Constraining PDFs and nPDFs with recent data

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At the heart of it all: Collinear factorisation of QCD

The cross section for producing an inclusive final state $k + X$ can be described as a convolution of...

\[
\frac{d\sigma^{AB \to k + X}}{(Q^2)} \overset{Q \gg \Lambda_{\text{QCD}}}{=} \sum_{i,j,X'} f^A_i(Q^2) \otimes \tilde{d}\sigma^{ij \to k + X'}(Q^2) \otimes f^B_j(Q^2) + \mathcal{O}(1/Q^2)
\]

...Coefficient Functions $d\tilde{\sigma}^{ij \to k + X'}$ which are calculable from perturbative QCD...

...and Parton Distribution Functions $f^A_i, f^B_j$ which contain long-range physics and cannot be obtained by perturbative means...

...plus “Higher Twist” corrections which are suppressed at high enough momentum scale $Q \gg \Lambda_{\text{QCD}}$

The PDFs $f^A_i(x, Q^2)$ are universal, process independent, and obey the DGLAP equations

\[
Q^2 \frac{\partial f^A_i}{\partial Q^2} = \sum_j P_{ij} \otimes f^A_j
\]

...this is the framework which every PDF analysis and application relies on and tests!
Global analysis – a multi-experiment–multi-observable fit

Multi-observable fit needed to constrain individual flavours, minimise:

\[ \chi_\text{tot}^2 = \sum_k \left( \frac{D_k - T_k}{C_k^{-1}} \right)^T C_k^{-1} \left( \frac{D_k - T_k}{C_k^{-1}} \right) \]

Correlations important!

Experimental data in CT18 PDF analysis

\[ N_{\text{data}} = 3681 \]

\[ \chi_\text{tot}^2 / N_{\text{data}} = 1.17 \]
Experimental data in CT18 PDF analysis

Fixed-target DIS and DY important in setting the large-\(x\) quark distributions (valence/sea and flavour separation)

New data still coming from Fermilab & JLab!

SeaQuest Collaboration, Nature 590 (2021) 561

\[ \chi^2_{\text{tot}} / N_{\text{data}} = 1.17 \]

\[ \sigma^{pd} \approx \frac{1}{2} \left[ 1 + \frac{d(x_{\text{target}})}{\bar{u}(x_{\text{target}})} \right] \]
Experimental data in CT18 PDF analysis

Collider DIS from HERA with large $x$, $Q^2$
lever arm $\rightarrow$ gluons through DGLAP


Part I: Proton PDFs
Global analysis – a multi-experiment–multi-observable fit

Experimental data in CT18 PDF analysis

Hadron colliders give access to new processes \( \rightarrow W^{\pm}, Z, \) jets, \( tt \ldots \)

19.7 fb\(^{-1}\) (8 TeV)

NLOJET++ (NLO\@EW\@NP)
nPDF 3.0
\( \mu = p_{T, \text{max}} 0.3 y^{*} \)
anti-\( k_t \) \( R = 0.7 \)

\[ N_{\text{data}} = 3681 \]
\[ \chi^2_{\text{tot}}/N_{\text{data}} = 1.17 \]
Jets important for constraining large-$x$ gluons
see e.g. Ball et al., arXiv:2109.02653

NNLO the new standard

Nonperturbative and electroweak corrections important at small and large $p_T$, respectively

NNLO improves fit quality particularly for LHC data
see e.g. Bailey et al., Eur. Phys. J. C 81 (2021) 341
LHC jets at NNLO in proton-PDF fits


5.2.3 Comparison to other PDF sets

Quark masses, are expected to be very small, since the dependence on the charm mass is almost entirely...c. l. and one-sigma uncertainties.

Figure 5.4. Comparison between the LO, NLO and NNLO NNPDF4.0 PDFs. The up, antiup, charm and gluon are shown at Q = 100 GeV. All results are normalized to the central value of the NNLO set. Solid and dashed bands correspond respectively to 68% c. l. and one-sigma uncertainties.

