NNLL resummation for squark-antisquark production

Irene Niessen

Radboud University Nijmegen

In collaboration with Wim Beenakker, Silja Brensing, Michael Krämer, Anna Kulesza and Eric Laenen

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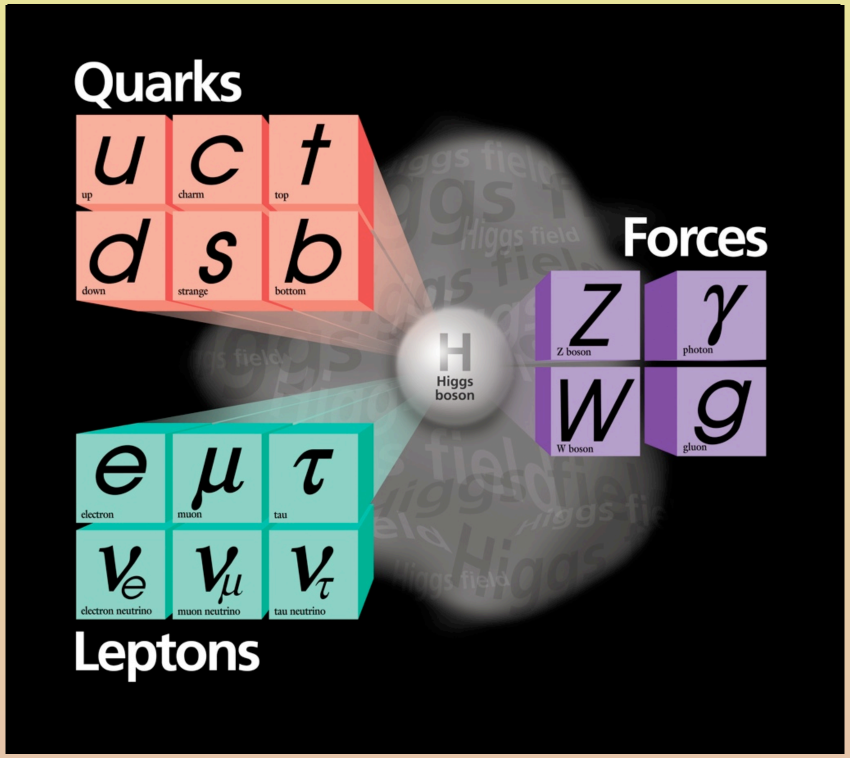
Outline

1. Motivation
2. Resummation
3. Ingredients for NNLL resummation
4. Results

Supersymmetry

- Hierarchy problem
- Gauge coupling unification
- Dark matter



Supersymmetry

- Hierarchy problem
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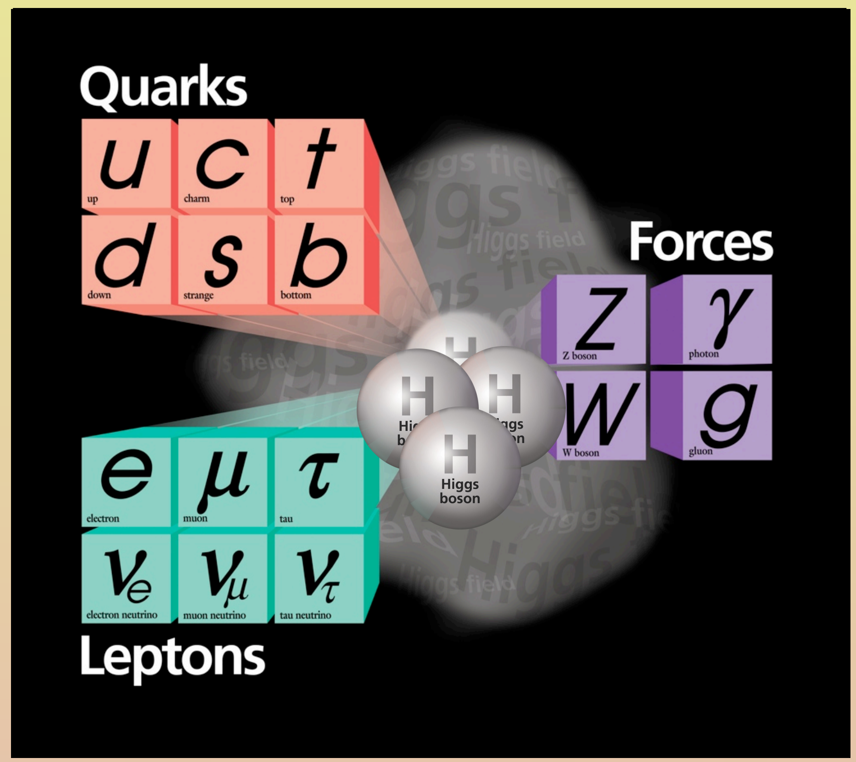
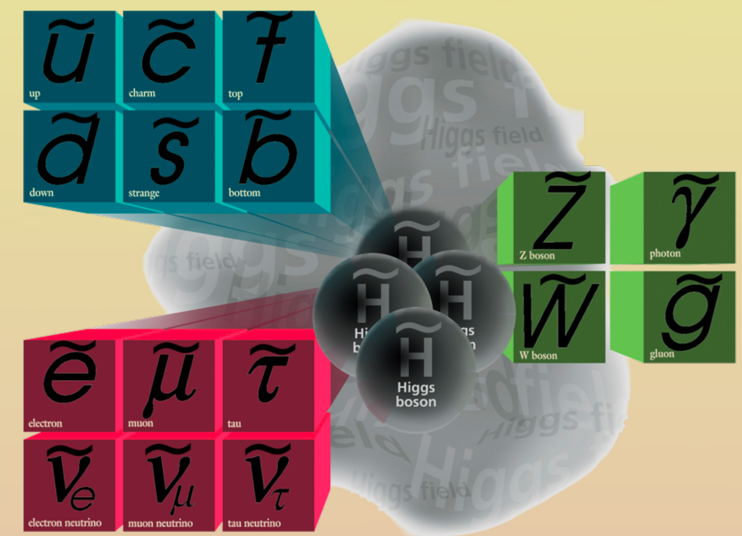
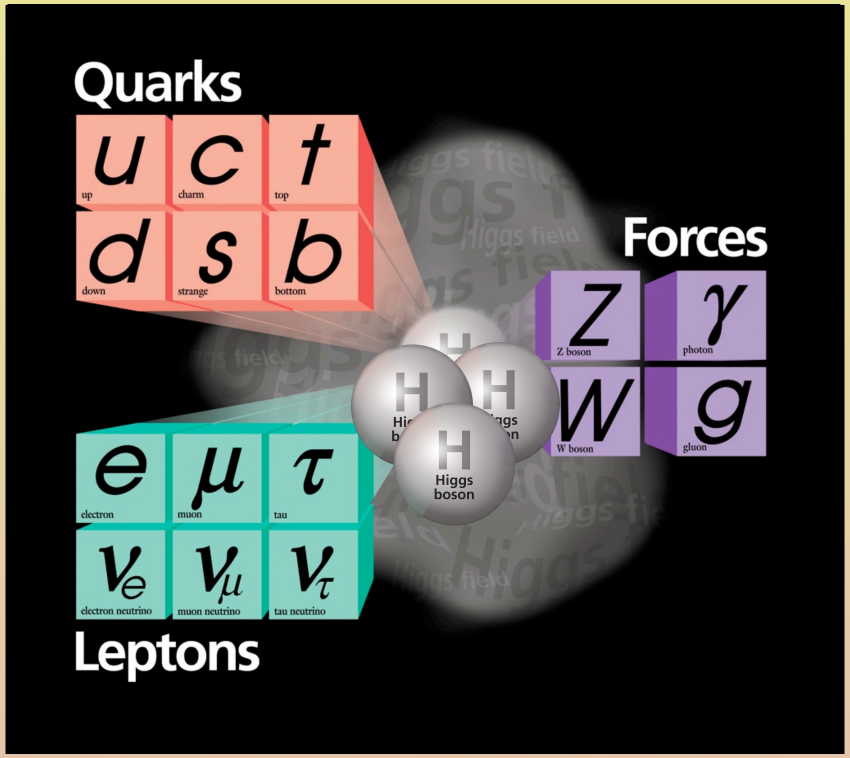
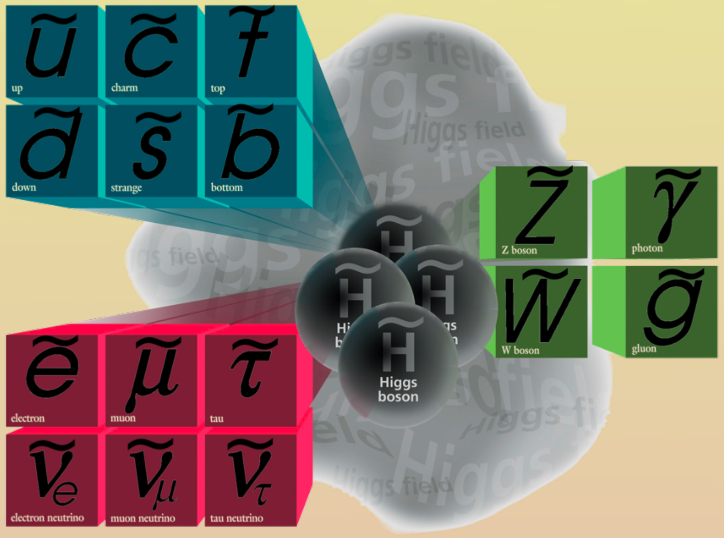




