Precision Calculations for Squark and Gluino Production at Threshold

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Outline

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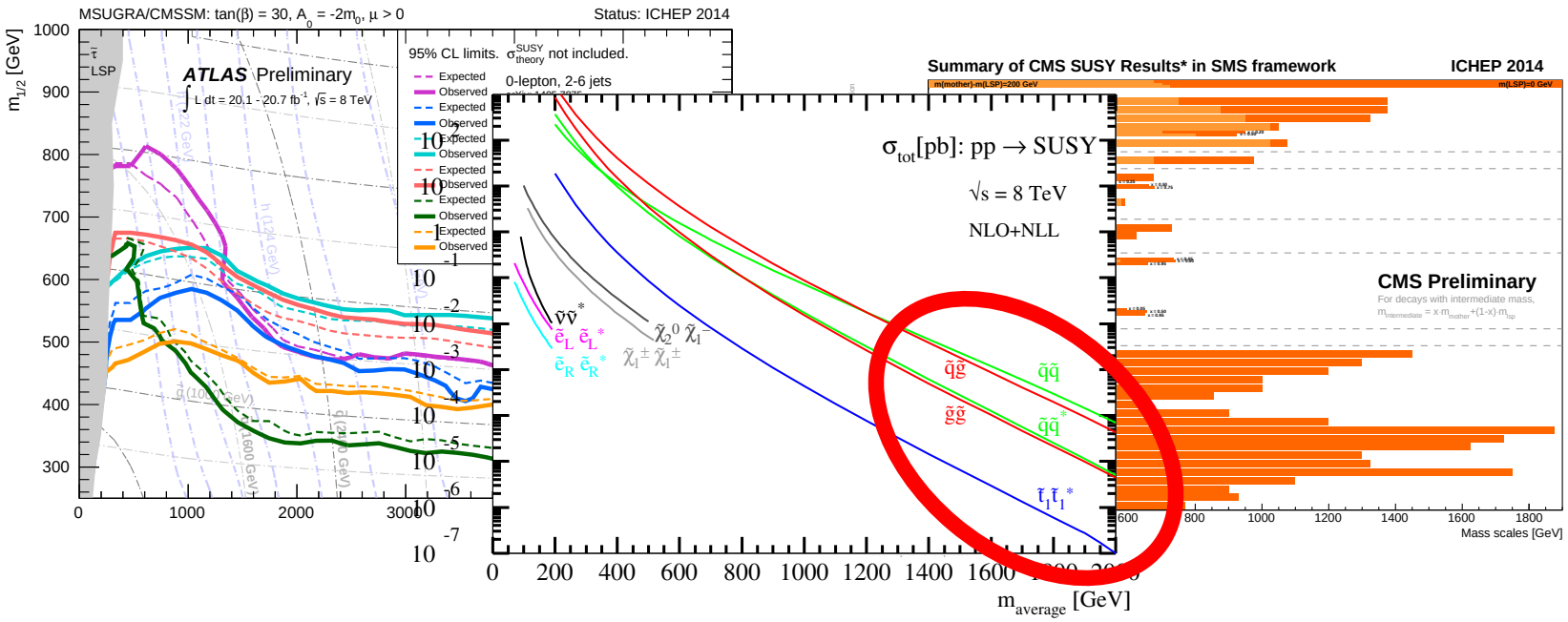
SUSY particle production at the LHC

Main sparticle production processes:

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



⇒ Cross sections needed at high precision for experimental searches

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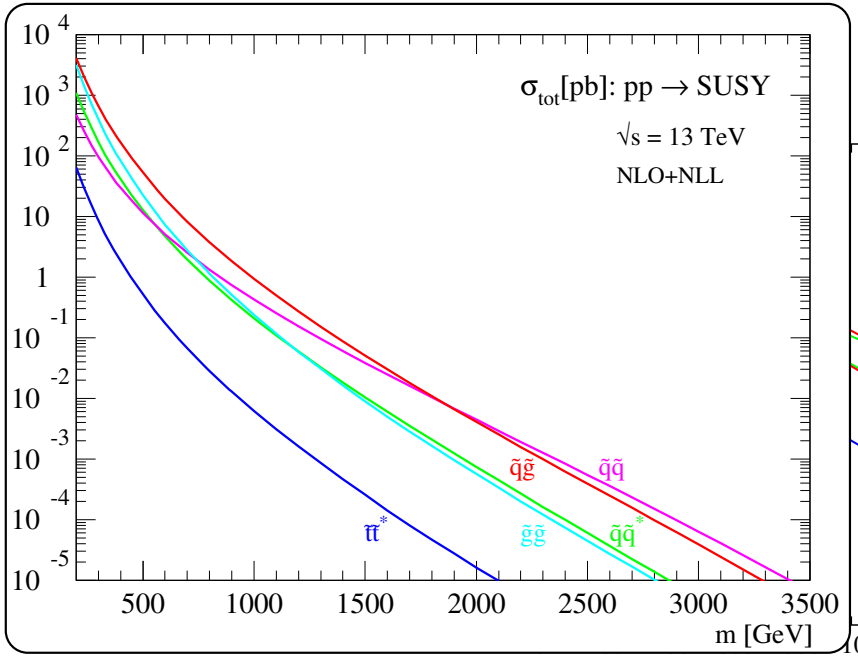

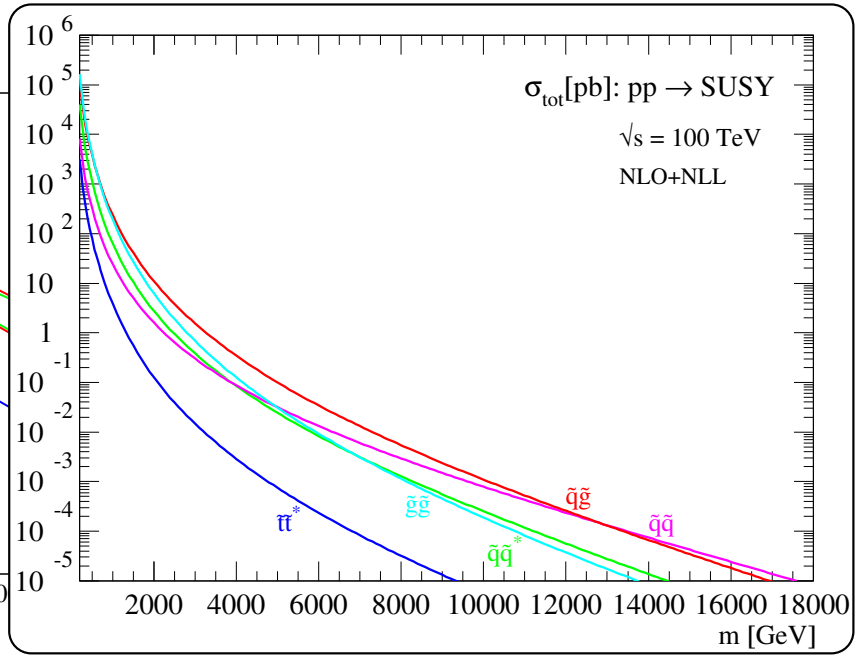

(see *[CB, Krämer, Kulesza, Mangano, Padhi, Plehn, Portell; EPJ C74 (2014) 12, 3174]*)

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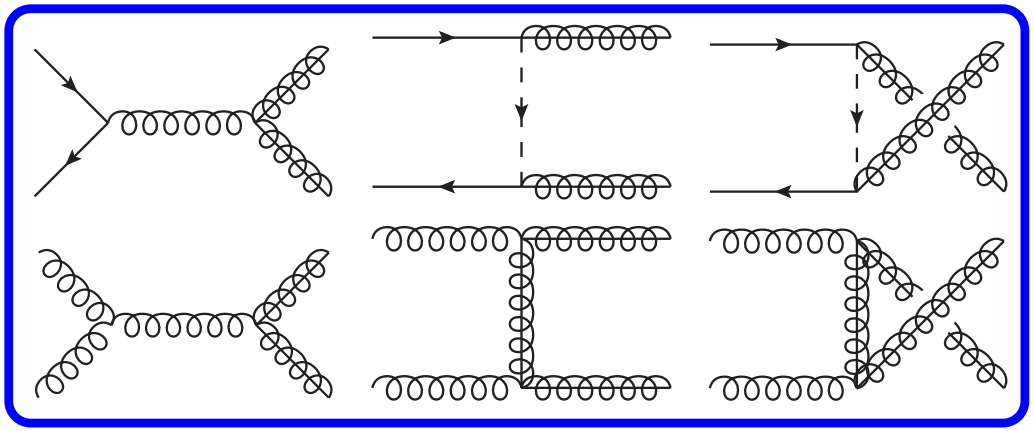
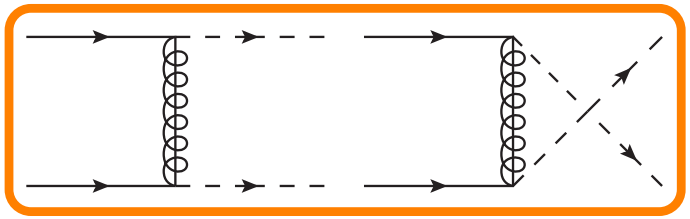
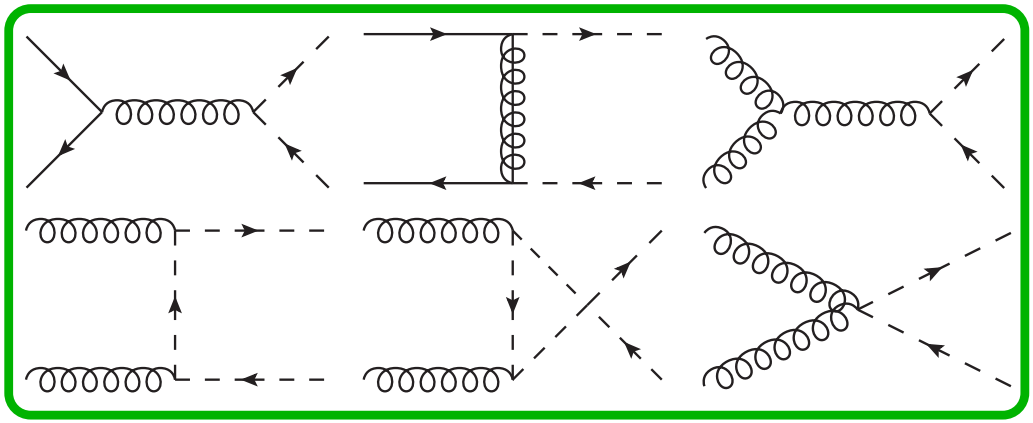
LO production of squarks and gluinos

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



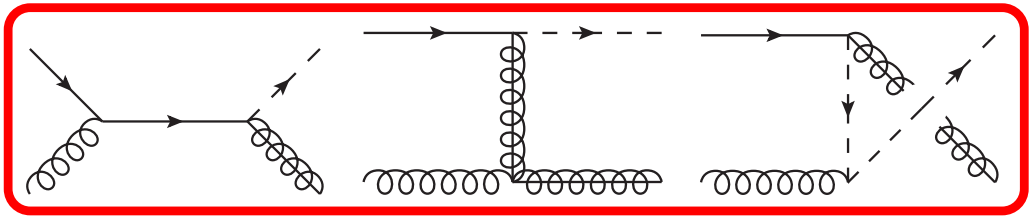
$\tilde{q}\tilde{q}$





$\tilde{q}\tilde{q}^*$

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



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Outline

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Particle production close to threshold

Heavy SUSY particles ⇒ production in the **threshold limit** $\sqrt{\hat{s}} \to 2m$:

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

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

⇒ Just enough energy to produce the two sparticles

⇒ **Real radiation processes are soft**

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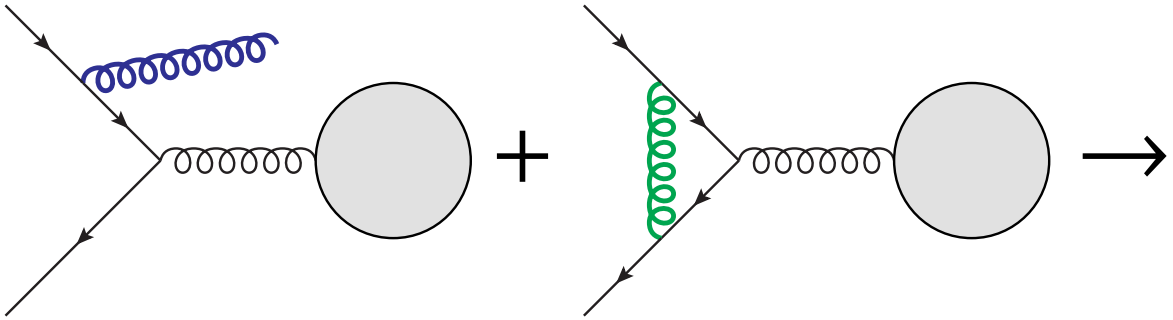
Remainder after cancellation of IR divergencies:



$$\sim \alpha_s^n \ln^m \beta^2, \quad m \leqslant 2n$$

Soft & collinear gluons

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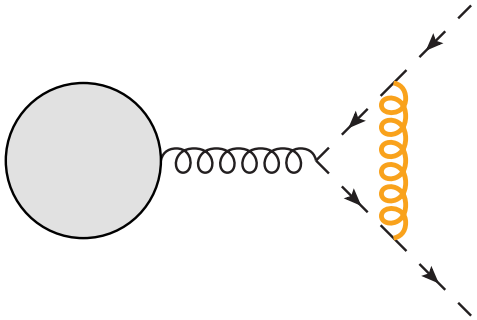
Additionally:



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

Coulomb gluons

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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: $\alpha_s^n/\beta^n \sim 1$

⇒ Endangering the perturbative series

⇒ Systematic treatment of these terms required

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The need for a Mellin transform

Basis for resummation of soft-collinear gluons: factorisation between **hard** and **soft** parts

→ Factorisation of matrix elements and phase space

→ **Matrix element**: factorises automatically in soft-collinear limit ✓

→ **Phase space**: momentum-conservation causes entanglement ✗

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→ **Phase space**: momentum-conservation causes entanglement ✗

In **Mellin-moment space**, the entanglement vanishes (momentum-conserving delta function turns into an exponential function)

$$\tilde{\sigma}_{\text{hadr.}}(N) := \sum_{i,j} \tilde{f}_i(N+1) \times \tilde{f}_j(N+1) \times \tilde{\sigma}_{ij\to kl}(N)$$

In $\tilde{\sigma}_{ij\to kl}(N)$, hard and soft parts now fully factorised

→ Additionally, convolution with PDFs turns into a simple product

Treating large logarithms

Threshold logarithms in **Mellin-moment space** (threshold limit: $\beta \to 0 \;\hat{=}\; N \to \infty$):

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

(neglect subleading terms $\mathscr{O}(1/N)$)

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

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

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LO $\sim \alpha_s^2$

$\sim$ **NLO**

$\sim$ **NNLO**

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

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

[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, Falgari, Schwinn '09][Czakon, Mitov, Sterman '09][Ferroglia, Neubert, Pecjak, Yang '09] ...

(Precision level: LL + NLL + NNLL)

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Factorised resummation formula

$$\tilde{\sigma}_{ij\to kl}(N) \overset{\hat{s}\to 4m^2}{\approx} \sum_{\text{colours } I} H_{ij\to kl,I}(\mu) \times \Delta_i(N,\mu)\Delta_j(N,\mu) S_{ij\to kl,I}(N,\mu)$$

with

- process dependent **hard part** $H_{ij\to kl,I}(\mu)$
- process independent **soft-collinear radiation factors** $\Delta_{i/j}(N,\mu)$
- **soft wide-angle radiation factor** $S_{ij\to kl,I}(N,\mu)$

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Obtain exponentiated forms of $\Delta_{i/j}(N,\mu)$ and $S_{ij\to kl,I}(N,\mu)$ from **renormalisation group equations**:

$\rightarrow$ Assume that the (physical) cross section is independent of the (unphysical) scale μ

$\rightarrow$ Scale dependence cancels out between the constitutents

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Matching coefficients

Higher order terms of different origin; **split-up close to threshold** *[Beneke, Falgari, Schwinn '09-10]*:

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

- $\mathscr{C}^{\mathrm{Hard}}(\alpha_s)$: **hard matching coefficients** (independent of N)
  - $\rightarrow$ Calculated from NLO contributions *[Beenakker, Janssen, Lepoeter, Krämer, Kulesza, Laenen, Niessen, Thewes, Van Daal '13][Broggio, Ferroglia, Neubert, Vernazza, Yang '13]*
- $\mathscr{C}^{\mathrm{Coul}}(N, \alpha_s)$: **Coulomb terms** (final state gluon exchange):
  - $\rightarrow$ Can also be resummed *[Kulesza, Motyka '09][Beneke, Falgari, Schwinn '10][Falgari, Schwinn, Wever '12]*, using non-relativistic methods *[Fadin, Khoze '87][Peskin, Strassler '91][Hagiwara, Yokoya '09][Kauth, Kühn, Marquard, Steinhauser '09-11][Kauth, Kress, Kühn '11]*

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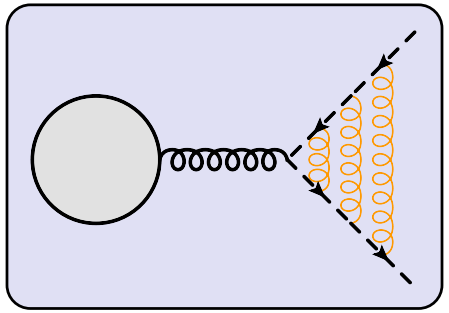

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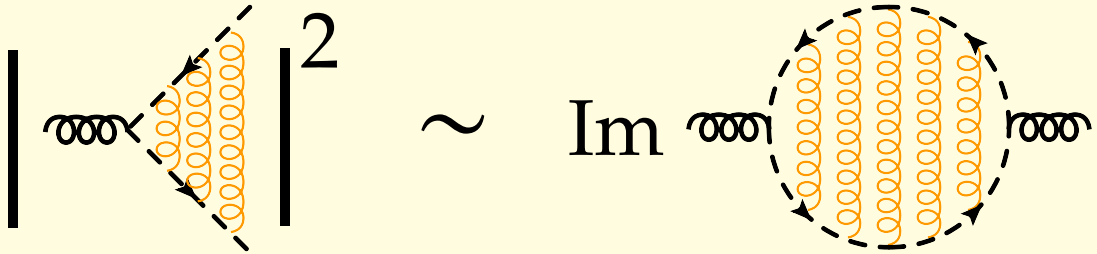
Coulomb Green's function



Calculation of ladder diagrams leads to **non-relativistic Schrödinger equation**:

$$\left\{\left[\frac{(-i\nabla)^2}{2m_{\mathrm{red}}} + V_C(\vec{r})\right] - (E + i\Gamma)\right\} G(\vec{r}, E + i\Gamma) = \delta^{(3)}(\vec{r})$$

with $E = \sqrt{\hat{s}} - 2m$: energy and Γ: average decay width of the final state particles, m_{red}: reduced mass,

and the **Coulomb potential**:

$$V_C(\vec{r}) = -D_{R_\alpha} \frac{\alpha_s}{|\vec{r}|} + \mathcal{O}(\alpha_s^2)$$

with D_{R_α}: colour factor related to Casimir invariants

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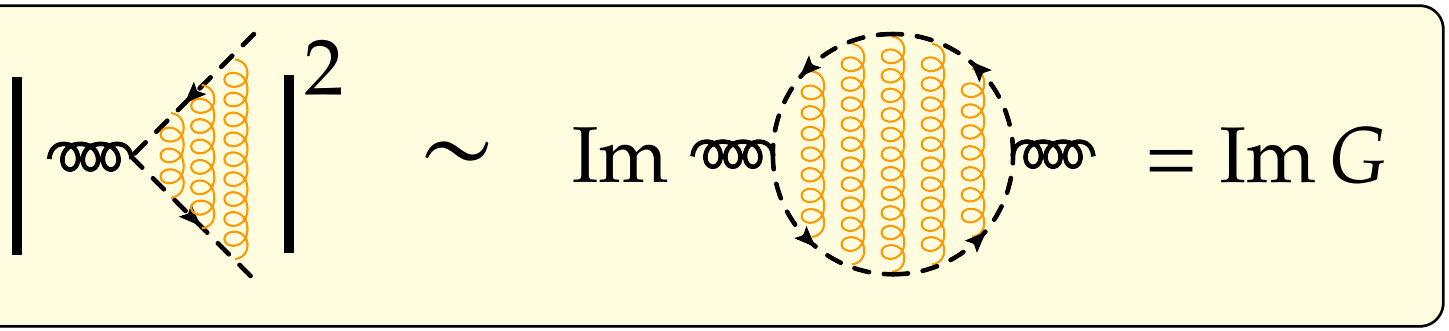

The solution at origin is *[Beneke, Signer, Smirnov '99][Pineda, Signer '06]*:

$$G(\vec{0}, E + i\Gamma) = i\frac{m_{\mathrm{red}}^2}{\pi} v + D_{R_\alpha} \frac{\alpha_s m_{\mathrm{red}}^2}{\pi} \left[g_{\mathrm{LO}} + \frac{\alpha_s}{4\pi} g_{\mathrm{NLO}} + \ldots \right]$$

with g_{LO} (g_{NLO}) contributions from LO (NLO) Coulomb potential ($g_{\mathrm{LO}} \sim$ Sommerfeld factor)

Incorporate into resummation framework (here: $\Gamma = 0$; $\tilde{q}$, $\tilde{g}$ stable):

$$\hat{\sigma}^{\mathrm{Coul},res} = \hat{\sigma}^{\mathrm{LO}} \times \frac{\mathrm{Im}\, G(\vec{0}, E)}{\mathrm{Im}\, G^{\mathrm{free}}(\vec{0}, E)}$$

with the velocity $v = \sqrt{\frac{E + i\Gamma}{2m_{\mathrm{red}}}} \approx \sqrt{\frac{m}{2m_{\mathrm{red}}}}\beta$

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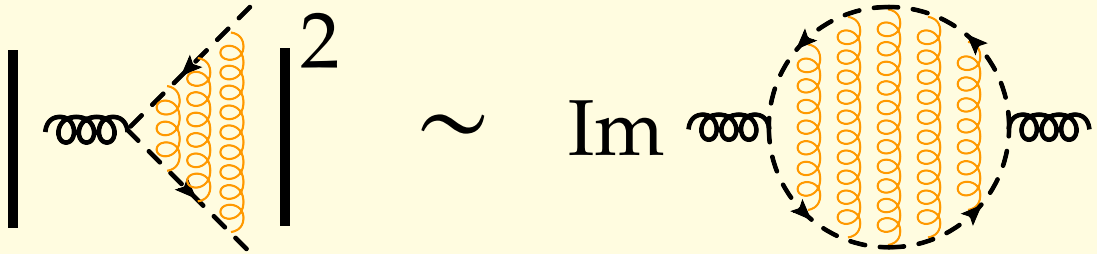
Coulomb Green's function: boundstates



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with g_{LO} (g_{NLO}) contributions from LO (NLO) Coulomb potential ($g_{\text{LO}} \sim$ Sommerfeld factor)

$G(\vec{0}, E + i\Gamma)$ develops poles **below** threshold $\rightarrow$ boundstates for attractive Coulomb potential ($D_{R_\alpha} > 0$):

$$G(\vec{0}, E + i\Gamma) = \sum_n \frac{|\Psi(0)|^2}{E_n - (E + i\Gamma)} \rightarrow \sum_n |\Psi(0)|^2 \pi\delta\left(E - E_n\right)$$

with the wave function for the boundstate system at origin $\psi(0)$

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Matching to fixed order

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

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

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

Total resummed cross section:

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

$\longrightarrow$ NNLO matching needed to avoid double counting

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PROSPINO

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Total resummed cross section:

PDFs in Mellin space

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$\rho = 4m^2/S$

→ NNLO matching needed to avoid double counting

Outline

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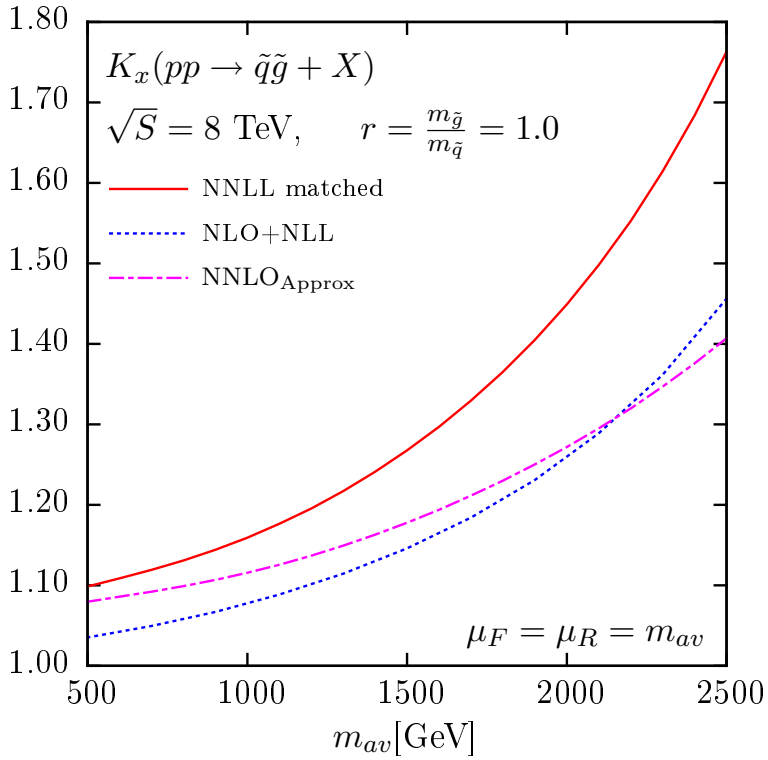
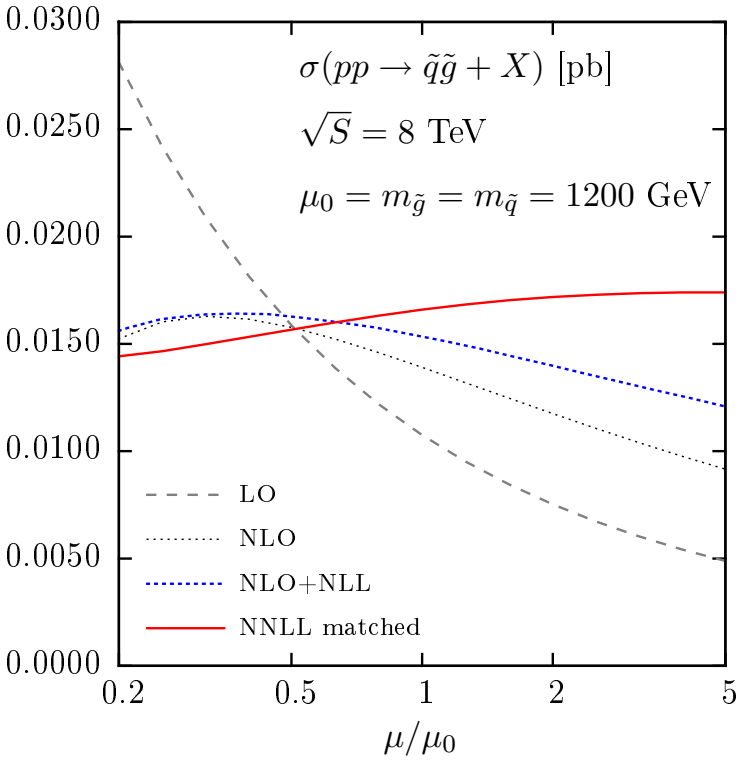
Results: $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}^*$, $\tilde{q}\tilde{g}$, $\tilde{q}\tilde{q}$ with soft gluon resum.

