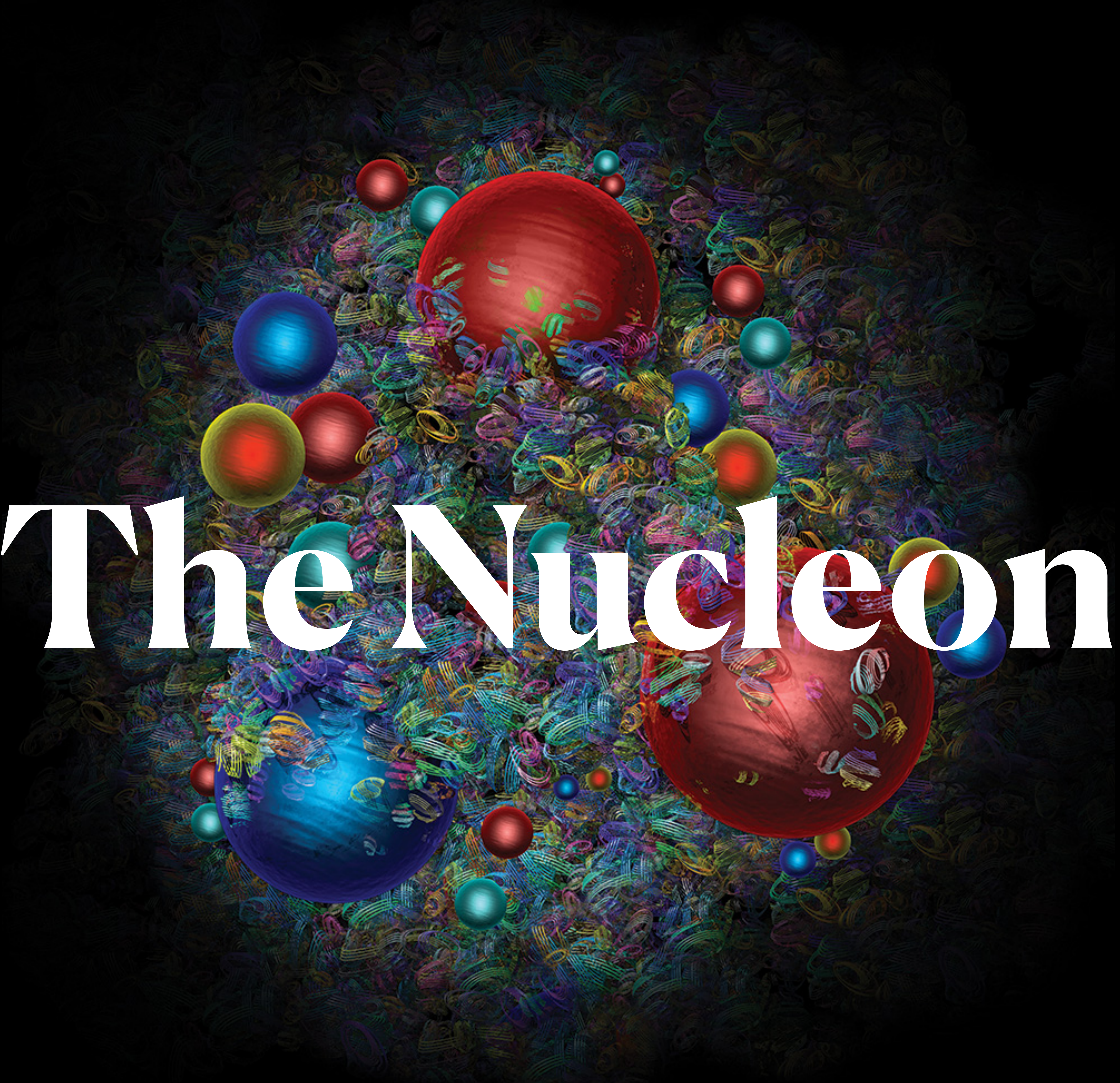
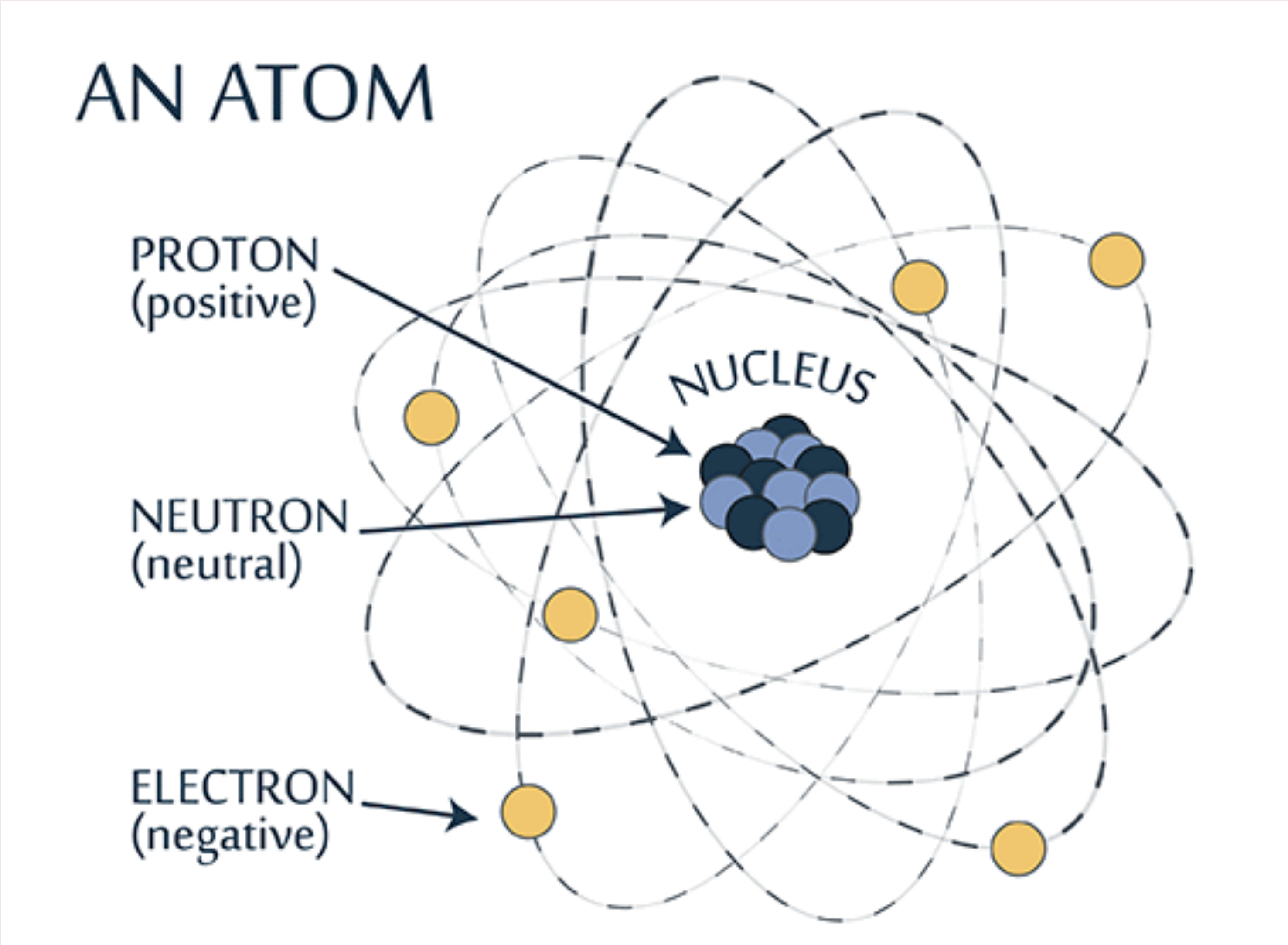


The Nucleon

Márcia Quaresma (marcia@lip.pt) - LIP Summer Internship 2020 - 15 July 2020

What is a nucleon?

- Nucleons are the particles inside the nucleus



- They constitute practically all the mass of the visible matter in the universe

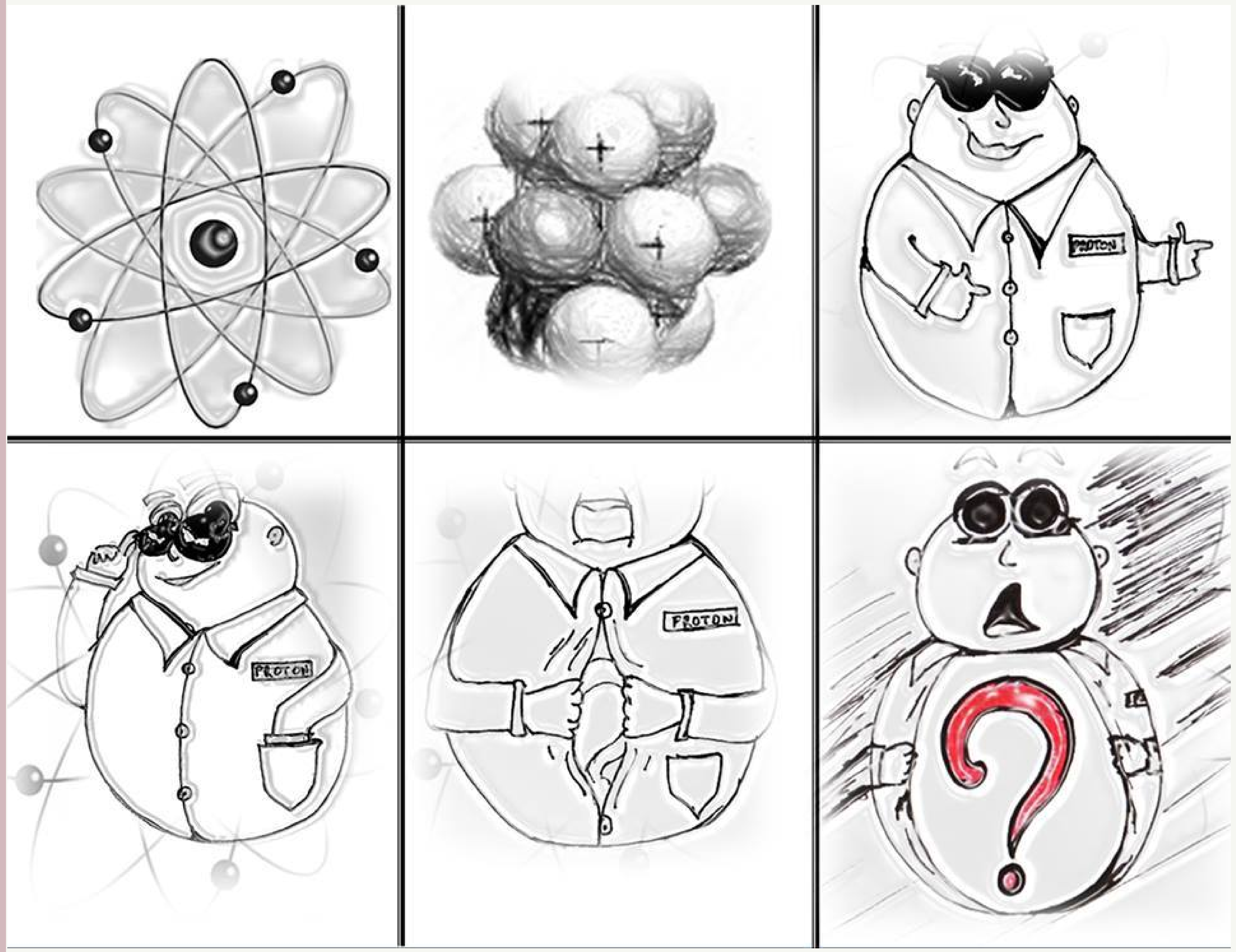
What is a proton?

- Depends on how you look at it, how hard you hit it.

- The nucleus was discovered in 1911 by Ernest Rutherford

- The proton was established as the constituent of the hydrogen nucleus in 1920, also by Rutherford

Is the proton an elementary particle?



What is inside the proton?

- In 1960s, at SLAC, similar experiments to that of the Rutherford but with electrons (instead of with alpha particles) revealed **point-like scattering centres** inside the proton

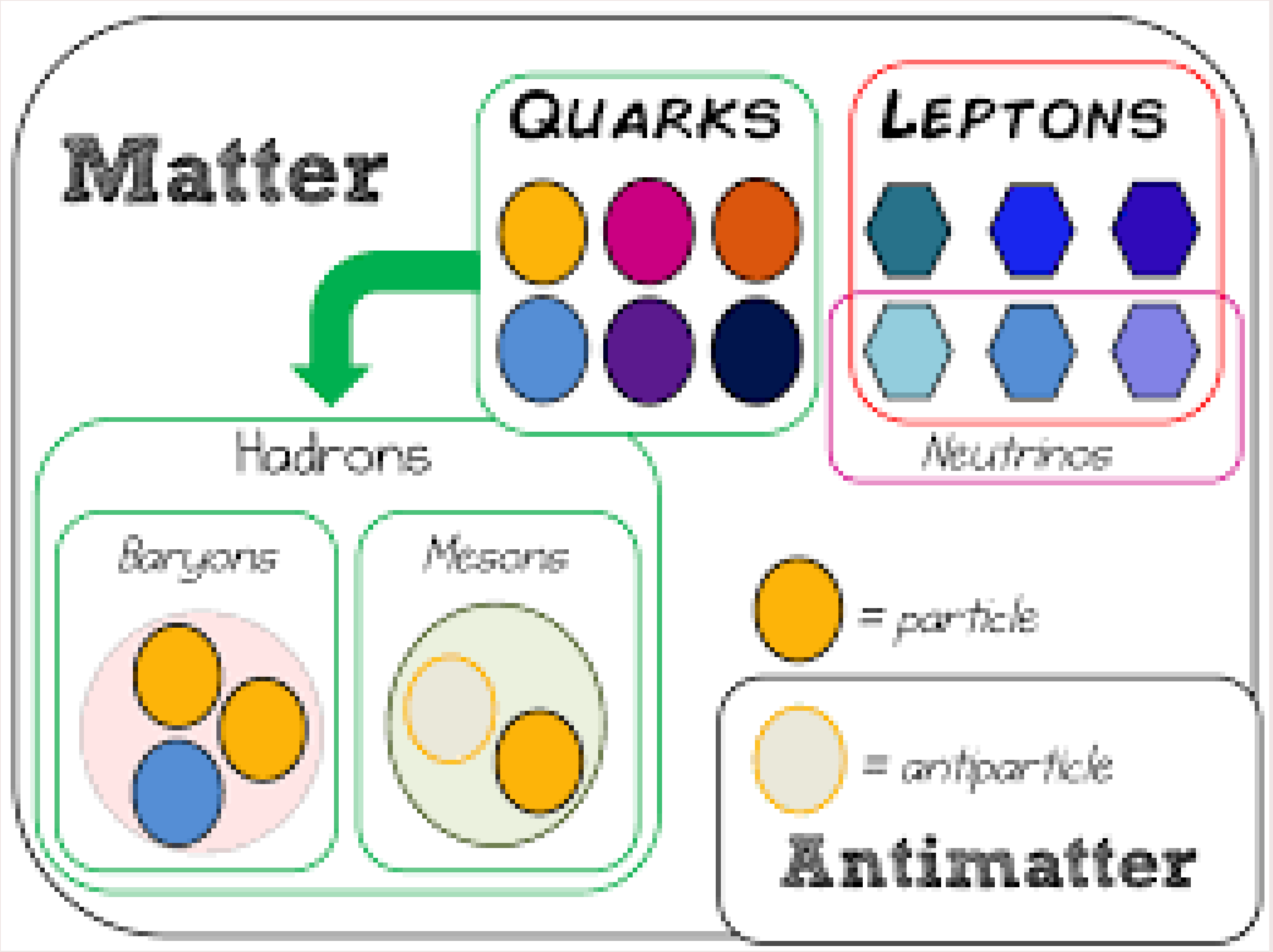
↓

today we know these to be quarks, anti-quarks and gluons

Usually we are introduced to quarks as objects with flavour quantum numbers that build up baryons and mesons in bound states of three and two

