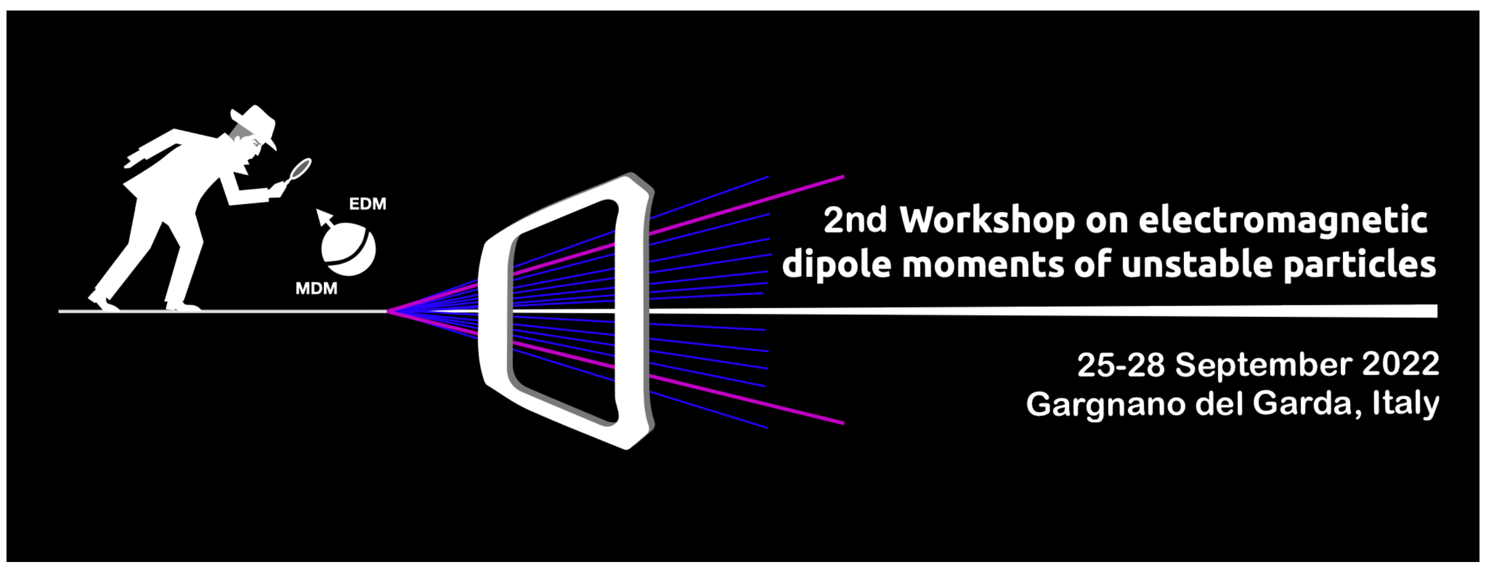
Heavy hadron production in the very forward region at the LHC

Juan Rojo, VU Amsterdam & Nikhef



2nd Workshop on Electromagnetic Dipole Moments of Unstable Particles

Gargnano del Garda, 25th June 2022

Forward particle production @ LHC

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

collinear factorisation

$\mathscr{L}_{ij}(\hat{s},s)$: *partonic luminosity (non-perturbative QCD, phenomenological extraction from data)*

$\tilde{\sigma}_{ij}(\hat{s},\alpha_s(M))$: *hard-scattering matrix element (perturbative QCD, evaluate from Feynman diagrams)*

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

f_i, f_j: *proton Parton Distribution Functions (PDFs)*

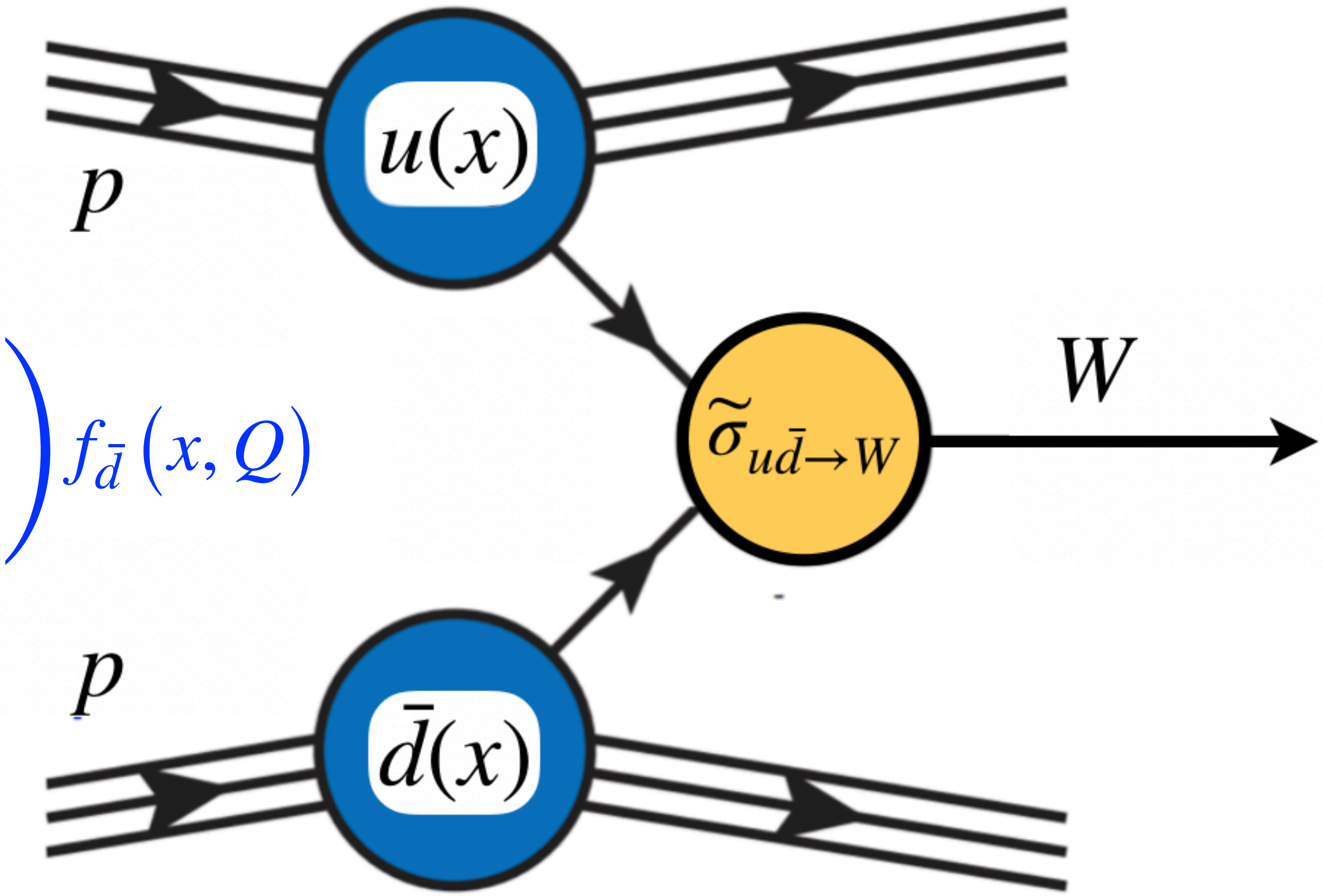
$f_j\left(x,Q\right)$: j – *flavour index*; x – *momentum fraction*; Q – *energy scale of partonic scattering*

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

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

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



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 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

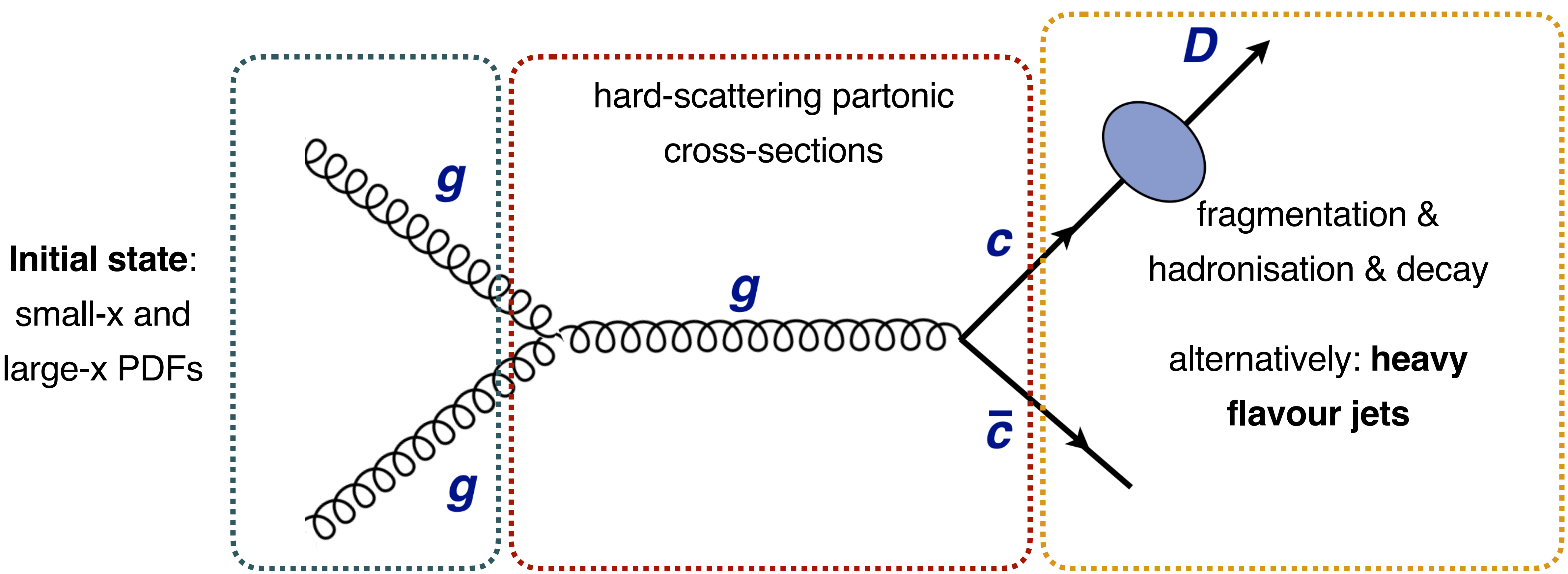
Precise predictions for **forward charm and bottom hadron production** requires:

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

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

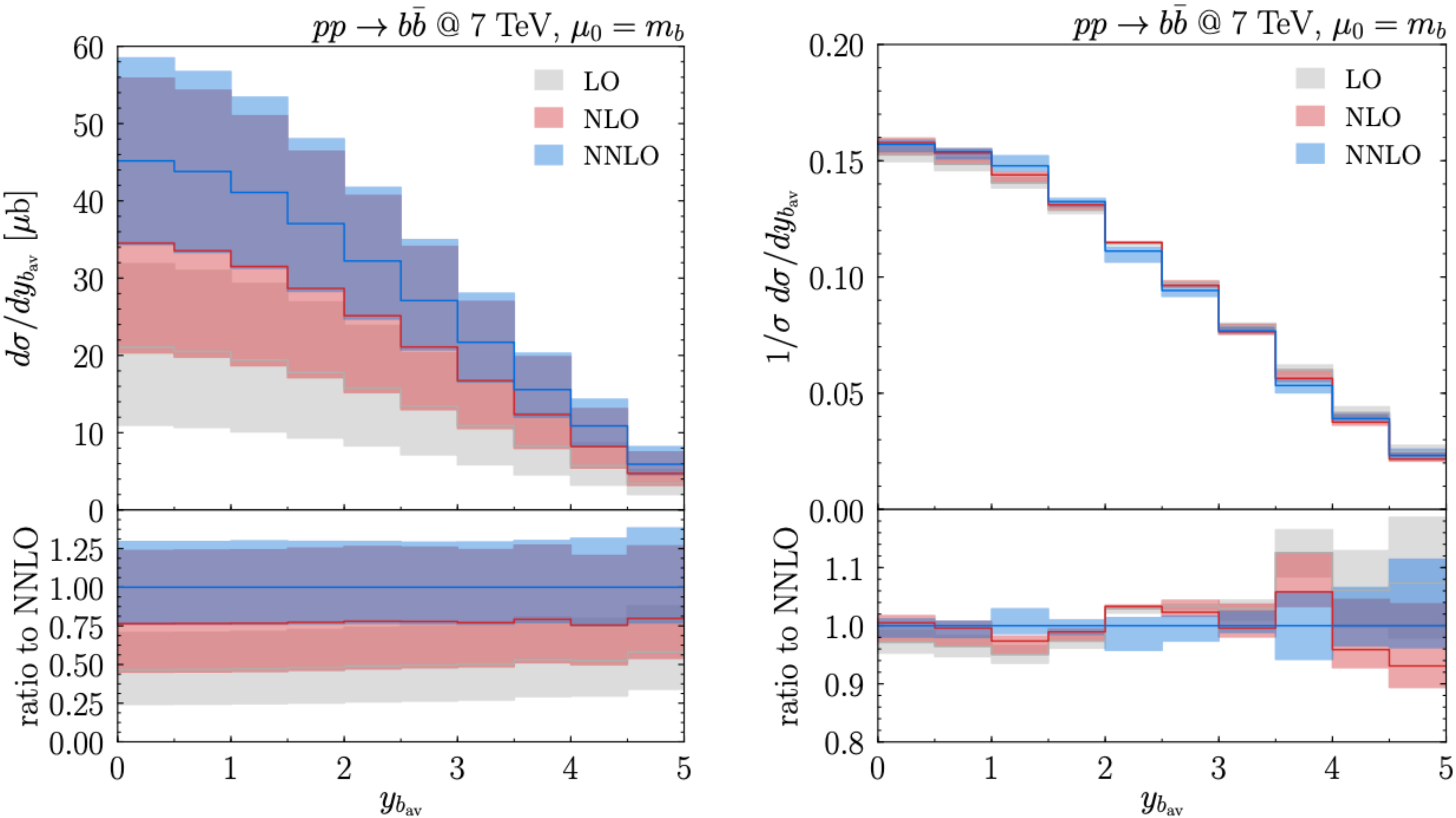
knowledge of **hard scattering cross-sections** at low masses

