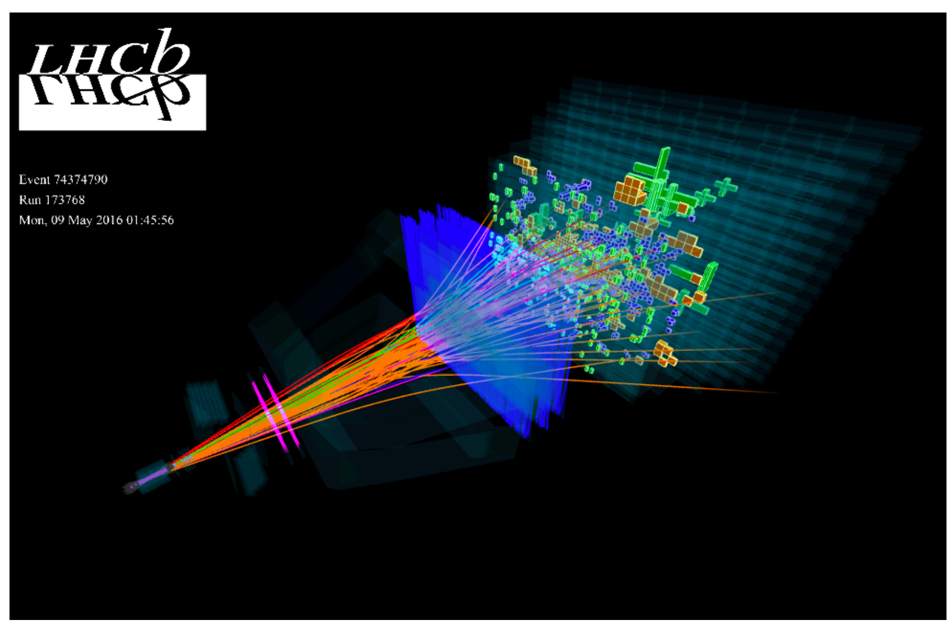
LHCb as a QCD Discovery Experiment

Juan Rojo, VU Amsterdam & Nikhef



LHCb General Meeting

5th April 2022 (Zoom)

LHCb as a QCD Explorer

LHCb as a QCD Machine

Master Formula for **LHC cross-sections:**

$$\sigma_{\mathrm{LHC}}(M,s) \propto \sum_{ij} \int_{M^2}^{s} d\hat{s}\; \mathscr{L}_{ij}(\hat{s},s)\, \widetilde{\sigma}_{ij}(\hat{s},\alpha_s(M))\,, \quad i,j = u,d,s,g,\ldots$$

partonic luminosity (non-perturbative QCD, phenomenological extraction from data)

hard-scattering matrix element (perturbative QCD, evaluate from Feynman diagrams)

$$\mathscr{L}_{ij}(Q,s) = \frac{1}{s}\int_{Q^2/s}^{1} \frac{dx}{x} f_i\left(\frac{Q^2}{sx},Q\right) f_j\left(x,Q\right),$$

proton Parton Distribution Functions (PDFs)

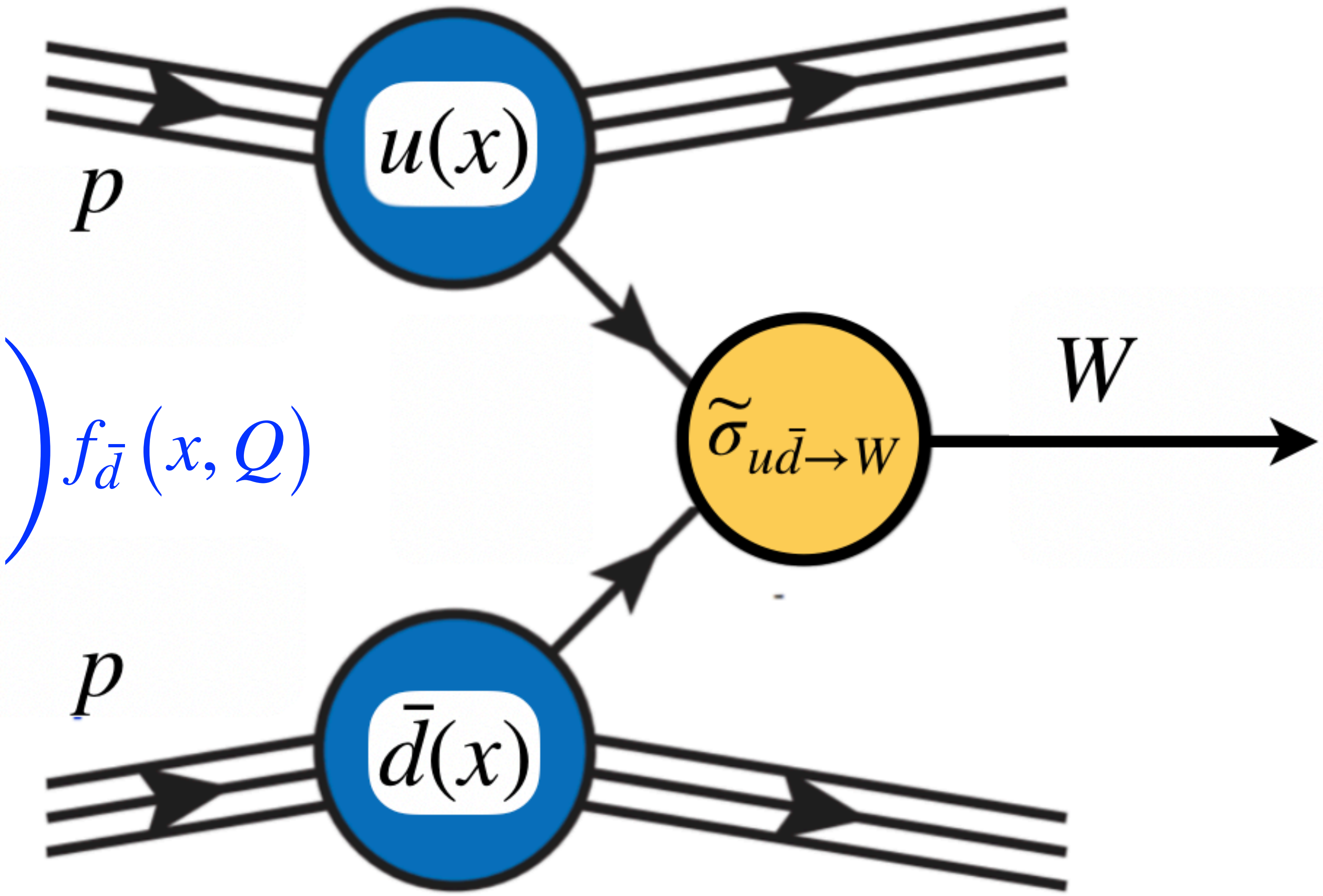
$$f_j\left(x,Q\right)$$

flavour index — *momentum fraction* — *energy scale of partonic scattering*

LHCb as a QCD Machine

$$\sigma_{W^+}(M,s) \propto \int_{M^2}^{s} d\hat{s}\; \mathscr{L}_{u\bar{d}}(\hat{s},s)\, \tilde{\sigma}_{u\bar{d}}(\hat{s},\alpha_s(M)) + \ldots$$

$$\mathscr{L}_{u\bar{d}}(Q,s) = \frac{1}{s}\int_{Q^2/s}^{1} \frac{dx}{x} f_u\left(\frac{Q^2}{sx}, Q\right) f_{\bar{d}}\,(x,Q)$$



Using leading-order kinematics:

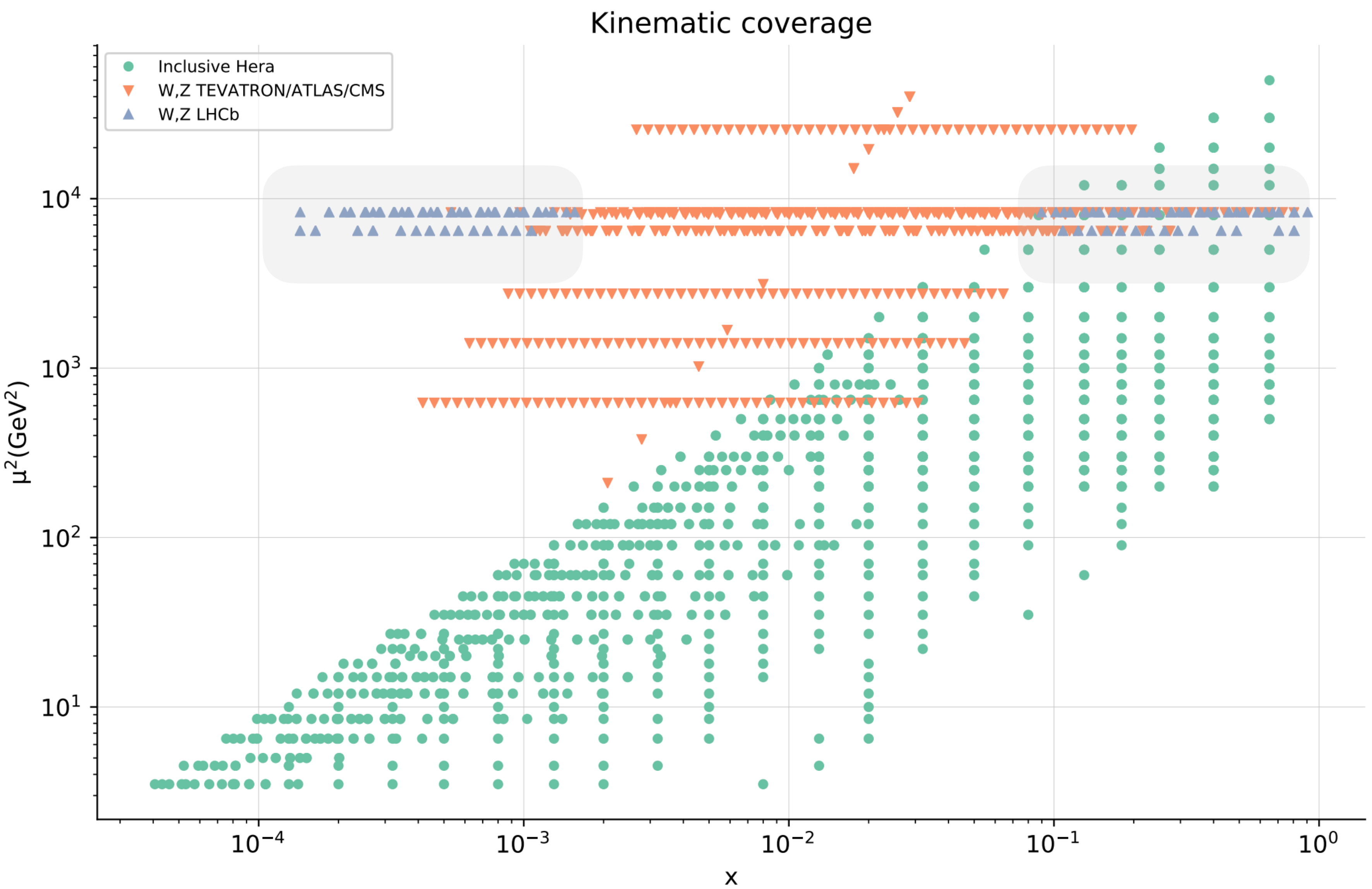
$$x_1 = \frac{M_W}{\sqrt{s}} e^{+y_W}, \quad x_2 = \frac{M_W}{\sqrt{s}} e^{-y_W}$$

forward rapidities probe **small and large *x*** (momentum fractions)

