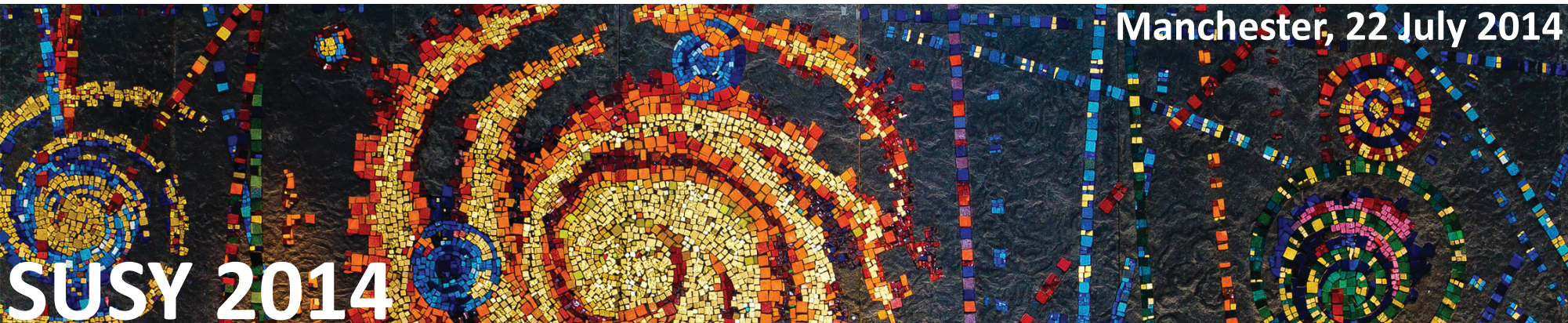
Latest Results for Squark and Gluino Production Cross Sections at the LHC: Threshold Resummation at NNLL

Christoph Borschensky

Westfälische Wilhelms-Universität Münster

arXiv:1404.3134 [hep-ph] with Wim Beenakker, Michael Krämer, Anna Kulesza, Eric Laenen, Vincent Theeuwes, Silja Thewes



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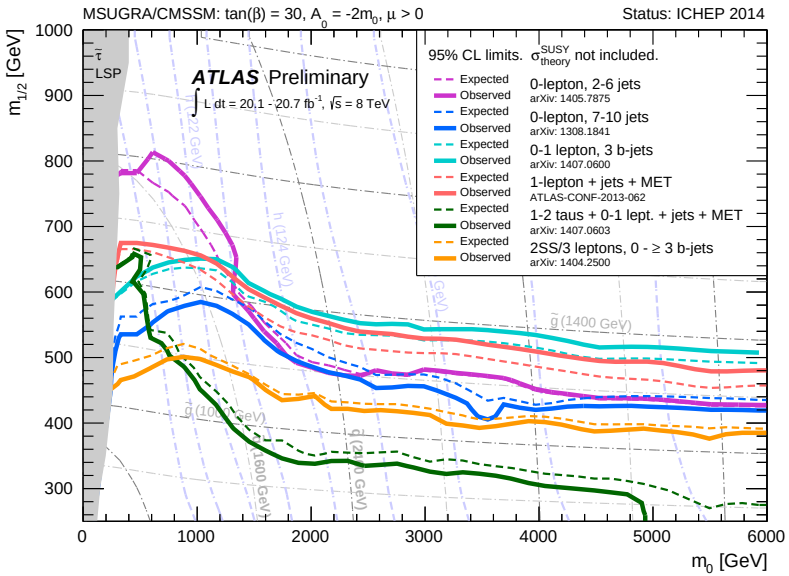
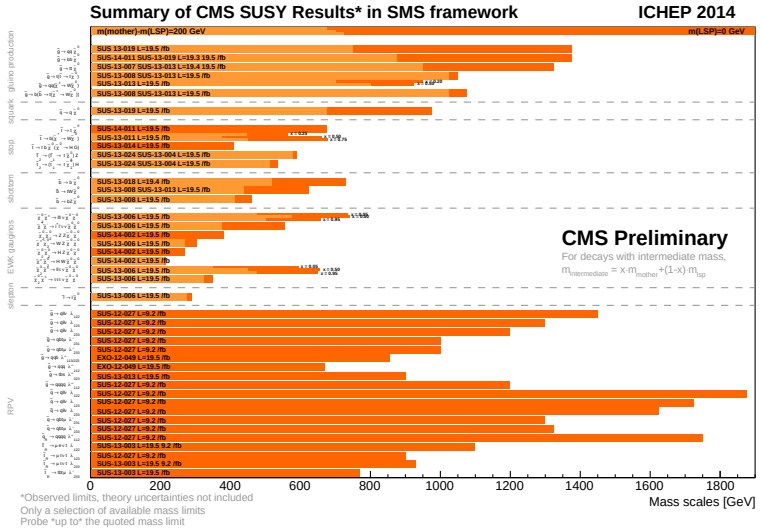
SUSY particle production at the LHC

Main sparticle production processes:

$$pp \quad \rightarrow \quad \tilde{g}\tilde{g} \quad , \quad \tilde{q}\tilde{q}^* \quad , \quad \tilde{q}\tilde{g} \quad , \quad \tilde{q}\tilde{q} \quad , \quad \tilde{t}_1\tilde{t}_1^*$$





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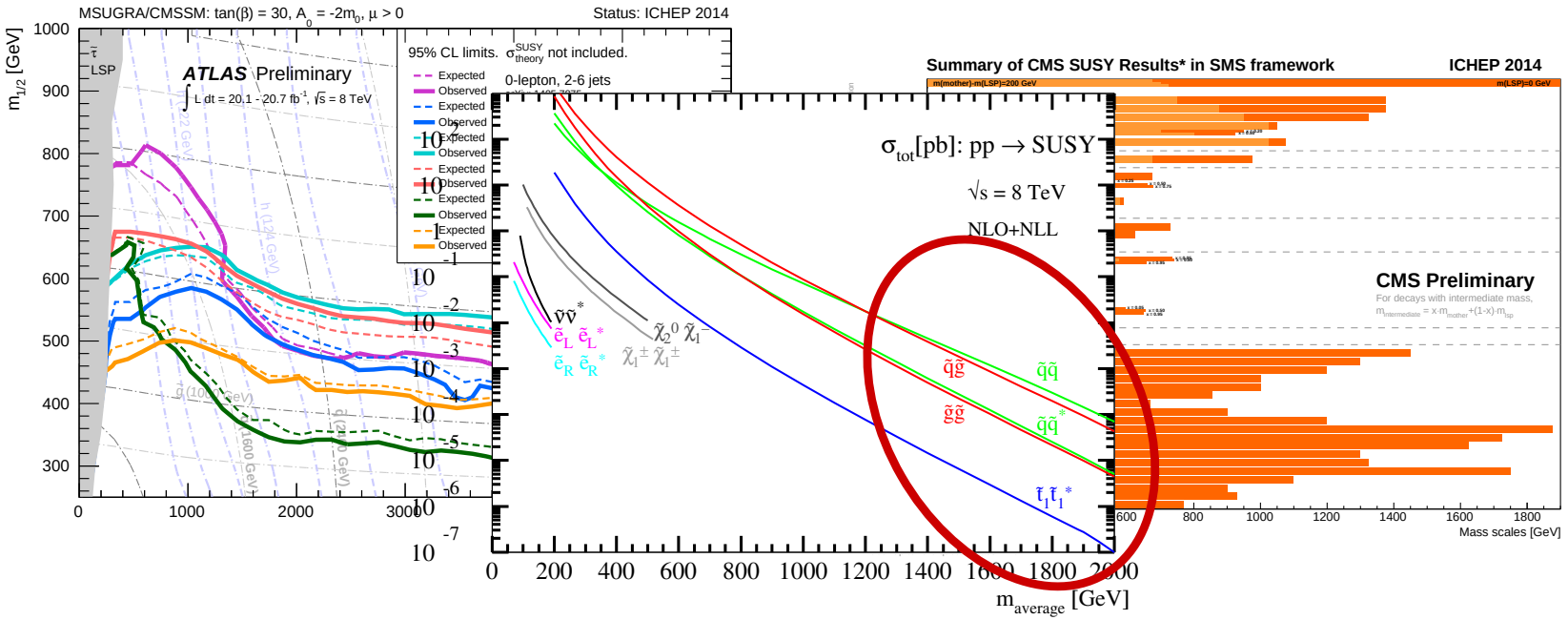


⇒ Cross sections needed at high precision for experimental searches

Particle production close to threshold

Heavy SUSY particles $\Rightarrow$ production in the **threshold limit** $s \to 4m^2$:

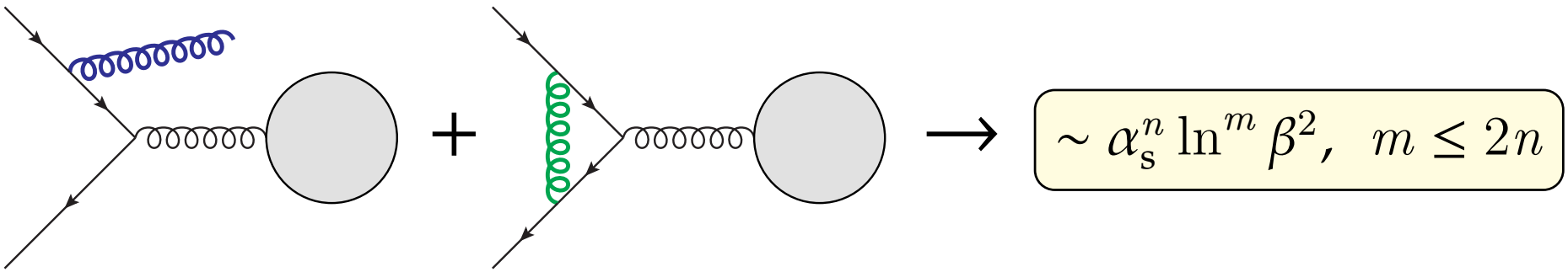
$$\beta \equiv \sqrt{1 - \frac{4m^2}{s}} \to 0$$

(with $\sqrt{s}$: partonic centre-of-mass energy, m: average mass of final state particles)

$\Rightarrow$ Just enough energy to produce the two sparticles

$\Rightarrow$ **Real radiation processes are soft**

Remainder after cancellation of IR divergencies:



Soft & collinear gluons

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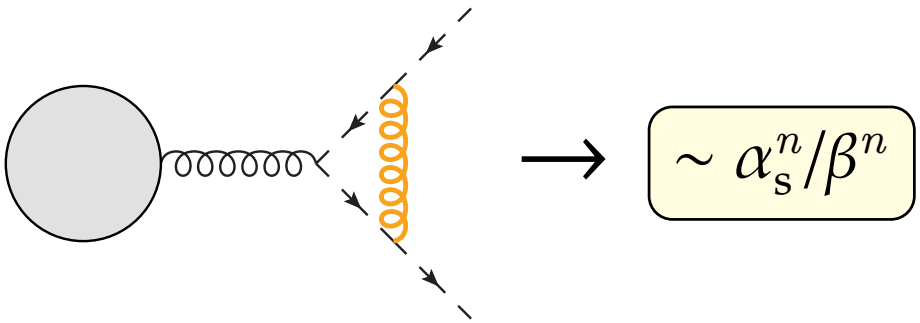
Additionally:



Coulomb gluons

Particle production close to threshold

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Enhanced partonic cross sections close to threshold:

- Soft & collinear gluons: $\alpha_s^n \ln^m \beta^2 \sim 1$
- Coulomb gluons: $\alpha_s^n/\beta^n \sim 1$

$\Rightarrow$ Endangering the perturbative series

$\Rightarrow$ Systematic treatment of these terms required

Treating large logarithms

For factorisation of σ: **Mellin-moment space**: $\tilde{f}(N) = \int_0^1 \mathrm{d}x\, x^{N-1} f(x)$

$$\ln \beta^2 \overset{\text{Mellin}}{\longrightarrow} \ln N \equiv L$$

(threshold limit $\beta \to 0 \;\hat{=}\; N \to \infty$)

Reordering of the perturbative series in α_s **and** L (schematically):

$$\tilde{\sigma} \sim \tilde{\sigma}^{(0)} \Big[1 + \alpha_s (L^2 + L + 1) + \alpha_s^2 (L^4 + L^3 + L^2 + L + 1) + \ldots \Big]$$

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LO $\sim \alpha_s^2$

Summation of all these terms $\longrightarrow$ exponential function (g_1, g_2, g_3 known):

$$\tilde{\sigma} \sim \tilde{\sigma}^{(0)} \times C(\alpha_s) \exp\Big[L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \ldots \Big]$$

[Kodaira, Trentadue'82][Sterman'87][Catani, D'Emilio, Trentadue'88][Catani, Trentadue'89][Kidonakis, Sterman'96][Kidonakis, Oderda, Sterman'98][Contopanagos, Laenen, Sterman'96][Catani, de Florian, Grazzini'01][Moch, Vermaseren, Vogt'04][Beneke, Fallgari, Schwinn'09][Czakon, Mitov, Sterman'09][Ferroglia, Neubert, Pecjak, Yang'09]

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LO $\sim \alpha_s^2$ — **NLO** — **NNLO**

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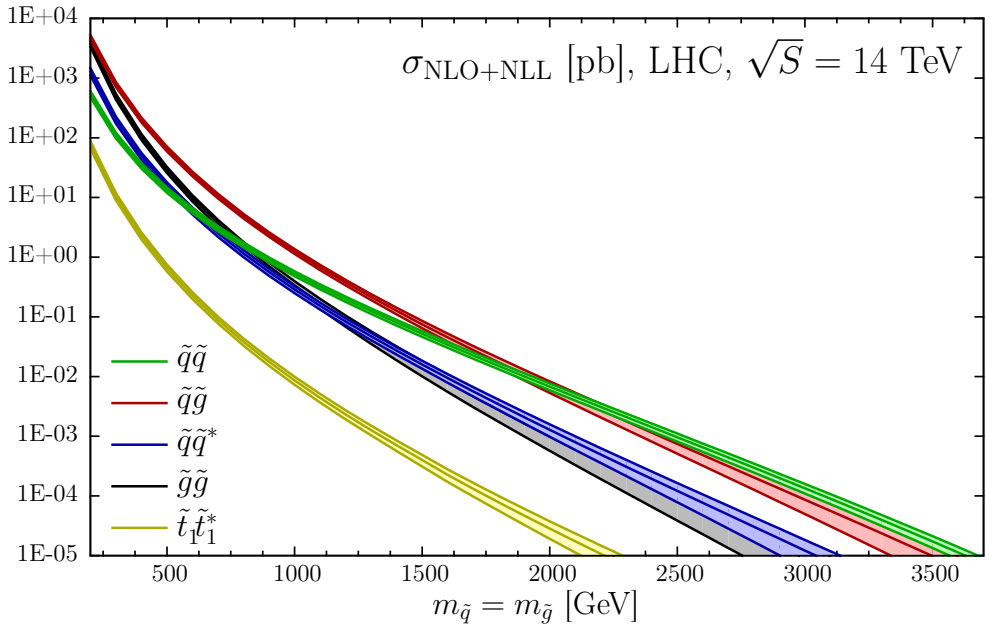
(Precision level: LL + NLL + NNLL)

Numerical package: NLL-fast

Code package to compute NLO+NLL cross sections

- $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}^*$, $\tilde{q}\tilde{g}$, $\tilde{q}\tilde{q}$, $\tilde{t}_1\tilde{t}_1^*$ and decoupling limit
- Including α_s, PDF, and scale variation
- At different LHC energies: $\sqrt{S} =$ **7 TeV**, **8 TeV**, **13 TeV**, 14 TeV, 33 TeV, 100 TeV, or upon request
- Used for current experimental analysis by ATLAS and CMS

[Krämer, Kulesza, van der Leeuw, Mangano, Padhi, Plehn, Portell'12]



NLL-fast

http://pauli.uni-muenster.de/~akule_01/nllwiki

[Kulesza, Motyka'08-'09][Beenakker, Brensing, Kulesza, Laenen, Niessen'09-'10]

