Small-x resummation and its impact for the FPF

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FPF 4 — 1 Feb 2022

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Small-x resummation

Perturbative coefficient functions and splitting functions contain logarithms of x that are single-logarithmically enhanced:

$$
\begin{aligned}
P(x,\alpha_s) \text{ or } C(x,\alpha_s) = \quad & a_0 \\
& + \alpha_s \left[a_1 \ln \frac{1}{x} + b_1 \right] \\
& + \alpha_s^2 \left[a_2 \ln^2 \frac{1}{x} + b_2 \ln \frac{1}{x} + c_2 \right] \\
& + \alpha_s^3 \left[a_3 \ln^3 \frac{1}{x} + b_3 \ln^2 \frac{1}{x} + c_3 \ln \frac{1}{x} + d_3 \right] \\
& + \alpha_s^4 \left[a_4 \ln^4 \frac{1}{x} + b_4 \ln^3 \frac{1}{x} + c_4 \ln^2 \frac{1}{x} + d_4 \ln \frac{1}{x} + e_4 \right] \\
& + \dots
\end{aligned}
$$

When $\alpha_s \ln \frac{1}{x} \sim 1$ the fixed-order expansion is no longer predictive!

$\Downarrow$

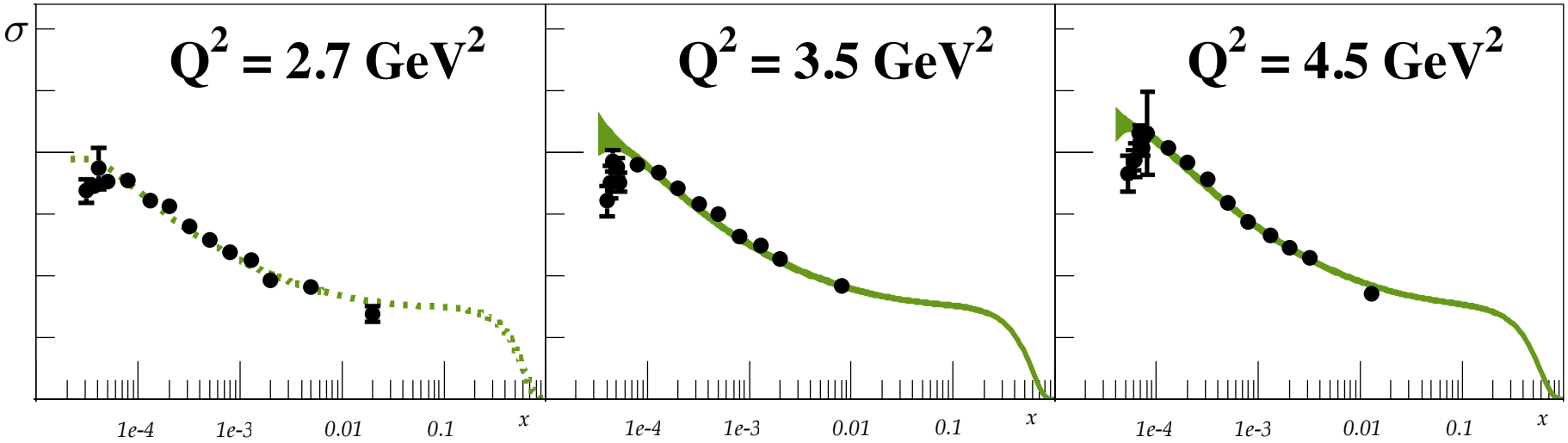
Resummation

PDF fits with small-x resummation

Low x at HERA: importance of resummation in PDF fits

Deep-inelastic scattering (DIS) data from HERA extend down to $x \sim 3 \times 10^{-5}$

Tension between HERA data at low Q^2 and low x with fixed-order theory



Also leads to a deterioration of the χ^2 when including low-Q^2 data

Attempts to explain this deviation with higher twists, phenomenological models, ...

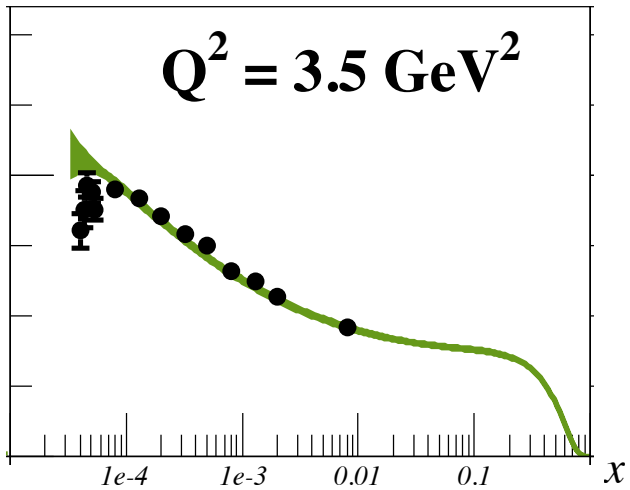
Successful description of this region when including small-x resummation!

