Questions in Hadron Physics

Introduction: History of Spin and Significance

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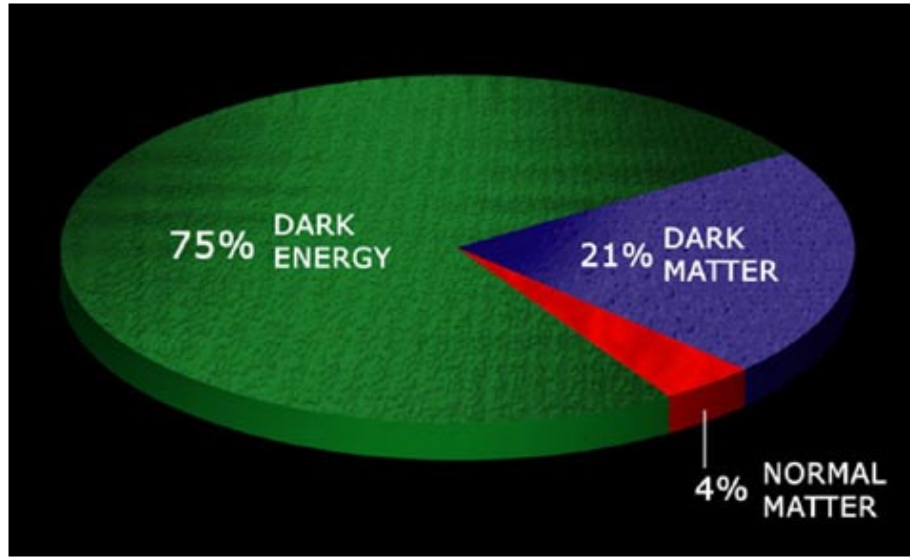
Our Universe:



- 75% Dark energy
- 21% Dark matter
- 4% Normal/visible matter
- What makes up the mass of the **visible universe?**

  Atomic mass (visible matter): 99.9% from nuclear mass

  Nuclear Mass: all of it form **nucleon mass**

  Nucleon mass? ➔ **energy of massless *gluons* and almost massless up & down quarks**

  ➔ *"Mass without mass" – John Wheeler*

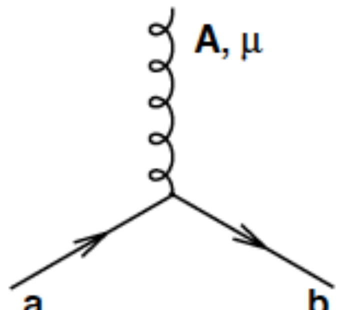
Gluon & quark interactions & dynamics make up the entire mass of the visible universe!

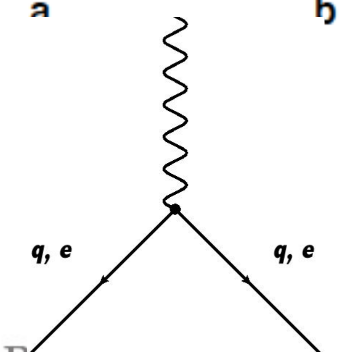
What distinguishes QCD from QED?

QED is mediated by photons (γ) which are charge-less

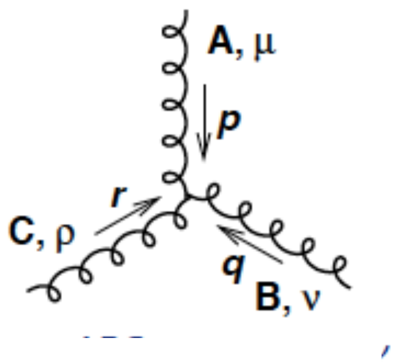
QCD is mediated by gluons (g), also chargeless but *are* colored!