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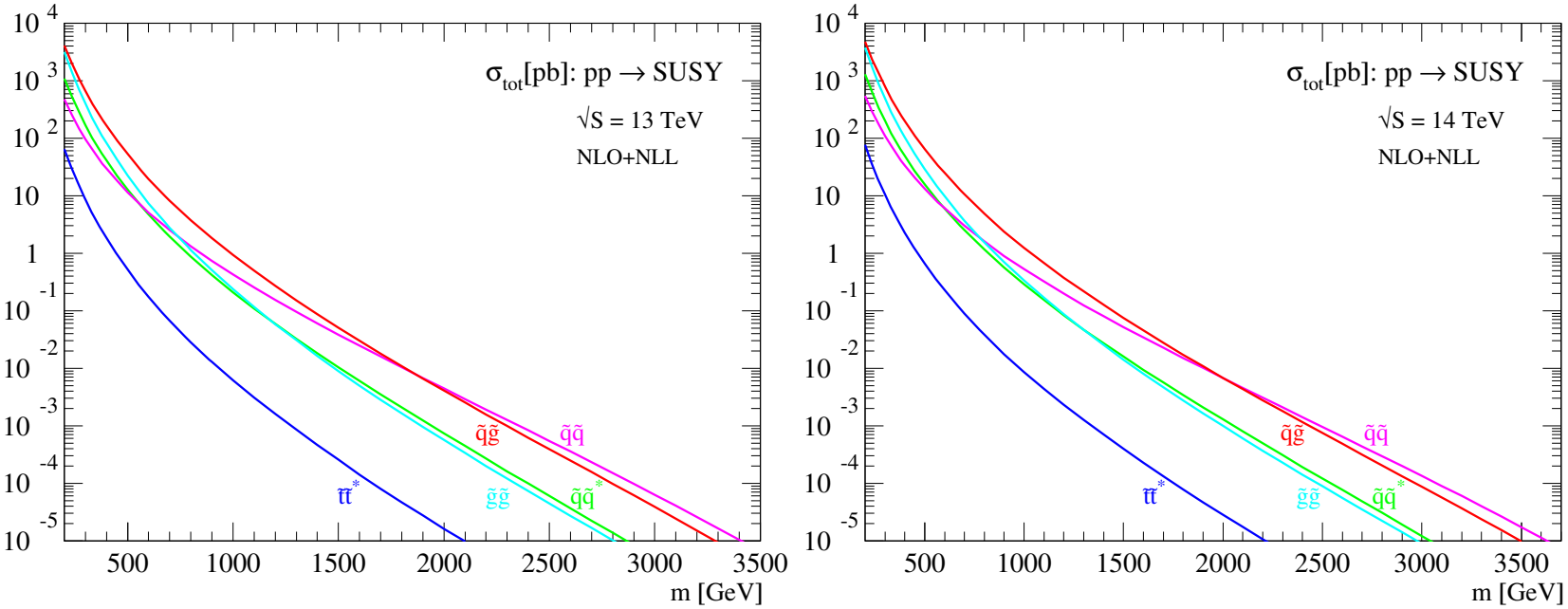
Predictions for future LHC and pp collider runs (1)

Cross section predictions for future LHC runs at 13, 14 TeV:

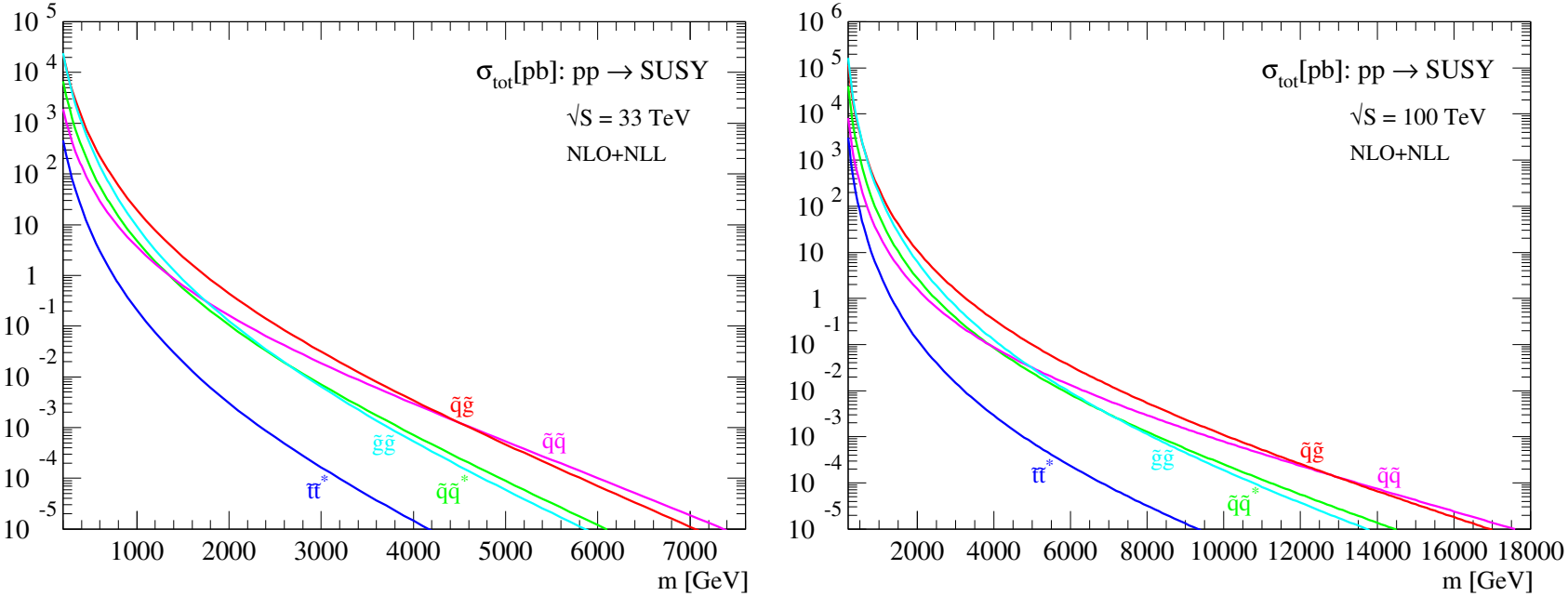


Reference paper for squark and gluino production at future LHC and pp collider energies: *[CB, Krämer, Kulesza, Mangano, Padhi, Plehn, Portell; arXiv: 1407.5066]*

See also: `https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections`

Predictions for future LHC and pp collider runs (1)

Cross section predictions for future pp colliders operating at 33, 100 TeV:



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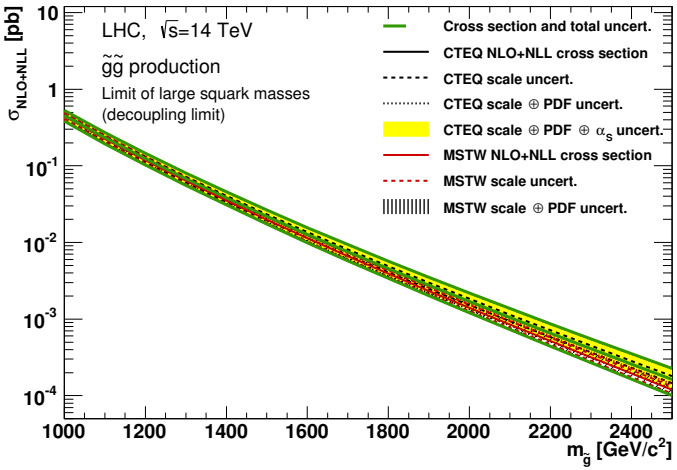
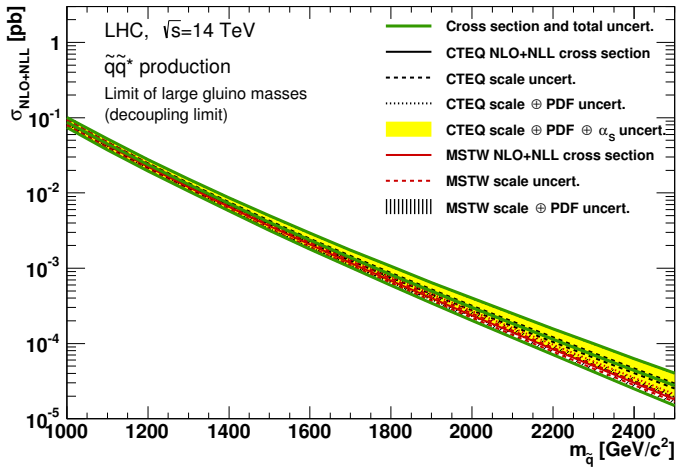
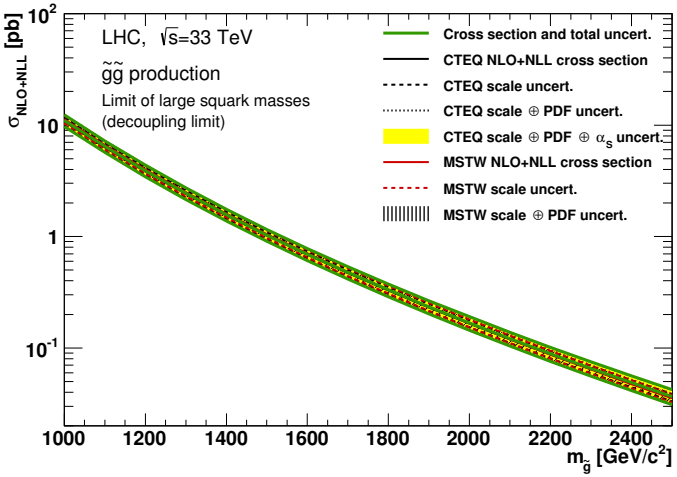
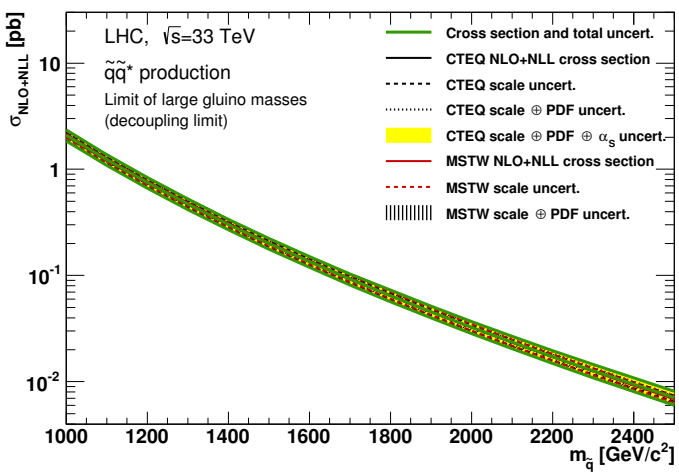
Detailed analysis of α_s, PDF, and scale uncertainties for $\tilde{g}\tilde{g}$ and $\tilde{q}\tilde{q}^*$ in the decoupling limit and $\tilde{t}_1\tilde{t}_1^*$ using CTEQ6.6M and MSTW2008 PDF sets:









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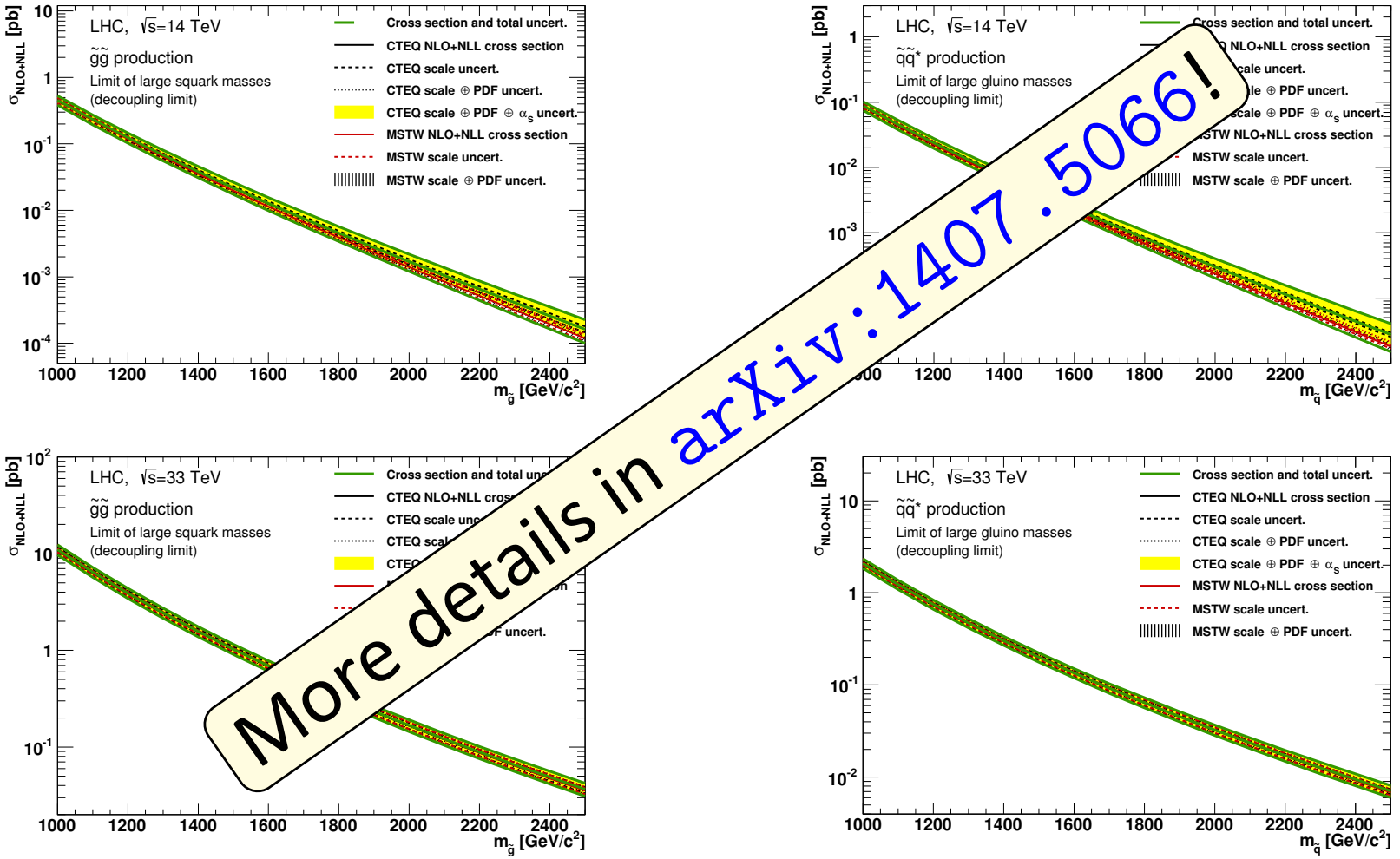

Matching coefficients

Reminder:

$$\tilde{\sigma} \sim \tilde{\sigma}^{(0)} \times C(\alpha_s) \exp\left[L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \ldots\right]$$

Higher order terms of different origin; split-up close to threshold *[Beneke, Falgari, Schwinn'10]*:

$$C(\alpha_s) = \mathcal{C}^{\mathrm{Hard}}(\alpha_s) \times \mathcal{C}^{\mathrm{Coul}}(N, \alpha_s)$$

- $\mathcal{C}^{\mathrm{Hard}}(\alpha_s)$: hard matching coefficients (independent of N)
  - $\rightarrow$ Calculated from NLO contributions *[Beenakker, Janssen, Lepoeter, Krämer, Kulesza, Laenen, Niessen, Thewes, Van Daal'13]*
- $\mathcal{C}^{\mathrm{Coul}}(N, \alpha_s)$: Coulomb terms (final state gluon exchange):
  - $\rightarrow$ 1st and 2nd order Coulomb effects included
  - $\rightarrow$ Can also be resummed *[Kulesza, Motyka'09][Beneke, Falgari, Schwinn'10][Falgari, Schwinn, Wever'12]*

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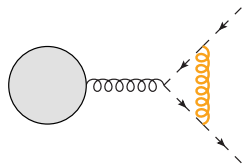

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Inverse Mellin transform

Resummed results added to fixed order cross section at NNLO$_{\text{approx.}}$:

$$\sigma_{\text{hadr.}}^{(\text{NNLO}_{\text{approx.}})} = \sigma_{\text{hadr.}}^{(\text{NLO})} + \Delta\sigma_{\text{hadr.}}^{(\text{NNLO}_{\text{approx.}})}$$

(NNLO$_{\text{approx.}}$ consists of dominant terms in β for $\beta \to 0$ for arbitrary colour representations *[Beneke, Czakon, Falgari, Mitov, Schwinn'09]*)

Total resummed cross section:

$$\sigma_{\text{hadr.}}^{(\text{NNLO}_{\text{approx.}}+\text{NNLL})}(\rho = \frac{4m^2}{S}) = \sigma_{\text{hadr.}}^{(\text{NNLO}_{\text{approx.}})}(\rho) + \sum_{i,j} \frac{1}{2\pi i} \int_{\text{CT}} \mathrm{d}N\, \rho^{-N} \tilde{f}_i(N+1)\tilde{f}_j(N+1) \times \left[\tilde{\sigma}_{ij\to kl}^{(\text{res.})}(N) - \tilde{\sigma}_{ij\to kl}^{(\text{res.})}(N)\Big|_{\text{NNLO}}\right]$$

NNLO matching needed to avoid double counting of terms up to NNLO.

Inverse Mellin transform

Resummed results added to fixed order cross section at $\text{NNLO}_{\text{approx.}}$:

$$\sigma_{\text{hadr.}}^{(\text{NNLO}_{\text{approx.}})} = \sigma_{\text{hadr.}}^{(\text{NLO})} + \Delta\sigma_{\text{hadr.}}^{(\text{NNLO}_{\text{approx.}})}$$

($\text{NNLO}_{\text{approx.}}$ consists of dominant terms in β for $\beta \to 0$ for arbitrary colour representations *[Beneke, Czakon, Falgari, Mitov, Schwinn'09]*)

Total resummed cross section:

PDFs in Mellin space

$$\sigma_{\text{hadr.}}^{(\text{NNLO}_{\text{approx.}}+\text{NNLL})}(\rho = \frac{4m^2}{S}) = \sigma_{\text{hadr.}}^{(\text{NNLO}_{\text{approx.}})}(\rho) + \sum_{i,j} \frac{1}{2\pi i} \int_{\text{CT}} \mathrm{d}N\, \rho^{-N} \tilde{f}_i(N+1)\tilde{f}_j(N+1) \times \left[\tilde{\sigma}_{ij\to kl}^{(\text{res.})}(N) - \tilde{\sigma}_{ij\to kl}^{(\text{res.})}(N)\Big|_{\text{NNLO}} \right]$$

