QCD for inclusive forward charm production at the LHC

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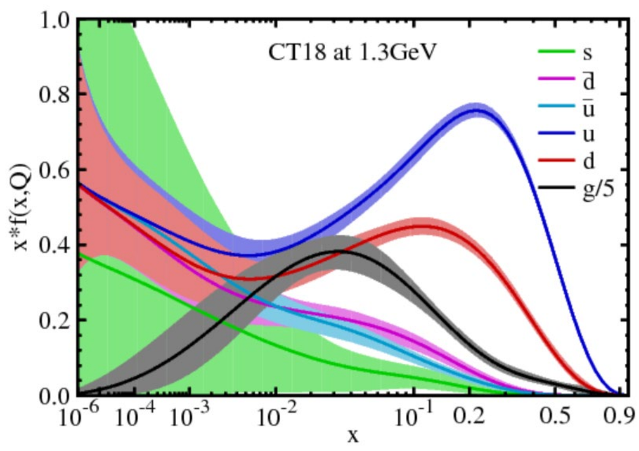


Based on studies with

CTEQ-TEA (Tung et al.) working group

1. PDFs at small momentum fractions x

T.-J. Hou et al.,arXiv:1912.10053

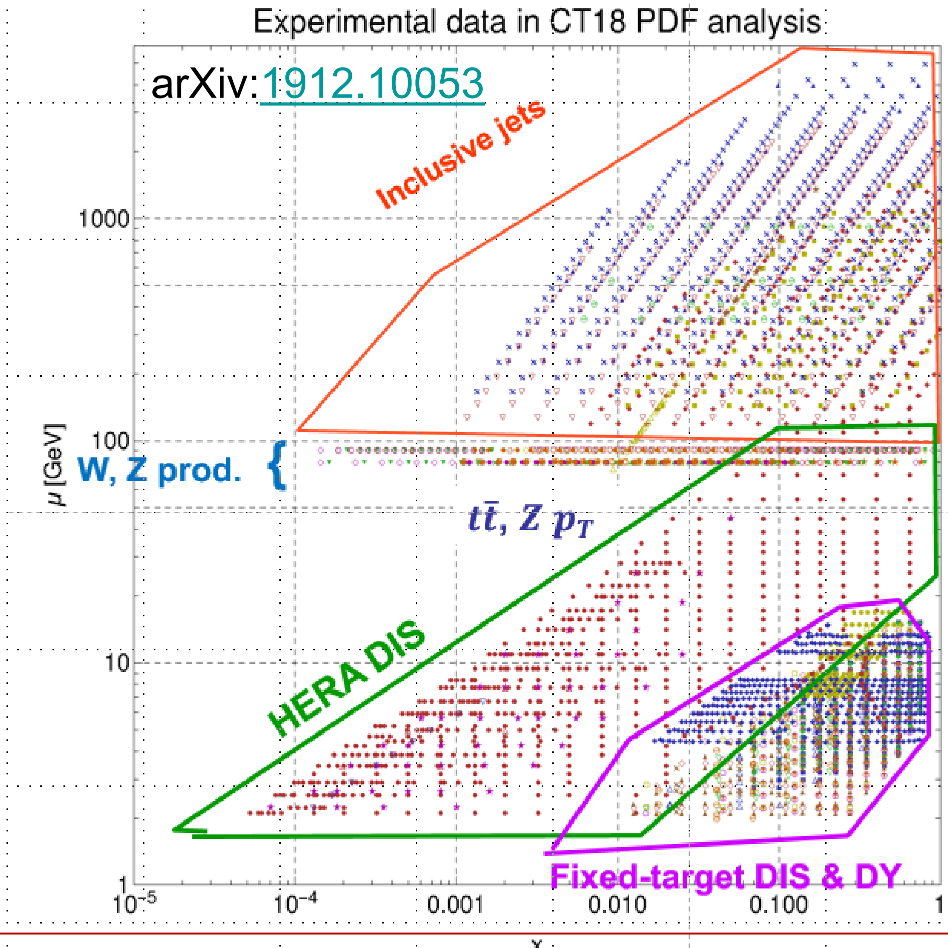
2. Intrinsic charm production at large x

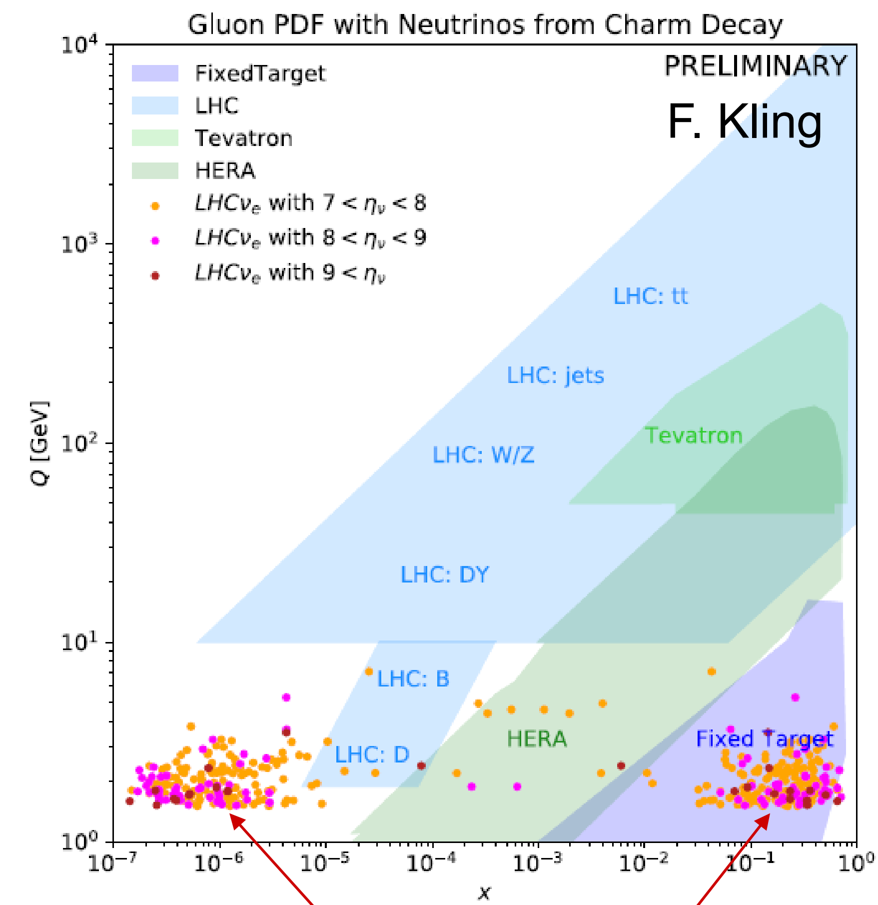
T.-J. Hou et al., arXiv:1707.00657

C T E Q

11/10/2020

A Forward Physics Facility at the LHC opens access to new momentum fractions x



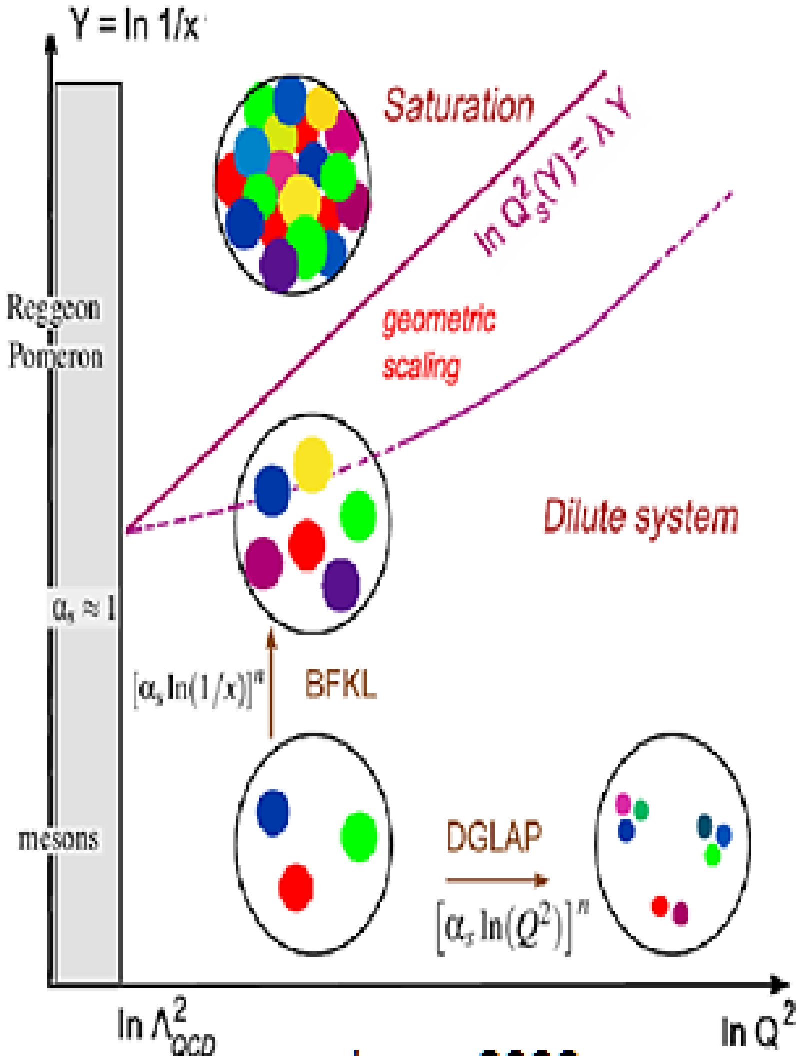


$pp \to (c \to D \to \nu)X$ production at FASERν

$\langle x_1 \rangle \sim 10^{-7}$ and $\langle x_2 \rangle \sim 0.02$ at $\langle Q \rangle \sim 2$ GeV

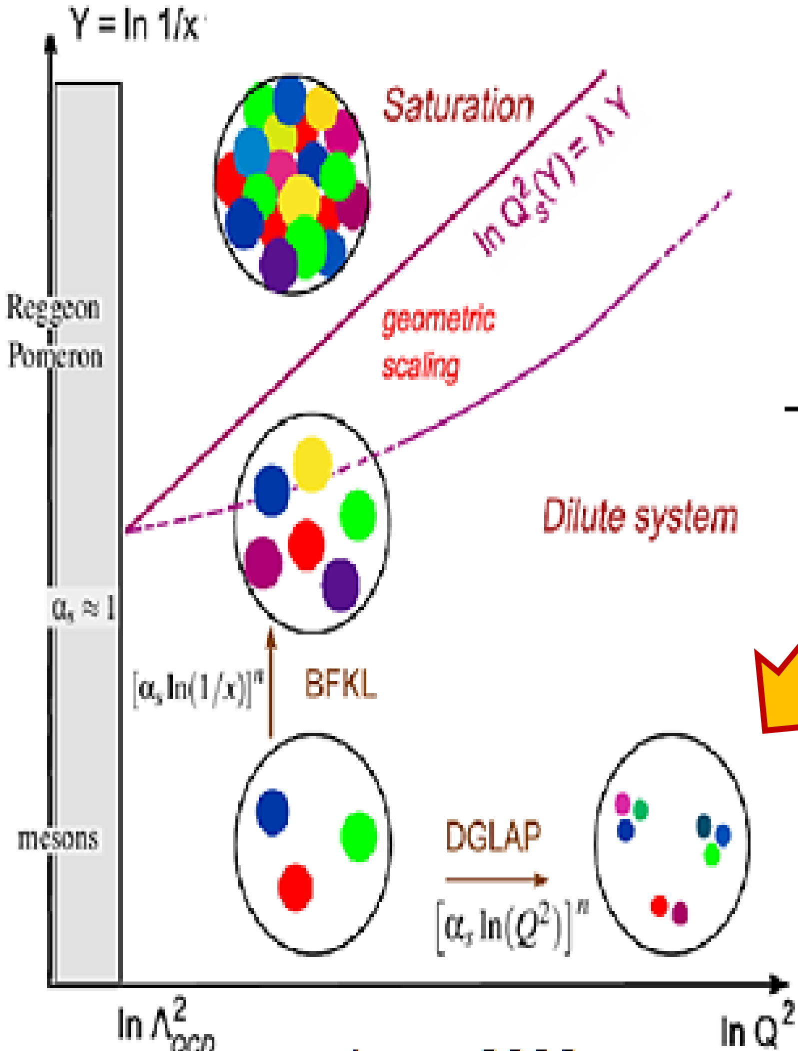
1. Little is known about QCD for charm production at such $\langle x \rangle$ ⇒ this talk
2. FASERν detects neutrinos via charged-current DIS on nuclear targets ⇒ M. Garzelli

QCD theoretical formalisms in the x and Q plane



Iancu:2006uc

QCD theoretical formalisms in the x and Q plane



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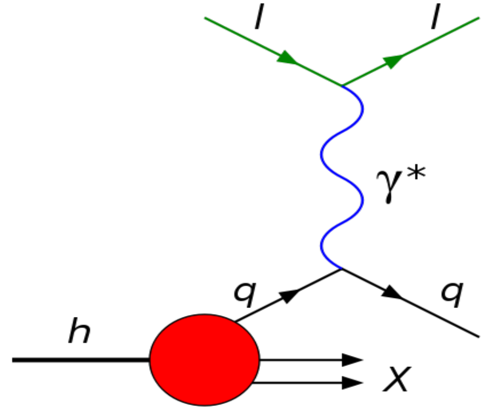
1. DGLAP: $Q > 1 - 2$ GeV, $x > 10^{-4} - 10^{-5}$



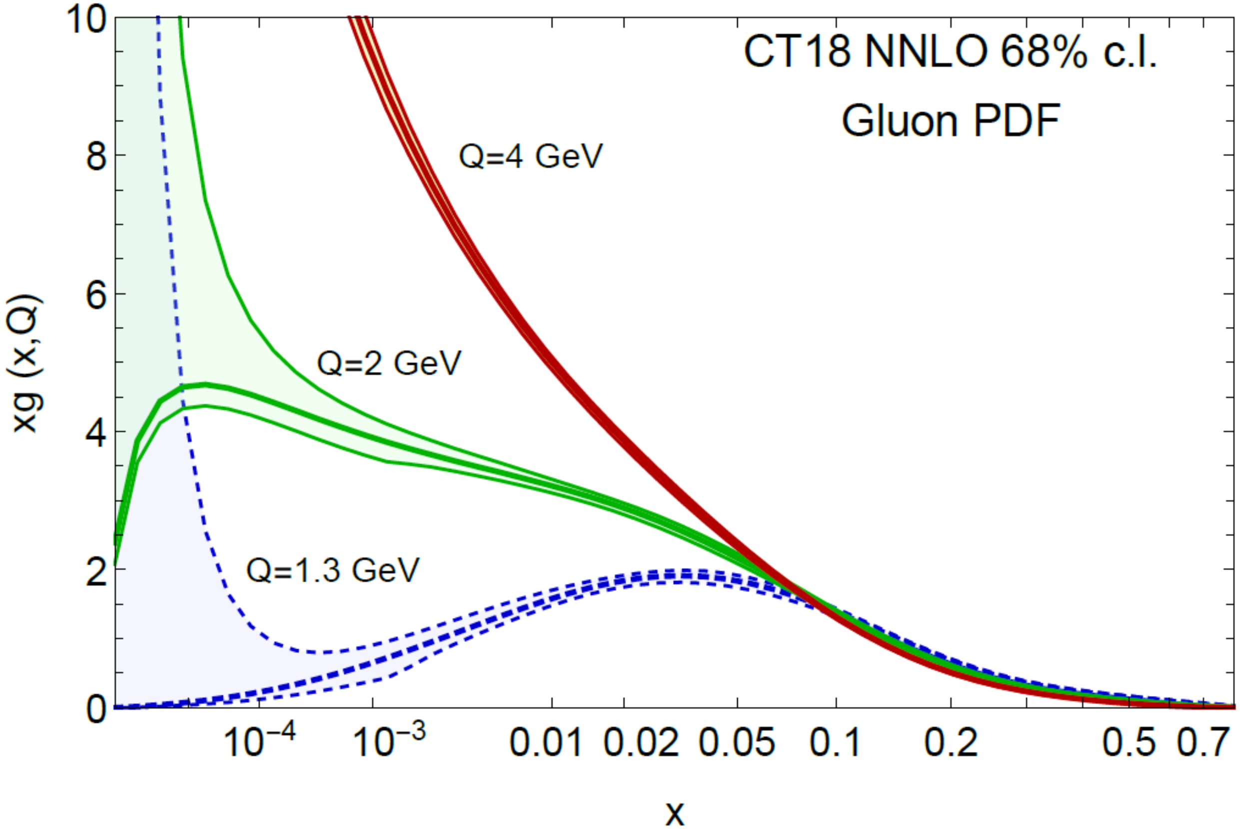
DGLAP factorization in terms of PDFs and hard cross sections

