

New insights on the proton's structure

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Istituto Nazionale di Fisica Nucleare



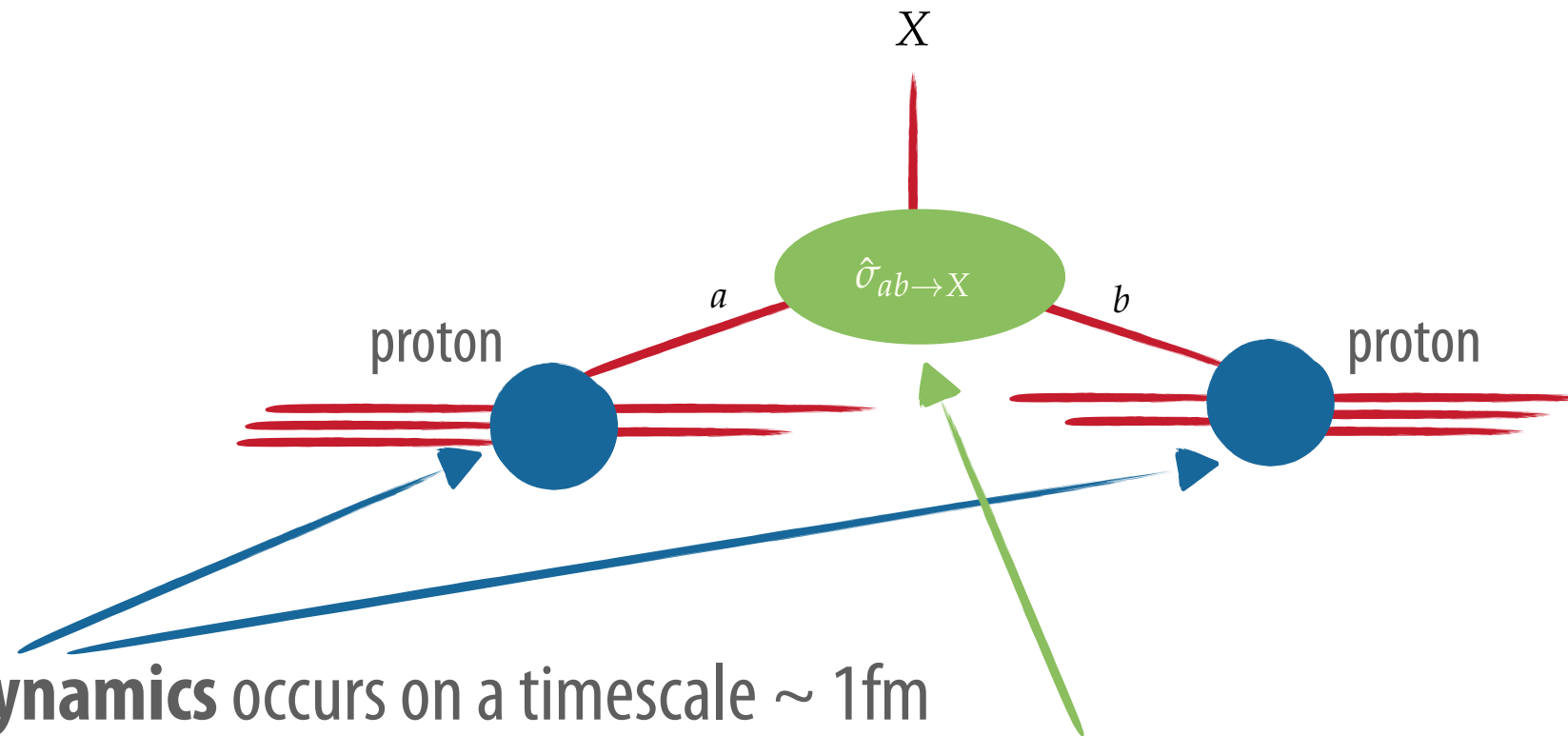
Motivation

I'm not very interested in the proton's structure per se
(it's a composite object, a real mess)

However, knowing some of its properties is fundamental for precision LHC phenomenology

And precision is the keyword for the future of LHC

QCD Collinear Factorization Theorem

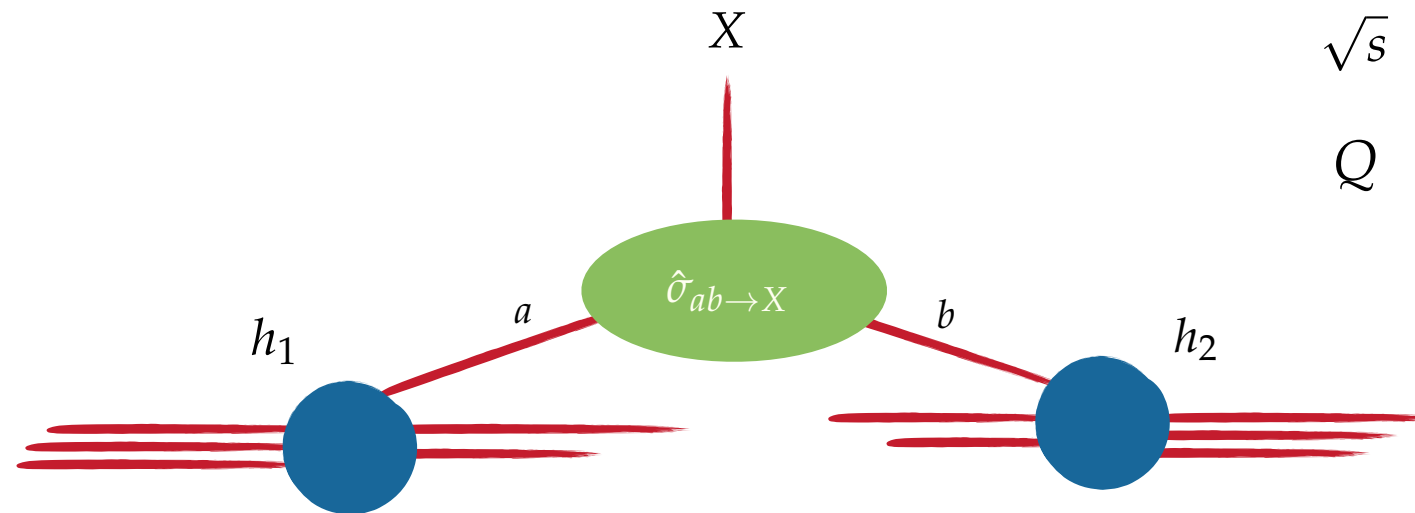


Proton's dynamics occurs on a timescale $\sim 1\text{fm}$

Production of a heavy particle e.g. Higgs Production (**hard process**)
occurs on timescale $1/M_X \sim 1/100 \text{ GeV} \sim 0.002 \text{ fm}$

Large separation between scales allows to separate the hard process and treat it **independently** from the hadronic dynamics: **collinear factorization**

QCD Collinear Factorization Theorem



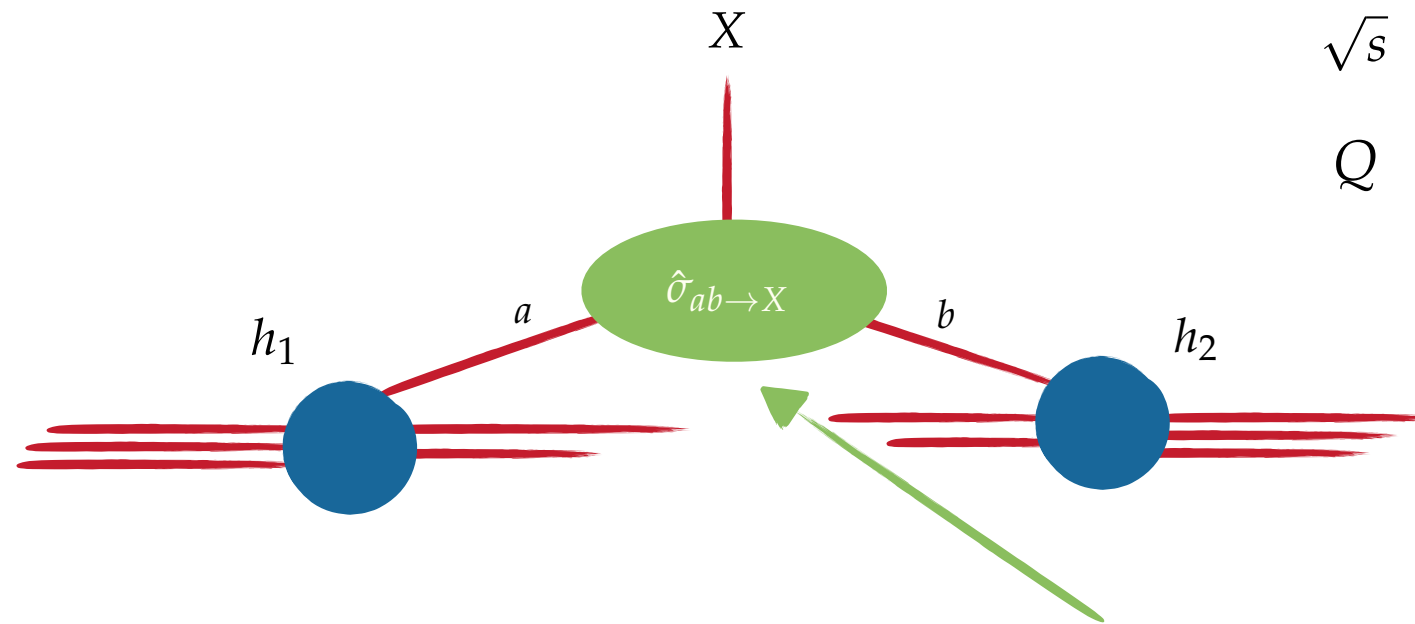
\sqrt{s} centre-of-mass energy

Q hard scale of the process

$$\sigma_X(s, Q^2) = \sum_{a,b} \int dx_1 dx_2 f_{a/h_1}(x_1, Q^2) f_{b/h_2}(x_2, Q^2) \hat{\sigma}_{ab \rightarrow X}(Q^2, x_1 x_2 s)$$

$$\sigma_X(Q^2, s) = \sum_{a,b} f_{a/h_1}(Q^2) \otimes f_{b/h_2}(Q^2) \otimes \hat{\sigma}_{ab \rightarrow X}(Q^2, s)$$

QCD Collinear Factorization Theorem



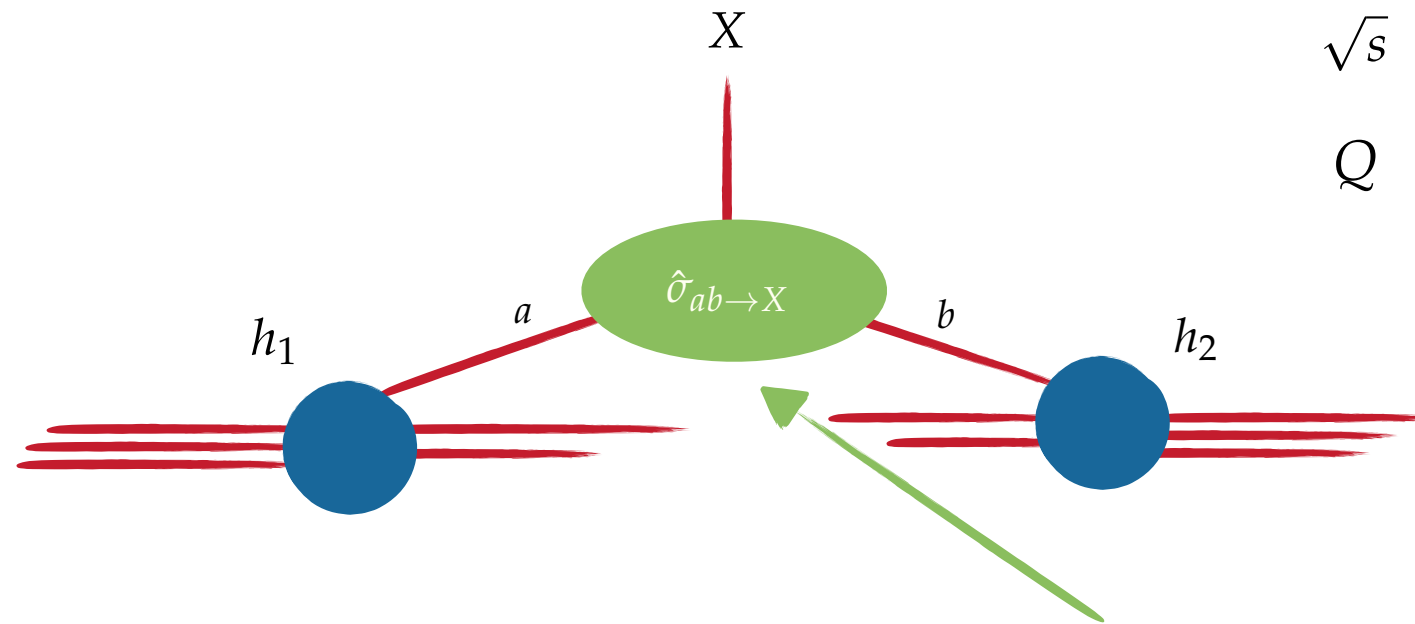
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partonic cross-section
short-distance: **perturbative**

QCD Collinear Factorization Theorem



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partonic cross-section

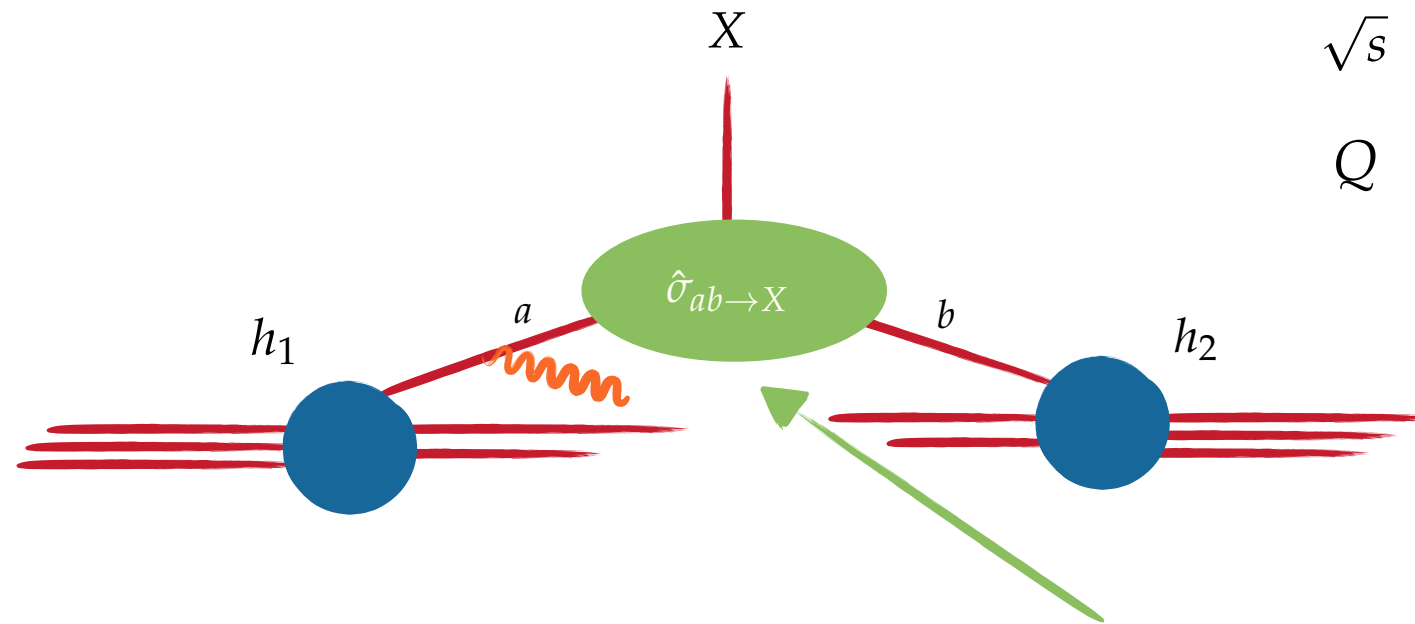
short-distance: **perturbative**

QCD at short distance is perturbative
(**asymptotic freedom**)

$$\hat{\sigma} = \hat{\sigma}_0(1 + \dots)$$

L0

QCD Collinear Factorization Theorem



\sqrt{s} centre-of-mass energy

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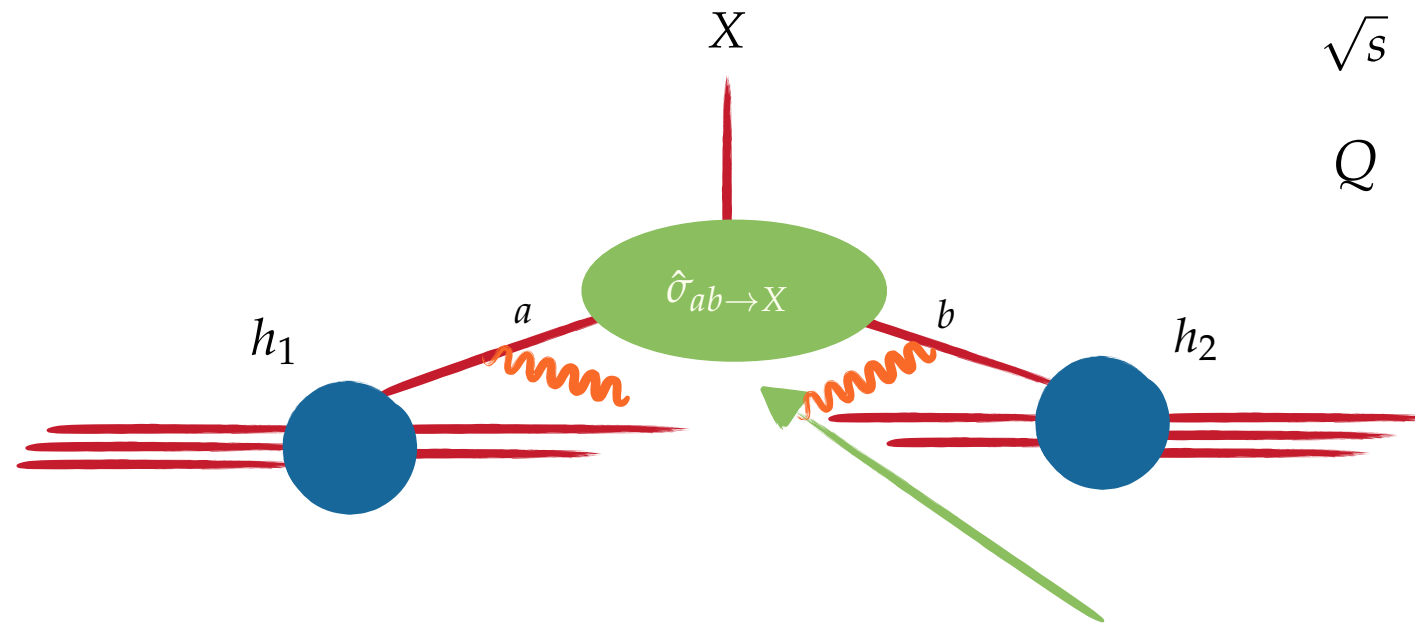
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QCD at short distance is perturbative
(**asymptotic freedom**)

partonic cross-section
short-distance: **perturbative**

$$\hat{\sigma} = \hat{\sigma}_0 (1 + \underbrace{\alpha_s c_1}_{\text{NLO}} + \alpha_s^2 c_2 + \dots)$$

QCD Collinear Factorization Theorem



\sqrt{s} centre-of-mass energy

Q hard scale of the process

$$\sigma_X(s, Q^2) = \sum_{a,b} \int dx_1 dx_2 f_{a/h_1}(x_1, Q^2) f_{b/h_2}(x_2, Q^2) \hat{\sigma}_{ab \rightarrow X}(Q^2, x_1 x_2 s)$$

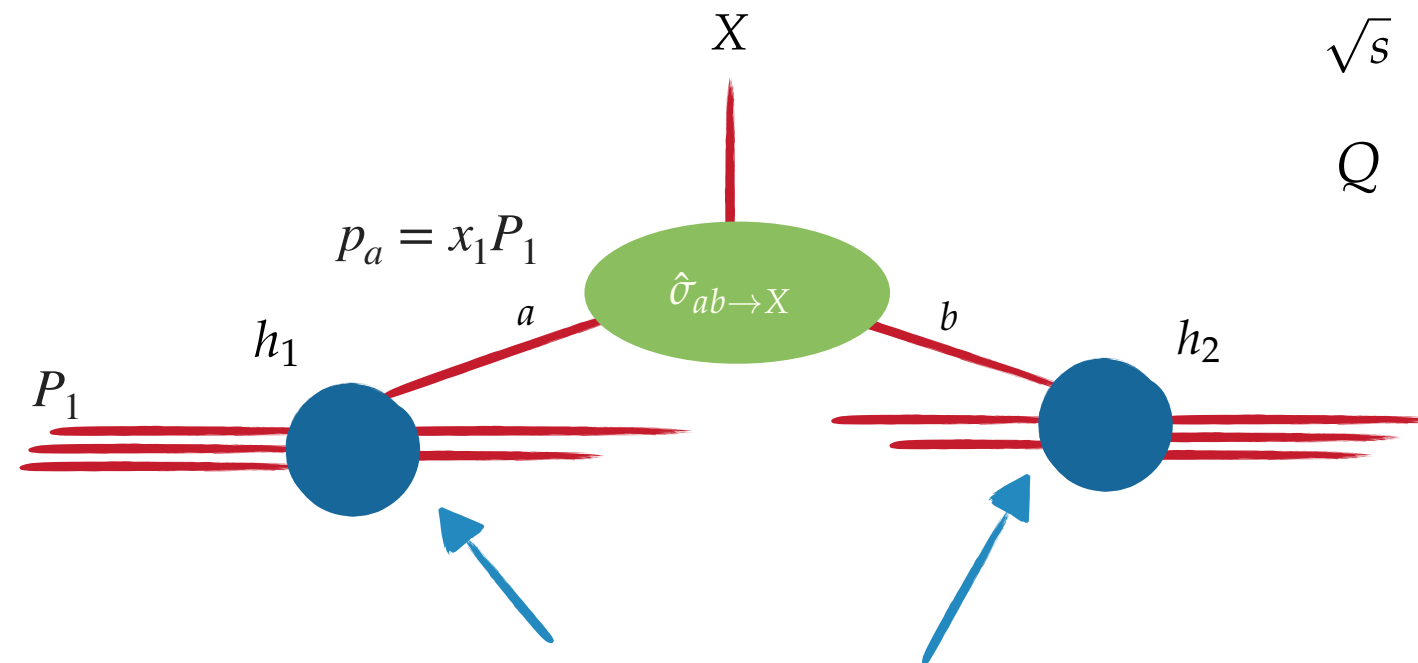
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short-distance: **perturbative**

$$\hat{\sigma} = \hat{\sigma}_0 (1 + \alpha_s c_1 + \alpha_s^2 c_2 + \dots)$$

NNLO

QCD Collinear Factorization Theorem



\sqrt{s} centre-of-mass energy

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Parton Distribution Functions (PDFs)

long-distance: **non-perturbative**

Parton distribution functions (PDFs) are **universal** objects which encode information on the substructure of the proton and which describe the dynamics of **quarks** and **gluons (partons)**

