The physics of the nucleon

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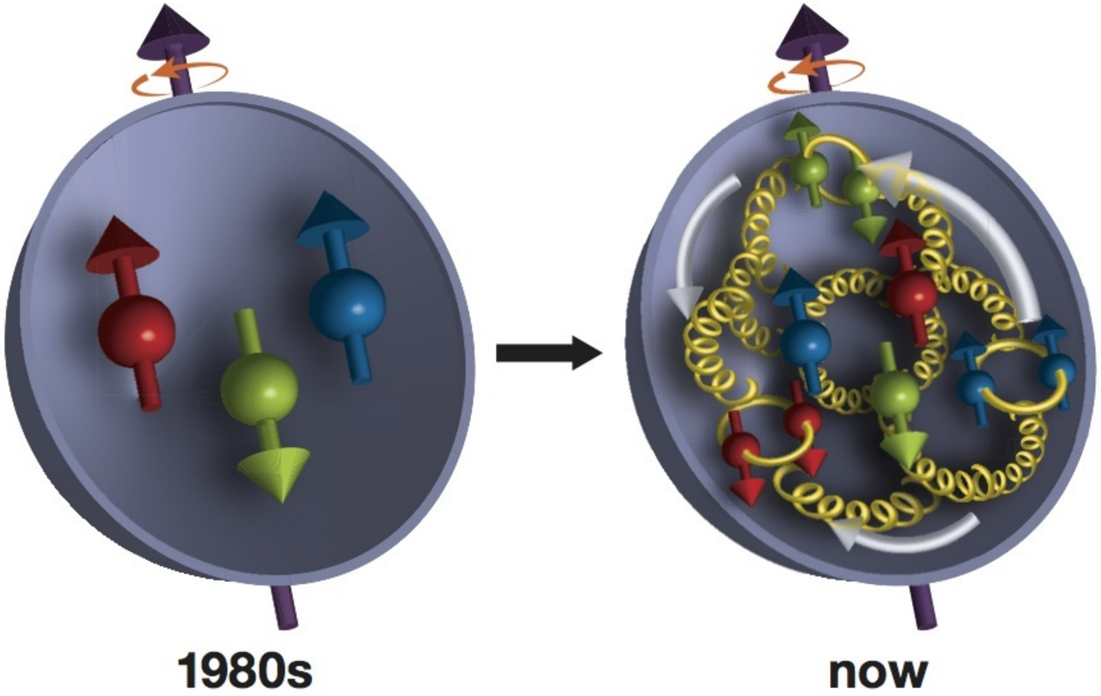
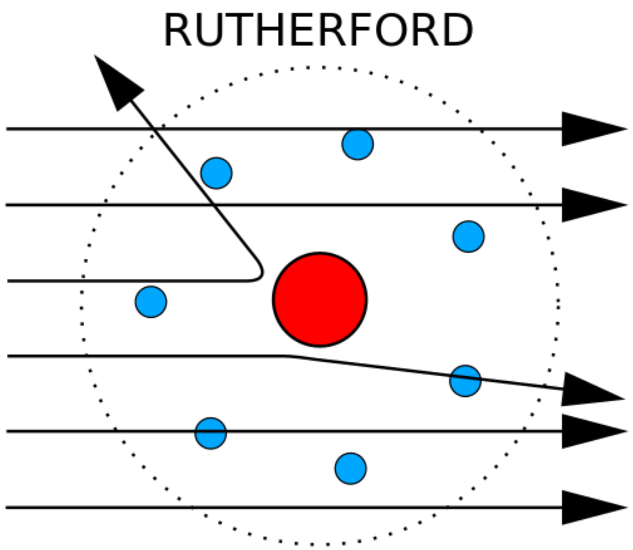


The origins

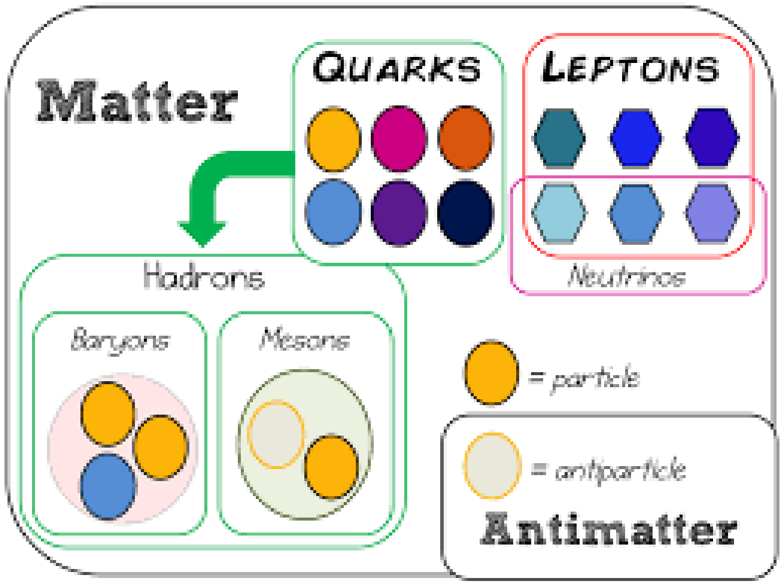
Nucleon is the term used to refer to **protons** and **neutrons**, i.e. **normal everyday massive matter**.

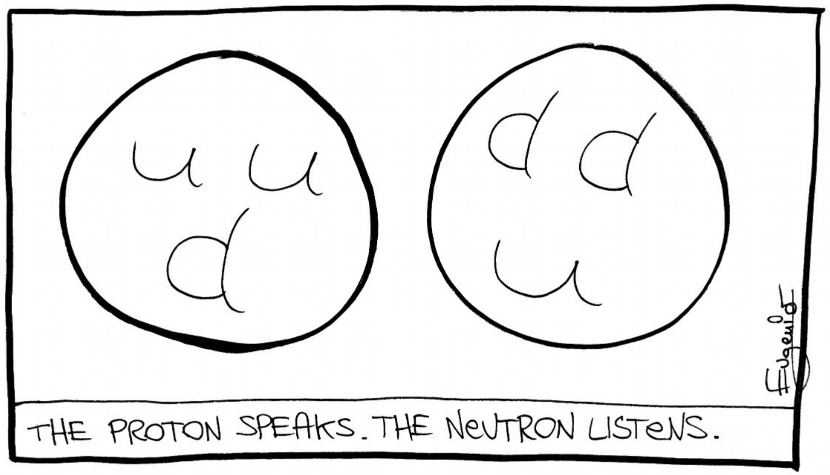
In the 1920's Ernest Rutherford started to use the word "proton" to refer to the hydrogen nucleus.



Contrary to what was believed at first, experiments revealed that the nucleons are not elementary, but **composite particles**.

How are nucleons inside?

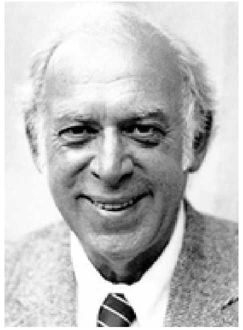
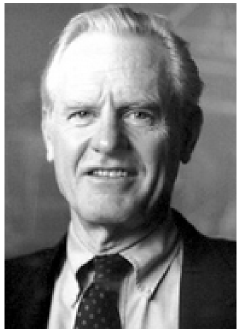
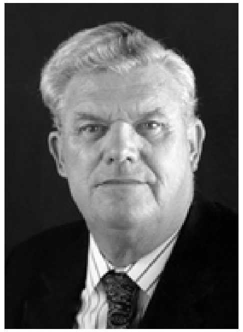




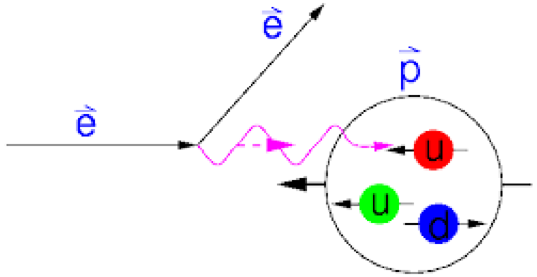
In the big zoo of composite particles, **nucleons** belong to the **baryon family**, while particles like **pions** and **kaons** belong to the **meson family**. Baryons and mesons form the **hadron species**.

↪But: **do they really look like this inside ???**

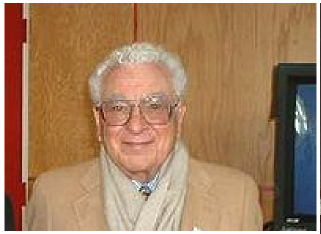
The evidence for quarks

1968: "Rutherford-like" experiments at SLAC gave first evidences of quarks as nucleon constituents.

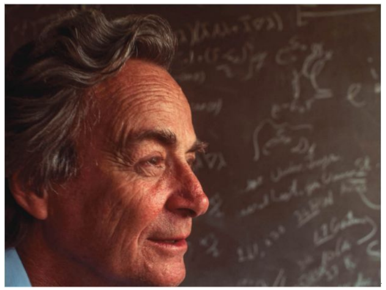
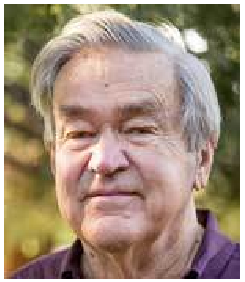


Friedman, Kendall and Taylor: Physics Nobel 1990




1964: Gell-Mann e Zweig proposed the model of quarks.

Physics Nobel 1969

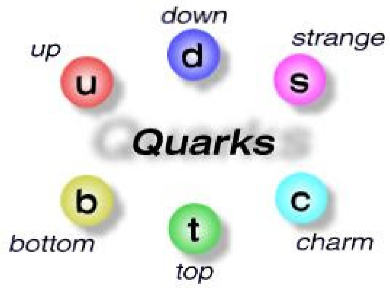



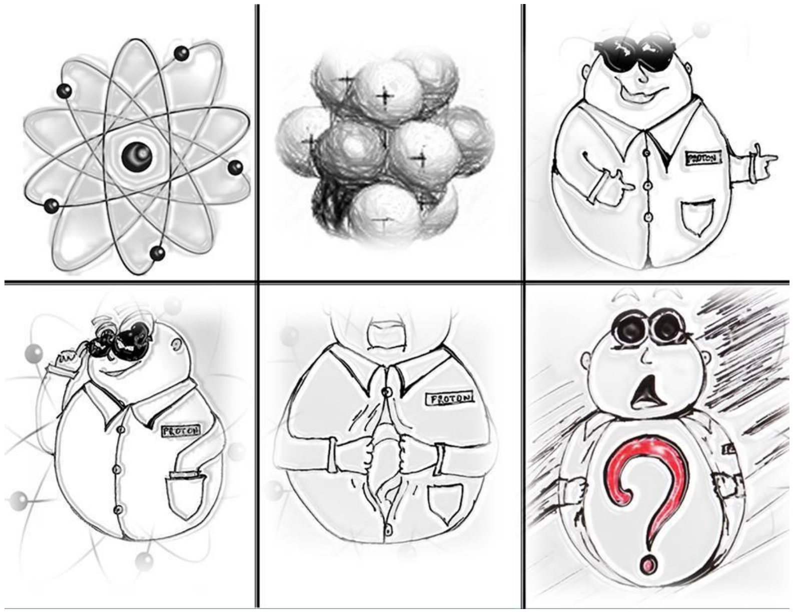
1969: Feynman and Bjorken proposed the parton model: at $p \to \infty$, baryons are made of 3 quarks, while mesons are made of quark-antiquark pairs.

Quark-Parton model

Quarks flavor and more

Quarks come in **6 different flavors**: down, strange and bottom (electric charge -1/3); up, charm and top (electric charge 2/3).



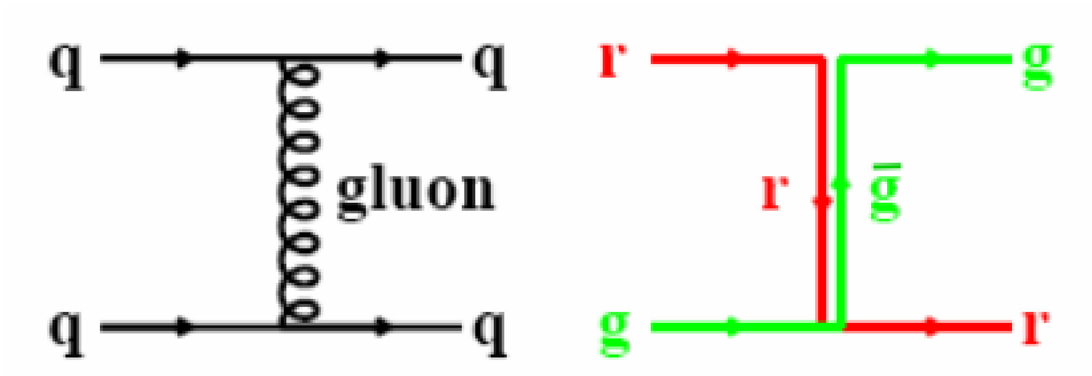


A proton **is not (u, u, d)**.

A proton is packed with quarks, antiquarks and gluons, but has 2 more u-quarks than u-antiquarks, and 1 more d-quark than d-antiquark – valence and sea quarks.

Quantum Chromodynamics

QCD is the theory of strong interactions that occur between quarks and gluons.



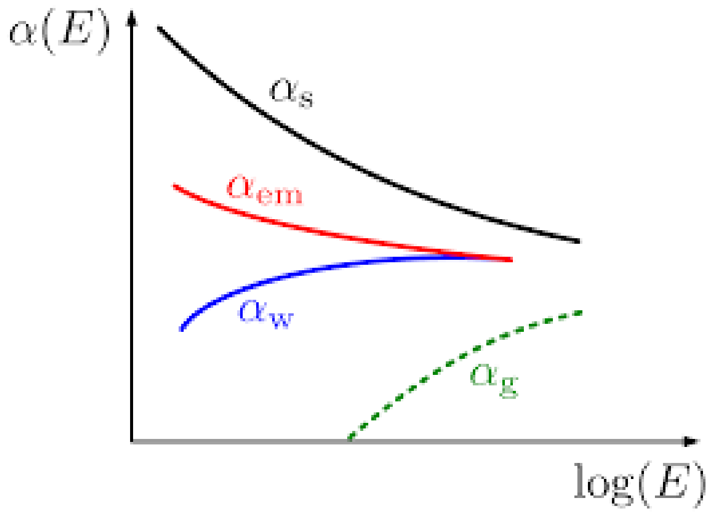
Gluons couple to color charge of quarks: R, G or B, with a strenght $\propto \sqrt{\alpha_S}$.

