Improving Predictions for Squark and Gluino Production at the LHC with the Help of Soft Gluon Resummation

Anna Kulesza

RWTH AACHEN

AK and L. Motyka, Phys. Rev. Lett. 102, 111802 (2009), Phys. Rev. D 80 (2009) 095004

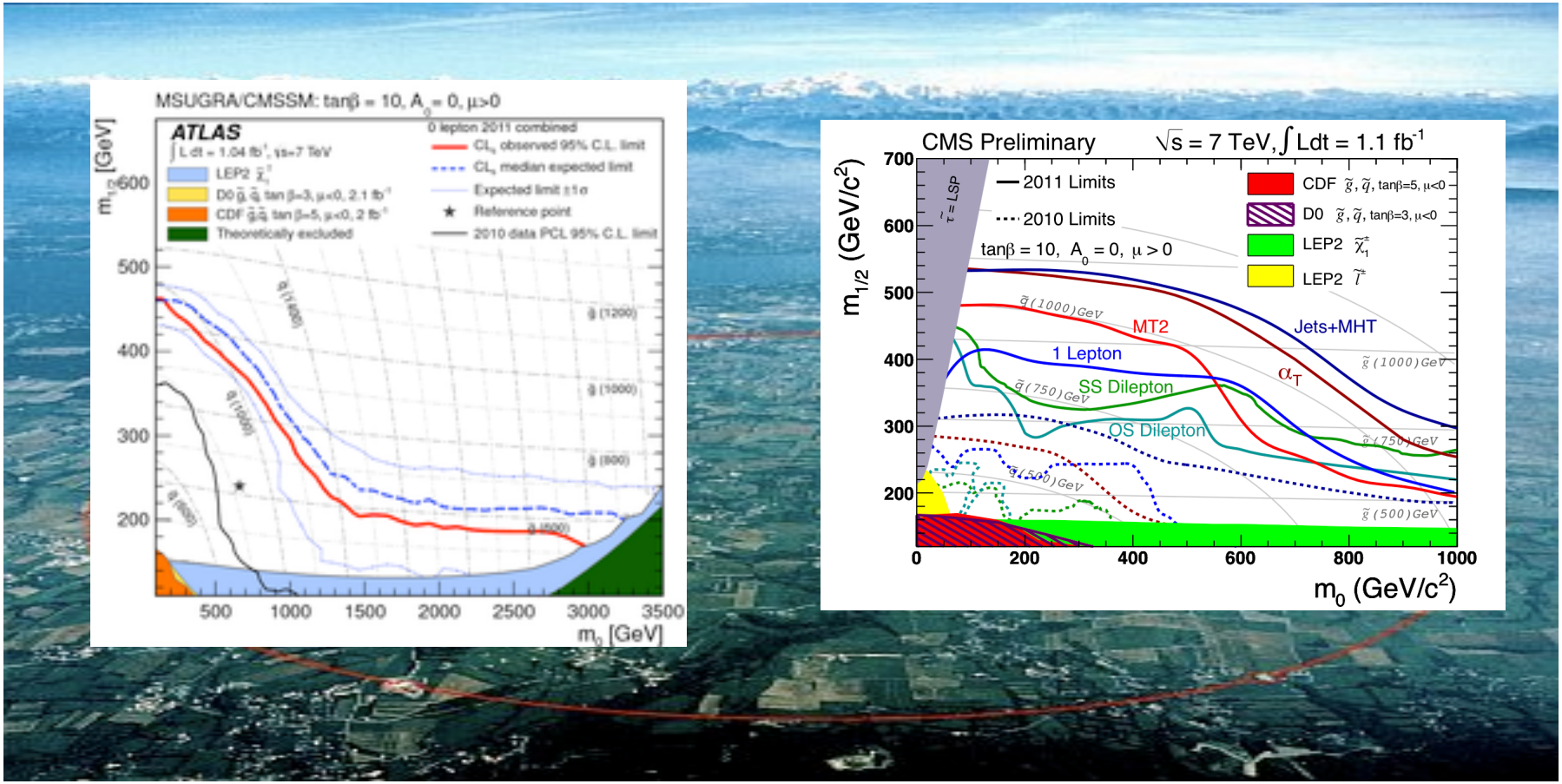
W. Beenakker, S. Brensing, M. Krämer, AK, E. Laenen and I. Niessen,
JHEP 12 (2009) 041, JHEP 08 (2010) 098, arXiv:1110.2446 [hep-ph]

W. Beenakker, S. Brensing, M. Krämer, AK, E. Laenen, L.Motyka and I. Niessen, IJMP A26 (2011) 2637

W. Beenakker et al., arXiv:1106.5647 [hep-ph]

5th Annual Workshop of the Helmholtz Alliance "Physics at the Terascale", Bonn, 7.12.2011

LHC Searches

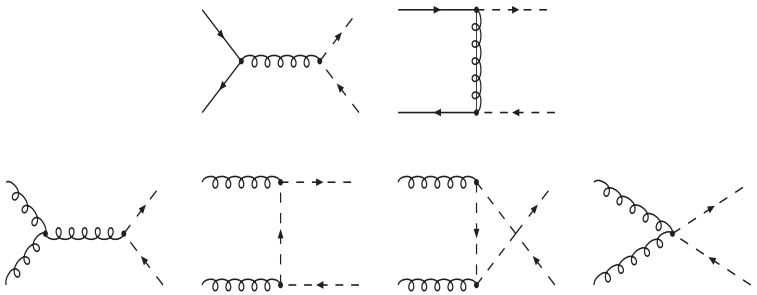


PARTONIC SUBPROCESSES

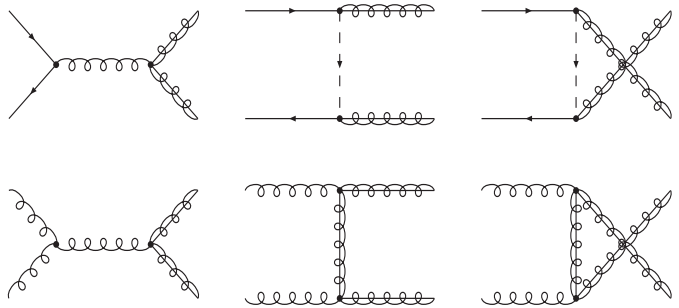
[Kane, Leveille'82][Harrison, Llewellyn Smith'84][Dawson, Eichten, Quigg'85]

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

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



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



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

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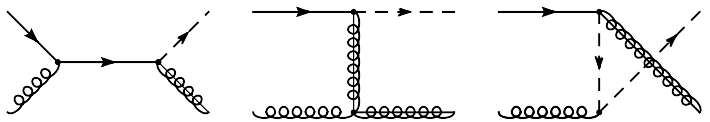
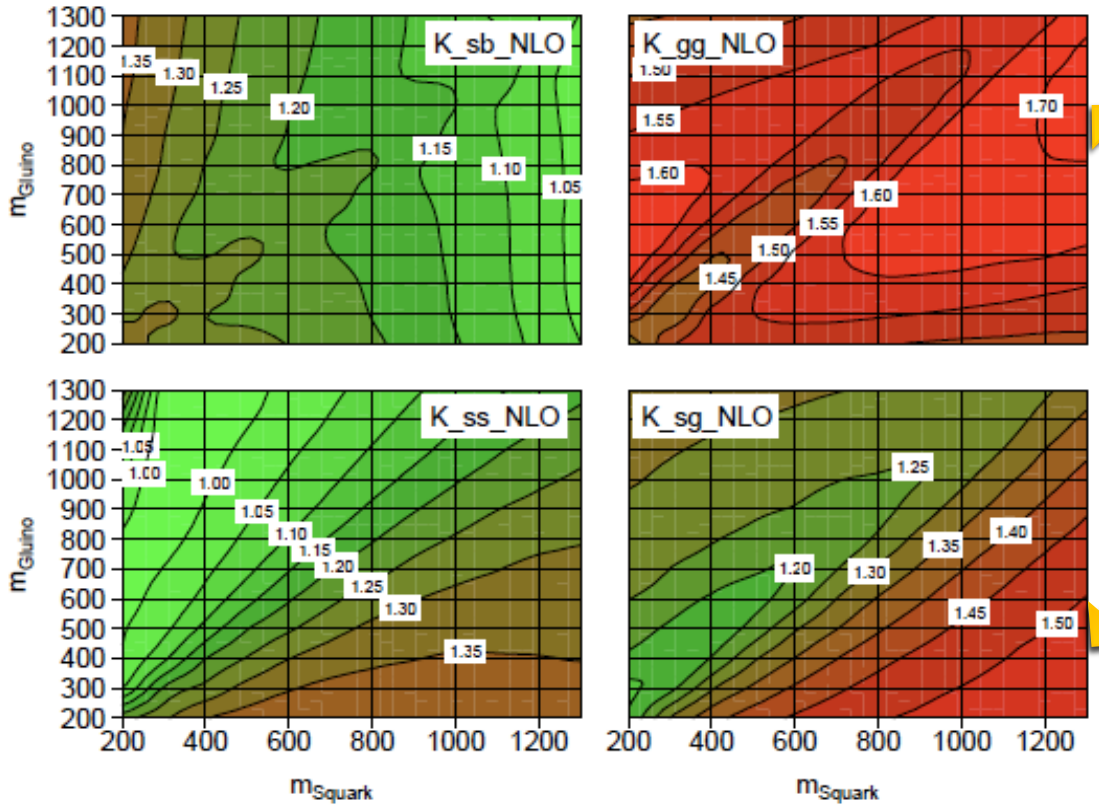