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**



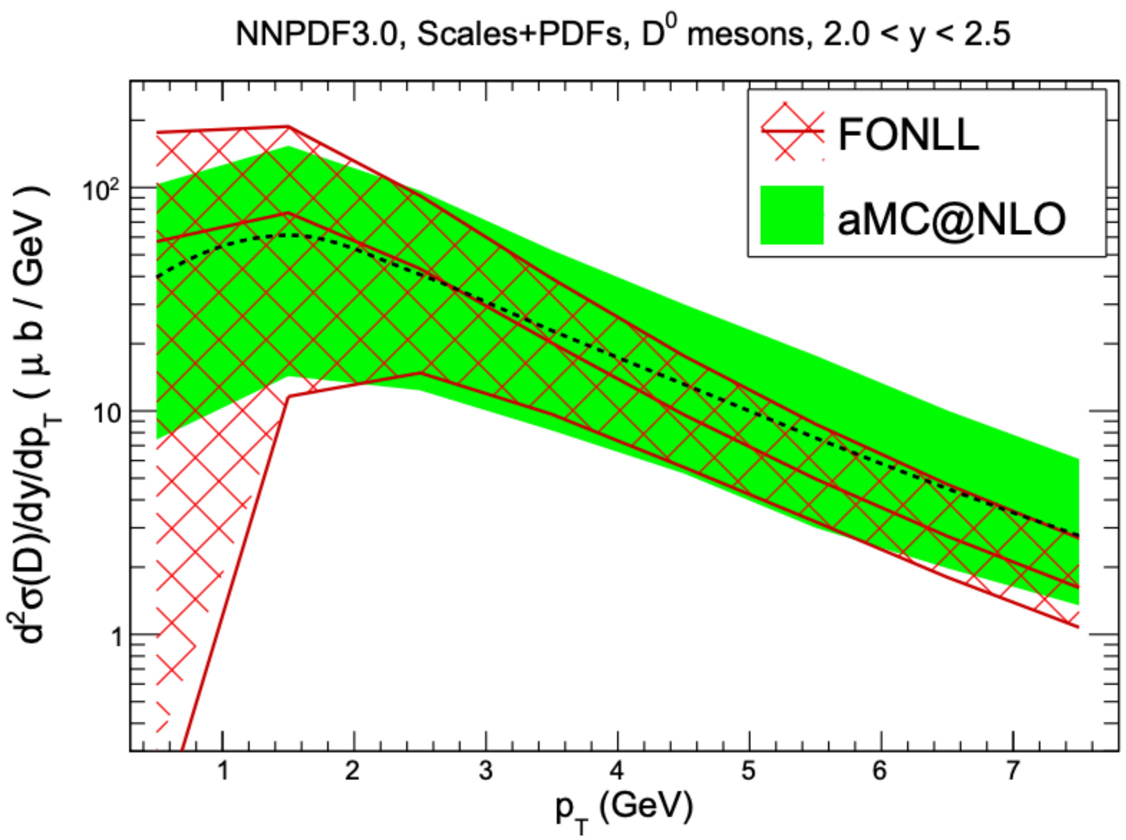
- Even at NNLO scale errors on absolute rates are O(25%), can be markedly reduced by working with **normalised distributions**

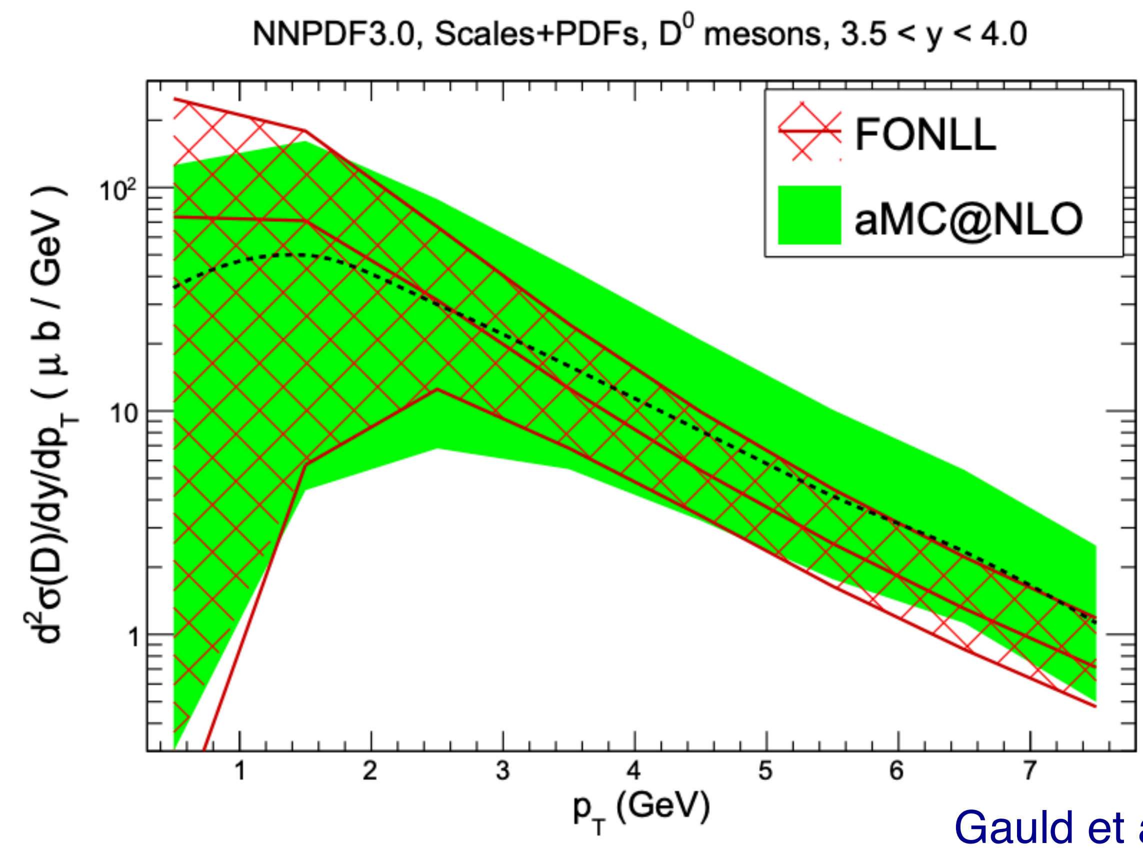
Catani et al 21

Heavy quark production

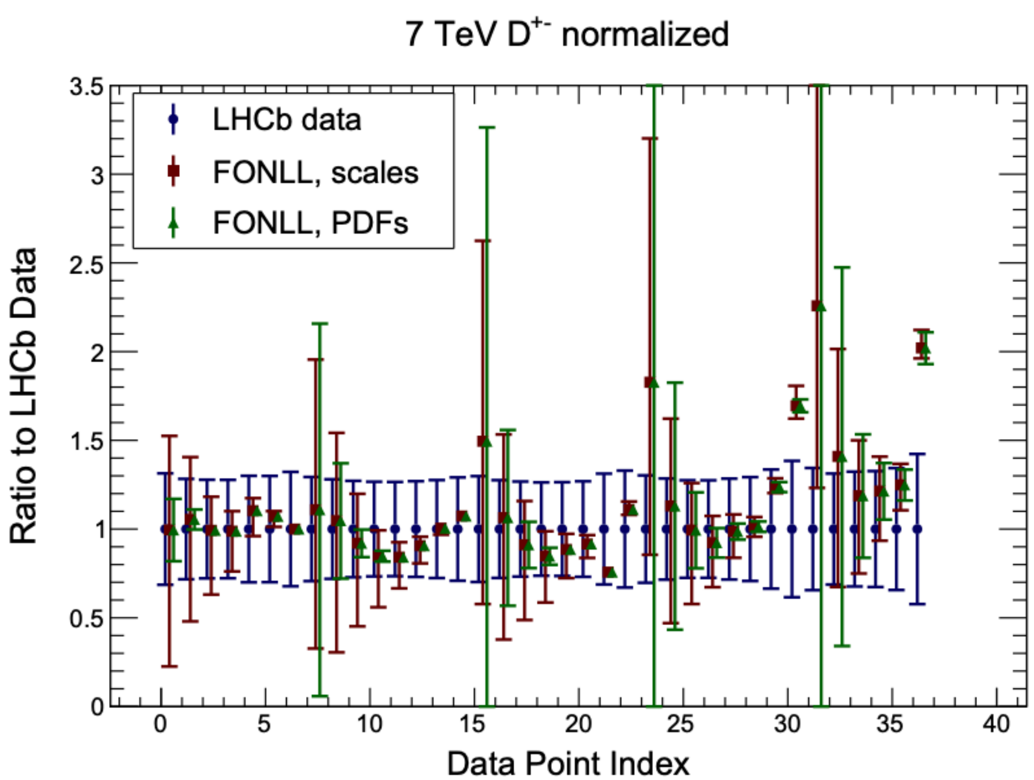
- For charm quarks NNLO is not available, state of the art is **NLO+resummation (FONLL)**