Supersymmetry

✓ Hierarchy problem
✓ Gauge coupling unification
✓ Dark matter





Supersymmetry

- ✓ Hierarchy problem
- ✓ Gauge coupling unification
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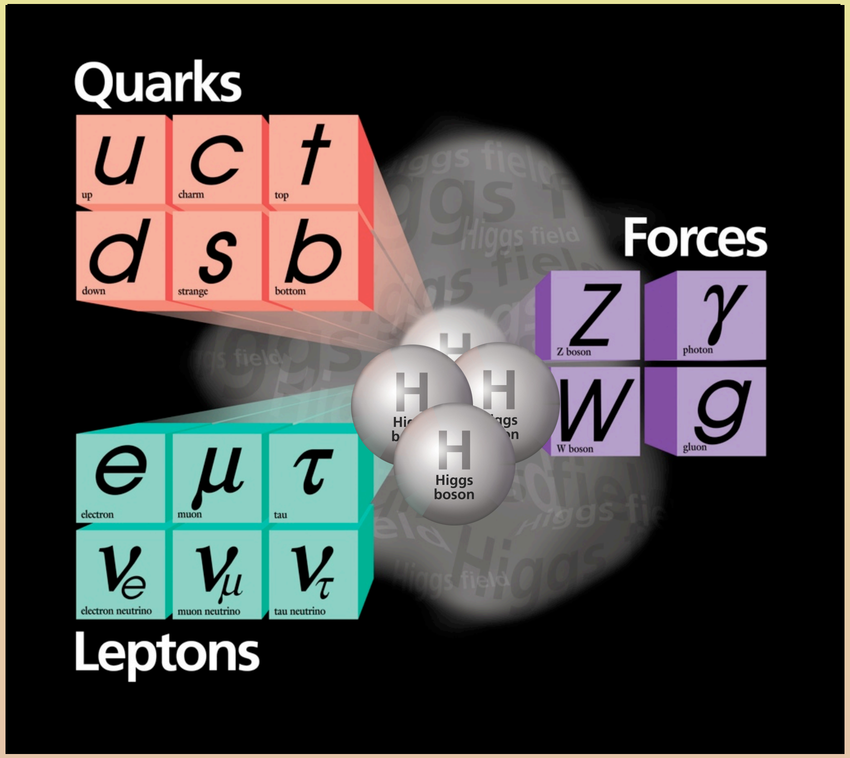
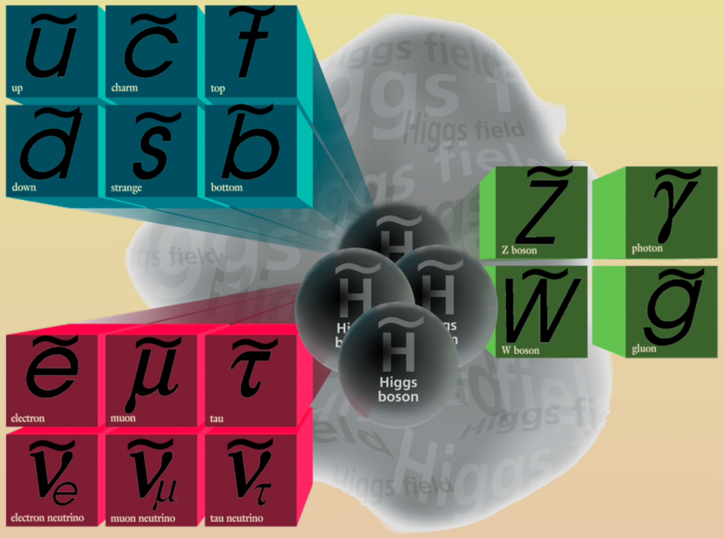
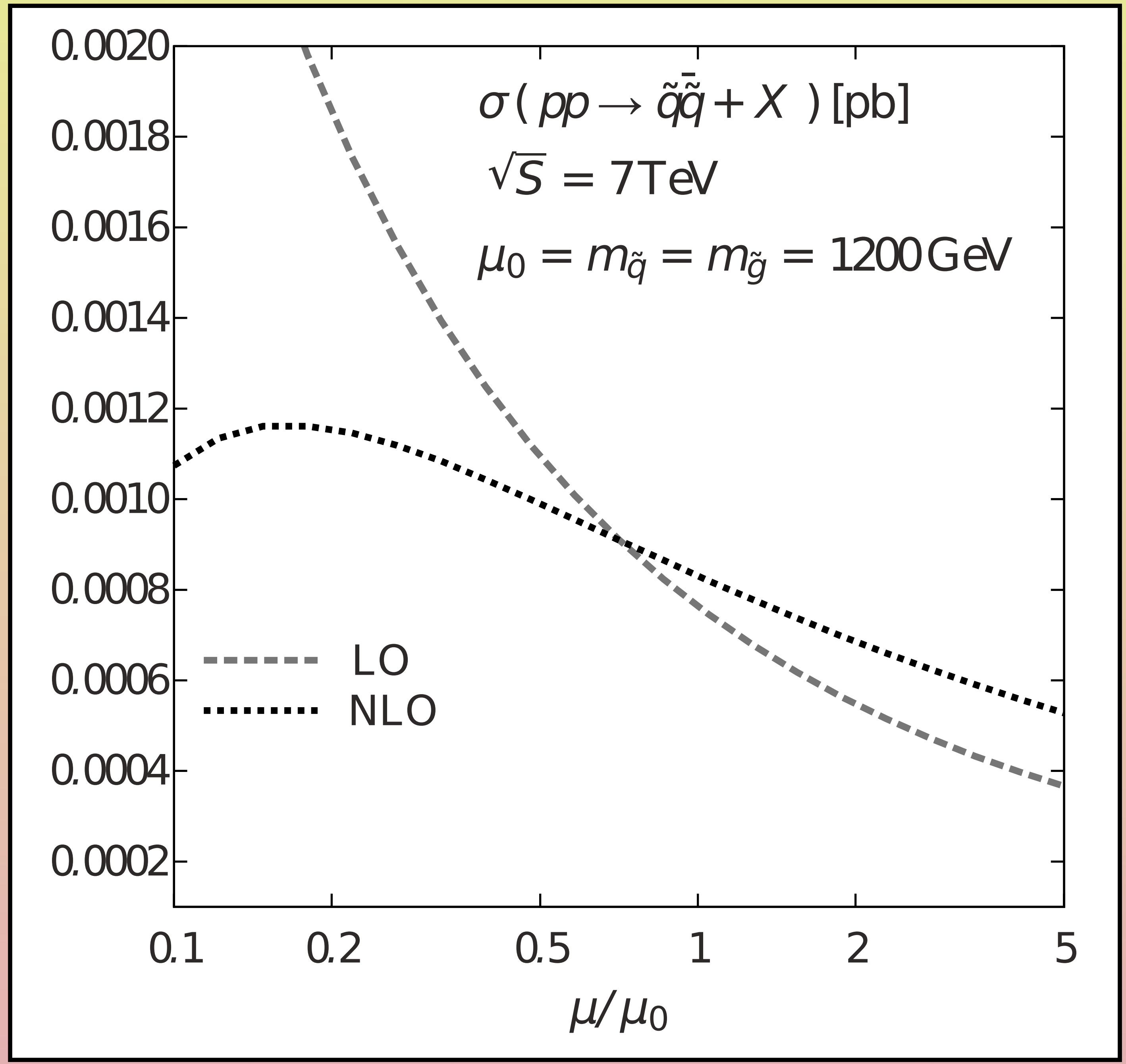


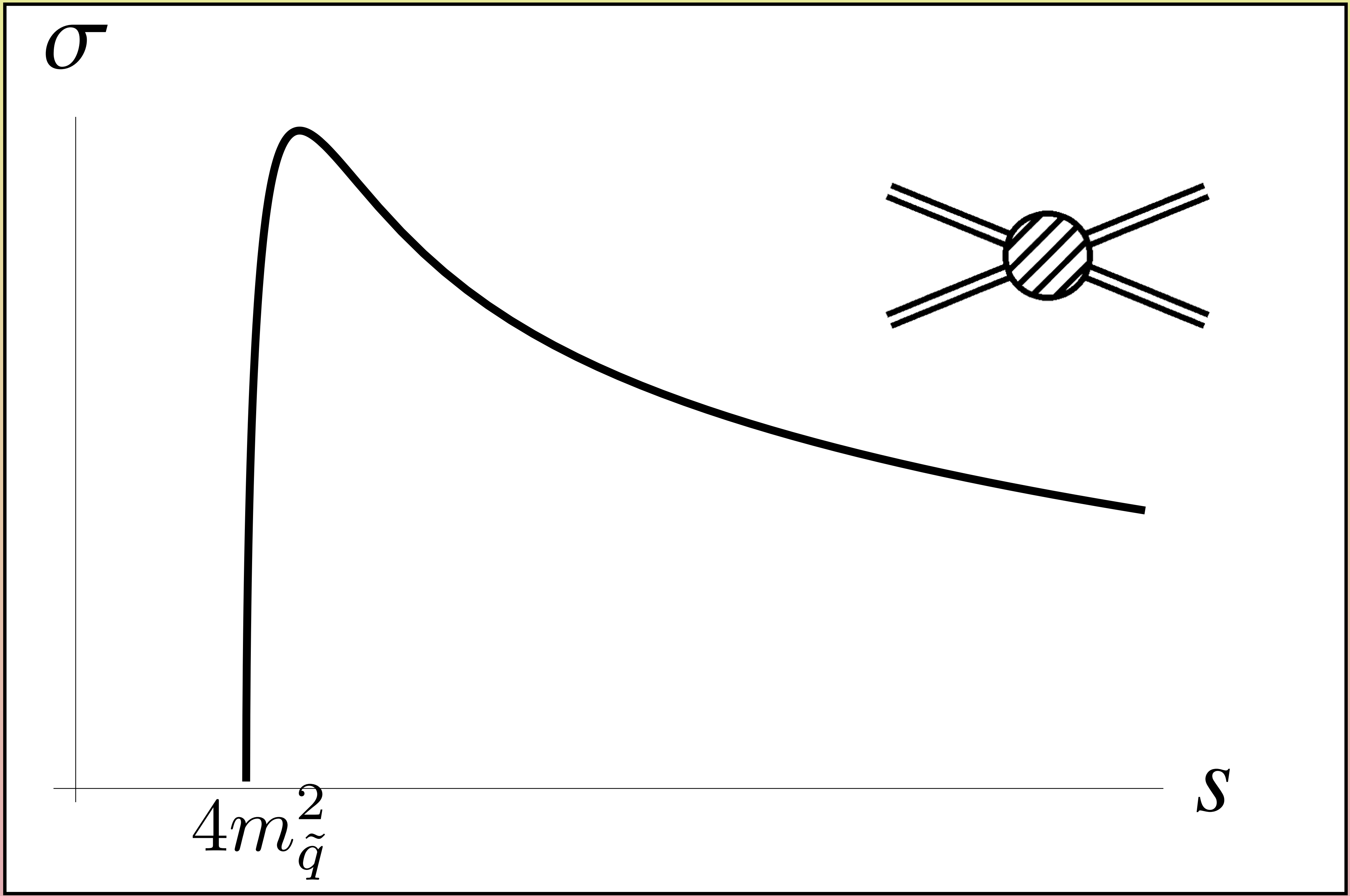


- SUSY particles are heavy
- Squark-antisquark production

Scale dependence



Threshold



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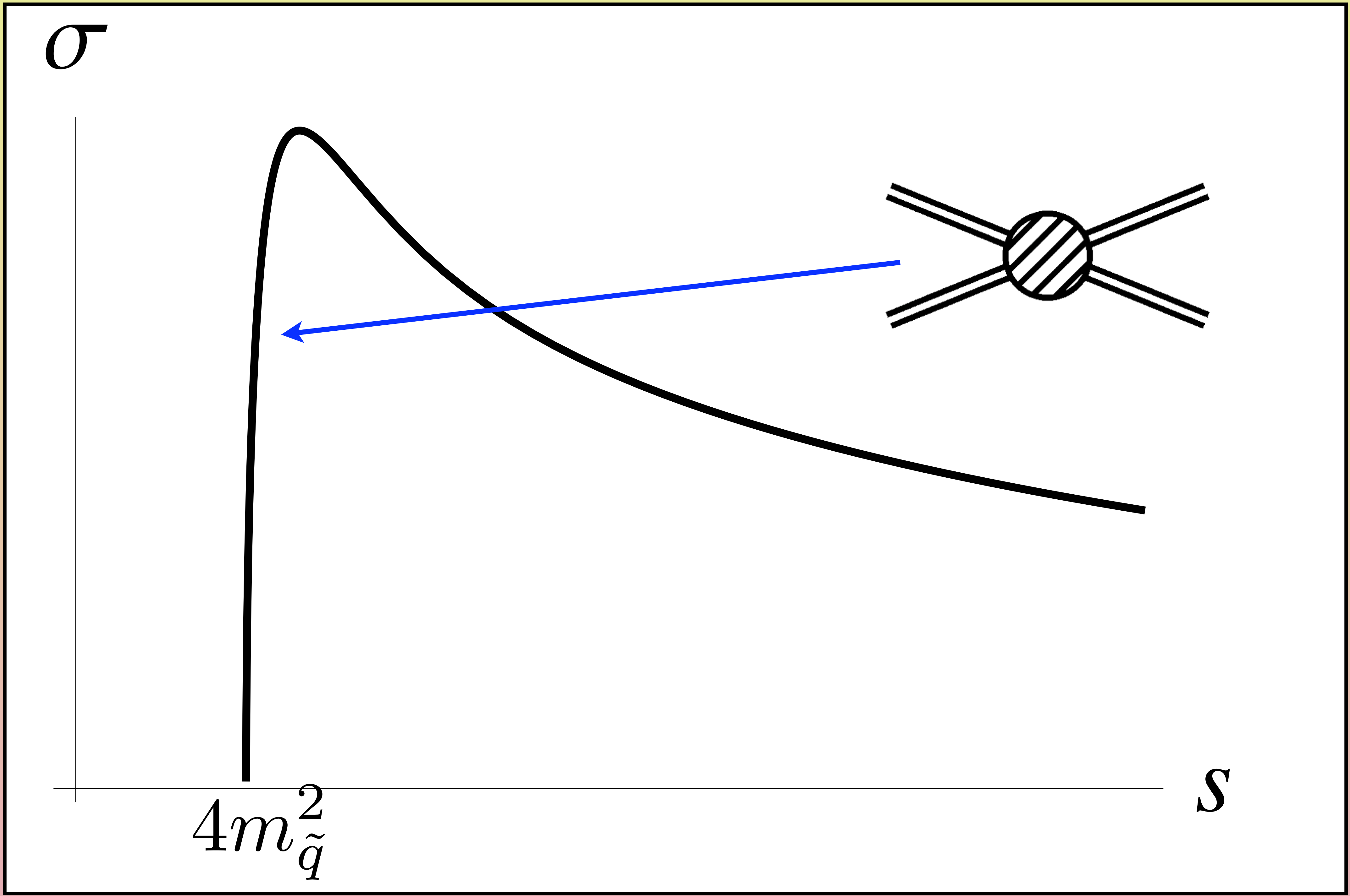