LO vs NLO

NLO SUSY QCD K-factors, LHC @ 7 TeV

[Beenakker, Höpker, Spira, Zerwas'97]

$K\_xx\_NLO = \sigma^{NLO}_{xx} / \sigma^{LO}_{xx}$



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

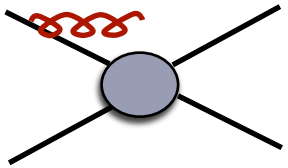
Currently used for determining exclusion limits : NLO SUSY-QCD predictions

NLO At Threshold

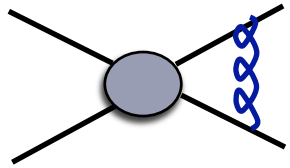
- Large masses of SUSY particles ⇒ production close to threshold $\hat{s} \sim 4m^2$
- General structure of the NLO correction in the threshold limit $\beta \to 0, \quad \beta^2 = 1 - 4m^2/\hat{s}$

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

Soft/collinear gluon emission



Coulomb gluons



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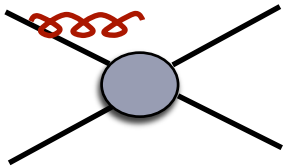

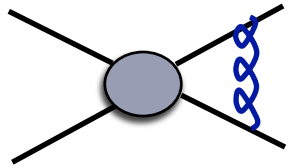

Large corrections in the limit of threshold production $\beta \to 0$

Higher Orders At Threshold

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Soft/collinear gluon emission

Coulomb gluons

At higher orders:

$$\sim \alpha_s^n \log^{2n}(\beta) \qquad \sim \alpha_s^n / \beta^n$$

Both types of corrections can be resummed to all orders

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Here: N(N)LL resummation of soft gluon corrections

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

→ Subleading Coulomb corrections and bound state effects analysed in NRQCD @NLO for $\tilde{g}\tilde{g}$ and $\tilde{q}\tilde{g}$ *[Hagiwara, Yokoya'09] [Kauth, Kühn, Marquard, Steinhauser'10-11] [Kauth, Kress, Kühn'11]*

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

Resummation for Squark and Gluino Production

- Resummation performed in the space of Mellin moments taken wrt. $4m^2/S$

$\log(\beta^2) \leftrightarrow \log(N) \equiv L$

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

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

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- Squark and gluino production: 2⇒2 processes with non-trivial color structures:

$\tilde{q}\bar{\tilde{q}}$	$\mathbf{3} \otimes \bar{\mathbf{3}}$	=	$\mathbf{1} \oplus \mathbf{8}$
$\tilde{q}\tilde{q}$	$\mathbf{3} \otimes \mathbf{3}$	=	$\bar{\mathbf{3}} \oplus \mathbf{6}$
$\tilde{q}\tilde{g}$	$\mathbf{3} \otimes \mathbf{8}$	=	$\mathbf{3} \oplus \bar{\mathbf{6}} \oplus \mathbf{15}$
$\tilde{g}\tilde{g}$	$\mathbf{8} \otimes \mathbf{8}$	=	$\mathbf{1} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{10} \oplus \bar{\mathbf{10}} \oplus \mathbf{27}$

  - soft wide-angle emission can change the colour structure of the underlying hard scattering; enters at NLL accuracy

NLL Resummation for 2→2 processes with colour and massive final states

[Kidonakis, Sterman'96-97][Bonciani, Catani, Mangano, Nason'98]

- In appropriately chosen colour basis

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

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

- At NLL, need 1-loop anomalous dimensions matrices for all colour structures ✔

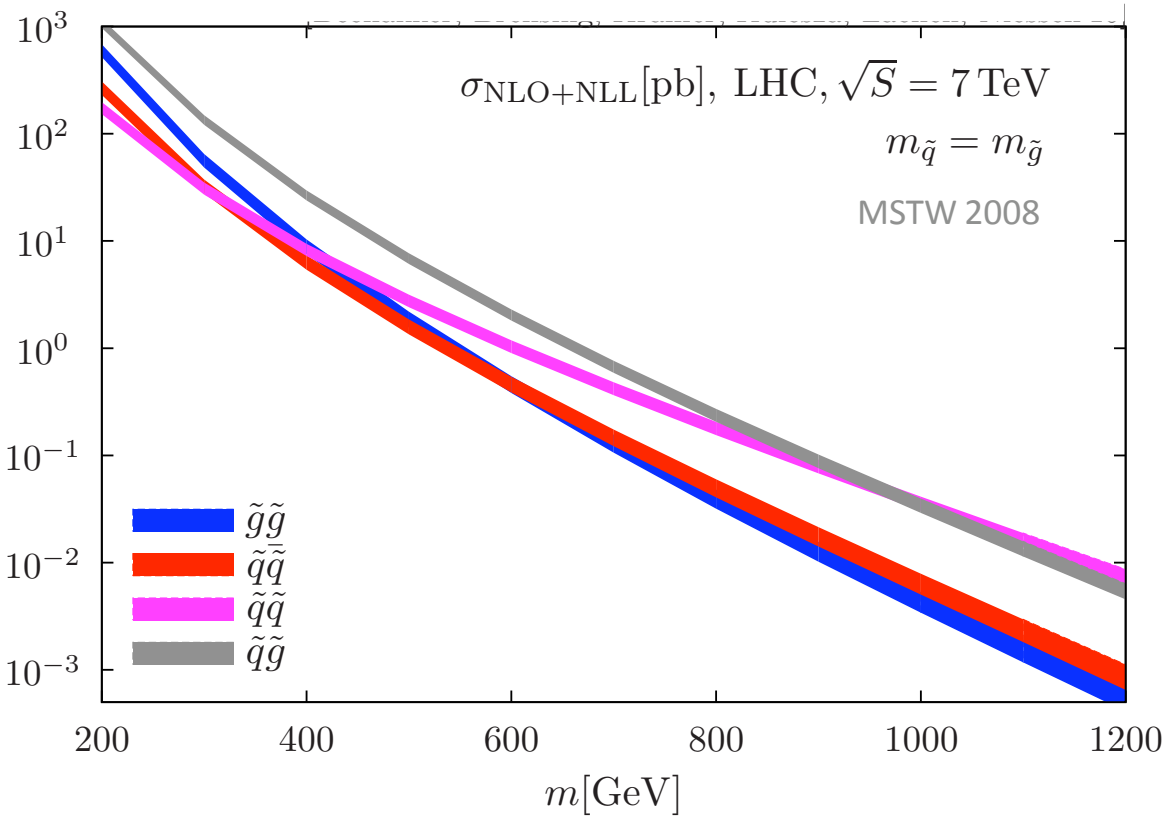
[AK, Motyka'09] [Beenakker, Brensing, Krämer, AK, Laenen, Niessen'09]

- Resummed expression matched with to the full NLO result ⇒ **NLL+NLO**

NLL+NLO RESULTS FOR 7 TEV

(for 14 TeV, see e.g. W. Beenakker, S. Brensing, M. Krämer, AK, E. Laenen, L.Motyka and I. Niessen, IJMP A26 (2011) 2637)

TOTAL NLL+NLO PRODUCTION RATES

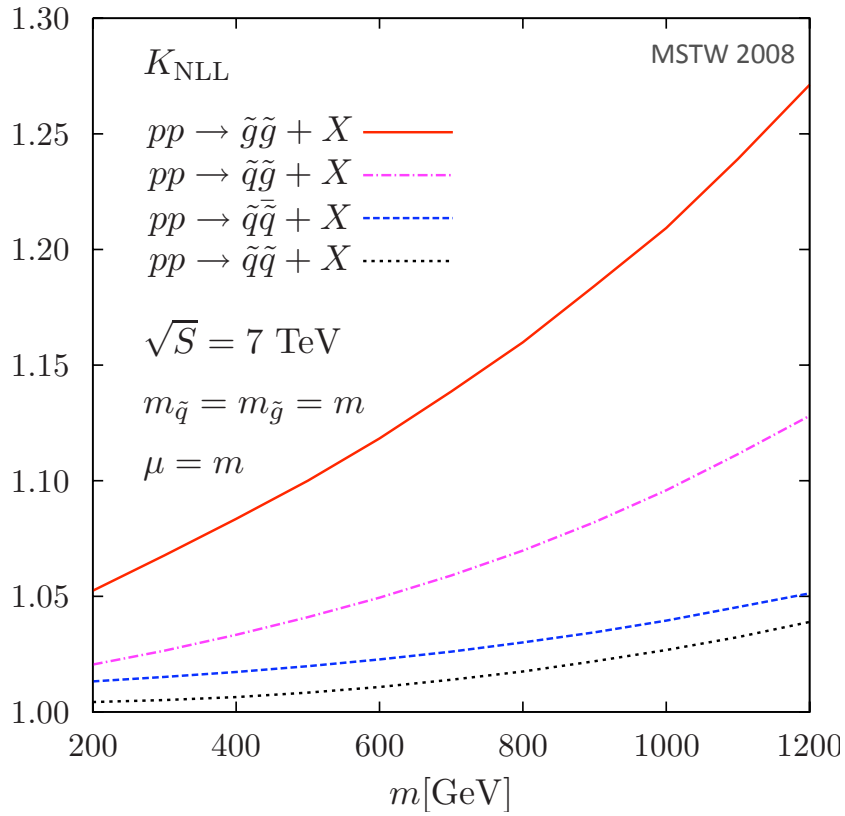


Width of the bands: theory error due to scale variation $0.5 < \mu/m < 2$, 68% C.L. pdf error and α_s error

