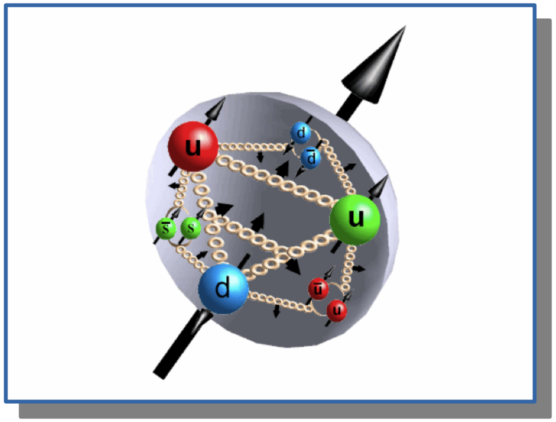
CISF
Run 2
2016

The inner structure of matter

Mariaelena Boglione



INFN Torino

UNIVERSITÀ DEGLI STUDI DI TORINO
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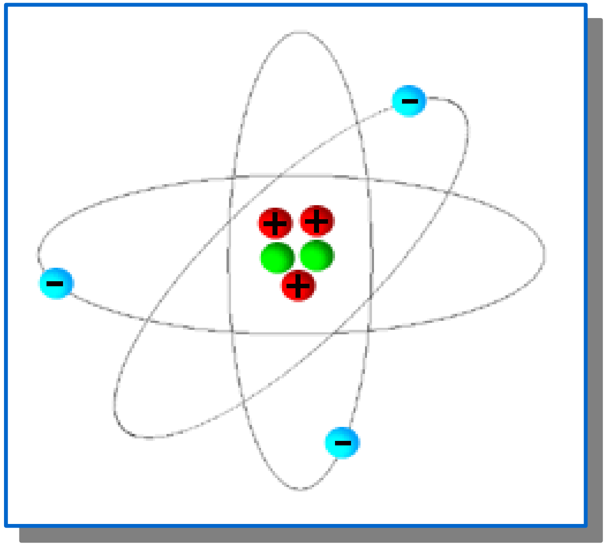
Scuola di Scienze della Natura

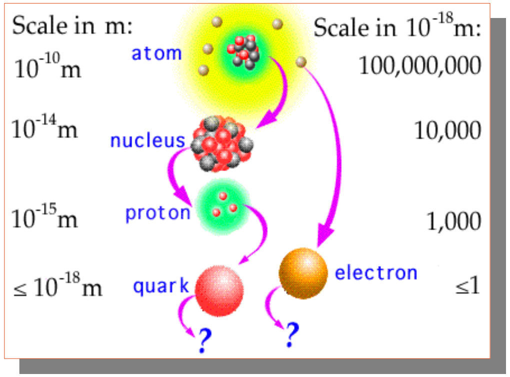
"To achieve great results, two things are needed:
a plan and not quite enough time"

Leonard Bernstein

Atoms, nuclei, protons and neutrons

- About a century ago, a series of table-top experiments conducted by Rutherford changed the way we understand the **structure of matter**.
- By observing rare but large deflections of high energy ionized helium gas particles impounding upon thin foils of gold, we understood that the building blocks of matter (atoms) are mostly empty space. In the center of the atom there is a tiny core (called nucleus) about 10000 times smaller than the atom, carrying almost all of the mass of the atom.





- This nucleus is made up of positively charged particles (called **protons**) and some slightly heavier electrically neutral particles (called **neutrons**).
- There is an equal number of protons in the nucleus as the electrons (which are almost 2000 times lighter than the protons), and these electrons are bound to the atom by the electrical attraction from the positively charged nucleus.

The strong force

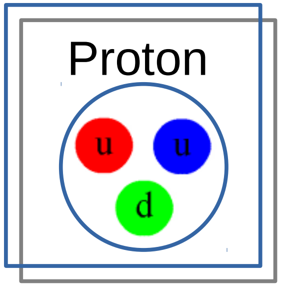
- Particles with same charge repel each other …

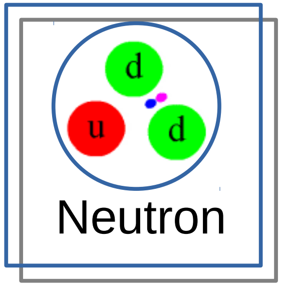
  So how do all those protons in the nucleus stay together without flying apart?

  There must be a different, stronger force binding them together!

- This is the **STRONG FORCE** which binds protons and neutrons (collectively called **nucleons**) together inside the nucleus.

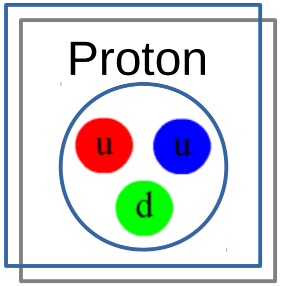
- In 1968, electron-proton scattering experiments were performed at SLAC, similar in spirit to the Rutherford scattering experiments, but at much higher energies. From the observed pattern of rare large angle scattering of the electrons, physicists concluded that **the protons are made up of 3 compact particles called quarks**. The quarks are found to have 2 allowed polarization states: they are spin 1/2 particles.



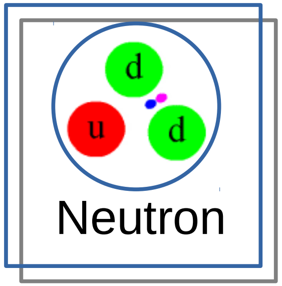


The quark constituent model

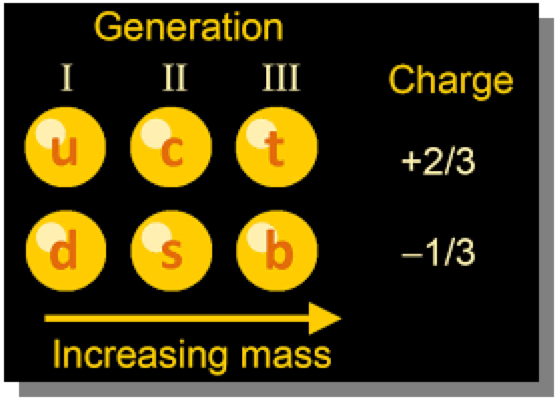
- To explain the observed pattern of mass and charge of all the known hadrons, they are understood to be made up of two quarks (mesons) or three quarks (baryons).
- This pattern works if we assign fractional charges to the quarks.



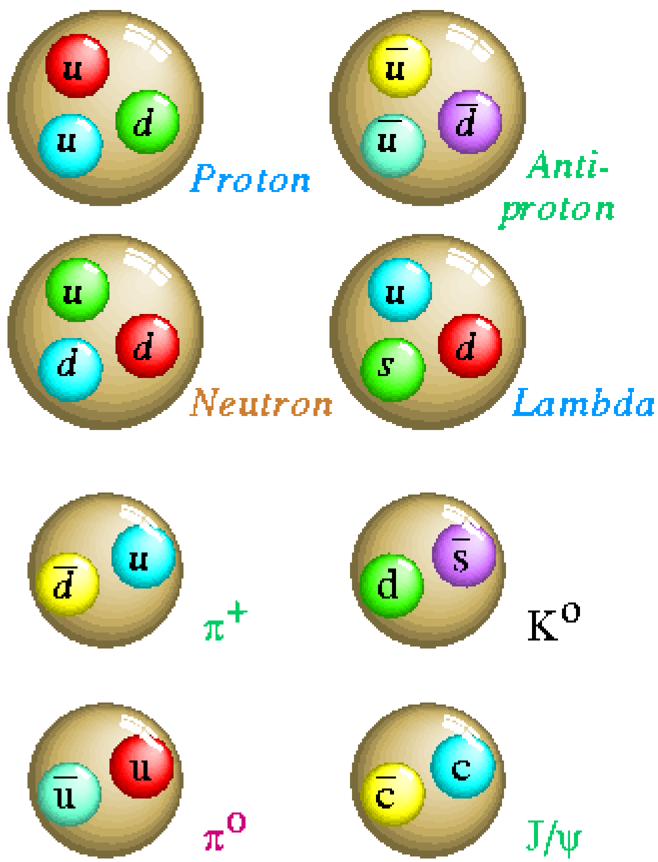
- The proton with charge +1 is made up from 2 quarks with charge +2/3 each and 1 quark with charge -1/3. The neutron with charge 0 is made up of 1 quark with charge +2/3 and 2 quarks with charge -1/3 each.



- Since then, physicists have discovered 2 more generations of quarks: each generation has one quark with charge -1/3 and one with charge +2/3.
- These new quarks are called: strange and charm (discovered in 1974), bottom (discovered in 1977) and top (discovered in 1995).



Hadron Structure in the quark model



- 6 flavors (and 3 colors):

  up, down, strange (light)
  charm, bottom, top (heavy)

  spin ½
  isospin (u = ½, d = – ½)
  strangeness (s = 1)

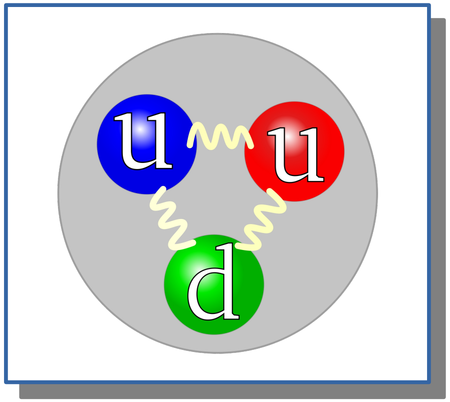
- confined in colorless hadrons
  - mesons – 2 quarks
  - baryons – 3 quarks

QCD and colors

- Two identical quarks cannot co-exist in the same quantum state, much like two electrons cannot share the same quantum state. As a consequence of this spin-statistics theorem, an odd number of identical spin 1/2 quarks cannot be combined to form a completely symmetric state.
- Fermi discovered (1951) a particle called a Δ^{++} carrying charge +2, which took part in the strong interactions. Adding up charges and masses of the constituent quarks suggested that Δ^{++} was made up of 3 u quarks, but this was a completely symmetric state (uuu) apparently in contradiction with Pauli's exclusion principle !