Hadrons can only be found in "colorless state" (i.e. color-singlet state):
color-anticolor (mesons), or red-green-blue (hadrons).

Gluons carry color themselves – reason why they can interact with each other.
They exist in 8 possible states of color-anticolor.

Running coupling α_s

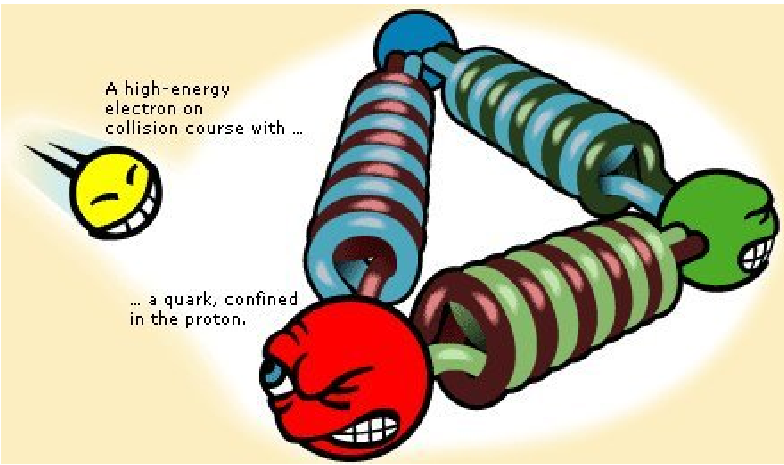
Interaction	QED	QCD
Conserved charge	electric charge e	colour charges r, g ,b
Coupling constant	$\alpha = e^2/4\pi$	$\alpha_S = g_S{}^2/4\pi$
Gauge boson	Photon	8 gluons
Charge carriers	fermions ($q \neq 0$)	quarks gluons

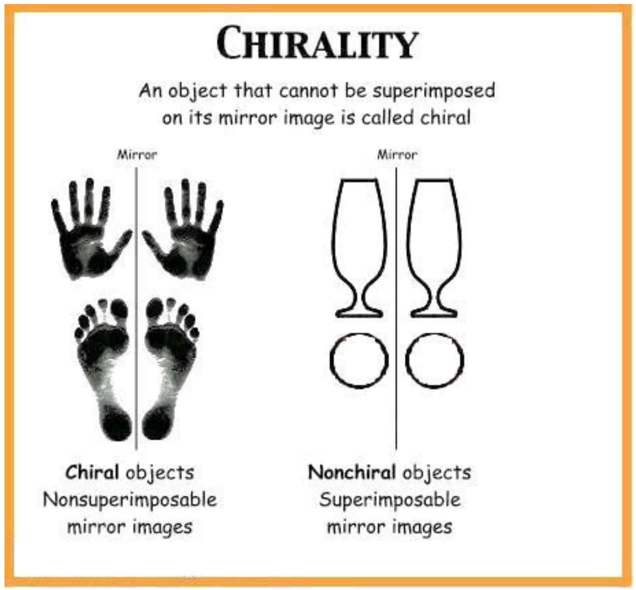


The more we try to separate a pair $q - \bar{q}$, the stronger gets the force glueing them together.

Main features of QCD

- **Confinement**
  Color charged particles – the quarks – cannot be observed isolated. The energy of the gluon field between 2 quarks which are thorn apart is enough to create another pair.
- **Asymptotic freedom**
  At small distances and large energies, α_S diminishes logarithmically, and quarks and gluons behave as quasi-free particles.
- **Chiral symmetry breaking**
  Due to the spontaneous symmetry breaking of the QCD vacuum, quarks confined in hadrons have a large "dynamical mass" (constituent mass).





Have a look "inside" the proton

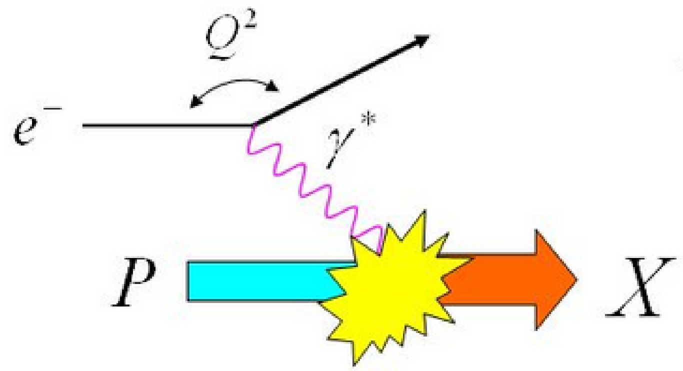
With energetic enough probing-particles, one gets enough **resolving power** to see the proton structure.

Deep Inelastic Scattering: $ep \to e'X$

A high-energy lepton hits a nucleon and gets deflected ("scattering").

The nucleon target absorbs part of the kinetic energy ("inelastic"), and might even break to new particles.

The very high energy of the lepton (thus "deep") means short wavelenght to probe distances much smaller than the nucleon dimension itself.



- photon virtuality : $Q^2 = -q^2$
- Bjorken-x: fraction of longitudinal momentum carried by the struck quark wrt his parent nucleon

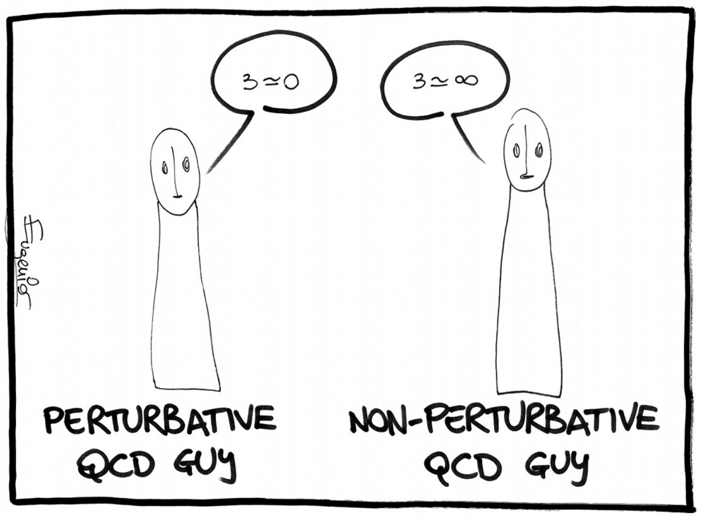
The DIS cross-section

The probability for a given reaction to occur is proportional to its **cross-section**.

For large enough energies (large Q^2), the DIS cross-section can be **factorized** as:

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

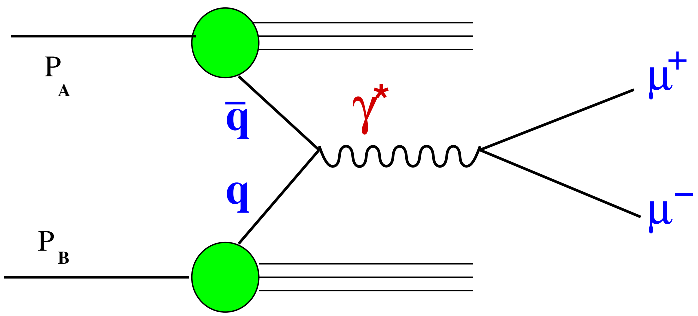
- $f_j(x, Q^2)$: **parton distribution function (PDF)** of the struck quark in the nucleon – **must be measured experimentally**
- $\hat{\sigma}_{\gamma^* j}(x, Q^2, ...)$: partonic cross-section of the virtual photon interaction – **can be calculated**



Another way to look "inside"

Drell-Yan process: $q\bar{q} \rightarrow \gamma^* \rightarrow l^+ l^- X$

In the high energy collision of 2 hadrons, the process of quark-antiquark annihilation produces a virtual photon, that converts in a pair of lepton-antilepton in the final state.



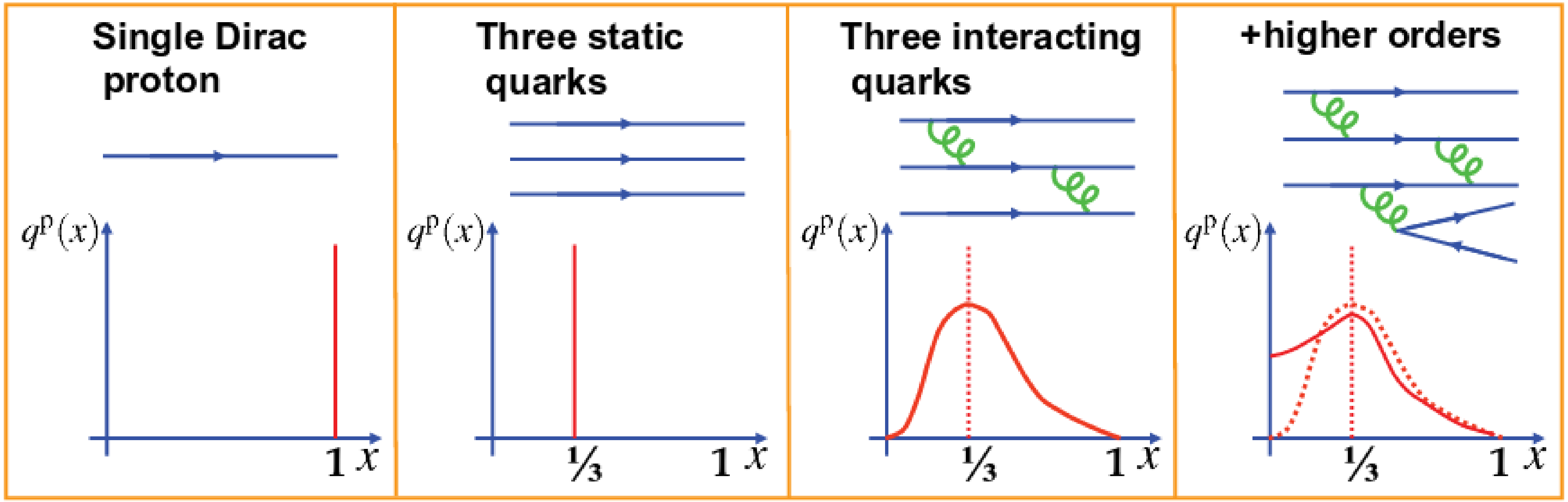
The hard process is characterized by the 2 quantities:

- $Q^2 \equiv M_{l^+l^-}$
- large dilepton $p_T \approx 1$ GeV/c

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

PDFs intuitively

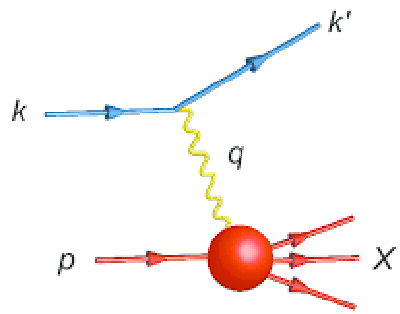
The fraction of momentum carried by each of the proton constituents:



How are PDFs determined?

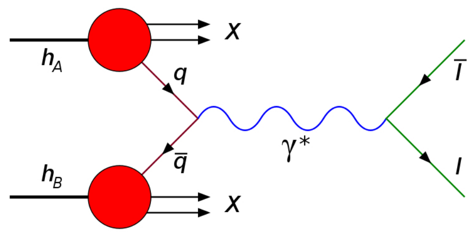
PDFs are universal – all available measurements are used together, in **global fits to world data**: (SI)DIS, pp, πp, e^+e^-, ...

