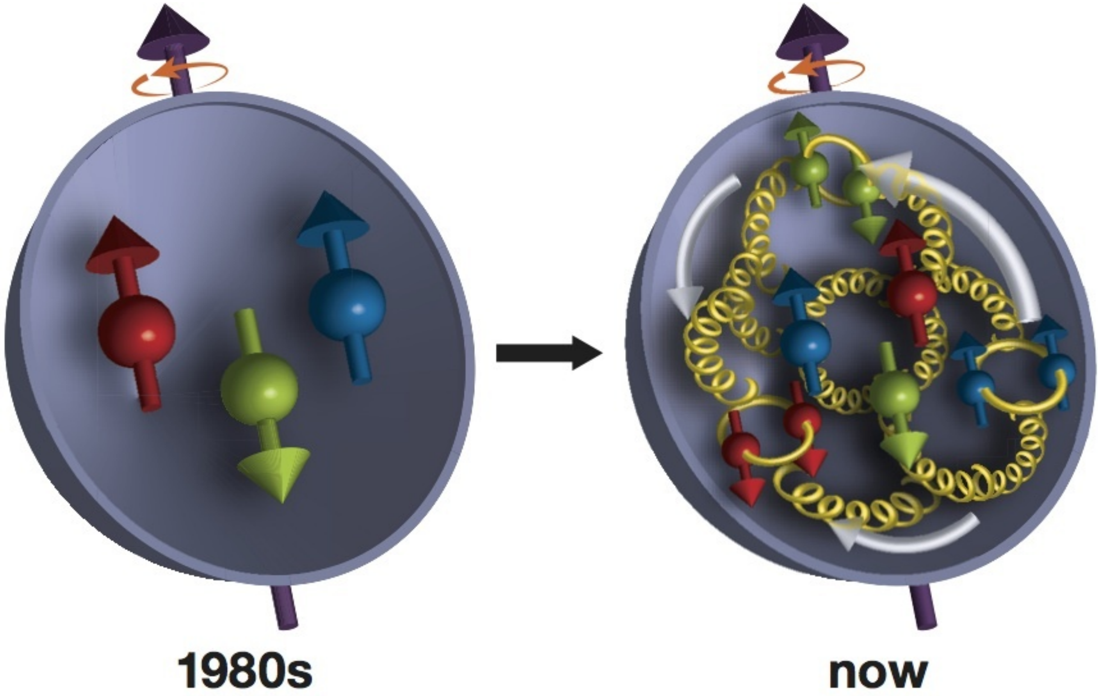
The physics of the nucleon

Catarina Quintans, LIP-Lisbon

18/07/2017

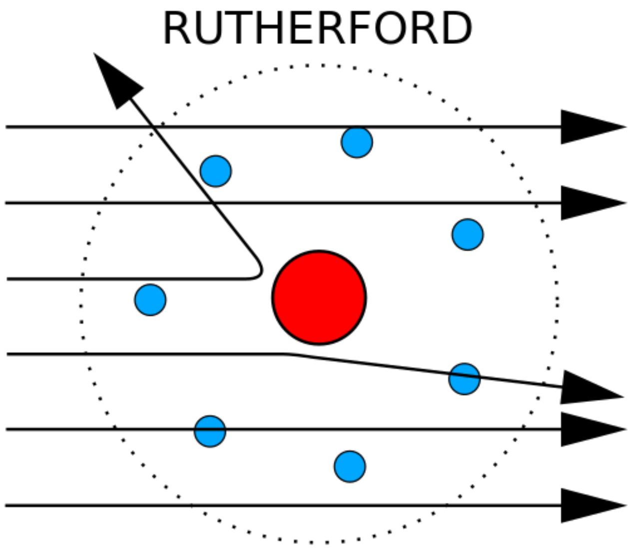


FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

The origins

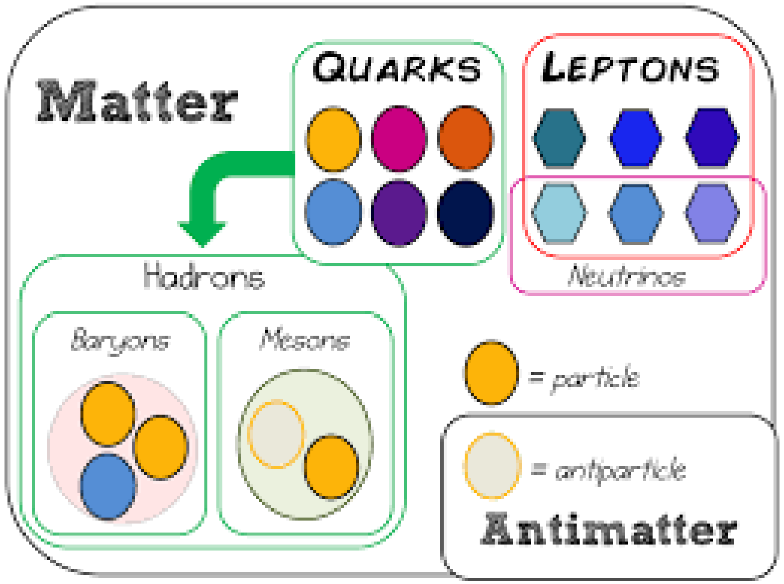
Nucleon is the term used to refer to **protons** and **neutrons**, i.e. **normal everyday massive matter**.

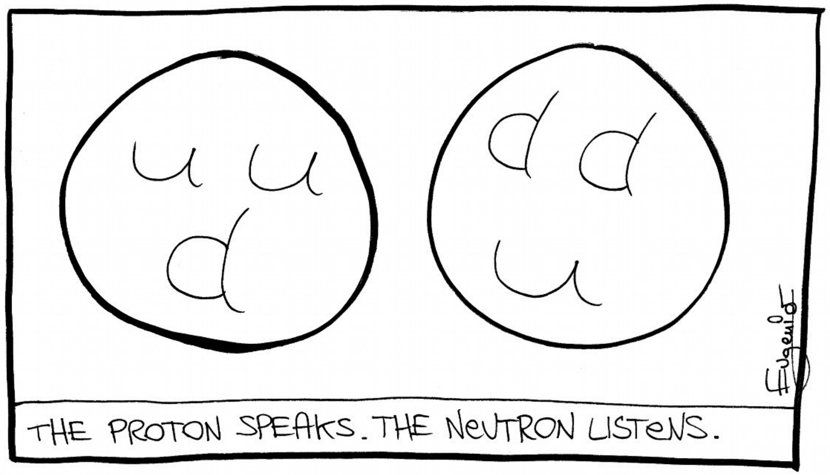
In the 1920's Ernest Rutherford started to use the word "proton" to refer to the hydrogen nucleus.



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

How are nucleons inside?

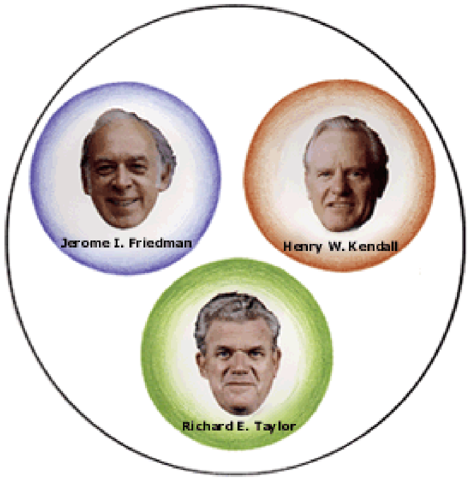




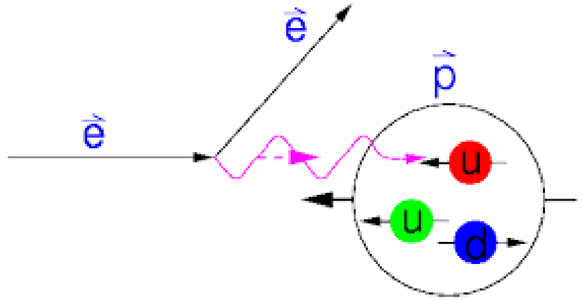
In the big zoo of composite particles, **nucleons** belong to the **baryon family**, while particles like **pions** and **kaons** belong to the **meson family**. Baryons and mesons form the **hadron species**.

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

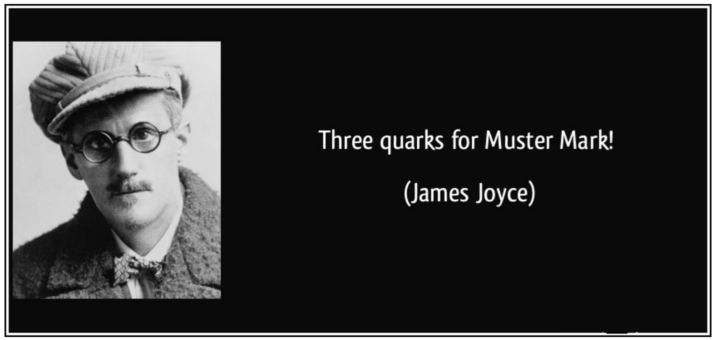
The evidence for quarks



1968: "Rutherford-like" experiments performed at SLAC gave the first evidences for the existence of quarks as the nucleons constituents.



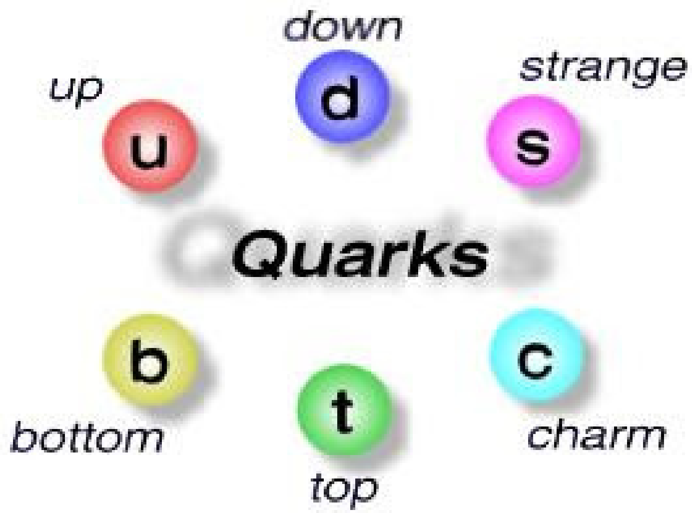
1964: Gell-Mann e Zweig proposed the model of quarks.

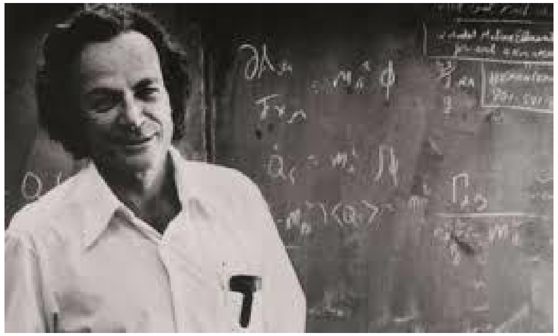


In reference to the 3 quark flavors considered at the time: up, down, strange. In fact, in total there are 6 quark flavors.

Quarks flavor

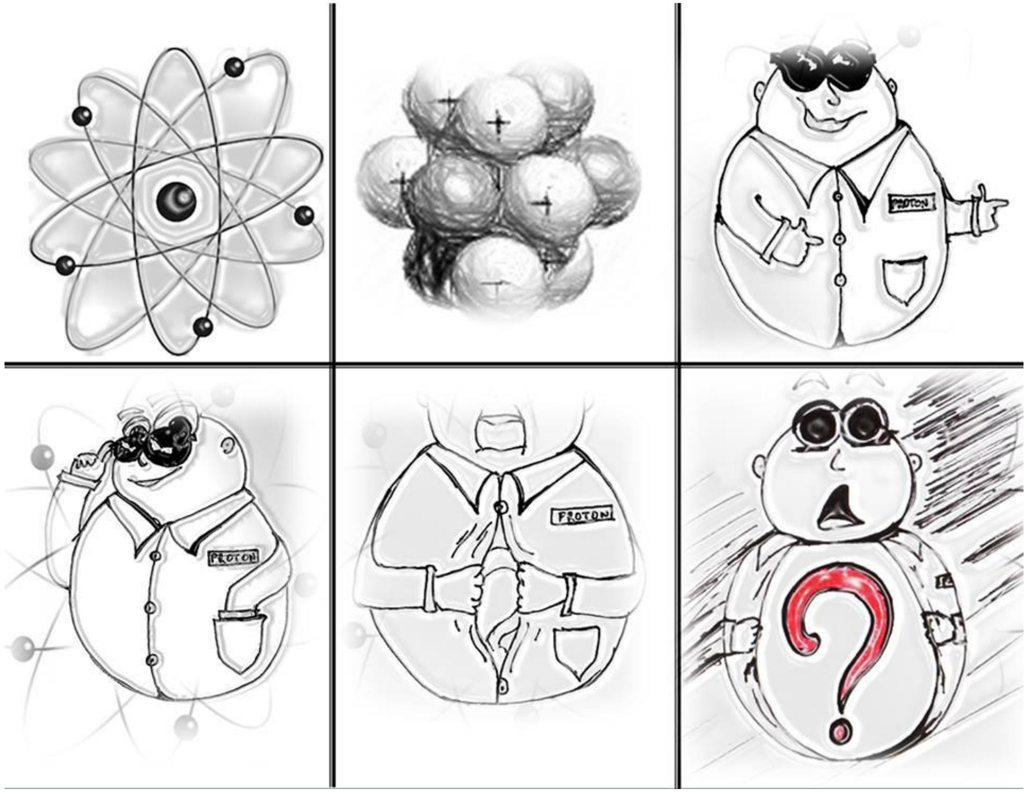
Quarks come in **6 different flavors**: down, strange and bottom (electric charge -1/3); up, charm and top (electric charge 2/3).





In 1969 Feynman proposed the parton model that explains hadrons in terms of point-like constituents, the "partons" (quarks and gluons). In this model baryons are made of 3 quarks, while mesons are made of quark- antiquark pairs.

The nucleon structure

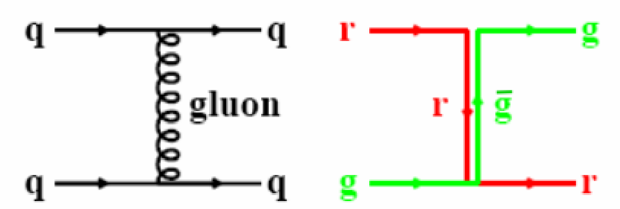


A proton **is not** **(u, u, d)**.

A proton is packed with quarks, antiquarks and gluões, 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.

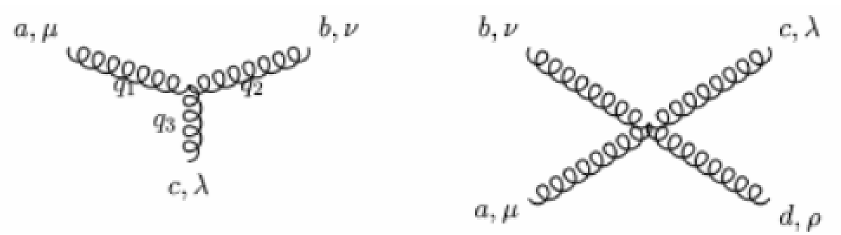


Gluons couple to color charge of quarks: R, G or B, with coupling strenght $\propto \sqrt{\alpha_S}$.