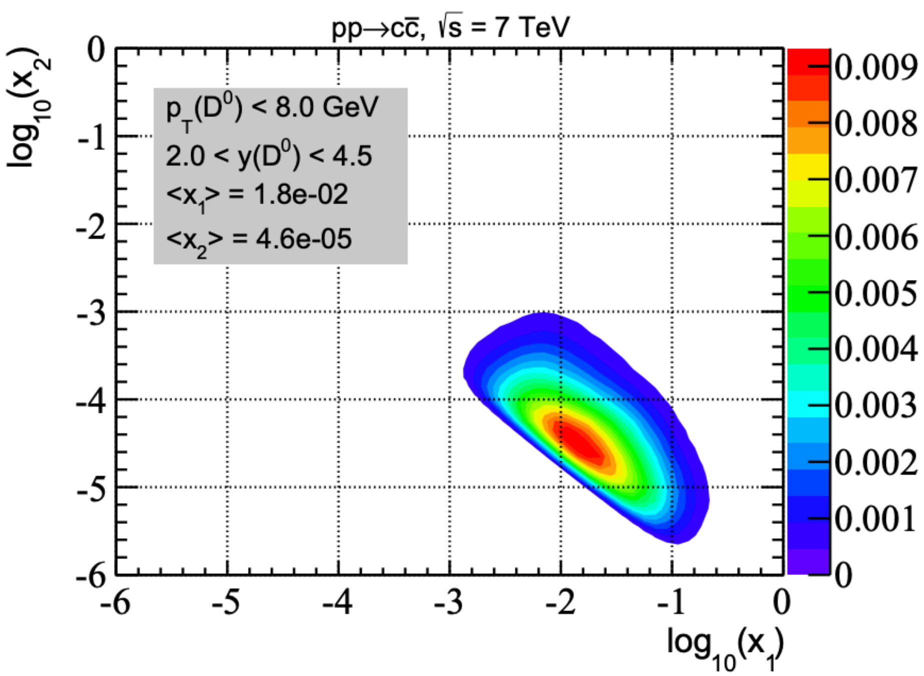
LHCb as a QCD Machine

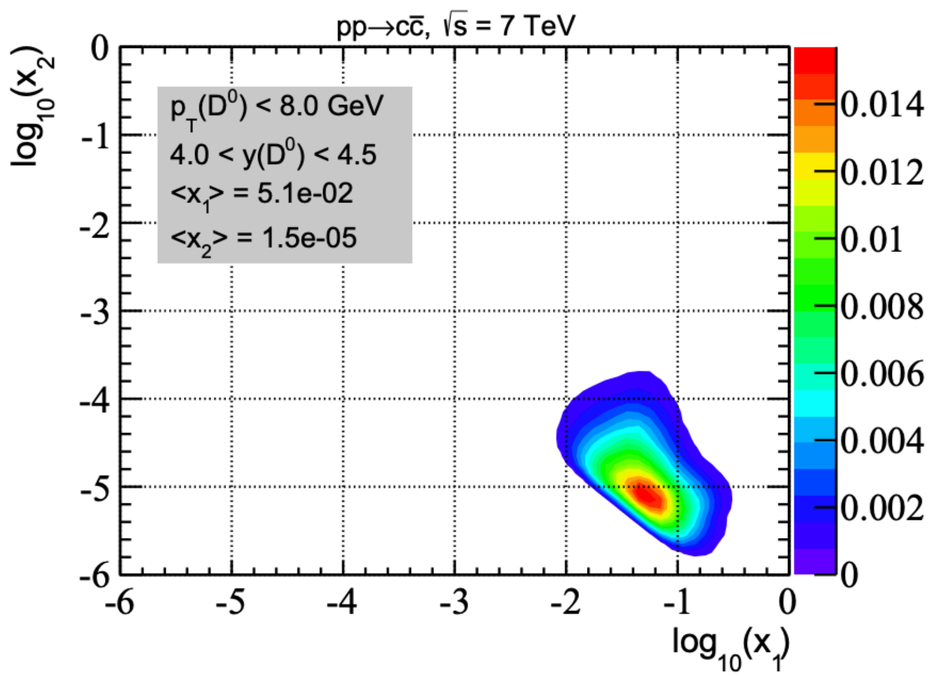
The unique feature of LHCb for QCD measurements is its coverage of a variety of **hard probes in the forward region**: from gauge bosons to D-mesons and top quarks

W, Z production



D-meson production





*Unique sensitivity to **proton structure** at large and small-x!*

LHCb as a QCD Machine

Master Formula for **LHC proton-lead cross-sections:**

$$\sigma^{\mathrm{pPb}}_{\mathrm{LHC}}(M,s) \propto \sum_{ij} \int_{M^2}^{s} d\hat{s}\; \mathcal{L}^{\mathrm{pPb}}_{ij}(\hat{s},s,A)\, \tilde{\sigma}^{\mathrm{pp}}_{ij}(\hat{s},\alpha_s(M))\,, \quad i,j = u,d,s,g,\ldots$$

partonic luminosity (non-perturbative QCD, phenomenological extraction from data)

hard-scattering matrix element (perturbative QCD, evaluate from Feynman diagrams)

$$\mathcal{L}^{\mathrm{pPb}}_{ij}(Q,s),A = \frac{1}{s}\int_{Q^2/s}^{1} \frac{dx}{x} f_i^{(\mathrm{Pb})}\left(\frac{Q^2}{sx},Q,A\right) f_j^{(\mathrm{p})}\left(x,Q\right)$$

lead PDFs

proton PDFs

$$f_j^{(\mathrm{Pb})}\left(x,Q,A\right)$$

flavour index

momentum fraction

energy scale of partonic scattering

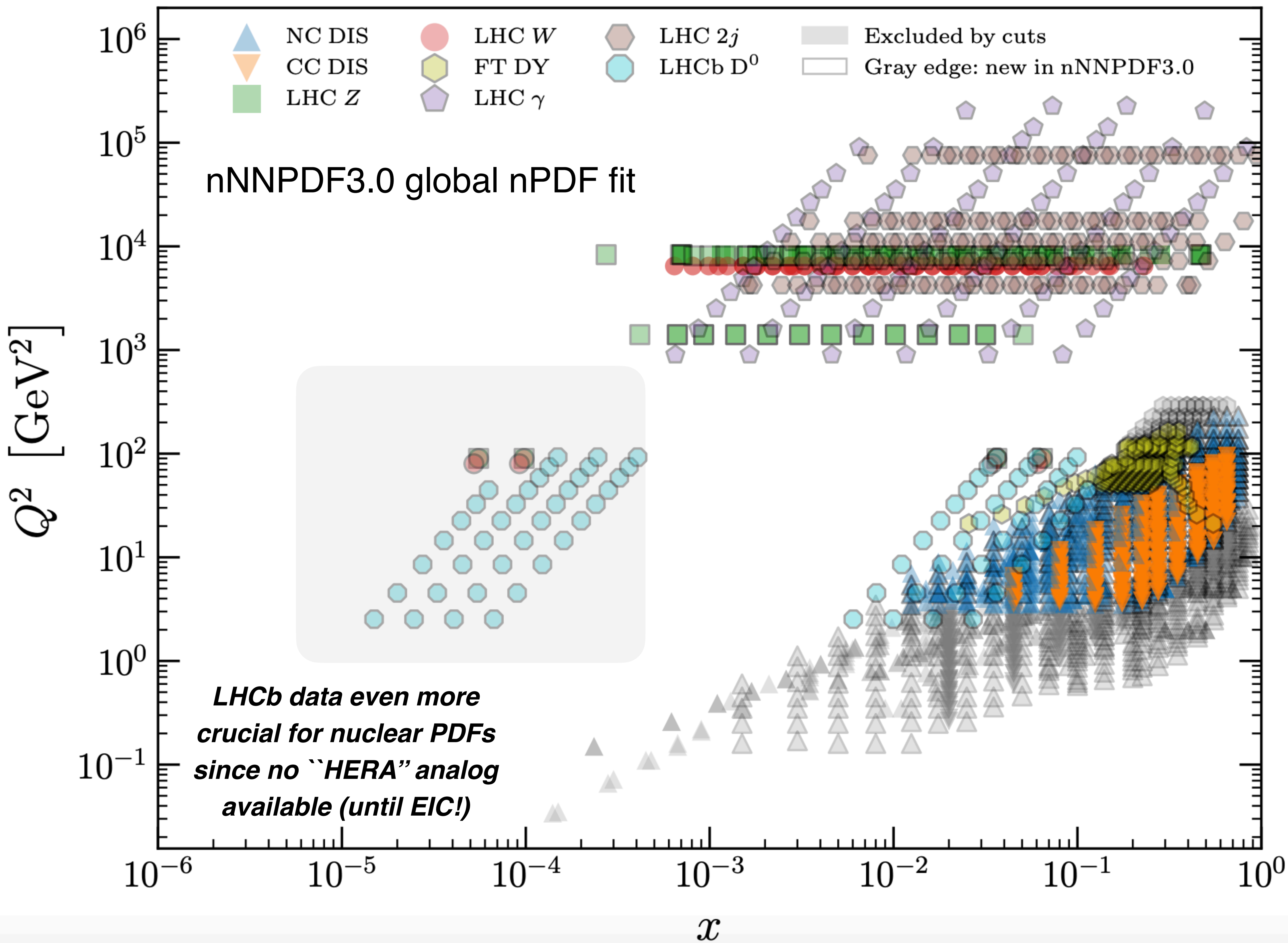
atomic mass number

cold nuclear matter effects

encoded into nuclear PDFs

LHCb as a QCD Machine

Kinematic coverage of **hard probes of nuclear PDFs**



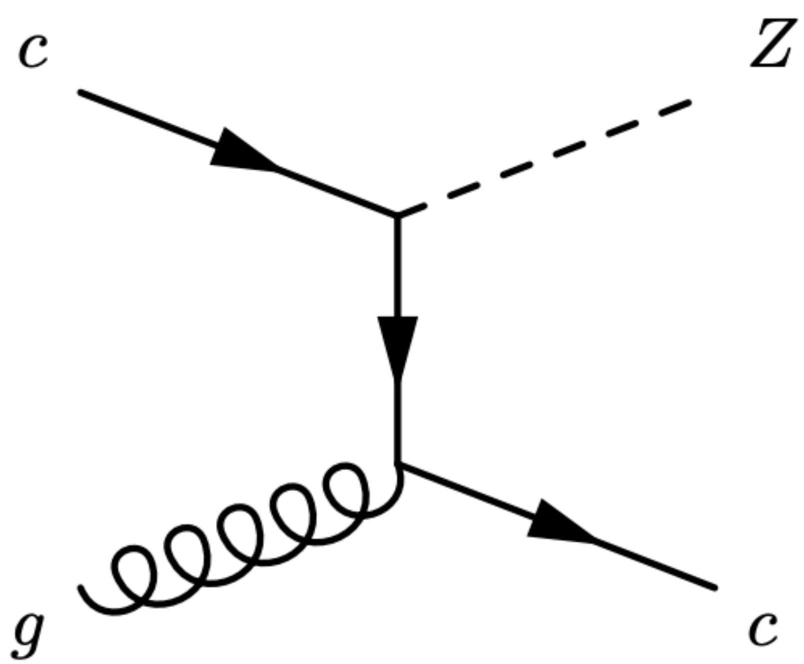
Evidence for intrinsic charm in the proton