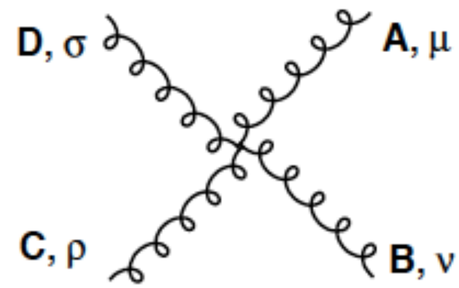
In QCD &
g → γ in QED



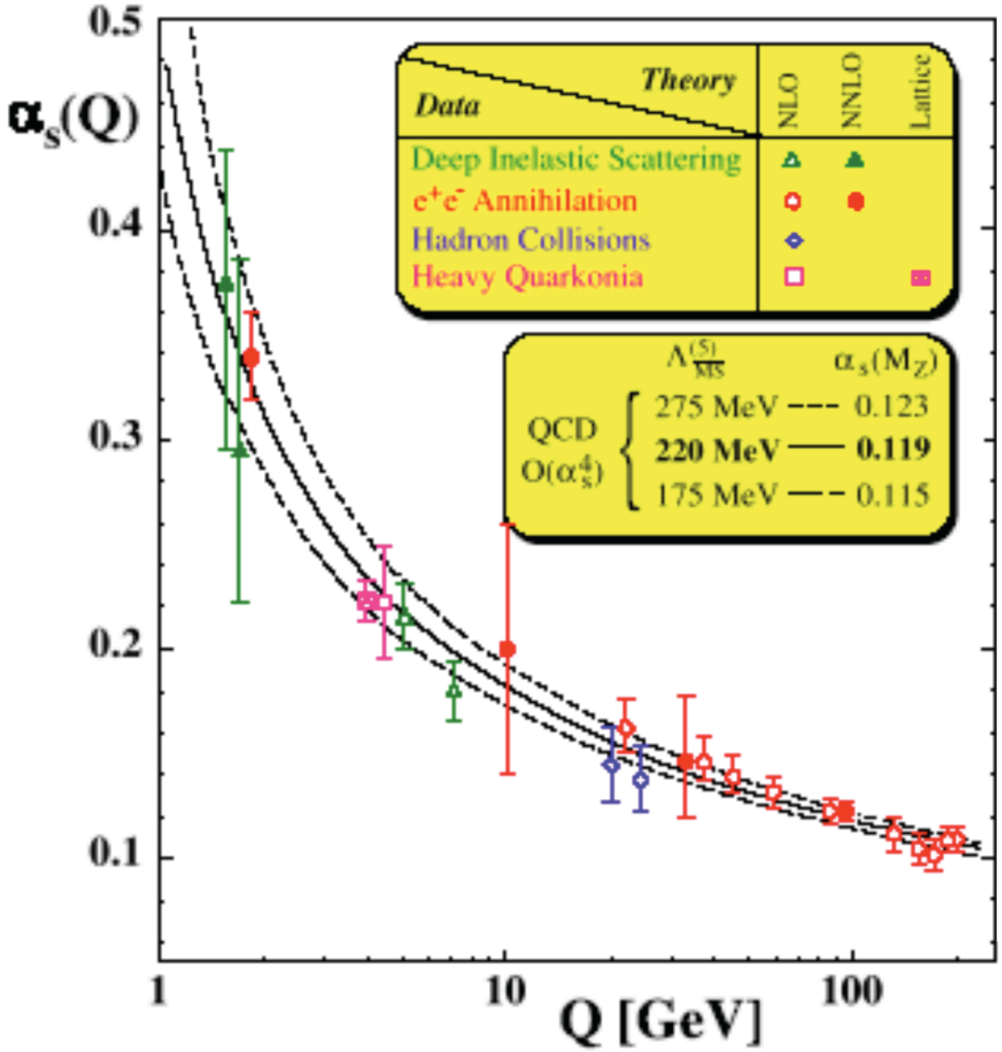


Only in QCD





What distinguishes QCD from QED?



