STRONG-2020

Public Lecture Series

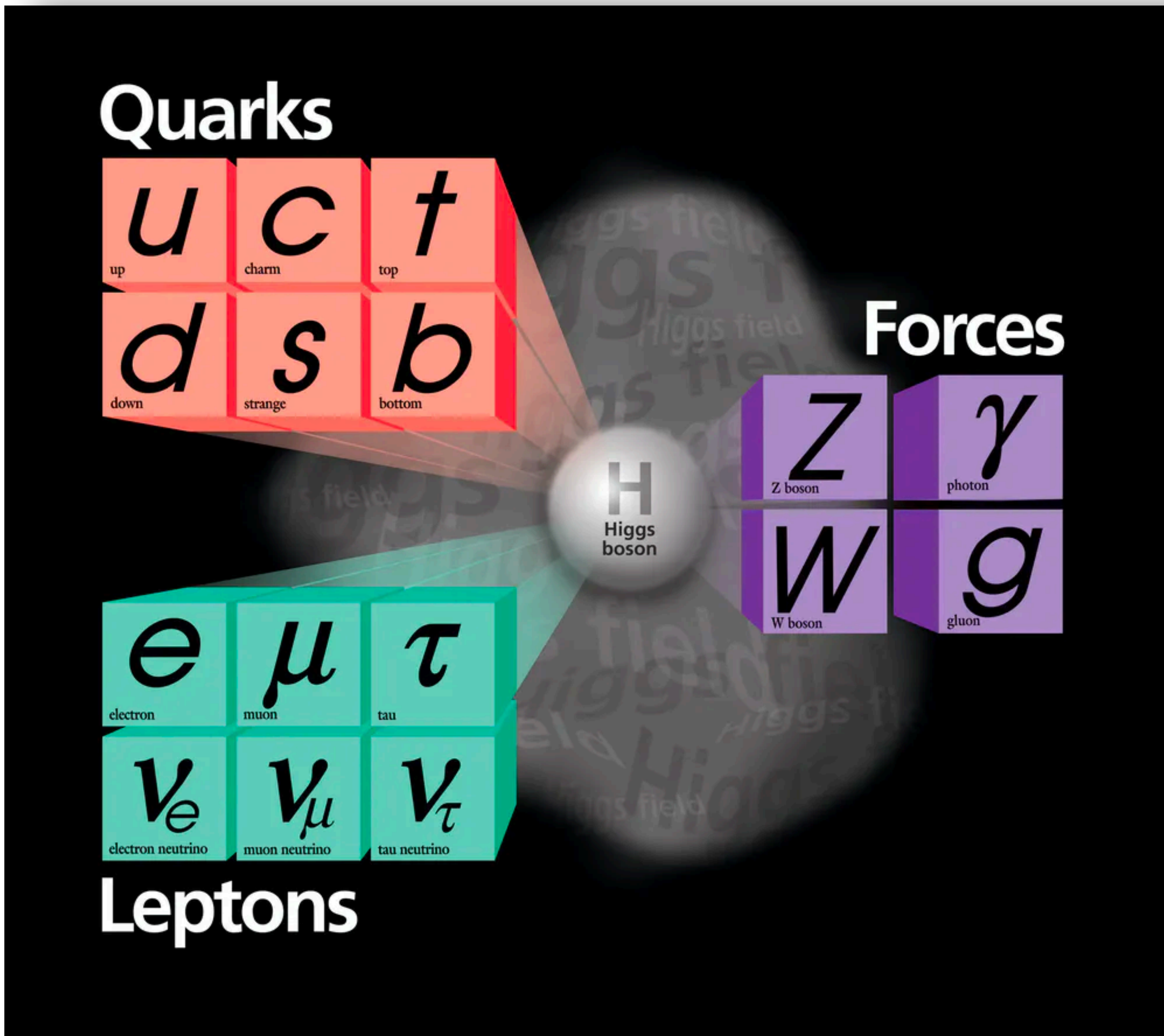
The Heart of Matter: The Secret Inner Life of Protons

Prof. Dr. Juan Rojo
Professor of Theoretical Physics
Department of Physics and Astronomy, VU Amsterdam

At the heart of matter: particle physics in the LHC era

The Standard Model

Standard Model of particle physics: hugely succesful, powerful framework describing **elementary particles** and their **interactions**



matter particles

- 6 quarks *(fractional charge)*
- 3 charged leptons (*e.g. electron*)
- 3 neutrinos *(only weak charge)*
- Organised in **3 generations:** identical (?) except for mass

force carriers

- photon (*electromagnetism*)
- gluon (*strong nuclear force*)
- weak bosons (*weak nuclear force*)

Higgs boson

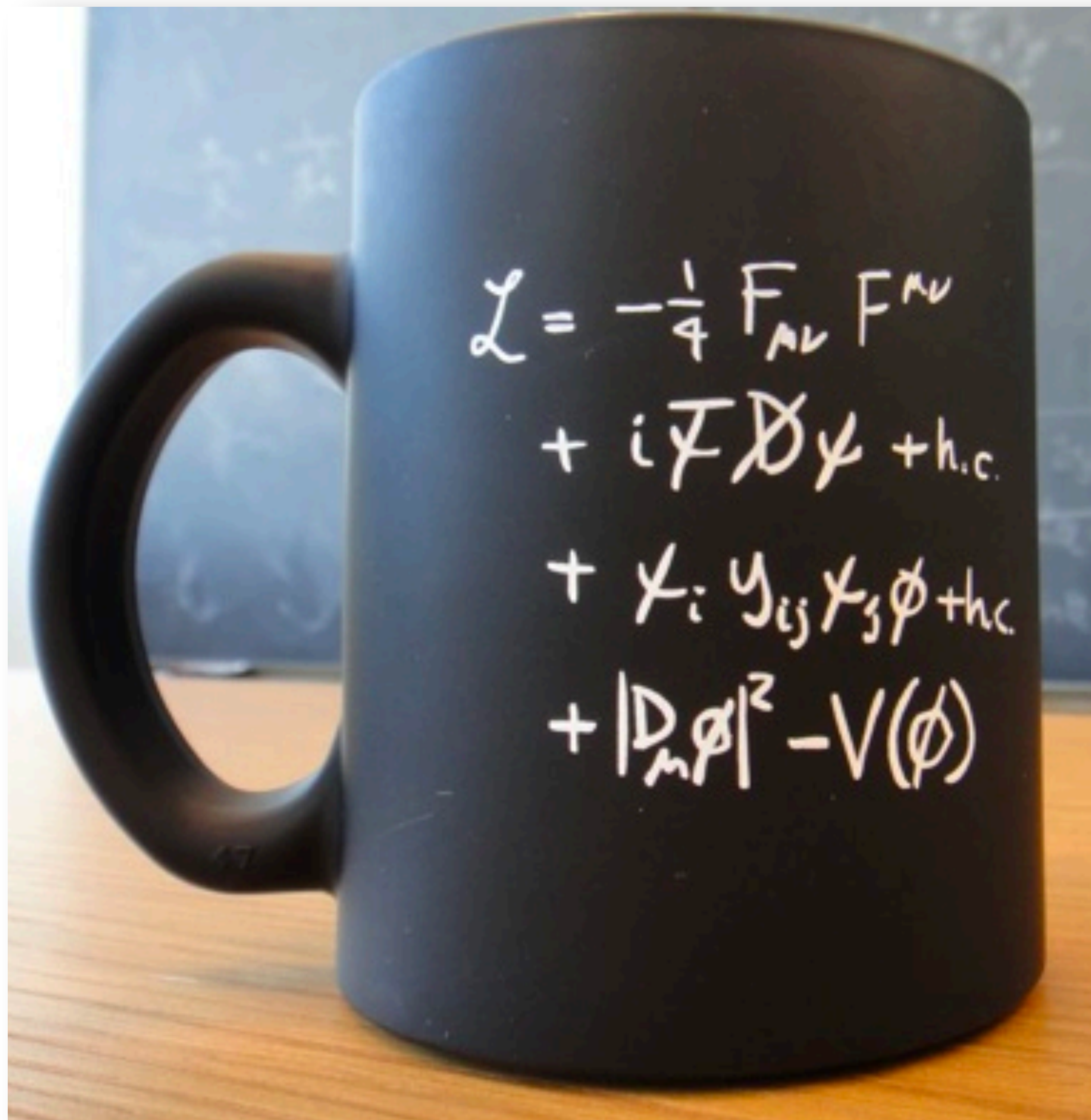
both matter particle and force carrier!

The (incomplete) Standard Model

Standard Model of particle physics: hugely succesful, but leaves many foundational questions unanswered

Origin of particle masses and Higgs force?

Where is all the missing Antimatter?



What is Dark Matter?

Quantum Gravity? Inflation?

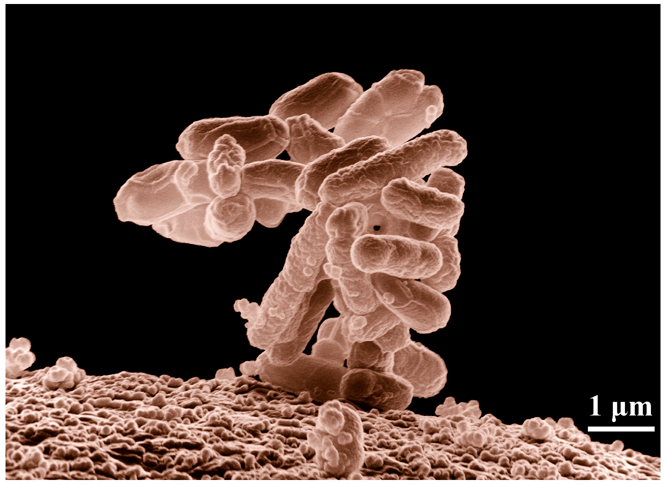
requires new particles and interactions beyond the Standard Model!

Journeys into the Zeptospace

lenght units $\rightarrow L = 10^{-10}$ m (Bohr's radius, size of H atom)

energy/mass units $\rightarrow E = 10^{9}$ eV $= 1$ GeV (mass of H atom, $E=mc^2$)

long distances
& low energies



bacteria (10^4 *L*)

short distances
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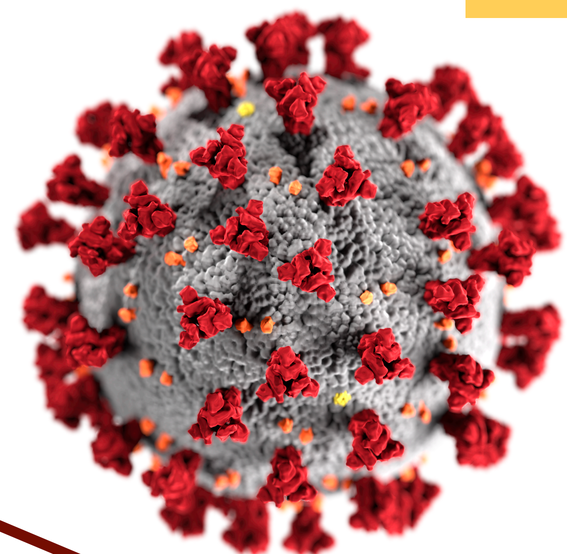
virus (10^3 *L*)



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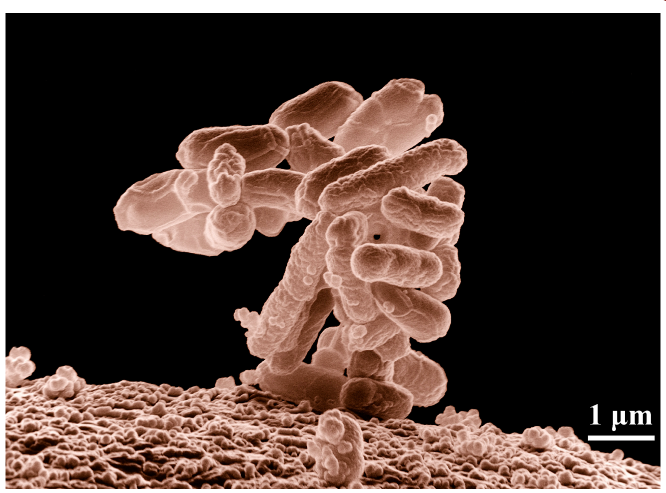

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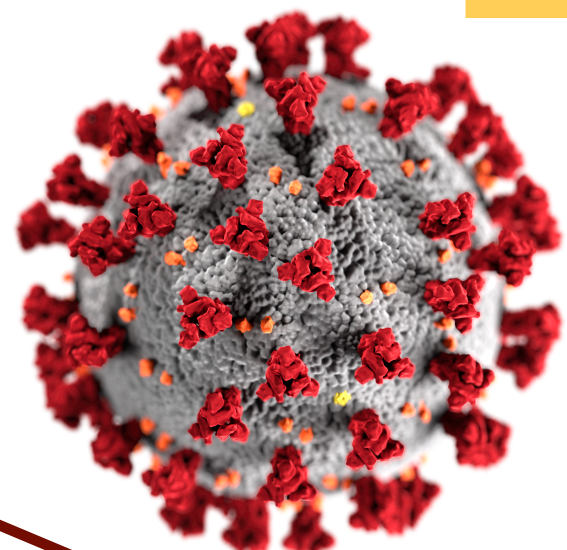
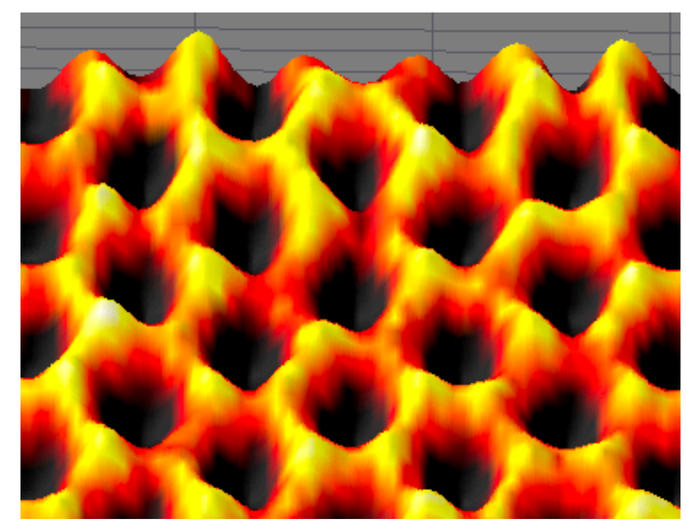
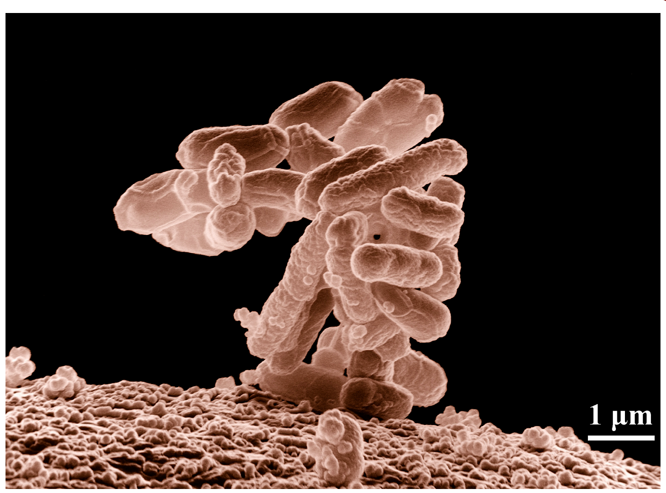


atoms (10^0 *L*, 10^0 *E*)





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short distances & large energies

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long distances & low energies

bacteria (10^4 *L*)

optical microscope (probe = 10^{-9} *E*)

virus (10^3 *L*)

scanning electron microscope

atoms (10^0 *L*, 10^0 *E*)

transmission electron microscope (probe = 10^{-5} *E*)

short distances & large energies

Journeys into the Zeptospace

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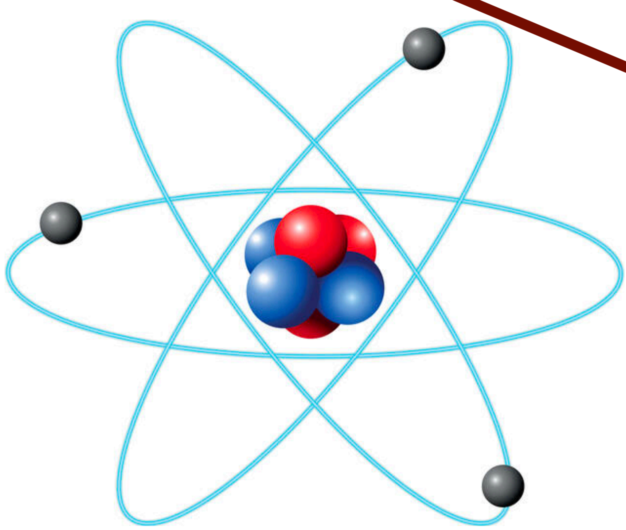
long distances & low energies



atomic nucleus (10^{-5} *L*)

short distances & large energies

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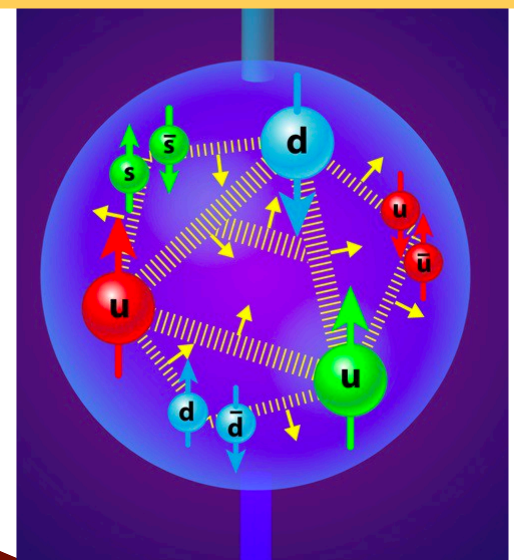
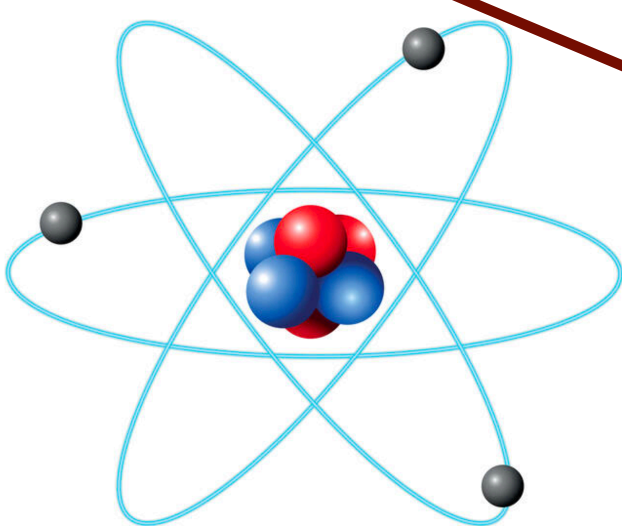
long distances & low energies

quark and gluon structure of protons (10^{-6} *L*)





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short distances & large energies

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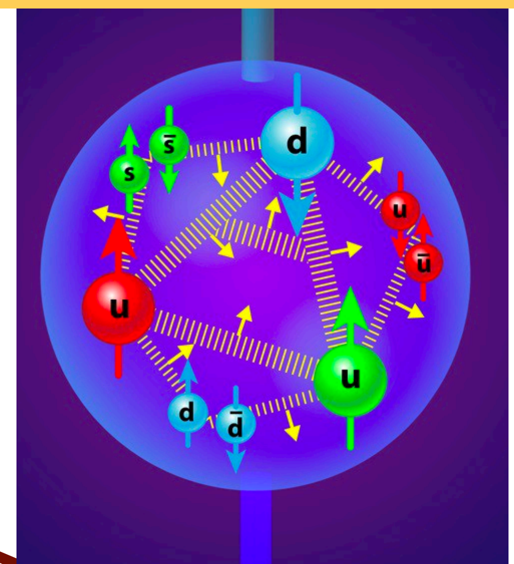
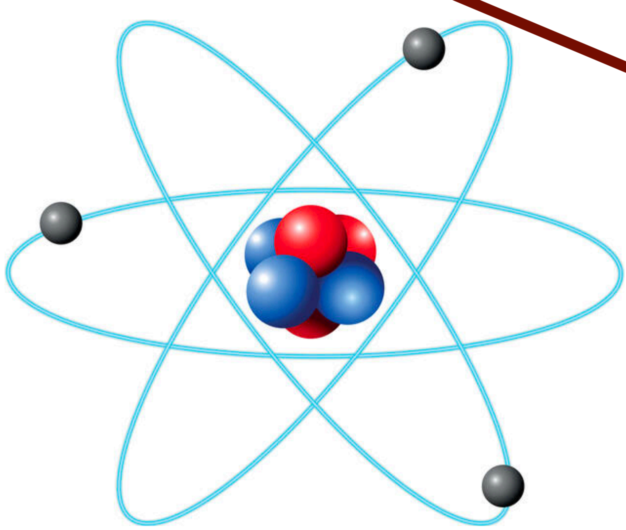
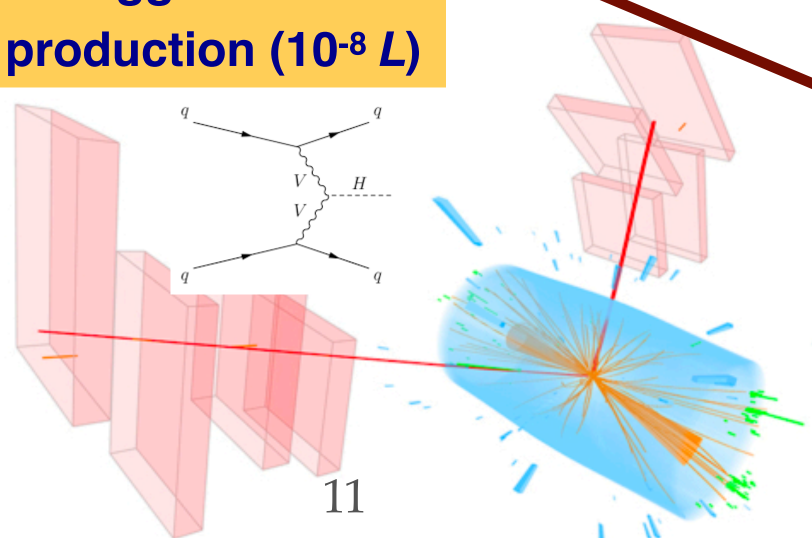




atomic nucleus (10^{-5} *L*)