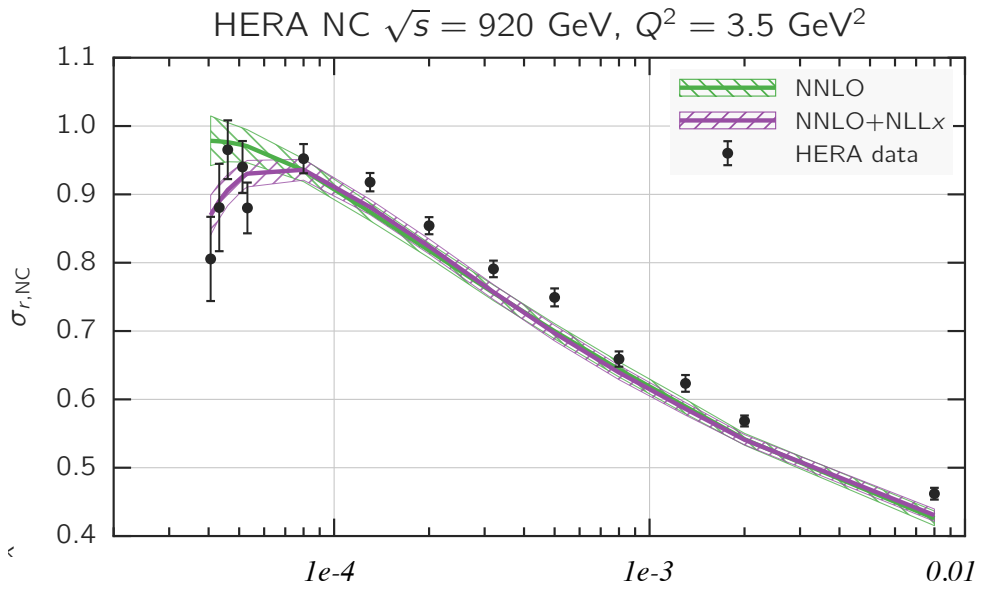
- NNPDF framework [Ball,Bertone,MB,Marzani,Rojo,Rottoli 1710.05935]
- xFitter framework [xFitterCollaboration+MB 1802.00064] [MB,Giuli 1902.11125]

Significantly improved description of the HERA data

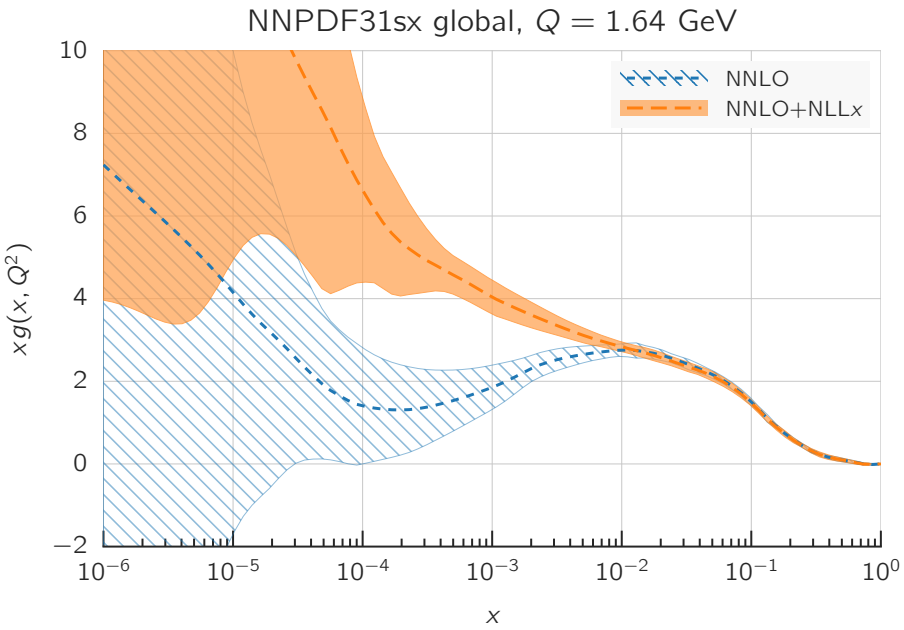
$\chi^2/N_{\rm dat}$	NNLO	NNLO+NLLx
xFitter	**1.23**	**1.17**
NNPDF3.1sx	**1.130**	**1.100**

