Probing the Internal Structure of the Nucleon: Experimental Overview

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National Research & Innovation Agency of Indonesia (BRIN)

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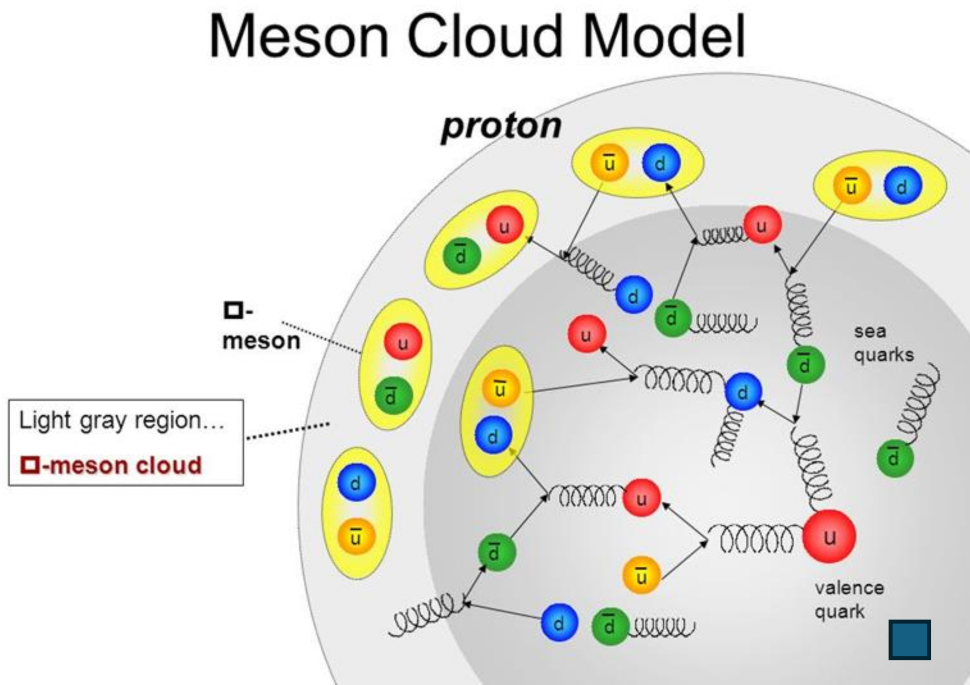


First, please allow me to introduce myself

- 2013 – 2018: Master's and PhD at the Florida State University
- 2018 – 2023: Research Associate at University of Virginia
- 2023 - Now: Senior Researcher at BRIN

Research Area: Experimental Nuclear & Particle Physics. Worked in Jefferson Lab and Fermilab and just join ALICE experiment at CERN

Jefferson Laboratory:
- Located in Virginia
- 12 GeV electron & photon beam
- Dedicated for spectroscopy and nucleon-structure research

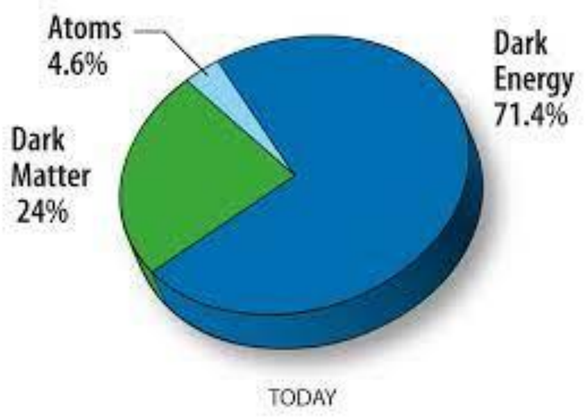
Fermilab:
- Located near Chicago
- 120 GeV proton beam
- Involved in the SpinQuest experiment (for probing the internal structure of the nucleon)
- Involved in the installation of the polarized target

ALICE at CERN:
- The HEP group at BRIN will be involved in the Forward Calorimeter detector upgrade

Outline

- Introduction
- Scattering & Discovery of Nucleon Structure
- Probing one-dimensional information of nucleon structure: Charge & Momentum Distribution & Spin Puzzle
- Unified picture of Nucleon Structure
- GPD & TMD: DVCS at Jefferson Lab, Sivers Measurement at Fermilab & Future Experiment at EIC
- Summary

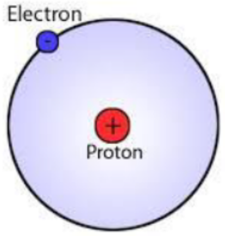
Why do we need to study the internal structure of the nucleon? Because we understand next to nothing about our universe



- 95% of the universe consists of dark energy and dark matter (something that we don't know yet)
- ~5% of the universe consists of mostly proton and neutron (neutron) (also something that we know a little)

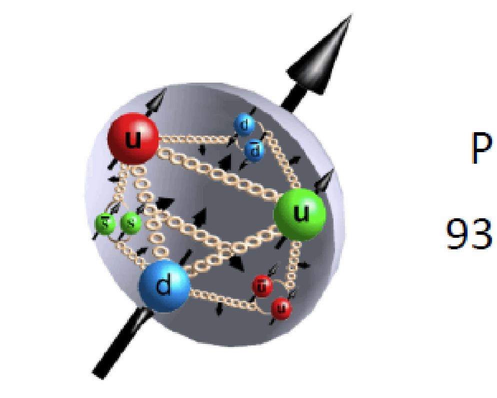
- Visible matter only constitutes ~5% of the universe (Standard Model of Particle Physics)
- ~100% of the visible-matter mass is concentrated in nuclei/nucleons

- We understand atoms quite well in term of its constituent and electromagnetic interaction:



Hydrogen mass	=	Proton mass	+	Electron mass	+	Electromagnetic interaction
938.790 MeV/c^2		938.2794 MeV/c^2		0.5110 MeV/c^2		-0.0000136 MeV/c^2
			(~100%)			

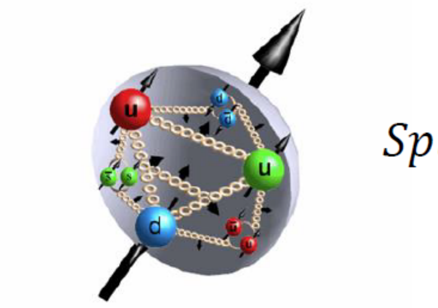
- We also learned that nucleon consist of three (valence) quarks
- But ~99% on nucleon mass comes from the strong interaction among quarks and gluons (Not fully understood)



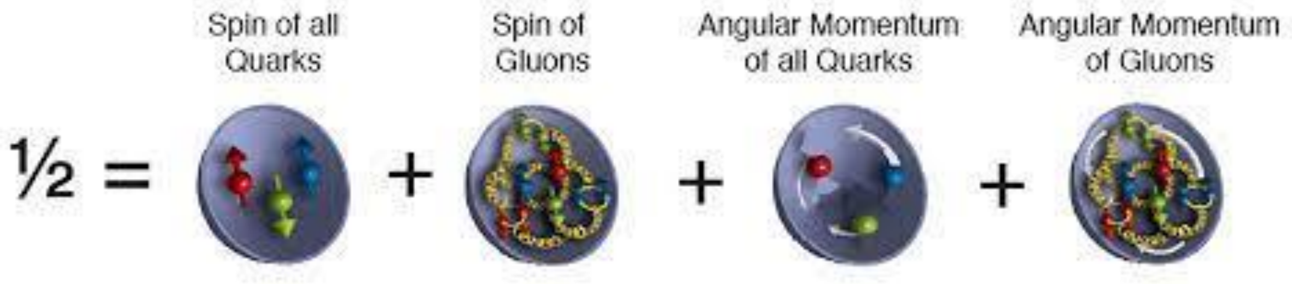
Proton mass	= 3 quark masses	+ Strong interaction
938.2794 MeV/c^2	9.8 MeV/c^2 (1 %)	928.5 MeV/c^2 (99 %)

Not only the origin of the nucleon mass, but other nucleon properties are also not fully understood (spin and radius)

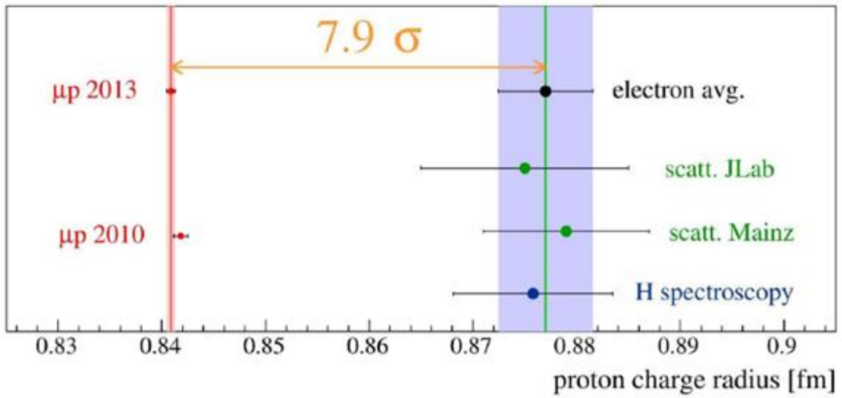
- Proton spin crisis



$$Spin_{proton} \neq \sum Spin_{quarks}$$



- Proton radius puzzle



Different results of proton radius measurement

A summary:

- So far, we only understand the visible matter which constitutes ~5% of the universe
- ~100% of this visible matter is concentrated in nucleons
- But we don't understand even the basic properties of the nucleon: the origin of its mass, proton spin crisis and the proton radius puzzle

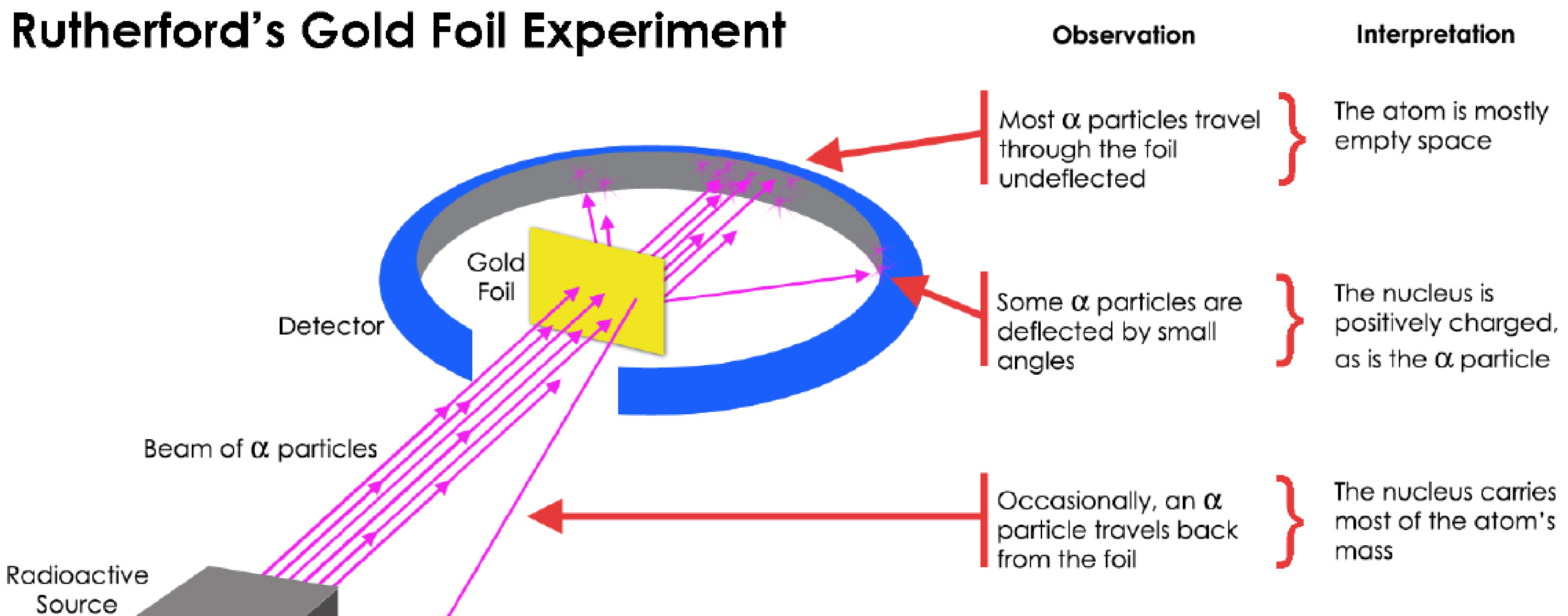
Therefore, understanding <u>nucleon structure</u> (along with <u>nucleon spectroscopy</u>) is a key to understanding our universe

Scattering & Discovery of the Nucleon Structure

How do we probe the nucleon structure? Scattering experiment!

Rutherford: The father of scattering experiment

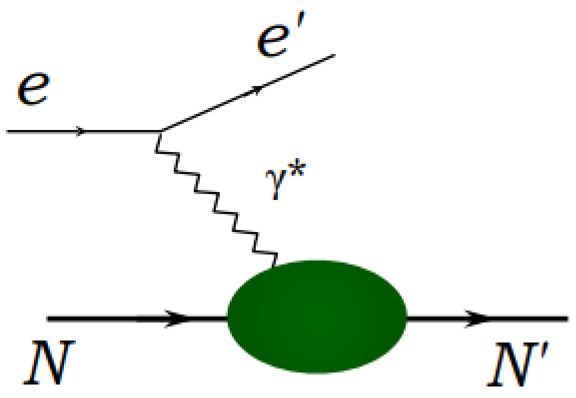
- ❑ Electron was discovered before proton
- ❑ Proton was discovered by Rutherford in the famous Gold foil experiment where the beam of α particles was shot to a gold foil
- ❑ It was expected that most of the α particles will be slightly deflected
- ❑ Surprisingly, some α particles were bounced back from the foil



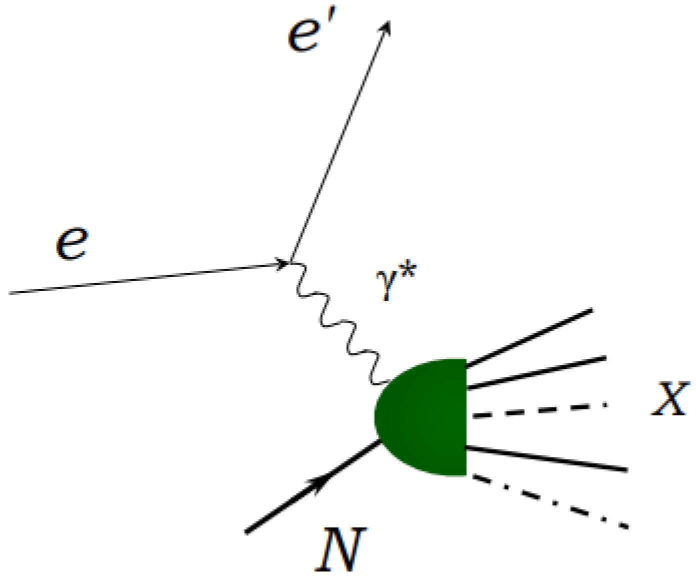
This experiment prove that an atom is mostly empty and something very solid and positively charge is inside (**proton**)

Some terminologies related to scattering

Elastic scattering: initial and final state is the same, only momenta change.



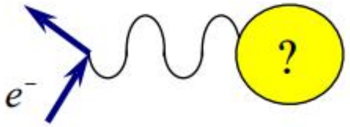
Deep inelastic scattering (DIS): state of the nucleon changed, new particles created.



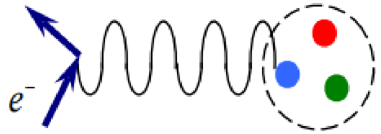
Measurements:

- ★ Inclusive — only the electron is detected
- ★ Semi-inclusive — electron and typically one hadron detected
- ★ Exclusive — all final state particles detected

→ Complementary information on the nucleon's structure



$Q^2 \sim MeV^2$



$Q^2 >> GeV^2$

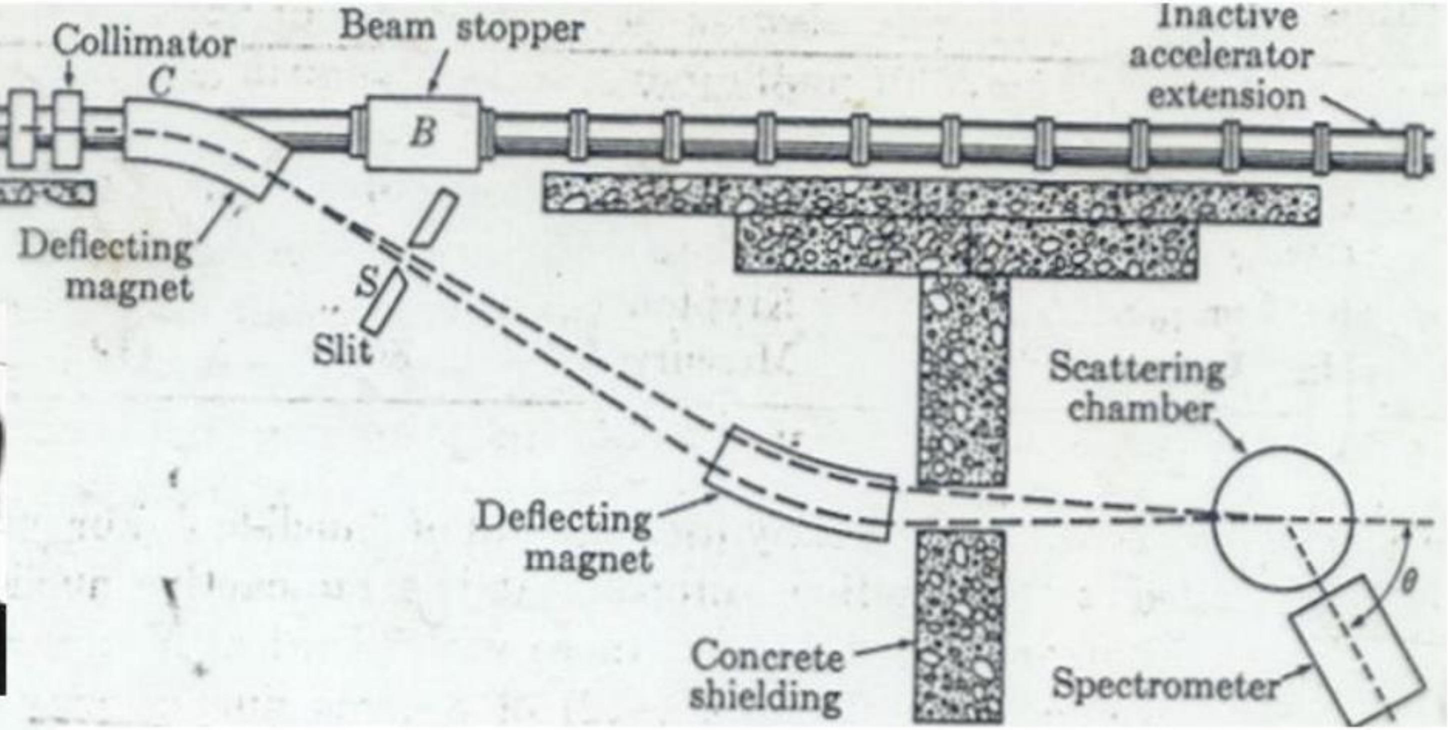
Equivalent wavelength of the probe:

$$\lambda \approx \frac{1}{\sqrt{Q^2}}$$

What we see depend on the resolution scale which depend on 4-momentum transfer (Q^2)

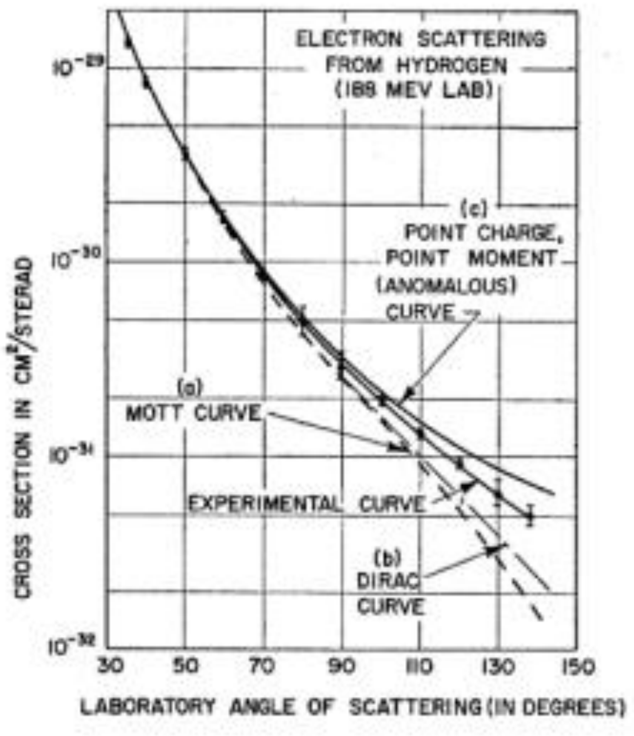
What you see depends on what you use to look...

