Extrinsic and intrinsic sea partons in a nucleon

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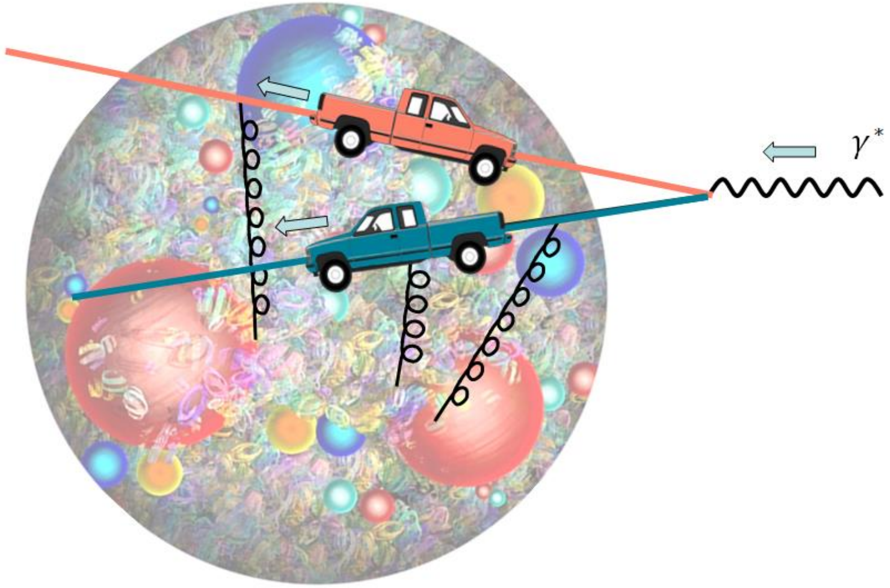
With A. Courtoy, M. Guzzi, T. Hobbs,
J. Huston, K. Xie, M. Yan, C.-P. Yuan

and members of the
CTEQ-TEA (Tung Et. Al.) working group



Fermilab SMU CTEQ

New insights about unpolarized sea parton distribution functions

Nonperturbative models and lattice QCD

NNLO global analyses of QCD data

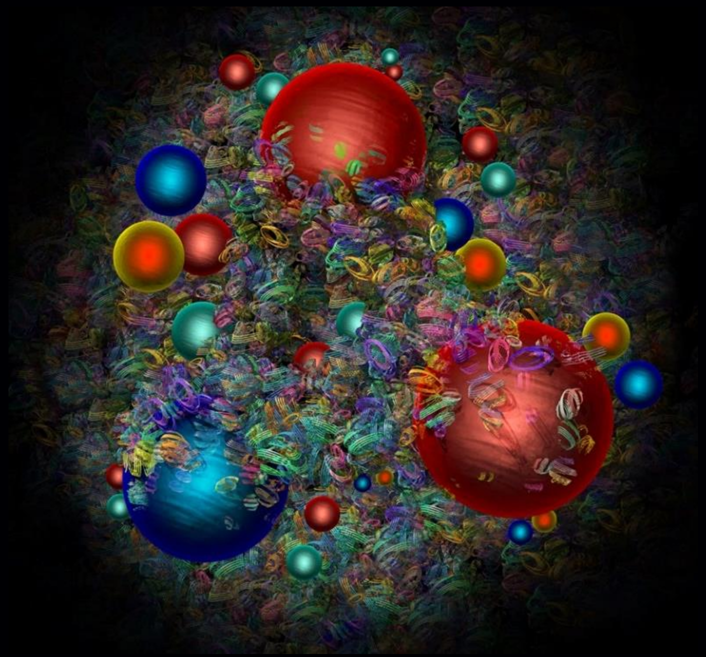
CONNECTION?

Flavor composition of (anti)quark sea

Precision tests at LHC, Jlab, EIC, AMBER, CERN FPF, …

A proton at rest

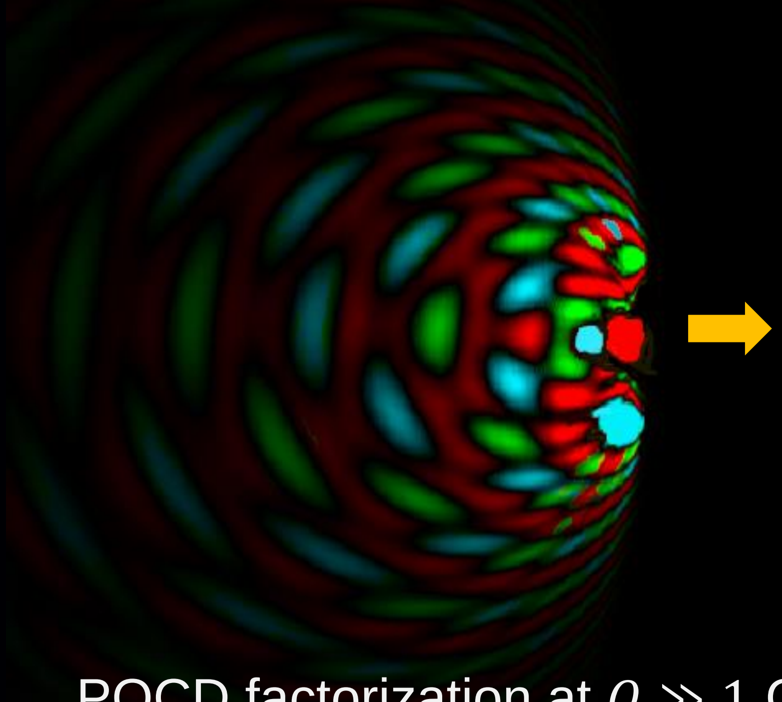
$V \approx 0$



Nonperturbative degrees of freedom
at $Q_0 < 1$ GeV
Models and lattice QCD

A proton at a collider

moving with speed $V \approx c$ to the right



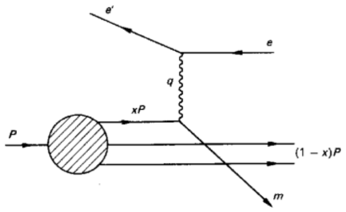
PQCD factorization at $Q \gg 1$ GeV
- short-distance perturbative expansions on the light front

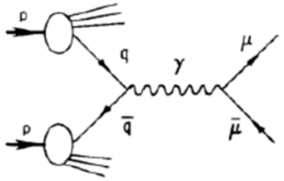
- **universal long-distance functions**

PDFs in nonperturbative QCD

Relevant for processes
at $Q^2 \approx 1\ GeV^2$?

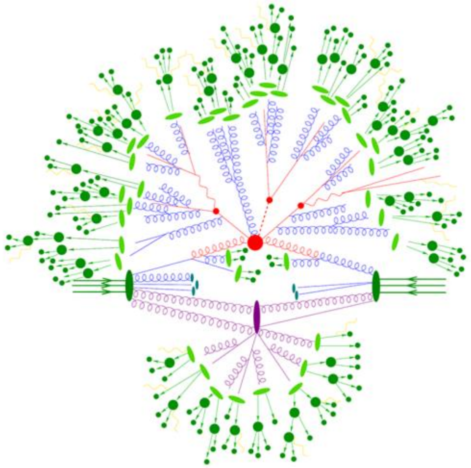
⇨ we can learn about nonperturbative dynamics by comparing predictions to data for the simplest scattering processes (DIS and DY)





Phenomenological PDFs

Determined from processes
at $Q^2 \gg 1\ GeV^2$

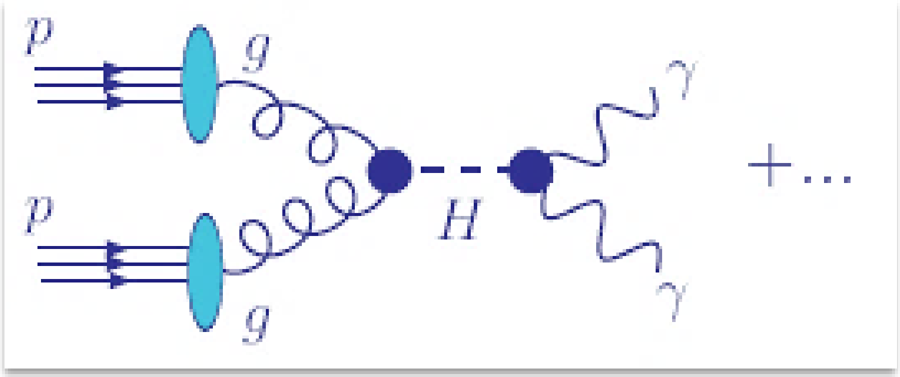


⇨ pheno PDFs are determined from analyzing many processes with complex scattering dynamics

How to relate the x dependence of the perturbative and nonperturbative pictures?

Does the evidence from primordial dynamics survive PQCD radiation?

Parton distributions describe long-distance dynamics in high-energy collisions



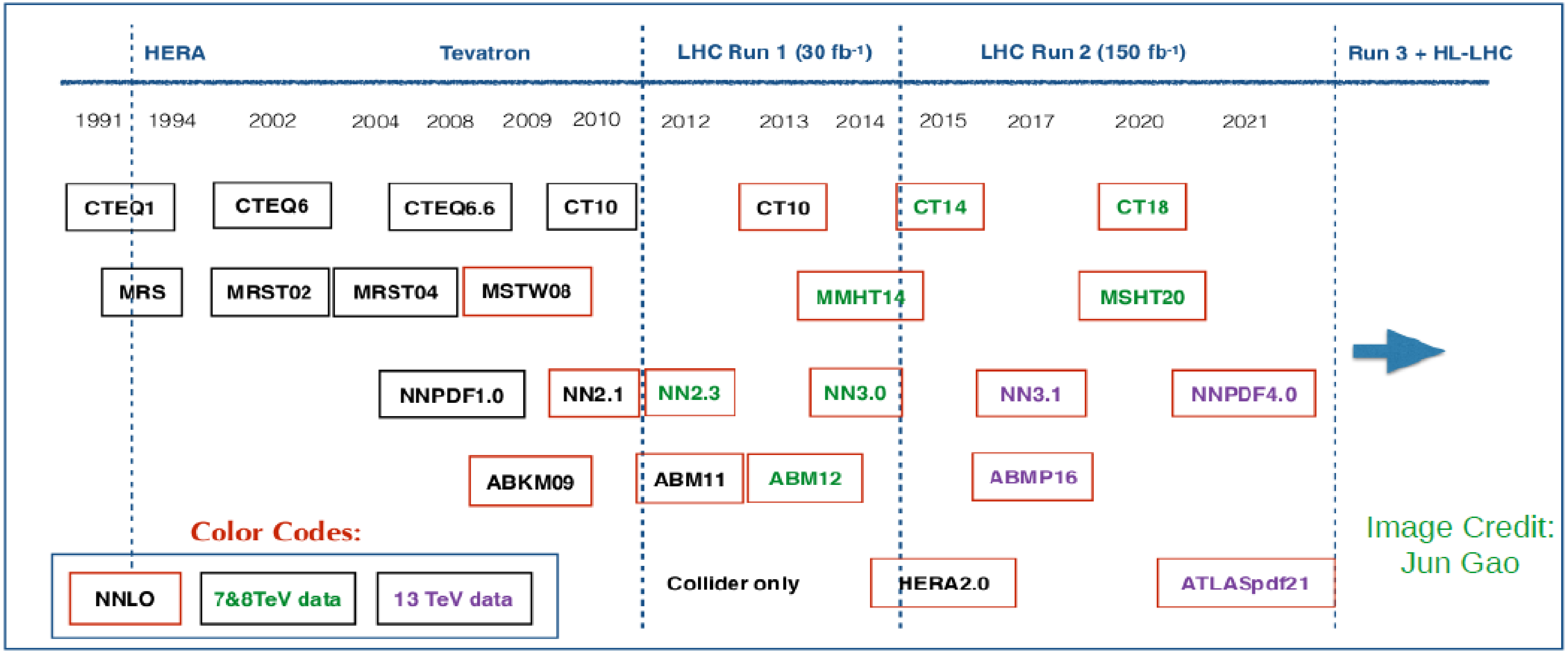
$$\sigma_{pp\to H\to\gamma\gamma X}(Q) = \sum_{a,b=g,q,\bar{q}} \int_0^1 d\xi_a \int_0^1 d\xi_b \hat{\sigma}_{ab\to H\to\gamma\gamma}\left(\frac{x_a}{\xi_a}, \frac{x_b}{\xi_b}, \frac{Q}{\mu_R}, \frac{Q}{\mu_F}; \alpha_s(\mu_R)\right)$$

$$\times f_a(\xi_a,\mu_F) f_b(\xi_b,\mu_F) + O\left(\frac{\Lambda_{QCD}^2}{Q^2}\right)$$

$\hat{\sigma}$ is the hard cross section; computed order-by-order in $\alpha_s(\mu_R)$

$\boldsymbol{f_a(x,\mu_F)}$ **is the distribution for parton $\boldsymbol{a}$ with momentum fraction $\boldsymbol{x}$, at scale $\boldsymbol{\mu_F}$**

Phenomenological PDF analyses for a nucleon



Pursued by several groups – ABM, ATLAS, **CTEQ-TEA (CT)**, CTEQ-Jlab, MSHT, NNPDF, JAM, …

Precision state-of-the art: NNLO QCD + NLO EW

Data from fixed-target experiments and colliders (HERA, Tevatron, LHC, …)

Snowmass'21 whitepaper:
Proton structrure at the precision frontier

S. Amoroso et al., Acta Physica Polonica B 53 (2022) 12, A1

A summary of recent trends in the global analysis of proton PDFs

1. Status of modern NNLO PDFs and their applications
2. Future experiments to constrain PDFs
3. Theory of PDF analysis at N2LO and N3LO
4. New methodological advancements
   - Experimental systematic uncertainties in PDF fits
   - Theoretical uncertainties in PDF fits
   - Machine learning/AI connections
5. Delivery of PDFs; PDF ensemble correlations in critical applications
6. PDFs and QCD coupling strength on the lattice
7. Nuclear, meson, transverse-momentum dependent PDFs
8. Public PDF fitting codes
9. Fast (N)NLO interfaces
10. PDF4LHC21 recommendation and PDF4LHC21 PDFs for the LHC analyses

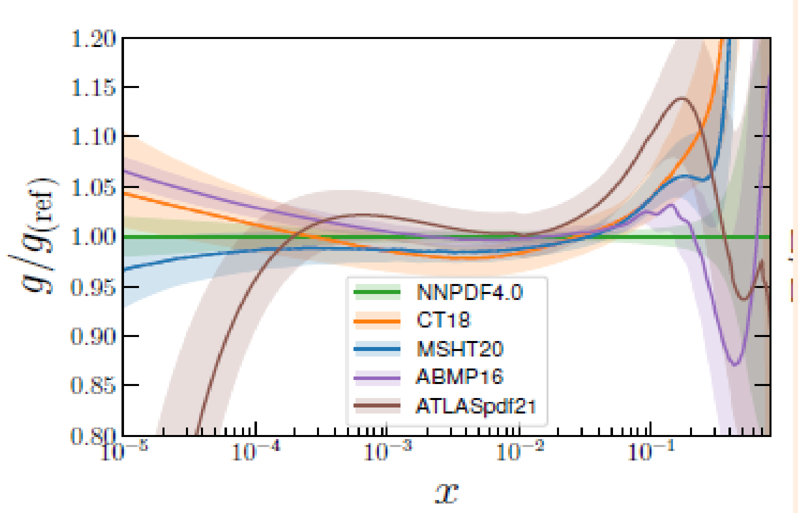
Progress in PDF analysis

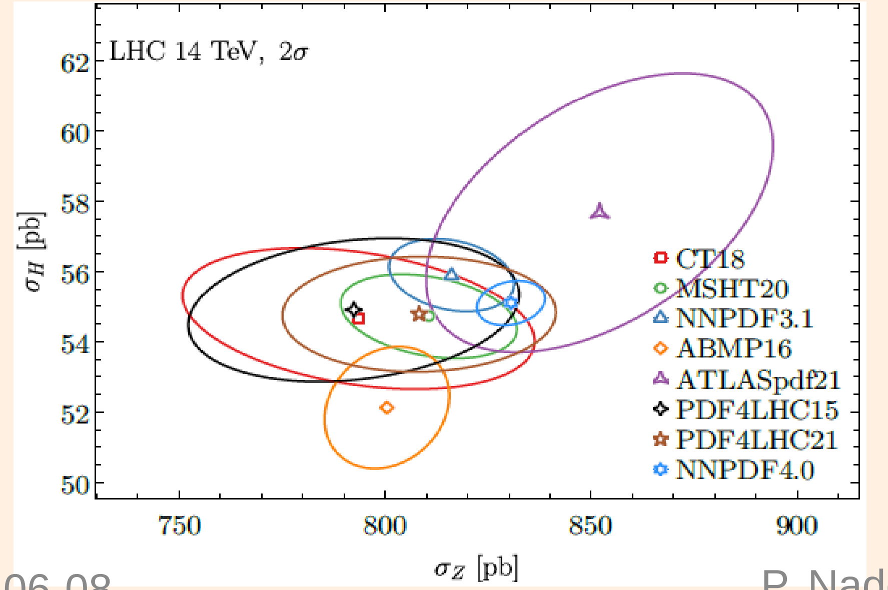
Snowmass 2021 whitepaper: Proton structure at the precision frontier

S. Amoroso et al., Acta Physica Polonica B 53 (2022) 12, A1

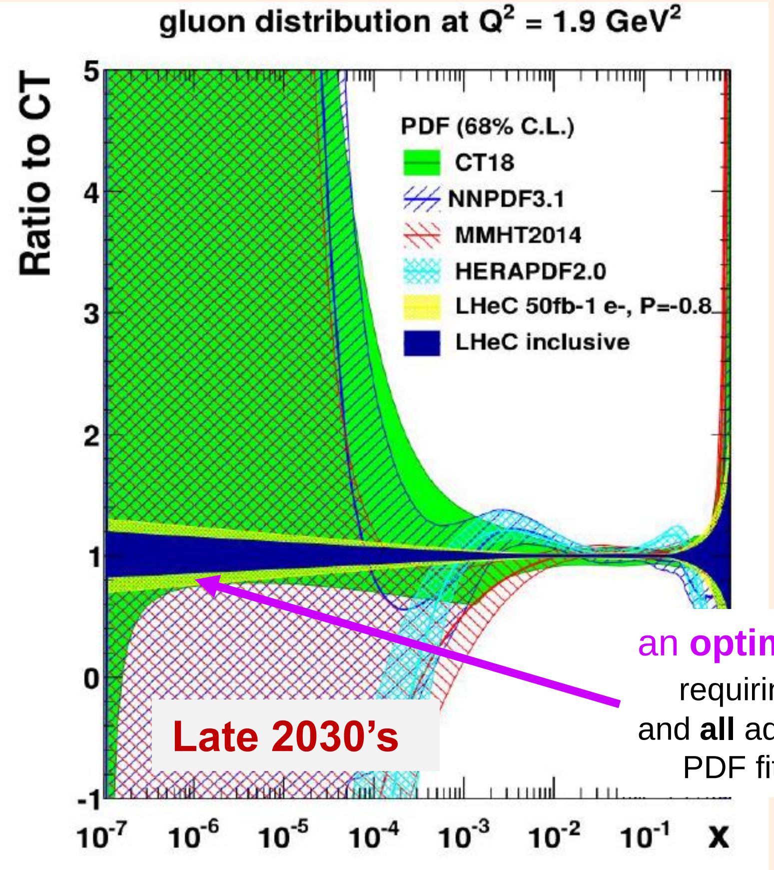
The current status

2022





...and future prospects



an **optimistic** uncertainty, requiring new measurements and **all** advancements in the PDF fitting methodology