Asymptotic Freedom ⇔ antiscreening

$$\text{QCD: } \frac{\partial \alpha_s(Q^2)}{\partial \ln Q^2} = \beta(\alpha_s) < 0$$

Compare

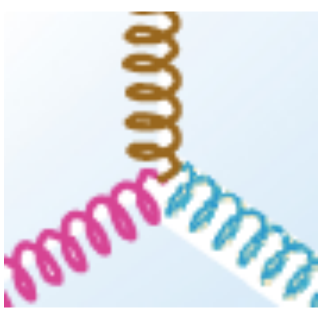
$$\text{QED: } \frac{\partial \alpha_{EM}(Q^2)}{\partial \ln Q^2} = \beta(\alpha_{EM}) > 0$$

D.Gross, F.Willczek, Phys.Rev.Lett 30, (1973)
H.Politzer, Phys.Rev.Lett. 30, (1973)

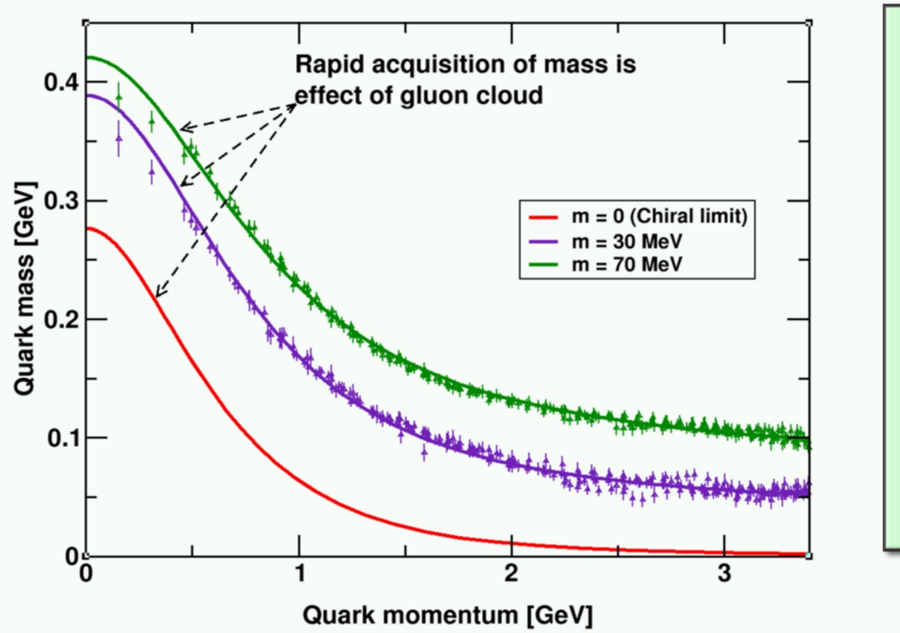
2004 Nobel Prize in Physics

Generation of mass in QCD

- 99% of the nucleon mass: self-generated gluon fields
- Similarity between p, n mass indicates ➔ **gluon self interactions** are identical & overwhelmingly important:



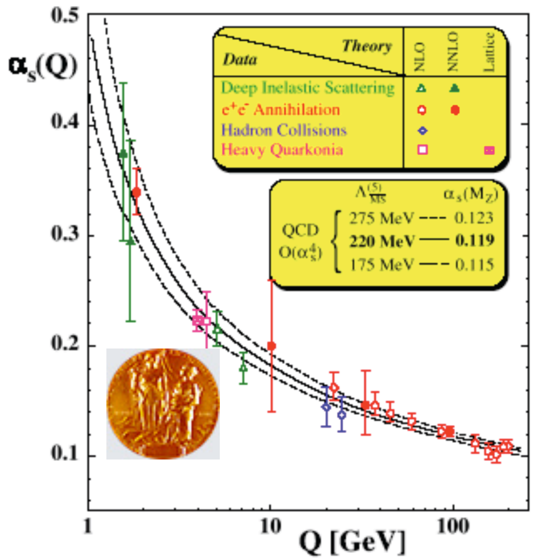
Bhagwat et al. arXiv:0710.2059 [nucl-th]