Higgs boson production (10^{-8} *L*)



short distances & large energies

Journeys into the Zeptospace

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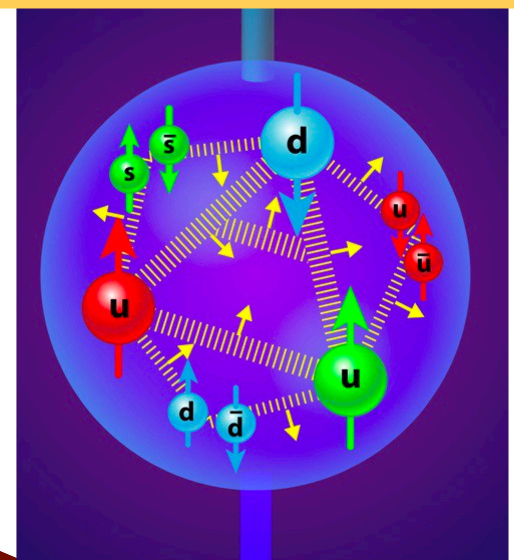
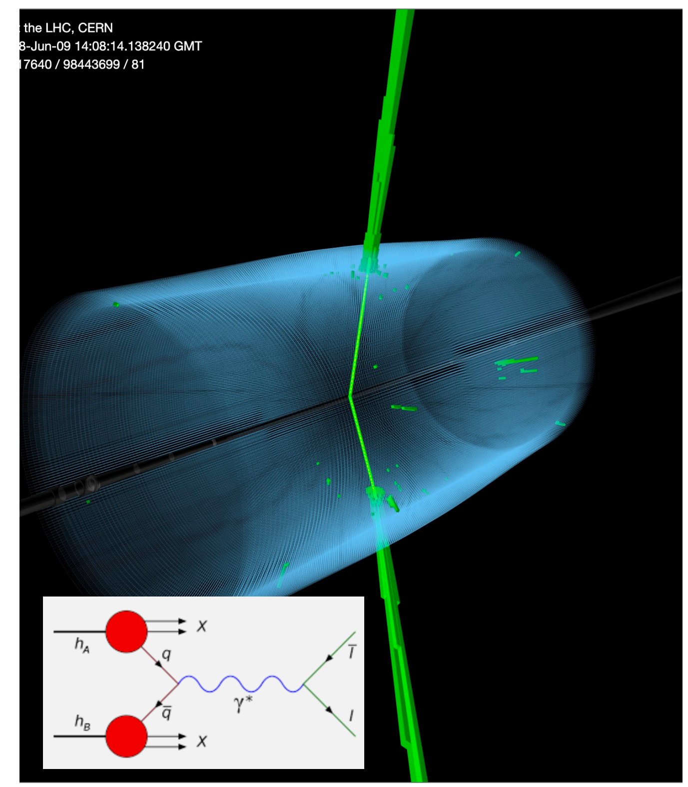
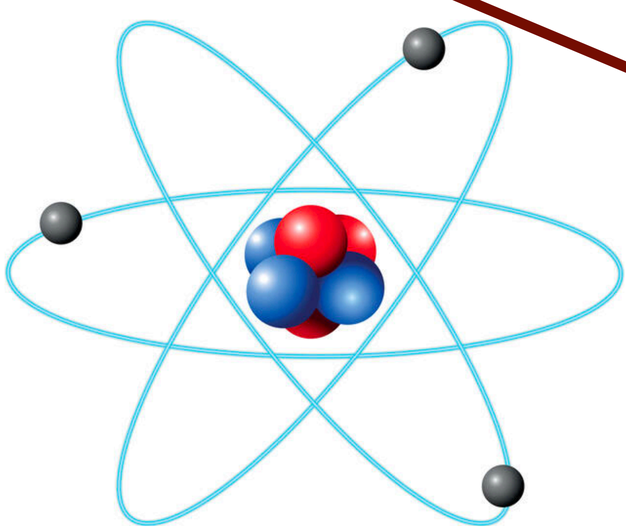
long distances & low energies

quark and gluon structure of protons (10^{-6} *L*)



high-mass Drell-Yan (10^{-10} *L*)





atomic nucleus (10^{-5} *L*)

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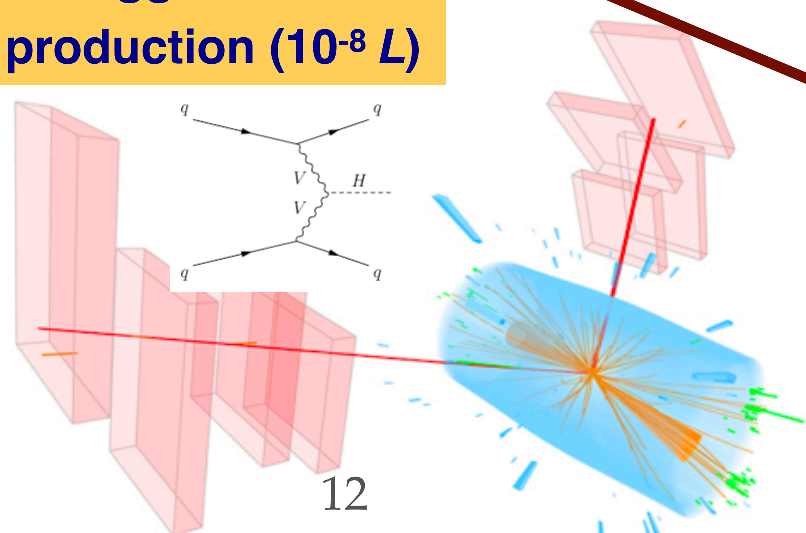

The Zeptospace! 10^{-11} L

short distances & large energies

Journeys into the Zeptospace

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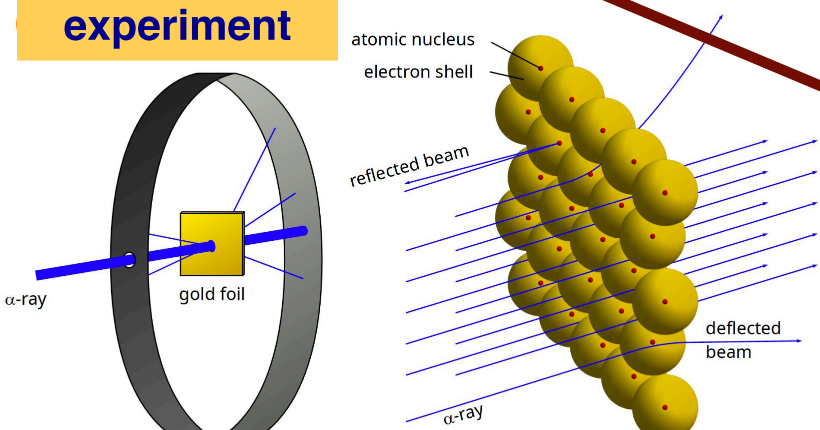
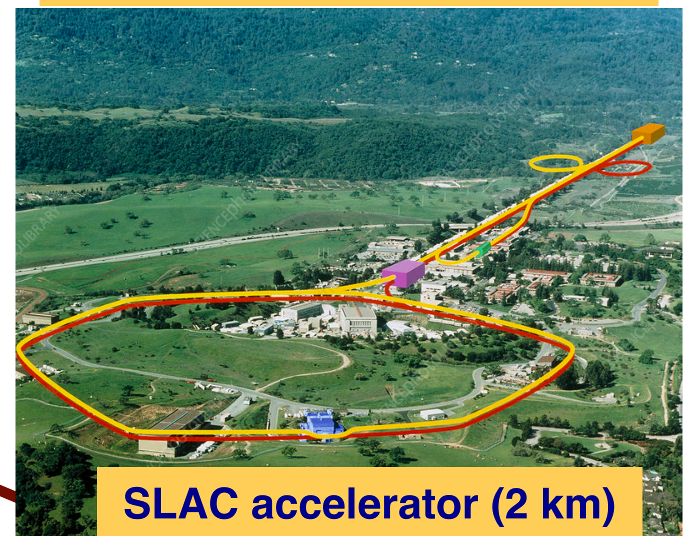
long distances & low energies

Rutherford's experiment



atomic nucleus (10^{-5} *L*, probe 10^{-3} E)

quark and gluon structure of protons (10^{-6} *L*, probe 10^{1} E)

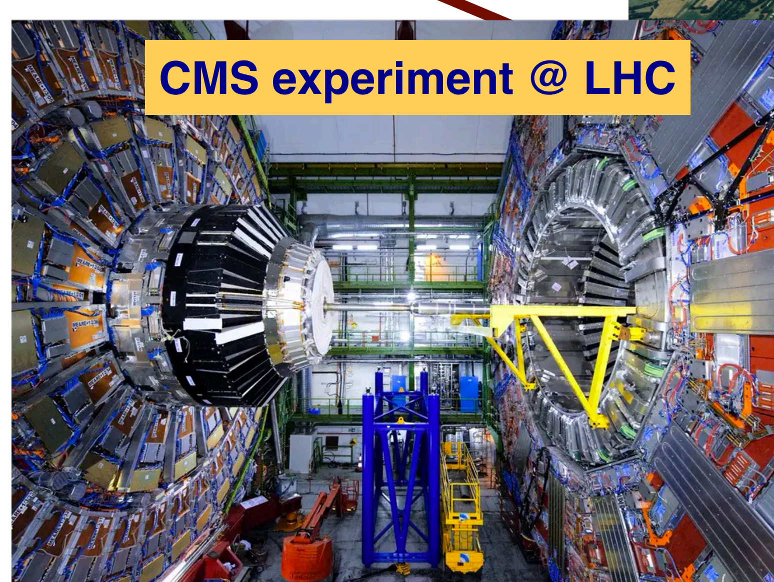


SLAC accelerator (2 km)

Higgs boson (10^{-8} *L*, probe 10^{3} *E*)

Drell-Yan (10^{-10} *L*, probe 10^{4} *E*)

Large Hadron Collider (27 km)



CMS experiment @ LHC

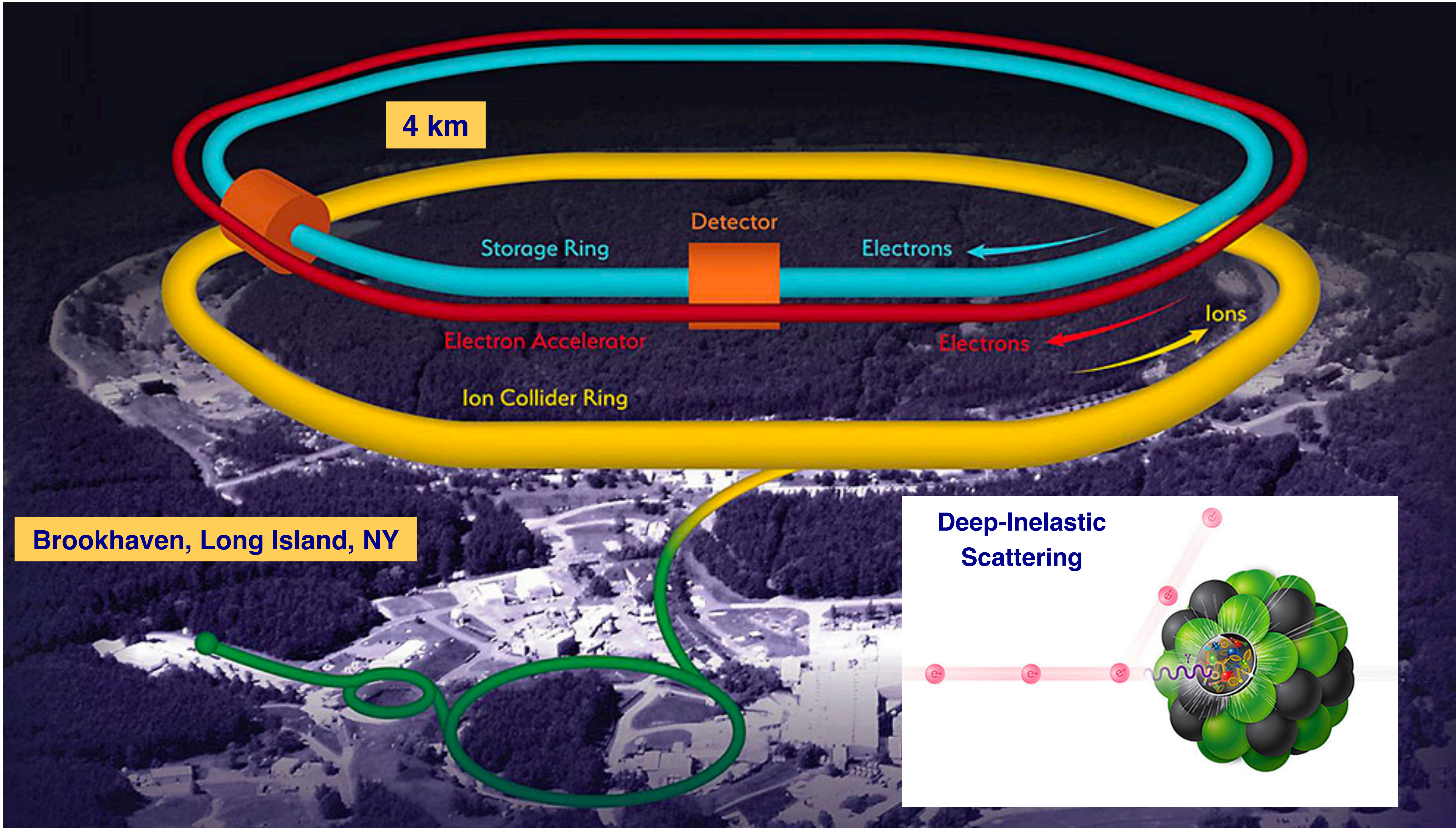
The Zeptospace! 10^{-11} L

short distances & large energies

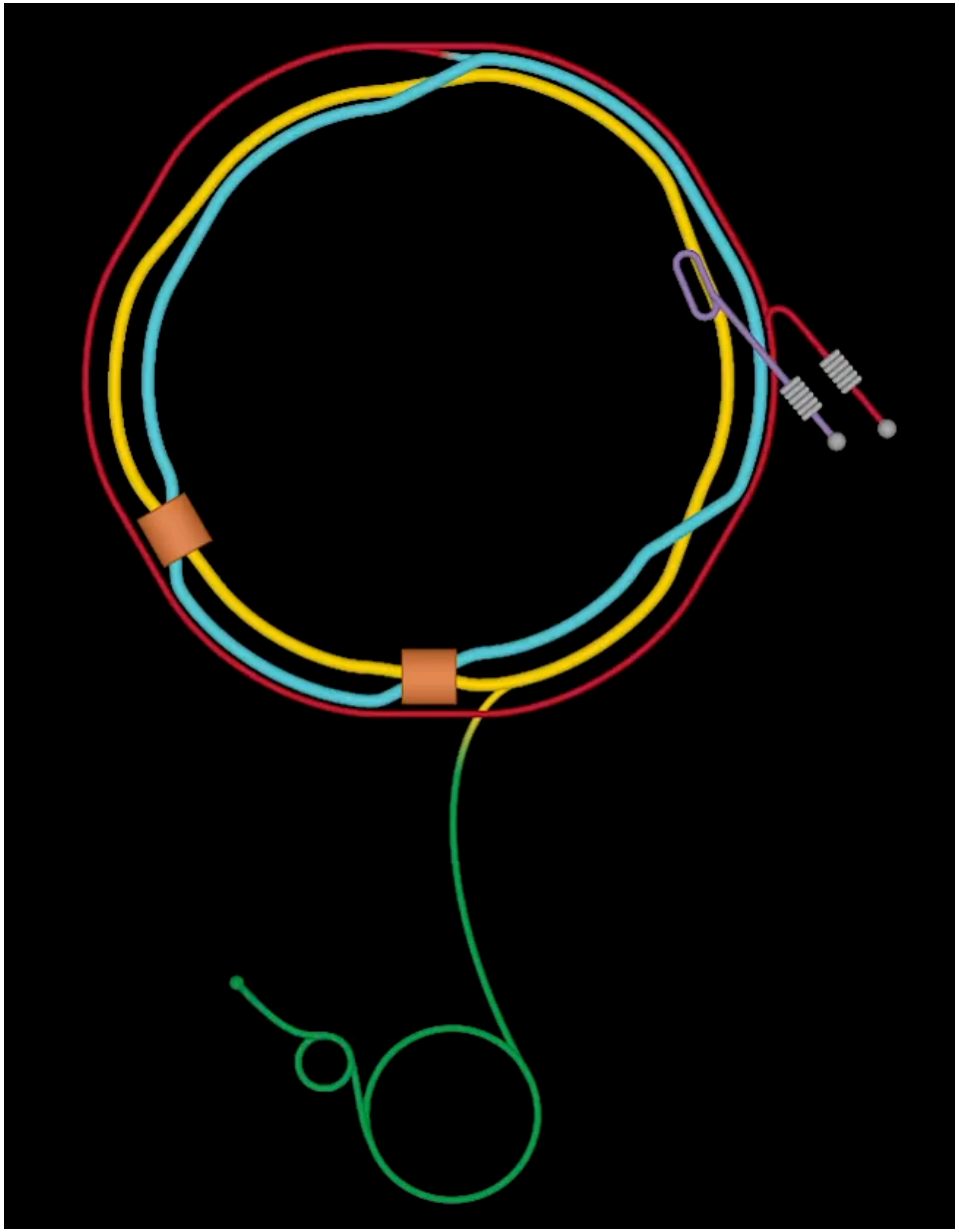
The Large Hadron Collider

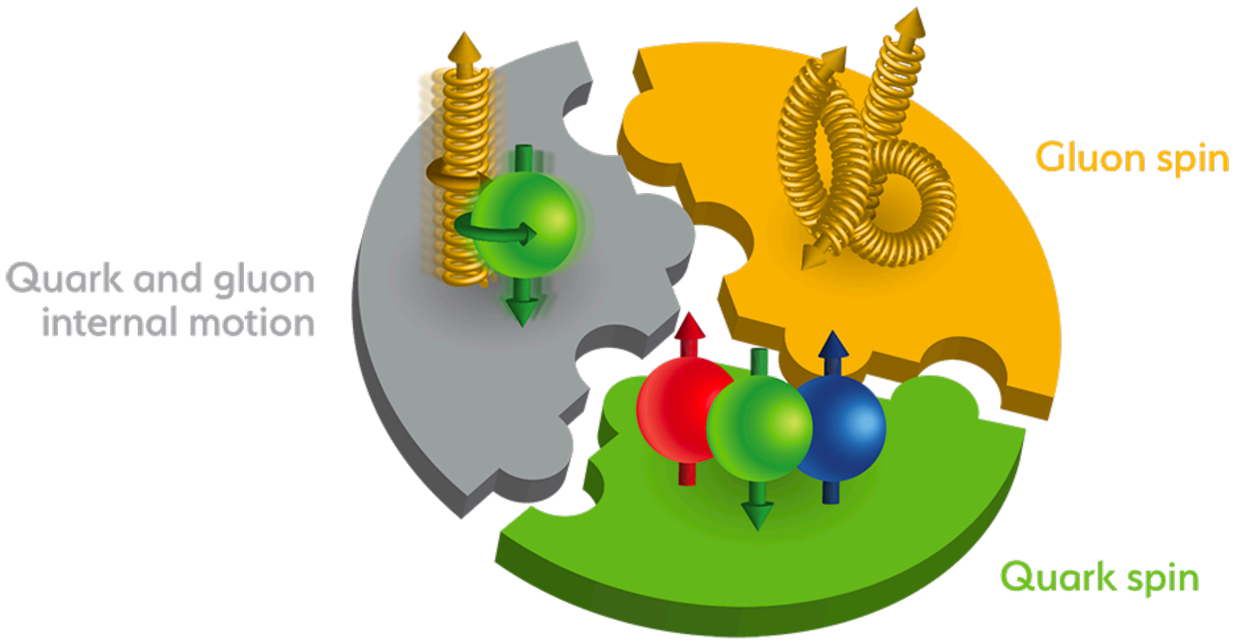
The Electron-Ion Collider

A **polarized electron-nucleus collider** to fingerprint the mysteries of the **strong nuclear force**