PDFs are currently **extracted from experiments**

Parton Distribution Functions

PDFs depend on two kinematic variables

$$f(x, Q^2)$$

fraction of the momentum of the proton

$$p = xP$$

$$0 < x \leq 1$$

Parton Distribution Functions

PDFs depend on two kinematic variables

$$f(x, Q^2)$$

factorization scale

The scale dependence is a consequence of the factorization of collinear infrared divergences from the partonic cross section into the PDFs

(similar to the renormalization scale)

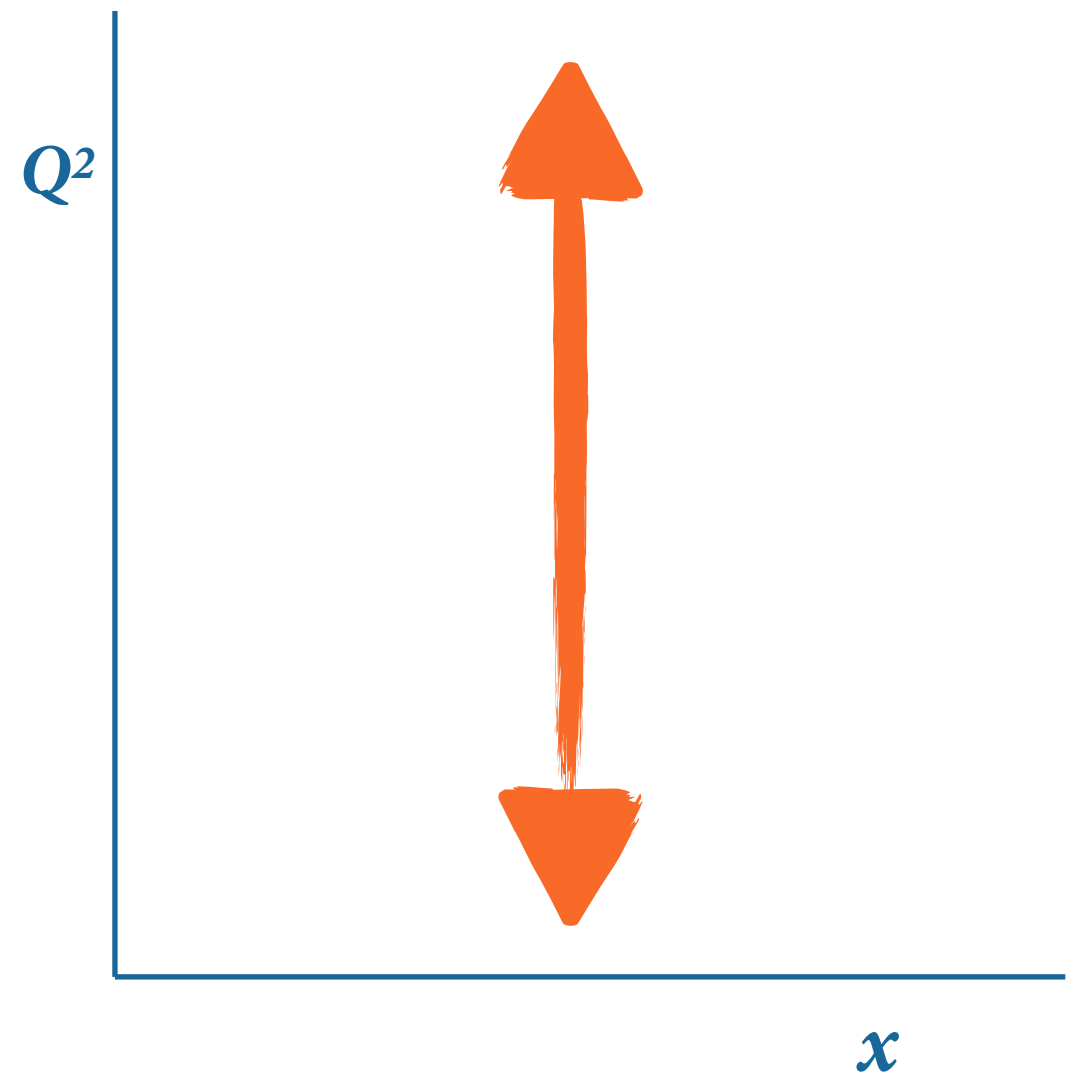
Parton Distribution Functions

PDFs depend on two kinematic variables

$$f(x, Q^2)$$

Q^2 dependence is encoded in the **DGLAP evolution equation**

$$Q^2 \frac{\partial}{\partial Q^2} f_i(x, Q^2) = \int_x^1 \frac{dz}{z} P_{ij} \left(\frac{x}{z}, \alpha_s(Q^2) \right) f_j(z, Q^2)$$



Parton Distribution Functions

PDFs depend on two kinematic variables

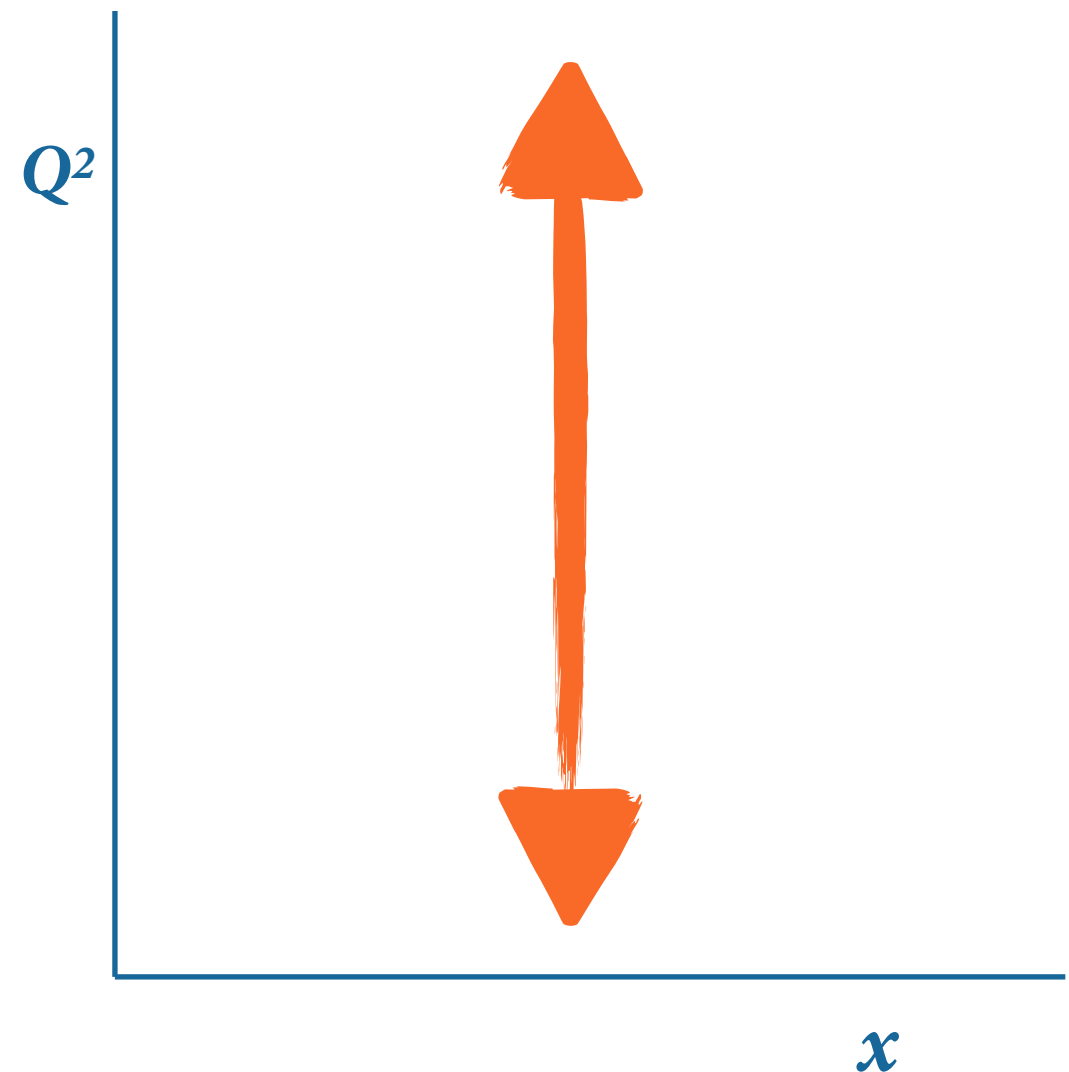
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splitting functions

$$P_{ij}(x, \alpha_s(Q^2)) = \alpha_s P_{ij}^{(0)}(x) + \alpha_s^2 P_{ij}^{(1)}(x) + \alpha_s^3 P_{ij}^{(2)}(x) + \dots$$



DGLAP equation

$$Q^2 \frac{\partial}{\partial Q^2} f_i(x, Q^2) = \int_x^1 \frac{dz}{z} P_{ij} \left(\frac{x}{z}, \alpha_s(Q^2) \right) f_j(z, Q^2)$$

$2n_f + 1$ **coupled** differential equation

number of (active) flavours

However, strong interactions do not tell apart quarks and antiquarks (**charge conjugation** and $SU(n_f)$ **flavour symmetry**)

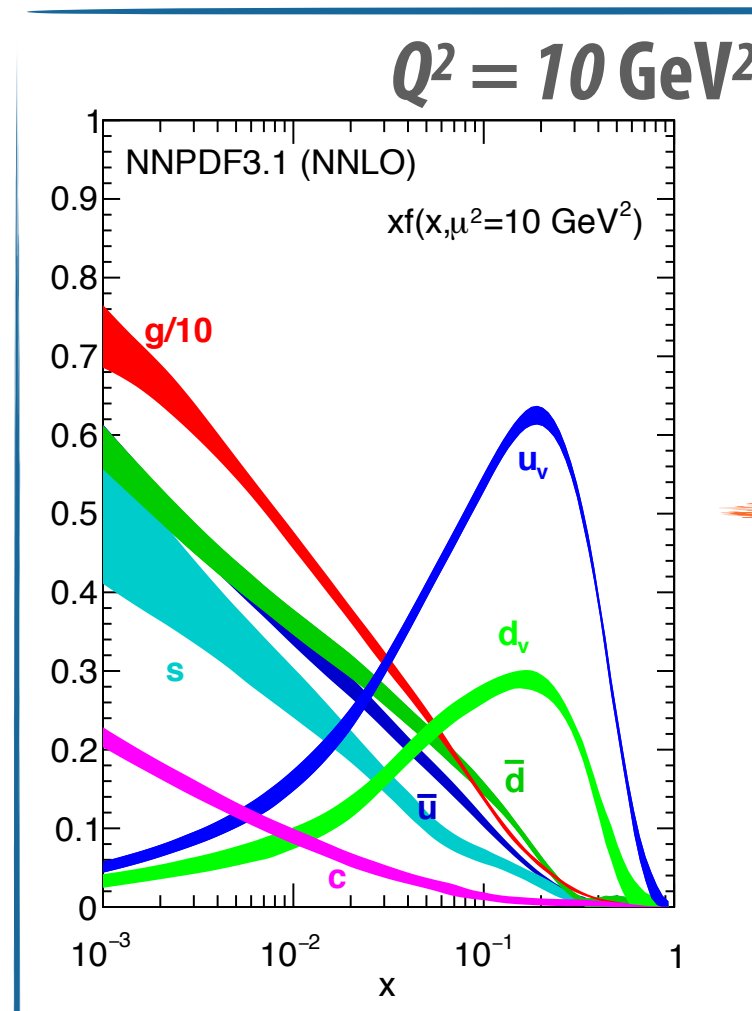
$$P_{q_i q_j} = P_{\bar{q}_i \bar{q}_j}, \quad P_{q_i \bar{q}_j} = P_{\bar{q}_i q_j}, \quad P_{q_i g} = P_{\bar{q}_i g} \equiv P_{qg}, \quad P_{g q_i} = P_{g \bar{q}_i} \equiv P_{gq}$$

Only **singlet combination** couples to **gluon**

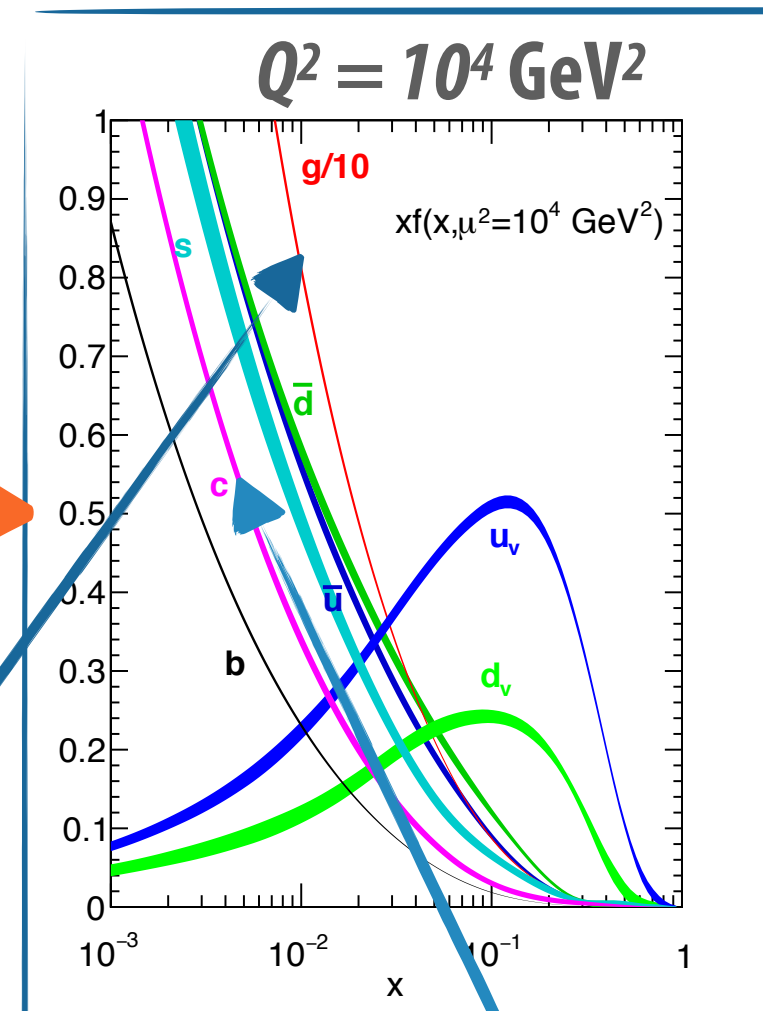
$$\Sigma(x, Q^2) = \sum_i [q_i(x, t) + \bar{q}_i(x, t)]$$

$$Q^2 \frac{\partial}{\partial \ln Q^2} \begin{pmatrix} \Sigma \\ g \end{pmatrix} = \begin{pmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} \Sigma \\ g \end{pmatrix}$$

DGLAP equation



Q^2 evolution



growth of small- x gluon

Parton loses momentum and shifts at smaller values of x

Variable Flavour Number Schemes

Consider heavy quark production in DIS.

Since the quark is massive, there are **no collinear divergences**
-> no need to factorize them into PDFs

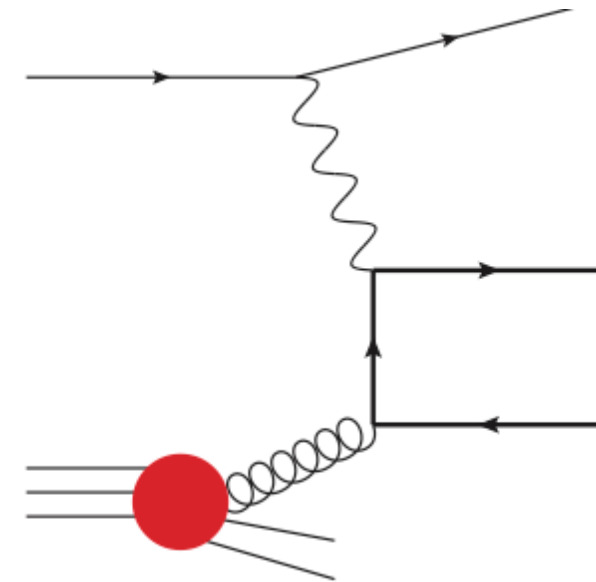
Moreover, charm, beauty and top are heavier than the proton
-> unlikely to be able to find them inside the proton

Naive approach: consider only light partons ($n_f=3$), and heavy quarks can be produced only via gluon splittings outside the proton

Caveat: $g \rightarrow Q\bar{Q}$ splittings behave as powers of $\log(m/Q)$, one extra power for each extra order in alphas

if $\alpha_s \log \frac{Q}{m} \sim 1$ then these logarithmic terms invalidate the perturbative expansion

Therefore, it is better to factorize these logs (which are basically regularized collinear divergences) into the PDFs once the scale Q is larger than a threshold $\mu_m \sim m$
In this way the log is resummed through DGLAP evolution



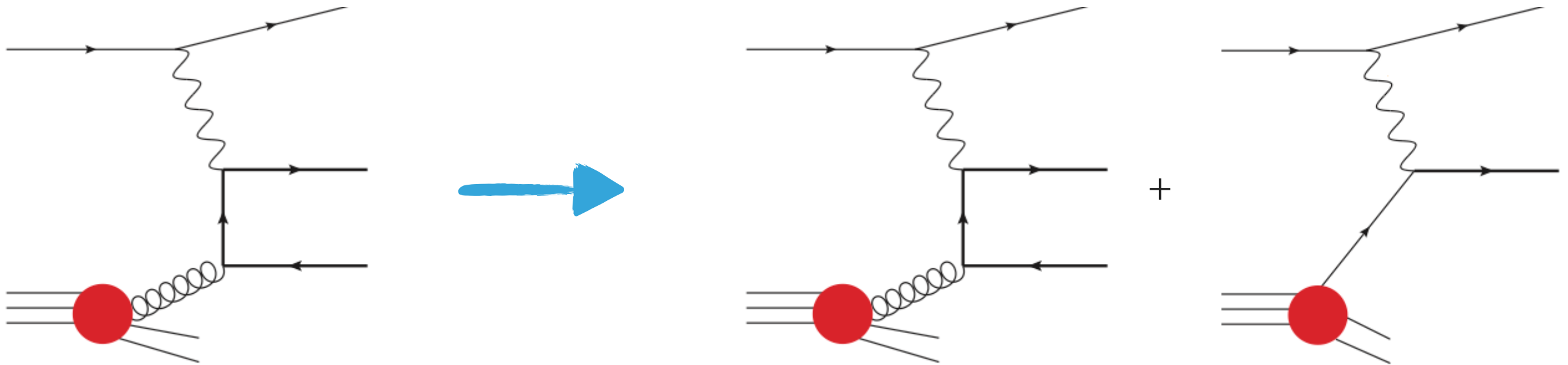
Variable Flavour Number Schemes

The number of active flavours, namely those "factorized" in the PDFs, changes with the scale
-> Variable Flavour Number Scheme

$$f_j^{[n_f+1]}(\mu_m^2) = \sum_{k=\text{light}} A_{ji}(m^2/\mu_m^2) \otimes f_i^{[n_f]}(\mu_m^2)$$

New Heavy flavour PDF is produced at threshold, through a "matching condition"

The process now includes a new contribution from the initial-state heavy flavour

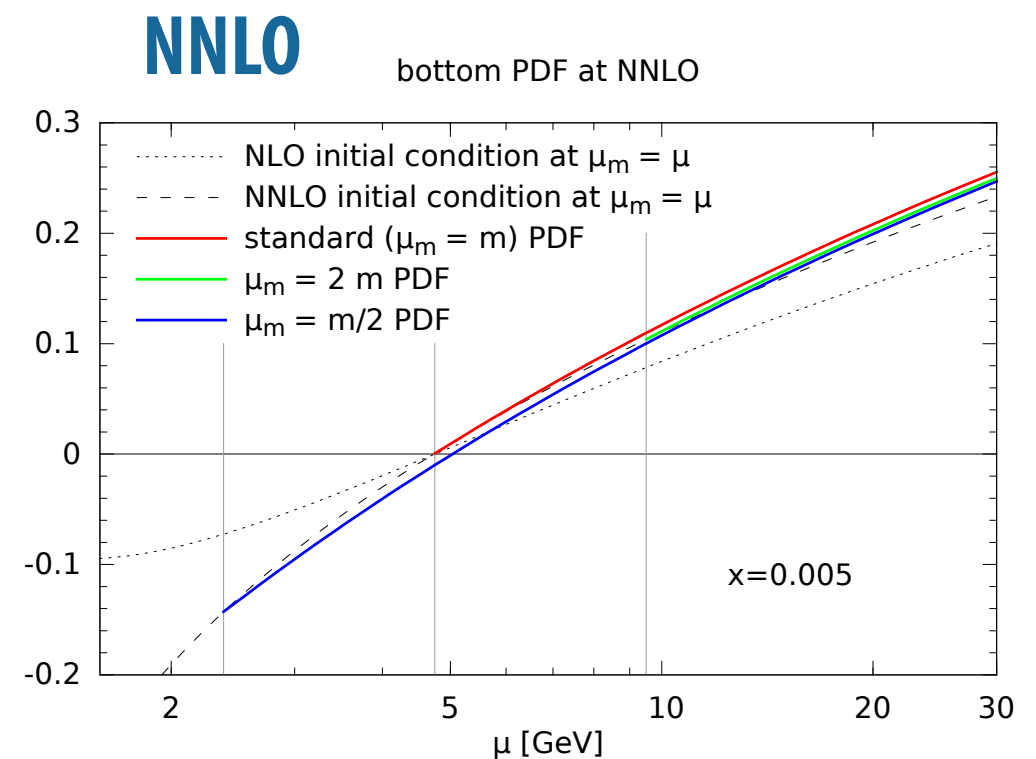
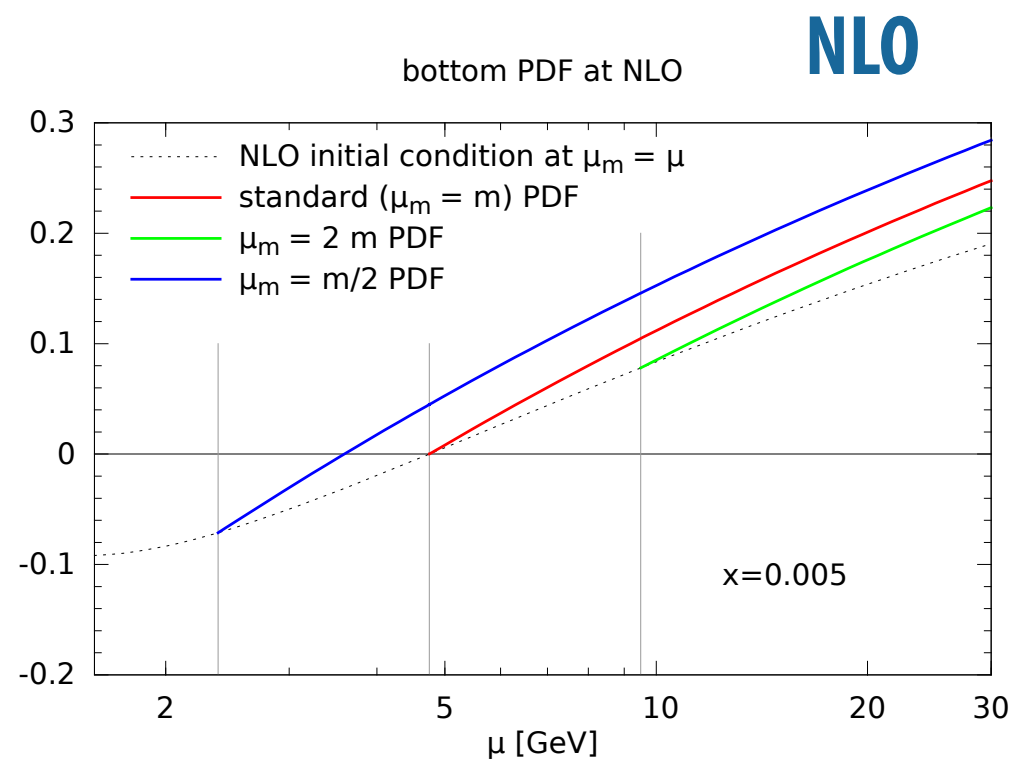


Partonic cross sections are **different** in the $n_f=4$ and $n_f=5$ scheme

Variable Flavour Number Schemes

The number of active flavours, namely those "factorized" in the PDFs, changes with the scale
-> Variable Flavour Number Scheme

PDFs formally independent of the matching scale; perturbative dependence remain



The dependence is reduced by including higher orders in the matching conditions (and in DGLAP)

Understanding what's in PDF sets

Most PDF sets are available through LHAPDF <https://lhapdf.hepforge.org>

They can be identified by their name, which is not very clear often...

