NNLO corrections to squark - antisquark - production at the LHC

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Outline

Introduction

The Standard Model (SM) has been tested to high precision.

However, many questions are still open:

- solution to hierarchy problem
  ($M_W = \mathcal{O}(100\,\mathrm{GeV}) \leftrightarrow M_{\text{Planck}} = \mathcal{O}(10^{19}\,\mathrm{GeV})$)
- window to gravity
- dark matter candidate
- CP-phases for baryon asymmetry, baryogenesis
- 19 free parameters in the SM

One solution to some of these questions is Supersymmetry (SUSY).

- symmetry between bosons and fermions
- minimal SUSY extension of SM $\rightarrow$ MSSM

Matter fields in the MSSM

Fermionic SM-field $s = \frac{1}{2}$	SUSY partner fields $s = 0$
up-quark $u_{L,a}$, down-quark $d_{L,a}$	sup $\tilde{u}_{L,a}$, sdown $\tilde{d}_{L,a}$
up-quark $u_{R,a}$	sup $\tilde{u}_{R,a}$
down-quark $d_{R,a}$	sdown $\tilde{d}_{R,a}$
electron e_L, Neutrino ν	selectron $\tilde{e}_L$, sneutrino $\tilde{\nu}$
electron e_R	selectron $\tilde{e}_R$