The Electron-Ion Collider



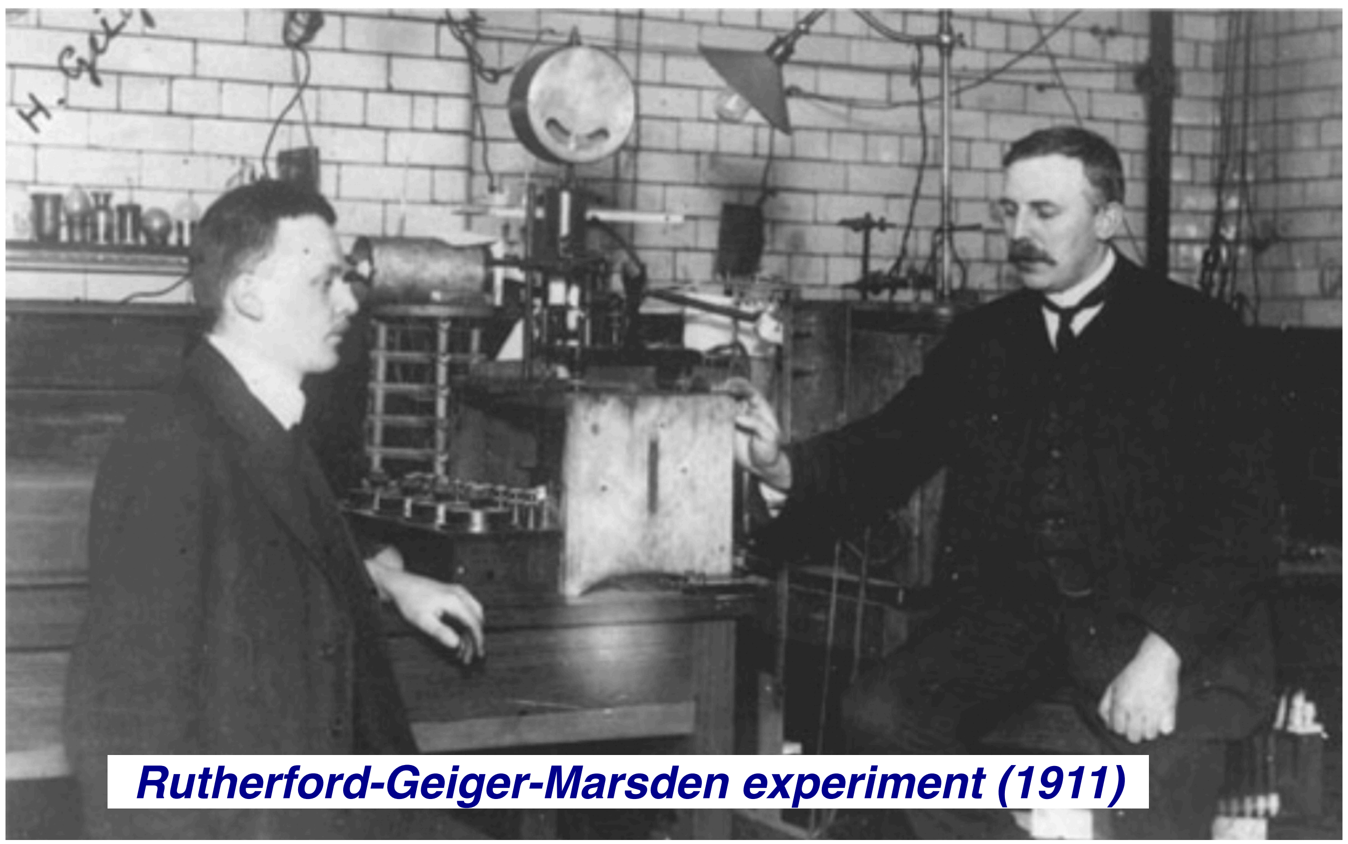


where does proton spin s=1/2 come from?

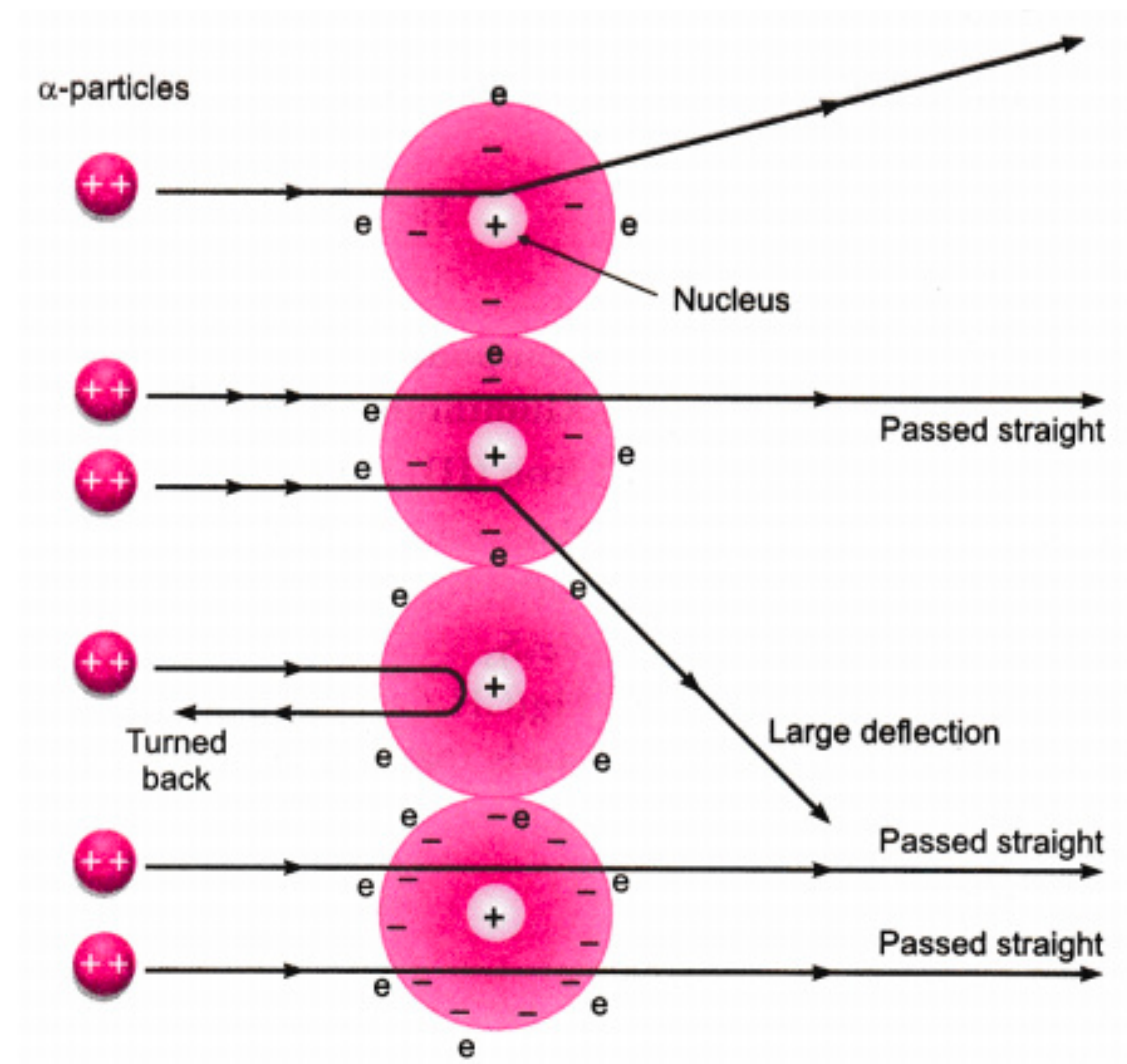
The inner life of protons: a microcosm by itself

Proton 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?

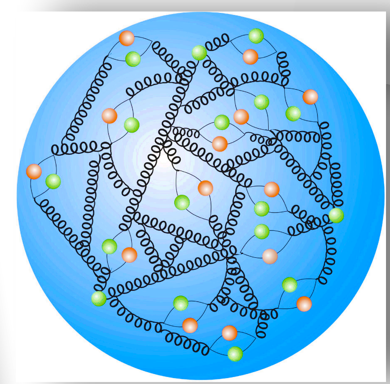


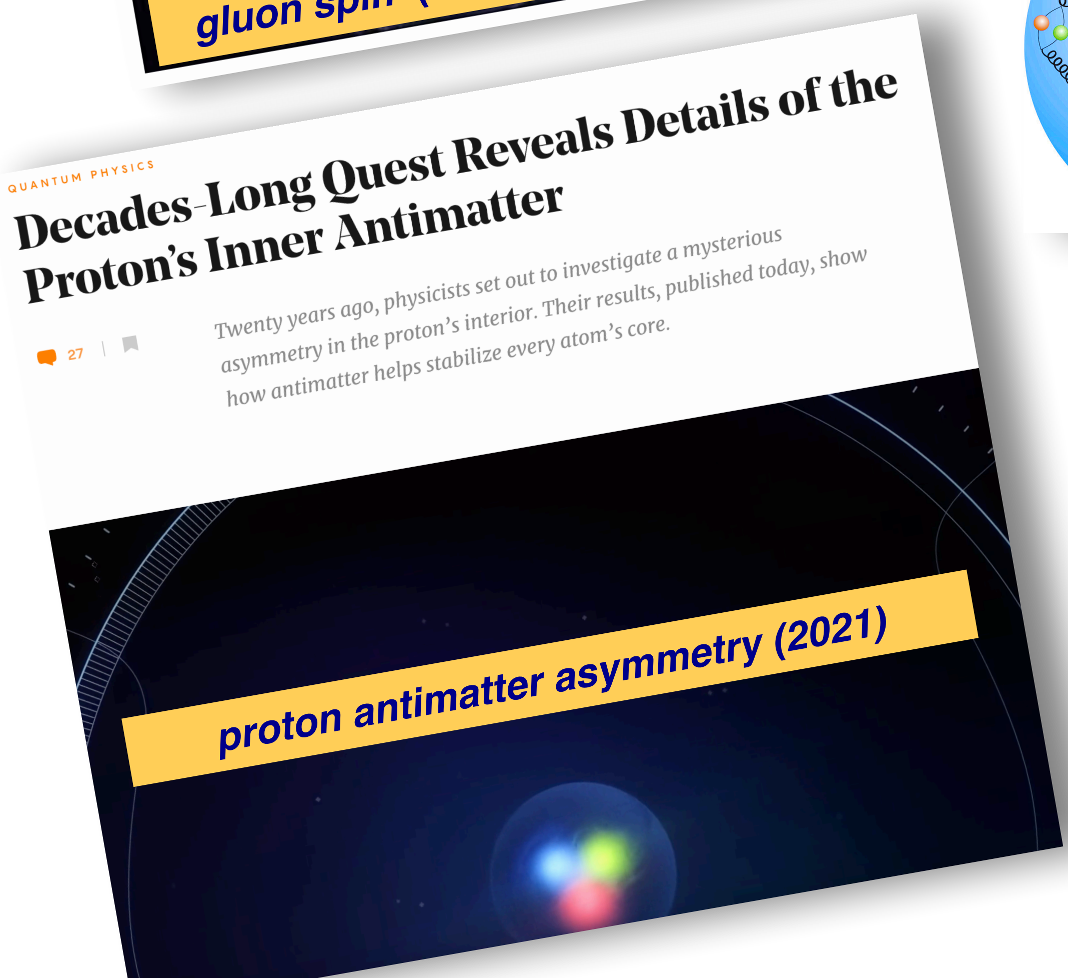
Rutherford-Geiger-Marsden experiment (1911)



nothing farther from reality!

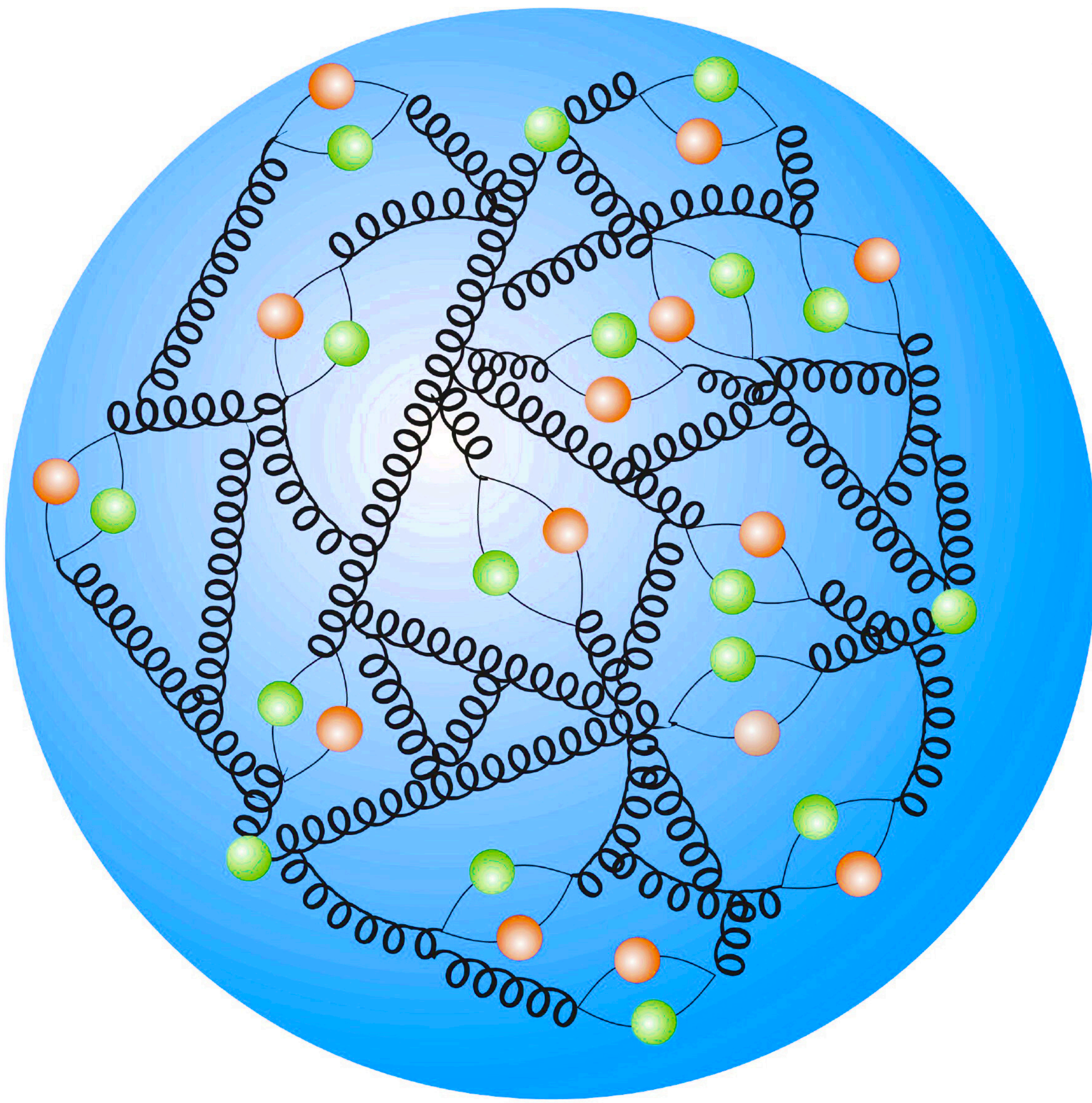
Unveiling new phenomena within the SM





The many faces of the proton

QCD bound state of **quarks** and **gluons**



- **Valence quarks (up and down)** give the proton its quantum numbers (e.g. electric charge)

$$|\Psi\rangle \approx |uud\rangle$$

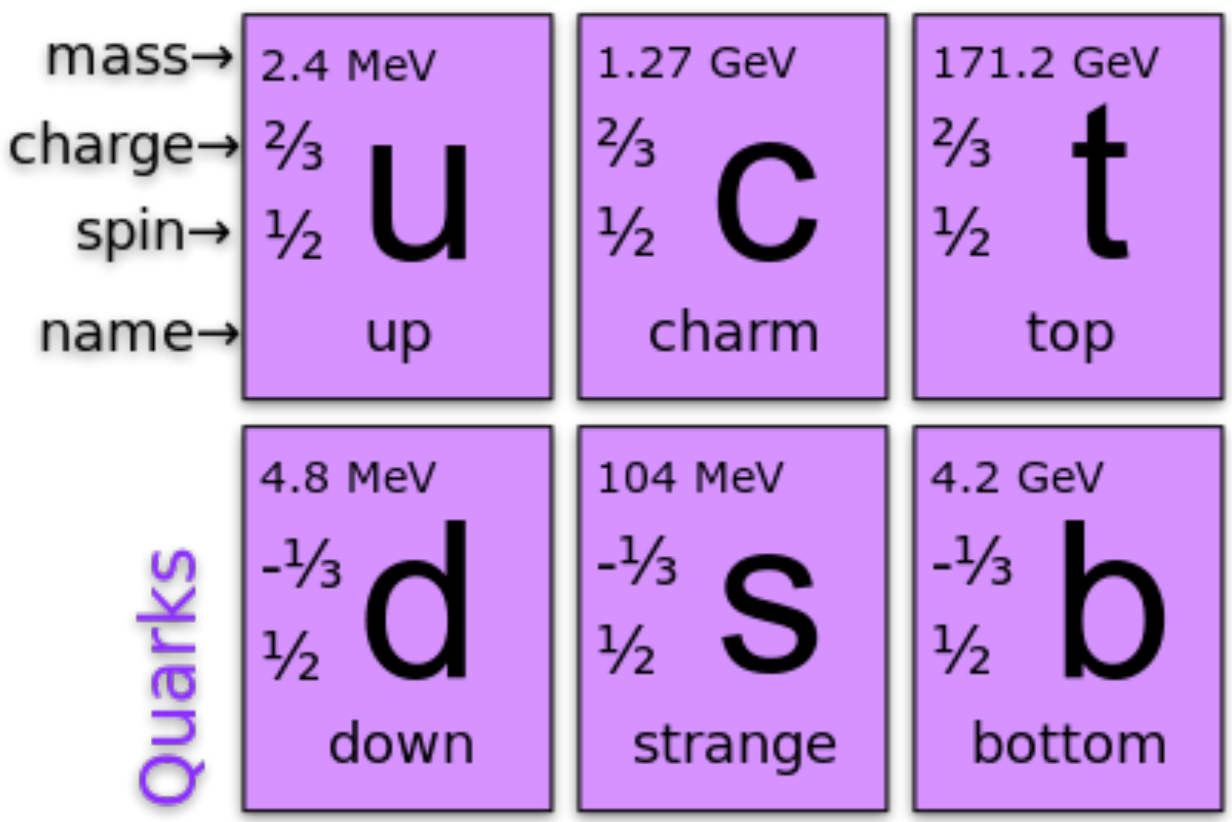
$$Q_p = +1 \qquad \begin{aligned} Q_u &= +2/3 \\ Q_d &= -1/3 \end{aligned}$$

- **Sea quarks (antiup, antidown, strange, …)** arise from quantum fluctuations

- Tightly held together by **gluons,** can only be broken in extremely energetic collisions

The many faces of the proton

QCD bound state of **quarks** and **gluons**



☑ **Valence quarks (up and down)** give the proton its quantum numbers (e.g. electric charge)

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☑ **Sea quarks (antiup, antidown, strange, …)** arise from quantum fluctuations

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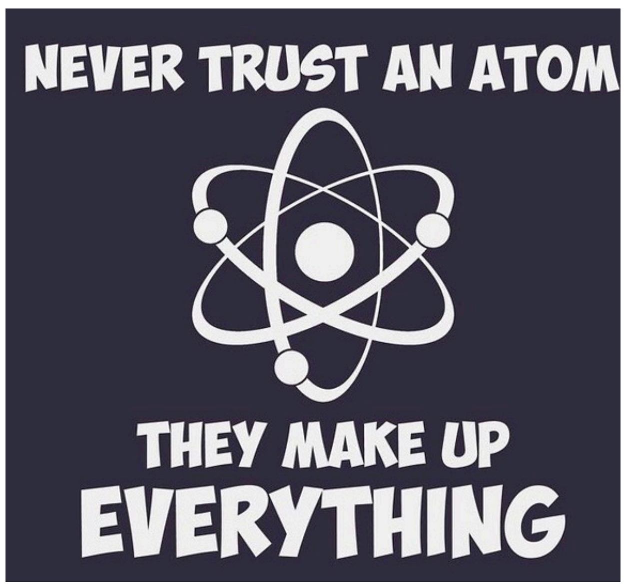
Proton Structure

