Artificial-Neural Network & Polarized-Target Technology for Probing Nucleon Structure

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Notes

I was graduated from FSU with dissertation about **Hadron Spectroscopy**: Hunting for missing N^* resonances via photoproduction of ω, η, and $K\Sigma$ at JLAB

Currently, I am working at the Polarized-target group at UVA with research on **Hadron Structure**:
- Setup polarized target for the SpinQuest experiment at Fermilab which aim to measure Sivers function (TMD)
- Involved in experiment at JLAB and analyze DVCS data from JLAB (GPD)

The goals of this talk are to provide:
- **General overview** of the nucleon-structure studies
- **One example** of the Artificial-Neural Network (ANN) implementation to extract physics observable from the experimental data
- **Description** of the polarized-target technology used for polarizing nucleons

This talk has ~90 slides (too many for ~45 minutes talk). So, I will only mention key points in each slides

I keep the rest and details for the sake of completeness & references for future discussions (also hopefully future collaboration)

Outline

- Probing Nucleon Structure – Experimental perspective
- GPD & TMD – Toward a unified picture of Nucleon Structure
- Artificial-Neural Network – A technique to exploit experimental data
- Polarized-Target technology – A necessary recipe to explore the internal structure of the nucleon

Probing Nucleon Structure

-Experimental Perspective-

Our Ultimate Questions

Can we understand the

mass, spin, size of hadrons

in terms of quarks and gluons?

Can we understand the

structure of hadrons

in terms of quarks and gluons?

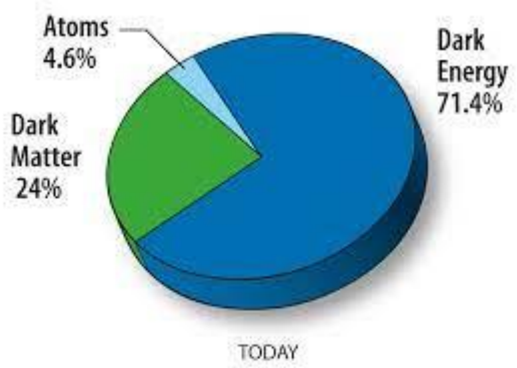
Hadrons = Particle that consist of quarks & gluons

- Baryons: proton, neutron, …
- Mesons: pion, kaon, ….

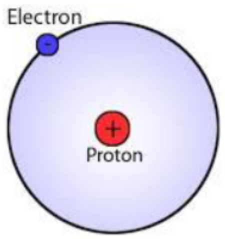
Hadrons interact via strong interaction

Why we need to understand the nucleon properties in term of quarks and gluons

Visible matter only constitute ~5% of the universe



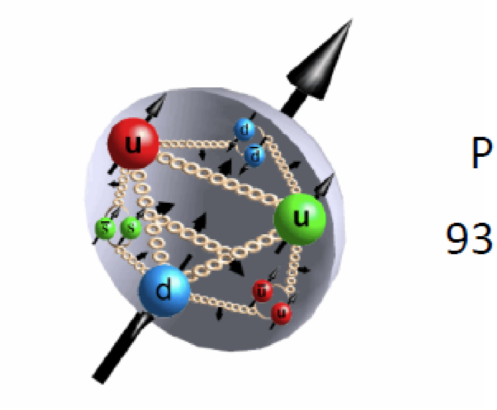
~100% of the visible-matter mass is concentrated in nuclei/nucleons



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%)				

Why we need to understand the nucleon properties in term of quarks and gluons

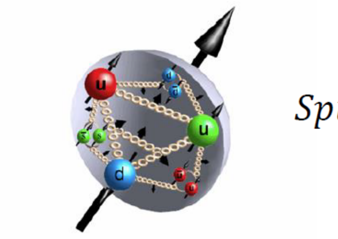
~99% on nucleon mass comes from the strong interaction among quarks and gluons



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

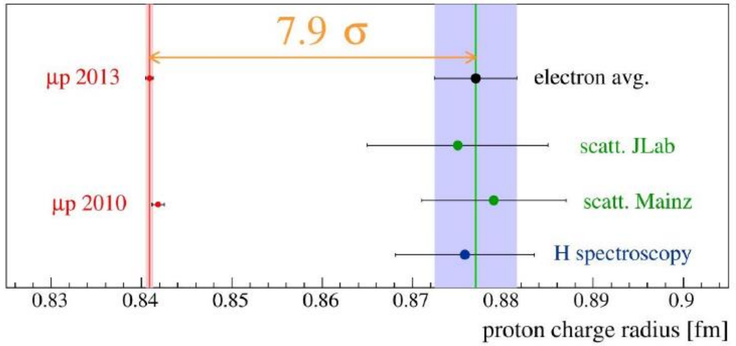
Other nucleon properties also not fully understood

- Proton spin crisis



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

- Proton radius puzzle

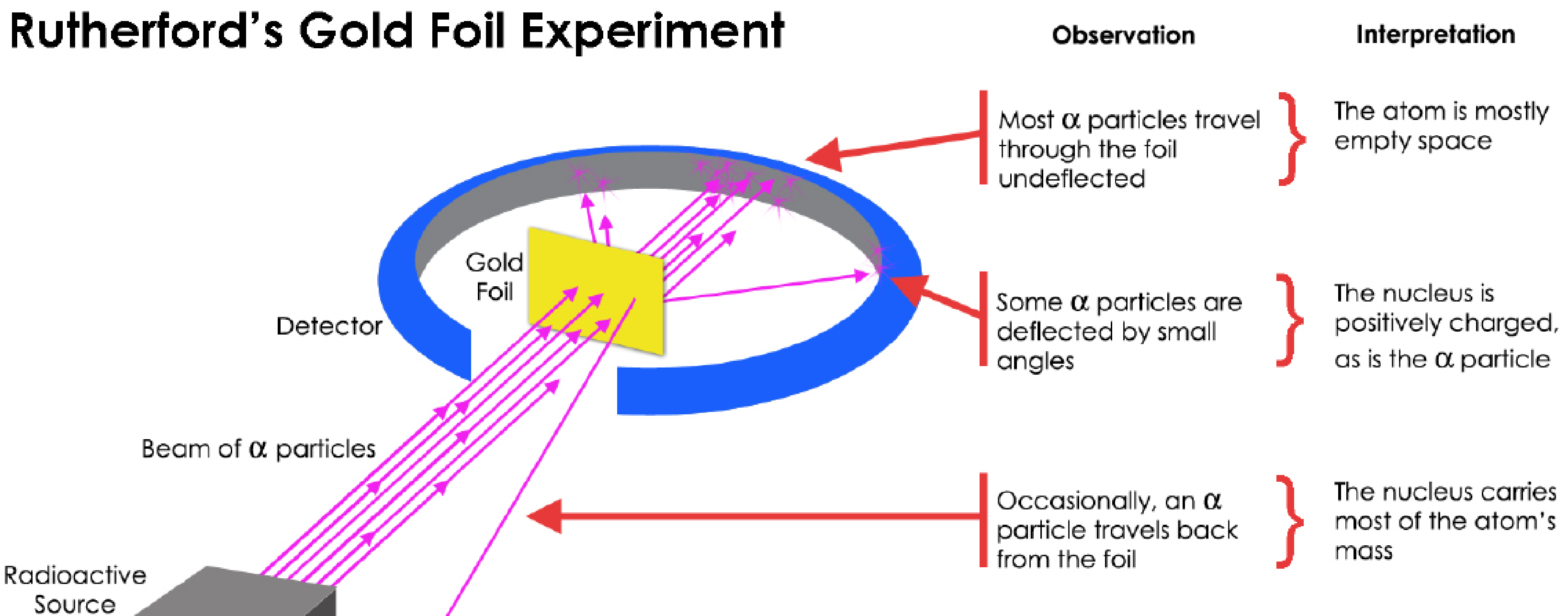


Different results of proton radius measurement

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

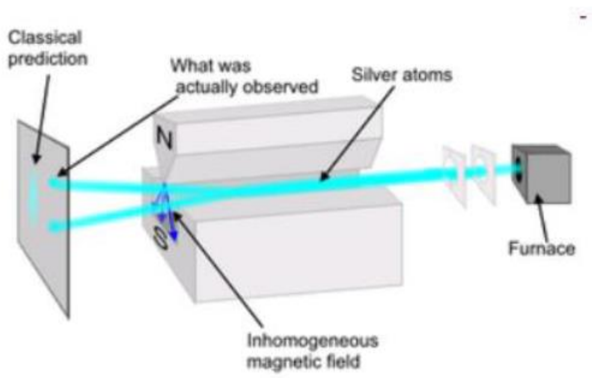


This experiment prove that an atom is mostly empty and something very solid and positively charge is inside (**proton**)

But is Proton a point-like particle?

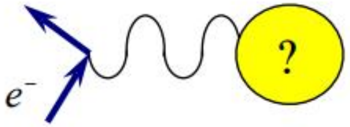
Stern's measurement on the proton magnetic moment indicated that proton is not a point-like particle

- The magnetic moment is the magnetic strength and orientation of a magnet or other object that produces a magnetic field
- The magnetic moment can be defined as a vector relating the aligning torque on the object from an externally applied magnetic field $\boldsymbol{\tau} = \mathbf{m} \times \mathbf{B}$
- If proton is a point-like particle the magnetic moment will be $\mu_N = \frac{e\hbar}{2m_p}.$
- But the observed values are $2.792\mu_N$ for proton and $-1.913\mu_N$ for neutron
- Therefore, both proton and neutron are not point-like particles
- Proton and neutron have a finite size
- How to probe the finite size of the proton?

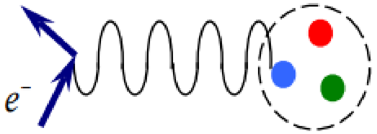


The original setup of Stern-Gerlach experiment that discovered the nature of spin. Measurement of the proton-magnetic moment utilize similar setup but use Hydrogen beam

Back to scattering experiment



$Q^2 \sim MeV^2$



$Q^2 >> GeV^2$

Equivalent wavelength of the probe:

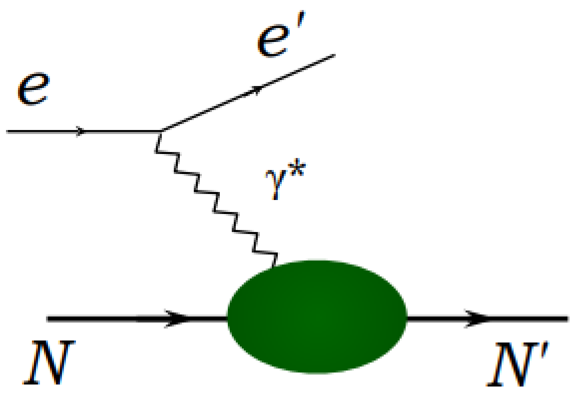
$$\lambda \approx \frac{1}{\sqrt{Q^2}}$$

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

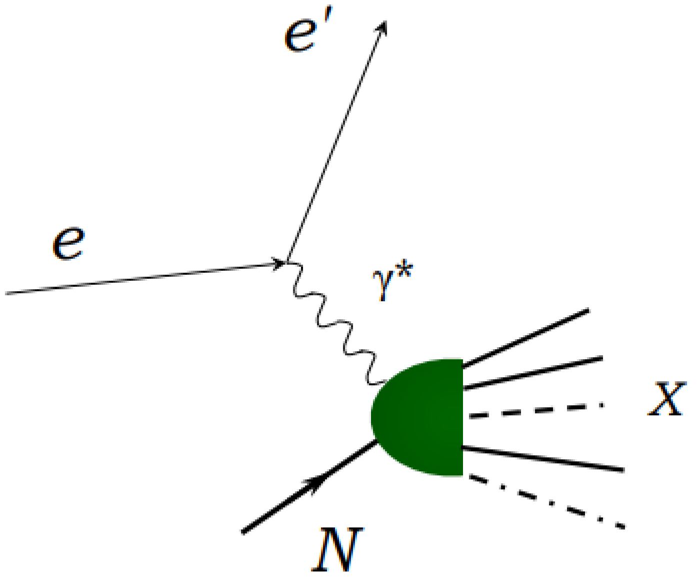
What you see depends on what you use to look...

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.

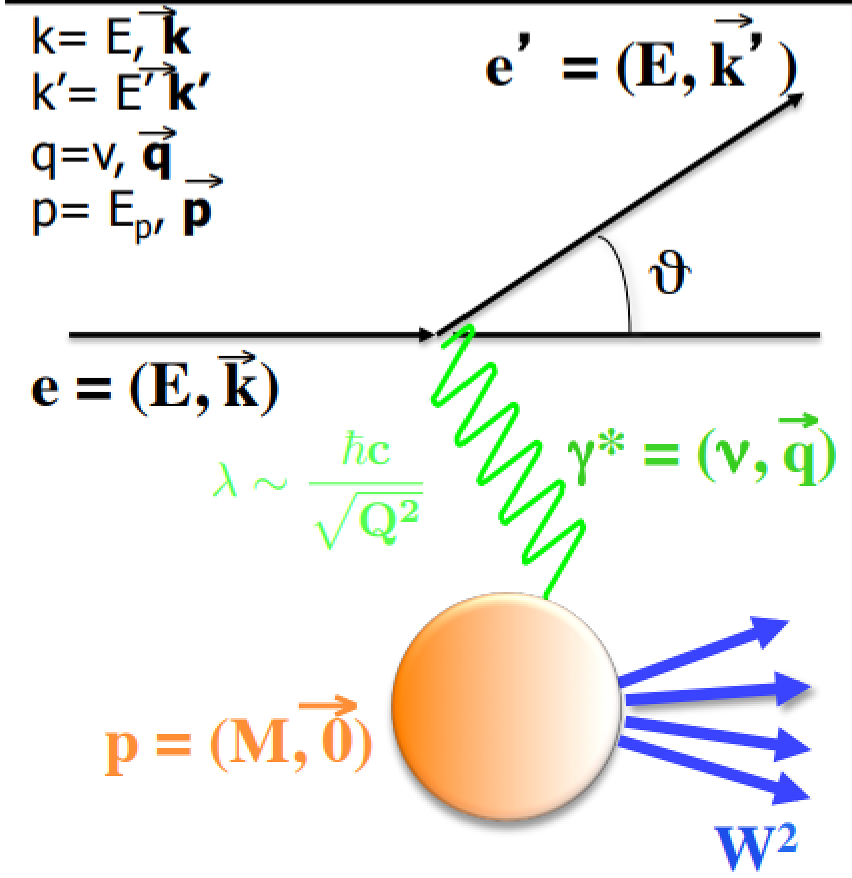


Measurements:

★ 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

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

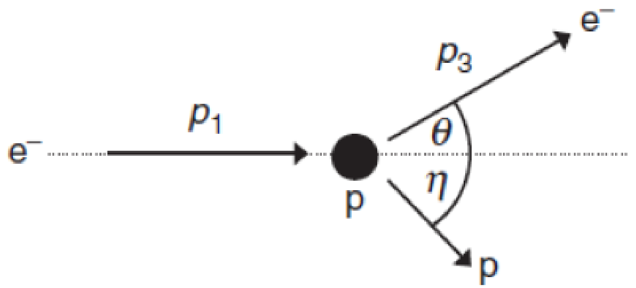
$Q^2 \gg M^2$ deep inelastic scattering

Form Factor: Probing the size & spatial distribution of Proton

- The experimental technique to probe the finite size of protons is elastic scattering using electron beam
- In elastic scattering the final state is also electron & proton (the proton does not break apart into many particles)
- The important measured quantity is cross section which determine the probability of a scattering event at a particular kinematics (angle) to occur
- More scattering event is observed if the cross section is higher
- The cross section of elastic scattering is determined by Mott formula. If proton is a point like scattering the cross section:

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

- E is the electron energy and θ is the scattering angle. α^2 is a constant



- If proton has a finite size, the Mott cross section formula is modified into

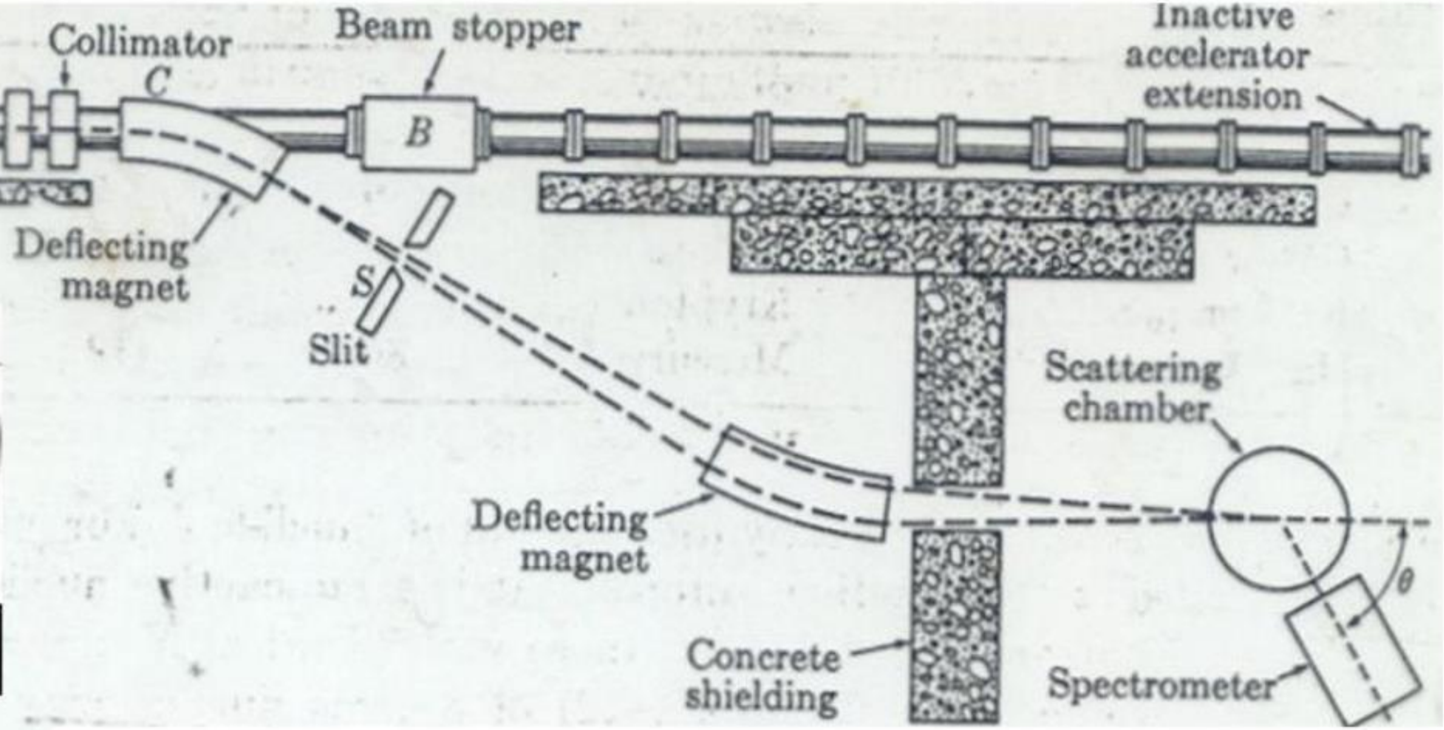
$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \to \frac{\alpha^2}{4E^2 \sin^4(\theta/2)} \cos^2\left(\frac{\theta}{2}\right) \left|F(\mathbf{q}^2)\right|^2.$$

- $F(q^2)$ is the **Form factor** which is the Fourier transform of the charge distribution. q^2 is the energy-momentum transferred to proton from electron beam

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

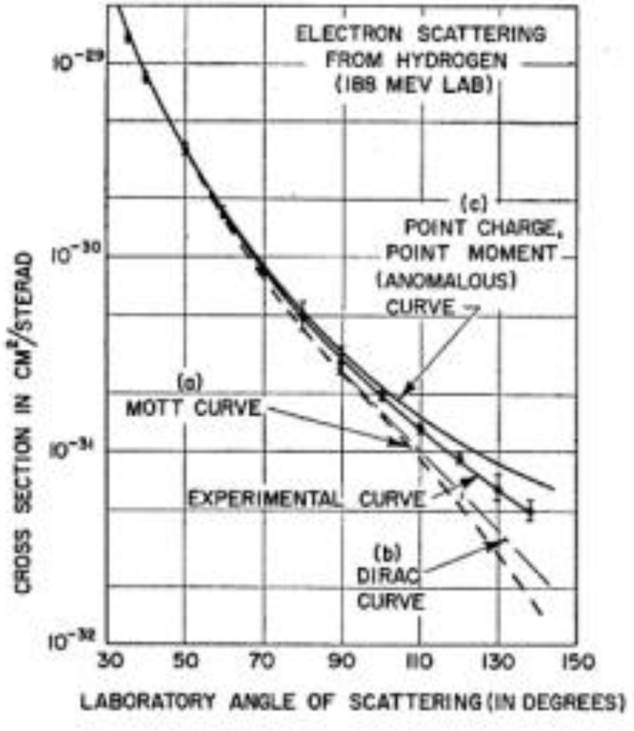
- $\rho(\mathbf{r})$ is the charge (density) distribution

Electron scattering at Stanford 1954 - 57

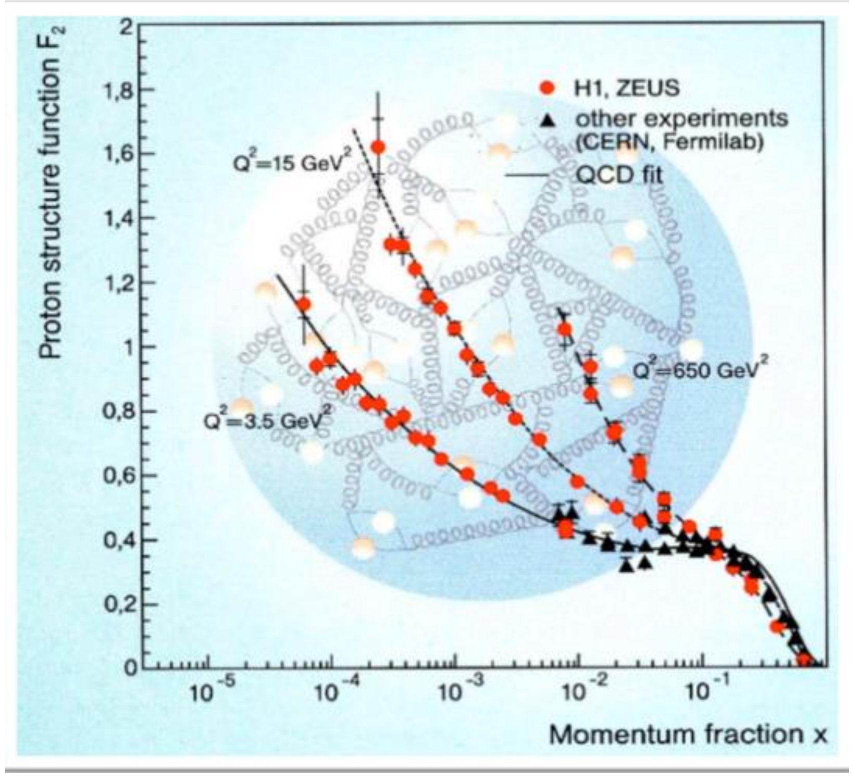


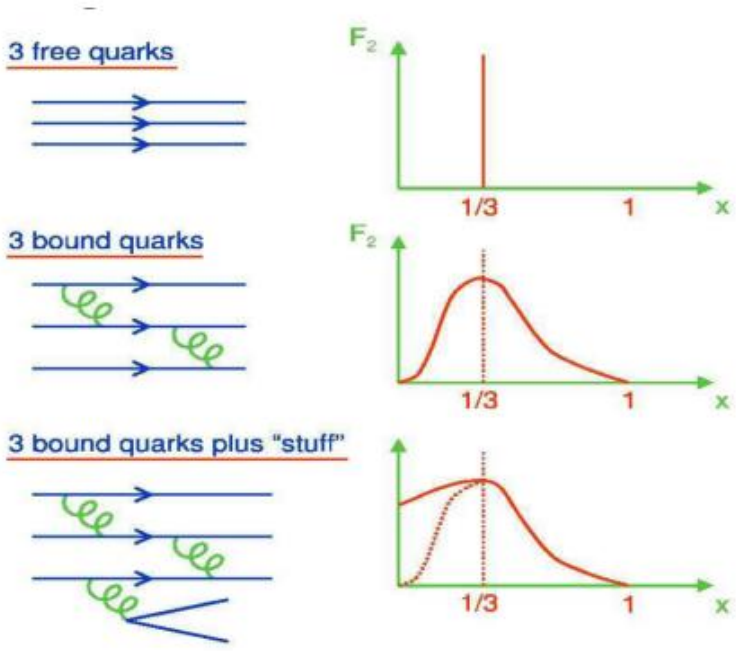
1961 Nobel Prize winner

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



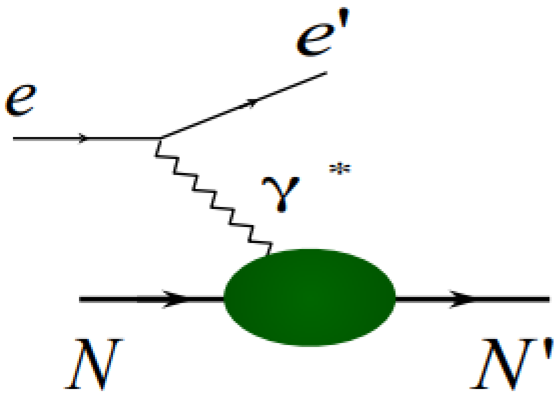


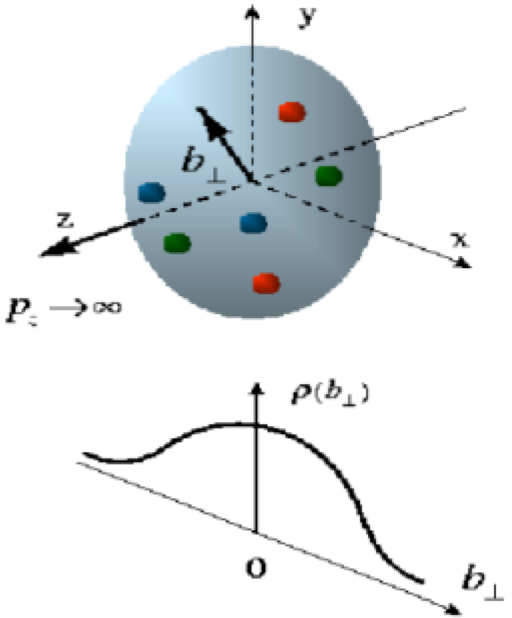
Form factor curve depends on the nucleon content

The 2D spatial image

Lepton (eg: electron, neutrino) scattering off a nucleon reveals different aspects of nucleon structure.