$a : SU(3)$ color index

- in this talk we look at squarks

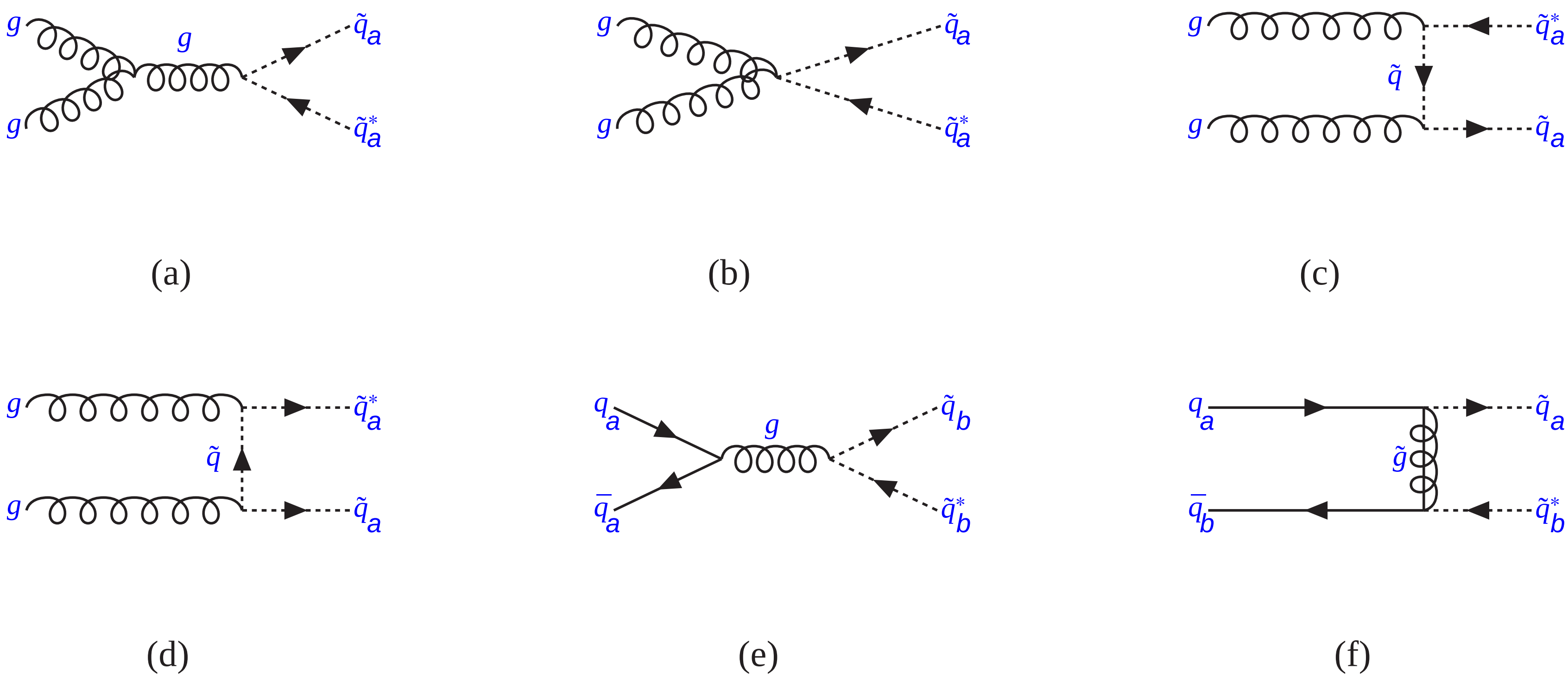
Squark search at hadron colliders

- energy frontier: Tevatron: 1.96 TeV, LHC: 14 TeV
- present exclusion limits:
  - $m_{\tilde{g}} < 280\,\text{GeV}$: all squark masses excluded in mSugra scenarios
  - $m_{\tilde{g}} = m_{\tilde{q}}$: $m_{\tilde{q},\tilde{g}} > 392\,\text{GeV}$
  - $m_{\tilde{q}} < 400\,\text{GeV} \Rightarrow m_{\tilde{g}} > 340\,\text{GeV}$
  - Ref: T. Aaltonen *et al.* [CDF Collaboration], arXiv:0811.2512 [hep-ex].
- in mSugra models: $m_{\tilde{g}} > m_{\tilde{q}}$,
  squark masses approximately degenerate, exception: stop mass (not considered here)
- hadronic cross section at hadron collider:

$$\sigma = \sum_{i,j=\text{all partons}} \text{PDF}_i \otimes \text{PDF}_j \otimes \hat{\sigma}_{ij}$$

The contributing Feynman diagrams for $\hat{\sigma}_{ij}$

The partonic level



- *a* and *b* are flavor indices

The contributing Feynman diagrams for $\hat{\sigma}_{ij}$

The partonic level

- gg initial state produces squark antisquark pairs of identical flavor
- $q_a\overline{q}_a$ as initial state allows both diagrams, for the s channel diagram, initial flavors must be equal, initial and final flavors may be different
- $q_a\overline{q}_b$ with $a \neq b$ as initial state allows only the t channel gluino exchange, initial and final flavors are identical

State of NLO calculation

- Full NLO calculation for squark and gluino production has been performed (W. Beenakker, R. Höpker, M. Spira and P. M. Zerwas, Nucl. Phys. B **492** (1997) 51 [arXiv:hep-ph/9610490].)
- separate calculation exists for stop pair production (W. Beenakker, M. Krämer, T. Plehn, M. Spira and P. M. Zerwas, Nucl. Phys. B **515** (1998) 3 [arXiv:hep-ph/9710451].)
- NLO calculation has been implemented in `Prospino` (W. Beenakker, R. Höpker and M. Spira, arXiv:hep-ph/9611232.)

The partonic cross section

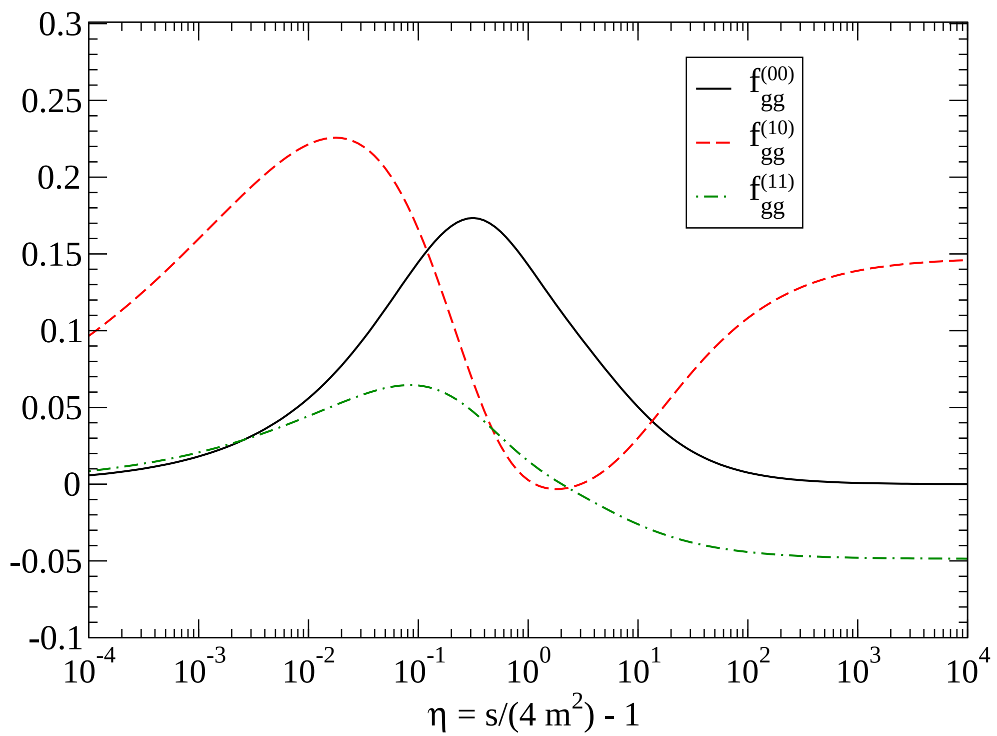
- Partonic cross section can be decomposed as