Highlights of recent work

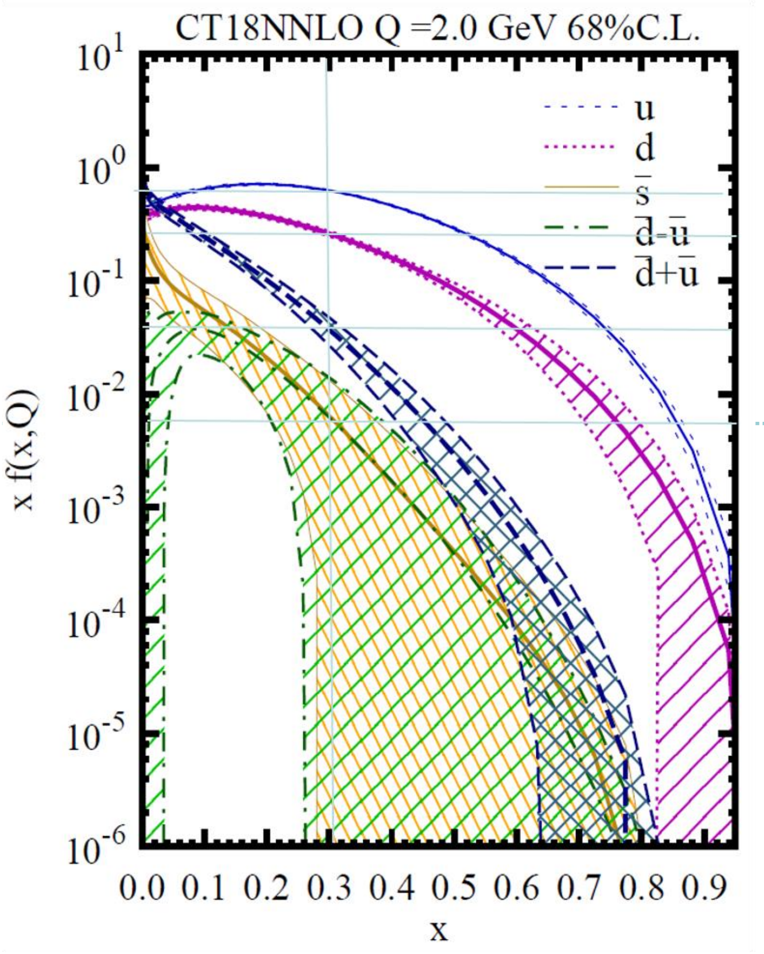
1. How do $\bar{u}$ and $\bar{d}$ PDFs behave at $x > 0.3$?

2. Is there intrinsic charm in the proton?

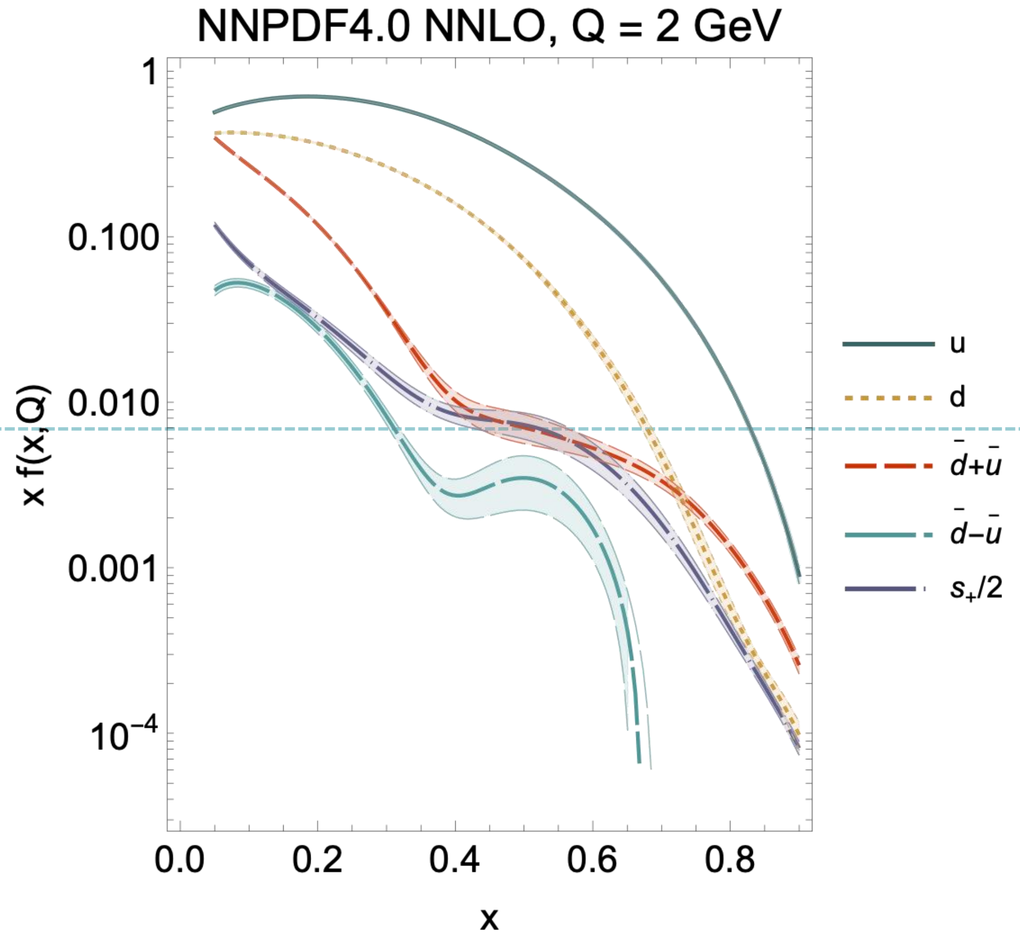
3. Are PDFs for the 2nd and 3rd quark generation $(s, c, \ldots)$ charge-symmetric?

1. How do $\bar{u}$ and $\bar{d}$ PDFs behave at $x > 0.3$?

$\bar{u}, \bar{d}, \bar{s}$ PDFs are still poorly known at $x > 0.3$



Low-sea scenario with smooth light sea quarks.



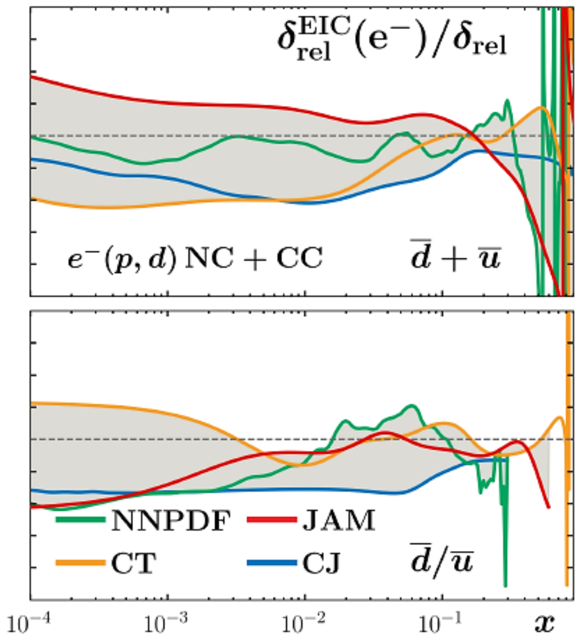
High-sea scenario with non-smooth light-sea quarks, with sea PDFs that can be larger than valence PDFs at large x.

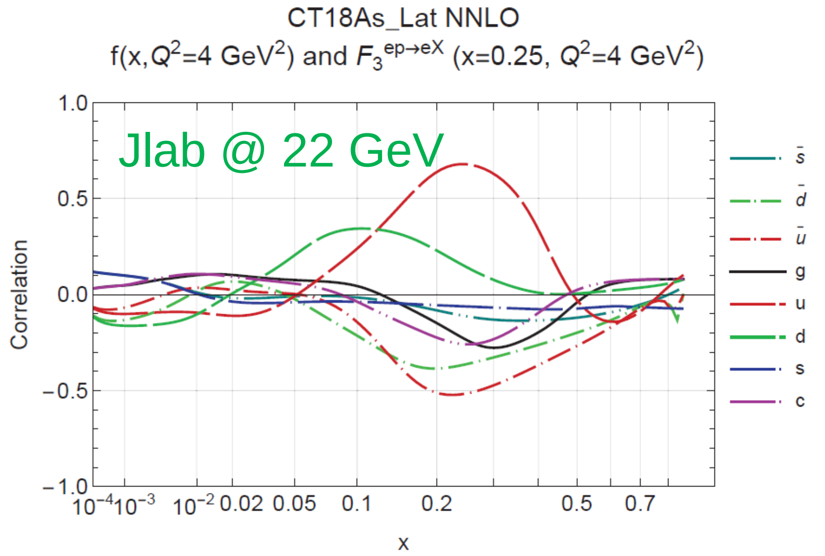
Both scenarios are compatible with current data. Uncertainties and even signs of PDFs vary among the groups (see, e.g., arXiv:2203.05506, 2205.10444)

Sensitivity of experiments to $\bar{u}$ and $\bar{d}$ at $x > 0.1$

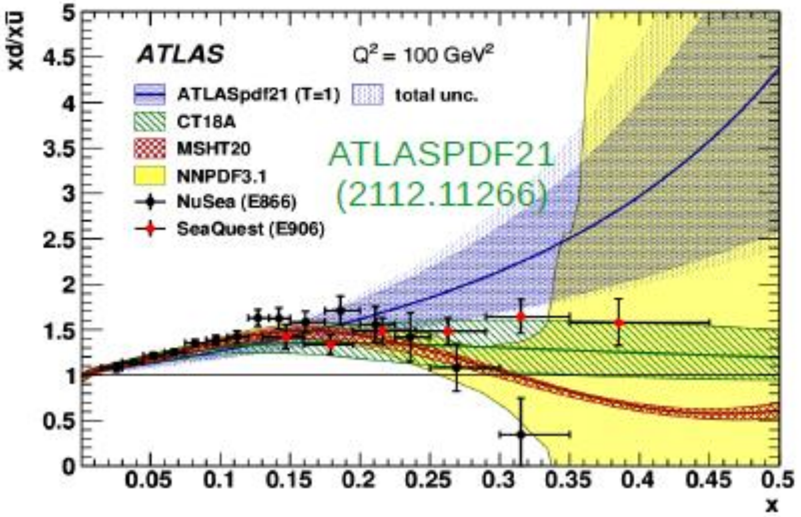
Inclusive DIS: sensitivity is limited as a result of dominance of u and d at $x \to 1$ (including in PVDIS at the EIC and SOLID). Sensitivity can be augmented by SIDIS data.

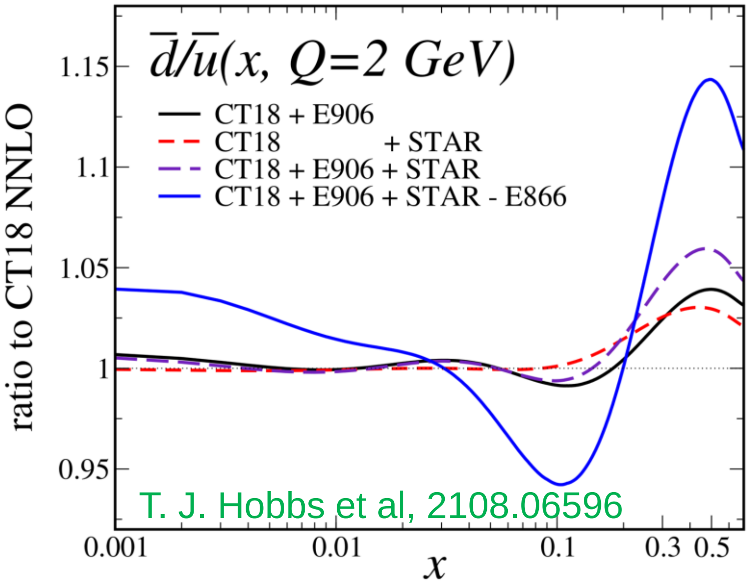
Projections for the EIC (2103.05419) and Jlab @ 22 GeV



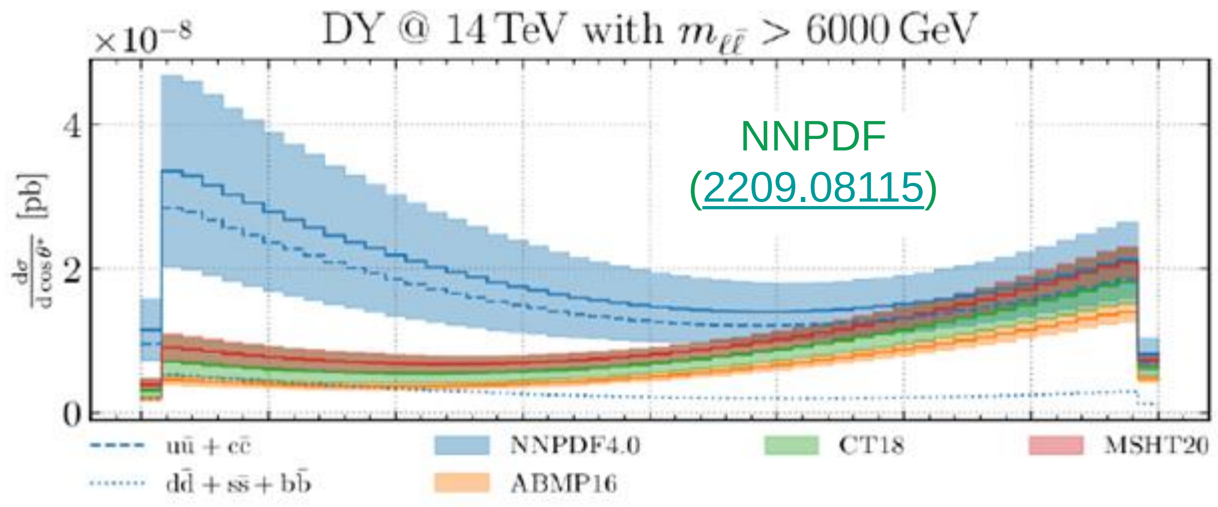


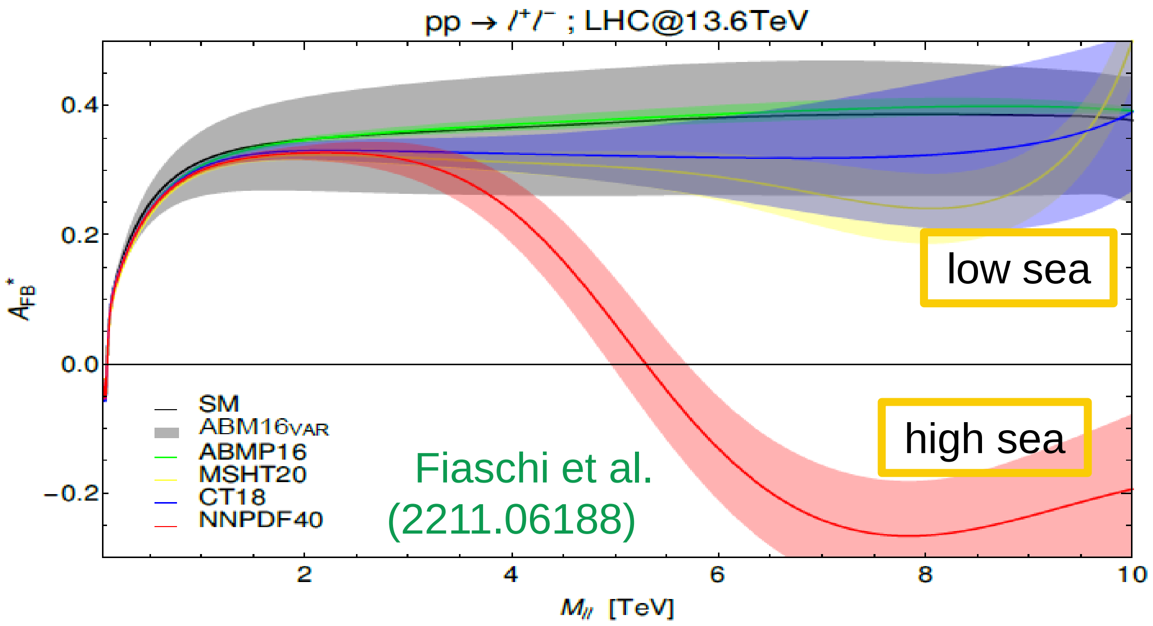
Drell-Yan process: good sensitivity. The σ_{pd}/σ_{pp} ratio by SeaQuest (E906) prefers $\bar{d} > \bar{u}$, is above the E866 ratio at $x > 0.25$. The net impact on PDFs is weak as a result of discrepancy. Uncertainties are still large