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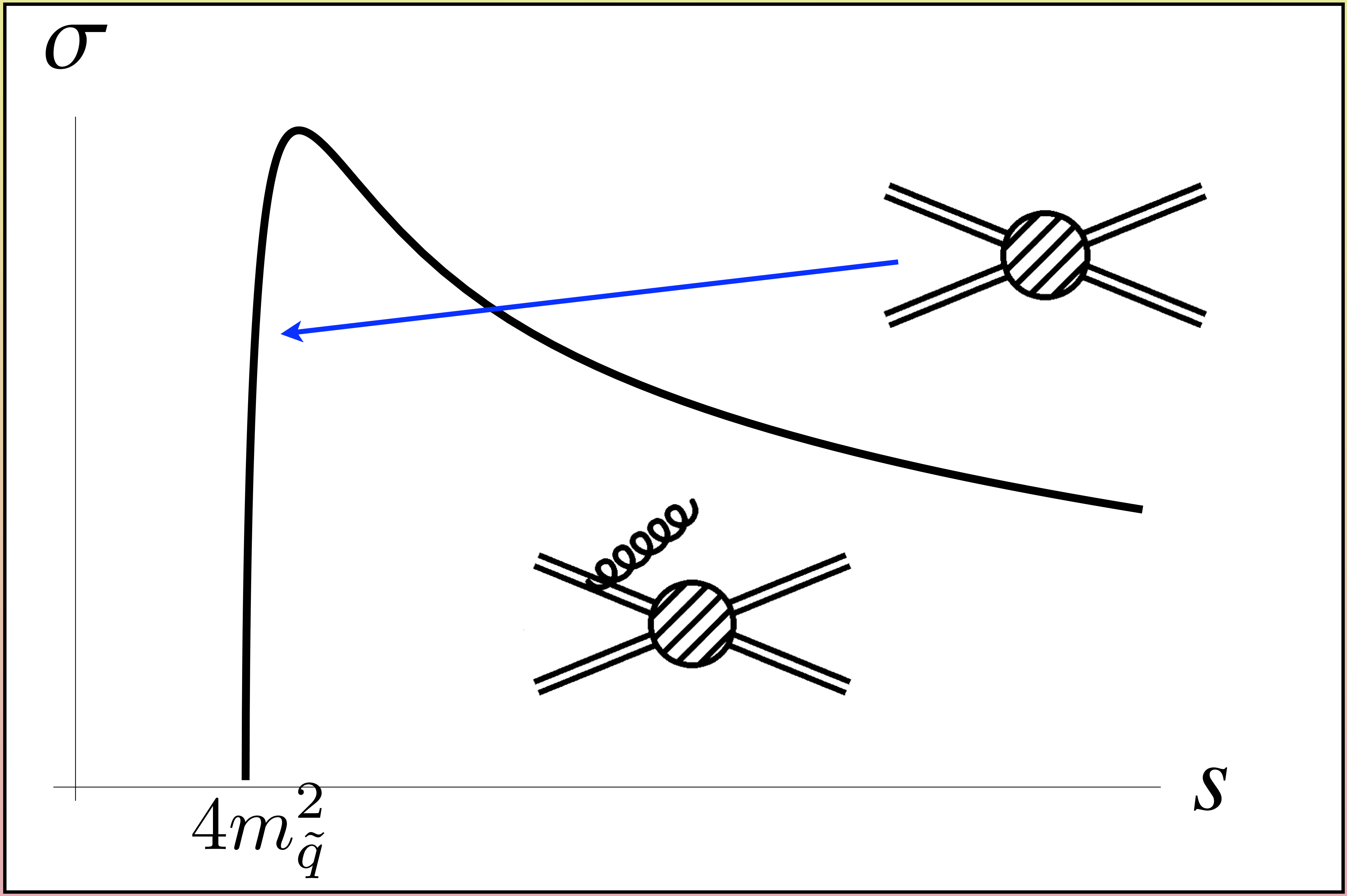

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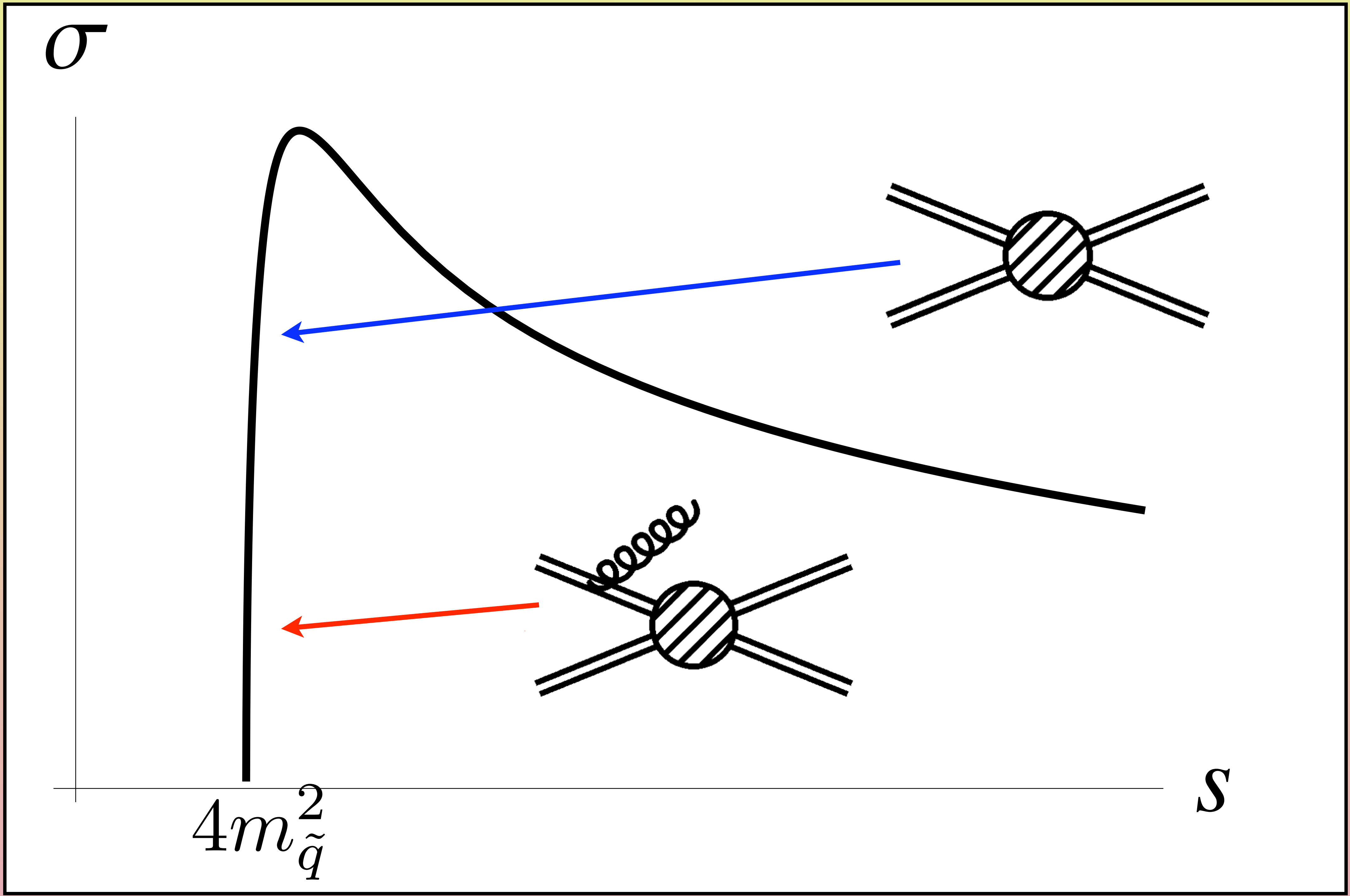

Resummation

LO	1						
NLO	$\alpha_s L^2$	$\alpha_s L$	α_s				
$NNLO$	$\alpha_s^2 L^4$	$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	α_s^2		
N^3LO	$\alpha_s^3 L^6$	$\alpha_s^3 L^5$	$\alpha_s^3 L^4$	$\alpha_s^3 L^3$	$\alpha_s^3 L^2$	$\alpha_s^3 L$	α_s^3
N^4LO	$\cdots$						

$$L = \log(8\beta^2) \qquad \beta = \sqrt{1-\rho} \qquad \rho = \frac{4m_{\tilde{q}}^2}{\hat{s}}$$

Resummation

$$\begin{array}{llllllll}
LO & 1 & & & & & & \\
NLO & \alpha_s L^2 & \alpha_s L & \alpha_s & & & & \\
NNLO & \alpha_s^2 L^4 & \alpha_s^2 L^3 & \alpha_s^2 L^2 & \alpha_s^2 L & \alpha_s^2 & & \\
N^3LO & \alpha_s^3 L^6 & \alpha_s^3 L^5 & \alpha_s^3 L^4 & \alpha_s^3 L^3 & \alpha_s^3 L^2 & \alpha_s^3 L & \alpha_s^3 \\
N^4LO & \cdots & & & & & &
\end{array}$$

$$\tilde{f}(N) = \int_0^1 d\rho \rho^{N-1} f(\rho)$$

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$$\tilde{f}(N) = \int_0^1 d\rho \rho^{N-1} f(\rho) \qquad L \to \log(N)$$

$$\tilde{\sigma}^{\mathrm{resum}} = \tilde{\sigma}^{\mathrm{thr}} e^{L P_1(\alpha_s L)} e^{P_2(\alpha_s L)} e^{\alpha_s P_3(\alpha_s L)}$$

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\begin{array}{llllllll}
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NNLL Resummation

$$\tilde{\sigma}^{(\mathrm{res})}_{ij\to\tilde{q}\bar{\tilde{q}}}\big(N,\{m^2\},\mu^2\big) = \sum_I \tilde{\sigma}^{(0)}_{ij\to\tilde{q}\bar{\tilde{q}},I}\big(N,\{m^2\},\mu^2\big)\, C_{ij\to\tilde{q}\bar{\tilde{q}},I}(N,\{m^2\},\mu^2)$$
$$\times\,\Delta_i(N+1,Q^2,\mu^2)\,\Delta_j(N+1,Q^2,\mu^2)\,\Delta^{(\mathrm{s})}_{ij\to\tilde{q}\bar{\tilde{q}},I}\big(Q/(N\mu),\mu^2\big)$$