Many sets contain some $nf=4$ or $nf=5$ or 3FS or similar in their name. What do they mean?

That's typically the **maximum** number of active flavours

CT14nnloIC
CT14nnlo_NF3
CT14nnlo_NF4
CT14nnlo_NF6
CT14nlo

$nf=5$ does not mean that at all scales there are 5 active flavours (it would be possible, but not convenient)

Rather, it means that the 6th flavour (top) matching scale is infinitely large.

It does not tell you anything about the matching scale of bottom or charm.

Much better would be to simply specify the values of the matching scales for all heavy flavours.

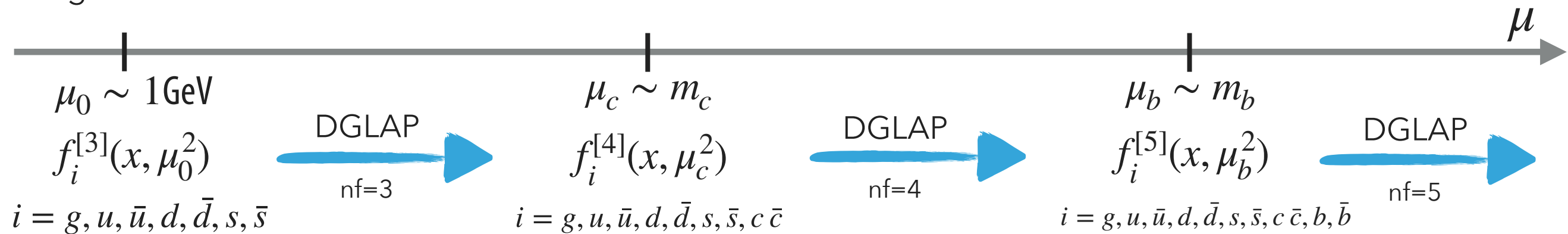
This info is available in LHAPDF (thanks to myself...), but only very few sets provide this metadata...

NOTE: it is very dangerous to use a random set without knowing what's inside it.

For instance, using a set which assumes a factorization scheme not compatible with the one adopted in your computation leads to very wrong results.

How is a PDF set determined?

Once all (active) PDFs are known at an "initial" (low) scale, they can be computed at all (higher) scales using DGLAP evolution



Given the initial-scale boundary condition, then PDFs at higher scales are fully determined by

- ▶ perturbative accuracy of DGLAP splitting functions P_{ij}
- ▶ quark masses m_i
- ▶ quark matching scales μ_i
- ▶ perturbative accuracy of matching conditions A_{ij}

A lot of the information on the PDF set is contained in the initial-scale PDFs $f_i^{[3]}(x, \mu_0^2)$

How are these determined?

Determining PDFs from first principles

Field-theoretically, (quark) PDFs are defined as

$$f_q(x) = \int \frac{d\xi^-}{4\pi} e^{-ix\xi^- P^+} \langle P | \bar{\psi}_q(\xi^-) \not{h}_- U_{n_-}(\xi^-, 0) \psi_q(0) | P \rangle$$

The definition is based on non-local operators separated by a light-cone distance.

Since PDFs are low-scale objects, they can't be computed in perturbation theory.

Lattice QCD instead could be the right tool for them.

However, in lattice QCD the space-time is euclidean, where the light-cone does not exist....

Possible ways out:

- ▶ Compute a different object (quasi-PDFs, pseudo-PDFs) which tends to the light-cone PDFs in some limit
- ▶ Compute properties of PDFs (e.g. Mellin moments)
- ▶ Compute scattering amplitudes and extract PDFs
- ▶

Fitting PDFs from data

More brute force, one can compare theoretical predictions with data to fit the PDFs at the initial scale

$$\sigma_X(Q^2, s) = \sum_{a,b} f_{a/h_1}(Q^2) \otimes f_{b/h_2}(Q^2) \otimes \hat{\sigma}_{ab \rightarrow X}(Q^2, s)$$
$$Q^2 \frac{d}{dQ^2} f_i(Q^2) = P_{ij}(\alpha_s(Q^2)) \otimes f_j(Q^2)$$

theoretical prediction (to be compared with data)

theoretical input

One parametrises the PDFs at the initial scale $f_i^{[3]}(x, \mu_0^2)$

Then using DGLAP evolution (including the proper matching of heavy quarks in a variable flavour number scheme) one computes them at the "data scale" Q^2

Finally PDFs are convoluted with partonic cross sections to obtain a physical prediction, which is compared to data through a suitable χ^2 which is minimized in the fit

PDF fitting groups

Various PDF fitting groups, differing by many aspects:

- ▶ MRST, MSTW, **MMHT**, ...
- ▶ CTEQ
 - **CT** (CTEQ-TEA)
 - CJ (CTEQ-JLab)
- ▶ **NNPDF**
- ▶ ABM, ABKM
- ▶ HERAPDF
- ▶ xFitter
- ▶

[**Bold**: part of the PDF4LHC15 recommendation]

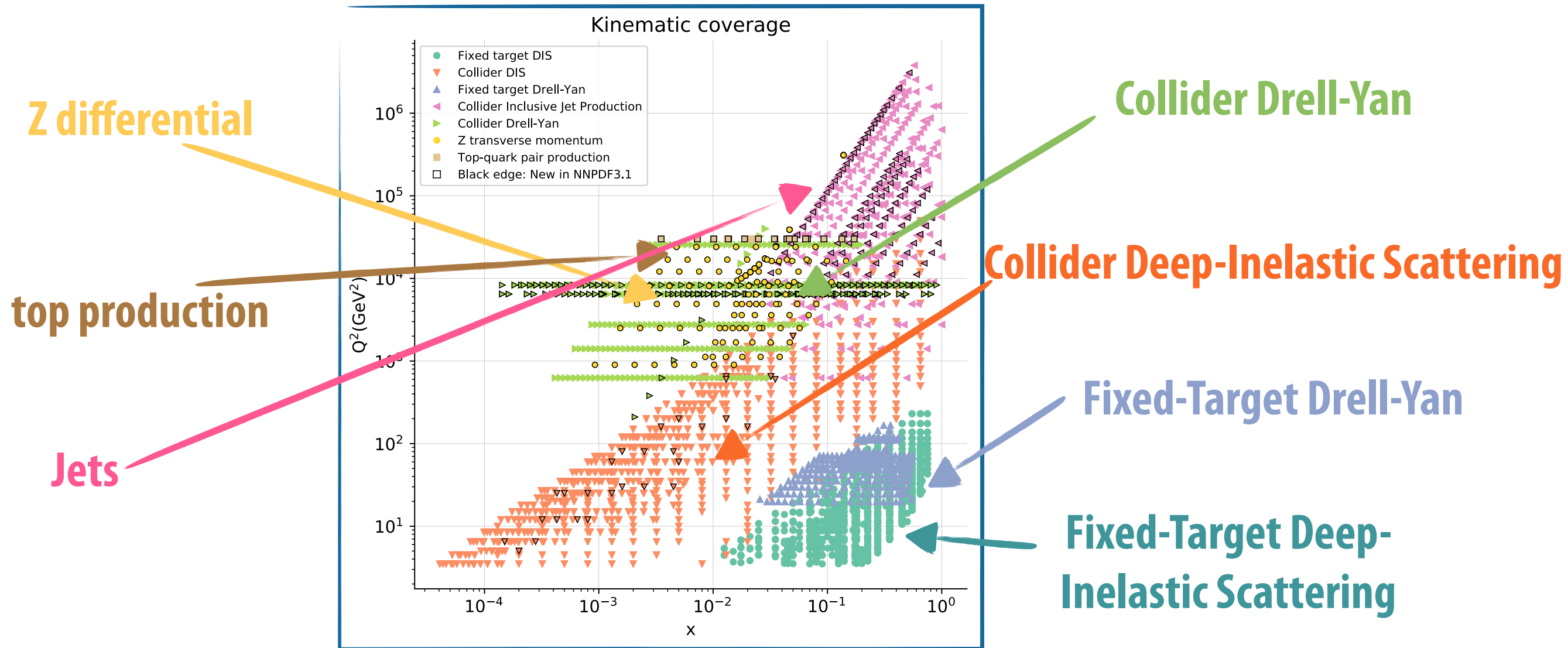
PDF4LHC: provides PDF recommendations for LHC studies

Differences:

- ▶ parametrizations
- ▶ datasets
- ▶ theory inputs
- ▶ fitting methodology
- ▶

Global PDF fits

Processes used in global PDF fits [NNPDF 3.1]



Theoretical ingredients of PDF fits

Fitted PDFs depend on

- ▶ perturbative accuracy of DGLAP splitting functions P_{ij}
- ▶ quark masses m_i
- ▶ quark matching scales μ_i
- ▶ perturbative accuracy of matching conditions A_{ij}
- ▶ perturbative accuracy of the partonic cross sections [process dependent]
- ▶ any other scales or parameters entering theoretical predictions [process dependent]
- ▶ any potential bias induced by the parametrization chosen

PDF fits are typically based on **fixed-order** theory...

$$\hat{\sigma} = \hat{\sigma}_0(1 + \alpha_s c_1 + \alpha_s^2 c_2 + \dots)$$

$$P_{ij}(x, \alpha_s(Q^2)) = \alpha_s P_{ij}^{(0)}(x) + \alpha_s^2 P_{ij}^{(1)}(x) + \alpha_s^3 P_{ij}^{(2)}(x) + \dots$$

...but is fixed-order theory always good enough?

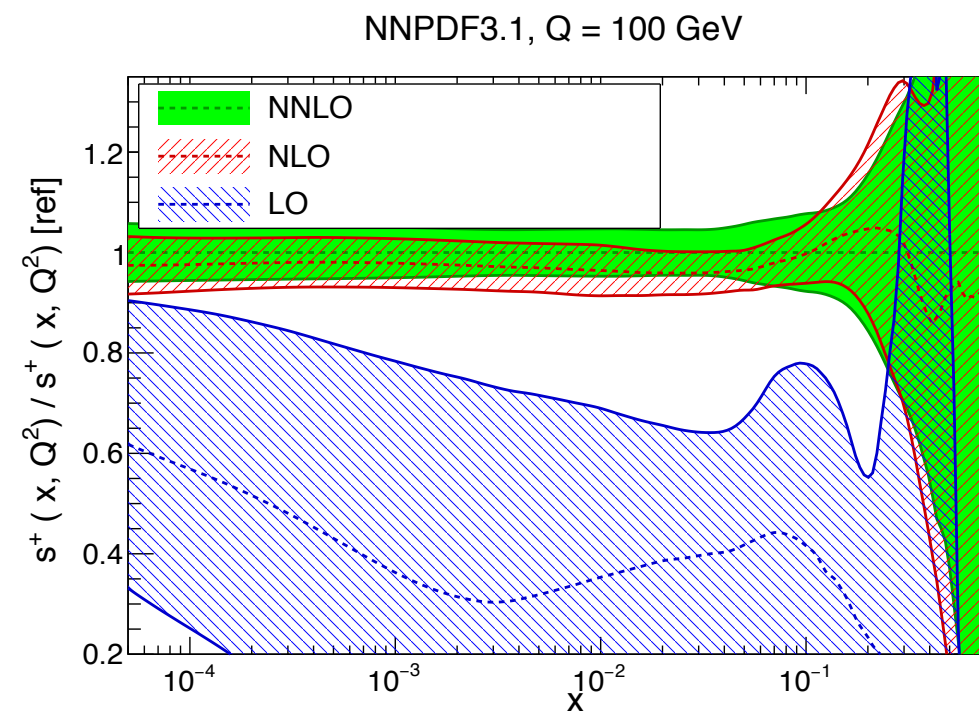
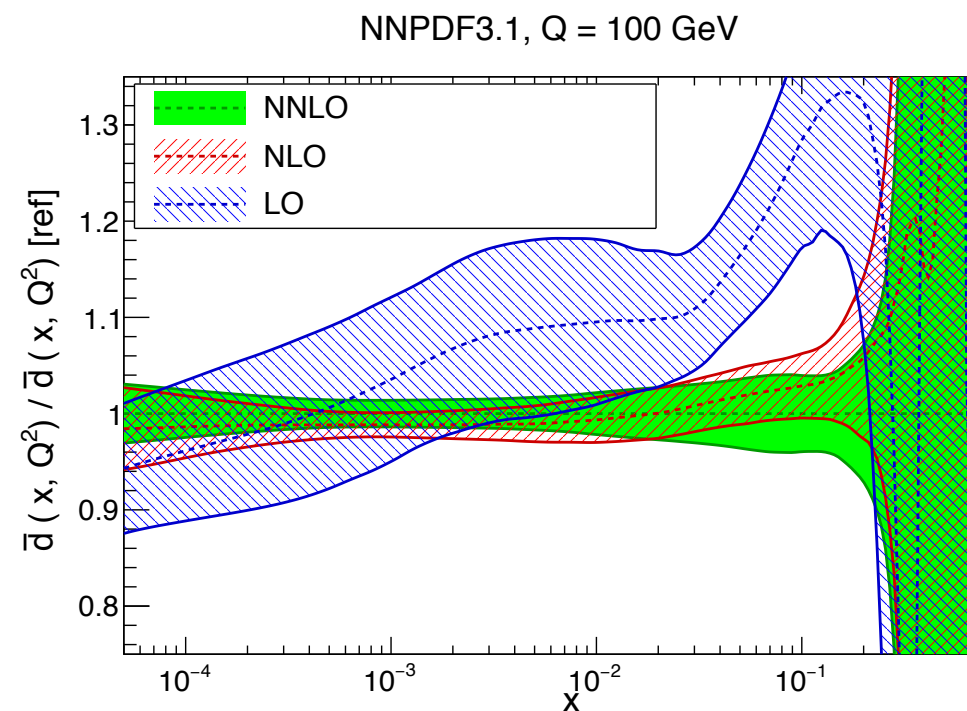
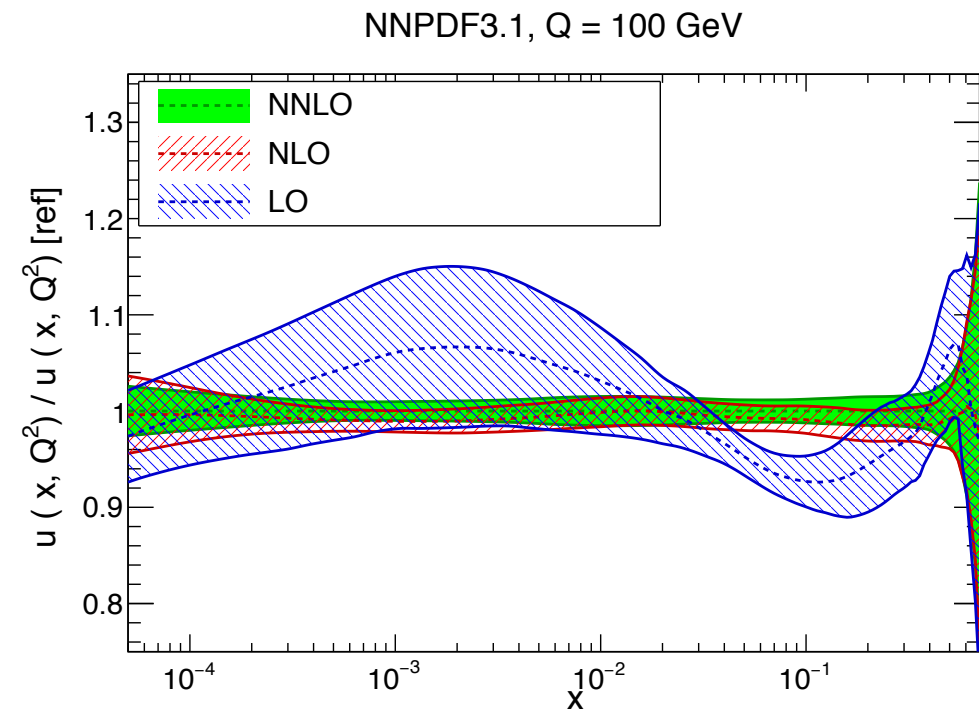
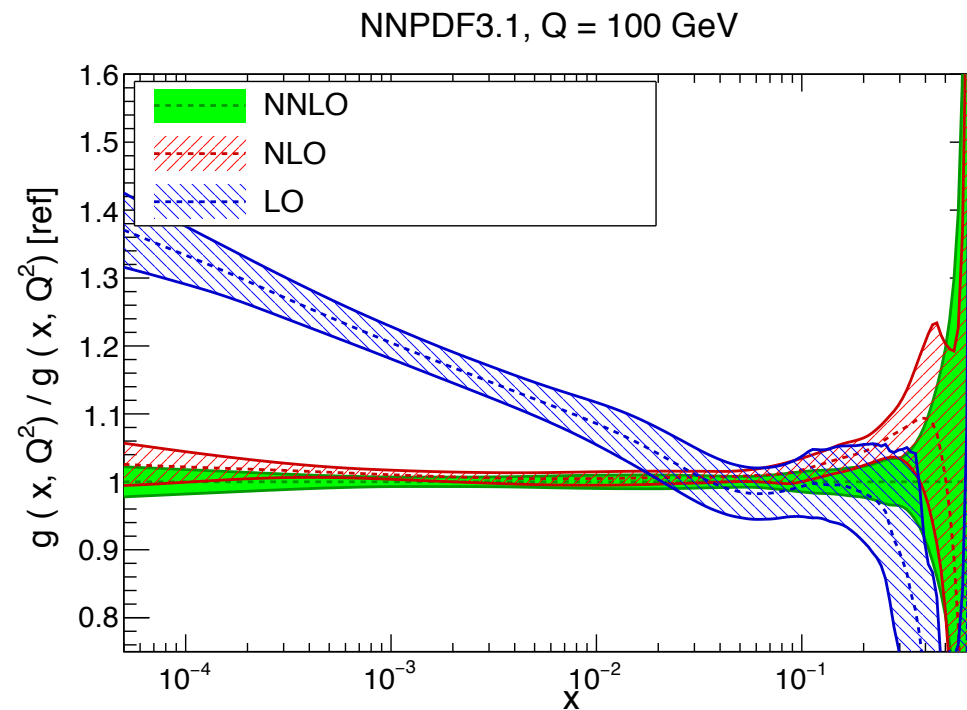
Dependence on the perturbative order

Over the years, PDFs fits moved from **LO** accuracy to **NLO** and to **NNLO** accuracy

1970s

1987

2000+

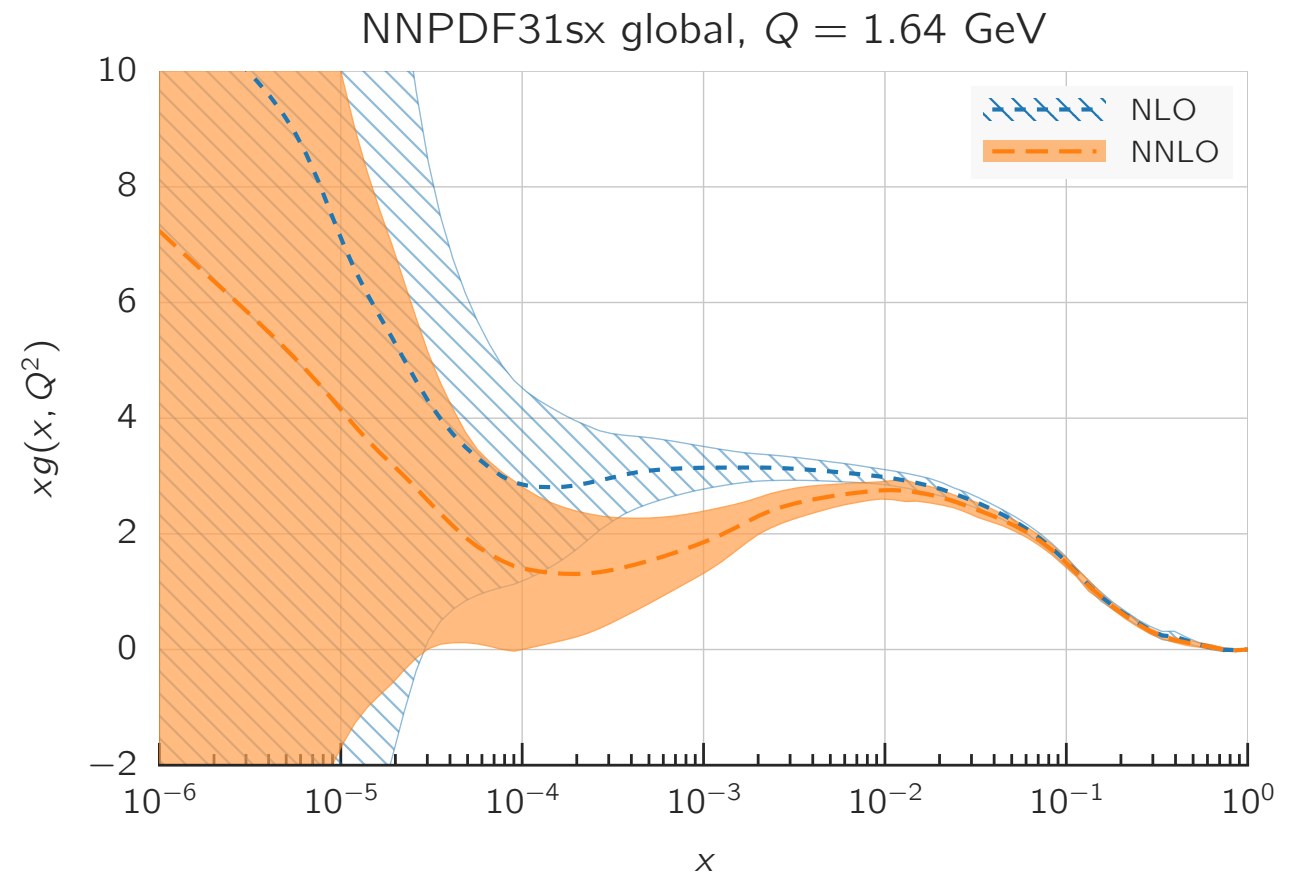


Dependence on the perturbative order

Depending on the PDF fit **details**, there can be significant differences also between NLO and NNLO fits

By "**details**" I basically mean how subleading contributions are treated

At low orders there is a more marked dependence on these details, which is significantly reduced at higher orders



Is NNLO enough?