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





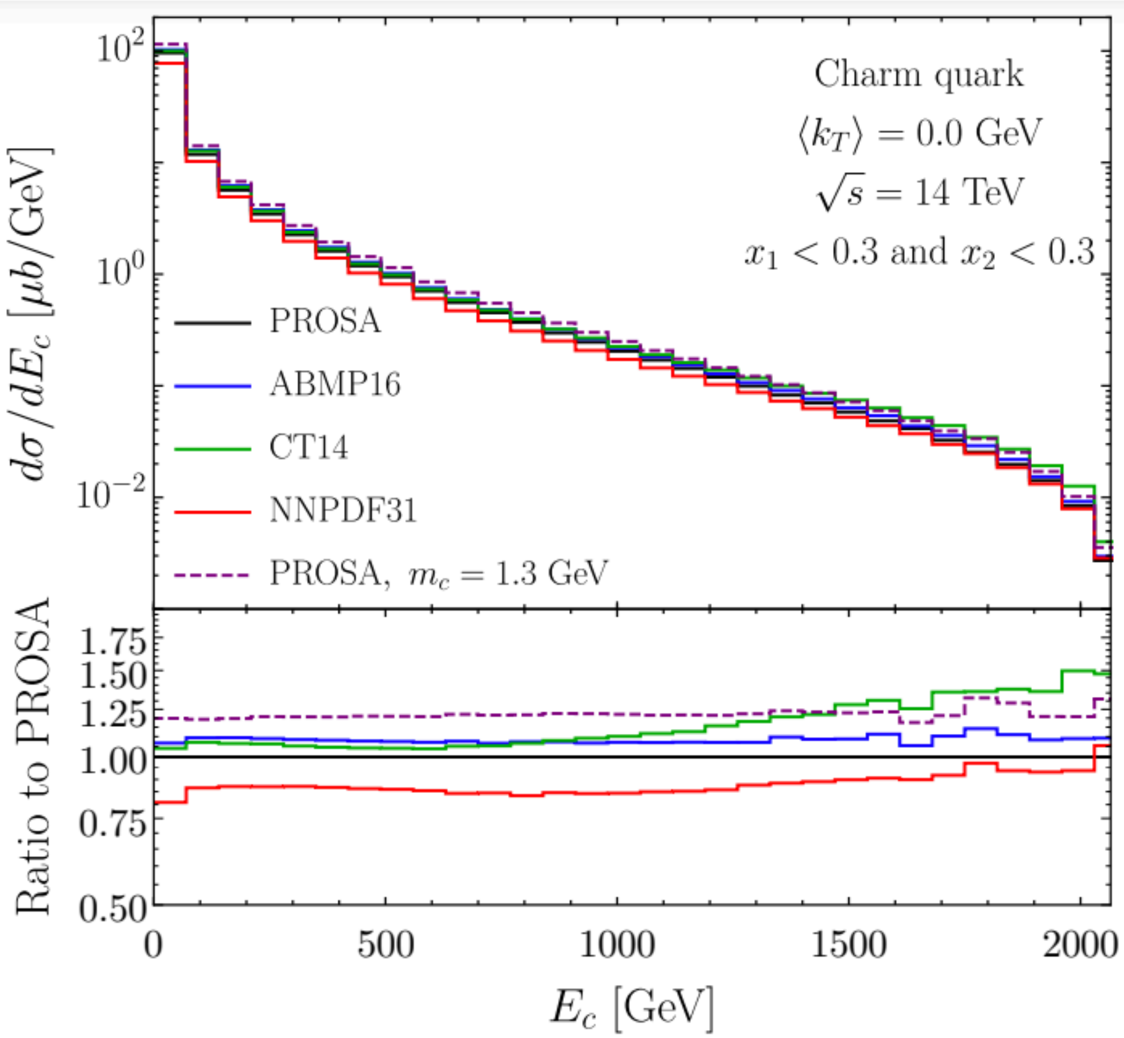
Gauld et al 15

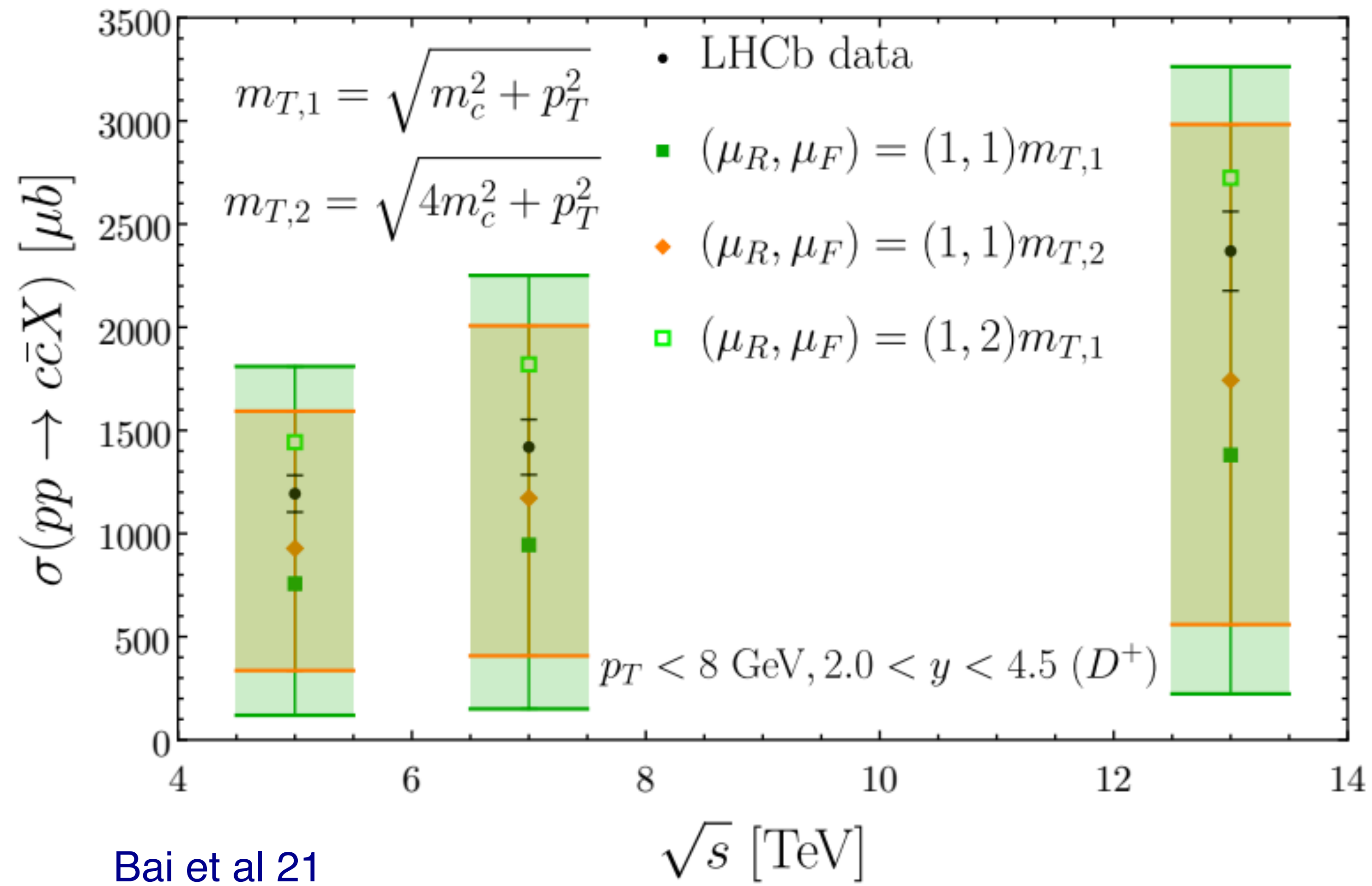


- Large scale uncertainties in NLO+NLL calculation
- Partially cancel out in **ratios** to e.g. reference bin of between CoM energies   Mangano and JR 12
- Perturbative expansion converges poorly at **Q = m_c**
- Comparison with data requires **fragmentation model**

Heavy quark production

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





Bai et al 21

- 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**

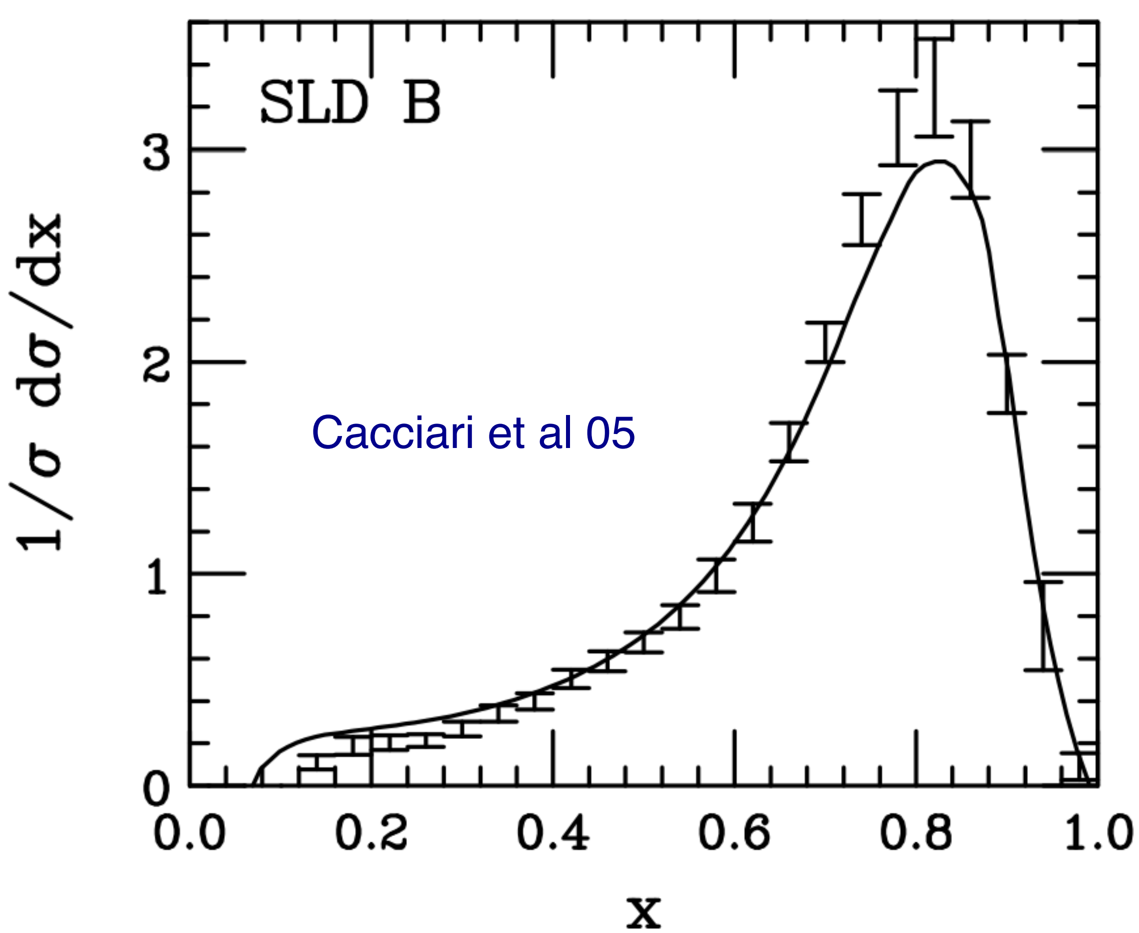
Heavy quark fragmentation

- 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

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

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

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 $f(z) \propto 1/[z(1-\frac{1}{z}-\frac{\varepsilon}{(1-z)})^2]$

z = ratio between partonic and hadronic energy

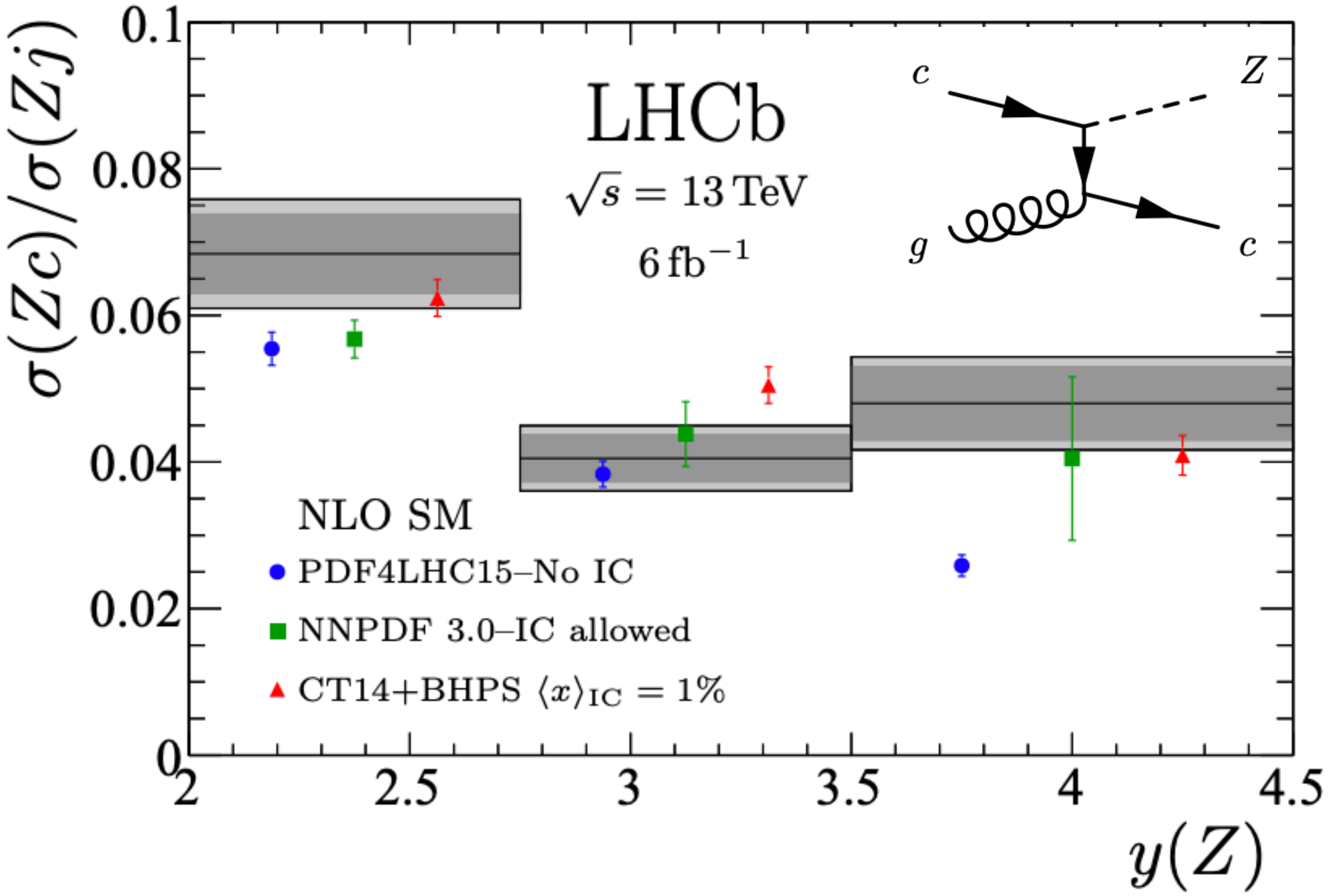
- Heavy quark hadronisation models in **MC event generators** are different from pQCD fragmentation

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**

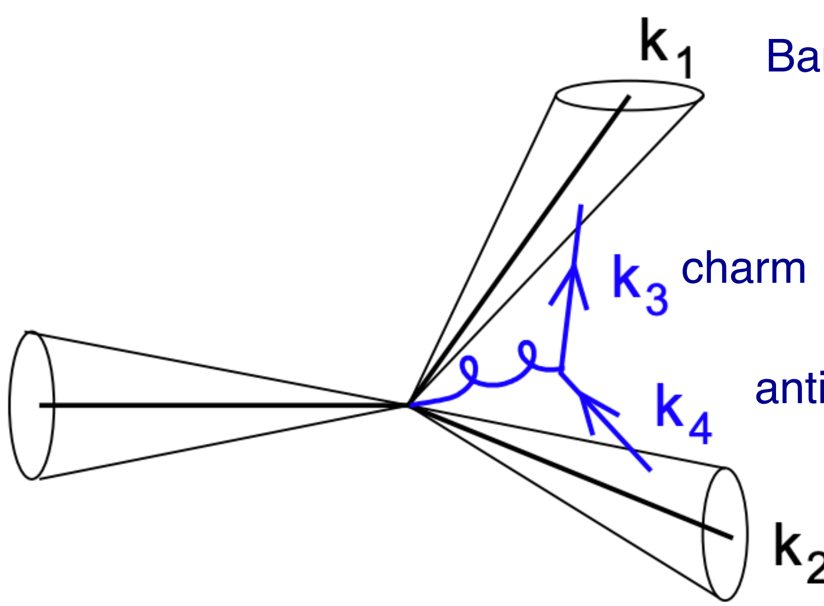
untagged jets

charm-tagged jets



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

Modify jet clustering algorithm, but challenge to implement it experimentally



Banfi et al 04

Parton Distributions

$$g(x, Q)$$

Energy of hard-scattering reaction**:** inverse of resolution length

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

x: fraction of proton momentum carried by gluon

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

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

constrain from data

- **Quark number conservation**

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

- **Energy conservation**: momentum sum rule

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

Parton Distributions

$$g(x, Q)$$

Energy of hard-scattering reaction**:** inverse of resolution length

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

x: fraction of proton momentum carried by gluon

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

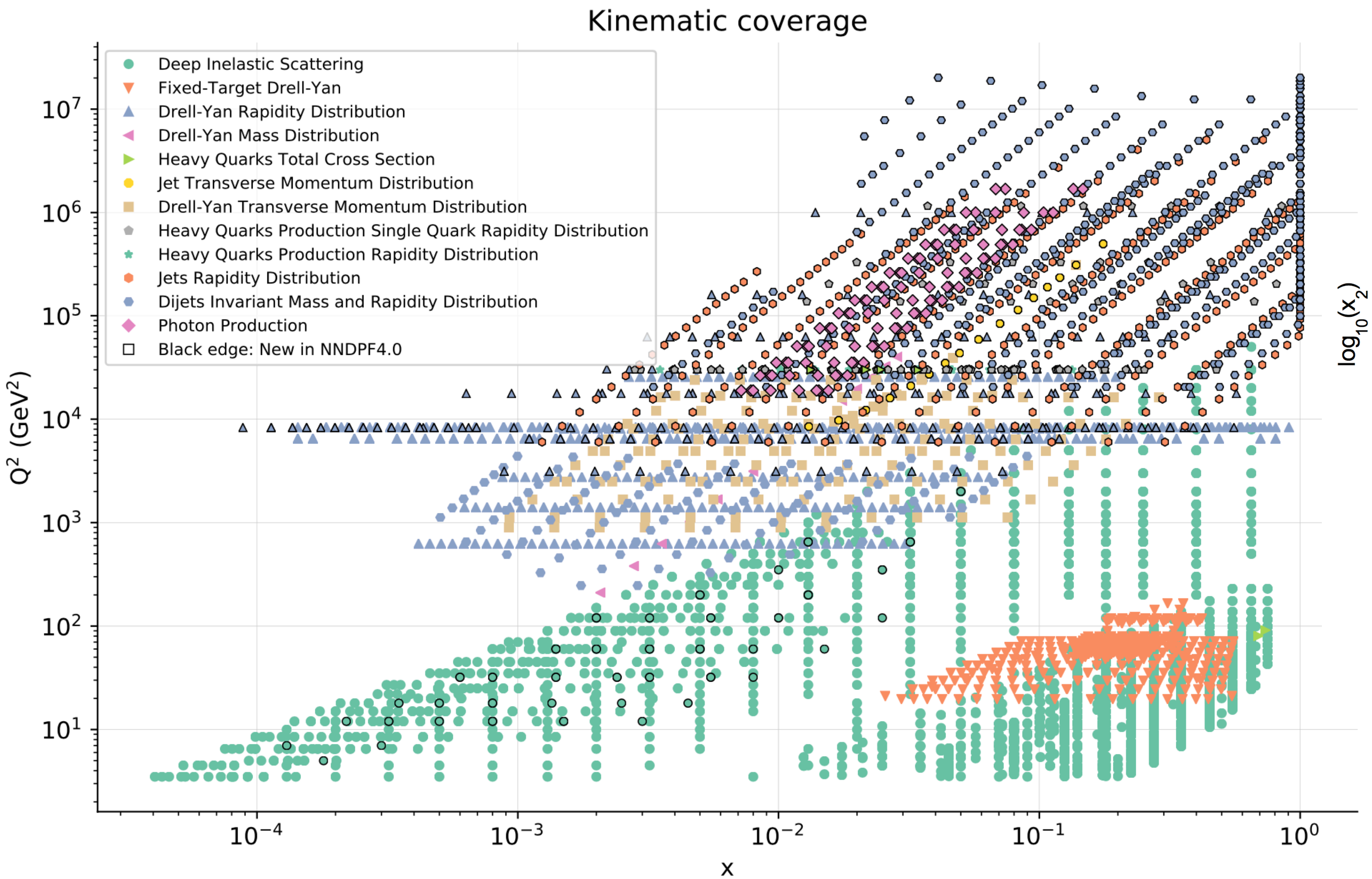
!