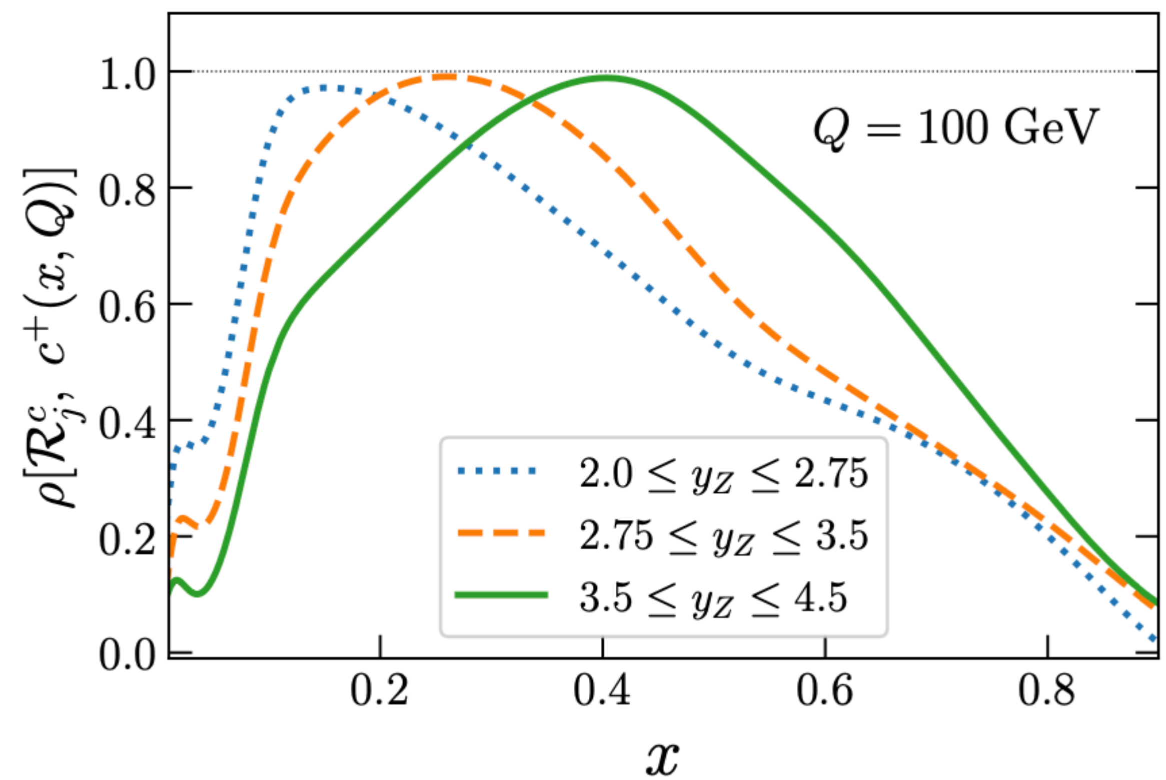
R. D. Ball , A. Candido , J. Cruz-Martinez , S. Forte , T. Giani , F. Hekhorn , K. Kudashkin , G. Magni, ***J. Rojo****,* ***``Charm in the Proton"****, under journal review*

``The simple hydrogen atom nucleus appears to be surprisingly charming"

Z+charm and proton structure

Direct handle on the **charm content of the proton**





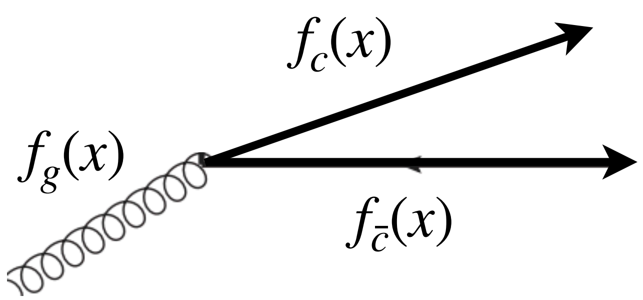
$$\mathcal{R}_j^c(y_Z) \equiv \frac{N(c \text{ tagged jets}; y_Z)}{N(\text{jets}; y_Z)} = \frac{\sigma(pp \to Z + \text{charm jet}; y_Z)}{\sigma(pp \to Z + \text{jet}; y_Z)}$$

Z+charm at forward rapidities (LHCb) sensitive to the **charm PDF up to *x*=0.5**

Why this is a big deal?

Intrinsic charm?

common assumption: the charm PDF is **generated perturbatively** (DGLAP evolution) from radiation off gluons and quarks:



$$f_c^{(n_f)} = 0 \quad \rightarrow \quad f_c^{(n_f+1)} \propto \alpha_s \ln \frac{Q^2}{m_c^2} \left(P_{qg} \otimes f_g^{(n_f+1)} \right) + \mathcal{O}\left(\alpha_s^2\right)$$

3FNS charm — **4FNS charm** — **4FNS gluon** — **``trivial'' charm PDF**

It does not need to be so! An **intrinsic charm component** predicted in many models

THE INTRINSIC CHARM OF THE PROTON

S.J. BRODSKY [1]
Stanford Linear Accelerator Center, Stanford, California 94305, USA

and

P. HOYER, C. PETERSON and N. SAKAI [2]
NORDITA, Copenhagen, Denmark

Received 22 April 1980

Recent data give unexpectedly large cross-sections for charmed particle production at high x_F in hadron collisions. This may imply that the proton has a non-negligible uudc$\bar{c}$ Fock component. The interesting consequences of such are explored.

Valence-like charm PDF predicted, peaked at x=0.4

Since original predictions 42 years ago, extensive searches for intrinsic charm but no unambiguous evidence

Need to **disentangle perturbative** from **intrinsic components** in the charm PDF extracted from data via a phenomenological global PDF determination

Disentangling intrinsic charm

$$c^{(n_f=4)}(x,Q) \simeq c^{(n_f=4)}_{\text{(pert)}}(x,Q) + c^{(n_f=4)}_{\text{(intr)}}(x,Q)$$

Extracted phenomenologically from data

from pQCD evolution and matching

from intrinsic component $c^{(n_f=3)}_{\text{(intr)}}(x) \neq 0$

4FNS Charm PDF constrained by experimental data for $Q > Q_0$

- NNPDF4.0 dataset
- NNLO QCD calculations

QCD evolution

starting point: NNPDF methodology

4FNS Charm PDF parametrised at Q_0

- Deep-learning parametrisation
- Monte Carlo representation of uncertainties

QCD evolution

subtract perturbative component

4FNS to 3FNS transformation

NNLO or N^{3}LO matching conditions

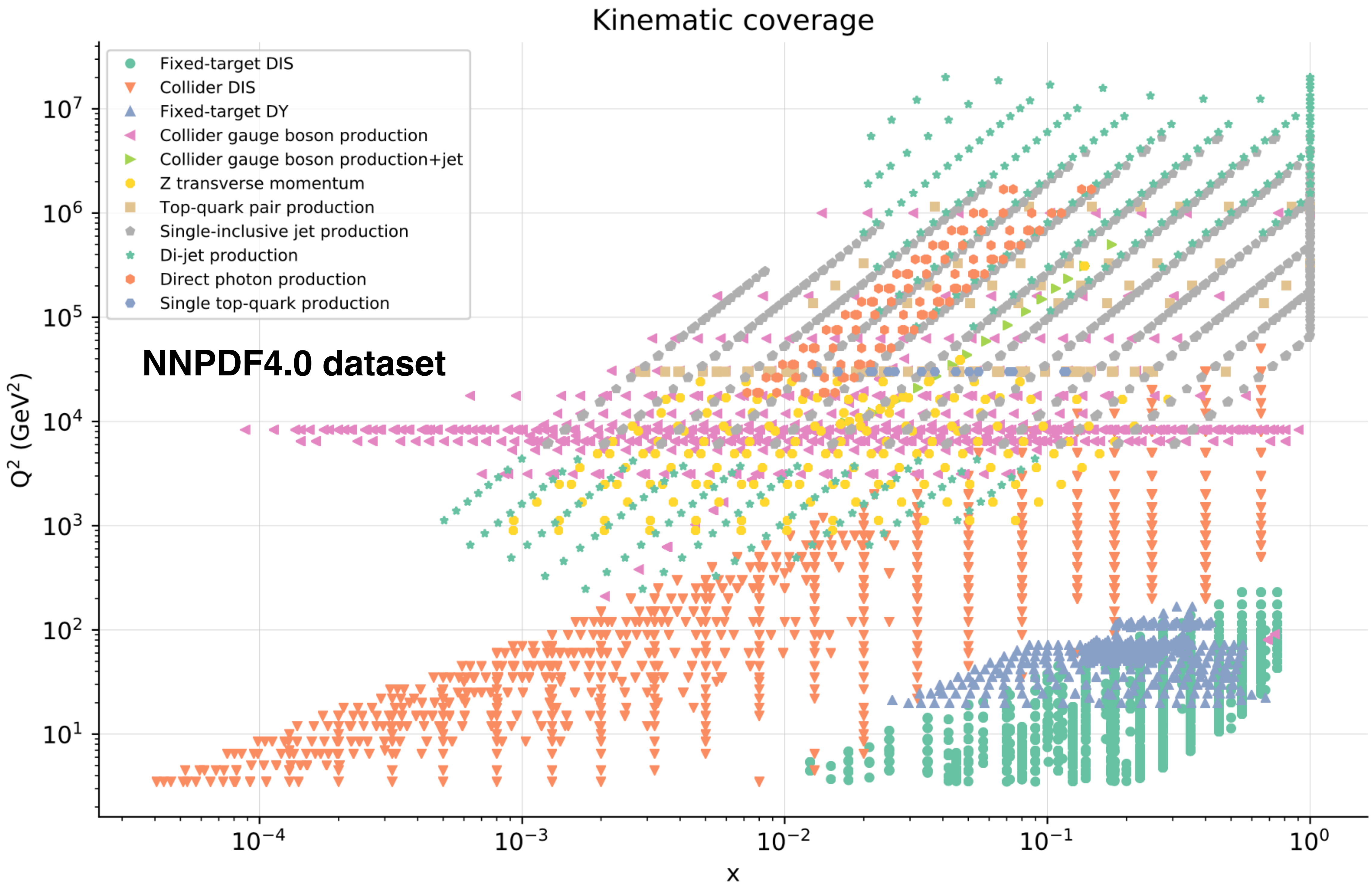
EKO
Evolution Kernel Operators

$$c^{(n_f=3)}(x,Q) = c_{\text{(intr)}}(x)$$

Intrinsic (3FNS) Charm

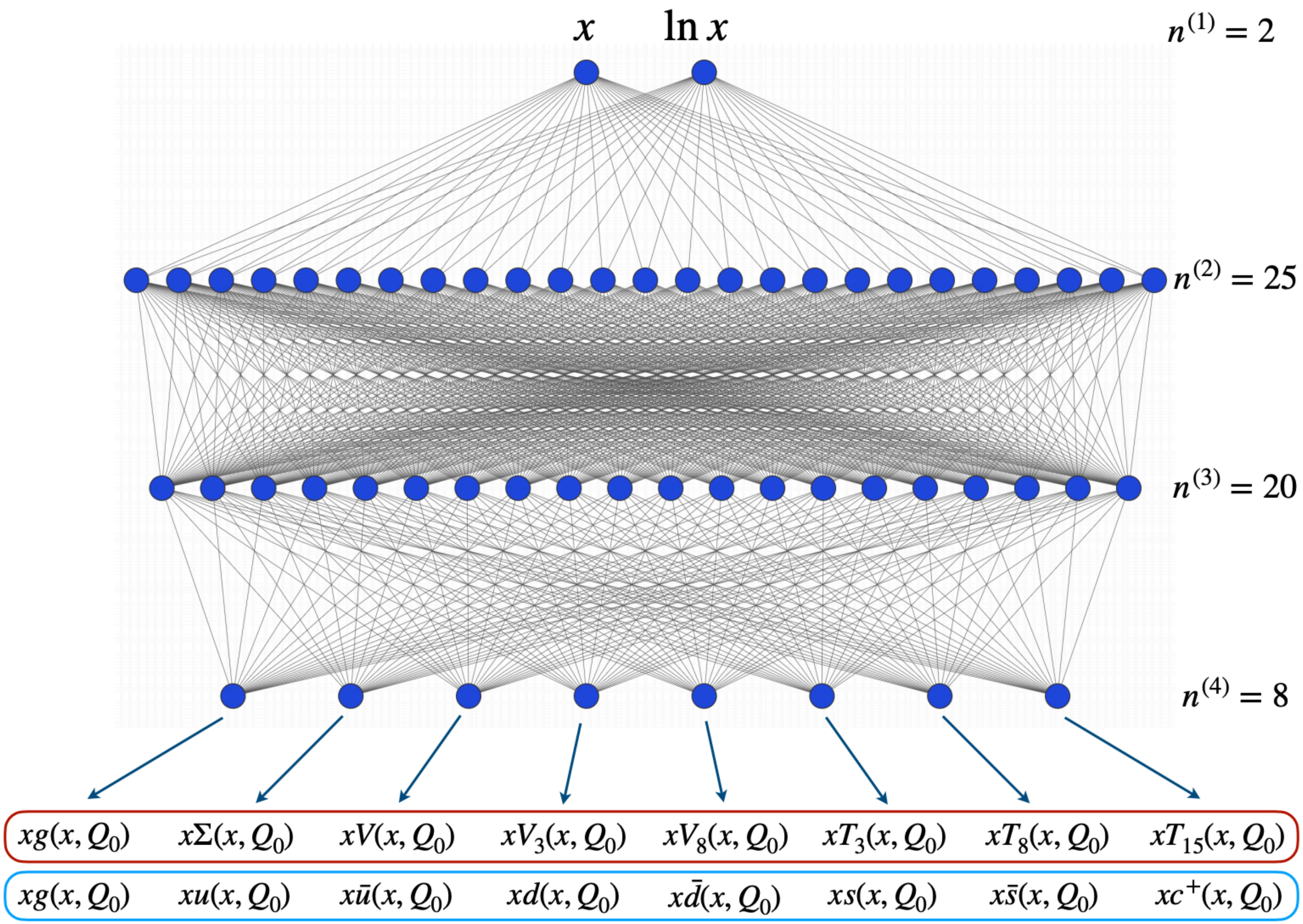
- Scale-independent
- PDF and MHO uncertainties