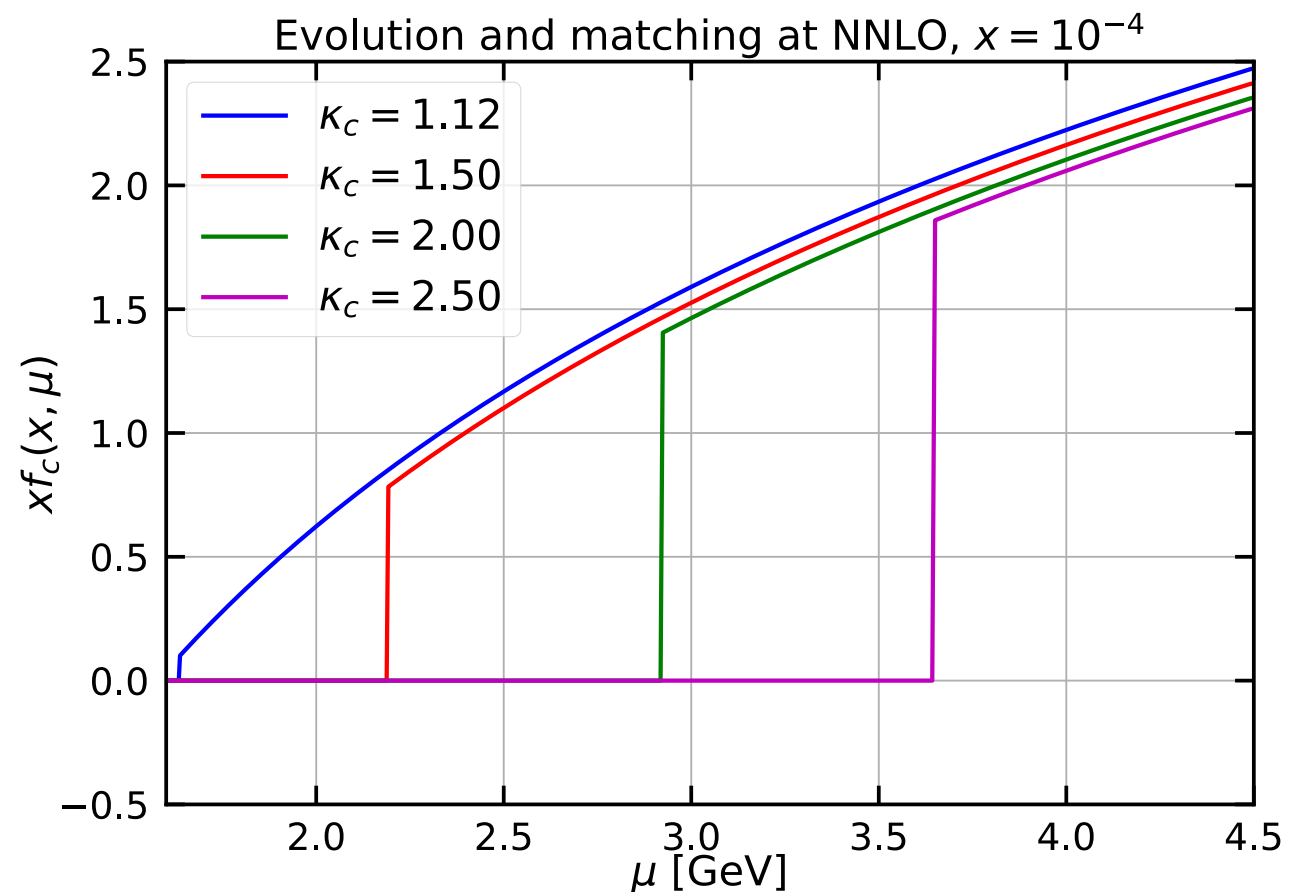
Perturbative charm PDF

Perturbatively generated charm PDF.
Same plot as before, but for charm.

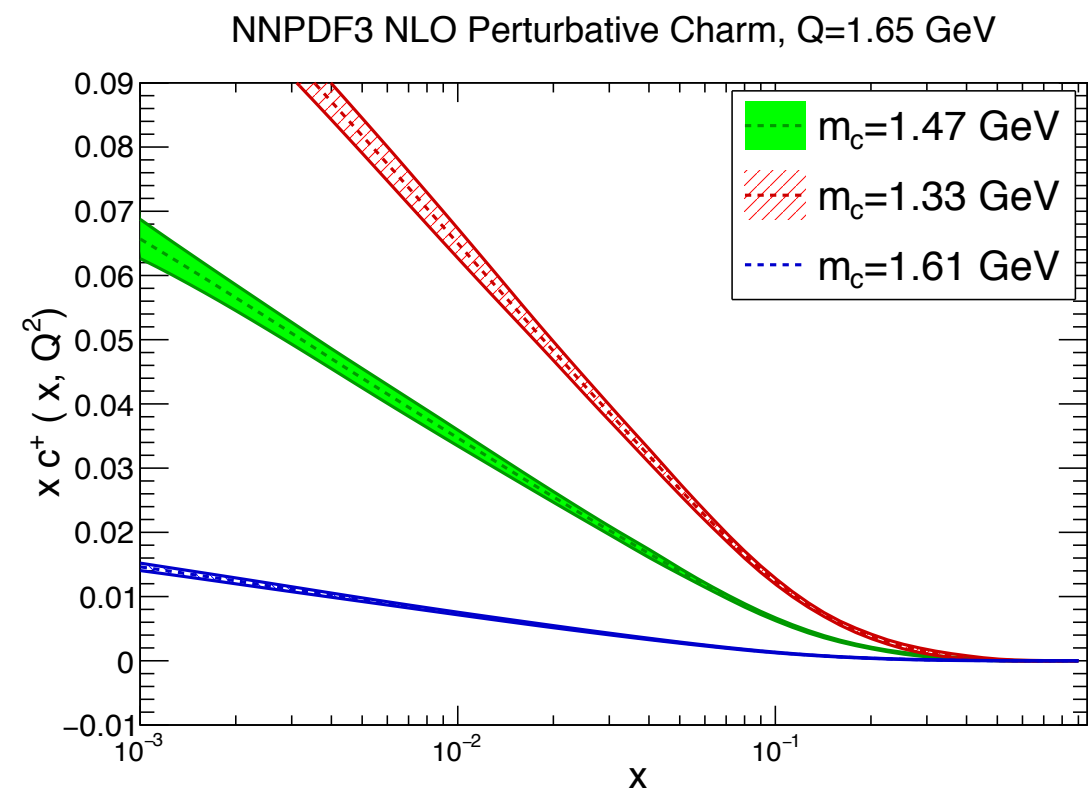
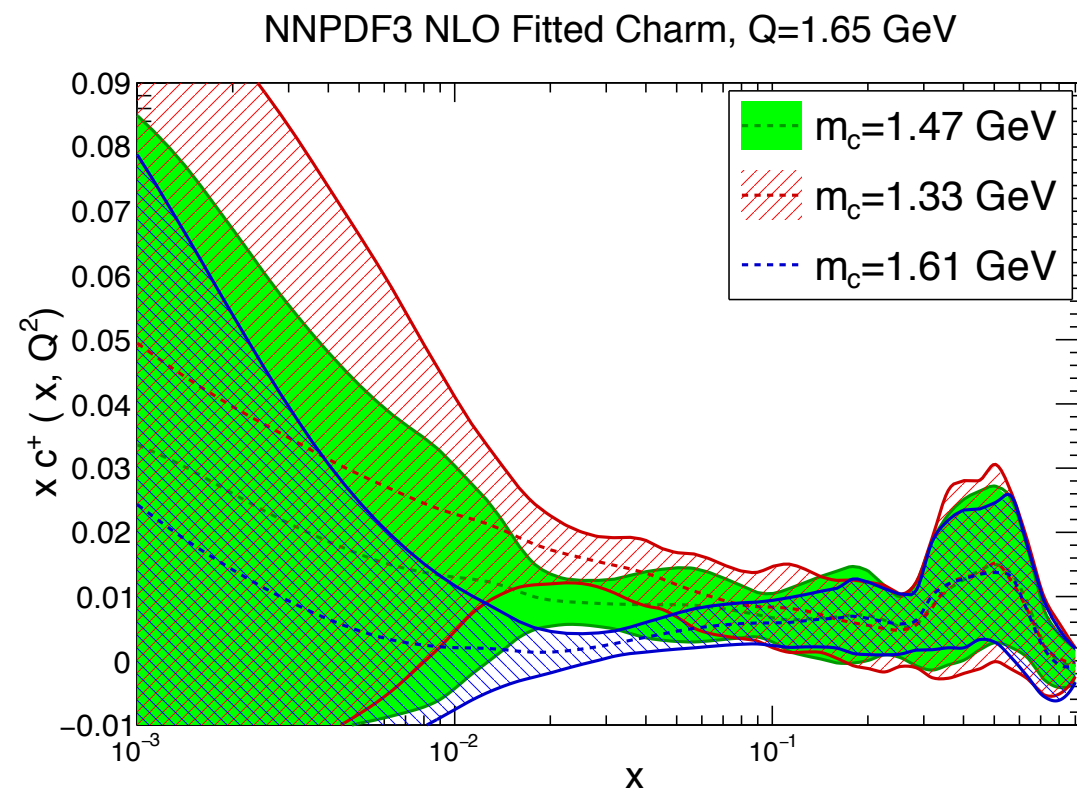
The scale is smaller, α_s is larger, missing higher order (N3LO) corrections are larger and important

Here NNLO is not enough to reach high precision...

$$\kappa_c = \mu_c / m_c$$



Here a possible (and good!) solution is to **fit the charm PDF** together with light-quark PDFs



Fitting the charm PDF there is no dependence anymore on the charm matching conditions, which suffer by large unknown higher order corrections

Moreover, if there is any intrinsic (non-perturbative) component of the charm PDF it can be reproduced as well

Large logarithms

Single (double) logarithmic enhancement

$$\alpha_s^k \ln^j \quad 0 \leq j \leq (2)k$$

Perturbative convergence is spoiled when


$$\alpha_s \ln^{(2)} \sim 1$$

Finite in the limit $x \rightarrow 0$

e.g. small- x behaviour of splitting functions

$$xP(x, \alpha_s) = \sum_{n=0}^{\infty} \left(\frac{\alpha_s}{2\pi} \right)^n \left[\sum_{m=1}^n A_{m-1}^{(n)} \ln^{m-1} \frac{1}{x} + x\bar{P}^{(n)}(x) \right]$$

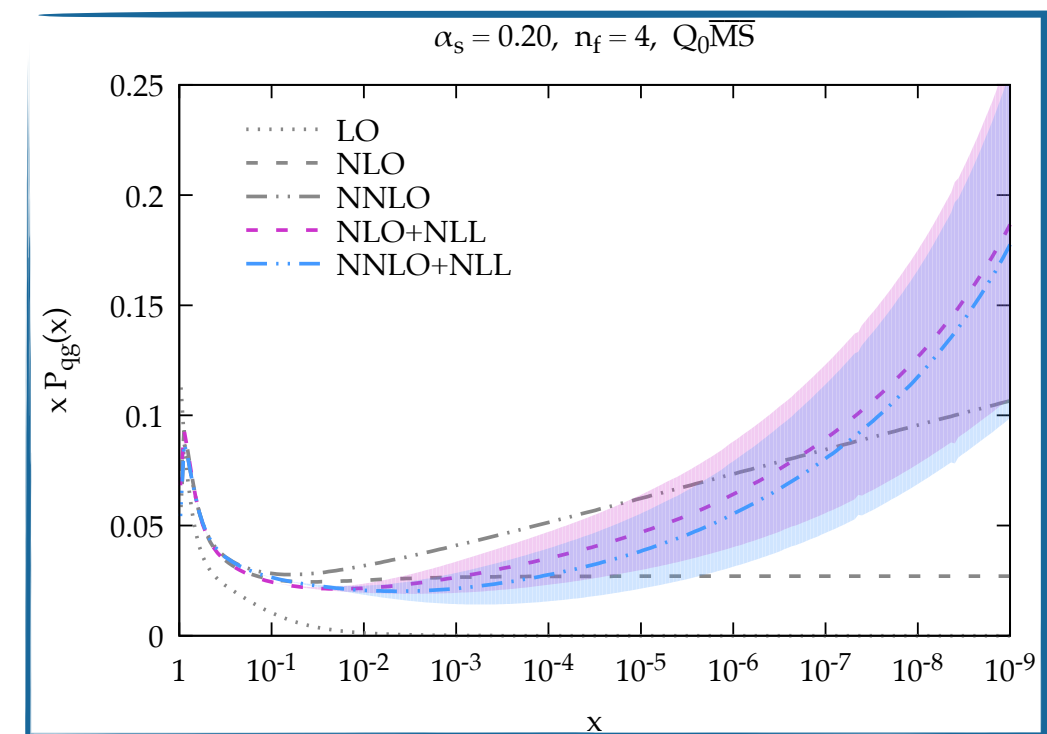
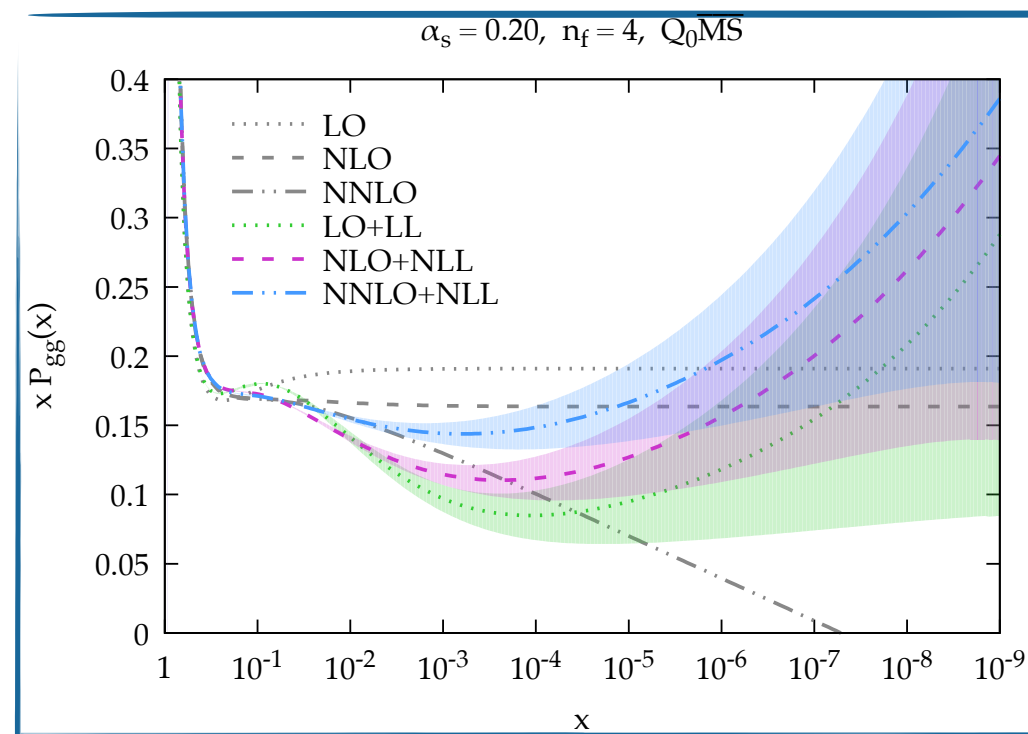
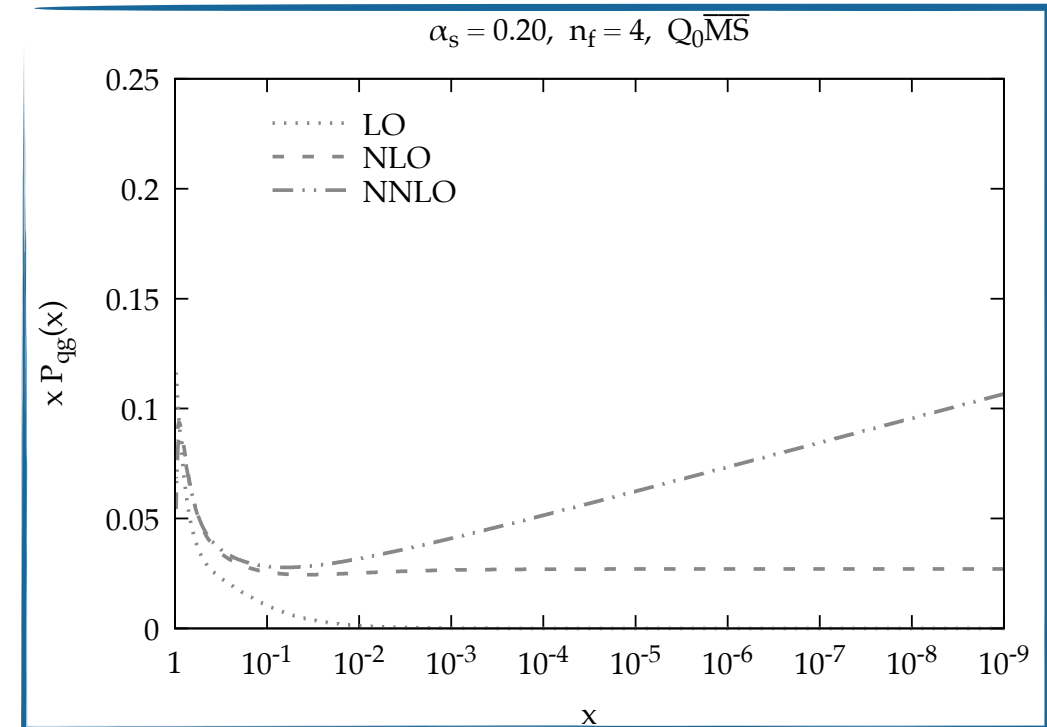
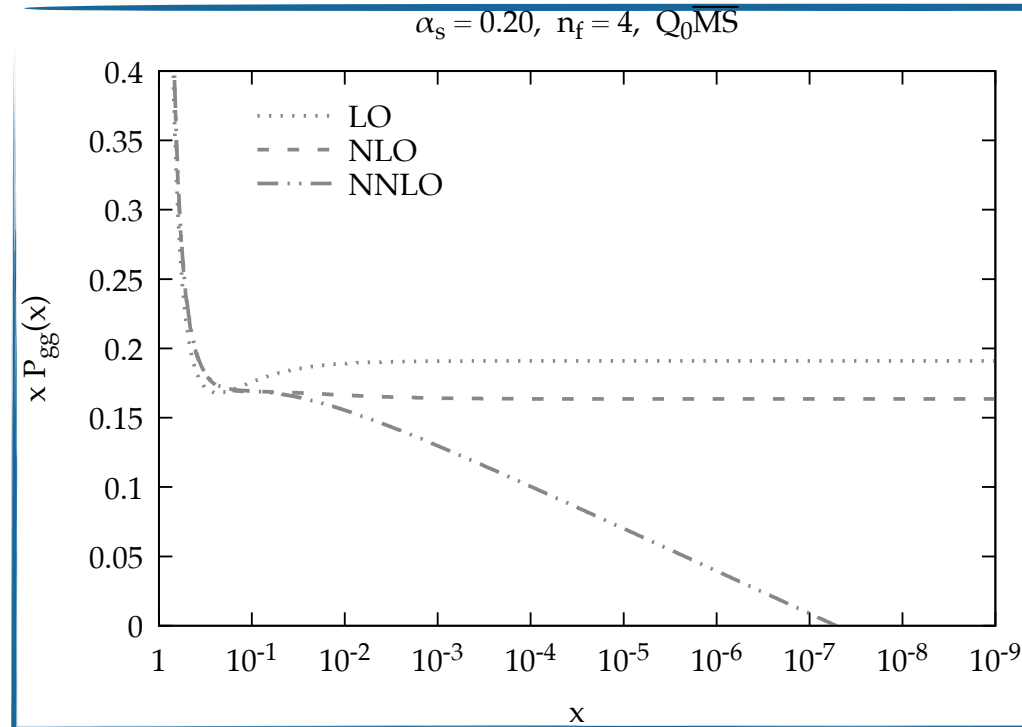
Instability at small- x



All-order **resummation** of the logarithmically enhanced terms

($n \geq 0, m=n$) leading-logarithm (LL x), ($n \geq 0, m=n, n-1$) next-to-leading-logarithm (NLL x), etc.