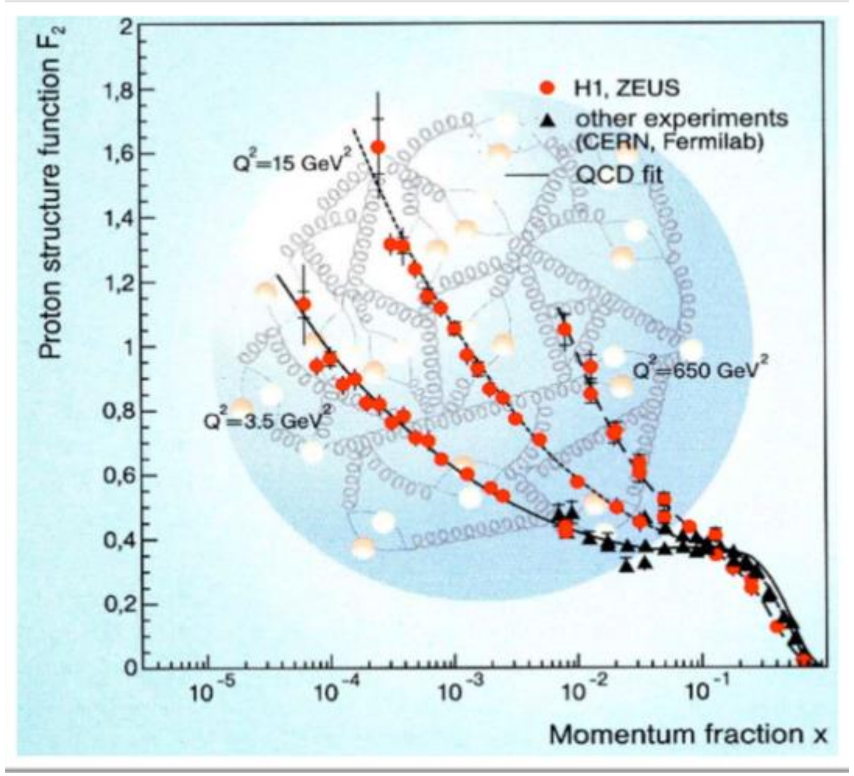
Electron scattering at Stanford 1954 - 57

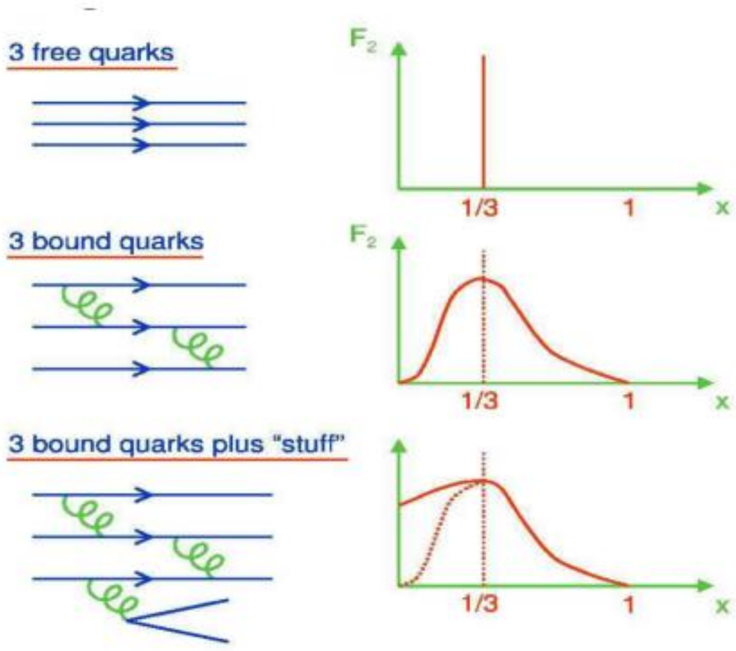


1961 Nobel Prize winner

Professor Hofstadter's group worked here at SLAC during the 1960s and were the first to find out about the charge distribution of protons in the nucleus – using high energy electron scattering.







Deviation from Mott curve showed that Nucleon has finite size

Form factor curve depends on the nucleon content

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{\alpha^2}{4E^2\sin^4(\theta/2)}\cos^2\frac{\theta}{2}.$$

Cross-section from point-like proton

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \to \frac{\alpha^2}{4E^2\sin^4(\theta/2)}\cos^2\left(\frac{\theta}{2}\right)\left|F(\mathbf{q}^2)\right|^2.$$

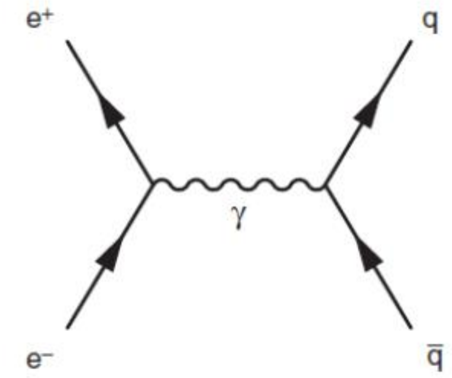
Cross section from proton with a finite size

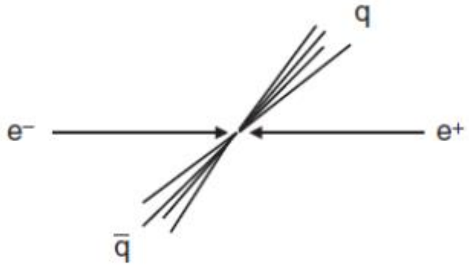
$$F(\mathbf{q}^2) = \int \rho(\mathbf{r})e^{i\mathbf{q}\cdot\mathbf{r}}\,d^3\mathbf{r}.$$

The discovery of finite-size proton and "particle zoo" in 1950's led to the Quarks model based on SU(3) symmetry

Evidence of Quarks & Gluons

- Another evidence of the quarks & gluons evidence is provided by the electron-positron annihilation experiment at DESY



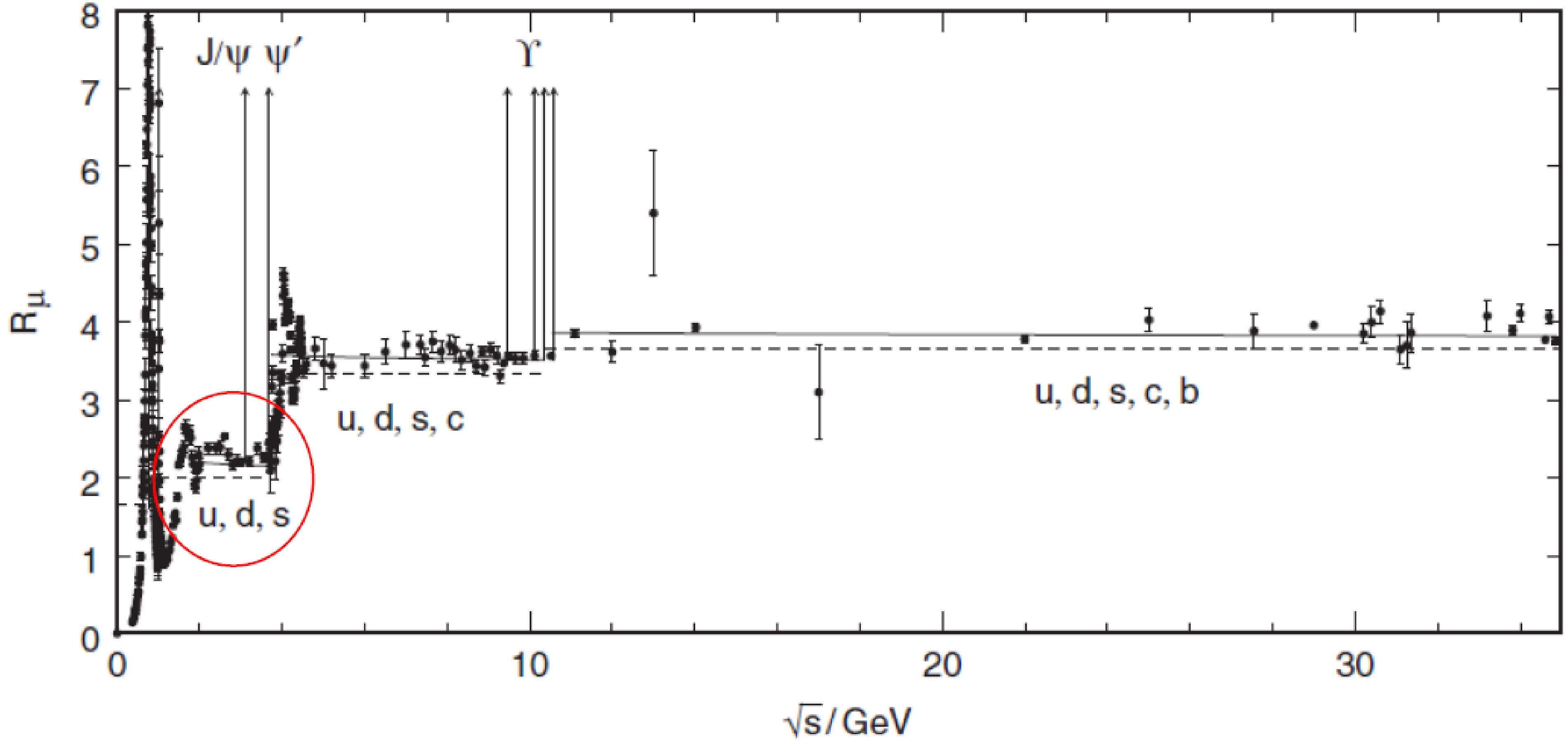


- This experiment measures the cross-section ratio of hadrons and muons production

$$R_\mu \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3 \sum_{\text{flavours}} Q_q^2.$$

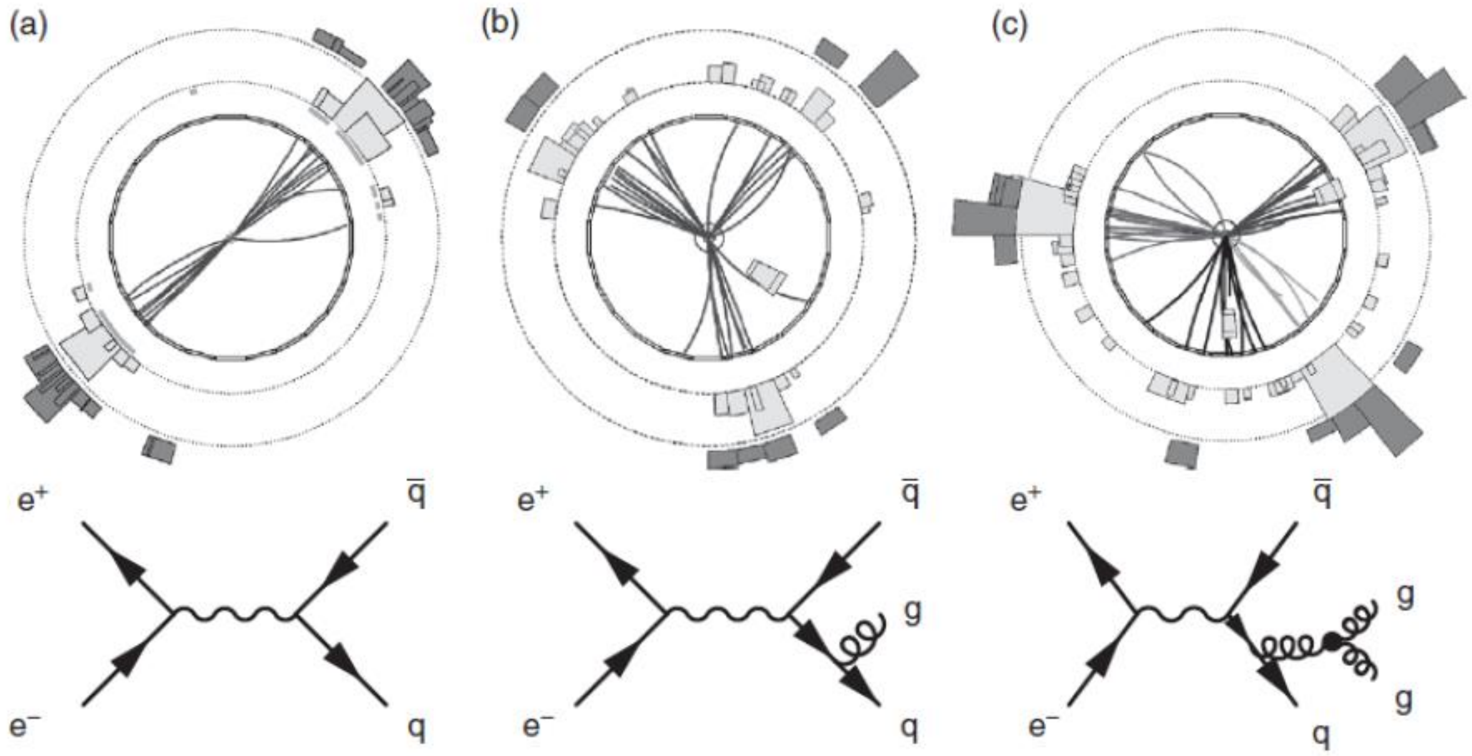
$$R_\mu^{\text{d,u,s}} = 3 \times \left(\frac{4}{9} + \frac{1}{9} + \frac{1}{9}\right) = 2. \longrightarrow$$ For 3 flavors of quarks (u, d, s)

- Experimental result:



- This experiment provides another victory for the quarks model

- [ ] This experiment also provides the evidence of gluons existence



Jet production in e^+e^- annihilation. The example events were recorded at $\sqrt{s} = 91$ GeV by the OPAL experiment at LEP in the mid 1990s. They correspond to (a) $e^+e^- \to q\bar{q} \to$ two-jets, (b) $e^+e^- \to q\bar{q}g \to$ three-jets and (c) $e^+e^- \to q\bar{q}gg \to$ four-jets. Reproduced courtesy of the OPAL collaboration. Also shown are possible Feynman diagrams corresponding to the observed events. In the case of four-jet production there are also diagrams where both gluons are radiated from the quarks.

The existence of gluons are shown in the multiple Jet tracks detected in the spectrometer

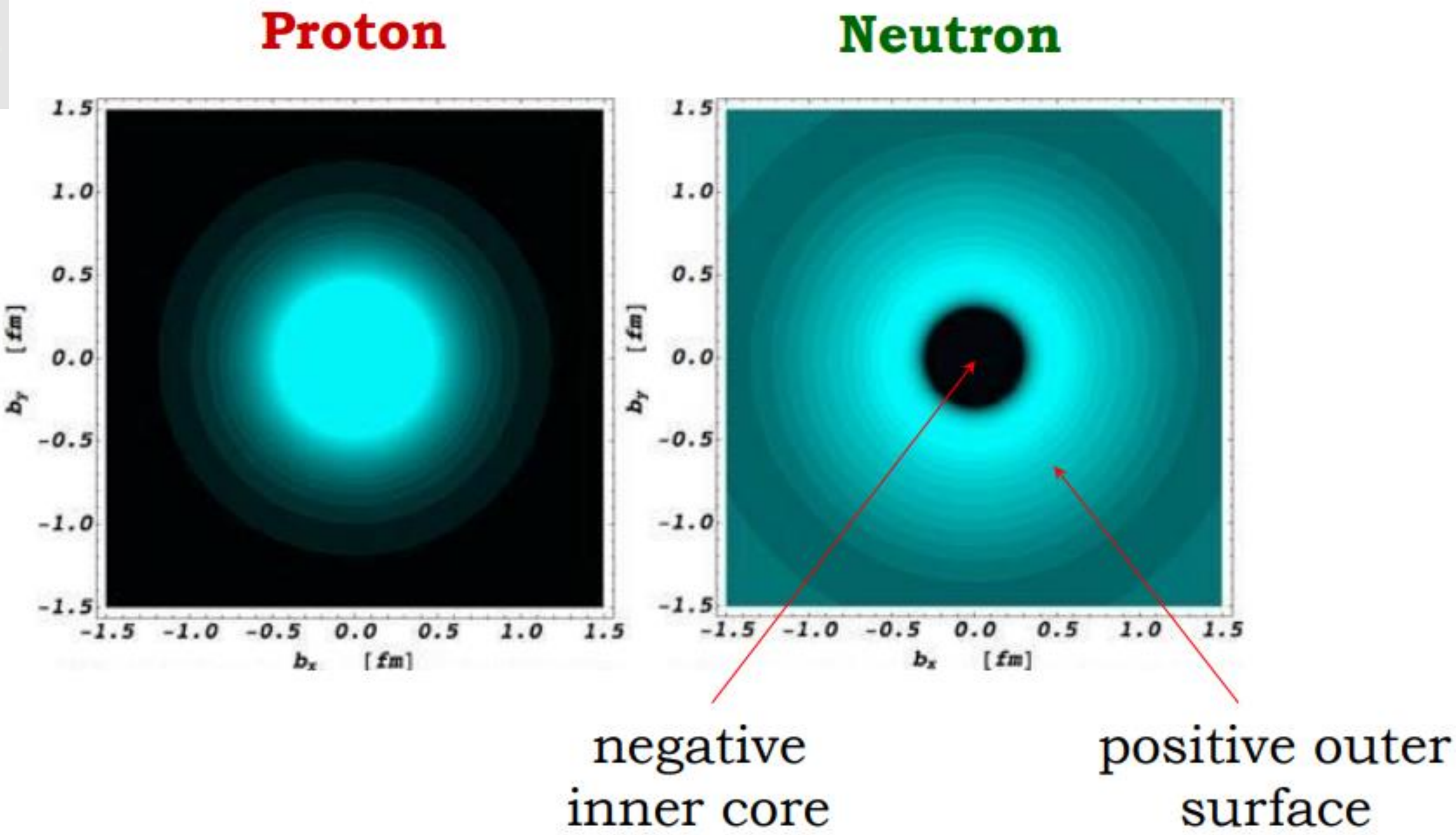
Probing one-dimensional information of nucleon structure

Charge & Momentum Distribution & Spin Puzzle

Charge density inside a nucleon

$$F(\mathbf{q}^2) = \int \rho(\mathbf{r}) e^{i\mathbf{q}\cdot\mathbf{r}}\, \mathrm{d}^3\mathbf{r}.$$

Elastic Scattering



C. Carlson, M. Vanderhaeghen
PRL 100, 032004 (2008)

Inelastic Scattering

- 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)

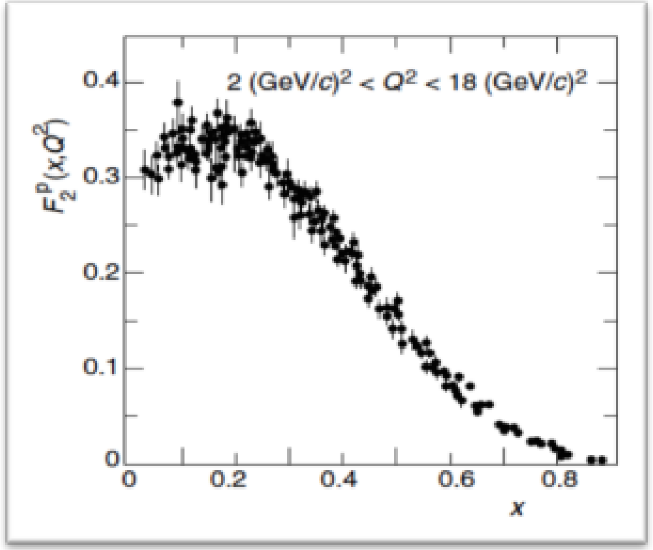
$$\frac{d\sigma^2}{d\Omega dE'} = \left(\frac{d\sigma}{d\Omega}\right)_M \times \left(W_2(Q^2,\nu) + 2W_1(Q^2,\nu)\tan^2\frac{\theta}{2}\right)$$

Electric interction (→ W_2) Magnetic interction (→ W_1)

- 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 $x=Q^2/2M\nu$.

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

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



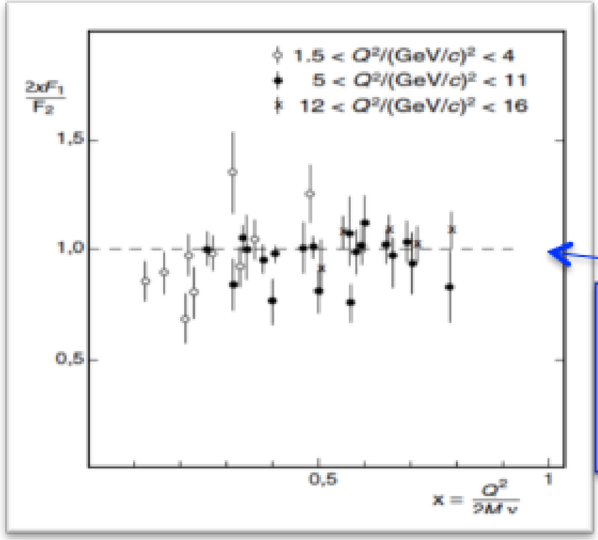
- At fixed values of x the structure functions F_1 (x,Q^2) and F_2 (x,Q^2) depend only weakly, or not at all, on Q^2

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

- 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 !