[Beenakker, CB, Krämer, Kulesza, Laenen, Theeuwes, Thewes; JHEP 1412 (2014) 023]



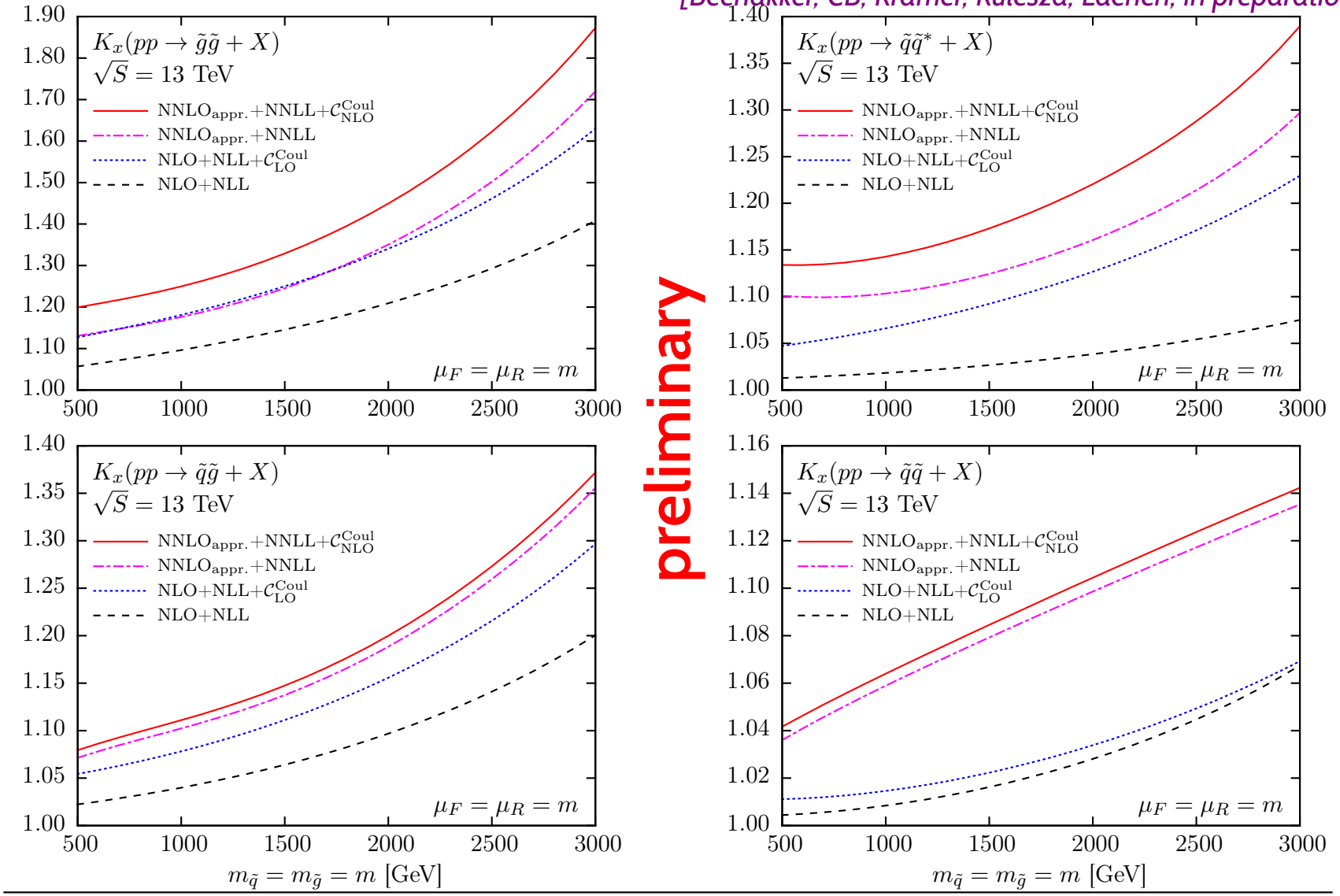


$$K_x = \frac{\sigma^x}{\sigma^{\text{NLO}}}$$

$\tilde{q}\tilde{q}$ & $\tilde{q}\tilde{g}$ dominant processes at high masses & energies

Results: $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}^*$, $\tilde{q}\tilde{g}$, $\tilde{q}\tilde{q}$ with soft + Coulomb resum.

[Beenakker, CB, Krämer, Kulesza, Laenen; in preparation]



$\mathcal{C}^{\text{Coul}}_{\text{(N)LO}}$: resummed Coulomb corrections; compare to SCET *[Beneke, Falgari, Piclum, Schwinn, Wever '13-'14]*

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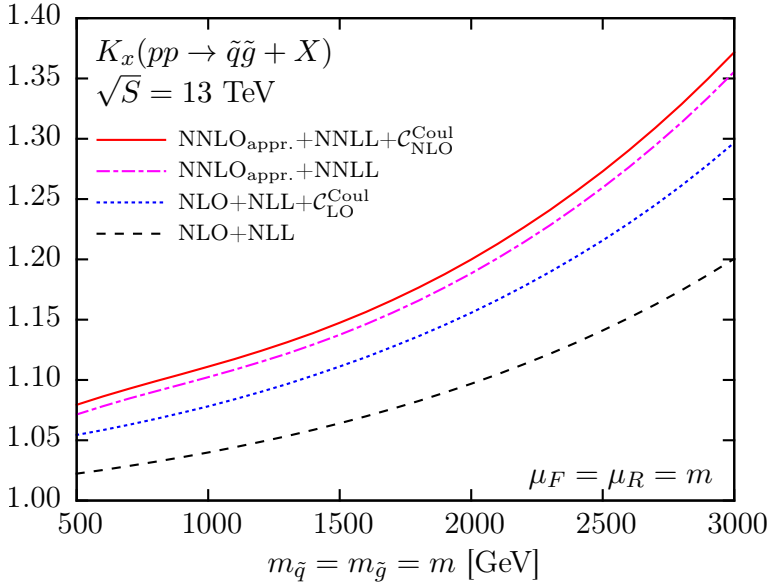

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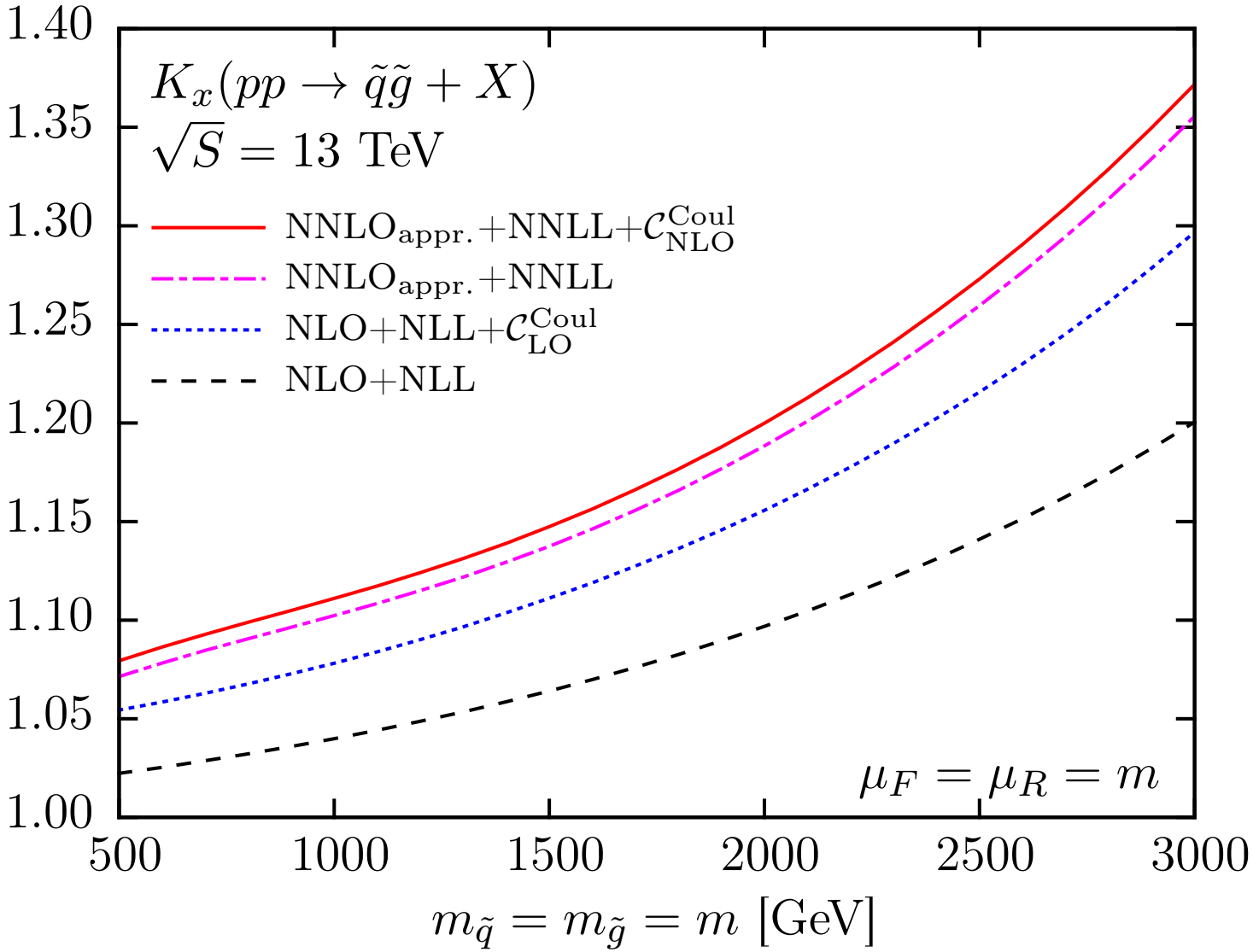