Elastic Scattering



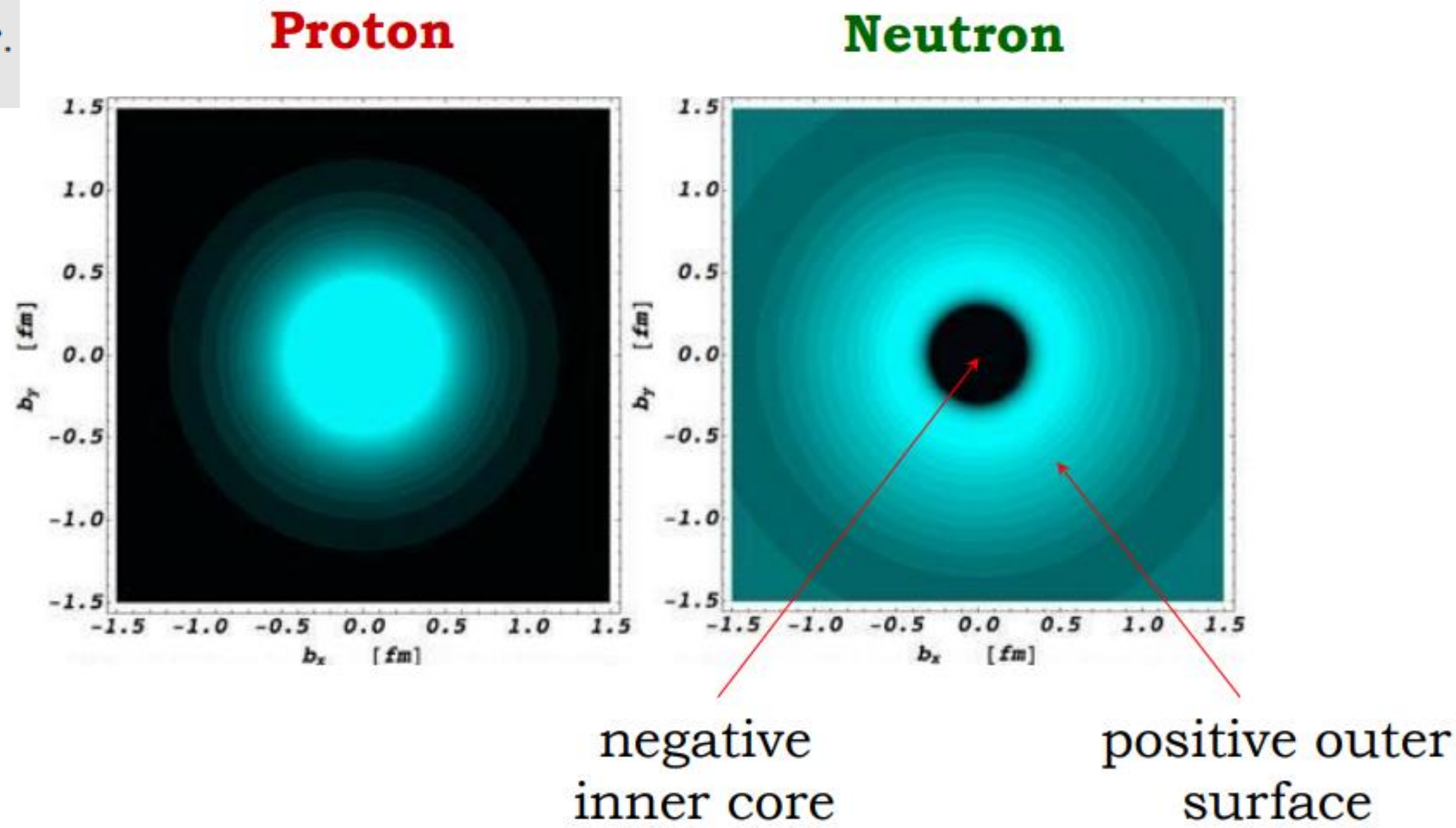


Cross-section parameterised in terms of Form Factors (Pauli, Dirac, axial, pseudo-scalar)

→ Transverse quark distributions: charge, magnetisation.

Charge density inside a nucleon

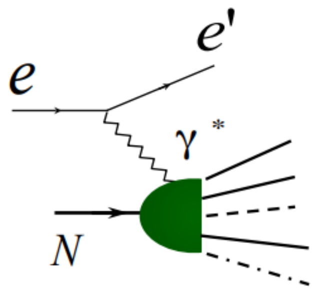
$$F(\mathbf{q}^2) = \int \rho(\mathbf{r}) e^{i\mathbf{q}\cdot\mathbf{r}}\, \mathrm{d}^3\mathbf{r}.$$

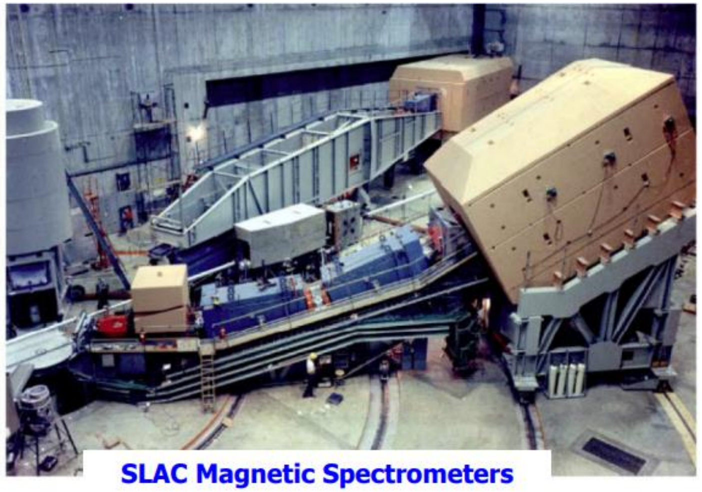


C. Carlson, M. Vanderhaeghen
PRL 100, 032004 (2008)

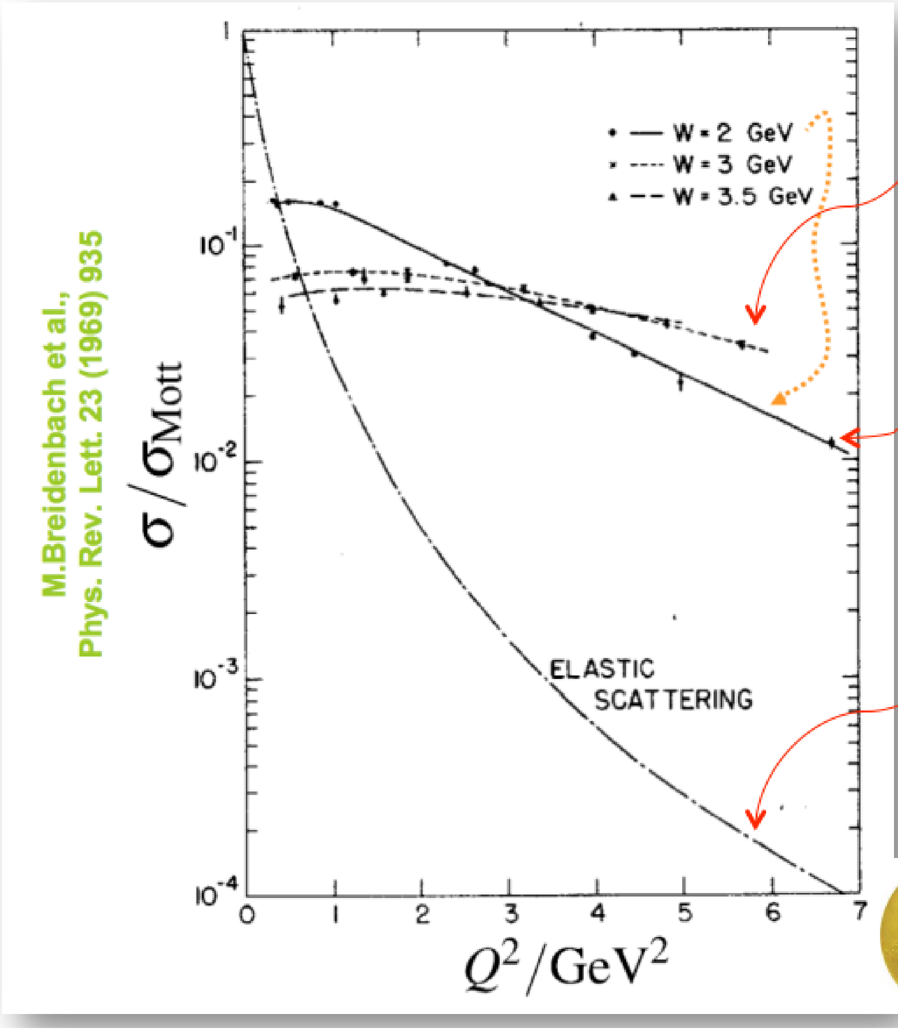
As the electron energy increase, the experiment enter Deep Inelastic Scattering regime

Deep Inelastic Scattering





SLAC Magnetic Spectrometers



- **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

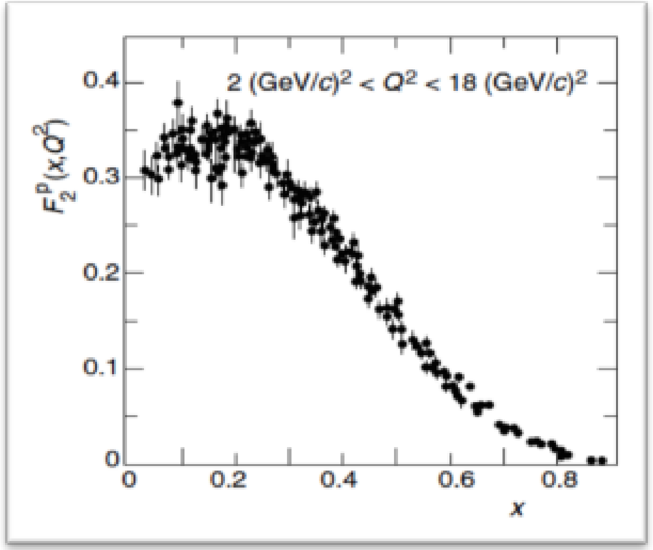
- The dynamics of such production processes may be, similar to the case of elastic scattering, described in terms of form factors.
- In the inelastic case the complex structure of the proton is described by two **structure functions: $\mathbf{W_1}$** and **$\mathbf{W_2}$.**
- In elastic scattering, at 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 $x=Q^2/2M\nu$.

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



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

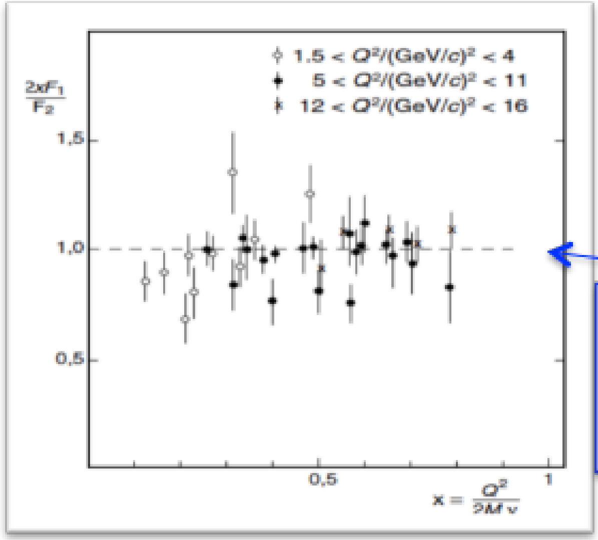
- At fixed values of x the structure functions F_1 (x,Q^2) and F_2 (x,Q^2) depend only weakly, or not at all, on Q^2

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

- 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 !

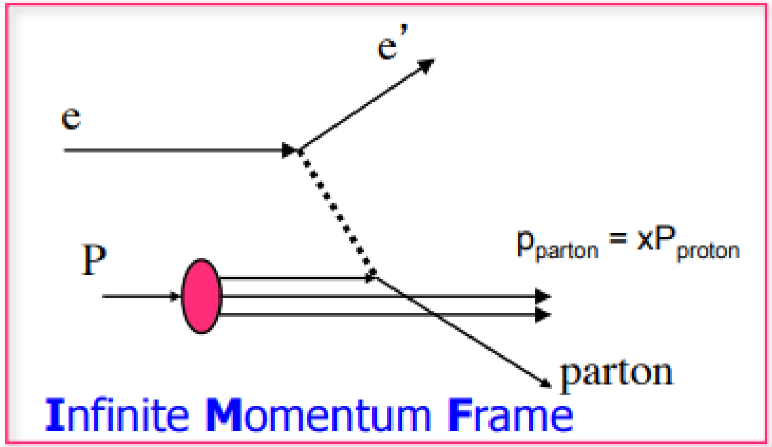
This model is discussed in a fast moving system (IMF)

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: $F_2(x) = \sum_i e_1^2 x f_i(x)$

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

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

$S(x) = \Sigma$ sea quarks

Experimentally:

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

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

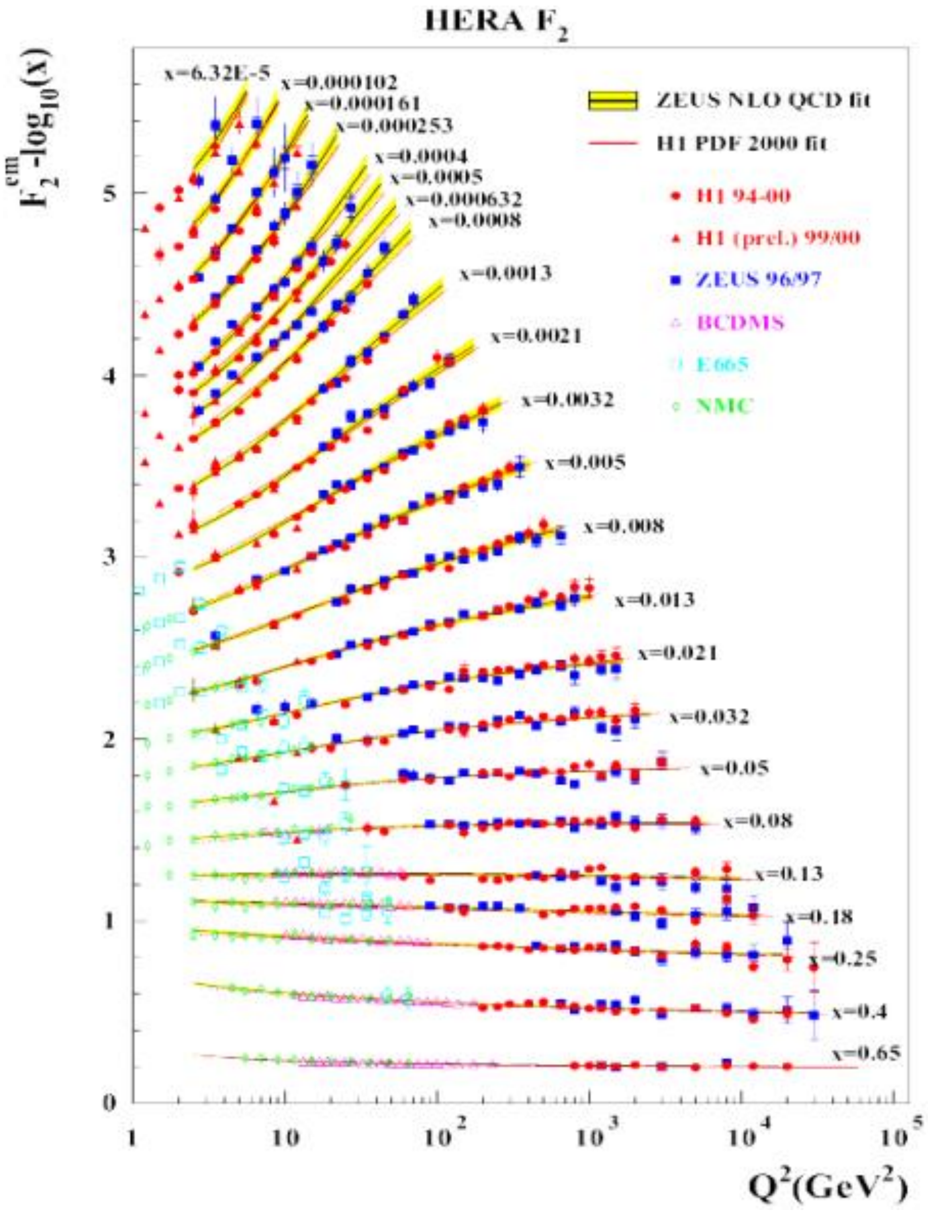
Neglecting the contribution of the s quark

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

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

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

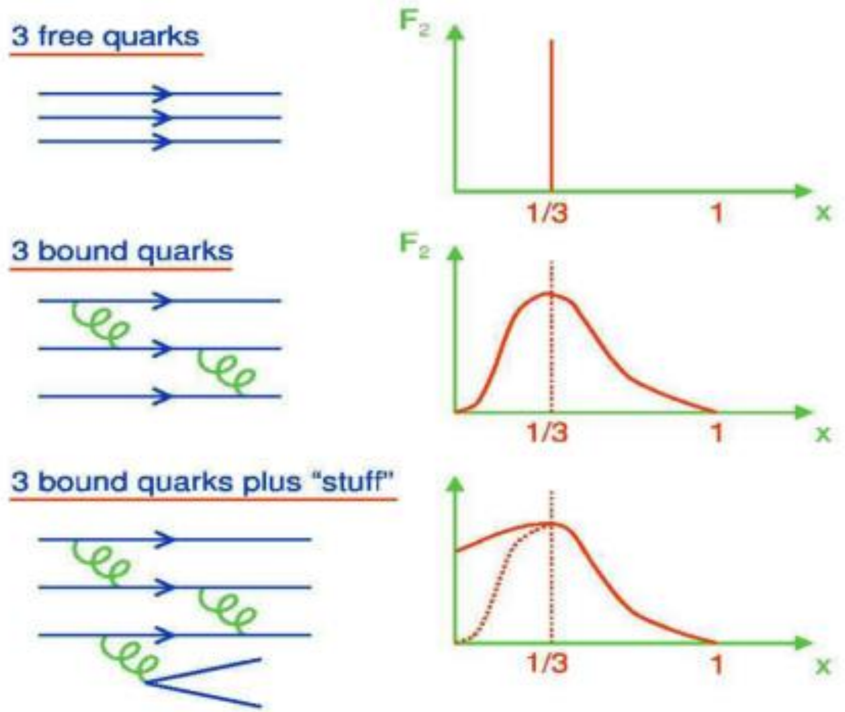
More kinematics exploration!!

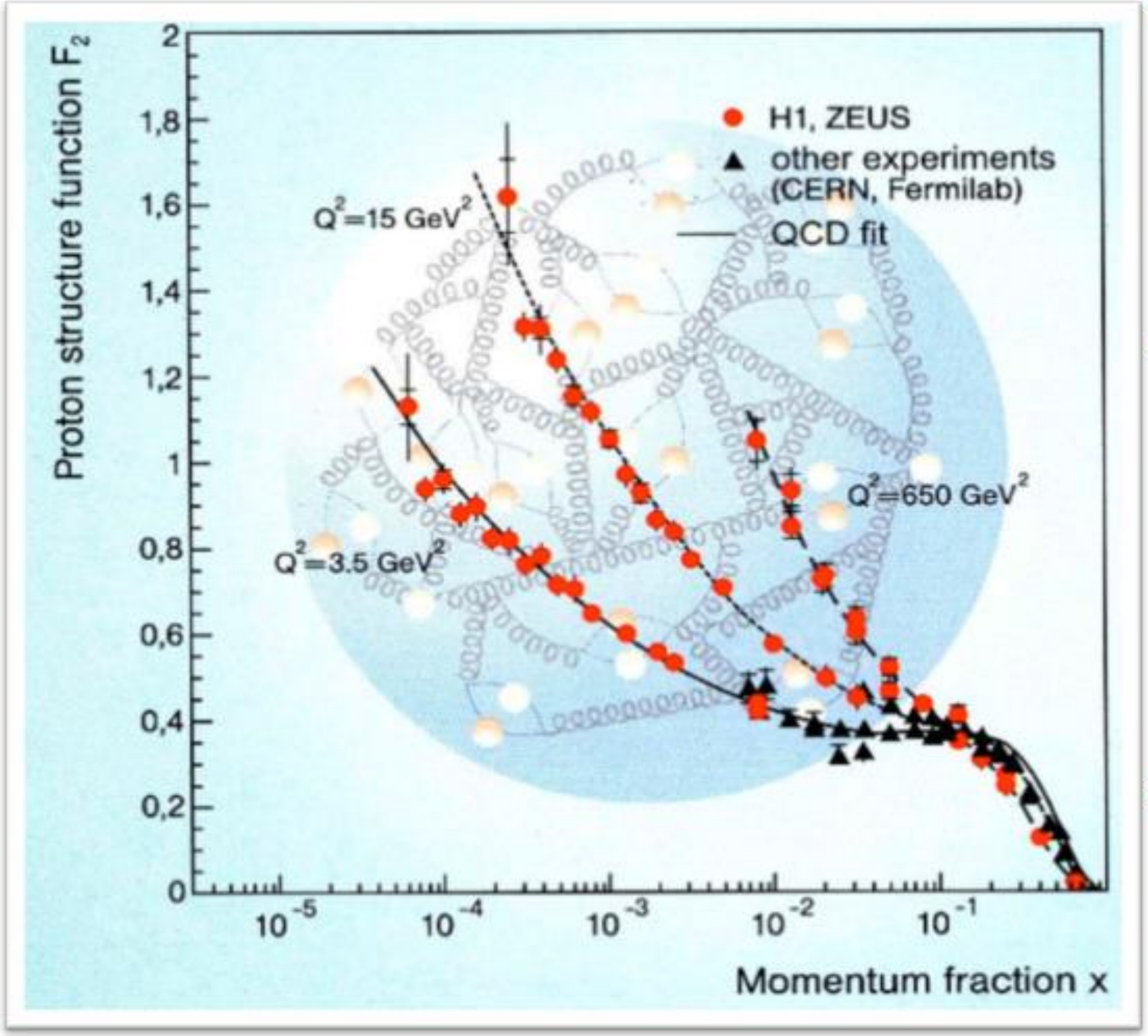


Deviations of F_2 from Bjorken scaling at high values of Q^2 and low values of x: $F_2 = F(Q^2, x)$

- 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.

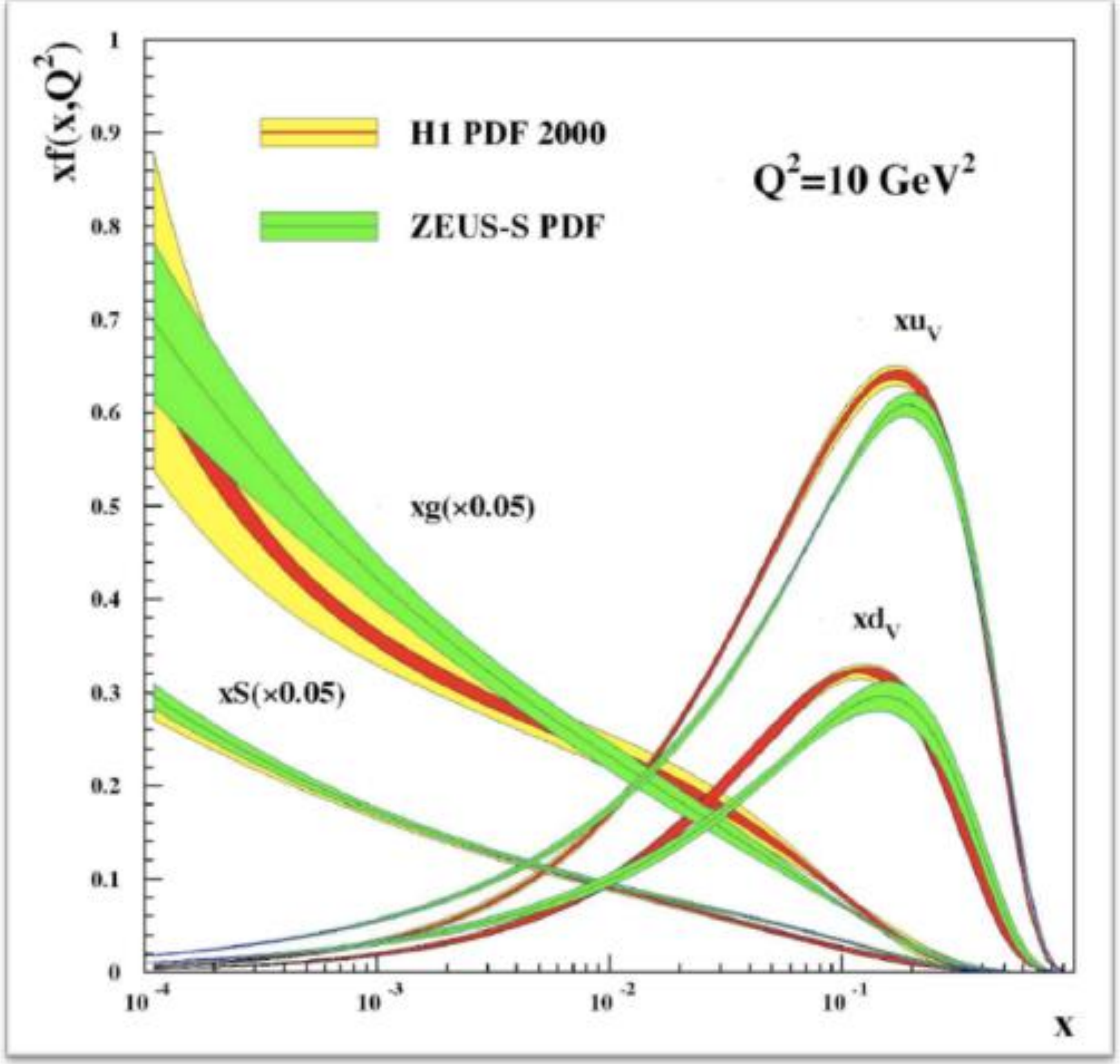




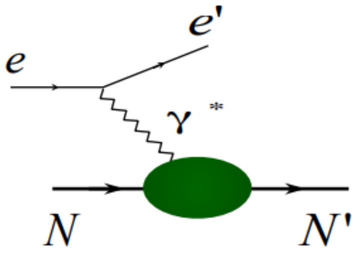
- Scaling violation is due to the fact that the quarks radiate gluons that can "materialize" as q-qbar pairs (sea quarks)
- With increasing Q^2 increases the resolution of the probe ($\sim\hbar/\sqrt{Q^2}$) and thus increases the number of partons that are "seen" bring a fraction x of the proton momentum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

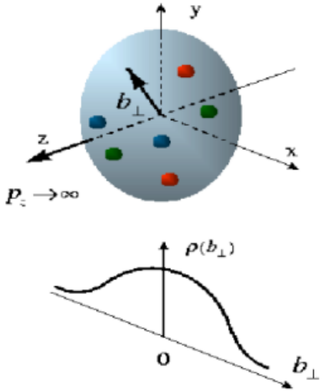
- All available deep inelastic and related hard scattering data involving incoming protons (and antiprotons) are used to determine the parton densities, f_i of the proton.

