3D maps of the PROTON

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The M.A.P. Collaboration
Multi-dimensional Analysis of Parton distributions

OUR GROUP

Quantum ChromoDynamics (QCD) is the theory describing the **Strong Interactions** and controls the structure of ordinary matter, which is composed almost entirely of protons and neutrons.

However, QCD cannot yet be solved from first principles to derive their properties (mass, radius, spin...) in terms of their elementary constituents: **quarks and gluons** (collectively called partons).

To explore the internal structure of the proton, we hit it with a probe that interacts with its internal constituents.

At the energy scale of the proton's mass (~1 GeV), the QCD coupling constant is large and we cannot use perturbative methods.

However, for several high-energy scattering processes **factorization theorems** allow us to separate the probe-parton hard scattering (calculable with perturbation theory) from the internal dynamics of partons (which is non perturbative).

cross section = hard scattering $\otimes$ partonic map

We extract partonic maps of the internal structure of protons and neutrons from experimental data

From https://www.bnl.gov/eic/
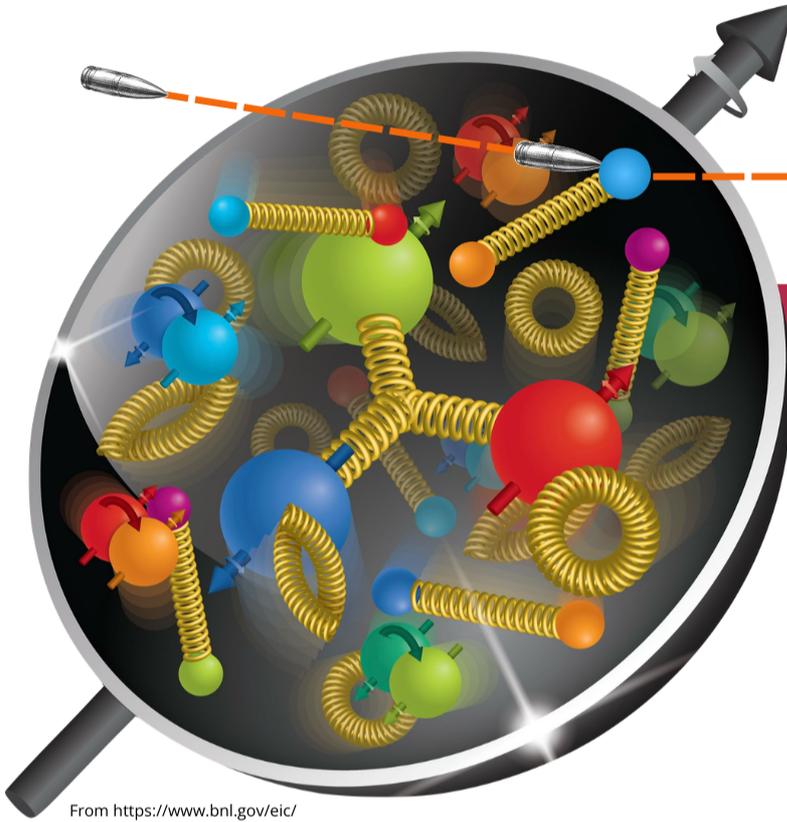
About 2000 data points from several experiments are used. The plot shows a representative ATLAS dataset.
The **Electron–Ion Collider** will deliver much larger data samples.

66 GeV < Q < 116 GeV
|y| < 2.5

NN
MAP22
ATLAS 13 TeV data

P.R.L. **135** (2025) 021904
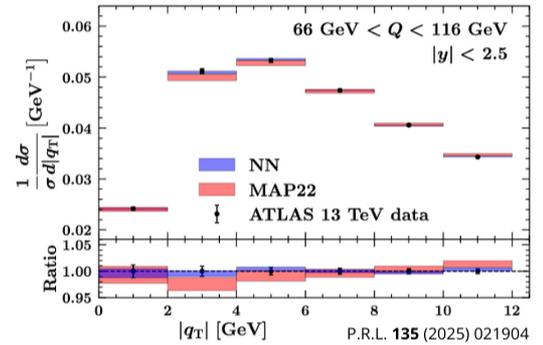
The plot on the **right** shows the **3D tomography** in momentum space of an unpolarized quark in an unpolarized proton. Partonic maps are universal and are essential to understand the full dynamics of partons.