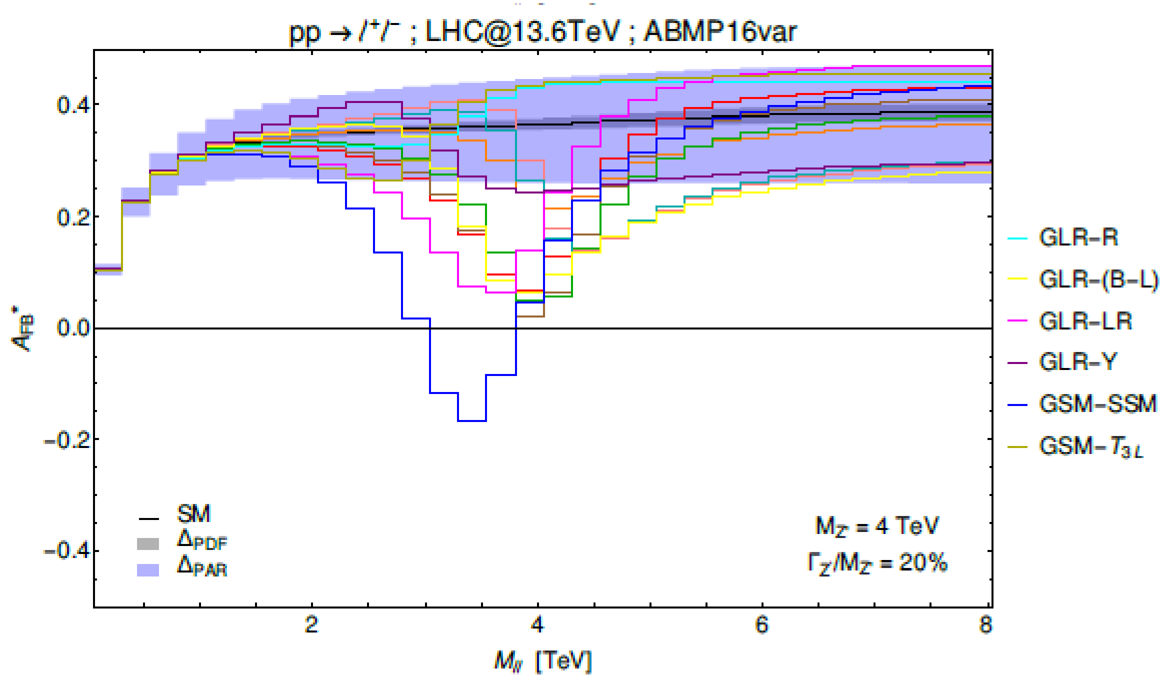


LHC high-mass Drell-Yan process probes $\bar{u}$ and $\bar{d}$





The forward-backward asymmetry for $M_{\ell\bar{\ell}} > 3$ TeV probes the $\bar{u}/u$ and $\bar{d}/d$ combinations at $x > 0.1$



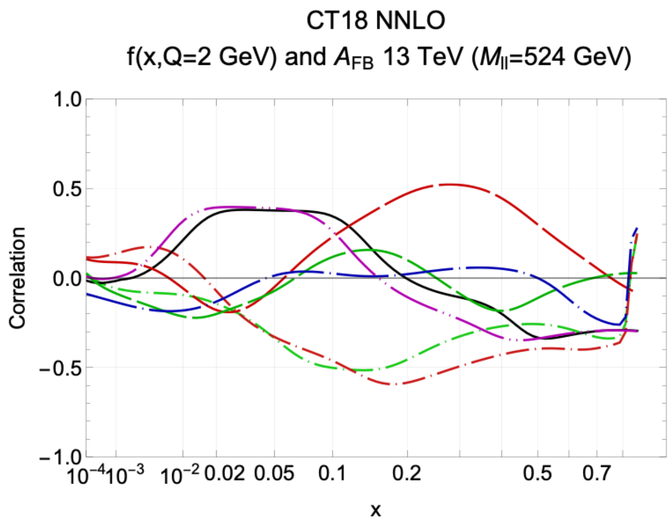
Relevant in searches for BSM resonances

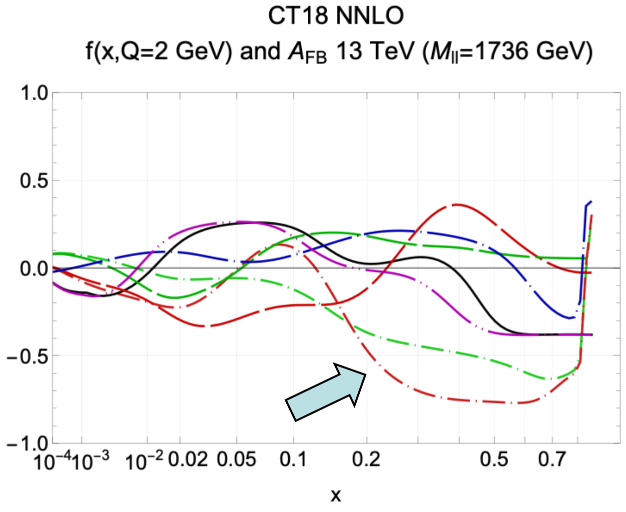
Forward-backward asymmetry

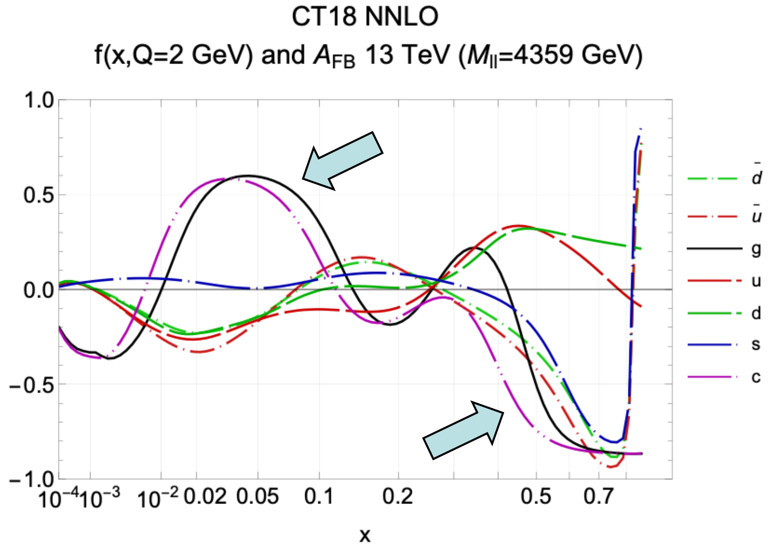
NEW:
Courtoy, Fu, Hou, Hobbs, PN, Yuan, 2023

Drell-Yan backward-forward dilepton production is sensitive to light sea and gluon for increasing $M_{\ell\bar{\ell}}$.

Strong anti-correlation of AFB with $\overline{u}$ and $\overline{d}$ (and gluon) at large x for increasing M_{ll}.







PRELIMINARY

Growing correlation of AFB with gluon at $x < 0.2$.

see also [Ball et al, EPJC 2022 82]

2. Is there intrinsic charm (IC) in the proton?

CTEQ-TEA analyses of fitted charm

1. T.-J. Hou et al., *JHEP* 02 (2018) 059; 57 pages, 19 figures: QCD factorization with the NP charm and CT14 IC NNLO pheno analysis
2. M. Guzzi, T. J. Hobbs, K. Xie, et al., *Phys.Lett.B* 843 (2023) 137975; **new** CT18 FC analysis with the LHC Run-1 and 2 data

A recorded ILCAC seminar at https://indico.knu.ac.kr/event/626/

NNPDF analyses of "intrinsic" charm

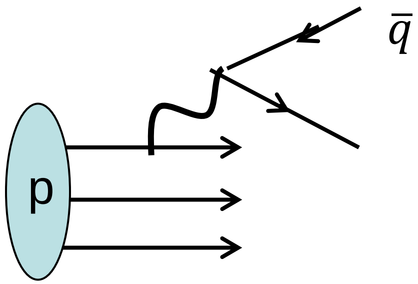
1. R. Ball et al., *Eur.Phys.J.C* 76 (2016) 11, 647
2. R. Ball et al., *Nature* 608, (2022) 483

IC from nonperturbative methods and models:

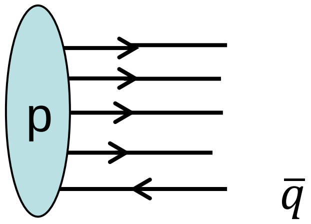
1. BHPS: Brodsky, Hoyer, Peterson, Sakai, PLB 93 (1980) 451
2. BHPS3: Bluemlein, PLB 753 (2016) 619
3. Meson-Baryon models (MBM): Hobbs, Londergan, Melnitchouk, PRD 89 (2014) 074008
4. Light-front WF models: Hobbs, Alberg, Miller, PRD 96 (2017) 7, 074023
5. Dyson-Schwinger equations, lattice QCD, …

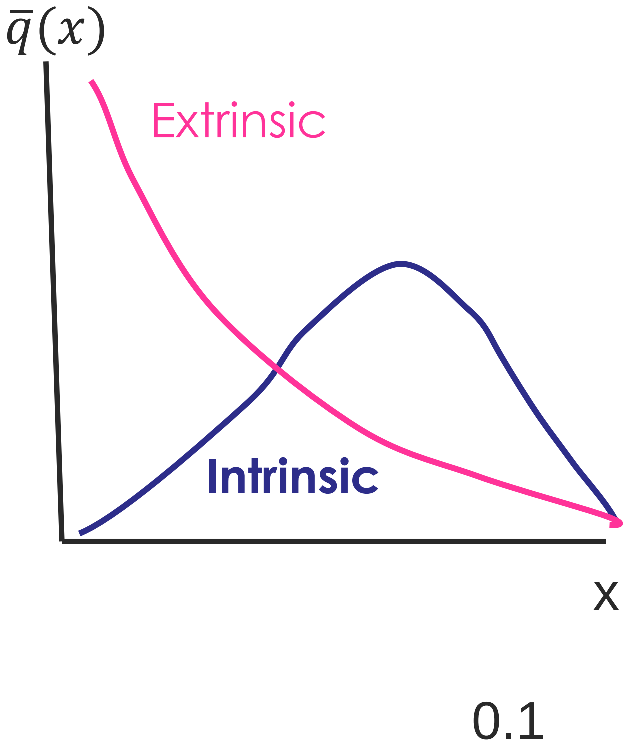
In nonperturbative models:

“Extrinsic” sea
[maps onto leading-power sea production from light flavors]



“Intrinsic” sea (excited Fock nonpert. states; beyond the leading-power production)

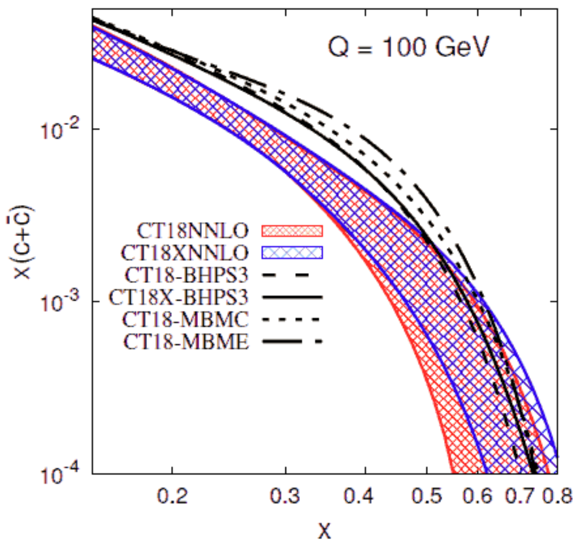




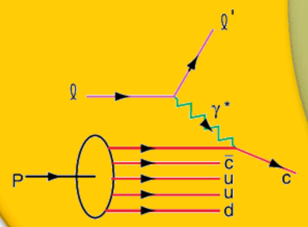
Do global PDF fits constrain intrinsic charm?

“Fitted charm” is a more direct term to describe the charm PDF found in the global QCD fit

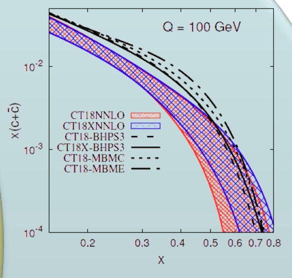
Analog: the fitted charm mass



intrinsic charm



fitted charm



- The concept of nonperturbative methods
- Can refer to a component of the hadronic Fock state or the type of the hard process
- Predicts a typical enhancement of the charm PDF at $x \gtrsim 0.2$

Connection?

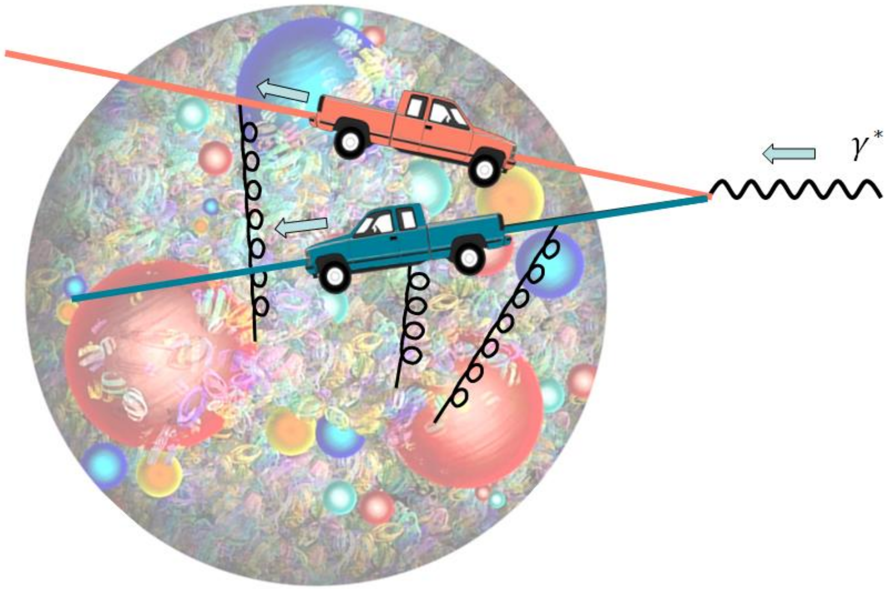
- A charm PDF parametrization at scale $Q_0 \approx 1$ GeV found by global fits [CT, NNPDF, …]
- Arises in perturbative QCD expansions over α_s and operator products
- May absorb process-dependent or unrelated radiative contributions

What is nonperturbative in the “nonperturbative charm”?

In perturbative QFT, extrinsic and intrinsic production mechanisms differ in topology of diagrams, not the strength of the coupling

Intrinsic contributions exist in QED, weakly coupled theories

In proton scattering, the intrinsic $c\bar{c}$ contribution emerges through power-suppressed diagrams with more than 1 gluon connection to the asymptotic Fock state



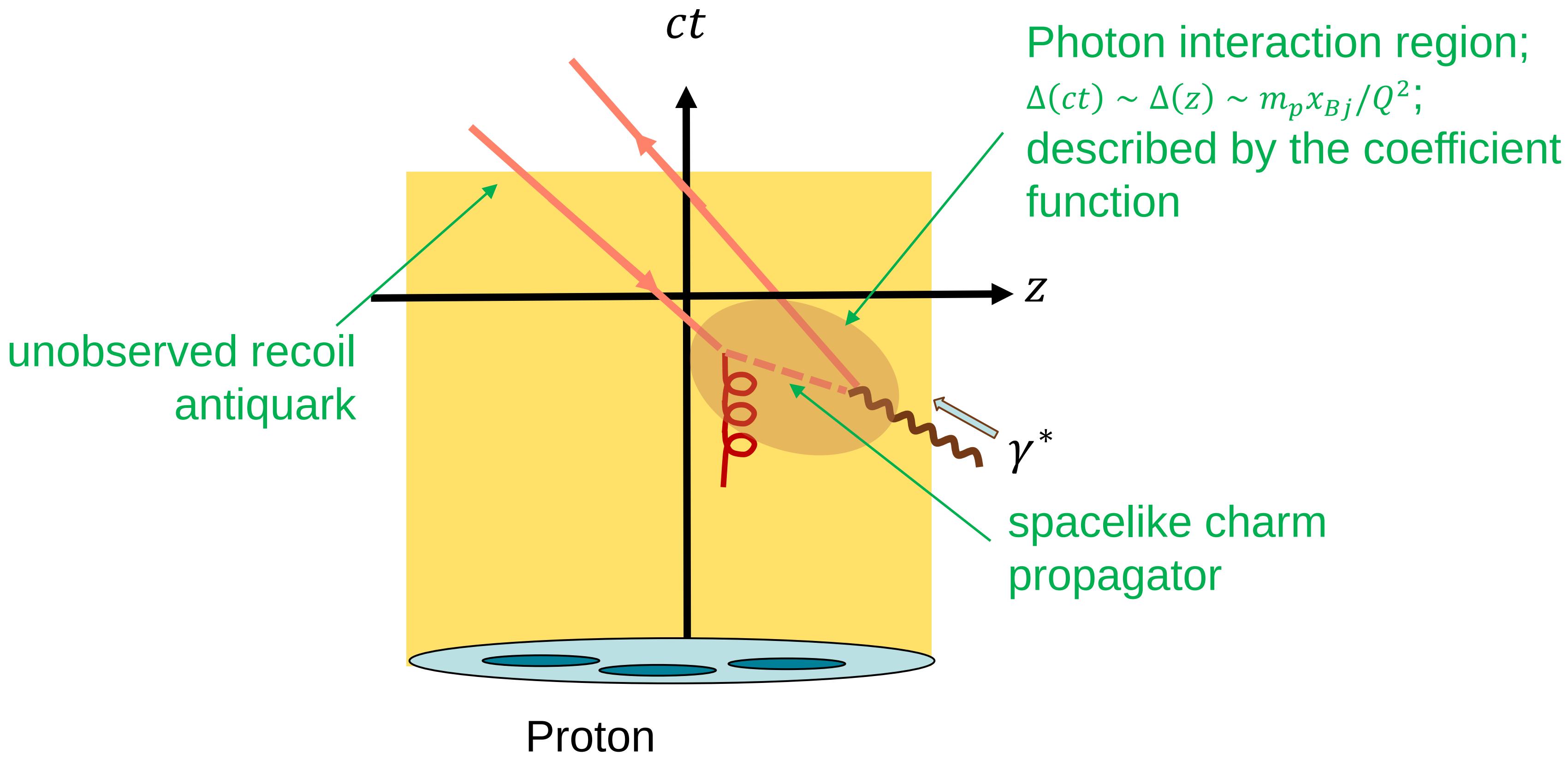
Intrinsic Chevrolets at the SSC

Stanley J. Brodsky (SLAC), John C. Collins (IIT, Chicago and Argonne), Stephen D. Ellis (Washington U., Seattle), John F. Gunion (UC, Davis), Alfred H. Mueller (Columbia U.)

