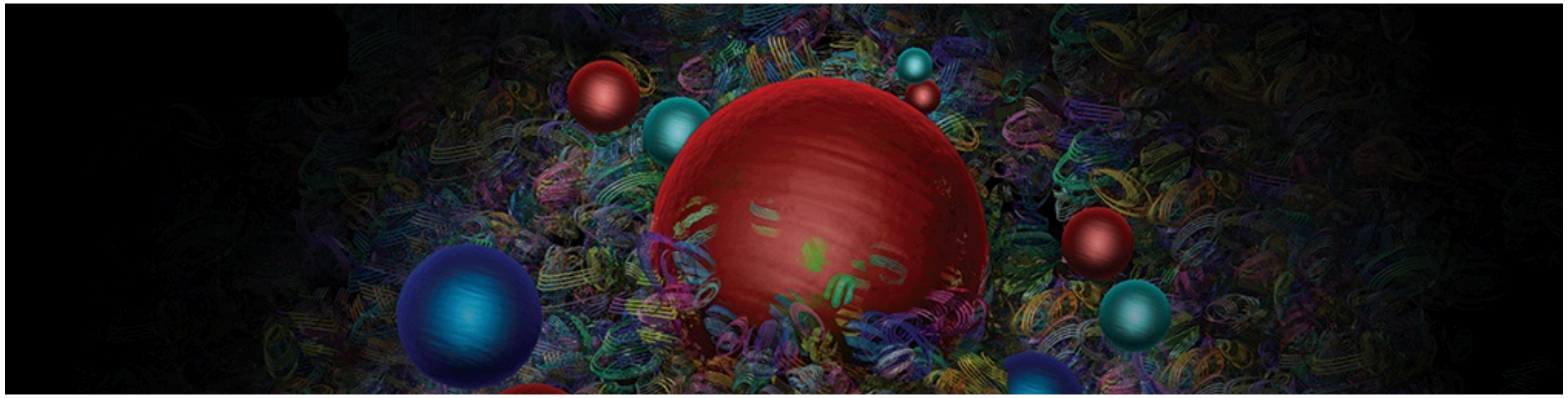
Evidence and Implications of Intrinsic Charm Quarks in the Proton

Juan Rojo, VU Amsterdam & Nikhef



12.10.2022, SLAC Theory Seminar

What I will be telling you about?

nature

View all journals | Search | Login

Explore content | About the journal | Publish with us | Sign up for alerts | RSS feed

nature > articles > article

Article | Open Access | Published: 17 August 2022

Evidence for intrinsic charm quarks in the proton

The NNPDF Collaboration

Nature **608**, 483–487 (2022) | Cite this article

30k Accesses | **1** Citations | **342** Altmetric | Metrics

Abstract

The theory of the strong force, quantum chromodynamics, describes the proton in terms of quarks and gluons. The proton is a state of two up quarks and one down quark bound by gluons, but quantum theory predicts that in addition there is an infinite number of quark–

Download PDF

Associated Content

Do protons have intrinsic charm? New evidence suggests yes

Benjamin Thompson & Nick Petrić Howe

Nature | **Nature Podcast** | 17 Aug 2022

Evidence at last that the proton has intrinsic charm

Ramona Vogt

Nature | **News & Views** | 17 Aug 2022

Richard D. Ball, Alessandro Candido, Juan Cruz-Martinez, Stefano Forte, Tommaso Giani, Felix Hekhorn, Kirill Kudashkin, Giacomo Magni & Juan Rojo, ***Nature* 608 (2022) 7923, 483-487**

Is it worth all the attention it has raised?

NEWSLETTERS
Sign up to read our regular email newsletters

NewScientist

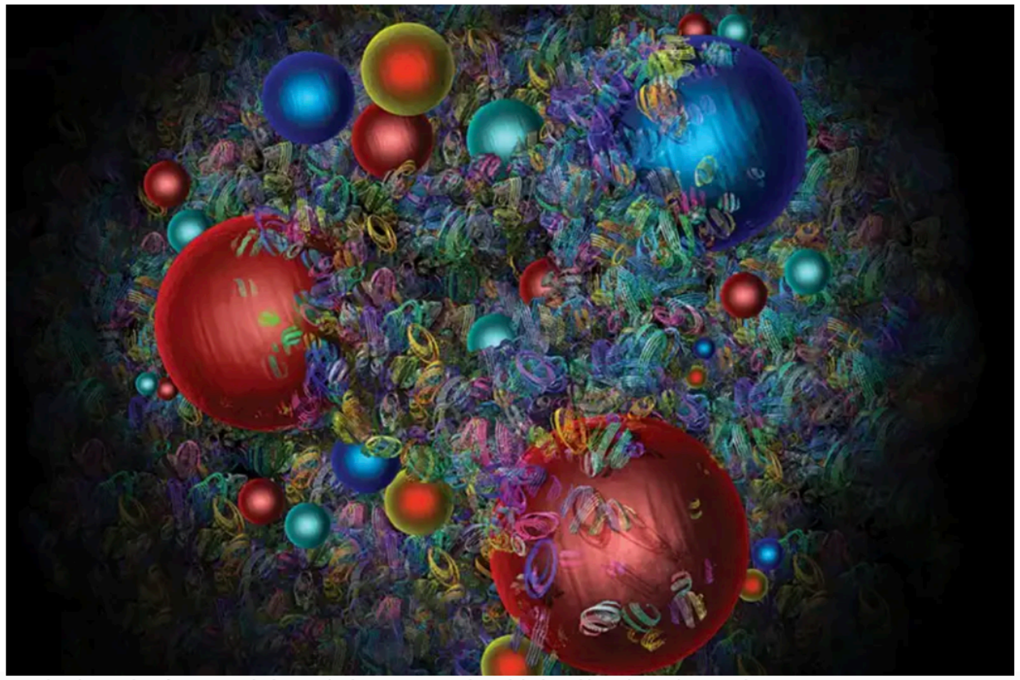
News Podcasts Video Technology Space Physics Health More Shop Courses Events

Physicists surprised to discover the proton contains a charm quark

The textbook description of a proton says it contains three smaller particles - two up quarks and a down quark - but a new analysis has found strong evidence that it also holds a charm quark

PHYSICS 17 August 2022

By Alex Wilkins



An artist's impression of a proton – the large red spheres are up quarks and the large blue sphere a down quark
CERN

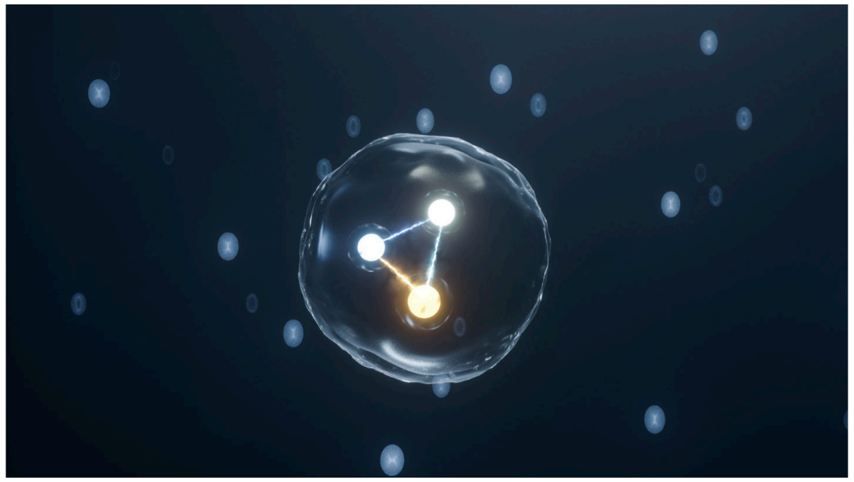
ScienceNews
INDEPENDENT JOURNALISM SINCE 1921

ALL TOPICS LIFE HUMANS EARTH SPACE

NEWS PARTICLE PHYSICS

Protons contain intrinsic charm quarks, a new study suggests

Understanding a proton's charm could refine intel from particle colliders



Protons are commonly thought to contain only three quarks — two up quarks and one down quark (illustrated). But there's new evidence that protons may also contain intrinsic charm quarks and antiquarks.
SEFA KAR/ISTOCK/GETTY IMAGES PLUS

physicsworld

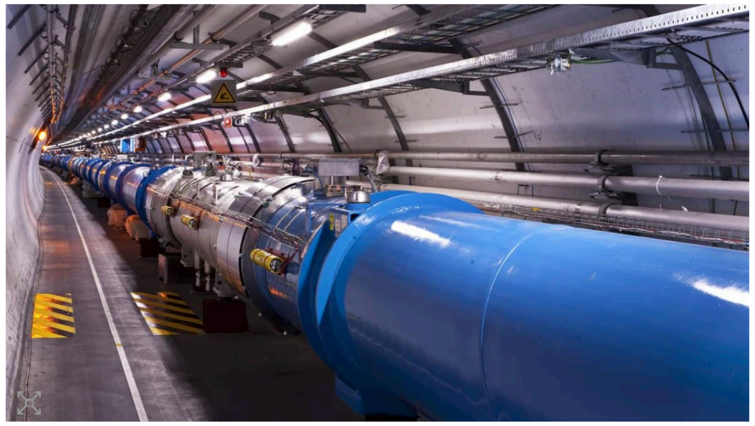
Magazine | La

particles and interactions

PARTICLES AND INTERACTIONS | RESEARCH UPDATE

Protons contain intrinsic charm quarks, machine-learning analysis suggests

23 Aug 2022

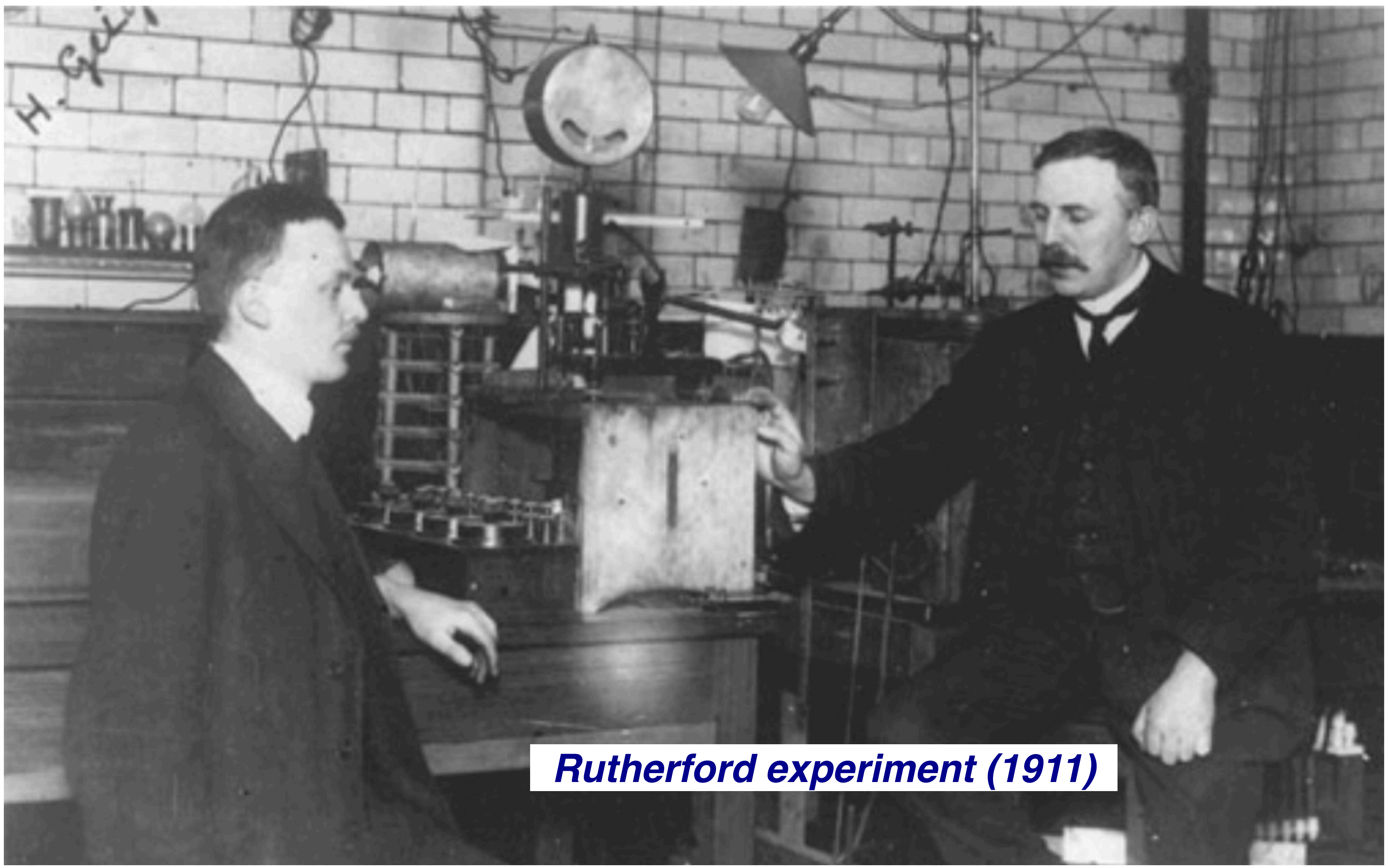


The Large Hadron Collider: evidence for intrinsic charm quarks in protons has been found in LHC data. (Courtesy: Maximilien Brice/CERN)

Why Nucleon Structure?

Why Nucleon Structure?

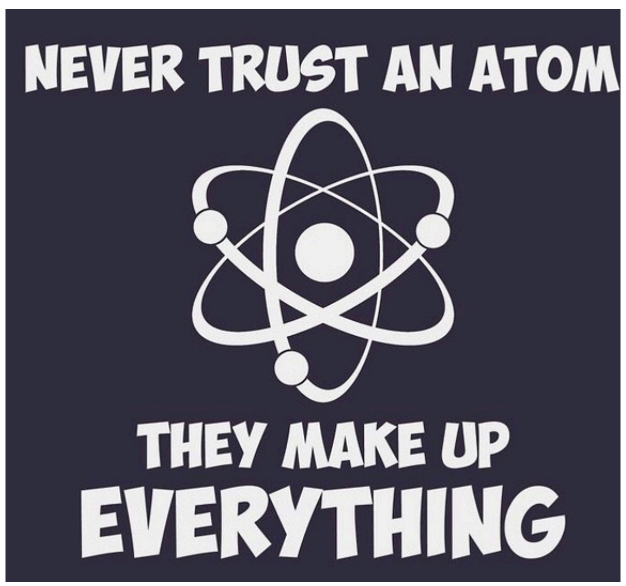
One may claim that the **nucleon is a rather ``boring" particle**, surely after **one century of studying it**, we know everything about the proton?



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**!



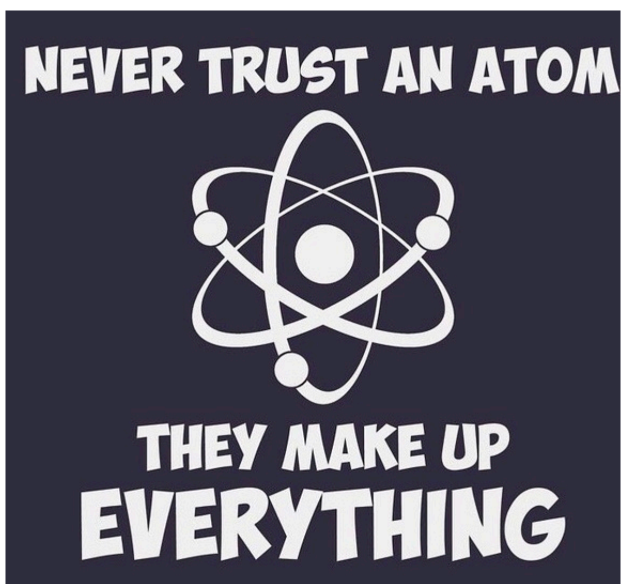
long distances / low energies → *short distances / high energies*

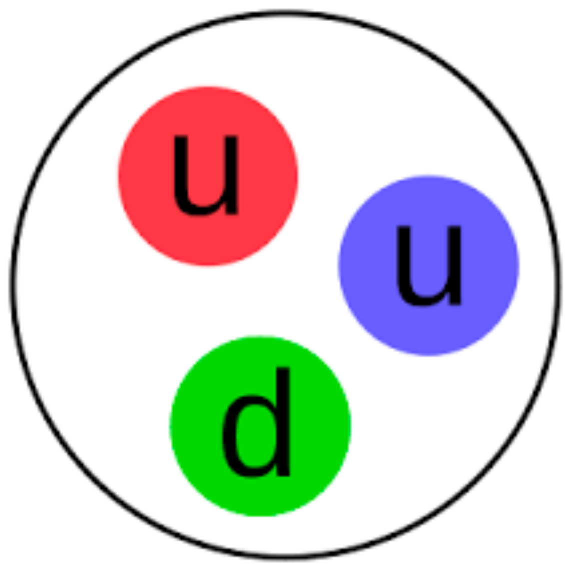
a point particle

$E \ll 1 \text{ GeV}$

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

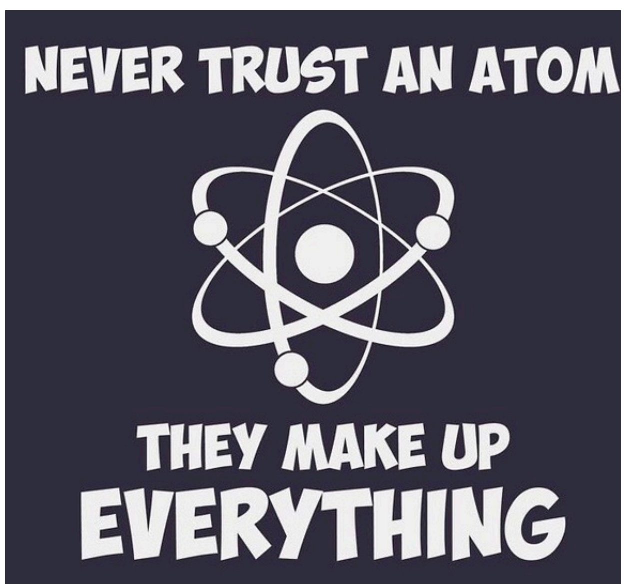
$E \ll 1\ \mathrm{GeV}$

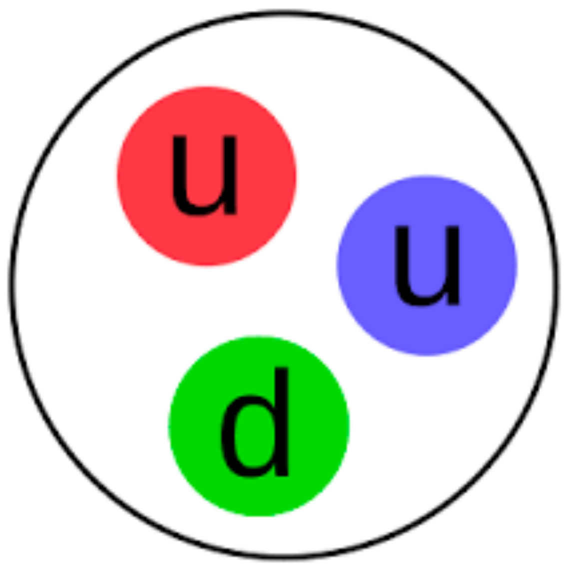
3 valence quarks

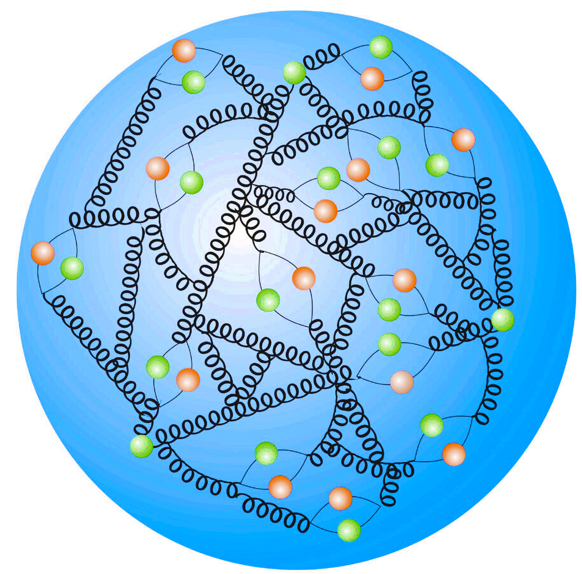
$E \sim \mathrm{few}\ \mathrm{GeV}$

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**!





