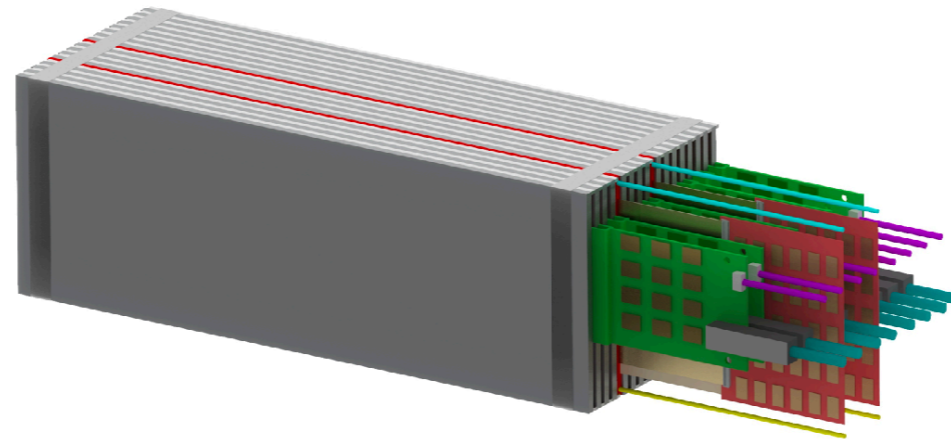


# Collinear (n)PDFs and constraints from forward particle production

Juan Rojo, VU Amsterdam & Nikhef



Workshop on the *exploration of small-x structure of nuclei and signals of saturation in forward measurements at the LHC*

**CERN, 22nd June 2022**

# **Why forward measurements?**

# Forward particle production @ LHC

$$\sigma_{\text{LHC}}(M, s) \propto \sum_{ij} \int_{M^2}^s d\hat{s} \mathcal{L}_{ij}(\hat{s}, s) \tilde{\sigma}_{ij}(\hat{s}, \alpha_s(M)), \quad i, j = u, d, s, g, \dots$$

**collinear factorisation**

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

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

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

$f_j(x, Q)$

flavour index      momentum fraction      energy scale of partonic scattering

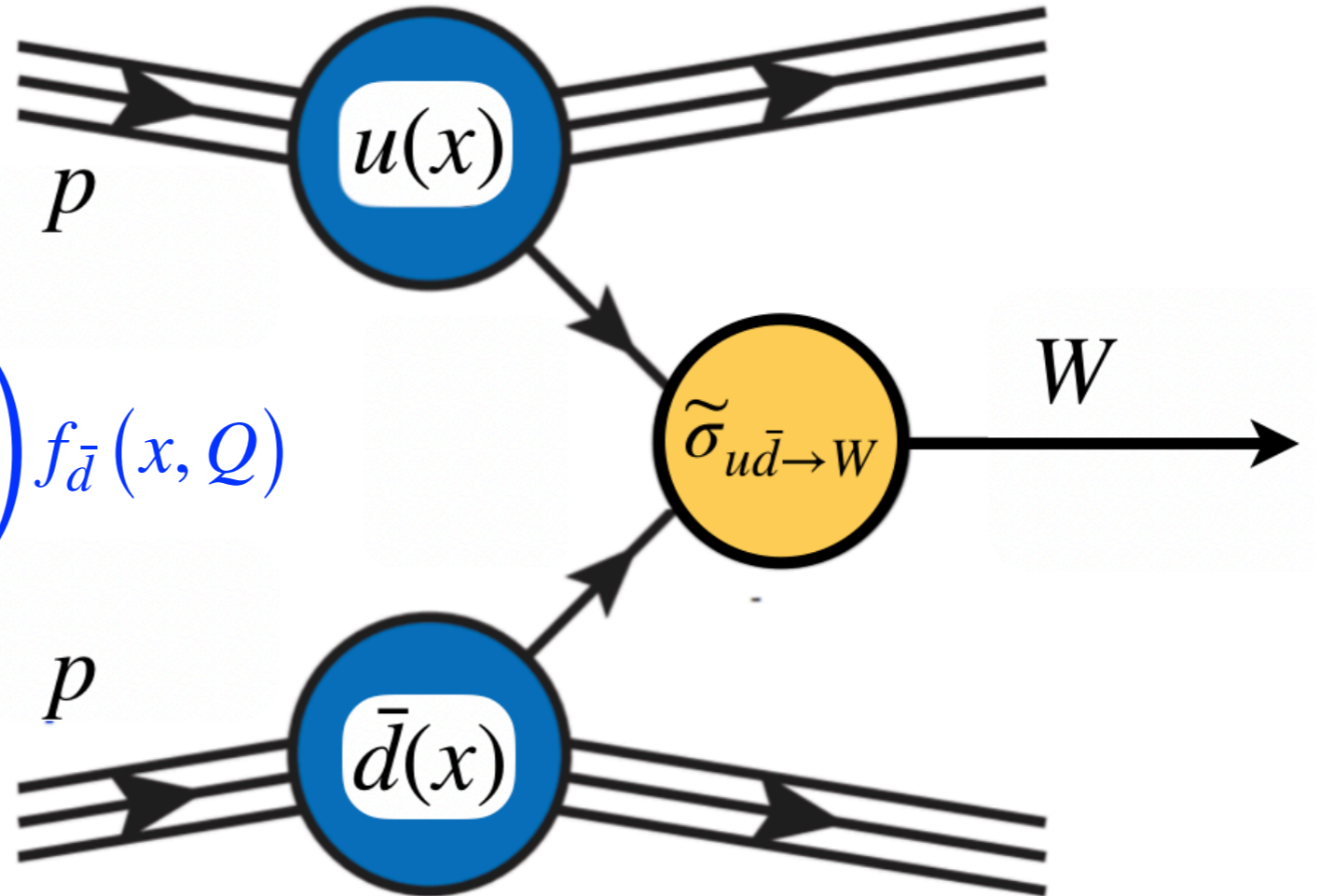
*proton Parton Distribution  
Functions (PDFs)*

*collinear factorisation can be extended with all-order resummation (e.g. **BFKL resummation at small-x**) but **cannot** describe non-linear or non-factorisable dynamics*

# Forward particle production @ LHC

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

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



Using leading-order kinematics:

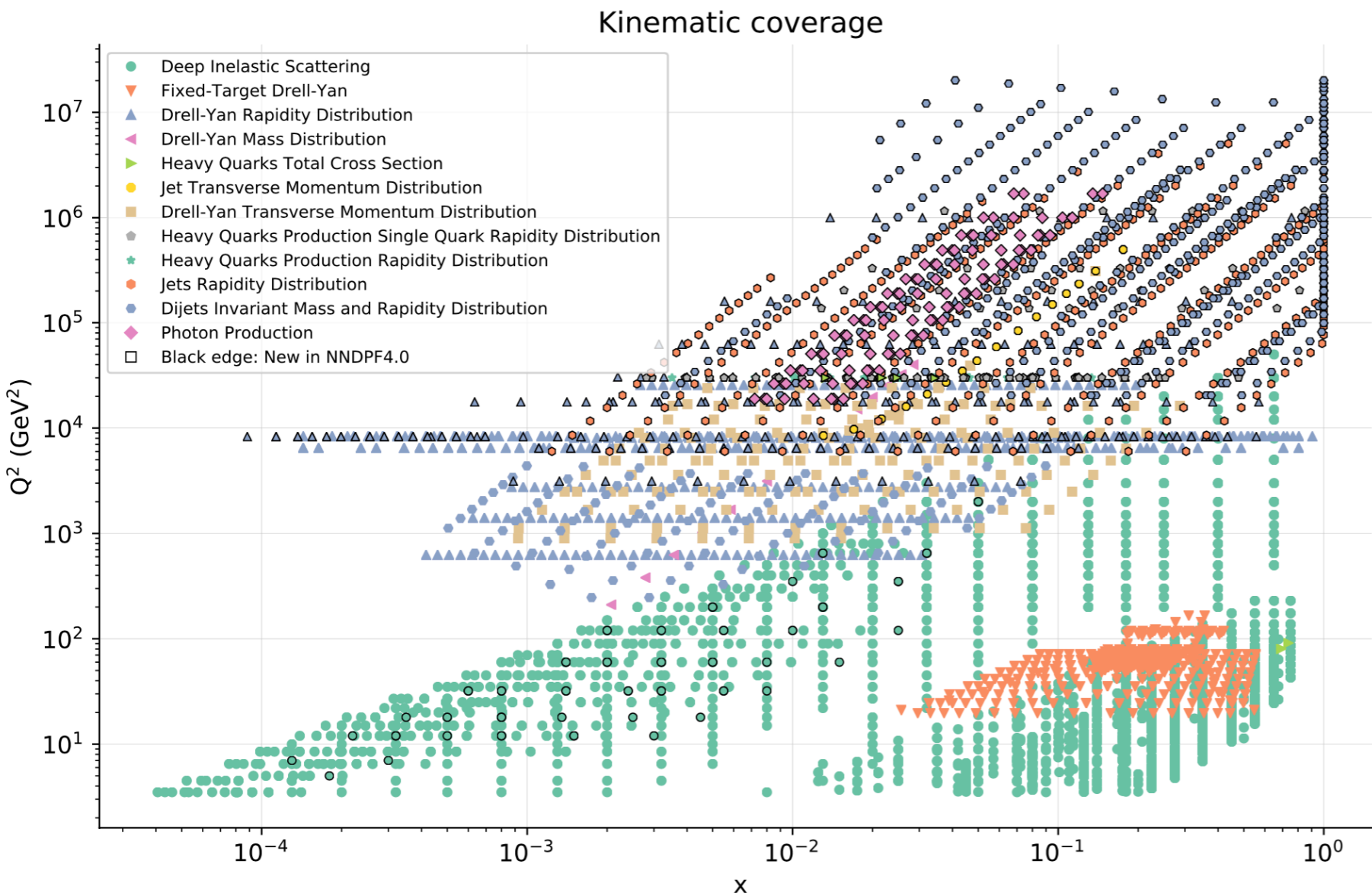
$$x_1 = \frac{M_W}{\sqrt{s}} e^{+y_W}, \quad x_2 = \frac{M_W}{\sqrt{s}} e^{-y_W}$$

**forward rapidities and low-mass final states probe smaller  $x$  values**

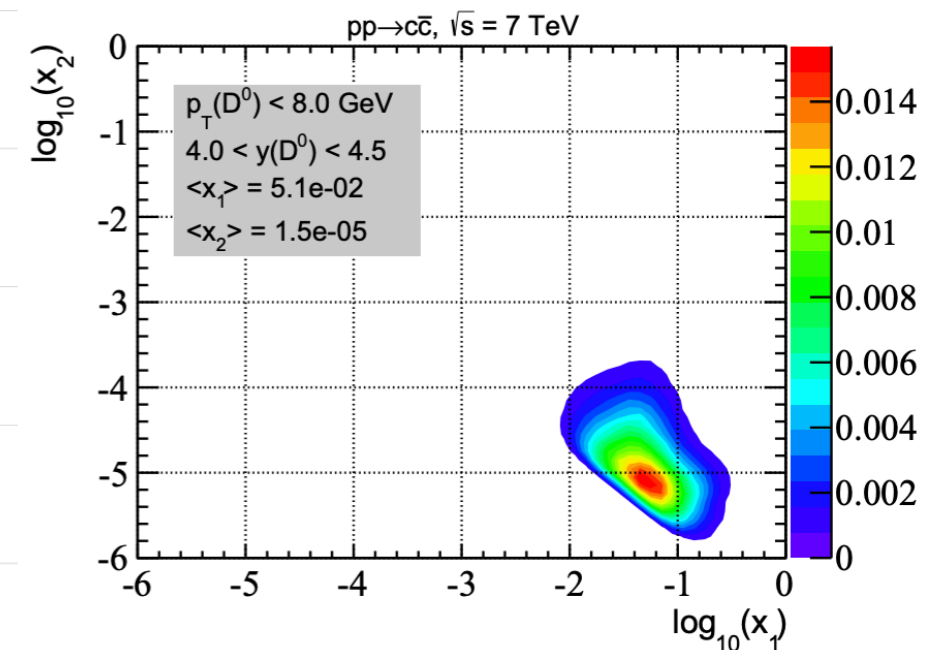
forward measurements of low invariant mass states provides direct access to **small- $x$  QCD phenomena and hadron structure**

# Forward measurements for proton PDFs

## NNPDF4.0: data set extension



## D-meson production @ LHCb



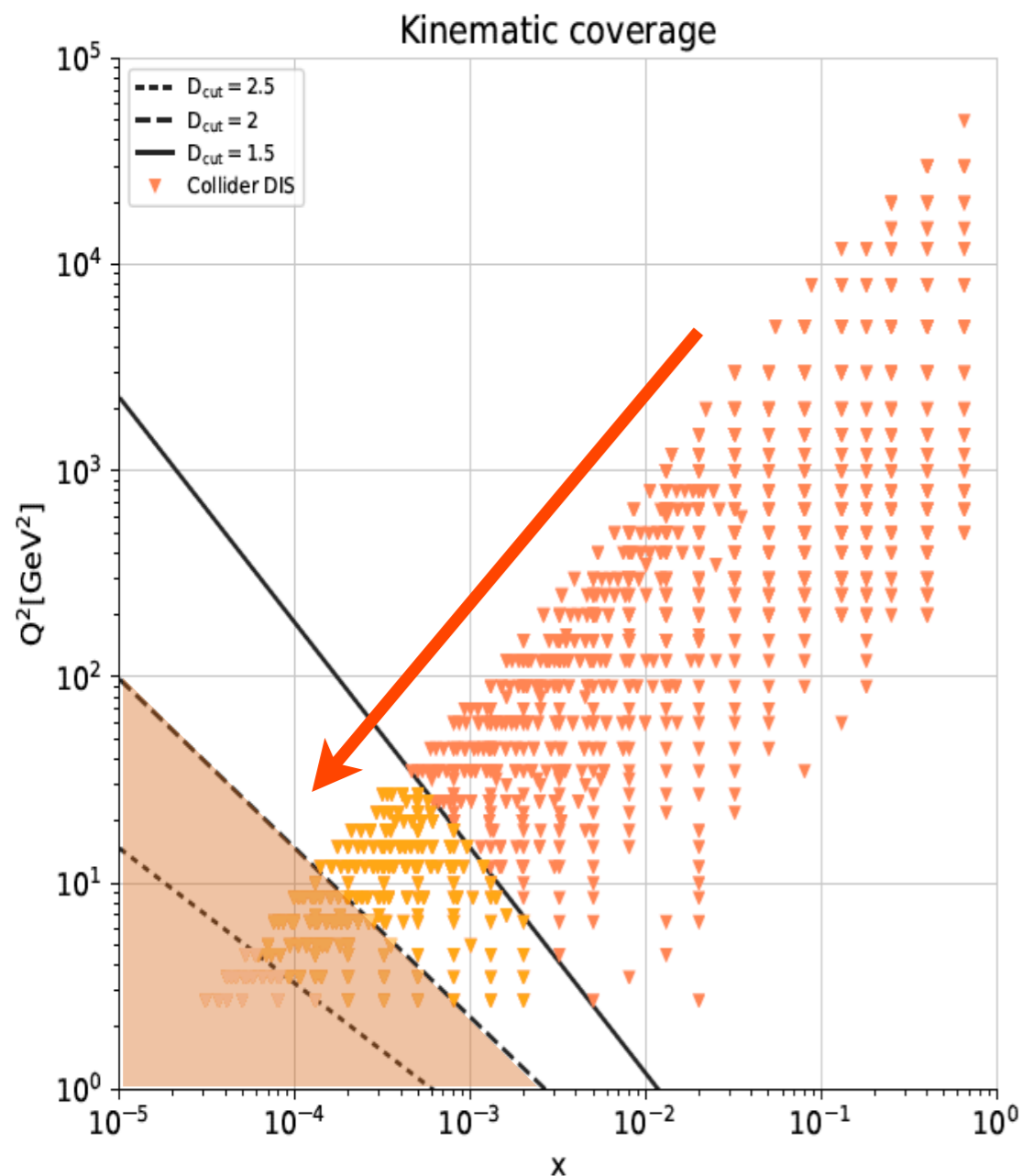
- 🚫 In global PDF fits, the small- $x$  region ( $x < 10^{-3}$ ) is constrained mostly by **inclusive and charm HERA** structure functions and by **inclusive  $W, Z$  production from LHCb**
- 🚫 **D-meson production at LHCb** has also been considered and **extends coverage down to  $x = 10^{-6}$**  but is only available at NLO and affected by large missing higher order uncertainties (MHOUs)
- 🚫 Within the next decade, several **new experiments will explore the small- $x$  region**: EIC, FoCal, Faser/FPF ...