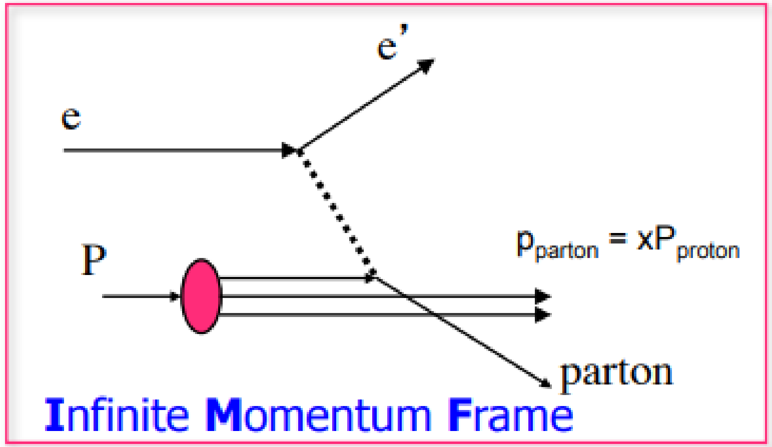
This model is discussed in a fast moving system (IMF)

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.

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

- 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).



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

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

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

Definition Bjorken scaling variable

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:

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

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

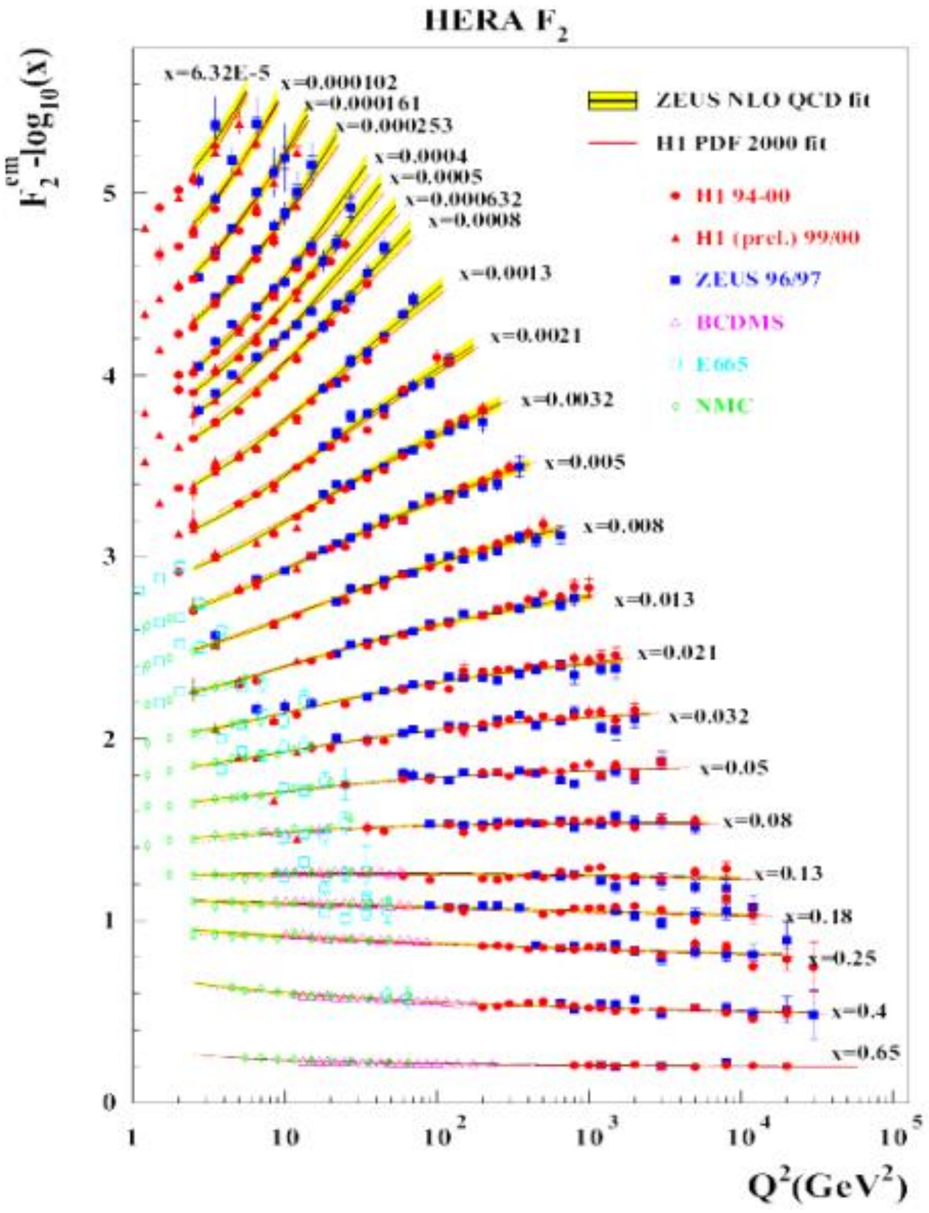
Neglecting the contribution of the s quark

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

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

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

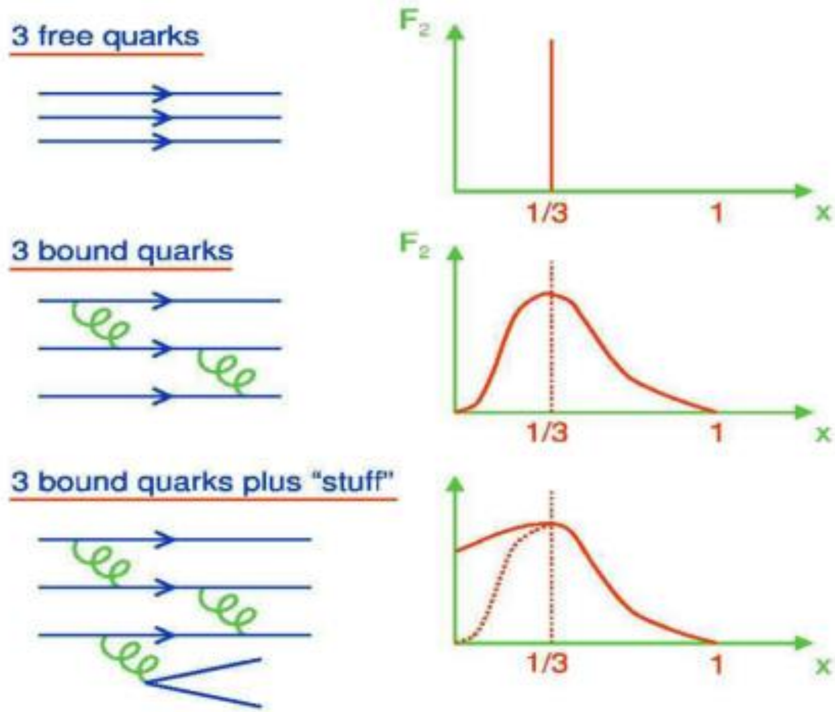
More kinematics exploration!!

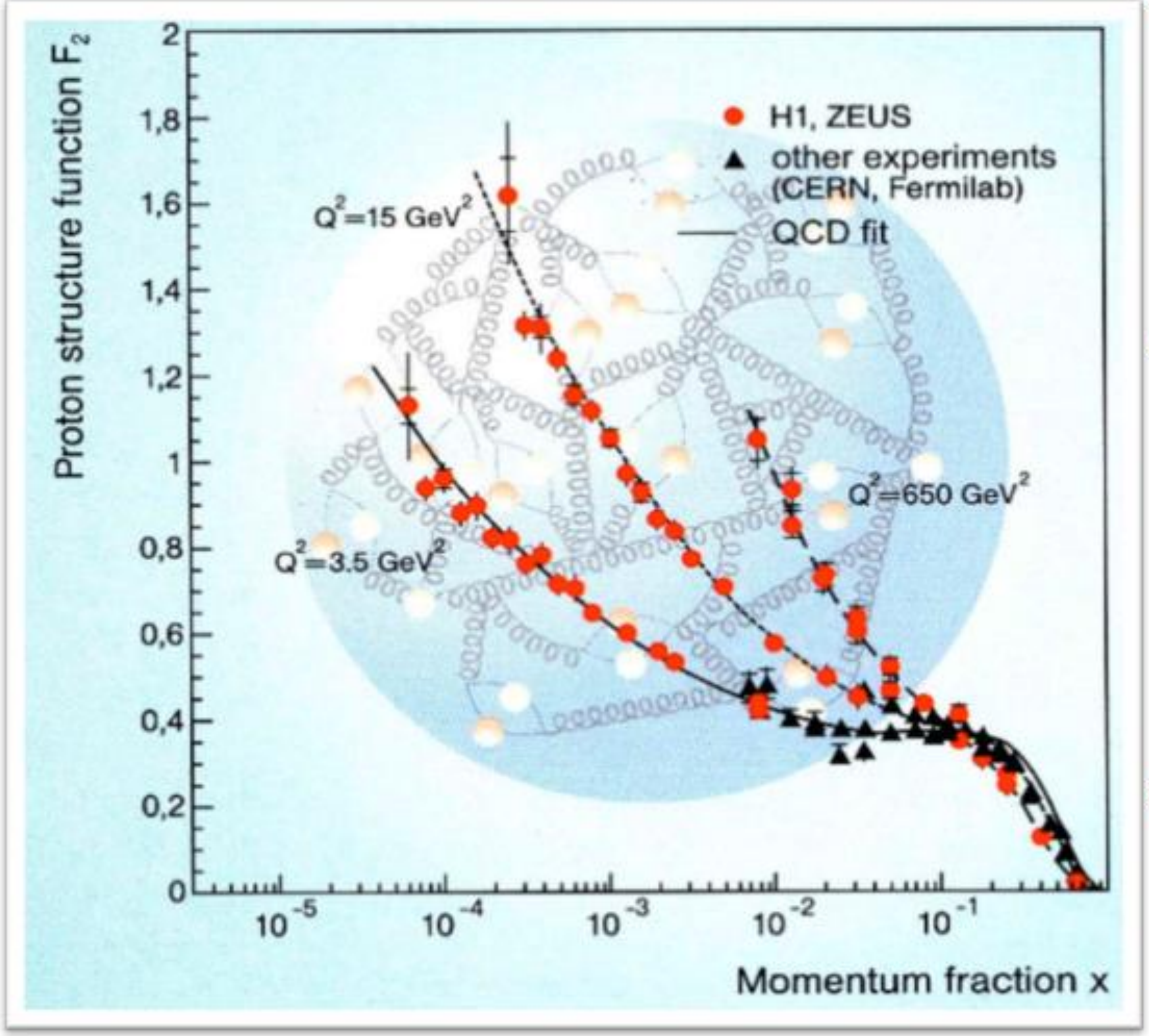


Deviations of F_2 from Bjorken scaling at high values of Q^2 and low values of x: $F_2 = F(Q^2, x)$

- 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.

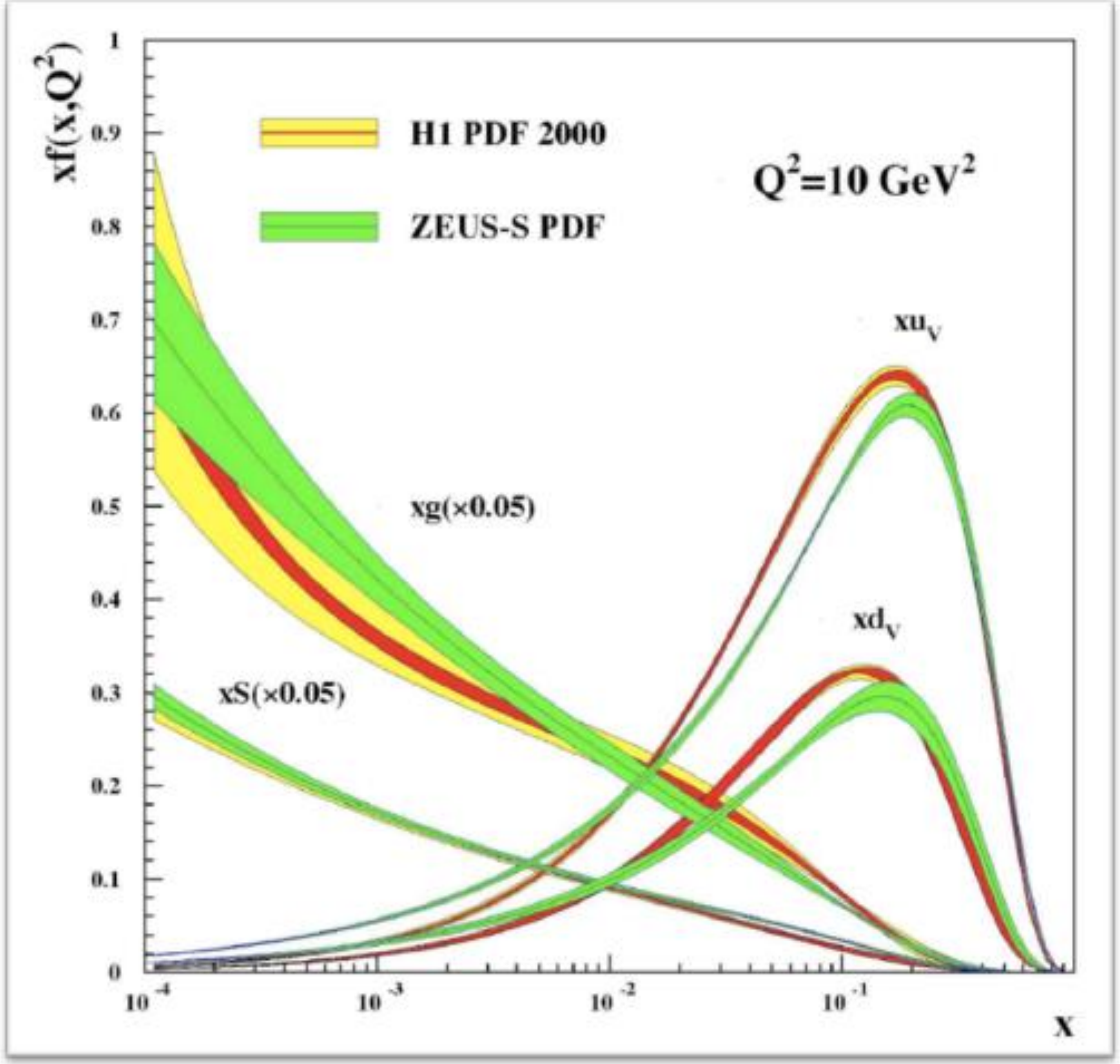




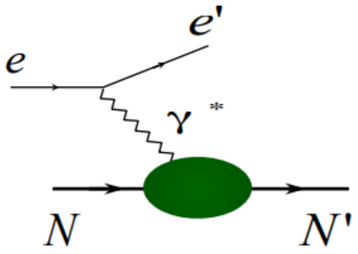
- Scaling violation is due to the fact that the quarks radiate gluons that can "materialize" as q-qbar pairs (sea quarks)
- With increasing Q^2 increases the resolution of the probe ($\sim\hbar/\sqrt{Q^2}$) and thus increases the number of partons that are "seen" bring a fraction x of the proton momentum
- 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

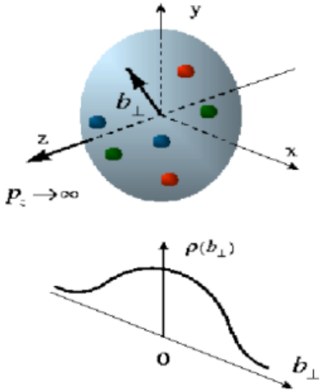
- All available deep inelastic and related hard scattering data involving incoming protons (and antiprotons) are used to determine the parton densities, f_i of the proton.

- 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

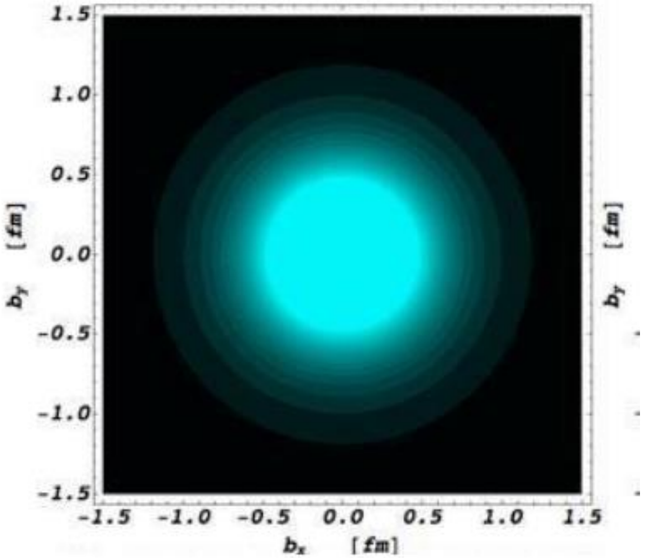


Elastic Scattering





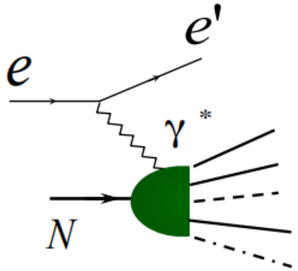
Proton

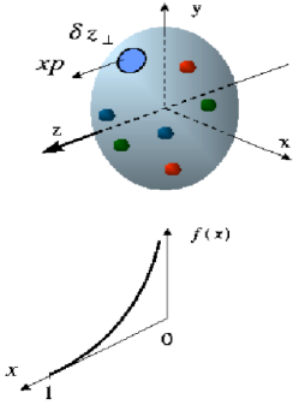


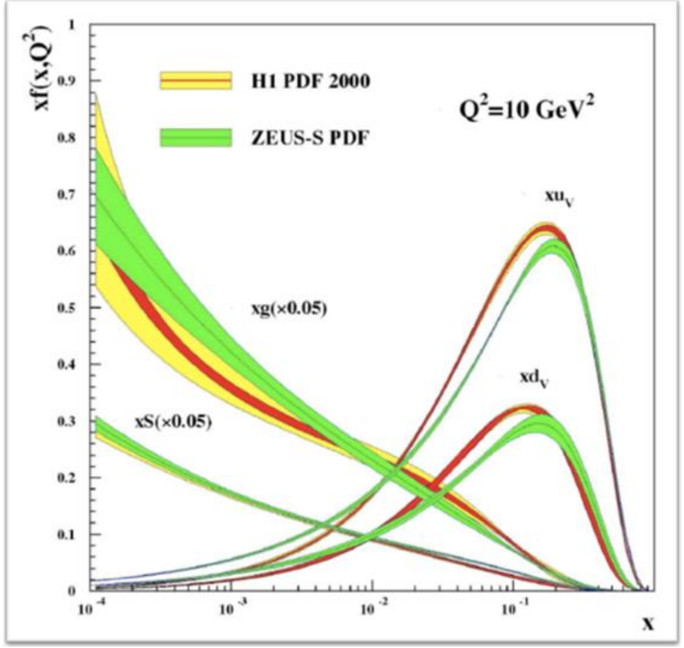
Cross-section parameterised in terms of Form Factors (Pauli, Dirac, axial, pseudo-scalar)

→ Transverse quark distributions: charge, magnetisation.