Small- x logarithms in DGLAP evolution



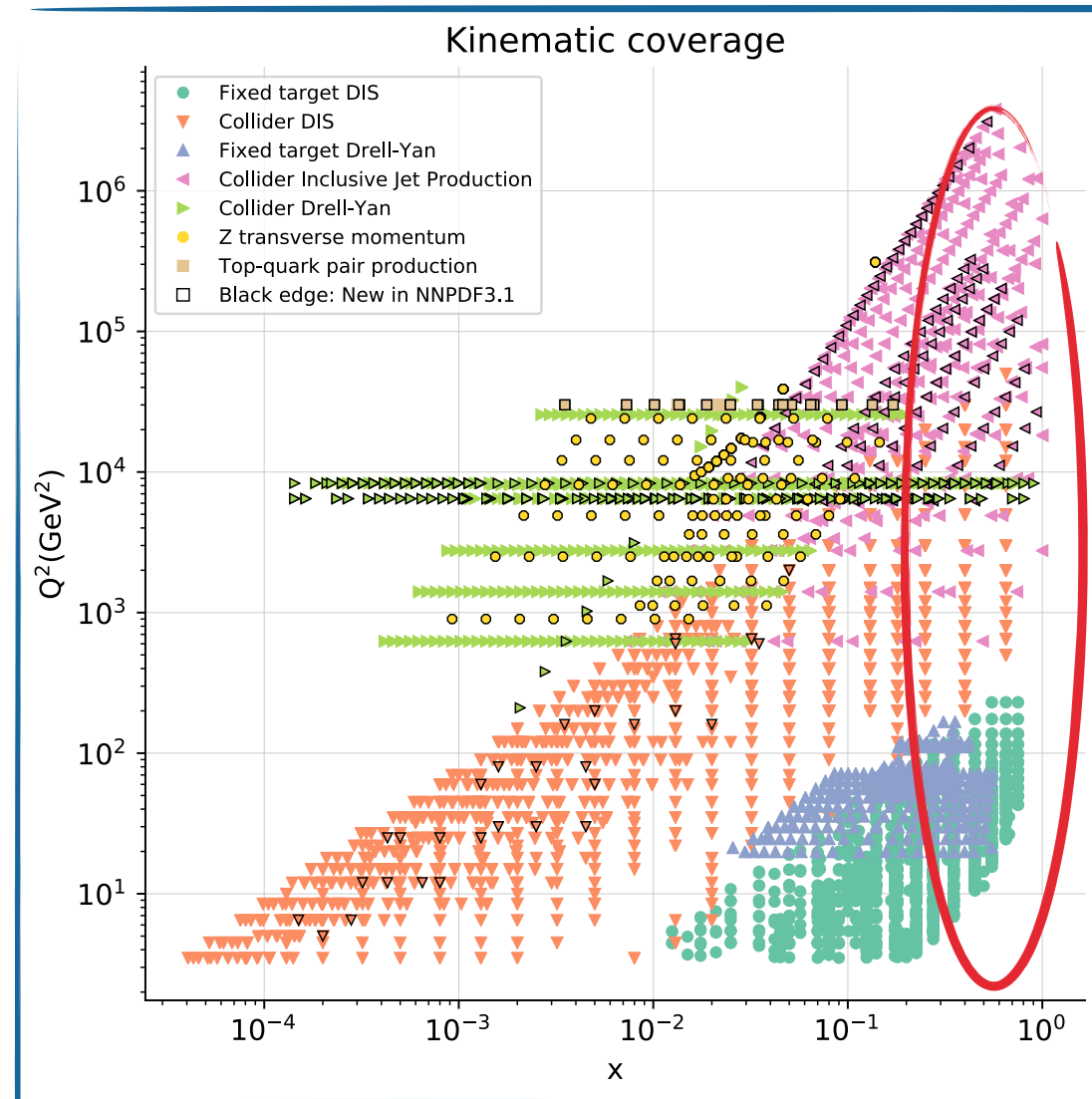
All-order resummations in PDF fits

Including resummations in PDF fits:

- ▶ provides **consistent predictions** when resummed computations are used
- ▶ improves the **quality** of the PDF fits
- ▶ helps in investigating the impact of **missing higher orders**

... it brings us closer to 'all-order' PDFs

Resummation in global PDF fits



Large x : **threshold** resummation

double logs due to **soft** gluon emission

$$\left(\frac{\ln^k(1-x)}{(1-x)} \right) +$$

[Bonvini,Marzani,Rojo,Rottoli,Ubiali,
Ball,Bertone,Carrazza,Hartland
1507.01006]

[Corcella,Magnea hep-ph/0506278]

Resummation in global PDF fits

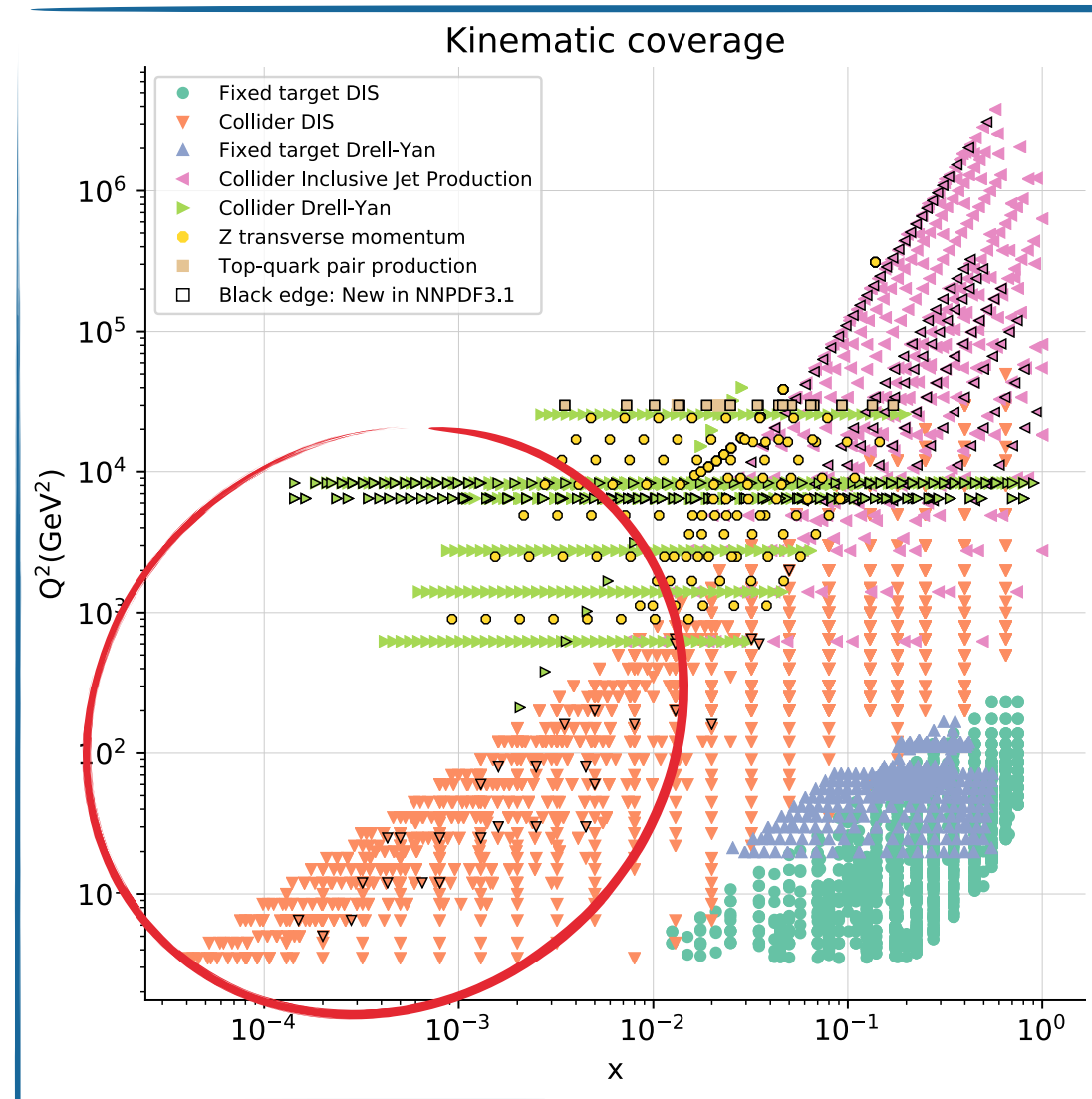
Small x : **high-energy** resummation

single logs due to high-energy gluon emission

$$\frac{1}{x} \ln^k x$$

[Ball,Bertone,Bonvini,Marzani,Rojo,
Rottoli 1710.05935]

[xFitter developer's team + Bonvini
1802.00064]



What can/should be resummed?

Resummation affects:

Observable (**coefficient functions**)

$$\sigma = \sigma_0 C(\alpha_s(\mu)) \otimes f(\mu) [\otimes f(\mu)]$$

Evolution (**splitting functions**)

and matching functions as well

$$\mu^2 \frac{d}{d\mu^2} f(\mu) = P(\alpha_s(\mu)) \otimes f(\mu)$$

	observable (coefficient unction)	evolution (splitting function)
small x	LLx*	NLLx
large x	(N)NNLL	— (in MSbar)

*means lowest non-vanishing order, usually it's NLLx

PDFs with large- x resummation

[Bonvini,Marzani,Rojo,Rottoli,Ubiali,Ball,Bertone,Carrazza,Hartland 1507.01006]

PDFs with large-x resummation: NNPDF3.0res

Datasets considered in NNPDF3.0res

process	observable	included?
DIS	$d\sigma/dx/dQ^2$ (NC, CC, F2c...)	✓
DY Z/ γ	$d\sigma/dy/dM^2$	✓
DY W	differential in lepton kinematics	✗ no public code available yet
tt	total σ	✓
jets	inclusive $d\sigma/dy/dp_T$	✗ NLL known to be poor

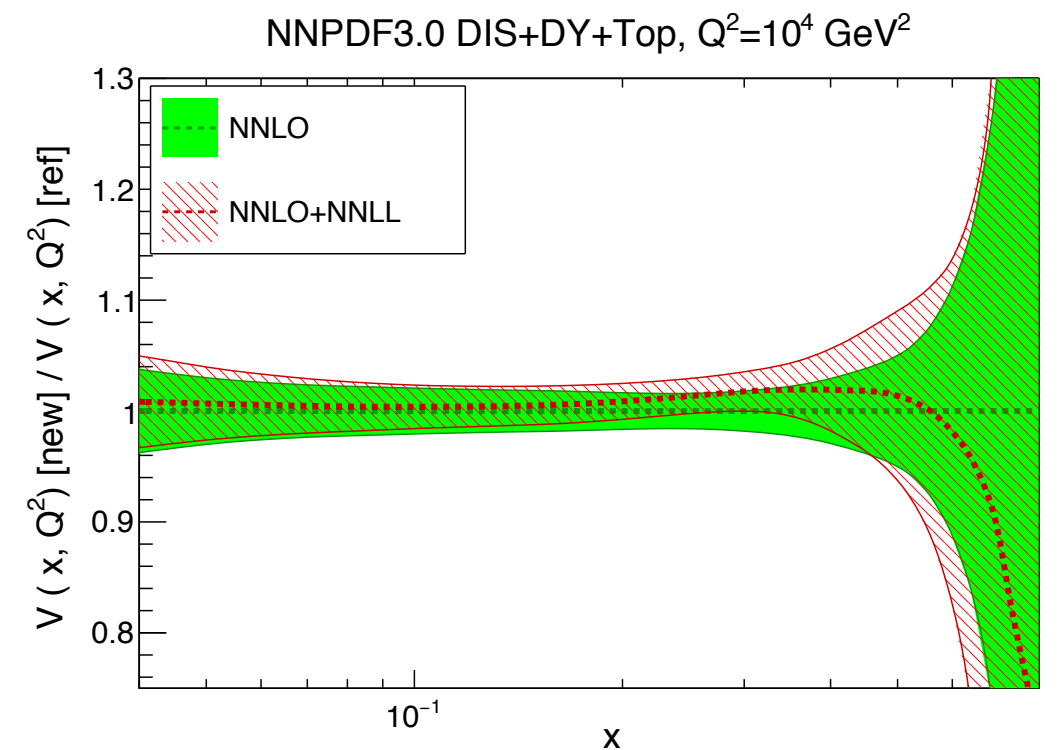
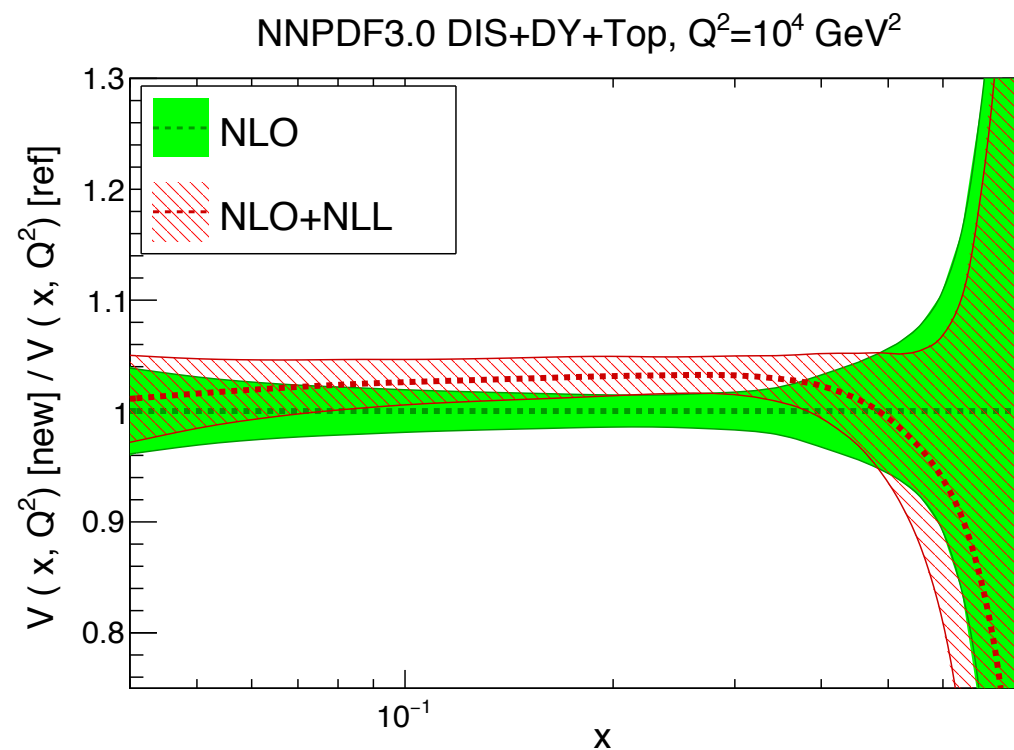
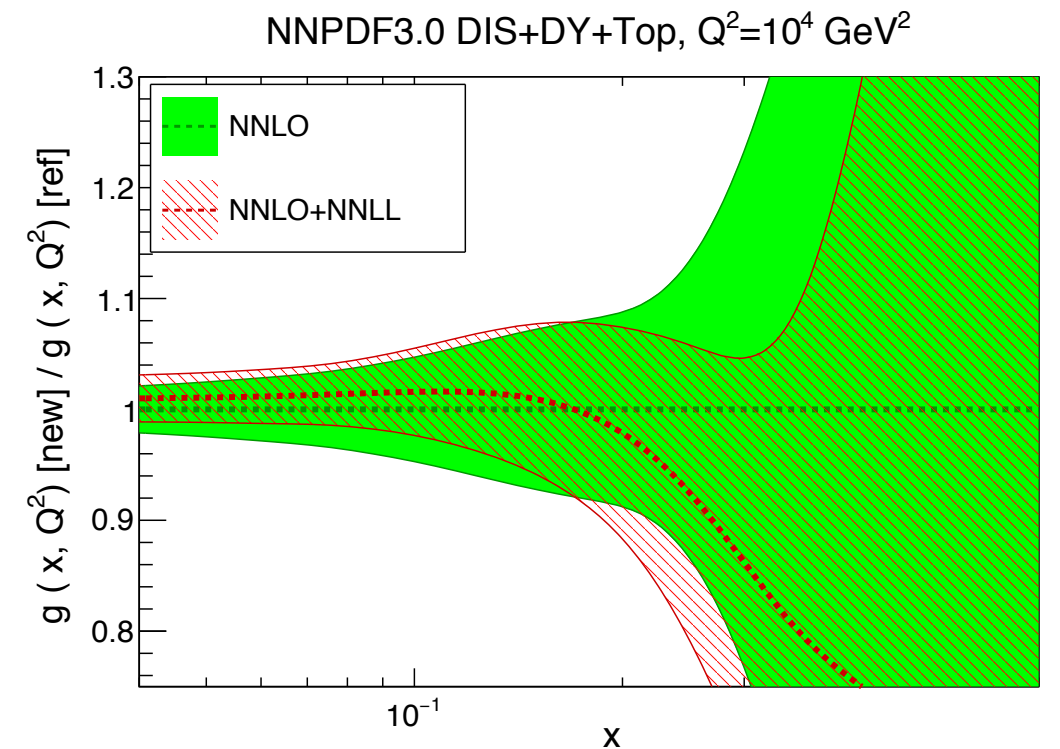
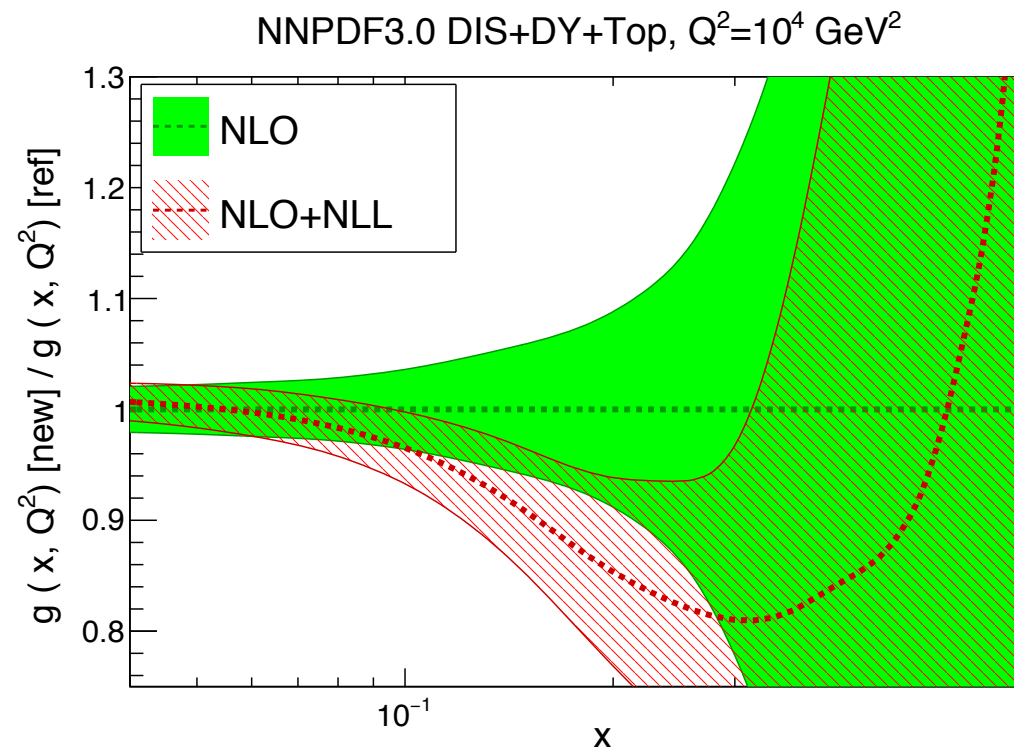
public code TROLL
www.ge.infn.it/~bonvini/troll

Accuracy is **not competitive** with global fit, especially for large-x gluon (jets not included)

Yet, it's the most precise global PDF fit with large-x resummation

PDFs with large- x resummation: NNPDF3.0res

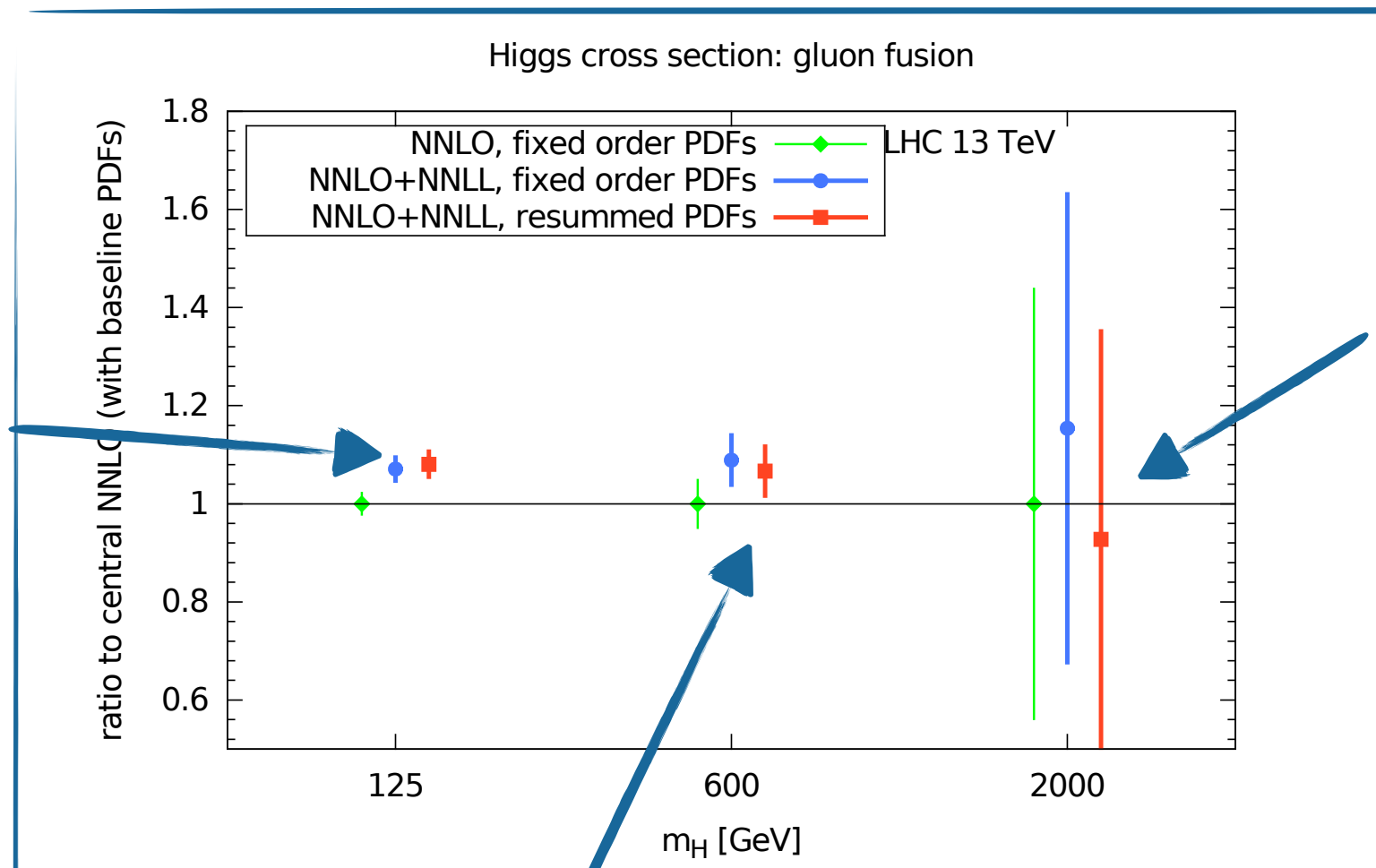
Impact on
PDFs



PDFs with large- x resummation: Impact on phenomenology

Higgs Production

SM Higgs is not affected by resummation of PDFs



$m_H \sim 2$ TeV NNLO+NNLL with resummed PDFs is similar to FO PDFs (larger uncertainty)