Table 5.6. Note that there are substantial di...w_1 and w_2, respectively

NNLO improves fit quality particularly for LHC data

see e.g. Bailey et al., Eur. Phys. J. C 81 (2021) 341

<table>
<thead>
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<th>Dataset</th>
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Jets important for constraining large-\( x \) gluons

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NNLO the new standard


Nonperturbative and electroweak corrections important at small and large \( p_T \), respectively

NNLO is achieved with an improved description of hadron jet production.

NNLO enables the inclusion of nonperturbative and electroweak corrections for the first time.
Proton strangeness from $\nu A$ DIS vs. LHC EW data

$K_s = \frac{\int_0^1 dx [s(x,Q^2)+\bar{s}(x,Q^2)]}{\int_0^1 dx [\bar{u}(x,Q^2)+\bar{d}(x,Q^2)]}$

Table 6.2: The CC neutrino DIS measurements used in recent determinations of proton and nuclear PDFs.

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Proton-PDF fits traditionally include neutrino-nucleus DIS for improved strange-quark constraints $\rightarrow$ suppressed strangeness

Complementary data from ATLAS EW-boson production confronts this view with preference for unsuppressed strange


Simultaneous fit feasible w/ NNLO $c$-quark mass corrections

Ball et al., arXiv:2109.02653

\[ K_s = \frac{\int_0^1 dx [s(x,Q^2)+\bar{s}(x,Q^2)]}{\int_0^1 dx [\bar{u}(x,Q^2)+\bar{d}(x,Q^2)]} \]
Nuclear uncertainties in proton-PDF fits

Nuclear effects can impact the proton-PDF fits!

**NPDF4.0:**
- Different large-$x$ sea-quark behaviour depending on whether the uncertainties from nNPDF2.0 nuclear PDFs were included or not
- Nuclear data found to constrain the proton PDFs even with nuclear uncertainties included

**MSHT20:** take nuclear corrections from DSSZ + additional 3-param. fit

**CT18:** does not report on any use of nuclear corrections

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Ball et al., arXiv:2109.02653
Nuclear PDFs (nPDFs) are fitted with similar global analyses as their free-proton counterparts:

- rely only to the QCD collinear factorisation
- model-agnostic way to study the nuclear effects

LHC is extending the $x, Q^2$ reach by orders of magnitude

Highlights in this talk:

- Run 1 dijets, $D^0$s
- Run 2 $W^\pm, Z$
Recent nPDF global fits – all new since QM2019!

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$Q, W$ cut in DIS
$P_T$ cut in $D^0, h$-prod.

- Data points
- Free parameters
- Error analysis
- Free-proton PDFs
- Free-proton corr.
- HQ treatment
- Indep. flavours

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## Recent nPDF global fits – all new since QM2019!

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Reference:

- KSASG20: NLO & NNLO
- nCTEQ15WZSIH: NLO
- TUJU21: NLO & NNLO
- EPPS21: NLO
- nNNPDF3.0: NLO
Dijets in EPPS21 and nNNPDF3.0


Eskola, PP, Paukkunen, Salgado, arXiv:2112.12462

Abdul Khalek et al., arXiv:2201.12363

Drastic reduction in the nPDF uncertainties!

→ Important constraints for the nuclear gluons!

Both EPPS21 and nNNPDF3.0 find difficulties in reproducing the most forward data points

→ missing data correlations important?
→ NNLO? non-pert. effects?
Drastic reduction in the nPDF uncertainties!

→ Important constraints for the nuclear gluons!

**Eskola, Helenius, PP, Paukkunen, JHEP 05 (2020) 037**
**Eskola, PP, Paukkunen, Salgado, arXiv:2112.12462**
**Abdul Khalek et al., arXiv:2201.12363**

nNNPDF3.0 with POWHEG+PYTHIA finds a large scale uncertainty → fit only forward data not seen in the S-ACOT-\(m_T\) GM-VFNS used in EPPS21

**Helenius & Paukkunen, JHEP 05 (2018) 196**
**Eskola, Helenius, PP, Paukkunen, JHEP 05 (2020) 037**
Complementary gluon constraints from $\pi^0$, $\pi^\pm$, $K^\pm$ production

*Fragmentation Functions* partially cancel in nuclear ratios

nCTEQ15WZSIH fits to the data from PHENIX, STAR and ALICE with a cut at $p_T > 3$ GeV

