How to Improve on Results of SUSY Searches: Higher Order Corrections To Squark and Gluino Production Cross Sections at the LHC

Anna Kulesza

RWTH AACHEN

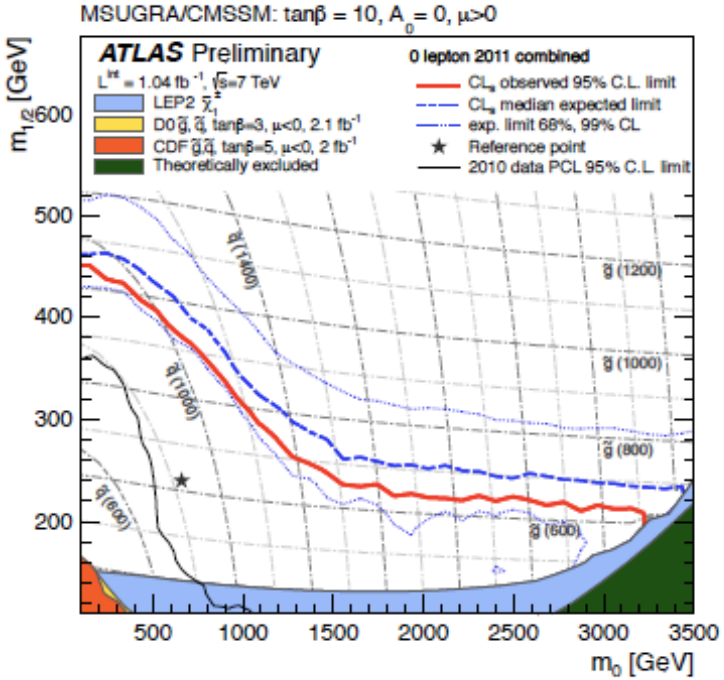
PHYSICS AT THE TERA SCALE Helmholtz Alliance

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, IJMP A26 (2011) 2637
W. Beenakker et al., arXiv:1106.5647 [hep-ph]

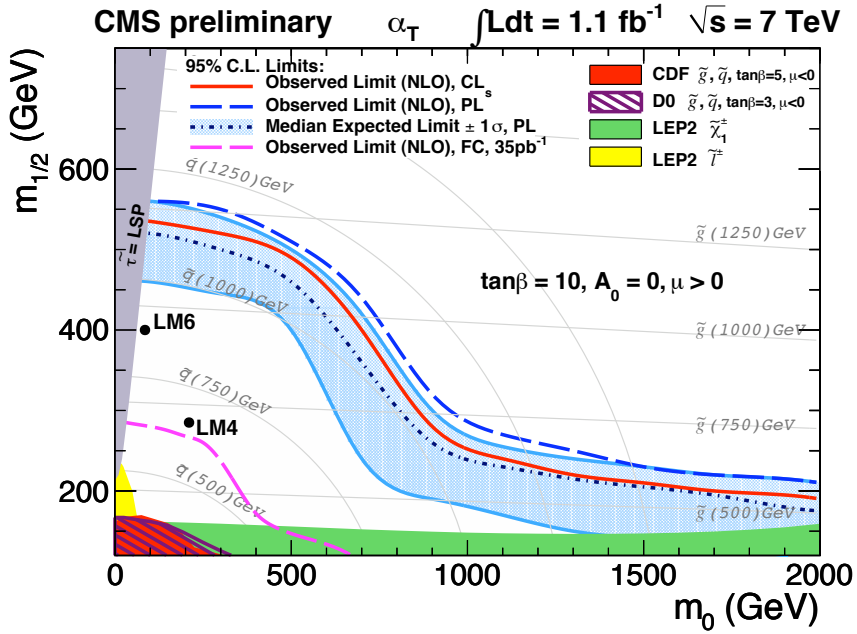
SUSY11, Fermilab, 08/28-09/02/2011

Motivation: LHC Searches

[ATLAS, talk at the EPS conference]



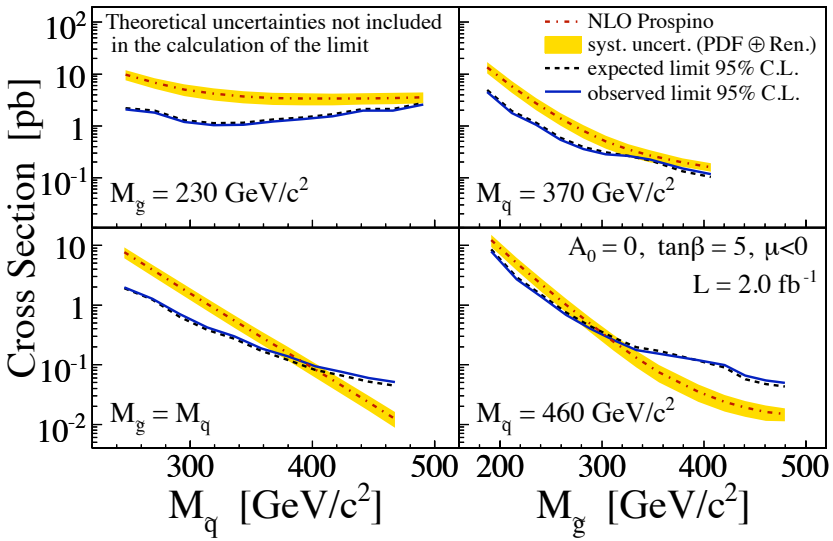
[CMS-PAS-SUS-11-003]

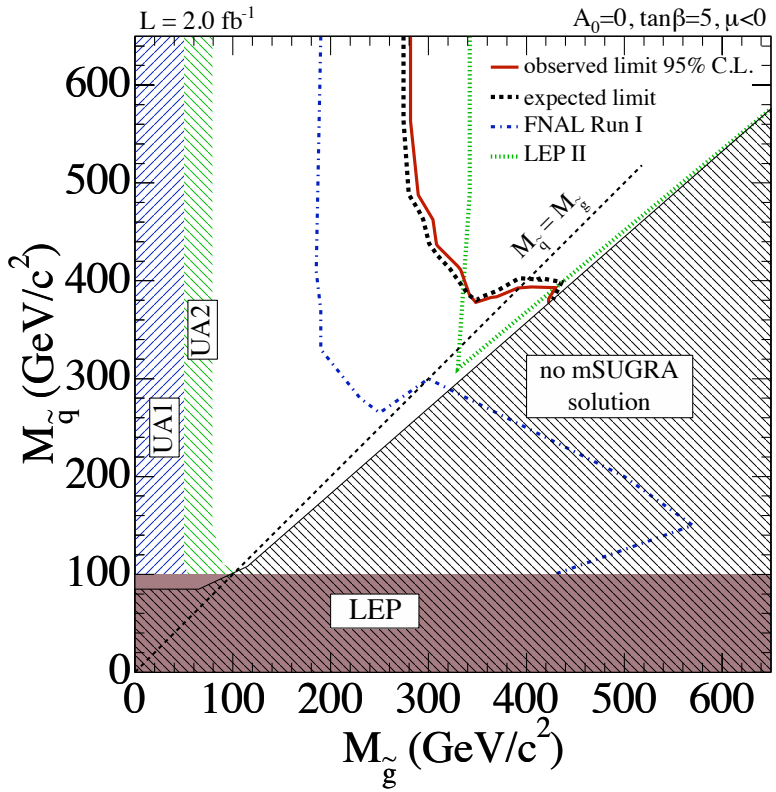


Predictions for total cross sections for production of squark and gluino are one of the most important theoretical inputs in determination of limits → predictions for # of signal events

REMINDER: TEVATRON SEARCHES

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





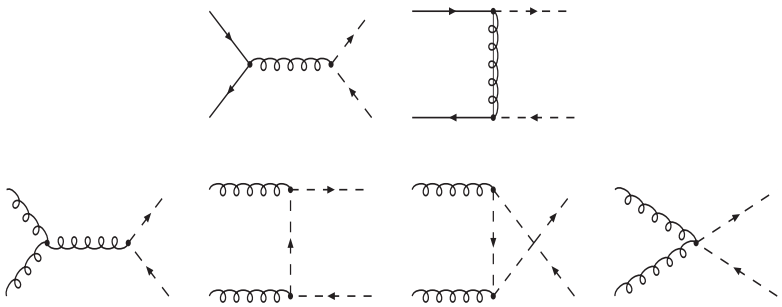
Essential to know total production cross sections for squarks and gluinos well

Partonic subprocesses

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

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

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



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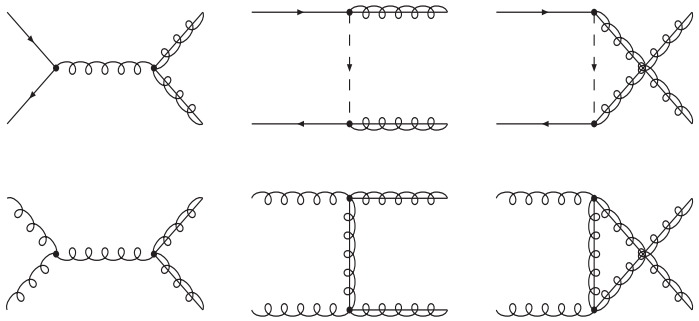

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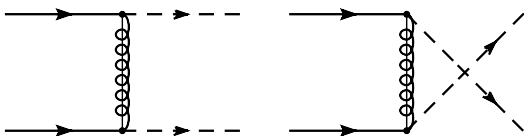

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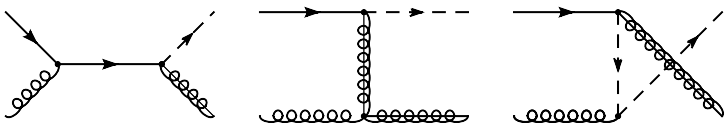


Theoretical Status: Fixed Order

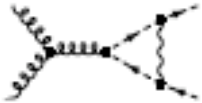
Corrections to $\mathcal{O}(\alpha_s^2)$ processes

- NLO SUSY-QCD corrections → $\mathcal{O}(\alpha_s^3)$ *[Beenakker, Höpker, Spira, Zerwas'96] [Beenakker, Krämer, Plehn, Spira, Zerwas'97]*

  e.g. ...

