(Intrinsic) Charm in the Proton

Juan Rojo, VU Amsterdam & Nikhef

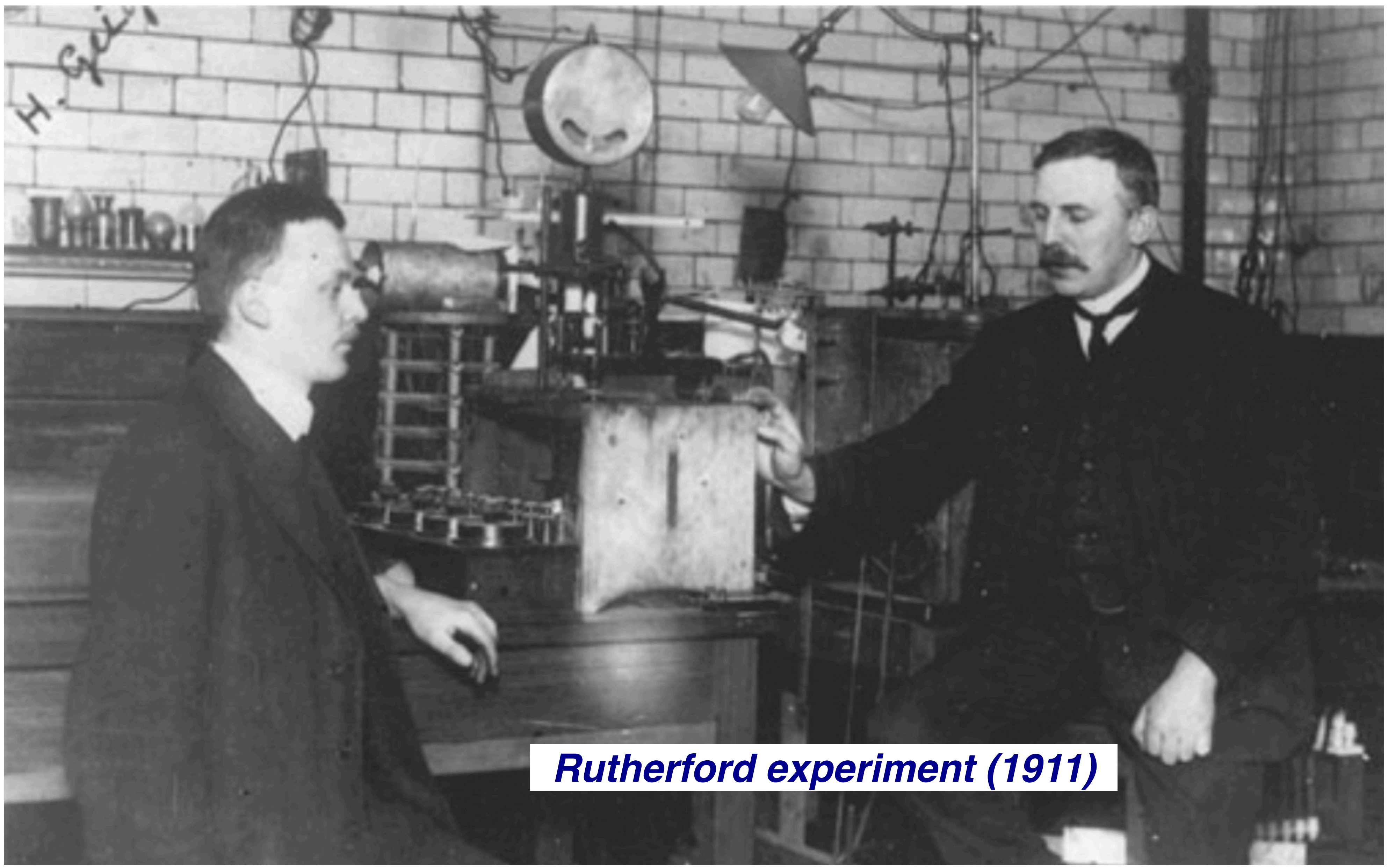
Nikhef Colloquium

22nd April 2022, Amsterdam Science Park

Why Nucleon Structure?

Why Nucleon Structure?

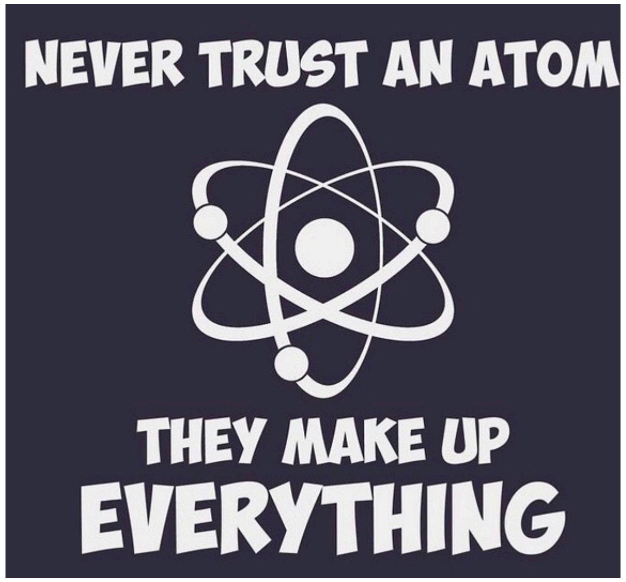
One may claim that the **nucleon is a rather ``boring" particle**, surely after **one century of studying it**, we know everything about the proton?



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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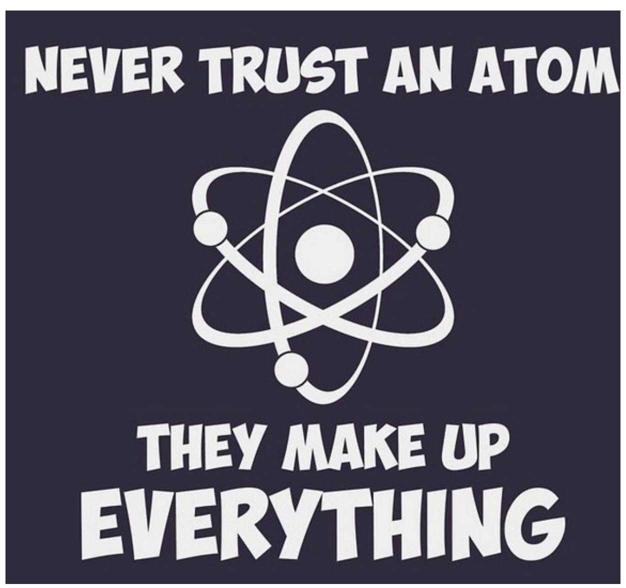

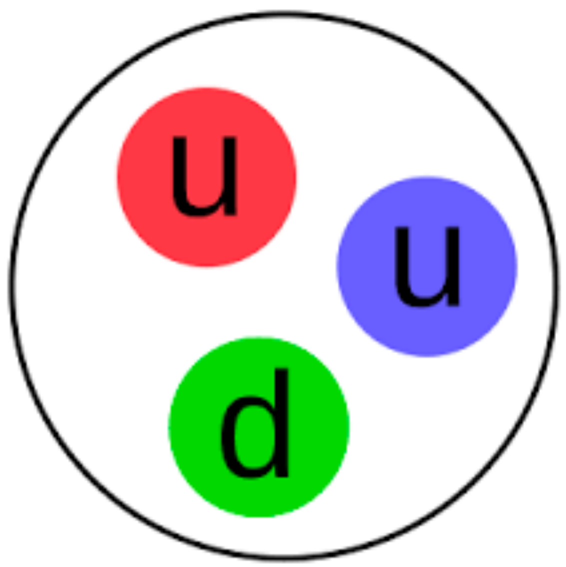

long distances / low energies → *short distances / high energies*

a point particle

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

3 valence quarks

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

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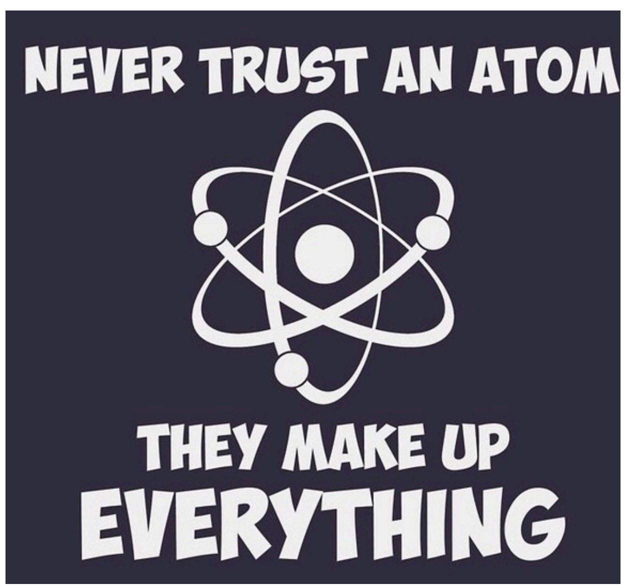

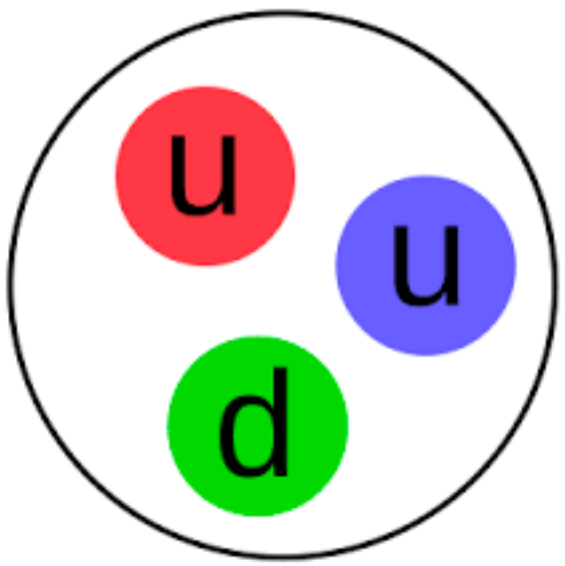

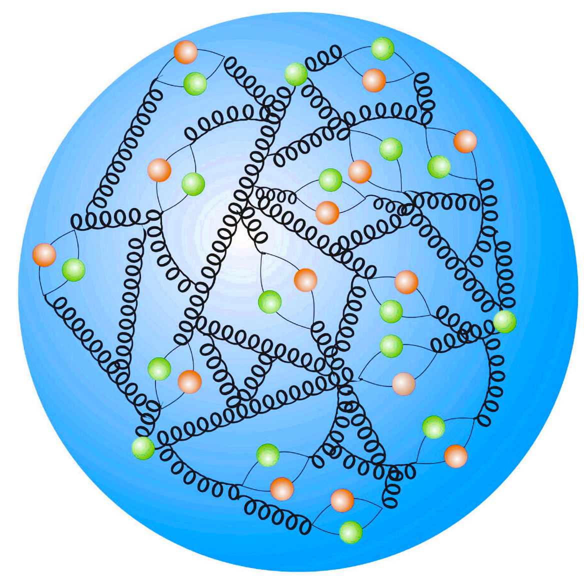

long distances / low energies → *short distances / high energies*

a point particle	3 valence quarks	sea quarks, gluons
$E \ll 1$ GeV	$E \sim$ few GeV	$E \sim 50$ GeV

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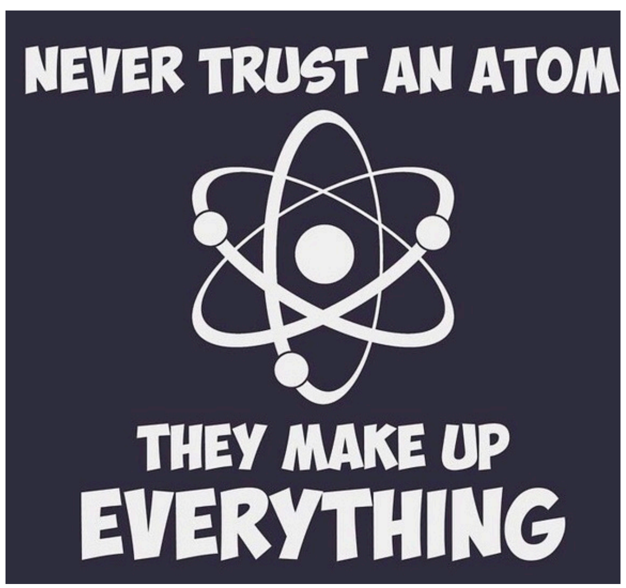
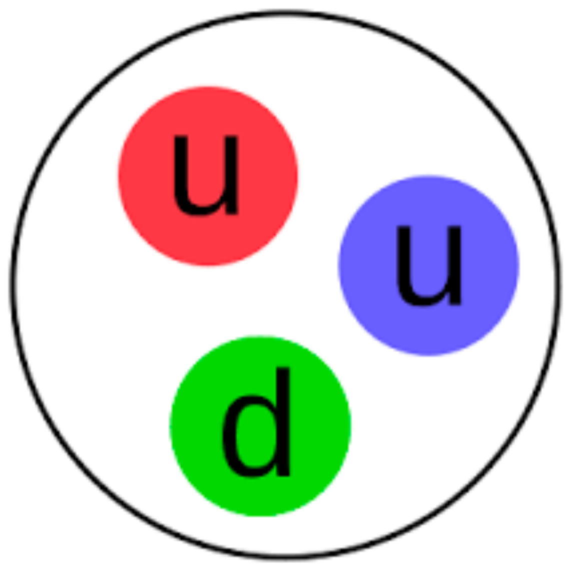
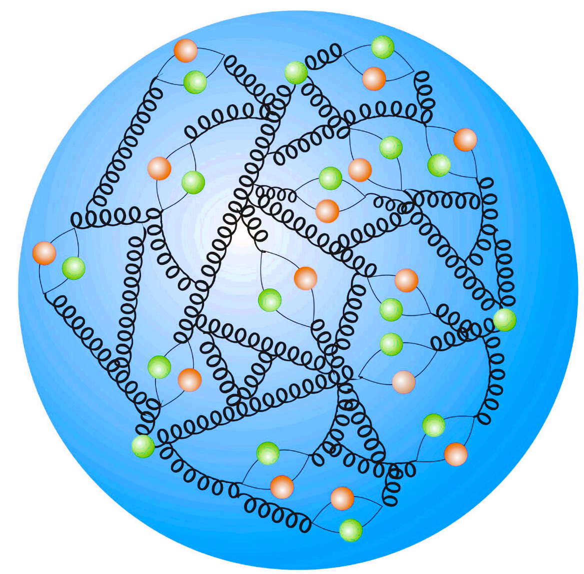
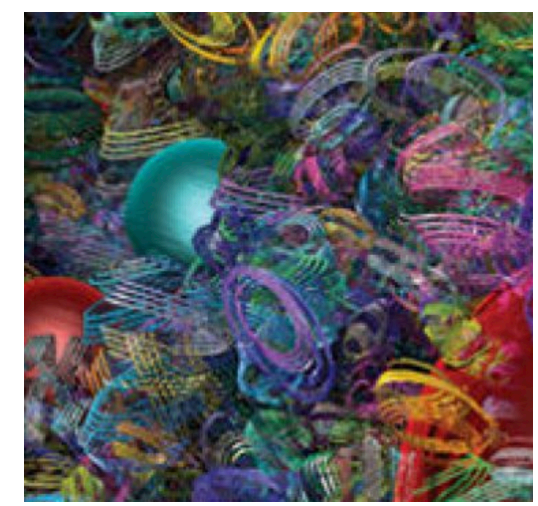








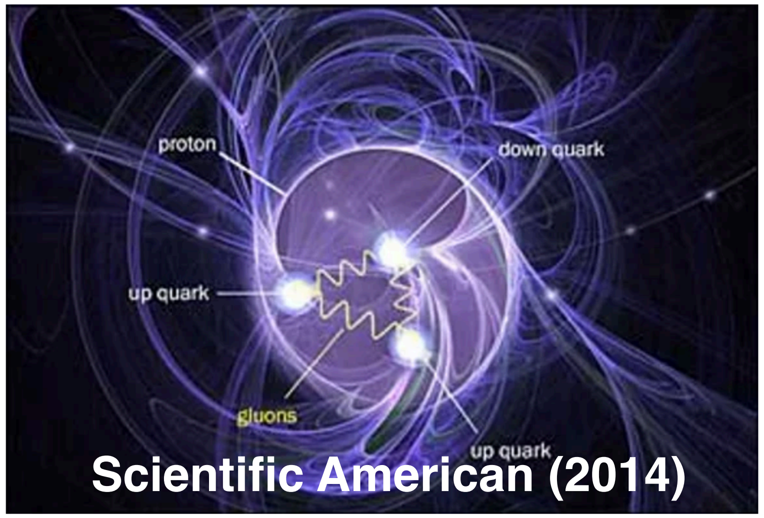
long distances / low energies — *short distances / high energies*

a point particle	3 valence quarks	sea quarks, gluons	heavy quarks, photons, leptons, Higgs bosons
$E \ll 1$ GeV	$E \sim$ few GeV	$E \sim 50$ GeV	$E \sim 1$ TeV

A gateway to unravelling QCD

THE SCIENCES

Proton Spin Mystery Gains a New Clue



Scientific American (2014)

Gluons contribute to proton spin

The proton keeps surprising us as an endless source of **fundamental discoveries!**