EW bosons important probes of flavour separation

- $\bar{u}d (\bar{c}s) \rightarrow W^+$
- $\bar{u}d (\bar{c}s) \rightarrow W^-$

Small-$x$, high-$Q^2$ quarks and gluons correlated by DGLAP evolution → sensitivity to gluons

nCTEQ15WZSIH, TUJU21 and nNNPDF3.0 fit to absolute cross sections

EPPS21 uses nuclear-modification ratios to cancel proton-PDF uncertainties

Z bosons in pPb at 8.16 TeV

New Run 2 data from CMS

- nNNPDF3.0 include both low-mass and on-peak data
- $R_{pPb}$ studied in EPPS21 → not included in the final fit

Both EPPS21 and nNNPDF3.0 observe some tension between the data and fit

- abrupt change in the shape at midrapidity
- NNLO to cure for the low-mass data?

Abdul Khalek et al., arXiv:2201.12363
High-\(x\) DIS – JLab Hall-C and CLAS

DIS in the “transition region” \(W \gtrsim 1.7\) GeV just above the resonance-dominated one

Target-mass corrections important!

Deuterium and higher-twist corrections can improve the fit


but are not necessary to describe the data


Eskola, PP, Paukkunen, Salgado, arXiv:2112.12462

Comparing nuclear and proton PDFs – \( u \) and \( d \)

- EPPS21 NLO, 90% CL errors
- CT18A NLO, 90% CL errors

\[
\frac{1}{208} x f^P_l(x, Q^2 = 10 \text{ GeV}^2)
\]

\[
x f^P_l(x, Q^2 = 10 \text{ GeV}^2)
\]

\[
R^P_l = \frac{f^P_l}{Zf^p_l + Nf^p_n}
\]

\( R^P_l \approx u \approx d \)
Comparing nuclear and proton PDFs – $u$ and $d$

EPPS21 NLO, 90% CL errors

CT18A NLO, 90% CL errors

$R_{i}^{Pb} = \frac{f_{i}^{Pb}}{Z f_{i}^{p} + N f_{i}^{n}}$

Fermi motion
Comparing nuclear and proton PDFs – $u$ and $d$

\[ \frac{1}{208} x f_{i}^{Pb}(x, Q^2 = 10 \text{ GeV}^2) \]

**EPPS21 NLO, 90% CL errors**

**CT18A NLO, 90% CL errors**

\[ R_{i}^{Pb} = \frac{f_{i}^{Pb}}{Z f_{i}^{P} + N f_{i}^{n}} \]

- Fermi motion
- EMC effect

$u \approx d$
Comparing nuclear and proton PDFs – $u$ and $d$

$R_{i}^{Pb} = \frac{f_{i}^{Pb}}{Zf_{i}^{p}+Nf_{i}^{n}}$

- Fermi motion
- antishadowing
- EMC effect

$\frac{1}{208}x f_{i}^{Pb}(x, Q^2 = 10 \text{ GeV}^2)$

$\frac{1}{208}x f_{i}^{p}(x, Q^2 = 10 \text{ GeV}^2)$
Comparing nuclear and proton PDFs – $u$ and $d$

$R_{i}^{Pb} = \frac{f_{i}^{Pb}}{Z f_{i}^{p} + N f_{i}^{n}}$

- Fermi motion
- antishadowing
- EMC effect
- shadowing

$\frac{1}{208} x f_{i}^{Pb}(x, Q^{2} = 10 \text{ GeV}^{2})$

$xf_{i}^{Pb}(x, Q^{2} = 10 \text{ GeV}^{2})$

CT18A NLO, 90% CL errors

EPPS21 NLO, 90% CL errors
Comparing nuclear and proton PDFs – $\bar{u}$ and $\bar{d}$

\[ \frac{1}{208} x f_{i}^{Pb}(x, Q^2 = 10 \text{ GeV}^2) \]

\[ R_{i}^{Pb} = \frac{f_{i}^{Pb}}{Z f_{i}^{p} + N f_{i}^{n}} \]

\[ \bar{u} \approx \bar{d} \]
Comparing nuclear and proton PDFs – $s$ and $c$
Comparing nuclear and proton PDFs – glue

\[ \frac{1}{208} x f_i^{Pb} (x, Q^2 = 10 \text{ GeV}^2) \]

\[ x f_i^p (x, Q^2 = 10 \text{ GeV}^2) \]

\[ R_i^{Pb} = \frac{f_i^{Pb}}{Z f_i^p + N f_i^n} \]
Comparing nuclear and proton PDFs – glue