Aug, 1984

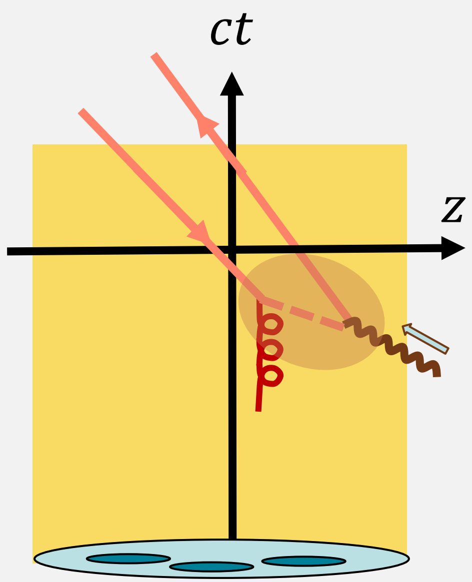
DIS in the rest frame of the proton, space-time diagram

Extrinsic production



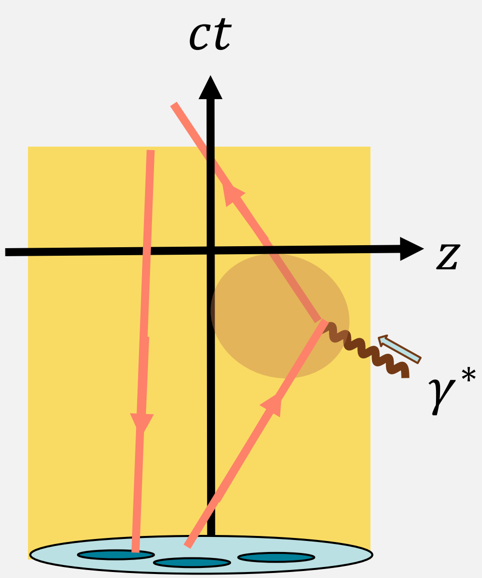
DIS in the rest frame of the proton, leading kinematic configurations

Extrinsic production



Leading power (twist-2): charm connected by 1 collinear gluon to the proton

Intrinsic production



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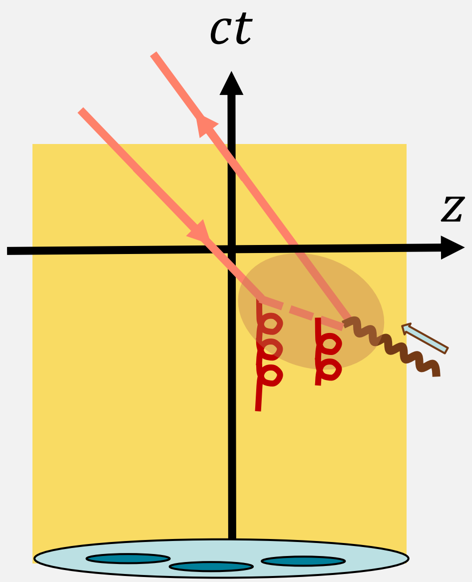


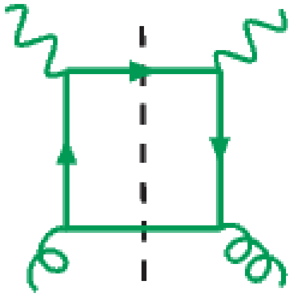
+…

<u>Negligible</u> mixing with excited asymptotic states ($|uudc\bar{c}\rangle$,…);

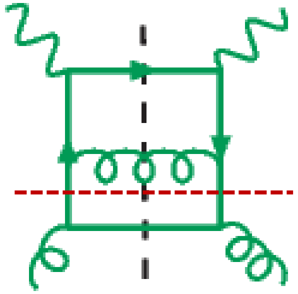
Higher powers in Λ^2/m_c^2 (not necessarily small): charm and proton connected by 2 or more gluons

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

Twist-2
$\gamma^* g \to c\bar{c}$



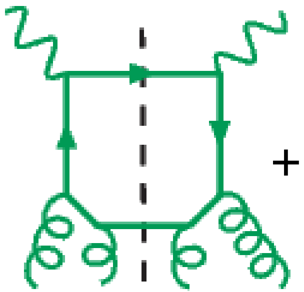
Order $\alpha_s(Q)$



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

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

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



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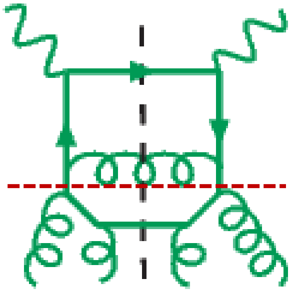


$\Lambda \lesssim 1$ GeV

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

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

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

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

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

obeys twist-2 DGLAP equations.

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 leading-power 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

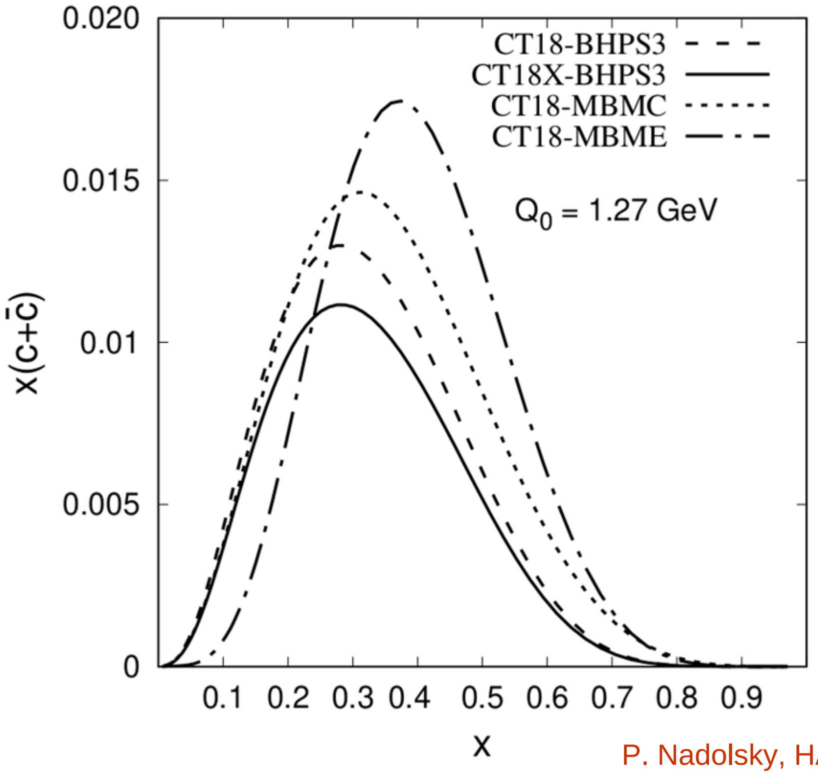
CT18 FC total charm PDFs

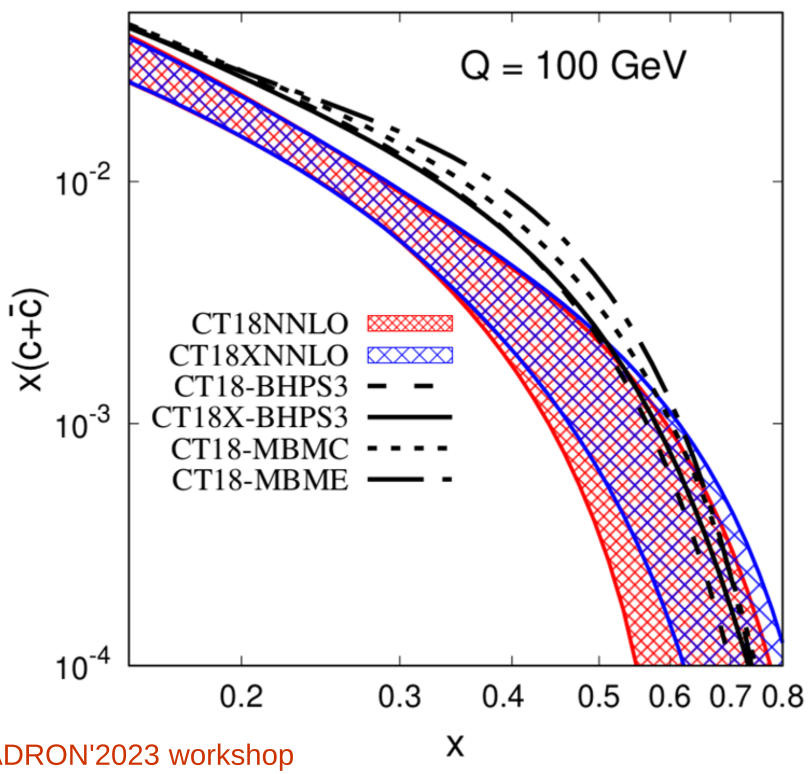
FC scenarios traverse range of high-*x* behaviors from IC models

- → fit implementation of BHPS from CT14IC (BHPS3) on CT18 or CT18X (NNLO)
- → fit two MBMs: MBMC (confining), MBME (effective mass) on CT18

investigate constraints from newer LHC data in CT18

central fits

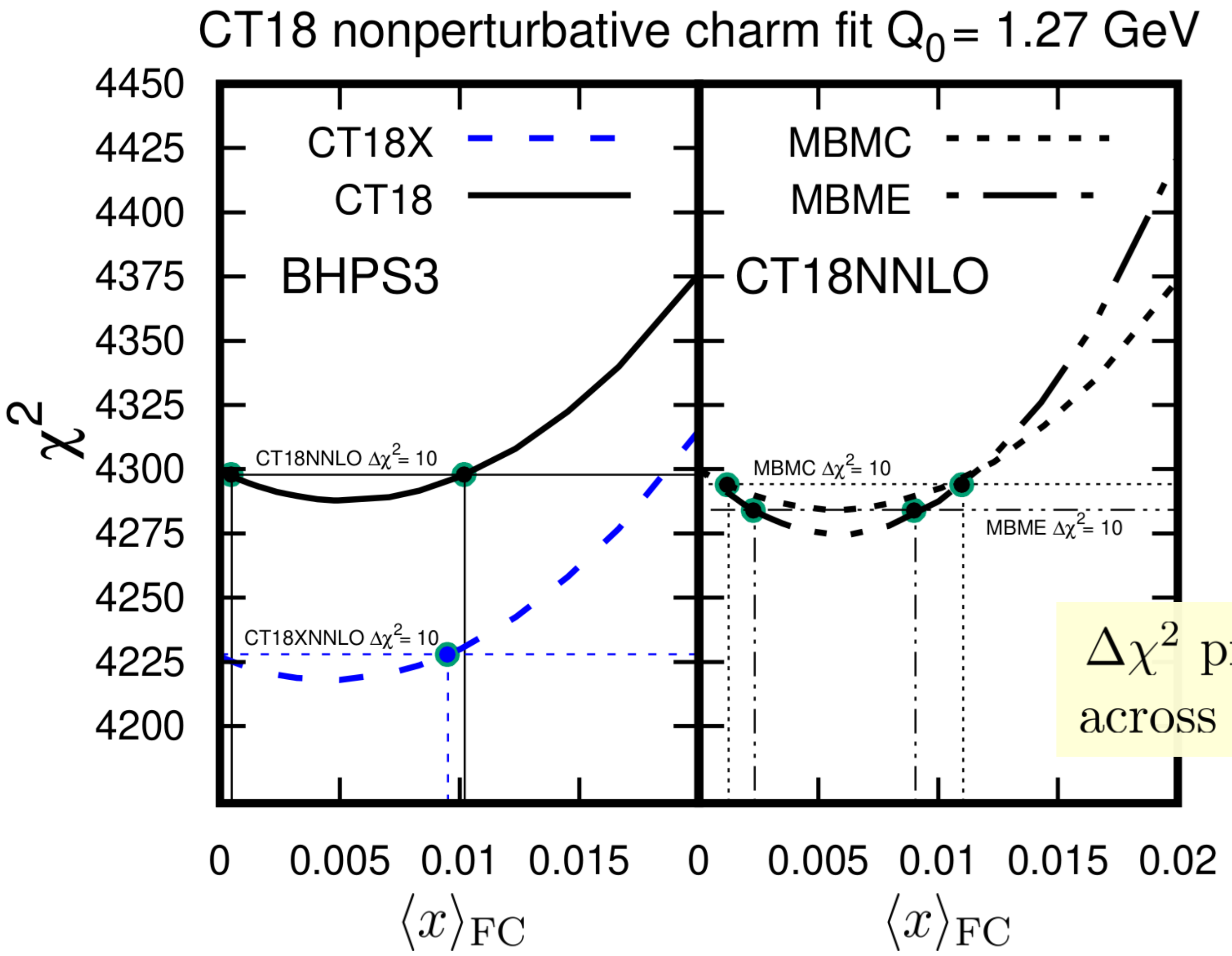




signal for FC in CT18 study, but with shallower $\Delta\chi^2$ than CT14 IC

FC uncertainty quantified by normalization via $\langle x \rangle_{\mathrm{FC}}$ for each input IC model

→ $\langle x \rangle_{\mathrm{FC}} \approx 0.5\%\ (\Delta\chi^2 \gtrsim -25)$ vs. $\langle x \rangle_{\mathrm{FC}} \approx 0.8-1\%\ (\Delta\chi^2 \gtrsim -40)$ CT14 IC



$\Delta\chi^2$ profiles similar across FC scenarios

FC PDF moments

moments of the FC PDFs often used to characterize magnitude, asymmetry

$$\langle x^n \rangle_{c\pm} = \int_0^1 dx\, x^n (c \pm \bar{c})[x, Q]$$

$$\langle x \rangle_{\rm FC} \equiv \langle x \rangle_{c^+}[Q_0 = 1.27\,\text{GeV}]$$ ...at NNLO.

$$= 0.0048\,{}^{+0.0063}_{-0.0043}\,\left({}^{+0.0090}_{-0.0048}\right),\ \text{CT18 (BHPS3)}$$

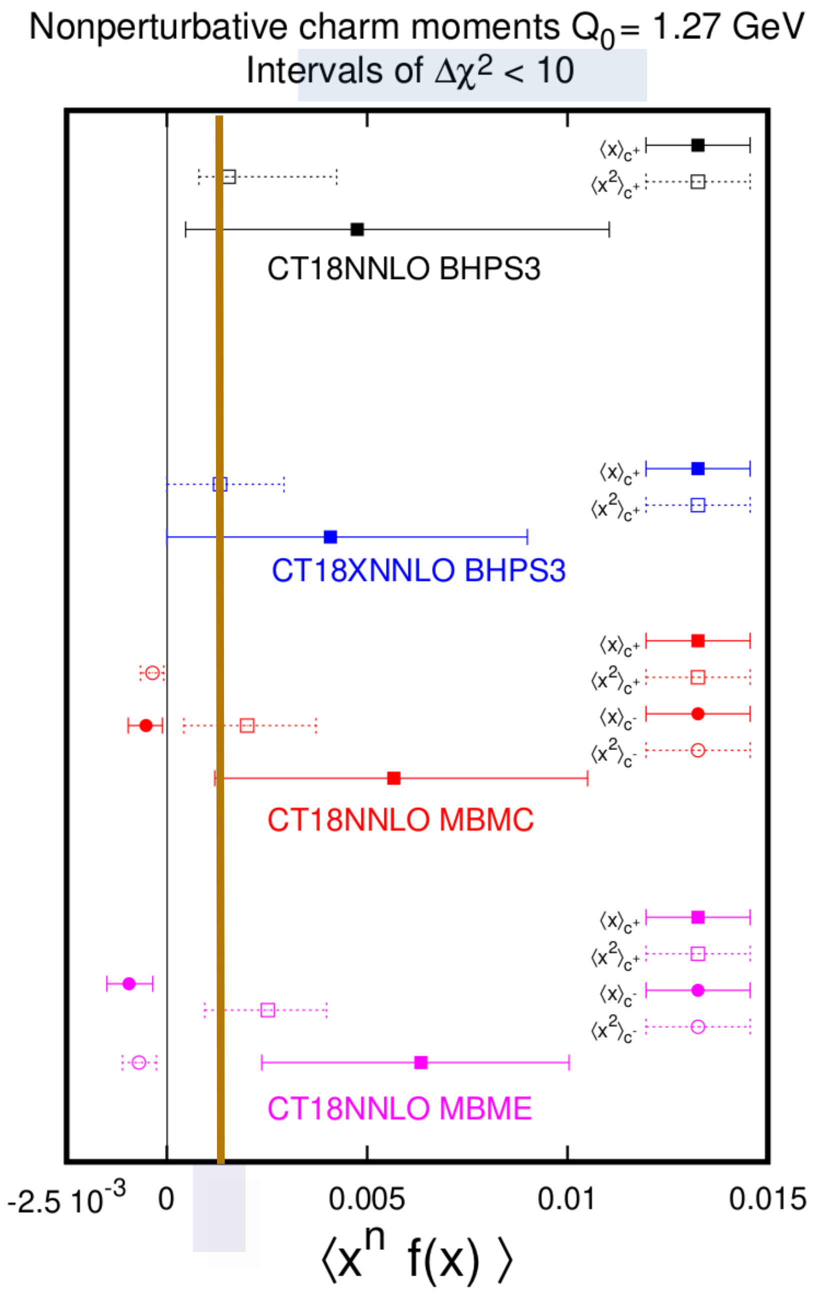
$$= 0.0041\,{}^{+0.0049}_{-0.0041}\,\left({}^{+0.0091}_{-0.0041}\right),\ \text{CT18X (BHPS3)}$$

$$= 0.0057\,{}^{+0.0048}_{-0.0045}\,\left({}^{+0.0084}_{-0.0057}\right),\ \text{CT18 (MBMC)}$$

$$= 0.0061\,{}^{+0.0030}_{-0.0038}\,\left({}^{+0.0064}_{-0.0061}\right),\ \text{CT18 (MBME)}$$

$\Delta\chi^2 \leq 10$ (restrictive tolerance)

$\Delta\chi^2 \leq 30$ (~CT standard tolerance)



FC PDF moments

even restrictive uncertainties give moments consistent with zero

- → broaden further for default CT tol.
- → lattice may give $\langle x \rangle_{c^+}$, $\langle x^2 \rangle_{c^-}$

$$\langle x \rangle_{\mathrm{FC}} \equiv \langle x \rangle_{c+}[Q_0 = 1.27\,\mathrm{GeV}]$$

$$= 0.0048\,{}^{+0.0063}_{-0.0043}\,\left({}^{+0.0090}_{-0.0048}\right),\ \mathrm{CT18\ (BHPS3)}$$