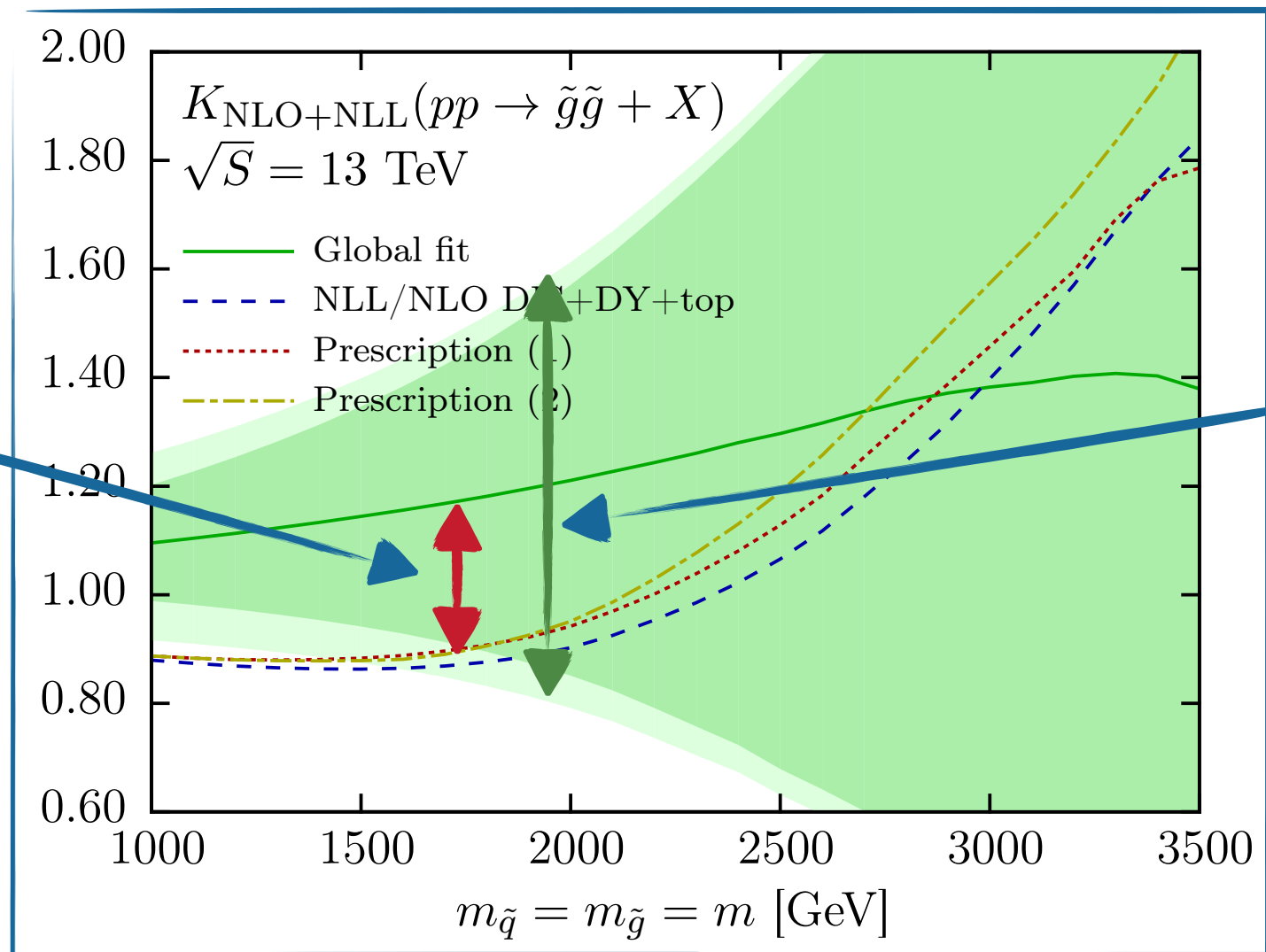
$m_H \sim 600$ GeV partial compensation of the enhancement

NNPDF3.0res: Impact on phenomenology

Susy particles

[Beenakker,Borschensky,Krämer,Kulesza,Laenen,Marzani,Rojo 1510.00375]

Predictions for
MSSM particles
are modified
when using
resummed PDFs



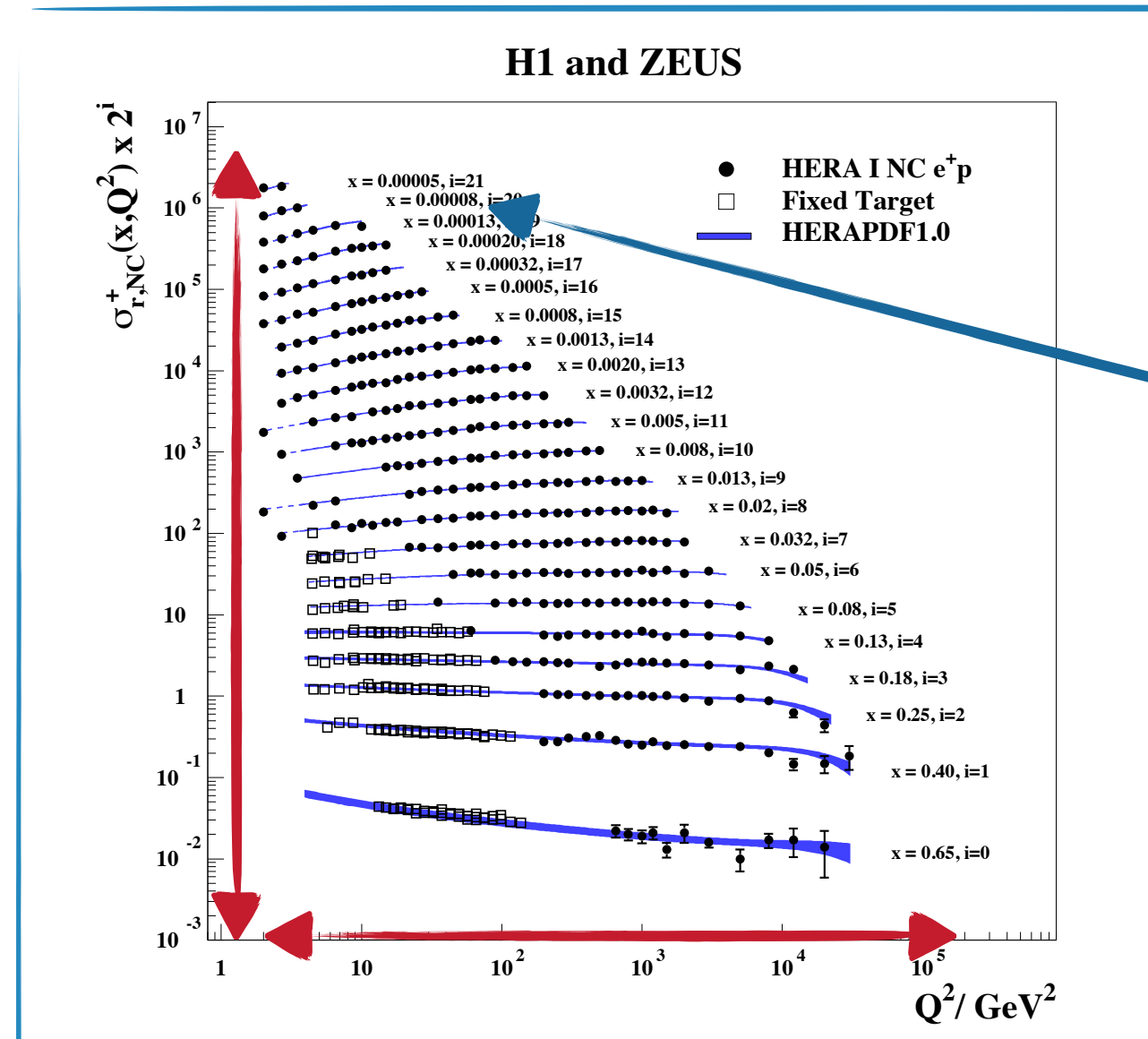
However, PDF
errors are very
large

PDFs with small- x resummation

[Ball,Bertone,Bonvini,Marzani,Rojo,LR 1710.05935]

Need for small-x resummation

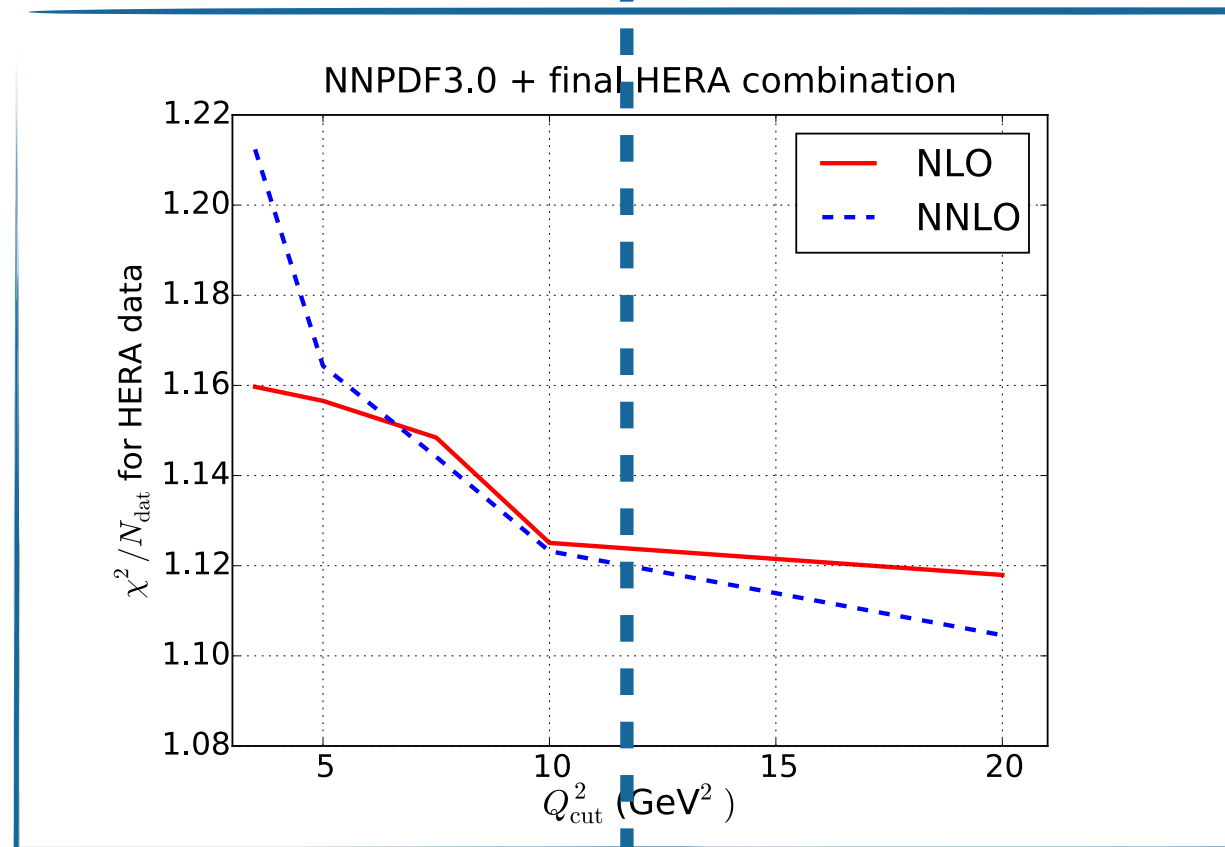
Deep Inelastic Scattering HERA dataset



data collected
down to very
low x

Very good
agreement over
vast range of x
and Q^2

However



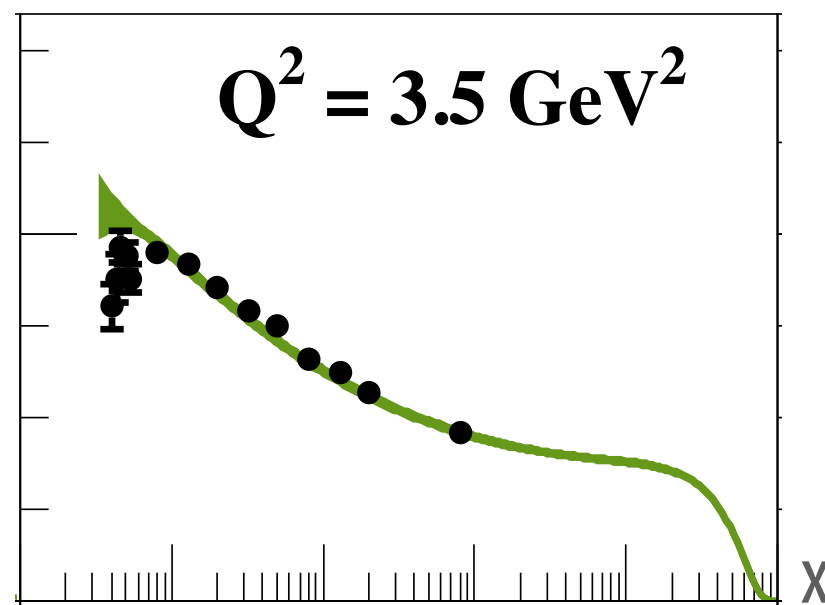
Description of HERA data poorer when data points at smaller values of x are included and fixed-order theory is used



Fixed order theory could be not sufficient to describe data points at small x and/or small Q^2

Effect is more pronounced if **NNLO** theory is used

more points
at small x
included



This may indicate the need
for **small- x resummation**

New insights on the proton's structure

Recent progress in small-x resummation

Small-x resummation based on kt-factorization and BFKL. Developed mostly in the 90s-00s

[Catani,Ciafaloni,Colferai,Hautmann,Salam,Stasto]
[Altarelli,Ball,Forte] [Thorne,White]

Affects both **evolution** (LLx, NLLx) and **coefficient functions** (LLx, lowest logarithmic order) in the singlet sector

Splitting functions are resummed using **ABF** (Altarelli,Ball,Forte) procedure

New formalism for **coefficient function** [Bonvini,Marzani,Peraro 1607.02153][Bonvini,Marzani,Muselli 1708.07510]

Novelties:

- ▶ Matching to NNLO, allowing **NNLO+NLLx** accuracy
- ▶ Full resummation of DIS structure functions and matching conditions

Resummed splitting functions and coefficient functions available through public code

HELL www.ge.infn.it/~bonvini/hell

Use in PDF fits possible thanks to the interface with APFEL apfel.hepforge.org

Towards a global small- x resummed fit

All ingredients for a PDF fit to **DIS data** are now available

In principle, one should add additional processes:

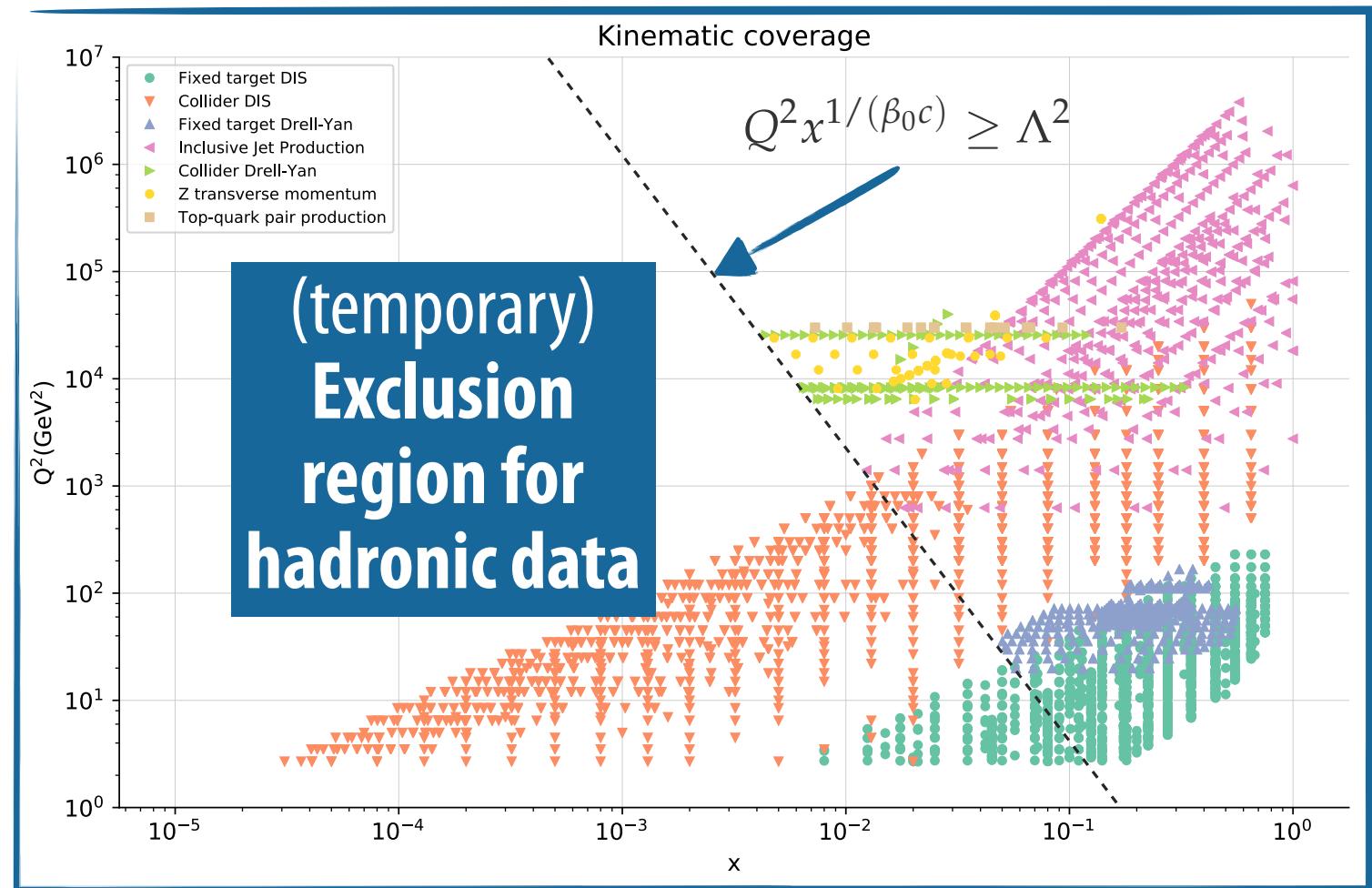
- ▶ DY
- ▶ Jets
- ▶ top
- ▶ ...