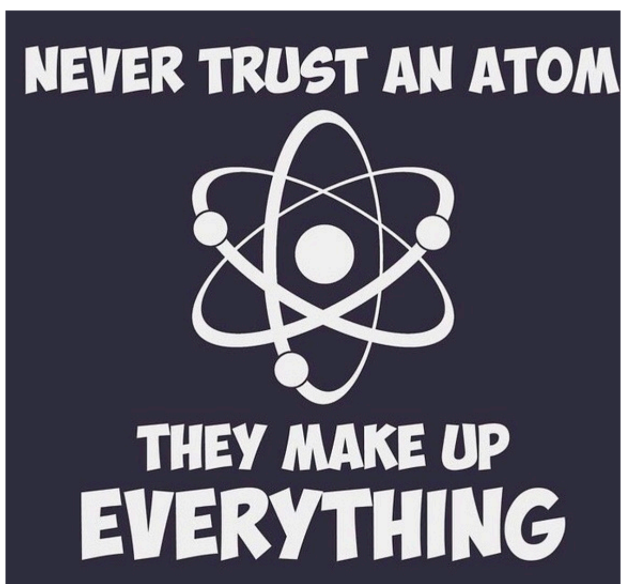


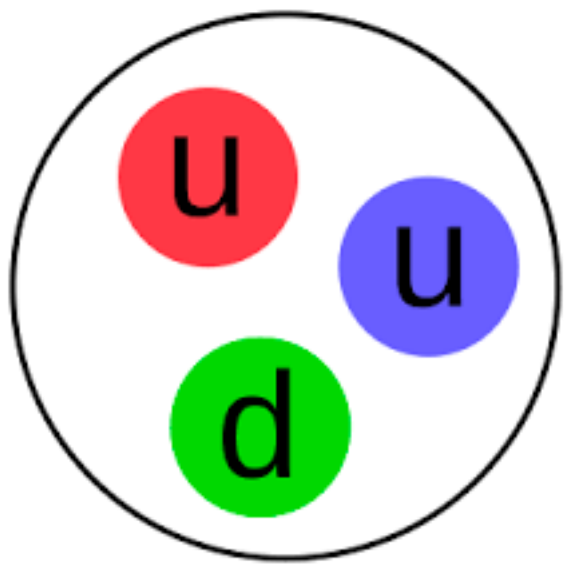
long distances / low energies → *short distances / high energies*

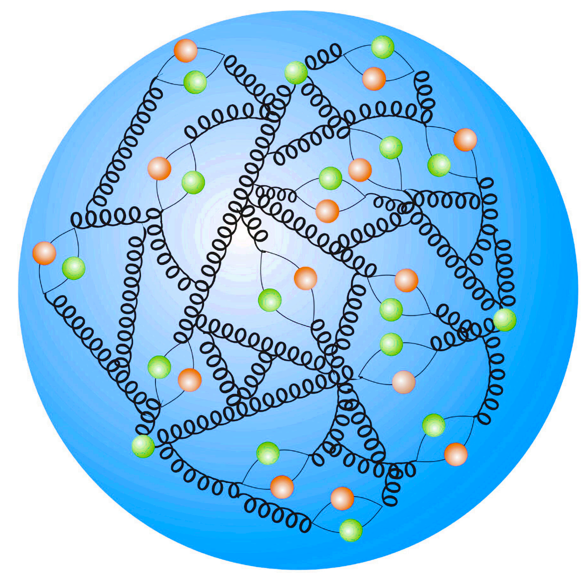
a point particle	3 valence quarks	sea quarks, gluons
$E \ll 1\ \mathrm{GeV}$	$E \sim \text{few GeV}$	$E \sim 50\ \mathrm{GeV}$

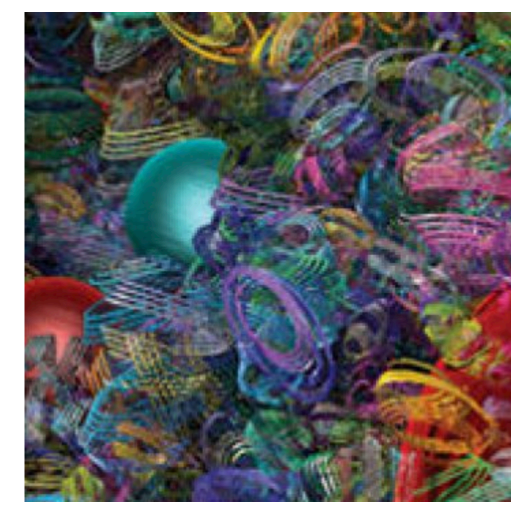
Why Nucleon Structure?

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**!









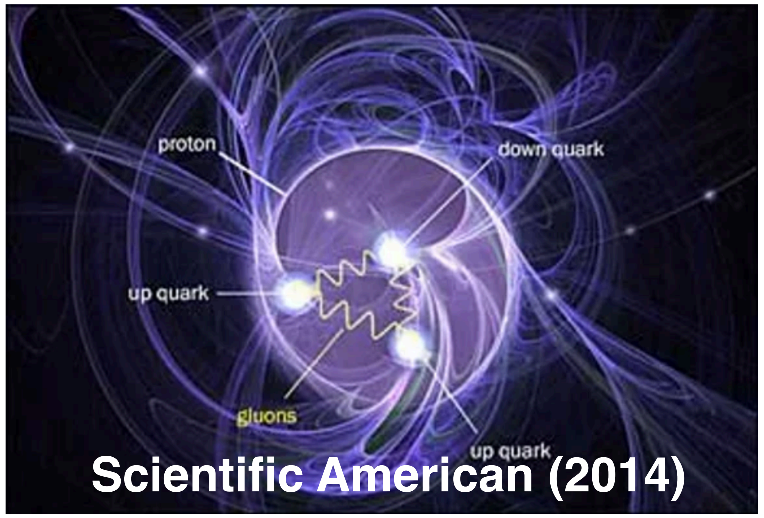
long distances / low energies → *short distances / high energies*

a point particle	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



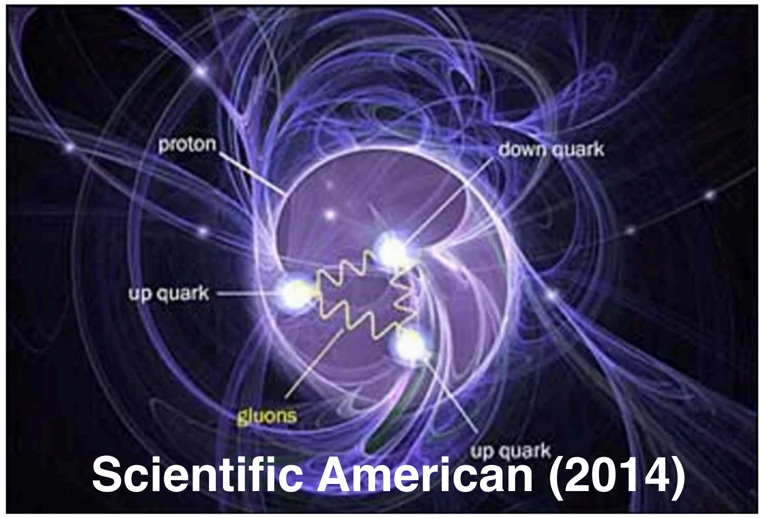
Gluons contribute to proton spin

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

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!**

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

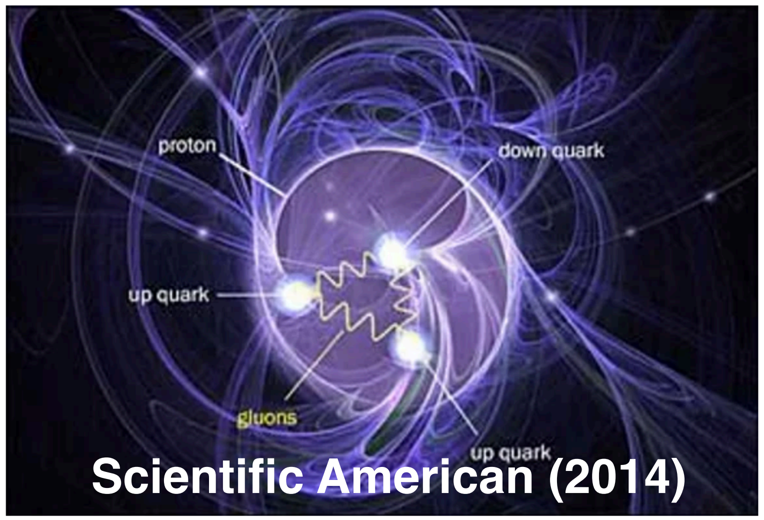

The Guardian (2017)

gluon-dominated state of matter

A gateway to unravelling QCD

THE SCIENCES

Proton Spin Mystery Gains a New Clue



Gluons contribute to proton spin

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

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

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

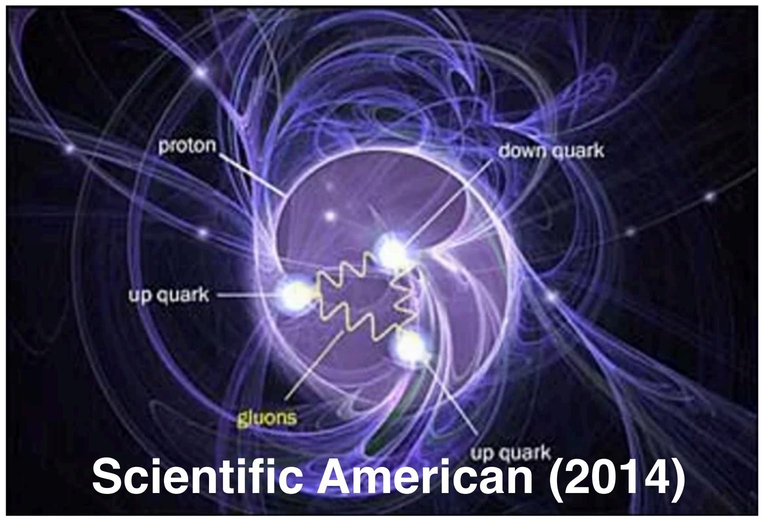
This was the year that analysis of data finally backed up a prediction, made in the mid 1970s, of a surprising emergent behaviour in the strong nuclear force

gluon-dominated state of matter

A gateway to unravelling QCD

THE SCIENCES

Proton Spin Mystery Gains a New Clue



Gluons contribute to proton spin

ScienceNews
INDEPENDENT JOURNALISM SINCE 1921

ALL TOPICS LIFE HUMANS EARTH SPACE

NEWS PARTICLE PHYSICS

Protons contain intrinsic charm quarks, a new study suggests

Understanding a proton's charm could refine intel from particle colliders

Protons are commonly thought to contain only three quarks — two up quarks and one down quark (illustrated). But there's new evidence that protons may also contain intrinsic charm quarks and antiquarks.

SEFA KAR/ISTOCK/GETTY IMAGES PLUS

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

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.

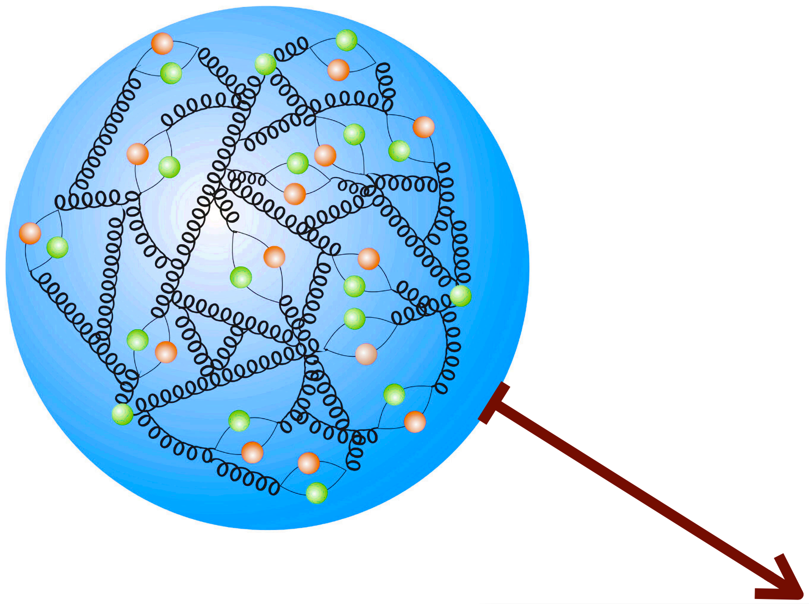
Antimatter asymmetry in the proton

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

gluon-dominated state of matter

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

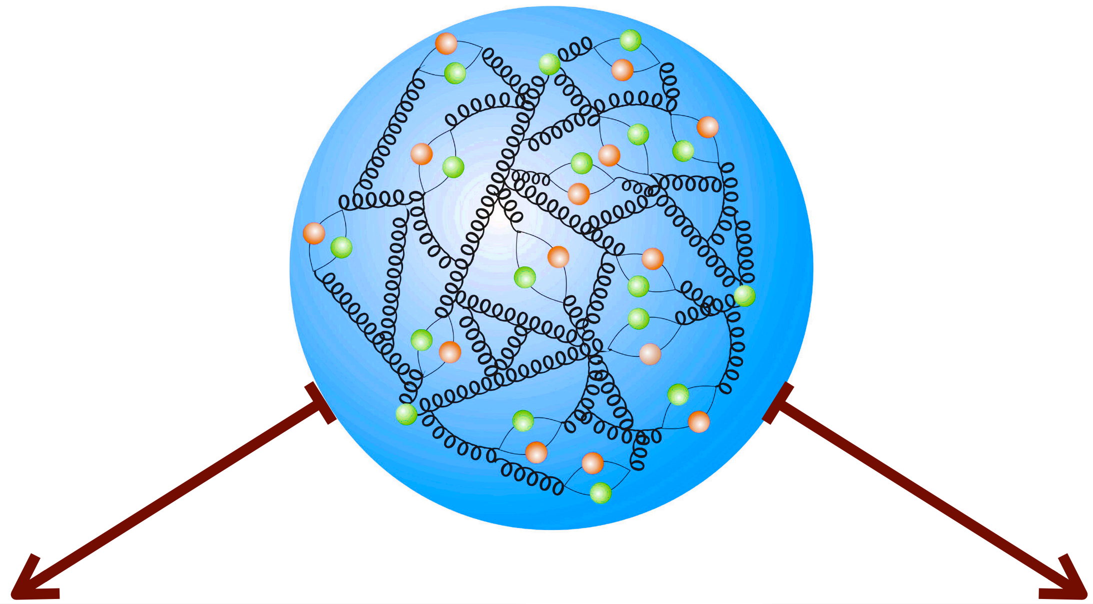
Why Nucleon Structure?



Address fundamental questions about Quantum Chromodynamics

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

Why Nucleon Structure?



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

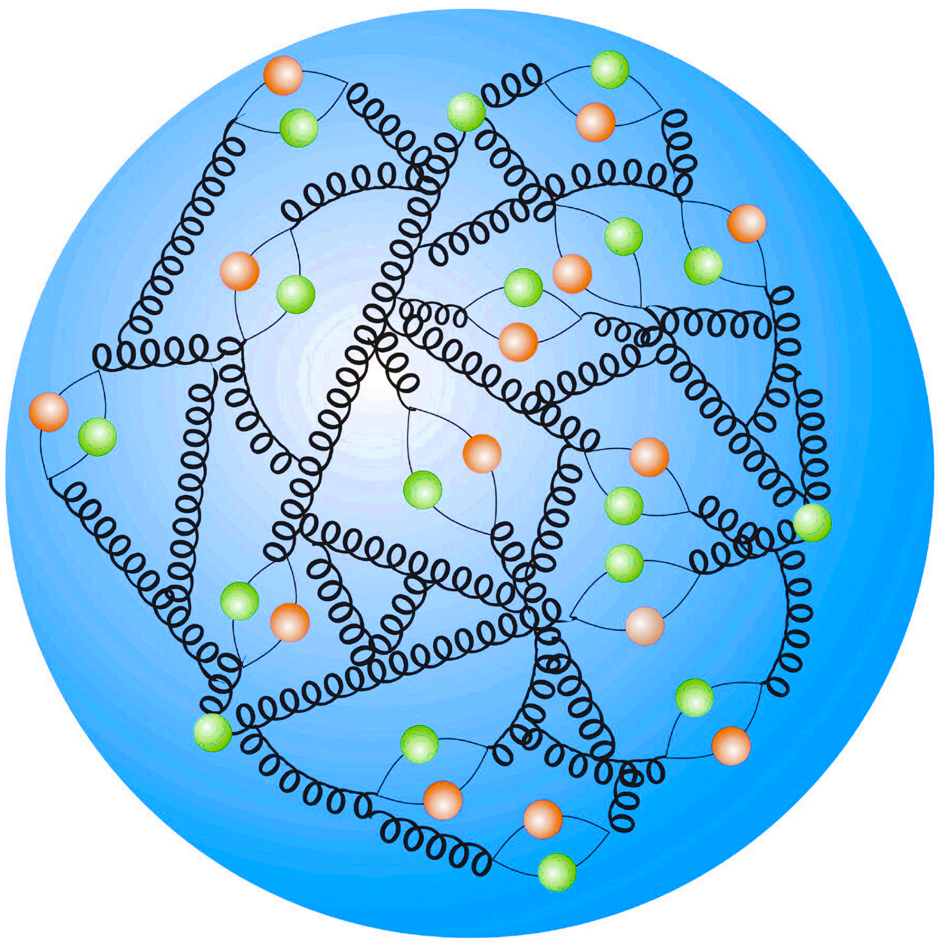
Address fundamental questions about Quantum Chromodynamics

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

Parton Distributions

Parton Distributions

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



Parton Distribution Functions (PDFs)

Determine from **data:**

Global QCD analysis

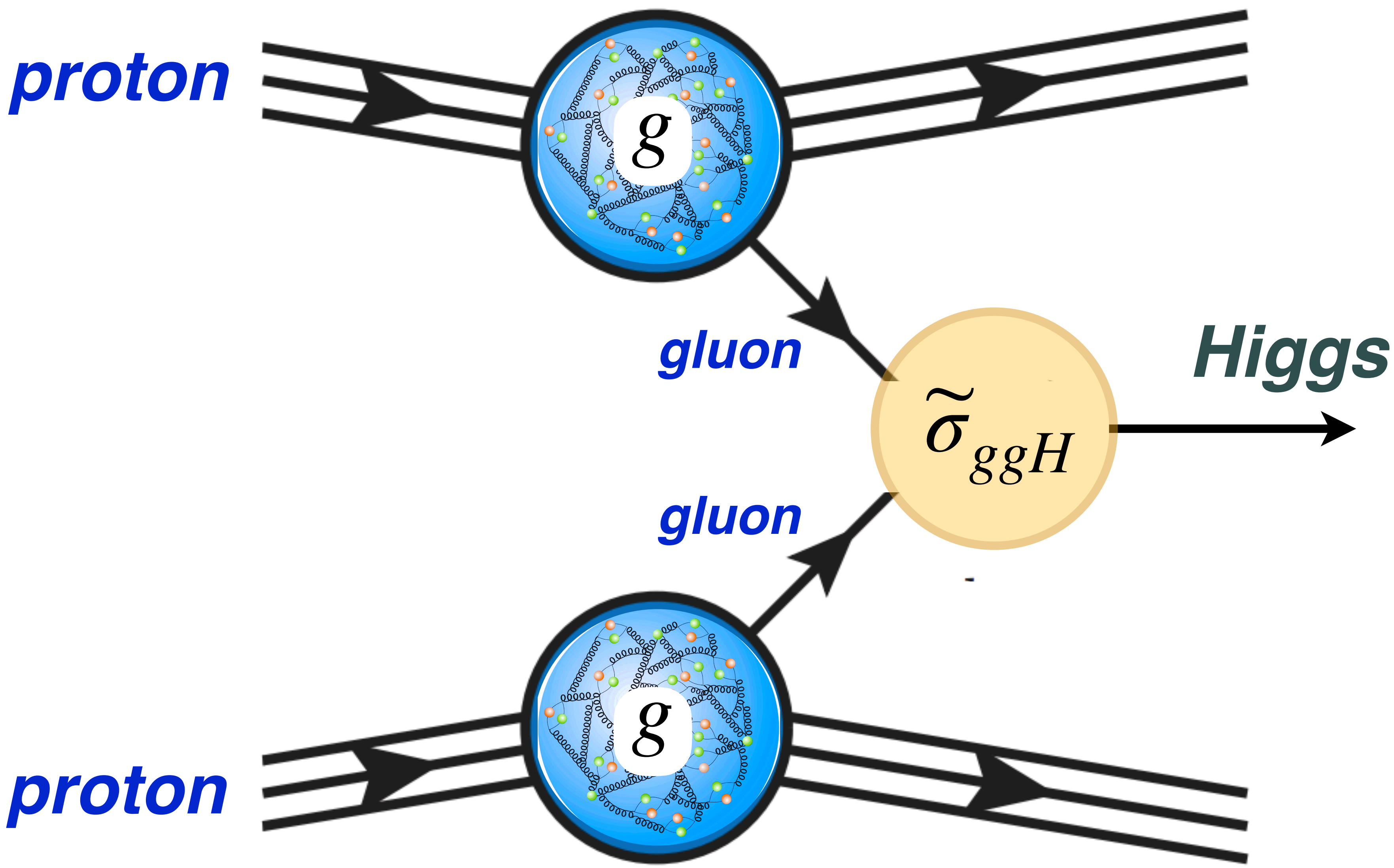
Also important recent results from lattice QCD!