DIS



$\sigma \propto PDF$

Drell-Yan



$\sigma \propto PDF \otimes PDF$

PDFs: Fractions of proton momentum carried by the constituent partons:

$$f_u = \int_0^1 dx[xu(x) + x\bar{u}(x)];\ f_d = \int_0^1 dx[xd(x) + x\bar{d}(x)]$$

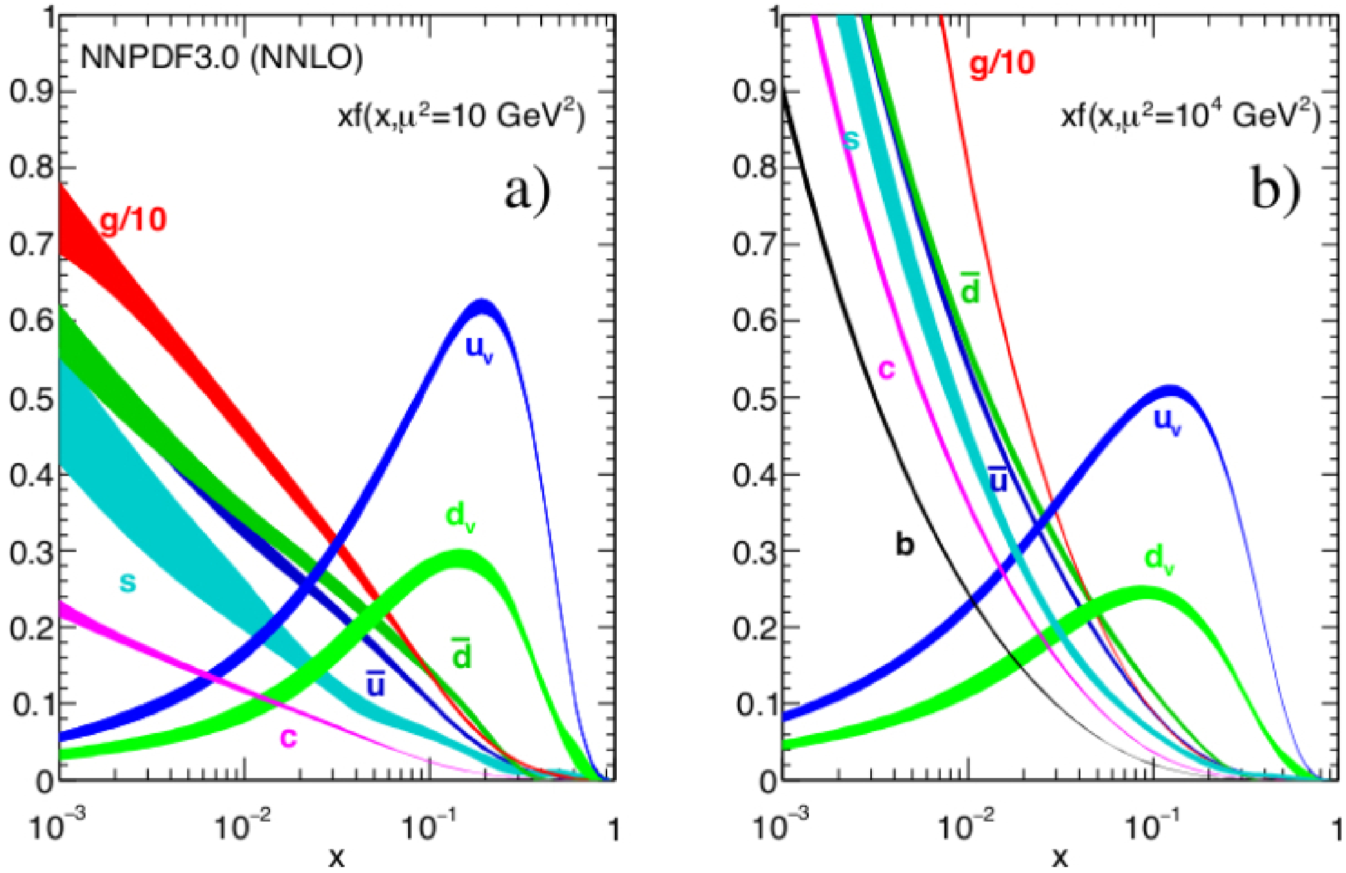
Experimentally: $f_u \approx 0.36$ and $f_d \approx 0.18$

$\hookrightarrow$ u-quarks in the proton carry twice as much momentum than d-quarks.

$\hookrightarrow$ In total quarks carry only ≈50% of the proton momentum. The rest is carried by gluons!

How well are proton PDFs known?

Proton PDFs NNPDF3.0 global analysis, Particle Data Group (PDG) 2016 review.



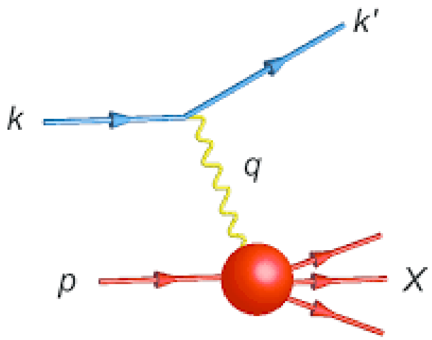
$$\mathbf{u_v = u - \bar{u}}$$

And how do quarks hadronize?

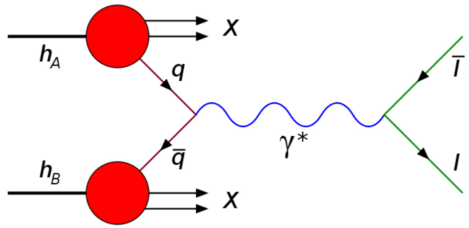
In the reverse process of Drell-Yan, e^+e^- annihilation, we care about the way the hard quarks produced end-up in detectable hadrons.

$\hookrightarrow$ another **universal**, **non-perturbative** object, that needs to be measured experimentally: **fragmentation functions**

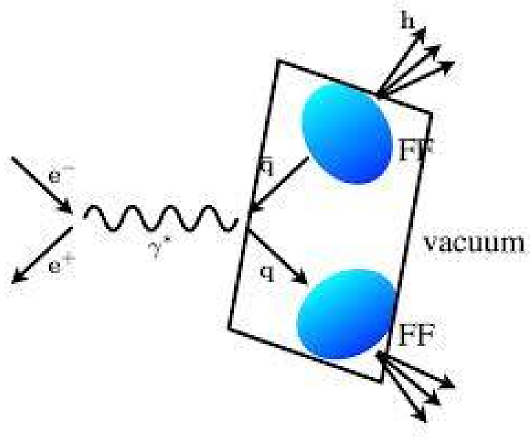
SIDIS



Drell-Yan



e^+e^-

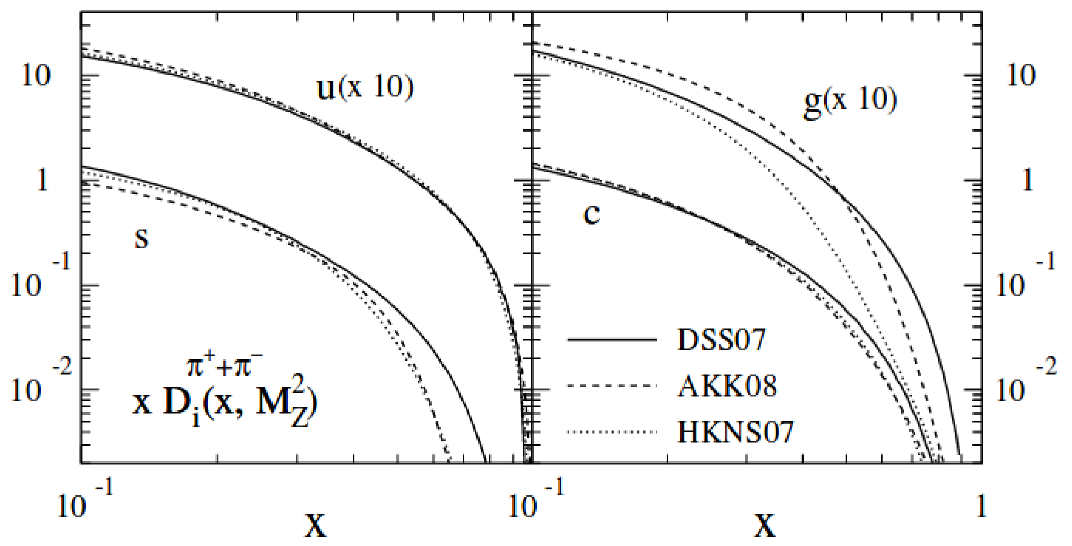


$\sigma \propto PDF \otimes FF$ $\sigma \propto PDF \otimes PDF$ $\sigma \propto FF$

FF – Fragmentation Function $D_i^h(z, Q^2)$: probability function that a quark i fragments into a hadron h carrying a fraction z of momentum.

Fragmentation functions

- **FF are universal**.
- They are **non-perturbative** objects.
- They are extracted from global fits to world data on e^+e^-, semi-inclusive DIS (aka SIDIS, i.e. DIS where final state hadrons are identified), and pp collisions.
- Parallelism with PDFs: We distinguish favored FFs, just as we talk of valence PDFs; and unfavored FFs, as in the case of sea PDFs.



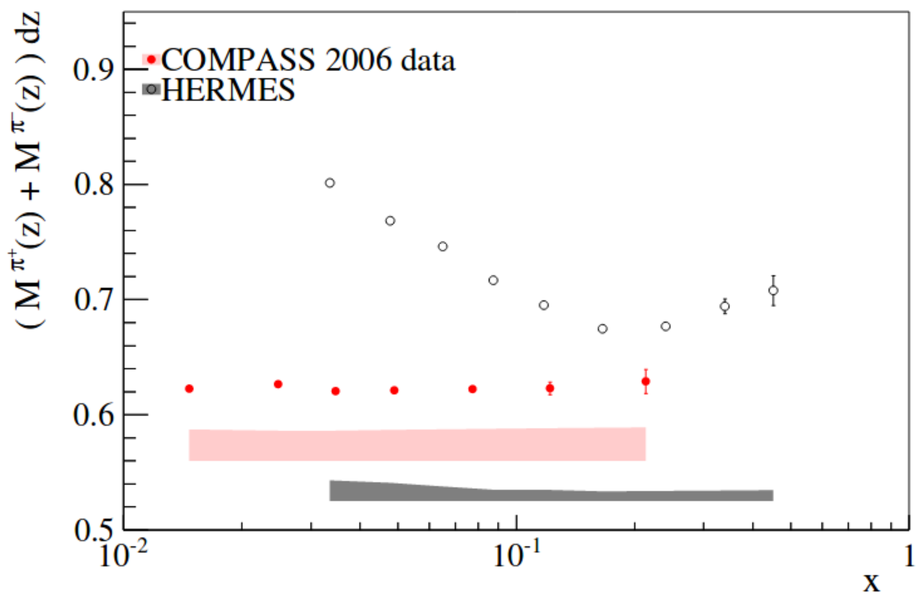
Extracting fragmentation functions

The multiplicity of a hadron species M^i is the number of hadrons produced per DIS event. At leading order:

$$\frac{dM^i(x,Q^2,z)}{d(x,Q^2,z)} = \frac{\sum_q e_q^2\ q(x,Q^2)\ D_q^i(z,Q^2)}{\sum_q e_q^2\ q(x,Q^2)}$$

where e_q is the electric charge of a quark flavor q and i is a given hadron species.

Measuring multiplicities seems simple, but might lead to puzzling discrepancies:

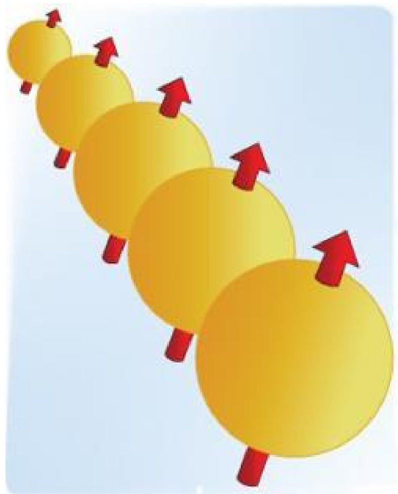


The proton spin

...But this is just the beginning of the PDFs/FFs story.

Protons are "**spin 1/2**" particles. Exactly **1/2**.

When their spin is forced to align in a given direction (by an external magnetic field) – i.e. in a material with polarized protons – different PDFs can be measured: **the polarized PDFs**.



The spin of particles

Wikipedia: spin is an intrinsic form of angular momentum carried by elementary particles, composite particles (hadrons), and atomic nuclei.

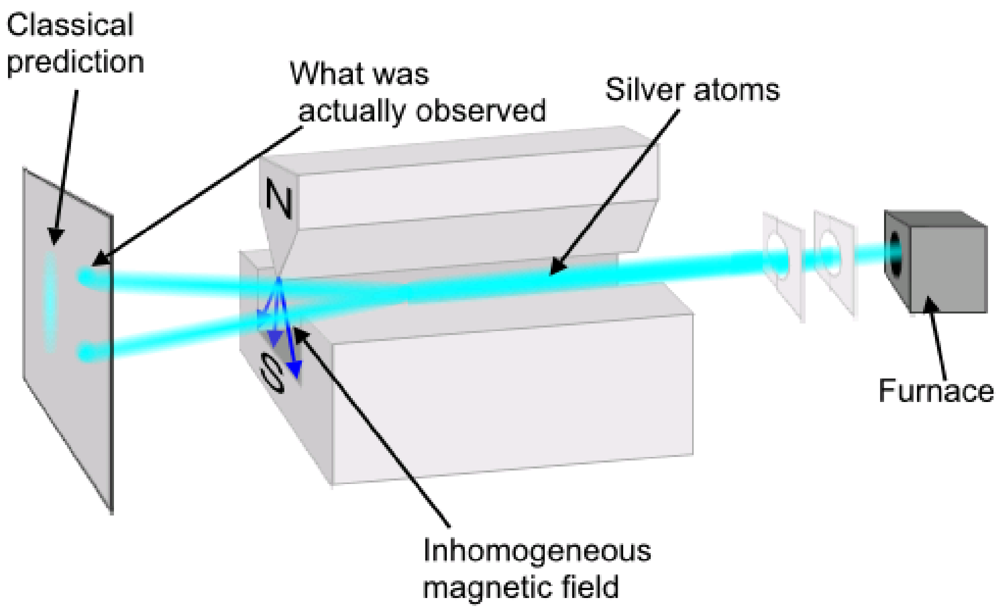
It is a concept from **quantum mechanics** – it has no parallel in classical physics.

The usual **analogies** are not really correct, but they help us understand better this non-intuitive reality.

Experimental evidence for spin

1922: Stern-Gerlach experiment

A beam of silver atoms $_{47}$Ag crossing a non-uniform magnetic field impinges in a photo-sensitive plate. The expected result was a continuum, resulting from the magnetic moment of the electron (an electric charge "looping" around a nucleus). But the obtained result was a pattern of 2 lines!!!



The spin concept historically

1924: Pauli was the first to propose the concept of spin. From 1927 he developed the mathematical theory tht allowed to understand electron spin and the Stern-Gerlach experimental result.

Physicists discussing spin, possibly at the famous Solvay conference in 1927.

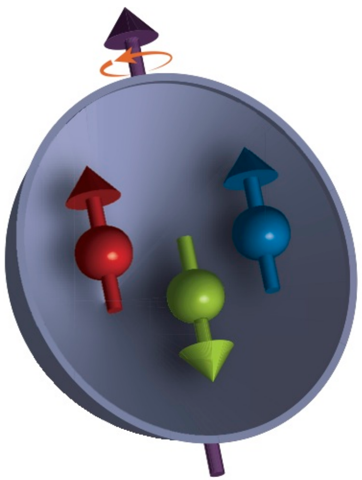
Pauli and Bohr demonstrating spin toy at the inauguration of the Institute of Physics at Lund, Sweden, 1954.

The spin of elementary particles

Spin is a **fundamental property of elementary particles**, just like mass, electric charge or color charge.