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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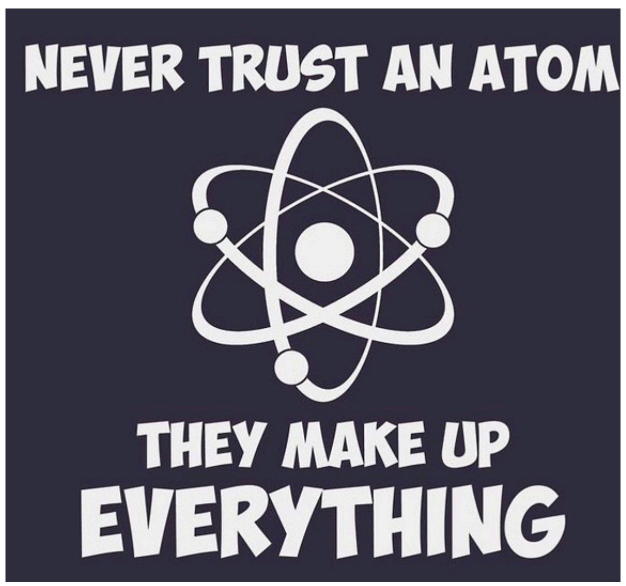

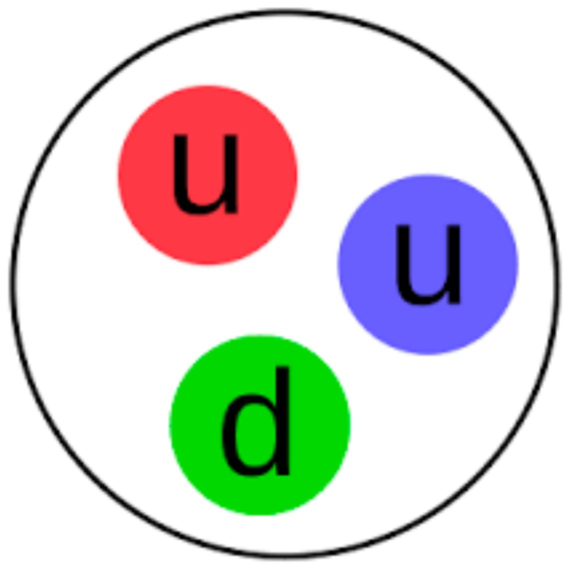

long distances / low energies → *short distances / high energies*

a point particle

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

3 valence quarks

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

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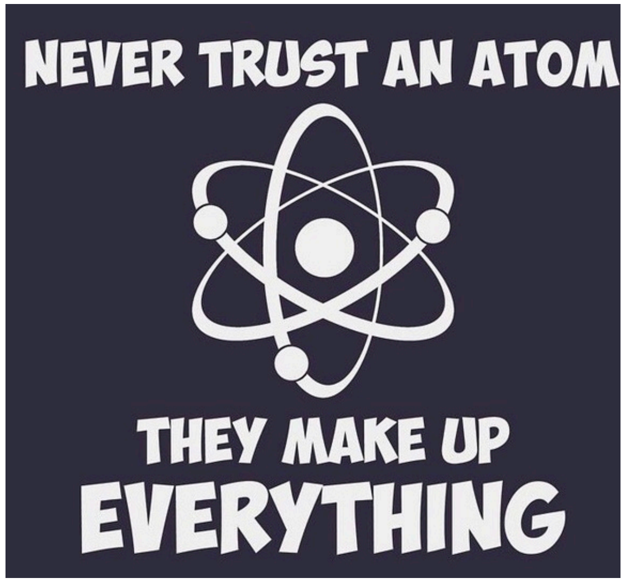

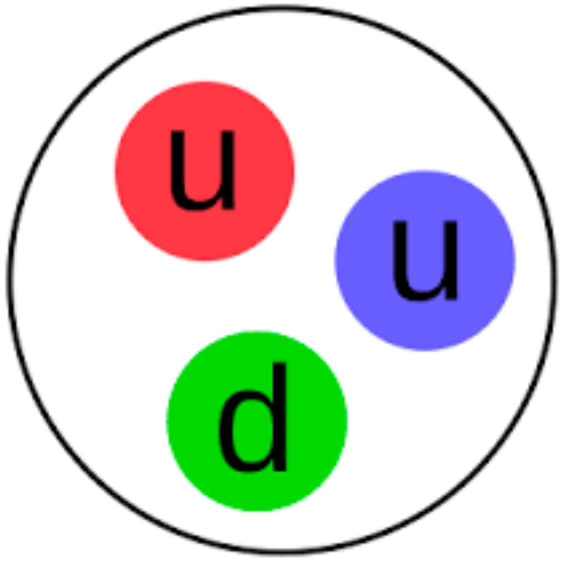

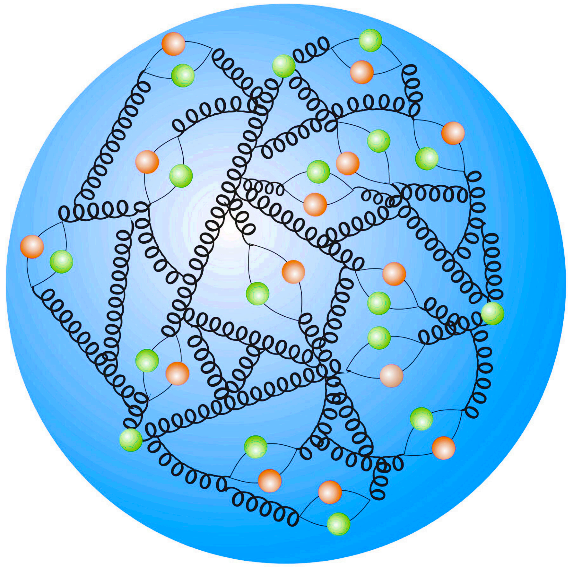

long distances / low energies → *short distances / high energies*

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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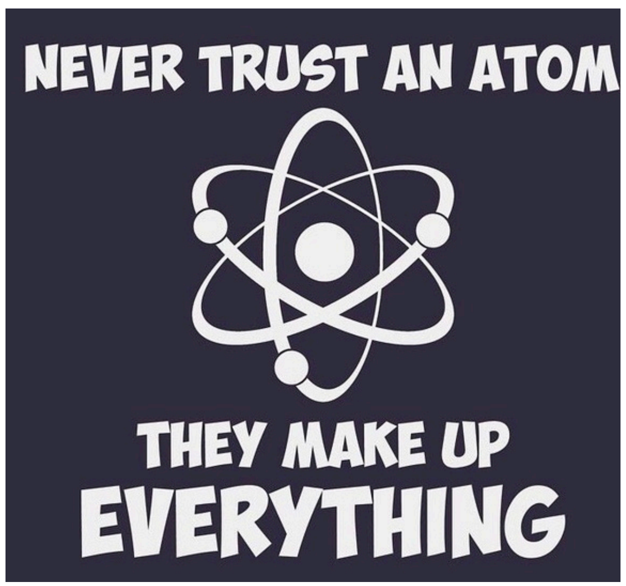
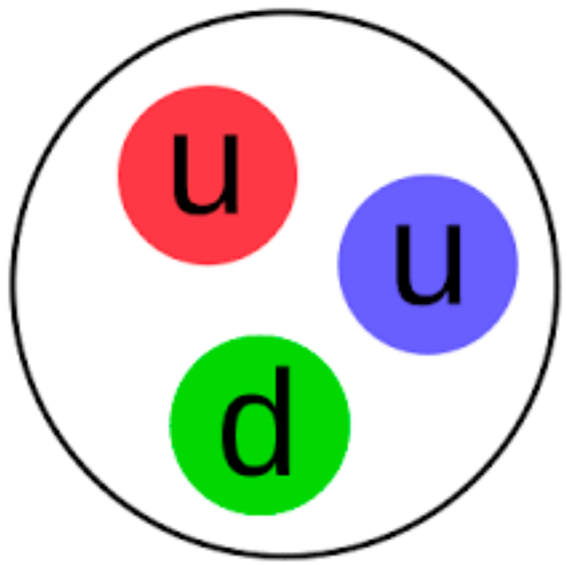
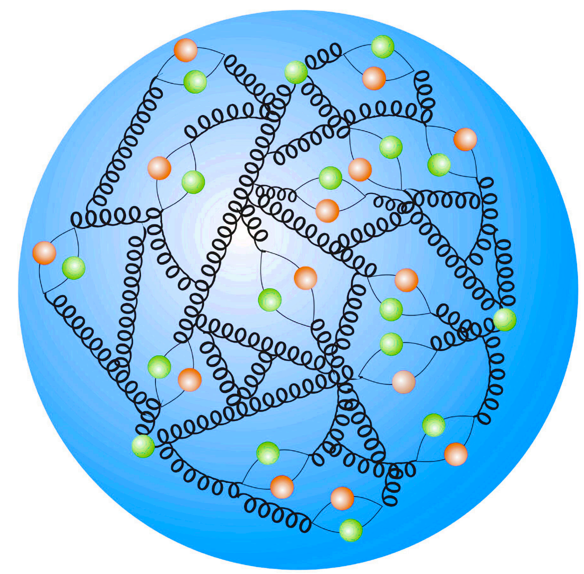
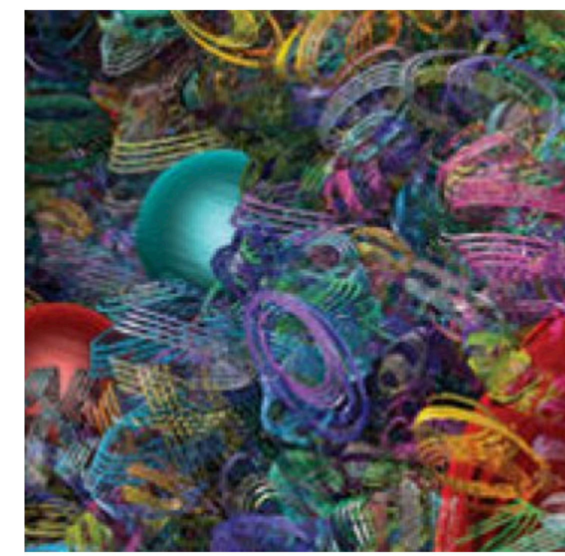








long distances / low energies → *short distances / high energies*

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

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

- Dependence with **resolution scale *Q***: DGLAP evolution, computable from first principles

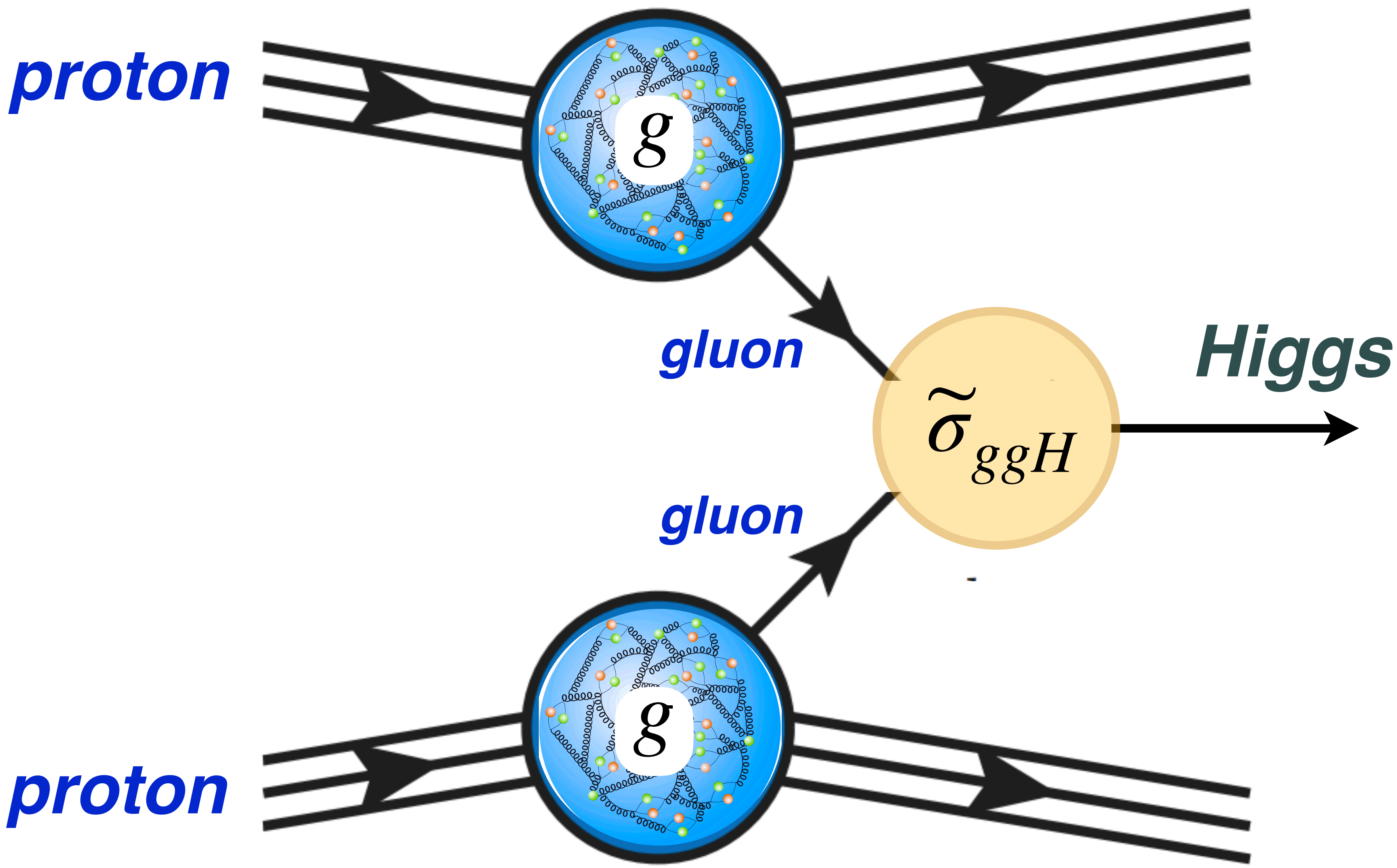
- **Energy conservation** and **quark number conservation** are fixed boundary conditions

Probing Proton Structure

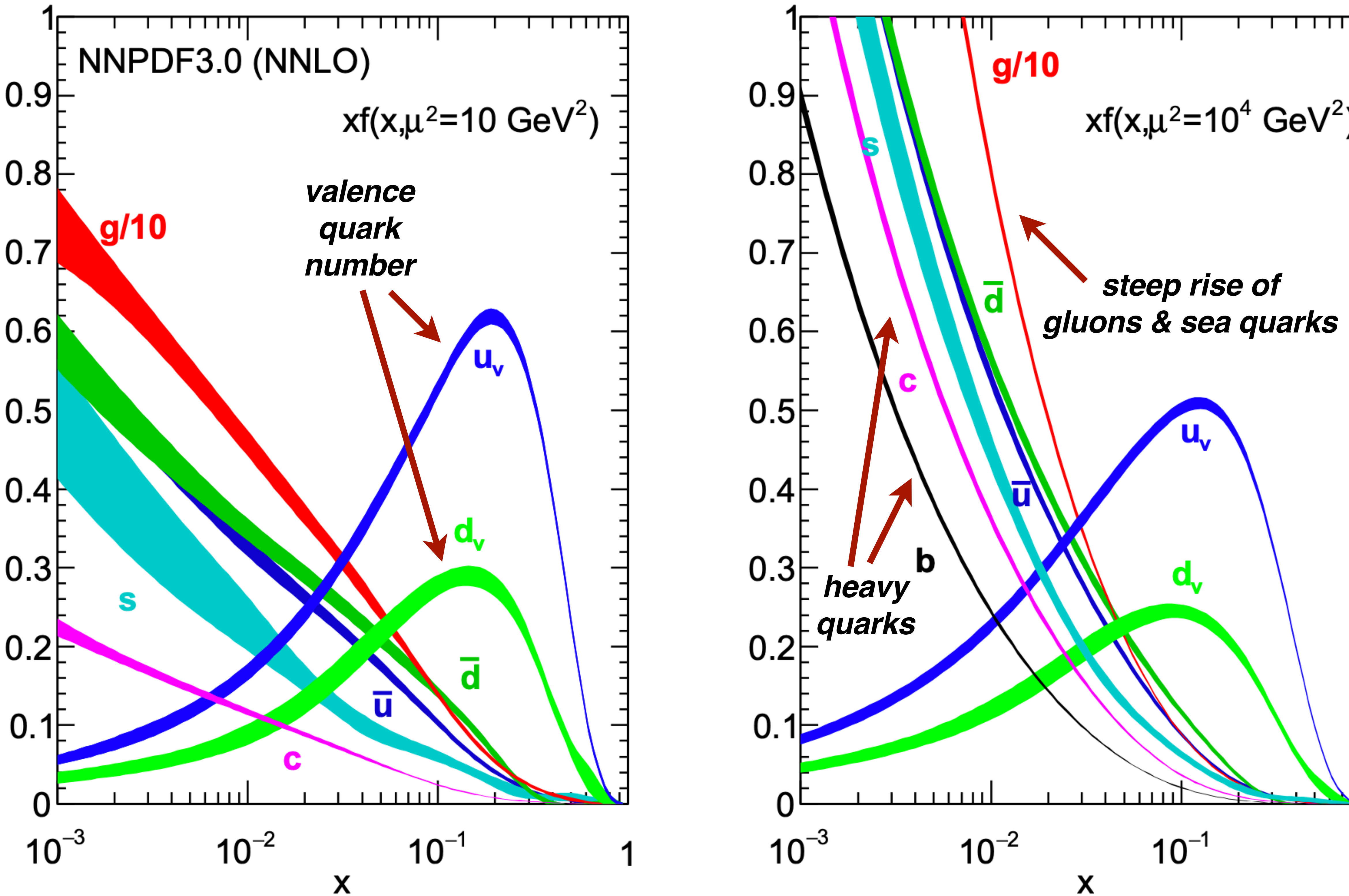
universal — *process-dependent*

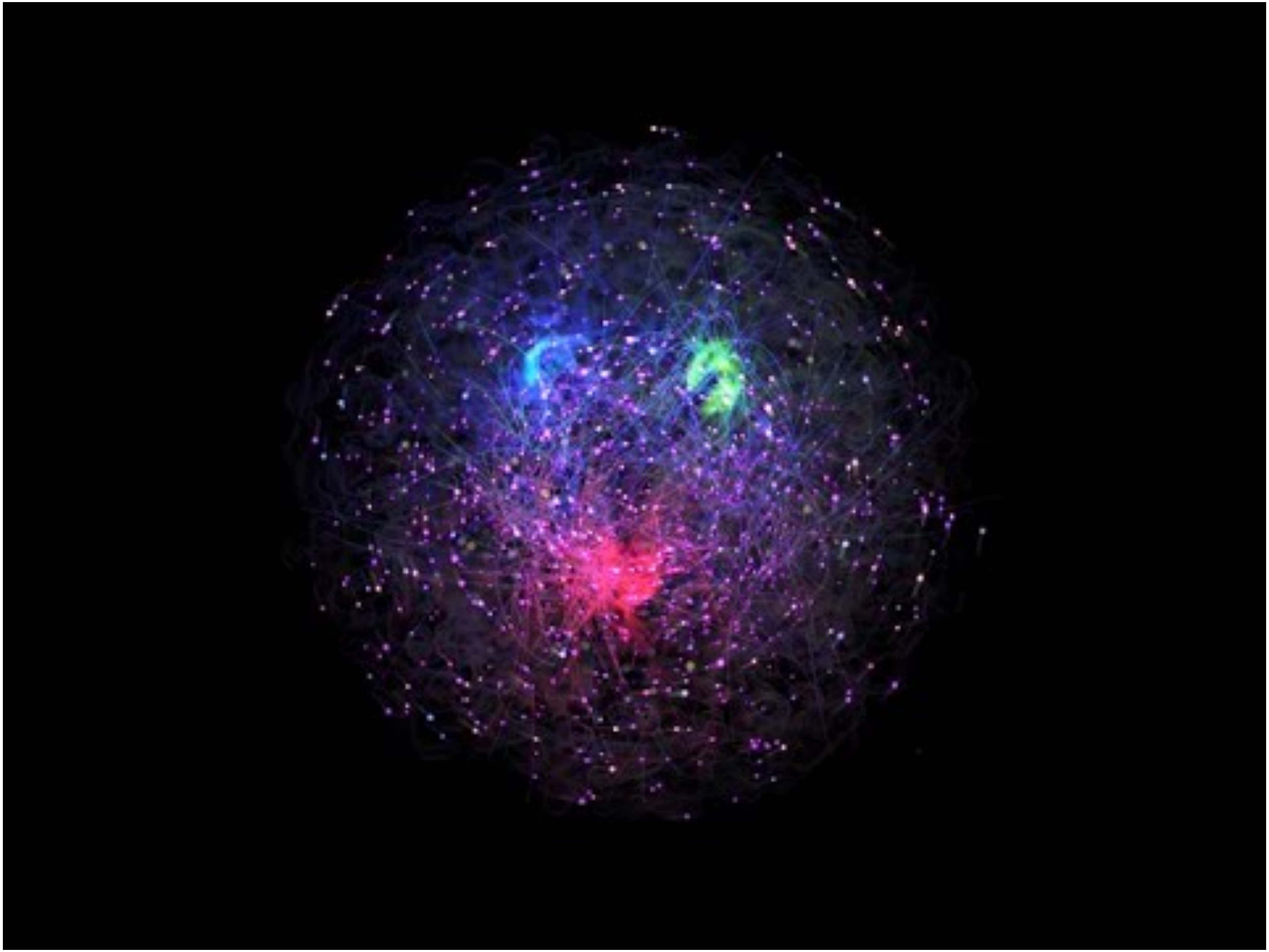
$$N_{\mathrm{LHC}}(H) \sim g \otimes g \otimes \tilde{\sigma}_{ggH}$$