- 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

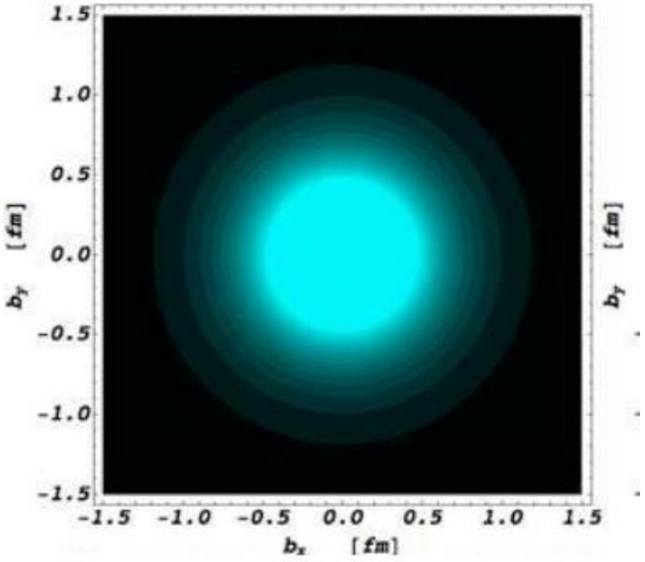




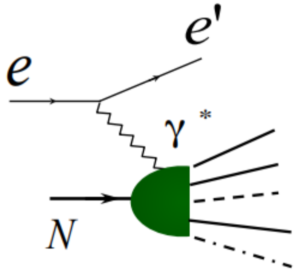
Cross-section parameterised in terms of Form Factors (Pauli, Dirac, axial, pseudo-scalar)

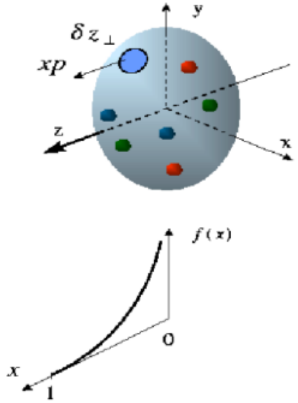
→ Transverse quark distributions: charge, magnetisation.

Proton



Deep Inelastic Scattering

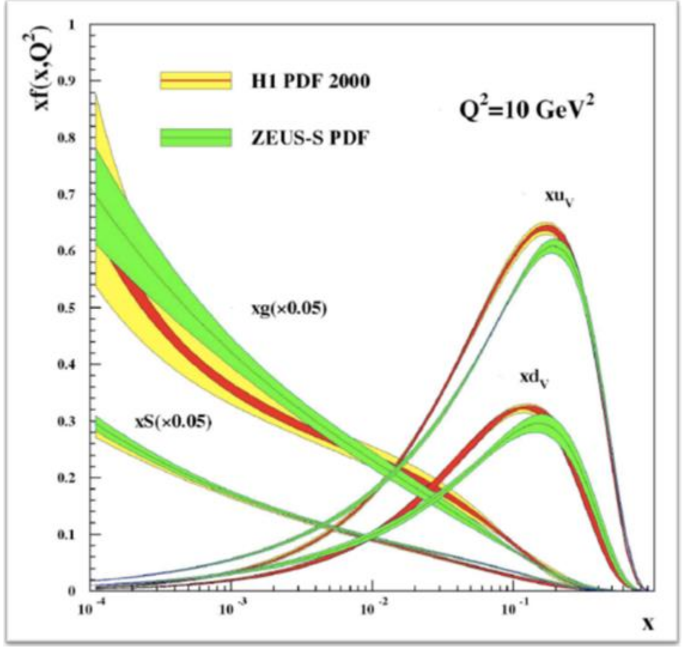




First experimental evidence of partons inside a nucleon

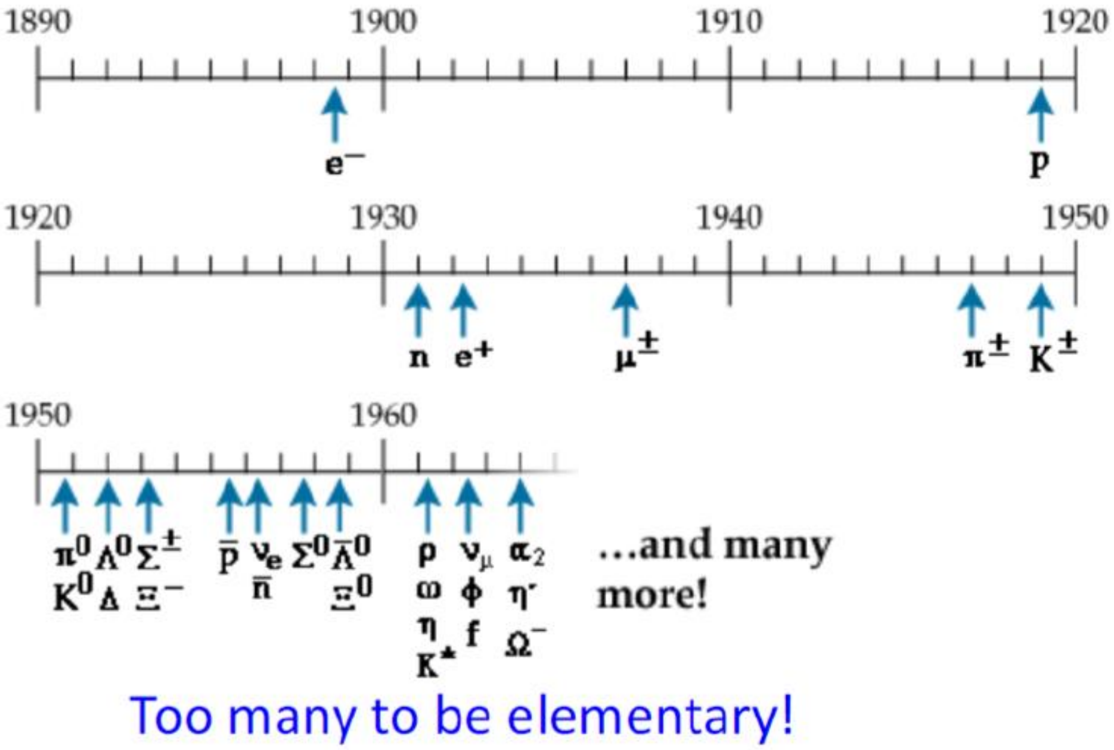
Cross-section parameterised in terms of polarised and unpolarised Structure Functions

→ Longitudinal momentum and helicity distributions of partons



Deep Inelastic Scattering and November Revolution (Discovery of Many Hadrons) established Partons theory (Quarks & Gluons). But do they really exist or are they only mathematical model?

- Since early 1950, a lot more particles have been discovered in accelerator particle
- Physicist were struggle to identify the elementary particles or more fundamental building block of all observed particles

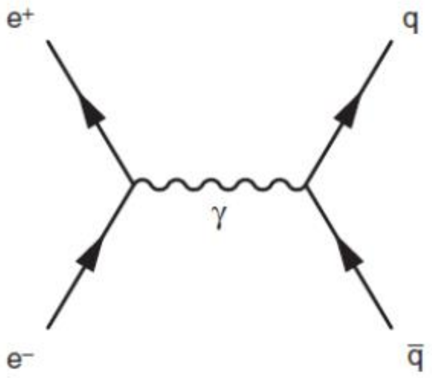


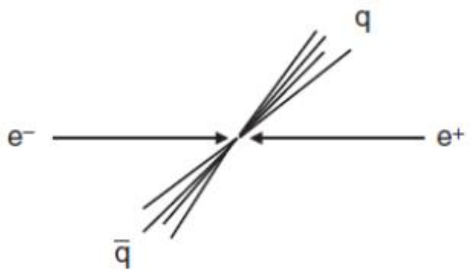
.... The finder of a new elementary particle used to be rewarded by a Nobel prize, but such a discovery now ought to be punished by $10,000 fine (Williamb Lamb)

Classification of many hadrons lead 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



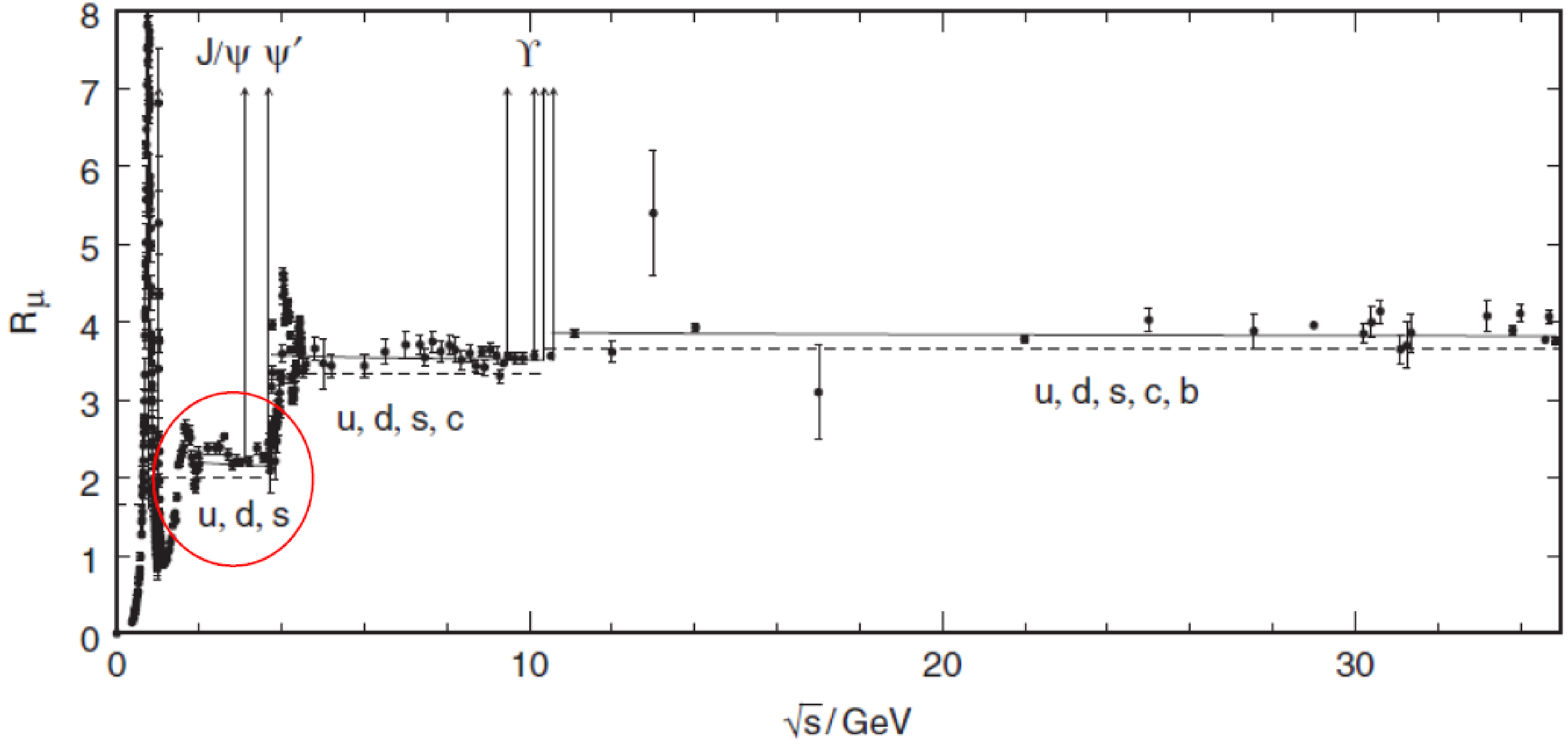


- This experiment measures the cross-section ratio of hadrons and muons production

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

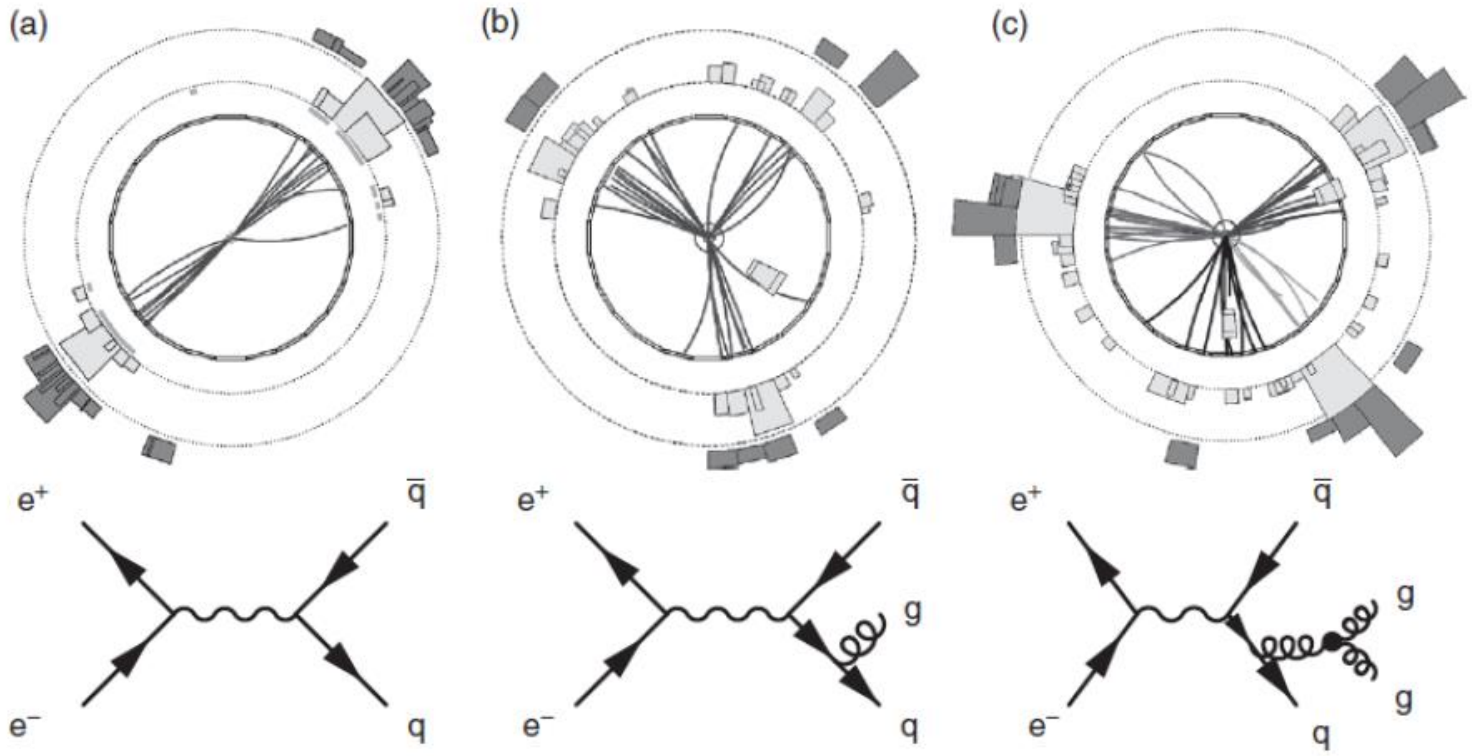
$$R_\mu^{\text{d,u,s}} = 3 \times \left(\frac{4}{9} + \frac{1}{9} + \frac{1}{9}\right) = 2.$$ → For 3 flavors of quarks (u, d, s)

❑ 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) $e^+e^- \rightarrow q\bar{q} \rightarrow$ two-jets, (b) $e^+e^- \rightarrow q\bar{q}g \rightarrow$ three-jets and (c) $e^+e^- \rightarrow q\bar{q}gg \rightarrow$ 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

- One of the victory of the quarks model is quark model could explain the magnetic moment of proton and neutron

- Proton wave function $|p\uparrow\rangle = \frac{1}{\sqrt{6}}(2u\uparrow u\uparrow d\downarrow - u\uparrow u\downarrow d\uparrow - u\downarrow u\uparrow d\uparrow),$

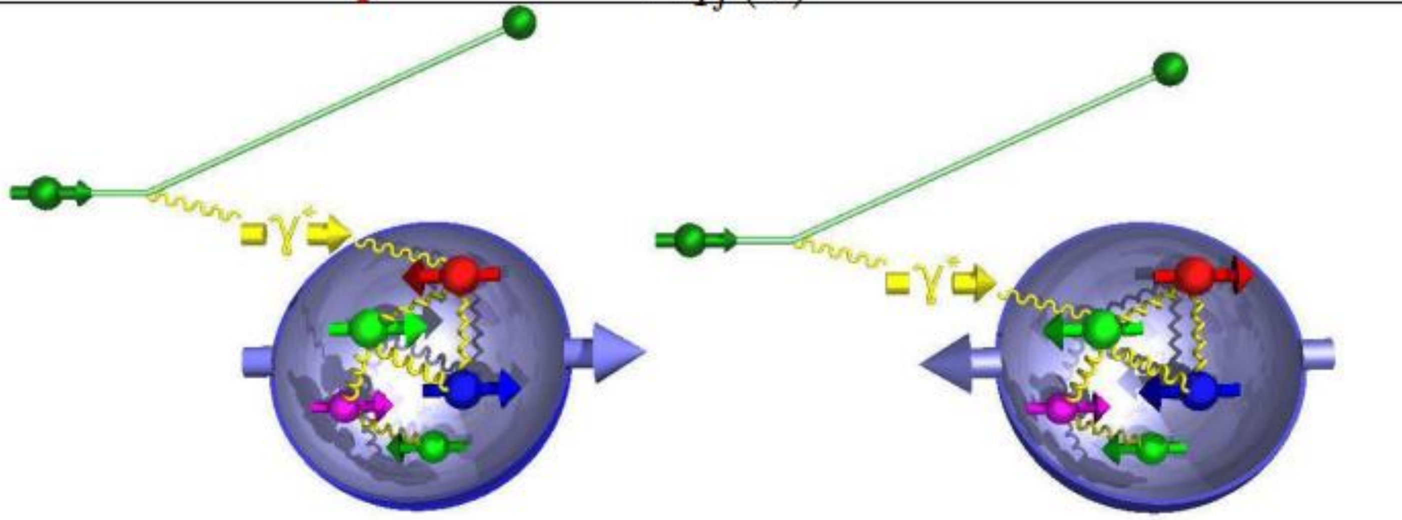
- By applying magnetic-moment operator to the proton wave function $\hat{\mu} = Q\frac{e}{m}\hat{\mathbf{S}}$

- We obtain the prediction of proton magnetic moment $\mu_p = \frac{4}{3}\mu_u - \frac{1}{3}\mu_d.$

- Assuming the same mass for u and d quarks, we obtain $\mu_p \approx 2.792\mu_N$ as experimentally observed

Deep Inelastic Scattering with polarized target and beam

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



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

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

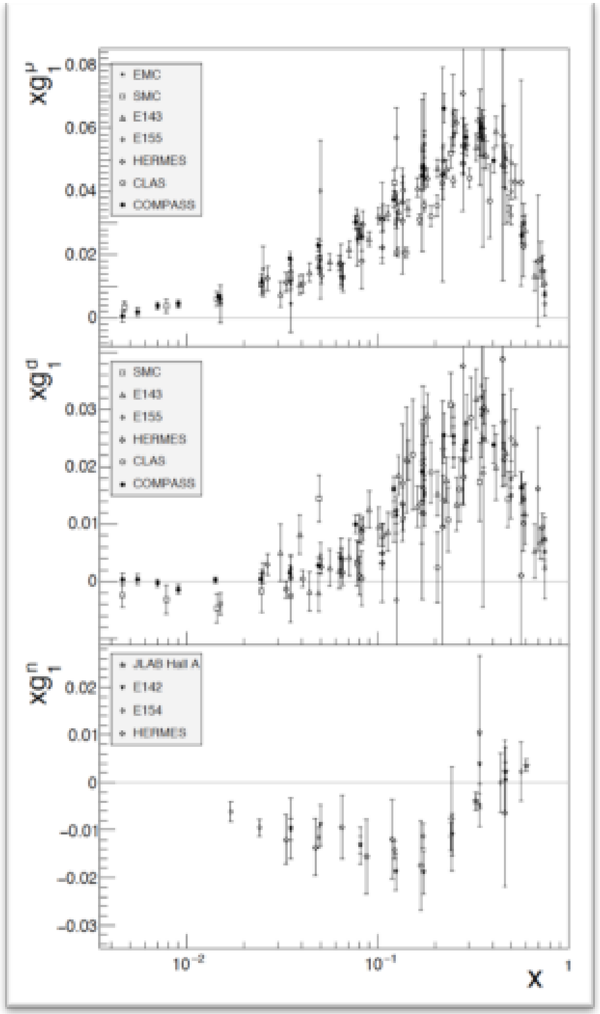
$$\Delta\Sigma \equiv (\Delta u(x) + \Delta\bar{u}(x)) + (\Delta d(x) + \Delta\bar{d}(x)) + (\Delta s(x) + \Delta\bar{s}(x))$$

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

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

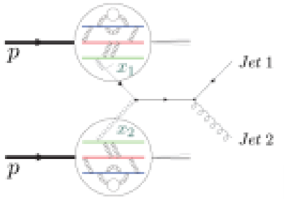
$$\Rightarrow \Delta\Sigma \approx 0.25$$



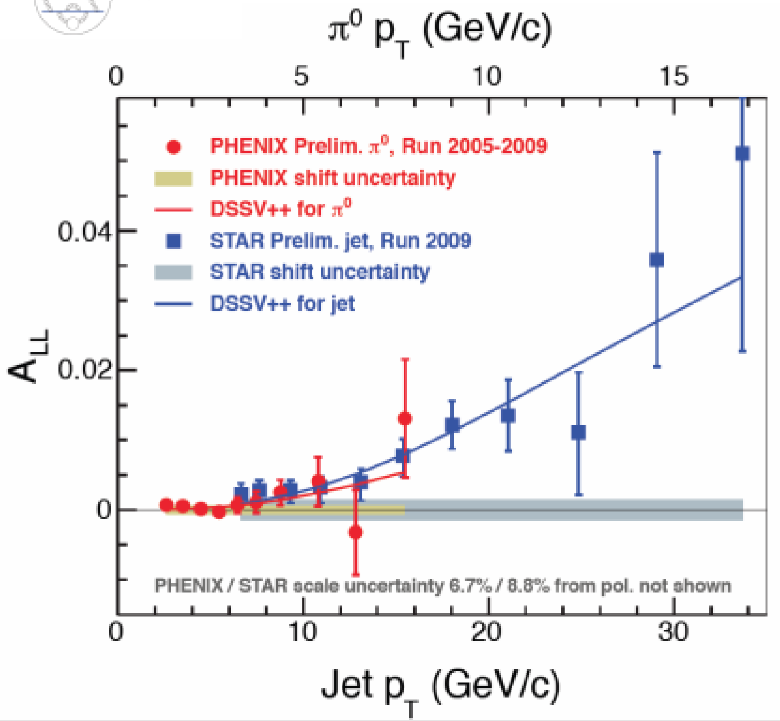
arX:1209.2803

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

Gluon Helicity

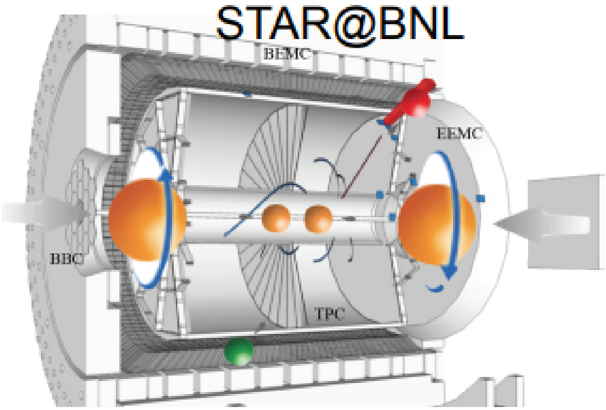


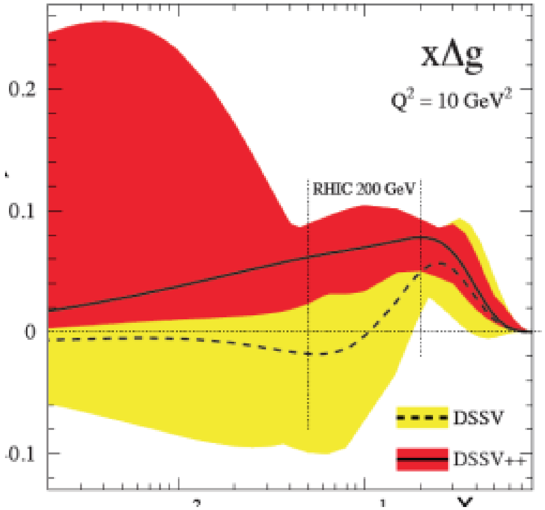
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_1 P_2} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$