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THE SCIENCES

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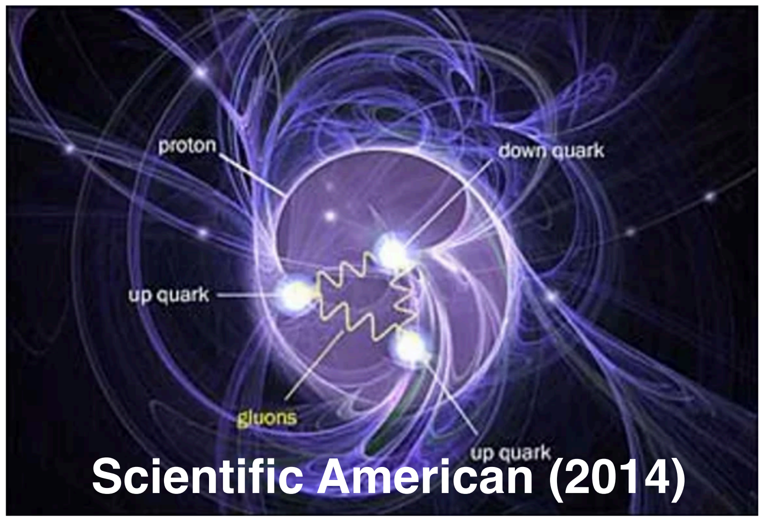

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After 40 years of studying the strong nuclear force, a revelation

This was the year that analysis of data finally backed up a prediction, made in the mid 1970s, of a surprising emergent behaviour in the strong nuclear force

gluon-dominated state of matter

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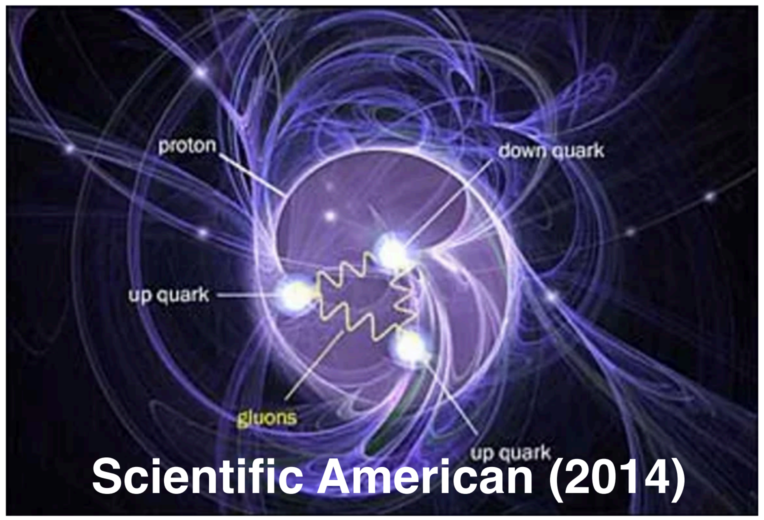

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QUANTUM PHYSICS

Decades-Long Quest Reveals Details of the Proton's Inner Antimatter

27

Twenty years ago, physicists set out to investigate a mysterious asymmetry in the proton's interior. Their results, published today, show how antimatter helps stabilize every atom's core.

Antimatter asymmetry in the proton

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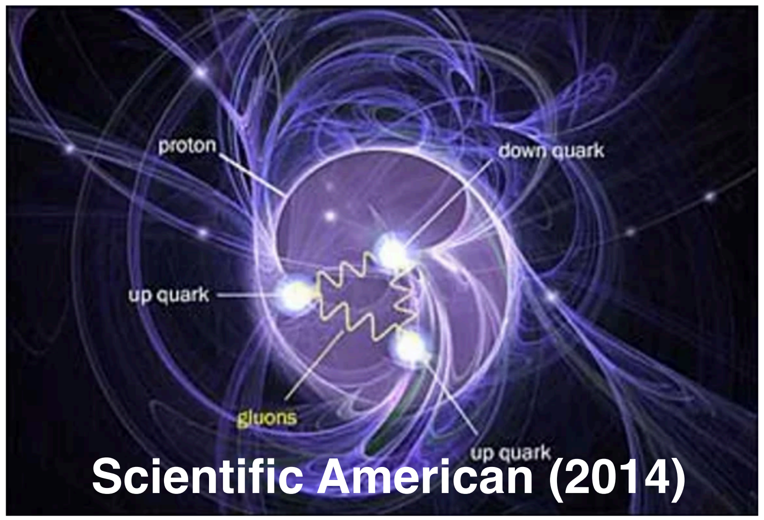

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Intrinsic Charm

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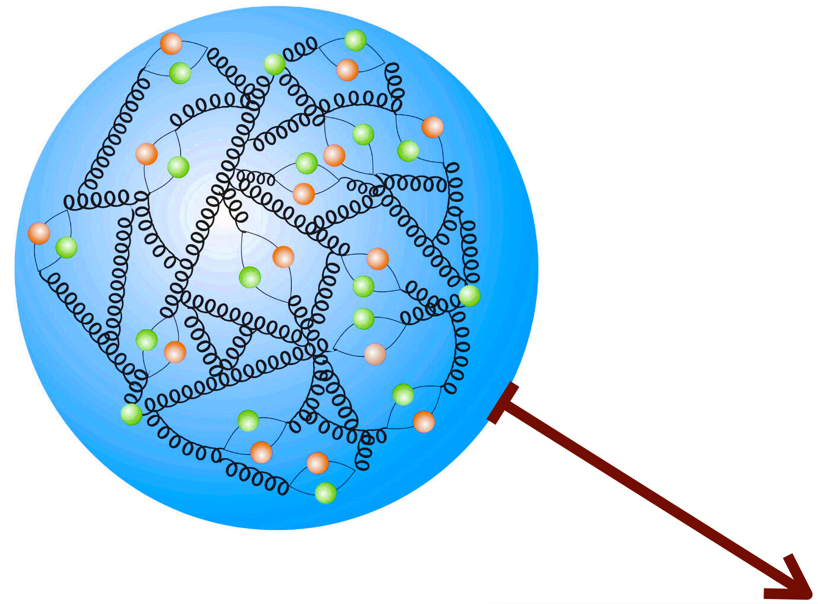

Address fundamental questions about Quantum Chromodynamics

- origin of mass & spin
- **heavy quark** & **antimatter content**
- 3D imaging
- gluon-dominated matter
- **nuclear modifications**
- Interplay with BSM e.g. via **SMEFT PDFs**

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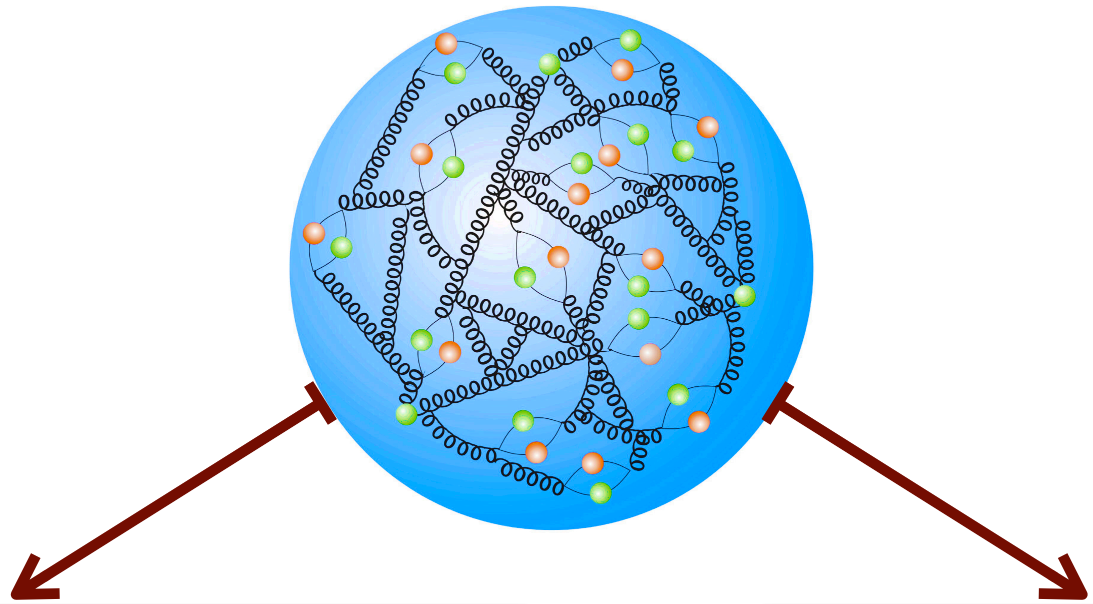

Key component of predictions for particle, nuclear, and astro-particle experiments

- **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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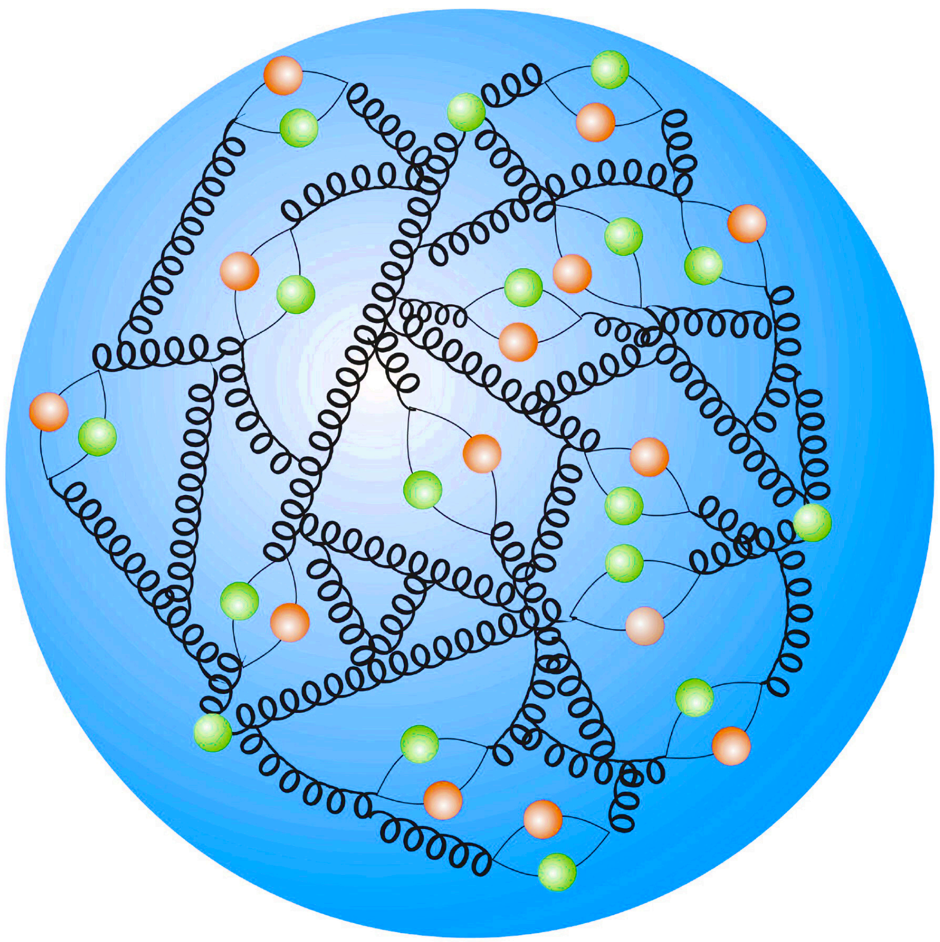
Parton Distributions

Parton Distributions

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



Parton Distribution Functions (PDFs)

↓

Determine from **data:**

Global QCD analysis

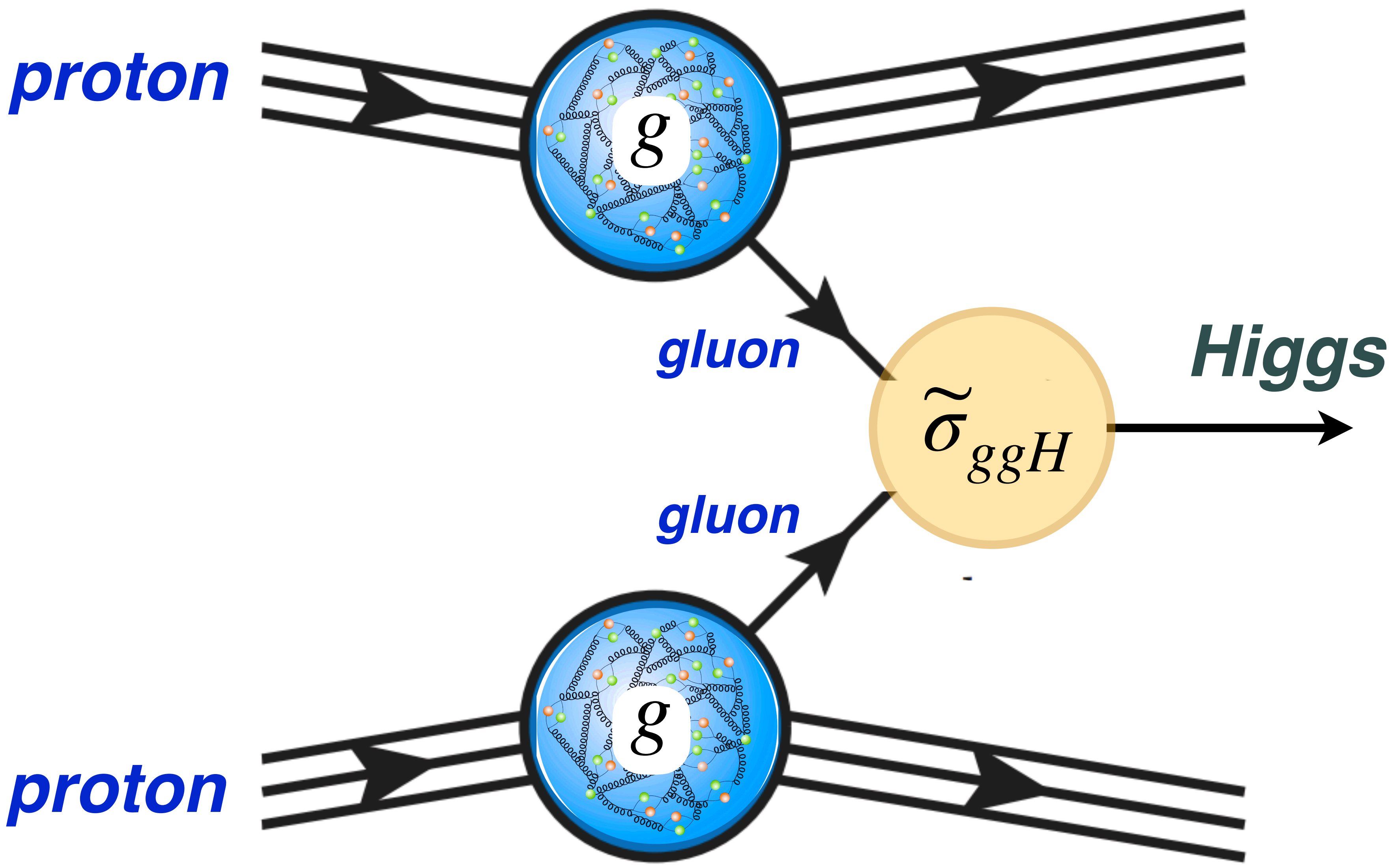
Also important recent results from lattice QCD!

What do we need to extract PDFs from data?