<u>Proton belongs to the baryons family</u>

BUT this is just a simplistic view of the proton



The existence of quarks

- In 1964, Gell-Man and Zweig proposed the existence of quarks (quark model)
- In 1968, SLAC experiments, measuring the elastic scattering by point-like electrons revealed the spatial distribution of the proton's charge

The cross-sections varied on how hard the proton was struck

- In 1969, Feynman and Bjorken worked out the formalism to understand this and proposed the parton model

The evidence of anti-quarks

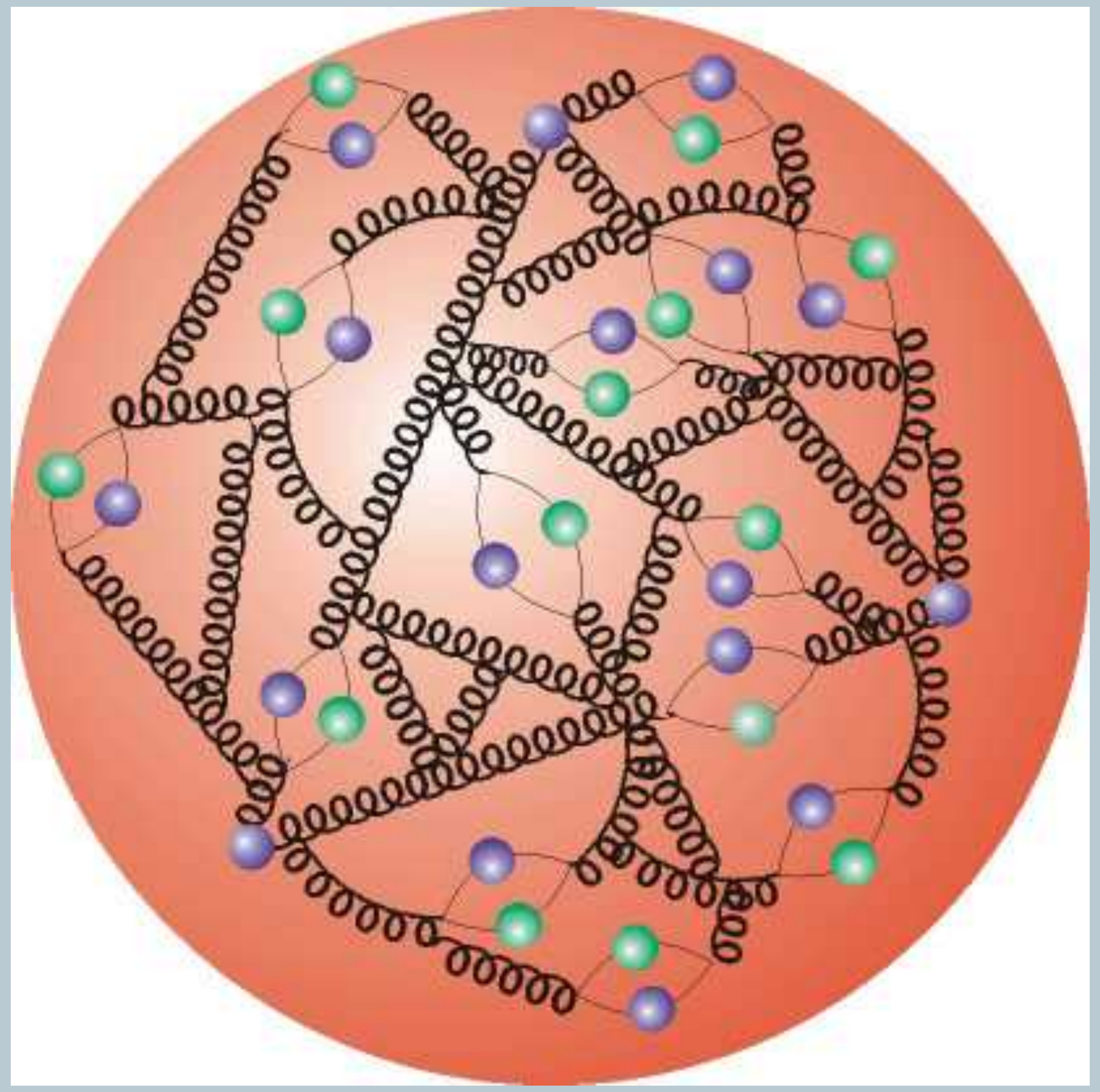
- In 1980s, scattering experiments with neutrinos and anti-neutrinos (special particles with a definite helicity) revealed the existence of anti-quarks

The weak interaction between neutrinos/anti-neutrinos with quarks/anti-quarks gives different angular distributions

- This led to the picture that: proton is made by three valence quarks immersed in a sea of $q\bar{q}$ pairs

The gluons birth

- The neutrinos scattering experiments also indicated that the total momentum carried by quarks and anti-quarks only amount to 50% of that of the proton



"Energy crisis"

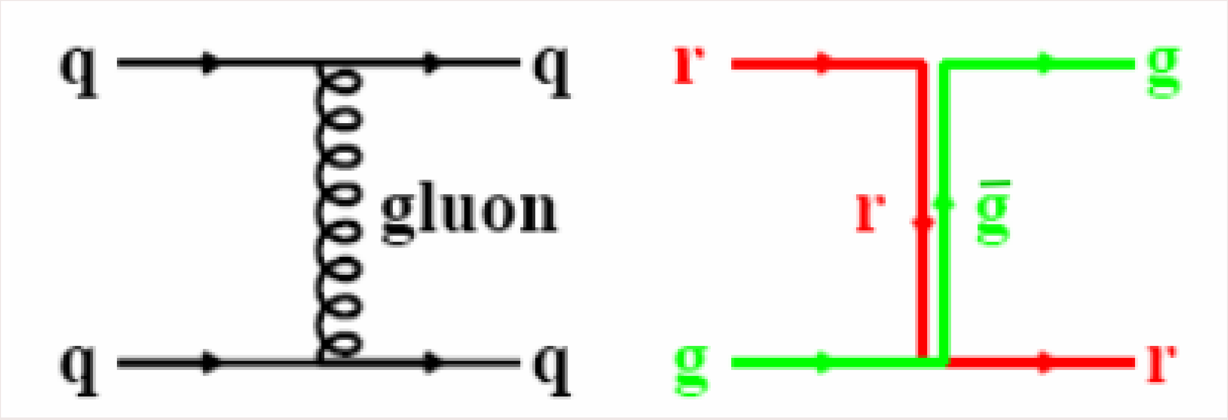
↓

solved by the existence of the gluons, which bind the quarks together and confine them inside the proton

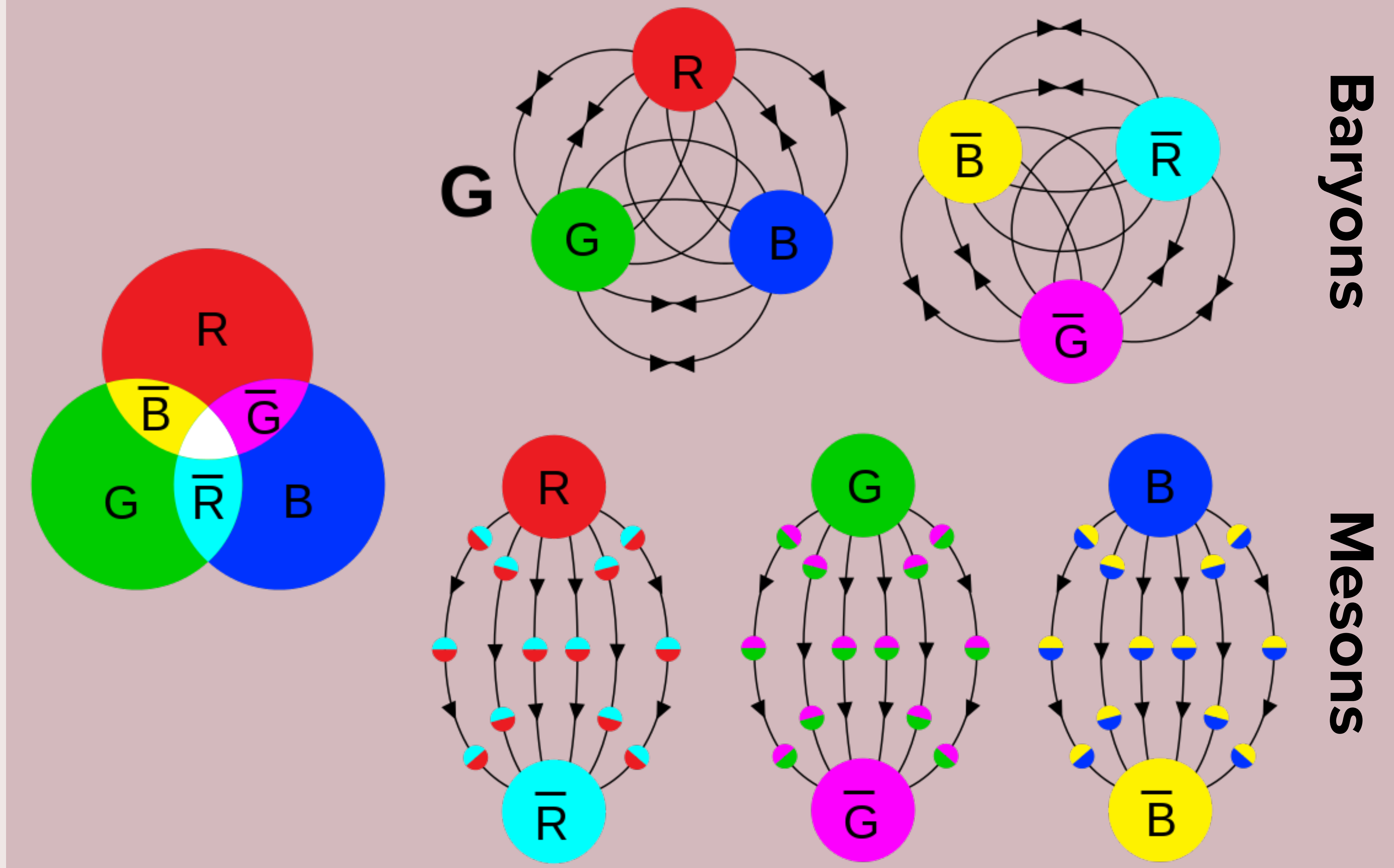
The quark-parton model was extended and became the field theory of the Quantum ChromoDynamics (QCD)

Quantum ChromoDynamics (QCD)

- Formulated in 1973
- The gluons are the field carriers just like photons in QED
- Much richer structure than QED
- A new quantum number is needed (color), which is carried by quarks and gluons
- The gluon can interact with itself as well as with the quarks
- There are 8 kinds of gluons



