# ELECTRON-ION COLLISIONS AND THEIR IMPORTANCE FOR PARTICLE PHYSICS

Marek Matas (Matas.Marek1@gmail.com)

# OUTLINE

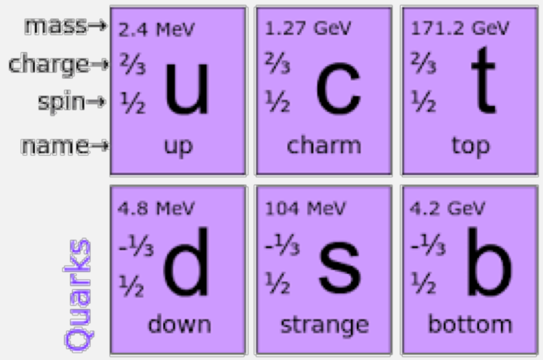
I. A bit of theory
   I. Parton Model
   II. Parton Distribution Functions and Universality
   III. Saturation
II. Connection to electron-ion collider (EIC)
III. Motivation for and electron-ion collider
IV. Plans for construction
V. Conclusions

# INTRODUCTION TO PARTON MODEL

# PARTON MODEL

The name "parton" was coined by Richard Feynman for any constituent particle inside hadrons.

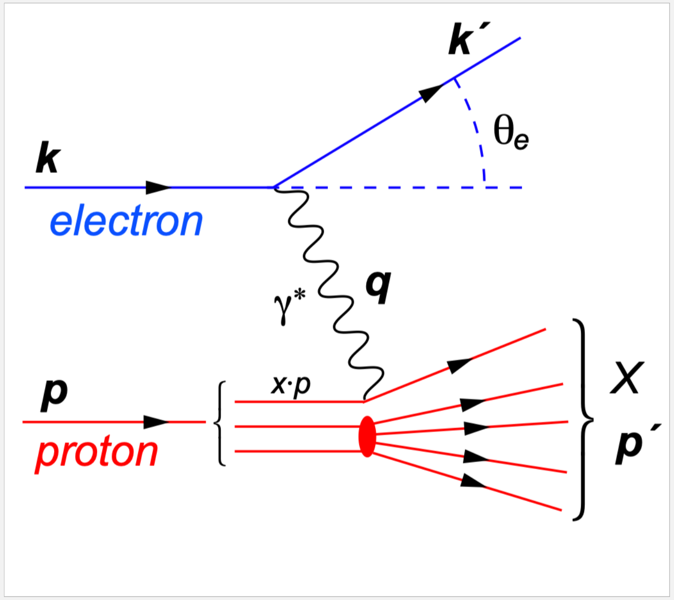
- Partons therefore relate to quarks and gluons
- Quarks that determine the quantum numbers of hadrons are called valence quarks
- There are six quarks, that make up known hadrons. They carry both spin and charge




# PARTON MODEL

In the three quark model, a proton is composed of two up quarks and one down quark.

- This model however does not match the measurements of Deep Inelastic Scattering.
- Valence quarks are embedded in a sea of virtual quark-antiquark pairs.
- These are generated by the gluons, which are the bosons responsible for binding protons together.
- Deep Inelastic Scattering processes are ideal for probing parton structure.



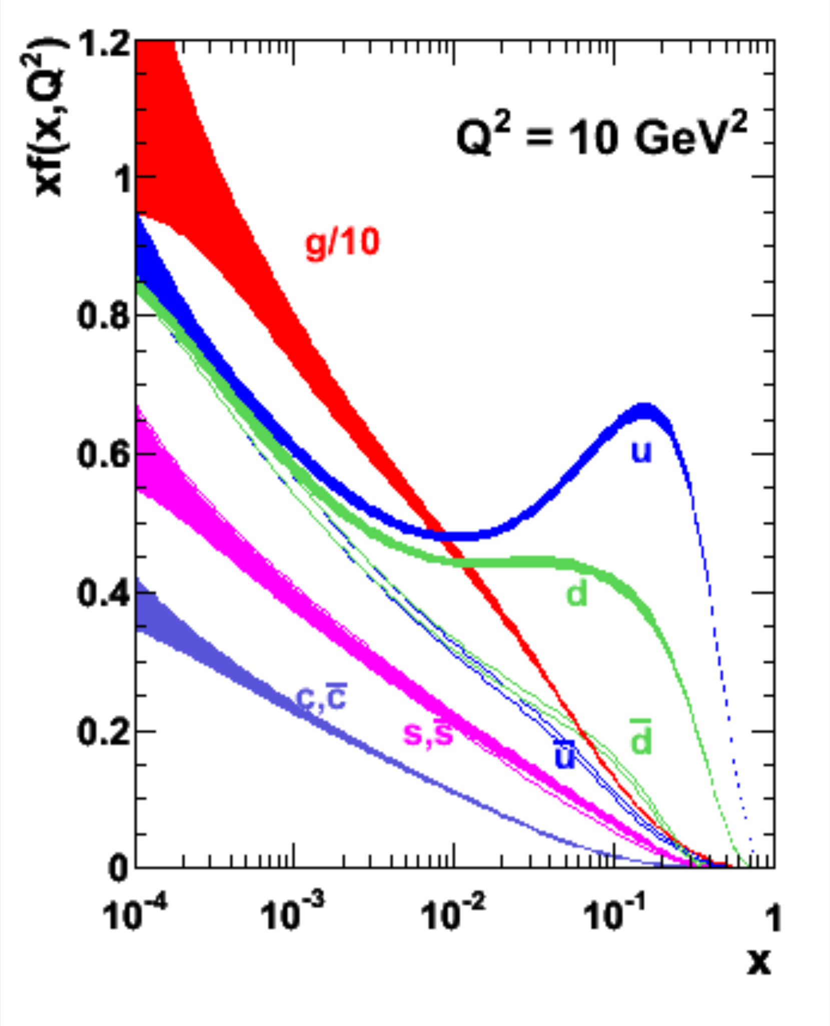
# PARTON DISTRIBUTION FUNCTIONS

# PARTON DISTRIBUTION FUNCTIONS

- To study the internal structure of hadrons, it is convenient to choose a frame, where the proton moves with very high momentum (infinite momentum frame)
- In this frame, we neglect all transversal motion of constituent partons.
- The variable, that describes a parton in this frame is the fraction of protons longitudinal momentum - x.
- The probability densities for finding a parton with a probe of vituality $Q^2$ (where $Q^2 = -q^2$) and momentum x are called the Parton Distribution Functions (PDFs)

# PARTON DISTRIBUTION FUNCTIONS

MSTW 2008 NLO PDFs




Measured parton distribution vs momentum fraction x at selected value of virtuality.

# PARTON DISTRIBUTION FUNCTIONS

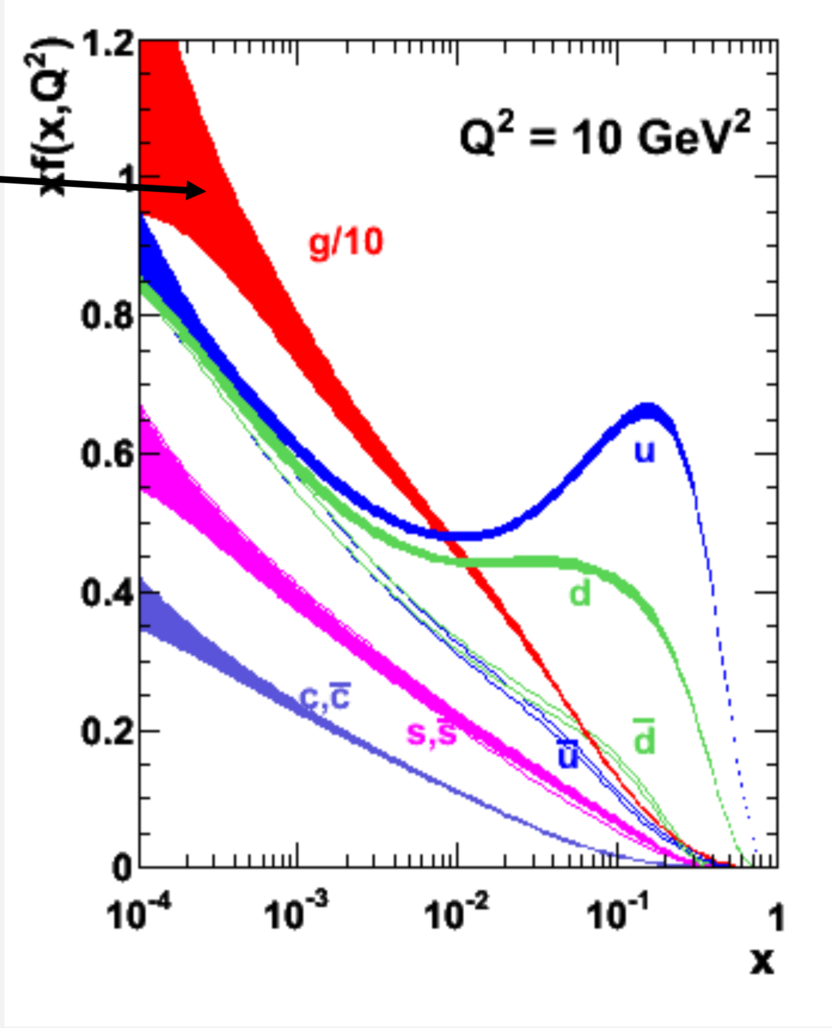
PDFs are very useful, do to a property called **universality**.

- This means, that once obtained PDFs are universal for all considered processes.
- In other words, the probability of an up quark being inside a proton does not change if we probe the quark with another quark or if we probe it with a gluon.
- This property allows us to measure these PDFs once (at an experiment) and from that point use them in our computation to determine probabilities, that some partons act in our collision.