Parton Distributions

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

Parton Distributions



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

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

$$g(x, Q)$$

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

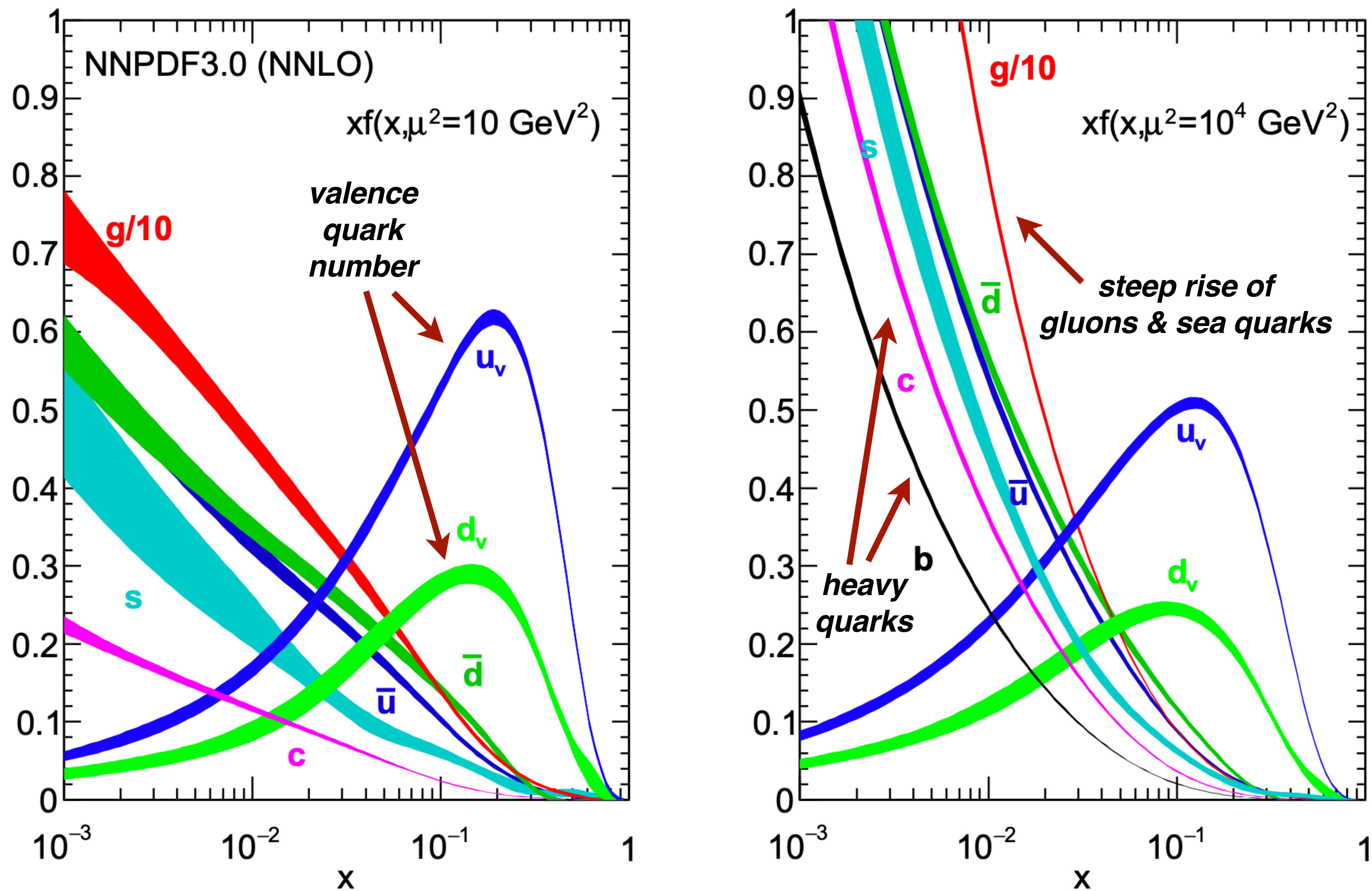
Energy of hard-scattering reaction**:** inverse of resolution length

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*

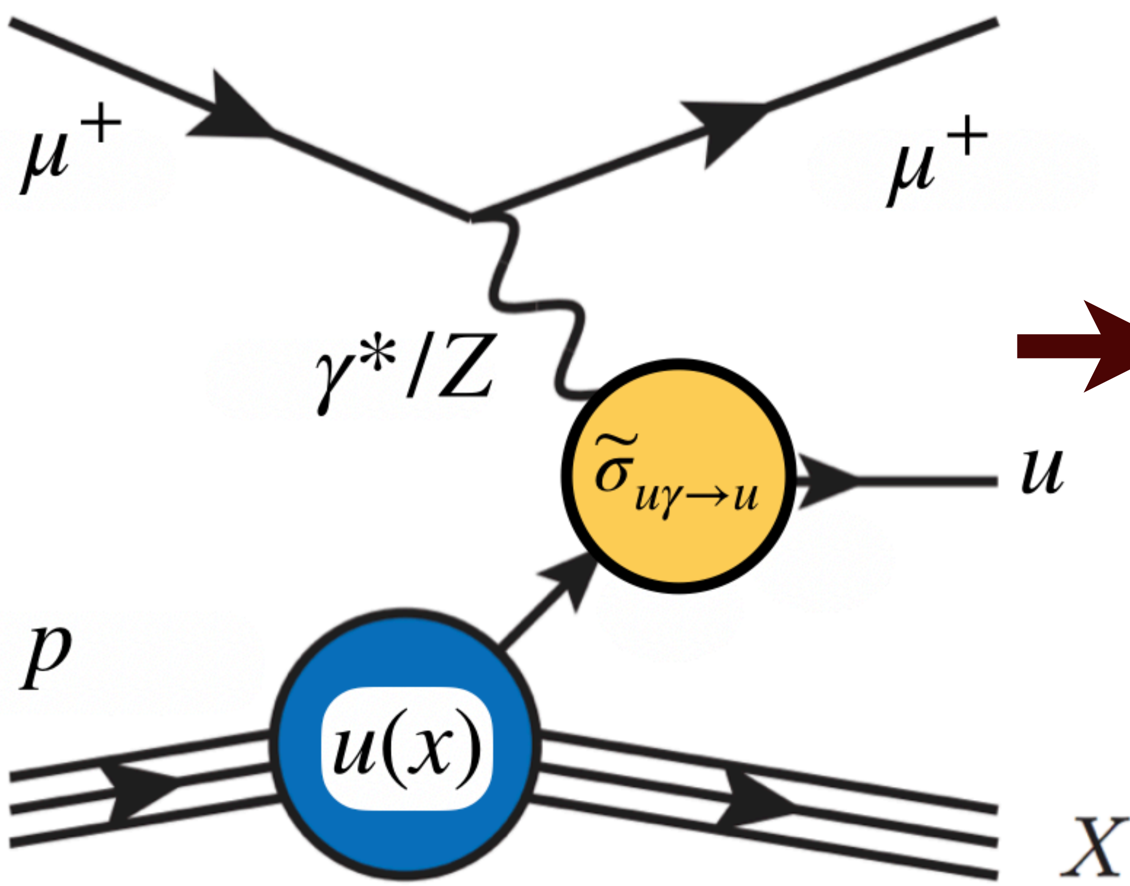
A proton structure snapshop

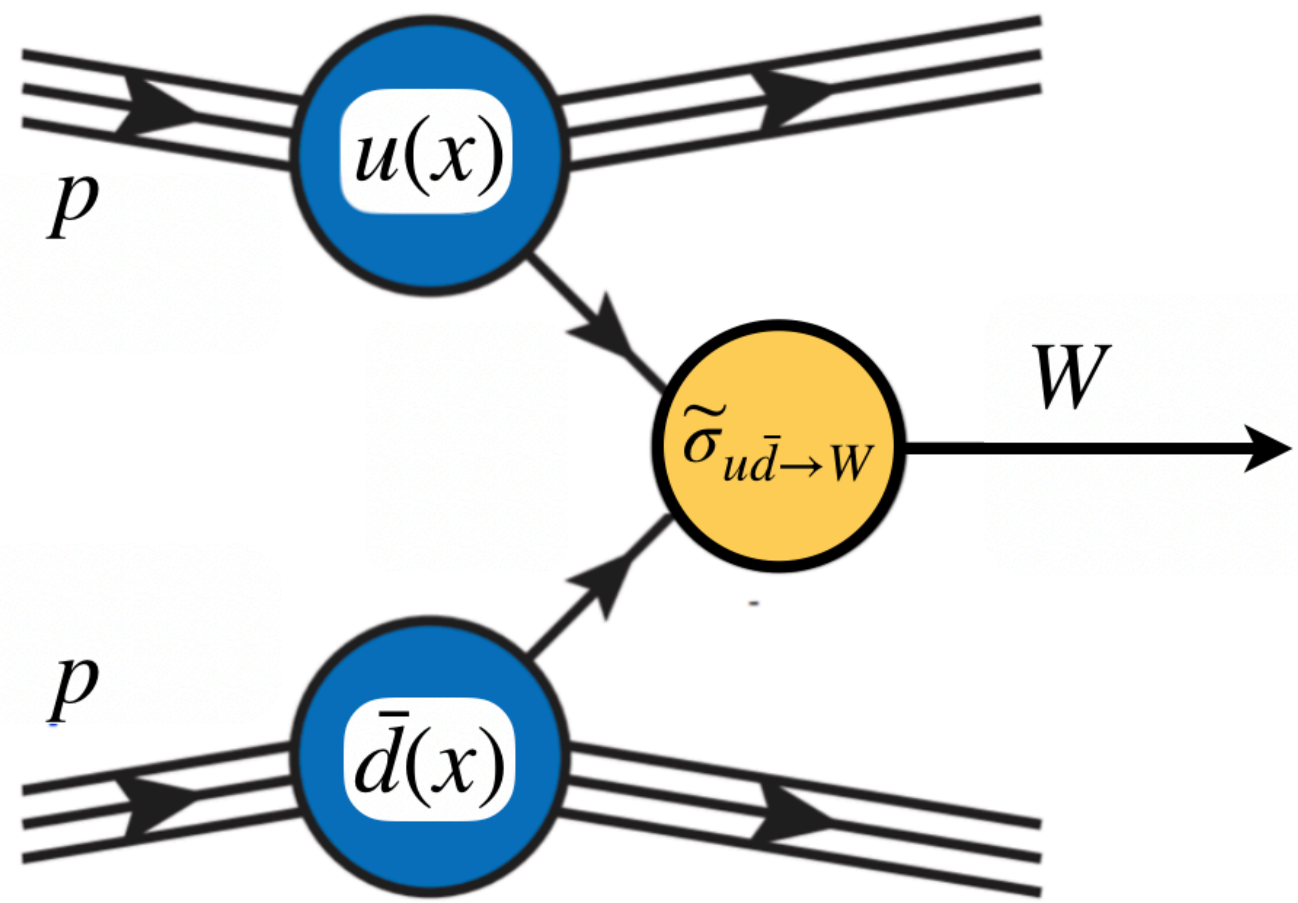


The global QCD analysis paradigm

QCD factorisation theorems**: PDF universality**

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



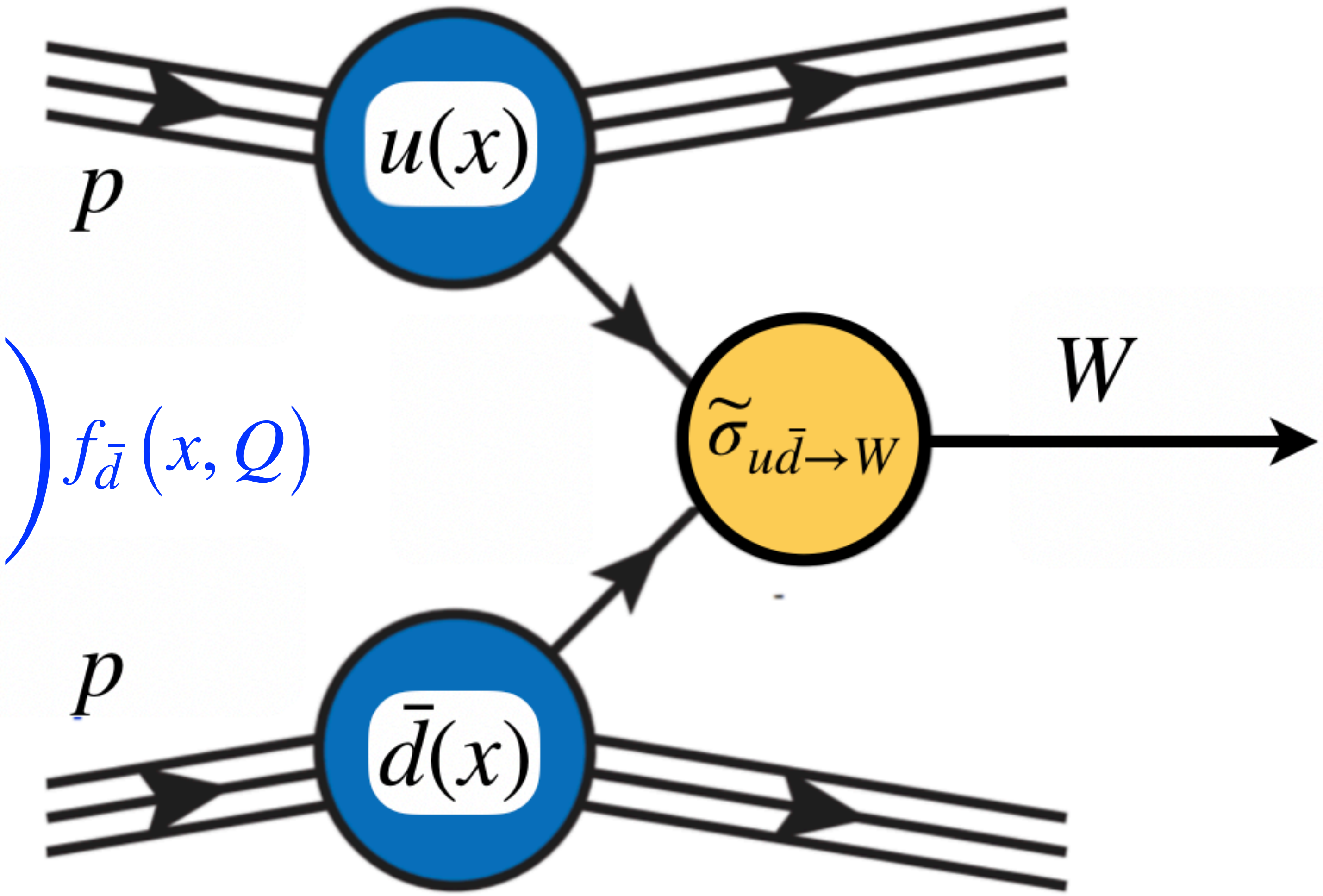


*Determine PDFs from **deep-inelastic scattering**…*

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

The global QCD analysis paradigm

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



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

Using leading-order kinematics:

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

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

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 log-likelihood maximisation

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

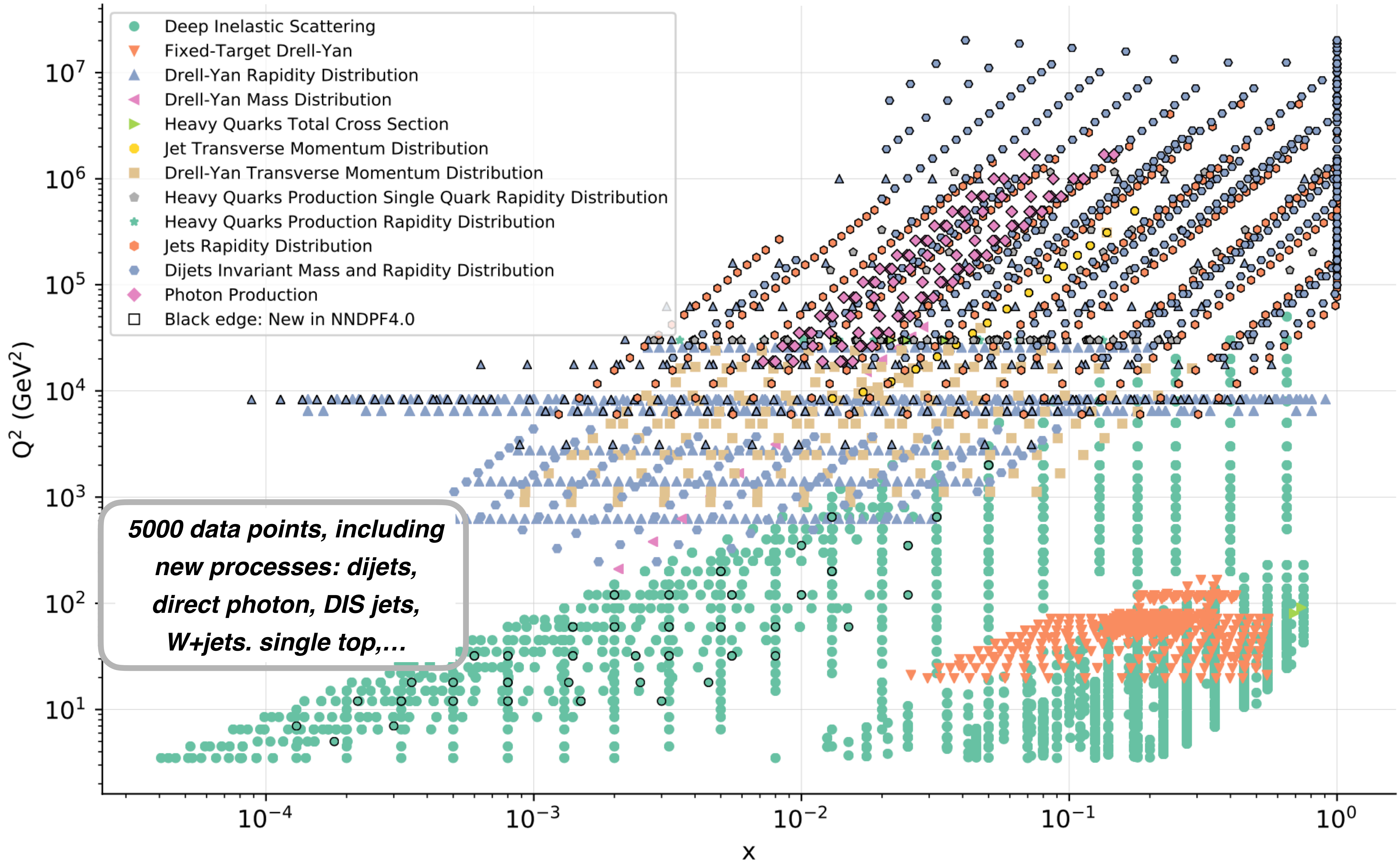
☑ Estimate the associated **uncertainties**

