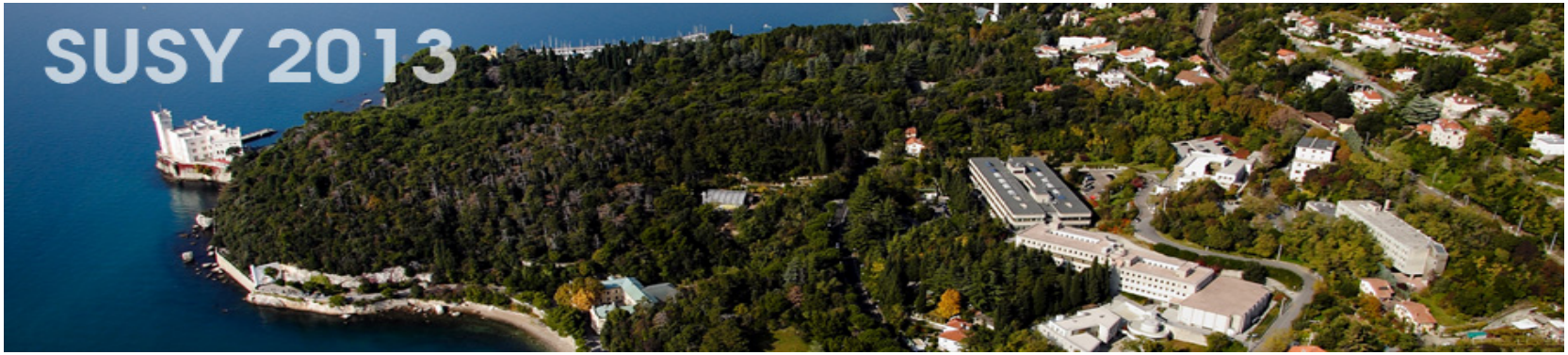
Improving Theoretical Predictions for processes of pair-production of coloured supersymmetric particles : an Update