# Forward measurements for proton PDFs

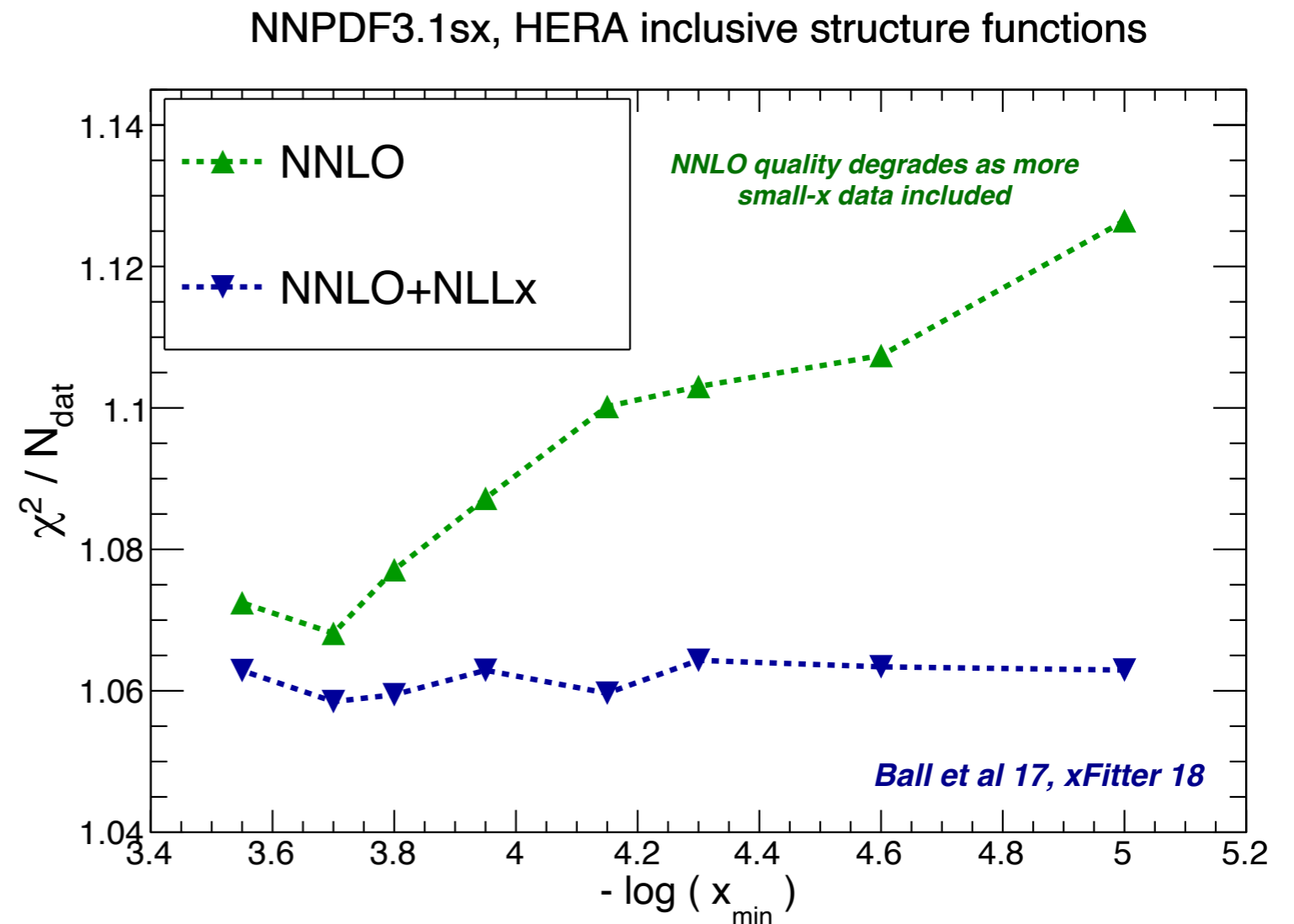
**BFKL dynamics established** from HERA data from inclusive and charm structure functions

Accessible also in forward measurements @ LHC? Interplay with **non-linear QCD studies?**

Similar techniques to pinpoint **saturation?**



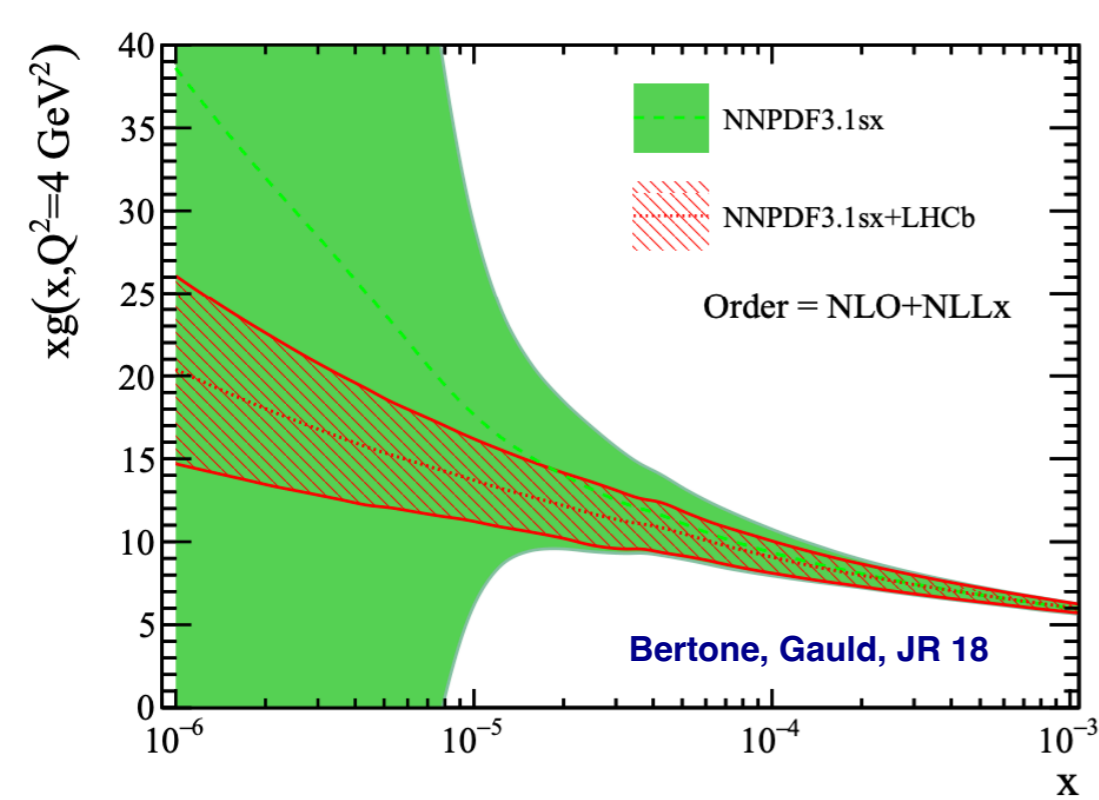
Monitor the fit quality in small- $x$  region



Best description of **small- $x$  HERA data: BFKL resummation**

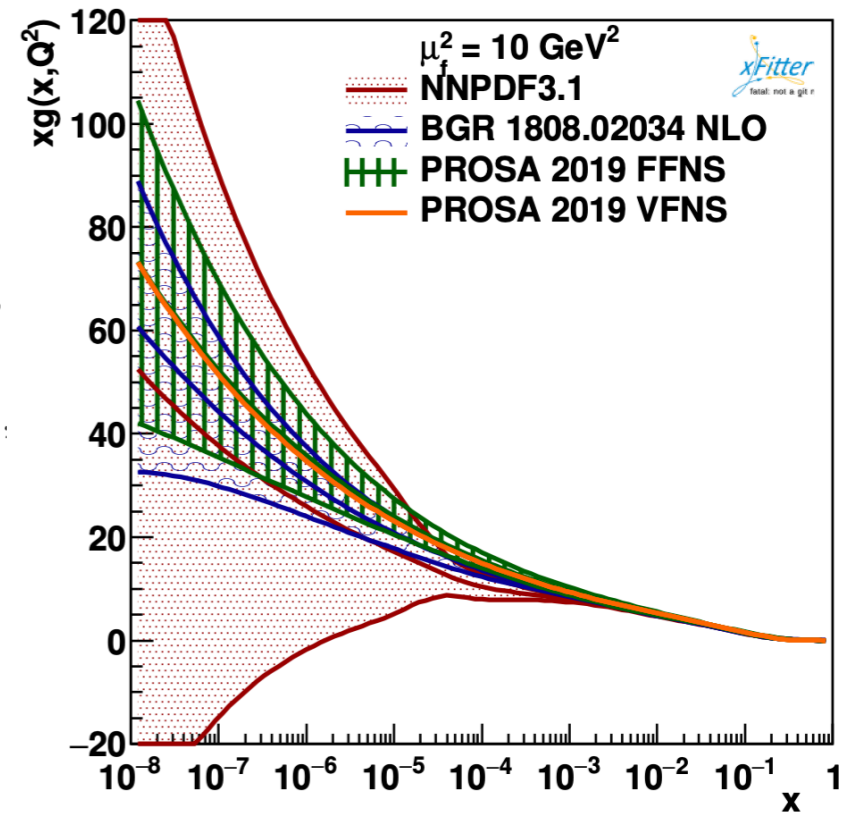
# Forward measurements for proton PDFs

LHCb data on **charm production** at 5, 7, 13 TeV used to constrain the small-x gluon PDF



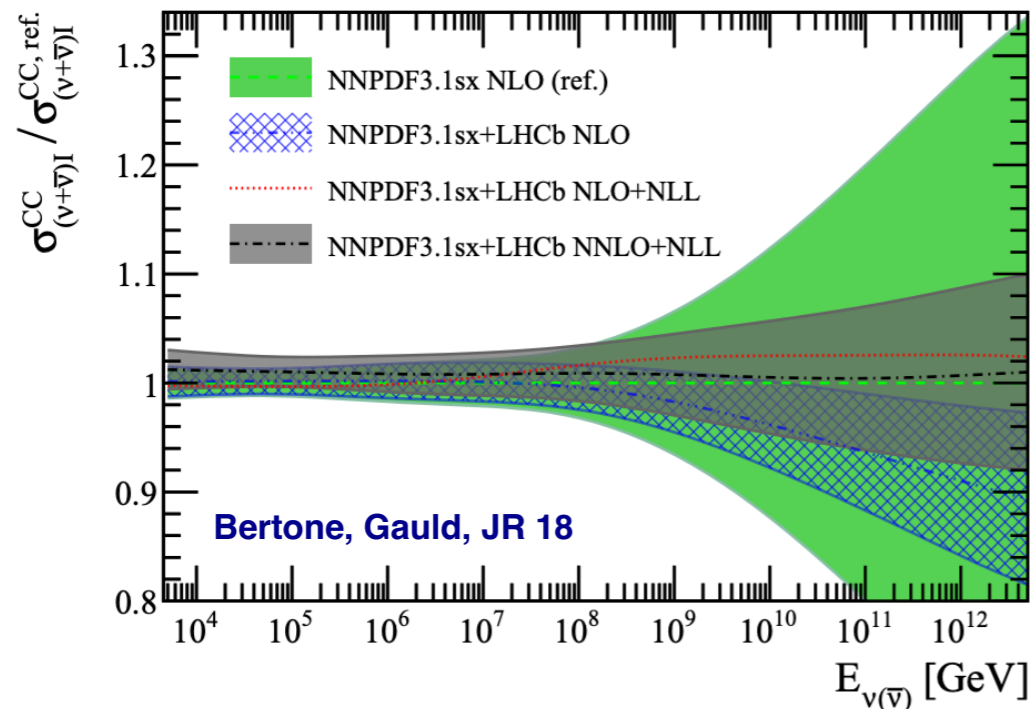
$$N_X^{ij} = \frac{d^2\sigma(X \text{ TeV})}{dy_i^D d(p_T^D)_j} \bigg/ \frac{d^2\sigma(X \text{ TeV})}{dy_{\text{ref}}^D d(p_T^D)_j},$$

$$R_{13/X}^{ij} = \frac{d^2\sigma(13 \text{ TeV})}{dy_i^D d(p_T^D)_j} \bigg/ \frac{d^2\sigma(X \text{ TeV})}{dy_i^D d(p_T^D)_j}$$

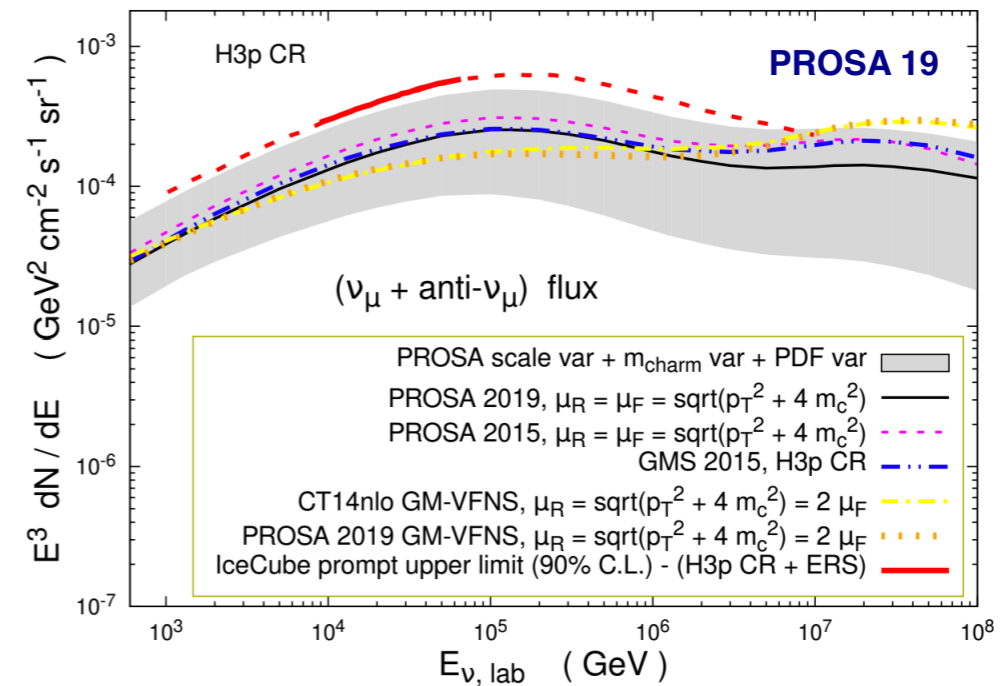


implications for **high-energy astroparticle physics:**

## UHE neutrino-nucleus cross-sections



## prompt neutrino fluxes from charm in CRs



# Forward measurements for nuclear PDFs

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

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

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

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

$f_j^{(\text{Pb})}(x, Q, A)$

- flavour index
- momentum fraction
- energy scale of partonic scattering
- atomic mass number