$$\hat{\sigma} = \frac{\alpha_s^2}{m_{\tilde{q}}^2} \Big[f_{00} + 4\pi\alpha_s \left(f_{10} + f_{11} \log(Q^2/m_{\tilde{q}}^2) \right) \\ + (4\pi\alpha_s)^2 \left(f_{20} + f_{21} \log(Q^2/m_{\tilde{q}}^2) + f_{22} \log^2(Q^2/m_{\tilde{q}}^2) \right) + \ldots \Big]$$

- f_{00} is calculated analytically, f_{10} numerically using `Prospino` and then approximated by a fit function $\longrightarrow$ next slide
- scale dependent terms f_{11}, f_{21}, and f_{22} can be calculated numerically from the previous order using RGEs, then approximated by a fit
- f_{20} calculated by soft gluon resummation (Tool for calculating approximated N^{k}LO results)
- See also A. Kulesza and L. Motyka, arXiv:0807.2405 [hep-ph].: NLL approximation

The partonic cross section

The fit function for f_{10}^{gg}



- first four terms represent the leading logs and the 1st order Coulomb correction $\Rightarrow$ the fit function is exact in the limit $\beta \longrightarrow 0$

The partonic cross section

The fit function

$$f_{gg}^{(10)} = \frac{7n_f}{192\pi}\beta\left(\frac{3}{2}\log^2\left(8\,\beta^2\right) - \frac{183}{28}\log\left(8\,\beta^2\right) + \frac{11\pi^2}{336\beta}\right) + h(\beta)$$

$$\begin{aligned}
h(\beta) = \quad & \beta\Big[a_1 + a_2\beta + a_3\beta^2\log(8\beta^2) + a_4\beta^3\log(8\beta^2) \\
& + a_5\frac{1}{\sqrt{1+\eta}}\log^2(1+\eta) + a_6\frac{1}{\sqrt{1+\eta}}\log(1+\eta) + a_7\frac{1}{1+\eta}\log\left(\tfrac{1+\beta}{1-\beta}\right) \\
& + a_8 x\log^2(\eta) + a_9 x\log(\eta) + a_{10}x^2\log^2(\eta) + a_{11}x^2\log(\eta) \\
& + a_{12}x^3\log^2(\eta) + a_{13}x^3\log(\eta) + a_{14}x^4\log^2(\eta) + a_{15}x^4\log(\eta) \\
& + a_{16}x^5\log^2(\eta) + a_{17}x^5\log(\eta)\Big]
\end{aligned}$$

$$\beta = \sqrt{1 - \frac{4m_{\tilde{q}}^2}{s}},\ \eta = \frac{s}{4m_{\tilde{q}}^2} - 1,\ x = \frac{\eta}{(1+\eta)^2}$$

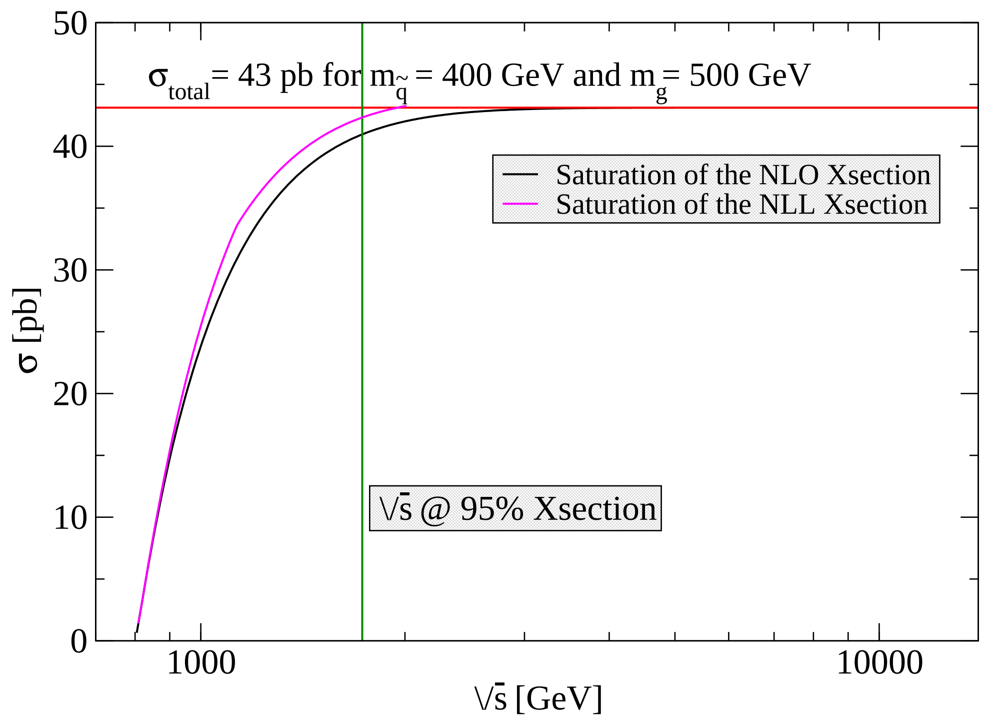
Why NNLO?

