Do protons really contain charm quarks?

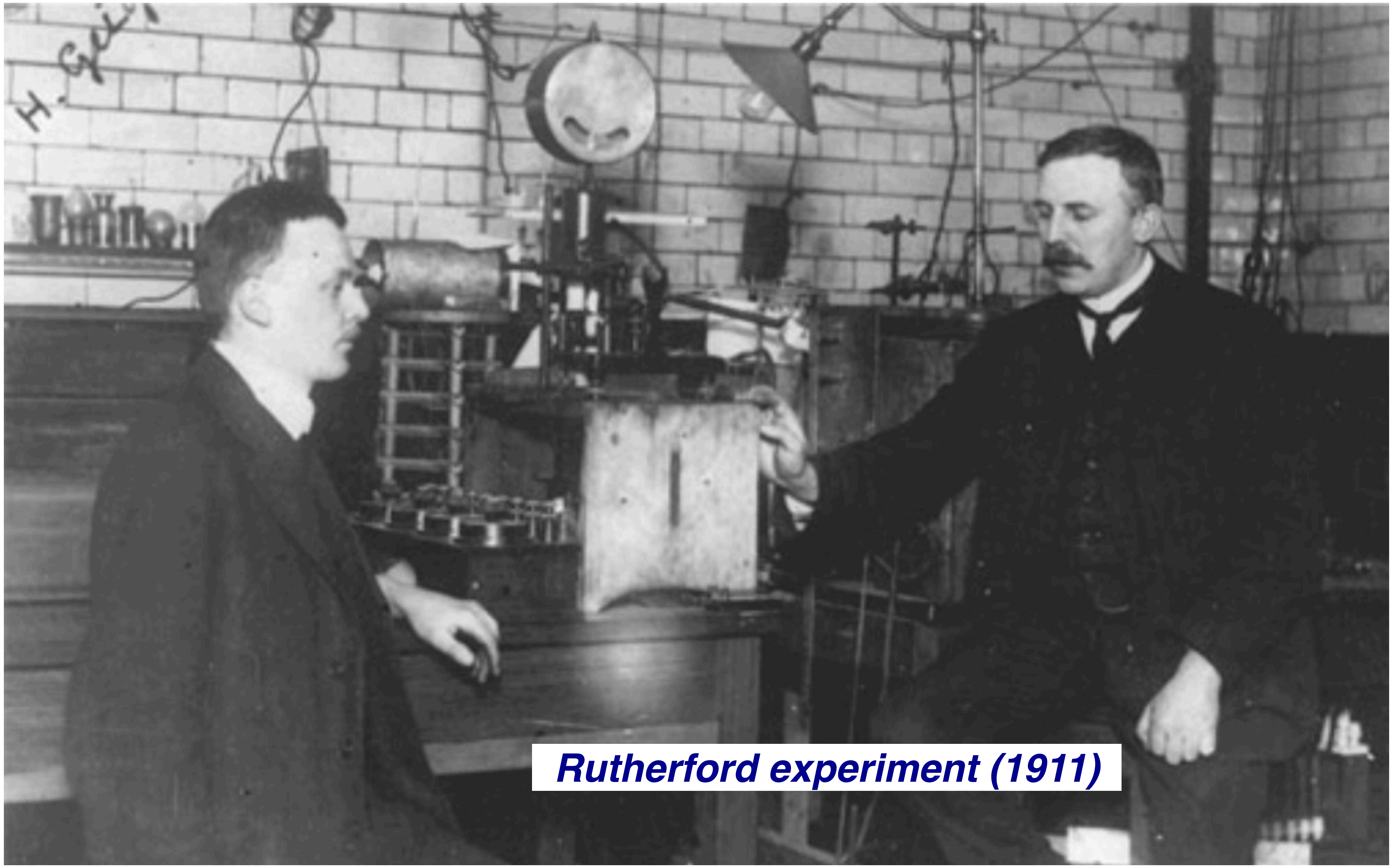
Juan Rojo, VU Amsterdam & Nikhef

19.01.2023, KIT Particle Physics Colloquium

Why Nucleon Structure?

Why Nucleon Structure?

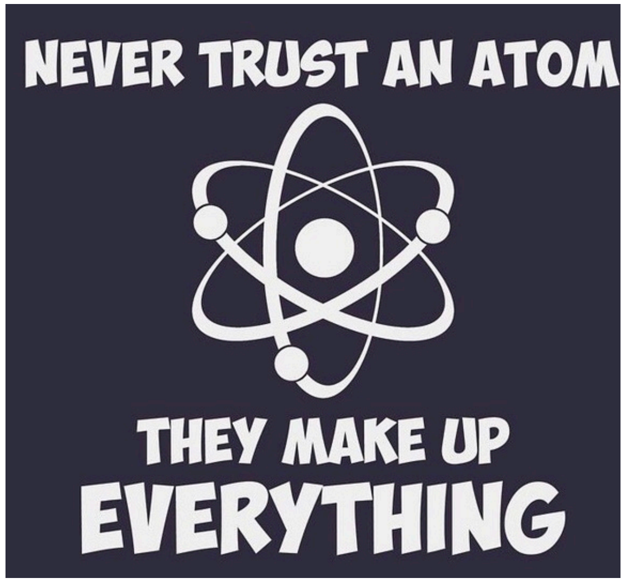
One may claim that the **nucleon is a rather ``boring" particle**, surely after **one century of studying it**, we know everything about the proton?



Rutherford experiment (1911)

Why Nucleon Structure?

nothing farther from reality: the proton is a beautiful example of the richness of quantum mechanics: what a **proton is** depends on the **resolution with which we examine it**



long distances / low energies → *short distances / high energies*

a point particle

$E \ll 1\ \text{GeV}$

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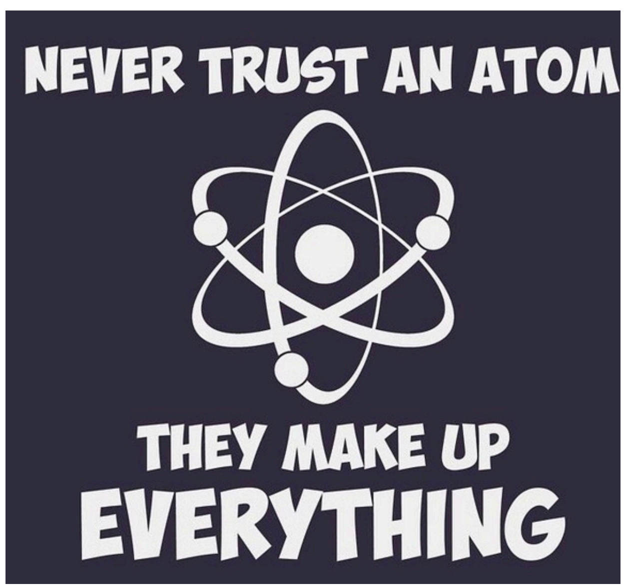

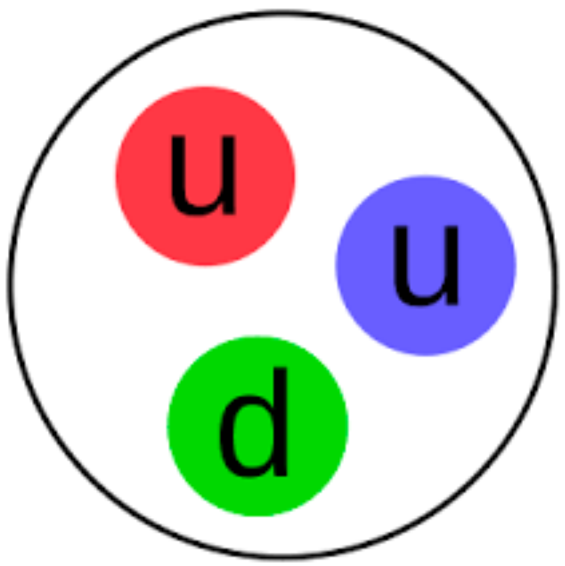

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3 valence quarks

$E \sim \text{few}\ \mathrm{GeV}$

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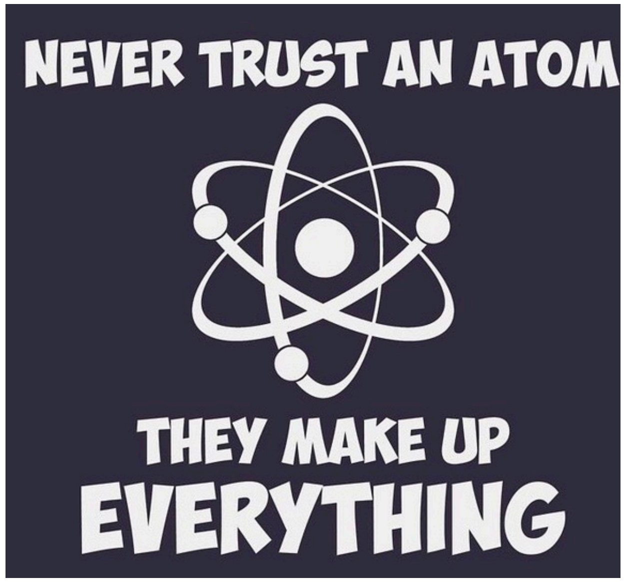

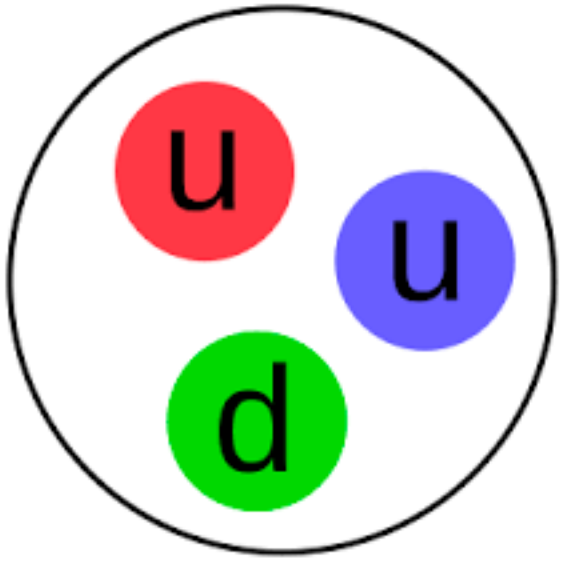

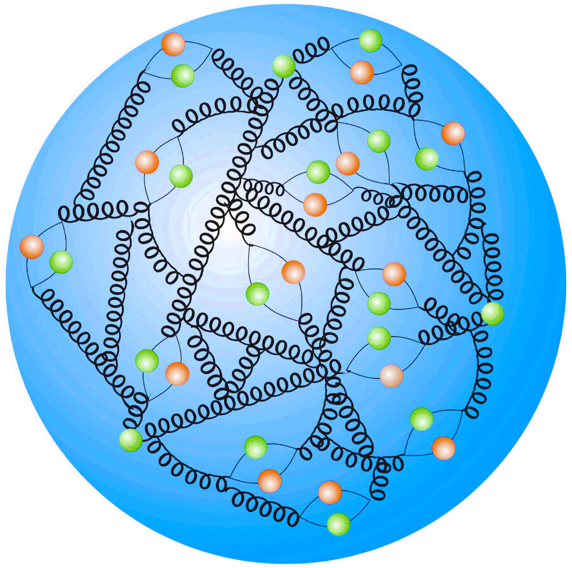

long distances / low energies → *short distances / high energies*

a point particle

$E \ll 1$ GeV

3 valence quarks

$E \sim$ few GeV

sea quarks, gluons

$E \sim 50$ GeV

Why Nucleon Structure?

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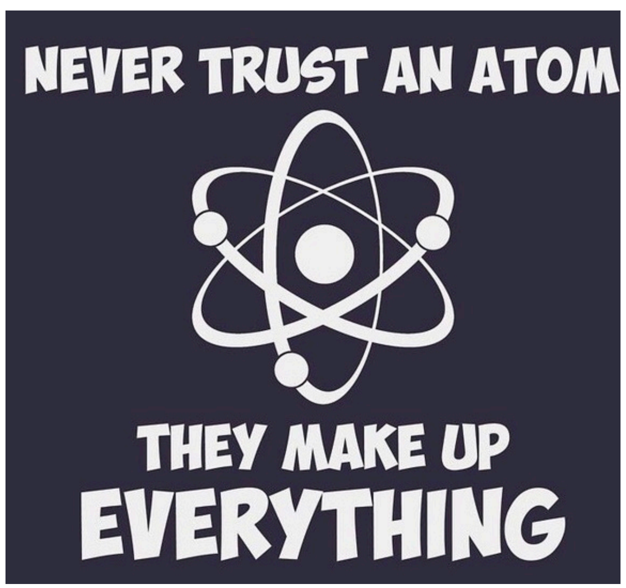
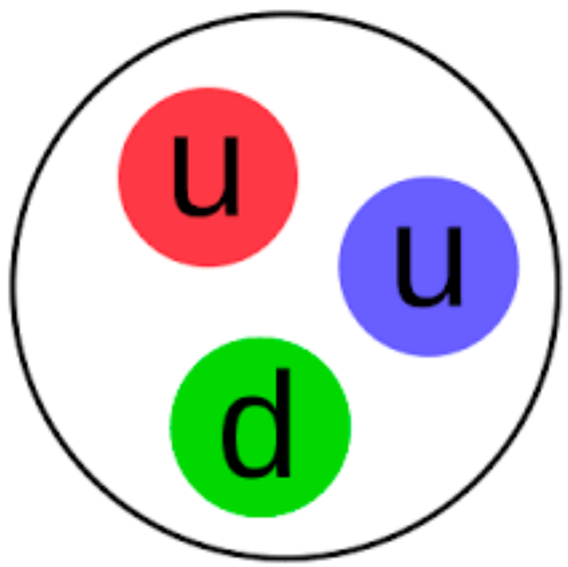
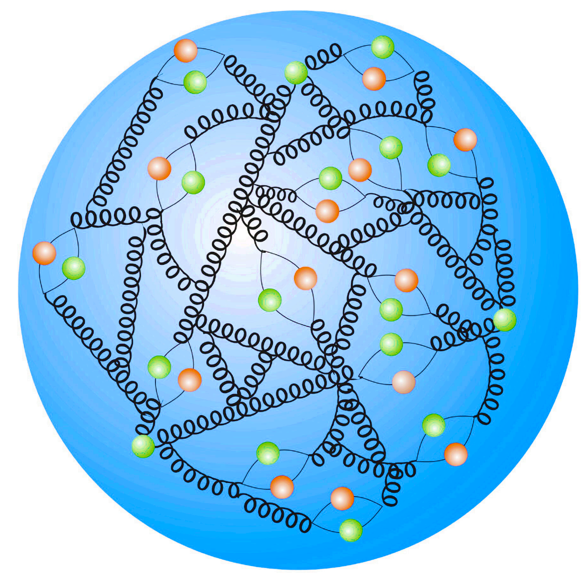
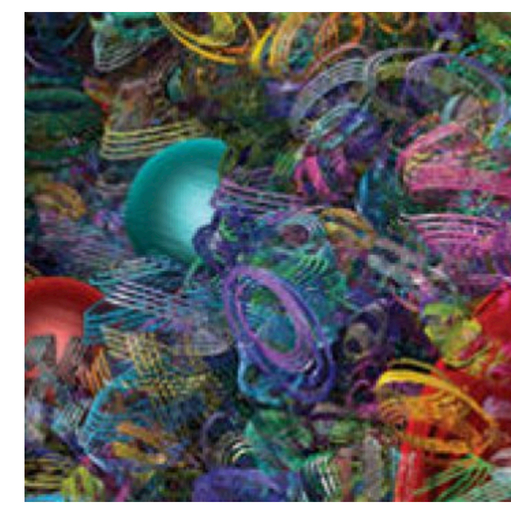








long distances / low energies — *short distances / high energies*

a point particle

$E \ll 1\ \mathrm{GeV}$

3 valence quarks

$E \sim \text{few GeV}$

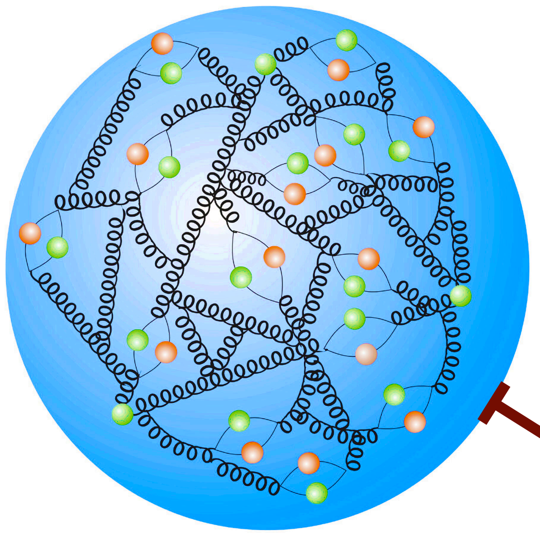
sea quarks, gluons

$E \sim 50\ \mathrm{GeV}$

heavy quarks, photons, leptons, Higgs bosons

$E \sim 1\ \mathrm{TeV}$

Why Nucleon Structure?

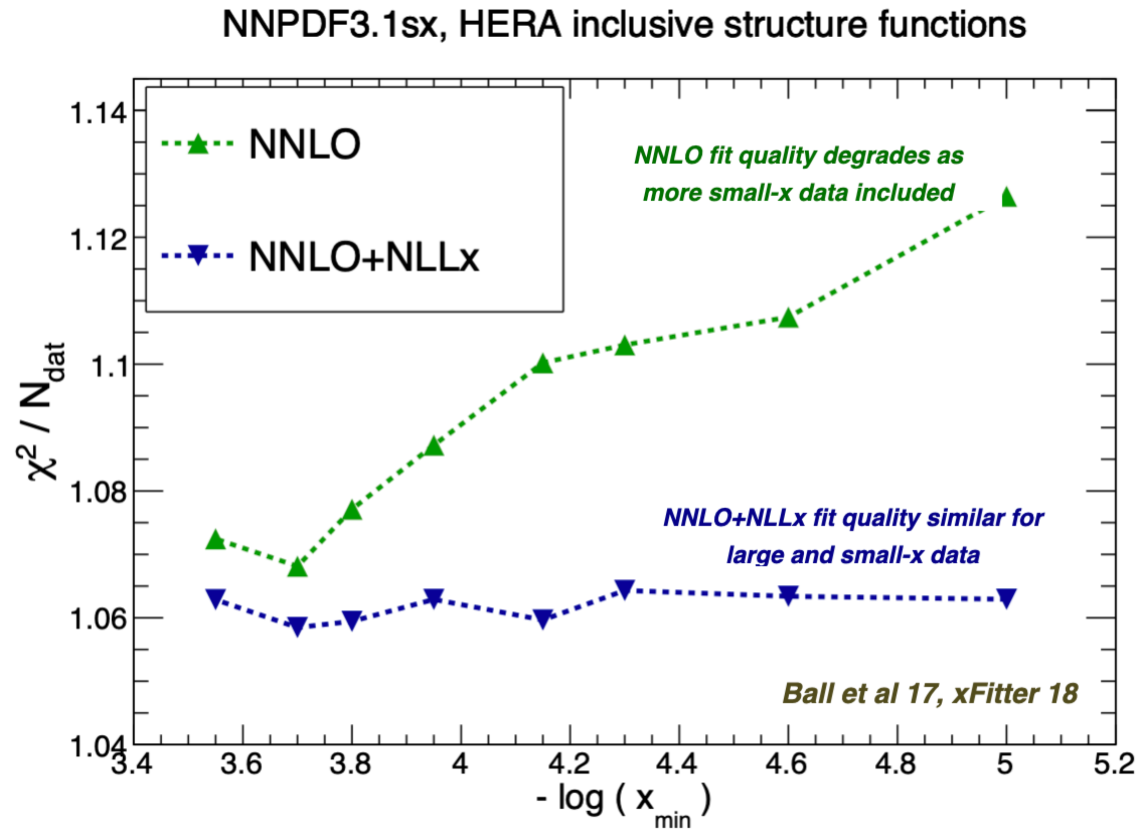


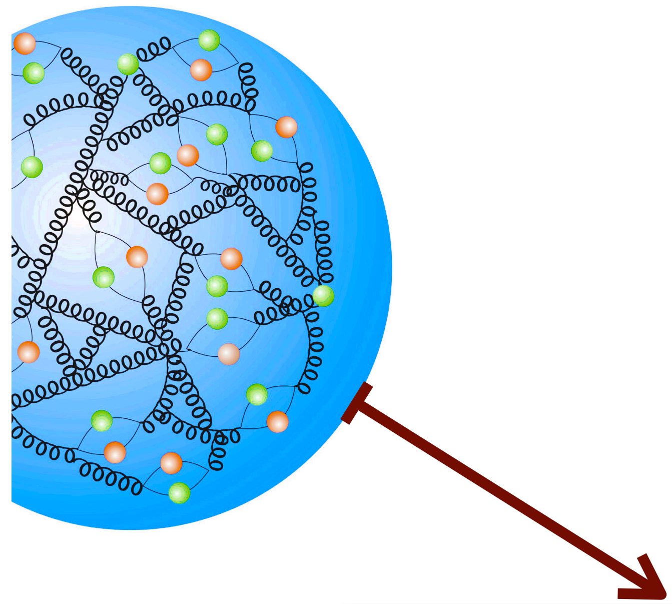
Address fundamental questions about Quantum Chromodynamics

- origin of mass & spin?
- **heavy quark** & **antimatter content?**
- 3D imaging?
- gluon-dominated matter?
- **nuclear modifications?**
- Interplay with BSM searches?

Why Nucleon Structure?

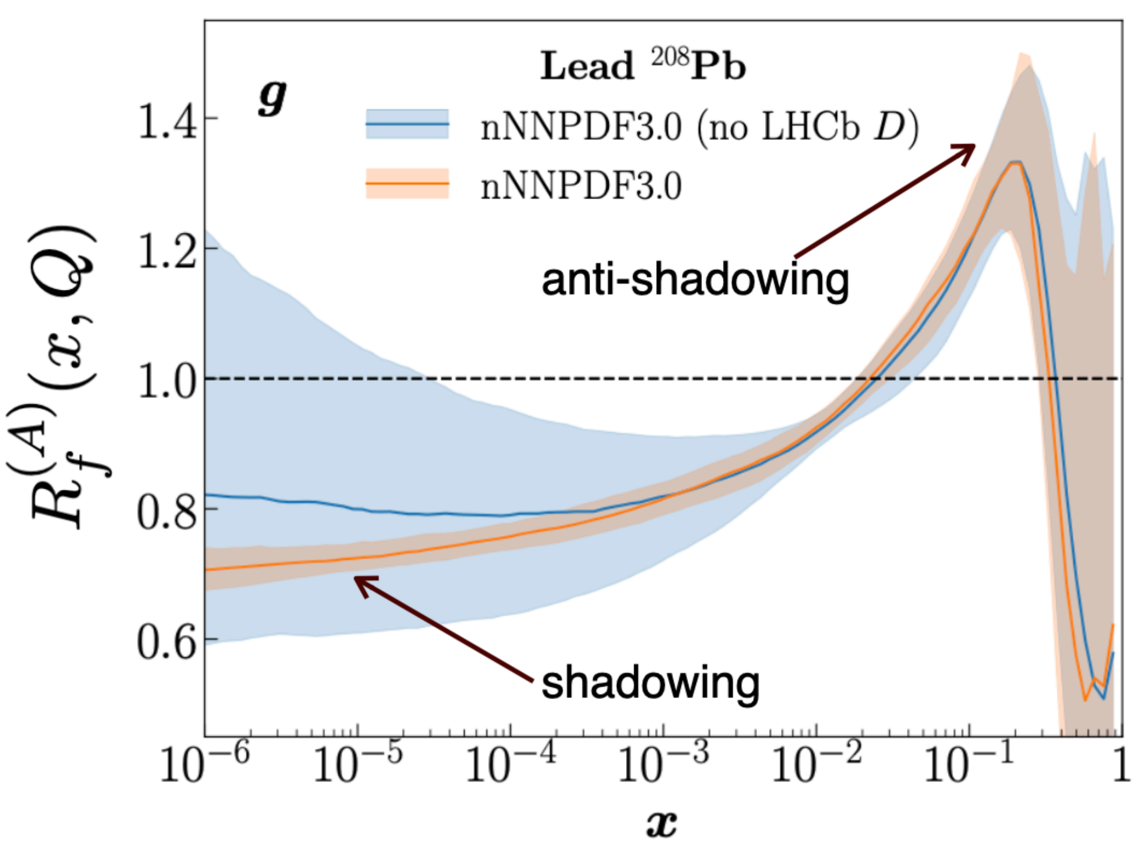
BFKL dynamics in HERA data





Address fundamental questions about Quantum Chromodynamics

Strong nuclear shadowing in lead gluons



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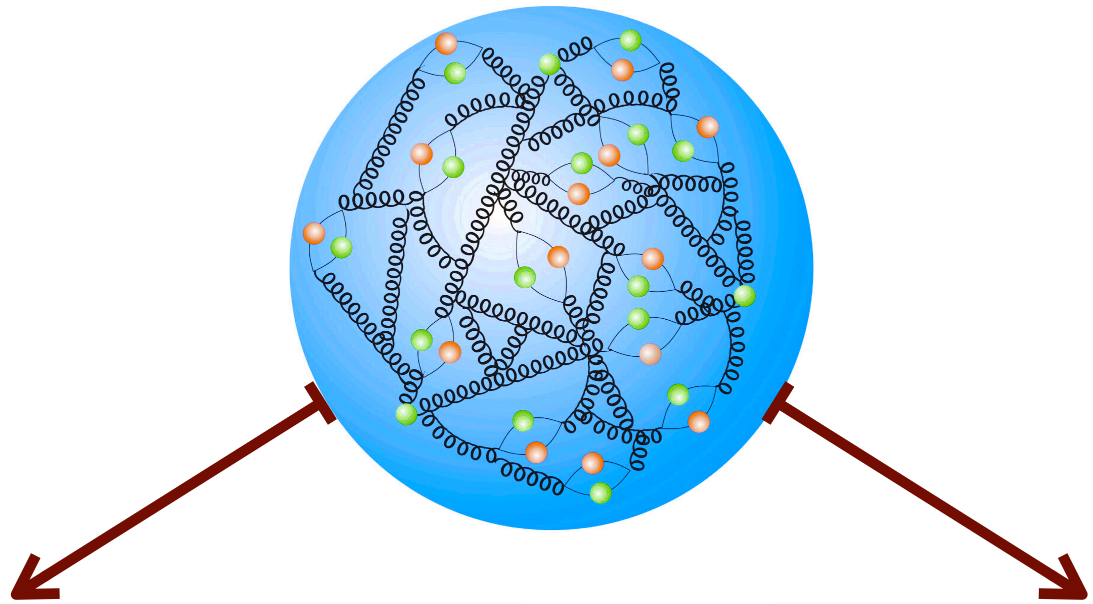

Key component of predictions for particle, nuclear, and astro-particle experiments

- **pp: ATLAS, CMS, LHCb, ALICE**
- ep: fixed target DIS, HERA
- neutrinos: IceCube, KM3NET, **Forward Physics Facility** @ LHC
- heavy ions: LHC Pb, LHC O, RHIC
- *pp (future): HL-LHC, FCC, SppS*
- ep (future): **Electron-Ion Collider,** LHeC, FCC-eh

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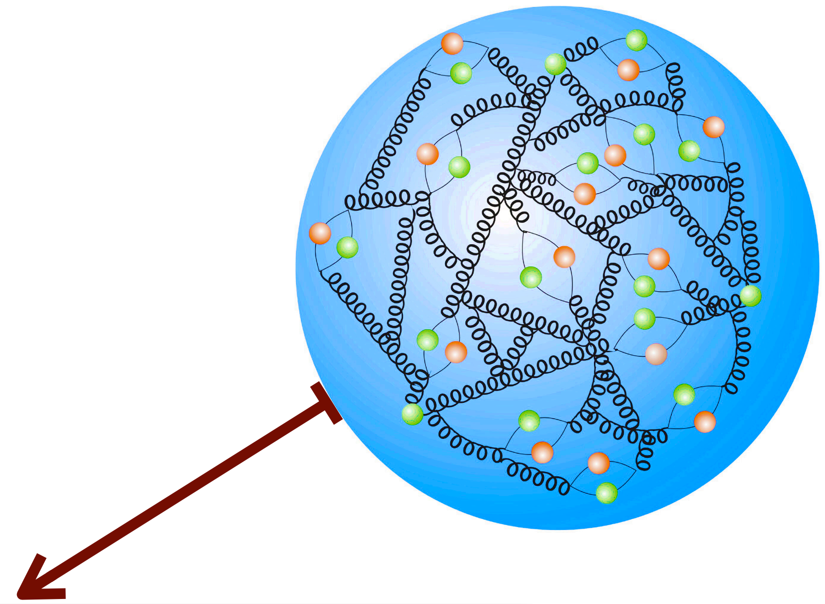

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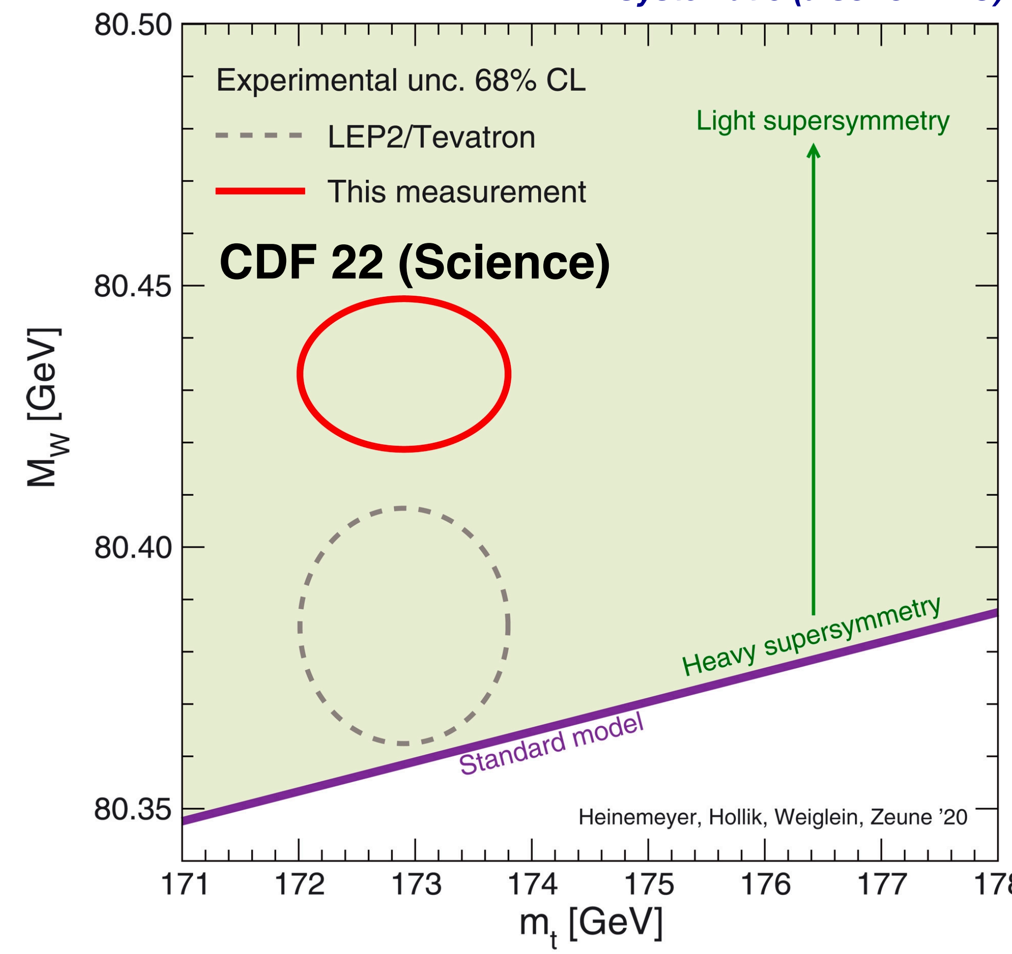
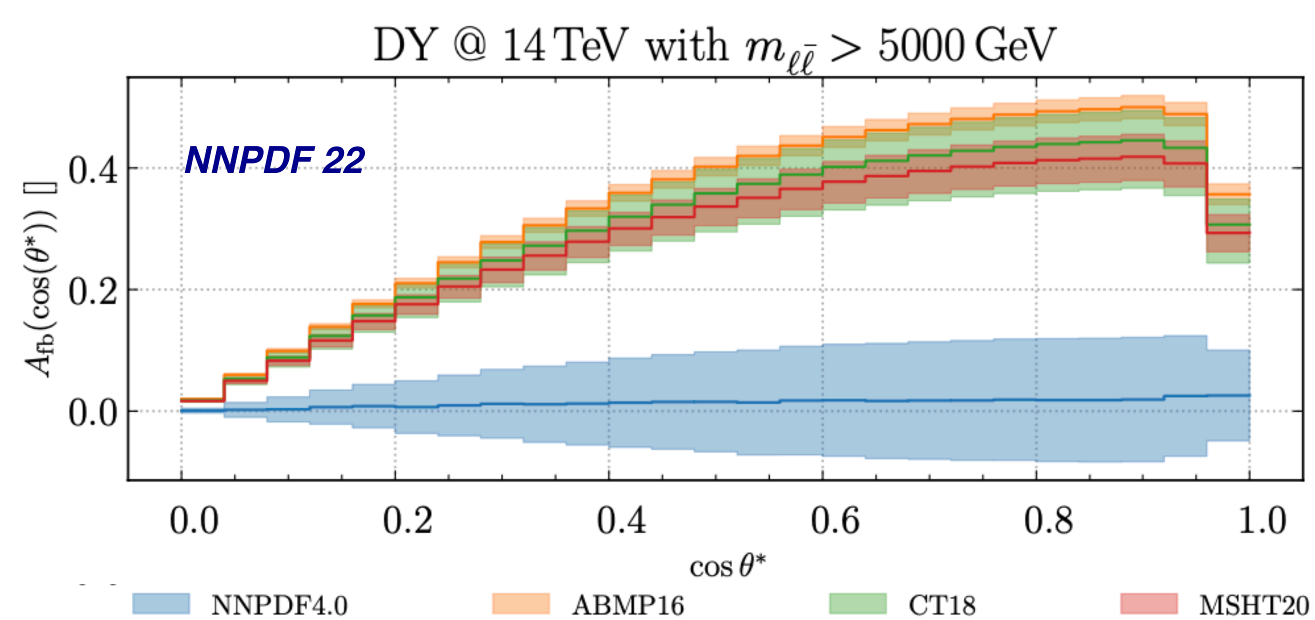
PDFs leading theory systematic (also for LHC)



high-mass Drell-Yan forward-backward asymmetry at LHC



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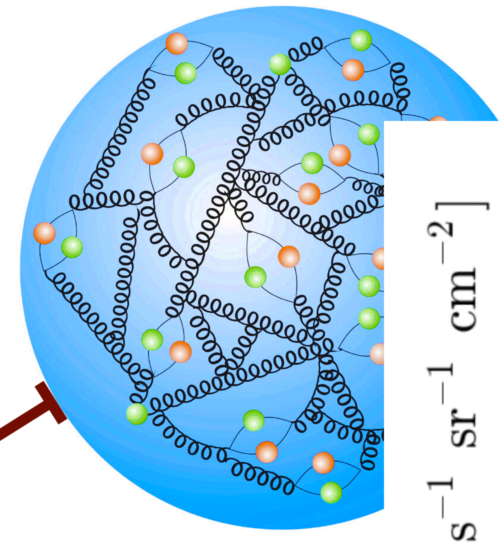