According to their spin, we classify particles as fermions or bosons:

	Fermions	Bosons
spin	half-integer	integer
statistics	Fermi-Dirac	Bose-Einstein
	electrons	photon
	neutrinos	$W^{\pm}$
	muons	Z
	taus	gluons
	quarks	Higgs
	...	...



The nucleon is a composite particle. Nevertheless, it behaves as a fermion, with spin 1/2. How come?

↪ The most obvious answer would be: The proton spin 1/2 is due to the spin of its valence quarks.

The spin crisis

In the 1970's the first polarized DIS experiments started.

EMC experiment: longitudinally polarized muon beam in a longitudinally polarized proton target.

- In 1988, they measured the sum of all quark and antiquark spins: $\Delta\Sigma = 0.12 \pm 0.09 \pm 0.14$ – **compatible with zero**!

↪Total contradiction with the prediction from the naive parton model: $\Delta\Sigma = 1$.

A spin puzzle

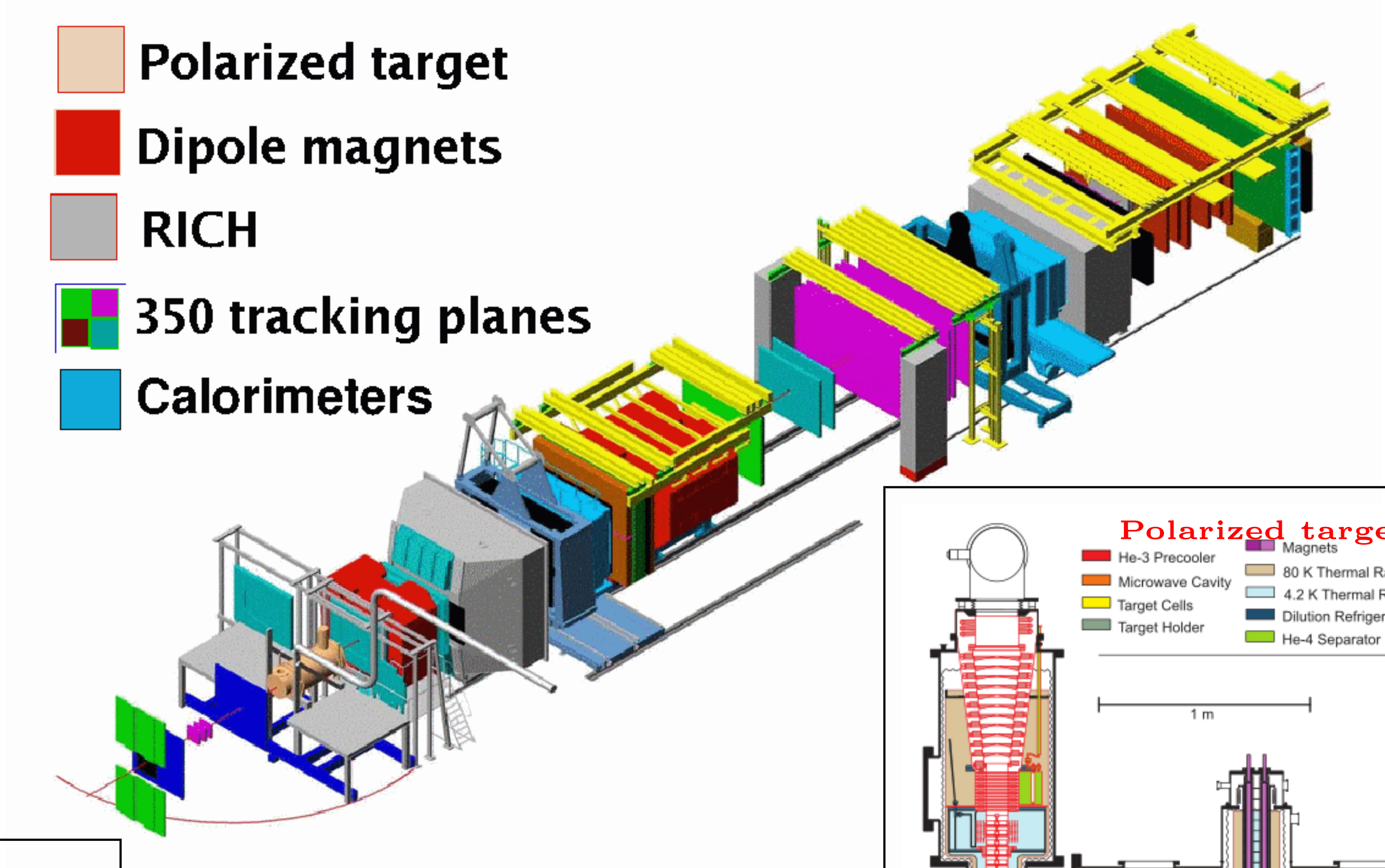
If protons are made of interacting quarks and gluons, a natural decomposition into possible contributions is:

$$\textbf{Nucleon spin: } \frac{1}{2} = \frac{1}{2}\,\Delta\Sigma + \Delta G + \langle\, L_Z \,\rangle$$

$\Downarrow$ quarks spin — $\Downarrow$ gluons spin — $\Downarrow$ orbital ang. mom.

Each of these contributions must be measured experimentally $\longrightarrow$ measuring polarized PDFs... and more.

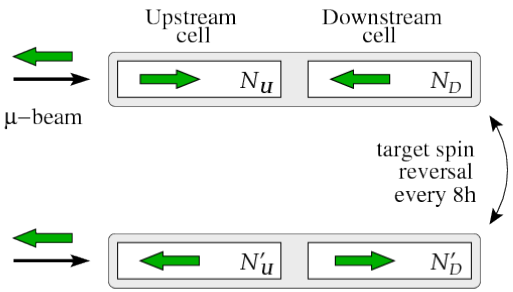
COMPASS: an experiment for spin physics

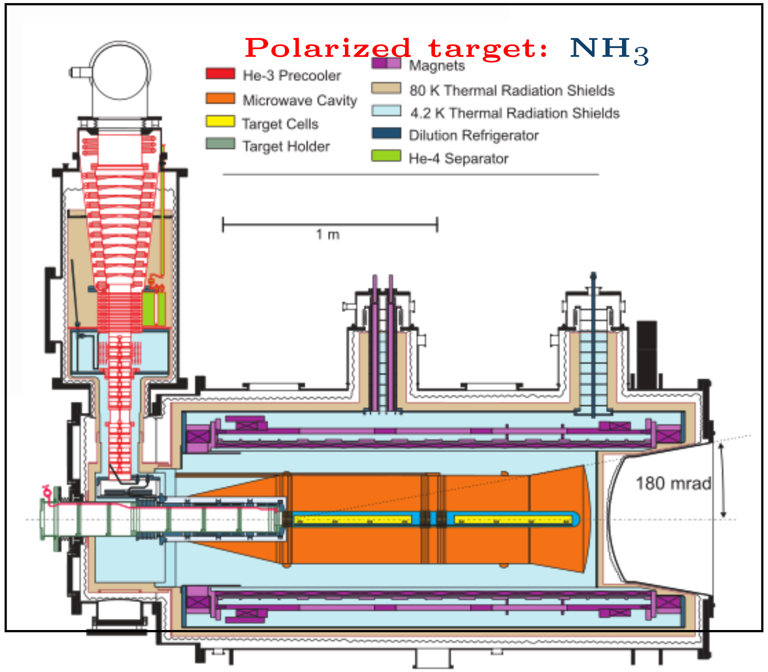


μ^+ beam,

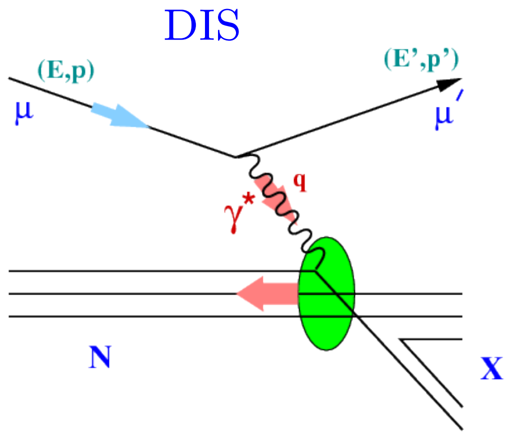
P_B=-76%

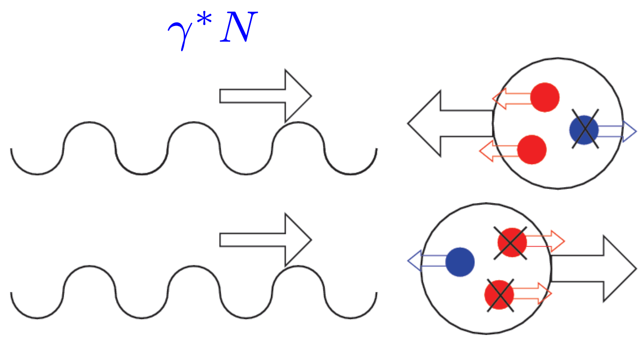
@160/200 GeV/c





Measuring the quarks spin contribution





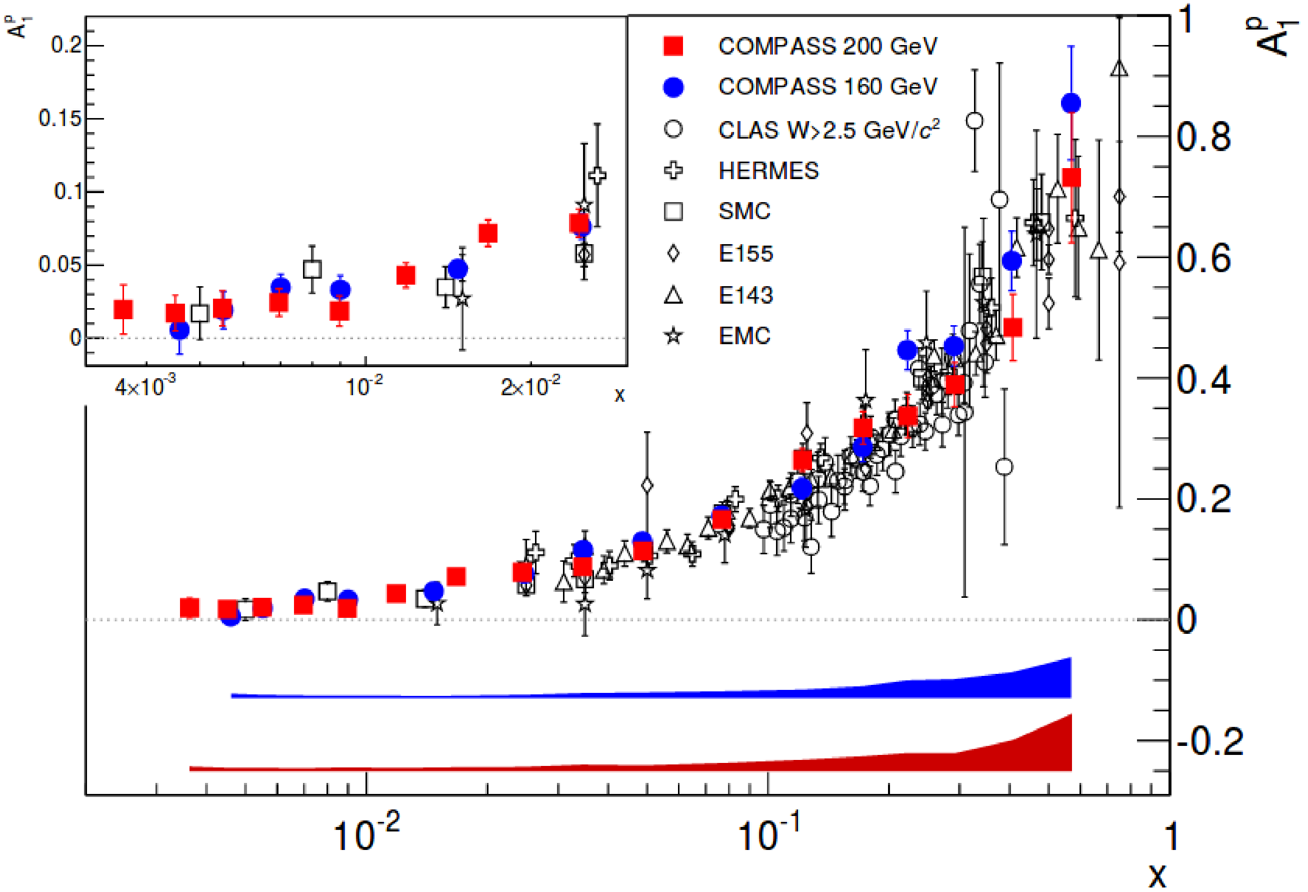
$$\frac{d^2\sigma}{d\Omega dE'} \sim \underbrace{c_1 F_1(x,Q^2) + c_2 F_2(x,Q^2)}_{\text{spin independent}} + \underbrace{c_3 g_1(x,Q^2) + c_1 g_2(x,Q^2)}_{\text{spin dependent}}$$

To access the **helicity function** g_1 we measure double longitudinal spin asymmetries.