# PARTON DISTRIBUTION FUNCTIONS

MSTW 2008 NLO PDFs

Gluon distribution

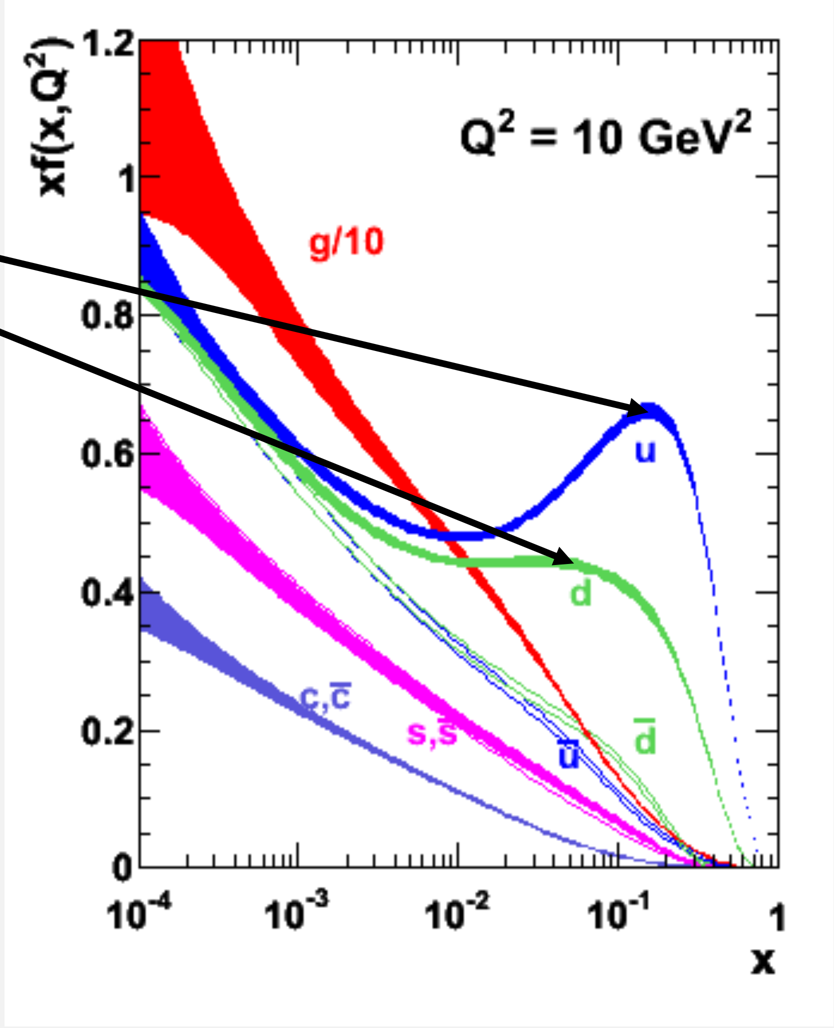



- As we can see, gluon distribution dominates the region of low x.
- This is due to the effect of gluon splitting, that is possible because gluons carry color charge.

# PARTON DISTRIBUTION FUNCTIONS

MSTW 2008 NLO PDFs

Quark distributions

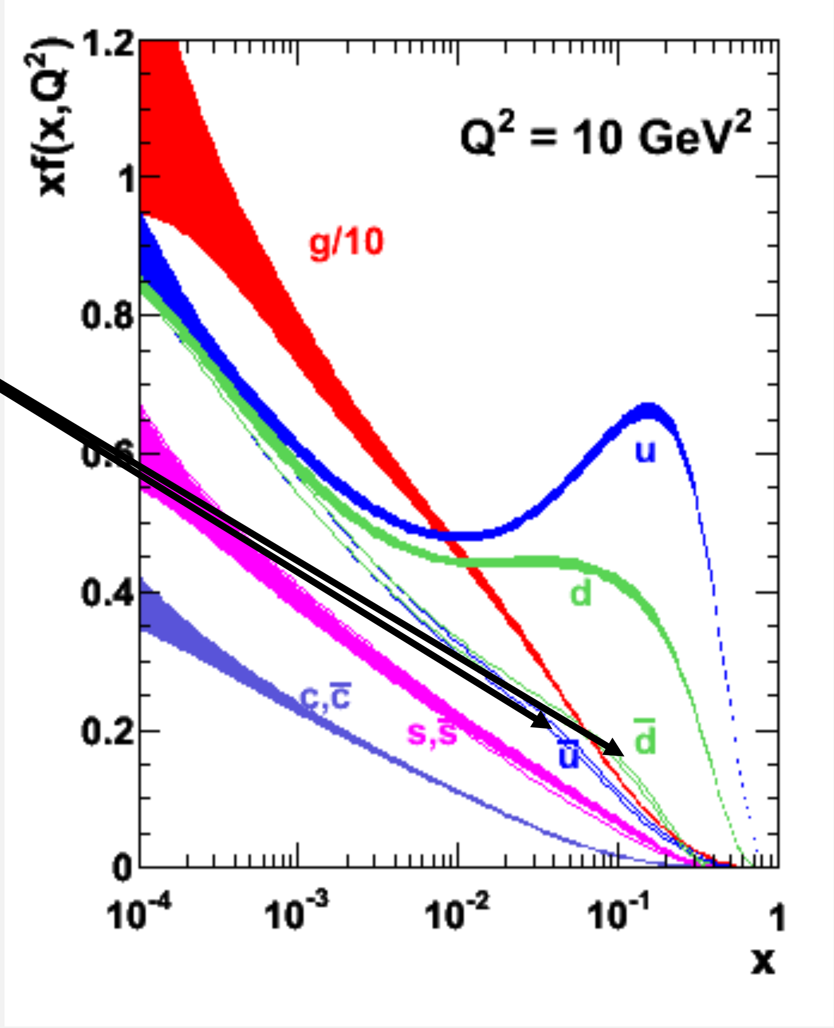



- Up and down quark distributions including the contribution from the sea quarks.

# PARTON DISTRIBUTION FUNCTIONS

MSTW 2008 NLO PDFs

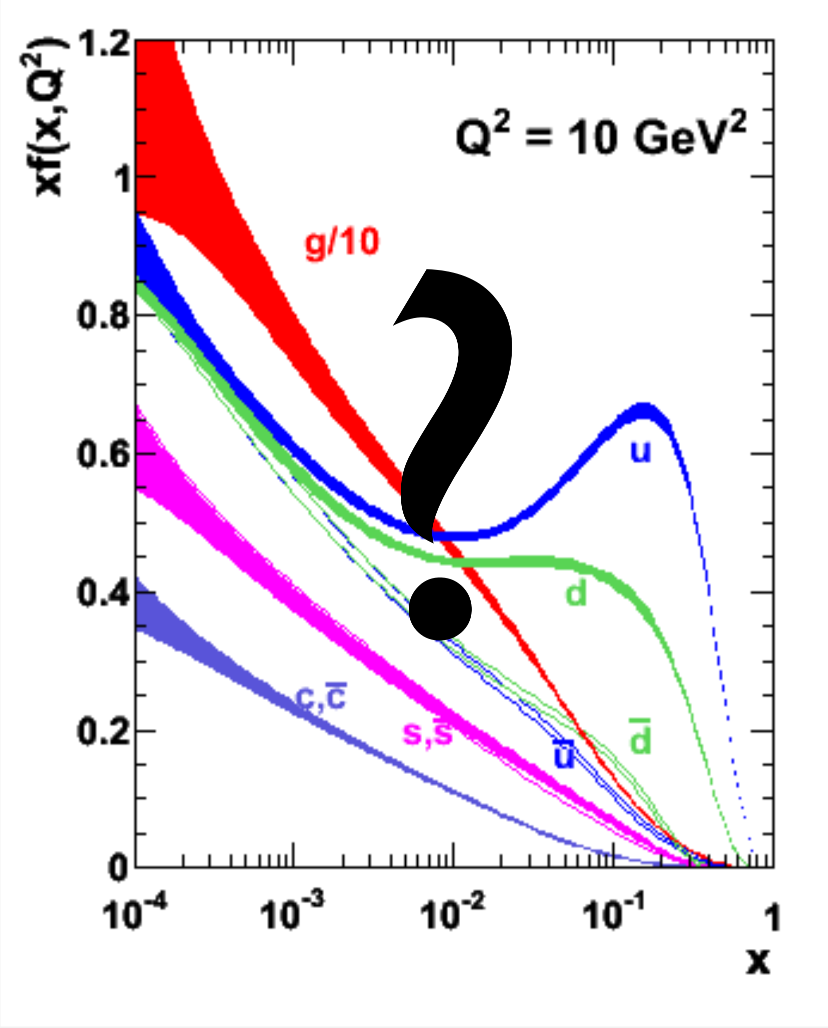
Anti-quark distributions




- Up and down anti-quark. These come solely from the sea distributions. Sea distributions are assumed to be the same for quarks and antiquarks.

# PARTON DISTRIBUTION FUNCTIONS

MSTW 2008 NLO PDFs



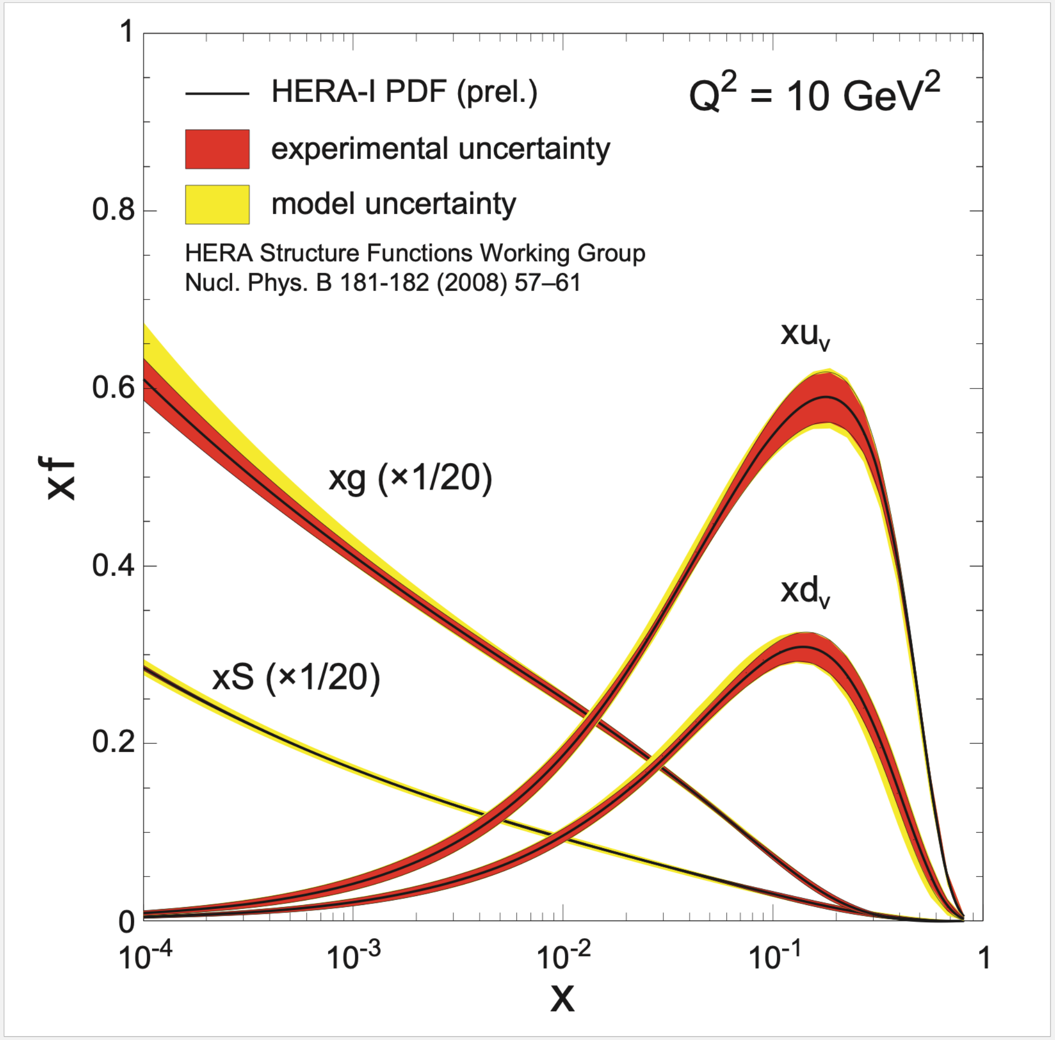

Valence quark distributions

- This fact allows us to subtract the sea distribution from the total distribution to obtain the valence quark distribution.

