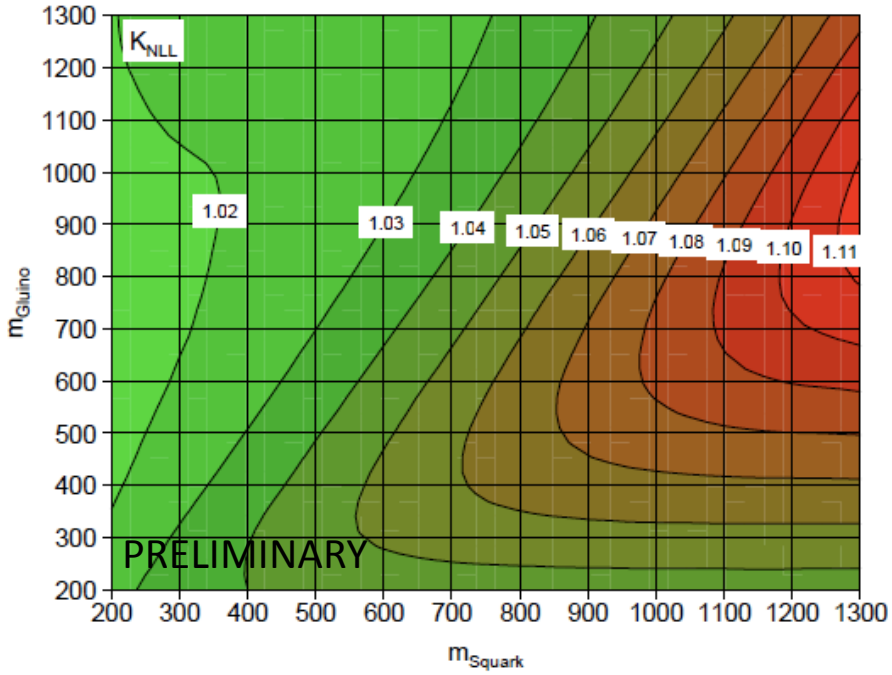
- Gluino-pair production



Significant improvement for the full theory error due to reducing the scale variation!

Total Inclusive Cross Section @ 7 TeV



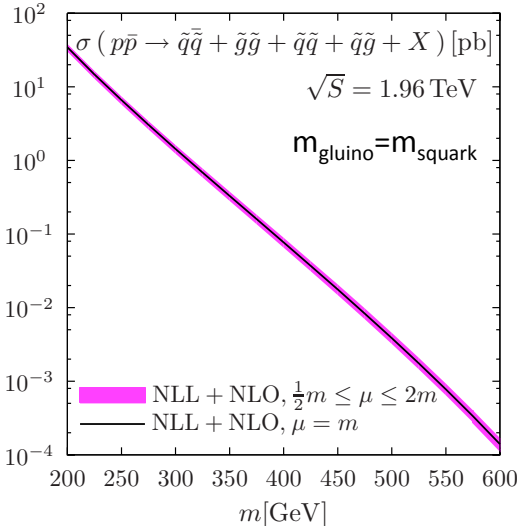


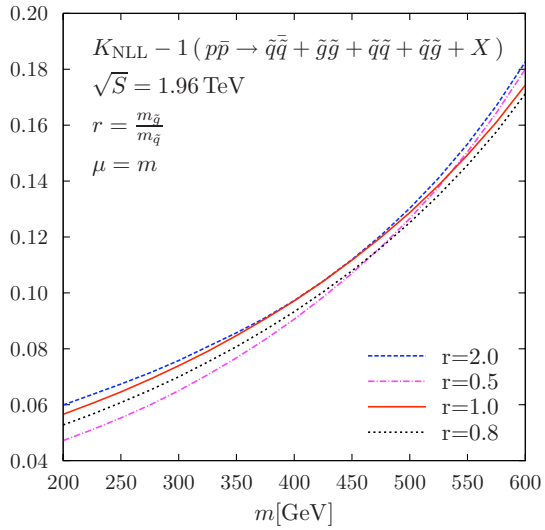
plot courtesy of S. Brensing

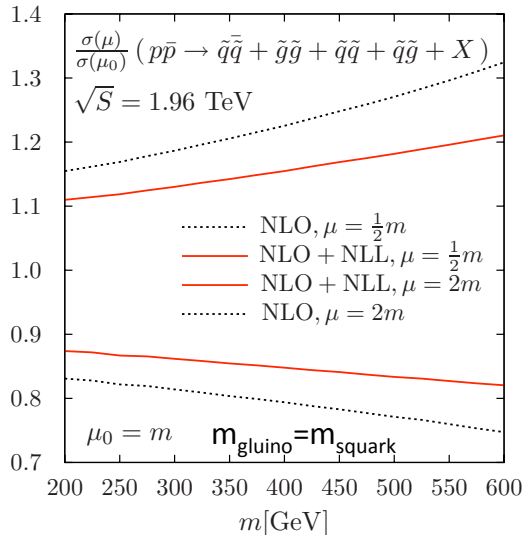
Most precise predictions for squark and gluino production rates currently available