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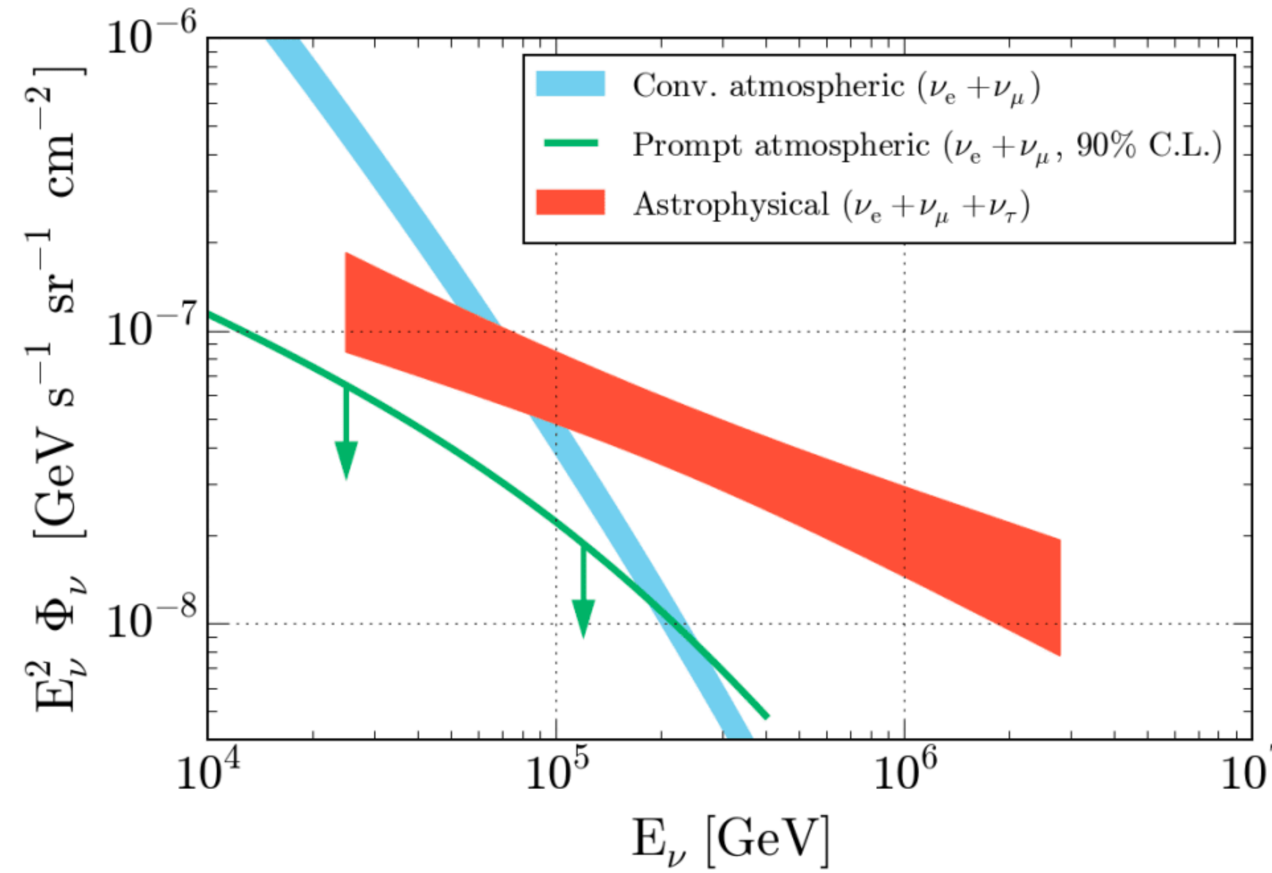
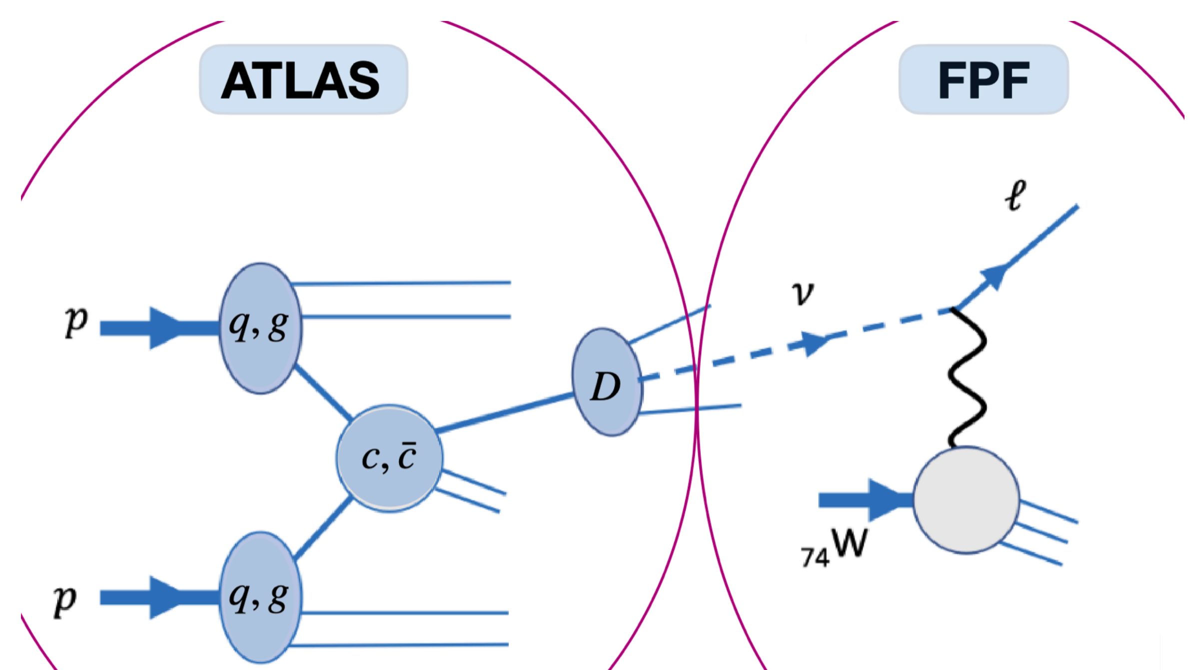
Neutrino cross-sections and prompt fluxes at IceCube



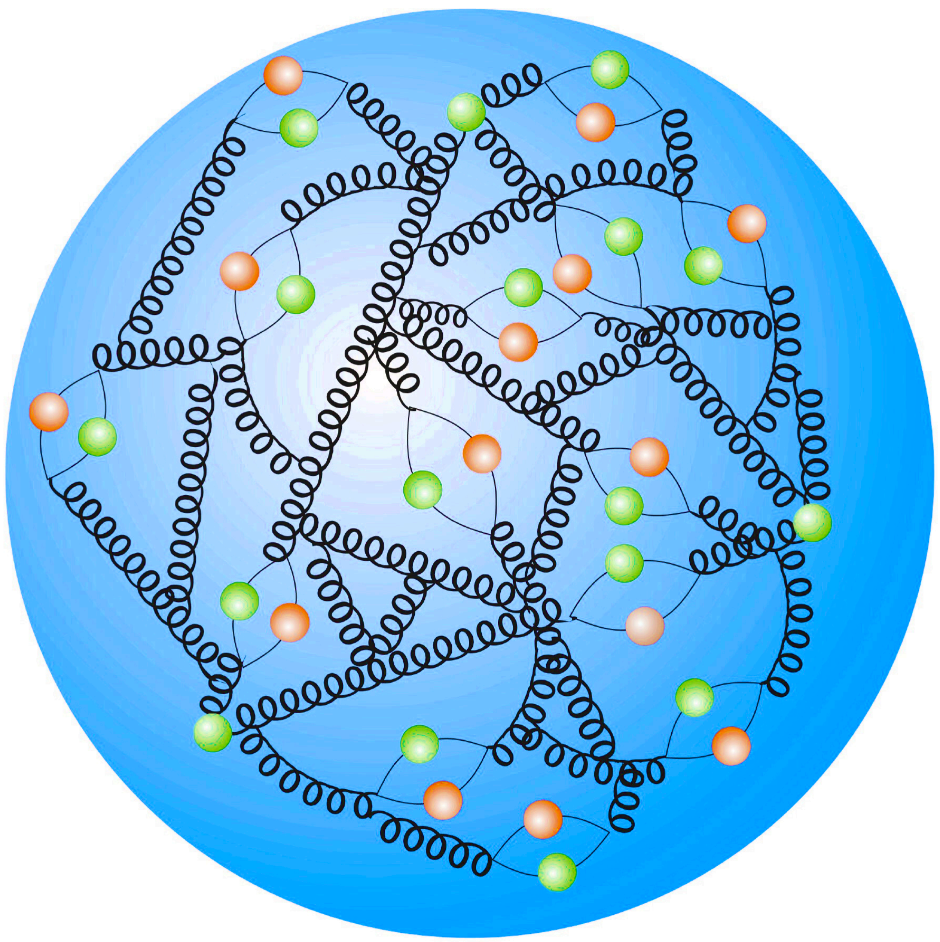
TeV Neutrino scattering at the LHC



Parton Distributions

Parton Distributions

Proton energy divided among constituents: **quarks** and **gluons**



Parton Distribution Functions (PDFs)

↓

Determine from **data:**

Global QCD analysis

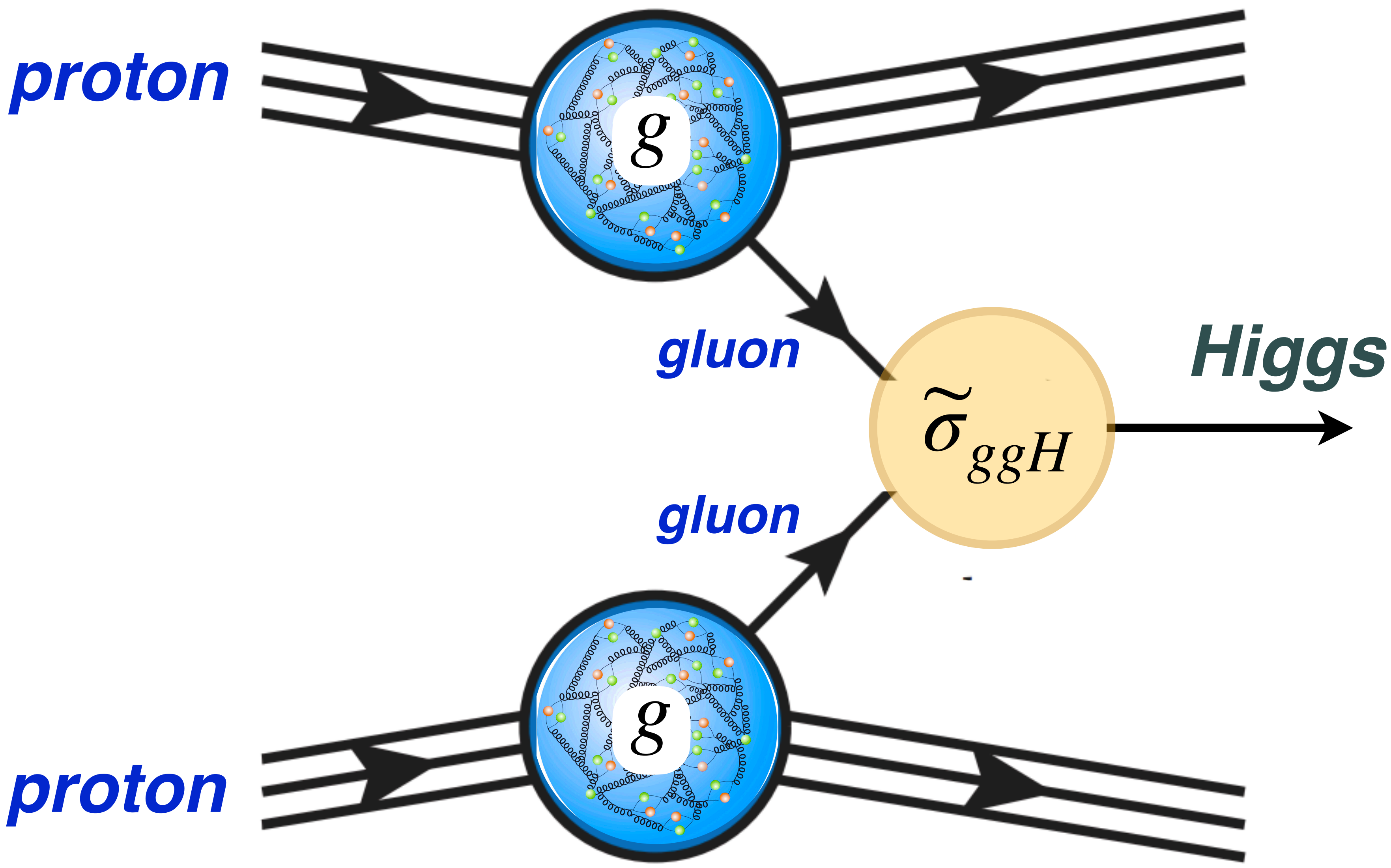
eventually to be complemented by input from lattice QCD calculations

What do we need to extract PDFs from data?

Parton Distributions

$$N_{\mathrm{LHC}}(H) \sim g \otimes g \otimes \tilde{\sigma}_{ggH}$$

Parton Distributions



All-order structure: **QCD factorisation theorems**

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***

x: fraction of proton momentum carried by gluon

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

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

Mathematically this is an ill-posed problem: reconstruct a function (infinite-dim quantity) from finite dataset. Requires assumptions to make the process tractable

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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

$$g(x, Q)$$

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

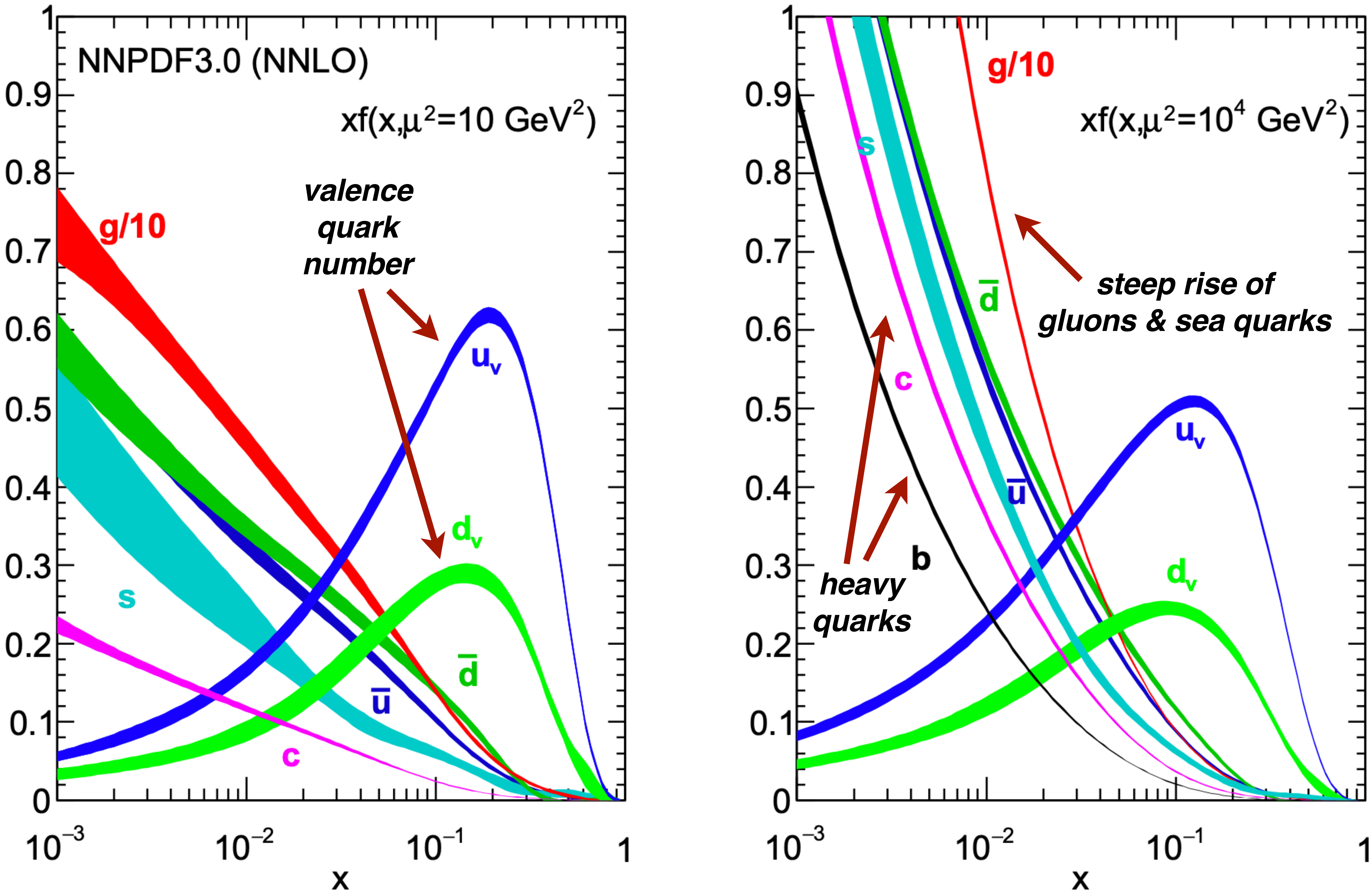
Energy of hard-scattering reaction**:** inverse of resolution length

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*

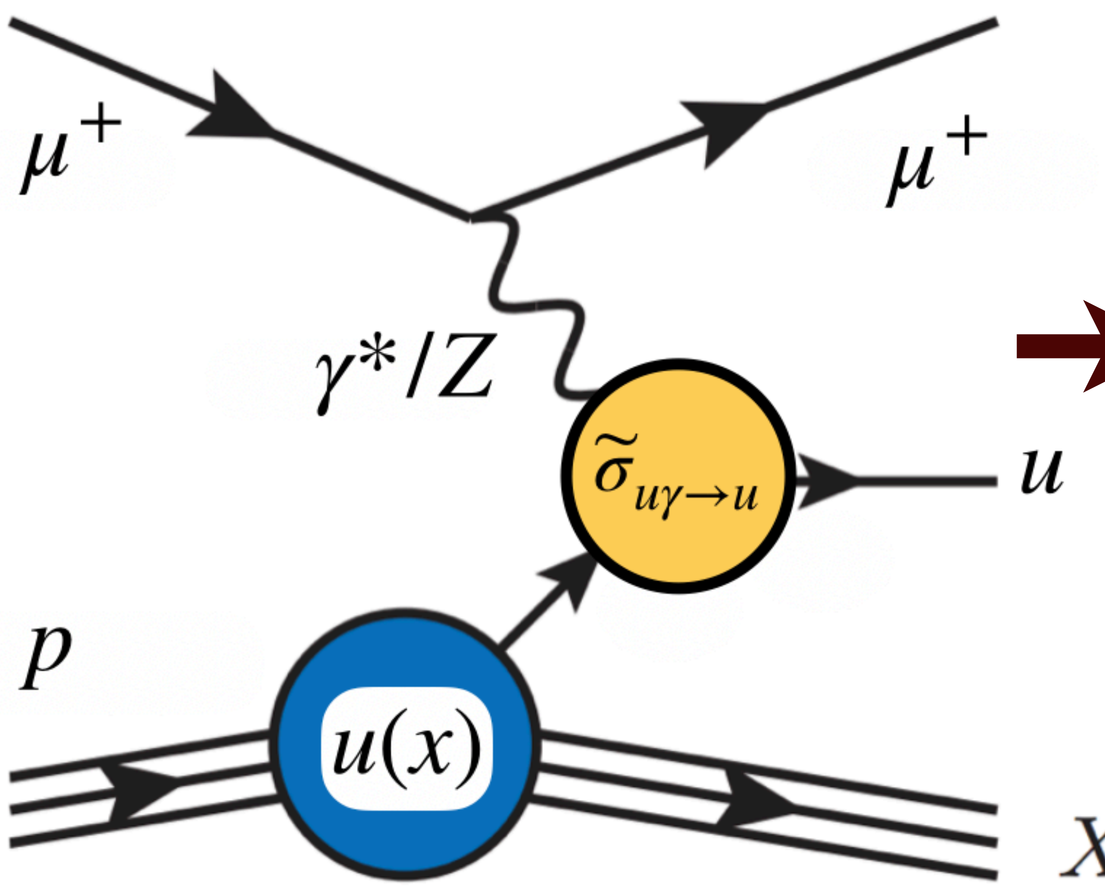
A proton structure snapshop

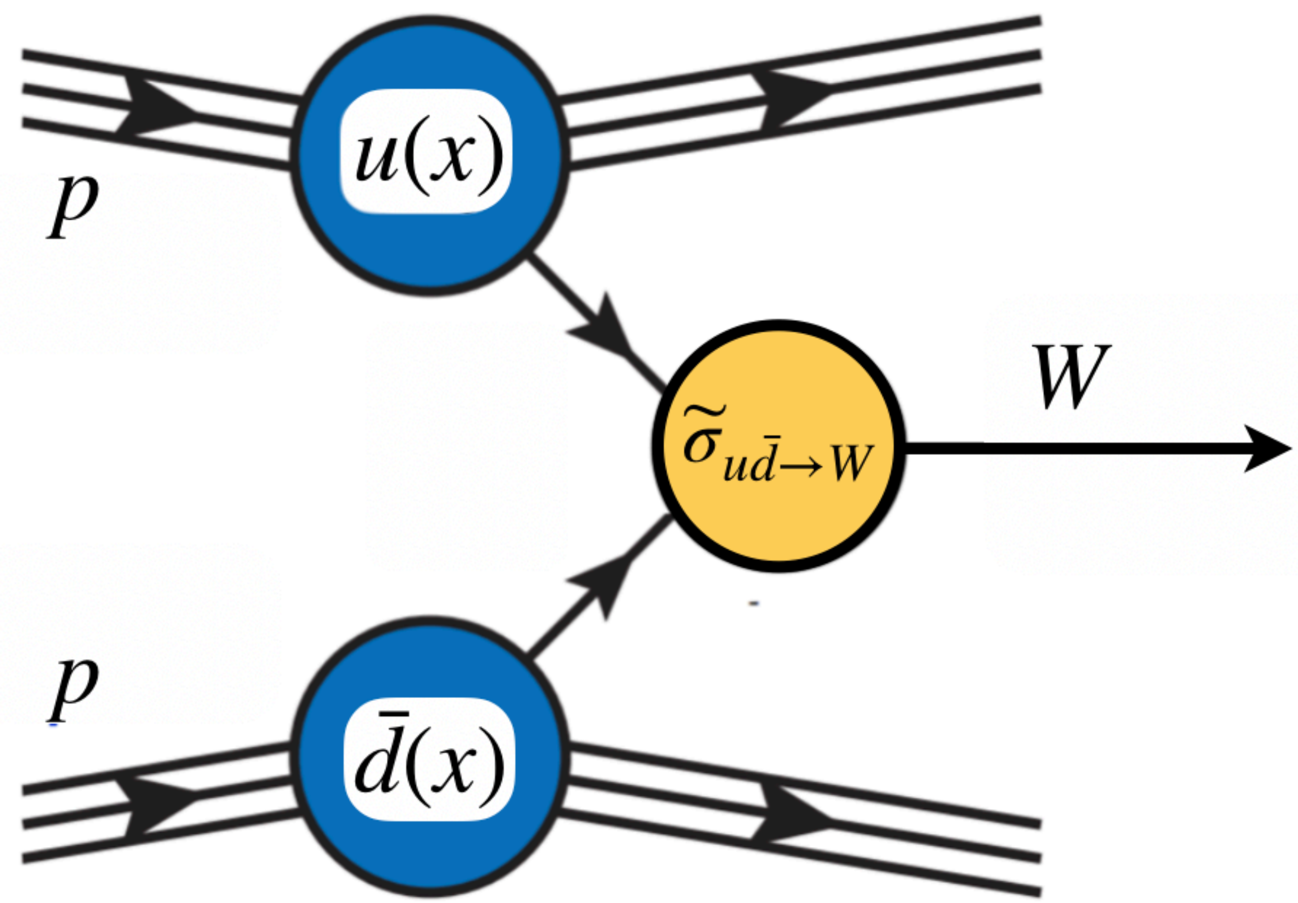


The global QCD analysis paradigm

QCD factorisation theorems**: PDF universality**

$$\sigma_{l\,p\to\mu\,X} = \widetilde{\sigma}_{u\gamma\to u} \otimes u(x) \;\rightarrow\; \sigma_{p\,p\to W} = \widetilde{\sigma}_{u\bar{d}\to W} \otimes u(x) \otimes \bar{d}(x)$$





*Determine PDFs from **deep-inelastic scattering**…*

*… and use them to compute predictions for **proton-proton collisions***

The global QCD analysis paradigm

☑ **Parametrise the PDFs** at the boundary (***Q = 1 GeV***) between perturbative and non-perturbative QCD

$$xg(x, Q_0 = 1\ \mathrm{GeV}, \{a\}) = f_g(x, a_g^{(1)}, a_g^{(2)}, \ldots)$$

☑ Evaluate predictions for LHC cross-sections using **QCD factorisation theorem**

$$\sigma_{\rm th}(M, s, \{a\}) \propto \sum_{ij} \int_{M^2}^{s} d\hat{s}\ \mathscr{L}_{ij}(\hat{s}, s, \{a_i^{(k)}\}, \{a_j^{(k)}\})\, \widetilde{\sigma}_{ij}(\hat{s}, \alpha_s(M))$$

☑ **Extract PDF parameters from data** via some optimisation process, *e.g.* log-likelihood maximisation

$$\chi^2\left(\{\boldsymbol{a}^{(k)}\}\right) = \frac{1}{n_{\rm dat}} \sum_{i,j=1}^{n_{\rm dat}} \left(\sigma_{\rm i,th}(\{\boldsymbol{a}^{(k)}\}) - \sigma_{\rm i,exp}\right) \left(\mathrm{cov}^{-1}\right)_{ij} \left(\sigma_{\rm j,th}(\{\boldsymbol{a}^{(k)}\}) - \sigma_{\rm j,exp}\right)$$

☑ Estimate the associated **uncertainties** in a way that can be propagated to pheno observables

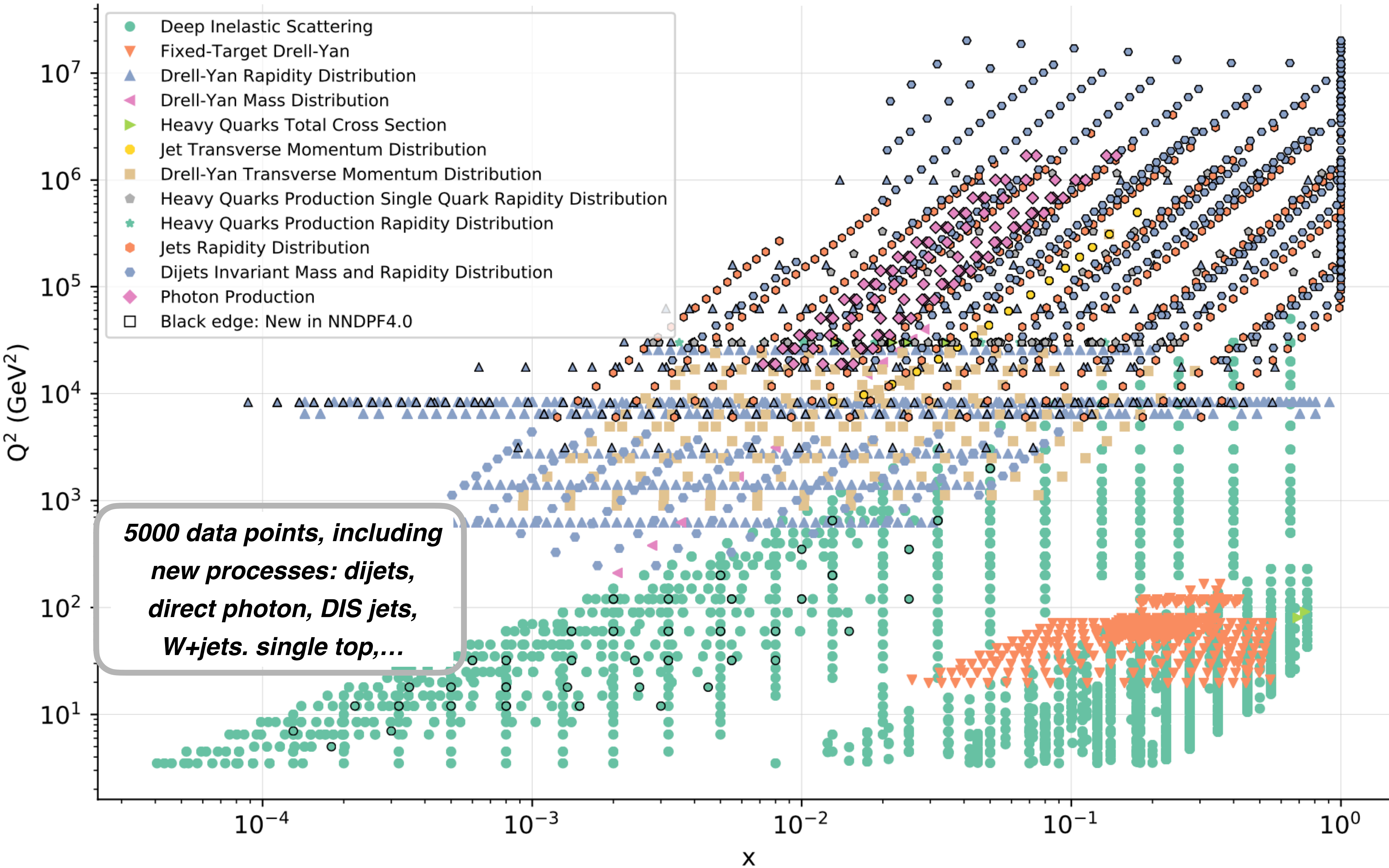
The resulting PDFs are then ready for applications in processes involving **proton/nuclear targets and/or projectiles**

The NNPDF4.0 Global PDF Determination

NNPDF Collaboration, arXiv:2109.02653

(see also arXiv:2211.12921 for a rebuttal of critical arguments)

The NNPDF4.0 dataset



$\mathcal{O}(50)$ data sets investigated; $\mathcal{O}(400)$ data points more in NNPDF4.0 than in NNPDF3.1

The Monte Carlo replica method

- Generate a large sample of **Monte Carlo replicas** to construct a representation of the **probability distribution** in the space of experimental data

$$\mathcal{O}_i^{(\mathrm{art})(k)} = \mathcal{O}_i^{(\mathrm{exp})}\left(1 + \sum_{\alpha=1}^{n_{\mathrm{sys}}} r_{i,\alpha}^{(k)}\sigma_{i,\alpha}^{(\mathrm{sys})} + r_i^{(k)}\sigma_i^{(\mathrm{stat})}\right) \qquad k = 1,\ \ldots\ N_{\mathrm{rep}},\ \ i = 1,\ldots,n_{\mathrm{dat}}$$

cross-section for k-th replica

central value (data)

correlated systematic uncertainties

statistical uncertainties

 # MC replicas

- Reproduces experimental covariance matrix, can be extended to theory uncertainties