Hadrons are colourless states

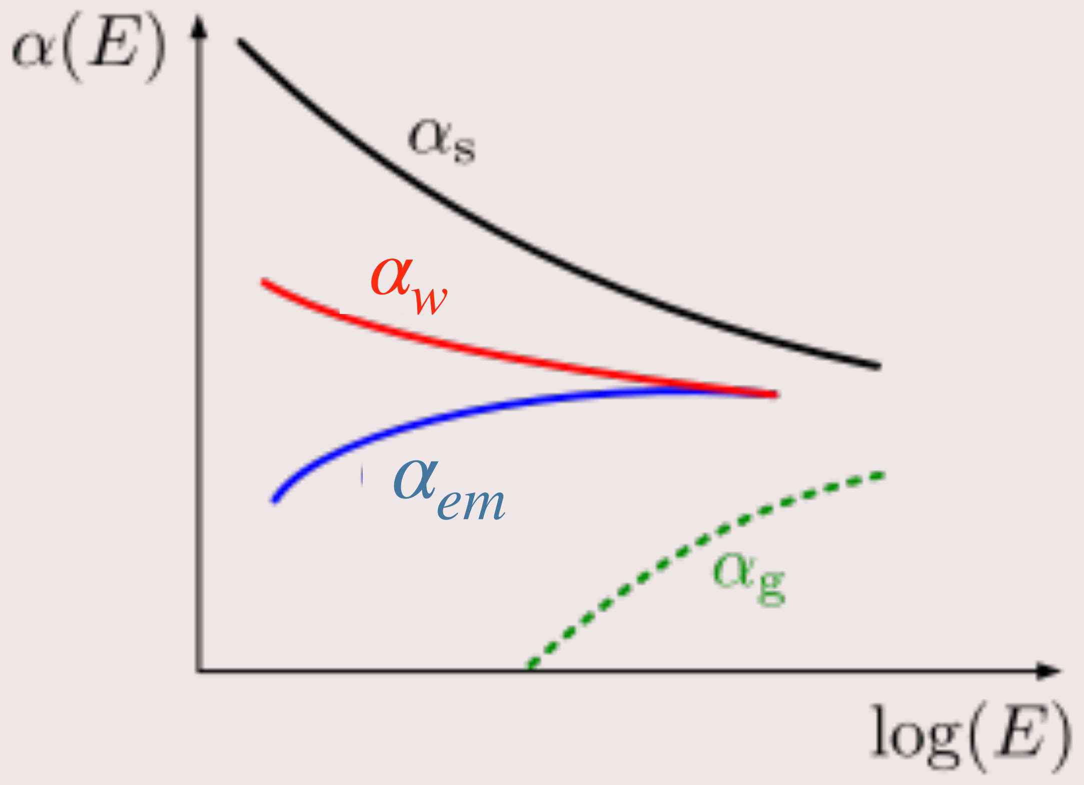


The establishment of the QCD

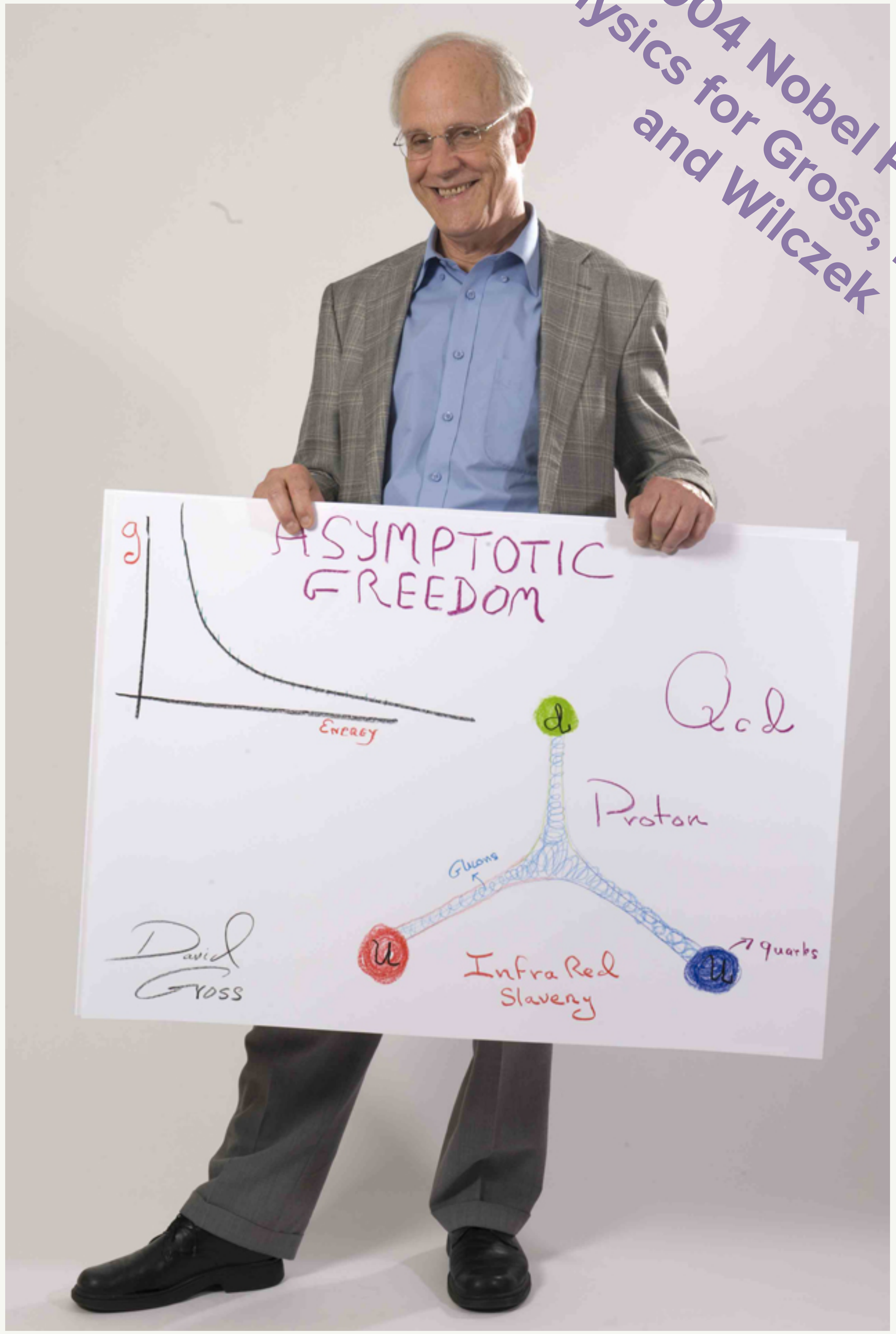
- Scattering experiments established that QCD was the correct theory of the strong force theory by testing some of the QCD predictions

- The strong coupling “constant” in analogy with the fine structure “constant” in QED was determined

They vary with the scale of the process



- Quarks become asymptotically free when examined at high energies BUT are strongly confined at low energies



2004 Nobel Prize in Physics for Gross, Politzer and Wilczek

The proton properties

1. Momentum
2. Spin
3. Radius
4. Mass
5. Decay

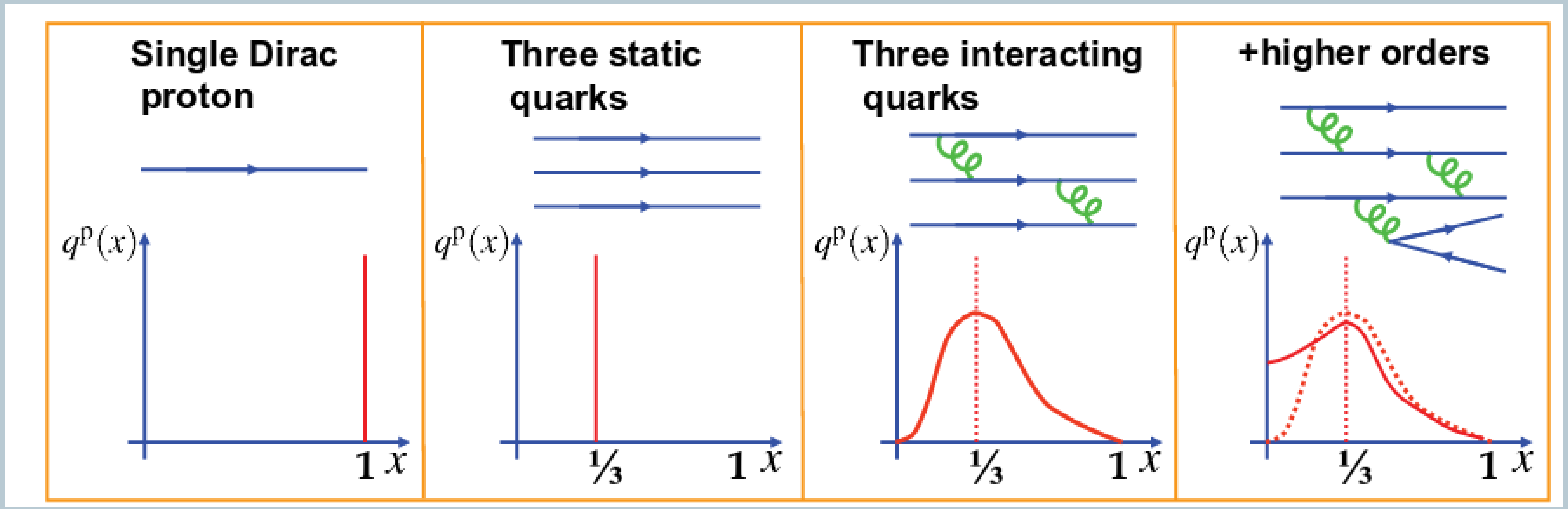
} Today's talk (items 1–4)

→ (5. Decay) Is the proton stable ?
Nowadays is established that
its half-life is $> 10^{34}$ *years*

The proton momentum

How to understand the structure of the proton?

When the QCD became a definite theory the focus turned to the measurement of the momentum distributions of the partons, the so called Parton Distribution Functions (PDFs)



PDFs are probability functions with respect to the fraction of momentum carried by each of the proton constituents

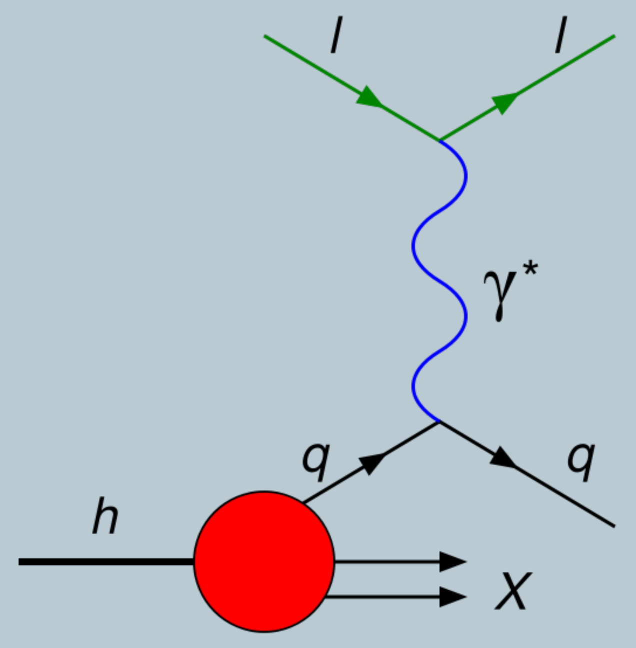
How can we access the PDFs?

The PDFs are **universal** and can be accessed through different processes

The partonic cross sections $\hat{\sigma}$ are calculable while the **PDFs have to be measured** experimentally

All the available measurements are used in **global fits**

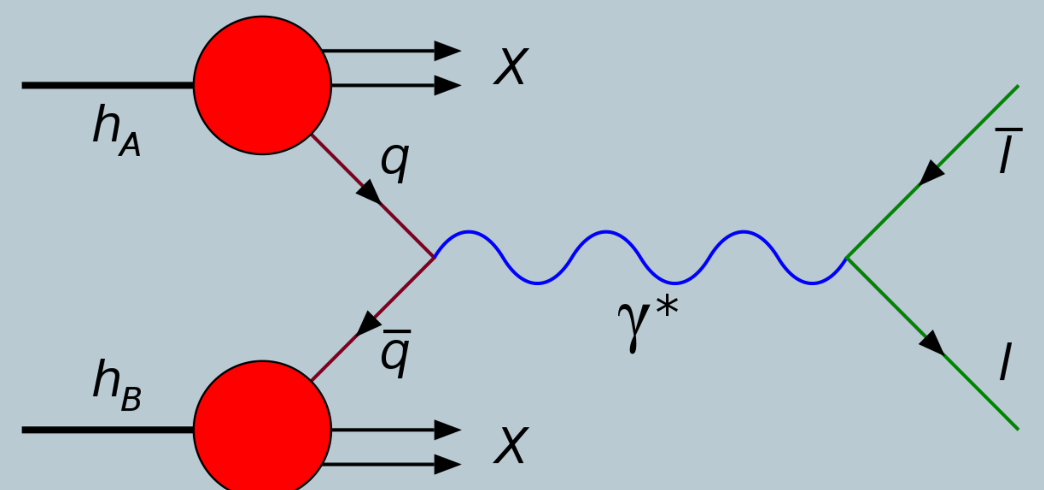
Deep Inelastic Scattering (DIS)



PDF

$$\sigma^{DIS} = \sum_j \int dx\, f_j(x, Q^2)\, \hat{\sigma}_{\gamma^* j}(x, Q^2, \ldots)$$

Drell-Yan



PDF PDF

$$\sigma^{DY} = \sum_{ab} \int dx_a \int dx_b\, f_a(x_a, Q^2)\, f_b(x_b, Q^2)\, \hat{\sigma}_{ab \to l\bar{l}}(x_a, x_b, \ldots)$$

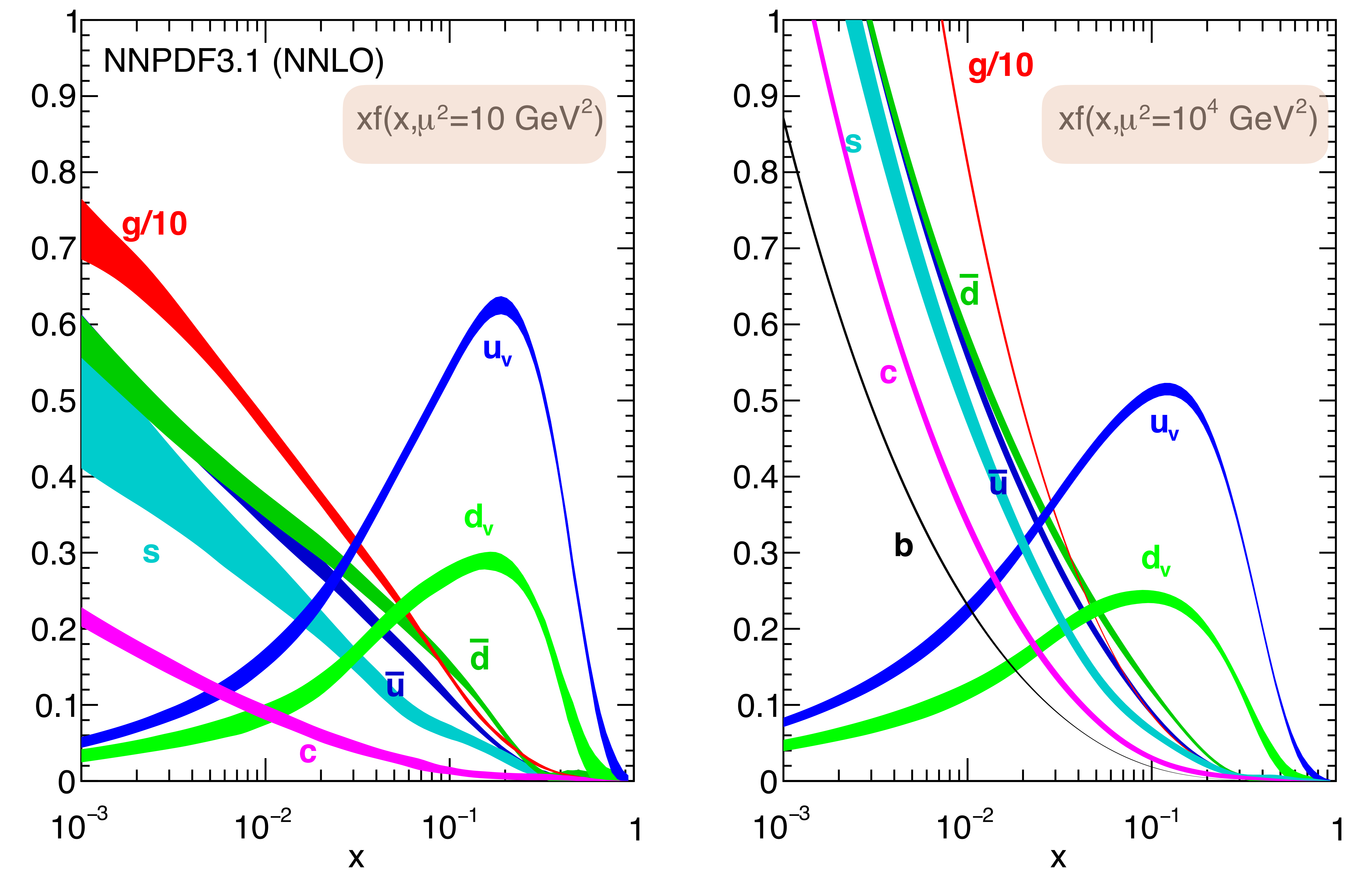
How well do we know proton PDFs?