Most precise predictions for squark and gluino production rates currently available

NLL Corrections

[W. Beenakker, S. Brensing, M. Krämer, AK, E. Laenen, L.Motyka and I. Niessen'11]



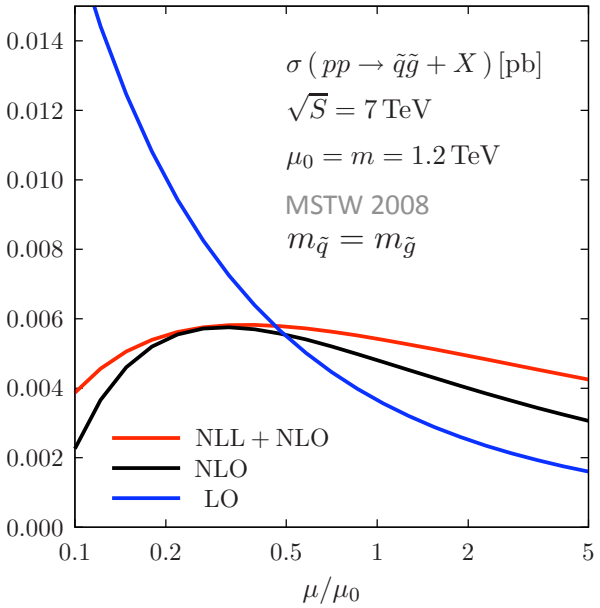
$$K_{\rm NLL} = \frac{\sigma^{\rm resummed,NLL}}{\sigma^{\rm NLO}}$$

- 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

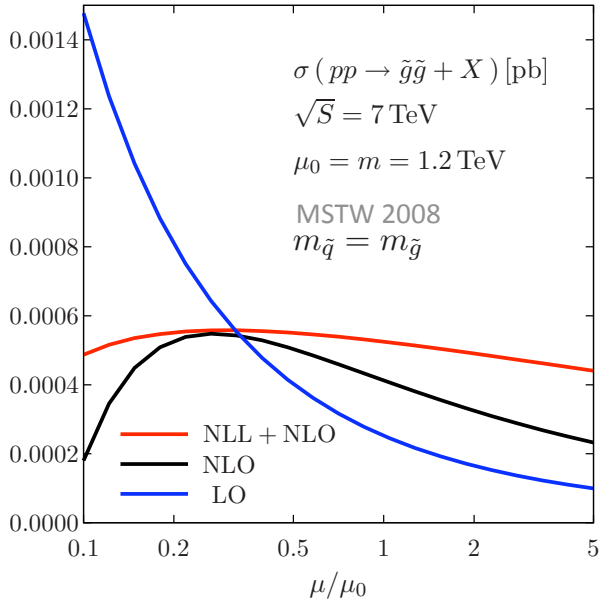
Scale variation

[W. Beenakker, S. Brensing, M. Krämer, AK, E. Laenen, L.Motyka and I. Niessen'11]

- Squark-gluino production



- Gluino-pair production

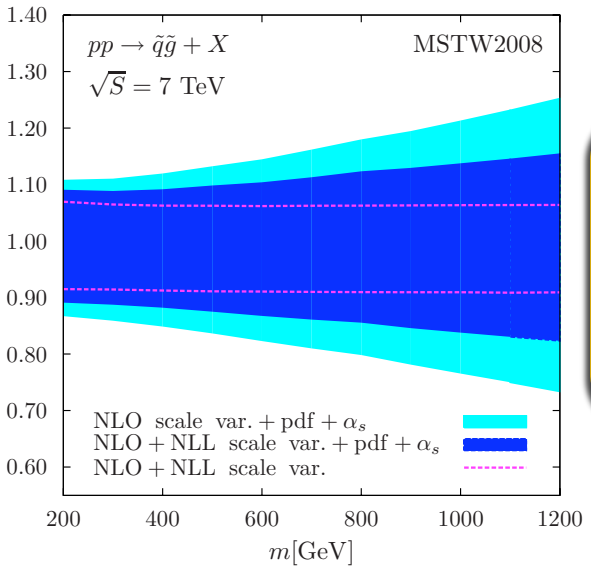


Significant reduction of the scale dependence for NLL+NLO compared to NLO, especially for gluino-pair production

THEORY ERROR

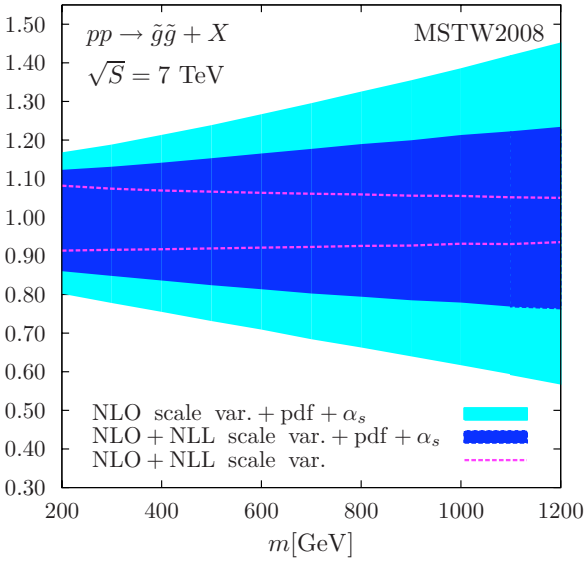
[W. Beenakker, S. Brensing, M. Krämer, AK, E. Laenen, L.Motyka and I. Niessen'11]

- Squark-gluino production



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

- Gluino-pair production

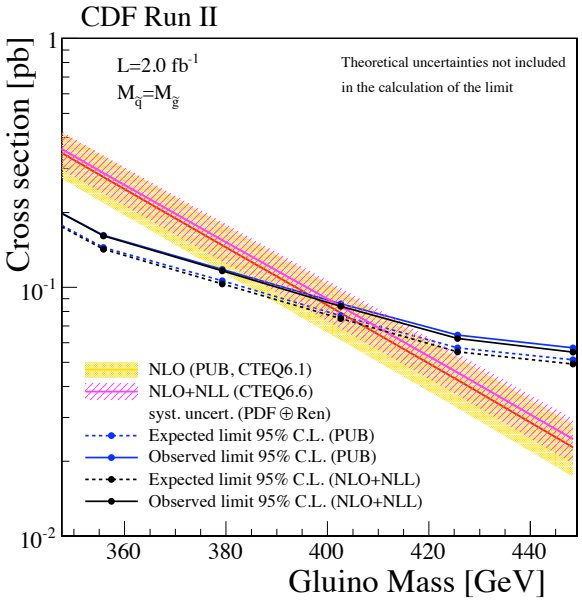


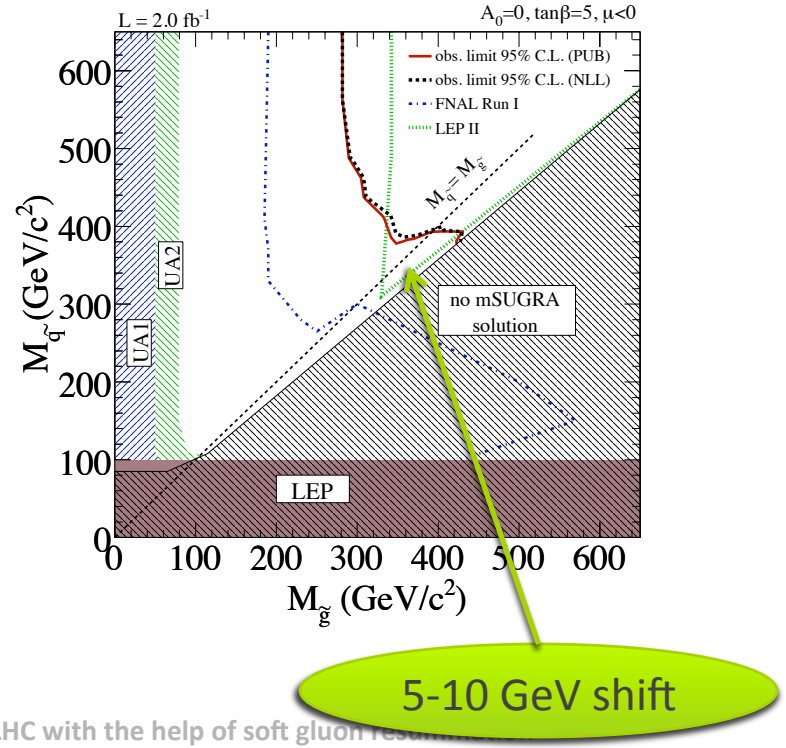
Significant reduction of the FULL theory error due to reducing the scale variation!