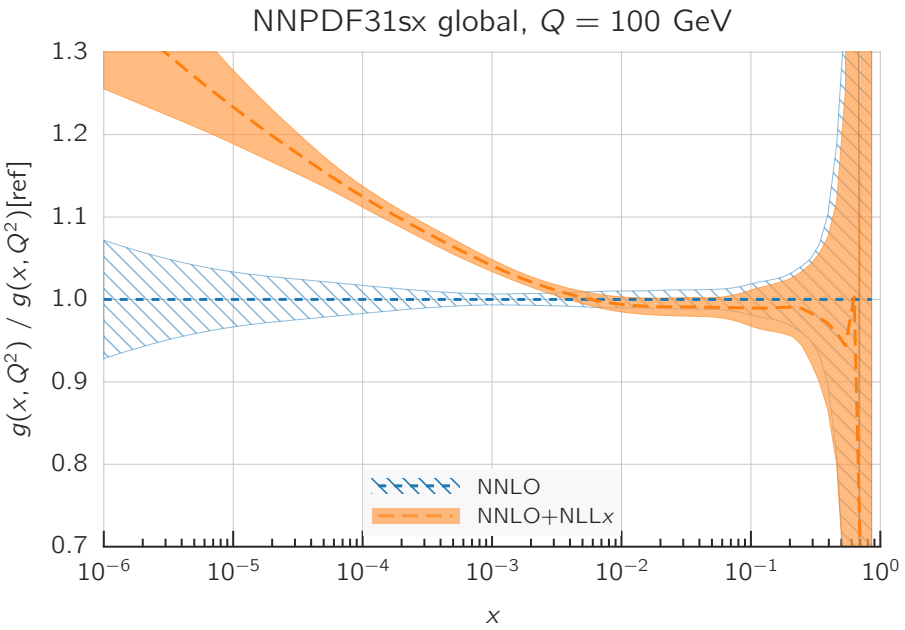
Substantial improvement due to better description of small-x low-Q^2 HERA data





