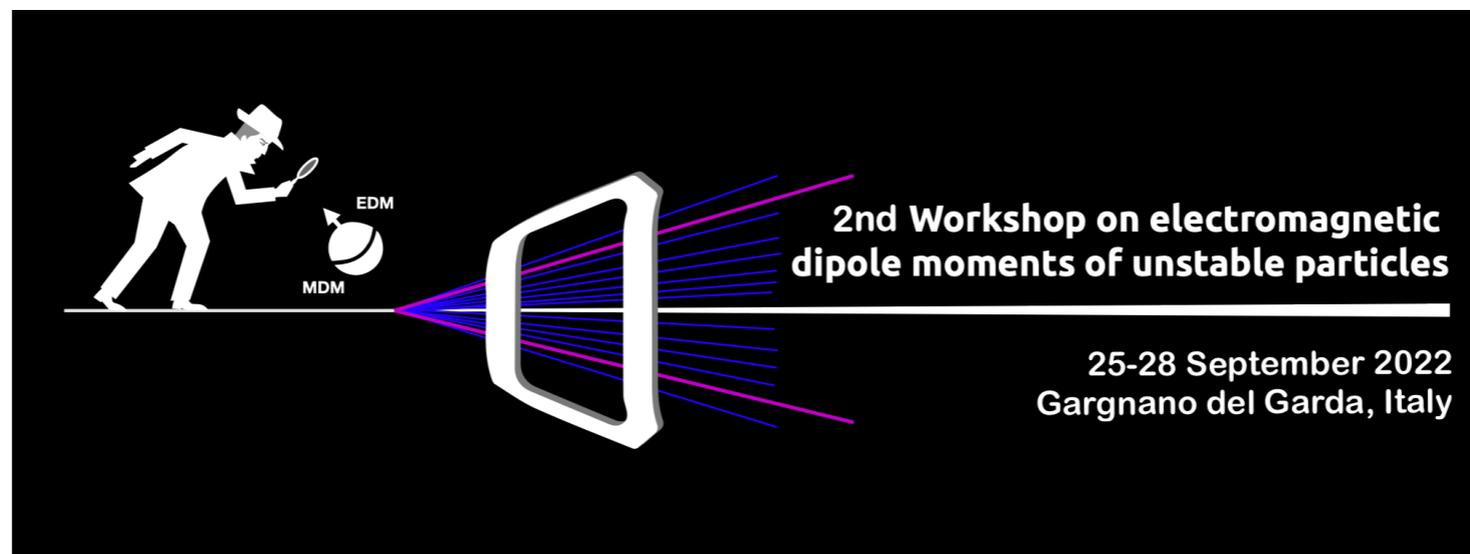


Heavy hadron production in the very forward region at the LHC

Juan Rojo, VU Amsterdam & Nikhef



2nd Workshop on Electromagnetic Dipole Moments of Unstable Particles

Gargnano del Garda, 26th September 2022

Forward particle production @ LHC

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

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

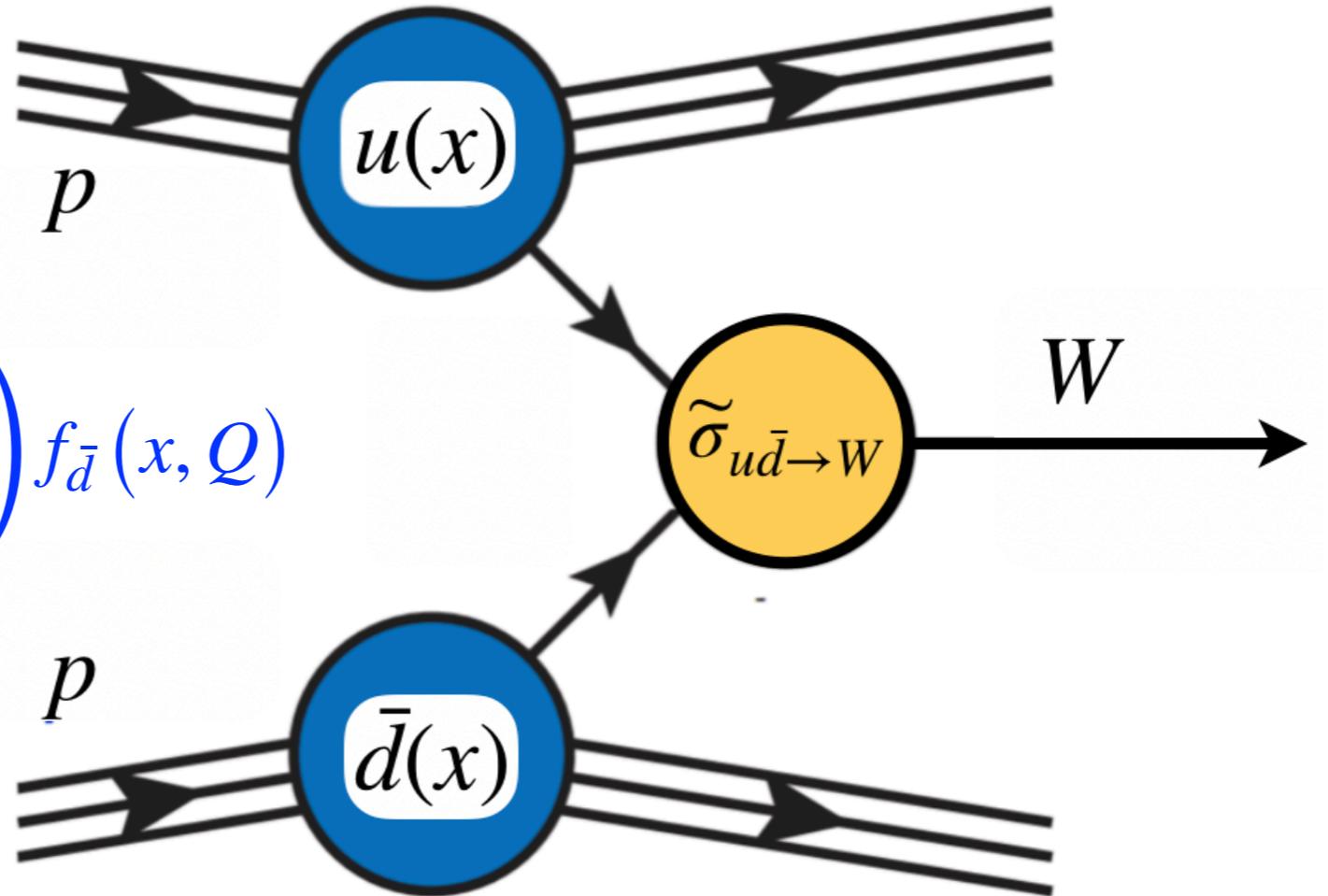
*proton Parton Distribution
Functions (PDFs)*

*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 particle production @ LHC

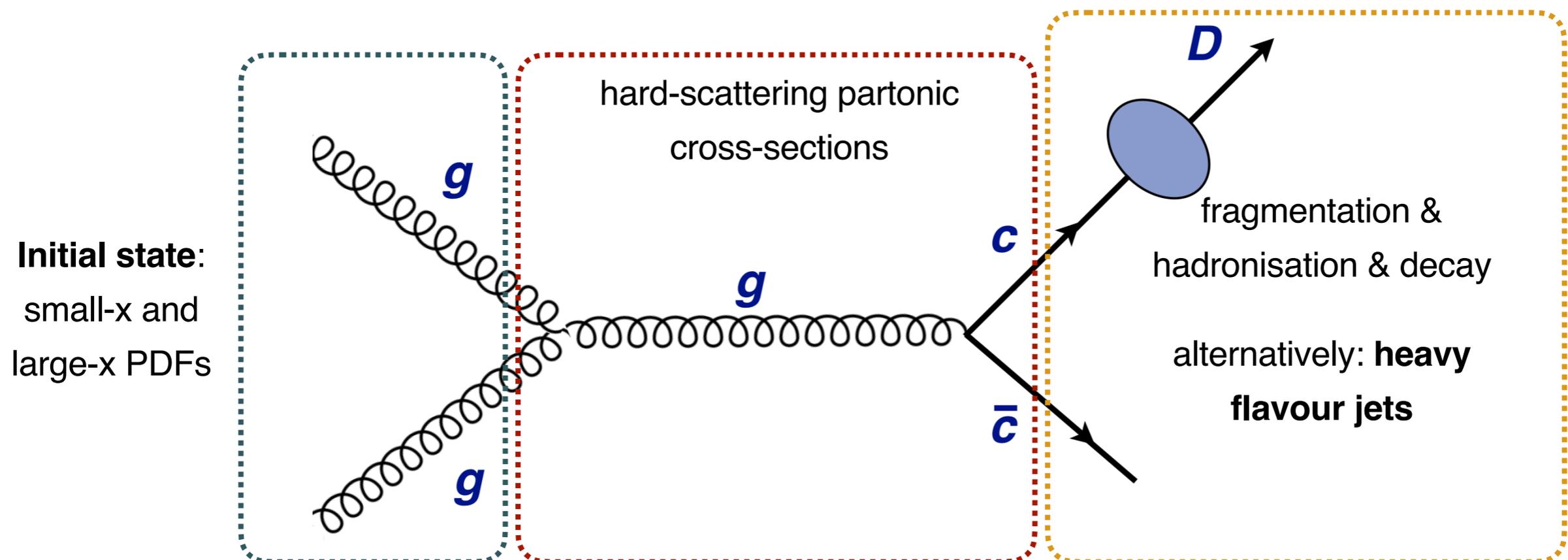
Precise predictions for **forward charm and bottom hadron production** requires:

$$\sigma_X(M_X, s) \sum_{i,j} \propto \int_{M_X^2}^s d\hat{s} \mathcal{L}_{ij}(\hat{s}, s) \tilde{\sigma}_{ij \rightarrow X}(\hat{s}, \alpha_s(M_X)) \quad x_{1,2} = \frac{M_X}{\sqrt{s}} e^{\pm y_W}$$

knowledge of **proton PDFs** at very small- and very large-x

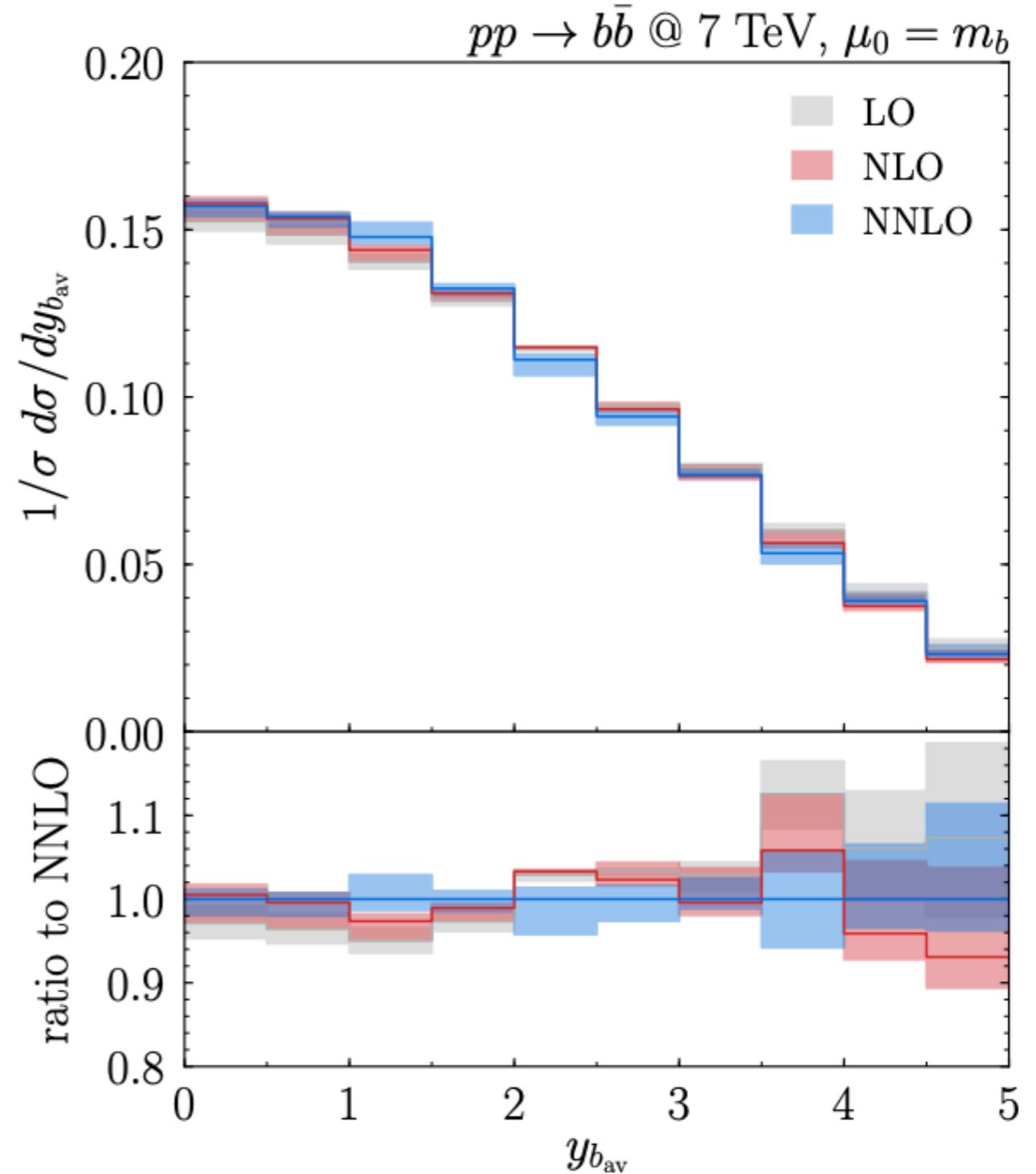
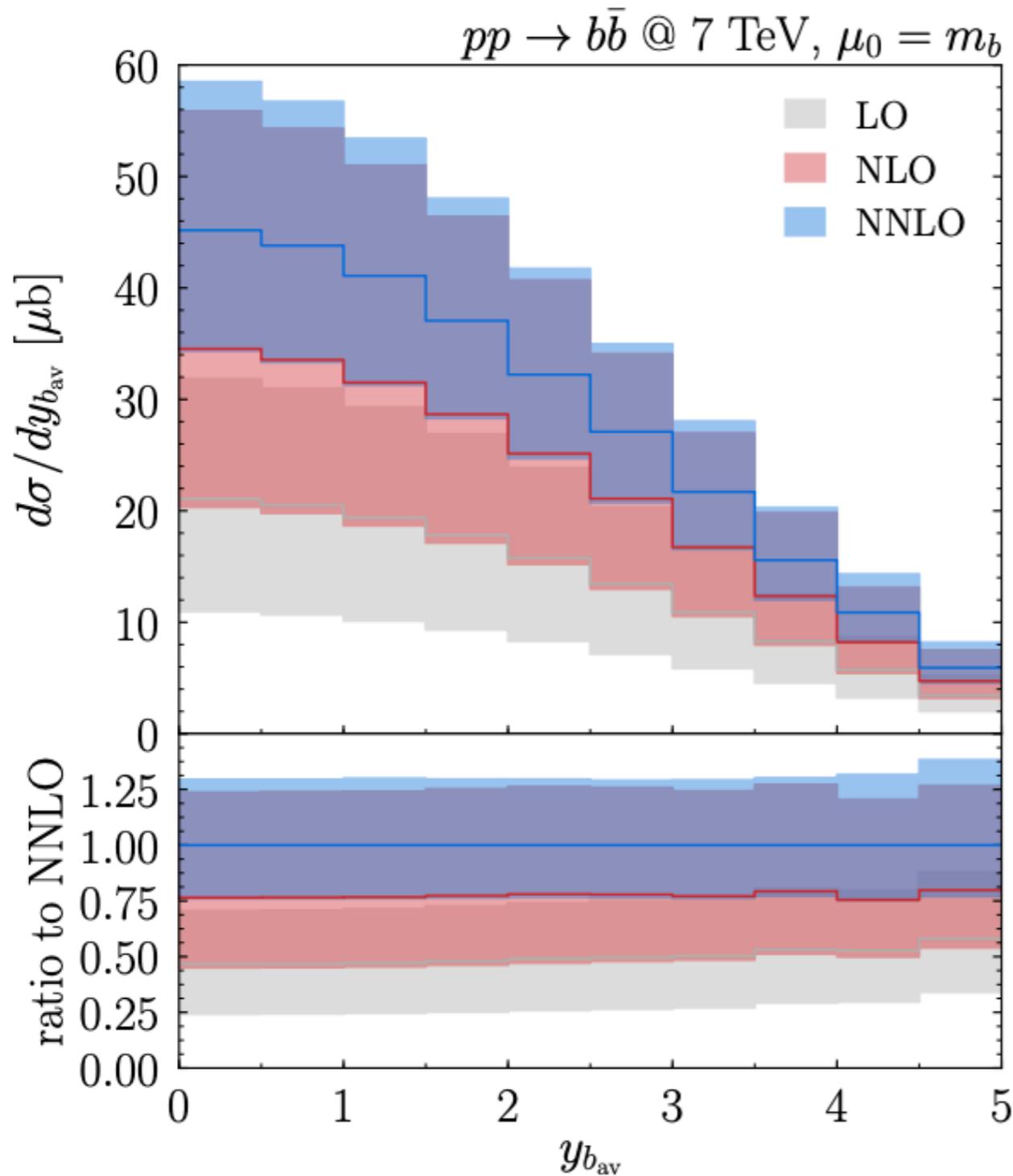
knowledge of **hard scattering cross-sections** at low masses

in addition, **heavy quark fragmentation/hadronisation** & decays need also to be modelled