  - For squark-antisquark and stop-antistop production:approximate NNLO contributions → $\mathcal{O}(\alpha_s^4)$ *[Langenfeld, Moch'09] [Langenfeld'10]*

- 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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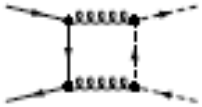
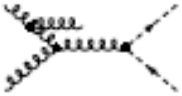
  e.g.   ...

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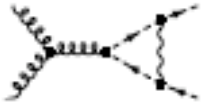
  e.g. 

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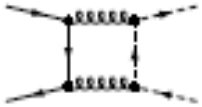
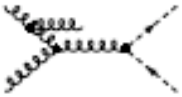
  e.g.   ...

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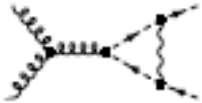
  e.g. 

Typically order of a few tens of percents

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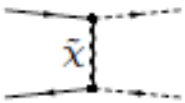

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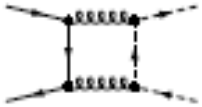
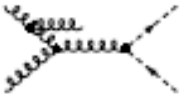
  e.g.   ...

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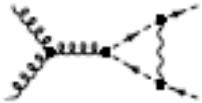
  e.g. 

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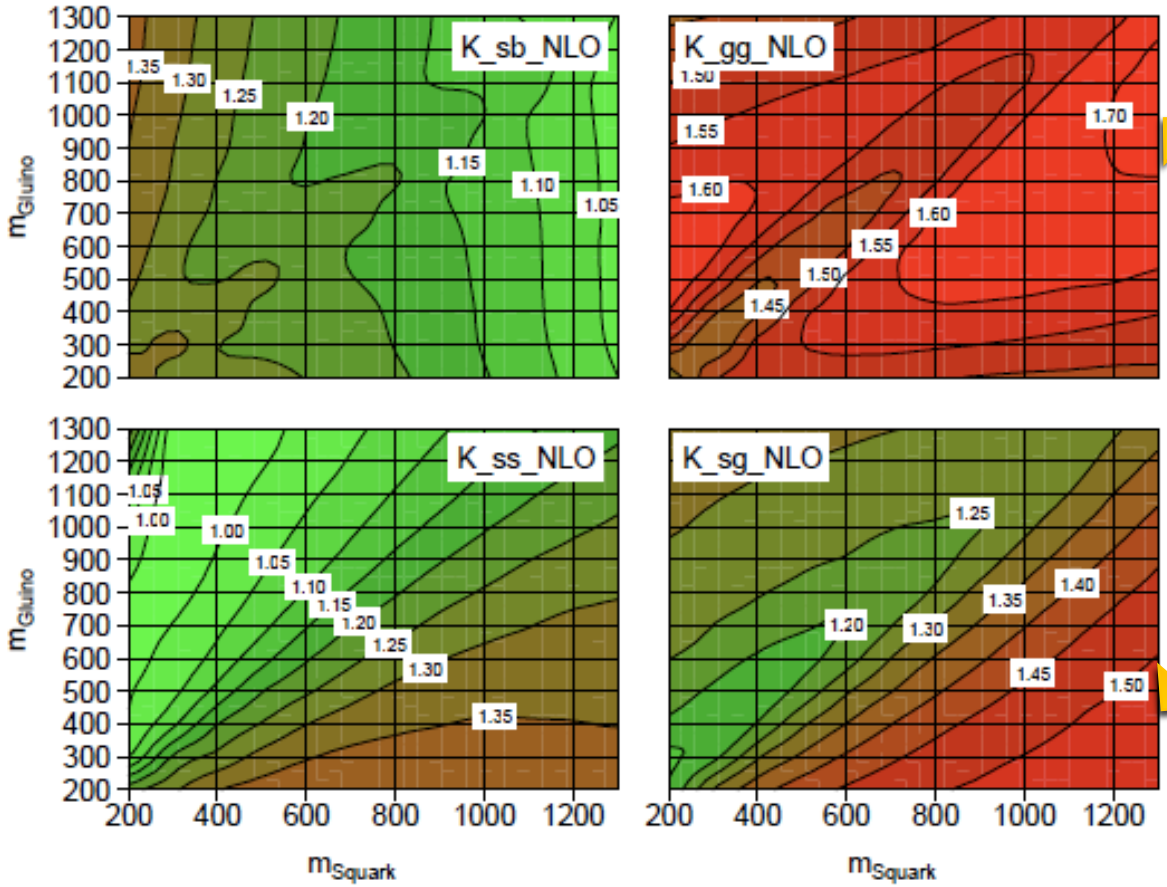
etc.

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

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

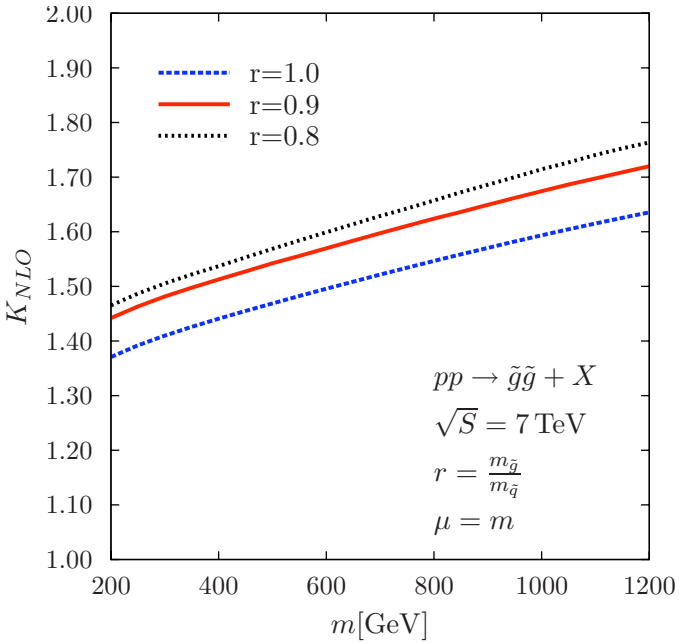
SUSY-QCD: only m_{squark} and m_{gluino} dependence

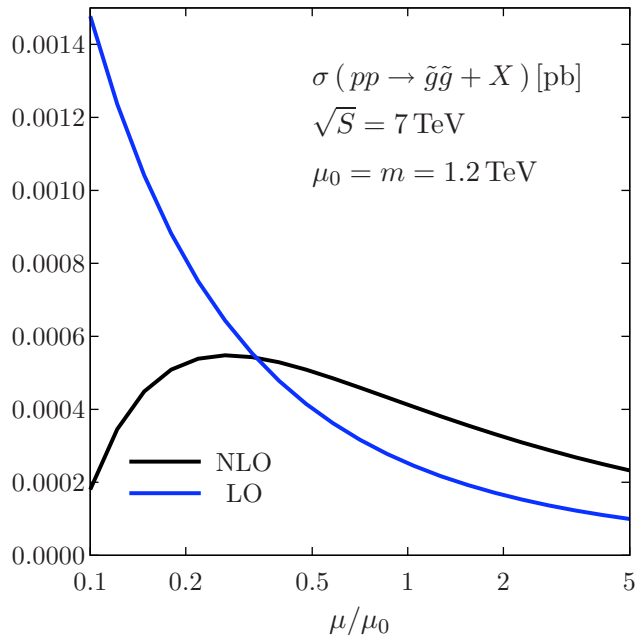
plot courtesy of S. Brensing

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





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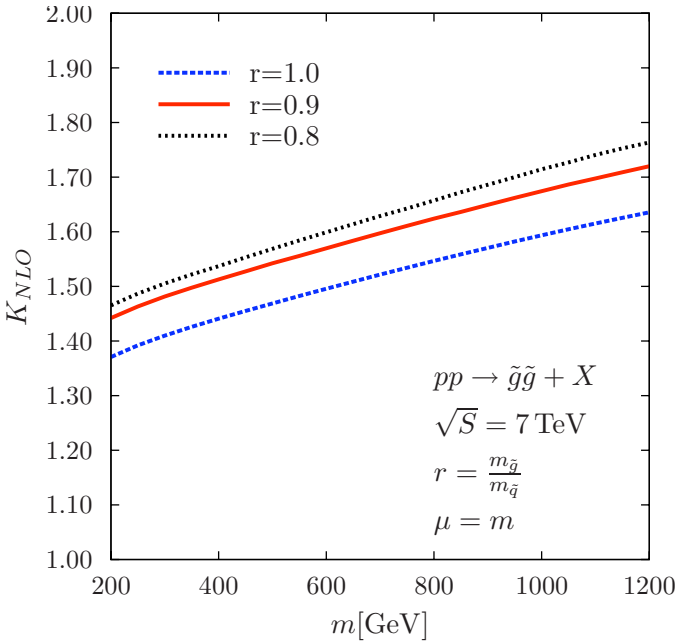