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

The NNPDF4.0 Global PDF Determination

NNPDF Collaboration, arXiv:2109.02653

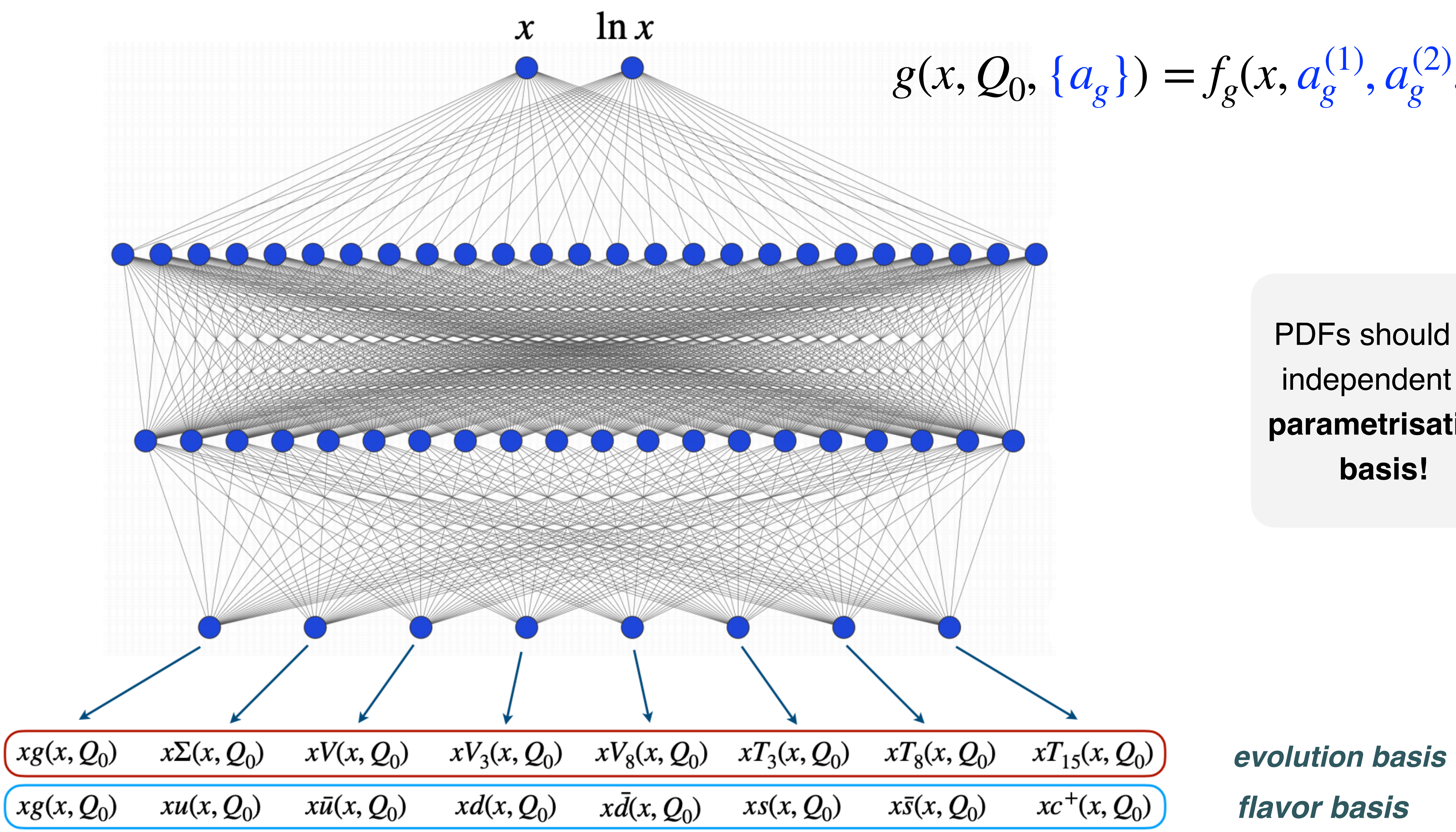
The NNPDF4.0 dataset



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

Fitting methodology

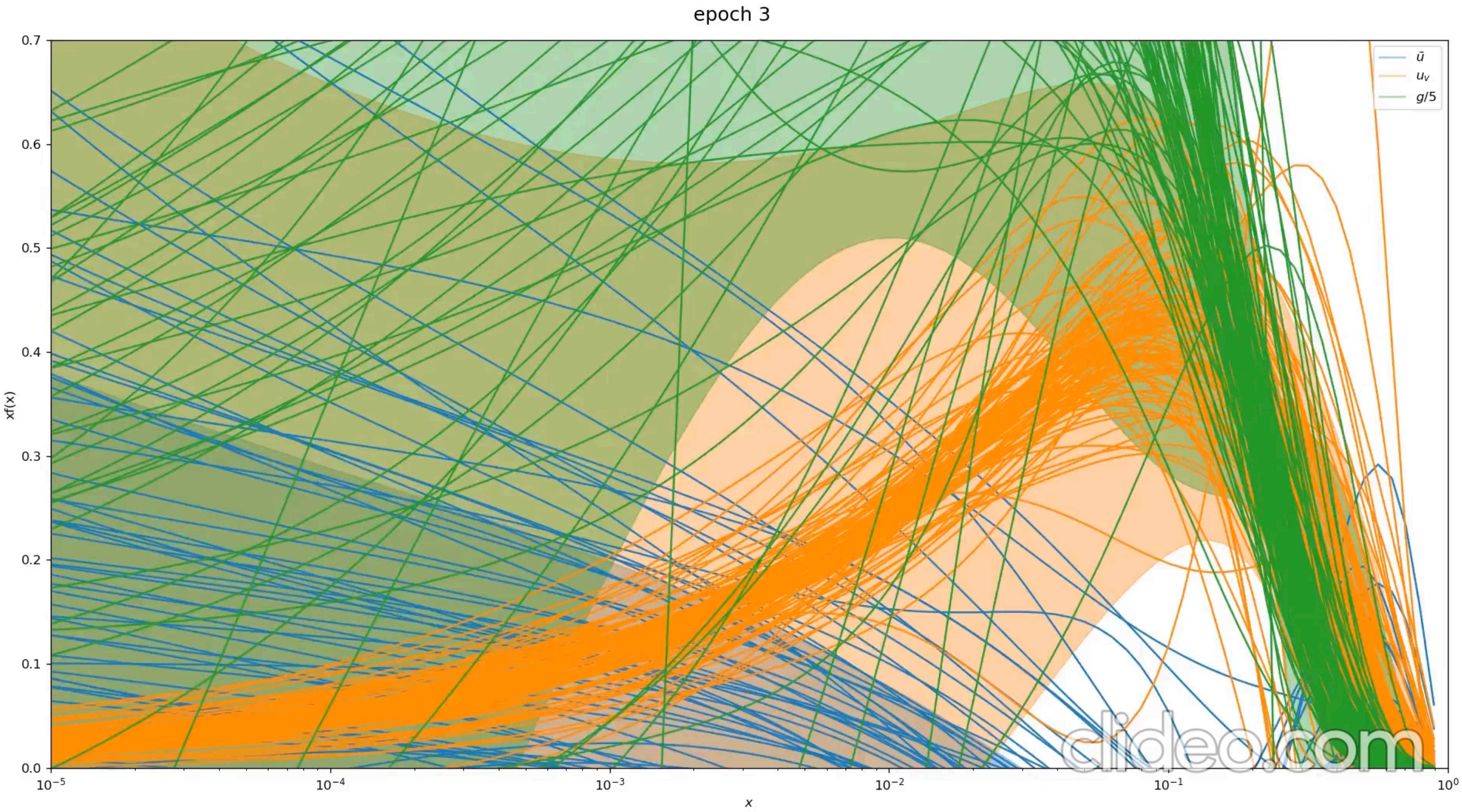
- Model-independent PDF parametrisation with neural networks as **universal unbiased interpolants**
- **Stochastic Gradient Descent** via TensorFlow for neural network training
- Automated model **hyperparameter optimisation:** NN architecture, minimiser, learning rates …
- Validation with **future tests**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



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

PDFs should be independent of **parametrisation basis!**

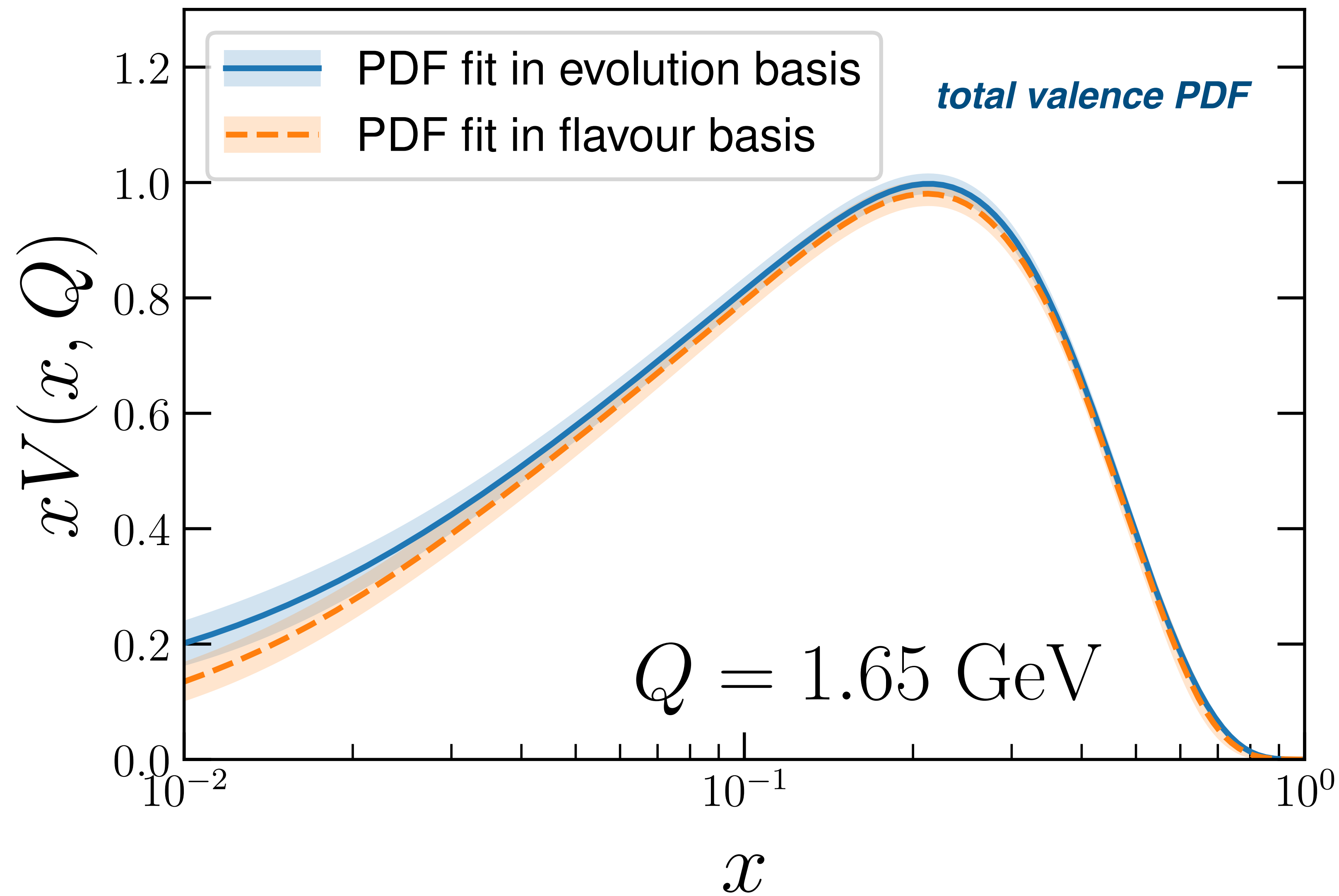
Fitting methodology



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

Parametrisation basis independence

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



Radically 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:

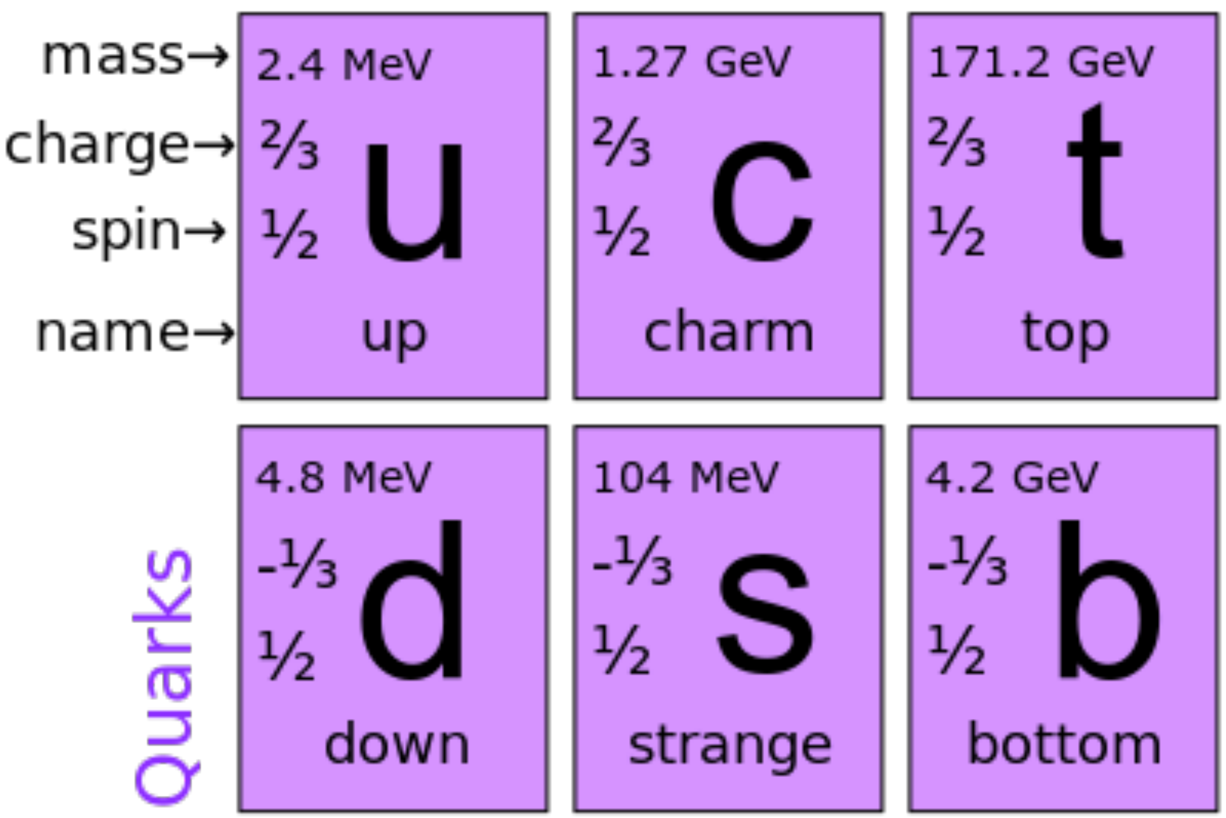
$$xV(x, Q_0) \propto \left(\mathrm{NN}_u(x) - \mathrm{NN}_{\bar{u}}(x) + \mathrm{NN}_d(x) - \mathrm{NN}_{\bar{d}}(x) + \mathrm{NN}_s(x) - \mathrm{NN}_{\bar{s}}(x)\right)$$

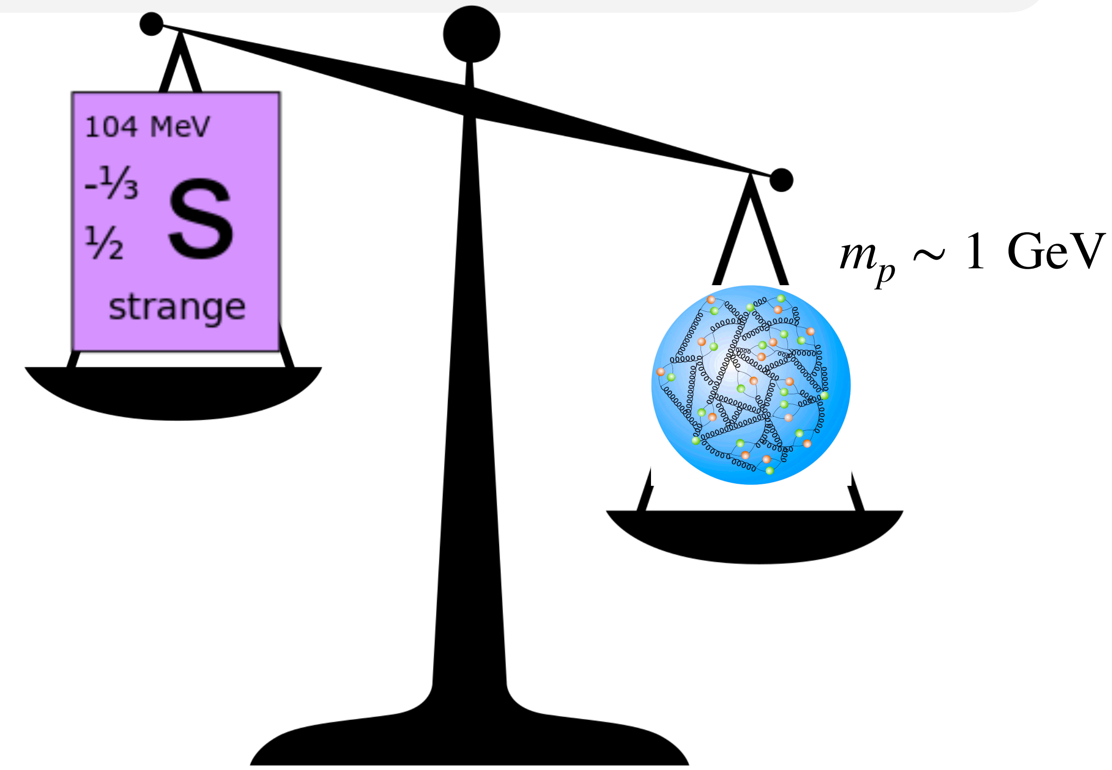
Evidence for intrinsic charm in the proton