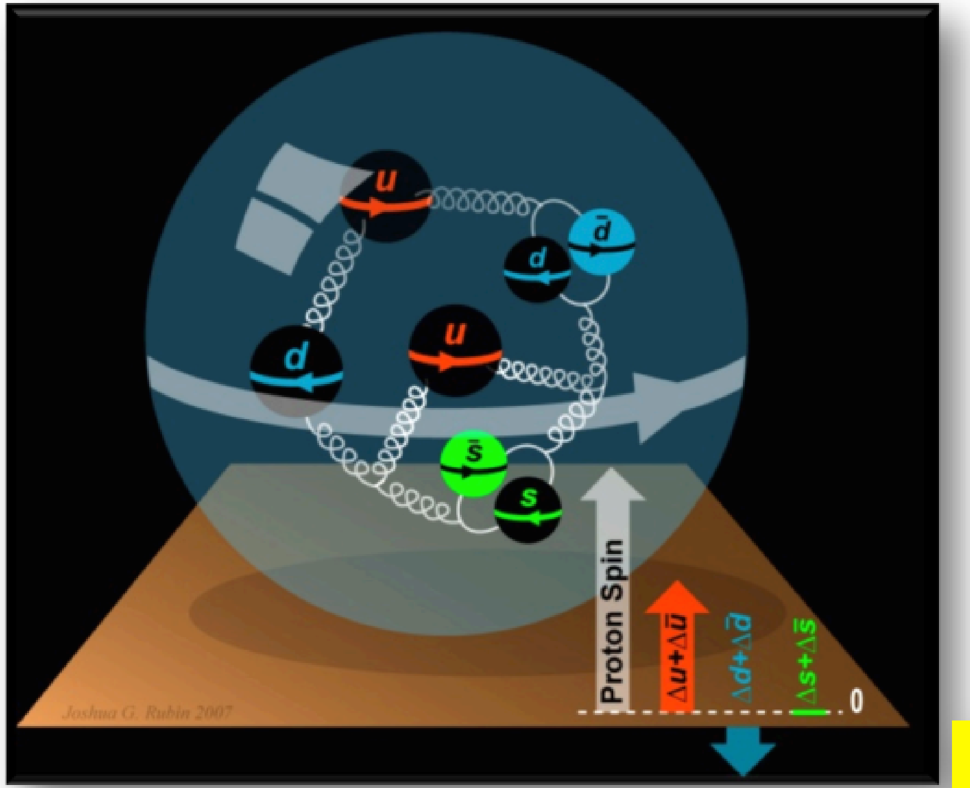
Indication of small, but non-0 **Δ**g from RHIC data, in particular STAR jet results

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





The Incomplete Nucleon: Spin Puzzle



- **DIS $\rightarrow \Delta\Sigma \cong 0.25$**
- **RHIC + DIS $\rightarrow \Delta G$**

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

  could be small
- $\rightarrow L_q$

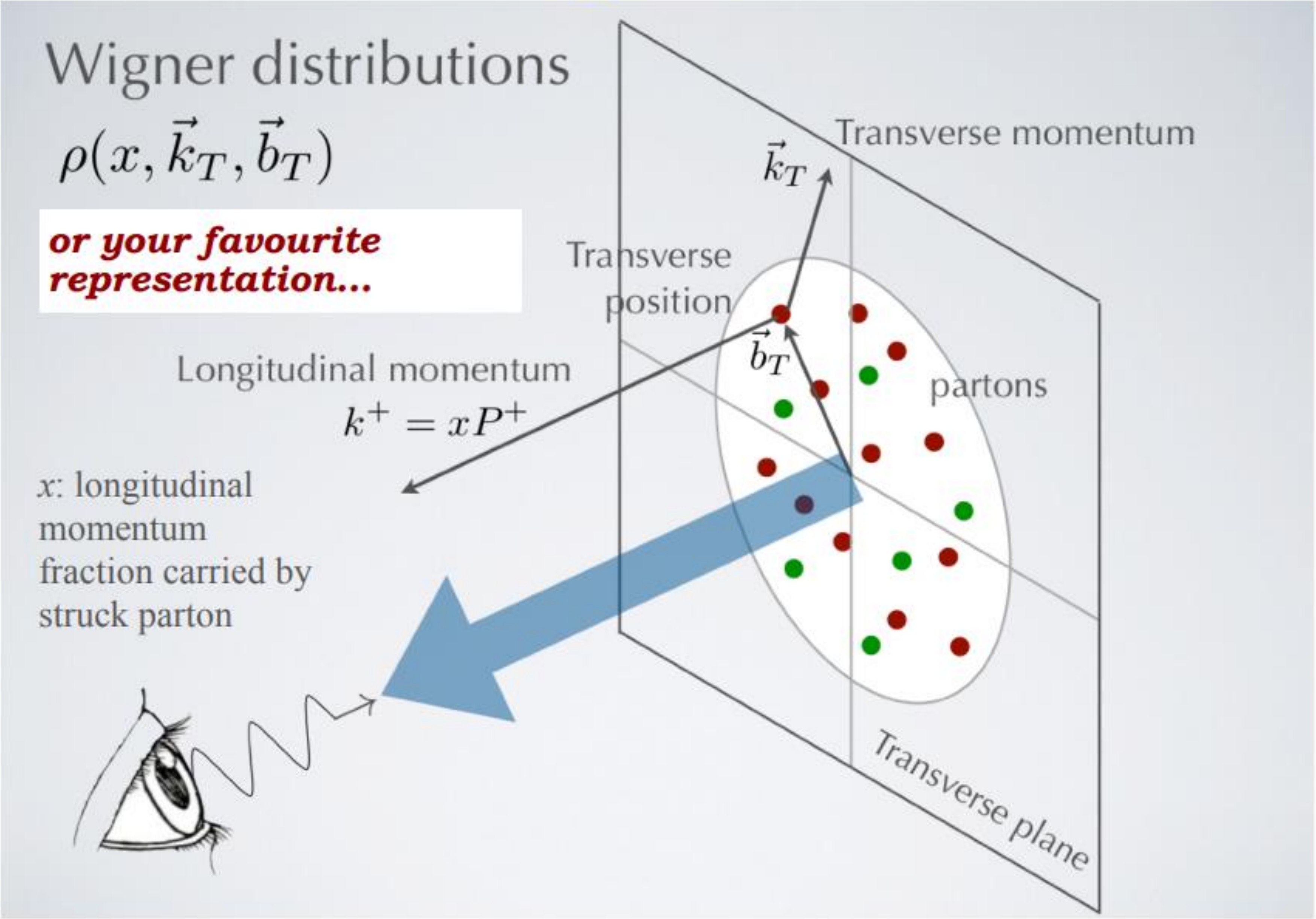
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

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

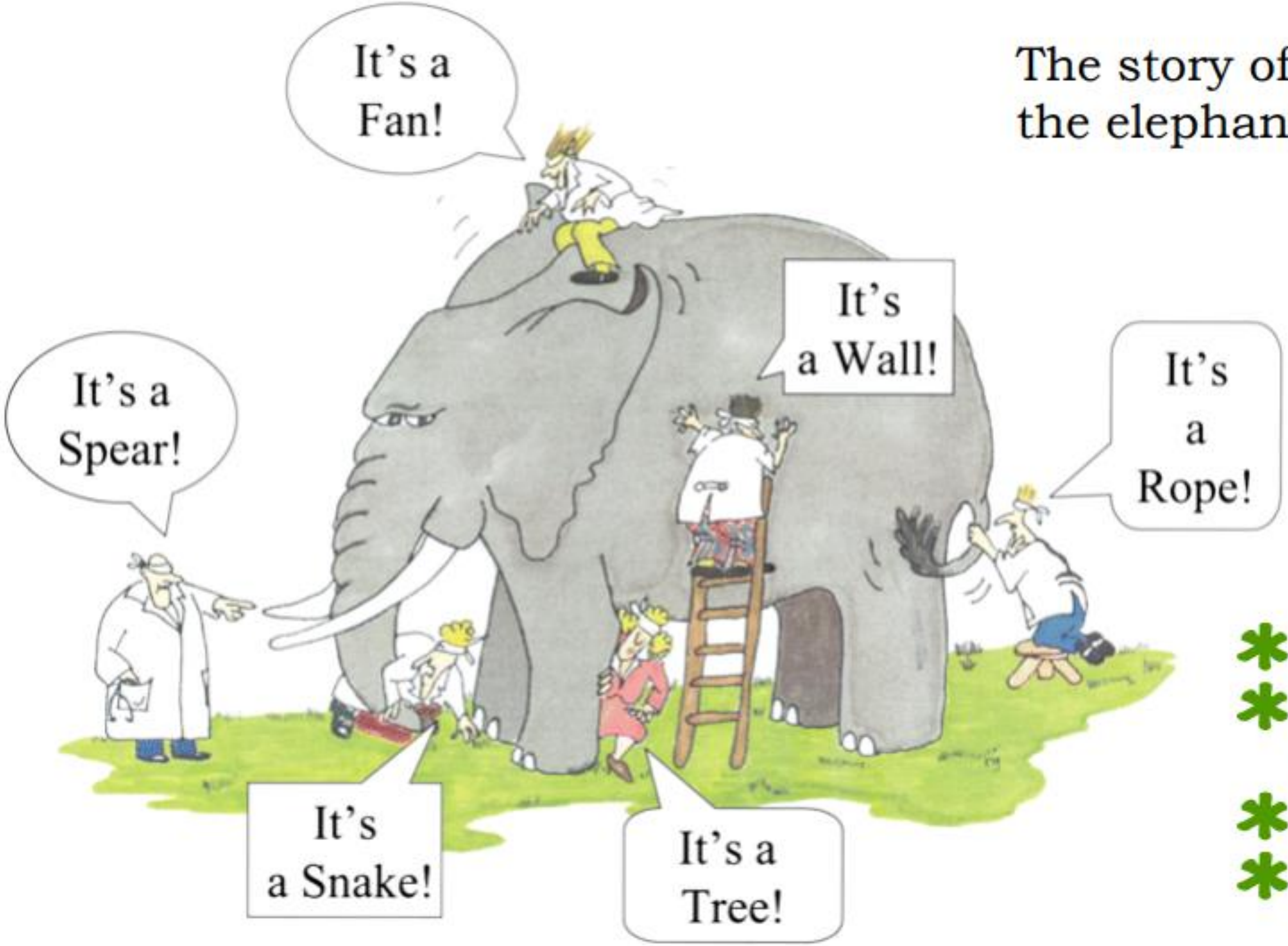
Generalized Parton Distributions (GPD) & Transverse Momentum Distributions (TMD)

-Toward Unified Picture of Nucleon Structure-

A full "knowledge" of the nucleon…



… is hard to come by



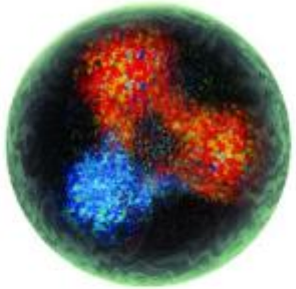
The story of the blind men and the elephant.

- 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

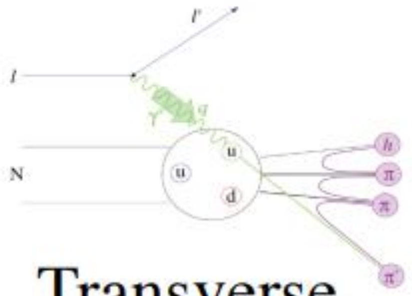


Wigner function:
full phase space parton
distribution of the nucleon

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

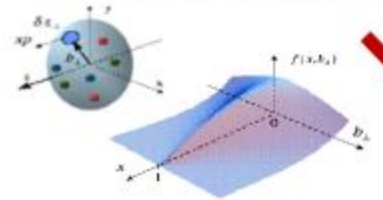
$\int d^2 k_T$

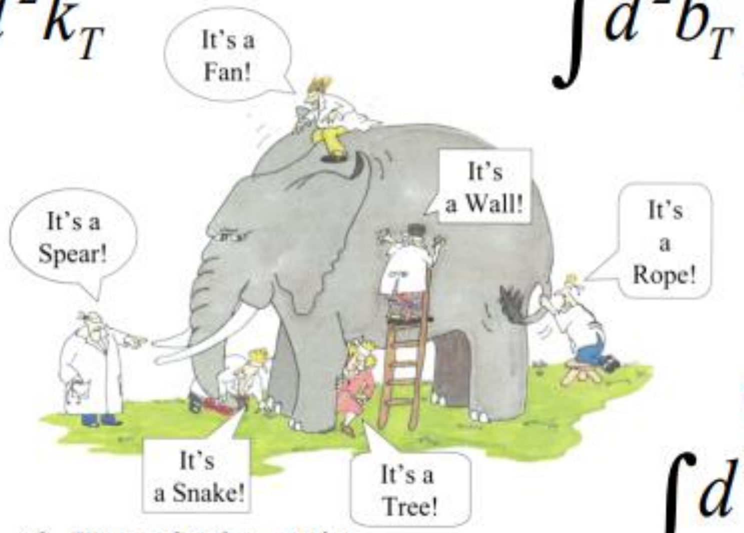
$\int d^2 b_T$



Transverse Momentum Distributions (TMDs)

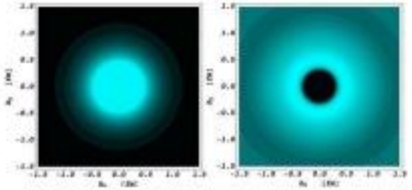
Generalised Parton Distributions (GPDs)





G. Renee Guzlas, artist.

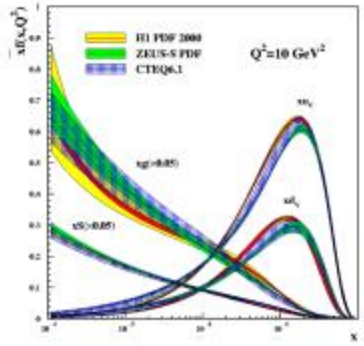
$\int dx$



Form Factors
eg: G_{E}, G_{M}

$\int d^2 k_T$

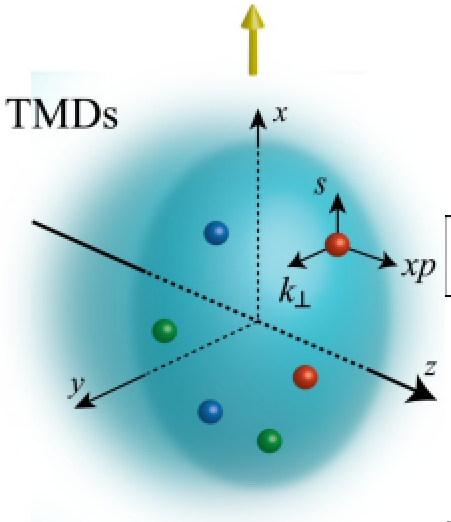
Parton Distribution Functions (PDFs)



Unified View of the Nucleon Structure

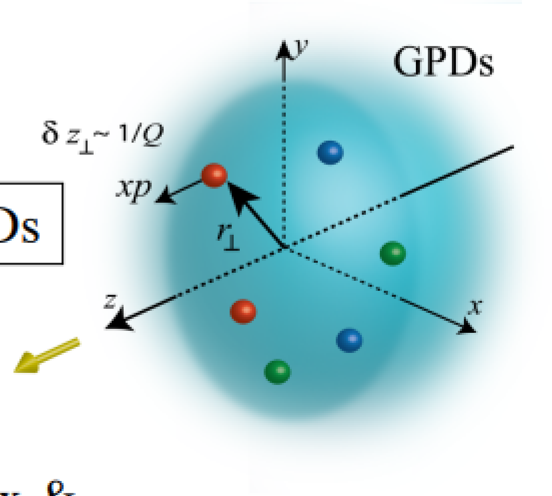
3D imaging

TMDs



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

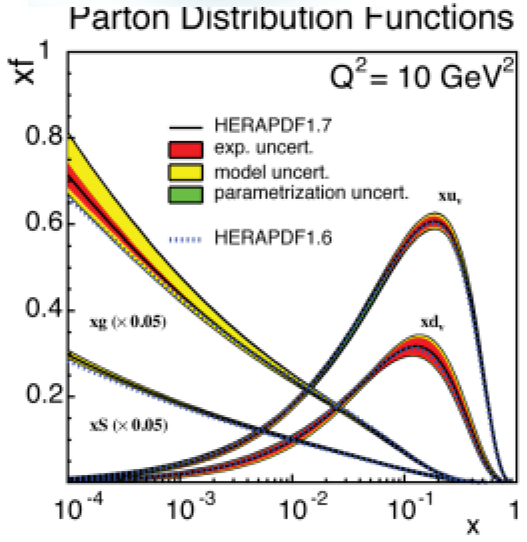
GPDs/IPDs



d^2k_T

d^2r_T

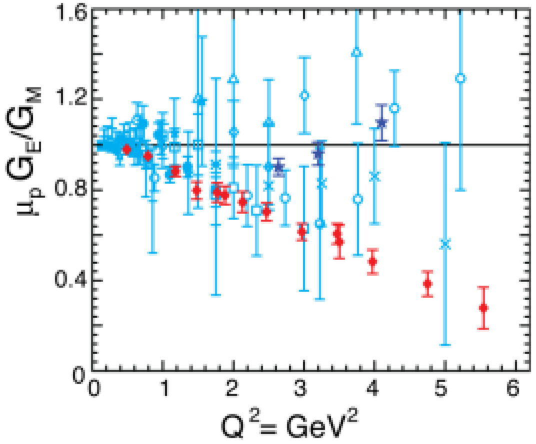
dx & Fourier Transformation



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

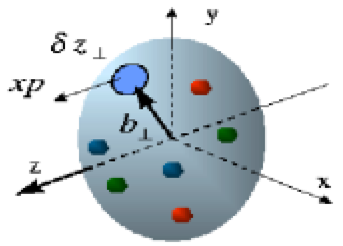
1D

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

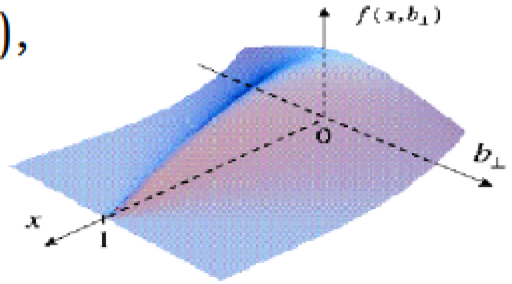


Generalised Parton Distributions (GPDs) —
proposed by Müller (1994), Radyushkin, Ji (1997).

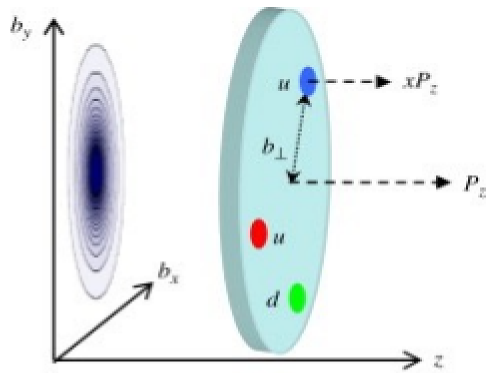
✱ *Directly related to the matrix element of the energy-momentum tensor evaluated between hadron states.*

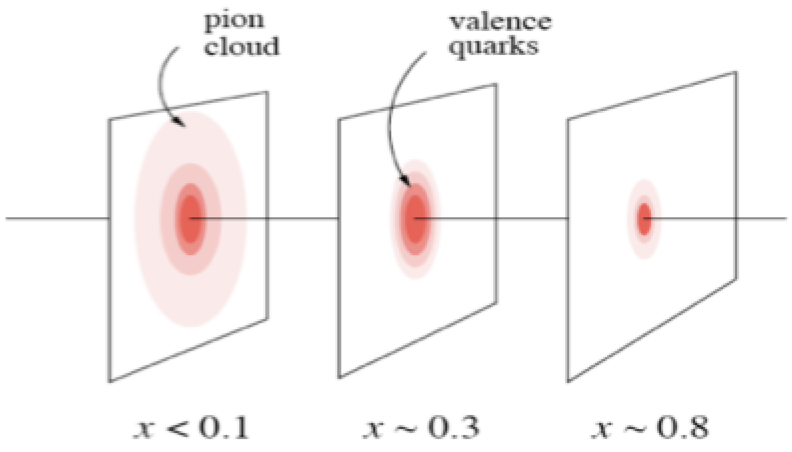


In the infinite momentum frame, can be interpreted as relating transverse position of partons (impact parameter), $b_\perp$, to their longitudinal momentum fraction (x).



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.

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

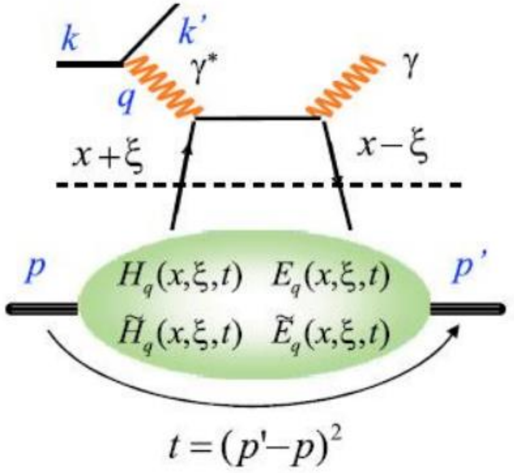
$$GPDs\,(x,\ \xi,\ t\ =\ \Lambda^2)$$

2 longitudinal momentum fractions (x, ξ)

squared momentum transfer to the proton (t)

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

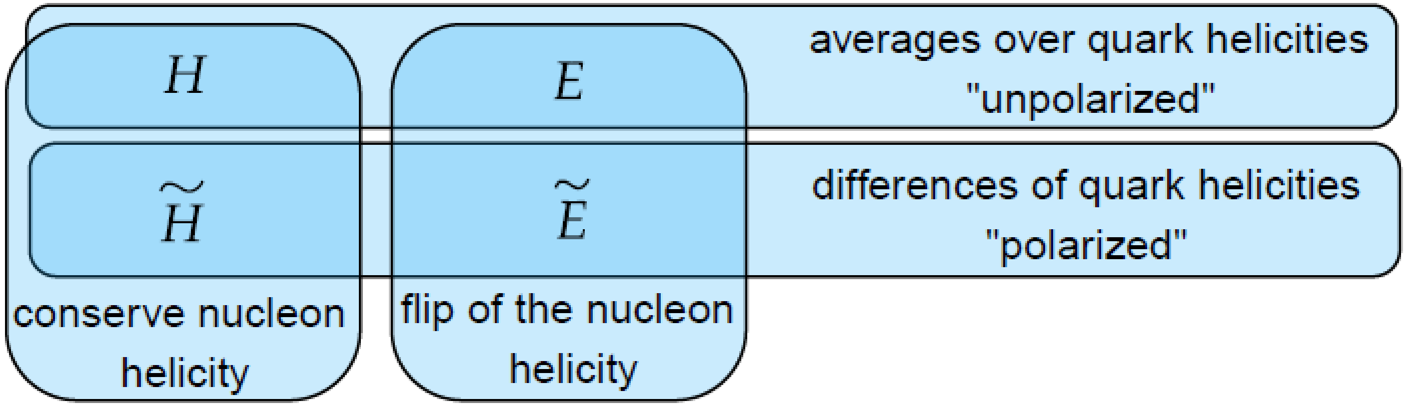
$$e\ p \rightarrow e'\ p'\ \gamma$$



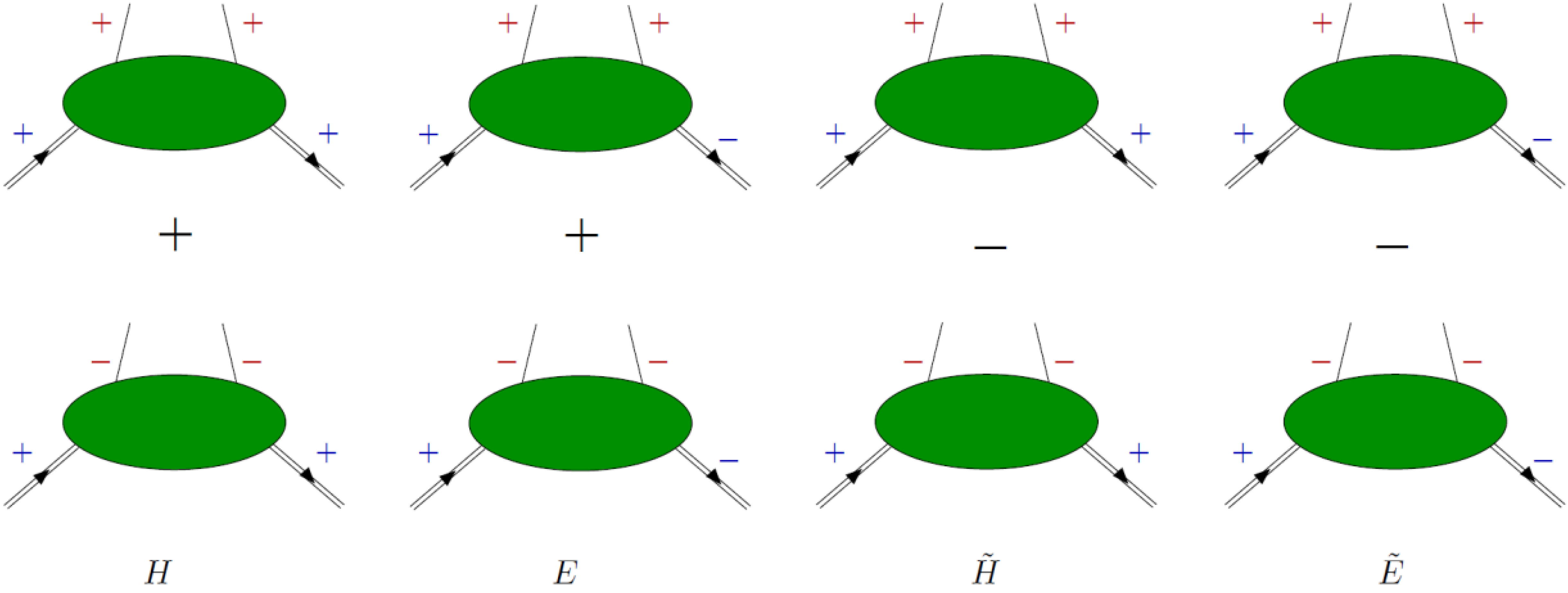
$$\gamma^*\ p \rightarrow p'\ \gamma$$

Deeply Virtual Compton Scattering (DVCS)