$\Downarrow$

- A new quantum number called **color charge** was introduced to label the quarks.
- The color charge of the quarks comes in three types: red, blue or green.
- Anti-quarks are given the anti-colors of anti-red, anti-blue, and anti-green.



- This factor of three was actually very successful. The observed rate of quark anti-quark pair production from electron anti-electron (called positron) annihilation was falling short of naive expectations by exactly this factor of three. Allowing quarks to be of three types varying in color solved that mystery as well.

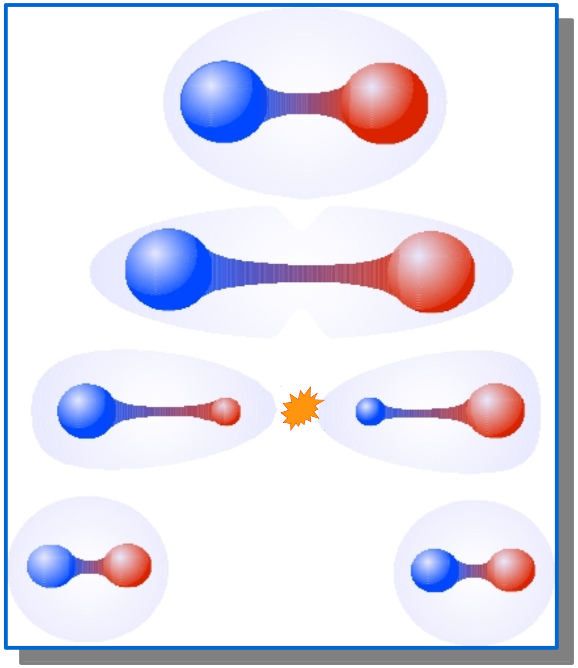
NOTE: This color has nothing whatsoever to do with the real color in everyday life! it just provides labels for three distinct quantum states.

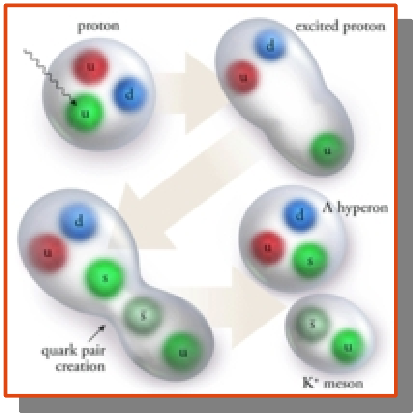
Color confinement

- **All observed particles in Nature are color neutral.**

  Thus, the mesons are formed out of combinations of quarks with color charge: (R and anti-R), or (B and anti-B), or (G and anti-G), and the baryons are formed out of combinations like: (RBG) or (anti-R anti-B anti-G).

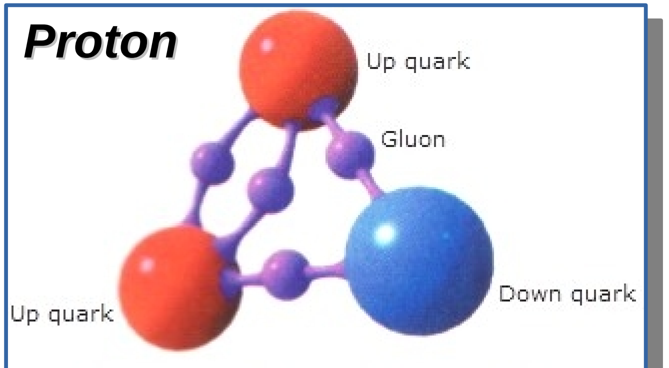
- **A free quark with its bare color charge can not be observed**, because if one tries to pull apart a color neutral hadron, new hadrons are produced which are again color neutral.





Gluons

- Quarks interact amongst each other by exchanging colorless states called **GLUONS**
- **Gluons** bind together the quarks !
- Direct experimental evidence of the gluon was first obtained at PETRA electron-positron collider in 1979, where emission of a gluon from two quarks left measurable signature in the experimental apparatus, distinct from the signatures of the two quarks themselves.
- Our familiar understanding of the theory of electromagnetism, called Quantum Electrodynamics (QED), is that there is only one mediator of the interaction which is the photon, without any electric charge of its own.
- One of the most remarkable feature of the theory of strong interaction, called Quantum Chromodynamics (QCD), is that there are **8 mediators** of the interaction which are the **gluons**, each carrying its own bicolor charge signature and capable of emitting more gluons! This has very interesting consequences ...



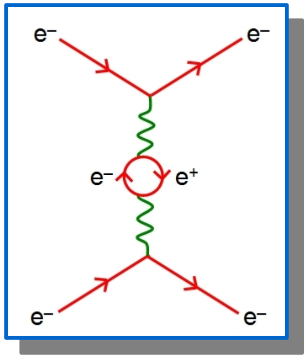
Gluons holding quarks together to form a proton (diagram from *Scientific American*)

QED vs QCD

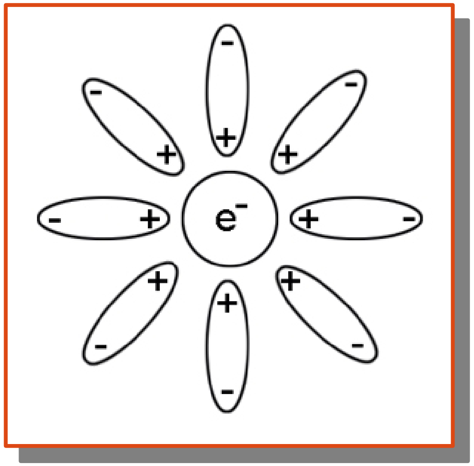
QED charge screening

An electron in the quantum theory can spontaneously emit photons (for a very short time, i.e. virtual photons), and these photons may form electron-positron pairs (virtual pairs), before they are absorbed back into the original electron.

- Thus if we probe at very short distances (or equivalently at very high energies), the original electron becomes surrounded by lots of such pairs with more positive charges pointing toward itself.
- As a result, the effective electric charge of the electron grows rapidly when probed closer and closer to the electron (with higher and higher energy probes).
- In the language of quantum theory, we say that the vacuum around the electron has become highly polarized: a phenomenon known as charge screening.



The QED vacuum is not empty at all !

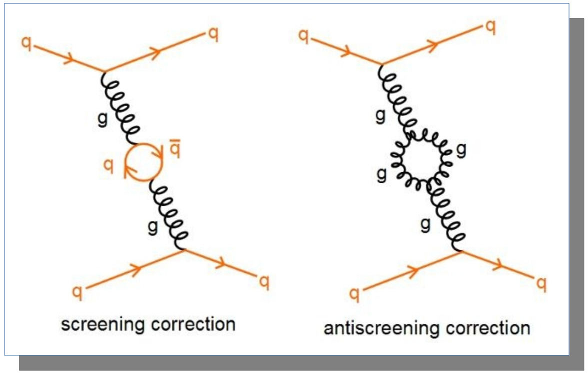


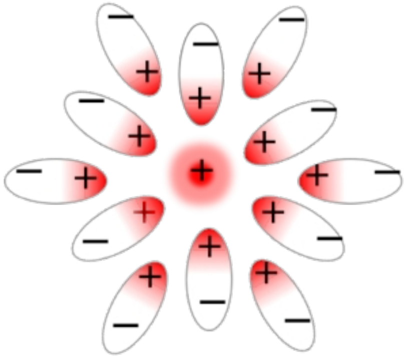
An electron sets up a screen making it look more charged when you get close to it.

QED vs QCD

QCD charge anti-screening

- In QCD, the gluons emitted by a quark when probed at very short distances (shorter than the range of the strong force) not only creates quark anti-quark pairs, but also emits more gluons.
- A red colored quark becomes surrounded by many bicolor gluons, but preferentially with more red colored charges pointing toward itself, as the other color anti-color charged pairs cancel each other!
- The net effect is a charge anti-screening, and the effective color charge of the quark actually decreases with larger energy scale (probing closer to the quark).



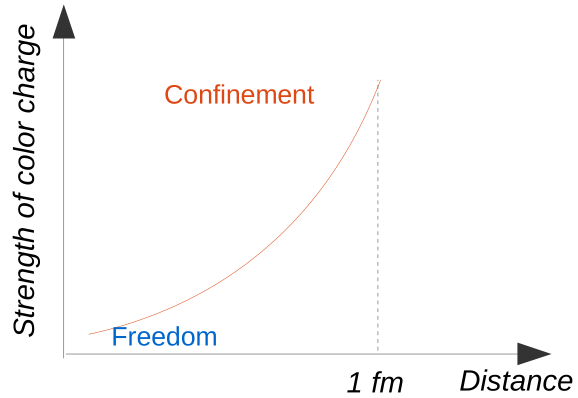


QCD

- Thus, on one hand, gluons un-glue the quarks (and nucleons deep inside the nucleus of an atom) when they are very close to each other (or equivalently at very high energies)
- On the other hand, they glue together the quarks (forming the edge of the nucleon) when the quark tries to move away from other quarks.
- Therefore, the color charge varies with respect to the distance at which the quark is probed. At distances of about a Fermi, the force between the color charges confine the quarks to within the boundary of the nucleus, while at very short distances the quarks do not feel the color force from any particular color charge and behave as if they are almost free!

ASYMPTOTIC FREEDOM

COLOR CONFINEMENT

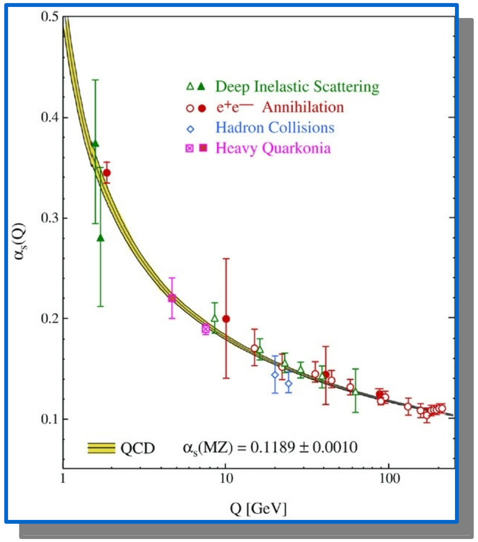


For small distances, little force is felt. But as the distance increases, more force is felt. This is why quarks prefer to stay together, not too far apart.