In DIS, we have in this region

$$\sigma_{tot}^{\gamma^* p \to X}(x, Q^2) = \sum_{q=u,\bar{u},d,\ldots} [c_q \otimes f_q](x, Q^2)$$

Multiple precise parametrizations of PDFs $f(\xi, \mu)$ from ABM, CT, HERA, MSHT, NNPDF, … are available at NNLO

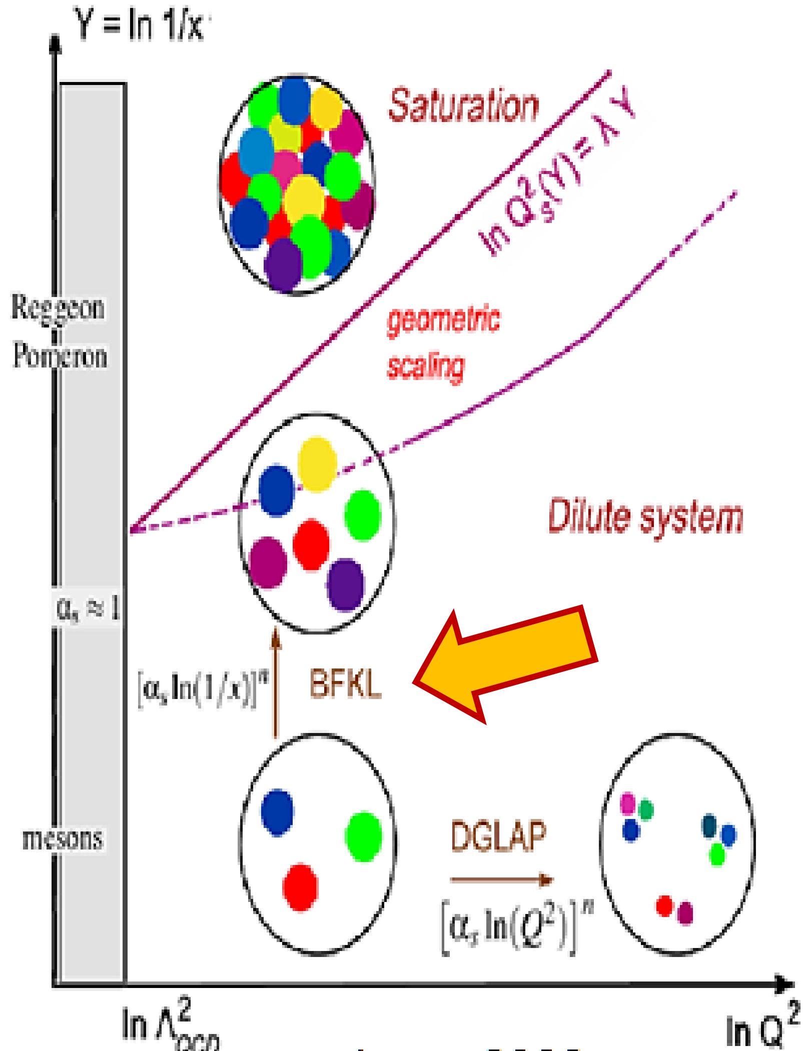
Fast growth of PDFs at $x \to 0$ and fixed Q



- The growth of parton densities must slow down at very small x because of unitarity of the scattering matrix

- At $x = 10^{-7}$ and $Q = 1 - 2$ GeV, gluon and other PDFs have large uncertainty and large Q dependence
- Fixed-order DGLAP predictions do not converge well here

QCD theoretical formalisms in the x and Q plane



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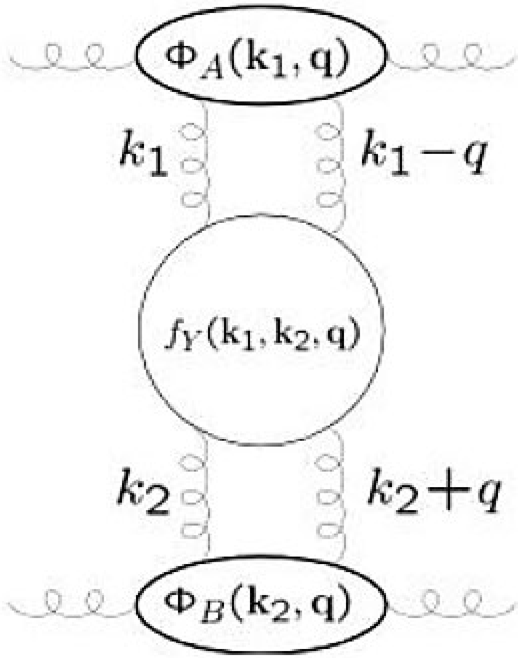
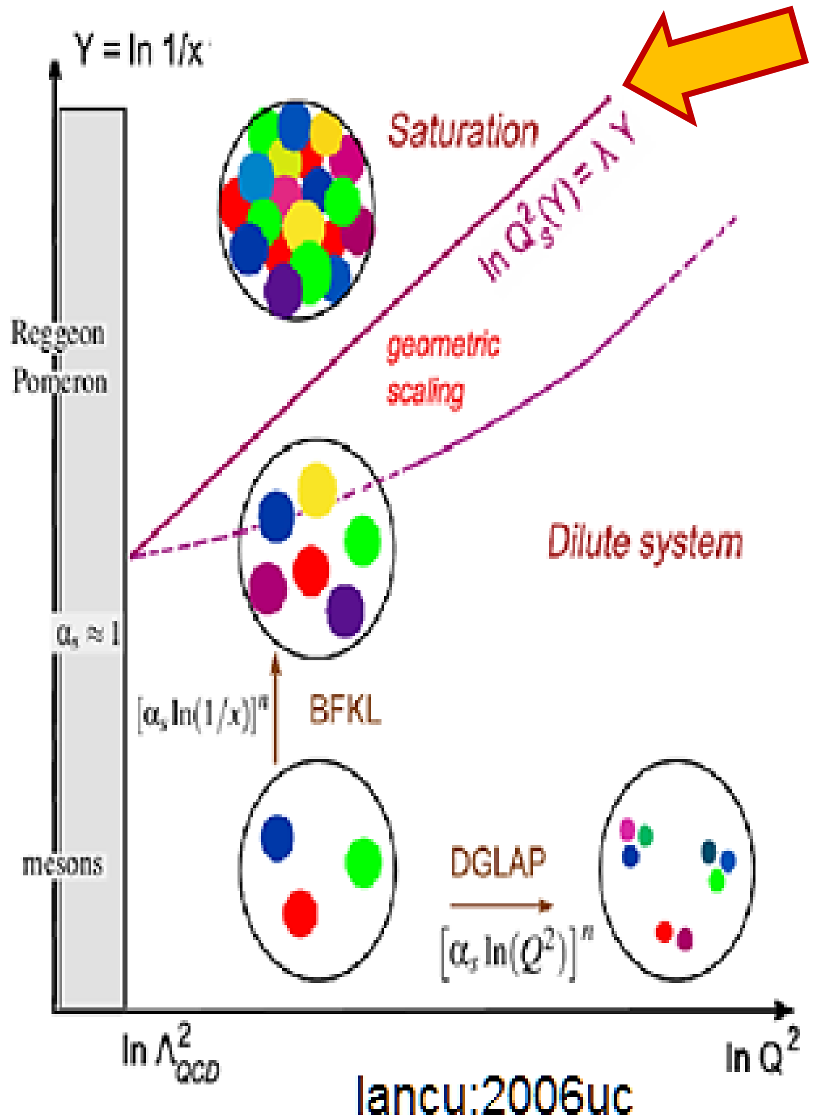
2. BFKL: $Q > 1 - 2$ GeV, $? < x < 10^{-4}$

k_T dependent factorization resums towers of $\alpha_s^k \log^p(1/x)$ when α_s is small



Some PDF fits implement the NLLx-NNLO approximation to the full BFKL solution in the Altarelli-Ball-Forte representation

QCD theoretical formalisms in the x and Q plane

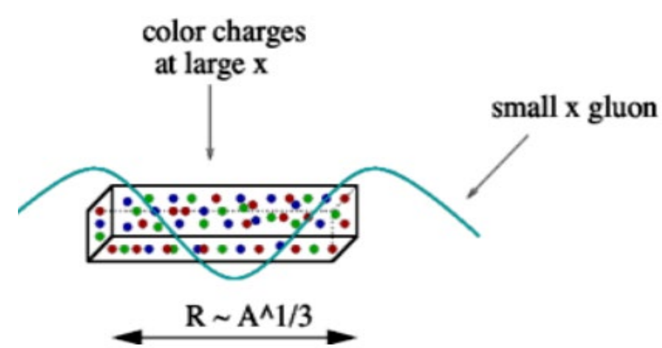


3a. Saturation: $Q^2 \lesssim Q_0^2\, x^{-0.3}$

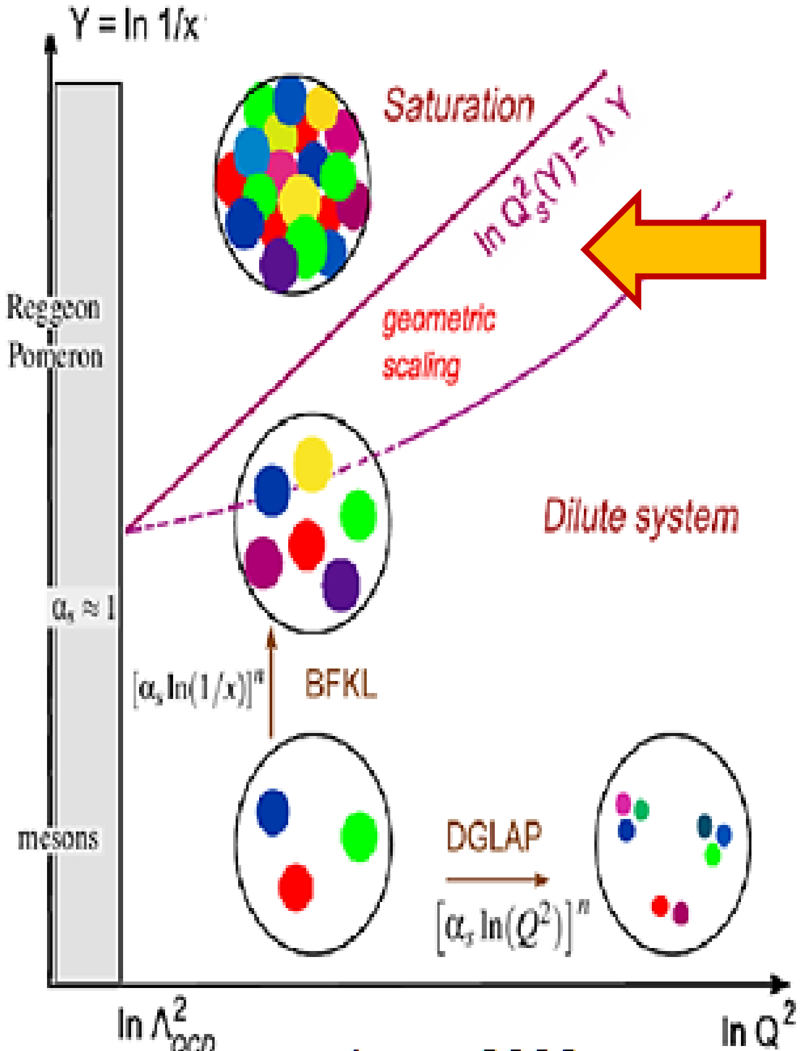
At such Q^2, the parton density is very high. Large parton recombination effects slow down the growth of PDFs with Q^2

Color **G**lass **C**ondensate: the relevant degrees of freedom in a hadron are classical QCD fields

The JIMWLK equation describes scattering of QCD dipoles on the CGC matter



QCD theoretical formalisms in the x and Q plane



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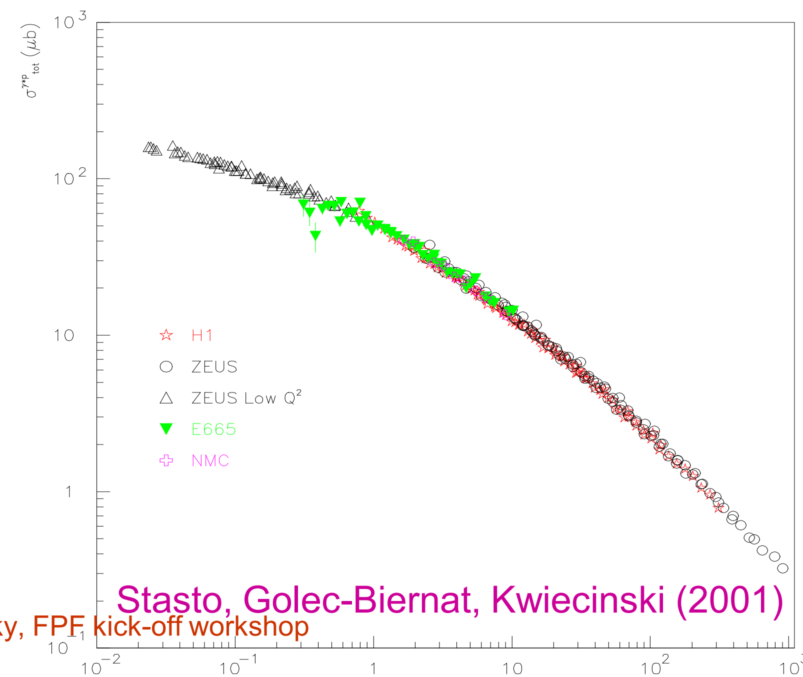
3b.: Saturation: $Q^2 \sim Q_0^2\, x^{-0.3}$

The Balitsky-Kovchegov (BK) equation realizes the JIMWLK equation when long-distance parton correlations are not large

The BK equation predicts geometric scaling. Geometric scaling is qualitatively observed in HERA DIS data. It is based on the fits that are not very precise.