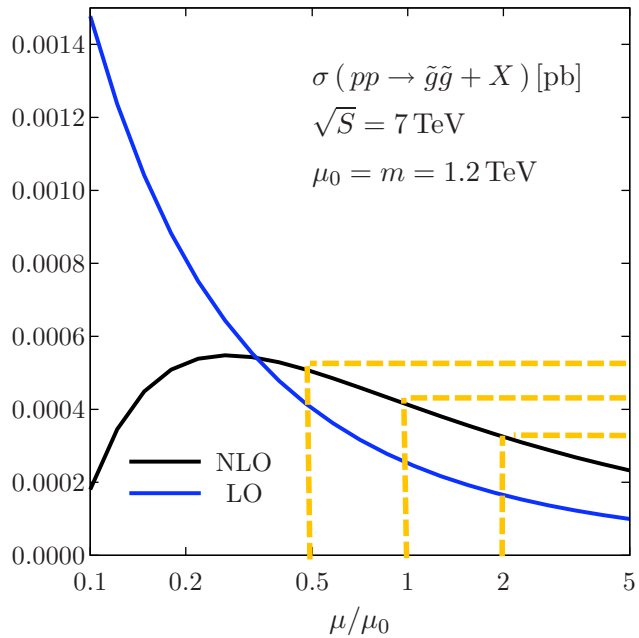

More than 20 % scale variation error

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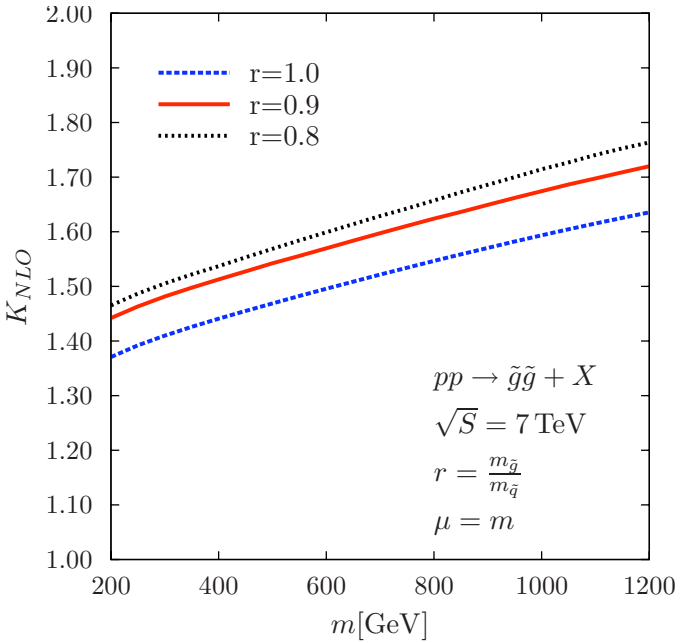
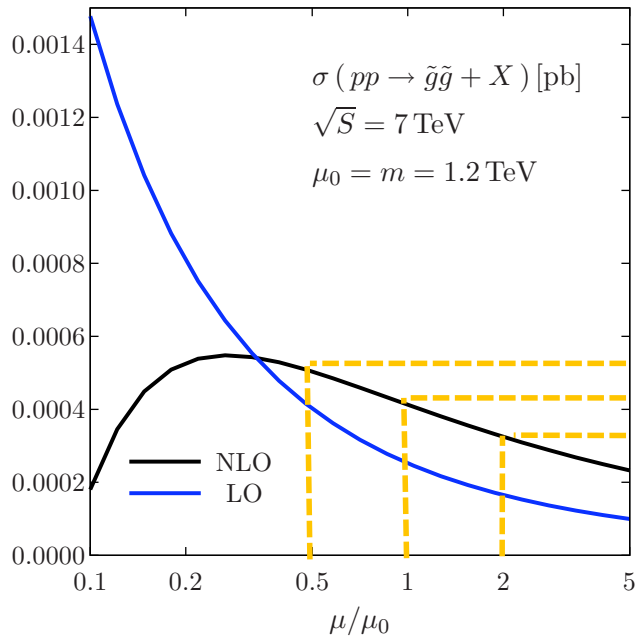




For higher masses, theory error due to scale variation will be bigger!

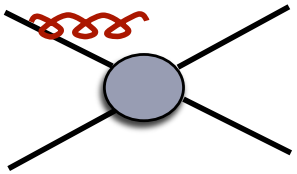
More than 20 % scale variation error

NLO At Threshold

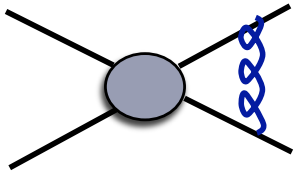
- Large masses of SUSY particles ⇒ production close to threshold $\hat{s} \sim 4m^2$
- General structure of the NLO correction in the threshold limit $\beta \to 0, \quad \beta^2 = 1 - 4m^2/\hat{s}$

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

Soft/collinear gluon emission



Coulomb gluons



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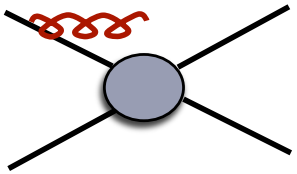

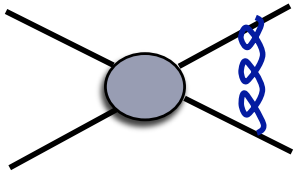

Large corrections in the limit of threshold production $\beta \to 0$

Higher Orders At Threshold

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Here: NLL resummation of soft gluon corrections

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Here: NLL 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]*

Disclaimer

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- This talk is not about how resumming of soft QCD corrections can be done…

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- … but about what resumming of these corrections can do to squark and gluino SUSY production cross sections

Soft gluon resummation

Systematic reorganization of perturbative series

$$\hat{\sigma} \sim c_{00} +$$

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

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

$\uparrow$ $\alpha_s^n \log^{2n}(\beta^2)$

$\uparrow$ $\alpha_s^n \log^{2n-1}(\beta^2)$

Soft gluon resummation

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$$\hat{\sigma} \sim c_{00} + \alpha_s \left(c_{12} \log^2(\beta^2) + c_{11} \log(\beta^2) + c_{10} \right) \leftarrow \text{NLO}$$

$$+ \alpha_s^2 \left(c_{24} \log^4(\beta^2) + c_{23} \log^3(\beta^2) + c_{22} \log^2(\beta^2) + \dots \right) \leftarrow \text{NNLO}$$

$$\dots \qquad \dots \qquad \dots$$

$\alpha_s^n \log^{2n}(\beta^2)$ $\alpha_s^n \log^{2n-1}(\beta^2)$

Factorization: space of Melin moments N ,taken wrt. $4m^2/S$ $\log(\beta^2) \leftrightarrow \log(N) \equiv L$

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

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

Resummation for Squark and Gluino Production

- Resummation performed in the space of Mellin moments
- NLL: soft wide-angle emission can change the colour structure of the underlying hard scattering
  - Accounted for by soft anomalous dimension matrices Γ_{ij}
  - Need to know 1-loop Γ_{ij} for for all four processes of squark and gluino production in order to resum up to NLL

    [AK, Motyka, Phys.Rev.Lett.102:111802,2009]
    [Beenakker, Brensing, Krämer, AK, Laenen, Niessen, JHEP 0912:041,2009]
  - Calculations confirm that soft gluon radiation only "feels" the total colour charge of the heavy-particle pair produced at threshold

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

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

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]*

Resummation-improved NLL+NLO total cross section

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

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

- 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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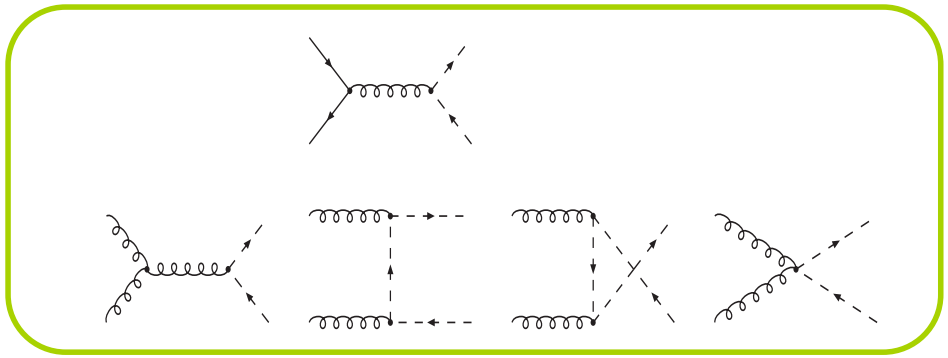
Stop-antistop



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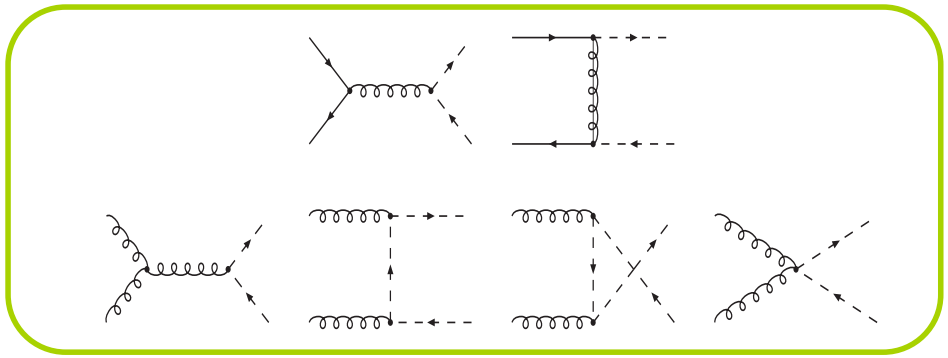
Squark-antisquark