Asymptotic freedom and color confinement

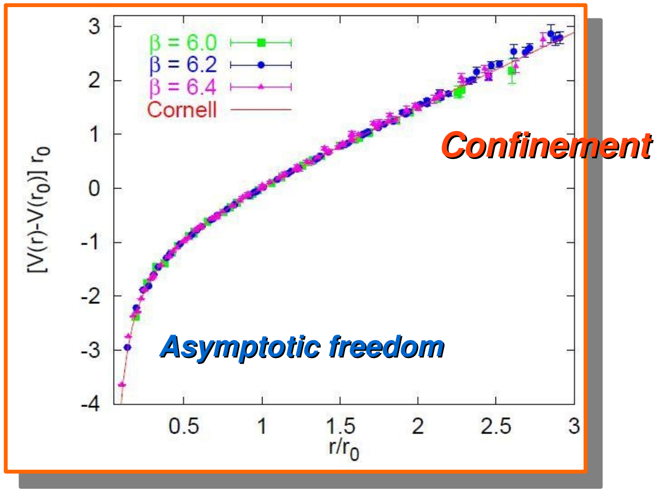
Asymptotic freedom:

- The coupling is small at short distances and large energies.
- There, QCD becomes a free theory, which can be solved with perturbative methods.
- Gluon self interactions are responsible for this behaviour.
- Renormalization group equations allow to determine the dependence of the running coupling on the scale.

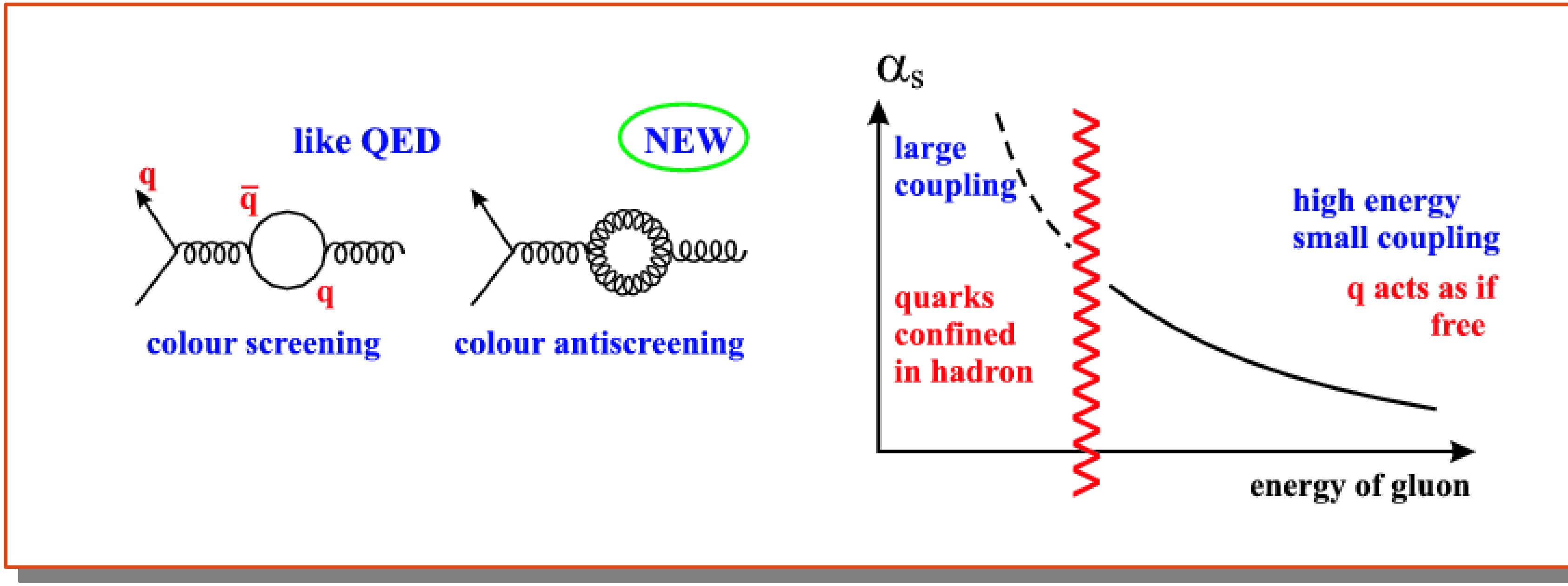


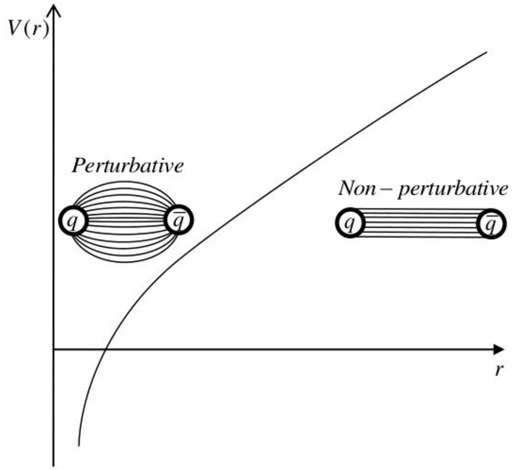
Confinement:

- The QCD coupling is large at large distances and low energy scales.
- Perturbation theory breaks down
- Confinement is a completely non-perturbative aspect of QCD
- Non-perturbative methods, like lattice QCD, show that the quark-antiquark potential increases with separation, as expected in a confining theory.



Asymptotic freedom and color confinement





- We still do not understand what dynamics lead to confinement and hadronization
- We cannot study confinement and hadronization with perturbation theory

The QCD Lagrangian

Of course everything is written in the QCD Lagrangian ...

$$L_{\mathrm{QCD}} = -\frac{1}{4} F^{(a)}_{\mu\nu} F^{(a)\mu\nu} + i \sum_q \overline{\psi}^i_q \gamma^\mu (D_\mu)_{ij} \psi^j_q - \sum_q m_q \overline{\psi}^i_q \psi_{qi} ,$$

$$F^{(a)}_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_s f_{abc} A^b_\mu A^c_\nu ,$$

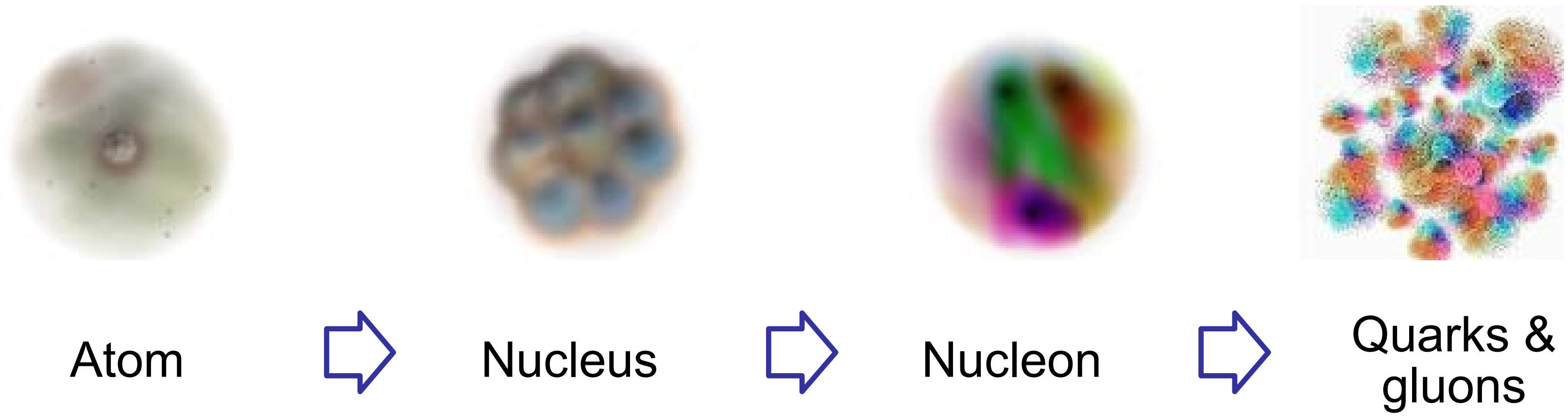
$$(D_\mu)_{ij} = \delta_{ij} \partial_\mu + i g_s \sum_a \frac{\lambda^a_{i,j}}{2} A^a_\mu ,$$


KEEP
CALM
AND
CARRY
ON


KEEP
CALM
AND
BARYON
p+

The quest for the inner structure of matter

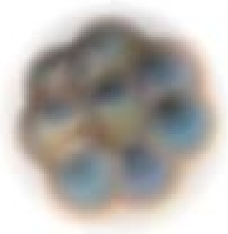
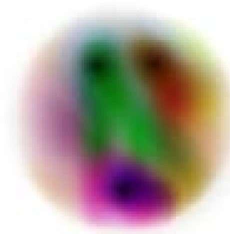
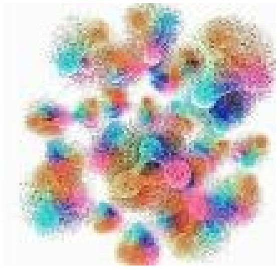
- The structure of the hadron drastically changes as the resolution of the “microscope” (scattering process) increases



- The theory describing the fundamental properties and the dynamics of these constituents is Quantum Chromodynamics (QCD). Among the most intriguing aspects of QCD is the relation between its basic degrees of freedom, quarks and gluons, and the observable physical states, i.e. hadrons such as the proton.

The quest for the inner structure of matter

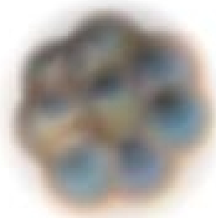
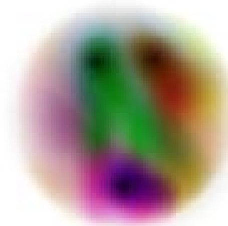
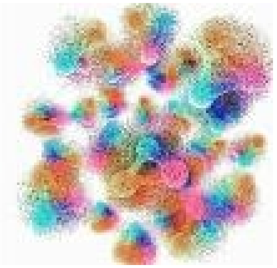
- The quantities that describe these relations are the universal **parton distribution functions** (PDFs), which appear in completely different hard processes in factorised expressions. Most of our knowledge about the nucleon comes from lepton-nucleon scattering, where the high-energy lepton provides a clean probe of nucleon structure with resolution much smaller than the nucleon size.