NNLL Resummation

LO cross section

$$\tilde{\sigma}^{(\mathrm{res})}_{ij\to\tilde{q}\bar{\tilde{q}}}(N,\{m^2\},\mu^2) = \sum_I \boxed{\tilde{\sigma}^{(0)}_{ij\to\tilde{q}\bar{\tilde{q}},I}(N,\{m^2\},\mu^2)}\, C_{ij\to\tilde{q}\bar{\tilde{q}},I}(N,\{m^2\},\mu^2)$$
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NNLL Resummation

LO cross section

NLO matching coefficient

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NNLL Resummation

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Jet functions

NNLL Resummation

LO cross section

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Jet functions

Soft function

NNLL Resummation

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NLO matching coefficient

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Jet functions

Colour sum

Soft function

NNLL Resummation

LO cross section

NLO matching coefficient

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Jet functions

Colour sum

Soft function

$$C^{\mathrm{NNLL}} = \left(1+\frac{\alpha_{\mathrm{s}}}{\pi}\,\mathcal{C}^{\mathrm{Coul},(1)}(N,\{m^2\},\mu^2)\right)\left(1+\frac{\alpha_{\mathrm{s}}}{\pi}\,\mathcal{C}^{(1)}(\{m^2\},\mu^2)\right)$$

Hard Matching Coefficients

$$\sigma_{LO}^{\text{thr}} \sim \beta$$

$$\sigma_{NLO}^{\text{thr}} = \sigma_{\log^2(8\beta^2)} + \sigma_{\log(8\beta^2)} + \sigma_{\text{Coulomb}} + \sigma_{\text{fin}}$$

Hard Matching Coefficients

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- log(N) in exponential
- finite terms from Mellin transform in σ_{fin}

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- Coulombic $1/\beta$ enhancement
- cancels phase space suppression

- log(N) in exponential
- finite terms from Mellin transform in σ_{fin}

Hard Matching Coefficients

$$\sigma^{\text{thr}}_{LO} \sim \beta$$

$$\sigma^{\text{thr}}_{NLO} = \boxed{\sigma_{\log^2(8\beta^2)} + \sigma_{\log(8\beta^2)}} + \boxed{\sigma_{\text{Coulomb}}} + \boxed{\sigma_{\text{fin}}}$$

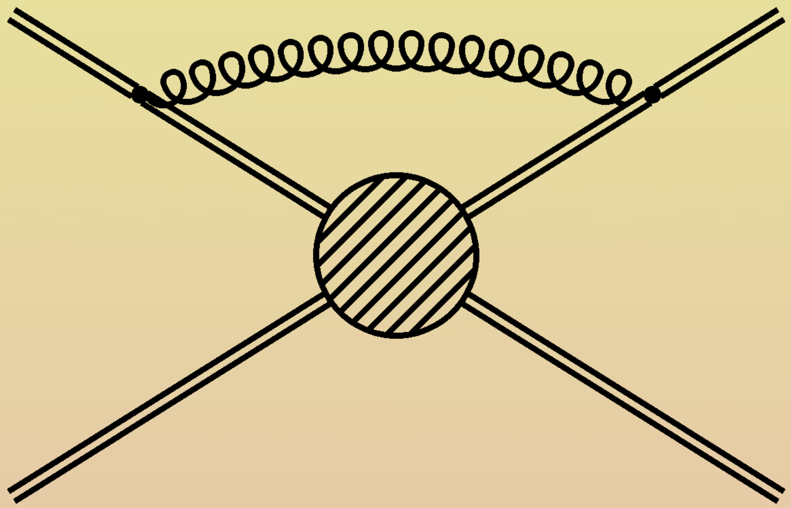
- Coulombic $1/\beta$ enhancement
- cancels phase space suppression

- log(N) in exponential
- finite terms from Mellin transform in σ_{fin}

- rest of the cross section
- linear term in β

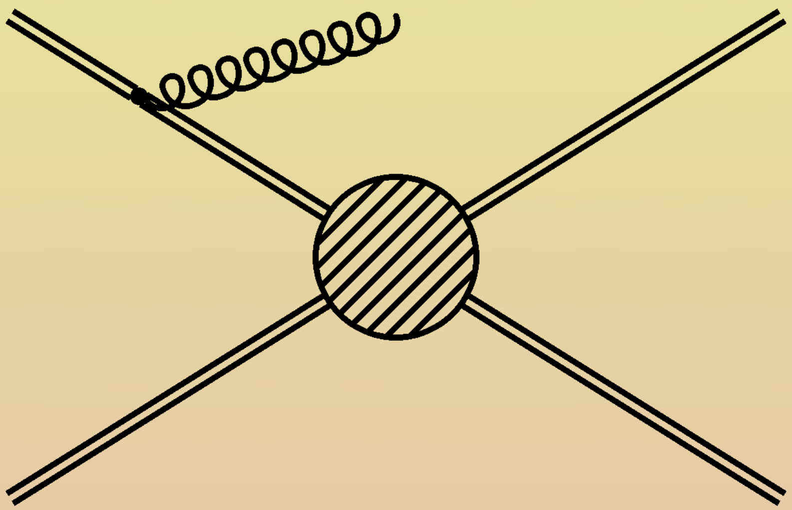
NLO calculation

Virtual



Coulomb terms
Finite terms

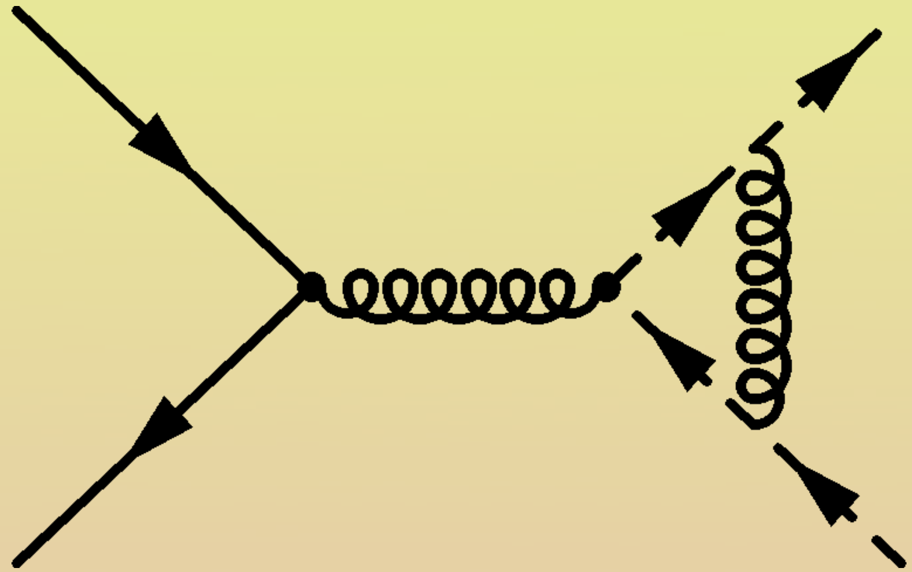
Real



Logarithmic terms
Finite terms

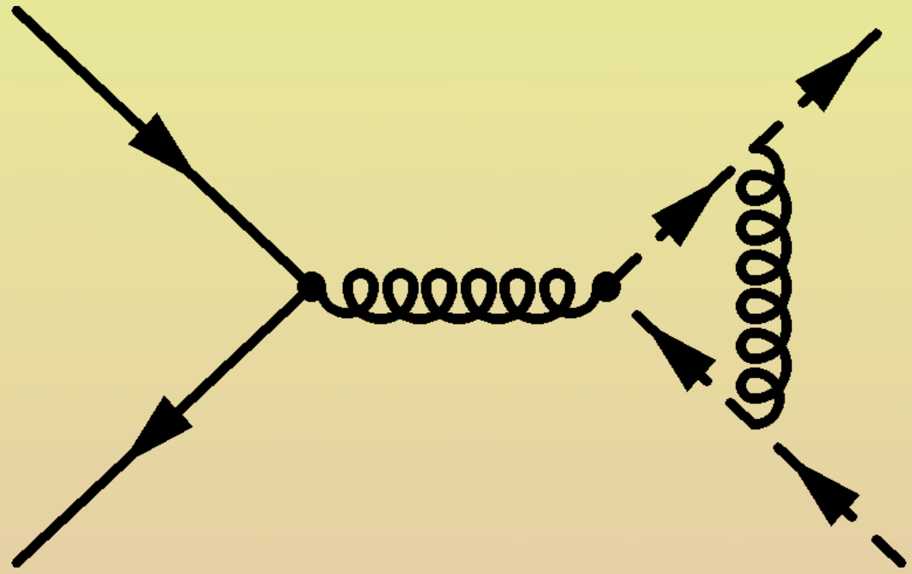
Calculate up to $O(\beta)$

Virtual: Coulomb



$$\propto \frac{1}{\beta} f(\beta)$$

Virtual: Coulomb



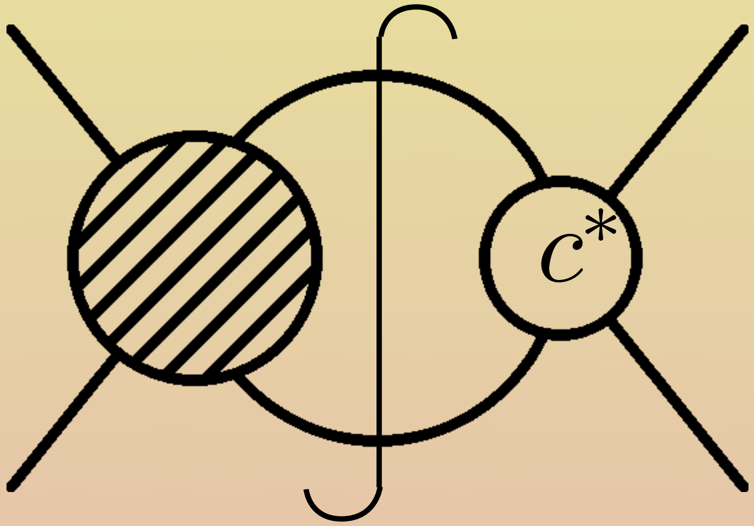
$$\propto \frac{1}{\beta} f(\beta)$$

$$\sigma^{\mathrm{Coul},(1)}_{ij\to\tilde{q}\bar{\tilde{q}},I} = -\frac{\alpha_{\mathrm{s}}}{\pi}\,\frac{\pi^2}{2\beta}\kappa_{ij\to\tilde{q}\bar{\tilde{q}},I}\,\sigma^{(0)}_{ij\to\tilde{q}\bar{\tilde{q}},I}$$

$$\kappa_{\mathbf{1}} = -\frac{4}{3} \qquad \kappa_{\mathbf{8}} = \frac{1}{6}$$

Virtual corrections

Colour decomposition: only LO



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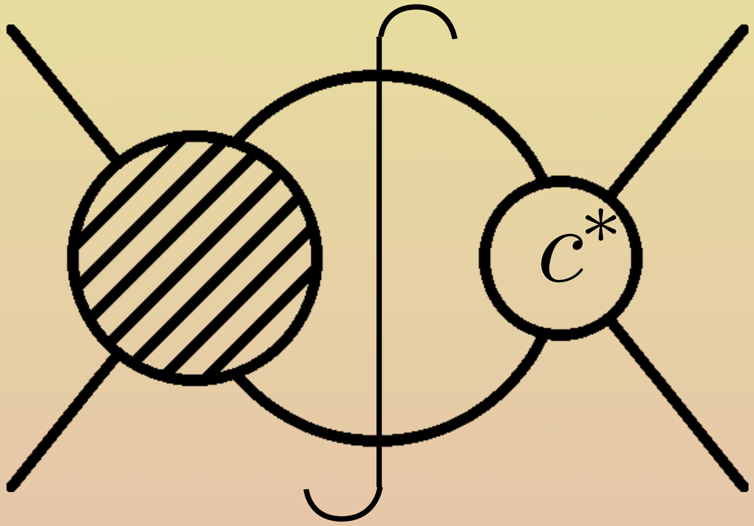