What do we need to extract PDFs from data?

Parton Distributions

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

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

- **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***

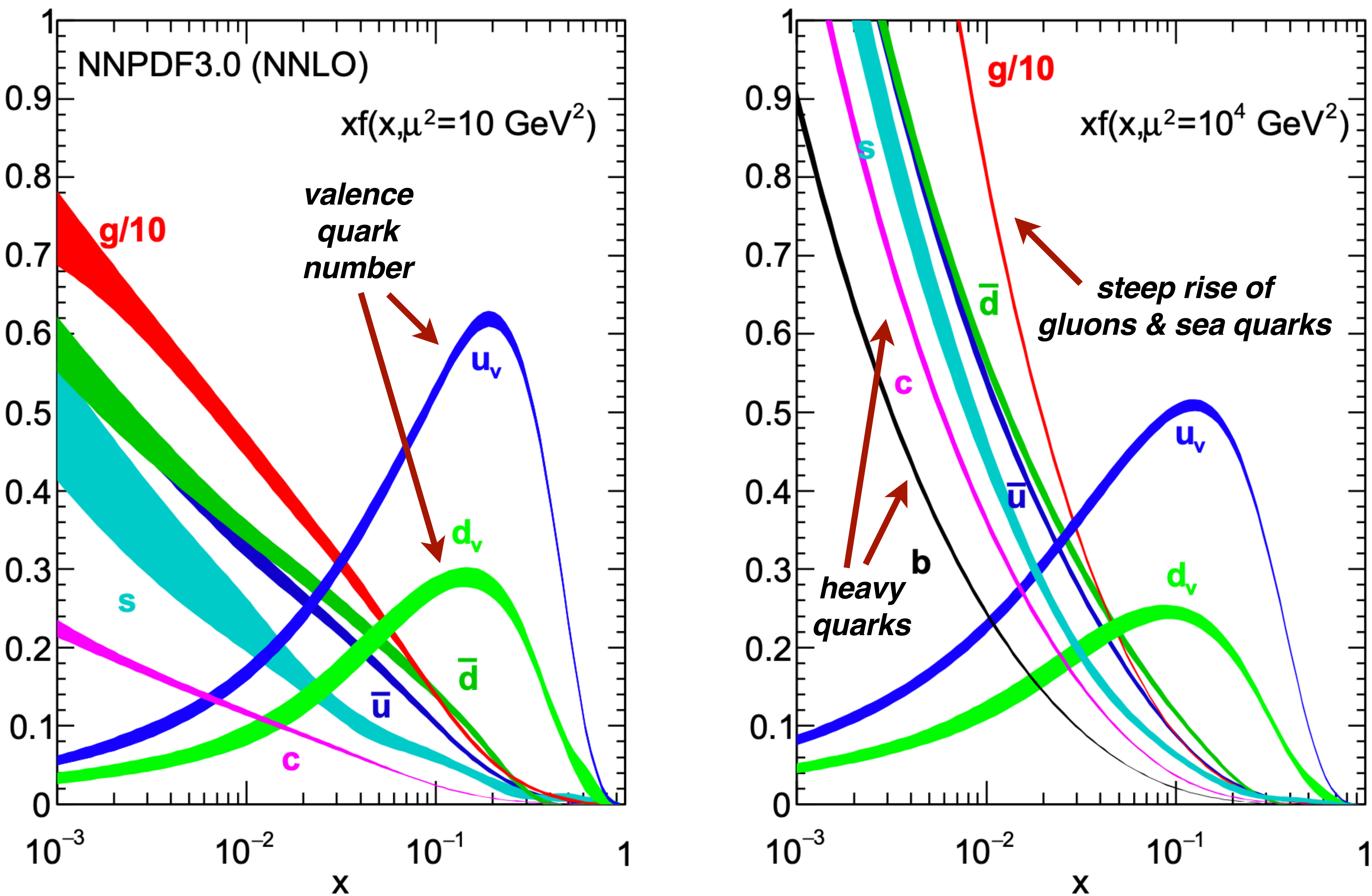
x: fraction of proton momentum carried by gluon

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*

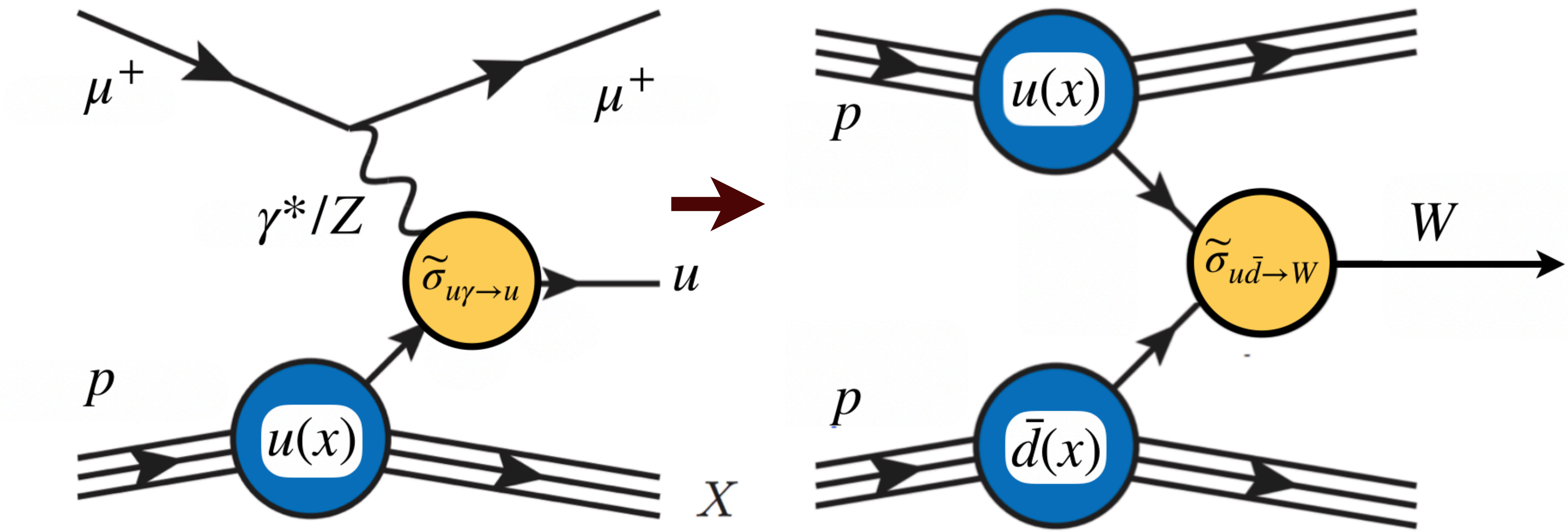
A proton structure snapshop



The global QCD analysis paradigm

QCD factorisation theorems**: PDF universality**

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



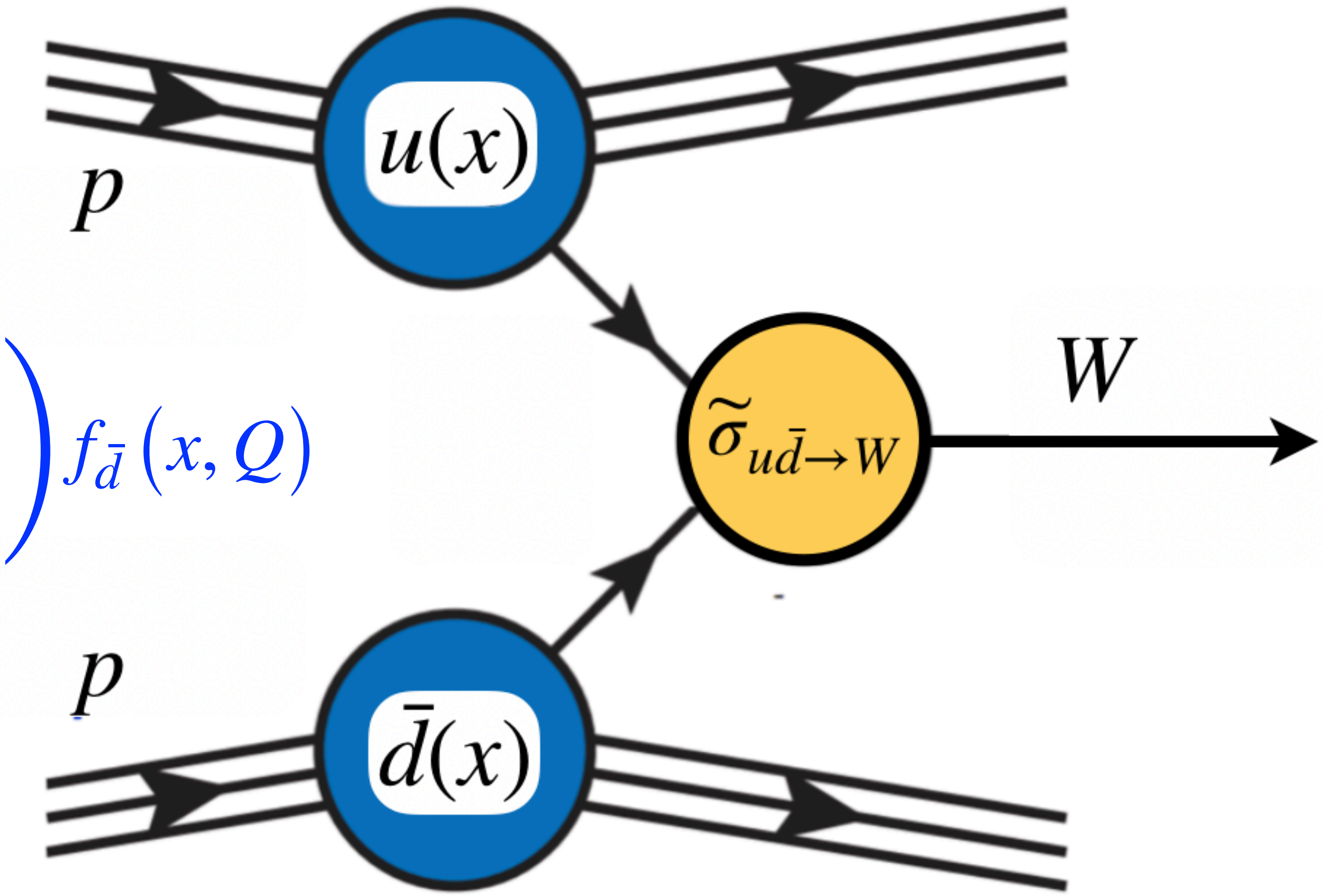
*Determine PDFs from **deep-inelastic scattering**…*

*… 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**

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

- **Extract PDF parameters from data** via log-likelihood maximisation

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

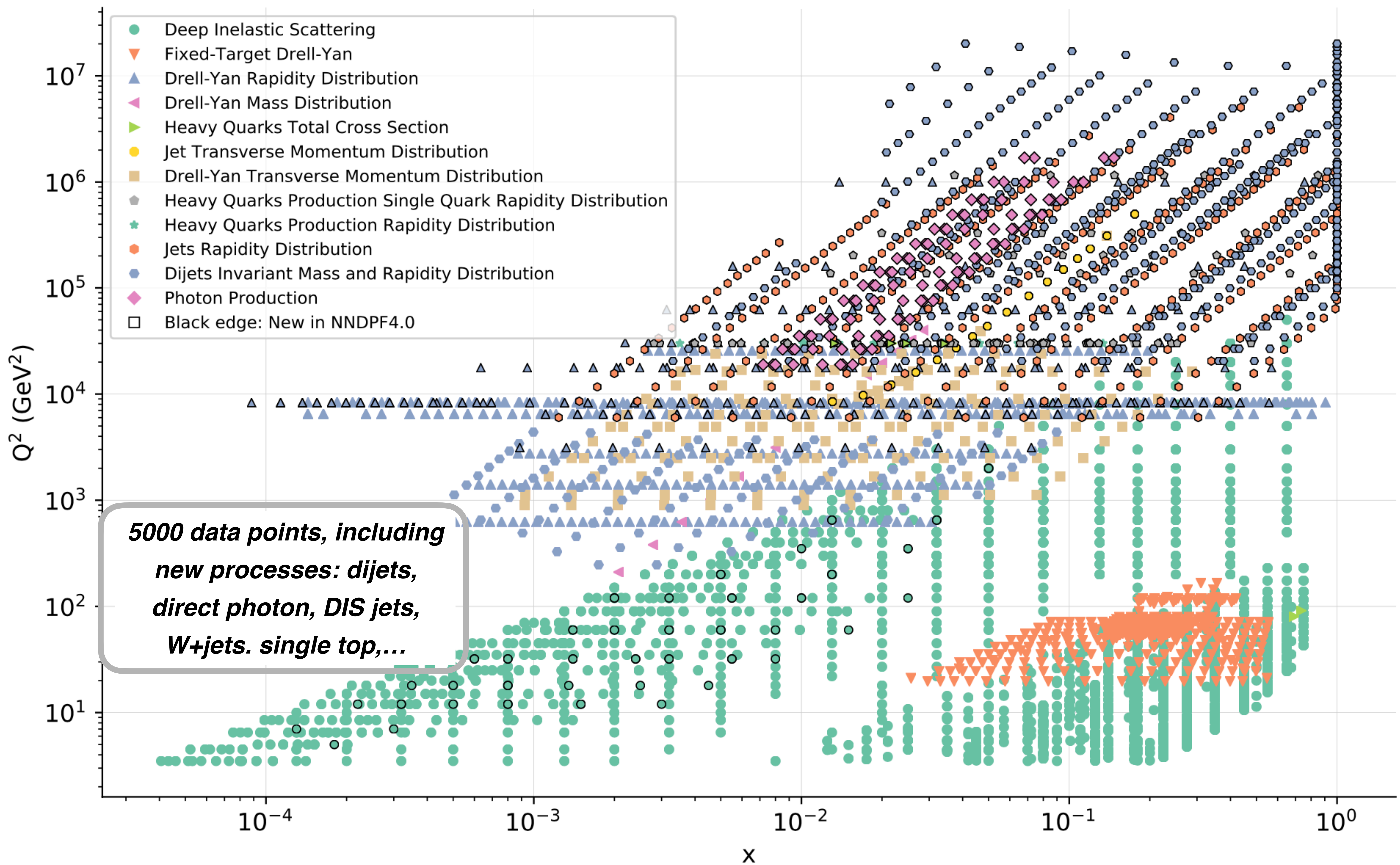
- Estimate the associated **uncertainties**

> 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

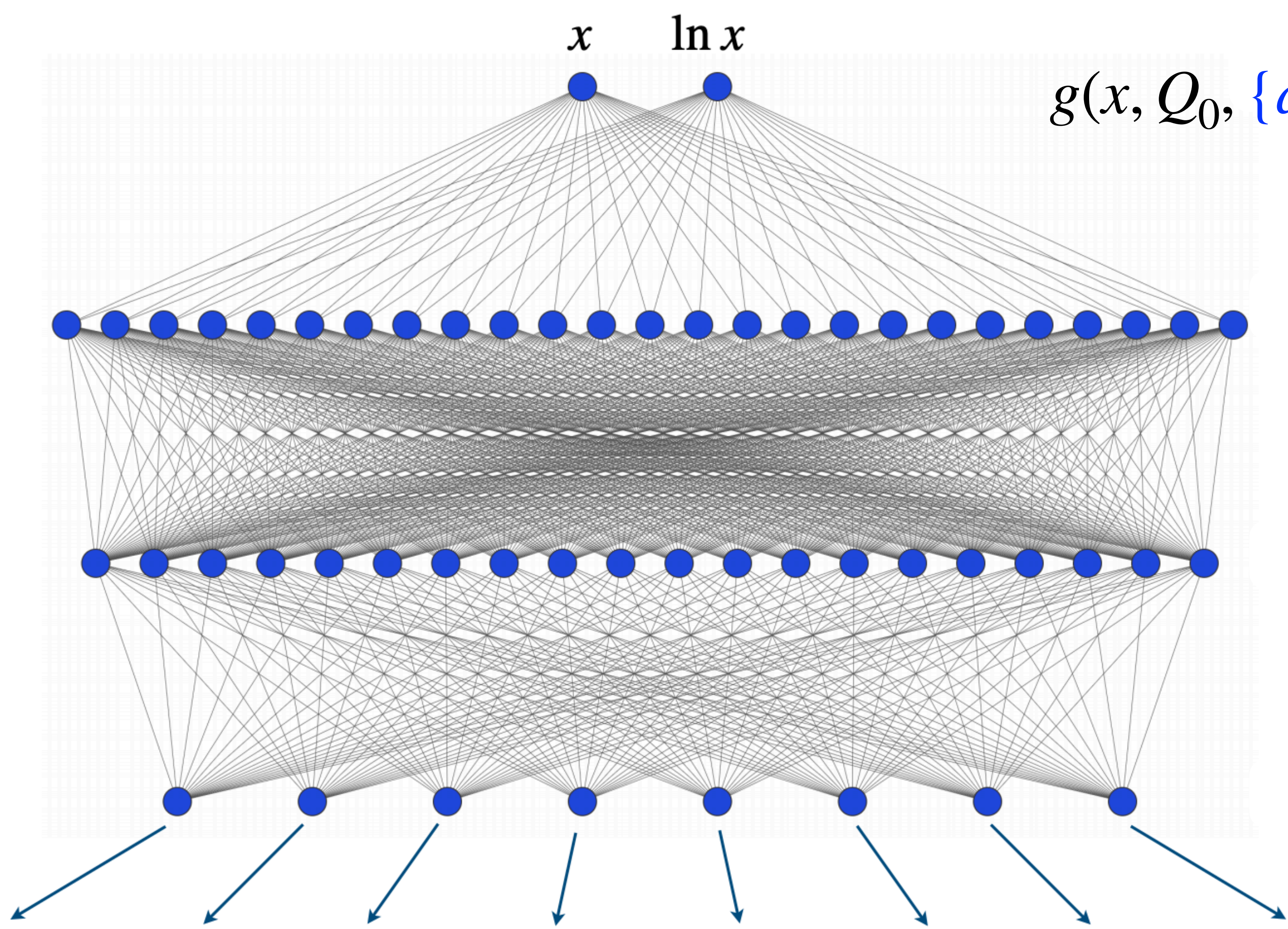
The NNPDF4.0 dataset



$\mathcal{O}(50)$ 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)