Atom ⇨ Nucleus ⇨ Nucleon ⇨ Quarks & gluons

- Over the last decade, new theoretical tools have been developed, which enable remarkable tomographic images of the quarks and gluons inside the nucleon. These new tools, the so-called GPDs (Generalized Parton Distributions) and TMDs (Transverse Momentum Dependent) distributions, allow to map out the inner structure of matter with unprecedented precision.

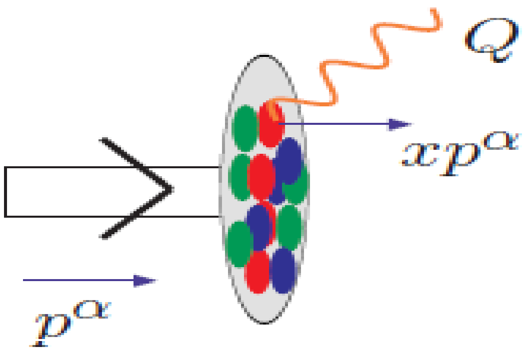
The inner world of a hadron

Atom → Nucleus → Nucleon → Quarks & gluons

PARTON DISTRIBUTION FUNCTIONS

Unpolarized collinear parton distribution functions $f_a(x,Q)$ are associated to the probability of finding a parton carrying a fraction x of the proton momentum at a resolution scale Q.

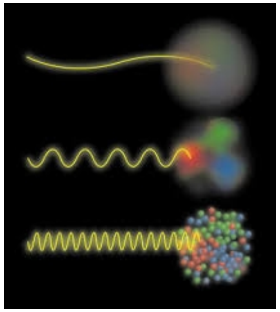


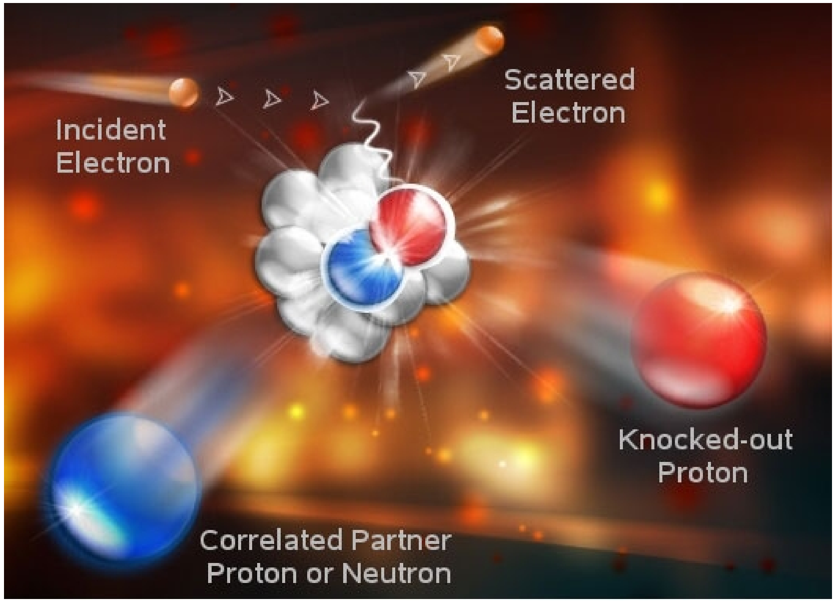
- PDFs are introduced in order to “parametrize” our ignorance about the hadron structure
- PDFs shape the probability of finding quarks and gluons within a proton.

How do we look inside a proton ?

Not with a microscope ...

.. with a femto-scope !





How do we look inside a proton ?

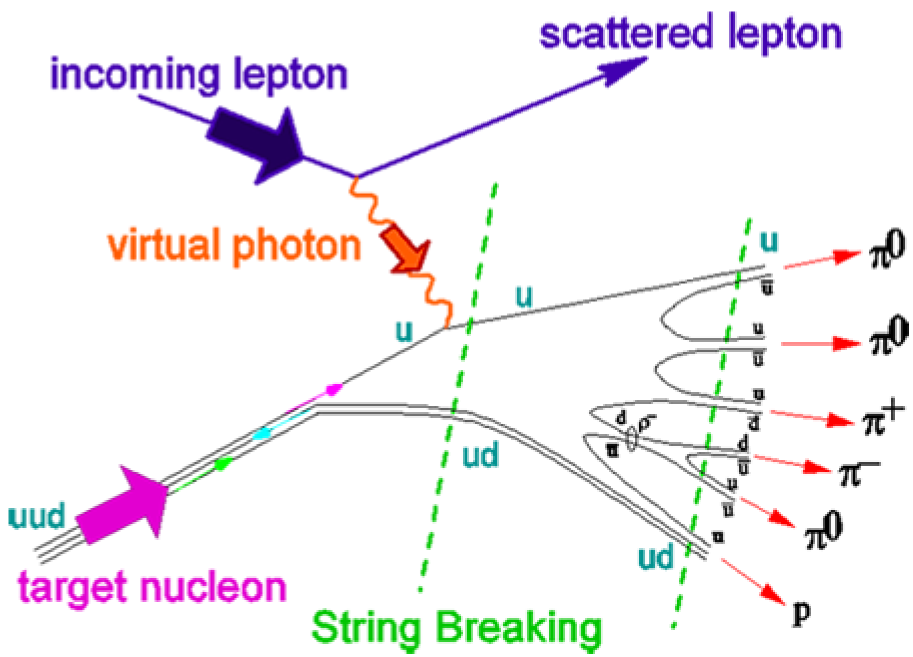
Probing the nucleon structure

↓

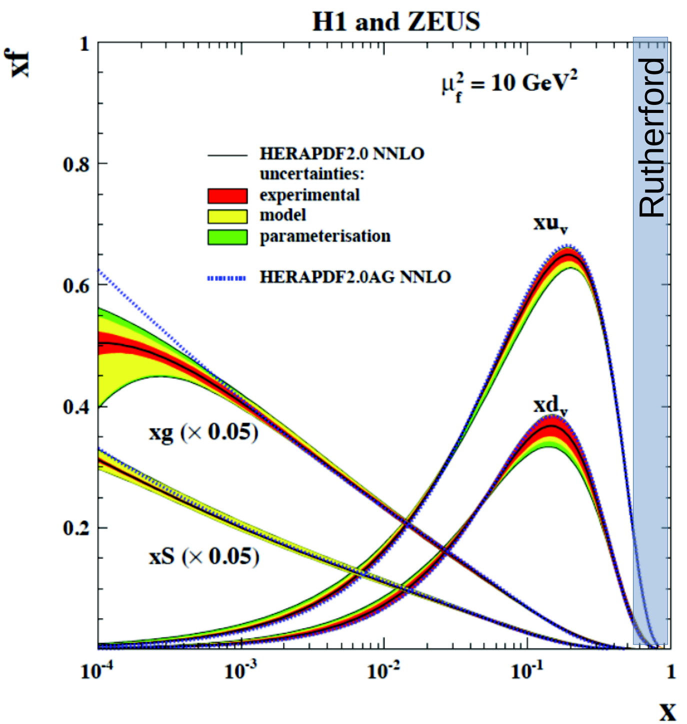
Electron - Nucleus Scattering
Electron - Proton Scattering
Deep Inelastic Scattering

↪ DIS provided first direct evidence for the existence of quarks inside nucleons (Nobel Prize 1990: Freedman, Kendall, Taylor)

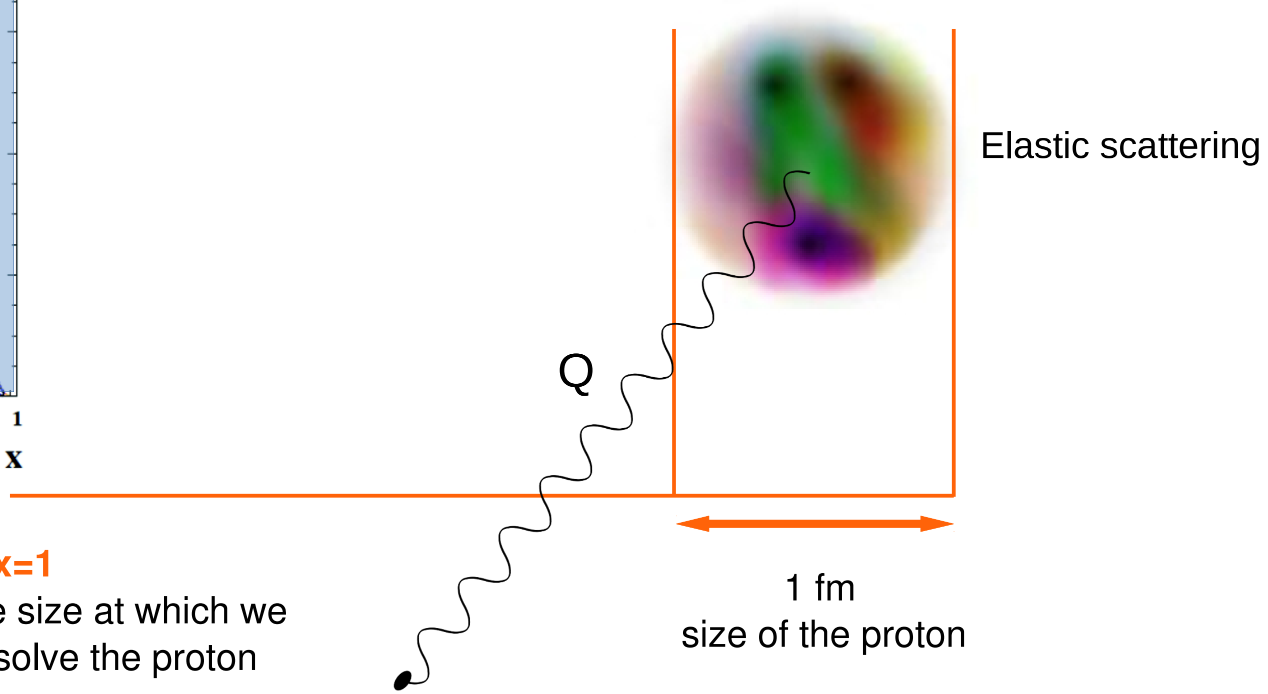
How do we look inside a proton ?