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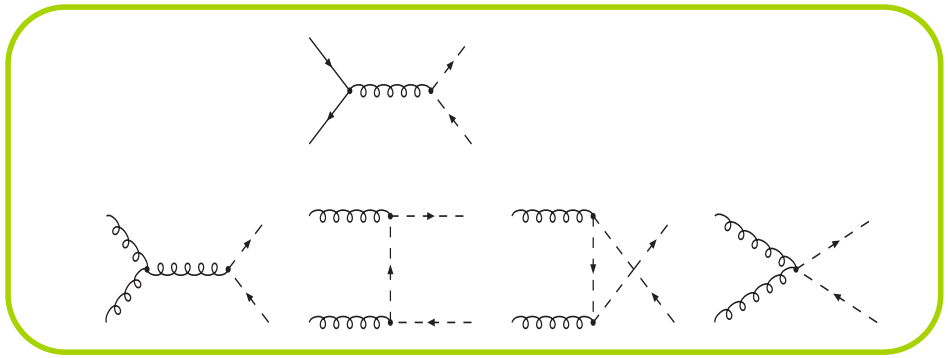

- Only diagonal i.e. $\tilde{t}_1\bar{\tilde{t}}_1$, $\tilde{t}_2\bar{\tilde{t}}_2$ pairs produced
- LO cross section depends only on the stop mass
- Note: for sbottom-pair $\tilde{b}_k\bar{\tilde{b}}_k$ production LO $b\bar{b}$ contribution negligible

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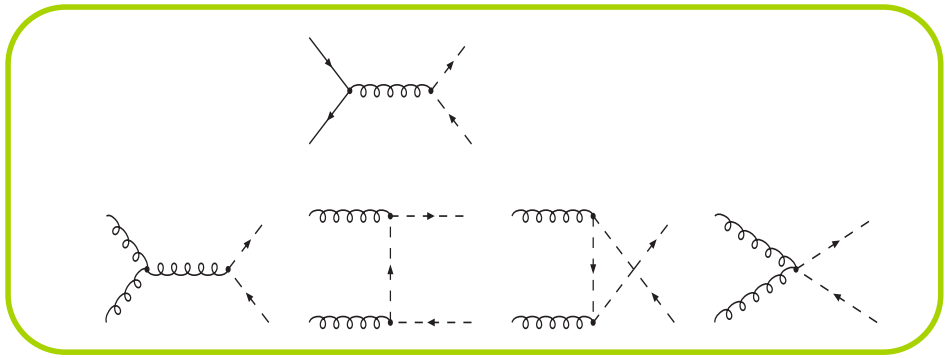
- At leading order

→ Resummation for stop-antistop and sbottom-antisbottom production

Stop-antistop



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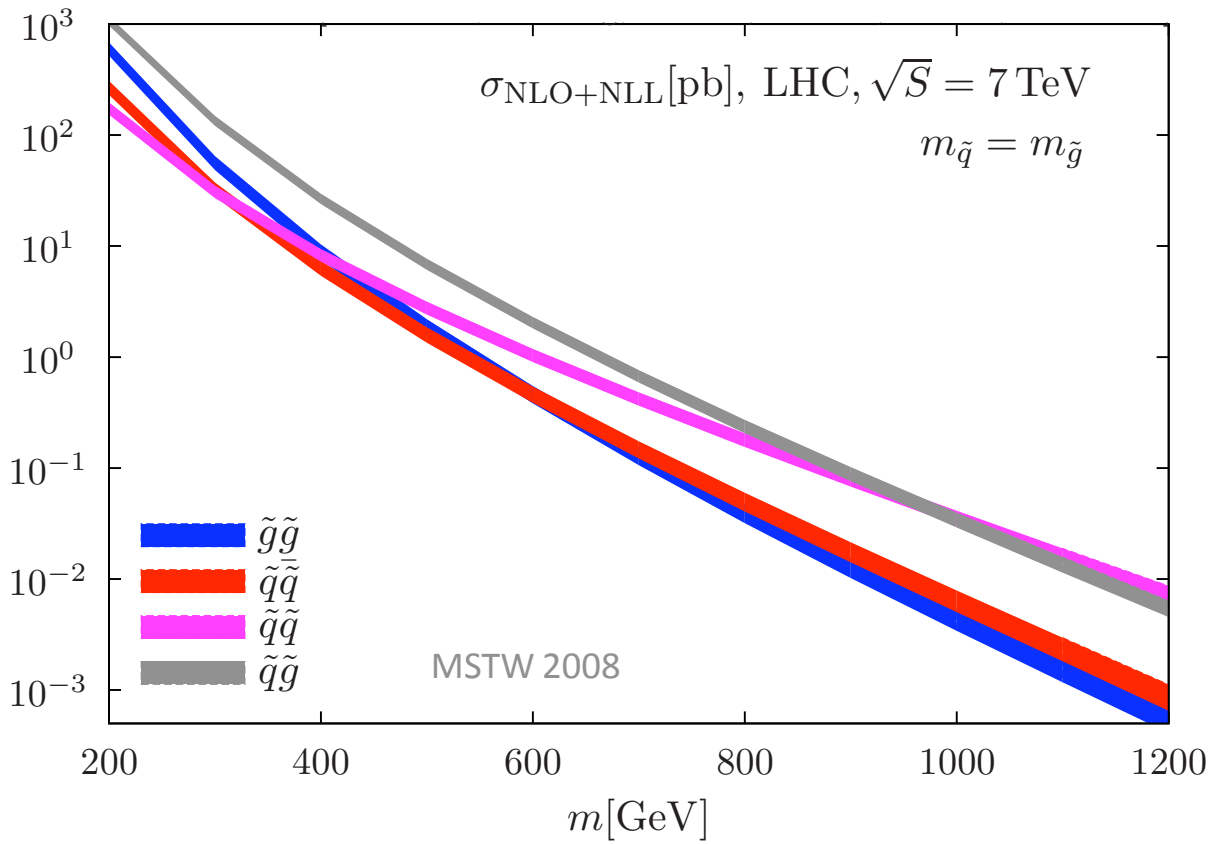
RESULTS FOR 7 TEV