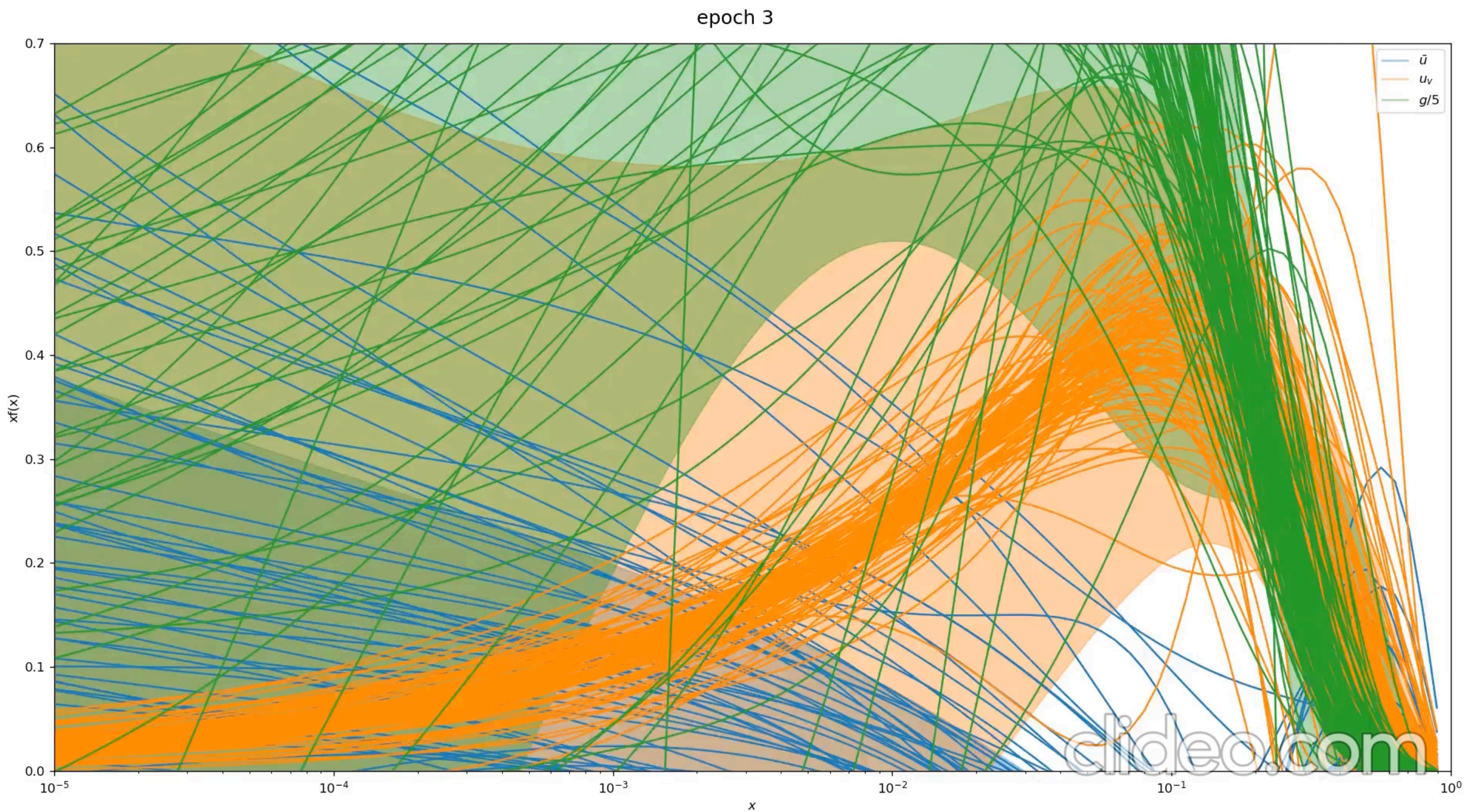


$$g(x, Q_0, \{a_g\}) = f_g(x, a_g^{(1)}, a_g^{(2)}, \dots)$$

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

$xg(x,Q_0)$	$x\Sigma(x,Q_0)$	$xV(x,Q_0)$	$xV_3(x,Q_0)$	$xV_8(x,Q_0)$	$xT_3(x,Q_0)$	$xT_8(x,Q_0)$	$xT_{15}(x,Q_0)$	***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***

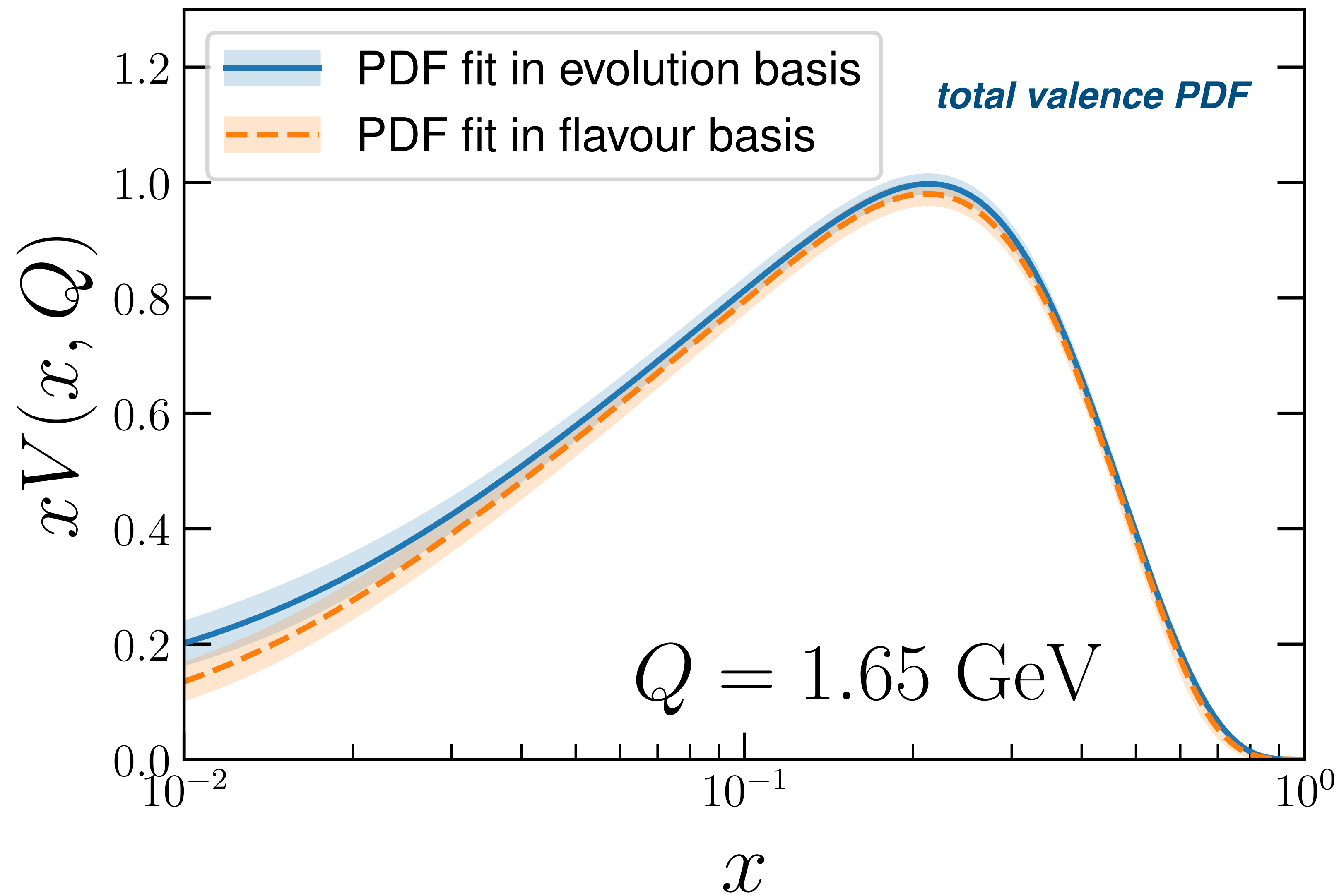
Fitting methodology



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

Parametrisation basis independence

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



evolution basis PDF parametrisation:

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

flavour basis PDF parametrisation:

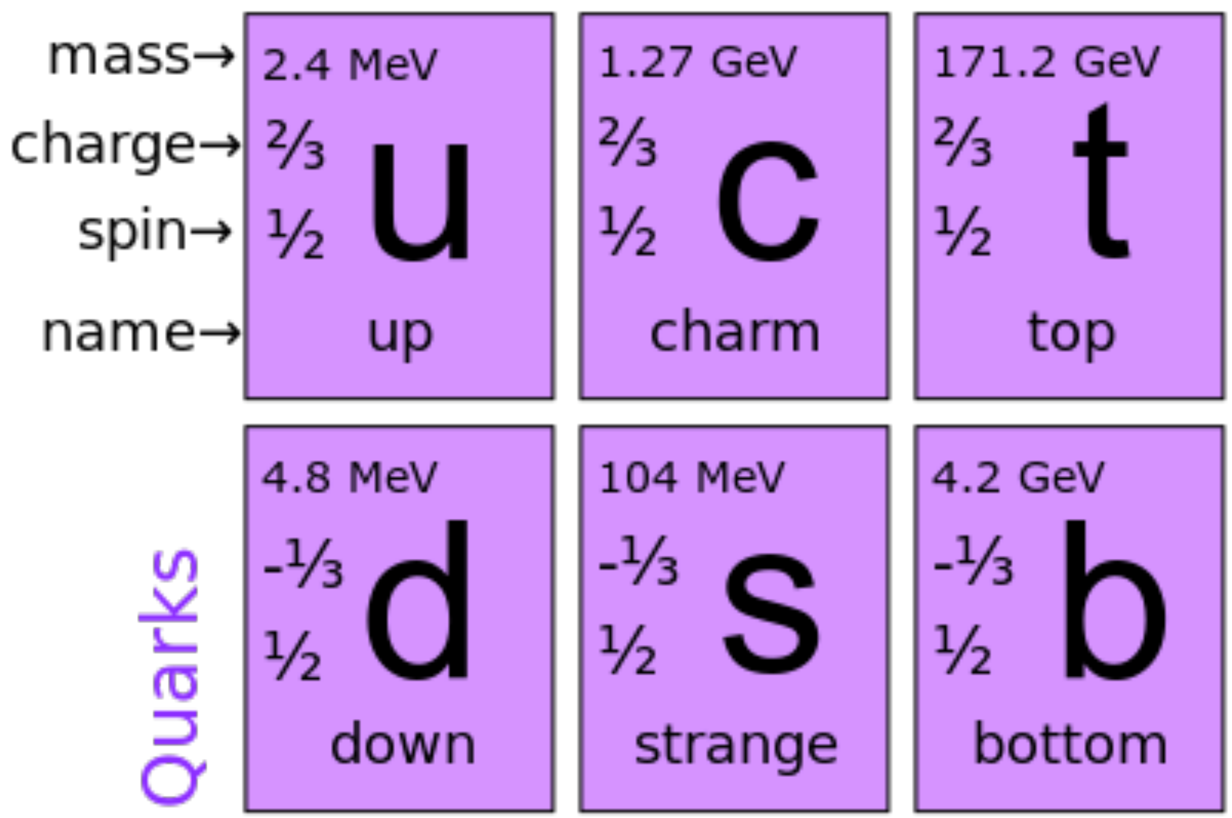
$$xV(x, Q_0) \propto \big(\mathrm{NN}_u(x) - \mathrm{NN}_{\bar{u}}(x) + \mathrm{NN}_d(x) - \mathrm{NN}_{\bar{d}}(x) + \mathrm{NN}_s(x) - \mathrm{NN}_{\bar{s}}(x)\big)$$

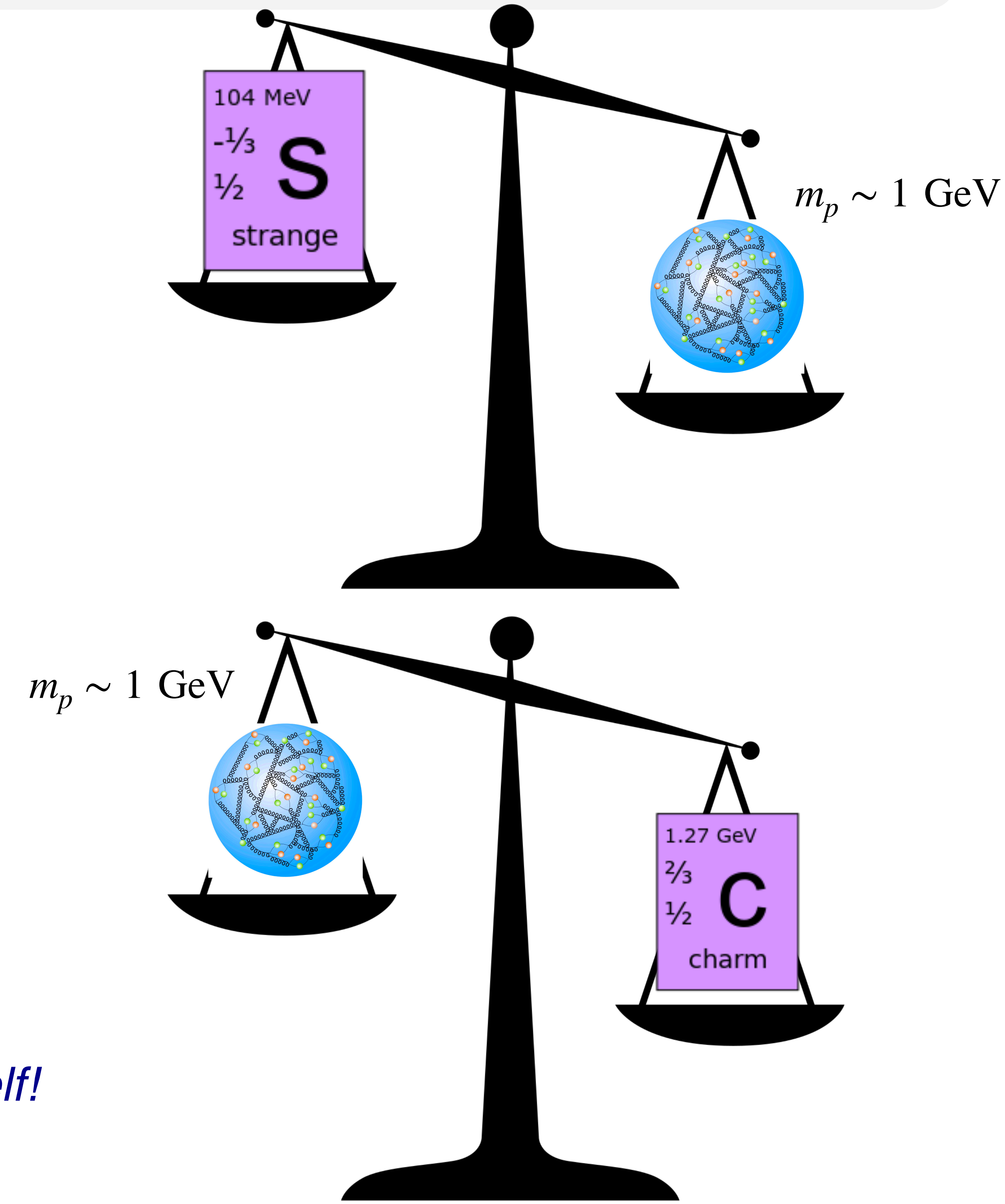
Radically different strategies to parametrize the **quark PDF flavour combinations** lead to identical results: ultimate test of **parametrisation independence**