Heavy quark production

☛ For bottom quarks, fully differential cross-sections available up to **NNLO in pQCD**



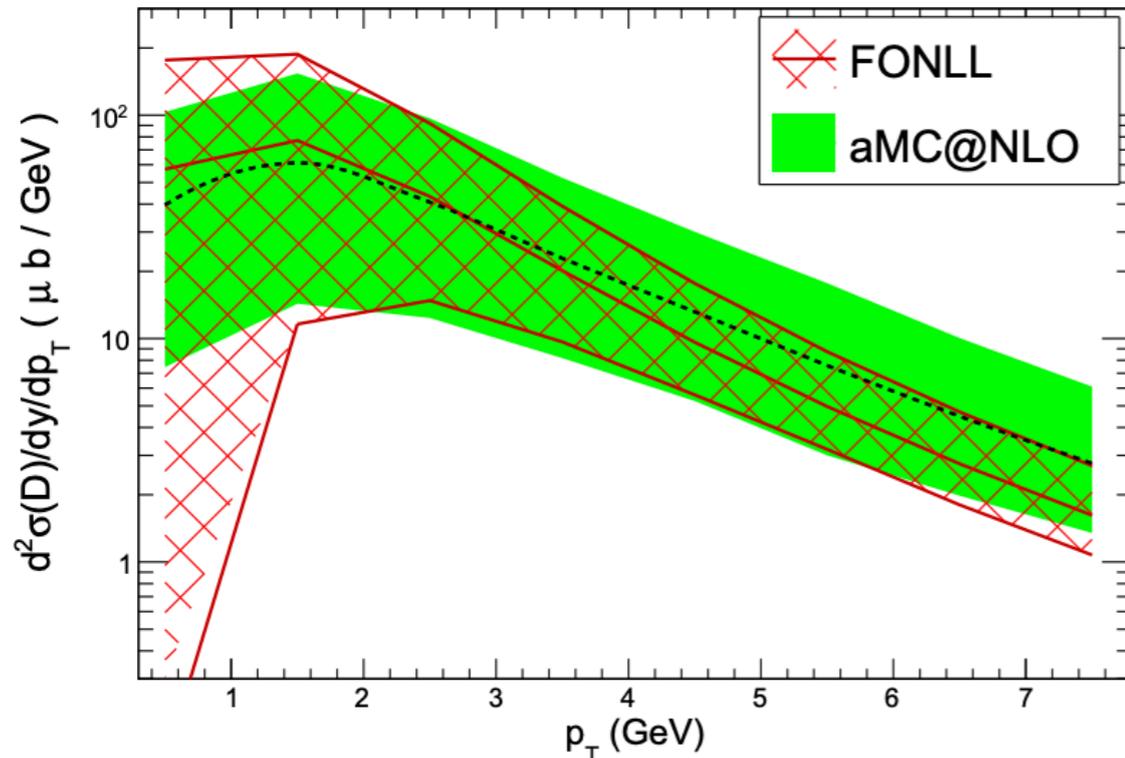
☛ Even at NNLO scale errors on absolute rates are $O(25\%)$, can be markedly reduced by working with **normalised distributions**

Heavy quark production

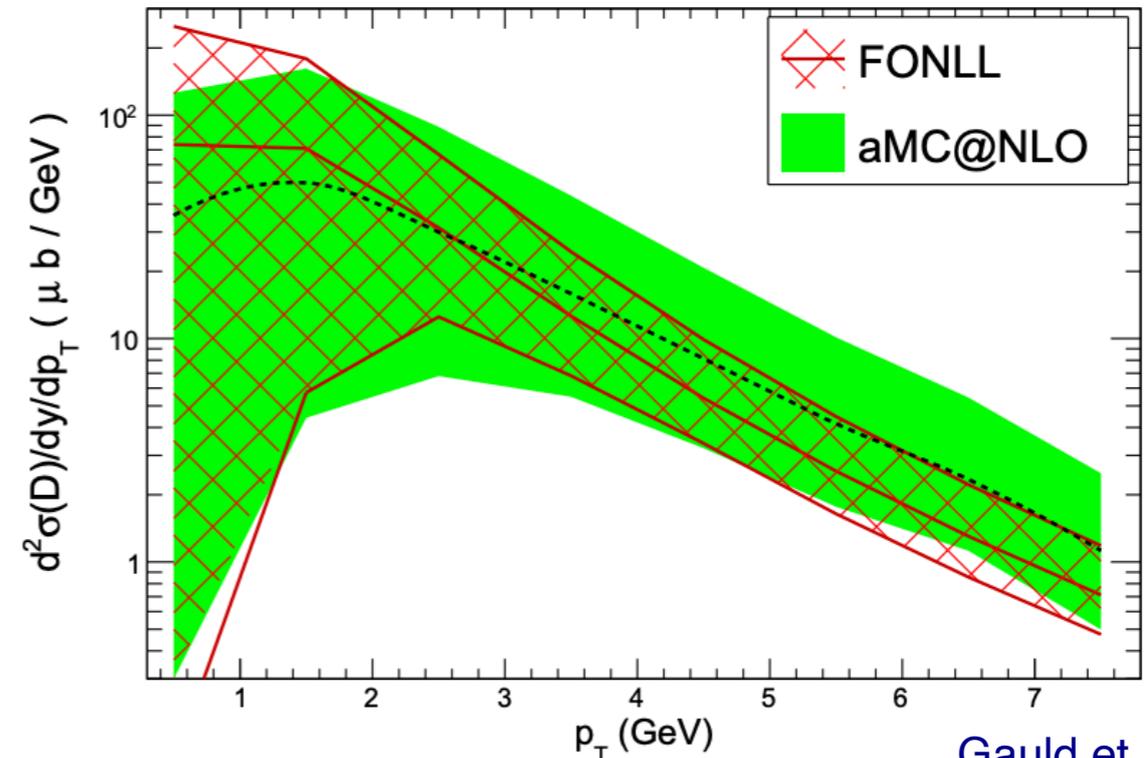
For charm quarks NNLO is not available, state of the art is **NLO+resummation (FONLL)**

All order resummation of logs of the form $\alpha_s^n(m_c)\log^m(p_T^c/m_c)$

NNPDF3.0, Scales+PDFs, D^0 mesons, $2.0 < y < 2.5$

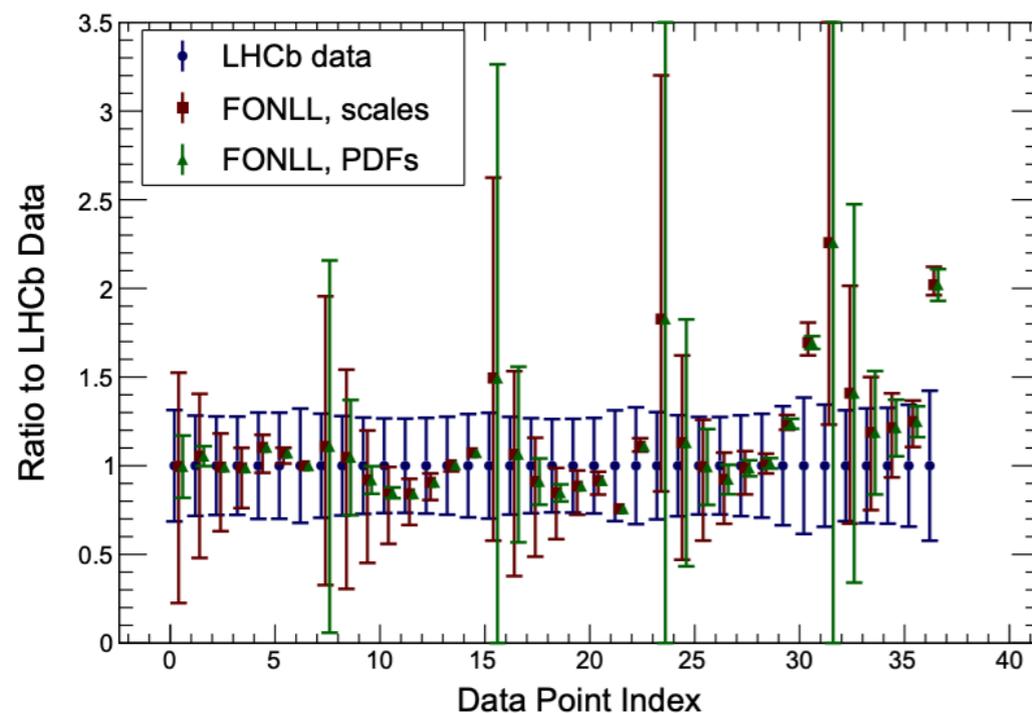


NNPDF3.0, Scales+PDFs, D^0 mesons, $3.5 < y < 4.0$



Gauld et al 15

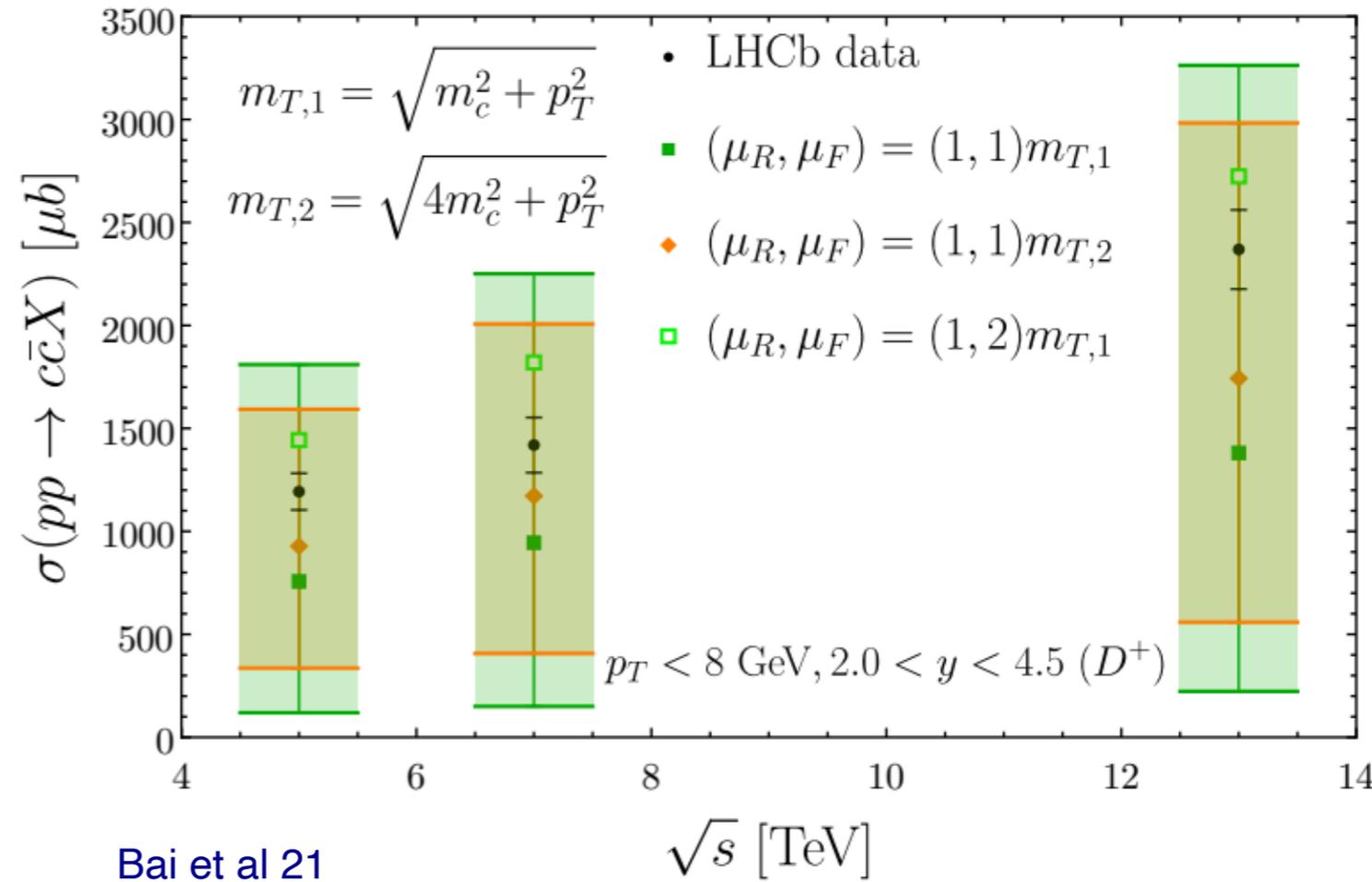
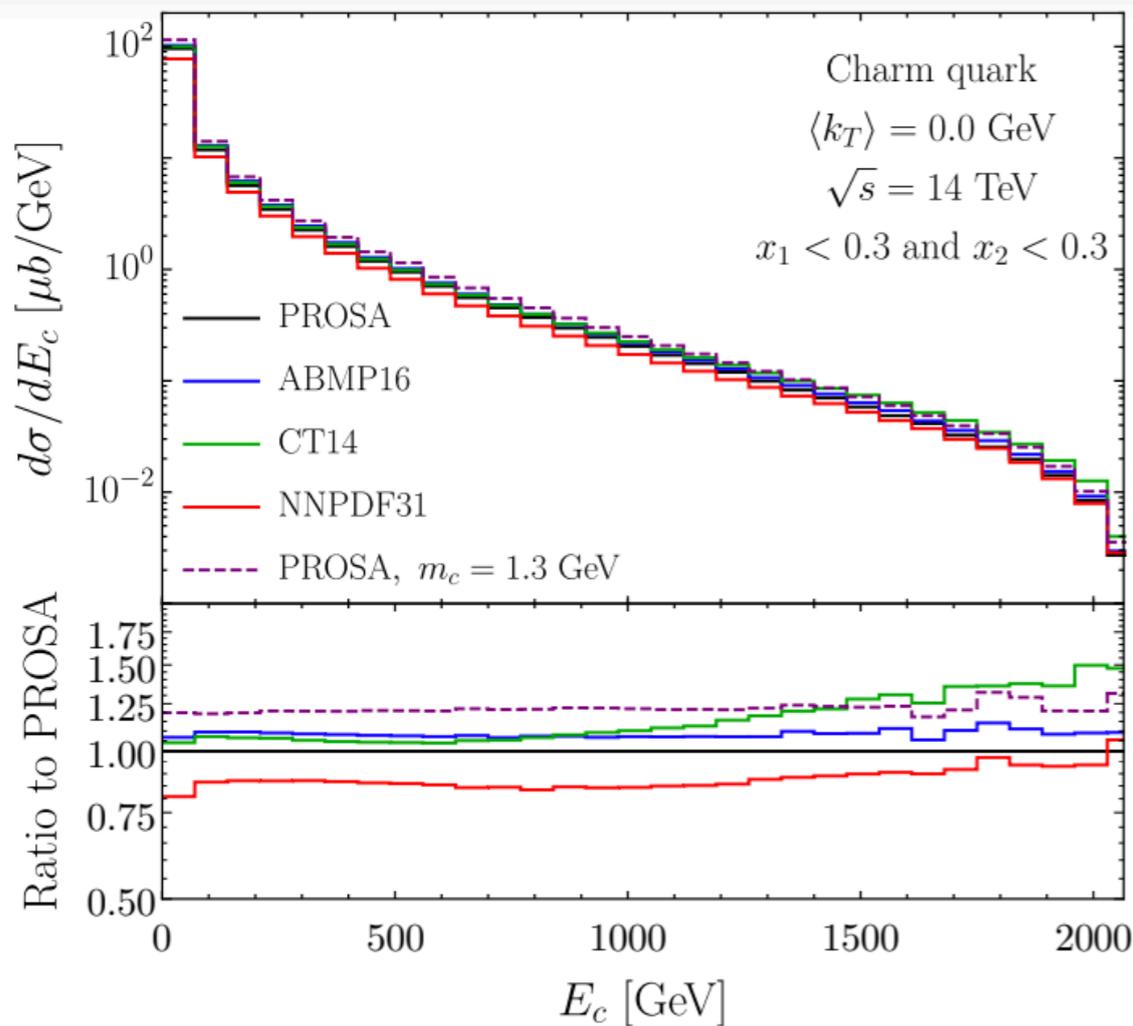
7 TeV D^{*+} normalized



