The Transverse Spin Structure of the Nucleon

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JEFFERSON LAB

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Lessons Scheme

LECTURES 1 & 2

- Introduction
- Deep Inelastic Scattering and 1D parton distribution functions
- From 1D to 3D nucleon structure: Transverse Momentum Dependent (TMD) parton distribution functions
- TMD Measurements @ Jlab in Hall B

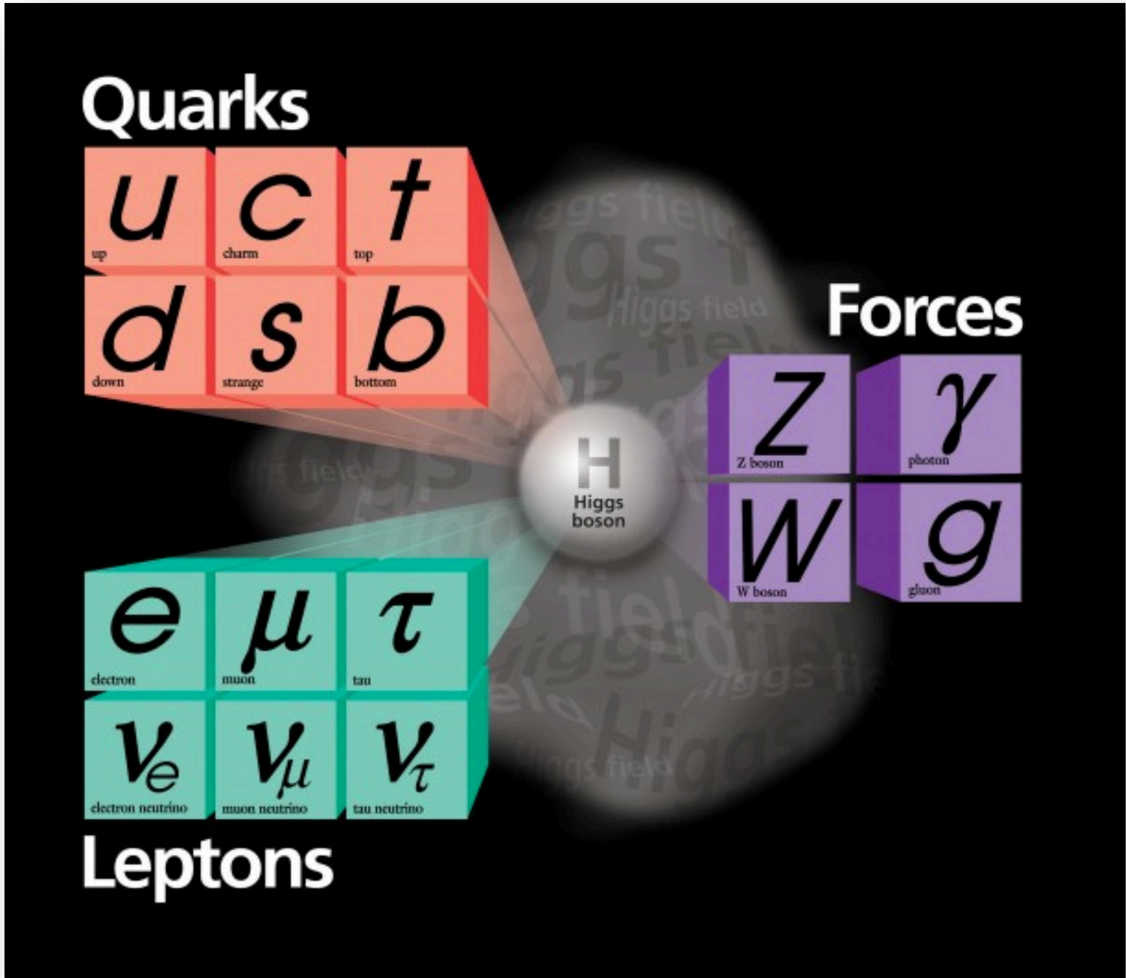
LECTURES 3 & 4

- Data analysis
- Monte Carlo simulations
- Asymmetries extraction
- TMDs extraction

LECTURE 5

- Where are we? What's next

The Standard Model



- simple and comprehensive theory that explains all the hundreds of particles and complex interactions
  - 6 quarks
  - Fractional charge
  - 6 leptons

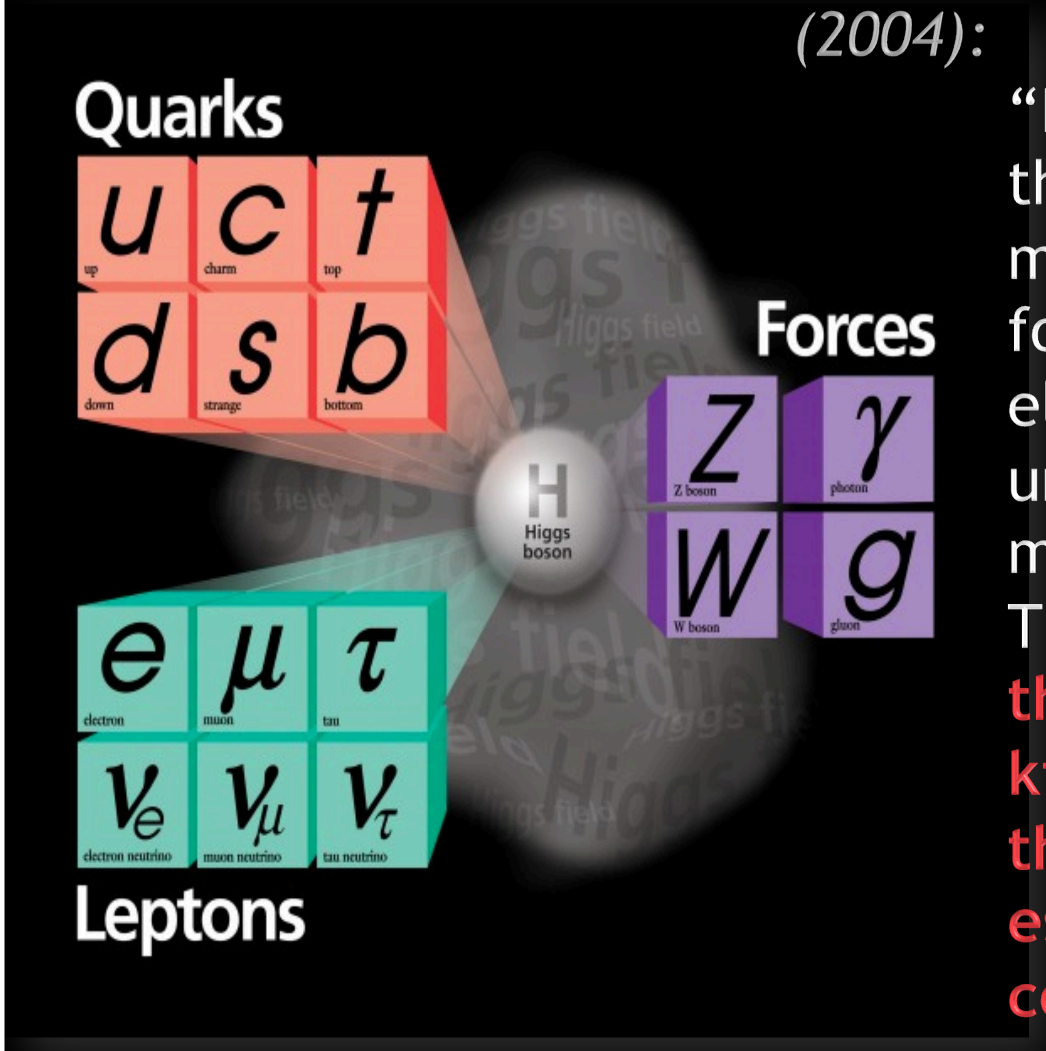
  split into 3 generations

  FERMIONS

  - 4 different forces carrying particles which lead to the interactions between particles.

  Bosons
- HIGGS

The Standard Model and our world

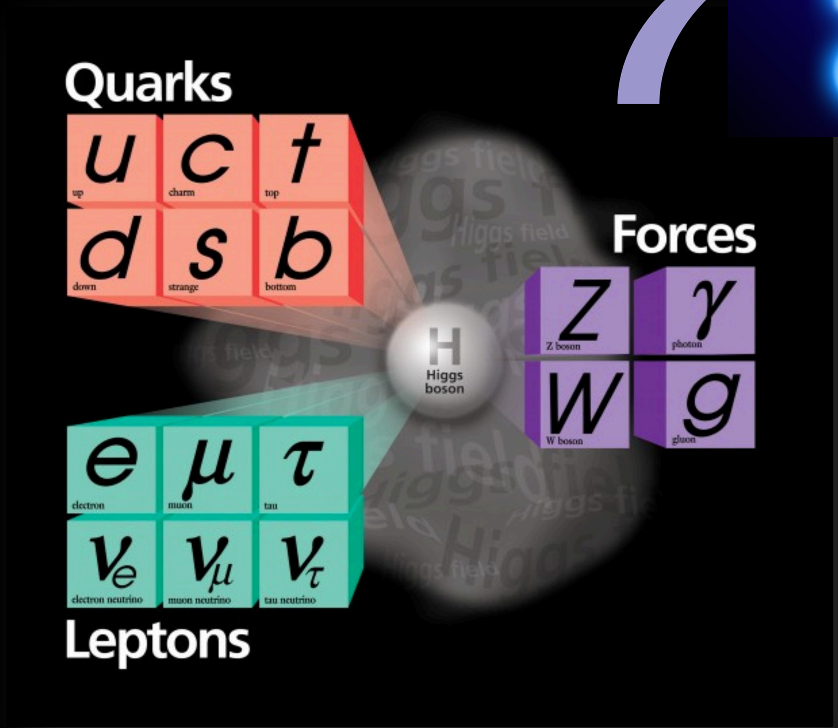


From the D. Gross Nobel Lecture (2004):

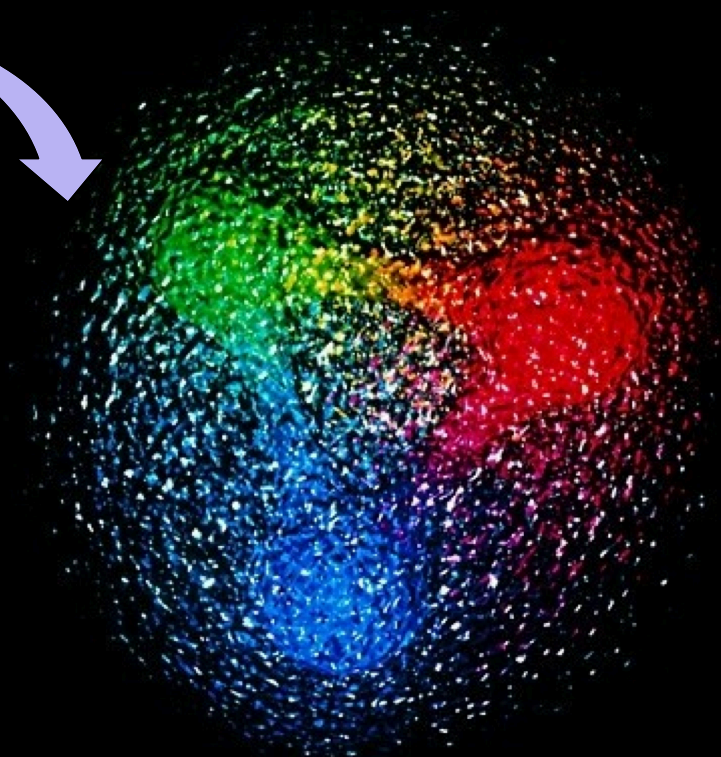
"It is sometimes claimed that the origin of mass is the Higgs mechanism that is responsible for the breaking of the electroweak symmetry that unbroken would forbid quark masses.
This is incorrect. **Most, 99%, of the proton mass is due to the kinetic and potential energy of the massless gluons and the essentially massless quarks, confined within the proton."**

The Standard Model & the QCD

Elementary Particles



Nucleon



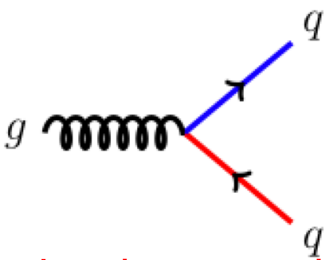
Proton Mass $\gg$ M(up) + M(up) + M(down) ~ 10 MeV