- reduce theoretical error of squark pair production cross section
- enlarge mass exclusion limits on squark masses
- need precise input data to ”predict” dark matter density

- Full NNLO: Very complex calculation
- Particles are produced near kinematical production threshold
- Our strategy: use soft gluon resummation to calculate approximated NNLO cross section
- SM example: $t\bar{t}$ production at the Tevatron/LHC

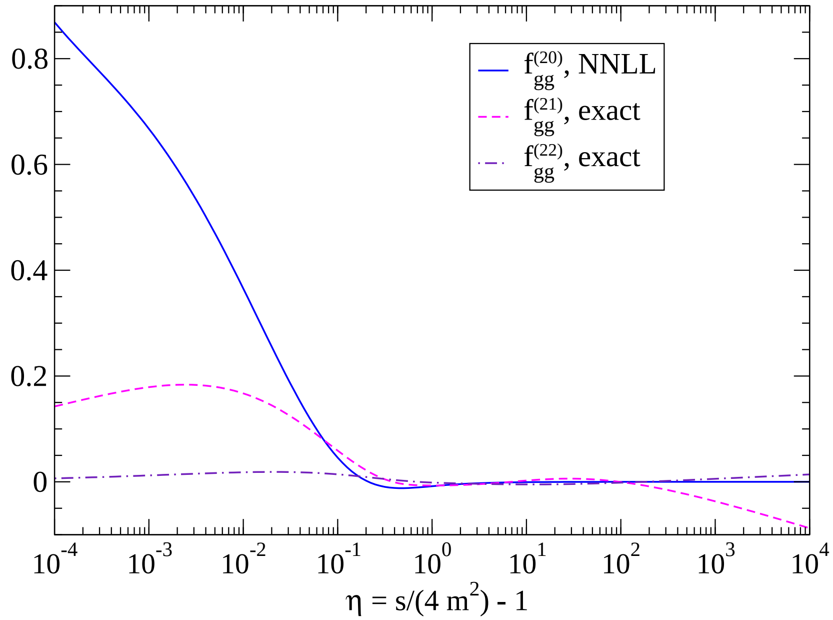
  S. Moch and P. Uwer, Phys. Rev. D **78** (2008) 034003 [arXiv:0804.1476 [hep-ph]].

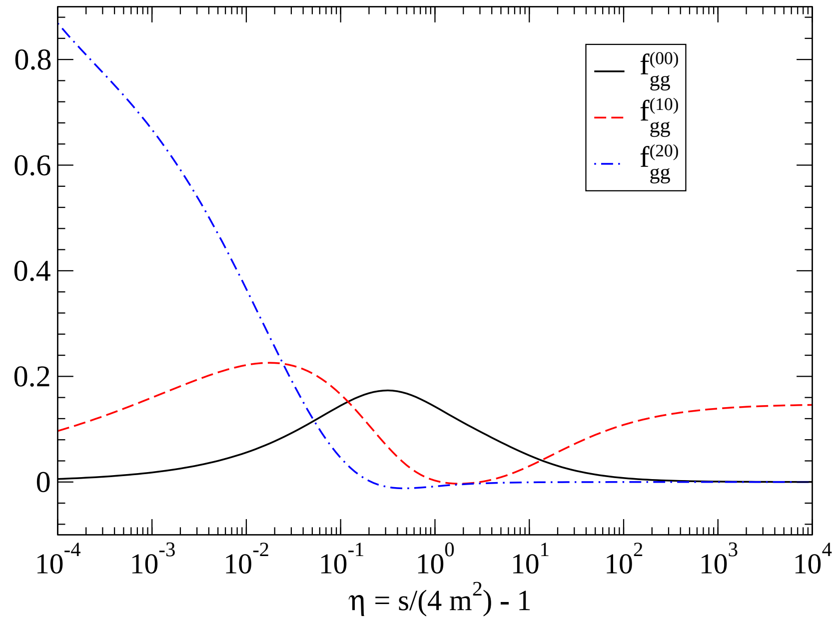
Why does soft gluon resummation work?