Parton Distributions



A proton structure snapshop



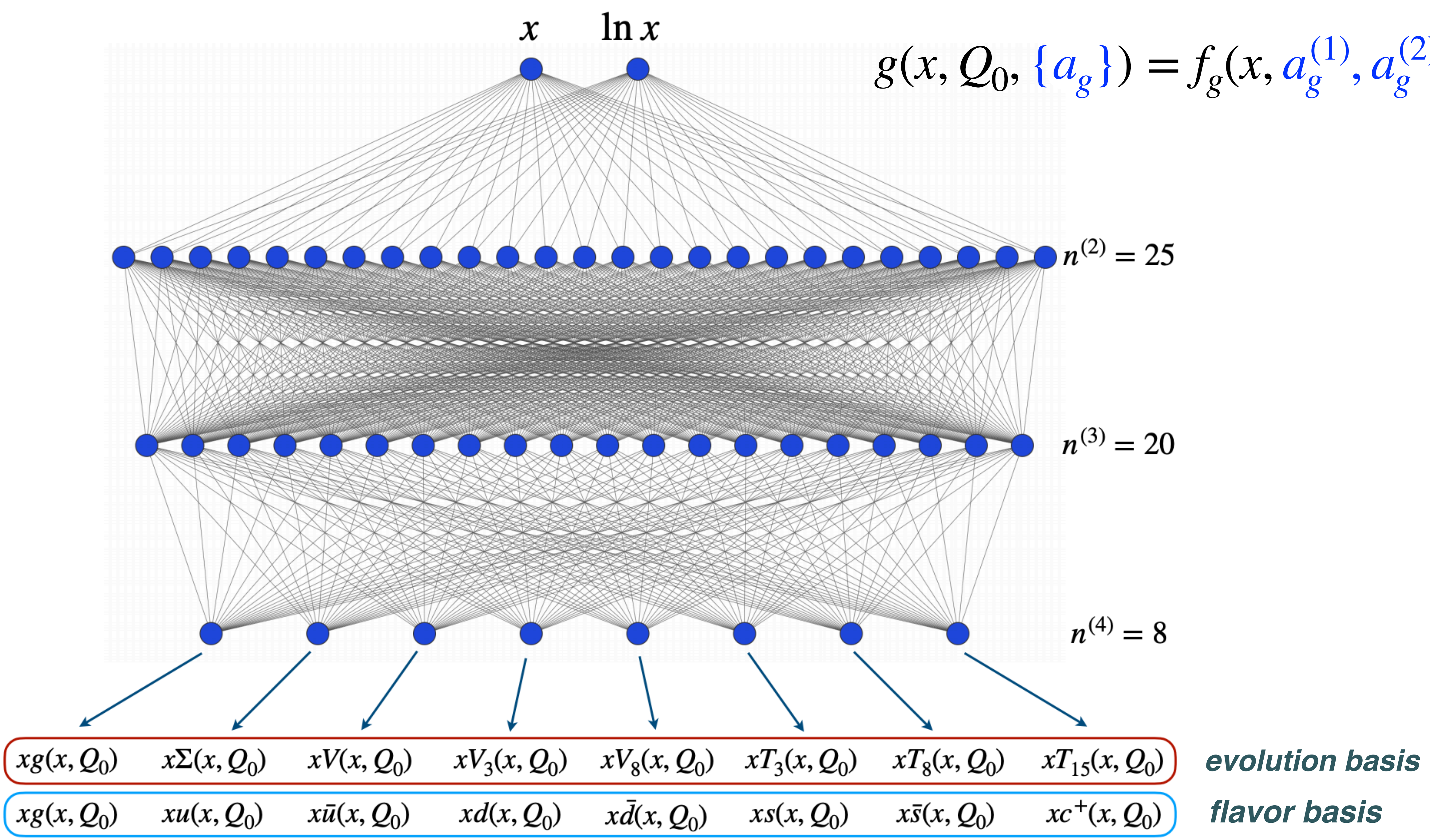


credit: *visualising the proton*, Arts at MIT (https://arts.mit.edu/visualizing-the-proton/)

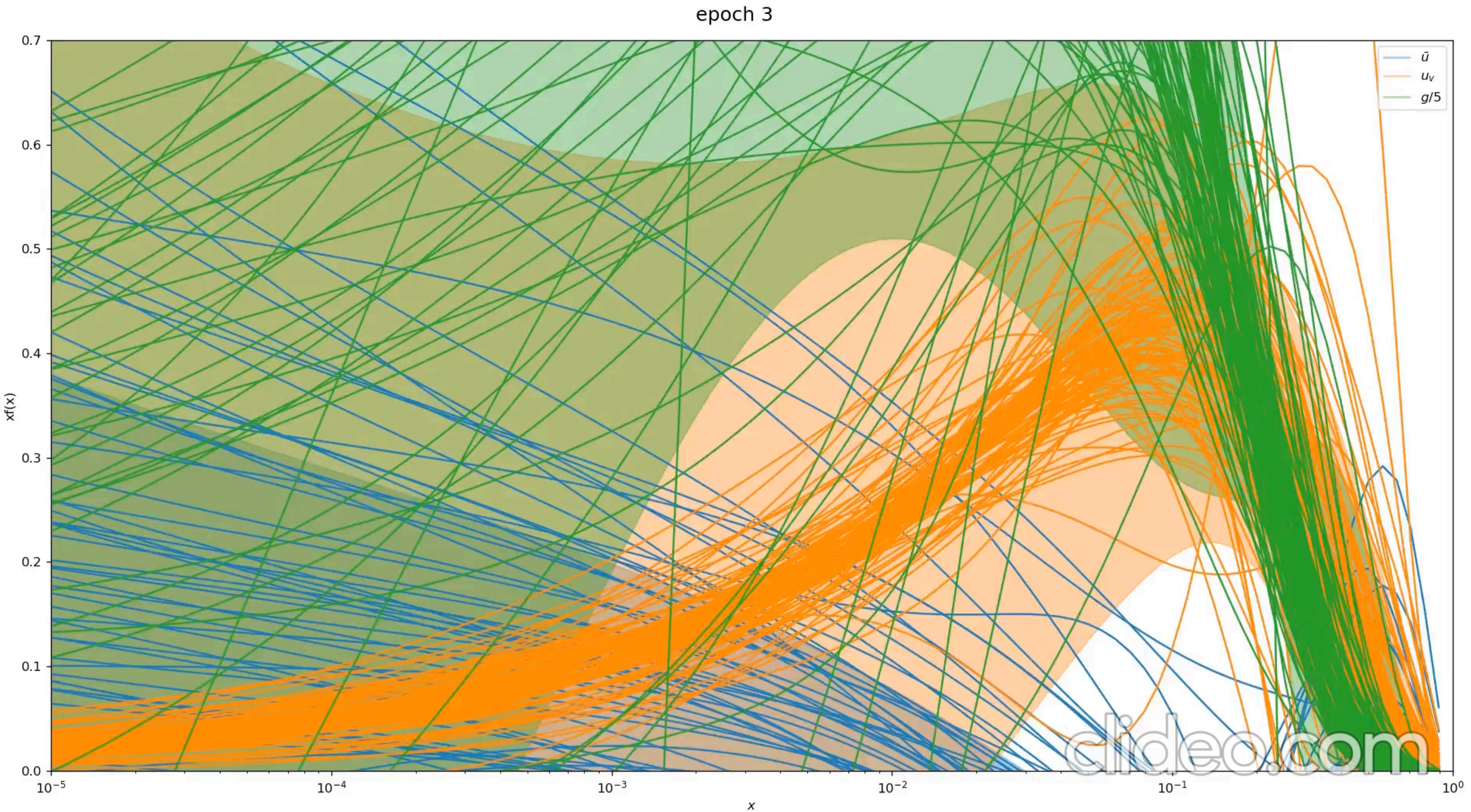
Machine Learning NNPDF

- 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 …

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



Machine Learning PDFs



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

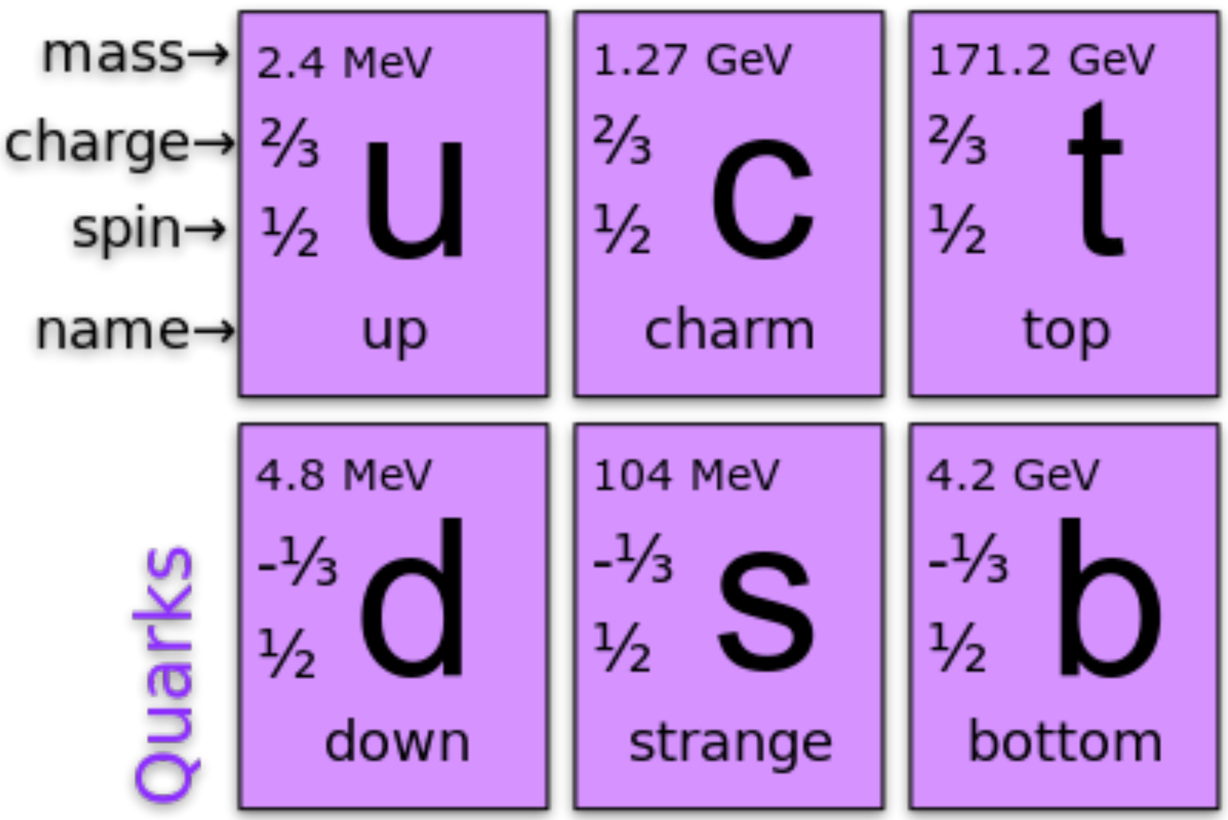
each curve is a separately trained neural network

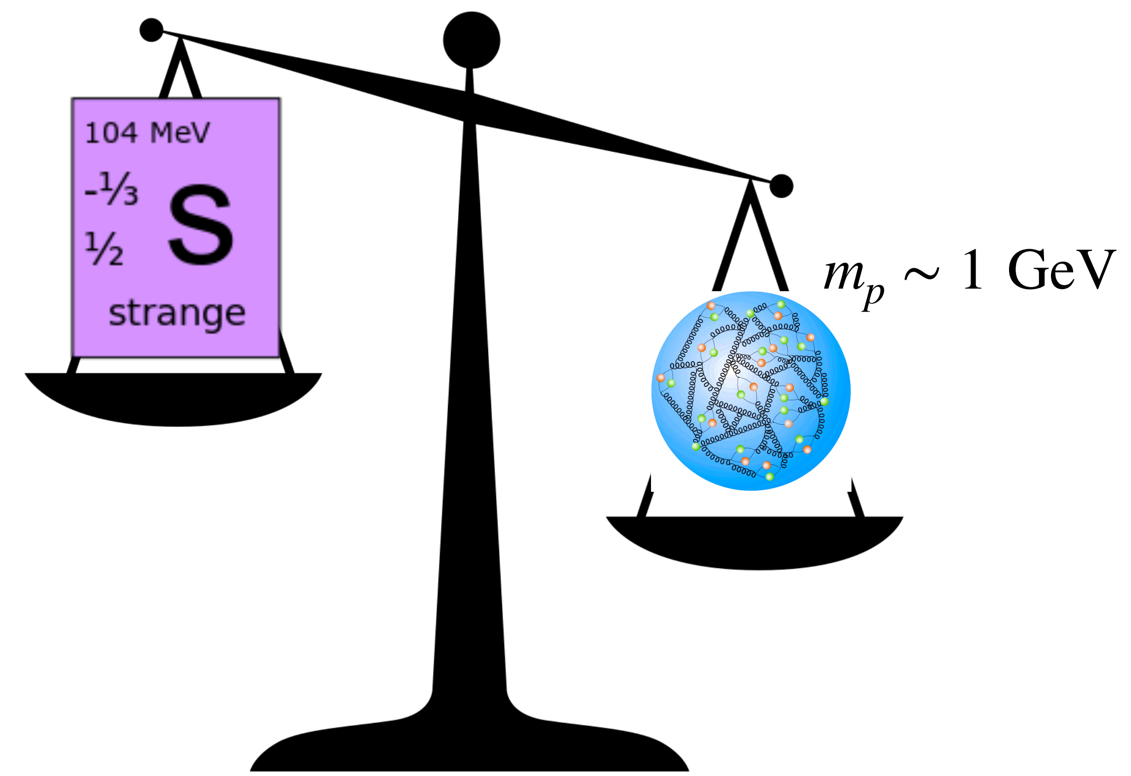
Charm quarks in the proton?

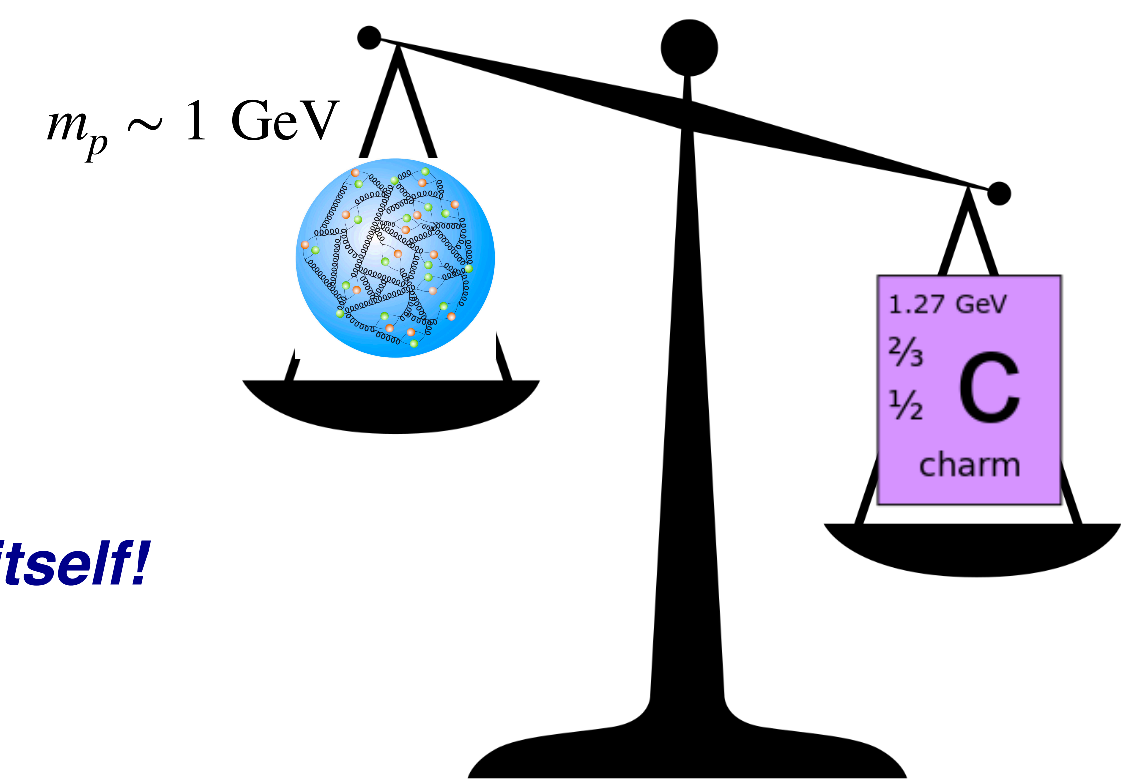
The charm content of the proton

common assumption: the 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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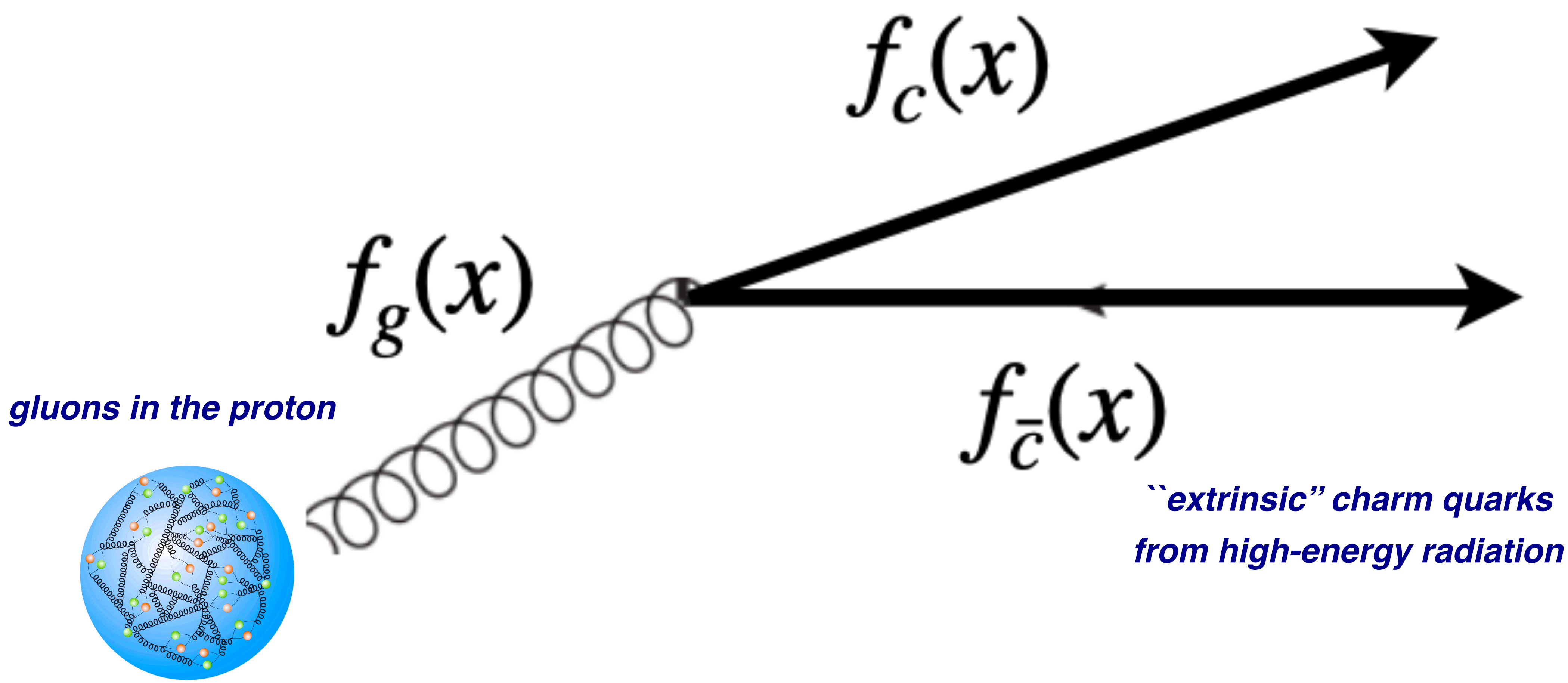
Charm quark **generated perturbatively** from radiation off gluons and quarks



If charm is radiatively **generated**, the charm content of the proton is **trivial**

The charm content of the proton

common assumption: the 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

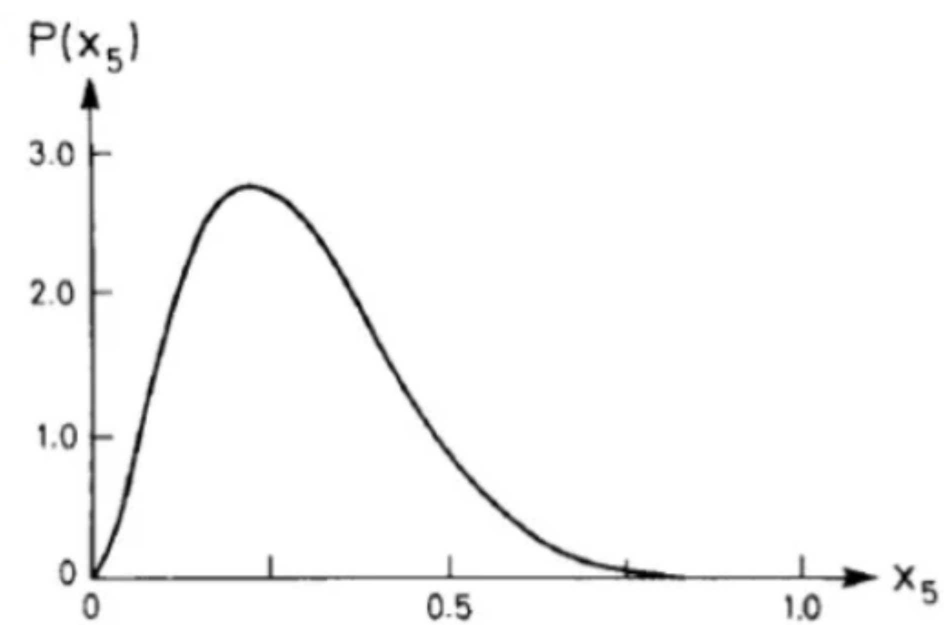
THE INTRINSIC CHARM OF THE PROTON

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



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

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 ….