Linear term in β:

- Most scalar integrals: $\beta = 0$
- Coulomb integrals: expand in β

Real Corrections

$$\sigma_{NLO} = \sigma^R + \sigma^V + \sigma^C$$

Real Corrections

$$\sigma_{NLO} = \sigma^R + \sigma^V + \sigma^C$$
$$= \int_3 \left[\mathrm{d}\sigma^{\mathrm{R}} - \mathrm{d}\sigma^{\mathrm{A}}\right]_{\epsilon=0} + \int_2 \left[\mathrm{d}\sigma^{\mathrm{V}} + \int_1 \mathrm{d}\sigma^{\mathrm{A}}\right]_{\epsilon=0} + \sigma^{\mathrm{C}}$$

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Real Corrections

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For a finite function:

$$\int_{1-\beta^2}^{1} f(x)dx \propto \beta^2$$

Real Corrections

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$$E_{g,max} = m_{av}\beta^2$$

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Real Corrections

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Real Corrections

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$$= \cancel{\sigma^{\{3\}}} + \sigma^{\{2\}} + \sigma^C = \boxed{\sigma^V + \sigma^A + \sigma^C}$$

$$E_{g,max} = m_{av}\beta^2$$

For a finite function:

$$\int_{1-\beta^2}^{1} f(x)dx \propto \beta^2$$

Result for $\mathrm{gg} \rightarrow \tilde{\mathrm{q}}\bar{\tilde{\mathrm{q}}}$

$$\mathcal{C}^{(1)}_{gg\to\tilde{q}\bar{\tilde{q}},I} = \mathrm{Re}\Bigg\{\pi^2\left(\frac{5N_c}{12} - \frac{C_F}{4}\right) + \gamma_g \log\left(\frac{\mu_R^2}{\mu_F^2}\right)$$

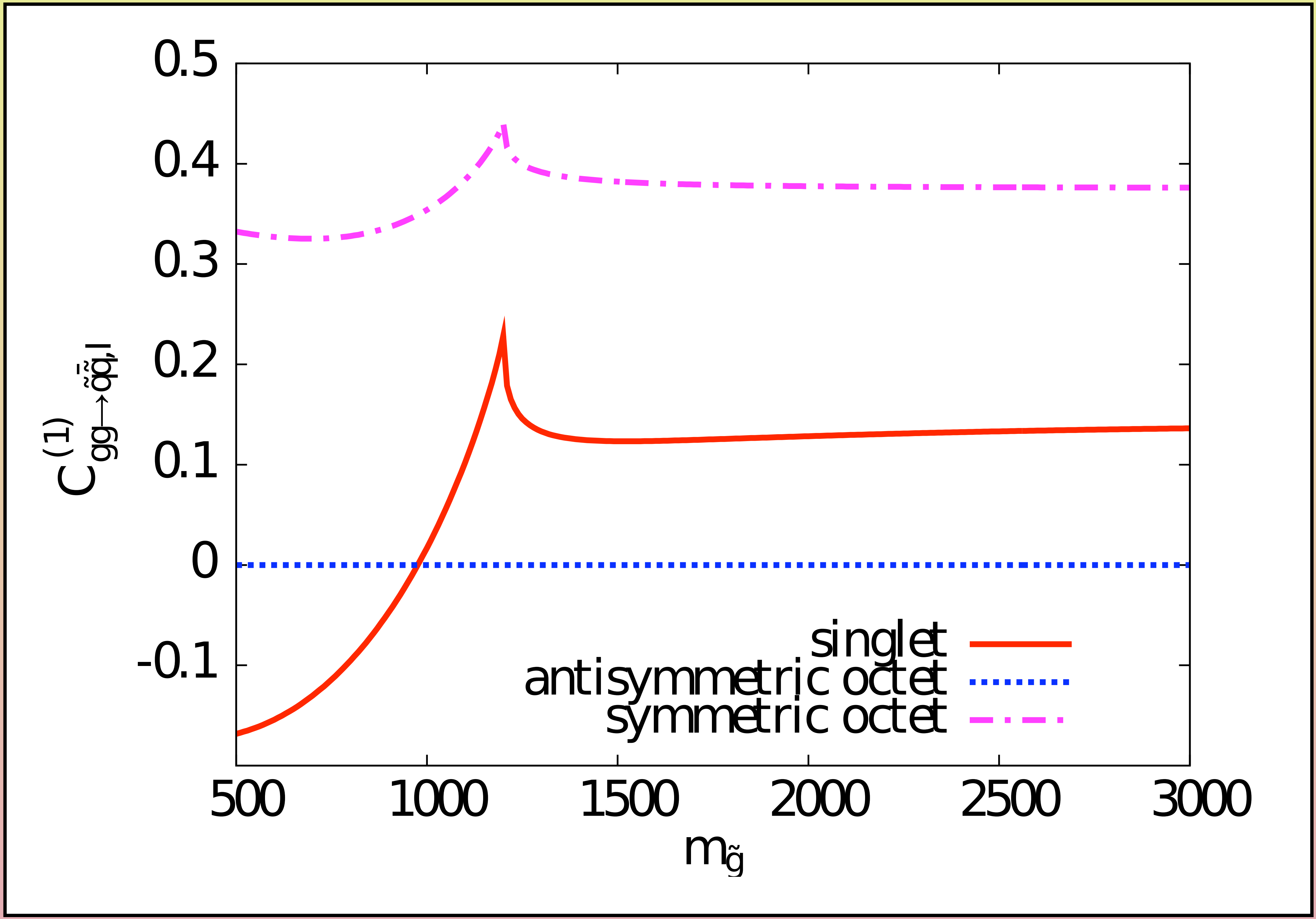
$$- \frac{m_{\tilde{g}}^2 N_c}{2m_{\tilde{q}}^2}\log^2\left(x_{\tilde{g}\tilde{g}}(4m_{\tilde{q}}^2)\right) + C_F\left(\frac{m_+^2 m_-^2}{2m_{\tilde{q}}^4}\log\left(\frac{m_+^2}{m_-^2}\right) - \frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2} - 3\right)$$

$$+ \frac{m_+^2 N_c}{2m_{\tilde{q}}^2}\left(\mathrm{Li}_2\left(-\frac{m_{\tilde{q}}^2}{m_{\tilde{g}}^2}\right) - \mathrm{Li}_2\left(\frac{m_{\tilde{q}}^2}{m_{\tilde{g}}^2}\right)\right)$$

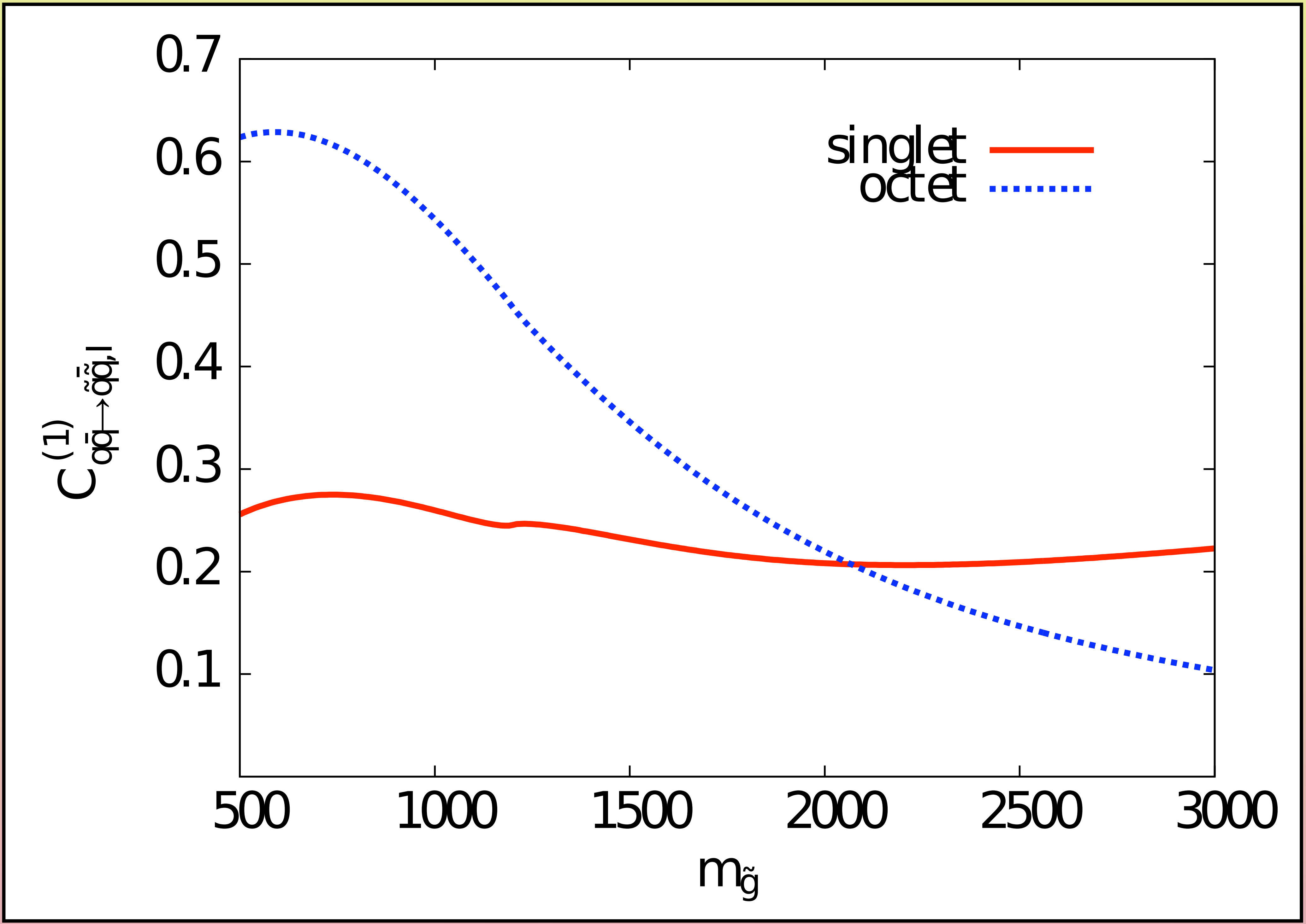
$$+ \left[\frac{\pi^2}{8} - \frac{1}{2}\mathrm{Li}_2\left(-\frac{m_{\tilde{q}}^2}{m_{\tilde{g}}^2}\right) + \frac{1}{2}\mathrm{Li}_2\left(\frac{m_{\tilde{q}}^2}{m_{\tilde{g}}^2}\right) + \frac{m_{\tilde{g}}^2}{4m_{\tilde{q}}^2}\log^2\left(x_{\tilde{g}\tilde{g}}(4m_{\tilde{q}}^2)\right)\right]C_2(I)$$

$$+ 2C_A\left(\gamma_E^2 - 2\gamma_E\log(2) + \gamma_E\log\left(\frac{\mu_F^2}{m_{\tilde{q}}^2}\right)\right) + (2+\gamma_E)\,C_2(I)\Bigg\}$$

$gg \to \tilde{q}\bar{\tilde{q}}$



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



Matching to NLO

$$\sigma^{(\mathrm{NNLL+NLO\ matched})}_{h_1 h_2 \to \tilde{q}\bar{\tilde{q}}}\big(\rho, \{m^2\}, \mu^2\big) = \sigma^{(\mathrm{NLO})}_{h_1 h_2 \to \tilde{q}\bar{\tilde{q}}}\big(\rho, \{m^2\}, \mu^2\big)$$

$$+ \sum_{i,j} \int_{\mathrm{CT}} \frac{dN}{2\pi i}\, \rho^{-N}\, \tilde{f}_{i/h_1}(N+1, \mu^2)\, \tilde{f}_{j/h_2}(N+1, \mu^2)$$

$$\times \left[\tilde{\sigma}^{(\mathrm{res,NNLL})}_{ij \to \tilde{q}\bar{\tilde{q}}}\big(N, \{m^2\}, \mu^2\big) - \tilde{\sigma}^{(\mathrm{res,NNLL})}_{ij \to \tilde{q}\bar{\tilde{q}}}\big(N, \{m^2\}, \mu^2\big)\big|_{(\mathrm{NLO})}\right]$$