EPPS21 NLO, 90% CL errors

CT18A NLO, 90% CL errors

$R_{i}^{Pb} = \frac{f_{i}^{Pb}}{Zf_{i}^{p} + Nf_{i}^{n}}$

antishadowing!

shadowing!
nPDF comparison – glue

\[ R_{Pb} = \frac{f_{Pb}^g}{Z f_{P}^g + N f_{n}^g} \]

EPPS21:
- incl.-$h^\text{RHIC}$
- $D^{\text{fwd}}_\text{bwd}$
- jets
- $W, Z$
nPDF comparison – glue

\[ R_{gb}^{Pb} = \frac{f_{gPb}^{Pb}}{Z f_{gPb}^{Pb} + N f_{gPb}^{n}} \]

EPPS21: incl.-h\(^{RHIC}\)

nNNPDF3.0:

\[ \text{D}_{0fwd}^{\text{jets}} \quad \text{W,Z} \]
nPDF comparison – glue

$R^P_g = \frac{f^g_{Pb}}{Z f^p + N f^n_g}$

EPPS21: incl.-$h^{RHIC}$

nNNPDF3.0: $D^{0\text{fwd}}_{\text{bwd}}$ jets $W,Z$

nCTEQ15WZSIH: incl.-$h^{RHIC}_{LHC}$

incl.-$h^{RHIC}_{LHC}$
nPDF comparison – glue

\[ R^P_g = \frac{f_g^{Pb}}{f_g^p + N f_g^n} \]

- **EPPS21:** incl.-h$_{RHIC}$
- **nNNPDF3.0:** D$_{0fwd}^{bwd}$ jets W,Z
- **nCTEQ15WZSIH:** incl.-h$_{RHIC}$
- **TUJU21:**
nPDF comparison – glue in oxygen

see also: PP, Phys. Rev. D 105 (2022) L031504

nPDFs a major source of uncertainty in testing small-system energy loss with OO

→ A. Mazeliauskas, Wed 9:40

EPPS21:
nNNPDF3.0:
nCTEQ15WZSIH:

incl.-$h^\text{RHIC}$ D$^{0fwd}_{\text{bwd}}$ jets W,Z

incl.-$h^\text{LHC}$

only dAu and pPb!
Triple-differential dijets in pPb?


Various observable choices possible, e.g. $X_A, X_B, y^*$

measurable!

$$X_B = \sum_{n \in \text{dijet}} \frac{E_{Tn}}{\sqrt{s}} e^{-y_n} \times \text{LO}$$

momentum fraction from the lead side


Triple-differential measurement fixes partonic kinematics at LO

→ powerful test of factorisation and PDFs

Measured in pp at 8 TeV


Should be feasible in pPb with Run 2/3 statistics?

Shen et al., arXiv:2112.11819
New mid-rapidity $\pi^0$ data from PHENIX

Contrary to nPDF expectations, measured “Cronin peak” size follows the ordering $^3\text{He} + \text{Au} < d + \text{Au} < p + \text{Au}$

At high $p_T$ the nPDF predictions overshoot the data, but mind the large normalisation uncertainties

LHCb measurements of $D^0$'s and $\pi^0$'s at 8.16 TeV and charged hadrons at 5.02 TeV in pPb

→ Ó. Boente García, Thu 11:10
→ B. Audurier, Thu 15:00
UPCs in collinear factorisation

First phenomenological implementation of the exclusive $J/\psi$ photoproduction NLO corrections


in ultraperipheral Pb+Pb

→ T. Löytäinen, Thu 12:50

Large scale uncertainty

→ perturbative convergence?
→ cancel with nuclear ratios?