- Large scale uncertainties in NLO+NLL calculation
- Partially cancel out in **ratios** to e.g. reference bin of between CoM energies [Mangano and JR 12](#)
- Perturbative expansion converges poorly at $Q = m_c$
- Comparison with data requires **fragmentation model**

Heavy quark production

As for bottom quarks, bulk of NLO scale error from **overall cross-section normalisation**



NLO pQCD predictions also available for distributions relevant for **fixed-target kinematics**, such as the total charm quark energy

Any prediction for heavy quark and meson production in p+p collisions needs to carefully assess the three intertwined sources of theory error: **PDFs, MHOUs, and fragmentation**

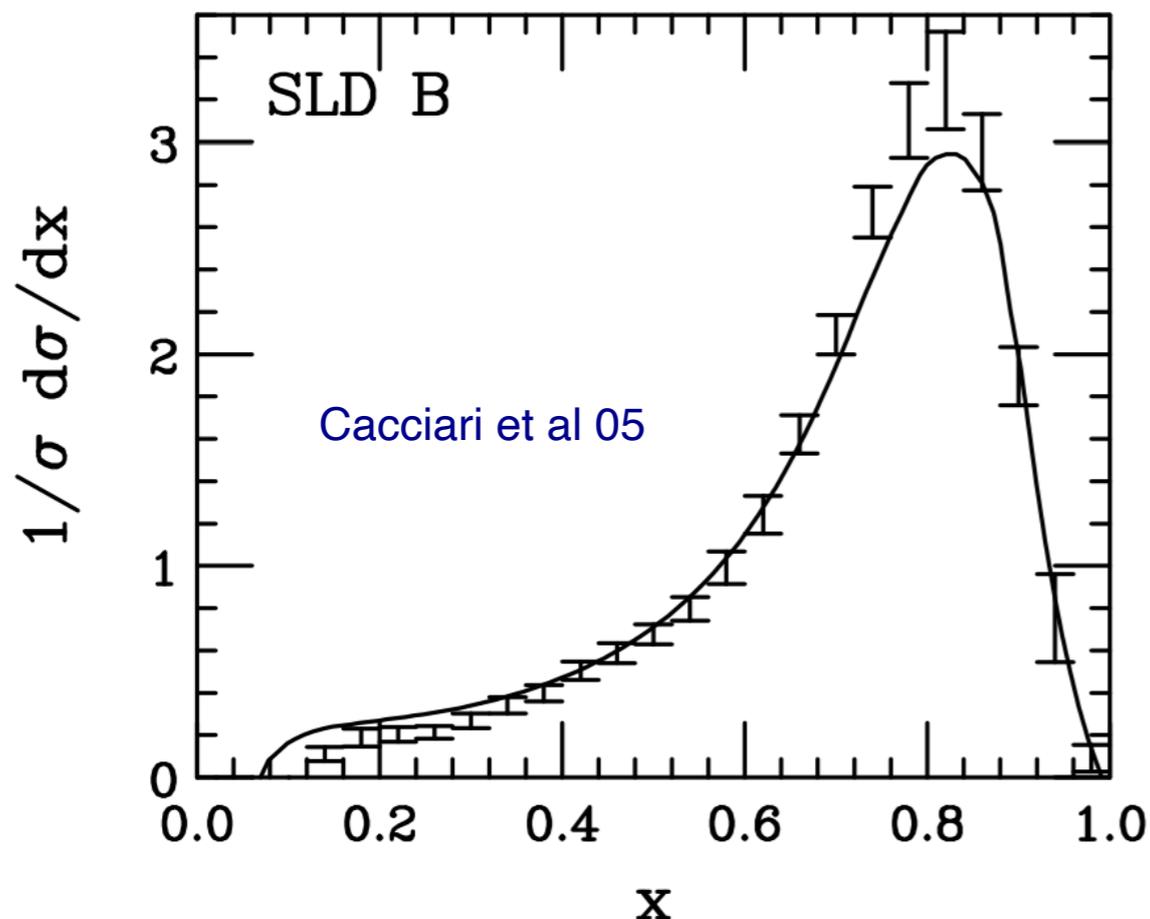
Heavy quark fragmentation

- Quarks are not observable: to connect theory with experiment we need theory predictions for either **heavy hadrons** or **heavy flavour jets**
- Heavy flavour **fragmentation functions** obey DGLAP-type evolution equations and the non-perturbative component can be extracted from experimental data

$$e^+e^- \rightarrow Z/\gamma (q) \rightarrow Q (p) + X \quad x \equiv \frac{2p \cdot q}{q^2}$$

$$\frac{d\sigma_{P,Q}}{dx}(x, q^2, m^2) = \sum_i \int_x^1 \frac{dz}{z} C_{P,i}(z, q^2, \mu^2) D_i\left(\frac{x}{z}, \mu^2, m^2\right)$$

heavy quark FF



- Existing FFs based on **electron-positron collider data**, constraints from LHC not exploited

- Different models for FF available

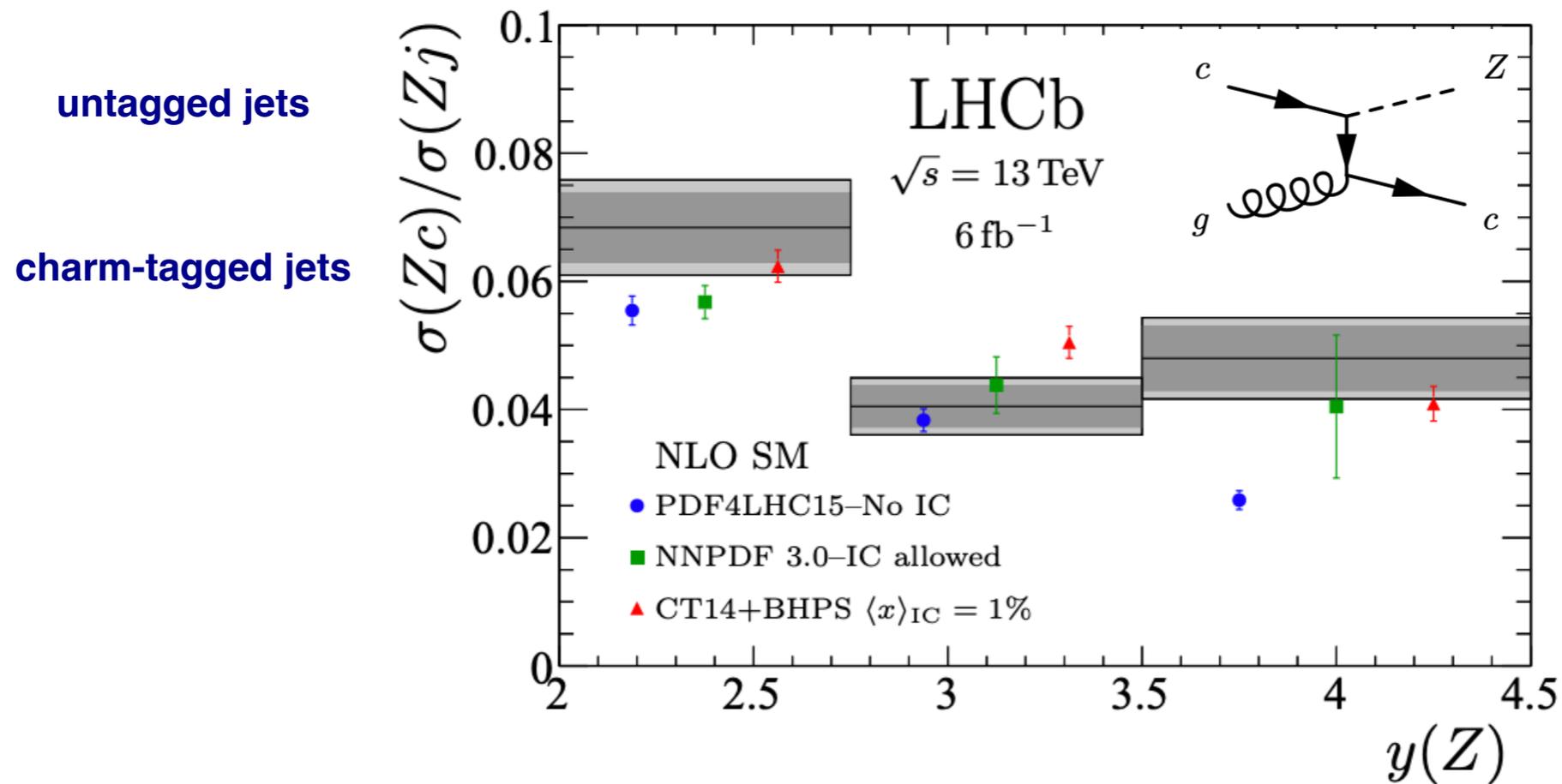
e.g Peterson FF $f(z) \propto 1/[z(1 - \frac{1}{z} - \frac{\epsilon}{(1-z)})^2]$

z = ratio between partonic and hadronic energy

- Heavy quark hadronisation models in **MC event generators** are different from pQCD fragmentation

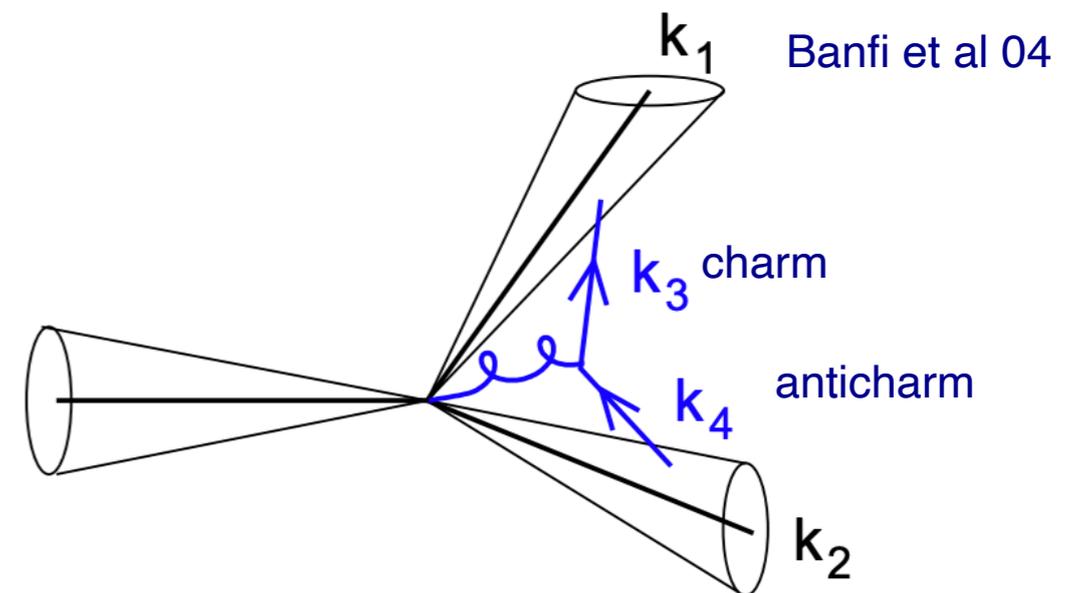
Heavy quark fragmentation

- 📍 **Heavy flavour jets** are jets containing a **heavy meson or hadron** among its constituents
- 📍 Used frequently in experimental measurements, e.g. LHCb **Z+c** measurement



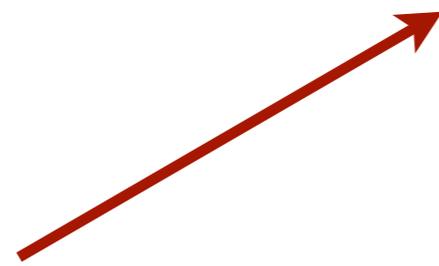
- 📍 Tension between exp. definitions and pQCD-based ones that **guarantee soft and collinear safety**

Modify jet clustering algorithm, but challenge to implement it experimentally

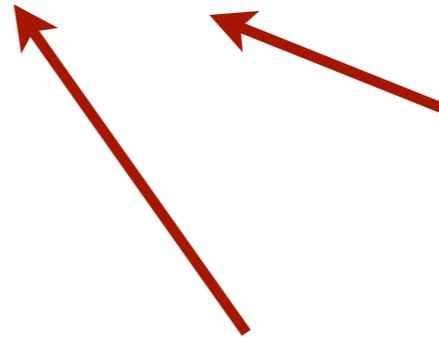


Parton Distributions

$$g(x, Q)$$



Probability of finding a gluon inside a proton, carrying a fraction x of the proton momentum, when probed with energy Q



Energy of hard-scattering reaction:
inverse of resolution length

x : fraction of proton momentum carried by gluon

Dependence on x fixed by **non-perturbative QCD dynamics**: extract from experimental data

$$g(x, Q_0, \{a_g\}) = f_g(x, a_g^{(1)}, a_g^{(2)}, \dots)$$

constrain from data

🔗 **Quark number conservation**

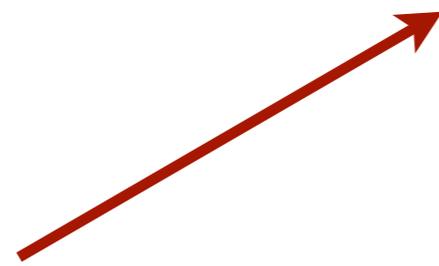
$$\int_0^1 dx (u(x, Q^2) - \bar{u}(x, Q^2)) = 2$$

🔗 **Energy conservation**: momentum sum rule

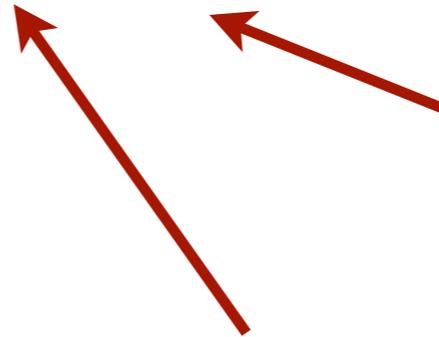
$$\int_0^1 dx x \left(\sum_{i=1}^{n_f} [q_i(x, Q^2) + \bar{q}_i(x, Q^2)] + g(x, Q^2) \right) = 1$$