- look at which parton energies the total cross section is saturated
- 95% of the total cross section saturated at $\approx 1700\,\text{GeV}$ cms energy
- NLL curve fits quite well

The NNLO scaling function

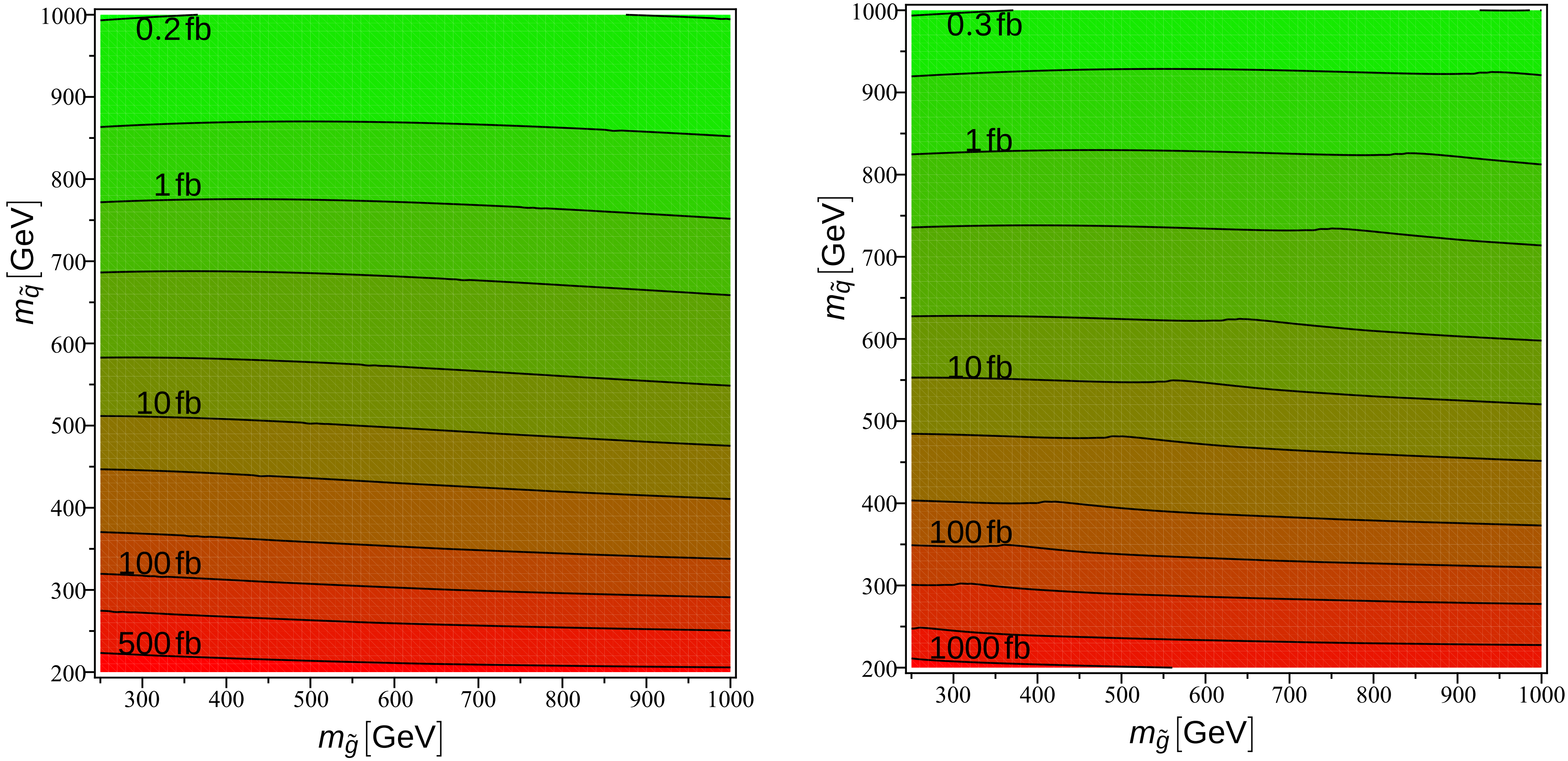




$$f_{gg}^{(20)} = \frac{f_{gg}^{(00)}}{\pi^4}\left[\frac{9}{8}\log(\beta^2)^4 + a_3\log(\beta^2)^3 + (a_2 + b_2/\beta)\log(\beta^2)^2 + (a_1 + b_1/\beta)\log(\beta^2) + \frac{b_2}{\beta} + \frac{b_3}{\beta^2}\right]$$