Eskola et al., arXiv:2203.11613

ATLAS inclusive dijet photoproduction measurement now fully unfolded

→ B. J. Gilbert, Tue 16:50

ATLAS-CONF-2022-021

Conclusions and Next Steps

• Photo-nuclear dijet production was measured by ATLAS in 5.02 TeV Pb+Pb collisions with 2018 data.
• Particle-Flow jets allow the measurement to be extended even lower in jet $p_T$ while maintaining systematic control.
• This measurement has been fully unfolded for detector response for the first time.
• The overall normalization of the cross-section is well-predicted by theoretical comparisons.
• A theoretical model of nuclear breakup is necessary to understand the total cross-section.
• This study is currently sensitive to nuclear PDF effects with a precision of up to 10% in some bins.
• Once final studies of low-$\mu$ jet response in ATLAS can be completed, substantial gains in systematic control can be achieved.
• These results are connected to early physics goals for the EIC.
Ample progress in incorporating new data in global PDF fits:

- LHC pp data precision requires NNLO proton-PDF fit
- LHC pPb data put unprecedented constraints on the gluon nPDF
- Ongoing work to understand the (cross)correlations between proton and nuclear PDF analyses

The future is bright!

- Both collider and fixed-target experiments keep providing new data
- LHC Run 3 just around the corner
- High-lumi LHC and EIC in the “near” sight

Many exiting experimental results:

Dijet photoproduction in 5 TeV PbPb at ATLAS  
→ B. J. Gilbert, Tue 16:50

$\pi^0$ in 8 TeV pPb and $h^{\pm}$ in 5 TeV pPb at LHCb  
→ O. Boente García, Thu 11:10

$D^0$ in 8 TeV pPb at LHCb  
→ B. Audurier, Thu 15:00

$Z$ in 8 TeV pPb and $Z+c$ in 13 TeV pp at LHCb  
→ T. Li, Thu 16:50

$W^{\pm}$ in 13 TeV pp, 8 TeV pPb and 5 TeV PbPb at ALICE  
→ S. Sakai, Thu 17:10

$Z/\gamma^*$ in 8 TeV pPb and 5 TeV PbPb at CMS  
→ A. Baty, Thu 17:30
Collider DIS – HERA I+II combined data

Completion of the H1+ZEUS inclusive and heavy-quark DIS combination work

\[ \sigma_{\text{r,NC}} \times 2^i \]


\[ \rightarrow \text{coherent data sets with reduced systematic uncertainties} \]

Backbone of any modern proton-PDF analysis

\[ \bullet \text{ Both neutral and charged current} \]

\[ \rightarrow \text{quark flavour separation} \]

\[ \bullet \text{ Large } Q^2 \text{ lever arm} \]

\[ \rightarrow \text{ constrain glue through DGLAP} \]

\[ \bullet \text{ Hints of small-} x \text{ BFKL dynamics / need for resummation?} \]

\[ \text{Ball et al., Eur. Phys. J. C 78 (2018) 321} \]

\[ \text{Abdolmaleki et al., Eur. Phys. J. C 78 (2018) 621} \]

EIC will provide the same for nPDF fits!
Fixed-target DY and DIS – Fermilab SeaQuest and JLab Marathon

SeaQuest Collaboration, Nature 590 (2021) 561

MARATHON Collaboration, arXiv:2104.05850

SeaQuest data favours proton $\bar{d} > \bar{u}$ without a large-$x$ reversal

$$\frac{\sigma^{pd}}{2\sigma^{pp}} \bigg|_{x_{\text{beam}} \gg x_{\text{target}}} \approx \frac{1}{2} \left[ 1 + \frac{f^p_d(x_{\text{target}})}{f^p_u(x_{\text{target}})} \right]$$

effect: neglect deuteron corrections and assume isospin symmetry: $f^n_u = f^p_d$

First DIS data on mirror nuclei!