Tevatron Searches

- NLL+NLO analysis also performed for production of squarks and gluinos at the Tevatron *[Beenakker, Brensing, Krämer, AK, Laenen, Niessen'09]*

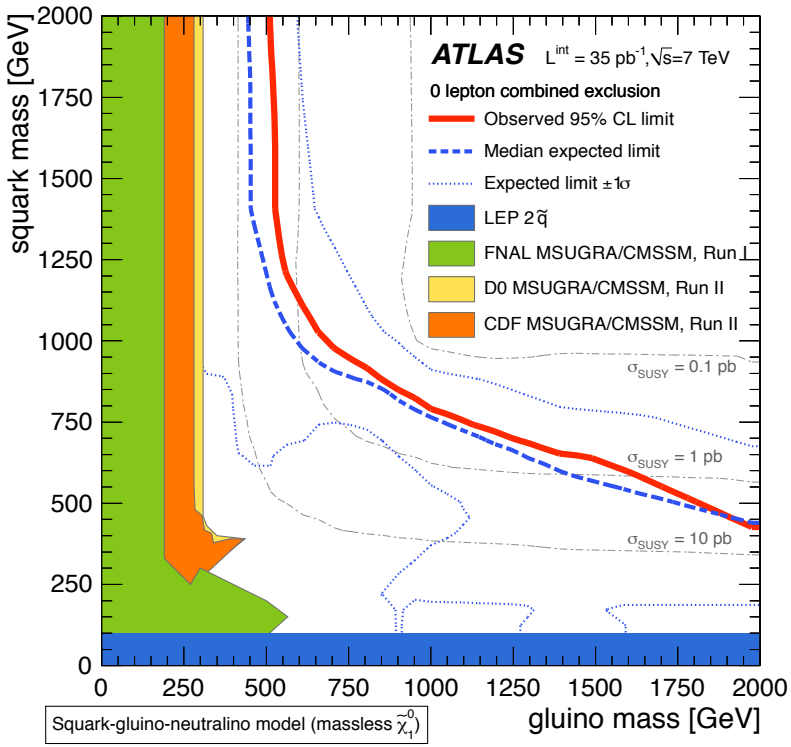
- CDF mass limits revisited *[Beenakker, Brensing, d'Onofrio, Krämer, AK, Laenen, Martinez, Niessen'11]*





Impact on LHC Searches

[ATLAS, PLB 701 (2011) 186]



- Auxiliary information publicly available, including signal acceptance times efficiency

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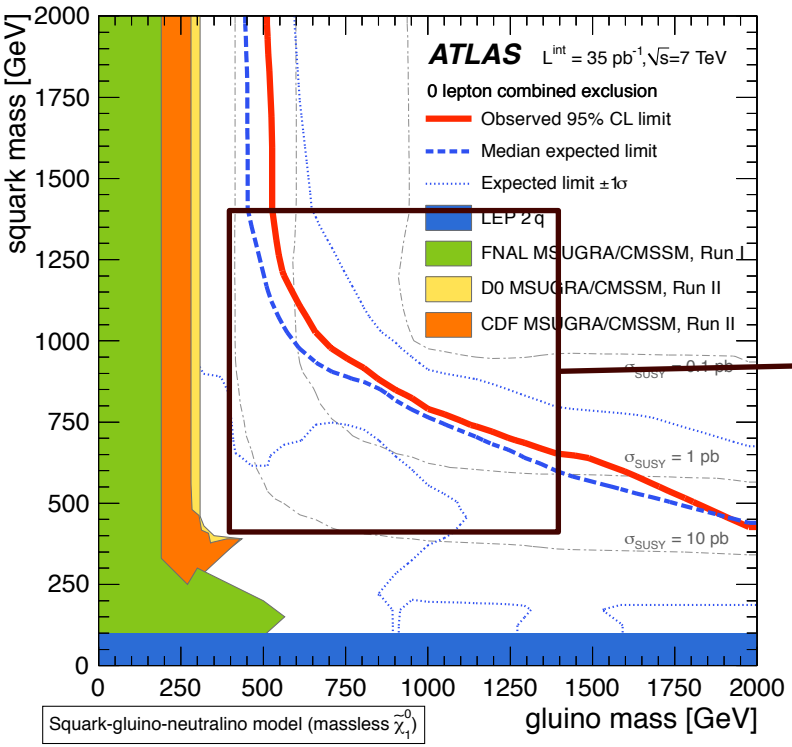
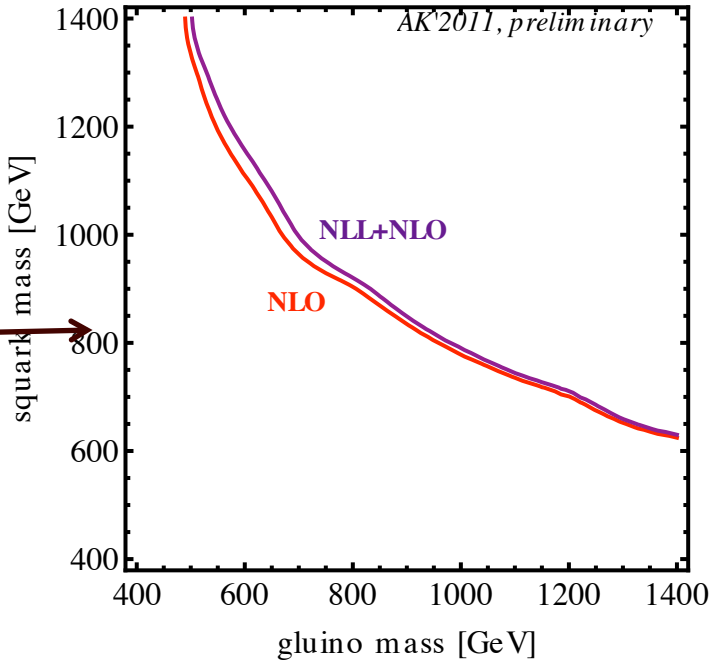
[ATLAS, PLB 701 (2011) 186]





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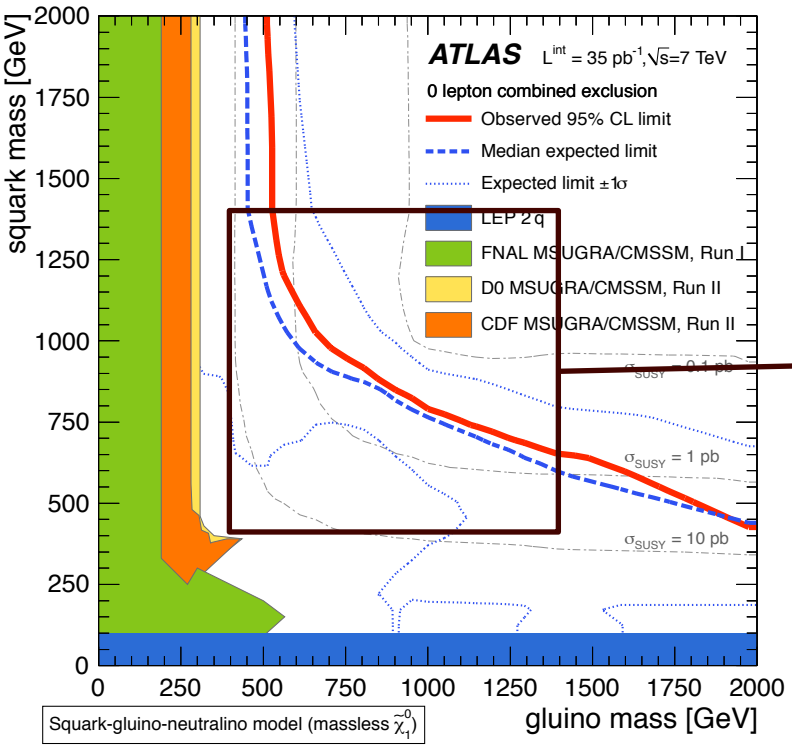