We use also **Machine Learning** techniques (Neural Networks, NN) to perform our fits of experimental data.
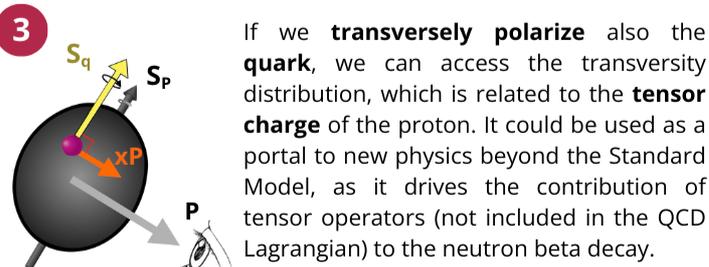
Input, variables: **x, k_T**
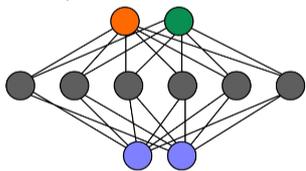
The advantage is that NN allow to create more flexible and less biased functional forms.

①

k_T

xP

P

The probe sees the proton Lorentz contracted along **P**.

JHEP06 (2017) 081
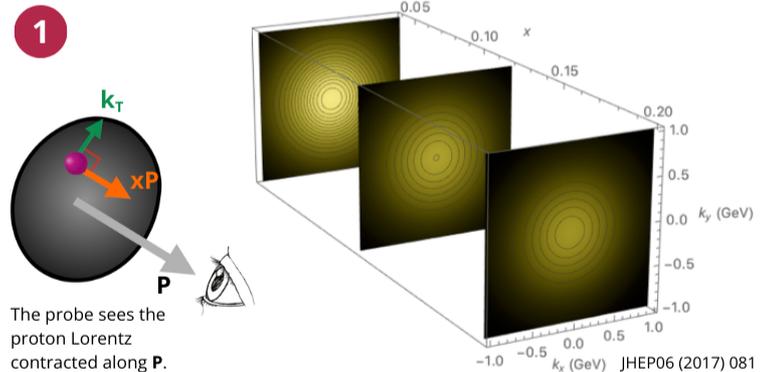
Distribution of **unpolarized** quarks in an **unpolarized** proton as a function of (k_x, k_y) and of the longitudinal fractional momentum x.

③

S_q

S_P

xP

P

If we **transversely polarize** also the **quark**, we can access the transversity distribution, which is related to the **tensor charge** of the proton. It could be used as a portal to new physics beyond the Standard Model, as it drives the contribution of tensor operators (not included in the QCD Lagrangian) to the neutron beta decay.

The transversity distribution can be extracted through Dihadron Fragmentation Functions:
V. Mahaut, L. Polano et al., JHEP02 (2026) 051

②

S_P

k_T

xP

P

$\rho_{p\uparrow}^d$ d

$\rho_{p\uparrow}^u$ u

x = 0.1

x = 0.1

Phys.Lett.B 827 (2022) 136961
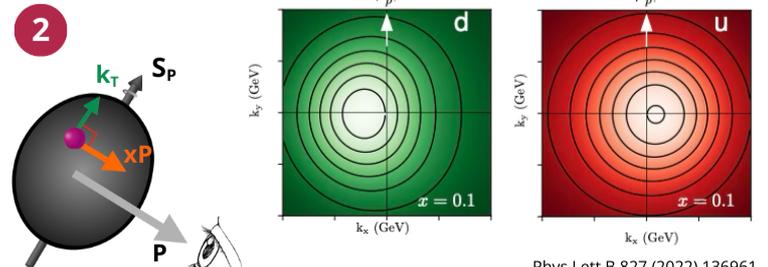
If the **proton** has a **transverse polarization S_P**, the quark distribution gets distorted, in opposite directions for the **up** (right) and **down** (left) quarks.