*lead PDFs*

*proton PDFs*

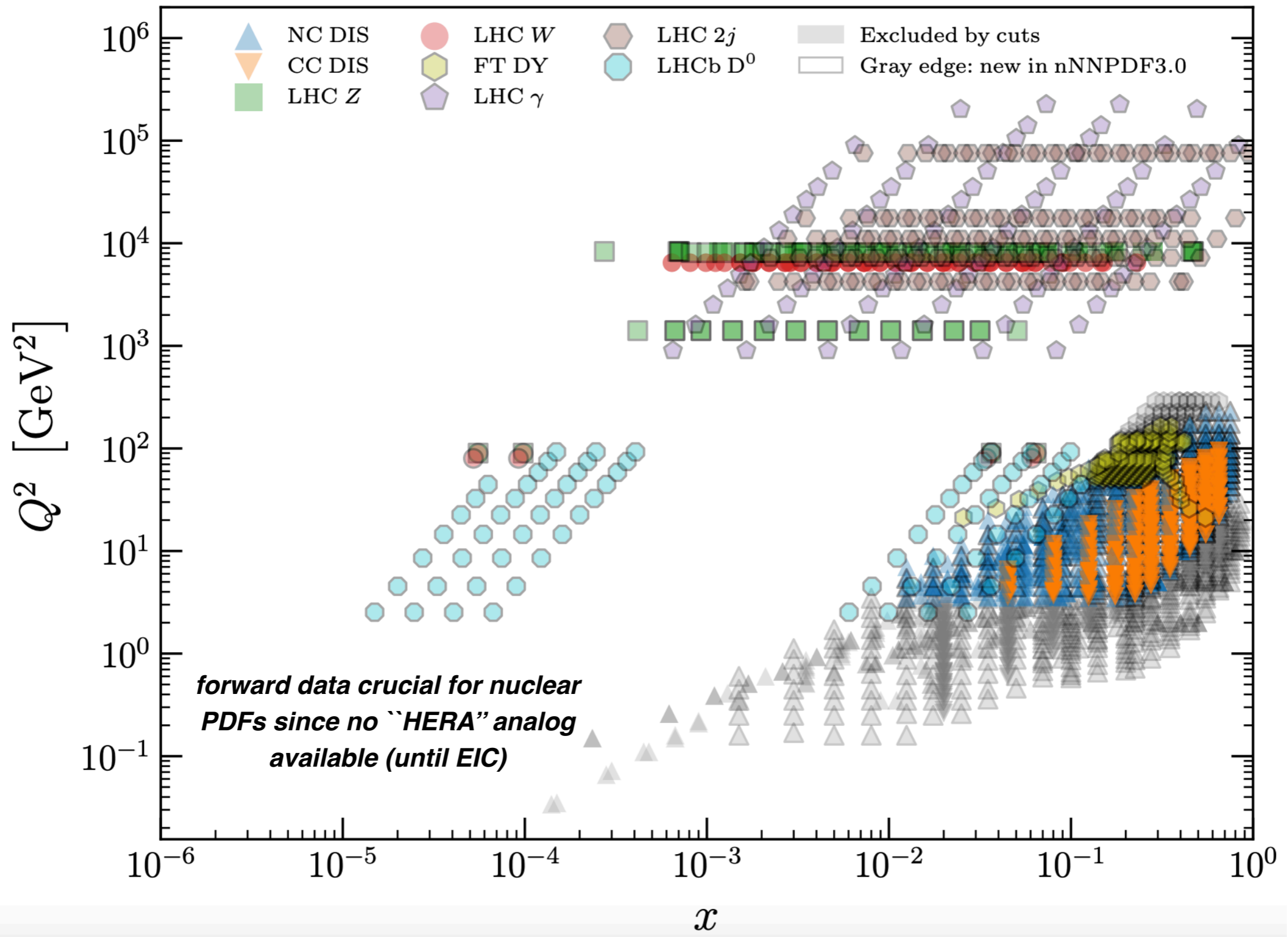
**cold nuclear matter effects**  
encoded into nuclear PDFs

also in the nuclear case, **forward measurements of low invariant mass states**  
provide direct access to **small-x QCD phenomena and nuclear structure**



# Forward measurements for nuclear PDFs

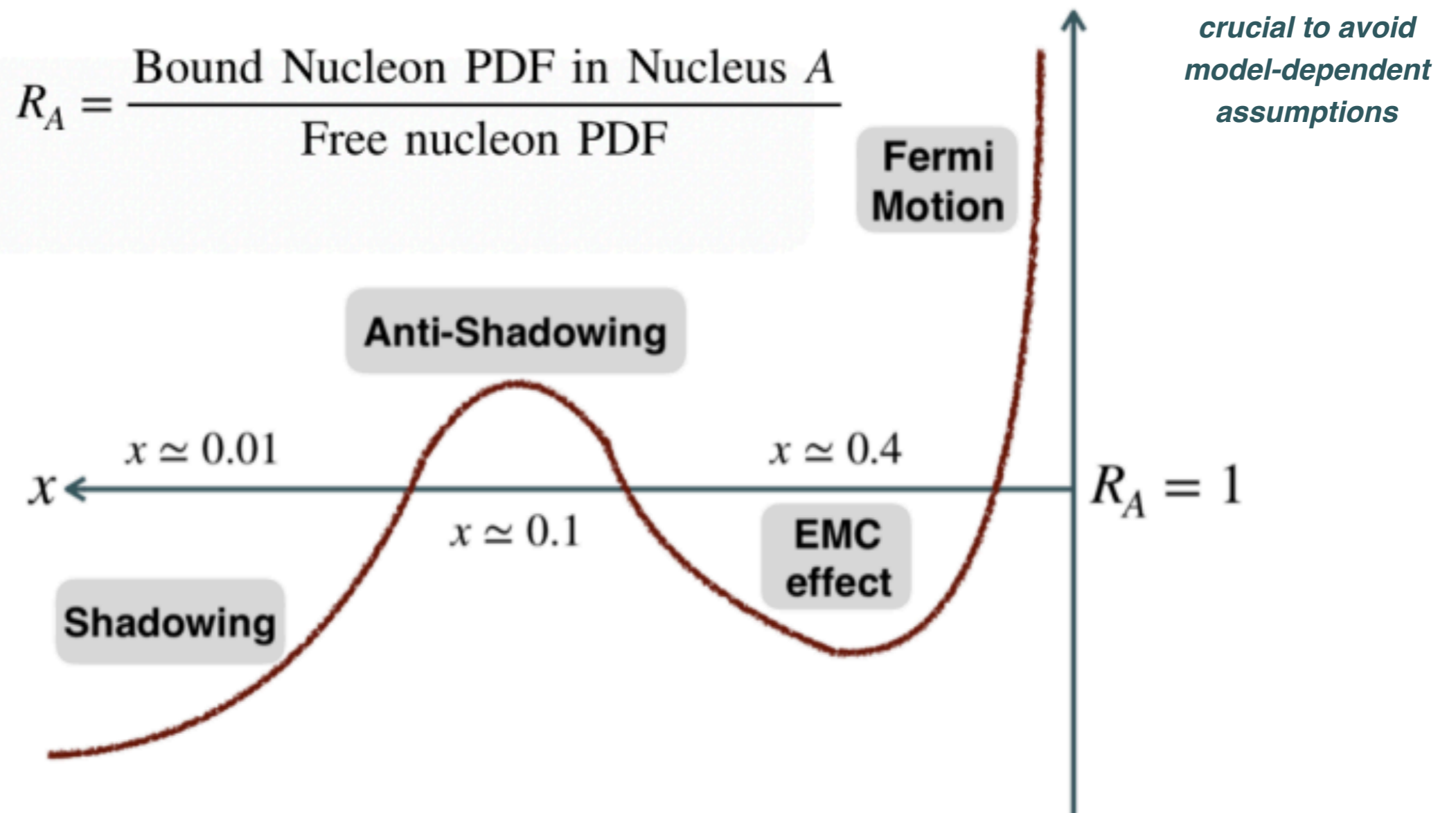
In global nPDF fits, the small- $x$  region ( $x < 10^{-3}$ ) can be constrained from ***D*-meson production**, inclusive light hadron production, quarkonia, and also with **prompt photon production**



# **Forward measurements and nPDF constraints**

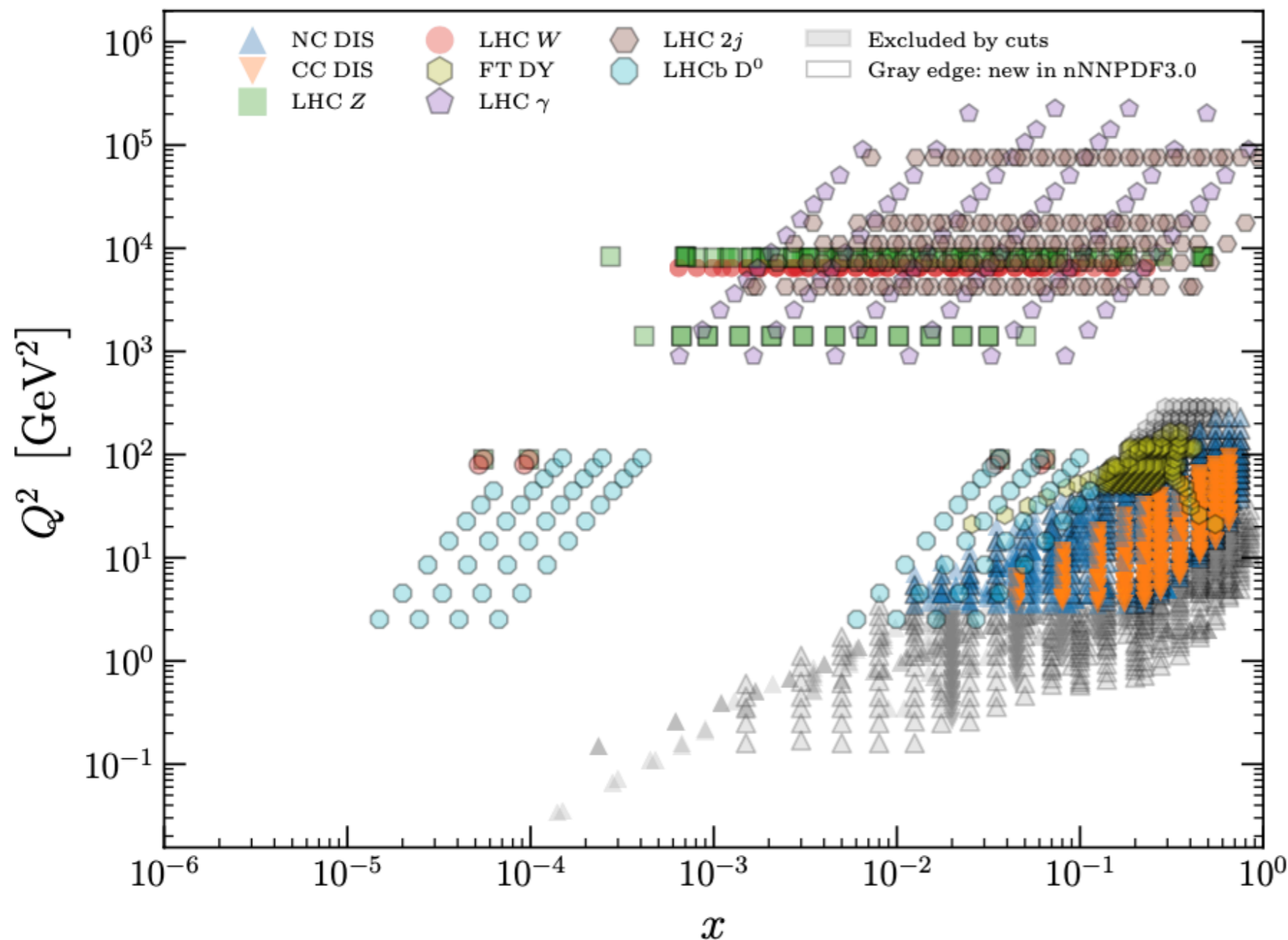
# Global nuclear PDF determinations

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- $x$  ...