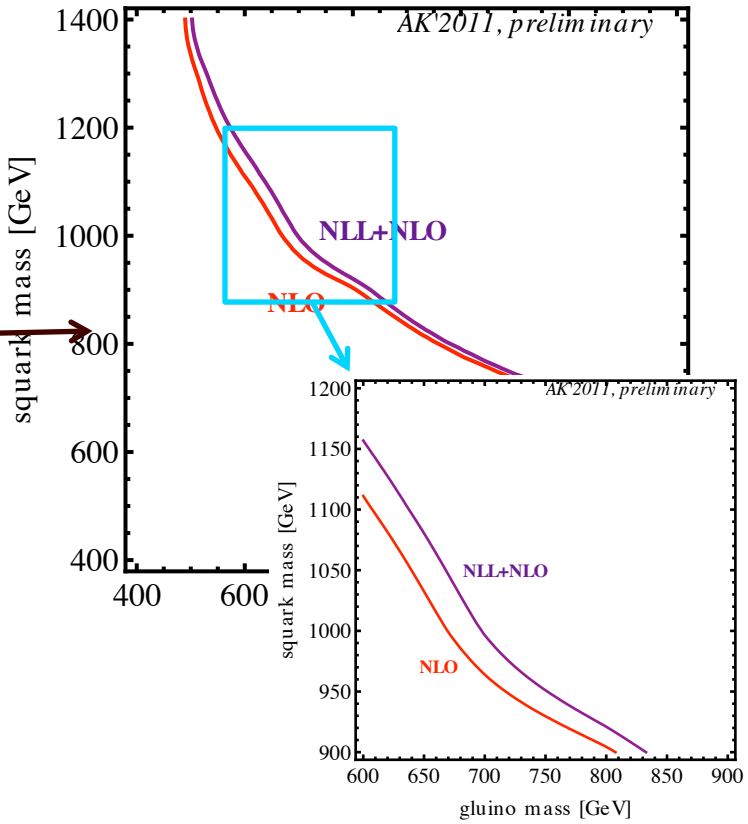

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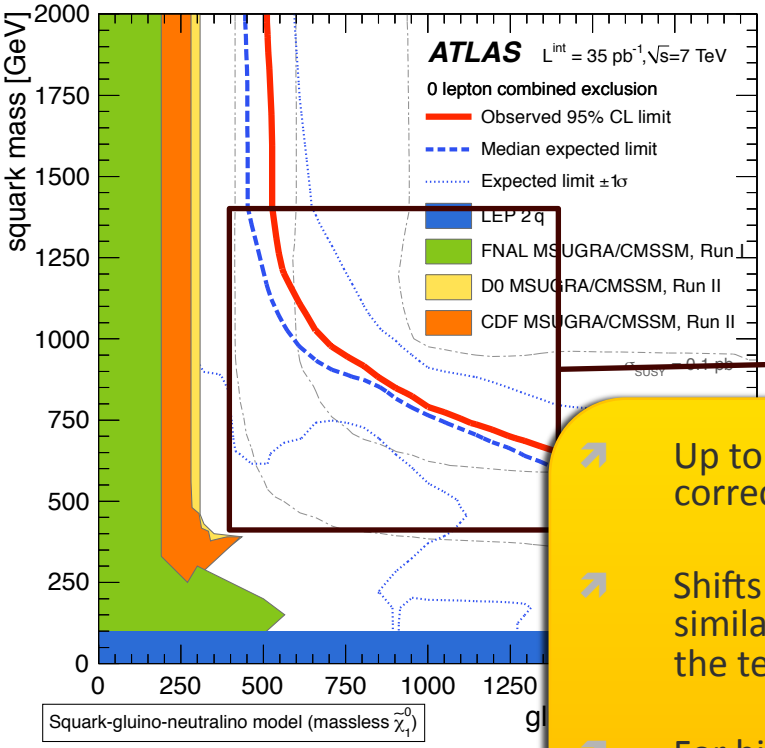
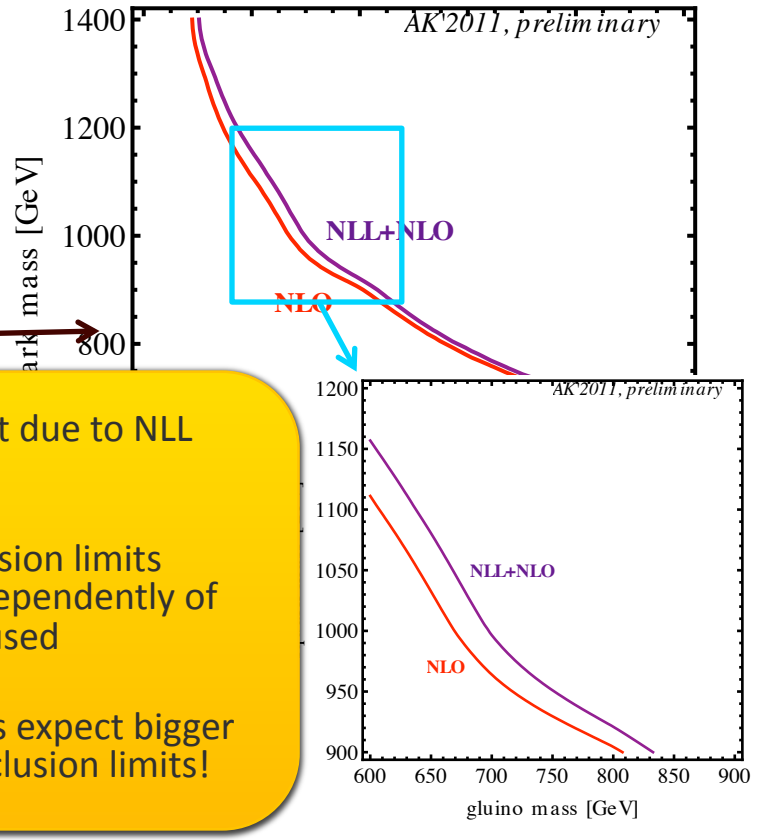




- Up to 50 GeV shift due to NLL corrections
- Shifts in the exclusion limits similar in size independently of the test statistic used
- For higher masses expect bigger impact on the exclusion limits!

PUBLIC CODE: NLL-FAST

- **All four processes of squark and gluino production at NLL+NLO**
- Available at

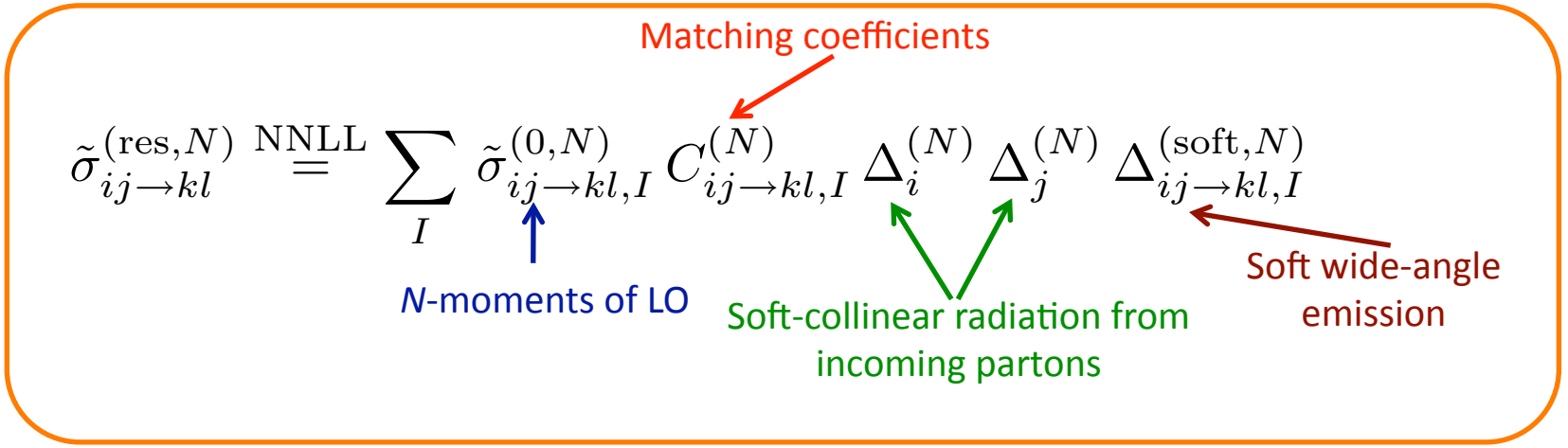
http://web.physik.rwth-aachen.de/service/wiki/bin/view/Main/BSMCrossSectionWorkingGroup

→ LPCC BSM Working group official recommendation

- For a given squark mass and a gluino mass the code returns:
  - ✓ LO and NLO central values (from PROSPINO)
  - ✓ NLL+NLO central value
  - ✓ upper and lower scale variation error on NLL+NLO
  - ✓ upper and lower pdf uncertainty
  - ✓ upper and lower α_s uncertainty
- To speed up calculation, interpolation of the provided grids for squark and gluino masses in the range of 500-2000 GeV

NNLL+NLO SQUARK-ANTISQUARK PRODUCTION AT 7 TEV

NNLL: How?



- Exponentials at NNLL accuracy

$$\Delta^{(N)}_i \Delta^{(N)}_j \Delta^{(\mathrm{soft}),\mathrm{N}}_{ij\to kl,I} = \exp\left[L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \dots\right]$$

  - Three-loop cusp anomalous dimension *[Moch,Vermaseren,Vogt'04]*
  - Two-loop soft anomalous dimensions *[Contopanagos, Laenen,Sterman'96][Catani, de Florian, Grazzini'01][Beneke, Falgari, Schwinn'09][Czakon, Mitov, Sterman'09] [Ferroglia, Neubert, Pecjak, Yang'09]*

- Matching coefficients

Matching Coefficients

- Soft-Coulomb factorization *[Bonciani, Catani, Mangano, Nason'98][Beneke, Falgari, Schwinn'09-10]*

$$C^{(N)}_{ij\to kl,I} \overset{\text{NNLL}}{=} \left(1+\frac{\alpha_s}{\pi}\,\mathcal{C}^{\text{Coul},(1)}_{ij\to kl,I}(N,\{m^2\},\mu^2)\right)\,\left(1+\frac{\alpha_s}{\pi}\,\mathcal{C}^{(1)}_{ij\to kl,I}(\{m^2\},\mu^2)\right)$$

- Form of the NLO Coulomb corrections known:

$$\sigma^{\text{Coul},(1)}_{ij,I} = -\frac{\alpha_s}{\pi}\,\frac{\pi^2}{2\beta}\kappa_{ij,I}\sigma^{(0)}_{ij,I}$$

