

NNLL-FAST v2.0: UPDATED PREDICTIONS FOR SQUARK AND GLUINO PRODUCTION AT THE LHC WITH $\sqrt{S} = 13.6$ TEV

Christoph Borschensky

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in collaboration with Anna Kulesza and Laura Moreno Valero

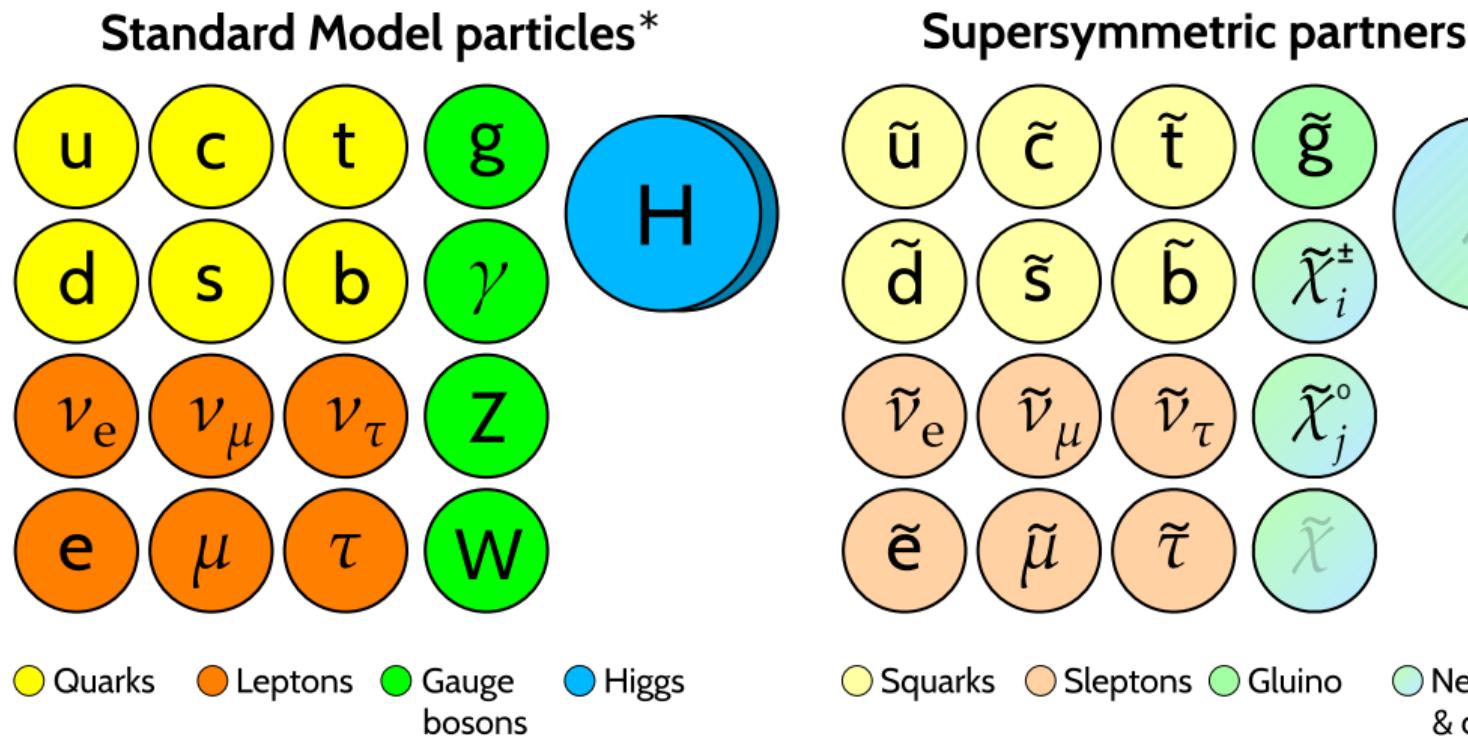
contributing: W. Beenakker, S. Brensing-Thewes, M. Krämer, E. Laenen, L. Motyka, I. Niessen, D. Schwartländer



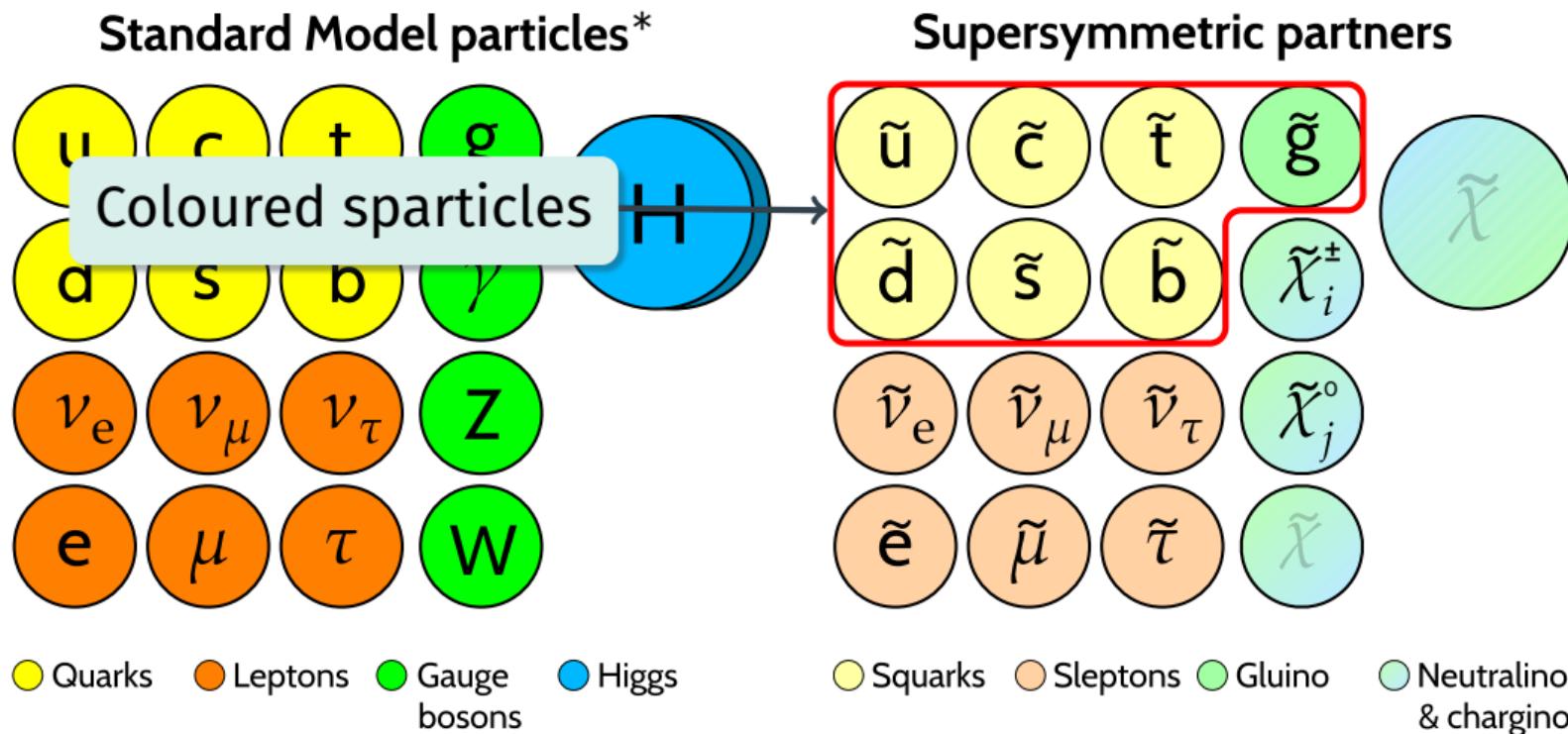
30TH INTERNATIONAL CONFERENCE ON SUPERSYMMETRY
AND UNIFICATION OF FUNDAMENTAL INTERACTIONS