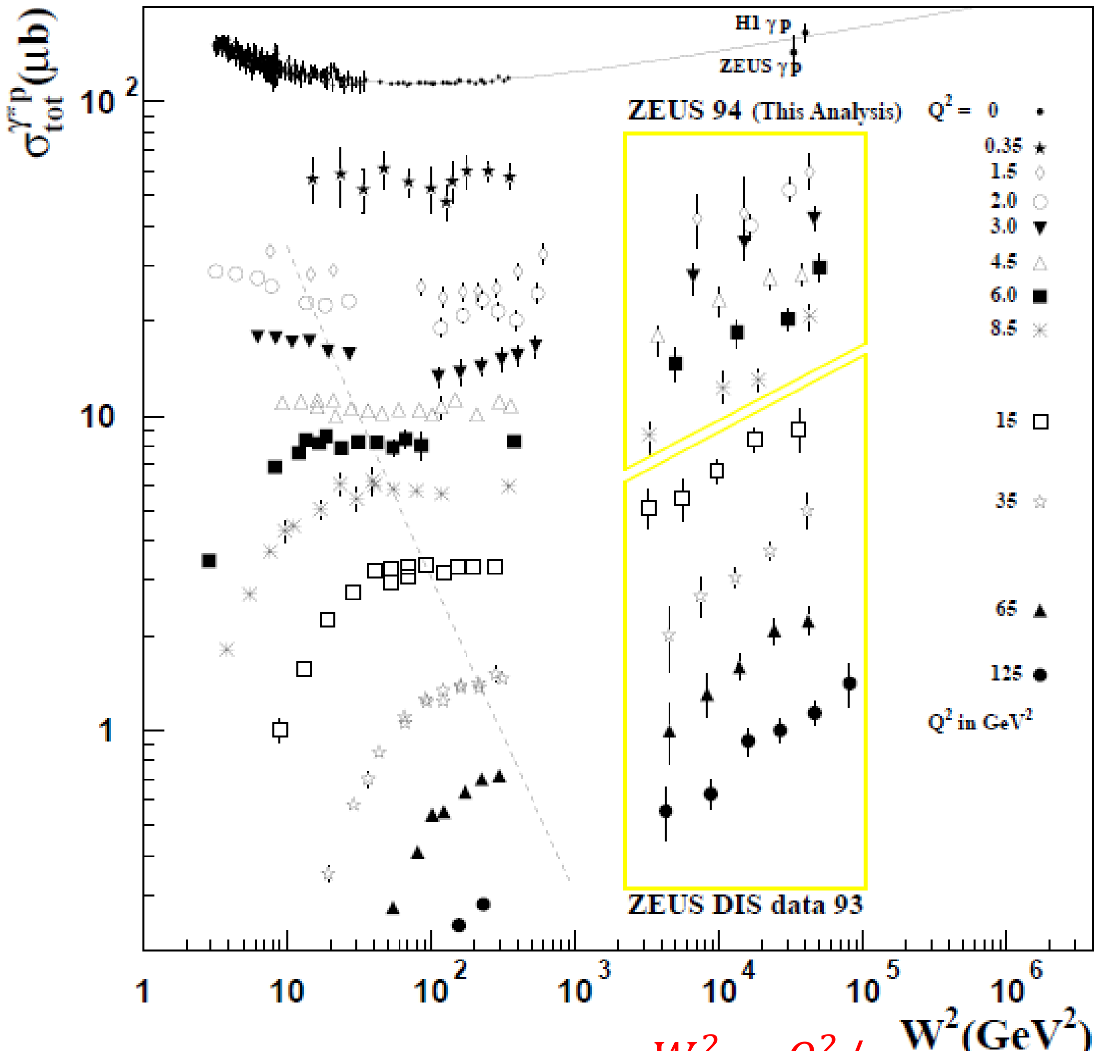


Stasto, Golec-Biernat, Kwiecinski (2001)

Which formalism(s) are relevant for FASERν?

QCD dynamics vs. Q and x

$\gamma^* p$ total cross sections
ZEUS, hep-ex/9510009



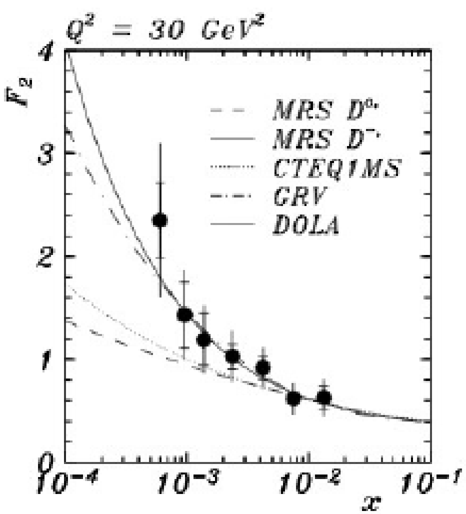
$W^2 \approx Q^2/x$

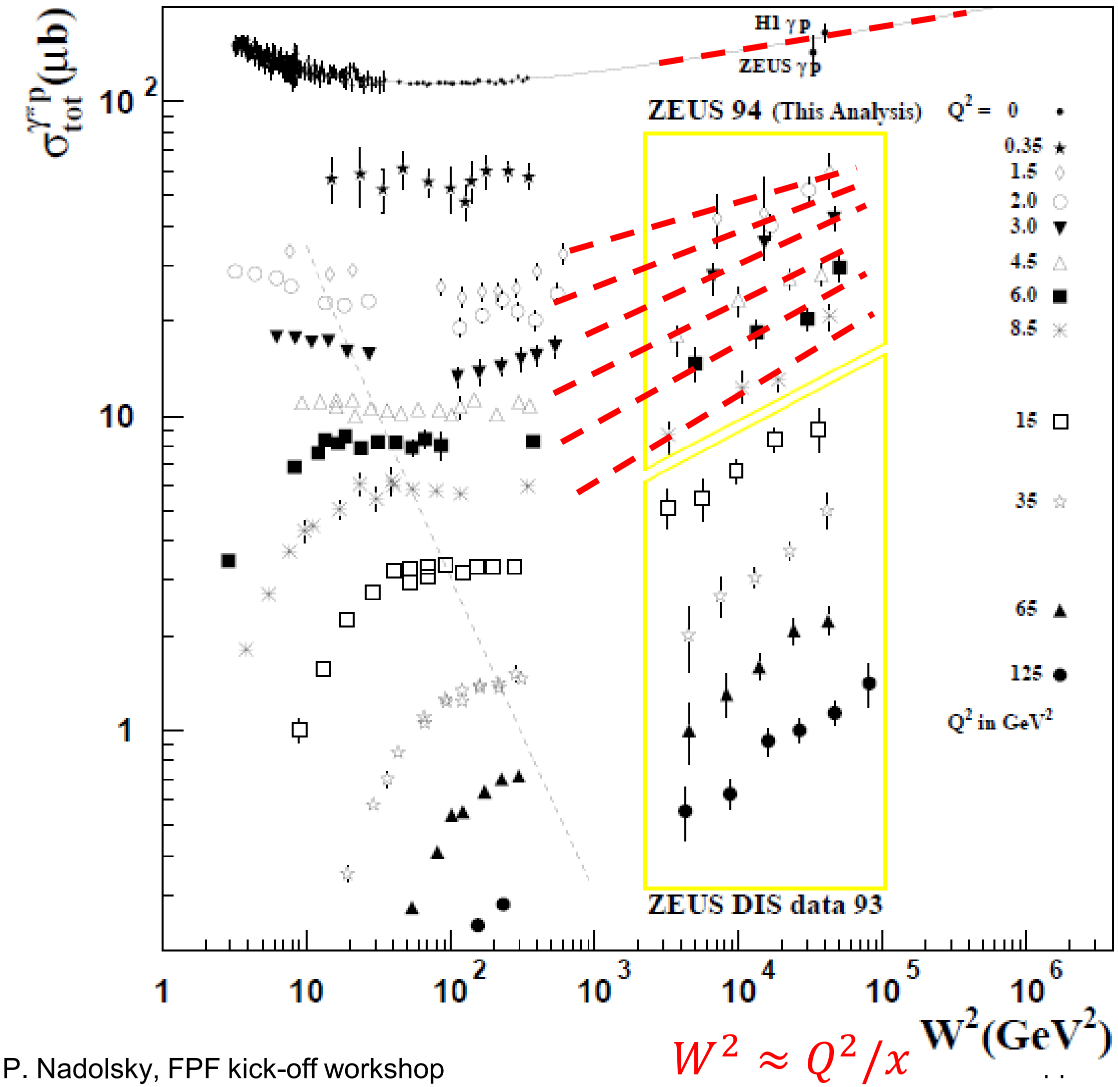
QCD dynamics vs. Q and x

$\gamma^* p$ total cross sections
ZEUS, hep-ex/9510009

Red lines "fit" $\sigma_{tot}^{\gamma^* p} \sim \sigma_{reduced}$ for a fixed Q

The slope of $\sigma_{tot}^{\gamma^* p} \sim \sigma_{red}$ vs. $1/x$ changes as a function of x and Q, predicting rapid growth of PDFs at $x \to 0$





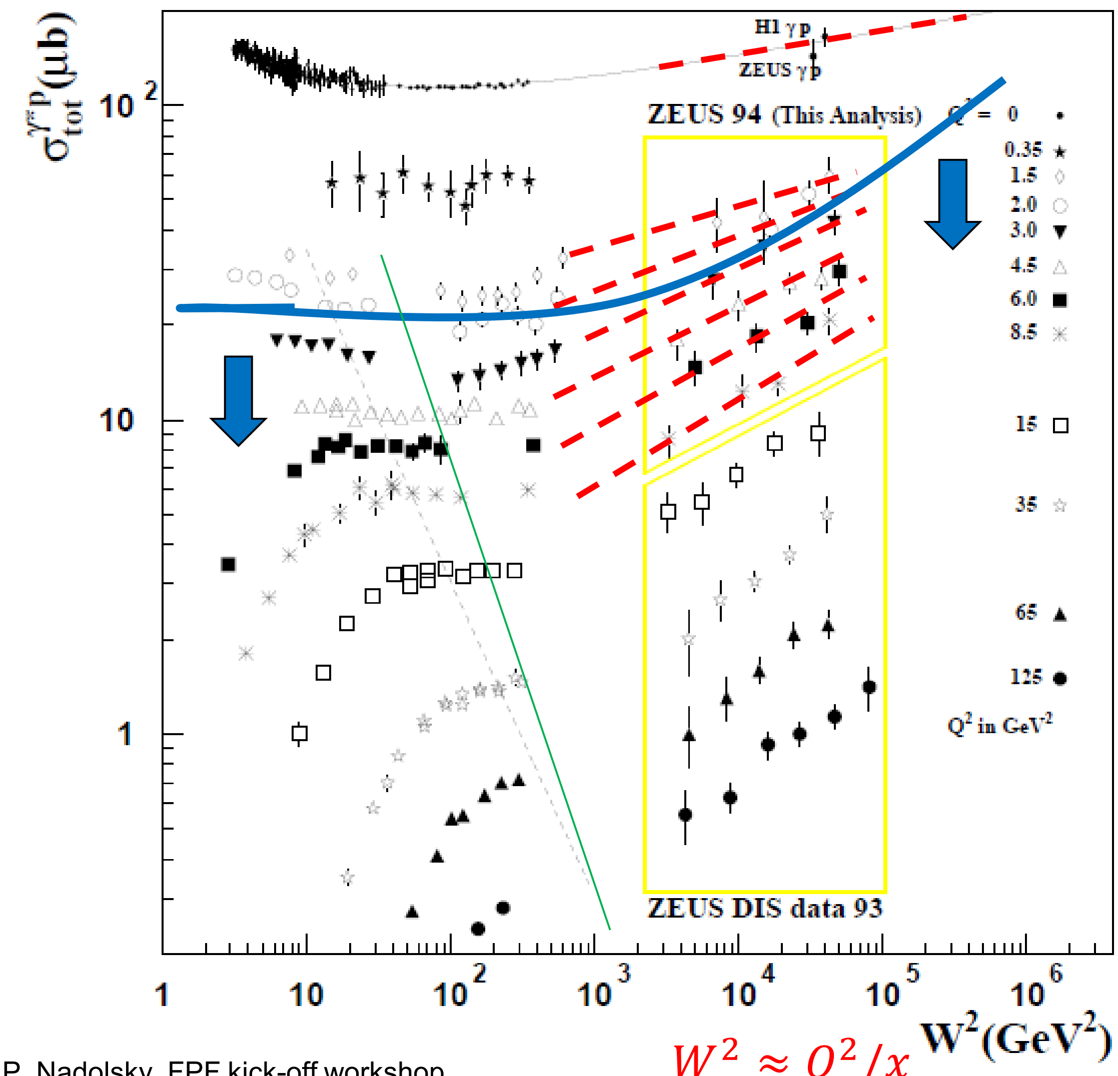
QCD dynamics vs. Q and x

$\gamma^* p$ total cross sections
ZEUS, hep-ex/9510009

For points below the blue line, expectations are consistent with DGLAP collinear factorization at NNLO

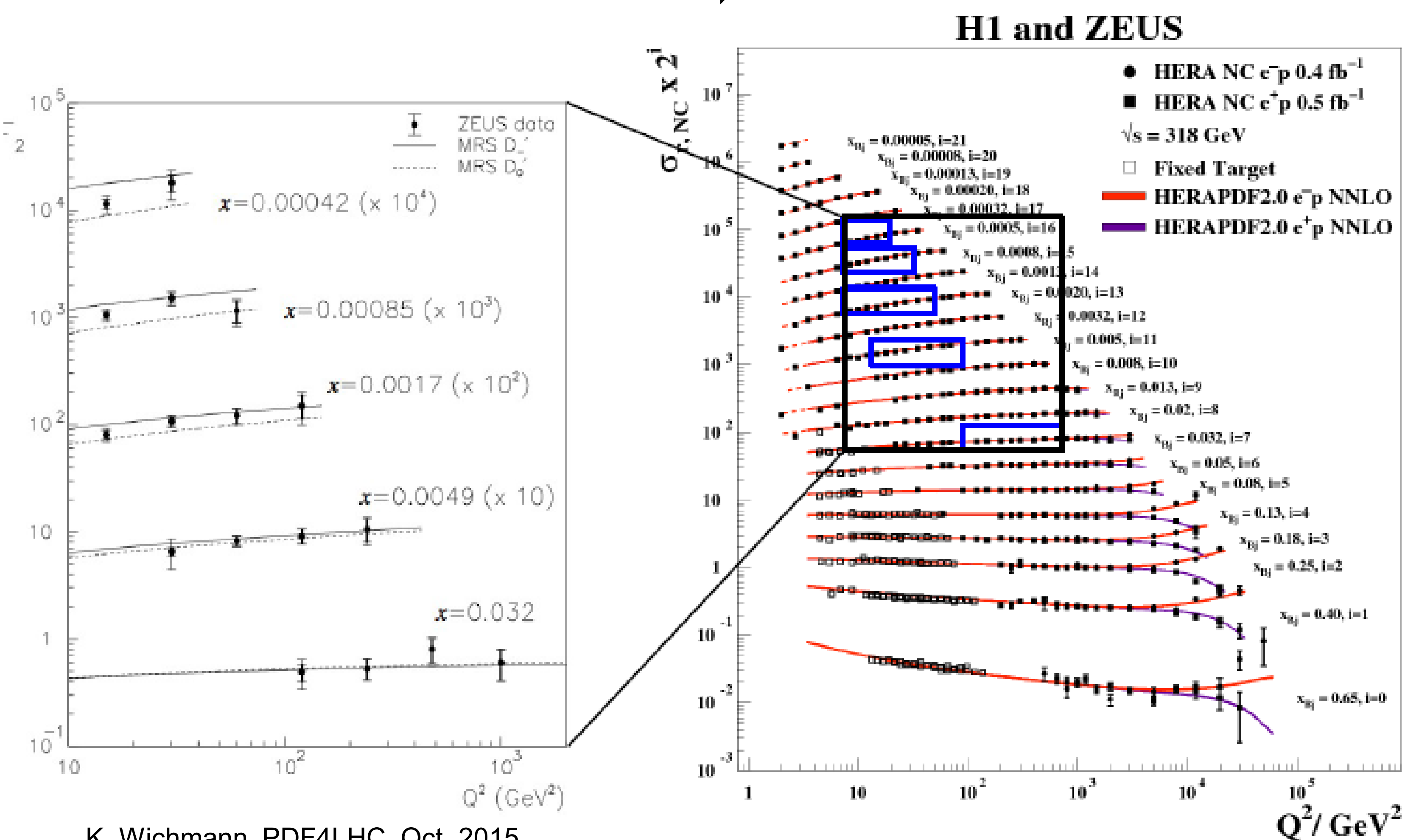
Above, we see deviations

The boundary has not been located precisely.