Disentangling intrinsic charm



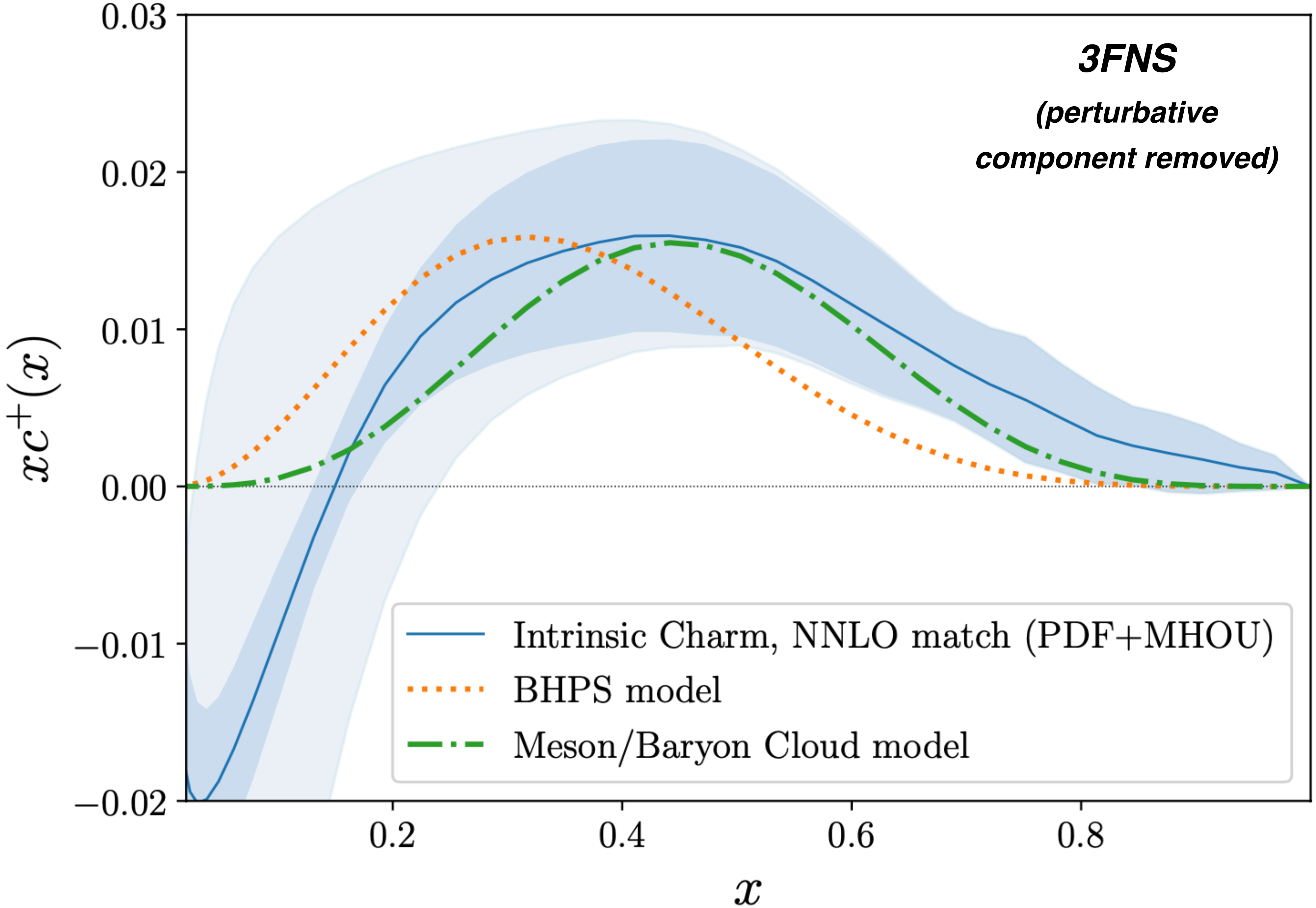
- Global analysis with **4700 data points**
- Indirect sensitivity to charm via inclusive *W,Z* (both CMS/ATLAS and **LHCb**) and fixed target and collider DIS
- LHCb measurements of **Z+charm** not included here

Model-independent fitted charm



- ☑ Charm PDF parametrised with **neural networks** on same footing as light quarks: let data decide whether there is an intrinsic charm component or not
- ☑ Stability with respect to choice of **parametrisation basis** (linear combination) demonstrated

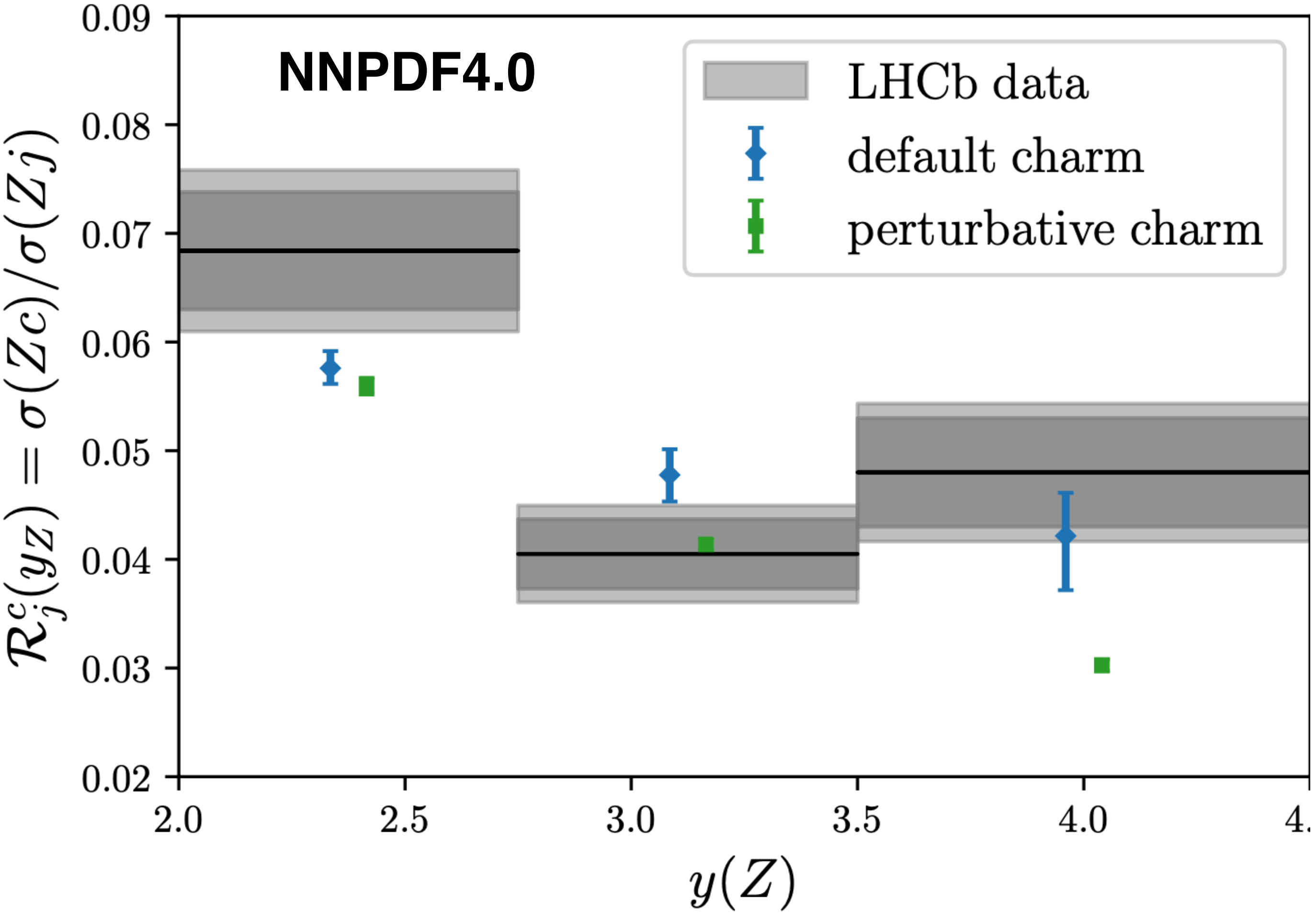
Intrinsic charm!