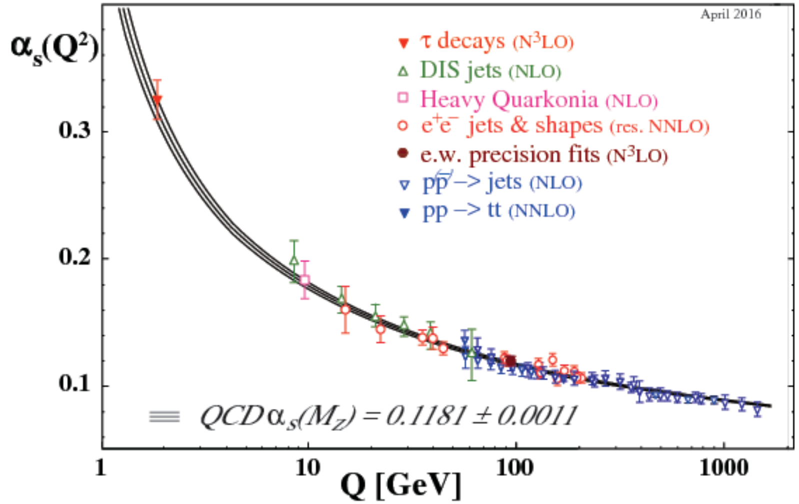
Interaction	QED	QCD
Conserved charge	electric charge e	colour charges r, g ,b
Coupling constant	$\alpha = e^2/4\pi$	$\alpha_S = g_S{}^2/4\pi$
Gauge boson	Photon	8 gluons
Charge carriers	fermions ($q \neq 0$)	quarks gluons

QCD is short range

Contrary to photons in QED, gluons can interact with each other:

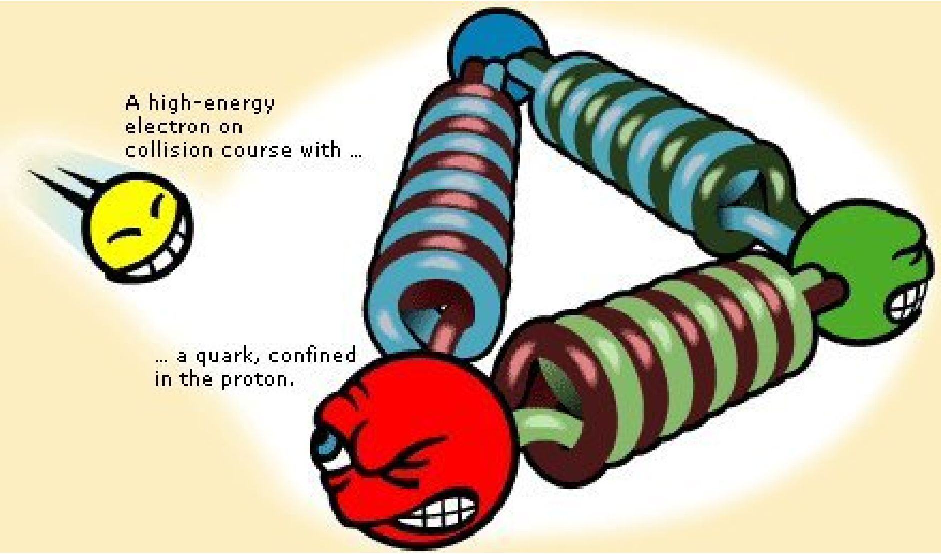


Because the strong coupling constant α_s is “small” in high energy or short distance interactions, it allows the use of perturbation theory techniques.



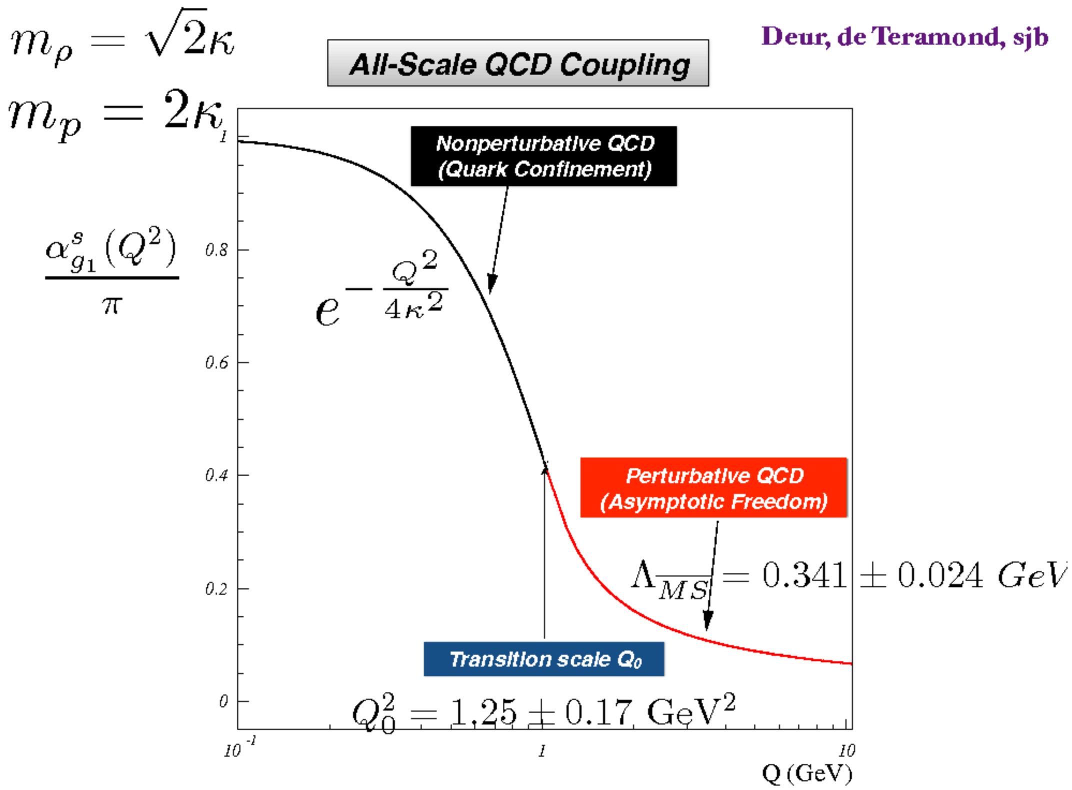
Main features of QCD

- **Confinement**
  Color charged particles – the quarks – cannot be observed isolated. The strong force does not diminish with distance. Instead, the energy of the gluon field between the 2 quarks thorn apart is enough to create another pair.



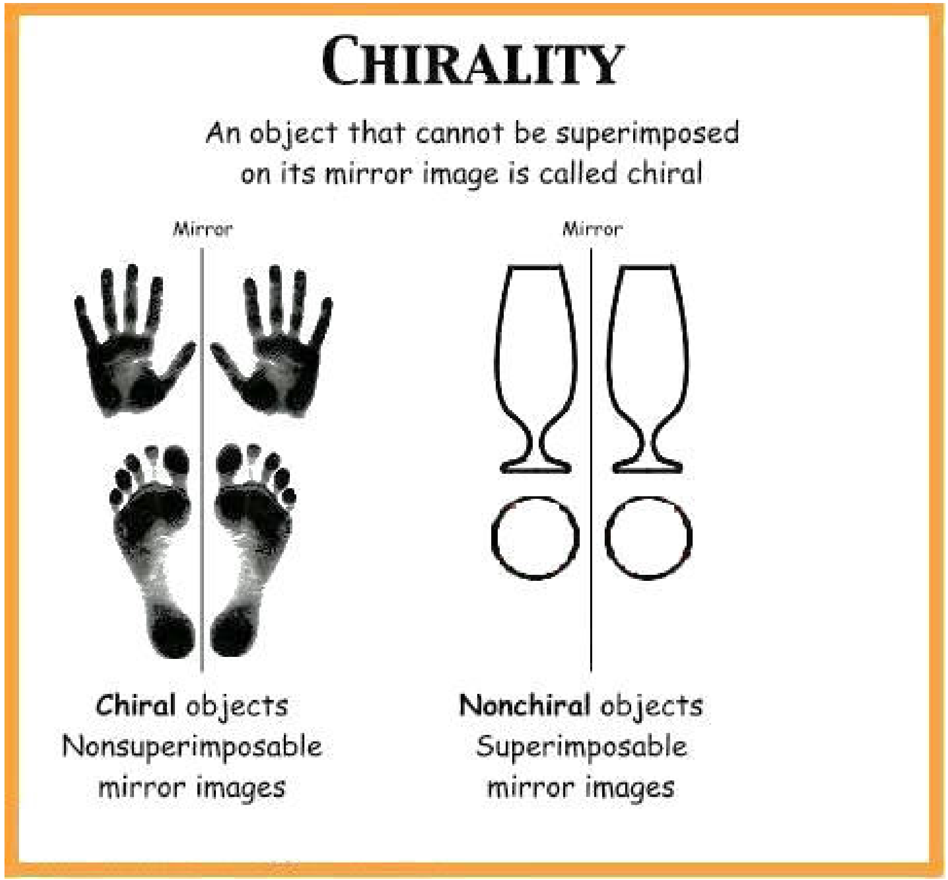
Main features of QCD

- **Asymptotic freedom**
  At small distances and large energies, α_S diminishes logarithmically, and quarks and gluons behave as quasi-free particles.



Main features of QCD

- **Chiral symmetry breaking**
  The spontaneous symmetry breaking of the QCD vacuum leads that, when confined (in hadrons) quarks show a large dynamical mass (constituent mass).

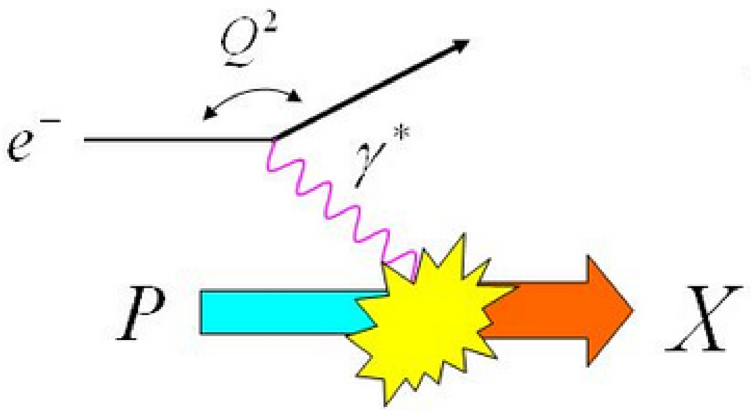


Deep inelastic scattering

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

The nucleon target absorbs part of the kinetic energy 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.



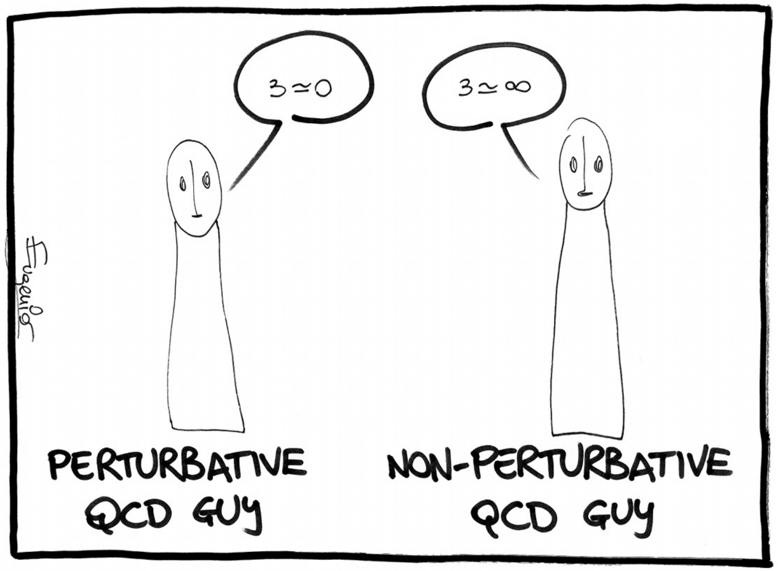
- photon virtuality : $Q^2 = -q^2$
- Bjorken-x: fraction of longitudinal momentum carried by the struck quark wrt his parent nucleon
  $x = \frac{Q^2}{2M(E_1 - E_3)}$

The DIS cross-section

The **QCD factorization theorem** implies that, for large enough energies (large Q^2), the cross-section can be written as:

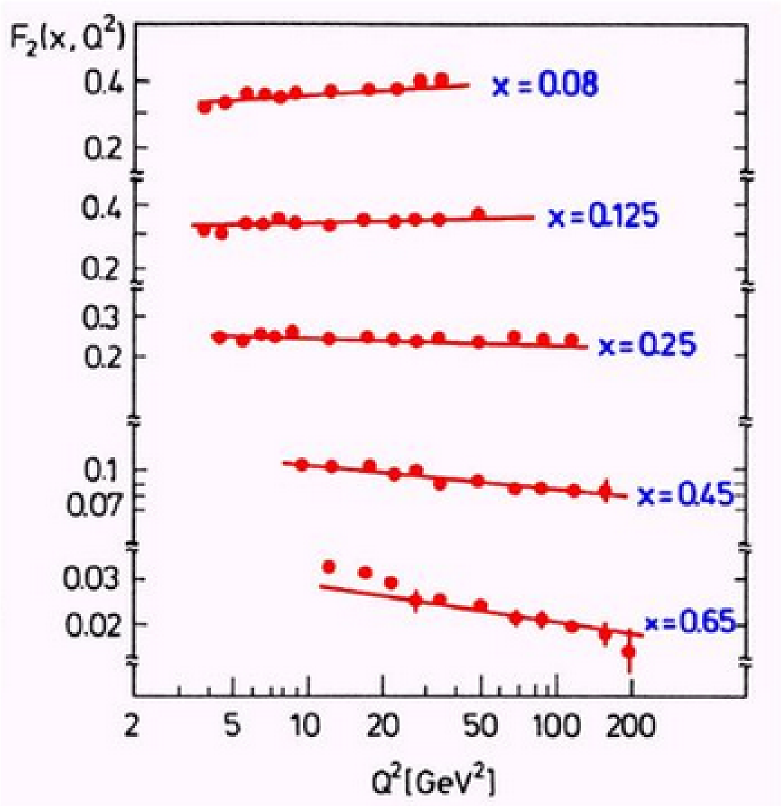
$$\sigma^{DIS} = \sum_j \int dx \; f_j(x, Q^2) \; \hat{\sigma}_{\gamma^* j}(x, Q^2, ...)$$

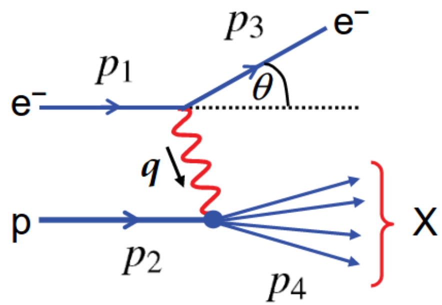
- $f_j(x, Q^2)$: parton distribution function (PDF) of the struck quark in the nucleon – **non-perturbative** part
- $\hat{\sigma}_{\gamma^* j}(x, Q^2, ...)$: partonic cross-section of the virtual photon interaction – **perturbatively** calculable



The proton structure functions

$$\frac{d^2\sigma^{DIS}}{dE_3 d\Omega} = \frac{\alpha^2}{4E_1^2 \sin^4\theta/2}\left(\frac{1}{E_1 - E_3}F_2(x,Q^2)\cos^2\frac{\theta}{2} + \frac{2}{M}F_1(x,Q^2)\sin^2\frac{\theta}{2}\right)$$





F_2: electromagnetic structure function;
F_1: purely magnetic structure function.