Proton Spin : Only 25% of the proton spin is carried by the quarks

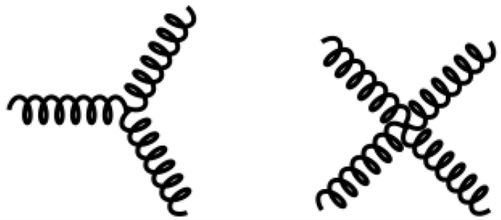
Quantum Chromo Dynamics

Gluons are the messengers for the quark-quark interactions

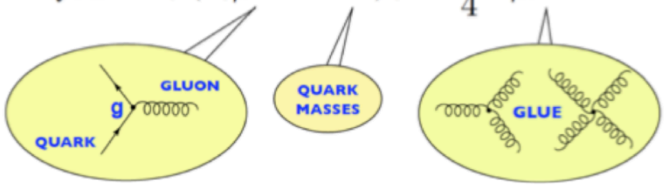
Quantum Chromo Dynamics (QCD) is the theory that governs their behaviour



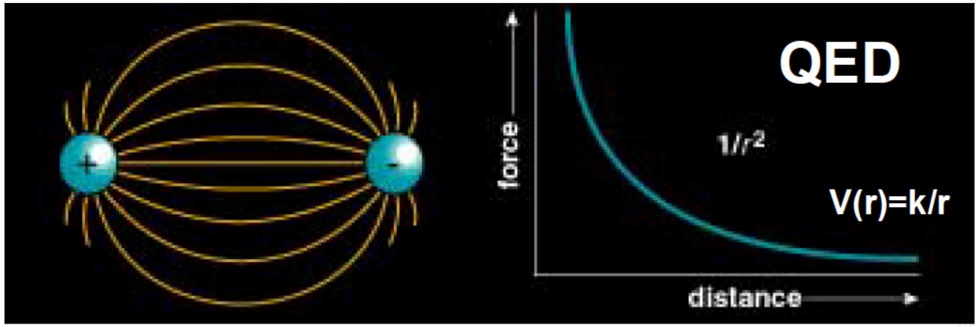
Gluons carry color charge, and we can draw 3- and 4- gluon diagrams (self-interaction)

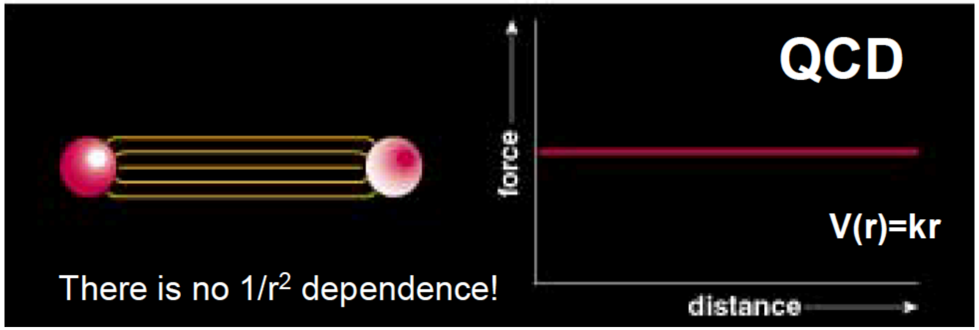


$$\mathcal{L}_{QCD} = \bar{\psi}(i\gamma_\mu D^\mu - m)\psi - \frac{1}{4}G_{\mu\nu}G^{\mu\nu}$$

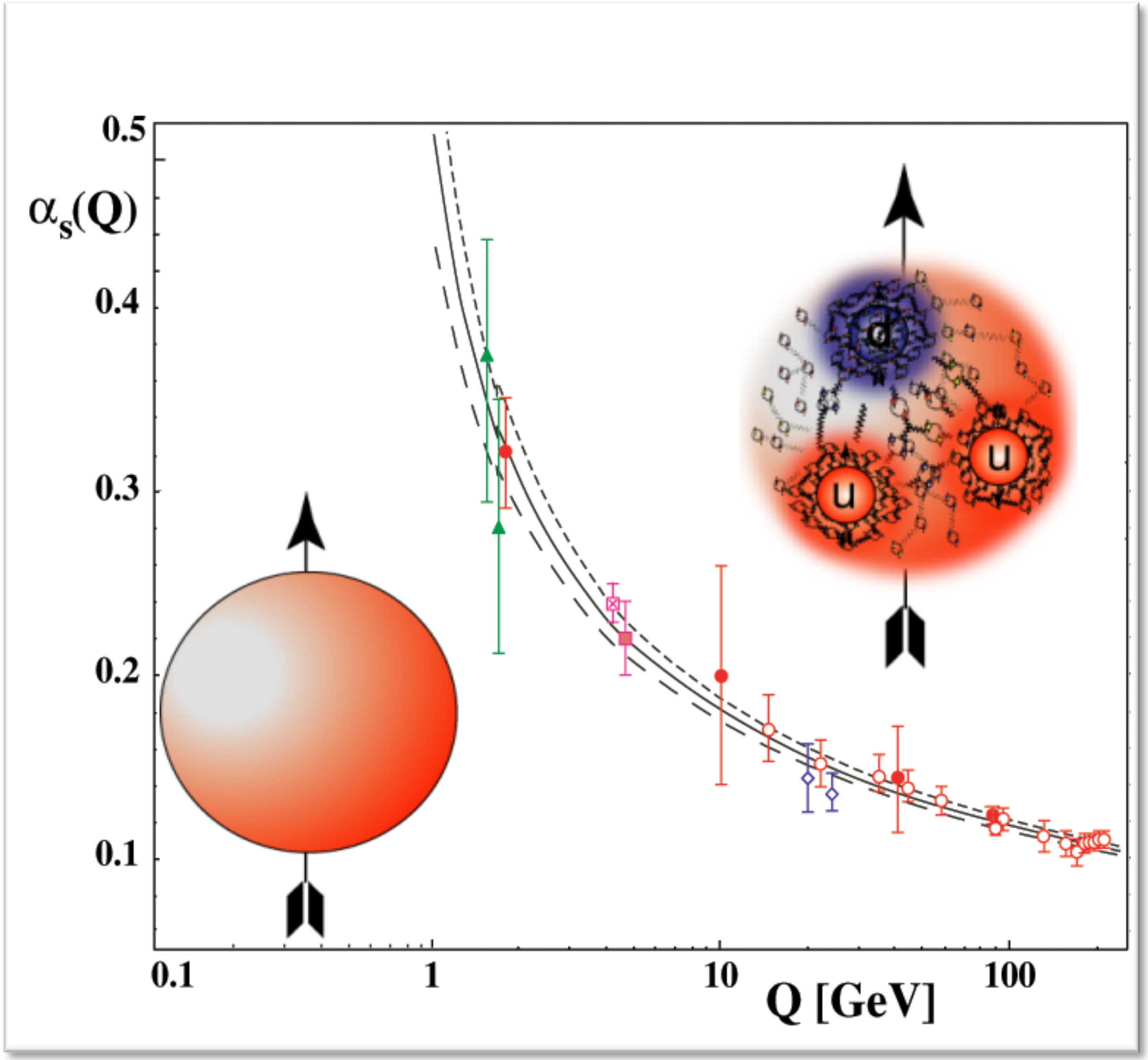


The strong force does not get weaker with large distances (opposite to the EM force) and blows up at distances around 10^{-15} m (the radius of the nucleon)





Quantum Chromo Dynamics



At short distances
quarks move as though they are free → **Asymptotic freedom**
Physics at short distance is understood through perturbation theory - $\alpha_s(m_Z)$= 0.1189(10)
Perturbative QCD tested up to 1% level

At longer distances
Confinement ensures that only hadronic final states are observed
Quarks can be removed from the proton, but cannot be isolated!!!
We never see a free quark
QCD still unsolved in non-perturbative region
Insights into soft phenomena exist through qualitative models and quantitative numerical (lattice) calculations

Lepton Scattering: a Powerful Tool

The best evidence we have on what nucleon looks like comes from electron scattering experiments

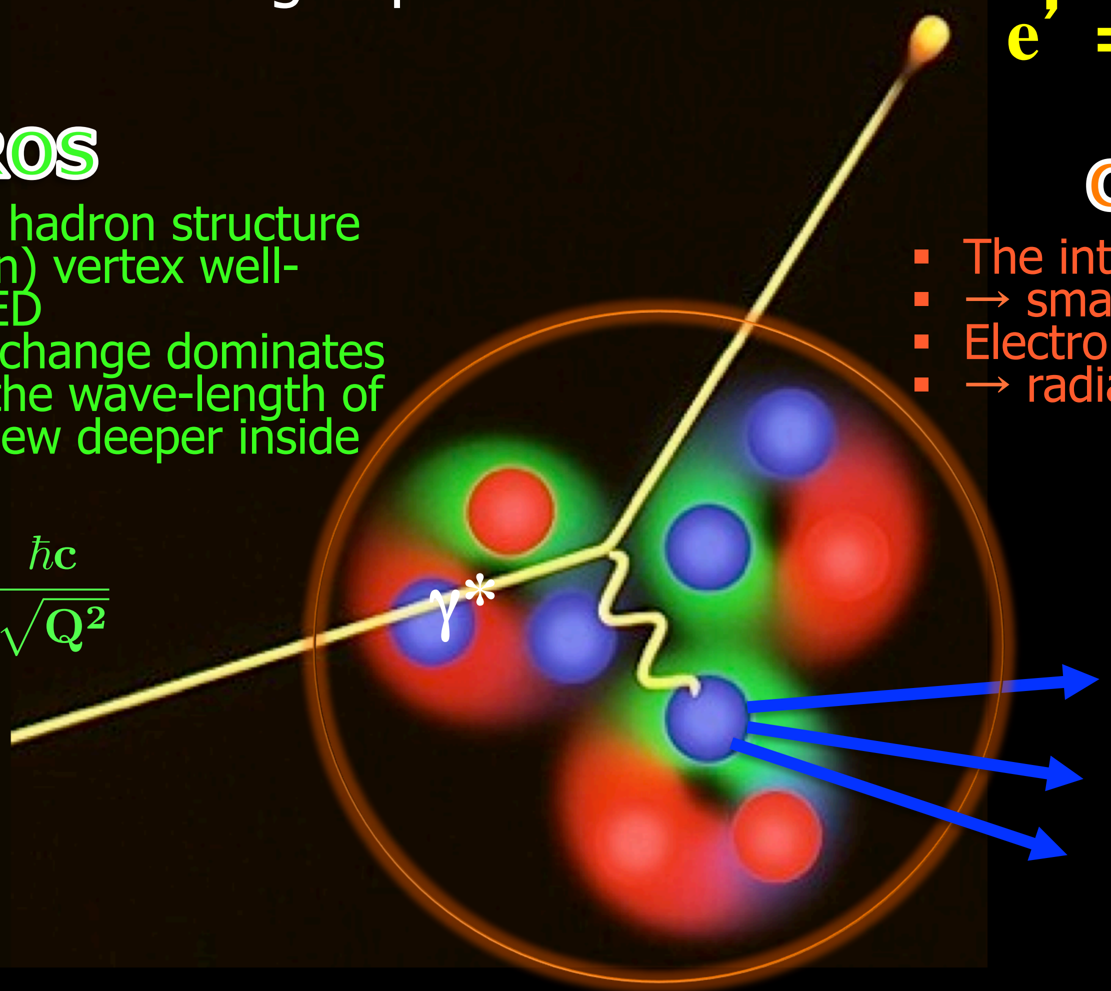
PROS

- Clean probe of hadron structure
- Electron (lepton) vertex well-known from QED
- One-photon exchange dominates
- One can vary the wave-length of the probe to view deeper inside the hadron