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^3LO matching conditions

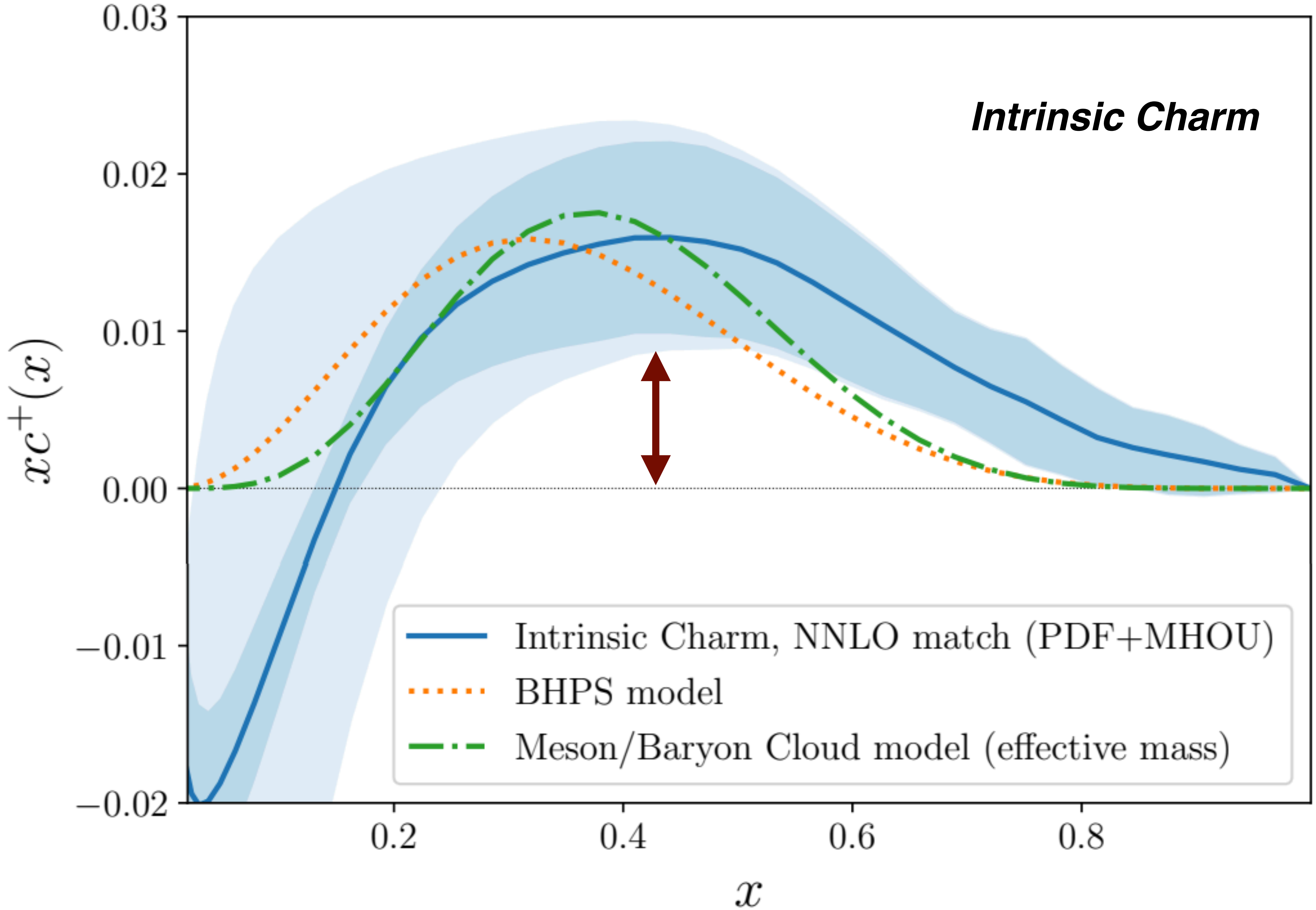
EKO
Evolution Kernel Operators

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

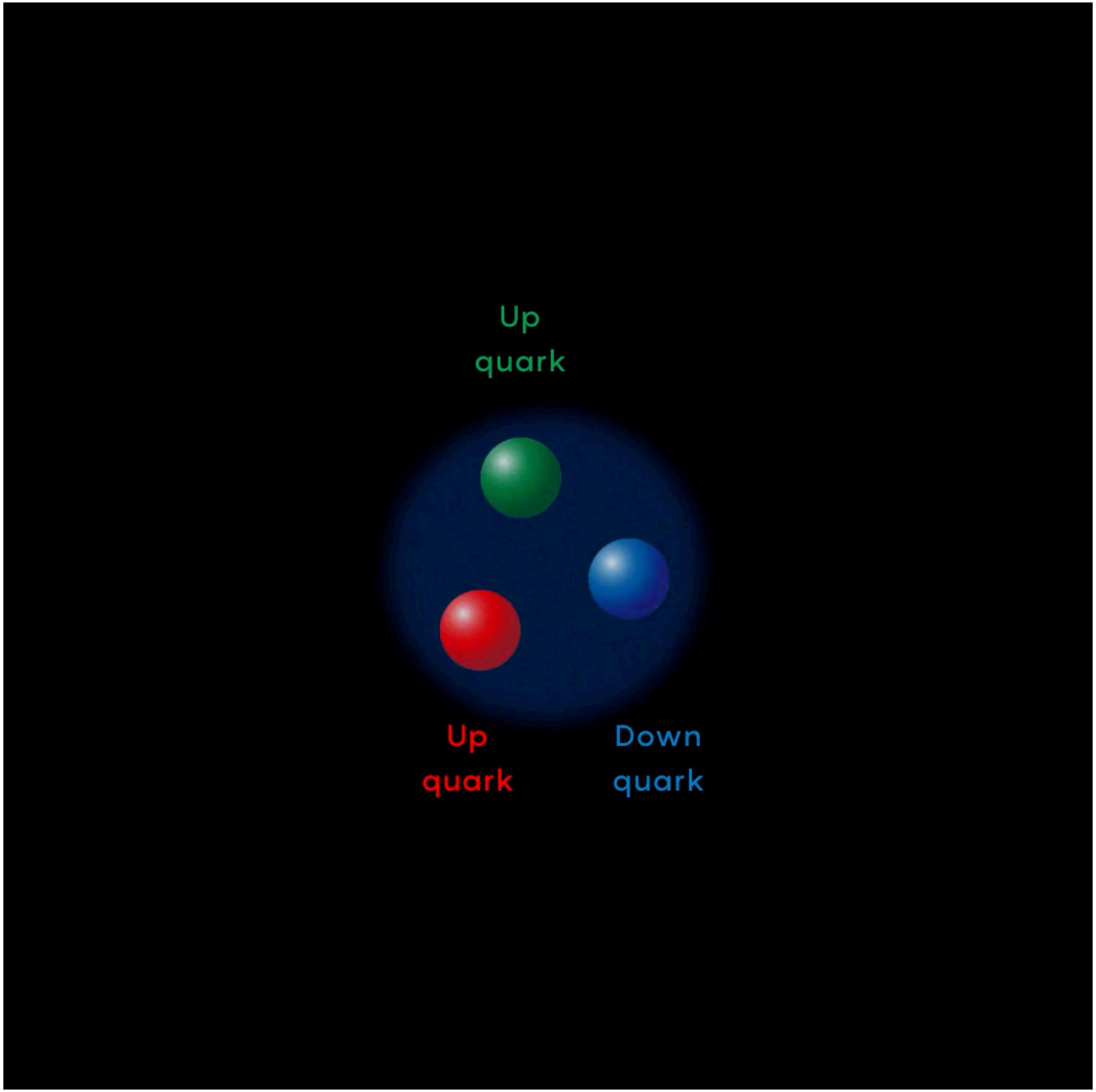
Intrinsic (3FNS) Charm

• Scale-independent • PDF and MHO uncertainties

Intrinsic Charm in the Proton



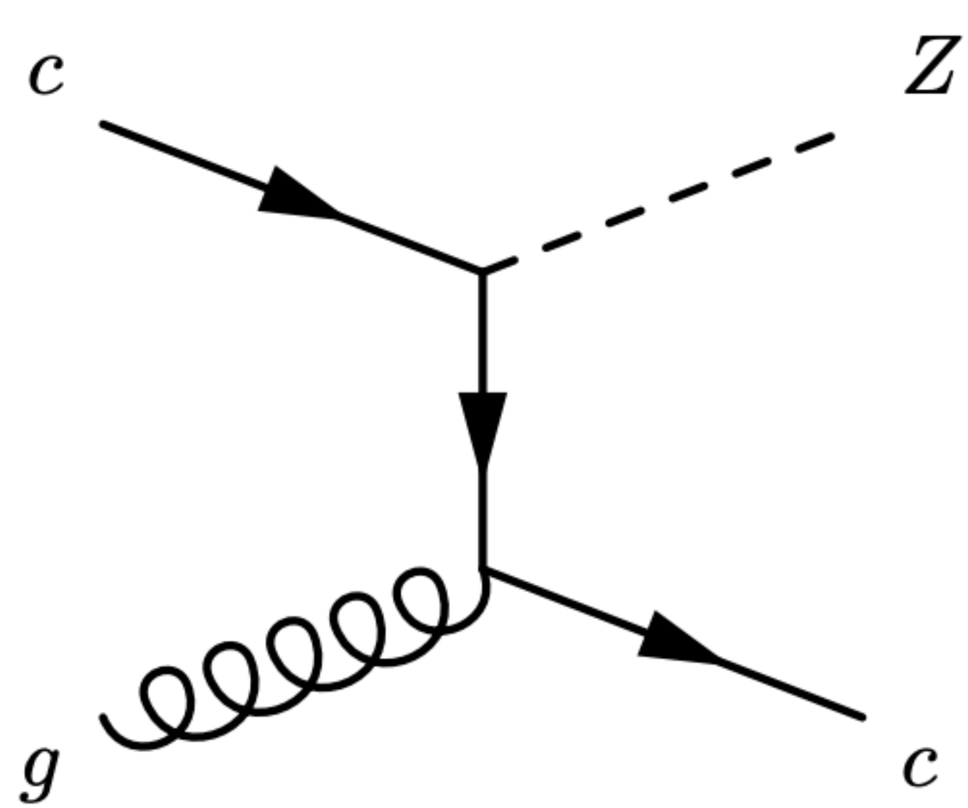
The 3FNS charm PDF displays **non-zero component** peaked at large-*x* which can be identified with **intrinsic charm**

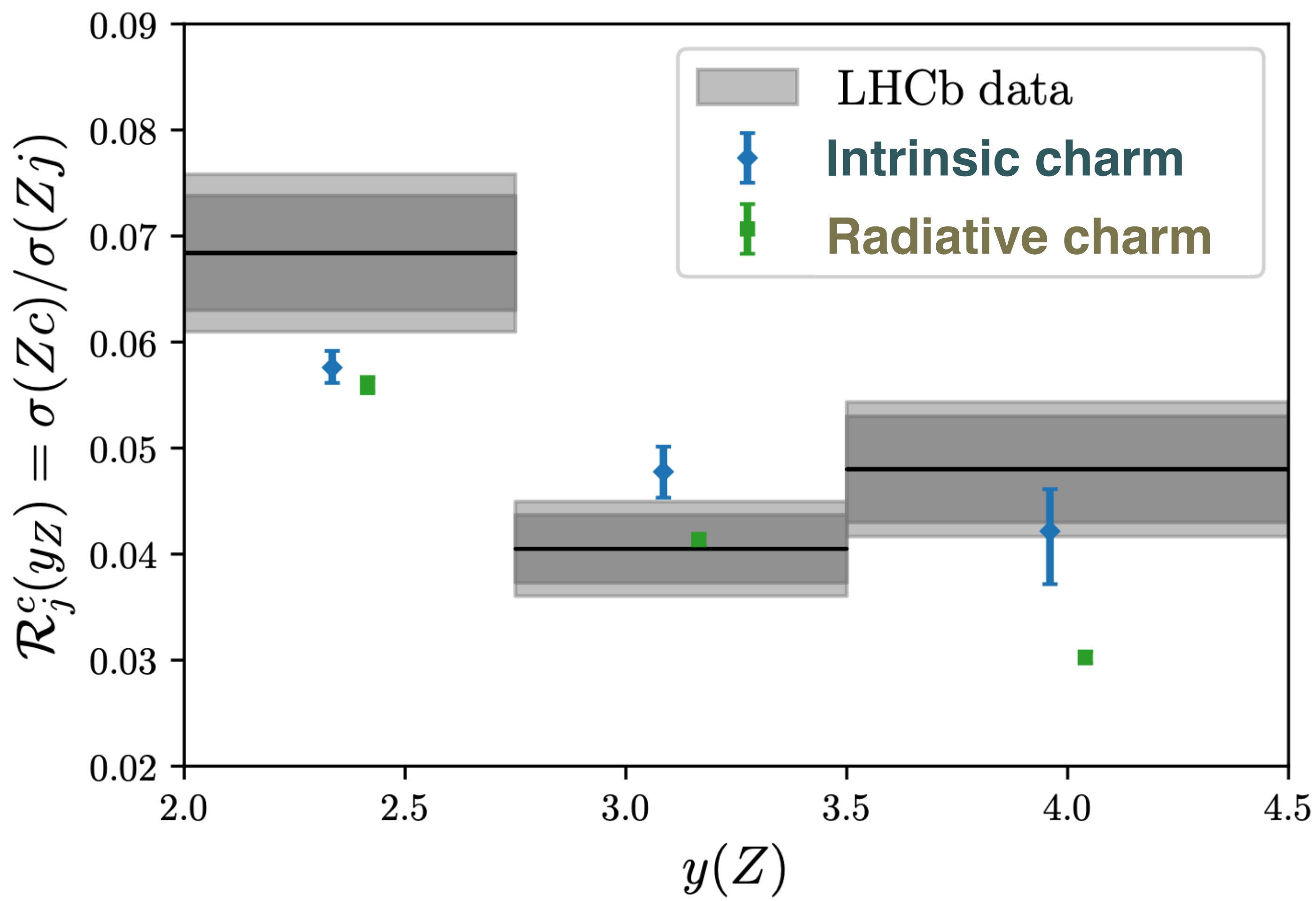


credits: https://www.quantamagazine.org/inside-the-proton-the-most-complicated-thing-imaginable-20221019/