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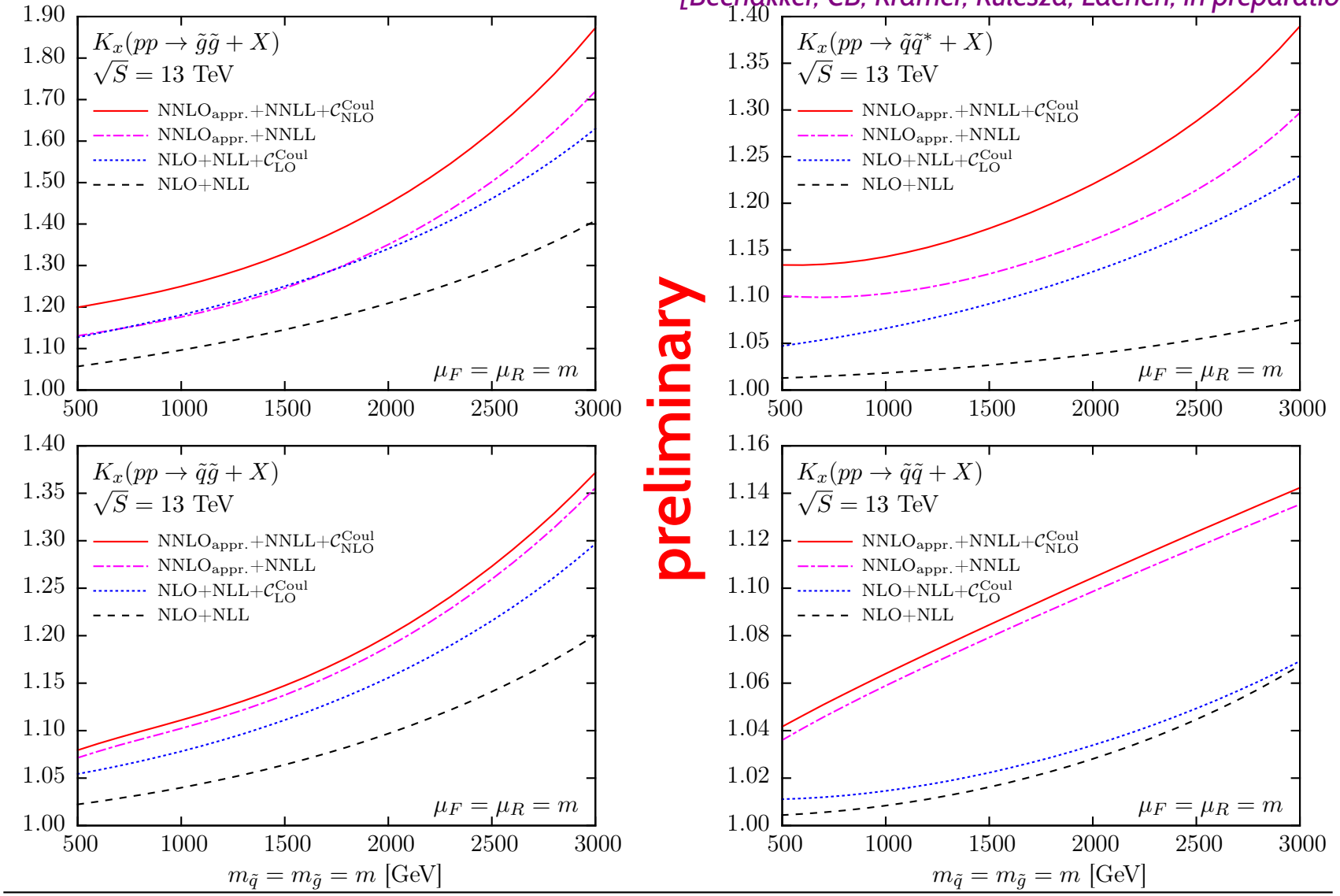

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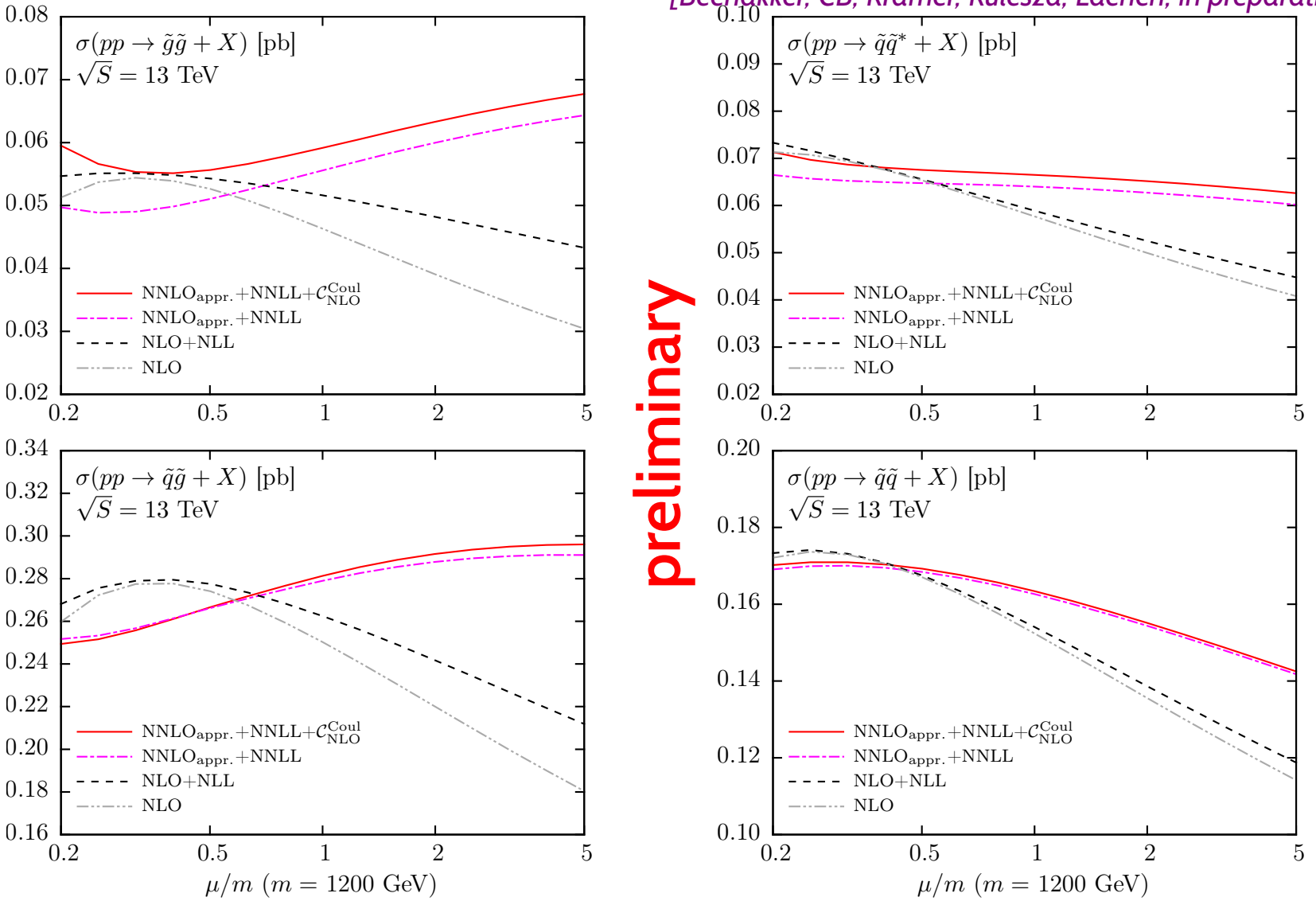

Using MSTW 2008 PDFs (NLO & NNLO); squark and gluino masses set to 1200 GeV

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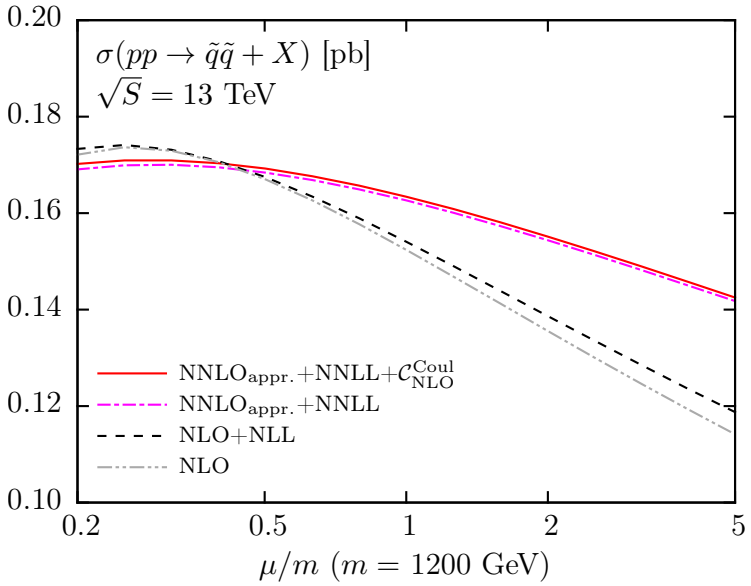

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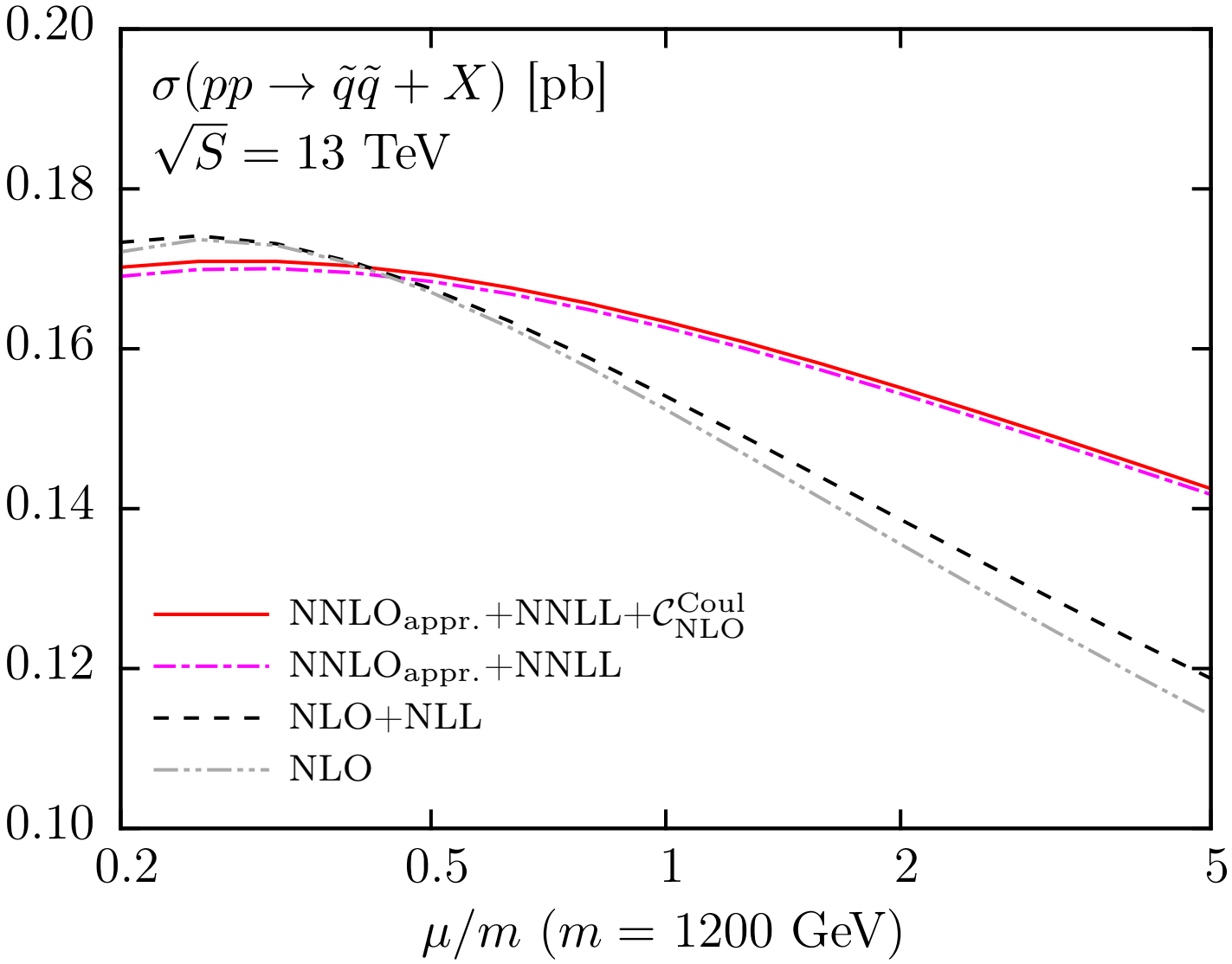