Ongoing work in this direction

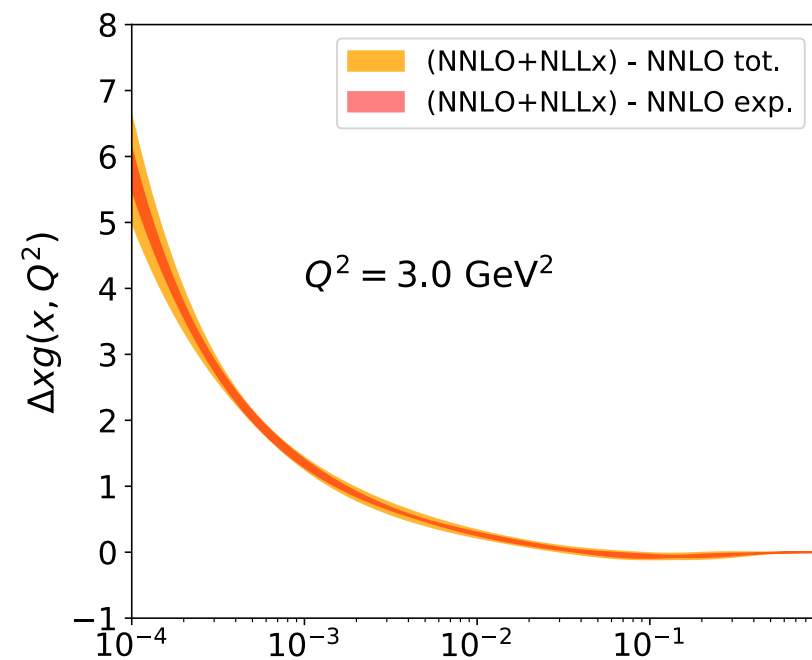
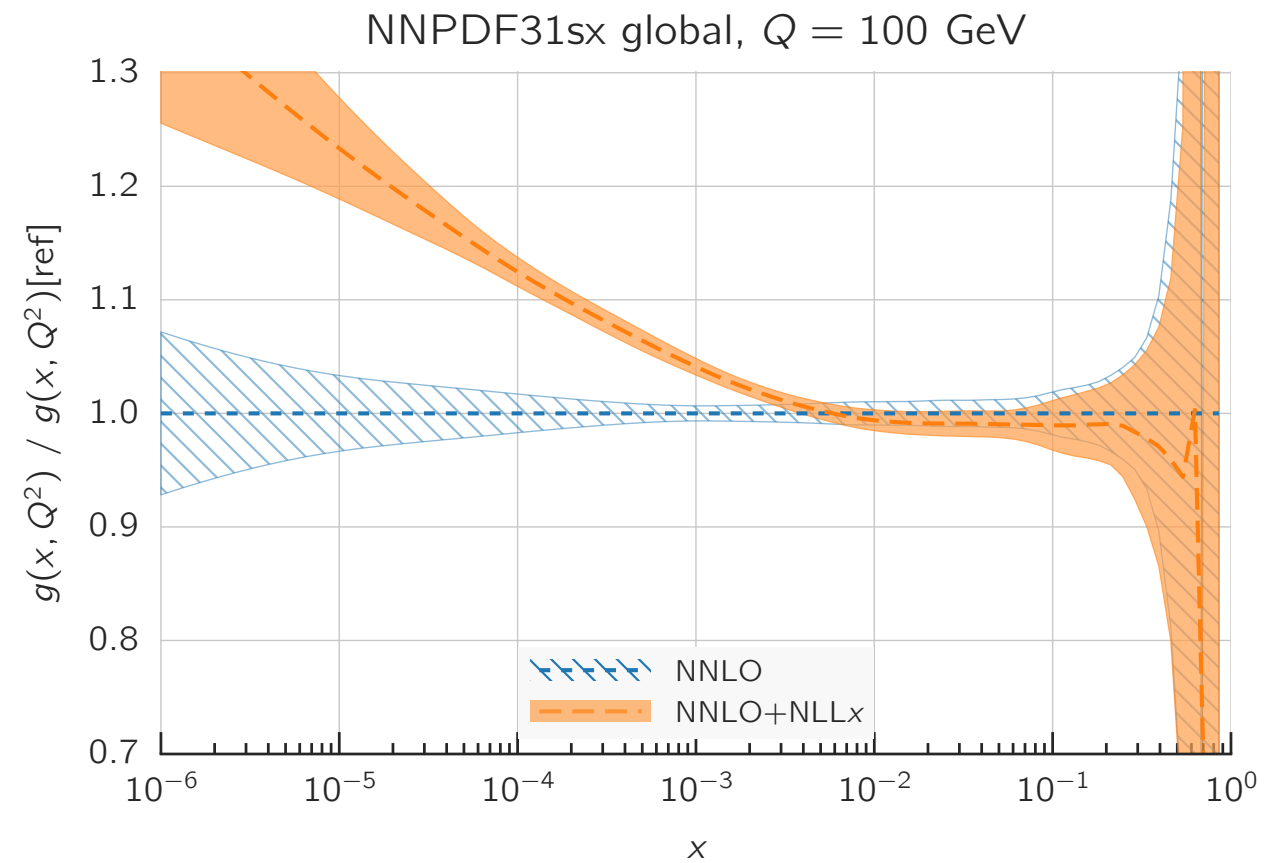
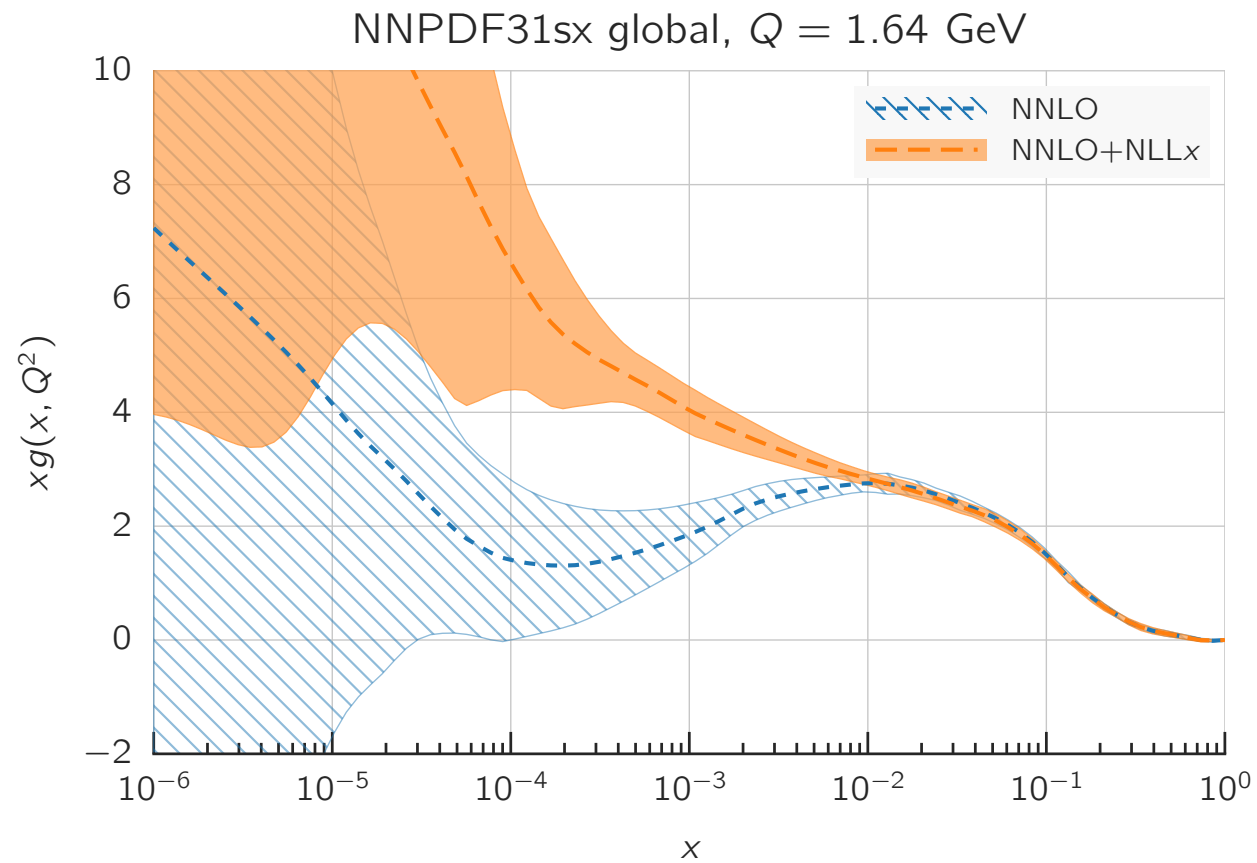
However, a global fit is possible if **conservative cuts** on hadronic data are applied and points which may feature small- x enhancement are excluded

$$\alpha_s(Q^2) \log \frac{1}{x} \geq c \sim 1$$

Value of c (slope of the line) selects the exclusion region

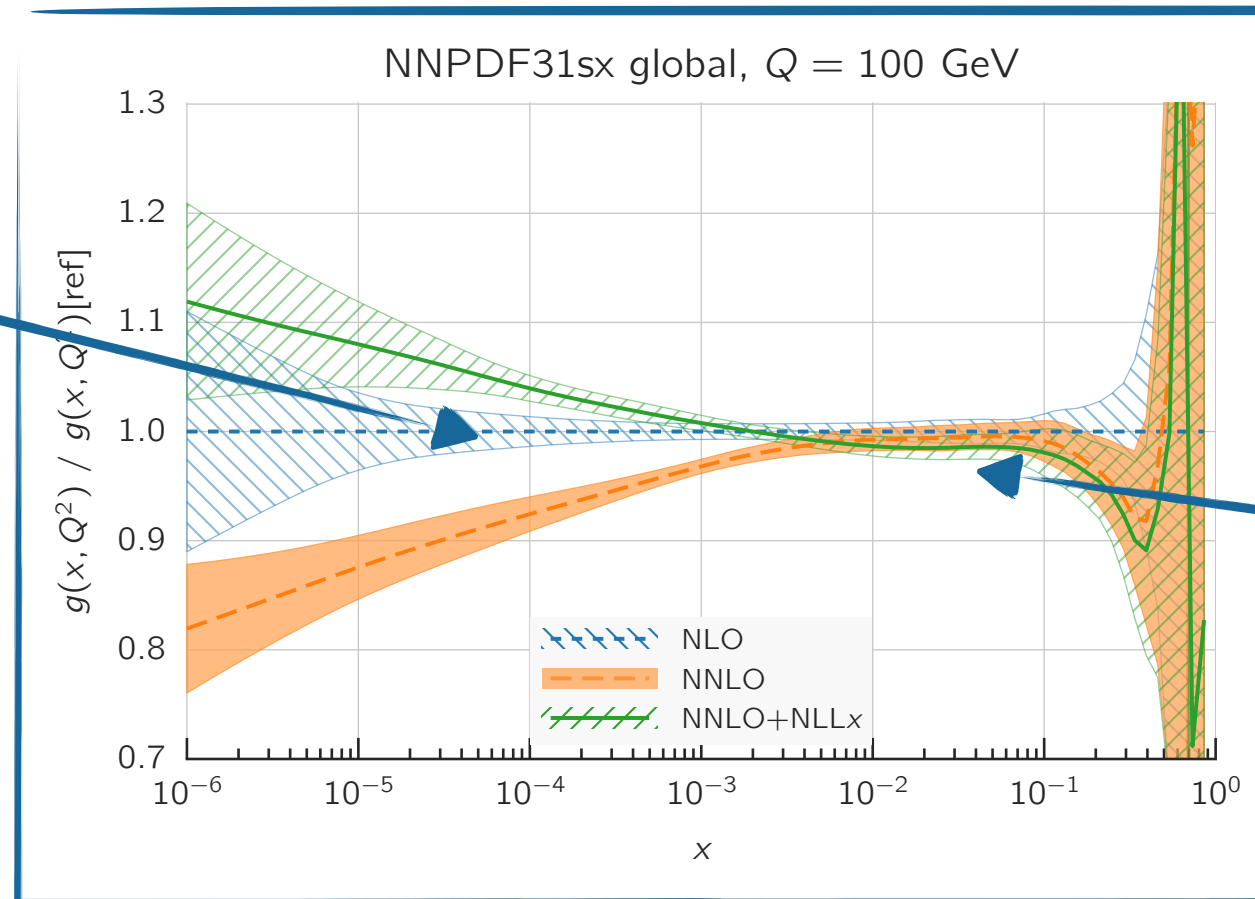


NNPDF31sx: impact on PDFs



NNPDF31sx: impact on PDFs

stabilization of the
gluon with respect
to the perturbative
order



PDFs compatible
within error at
medium and
large x

Similar conclusion found from a xFitter analysis using only HERA data

[xFitter developer's team + Bonvini 1802.00064]

NNPDF31sx: fit quality

χ^2/N_{dat}	NLO	NLO+NLL x	NNLO	NNLO+NLL x		
xFitter			1.23	1.17		
NNPDF3.1sx	1.117	1.120	1.130	1.100		
	these are similar		largest	smallest		
	χ^2/N_{dat}			$\Delta\chi^2$		
	NLO	NLO+NLL x	NNLO	NNLO+NLL x		
NMC	1.31	1.32	+5	1.31	1.32	+4
SLAC	1.25	1.28	+2	1.12	1.02	-8
BCDMS	1.15	1.16	+7	1.13	1.16	+14
CHORUS	1.00	1.01	+9	1.00	1.03	+26
NuTeV dimuon	0.66	0.56	-8	0.80	0.75	-4
HERA I+II incl. NC	1.13	1.13	+6	1.16	1.12	-47
HERA I+II incl. CC	1.11	1.09	-1	1.11	1.11	-
HERA σ_e^{NC}	1.44	1.35	-5	2.45	1.24	-57
HERA F_2^b	1.06	1.14	+2	1.12	1.17	+2
Total	1.113	1.119	+17	1.139	1.117	- 70

Most of the reduction
coming from HERA

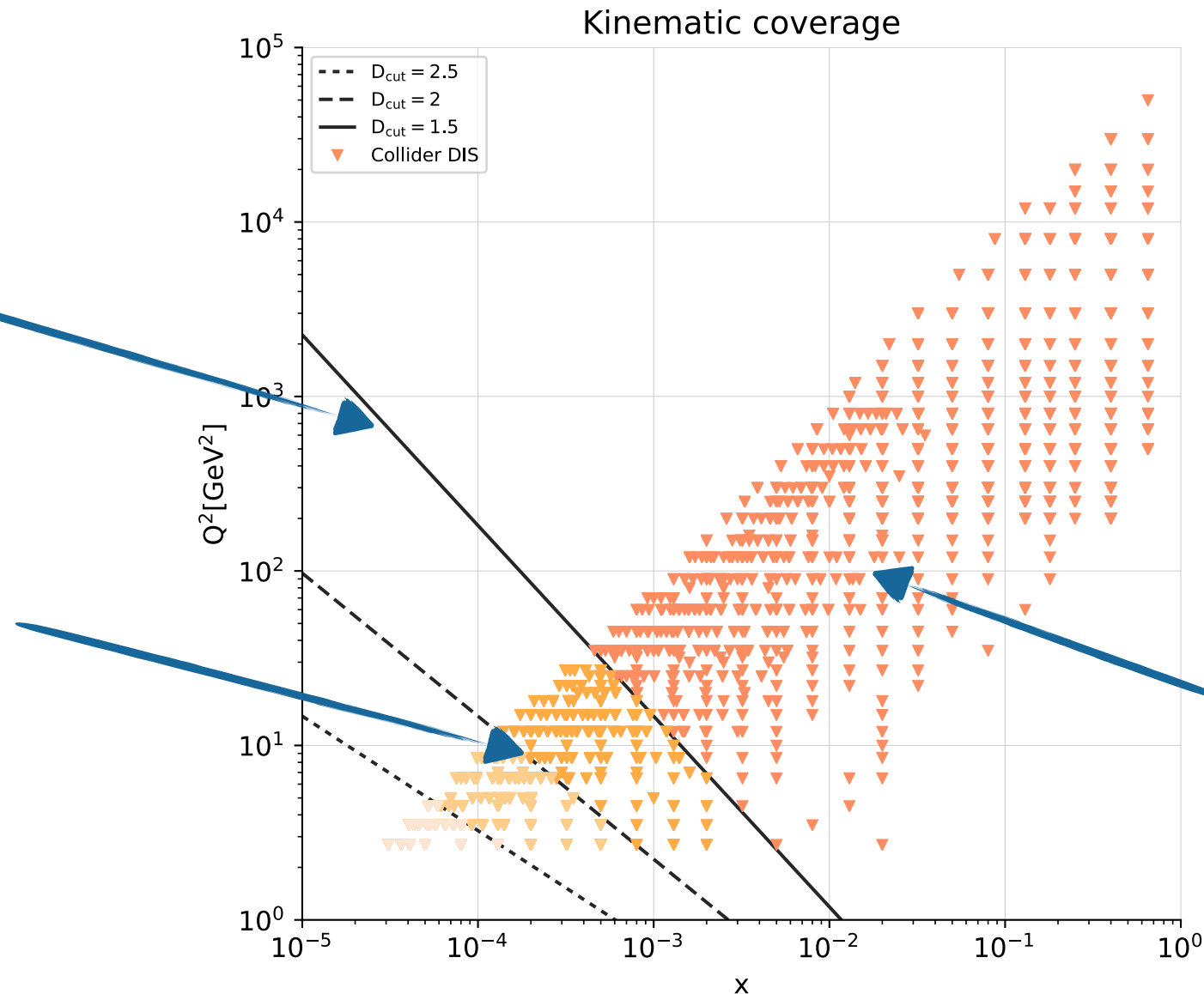
The onset of BFKL dynamics

Compute the χ^2 removing data points in the region where resummation effects are expected

cuts on DIS data

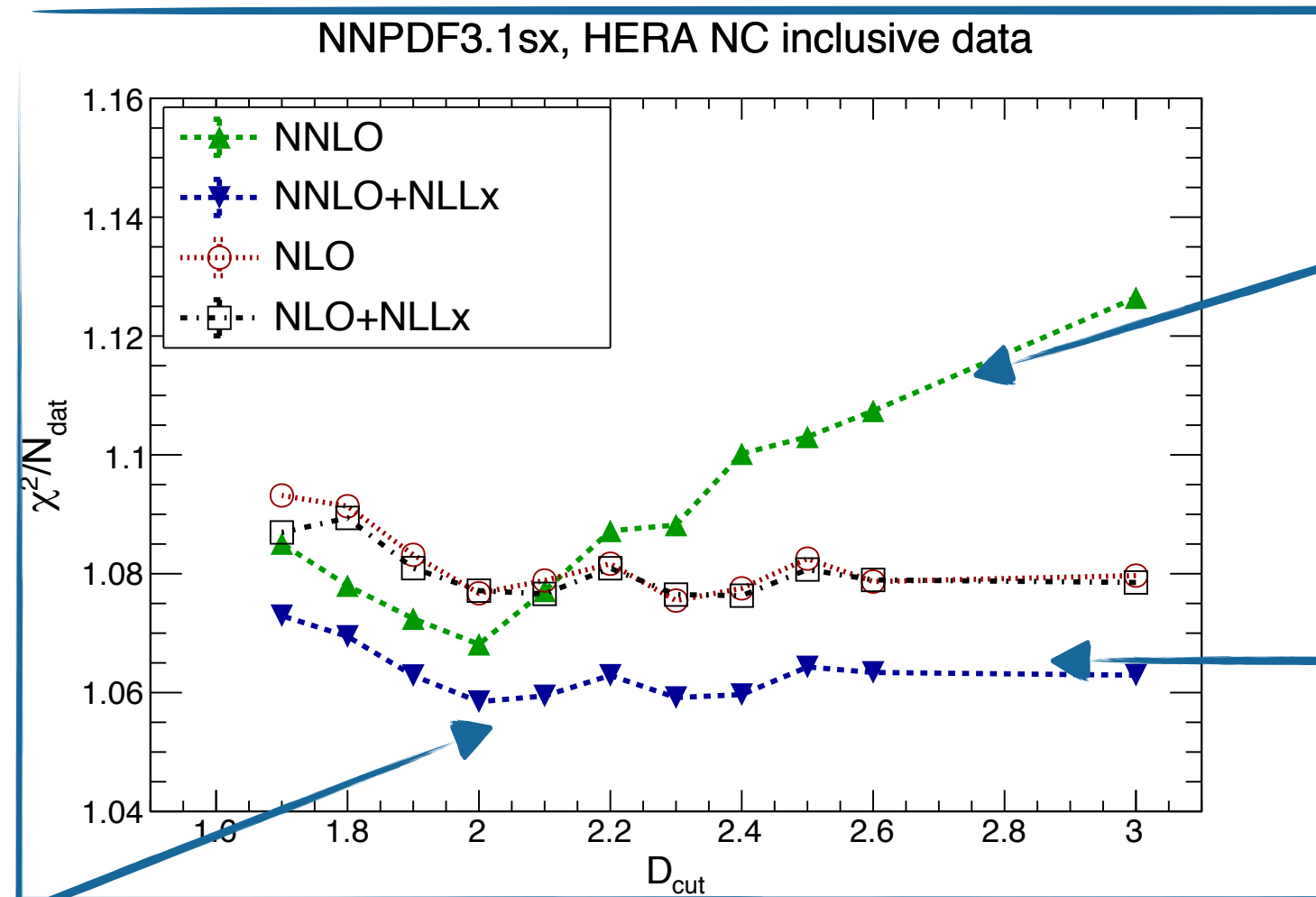
$$\alpha_s(Q^2) \ln\left(\frac{1}{x}\right) \geq D_{\text{cut}}$$