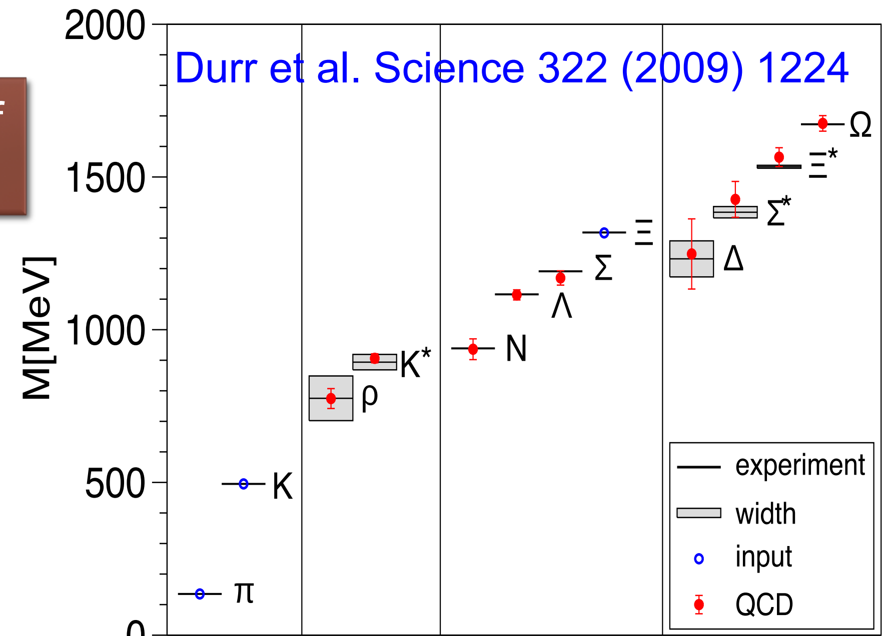
Success of QCD!

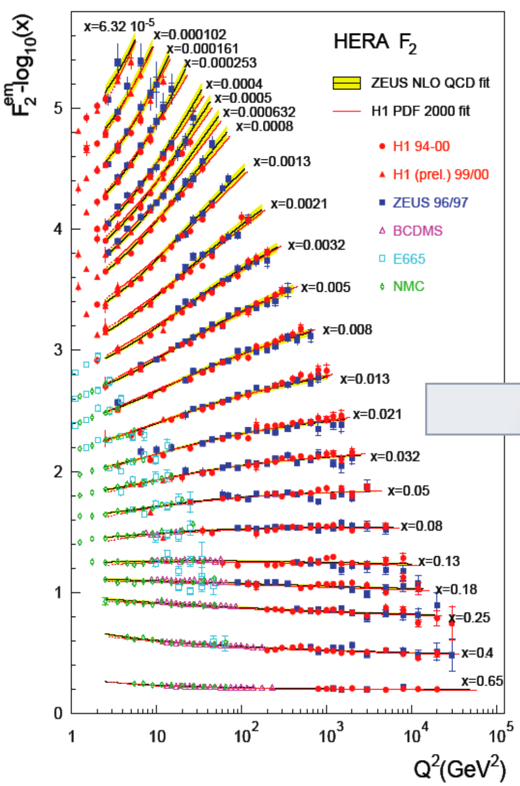
Higgs boson plays no role here.