Evidence for intrinsic charm in the proton

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

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

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

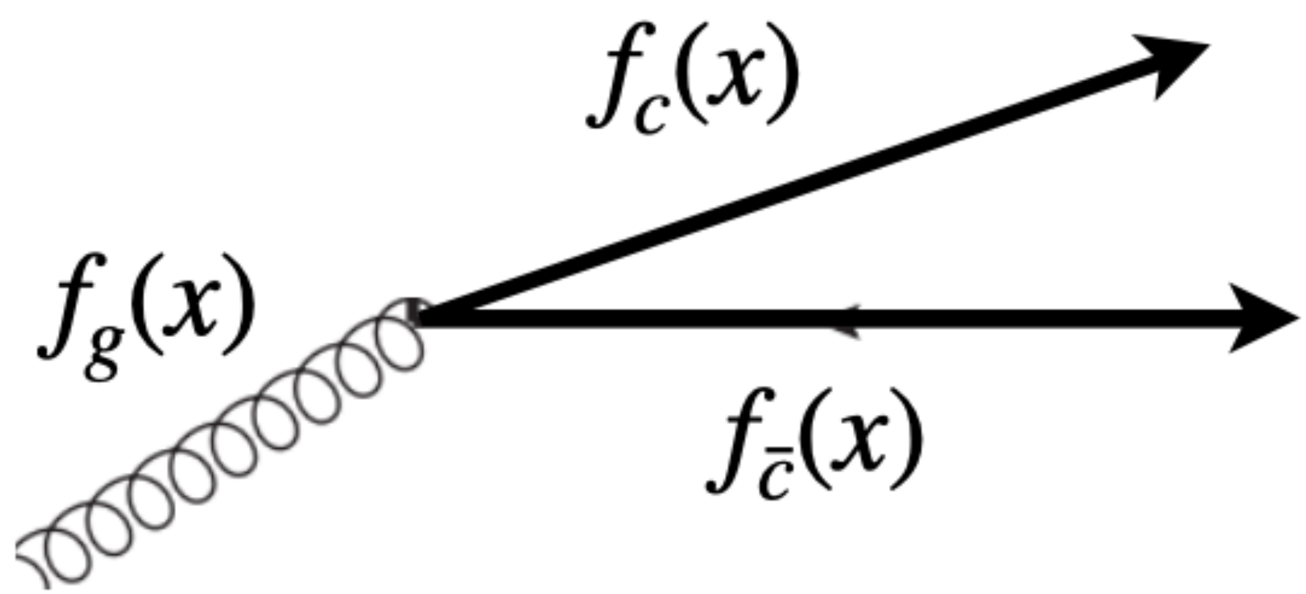
4 flavour scheme, $Q > m_c$

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

↕ ↕

3 flavour scheme, $Q < m_c$

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



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

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

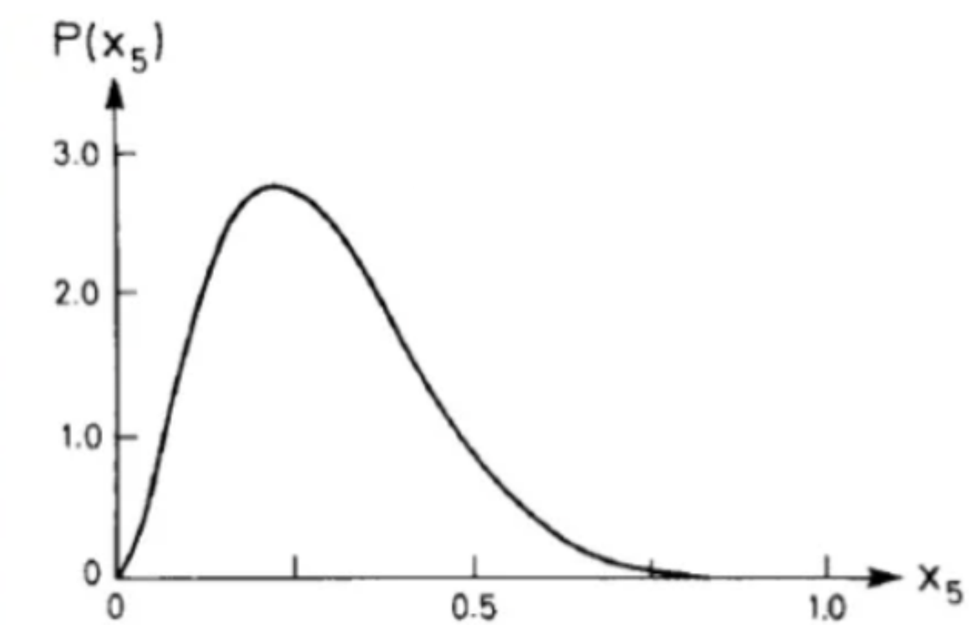
THE INTRINSIC CHARM OF THE PROTON

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**

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

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

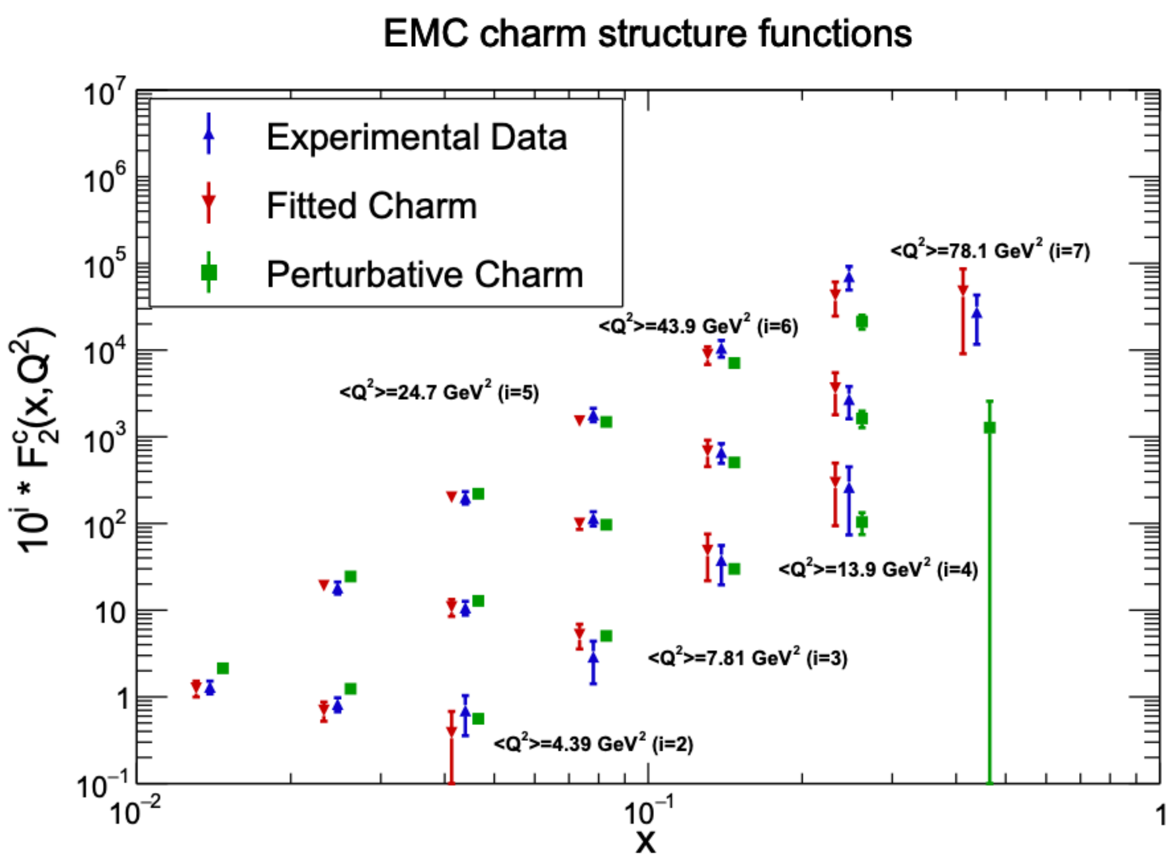
from QCD evolution and matching

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

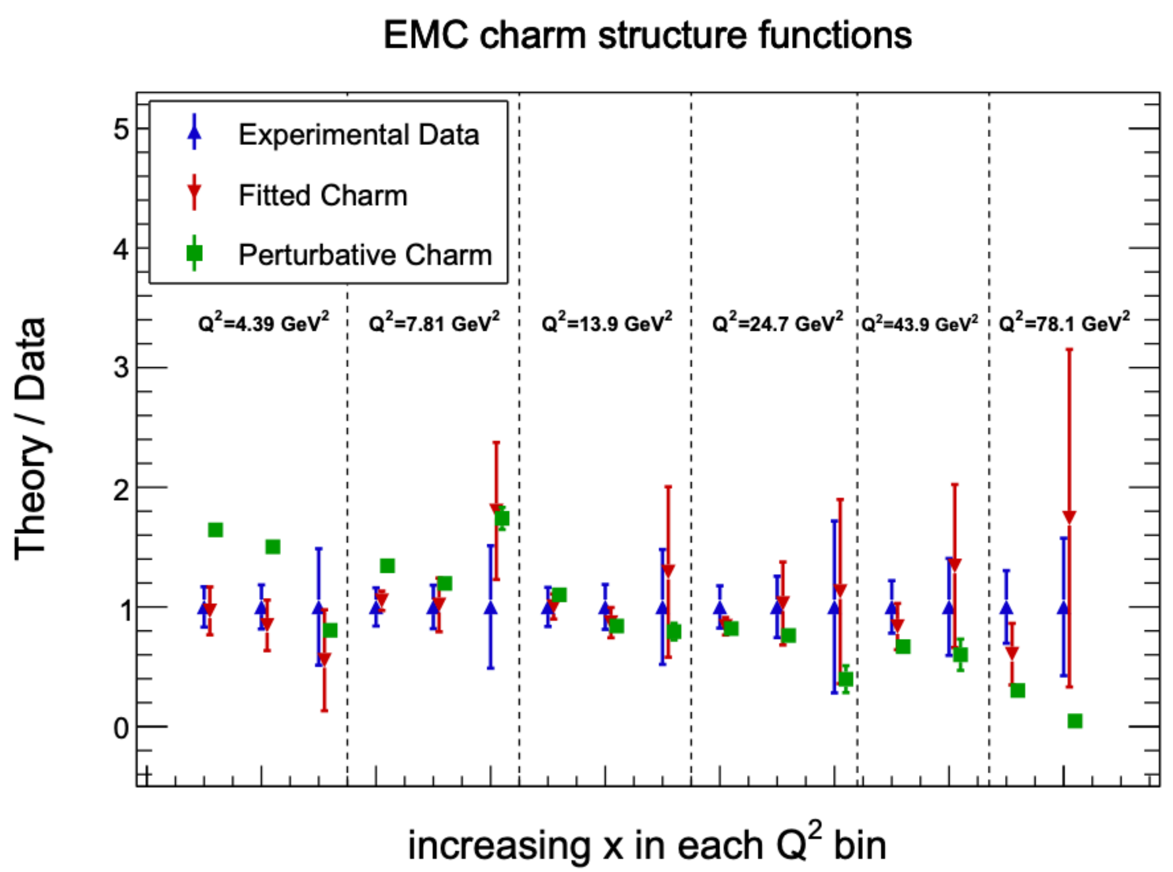
How to **disentangle perturbative** from **intrinsic components?**

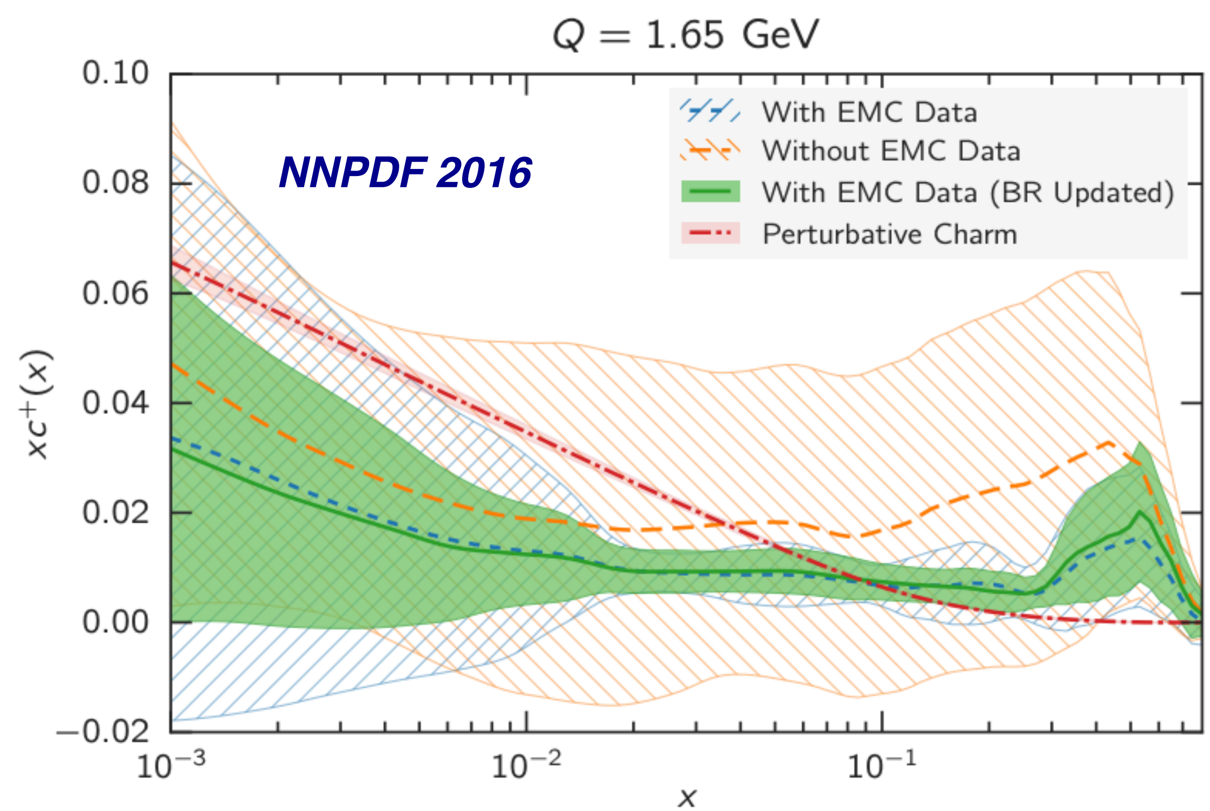
40 years of extensive searches for intrinsic charm: no unambiguous evidence ….

Back to the future



- **EMC charm structure functions** (1981): one of first 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**





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

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

Extracted phenomenologically from data

from pQCD evolution and matching

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

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

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

Extracted phenomenologically from data

from pQCD evolution and matching

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

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

$Q_0 =$ 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

EKO
Evolution Kernel Operators

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

↓

Intrinsic (3FNS) Charm
- Scale-independent
- PDF and MHO uncertainties

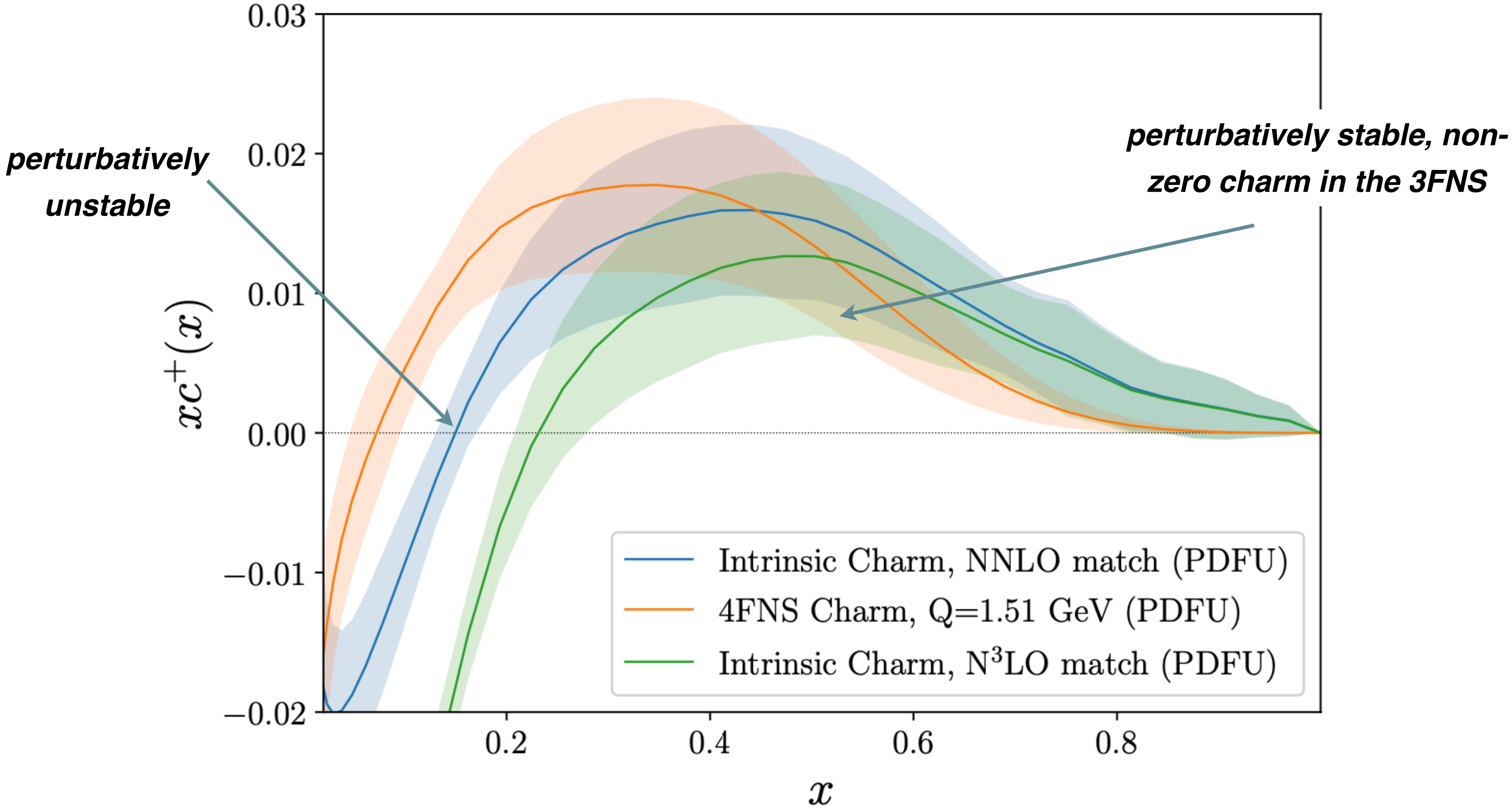
4FNS to 3FNS transformation

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

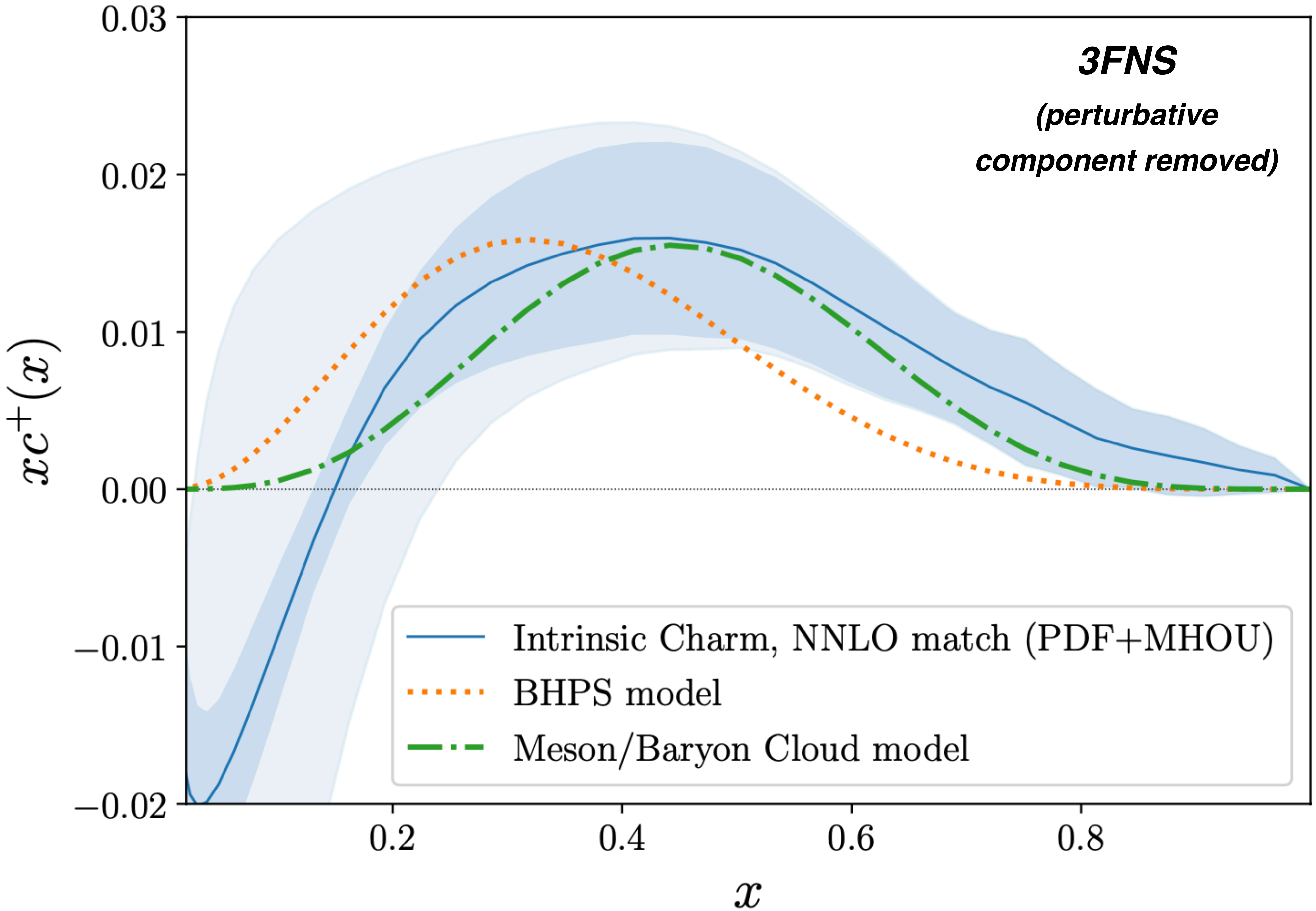
4FNS PDFs | **DGLAP kernel** | **scheme matching conditions** | **DGLAP kernel** | **3FNS PDFs**

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

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



Intrinsic charm!

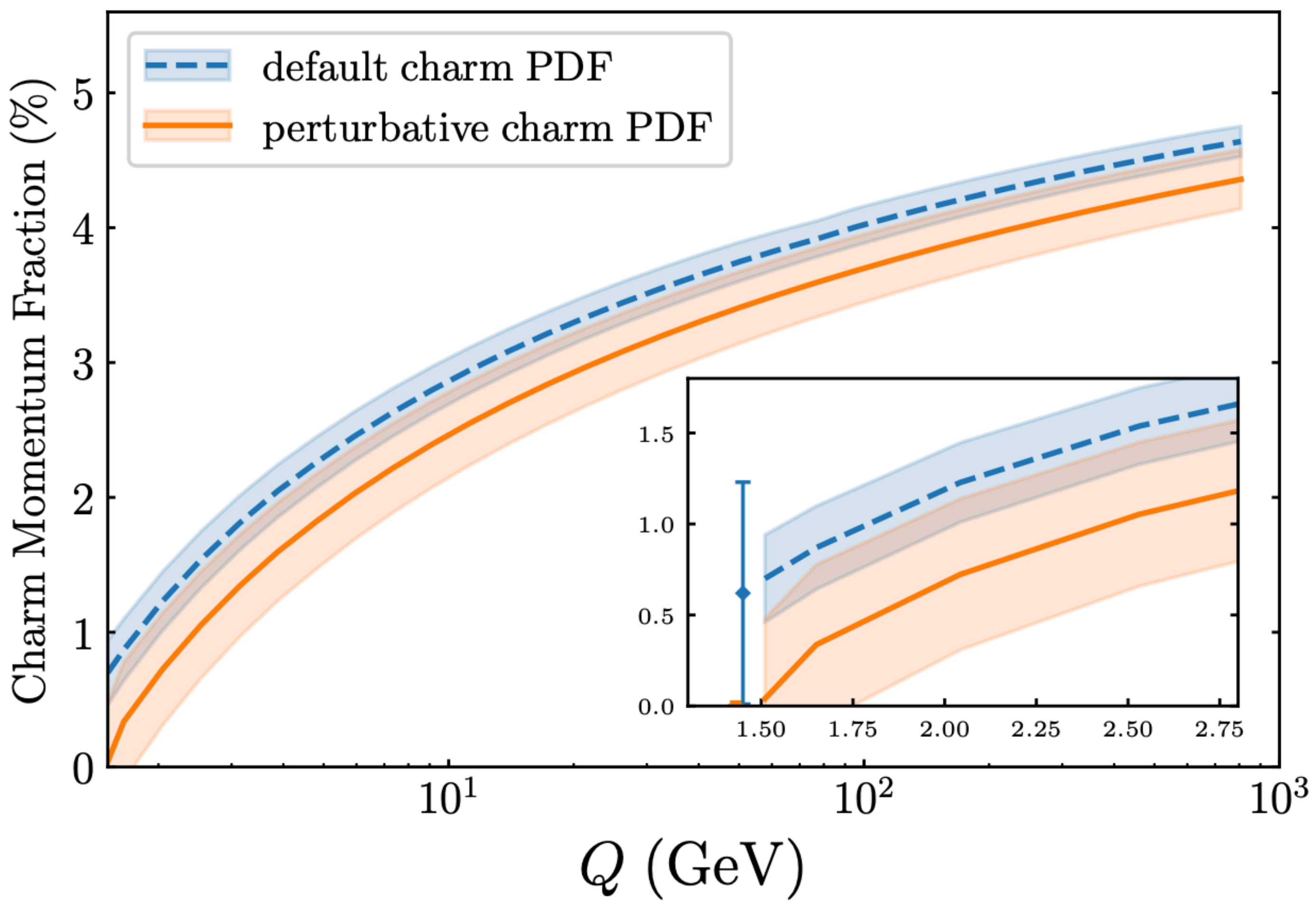


The 3FNS charm PDF displays **non-zero component** peaked at large-*x* **(3σ local significance)** identified with **intrinsic charm**