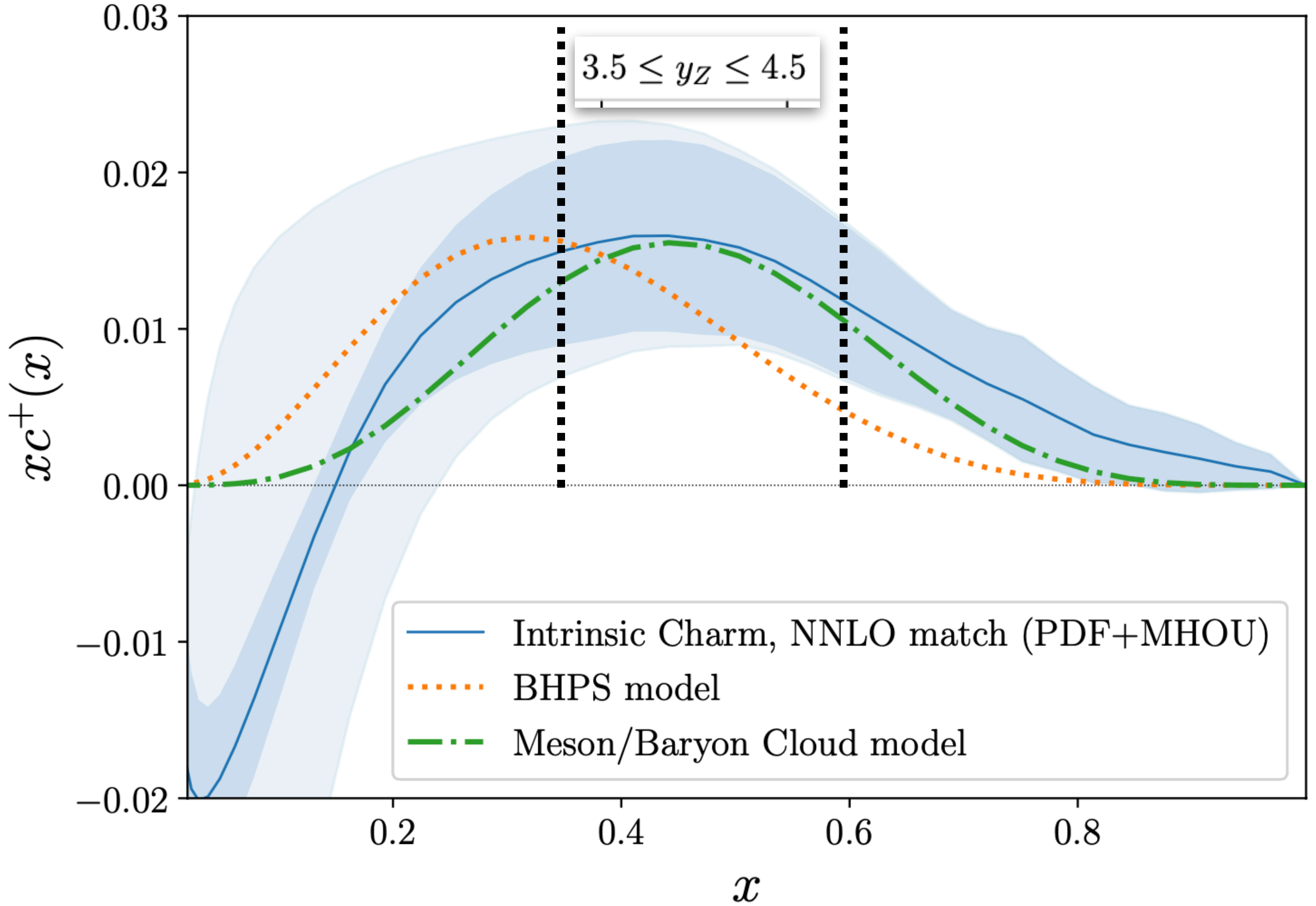


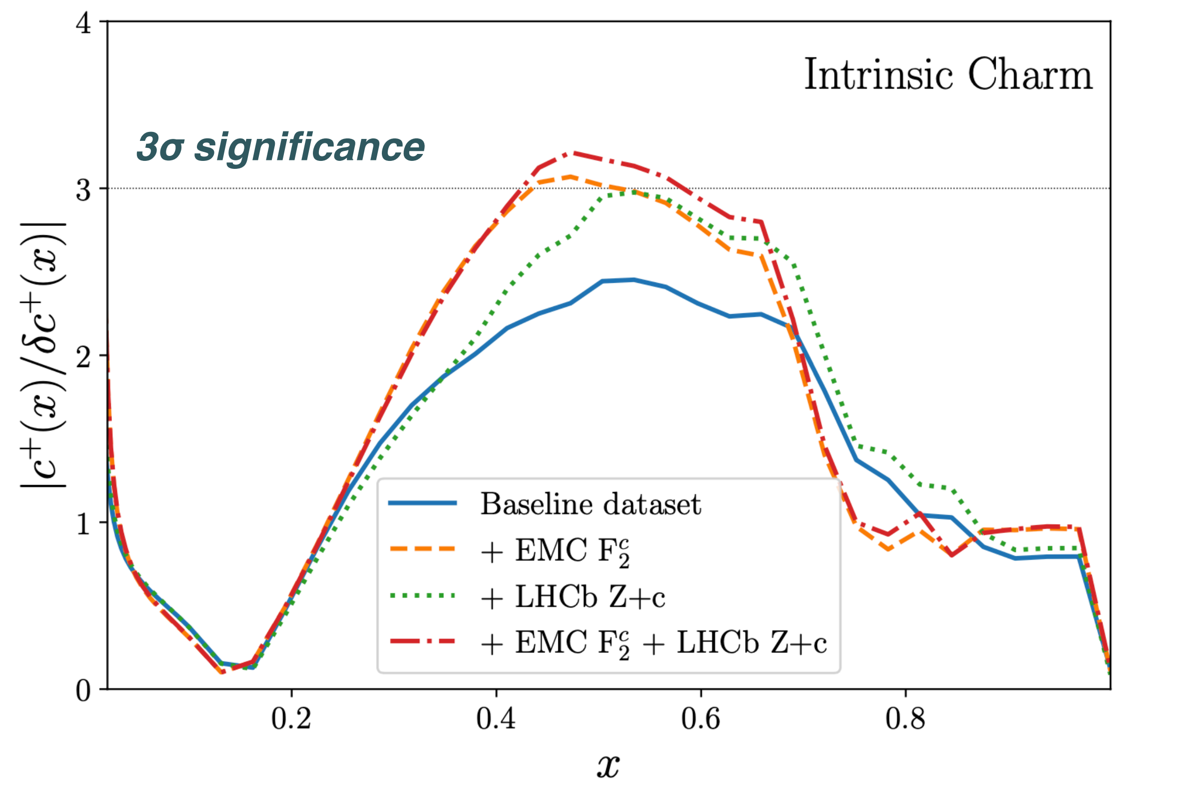
The 3FNS charm PDF displays **non-zero component** peaked at large-*x* **(3σ local significance)** identified with **intrinsic charm**

in excellent agreement with model predictions, specially from the Meson/Baryon Cloud model