Other successes of QCD: ➔



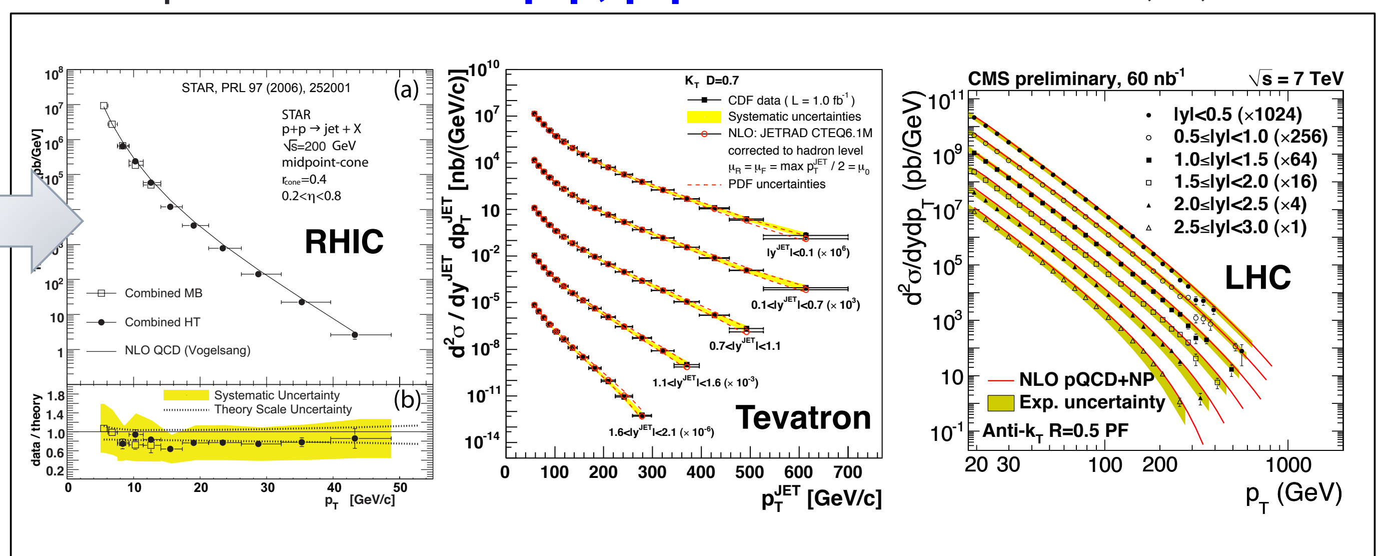
Successes of QCD





Measure **e-p** 0.3 TeV:

➔ Use pQCD Calculate **p-p, p-pbar Jet x-sctn** at 0.2, 2, 7 TeV



QCD

"Folks, we need to stop "testing" QCD
and start understanding it"

Yuri Dokshitzer

1998, ICHEP Vancouver, CA in his Summary Talk

2004 For the discovery of asymptotic freedom in QCD





QCD is no doubt correct, but there remain many unsolved, compelling questions!

- **How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?** How are these quark and gluon distributions correlated with overall nucleon properties, such as spin direction? What is the role of the orbital motion of sea quarks and gluons in building the nucleon spin?

- **Where does the saturation of gluon densities set in?** Is there a simple boundary that separates this region from that of more dilute quark-gluon matter? If so, how do the distributions of quarks and gluons change as one crosses the boundary? Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?

- **How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?** How does the transverse spatial distribution of gluons compare to that in the nucleon? How does nuclear matter respond to a fast moving color charge passing through it? Is this response different for light and heavy quarks?

Lets focus on:

“Spin, rotation…” always make us *think!*

1955
Bohr & Pauli
Trying to understand
The tippy top toy

Spin surprises in the last century….

- Stern and Gehrlach (1921)
  Space quantization associated with the direction
- Goudschmidt & Uhlenbeck (1926)
  Atomic fine structure & electron spin magnetic moment
- Stern (1933)
  Proton anomalous magnetic moment μ_N = 2.79
- Kusch (1947)
  Electron anomalous magnetic moment m_0= 1.00119
- Yale-SLAC Collaboration (Prescott et al.)
  Electro-Weak interference in polarized e-D DIS: parity non-conservation
- European Muon Collaboration (EMC) (1989)
  The Spin Crisis/Puzzle

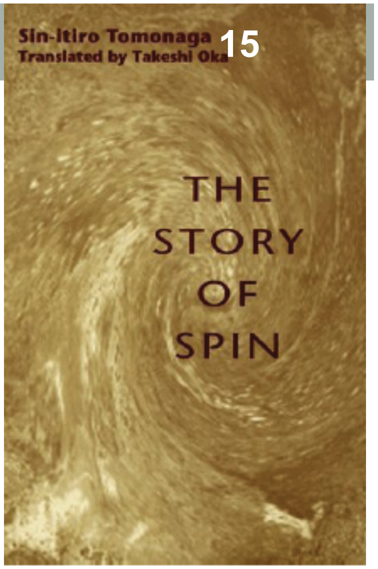
- It can be argued that indeed the 20th century was a

Century of Spin Surprises

- In fact, it has been noted:

"Experiments with "spin" have killed more theories than any other single physical property" E. Leader

"If theorists had their way, they would ban all experiments with spin" J. D. Bjorken