# PARTON DISTRIBUTION FUNCTIONS

Valence quark distributions

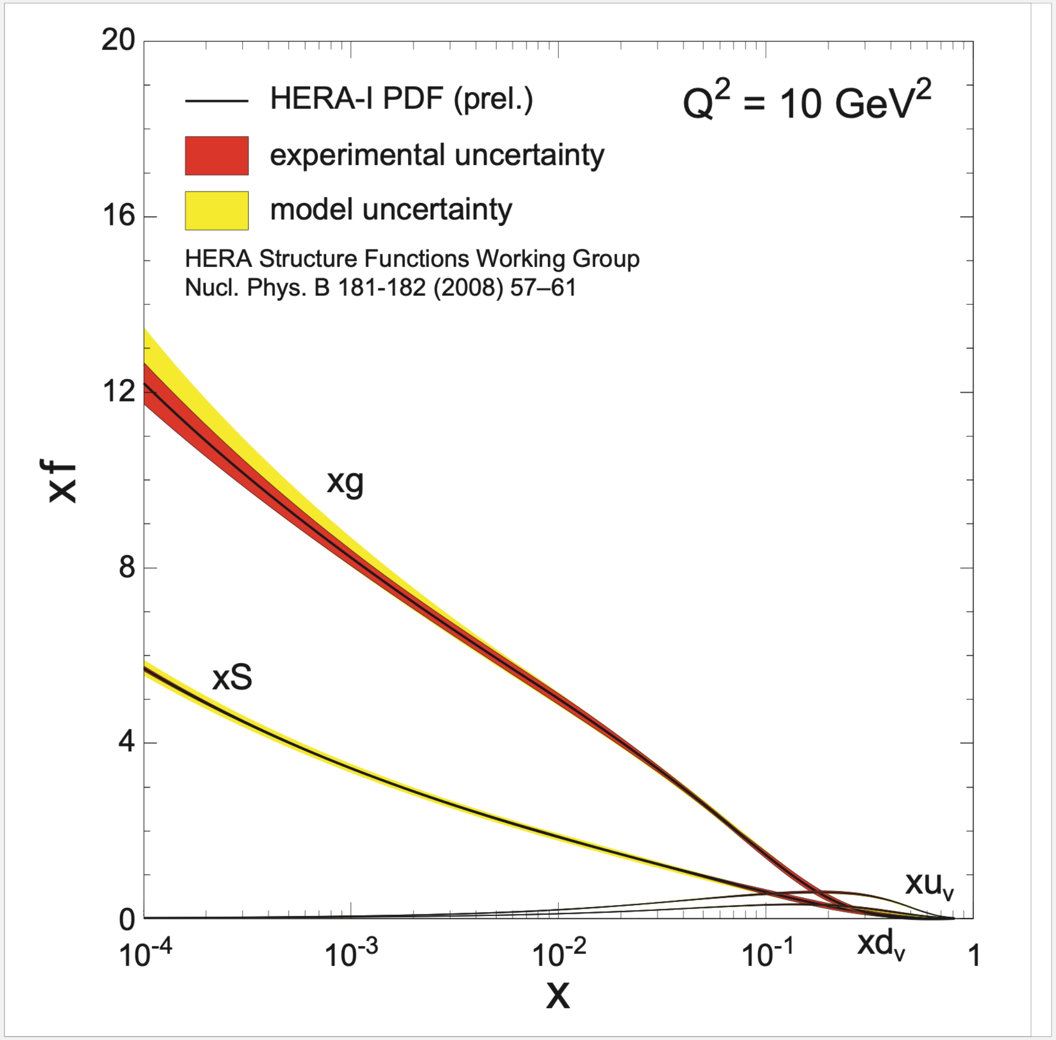
- After the subtraction, we can clearly see, at what momentum do the valence quarks sit.
- We impose such normalization, so that the integral over the valence quarks would be 2 for up and 1 for down quarks.



# PARTON DISTRIBUTION FUNCTIONS

Valence quark distributions

- Proton is almost entirely glue for $x<0.1$!
- Here goes the naive picture that protons are made of 3 quarks



# PARTON DISTRIBUTION FUNCTIONS

Valence quark distributions

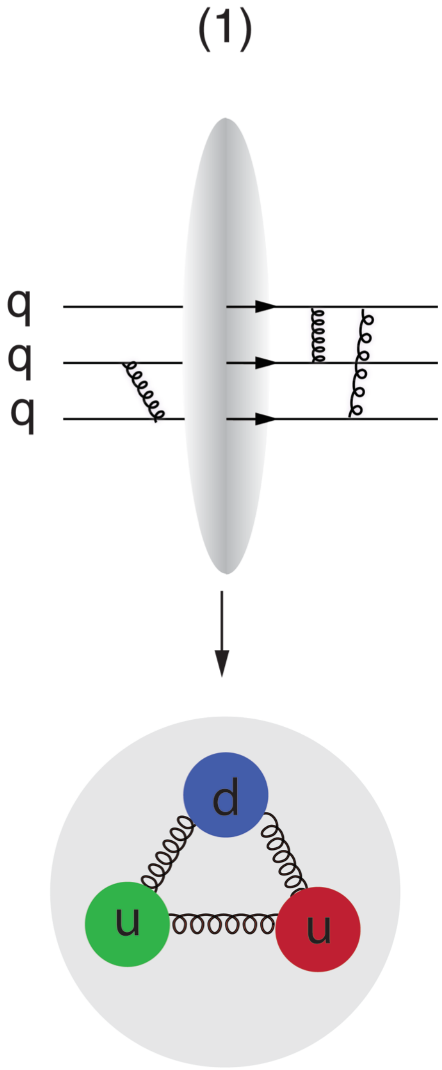
- If we integrate the valence distributions to determine their x-contribution to proton. We find out, it makes up only 54% of proton.
- The rest is carried by other constituent particles.

$$F_2^p(x)dx = \sum_i xQ_i^2 f_i(x) = \frac{4}{9}xu(x) + \frac{1}{9}xd(x)$$

$$F_2^n(x)dx = \sum_i xQ_i^2 f_i(x) = \frac{4}{9}xd(x) + \frac{1}{9}xu(x)$$

$$\int_0^1 xu(x)dx = 0.36$$

$$\int_0^1 xd(x)dx = 0.18$$




At large values of x (carried momentum fraction),
the proton is made of valence quarks

(1)

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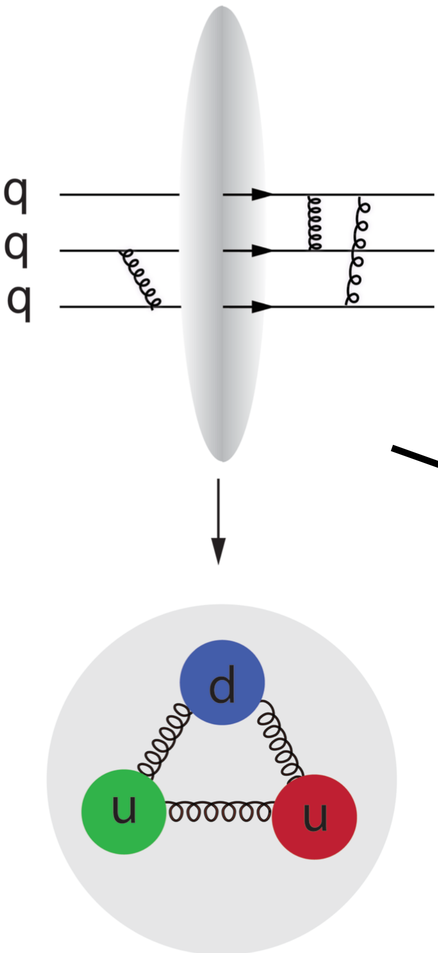
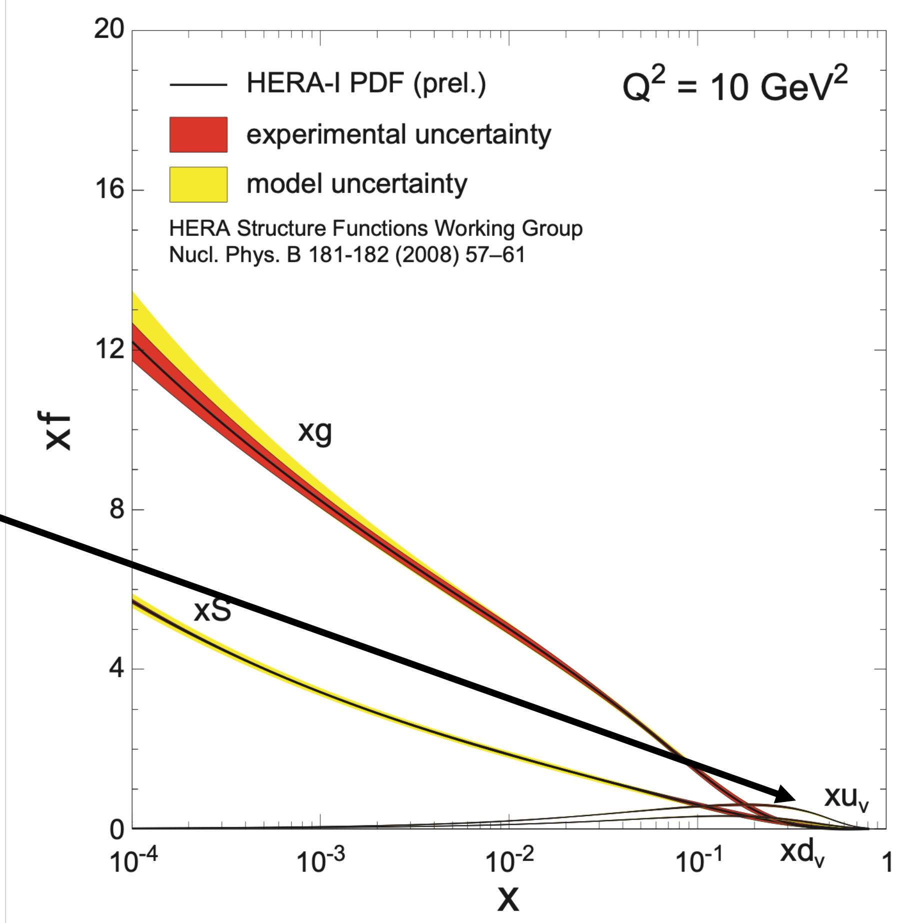
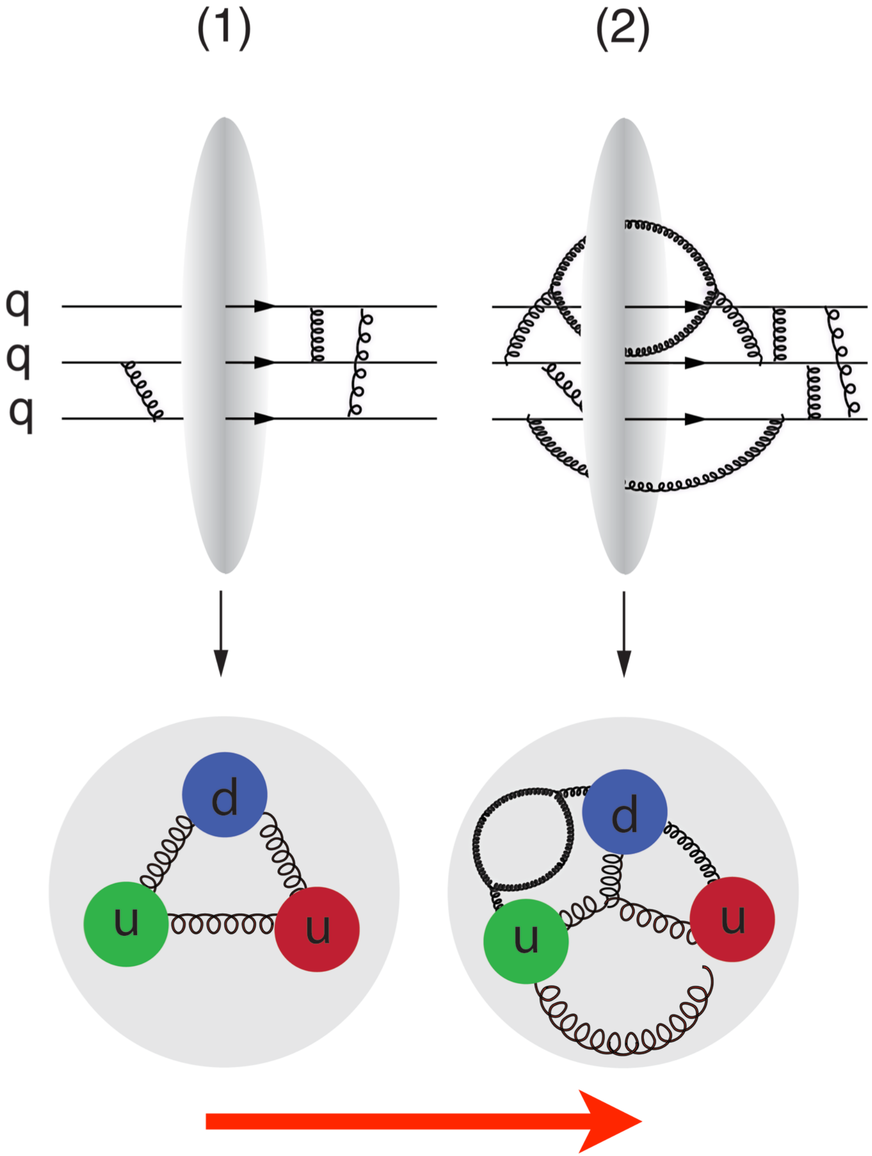