Z+charm @ LHCb

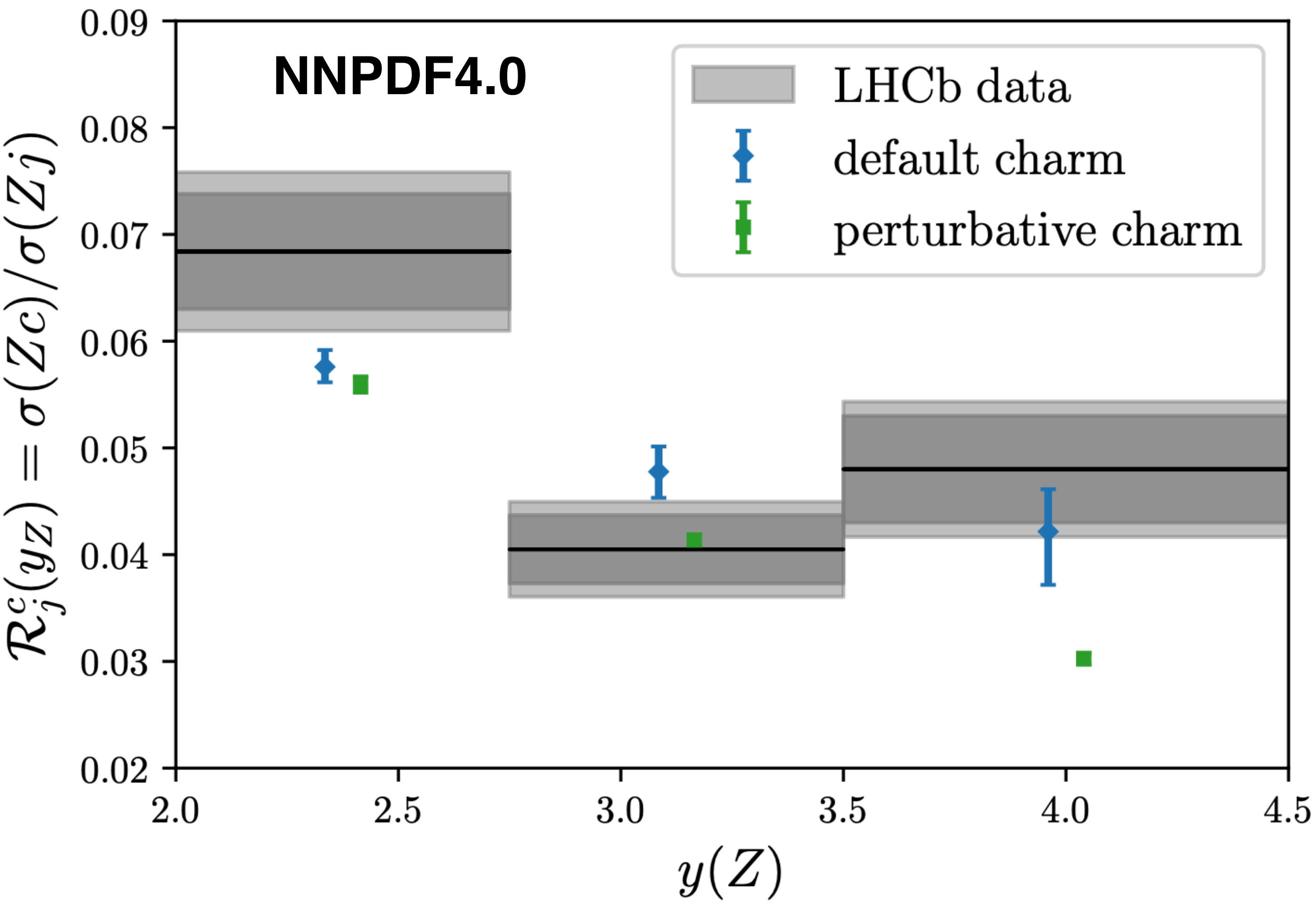


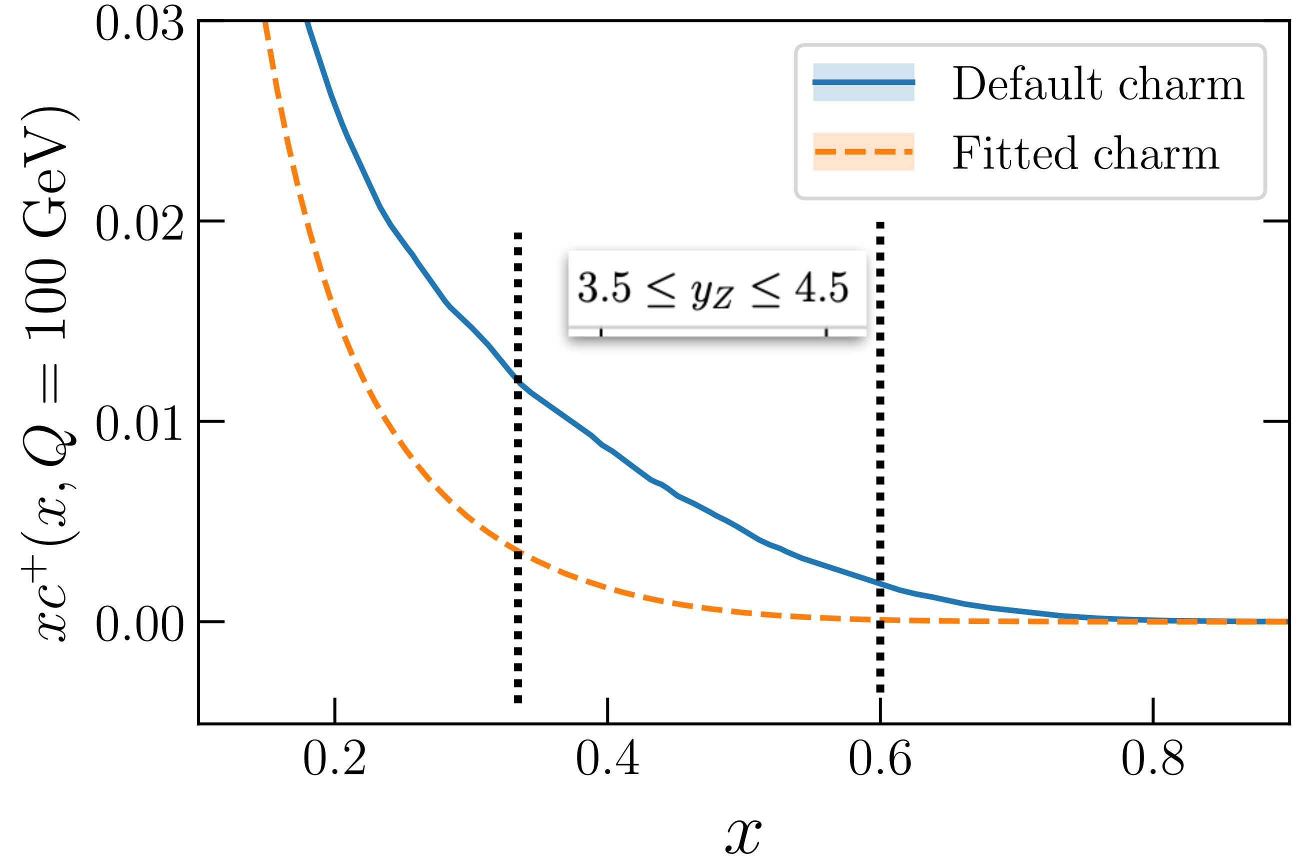


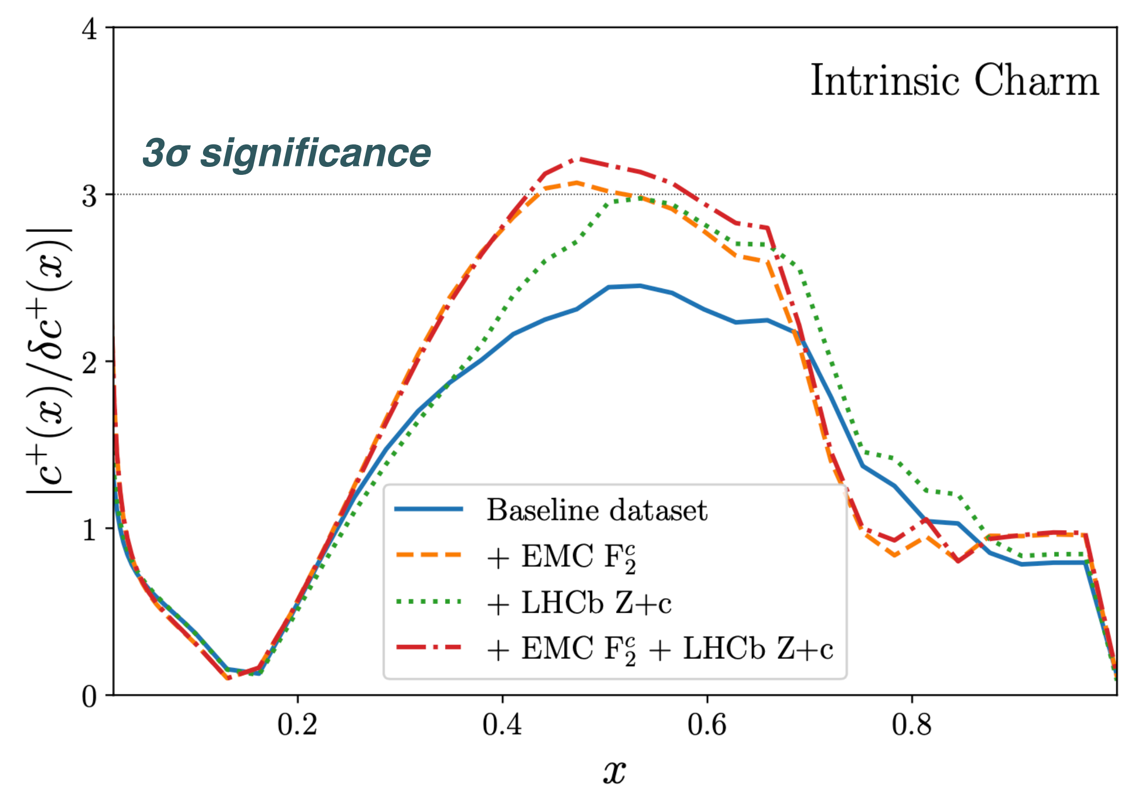


- ☑ A perturbative charm PDF **disagrees** with the LHCb forward Z+charm data
- ☑ LHCb data favour intrinsic charm hypothesis, with IC carrying **0.5% of proton's momentum**
- ☑ Striking consistency between **direct** (Z+c, F_2^c) **and indirect constraints** on the charm PDF

Z+charm @ LHCb







- A perturbative charm PDF **disagrees** with the LHCb forward Z+charm data
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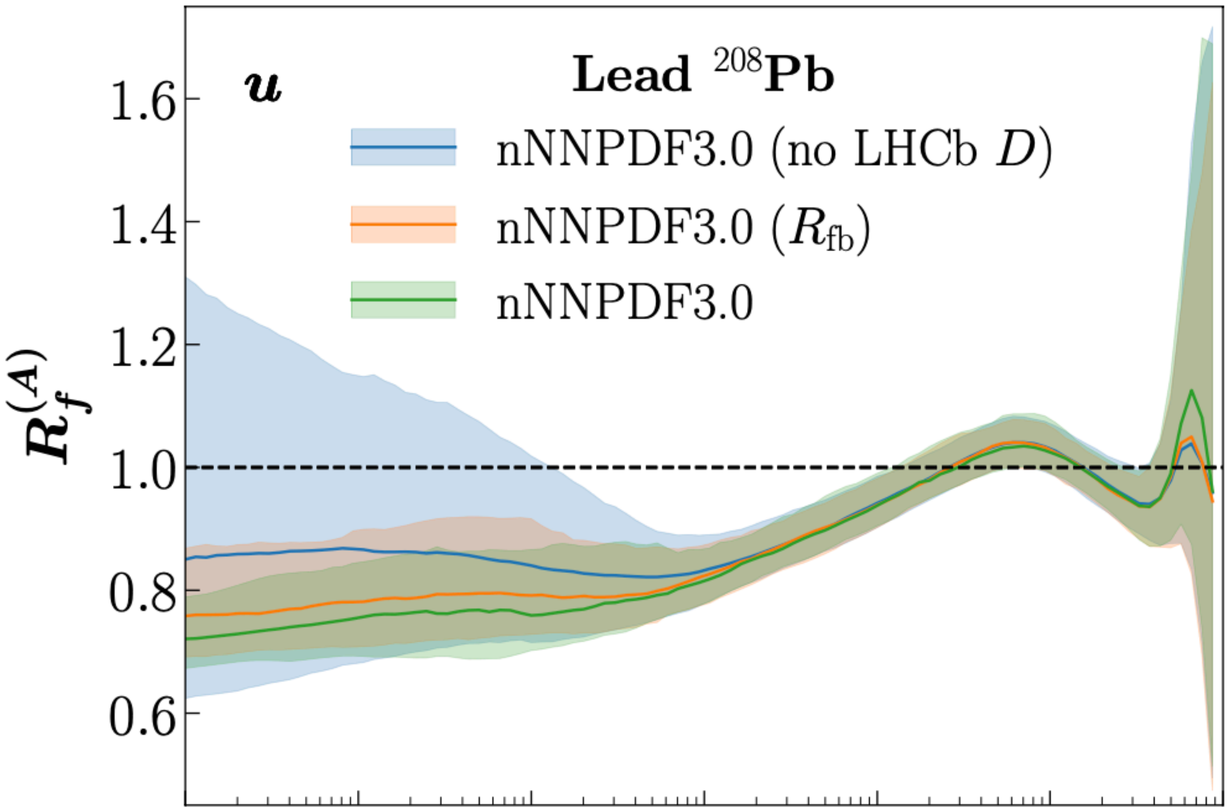
- Striking consistency between **direct** (Z+c, F_2^c) **and indirect constraints** on the charm PDF

Evidence for gluon shadowing in lead

*R. Abdul Khalek, R. Gauld, T. Giani, E. R. Nocera, T. R. Rabemanajara, Juan Rojo, ``**NNPDF3.0: Evidence for a modified partonic structure in heavy nuclei",** arXiv:2201.12363*



Global nuclear PDF determinations

Master Formula for **LHC** **proton-lead** **cross-sections:**

$$\sigma^{\rm pPb}_{\rm LHC}(M,s) \propto \sum_{ij}\int_{M^2}^{s} d\hat{s}\; \mathcal{L}^{\rm pPb}_{ij}(\hat{s},s,A)\;\widetilde{\sigma}^{\rm pp}_{ij}(\hat{s},\alpha_s(M))\,, \quad i,j=u,d,s,g,\ldots$$

partonic luminosity (non-perturbative QCD, phenomenological extraction from data)

hard-scattering matrix element (perturbative QCD, evaluate from Feynman diagrams)

$$\mathcal{L}^{\rm pPb}_{ij}(Q,s),A = \frac{1}{s}\int_{Q^2/s}^{1}\frac{dx}{x} f_i^{\rm (Pb)}\left(\frac{Q^2}{sx},Q,A\right) f_j^{\rm (p)}\left(x,Q\right)$$