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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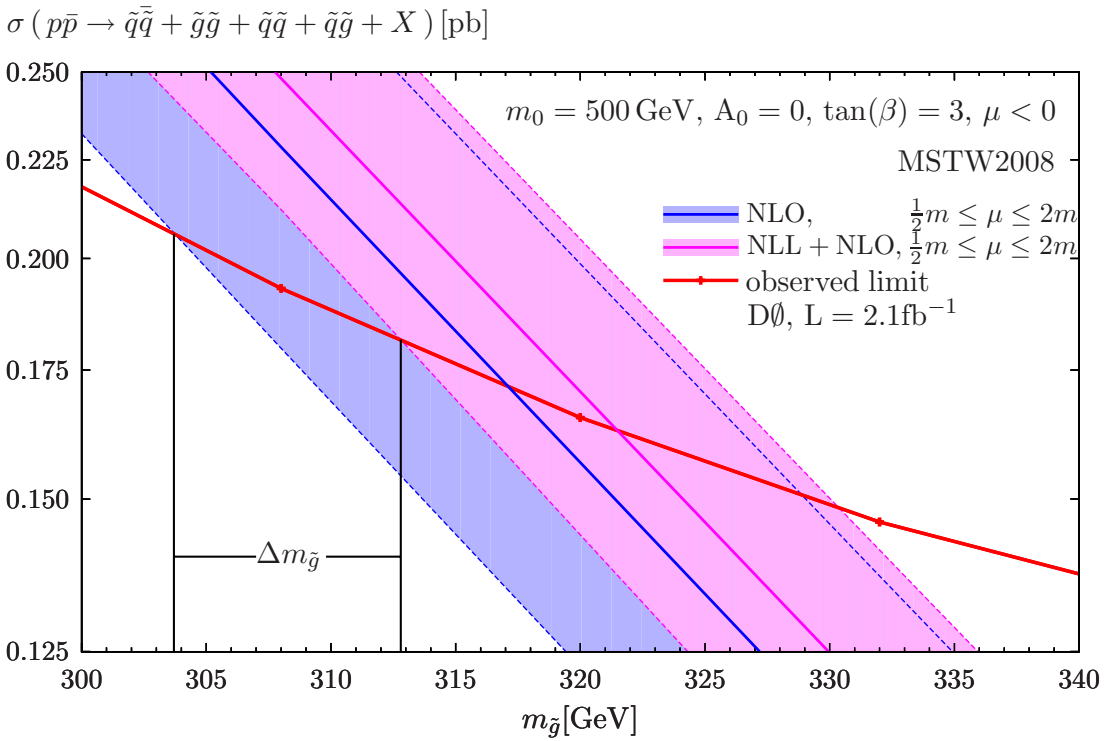
TEVATRON MASS LIMITS REVISITED



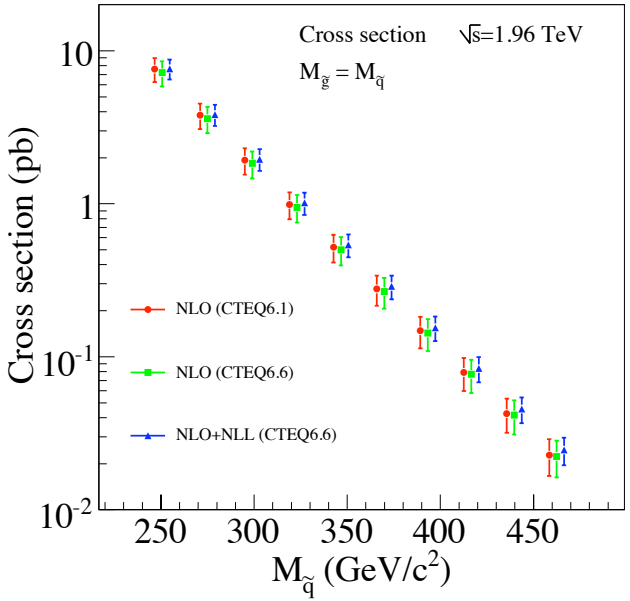
- Reduced theory error due to scale variation
- Shift of the central value and the error band