The Proton structure through PDFs



PARTON DISTRIBUTION FUNCTIONS

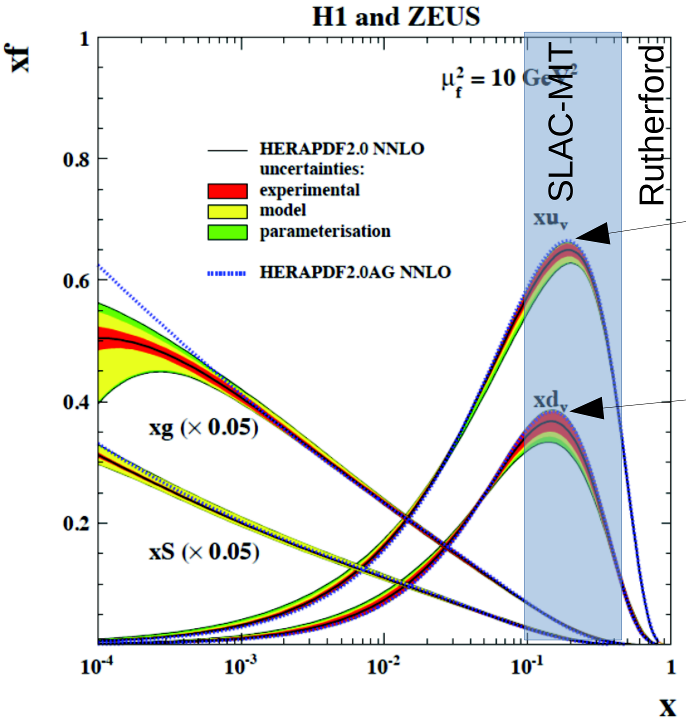


x=1

x is the size at which we can resolve the proton

At x = 1 the photon sees the proton as a whole

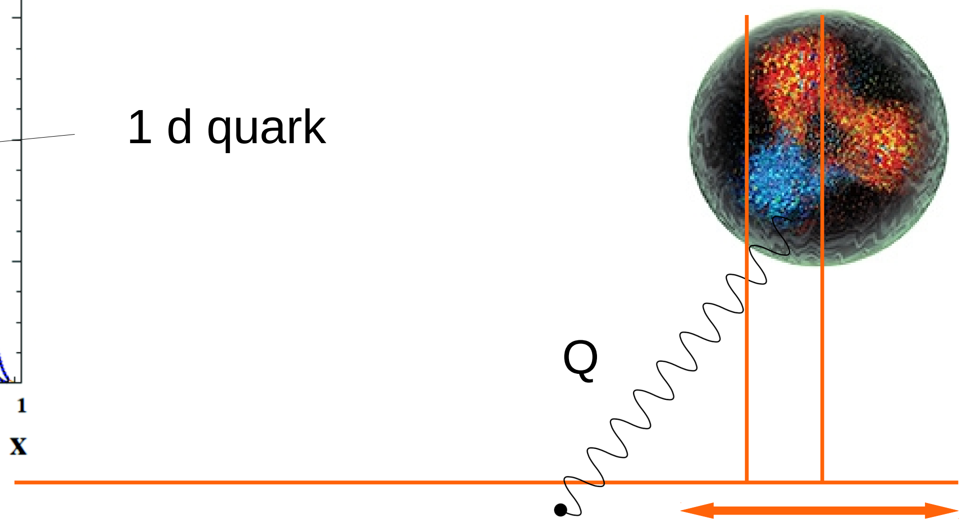
The Proton structure through PDFs



PARTON DISTRIBUTION FUNCTIONS

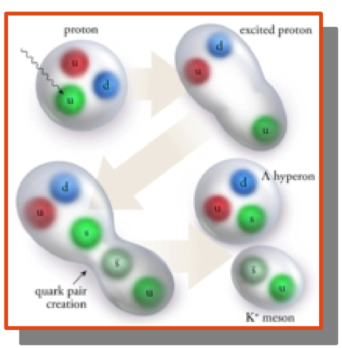
2 u quarks

1 d quark



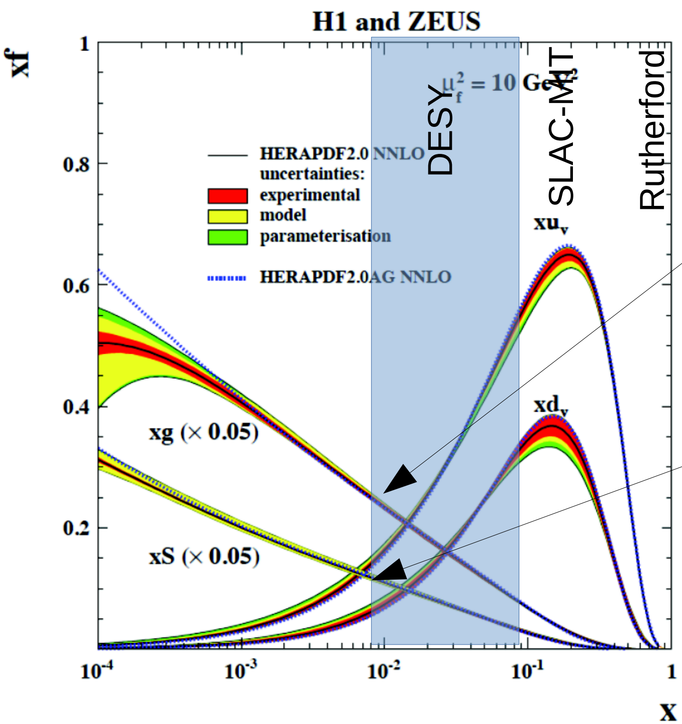
X ~ 1/10
x is the size at which we can resolve the proton