Deep Inelastic Scattering







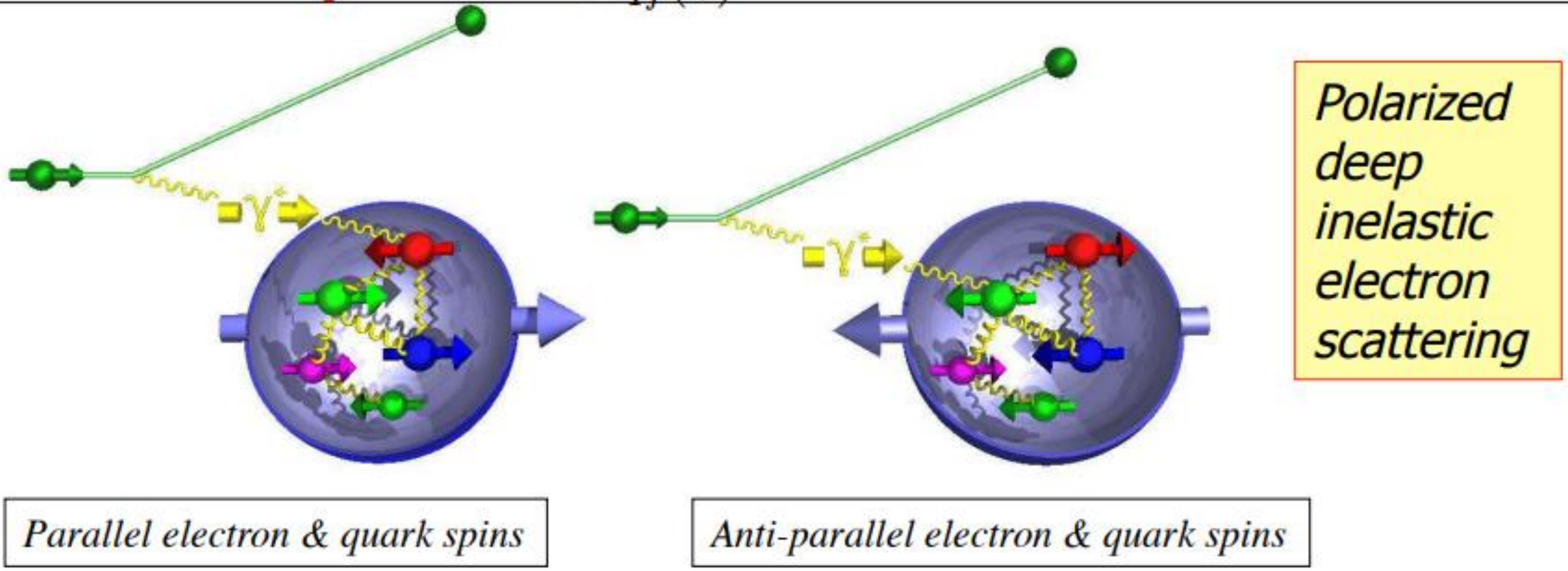
First experimental evidence of partons inside a nucleon

Cross-section parameterised in terms of polarised and unpolarised Structure Functions

→ Longitudinal momentum and helicity distributions of partons

Deep Inelastic Scattering with polarized target and beam

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



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

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

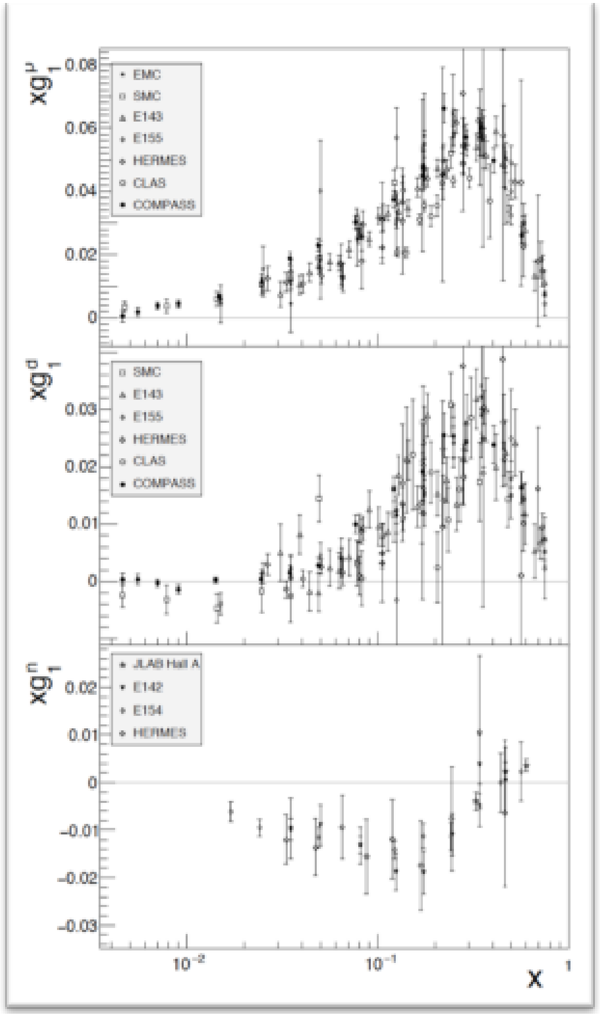
$$\Delta\Sigma \equiv (\Delta u(x) + \Delta\bar{u}(x)) + (\Delta d(x) + \Delta\bar{d}(x)) + (\Delta s(x) + \Delta\bar{s}(x))$$

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

From hyperon decays

- Mesurement of $\Gamma_1{}^p$, $\Gamma_1{}^n$
- Constraint based on the hyperon beta decay lifetimes
- Assumption of SU(3) flavou symmetry
- Global fit with DGLAP Q^2 evolution

$$\Rightarrow \Delta\Sigma \approx 0.25$$



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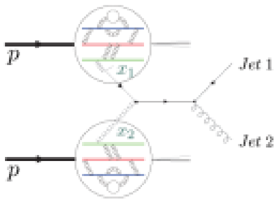
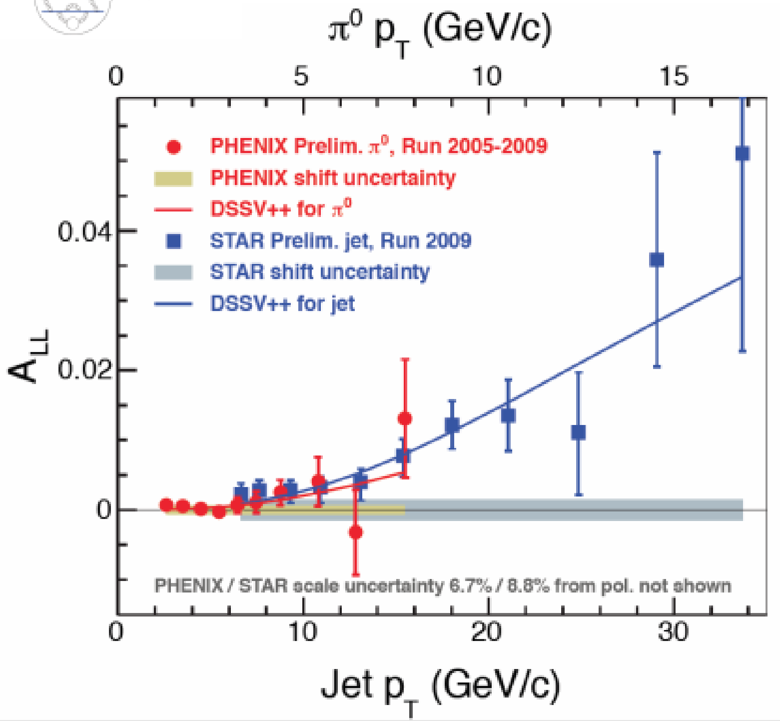
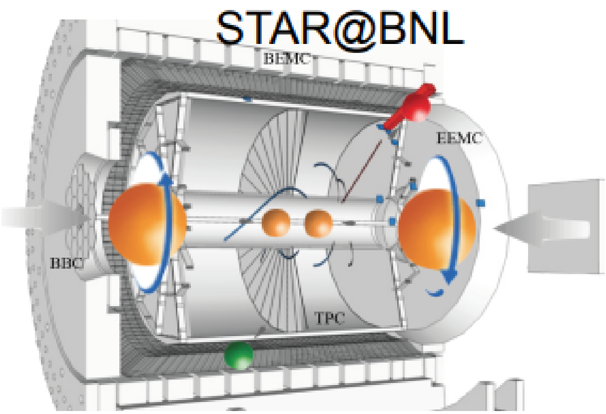
Only small fraction of the proton spin is carried by the quarks & antiquarks!!

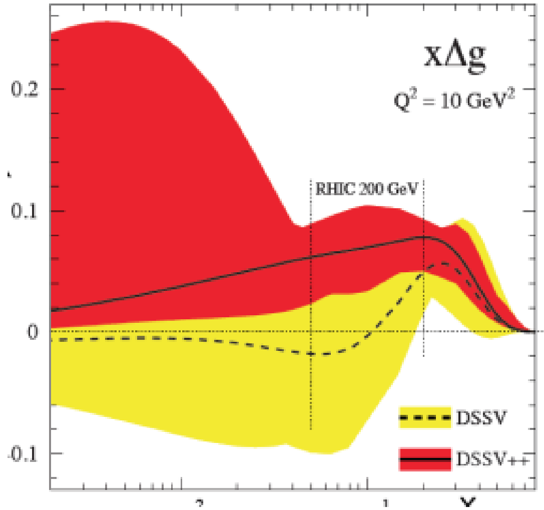
Gluon Helicity



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



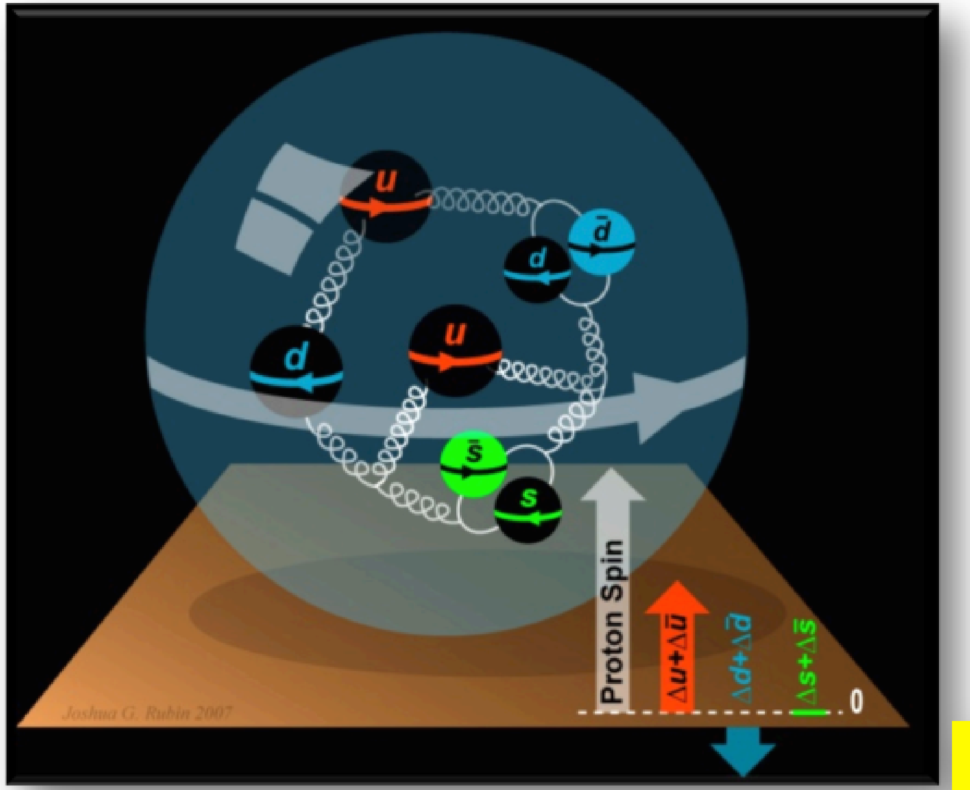




Indication of small, but non-0 **Δ**g from RHIC data, in particular STAR jet results

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

The Incomplete Nucleon: Spin Puzzle



- **DIS → ΔΣ ≅ 0.25**
- **RHIC + DIS → ΔG**

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

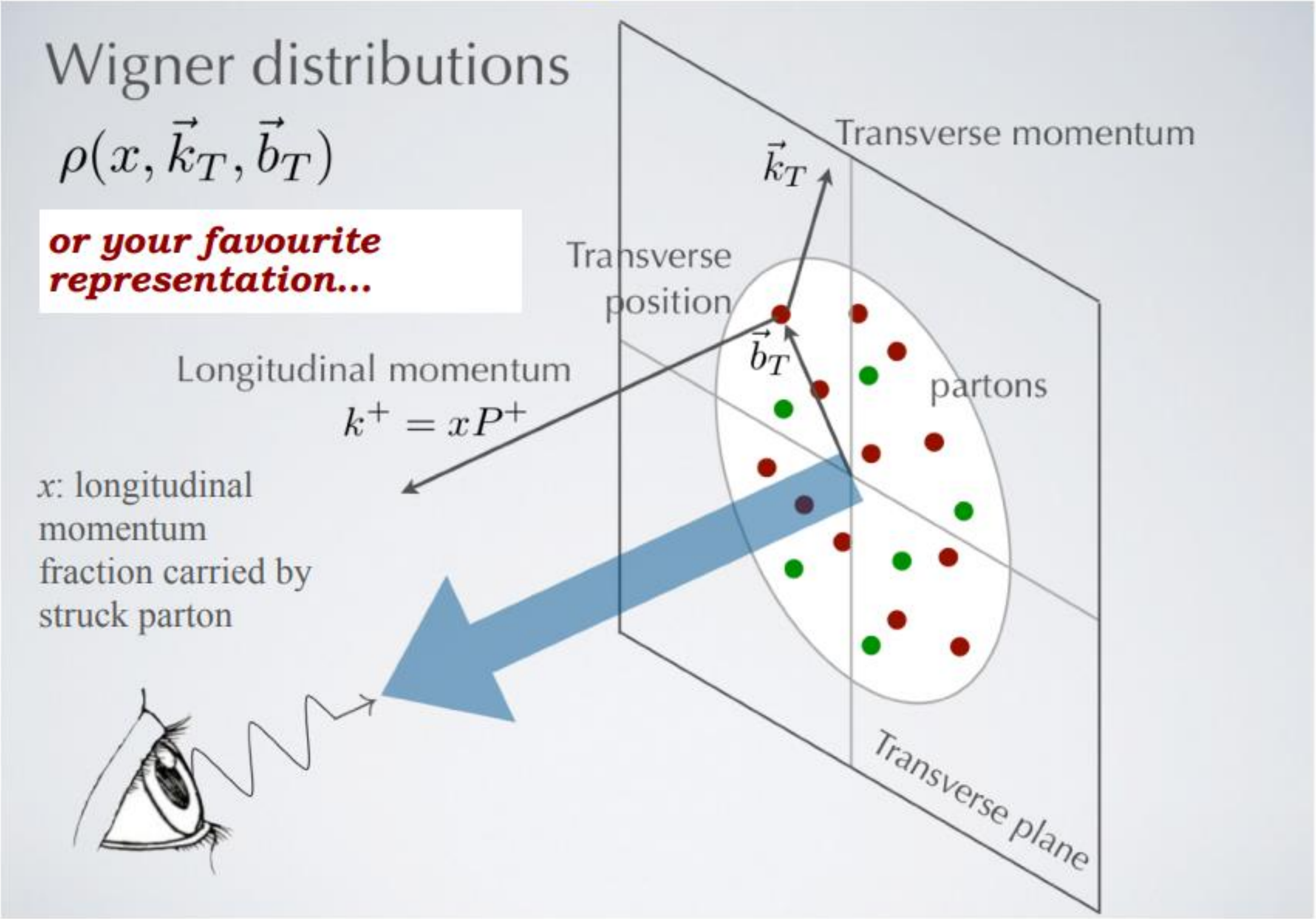
  could be small
- **→ L_q**

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

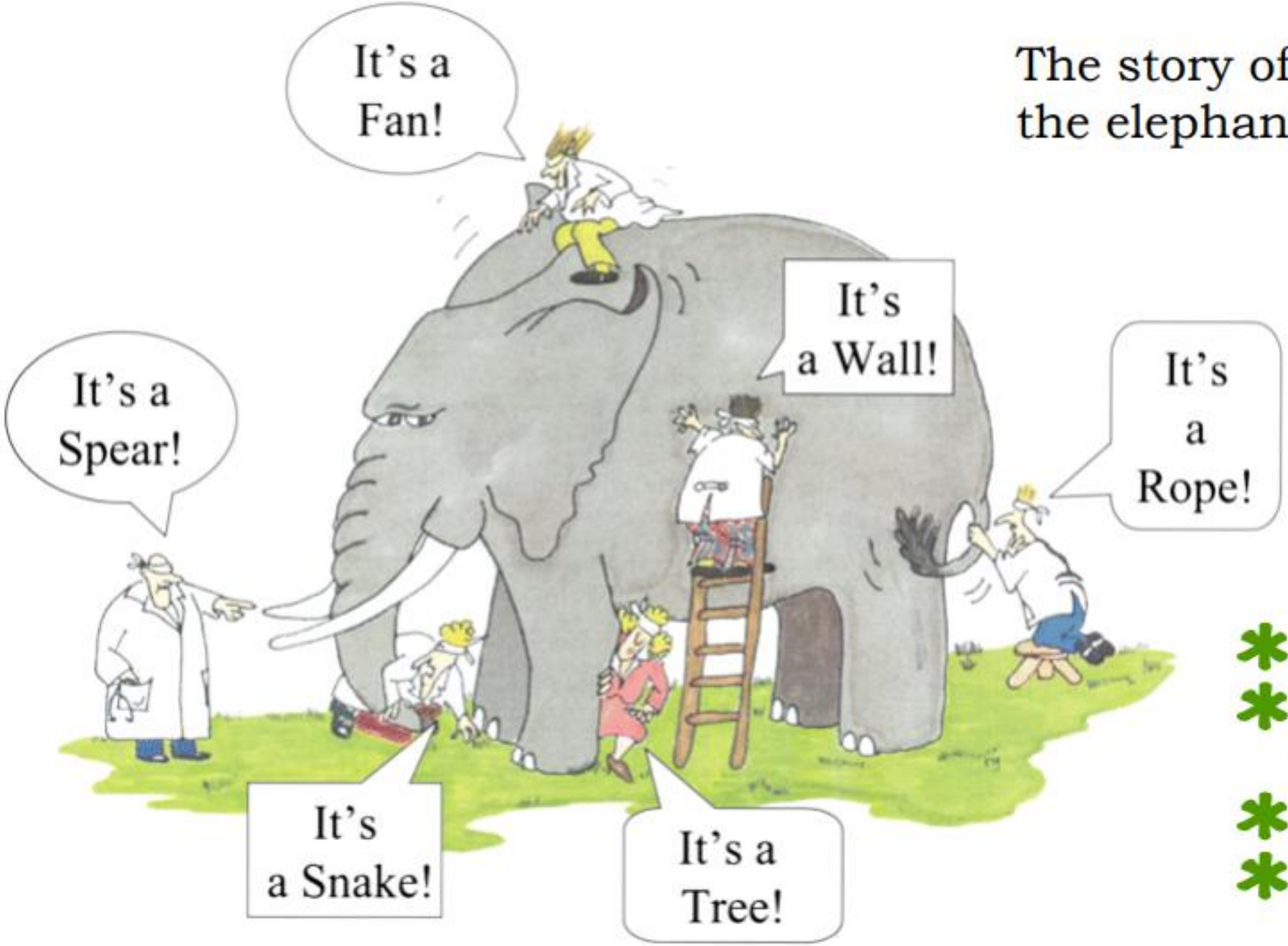
Significant proton spin might be carried by the angular momentum of the parton!!

Unified Picture of Nucleon Structure

A full "knowledge" of the nucleon…



… is hard to come by



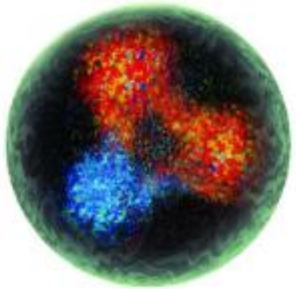
The story of the blind men and the elephant.