From first DIS experiments, there seemed to be no dependence on Q^2 – Bjorken scaling

F_1 and F_2 are not independent:

$F_2(x) = 2xF_1(x)$ – Callan-Gross relation

↪ Evidence for quarks being spin 1/2

PDFs and structure functions

The F_2 structure function is proportional to the parton distribution functions of the proton:

$$F_2^{ep}(x) = x \sum_q e_q^2 \; q^p(x) \quad \Longrightarrow \quad \int_0^1 dx \; F_2^{ep}(x) = \frac{4}{9} f_u + \frac{1}{9} f_d$$

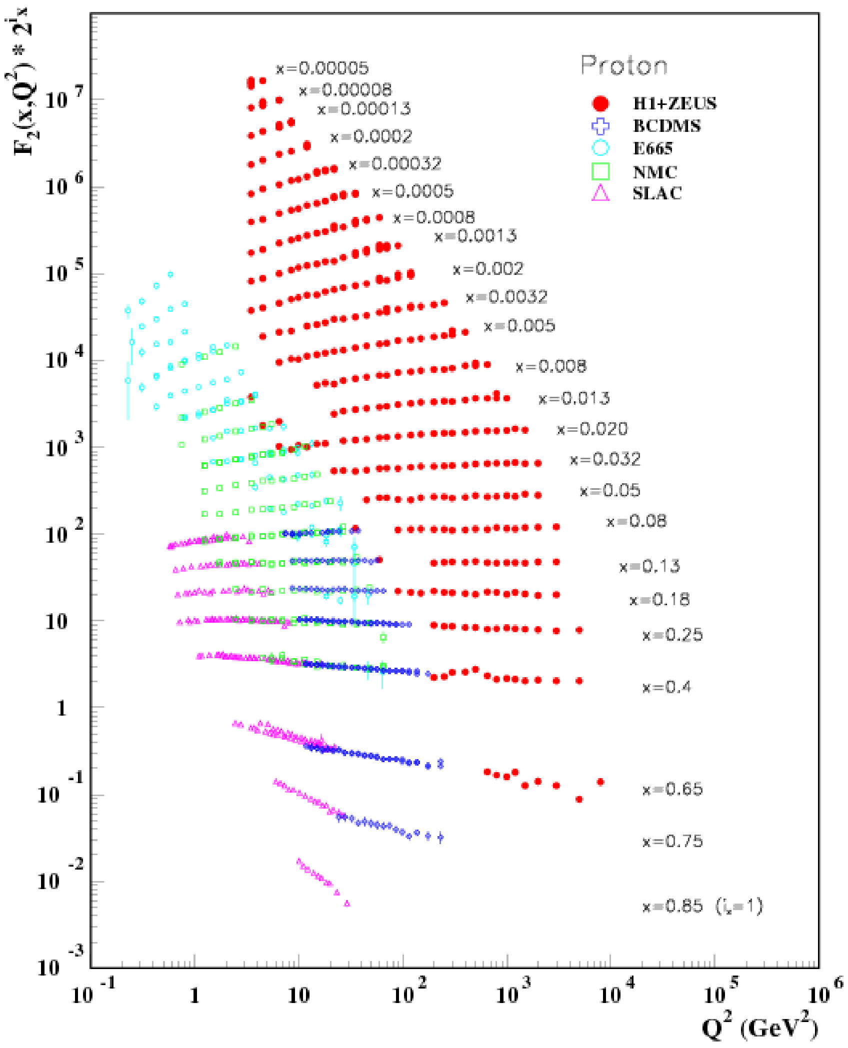
$f_u = \int_0^1 dx[xu(x) + x\bar{u}(x)]$: fraction of proton momentum carried by u and $\bar{u}$ quarks.

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!

Q^2 evolution of PDFs



With increasing precision of DIS experiments, it became evident that Bjorken scaling is only approximate. The structure functions do depend on Q^2

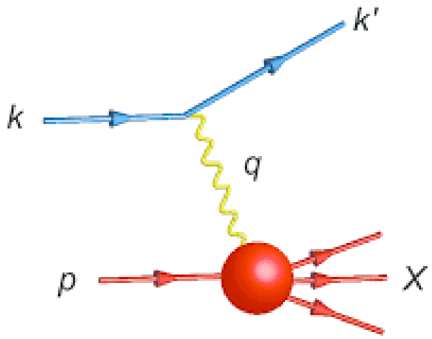
$\hookrightarrow$The F_2 dependence on Q^2 reveals a non-zero gluon PDF.

If we want to compare results from experiments measuring at different scales (ex: different Q^2) we need to **evolve** these results to a common scale – use DGLAP equations.

How are PDFs determined?

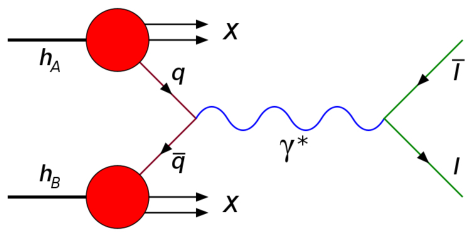
PDFs are universal – all available measurements are used together, in **global fits to world data**.

SIDIS



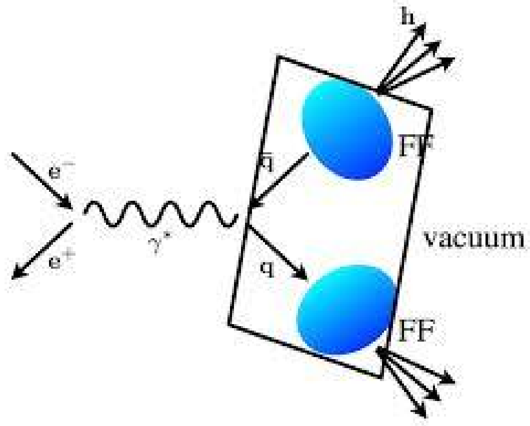
$\sigma \propto PDF \otimes FF$

Drell-Yan



$\sigma \propto PDF \otimes PDF$

e^+e^-

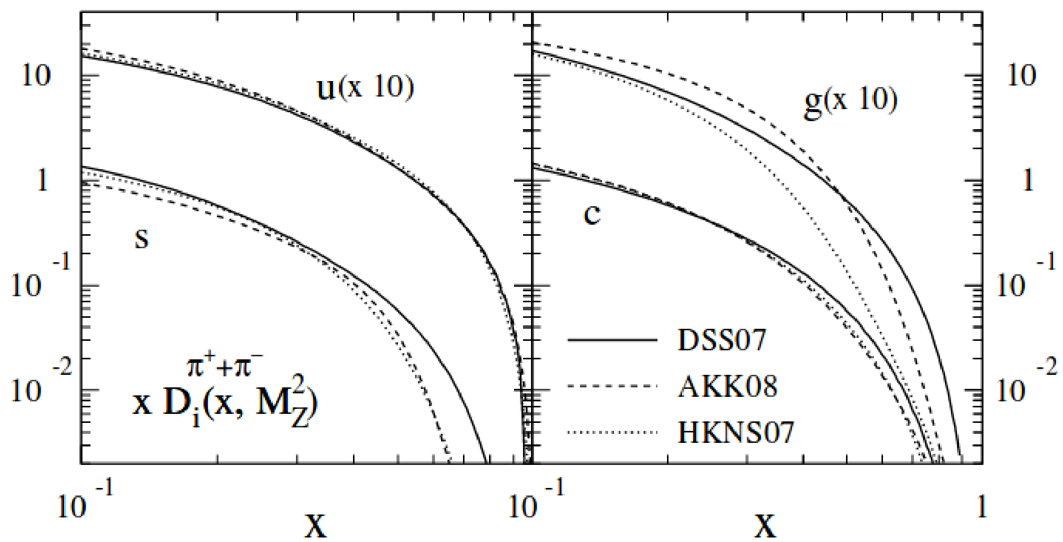


$\sigma \propto FF$

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 the parton's 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.



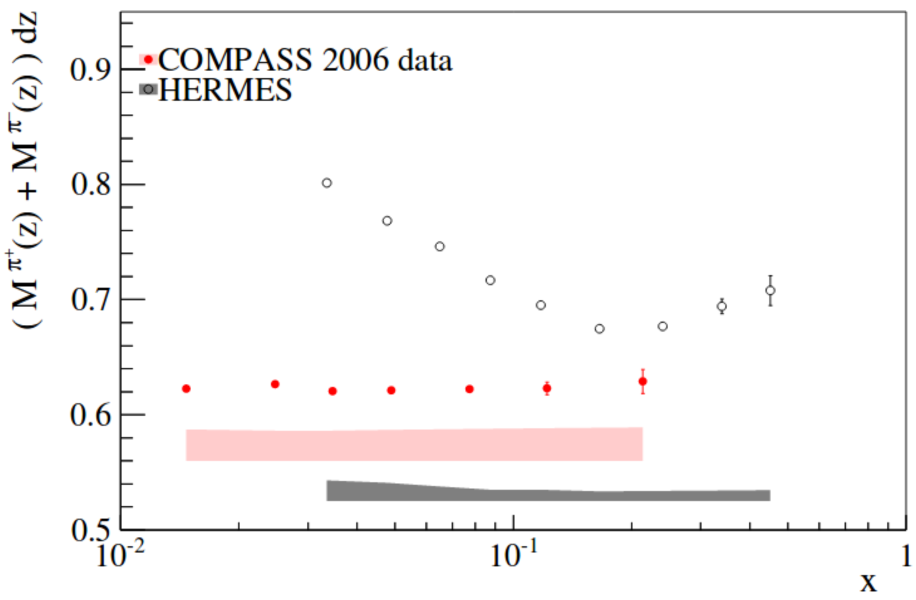
Extracting fragmentation functions

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

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

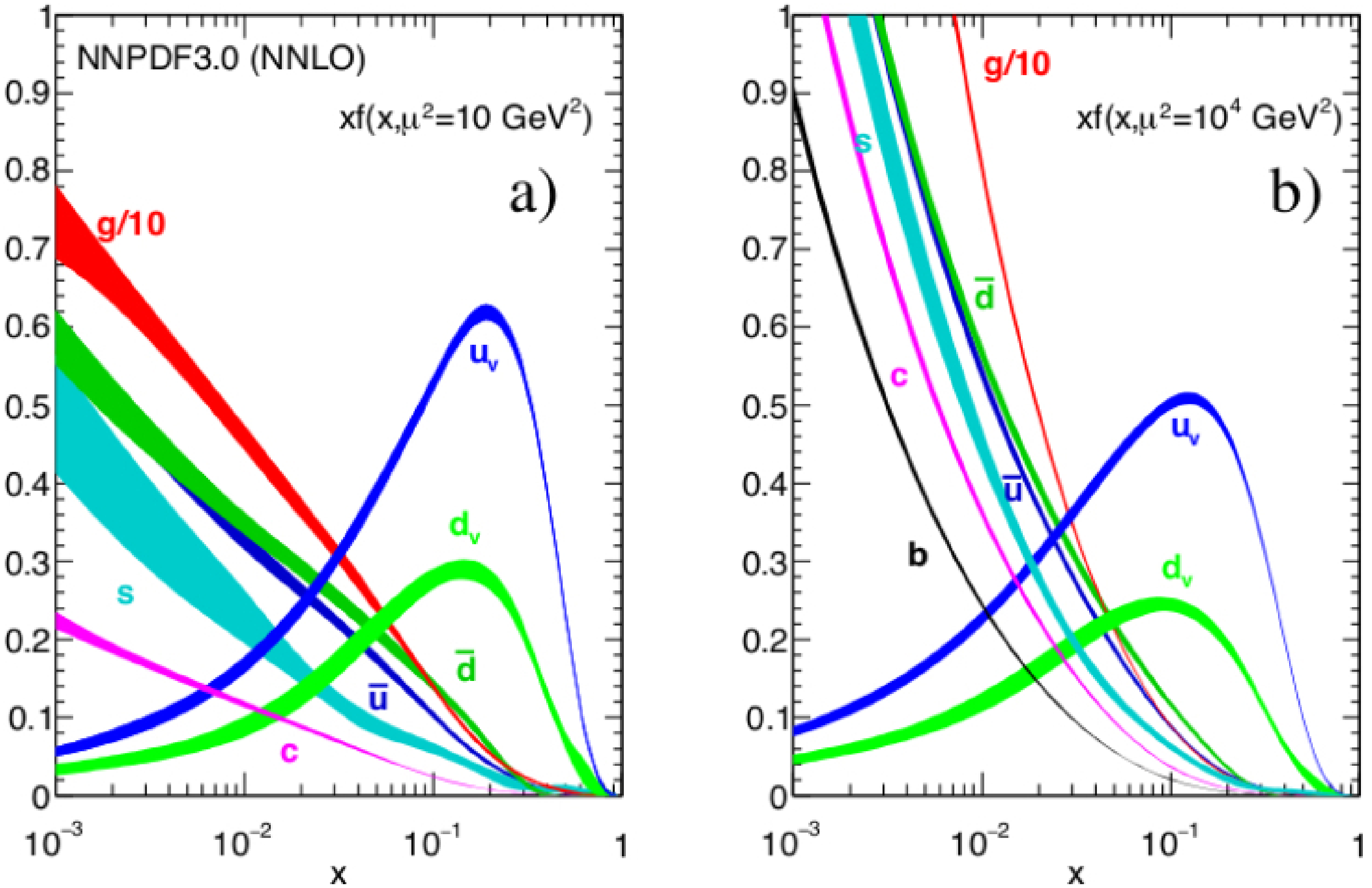
where e_q is the electric charge of a quark flavor q and i is a given hadron species.

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



How well are proton PDFs known?

NNPDF3.0 global analysis of parton distributions, in Particle Data Group (PDG) 2016 review.



The spin of particles

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

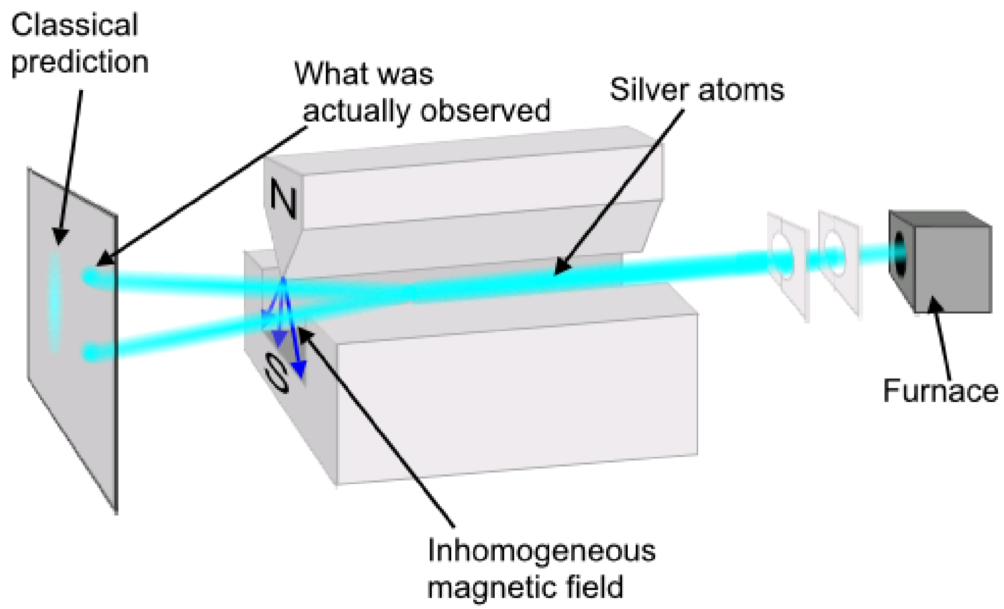
It is a concept from **quantum mechanics** – it has no parallel in classical physics.

