

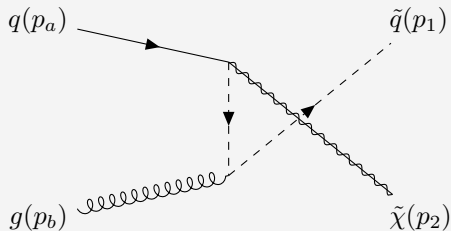
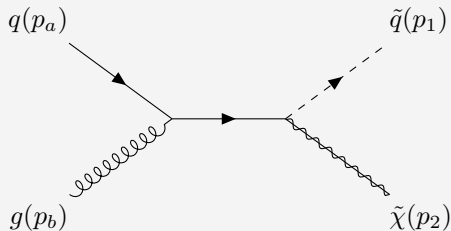
Soft gluon resummation for associated squark-electroweakino production at the LHC [arXiv: 2202.13416 (hep-ph)]

J. Fiaschi, B. Fuks, M. Klasen, [A. Neuwirth](#)



Squark and Electroweakino Production

- ▶ In the MSSM R-Parity implies production of SUSY particles in even numbers
- ▶ Expect dominant production of squark pairs and gluino pairs
- ▶ Might be restricted by heavy masses



- ▶ Squark and (lighter) electroweakino better LHC production candidate

Resummation

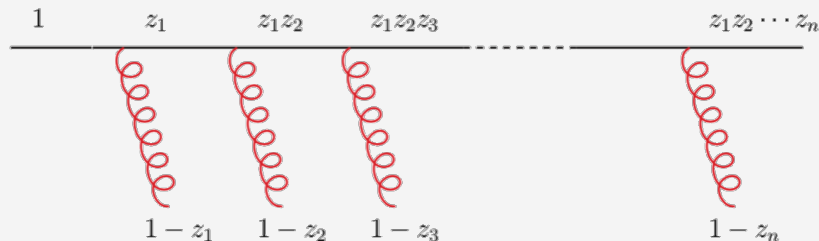
- ▶ Massive particles are mostly produced close to threshold ($M^2/s = z \rightarrow 1$)¹
- ▶ Perturbative expansion in α_s is spoiled by

Large Sudakov logarithms ($m \leq 2n - 1$)

$$\left(\frac{\alpha_s}{2\pi}\right)^n \frac{\log^m(1-z)}{1-z}$$

$$\left(\frac{\alpha_s}{2\pi}\right)^n \log^m \left(\frac{M^2}{p_T^2}\right)$$

- ▶ Solution: Resummation of all soft emitted gluons



¹Catani, S. & Trentadue, L. *Nucl. Phys. B* **327**, 323–352 (1989).

Resummation

► Transforming to Mellin space

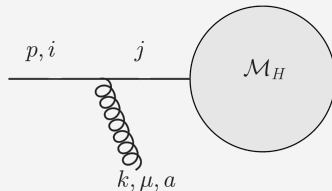
$$F(N) = \int_0^1 dy y^{N-1} F(y) \quad \Rightarrow \quad \left[\frac{\log^m(1-z)}{1-z} \right]_+ \xrightarrow{F} \sim \log^{m+1} N + \dots$$

factorizes the phase space

$$\int dz z^{N-1} d\phi_{2+n}(z) \approx d\phi_2 \times d\phi_n(N)$$

► Dynamical Factorisation is achieved by the eikonal approximation

$$\Gamma_{\text{eik}}^\mu = g_s T^j \frac{\Delta_i v^\mu}{\delta_i v \cdot k + i\epsilon}$$



Resummation

- ▶ From factorization theorem we split hard and long distance behaviour

$$\sigma(M^2, m^2) = \mathcal{H}(M^2/\mu_F^2) \mathcal{S}(m^2/\mu_F^2)$$

- ▶ Require independence on scale μ_F

$$\sigma(M^2, m^2) = \mathcal{H}(1) \mathcal{S}(1) \exp \left[- \int_{m^2}^{M^2} \frac{dk}{k^2} \gamma_s(k^2) \right]$$

- ▶ From applying the RGEs we get²:

$$\sigma^{\text{Res.}}(N, M^2, \mu_R^2, \mu_F^2) = \mathcal{H}_{ab}(M^2, \mu_R^2, \mu_F^2) \exp [G_{ab}(N, M^2, \mu_R^2, \mu_F^2)] + \mathcal{O} \left(\frac{1}{N} \right)$$

with

$$G_{ab}(N, M^2, \mu_R^2, \mu_F^2) = \underbrace{LG_{ab}^{(1)}(N)}_{\text{Leading Log } \sim \log^2(N)} + \underbrace{G_{ab \rightarrow ij}^{(2)}(N, M^2, \mu_F^2, \mu_R^2)}_{\text{Next-to-Leading Log } \sim \log(N)} + \dots$$