Presently there is agreement between theory and experiments within a few percent across a very wide range of x and Q^2

Still NOT GOOD enough

Knowledge of the PDFs is increasingly vital for the discovery of (new) physics at the LHC

The predictions of either Standard Model cross sections or beyond SM need to use PDFs as input



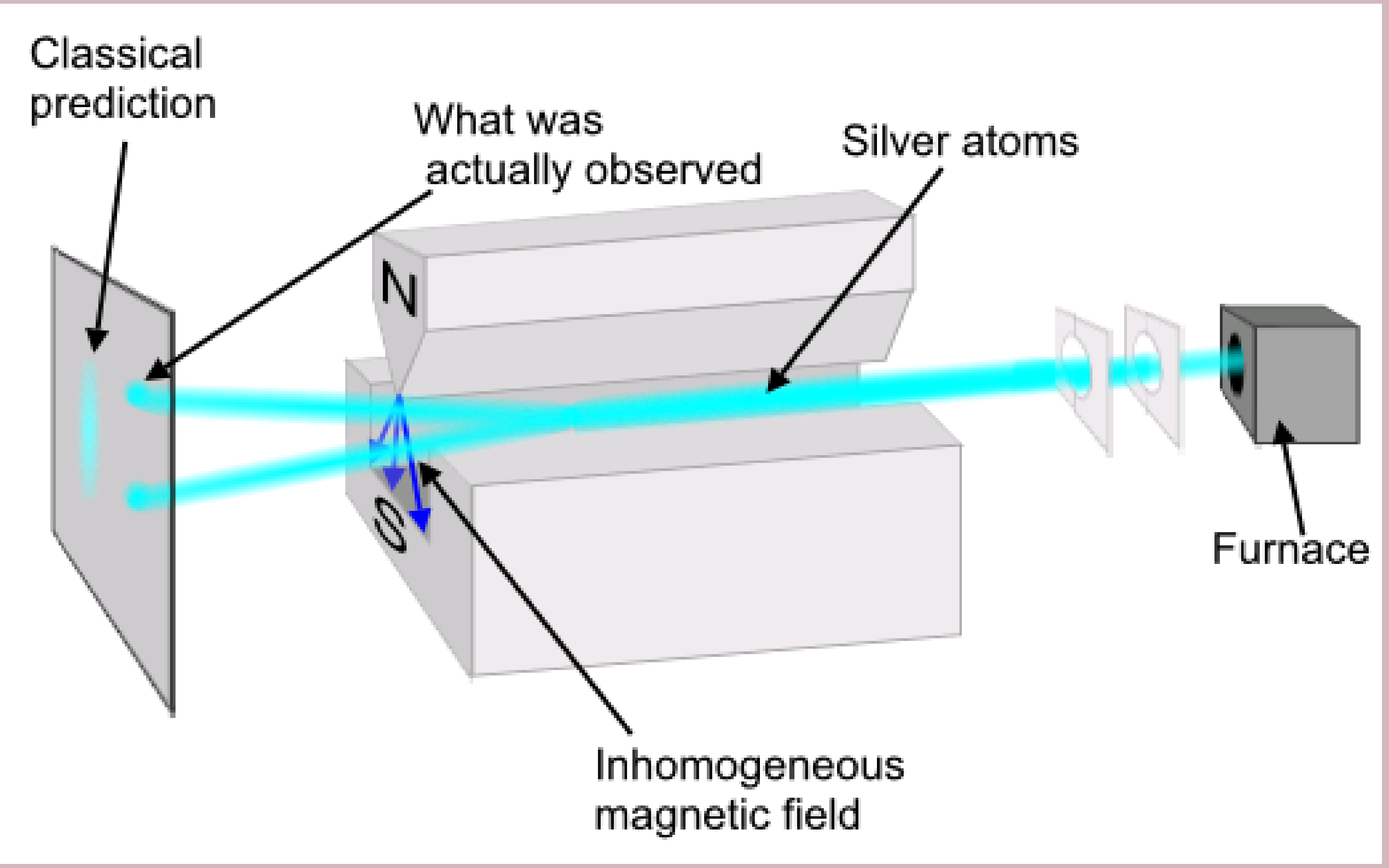
The proton spin

What is the spin?

- The spin is an intrinsic form of angular momentum, carried by elementary particles, composite particles (hadrons) and atomic nuclei
- This is an intrinsic property (such as mass or charge) in quantum mechanics and has no parallel in classical physics
- Spin was proposed for the first time in 1924 by Pauli
- In 1927 Pauli proposed the mathematic formulation that allowed to understand the electron spin and the Stern-Gerlach experimental result

Pauli and Bohr playing with a spin toy at the inauguration of the Institute of Physics at Lund, Sweden, 1954

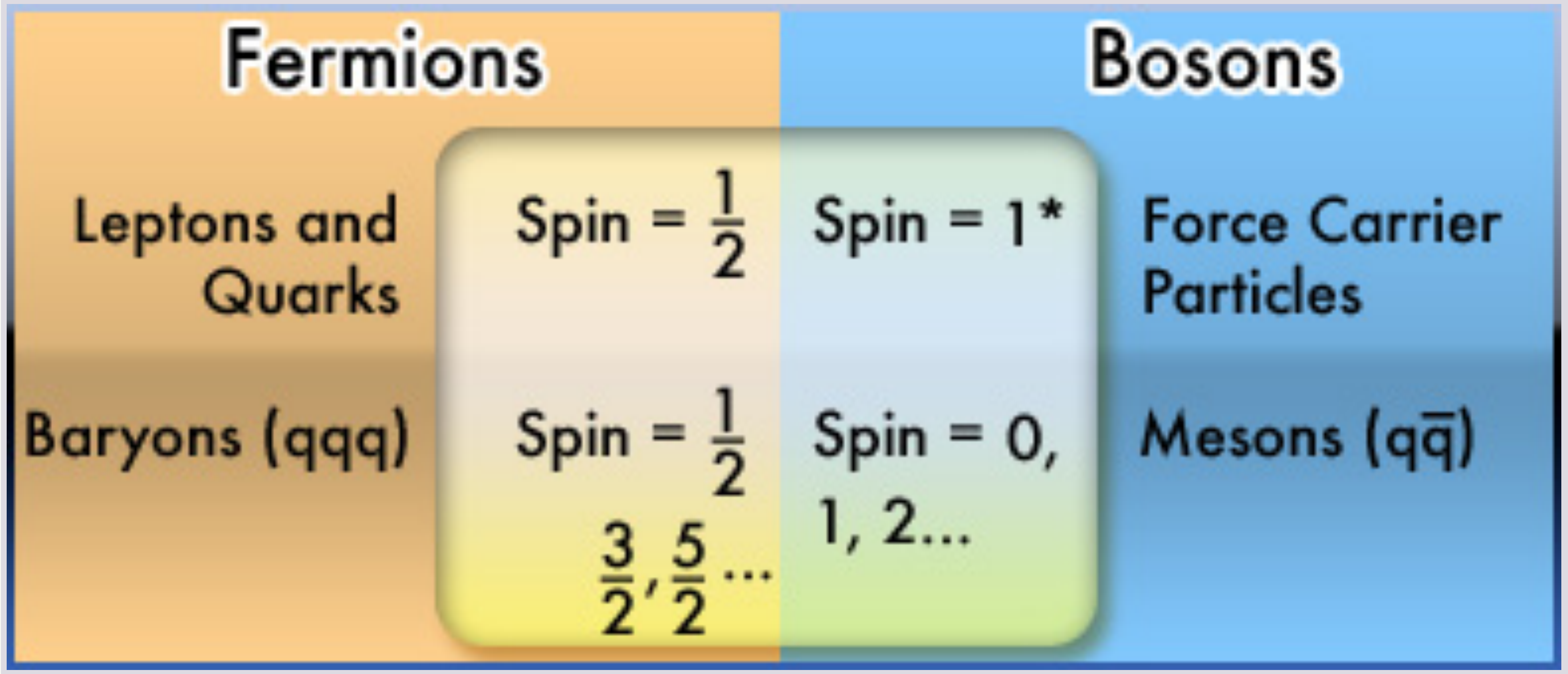
Stern-Gerlach experiment (1922)



The expected result was a continuum resulting from the magnetic moment of the electron (an electric charge looping around the nucleus)

BUT the obtained result was a pattern of two lines

The spin of particles



* the predicted graviton has a spin of 2

Fermi-Dirac statistics

Bose-Einstein statistics

The proton spin

Naively one would think that the proton spin comes from the arithmetic of the three quarks spins that align themselves such that two point "up" and one point "down"

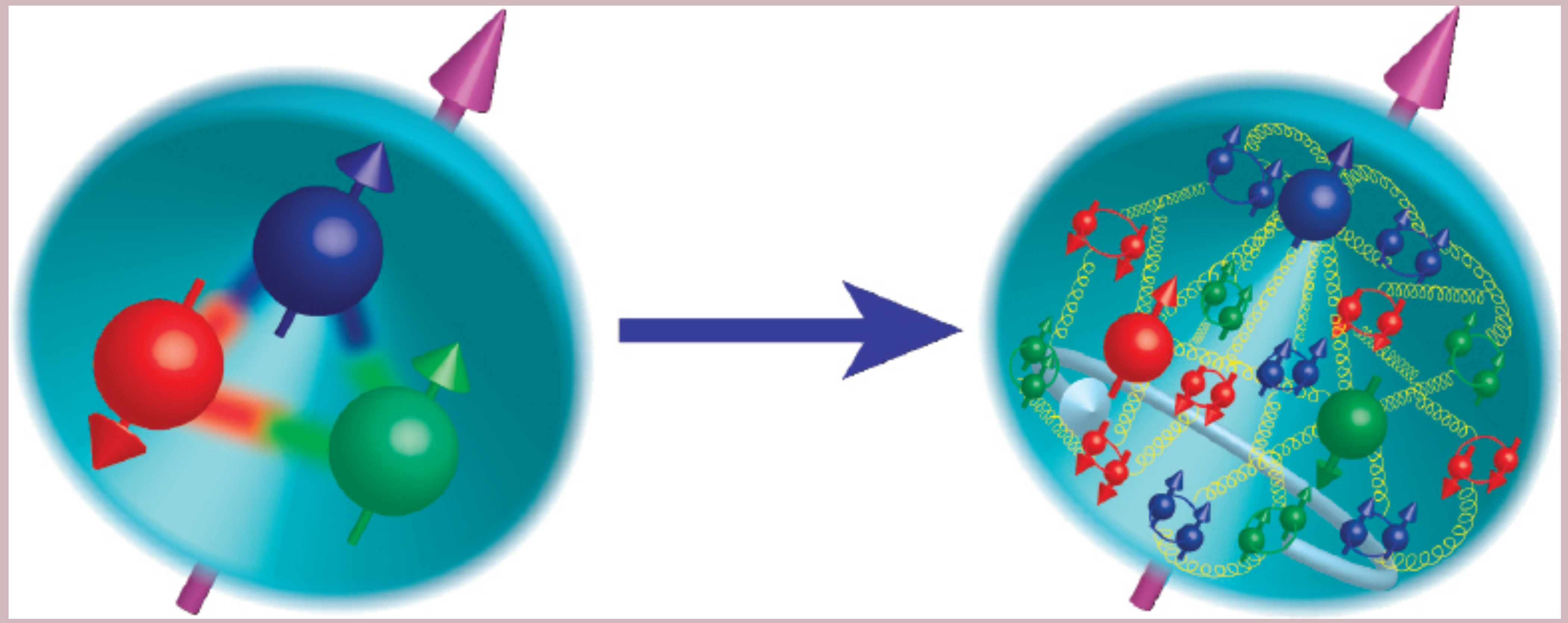
NOT THE CASE
at all

SPIN
crisis

In 1987, EMC at CERN, revealed that the quarks account for less than 1/3 (even compatible with 0) of the total spin of the proton

Attempts to fully solve it still remain the goal of experiments today

The proton spin puzzle



The proton spin may arise from contributions from their different constituents, quarks and gluons, and also from the orbital angular momentum

Each contribution must be measured experimentally

How can this be done?

COMPASS experiment at CERN: An experiment for spin physics
and more...