The usual **analogies** are not really correct, but they help up to 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

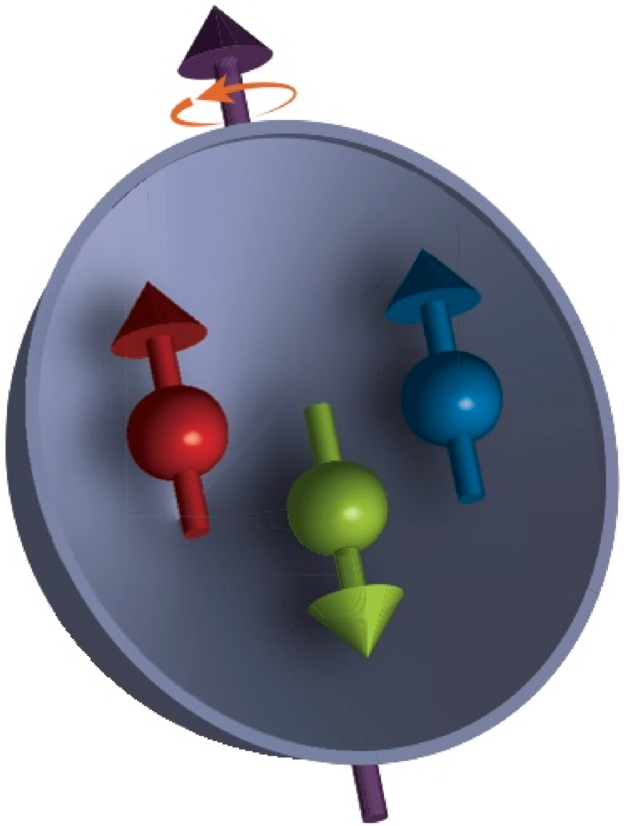
It is a **fundamental property of elementary particles**, just like mass, electric charge or color charge.

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 spin of the nucleon

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



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

The spin crisis

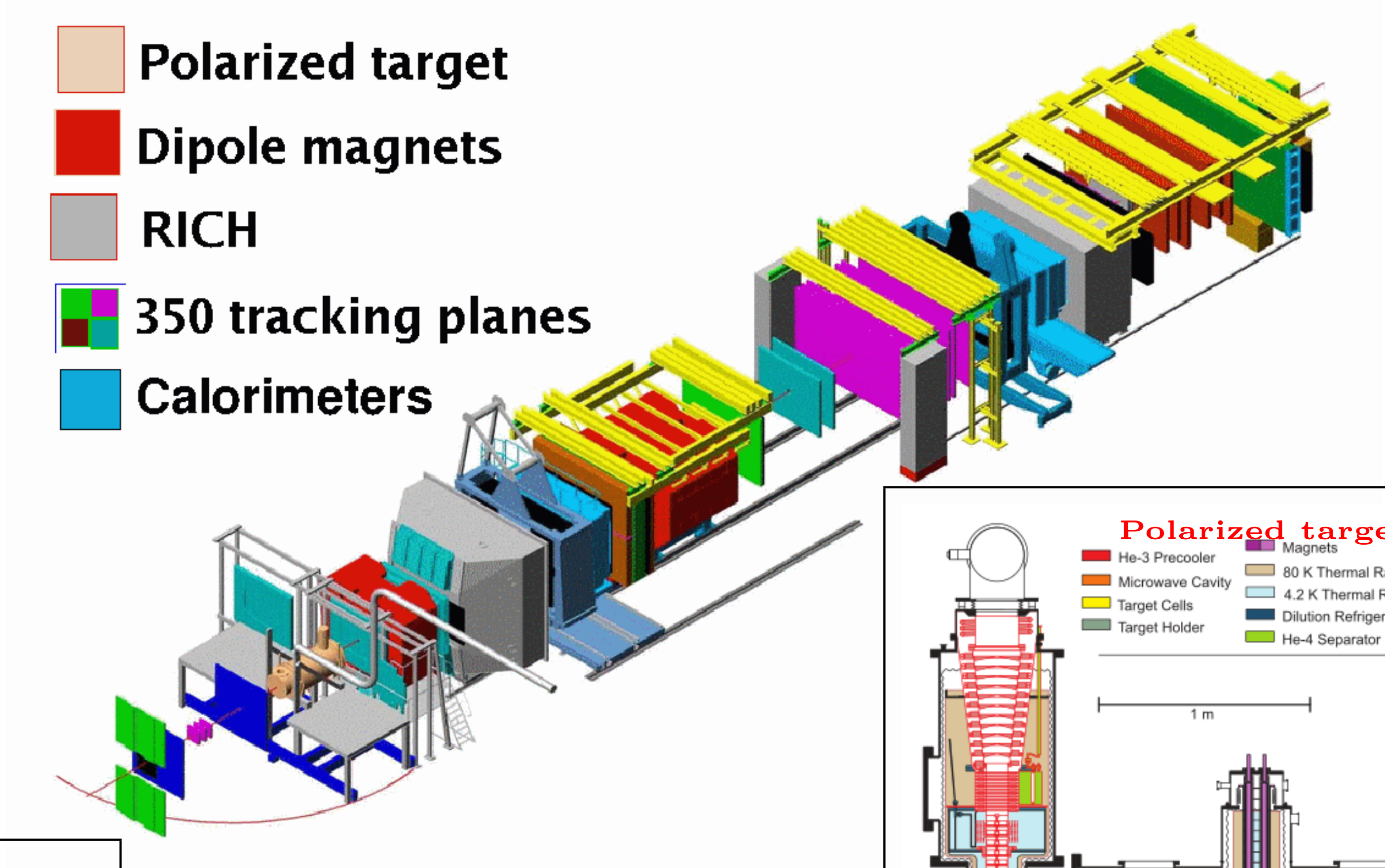
In the 1970's the first polarized DIS experiments started.

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

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

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

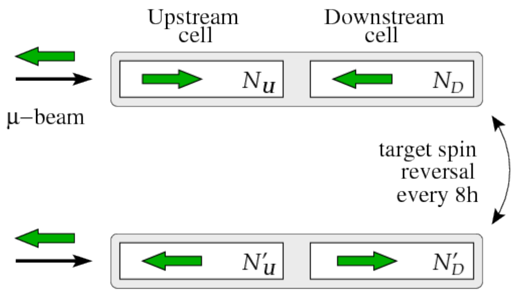
COMPASS: an experiment for spin physics

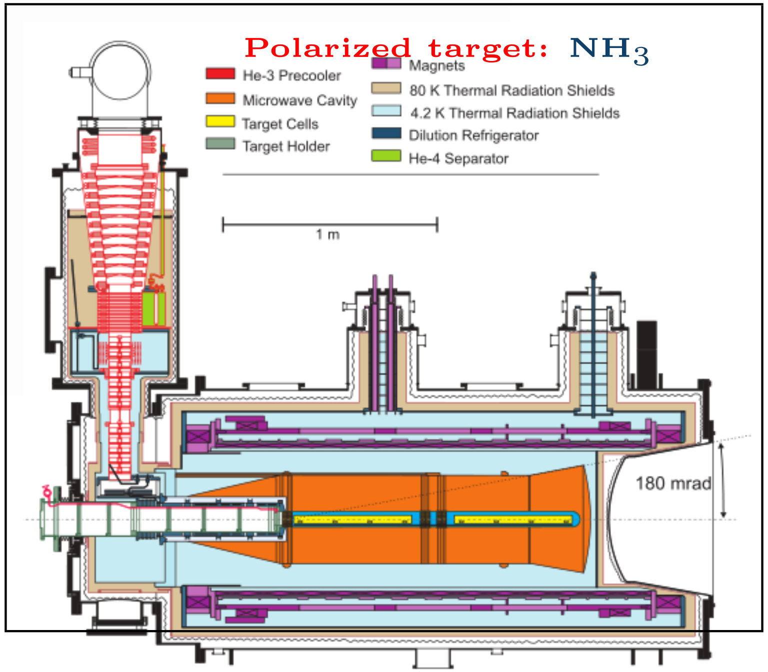


μ^+ beam,

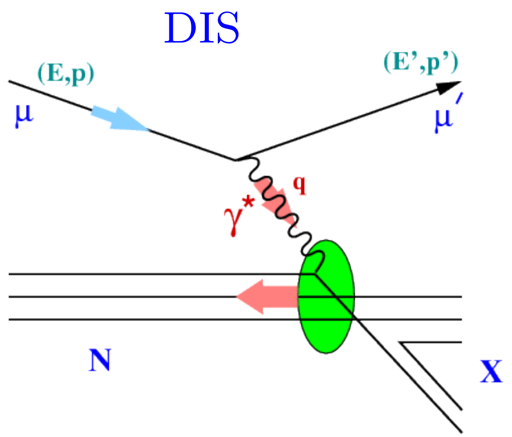
P_B=-76%

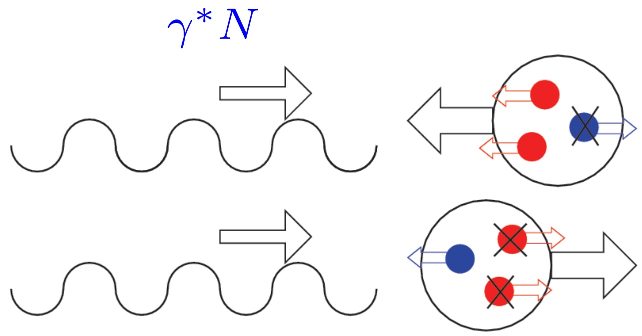
@160/200 GeV/c





Measuring the quarks spin contribution





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

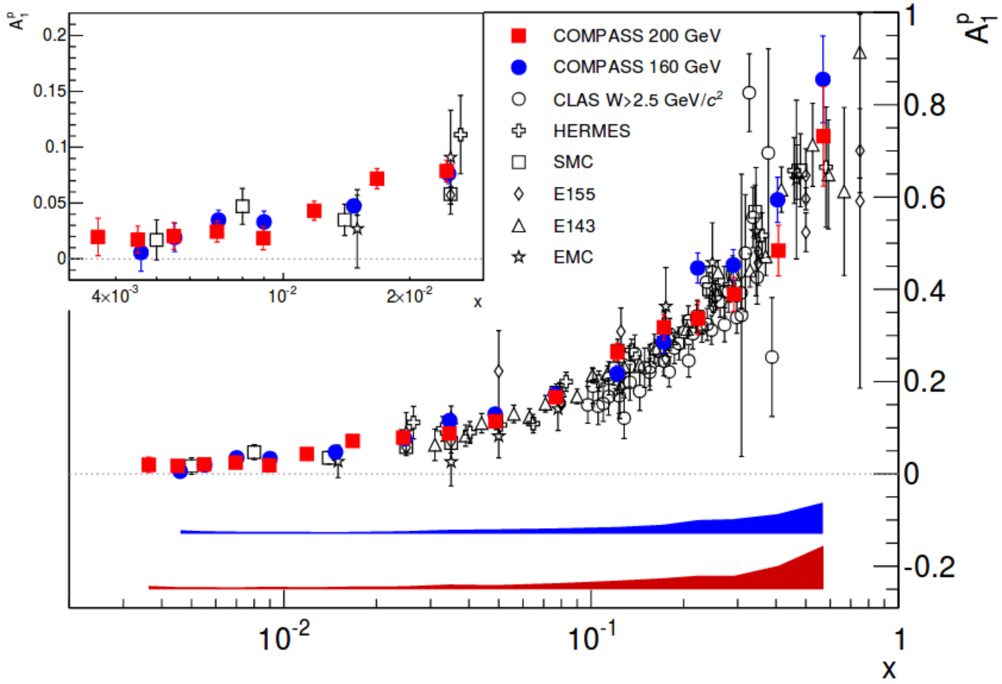
To access the **helicity function** g_1 we measure double longitudinal spin asymmetries.

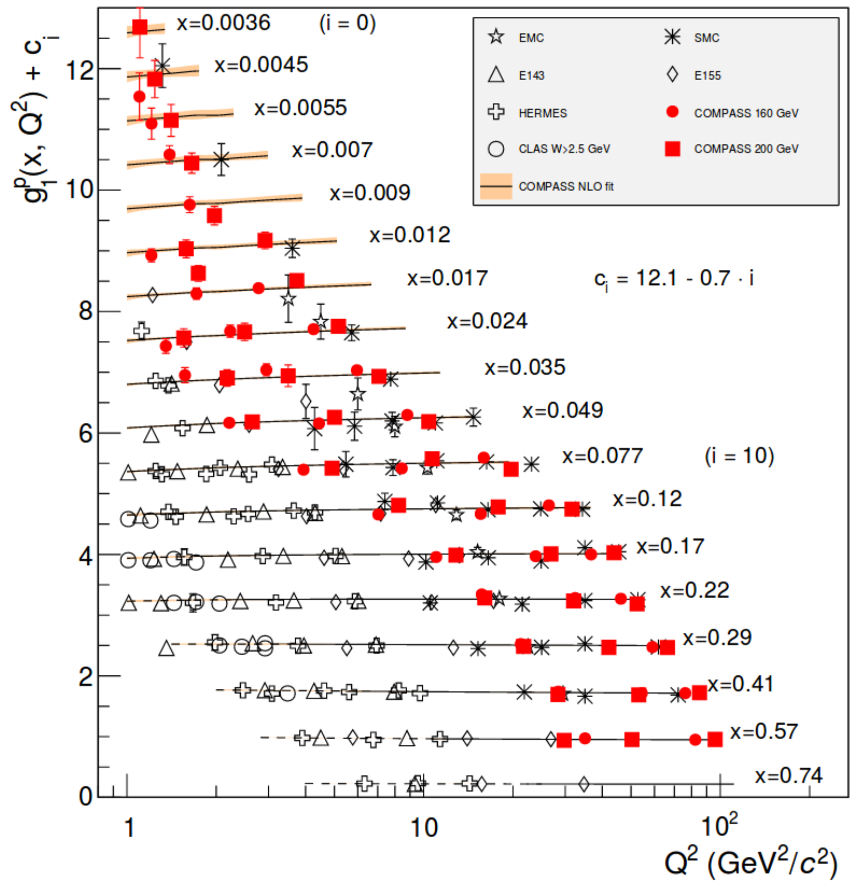
The μ-proton asymmetry is measured from the difference between cross-sections from 2 opposite spin configurations:

$$A^{\mu N} = \frac{1}{f P_T P_B} \left(\frac{N^{\rightleftarrows} - N^{\leftleftarrows}}{N^{\rightleftarrows} + N^{\leftleftarrows}} \right)$$

This measured asymmetry relates to the γ^*-proton asymmetries: $\frac{A^{\mu N}}{D} \approx A_1$.