Results

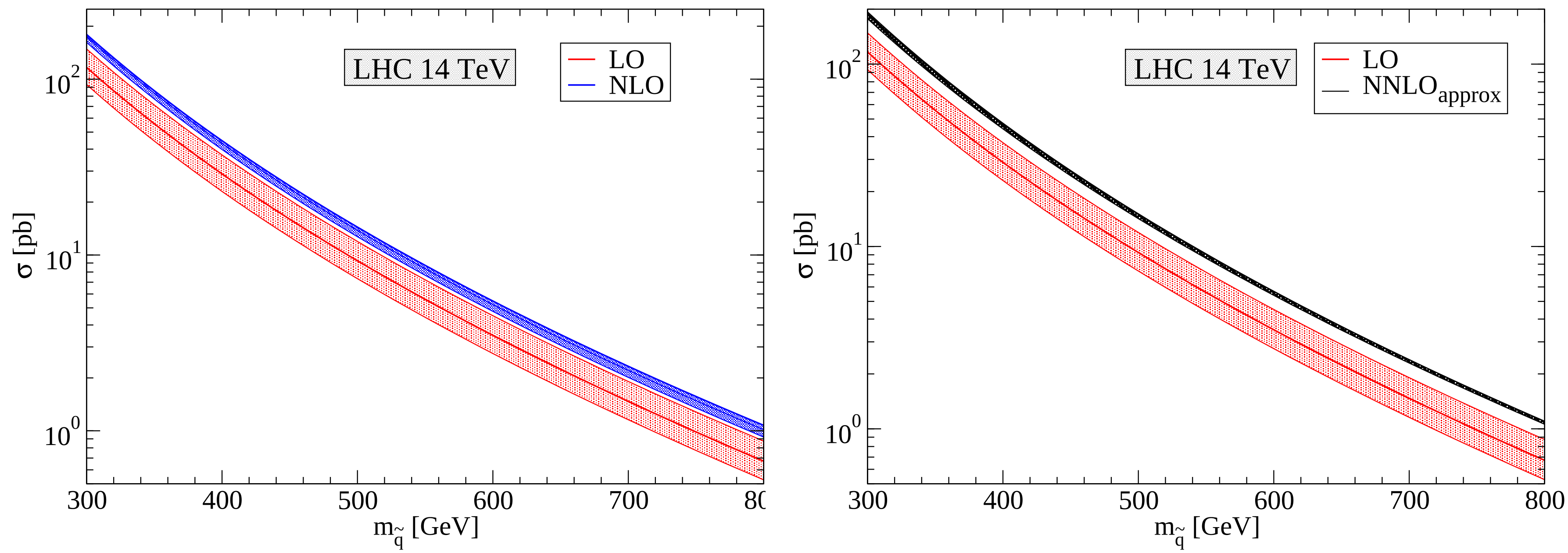
Total cross section: Contour lines in $m_{\tilde{q}} - m_{\tilde{g}}$ plane for LO and NNLO cross section



- weak dependence of the total hadronic cross section on the gluino mass
- strong enhancement due to NLO and NNLO contributions