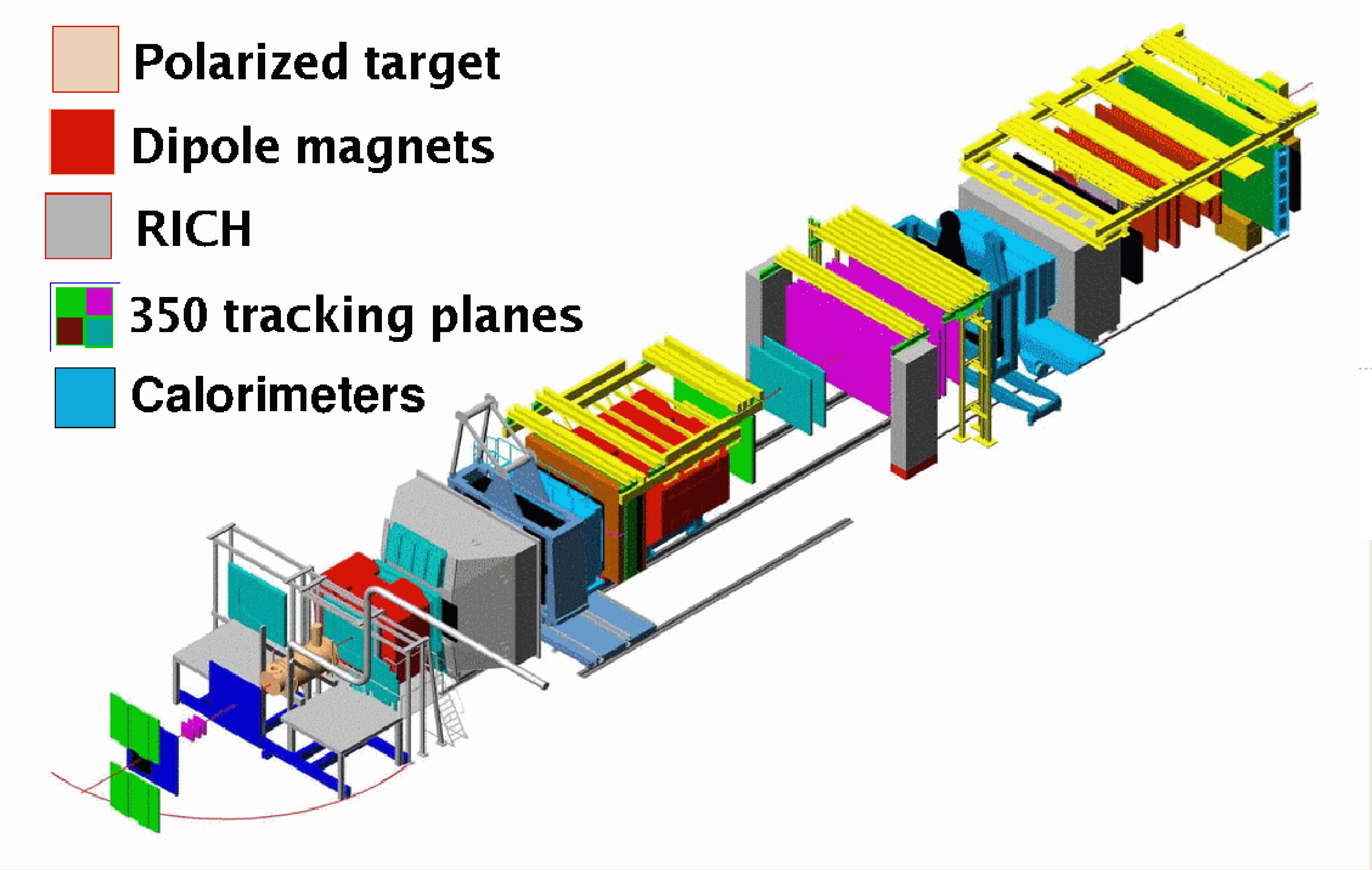
Common Muon Proton Apparatus for Structure and Spectroscopy

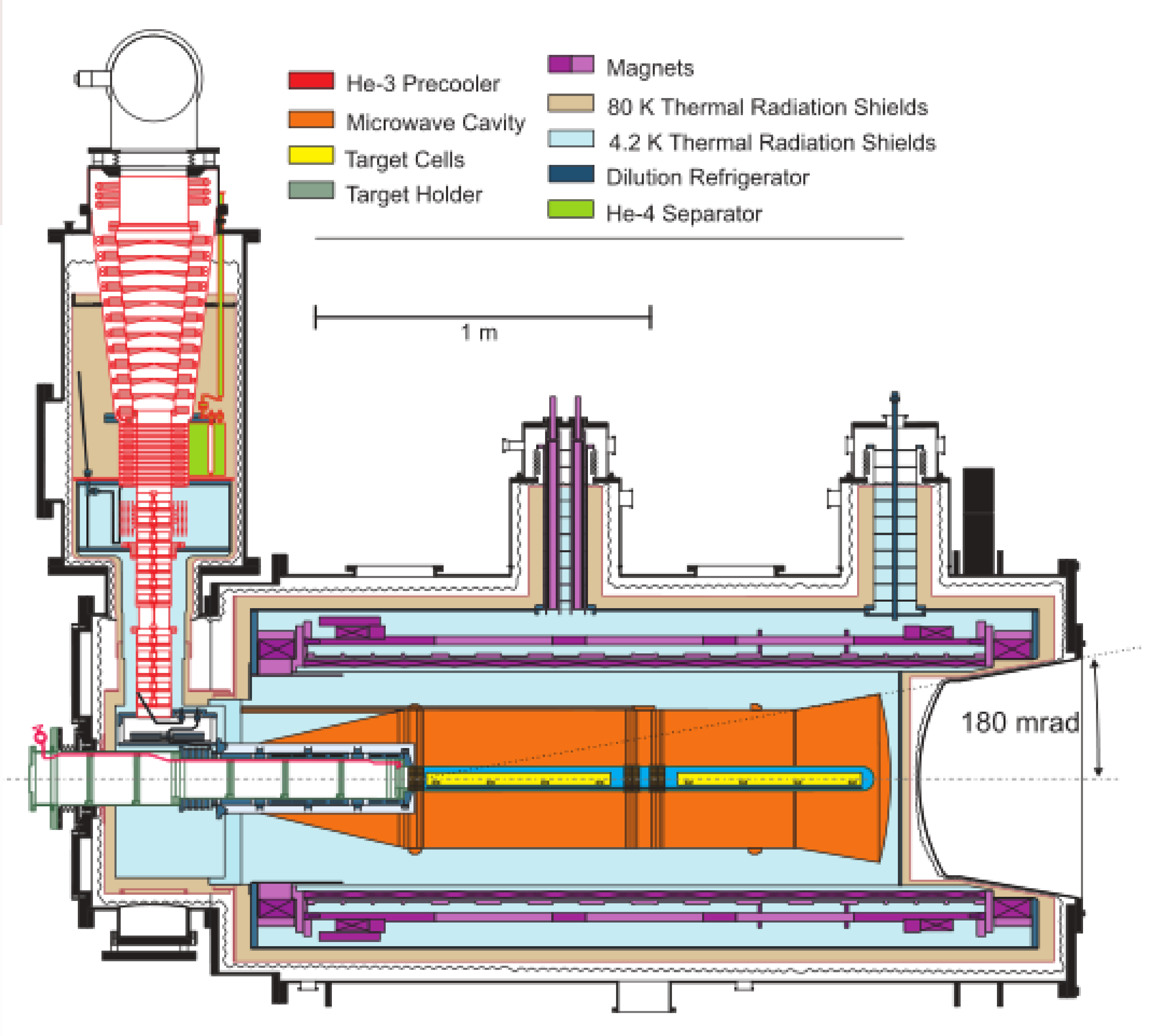
Fixed target experiment - General purpose spectrometer:

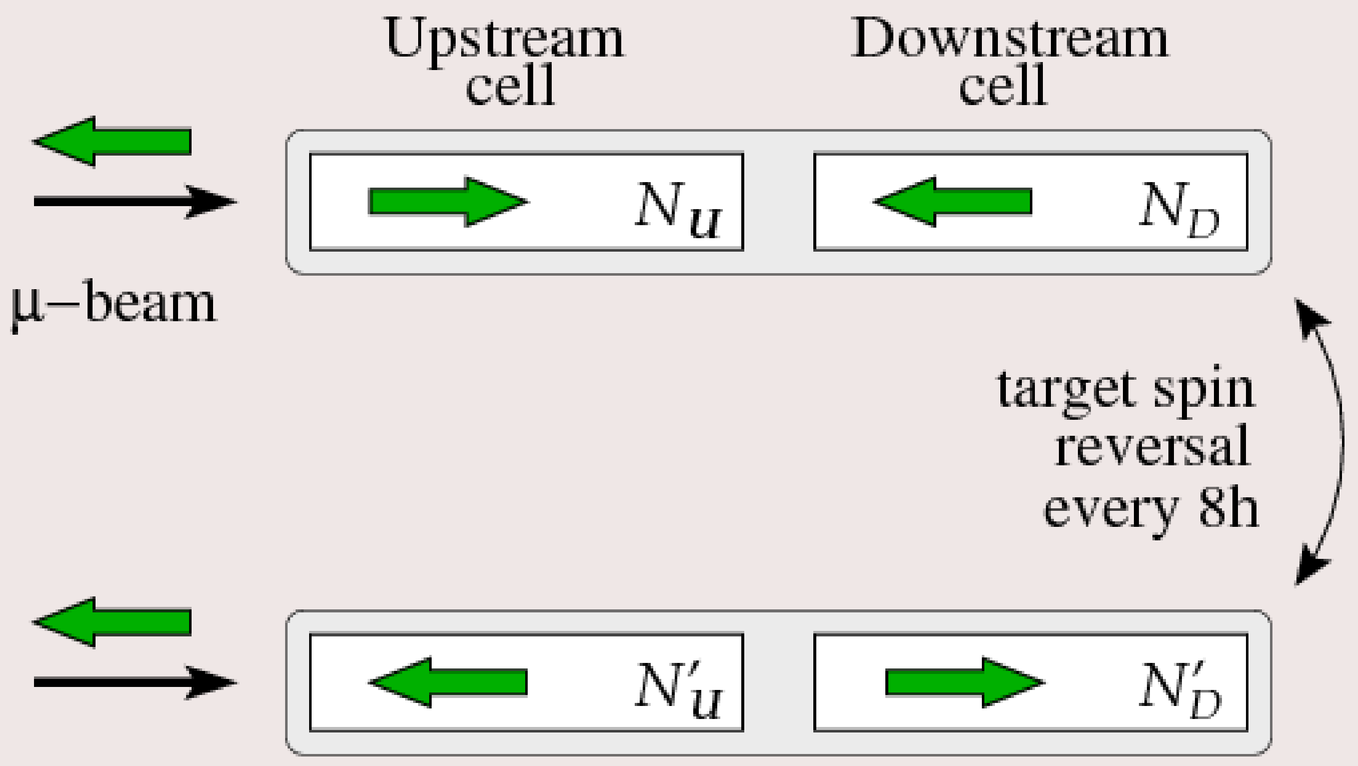
* Muon and hadron beams
* Polarised target (longitudinally and transversely polarised NH_3 and ^6LiD)

2002	deuteron SIDIS	20% trans., 80% long.
2003	deuteron SIDIS	20% trans., 80% long.
2004	deuteron SIDIS	20% trans., 80% long.
2005	shutdown	
2006	deuteron SIDIS	longitudinal
2007	proton SIDIS	50% trans., 50% long.
2008	Hadron run	
2009		
2010	proton SIDIS	transverse
2011	proton SIDIS	longitudinal
2012	Hadron run/DVCS run	
2013	shutdown	
2014		
2015	Drell-Yan run	transverse
2016	DVCS run, proton SIDIS	unpolarised
2017	DVCS run, proton SIDIS	unpolarised
2018	Drell-Yan run	transverse
2019	shutdown	
2020		
2021	deuteron SIDIS	transverse

COMPASS spectrometer







$$A \propto \frac{N^{\rightarrow} - N^{\leftarrow}}{N^{\rightarrow} + N^{\leftarrow}}$$

Polarised PDFs

q(x) : number density or unpolarised distribution

probability of finding a quark with a fraction x of the longitudinal momentum of the parent nucleon

Δq(x) = q⇉ - q⇆: longitudinal polarization or helicity distribution

in a longitudinally polarised nucleon, probability of finding a quark with a momentum fraction x and spin parallel to that of the parent nucleon

$\Delta_T q(x) = q^{\uparrow\uparrow} - q^{\downarrow\uparrow}$: transverse polarization or transversity distribution

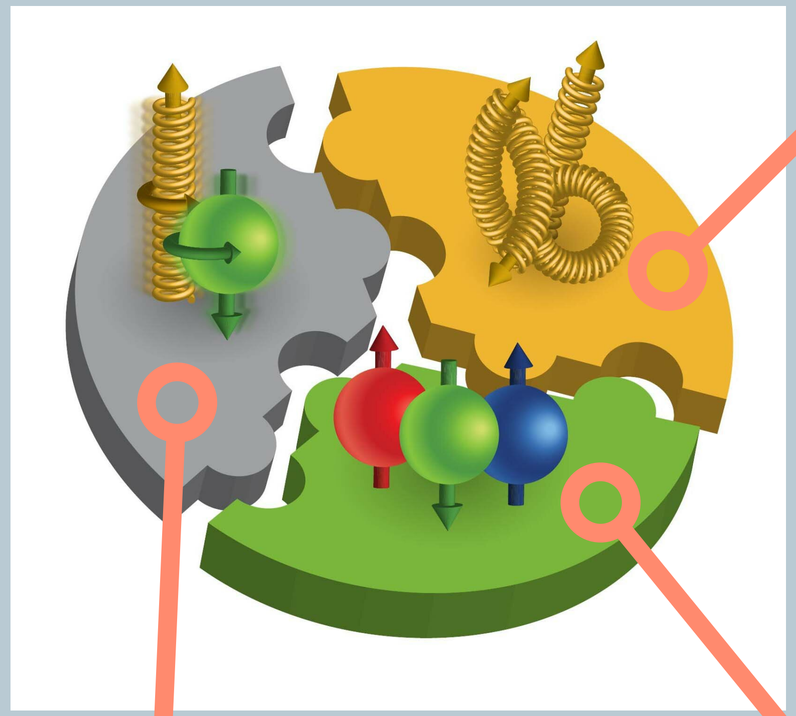
in a transversely polarised nucleon, probability of finding a quark with a momentum fraction x and polarisation parallel to that of the parent nucleon