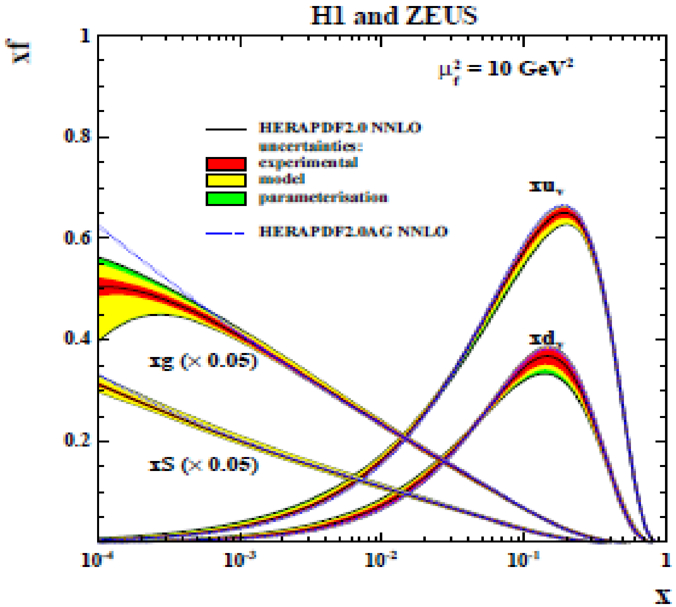


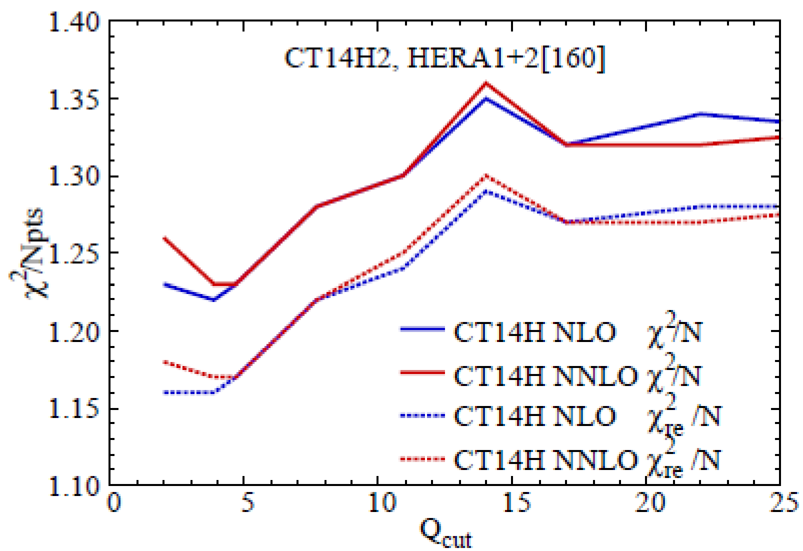
We can test DGLAP factorization with combined HERAI+II data!

1993 → **arXiv:1506.06042**



K. Wichmann, PDF4LHC, Oct. 2015





χ^2/N_{pts} with (top) and without (bottom) penalty for syst. shifts

The combined HERA1+2 data are included in HERA2.0, CT14H2, MMHT, and NNPDF3.1 analyses

$\chi^2/d.o.f. \sim 1.2$ for HERA1+2 tends to be elevated across all analyses, compared to $\chi^2/d.o.f. < 1.1$ for combined HERA1 data

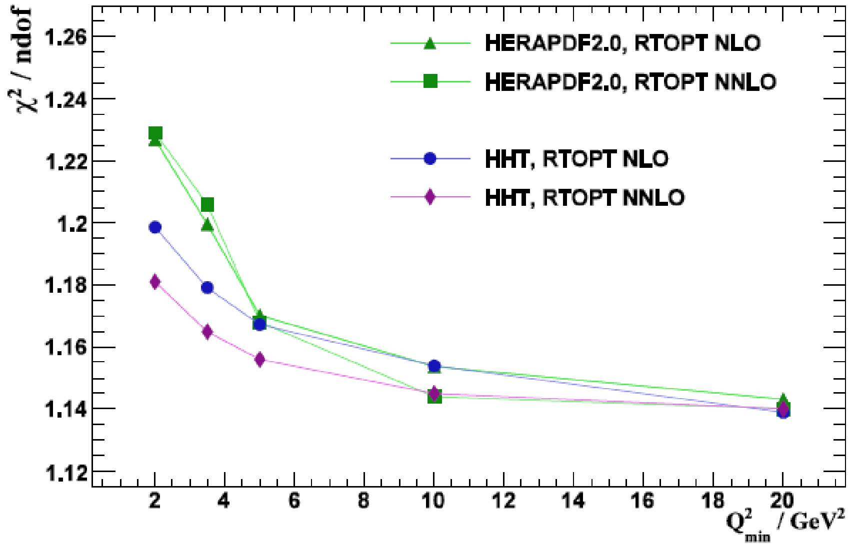
$\Rightarrow$ This tension may arise from several sources

- Twist-4 correction to $F_L(x, Q)$
- Small-x/saturation
- Experimental systematics

The impact on global PDFs is mild, changes in PDFs do not exceed uncertainties

Modifications to the HERAPDF2.0 fit called HHT

By I.Abt, **A.M.Cooper-Sarkar**, B.Foster, V.Myronenko, K.Wichmann, M.Wing

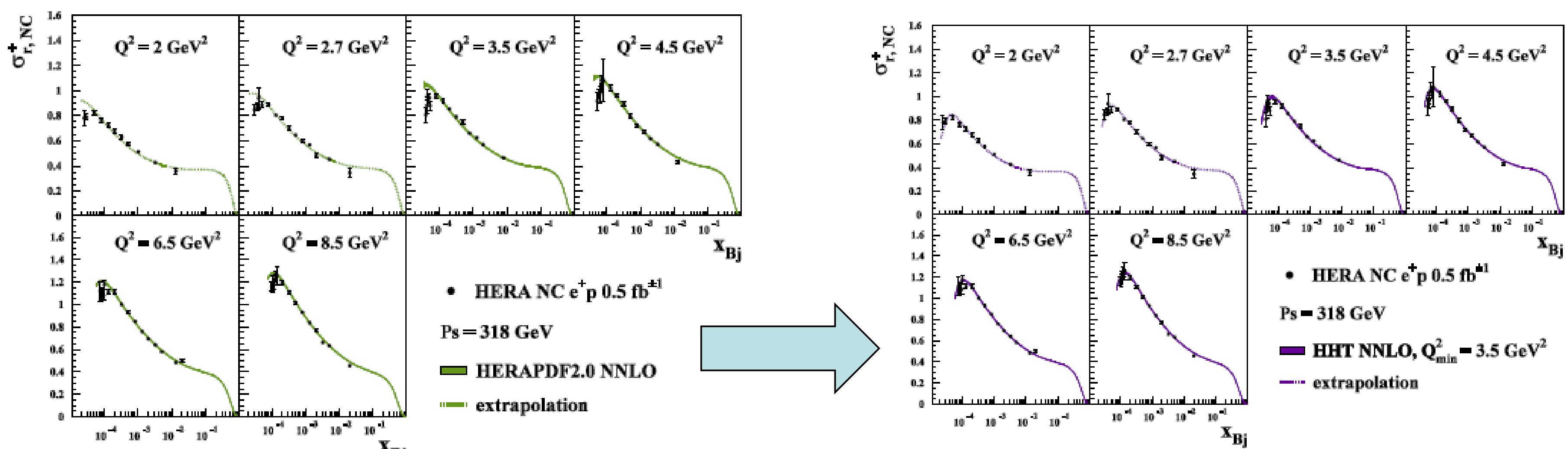


$$F_{2,L} = F_{2,L}\,(1 + A_{2,L}^{HT}/Q^2)$$

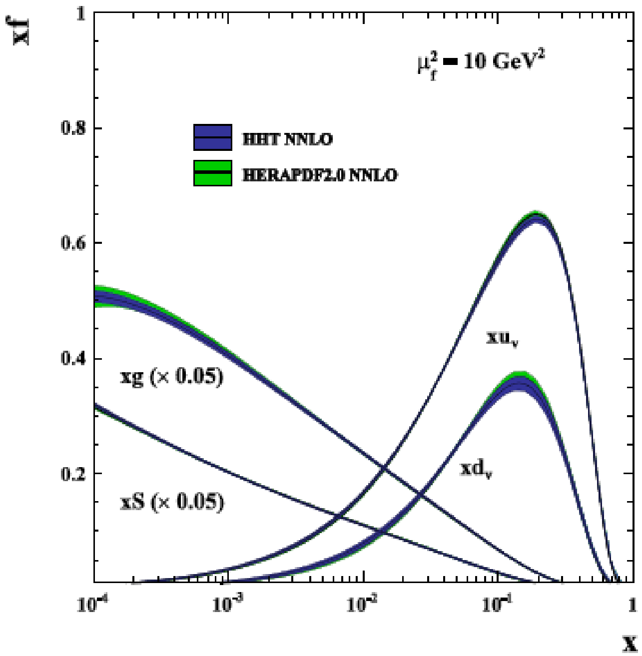
Addition of Higher Twist terms

- requires only modification of F_L
- and is only important for low-x

Greatly improves the description of low-Q^2, low-x and high-y data particularly at NNLO

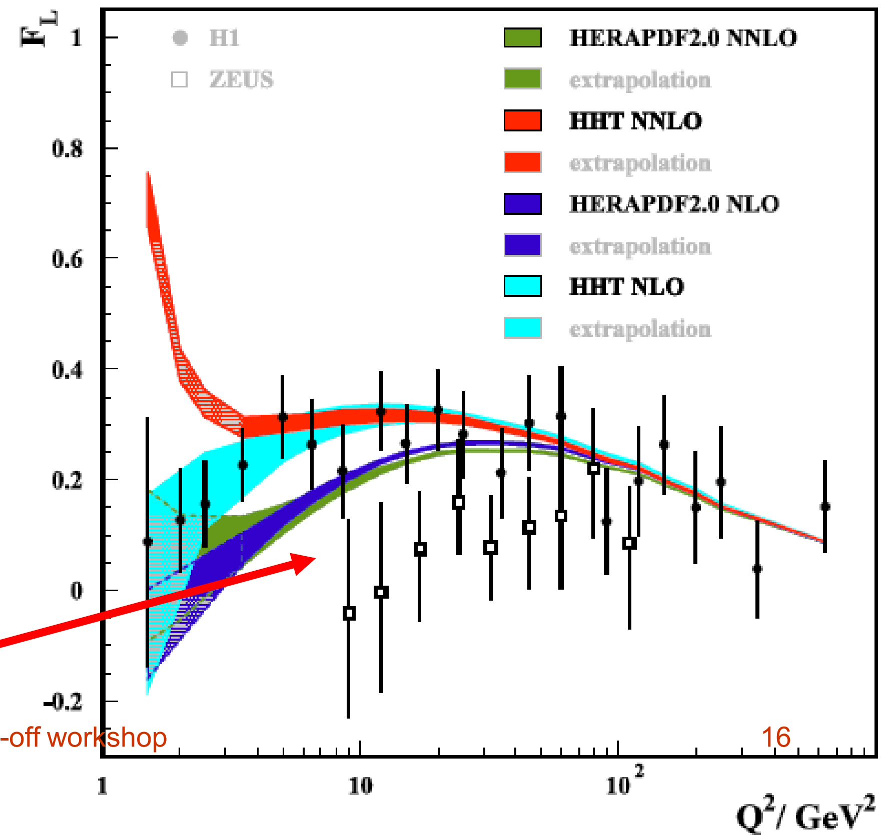


PDFs – and hence high Q^2 physics - not changed



Predicted FL - compared to the measured FL from H1 and ZEUS – is enhanced for $Q^2 < 50$ GeV^2.