Southampton, 17 July 2023

Supersymmetry and the need for precision predictions



Supersymmetry and the need for precision predictions



Outline

1 Threshold resummation

Particle production close to threshold

Ingredients for soft-gluon resummation

2 NNLL-fast v2.0

Effects of energy upgrade and PDF update

Uncertainties and K -factors

3 Summary

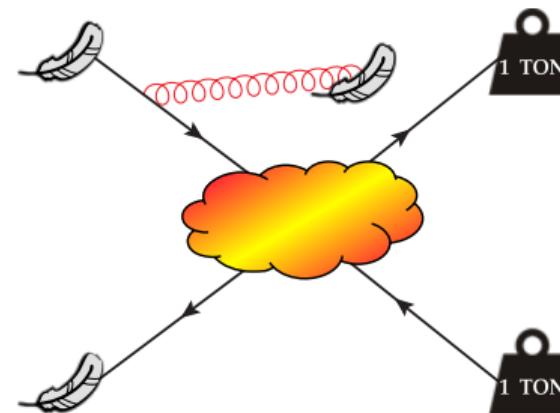
Particle production close to threshold

Heavy SUSY particles \Rightarrow produced in the **threshold limit** $\sqrt{\hat{s}} \rightarrow 2M$:

$$\beta := \sqrt{1 - \frac{4M^2}{\hat{s}}} \rightarrow 0$$

$\sqrt{\hat{s}}$: partonic c.m. energy,
 M : avg. mass of final state particles

- \Rightarrow Just enough energy to produce the two (s)particles
- \Rightarrow Higher orders in α_s : **real radiation processes are soft**



Particle production close to threshold

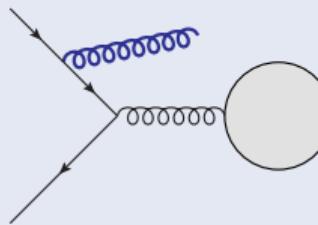
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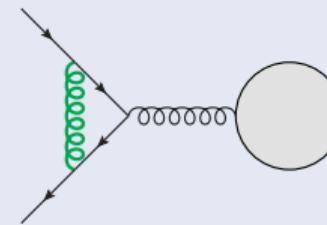
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Remainder after cancellation of IR divergencies (soft & collinear gluons):



+



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

Particle production close to threshold

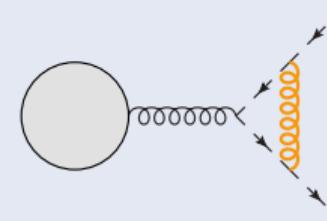
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Heavy and slowly moving final-state particles (**Coulomb gluons**):



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

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

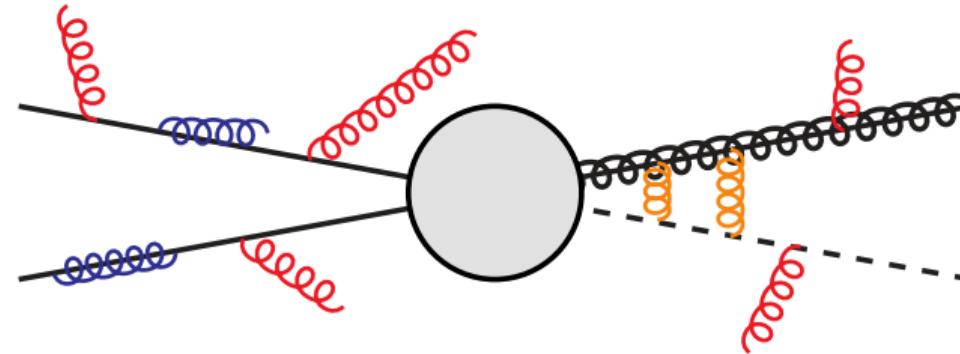


Endangering the perturbative series in α_s !
Systematic treatment of these terms required

Soft-gluon resummation

Threshold region $\sqrt{\hat{s}} \rightarrow 2M$ increasingly relevant

- Enhanced $\ln \beta^2$ stemming from soft-gluon emission



Soft-gluon resummation

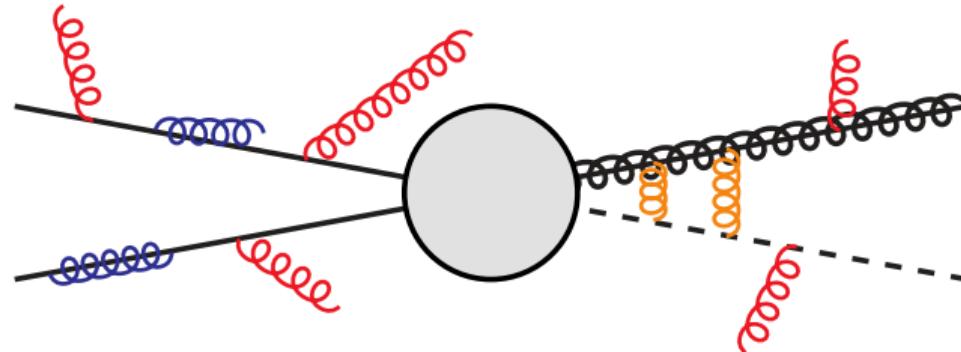
Threshold region $\sqrt{\hat{s}} \rightarrow 2M$ increasingly relevant

- Enhanced $\ln \beta^2$ stemming from soft-gluon emission
- Factorisation of cross section in Mellin space ($\ln \beta^2 \rightarrow \ln N$ for $N \rightarrow \infty$):

$$\tilde{f}(N) := \int_0^1 dx x^{N-1} f(x)$$

$$\tilde{\sigma}_{ij \rightarrow kl}^{(\text{resum})} = \sum_{\text{colours } I} H_{ij \rightarrow kl, I}^{(N)} \times \Delta_i^{(N)} \Delta_j^{(N)} \times S_{ij \rightarrow kl, I}^{(N)}$$

i, j : partons
 k, l : squark, gluino



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with

- 👉 ▶ $H_{ij \rightarrow kl, I}^{(N)}$: matching coefficient (non-vanishing hard & Coulomb-gluon contributions)
- ▶ $\Delta_i^{(N)}, S_{ij \rightarrow kl, I}^{(N)}$: resummed logs from soft-collinear and soft wide-angle radiation

$$H_{ij \rightarrow kl, I}^{(N)} = \tilde{\sigma}_{\text{Born}}^{(N)} \times \mathcal{C}_{ij \rightarrow kl, I}^{\text{Coul}, (N)} \times \left(1 + \frac{\alpha_s}{\pi} \mathcal{C}_{ij \rightarrow kl, I}^{(1)} + \dots \right)$$

[Beenakker et al. '13][Broggio et al. '13][Beenakker et al. '16]

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Factorisation leads to exponentiation and thus **all-order resummation** of threshold logs

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$$\Delta_i^{(N)} \Delta_j^{(N)} S_{ij \rightarrow kl, I}^{(N)} = \exp [L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \dots]$$

[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] ...