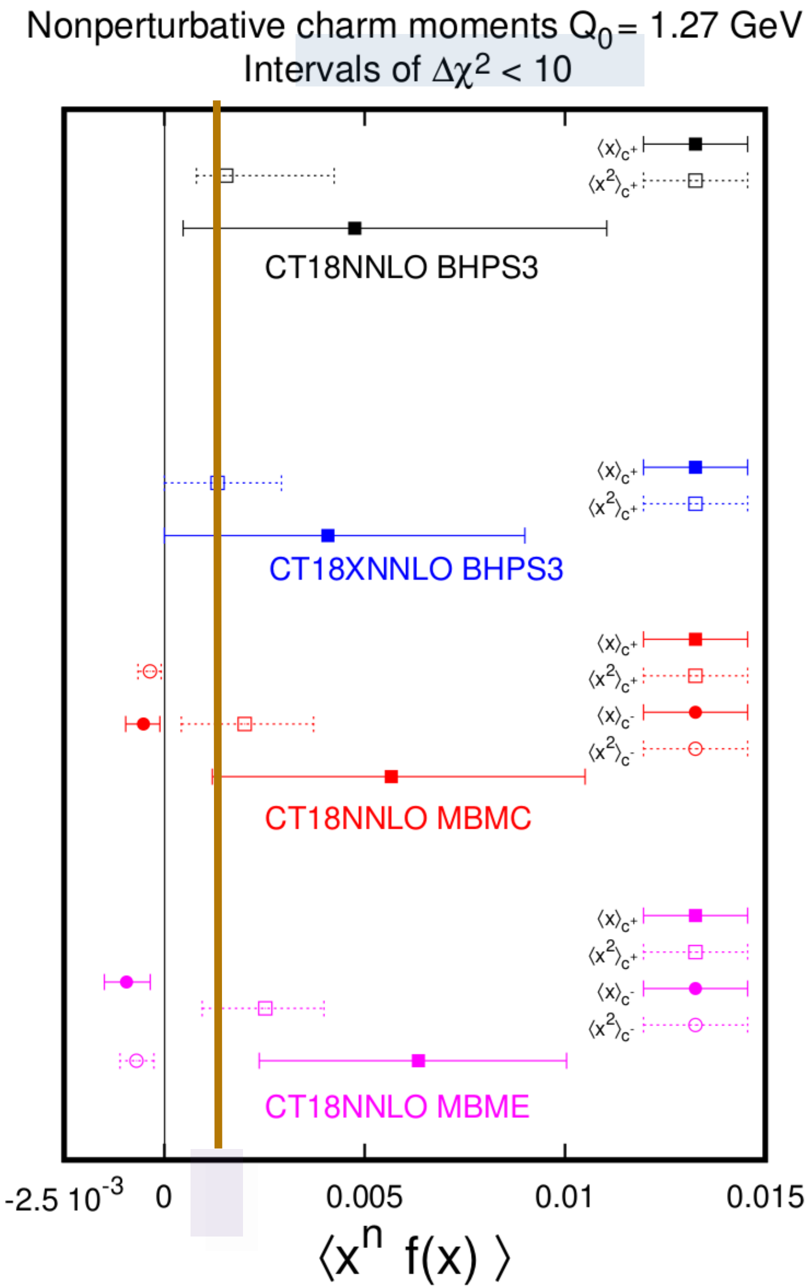
$$= 0.0041\,{}^{+0.0049}_{-0.0041}\,\left({}^{+0.0091}_{-0.0041}\right),\ \mathrm{CT18X\ (BHPS3)}$$

$$= 0.0057\,{}^{+0.0048}_{-0.0045}\,\left({}^{+0.0084}_{-0.0057}\right),\ \mathrm{CT18\ (MBMC)}$$

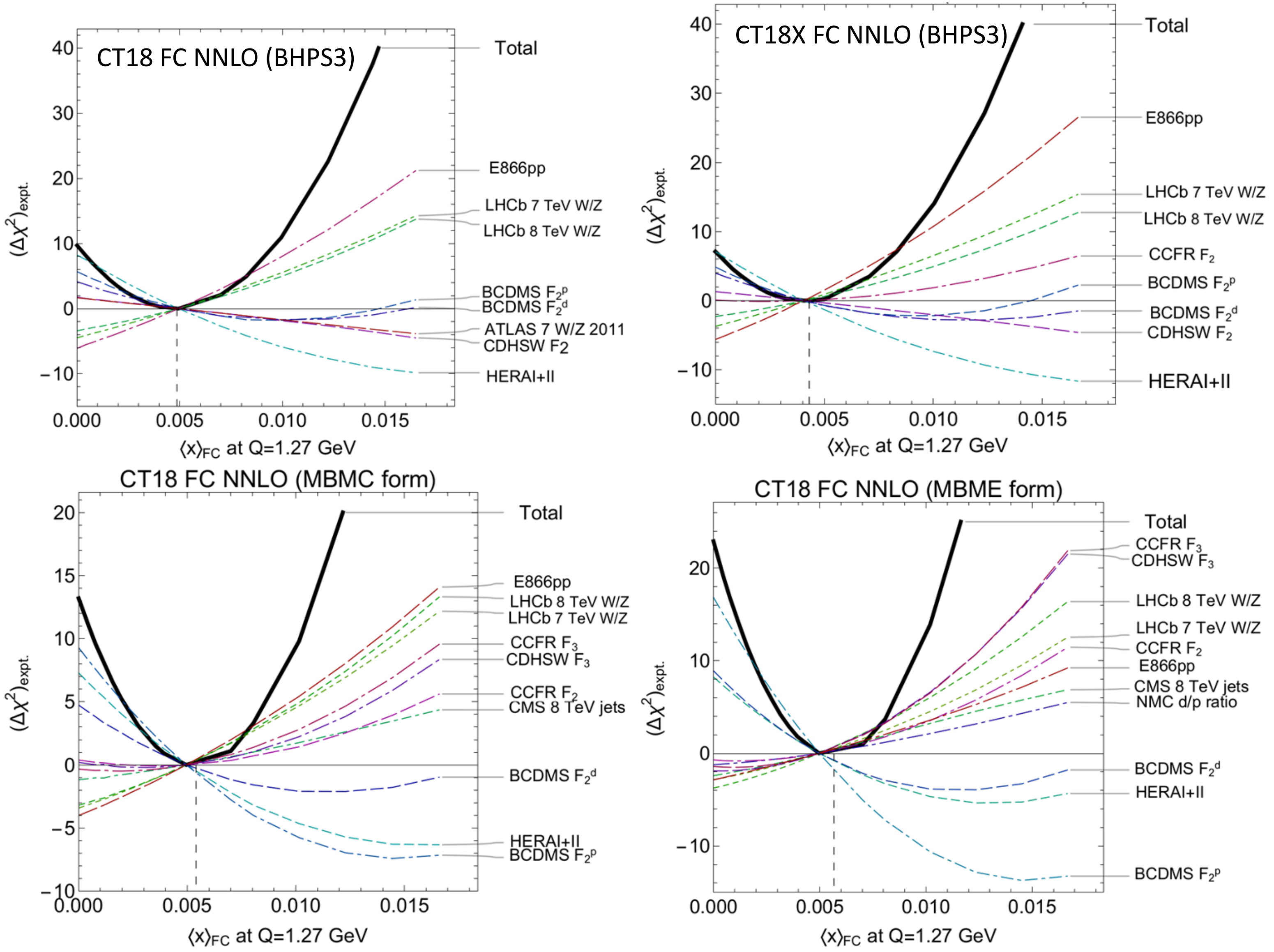
$$= 0.0061\,{}^{+0.0030}_{-0.0038}\,\left({}^{+0.0064}_{-0.0061}\right),\ \mathrm{CT18\ (MBME)}$$

$\Delta\chi^2 \leq 10$ (restrictive tolerance)

$\Delta\chi^2 \leq 30$ (~CT standard tolerance)



data pull opposingly on $\langle x \rangle_{\mathrm{FC}}$; depend on FC scenario, enhancing error

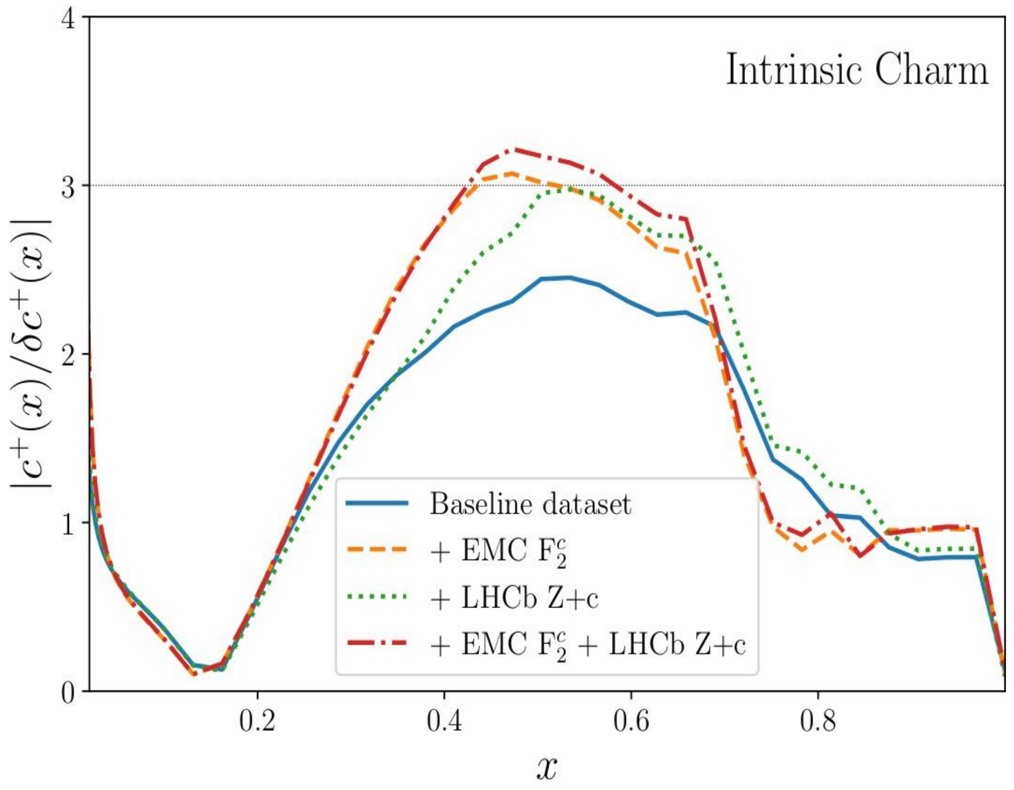


Revisiting the significance in NNPDF4.0 IC

R. Ball et al., Nature 608 (2022) 483

By considering important additional uncertainties:

- In the baseline fit due to sampling of MC replicas (Courtoy et al., *Phys.Rev.D* 107 (2023) 034008)
- In the NLO LHCb $Z + c$ analysis due to MHOU and final-state showering
- In the EMC F_2^c due to insufficient control of syst. uncertainties and LO analysis



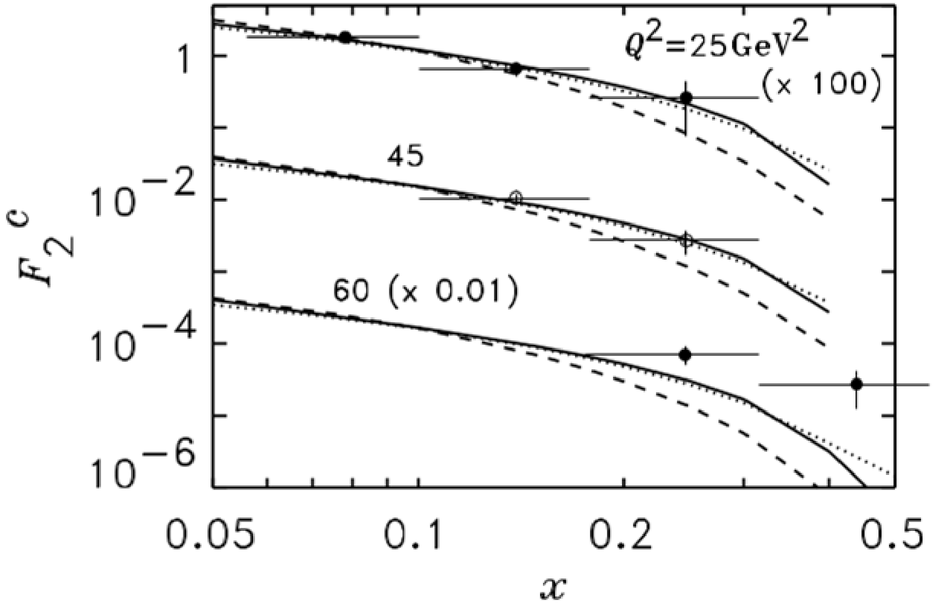
∴ … we expect no significant evidence for NNPDF4.0 IC, in compliance with CT18 FC observations

few expts with ‘smoking gun’ sensitivity to FC; but **EMC data** (?)

historically, charm structure function data, $F_2^{c\bar{c}}$, from EMC were suggestive

J. J. Aubert *et al.* (EMC), NPB**213** (1983) 31–64.

F. M. Steffens, W. Melnitchouk and A. W. Thomas, Eur. Phys. J. C **11**, 673 (1999) [hep-ph/9903441].



- → hint of high-x excess in select Q^2 bins
- → data were analyzed only at LO
- → show anomalous Q^2 dependence
- → EMC data fit poorly in CT14 IC study

we do not include EMC in CT18 FC

CT14 IC, arXiv: 1707.00657.

Candidate NNLO PDF fits	$\chi^2/N_{\rm pts}$			
	All Experiments	HERA inc. DIS	HERA $c\bar{c}$ SIDIS	EMC $c\bar{c}$ SIDIS
CT14+EMC (weight=0), no IC	1.10	1.02	1.26	3.48
CT14+EMC (weight=10), no IC	1.14	1.06	1.18	2.32
CT14+EMC in BHPS model	1.11	1.02	1.25	2.94
CT14+EMC in SEA model	1.12	1.02	1.28	3.46

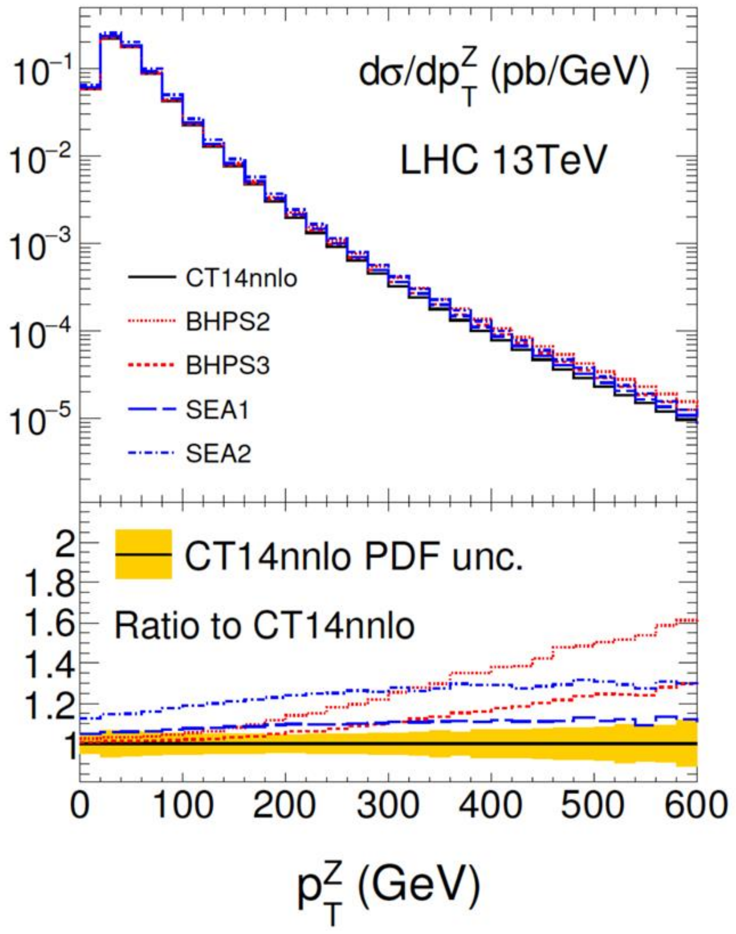
FC at LHC: *Z+c* suggested as sensitive probe

T. Boettcher, P. Ilten, M. Williams, 1512.06666; Bailas, Goncalves, 1512.06007

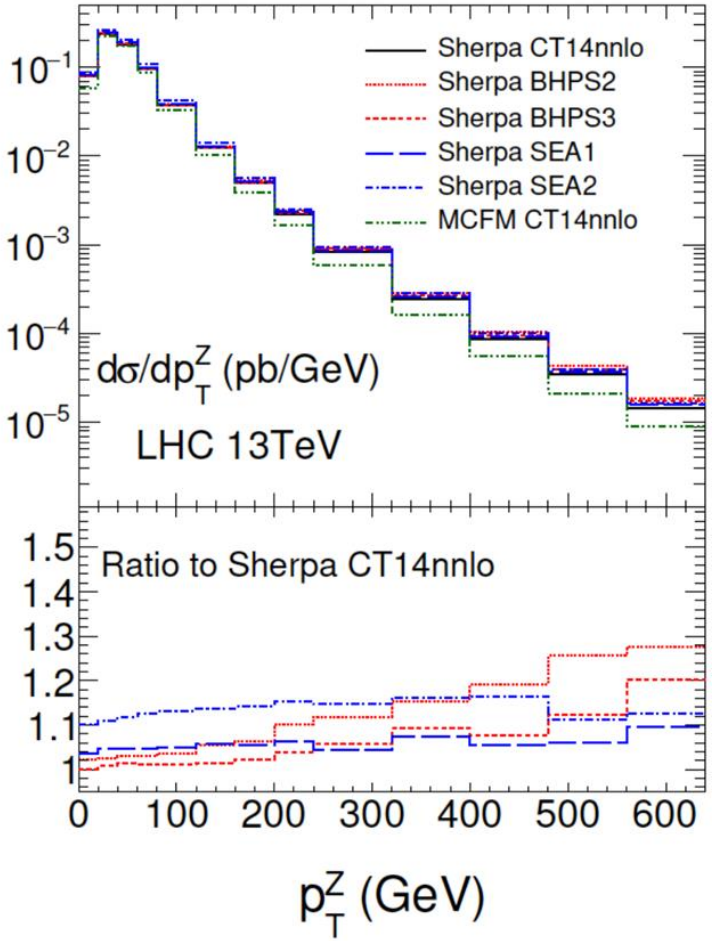
p_T spectra, rapidity dists nominally sensitive to high-*x* charm PDF

→ parton-shower effects can dampen high-p_T tails

Z+c NLO LHC 13 TeV



[Hou et al., arXiv:1707.00657]