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  $A=1$  &  $A=208$

*weak sensitivity to  $A$ -dependence,  
soon constrains from  $pO$  runs*

*lead-to-proton ratios*

$$R_{pPb}(y^{D^0}, p_T^{D^0}) = \frac{d\sigma^{pPb}(y^{D^0}, p_T^{D^0})}{dy^{D^0} dp_T^{D^0}} \bigg/ \frac{d\sigma^{pp}(y^{D^0}, p_T^{D^0})}{dy^{D^0} dp_T^{D^0}}$$

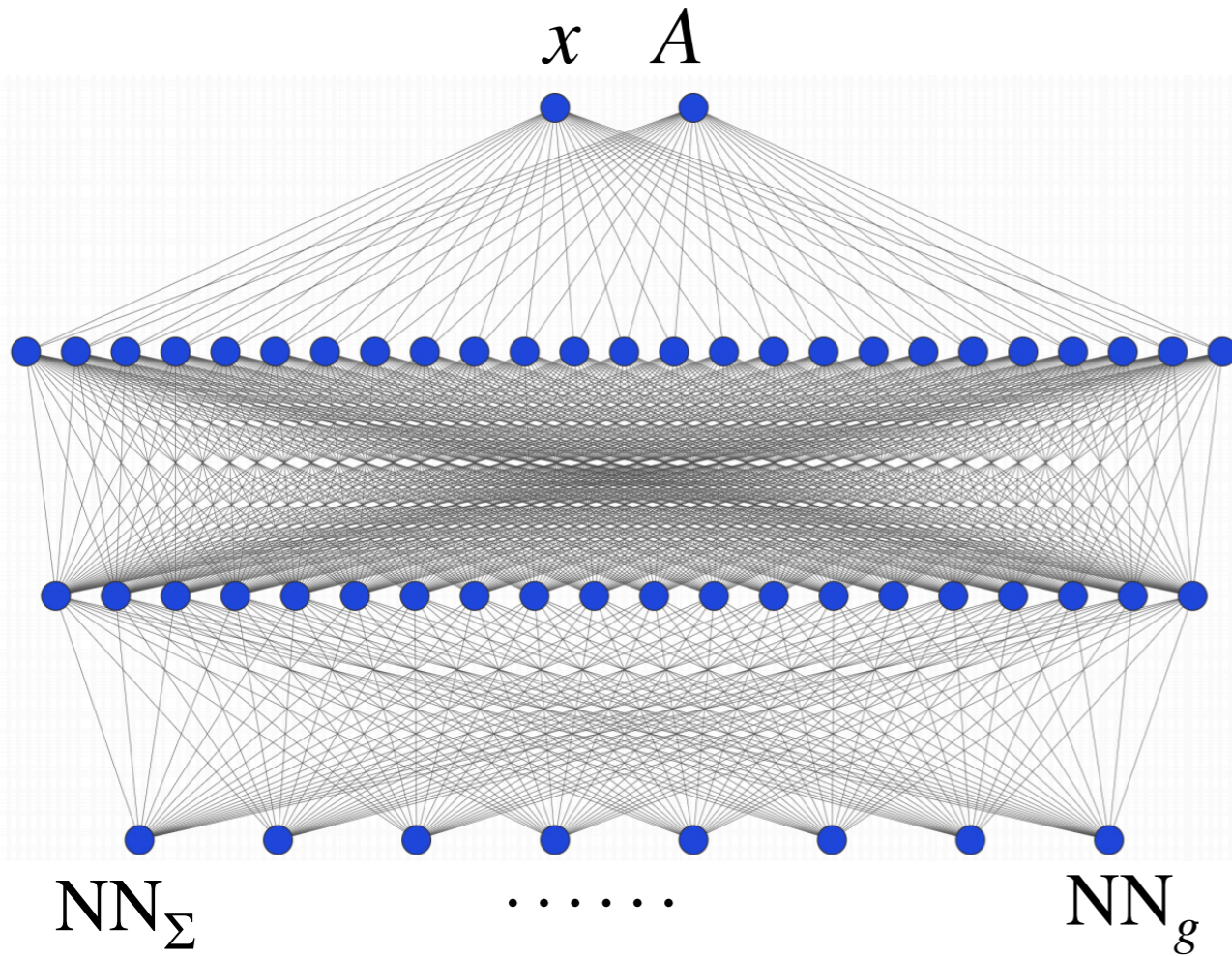
*forward-backward ratios*

$$R_{fb}(y^{D^0}, p_T^{D^0}) = \frac{d^2\sigma^{pPb}(y^{D^0}, p_T^{D^0})}{dy^{D^0} dp_T^{D^0}} \bigg/ \frac{d^2\sigma^{PbP}(-|y^{D^0}|, p_T^{D^0})}{dy^{D^0} dp_T^{D^0}}$$

***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**



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

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

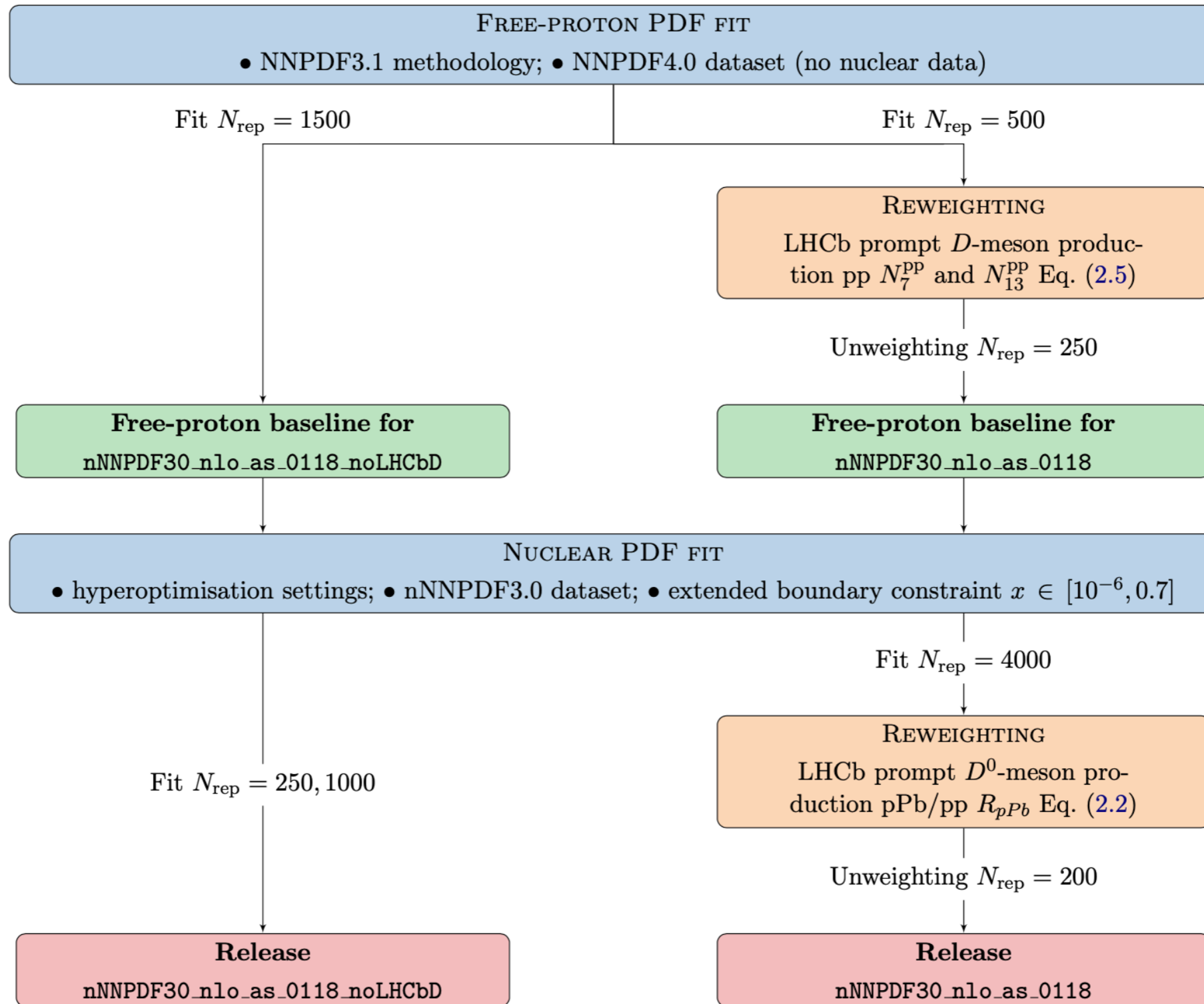
$$\chi_{\text{fit}}^2 = \chi_{t_0}^2 + \kappa_{\text{pos}}^2 + \kappa_{\text{BC}}^2$$

$$\chi_{t_0}^2 = \sum_{ij}^{n_{\text{dat}}} (T_i - D_i) (\text{cov}_{t_0})_{ij}^{-1} (T_j - D_j)$$

$$\kappa_{\text{BC}}^2 = \lambda_{\text{BC}} \sum_f \sum_{j=1}^{n_x} \left( f^{(p/A)}(x_j, Q_0, A=1) - f^{(p)}(x_j, Q_0) \right)^2$$

*NNPDF3.1-like  
proton PDFs*

# nNNPDF3.0: methodology

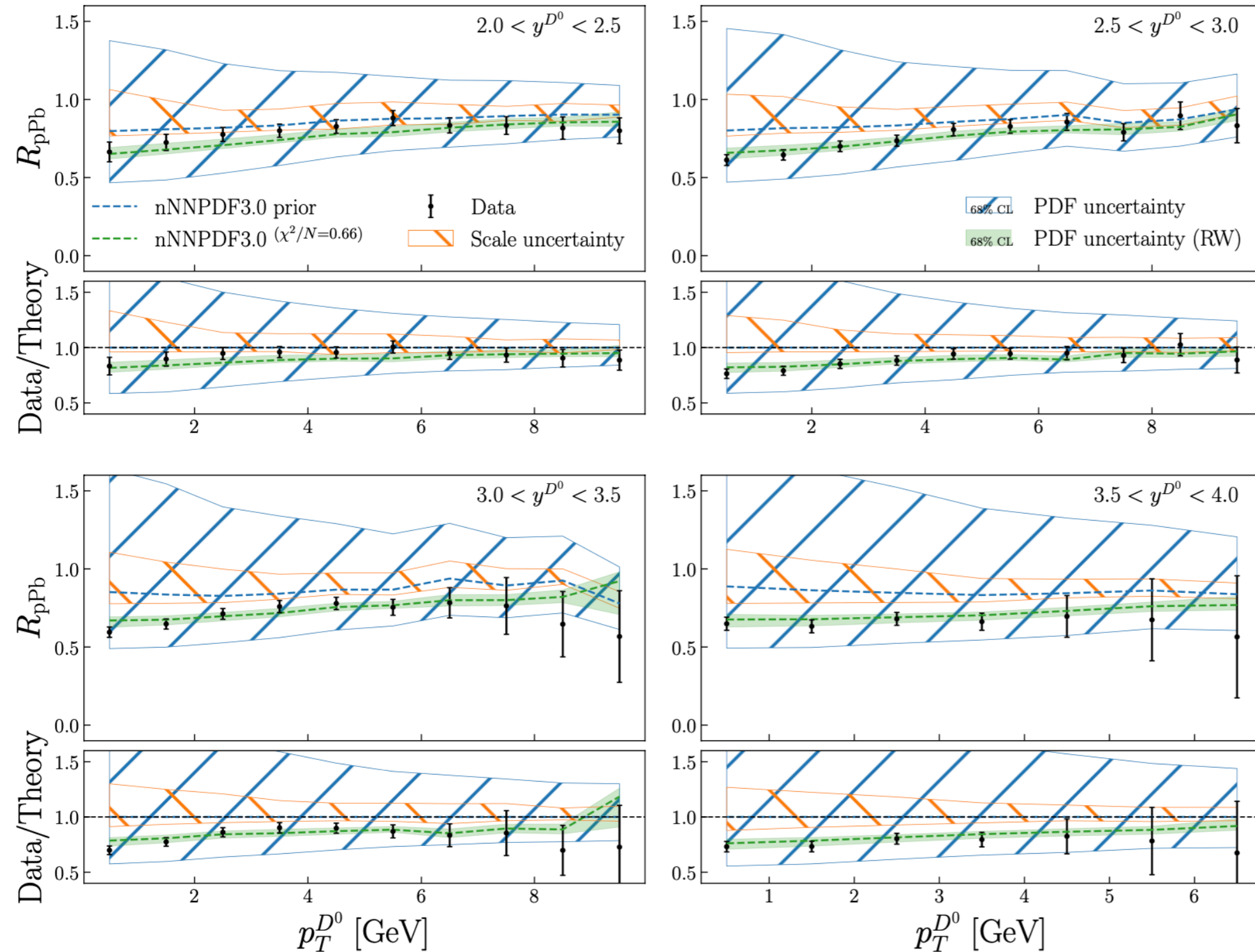


***Fully consistent theory, data, and methodology for proton and nuclear fits!***

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

# nNNPDF3.0: results

pPb/pp LHCb Prompt  $D^0$  prod.  $\sqrt{s} = 5.02$  TeV (forward rapidities)



✓ Excellent description of **LHCb  $D$ -meson data**

✓ Huge reduction of PDF uncertainties, dominated by **small- $x$  gluon**

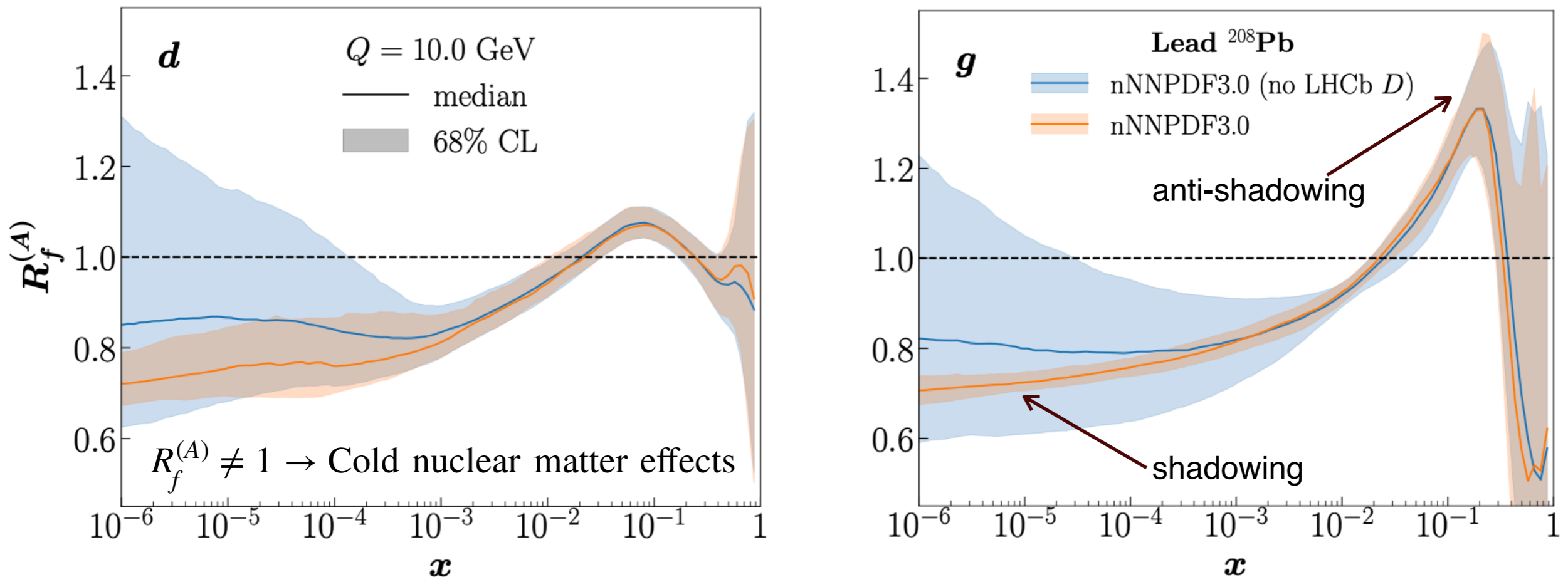
✓ Constraints on  **$A=1$  (proton) PDFs** from LHCb charm already accounted for