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LL

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NLL

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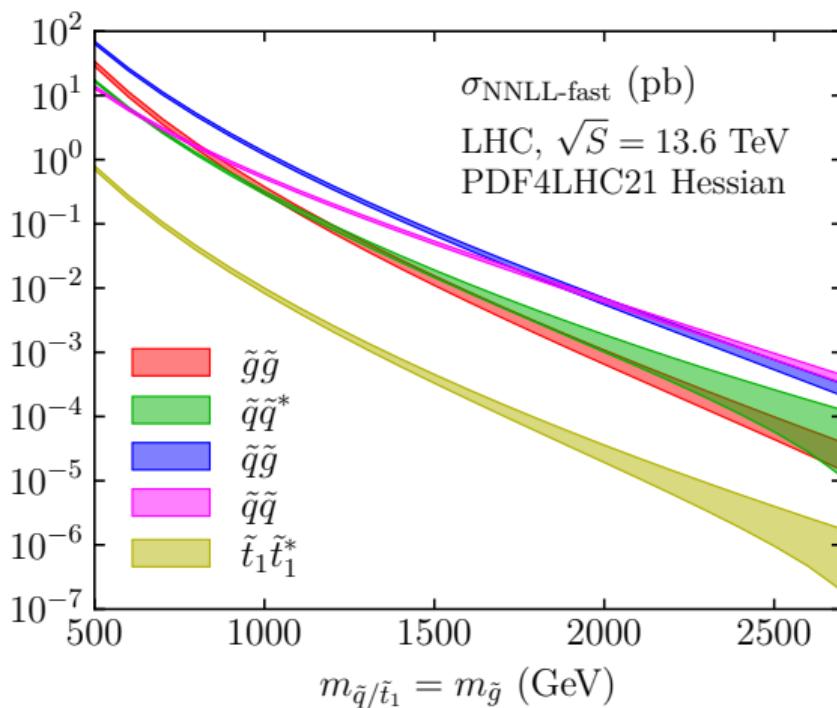
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Inverse Mellin transform, matching to NNLO to avoid double counting:

[Catani, Mangano, Nason, Trentadue '96]

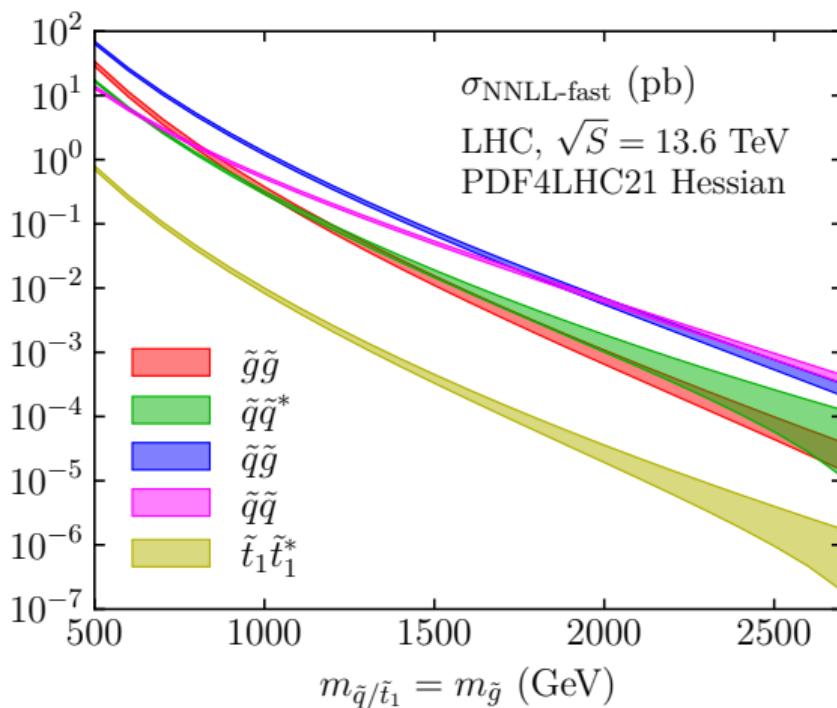
$$\sigma_{ij \rightarrow kl}^{\text{NNLO}_{\text{Approx}} + \text{NNLL}} = \sigma_{ij \rightarrow kl}^{\text{NNLO}_{\text{Approx}}} + \int_{\text{CT}} dN (...) \left[\tilde{\sigma}_{ij \rightarrow kl}^{(\text{resum})} - \tilde{\sigma}_{ij \rightarrow kl}^{(\text{resum})} \Big|_{\text{NNLO}} \right]$$

NNLL-fast v2.0 for the LHC Run III @ $\sqrt{S} = 13.6$ TeV



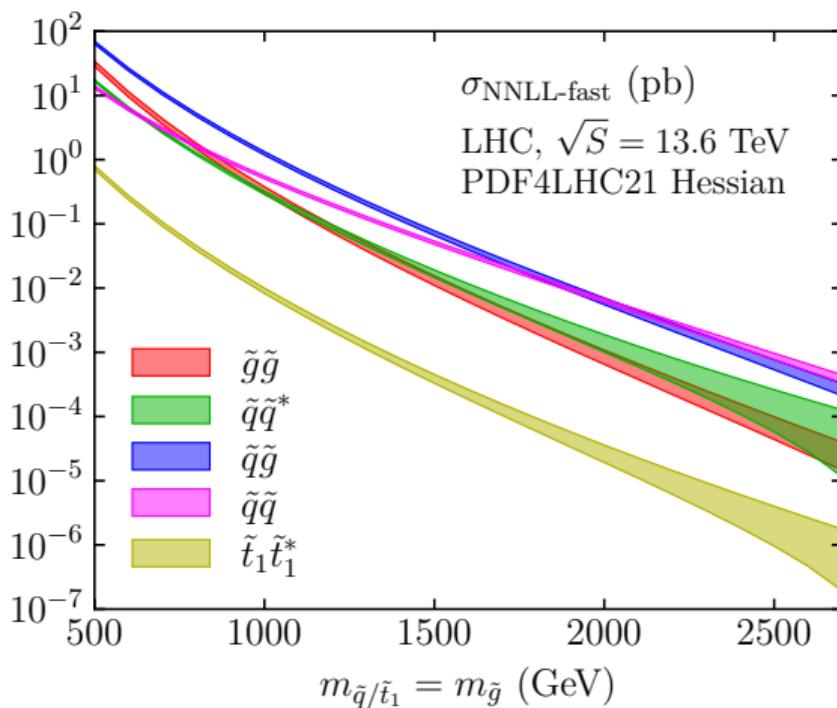
- ▶ Total cross sections for **gluino-pair**, **squark-antisquark**, **squark-gluino**, **squark-pair**, **stop-antistop**