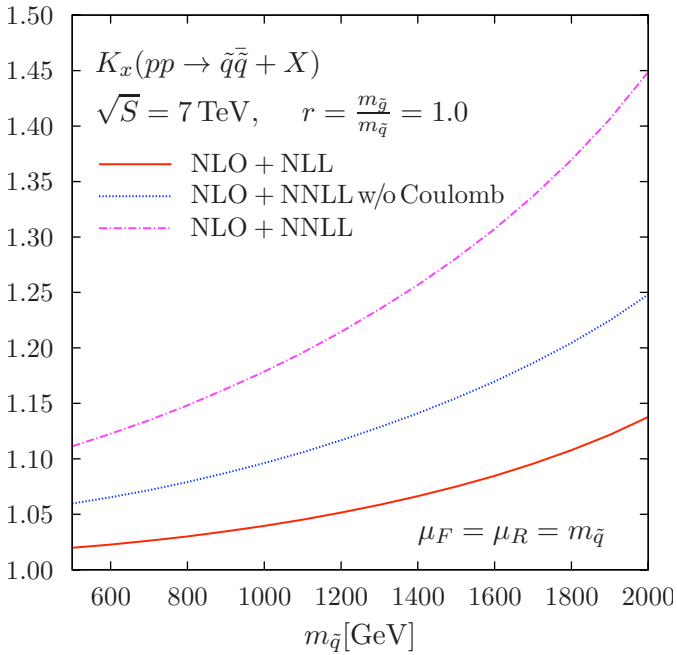
$$\kappa_{q\bar{q},\mathbf{1}} = -\frac{4}{3}, \qquad \kappa_{q\bar{q},\mathbf{8}} = \frac{1}{6}, \qquad \kappa_{gg,\mathbf{1}} = -\frac{4}{3}, \qquad \kappa_{gg,\mathbf{8_A}} = \frac{1}{6}, \qquad \kappa_{gg,\mathbf{8_S}} = \frac{1}{6}$$

- Hard-matching coefficients $C^{(1)}_{ij,I}$: Analytical results ✔
  - obtained from NLO corrections considered in the threshold limit

SQUARK-ANTISQUARK PRODUCTION AT NNLL

[W. Beenakker, S. Brensing, M. Krämer, AK, E. Laenen, L.Motyka and I. Niessen'11]

$$K_x = \frac{\sigma_x}{\sigma_{NLO}}$$



NNLL +NLO: → up to 30% increase of the total cross section wrt NLO for squarks with mass of 1.5 TeV

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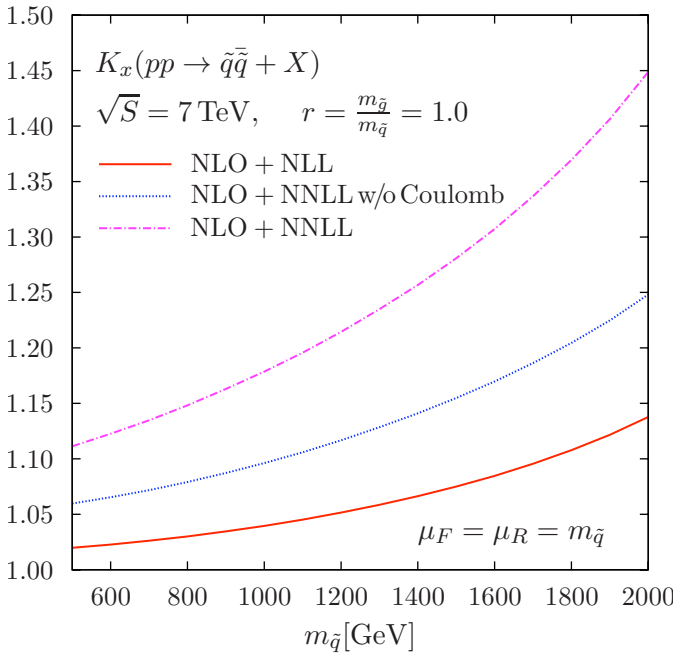

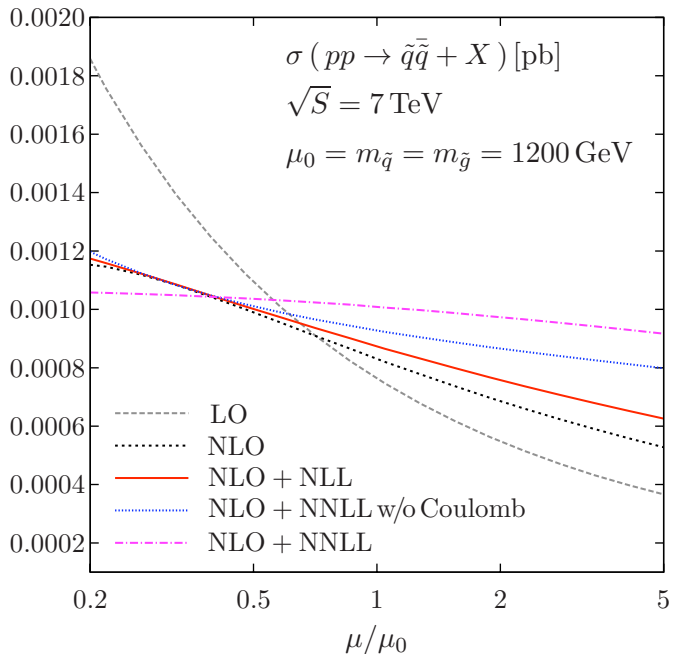

NNLL +NLO: → up to 30% increase of the total cross section wrt NLO for squarks with mass of 1.5 TeV
→ significant reduction of the scale dependence

SUMMARY

- 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
- NNLL+NLO: squark-antisquark production
- 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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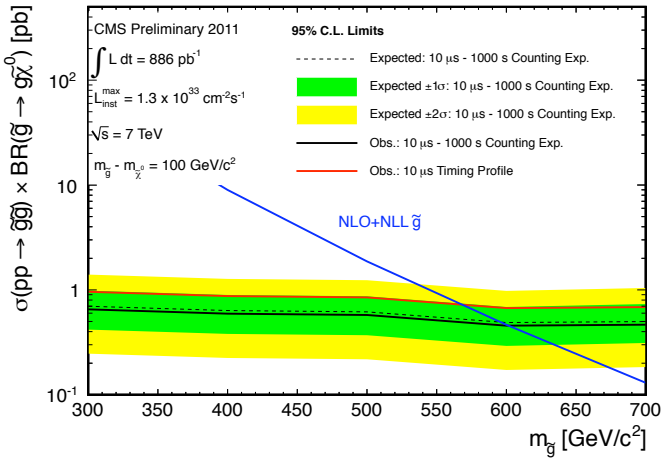

CMS search for stopped HSCPs, CMS-EXO-11020

SUMMARY

- 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
- NNLL+NLO: squark-antisquark production
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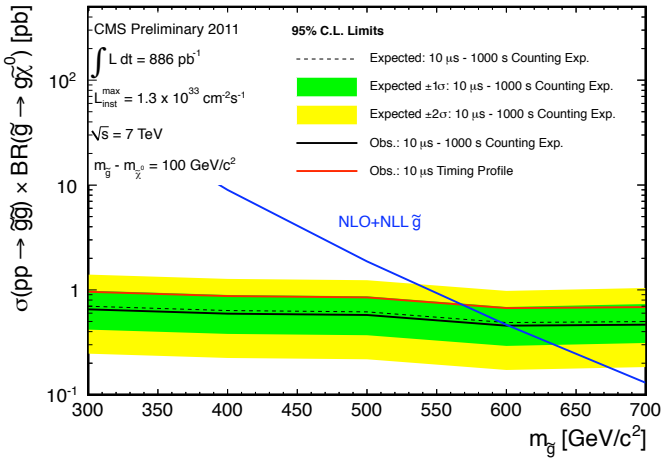
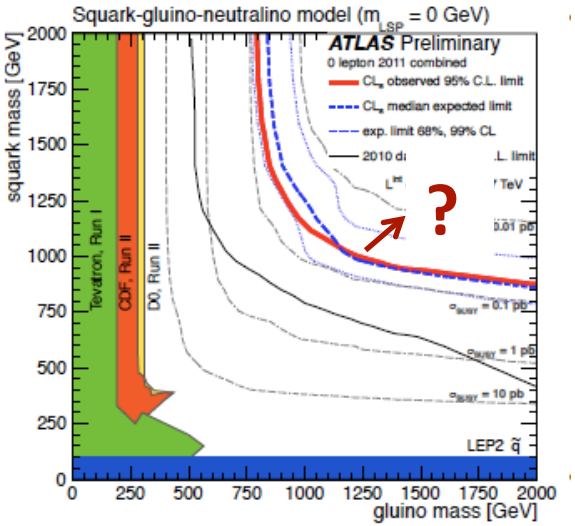


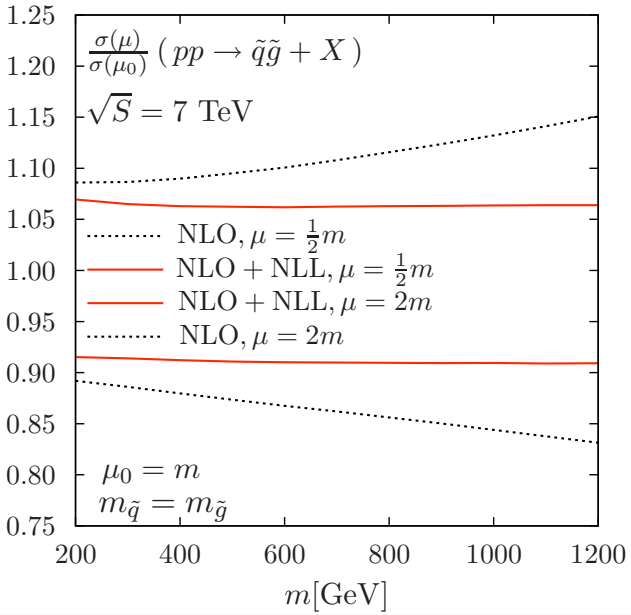


CMS search for stopped HSCPs, CMS-EXO-11020

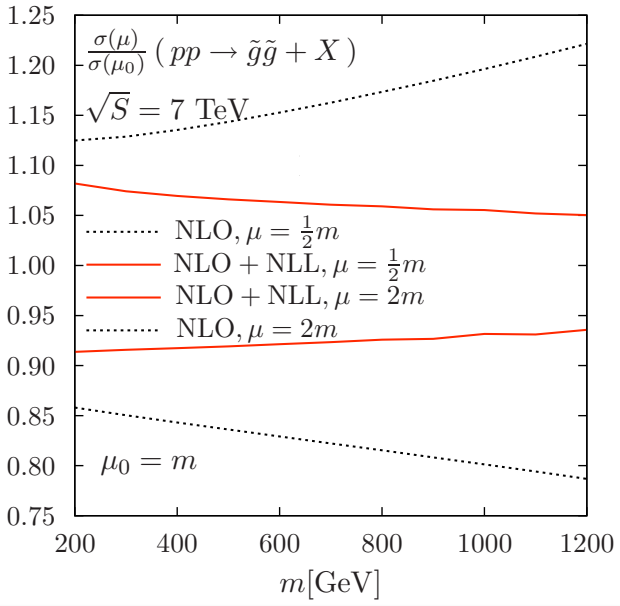
SCALE VARIATION CTND.