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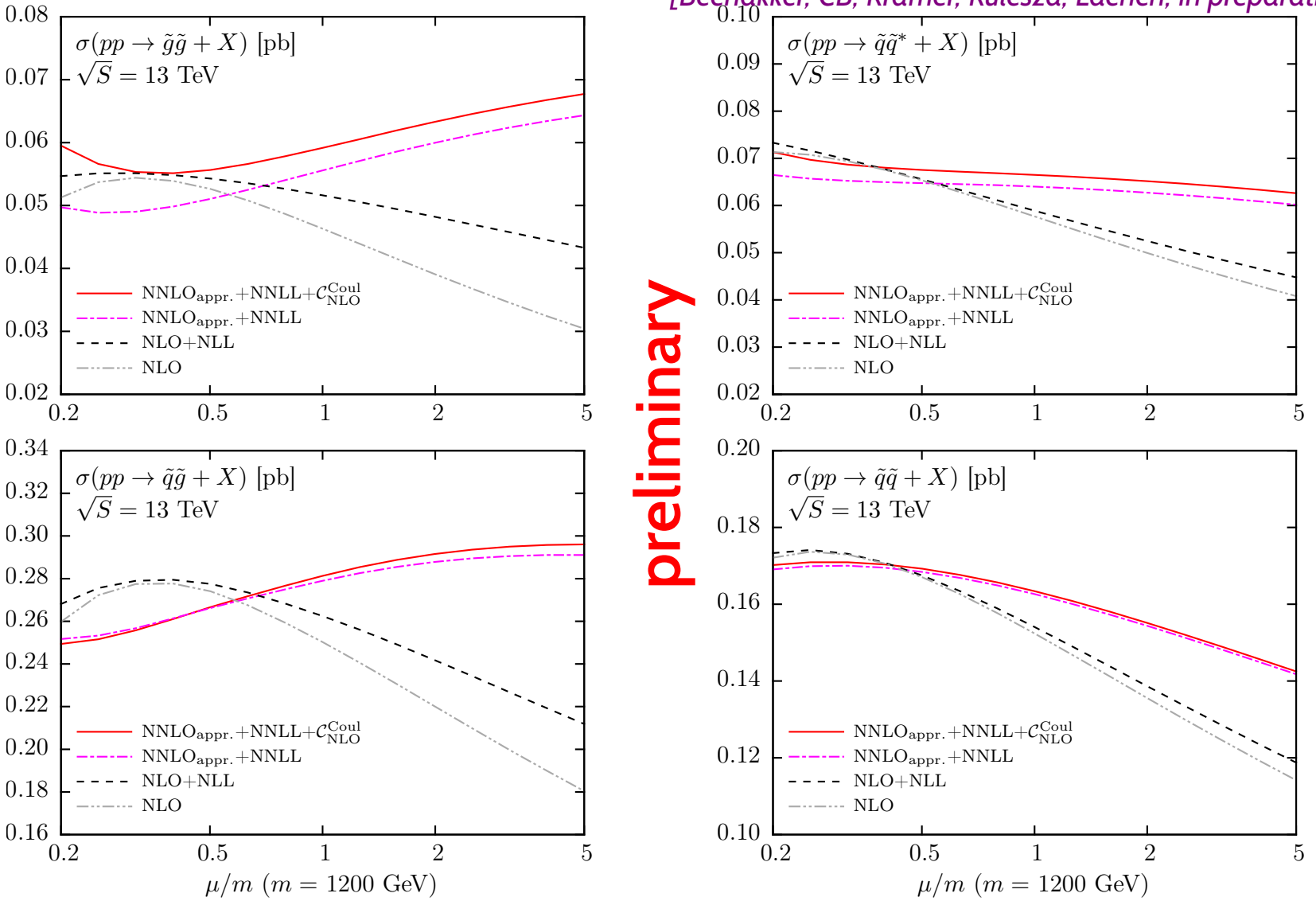

Using MSTW 2008 PDFs (NLO & NNLO); squark and gluino masses set to 1200 GeV

Intermezzo: why are stops different?

Stops in the weak interaction basis do not correspond to physical states

→ From the MSSM Lagrangian, mass terms for the stops can be extracted:

$$\mathscr{L}_{\text{MSSM}} \to \begin{pmatrix} \tilde{t}_L^* & \tilde{t}_R^* \end{pmatrix} \begin{pmatrix} M^2_{\tilde{t},LL} & \Delta_{\tilde{t},LR} \\ \Delta_{\tilde{t},RL} & M^2_{\tilde{t},RR} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

(in the basis of "left-" and "right-handed" stop fields, non-physical basis)

Eigenvalues correspond to the physical masses $m^2_{\tilde{t}_i}$ of the stops ($i = 1, 2$)

→ $\boxed{\Delta_{\tilde{t},LR} = \Delta^*_{\tilde{t},RL} \propto m_t \gg 0}$: $m^2_{\tilde{t}_i}$ contain a mixture of L and R

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Intermezzo: why are stops different?

Stops in the weak interaction basis do not correspond to physical states

$\Rightarrow$ Rotate into physical basis:

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{t}} & \sin\theta_{\tilde{t}} \\ -\sin\theta_{\tilde{t}} & \cos\theta_{\tilde{t}} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

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Additional parameters in Feynman rules: $\theta_{\tilde{t}}, m_{\tilde{q}}, m_{\tilde{g}}, m_{\tilde{t}_2}$

$\rightarrow$ From benchmark point 40.2.5 *[AbdusSalam, Allanach, Dreiner, Ellis et al.; arXiv: 1109.3859]*

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In many SUSY scenarios, $\tilde{t}_1$ is among the lightest sparticles $\Rightarrow$ easy detection?

Otherwise similar to $\tilde{q}\tilde{q}^*$ production with certain production channels suppressed by very small PDFs

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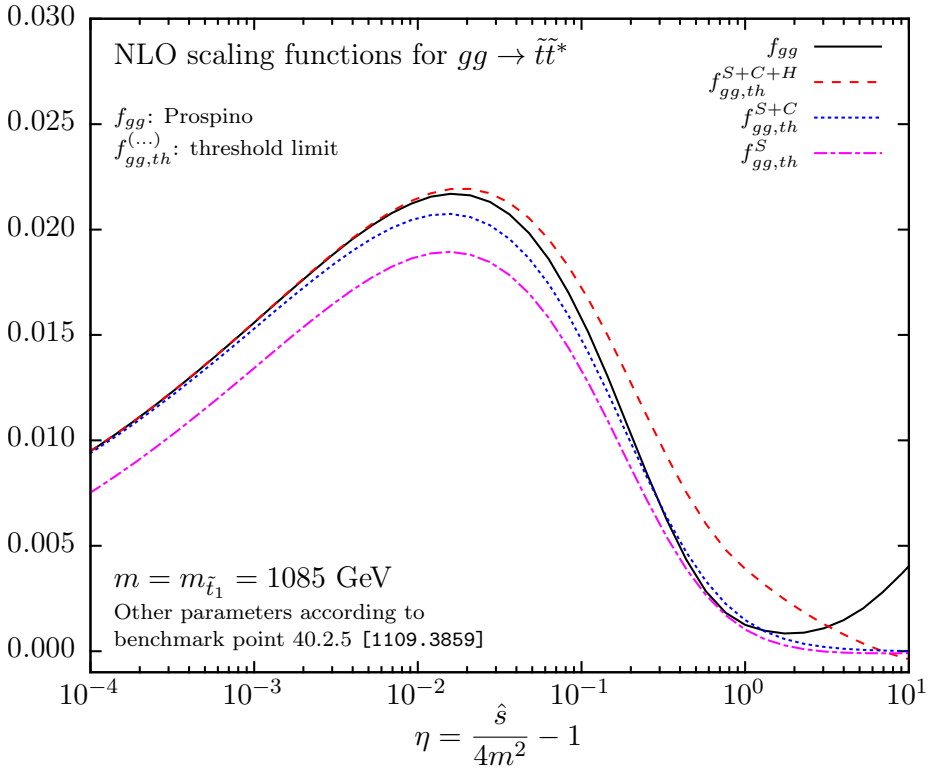
Results: $\tilde{t}_1\tilde{t}_1^*$ production



preliminary

From:

$$\hat{\sigma}_{ij} = \frac{\alpha_s^2}{m_{\tilde{t}_1}^2}\left\{f_{ij}^B + 4\pi\alpha_s\left[f_{ij} + \bar{f}_{ij}\ln\left(\frac{\mu^2}{m_{\tilde{t}_1}^2}\right)\right]\right\}$$

with:
- S: soft-gluon logarithms
- C: Coulomb terms
- H: hard-matching coefficient *[Broggio et al. '13]*

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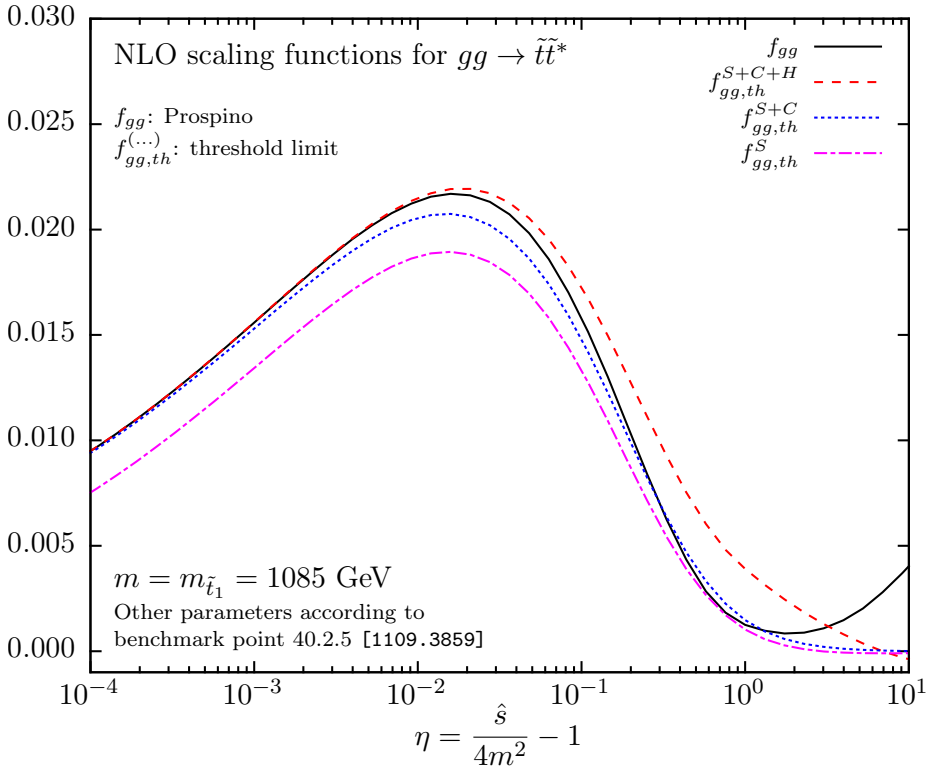

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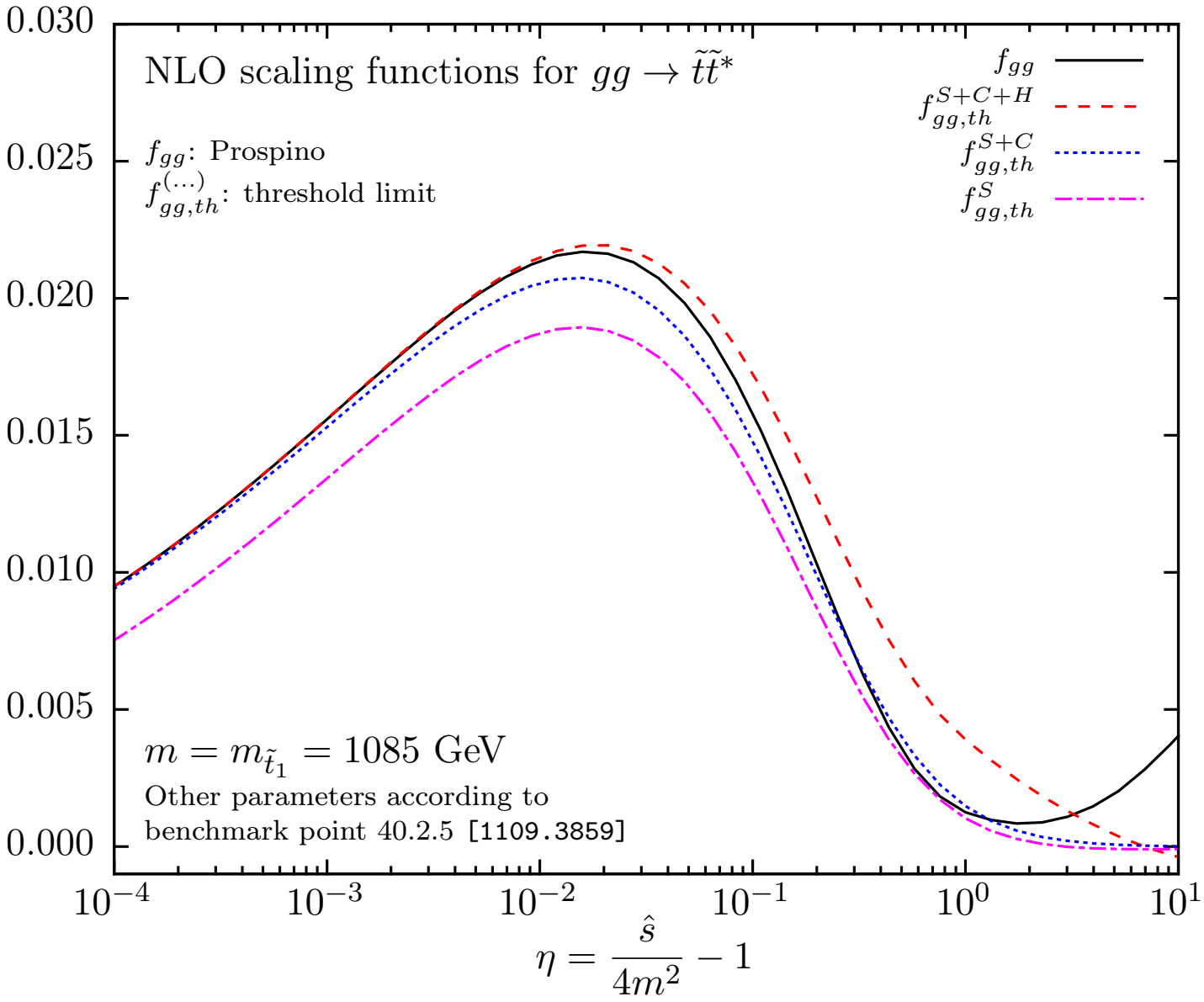