²Kidonakis, N. et al. [Nucl. Phys. B 525, 299–332. arXiv: hep-ph/9801268 \(1998\).](#)

Matching

- ▶ Fixed order calculation with CS-dipole subtraction³:

$$\sigma^{\text{NLO}} = \int_3 \left[d\sigma^{\text{R}} - d\sigma^{\text{A}} \right]_{\epsilon=0} + \int_2 \left[d\sigma^{\text{V}} + \int_1 d\sigma^{\text{A}} \right]_{\epsilon=0} + \int_0^1 dx \int_2 \left[d\sigma^{\text{B}}(xp) \otimes (\mathbf{P} + \mathbf{K})(x) \right]_{\epsilon=0}$$

- ▶ Hard matching coefficients $C_{ab \rightarrow ij}^{(i)}(M^2, \mu_F^2, \mu_R^2)$

- ▶ LO: $C^{(0)} = 1$

$$\mathcal{H}_{ab \rightarrow ij}^{(0)}(M^2, \mu_F^2, \mu_R^2) = \sigma_{ab \rightarrow ij}^{(0)}(M^2)$$

- ▶ NLO: compute $C^{(1)} = \sigma_{ab \rightarrow ij}^{(1)}(M^2) / \sigma_{ab \rightarrow ij}^{(0)}(M^2)$ with suppressed 3 particle phase space contributions

$$\mathcal{H}_{ab \rightarrow ij}^{(1)}(M^2, \mu_F^2, \mu_R^2) = \sigma_{ab \rightarrow ij}^{(0)}(M^2) C_{ab \rightarrow ij}^{(1)}(M^2, \mu_F^2, \mu_R^2)$$

³Catani, S. et al. *Nucl. Phys. B* **627**, 189–265. arXiv: [hep-ph/0201036](https://arxiv.org/abs/hep-ph/0201036) (2002).

Re-expansion

- To avoid double counting in:

$$\sigma_{ab} = \sigma_{ab}^{\text{NLO}} + \underbrace{\sigma_{ab}^{\text{Res.}} - \sigma_{ab}^{\text{Exp.}}}_{\sigma_{ab}^{\text{NLL}}}$$

- Subtract expansion in α_s :

$$\begin{aligned} \sigma_{ab}^{\text{Exp.}} &= \mathcal{H}_{ab \rightarrow ij}^{(0)}(M^2, \mu^2) + \frac{\alpha_s}{2\pi} \mathcal{H}_{ab \rightarrow ij}^{(1)}(M^2, \mu^2) + \frac{\alpha_s}{2\pi} \mathcal{H}_{ab \rightarrow ij}^{(0)}(M^2, \mu^2) \\ &\times \left(\left(A_a^{(1)} + A_b^{(1)} \right) \left(\log \bar{N} + \log \frac{\mu_F^2}{s} \right) - 2D_{ab \rightarrow ij}^{(1)} \right) \log \bar{N} \end{aligned}$$

- PDFs fitted in Mellin space

- Inverse Mellin transformation with the integration contour following the principal value procedure and minimal prescription:

$$M^2 \frac{d\sigma_{AB}}{dM^2}(\tau) = \frac{1}{2\pi i} \int dN \tau^{-N} M^2 \frac{d\sigma_{AB}}{dM^2}(N).$$

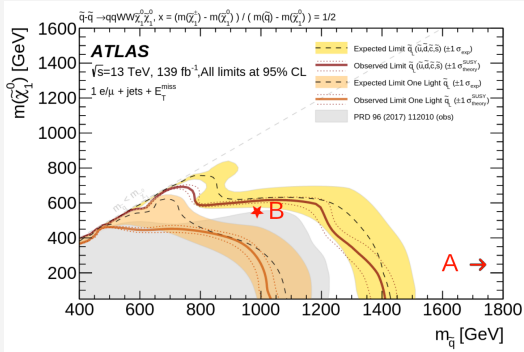
Scenarios

pMSSM-11 scenario A [TeV]		
M_1 0.25	M_2 0.25	M_3 −3.86
$M_{(U,D,Q)_{1,2}}$ 4.0	$M_{(U,D,Q)_3}$ 1.7	μ 1.33
$M_{(L,E)_{1,2}}$ 0.35	$M_{(L,E)_3}$ 0.47	$\tan \beta$ 36
M_A 4.0	A_0 2.8	
$m_{\tilde{\chi}_1^0}$ 0.249	$m_{\tilde{u}}$ 4.07	$m_{\tilde{g}}$ 3.90