Fit results: impact on gluon PDF

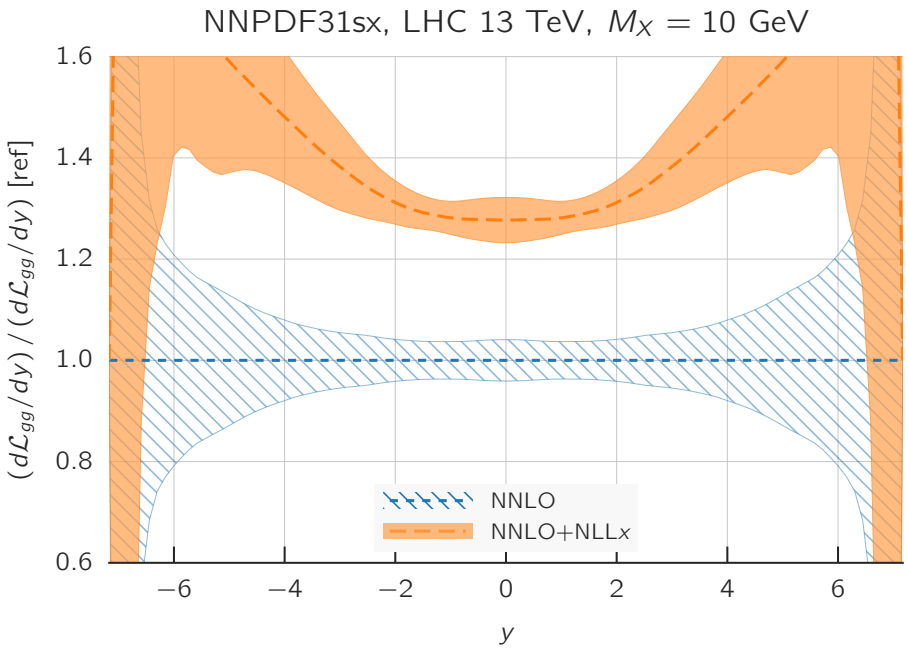


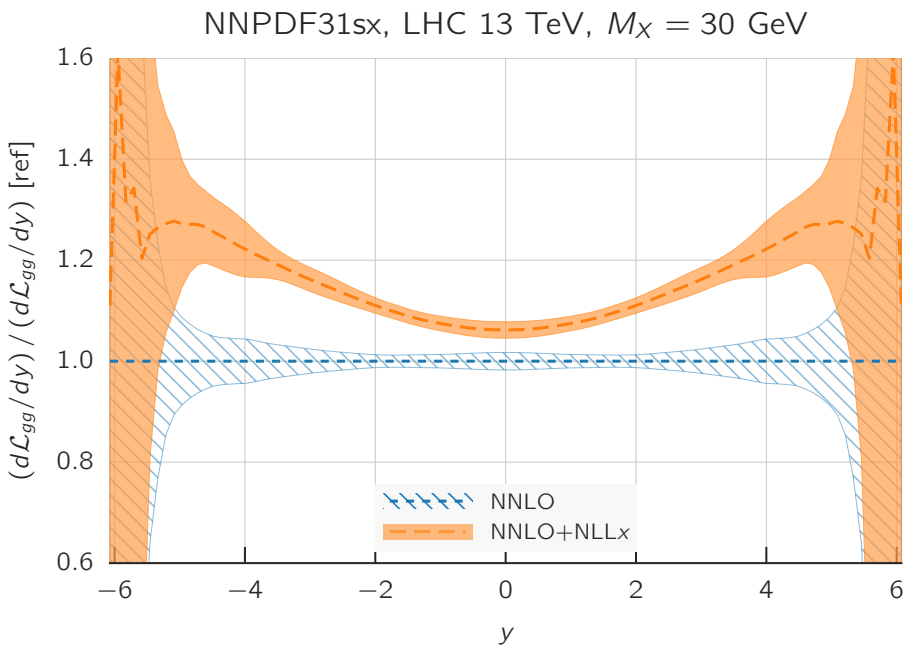


Note: future higher energy colliders will probe smaller values of x $\left(x_{\min} \sim Q^2/s\right)$
$\rightarrow$ small-x resummation will be even more important in future!

Impact on parton luminosities

Gluon-gluon parton luminosities

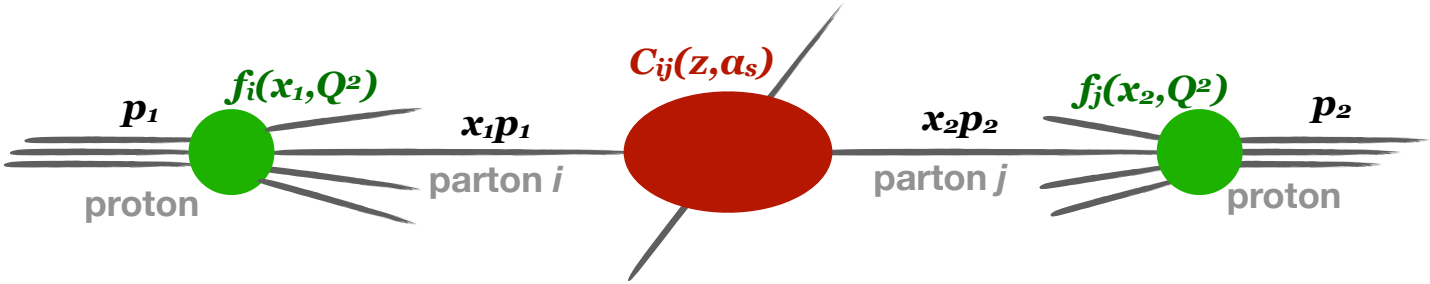




Significant impact for small invariant masses, especially at large rapidities

LHC phenomenology

Resummation of LHC observables



Challenges:

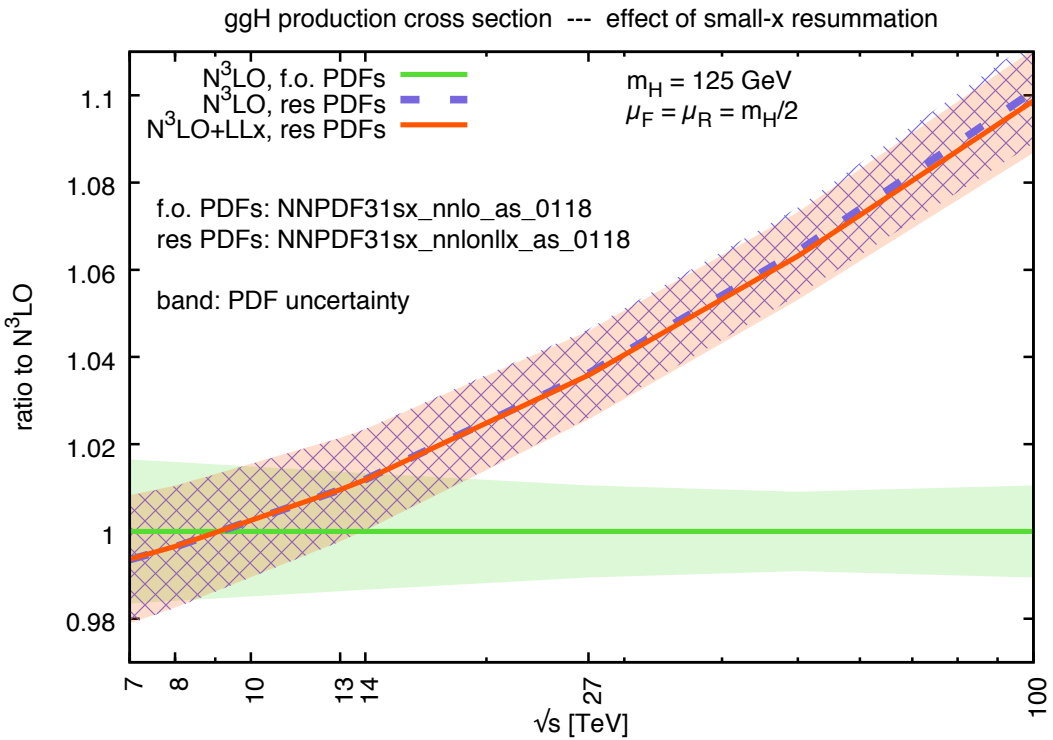
- two protons in the initial state ✓
- want to describe differential distributions ✓