Chiral even GPDs: quark helicity is conserved

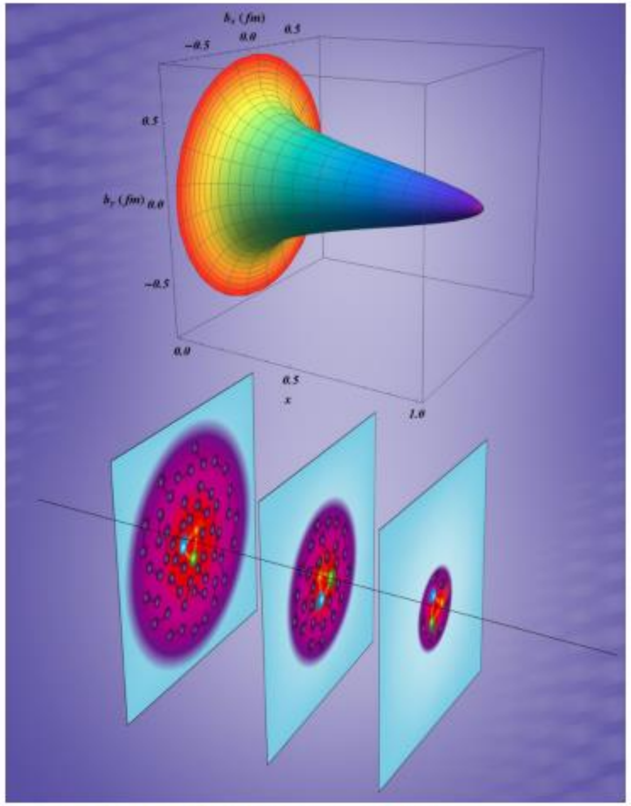


Generalized Parton Distribution (GPDs)



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

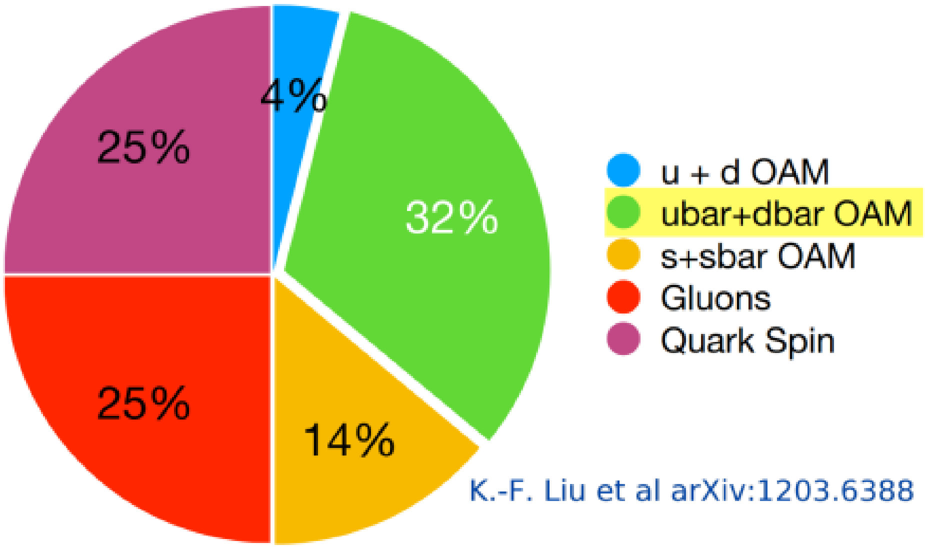
- Nucleon Tomography:
- Angular momentum of the partons



R. Dupre et al arXiv:1704.07330

Ji's angular momentum sum rule

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



K.-F. Liu et al arXiv:1203.6388

Proton spin contributions from Lattice QCD

Jaffe-Manohar decomposition

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

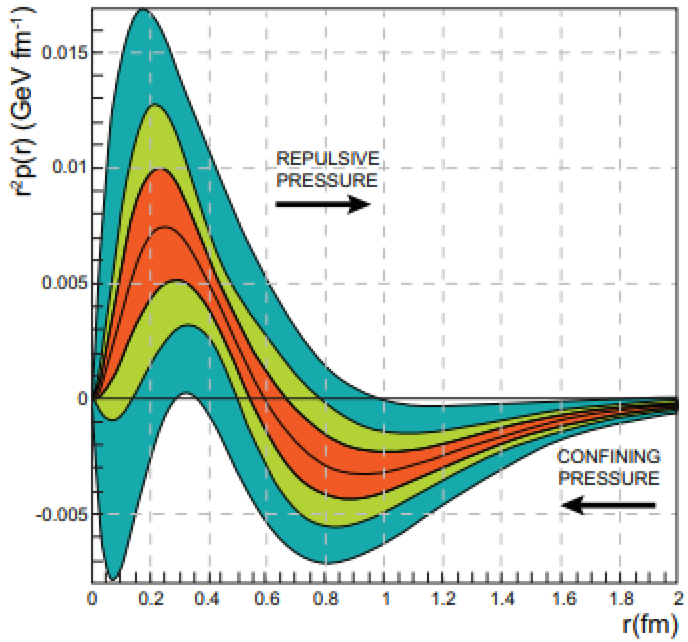
Gluon total angular momentum

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]

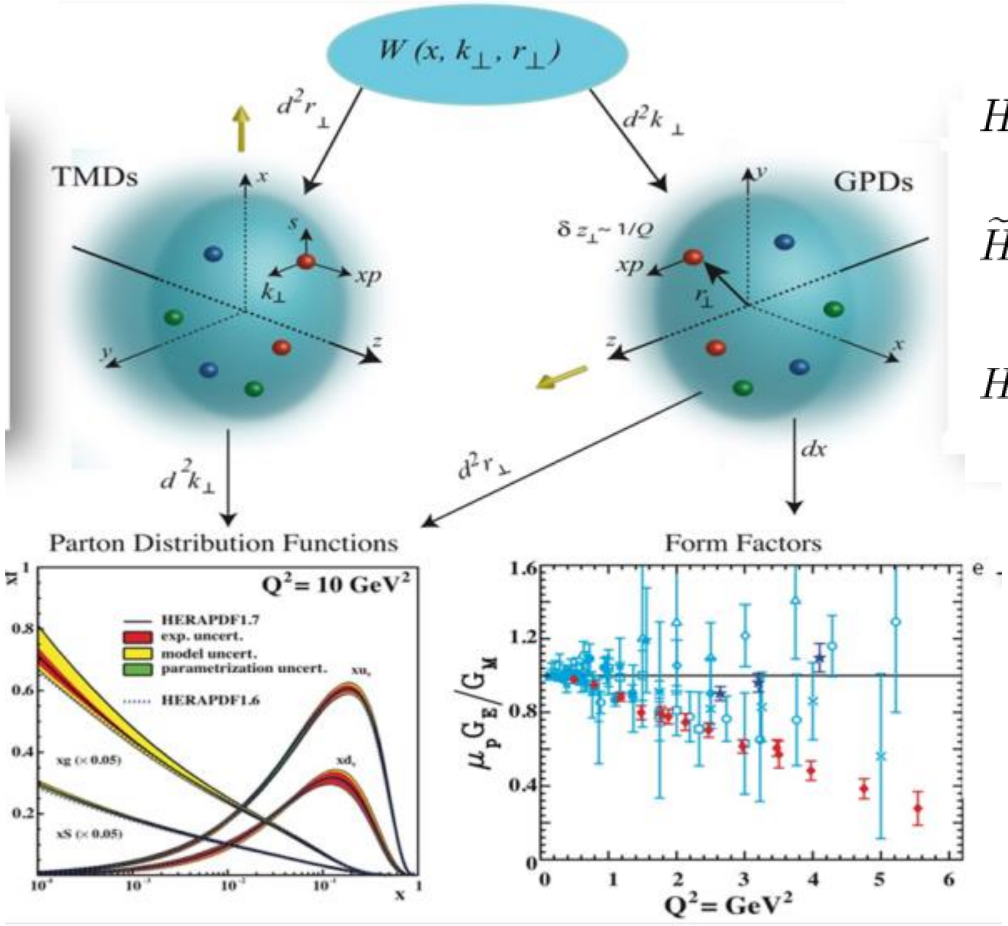
Mass and force/pressure distributions

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

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

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

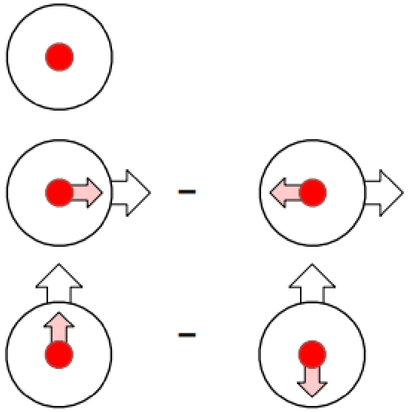
- Access to PDFs and Elastic Forms Factors



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

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

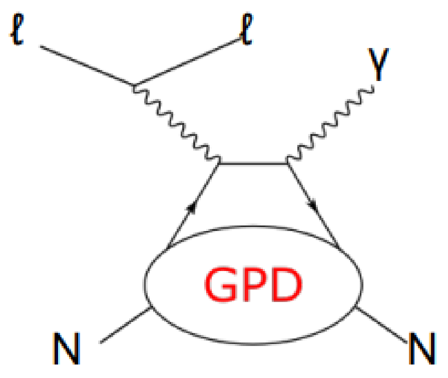
$$H_T^q(x,0,0) \equiv h_1(x)$$



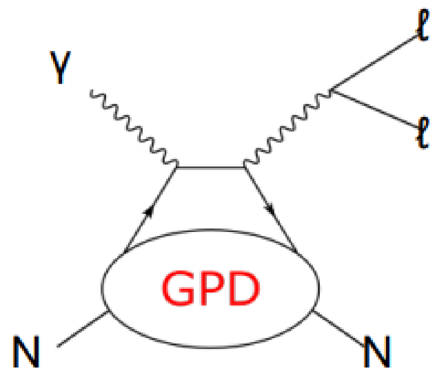
$$\int_{-1}^{1} dx\, H^q(x,\xi,t) \equiv F_1^q(t) \qquad \int_{-1}^{1} dx\, E^q(x,\xi,t) \equiv F_2^q(t)$$

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

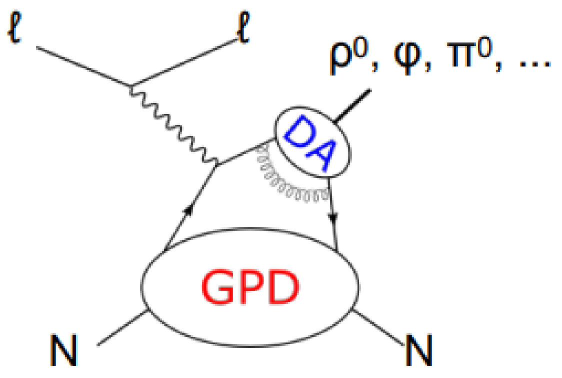
GPDs are accessible from various production channels:



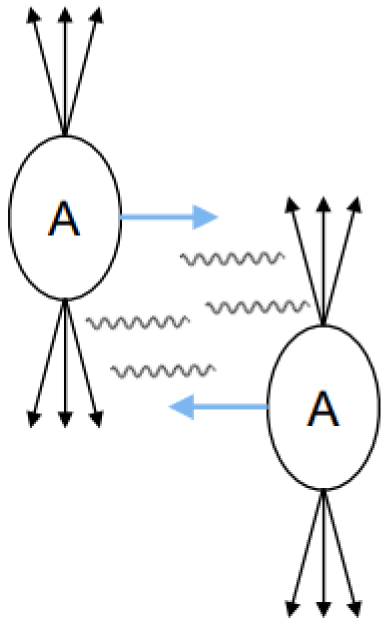
DVCS
Deeply Virtual Compton Scattering



TCS
Timelike Compton Scattering



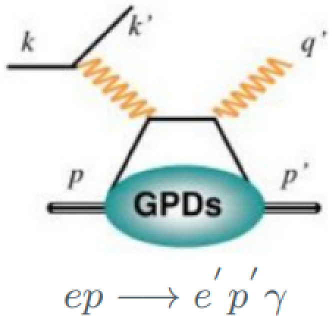
HEMP
Hard Exclusive Meson Production

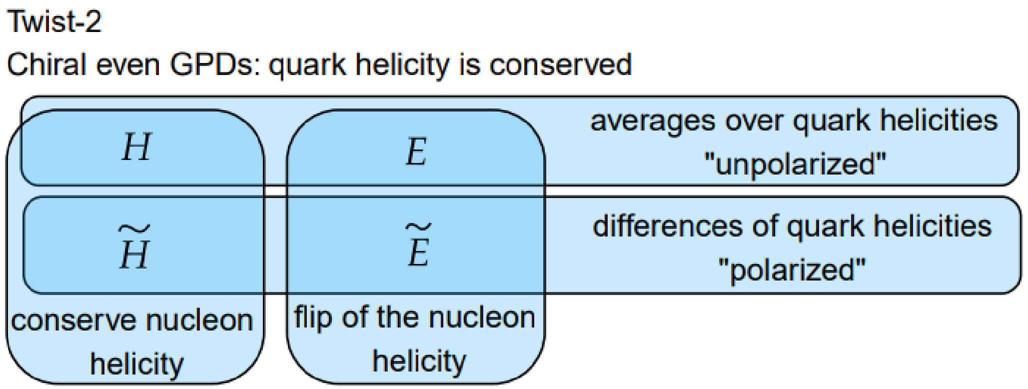


UPC
Ultra Peripheral Collisions

Channel of interest

4 chiral even GPDs can be accessed via DVCS





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

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

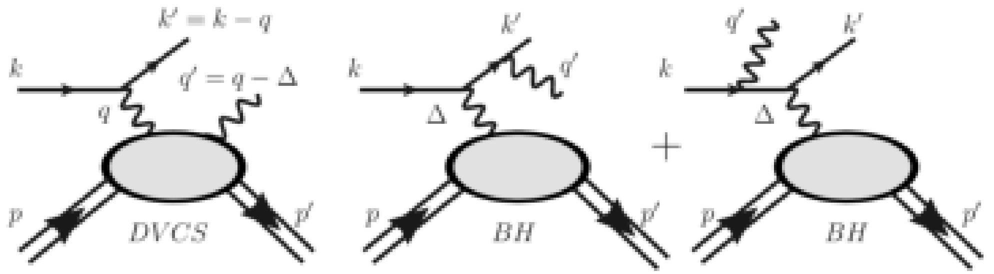
CFFs extractions (access directly via cross section or asymmetry measurements) is a good way to obtain GPDs

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

CFFs are observables that could access directly from experiments

DVCS channel

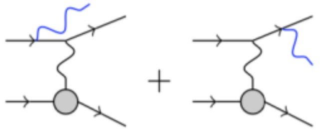
Cross sections = DVCS + Bethe-Heitler (BH)



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

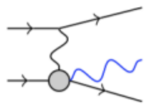
$$\underbrace{\frac{d^5\sigma}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} = \frac{\alpha^3 x_B y^2}{16\pi^2 Q^4\sqrt{1+\epsilon^2}}\frac{1}{e^6}\left[|\mathcal{T}^{BH}|^2 + |\mathcal{T}^{DVCS}|^2 + \mathcal{I}\right]}_{f(k,Q^2,x_B,t,\phi)}$$

Bethe-Heitler process



calculable within QED

DVCS



parametrised by CFFs

- 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:

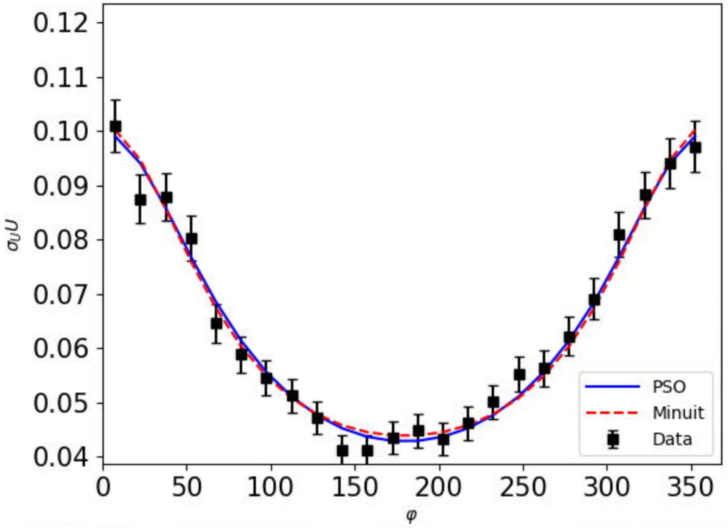
- VGG (Vanderhaeghen, Guichon, Guidal, 1999)
- GK (Goleskokov, Kroll, 2005)
- KM (Kumericki, Muller): KM09, KM10, KM15
- KMM12 (Kumericki, Muller, Murray, 2012)
- VA-reggeized spectator (B. Kriesten, S. Liuti, 2021)

Each model has different GPD parameterization

Scope of Works

DVCS Data on Cross sections and Asymmetries:

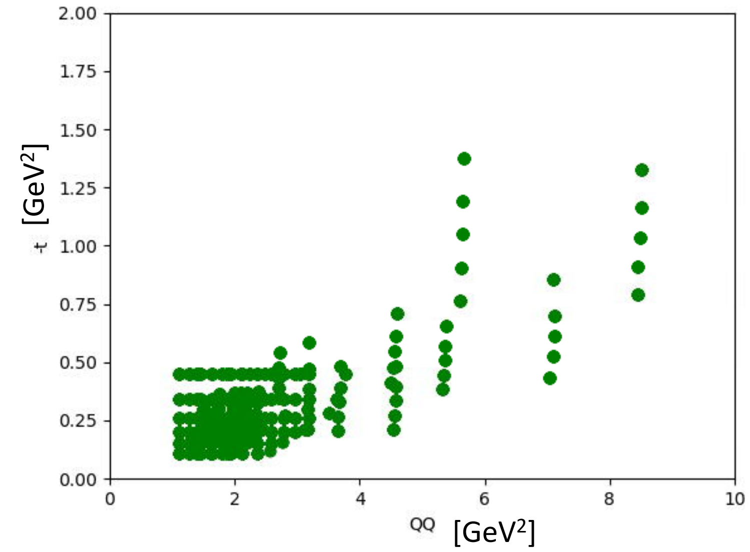
- No φ-dependence: HERMES, COMPASS, ZEUS, A1
- High statistics with φ-dependence: JLAB Hall A, CLAS (Hall B)

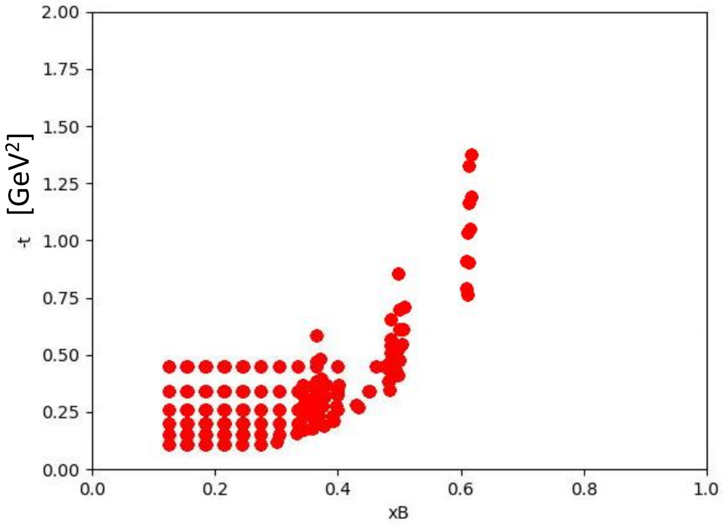


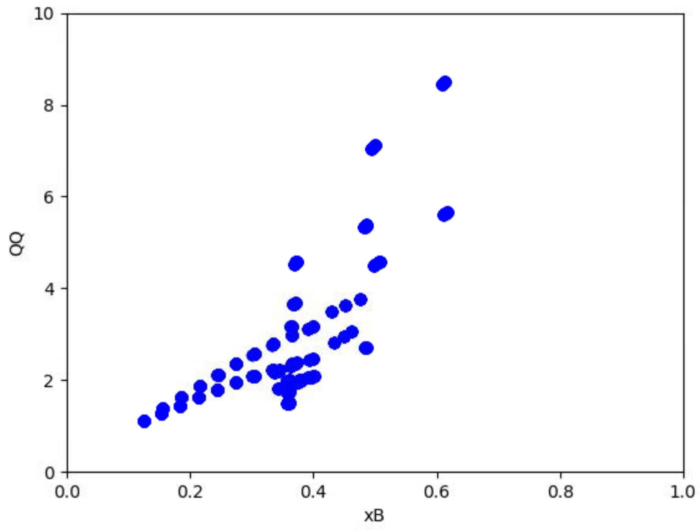
Data used in this work: All φ-dependence cross-sections

- 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







Scope of Works

We us BKM10 Formulism at leading twist

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

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

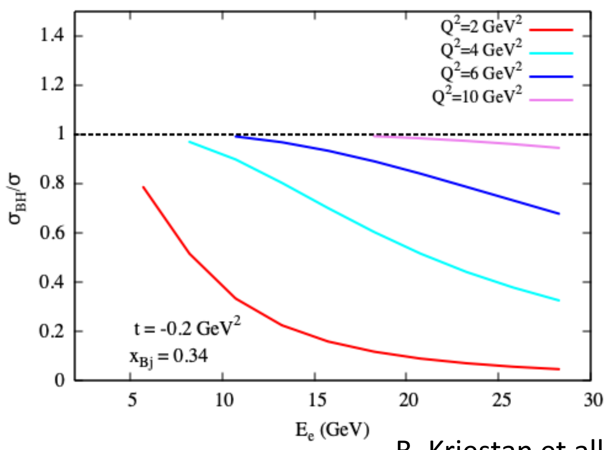
$$|\mathcal{T}_{DVCS}|^2 = \frac{e^6}{y^2Q^2}\left\{2(2-2y-y^2)\right\}\underbrace{C_{unp}^{DVCS}(\mathcal{F},\mathcal{F}^*)}_{\text{8 CFFs}}$$

4 fit parameters:

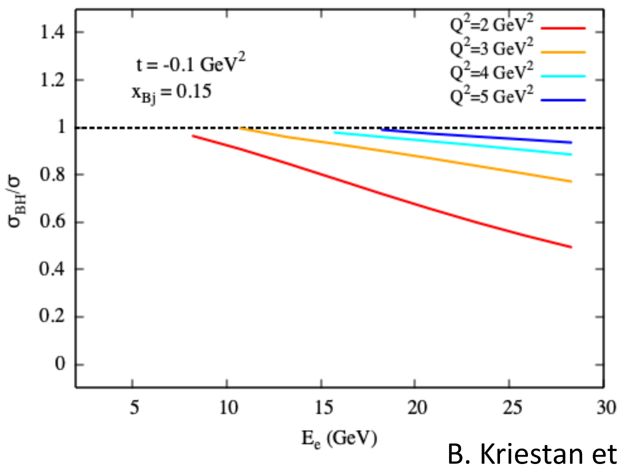
$\Re e\mathcal{H}, \Re e\mathcal{E}, \Re e\widetilde{\mathcal{H}},$
pure DVCS

Scope of Works

Challenge: Huge BH background



B. Kriestan et all



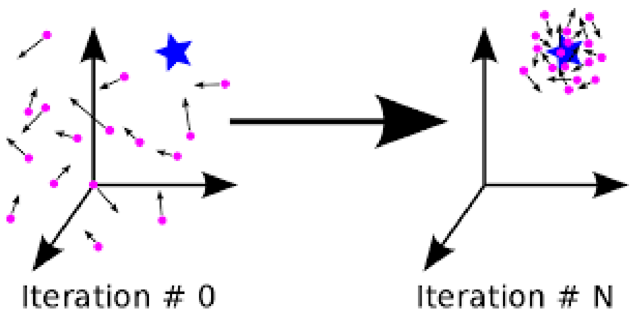
B. Kriestan et all

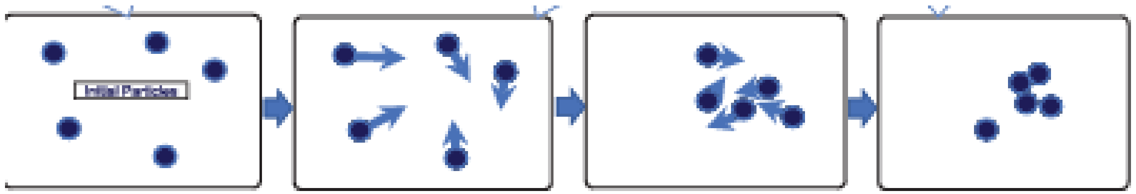
Approach:

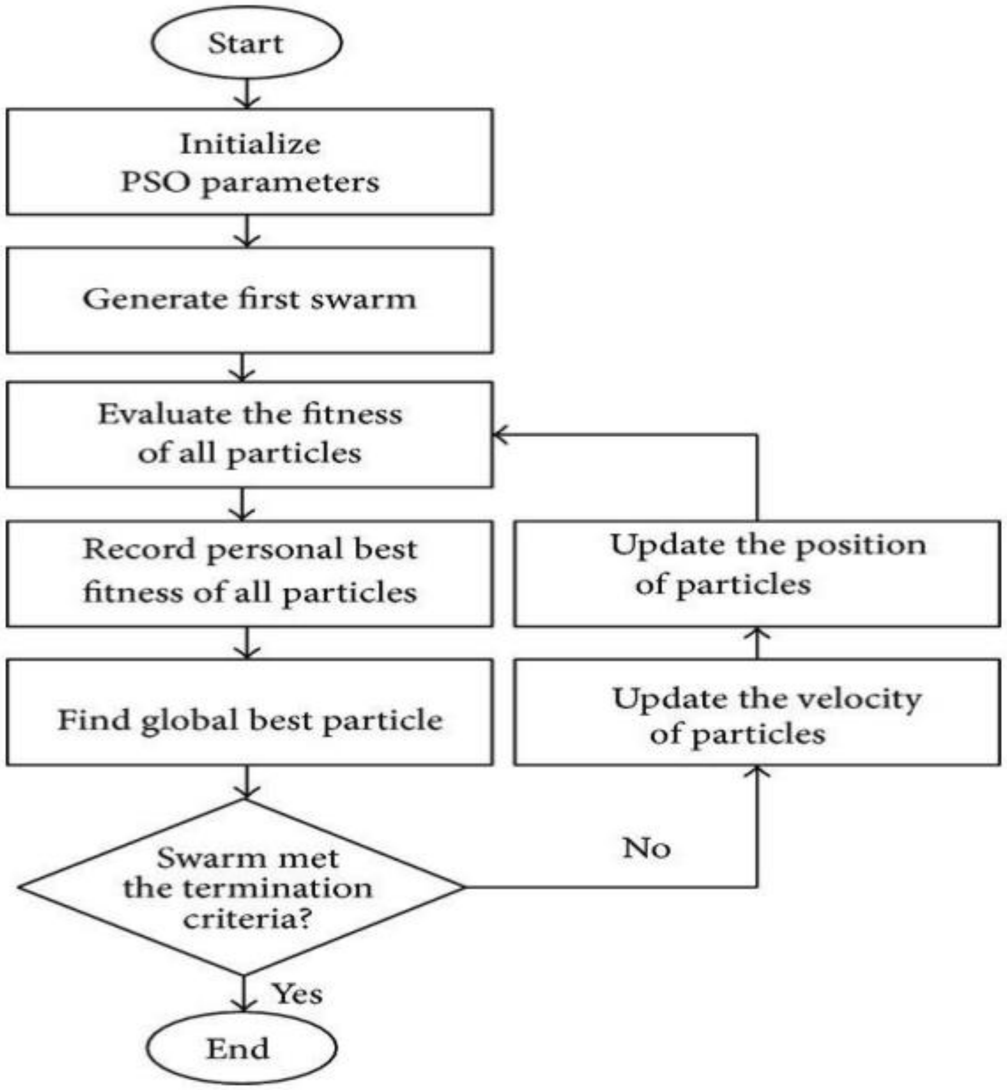
- Local fit to obtain CFFs for each kinematic sets using Root-Minuit & Particle Swarm Optimization (PSO)
- Global Fit using Neural Network
- Test the methods to the pseudo data generated using KM15 model and smeared according to the experimental uncertainty
- The pseudo data are generated with mimicking real data kinematics (195 sets) and uncertainties

Particle Swarm Optimization (PSO)

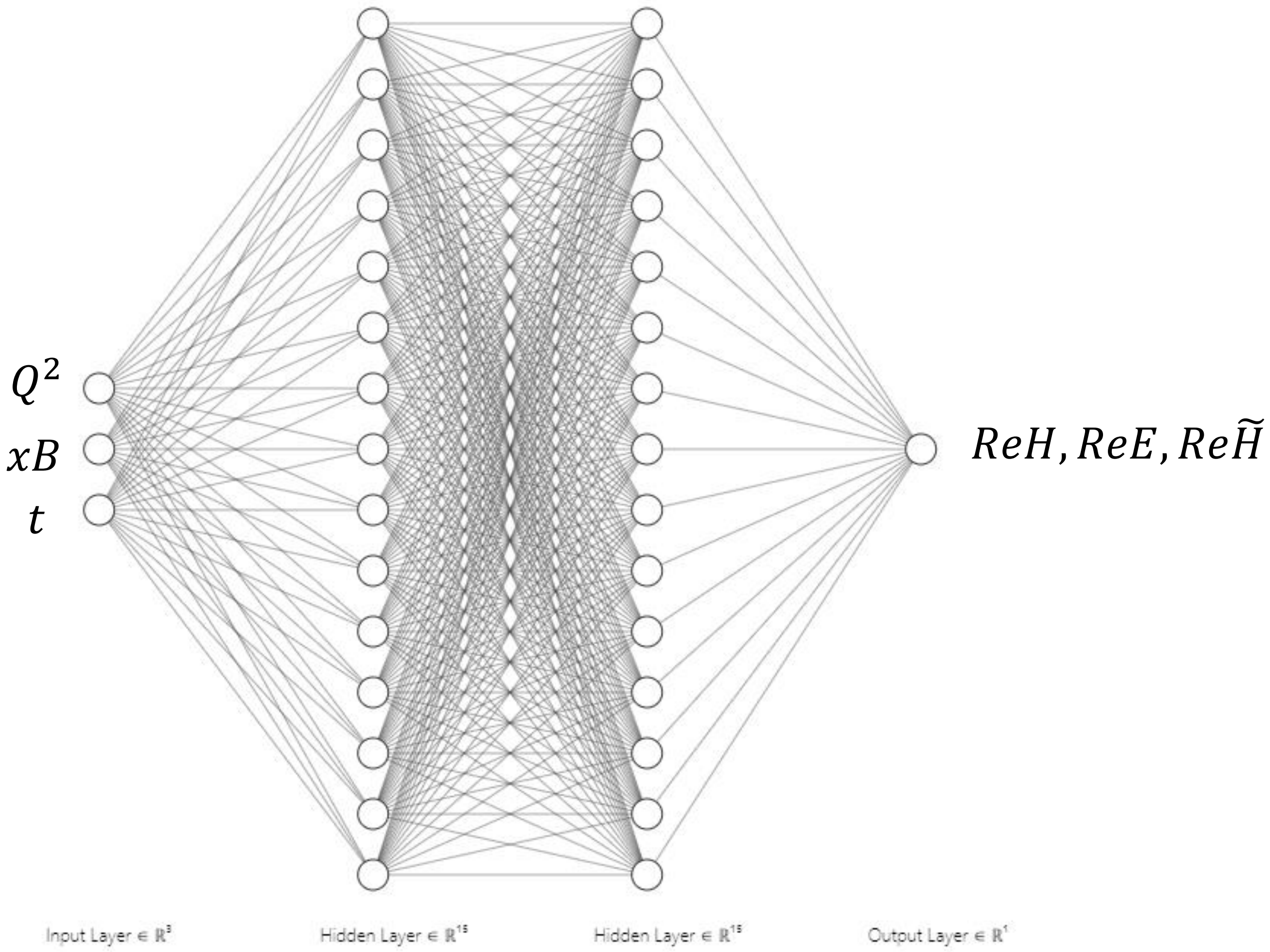
- Inspired from the nature social behavior and dynamic movements with communications of insects, birds and fish
- Uses a number of agents (particles) that constitute a swarm moving around in the search space looking for the best solution
- Each particle in search space adjusts its “flying” according to its own flying experience as well as the flying experience of other particles
- Each particle has three parameters position (velocity, and previous best position). Particle with best fitness value is called as global best position







Neural Net Architecture

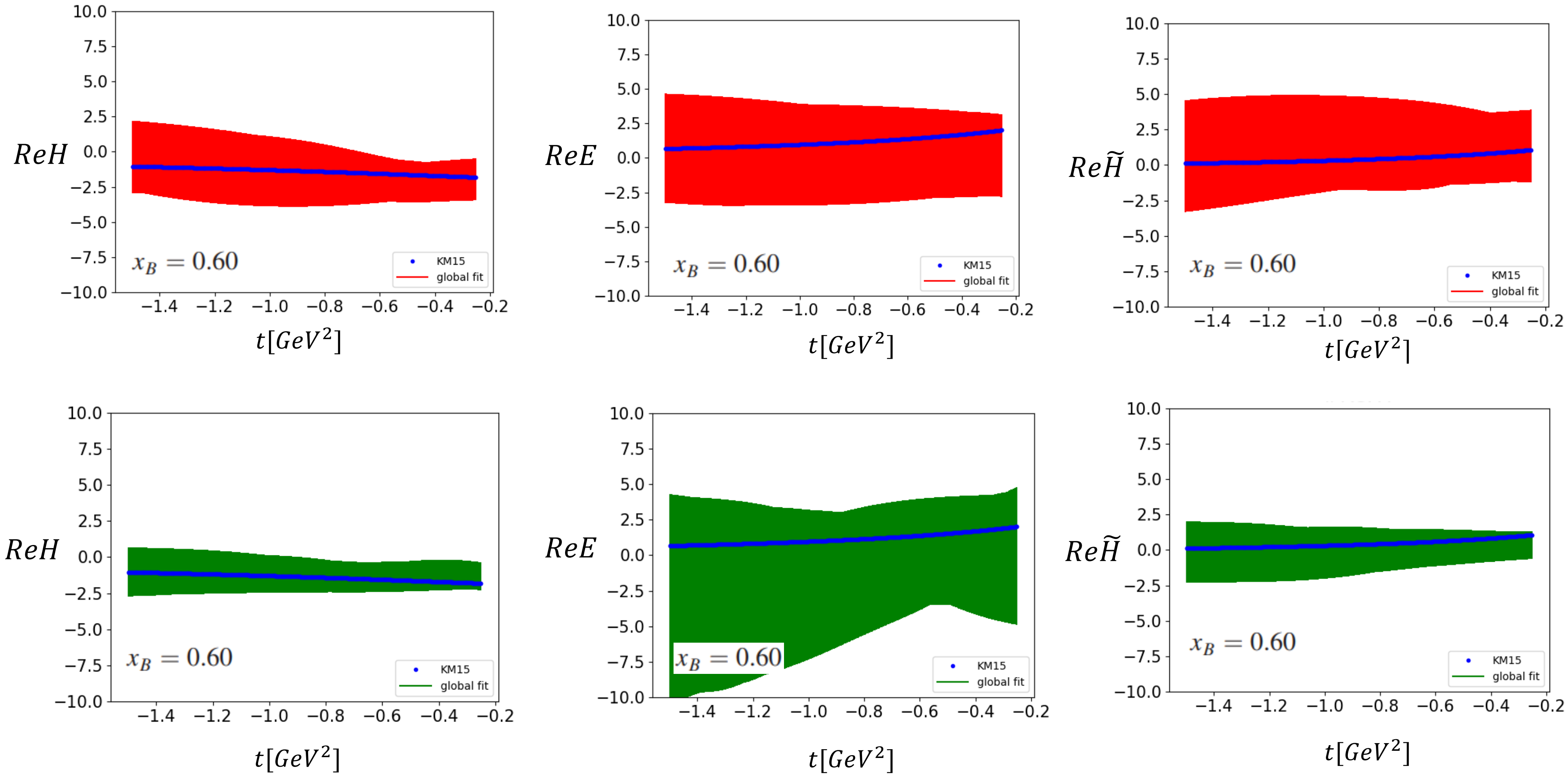


NN architecture & features:

- Each CFFs are global-fitted separately
- 3 input neurons, 1 output neuron
- 2 x 15 hidden layers
- Set splitting (training & validation)
- Multi-Step decay learning rate
- $tanh$ activation function
- Adam optimizer
- Input normalization
- Early stopping on Validation set
- Replicas by smearing the CFFs according to the uncertainty from local fit
- 1000 Replicas
- MSE loss function

Neural network is a universal approximator which provide a model independent regression (fitting)

Preliminary Results: Pseudo data

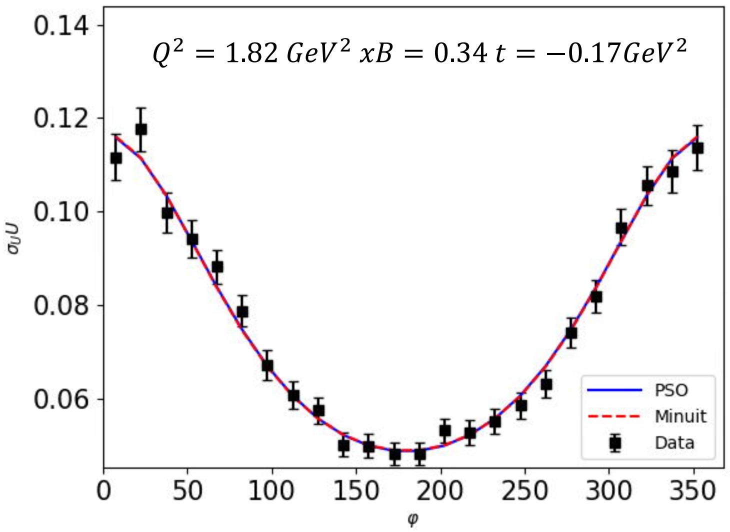


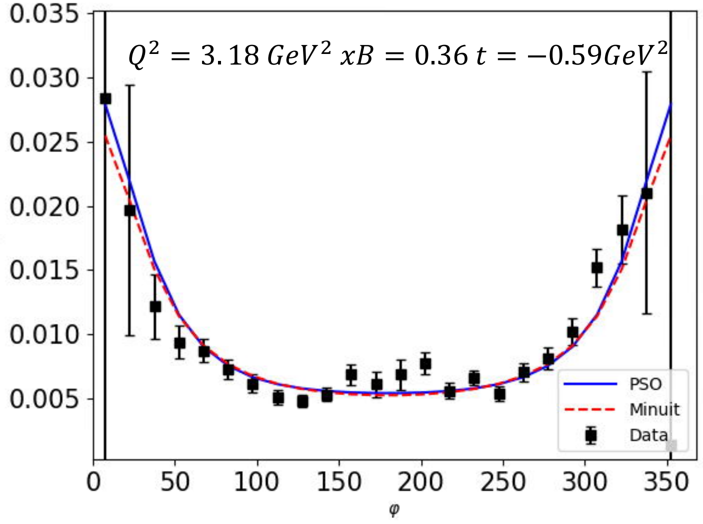
PSO

Minuit

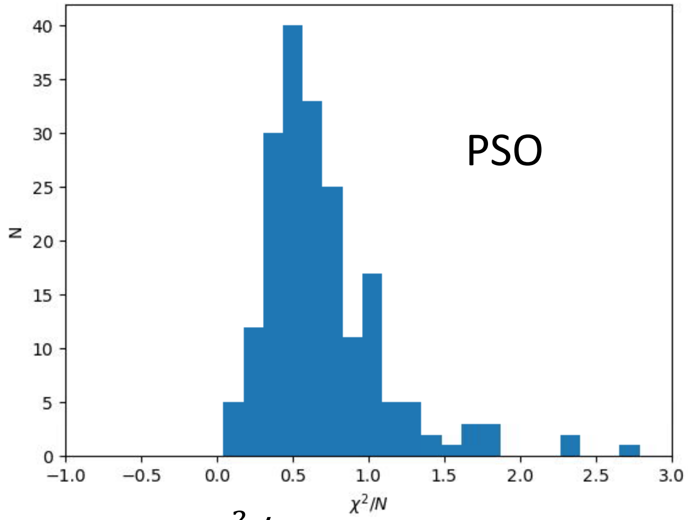
Note: Band represents all values from 1000 replicas