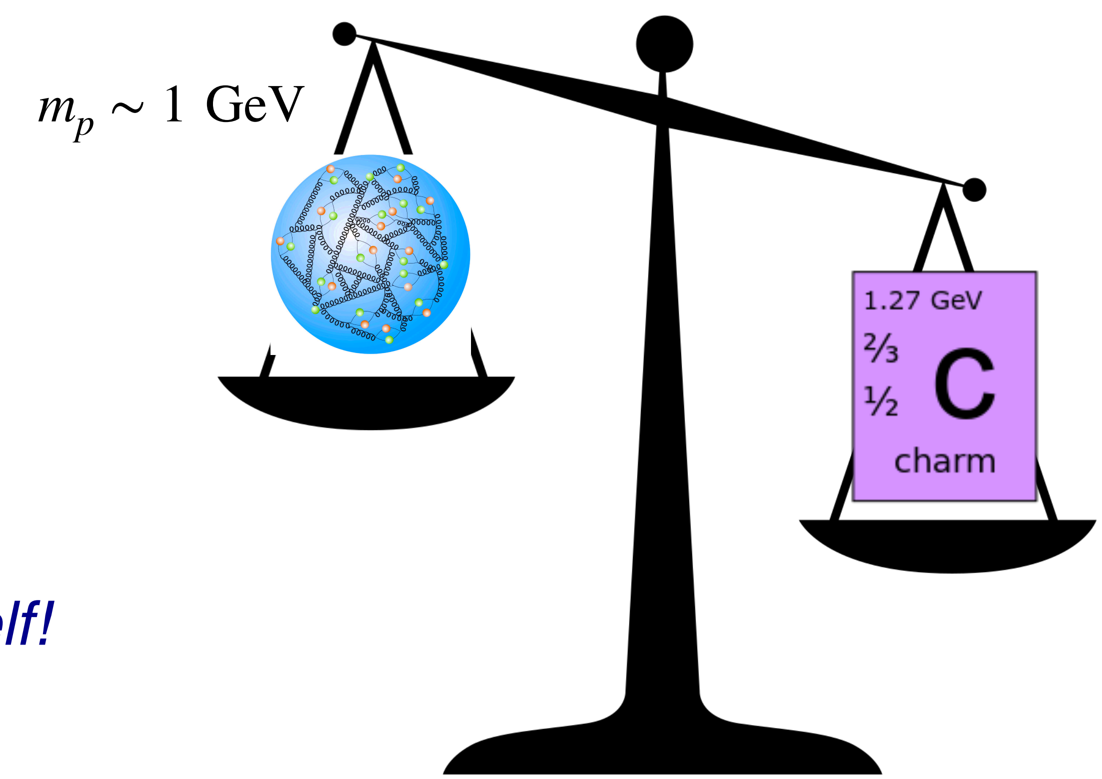
R. D. Ball , A. Candido , J. Cruz-Martinez , S. Forte , T. Giani , F. Hekhorn , K. Kudashkin , G. Magni, ***J. Rojo****,* ***``Charm in the Proton”****, under journal review*

The 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

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

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

3FNS charm — *4FNS charm* — *4FNS gluon*

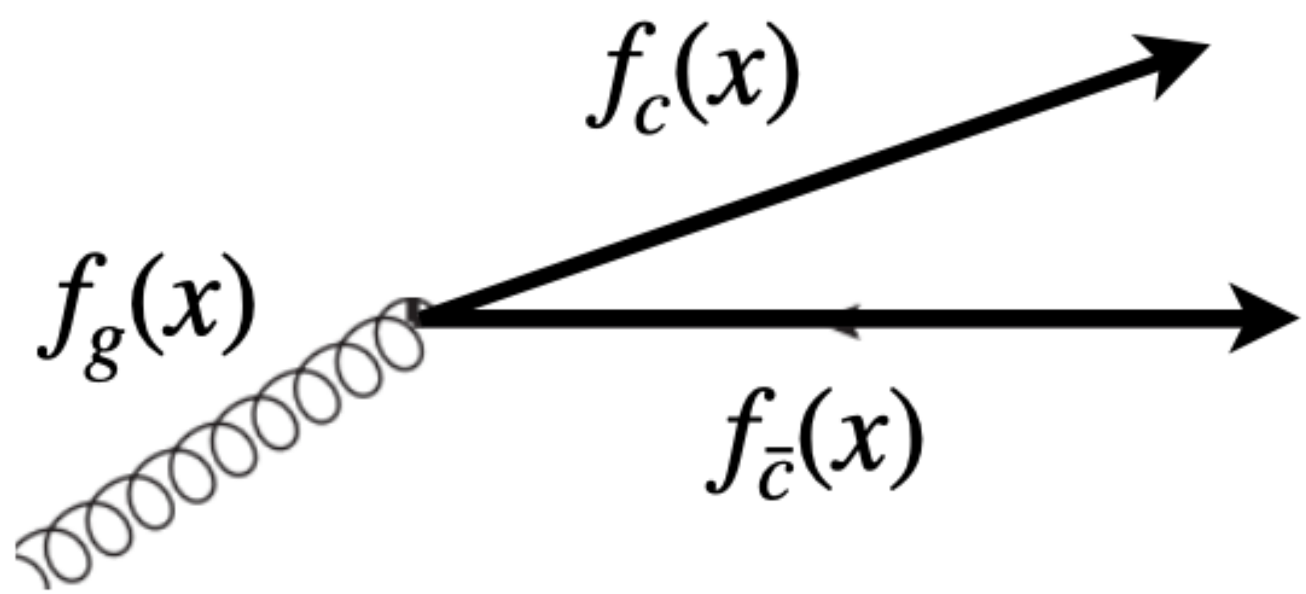
4 flavour scheme, $Q > m_c$

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

↕ ↕

3 flavour scheme, $Q < m_c$

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



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

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

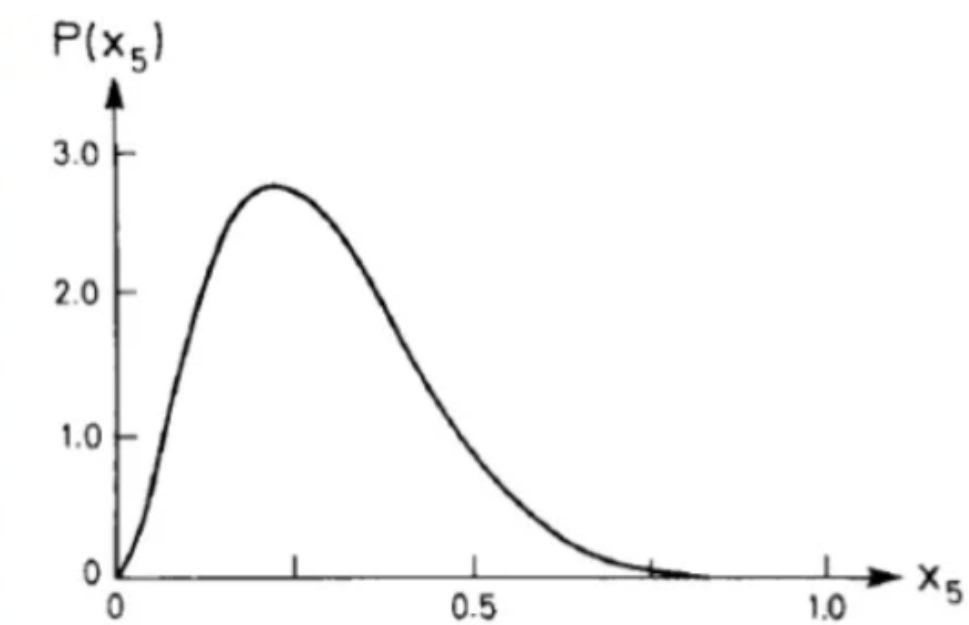
THE INTRINSIC CHARM OF THE PROTON

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



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

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

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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?**

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

4FNS Charm PDF parametrised at Q_0

- Deep-learning parametrisation
- Monte Carlo representation of uncertainties

$Q_0 =$ 1.65 GeV

Disentangling intrinsic charm

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

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↑ **QCD evolution**

starting point: NNPDF 4.0 methodology

$Q_0 =$ 1.65 GeV

4FNS Charm PDF parametrised at Q_0

- Deep-learning parametrisation
- Monte Carlo representation of uncertainties

↓ **QCD evolution**

subtract perturbative component

4FNS to 3FNS transformation

NNLO or N^{3}LO matching conditions

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

EKO — Evolution Kernel Operators

Intrinsic (3FNS) Charm

- Scale-independent
- PDF and MHO uncertainties

4FNS to 3FNS transformation

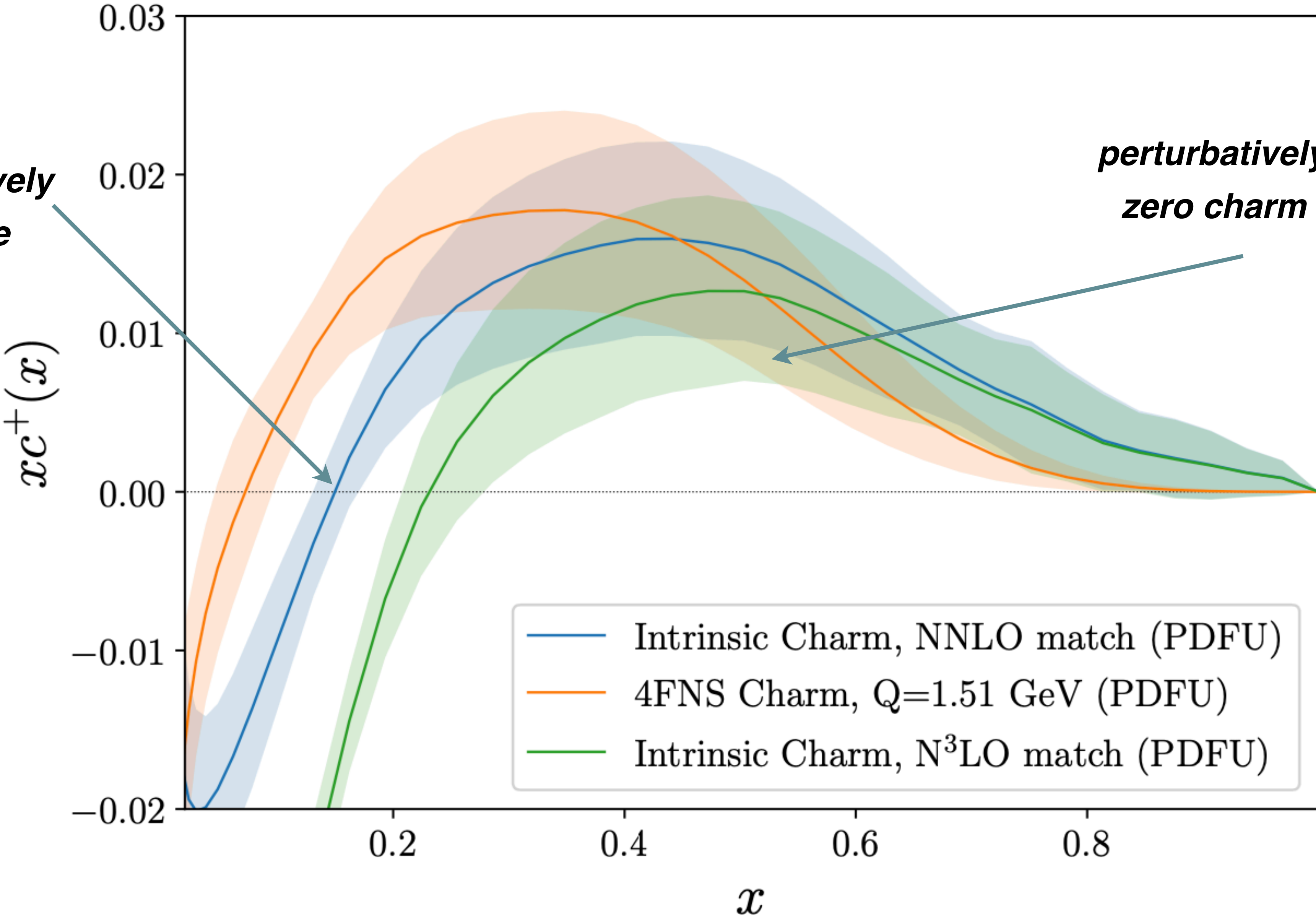
$$\mathbf{f}^{(n_f+1)}(Q_1^2) = \left[\mathbf{E}^{(n_f+1)}(Q_1^2 \leftarrow Q_h^2)\mathbf{A}^{(n_f)}(Q_h^2)\mathbf{E}^{(n_f)}(Q_h^2 \leftarrow Q_0^2)\right] \otimes \mathbf{f}^{(n_f)}(Q_0^2)$$

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

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

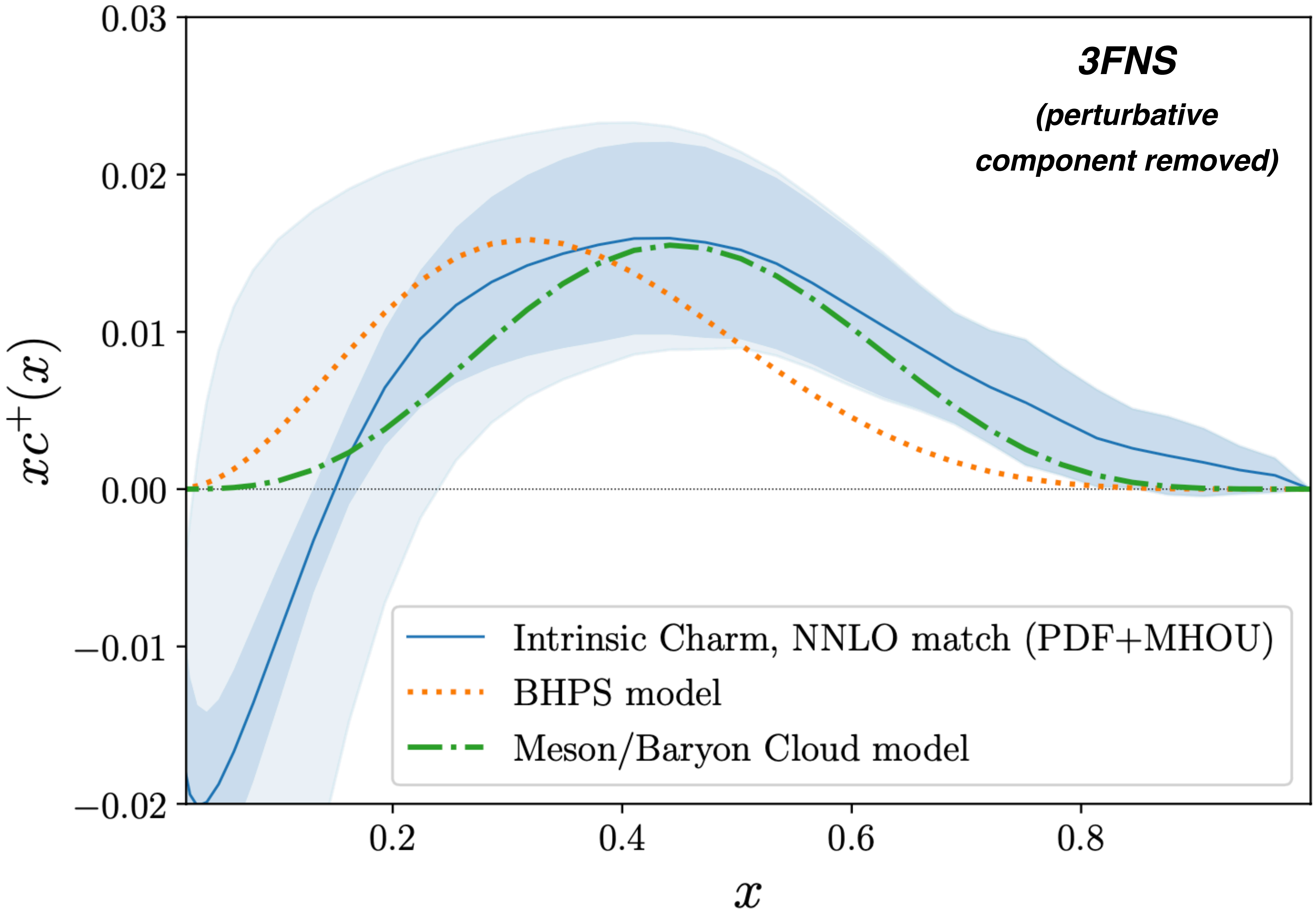
NNLO | **NNLO** | **N3LO** | **NNLO**

perturbatively unstable



perturbatively stable, non-zero charm in the 3FNS

Intrinsic charm!