- Carry out an individual PDF fit to each replica to obtain a representation of the **probability distribution** in the space of PDFs, for which statistical estimators can be evaluated

e.g. standard deviation on the gluon PDF

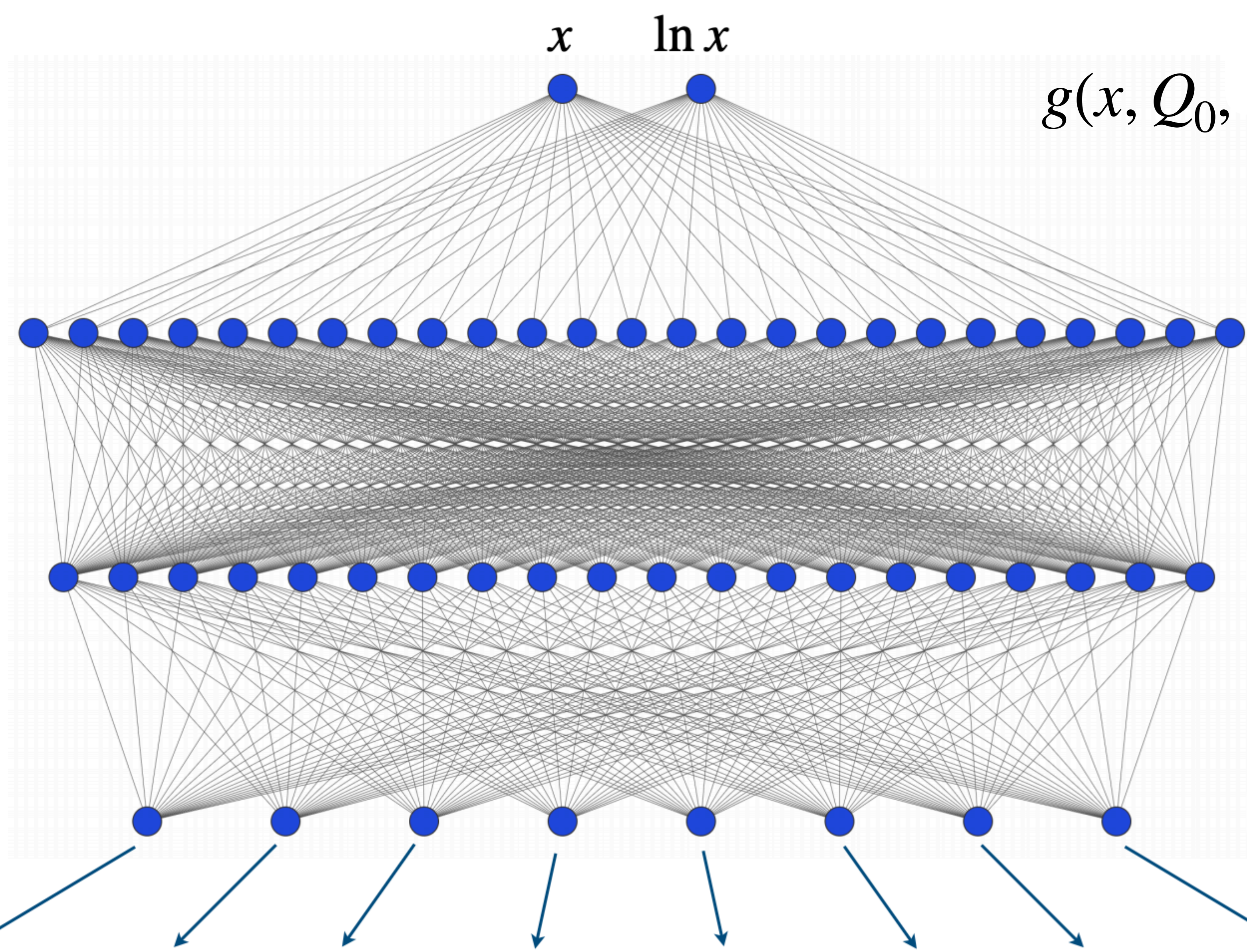
$$\delta g\left(x,Q\right) = \left(\sum_{k=1}^{N_{\mathrm{rep}}}\left(g^{(k)}\left(x,Q\right)\right)^2 - \left(\sum_{k=1}^{N_{\mathrm{rep}}} g^{(k)}\left(x,Q\right)\right)^2\right)^{1/2}$$

equivalent to Hessian method for fixed functional form

Fitting methodology

- ☑ Model-independent PDF parametrisation with neural networks as **universal unbiased interpolants**
- ☑ Automated model **hyperparameter optimisation:** NN architecture, minimiser, learning rates …
- ☑ Validation with **future tests** (forecasting new datasets) and **closure tests** (data based on known PDFs)

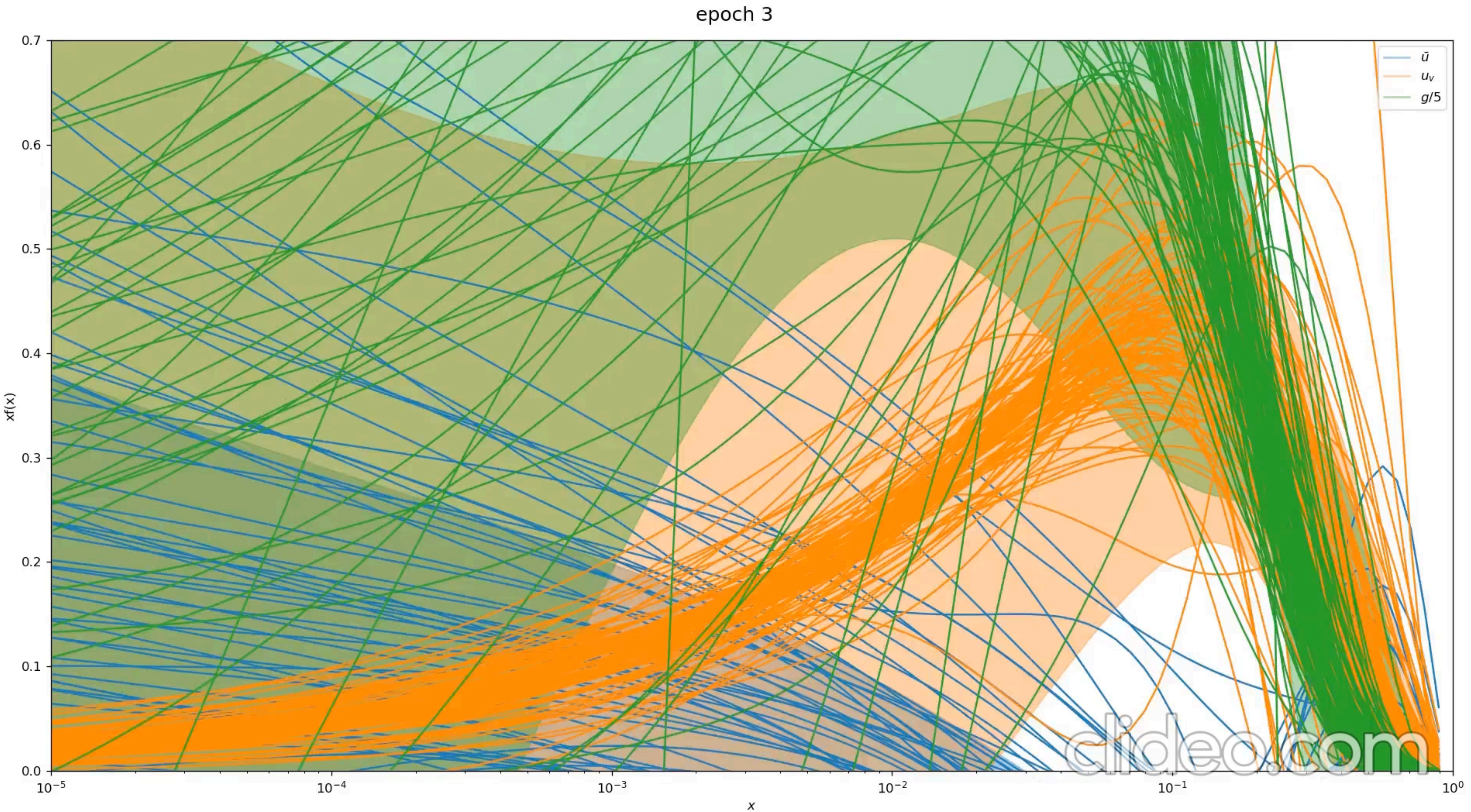
$$g(x, Q_0, \{a_g\}) = f_g(x, a_g^{(1)}, a_g^{(2)}, \ldots)$$



$xg(x,Q_0)$	$x\Sigma(x,Q_0)$	$xV(x,Q_0)$	$xV_3(x,Q_0)$	$xV_8(x,Q_0)$	$xT_3(x,Q_0)$	$xT_8(x,Q_0)$	$xT_{15}(x,Q_0)$	***evolution basis***
$xg(x,Q_0)$	$xu(x,Q_0)$	$x\bar{u}(x,Q_0)$	$xd(x,Q_0)$	$x\bar{d}(x,Q_0)$	$xs(x,Q_0)$	$x\bar{s}(x,Q_0)$	$xc^+(x,Q_0)$	***flavor basis***

PDFs should be independent of **parametrisation basis**

Fitting methodology



Error estimate based on **Monte Carlo replica method** (band: standard deviation over the MC replicas)

Closure and future tests

Closure tests

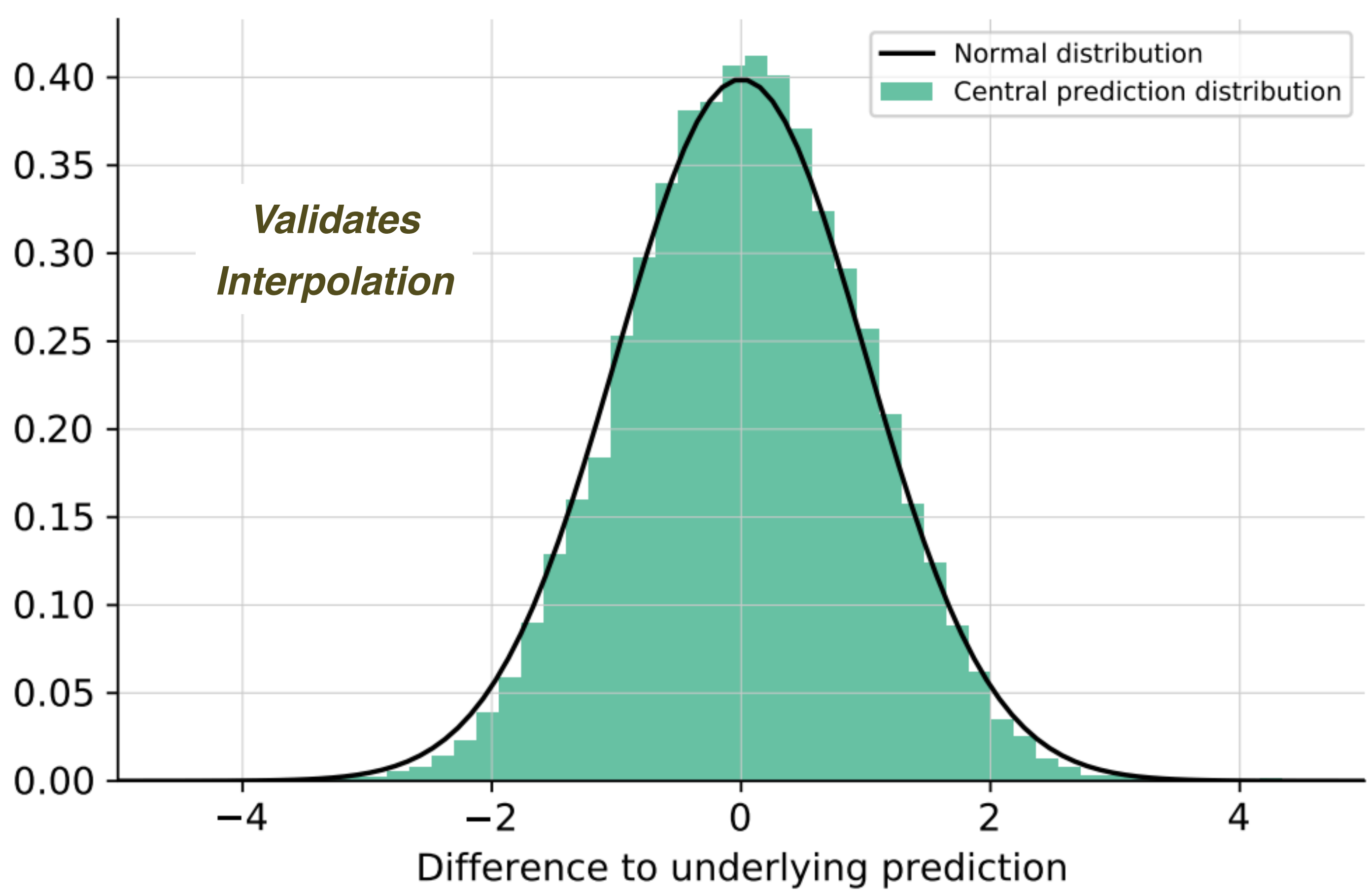
Generate **toy data** based on some known PDF, check *a posteriori* that the **true underlying law is reproduced** within errors

mean NN prediction *true central value*

generate many toys

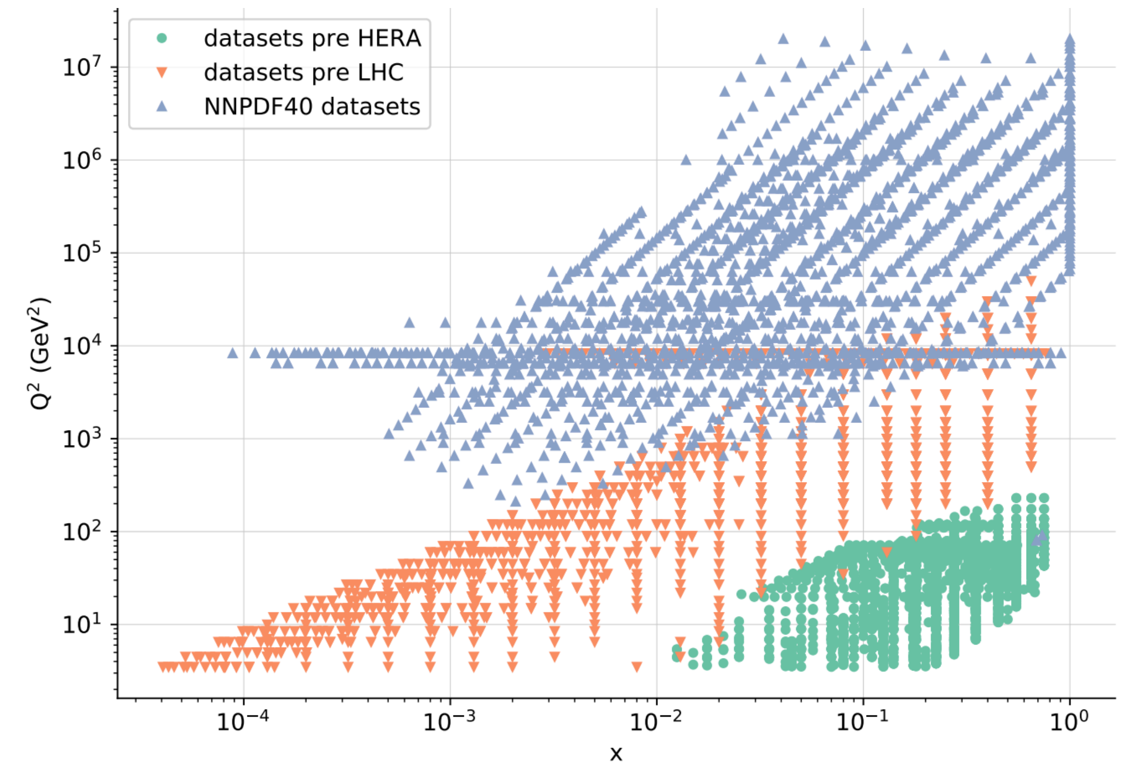
$$\delta_i^{(l)} \equiv \frac{\left(\mathbf{E}_\epsilon\left[g_i\right]^{(l)} - f_i\right)}{\sigma_i^{(l)}}$$

data index *PDF uncertainty*



Future tests

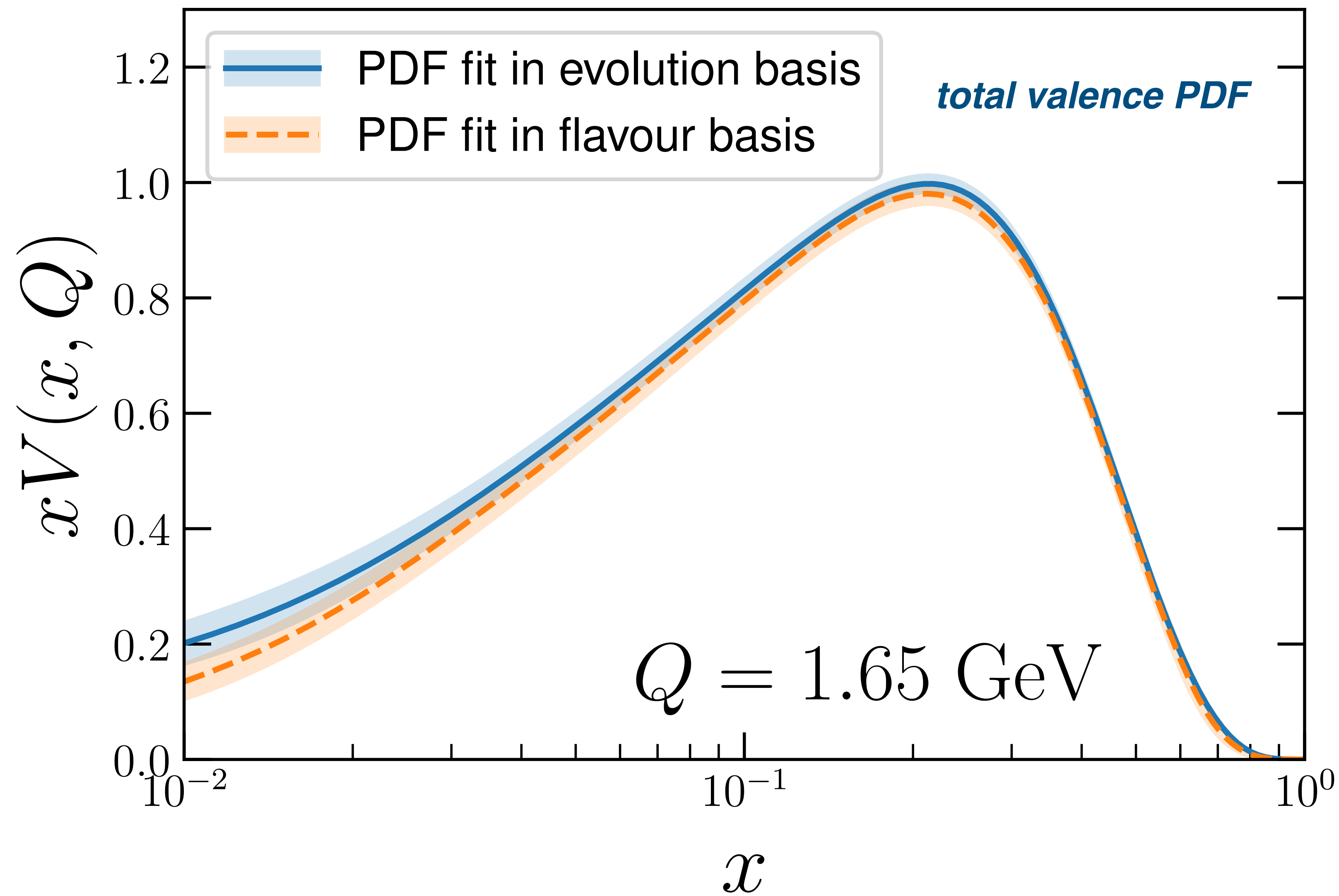
Fit data restricted to specific kinematic regions, then verify **succesful extrapolation**



Process	χ^2 pre-HERA	χ^2 pre-LHC	χ^2 Global
Fixed target NC DIS	1.05	1.18	1.23
Fixed target CC DIS	0.80	0.85	0.87
Fixed target Drell-Yan	0.92	1.27	1.59
HERA	*27.20* (**1.23**)	1.22	1.20
Collider Drell-Yan (Tevatron)	*5.52* (**1.02**)	0.99	1.11
Collider Drell-Yan (LHC)	*18.91* (**1.31**)	*2.63* (**1.58**)	1.53
Top quark production	*20.01* (**1.06**)	*1.30* (**0.87**)	1.01
Jet production	*2.69* (**0.98**)	*2.12* (**1.10**)	1.26

Parametrisation basis independence

$$V(x, Q_0) = \left((u - \bar{u}) + (d - \bar{d}) + (s - \bar{s})\right)(x, Q_0)$$



different strategies to parametrize the **quark PDF flavour combinations** lead to identical results: ultimate test of **parametrisation independence**

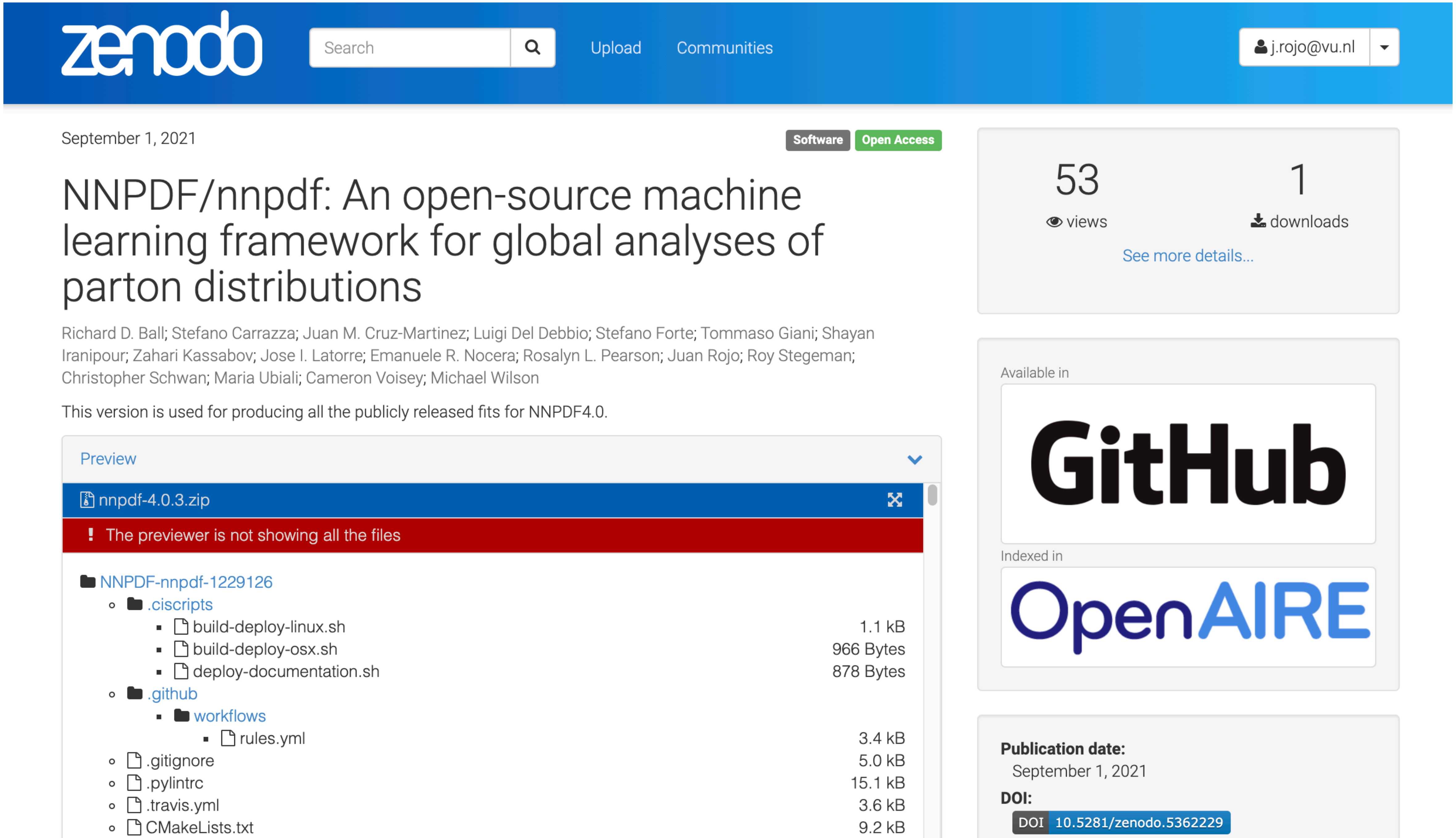
evolution basis PDF parametrisation:

$$xV(x, Q_0) \propto \mathrm{NN}_V(x)$$

flavour basis PDF parametrisation:

$$xV(x, Q_0) \propto \left(\mathrm{NN}_u(x) - \mathrm{NN}_{\bar{u}}(x) + \mathrm{NN}_d(x) - \mathrm{NN}_{\bar{d}}(x) + \mathrm{NN}_s(x) - \mathrm{NN}_{\bar{s}}(x)\right)$$

A ML open-source QCD fitting framework



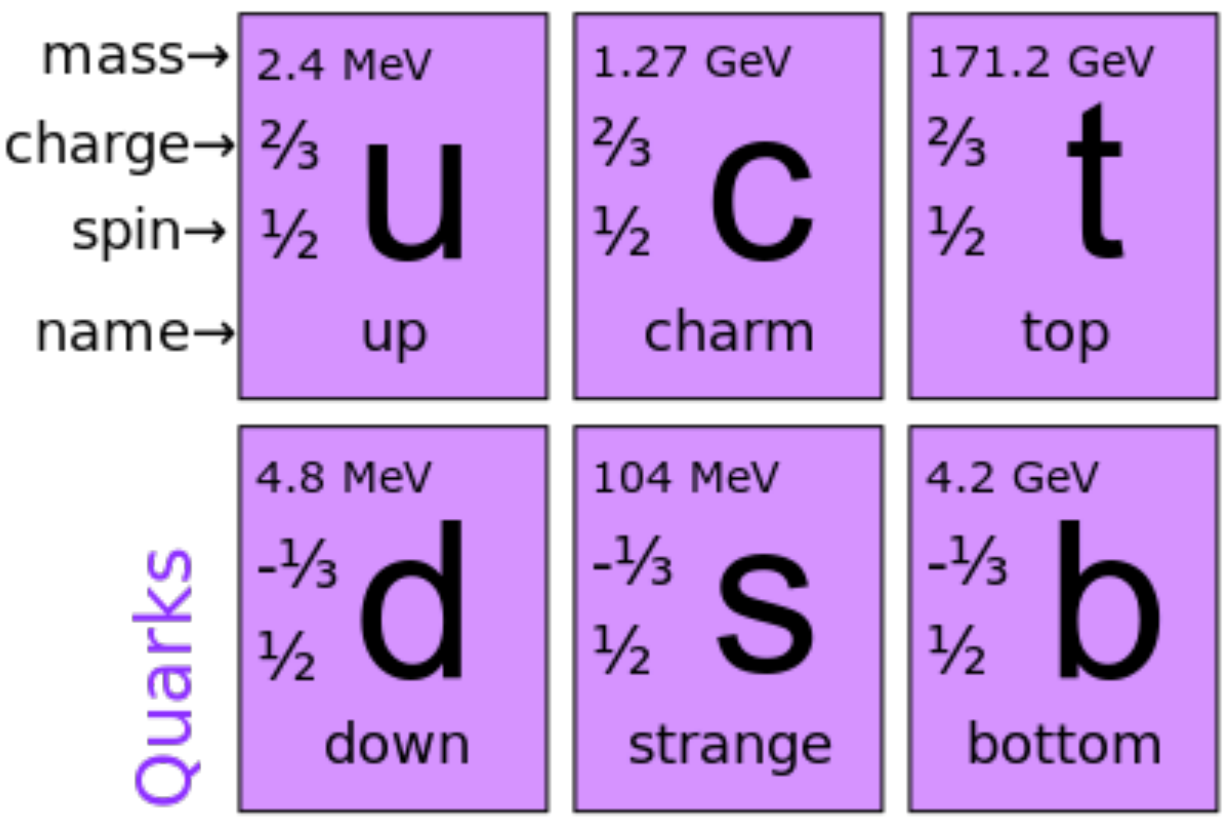
The full **NNPDF machine learning fitting framework** has been publicly released open source, together with extensive documentation and user-friendly examples

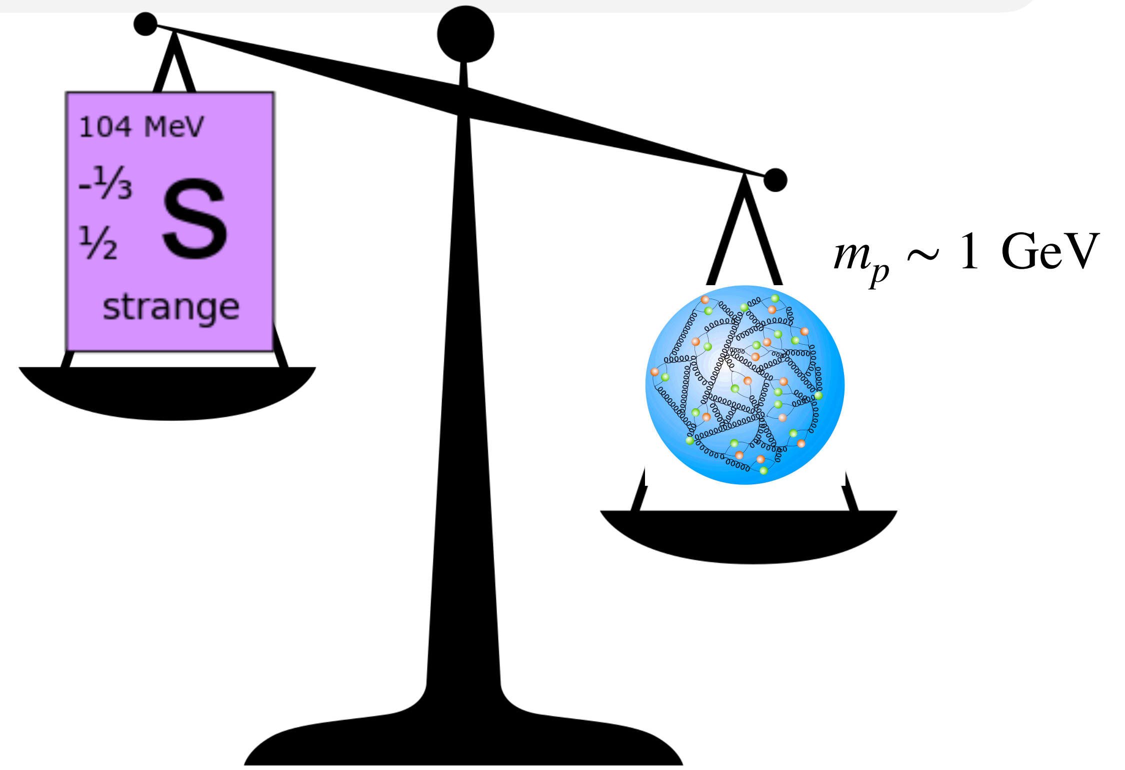
Evidence for intrinsic charm in the proton

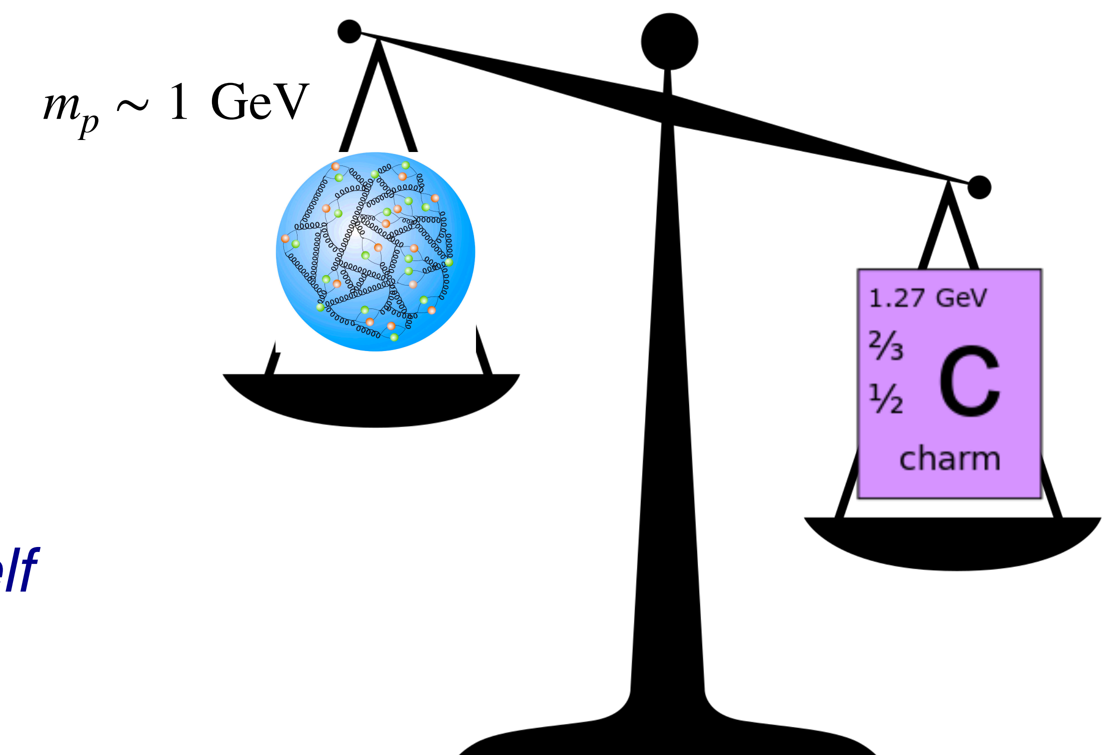
R. D. Ball, A. Candido, J. Cruz-Martinez, S. Forte, T. Giani, F. Hekhorn, K. Kudashkin, G. Magni & J. Rojo, ***Nature*** **608 (2022) 7923, 483-487**