NNLL-fast v2.0 for the LHC Run III @ $\sqrt{S} = 13.6$ TeV



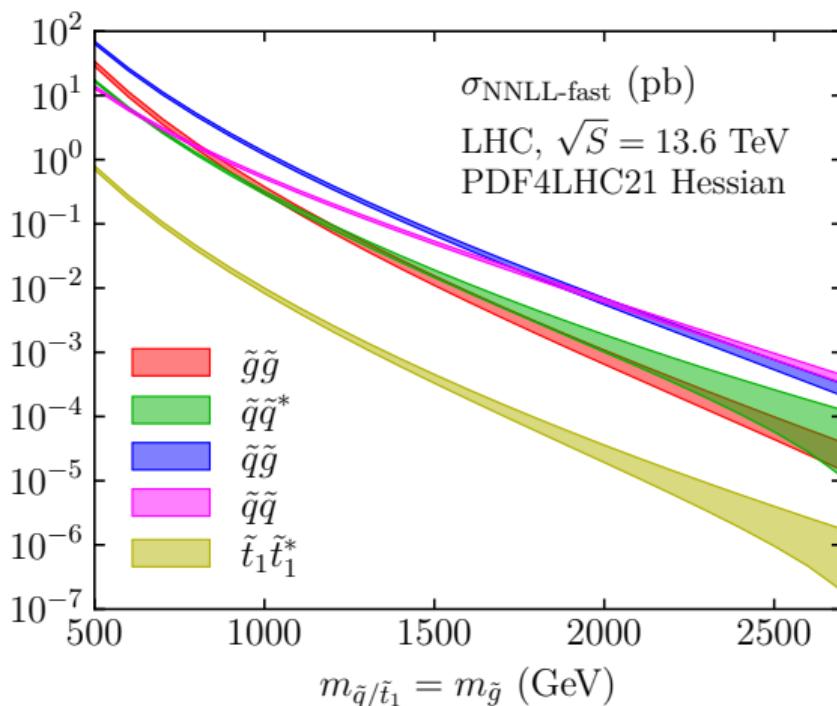
- ▶ Total cross sections for **gluino-pair**, **squark-antisquark**, **squark-gluino**, **squark-pair**, **stop-antistop**
- ▶ At **NNLO_{Approx} +NNLL** including soft-gluon & Coulomb resummation and bound-state corrections; NLO from **Prospino 2**
[*Beenakker, Höpker, Krämer, Plehn, Spira, Zerwas '96ff*]
- ▶ Scale and PDF+ α_s uncertainties included

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- ▶ At $\sqrt{S} = 13.6$ TeV with **latest PDF4LHC21 sets**

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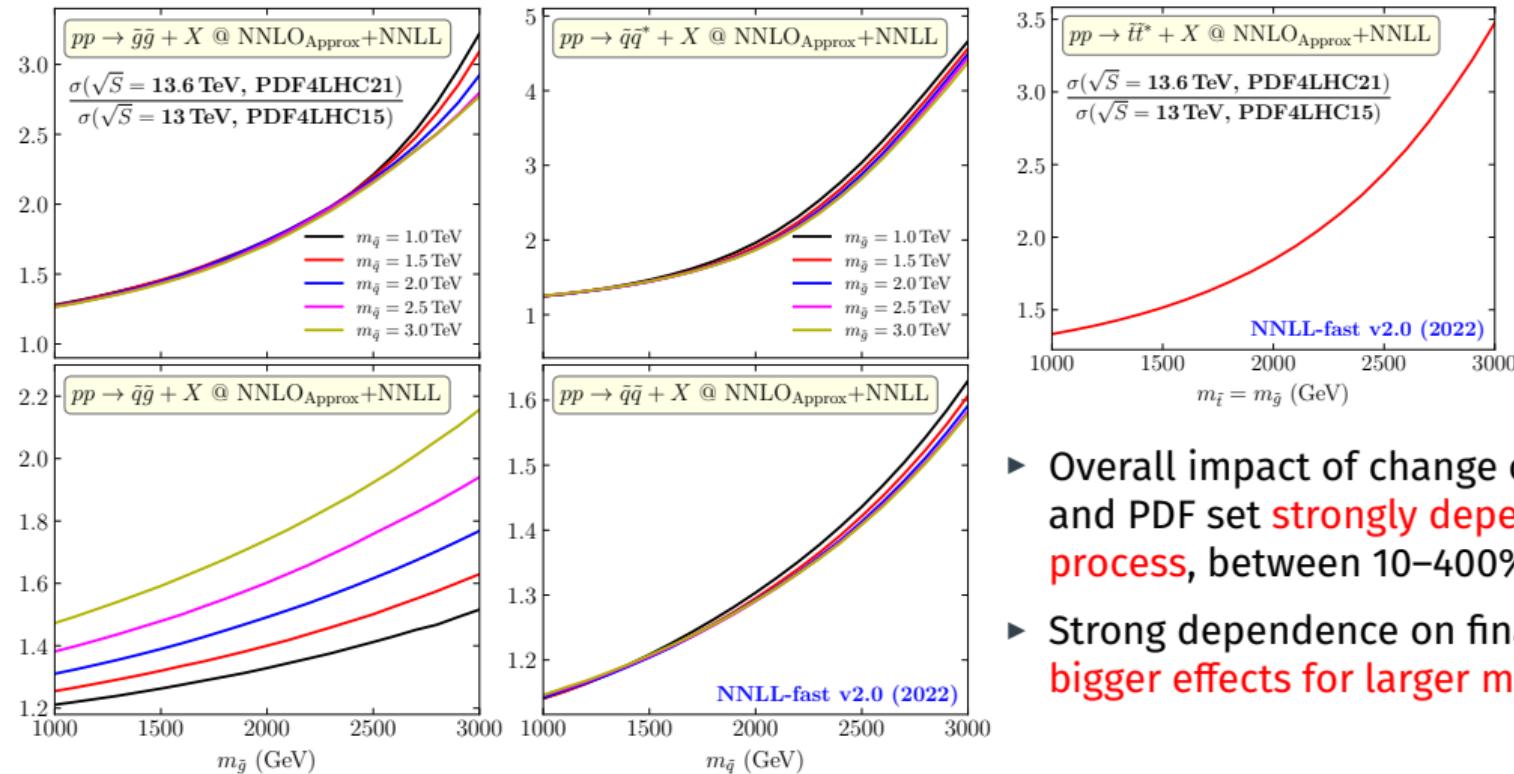


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- ▶ Scale and PDF+ α_s uncertainties included
- ▶ At $\sqrt{S} = 13.6$ TeV with latest PDF4LHC21 sets
- ▶ Numerical grids in $m_{\tilde{q}}^{(*)}$ and $m_{\tilde{g}}$ & fast interpolation code available from:

https://www.uni-muenster.de/Physik.TP/~akule_01/nnllfast

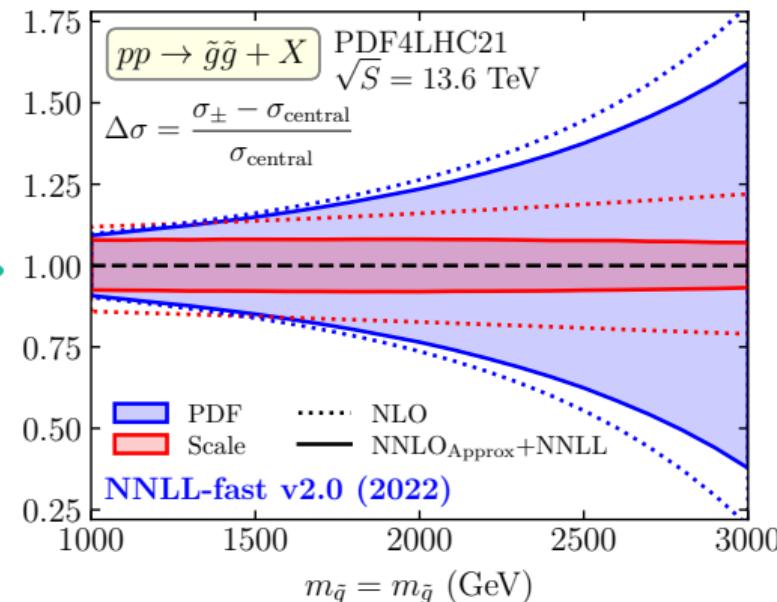
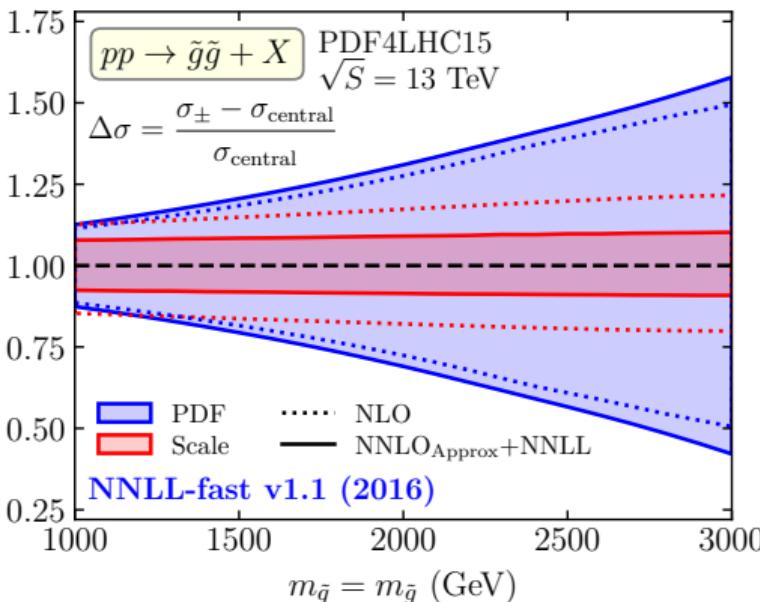
(*) assuming 10-fold squark degeneracy ($\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{b}; L$ and R)