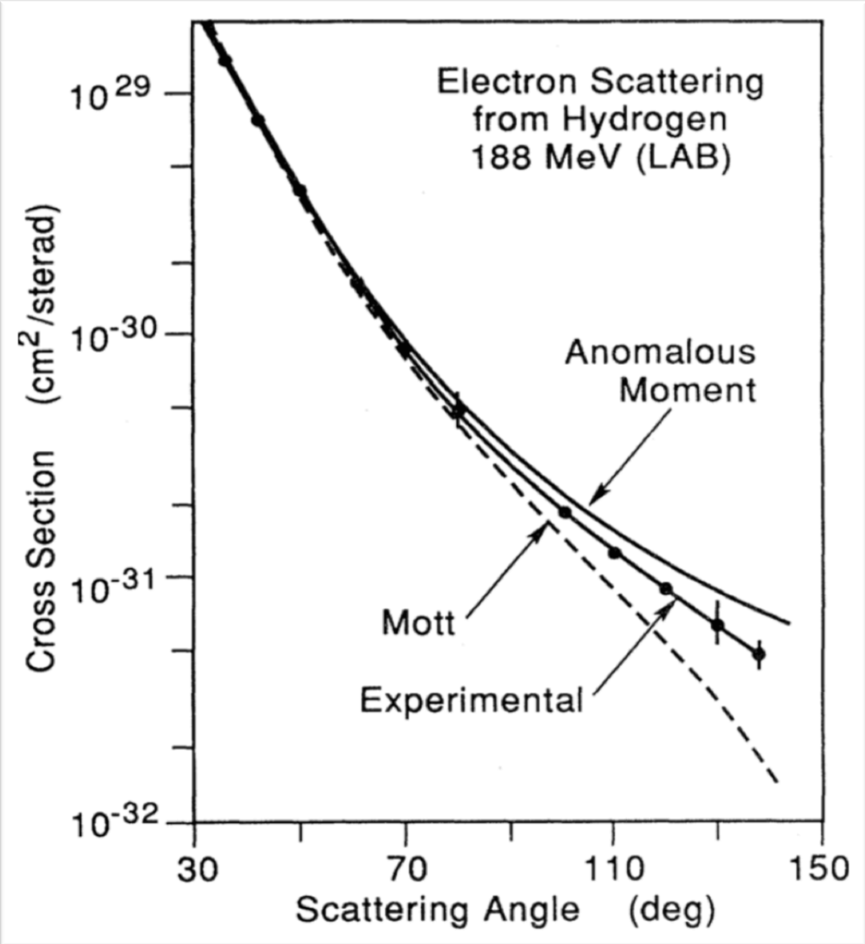
$$\lambda \sim \frac{\hbar c}{\sqrt{Q^2}}$$

CONS

- The interaction is weak
- → small cross sections
- Electron Bremsstrahlung
- → radiative corrections



The Structure of the Nucleon



R. Hofstadter Nobel prize in 1961

1950-1960: Elastic Scattering

In the 50 'Hofstadter used 100-500 MeV electrons to probe the charge distribution of the nuclei.
The results of the experiments showed that the proton is not a point particle and made it possible to measure its size.

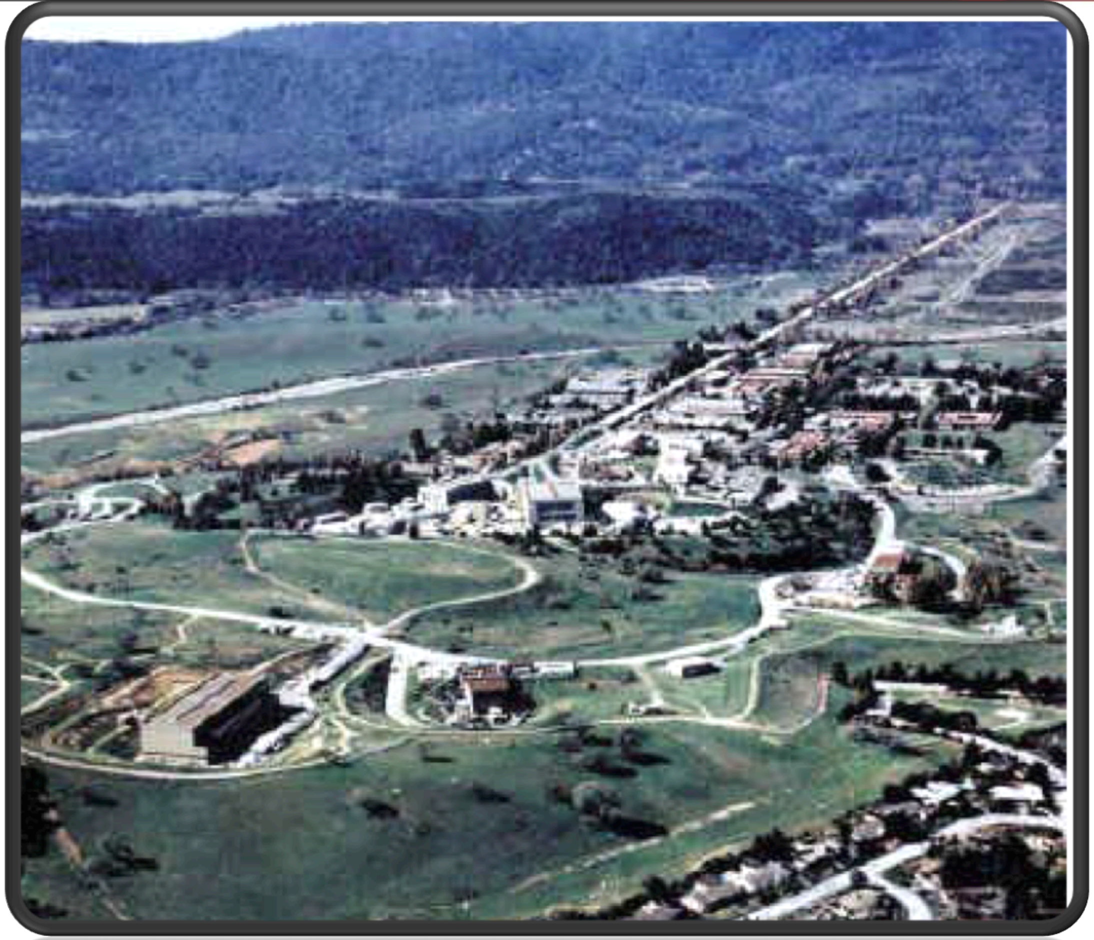
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_M \times \left(G_1(Q^2) + 2\tau G_2(Q^2) tan^2\frac{\theta}{2}\right)$$

$$G_1(Q^2) = \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} \qquad G_2(Q^2) = G_M^2(Q^2)$$

$$\left(\frac{d\sigma}{d\Omega}\right)_M = \frac{4\alpha^2 E'^2}{Q^4} cos^2\frac{\theta}{2}\frac{E'}{E} \qquad \tau = \frac{Q^2}{4M^2}$$

The proton has finite size and structure!

The beginning of the journey

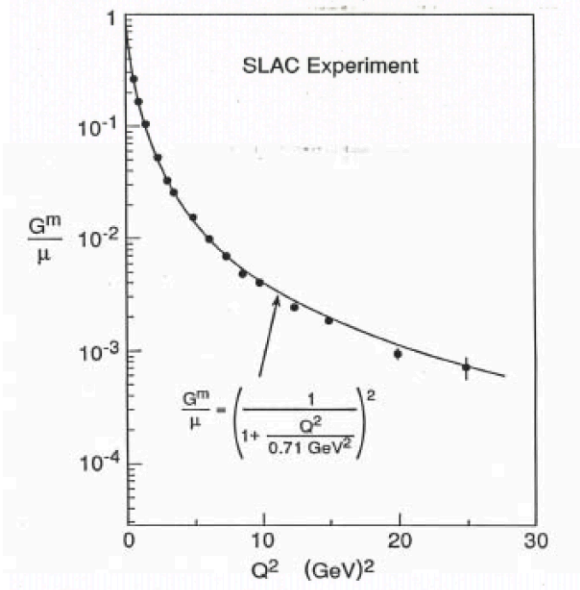


At SLAC, a laboratory near San Francisco, in 1966, the "monster" comes into operation: a linear accelerator of 20 GeV electrons, 2 miles long

First SLAC Results

SLAC Magnetic Spectrometers

First measurements on elastic scattering:
extended earlier measurements at CEA and DESY



In 1967 a change in the program: inelastic vs elastic scattering

$$e\ p \rightarrow e + \text{Anything}$$

Inelastic vs. Elastic Scattering

- Elastic Scattering provides information about the charge and magnetic moment distributions averaged over time
- Inelastic scattering can provide a "snapshot" of the structure