Asymmetry A_1^p and Helicity function g_1^p



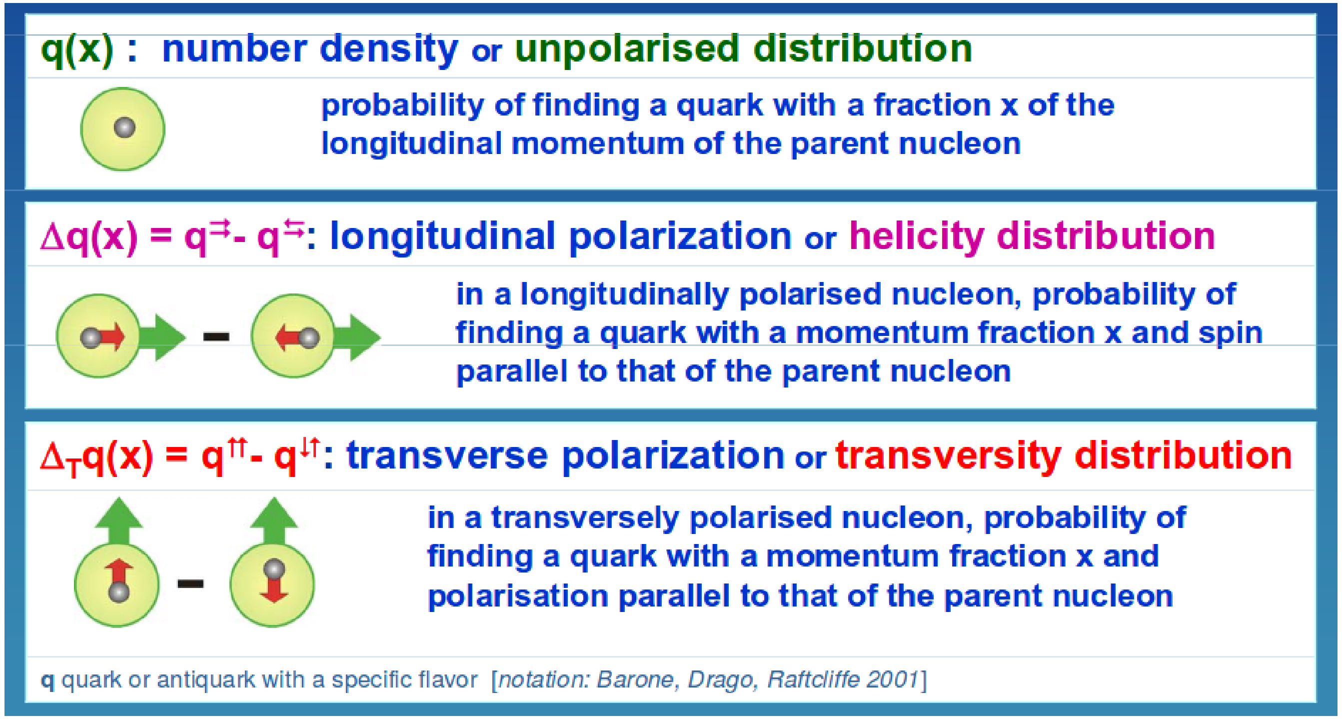


$$g_1^p \propto A_1^p \; F_2$$

It is from the first moment of g_1 that one can obtain $\Delta\Sigma$

The Transversity function h_1^p

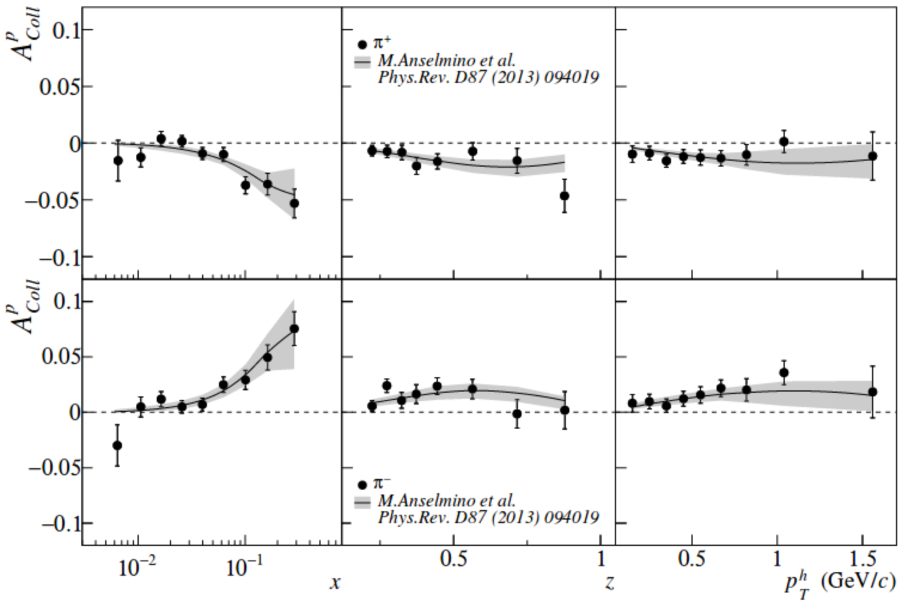
In the **collinear case** (of struck quark wrt parent proton) at leading order, three structure functions are needed to fully describe the nucleon structure:



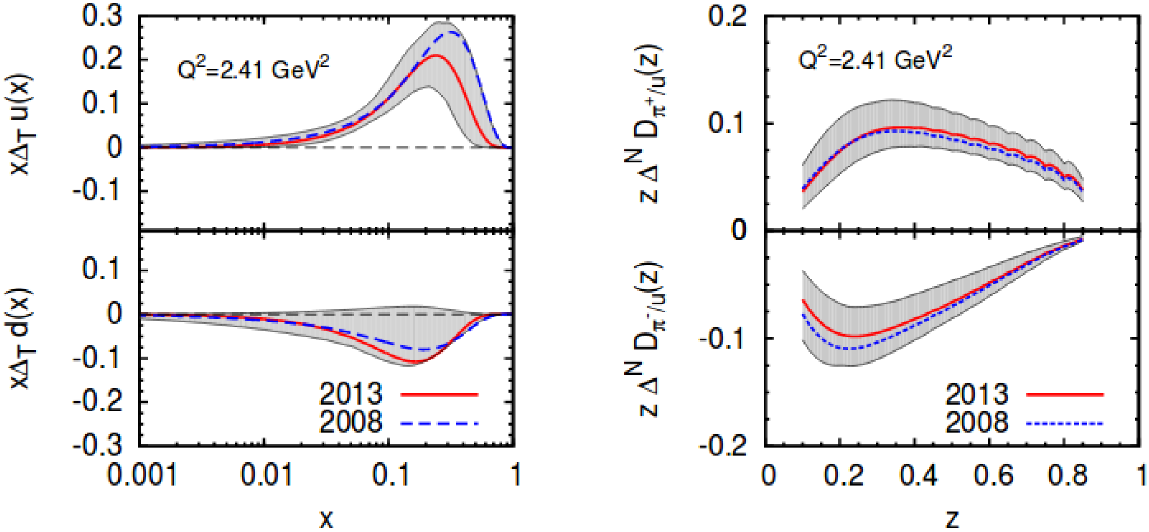
Transversity can only be accessed in SIDIS, from the azimuthal modulation of the final state hadrons wrt the lepton plane: Collins asymmetry.

$$A^{Coll} \propto h_1 \otimes \Delta D_q^h$$

The transversity PDFs extraction



COMPASS data on $p^{\uparrow}$ target, 2007 + 2010
COMPASS Coll., PLB 744 (2015) 250

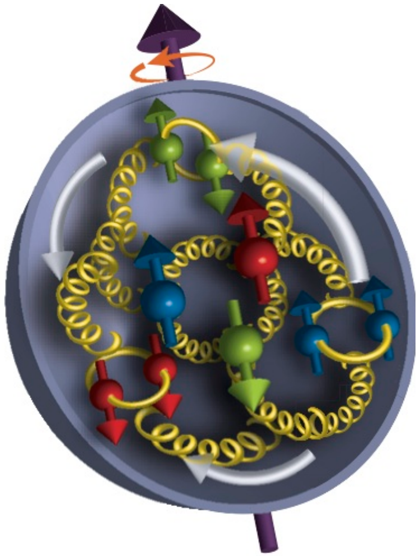


HERMES, COMPASS and BELLE data
Anselmino et al, Phys.Rev.D 87, 094019 (2013)

The nucleon spin puzzle

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.



- Latest results:

First moment	Value range at $Q^2 = 3\,(\mathrm{GeV}/c)^2$
$\Delta\Sigma$	[0.26 , 0.36]
$\Delta u + \Delta\bar{u}$	[0.82 , 0.85]
$\Delta d + \Delta\bar{d}$	[−0.45 , −0.42]
$\Delta s + \Delta\bar{s}$	[−0.11 , −0.08]

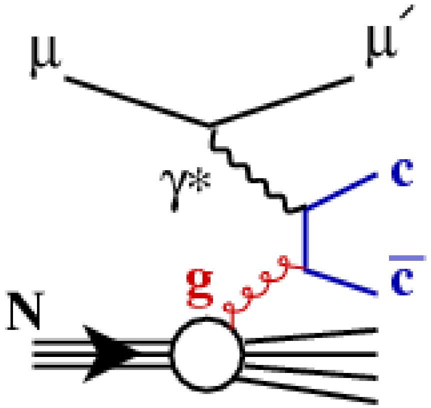
$\mapsto$ COMPASS Coll., PLB 753 (2016) 18

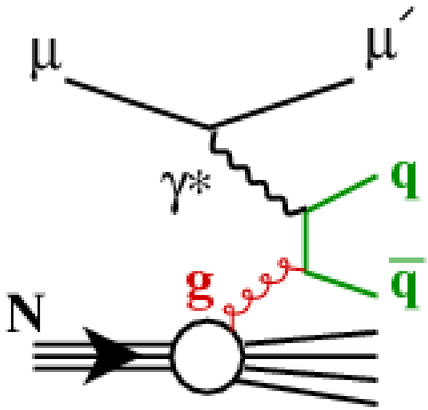
- The quarks spin is responsible for only 30% of the proton spin!
- The other contributions must be measured.

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.

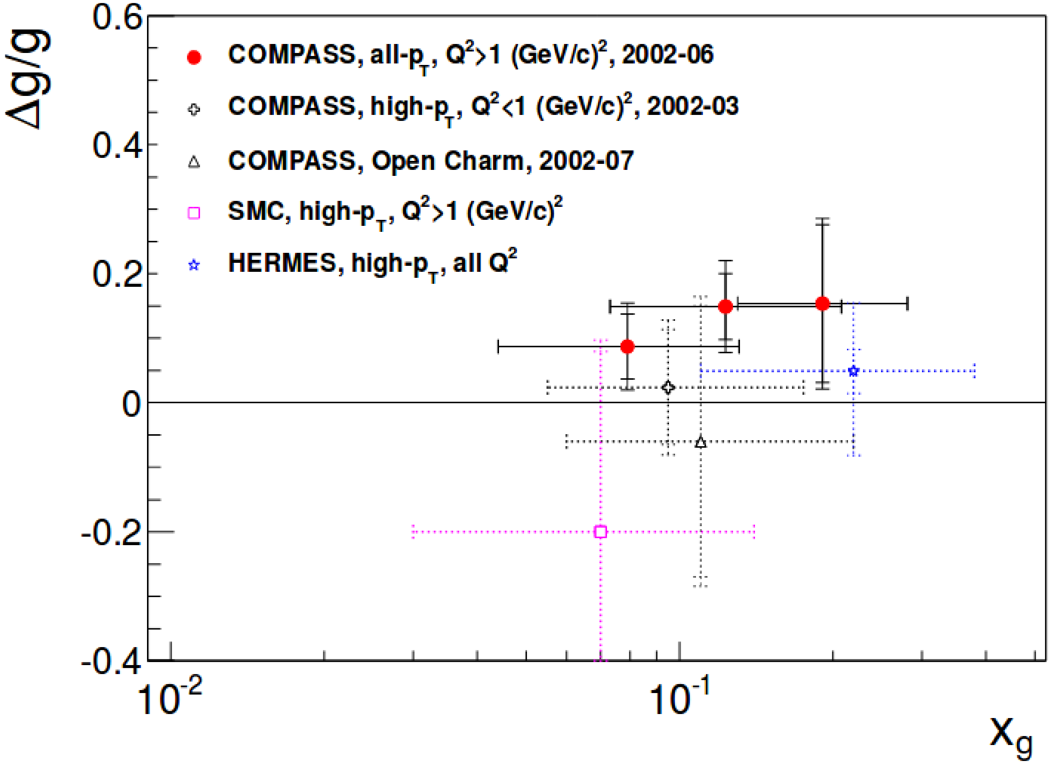




PGF events are selected by analysing:

- Open Charm production (D^0, D^*)
  - Very clean: almost no physics background
  - Low statistics
- High p_T hadron pairs
  - Large statistics available
  - Very dependent on Monte-Carlo
- All p_T hadron pairs
  - Even larger statistics
  - Very dependent on Monte-Carlo

“Direct” measurements of gluon polarization



Open-charm analysis (LO):
$\Delta G/G = -0.06 \pm 0.21(stat) \pm 0.08(syst)$
at $\langle x_g \rangle = 0.11$ and $\langle \mu^2 \rangle = 13$ GeV^2

Open-charm analysis (NLO):
$\Delta G/G = -0.13 \pm 0.15(stat) \pm 0.15(syst)$
at $\langle x_g \rangle = 0.20$ and $\langle \mu^2 \rangle = 13$ GeV^2

All p_T analysis (LO): $\Delta G/G = 0.113 \pm 0.038(stat) \pm 0.036(syst)$
at $\langle x_g \rangle = 0.10$ and $\langle \mu^2 \rangle = (\langle Q^2 \rangle) = 3$ GeV^2

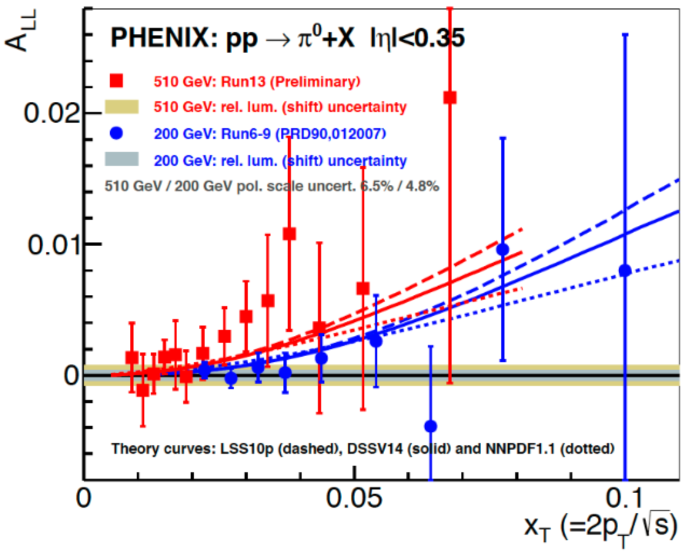
RHIC-SPIN results

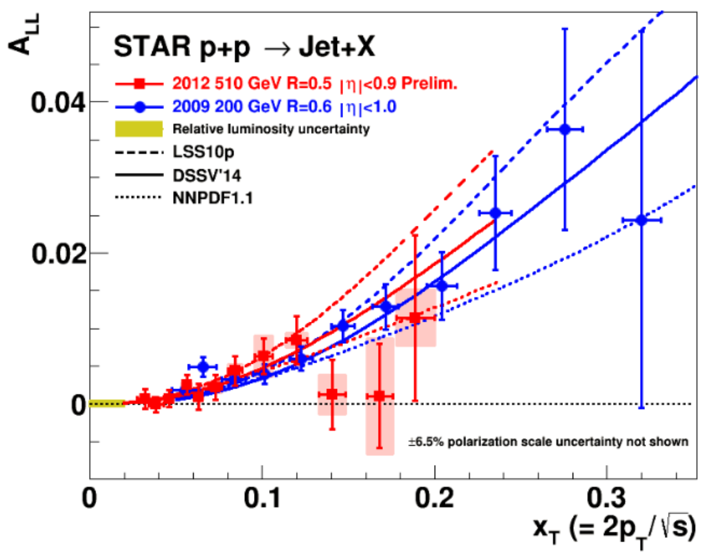
RHIC is a pp ($\sqrt{s}$=200, 500 GeV) collider at Brookhaven with possibility of having both proton beams polarized.