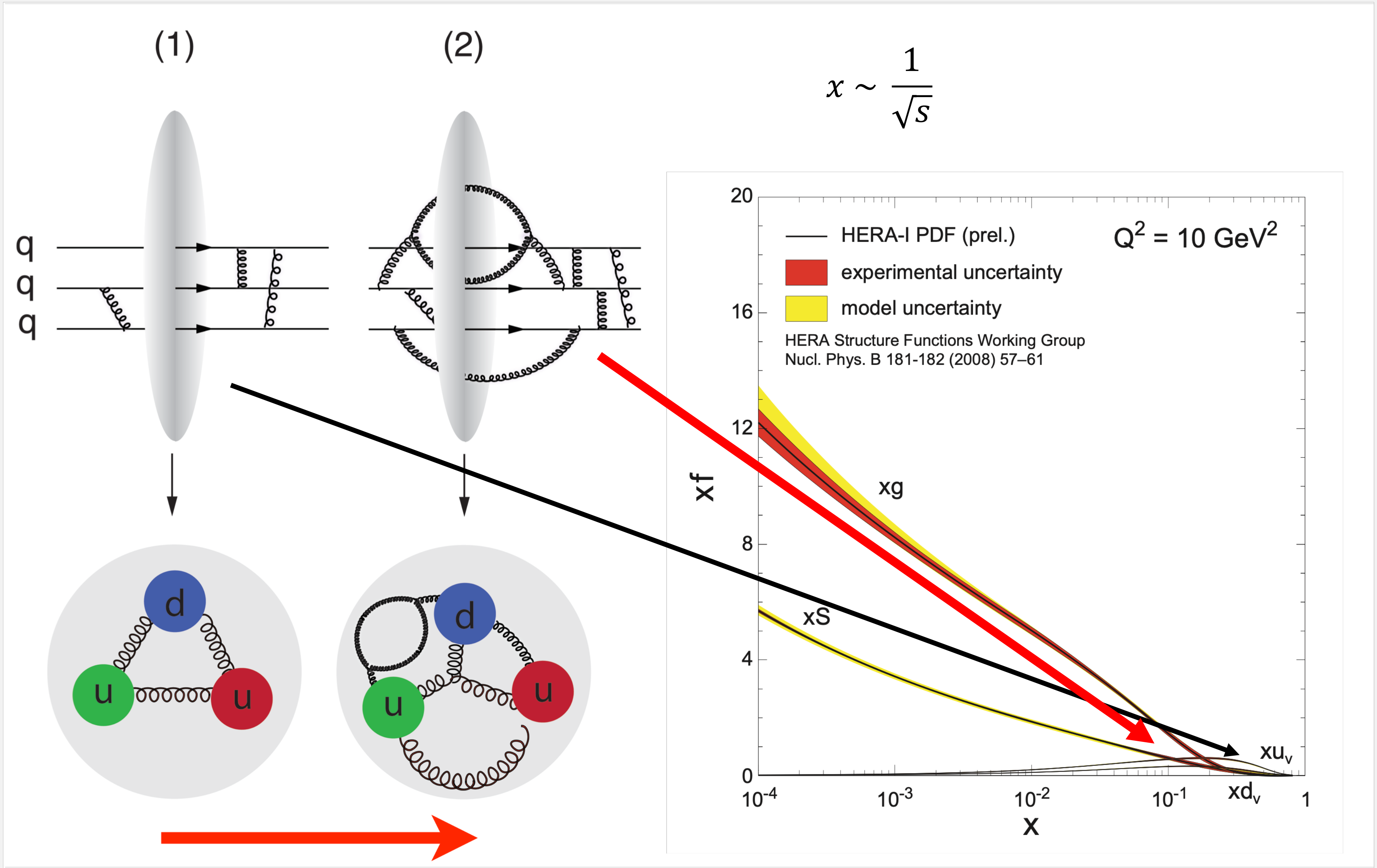





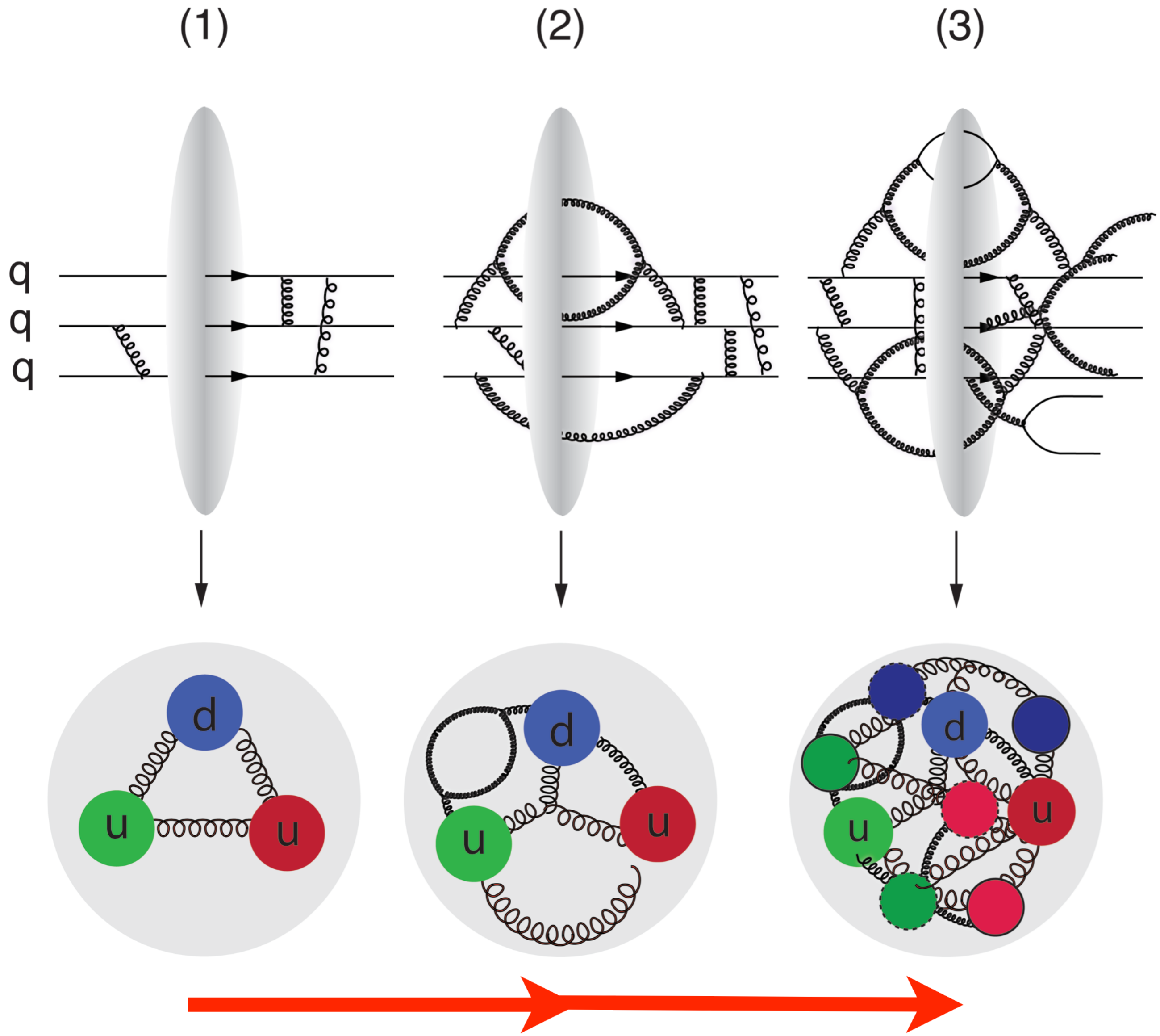

$$x \sim \frac{1}{\sqrt{s}}$$

Increasing the energy of the collision means reaching lower values of x.