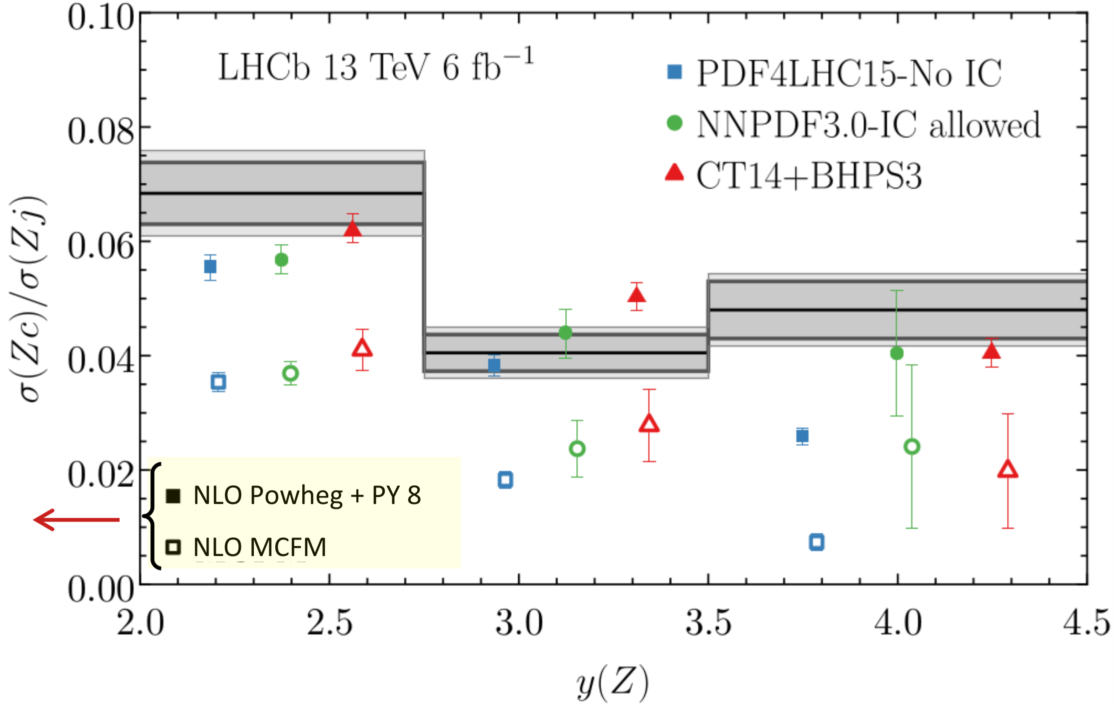


Z+c theory predictions carry sizable uncertainties

2022 LHCb 13 TeV data: (Z+c) / (Z+jet) ratios; 3 rapidity bins

→ calculated **NLO** cross-section ratio similarly depends on showering, hadronization

R. Aaij, *et al*. (LHCb); arXiv: 2109.08084.



differ due to large FSR correction

$$x \sim \frac{Q}{\sqrt{s}} \exp y$$

NNLO calculations recently available, but not implemented in PDF fits

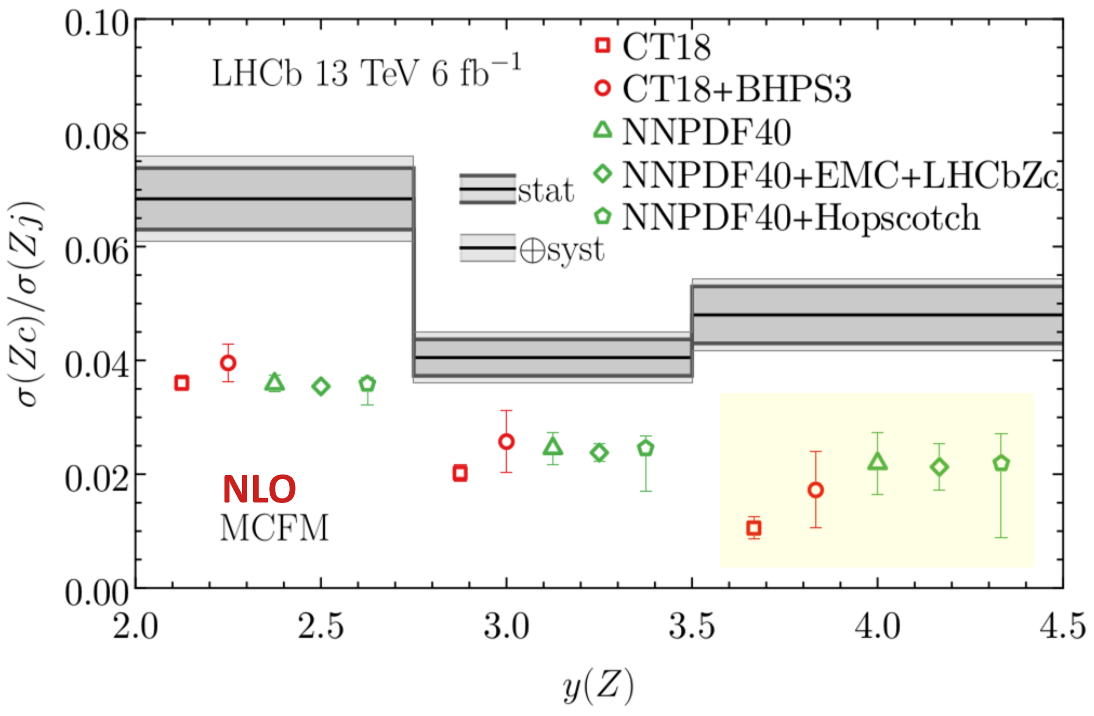
R. Gauld, *et al*.; arXiv: 2005.03016.
M. Czakon, *et al*.; arXiv: 2011.01011.

theory uncertainties currently larger than PDF variations

assuming MCFM at NLO, can vary underlying PDFs, test inclusion of FC

→ FC slightly enhances ratio; not enough to improve agreement with data

R. Aaij, *et al*. (LHCb); arXiv: 2109.08084.



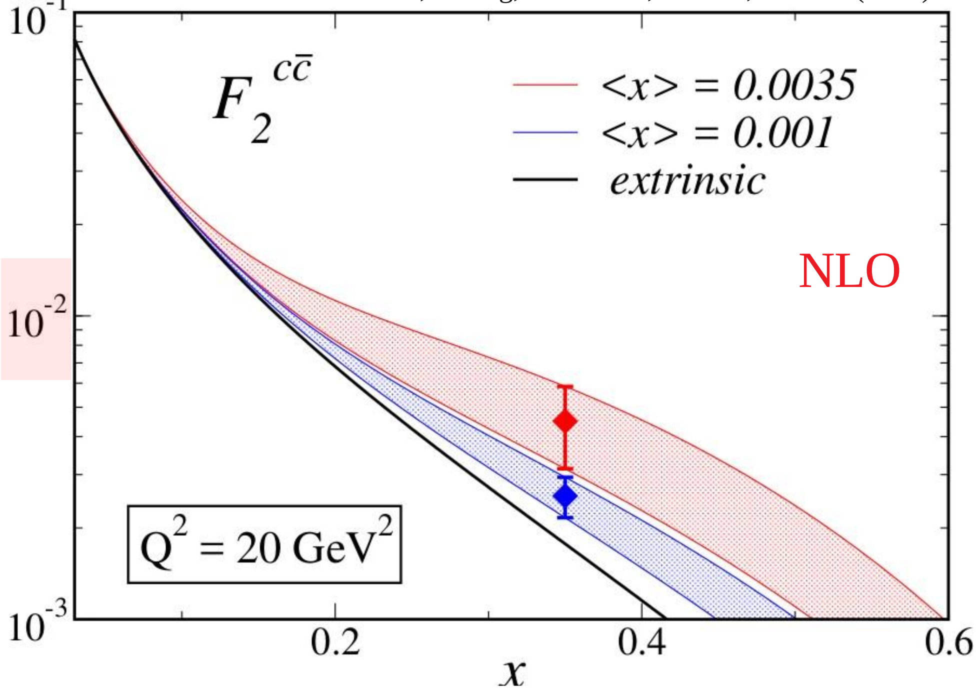
$$x \sim \frac{Q}{\sqrt{s}} \exp y$$

theory accuracy not yet sufficient to leverage expt. precision for PDFs

→ need NNLO theory interface; control over showering, final-state effects

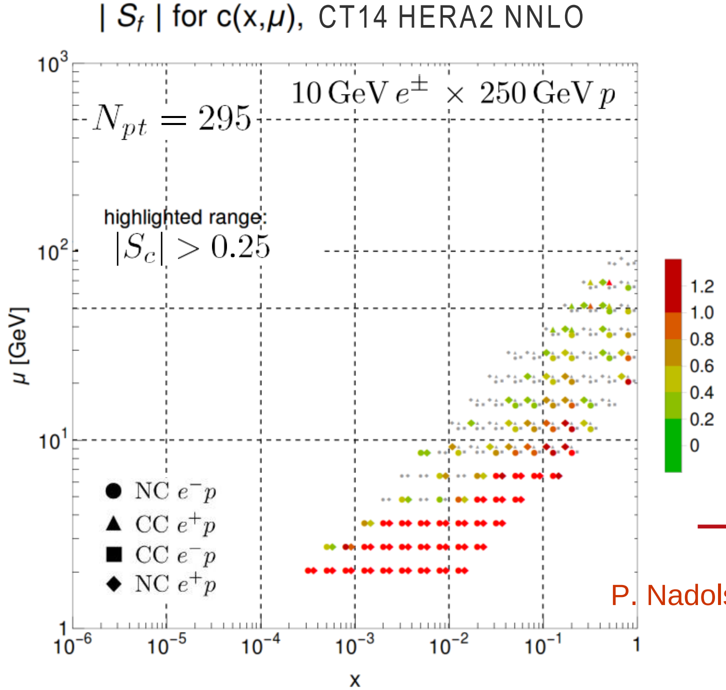
future data will inform FC

TJH, Alberg, and Miller; PRD96, 074023 (2017).



EIC + lattice QCD will constrain FC scenarios

enhanced FC momentum implied by EMC data → small high-x effects in structure function; need high precision

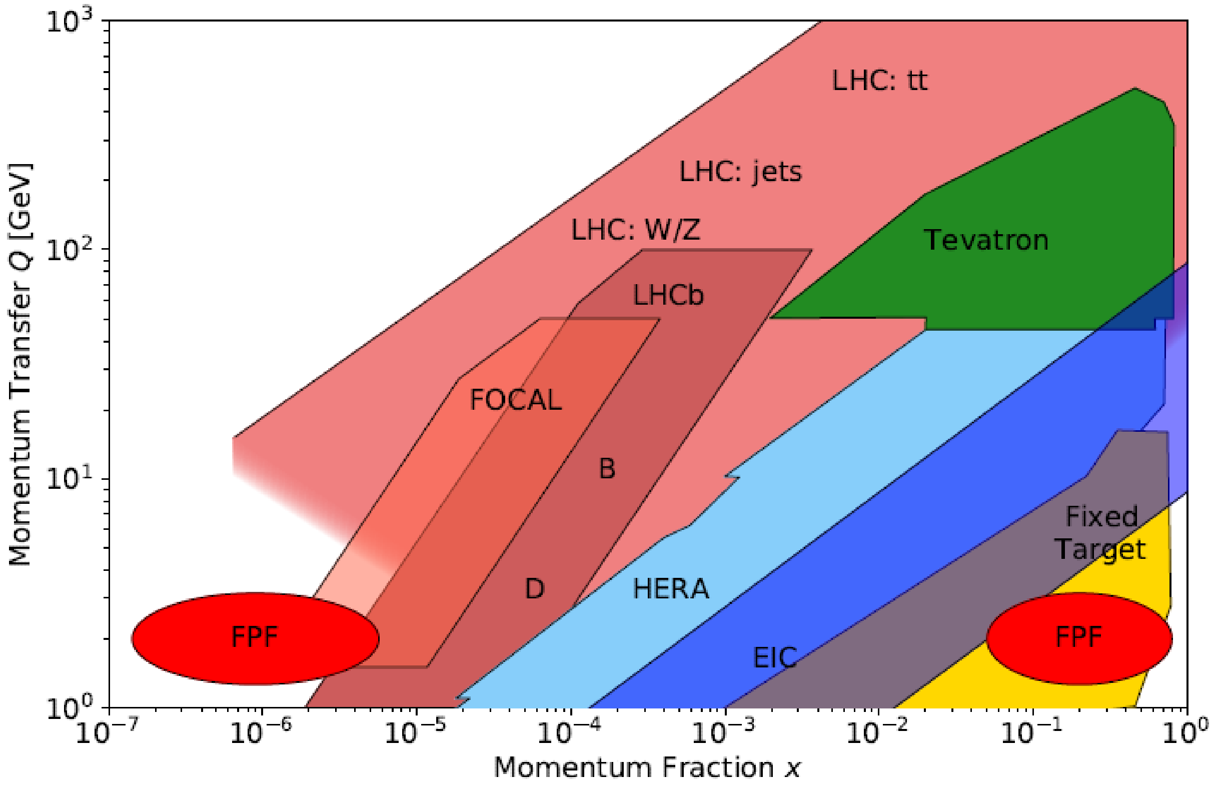


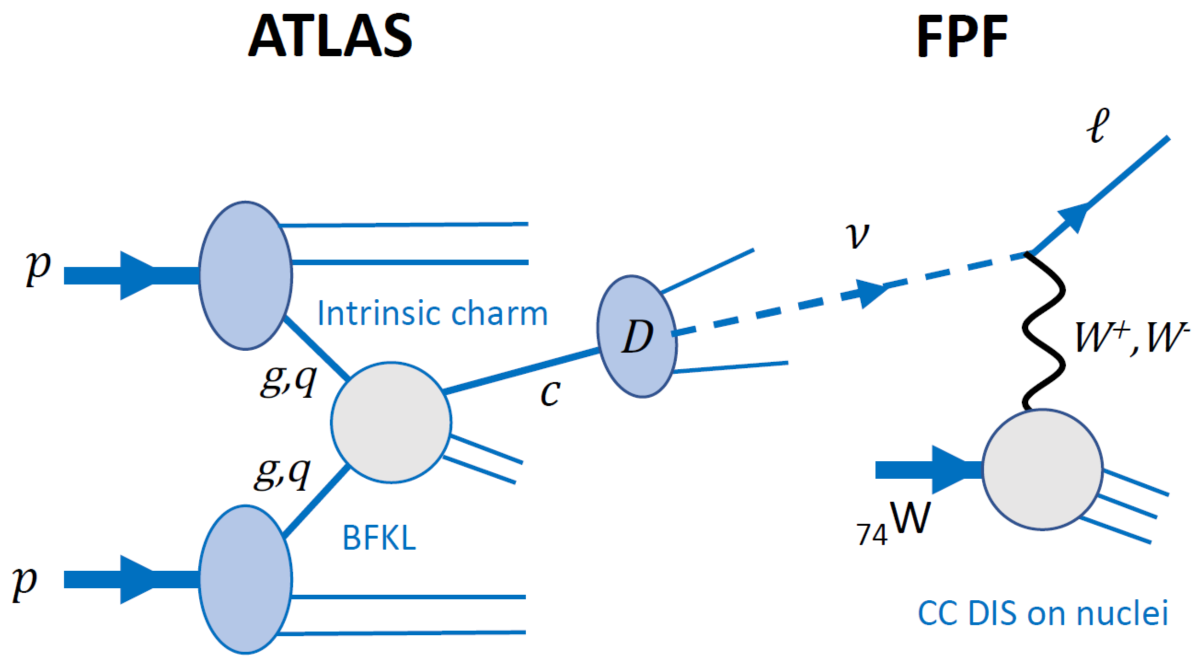
essential complementary input from LHC; CERN FPF

EIC will measure precisely in the few-GeV, high-x region where FC signals are to be expected

The Forward Physics Facility at CERN

L. A. Anchordoqui *et al.*, "The Forward Physics Facility: Sites, Experiments, and Physics Potential," arXiv:2109.10905 [hep-ph].
J. L. Feng *et al.*, "The Forward Physics Facility at the High-Luminosity LHC," arXiv:2203.05090





The FPF can clarify multiple aspects of QCD in the new forward region **in coordination** with the HL-LHC and EIC, including intrinsic charm

1. How do $\bar{u}$ and $\bar{d}$ PDFs behave at $x > 0.3$?

2. Is there intrinsic charm in the proton?

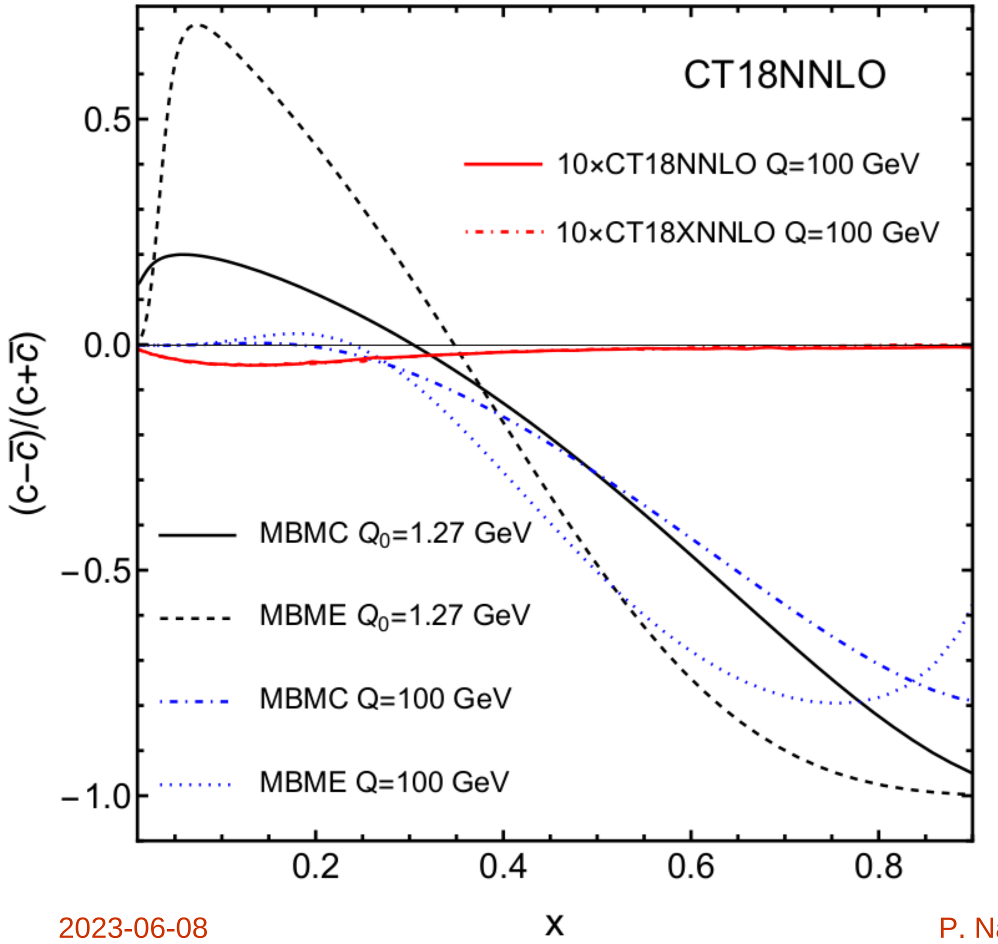
3. Are PDFs for the 2nd and 3rd quark generation (s, c, …) charge-symmetric?