1 fm
size of the proton



At x ~ 0.1 the photon resolves 3 valence quarks, 2 u and 1 d

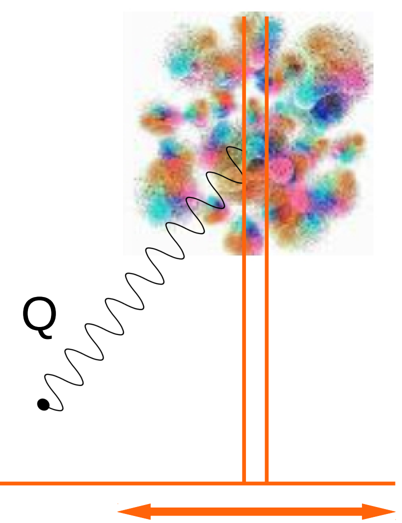
The Proton structure through PDFs



PARTON DISTRIBUTION FUNCTIONS

gluons

sea quarks

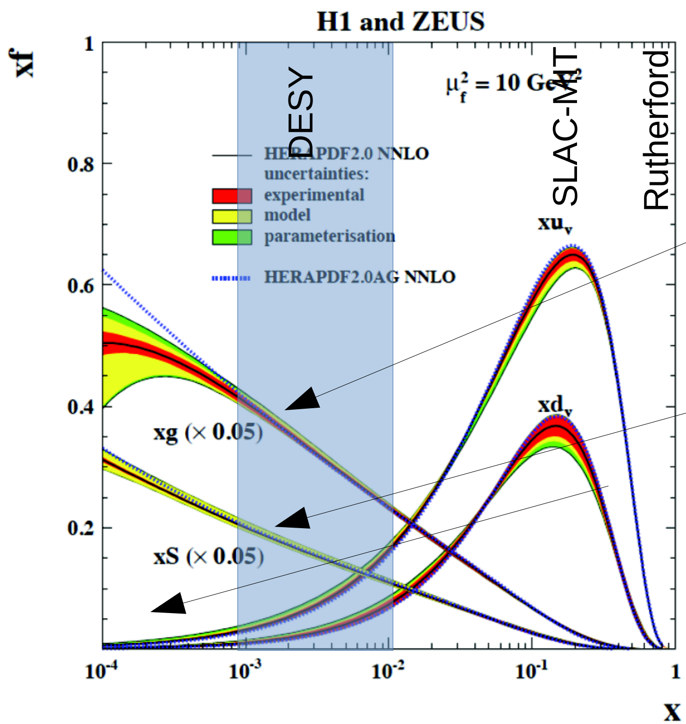


X = 1/100
x is the size at which we
can resolve the proton

1 fm
size of the proton

At x ~ 0.01 the photon sees a large number of quark-antiquark pairs from the see

The Proton structure through PDFs

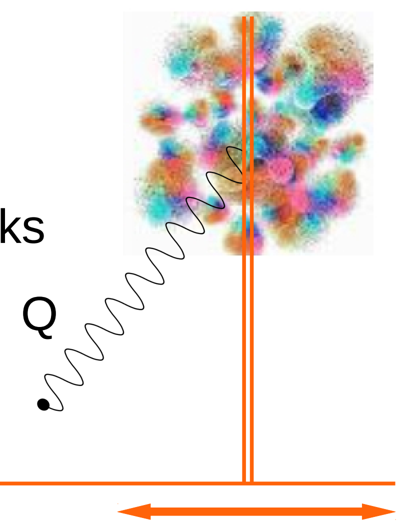


PARTON DISTRIBUTION FUNCTIONS

Many gluons

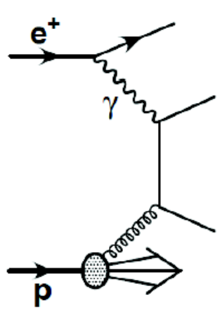
Many sea quarks

Fewer valence quarks



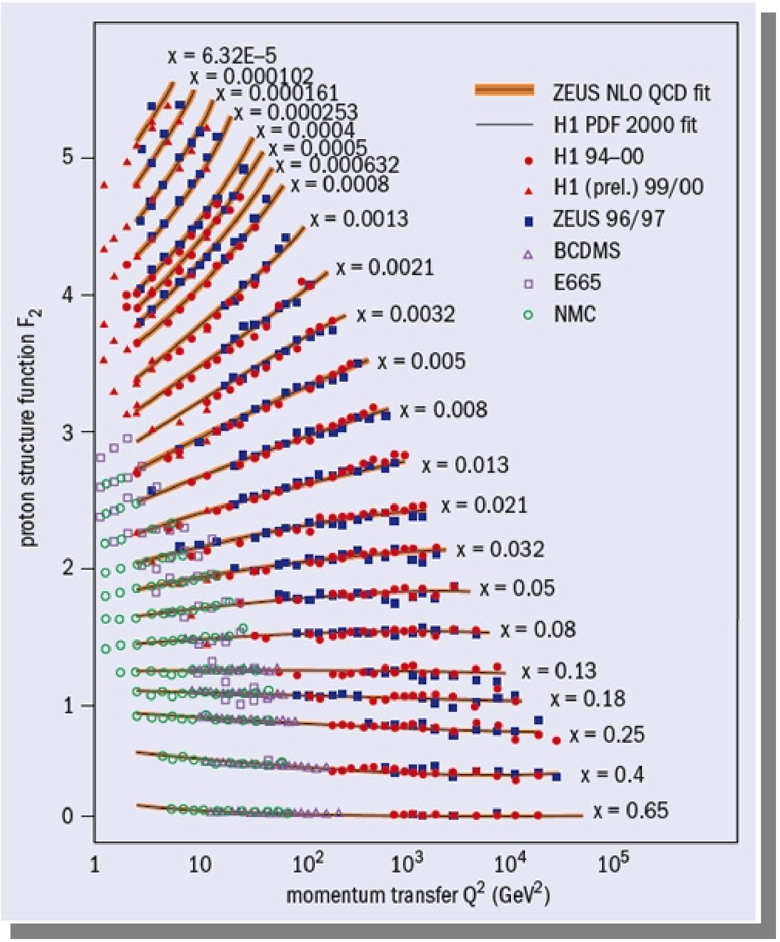
X = 1/1000
x is the size at which we
can resolve the proton

1 fm
size of the proton

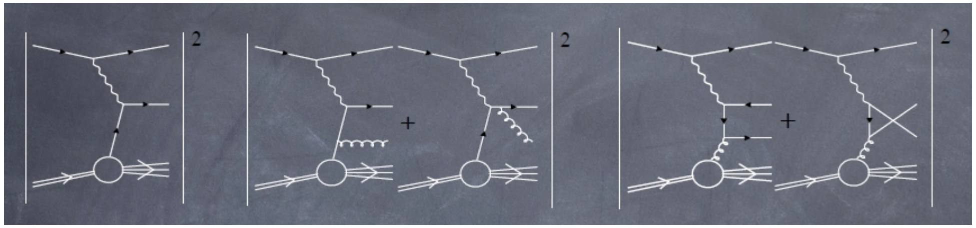


At x ~ 0.001 the photon sees an increasingly large number of gluons and interacts with them through sea quark pairs

Scale breaking and scale evolution



Scale breaking



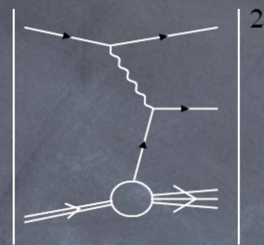
Scaling

QCD predicts this scale evolution through renormalization group equations

Scale breaking and scale evolution

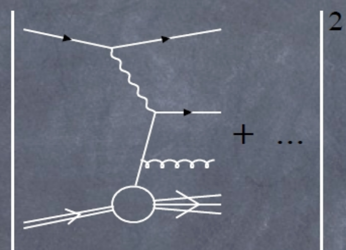
LO, NLO, NNLO...

naive



$$\sigma_q^0 \otimes f_q(x)$$

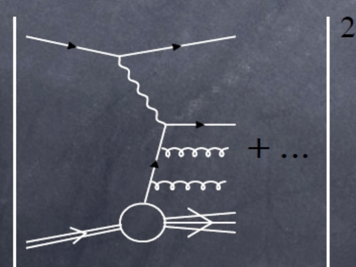
LO



$$\sigma_q^1 \otimes f_q(x) + \sigma_g^1 \otimes f_g(x)$$

$$\sigma_q^0 \otimes f_q^{LO}(x, Q^2)$$

NLO



$$\sigma_q^2 \otimes f_q(x) + \sigma_g^2 \otimes f_g(x)$$

$$\sigma_q^1 \otimes f_q^{NLO}(x, Q^2) + \sigma_g^1 \otimes f_g^{NLO}(x, Q^2)$$

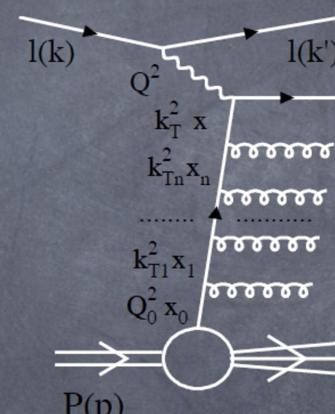
Scale breaking and scale evolution

Why not just a fixed order calculation?

fixed order may miss some contributions: gluon dynamics in DIS at $\mathcal{O}(\alpha_s^1)$

cross sections from the previous order are much simpler!

resummation:



running $\alpha_s^{1-loop}(Q^2)$ + $f_i^{LO}(x, Q^2)$ $\qquad$ $\alpha_s^n(\mu^2)[\log(\frac{Q^2}{\mu^2})]^n$

"leading $\log(Q^2)$"

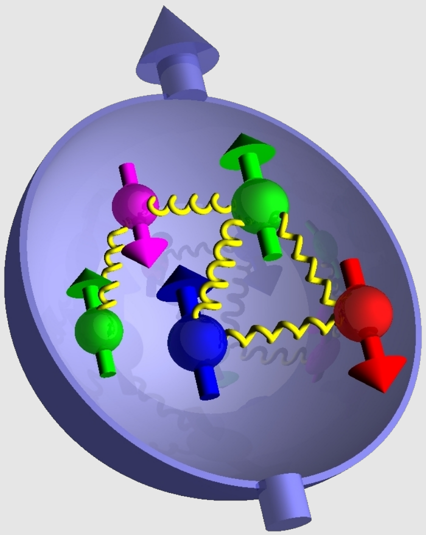
$\alpha_s^{2-loop}(Q^2)$ + $f_i^{NLO}(x, Q^2)$ $\qquad$ $\alpha_s^n(\mu^2)[\log(\frac{Q^2}{\mu^2})]^n$ + $\alpha_s^n(\mu^2)[\log(\frac{Q^2}{\mu^2})]^{n-1}$

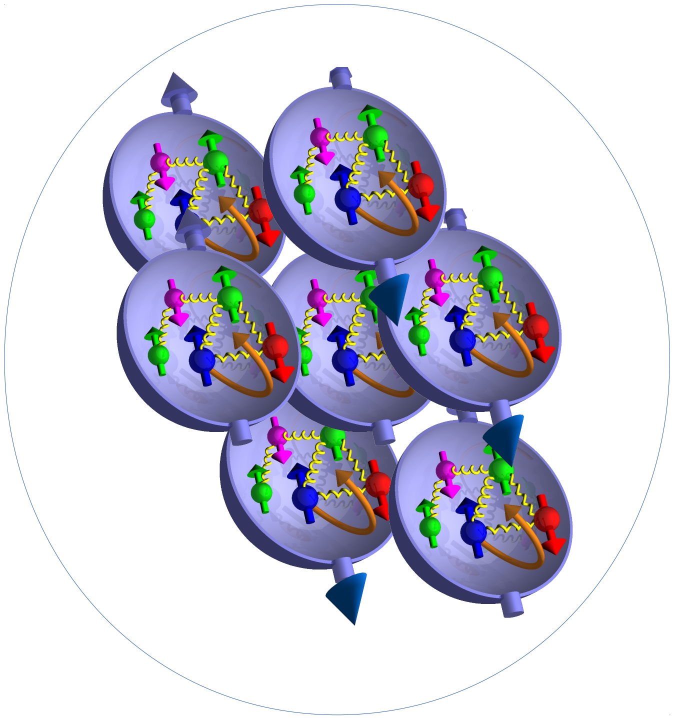
Let's summarize ...

Hadron Structure

Nucleons are made of three (valence) quarks, spinning and orbiting around, kept together by a special glue, made of gluons.

Moreover, inside hadrons there is an arbitrary number of quark-antiquark pairs, made of sea quarks originated from gluons via g→qq (themeselves radiated from quarks).

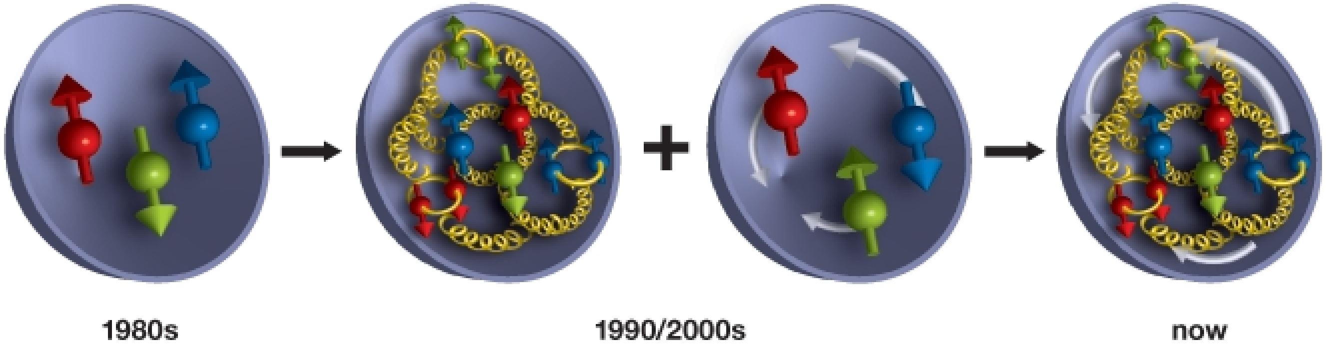




Nucleons and their elementary constituents, quarks and gluons, interact with each other inside nuclei