Z+charm @ LHCb

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



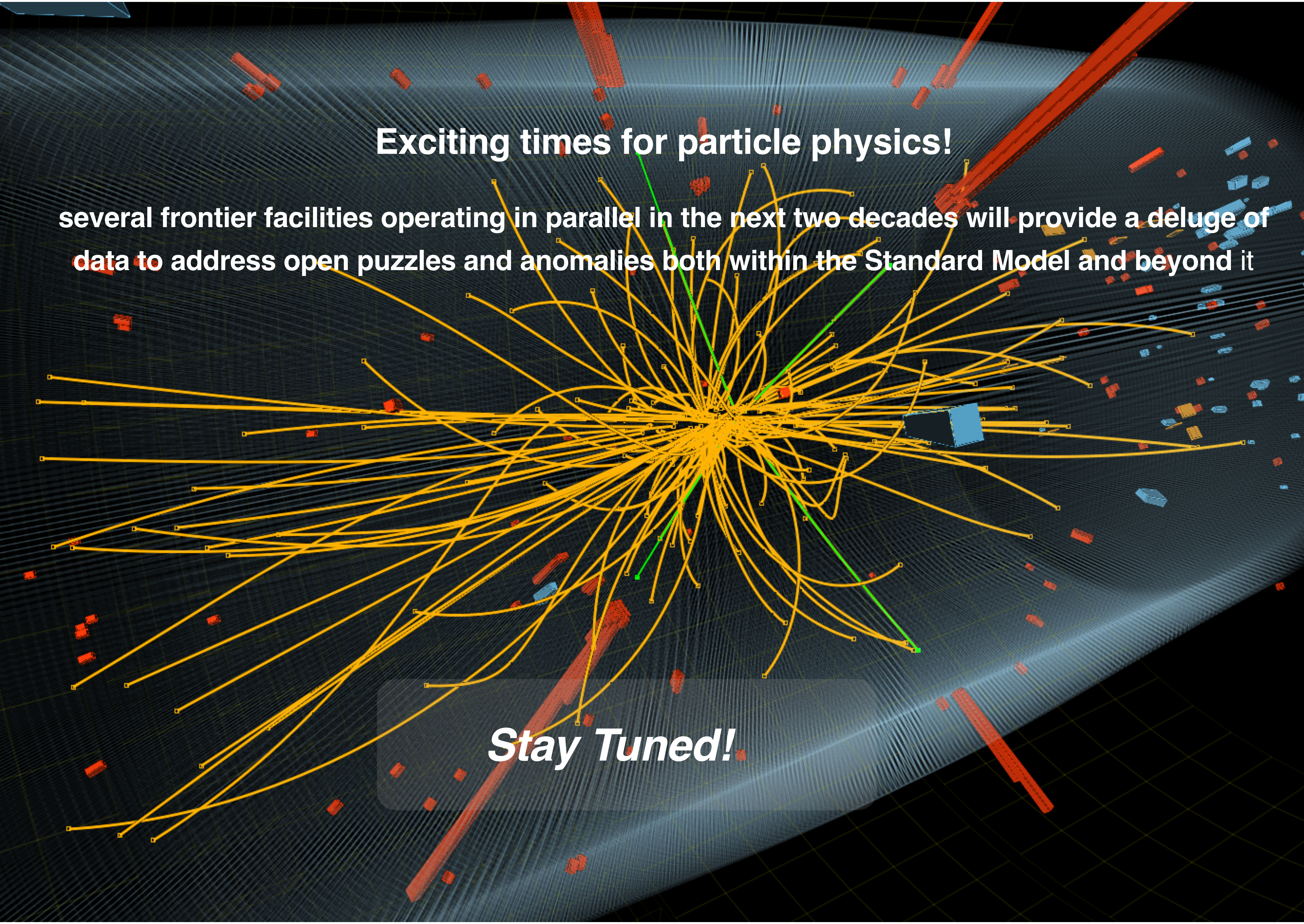


Z+charm at forward rapidities (LHCb) sensitive to the **charm PDF**

Independent confirmation of a preference for intrinsic charm in the proton

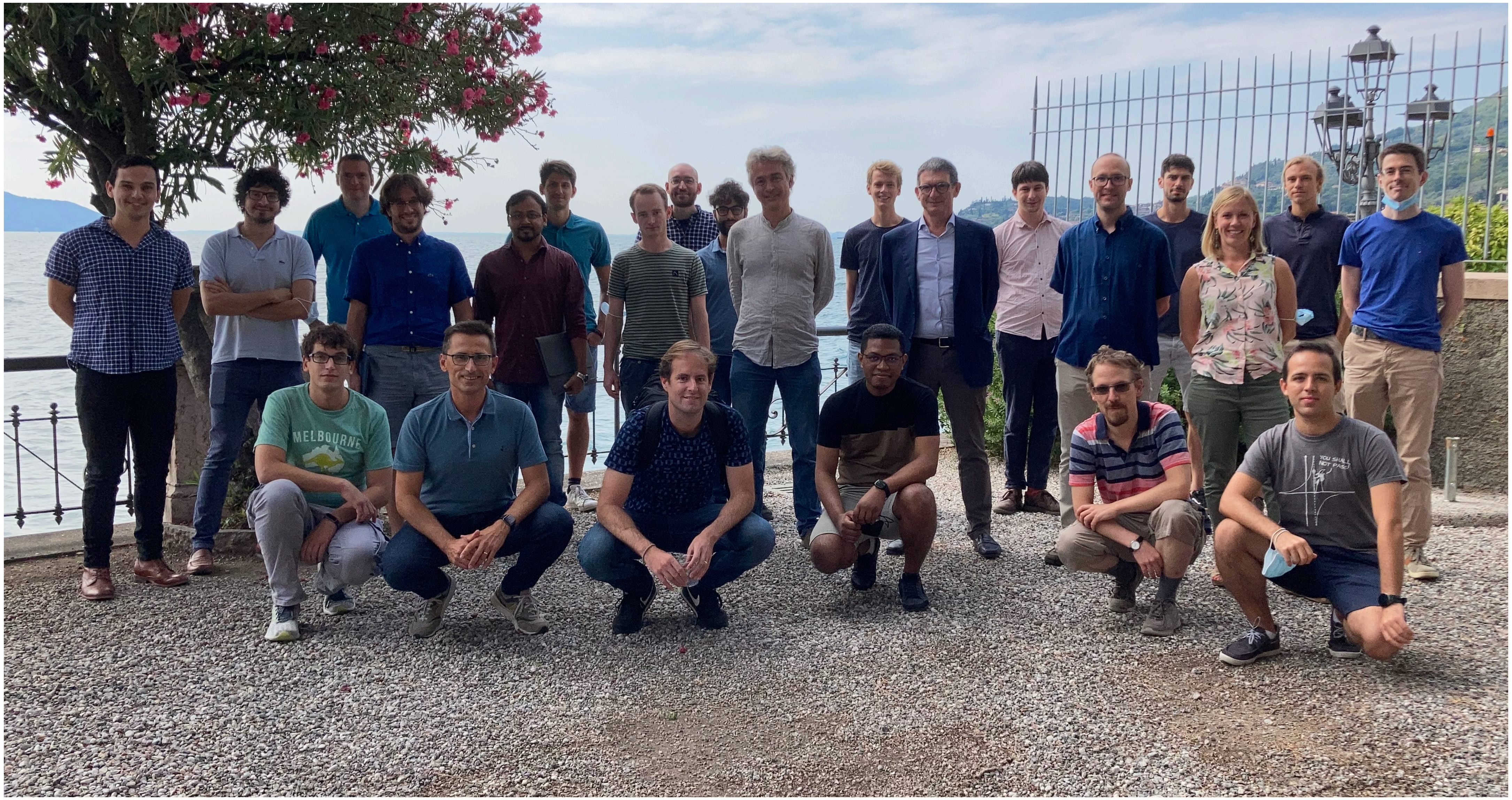
Exciting times for particle physics!

several frontier facilities operating in parallel in the next two decades will provide a deluge of data to address open puzzles and anomalies both within the Standard Model and beyond it



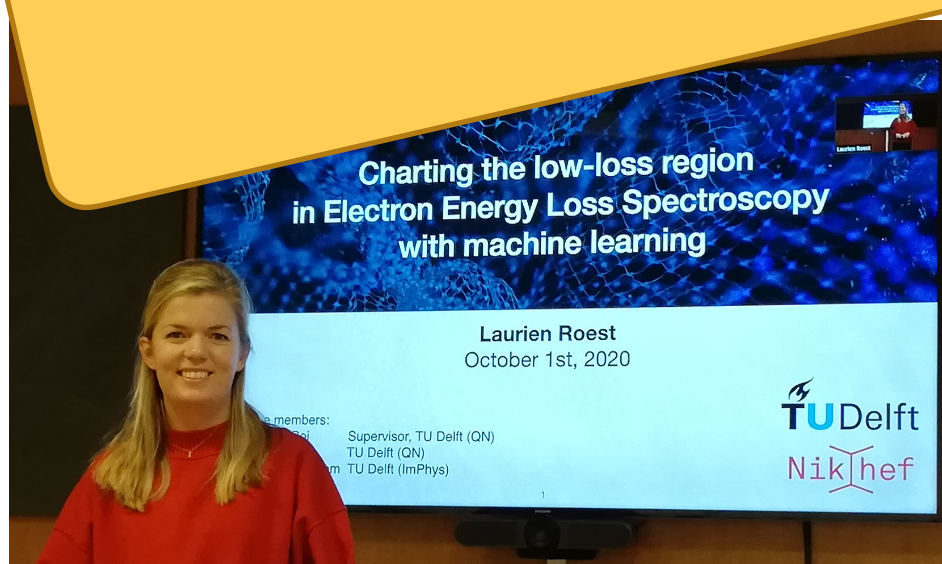
Stay Tuned!

Many thanks to my collaborators!



Many thanks to my collaborators!

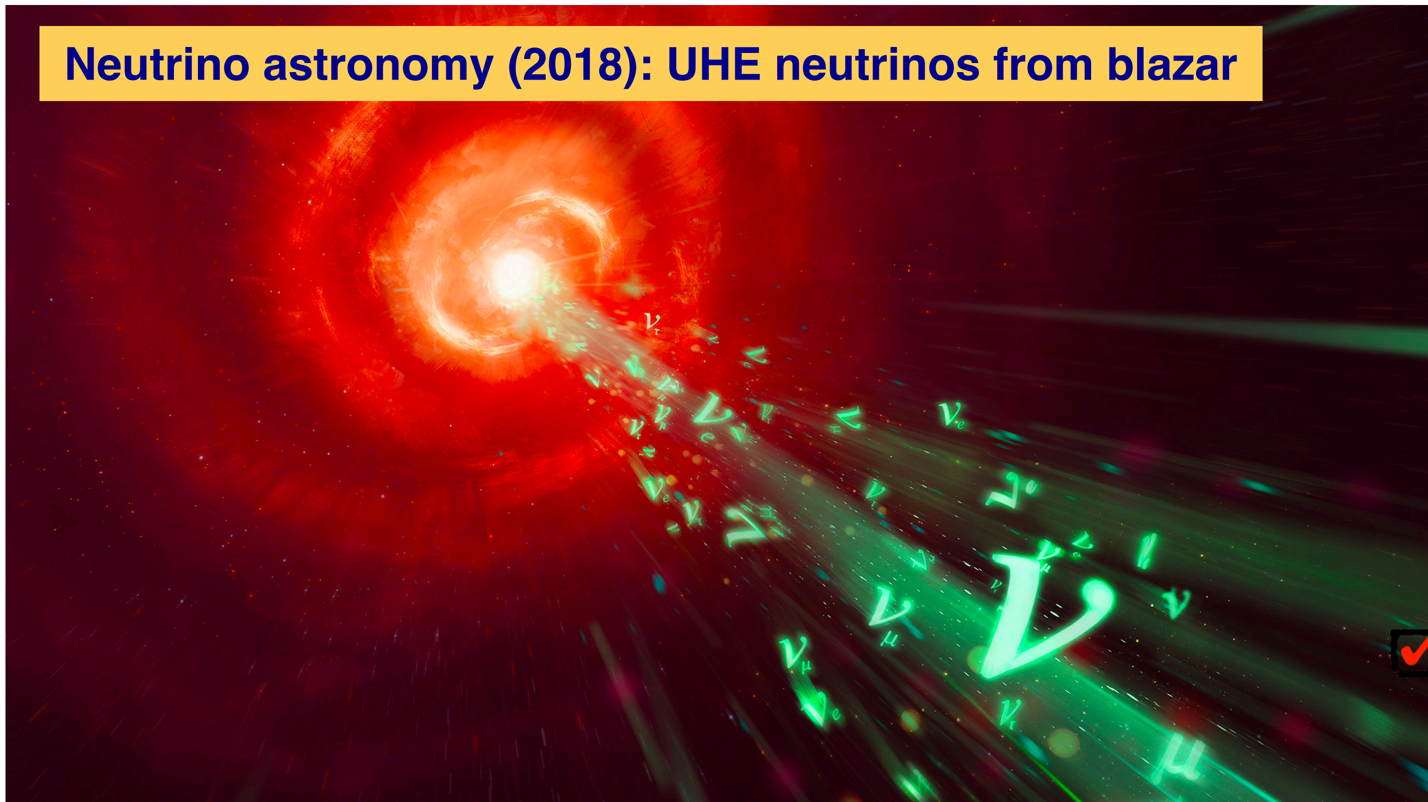
Thanks for your attention!



Extra Material

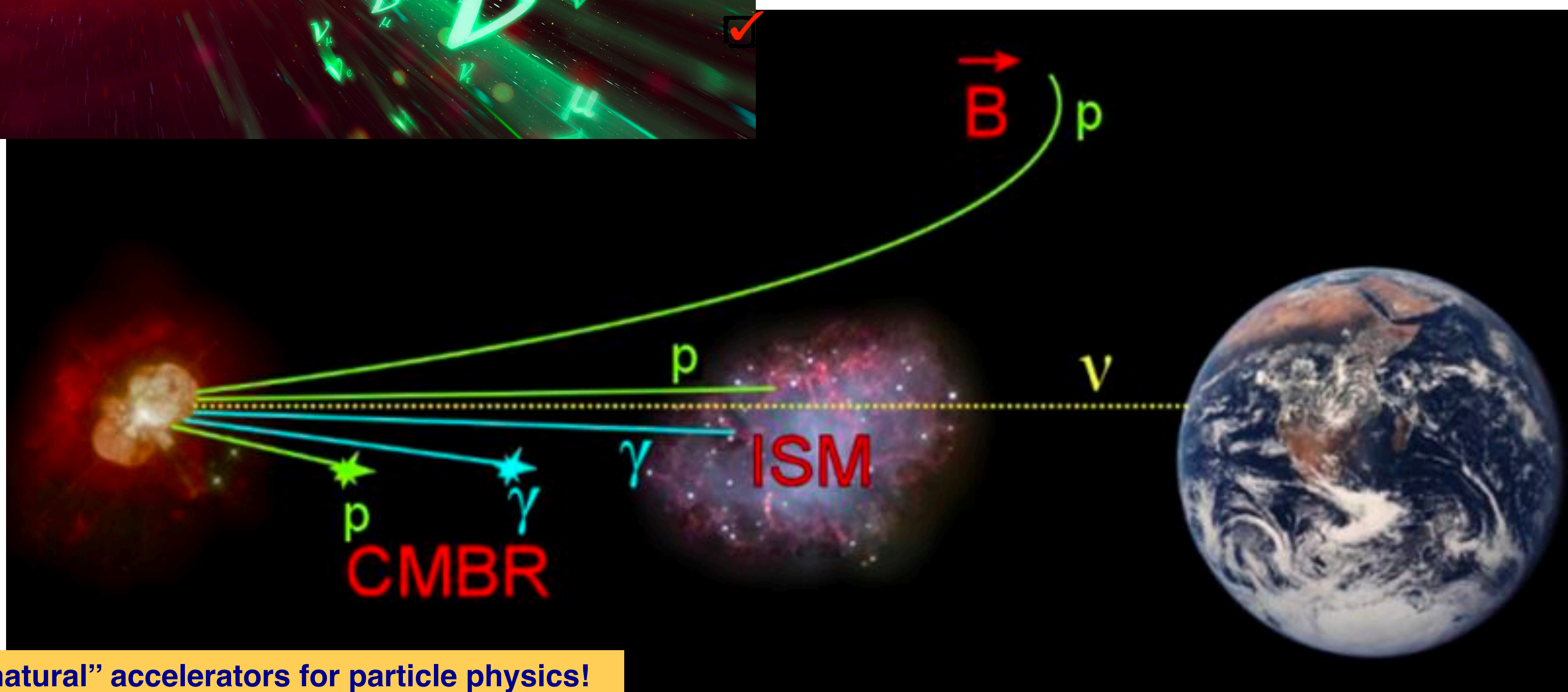
Neutrino telescopes

Ultra-high energy (UHE) neutrinos: novel window to the **extreme Universe**



Neutrino astronomy (2018): UHE neutrinos from blazar

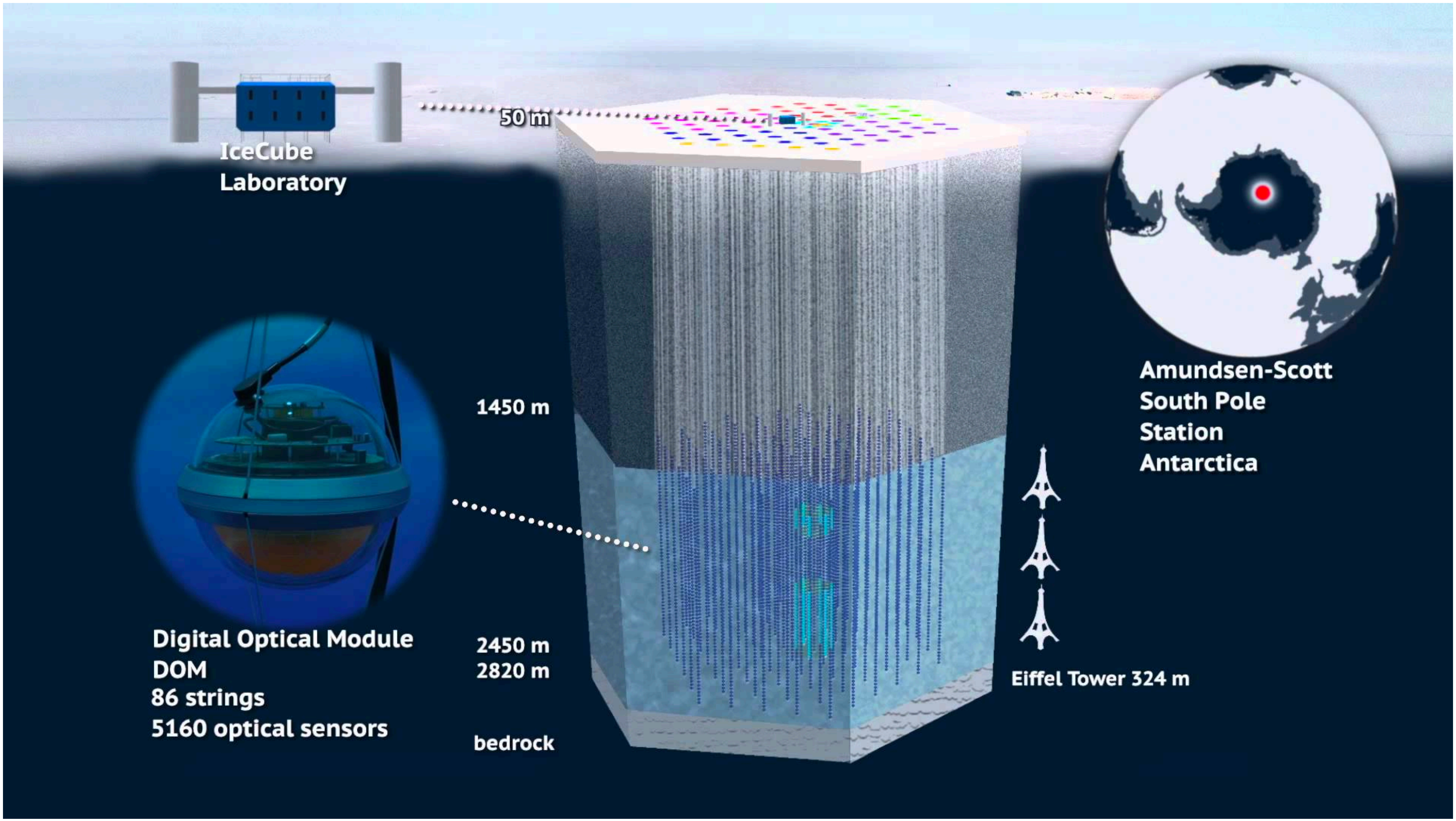
- Neutrinos are the only **cosmic messengers** neither deflected nor attenuated
- Neutrino interactions are very weak and require **large-volume detectors**



exploit ``natural" accelerators for particle physics!

Neutrino telescopes

IceCube: **instrumented 1 km³ of ice in Antartica** for high-energy neutrino detection!