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

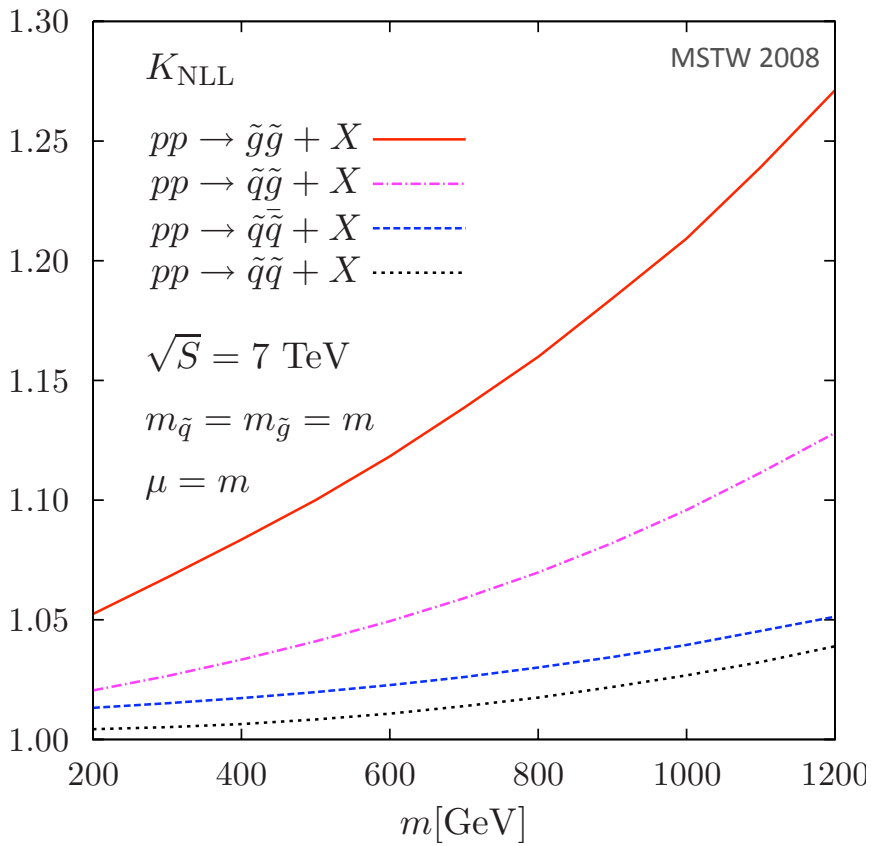
Total NLL+NLO production rates



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

NLL Corrections

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

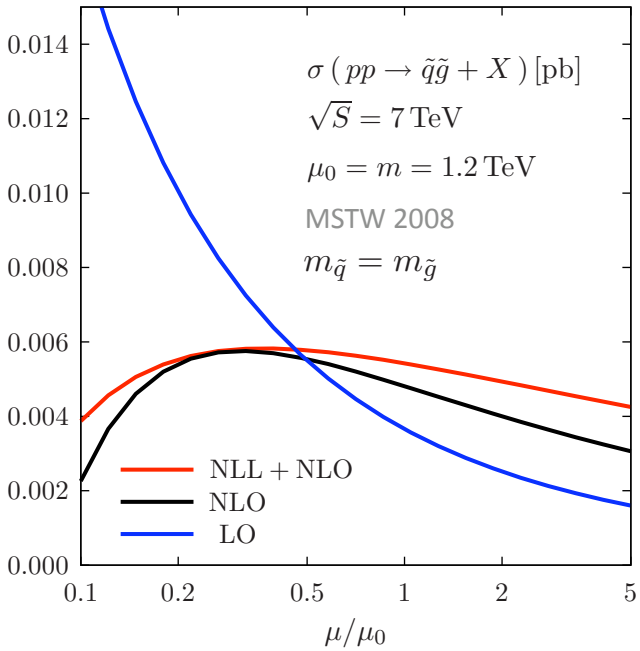


$$K_{\rm NLL} = \frac{\sigma^{\rm resummed,NLL}}{\sigma^{\rm NLO}}$$

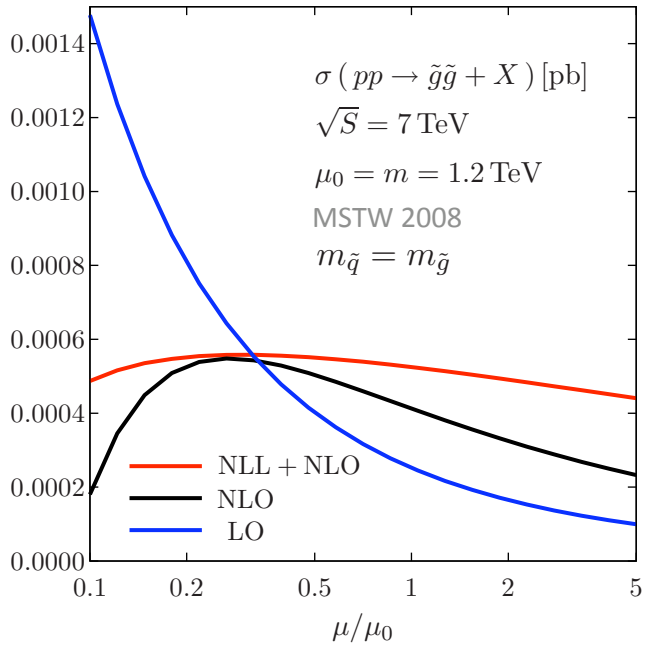
- Soft-gluon resummation enhances the cross sections
- Highest corrections for the gluino-pair production: 20% correction to the NLO results for m_{gl}= 1 TeV
- For the squark-gluino channel, NLL correction reaches 10% at m_{sq}= m_{gl}= 1 TeV

Scale variation

- Squark-gluino production



- Gluino-pair production

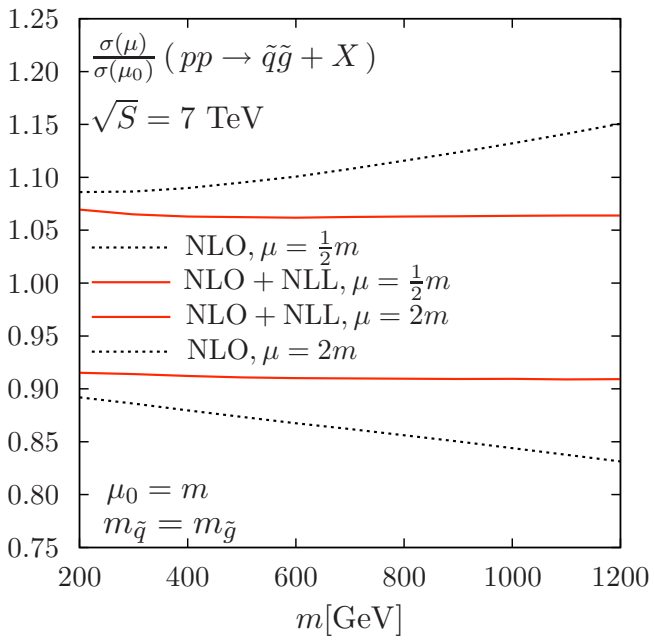


Significant reduction of the scale dependence for NLL+NLO compared to NLO, especially for gluino-pair production

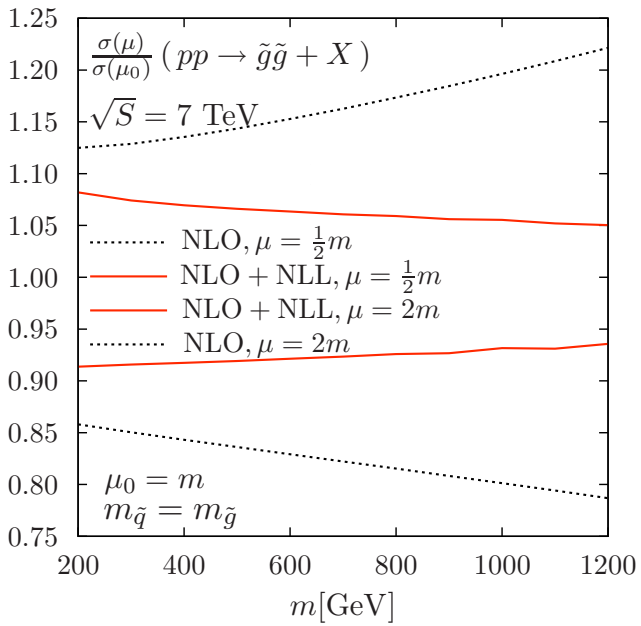
Scale variation ctnd.

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

- Squark-gluino production



- Gluino-pair production

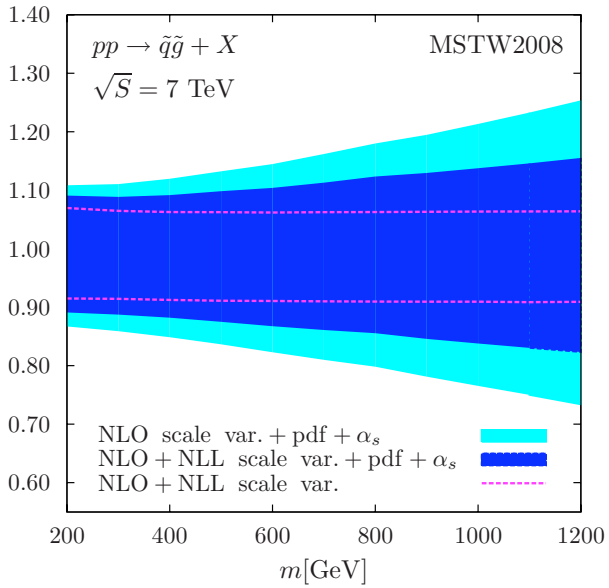


Theory error due to scale variation below 10% for NLL+NLO
down by a factor of 2 (squark-gluino) or a factor of 4 (gluino-pair) for masses > 1 TeV