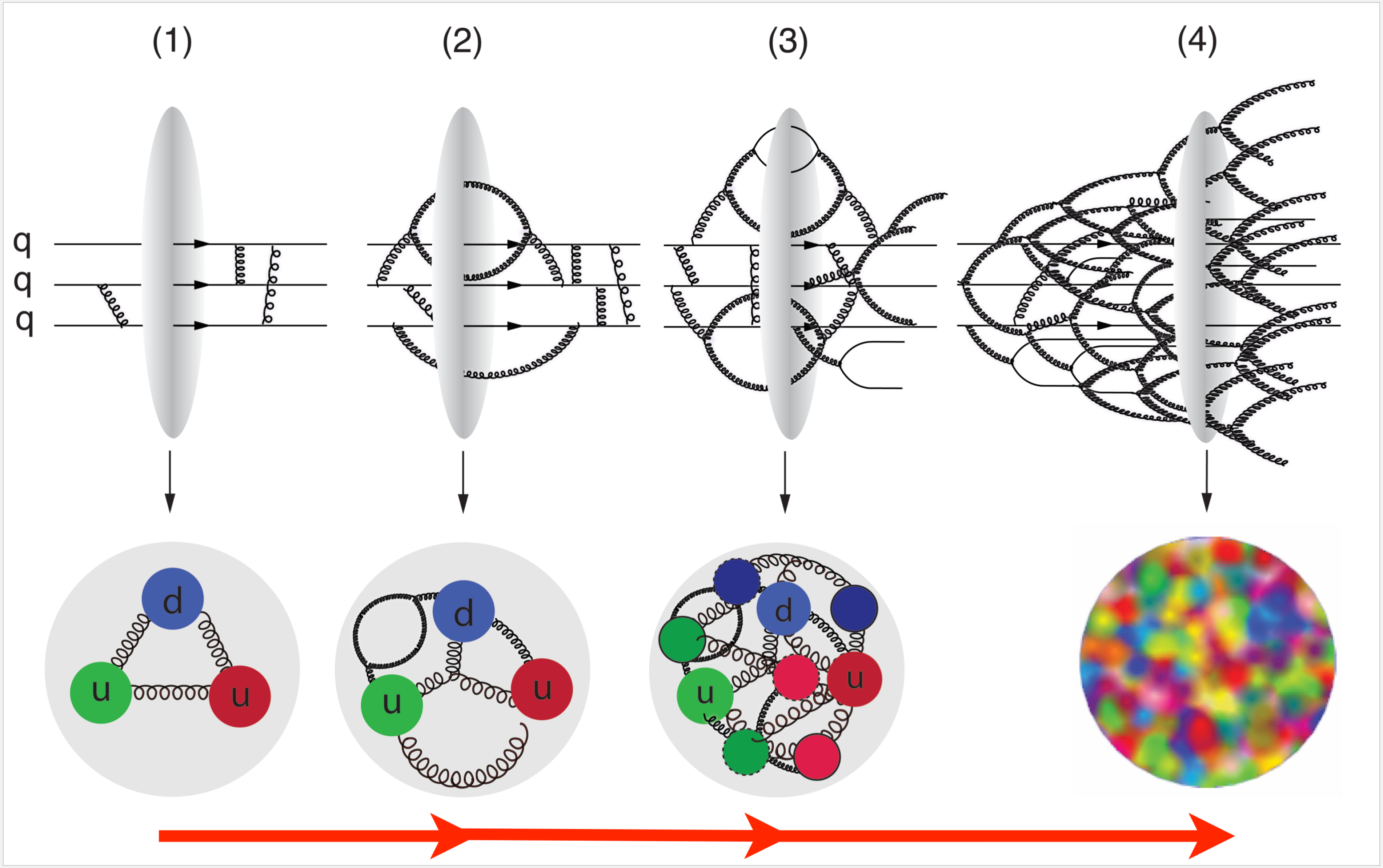
Energy of the collision



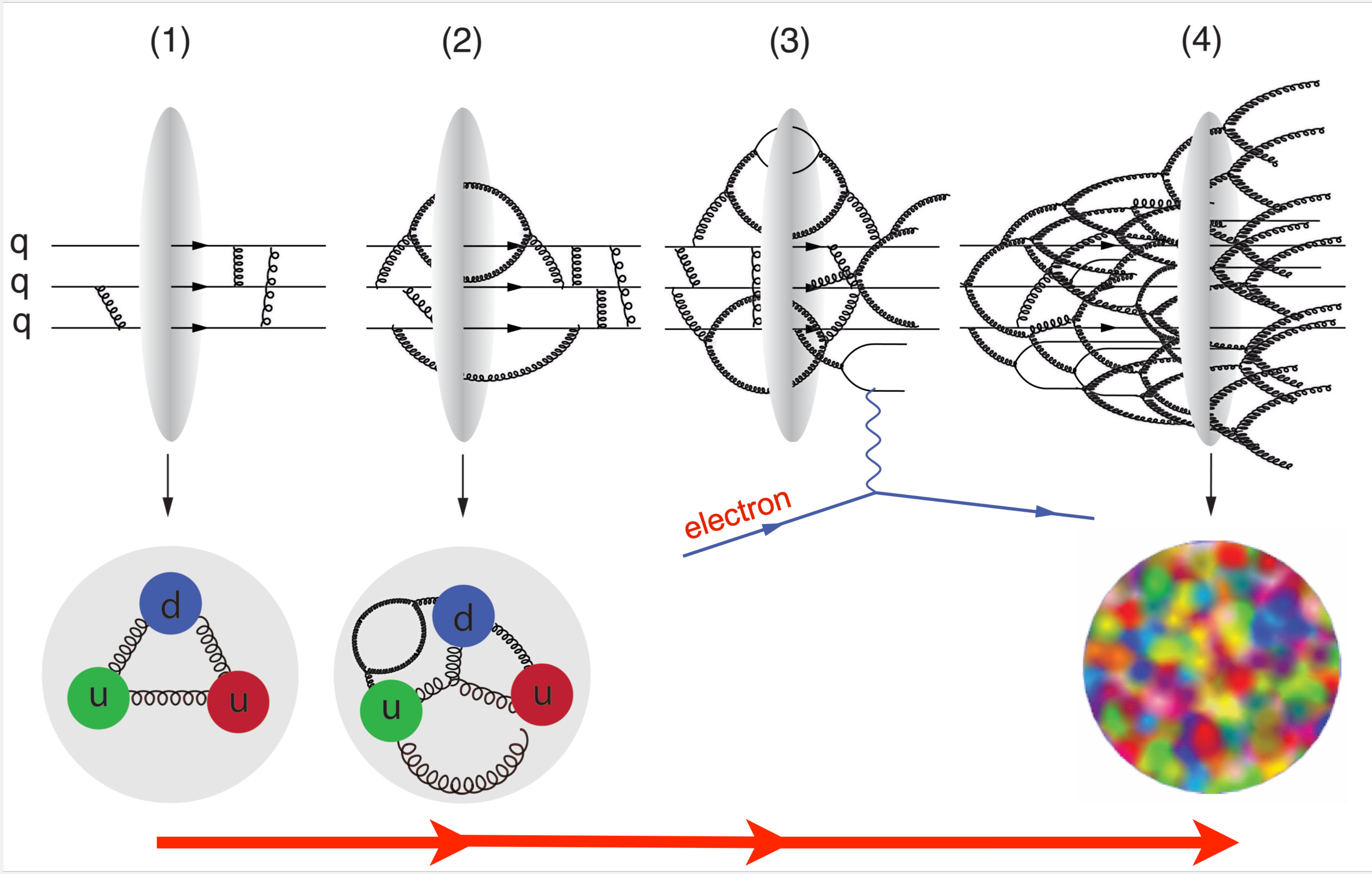

Energy of the collision




Energy of the collision




Energy of the collision



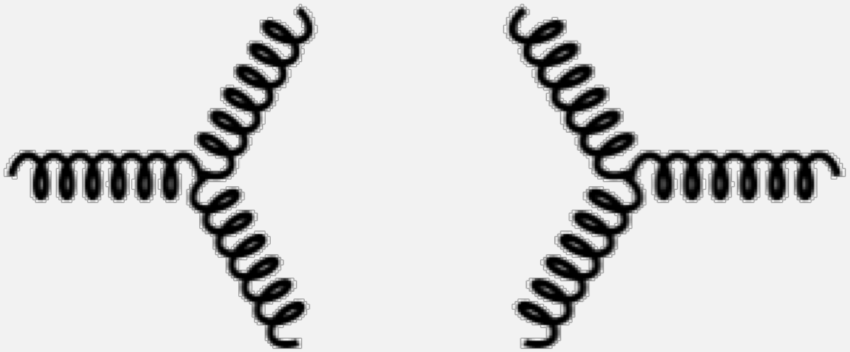

Energy of the collision

# SATURATION

- If gluon numbers only grow toward region of low-x, the gluon distribution would diverge.
- This growth is governed by the BFKL equation.
- The rate of this growth is unphysical and gives us too high cross sections.
- Additional effects need to be taken into account!

# SATURATION

- BFKL equation includes only the gluon radiation effects.
- Other non-linear evolution equation such as the BK equation takes gluon recombination into account.
- This slows down the evolution and tames the unphysical divergences.