Parton Distributions

$$g(x, Q)$$



Probability of finding a gluon inside a proton, carrying a fraction x of the proton momentum, when probed with energy Q



Energy of hard-scattering reaction:
inverse of resolution length

x : fraction of proton momentum carried by gluon

Dependence on Q fixed by **perturbative QCD dynamics**: computed up to $\mathcal{O}(\alpha_s^4)$

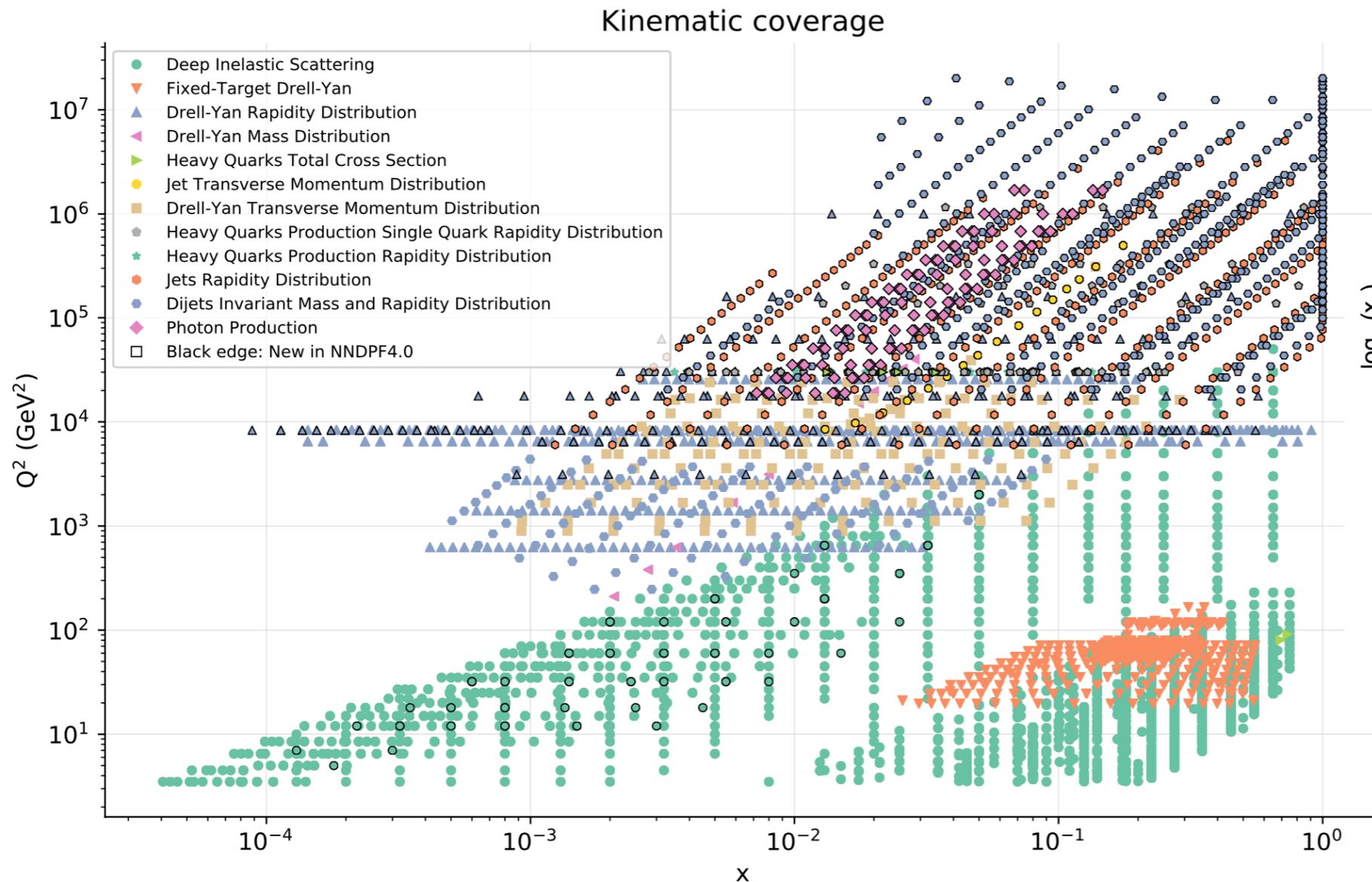
$$\frac{\partial}{\partial \ln Q^2} q_i(x, Q^2) = \int_x^1 \frac{dz}{z} P_{ij} \left(\frac{x}{z}, \alpha_s(Q^2) \right) q_j(z, Q^2)$$

DGLAP parton evolution equations

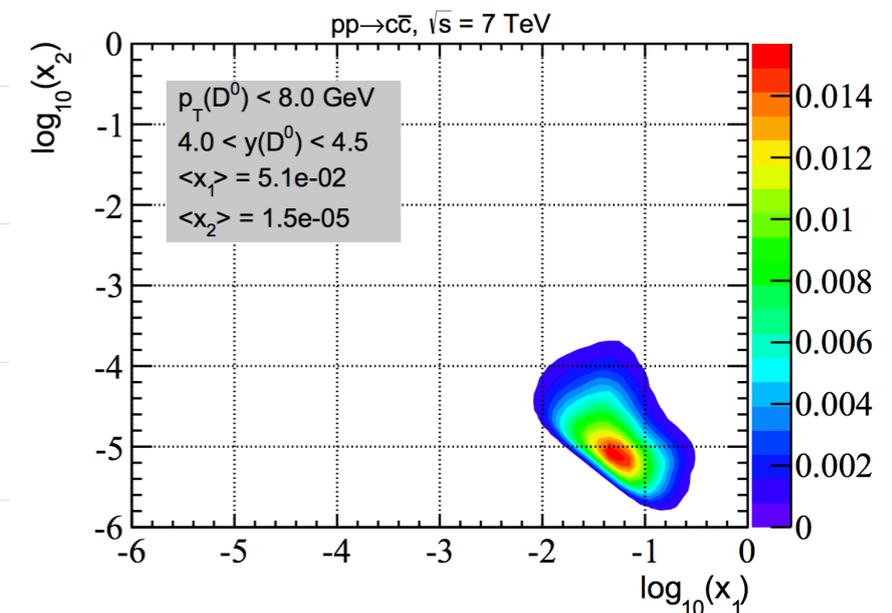
!

Forward measurements for proton PDFs

NNPDF4.0: data set extension

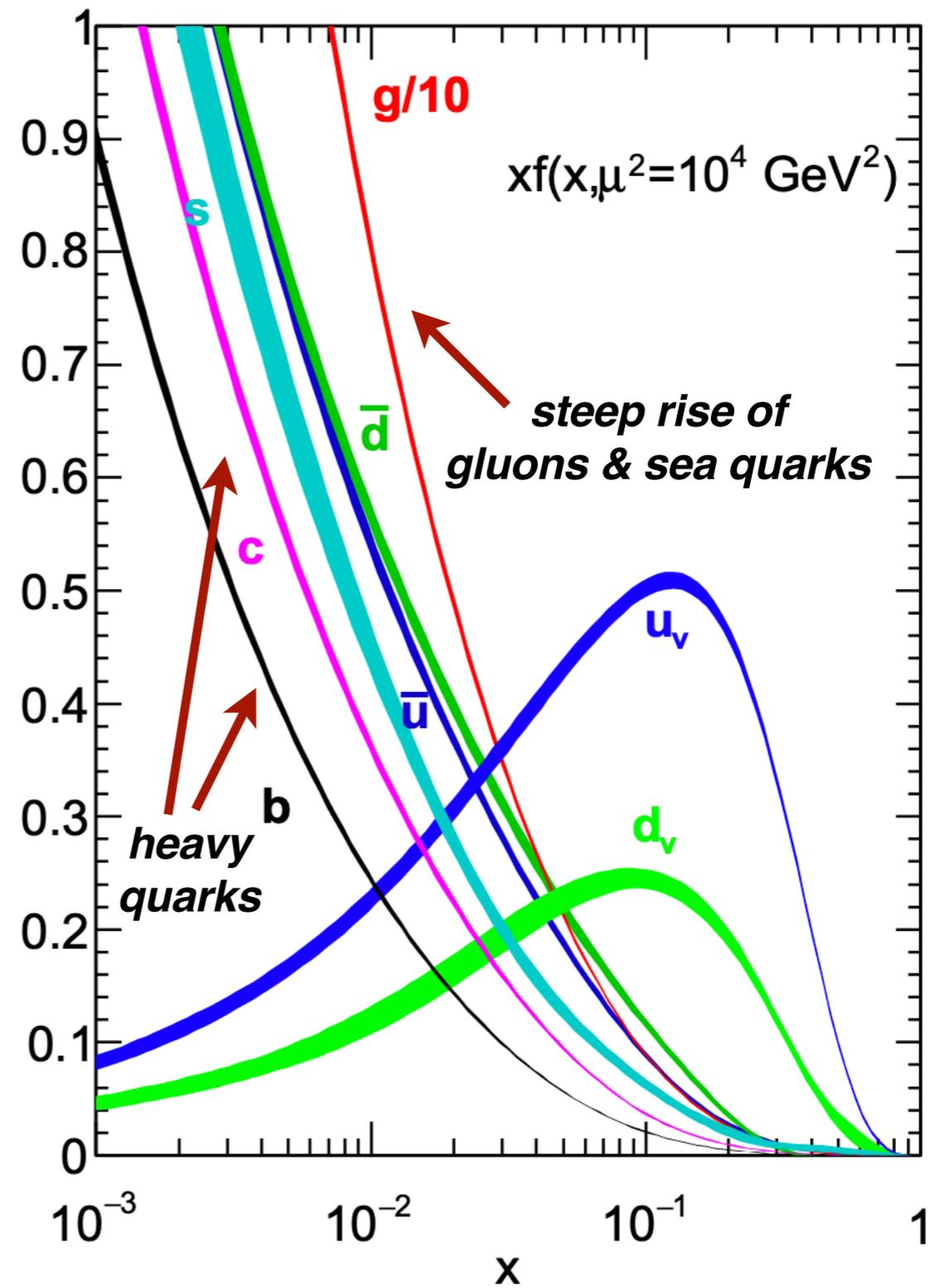
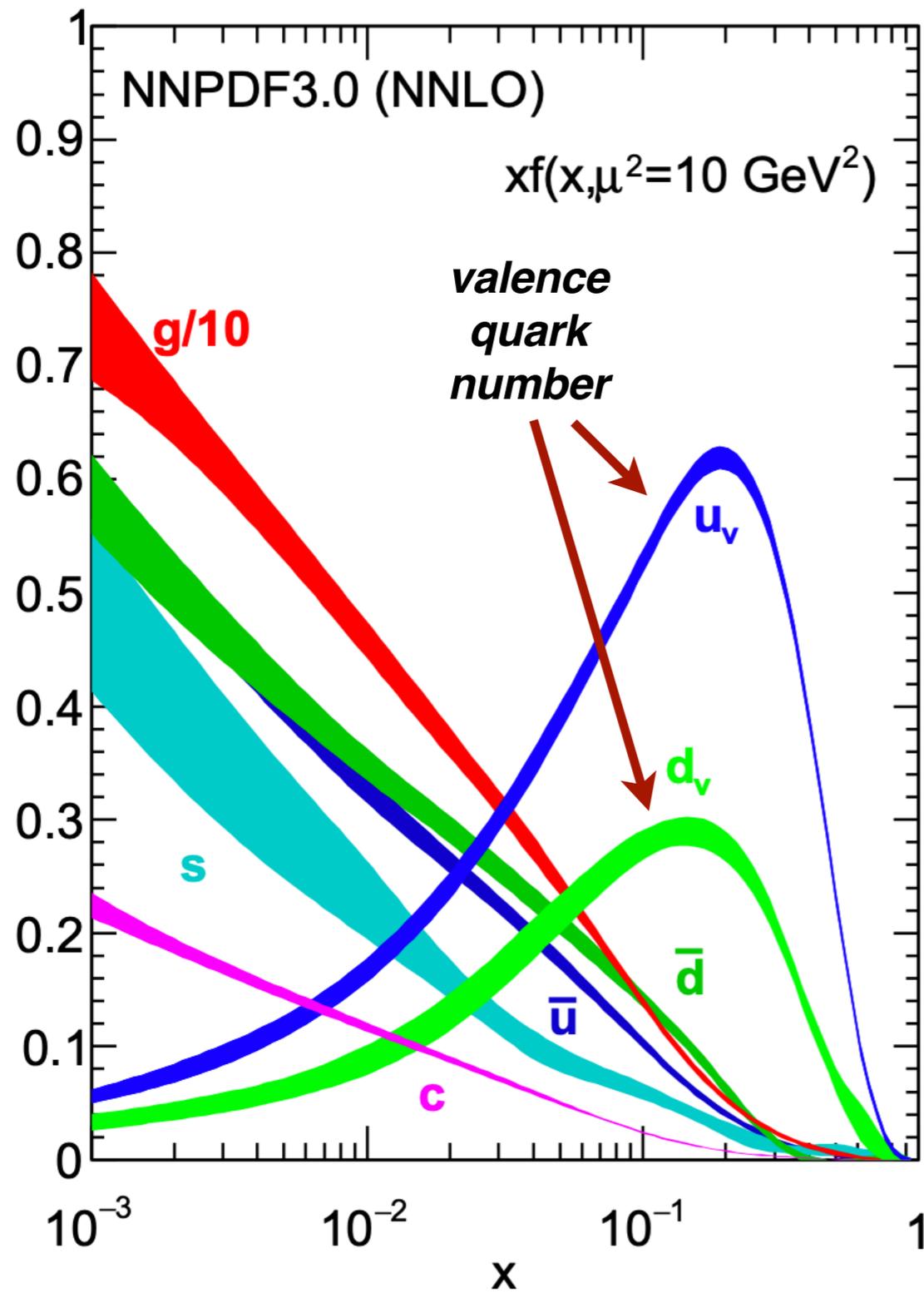