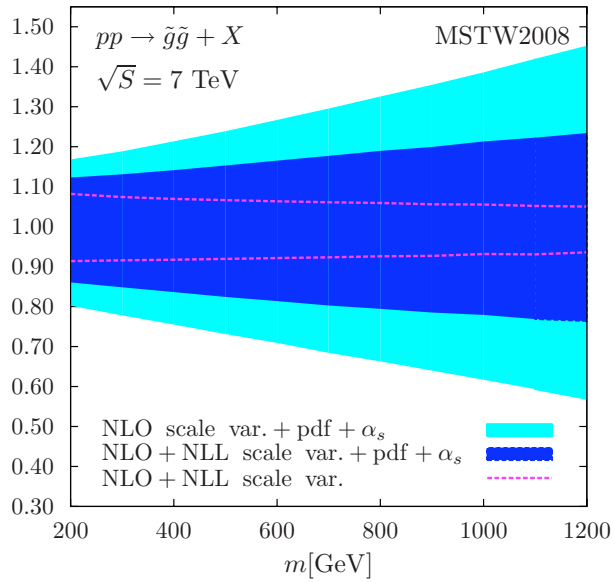
Theory Error

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

- Squark-gluino production

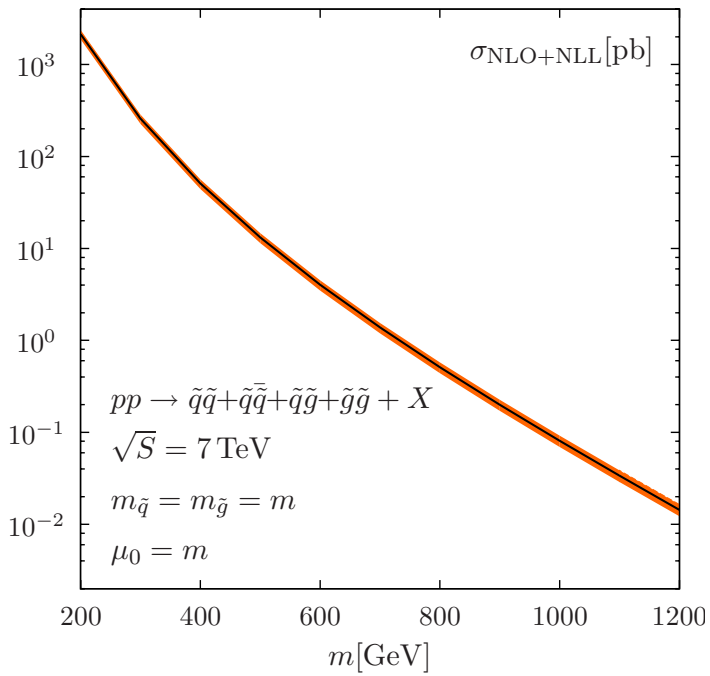


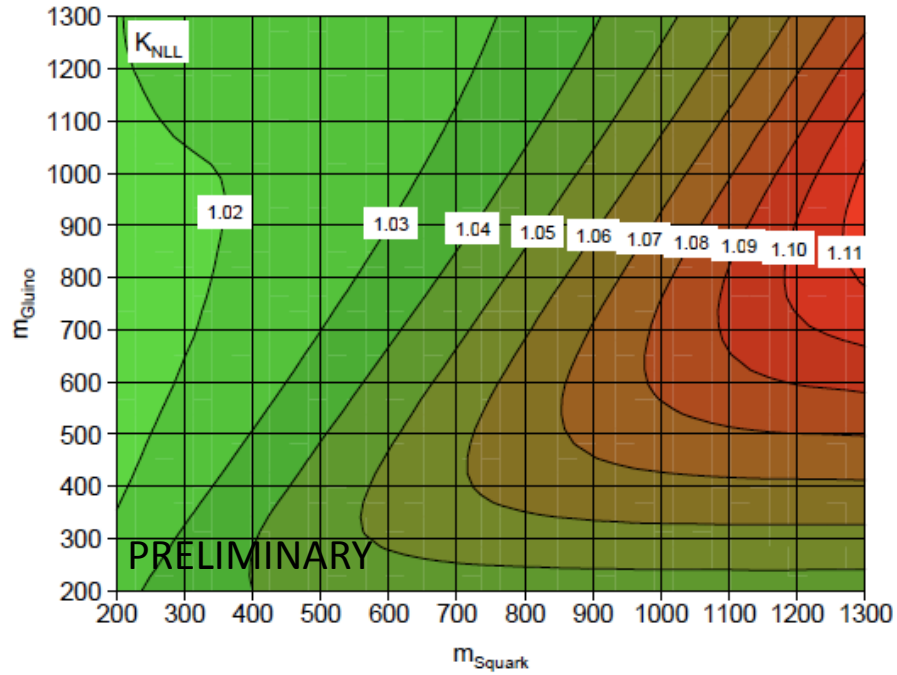
- Gluino-pair production



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

Total Inclusive Cross Section @ 7 TeV





plot courtesy of S. Brensing

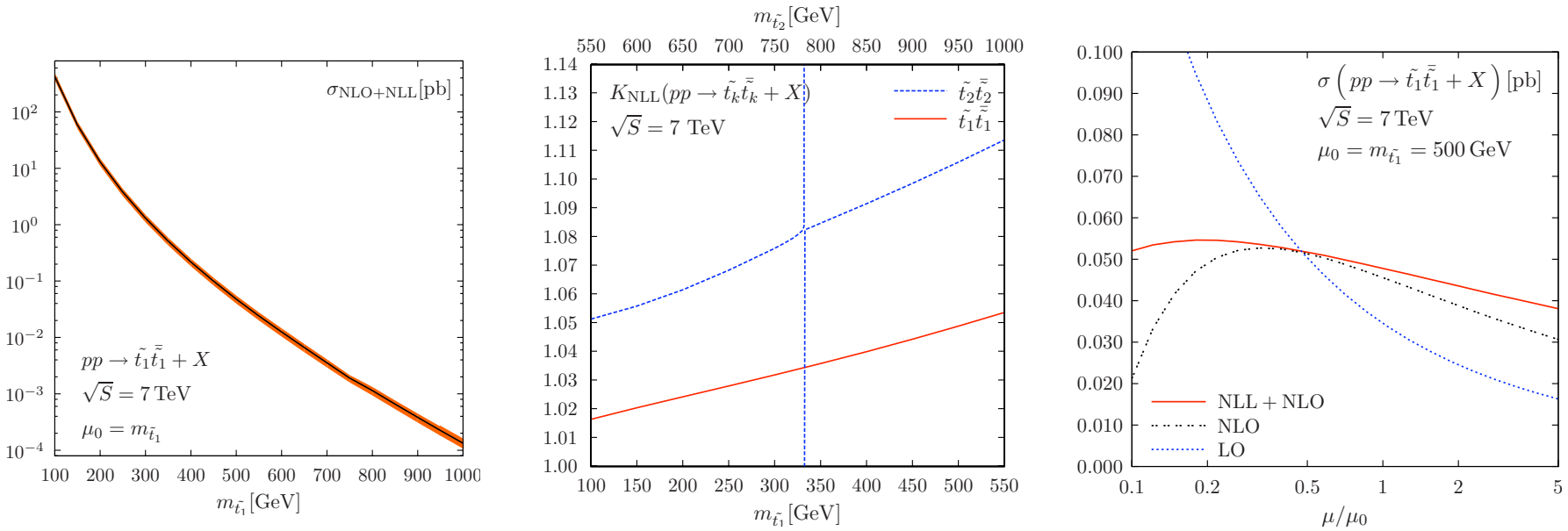
Most precise predictions for squark and gluino production rates currently available

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]*

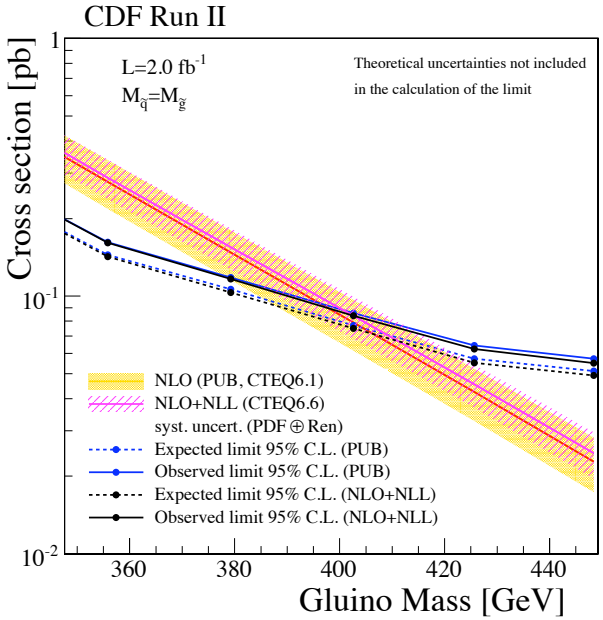


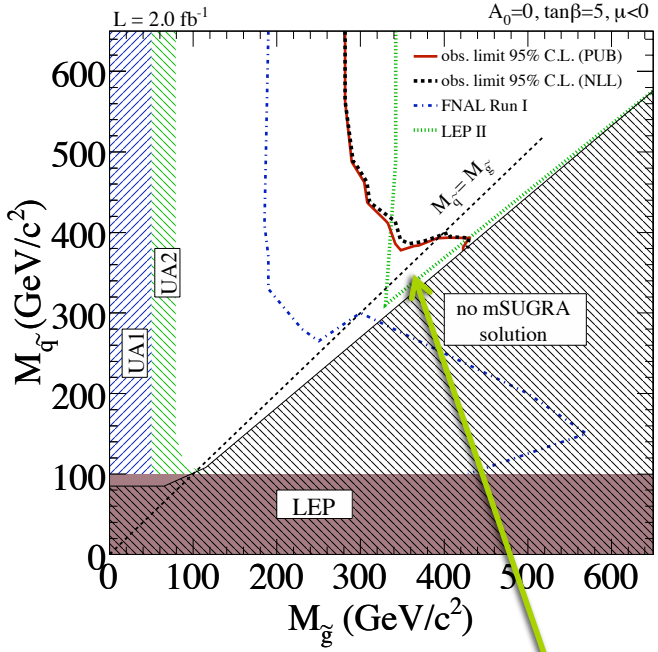
Reduction of the scale dependence for NLO+NLL predictions, compared with NLO

Tevatron Searches

- NLL+NLO analysis also performed for production of squarks and gluinos at the Tevatron *[Beenakker, Brensing, Krämer, AK, Laenen, Niessen, JHEP 0912:041,2009]*

- CDF mass limits revisited
  [Beenakker, Brensing, d'Onofrio, Krämer, AK, Laenen, Martinez, Niessen, arXiv:1106.5647]

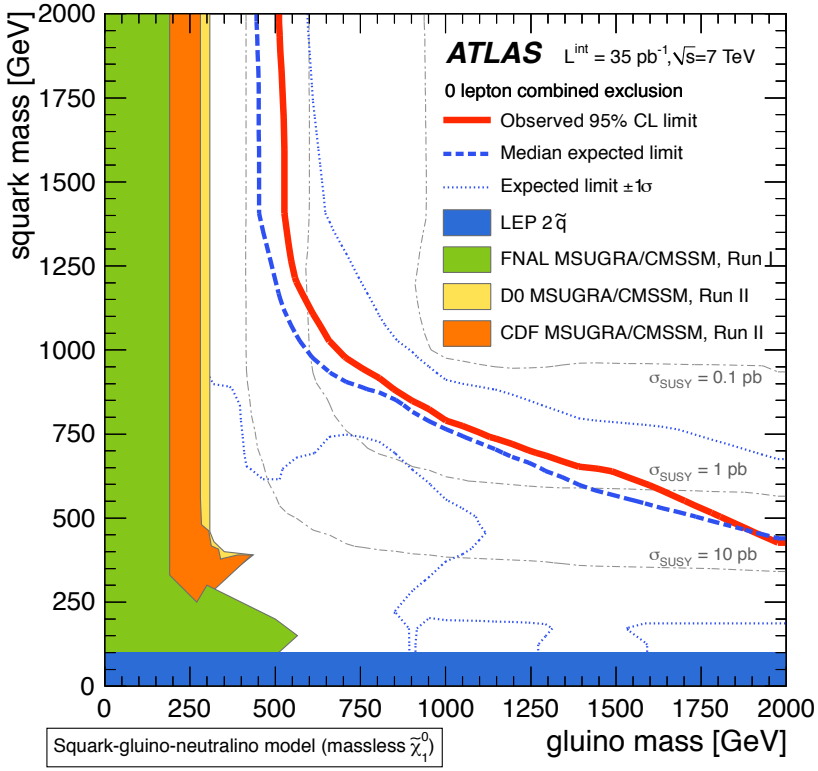




5-10 GeV shift

Impact on LHC Searches

[ATLAS, PLB 701 (2011) 186]