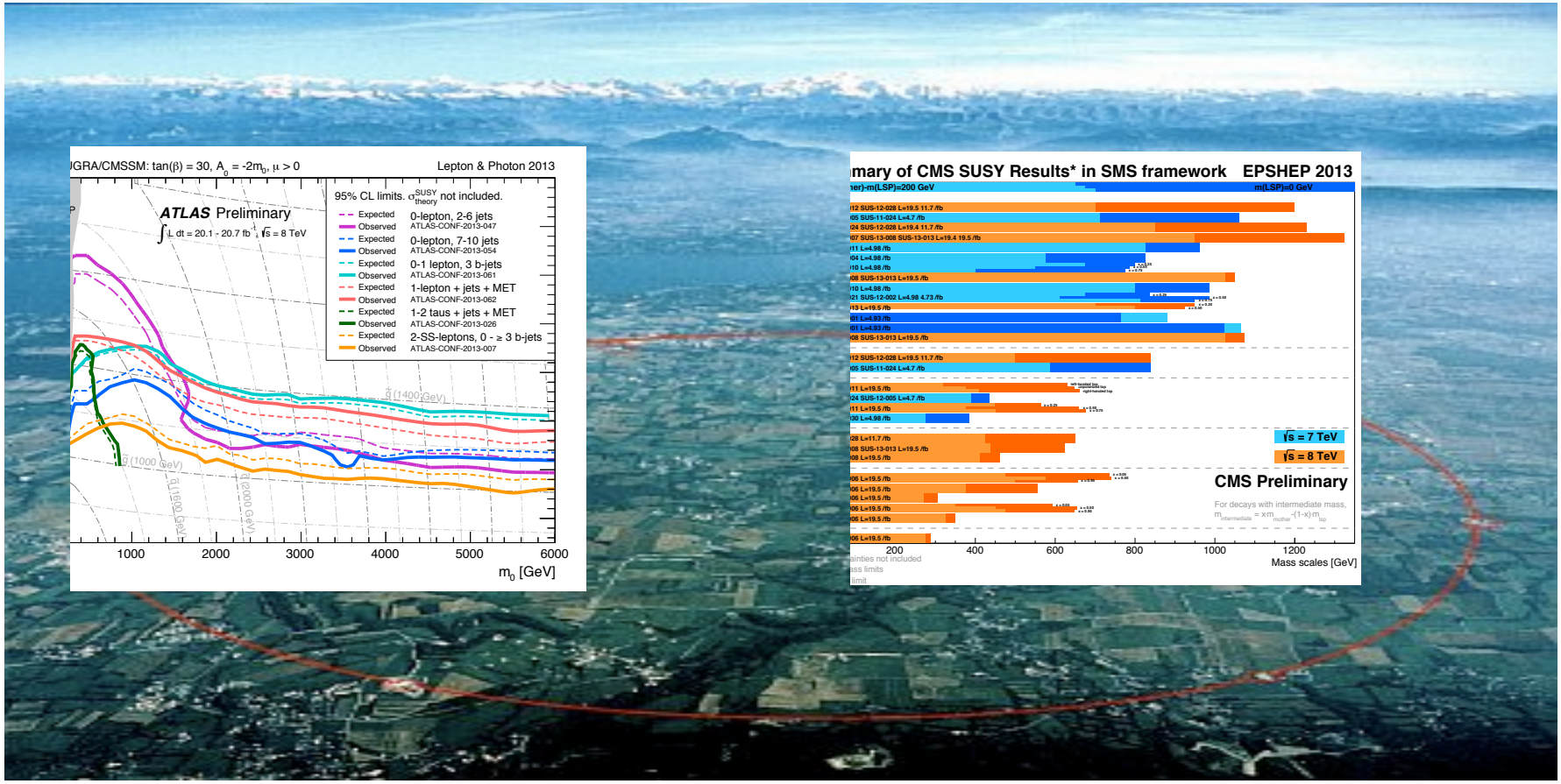
Anna Kulesza

Westfälische Wilhelms-Universität Münster



Trieste, 29.08.2013

LHC Searches



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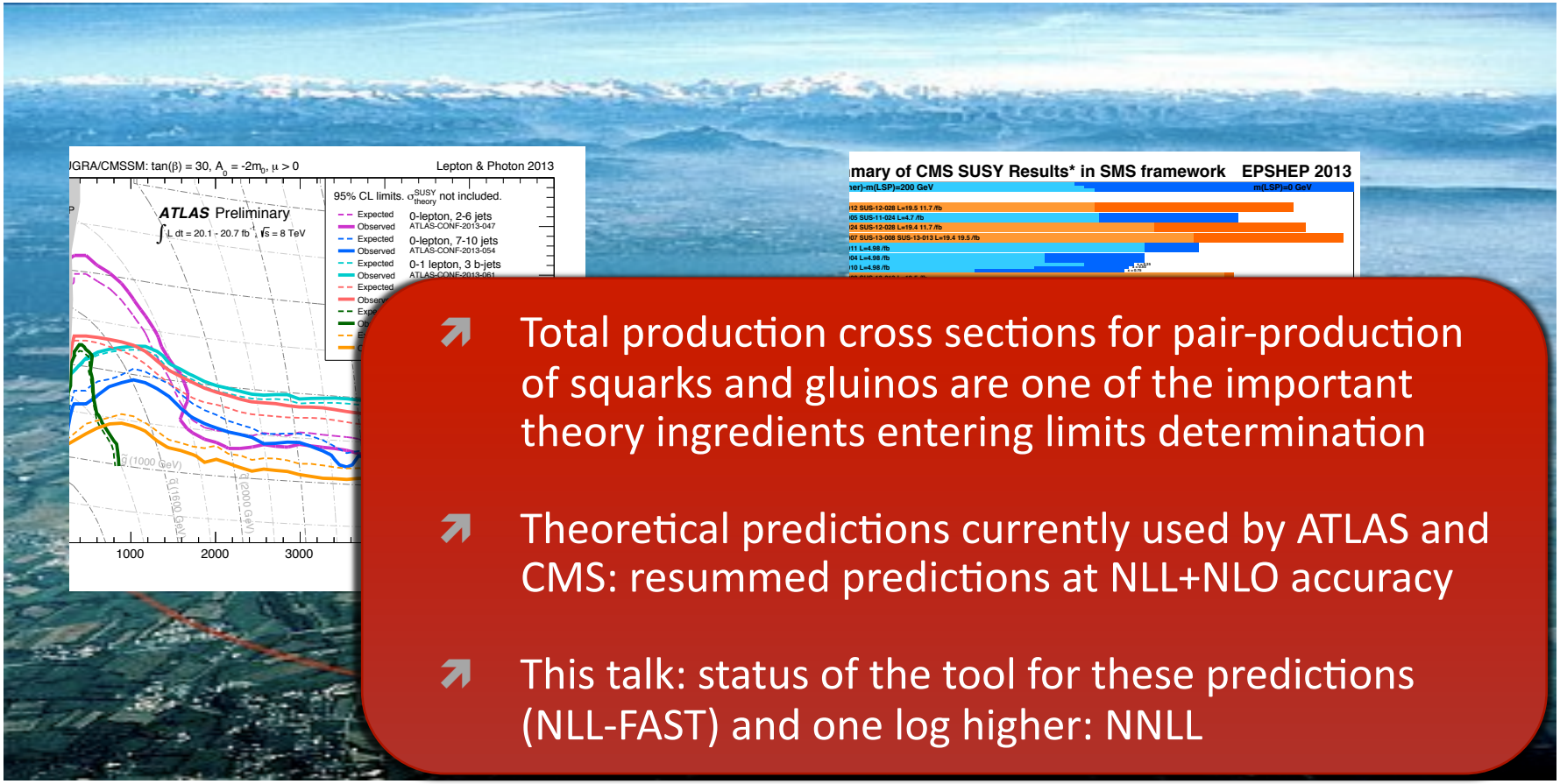