Charm @ LHCb

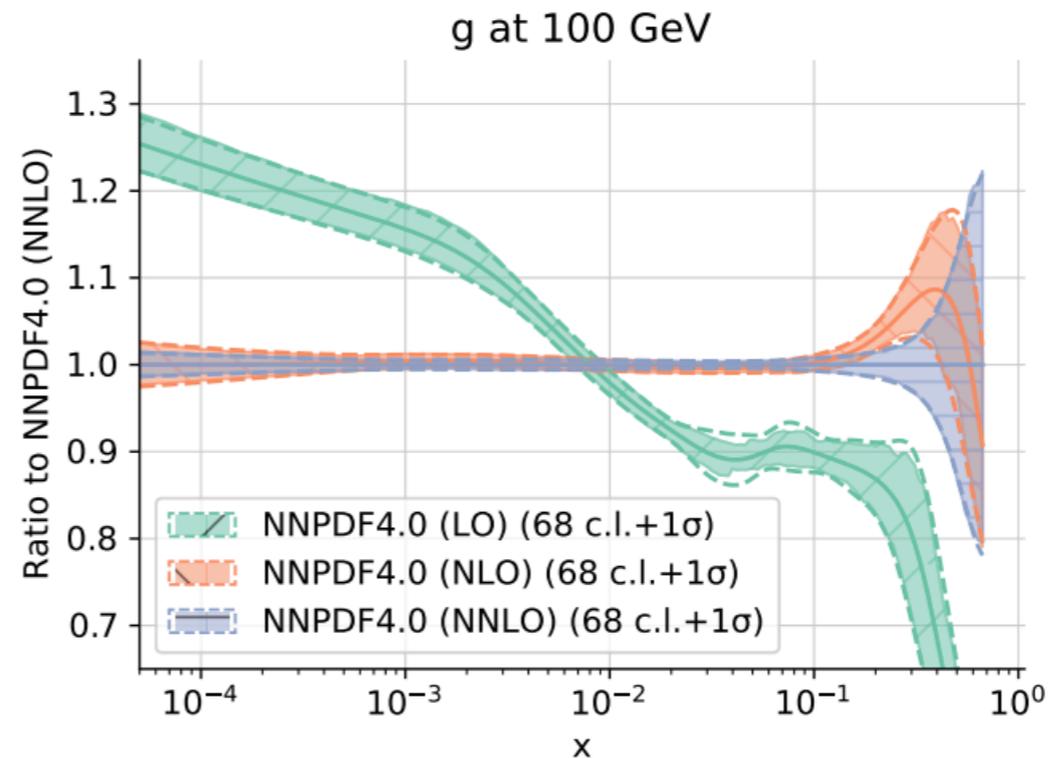
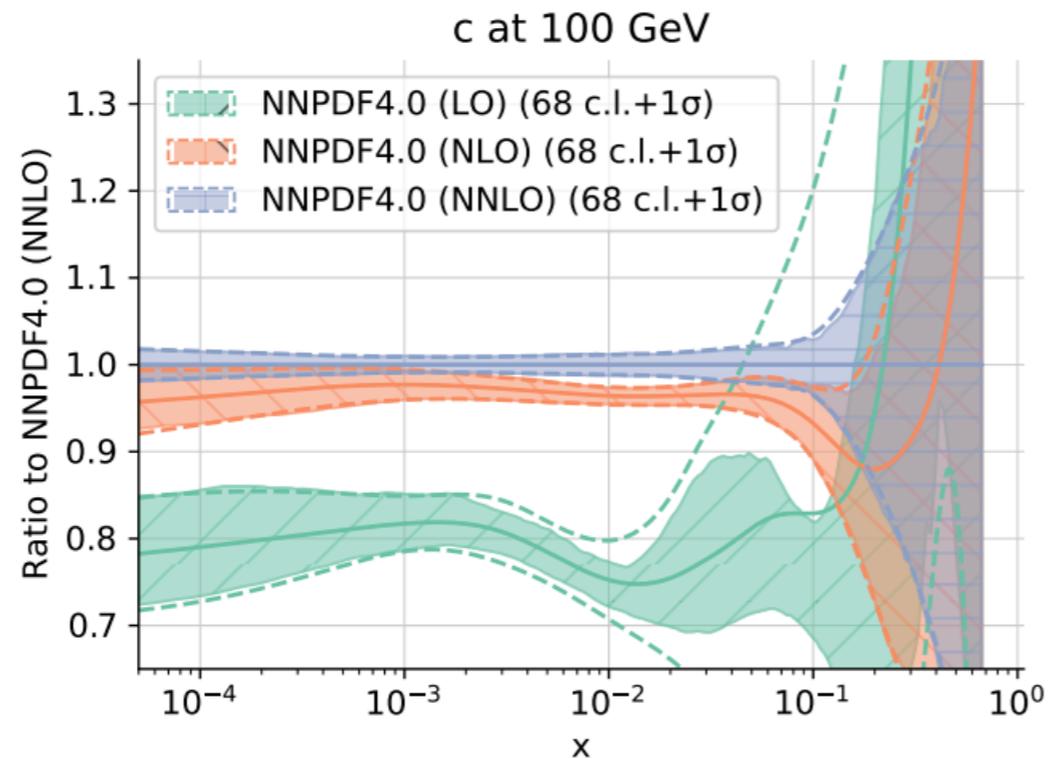
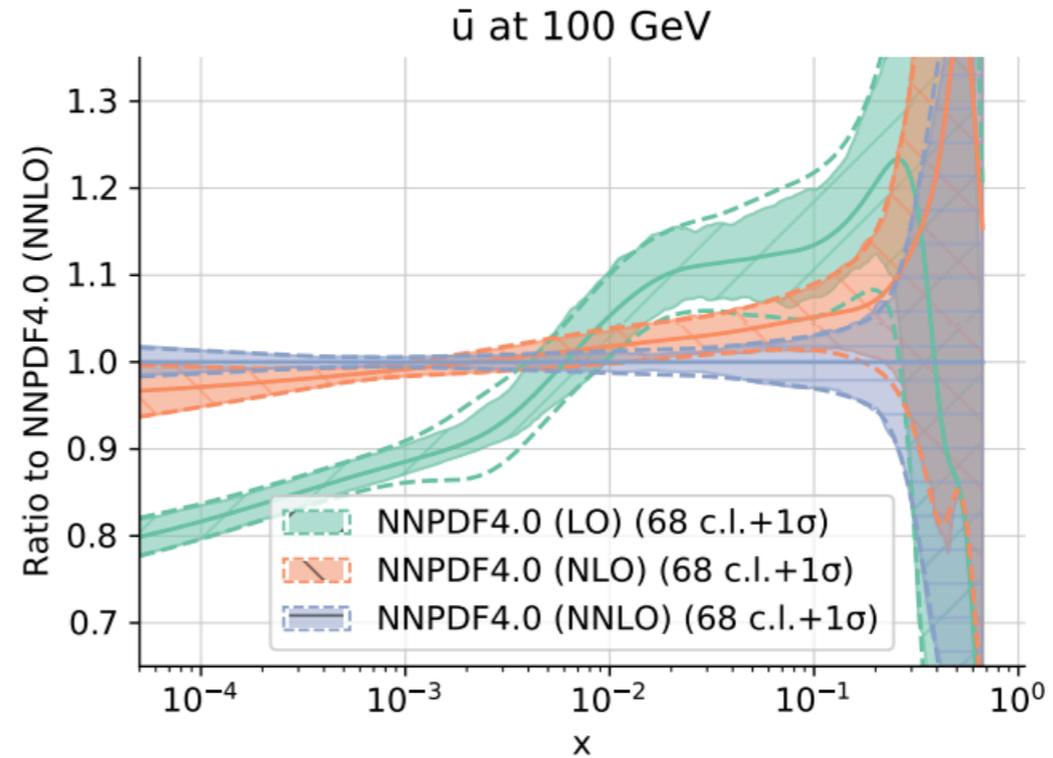
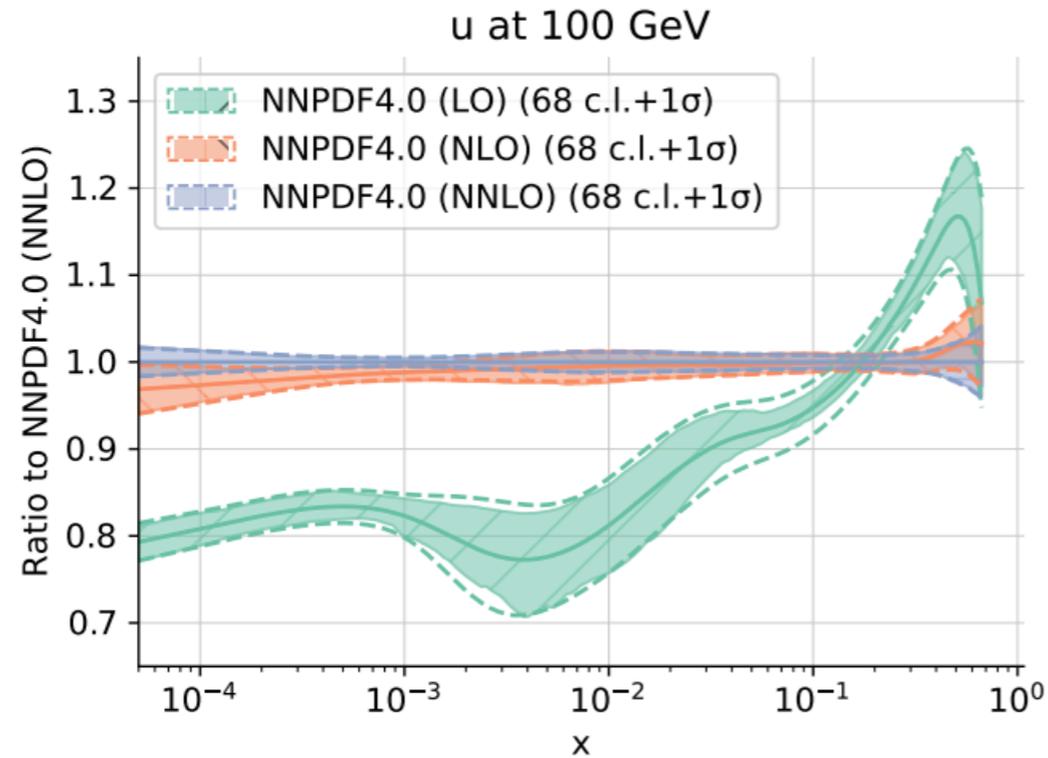


- In global PDF fits, the small- x region ($x < 10^{-3}$) is constrained mostly by **inclusive and charm HERA** structure functions and by **inclusive W, Z production from LHCb**
- D -meson production at LHCb** has also been considered and **extends coverage down to $x = 10^{-6}$** but is only available 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 ...

A proton structure snapshot



Perturbative stability



LO PDFs fail to describe available HERA and LHC data and differ significantly from NLO/
NNLO PDFs: not recommended for phenomenology

**Use modern NNLO PDFs also
with LO simulations!**

Forward charm production

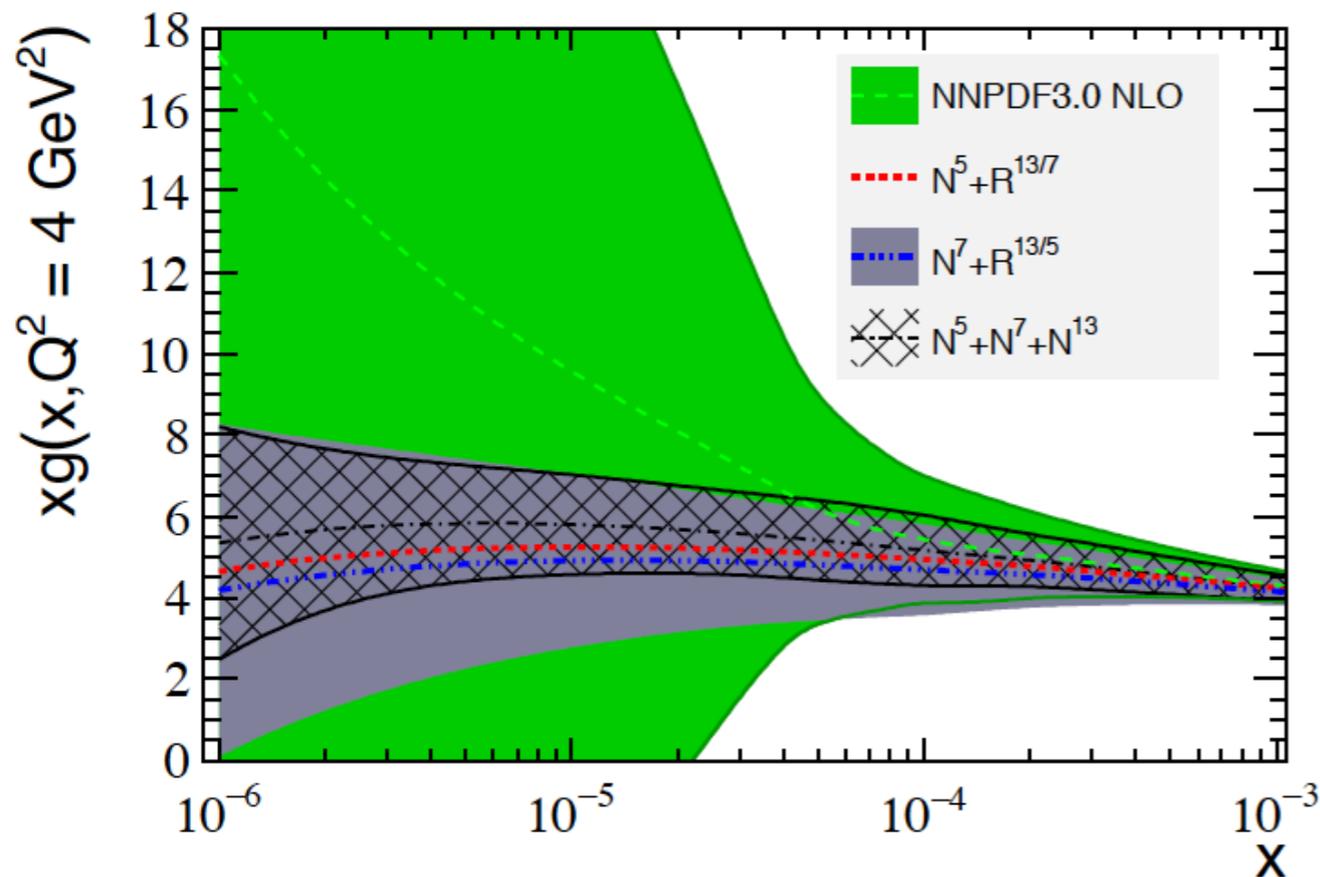
- Include LHCb D meson production at **5, 7, 13 TeV**
- Fit **normalised distributions & ratios** between CoM energies to reduce MHOUs

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

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

gluon PDF uncertainties reduced
by **factor 10** at $x \approx 10^{-6}$

Excellent description of all LHCb datasets
and ratios (after **errata** corrected)

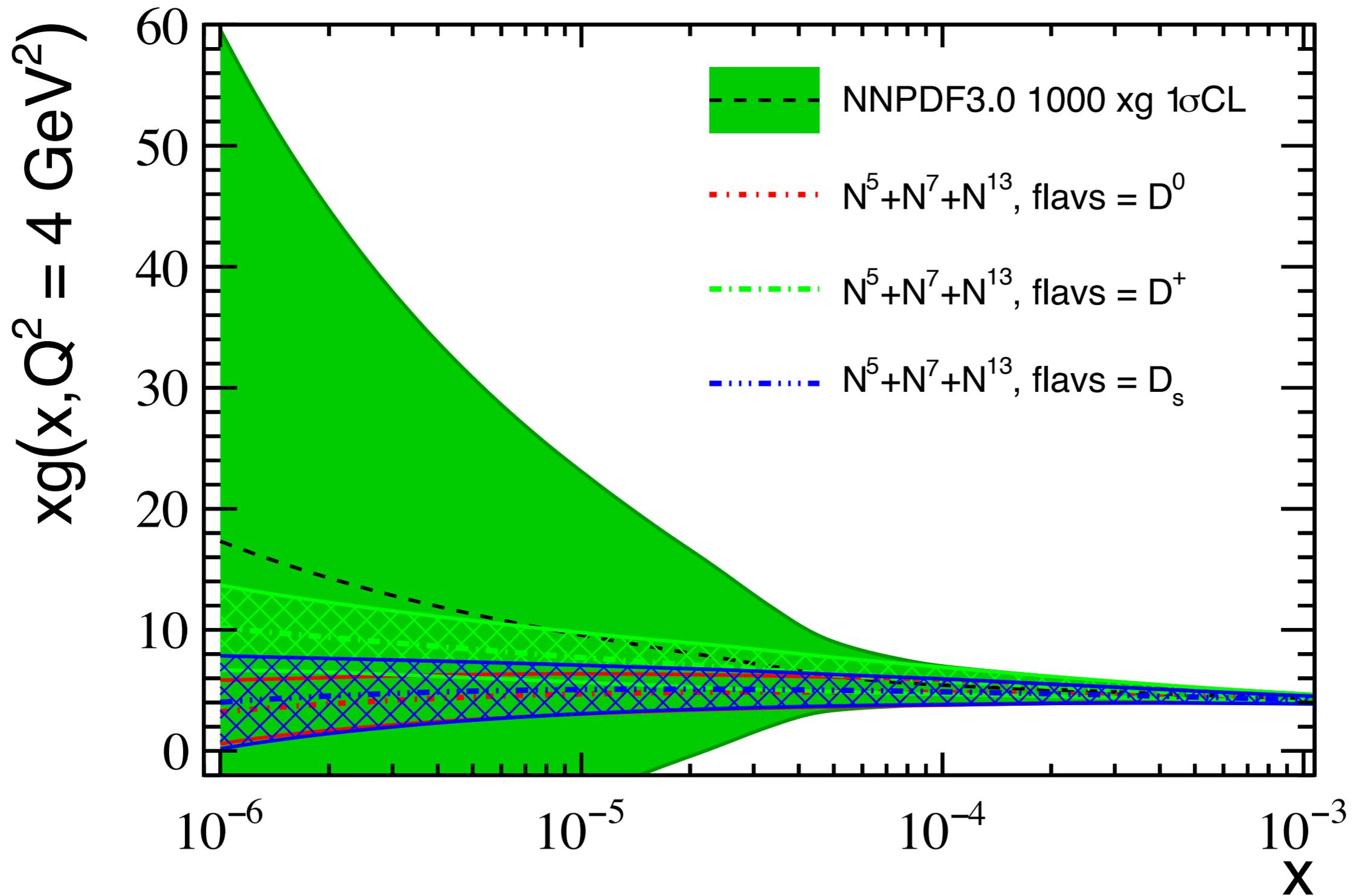


$N_5(84)$	$N_7(79)$	$N_{13}(126)$	$R_{13/5}(107)$	$R_{13/7}(102)$
1.97	1.21	2.36	1.36	0.80
0.86	0.72	1.14	1.35	0.81
1.31	0.91	1.58	1.36	0.82
0.74	0.66	1.01	1.38	0.80
1.08	0.81	1.27	1.29	0.80
1.53	0.99	1.73	1.30	0.81
1.07	0.81	1.34	1.35	0.81
0.82	0.70	1.07	1.35	0.81
0.84	0.71	1.10	1.36	0.81