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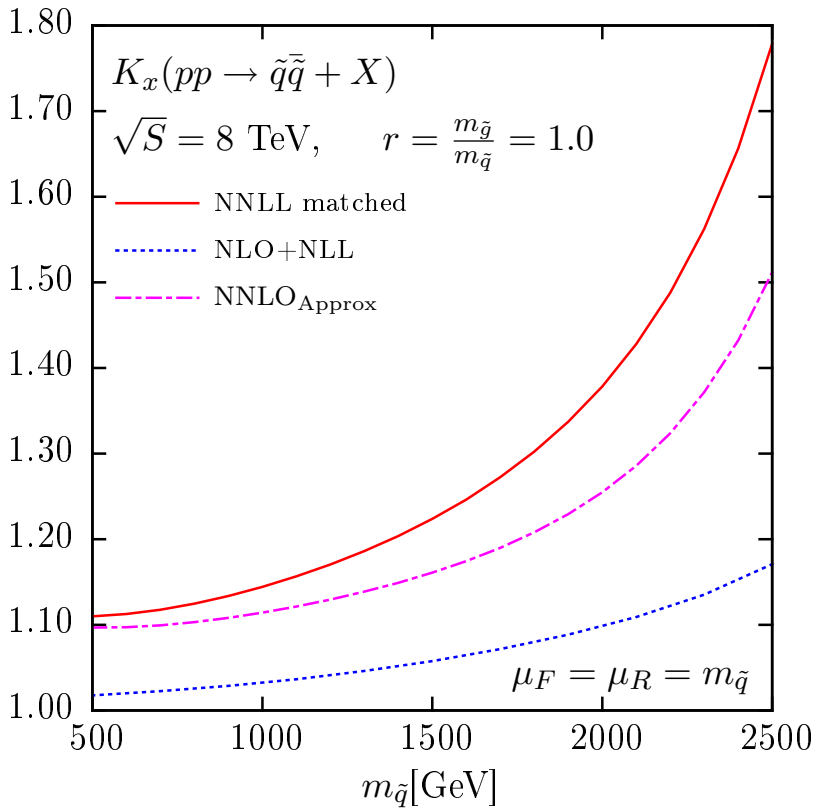
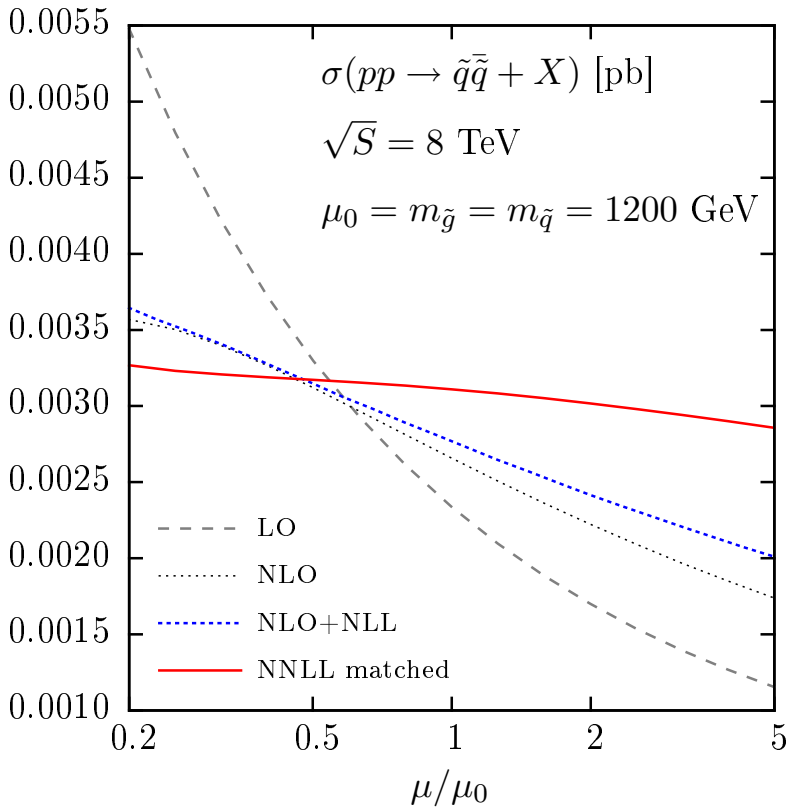
Results: $\tilde{q}\tilde{q}^*$ production

[Beenakker, CB, Krämer, Kulesza, Laenen, Theeuwes, Thewes; arXiv: 1404.3134]

K factor: $K_x = \sigma_x/\sigma_{\rm NLO}$

PDFs used: MSTW2008NNLO





Update for *[Beenakker, Brensing, Kulesza, Laenen, Niessen'11]*:

NNLO matching and NNLO Coulomb contributions

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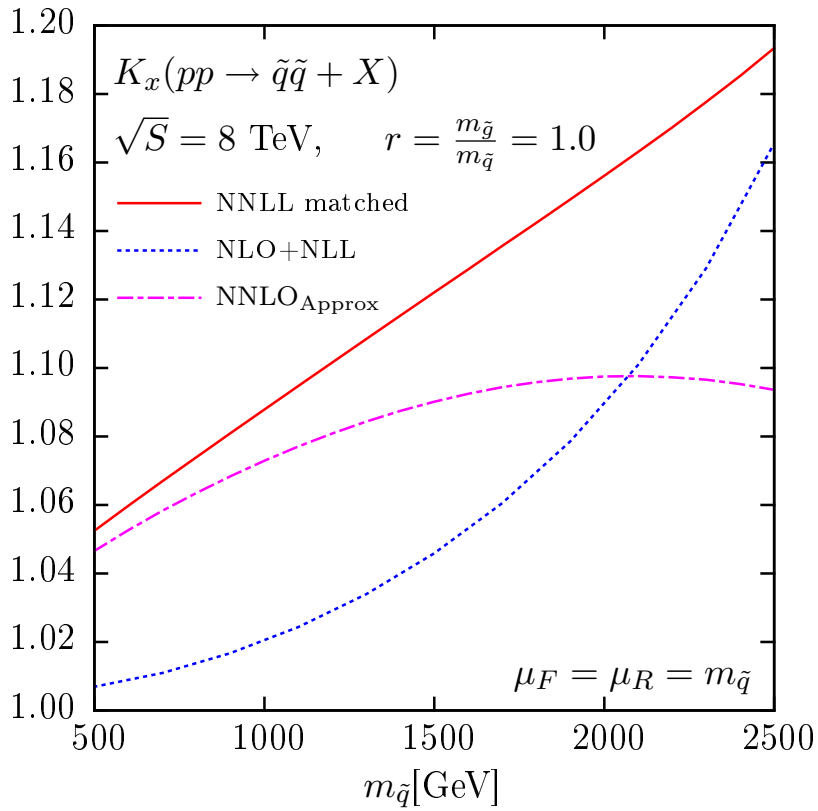
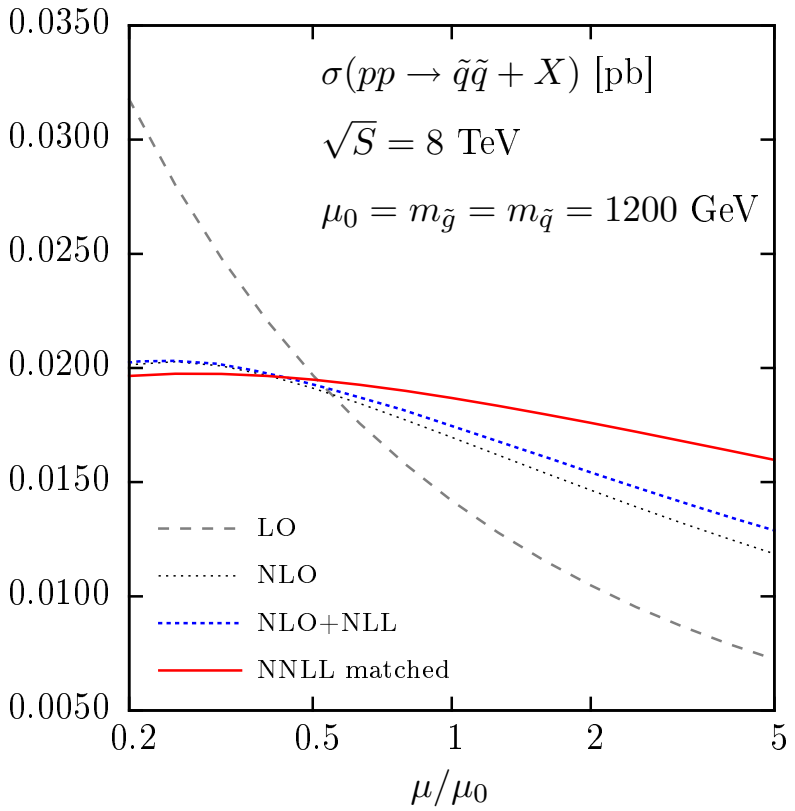
PDFs used: MSTW2008NNLO





Coulomb contributions for the two colour channels $\bar{\mathbf{3}}$ and $\mathbf{6}$ have different signs;