The charm content of the proton

common assumption in PDF fits: the static proton wave function does not contain charm quarks:
the proton contains **intrinsic up, down, strange (anti-)quarks** but **no intrinsic charm quarks**







charm quarks heavier than the proton itself

The charm content of the proton

common assumption in PDF fits: the static proton wave function does not contain charm quarks: the proton contains **intrinsic up, down, strange (anti-)quarks** but **no intrinsic charm quarks**

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

$$\underbrace{f_c^{(n_f)}}_{\text{3FNS charm}} = 0 \quad \rightarrow \quad \underbrace{f_c^{(n_f+1)}}_{\text{4FNS charm}} \propto \alpha_s \ln \frac{Q^2}{m_c^2} \left(P_{qg} \otimes \underbrace{f_g^{(n_f+1)}}_{\text{4FNS gluon}} \right) + \mathcal{O}\left(\alpha_s^2\right)$$

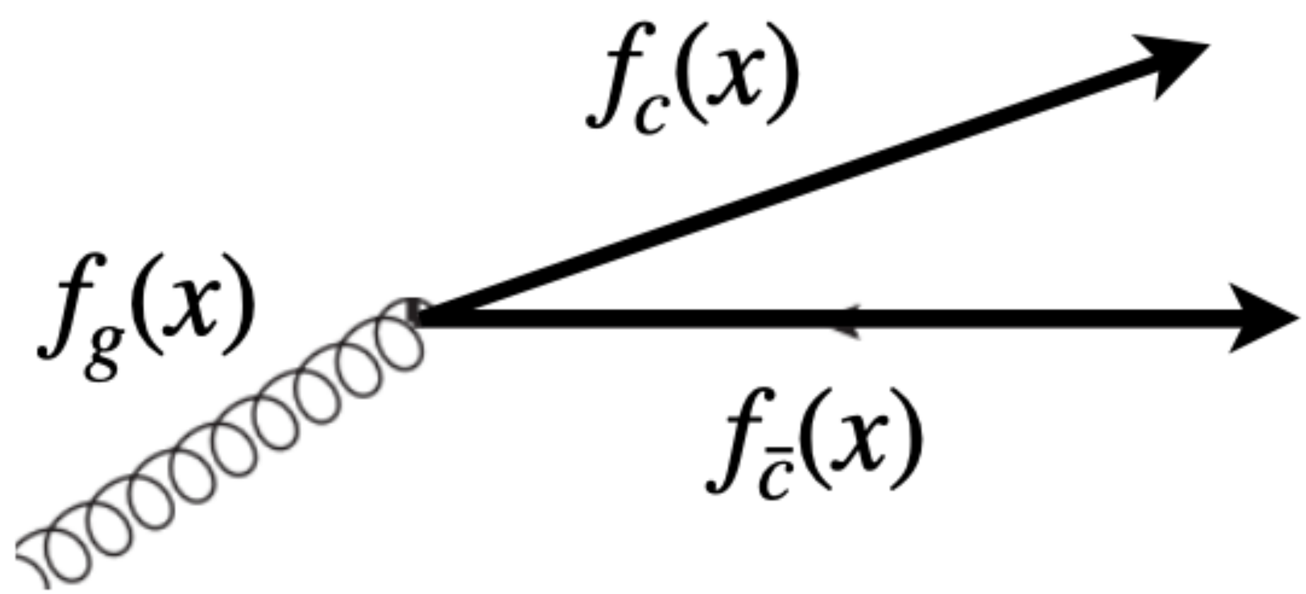
NLO matching

4 flavour scheme, $Q > m_c$

$u^{(4)}, d^{(4)}, s^{(4)}, c^{(4)} g^{(4)}$

3 flavour scheme, $Q < m_c$

$u^{(3)}, d^{(4)}, s^{(3)}, g^{(3)}$



If charm is **perturbatively generated**, the charm PDF is **trivial**

The charm content of the proton

common assumption in PDF fits: the static proton wave function does not contain charm quarks: the proton contains **intrinsic up, down, strange (anti-)quarks** but **no intrinsic charm quarks**

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

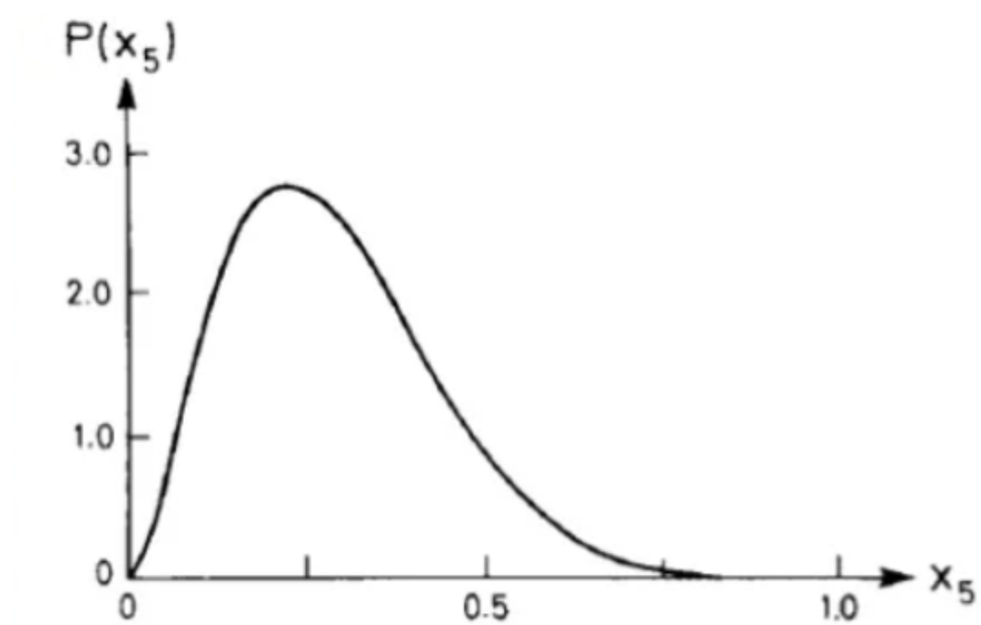
THE INTRINSIC CHARM OF THE PROTON

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



$$|p\rangle = \mathscr{P}_{3q}\,|uud\rangle + \mathscr{P}_{5q}\,|uudc\bar{c}\rangle + \ldots$$

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 a hypothesis are explored.

40 years of extensive searches for intrinsic charm: no unambiguous evidence ….

The charm content of the proton

common assumption in PDF fits: the static proton wave function does not contain charm quarks: the proton contains **intrinsic up, down, strange (anti-)quarks** but **no intrinsic charm quarks**

in this scenario, the charm PDF extracted from data in the global fit is the combination of the **perturbative** (DGLAP) and the **intrinsic** components

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

Extracted phenomenologically from data

from QCD evolution and matching

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

How to **disentangle perturbative** from **intrinsic components?**

*nb we **define IC** as the charm PDF once know perturbative component is removed*

40 years of extensive searches for intrinsic charm: no unambiguous evidence ….

Disentangling intrinsic charm

$Q_0 =$ 1.65 GeV

4FNS Charm PDF parametrised at Q_0

- Deep-learning parametrisation
- Monte Carlo representation of uncertainties

Disentangling intrinsic charm

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

Extracted phenomenologically from data

from pQCD evolution and matching

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

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

- NNPDF4.0 dataset
- NNLO QCD calculations

QCD evolution

starting point: NNPDF 4.0 methodology

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Disentangling intrinsic charm

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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

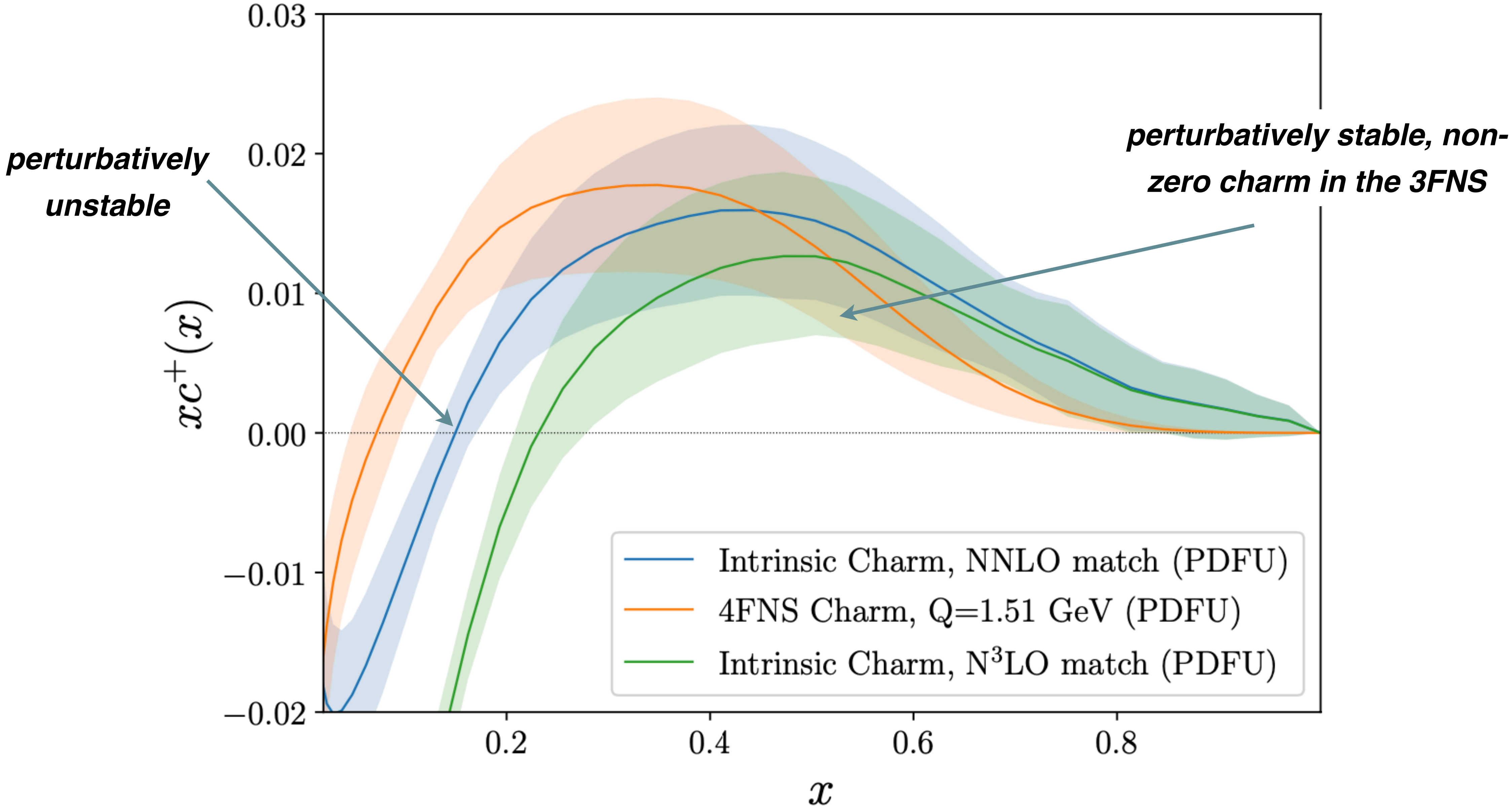
4FNS to 3FNS transformation

$$\mathbf{f}^{(n_f+1)}(Q_1^2) = \left[\mathbf{E}^{(n_f+1)}(Q_1^2 \leftarrow Q_h^2)\mathbf{A}^{(n_f)}(Q_h^2)\mathbf{E}^{(n_f)}(Q_h^2 \leftarrow Q_0^2)\right] \otimes \mathbf{f}^{(n_f)}(Q_0^2)$$

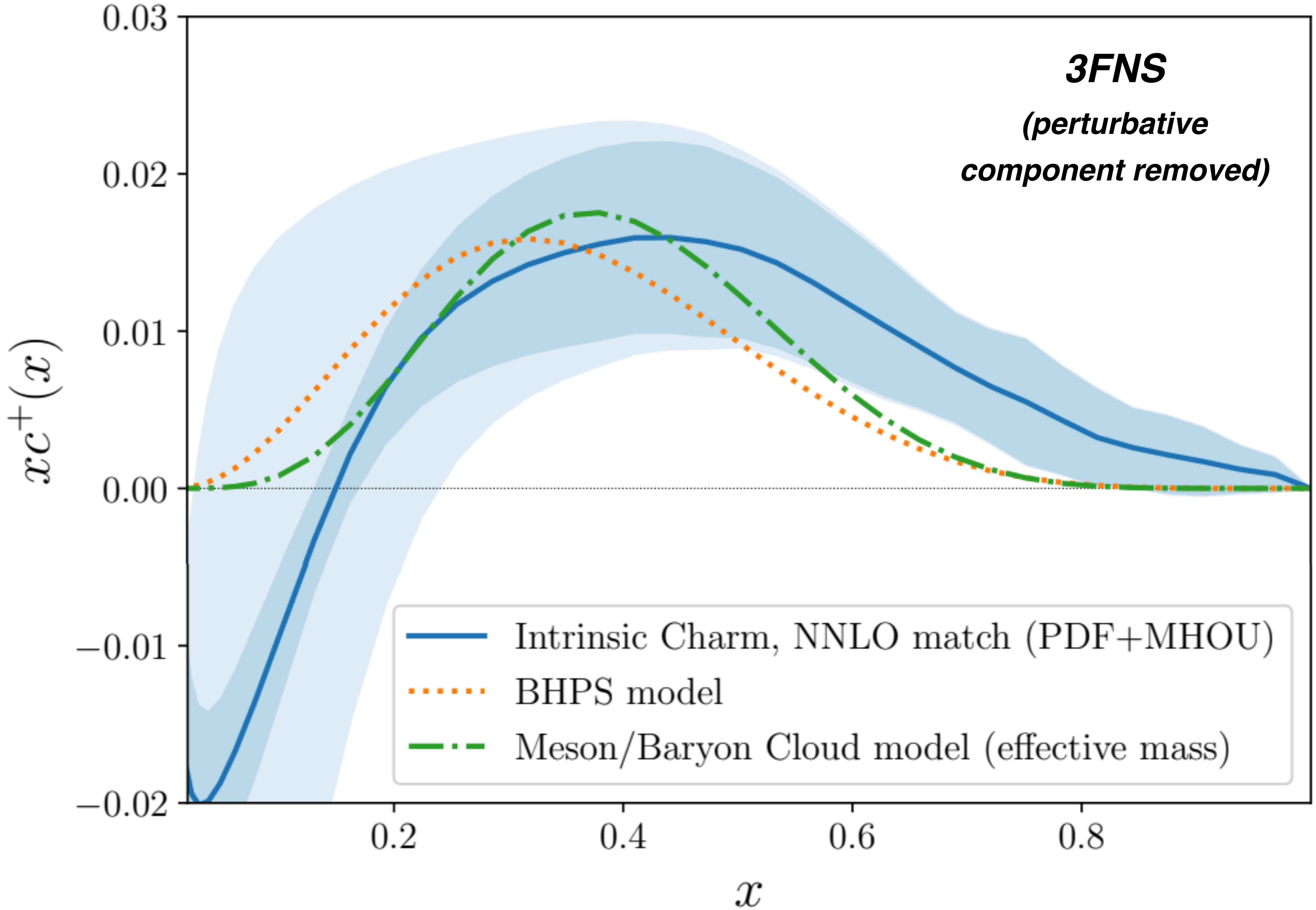
4FNS PDFs | **DGLAP kernel** | **scheme matching conditions** | **DGLAP kernel** | **3FNS PDFs**

$\mathcal{O}\left(\alpha_s^3\right)$ | $\mathcal{O}\left(\alpha_s^2\right)$ & $\mathcal{O}\left(\alpha_s^3\right)$ | $\mathcal{O}\left(\alpha_s^3\right)$

NNLO | **NNLO** | **N3LO** | **NNLO**



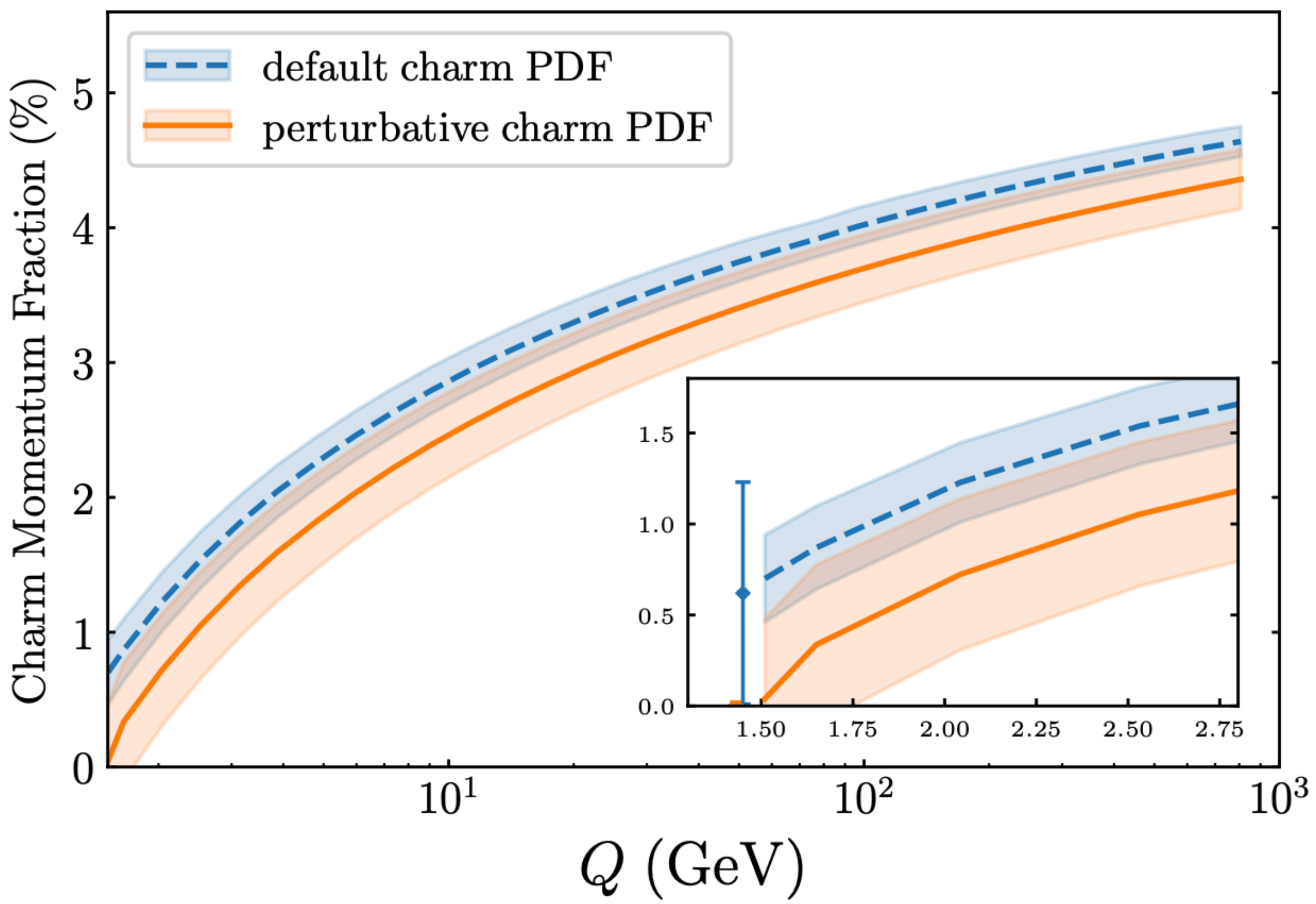
4FNS to 3FNS transformation



The 3FNS charm PDF displays **non-zero component** peaked at large-*x* which can be identified with **intrinsic charm**

The charm momentum fraction

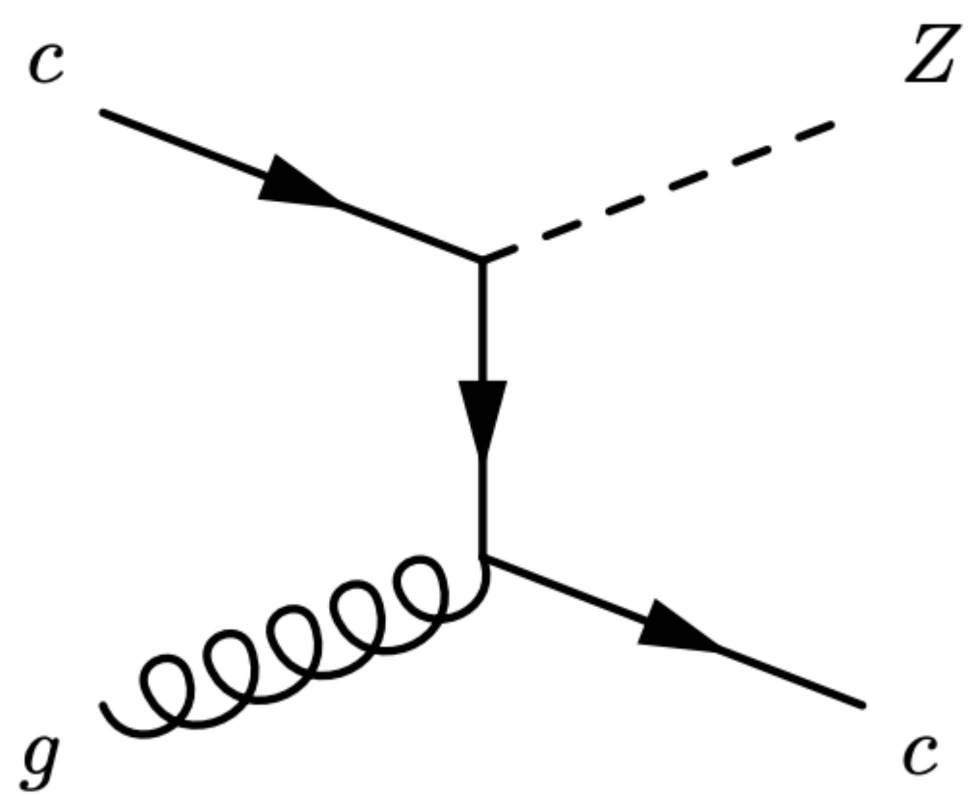
Scheme	Q	Charm PDF	m_c	$[c]$ (%)
3FNS	–	default	1.51 GeV	$0.62 \pm 0.28_{\rm pdf} \pm 0.54_{\rm mhou}$
3FNS	–	default	1.38 GeV	$0.47 \pm 0.27_{\rm pdf} \pm 0.62_{\rm mhou}$
3FNS	–	default	1.64 GeV	$0.77 \pm 0.28_{\rm pdf} \pm 0.48_{\rm mhou}$
4FNS	1.65 GeV	default	1.51 GeV	$0.87 \pm 0.23_{\rm pdf}$
4FNS	1.65 GeV	default	1.38 GeV	$0.94 \pm 0.22_{\rm pdf}$
4FNS	1.65 GeV	default	1.64 GeV	$0.84 \pm 0.24_{\rm pdf}$
4FNS	1.65 GeV	perturbative	1.51 GeV	$0.346 \pm 0.005_{\rm pdf} \pm 0.44_{\rm mhou}$
4FNS	1.65 GeV	perturbative	1.38 GeV	$0.536 \pm 0.006_{\rm pdf} \pm 0.49_{\rm mhou}$
4FNS	1.65 GeV	perturbative	1.64 GeV	$0.172 \pm 0.003_{\rm pdf} \pm 0.41_{\rm mhou}$

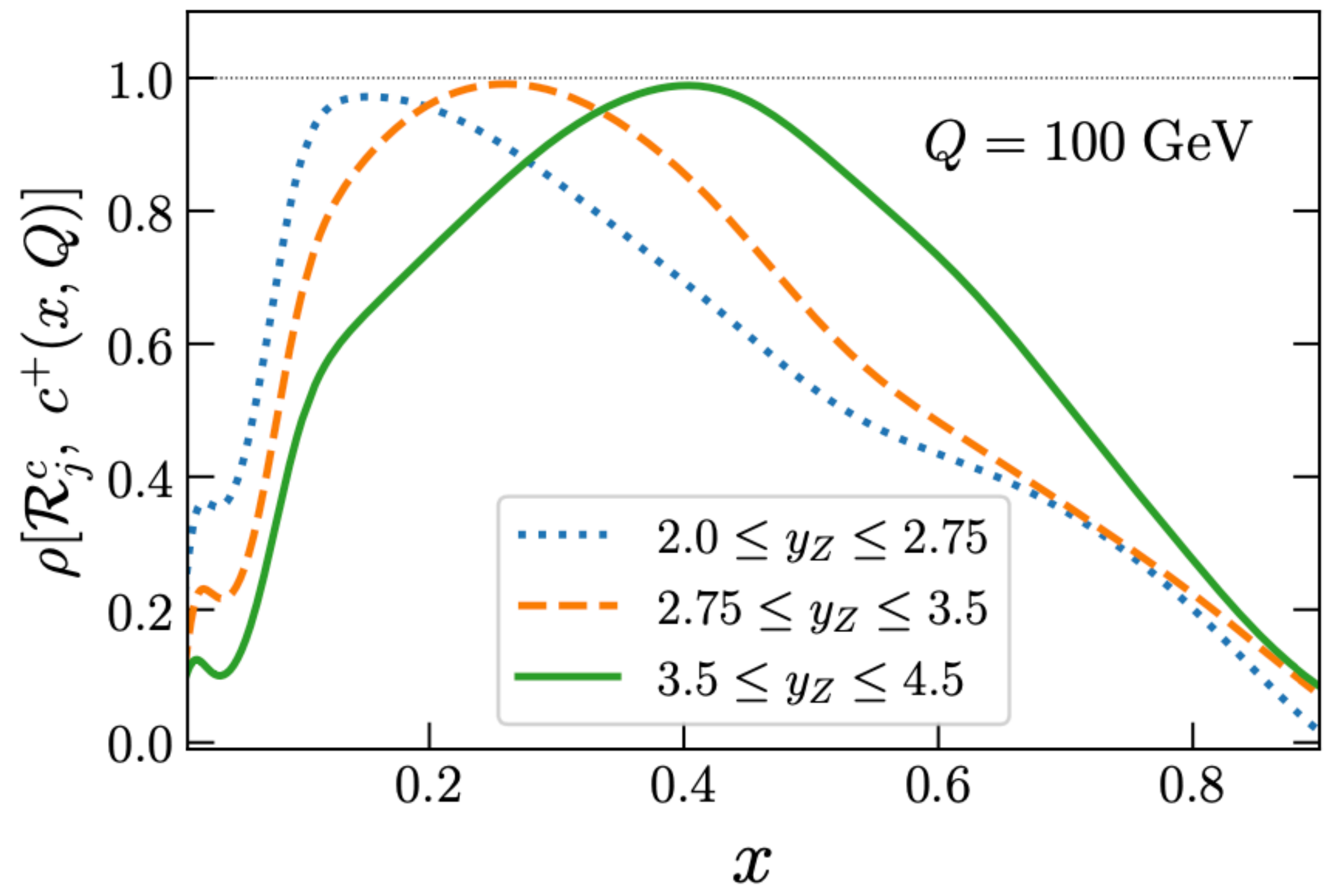


Intrinsic charm carries around **0.5%** of the proton's total momentum

Z+charm @ LHCb

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

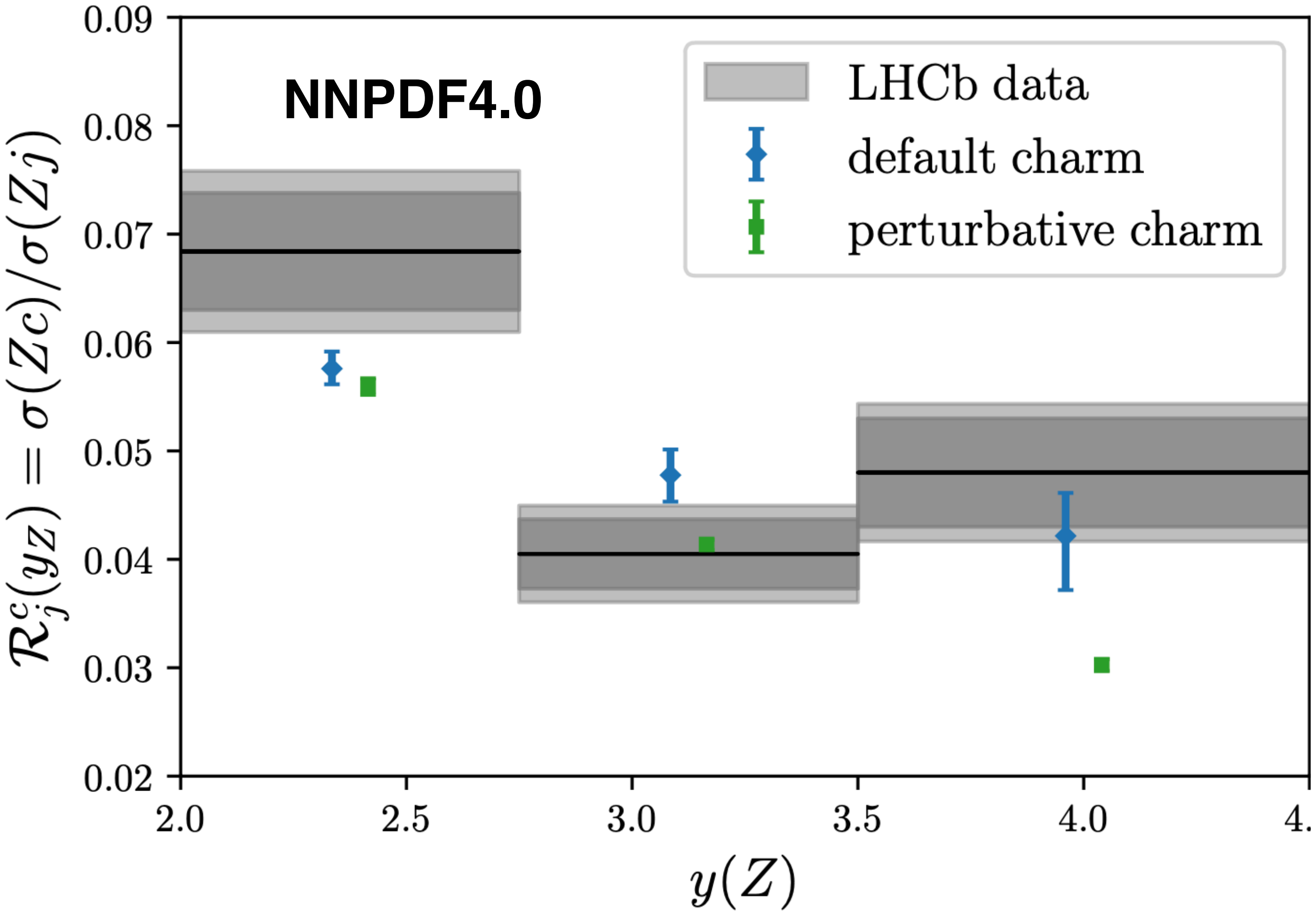


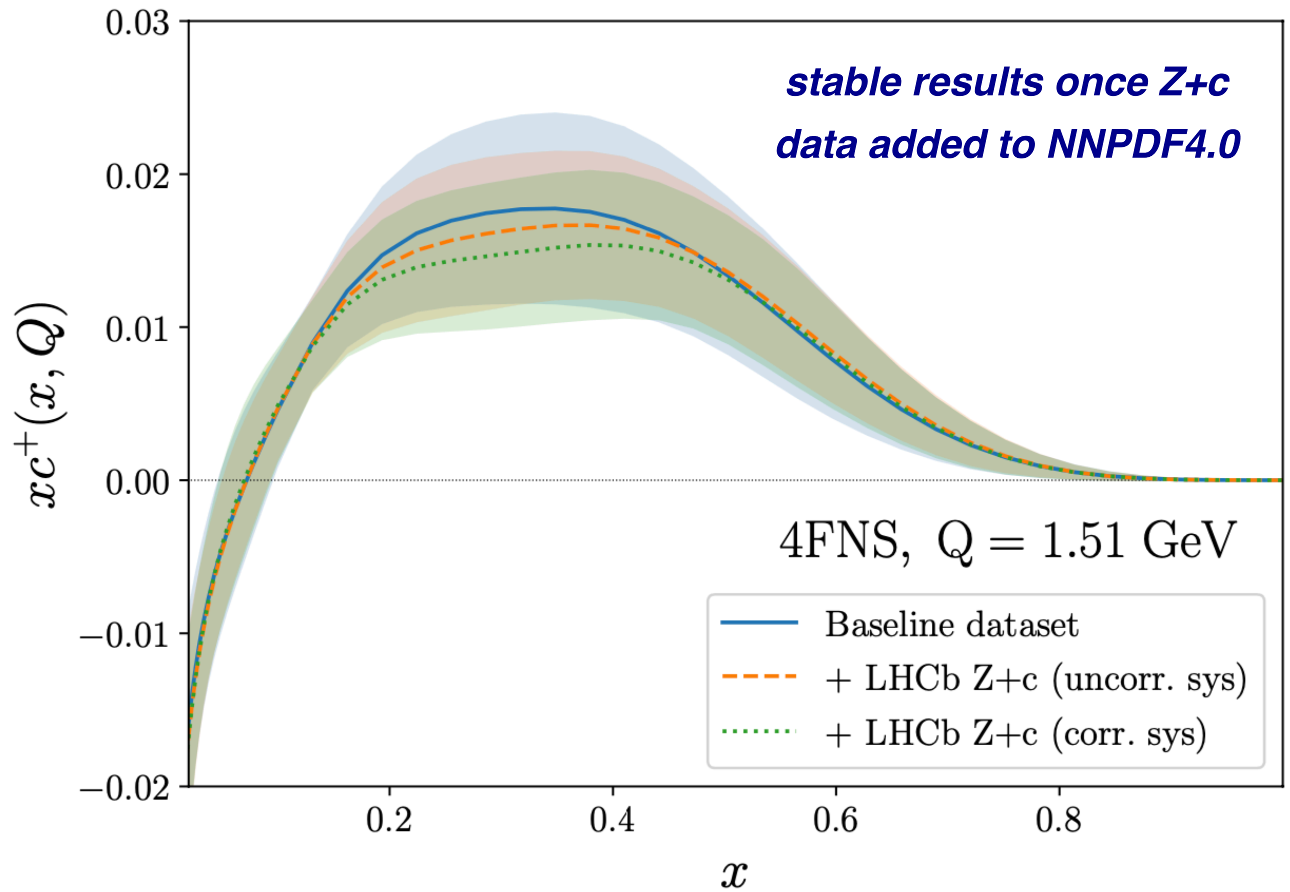


$$\mathcal{R}_j^c(y_Z) \equiv \frac{N(c\ \text{tagged jets}; y_Z)}{N(\text{jets}; y_Z)} = \frac{\sigma(pp \to Z + \text{charm jet}; y_Z)}{\sigma(pp \to Z + \text{jet}; y_Z)}$$