Combined effect 13.6 TeV and PDF update



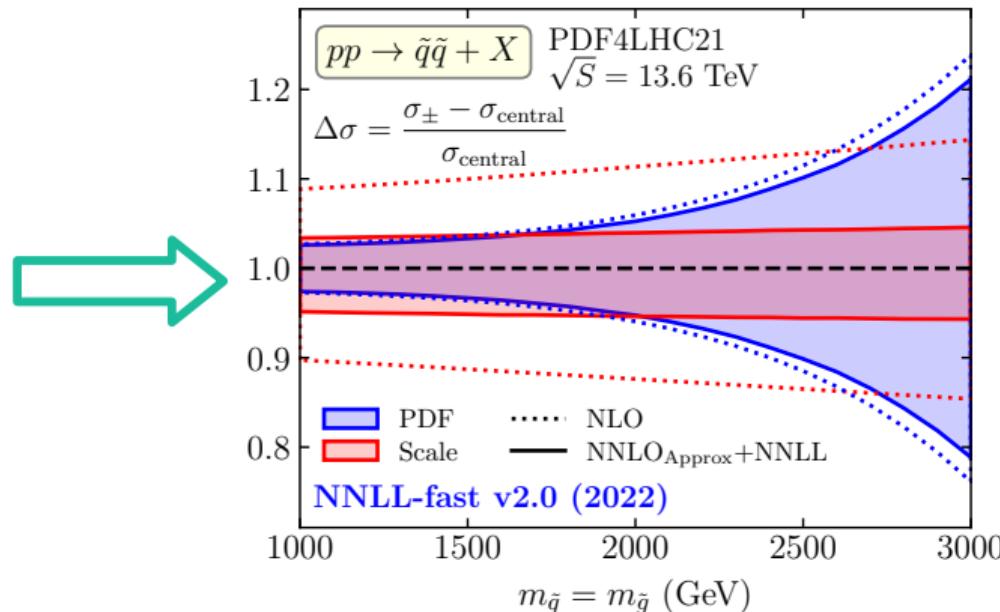
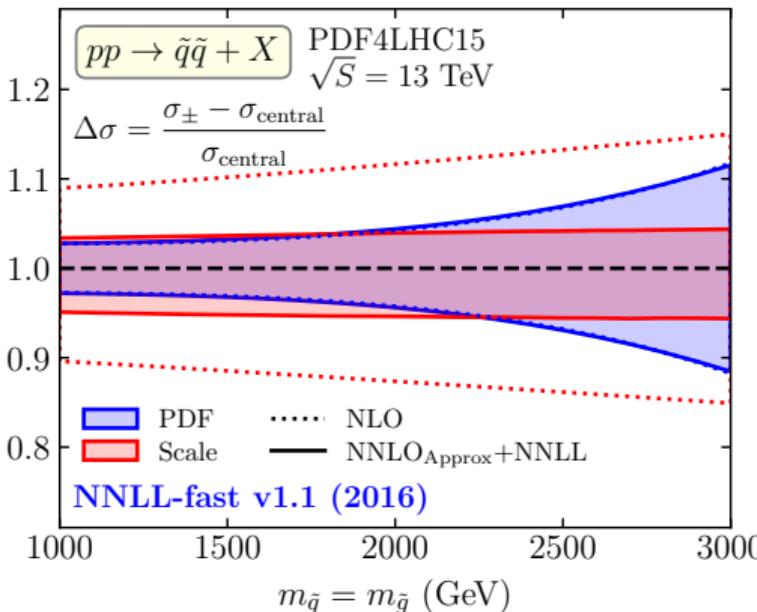
- ▶ Overall impact of change of c.m. energy and PDF set **strongly dependent on process**, between 10–400% increase
- ▶ Strong dependence on final-state mass, **bigger effects for larger masses**

13.6 TeV updates: uncertainties (gluino-pair production)



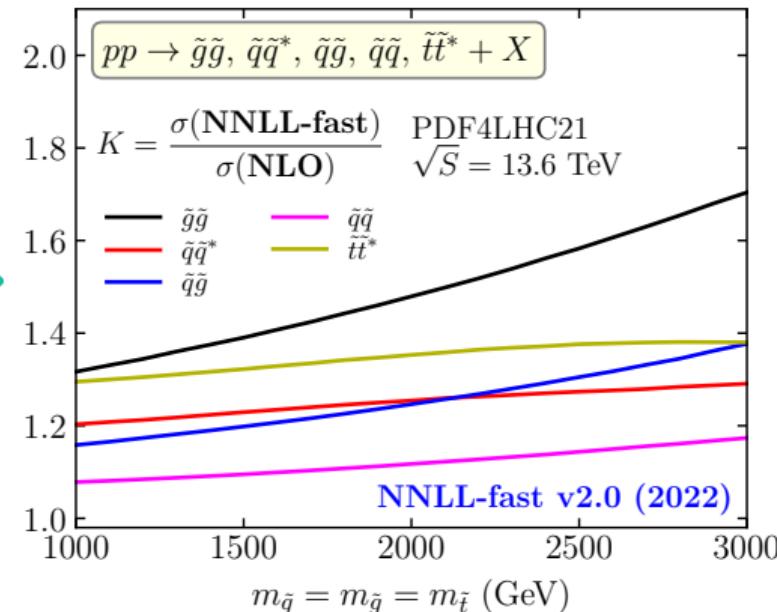
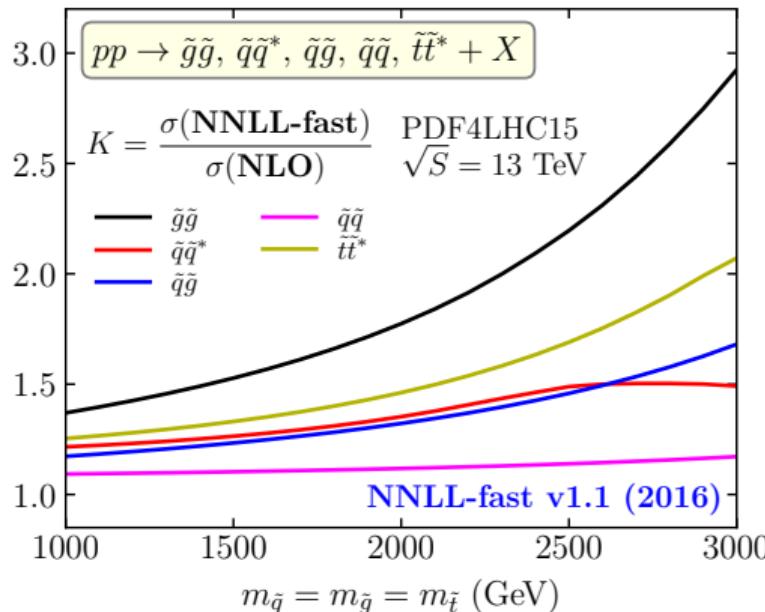
- ▶ NLO with NLO (NNLO) PDFs for 13 TeV (13.6 TeV); NNLO_{Approx}+NNLL with NNLO PDFs
- ▶ Reduction of scale uncertainty from NLO to NNLO_{Approx}+NNLL
- ▶ Similar size of uncertainties for 13 TeV vs. 13.6 TeV