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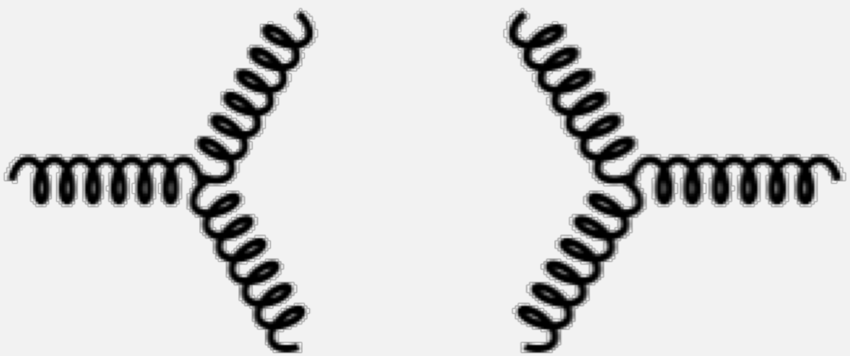

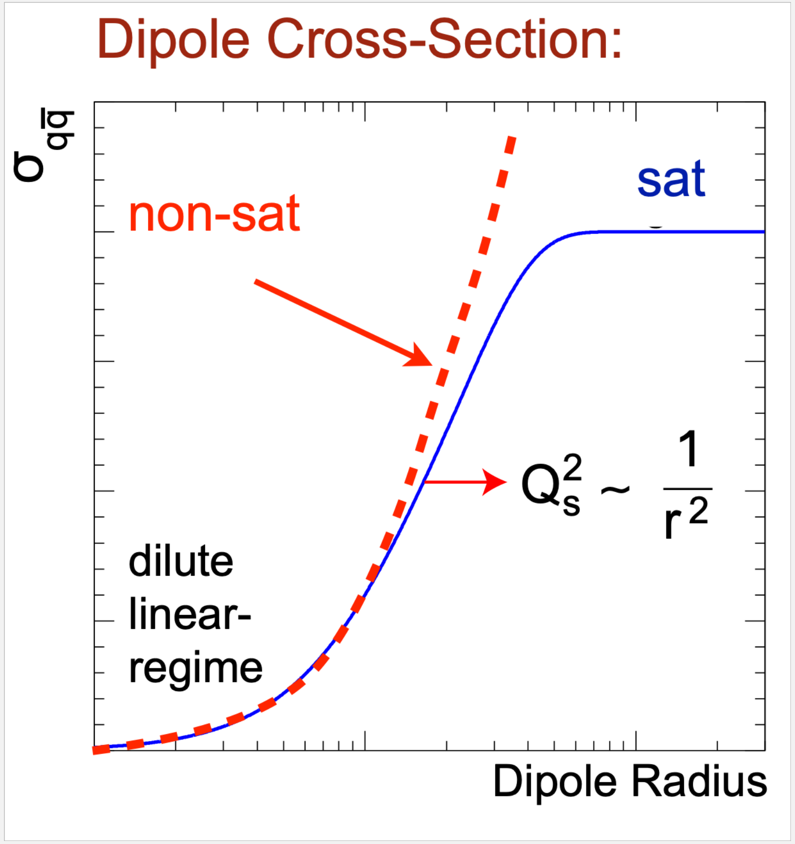

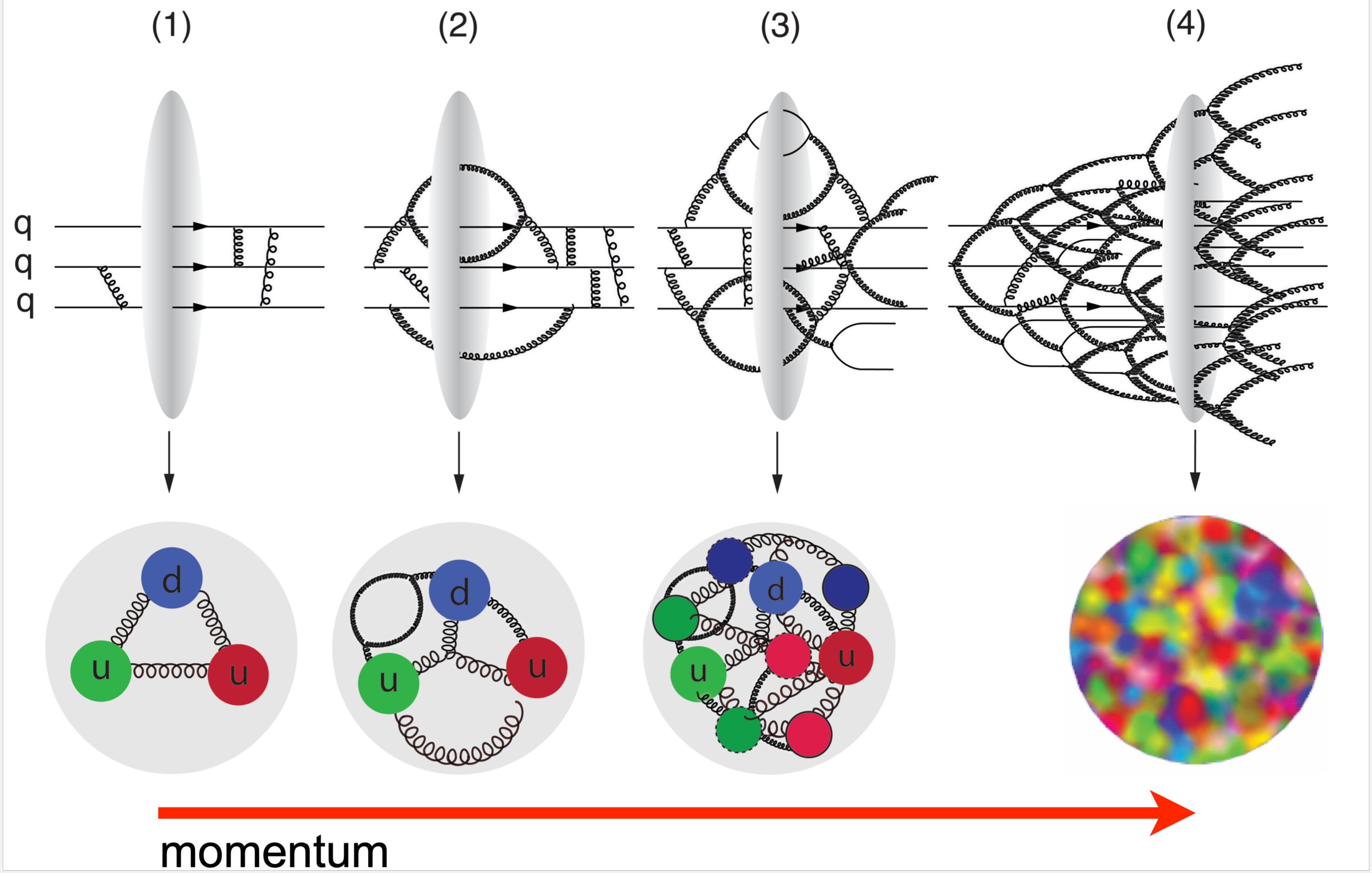
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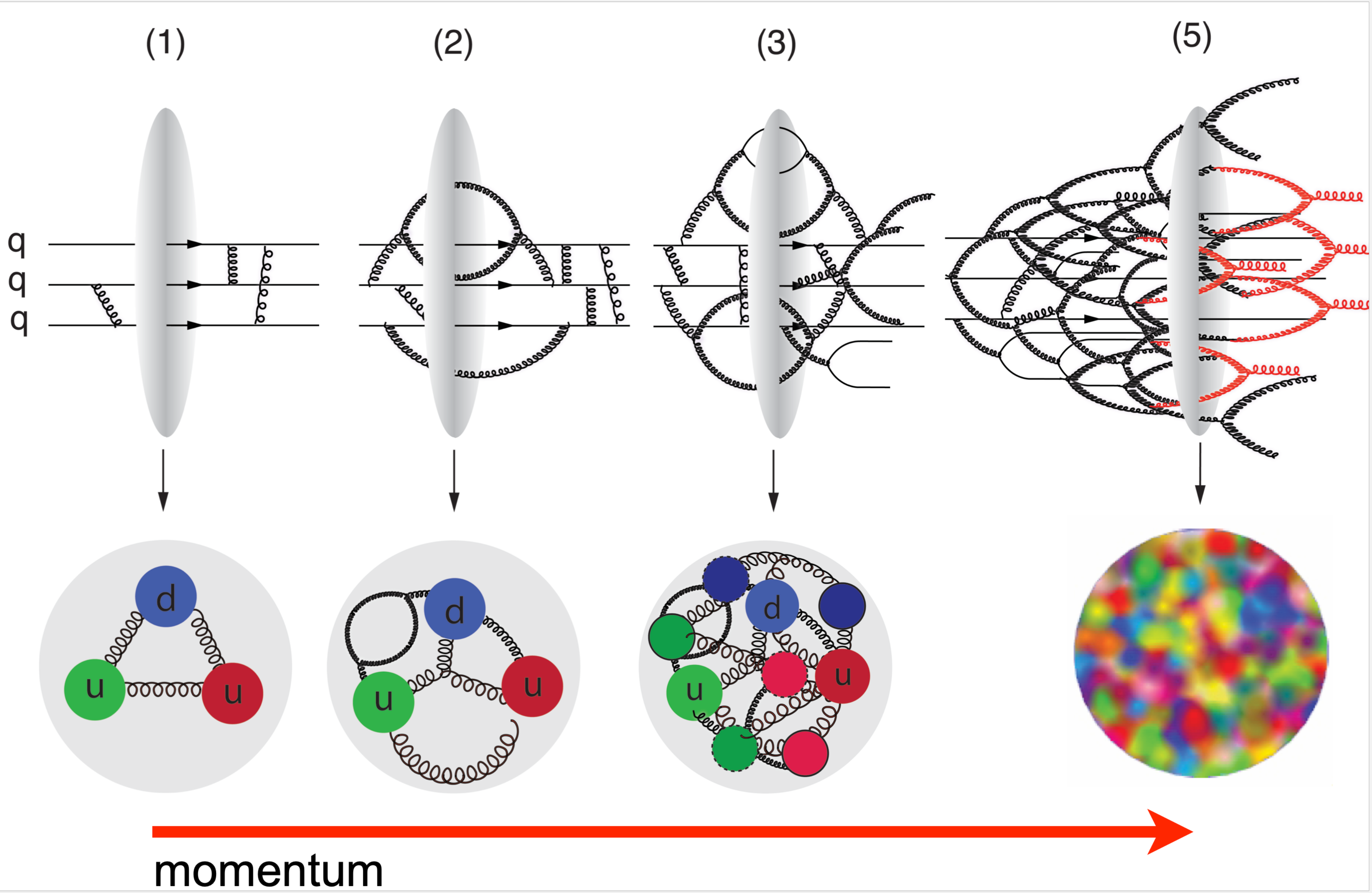
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# IS SATURATION REAL?

The answer is „*We do not know.*“

There are strong hints, that it is, but it can be described by other phenomena.

EIC could provide us with an ultimate convincing evidence!

# HOW DOES ALL THIS WORK IN NUCLEI?

Those were the protons, but how about nuclei?

There is not much data for that!

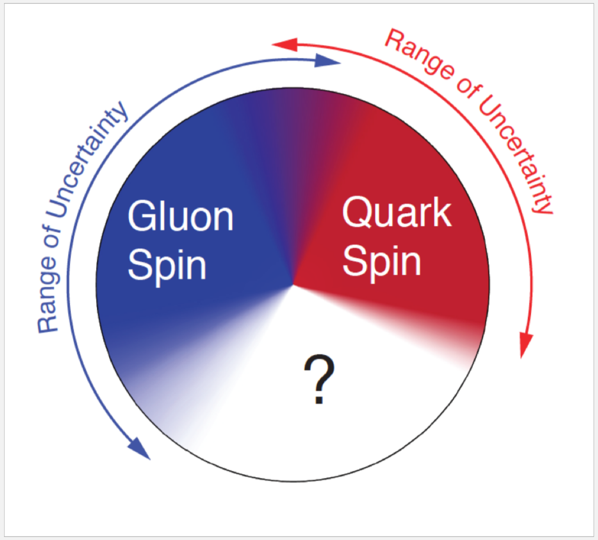
Measuring Deep Inelastic Scattering on Ions is crucial for us to determine the PDFs, that have shown so much use and success in protons.