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

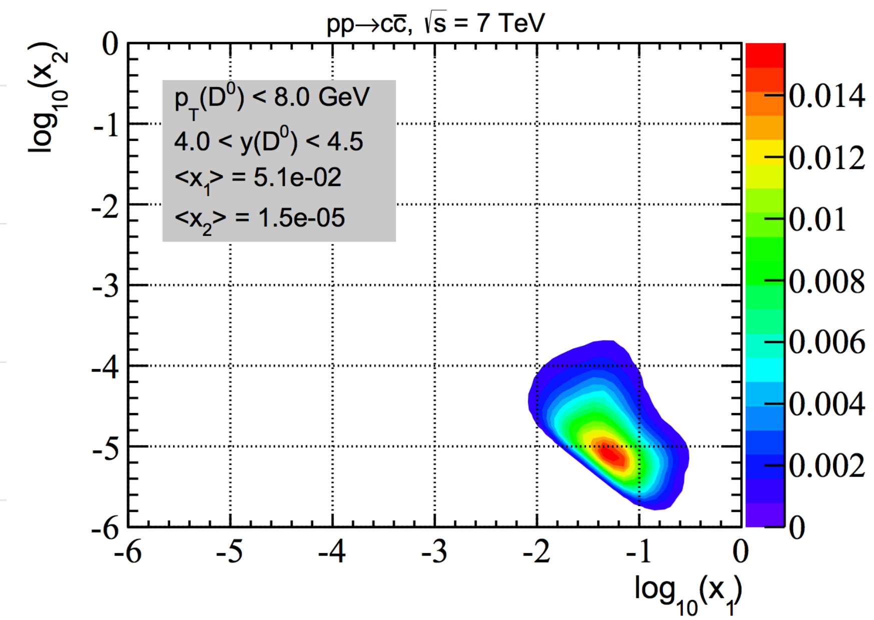
***DGLAP** parton evolution equations*

Forward measurements for proton PDFs

NNPDF4.0: data set extension

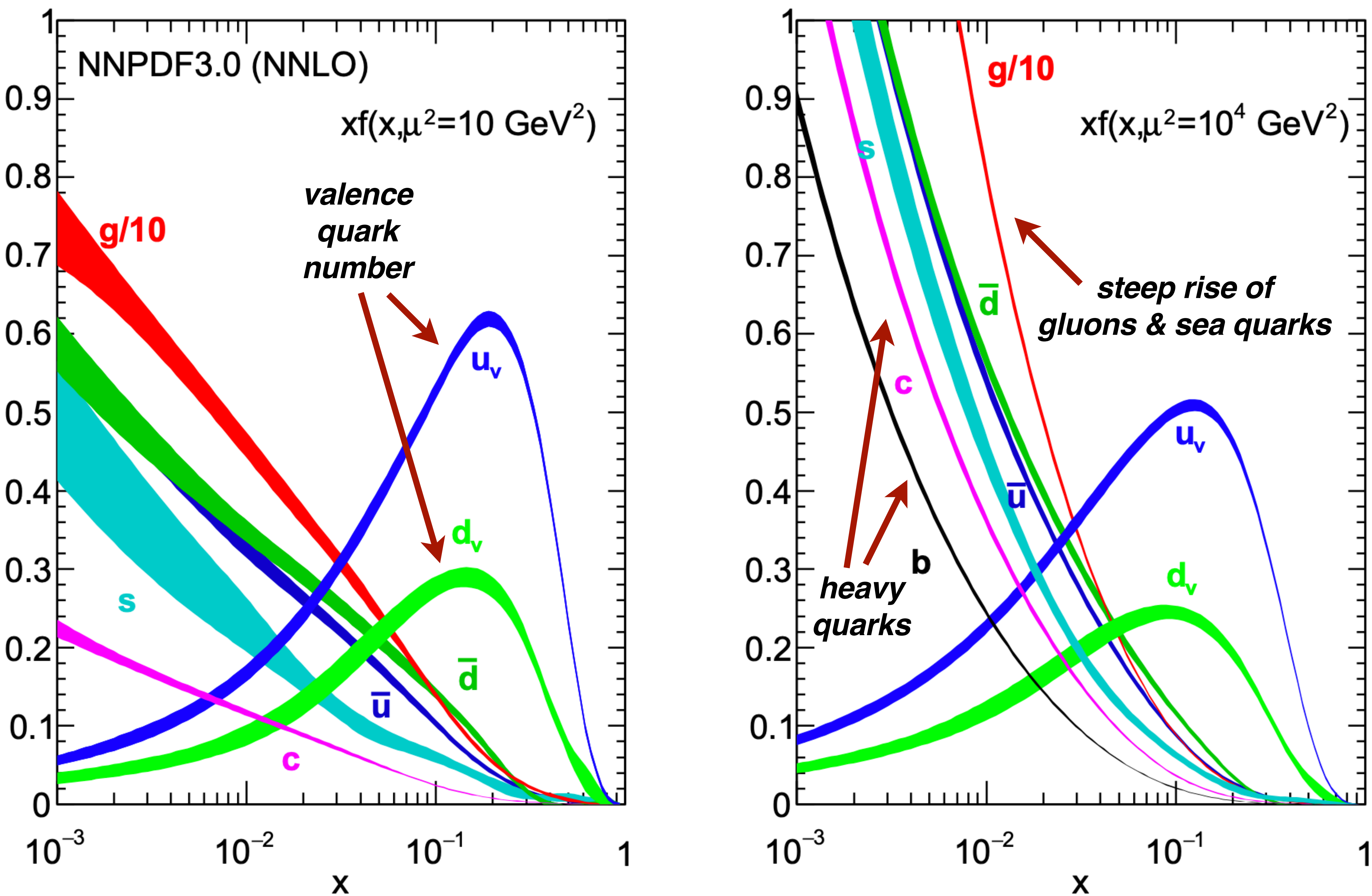


Charm @ LHCb

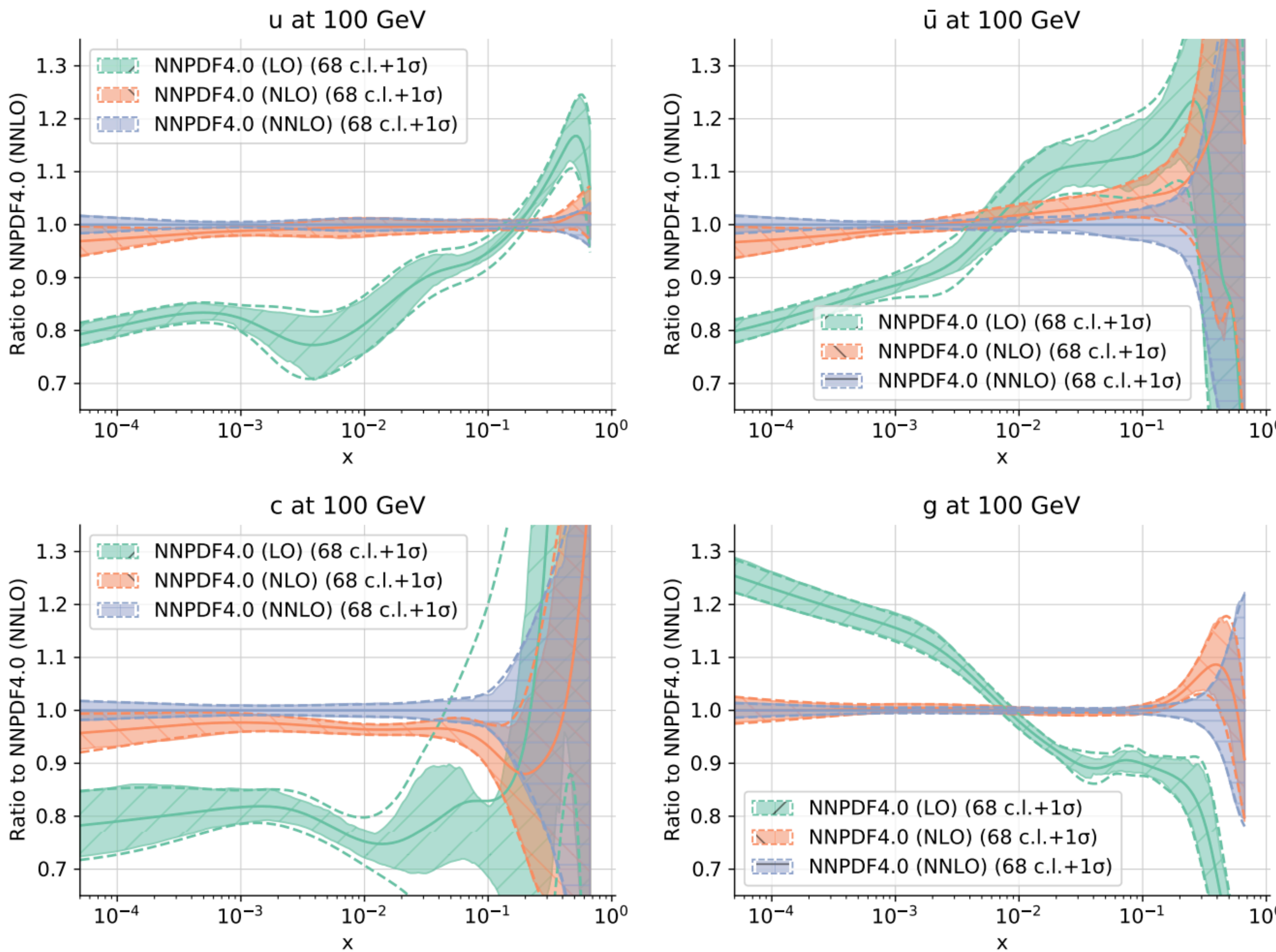


- In global PDF fits, the small-x region ($x < 10^{-3}$) is constrained mostly by **inclusive and charm HERA** structure functions and by **inclusive *W, Z* production from LHCb**
- ***D*-meson production at LHCb** has also been considered and **extends coverage down to x = 10^{-6}** but is only available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



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

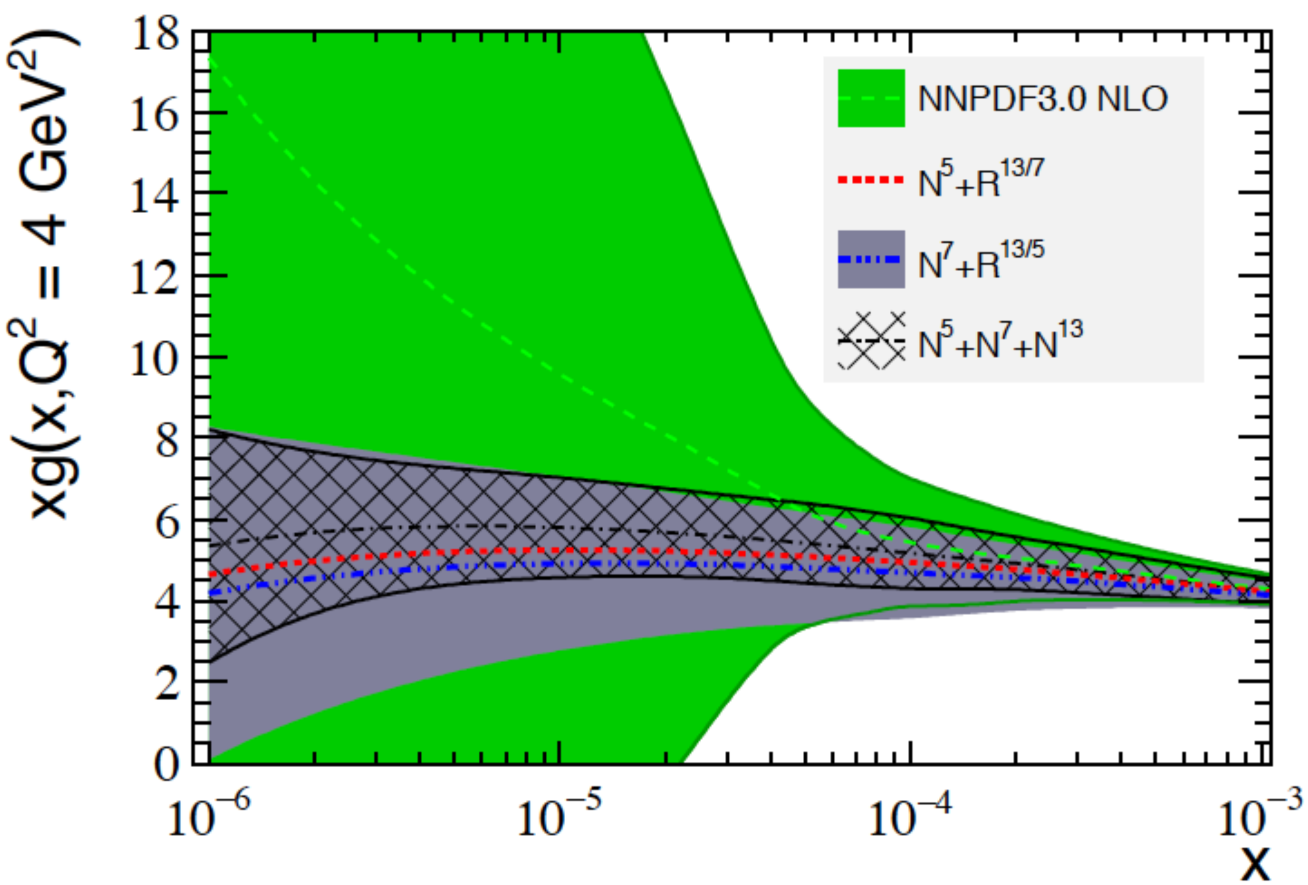
- Include LHCb D meson production at **5, 7, 13 TeV**
- Fit **normalised distributions** & **ratios between CoM energies** to reduce MHOUs