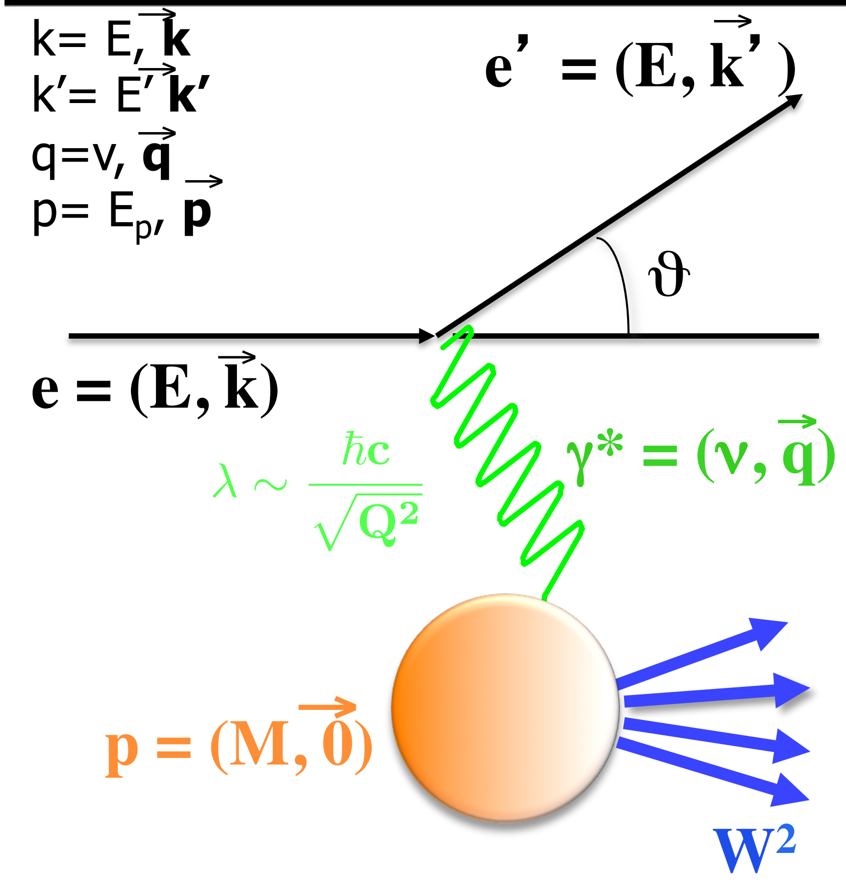
$$\Delta t = \frac{h}{\Delta E}$$

ΔE = energy lost by electron

If ΔE = 2 GeV ➡ Δt = 3×10^{-25} sec ➡ motion during "snapshot" is 10^{-14} cm

Deep Inelastic Scattering required for large ΔE

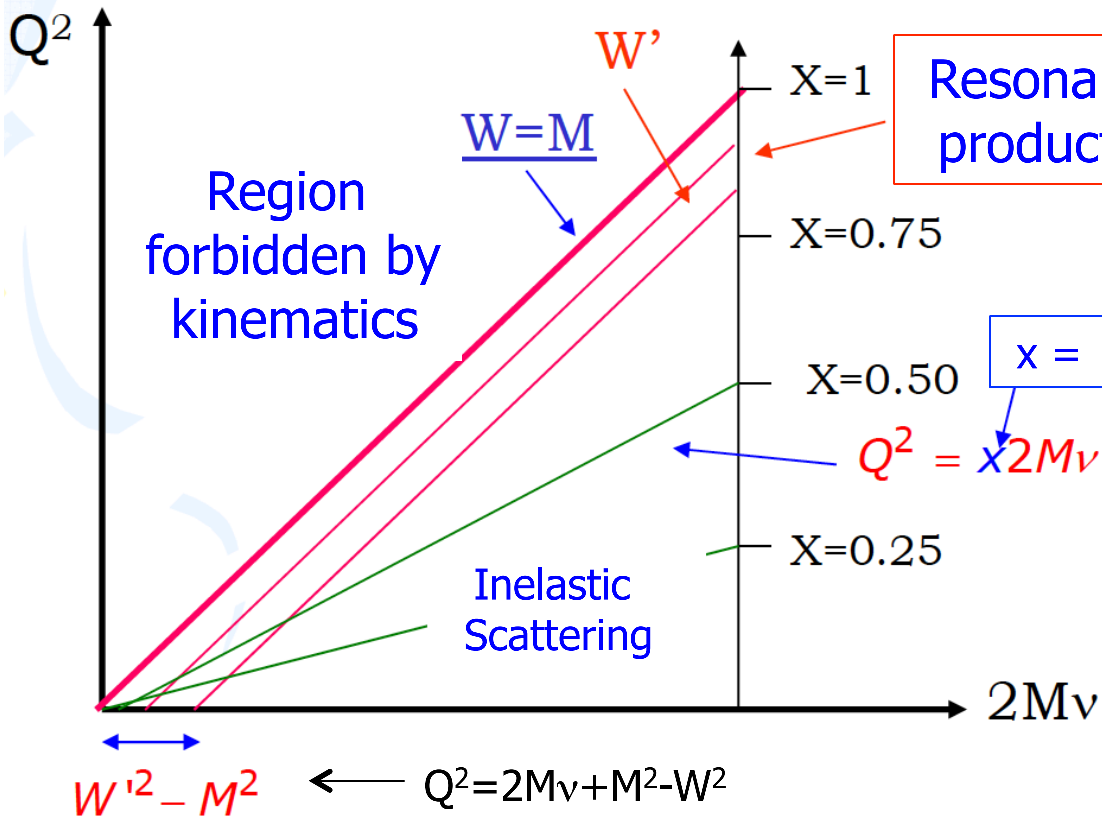
Electron Scattering: Kinematics



Lorentz inv.		Lab frame	Meaning
$q^2 = -Q^2$	$(k-k')^2$	$-4EE' sin^2(\frac{\theta}{2})$	Virtuality
x_B	$\frac{-q^2}{2p \cdot q}$	$\frac{Q^2}{2M\nu}$	Bjorken scaling variable; Inelasticity of the process
ν	$\frac{p \cdot q}{\sqrt{(p^2)}}$	$E - E'$	Energy lost by the incoming lepton
W^2	$(p+q)^2$	$M^2 + 2M\nu - Q^2$	Inv. mass squared of the final state
y	$\frac{p \cdot q}{p \cdot k}$	$\frac{\nu}{E}$	Fraction of the electron energy carried by the γ^*
s	$(p+k)^2$	$\approx M^2 + 2M\nu$	Center of mass energy

$W^2 = M^2$ $X_B = 1$ elastic scattering
$W^2 \neq M^2$ $X_B < 1$ inelastic scattering
$Q^2 \gg M^2$ deep inelastic scattering

Kinematics Relations: x and Q^2



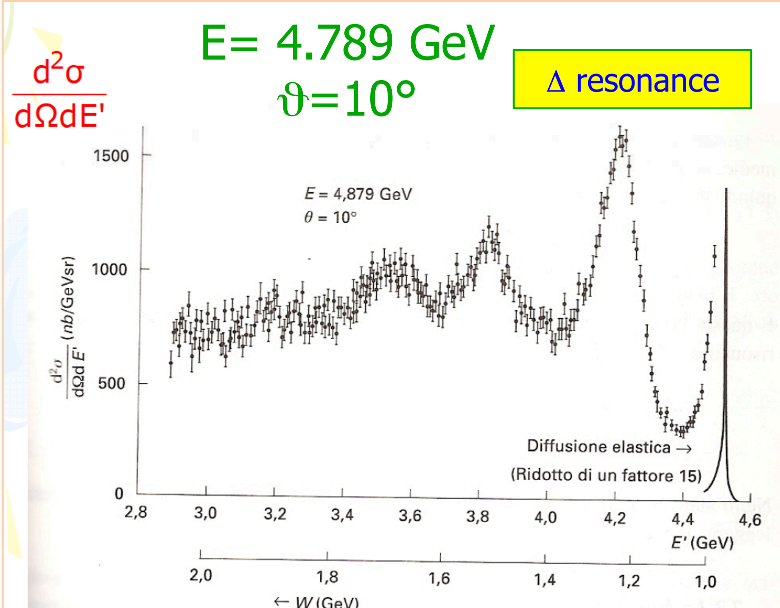
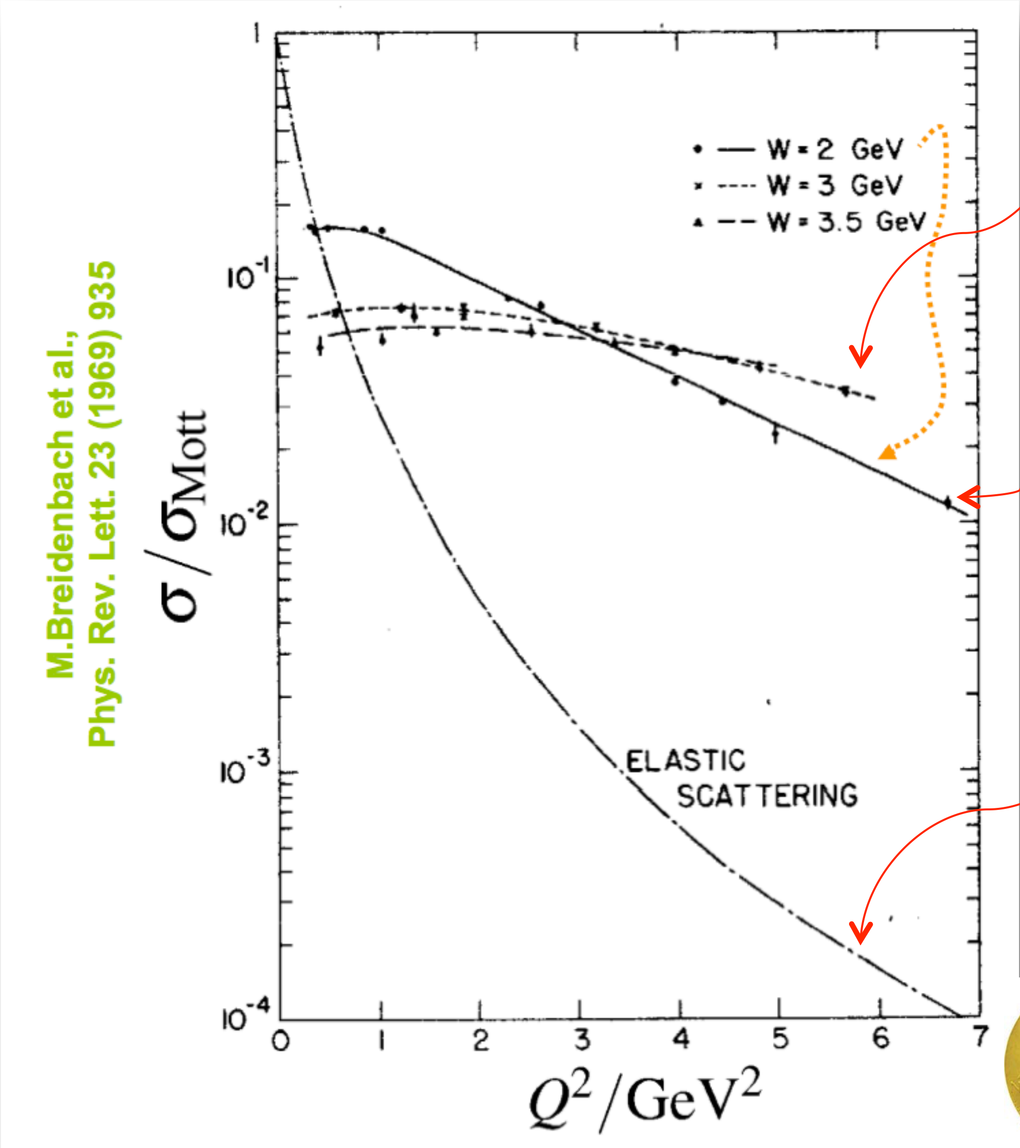


Figura 7.1
Spettro degli elettroni diffusi nell'urto elettrone-protone. L'energia degli elettroni incidenti è $E = 4.879$ GeV e l'angolo di diffusione è $\theta = 10°$ (da [Ba68]).

In the limit $Q^2 \to \infty$, $\nu \to \infty$

Deep Inelastic Scattering (DIS)

Looking deep inside the Proton



- **Deep Inelastic scattering** cross sections almost independent of Q^2!
  i.e. "Form factor" ➔1

Scattering off point-like objects within the proton ???

- **Inelastic scattering** cross sections only weakly dependent on Q^2

- **Elastic scattering** falls of rapidly with Q^2 due to the proton not being point-like (i.e. form factors)

$$\frac{\sigma}{\sigma_{\mathrm{Mott}}} = \left(\frac{1}{(1+Q^2/0.71)^2}\right)^2 \propto Q^{-8}$$

J. Friedman, H.Kendall, R.Taylor
Nobel Prize 1990

Looking deep inside the Proton

- The dynamics of such production processes may be, similar to the case of elastic scattering, described in terms of form factors.
- In the inelastic case the complex structure of the proton is described by two **structure functions: $\mathbf{W_1}$ and $\mathbf{W_2}$.**
- In elastic scattering, at a given beam energy E , only one of the kinematical parameters may vary freely. (Ex: ϑ fixed ➔ Q^2,ν fixed since $2M\nu - Q^2 = 0$)
- In inelastic scattering the excitation energy of the proton adds a further degree of freedom → structure functions and cross-sections are functions of **two independent, free parameters**, e. g., (E, ϑ) or (Q^2, ν)

$$\frac{d\sigma^2}{d\Omega dE'} = \left(\frac{d\sigma}{d\Omega}\right)_M \times \left(W_2(Q^2,\nu) + 2W_1(Q^2,\nu) tan^2 \frac{\theta}{2} \right)$$

Electric interaction

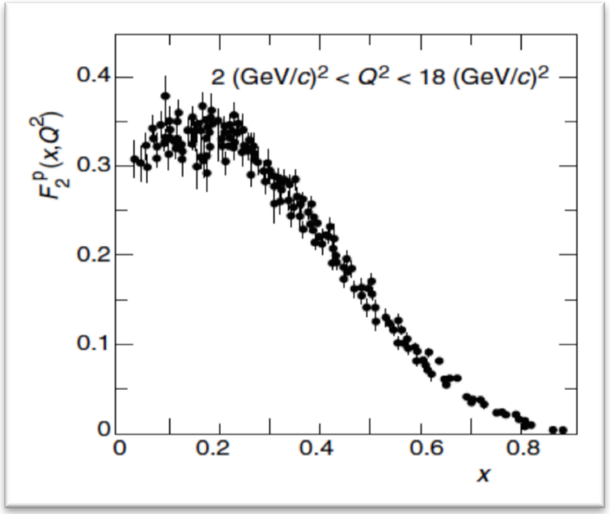
Magnetic interaction

- The experimental observation of the cross section almost independent of Q^2 suggested that the process could be described as **the incoherent elastic scattering off point-like particles** ➔the cross section is scale invariant (doesn't depend on Q^2) and depends only of the ratio $x=Q^2/2M\nu$.

Structure Functions

- The structure functions W_1 (Q^2,ν) and W_2 (Q^2, ν) are usually replaced by two dimensionless structure functions:

$$F_1(x,Q^2) = MW_1(Q^2,\nu) \quad F_2(x,Q^2) = \nu W_2(Q^2,\nu)$$



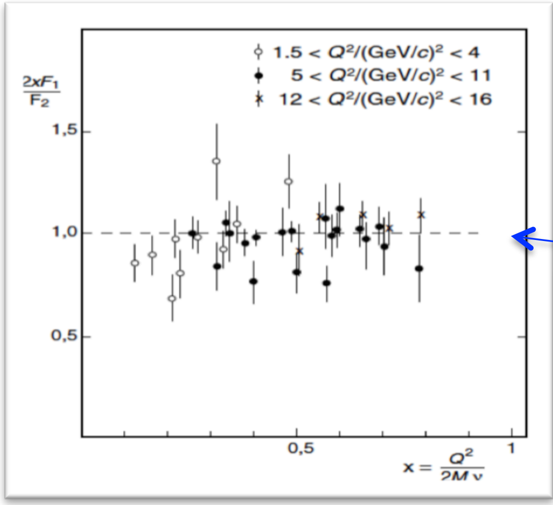
- At fixed values of x the structure functions F_1 (x,Q^2) and F_2 (x,Q^2) depend only weakly, or not at all, on Q^2

$$F_{1,2}(x,Q^2) \approx F_{1,2}(x)$$

- Comparing the DIS cross section formula with the Mott and Dirac elastic cross sections for particles of mass m = xM and spin 1/2

$$F_2(x) = 2xF_1(x)$$

Callan-Gross relation



Same as if target was a free spin ½ particle: the photon is scattering on quasi-free quark !