Gauld, JR 16

Forward charm production

Results stable wrt choice of **fitted D meson species**



BFKL dynamics at small- x

- 📌 **QCD calculations in the DGLAP factorisation framework** successful in describing data from proton-proton and electron-proton collisions
- 📌 Need to go **beyond DGLAP**: at small- x , logarithmically enhanced terms in $1/x$ become dominant and need to be **resummed to all orders**
- 📌 **BFKL (high-energy, small- x) resummation** can be matched to DGLAP collinear framework and included into PDF fits

DGLAP
Evolution in Q^2

$$\frac{\partial}{\partial \ln Q^2} f_i(x, Q^2) = \int_x^1 \frac{dz}{z} P_{ij} \left(\frac{x}{z}, \alpha_s(Q^2) \right) f_j(z, Q^2)$$

BFKL
Evolution in x

$$\frac{\partial}{\partial \ln 1/x} f_+(x, Q^2) = \int_0^\infty \frac{d\nu^2}{\nu^2} K \left(\frac{Q^2}{\nu^2}, \alpha_s(Q^2) \right) f_+(x, \nu^2)$$

ABF, CCSS, TW
+ others, 94-08

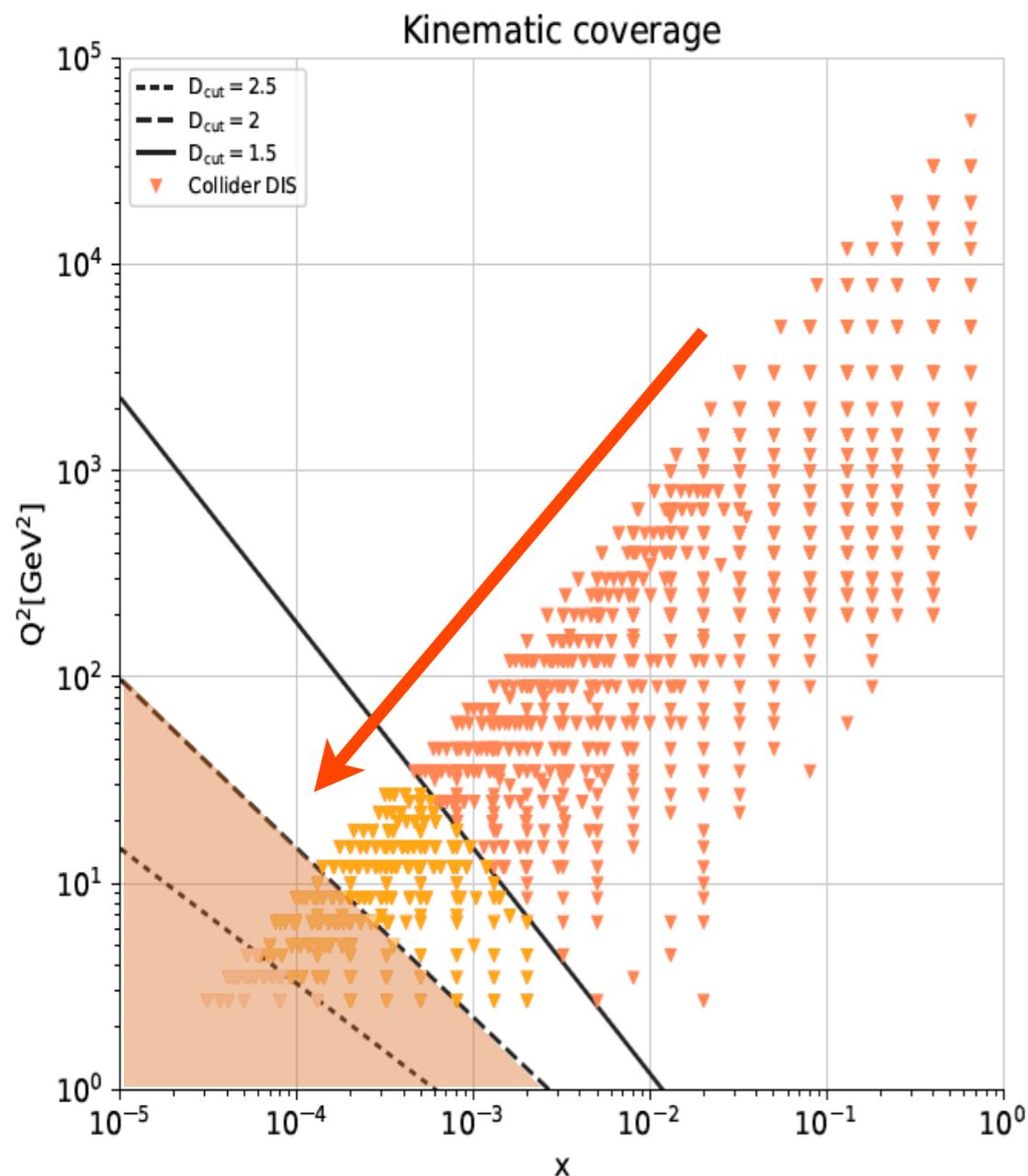
$$P_{ij}^{\text{N}^k \text{LO} + \text{N}^h \text{LL}x}(x) = P_{ij}^{\text{N}^k \text{LO}}(x) + \Delta_k P_{ij}^{\text{N}^h \text{LL}x}(x)$$

Forward measurements for proton PDFs

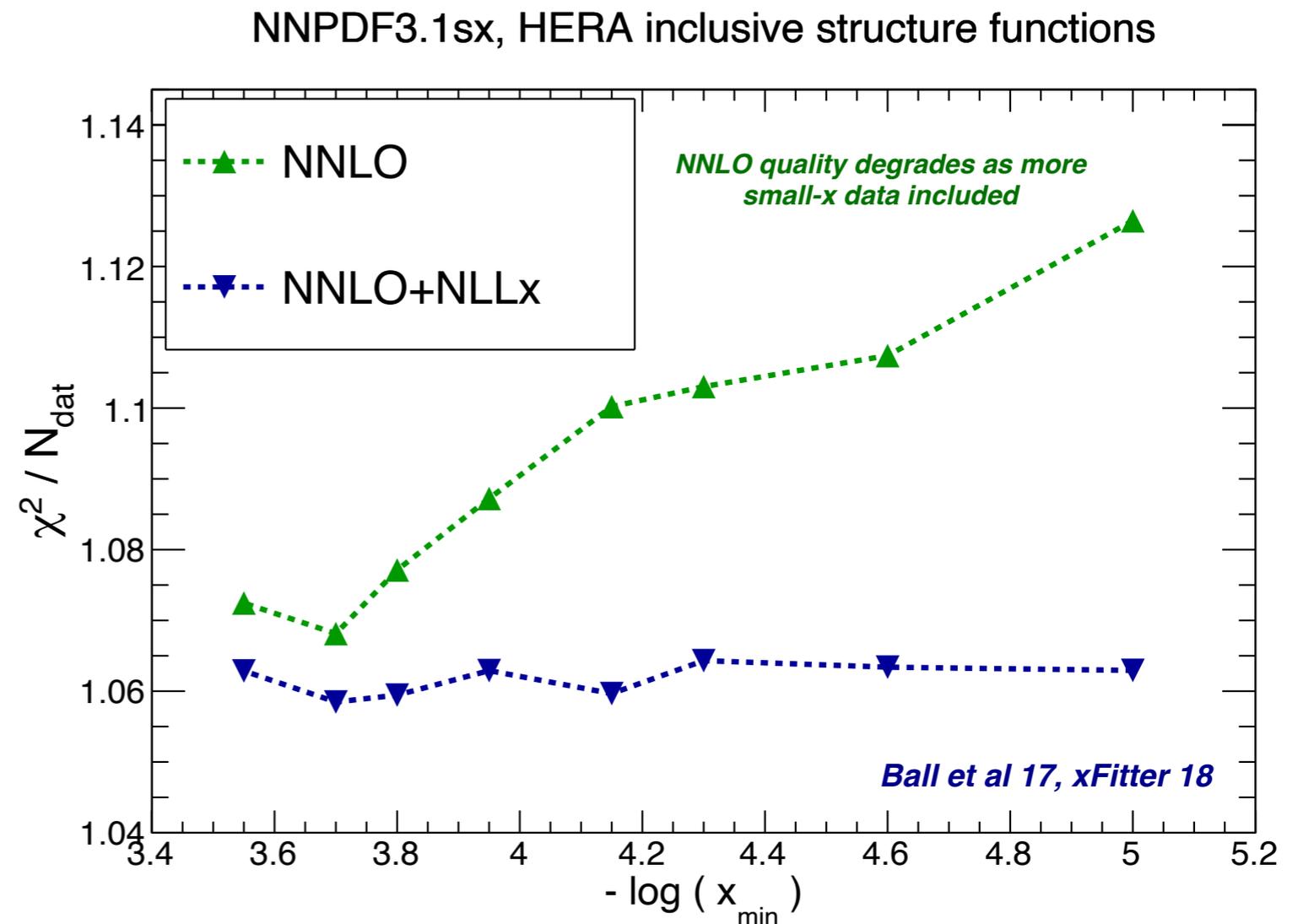
BFKL dynamics established from HERA data from inclusive and charm structure functions