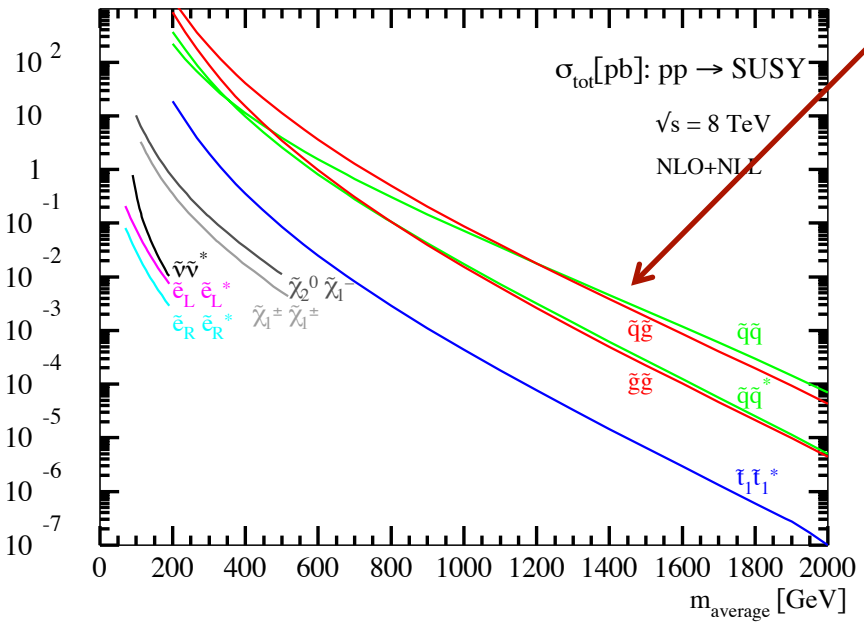
- Total production cross sections for pair-production of squarks and gluinos are one of the important theory ingredients entering limits determination
- Theoretical predictions currently used by ATLAS and CMS: resummed predictions at NLL+NLO accuracy
- This talk: status of the tool for these predictions (NLL-FAST) and one log higher: NNLL

Squarks and gluinos at the LHC

MSSM: pair-production of coloured sparticles dominates at the LHC

$$p\,p \longrightarrow \tilde{t}_k\bar{\tilde{t}}_k,\ \tilde{q}\bar{\tilde{q}},\ \tilde{q}\tilde{q},\ \tilde{q}\tilde{g},\ \tilde{g}\tilde{g}$$

NLO+NLL SUSY-QCD for strong processes
NLO for EW processes



SQUARKS AND GLUINOS AT THE LHC

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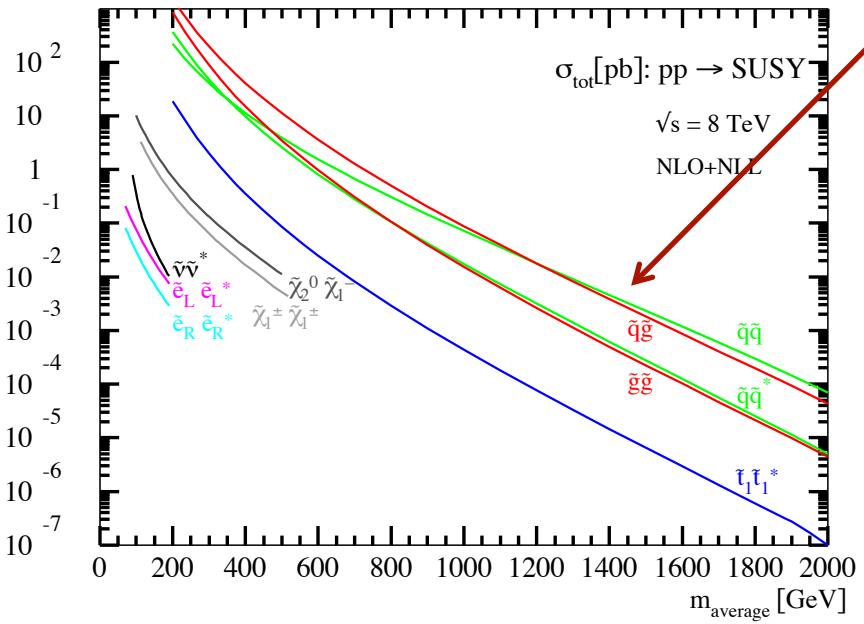


Why NLO+NLL?

Resummation:

- systematically takes into acoount dominant parts of the higher order corrections
- reduces theory (scale variation) error

Theoretical Status: Fixed Order

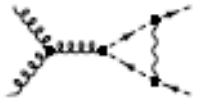
Corrections to $\mathcal{O}(\alpha_s^2)$ = LO QCD processes

- 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 gluino-gluino production: approximate NNLO contributions → $\mathcal{O}(\alpha_s^4)$ *[Langenfeld, Moch'09] [Langenfeld. Moch,Pfoh'12]*

- 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. 

PROSPINO
MadGolem

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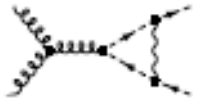
  e.g. 

PROSPINO
MadGolem

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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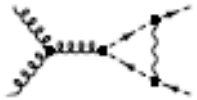
  e.g. 

Typically order of a few tens of percents

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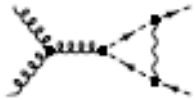
e.g. 

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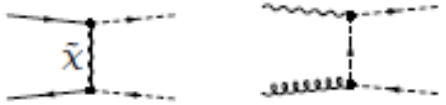
 etc.