Preliminary Results: Local Fit on Experimental Data

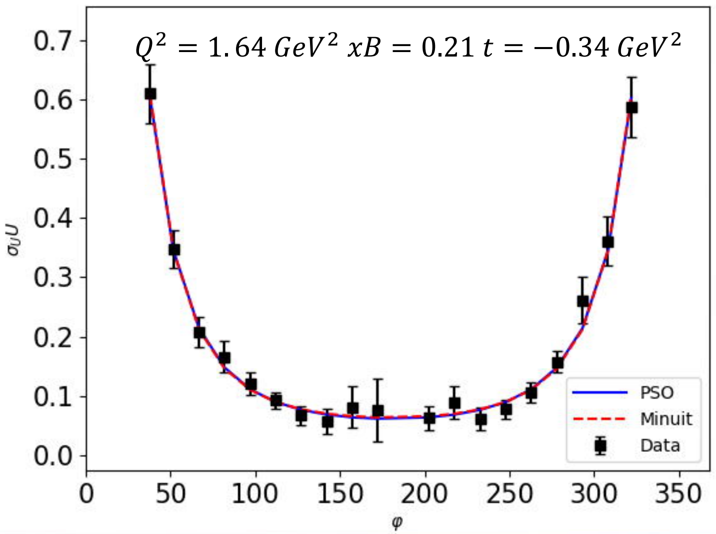


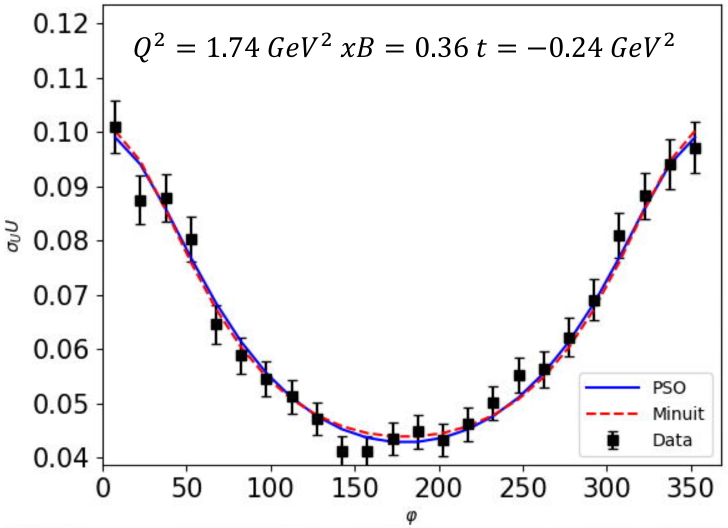


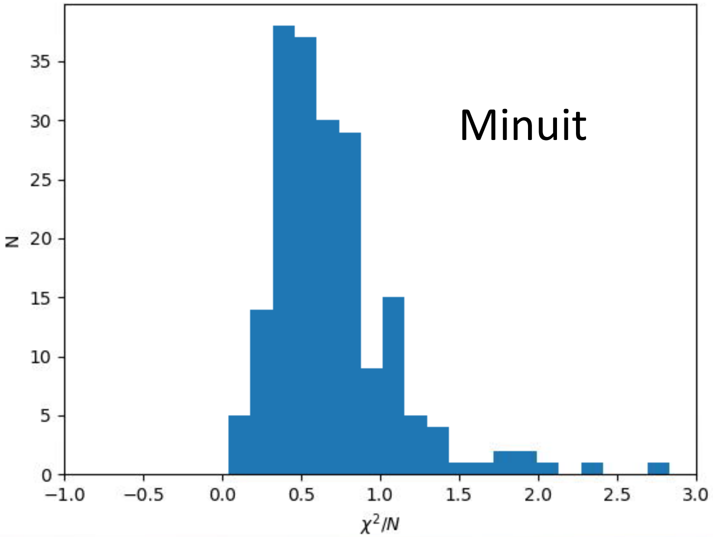
PSO $\chi^2/_{Ntotal} = 0.73902$



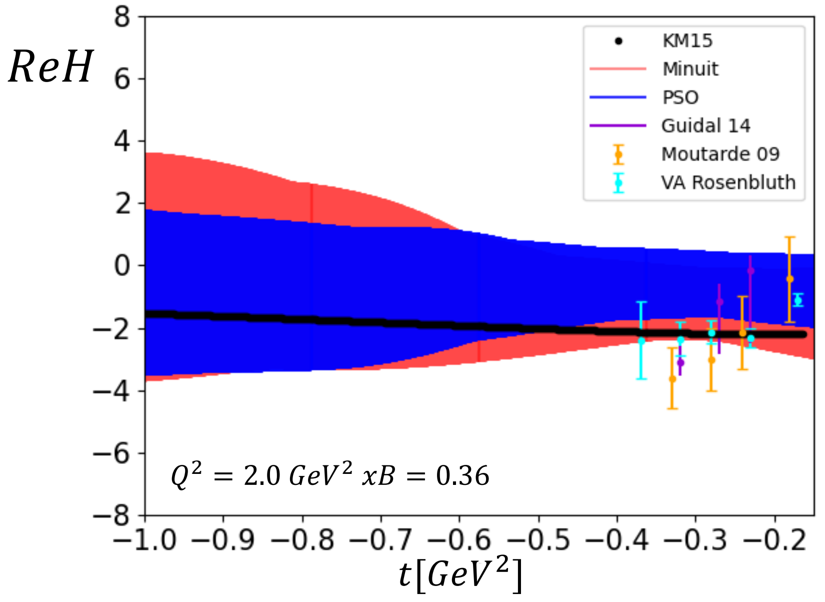
Minuit $\chi^2/_{Ntotal} = 0.73996$

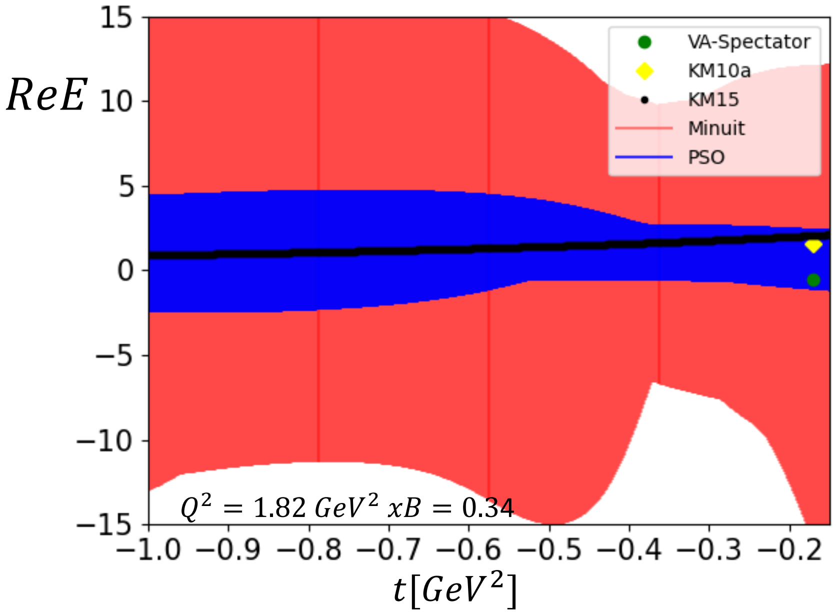


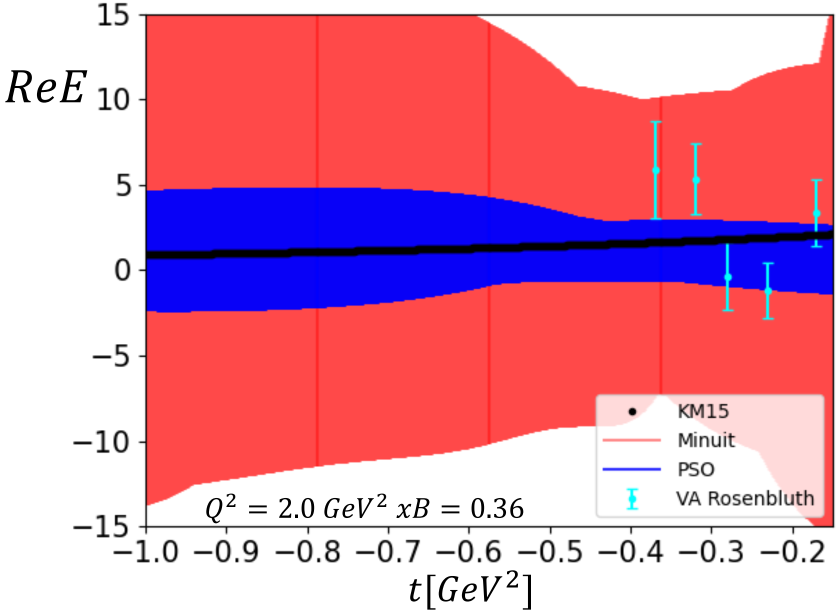


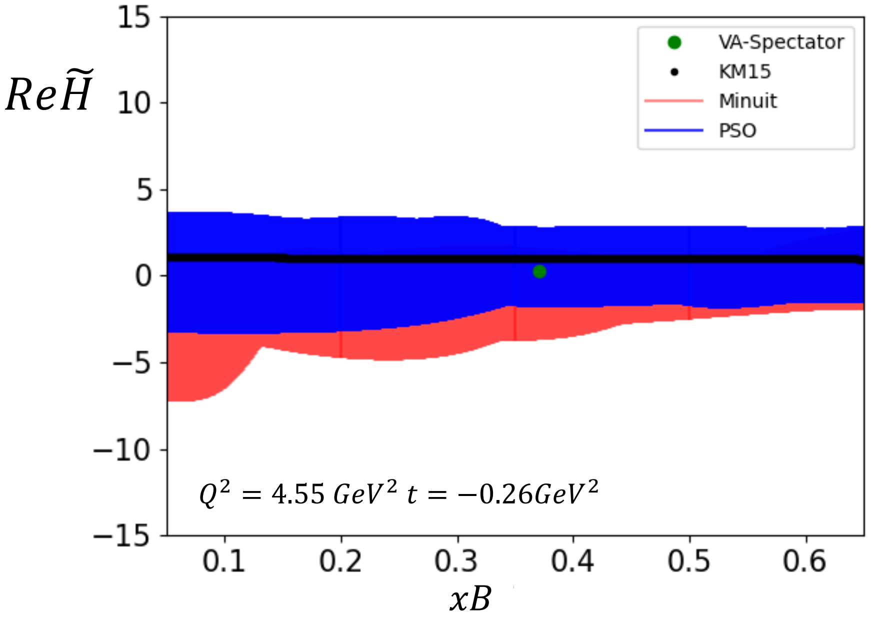


Preliminary Results: Global Fit on Data





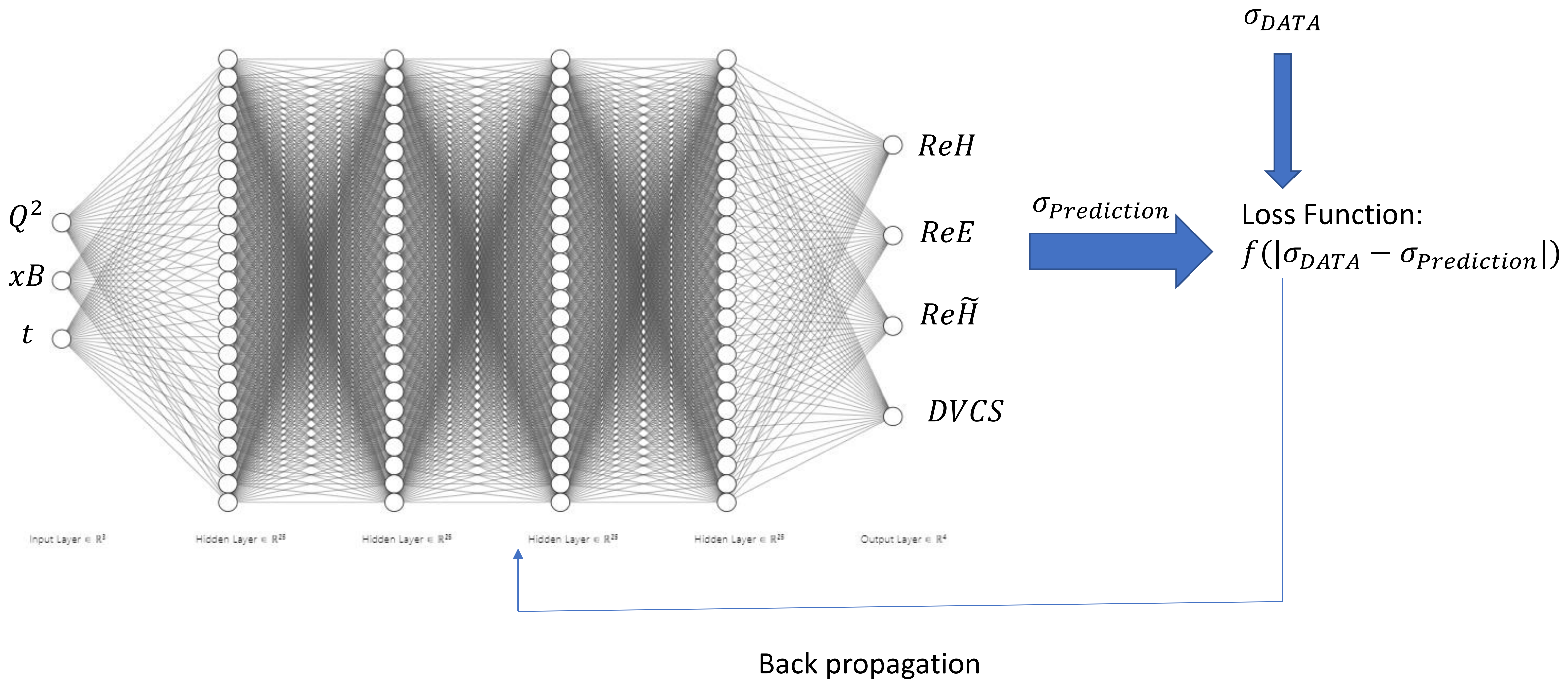




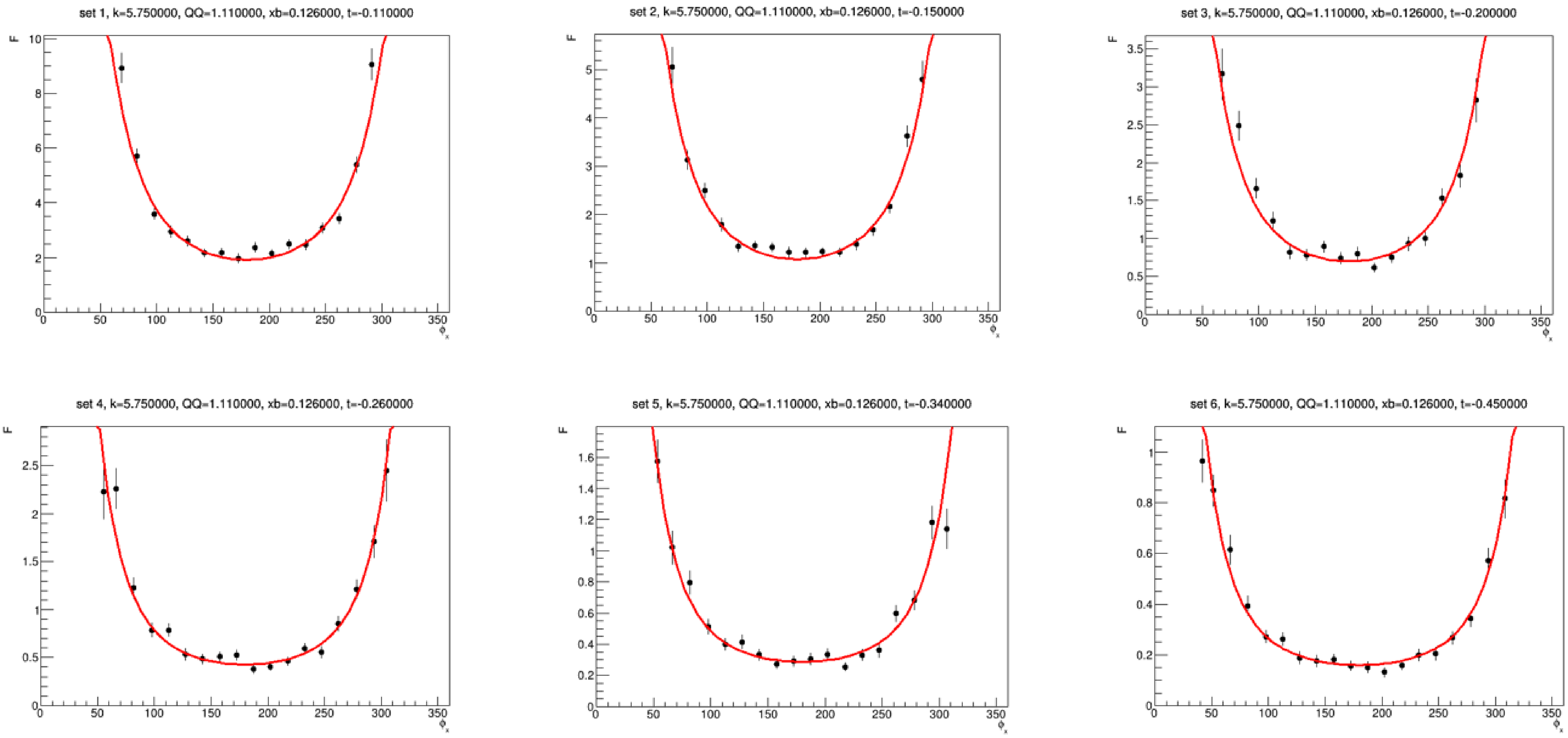
Note:

- Band represents all values from 1000 replicas
- Data points for comparison were extracted from B.Kriesten et all

- Deep Neural Net for local & global fit (different architecture)



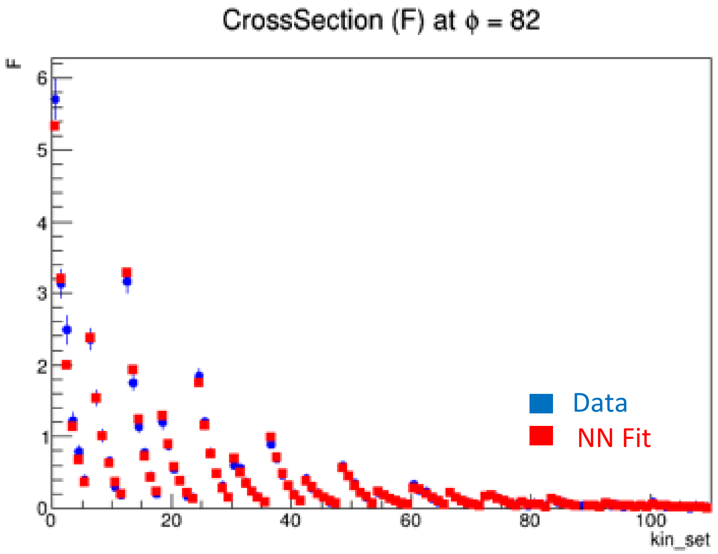
• Deep Neural Net for local & global fit (different architecture): preliminary results

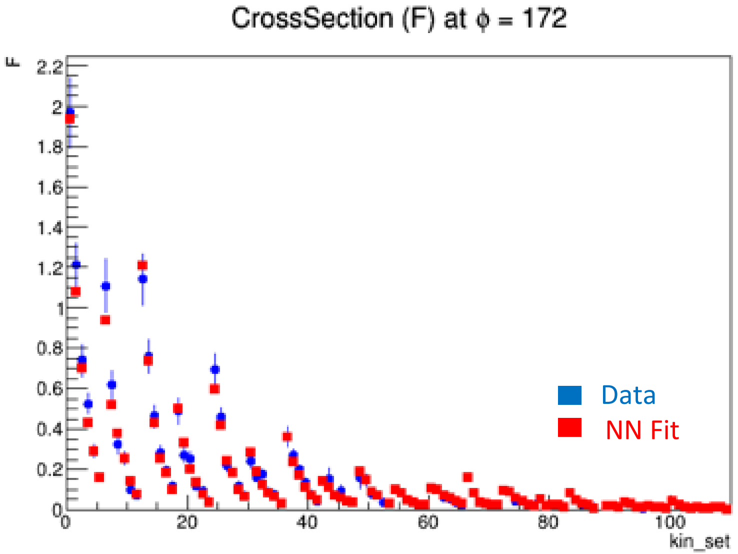


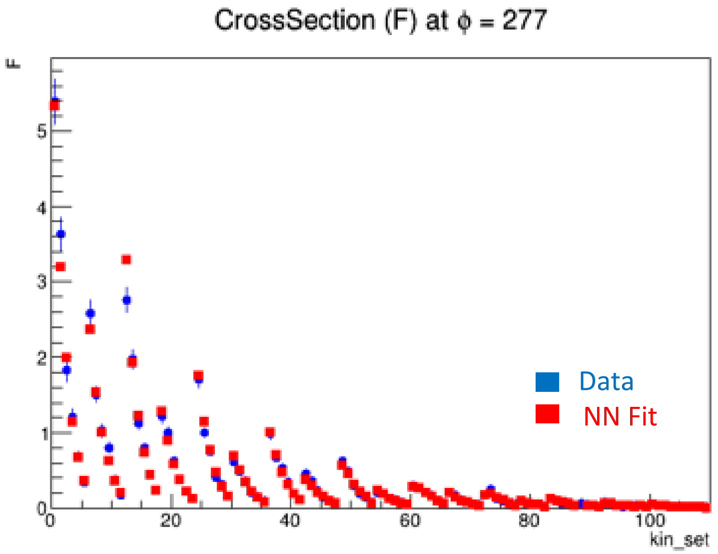
Outlook

- Deep Neural Net for local & global fit (different architecture): preliminary results

The comparison of predicted cross sections (F) and real data from CLAS e1-DVCS (110 kinematic sets)

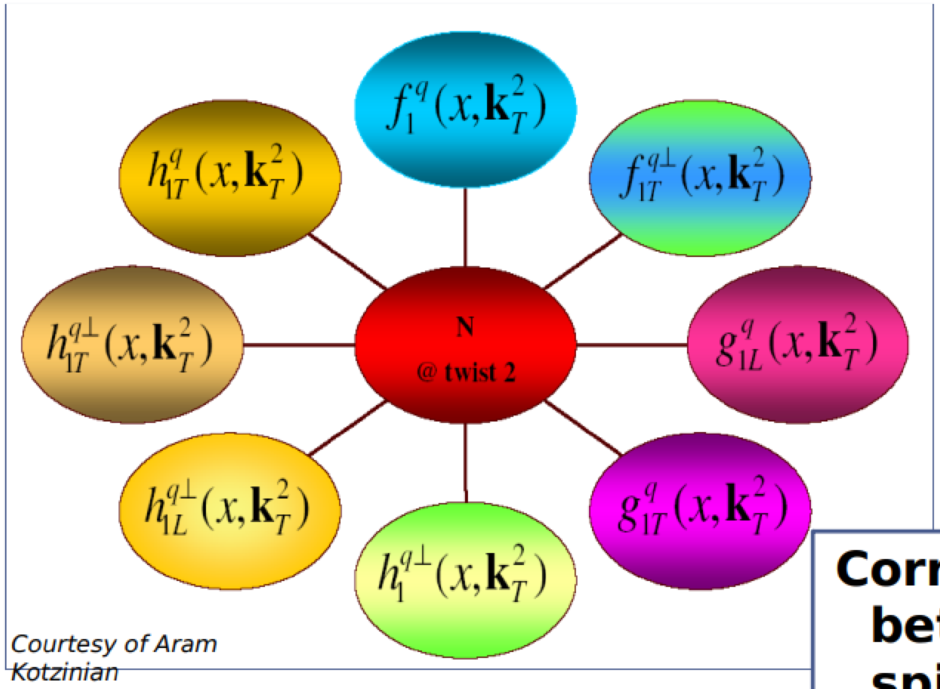


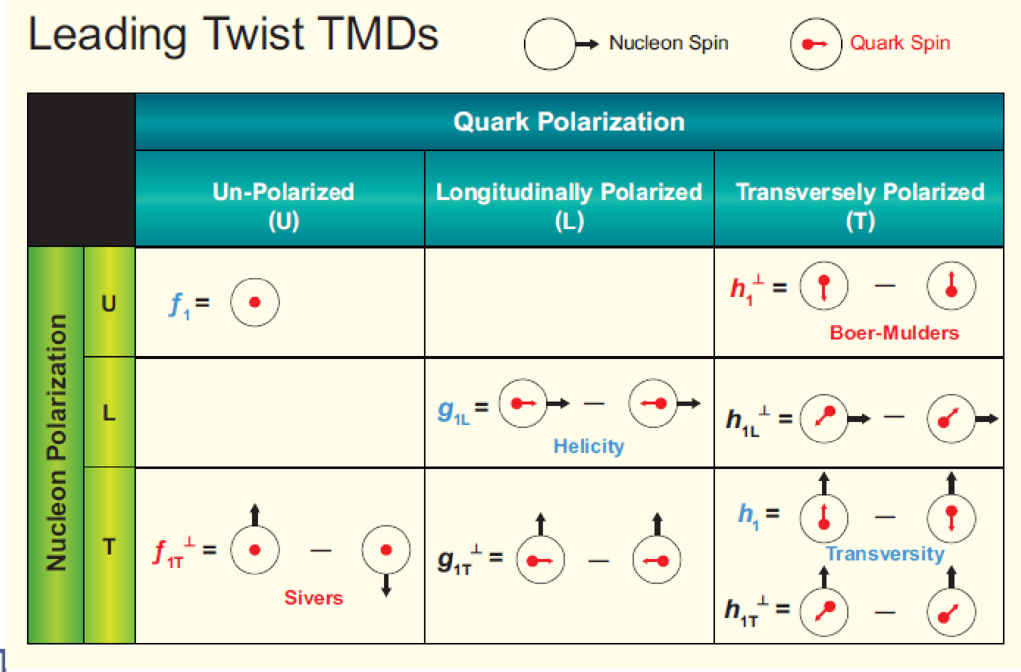




- Include more data (asymmetry) from JLAB and other experiments
- Higher twist
- Systematics study by generating pseudo data from various models &formulism and study the differences between fitted and truth values

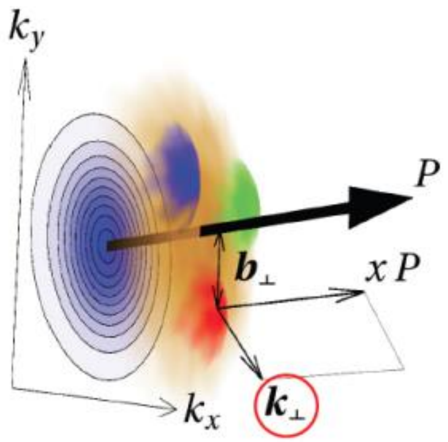
TMD distribution functions



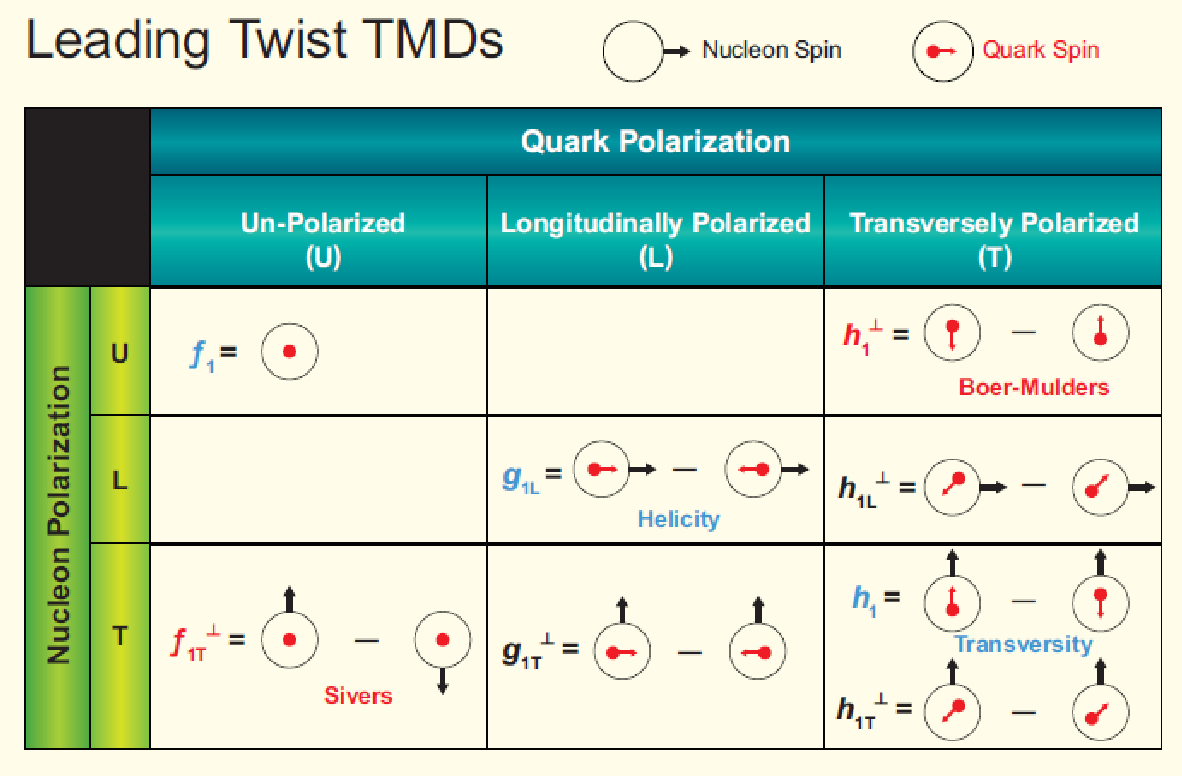


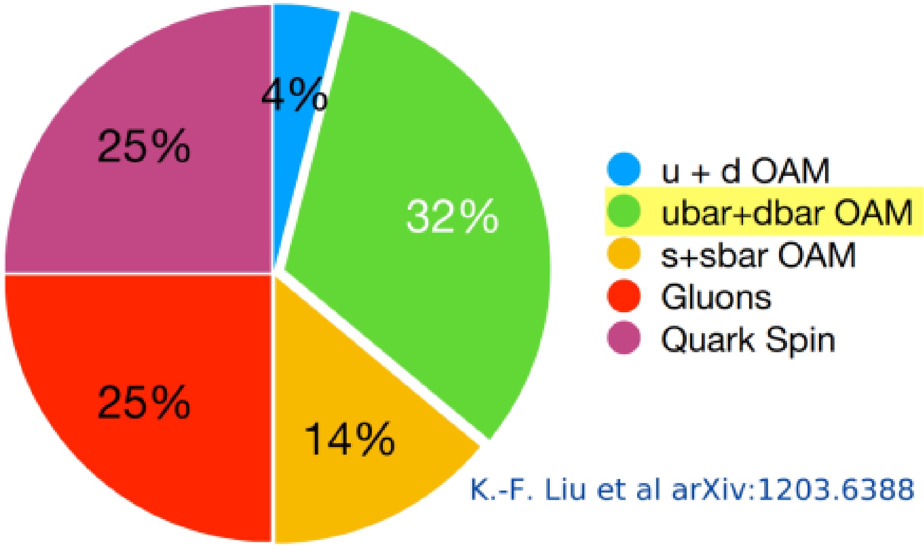
Correlation between spin and transverse momentum

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





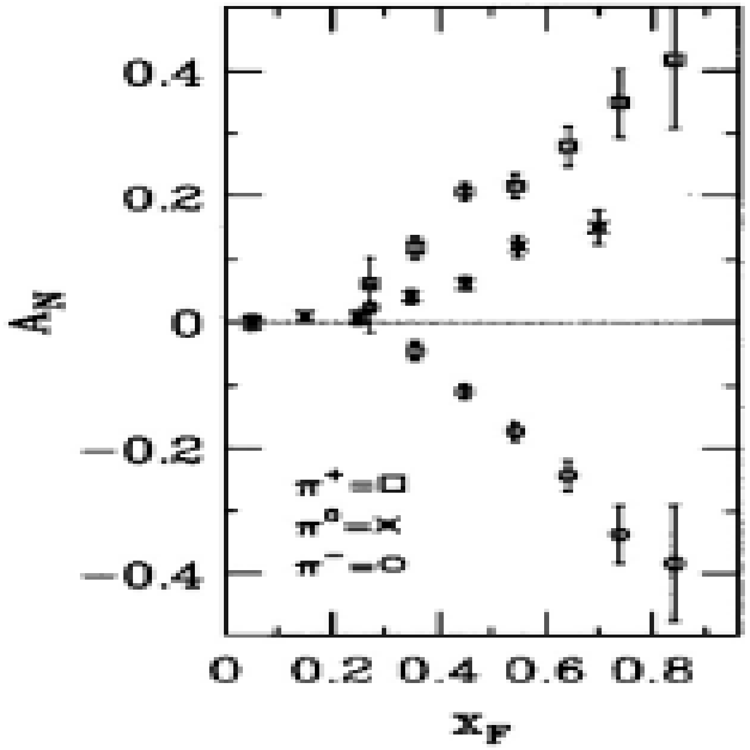
Proton spin contributions from Lattice QCD

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

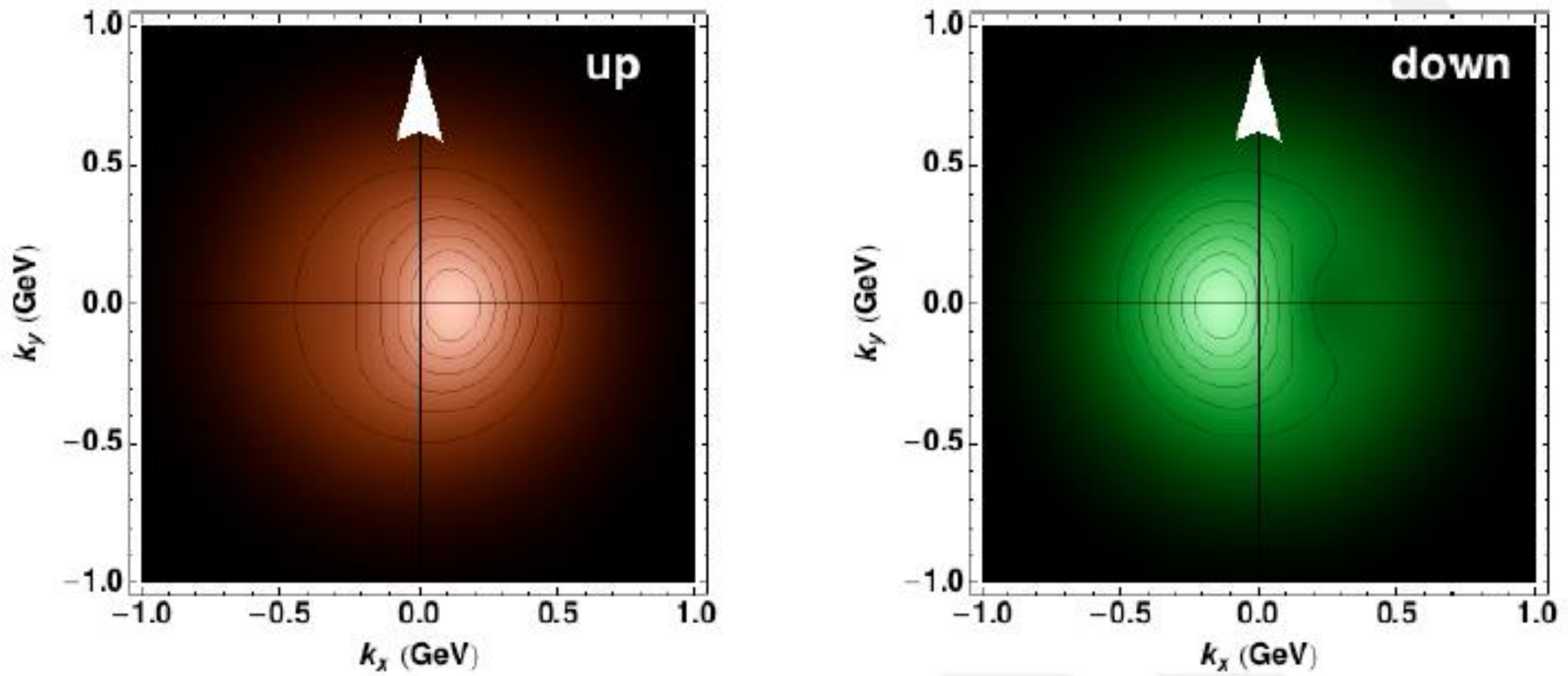
Sivers function initially was formulated to explain large left-right asymmetry in the pion production from pp scattering



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

Transverse Momentum Distribution (TMD) & Sivers Function

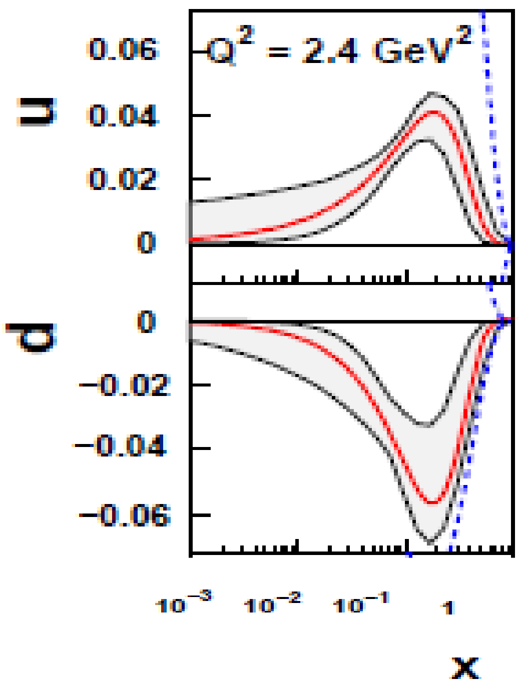
Supposed the proton is moving toward us and its spin is pointing upward. it turns out that we see up quarks moving preferentially to the right and down quarks to the left



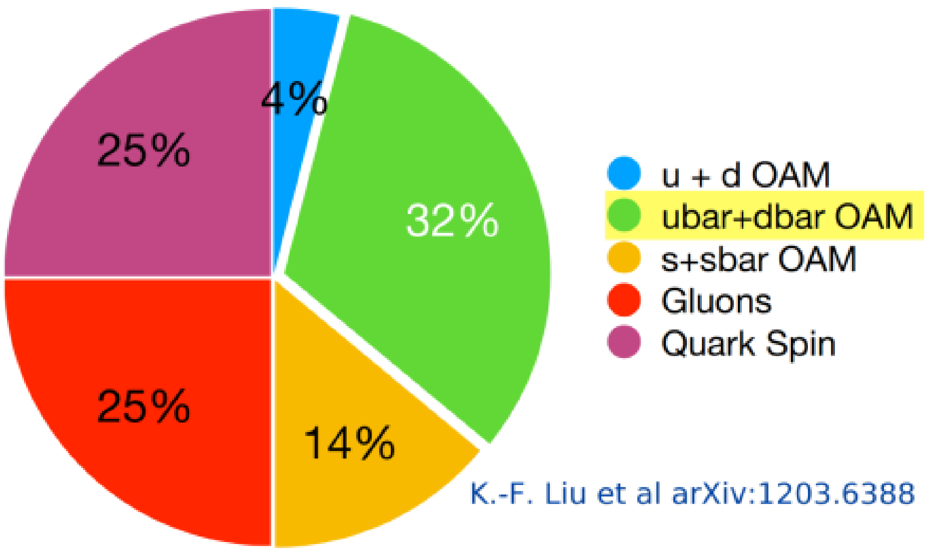
The up and down quark density distortion in transverse-momentum space, obtained by studies of the Sivers function

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.