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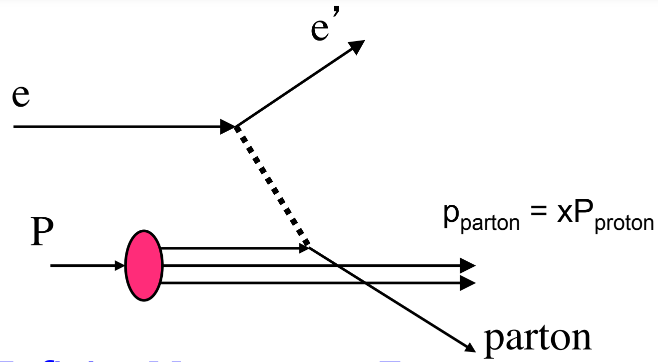
The Quark-Parton Model

This model is discussed in a fast moving system (IMF)

The proton has a very large momentum **P**

- The photon is interacting with **free** charged point-like particles (partons) inside the proton (the relativistic time dilation slows down the rate with which the quarks interact with each other).
- The partons will have collinear momentum with the proton and each parton of charge e_i has a probability $f_i(x)$ to carry a fraction x of the parent proton momentum.

$$\sum_i \int x f_i(x) dx = 1$$



Infinite **M**omentum **F**rame

$$(xP+q)^2 = p'^2_{quark} = m^2_{quark} \approx 0$$

Since $xP^2 \le M^2 << Q^2$ it follows

$$2xP\cdot q + q^2 \approx 0 \rightarrow \boxed{x = \frac{Q^2}{2Pq} = \frac{Q^2}{2M\nu}}$$

Definition Bjorken scaling variable

- The proton (partons) move along the z-axis; the parton (proton) has:
  - energy xE (E)
  - longitudinal momentum xp_L (p_L)
  - transversal momentum $p_T = 0$ $(p_T = 0)$
  - mass xM (M).

It is easy to demonstrate that: $F_2(x) = \sum_i e_1^2 x f_i(x)$

$$F_2^{ep} = \frac{x}{9}[4\cdot u_v(x) + d_v x] + \frac{4}{3}x\cdot Sx)$$

$$F_2^{en} = \frac{x}{9}[u_v(x) + 4\cdot d_v(x)] + \frac{4}{3}x\cdot S(x)$$

S(x) = Σ sea quarks

Experimentally:

$$\int F_2^{ep} dx = \frac{4}{9}f_u + \frac{1}{9}f_d \approx 0.18$$

$$\int F_2^{en} dx = \frac{4}{9}f_d + \frac{1}{9}f_u \approx 0.12$$

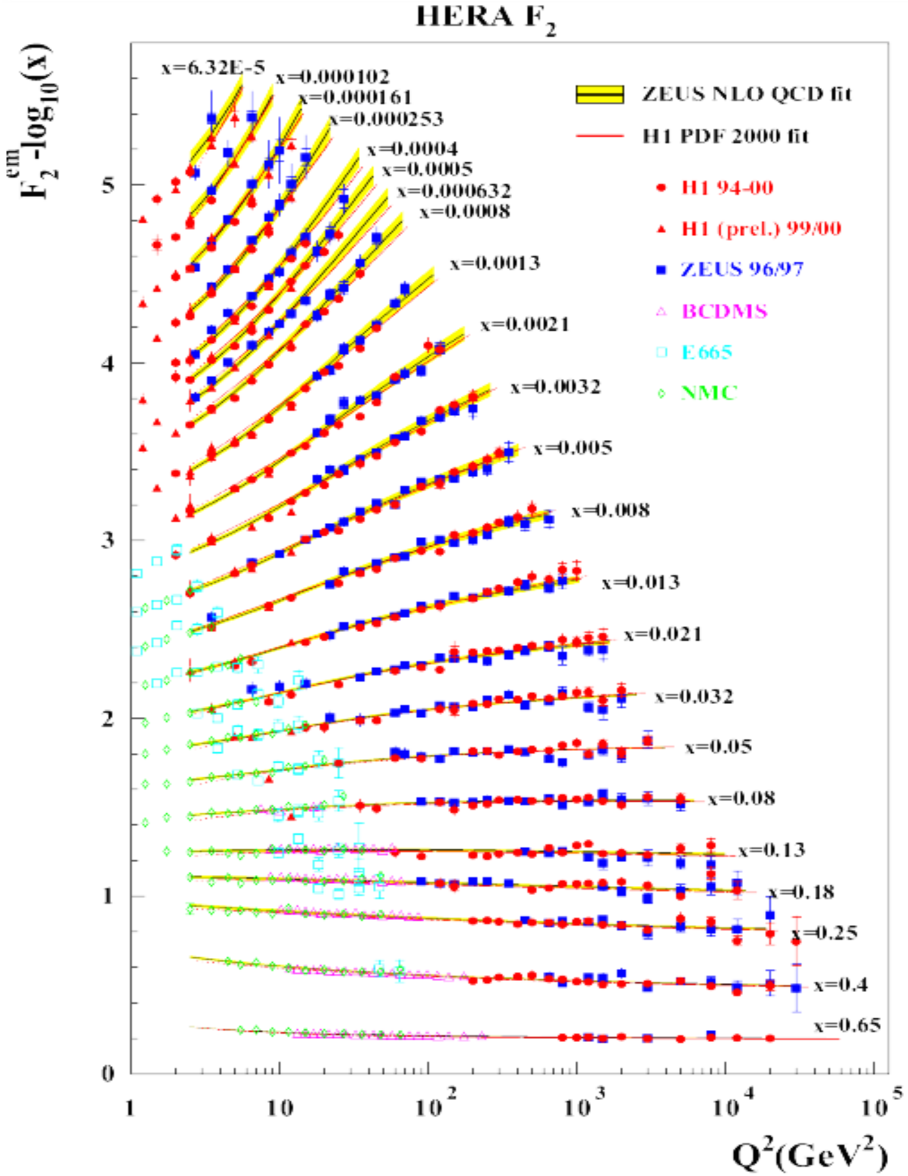
Neglecting the contribution of the s quark

$$f_u \approx 0.36$$
$$f_d \approx 0.18$$

$$f_u = \int_0^1 x(u+\bar{u})dx$$

Only 50% of the proton momentum is carried by the quarks & antiquarks

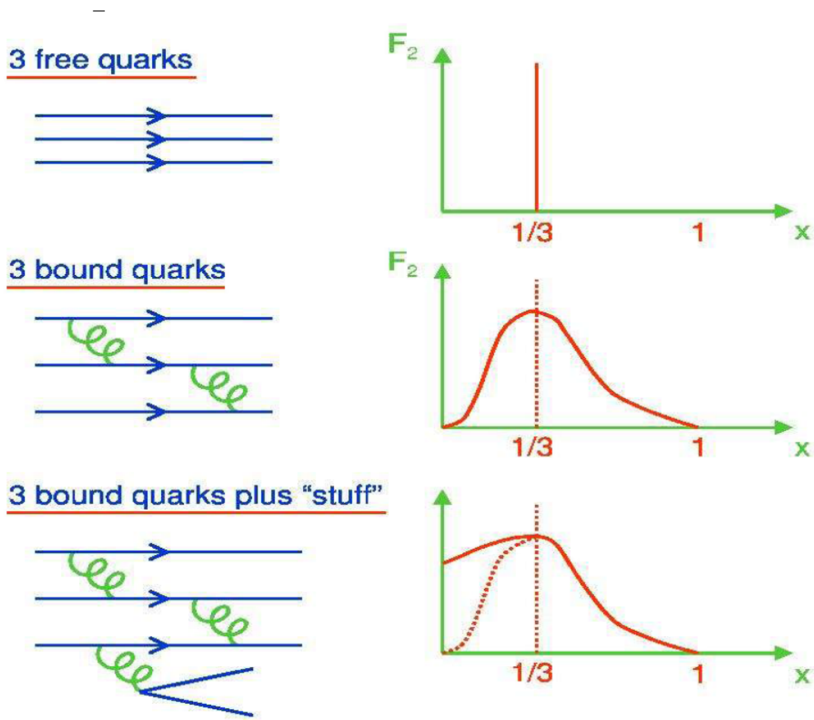
Scaling Violations



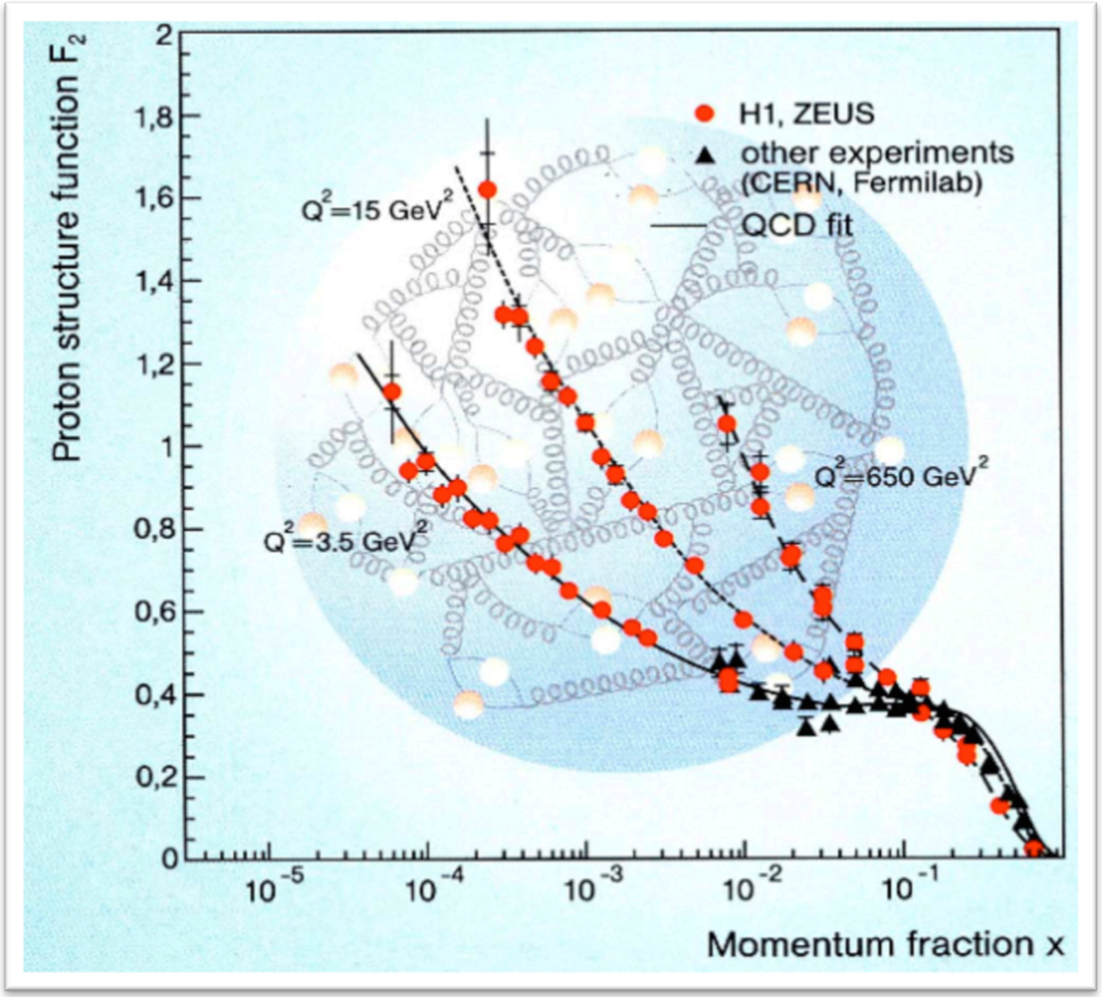
Deviations of F_2 from Bjorken scaling at high values of Q^2 and low values of x: $F_2 = F(Q^2, x)$

- F_2 increases with Q^2 at low x

This violation is **not** due to a finite size of partons, but to the QCD processes that describe the interaction between the constituents of the nucleons.