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

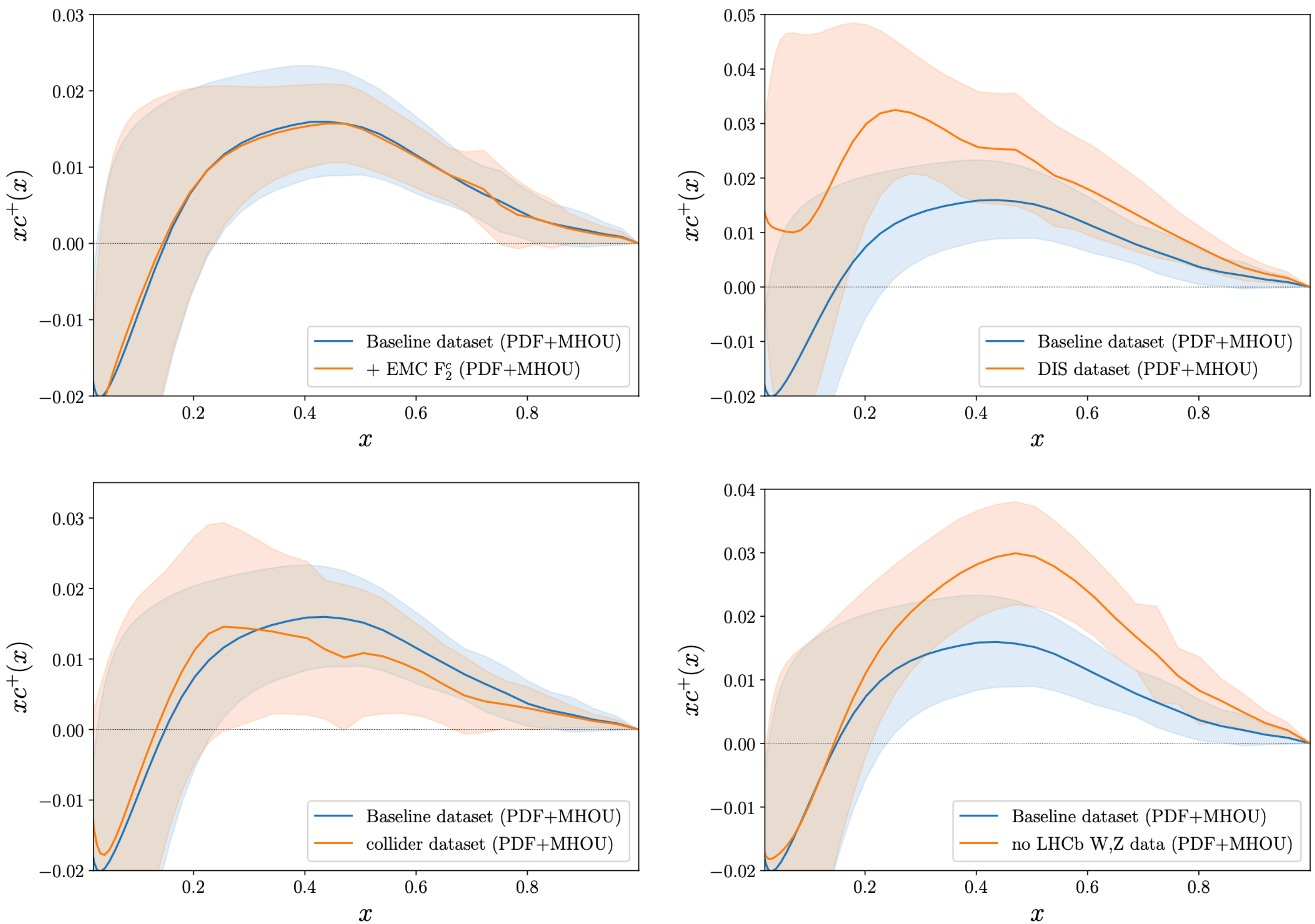
The charm momentum fraction

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

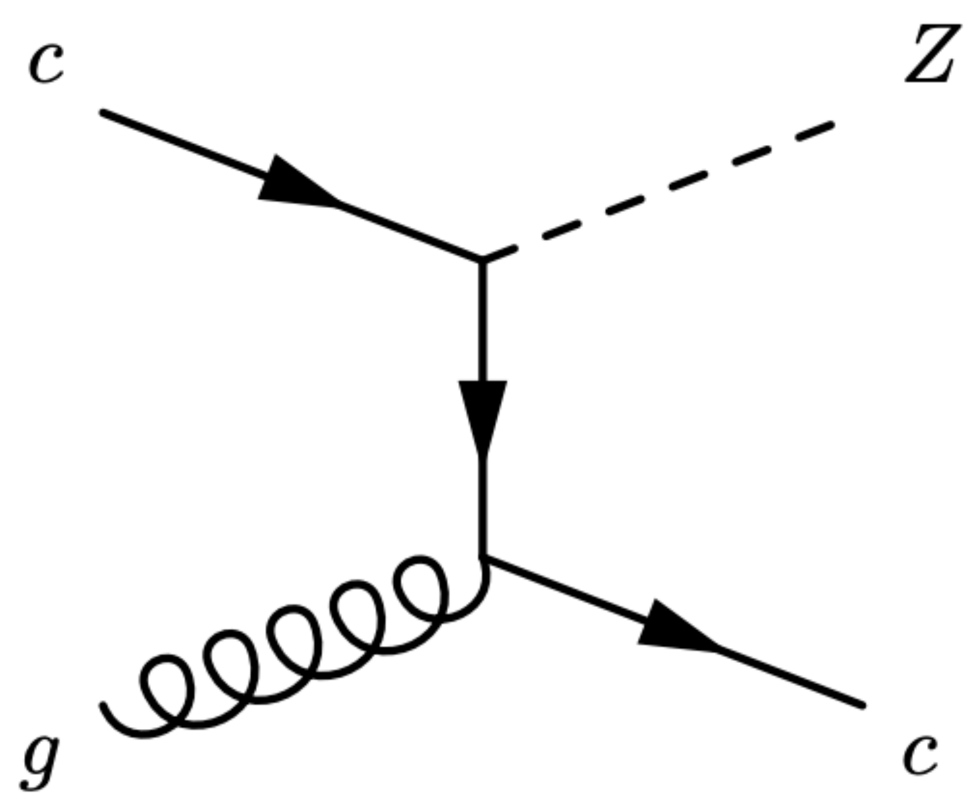


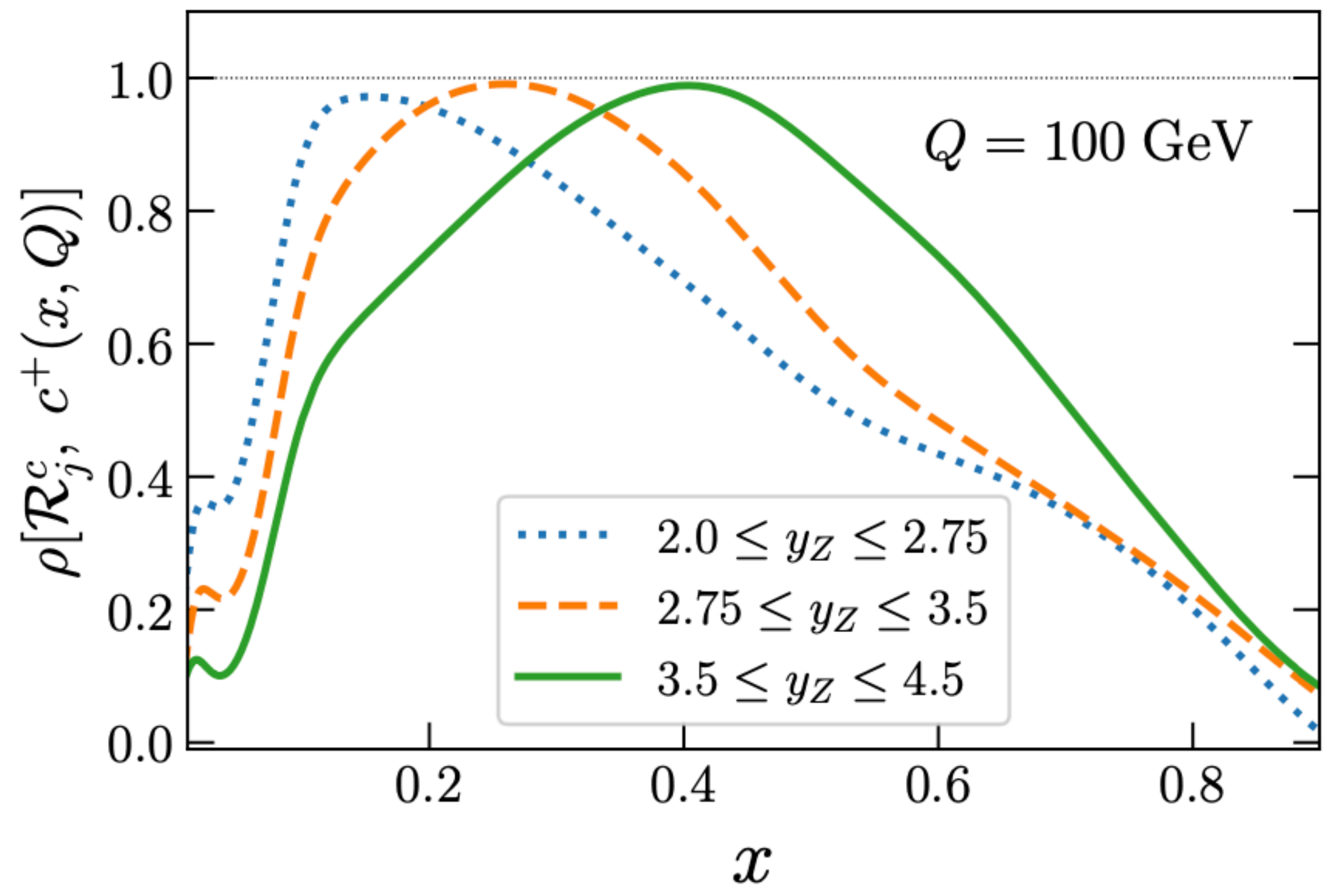
Consistent results for **DIS-only** and **collider-only fits**: no single dataset dominates the charm PDF

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

Z+charm @ LHCb

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

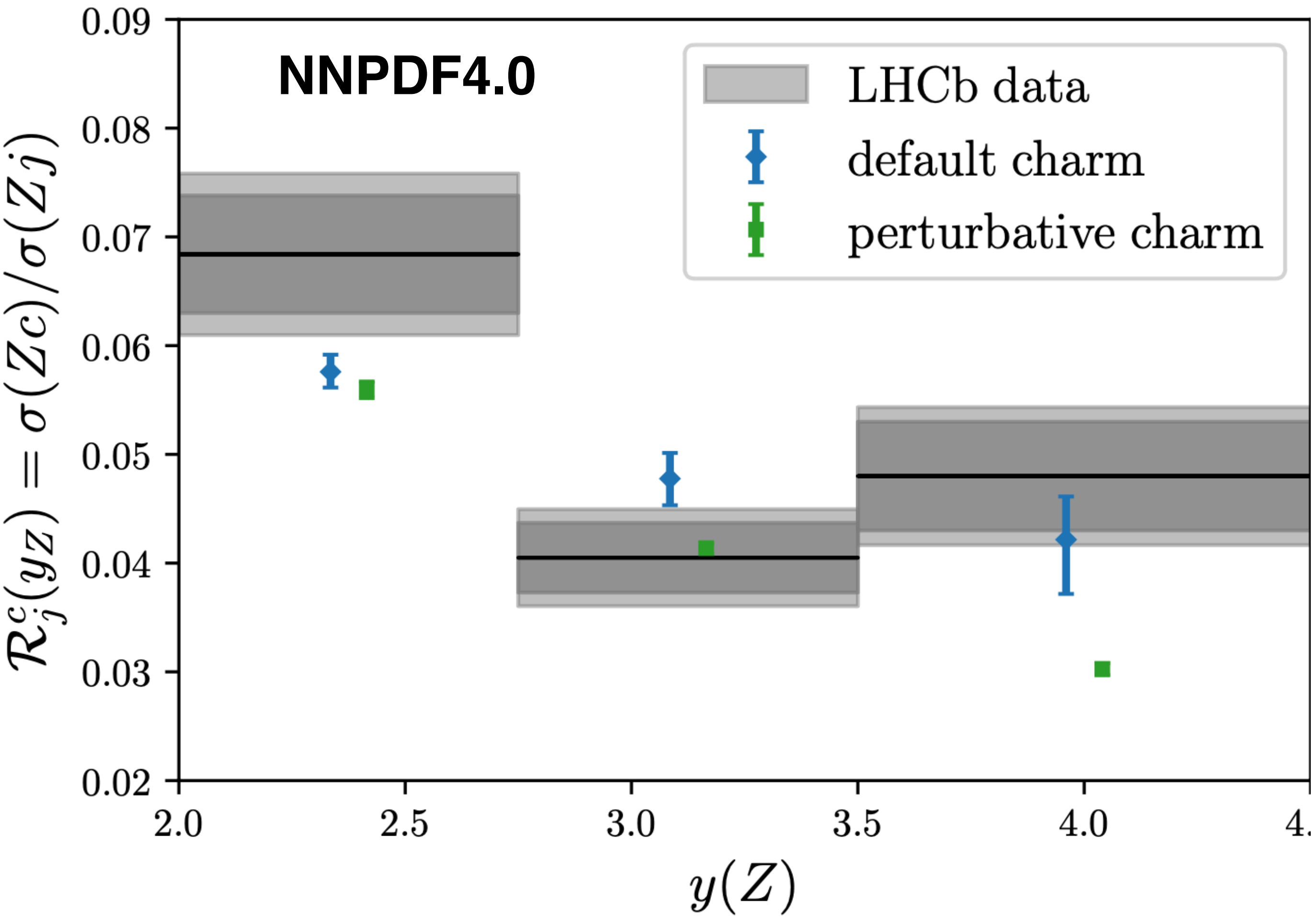


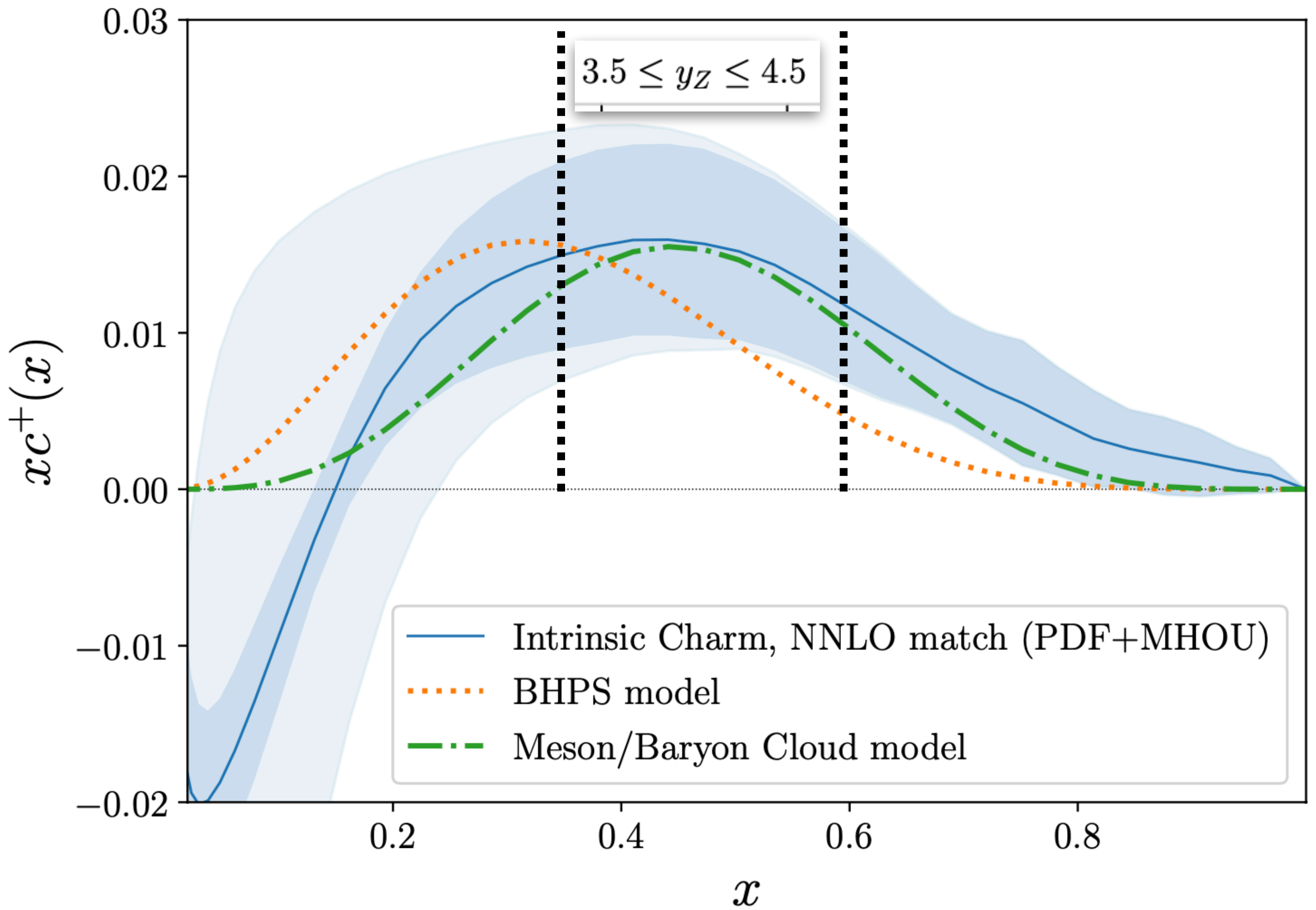


$$\mathcal{R}_j^c(y_Z) \equiv \frac{N(c\text{ tagged jets}; y_Z)}{N(\text{jets}; y_Z)} = \frac{\sigma(pp \to Z + \text{charm jet}; y_Z)}{\sigma(pp \to Z + \text{jet}; y_Z)}$$