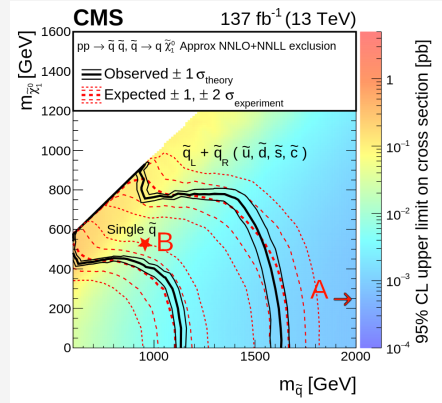
pMSSM-11 scenario B [TeV]		
M_1 0.51	M_2 0.48	M_3 3.00
$M_{(U,D,Q)_{1,2}}$ 0.9	$M_{(U,D,Q)_3}$ 2.0	μ −9.4
$M_{(L,E)_{1,2}}$ 1.85	$M_{(L,E)_3}$ 1.33	$\tan \beta$ 33
M_A 3.0	A_0 −3.4	
$m_{\tilde{\chi}_1^0}$ 0.505	$m_{\tilde{u}}$ 0.96	$m_{\tilde{g}}$ 2.94

Current Limits

ATLAS⁴



CMS⁵

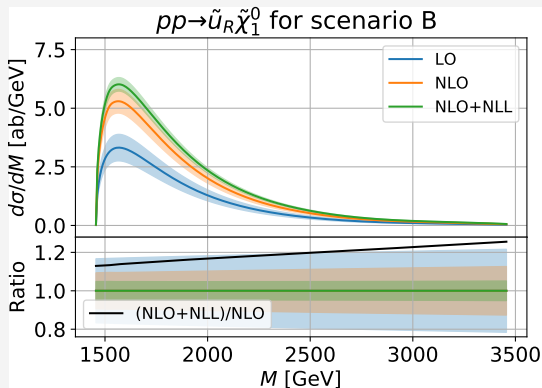
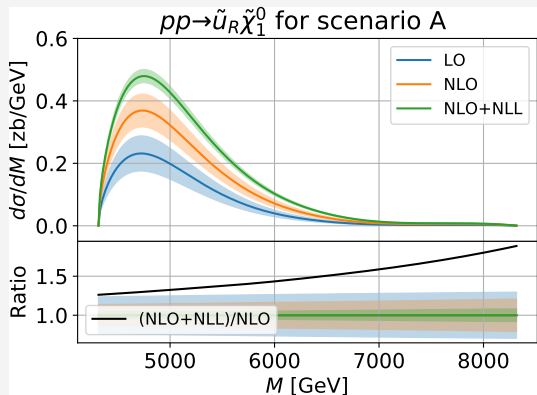


⁴Aad, G. et al. *Eur. Phys. J. C* **81**. [Erratum: *Eur.Phys.J.C* 81, 956 (2021)], 600. arXiv: 2101.01629 [hep-ex] (2021).

⁵Sirunyan, A. M. et al. *JHEP* **10**, 244. arXiv: 1908.04722 [hep-ex] (2019).