✓ Similar qualitative findings when fitting the forward-backward ratio

✓ Caveat: **MHOUs not accounted for** in the fitting procedure

# nNNPDF3.0: results

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



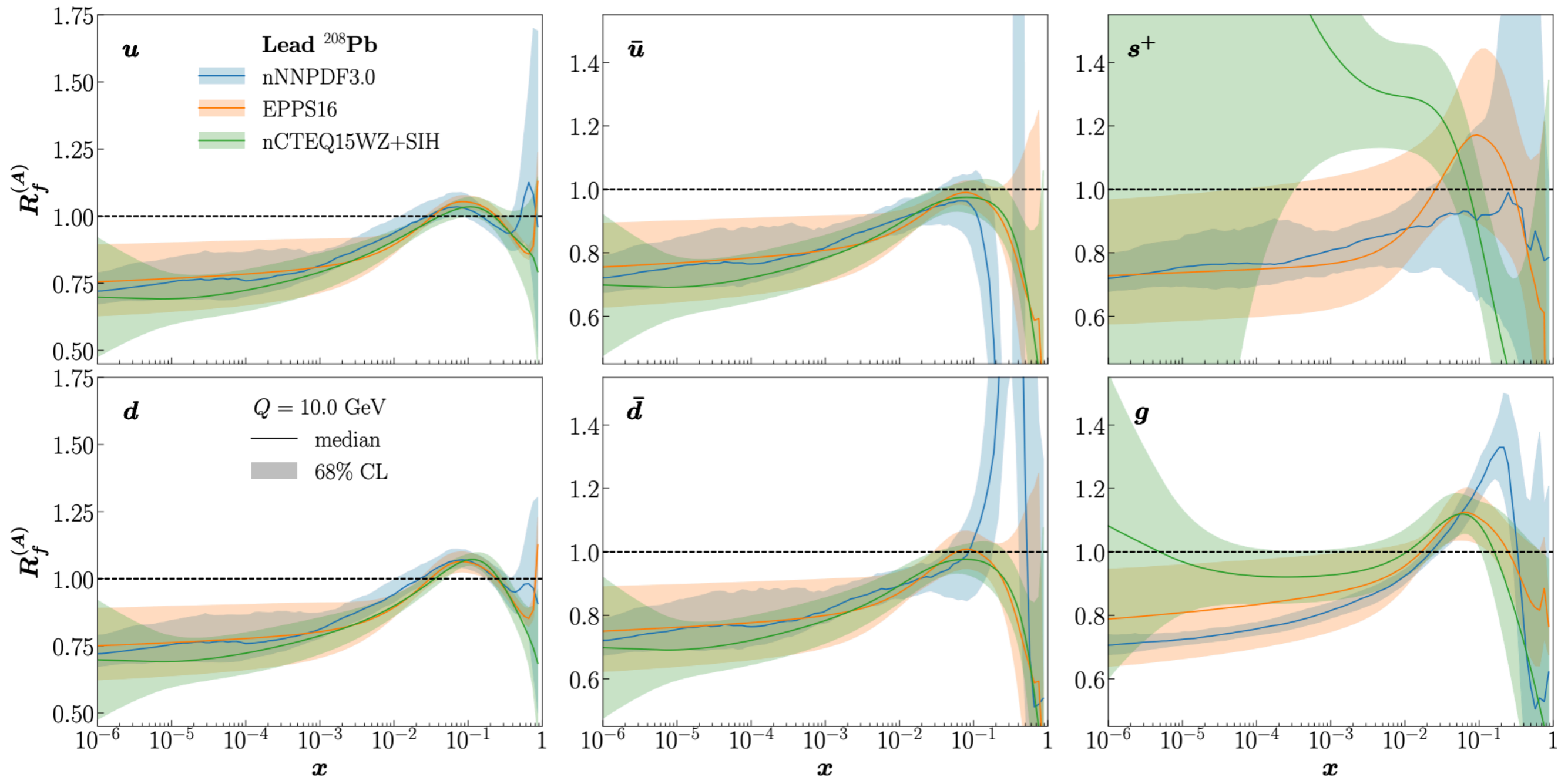
Statistically significant **evidence** for **gluon and quark shadowing at small- $x$**

- ✓ LHCb  $D$ -meson data dominates constraints for  $x < 10^{-3}$
- ✓ **Gluon anti-shadowing** also established, in this case thanks to the CMS dijet production 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)



# Comparison with other nPDF analyses

- ☑ Remarkable agreement for **up and down quark nuclear modifications**, ditto for small- $x$  sea quarks
- ☑ Larger differences for **large- $x$  antiquarks**, for **strangeness**, and for the **gluon** nuclear modifications

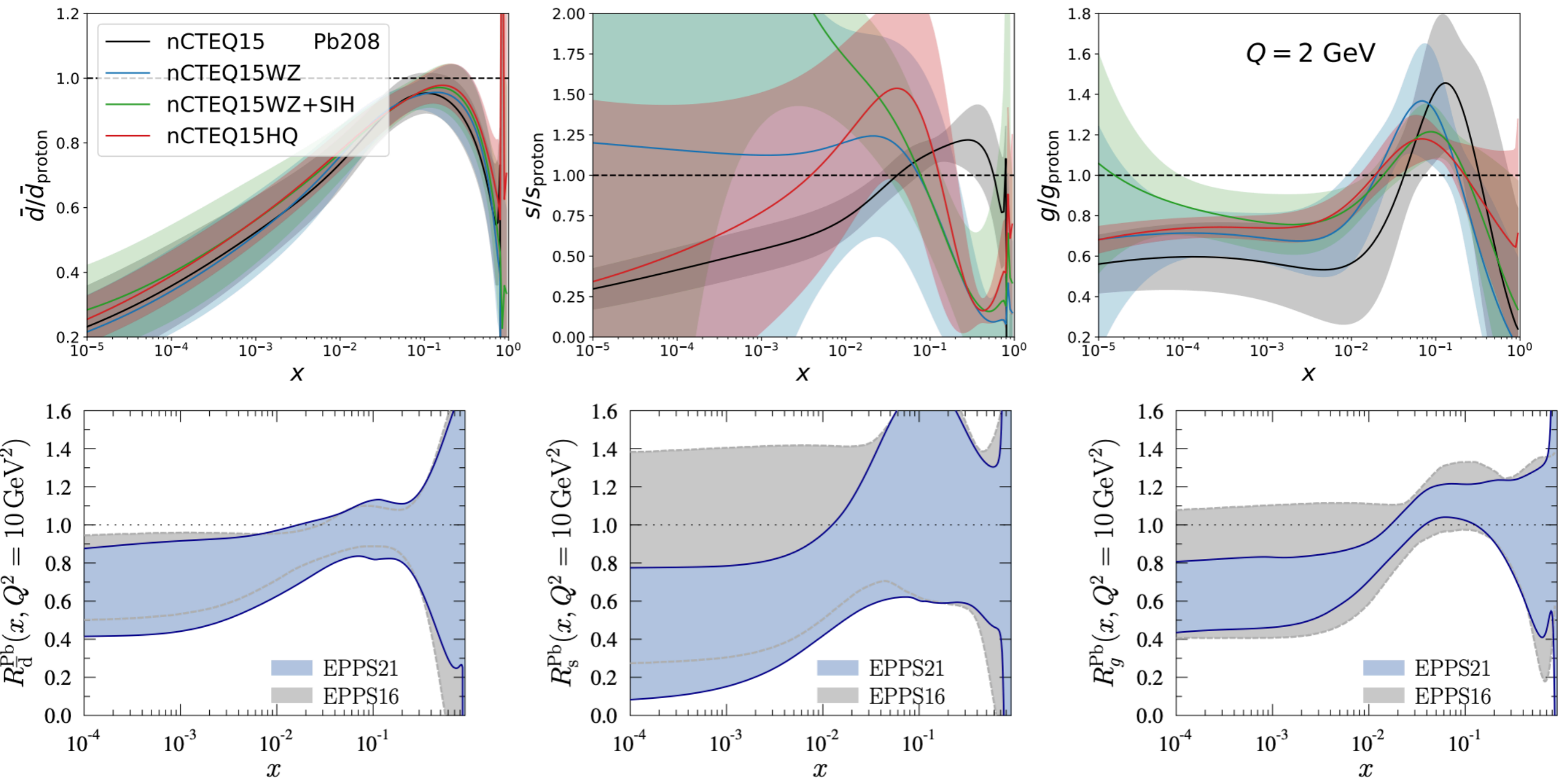


In this comparison, only nNNPDF3.0 includes **charm data**, and only nCTEQ includes **single inclusive hadron production**

A robust understanding of small- $x$  nPDFs crucial to disentangle **signals of non-linear QCD phenomena!**

# Comparison with other nPDF analyses

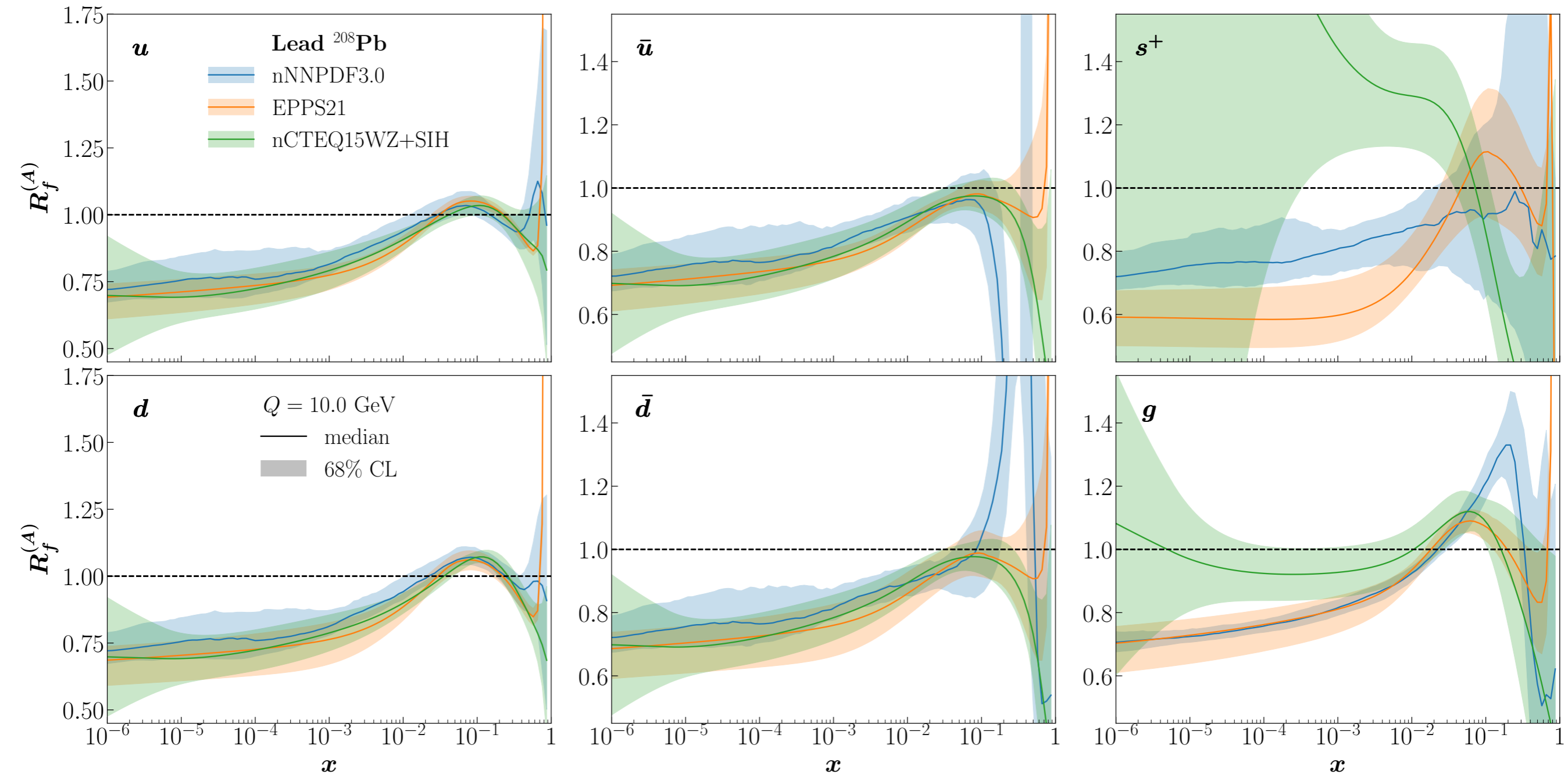
- nCTEQ has presented fit variants with **single inclusive light hadron production (SIH)** and with **quarkonia and *D*-meson production** in pA collisions
- EPPS21 includes ***D*-mesons (LHCb)** and **dijet (CMS)** data to constrain **small-*x* nuclear gluon**



High time for **PDF4LHC-like benchmarking** exercise now for nuclear PDF determinations!