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

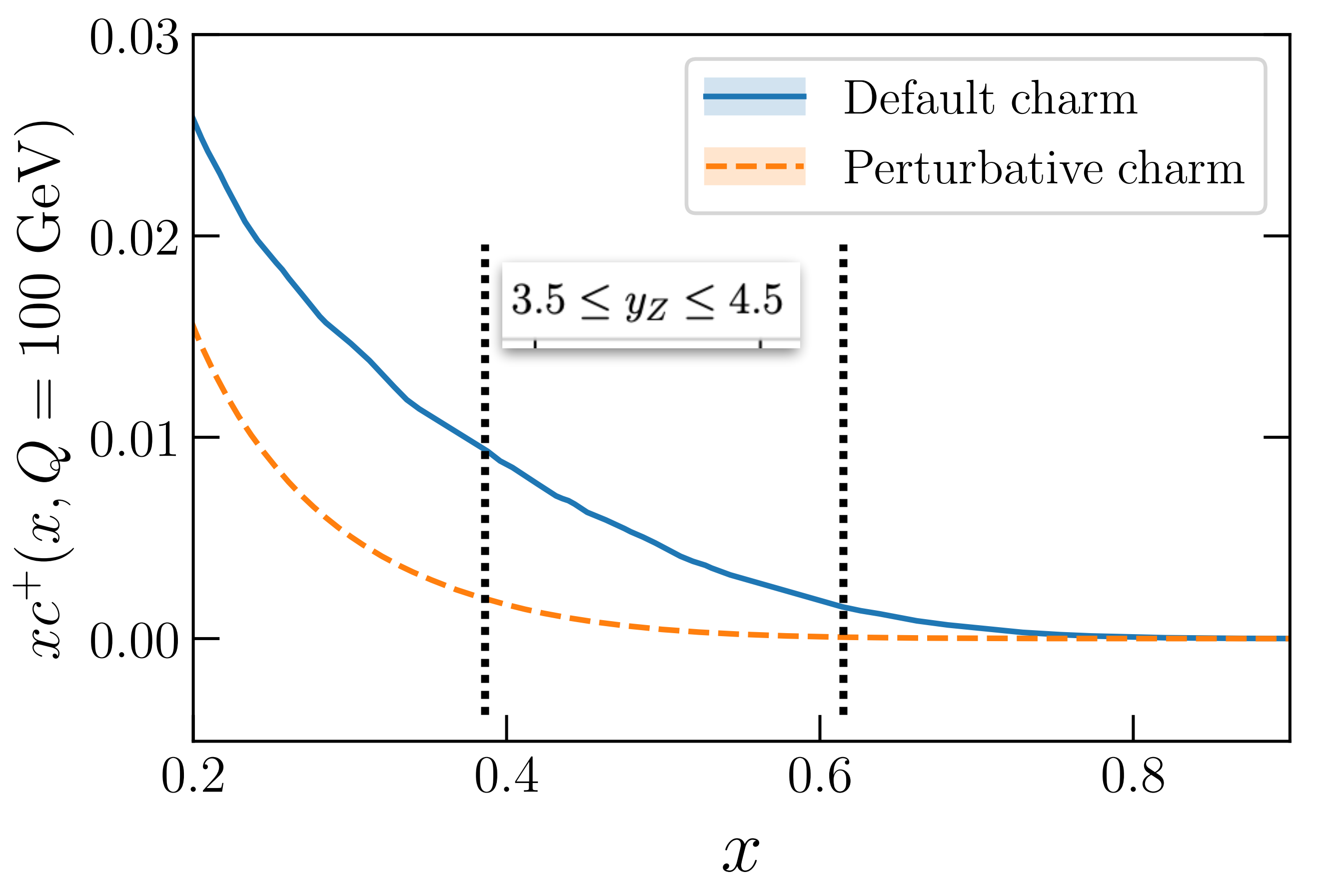
Z+charm @ LHCb



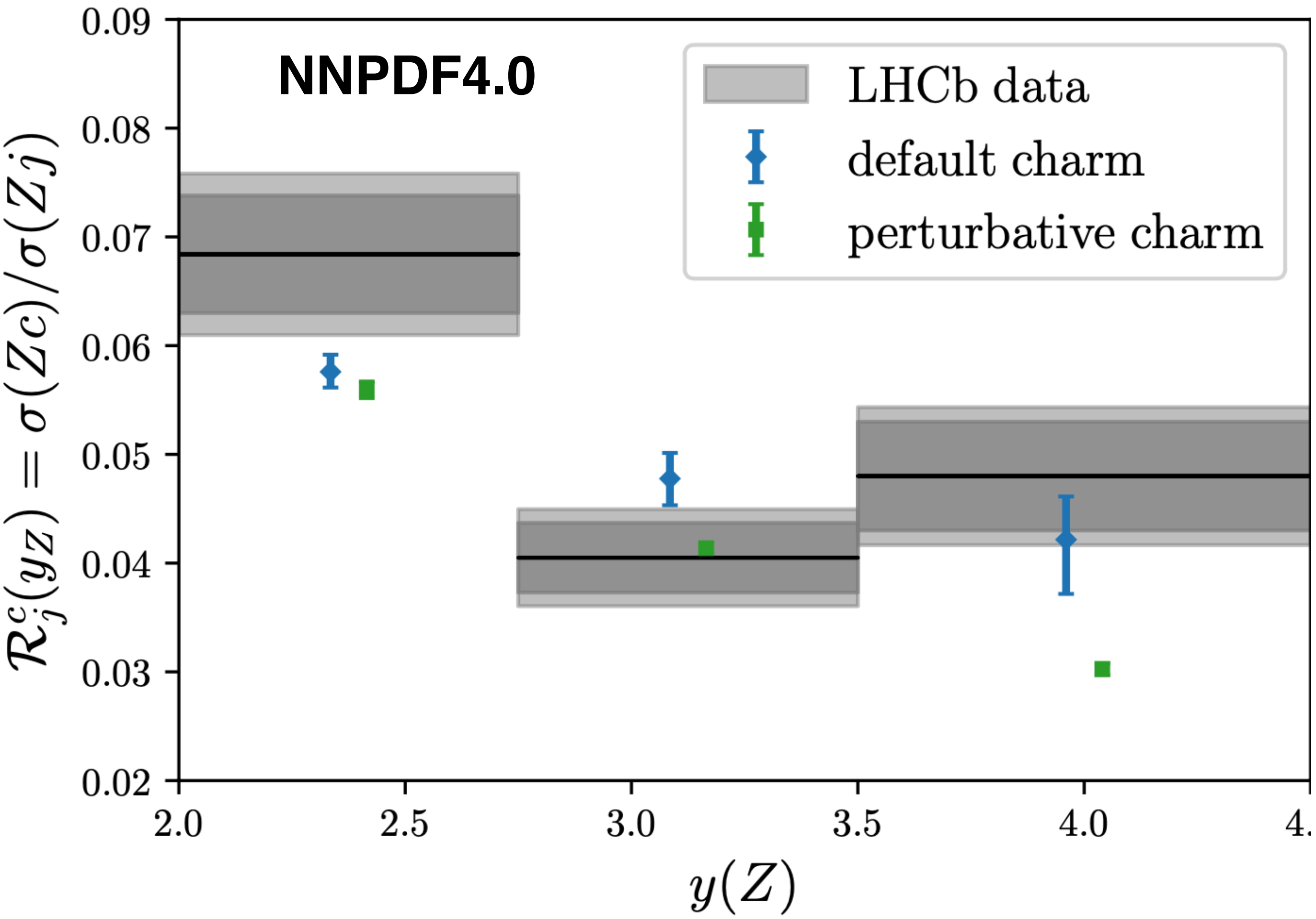


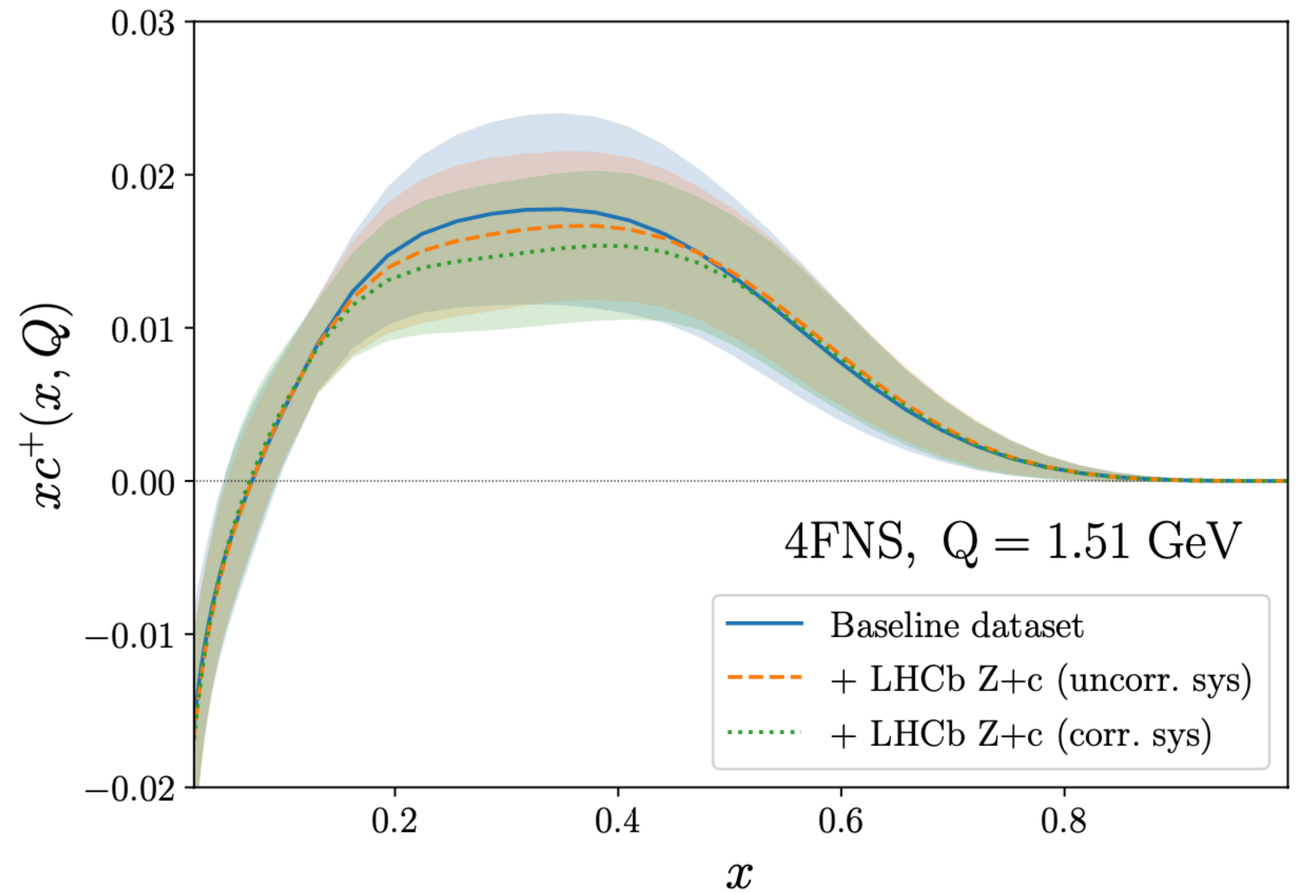
- A perturbative charm PDF **disagrees** with the LHCb forward Z+charm data

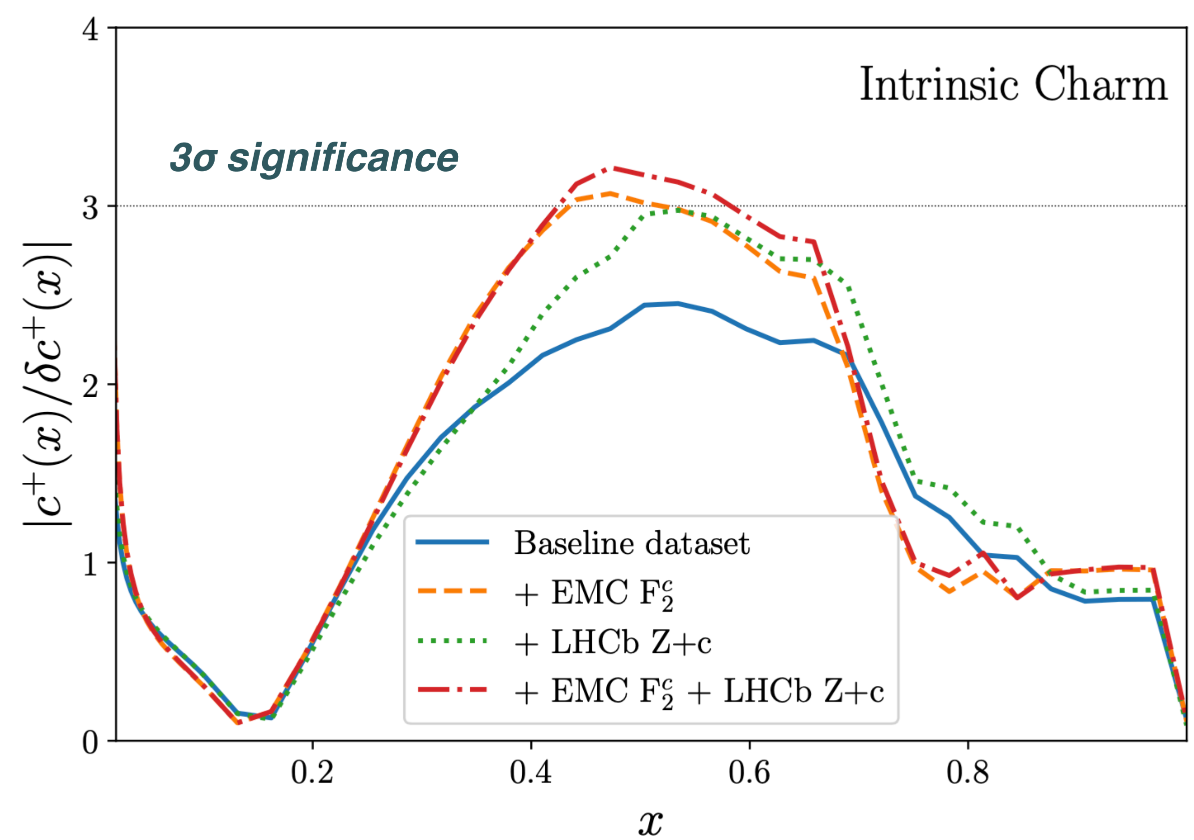
- LHCb data favour intrinsic charm hypothesis, with IC carrying **0.5% of proton's momentum**



Z+charm @ LHCb







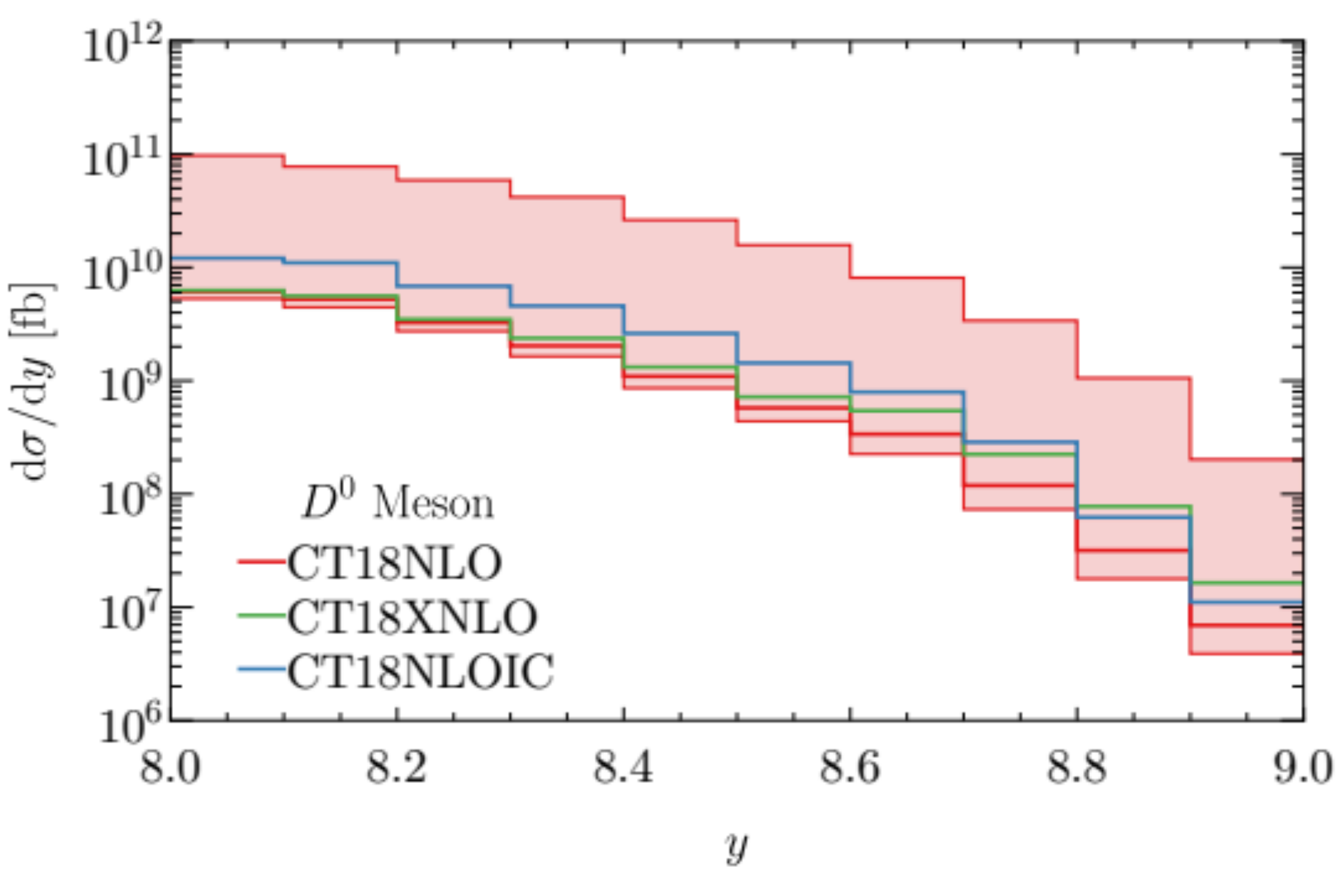
- A perturbative charm PDF **disagrees** with the LHCb forward Z+charm data
- LHCb data favour intrinsic charm hypothesis, with IC carrying **0.5% of proton's momentum**
- Striking consistency between **direct** (Z+c, EMC F_2^c) **and indirect constraints** on the charm PDF

Implications

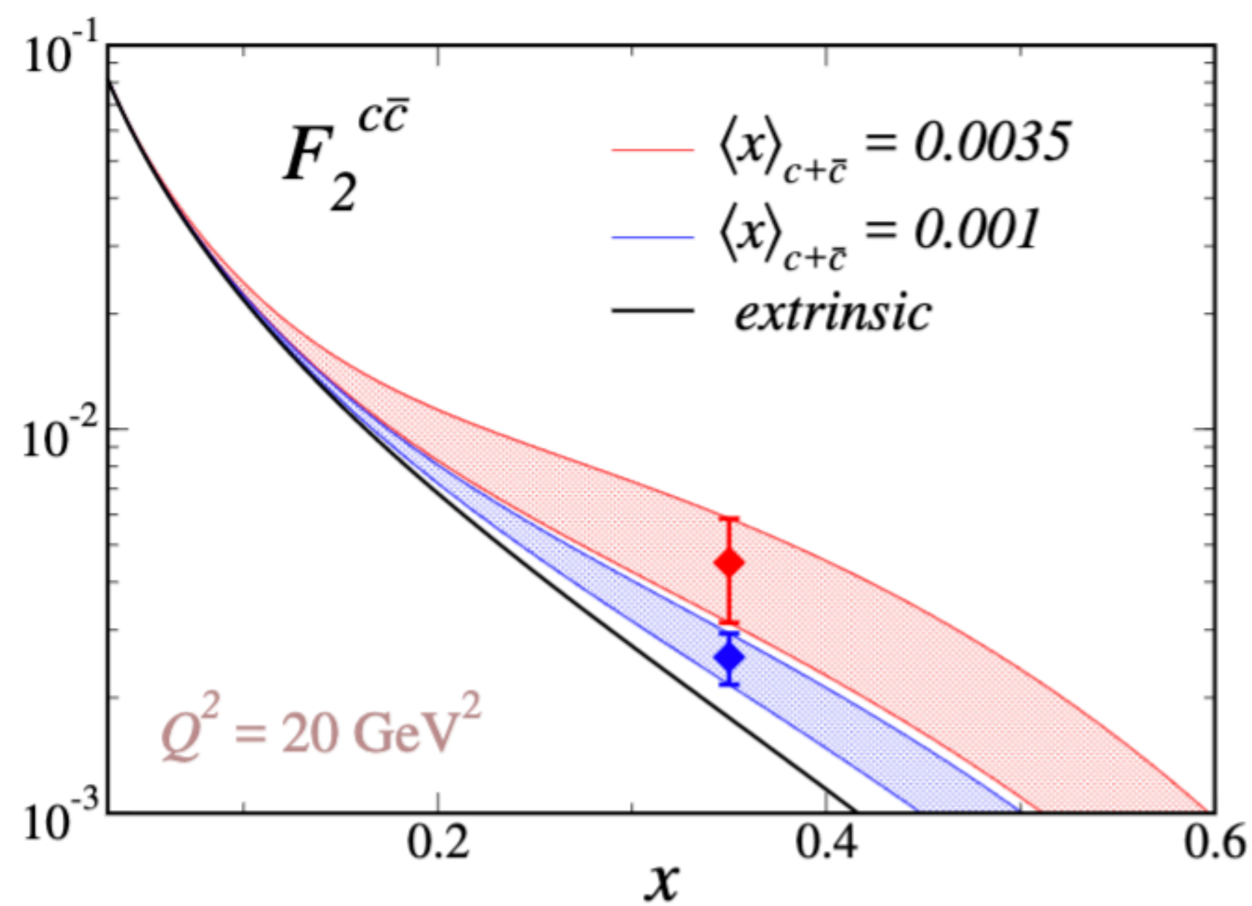
Further testing intrinsic heavy quarks

- With more LHC data, study also the possibility of **intrinsic bottom quarks** and of an **intrinsic charm/anticharm asymmetry**
- 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