Invariant Mass

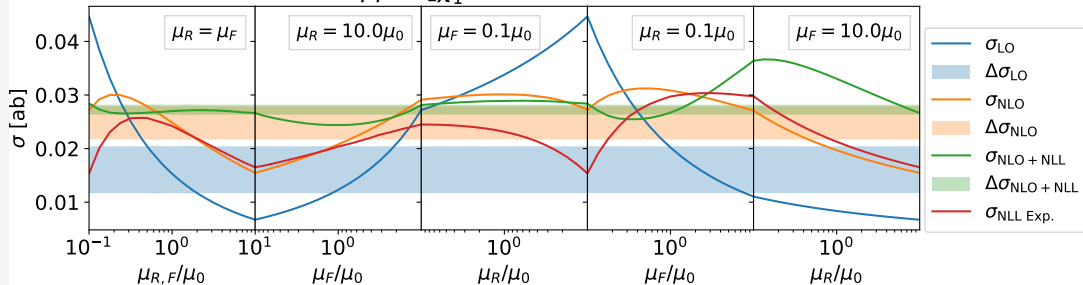
- ▶ $\sqrt{S} = 13$ TeV and MSHT20 PDF



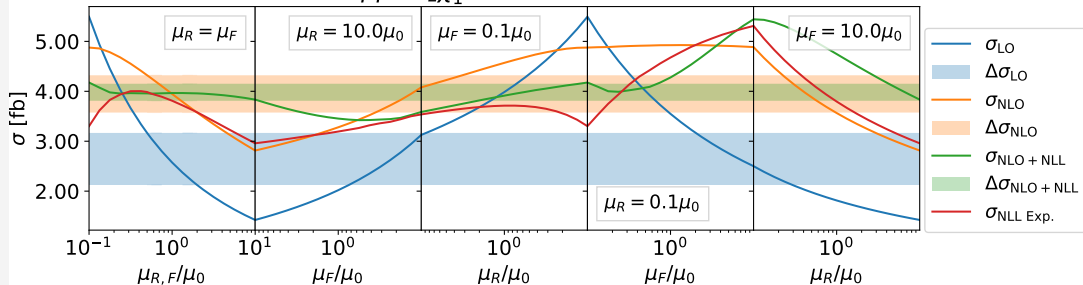
- ▶ Large resummation contributions very close to threshold
- ▶ Seven-point method around scale $\mu = M$ to estimate scale uncertainties

Scale Variation

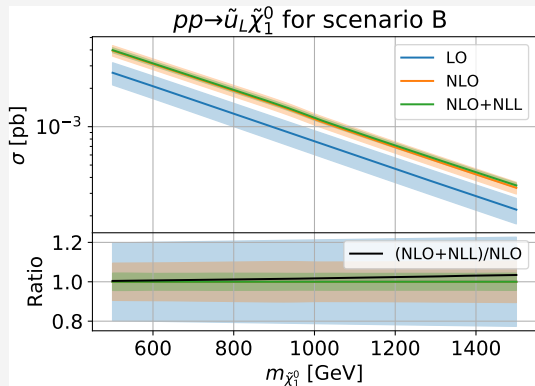
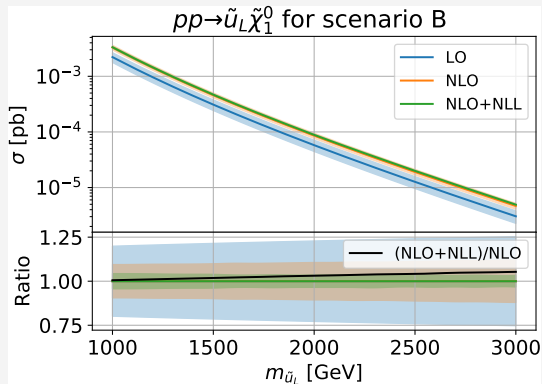
$pp \rightarrow \tilde{u}_L \tilde{\chi}_1^0$ for scenario A



$pp \rightarrow \tilde{u}_L \tilde{\chi}_1^0$ for scenario B

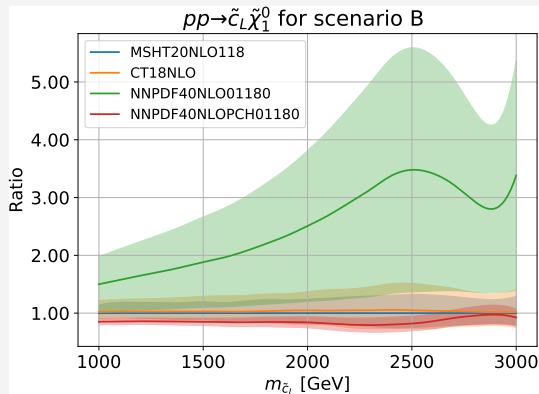
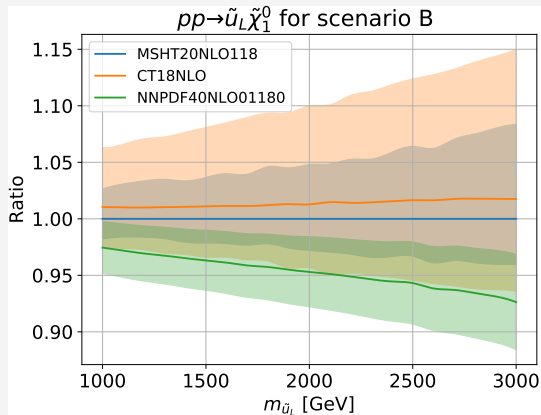