Processes considered so far in HELL:

- $gg \to H$ (inclusive cross section) ✓
- $c\bar{c}$, $b\bar{b}$ pair production (fully differential) *(almost done)*
- Drell-Yan (fully differential) *(in progress)*

Impact of resummation in ggH

$gg \to H$ inclusive cross section [MB,Marzani 1802.07758] [MB 1805.08785]

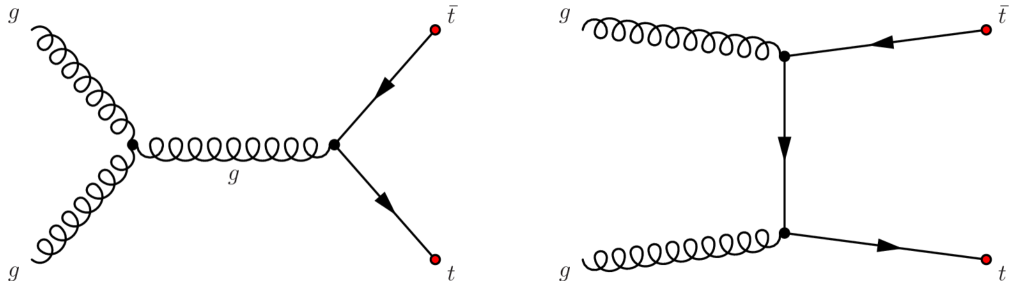


ggH cross section at FCC-hh can be $\sim 10\%$ larger than expected with NNLO PDFs!

At LHC $+1\%$ effect

Charm (and bottom) pair production at LHC

Fully differential heavy-quark pair production [MB,FS (in preparation)]



We have resummed the cross section for different kinematics:

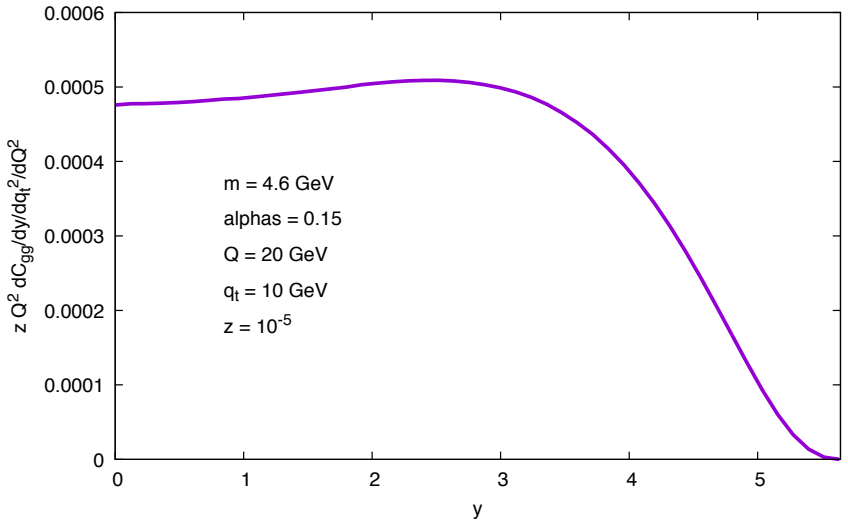
- heavy-quark pair: $\dfrac{d\sigma}{dQ^2\, dY\, dq_t}$
- single heavy quark: $\dfrac{d\sigma}{dy\, dp_t}$