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

Higher Orders At Threshold

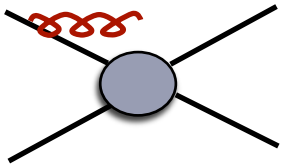
→ Large masses of SUSY particles ⇒ production close to threshold $\hat{s} \sim 4m^2$

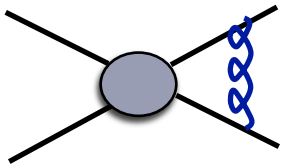
→ General structure of the NLO correction in the threshold limit $\beta \to 0, \quad \beta^2 = 1 - 4m^2/\hat{s}$

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

Soft/collinear gluon emission

Coulomb gluons





At higher orders:

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

$\sim \alpha_s^n / \beta^n$

Both types of corrections can be resummed to all orders

Soft gluon resummation

Systematic reorganization of perturbative series

$$\hat{\sigma} \sim c_{00} + \alpha_s \left(c_{12} \log^2(\beta^2) + c_{11} \log(\beta^2) + c_{10} \right) + \alpha_s^2 \left(c_{24} \log^4(\beta^2) + c_{23} \log^3(\beta^2) + c_{22} \log^2(\beta^2) + \ldots \right) + \ldots$$

NLO

NNLO

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

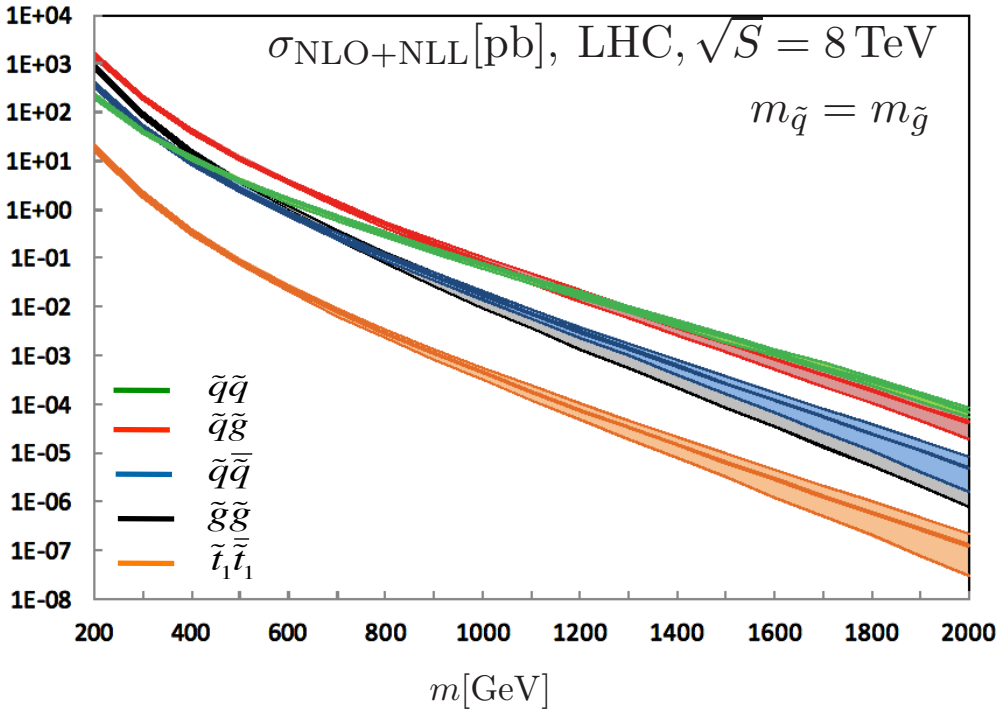
Factorization: space of Melin moments N ,taken wrt. $4m^2/S$ $\log(\beta^2) \leftrightarrow \log(N) \equiv L$

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

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

SQUARK AND GLUINO PRODUCTION AT NLL+NLO

After matching consistently with the NLO predictions (PROSPINO)



full theory error: scale variation, pdf and α_s uncertainty

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

PUBLIC CODE: NLL-FAST

- **NLL-fast = public tool producing NLL+NLO results for:**
  - **squark and gluino pair-production**
  - **stop-antistop (sbottom-antisbottom) production**
  - **gluino pair-production in the decoupling limit of large squark masses and vice versa**

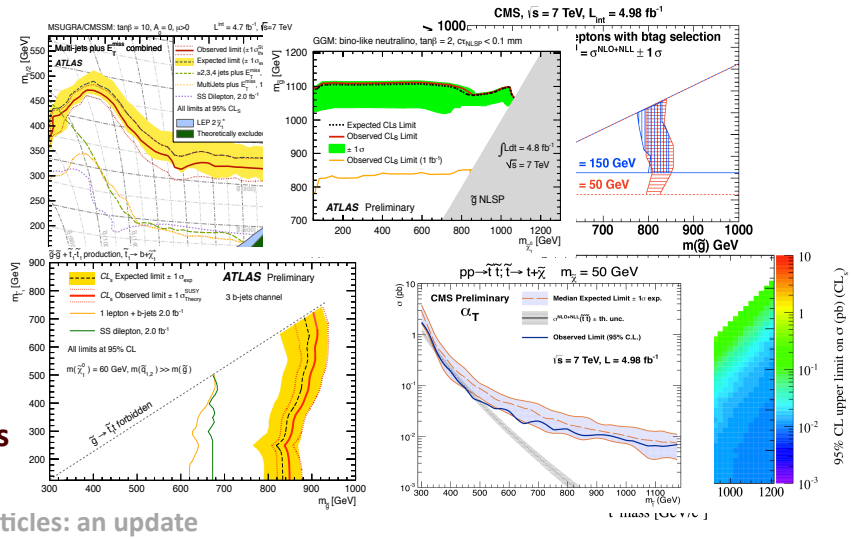
http://web.physik.rwth-aachen.de/service/wiki/bin/view/Main/BSMCrossSectionWorkingGroup