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

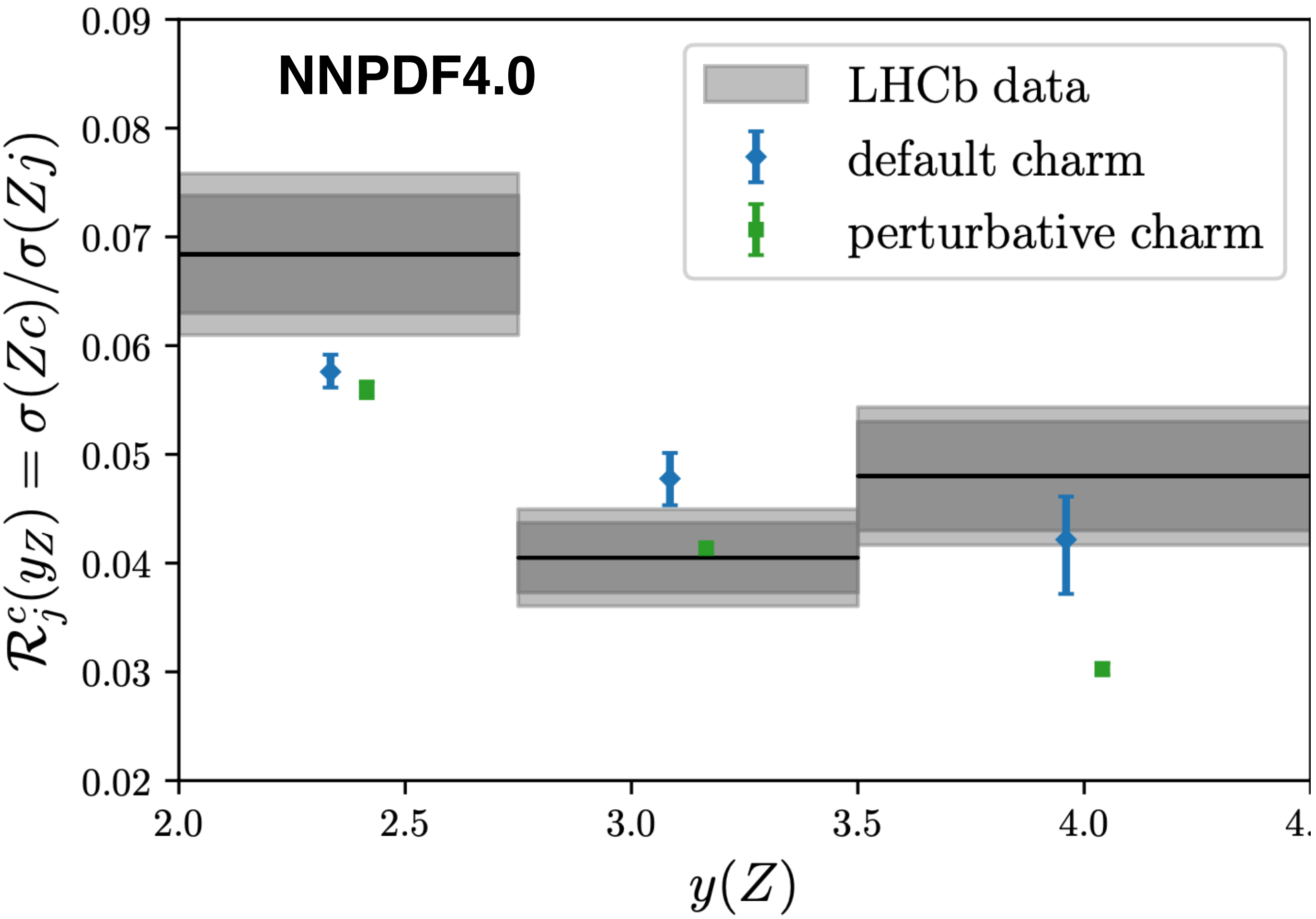
Z+charm @ LHCb

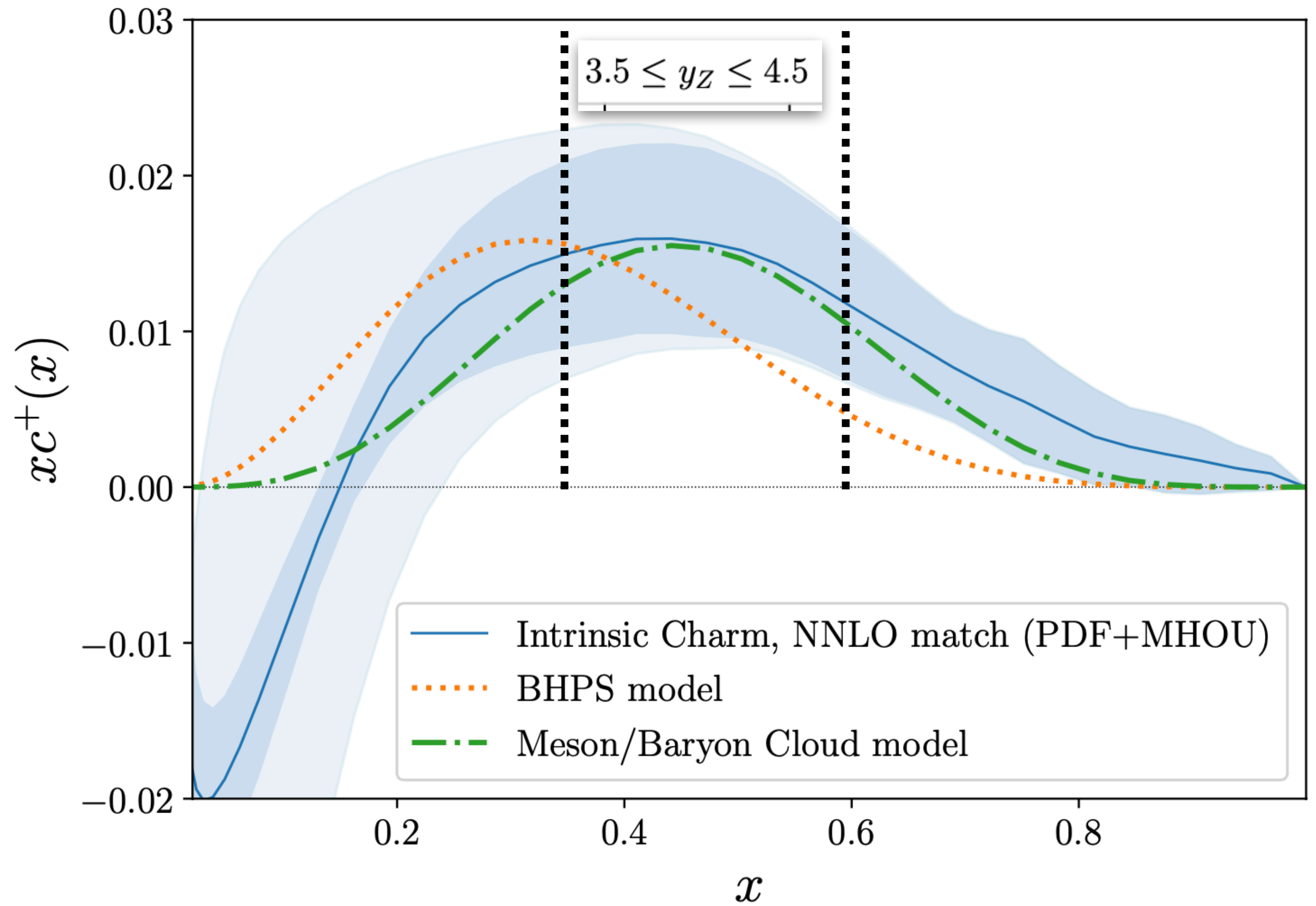


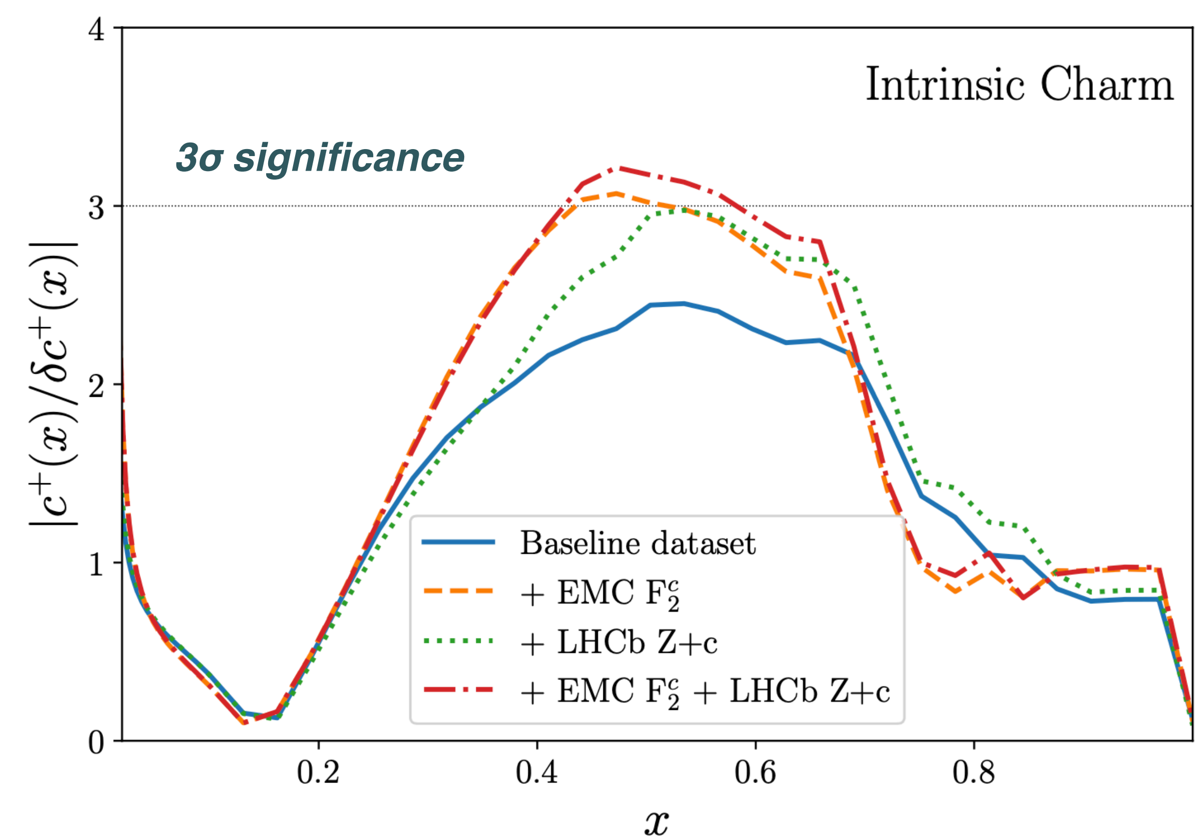


- Calculations settings: **NLO+Pythia8 via the POWHEG-BOX** (charm fragmentation from shower), accounting for MHO and PDF uncertainties (MHOUs cancel partially in ratio)
- Charm jets defined by **overlap of anti-k_t jets with reconstructed *D*-mesons** to reproduce experimental analyses: includes contribution from g => c+cbar splittings
- However, there are *i)* suppressed in forward region where IC effects stronger and *ii)* do not affect shape
- Fixed-order QCD cannot be used to compare with (current) data due to **lack of flavour IR-safe definition**

Z+charm @ LHCb



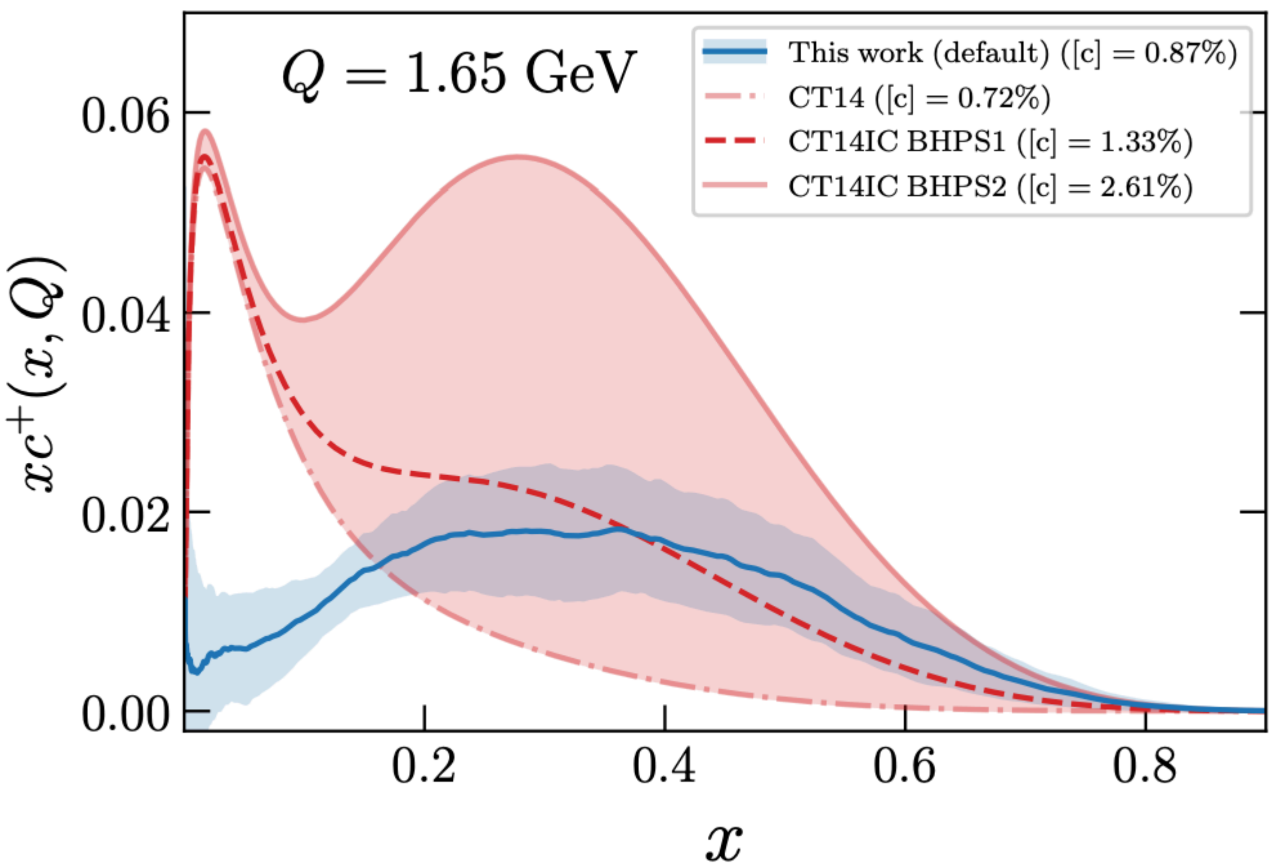


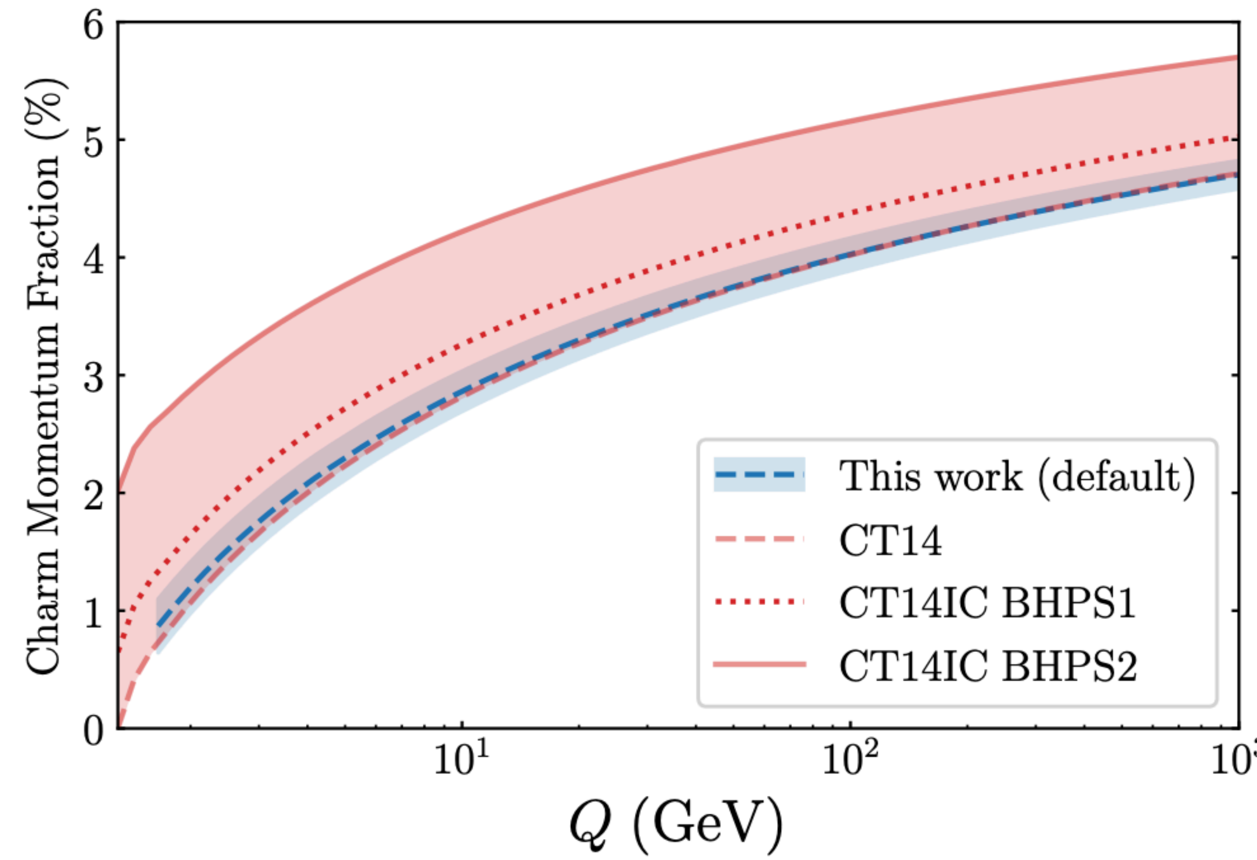


- Perturbative charm PDF disfavoured **by** the LHCb forward Z+charm data
- LHCb data consistent with IC carrying **0.5% of proton's momentum**
- Consistency between **direct** (Z+c, EMC F_2^c) **and indirect constraints** on the charm PDF

Comparison with CT14IC analysis

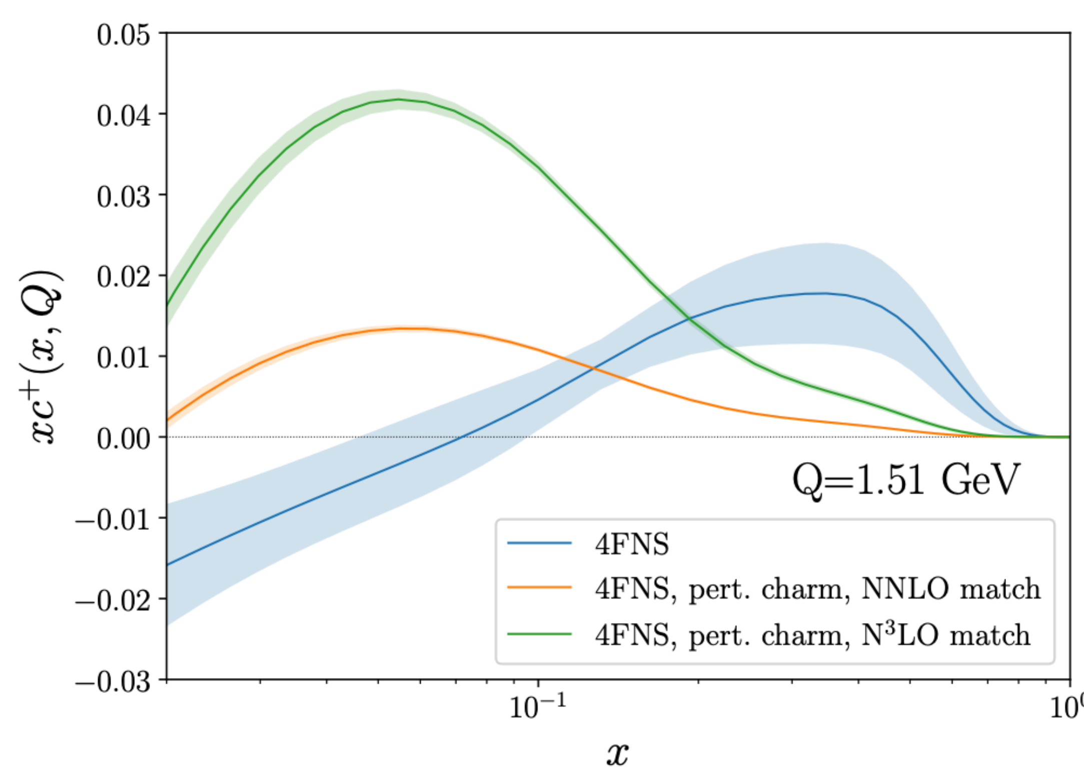
CT14IC consistent with NNPDF4.0 within uncertainties in the **region $x > 0.2$ where IC is important**





- For $x < 0.2$, the **charm PDF is affected by large theory uncertainties** due to *i)* choice of m_c value and *ii)* MHOUs in 3FNS => 4FNS matching

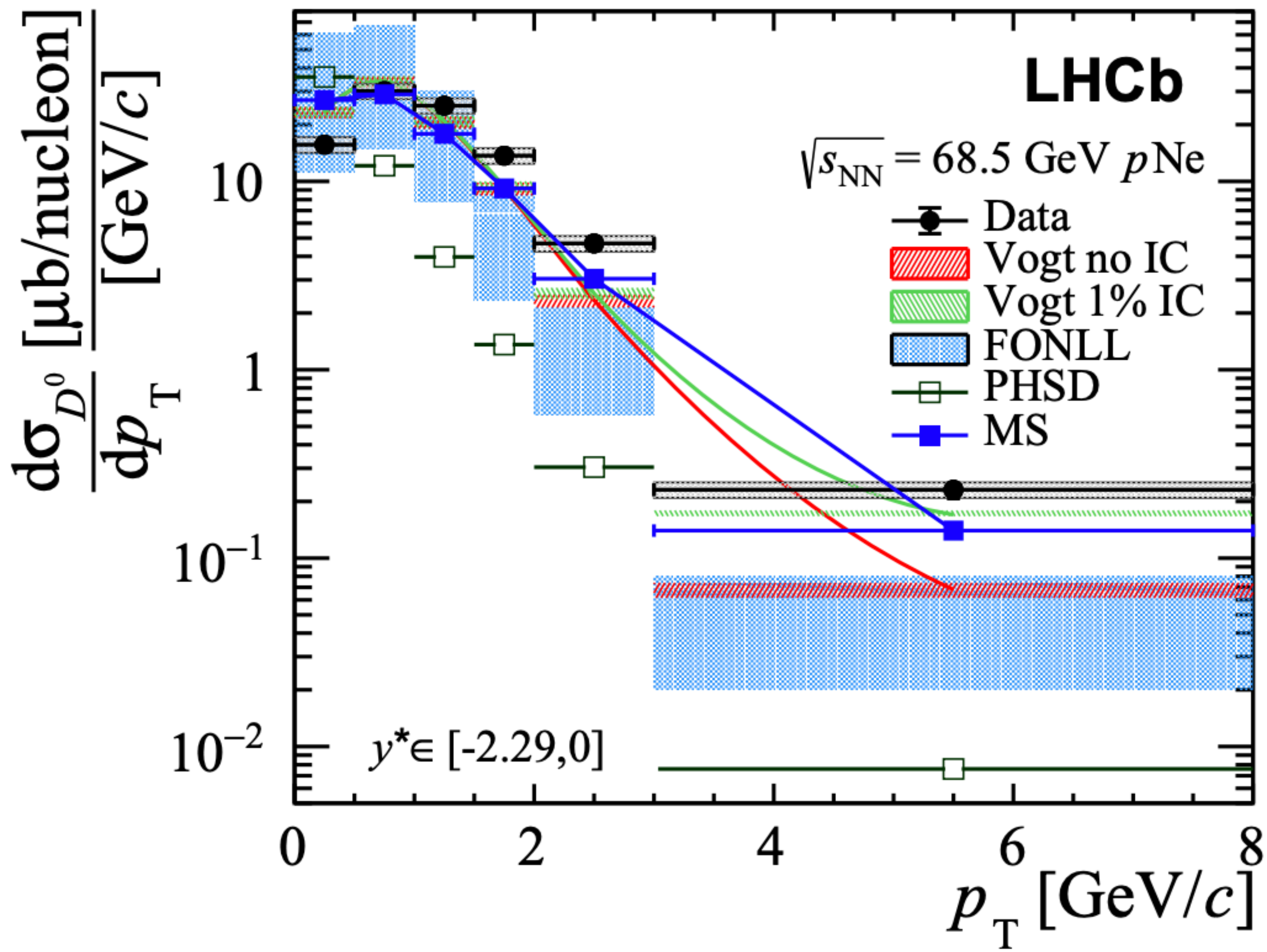
- Both sources of theory errors avoided when charm PDF is parametrised and fitted, regardless of whether there is IC



What comes next?

Further testing intrinsic heavy quarks

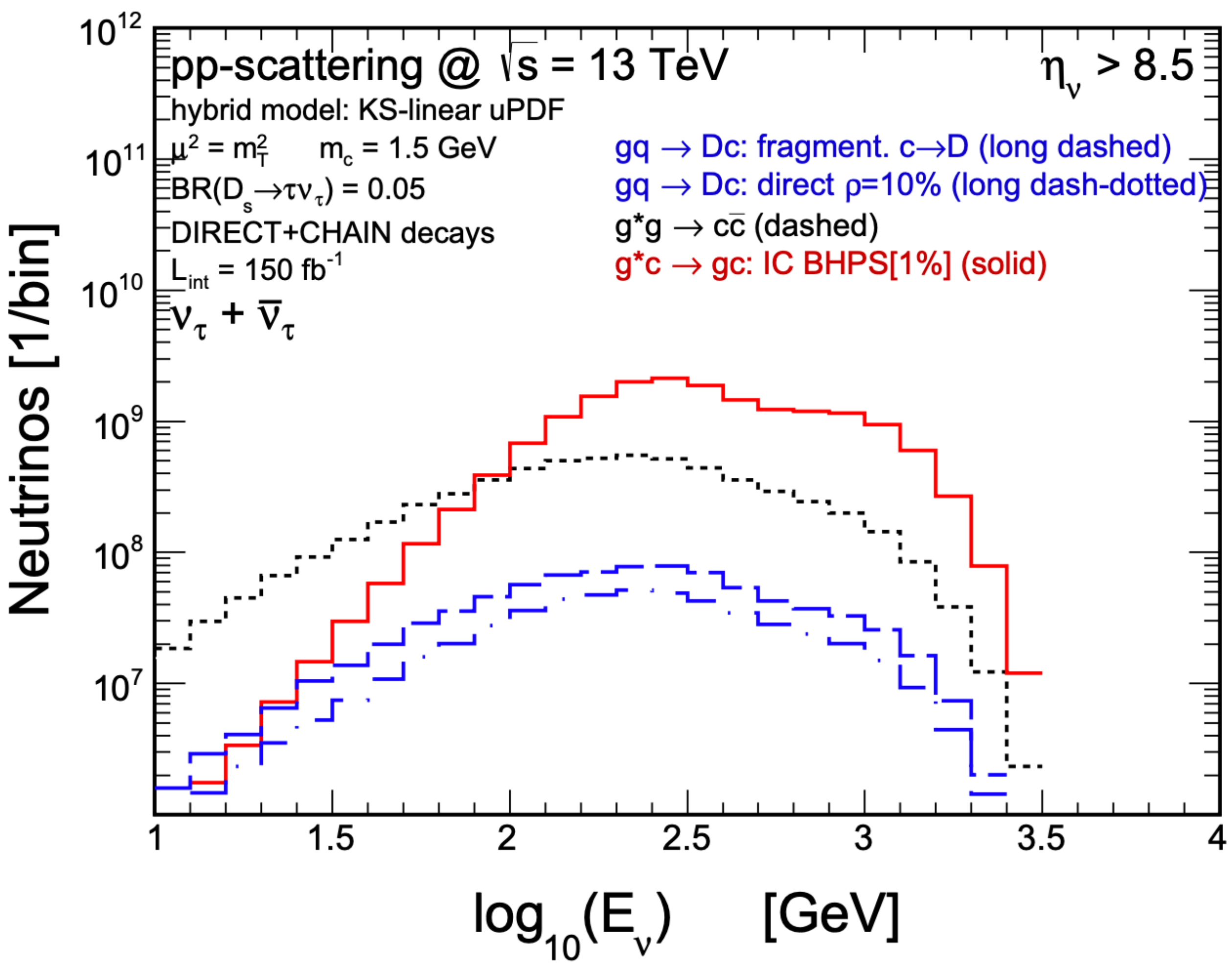
- Revisit Z+charm with **higher stats** and **flavour IR-safe jet algorithm** (of NNLO *D* fragmentation)
- Study other LHC processes sensitive to **initial state charm**