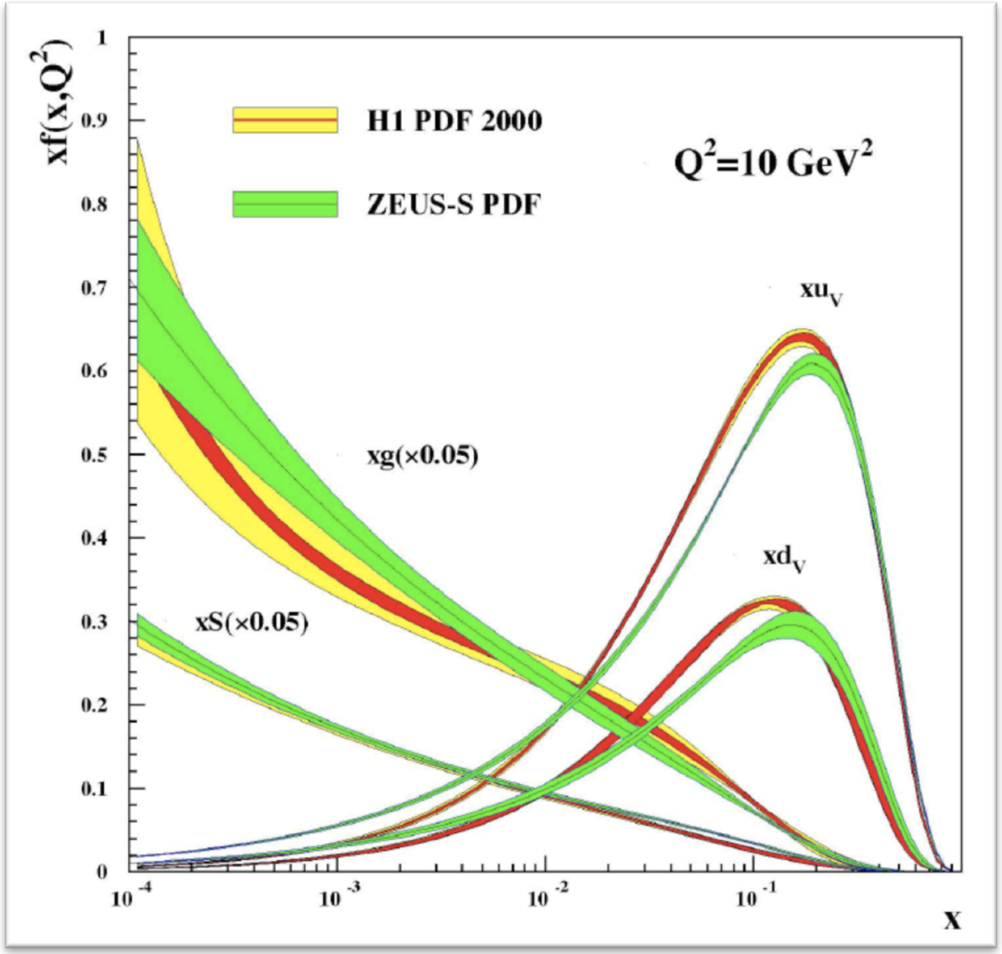
Scaling Violations



- Scaling violation is due to the fact that the quarks radiate gluons that can "materialize" as q-qbar pairs (sea quarks)
- With increasing Q^2 increases the resolution of the probe ($\sim\hbar/\sqrt{Q^2}$) and thus increases the number of partons that are "seen" bring a fraction x of the proton momentum
- The parton distribution functions (PDFs) can not be calculated from first principle of QCD but their Q^2 dependence is calculable in perturbative QCD using the DGLAP evolution equations

PDFs Extraction

- All available deep inelastic and related hard scattering data involving incoming protons (and antiprotons) are used to determine the parton densities, f_i of the proton.
- The procedure is to parametrize the x dependence of $f_i(x,Q^2_0)$ at some low, yet perturbative, scale Q^2_0. Then to use the DGLAP equations to evolve the f_i up in Q^2, and to fit to all the available data (DIS structure functions, Drell-Yan production, Tevatron jet and W production...) to determine the values of the input parameters

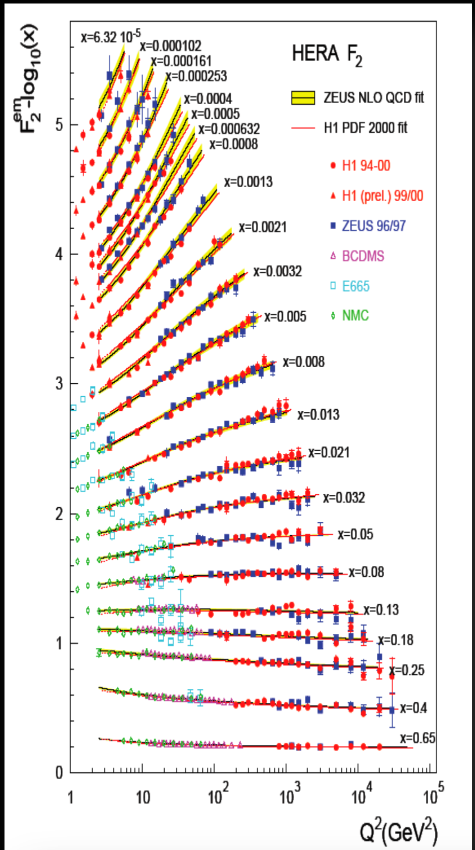


Factorization

The fundamental assumptions of the Quark Parton Model is the factorization:

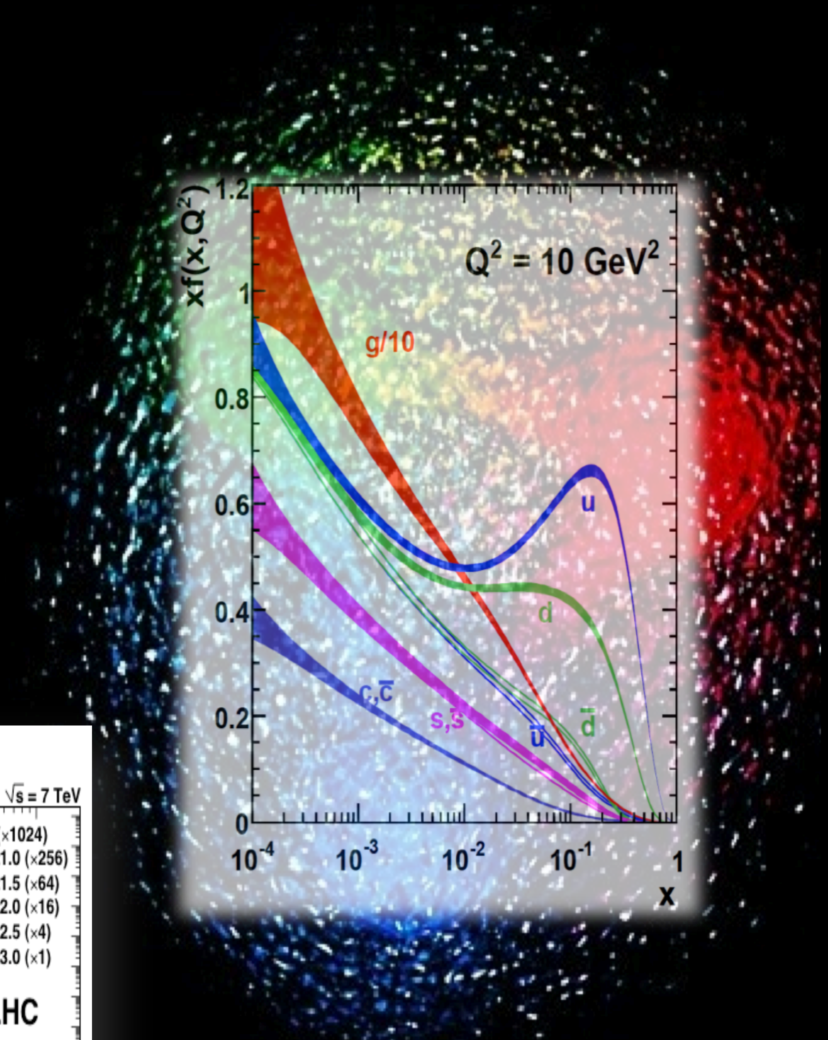
The process of hadronization occurs on longer time scales compared to the elementary lepton - parton scattering , so it is possible to conclude that there is a factorization between hard scattering process lepton - parton and processes between soft partons , leading to their recombination to form colorless hadrons.
In other words the two phenomena , in good approximation, are decoupled .
The former are calculable using perturbative QCD (pQCD), in principle, with arbitrary accuracy; the latter, instead, are parameterized in the form of phenomenological functions a priori unknown, e.g. Parton Distribution Functions.
They can therefore be extracted from the comparison with the experimental data of a certain process, and to be reinserted in the calculation of the cross section of a another hard process to make predictions
➥ **Factorization and universality test**

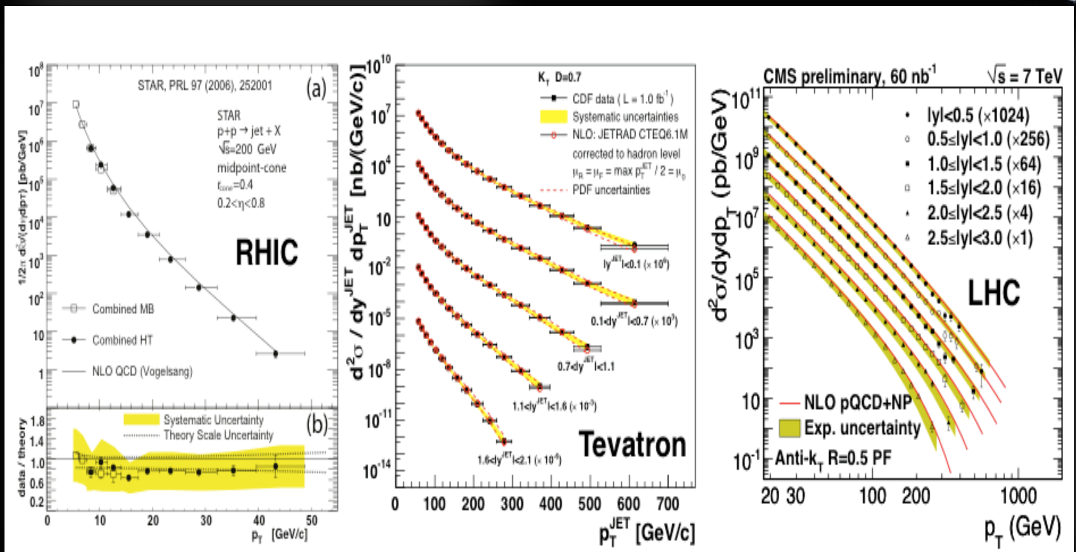
QCD Success !