and **http://http://pauli.uni-muenster.de/~akule_01/nllwiki/index.php/NLL-fast**

- Starting from 2011, NLL-fast used in the analysis of experimental data for 7 and 8 TeV by both ATLAS and CMS as documented in *[Krämer, AK, van der Leeuw, Mangano, Padhi, Plehn, Portell, arXiv:1206.2892],*

see also

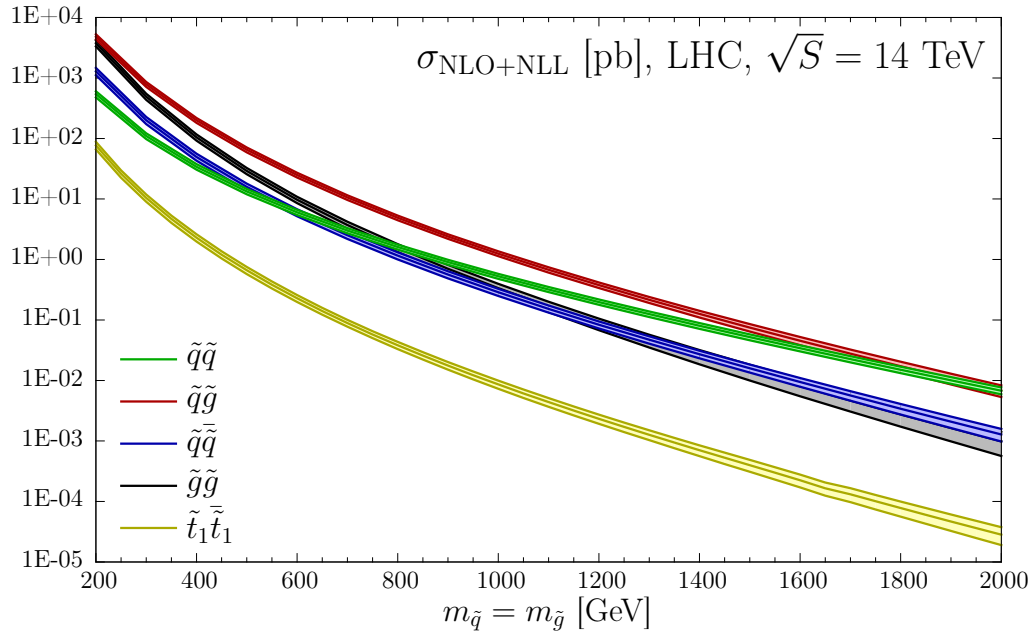
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections



NLL-fast for Next LHC run(s)

- Available versions of NLL-fast deliver predictions for all processes of squark and gluino production, including stop and decoupling limits at √s = 7, 8 and 13 TeV

  http://http://pauli.uni-muenster.de/~akule_01/nllwiki/index.php/NLL-fast

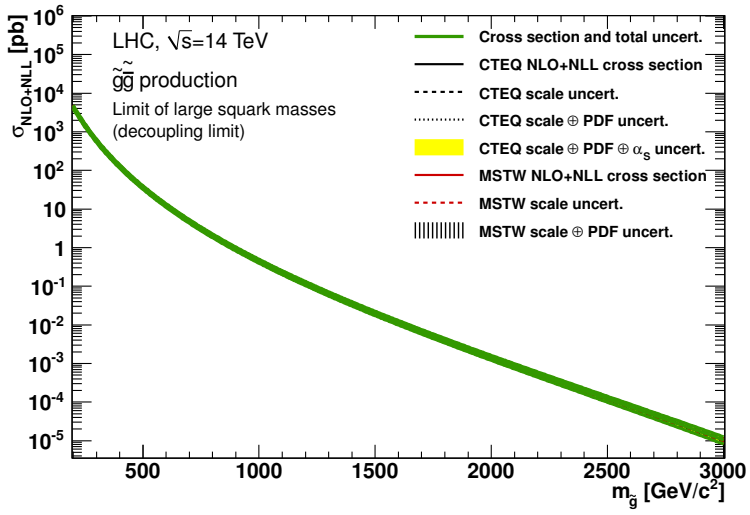


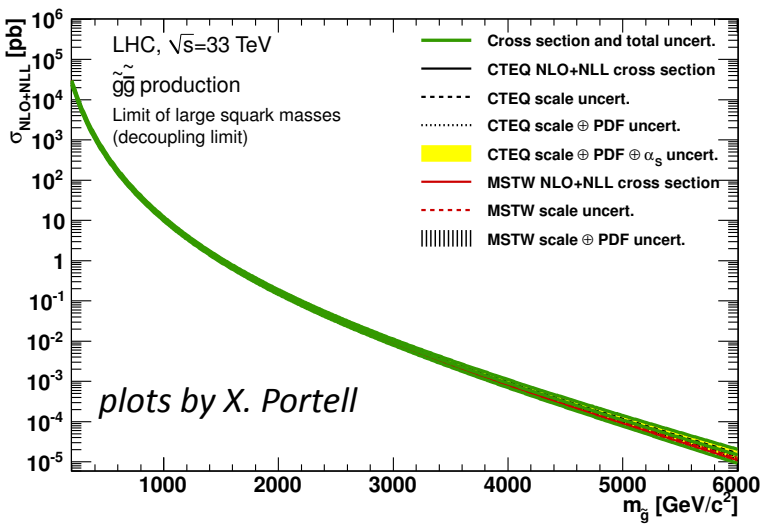
- A full version of NLL-fast for √s = 14 TeV in preparation