# Comparison with other nPDF analyses

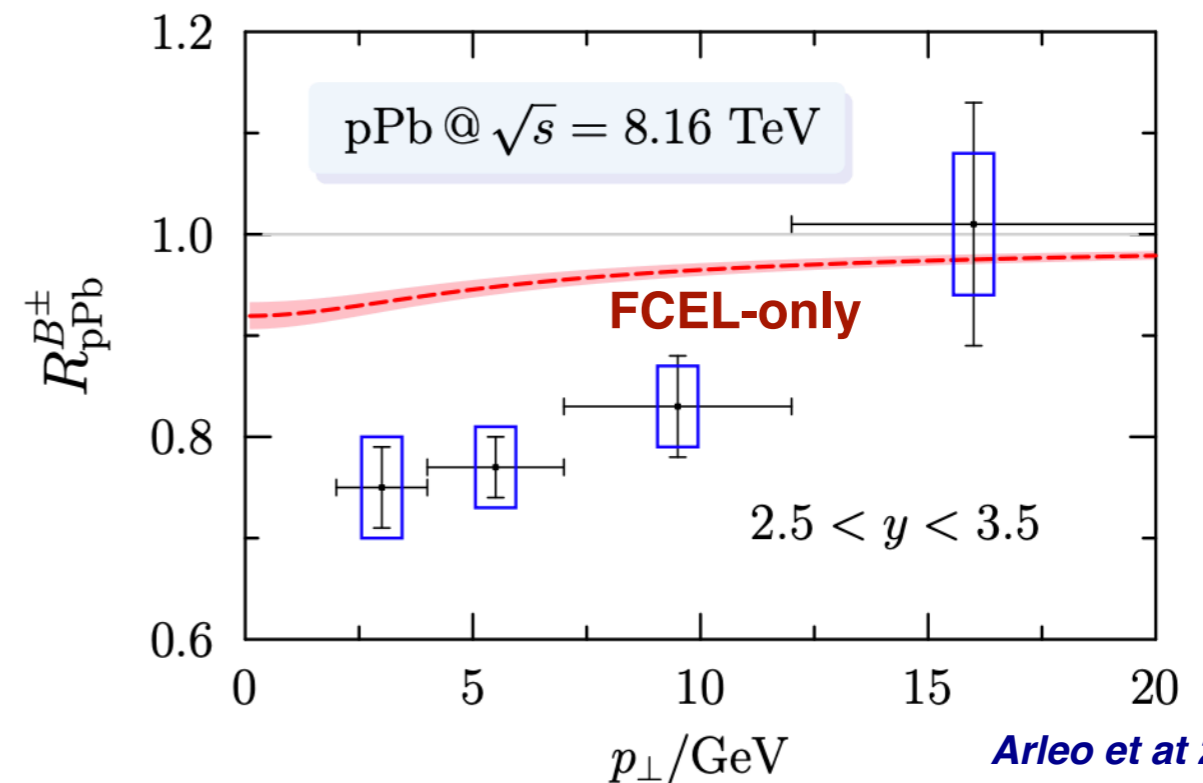
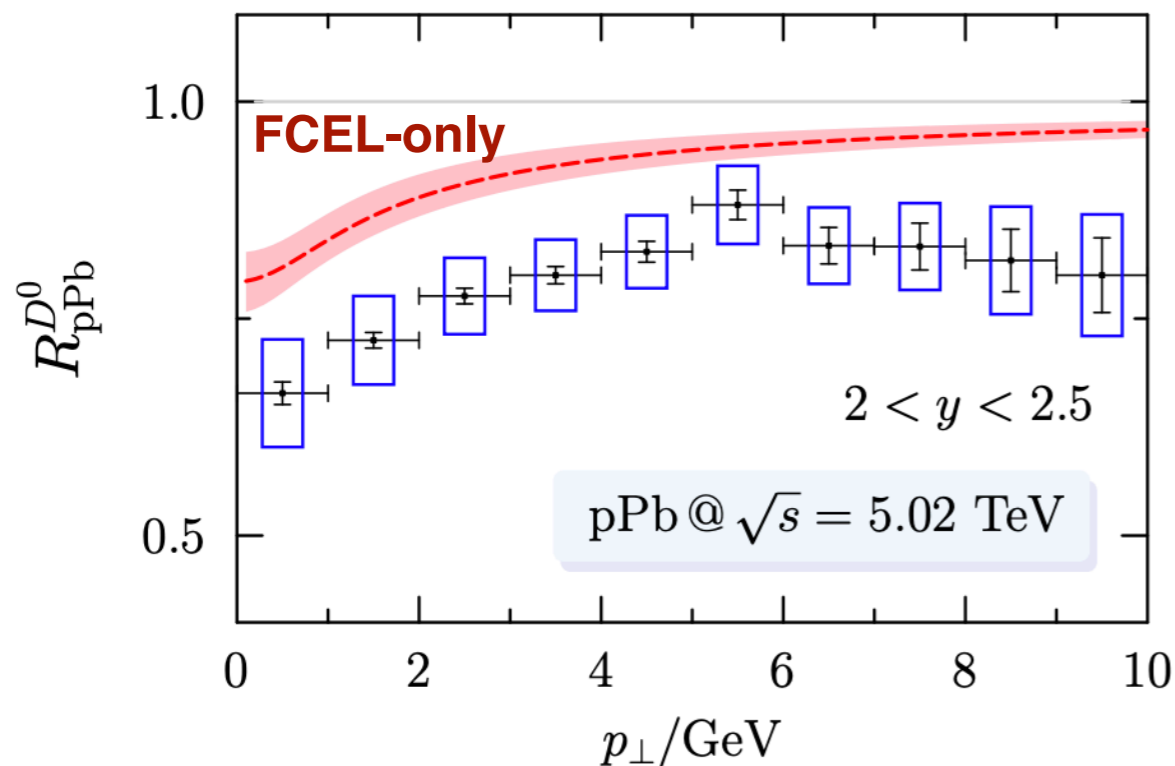
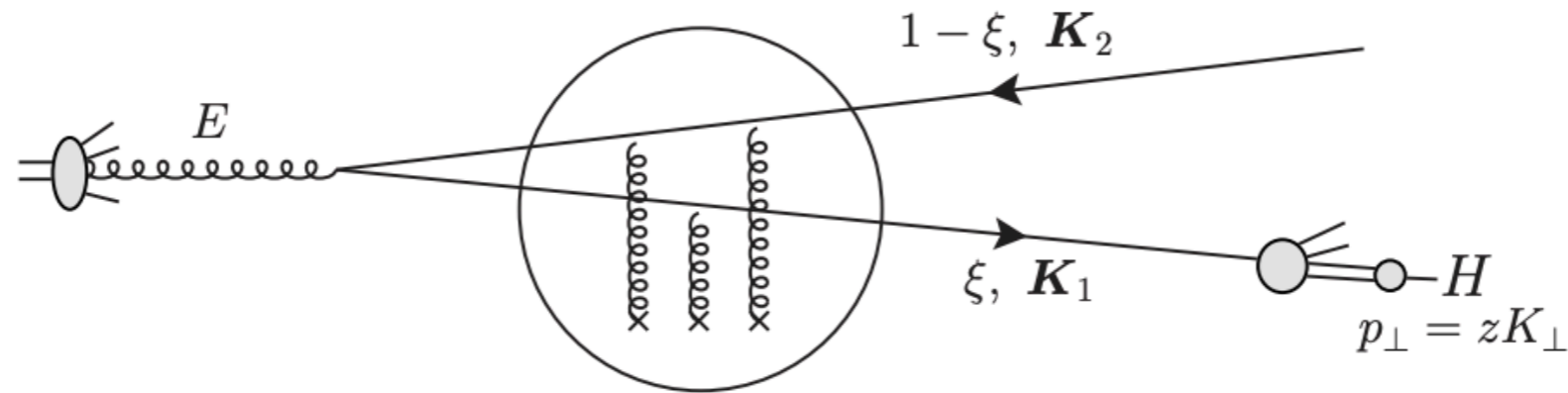
📍 EPPS21 includes **D-mesons** (LHCb) and **dijet** (CMS) data to constrain **small-x nuclear gluon**



Good agreement at small- $x$  between **EPPS21** and **nNNPDF3.0**, but in both cases relying on forward charm data

# Fully Coherent Energy Loss (FCEL)

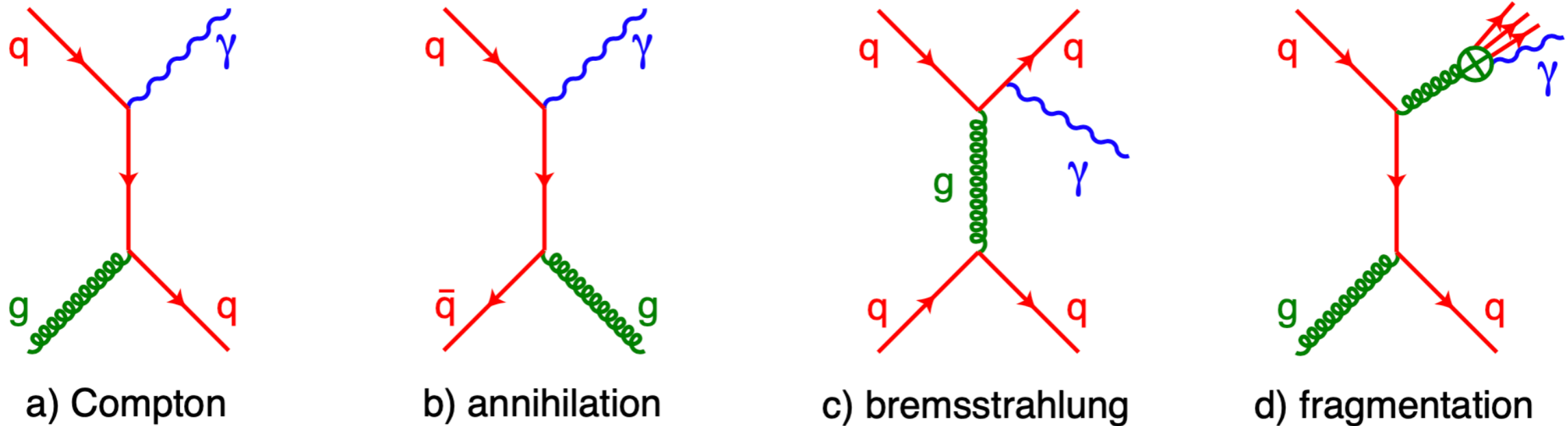
- In addition to **nPDF-related shadowing** or **saturation effects**, forward hadron production in pA collision (including charm) has been argued to **be affected by FCEL**
- The underlying partonic process is forward scattering (in the target nucleus rest frame) of an incoming high-energy parton **to an outgoing colour charge or colourful system of partons**
- Emphasises key role of **non-hadronic (photons, leptons) probes** of small-x QCD phenomena with heavy nuclei



# **Forward photons and nPDF constraints**

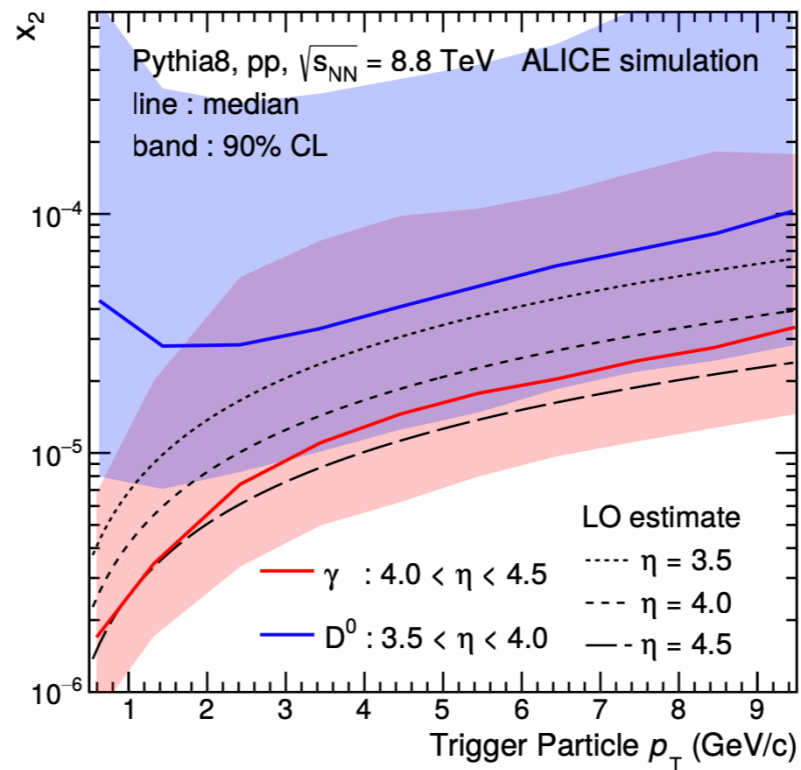
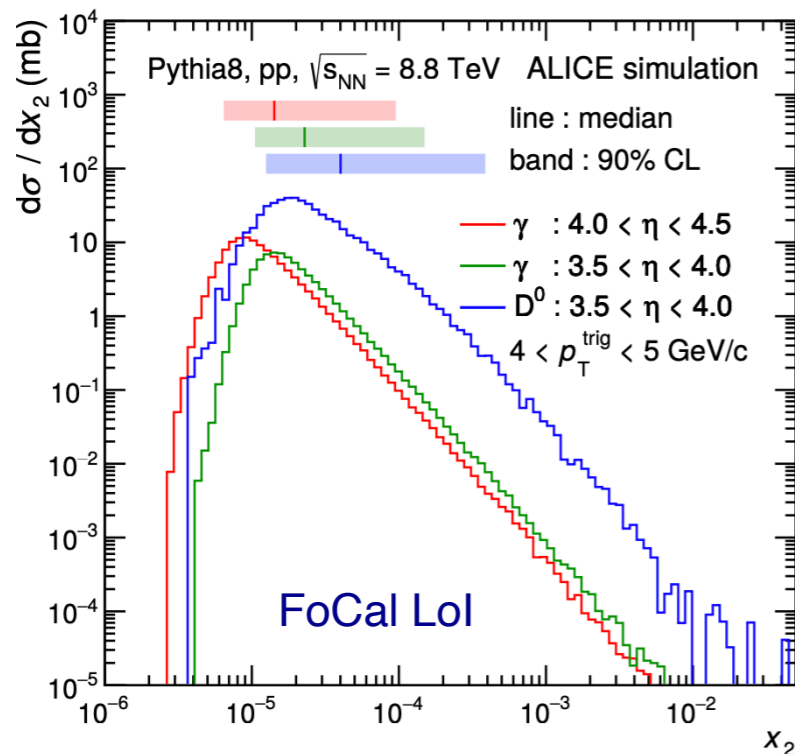
# Forward photons at the LHC

The new **Forward Calorimeter (FoCal)** of ALICE will be able to measure **prompt photons in the forward region**



Directly sensitive to the **(nuclear) gluon PDF** via the QCD Compton scattering process