However it is clear that this approach cannot be pushed to very low $Q^2 <$ ~2 GeV^2



P.N.: Notice differences between H1 and ZEUS

Alternative formalisms for low-x DIS data

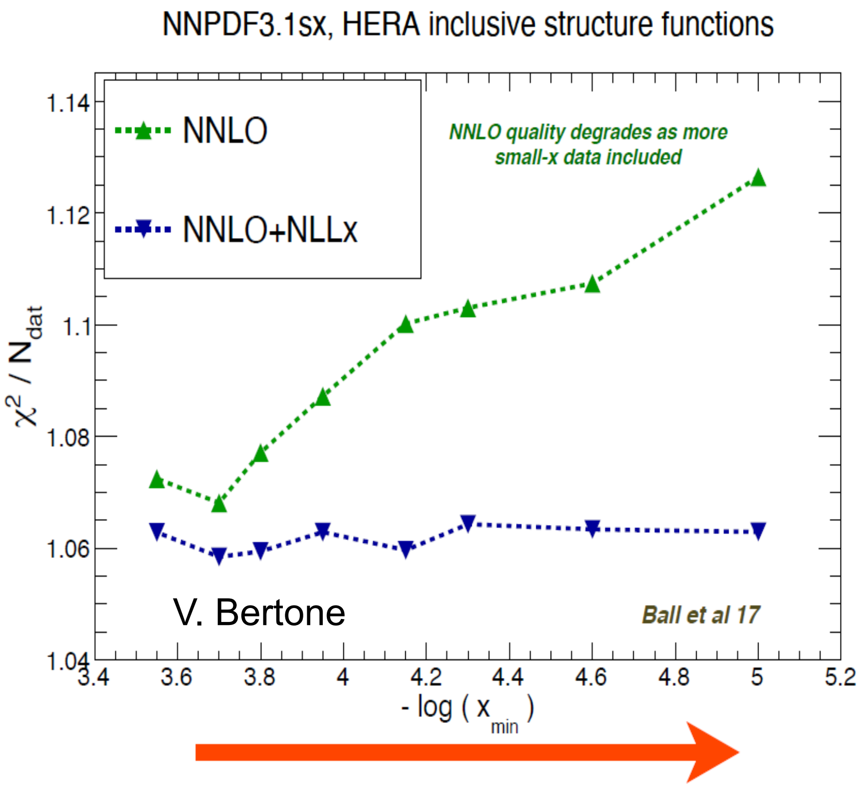
- NNPDF [arXiv:1710.05935] and xFitter [1802.0064] :
  BFKL to resum the small-x logarithms

- CT18 [arXiv:1912.10053]:
  an x-dependent DIS scale, motivated by the saturation models

PDF ensemble	Factorization scale in DIS	ATLAS 7 Z/W data included?	CDHSW $F_2^{p,d}$ data included?	Pole charm mass, GeV
CT18	$\mu_{F,DIS}^2 = Q^2$	No	Yes	1.3
CT18X	$\mu_{F,DIS}^2 = 0.8^2\left(Q^2 + \frac{0.3\ GeV^2}{x^{0.3}}\right)$	No	Yes	1.3
CT18A	$\mu_{F,DIS}^2 = Q^2$	Yes	Yes	1.3
CT18Z	$\mu_{F,DIS}^2 = 0.8^2\left(Q^2 + \frac{0.3\ GeV^2}{x^{0.3}}\right)$	Yes	No	1.4

A new regime of QCD: low x, BFKL resummation, saturation

PDF fits based on **fixed order** (NNLO) and **small-*x* resumed** (NNLO+NLLx) theory

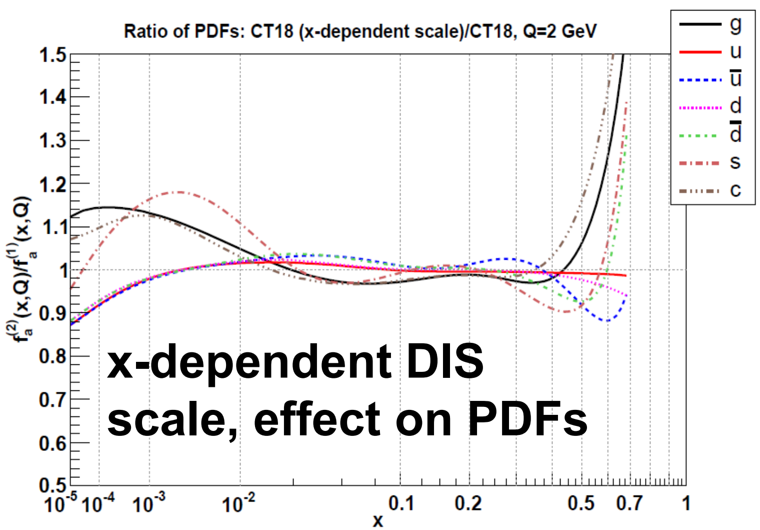


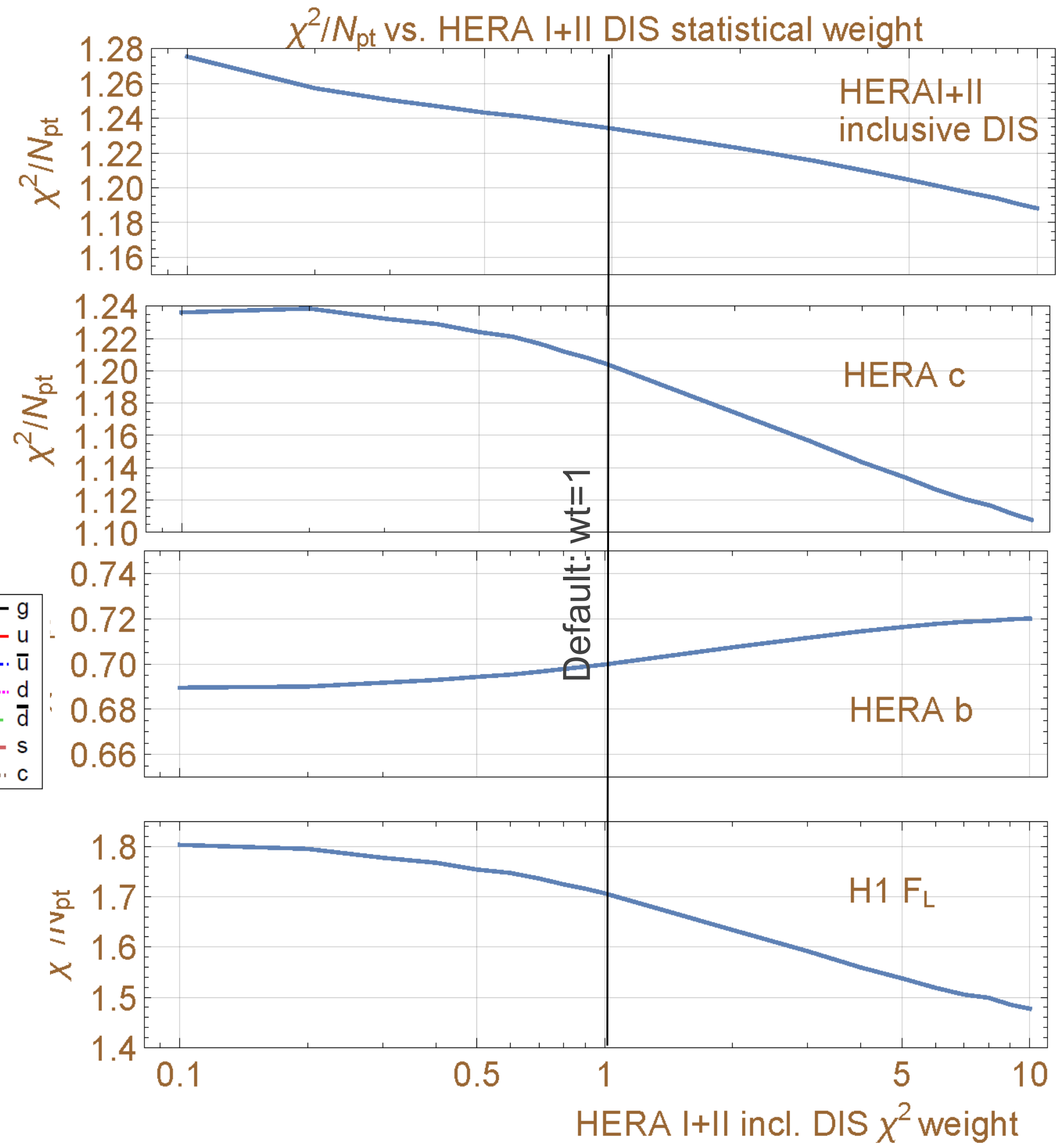
Resummation stabilizes fixed-order QCD at $x < 10^{-3}$; inclusive cross sections are not ideal for discrimination between DGLAP and BKFL scenarios

CT18X and Z: a special factorization scale in DIS

The CT18Z fits uses a $\mu_{DIS,X}$ scale that reproduces many features of NNLO-NLLx fits with $\ln(1/x)$ resummation by the NNPDF [arXiv:1710.05935] and xFitter [1802.0064] groups.

$$\mu_{DIS,X}^2 = 0.8^2\left(Q^2 + \frac{0.3\ GeV^2}{x^{0.3}}\right)$$

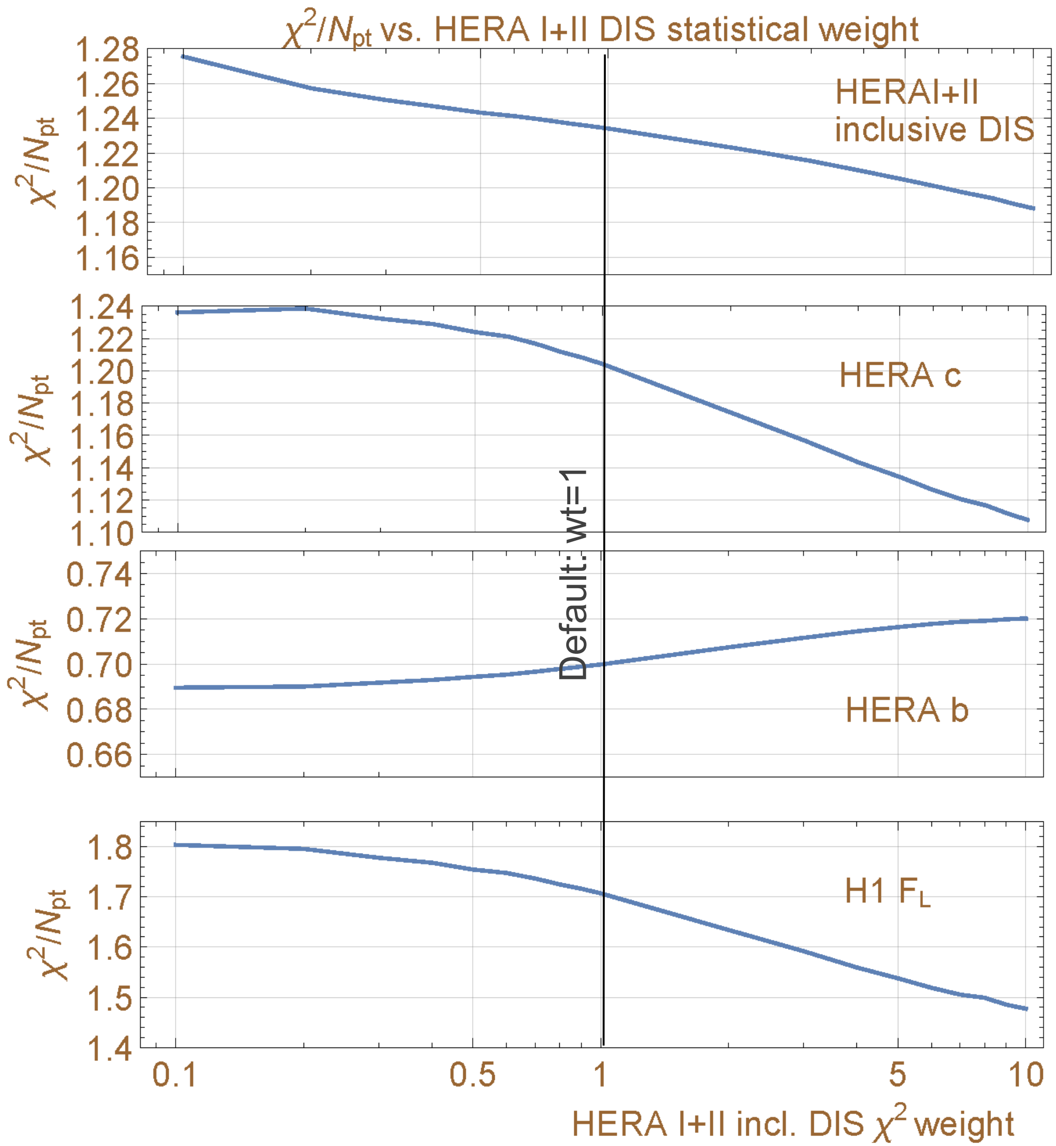




CT18X and Z: a special factorization scale in DIS

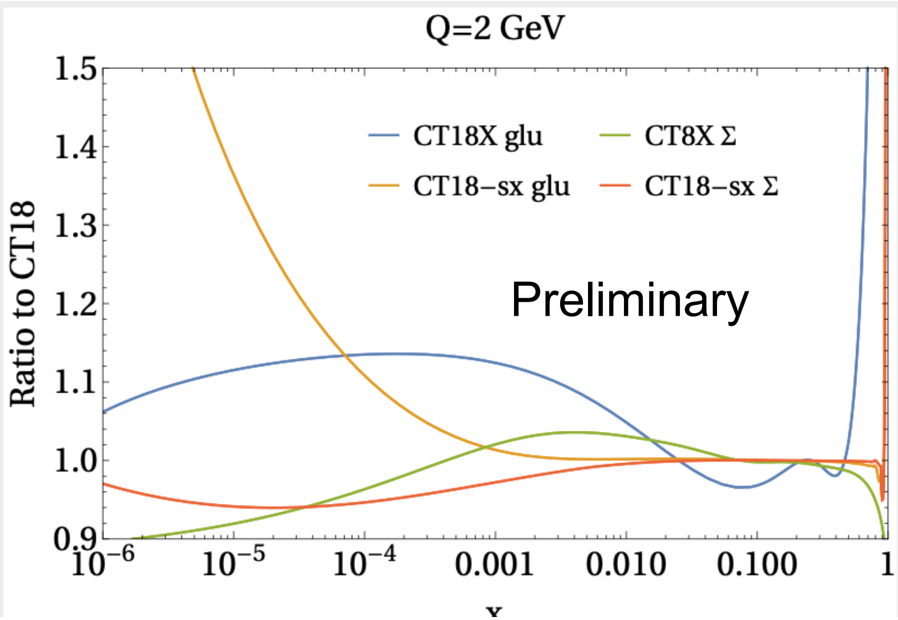
Right: when the χ^2 weight for the **inclusive** HERA I+II DIS is increased to $wt = 10$ to suppress pulls from the other experiments, χ^2_{CT18Z}/N_{pt} for HERA I+II DIS **and** HERA charm production decreases to about the same levels as in HERA-only NNLO+NLLx fits by other groups.