The μ-proton asymmetry is measured from the difference between cross-sections from 2 opposite spin configurations:

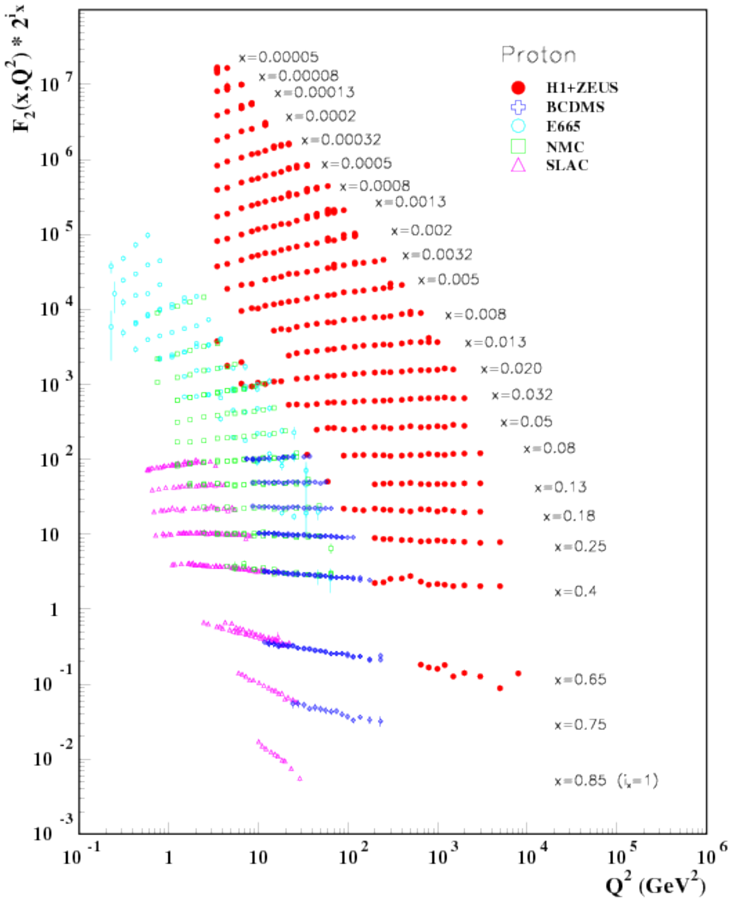
$$A^{\mu N} \propto \frac{N^{\leftrightarrows} - N^{\leftleftarrows}}{N^{\leftrightarrows} + N^{\leftleftarrows}}$$

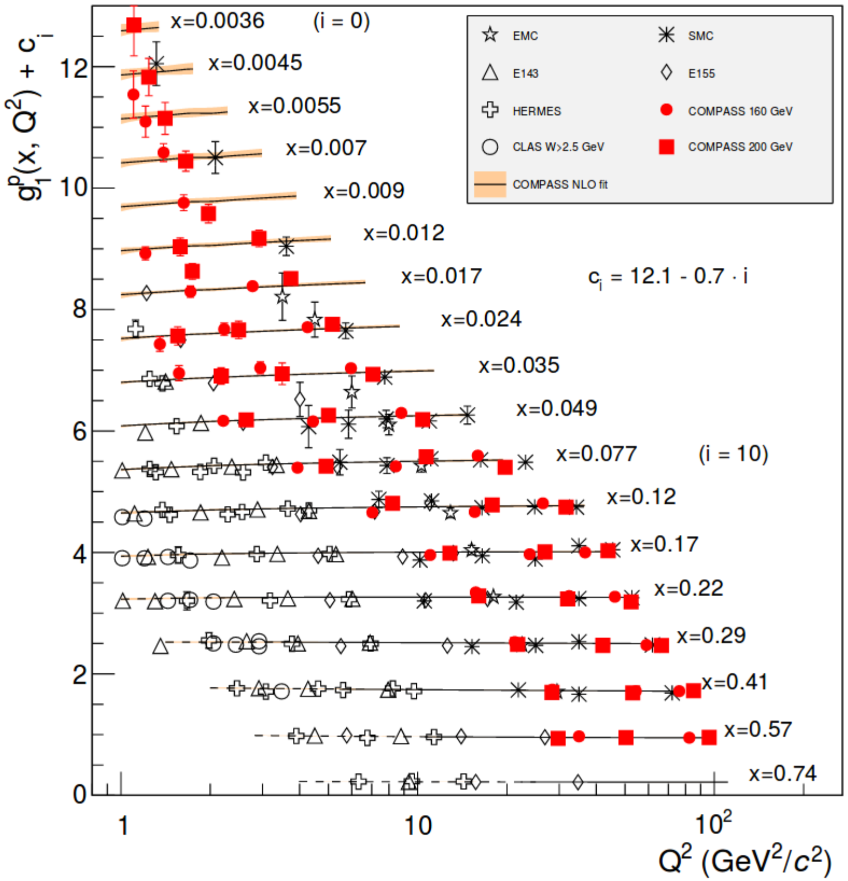
Double longitudinal Asymmetry A_1^p



$$g_1^p \propto A_1^p \; F_2$$

Helicity function g_1^p





From the first moment of g_1 one obtains $\Delta\Sigma$, the contribution of quarks spin to the spin of the proton

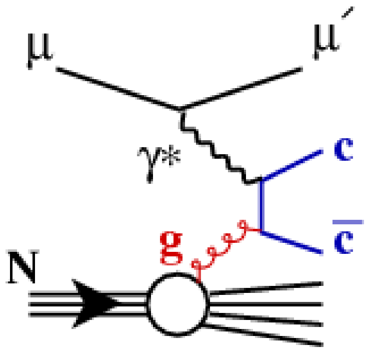
$$\Delta\Sigma\text{: } 0.26 \text{ - } 0.36 \text{ at } Q^2 = 3\ (\text{GeV/c})^2$$

The gluon spin contribution

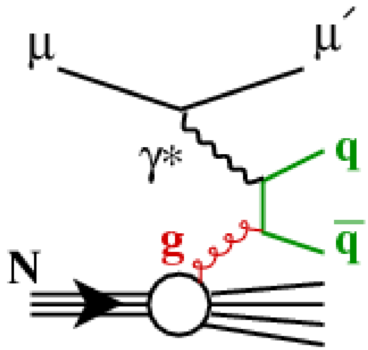
The direct measurement of ΔG is of crucial importance for the understanding of the spin puzzle.

$\hookrightarrow$ Access it via the **photon-gluon fusion** (PGF) process.

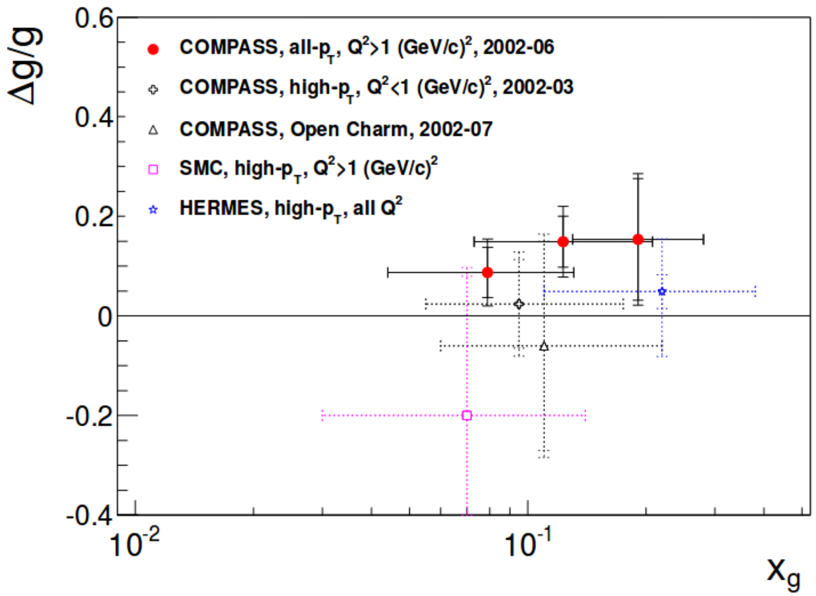
Open-charm production



high p_T hadron pairs



Results



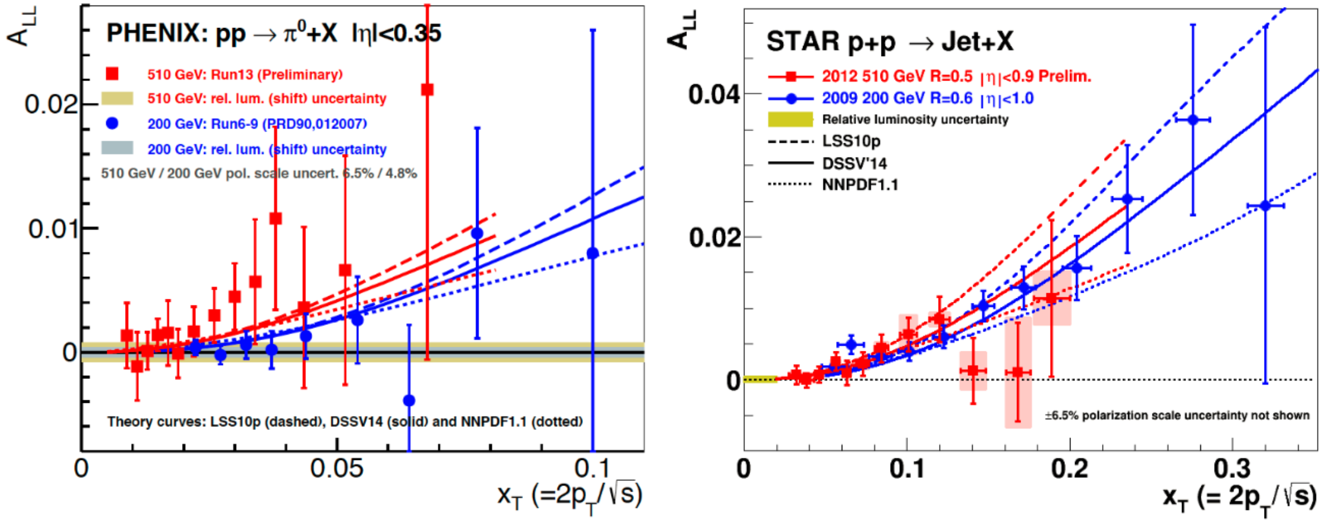
Spin asymmetries of the produced hadrons are proportional to the gluon spin contribution ΔG.

Towards a gluon polarization determination

Identically, at the RHIC Collider with polarized proton beams, they measure the spin asymmetry of produced π^0 or of jets.

$$A_{LL} = \frac{1}{P_B \cdot P_Y} \frac{N^{++} - r \cdot N^{+-}}{N^{++} + r \cdot N^{+-}} \qquad r = \frac{L^{++}}{L^{+-}}$$

Combined published data and recent results of asymmetries

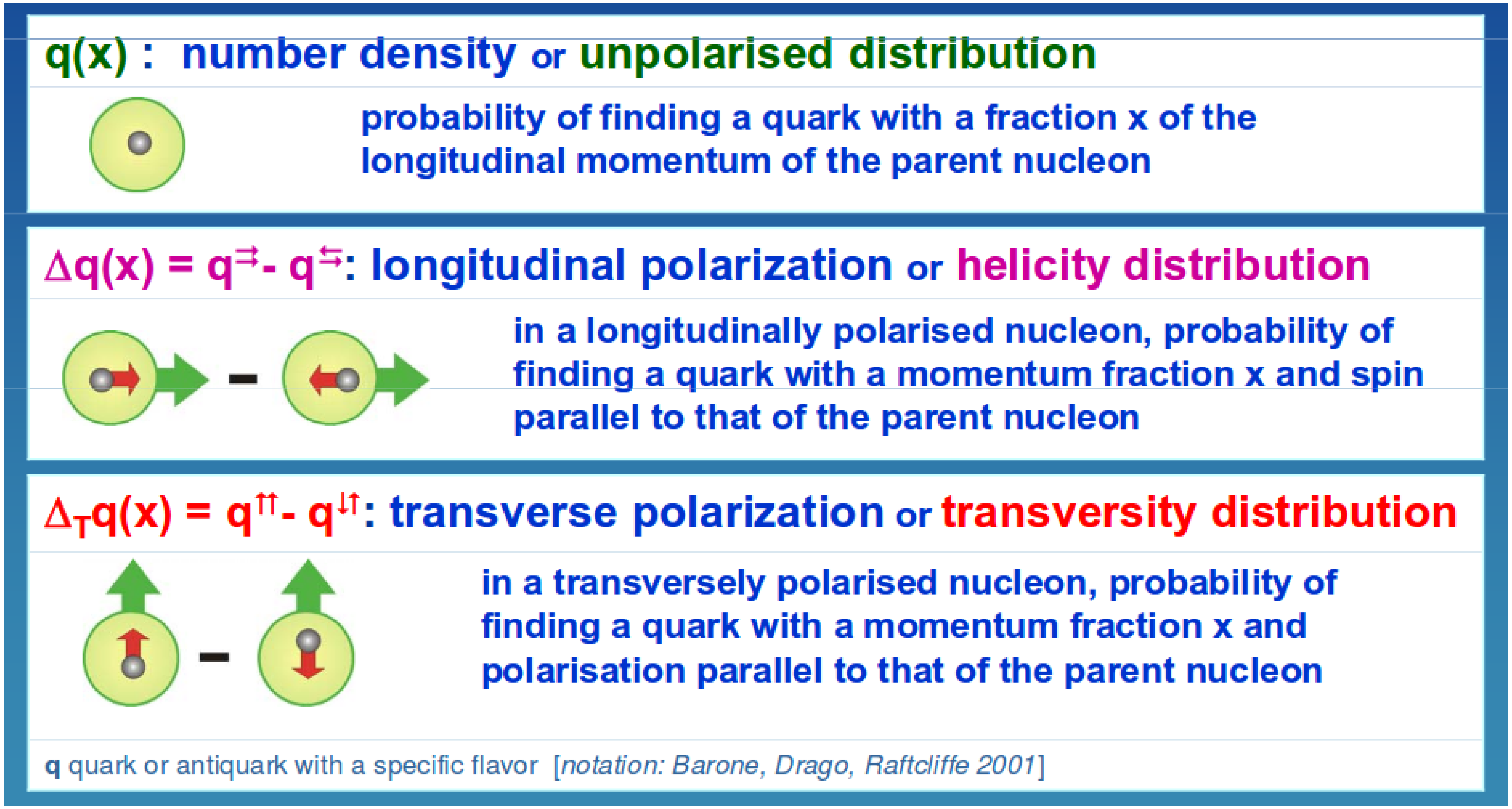


Indirect: the global PDF analyses (theory curves) determine which gluon contribution best fits the data.