[W. Beenakker, S. Brensing, M. Krämer, AK, E. Laenen, L.Motyka and I. Niessen, IJMP A26 (2011) 2637]

- Squark-gluino production



- Gluino-pair production

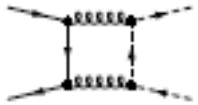
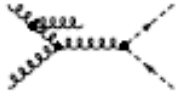


Theory error due to scale variation below 10% for NLL+NLO
down by a factor of 2 (squark-gluino) or a factor of 4 (gluino-pair) for masses > 1 TeV

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]*

  e.g.   ...

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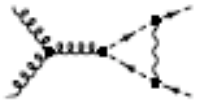
- EW corrections → $\mathcal{O}(\alpha_s^2\,\alpha)$ *[Hollik, Kollar, Trenkel'07][Hollik, Mirabella'08] [Hollik, Mirabella, Trenkel'08] [Beccaria et al.'08] [Mirabella'09] [Germer, Hollik, Mirabella, Trenkel'10]] [Germer, Hollik, Mirabella'11]*

  e.g. 

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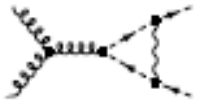
e.g. 

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]*

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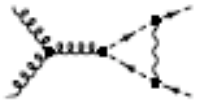
e.g. 

Typically order of a few tens of percents

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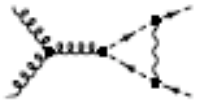
  e.g. 

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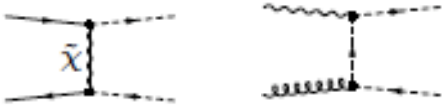


etc.

Typically order of a few percents (for the total cross section)

RESUMMATION-IMPROVED NLL+NLO TOTAL CROSS SECTION

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

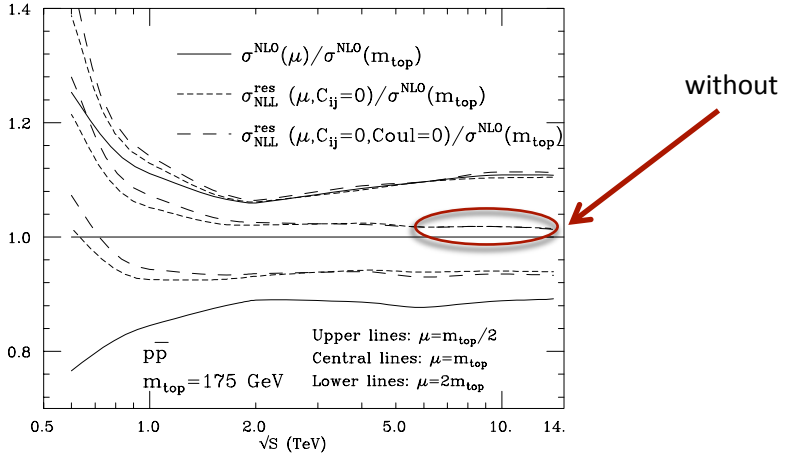
$$\sigma^{(\mathrm{match})}_{h_1 h_2 \to kl}(\rho, \{m^2\}, \mu^2) = \sum_{i,j=q,\bar{q},g} \int_{C_{MP}-i\infty}^{C_{MP}+i\infty} \frac{dN}{2\pi i}\, \rho^{-N}\, f^{(N+1)}_{i/h_1}(\mu^2)\, f^{(N+1)}_{j/h_2}(\mu^2)$$
$$\times \left[\hat{\sigma}^{(\mathrm{res},N)}_{ij\to kl}(\{m^2\}, \mu^2) - \hat{\sigma}^{(\mathrm{res},N)}_{ij\to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

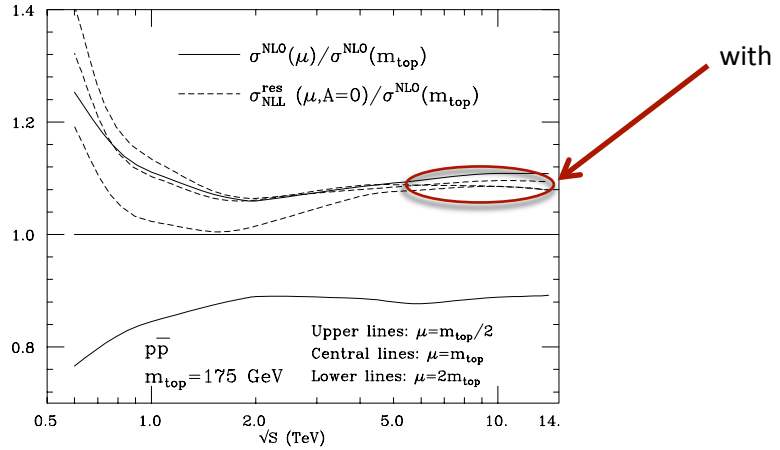
- Inverse Mellin transform evaluated using a contour in the complex *N* space according to 'Minimal Prescription' *[Catani, Mangano, Nason Trentadue'96]*

- 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/]*

NNLL: WHY?

- NNLL contributions important for $t\bar{t}$ production *[Bonciani, Catani, Mangano, Nason'98]*

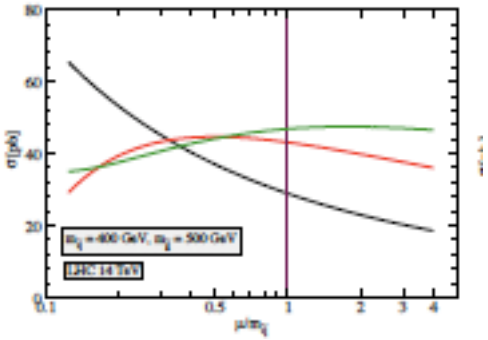




- Approximate NNLO cross sections: reduced scale-dependence

Squark-antisquark *[Langenfeld and Moch'09]*

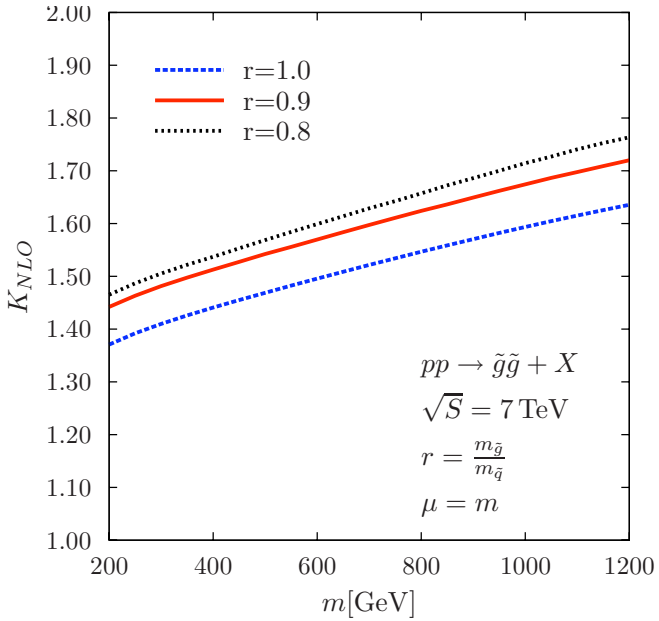
LO
NLO
approx. NNLO

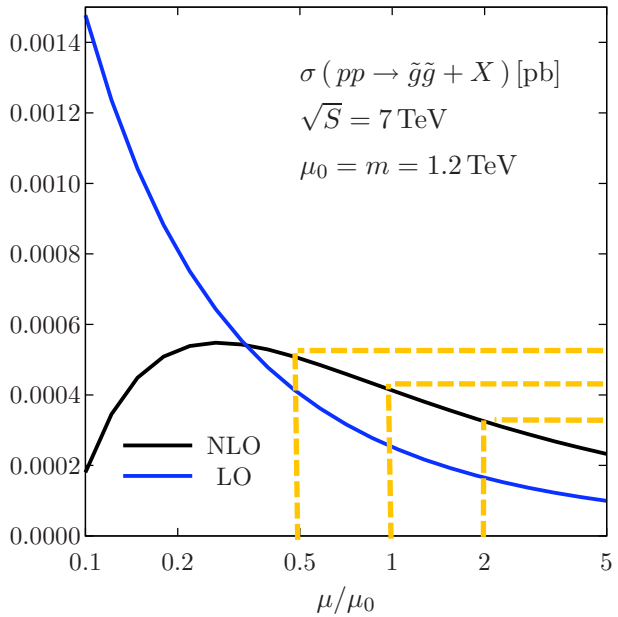


GLUINO-PAIR PRODUCTION AT THE LHC

Currently used for determining exclusion limits : NLO SUSY-QCD predictions

$pp \to \tilde{g}\tilde{g} + X$ LHC @ 7 TeV





For higher masses, theory error due to scale variation will be bigger!