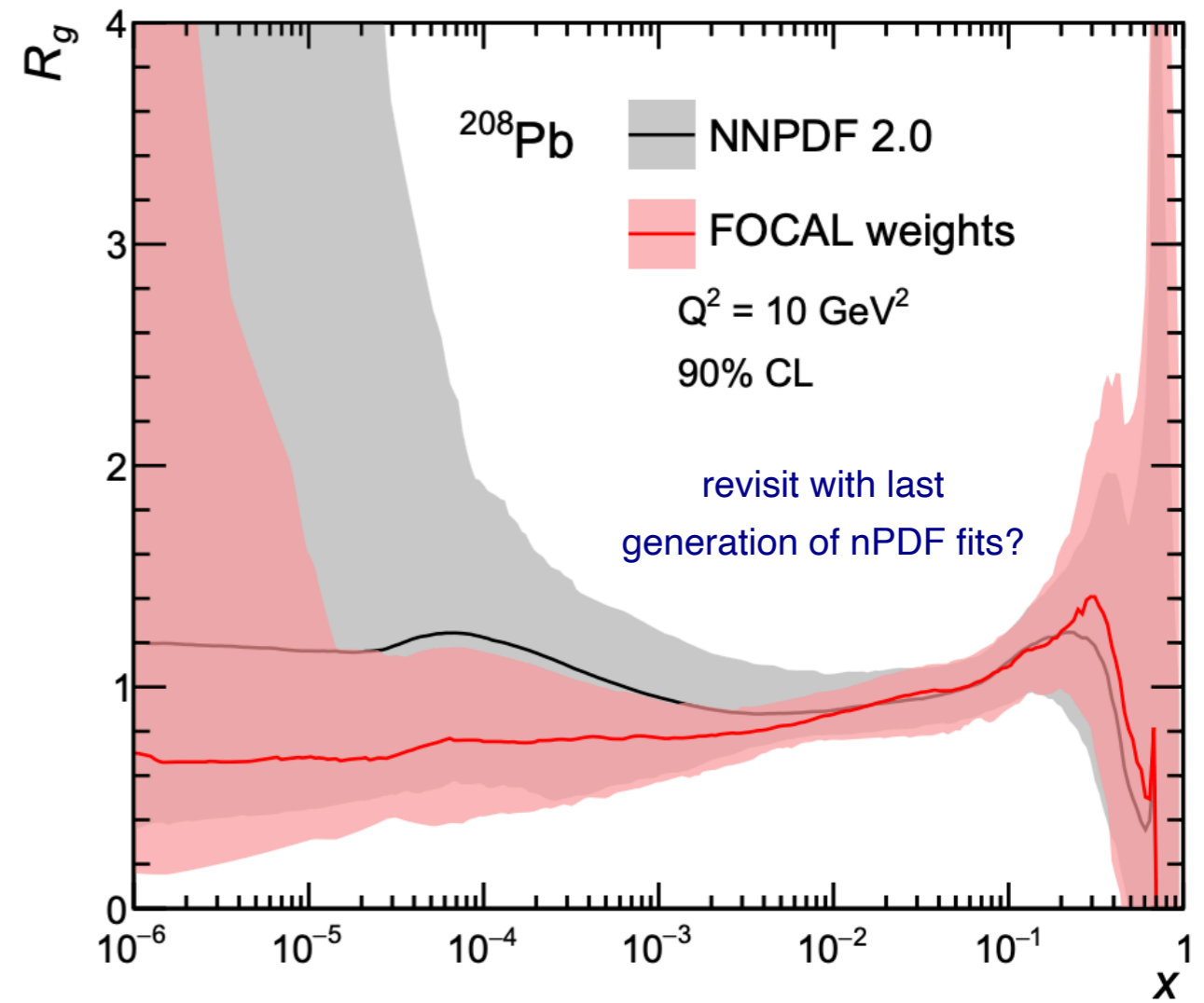
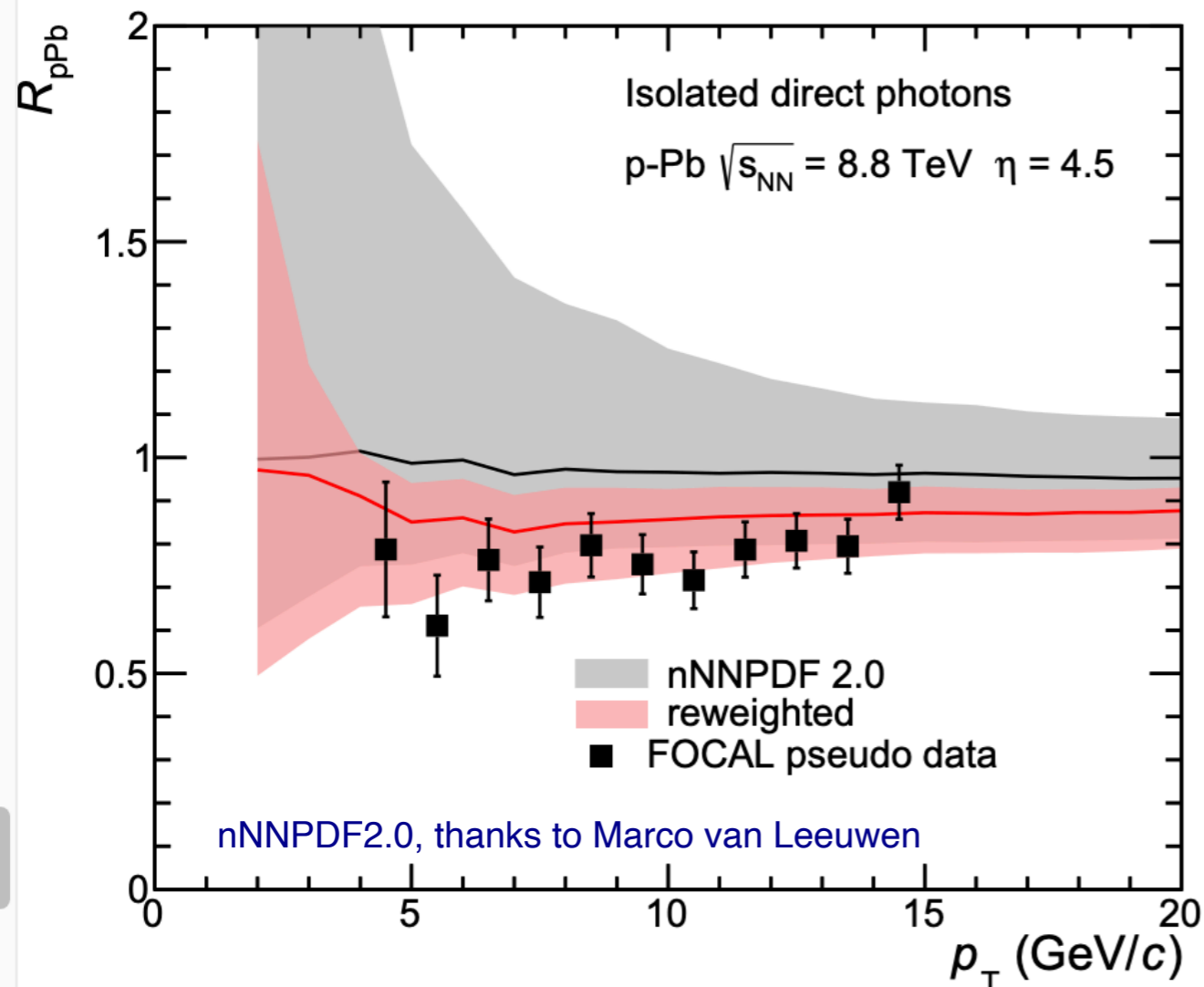
Coverage of the small- $x$  region **comparable or better than D-meson production** with very different theory and experimental systematics: **fully complementary probes** of small- $x$  QCD phenomena



**photon production** does not affected by final state or FCEL effects

# Forward photons at the LHC

- Several projection studies for the **physics reach of FoCal** have been carried out
- The ultimate sensitivity depends on the **amount of quark and gluon small-x shadowing**
- Clear sensitivity down to (at least)  $x = 10^{-5}$  demonstrated, precise and accurate QCD calculations available

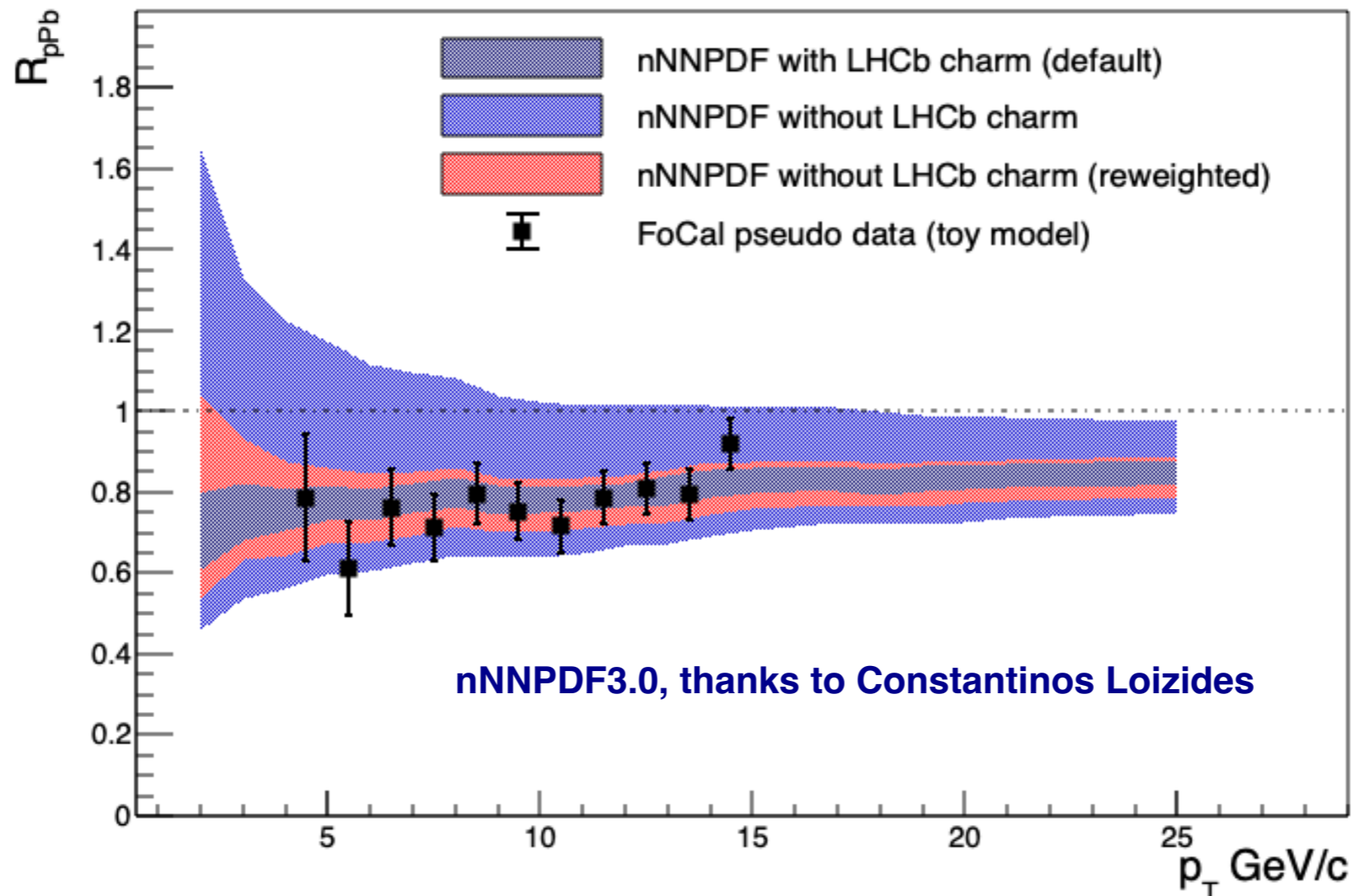


Non-linear & CGC dynamics, if present, could be **reabsorbed in the nuclear PDF fit**

Crucial to combine information from **different probes of small-x QCD** and study the kinematical dependence of the constraints and fit quality (e.g. discovery of BFKL dynamics at HERA)

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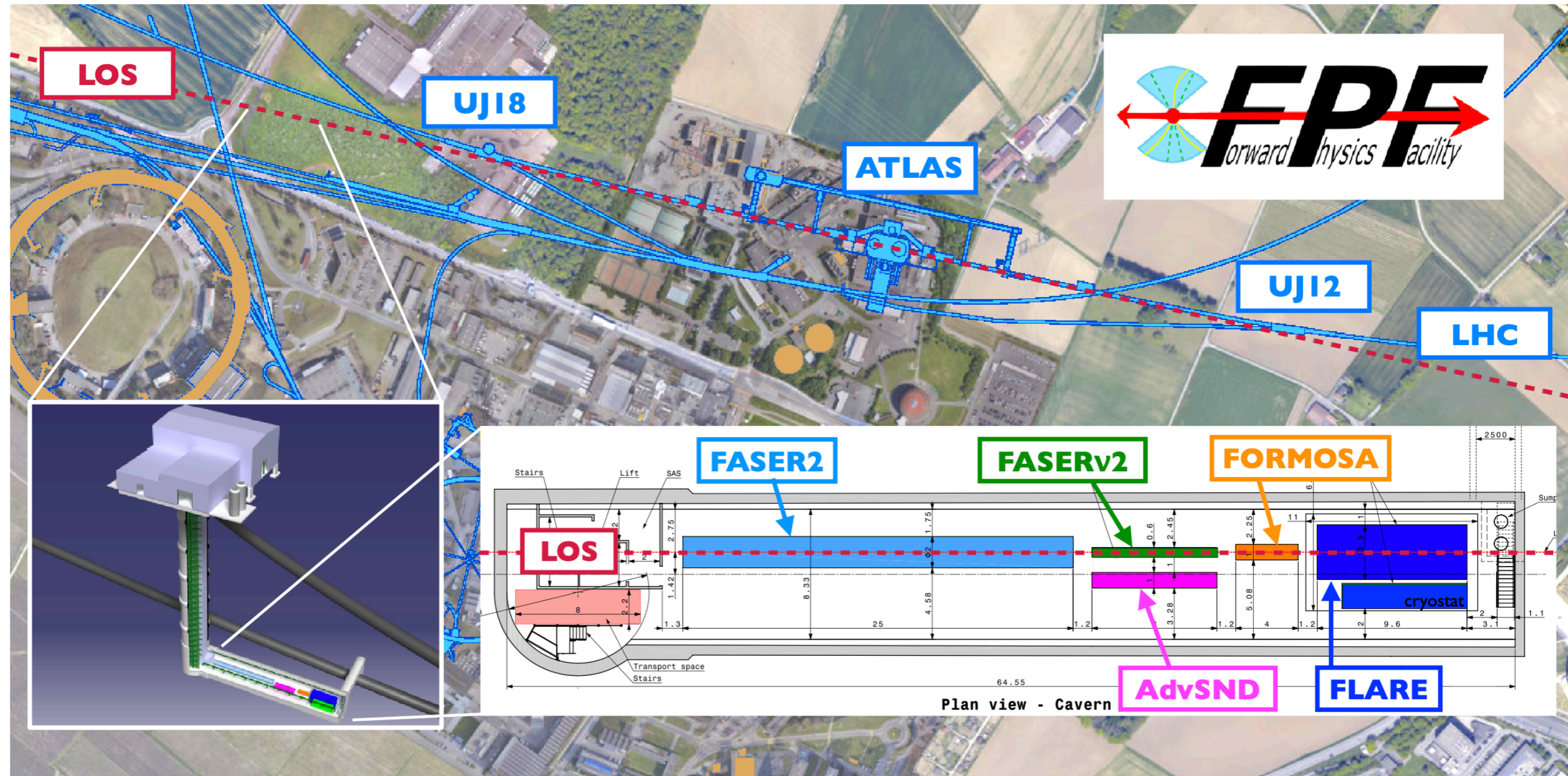
Crucial to combine information from **different probes of small-x QCD** and study the kinematical dependence of the constraints and fit quality (e.g. discovery of BFKL dynamics at HERA)



# **The Forward Physics Facility @ HL-LHC**

# The Forward Physics Facility

A proposed new facility in a tailor-made underground cavern hosting a suite of **far-forward experiments** suitable to detect **long-lived BSM particles** and **neutrinos** produced at the **High-Luminosity LHC** (ATLAS interaction point)



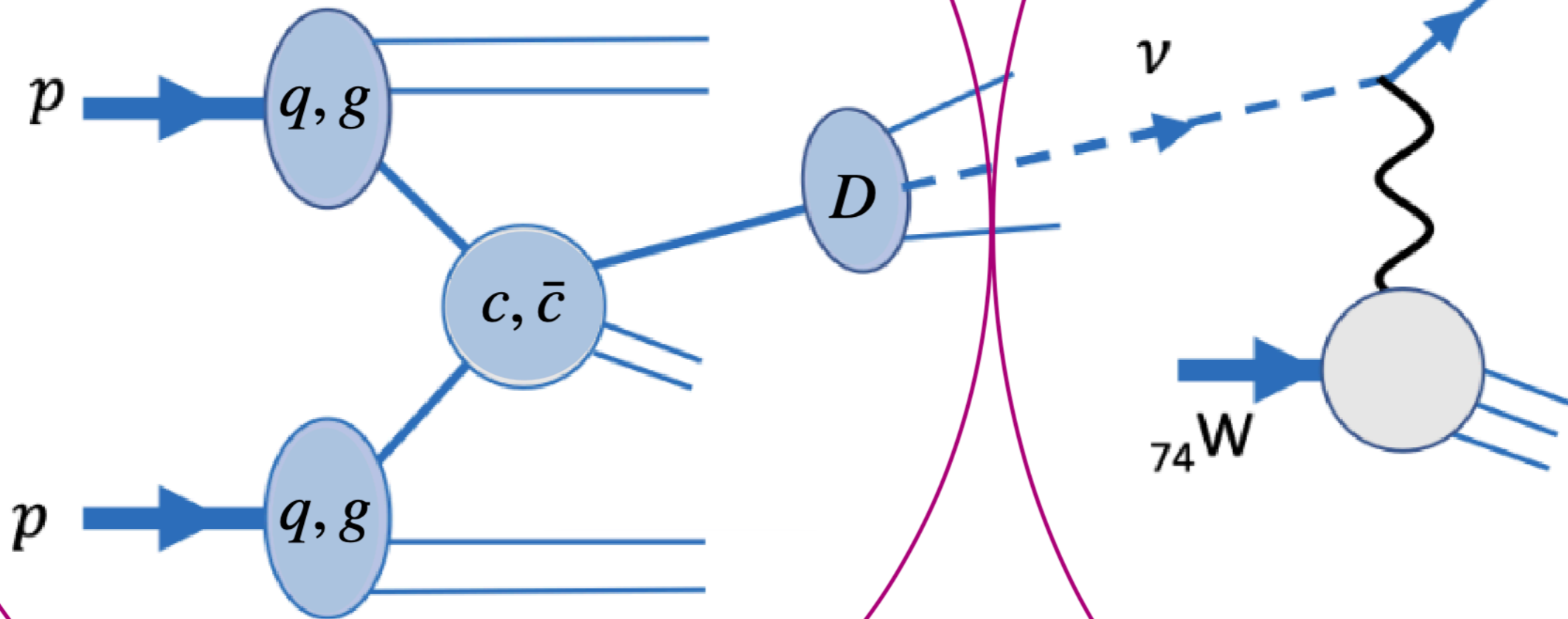
**No modifications to the HL-LHC operations required**

# The Forward Physics Facility

$$\sqrt{s} = 14 \text{ TeV}$$

**ATLAS**

**FPF**



Huge **neutrino** fluxes produced in LHC collisions: **blind spot** of planned LHC operations!