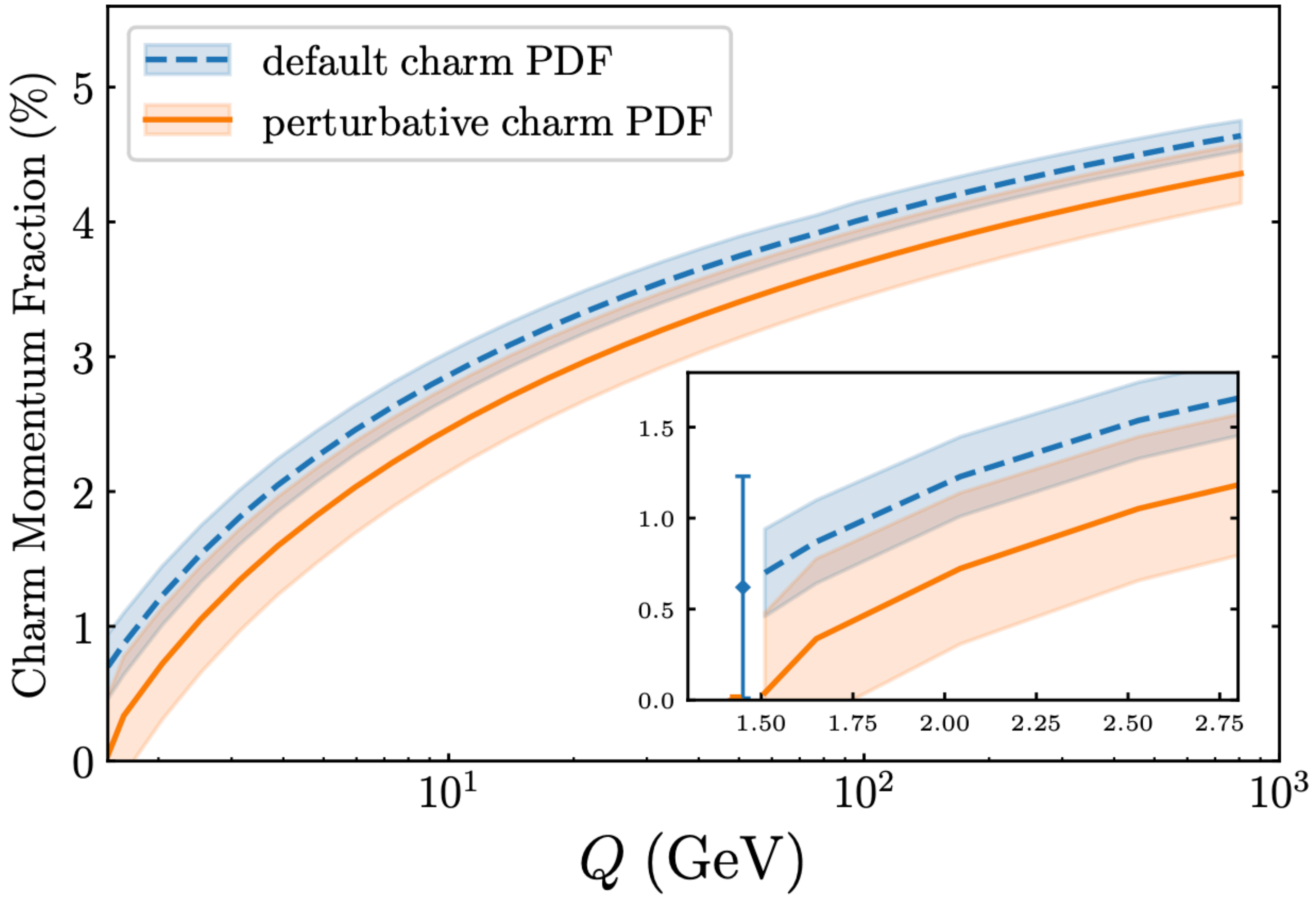


The 3FNS charm PDF displays **non-zero component** peaked at large-*x* **(3σ local significance)** identified with **intrinsic charm**

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

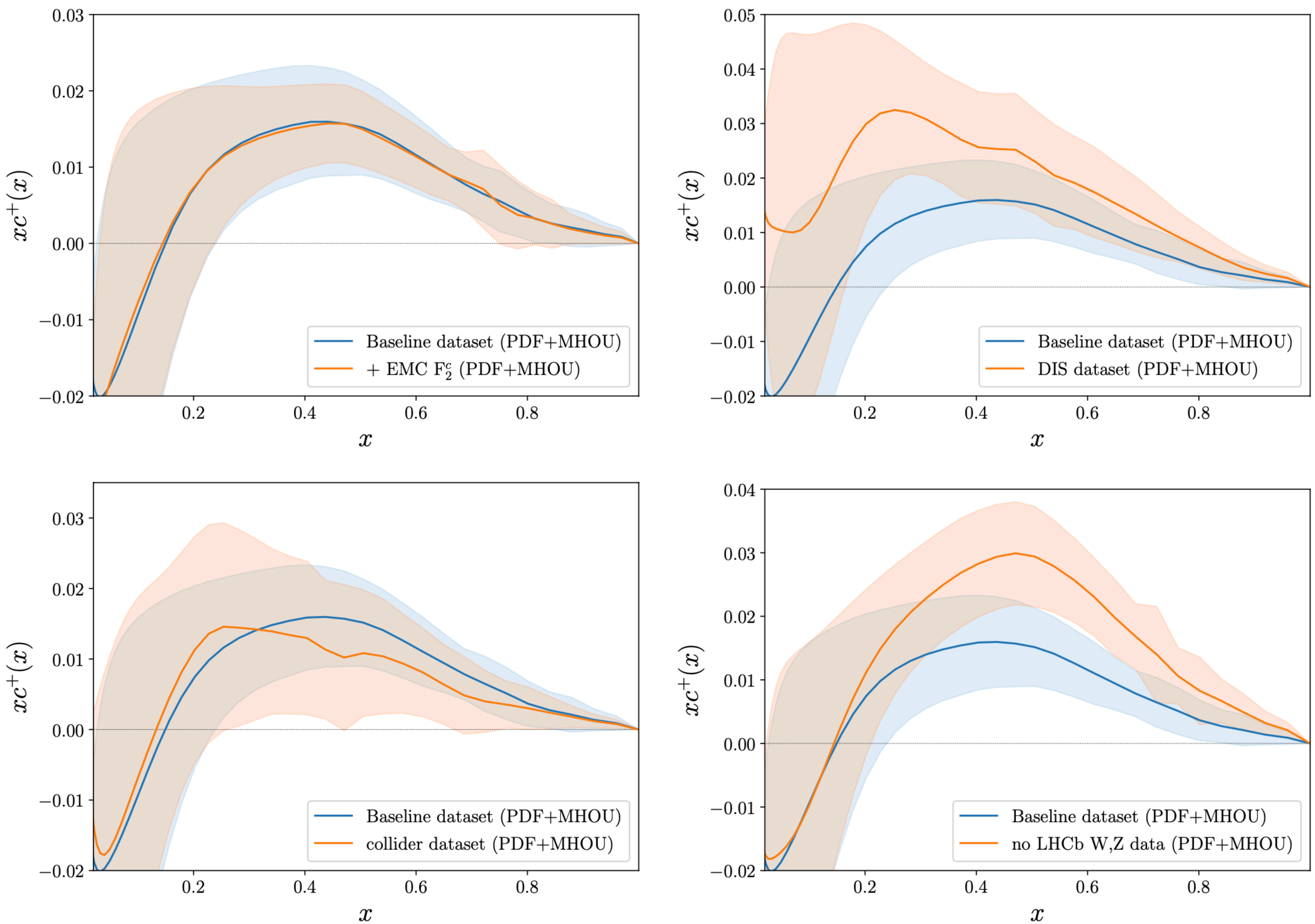
The charm momentum fraction

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

Dataset dependence

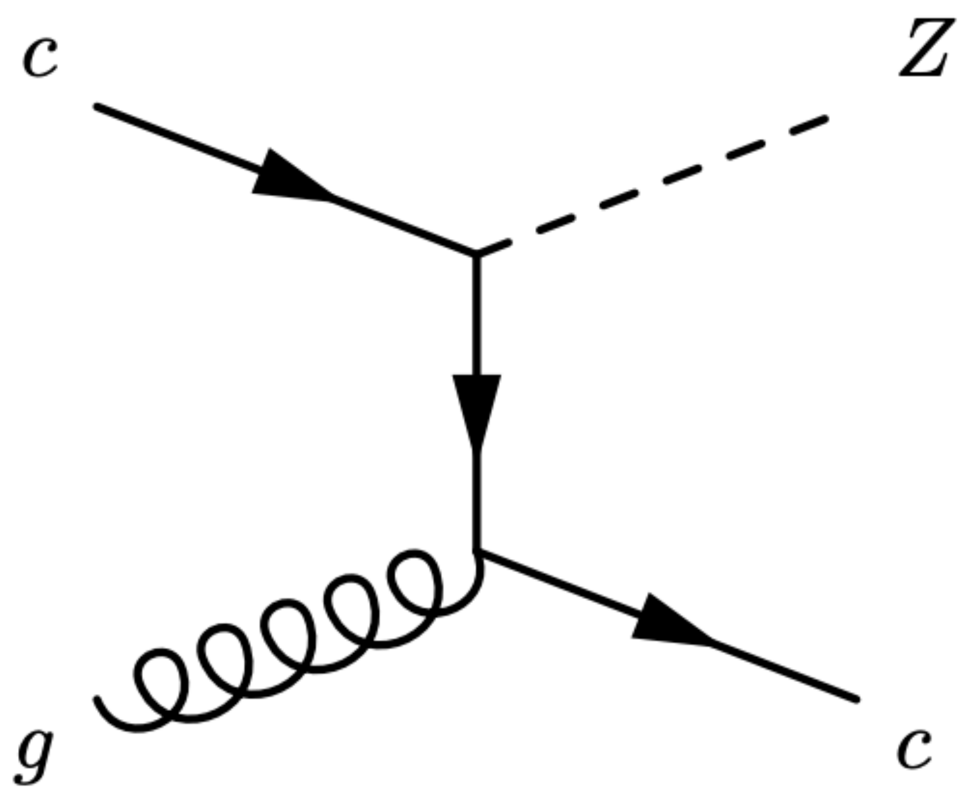


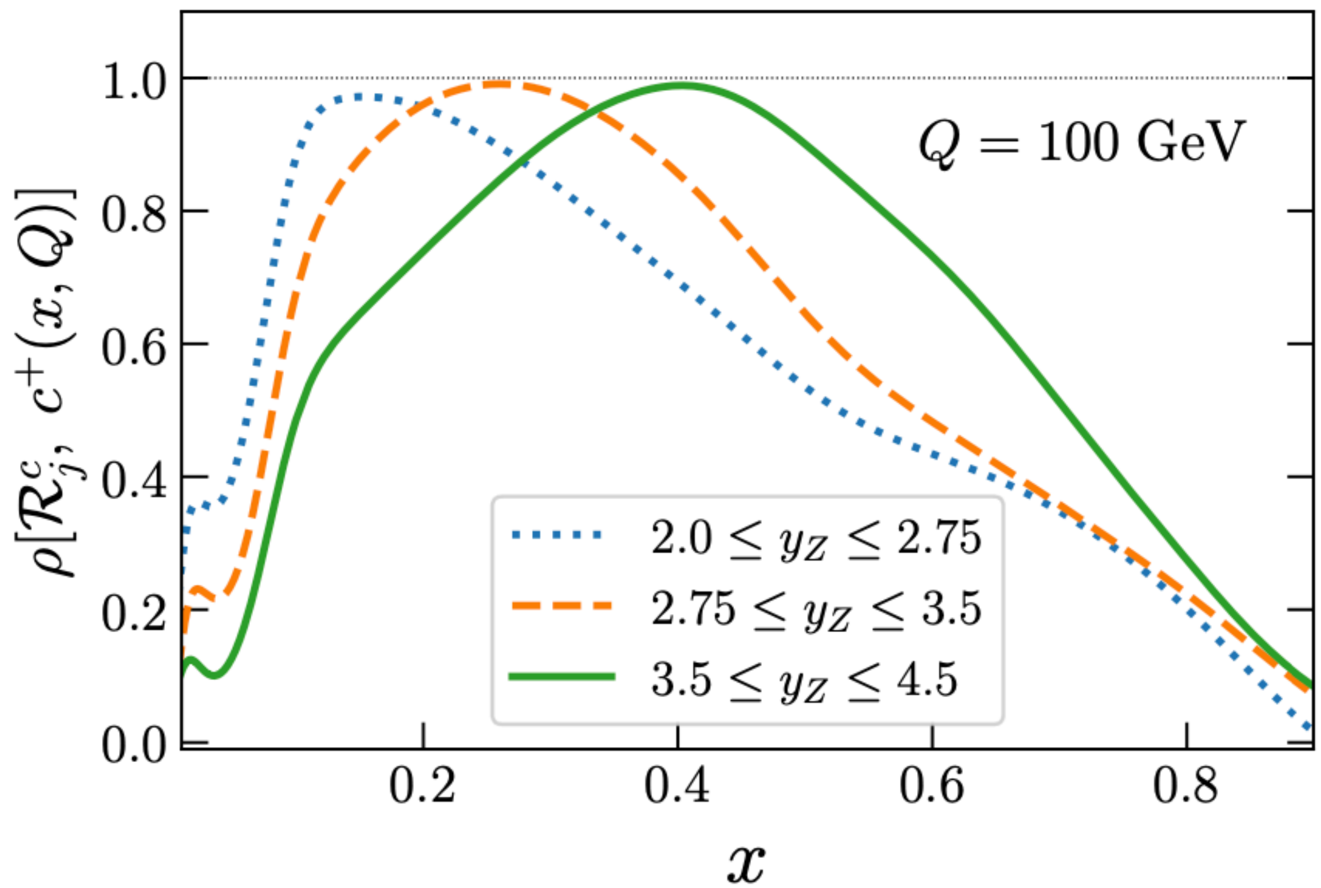
Consistent results for **DIS-only** and **collider-only fits**: no single dataset dominates the charm PDF