13.6 TeV updates: uncertainties (squark-pair production)



- ▶ NLO with NLO (NNLO) PDFs for 13 TeV (13.6 TeV); NNLO_{Approx}+NNLL with NNLO PDFs
- ▶ Reduction of scale uncertainty from NLO to NNLO_{Approx}+NNLL
- ▶ Increase of PDF uncertainty from PDF4LHC15 to PDF4LHC21

13.6 TeV updates: K-factor



- From PDF4LHC14 (with MC method) to PDF4LHC21 (with Hessian method, positive definite!)
- No NLO PDF set for PDF4LHC21, therefore smaller K-factors than for PDF4LHC15

Summary and outlook

NNLL-fast v2.0

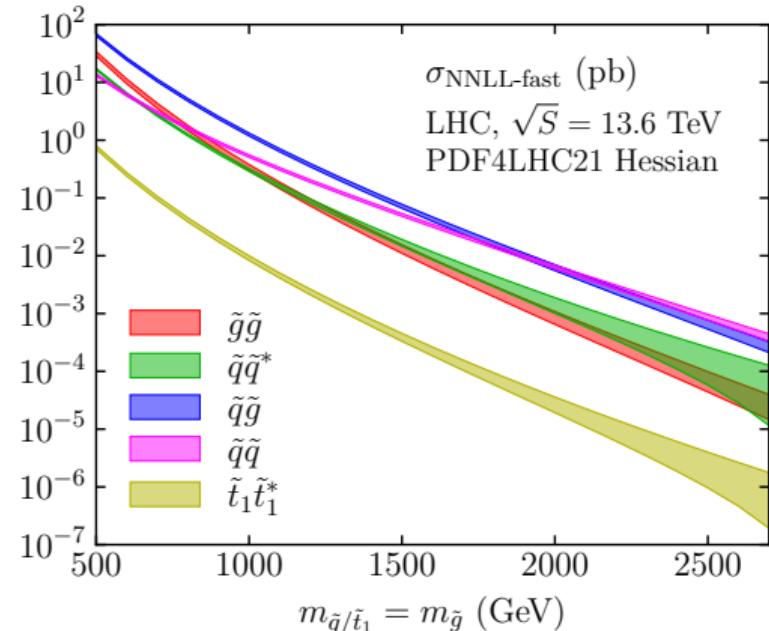
https://www.uni-muenster.de/Physik.TP/~akule_01/nnllfast

- ▶ Precision predictions for squark and gluino production at the LHC
- ▶ At $\sqrt{S} = 13.6$ TeV with PDF4LHC21 PDFs
- ▶ Other \sqrt{S} and mass ranges on request

Outlook

Soft-gluon resummation for squark and gluino production in the MRSSM

[CB, F. Frisenna, W. Kotlarski, A. Kulesza, D. Stöckinger; in preparation]



Summary and outlook

NNLL-fast v2.0

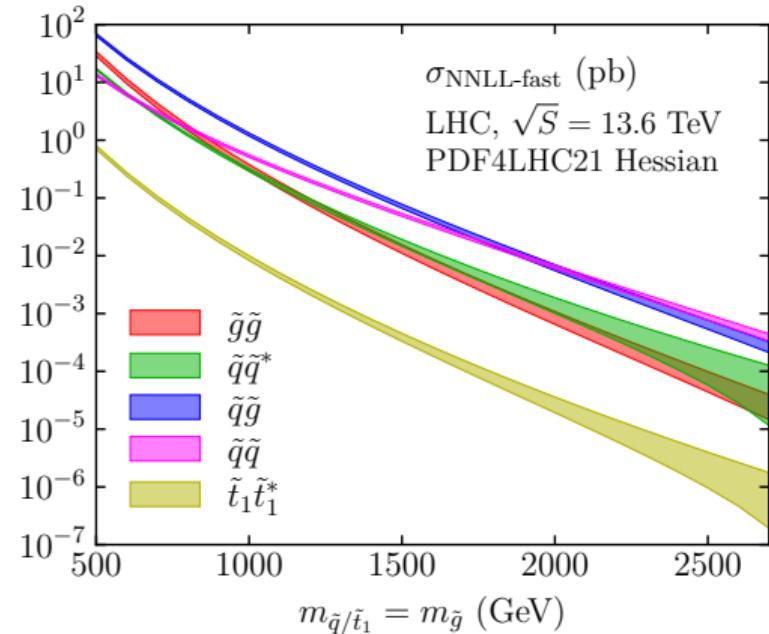
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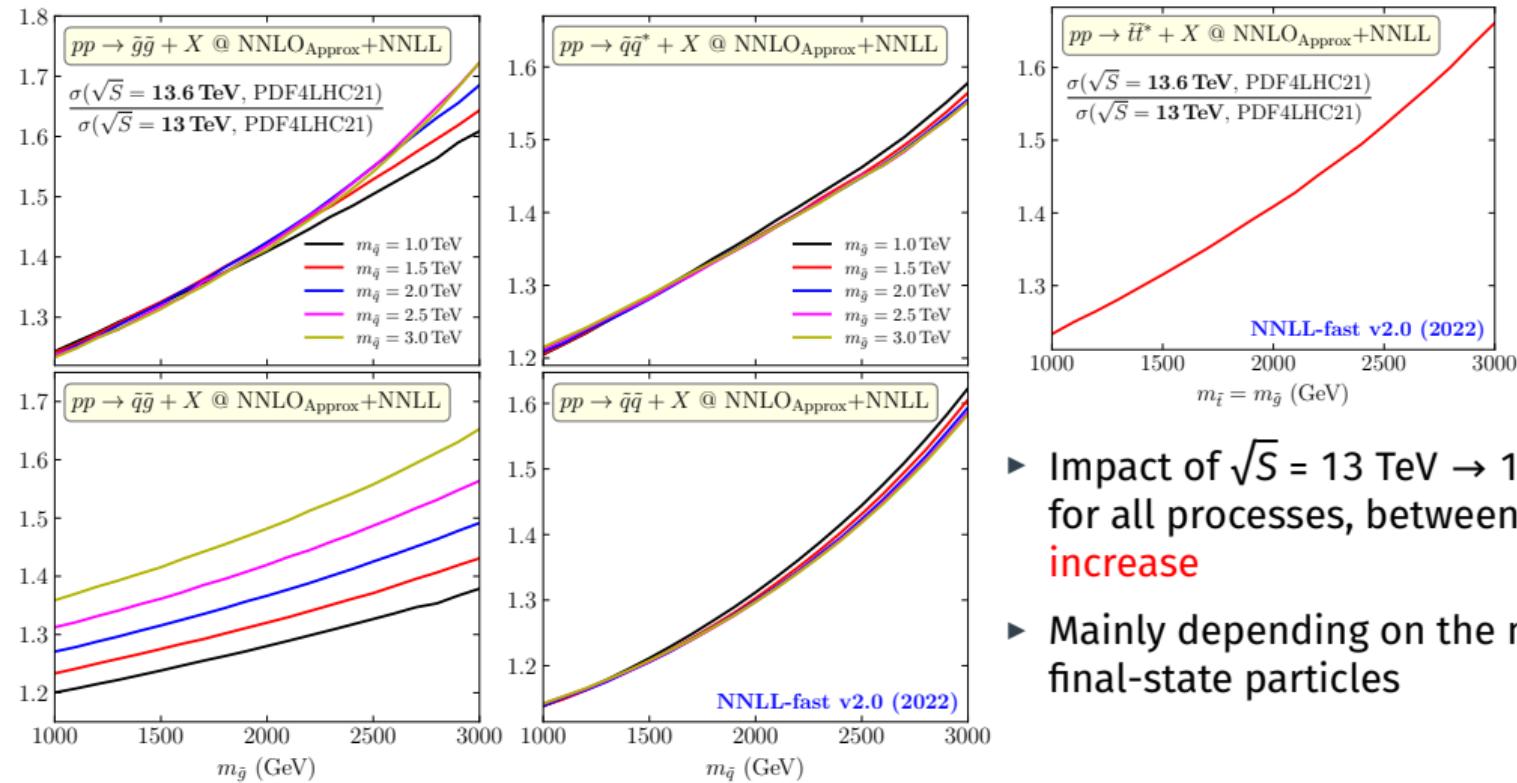
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THANK YOU FOR YOUR ATTENTION! 😊