Matching to NLO

$$\sigma^{(\mathrm{NNLL+NLO\ \ matched})}_{h_1 h_2 \to \tilde{q}\bar{\tilde{q}}}\big(\rho, \{m^2\}, \mu^2\big) = \boxed{\sigma^{(\mathrm{NLO})}_{h_1 h_2 \to \tilde{q}\bar{\tilde{q}}}\big(\rho, \{m^2\}, \mu^2\big)}$$

$$+ \sum_{i,j} \int_{\mathrm{CT}} \frac{dN}{2\pi i}\, \rho^{-N}\, \tilde{f}_{i/h_1}(N+1, \mu^2)\, \tilde{f}_{j/h_2}(N+1, \mu^2)$$

$$\times \left[\tilde{\sigma}^{(\mathrm{res,NNLL})}_{ij \to \tilde{q}\bar{\tilde{q}}}\big(N, \{m^2\}, \mu^2\big) - \tilde{\sigma}^{(\mathrm{res,NNLL})}_{ij \to \tilde{q}\bar{\tilde{q}}}\big(N, \{m^2\}, \mu^2\big)\,\big|_{(\mathrm{NLO})}\right]$$

Matching to NLO

$$
\begin{aligned}
\sigma^{(\mathrm{NNLL+NLO\ matched})}_{h_1 h_2 \to \tilde{q}\bar{\tilde{q}}}\left(\rho, \{m^2\}, \mu^2\right) &= \boxed{\sigma^{(\mathrm{NLO})}_{h_1 h_2 \to \tilde{q}\bar{\tilde{q}}}\left(\rho, \{m^2\}, \mu^2\right)} \\
&+ \boxed{\sum_{i,j} \int_{\mathrm{CT}} \frac{dN}{2\pi i}\, \rho^{-N}}\, \tilde{f}_{i/h_1}(N+1, \mu^2)\, \tilde{f}_{j/h_2}(N+1, \mu^2) \\
&\times \left[\tilde{\sigma}^{(\mathrm{res,NNLL})}_{ij \to \tilde{q}\bar{\tilde{q}}}\left(N, \{m^2\}, \mu^2\right) - \tilde{\sigma}^{(\mathrm{res,NNLL})}_{ij \to \tilde{q}\bar{\tilde{q}}}\left(N, \{m^2\}, \mu^2\right)\big|_{(\mathrm{NLO})}\right]
\end{aligned}
$$

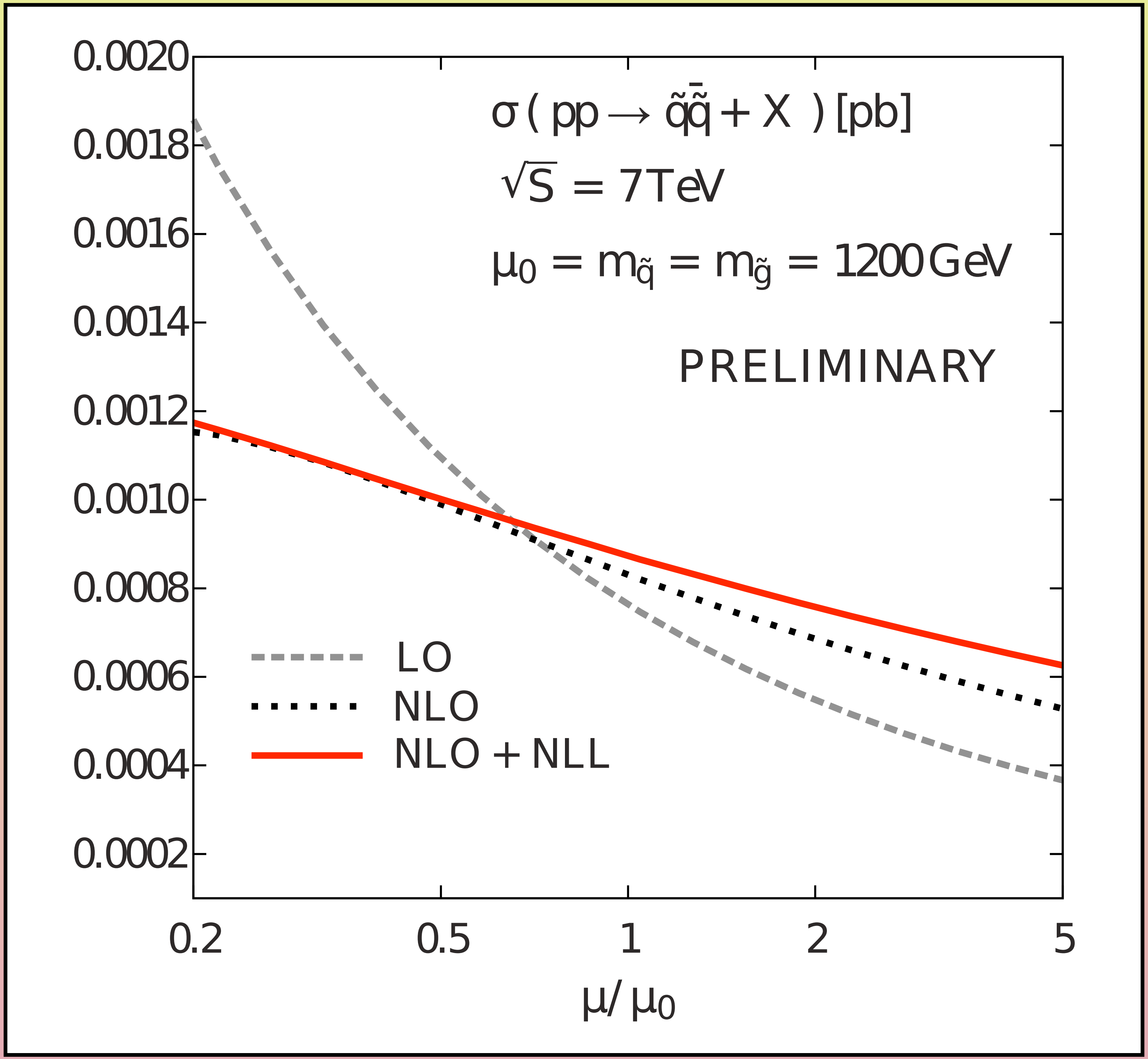
Matching to NLO

$$\sigma^{(\mathrm{NNLL+NLO\ matched})}_{h_1 h_2 \to \tilde{q}\bar{\tilde{q}}}(\rho, \{m^2\}, \mu^2) = \boxed{\sigma^{(\mathrm{NLO})}_{h_1 h_2 \to \tilde{q}\bar{\tilde{q}}}(\rho, \{m^2\}, \mu^2)}$$

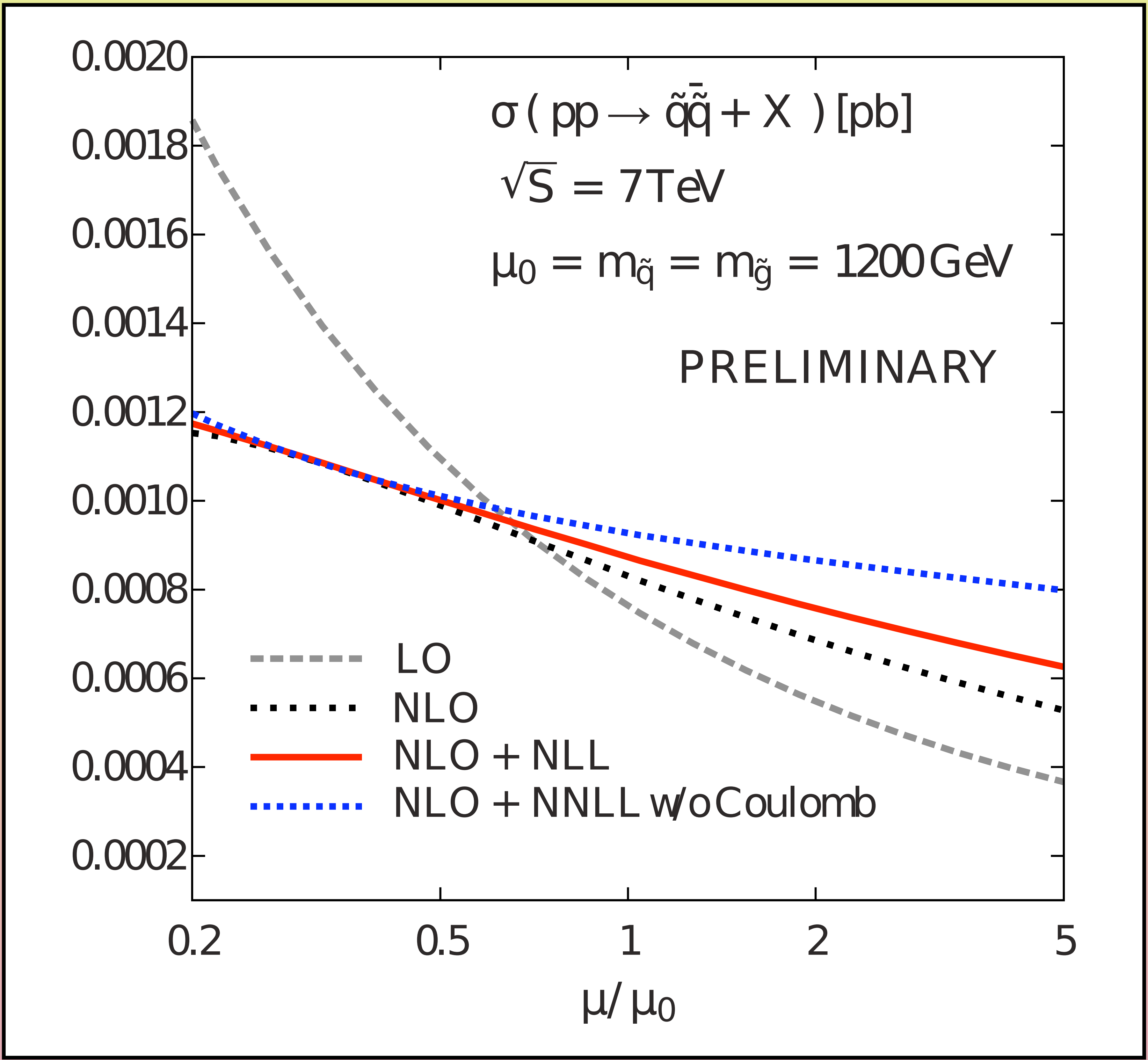
$$+ \boxed{\sum_{i,j} \int_{\mathrm{CT}} \frac{dN}{2\pi i}\, \rho^{-N}} \tilde{f}_{i/h_1}(N+1, \mu^2)\, \tilde{f}_{j/h_2}(N+1, \mu^2)$$

$$\times \left[\tilde{\sigma}^{(\mathrm{res,NNLL})}_{ij \to \tilde{q}\bar{\tilde{q}}}(N, \{m^2\}, \mu^2) - \boxed{\tilde{\sigma}^{(\mathrm{res,NNLL})}_{ij \to \tilde{q}\bar{\tilde{q}}}(N, \{m^2\}, \mu^2)\,|_{(\mathrm{NLO})}}\right]$$