Total Cross sections



- ▶ NLL contributions of up to 6%
- ▶ Scale uncertainty reduced to $< 5\%$

Parton density uncertainties



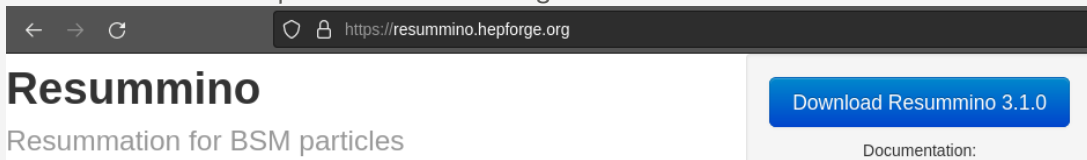
- ▶ Up-PDF uncertainties at 90% CL are consistent
- ▶ For 2 TeV up-squarks they range from $\pm 3.8\%$ to $\pm 7.05\%$
- ▶ Discrepancy in NNPDF40's fitted charm and perturbative charm treatment.

Conclusion

- ▶ Production of squark/gluino with gaugino relevant if squark and gluino pair production are too heavy for the LHC
- ▶ We computed QCD-NLO corrections with CS-dipoles and OS-subtraction for the NLL matching of soft gluon emissions
- ▶ Resummation increases the σ_{tot} by 2% to 6% for squark masses ranging from 1 TeV to 3 TeV
- ▶ Renormalisation and Factorisation scale dependence is reduced from 20% (LO) to 10% (NLO) to <5% (NLO+NLL)
- ▶ Current PDF uncertainties are of the same order as Resummation

Resummino

- ▶ Resummino 3.1 code published on HEPForge:



- ▶ approximate NNLO+NNLL for slepton-pair⁶, electroweakino-pair⁷, Z' and W' ⁸ production
- ▶ NLO+NLL for gaugino-gluino⁹ and gaugino-squark¹⁰ production

⁶Fiaschi, J. et al. *JHEP* **04**, 049. arXiv: 1911.02419 [hep-ph] (2020).

⁷Fiaschi, J. & Klasen, M. *Phys. Rev. D* **102**, 095021. arXiv: 2006.02294 [hep-ph] (2020).

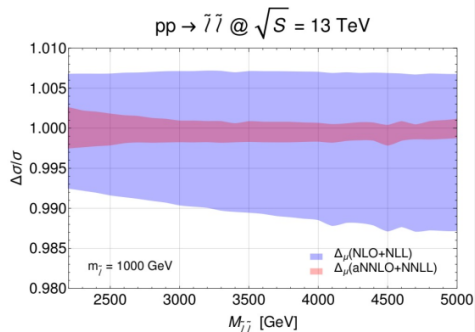
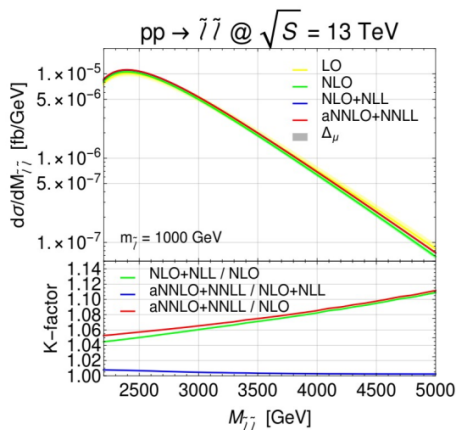
⁸Jezo, T. et al. *JHEP* **12**, 092. arXiv: 1410.4692 [hep-ph] (2014).

⁹Fuks, B. et al. *JHEP* **07**, 053. arXiv: 1604.01023 [hep-ph] (2016).

¹⁰Fiaschi, J. et al. arXiv: 2202.13416 [hep-ph] (Feb. 2022).

Thank you!

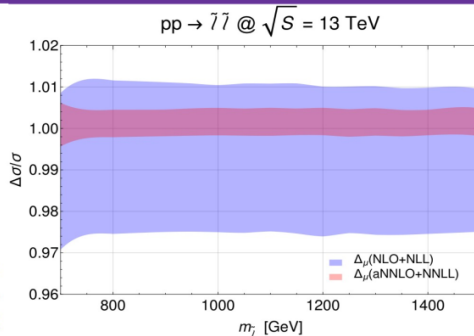
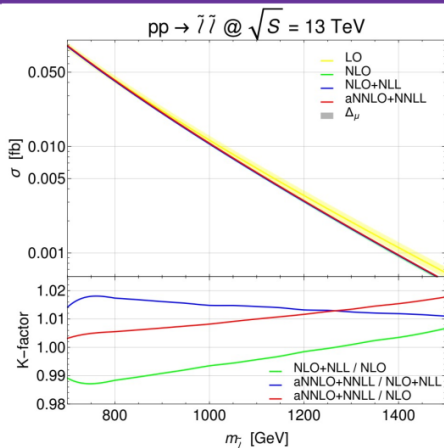
Slepton pair production



➤ Visible reduction of scale uncertainty from about 1% to about 0.1%.