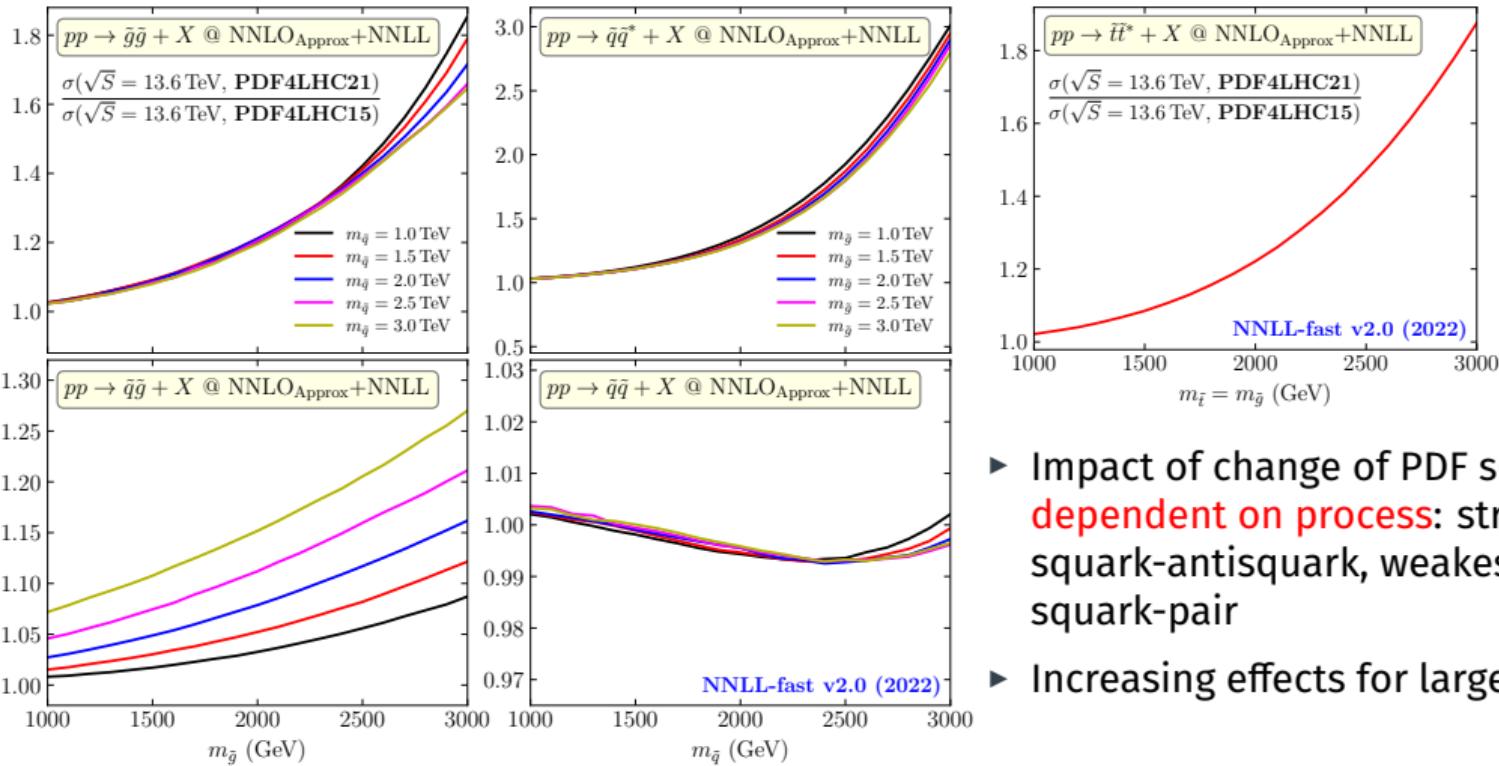
Backup

Effect of increase in c.m. energy (13 TeV → 13.6 TeV)



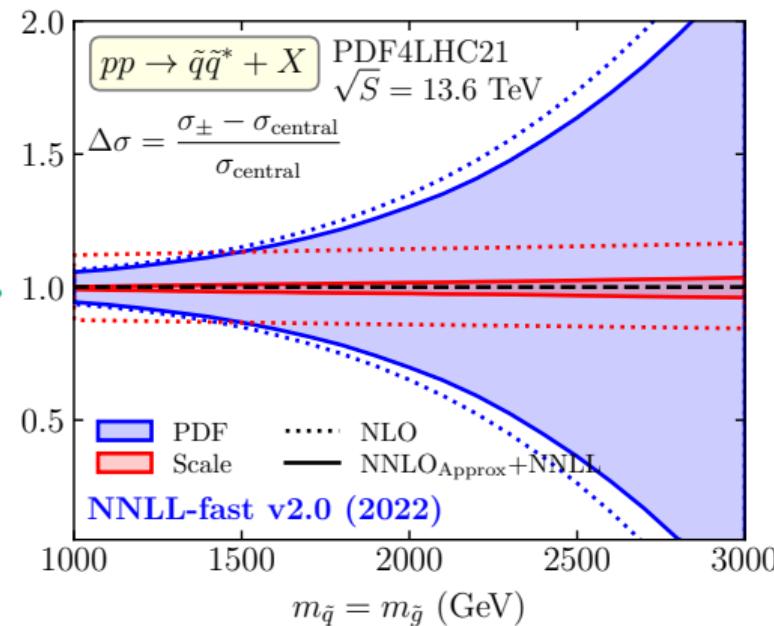
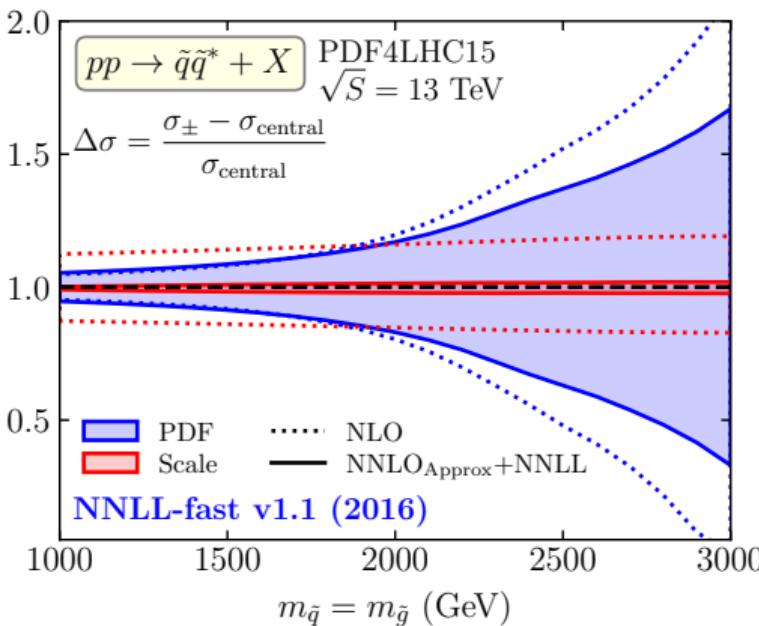
- ▶ Impact of $\sqrt{S} = 13$ TeV → 13.6 TeV similar for all processes, between **10–80% increase**
- ▶ Mainly depending on the mass of the final-state particles