TEVATRON MASS LIMITS REVISITED

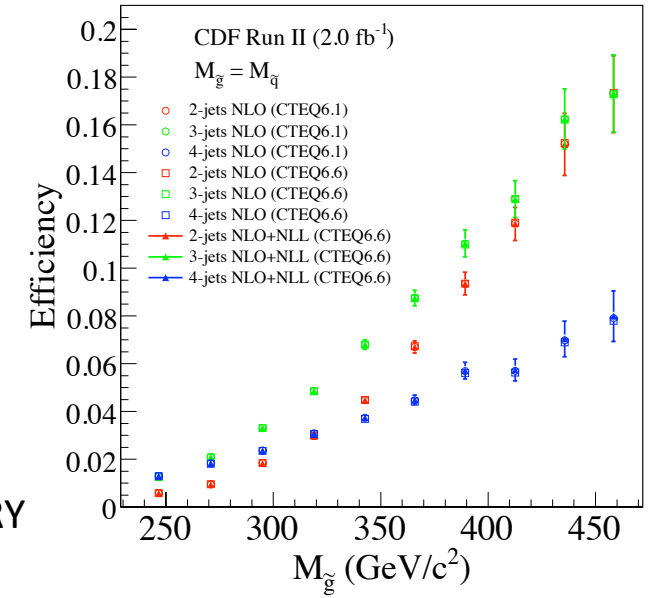
- More advanced study needed to fully determine the impact on the Tevatron exclusion bounds → improved analysis of the CDF mass bounds

[Beenakker, Brensing, D'Onofrio, Krämer, A.K., Laenen, Martinez, Niessen, in preparation]

- Cross sections change



- Signal selection efficiencies can change



PRELIMINARY

- Last word on mass exclusion limits from Tevatron : for equal squark and gluino masses improvement of 5-8% on previous values

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 pair-production, as well as stop-pair production
- Significant reduction of the theory error due to scale variation
- NLL+NLO results are the most accurate predictions currently available for all channels of squark and gluino production, should be used for determination of mass limits at the LHC

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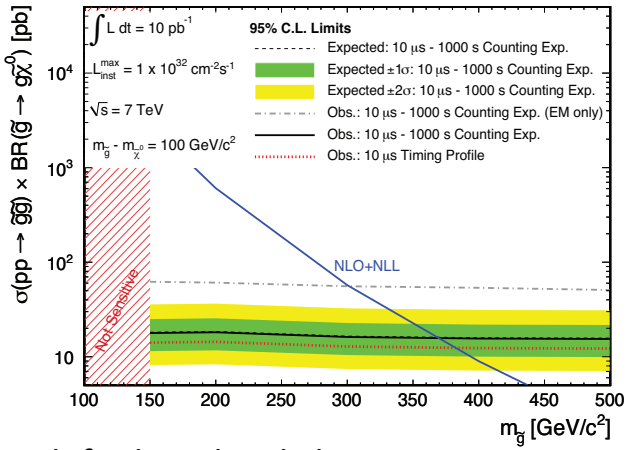

CMS search for long-lived gluinos, arXiv 1011.5861

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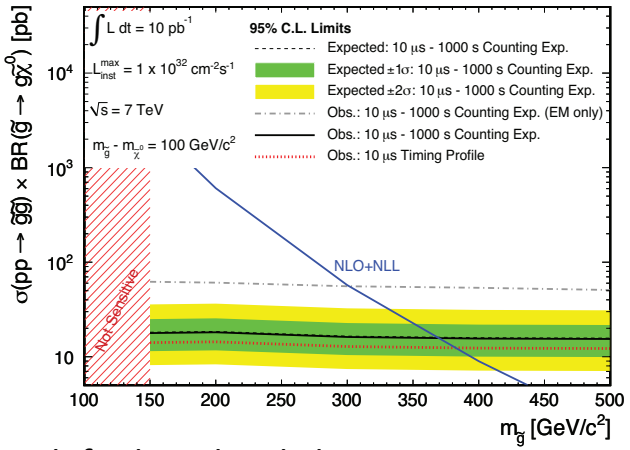

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