Measure e-p @ 0.3 TeV (HERA)

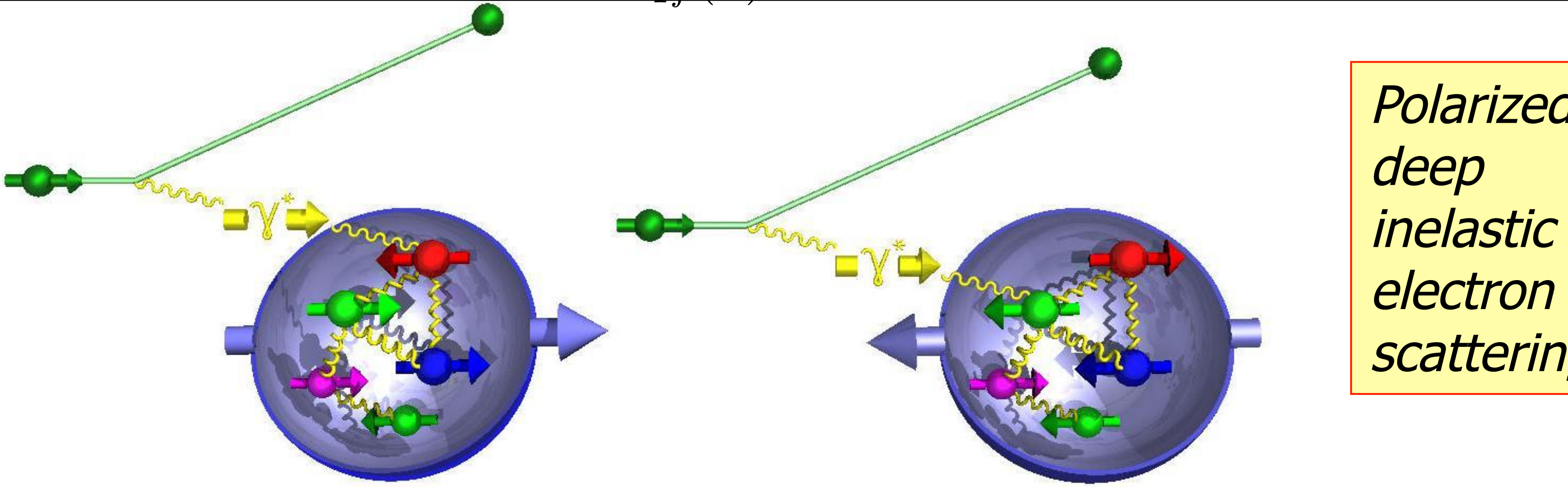
p-p and p-$\bar{p}$ at 0.2, 1.96, and 7 TeV





The Polarized Structure Functions

$$g_1(x) = \frac{1}{2}\sum_i e_i^2 \underbrace{[\Delta q_i(x) + \Delta \bar{q}_i(x)]}_{\Delta q_f(x)} \qquad \Delta q_i(x) = q_i^+ - q_i^-$$



Polarized deep inelastic electron scattering

Parallel electron & quark spins

Anti-parallel electron & quark spins

Measure yield asymmetry:

$$A_1 = \frac{1}{DP_T P_B}\frac{N_{\uparrow\downarrow} - N_{\uparrow\uparrow}}{N_{\uparrow\downarrow} + N_{\uparrow\uparrow}}$$

In the Quark-Parton Model:

$$A_1 \approx \frac{g_1(x)}{F_1(x)} = \frac{1}{F_1(x)}\sum_f e_f^2 \Delta q_f(x)$$

Spin-dependent Structure Function

Polarized Parton Distributions

$$\Gamma_1^{p,n} \equiv \int_0^1 g_1^{p,n}(x_B)dx_B = \frac{1}{2}\sum_f e_f^2(\Delta q_f^{p,n} + \Delta\bar{q}_f^{p,n})$$

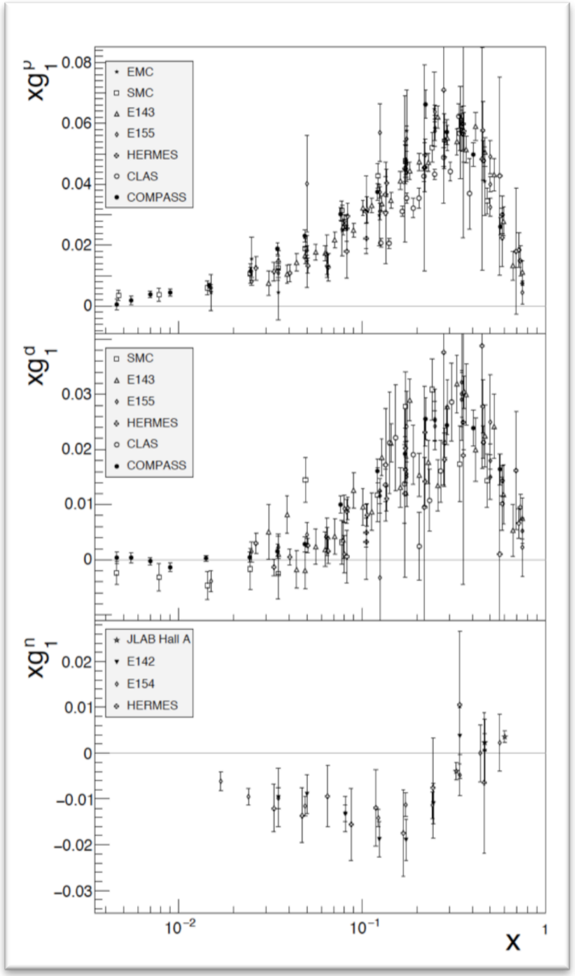
$$\Delta\Sigma \equiv (\Delta u(x) + \Delta\bar{u}(x)) + (\Delta d(x) + \Delta\bar{d}(x)) + (\Delta s(x) + \Delta\bar{s}(x))$$

$$\Gamma_1 \equiv \int_0^1 g_1(x_B)dx_B = \underbrace{\frac{1}{6}F + \frac{1}{18}D}_{\text{From hyperon decays}} + \frac{1}{9}\Delta\Sigma$$

From hyperon decays

- Mesurement of Γ_1^p, Γ_1^n
- Constraint based on the hyperon beta decay lifetimes
- Assumption of SU(3) flavou symmetry
- Global fit with DGLAP Q^2 evolution

$$\Delta\Sigma \approx 0.25$$



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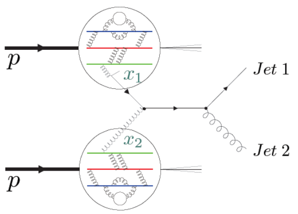
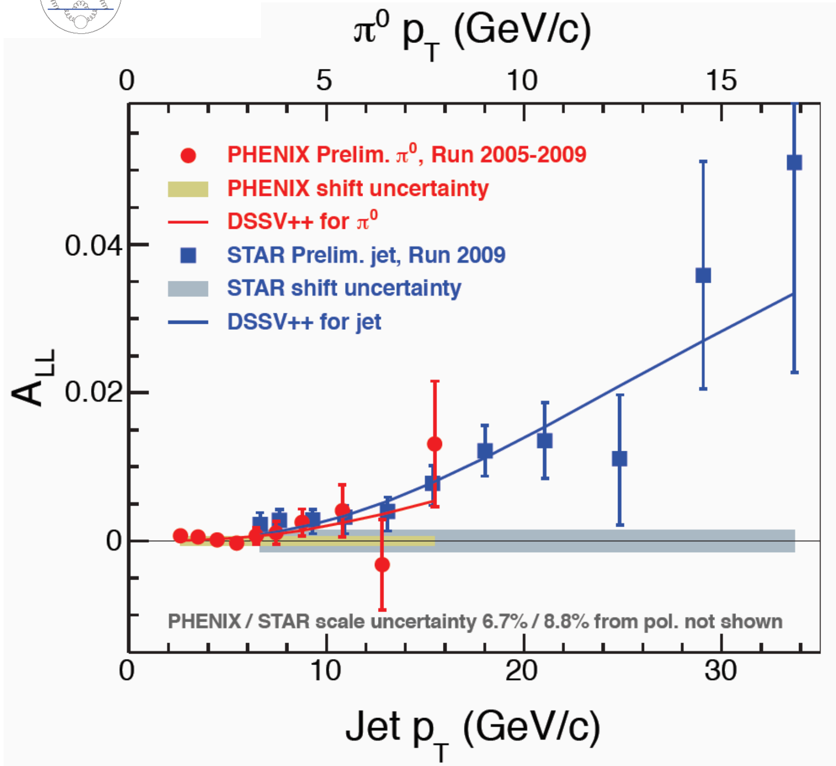
Only small fraction of the proton spin is carried by the quarks & antiquarks!!

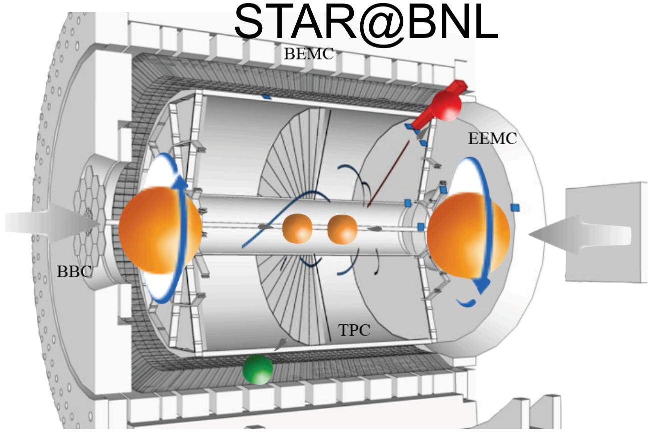
Gluon Helicity



$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_1 P_2} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$

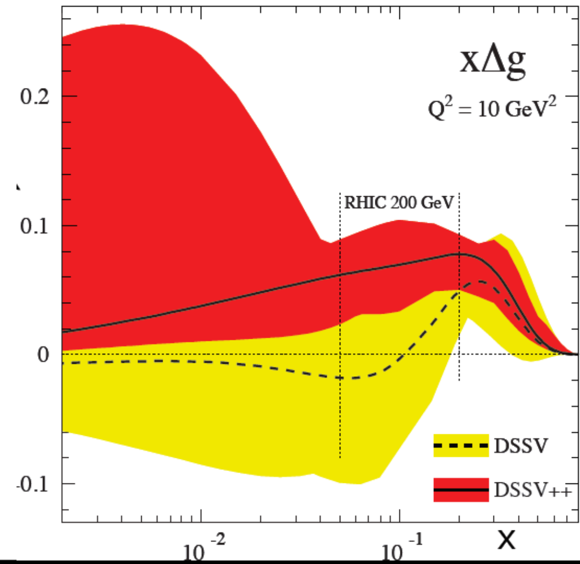


STAR@BNL



Indication of small, but non-0 Δg from RHIC data, in particular STAR jet results

$$\int_{0.05}^{0.2} \Delta g(x)\,dx = 0.1 \pm^{0.06}_{0.07}$$



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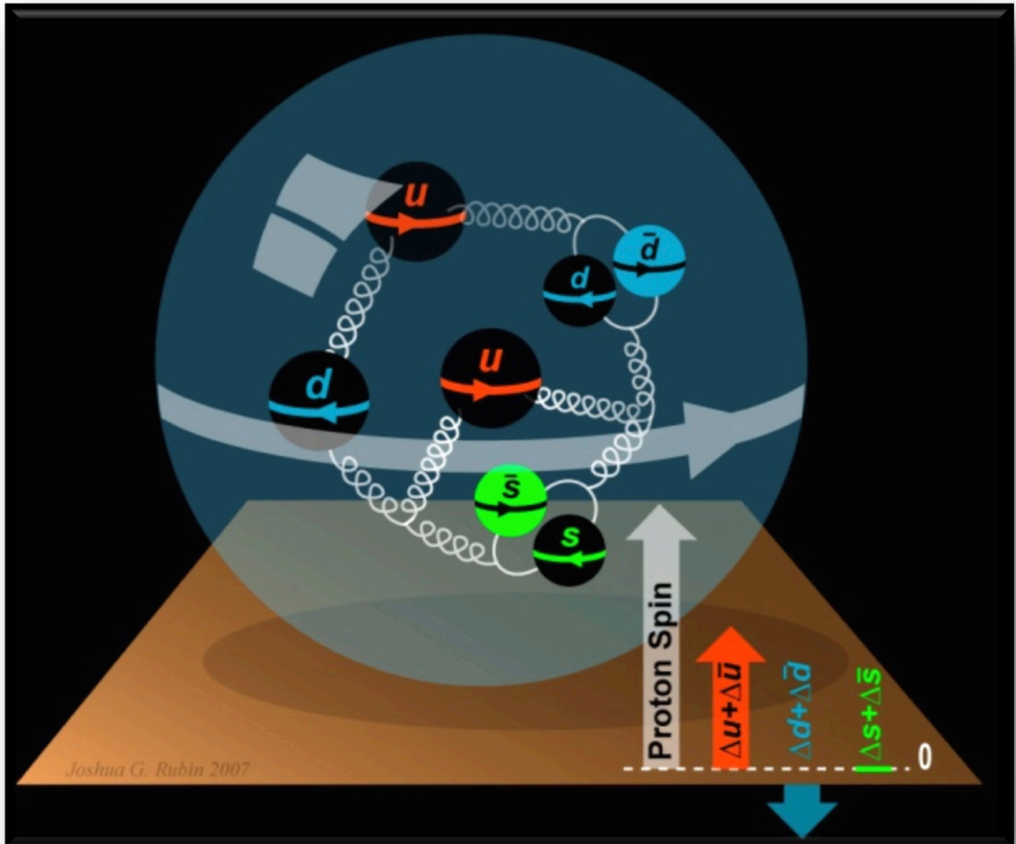
The Incomplete Nucleon: Spin Puzzle