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

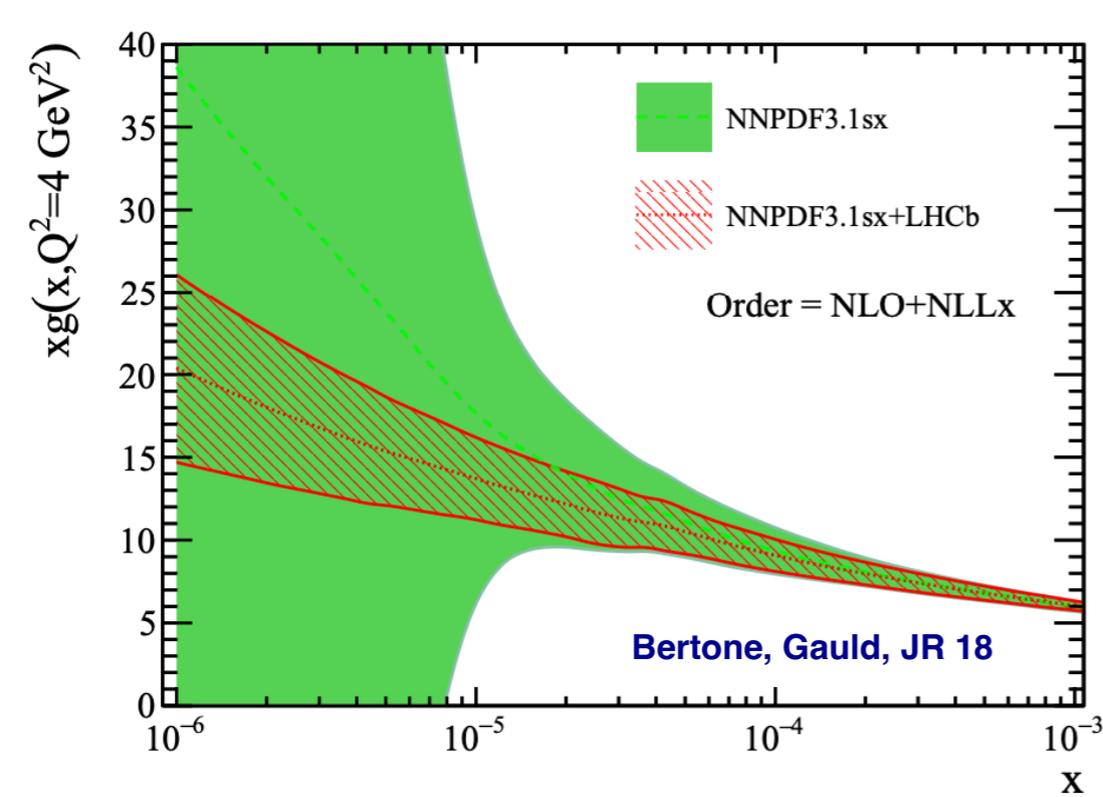


Best description of **small-x HERA data: BFKL resummation**

Will also affect heavy hadron production @ LHC in forward region

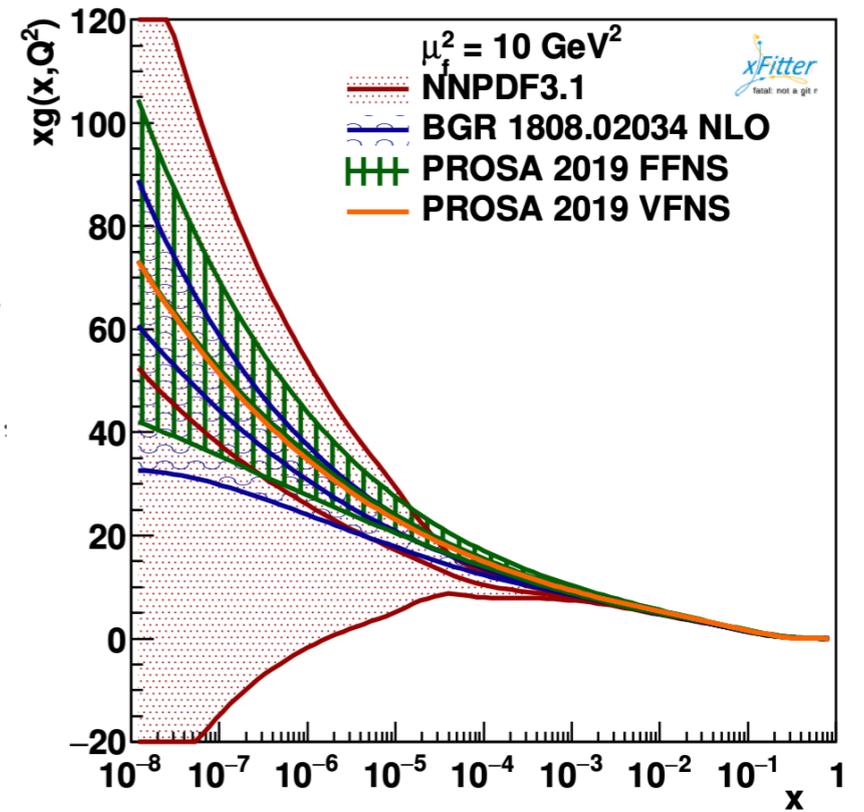
From the LHC to neutrino telescopes

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



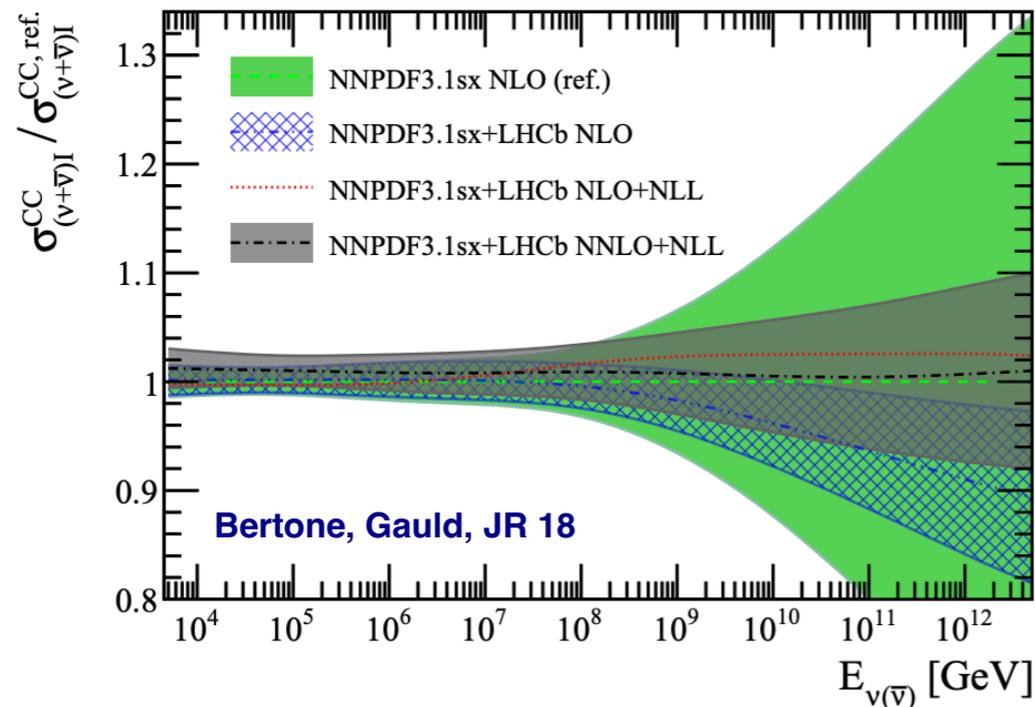
$$N_X^{ij} = \frac{d^2\sigma(X \text{ TeV})}{dy_i^D d(p_T^D)_j} \bigg/ \frac{d^2\sigma(X \text{ TeV})}{dy_{\text{ref}}^D d(p_T^D)_j},$$

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

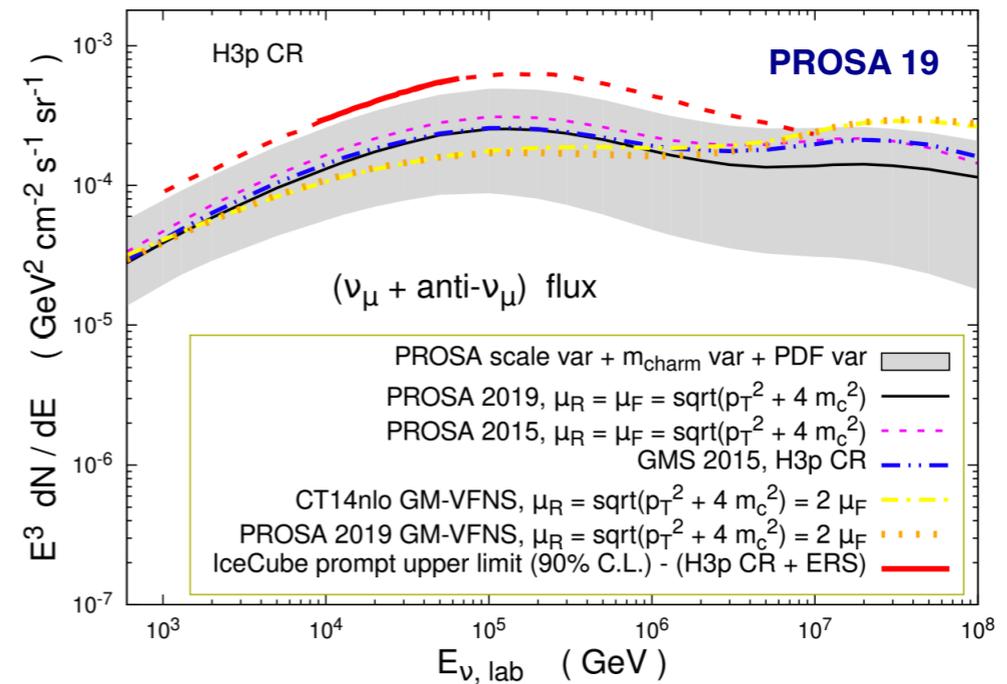


implications for **high-energy astroparticle physics:**

UHE neutrino-nucleus cross-sections

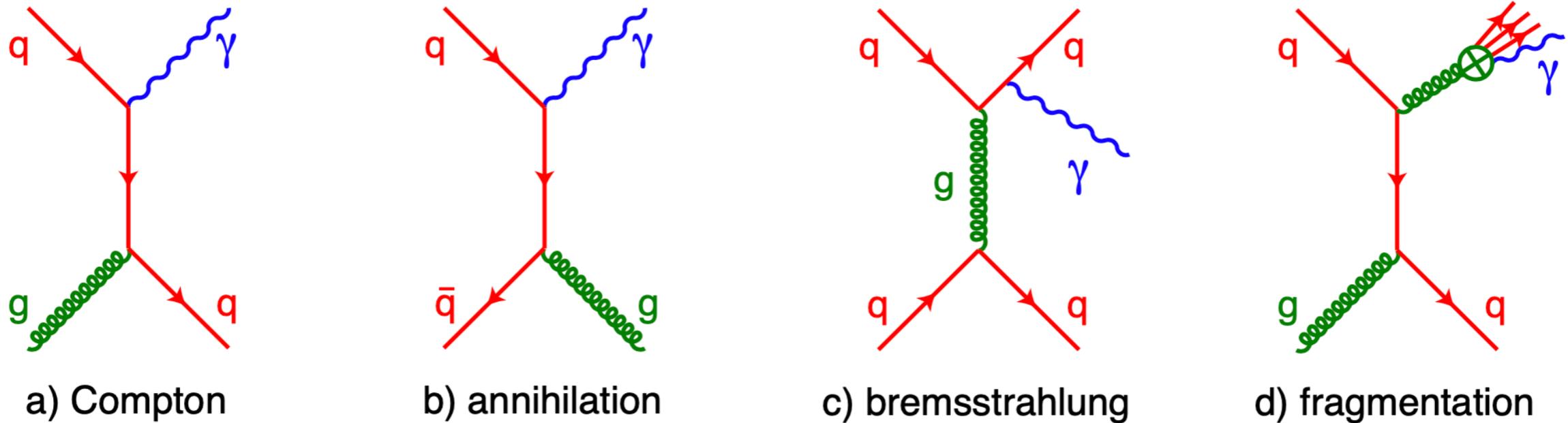


prompt neutrino fluxes from charm in CRs



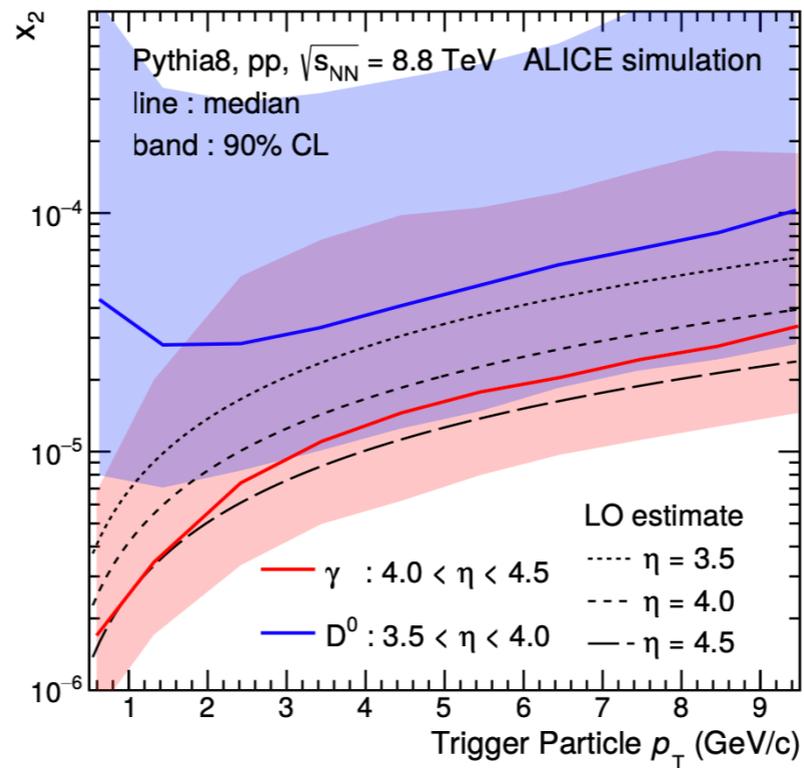
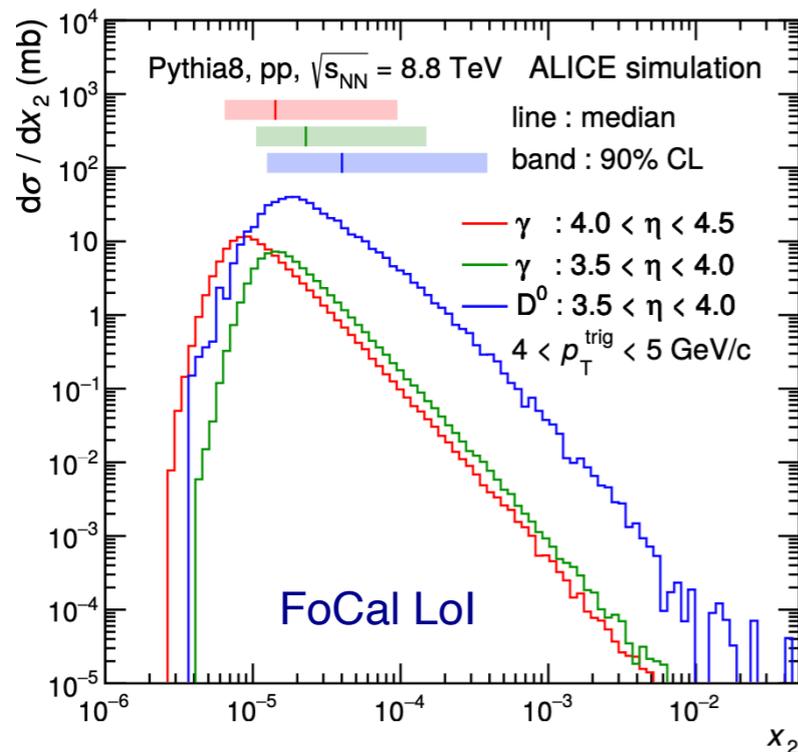
Forward photons at the LHC

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

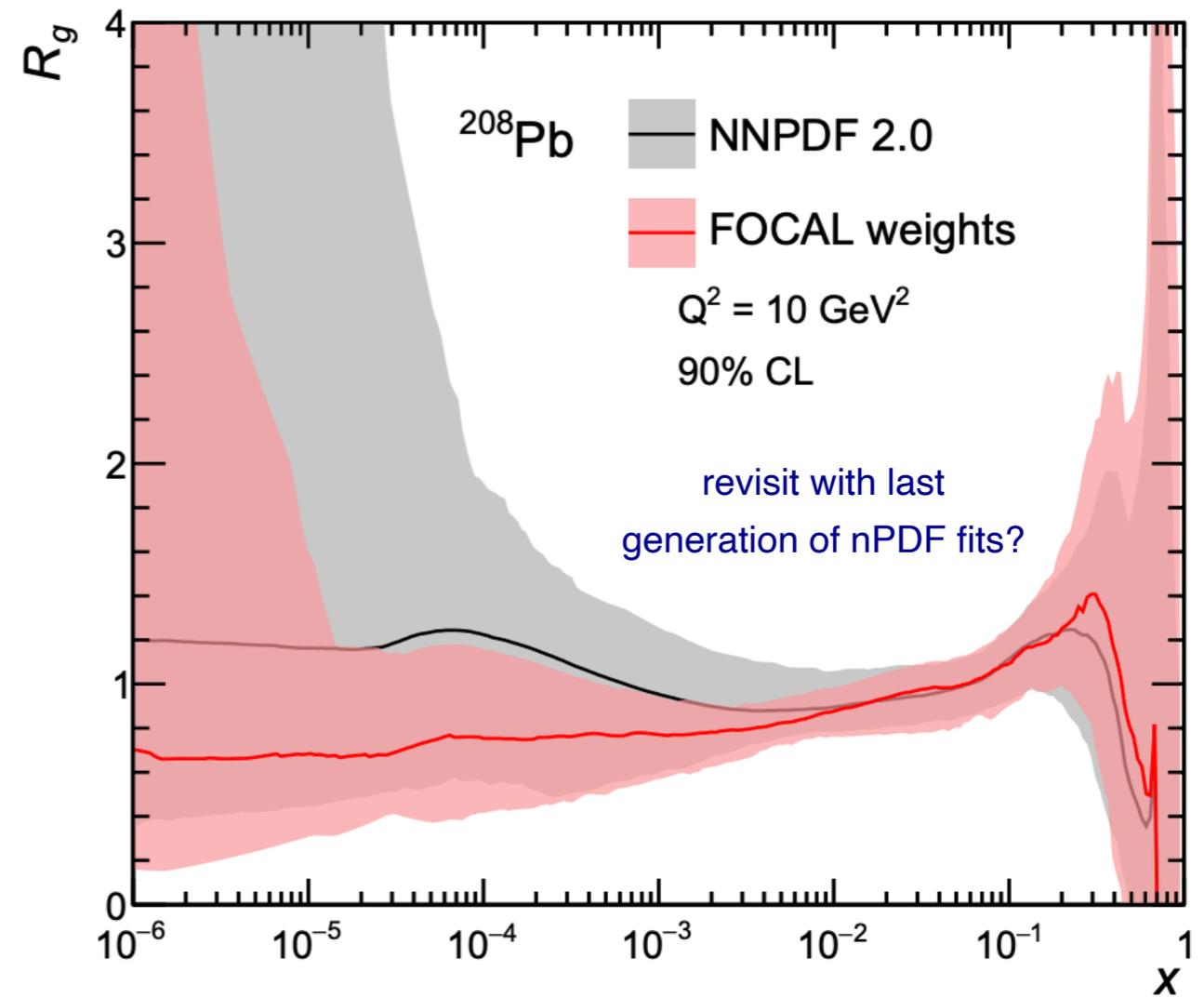
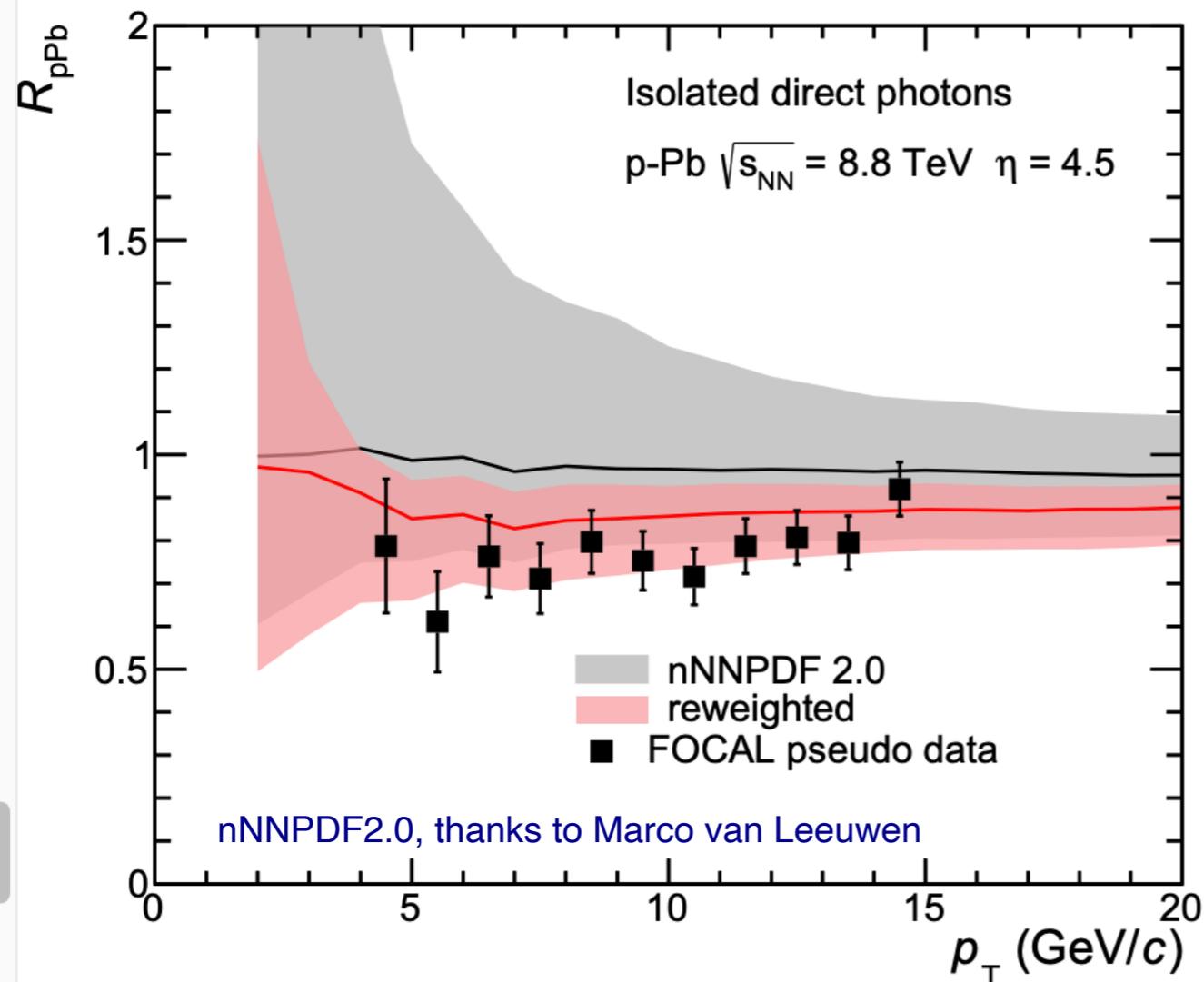
Coverage of the small- x region **comparable or better than D-meson production** with very different theory and experimental systematics: **fully complementary probes** of small- x QCD phenomena