resummation
effects might be
important here



fixed-order
description should
be good here

The onset of BFKL dynamics

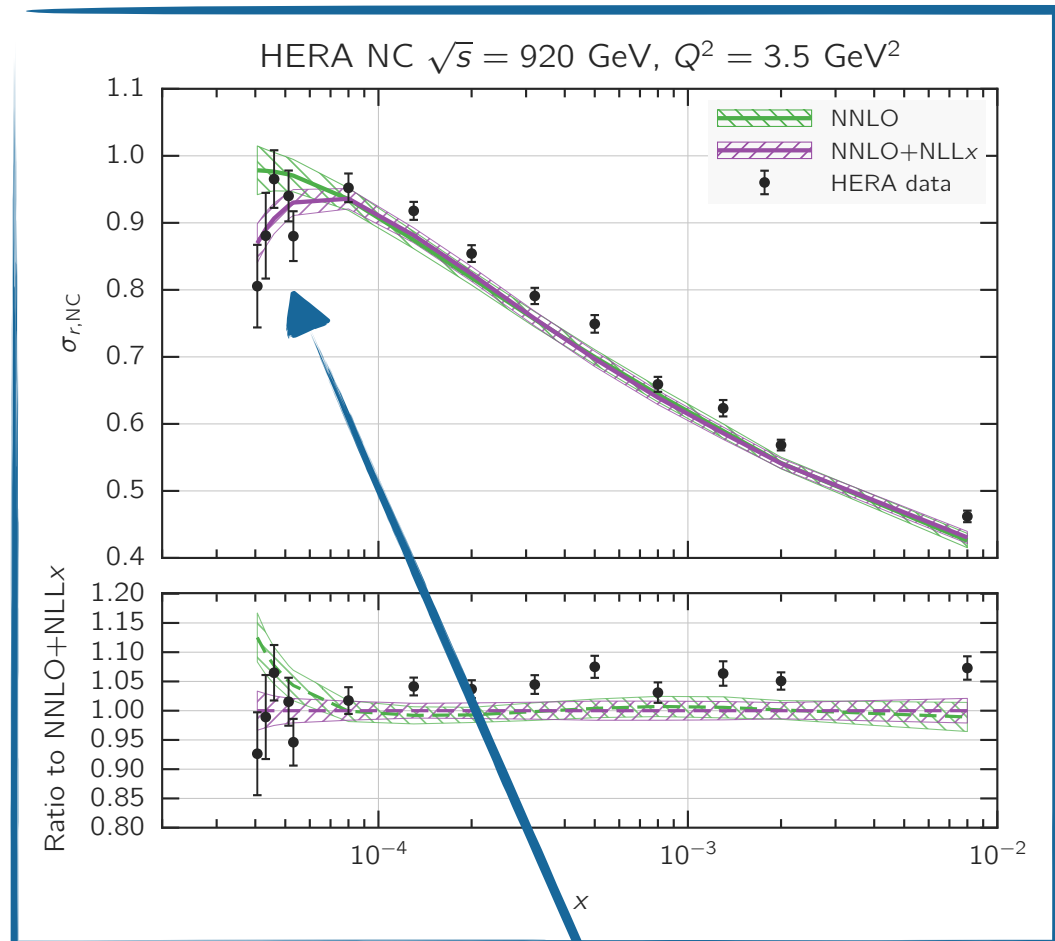


NNLO worsens if
small- x data are
included

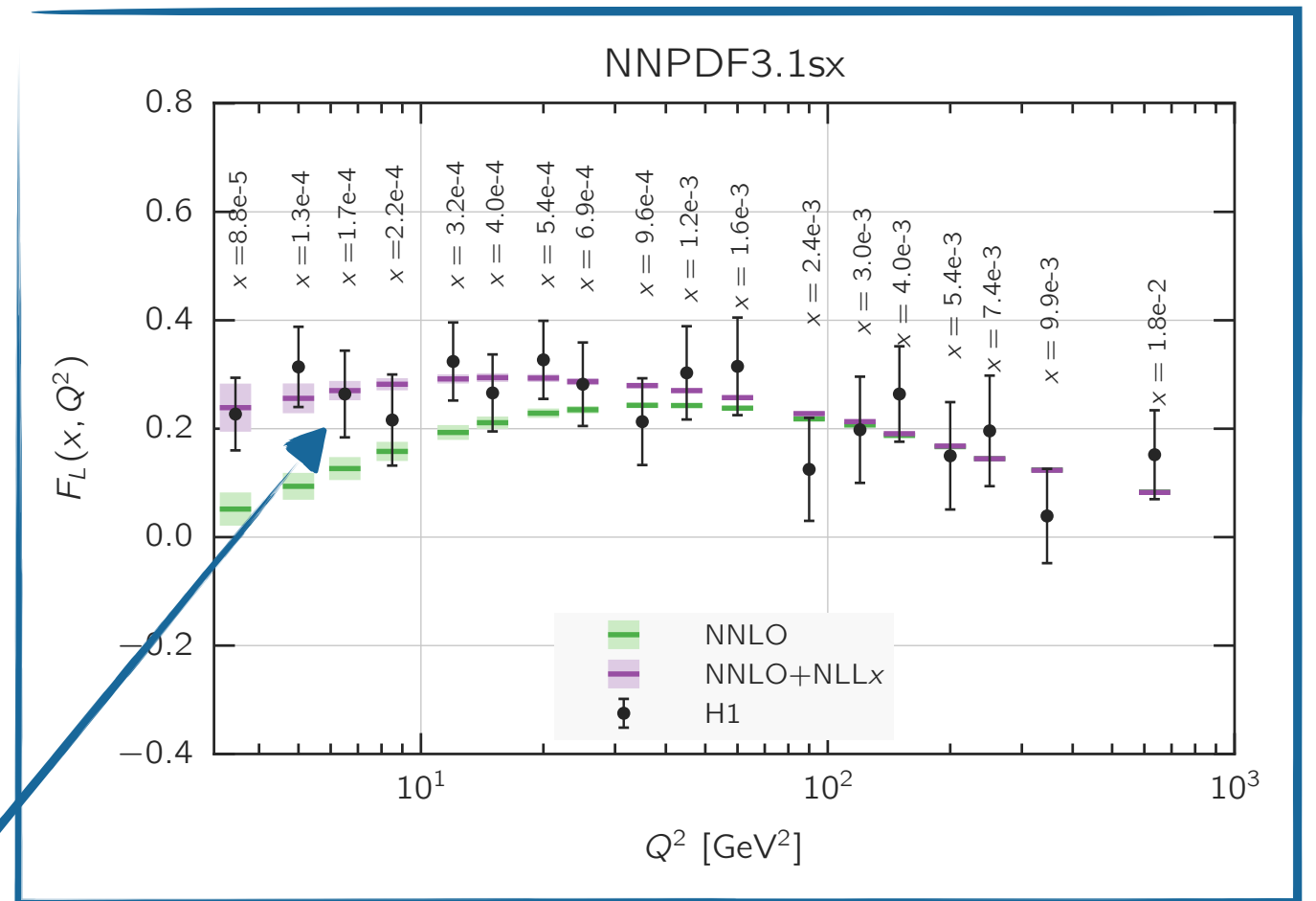
NNLO+NLLx χ^2
flattens at larger
values of D_{cut}

NNLO+NLLx
offers the best
description

The origin of the improved agreement



improved description
of data at small- x and
their slope

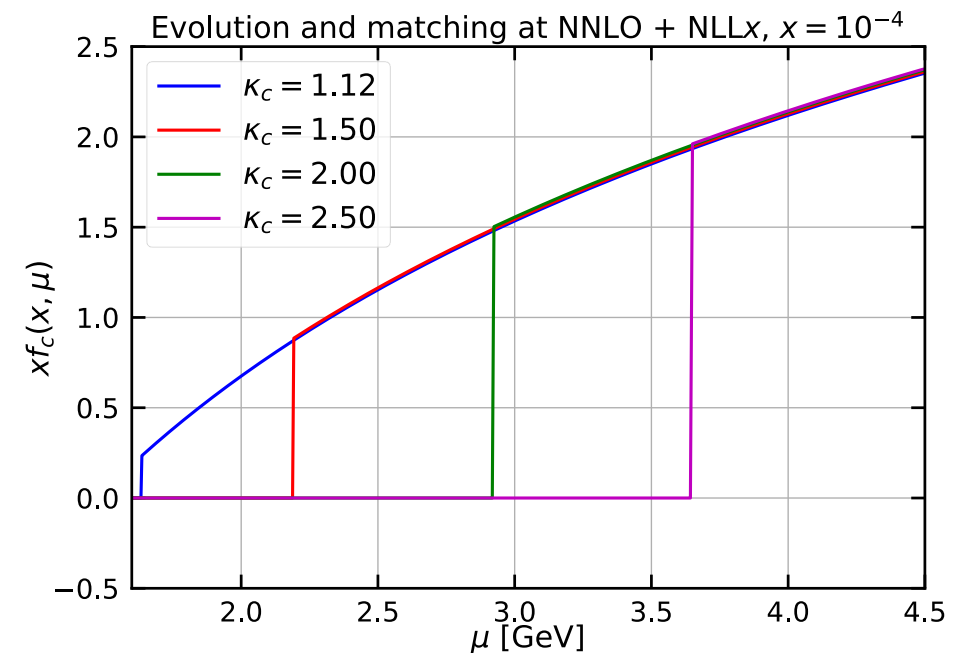
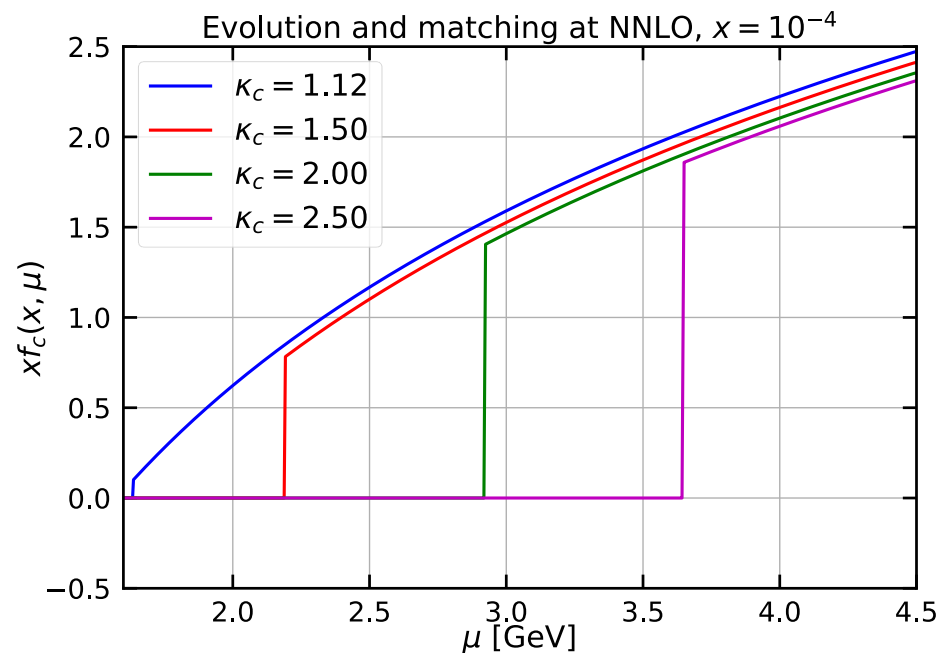


The better description mostly
comes from F_L

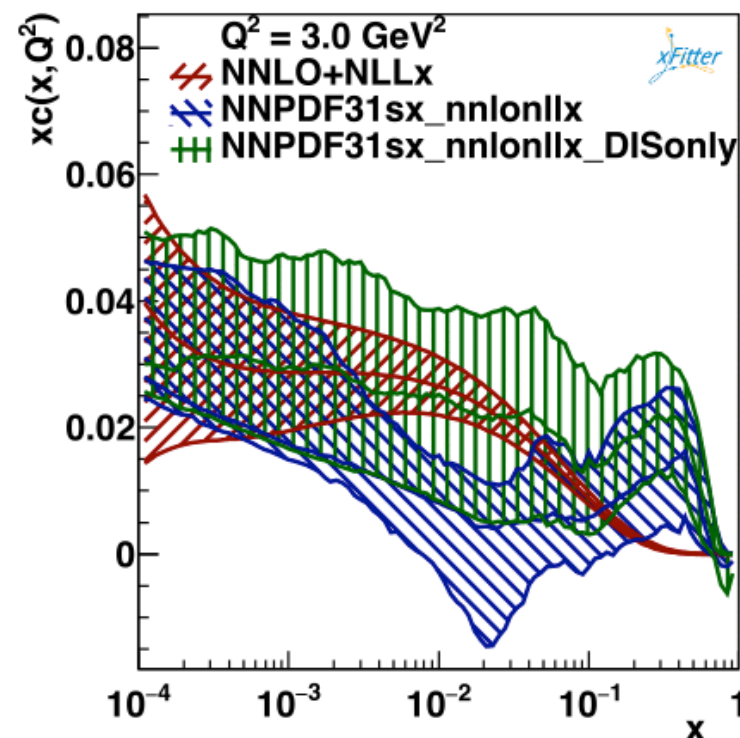
$$\sigma_{r,\text{NC}} = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$

Matching conditions for charm with resummation

$$\kappa_c = \mu_c / m_c, \quad \mu_c = \text{charm matching scale (threshold)}$$



The perturbatively generated charm PDF is much less dependent on the (**unphysical**) matching scale when small- x resummation is included!



Fitted charm and perturbative charm at fixed order differ at small x

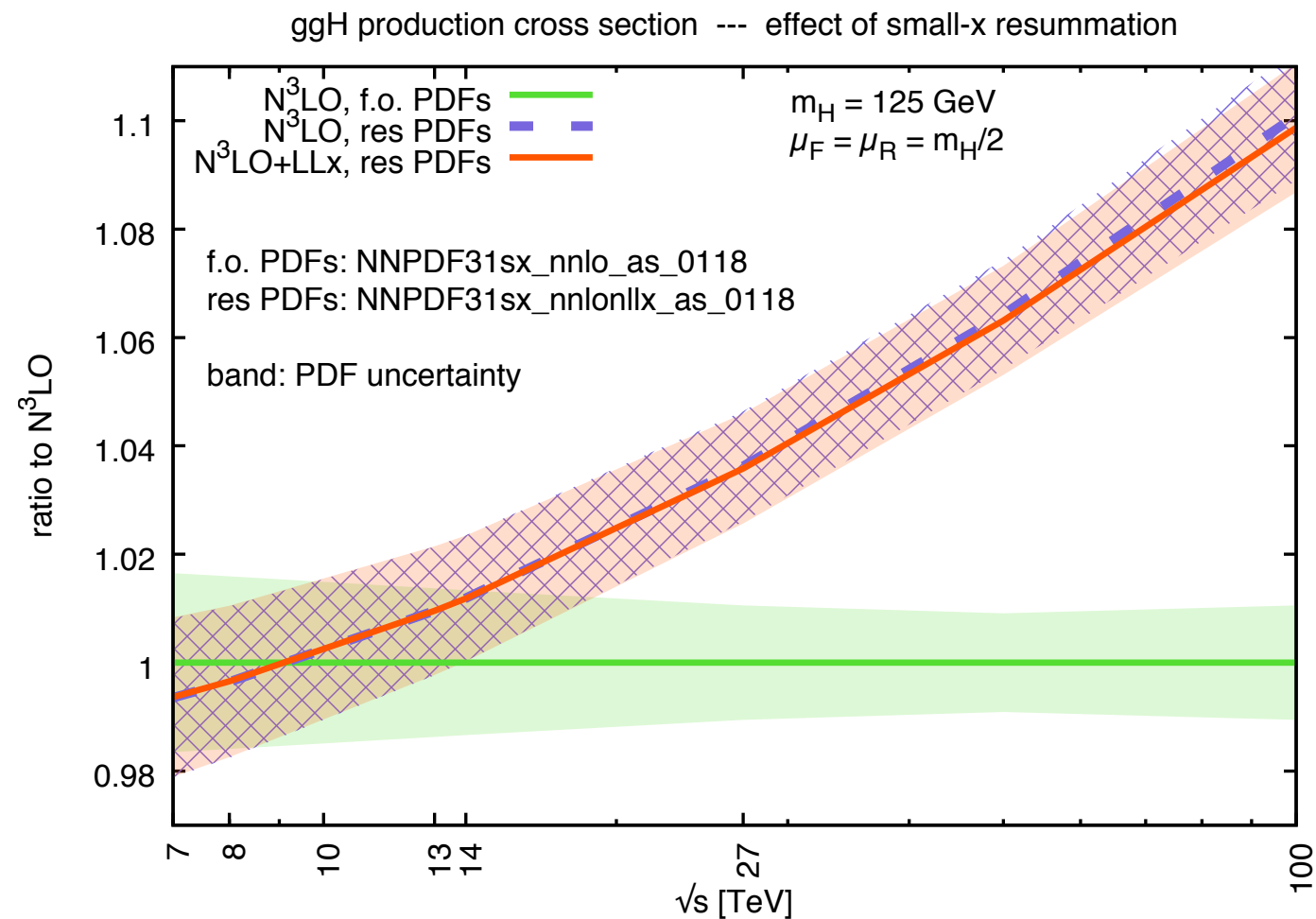
Difference likely reduced when resummation included, but dedicated study is needed

[NNPDF 1605.06515]

Impact at LHC and future colliders

Hadron-hadron collider processes in HELL 3.x:

- Drell-Yan: work in progress
- $gg \rightarrow H$ inclusive cross section: done [MB, Marzani 1802.07758] [MB 1805.08785]



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

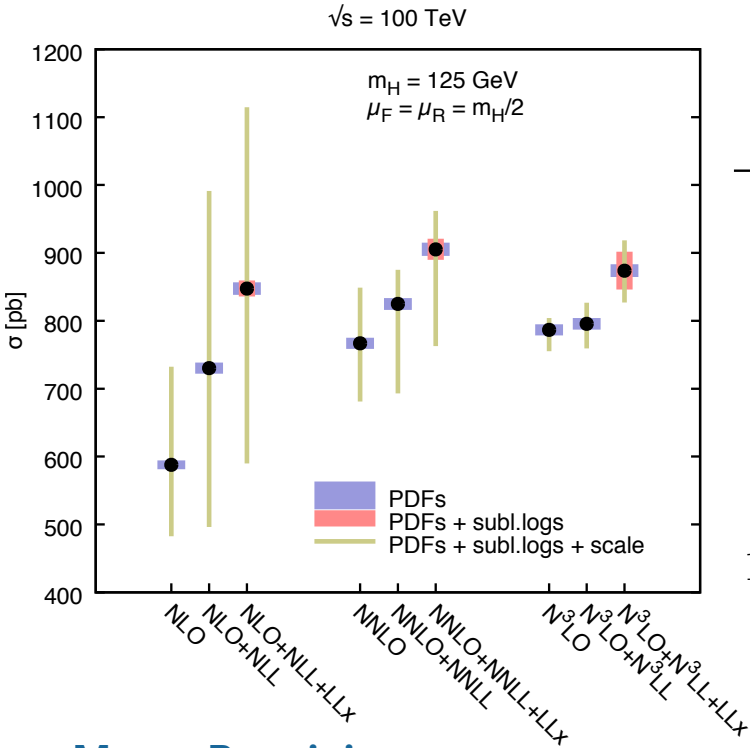
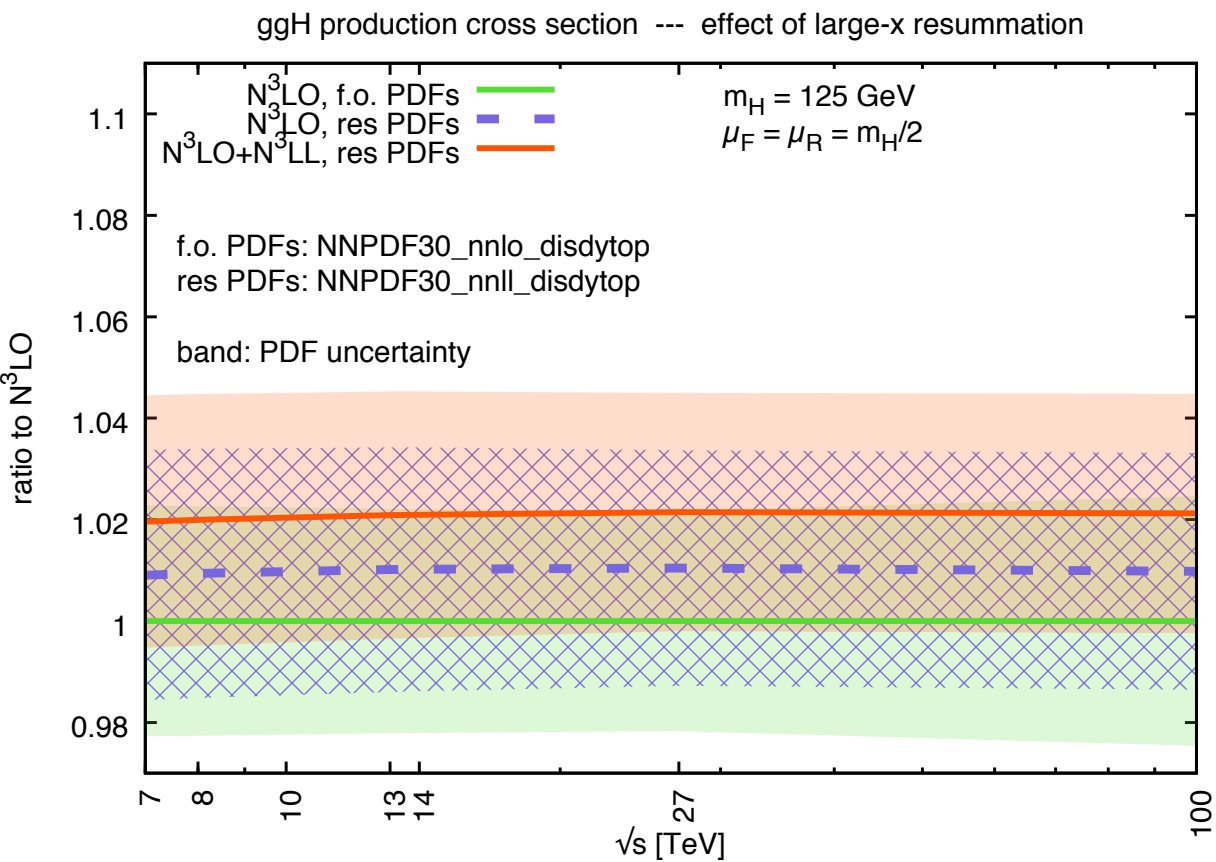
At LHC $+1\%$ effect (plus another 1% from threshold resummation)

Impact at LHC and future colliders: double resummation

Impact of threshold resummation in PDF minor for Higgs production

Double-resummed predictions based on small-x resummed PDF set

Significant impact at future colliders
Larger impact at LHC for differential observables



\sqrt{s}	NNPDF31sx_nnlo_as_0118			NNPDF31sx_nnlonllx_as_0118				
	$\sigma_{N^3\text{LO}}$	δ_{scale}	δ_{PDFs}	$\sigma_{N^3\text{LO}+N^3\text{LL}+\text{LLx}}$	$\delta_{\text{scale}}^{42\text{var}}$	δ_{PDFs}	$\delta_{\text{subl.logs}}$	$\Delta\sigma_{b,c}$
7 TeV	16.76 pb	$^{+0.7\%}_{-3.7\%}$	$\pm 1.7\%$	16.83 pb	$^{+4.2\%}_{-3.6\%}$	$\pm 1.5\%$	$\pm 1.3\%$	-1.01 pb
8 TeV	21.32 pb	$^{+0.7\%}_{-3.7\%}$	$\pm 1.6\%$	21.47 pb	$^{+4.1\%}_{-3.6\%}$	$\pm 1.4\%$	$\pm 1.4\%$	-1.26 pb
13 TeV	48.28 pb	$^{+0.9\%}_{-3.7\%}$	$\pm 1.4\%$	49.26 pb	$^{+4.0\%}_{-3.8\%}$	$\pm 1.2\%$	$\pm 1.8\%$	-2.66 pb
14 TeV	54.32 pb	$^{+0.9\%}_{-3.7\%}$	$\pm 1.3\%$	55.56 pb	$^{+4.0\%}_{-3.8\%}$	$\pm 1.2\%$	$\pm 1.9\%$	-2.96 pb
27 TeV	144.7 pb	$^{+0.9\%}_{-3.7\%}$	$\pm 1.1\%$	151.6 pb	$^{+4.0\%}_{-4.0\%}$	$\pm 1.0\%$	$\pm 2.3\%$	-7.2 pb
100 TeV	786.7 pb	$^{+1.9\%}_{-3.8\%}$	$\pm 1.1\%$	873.9 pb	$^{+4.0\%}_{-4.3\%}$	$\pm 1.2\%$	$\pm 3.0\%$	-32.0 pb

Other new interesting recent progress

- ▶ Photon PDF (LUXqed) [[Manohar,Nason,Salam,Zanderighi 1607.04266 1708.01256](#)]
- ▶ Tools for conversion from MC error to Hessian and vice versa [[Carrazza et al](#)]
- ▶ PDFs with theory uncertainties
- ▶ Some progress towards N3LO evolution and N3LO PDFs
- ▶ Tons of new data from LHC included in PDF fits
- ▶ More flexible parametrizations (e.g. Neural Networks in NNPDF)
- ▶ Various benchmarking and procedural improvements by the various groups, mostly driven by the PDF4LHC activity
- ▶ Nuclear PDFs
- ▶

Conclusions

- ▶ Our knowledge of PDFs has increased significantly over the last years
- ▶ First **unbiased determination of the charm PDF**
- ▶ **First global fits** with threshold and small- x resummation in the NNPDF framework
- ▶ Threshold resummed PDFs useful for **searches**, but need to improve precision
- ▶ Small- x resummation important at high collider energy and/or small masses
- ▶ Evidence that **NNLO+NLL x improves** with respect to NNLO
- ▶ Rather different PDFs when small- x resummation is included
- ▶ Impact at LHC and beyond potentially large

In the recent years our knowledge on the proton's structure improved significantly,
but there's a lot yet to be done