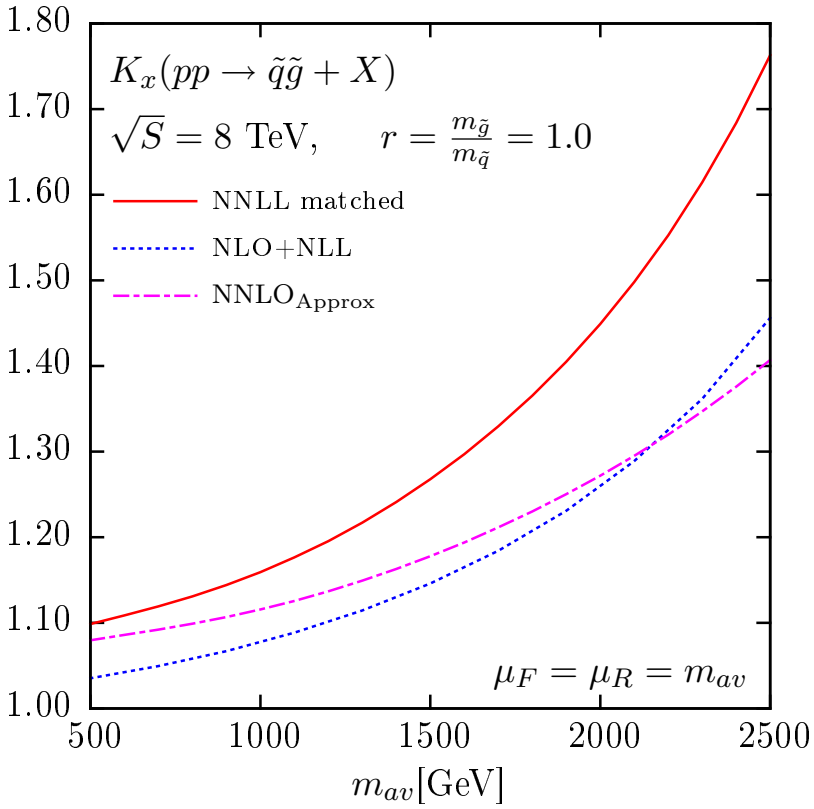
differences between NLO and NNLO PDFs

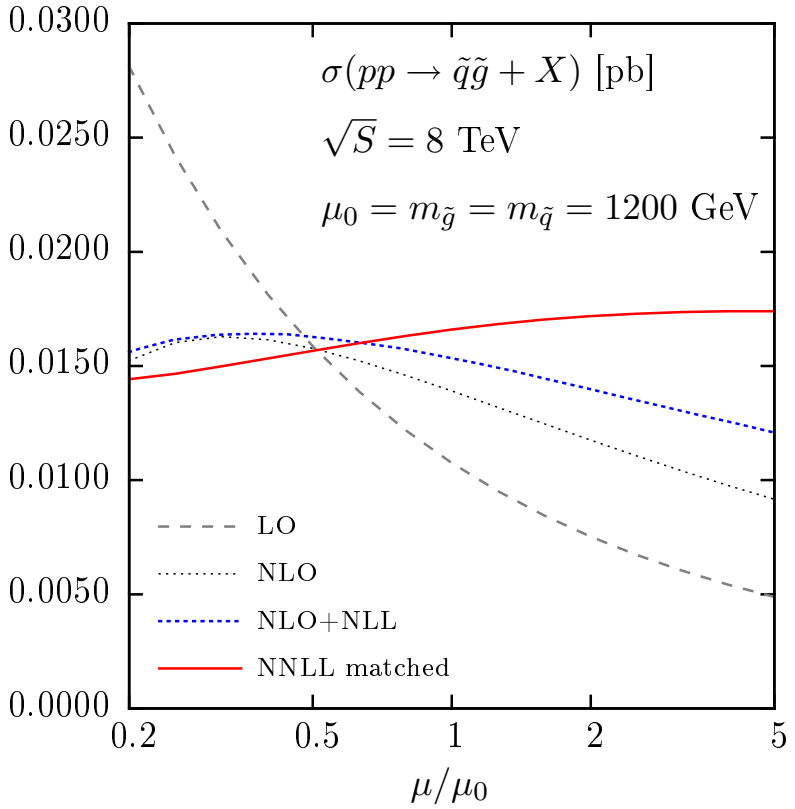
Results: $\tilde{q}\tilde{g}$ production

[Beenakker, CB, Krämer, Kulesza, Laenen, Theeuwes, Thewes; arXiv: 1404.3134]

K factor: $K_x = \sigma_x/\sigma_{\text{NLO}}$

PDFs used: MSTW2008NNLO





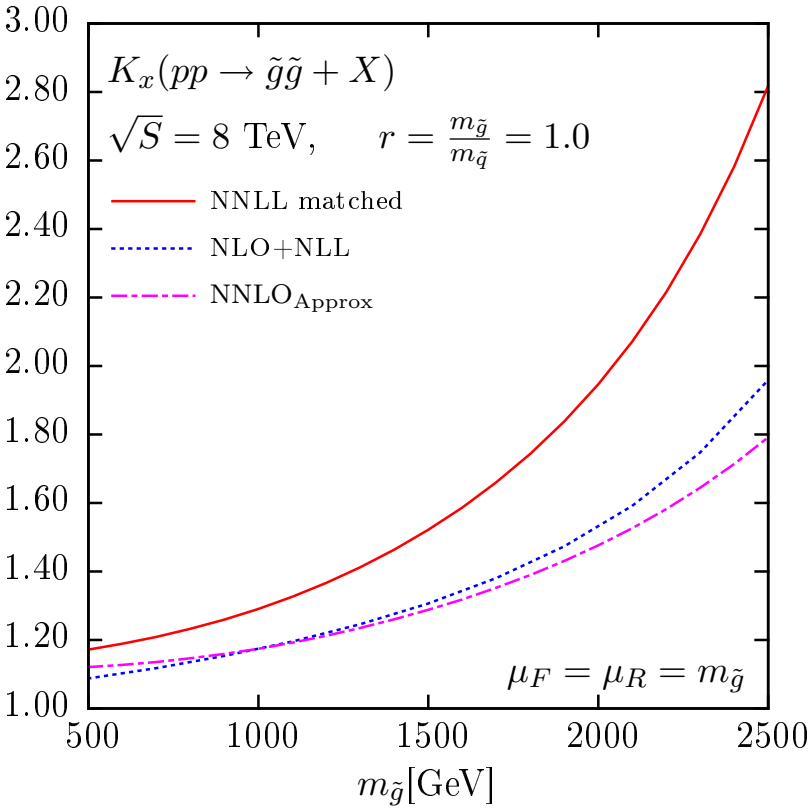
with $m_{av} = \frac{1}{2}\left(m_{\tilde{q}} + m_{\tilde{g}}\right)$

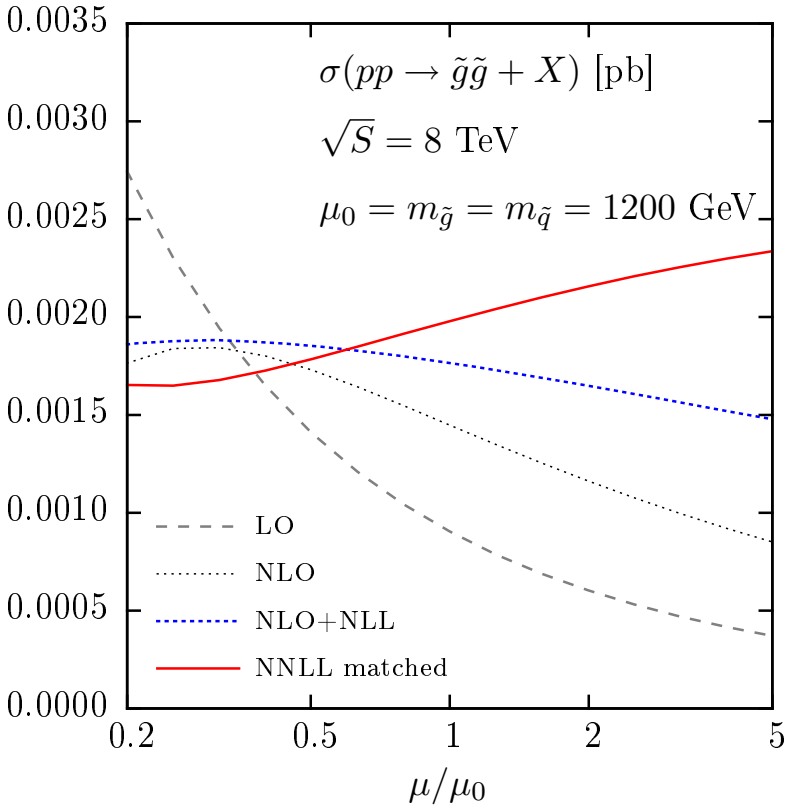
Results: $\tilde{g}\tilde{g}$ production

[Beenakker, CB, Krämer, Kulesza, Laenen, Theeuwes, Thewes; arXiv: 1404.3134]