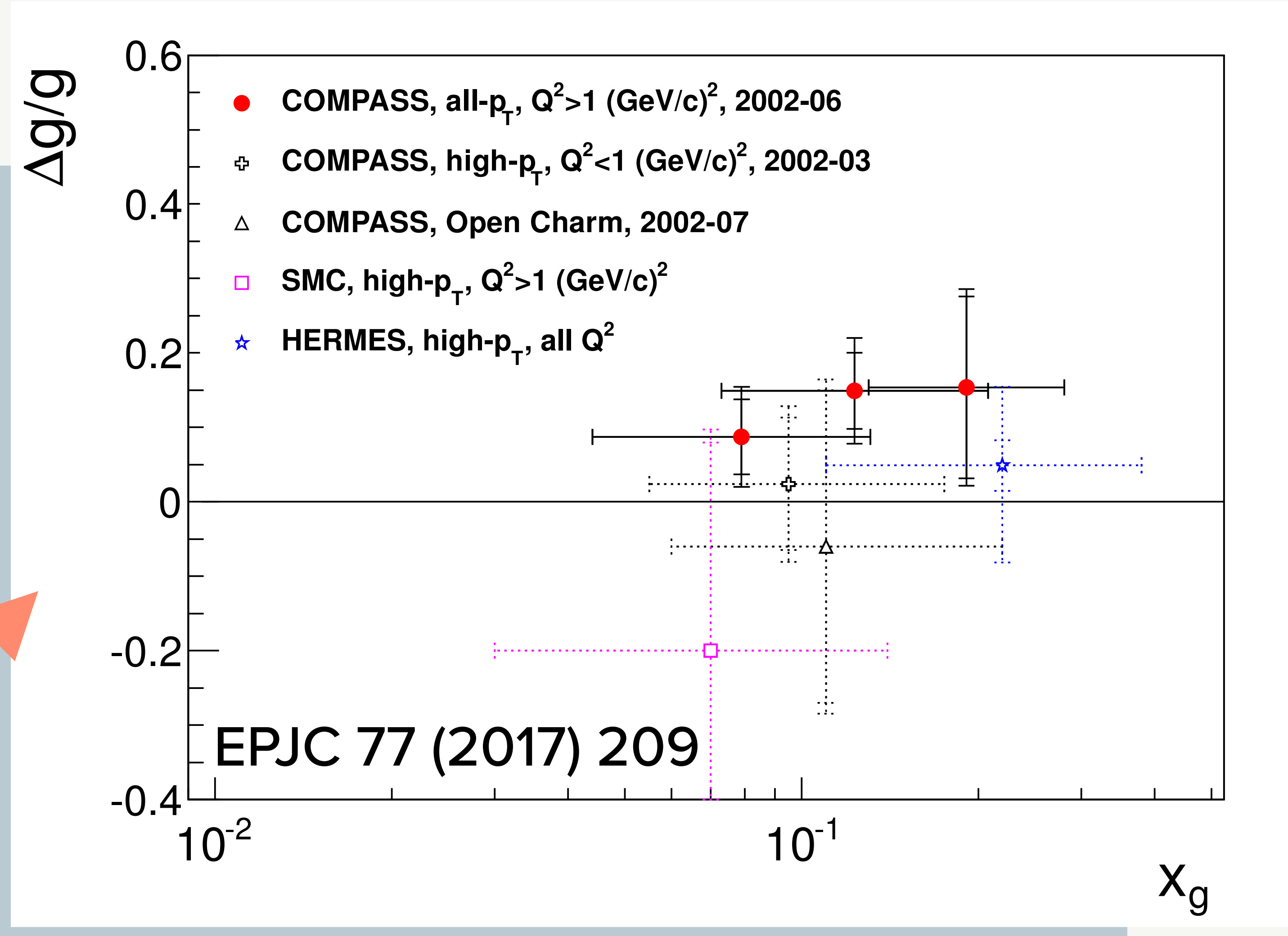
q quark or antiquark with a specific flavor [*notation: Barone, Drago, Raftcliffe 2001*]

The helicity and transversity distributions can be accessed through the spin asymmetries

$$A \propto \frac{N^{\rightarrow} - N^{\leftarrow}}{N^{\rightarrow} + N^{\leftarrow}} \qquad A \propto \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

Proton spin decomposition





Around 20% but still very uncertain

PLB 769 (2017) 34 - all d data

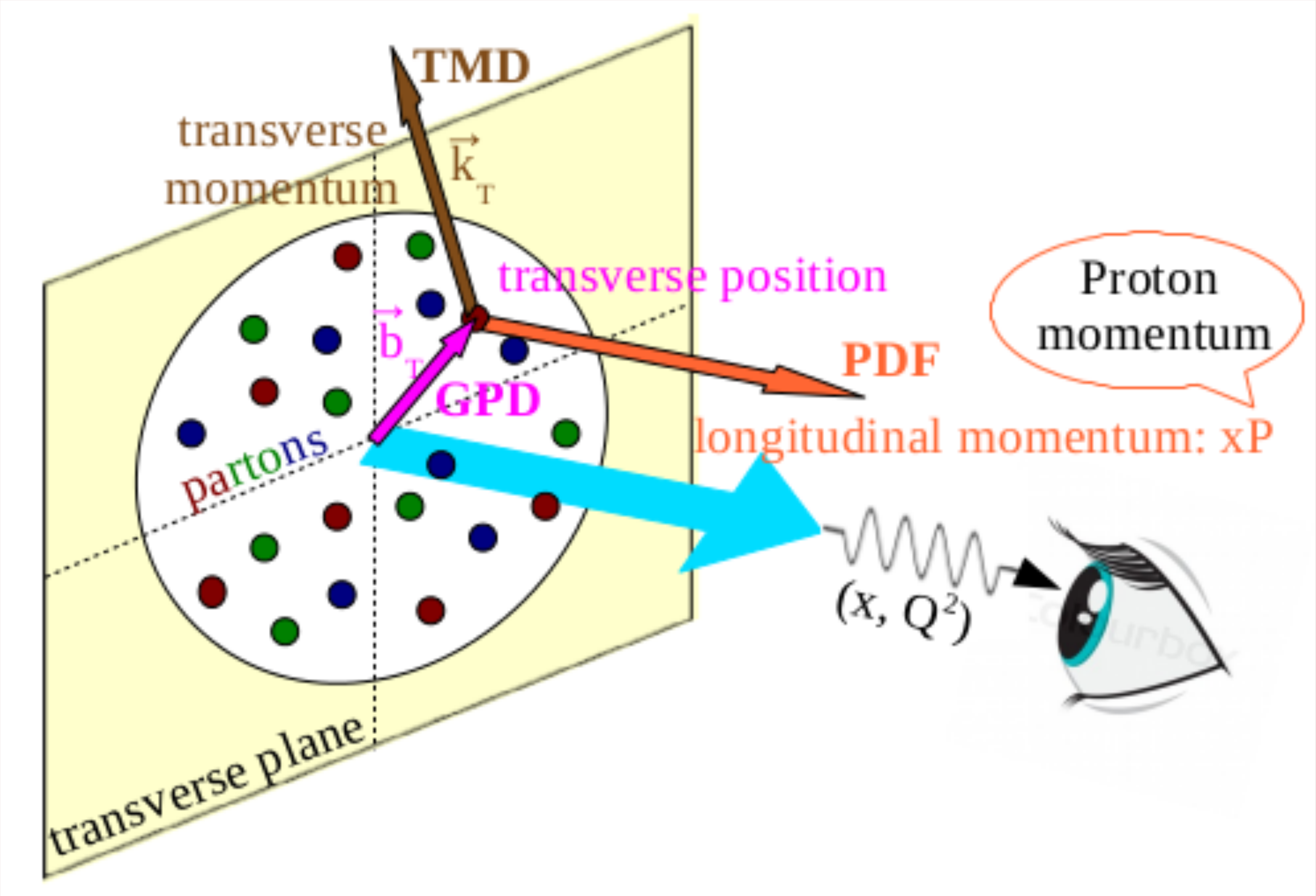
$$\Delta\Sigma = 0.32 \pm 0.02_{stat} \pm 0.04_{syst} \pm 0.05_{evol}$$

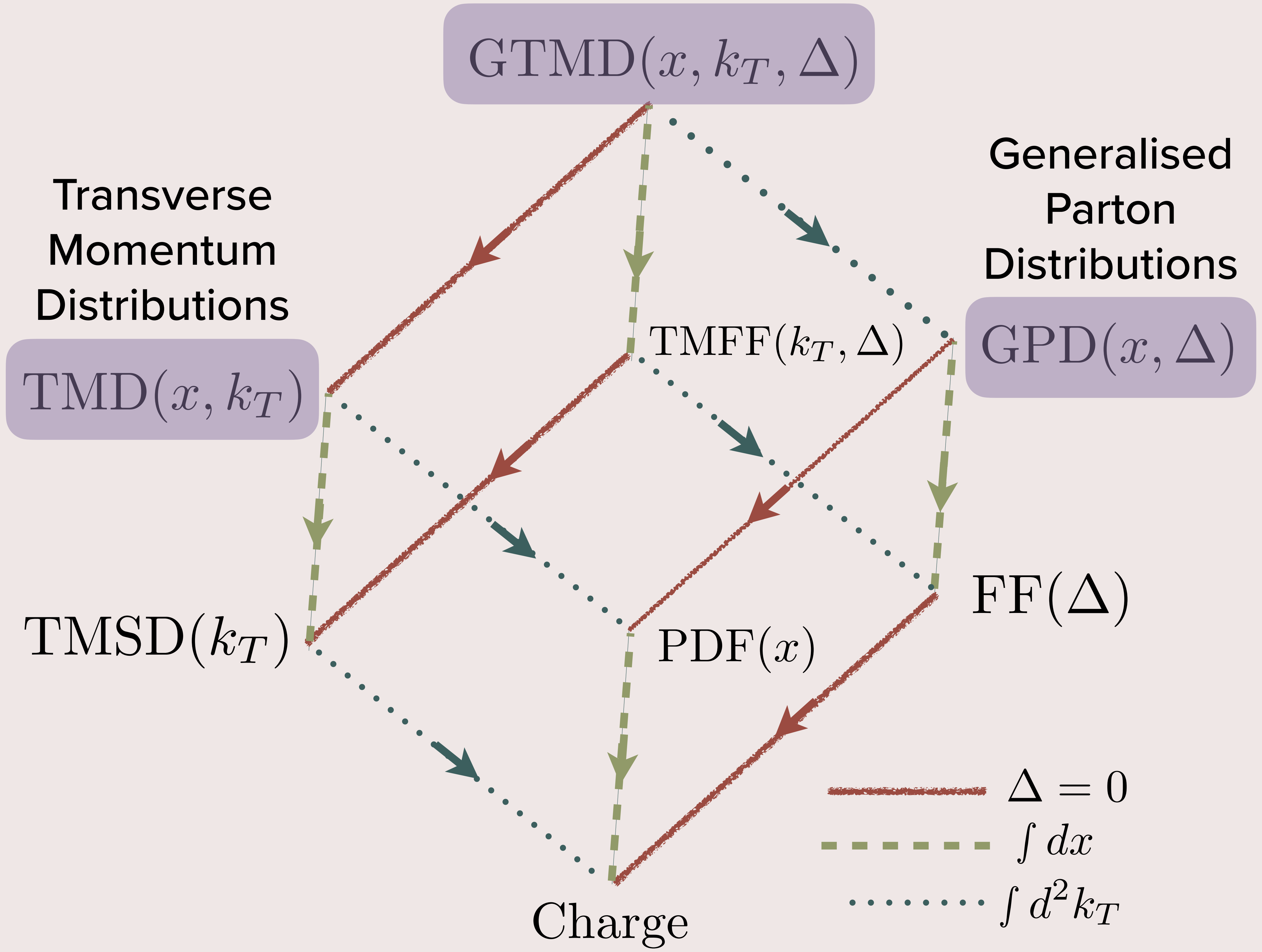
Around 50% of the proton spin may come from the orbital angular momentum

How can we access the orbital angular momentum?

Go beyond the collinear approximation

The multi-dimensional structure of the proton

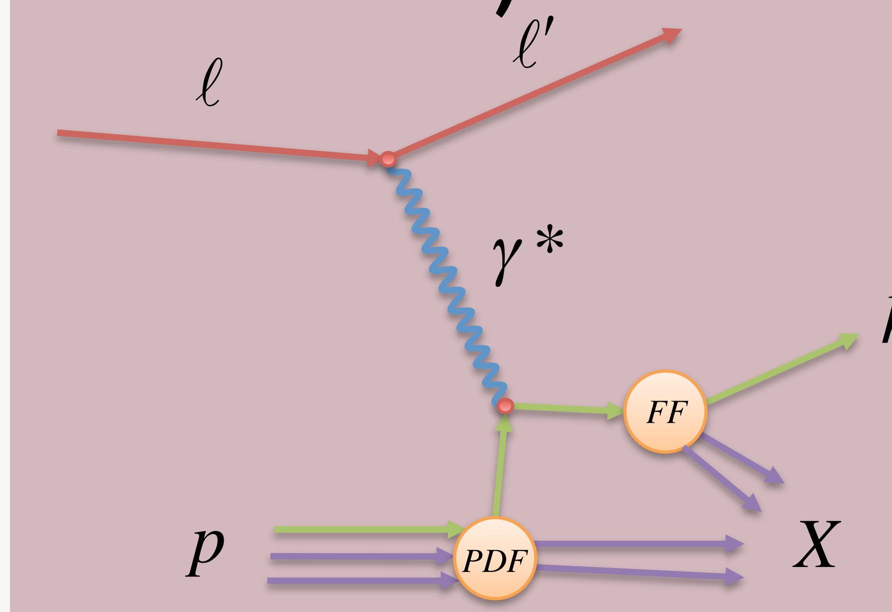


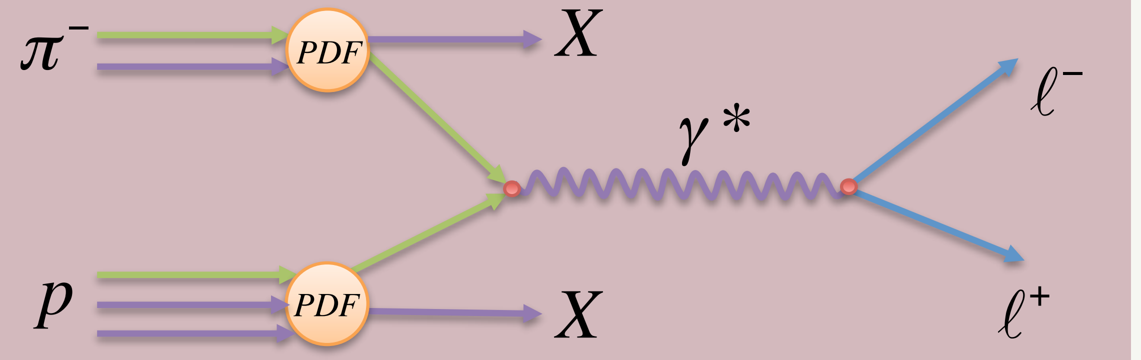


TMD PDFs

Taking the intrinsic transverse momentum into account:

- 8 TMD PDFs are needed to describe the nucleon
- related to correlations between the nucleon spin, the quark spin and its intrinsic transverse momentum
- a special focus goes for Sivers TMD PDF, which sign is process dependent (has an opposite sign when accessed from Drell-Yan or SIDIS)