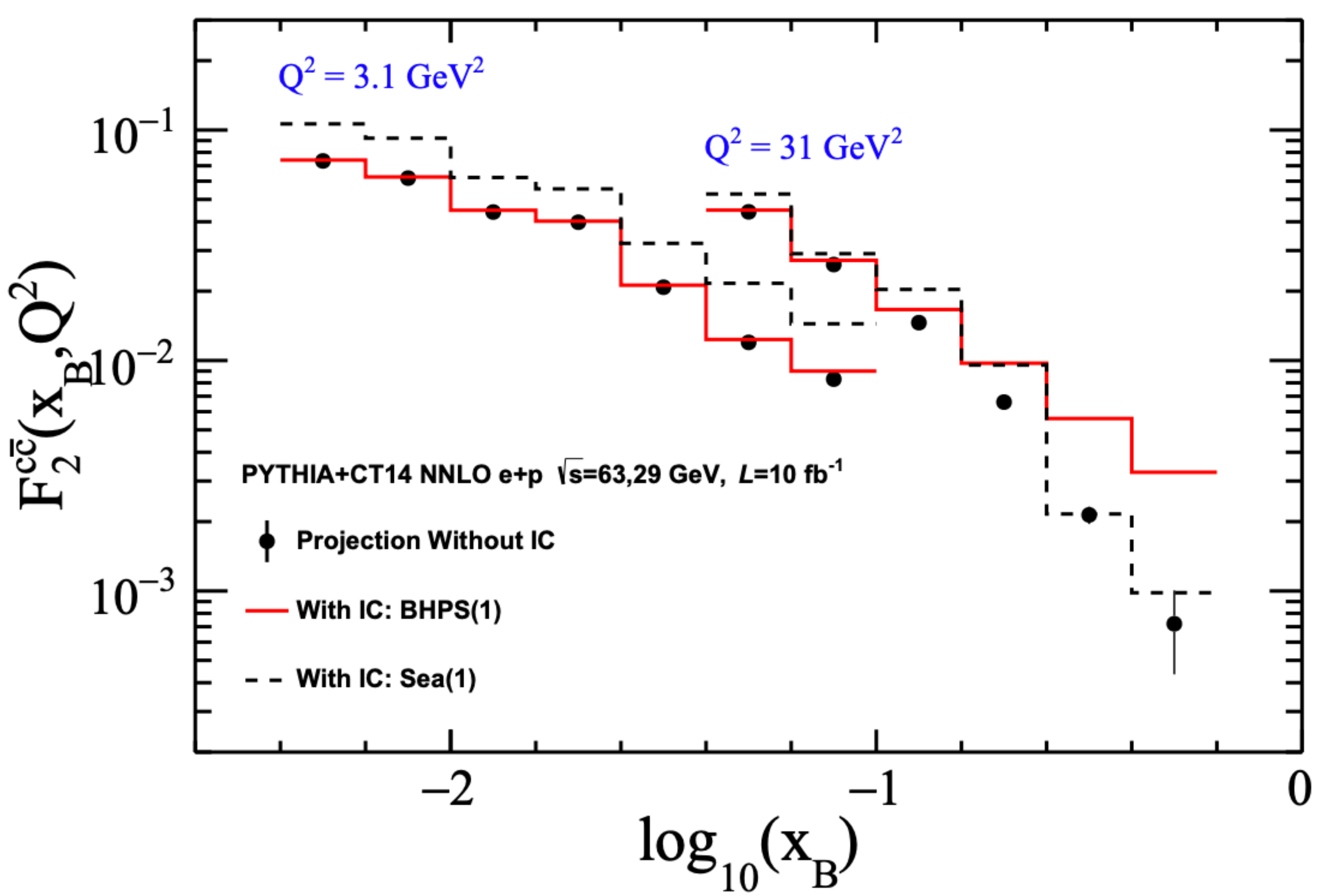
Further testing intrinsic heavy quarks

- With more LHC data, study also the possibility of **intrinsic bottom quarks** and of an **intrinsic charm - anticharm asymmetry** (WIP, ask me after the talk …)
- Better charm structure function measurements to become available at **Electron Ion Collider**
- IC will also affect rates for **prompt neutrino fluxes** in neutrino telescopes, main background for extraterrestrial high-energy neutrinos

forward charm production

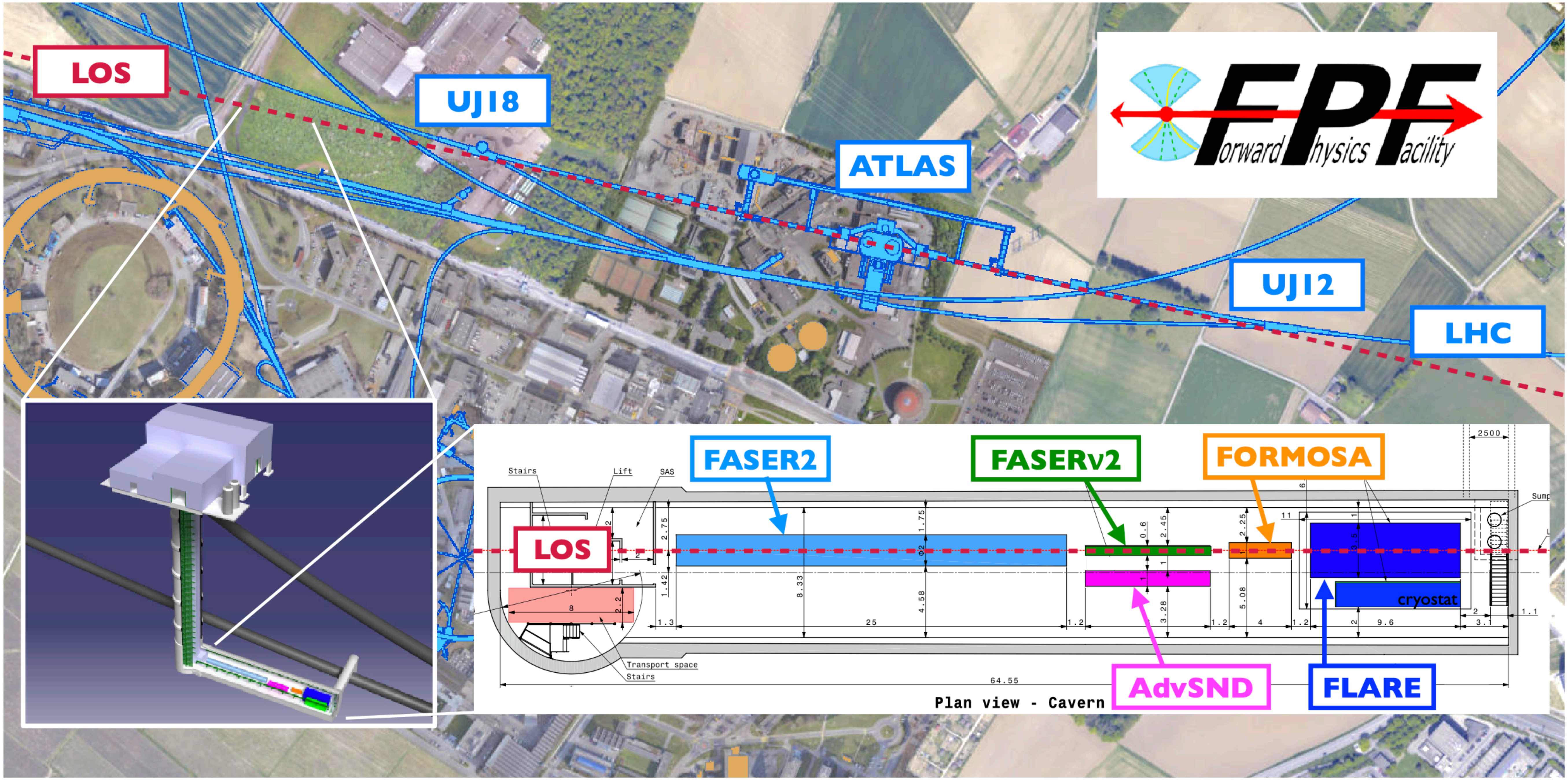


charm @ Electron Ion Collider



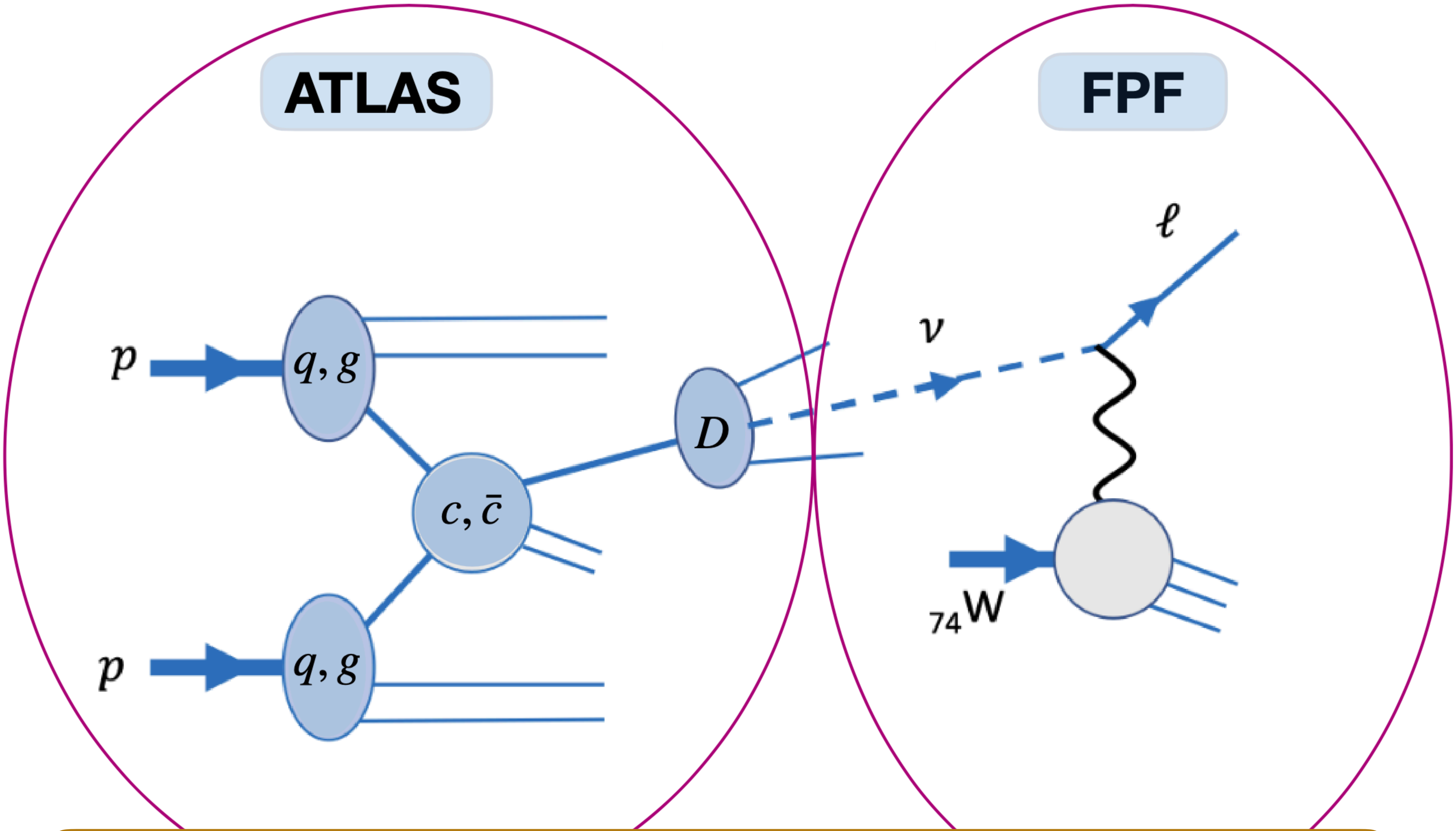
The Forward Physics Facility

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)



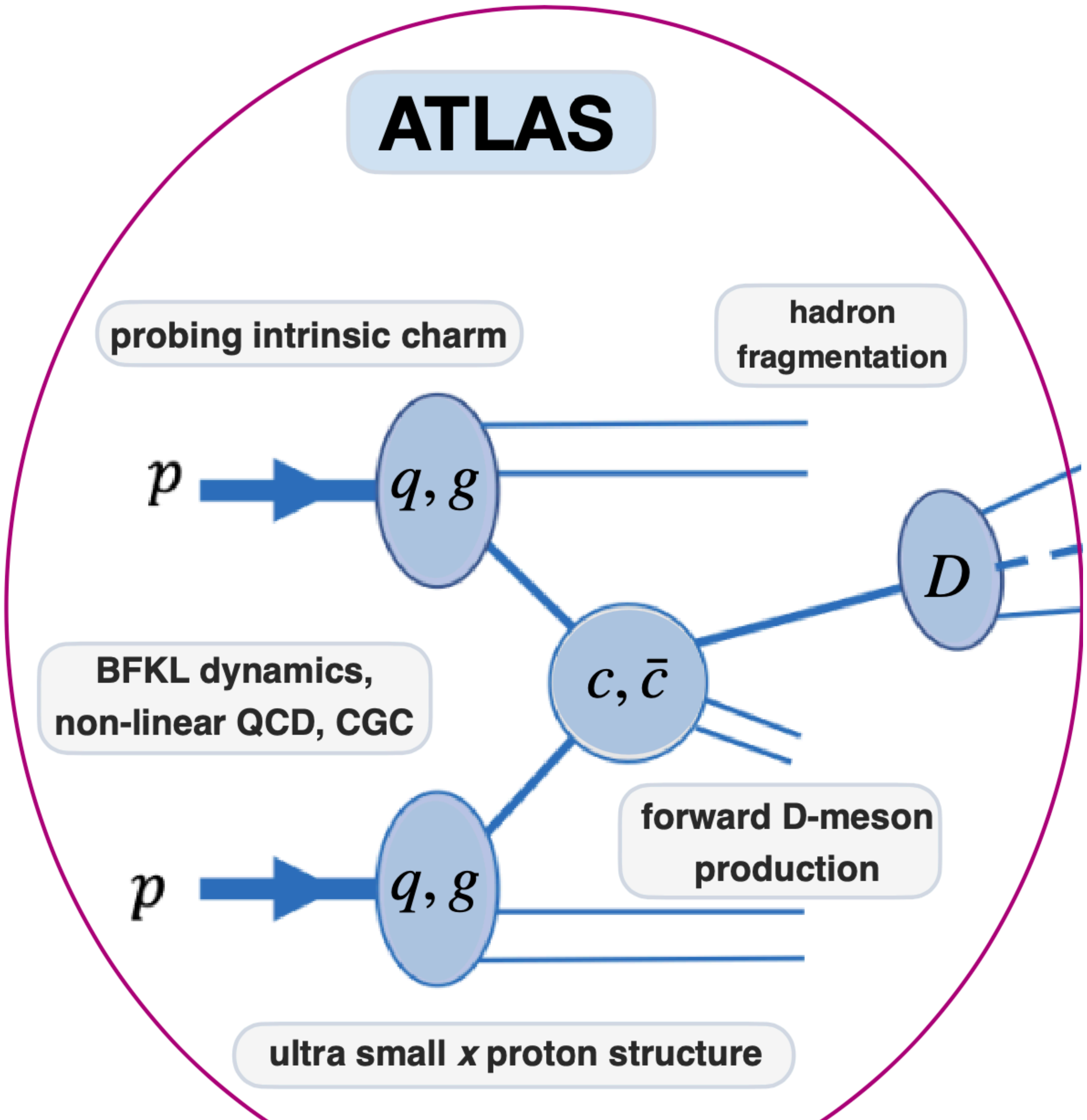
No modifications to the HL-LHC required!

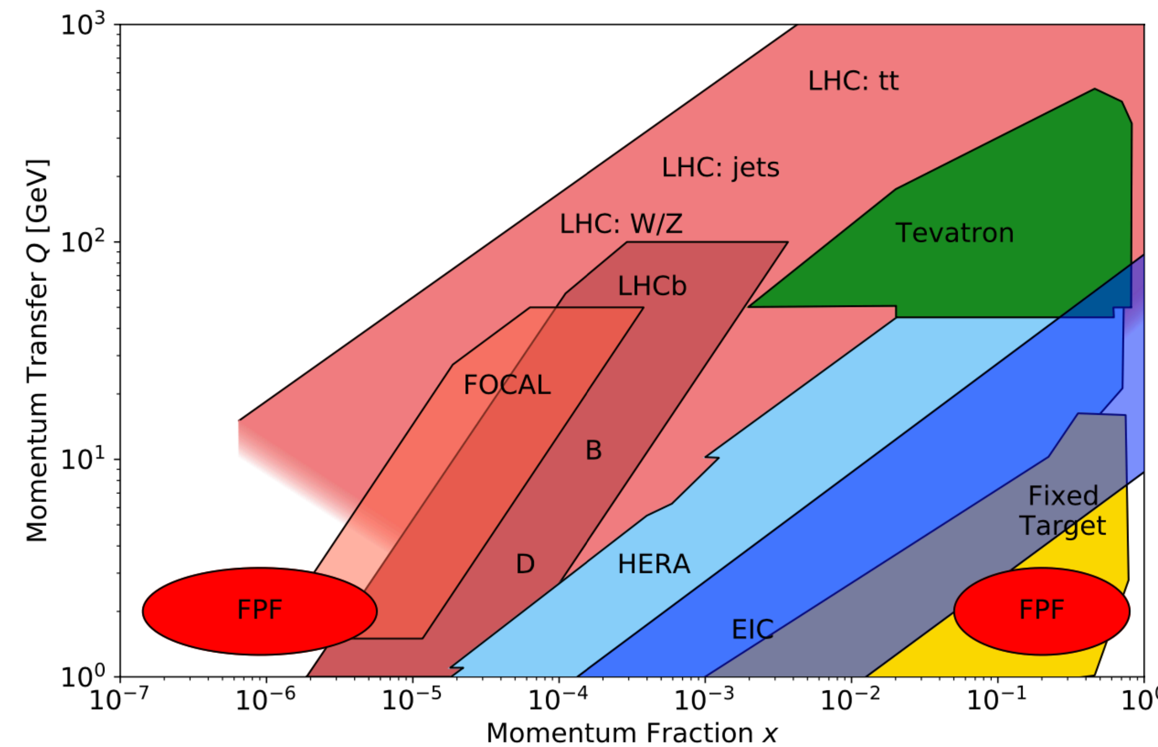
The Forward Physics Facility



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

QCD at the FPF

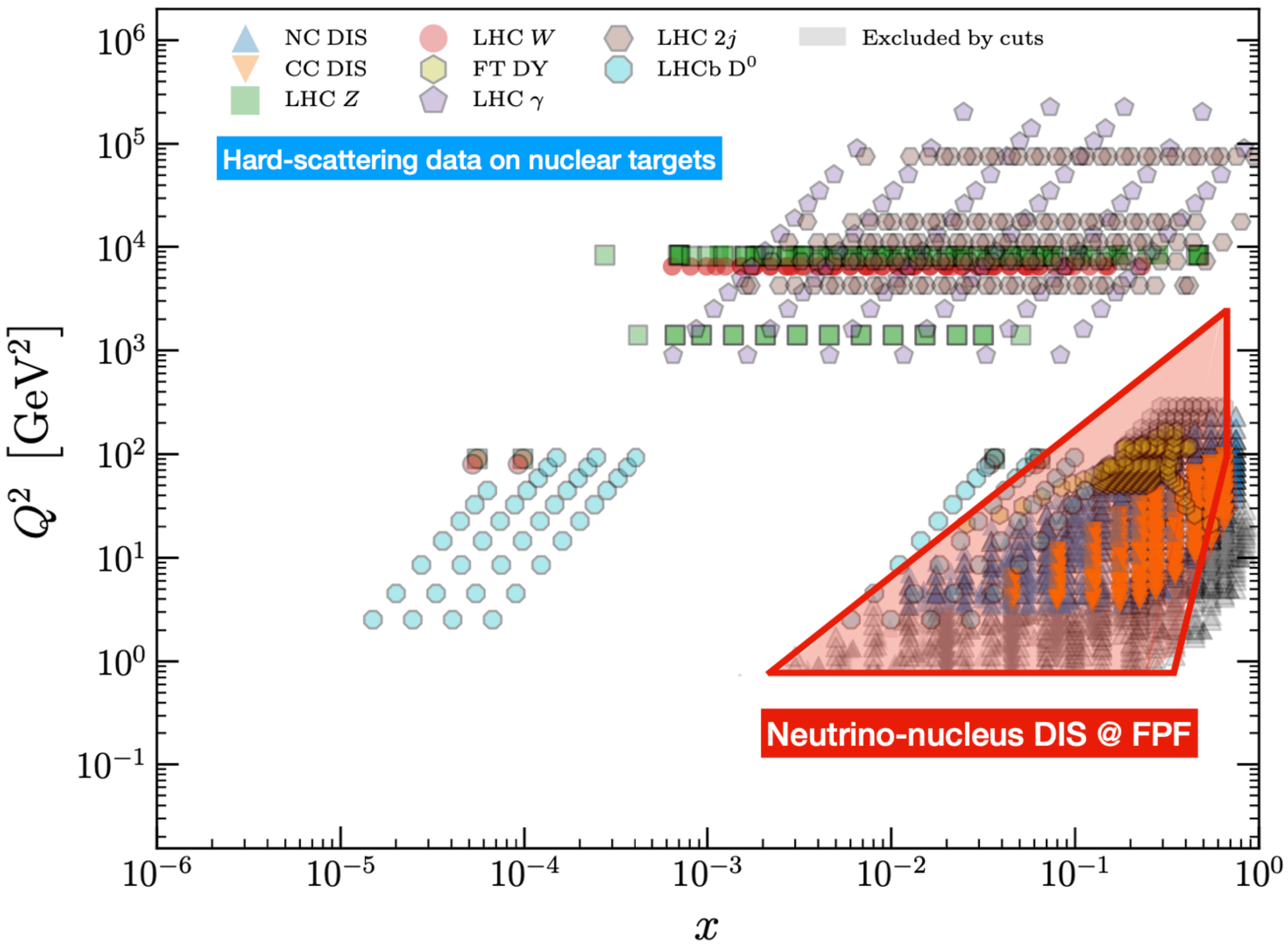




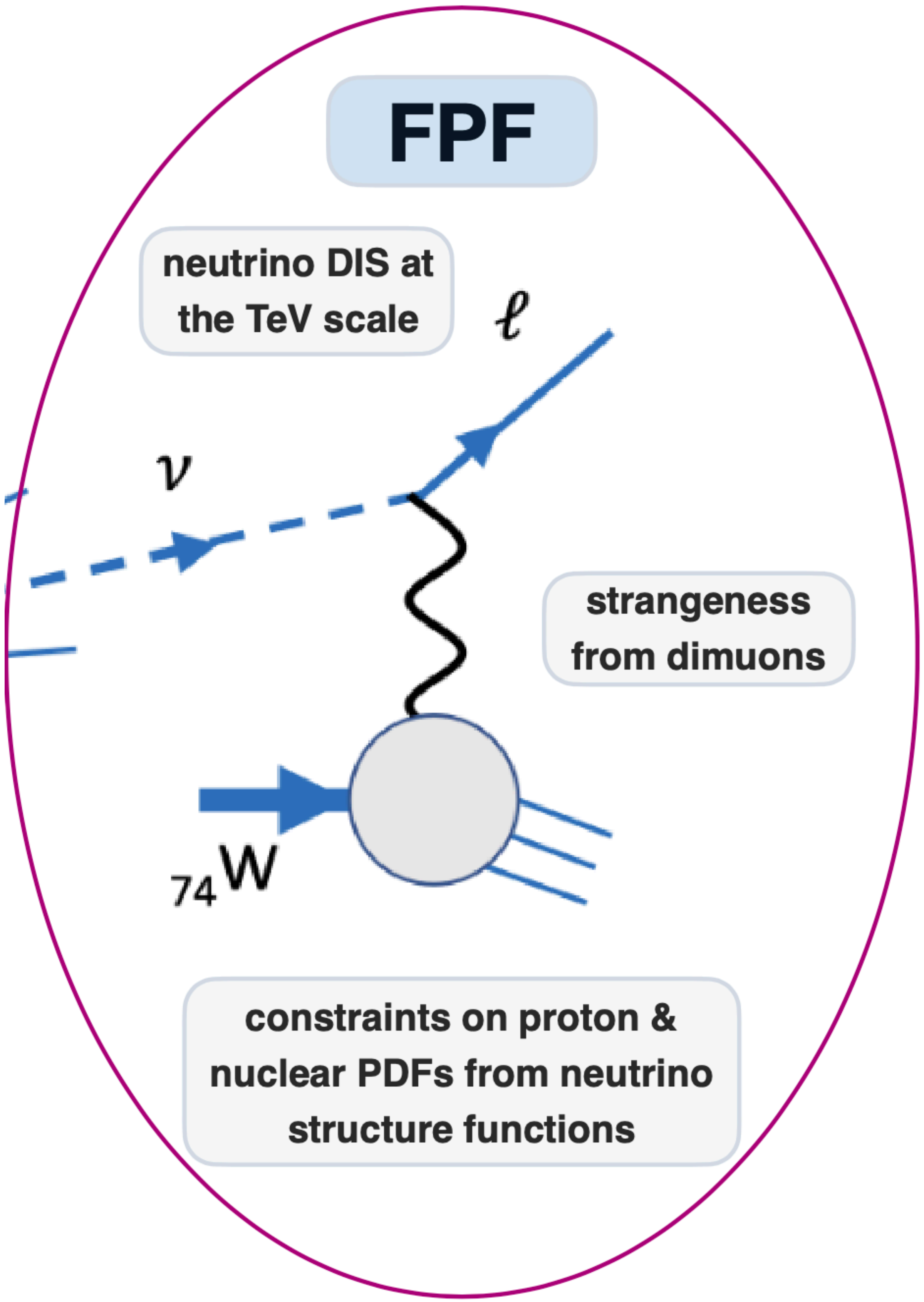
+ unique inputs for **high-energy neutrino** and **cosmic ray** astroparticle physics experiments

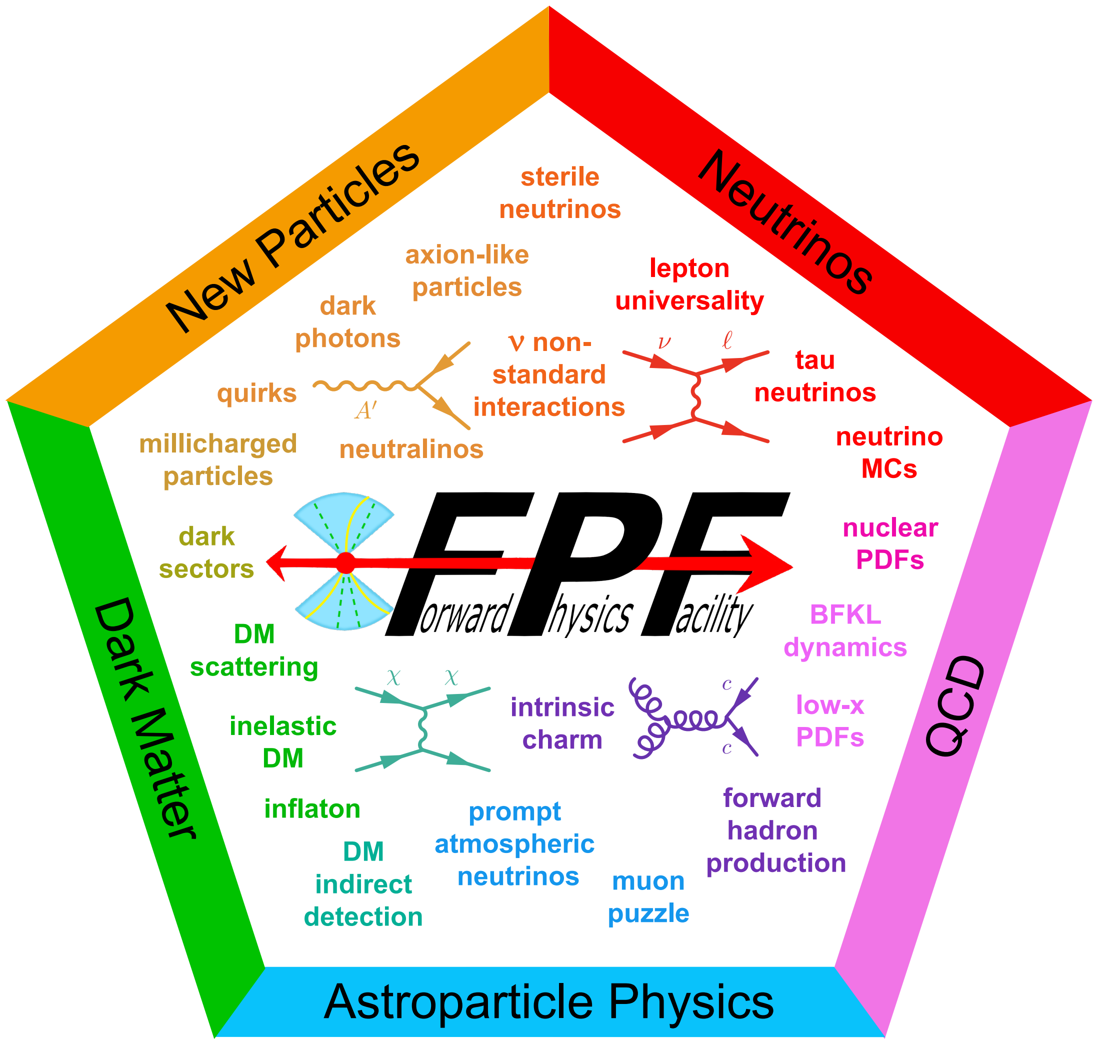
- **Forward particle production** (light hadrons & D-mesons) sensitive down to $x=10^{-7}$
- Ultra small-x proton structure & **BFKL / non-linear QCD** dynamics
- Tune models of forward hadron fragmentation
- Constraints on **intrinsic charm**

QCD at the FPF



- Deep-inelastic CC scattering with **TeV neutrinos**
- Continue succesful program of neutrino **DIS experiments @ CERN**
- Constrain proton & nuclear **light (anti-)quark PDFs**





- **430 pages** describing scientific case, infrastructure, detectors, and simulations
- Several **Working Groups** now assembled towards preparing a CDR: **get in touch if you want to contribute!**

arXiv:2203.05090v1 [hep-ex] 9 Mar 2022

The Forward Physics Facility at the High-Luminosity LHC

High energy collisions at the High-Luminosity Large Hadron Collider (LHC) produce a large number of particles along the beam collision axis, outside of the acceptance of existing LHC experiments. The proposed Forward Physics Facility (FPF), to be located several hundred meters from the ATLAS interaction point and shielded by concrete and rock, will host a suite of experiments to probe Standard Model (SM) processes and search for physics beyond the Standard Model (BSM). In this report, we review the status of the civil engineering plans and the experiments to explore the diverse physics signals that can be uniquely probed in the forward region. FPF experiments will be sensitive to a broad range of BSM physics through searches for new particle scattering or decay signatures and deviations from SM expectations in high statistics analyses with TeV neutrinos in this low-background environment. High statistics neutrino detection will also provide valuable data for fundamental topics in perturbative and non-perturbative QCD and in weak interactions. Experiments at the FPF will enable synergies between forward particle production at the LHC and astroparticle physics to be exploited. We report here on these physics topics, on infrastructure, detector, and simulation studies, and on future directions to realize the FPF's physics potential.