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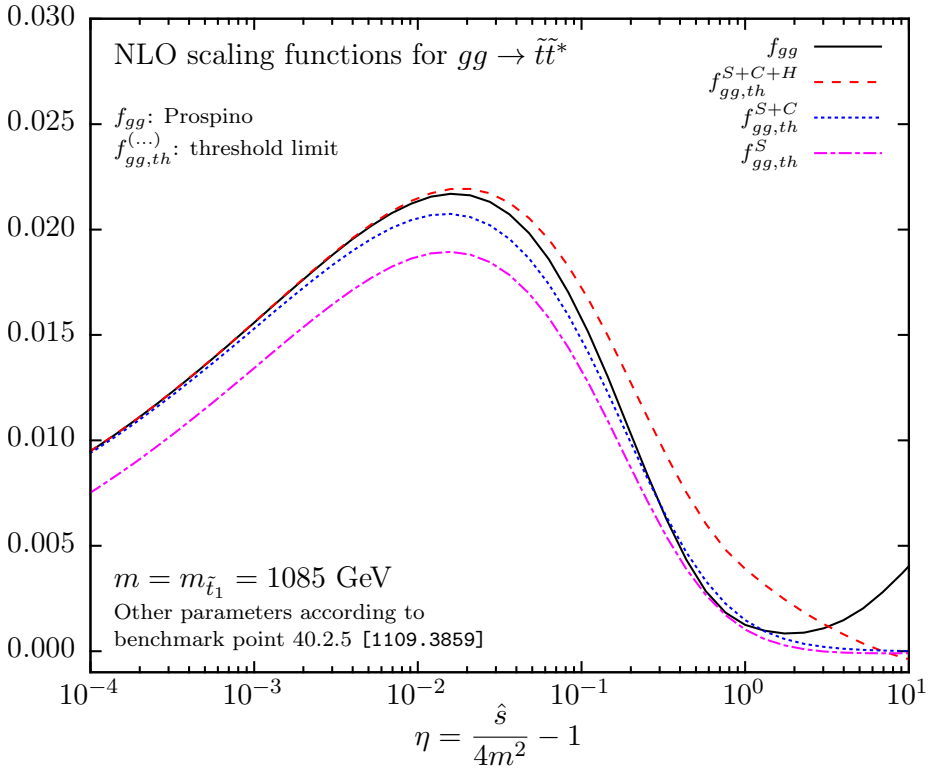

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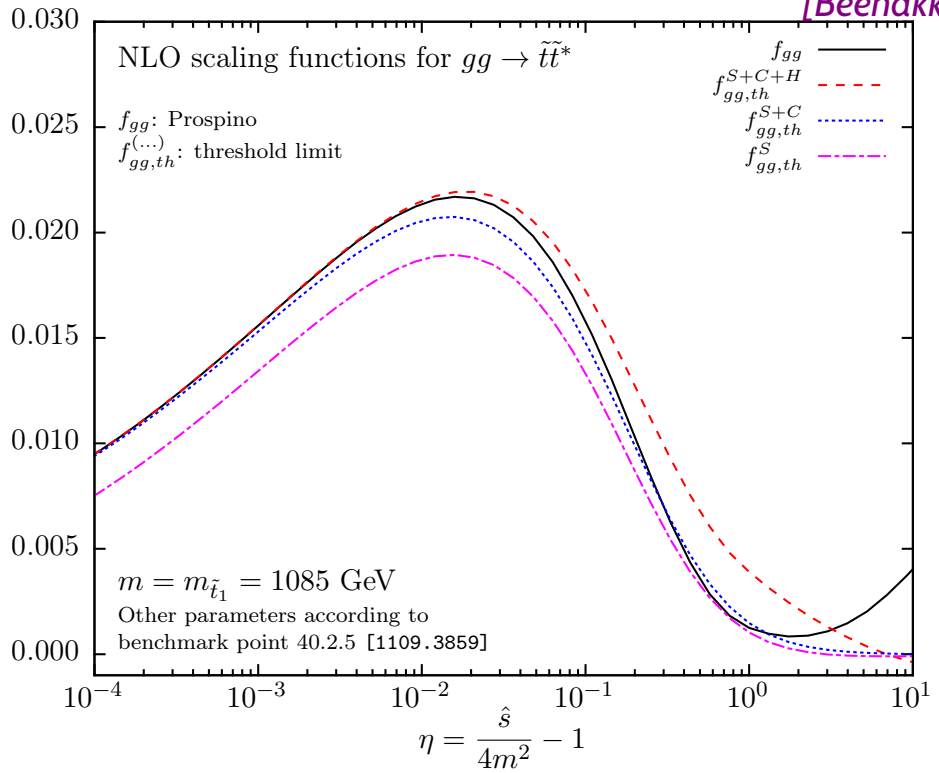

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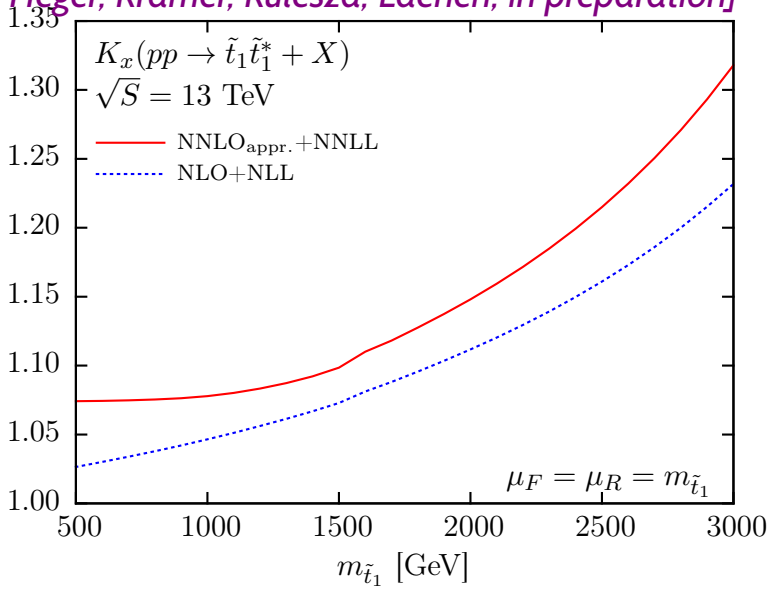
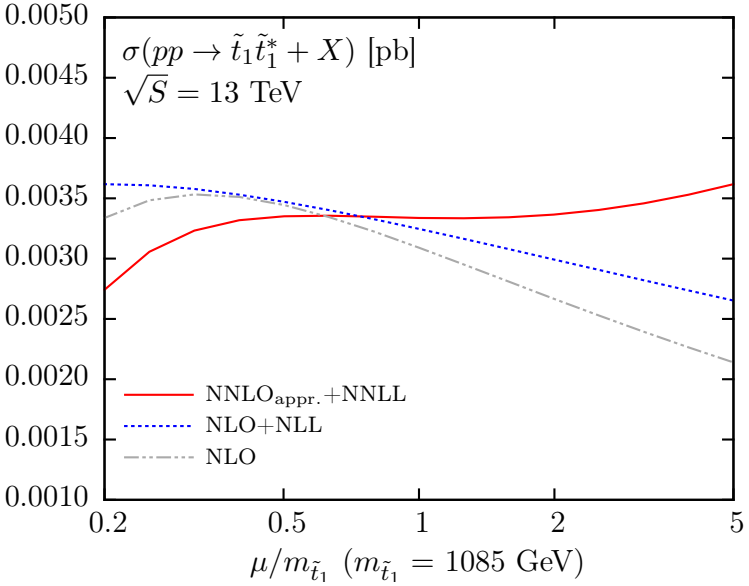




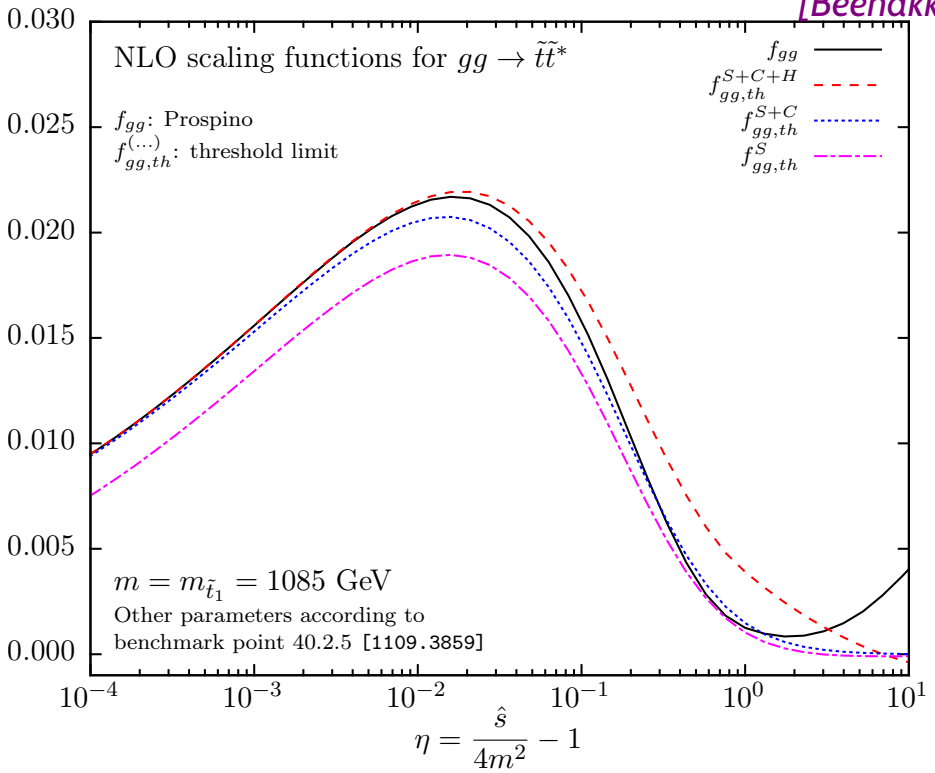
Benchmark point 40.2.5

[arXiv: 1109.3859]

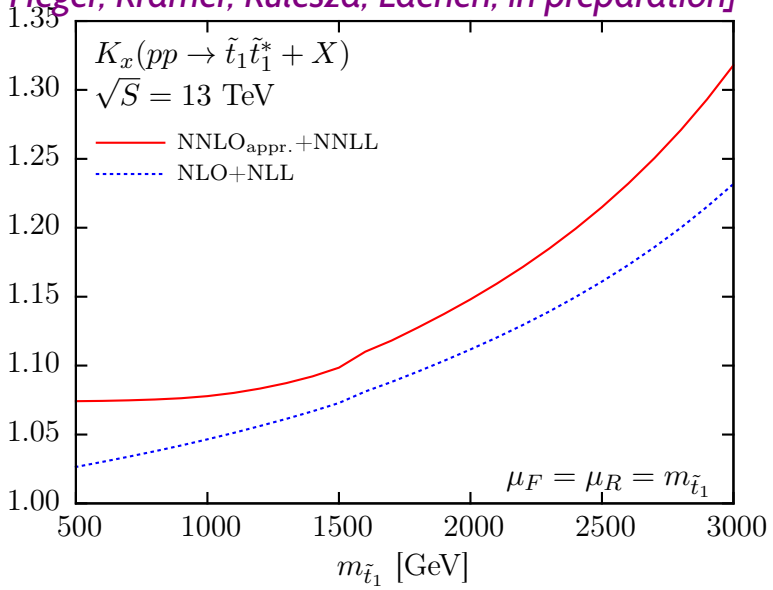
$$\begin{cases} \sin 2\theta_{\tilde{t}} = 0.669 \\ m_{\tilde{q}} = 1496 \text{ GeV} \\ m_{\tilde{g}} = 1493 \text{ GeV} \\ m_{\tilde{t}_2} = 1321 \text{ GeV} \end{cases}$$

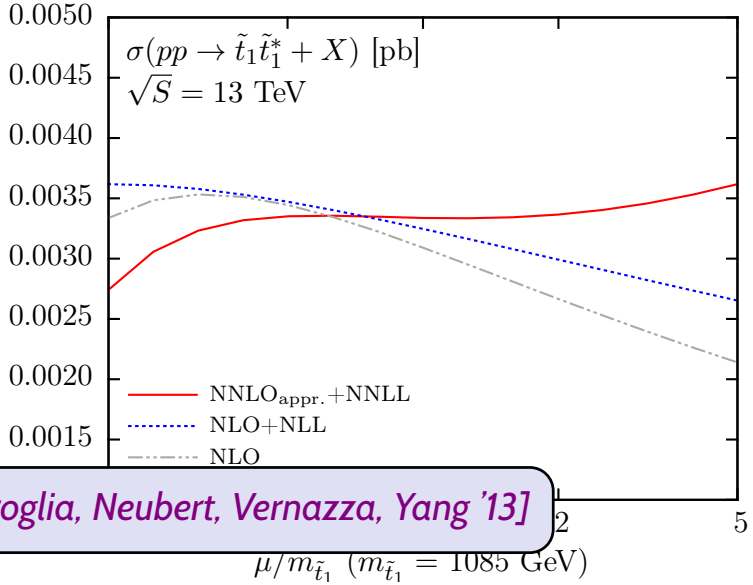
Results: $\tilde{t}_1\tilde{t}_1^*$ production