K factor: $K_x = \sigma_x/\sigma_{\rm NLO}$

PDFs used: MSTW2008NNLO





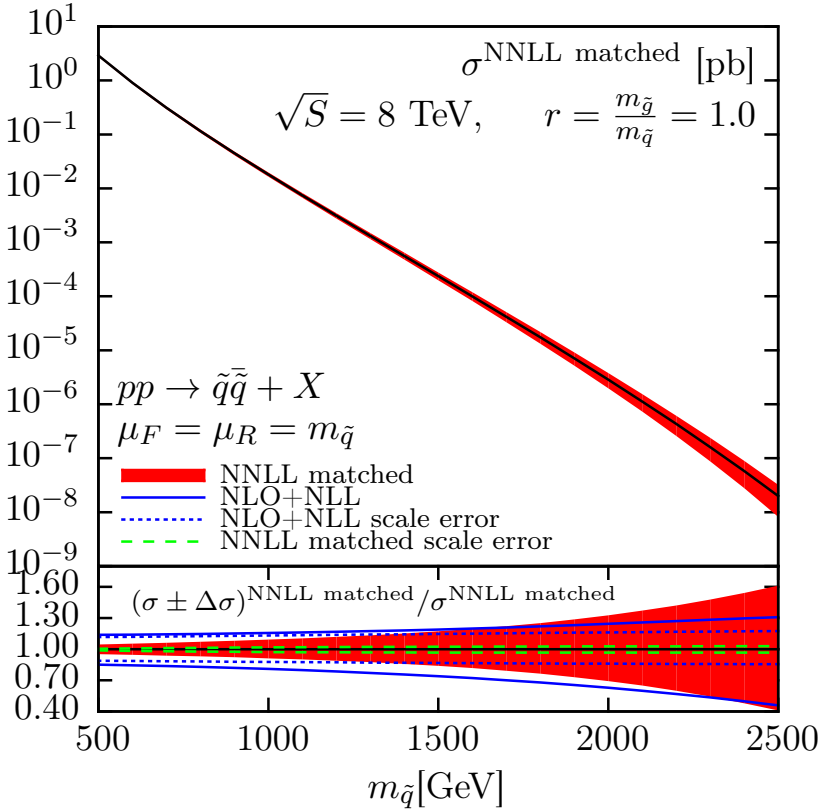
Increased scale dependence due to scale dependent terms in the exponentials and one-loop Coulomb contributions

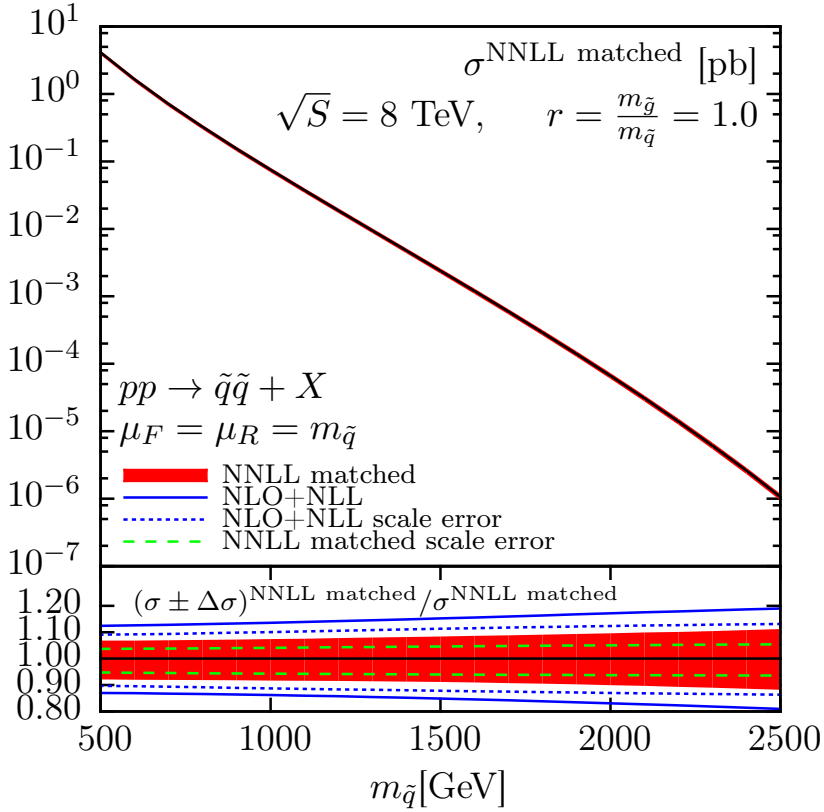
Results: total cross sections for $\tilde{q}\tilde{q}^*$ and $\tilde{q}\tilde{q}$

[Beenakker, CB, Krämer, Kulesza, Laenen, Theeuwes, Thewes; arXiv: 1404.3134]

$\sqrt{S} = 8$ TeV

PDFs used: MSTW2008NNLO





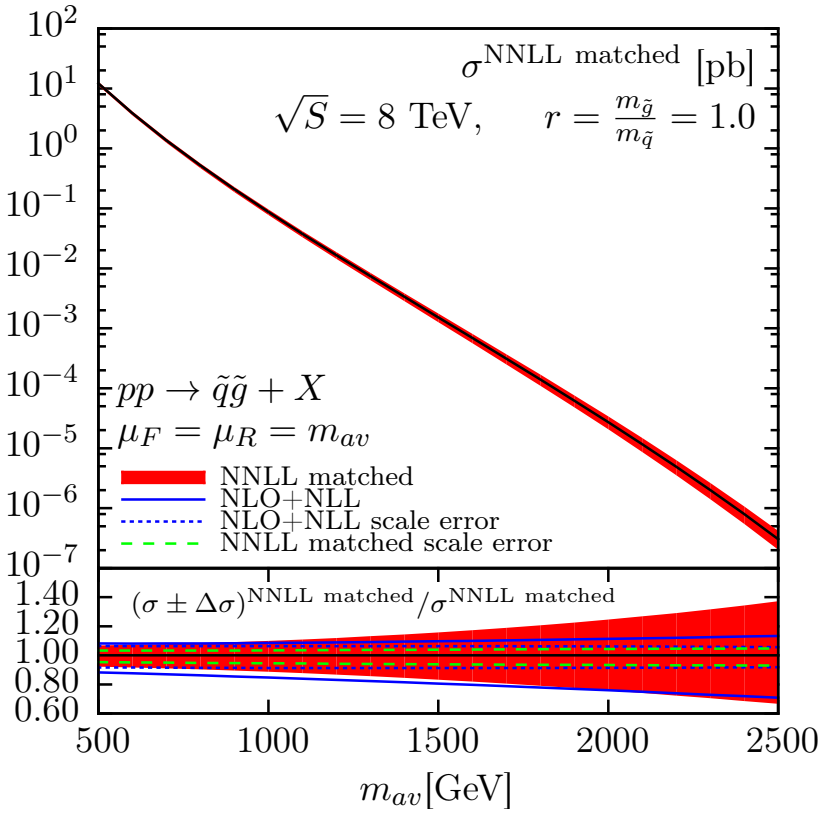
Significant reduction of the scale and total uncertainty for dominant process $\tilde{q}\tilde{q}$

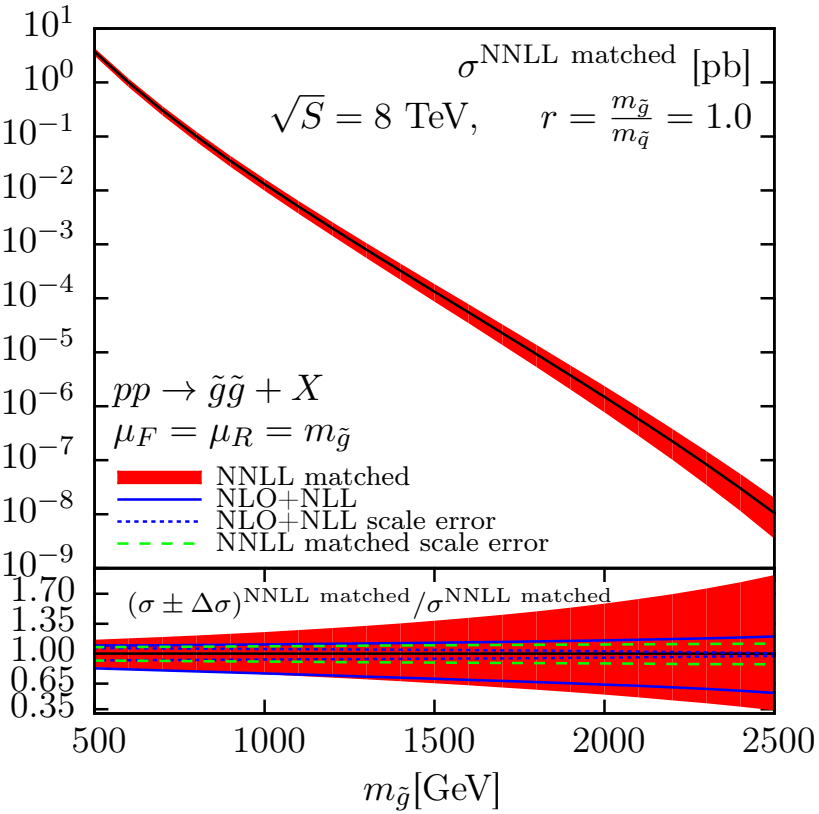
Results: total cross sections for $\tilde{q}\tilde{g}$ and $\tilde{g}\tilde{g}$