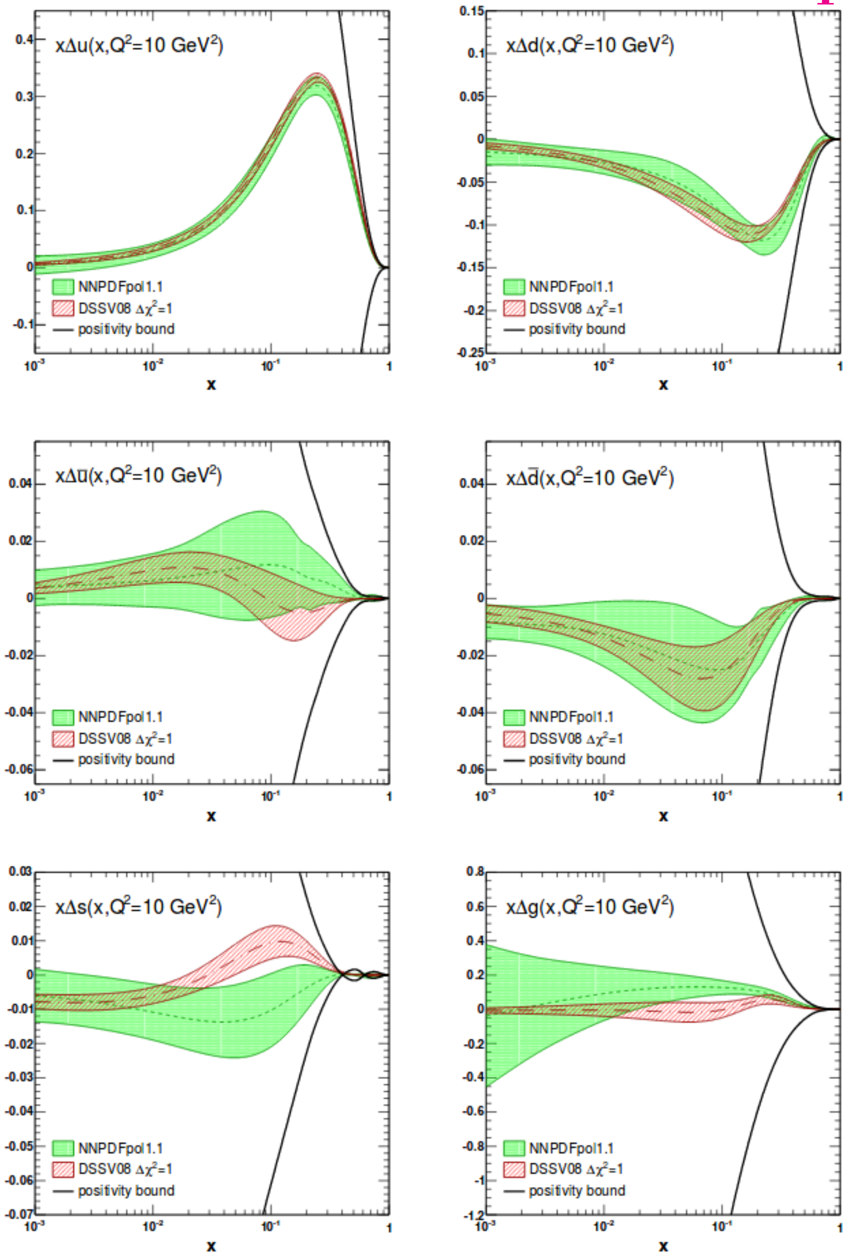
DSSV14 global analysis (with 2009 RHIC data): $\int_{0.05}^{1} dx\ \Delta g(x) = 0.2^{+0.06}_{-0.07}$

Polarized PDFs

In the **collinear case** (of struck quark wrt parent proton) at leading order, three structure functions (i.e. linear combinations of PDFs) are needed to fully describe the nucleon structure:



Recent polarized PDFs



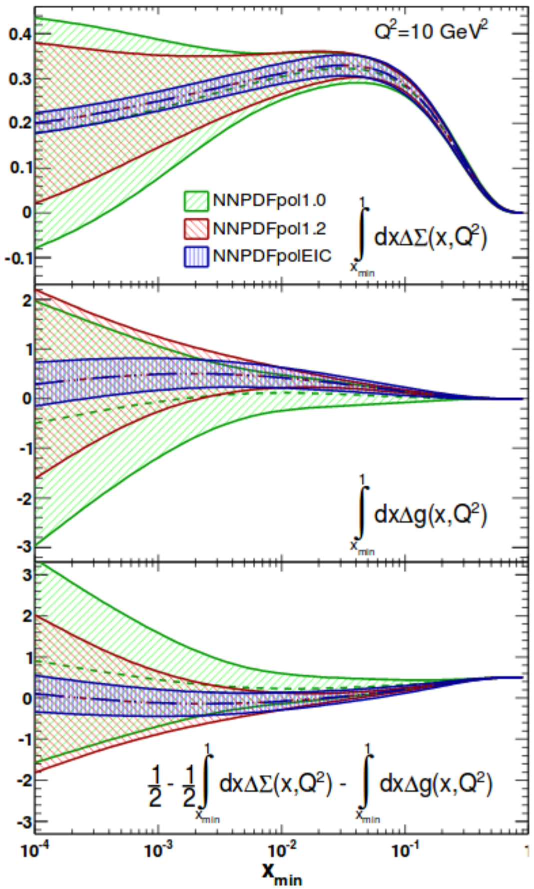
NNPDFpol 1.1,
Nucl.Phys. B887 (2014) 276-308

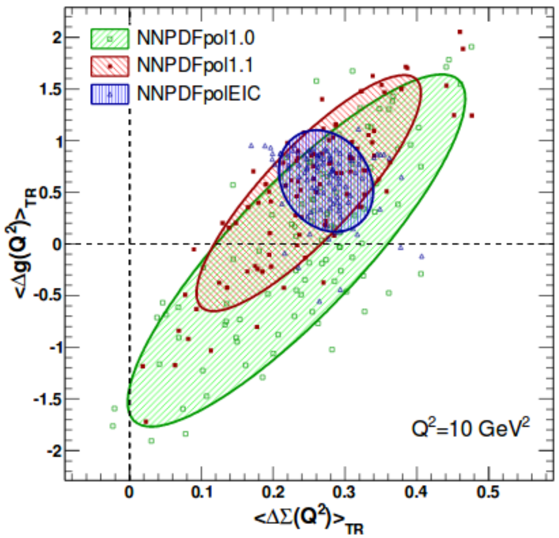
Is the proton spin puzzle solved?

...well, no. Not until we measure all the contributions, and in an extended x range.

The next steps

From Emanuele Nocera, HUGS 2017 at Jefferson Lab, 14/06/2017:





$Q^2 = 10$ GeV^2	$\int_{10^{-3}}^{1} dx\, \Delta\Sigma$	$\int_{10^{-3}}^{1} dx\, \Delta g$
NNPDFpol1.0	$+0.23 \pm 0.15$	-0.06 ± 1.12
NNPDFpol1.2	$+0.25 \pm 0.10$	$+0.49 \pm 0.75$
NNPDFpolEIC	$+0.24 \pm 0.04$	$+0.49 \pm 0.25$

quarks and antiquarks $\sim 20\% - 30\%$
gluons $\sim 70\%$
OAM $\sim 0\%$

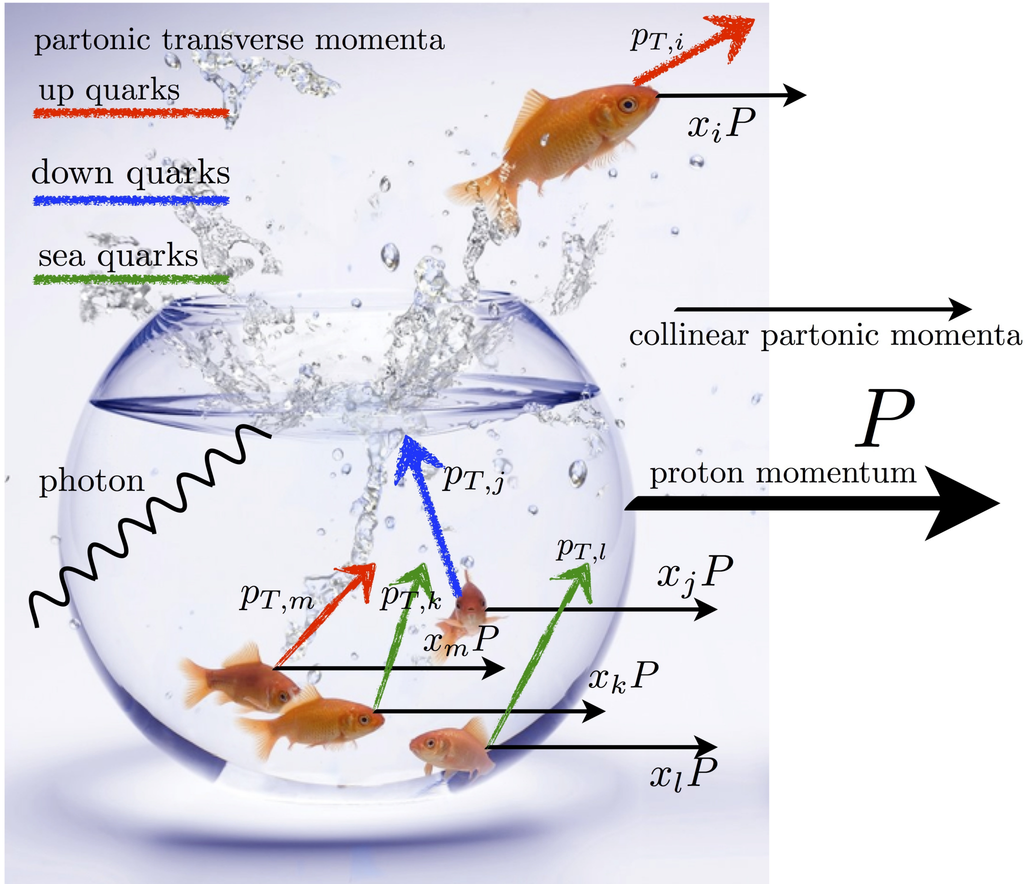
The blue curves illustrate the need of a new polarized *ep* collider, EIC, that will dramatically decrease uncertainties.

Integrals of the contributions given here are, at the moment, highly speculative.

Proton: 1D versus multi-D

Our world is not 1D. Why would the picture of confined quarks and gluons moving solidary with their parent quark, in the exact same direction, be true?

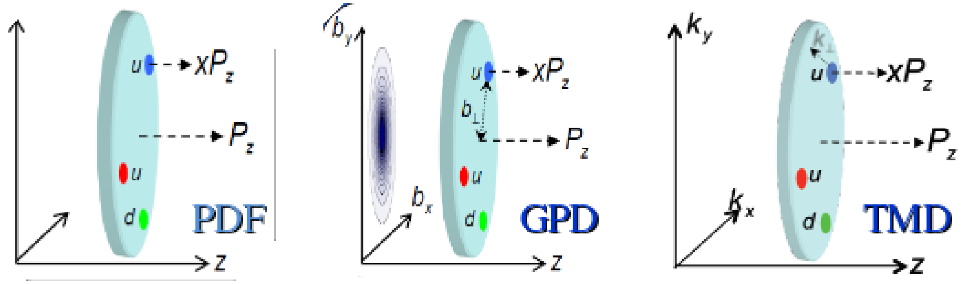
Going beyond the collinear approximation

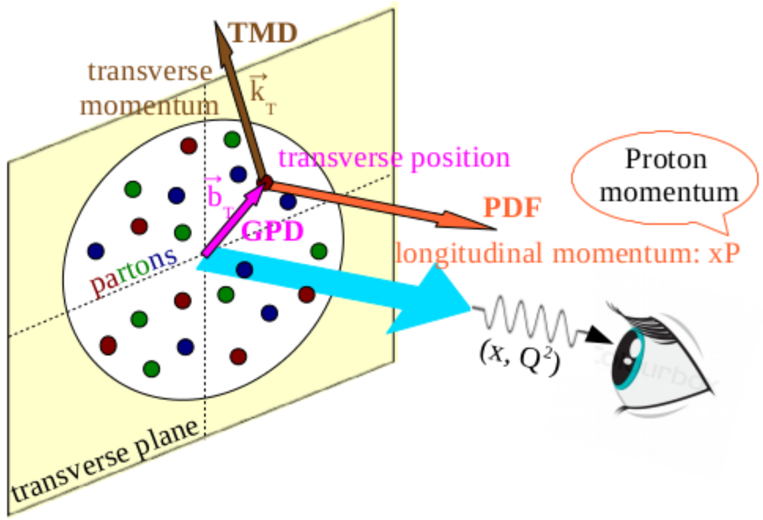


Quarks and gluons have not only a longitudinal momentum (fraction x of the proton momentum), but also an intrinsic transverse momentum k_T.