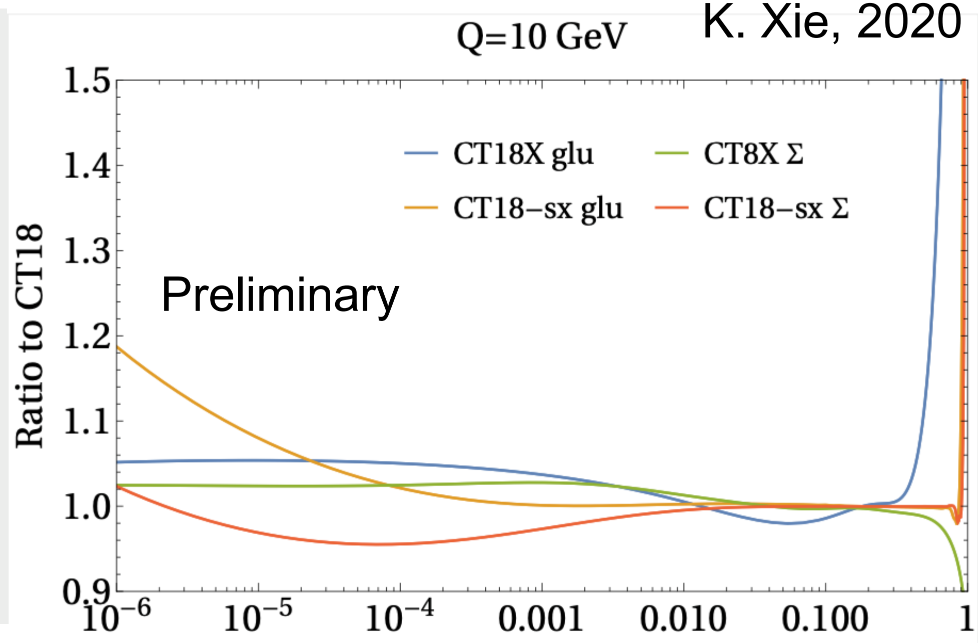
- **NNLO with an x-dependent scale is statistically indistinguishable from BFKL resummation in the CT18 x-Q region (Q > 2 GeV)**

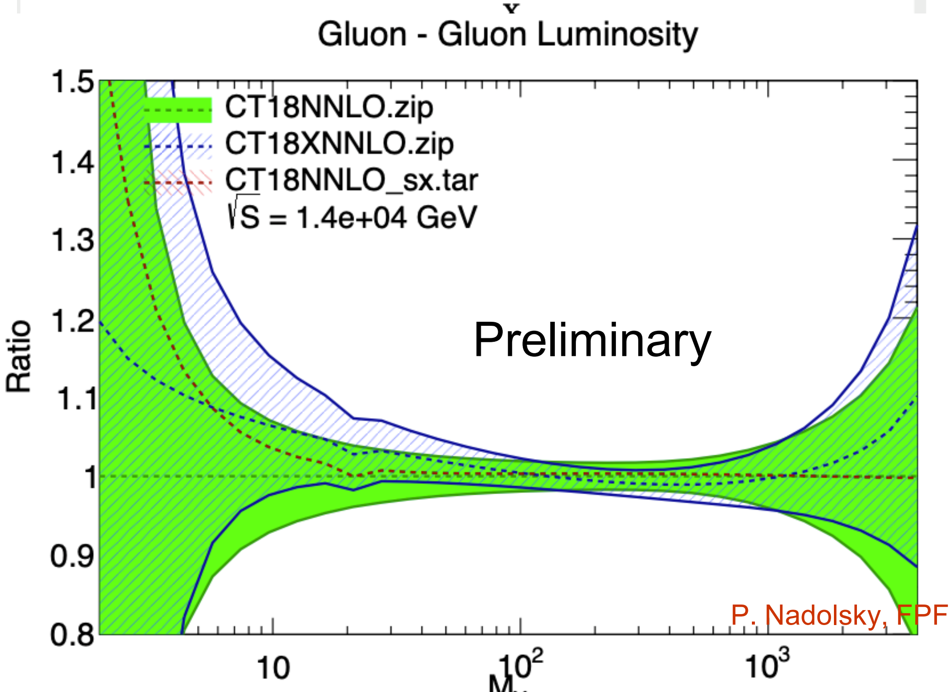


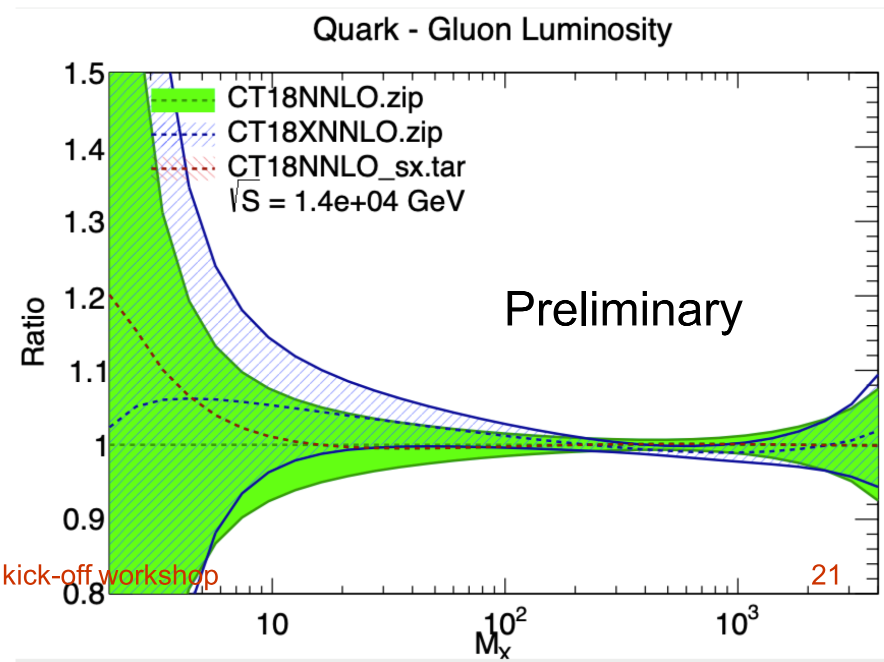
CT18X NNLO compared to NLLx-NNLO (CT18-sx) PDFs

K. Xie, 2020

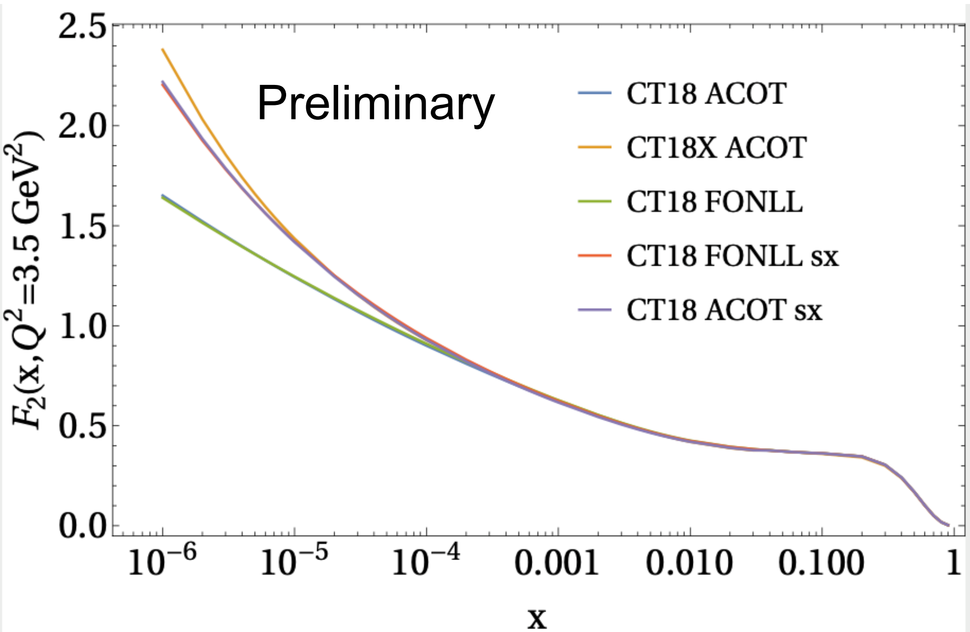


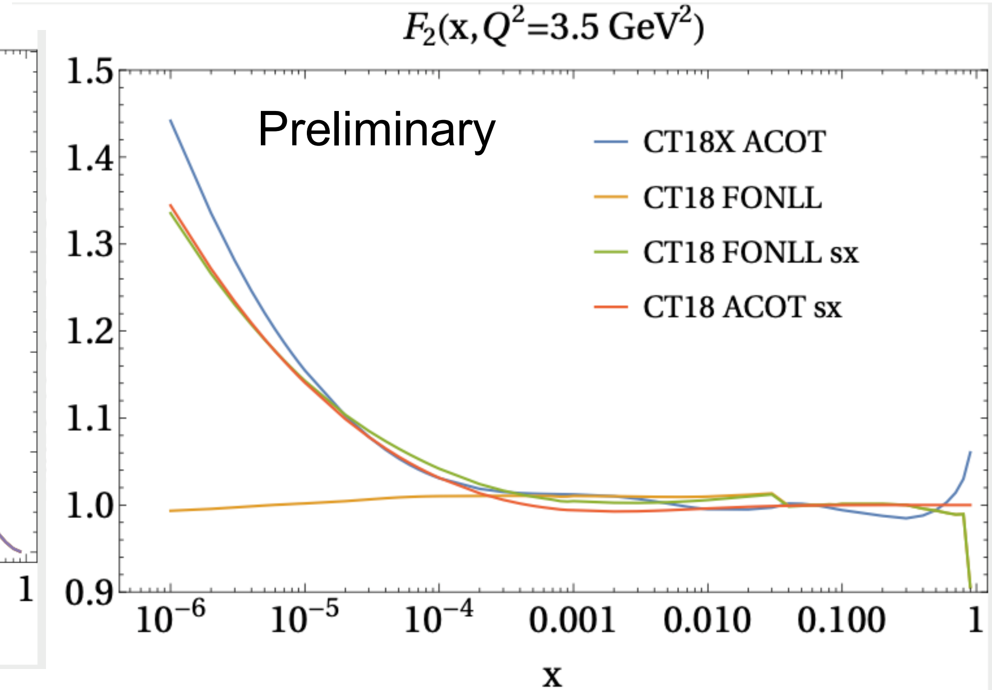






Structure function $F_2(x, Q^2)$





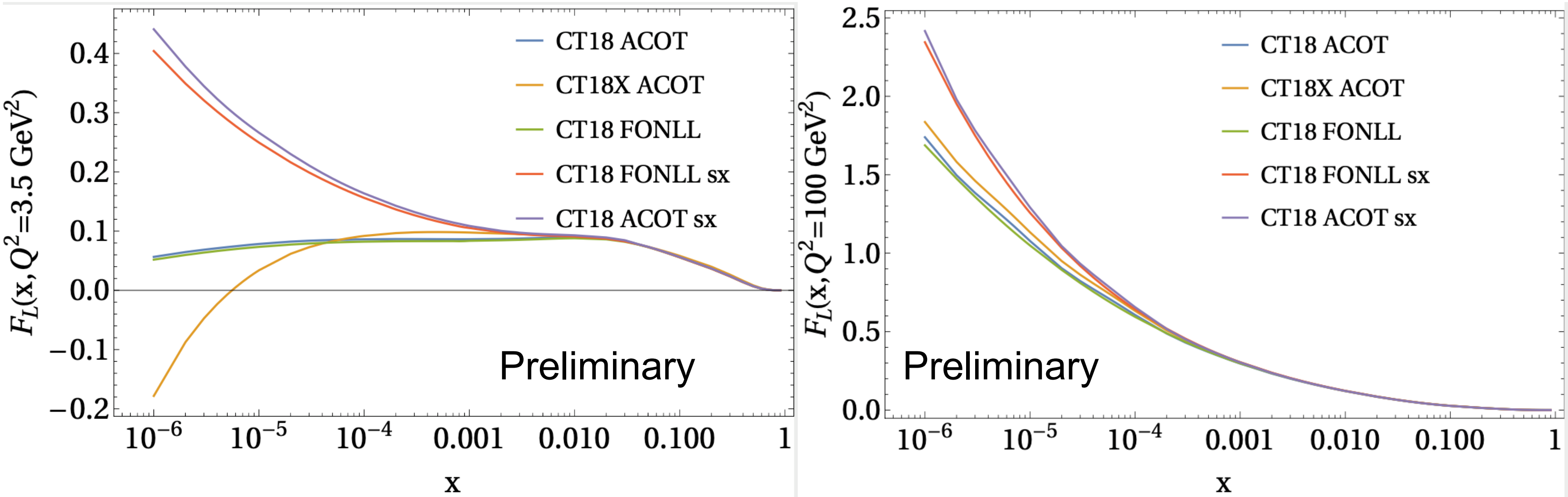
- ➢ CT utilizes the ACOT scheme, which agrees with the NNPDF's FONLL scheme.
- ➢ The CT18 ACOT small x (sx) resummed F2 is obtained with the K-factor approach

$$CT18\ ACOT\ sx = CT18\ ACOT\ \frac{FONLL\ sx}{FONLL}$$

➢ For F2, the CT18X is indistinguishable with the small x resummed structure function down to $x{\sim}10^{-5}$. It only takes off below this x value.

➢ At higher Q~10 GeV, both small x resummation and the CT18X prescription (x-dependent scale choice) give the same prediction as the standard DGLAP one (CT18).

Structure function $F_L(x, Q^2)$

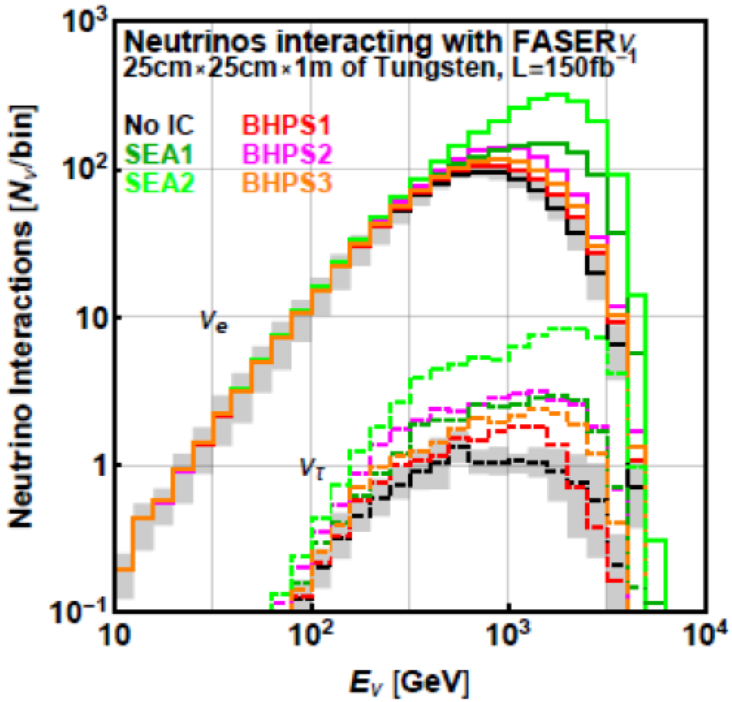


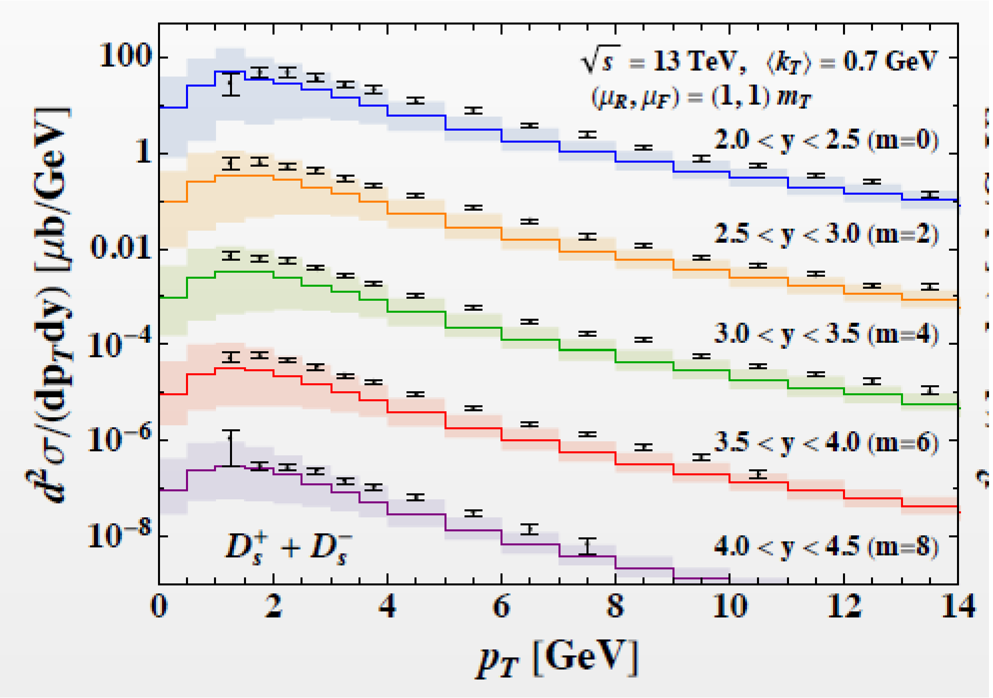
- At low Q and $x < 10^{-5}$, CT18X reduces F_L, while the small-x resummation enhances it.
- At high Q, both enhance F_L, while the CT18X prescription is sizably smaller.
- It would be very interesting to see which behavior is preferred by data.