[Beenakker, CB, Krämer, Kulesza, Laenen, Theeuwes, Thewes; arXiv: 1404.3134]

$\sqrt{S} = 8$ TeV

PDFs used: MSTW2008NNLO





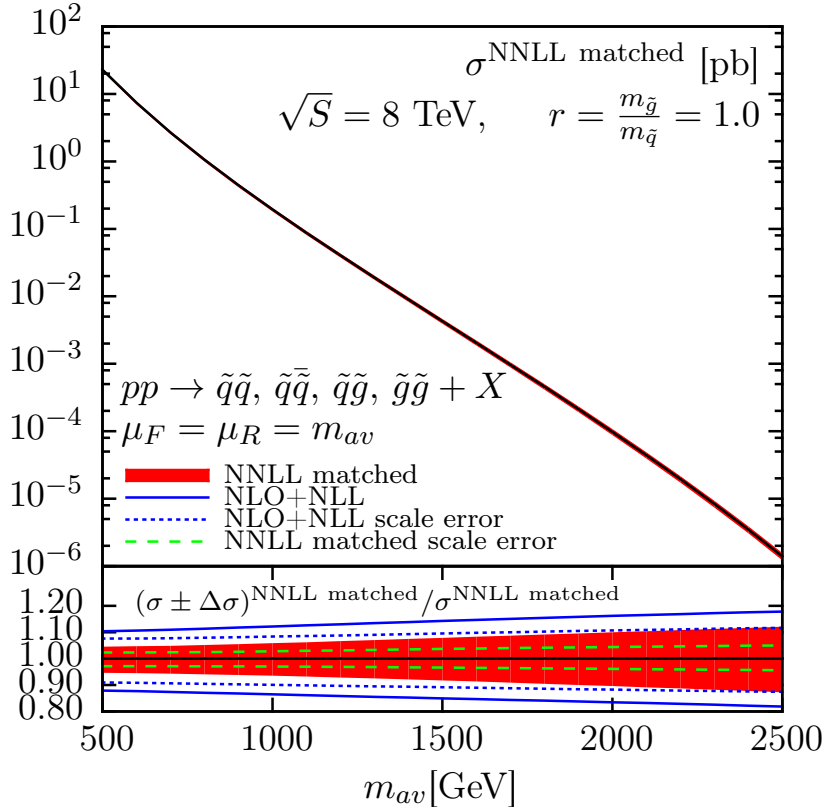
Change in PDF sets from MSTW2008NLO to MSTW2008NNLO from NLO+NLL to NNLL matched; minor contribution from $\tilde{g}\tilde{g}$ for high masses compared to the other processes

Results: inclusive coloured sparticle production

[Beenakker, CB, Krämer, Kulesza, Laenen, Theeuwes, Thewes; arXiv: 1404.3134]

$\sqrt{S} = 8$ TeV

PDFs used: MSTW2008NNLO



Reduction of the total uncertainty with regard to the NLL-level;

dominant contribution for high masses: $\tilde{q}\tilde{q}$

Summary

Conclusions:

- ✓ Predictions for future LHC and pp collider runs available @ NLO+NLL
  - ➥ NLL-fast for 13, 14, 33, 100 TeV
- ✓ $\tilde{q}\tilde{q}$ and $\tilde{q}\tilde{g}$ most important processes at the LHC for large $m_{\tilde{q}}$ and $m_{\tilde{g}}$
- ✓ Ingredients for NNLL: exponentials, hard matching and Coulomb coefficients, $\text{NNLO}_{\text{approx.}}$ matching $\Rightarrow$ improved precision
- ✓ Enhancement of the K factor and reduction of the theoretical uncertainty due to reduced scale dependence (except for $\tilde{g}\tilde{g}$)

Outlook:

- ✍ Effect of Coulomb resummation
- ✍ Comparison with SCET resummation method
- ✍ Predictions for higher energies (14, 33, …TeV) @ $\text{NNLO}_{\text{approx.}}$+NNLL
- ✍ Public code for NNLL results

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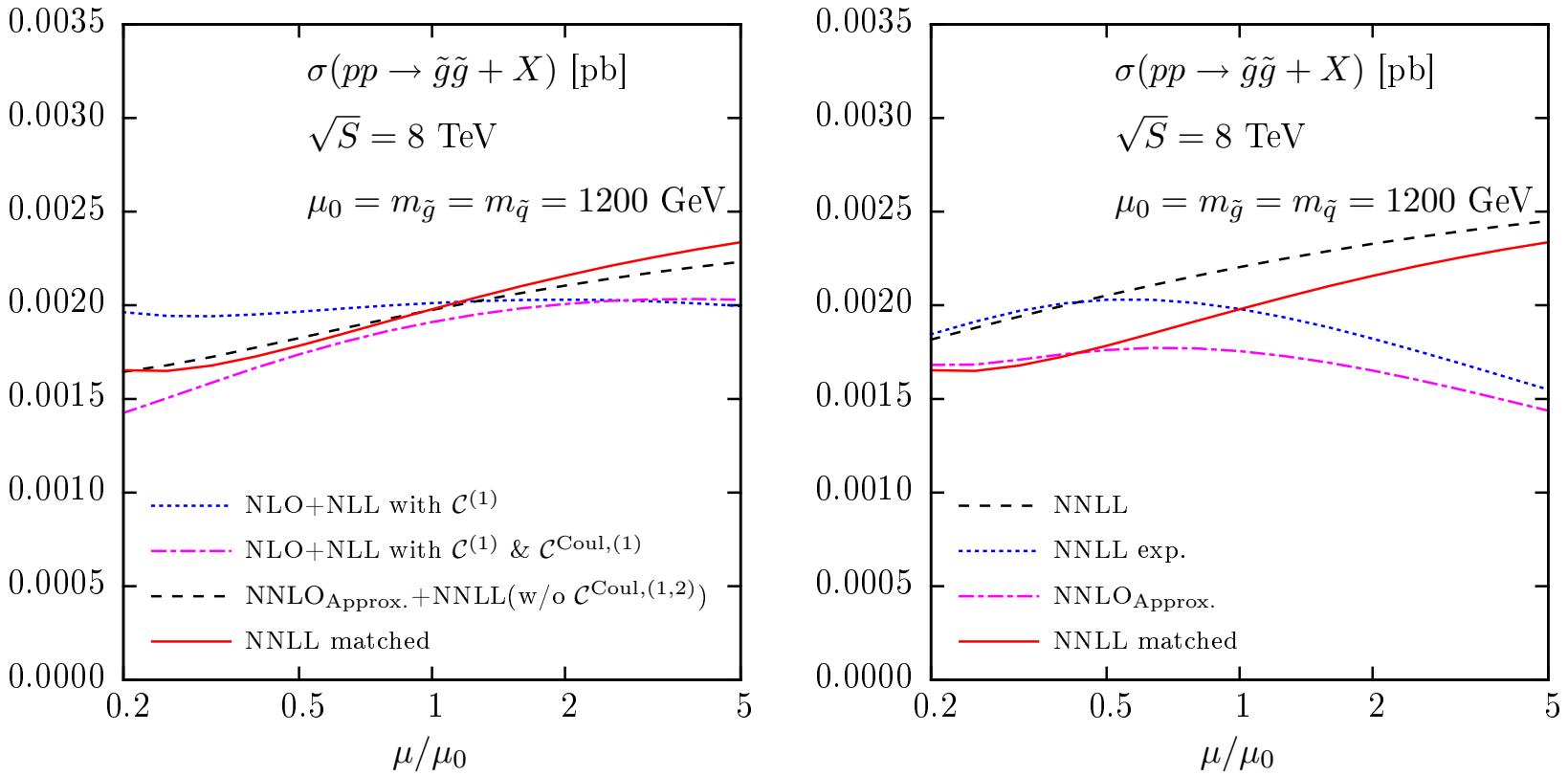
A closer look at the $\tilde{g}\tilde{g}$ scale dependence

[Beenakker, CB, Krämer, Kulesza, Laenen, Theeuwes, Thewes; arXiv: 1404.3134]

$\sqrt{S} = 8$ TeV

PDFs used: MSTW2008NNLO



$\tilde{g}\tilde{g}$ scale dependence for intermediate levels of accuracy, and NNLL matched split up into resummed and expanded parts