Going beyond the collinear approximation

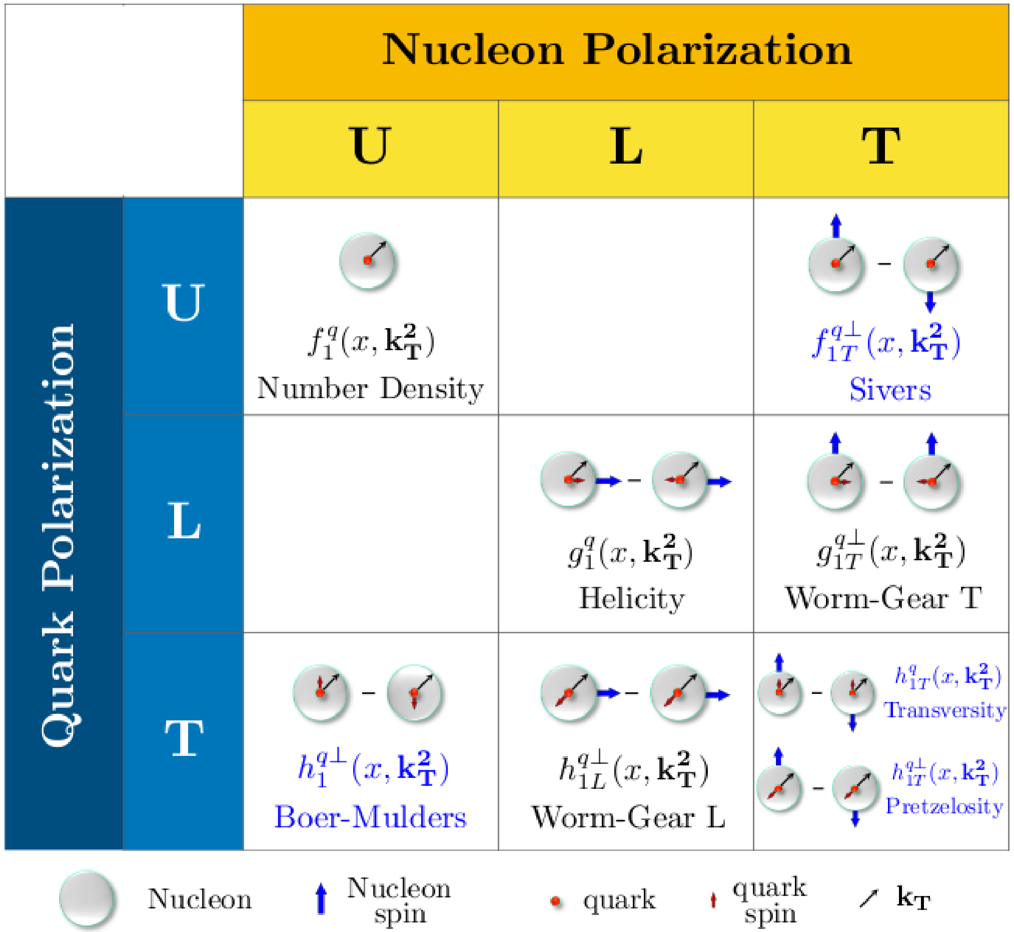
- In the configurations space: Generalized Parton Distributions
  $\mathrm{GPD}(x, b_T; Q^2)$
- In the momentum space: Transverse Momentum Dependent PDFs
  $\mathrm{TMD}(x, k_T; Q^2)$





A tomography of the proton

TMD PDFs



Taking into account the partons transverse motion (k_T), 8 TMD PDFs are needed to describe the nucleon.

Transversely polarized proton target:
Access to

- Sivers,
- transversity,
- pretzelosity,
- unpolarized Boer-Mulders

via **SIDIS** or **Drell-Yan**.

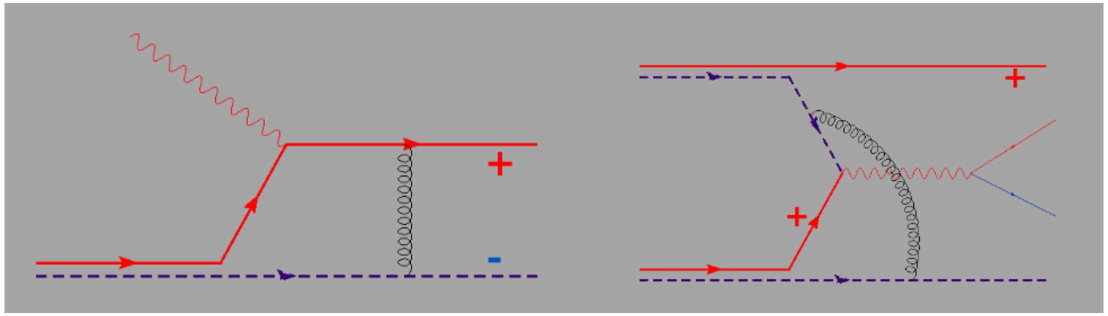
$\hookrightarrow$ **Transverse Spin Asymmetries:**

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

The Sivers TMD PDF

The Sivers effect is the result of the **correlation between the hadron spin and the quark intrinsic transverse momentum**, that will generate a left-right asymmetry in the final state particles.

The Sivers TMD is naive time reversal odd! – i.e. depends on the process

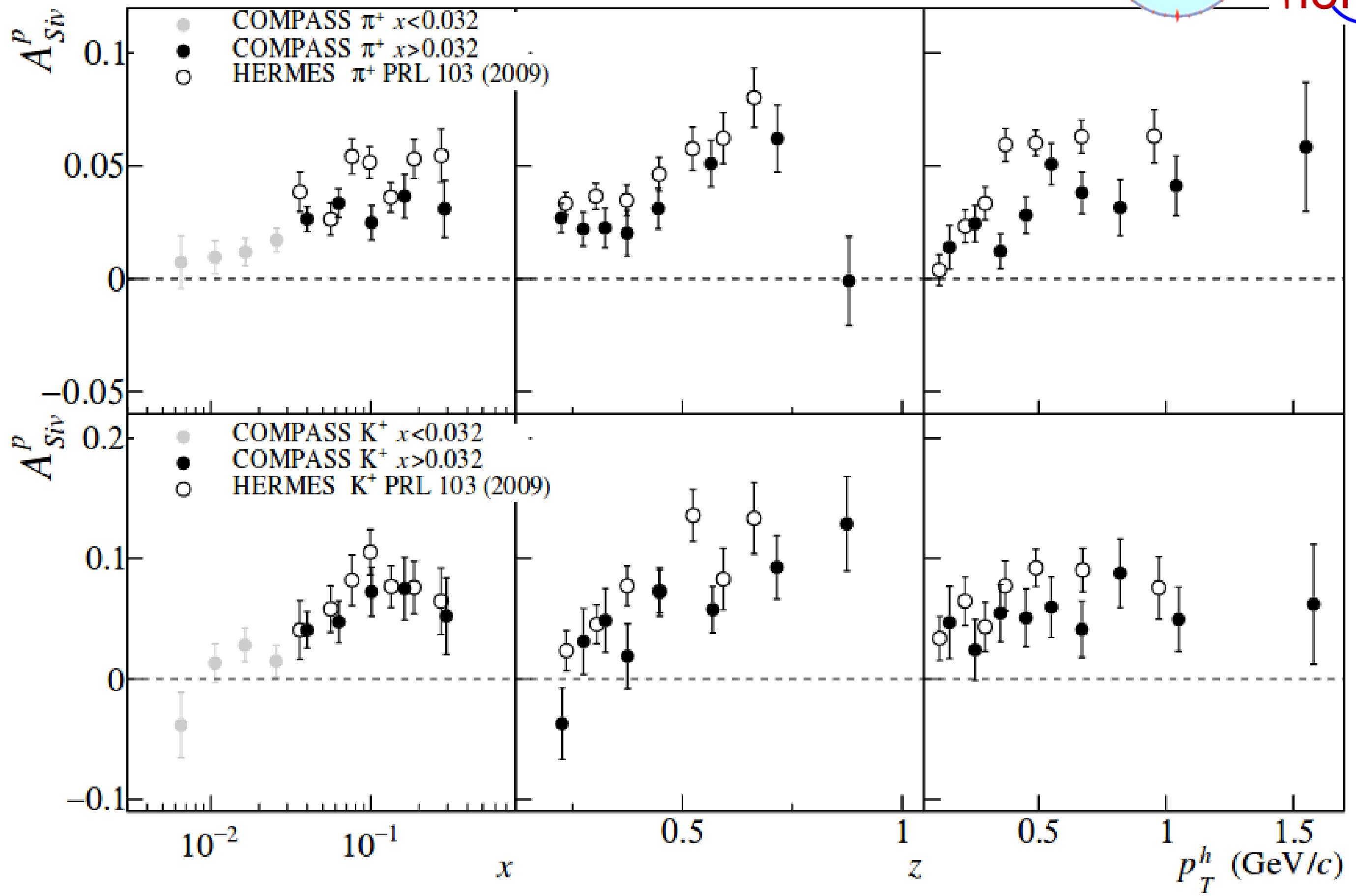


$$f_{1T}^{\perp}(\text{SIDIS}) = - f_{1T}^{\perp}(\text{DY})$$

Colored object are surronded by gluons → deep consequences.

The Sivers function has opposite sign when the gluon couples after the quark scatters (SIDIS – FSI) or before the quark annihilates (DY – ISI).

Sivers TMD measured in SIDIS



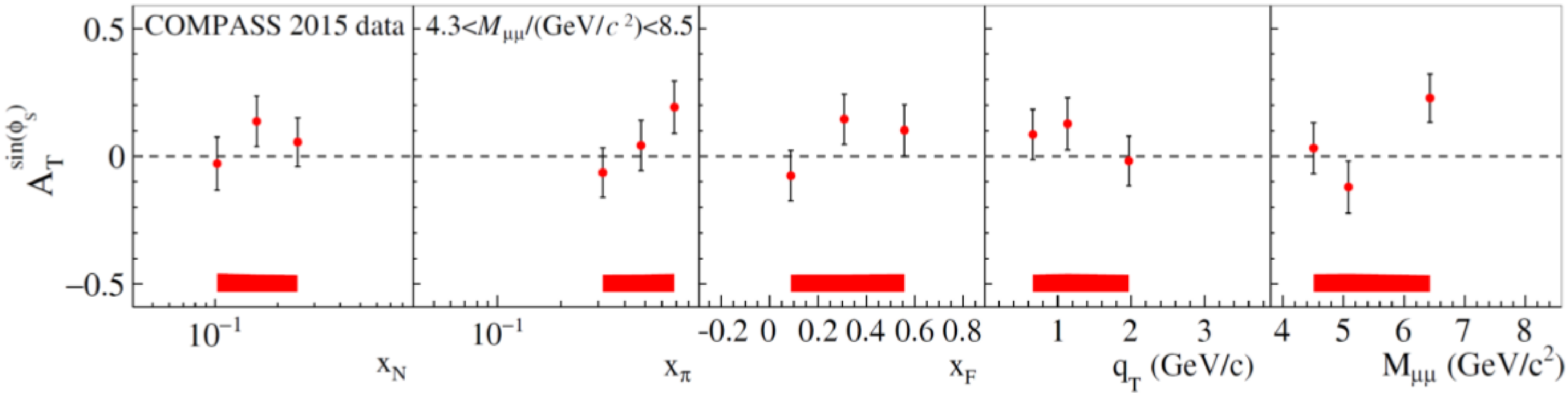
Sizable Sivers effect measured for positive hadrons – qualitatively, this can only mean sizable **orbital angular momentum** of quarks inside the proton.

The Drell-Yan Sivers asymmetry

The experimental check of the **sign change** in Sivers TMD is a crucial test of the TMD approach, and of non-perturbative QCD itself

$$A_T^{\sin\phi_S} \propto f_{1T,\pi}^{q} \otimes f_{1T,p}^{\perp p}$$

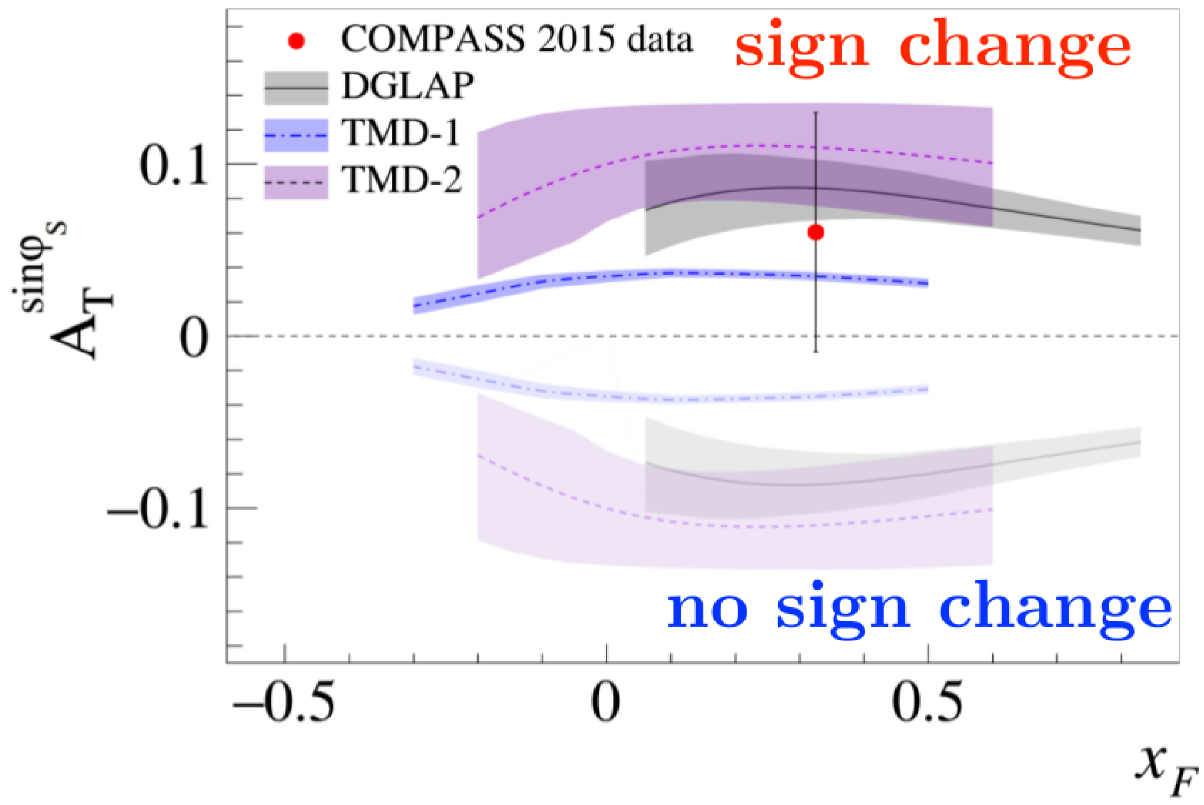
COMPASS, Phys.Rev.Lett. 119 (2017) 112002



Positive, at $\approx 1\sigma$ from zero.