# small-x QCD at the FPF

**ATLAS**

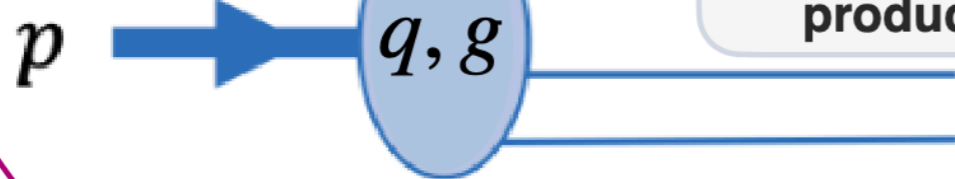
probing intrinsic charm

hadron fragmentation

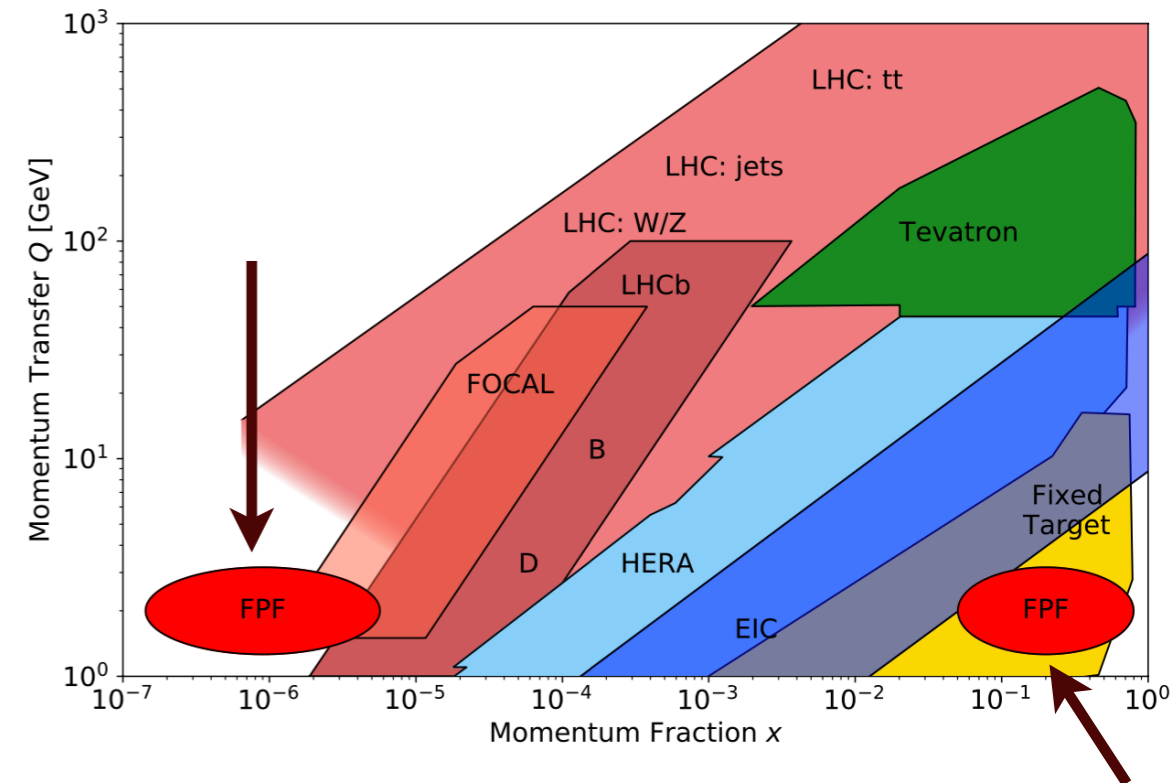


BFKL dynamics, non-linear QCD, CGC

forward D-meson production

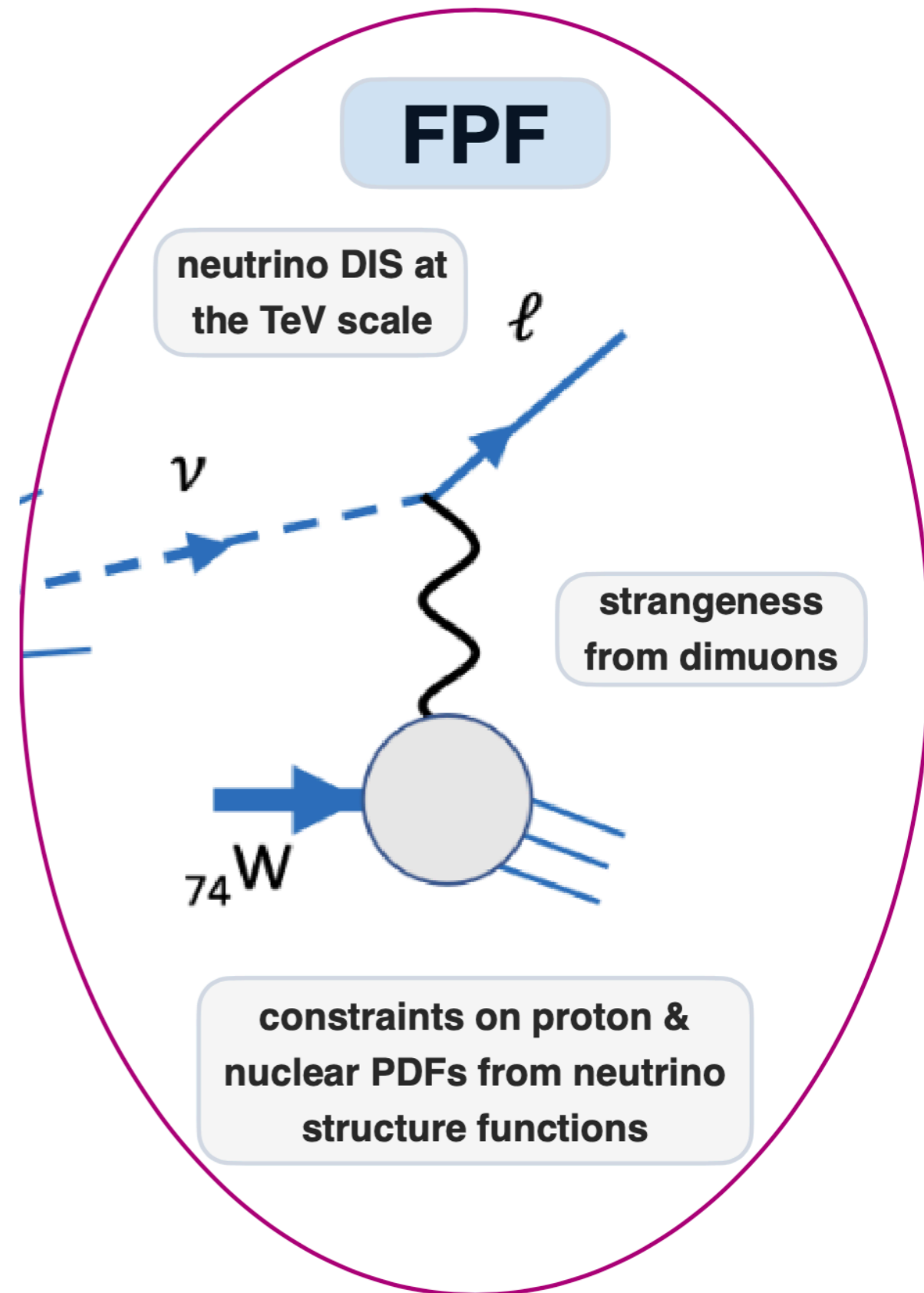
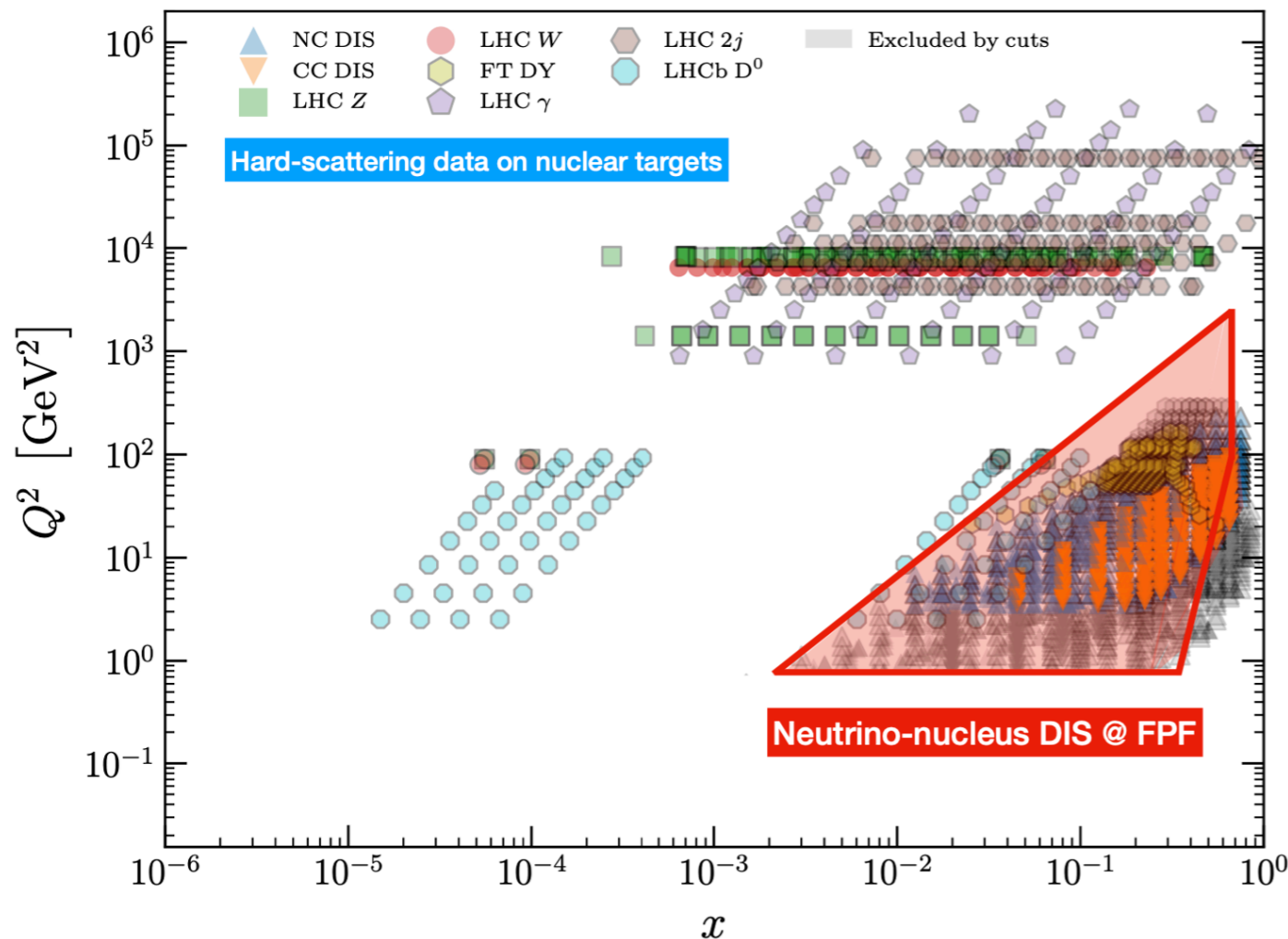


ultra small x proton structure



- **Forward particle production** (light hadrons & D-mesons) sensitive down to  $x=10^{-7}$
- Ultra small-x proton structure & **BFKL / non-linear QCD** dynamics
- Tune models of forward hadron fragmentation (for e.g. cosmic rays)
- Constraints on **intrinsic charm** from large-x D-meson production

# Neutrino DIS at the LHC



- Deep-inelastic CC scattering with **TeV neutrinos**: validate our understanding of neutrino cross-sections (relevant for oscillation experiments)
- Continue successful program of neutrino **DIS experiments @ CERN**
- Constrain proton & nuclear **light (anti-)quark PDFs** including strangeness

# Overview of forward processes for (n)PDFs

Process	Availability	Strengths	Weaknesses
<i>D</i> -meson production	LHCb (pp & pA)	Large production xsec Clean identification BFKL resummation wip	Large MHOUs, dependence on charm fragmentation, interplay with IC, impact of FCEL
Prompt photon	FoCal@ALICE pp & pA (> 2027)	Electroweak probe NNLO QCD + NLO EW xsec Gluon PDF from QCD-Compton	Fragmentation component?
Single inclusive light hadron production	RHIC, TeVatron & LHC (pp & pA)	Large production xsecs	Dependence on fragmentation functions, impact of FCEL
Quarkonia production	RHIC & LHC (pp & pA)	Large statistics, well-understood measurement in HI collisions	Modelling of production matrix elements, final state effects
Deep-Inelastic Scattering	HERA (ep) EIC (ep & eA) (> 2030)	Very clean EW elementary probe Access different <i>A</i> -nuclei Inclusive & exclusive (charm)	Reach in ep of the EIC not competitive with HERA
Inclusive weak boson & Drell-Yan production	LHCb (pp & pA)	Clean EW probe High-precision of QCD differential calculations	Limited statistics in pA Initial state quark-dominated
Neutrinos @ LHC	FaserNu & SND@LHC (Run III) Forward Physics Facility (>2030)	Coverage of ultra low-x region from charm production	Disentangle neutrino flux from charm, interplay with neutrino DIS at the target

# Summary and outlook

- ✓ **Forward particle production** in pp and pA collisions provides direct access to many exciting phenomena in **small-x QCD** and **hadronic & nuclear structure**
- ✓ In the collinear factorisation framework, different forward processes **exhibit complementary strengths and weaknesses to probe small-x QCD**, e.g. *D*-meson production is abundant but suffers from large MHOUs while prompt photons provide a clean electroweak probe
- ✓ Disentangling **nPDF shadowing** and **BFKL resummation dynamics** from non-linear QCD & CGC effects and other phenomena (such as FCEL) demands a **coherent global theory interpretation** of relevant forward processes in pp and pA combining the information from **HERA and the (HL-)LHC** with future experiments such as **FoCal, the EIC, and the FPF**