Results

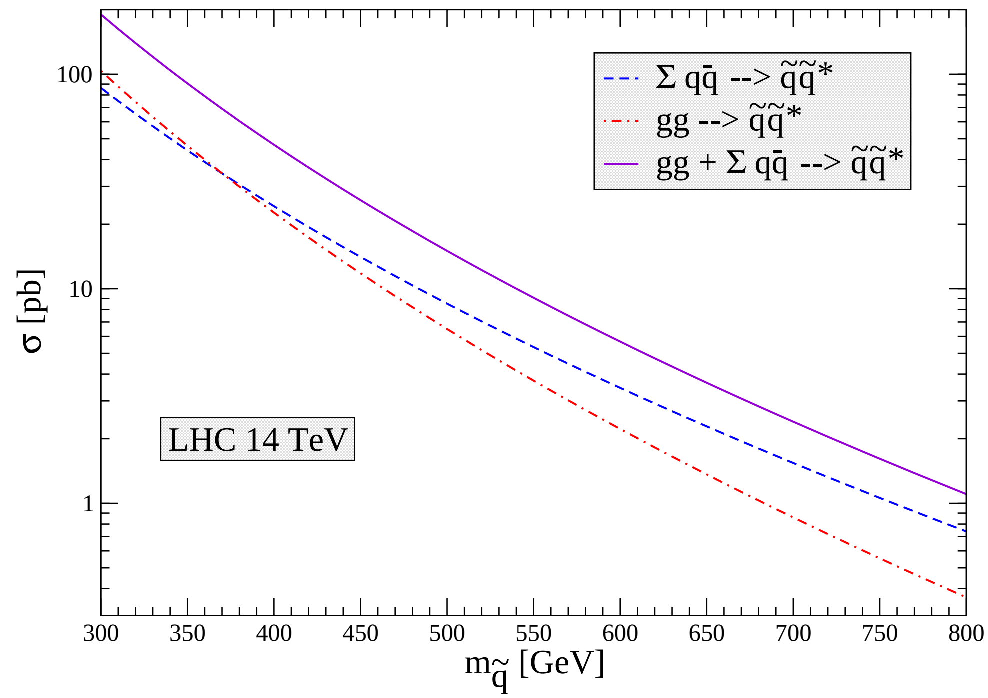
Total cross section



- NNLO correction are about $5 - 10\%$ of the NLO cross section
- Raising of mass bounds: 30 pb @ 397 GeV LO, 430 GeV NLO, 437 GeV NNLO.

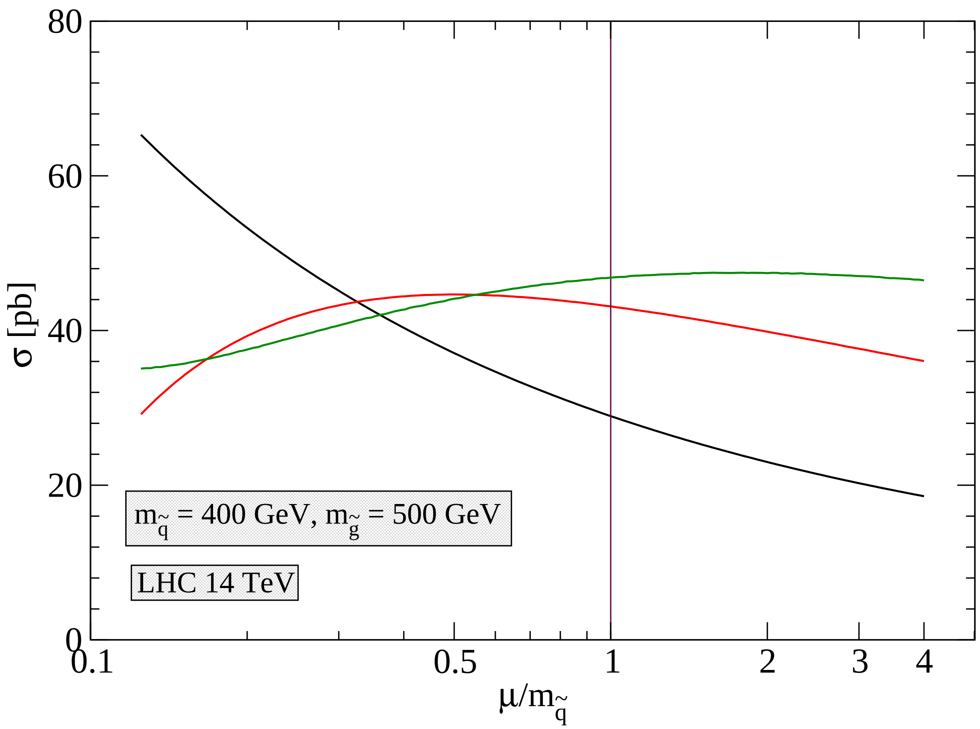
Results

Total cross section: Contribution of the two channels



- gg channel dominant up to $m_{\tilde{q}} = 370\,\text{GeV}$, $\approx 33\%$ contr. at $m_{\tilde{q}} = 800\,\text{GeV}$
- gg channel: 10 subprocesses, $q\bar{q}$ channel: 140 subprocesses
- for comparison: $t\bar{t}$ @ LHC: gg contribution $\approx 85\%$