NLL-fast For 14 and 33 TeV

- A "light" version of NLL-fast for √s = 14 and 33 TeV is also available, covering stop-antistop as well as gluino and squark production in the decoupling limits

Example: gluino production in the decoupling limit of large squarks masses





http://http://pauli.uni-muenster.de/~akule_01/nllwiki/index.php/NLL-fast

→ *a write-up in preparation*

Squark and Gluino production: Resummation

Resummation of soft gluon corrections

- @NLL+NLO for ALL processes *[AK, Motyka '08-'09][Beenakker, Brensing, AK, Laenen,Niessen'09-'10]*

  → **NLL-FAST**

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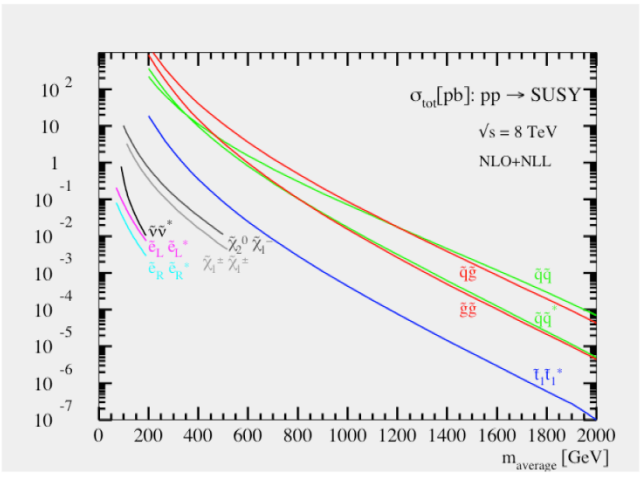
- @NNLL+NLO for $\tilde{q}\bar{\tilde{q}}$ *[Beenakker, Brensing, AK, Laenen,Niessen'11]*, $\tilde{g}\tilde{g}$ @NNLL+NNLO$_{\text{approx}}$ *[Pfoh'13]* and $\tilde{t}\,\bar{\tilde{t}}$ *[Broggio et al'13]*

- This talk: remaining processes @NNLL+NNLO$_{\text{approx}}$



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- This talk: remaining processes @NNLL+NNLO$_{\text{approx}}$

Resummation of Coulomb 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]*

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Resummation of soft and Coulomb corrections together

- in momentum space, using SCET and NRQCD, for ALL processess @NLL +NLO *[Beneke, Schwinn, Falgari '09-'10] [Falgari, Schwinn, Wever'12]*. Finite width effects studied in *[Falgari, Schwinn, Wever'13]*.

Resummed cross sections

Partonic cross section in orthogonal basis in colour space for which Γ_{IJ} is diagonal in the threshold limit (s-channel basis *[AK, Motyka' 09], [Beneke, Falgari, Schwinn'09]*)

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

sum over colour channels

Hard function

Soft-collinear radiation from incoming partons, universal, known

Soft, wide-angle emission, process dependent

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

LL NLL NNLL

NLL: currently used in experimental analysis

NNLL recently finished for all processes -> this talk

TOWARDS NNLL

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

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

Shopping list for NNLL:

- Exponentials at NNLL accuracy (need the NNLL function g_3) → available ✔
  [Moch,Vermaseren,Vogt'04][Contopanagos, Laenen,Sterman'96][Catani, de Florian, Grazzini'01][Beneke, Fallgari, Schwinn'09][Czakon, Mitov, Sterman'09] [Ferroglia, Neubert, Pecjak, Yang'09]

- Matching coefficients

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

  - Soft-Coulomb factorization *[Bonciani, Catani, Mangano, Nason'98][Beneke, Falgari, Schwinn'09-10]*
    - 1st and 2nd order Coulomb effects also known ✔
    - Remaining hard matching coefficients → need to be calculated

[Beenakker, Janssen, Lepoeter, Krämer, AK, Laenen, Niessen,Thewes, Van Dal'13]

RESUMMATION-IMPROVED CROSS SECTIONS

- Resummed expression is matched with the perturbative result to avoid double counting

$$\sigma^{(\mathrm{match})}_{h_1h_2\to kl}(\rho,\{m^2\},\mu^2) = \sum_{i,j=q,\bar{q},g}\int_{C_{\mathrm{MP}}-i\infty}^{C_{\mathrm{MP}}+i\infty}\frac{dN}{2\pi i}\,\rho^{-N}\,f^{(N+1)}_{i/h_1}(\mu^2)\,f^{(N+1)}_{j/h_2}(\mu^2)$$
$$\times\left[\,\hat{\sigma}^{(\mathrm{res},N)}_{ij\to kl}(\{m^2\},\mu^2) - \hat{\sigma}^{(\mathrm{res},N)}_{ij\to kl}(\{m^2\},\mu^2)\Big|_{\text{f.-o.}}\,\right]$$
$$+\quad \sigma^{\text{f.-o.}}_{h_1h_2\to kl}(\rho,\{m^2\},\mu^2)\,,$$