- Resummation effects at NLL are more important at production threshold.
- K-factor increases from 4.5% to 11%
- The increase from NLO+NLL to aNNLO+NNLL is about 1%

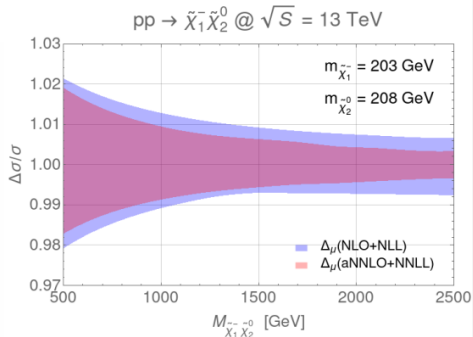
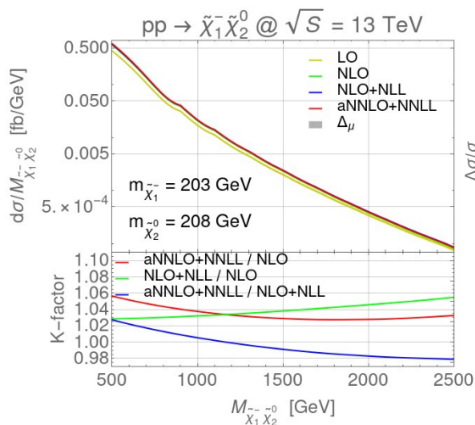
Slepton pair production



- Visible reduction of scale uncertainty from few % to few 0.1%.

- These cross sections correspond to:
 - more than 10 events at 700 GeV at current integrated luminosity of 139 fb^{-1} ;
 - 3 events at 1 TeV for LHC Run 3 goal of 300 fb^{-1} ;
 - Few events at 1.5 TeV for HL-LHC goal of 3 ab^{-1}
- aNNLO(+NNLL) corrections increase the NLO(+NLL) prediction by 1% - 2%.

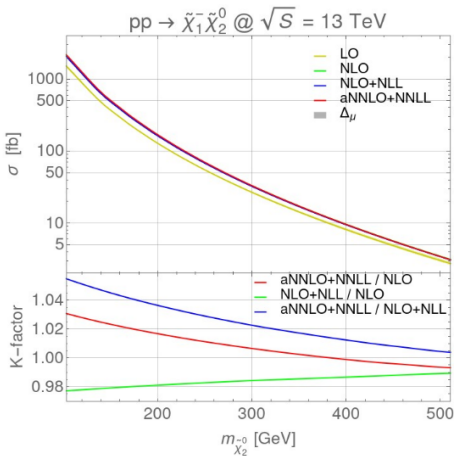
Mostly Higgsino Electroweakinos



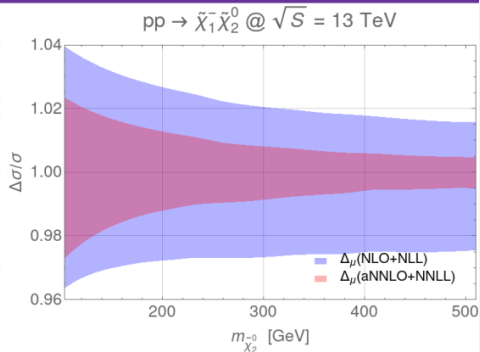
- Visible reduction of scale uncertainty from about from $\pm 2.1\%$ to $\pm 1.8\%$ ($\pm 0.6\%$ to $\pm 0.4\%$) at low (large) invariant masses.

- NLO corrections enhance the LO cross section by about 30%.
- NLL corrections enhance the NLO cross section by another 3-5%.
- aNNLO+NNLL give another $\pm 2\%$ correction to the NLO+NLL cross section.