Effect of change of PDF set (PDF4LHC15 → PDF4LHC21)



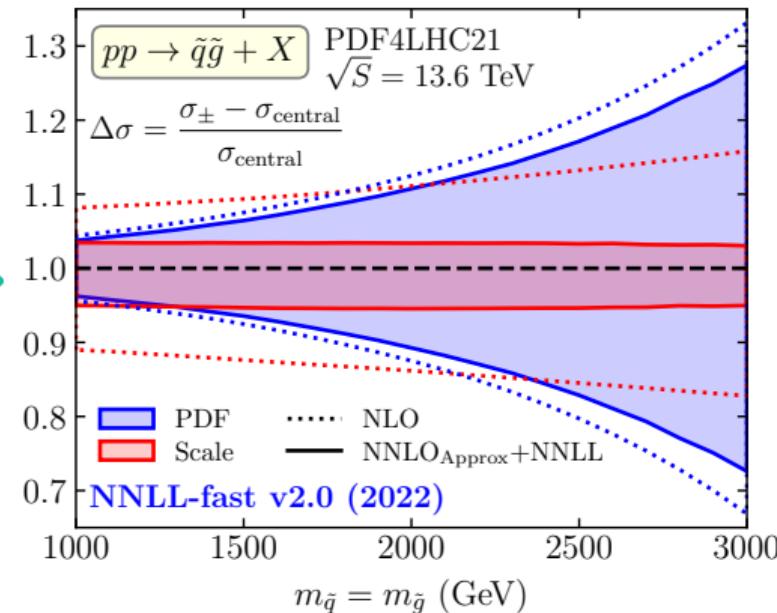
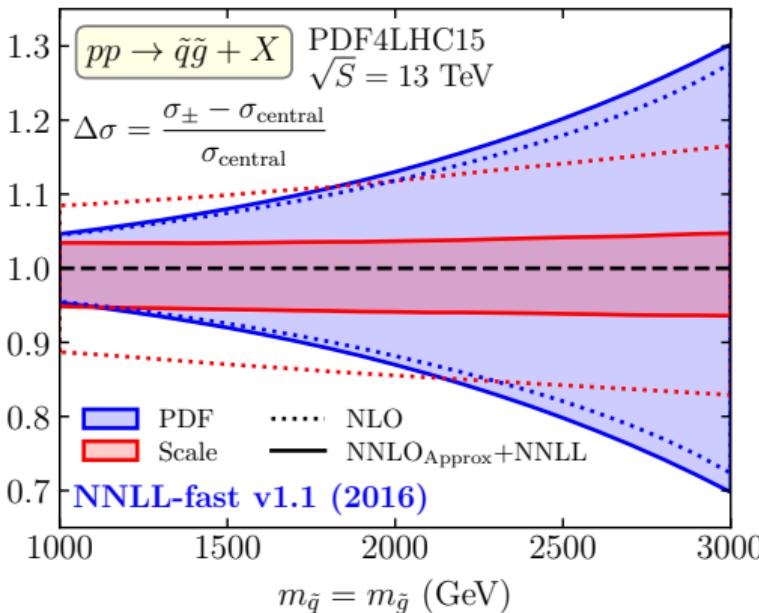
- ▶ Impact of change of PDF sets **strongly dependent on process**: strongest for squark-antisquark, weakest for squark-pair
- ▶ Increasing effects for larger masses

13.6 TeV updates: uncertainties (squark-antisquark production)



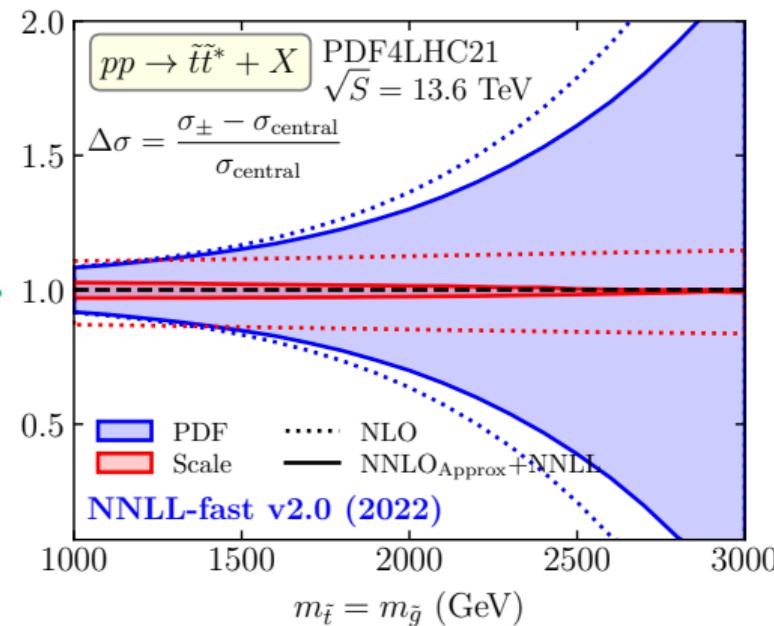
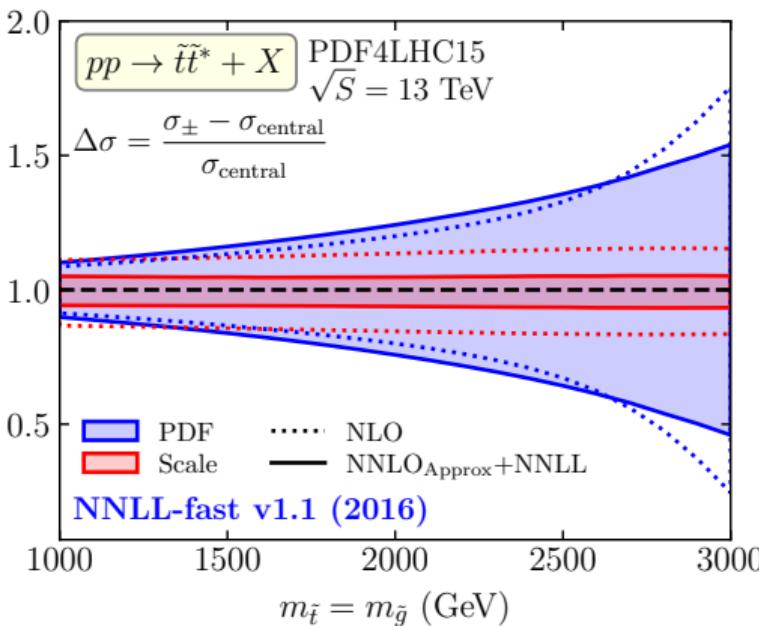
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13.6 TeV updates: uncertainties (stop-antistop production)



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