Snowmass Working Groups
EF4,EF5,EF6,EF9,EF10,NF3,NF6,NF8,NF9,NF10,RP6,CF7,TF07,TF09,TF11,AF2,AF5,IF8

Lead Conveners

Jonathan L. Feng[1*], Felix Kling[2], Mary Hall Reno[3], Juan Rojo[4,5], Dennis Soldin[6]

Topical Conveners

Luis A. Anchordoqui[7], Jamie Boyd[8], Ahmed Ismail[9], Lucian Harland-Lang[10,11], Kevin J. Kelly[12], Vishvas Pandey[13], Sebastian Trojanowski[14,15], Yu-Dai Tsai[1],

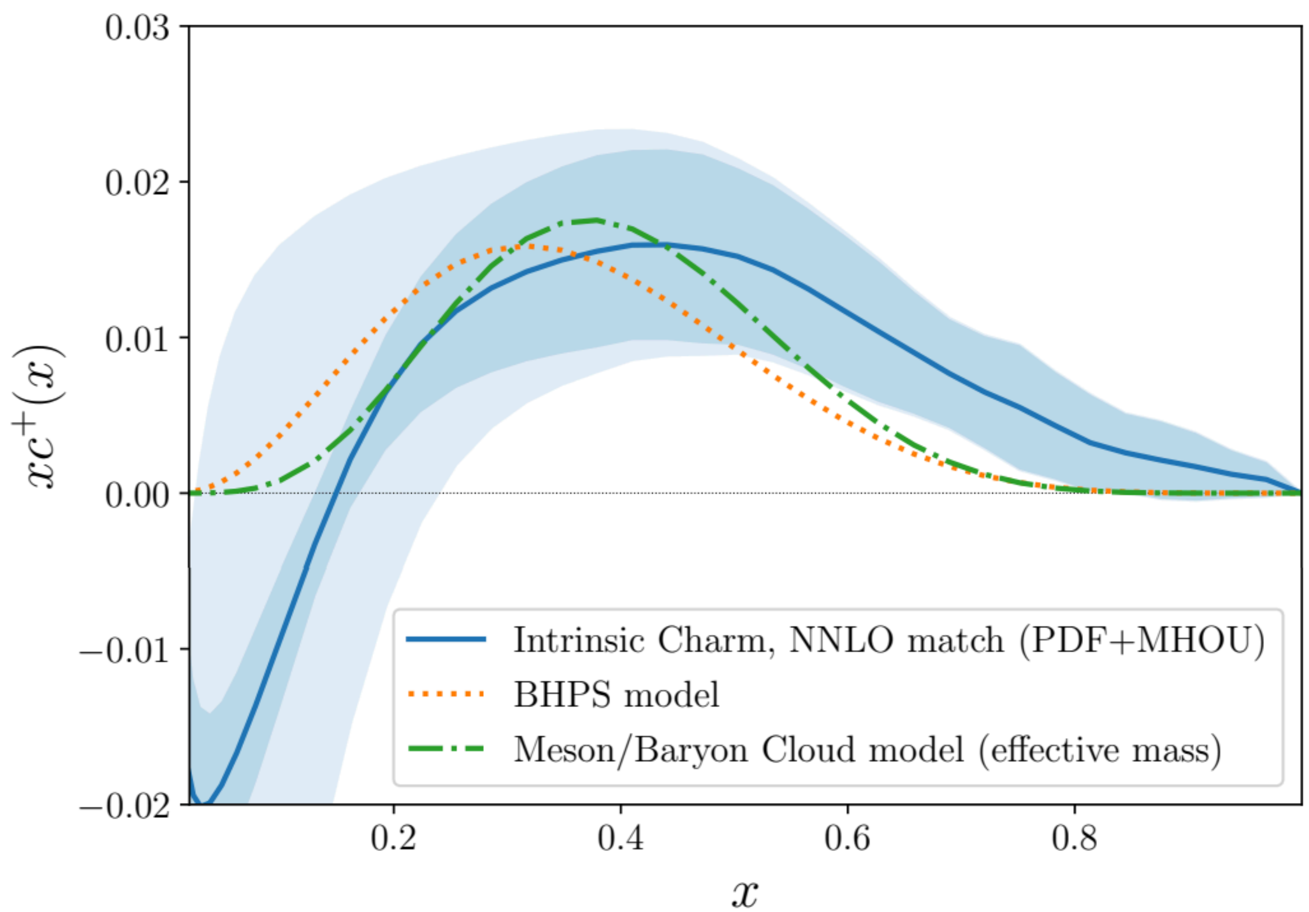
Summary

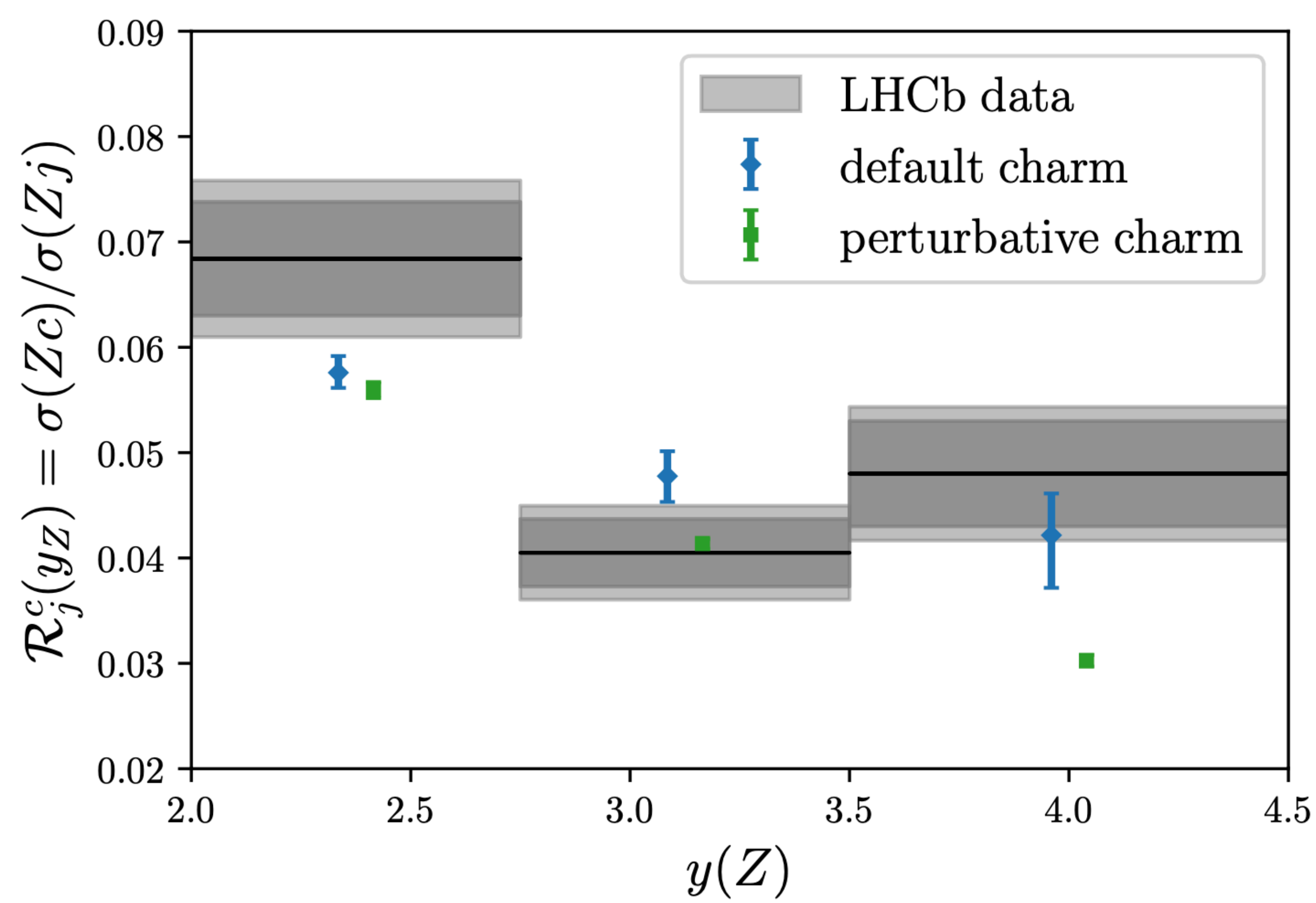
- For more than four decades, the question of **whether the proton contain charm quarks** has been passionately investigated, with no clear conclusions until recently

- The NNPDF4.0 global analysis reveals **evidence for intrinsic charm in the proton**, consistent with BHPS and meson/baryon could models with around 0.5% momentum fraction

- NNPDF4.0 predictions in agreement with independent constraints provided by the **LHCb Z+charm data** in the forward region

- IC (and its asymmetry) will be further scrutinised by **upcoming LHC analyses** as well as by the **EIC**, the **FPF**, as well as at high-energy astroparticle physics facilities

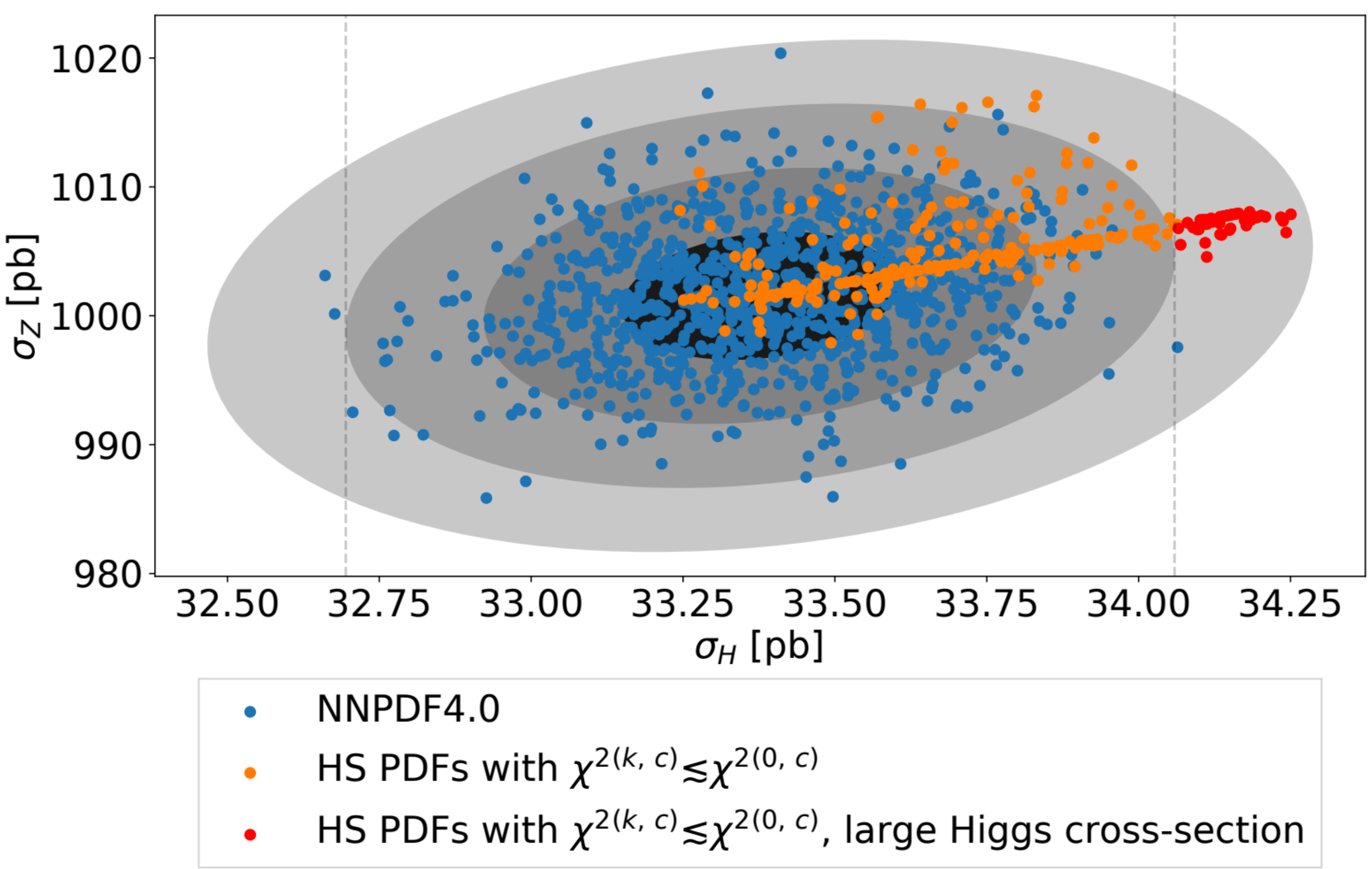


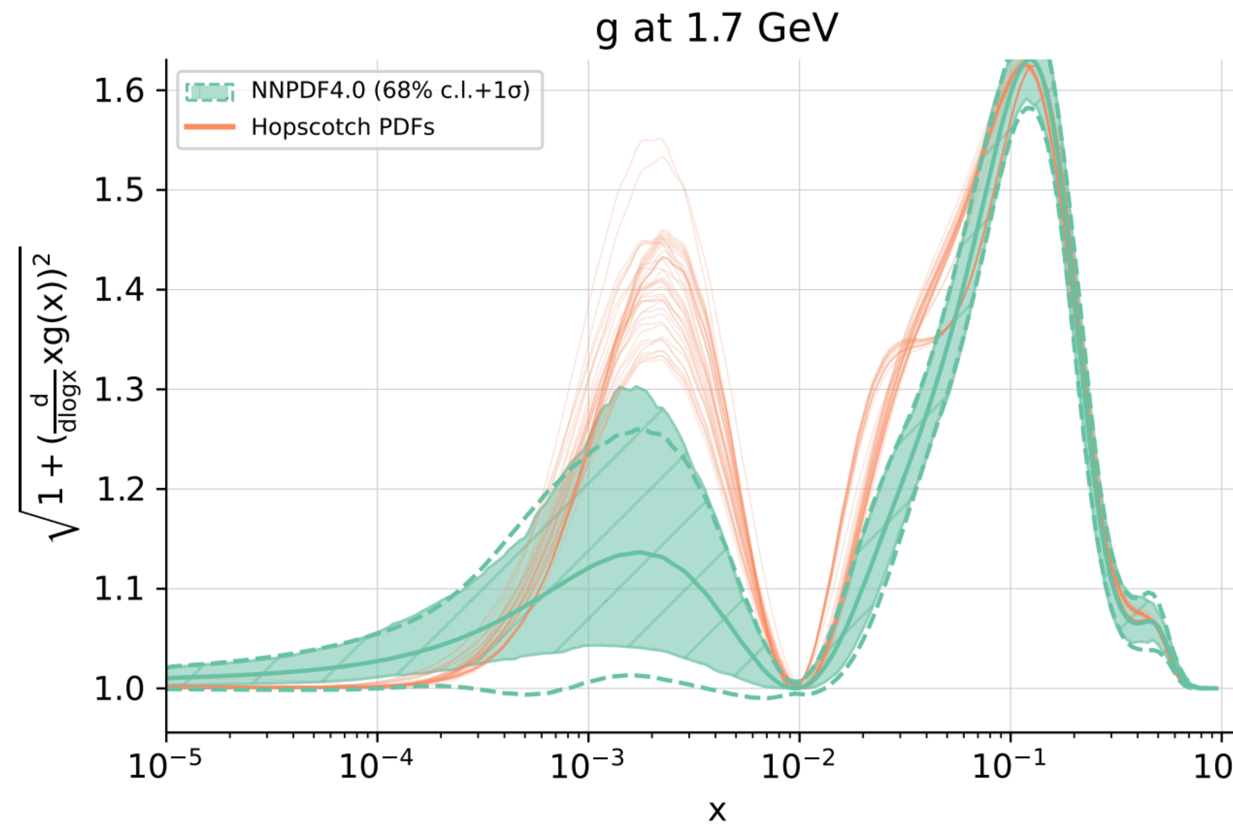


Extra Material

The hopscotch PDFs

- **Linear combinations of NNPDF4.0 replicas**, some of them with lower χ^2 than the average NNPDF4.0 PDF set, constructed using NNPDF open-source code



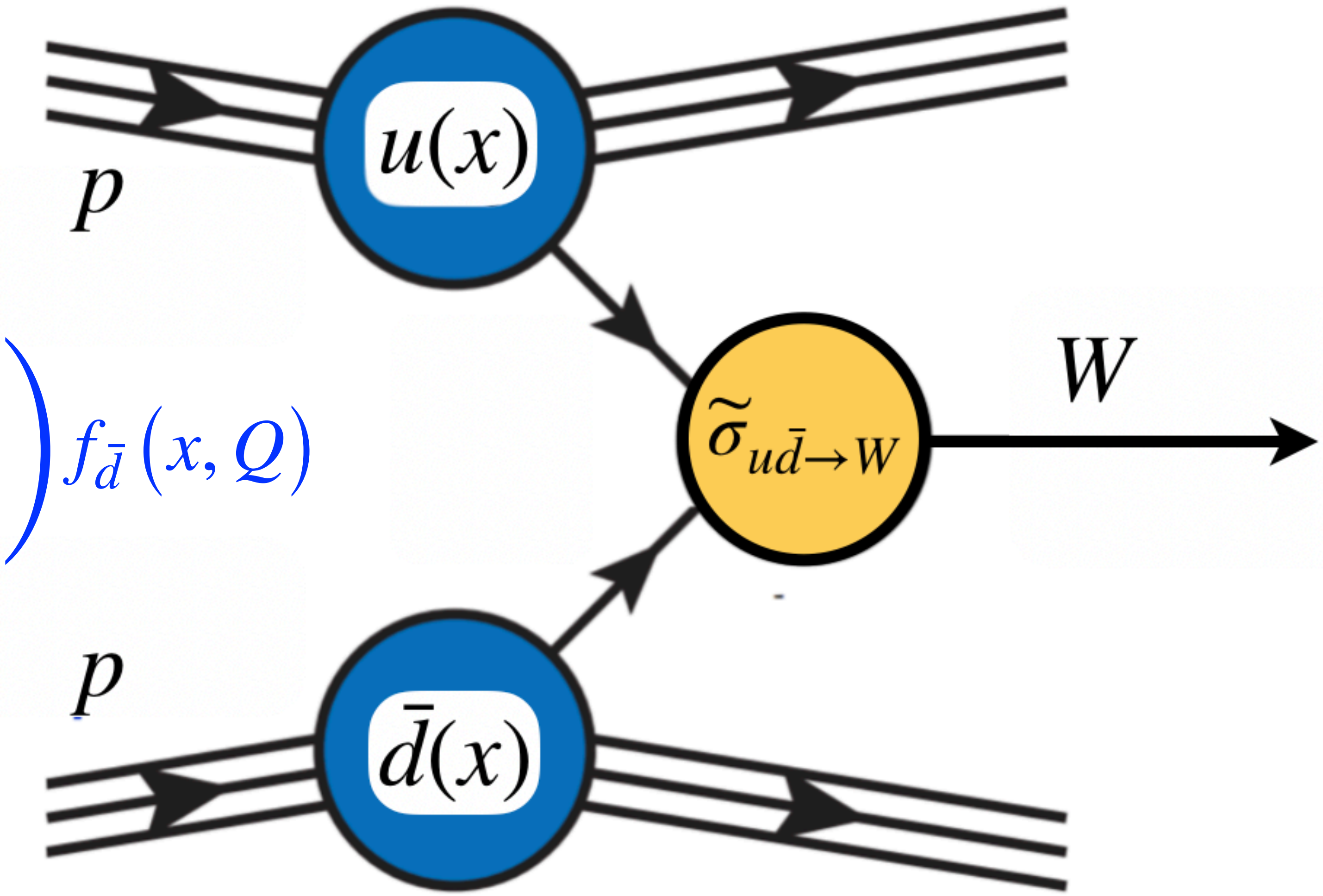


- HS PDFs **do not provide representative sampling,** *e.g.* cannot be used to determine PDF errors
- Similar PDFs can be found with the NNPDF methodology, albeit with **very low probability**
- **Kinetic energy** (local measure of non-smoothness) systematically higher in HS PDFs

The global QCD analysis paradigm

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

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

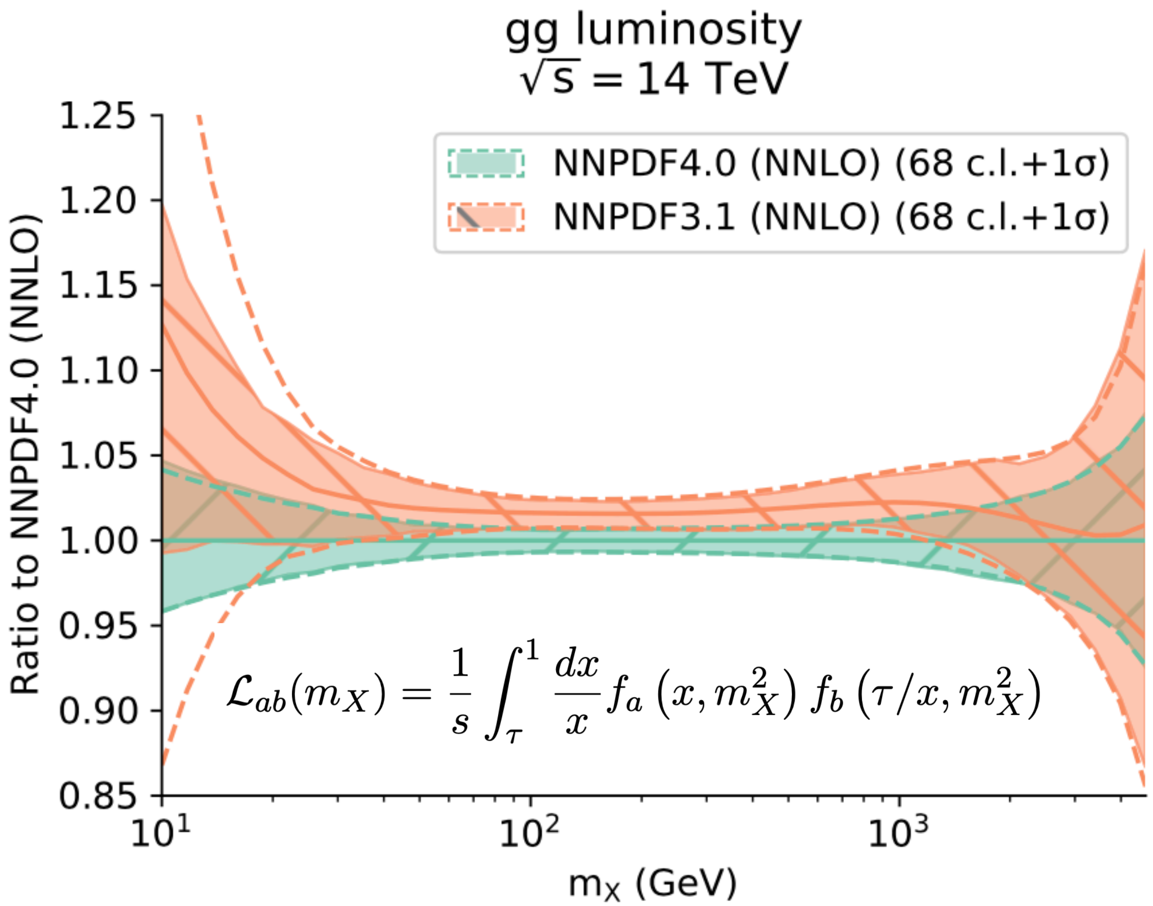


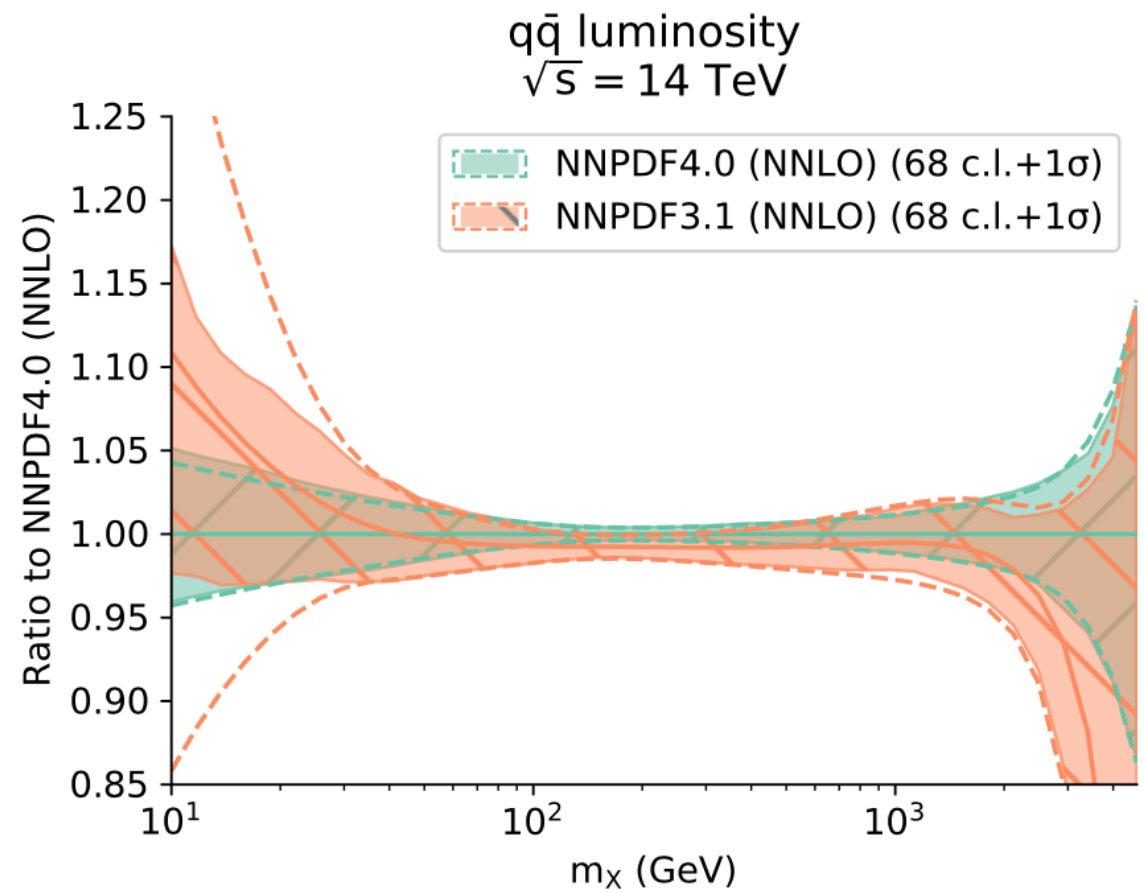
Using leading-order kinematics:

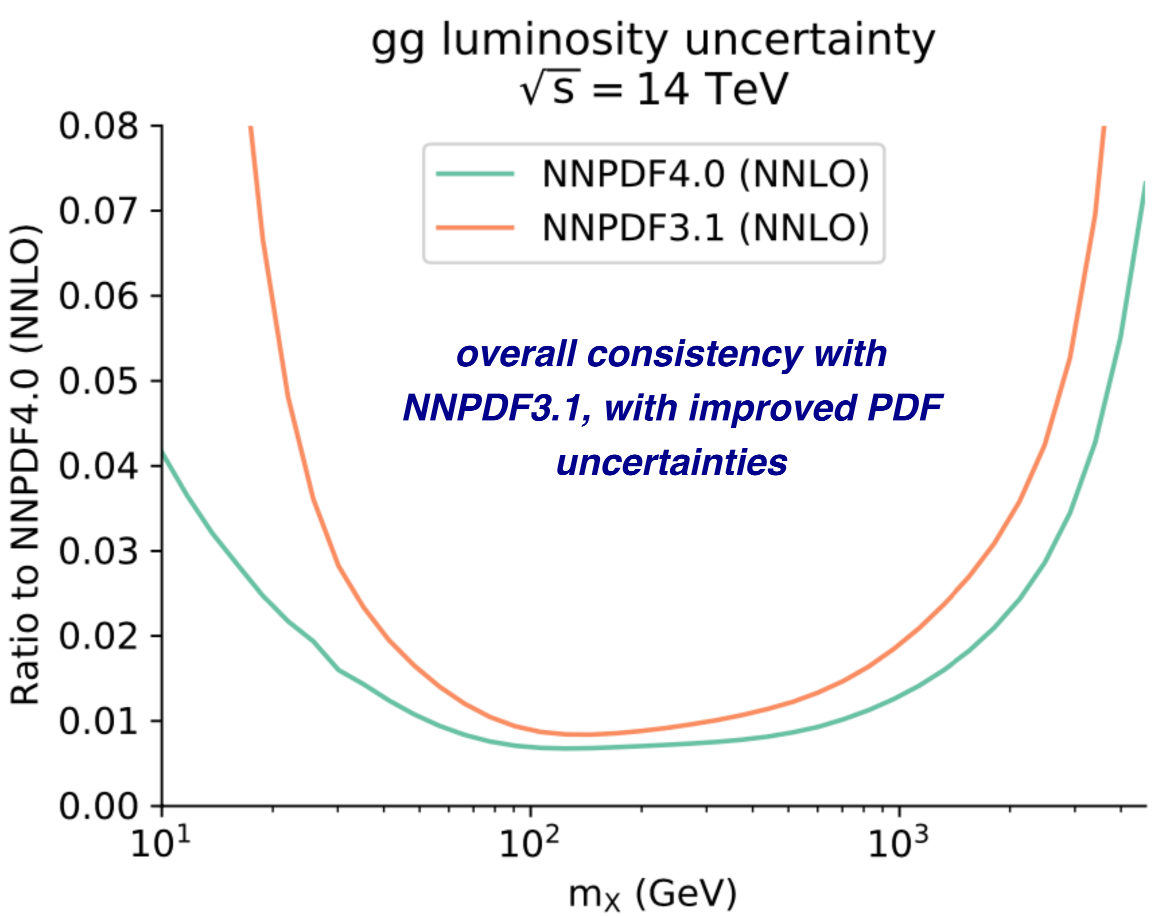
$$x_1 = \frac{M_W}{\sqrt{s}}e^{+y_W}, \quad x_2 = \frac{M_W}{\sqrt{s}}e^{-y_W}$$

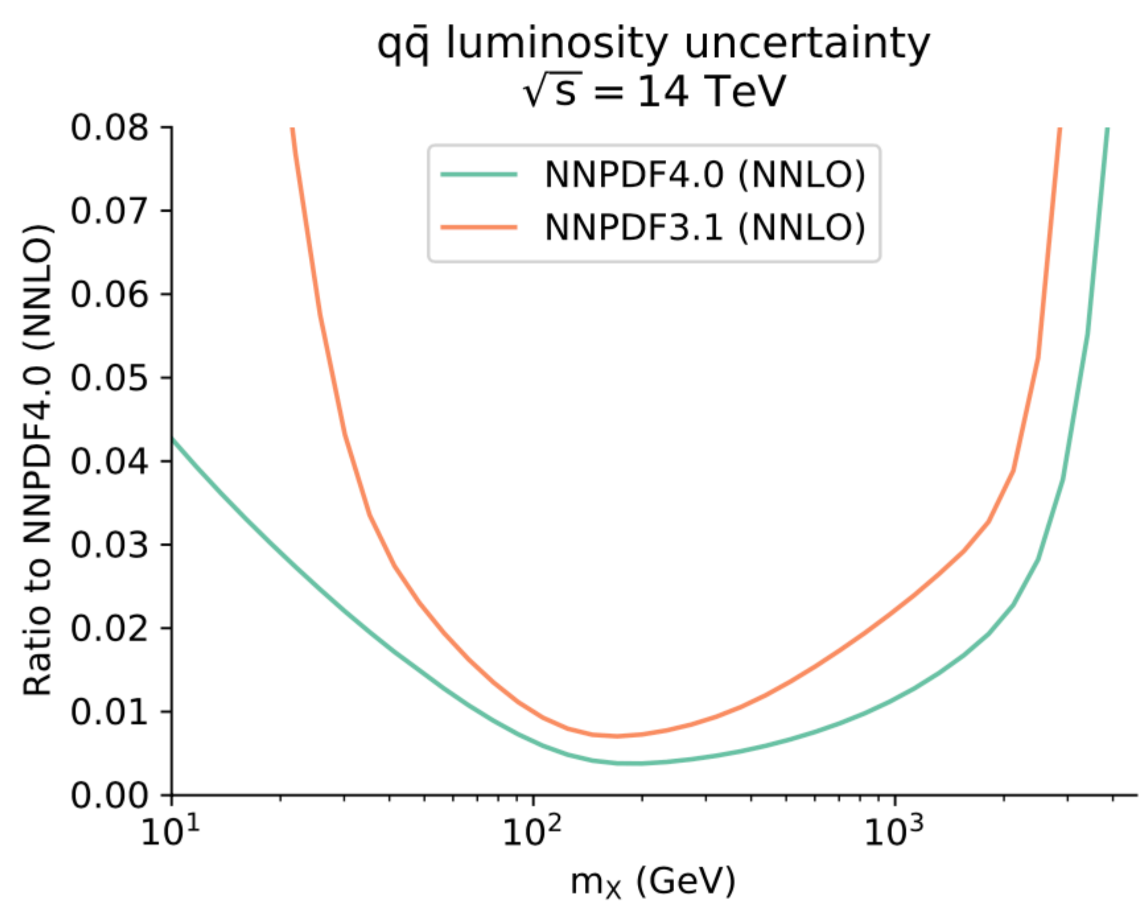
$\rightarrow$ **forward rapidities** probe **small and large *x*** (momentum fractions)