Two experiments performed double longitudinal spin asymmetries A_{LL}: STAR and PHENIX.

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

Combined published data and recent results of asymmetries



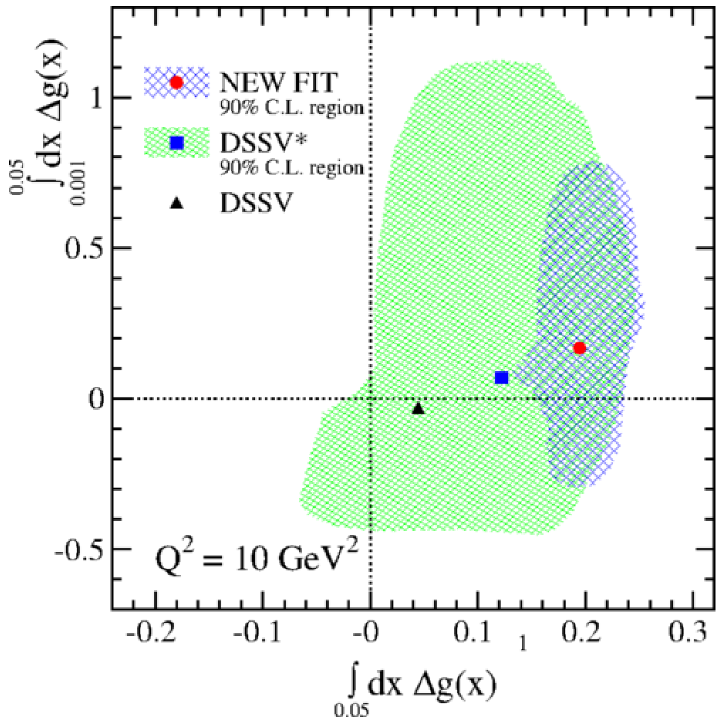


Gluon polarization: RHIC-SPIN results

RHIC $\vec{p}\vec{p}$ measurement are in the range $0.05 < x_g < 0.2$

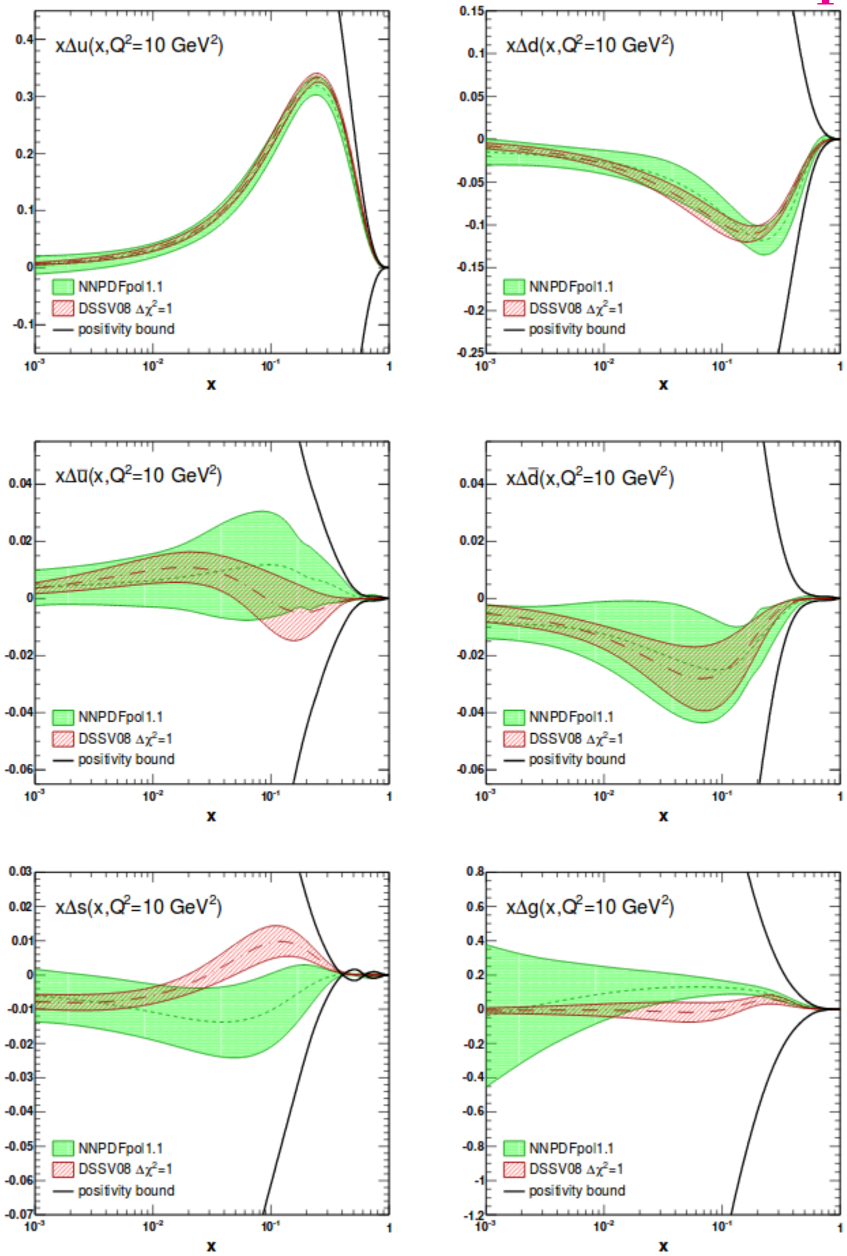
The new DSSV14 global analysis including 2009 RHIC data leads to:

$$\int_{0.05}^{1} dx\ \Delta g(x) = 0.2^{+0.06}_{-0.07}$$



$\hookrightarrow$Evidence for positive ΔG, just as also suggested by the COMPASS data.

Recent polarized PDFs



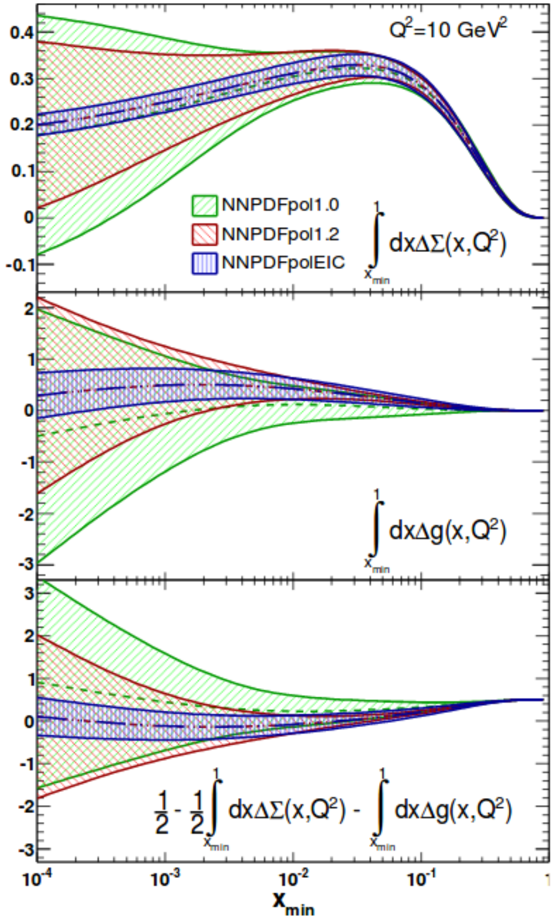
NNPDFpol 1.1,
Nucl.Phys. B887 (2014) 276-308

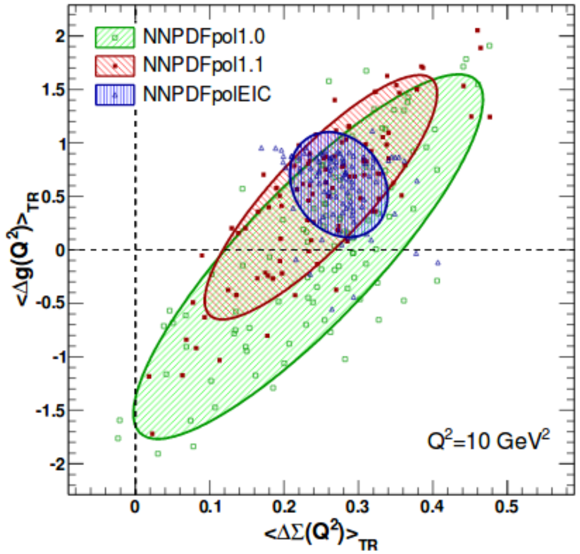
Open issues include:

- RHIC data at $\sqrt{s} = 500$ GeV (2013) still not included
- Several COMPASS results are at LO, thus cannot be included
- All PDF determinations based on DIS data only obtain Δs negative. If SIDIS data on kaons is also included, the result comes either positive or negative depending on the FF set used.

Is the proton spin puzzle solved?

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	$+0.24 \pm 0.04$	$+0.49 \pm 0.25$

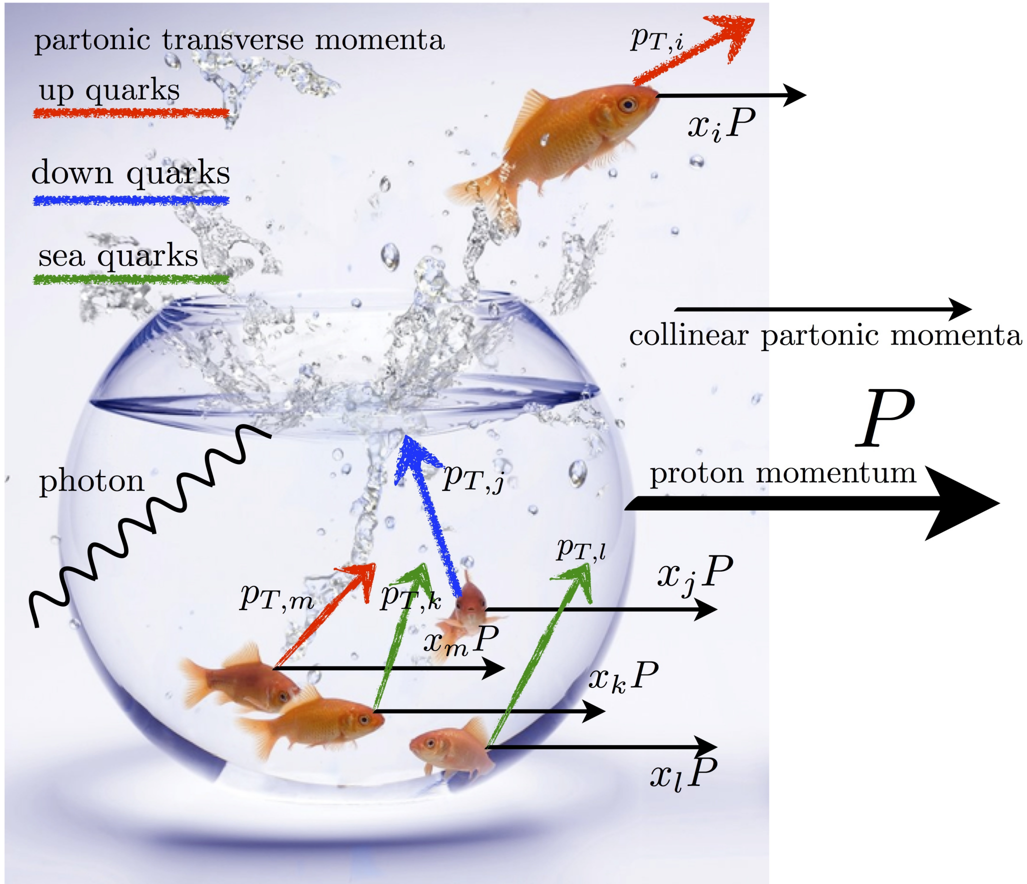
quarks and antiquarks $\sim 20\% - 30\%$
gluons $\sim 70\%$
OAM $\sim 0\%$

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

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?

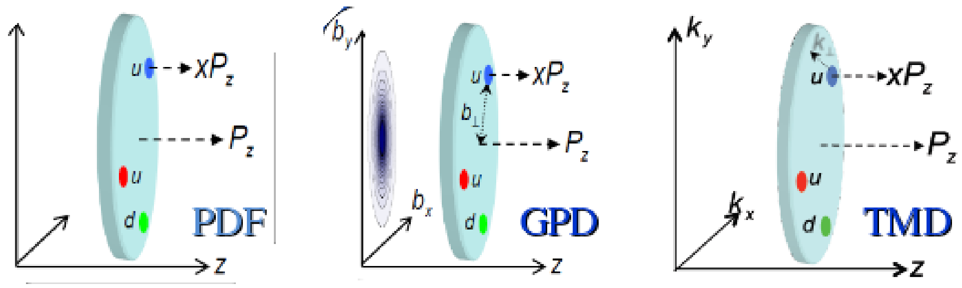
Going beyond the collinear approximation

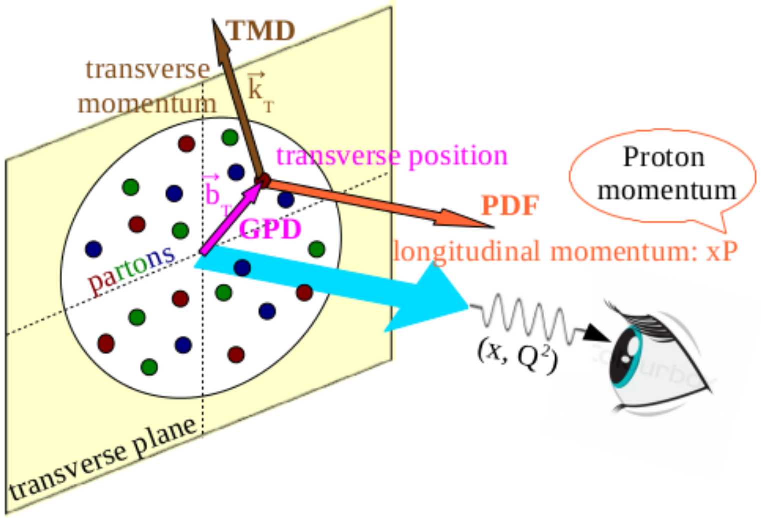


Quarks and gluons have not only a longitudinal momentum (fraction x of the proton momentum), but also an intrinsic transverse momentum k_T.