[Beenakker, CB, Heger, Krämer, Kulesza, Laenen; in preparation]



preliminary





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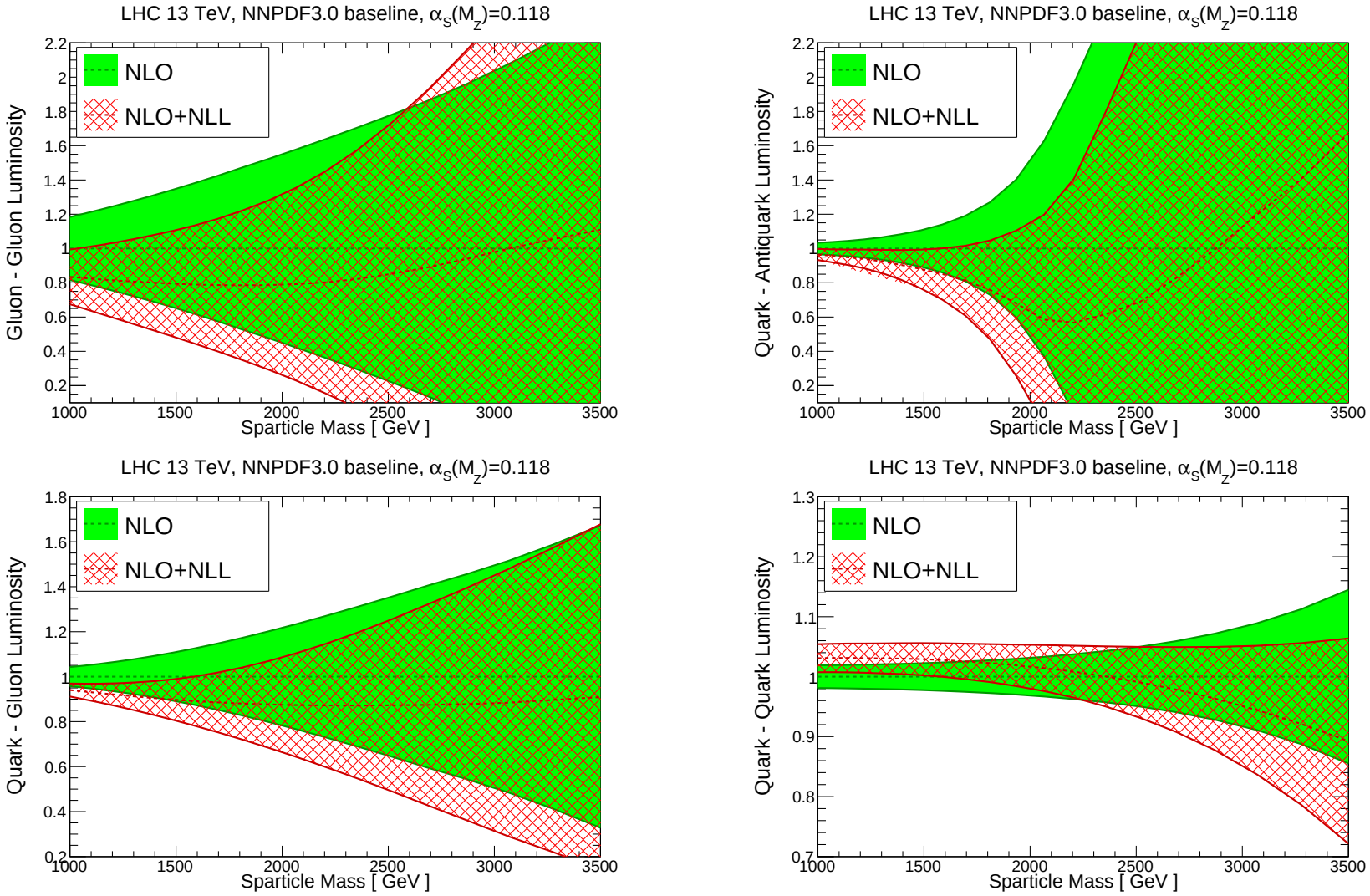
[arXi

Compare to NLO+NNLL SCET results [Broggio, Ferroglia, Neubert, Vernazza, Yang '13]

NNPDF3.0 with resummation: luminosities

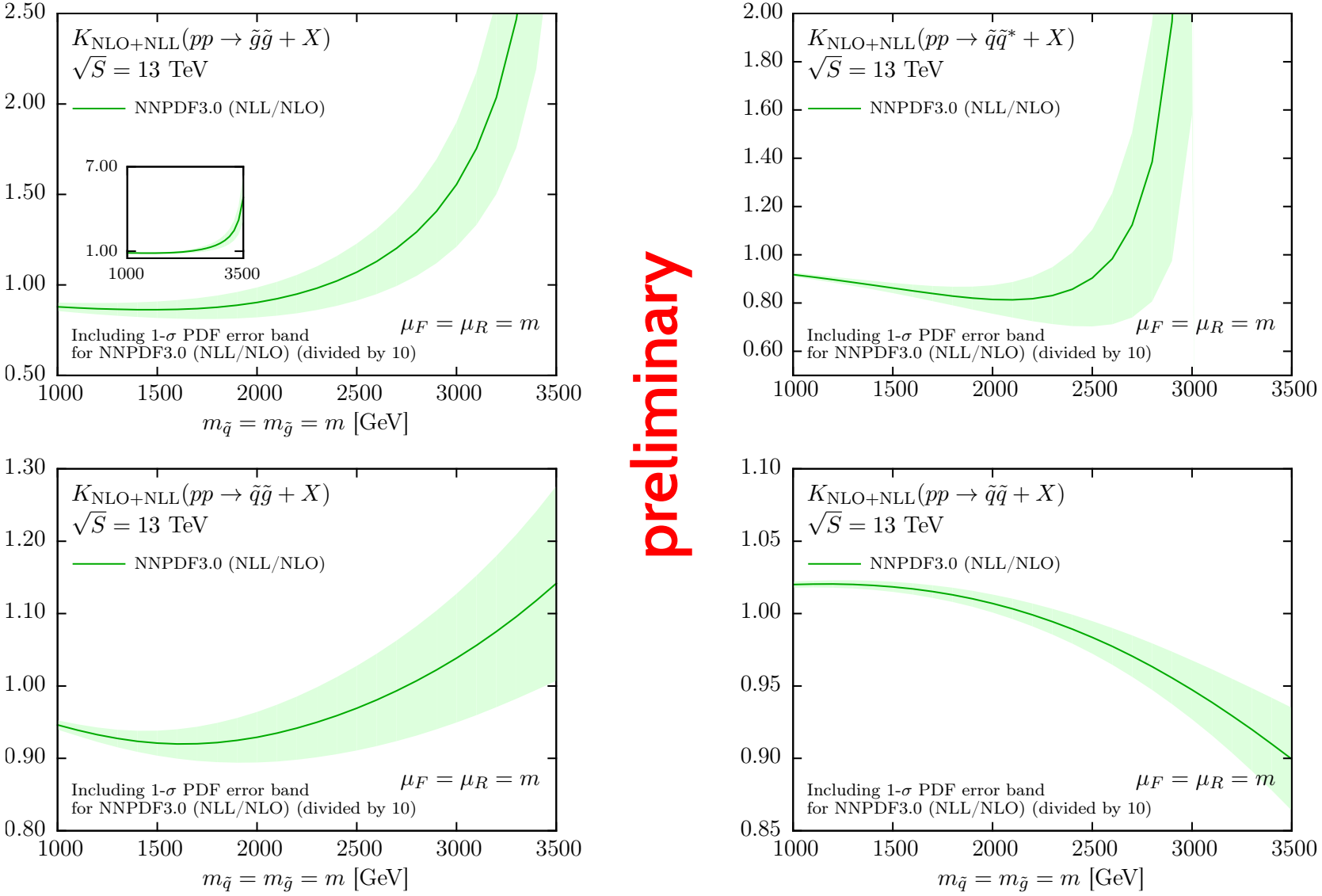
[Bonvini, Marzani, Rojo, Rottoli, Ubiali, Ball, Bertone, Carrazza, Hartland '15]



Baseline fits (reduced data sets compared to global NNPDF3.0 analysis)

NNPDF3.0 with resummation: predictions (1)

[Beenakker, CB, Krämer, Kulesza, Laenen, Marzani, Rojo, Ubiali; in preparation]



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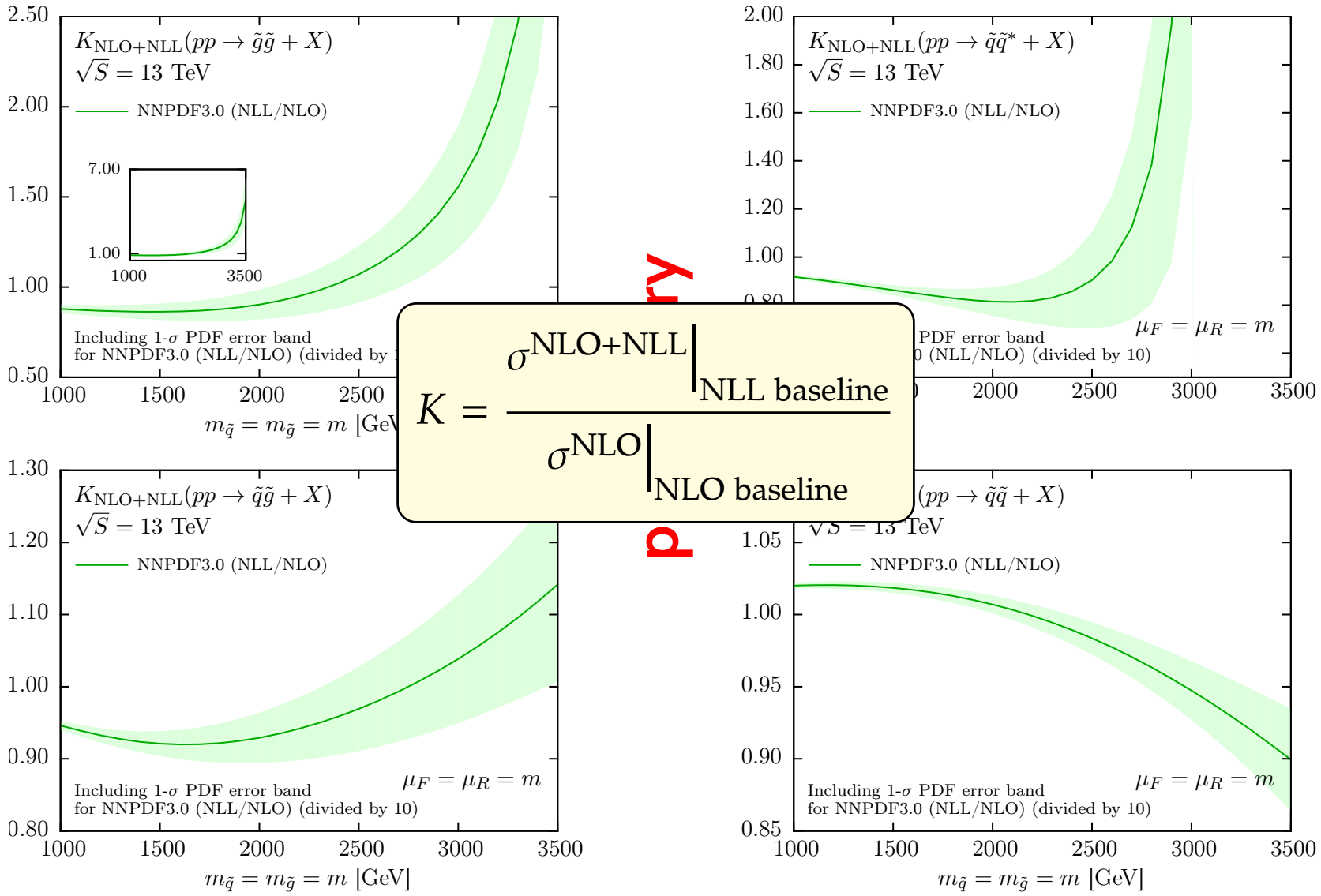
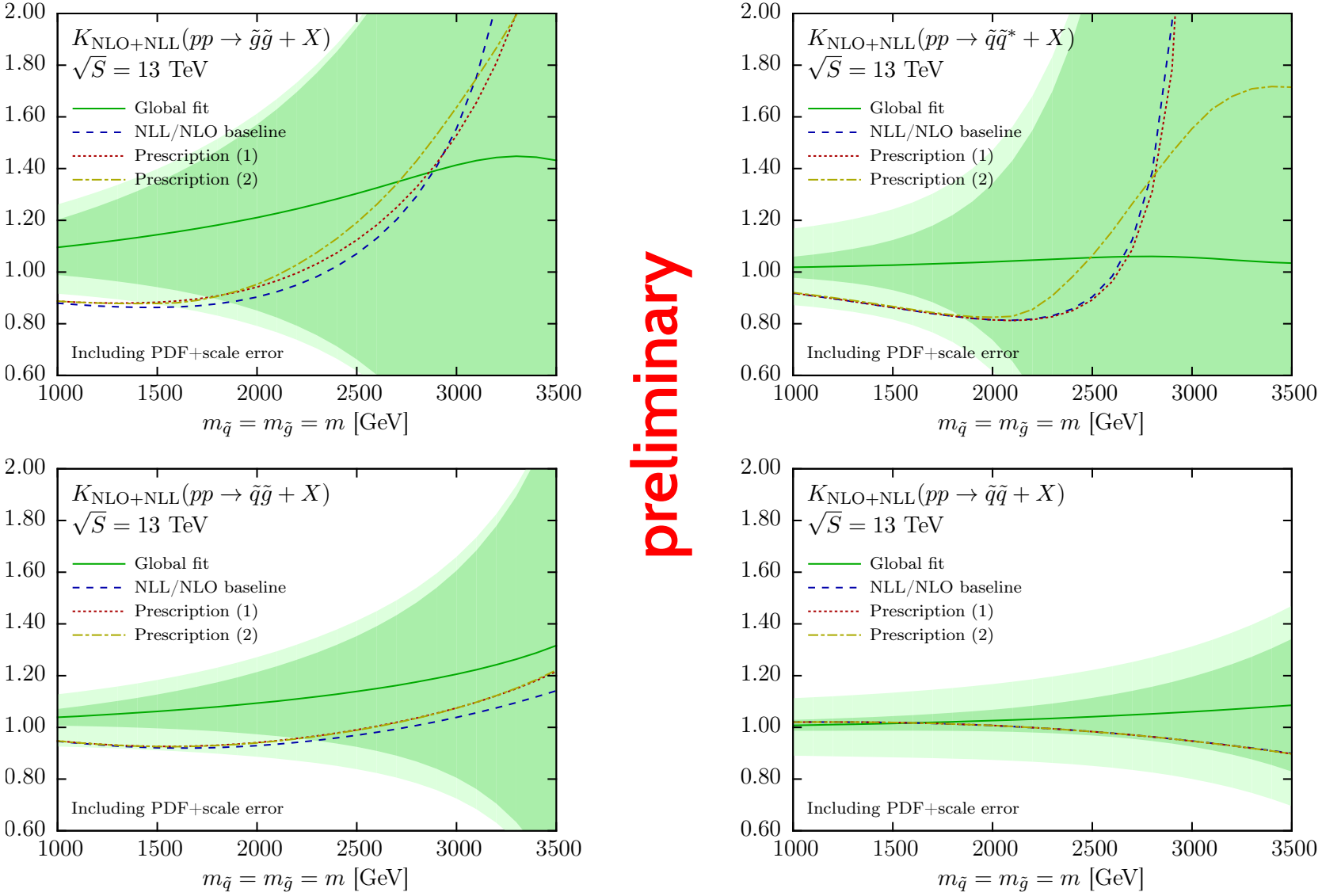