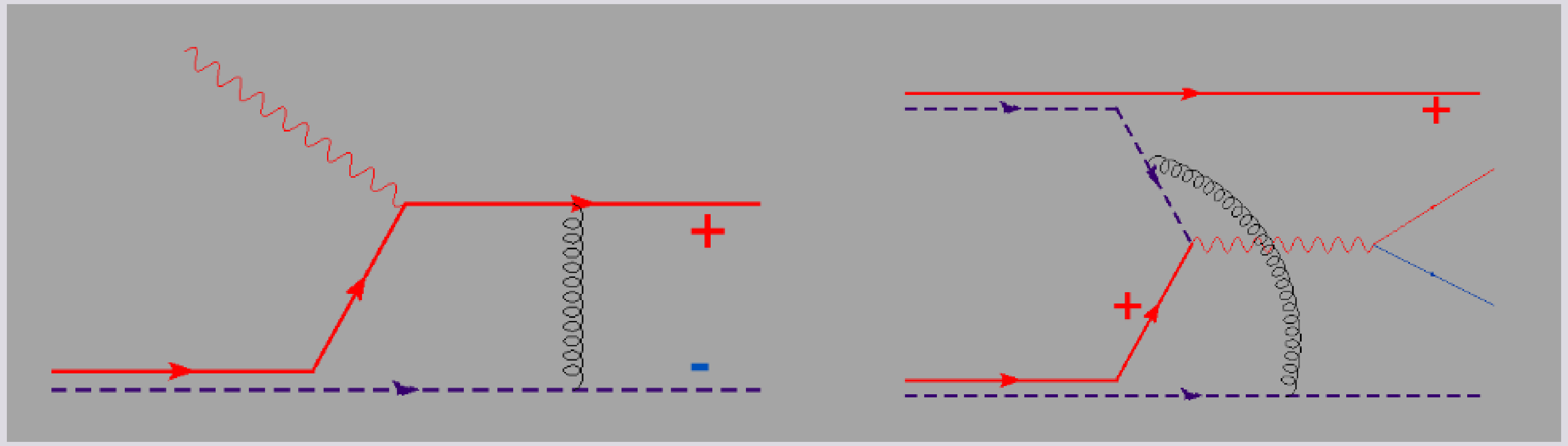
Note: The Fragmentation Functions (FF) describe how the quarks re-join to form hadrons

		Nucleon		
		unpolarised	longitudinally polarised	transversely polarised
Quark	unpolarised	f_1 unpolarised PDF		$f_{1T}^{\perp}$ (k_T) Sivers
	longitudinally polarised		g_1 helicity	$g_{1T}^{\perp}$ worm-gear T
	transversely polarised	$h_1^{\perp}$ Boer-Mulders	$h_{1L}^{\perp}$ worm-gear L	h_1 transversity $h_{1T}^{\perp}$ pretzelosity

The Sivers sign change

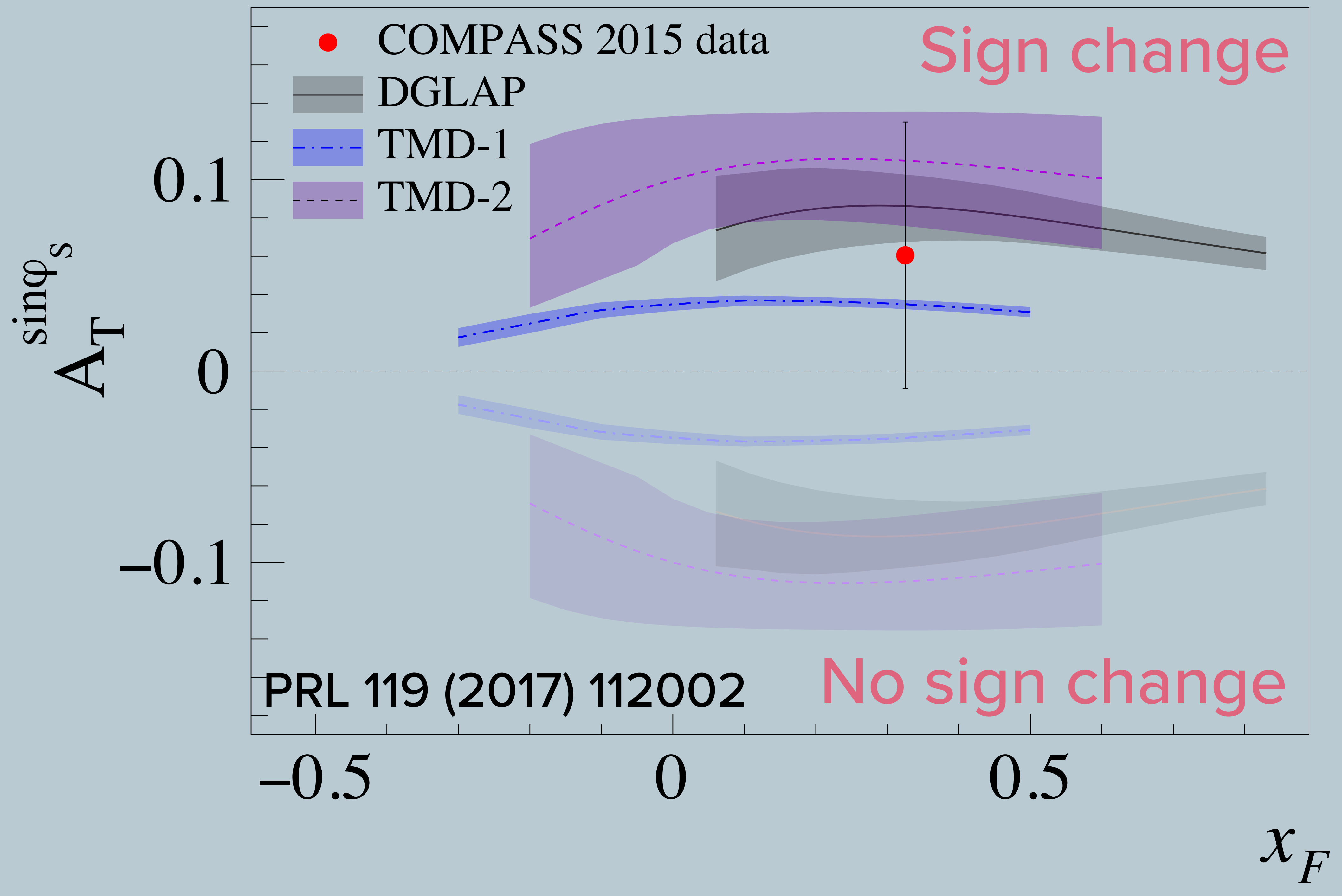
PDFs are "universal" but some depend on the way they are measured

$$f_{1T}^{\perp}\ (SIDIS) = -f_{1T}^{\perp}\ (DY)$$



QCD predicts that the Sivers TMD PDF has opposite sign between SIDIS and DY because it arises from a final state interaction in the case of SIDIS and from a initial state one in the case of Drell-Yan

Sivers was measured in COMPASS through SIDIS and Drell-Yan

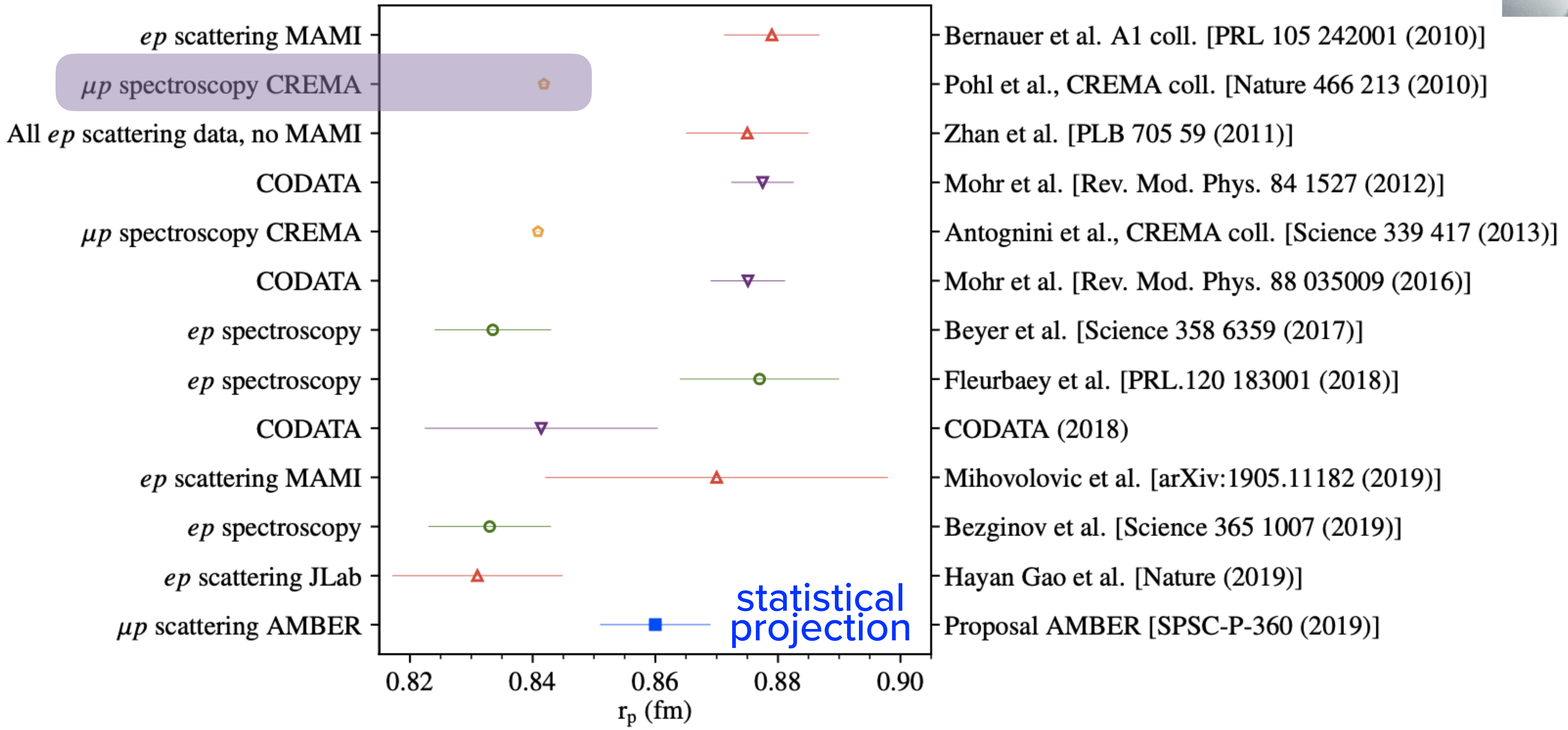


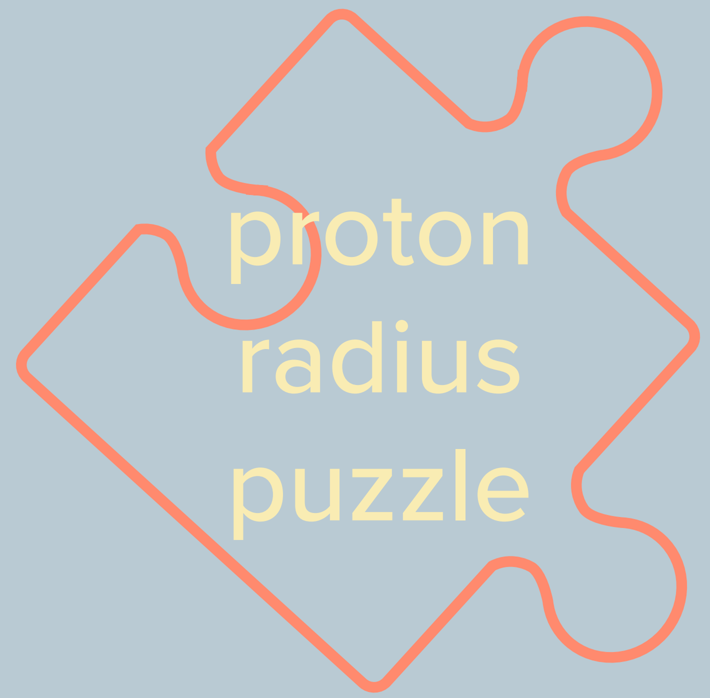
The experimental result favours the sign change <u>but</u> it is still statistically inconclusive

The proton radius

How much is the proton radius?

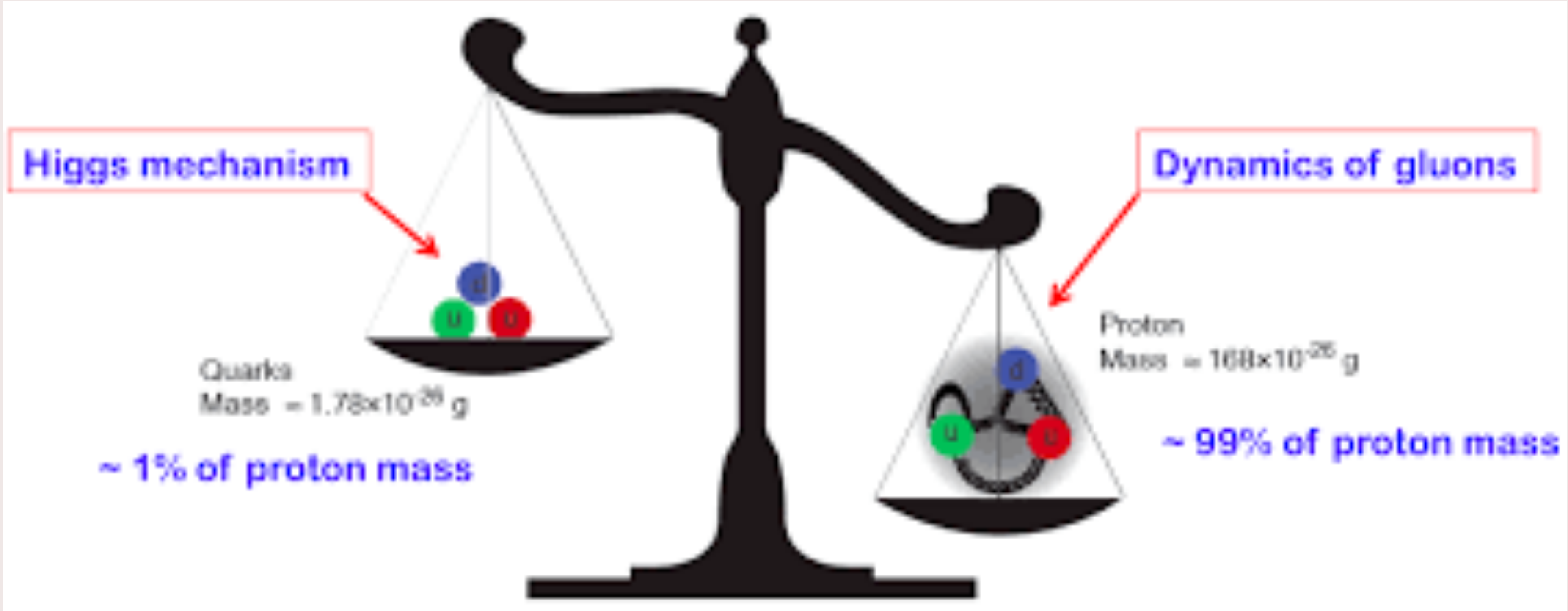
$r_p^{spectroscopy} \approx 0.84\ fm$ $r_p^{elastic\ scattering} \approx 0.88\ fm$





The proton mass

What is the origin of the proton mass?