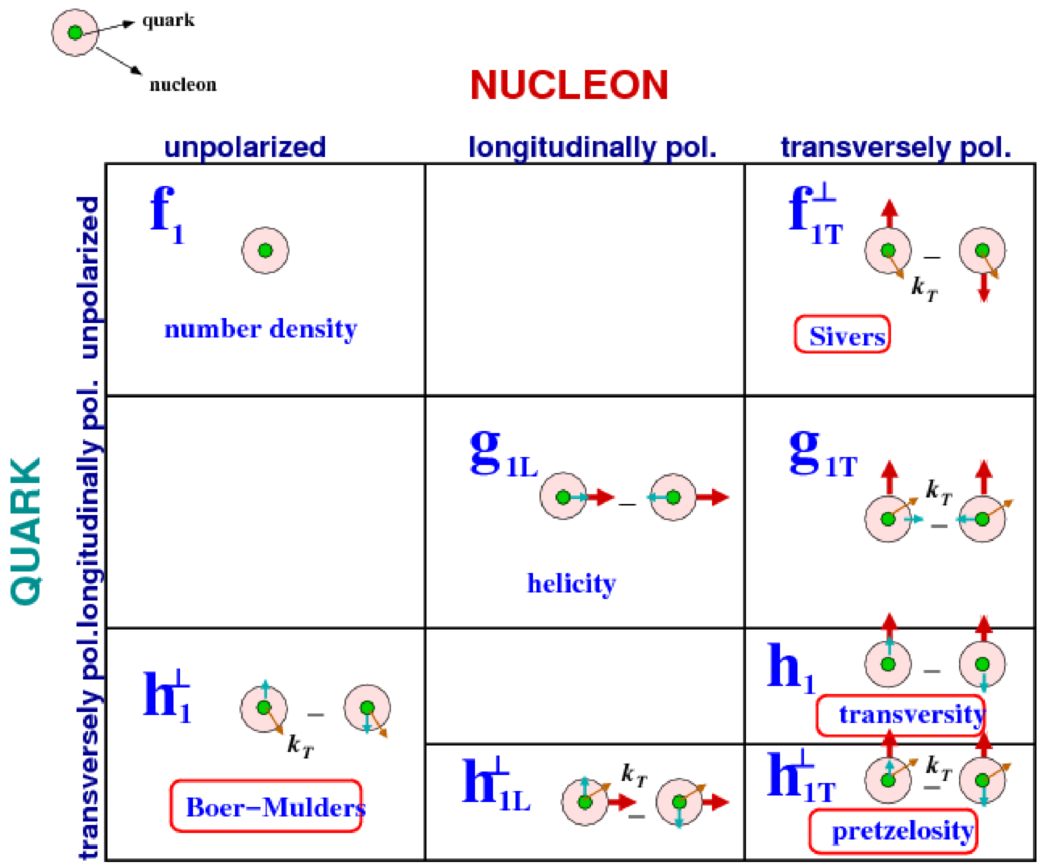
Going beyond the collinear approximation

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





TMD PDFs



At leading order, 3 PDFs are needed to describe the structure of the nucleon in the collinear approximation.

But if one takes into account also the quarks k_T, 8 TMD PDFs are needed.

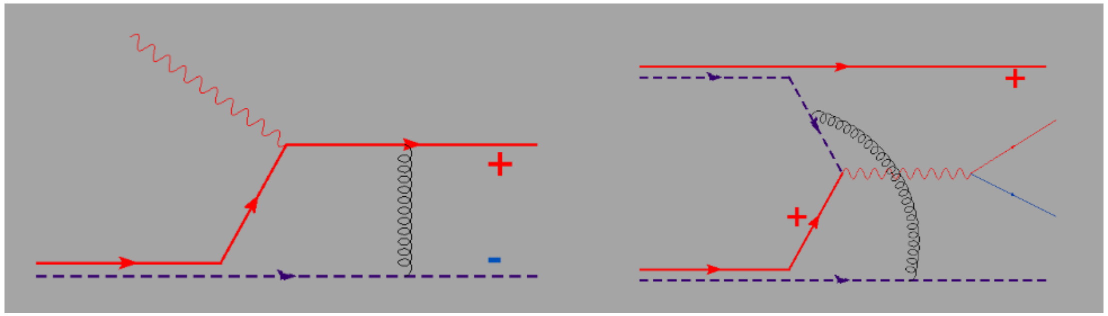
- Having a transversely polarized proton target one can access Sivers, transversity, pretzelosity, and also the unpolarized Boer-Mulders TMD PDFS, via **SIDIS** or **Drell-Yan** processes.

  ↪**single transverse spin asymmetries**

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

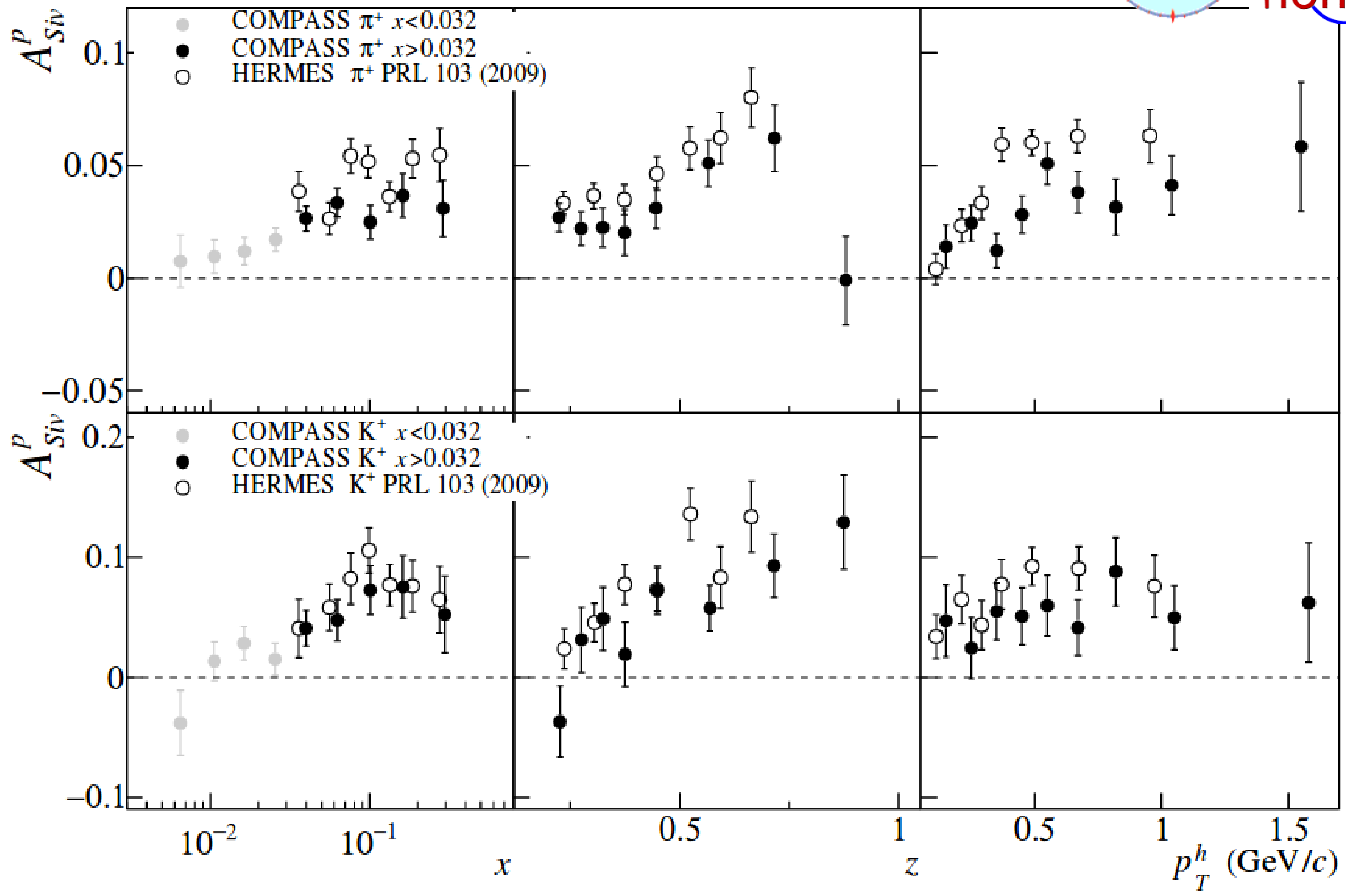


$$f_{1T}^{\perp}(\mathrm{SIDIS}) = - \; f_{1T}^{\perp}(\mathrm{DY})$$

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

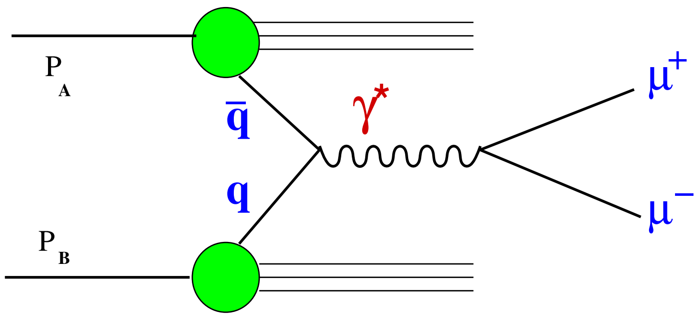


Sizable Sivers effect measured for positive hadrons – qualitatively, this can only mean sizable **orbital angular momentum** of quarks inside the proton.

Sivers TMD measured in DY

The experimental check of the **sign change** in Sivers TMD is a crucial test of the TMD approach, and of the non-perturbative QCD itself
(btw, the same is true for the Boer-Mulders TMD, which is also T-odd).

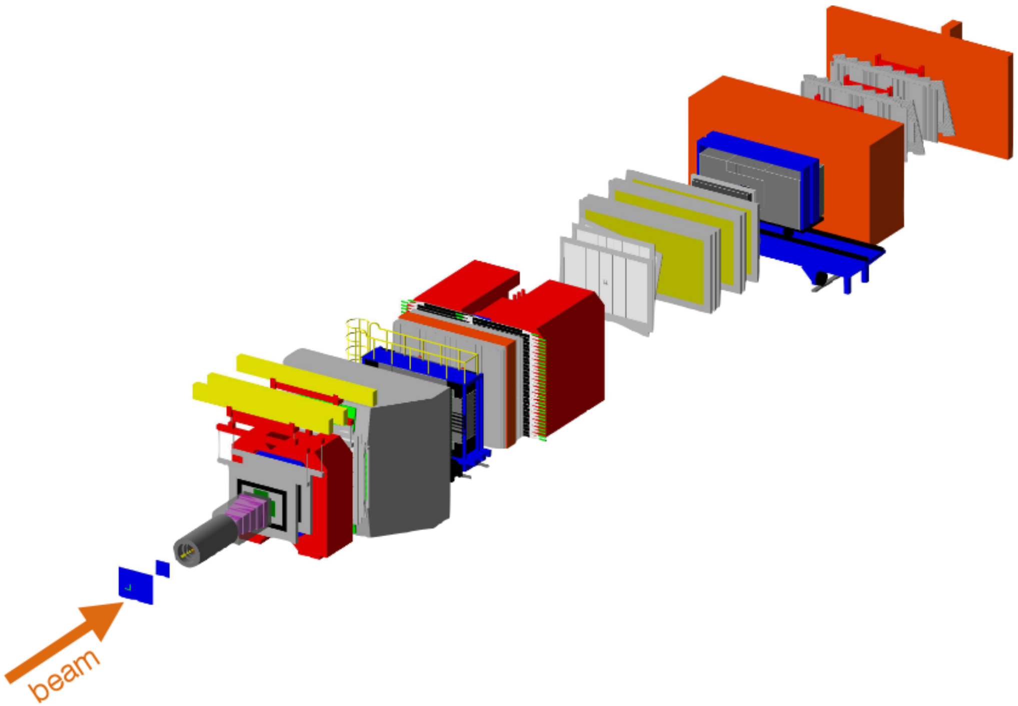
$$f_{1T}^{\perp}(\text{SIDIS}) = - f_{1T}^{\perp}(\text{DY})$$

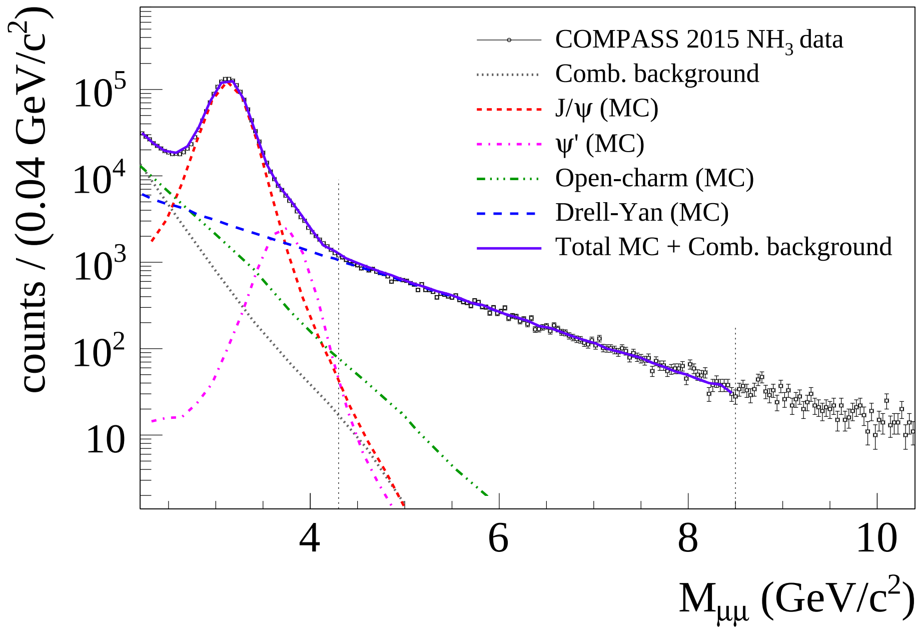


- Drell-Yan can be also generalized to $q\bar{q} \to \gamma^*/Z^0 \to l^+l^-$ or $q\bar{q} \to W^{\pm} \to l\nu$.
- Drell-Yan is **time-like**: $Q \equiv M_{l^+l^-}$
- In COMPASS@CERN: pion induced DY – probing valence u-quarks
- STAR@RHIC: *pp* collisions – probing quarks sea

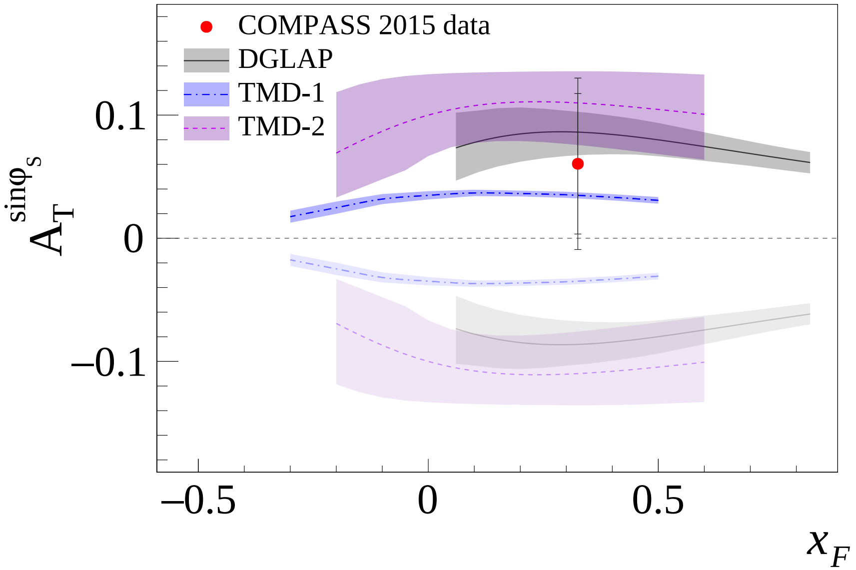
COMPASS polarized DY measurements

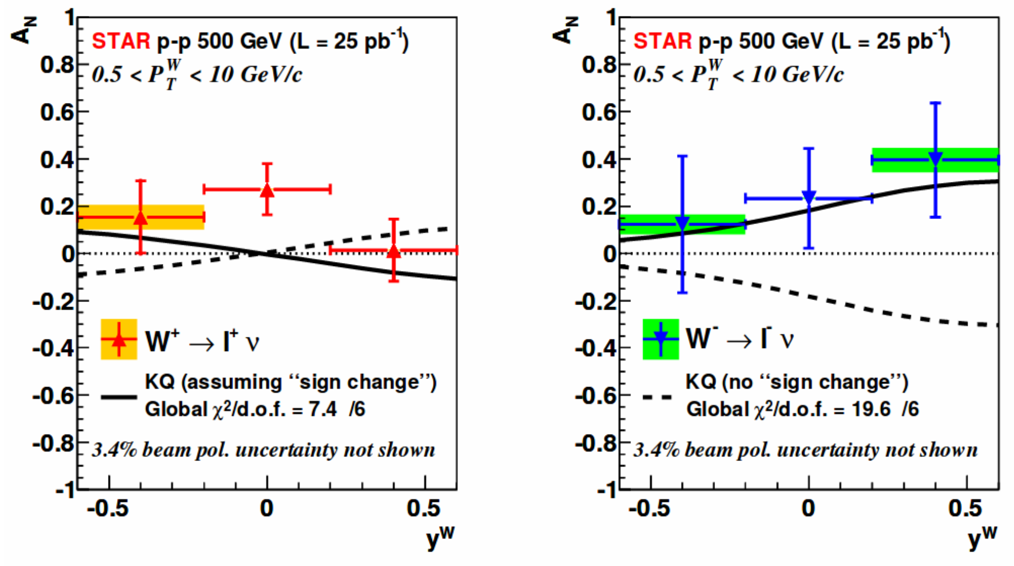
- pion beam of 190 Ge/c momentum
- a transversely polarized target of NH_3 (i.e. 3 polarized protons per molecule)
- a muon pairs trigger
- an hadron absorber downstream of the target, to stop everything but muons
- Good enough azimuthal angle resolution
- same spectrometer as for SIDIS