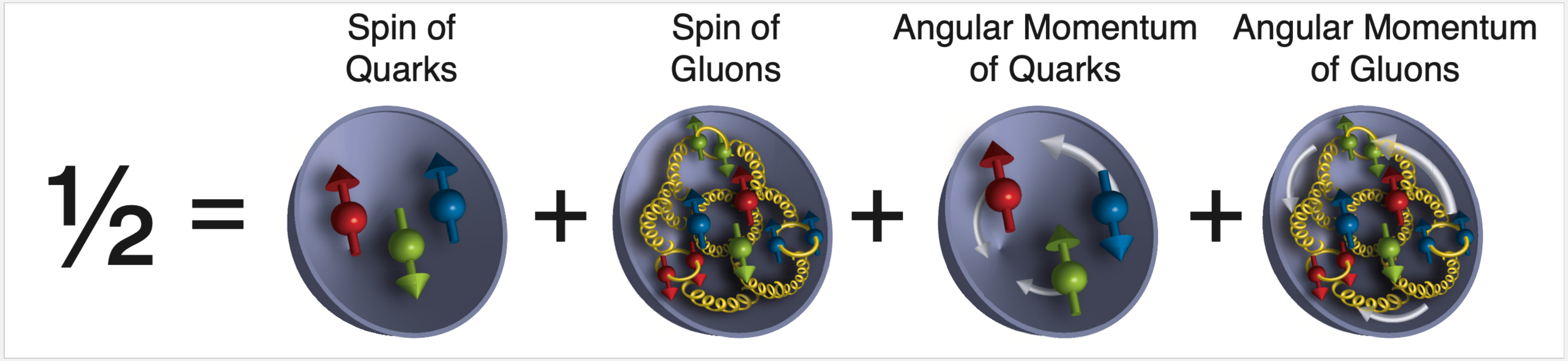
# ELECTRON-ION COLLIDER

# WHY BOTHER?

**Proton spin puzzle**

- Quarks (valence and sea): ~30%
- Gluons: ~20%
- Where is the rest?
- How do quark and gluon dynamics generate the proton spin?
- What is the role of the orbital motion of sea quarks and gluons in building up the nucleon spin?



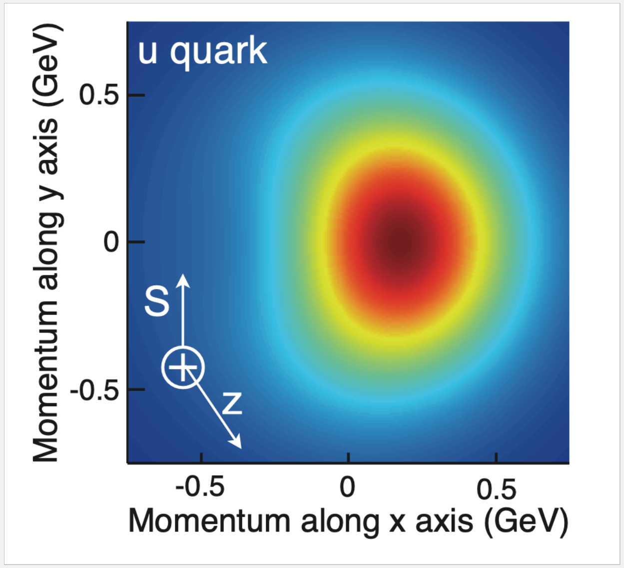



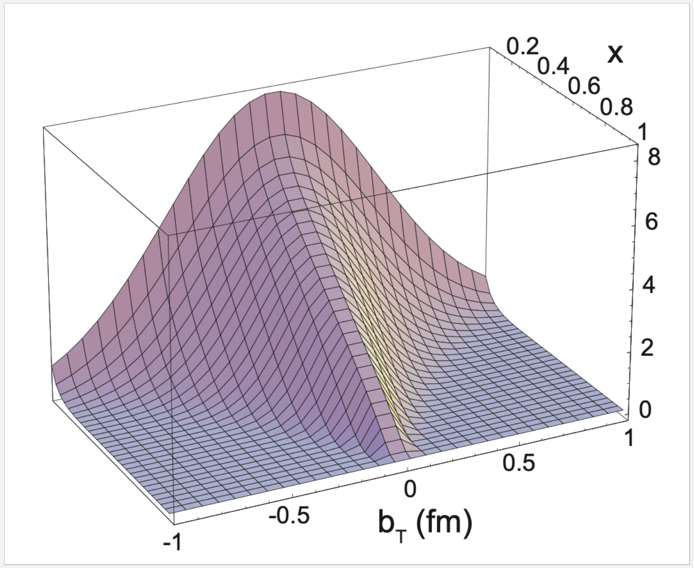
# WHY BOTHER?

**3D imaging – adding dimensions to PDFs**

- Polarized TMDs (Transverse Momentum Distributions)
- Carry information about transverse momentum of a parton

- GPDs (Generalized Parton Distributions)
- Carry information about impact parameter profile of the target.



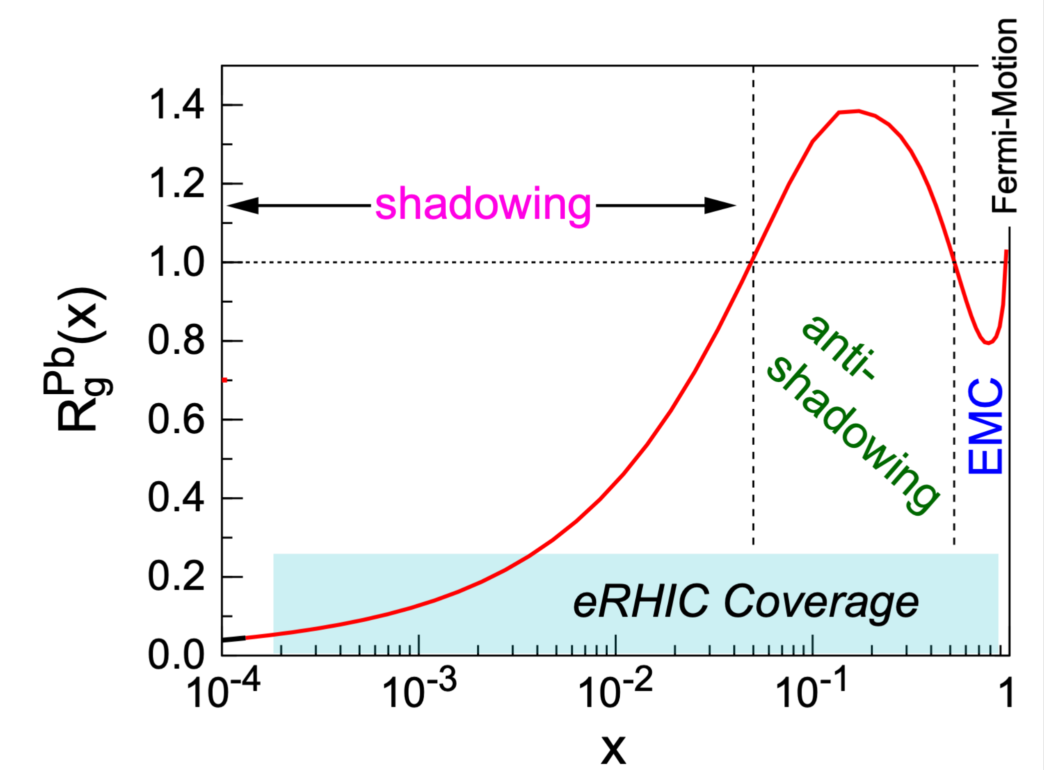
# WHY BOTHER?

**Shadowing**

- 3 distinguished regions:
- Shadowing
- anti-shadowing
- EMC effect region

**none is understood**

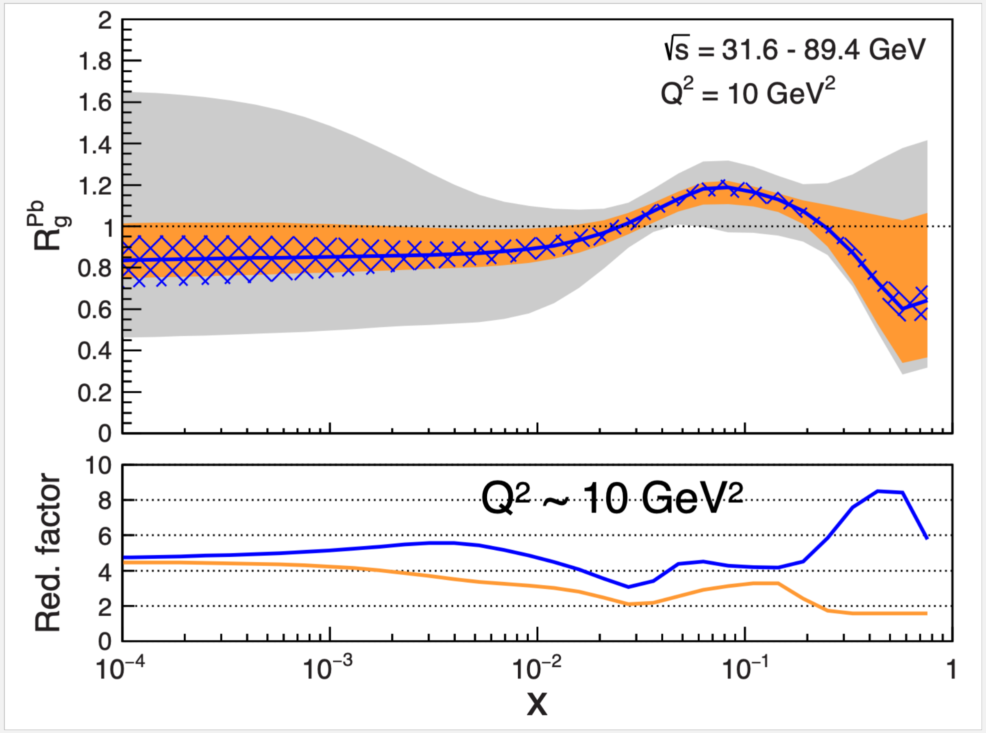
$$R^A_{i=g,u,d,\ldots}(x,Q^2) = \frac{f_i^A(x,Q^2)}{f_i^p(x,Q^2)}$$



# WHY BOTHER?

**Nuclear PDFs**

- nPDFs are of interest in their own right but are also important for other fields (Heavy-Ions, Cosmic Rays etc)
- nPDFs less well known due to lack of data
- What is the fundamental quark-gluon structure of atomic nuclei?