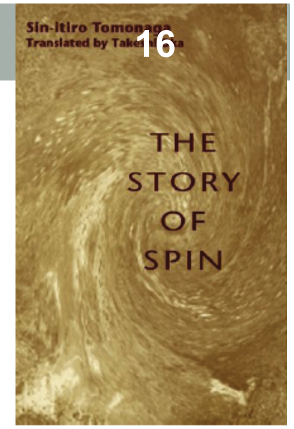
Brief history of spin:

- Measurement by Stern and Gerhlach (1922)
  "How a bad cigar helped reorient atomic physics"
  Physics Today,
  http://www.chem.harvard.edu/herschbach/How_a_bad_cigar.pdf

- Introduced as a fundamental observable of sub-atomic physics by Goudshmidt and Uhlenbeck (1926)
  P. Ehrenfest (reviewed the paper):
  "This is a good idea. Your idea may be wrong, but since both of you are so young without any reputation, you would not loose anything making a stupid mistake"

- Other principle players in this drama:
  Bohr-Sommerfield, Pauli, Dirac…. All in the 1920's

Story of Proton spin:



- Begins in 1927:
  - Hund, rotational part of specific heat of H_2 molecule
  - Hori: observed the band spectrum of H_2
  - Dennison: resolves the discrepancy between their results and concludes in a paper June 16, 1927 that:

    Proton is a fermion of spin ½

Today we know proton is a very complicated object:

Composite of quarks, gluons

It's spin (= ½) could get contributions from quarks, gluons and their possible orbital motion

Would it not be cool to look inside the Proton?

Spin… not just a discovery tool… but also a “precision” tool

$\mathrm{Sin}^2\Theta_W$: Weak mixing angle (Weinberg)

- Angle by which spontaneous symmetry breaking rotates the original W^0 and B^0 vector bosons in the theory to the observed Z^0 and γ

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

- It also gives the relation between the masses of W and Z bosons:

$$m_Z = \frac{m_W}{\cos\theta_W}$$

- The value varies as a function of momentum transfer Q, a key prediction of electroweak theory. It was important that it be measured at different scales directly, and has been measured….. Very precisely, using ***polarized*** electron beams.

High discovery potential !

"Spin" a precision tool…

$$\sin^2 \theta_W^{\text{eff}} = 0.23061 \pm 0.00047$$

- In the 1990's the world's most precise measurement of Weinberg angle:
  - SLD detector at SLAC with polarized electron beams, a factor 25 improvement compared to un-polarized beams
- In e^+e^- Colliders (e.g. LEP) the most precise beam-energy calibration comes from resonant depolarization of beams
- Spin played a crucial role in understanding the V-A nature of the Electro-Weak Lagrangian; demonstrated by the parity violation experiments

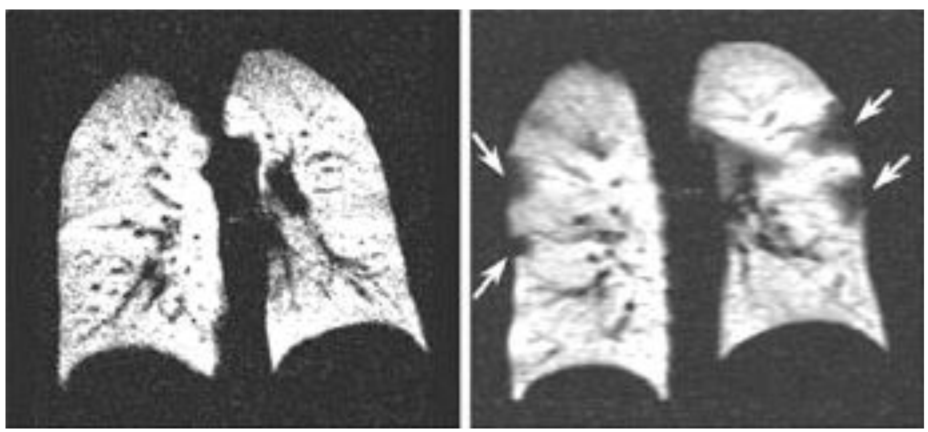
Spin is useful, not just in particle, nuclear physics… but also in your day to day life….