More than 20 % scale variation error

A. Kulesza, Improving predictions for squark and gluino production at the LHC with the help of soft gluon resummation

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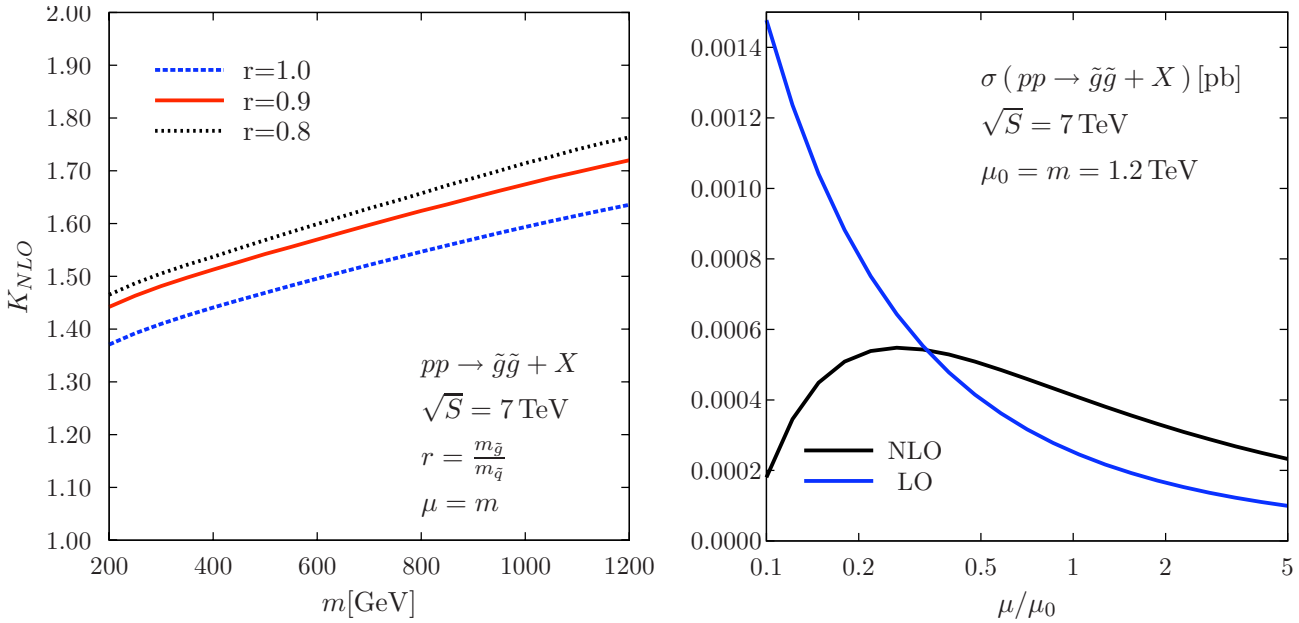

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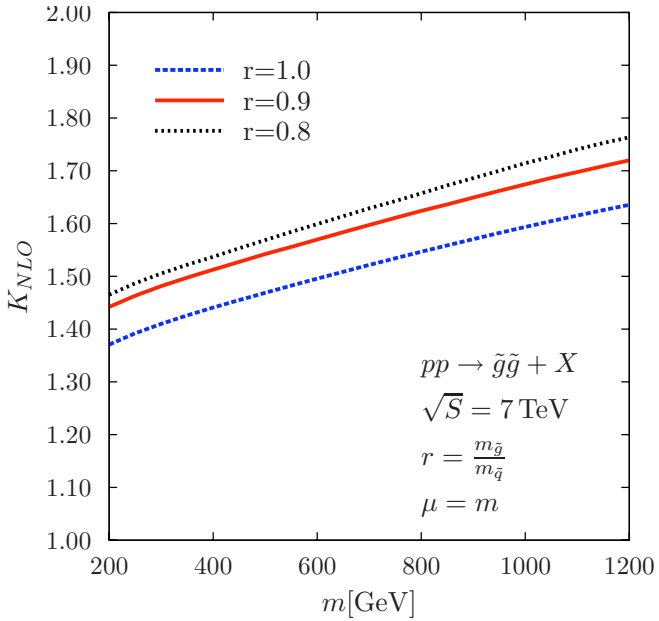

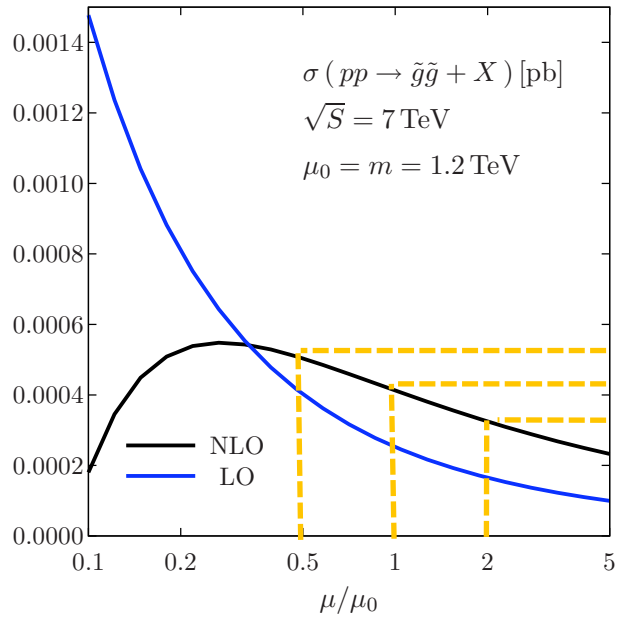

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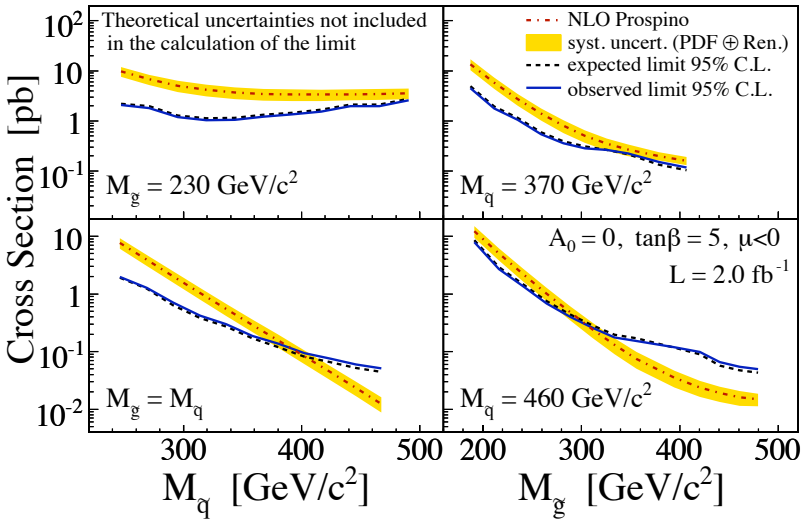
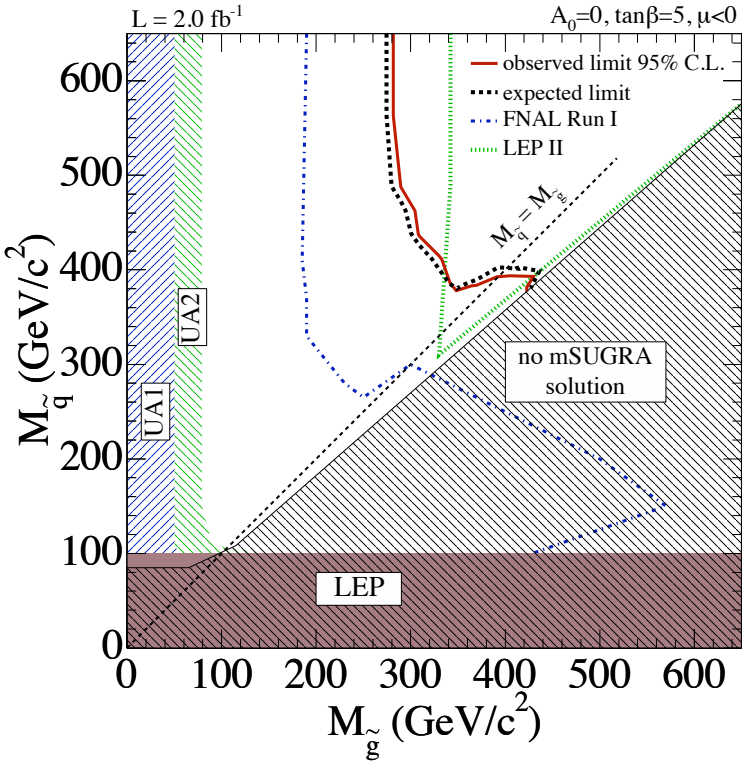
A. Kulesza, Improving predictions for squark and gluino production at the LHC with the help of soft gluon resummation

REMINDER: TEVATRON SEARCHES

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





Essential to know total production cross sections for squarks and gluinos well