- Elastic scattering
- Deep Inealstic Scattering (DIS)
- Semi-inclusive DIS
- Deep exclusive reactions

G. Renee Guzlas, artist.

What you see depends also on how you look…

Images of the nucleon

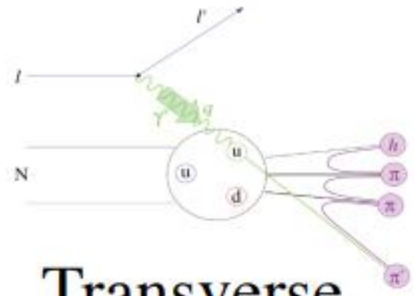


Wigner function:
full phase space parton
distribution of the nucleon

Wigner distributions
$\rho(x, \vec{k}_T, \vec{b}_T)$

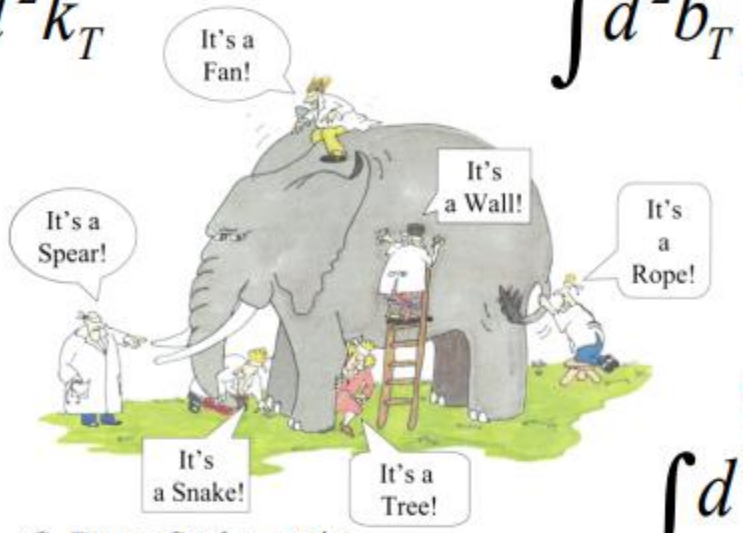
$\int d^2k_T$

$\int d^2b_T$

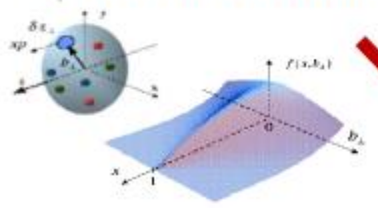


Transverse Momentum Distributions (TMDs)

Generalised Parton Distributions (GPDs)

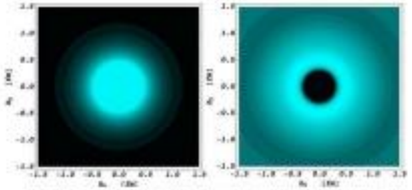


G. Renee Guzlas, artist.



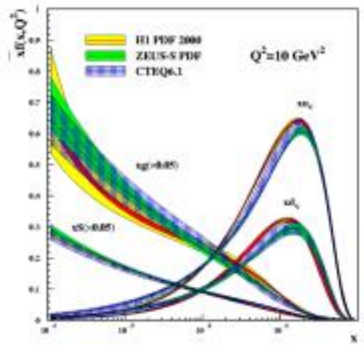
$\int dx$

$\int d^2k_T$

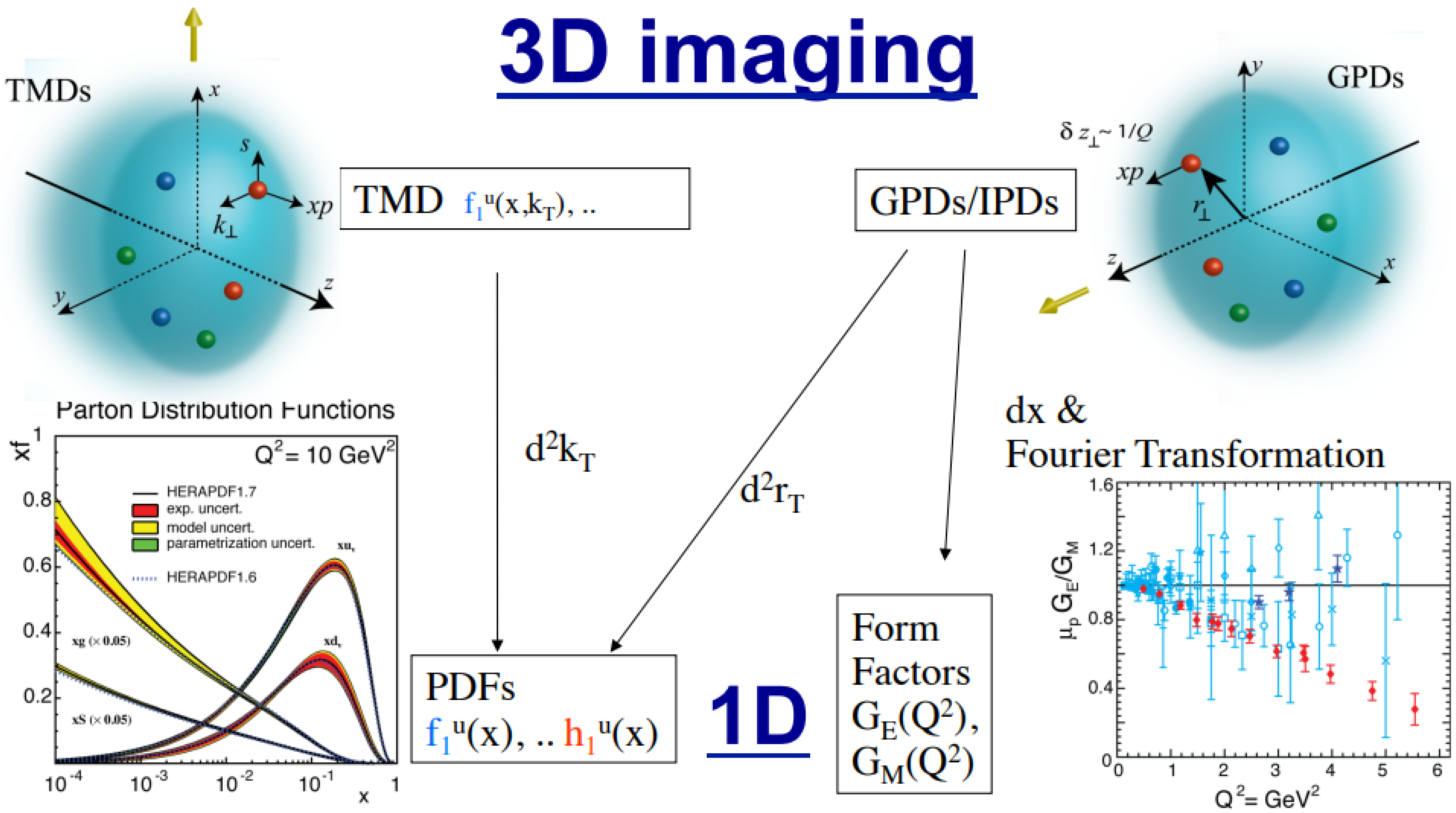


Form Factors
eg: G_{E}, G_M

Parton Distribution Functions (PDFs)

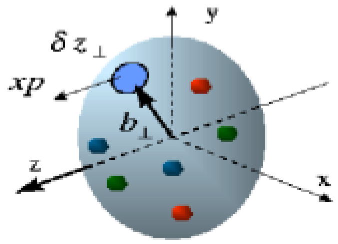


Unified View of the Nucleon Structure

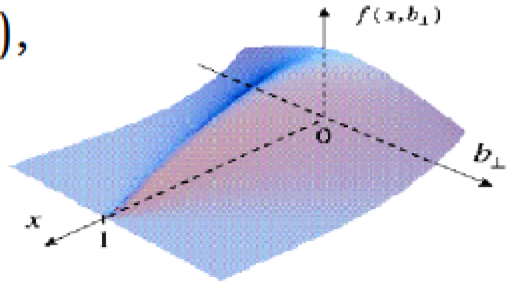


Generalised Parton Distributions (GPDs) —
proposed by Müller (1994), Radyushkin, Ji (1997).

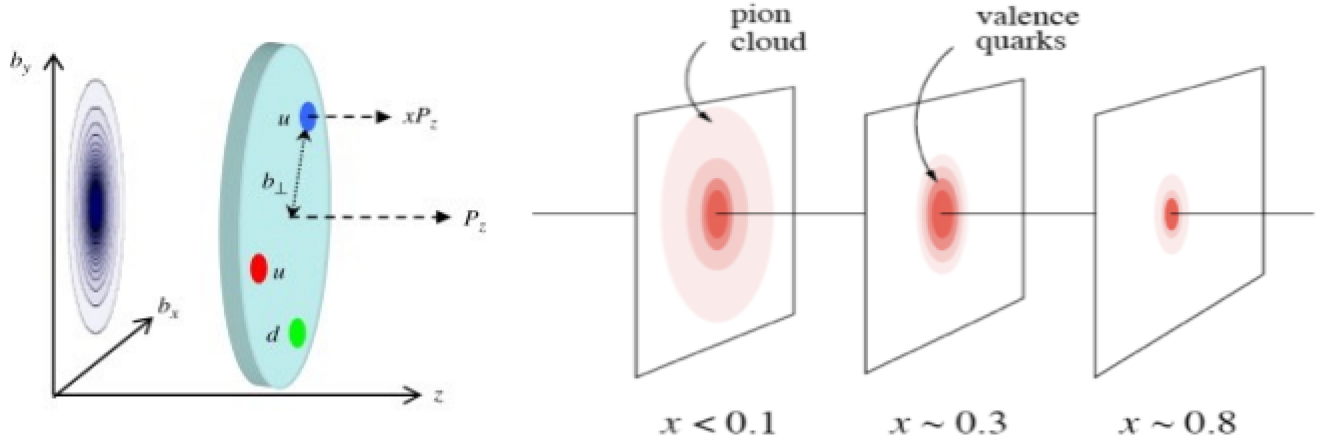
✱ *Directly related to the matrix element of the energy-momentum tensor evaluated between hadron states.*



In the infinite momentum frame, can be interpreted as relating transverse position of partons (impact parameter), $b_\perp$, to their longitudinal momentum fraction (x).



Tomography: 3D image of the nucleon.



✱ First studies at JLab and DESY (HERMES), currently at JLab and CERN (COMPASS). A crucial part of the JLab12 programme — and, in the future, of the EIC.

GPD & TMD

DVCS at Jefferson Lab, Sivers Measurement at Fermilab & Future Experiment at EIC

Generalized Parton Distributions (GPDs) provide correlated information of the **transverse position** and the **longitudinal momentum** distributions of partons.

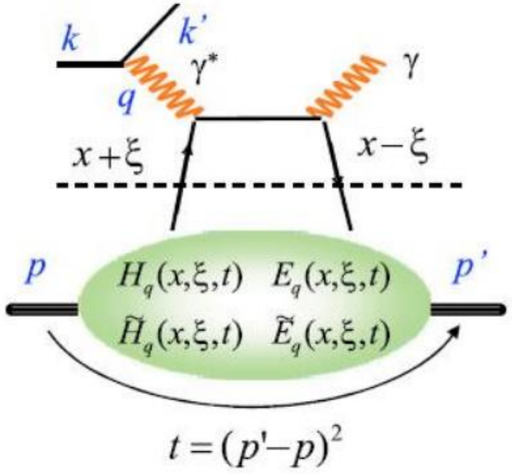
$$GPDs\,(x,\ \xi,\ t\ =\ \Lambda^2)$$

2 longitudinal momentum fractions (x, ξ)

squared momentum transfer to the proton (t)

$$t \rightarrow \Delta_T \xrightarrow{Fourier\ transform} \mathbf{b}\ (transverse\ position)$$

$$e\ p \rightarrow e'\ p'\ \gamma$$



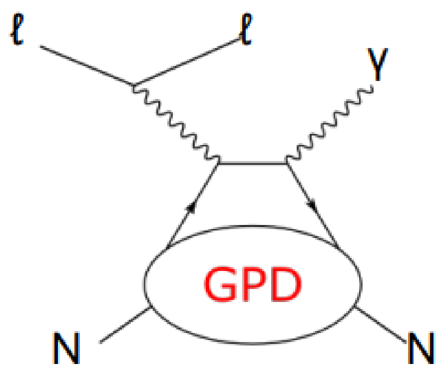
$$\gamma^*\ p \rightarrow p'\ \gamma$$

Deeply Virtual Compton Scattering (DVCS)

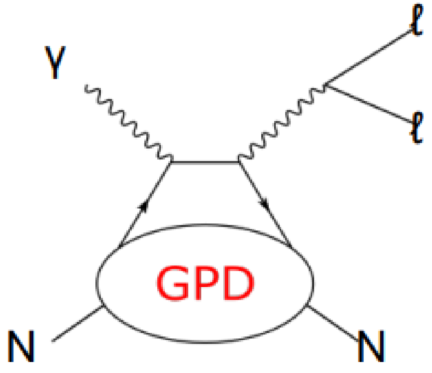
Chiral even GPDs: quark helicity is conserved

	H	E	averages over quark helicities "unpolarized"
	$\widetilde{H}$	$\widetilde{E}$	differences of quark helicities "polarized"
	conserve nucleon helicity	flip of the nucleon helicity	

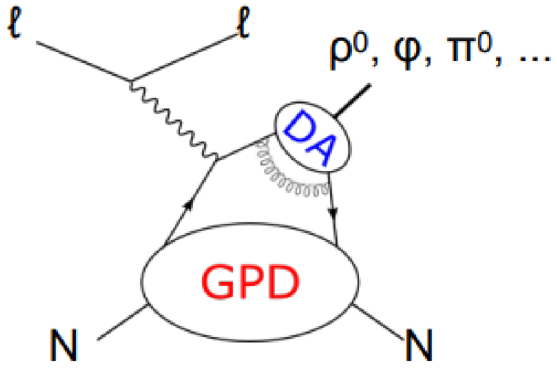
GPDs are accessible from various production channels:



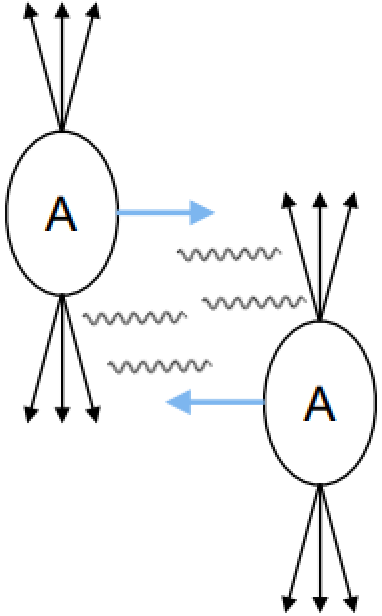
DVCS
Deeply Virtual Compton Scattering



TCS
Timelike Compton Scattering



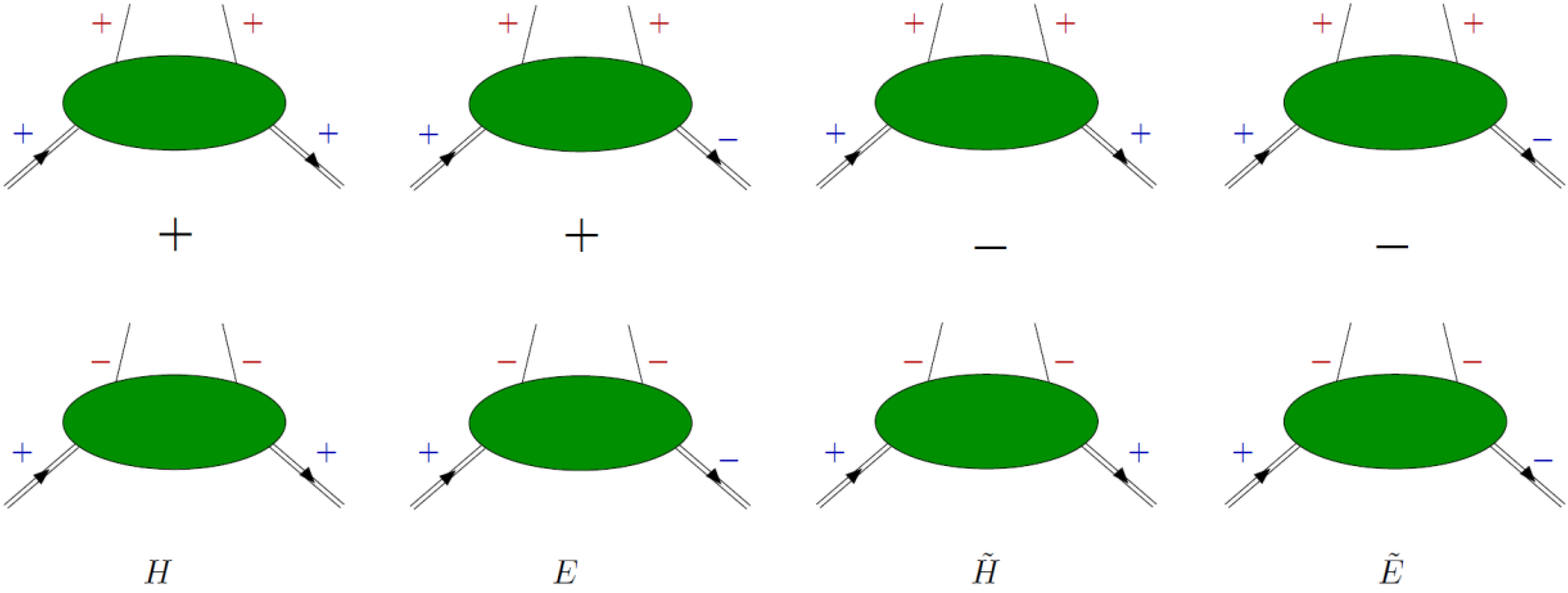
HEMP
Hard Exclusive Meson Production



UPC
Ultra Peripheral Collisions

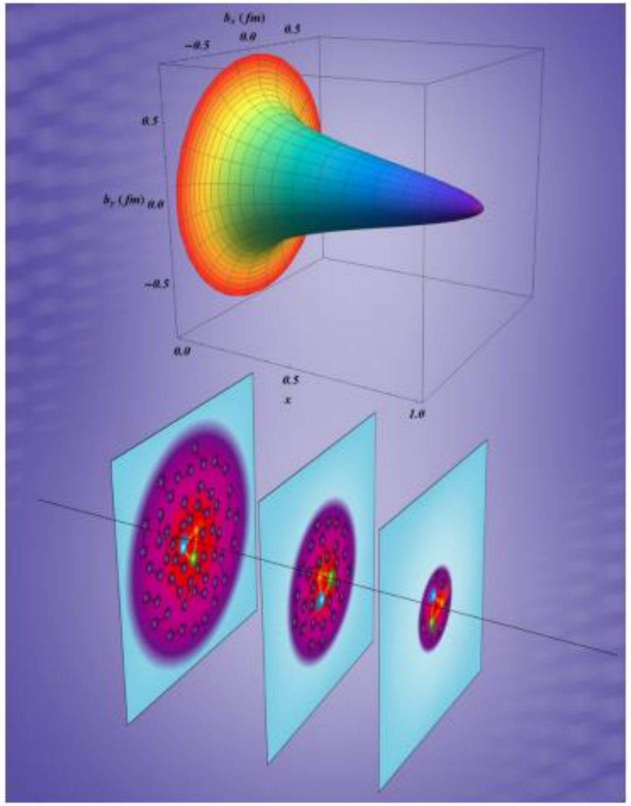
Channel of interest

Generalized Parton Distribution (GPDs)



Generalized Parton Distributions (GPDs) provide key access to important nucleon properties:

- Nucleon Tomography:

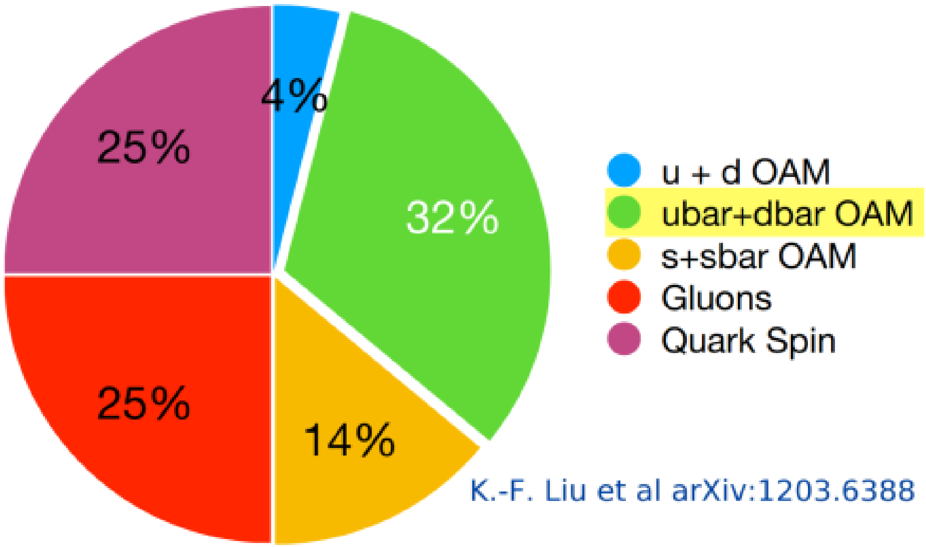


R. Dupre et al arXiv:1704.07330

- Angular momentum of the partons

Ji's angular momentum sum rule

$$\int_{-1}^{+1} dx\, x \left\{ H^q(x,\xi,0) + E^q(x,\xi,0) \right\} = A(0) + B(0) = 2J^q$$



K.-F. Liu et al arXiv:1203.6388

Proton spin contributions from Lattice QCD

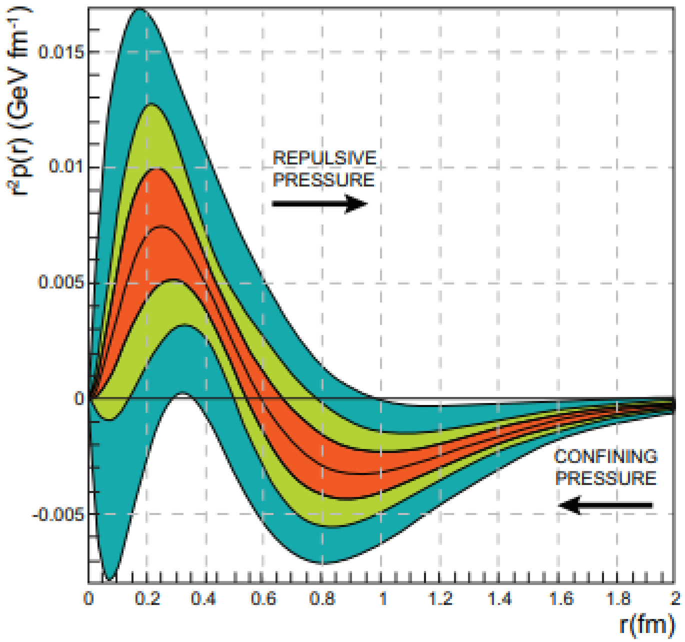
Jaffe-Manohar decomposition

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \boxed{\Delta G + L_g} + \boxed{L_q} + \boxed{L_{\bar{q}}}$$

Gluon total angular momentum; Valence quarks' OAM; Sea-quarks' OAM

Generalized Parton Distributions (GPDs) provide key access to important nucleon properties:

- Mechanical properties of the nucleons (pressure, force, …)



Pressure distributions inside proton

- without JLab 6 GeV data
- with JLab 6 GeV data
- with JLab 12 GeV data (projected)

V. D. Burkert[1]*, L. Elouadrhiri[1] & F. X. Girod[1]

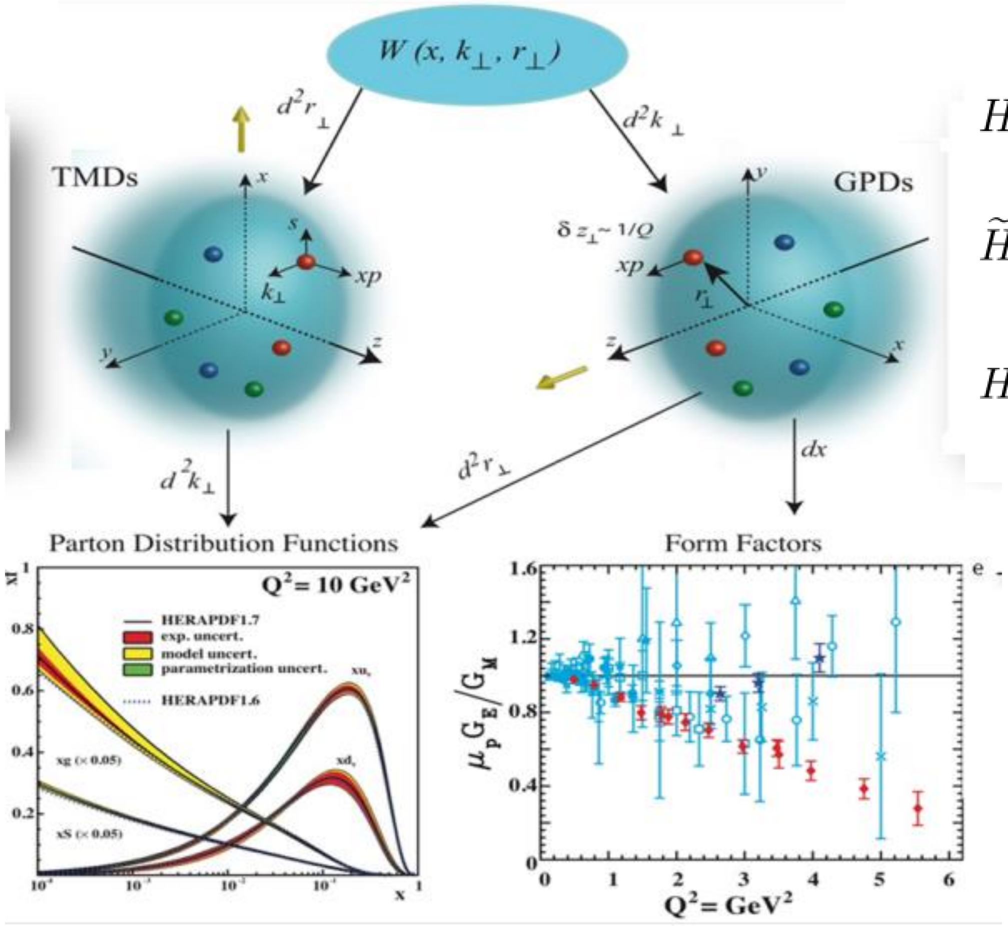
Mass and force/pressure distributions

$$M_2^q(t) + \frac{4}{5} d_1(t)\xi^2 = \frac{1}{2}\int_{-1}^{1} dx\, xH^q(x,\xi,t)$$

$$d_1(t) \propto \int \frac{j_0(r\sqrt{-t})}{2t} p(r) d^3r$$

Generalized Parton Distributions (GPDs) provide key access to important nucleon properties:

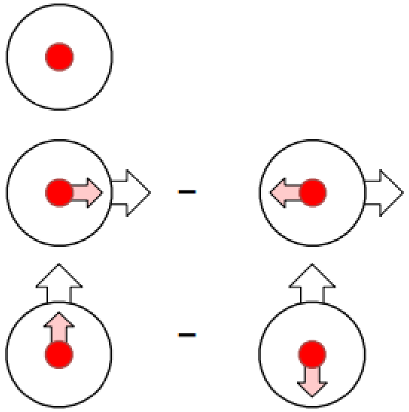
- Access to PDFs and Elastic Forms Factors



$$H^q(x,0,0) \equiv q(x)$$

$$\widetilde{H}^q(x,0,0) \equiv \Delta q(x)$$

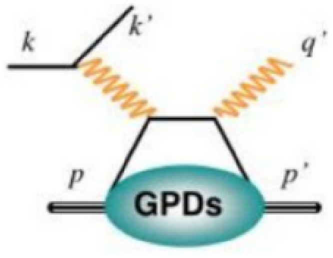
$$H_T^q(x,0,0) \equiv h_1(x)$$



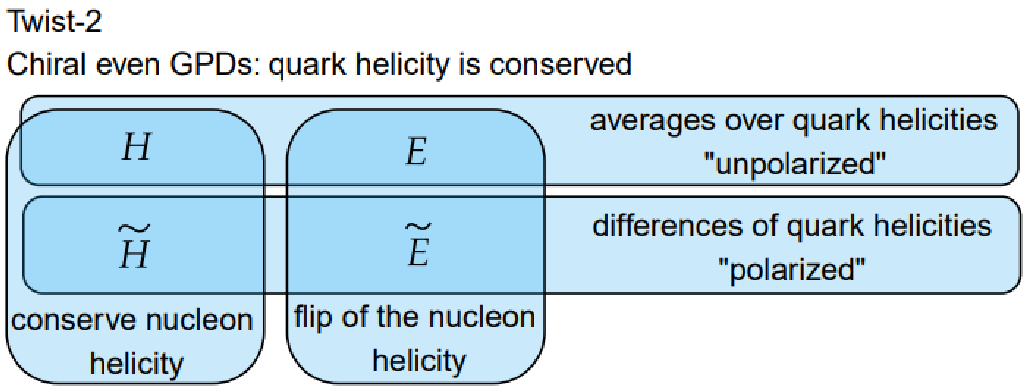
$$\int_{-1}^{1} dx\, H^q(x,\xi,t) \equiv F_1^q(t) \qquad \int_{-1}^{1} dx\, E^q(x,\xi,t) \equiv F_2^q(t)$$

$$\int_{-1}^{1} dx\, \widetilde{H}^q(x,\xi,t) \equiv g_A^q(t) \qquad \int_{-1}^{1} dx\, \widetilde{E}^q(x,\xi,t) \equiv g_P^q(t)$$

4 chiral even GPDs can be accessed via DVCS



$ep \longrightarrow e'p'\gamma$



GPDs are related to Compton-Form Factors (CFFs) via convolution:

$$\mathcal{H}\left(x_B,\, t,\, Q^2\right) = \int_{-1}^{1} dx \left[\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right] H\left(x,\, \xi,\, t,\, Q^2\right)$$

CFFs extractions (access directly via cross section or asymmetry measurements) is a good way to obtain GPDs

- Past: PDFs from FFs extractions
- Present: GPDs from CFFs extractions

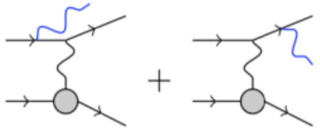
CFFs are observables that could access directly from experiments

DVCS channel

Cross sections = DVCS + Bethe-Heitler (BH)

$$\sigma \propto |\mathscr{A}|^2 = |\mathscr{A}_{BH} + \mathscr{A}_{DVCS}|^2 = |\mathscr{A}_{BH}|^2 + |\mathscr{A}_{DVCS}|^2 + \mathscr{I}$$

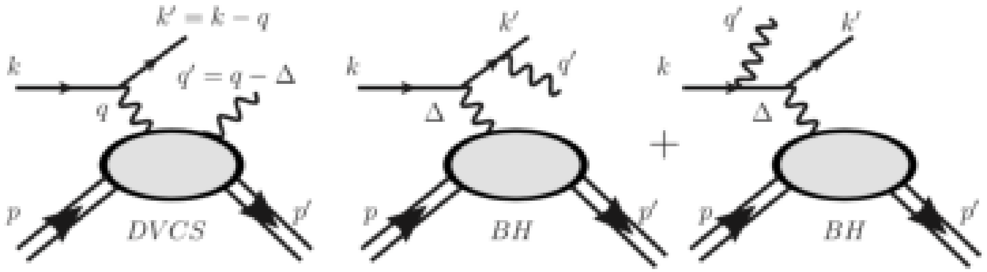
Bethe-Heitler process



calculable within QED

DVCS

parametrised by CFFs



$$\underbrace{\frac{d^5\sigma}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} = \frac{\alpha^3 x_B y^2}{16\pi^2 Q^4\sqrt{1+\epsilon^2}}\frac{1}{e^6}\left[|\mathcal{T}^{BH}|^2 + |\mathcal{T}^{DVCS}|^2 + \mathcal{I}\right]}_{f(k,Q^2,x_B,t,\phi)}$$

- k Energy of the incoming electron.
- Q^2 Electron squared momentum transfer: $-(k-k')^2$
- t Squared momentum transfer to the proton: $(p'-p)^2$
- x_B Bjorken variable: $x_B = \frac{Q^2}{2(pq)}$
  Momentum fraction of the quark or gluon on which the photon scatters.

DVCS Cross sections formulas:

- Ji (1996)
- BKM (Belitsky, Muller, Kirchner): BKM02, BKM10
- BMJ (Belitsky, Muller, Ji, 2012)
- BMMP (Braun, Manashov, Muller, Pirnay, 2014)
- VA (B. Kriesten et all,): VA 19, VA 21
- Yuxun Guo et all, 2021

CFFs Model:

- VGG (Vanderhaeghen, Guichon, Guidal, 1999)
- GK (Goleskokov, Kroll, 2005)
- KM (Kumericki, Muller): KM09, KM10, KM15
- KMM12 (Kumericki, Muller, Murray, 2012)
- VA-reggeized spectator (B. Kriesten, S. Liuti, 2021)

Each model has different GPD parameterization

DVCS at JLAB

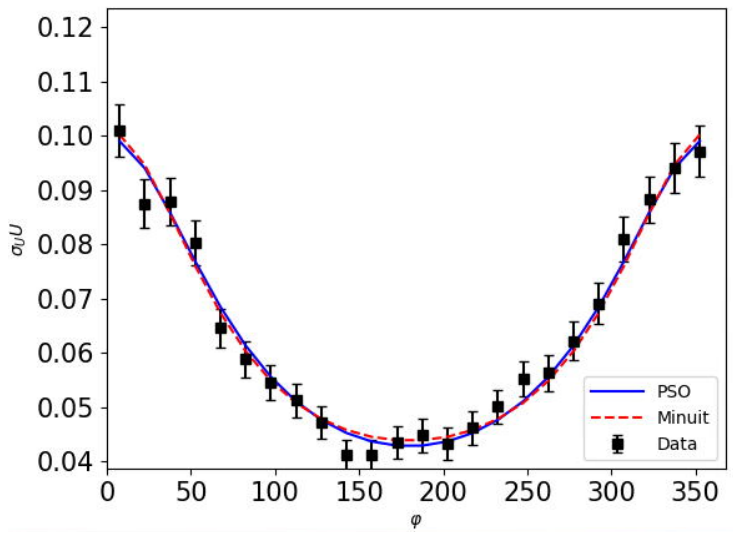
DVCS Data on Cross sections and Asymmetries:

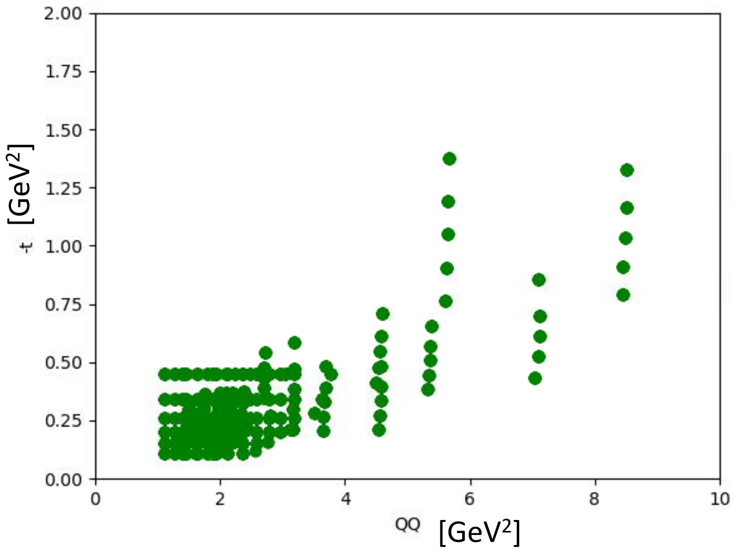
- No ϕ-dependence: HERMES, COMPASS, ZEUS, A1
- High statistics with ϕ-dependence: JLAB Hall A, CLAS (Hall B)

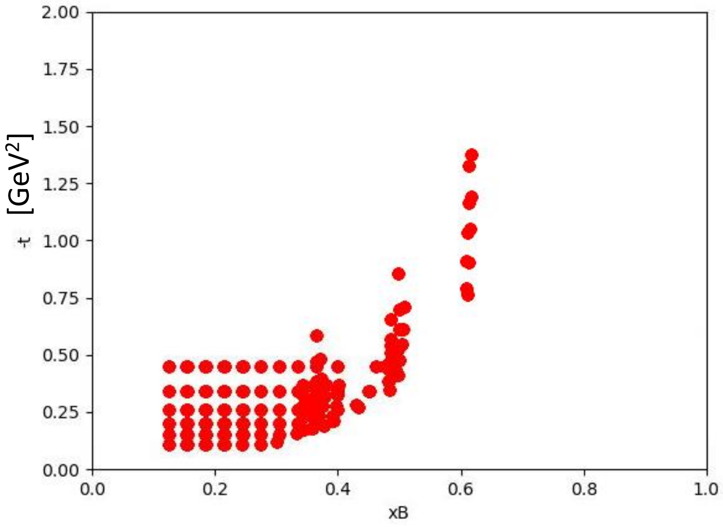
Data used in this work: All ϕ-dependence cross-sections

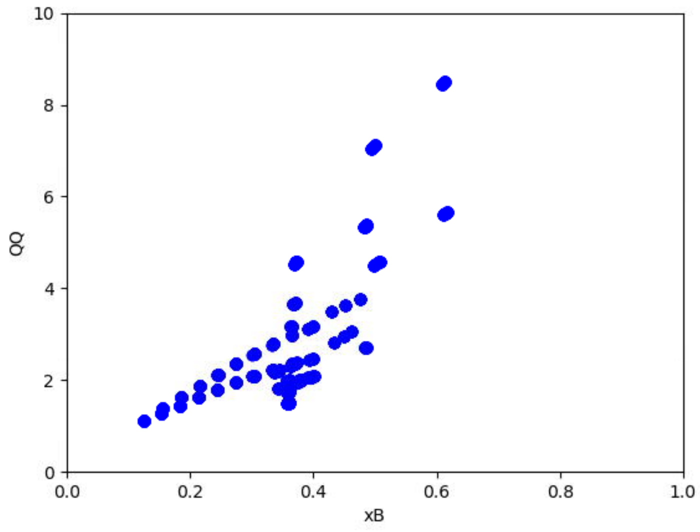
- JLAB Hall A experiment: E00-110 (2015), E07-007 (2017), E12-06-114 (2022)
- JLAB Hall B experiment: e1-DVCS1 (2015)

A total of 195 kinematic sets (3882 data points) are used in this analysis









Extracting Compton Form Factors from DVCS Cross Sections

BKM10 Formulism at leading twist

$$\frac{d^5\sigma}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} = \frac{\alpha^3 x_B y^2}{16\pi^2 Q^4\sqrt{1+\epsilon^2}}\frac{1}{e^6}\left[\underbrace{|\mathcal{T}^{BH}|^2}_{\text{Exact (QED) FFs: } F_1,\, F_2} + \underbrace{|\mathcal{T}^{DVCS}|^2}_{\phi\text{-indep}} + \underbrace{\mathcal{I}}_{\text{3 CFFs}}\right]$$

$$\mathcal{I}^{BMK} = \frac{e^6}{x_B y^3 t \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\Big[A_{UU}^{BKM}\left(F_1 \Re e\mathcal{H} - \frac{t}{4M^2}F_2\Re e\mathcal{E}\right) + B_{UU}^{BKM}G_M\left(\Re e\mathcal{H} + \Re e\mathcal{E}\right) + C_{UU}^{BKM}G_M\Re e\widetilde{\mathcal{H}}\Big]$$

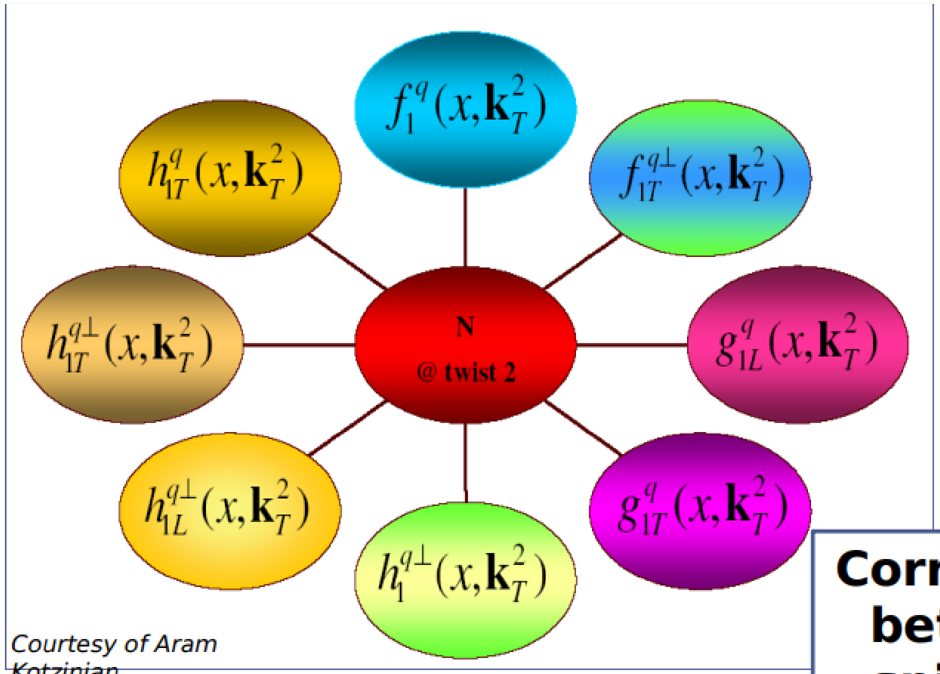
$$|\mathcal{T}_{DVCS}|^2 = \frac{e^6}{y^2Q^2}\left\{2(2-2y-y^2)\right\}\underbrace{C_{unp}^{DVCS}(\mathcal{F},\mathcal{F}^*)}_{\text{8 CFFs}}$$

4 fit parameters:

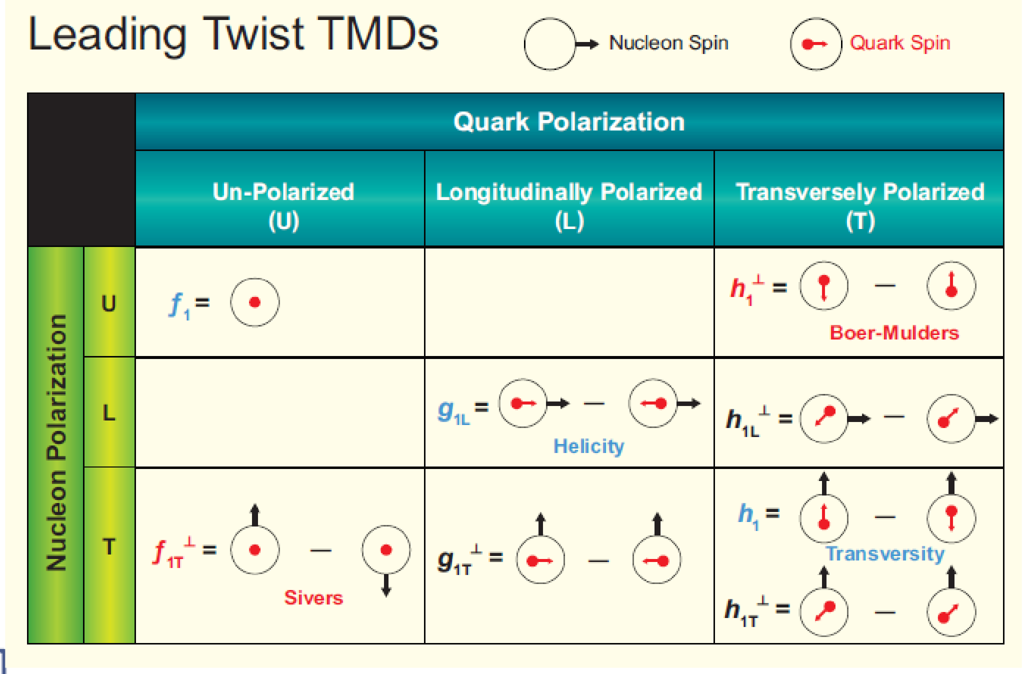
$\Re e\mathcal{H}$, $\Re e\mathcal{E}$, $\Re e\widetilde{\mathcal{H}}$, pure DVCS