$$f_j^{\rm (Pb)}\left(x,Q,A\right)$$

flavour index

momentum fraction

energy scale of partonic scattering

atomic mass number

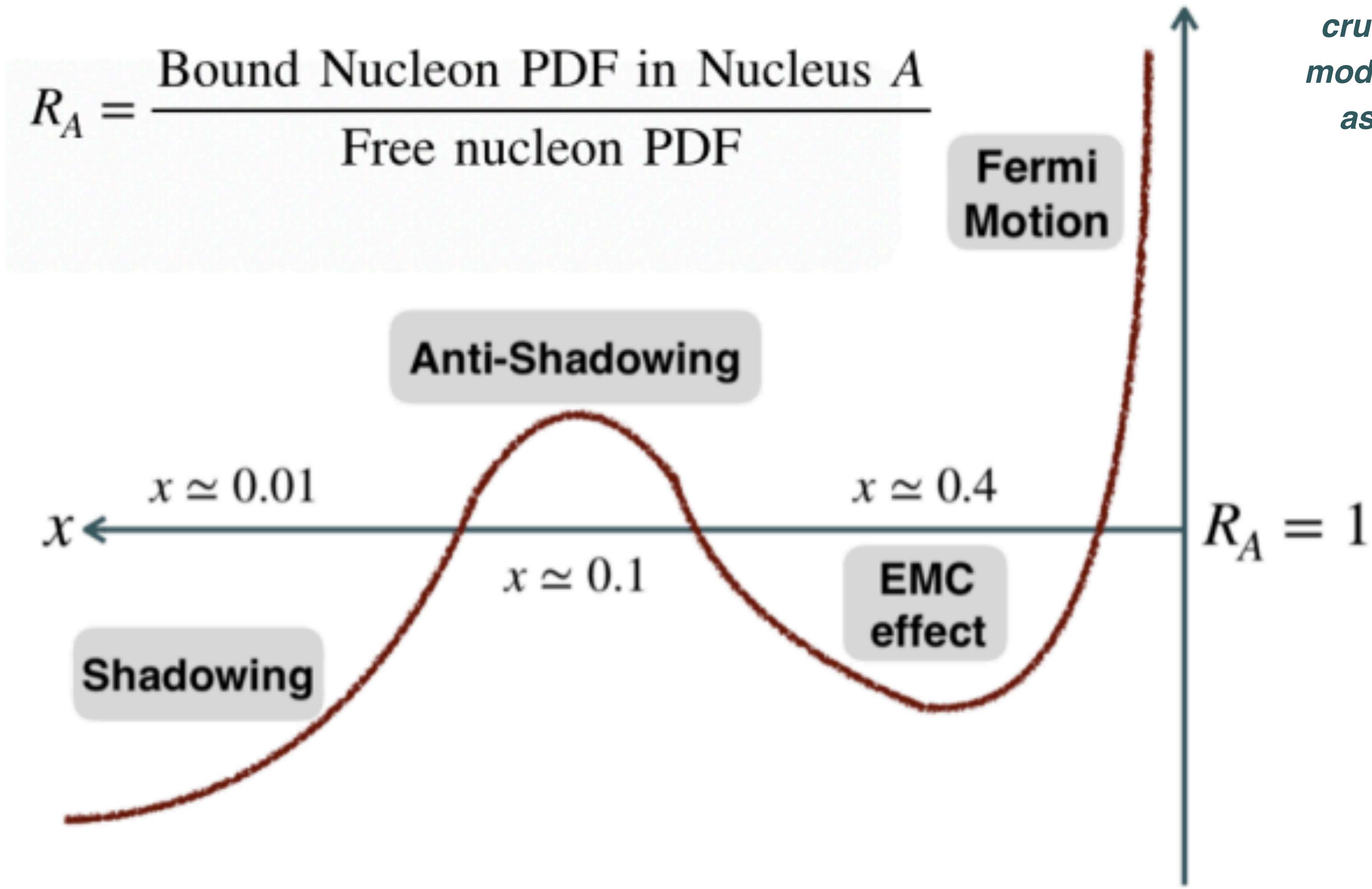
lead PDFs

proton PDFs

extract nuclear PDFs by fitting on a wide global dataset with nuclear targets

Global nuclear PDF determinations

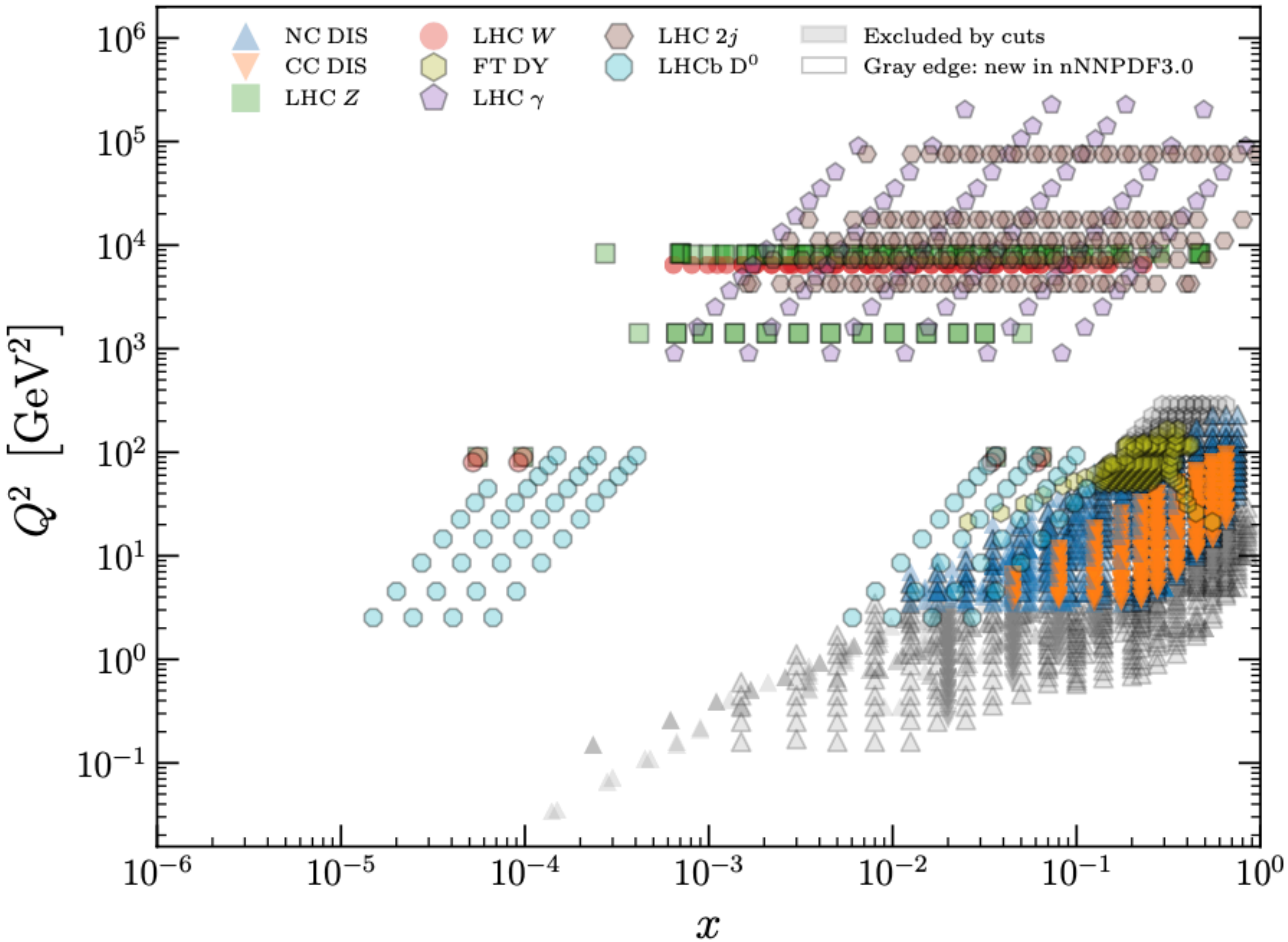
PDFs of bound nucleons are **expected** to differ from those of free protons due to a variety of **nuclear effects**: EMC effect, Fermi motion, shadowing at small-*x* …



crucial to avoid model-dependent assumptions

until very recently, no unambiguous evidence of **e.g. gluon shadowing**

nNNPDF3.0: input data



- **2200 data points** (400 from LHC!)
- ATLAS/CMS/ALICE data on dijet, direct photon, and *W,Z* production
- **LHCb** data on ***W,Z*** and ***D*-meson** production
- Broad kinematic coverage in (x,Q)
- Collider data only for **A=1 & A=208**

soon constrains from pO runs

lead-to-proton ratios

$$R_{\rm pPb}(y^{D^0}, p_{\rm T}^{D^0}) = \frac{d\sigma^{\rm pPb}(y^{D^0}, p_{\rm T}^{D^0})}{dy^{D^0} dp_{\rm T}^{D^0}} \Bigg/ \frac{d\sigma^{\rm pp}(y^{D^0}, p_{\rm T}^{D^0})}{dy^{D^0} dp_{T}^{D^0}}$$

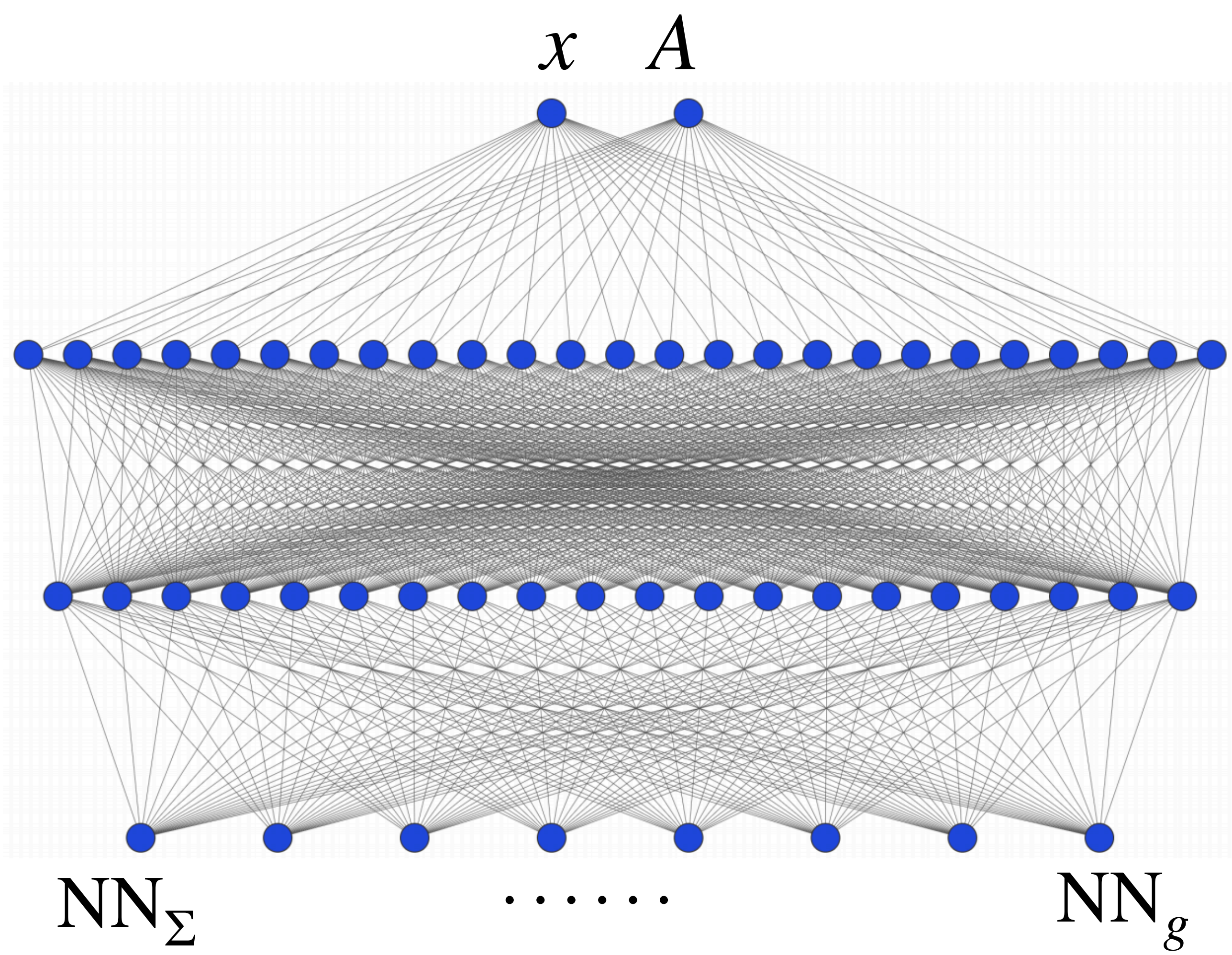
forward-backward ratios

$$R_{\rm fb}(y^{D^0}, p_{\rm T}^{D^0}) = \frac{d^2\sigma^{\rm pPb}(y^{D^0}, p_{\rm T}^{D^0})}{dy^{D^0} dp_{\rm T}^{D^0}} \Bigg/ \frac{d^2\sigma^{\rm Pbp}(-|y^{D^0}|, p_{\rm T}^{D^0})}{dy^{D^0} dp_{\rm T}^{D^0}}$$

Impact of LHCb D-meson data robust upon variation of the observables

nNNPDF3.0: methodology

Model-independent parametrisation of *(x,A)* dependence with **neural networks**



$$
\begin{aligned}
x\Sigma^{(p/A)}(x,Q_0) &= x^{\alpha_\Sigma}(1-x)^{\beta_\Sigma}\mathrm{NN}_\Sigma(x,A)\,,\\
xT_3^{(p/A)}(x,Q_0) &= x^{\alpha_{T_3}}(1-x)^{\beta_{T_3}}\mathrm{NN}_{T_3}(x,A)\,,\\
xT_8^{(p/A)}(x,Q_0) &= x^{\alpha_{T_8}}(1-x)^{\beta_{T_8}}\mathrm{NN}_{T_8}(x,A)\,,\\
xV^{(p/A)}(x,Q_0) &= B_V x^{\alpha_V}(1-x)^{\beta_V}\mathrm{NN}_V(x,A)\,,\\
xV_3^{(p/A)}(x,Q_0) &= B_{V_3} x^{\alpha_{V_3}}(1-x)^{\beta_{V_3}}\mathrm{NN}_{V_3}(x,A)\\
xg^{(p/A)}(x,Q_0) &= B_g x^{\alpha_g}(1-x)^{\beta_g}\mathrm{NN}_g(x,A)\,,
\end{aligned}
$$