Neutrino telescopes

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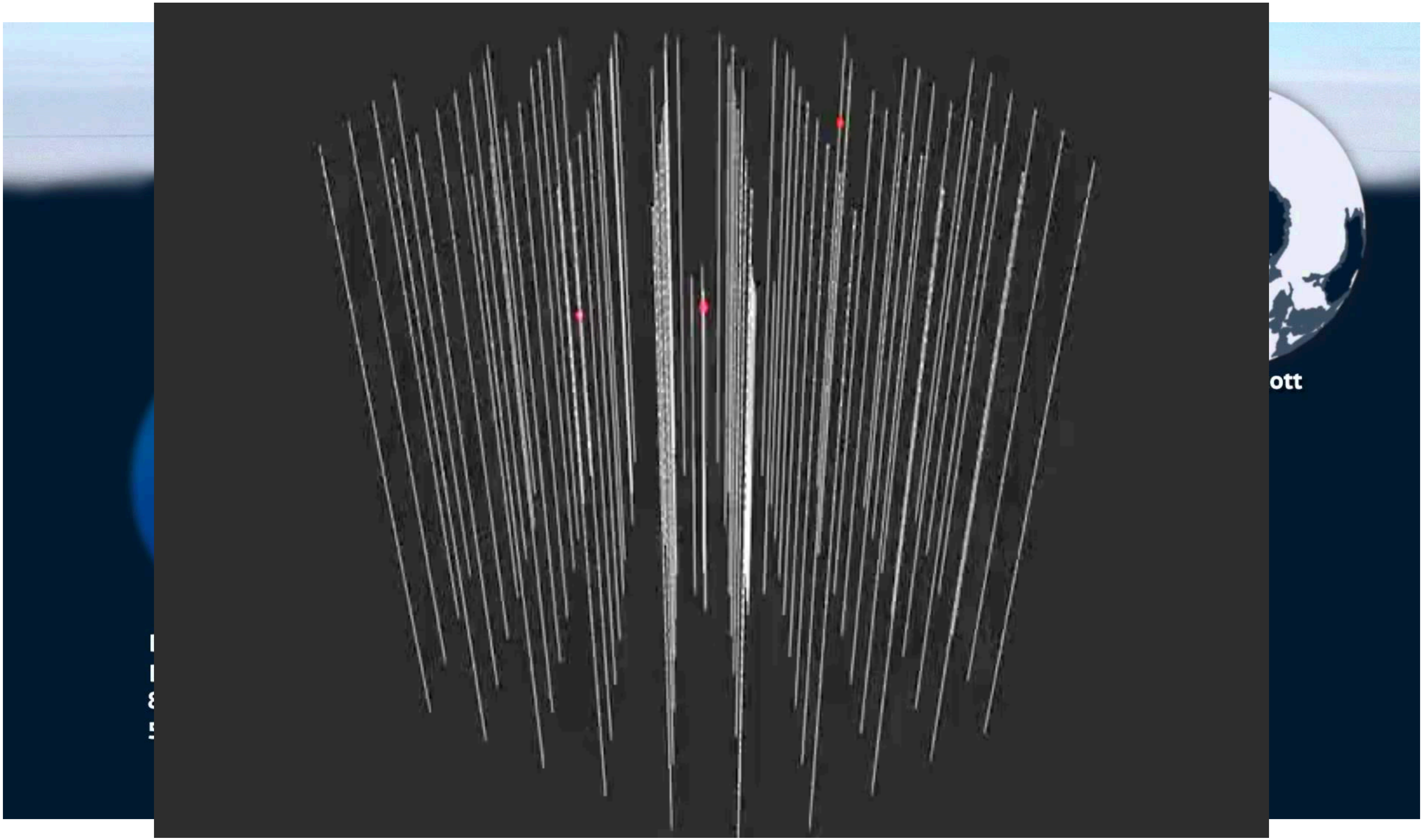
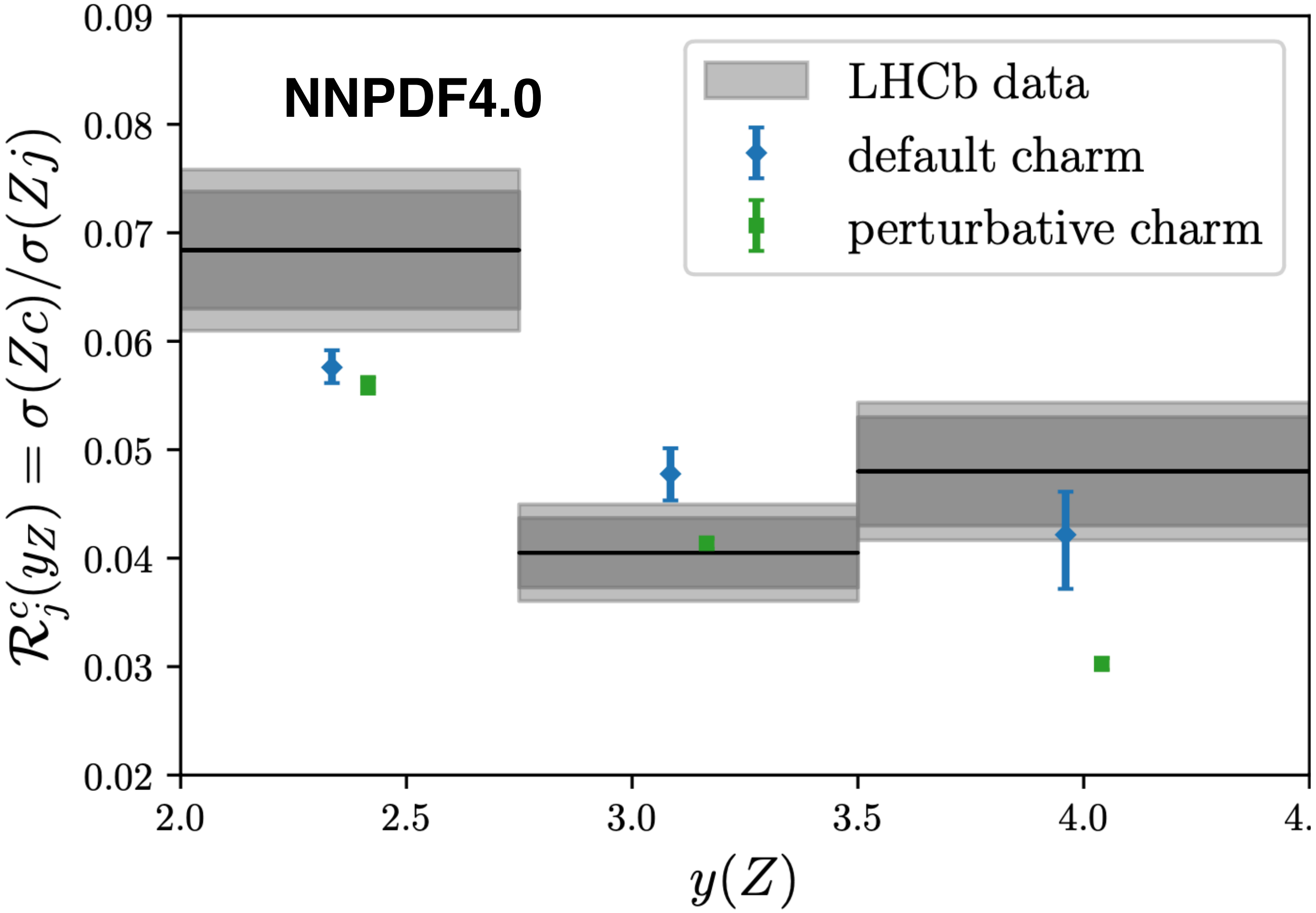
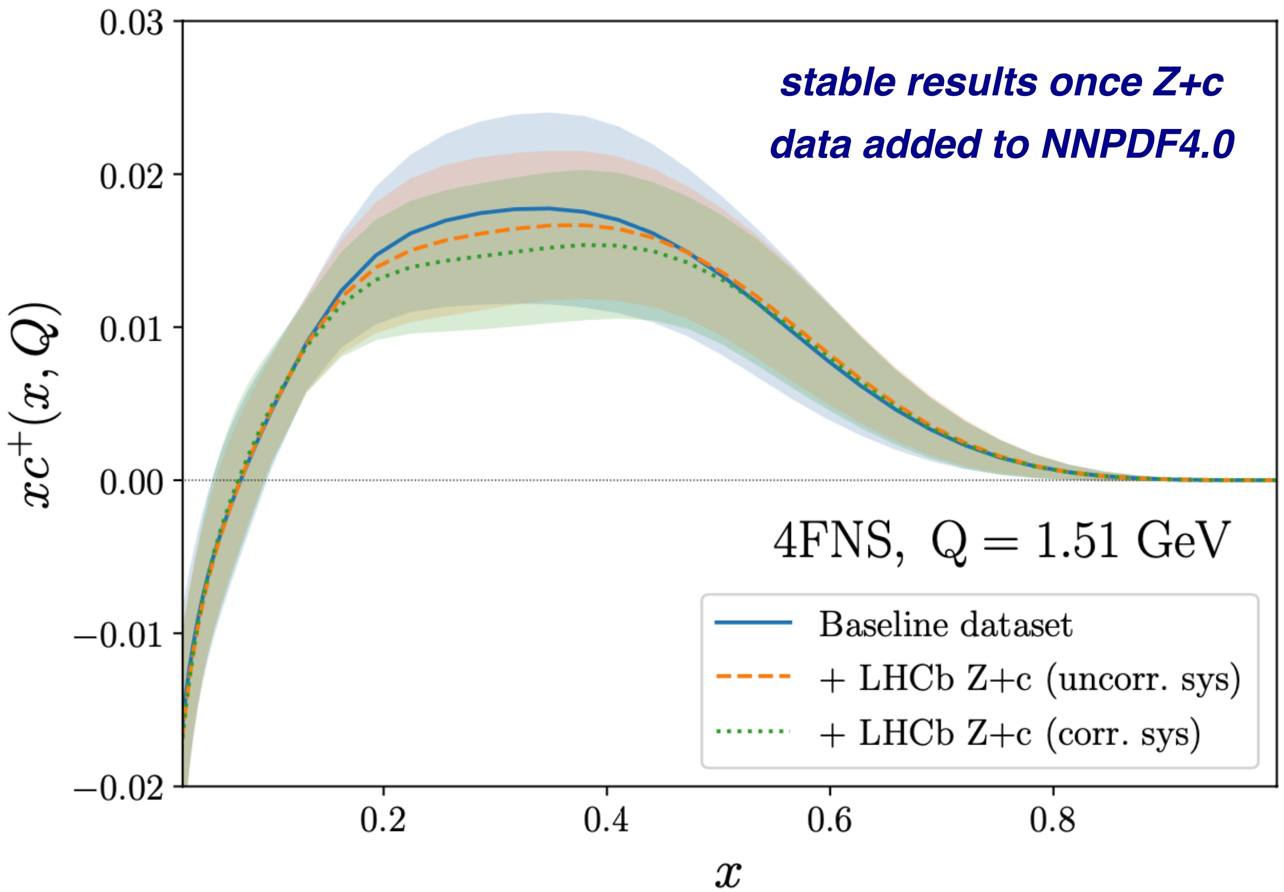


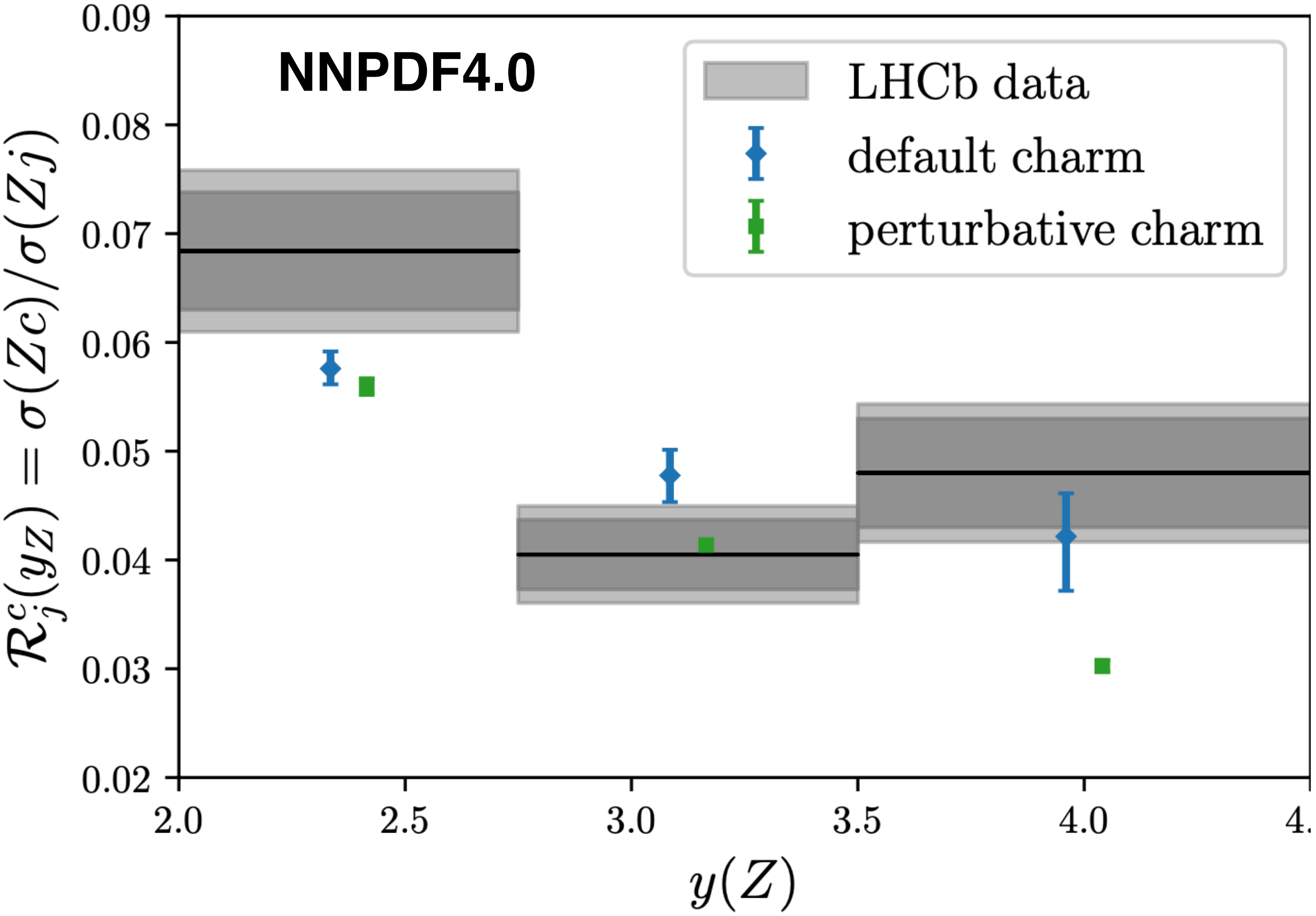
Z+charm @ LHCb

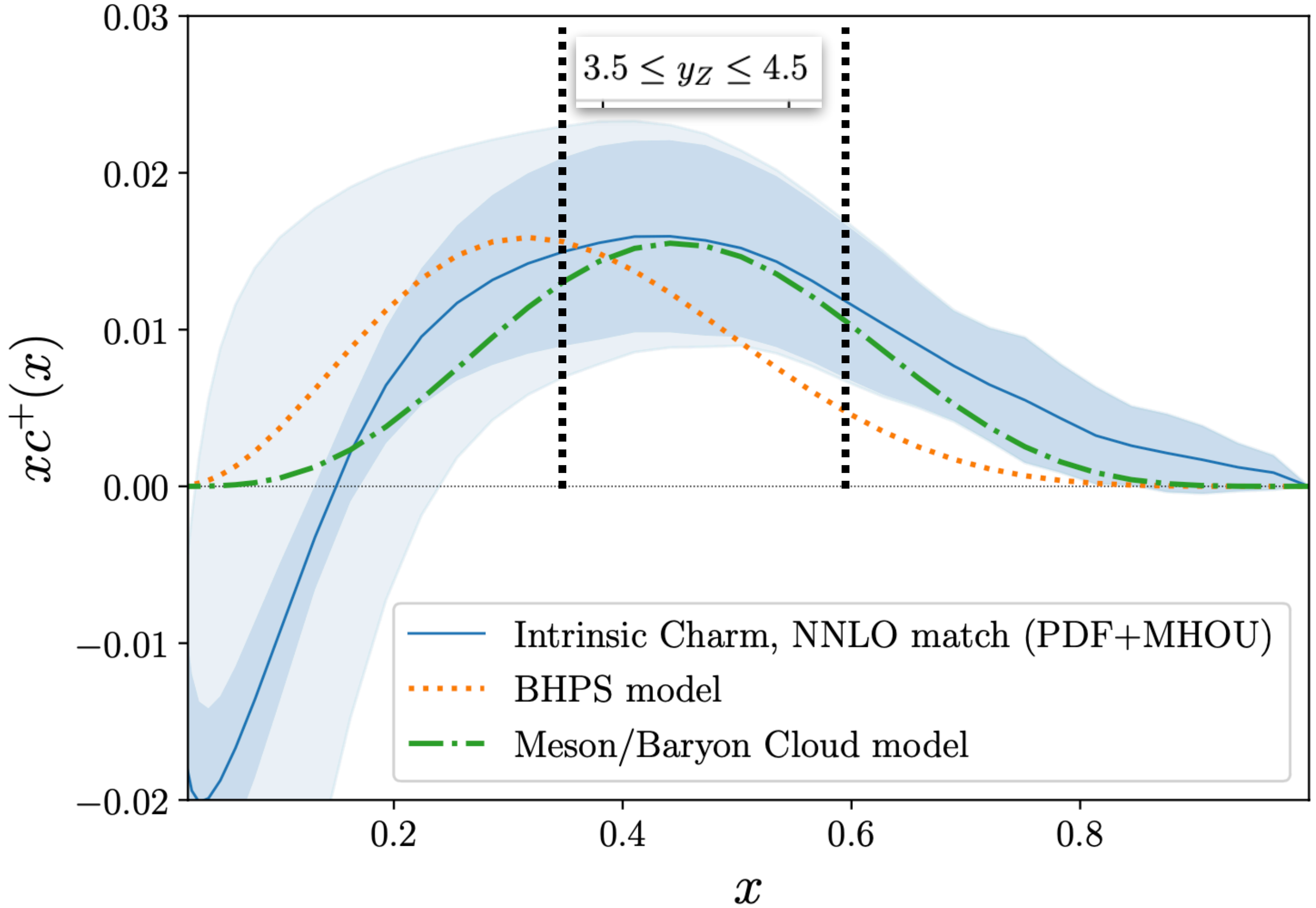




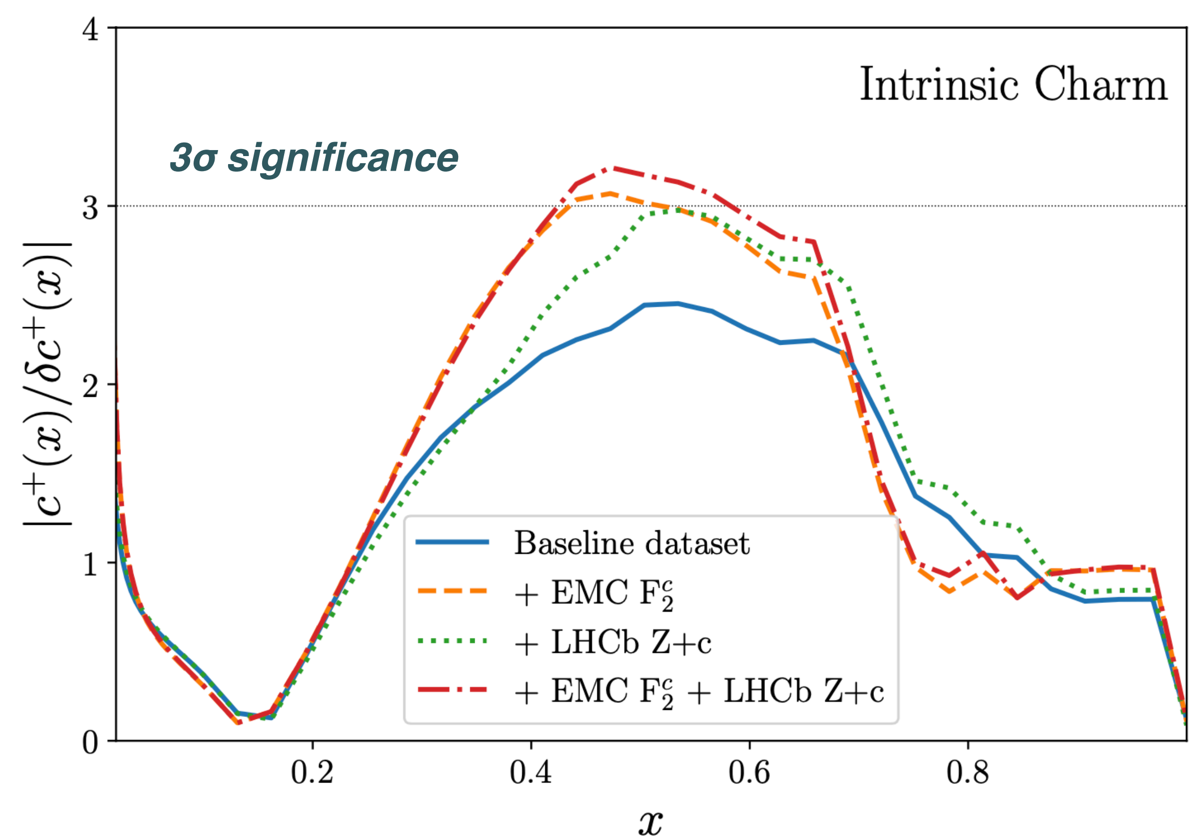
- Calculations settings: **NLO+Pythia8 via the POWHEG-BOX** (charm fragmentation from shower), accounting for MHO and PDF uncertainties (MHOUs cancel partially in ratio)
- Charm jets defined by **overlap of anti-k_t jets with reconstructed *D*-mesons** to reproduce experimental analyses: includes contribution 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





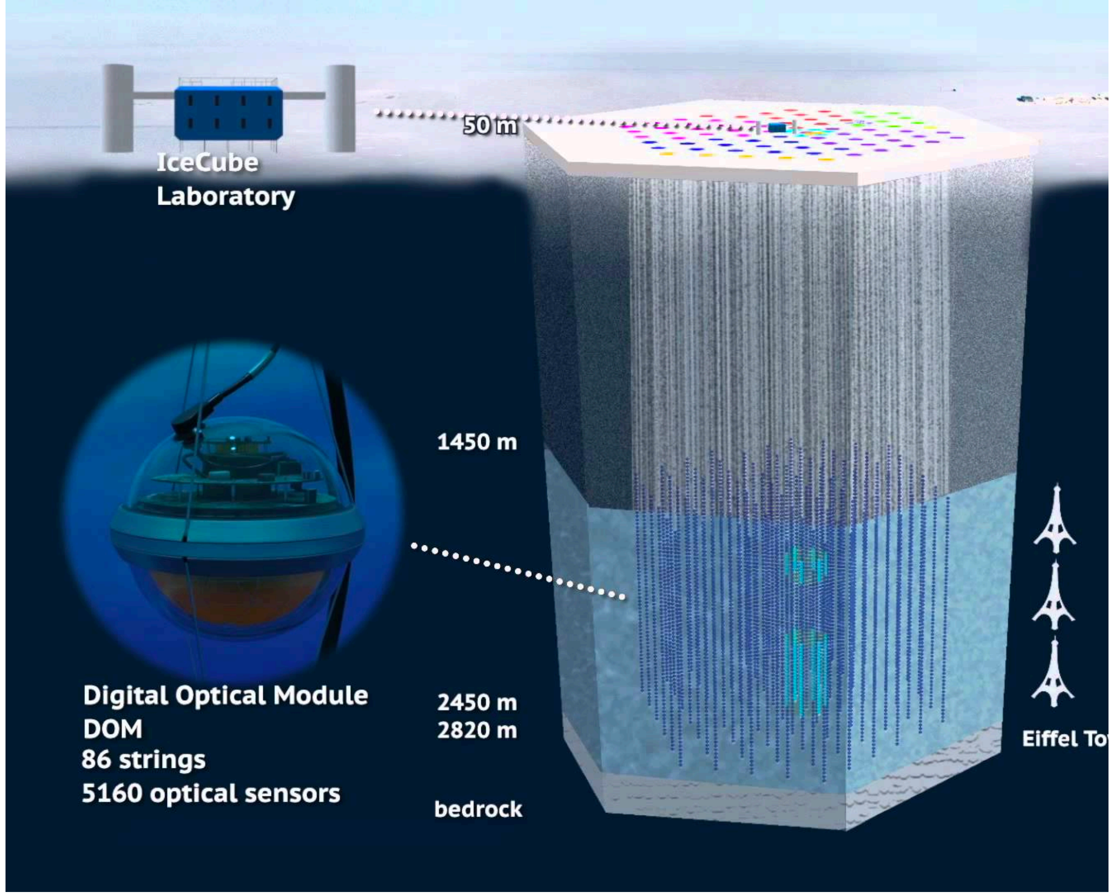
- Perturbative charm PDF disfavoured **by** the LHCb forward Z+charm data
- LHCb data consistent with IC carrying **0.5% of proton's momentum**
- Consistency between **direct** (Z+c, EMC F_2^c) **and indirect constraints** on the charm PDF



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 @ IceCube & LHC neutrinos



charm production @ Electron Ion Collider