Applications of Spin ½ … MRIs

H-MRI of the chest, black area: Lungs

^{3}He-MRI Lung is visible in detail

Non Smoker



Smoker
Arrows: ventilation defects

Prof. Werner Heil, Institute of Physics, Johannes Gutenberg University

In these lectures we will go essentially along the time line…

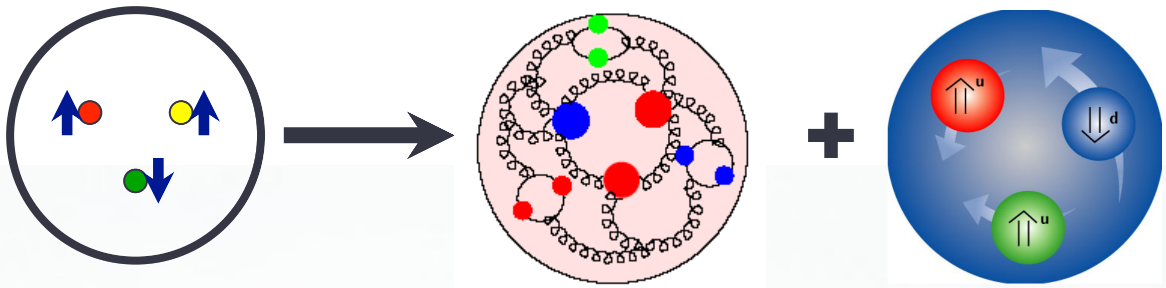
… explore how we thought of looking inside the proton

… how we learnt to explore the internal spin dynamics

… what is being done to understand the proton spin now

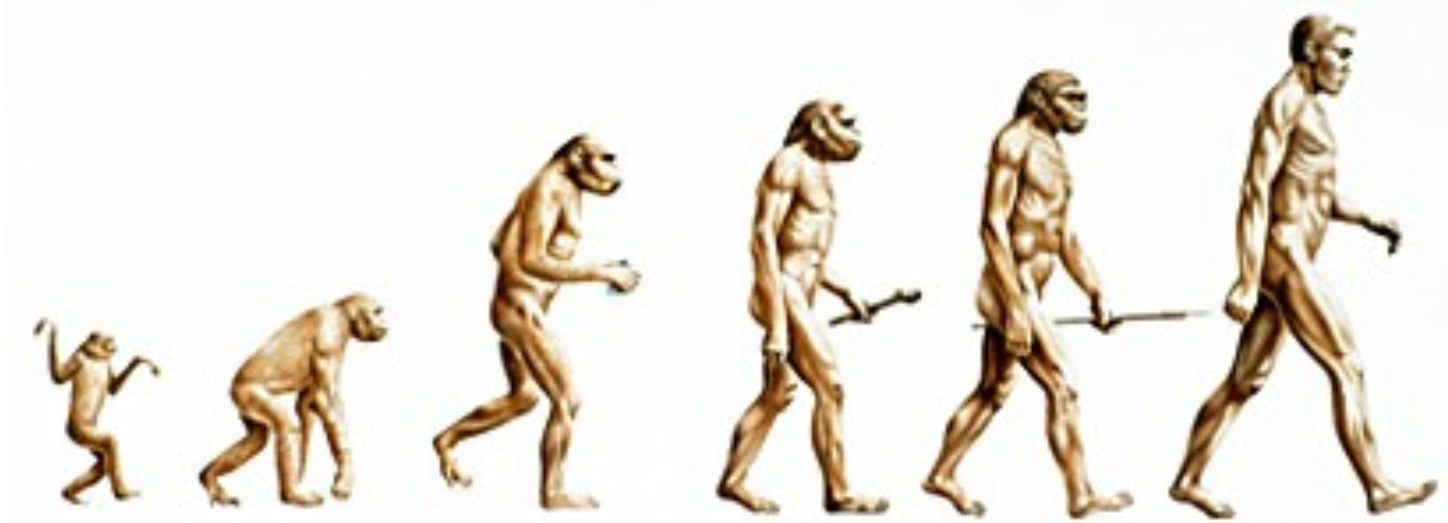
… what needs to be done in the future

Evolution: Our Understanding of Nucleon Spin



1980s

1990/2000s



We have come a long way, but do we understand nucleon spin?