→ Access to GPD via Compton Form Factors

TMD distribution functions

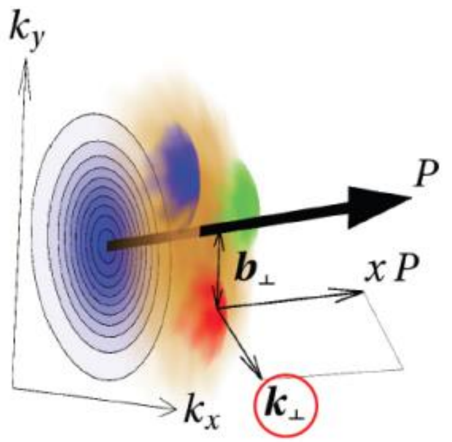


Courtesy of Aram Kotzinian

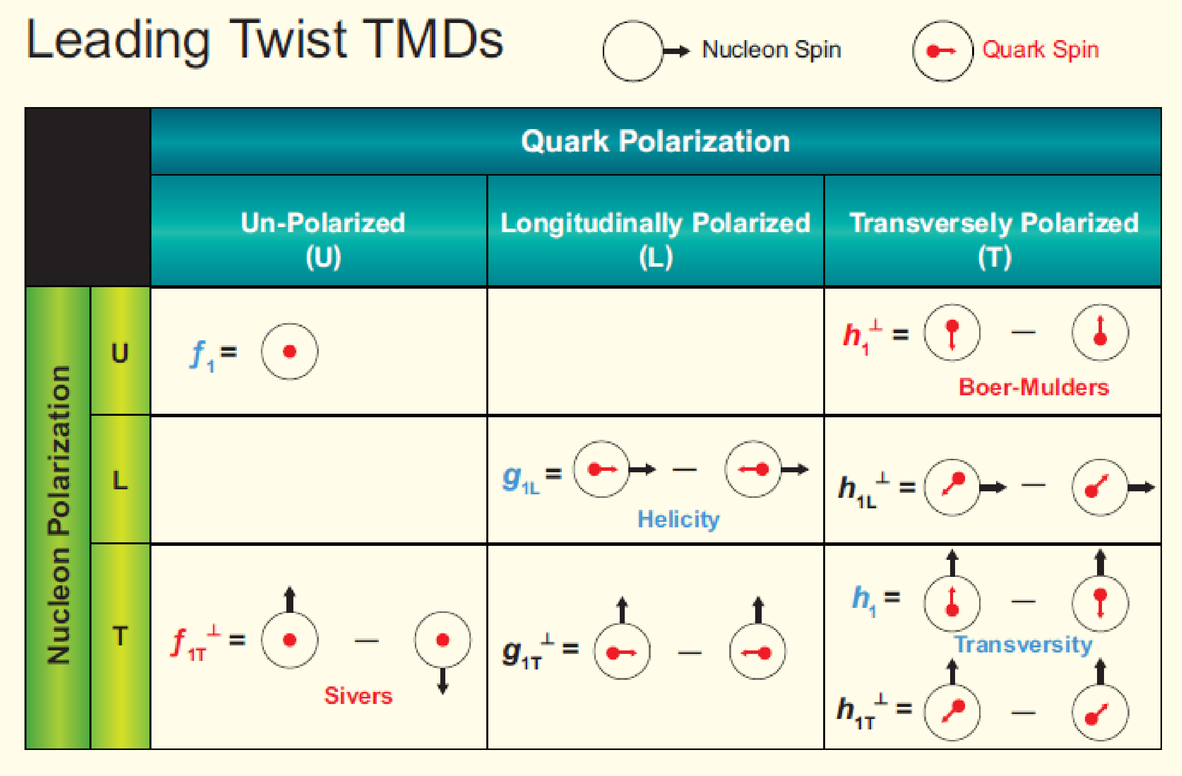


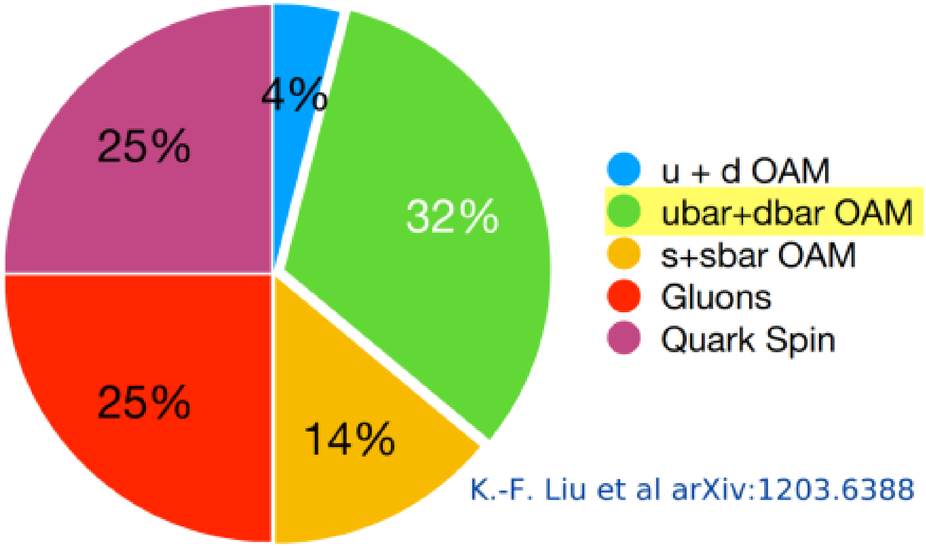
Correlation between spin and transverse momentum

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



Sivers Function to probe orbital-angular momentum of the partons





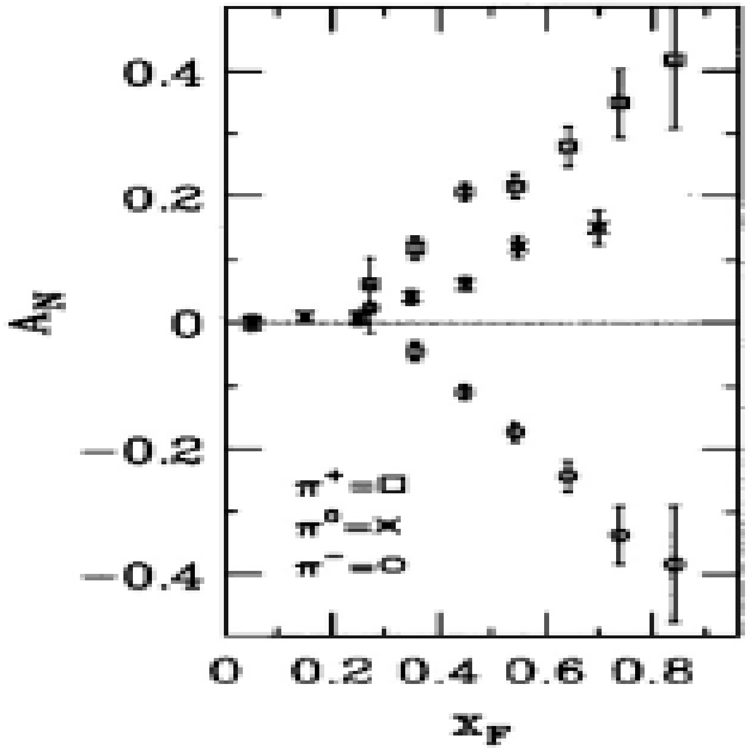
Proton spin contributions from Lattice QCD

Sivers function describes the distribution of unpolarized quarks inside a transversely polarized nucleon, through a correlation between the quark transverse momentum and the nucleon transverse spin.

Non-zero Sivers function/asymmetry implies a non-zero OAM

Transverse Momentum Distribution (TMD) & Sivers Function

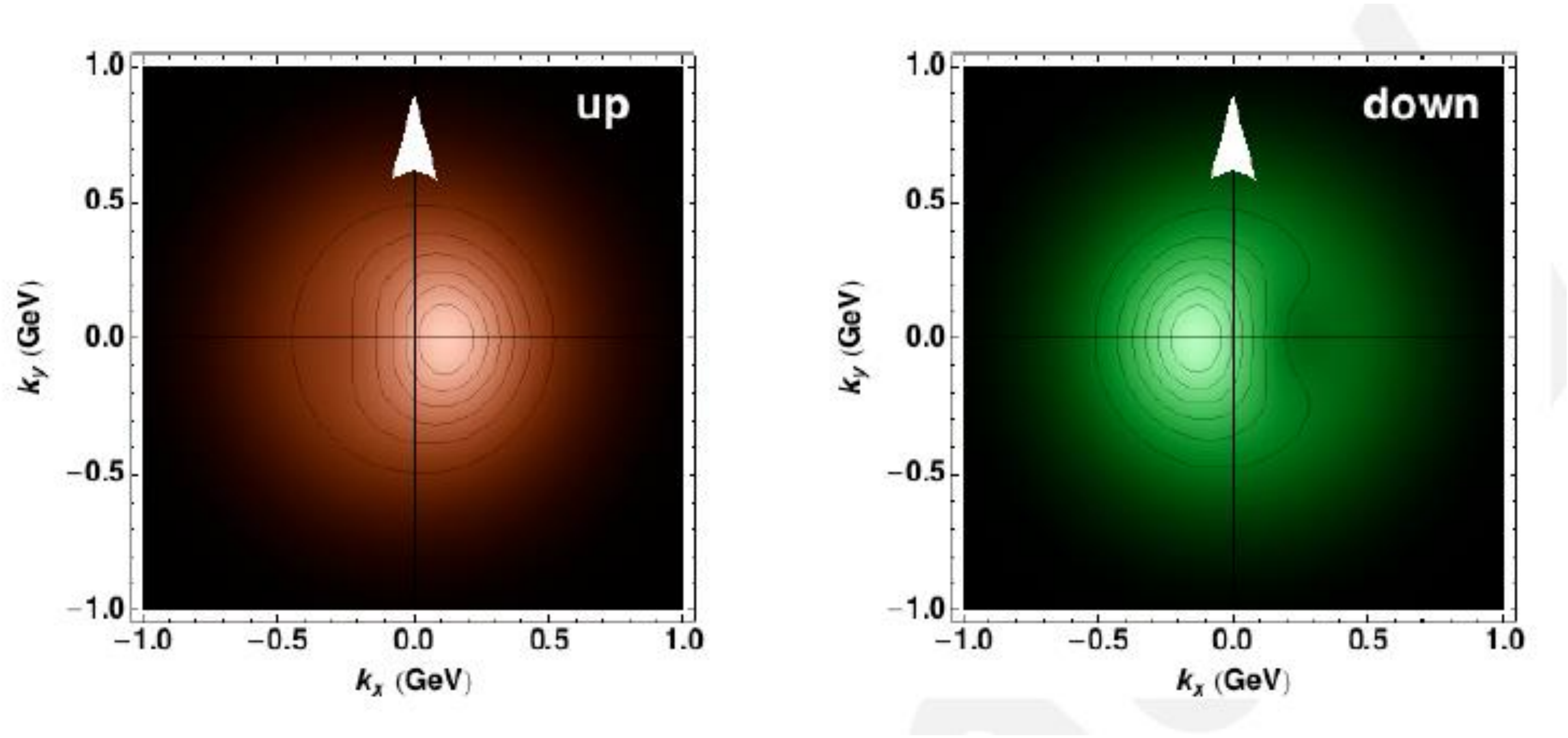
<u>Sivers function</u> initially was formulated to explain large left-right asymmetry in the pion production from pp scattering



Pion asymmetry observed in $pp^{\uparrow} \to \pi X$ from E704 Experiment

Transverse Momentum Distribution (TMD) & Sivers Function

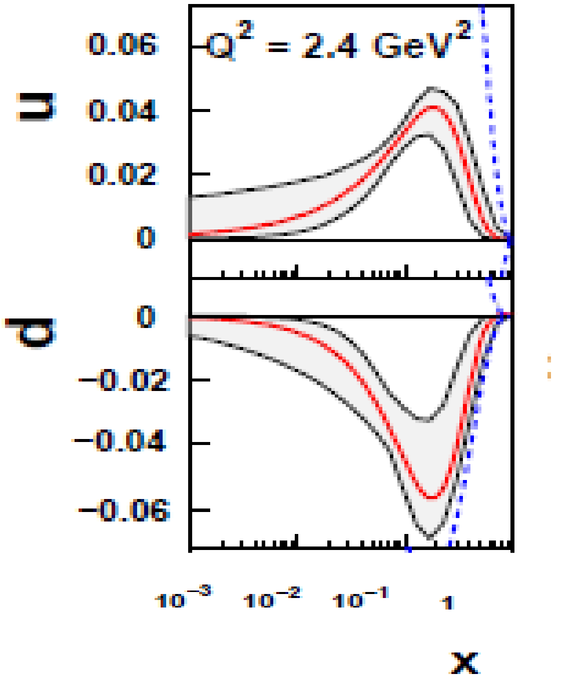
Supposed the proton is moving toward us and its spin is pointing upward. it turns out that we see up quarks moving preferentially to the right and down quarks to the left



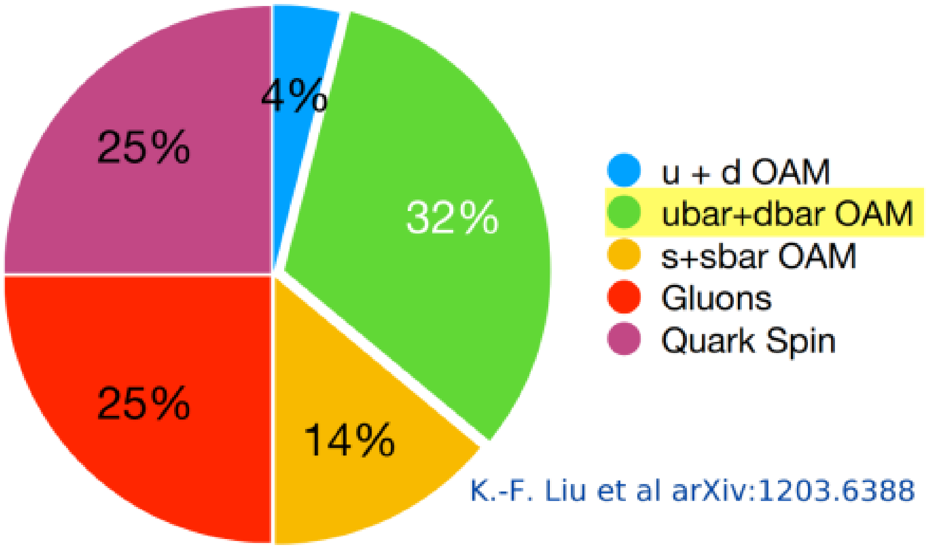
The up and down quark density distortion in transverse-momentum space, obtained by studies of the Sivers function

Why the Sea quarks are important?

HERMES, COMPASS and Jlab have measured nonzero values of the Sivers function of the nucleon, with the data indicating that the valence d-quark and u-quark Sivers functions are approximately equal and opposite in sign (zero contribution to the overall nucleon spin)



The Sivers distribution for u and d quarks flavors.



K.-F. Liu et al arXiv:1203.6388

Proton spin contributions from Lattice QCD

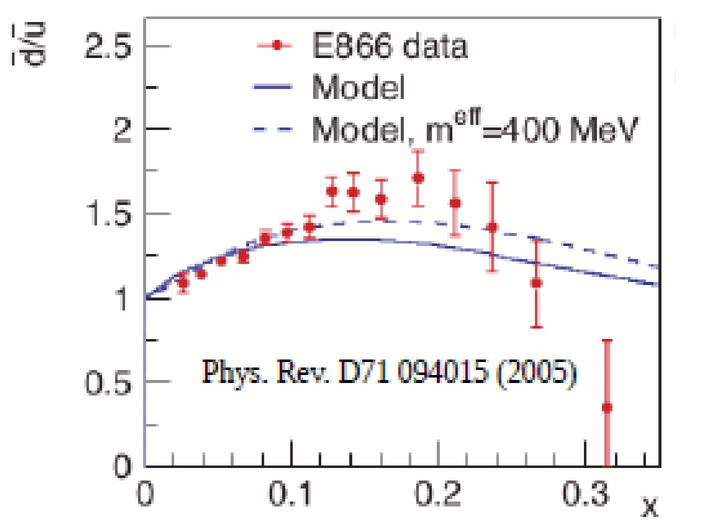
Jaffe-Manohar decomposition

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \boxed{\Delta G + L_g} + \boxed{L_q} + \boxed{L_{\bar{q}}}$$

Gluon total angular momentum | Valence quarks' OAM | Sea-quarks' OAM

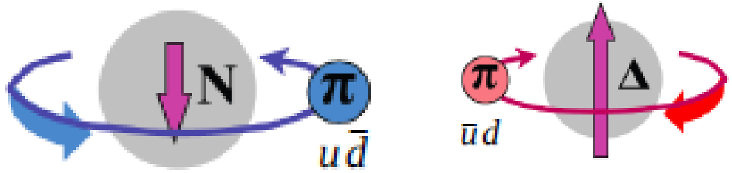
Why the Sea quarks are important?

The E866 Experiment at FermiLab shows the asymmetry between $\bar{d}/\bar{u}$. E866 results might point to Sea quarks OAM according to the pion-cloud model.



The distribution ratio of $\bar{d}/\bar{u}$

$$|p\rangle \propto |p_0\rangle + |n\pi^+\rangle + |\Delta^{++}\pi^-\rangle + \ldots$$

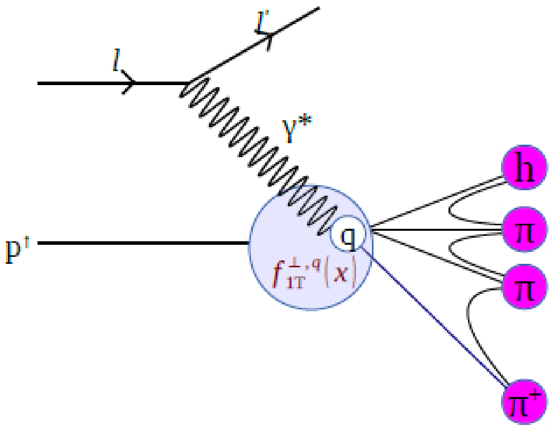


To conserve parity, pion in $N\pi$ system should have the orbital angular momentum. Therefore, the $\bar{d}$ excess in the nucleon should have nonzero OAM.