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

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

gluon PDF uncertainties reduced by **factor 10** at **x** ≃ **10^{-6}**

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

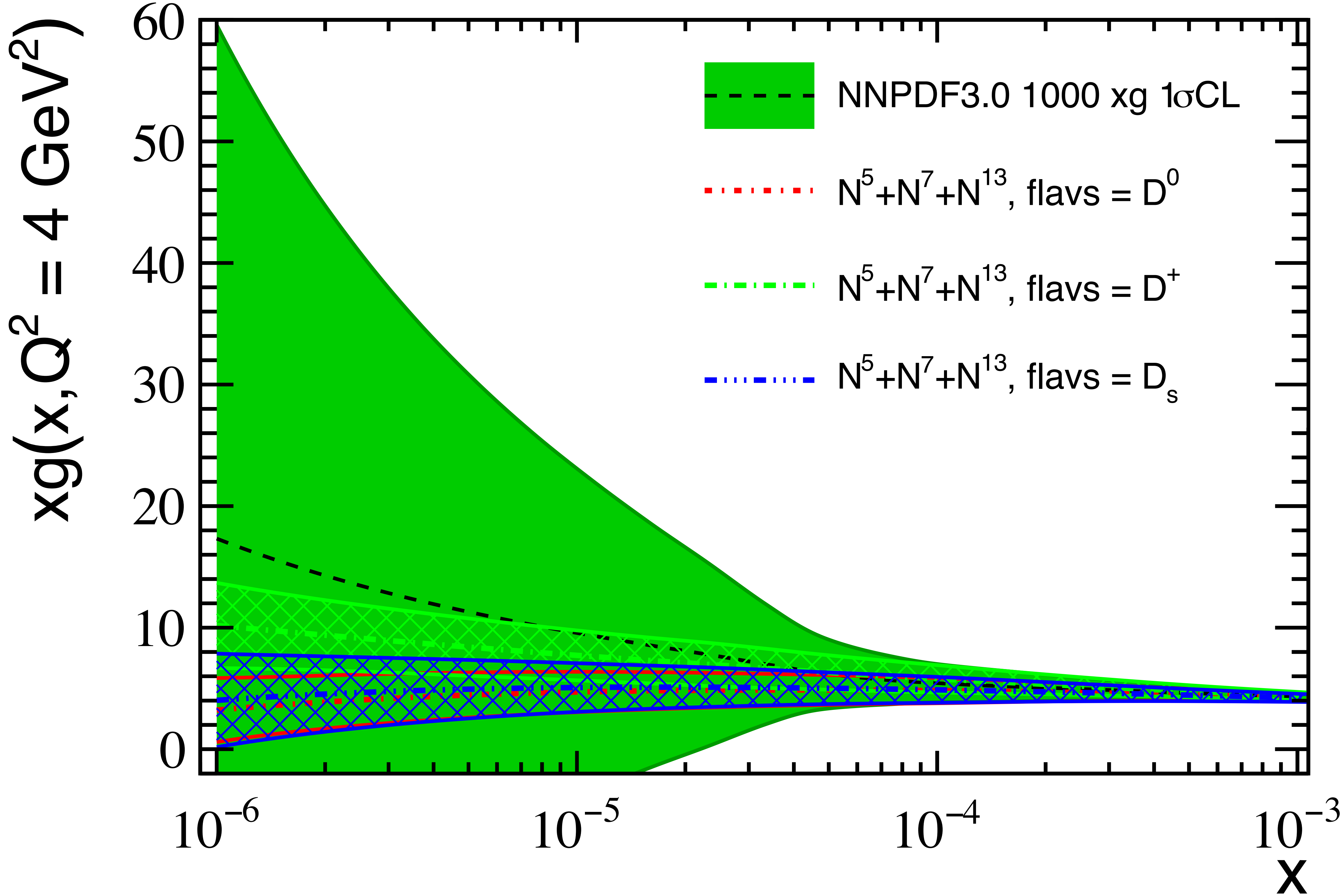


$N_5(84)$	$N_7(79)$	$N_{13}(126)$	$R_{13/5}(107)$	$R_{13/7}(102)$
1.97	1.21	2.36	1.36	0.80
0.86	0.72	1.14	1.35	0.81
1.31	**0.91**	1.58	1.36	0.82
0.74	0.66	**1.01**	1.38	0.80
1.08	0.81	1.27	**1.29**	0.80
1.53	0.99	1.73	1.30	**0.81**
1.07	0.81	1.34	1.35	**0.81**
0.82	**0.70**	1.07	**1.35**	0.81
0.84	**0.71**	**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 Q²

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

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

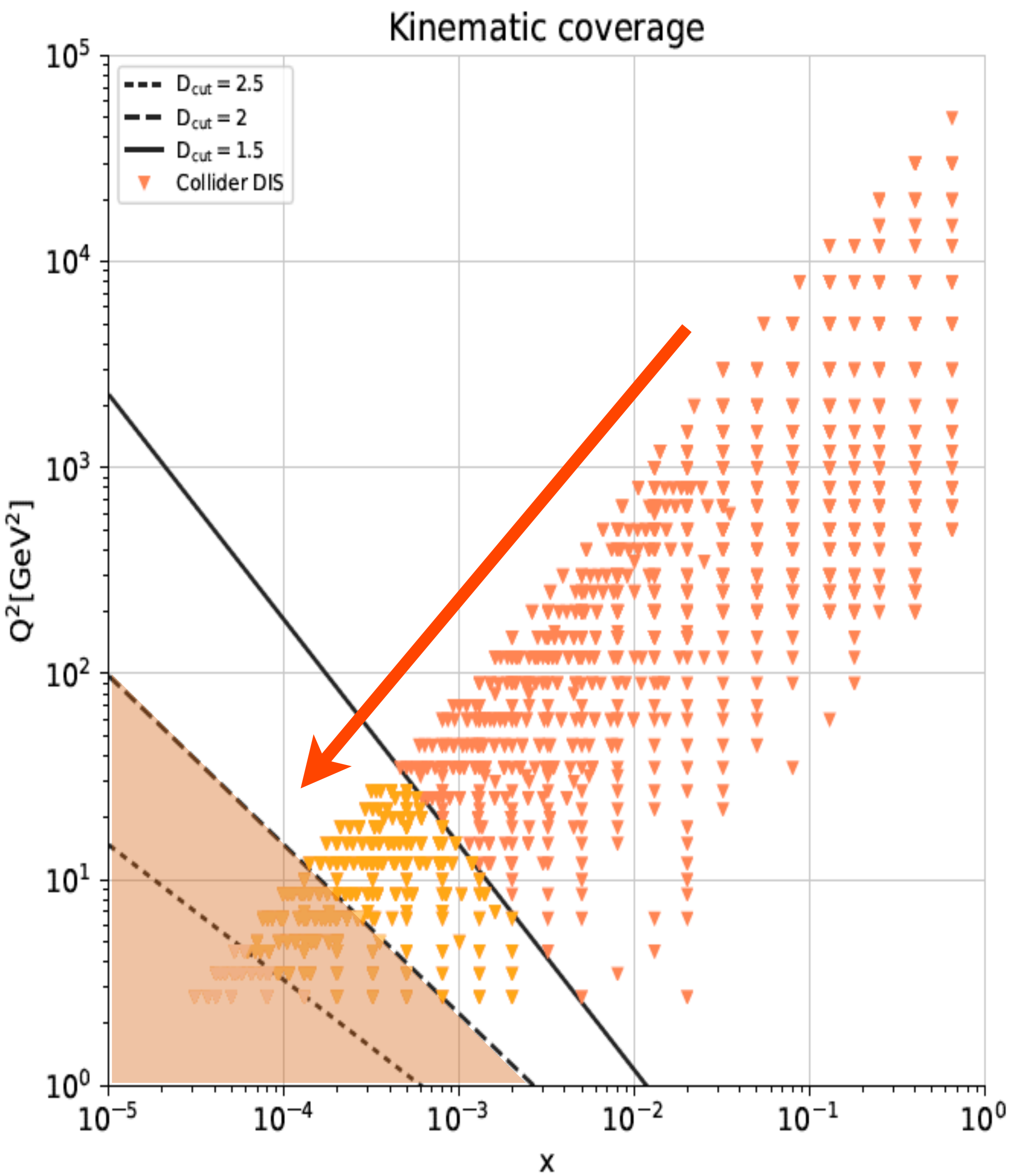
$$P_{ij}^{\mathrm{N}^k\mathrm{LO}+\mathrm{N}^h\mathrm{LL}x}(x) = P_{ij}^{\mathrm{N}^k\mathrm{LO}}(x) + \Delta_k P_{ij}^{\mathrm{N}^h\mathrm{LL}x}(x)$$

Forward measurements for proton PDFs

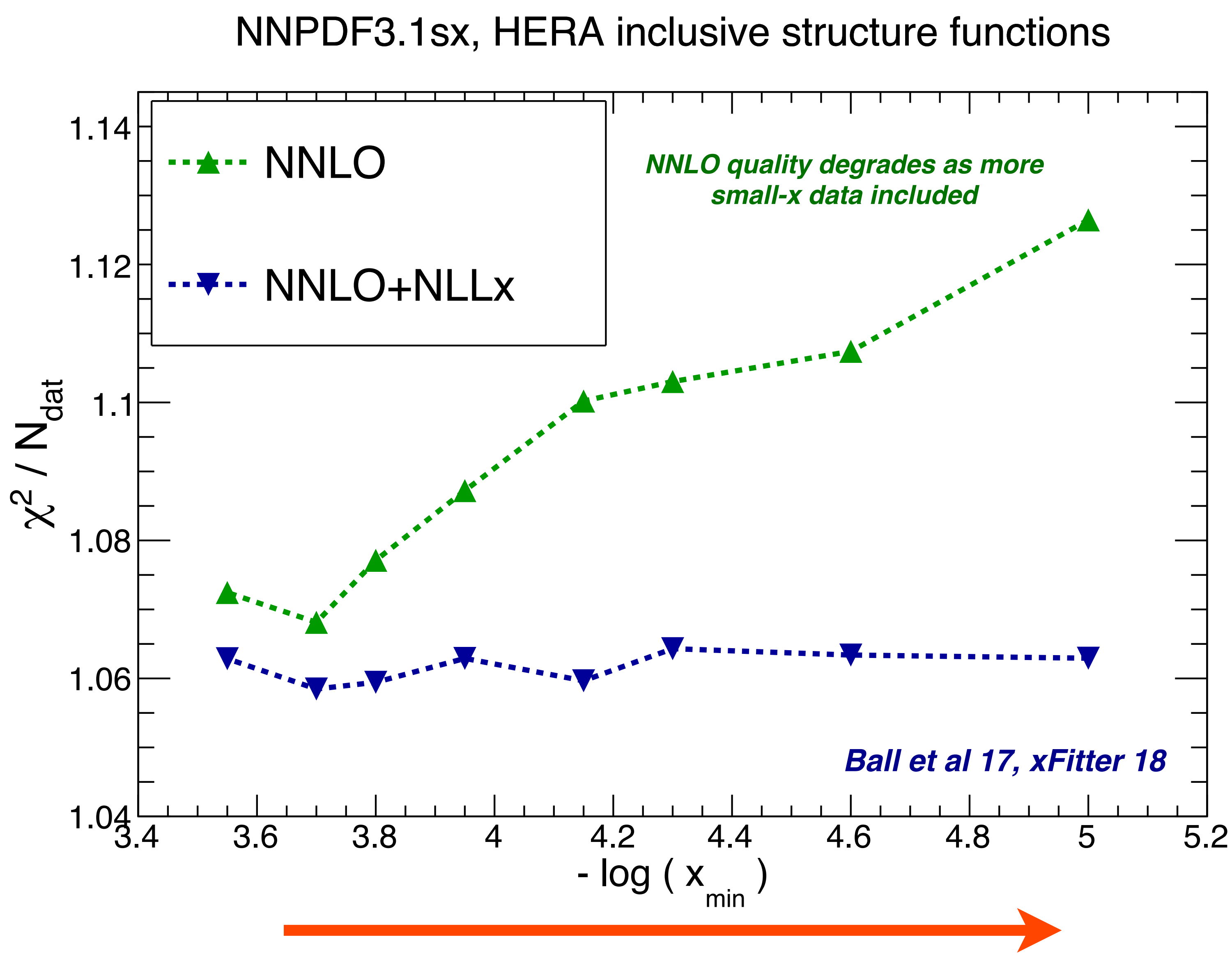
BFKL dynamics stablished from HERA data from inclusive and charm structure functions