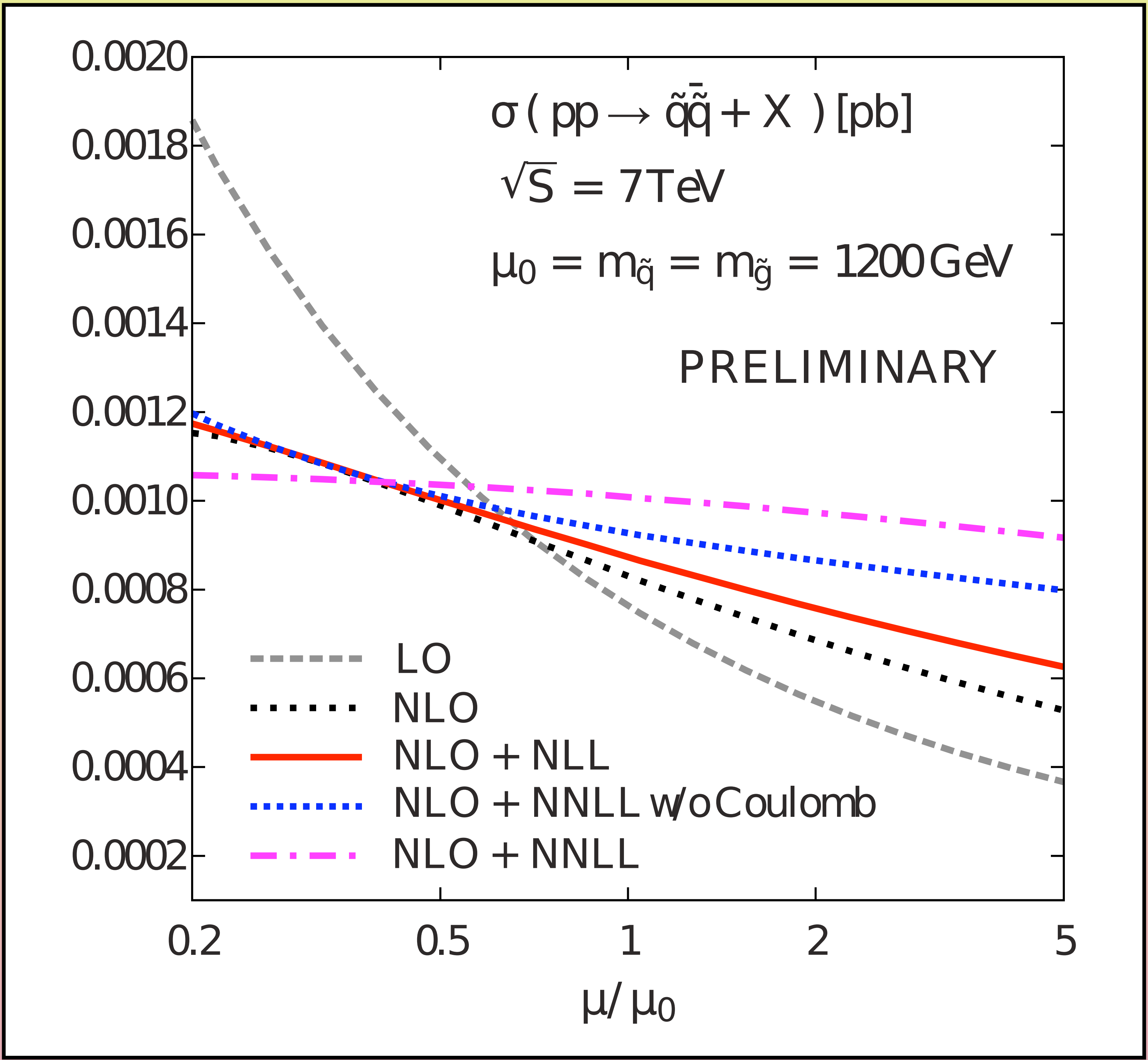
Scale dependence



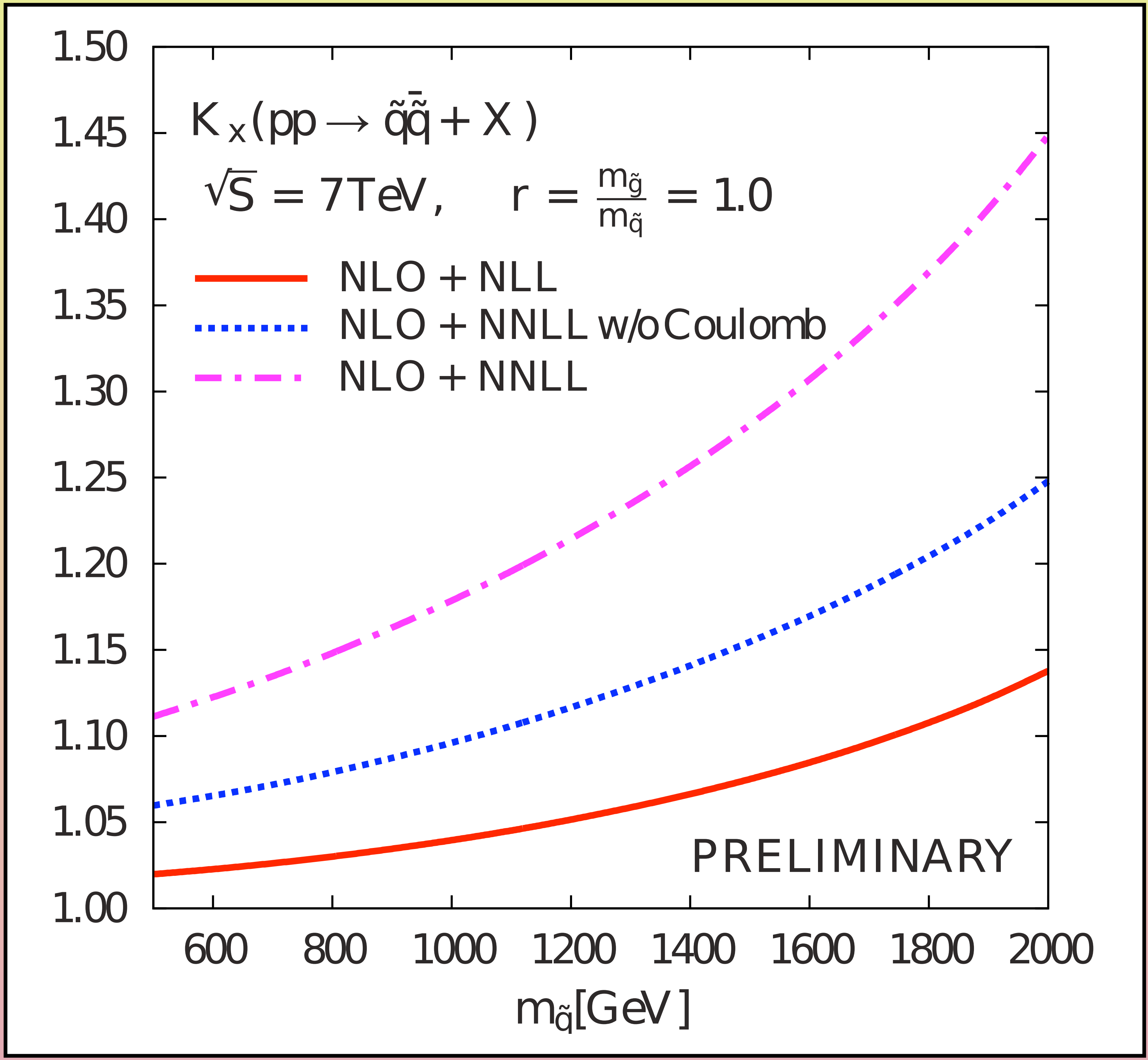
Scale dependence



Scale dependence



K factor@central scale



Conclusion

NNLL resummation for squark-antisquark production performed

- Scale dependence reduced
- Cross section increased at central scale

Conclusion

NNLL resummation for squark-antisquark production performed

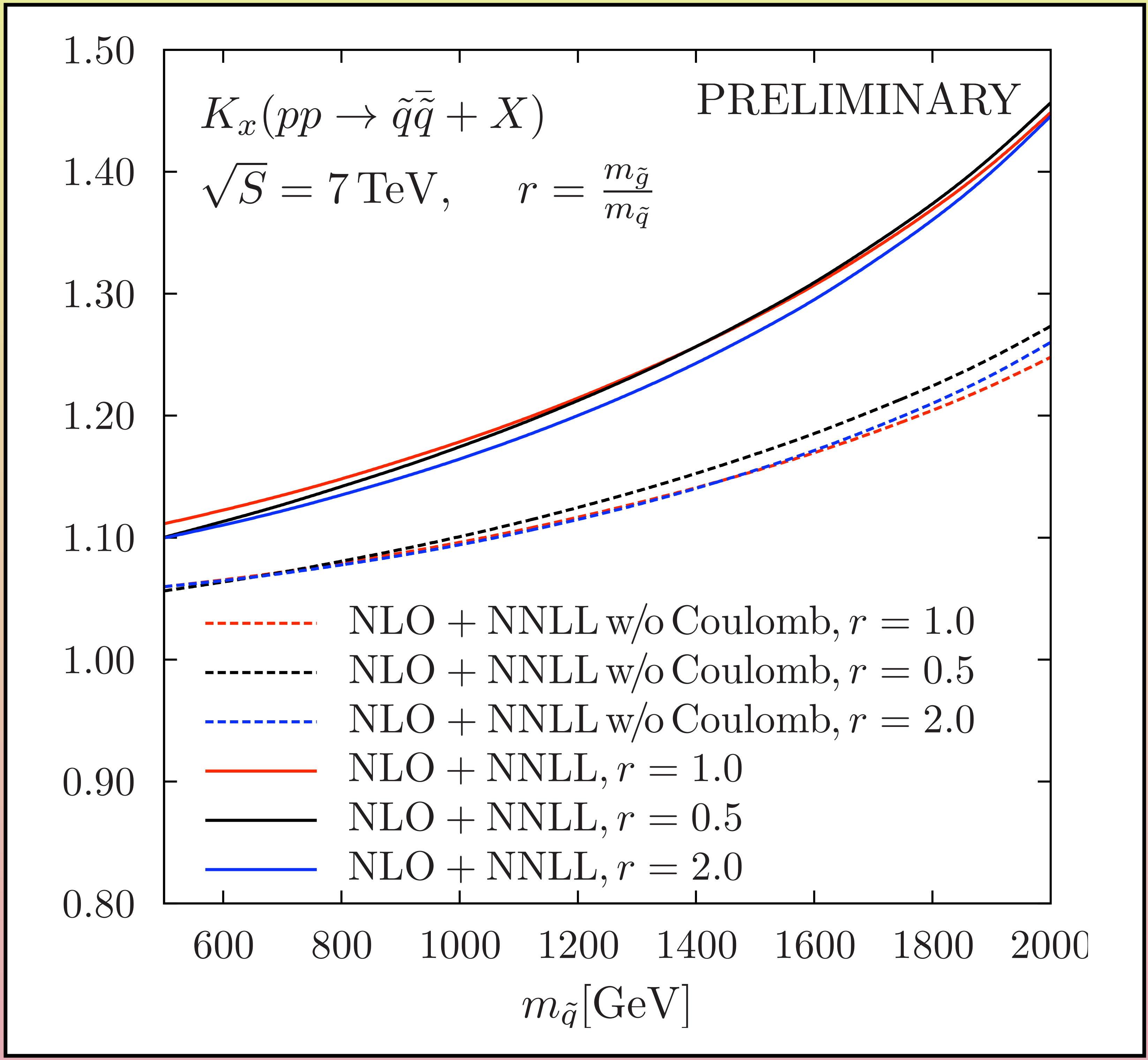
- Scale dependence reduced
- Cross section increased at central scale