Mostly Higgsino Electroweakinos



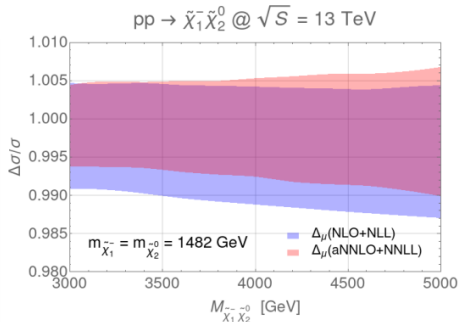
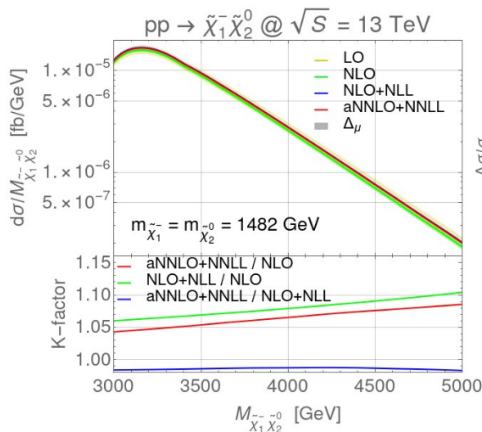
- NLL corrections reduce the NLO cross section by 1% to 2%.
- aNNLO+NNLL corrections increase the NLO+NLL cross section by up to 5% for low higgsino masses.



- Visible reduction of scale uncertainty from about from $\pm 4\%$ to $\pm 2.5\%$ (+1.5% and -2.5% to $\pm 0.5\%$) for light (heavy) Higgsinos

(Scale uncertainties are not so small, because of the relatively light Higgsino masses)

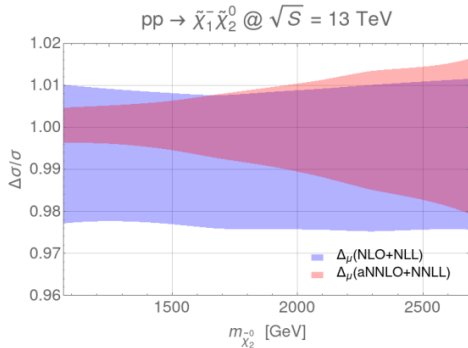
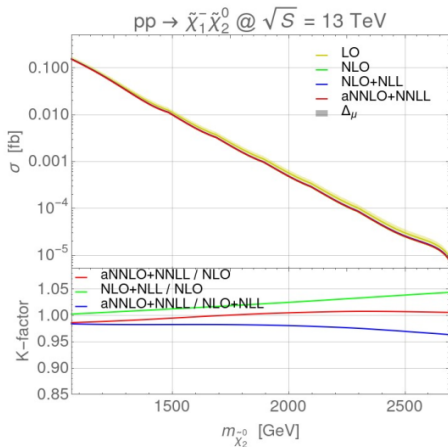
Mostly gauginos Electroweakinos



- Reduction of scale uncertainty on the lower bound from -0.9% to -0.6% at low invariant masses.

- NLL corrections increase the cross section between 5% to 10%.
- A decrease for all invariant masses is observed from NLO+NLL to aNNLO+NNLL.
- This behavior is correlated with large t - and u -channel contributions and large cancellations of the squared s -channel contribution with its interference terms.

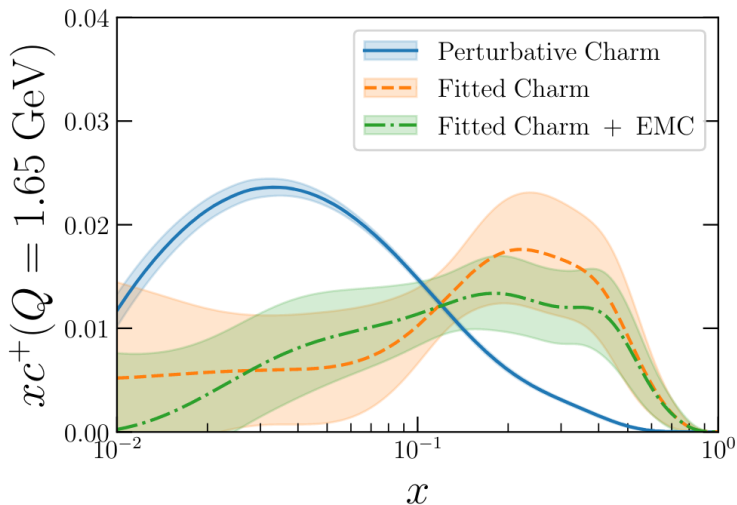
Mostly gauginos Electroweakinos



- NLL corrections increase the NLO cross section by up to 5%.
- aNNLO+NNLL corrections reduce the NLO+NLL cross section by up to 4% for high gaugino masses.