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

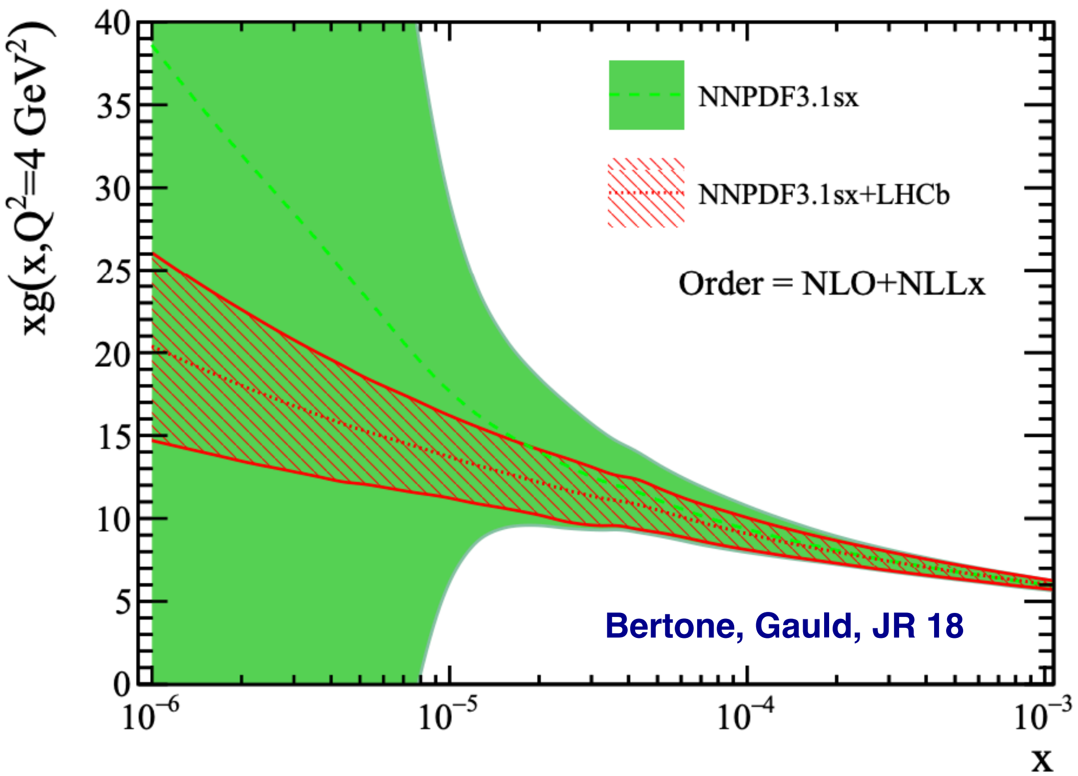


Best description of **small-*x* HERA data: BFKL resummation**

Will also affect heavy hadron production @ LHC in forward region

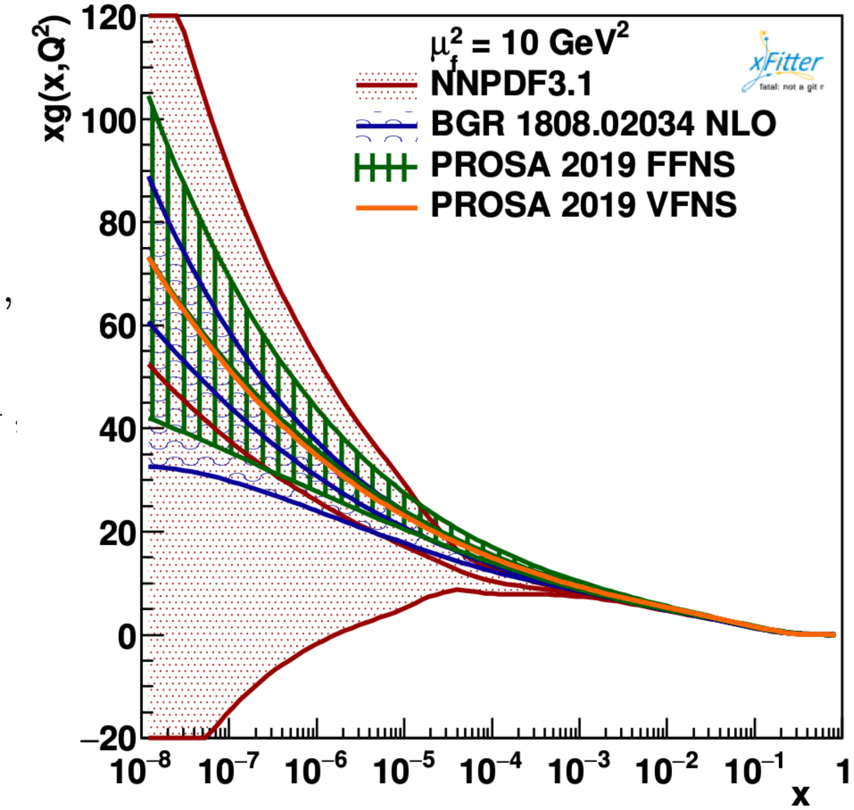
From the LHC to neutrino telescopes

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



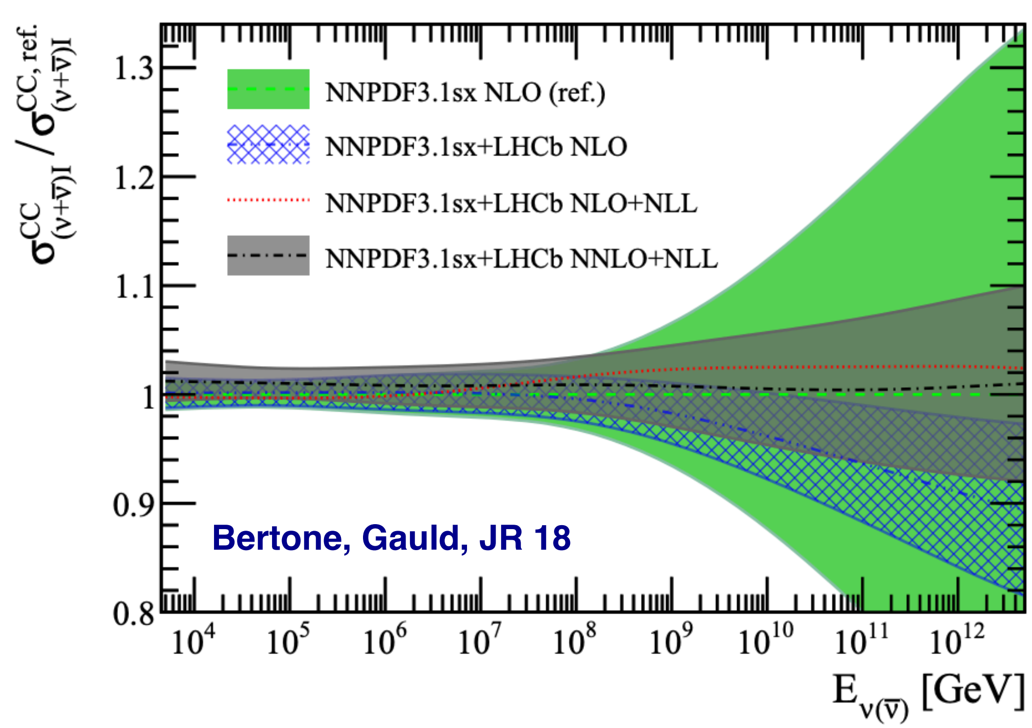
$$N_X^{ij} = \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_i^D d(p_T^D)_j} \Big/ \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_{\mathrm{ref}}^D d(p_T^D)_j},$$