“Intrinsic charm” (IC) production at large momentum fractions

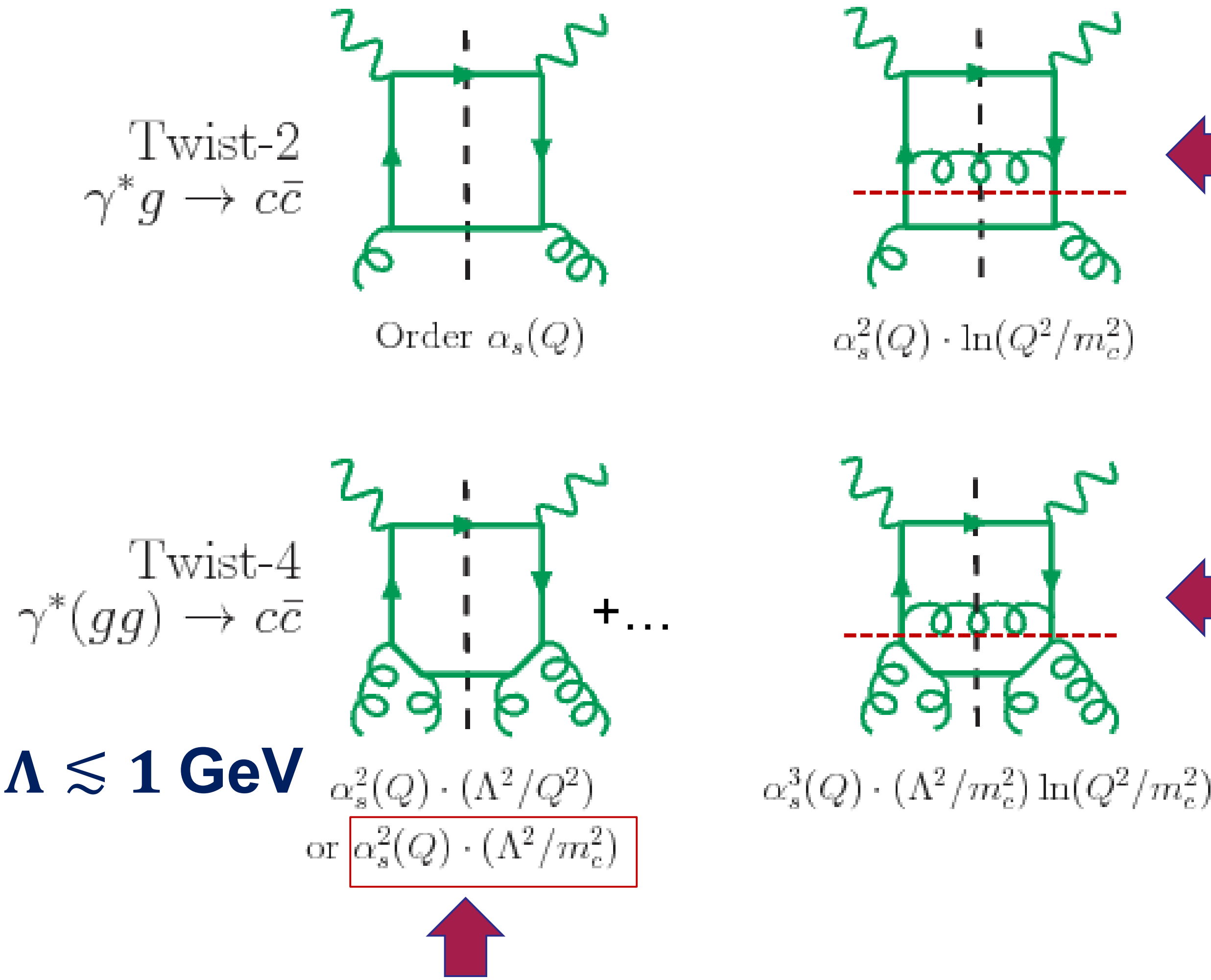
"Intrinsic charm" (IC) production at large momentum fractions

- Better understood in DIS
- Arises from higher-twist terms with a potentially process-dependent hard component (different in $ep \to ecX$ and $pp \to cX$)
- May strongly enhance the neutrino flux at FASERν
- LHCb measurements of charm production may help to constrain!





A twist-4 contribution in HERA DIS charm production ($\subset$ "intrinsic charm")



A ladder; must be resummed in $c(x,Q)$ in the $N_f = 4$ scheme at $Q^2 \gg m_c^2$; e.g., in the ACOT scheme

The ladder subgraphs can be resummed as a part of $c(x,Q)$ in the $N_f = 4$ scheme at $Q^2 \gg m_c^2 > \Lambda^2$;

contribute to the boundary condition for $c(x,Q_0)$ at $Q_0 \approx m_c$;

obey twist-2 DGLAP equations.

Can be of order ~10% of the twist-2 α_s^2 term

CT14 IC study: answers to important questions

T.-J. Hou et al., arXiv:1707.00657

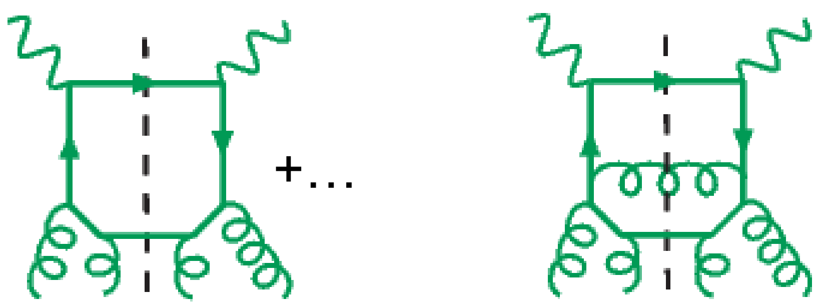
What are phenomenological constraints on the "intrinsic charm" from the global QCD data?

⇒ The CT14 charm PDFs allow a "nonperturbative" component carrying a total momentum fraction of $1-2\%$ in DIS at $Q \approx m_c$.

Can we estimate its impact on the LHC predictions?

Yes, based on the simplest approximation of the "nonperturbative" charm contribution. In most cases, the estimated impact is less than the net CT14 PDF uncertainty.

Twist-4
$\gamma^*(gg) \to c\bar{c}$



$\alpha_s^2(Q)\cdot(\Lambda^2/Q^2)$
or $\boxed{\alpha_s^2(Q)\cdot(\Lambda^2/m_c^2)}$

$\alpha_s^3(Q)\cdot(\Lambda^2/m_c^2)\ln(Q^2/m_c^2)$

Note:
"intrinsic charm" ≠ "fitted charm"

PDF fits may include a ``fitted charm'' PDF

``Fitted charm'' = ``higher-twist charm''
+ other (possibly not universal)
higher O(α_s) / higher power terms

QCD factorization theorem for DIS structure function $F(x,Q)$ [Collins, 1998]:

All α_s orders:

$$F(x,Q) = \sum_{a=0}^{N_f} \int_x^1 \frac{d\xi}{\xi} \mathcal{C}_a\left(\frac{x}{\xi}, \frac{Q}{\mu}, \frac{m_c}{\mu}; \alpha(\mu)\right) f_{a/p}(\xi,\mu) + \mathcal{O}(\Lambda^2/m_c^2, \Lambda^2/Q^2).$$

The PDF fits implement this formula up to (N)NLO ($N_{ord} = 1$ or 2):

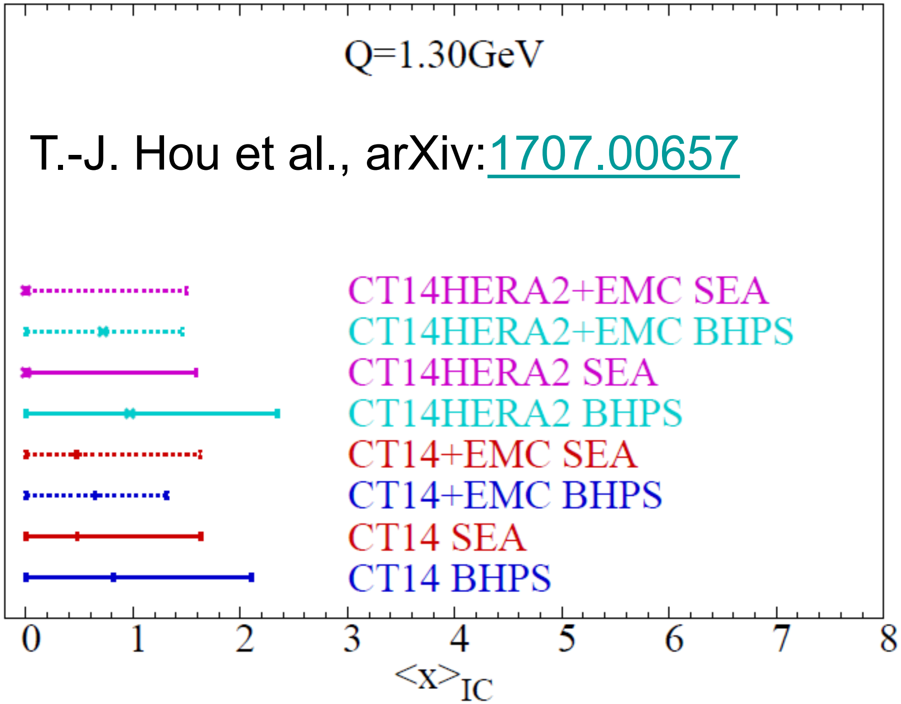
PDF fits:

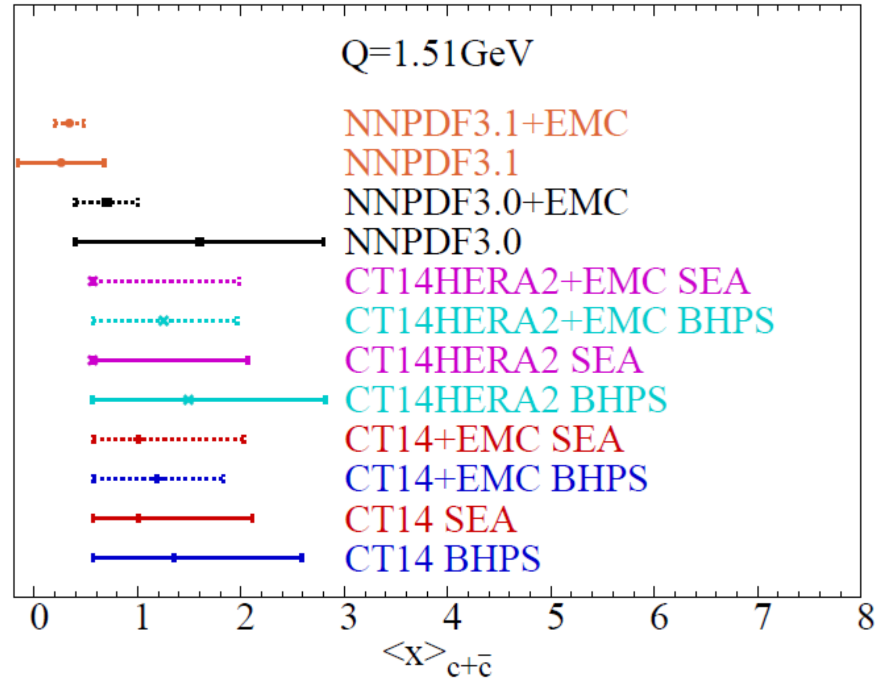
$$F(x,Q) = \sum_{a=0}^{N_f} \int_x^1 \frac{d\xi}{\xi} \mathcal{C}_a^{(N_{ord})}\left(\frac{x}{\xi}, \frac{Q}{\mu}, \frac{m_c}{\mu}; \alpha(\mu)\right) f_{a/p}^{(N_{ord})}(\xi,\mu).$$

The perturbative charm PDF component cancels at $Q \approx m_c$ up to a higher order

The 'fitted charm component' may approximate for missing terms of orders α_s^p with $p > N_{ord}$, or Λ^2/m_c^2, or Λ^2/Q^2

Allowed $c + \bar{c}$ momentum fractions

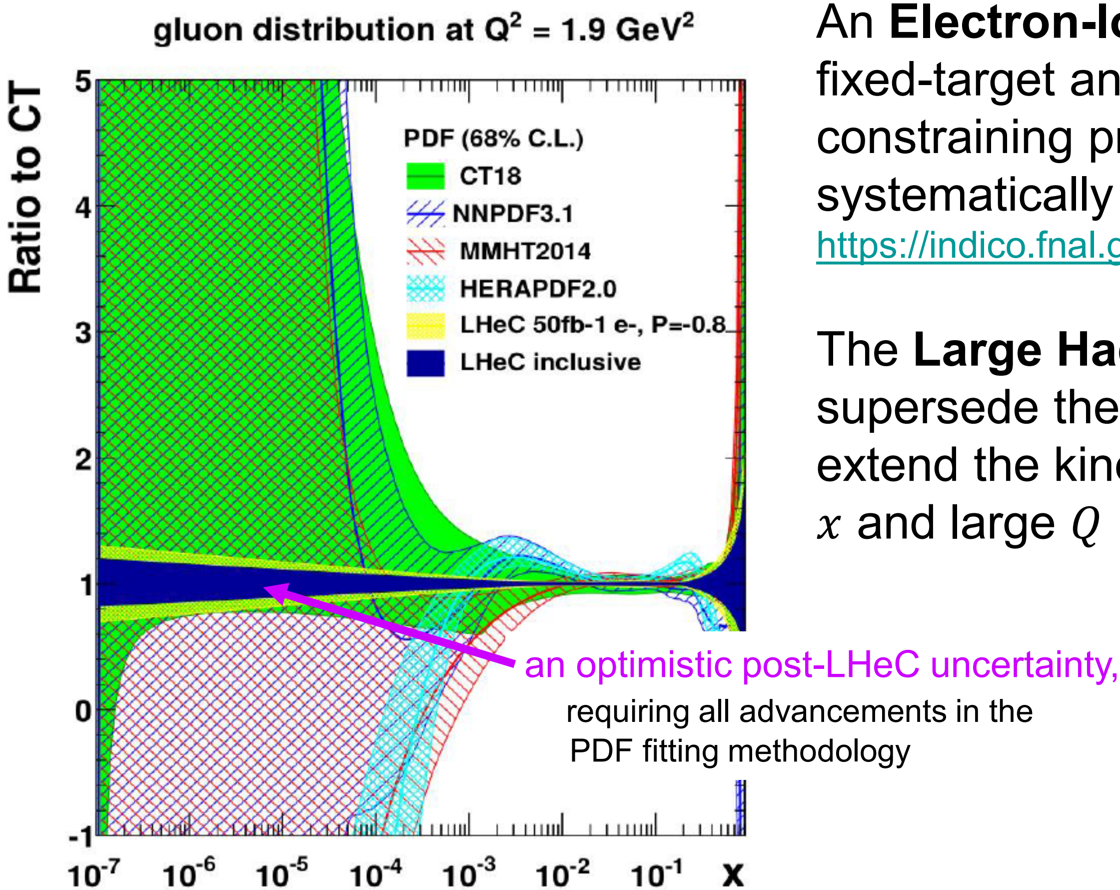




Sources of differences	CT14 IC	NNPDF3.x
α_s order	NNLO only	NLO, NNLO
Settings	90% c.l., $Q_0 = m_c^{pole} = 1.3$ GeV	68% c.l., $Q_0 = m_c^{pole} = 1.51$ GeV
LHC 8 TeV W, Z	Under validation; mild tension with HERA DIS data	Included; strong effect despite a smallish data sample
1983 EMC F_{2c} data included?	Only as a cross check (unknown syst. effects in EMC data)	Optional, strong effect on the PDF error