Comparison with NNPDF3.1

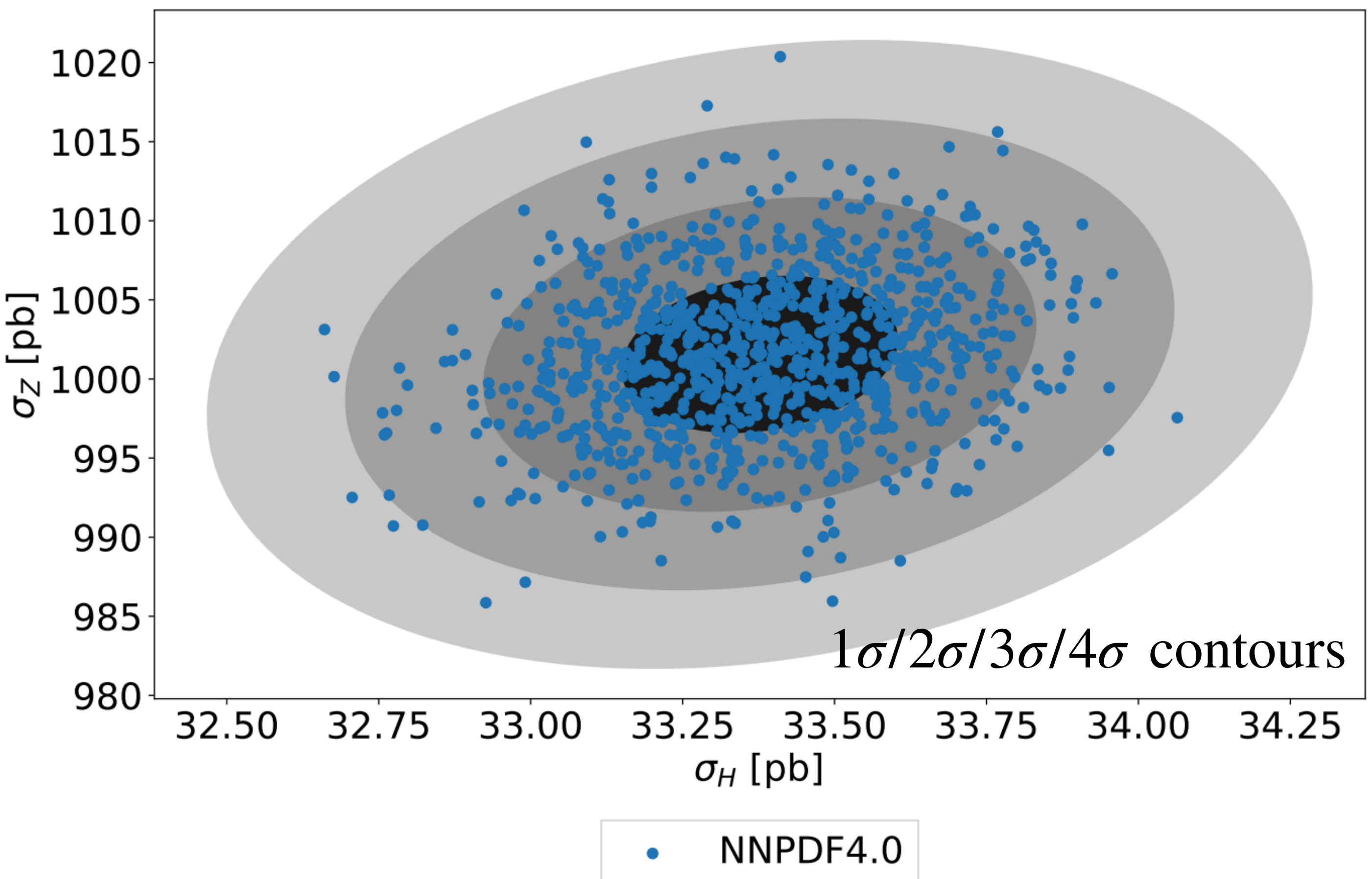






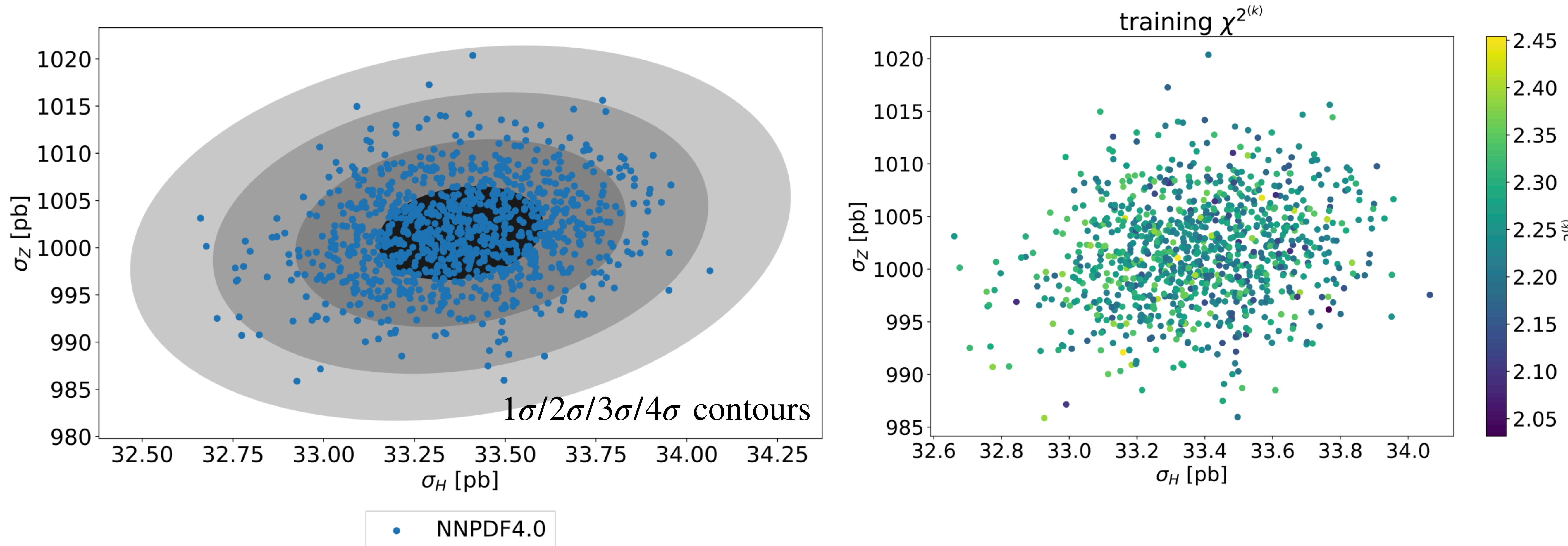


Representative sampling in NNPDF



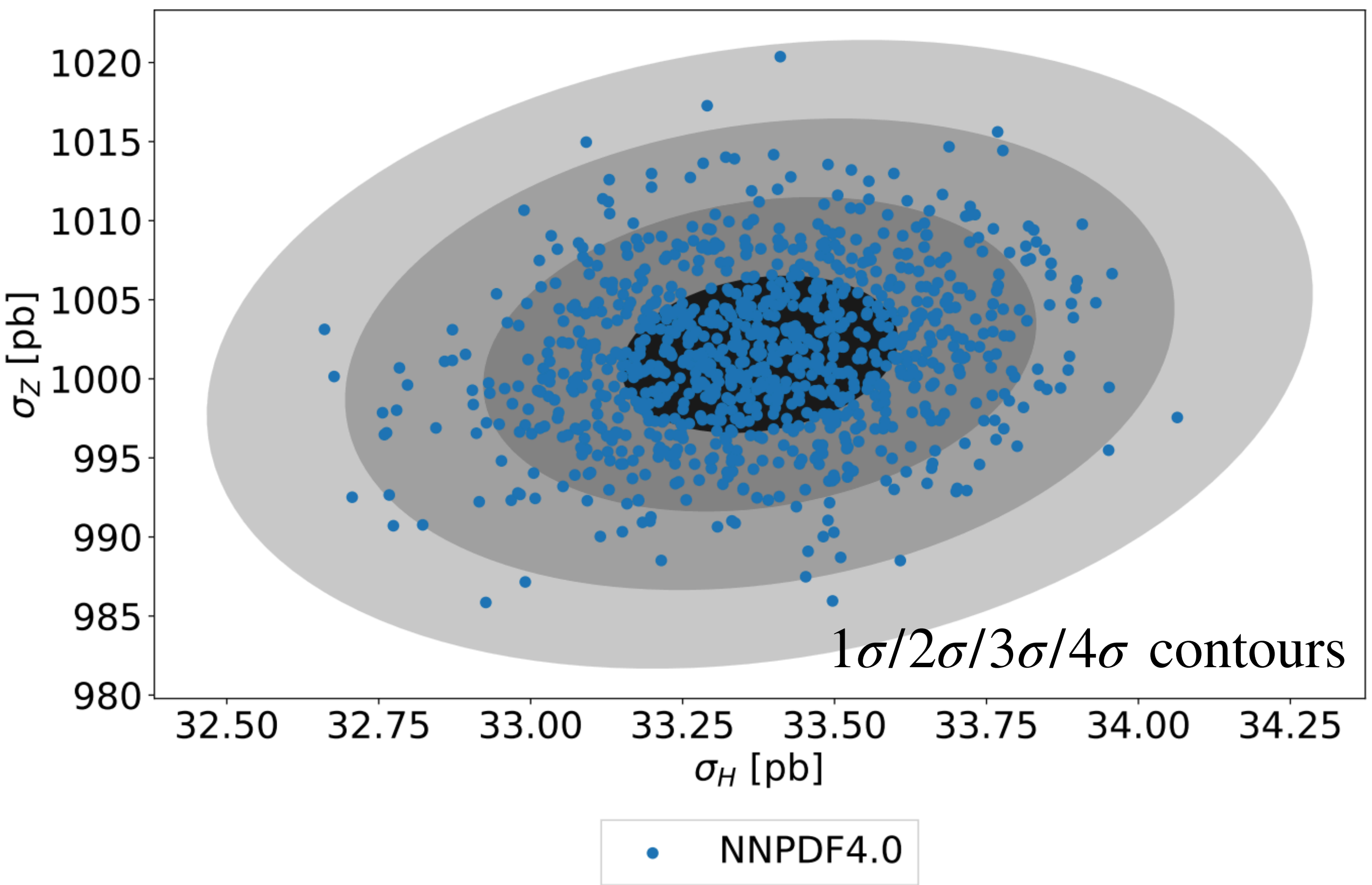
- NNPDF4.0 replicas behave as expected for **representative sampling** e.g. around 50 replicas out of a sample of 1000 fall outside 95% CL contours

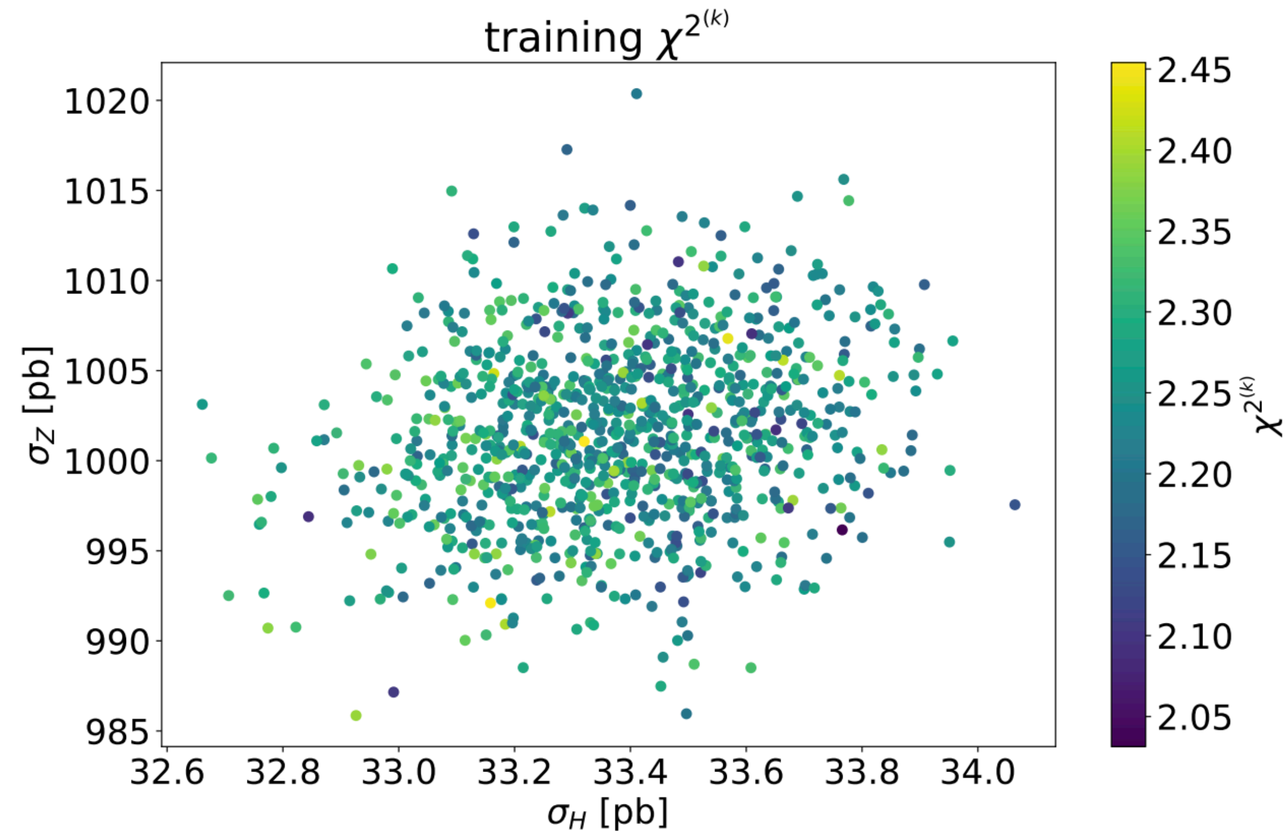
Representative sampling in NNPDF

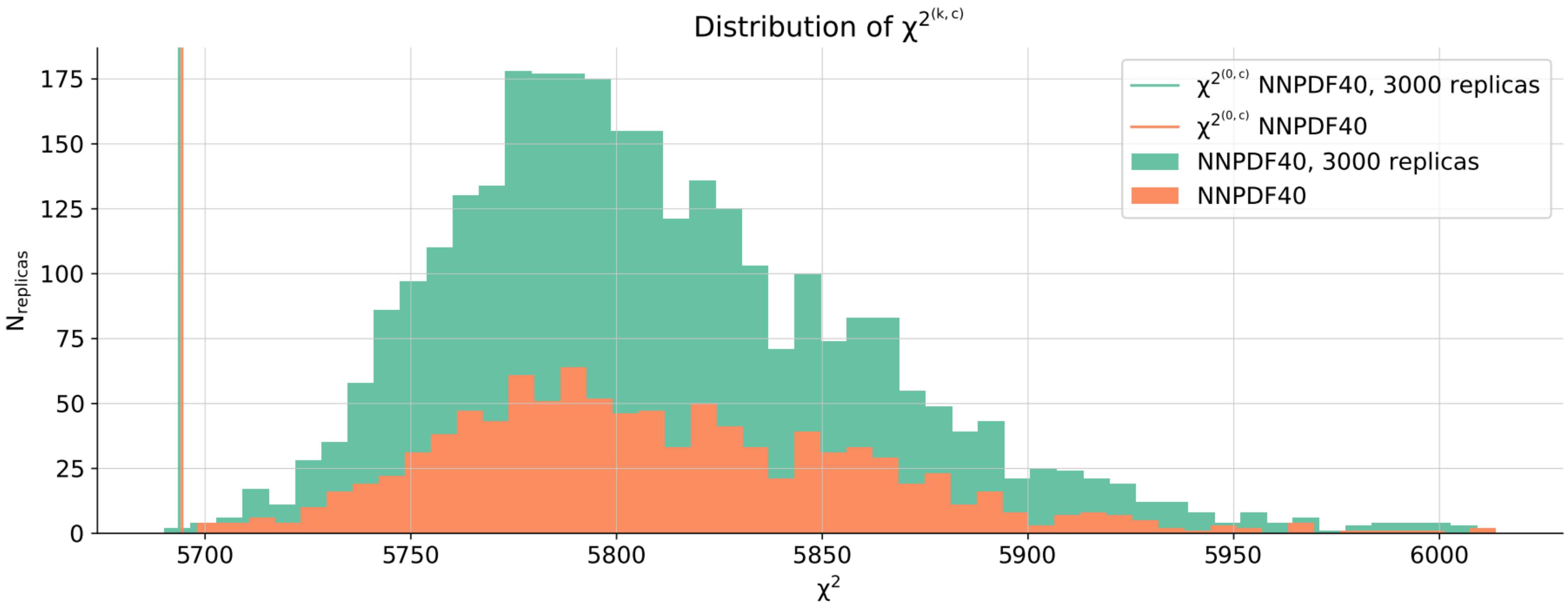


- NNPDF4.0 replicas behave as expected for **representative sampling** e.g. around 50 replicas out of a sample of 1000 fall outside 95% CL contours
- The χ^2 is **not the only measure of the likelihood of a replica**, theory and methodological constraints (e.g. integrability, smoothness) are also accounted for
- For a sufficiently large number of sampled replicas, **solutions with lower χ^2** than the ``central'' (average) replica are guaranteed to be found

Representative sampling in NNPDF



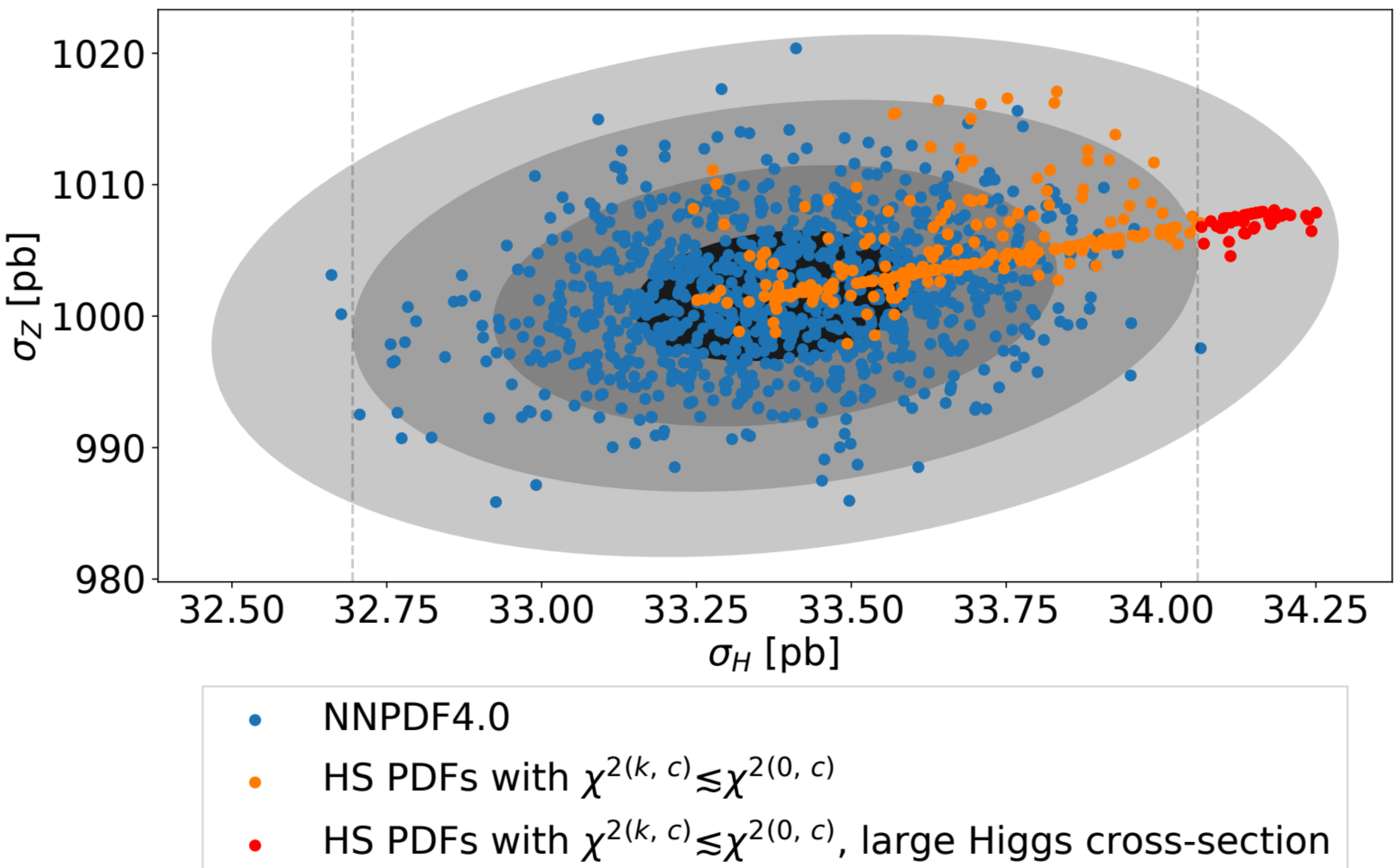


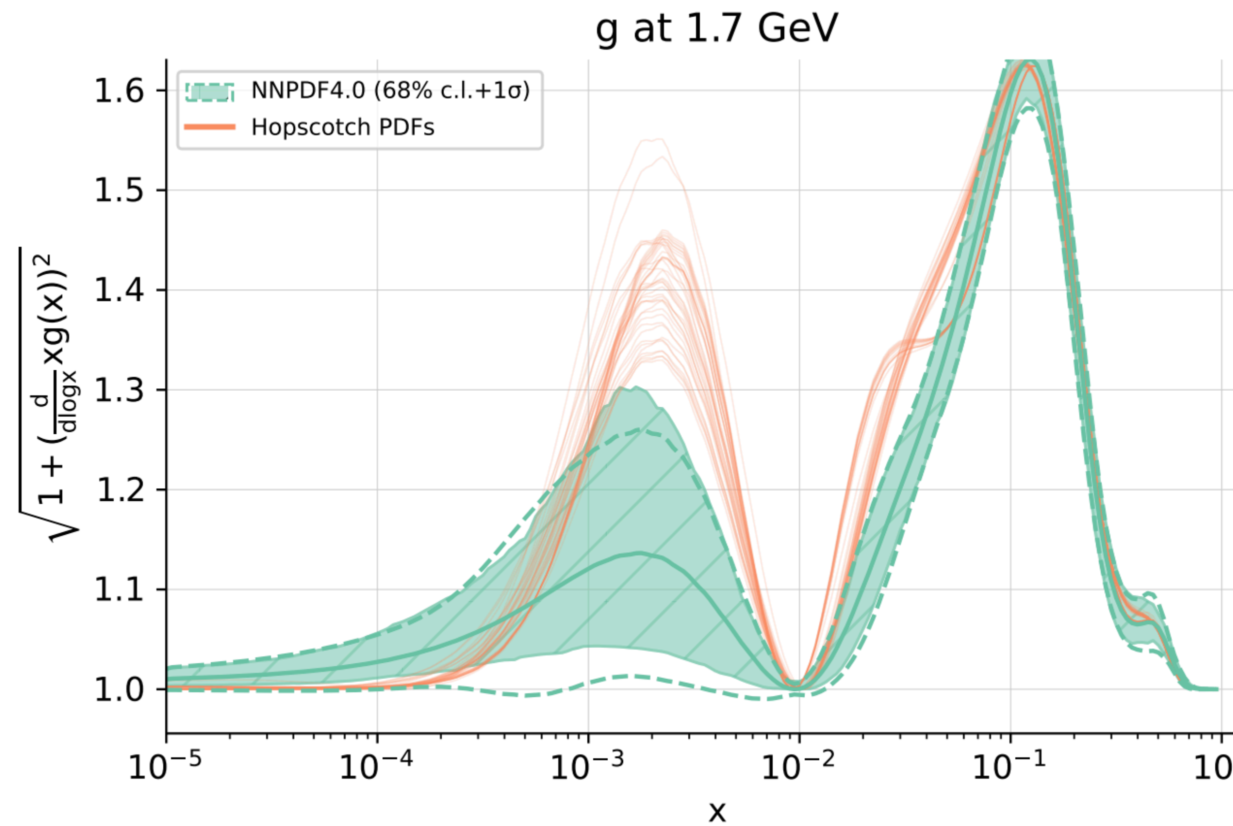


The hopscotch PDFs

CT Hopscotch (HS) PDFs: arXiv:2205.10444

- **Linear combinations of NNPDF4.0 replicas**, some of them with lower χ^2 than the average NNPDF4.0 PDF set, constructed using NNPDF open-source code





- HS PDFs **do not provide representative sampling,** *e.g.* cannot be used to determine PDF errors
- Similar PDFs can be found with the NNPDF methodology, albeit with **very low probability**
- **Kinetic energy** (local measure of non-smoothness) systematically higher in HS PDFs

Large-x extrapolation

- Reliable estimates of **PDF uncertainties at large-*x*** crucial for BSM searches at LHC
- Take the **forward-backward asymmetry** in high-mass neutral current Drell-Yan as case study

$$\frac{d^3\sigma}{dm_{\ell\bar{\ell}}\,dy_{\ell\bar{\ell}}\,d\cos\theta^*} = \frac{\pi\alpha^2}{3m_{\ell\bar{\ell}}s}\left(\underbrace{(1+\cos^2(\theta^*))\sum_q S_q\mathcal{L}_{S,q}(m_{\ell\bar{\ell}},y_{\ell\bar{\ell}})}_{\textit{symmetric in }\cos\theta^*} + \underbrace{\cos\theta^*\sum_q A_q\mathcal{L}_{A,q}(m_{\ell\bar{\ell}},y_{\ell\bar{\ell}})}_{\textit{antisymmetric in }\cos\theta^*}\right)$$

$$\mathcal{L}_{S,q}(m_{\ell\bar{\ell}},y_{\ell\bar{\ell}}) \equiv f_q(x_1,m^2_{\ell\bar{\ell}})f_{\bar{q}}(x_2,m^2_{\ell\bar{\ell}}) + f_q(x_2,m^2_{\ell\bar{\ell}})f_{\bar{q}}(x_1,m^2_{\ell\bar{\ell}})\,,$$
$$\mathcal{L}_{A,q}(m_{\ell\bar{\ell}},y_{\ell\bar{\ell}}) \equiv \mathrm{sign}(y_{\ell\bar{\ell}})\left[f_q(x_1,m^2_{\ell\bar{\ell}})f_{\bar{q}}(x_2,m^2_{\ell\bar{\ell}}) - f_q(x_2,m^2_{\ell\bar{\ell}})f_{\bar{q}}(x_1,m^2_{\ell\bar{\ell}})\right]$$

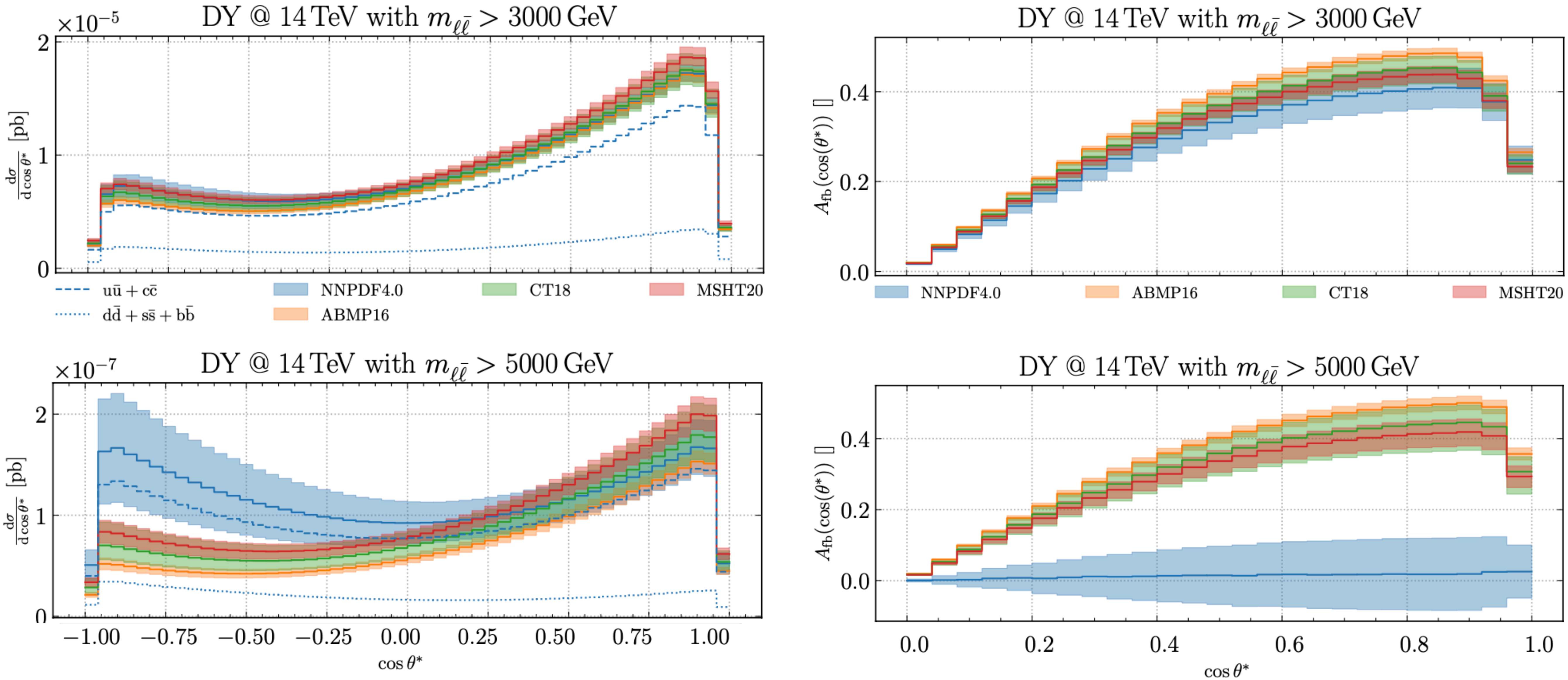
- Relevant for non-resonant BSM searches and for determination of precision SM parameters

$$A_{\rm fb}(\cos\theta^*) \equiv \frac{\frac{d\sigma}{d\cos\theta^*}(\cos\theta^*) - \frac{d\sigma}{d\cos\theta^*}(-\cos\theta^*)}{\frac{d\sigma}{d\cos\theta^*}(\cos\theta^*) + \frac{d\sigma}{d\cos\theta^*}(-\cos\theta^*)}\,,\qquad \cos\theta^* > 0\,,$$

- PDF sets based on fixed-functional forms and NNPDF agree for symmetric (in Collins-Soper angle) distributions, **different results for antisymmetric ones like A_{FB}**

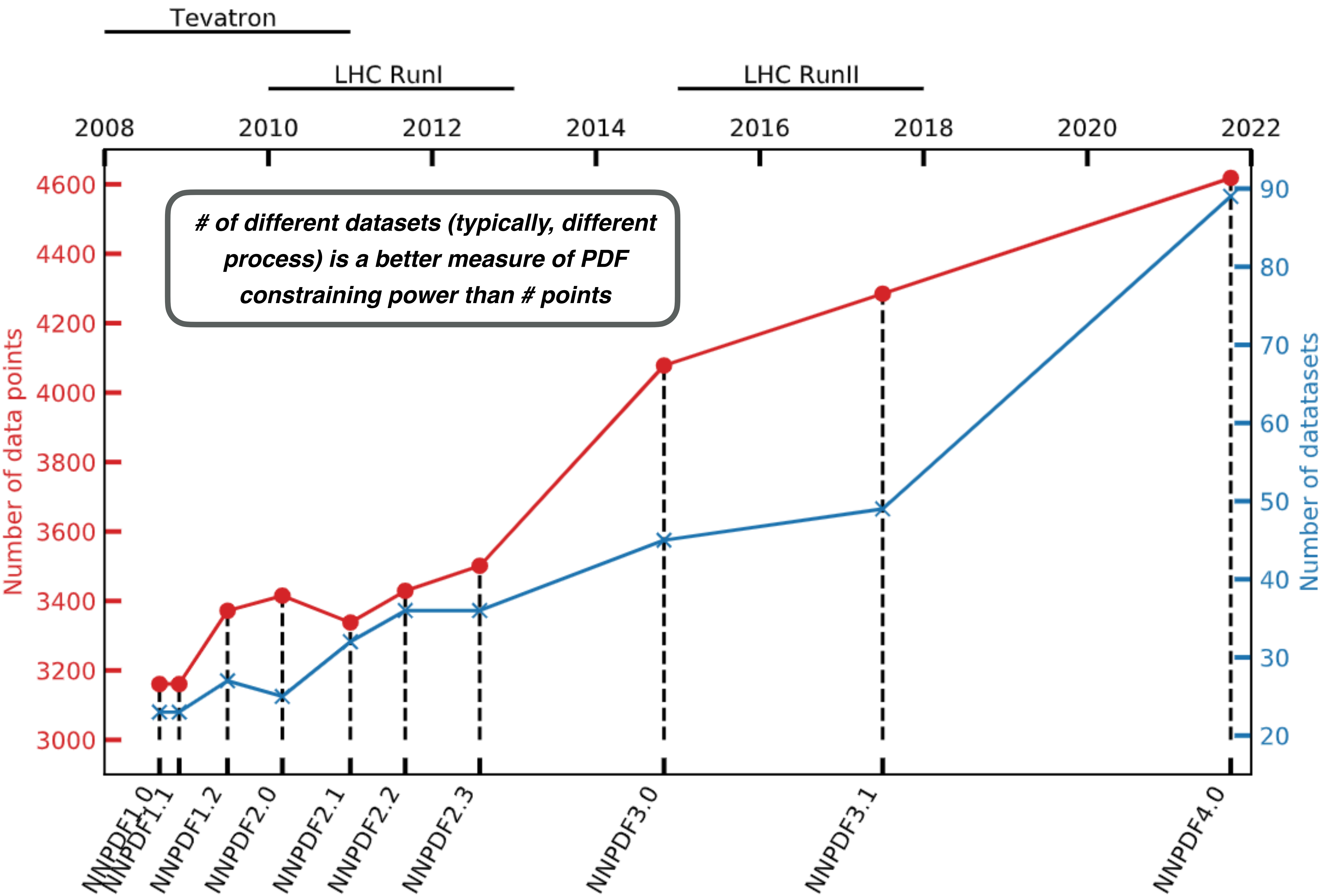
NNPDF, arXiv:2209.08115

Large-x extrapolation

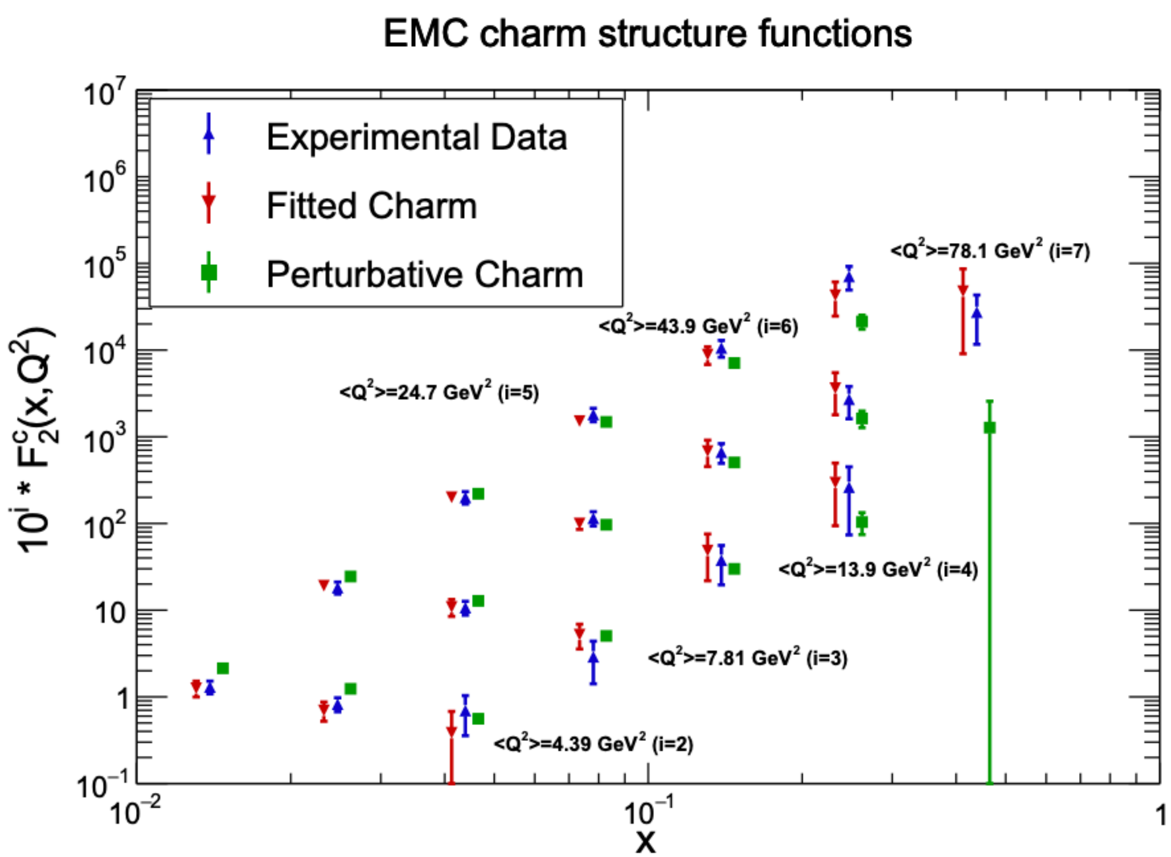


- Extrapolation of CT, MSHT, ABMP determined by **choice of large-*x* functional form**, not the case in NNPDF (verified by computing effective large-*x* exponents)
- The forward-backward asymmetry is hence **not positive-definite in the SM,** unlike what is assumed in some LHC searches
- NNPDF4.0 displays the **largest PDF uncertainties** in extrapolation region

From NNPDF1.0 to NNPDF4.0



Back to the future



- **EMC charm structure functions** (1981): one of original motivations of intrinsic charm
- A purely perturbative charm PDF disfavoured by the data
- A model-independent determination of the charm PDF describes well the EMC data, but **limited statistical significance**