The nucleon internal structure

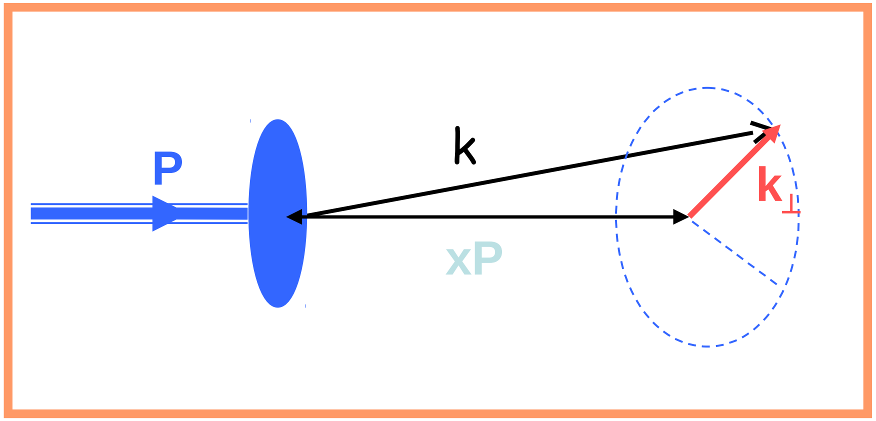
- Our understanding of nucleons evolves

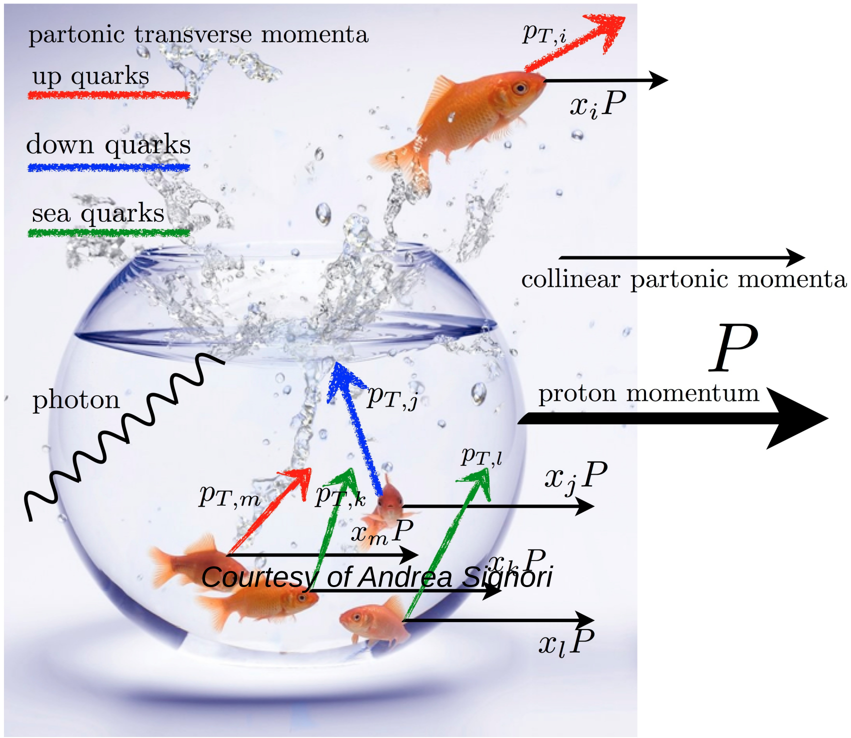


- A nucleon is a strongly interacting, relativistic bound state of quarks and gluons
- QCD bound states: neither quarks nor gluons appear isolated
- Intellectual challenges:
  - probe the nucleon structure without “seing” quarks and gluons
  - Learn about the 3D structure of hadrons !!!

A multidimensional picture of the proton

The 3D structure of nucleons





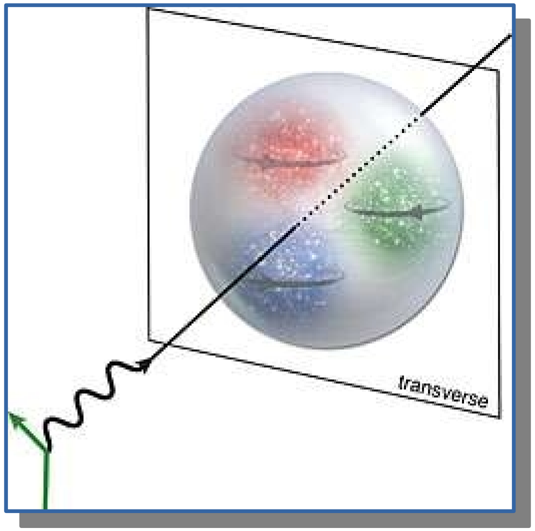
Transverse motion is usually integrated over, but there are important spin-$k_\perp$ correlations !!

We cannot learn about the spin structure of the nucleon without taking into rigorous account the transverse motion of the partons inside it !!

A transverse look into the proton

- The knowledge of the multi-dimensional structure of protons allows the analysis of properties otherwise inaccessible.

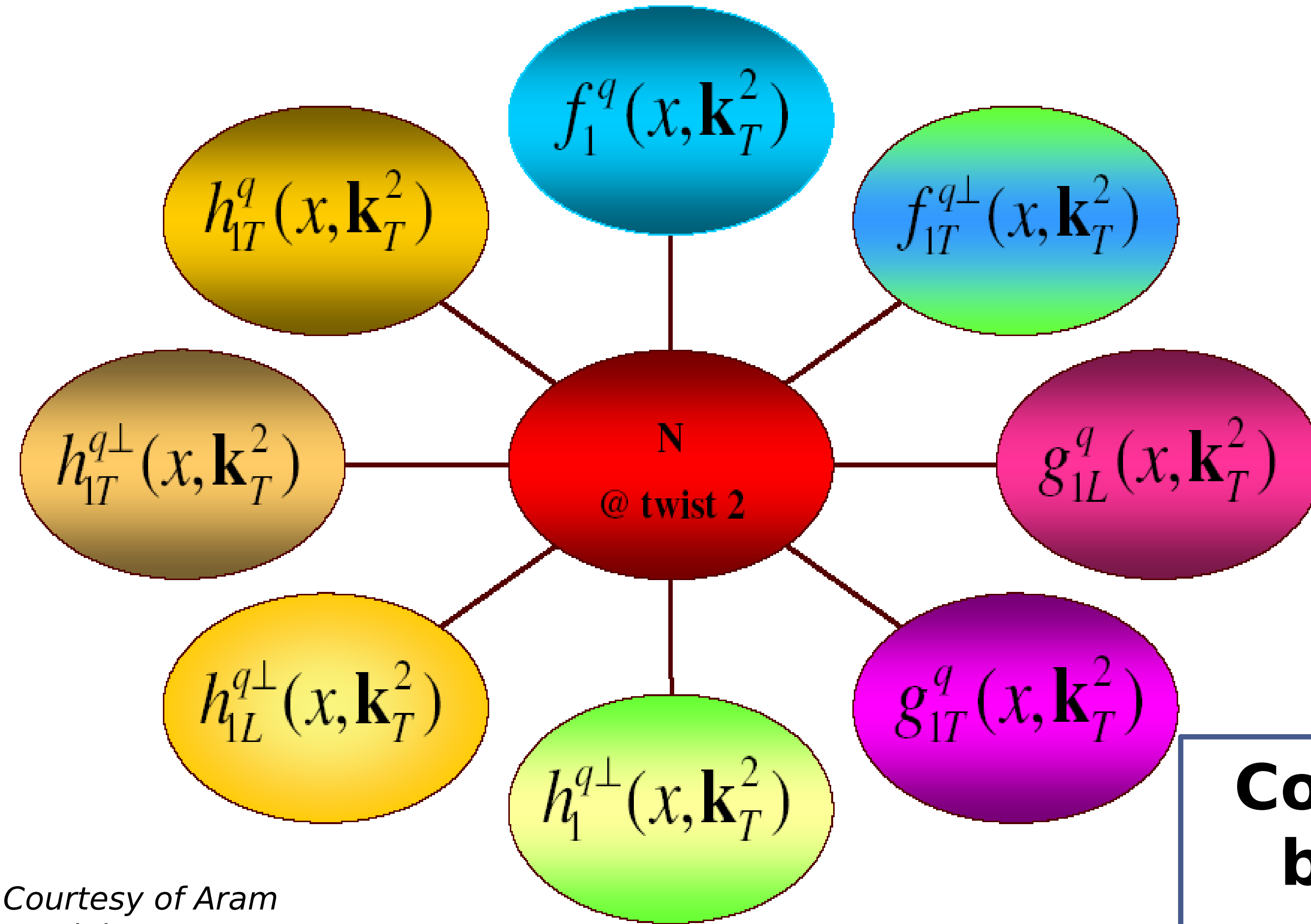
- The situation may be compared to diagnostic studies: electrocardiography, for example, gives us mono-dimensional information about the hearth activity. It is of fundamental importance, but it does not give detailed information about the multidimensional inner structure. Instead, more important for this purpose are multi-dimensional tomographies of heart activity (MRI, CT and others). In a similar way, the latest “multi-dimensional” pictures of the nucleon obtained with QCD phenomenology can improve the current status of hadronic physics and aim at better understanding particle physics in general.



- Although one-dimensional (collinear) parton distribution functions are extremely useful for studying any process involving hadrons (including the proton-proton collisions taking place at the LHC), from the point of view of nucleon tomography they are rather limited, because they describe the distribution of partons in a single dimension.

- More informative distributions are the so-called transverse-momentum-dependent distributions (TMDs). They represent pictures of three-dimensional probabilities in momentum space. The distributions change depending on the energy scale at which they are probed (in a way that is calculable using evolution equations from perturbative QCD) and on the value of the longitudinal fractional momentum.