- Drell-Yan can be also generalized to $q\bar{q} \to \gamma^*/Z^0 \to l^+l^-$ or $q\bar{q} \to W^\pm \to l\nu$.
- In COMPASS@CERN: pion induced DY – probing valence u-quarks
- STAR@RHIC: pp collisions – probing sea quarks

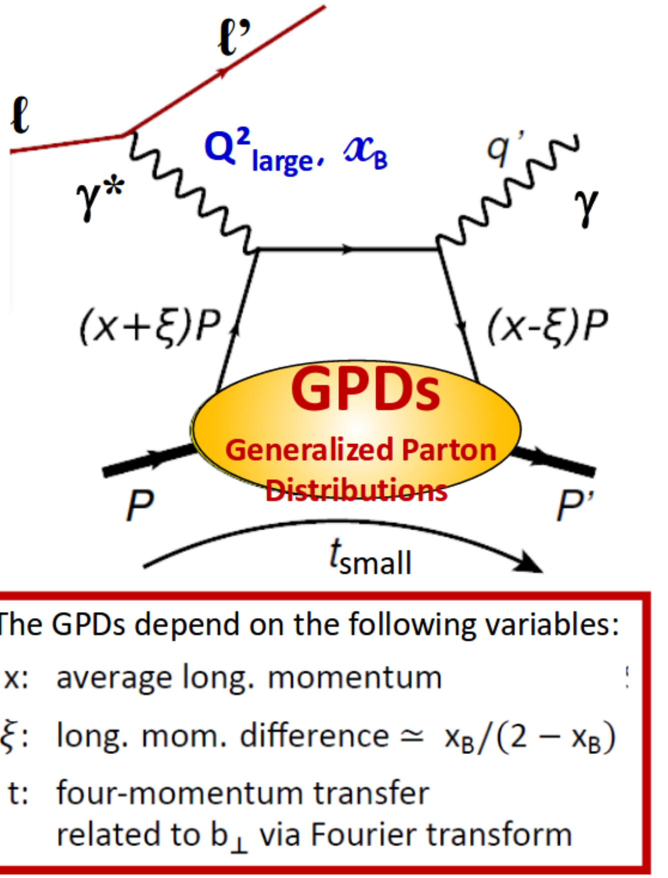
The Sivers sign change



There is a "hint" that indeed the Sivers TMD PDF has opposite sign in SIDIS and DY reactions. But statistically this is not yet conclusive.

Generalized Parton Distributions

GPDs: a 3D picture (tomography) of the nucleon, by adding information about the transverse distance of the constituent quark.

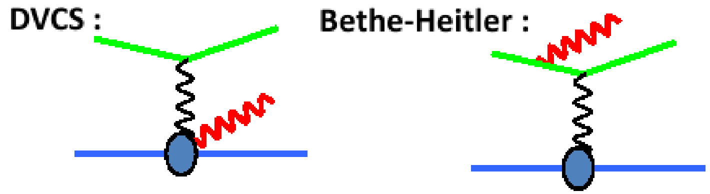


Deeply Virtual Compton Scattering

- 4 GPDs: H, E, $\tilde{H}$ and $\tilde{E}$, for each quark flavor and gluons.
- allows access to orbital angular momentum in the nucleon
- **DVCS**: exclusive process, golden channel for acessing GPDs
  $\mu p \rightarrow \mu' p' \gamma$

Measuring DVCS

$$\frac{d\sigma}{dt} \approx e^{-Bt}; \qquad B \approx \langle r_\perp^2 \rangle / 2$$



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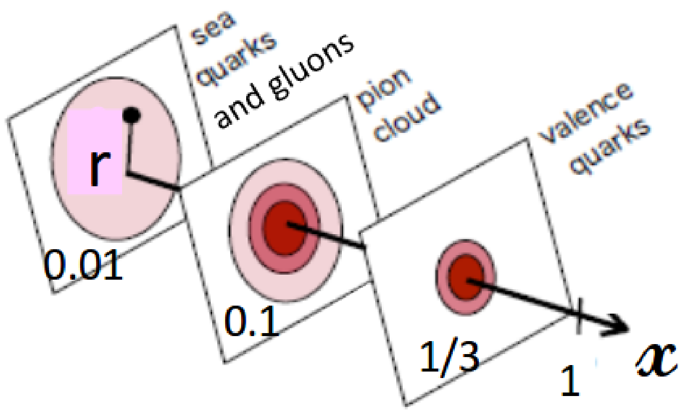
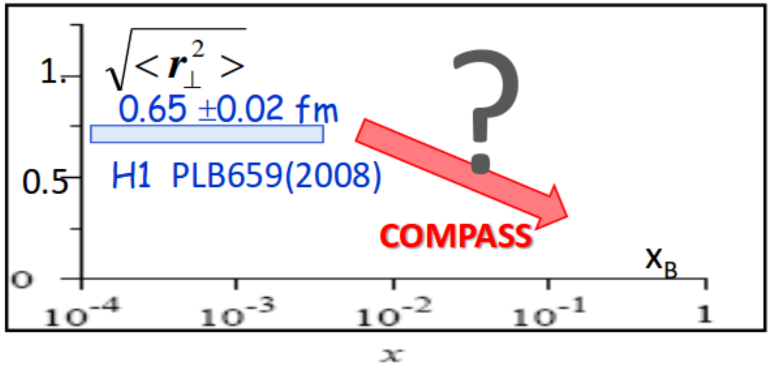
competing processes:
DVCS and Bethe-Heitler
– Low x: BH;
– High x: DVCS;
– intermediate x:
interference DVCS-BH.

BH is well-known:
used as reference process.

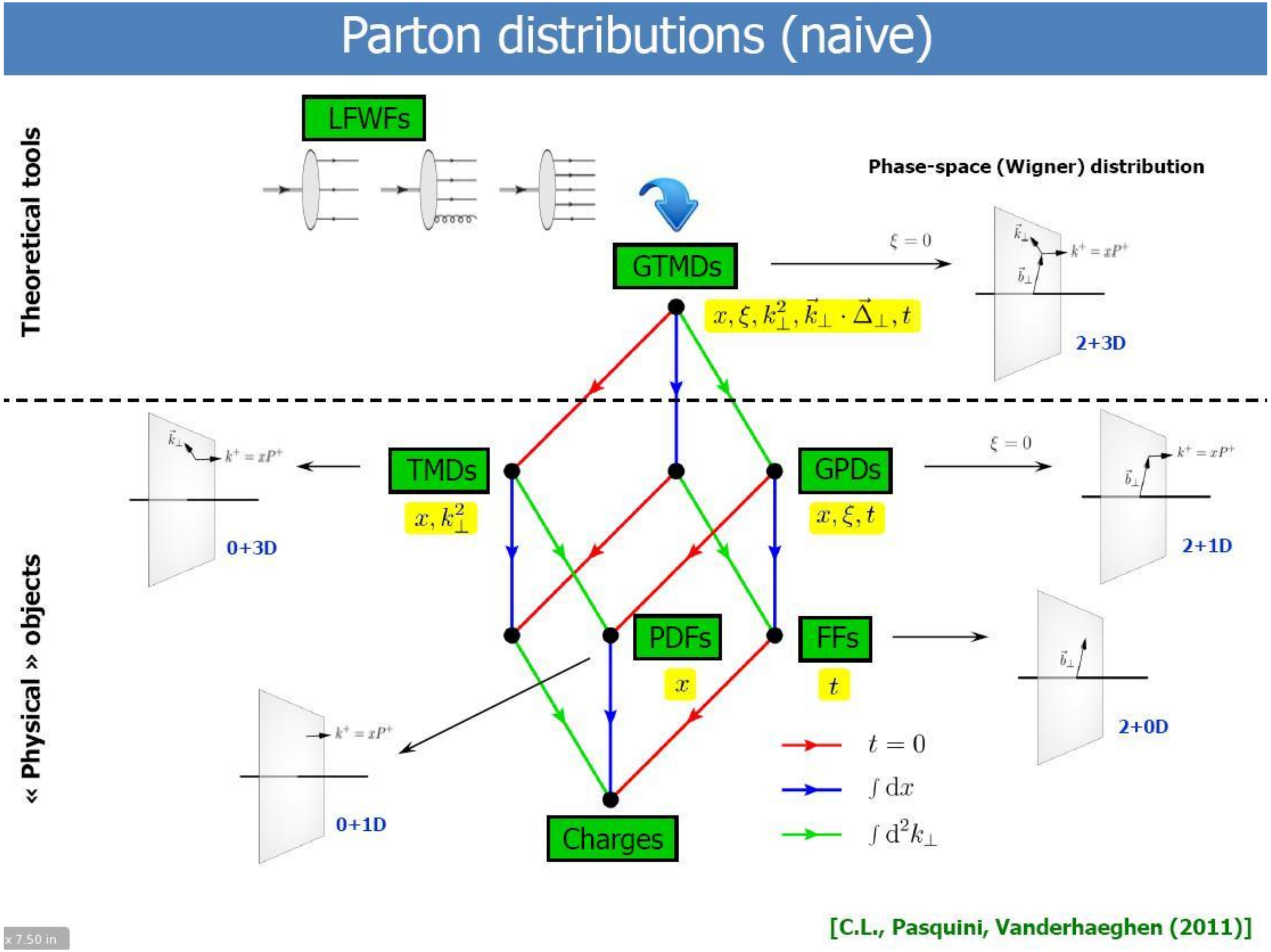




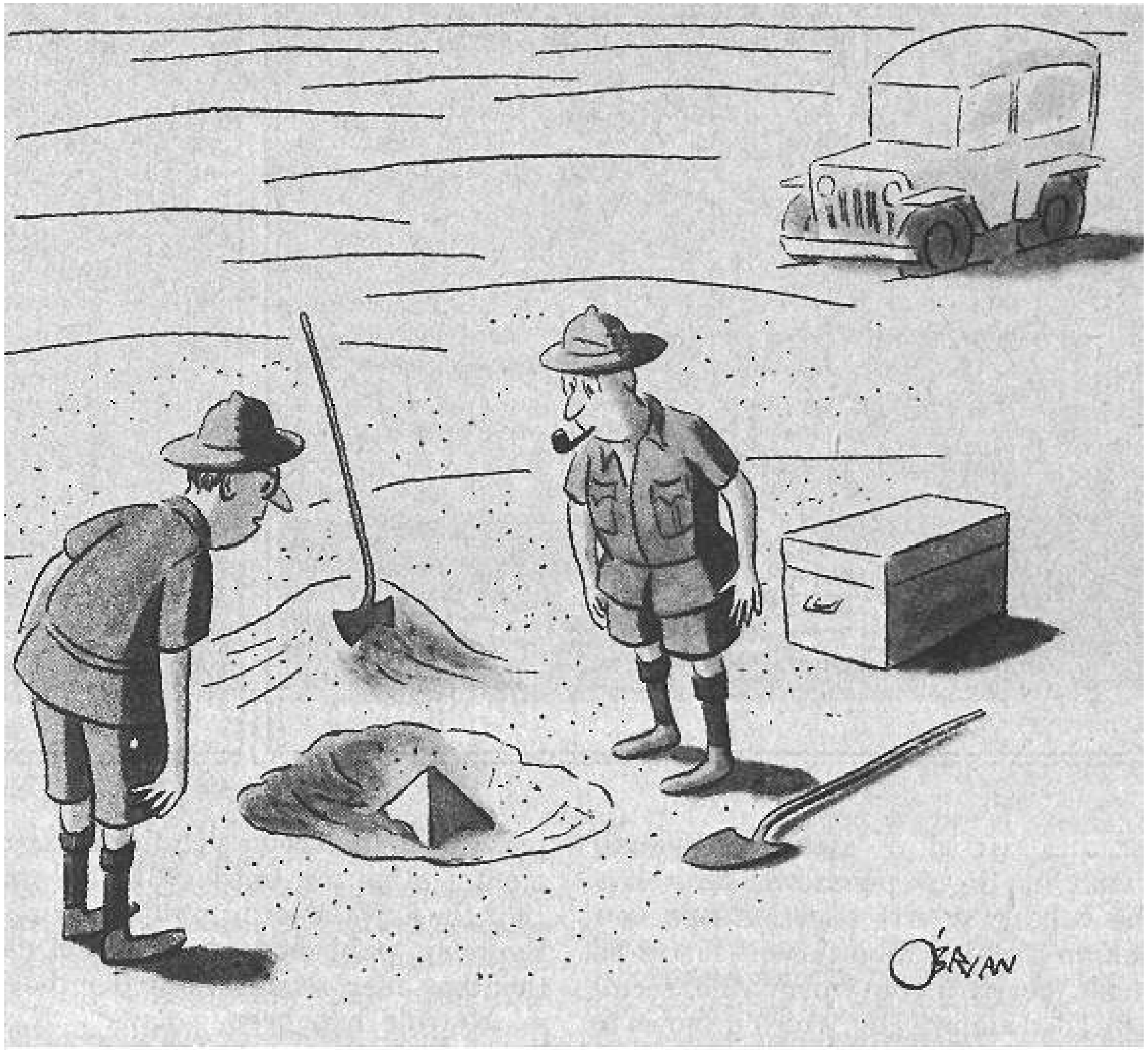
$\mu^{+\downarrow}$ and $\mu^{-\uparrow}$ beams off an unpolarized liquid H_2 target $\Rightarrow$ GPD H.

$\mu^{+\downarrow}$ and $\mu^{-\uparrow}$ beams off a transversely polarized NH_3 target $\Rightarrow$ GPD E.

The ultimate goal: Wigner functions



But: expect the unexpected...



"This could be the discovery of the century. Depending, of course, on how far down it goes."

Concluding remarks

- Nucleons are stable, contrary to all other known hadrons. Pions, the simplest hadronic system possible, is not stable
- Valence of proton is (u,u,d), while valence of pion is (u,$\bar{d}$). But a proton weights 1GeV and the pion only 0.14MeV... – the mass hierarchy puzzle
- Nucleons are composite particles. Still their spin is exactly 1/2. And this is not due to their valence quarks spin... – the proton spin puzzle
- The charge radius of the proton is 0.85fm. But: measured via lepton-proton elastic scattering or via laser spectroscopy of muonic hydrogen it leads to a significantly different value – the proton radius puzzle.

Understanding the proton remains a challenge.

The uncertainty of the nucleon PDFs enters as a systematic to many Standard Model precision measurements.

The role of the gluons is extremely relevant: after all, 99.8% of the proton mass is due to gluons (... not the Higgs field).