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

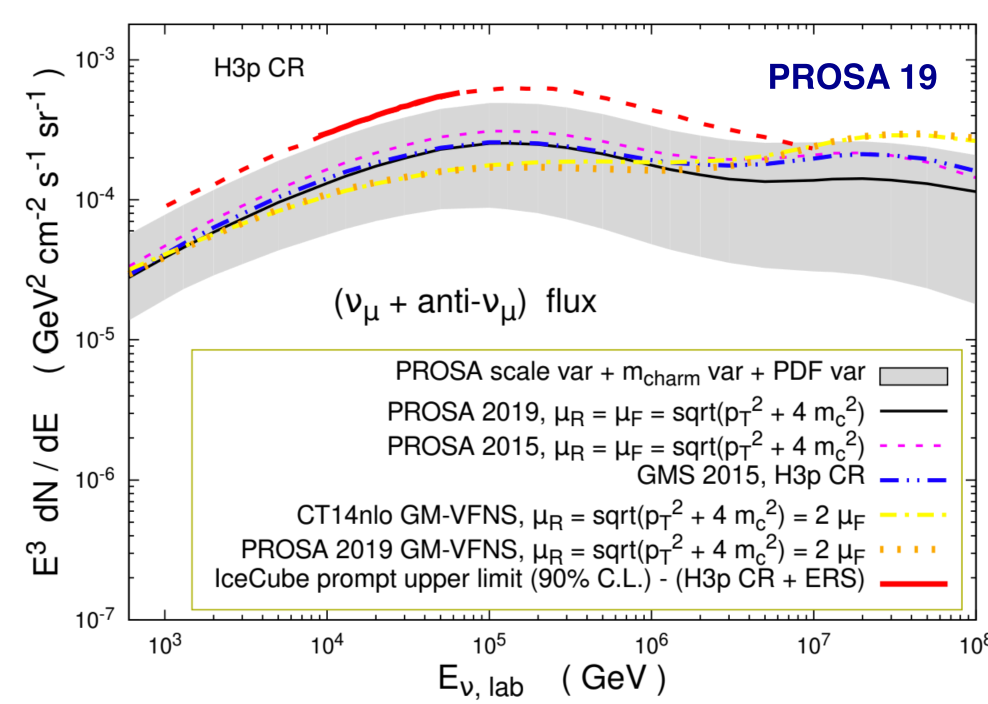


implications for **high-energy astroparticle physics:**

UHE neutrino-nucleus cross-sections

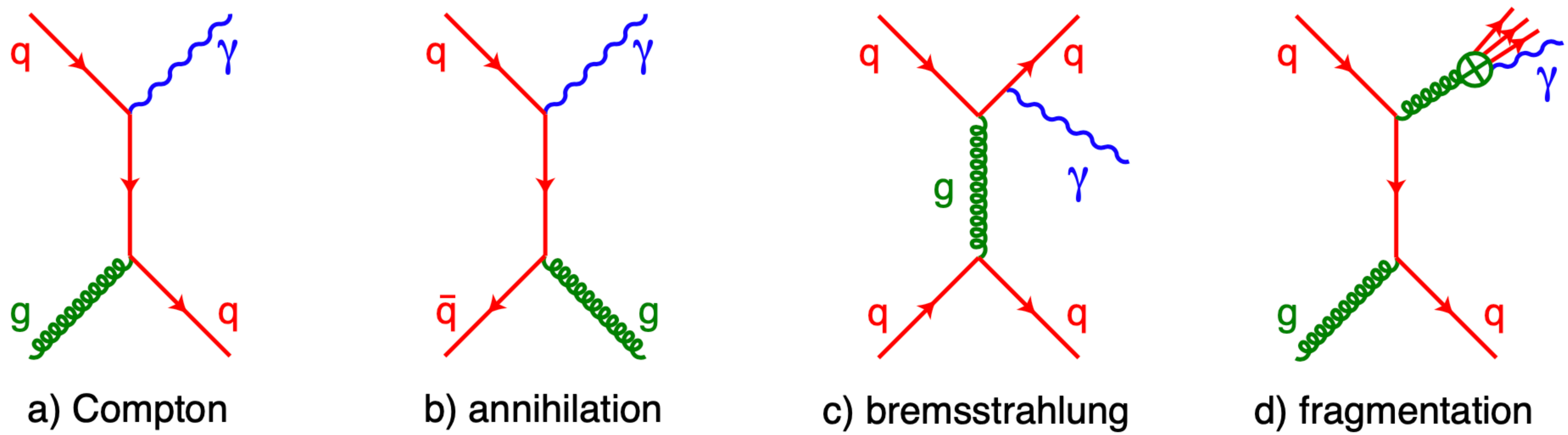


prompt neutrino fluxes from charm in CRs

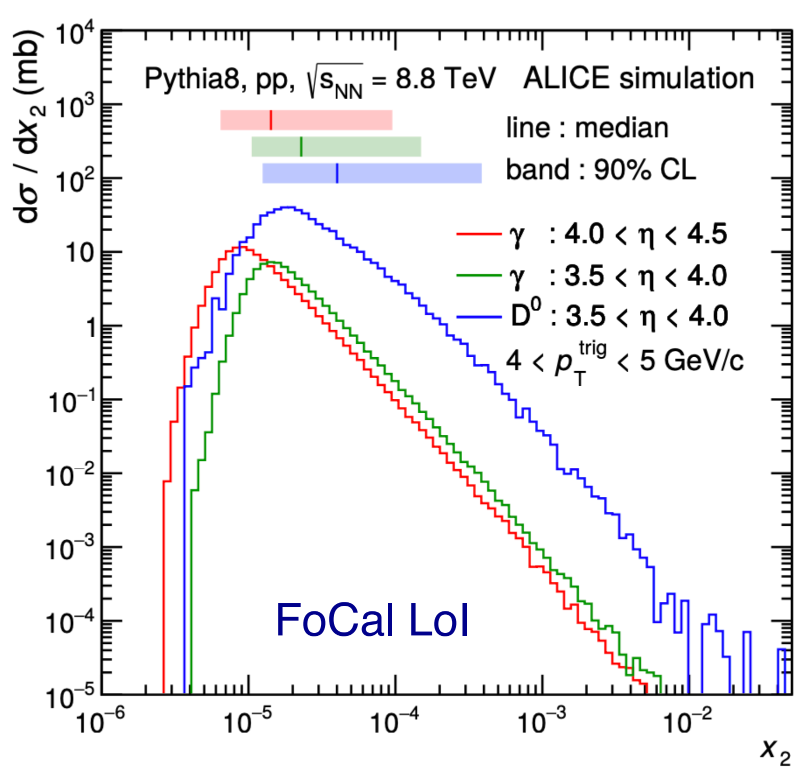


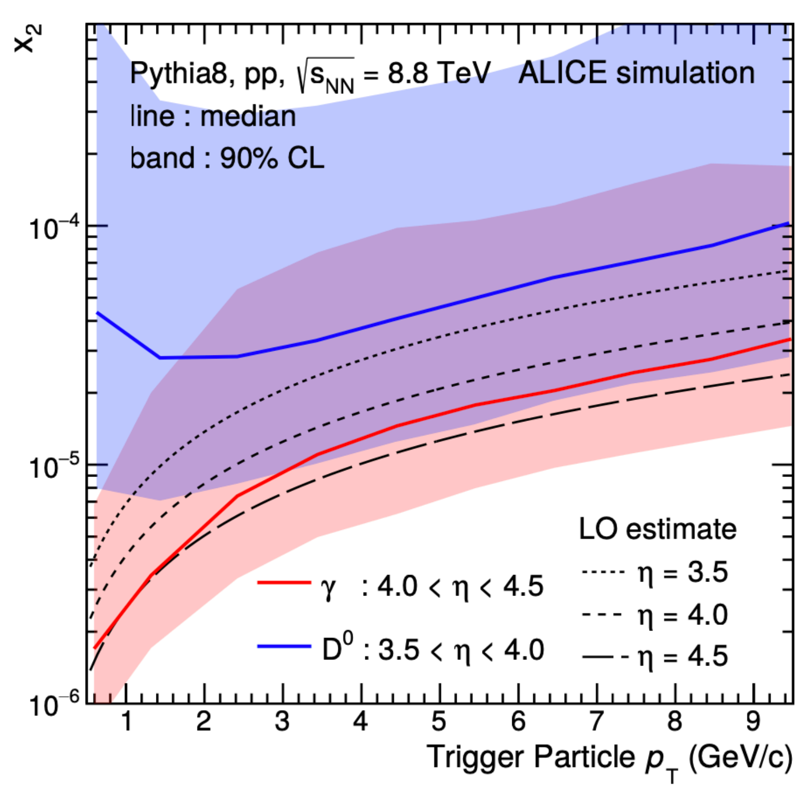
Forward photons at the LHC

- 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

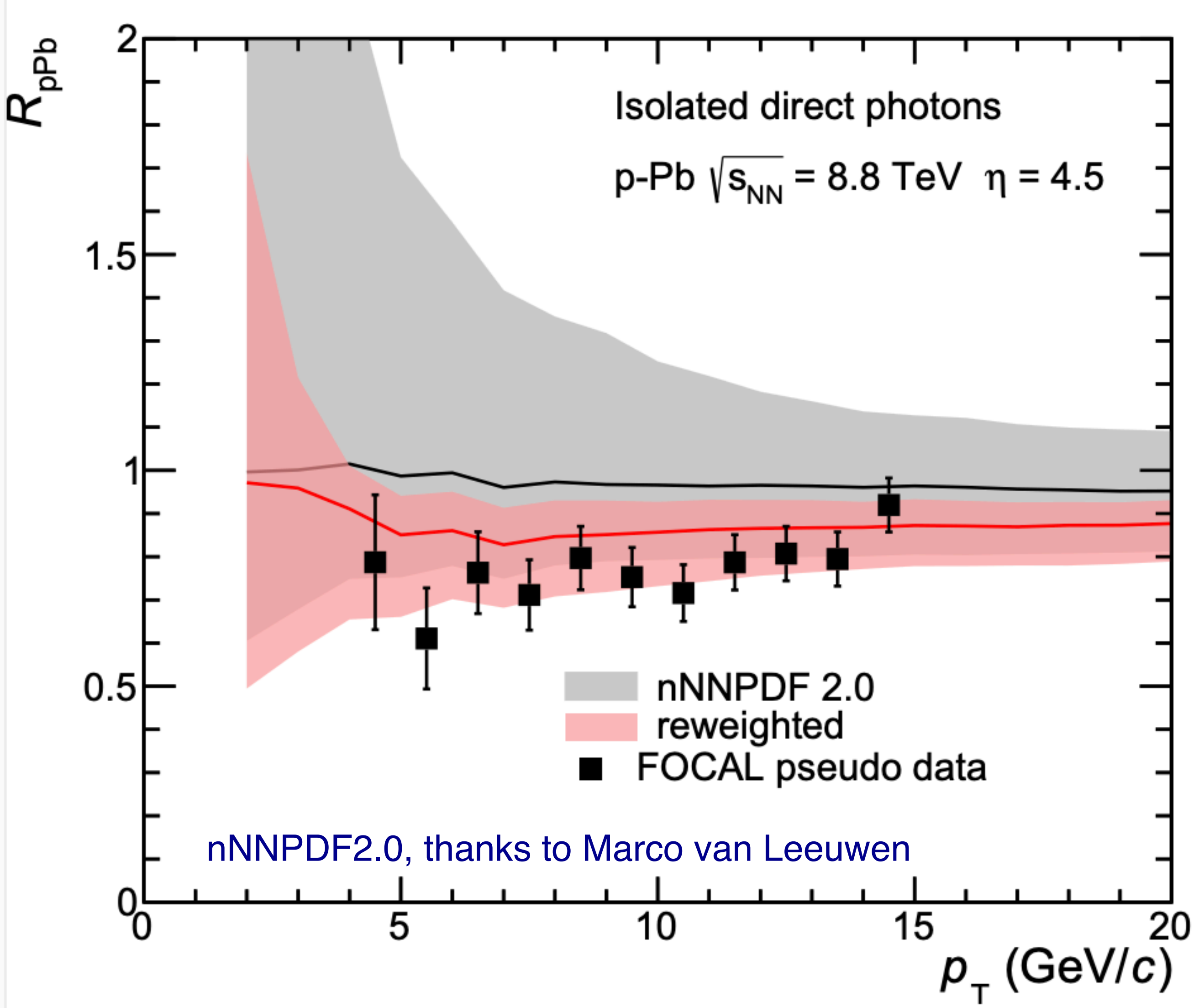


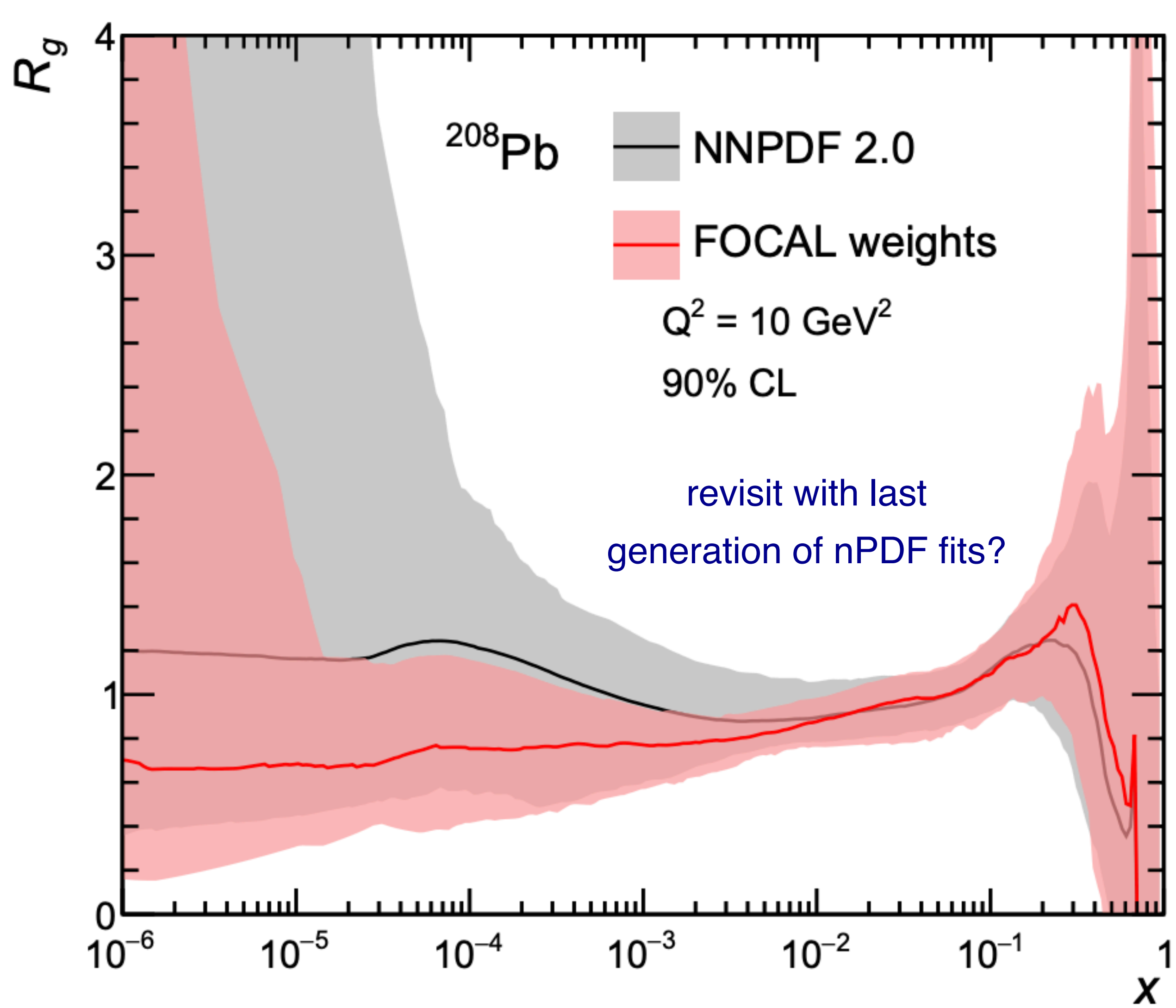


photon production does not affected by final state or FCEL effects

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



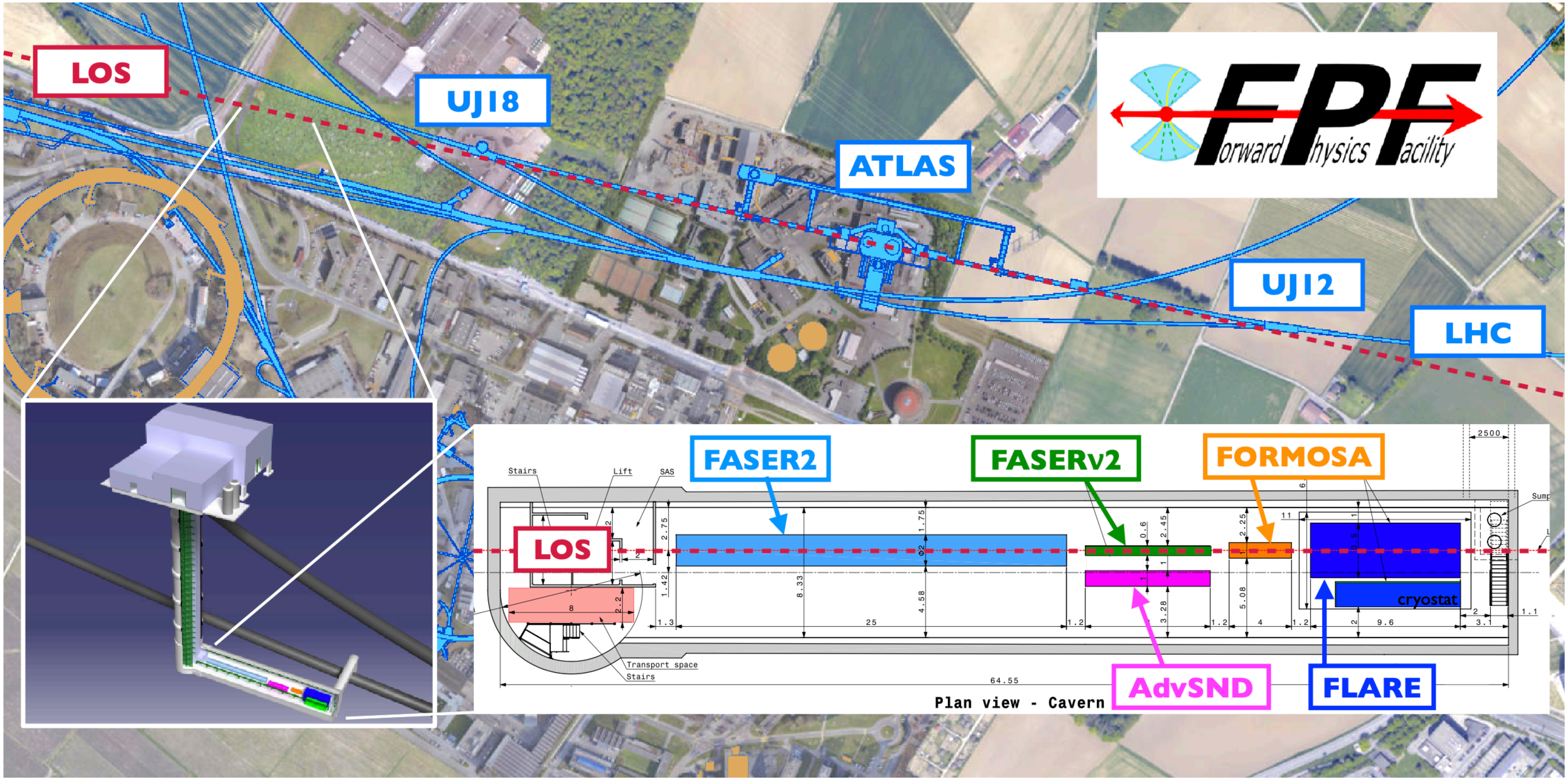


Non-linear & CGC dynamics, if present, could be **reabsorbed in the nuclear PDF fit**

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)