possible charm-anticharm asymmetries

pQCD only very weakly breaks $c = \bar{c}$ through HO corrections

→ large(r) charm asymmetry would signal nonpert dynamics, IC

→ MBM breaks $c = \bar{c}$ through hadronic interactions



consider two MBM models as ***examples*** (<u>not predictions</u>)

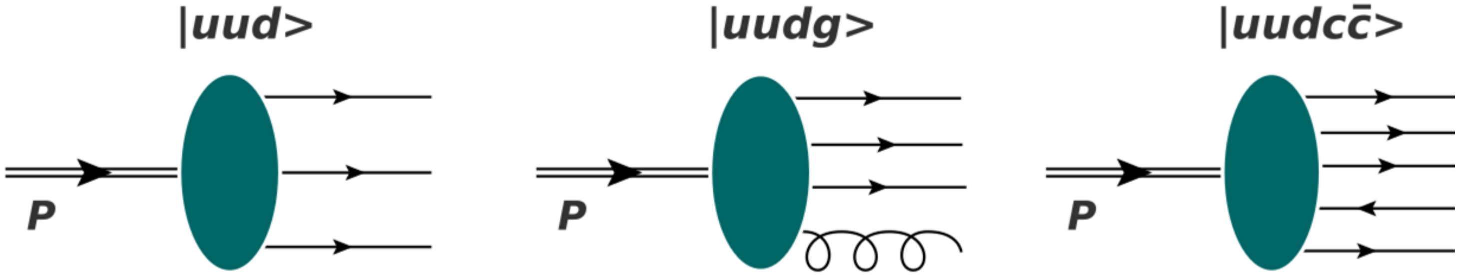
→ asymptotically small, but ratio can be bigger; will be hard to extract from data

T. J. Hobbs, J. T. Londergan, W. Melnitchouk, *Phys. Rev. D* 89 (2014) 074008

nonperturbative QCD can generate a low-scale charm PDF

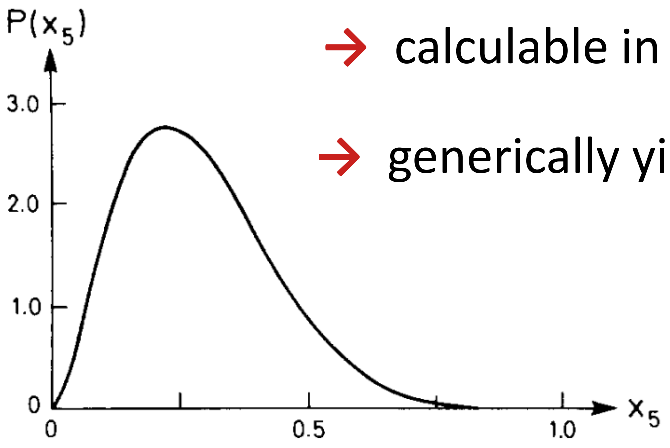
Fock expansion

Brodsky, Hoyer, Peterson, Sakai (**BHPS**); Phys. Lett. **B93** (1980) 451.



IC PDF: transition matrix element, $|\mathrm{proton}\rangle \to |uudc\bar{c}\rangle$

$$P(p \to uudc\bar{c}) \sim \left[M^2 - \sum_{i=1}^{5} \frac{k_{\perp i}^2 + m_i^2}{x_i} \right]^{-2}$$



→ calculable in old-fashioned perturbation theory; **scalar** field theory

→ generically yields valence-like shape; governed by charm masses

$$m_c = m_{\bar{c}} \implies c^{\mathrm{BHPS}}(x) = \bar{c}^{\mathrm{BHPS}}(x)$$

alternative but similar representations exist

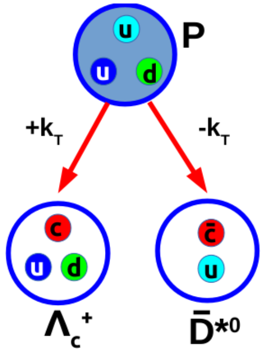
Blumlein; Phys. Lett. **B753** (2016) 619.

meson-baryon models (MBMs): 5-quark states from hadronic interactions

- we implement a framework which *conserves* **spin/parity**

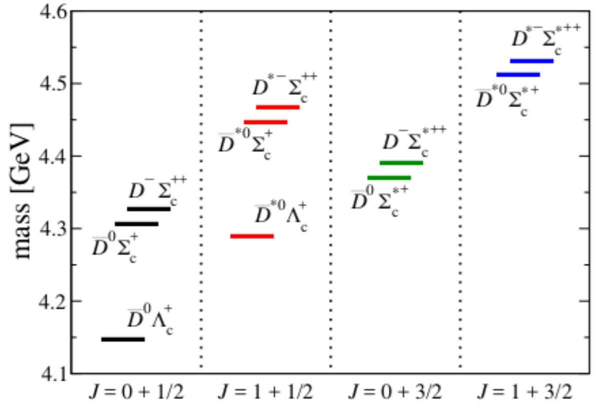
- **nonperturbative** mechanisms are needed to break
  $$c(x, Q^2 \le m_c^2) = \bar{c}(x, Q^2 \le m_c^2) = 0!$$

We build an **EFT** which connects IC to properties of the hadronic spectrum: [**TJH**, **J. T. Londergan and W. Melnitchouk, Phys. Rev. D89, 074008 (2014).**]



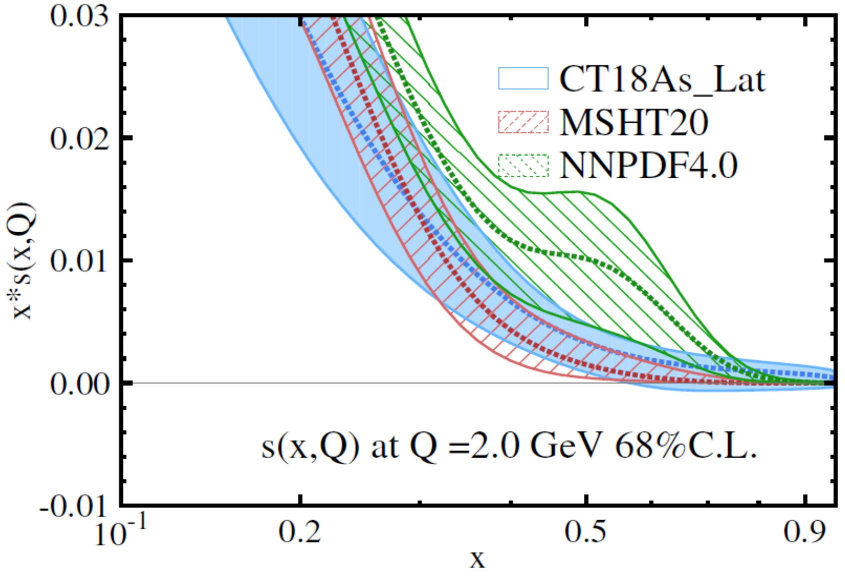
- $$|N\rangle \;=\; \sqrt{Z_2}\,|N\rangle_0 \;+\; \sum_{M,B} \int dy\, \boldsymbol{f_{MB}(y)}\, |M(y); B(1-y)\rangle$$
  $$y = k^+/P^+:\; k \text{ meson},\; P \text{ nucleon}$$

$$c(x) = \sum_{B,M} \left[\int_x^1 \frac{d\bar{y}}{\bar{y}}\, f_{BM}(\bar{y})\, c_B\!\left(\frac{x}{\bar{y}}\right) \right]$$



- a similar *convolution* procedure may be used for $\bar{c}(x)$ ...

CT18As_Lat NNLO: Strangeness asymmetry with a lattice QCD constraint

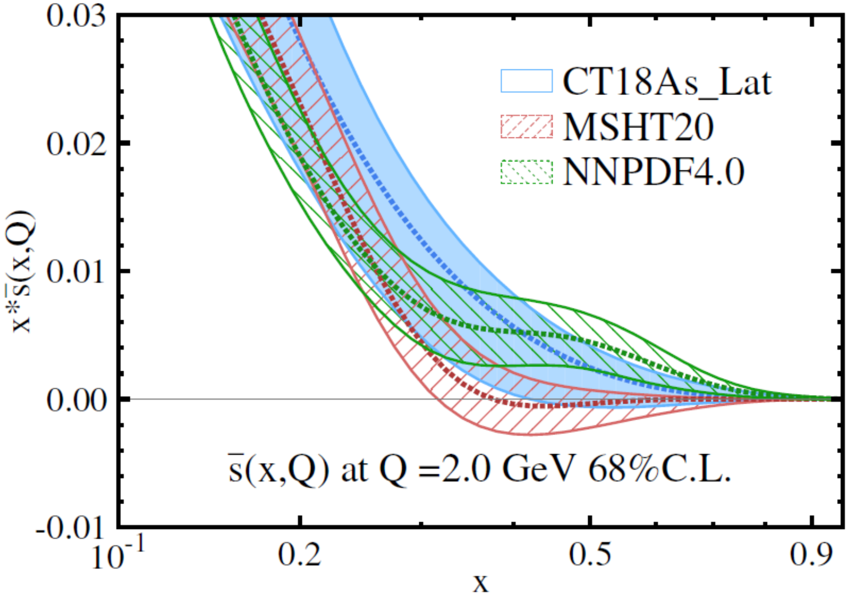


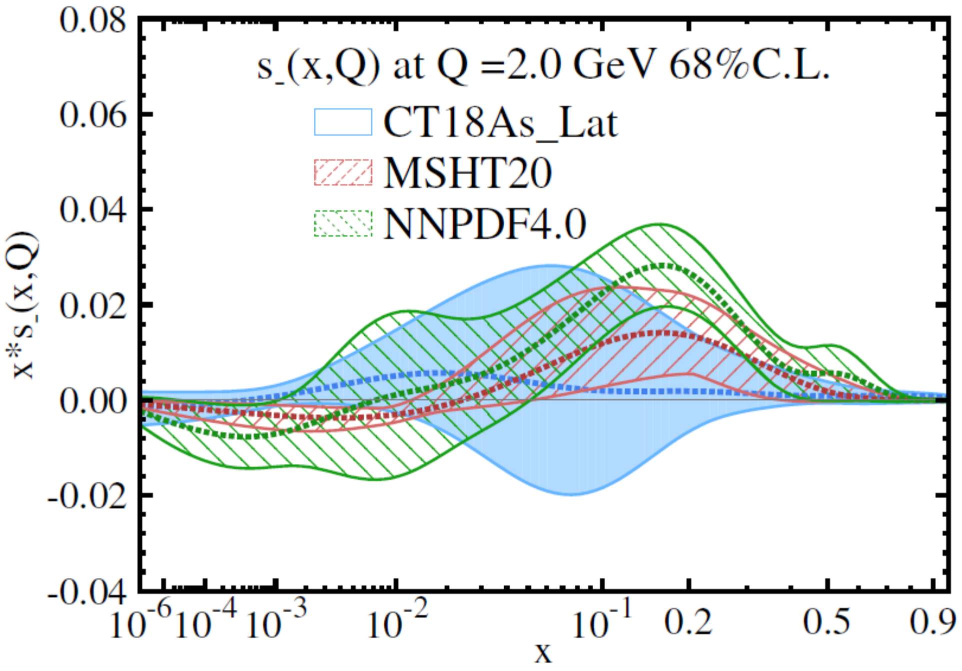
T.-J. Hou et al., arXiv: 2211.11064

CT18As: CT18A with $s_- \equiv s - \bar{s} \neq 0$

CT18As_Lat: CT18As with a lattice constraint on $s_-(x)$ at $0.3 \leq x \leq 0.8$.

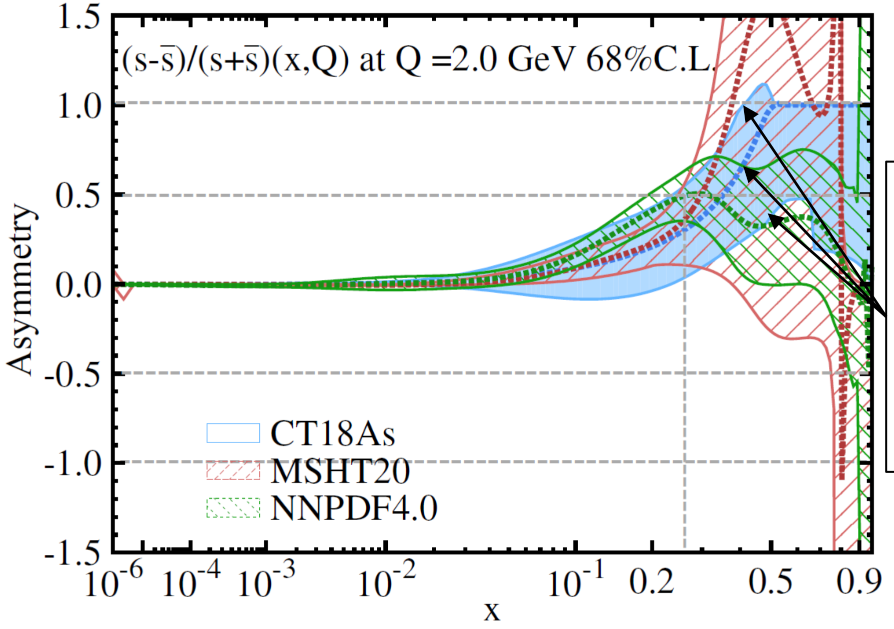
$$\int_0^1 s_-(x)dx = 0$$





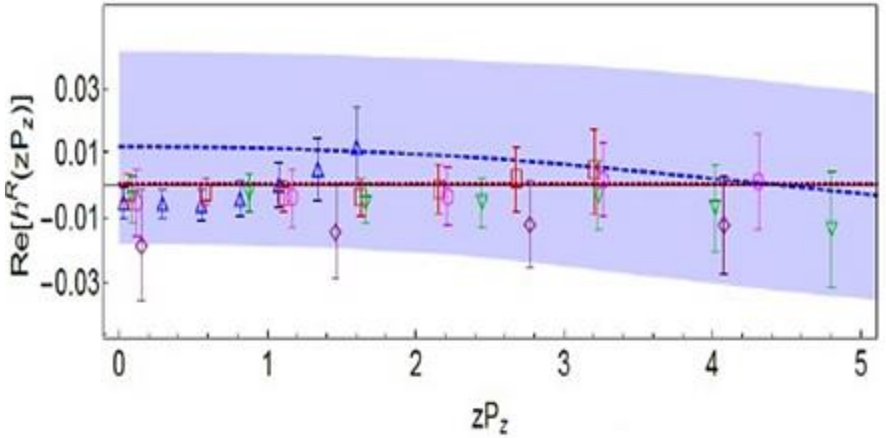
CT18As NNLO: Strangeness asymmetry with a lattice QCD constraint

T.-J. Hou et al., arXiv: 2204.07944



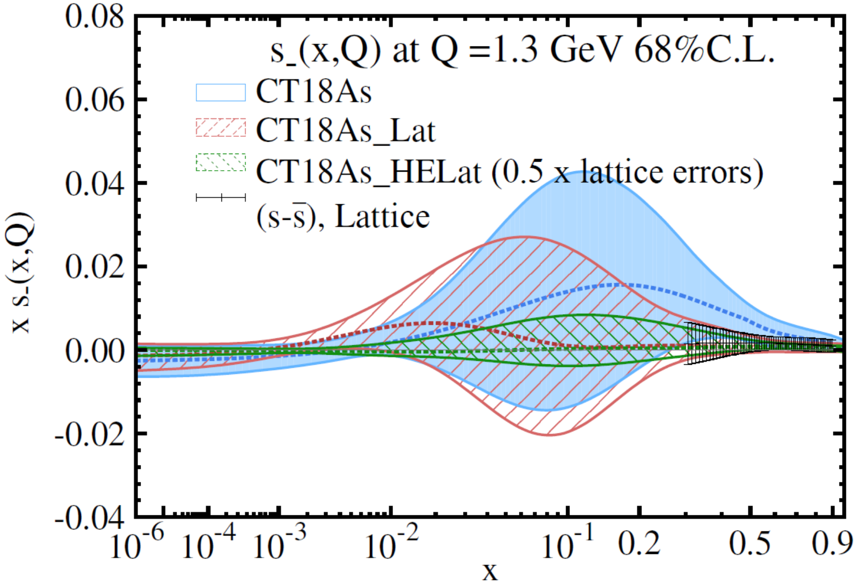
differences reflect the pulls of LHC and other experiments

Asymmetry nominally reaches $\approx 50\%$ at $x \approx 0.25$ in three global fits. **Is there a dynamical mechanism to produce it at such x?**



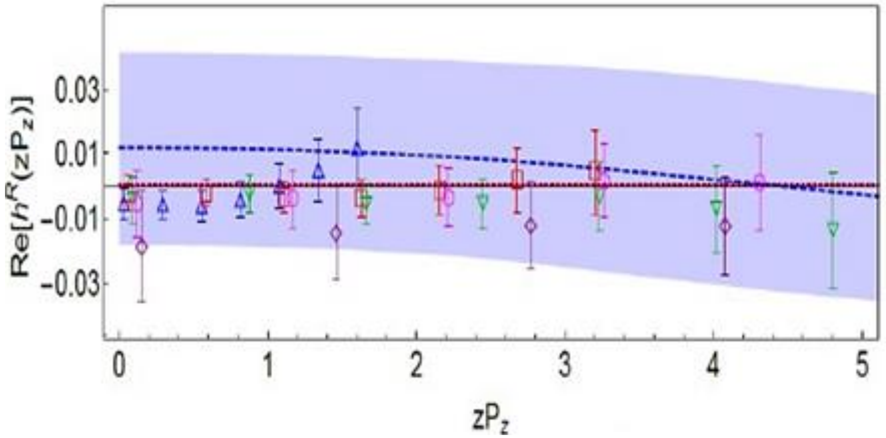
Include lattice data on s_- obtained by the MSULat/quasi-PDF method (2005.12015, Zhang, Lin, Yoon)

The lattice QCD prediction disfavors a large $s_-(x,Q)$ at $x > 0.3 \Rightarrow$ reduction in $s_-(x,Q)/s_+(x,Q)$ in CT18As_Lat fit