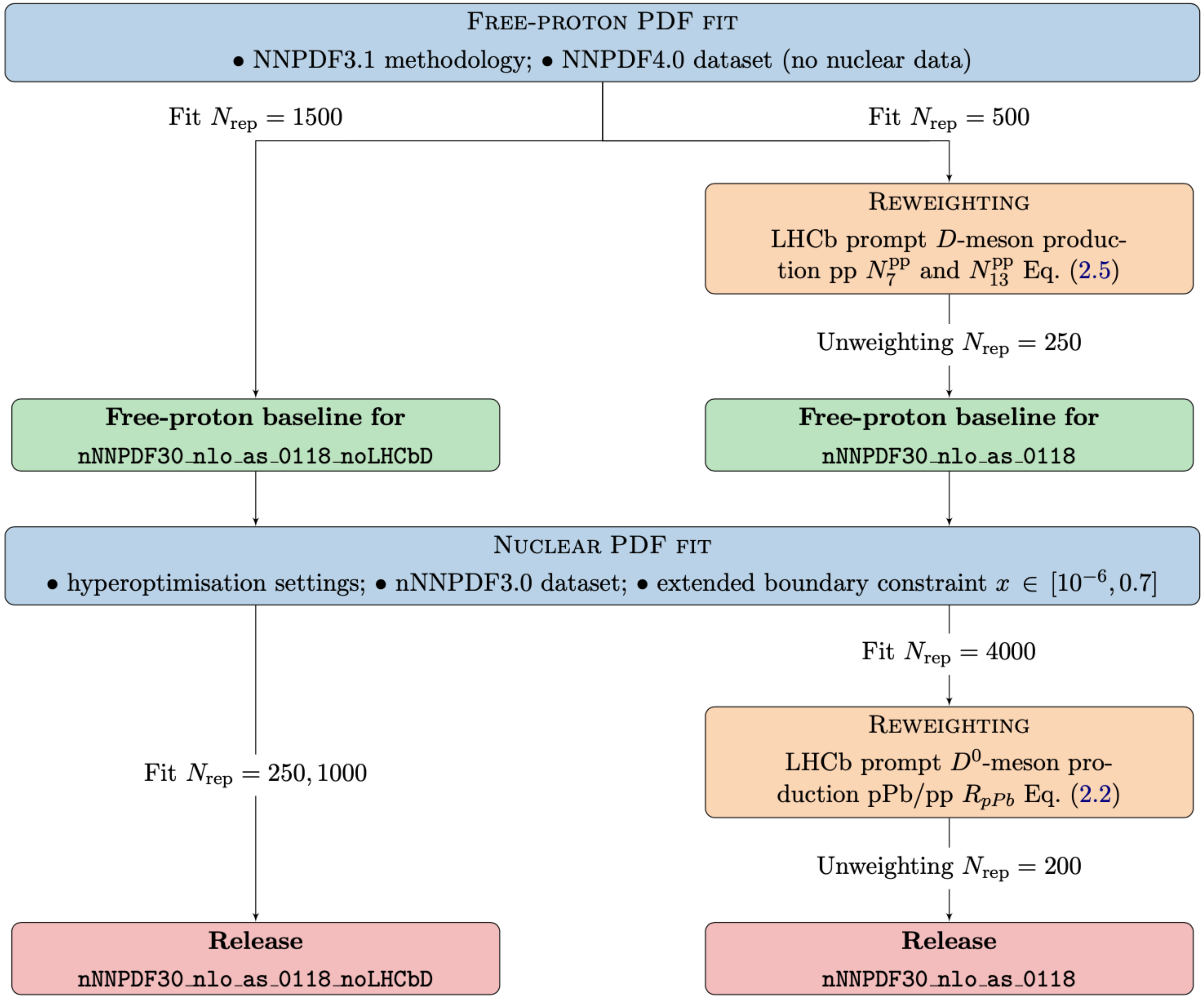
Free-proton boundary condition (*A=1* limit) imposed to be tailored version of NNPDF3.1

$$\chi^2_{\rm fit} = \chi^2_{t_0} + \kappa^2_{\rm pos} + \kappa^2_{\rm BC}$$

$$\chi^2_{t_0} = \sum_{ij}^{n_{\rm dat}}(T_i - D_i)\ (\mathrm{cov}_{t_0})^{-1}_{ij}\ (T_j - D_j) \qquad \kappa^2_{\rm BC} = \lambda_{\rm BC}\sum_f\sum_{j=1}^{n_x}\left(f^{(p/A)}(x_j,Q_0,A=1) - f^{(p)}(x_j,Q_0)\right)^2$$

NNPDF3.1-like proton PDFs

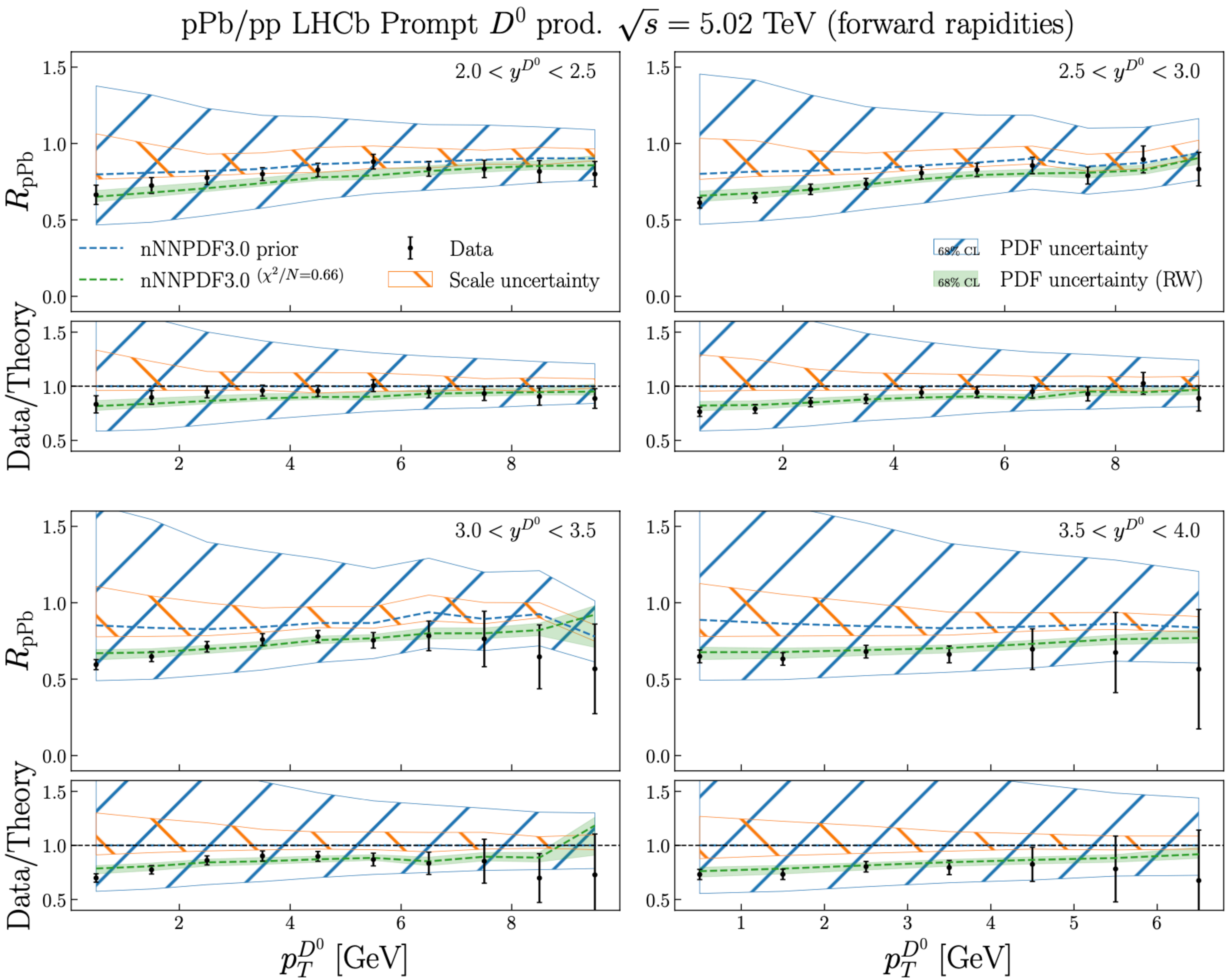
nNNPDF3.0: methodology



Fully consistent theory, data, and methodology for proton and nuclear fits!

In particular, LHCb *D*-meson constraints accounted for both in proton and nuclear PDFs

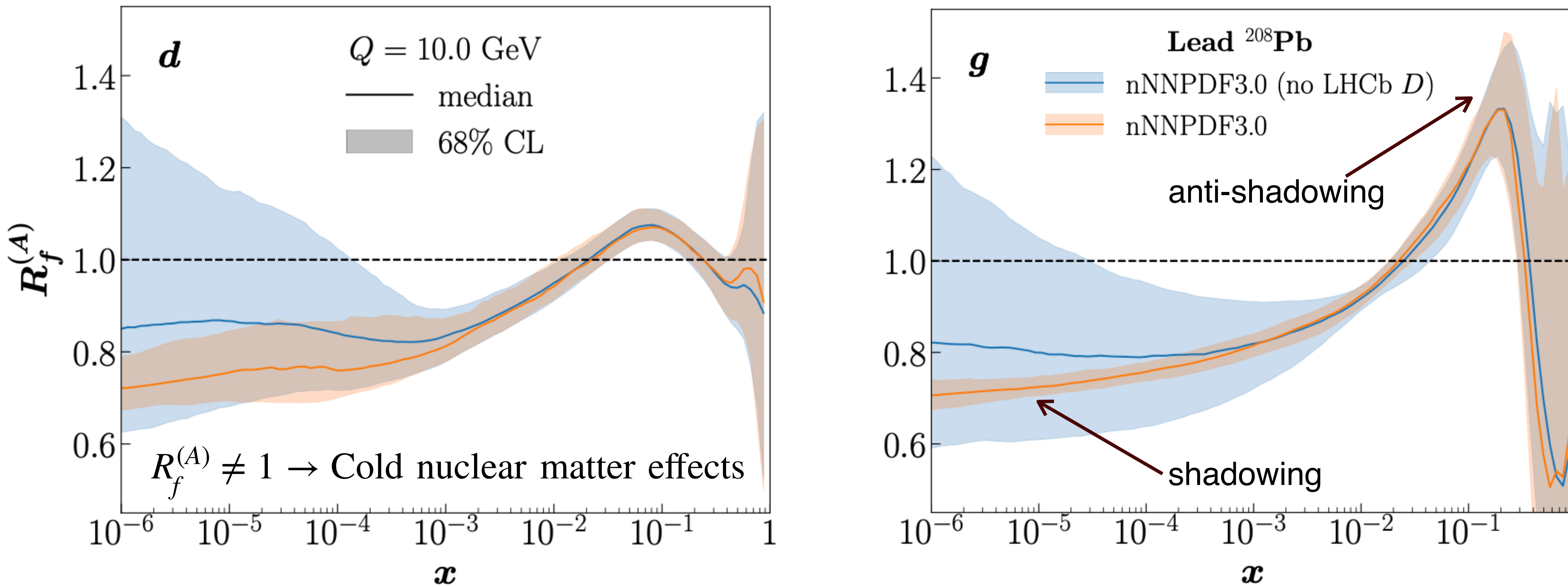
nNNPDF3.0: results



- Excellent description of **LHCb *D*-meson data**
- Huge reduction of PDF uncertainties, dominated by **small-*x* gluon**
- Constraints on ***A=1* (proton) PDFs** from LHCb charm already accounted for
- Similar qualitative findings when fitting the forward-backward ratio

nNNPDF3.0: results

$$R_f^{(A)}(x,Q) \equiv \frac{f^{(N/A)}(x,Q)}{\frac{Z}{A} f^{(p)}(x,Q) + \frac{(A-Z)}{A} f^{(n)}(x,Q)}$$



Statistically significant **evidence** for **gluon and quark shadowing at small-*x*!**

- ☑ LHCb *D*-meson data dominates constraints for $x < 10^{-3}$
- ☑ **Gluon anti-shadowing** also stablished, in this case thanks to the CMS dijet prodiction data
- ☑ Small-*x* gluons and quarks connected via **DGLAP evolution**
- ☑ Significance reduced for **lighter nuclei**: need data for other *A* (upcoming p+O & O+O runs)

Summary and outlook

- The unique forward coverage of LHCb makes it a unique explorer of **novel phenomena in QCD and proton/nuclear structure**

- The NNPDF4.0 global analysis reveals **evidence for intrinsic charm in the proton**, consistent with the independent constraints from the LHCb Z+charm data

- The nNNPDF3.0 nuclear PDF determination obtains **strong evidence for gluon shadowing in lead nuclei** at small-*x*