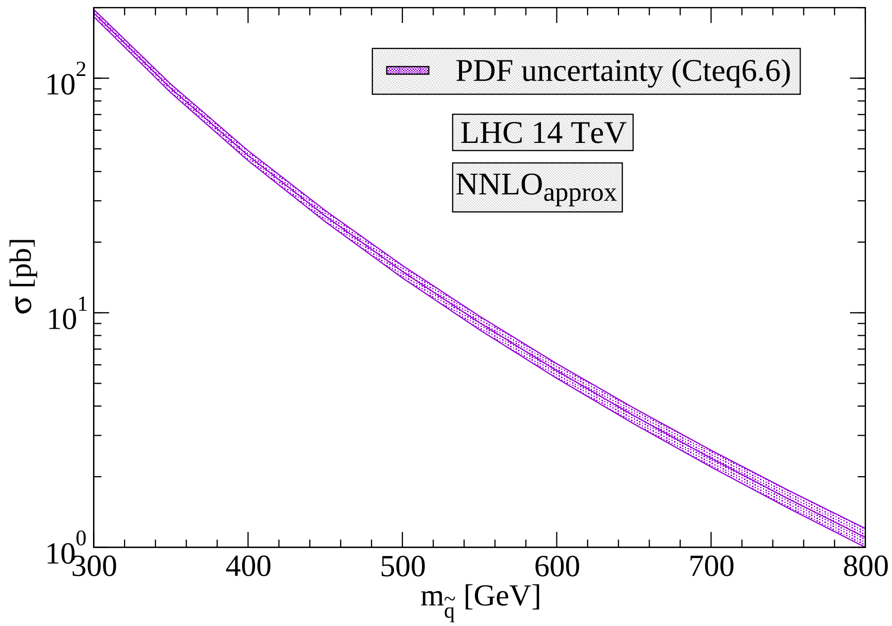
Results
Scale dependence

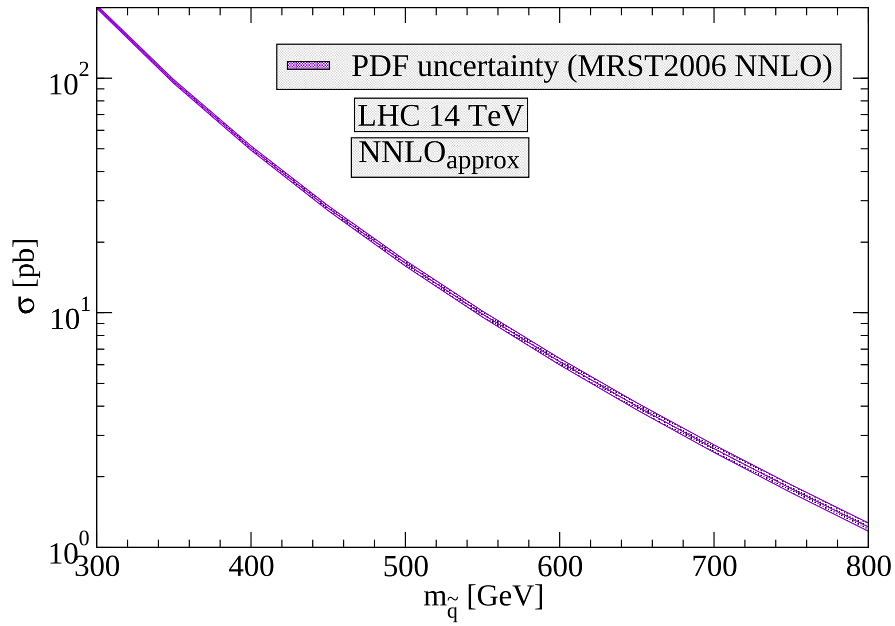


- curves become flatter from LO $\longrightarrow$ NLO $\longrightarrow$ NNLO

Results

Error of the total hadronic cross section due to Pdf uncertainty





- Cteq6.6(1 + 44): rel. error increases from $\approx 5\%$ of total cross section at $m_{\tilde{q}} = 300\,\text{GeV}$ to $\approx 10\%$ at $m_{\tilde{q}} = 1000\,\text{GeV}$
- MRST2006nnlo(1 + 30): rel. error increases from $\approx 1.5\%$ of total cross section at $m_{\tilde{q}} = 300\,\text{GeV}$ to $\approx 4\%$ at $m_{\tilde{q}} = 1000\,\text{GeV}$

Summary

- We calculated NNLO corrections for squark pair production at the LHC.
- For the NLO scaling functions, we calculated fit functions.
- We need NNLO precision for the squark pair production cross section because
  - the scale uncertainty reduces to a small error interval,
  - and the lower mass bounds for squark masses are raised.
- We analyzed
  - the total hadronic cross section
  - the contributions of the two initial channels
  - the NNLO scale dependence
  - the error on the cross section due to PDF uncertainties