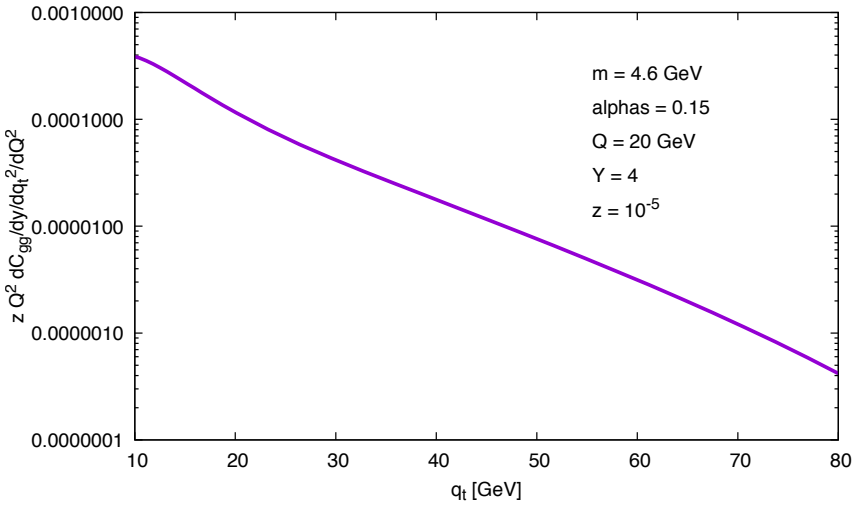
Small-x resummation crucial for **charm and bottom production**

- sensitive to very small $x \to$ useful to constrain the PDFs
- key process for FPF physics

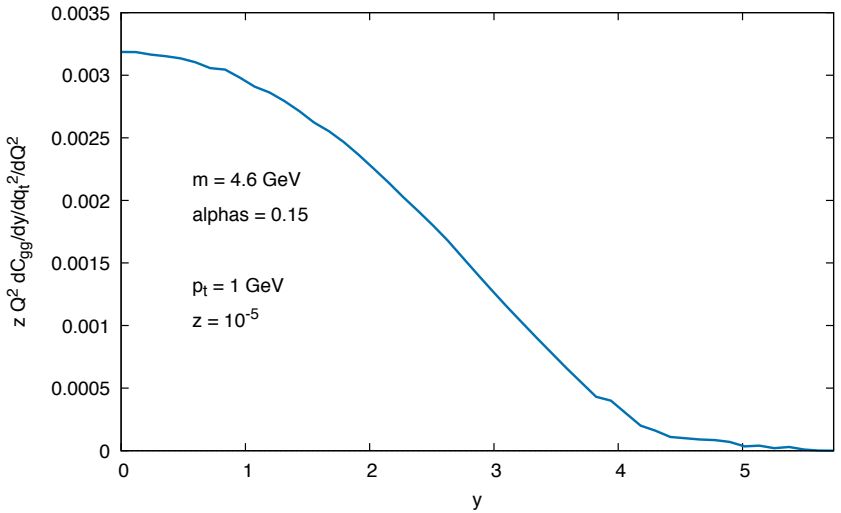
Heavy-quark pair production at LHC: preliminary results

Parton-level purely-resummed results for $\frac{d\sigma}{dQ^2\, dY\, dq_t}$ (pair kinematics)





Parton-level purely-resummed results for $\frac{d\sigma}{dy\, dp_t}$ (single-quark kinematics)



numerical instabilities still around

code optimization in progress

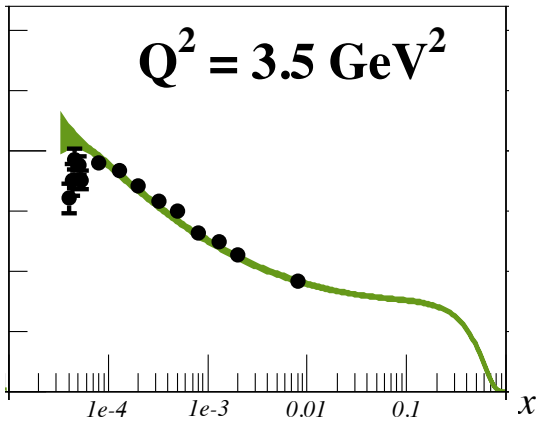
Concluding remarks

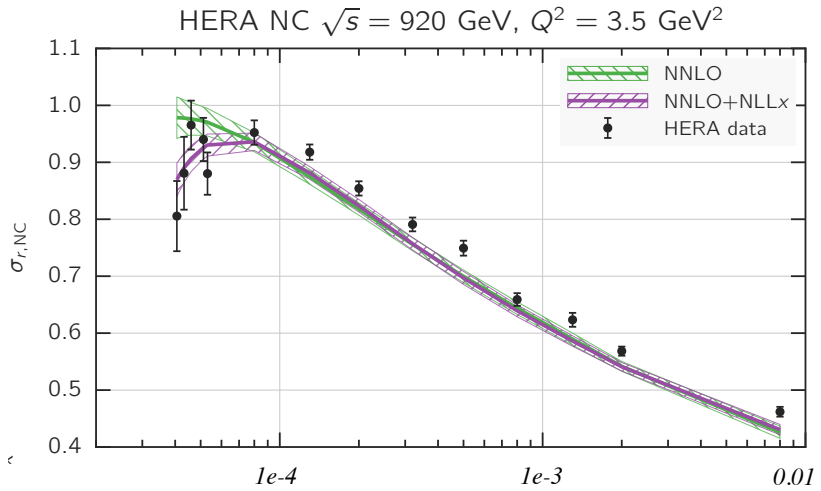
Key messages:

- resummation is needed at small-x
- it stabilizes perturbative behaviour
- improved PDF fits
- large impact on gluon PDF for $x \lesssim 10^{-3}$
- significant impact expected at LHC at low invariant mass and large rapidity

Backup slides

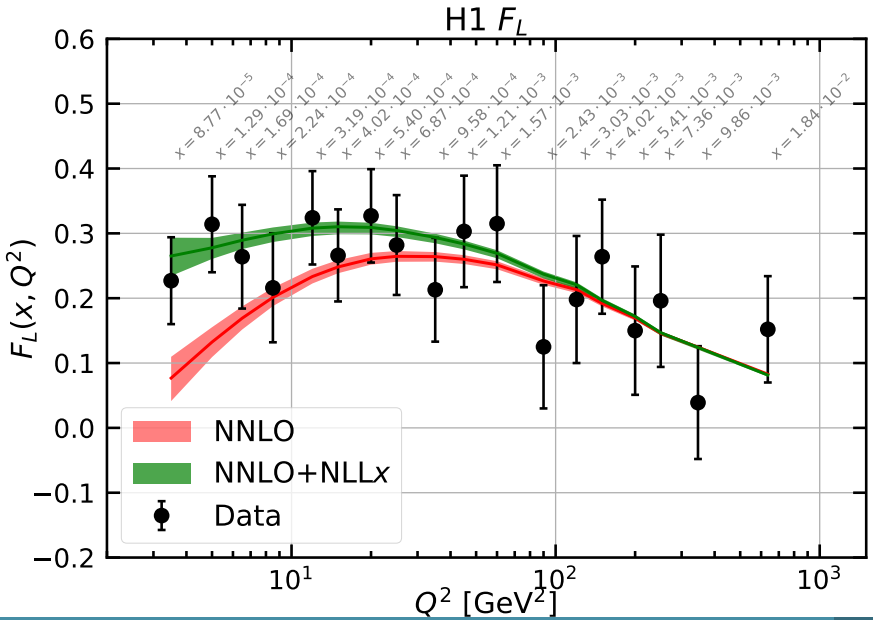
How resummation reproduces the turnover in HERA data





$$\sigma_{r,\mathrm{NC}} = F_2(x_{\mathrm{Bj}}, Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x_{\mathrm{Bj}}, Q^2) \qquad y = \frac{Q^2}{x_{\mathrm{Bj}} s}$$