# WHY ELECTRONS?

*Scattering of protons on protons*
*is like colliding Swiss watches to find out how they are build.*

R. Feynman

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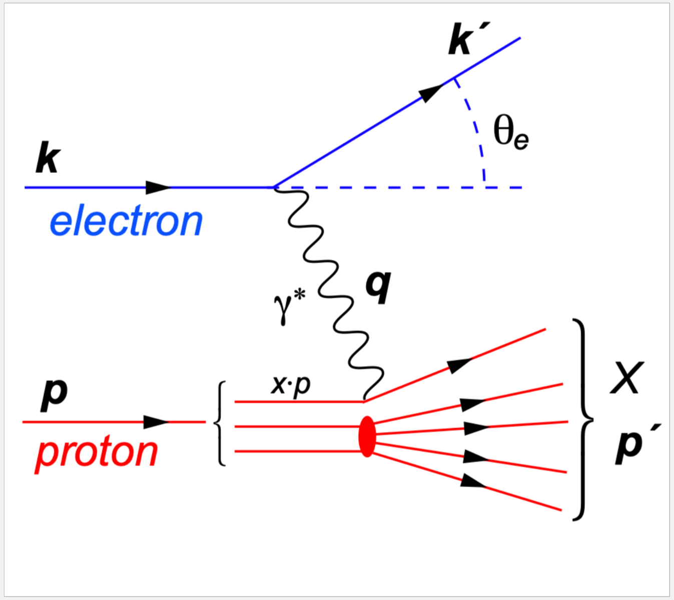
Colliding electrons with hadrons simplifies our work a lot!



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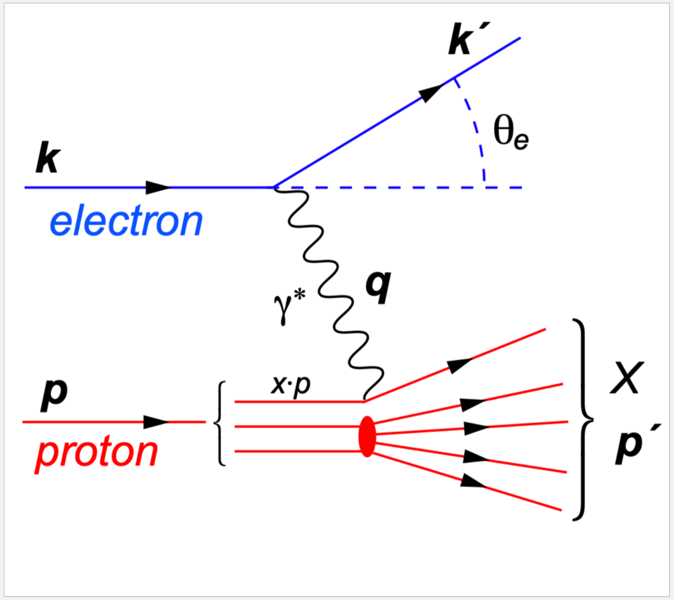



"In 2015, the Department of Energy Nuclear Science Advisory Committee (NSAC) named the construction of an electron–ion collider one of the top priorities for the near future in nuclear physics in the United States."

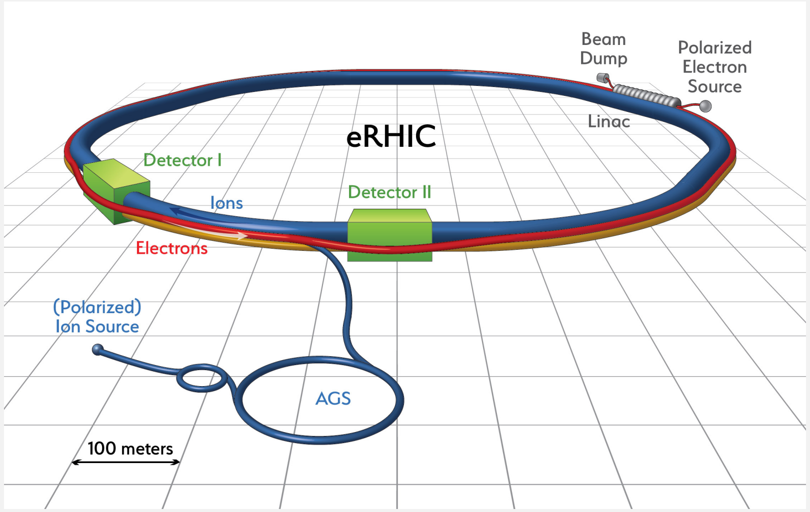
# THE ELECTRON-ION COLLIDER DOES NOT EXIST YET!!


Over 800 people from 169 institutions and 29 countries are working hard to make it happen within the next decade.

# DESIGNS

# eRHIC (BNL)

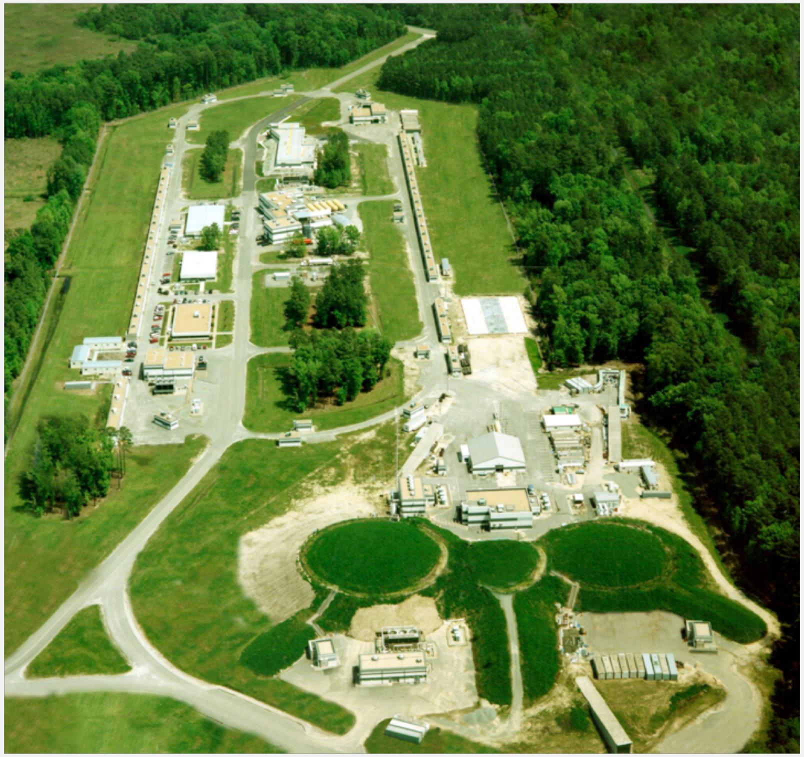
- Add e Rings to RHIC facility: Ring- Ring (alt. recirculating Linac-Ring)
- Electrons up to 18 GeV

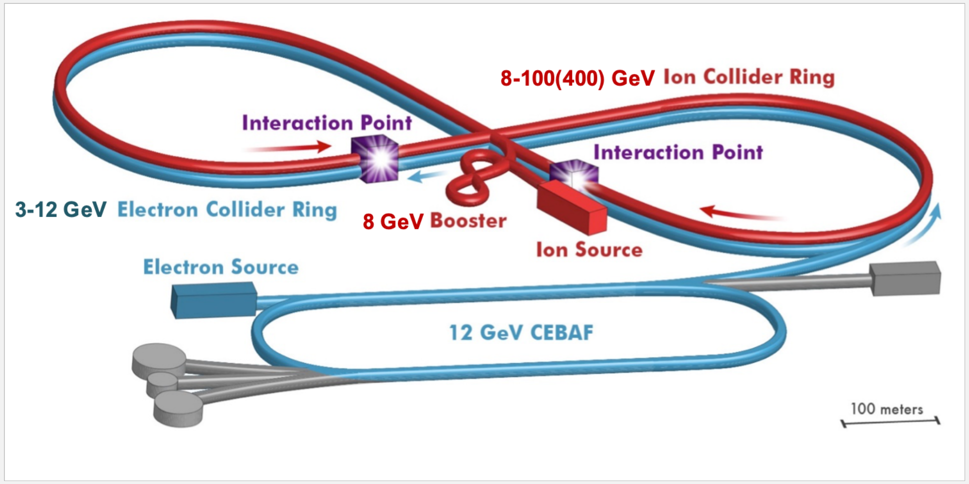




- Protons up to 275 GeV $\sqrt{s}$=30-140 $\sqrt{(Z/A)}$ GeV
- L ≈ 1×1034 $cm^{-2}s^{-1}$ at $\sqrt{s}$=105 GeV

# JLEIC (JLAB)

- Electrons 3-10 GeV
- Protons 20-100 GeV






- e+A up to √s=40 GeV/u
- e+p up to √s= 64 GeV
- $L \approx 2\times1034\ cm^{-2}\ s^{-1}$ at √s=45 GeV

# EIC ADVANTAGES

- Note that the energy of this accelerator cannot compete with that of HERA!

Its main advantage are

1. High luminosity
2. Polarised beams
3. Ion collisions

# EIC ADVANTAGES

That being said, there are other plans for electrion-ion colliders in the world!

Past — Future

| | HERA@DESY | LHeC@CERN | HIAF@CAS | ENC@GSI | JLEIC@JLab | eRHIC@BNL |
|---|---|---|---|---|---|---|
| **$\sqrt{s}$ (GeV)** | 320 | 800-1300 | 12-65 | 14 | 20-64 | 32-140 |
| **Proton $x_{min}$** | $1\times10^{-5}$ | $5\times10^{-7}$ | $3\times10^{-4}$ | $5\times10^{-3}$ | $3\times10^{-4}$ | $5\times10^{-5}$ |
| **Ions** | p | p … Pb | p … U | p … Ca | p … Pb | p … U |
| **L ($cm^{-2}s^{-1}$)** | $2\times10^{31}$ | $\sim10^{34}$ | $\sim10^{32-35}$ | $\sim10^{32}$ | $\sim10^{33-35}$ | $\sim10^{33-34}$ |
| **IRs** | 2 | 1 | 1 | 1 | 2+ | 2+ |
| **Year** | 1992-2007 | post ALICE | > 2020 | Fair Upgrade | post 12 GeV | post RHIC |

High-Energy Physics — Nuclear Physics

# CONCLUSIONS

- There is a tremendous pressure from the community to build an electron-ion collider.

- The US-based EIC project is on a good way of getting funded and constructed.

- This will hopefully enable us to tackle some of the most interesting problems such as

    1. Proton spin puzzle
    2. Properties of nuclear matter
    3. 3D imaging of the proton and nuclei

# THANK YOU FOR YOUR ATTENTION

*No matter what, don’t lose hope. We are all bombastic.*

- Dan Nekonečný

# REFERENCES

- EIC - related plots from the lecture of Thomas Ullrich from Ecole Joliot-Curie