Idea:

$$2\mathcal{R}_{ht} - \frac{\sigma_h}{\sigma_t} \approx \frac{F^h_n}{F^p_n} \approx \frac{1}{4} + \frac{f^p_d(x)}{f^p_u(x)}$$

$\mathcal{R}_{ht} = \frac{F^h_d/(2F^p_d + F^h_n)}{F^p_d/(2F^p_n + 2F^p_d)} \approx 1$ from models
EW bosons give access to flavours that are otherwise poorly constrained $\rightarrow$ strange and charm

Associated production with a heavy quark to enhance contribution from certain flavours

- $W^{\pm} + c \rightarrow$ strangeness
- $Z + c \rightarrow$ intrinsic charm

Differences in the resulting strange across recent global analyses

Perturbative vs. fitted charm makes a big difference

Ball et al., arXiv:2109.02653

LHC EW data in proton-PDF fits

EW bosons give access to flavours that are otherwise poorly constrained → strange and charm

Associated production with a heavy quark to enhance contribution from certain flavours

- $W^\pm + c \rightarrow$ strangeness
- $Z + c \rightarrow$ intrinsic charm

Differences in the resulting strange across recent global analyses

Perturbative vs. fitted charm makes a big difference

Ball et al., arXiv:2109.02653
**Perturbative stability and missing higher orders**

**NNLO improves fit quality particularly for LHC data**

*see e.g. Bailey et al., Eur. Phys. J. C 81 (2021) 341*

**Ongoing work to include theoretical uncertainties from missing higher orders in the fits**

- Use e.g. a *theory covariance matrix* evaluated from scale variations
  

→ **Need a way to consistently propagate these into the predictions**


**χ^2** = (D − T)^T (C + S)^−1 (D − T)

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Mitigating free-proton PDF uncertainty

Absolute pPb cross sections sensitive to proton-PDF uncertainties!

Difficult to disentangle nuclear modifications from free-proton d.o.f.s

nCTEQ15WZSIH, TUJU21 and nNNPDF3.0 fit to absolute cross sections

Wherever possible, EPPS21 uses nuclear modification ratios to cancel the free-proton-PDF and scale uncertainties

↓ Cancel proton-PDF uncertainty ↓
EPPS21: fit nuclear modifications for each CT18A error set separately → subleading effect

nNNPDF3.0 uses similar approach in Monte Carlo framework
Dijets in pPb at 5.02 TeV

Ratio of ratios: \[ R_{\text{pPb}}^{\text{norm.}} = \frac{d^2\sigma_{\text{pPb}}}{d\sigma_{\text{pPb}} / dp_T^{\text{ave}} d\eta_{\text{dijet}}} \bigg/ \frac{d^2\sigma_{\text{pp}}}{d\sigma_{\text{pp}} / dp_T^{\text{ave}} d\eta_{\text{dijet}}} \]


Double ratio convenient for:

- Cancellation of hadronization and luminosity uncertainties separately for pPb and pp
  \[ \rightarrow \] do not expect strong final-state effects

- Cancellation of free-proton-PDF and scale uncertainties in pPb/pp
  \[ \rightarrow \] direct access to nuclear modifications


Good resolution to gluon nuclear modifications for \( 10^{-3} < x < 0.5 \)
Heavy-flavour production mass schemes

**FFNS**
In *fixed flavour number scheme*, valid at small $p_T$, heavy quarks are produced only at the matrix element level.

Contains $\log(p_T/m)$ and $m/p_T$ terms

**ZM-VFNS**
In *zero-mass variable flavour number scheme*, valid at large $p_T$, heavy quarks are treated as massless particles produced also in ISR/FSR.

Resums $\log(p_T/m)$ but ignores $m/p_T$ terms

**GM-VFNS**
A *general-mass variable flavour number scheme* combines the two by supplementing subtraction terms to prevent double counting of the resummed splittings, valid at all $p_T$.

Resums $\log(p_T/m)$ and includes $m/p_T$ terms in the FFNS matrix elements.

*Important:* includes also *gluon-to-HF fragmentation* – large contribution to the cross section!
Gluon constraints from EIC

EIC will significantly widen the kinematic range of DIS constraints for nPDFs

- Comparing with LHC measurements will put collinear factorization with nuclei to a stringent test

With the $F_L$ extraction capability, EIC provides a clean probe to study small-$x$ gluons

- Good constraining power to well down to $10^{-2}$ in a high-energy scenario

Charm-tagged cross-section measurement can vastly reduce high-$x$ gluon uncertainty

see also: Kelsey et al., Phys.Rev.D 104 (2021) 054002