*crucial constraints provided by the **LHCb inclusive W,Z production data!***

Z+charm @ LHCb

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

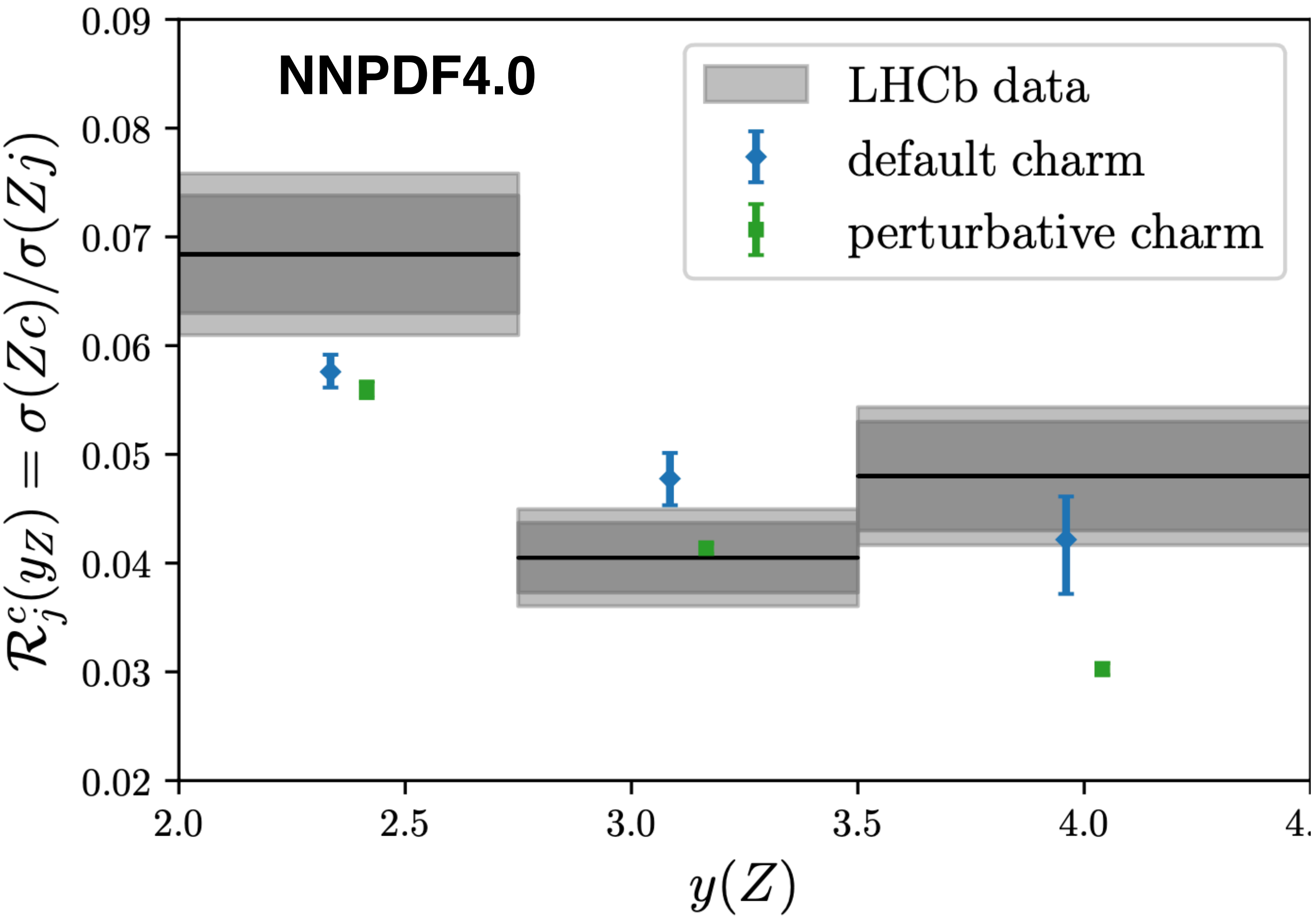


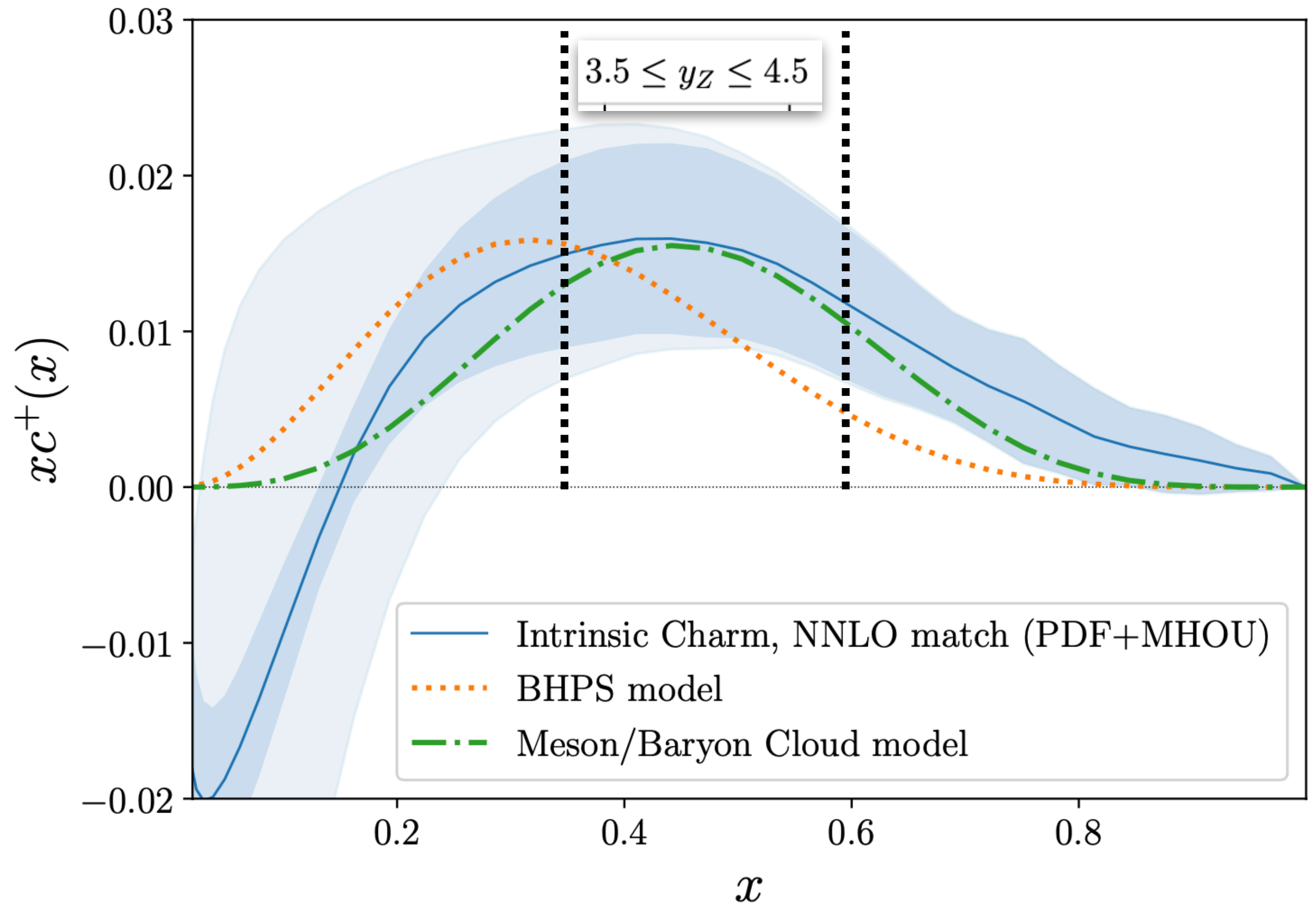


$$\mathcal{R}_j^c(y_Z) \equiv \frac{N(c\text{ tagged jets}; y_Z)}{N(\text{jets}; y_Z)} = \frac{\sigma(pp \to Z + \text{charm jet}; y_Z)}{\sigma(pp \to Z + \text{jet}; y_Z)}$$

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

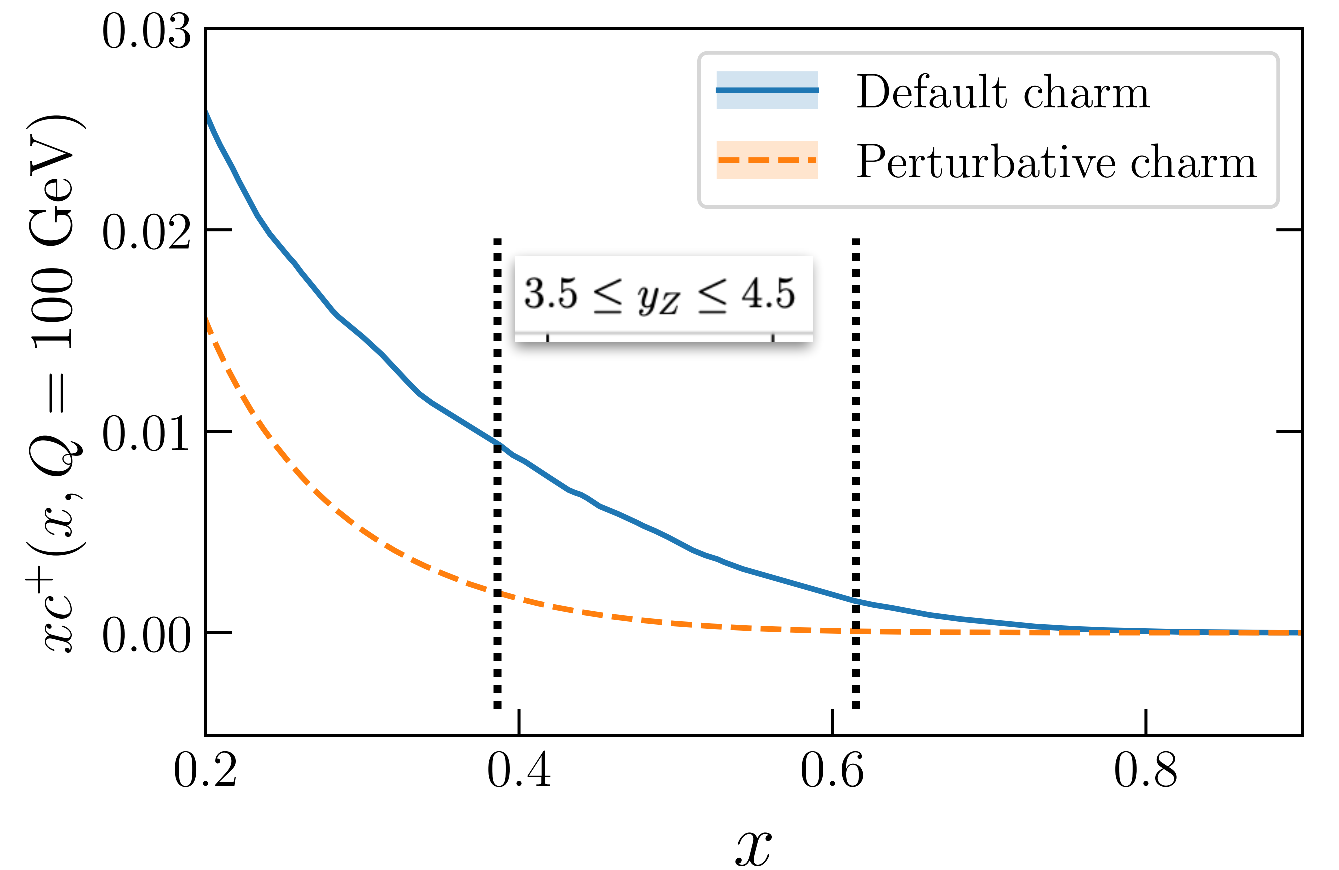
Z+charm @ LHCb



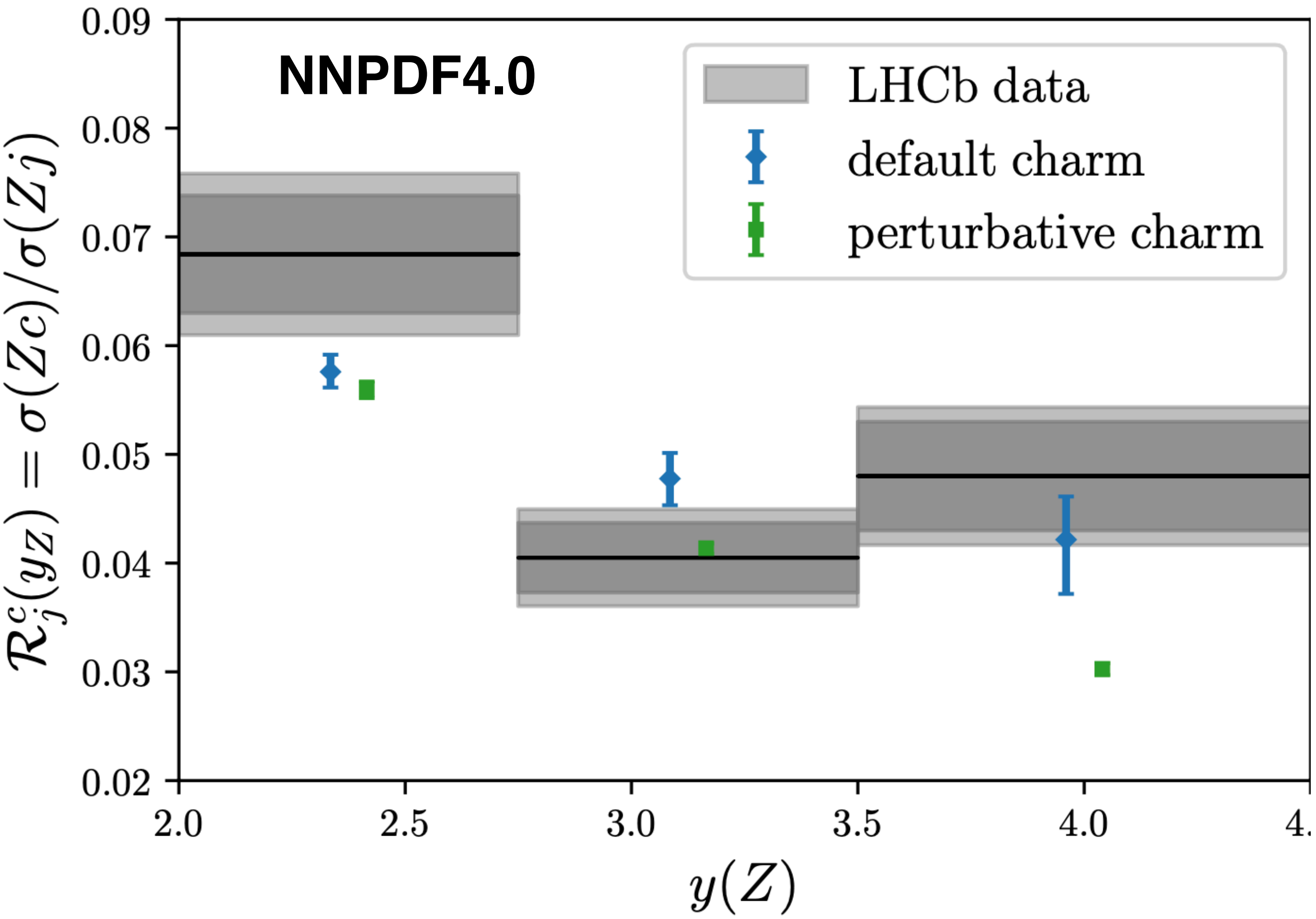


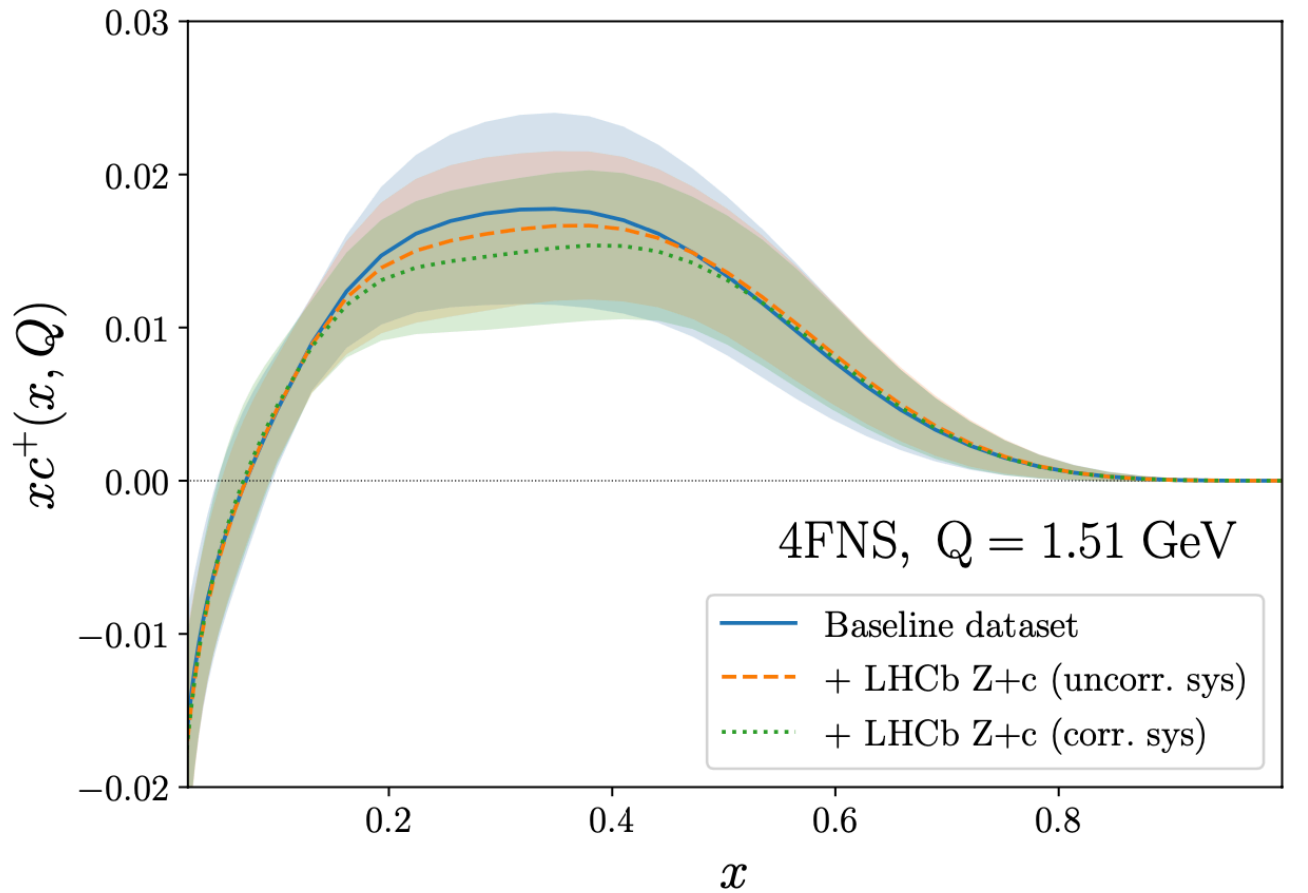
- ☑ A perturbative charm PDF **disagrees** with the LHCb forward Z+charm data

- ☑ LHCb data favour intrinsic charm hypothesis, with IC carrying **0.5% of proton's momentum**