- NNLL matched to NNLO$_{\text{approx}}$

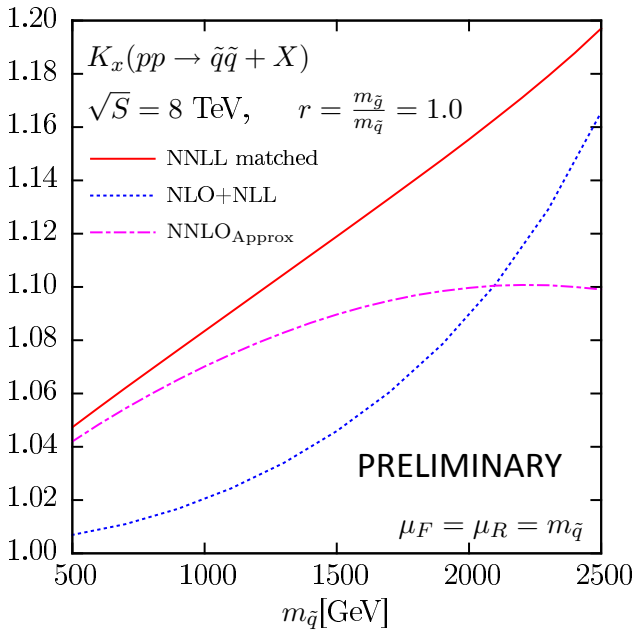
$$\sigma^{NNLO,\,approx}_{h_1h_2\to kl} = \sigma^{NLO}_{h_1h_2\to kl} + \Delta\sigma^{NNLO,\,approx}_{h_1h_2\to kl}$$

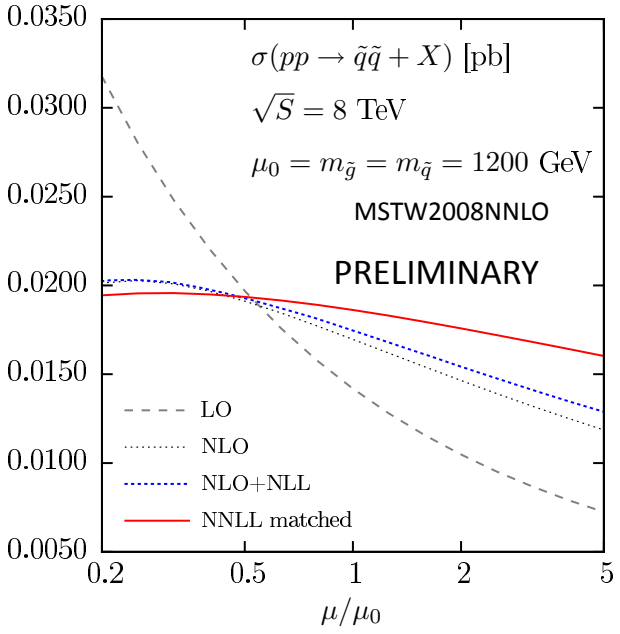
  - 2nd order correction constructed out of dominant terms in β as β→0 for arbitrary colour representation *[Beneke et al'09]*

NNLL+NNLO$_{\text{APPROX}}$ FOR SQUARK-SQUARK PRODUCTION

[Beenakker, Borschensky, Krämer, AK, Laenen, Theeuwes, Thewes, in preparation]