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**

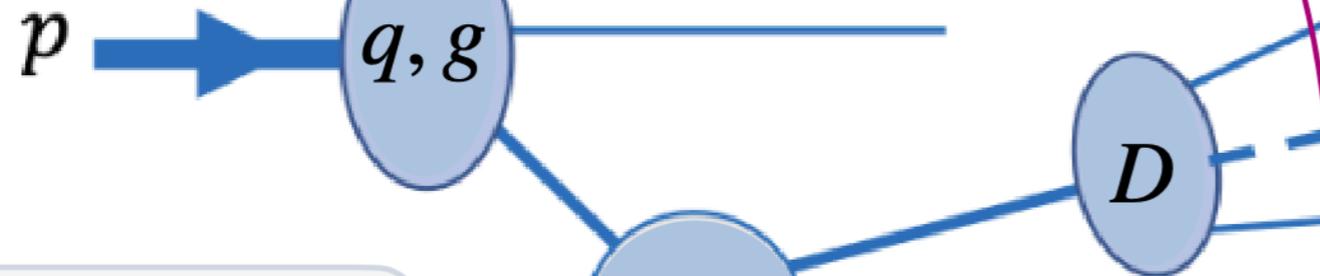
Crucial to combine information from **different probes of small- x QCD** and study the kinematical dependence of the constraints and fit quality (e.g. discovery of BFKL dynamics at HERA)

small- x QCD at the FPF

ATLAS

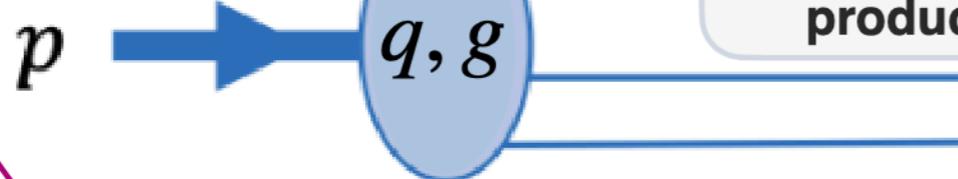
probing intrinsic charm

hadron fragmentation

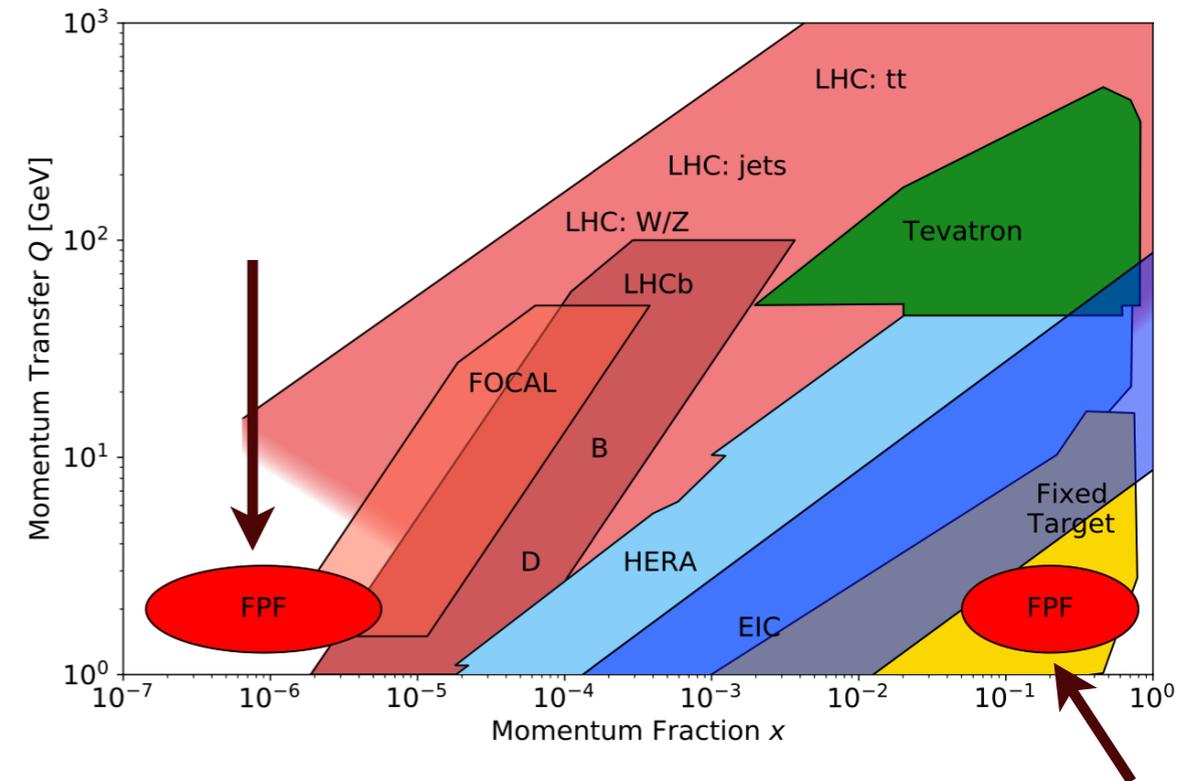


BFKL dynamics, non-linear QCD, CGC

forward D-meson production

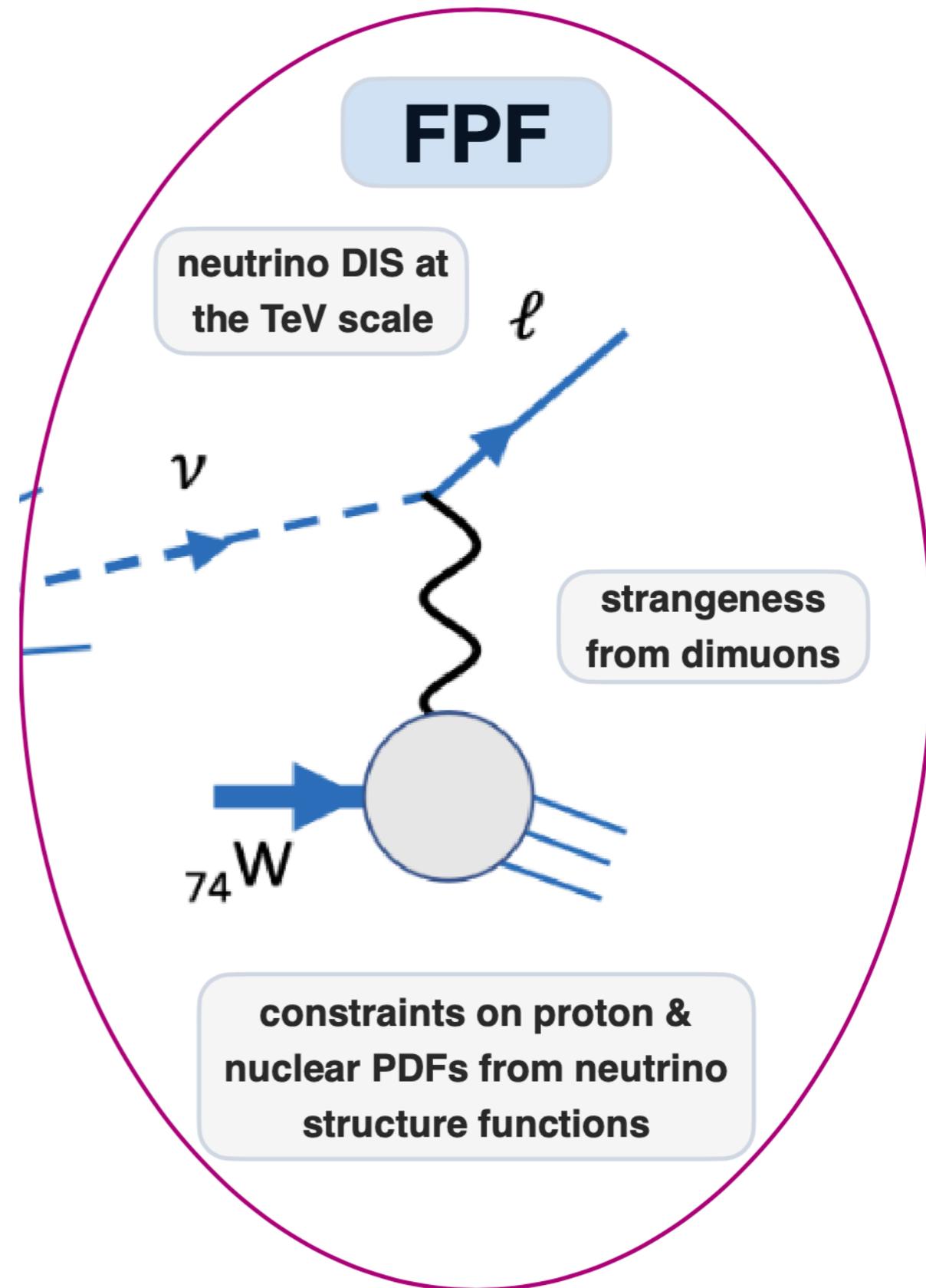
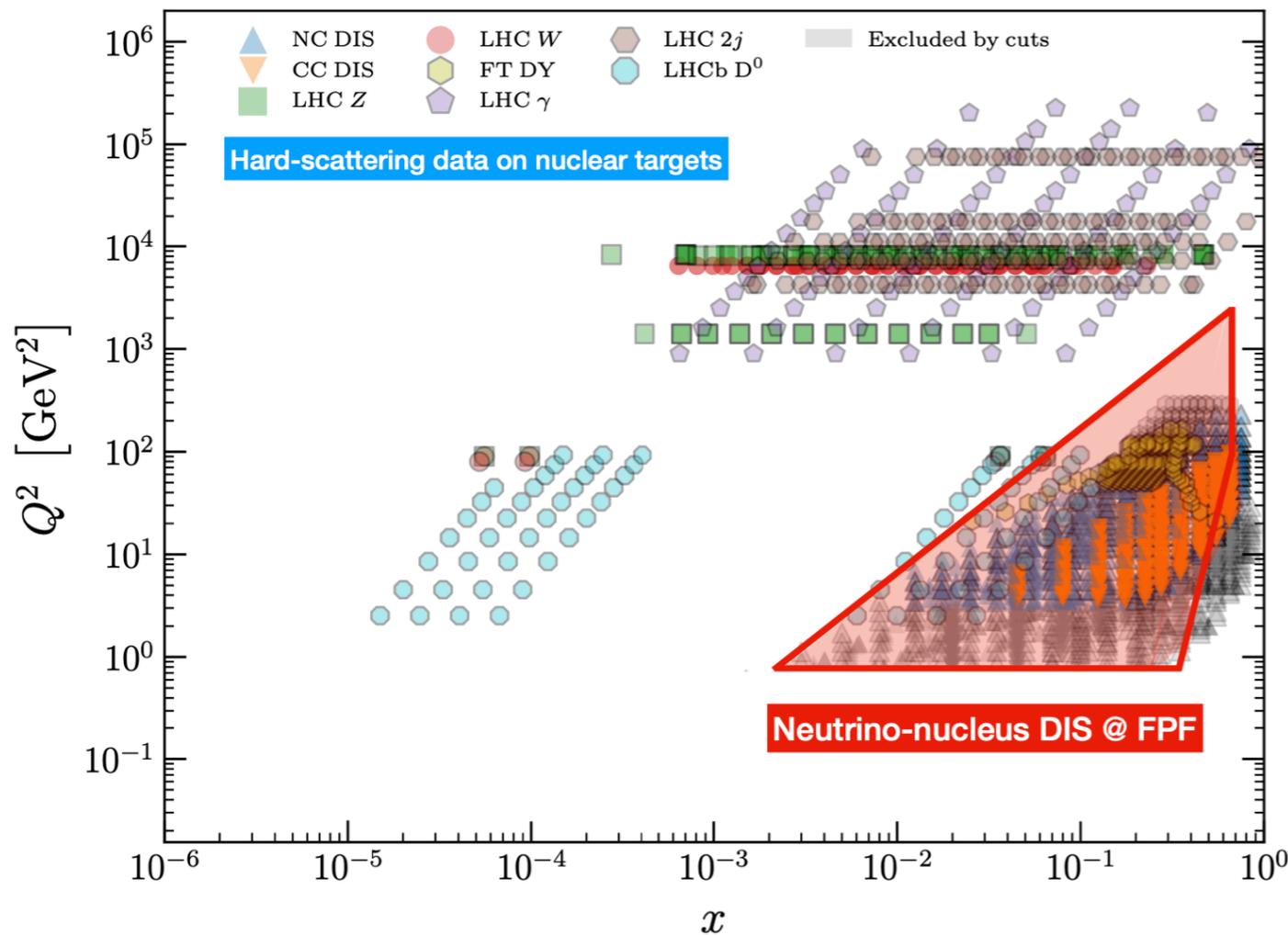


ultra small x proton structure



- **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
- ✓ Upcoming experiments from the **HL-LHC** to the **EIC** and the **FPF** will shed further light on QCD at small-x and on predictions for heavy hadron production in the forward region
- ✓ Potentially useful constraints also from **heavy hadron production in fixed-target LHC mode!**