- Auxiliary information publicly available, including signal acceptance times efficiency

Impact on LHC Searches

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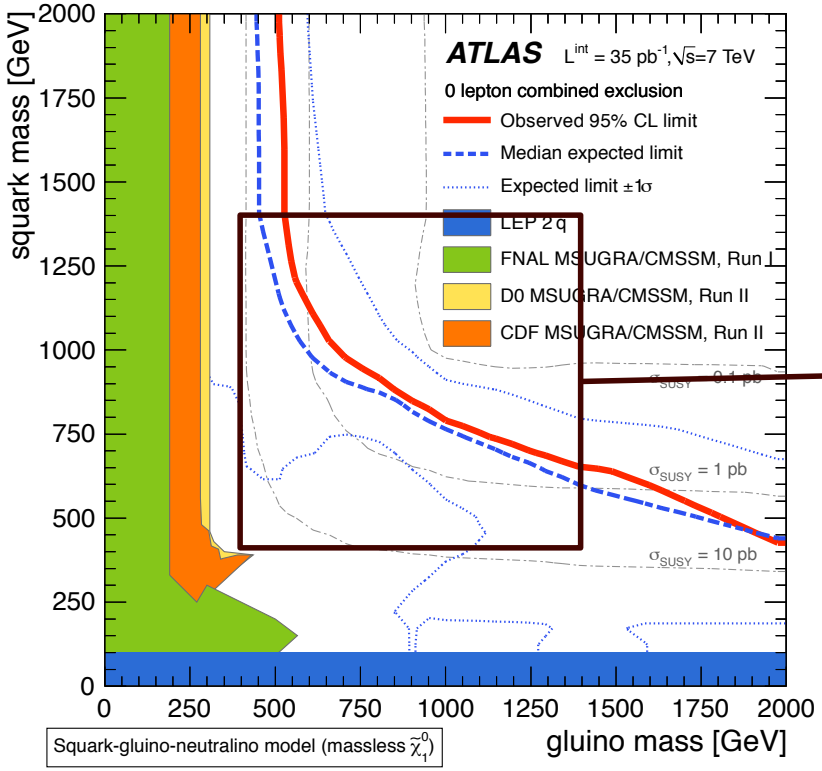

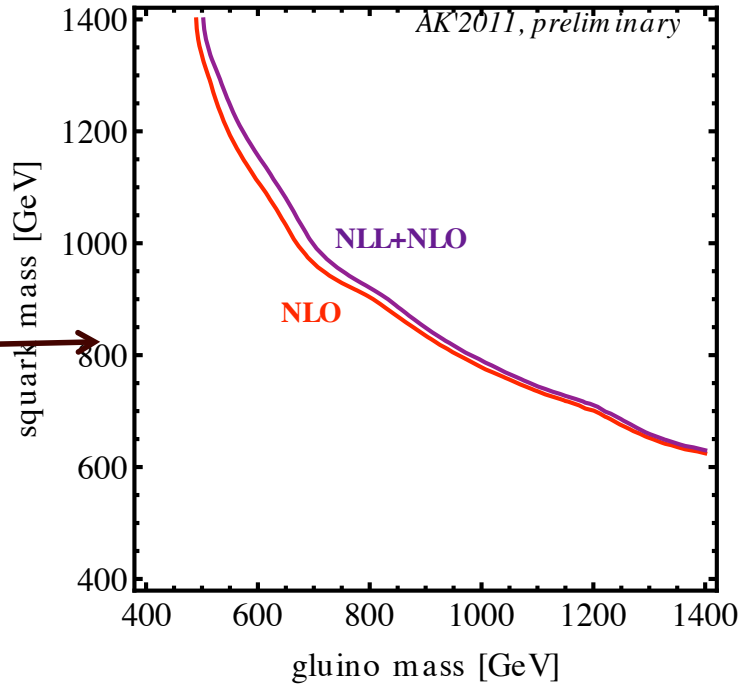

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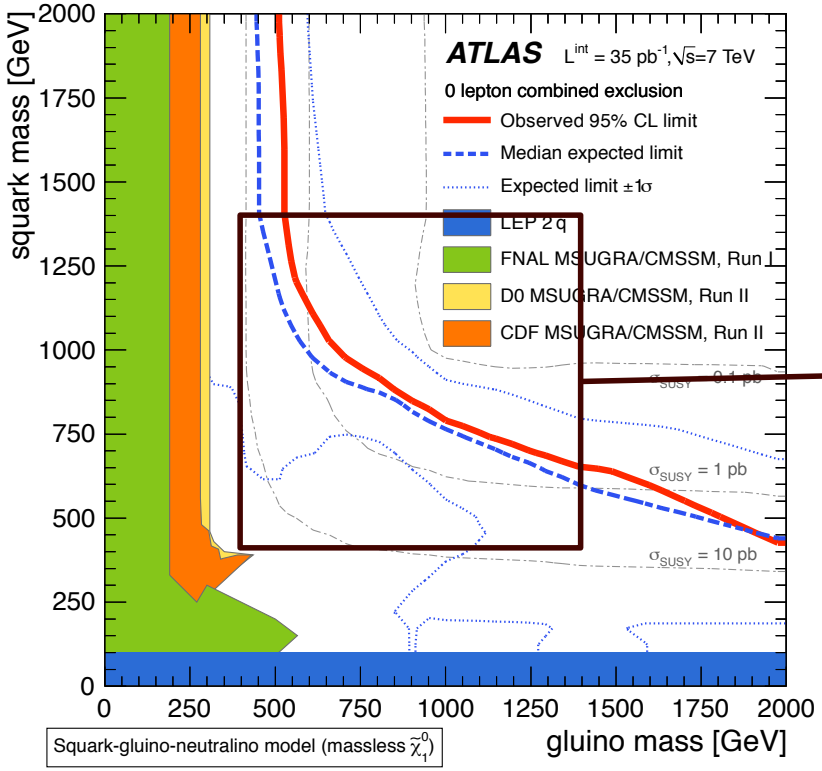