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



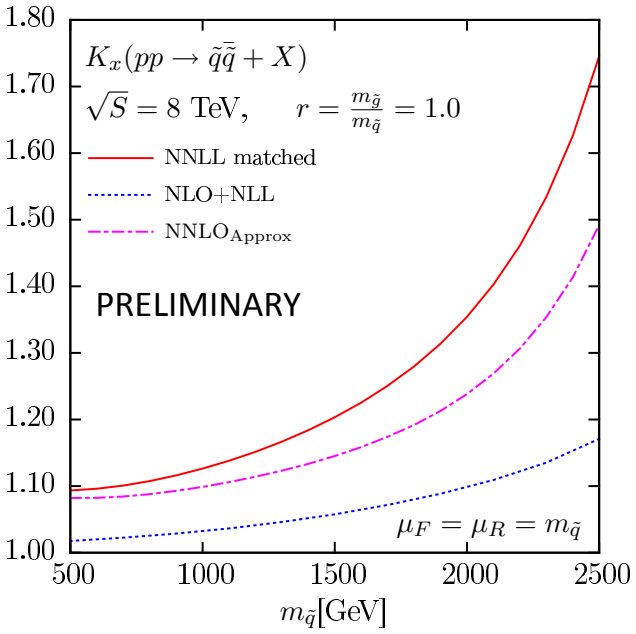


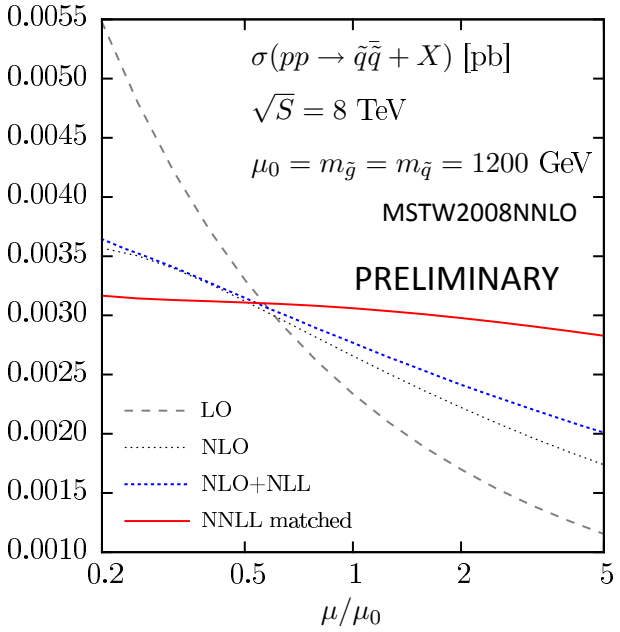
- 1-loop Coulomb coefficients $\kappa_{ij,I}$ for I= **3** and $\overline{\mathbf{6}}$ have opposite signs → dampens the growth of the corrections with mass, as compared to NLL+NLO. Additional dampening due to differences between NNLO and NLO quark pdfs

NNLL+NNLO$_{\text{APPROX}}$ FOR SQUARK-ANTISQUARK PRODUCTION

[Beenakker, Borschensky, Krämer, AK, Laenen, Theeuwes, Thewes, in preparation]

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



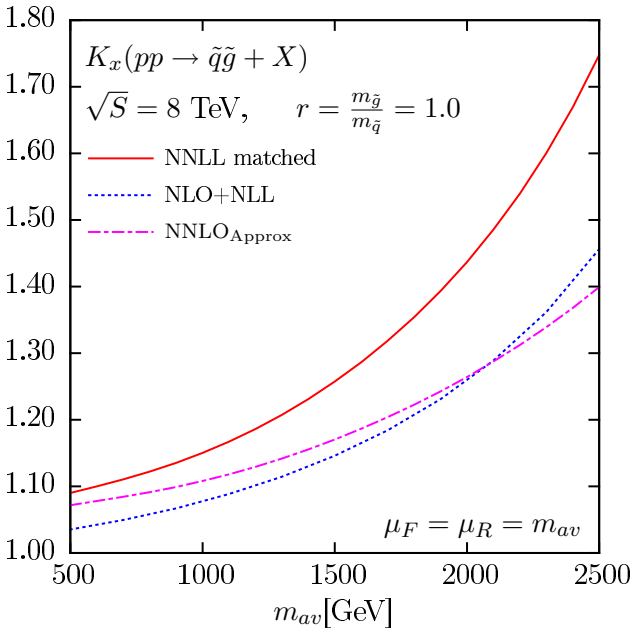


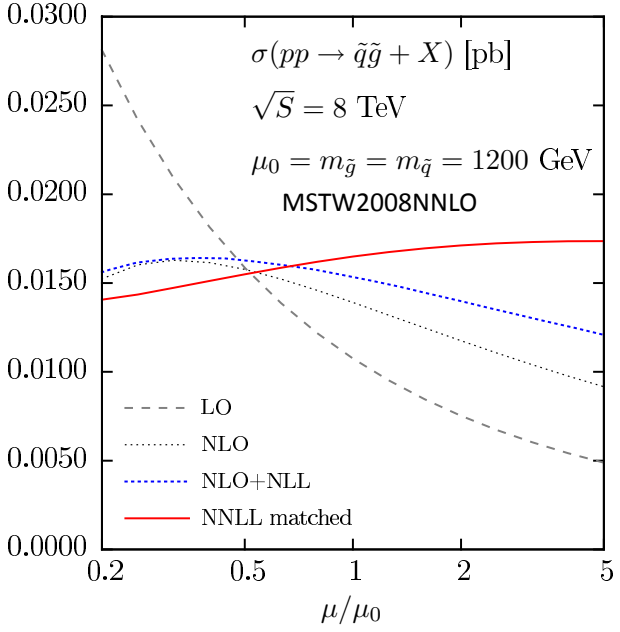
- Update on *[Beenakker, Brensing, AK, Laenen,Niessen'11]*

NNLL+NNLO$_{\text{APPROX}}$ FOR SQUARK-GLUINO PRODUCTION

[Beenakker, Borschensky, Krämer, AK, Laenen, Theeuwes, Thewes, in preparation]

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





PRELIMINARY

Summary

- Total cross sections for ALL pair-production processes of squark and gluino, including stop and sbottom, are known at NLO+NLL (soft and soft+Coulomb); tools are available

  → NLL-FAST for 7, 8, 13, 14 and 33 TeV

- New results, increasing accuracy of resummation: NNLL resummation for all processes of squark and gluino, matched to approximated NNLO result

- For the processed discussed here we observe the new results lead to very significant increase of the K-factor wrt. NLO

- Reduction of the theory error due to decreased scale dependence