- **DIS → $\Delta\Sigma \cong 0.25$**

- **RHIC + DIS → ΔG**

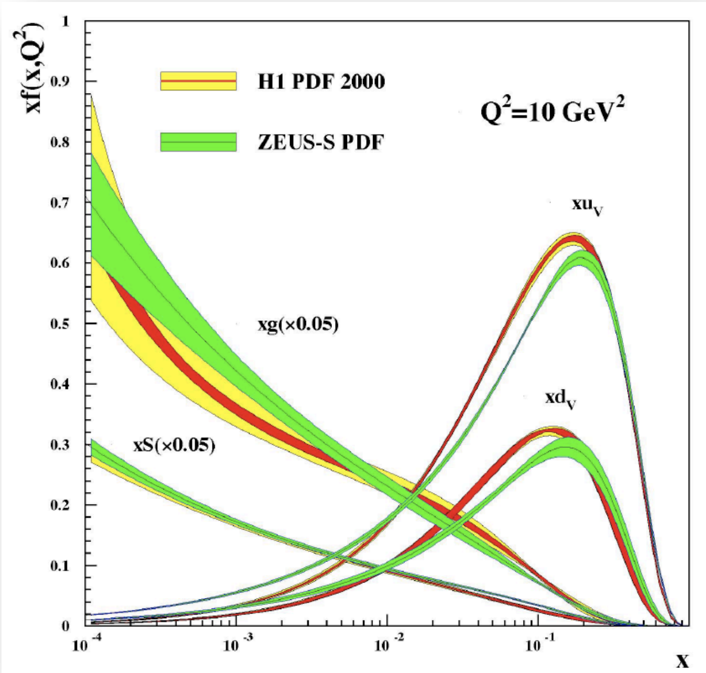
$$\int_{0.05}^{0.2} \Delta g(x)\,dx = 0.1 \pm^{0.06}_{0.07}$$

could be small

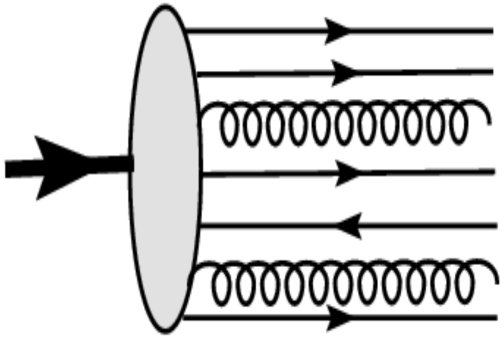
- **→ L_q**

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

From 1D to 3D



Fast moving frame

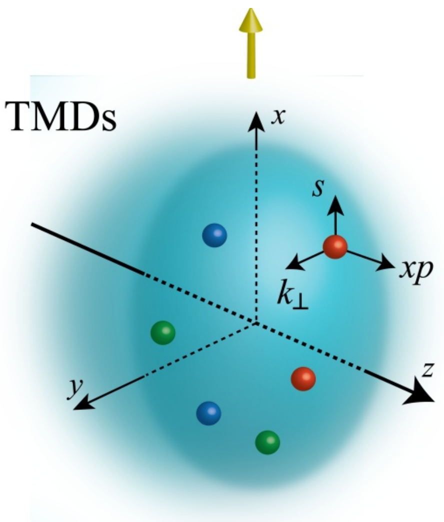


Simplified picture may miss some relevant info

Courtesy of H. Avakian

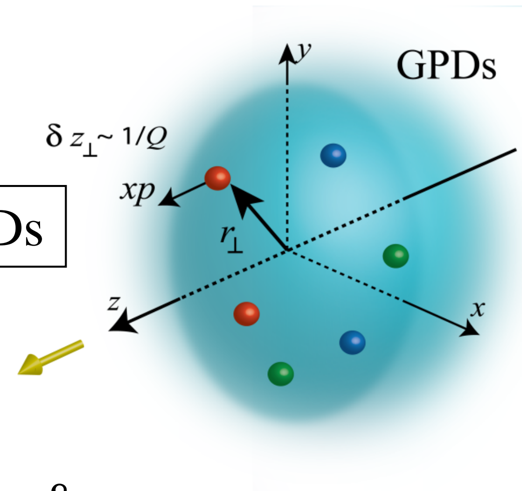
Unified View of the Nucleon Structure

3D imaging



TMD $f_1^u(x,k_T)$, ..

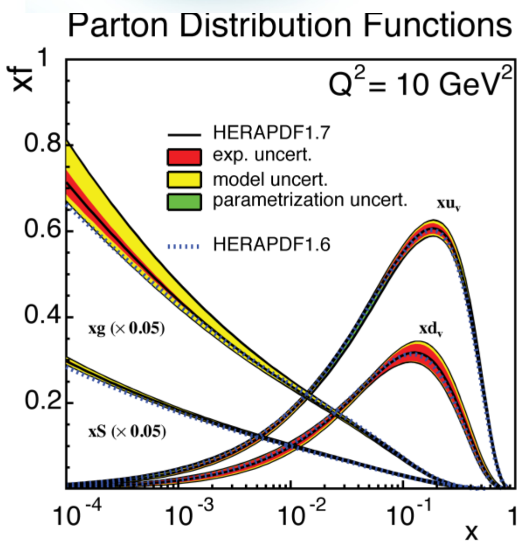
GPDs/IPDs



d^2k_T

d^2r_T

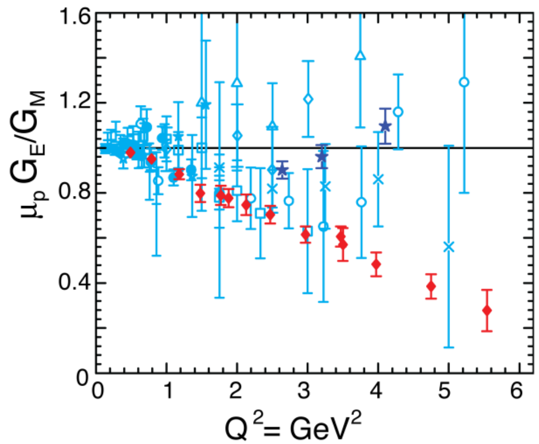
dx &
Fourier Transformation

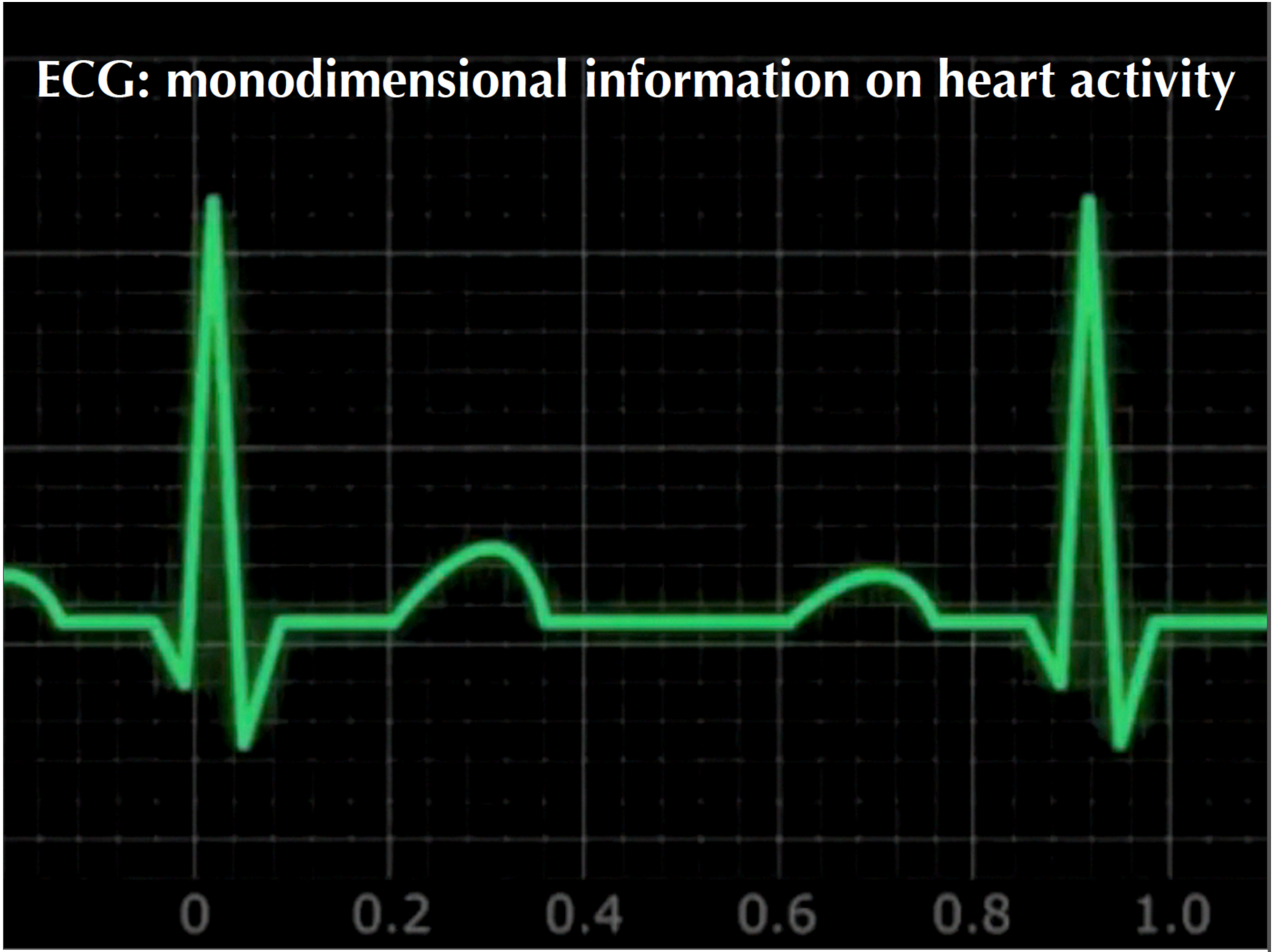


PDFs
$f_1^u(x)$, .. $h_1^u(x)$

1D

Form Factors
$G_E(Q^2)$,
$G_M(Q^2)$

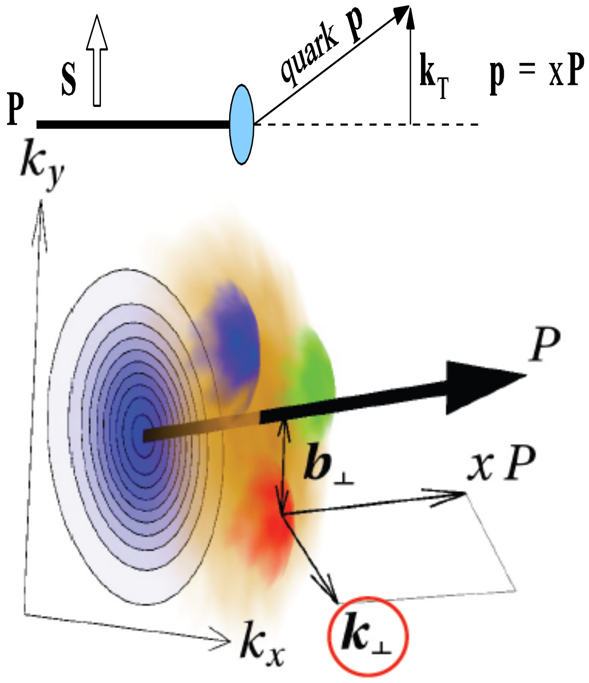



ECG: monodimensional information on heart activity
0
0.2
0.4
0.6
0.8
1.0

Functional MRI:
tomography of heart activity

TMDs: multidimensional structure of the nucleon in momentum space

Transverse Momentum Dependent (TMD) Distributions



$$f = f(x, k_T)$$

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Boer-Mulders

Sivers

transversity

Transverse Momentum Distributions (TMDs) of partons describe the distribution of quarks and gluons in a nucleon with respect to x and the intrinsic transverse momentum k_T carried by the quarks