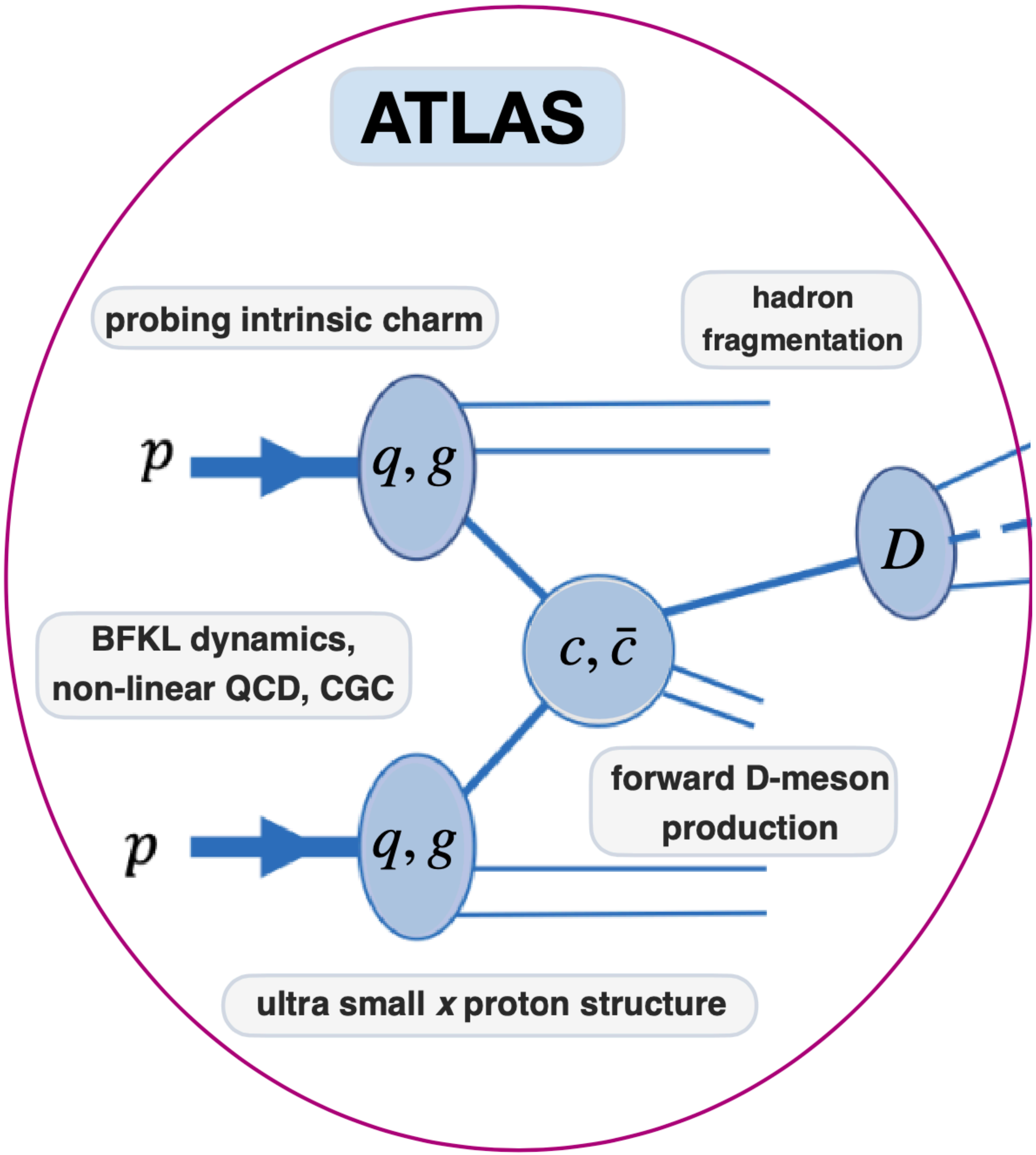
The Forward Physics Facility

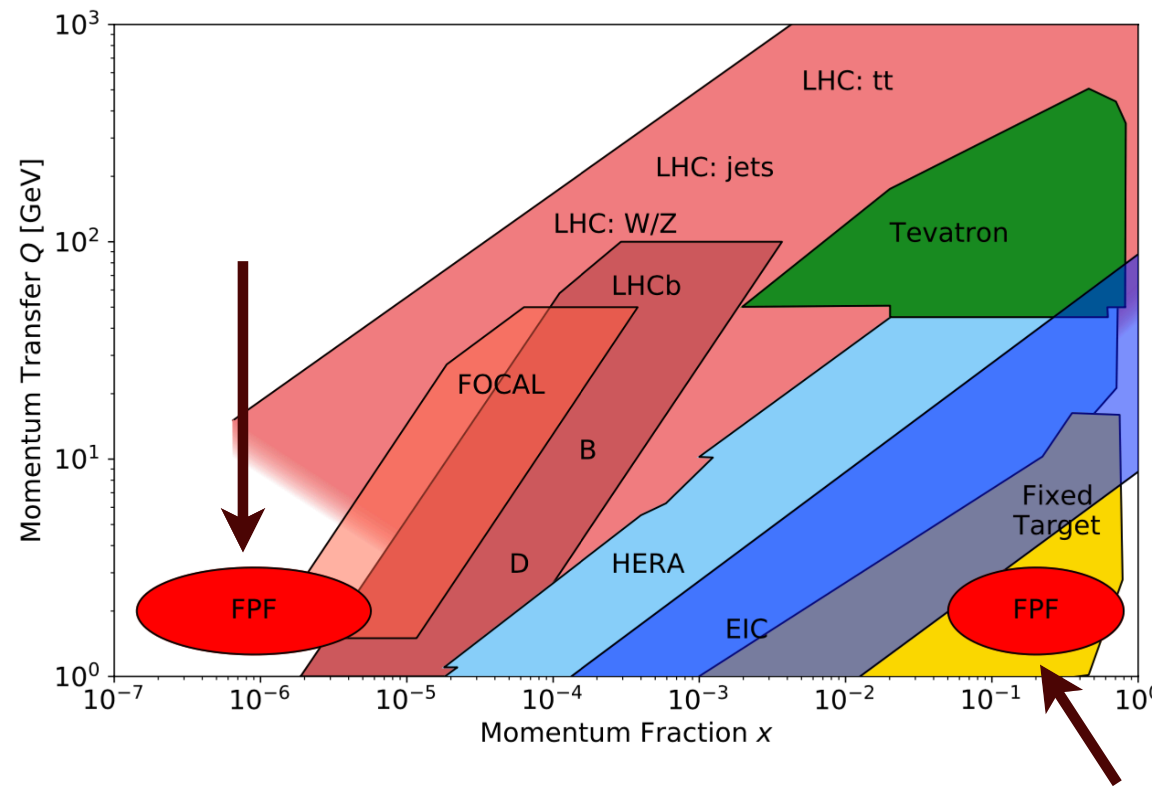
A proposed new facility in a tailor-made underground cavern hosting a suite of **far-forward experiments** suitable to detect **long-lived BSM particles** and **neutrinos** produced at the **High-Luminosity LHC** (ATLAS interaction point)



No modifications to the HL-LHC operations required

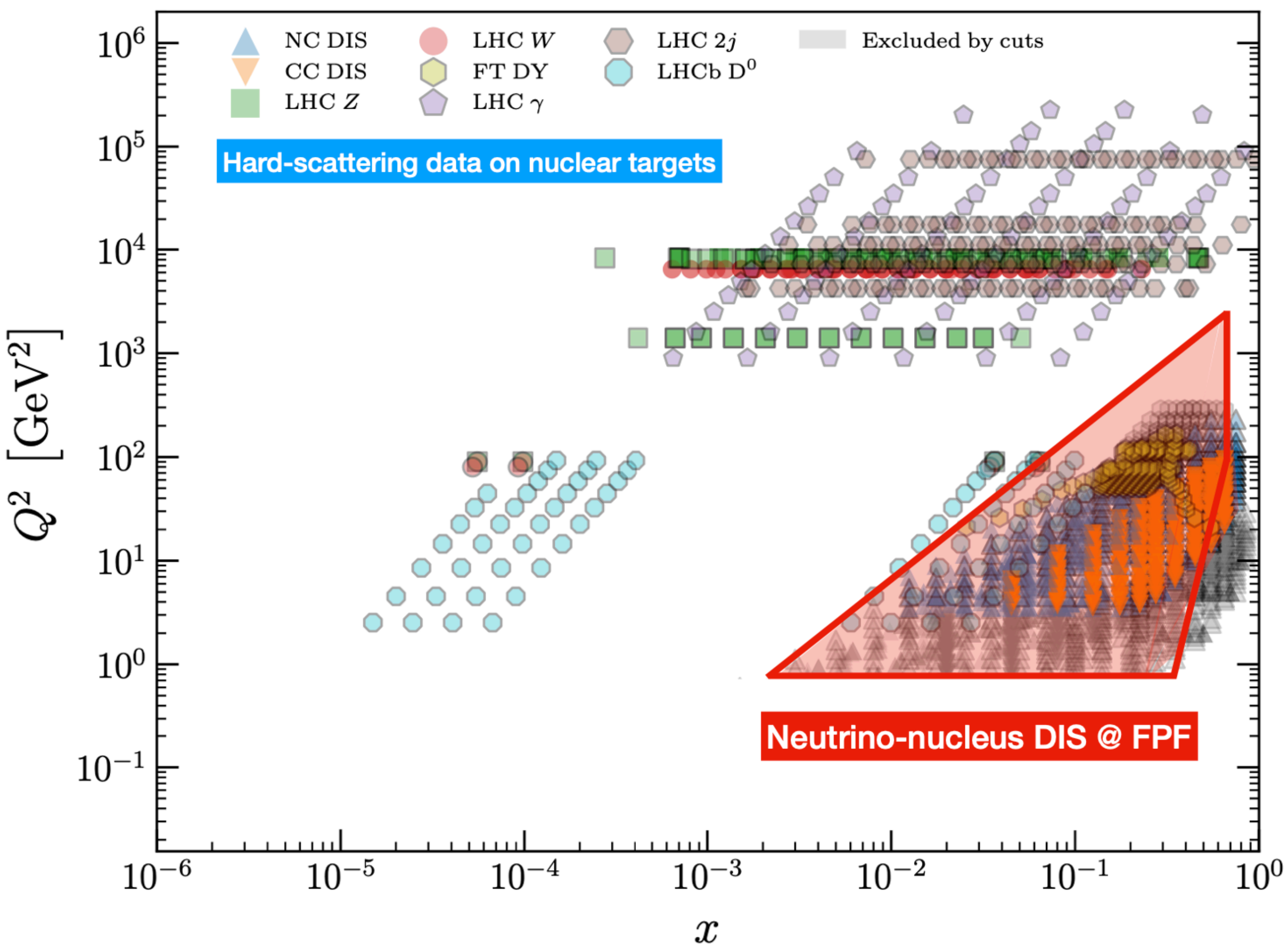
small-*x* QCD at the FPF

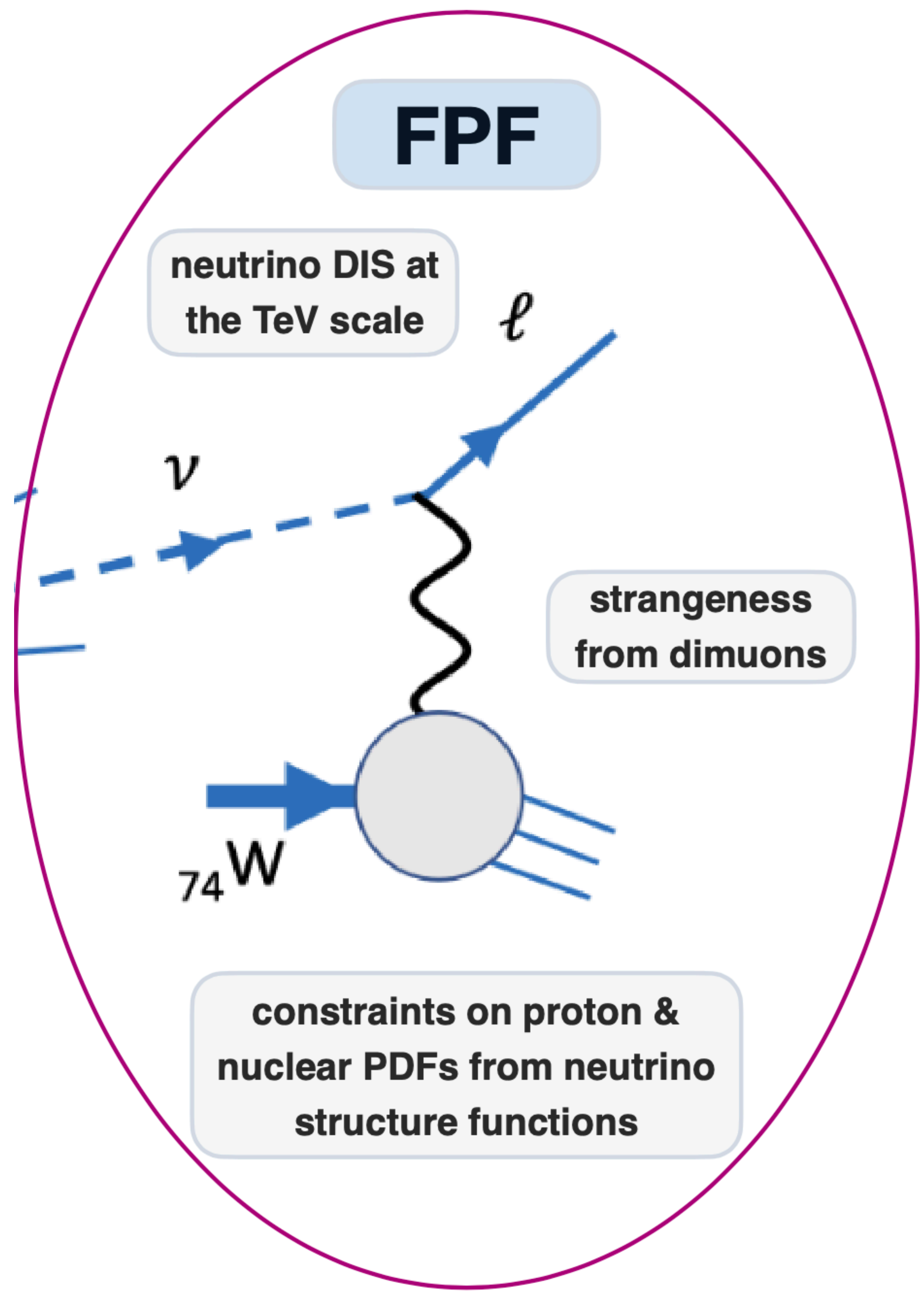




- **Forward particle production** (light hadrons & D-mesons) sensitive down to ***x*=10^{-7}**
- Ultra small-*x* proton structure & **BFKL / non-linear QCD** dynamics
- Tune models of forward hadron fragmentation (for e.g. cosmic rays)
- Constraints on **intrinsic charm** from large-*x* D-meson production

Neutrino DIS at the LHC





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

Overview of forward processes for (n)PDFs

Process	Availabilty	Strenghts	Weakneses
***D*-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 *A*-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!**