Z+charm @ LHCb

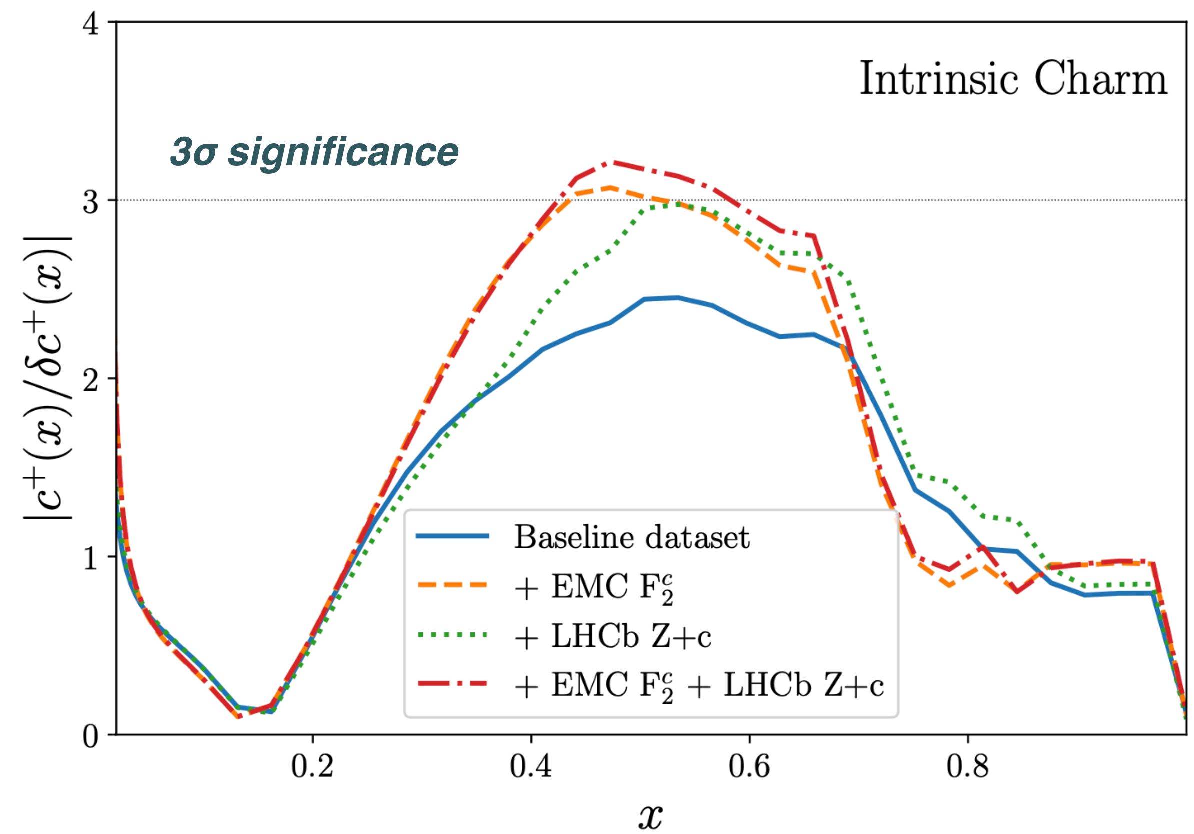




- A perturbative charm PDF **disagrees** with the LHCb forward Z+charm data

- LHCb data favour intrinsic charm hypothesis, with IC carrying **0.5% of proton's momentum**

- Striking consistency between **direct** (Z+c, F_2^c) **and indirect constraints** on the charm PDF

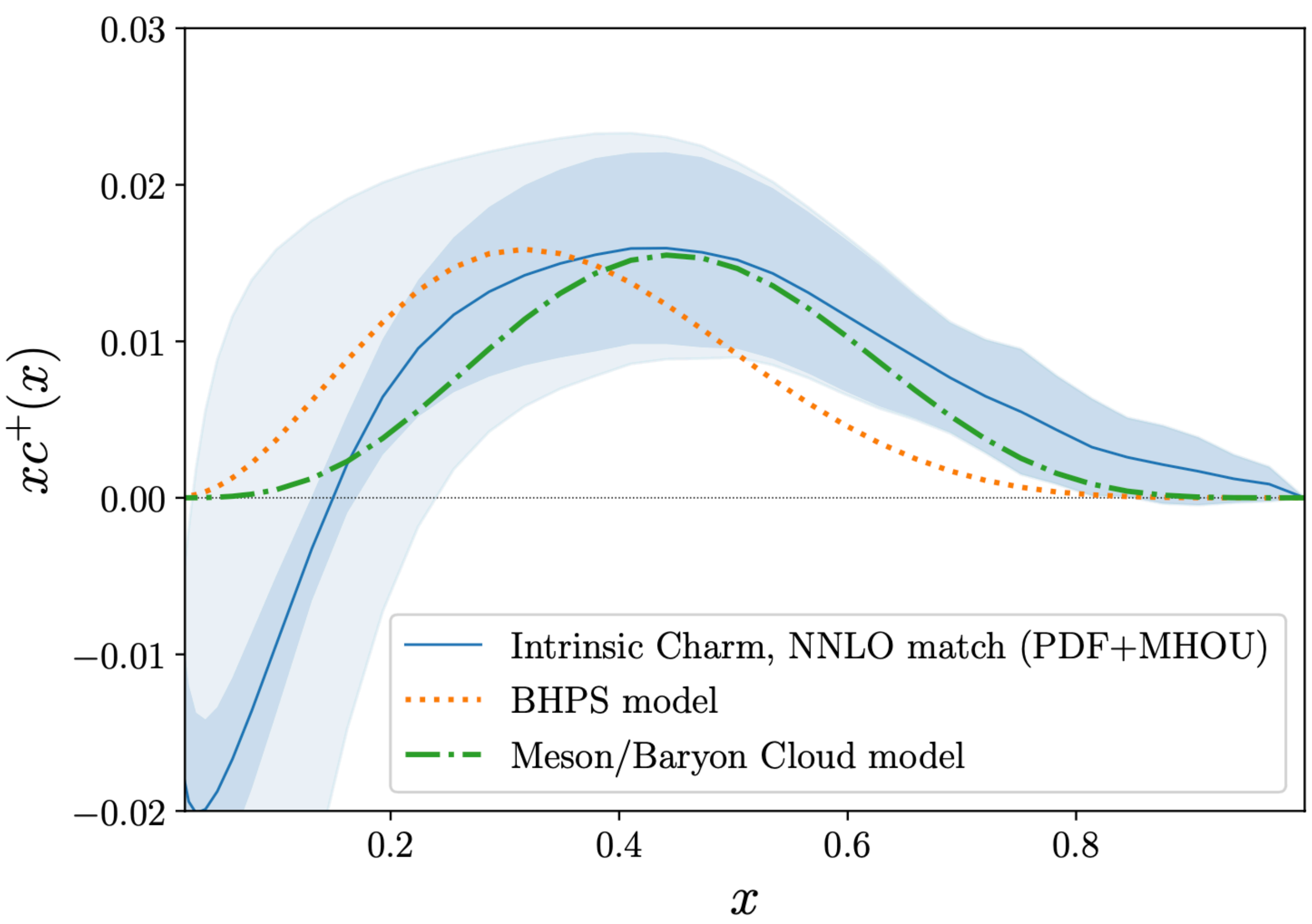


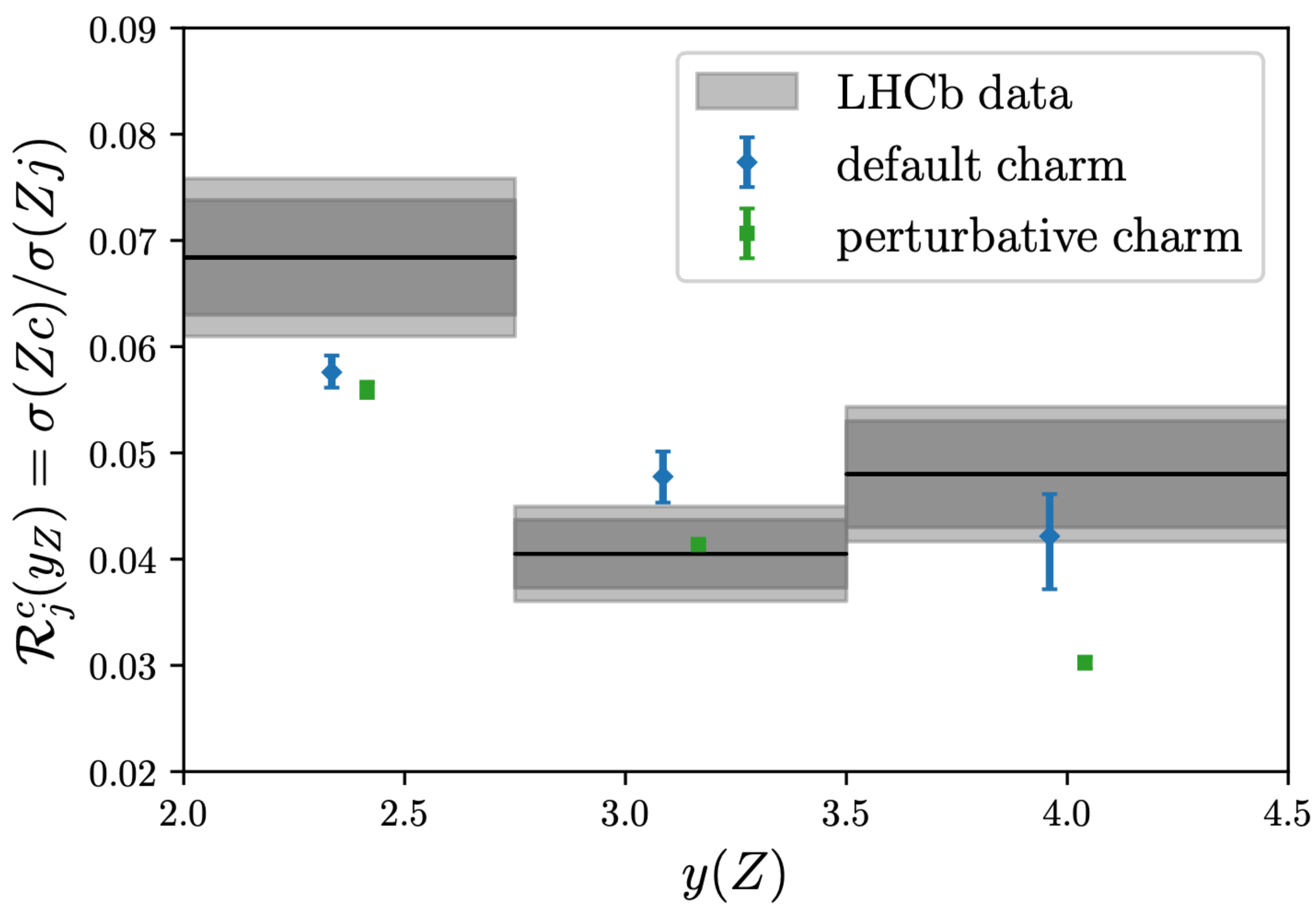
Summary

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

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

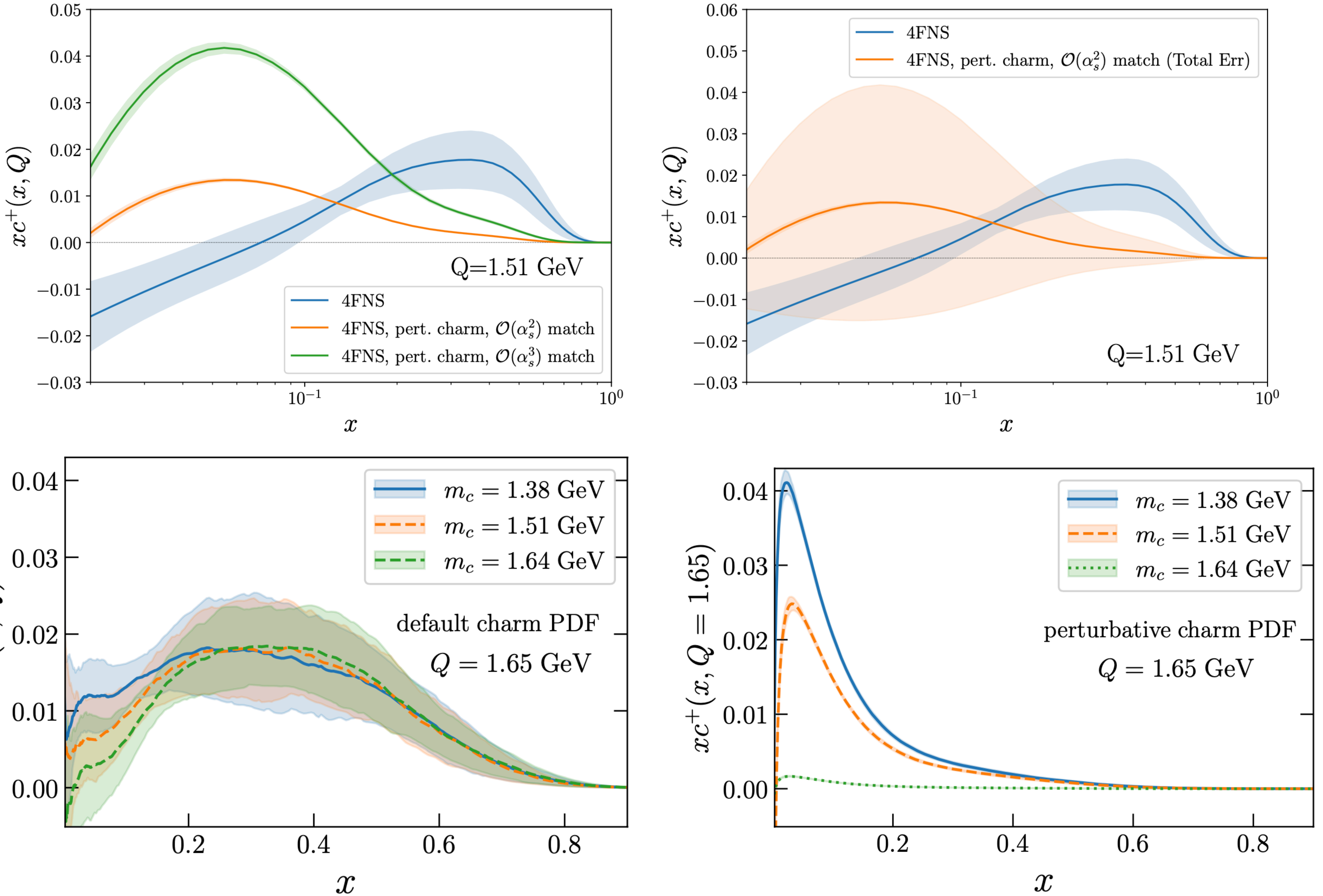
- The NNPDF4.0 predictions are in excellent agreement with the independent constraints provided by the **LHCb Z+charm data** in the forward region



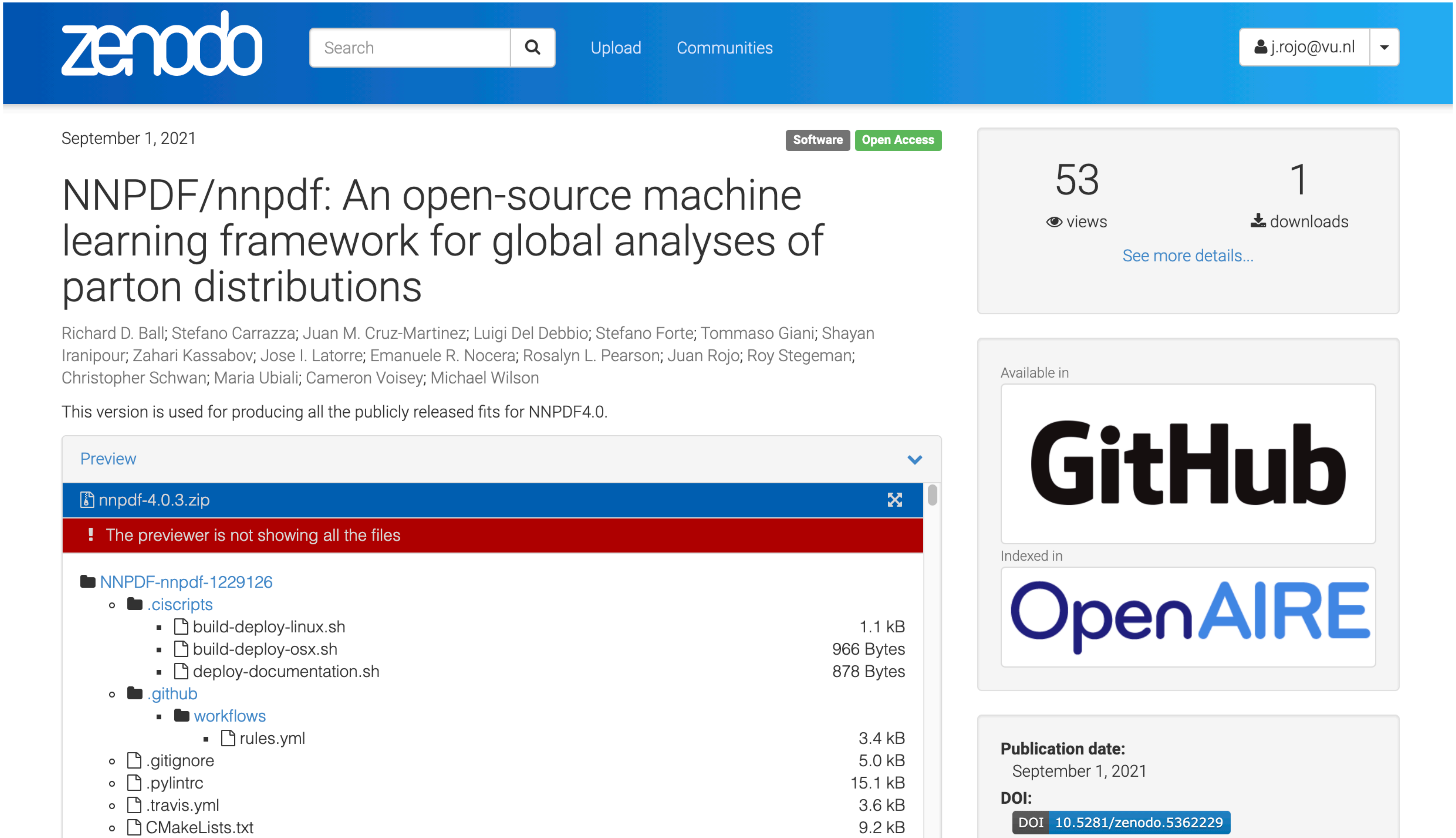


Extra Material

Perturbative charm PDF



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

The global QCD analysis paradigm

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

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

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

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

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

proton Parton Distribution Functions (PDFs)

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

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