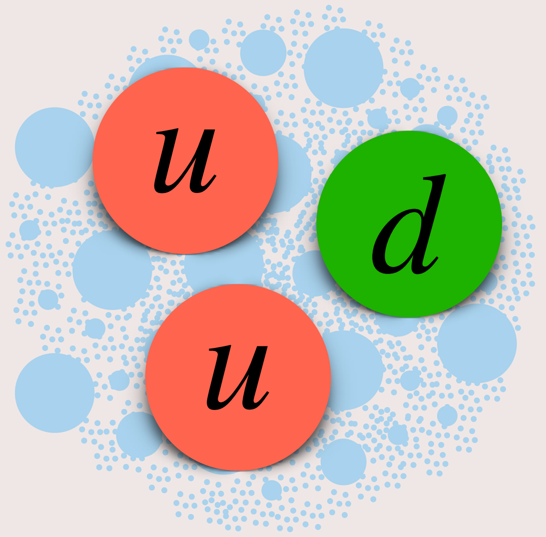
The Higgs mechanism accounts for 1% of the proton mass

WHILE

the dynamics of the gluons amounts for 99%

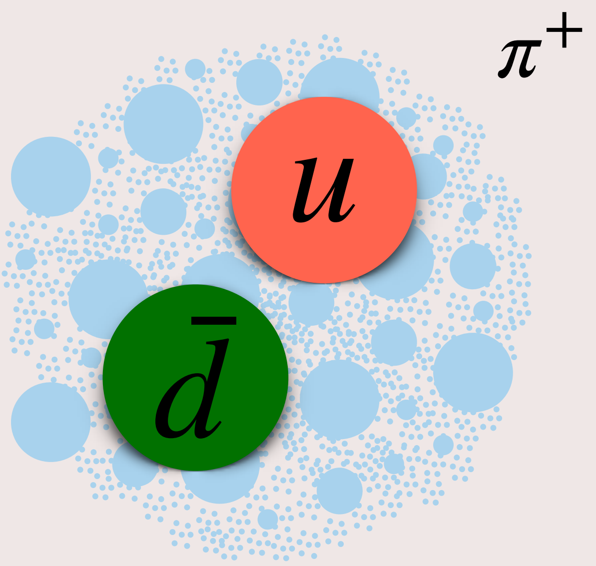
The mass hierarchy puzzle

Proton



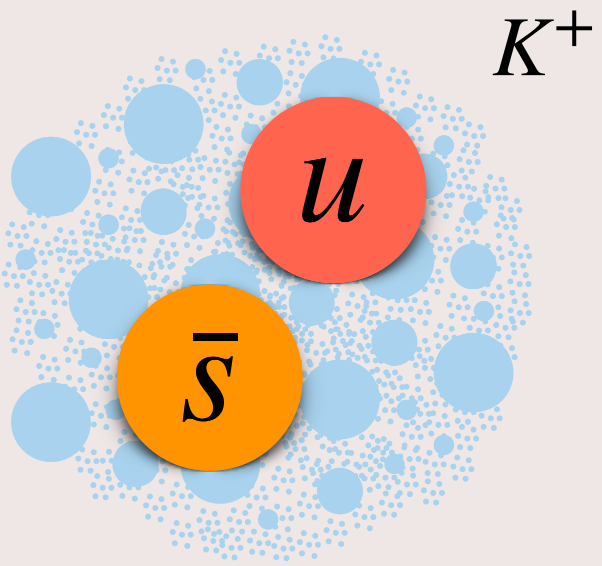
$M_p \sim 940\ MeV/c^2$

Pion



$M_\pi \sim 140\ MeV/c^2$

Kaon



$M_K \sim 490\ MeV/c^2$

The nucleon and the meson PDFs may be the key to understand the mass budget

AMBER experiment at CERN

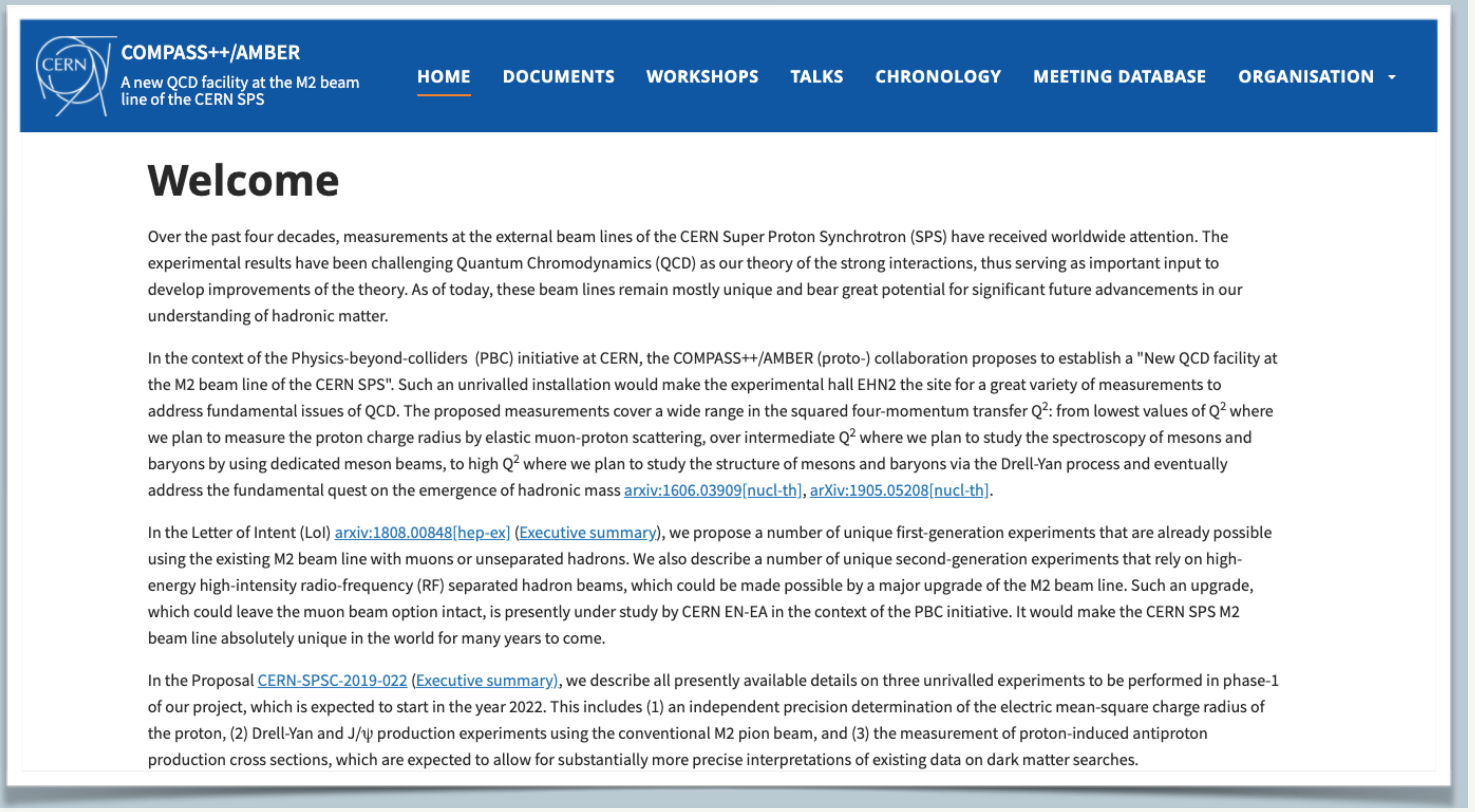
Apparatus for Meson and Baryon Experimental Research

To continue to pursue the QCD studies at CERN

- The proton radius puzzle
- The emergence of the hadronic mass
- and more….

To start in 2022 in the same experimental hall of COMPASS

https://nqf-m2.web.cern.ch/



COMPASS++/AMBER
A new QCD facility at the M2 beam line of the CERN SPS

HOME DOCUMENTS WORKSHOPS TALKS CHRONOLOGY MEETING DATABASE ORGANISATION

Welcome

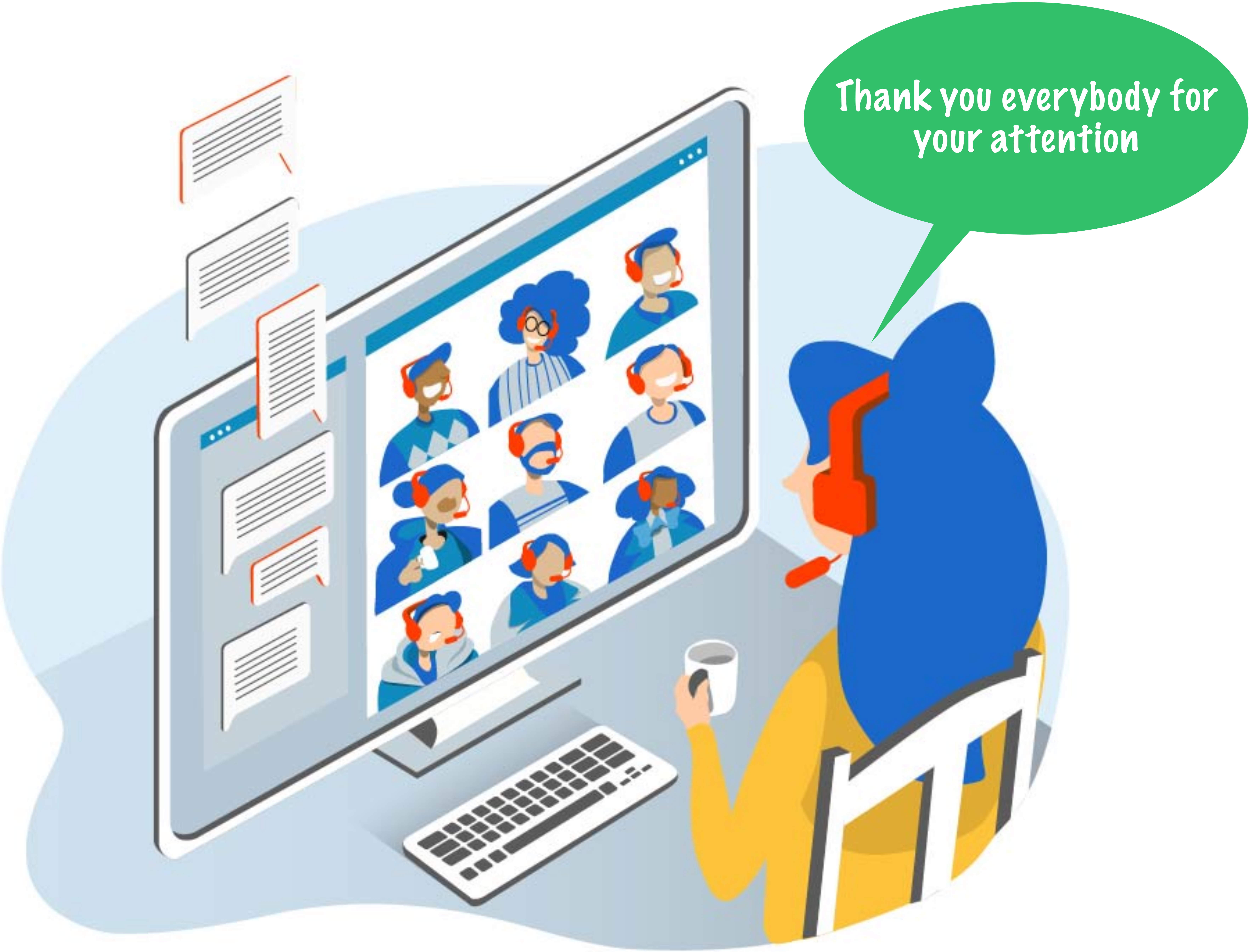
Over the past four decades, measurements at the external beam lines of the CERN Super Proton Synchrotron (SPS) have received worldwide attention. The experimental results have been challenging Quantum Chromodynamics (QCD) as our theory of the strong interactions, thus serving as important input to develop improvements of the theory. As of today, these beam lines remain mostly unique and bear great potential for significant future advancements in our understanding of hadronic matter.

In the context of the Physics-beyond-colliders (PBC) initiative at CERN, the COMPASS++/AMBER (proto-) collaboration proposes to establish a "New QCD facility at the M2 beam line of the CERN SPS". Such an unrivalled installation would make the experimental hall EHN2 the site for a great variety of measurements to address fundamental issues of QCD. The proposed measurements cover a wide range in the squared four-momentum transfer Q^2: from lowest values of Q^2 where we plan to measure the proton charge radius by elastic muon-proton scattering, over intermediate Q^2 where we plan to study the spectroscopy of mesons and baryons by using dedicated meson beams, to high Q^2 where we plan to study the structure of mesons and baryons via the Drell-Yan process and eventually address the fundamental quest on the emergence of hadronic mass arxiv:1606.03909[nucl-th], arXiv:1905.05208[nucl-th].

In the Letter of Intent (LoI) arxiv:1808.00848[hep-ex] (Executive summary), we propose a number of unique first-generation experiments that are already possible using the existing M2 beam line with muons or unseparated hadrons. We also describe a number of unique second-generation experiments that rely on high-energy high-intensity radio-frequency (RF) separated hadron beams, which could be made possible by a major upgrade of the M2 beam line. Such an upgrade, which could leave the muon beam option intact, is presently under study by CERN EN-EA in the context of the PBC initiative. It would make the CERN SPS M2 beam line absolutely unique in the world for many years to come.

In the Proposal CERN-SPSC-2019-022 (Executive summary), we describe all presently available details on three unrivalled experiments to be performed in phase-1 of our project, which is expected to start in the year 2022. This includes (1) an independent precision determination of the electric mean-square charge radius of the proton, (2) Drell-Yan and J/ψ production experiments using the conventional M2 pion beam, and (3) the measurement of proton-induced antiproton production cross sections, which are expected to allow for substantially more precise interpretations of existing data on dark matter searches.

100 years passed since the discovery of the proton and it is clear that much remained to be learned about the structure of this complex and omnipresent particle


Thank you everybody for your attention