Still to do:

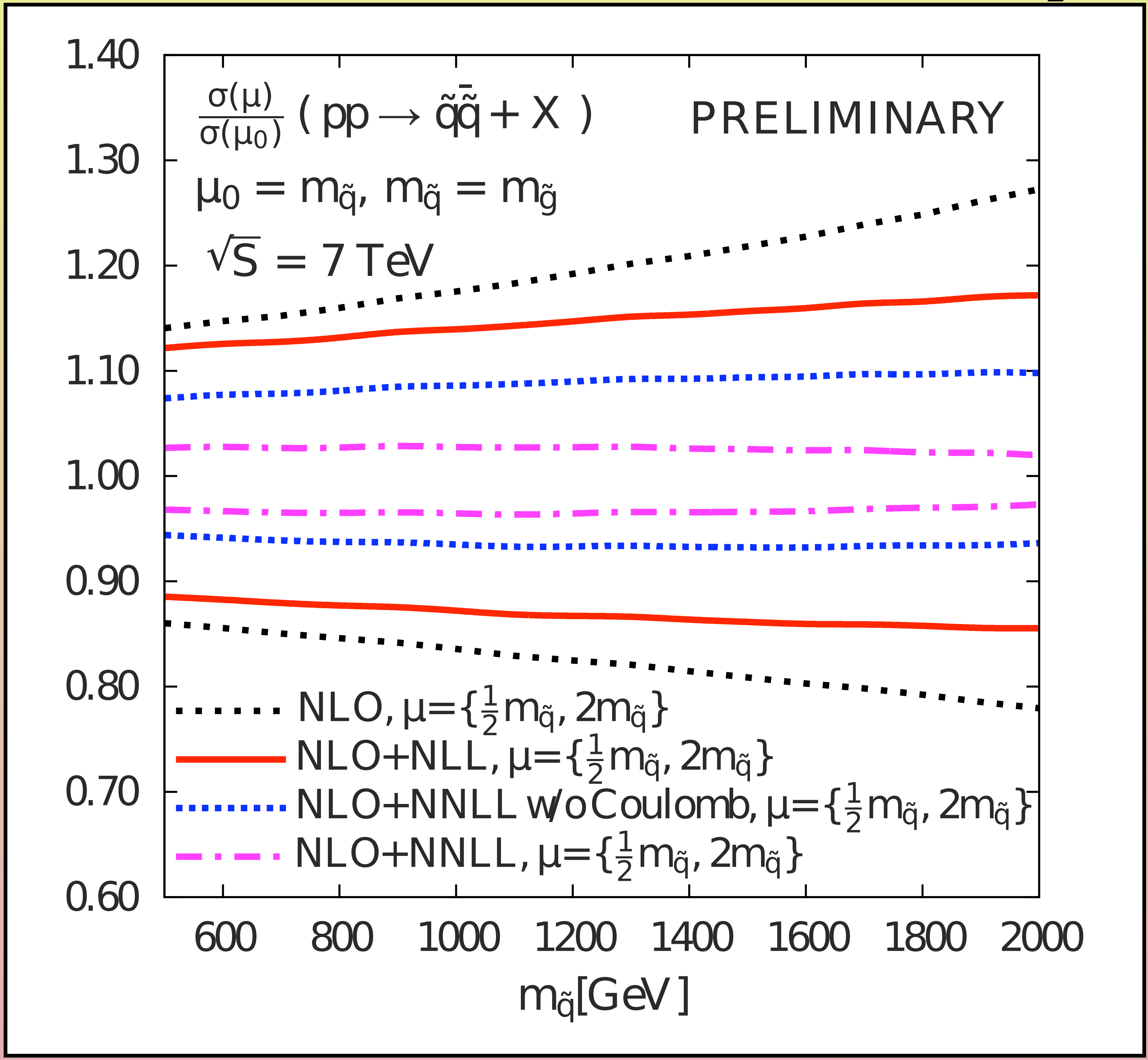
- Include other processes
- Apply this to exclusion bounds

Backup

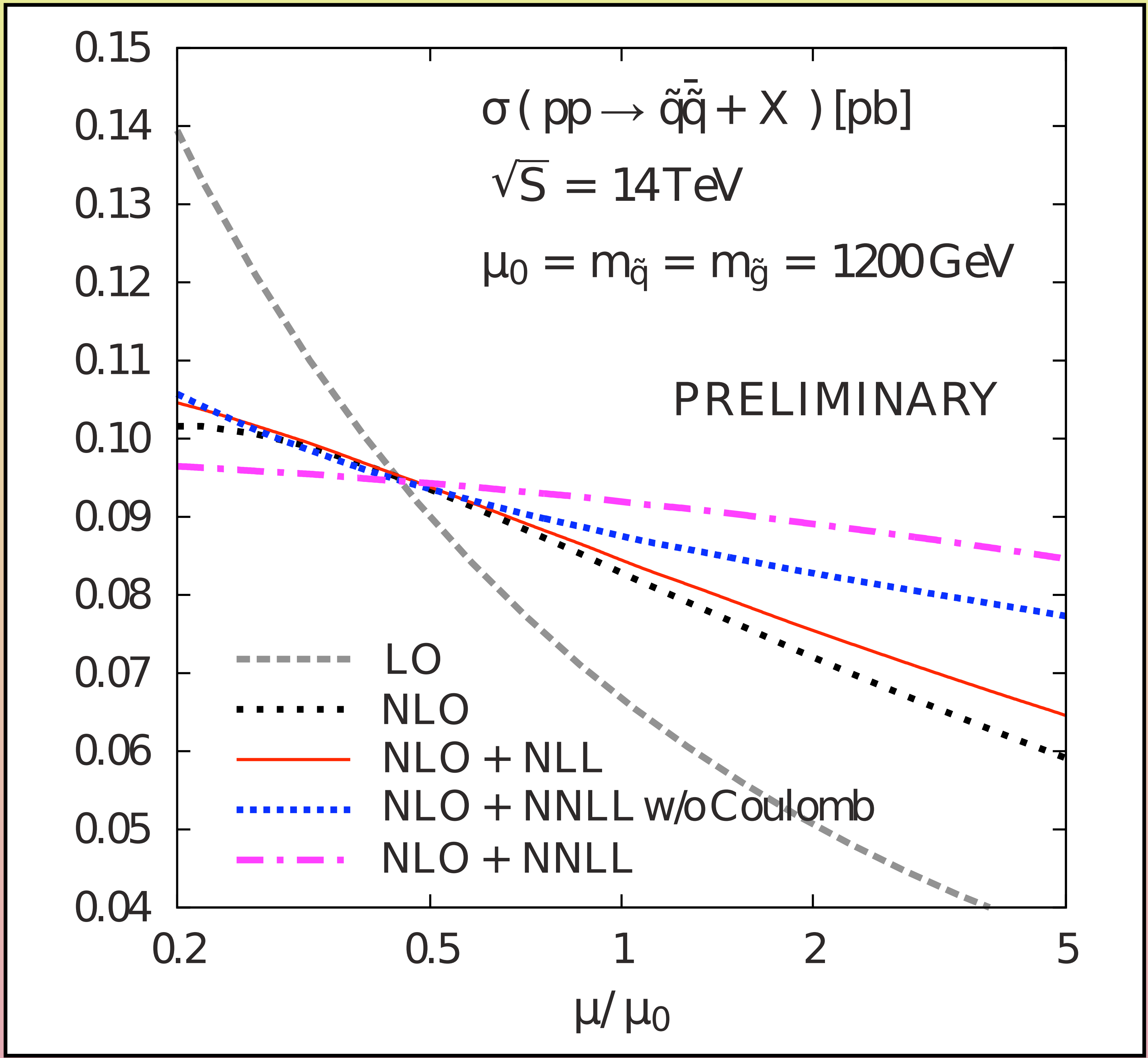
Gluino mass dependence



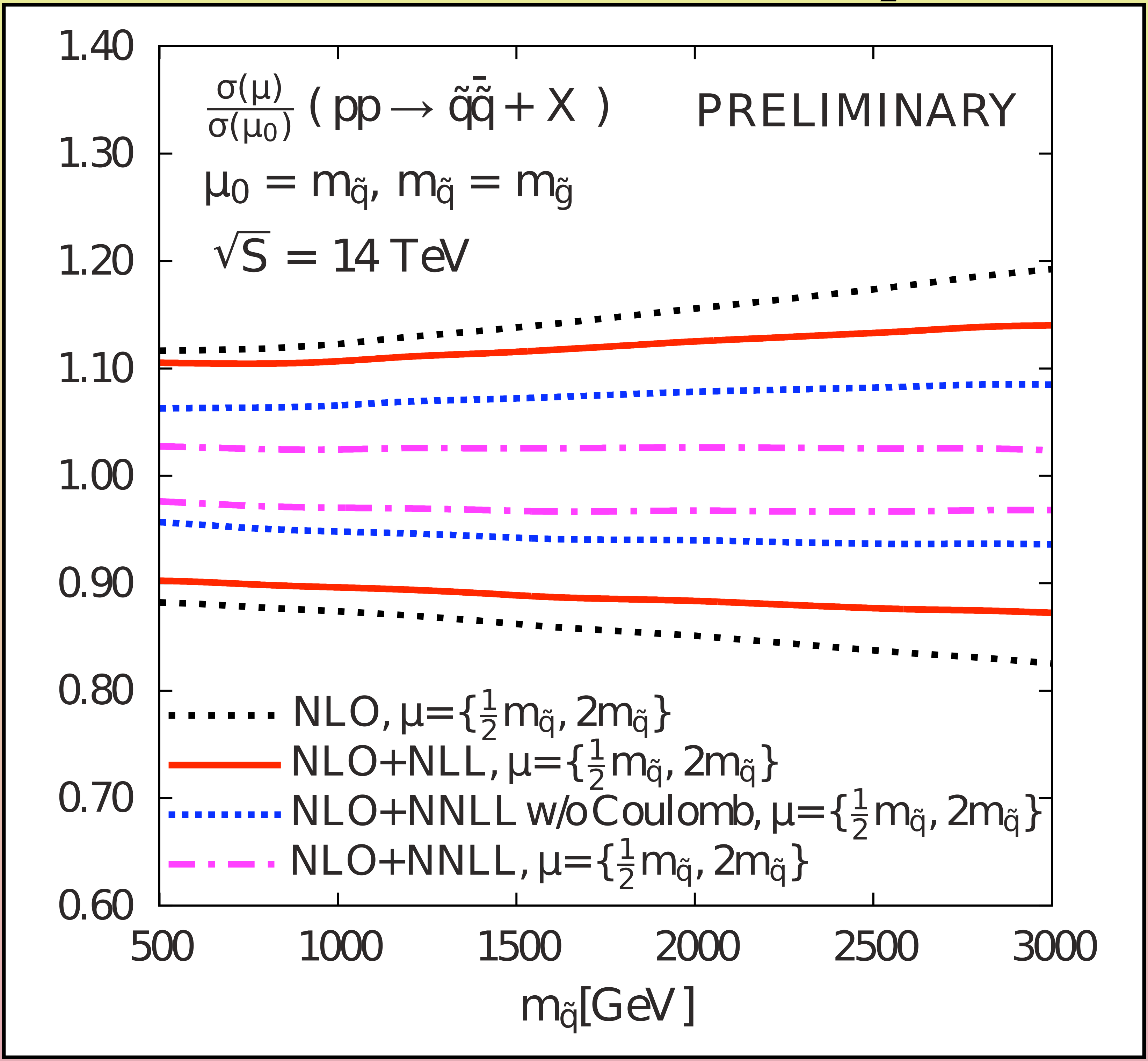
Scale uncertainty



Scale dependence 14 TeV



Scale uncertainty 14 TeV



K factor 14 TeV