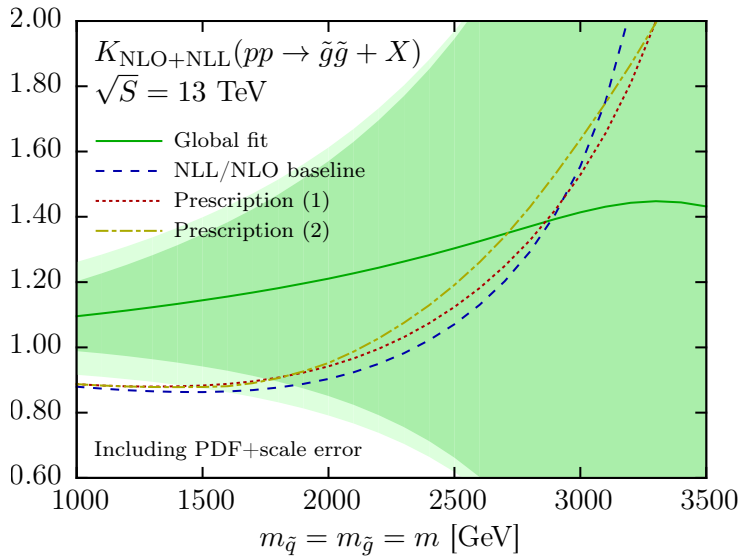
$$K = \frac{\sigma^{\mathrm{NLO+NLL}}\Big|_{\text{NLL baseline}}}{\sigma^{\mathrm{NLO}}\Big|_{\text{NLO baseline}}}$$

NNPDF3.0 with resummation: predictions (2)

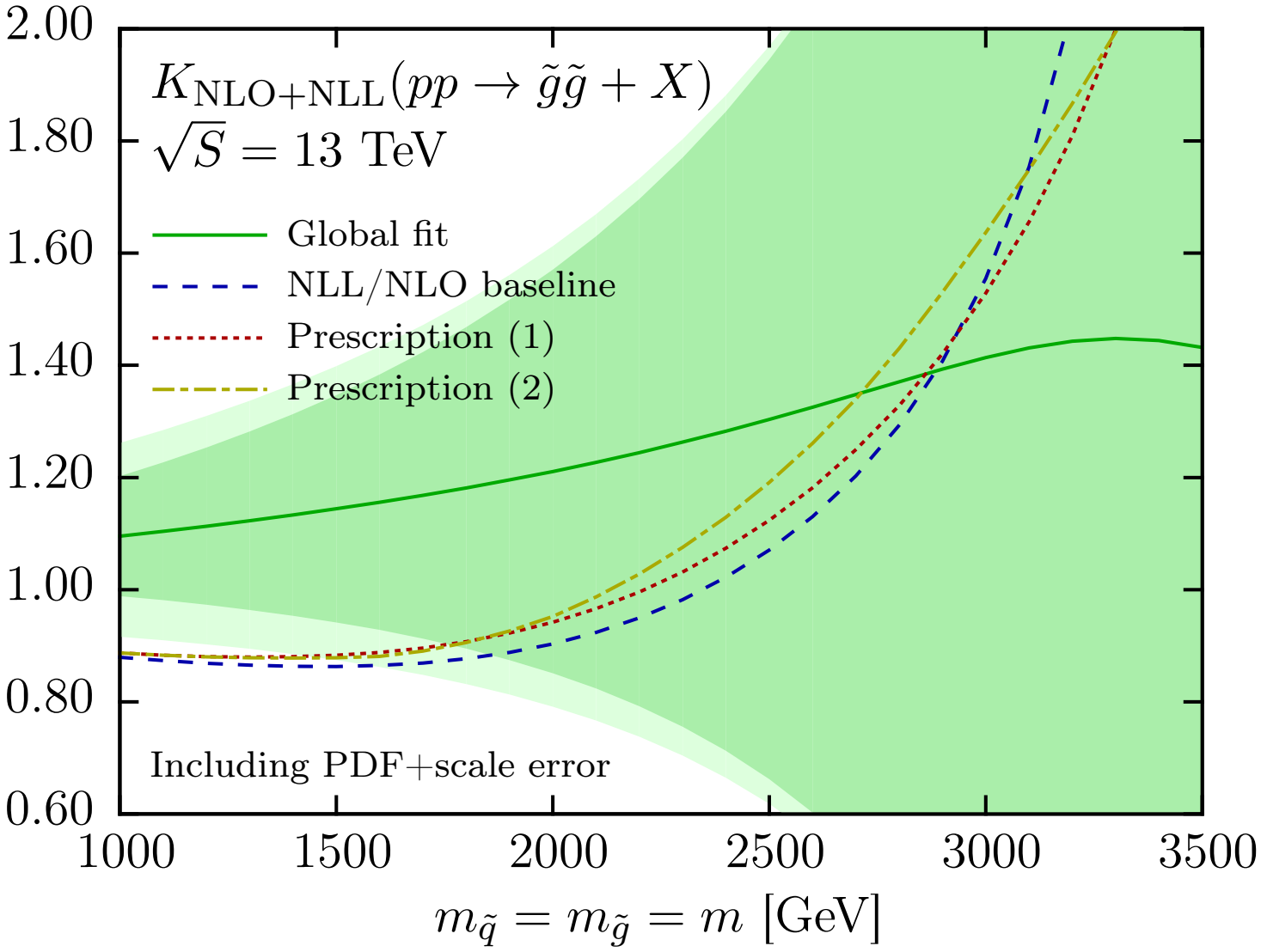
[Beenakker, CB, Krämer, Kulesza, Laenen, Marzani, Rojo, Ubiali; in preparation]



NNPDF3.0 with resummation: predictions (2)



NNPDF3.0 with resummation: predictions (2)



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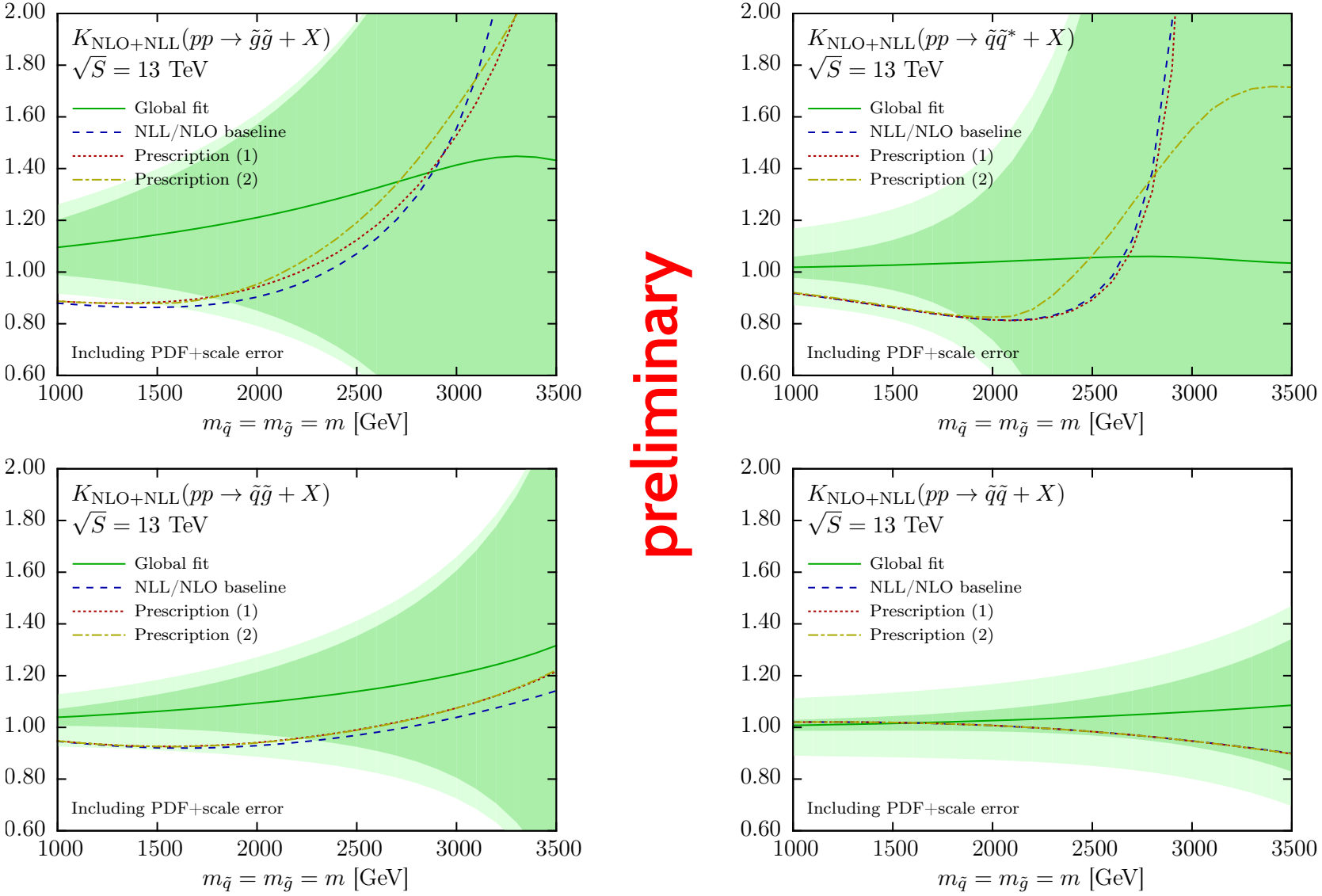

Conclusions and outlook

Conclusions:

- ✓ Corrections from **soft-gluon** and **Coulomb effects** can be sizeable
  → Coulomb contributions mainly covered by two-loop terms
- ✓ $\tilde{q}\tilde{q}$ and $\tilde{q}\tilde{g}$ **largest processes at the LHC** for high $m_{\tilde{q}}$ and $m_{\tilde{g}}$
- ✓ **Enhancement of the K factor** and **improvement of the theoretical uncertainty**
- ✓ $\tilde{t}_1\tilde{t}_1^*$ **dependence on additional SUSY parameters increased** at NNLL level with respect to NLO due to hard-matching coefficients
- ✓ NNPDF3.0 with threshold resummation change both the **quantitative** and **qualitative** behaviour of the cross sections
  → Changes within the PDF uncertainty of global NNPDF3.0

Outlook:

- ✍ Public code: NNLL-fast, update to recent PDF sets
- ✍ Comparison with results from SCET

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