TMDs



Courtesy of Aram Kotzinian

Correlation between spin and transverse momentum

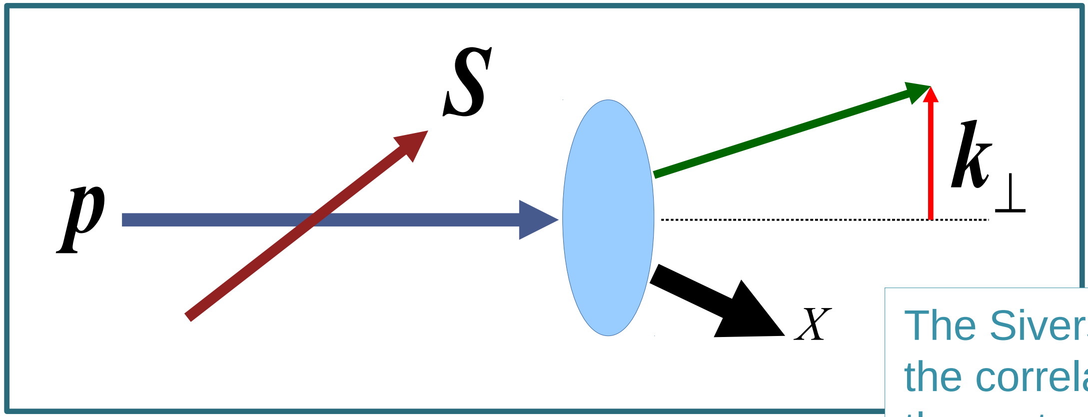
The Sivers function

$$f_{q/p,S}(x,\boldsymbol{k}_\perp) = f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q/p^\uparrow}(x,k_\perp)\,\boldsymbol{S}\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$

$$= f_{q/p}(x,k_\perp) - \frac{k_\perp}{M} f_{1T}^{\perp q}(x,k_\perp)\,\boldsymbol{S}\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$

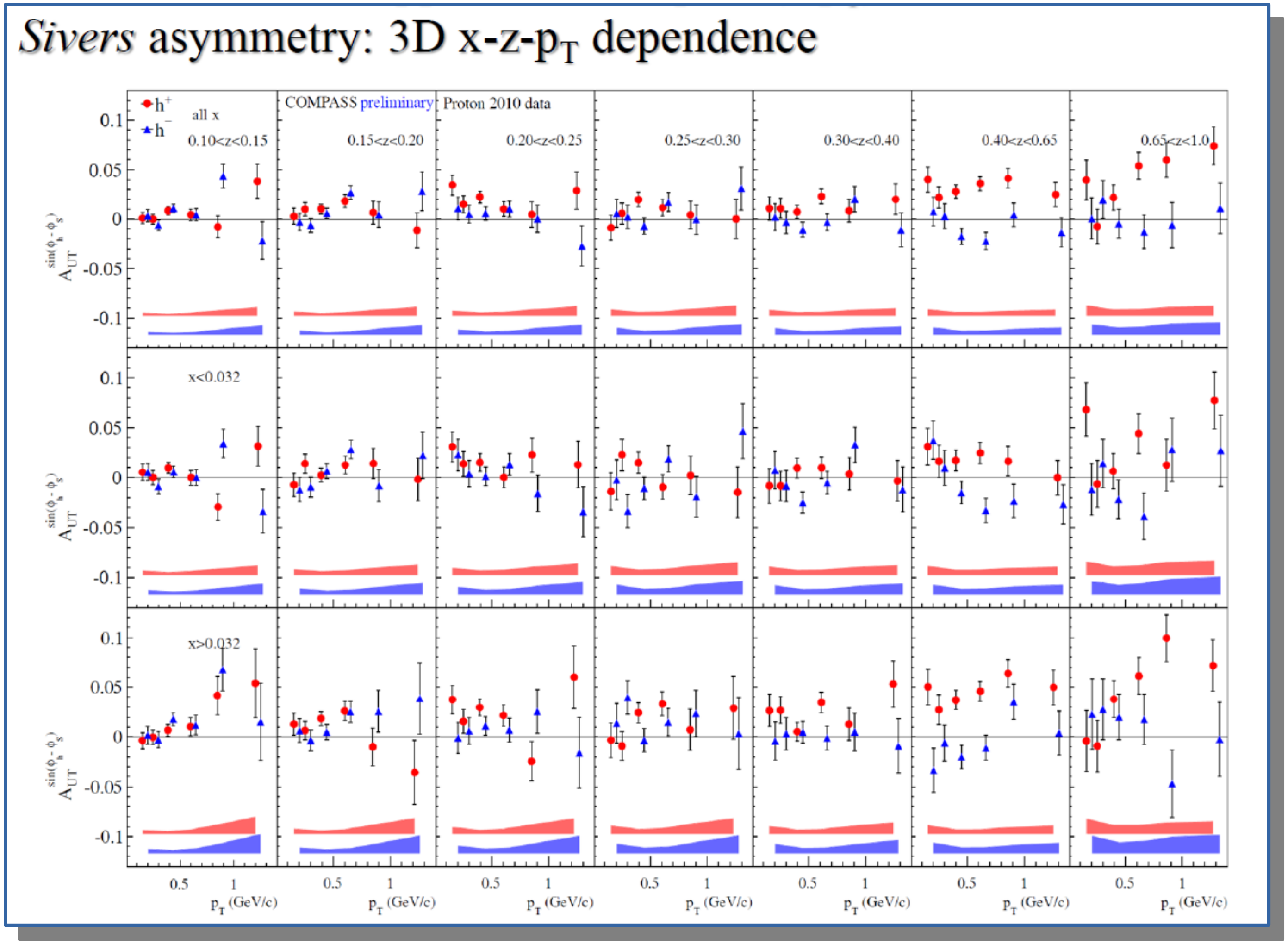
The Sivers function is related to the probability of finding an unpolarized quark inside a transversely polarized proton

The Sivers function is T-odd



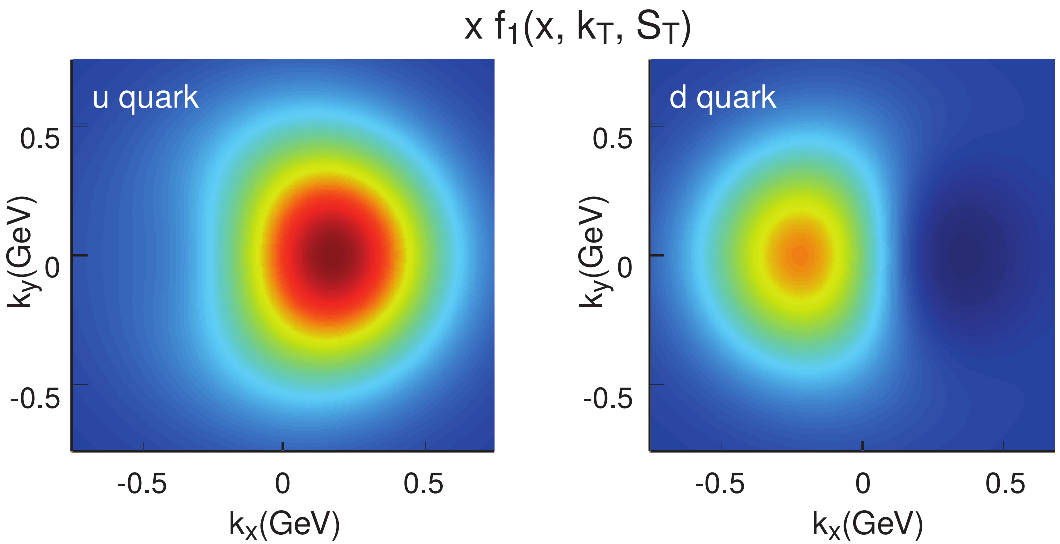
The Sivers function embeds the correlation between the proton spin and the quark transverse momentum

The Sivers function

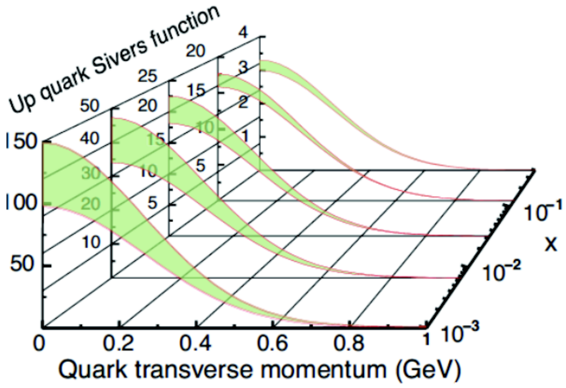


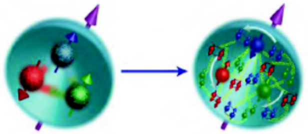
Courtesy of Bakur Parsamyan

Multidimensional imaging in the transverse momentum direction



Proton Tomography



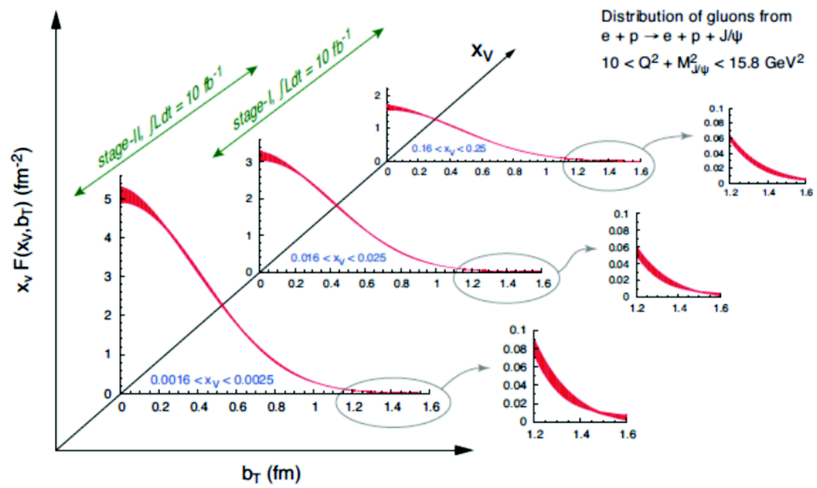


Correlations between parton momenta:

Sivers TMD distribution is single transverse spin Asymmetry → low x

Correlations between parton longitudinal momenta and transverse positions:

GPDs… from DVCS & Vector Mesons



Thank you for having me with you today …

and see you next time !