How to probe sea quark's sivers function

$$e + p^{\uparrow} \rightarrow e'\pi X$$

① Polarized Semi-Inclusive DIS

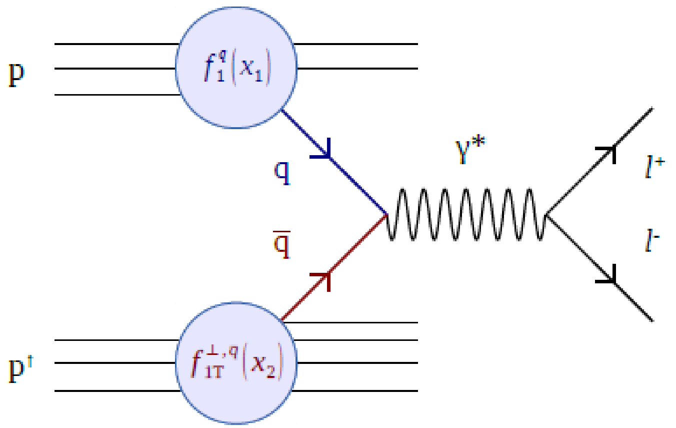


$$A_{UT}^{SIDIS} \propto \frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x) \otimes D_1^q(z)}{\sum_q e_q^2 f_1^q(x) \otimes D_1^q(z)}$$

- L-R asymmetry in hadron production
- quark to hadron fragmentation function
- valence-sea quark: mixed

$$p + p^{\uparrow} \rightarrow \mu^+\mu^- X$$

② Polarized Drell-Yan



$$A_N^{DY} \propto \frac{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftrightarrow 2 \right]}{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + 1 \leftrightarrow 2 \right]}$$

- L-R asymmetry in Drell-Yan production
- no fragmentation function
- valence-sea quark: isolated

E1039 EXPERIMENT

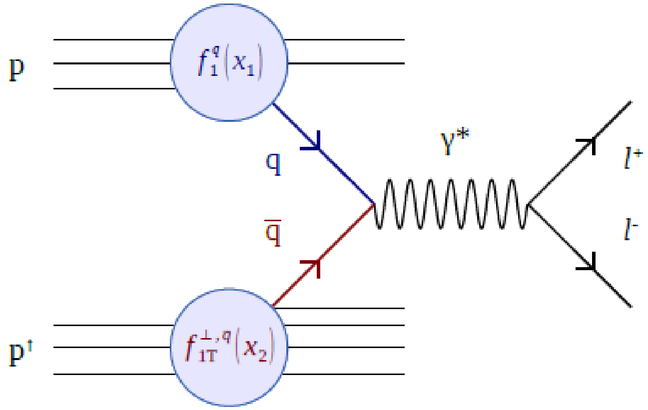
- has not been tried yet
  - only experiment sensitive to sea quarks at large x

quark	SIDIS	Drell-Yan
valence	known	COMPASS
sea	poor sensitivity	**unknown E1039**

- selects sea quark from target
  - $$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{9x_b x_t}\frac{1}{s}\sum_i e_i^2 \times \{q_i(x_b)\bar{q}_i(x_t) + \bar{q}_i(x_b)q_i(x_t)\}$$
  - for E1039 kinematic configuration first term dominates
- measure Sivers asymmetry for both
  - $\bar{u}(x), \bar{d}(x)$
  - determine possible flavor asymmetry

$$p + p^{\uparrow} \rightarrow \mu^+\mu^- X$$

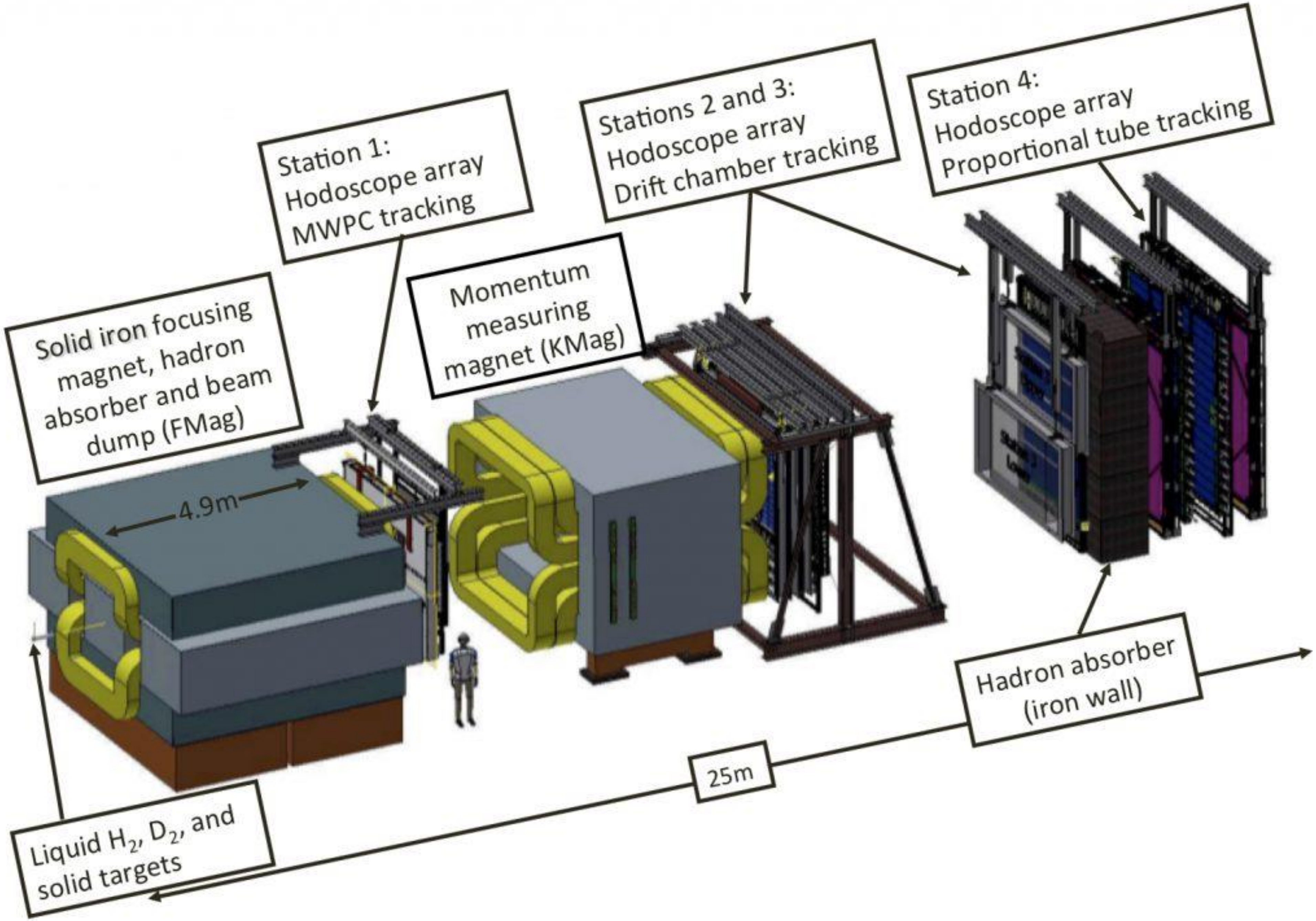
② Polarized Drell-Yan



$$A_N^{DY} \propto \frac{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftrightarrow 2 \right]}{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + 1 \leftrightarrow 2 \right]}$$

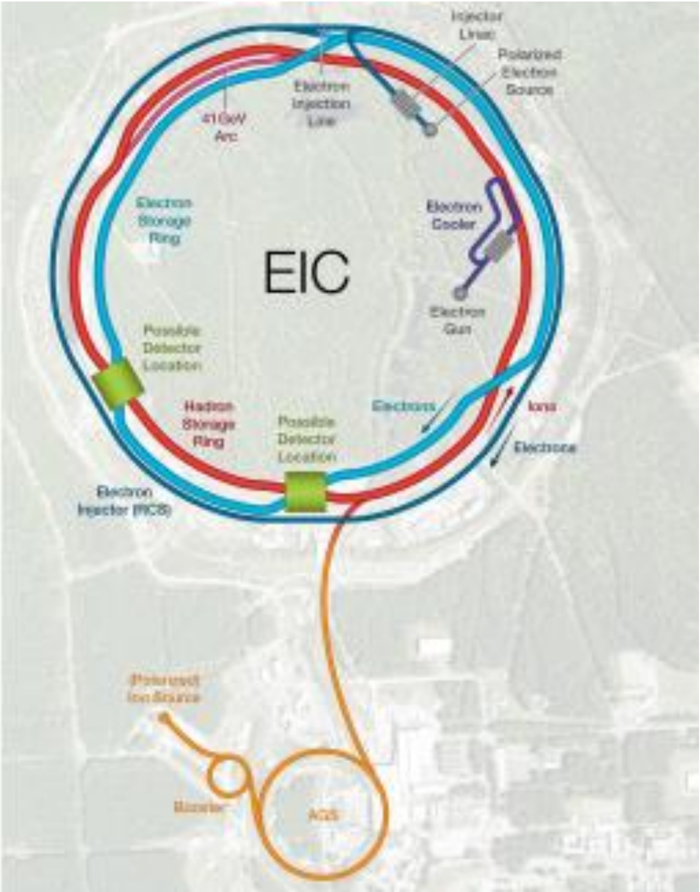
- L-R asymmetry in Drell-Yan production
- no fragmentation function
- valence-sea quark: isolated

E1039 EXPERIMENT



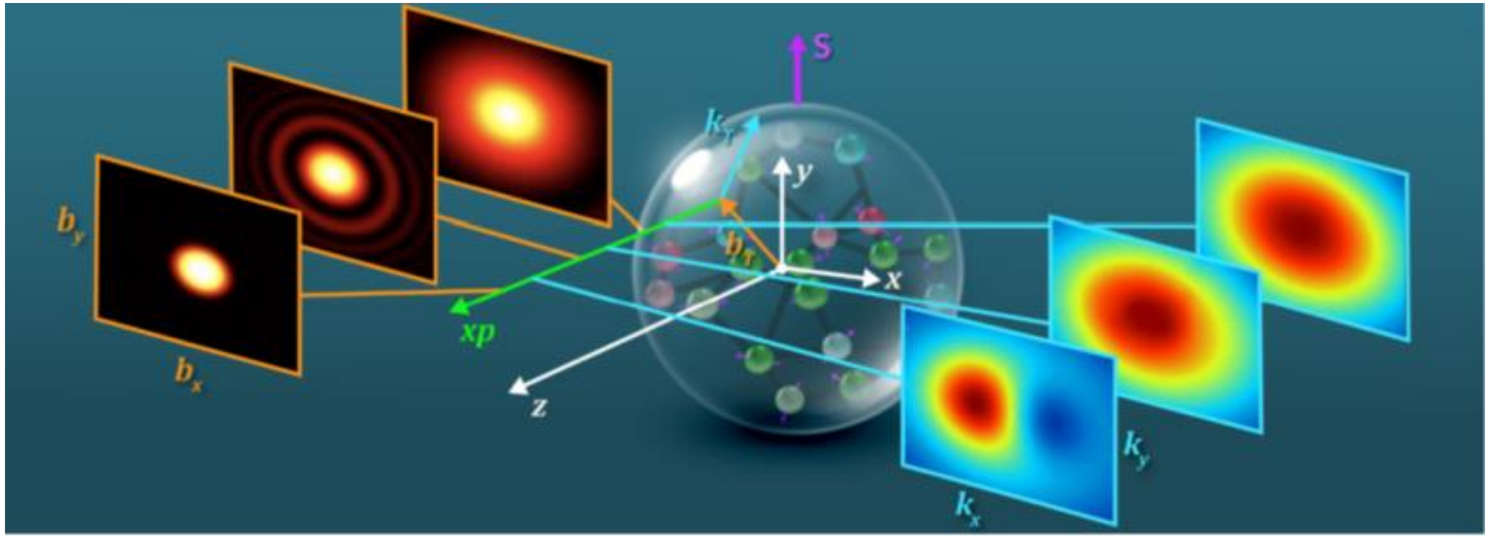
SpinQuest Experiment

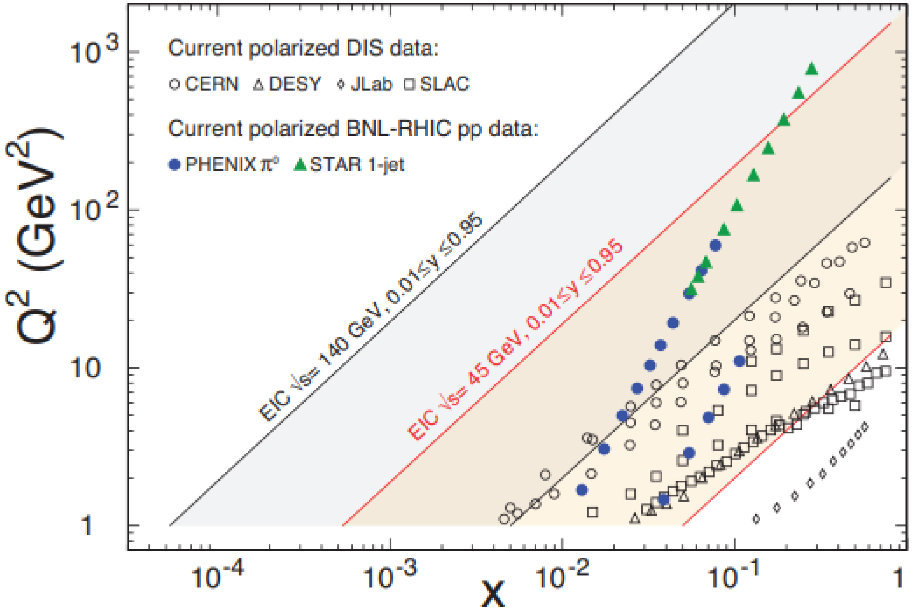
EIC: Electron – Ion Collider at Brookhaven, USA



- Highly polarized electron ($\sim$70%) and proton ($\sim$70%) beams;
- Ion beams from deuterons to heavy nuclei such as gold, lead, or uranium;
- Variable $e+p$ center-of-mass energies from 29–140 GeV;
- High collision electron-nucleon luminosity 10^{33}–10^{34} cm^{-2} s^{-1};
- The possibility to have more than one interaction region.

EIC: Electron – Ion Collider at Brookhaven, USA



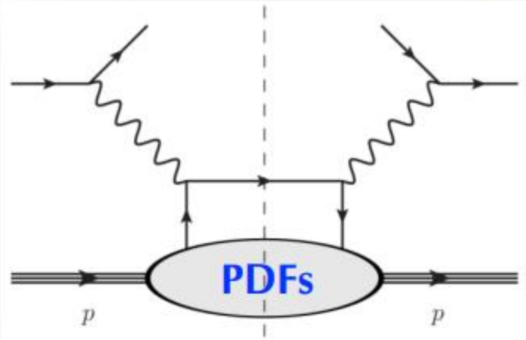


EIC will probe low-x regime or gluon and sea quarks rich environment

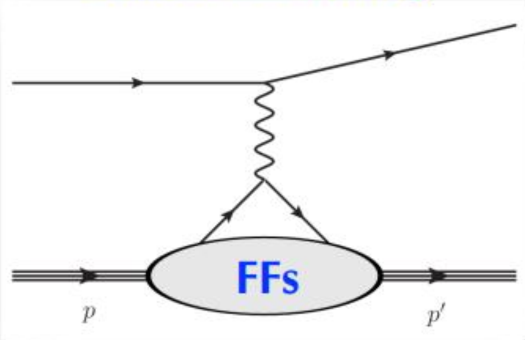
Summary

Goal: understanding the partonic structure of the nucleon

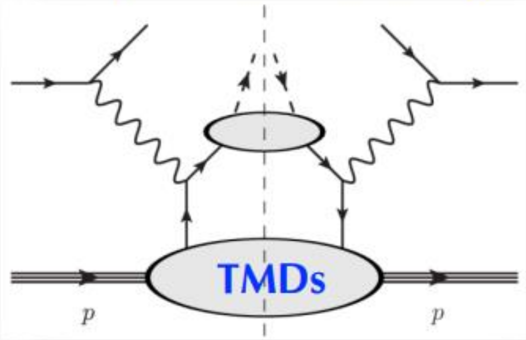
Deep Inelastic Scattering



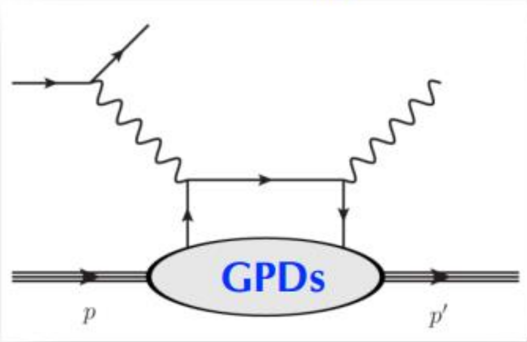
Elastic Scattering



Semi-Inclusive
Deep Inelastic Scattering



Deeply Virtual Compton
Scattering



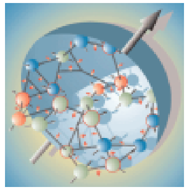
Complete Proton Tomography
in 3+2 D
from phase-space distributions

GTMDs ⟷ Wigner distr.

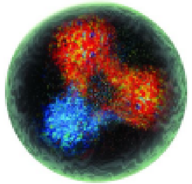
Momentum Space

Transverse Coordinate Space

Nucleon at different scales

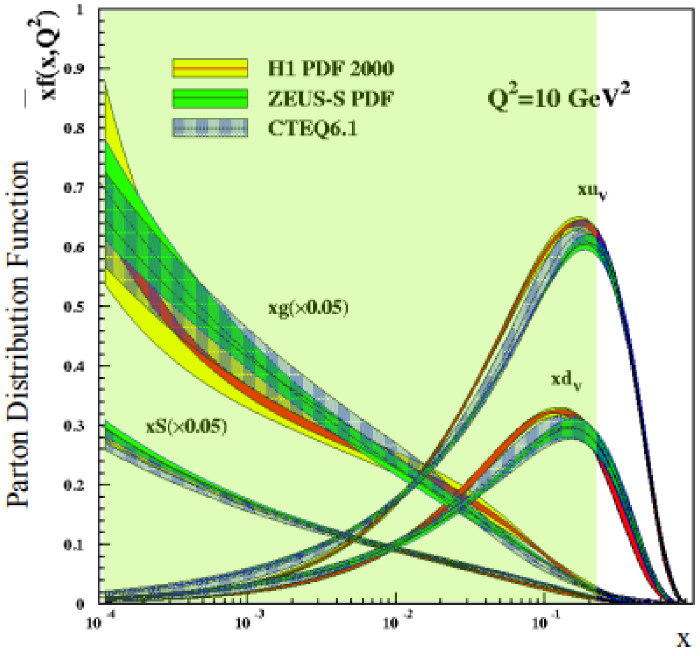


Valence quarks



Jefferson Lab: fixed-target electron scattering

$$0.1 < x_B < 0.7$$



Sea quarks

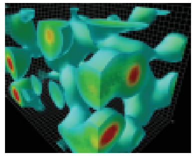
HERMES: fixed gas-target electron/positron scattering

$$0.02 < x_B < 0.3$$

COMPASS: fixed-target muon scattering

$$0.01 < x_B < 0.1$$

The glue



Derek Leinweber

ZEUS/H1: electron/ positron-proton collider

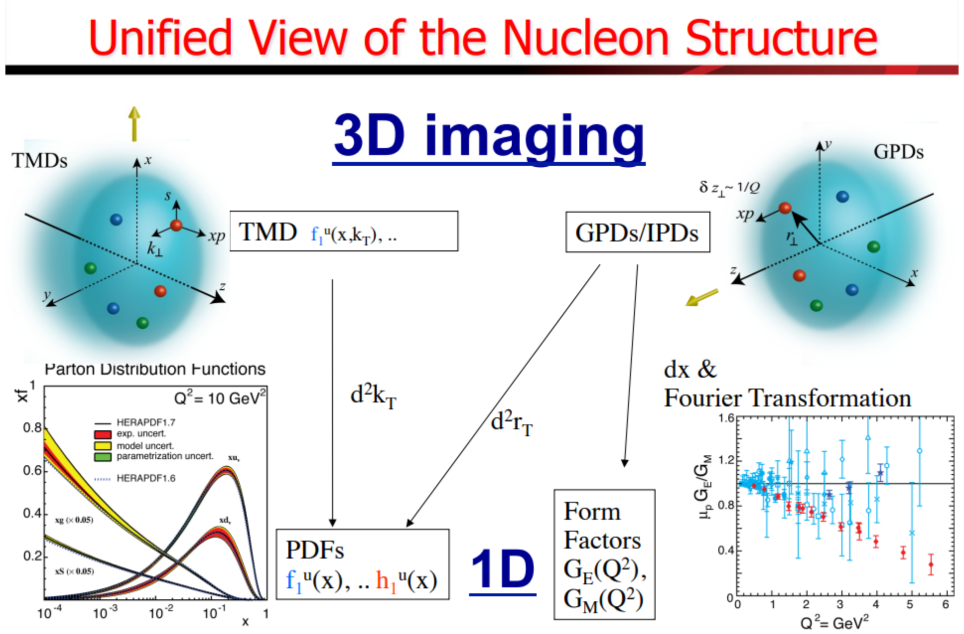
$$10^{-4} < x_B < 0.02$$

EIC: $10^{-4} < x_B < 0.2$

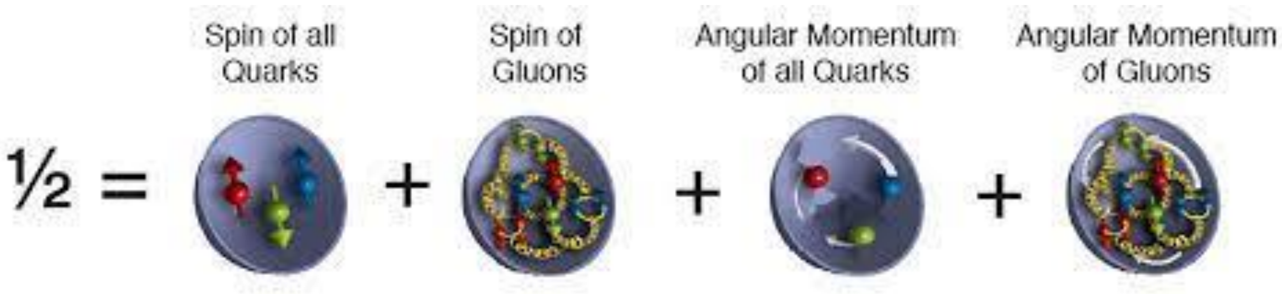
Luminosity 100 - 1000 times that of HERA

A complete picture on Nucleon require many experiments probing the whole kinematic range and all configuration of the beam/**target polarization**

Thank You



Unified View of the Nucleon Structure
3D imaging
TMDs
GPDs
TMD $f_1^u(x,k_T)$, ..
GPDs/IPDs
Parton Distribution Functions
d^2k_T
d^2r_T
dx &
Fourier Transformation
PDFs
$f_1^u(x)$, .. $h_1^u(x)$
1D
Form
Factors
$G_E(Q^2)$,
$G_M(Q^2)$



Spin of all Quarks
Spin of Gluons
Angular Momentum of all Quarks
Angular Momentum of Gluons
½ = + + +