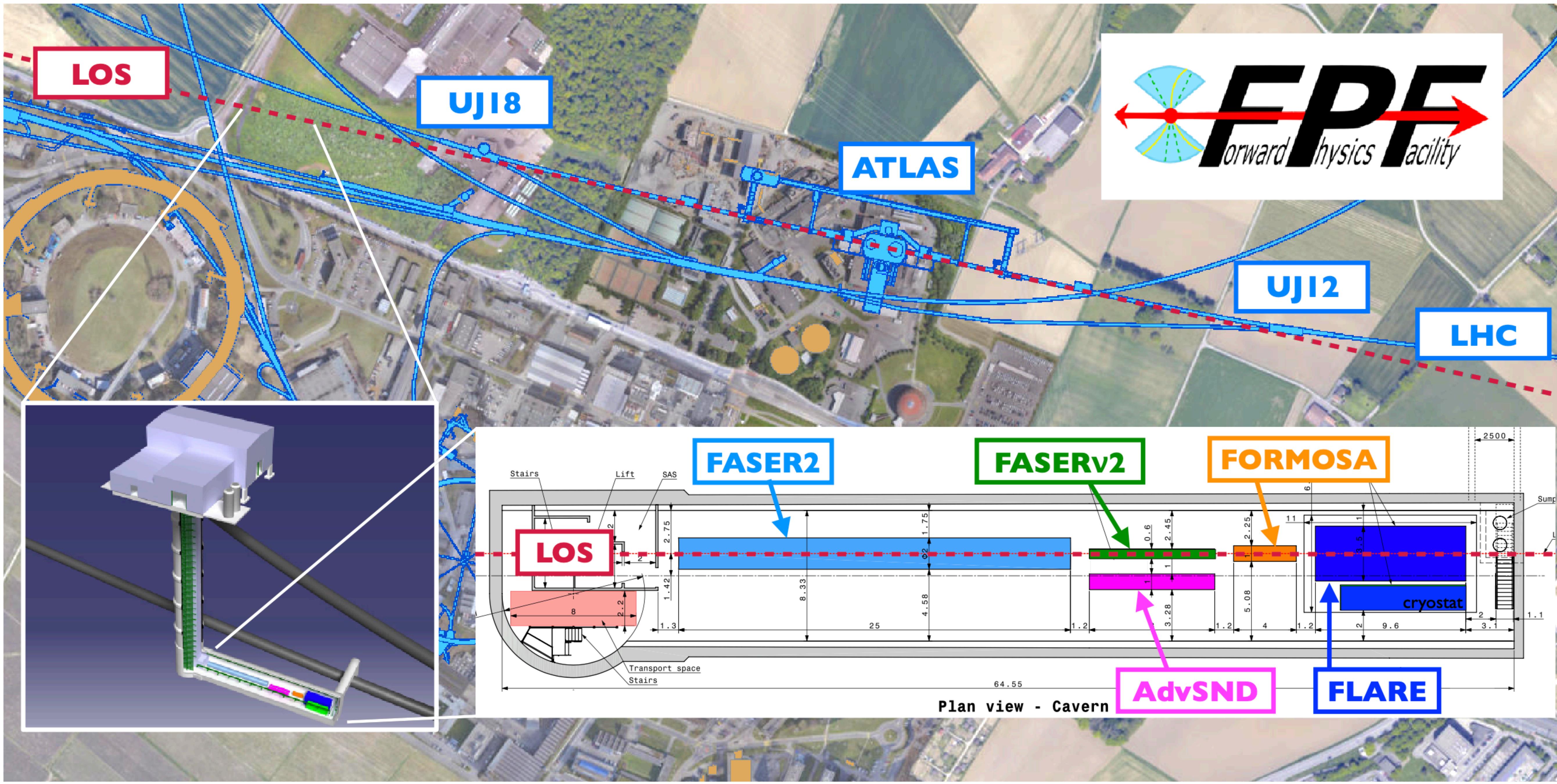


charm @ EIC



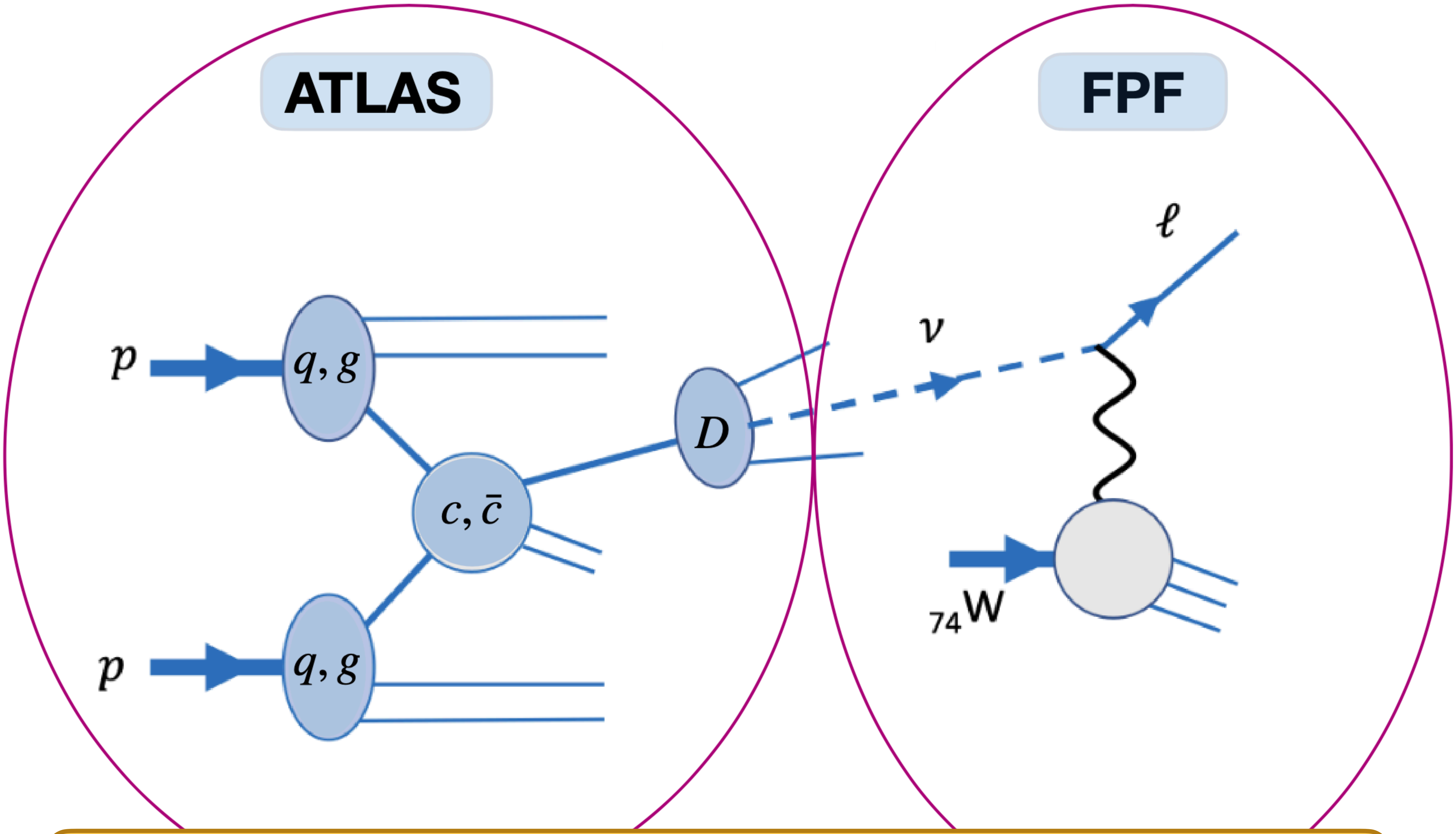
The Forward Physics Facility

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)



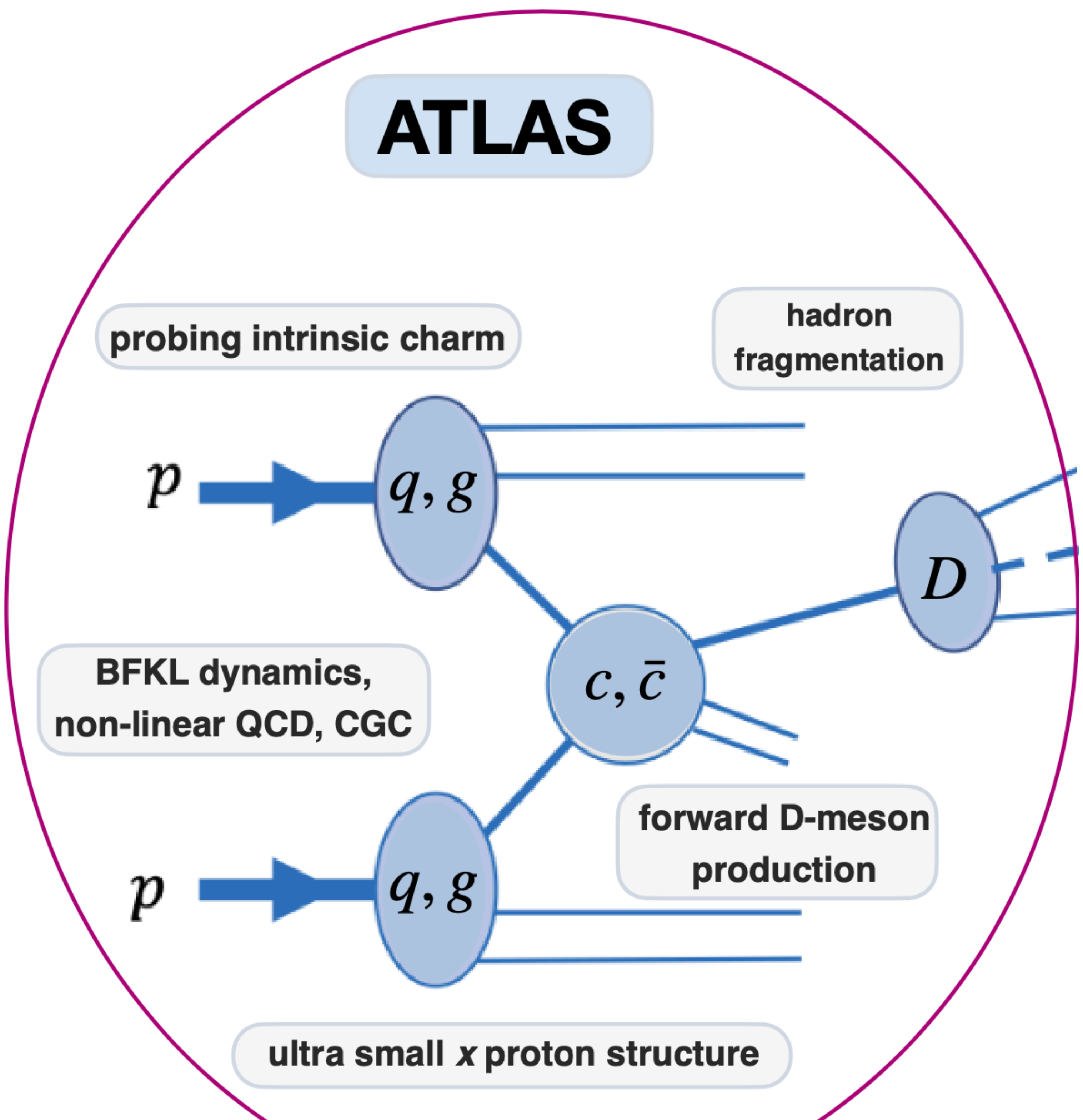
No modifications to the HL-LHC required!

The Forward Physics Facility

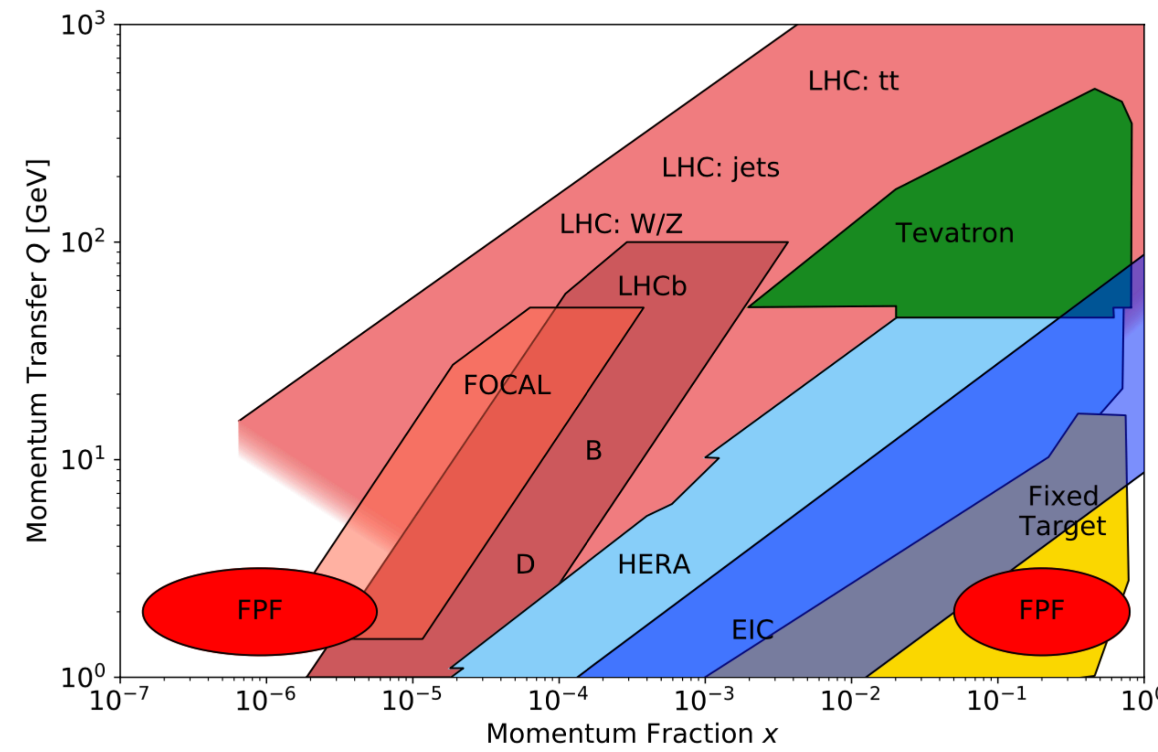


Huge **neutrino** fluxes produced in LHC collisions: **blind spot** of planned LHC operations!

QCD at the FPF

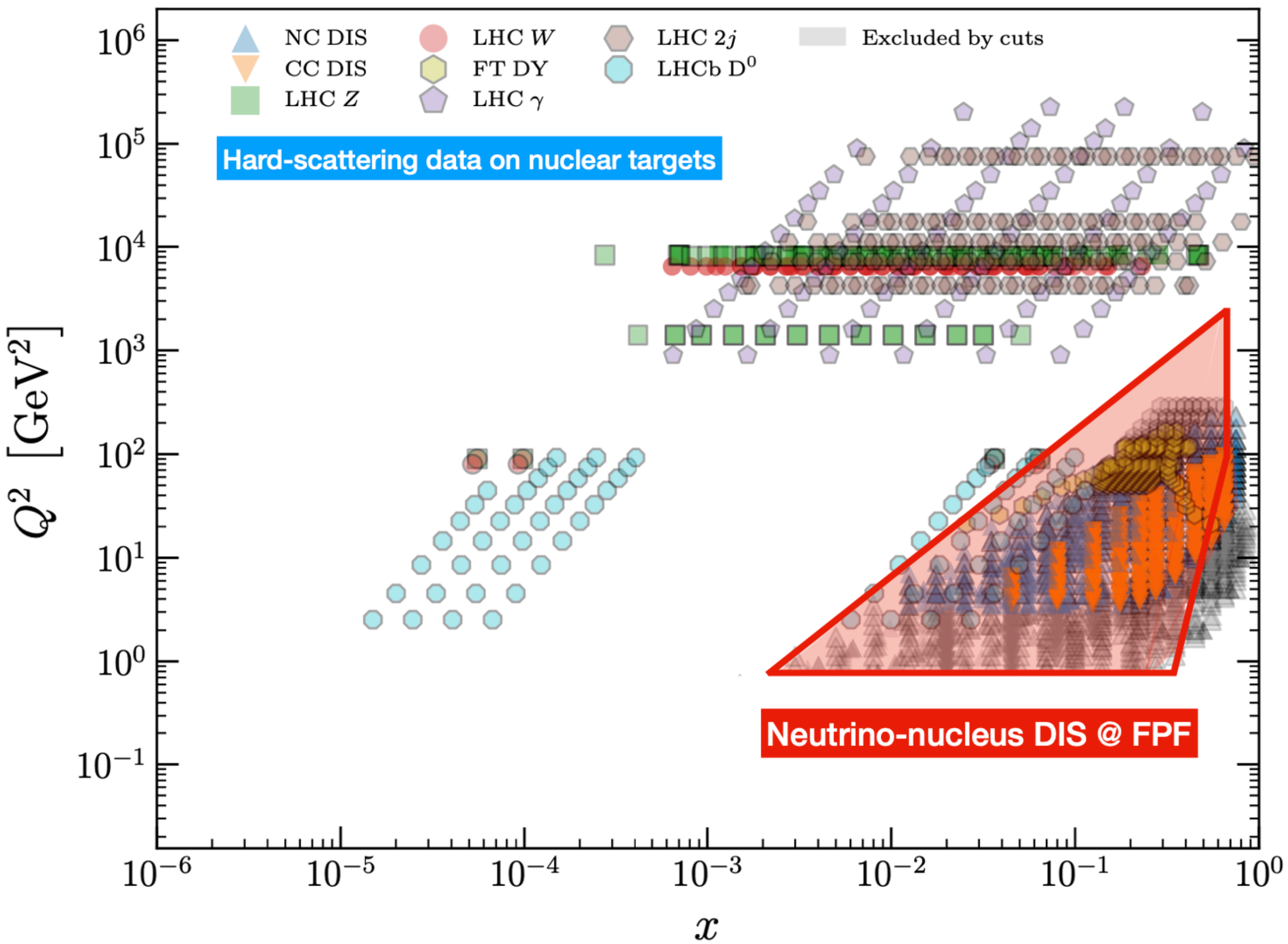


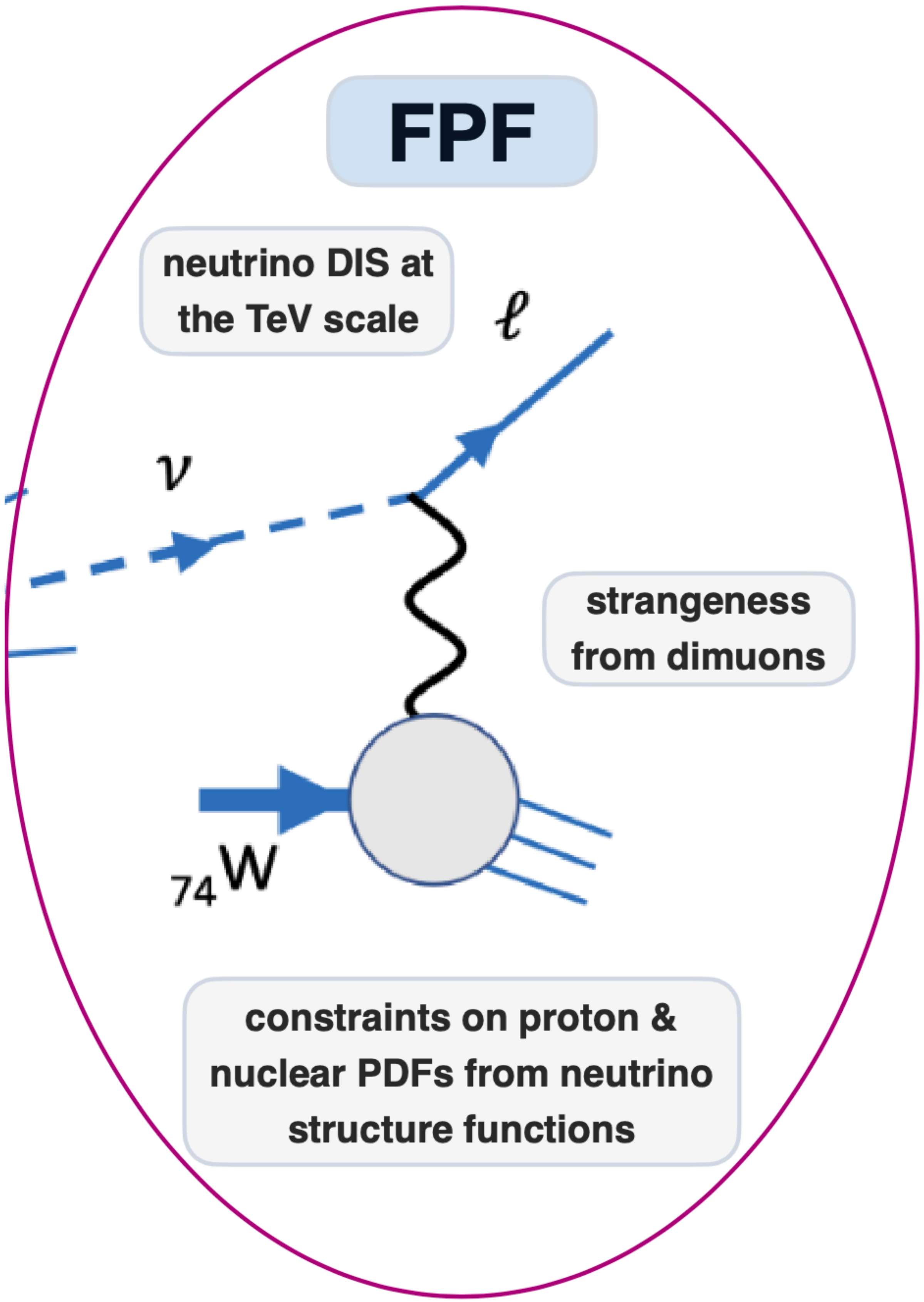
+ unique inputs for **high-energy neutrino** and **cosmic ray** astroparticle physics experiments



- **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**

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

- IC will be further tested by **upcoming LHC analyses** as well as by the **EIC**, the **FPF**, as well as at high-energy astroparticle physics facilities