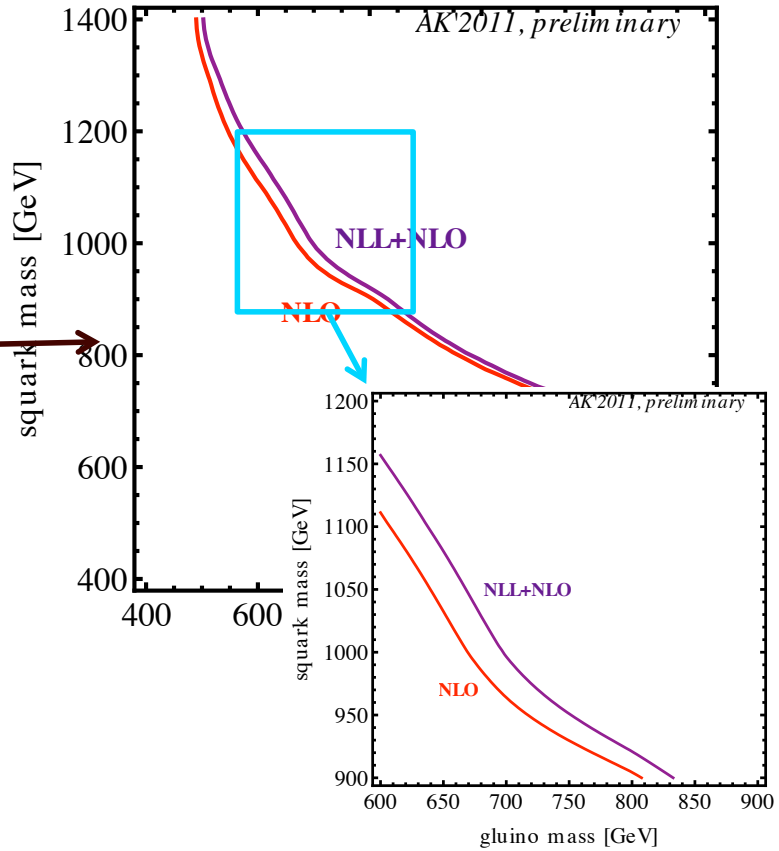

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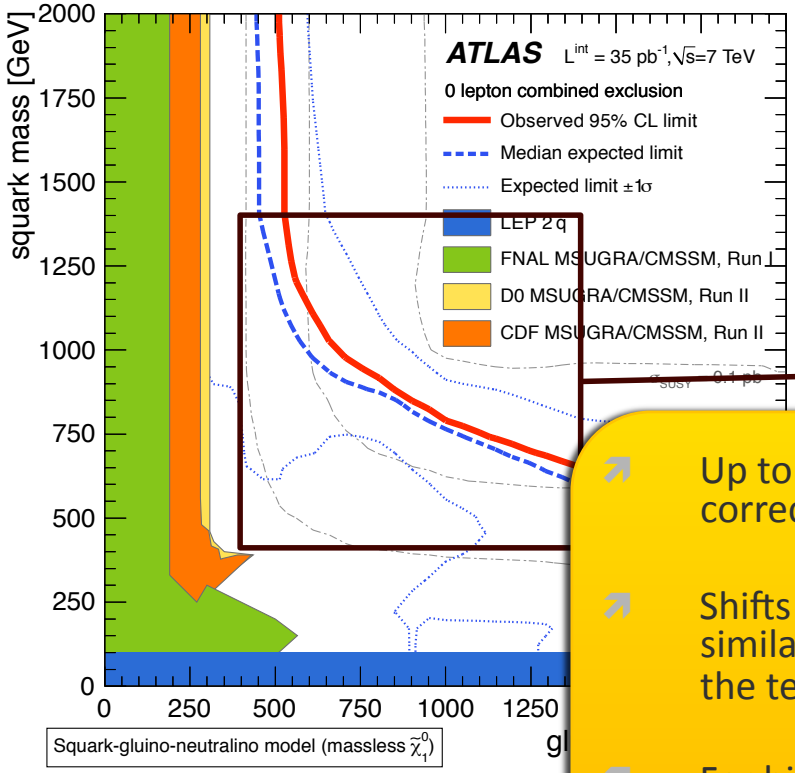
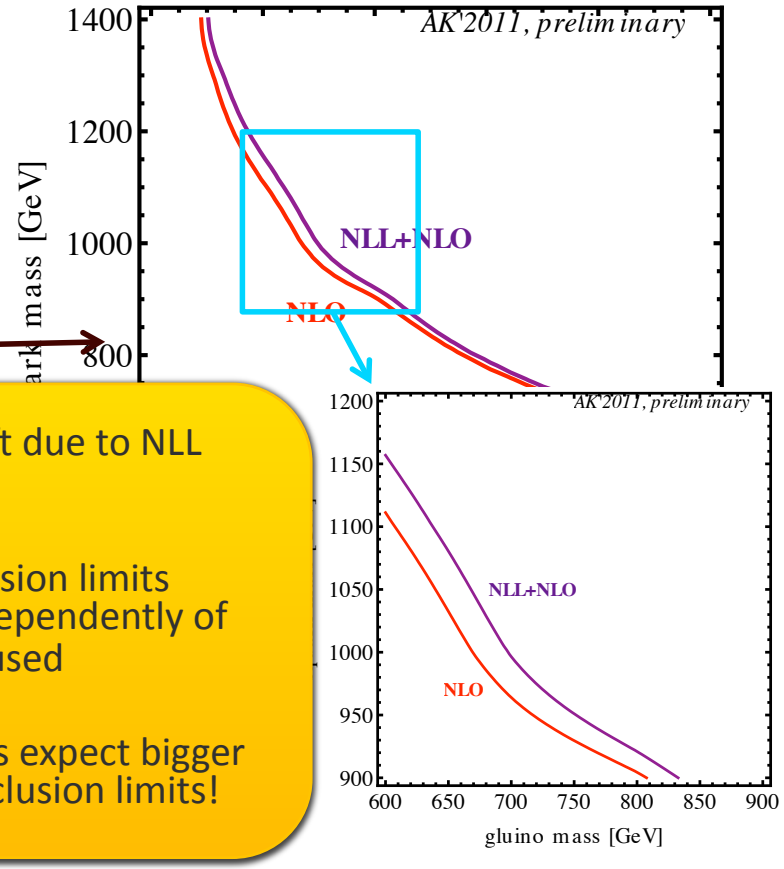




- Up to 50 GeV shift due to NLL corrections
- Shifts in the exclusion limits similar in size independently of the test statistic used
- For higher masses expect bigger impact on the exclusion limits!

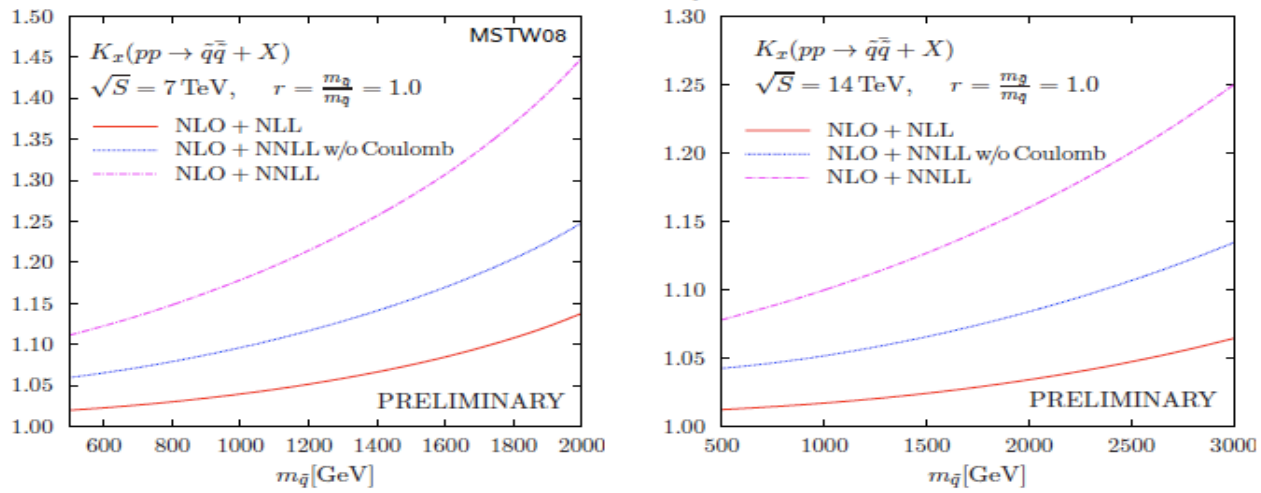
… And It Only Gets (Theoretically) More Interesting…

- Our new calculations of the NNLL cross section for squark-antisquark production show that contributions of higher order (i.e. above NLL+NLO) can be very important (significance of Coulomb terms → *[Beneke,Falgari,Schwinn'10]*)

→ talk by Silja Brensing

$K_{\mathrm{NNLL}} = \sigma_{\mathrm{NLO+NNLL}}/\sigma_{\mathrm{NLO}}$ at the LHC

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



- K_{NNLL}-factors grow with increasing sparticle mass due to importance of threshold region
- large corrections beyond NLL
  - can be mostly attributed to incorporating hard matching coefficients and leading Coulomb corrections

Silja Brensing (DESY) NNLL resummation for squark-antisquark SUSY 2011 16 / 20

Public Code: NLL-Fast

- **All four processes of squark and gluino production at NLL+NLO**
- Beta-version available at

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

  → LPCC BSM Working group
- 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 200-2000 GeV

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
- 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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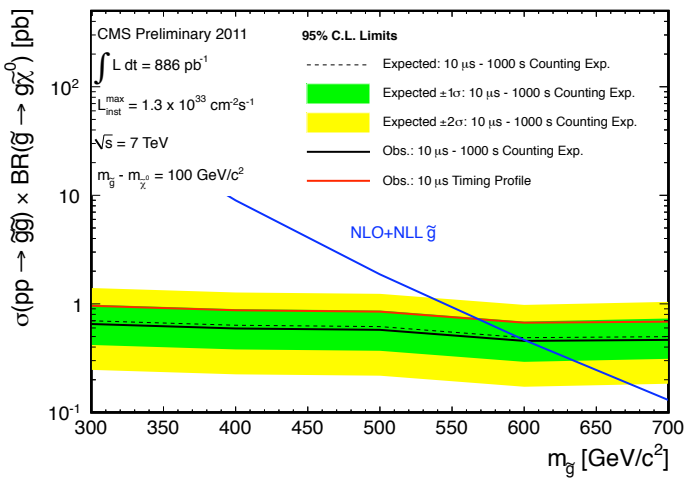

CMS search for stopped HSCPs, EXO-11020

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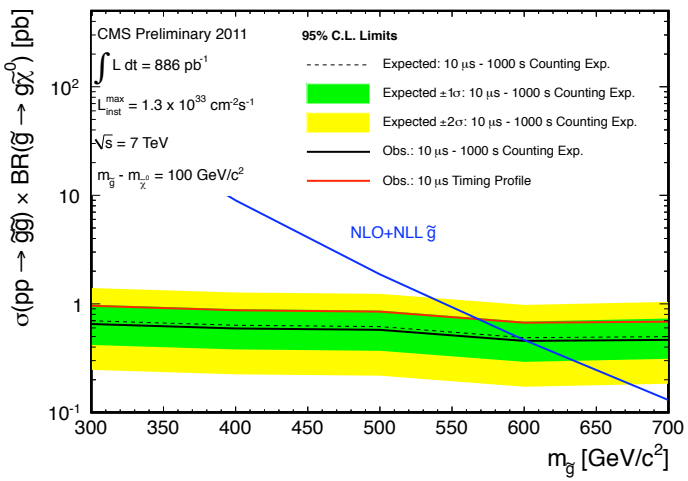
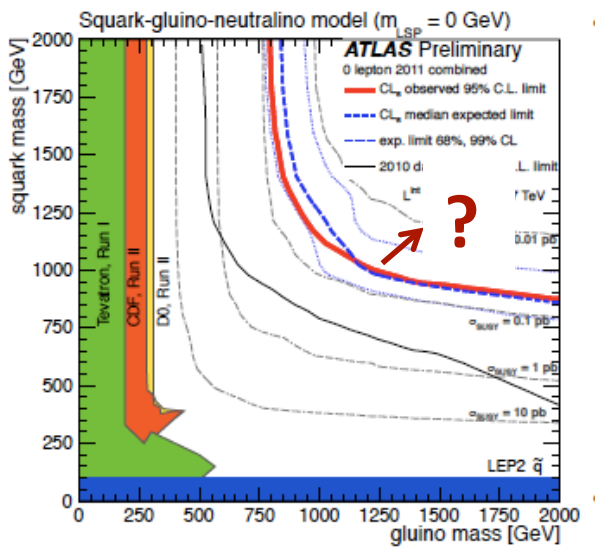
CMS search for stopped HSCPs, EXO-11020