The Sivers sign change





$x_F = x_\pi(beam) - x_p(target)$: Feynman-x

$y^W = \frac{1}{2} ln(\frac{E+p_z}{E-p_z})$: $W^\pm$ rapidity

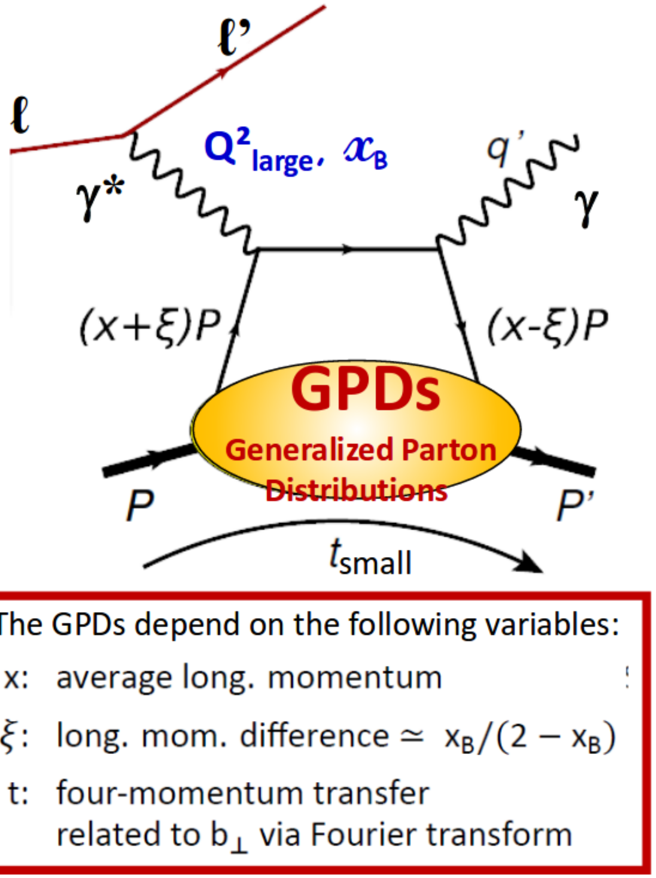
$A_T^{\sin\phi_S}$: Sivers azimuthal transverse spin asymmetry

A_N: left-right asymmetry of the produced Ws

Not yet a proof of the Sivers sign change, due to very limited statistics. For the moment, only a hint...

Generalized Parton Distributions

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

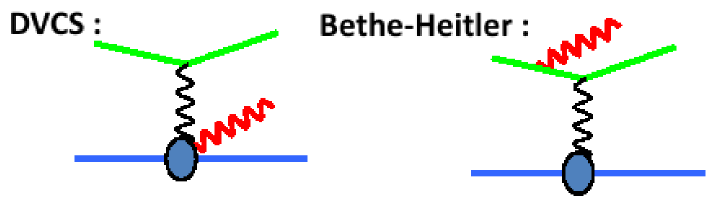


Deeply Virtual Compton Scattering

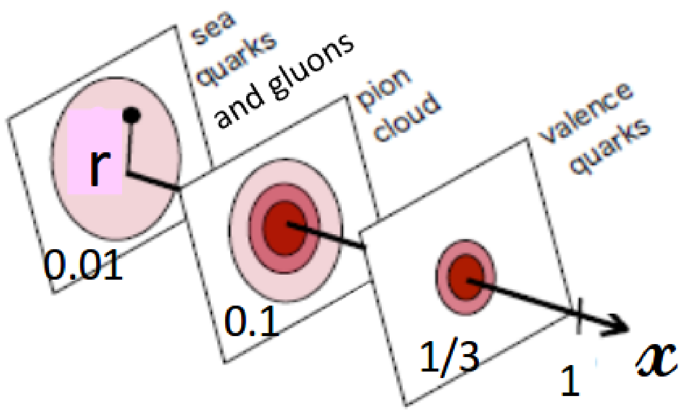
- 4 GPDs: H, E, $\tilde{H}$ and $\tilde{E}$, for each quark flavor and gluons, functions of (x, ξ, t).
- allows access to orbital angular momentum in the nucleon:
  Ji sum rule
  $$2J^q = lim_{t\to 0} \int x\ (H^q\ +\ E^q)\ dx$$
- **DVCS**: exclusive process, golden channel for acessing GPDs
  $\mu p \to \mu' p' \gamma$

Measuring DVCS

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

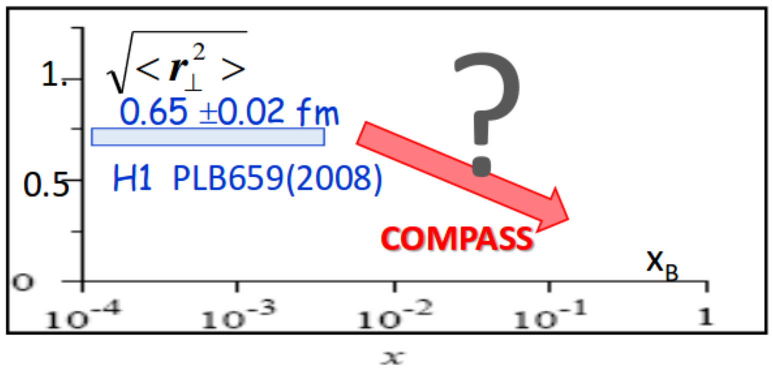


2



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

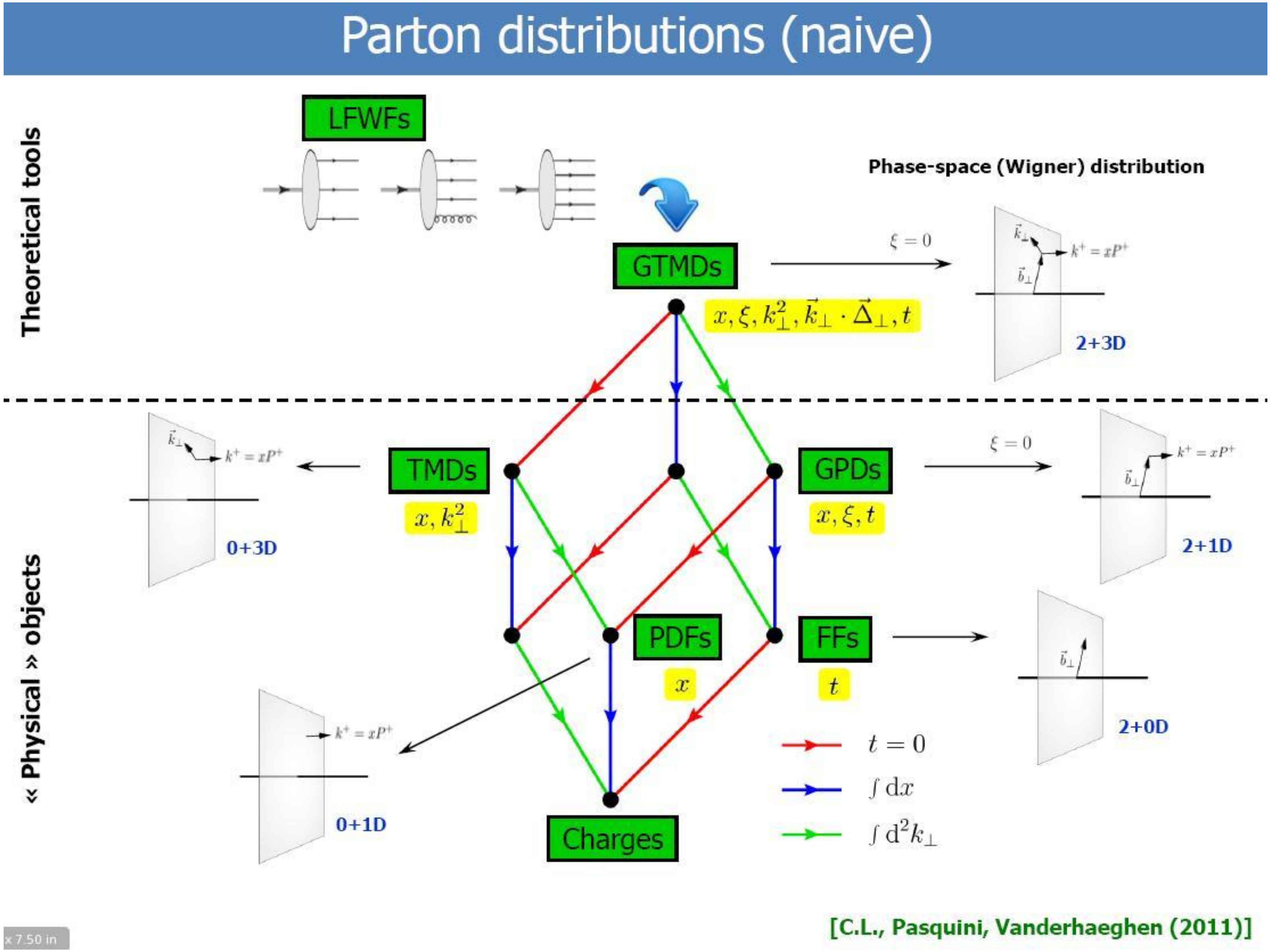
BH is well-known:
used as reference process.



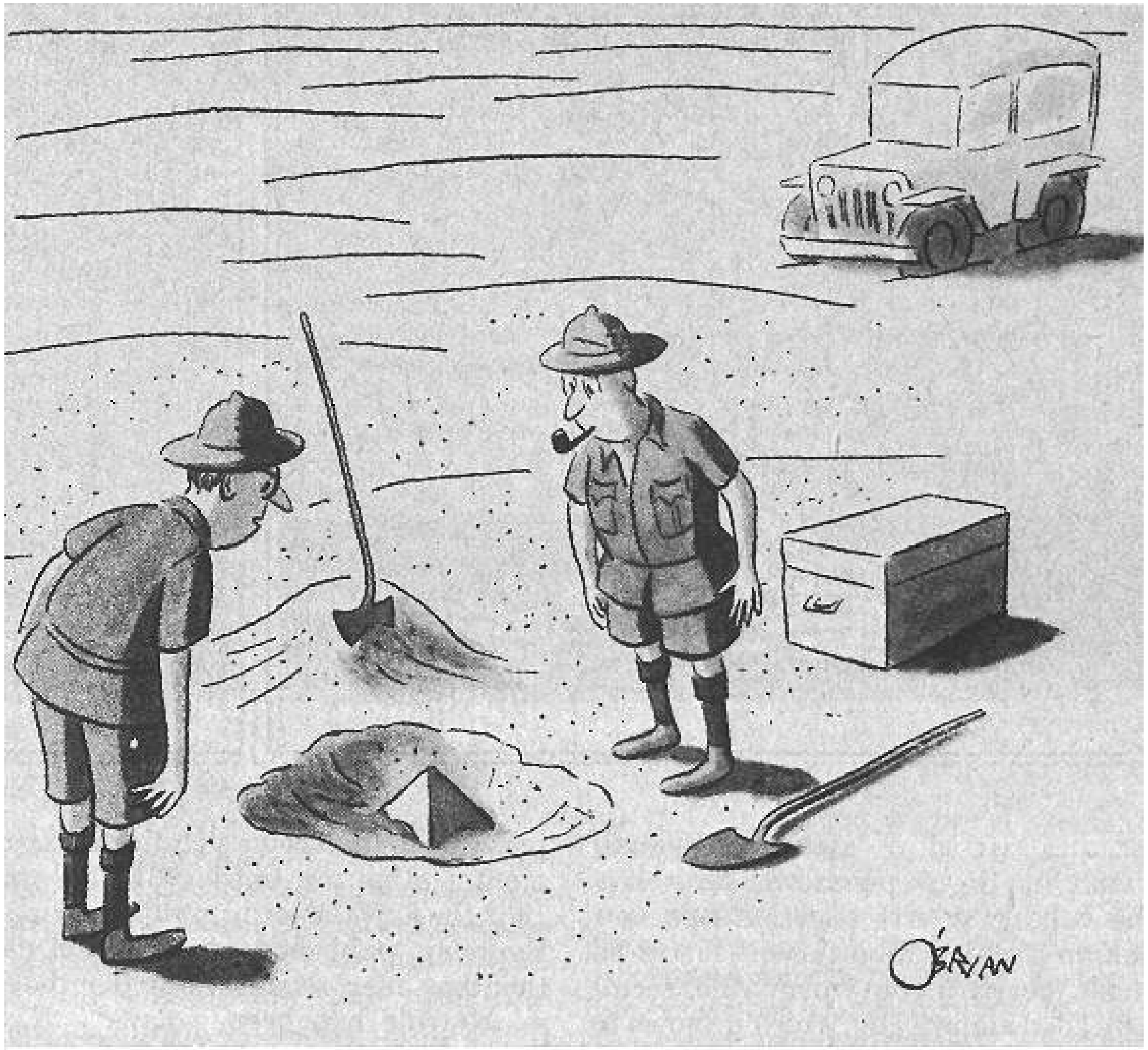
$\mu^{+\downarrow}$ and $\mu^{-\uparrow}$ beams off an unpolarized liquid H_2 target $\Rightarrow$ GPD H.

$\mu^{+\downarrow}$ 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."

Some final considerations

- QCD is not a finalized theory: too many unknowns, too many parameters...
- Namely in the non-perturbative regime, initial parameters are required, that can only be obtained experimentally
- Nobody knows yet how to make the matching between the perturbative and the non-perturbative regimes
- Understanding the proton remains a challenge. We no longer talk about a "spin crisis", but the puzzle will not be solved until we measure it all.
- The uncertainty with which we know the PDFs enters as a systematic to many Standard Model precision measurements
- The role of the gluons is probably extremely relevant: after all, 99.8% of the hadrons mass is due to gluons (... not the Higgs field)