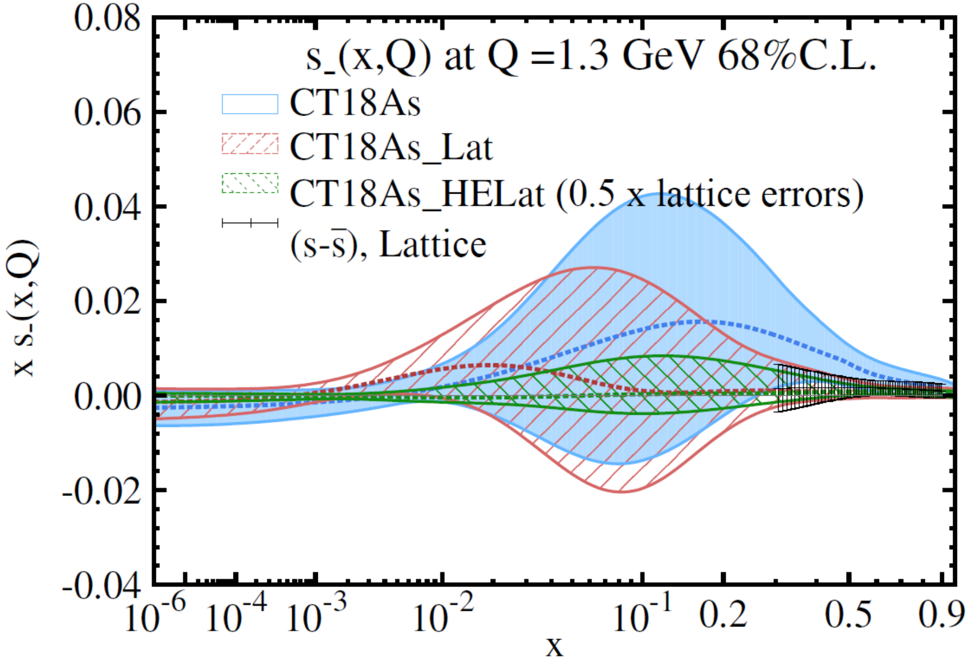
CT18AsLat NNLO

T.-J. Hou et al., arXiv: 2204.07944



$$\mathrm{Re}[h(z)] \propto \int dx(s(x) - \bar{s}(x)) \cos(xzP_z)$$

Include lattice data on s_- obtained by the MSULat/quasi-PDF method (2005.12015, Zhang, Lin, Yoon)



The lattice QCD prediction disfavors a large $s_-(x,Q)$ at $x > 0.3$

$\Rightarrow$ reduction in $s_-(x,Q)/s_+(x,Q)$ at $x < 0.3$ (depending on the parametrization form)

CT18As_HELat: PDFs if the lattice errors are reduced by 1/2

Key points

1. High-luminosity Drell-Yan pair production at the LHC will distinguish between the low-sea and high-sea scenarios for light antiquarks at $x \to 1$

- Consequences for QCD models, BSM searches

2. Size, shape of nonperturbatve charm remain uncertain

- unresolved theoretical ambiguities in connecting intrinsic charm (IC) and fitted charm (FC)
- FC currently consistent with zero; $\langle x \rangle_{FC} \sim 0.5\%$, below evidence-level
- need more NNLO and better showering calculations (e.g., for $Z + c$)
- promising experiments at the LHC; EIC; CERN FPF

3. Strangeness and charm charge asymmetries are valuable pheno probes of nonpertubative dynamics

- First lattice QCD calculations predict vanishing $s(x) - \bar{s}(x)$ at $x \to 1$
- Meson-baryon models predict large $c(x) - \bar{c}(x)$ at $x \to 1$

More studies are needed

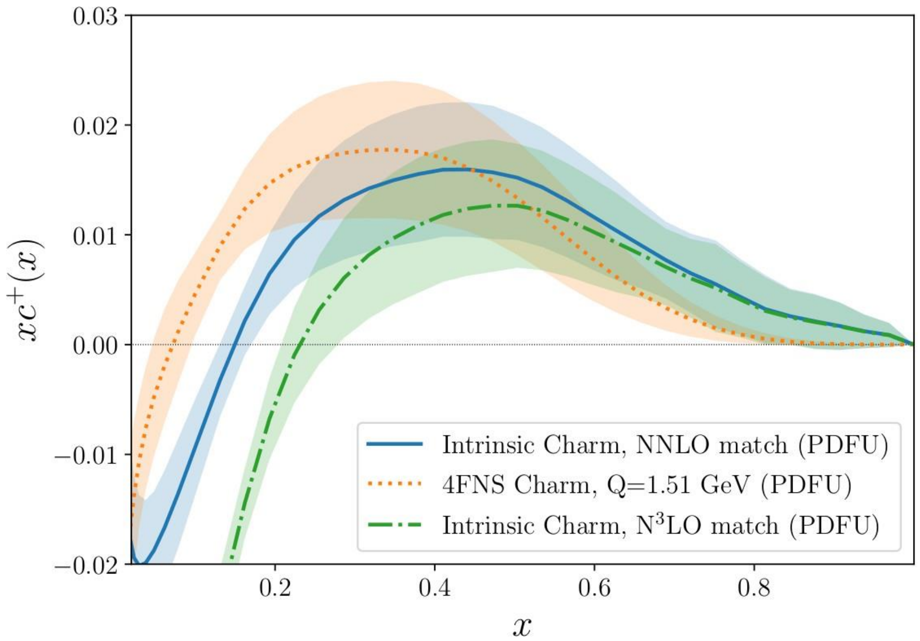
Backup

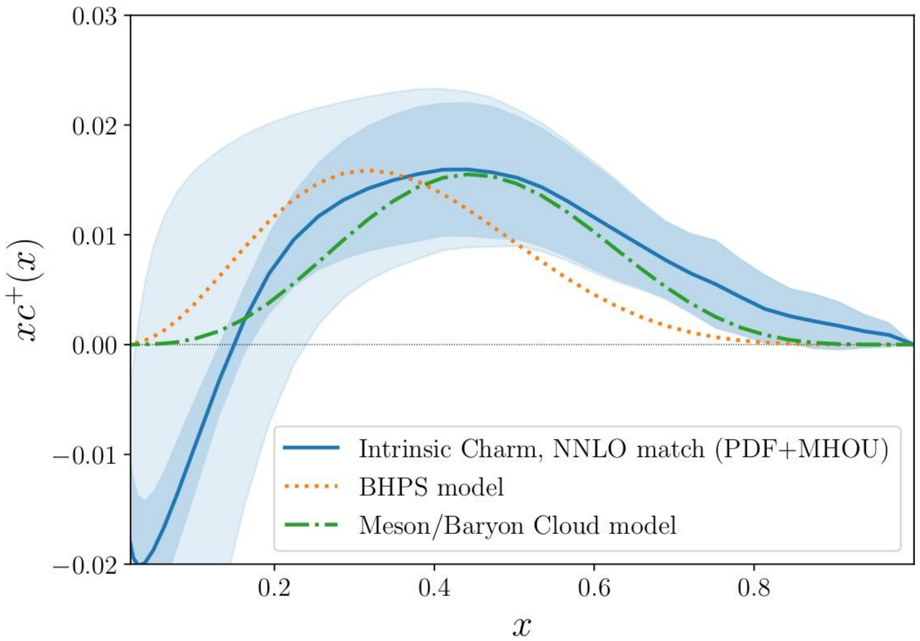
NNPDF IC PDFs and moments

NNPDF, Nature 608 (2022) 7923, 483.

- large perturbative instability from MHOU in DGLAP affects low-x behavior

  → matching at fixed NNLO gives negative FC, unlike IC models

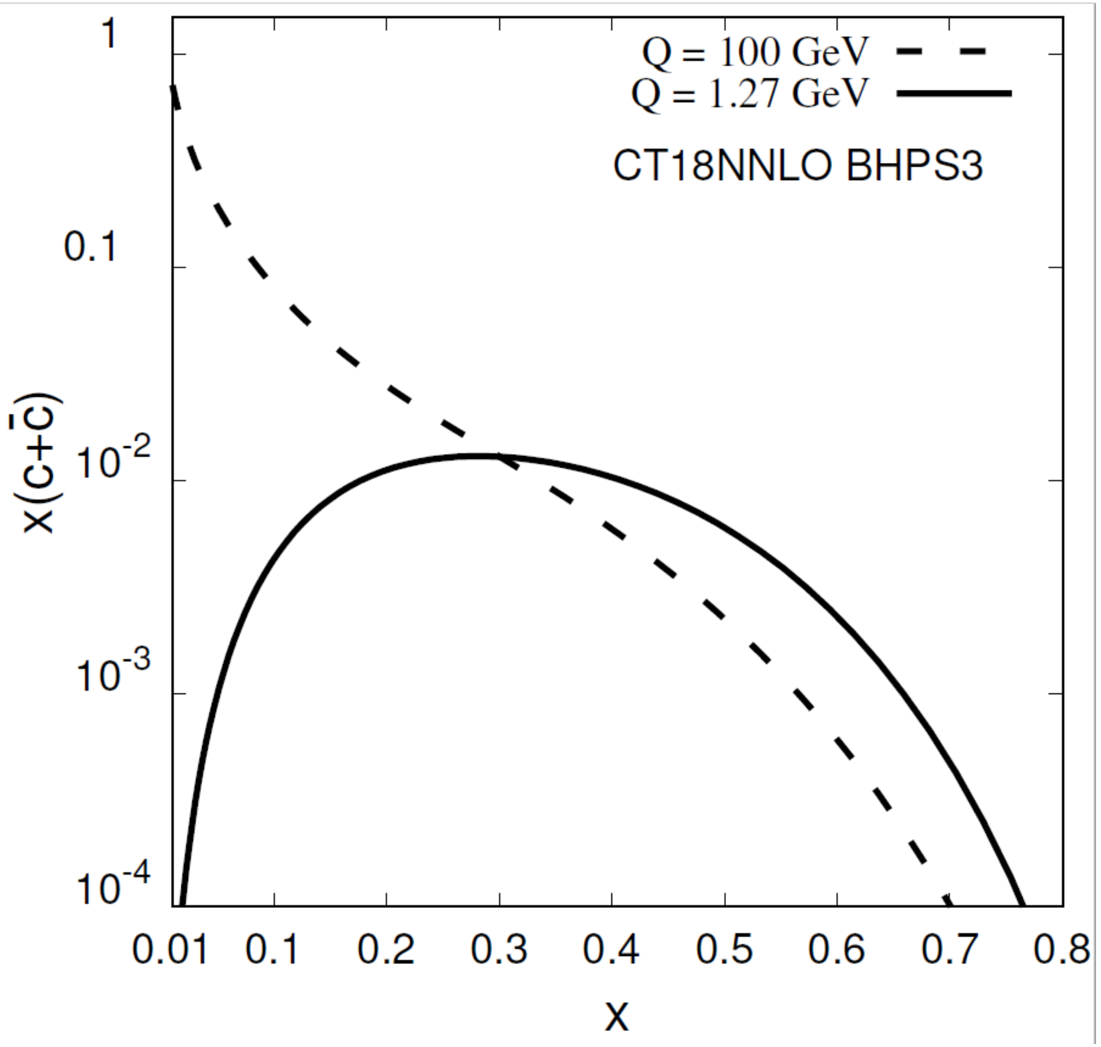




→ MHOU excluded to obtain a nominal charm fraction, $\langle x\rangle_{\mathrm{FC}} = 0.62 \pm 0.28\%$

→ if MHOU is included, consistency with zero: $\langle x\rangle_{\mathrm{FC}} = 0.62 \pm 0.61\%$

Backward DGLAP evolution is approximate



Data constrain the PDFs at $Q > 2$ GeV.

When PDFs are evolved at N2LO down to $Q \approx 1.3$ GeV, the charm PDF is increased at $x \gtrsim 0.3$ and decreased at $x \lesssim 0.3$.

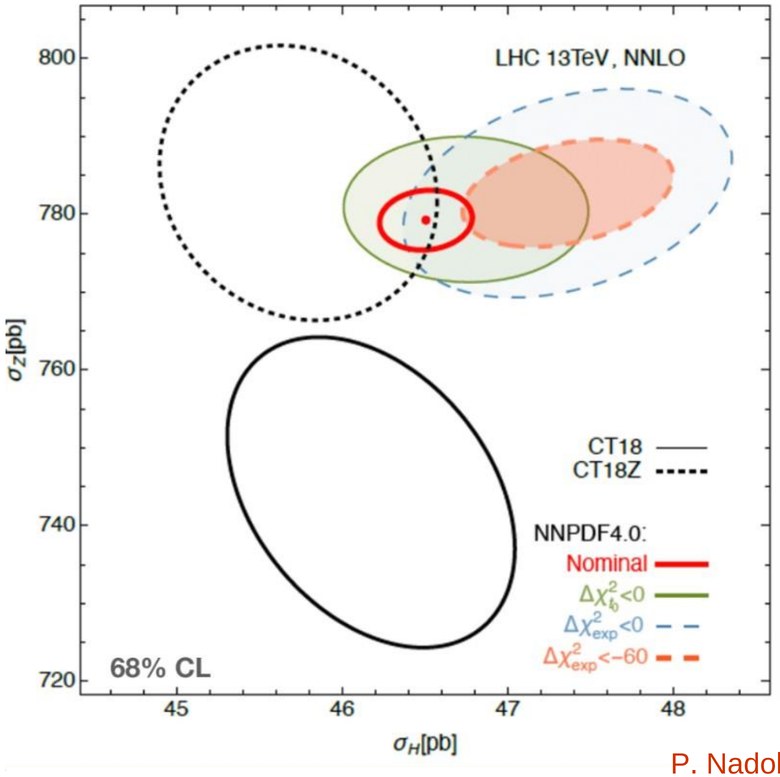
MHOU in DGLAP evolution can produce the bump-like shape.

more representative sampling can enlarge MC uncertainties

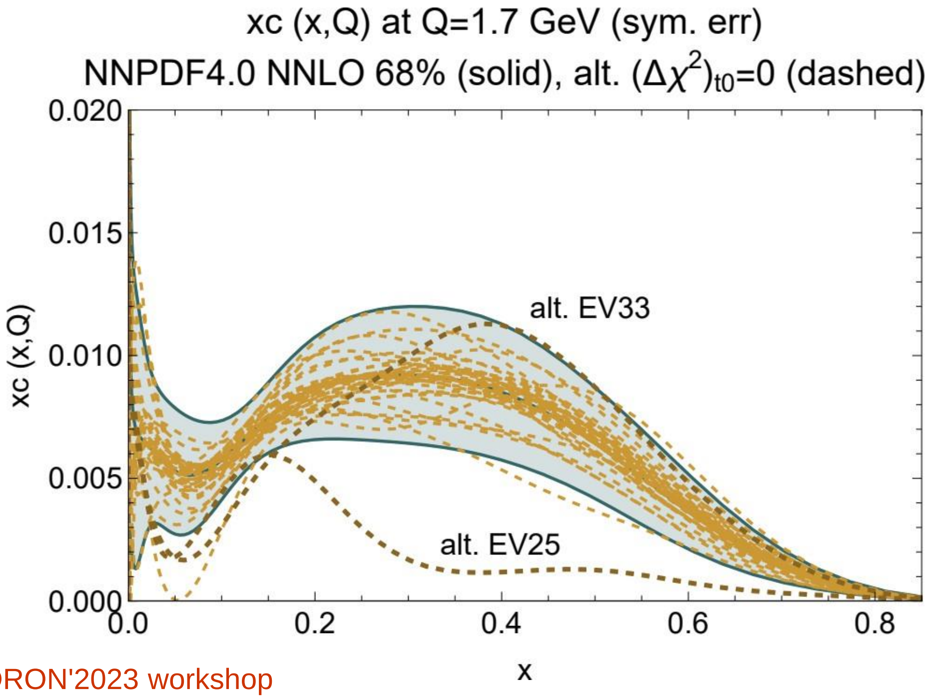
Courtoy *et al.*, arXiv: 2205.10444.

- default replica-training in MC studies may omit otherwise acceptable solutions

- more comprehensive sampling with the public NNPDF4.0 code impacts PDF errors of cross sections



- substantially broadens high-x FC error

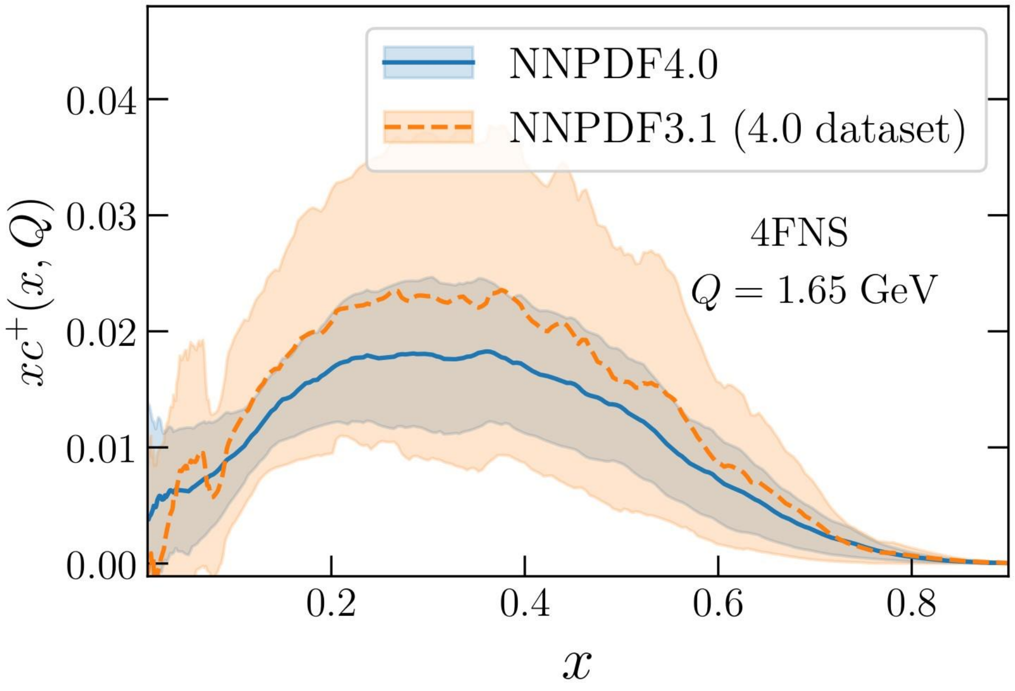


more representative sampling can enlarge MC uncertainties

Courtoy *et al.*, arXiv: 2205.10444.

- default replica-training in MC studies may omit otherwise acceptable solutions

more comprehensive sampling impacts PDF errors of cross sections
$\rightarrow$ alternate fitting methodologies (NNPDF3.1 vs. 4.0) produce
significant differences in the PDF uncertainty



both curves based on same underlying data