Synergy between future ep/eA colliders and FPF

An ep collider operating concurrently with the HL-LHC and LHC FPF can contribute critical **independent** measurements of PDF that are free of the LHC systematic effects and igh-mass BSM contributions



An **Electron-Ion Collider** can replace most of fixed-target and nuclear-target measurements constraining proton PDFs at large x. It will systematically study PDFs for heavy nuclei. https://indico.fnal.gov/event/44510/

The **Large Hadron-Electron Collider** will supersede the HERA DIS measurements and extend the kinematic reach of DIS to very small x and large Q

EIC, NC charm production

Orders-of-magnitude more events for some IC models

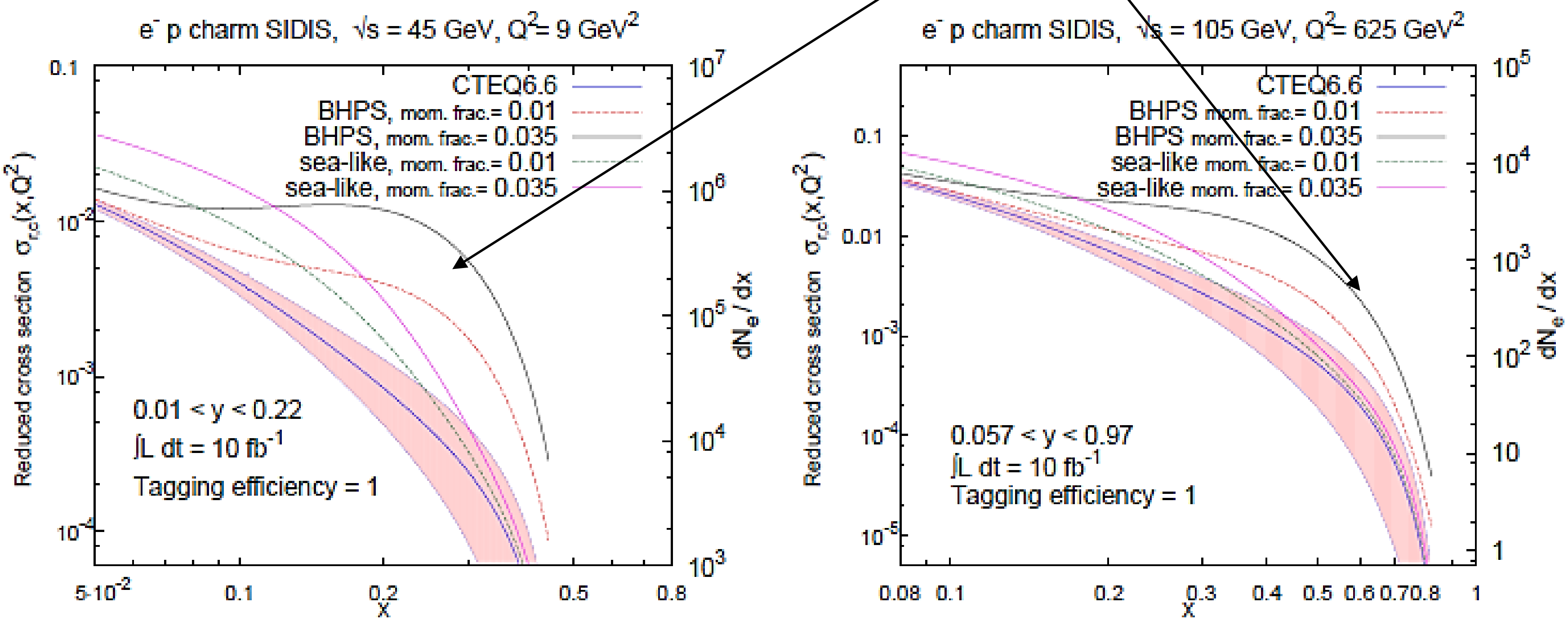
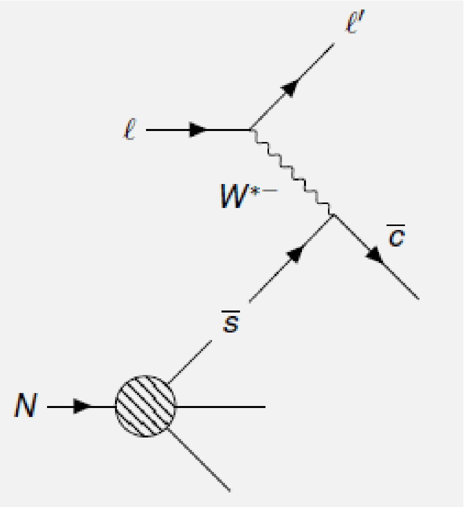


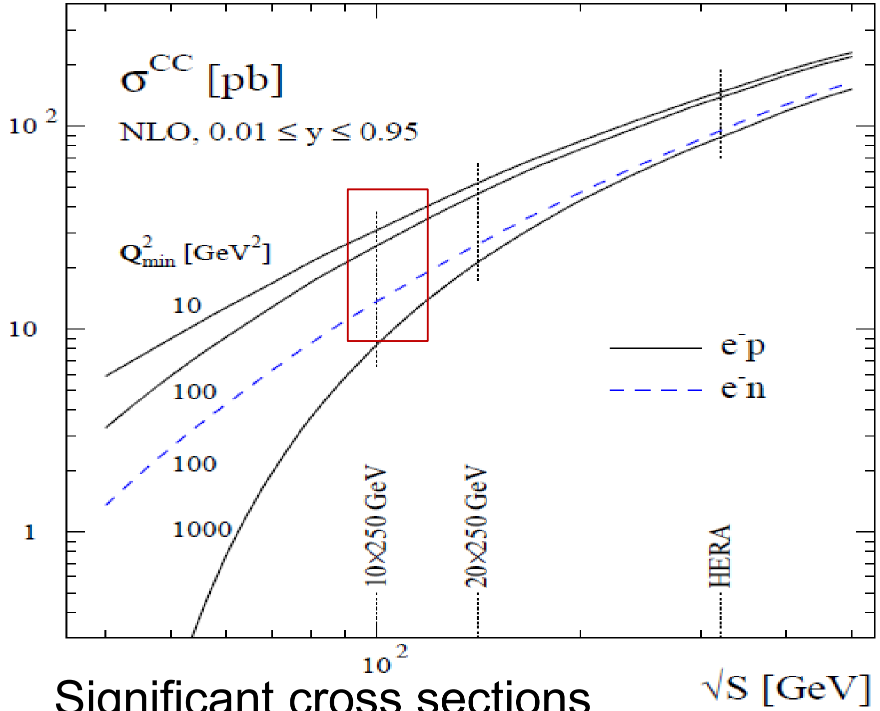
Figure 1.20. Charm contribution to the reduced NC e^-p DIS cross section at $\sqrt{s} = 45$ and 105 GeV. For each IC model, curves for charm momentum fractions of 1% and 3.5% are shown. For comparison we display the number of events dN_e/dx for $10\,\text{fb}^{-1}$, assuming perfect charm tagging efficiency.

[Guzzi, Nadolsky, Olness, in arXiv:1108.1713; T. Hobbs, arXiv:1707.06711; Arratia et al., arXiv:2006.12520]

EIC, CC charm production

A reverse process of neutrino detection at FASER ν
EIC: $\ell = e$, $\ell' = \nu$;   FASERν: $\ell = \nu$, $\ell' = e$
Can be studied with multiple nuclear beams N

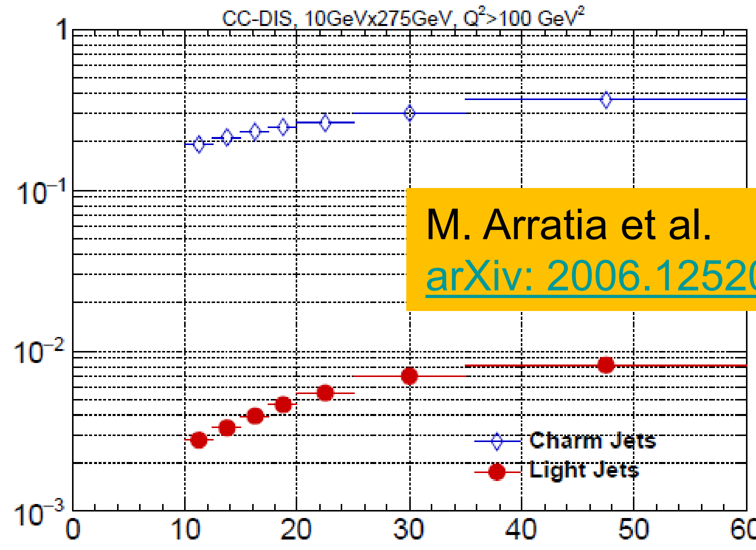




Significant cross sections at the projected EIC $\sqrt{s}$

[E. Aschenauer et al. 1309.5327]

Flavor Tagging Efficiency



M. Arratia et al. arXiv: 2006.12520

~ 6000 tagged charm jet events with $100\ fb^{-1}$

Conclusions

FASERν will test QCD in novel kinematic regimes where little or no experimental measurements exist.

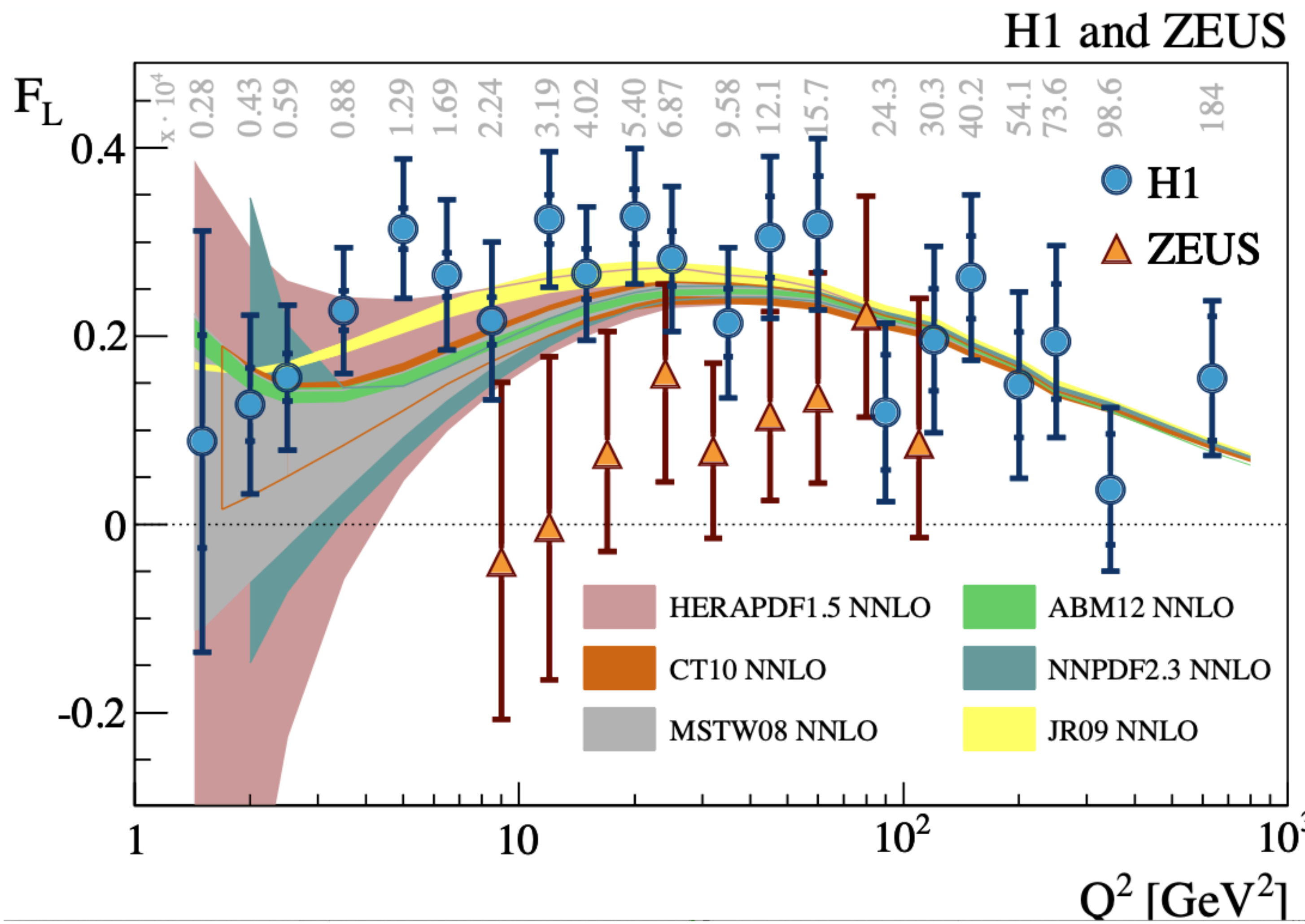
We don't know which QCD formalism(s) are appropriate in these regimes

We can test transition to small-x factorization, higher-twist enhancements in charm production, charged-current DIS on heavy nuclei

FASERν will be most successful as a part of a larger physics program that includes efforts at LHCb, the EIC, and possibly LHeC.

Thank you for your attention!

Backup


H1 and ZEUS
F_L
0.4
0.2
0
-0.2
x · 10^4
0.28
0.43
0.59
0.88
1.29
1.69
2.24
3.19
4.02
5.40
6.87
9.58
12.1
15.7
24.3
30.3
40.2
54.1
73.6
98.6
184
H1
ZEUS
HERAPDF1.5 NNLO
ABM12 NNLO
CT10 NNLO
NNPDF2.3 NNLO
MSTW08 NNLO
JR09 NNLO
1
10
10^2
10^3
Q^2 [GeV^2]