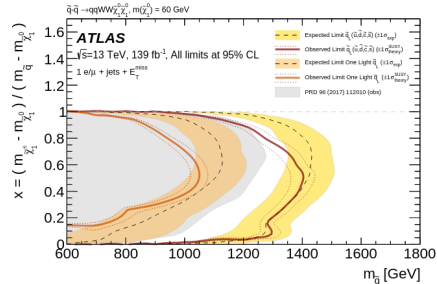
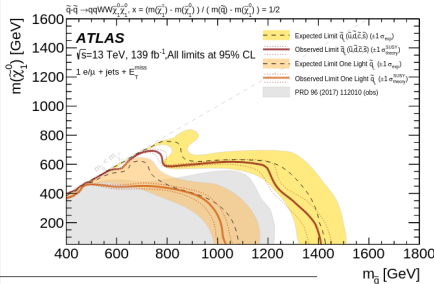
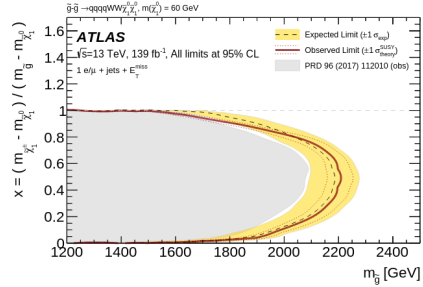
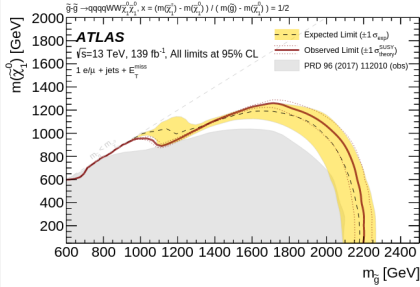
➤ Scale uncertainty gets reduced from 3% to about 1% for light gauginos, while it is stable at around 3% for heavy gauginos

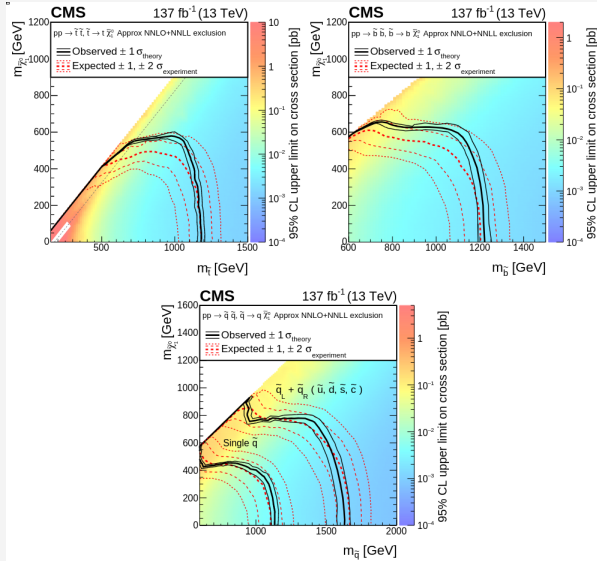
NNPDF40 charm



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¹¹Rojo, J. in 55th Rencontres de Moriond on QCD and High Energy Interactions (Apr. 2021). arXiv: 2104.09174 [hep-ph].





PDF fitting

To perform our computation in Mellin space we still need to transform the PDFs. This is achieved by fitting them in x-space to the function used by the MSTW collaboration

$$f(x) = A_0 x^{A_1} (1-x)^{A_2} (1 + A_3 \sqrt{x} + A_4 x + A_5 x^{\frac{3}{2}}) + A_6 x^2 + A_7 x^{\frac{5}{2}},$$

with the analytical result in Mellin space

$$F(x) = A_0 \Gamma(y) B'(A_1 + N, y) + A_3 B'(A_1 + N + \frac{1}{2}, y) + A_4 B'(A_1 + N + 1, y) \\ + A_5 B'(A_1 + N + \frac{3}{2}, y) + A_6 B'(A_1 + N + 2, y) + A_7 B'(A_1 + N + \frac{5}{2}, y)$$

and

$$B'(x, y) = B'(x, A_2 + 1) = B(x, y) / \Gamma(y) = B(x, y) / \Gamma(y).$$