The better description mostly comes from a larger resummed F_L

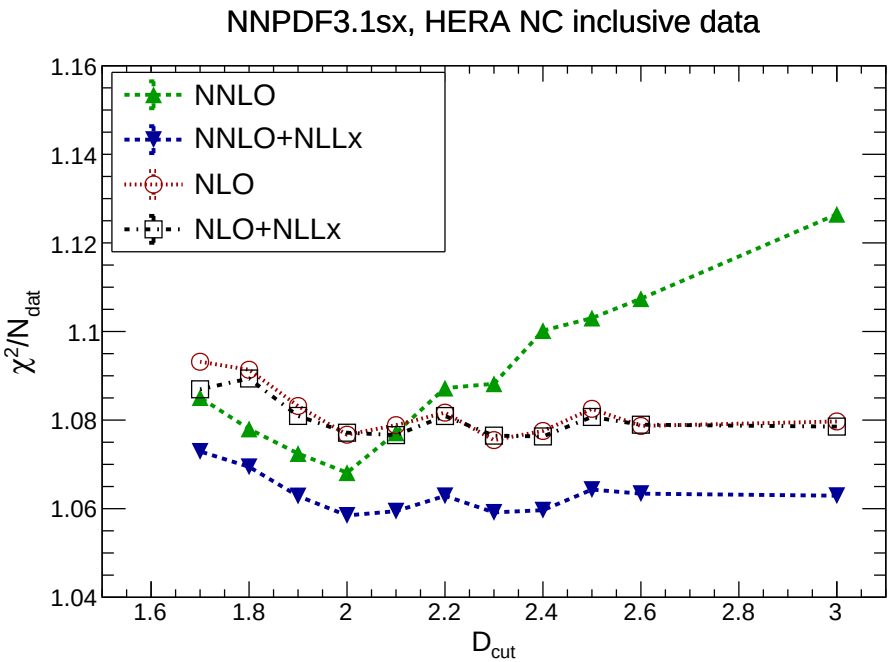


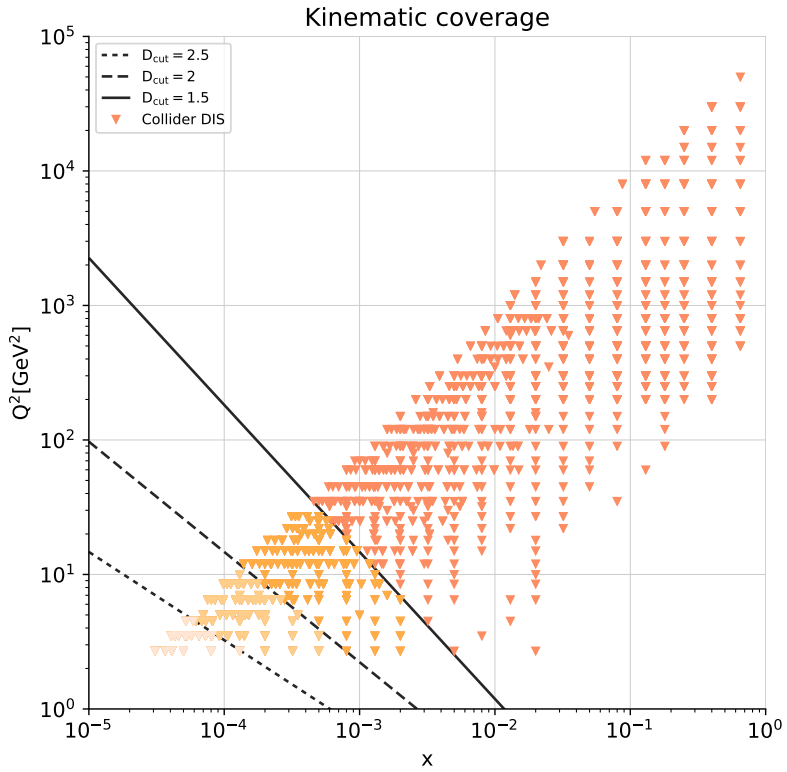
Fit results: χ^2 as quality estimator and the onset of BFKL dynamics

$\chi^2/N_{\rm dat}$	NLO	NLO+NLLx	NNLO	NNLO+NLLx
xFitter			**1.23**	**1.17**
NNPDF3.1sx	**1.117**	**1.120**	**1.130**	**1.100**
	these are similar		largest	smallest

Hierarchy as expected from splitting function behaviour!

Mostly due to HERA data: we study the $\chi^2/N_{\rm dat}$ profile as we cut out HERA data at small x small Q^2





Why is the effect of resummation mostly driven by the PDFs?

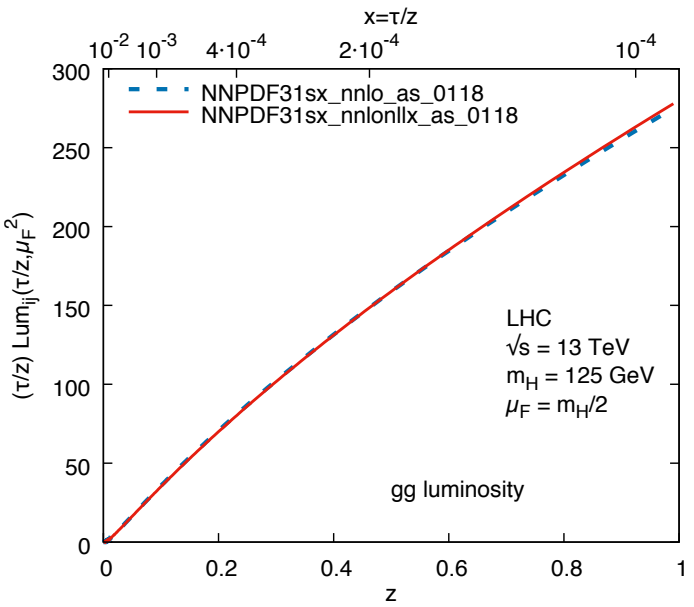
Let's consider the collinear factorization formula

$$\frac{d\sigma}{dQ^2 dY...} = \int_\tau^1 \frac{dz}{z} \int d\hat{y}\, f_i\left(\sqrt{\frac{\tau}{z}} e^{\hat{y}}, Q^2\right) f_j\left(\sqrt{\frac{\tau}{z}} e^{-\hat{y}}, Q^2\right) \frac{dC_{ij}}{dy...}(z, Y - \hat{y}, ..., \alpha_s)$$

The small z integration region, where logs in C are large, is weighted by the PDFs at large momentum fractions $x = \sqrt{\frac{\tau}{z}} e^{\pm \hat{y}}$
Since PDFs die fast at large x, especially the gluon, the small-z region is suppressed!

Rather, the large z region is enhanced by the gluon-gluon luminosity
In that region, the difference between fixed-order and resummed PDFs is large

LHC:



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