Proton spin contributions from Lattice QCD

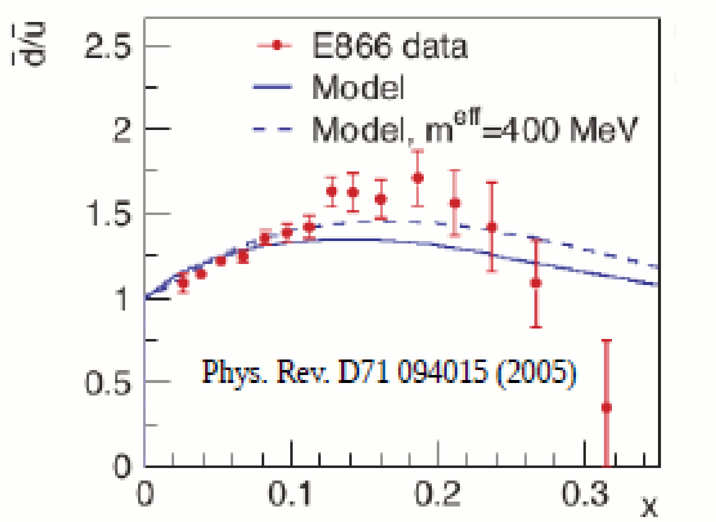
Jaffe-Manohar decomposition

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

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

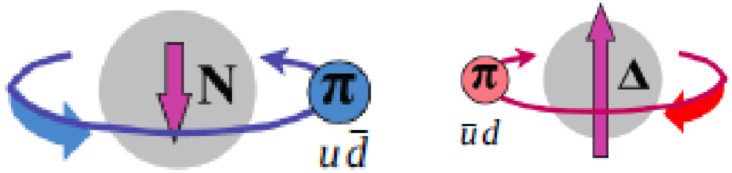
Why the Sea quarks are important?

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 $\bar{d}/\bar{u}$

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

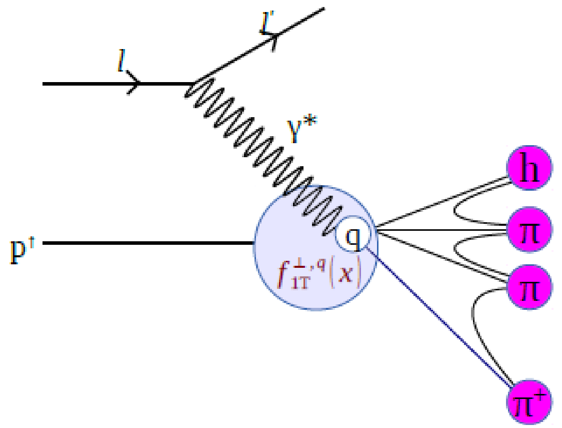


To conserve parity, pion in $N\pi$ system should have the orbital angular momentum. Therefore, the $\bar{d}$ excess in the nucleon should have nonzero OAM.

How to probe sea quark's sivers function

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

① Polarized Semi-Inclusive DIS

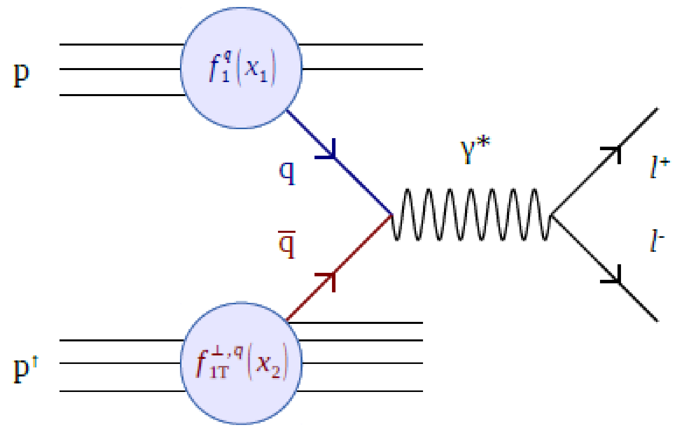


$$A_{UT}^{SIDIS} \propto \frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x) \otimes D_1^q(z)}{\sum_q e_q^2 f_1^q(x) \otimes D_1^q(z)}$$

- 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



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

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

E1039 EXPERIMENT

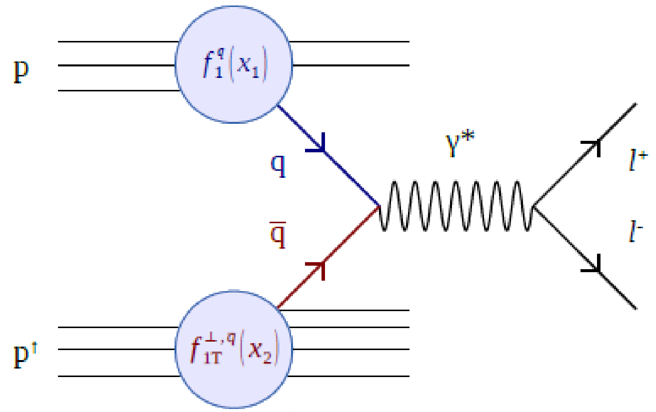
- has not been tried yet
  - only experiment sensitive to sea quarks at large x

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

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

② Polarized Drell-Yan



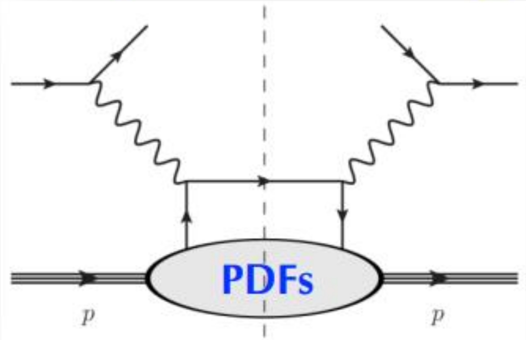
$$A_N^{DY} \propto \frac{\sum_q e_q^2 [f_1^q(x_1)\cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftrightarrow 2]}{\sum_q e_q^2 [f_1^q(x_1)\cdot f_1^{\bar{q}}(x_2) + 1 \leftrightarrow 2]}$$

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

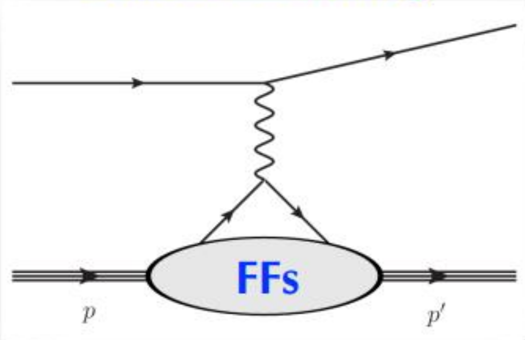
E1039 EXPERIMENT

Goal: understanding the partonic structure of the nucleon

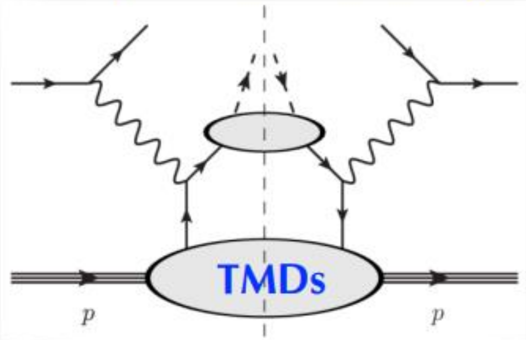
Deep Inelastic Scattering



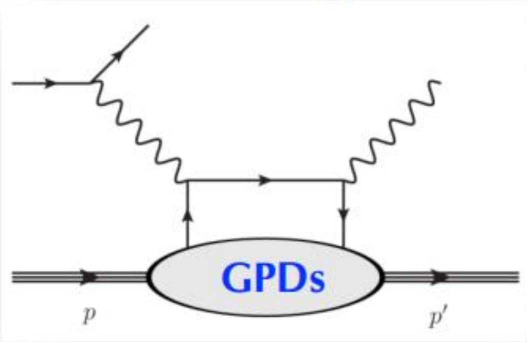
Elastic Scattering



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

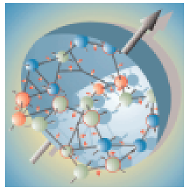
A brief summary:

- Rutherford scattering provide the existence of proton
- Stern measurement on the proton magnetic moment indicated that proton is not a point-like particle
- Elastic-scattering experiment probed the finite size of proton which quantified in Form-Factor observable
- Deep-Inelastic Scattering (DIS) provided evidence of the point-like nature of nucleon's constituents (partons)
- Polarized DIS experiment by EMC collaboration showed that quark spin provide small contribution to the total spin of nucleon
- The missing contribution likely from orbital-angular momentum of sea quarks as indicated by lattice calculation
- DIS experiment provide longitudinal momentum distribution of the partons (PDF)
- Additional information on the transverse position of partons is provided by GPD which can be accessed via Deeply Virtual Compton Scattering experiment (DVCS)
- GPD also provide information on the spin contribution and mechanical properties of the nucleon
- Additional information on the transverse momentum of partons is provided by TMD which can be accessed via Semi Inclusive Deep Inelastic Scattering experiment (SIDIS) and Drell-Yan experiment
- Sivers function, one of the TMDs provide orbital-angular momentum information of the partons
- The future SpinQuest (E1039) experiment at Fermilab will probe the orbital angular momentum of the SeaQuarks

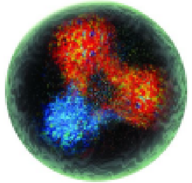
Polarized-Target Technology

- A necessary recipe to explore the internal structure of the nucleon-

Nucleon at different scales

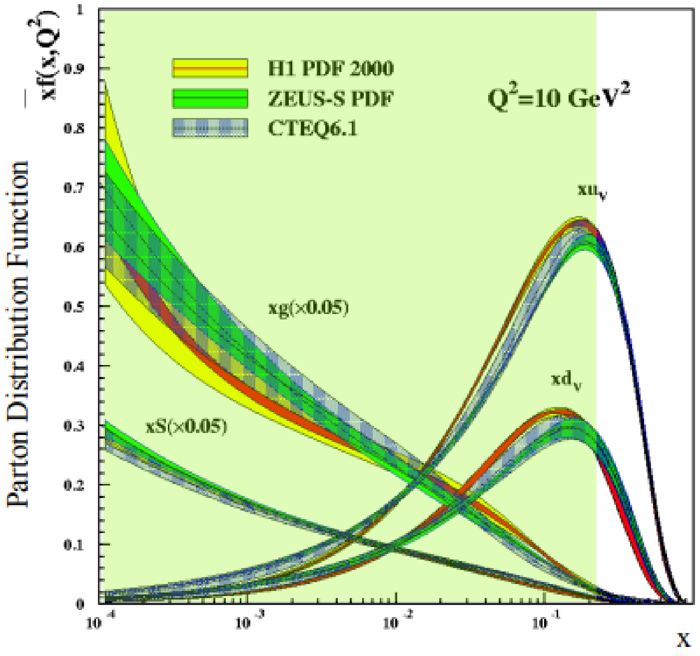


Valence quarks



Jefferson Lab: fixed-target electron scattering

$0.1 < x_B < 0.7$



Sea quarks

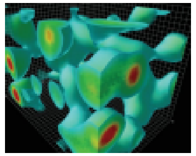
HERMES: fixed gas-target electron/positron scattering

$0.02 < x_B < 0.3$

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

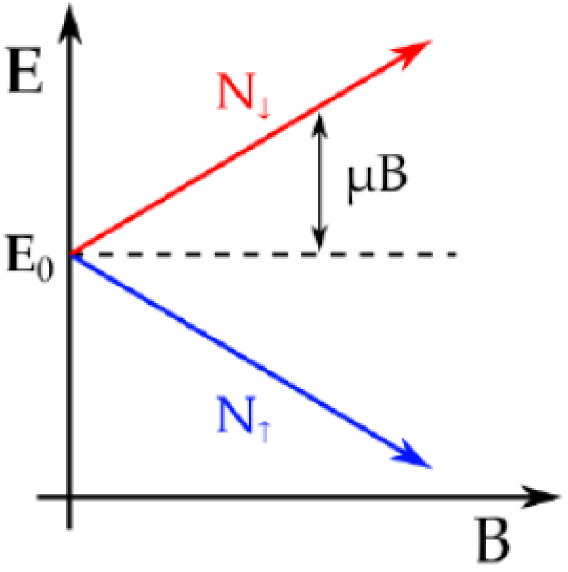
Luminosity 100 - 1000 times that of HERA

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

How do we obtain significant nucleon polarization?

Brute-Force Method:

- Use high-B at low-T via Zeeman-splitting mechanism



Courtesy of James Maxwell

- Degree of polarization at thermal equilibrium

$$P = tanh\left(\frac{\mu B}{kT}\right)$$

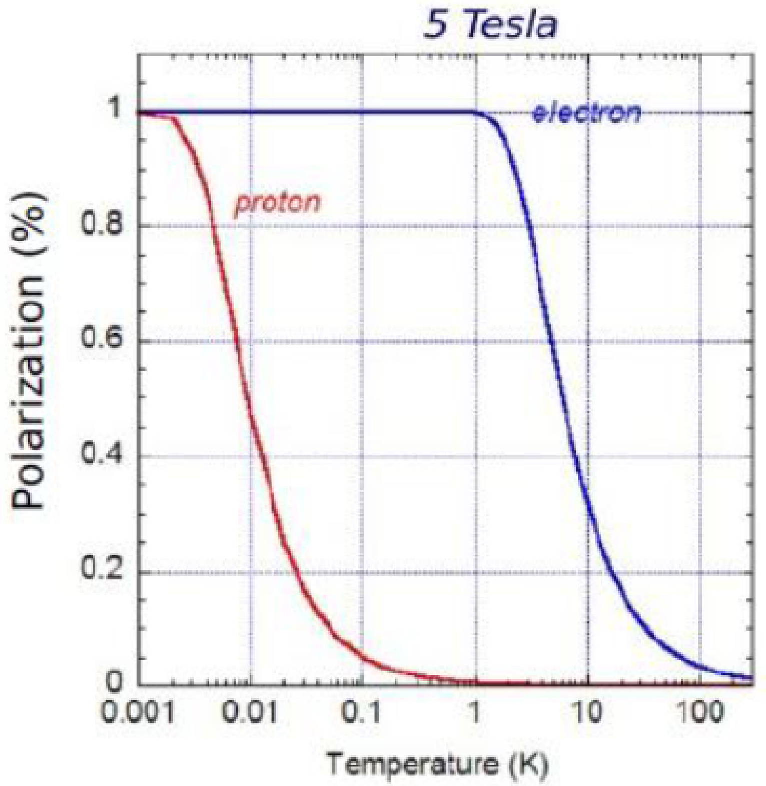
- Proton has small magnetic moment

$$\mu_e \approx 660\mu_p$$

- At B = 5 Tesla & T = 1 K

$$P_e = \sim 98\%, P_p = 0.51\%$$

- We need a better method!



How do we obtain significant nucleon polarization?

Dynamic-Nuclear Polarization (DNP):

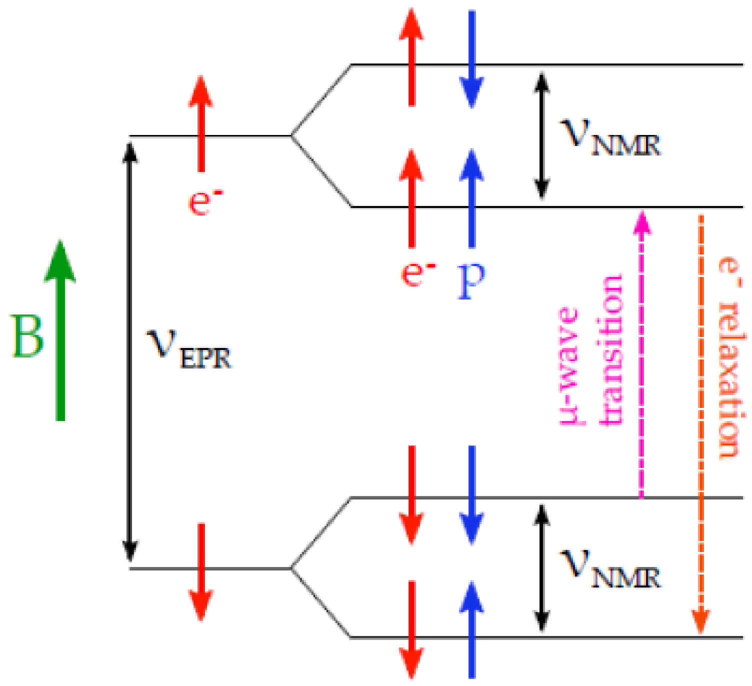
- The coupling between (unpaired) electron & proton introduces hyper-fine splitting H_{SS}

$$H = -\mu_e B - \mu_p B + H_{SS}$$

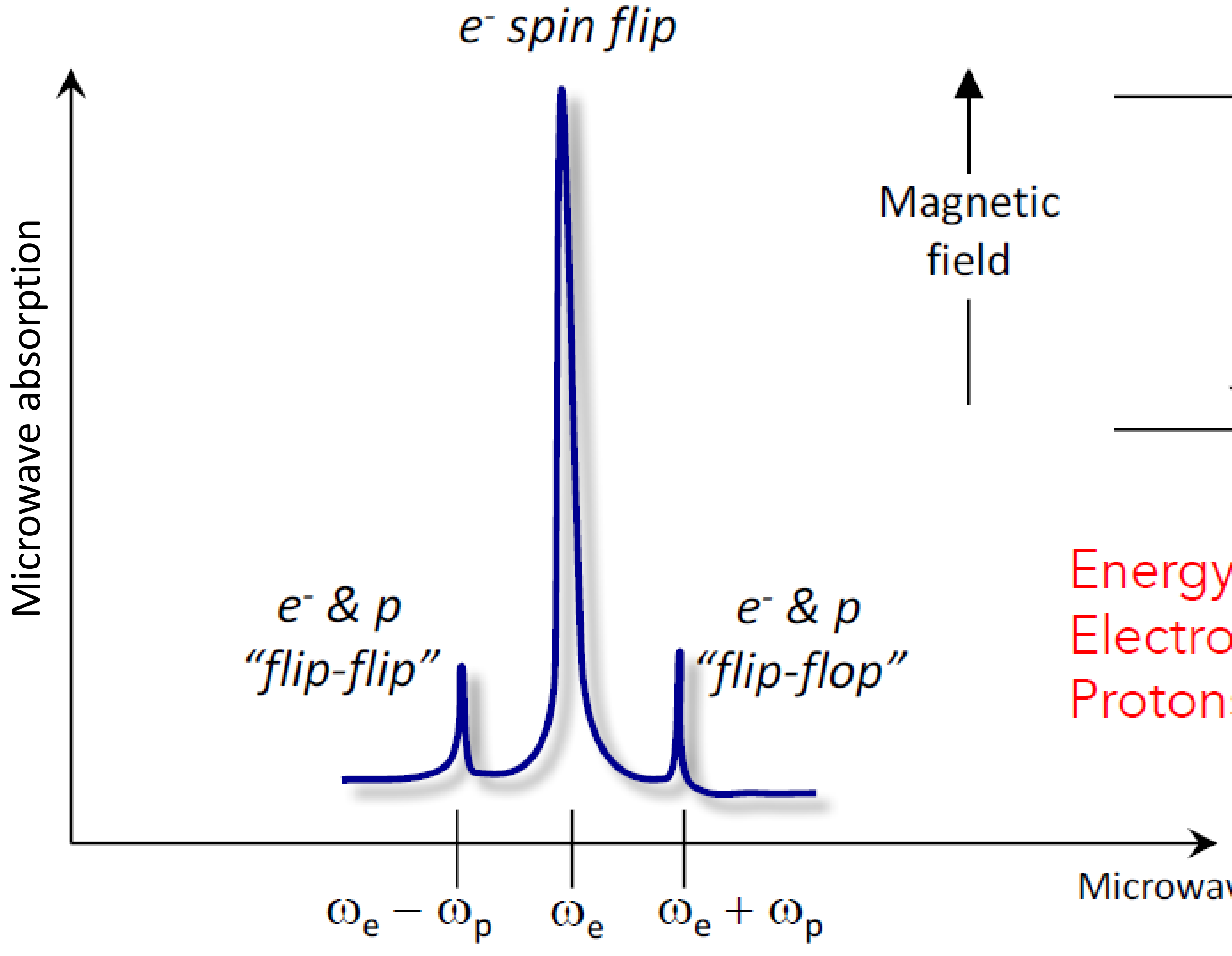
- Applying an RF-field at the correct frequency, we can drive the nucleons state into desired proton-state

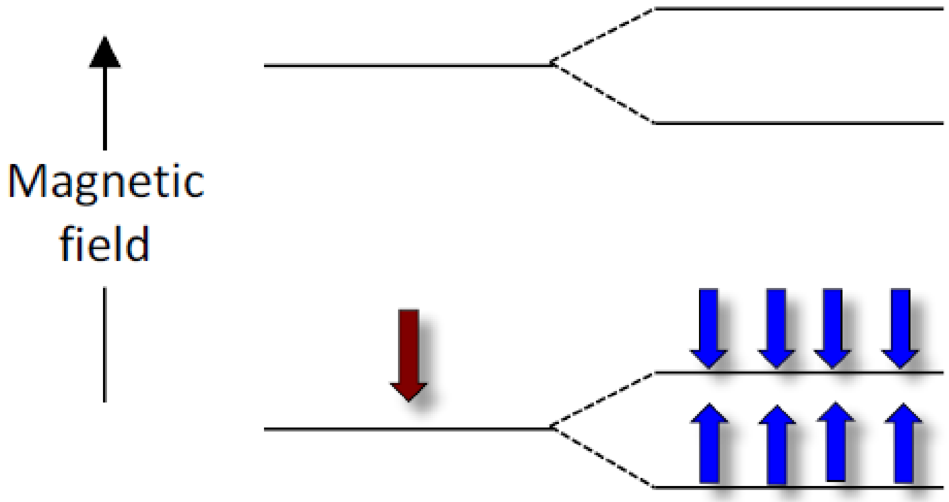
- The disparity in relaxation times between the electron (ms) and proton (tens of minutes) at 1K is crucial to continue proton polarization

- Allow to achieve proton polarization of > 90%
- During a cooldown at UVA, we achieve 95% of proton polarization



DNP (Pumping Mechanism) for Spin $^1/_2$

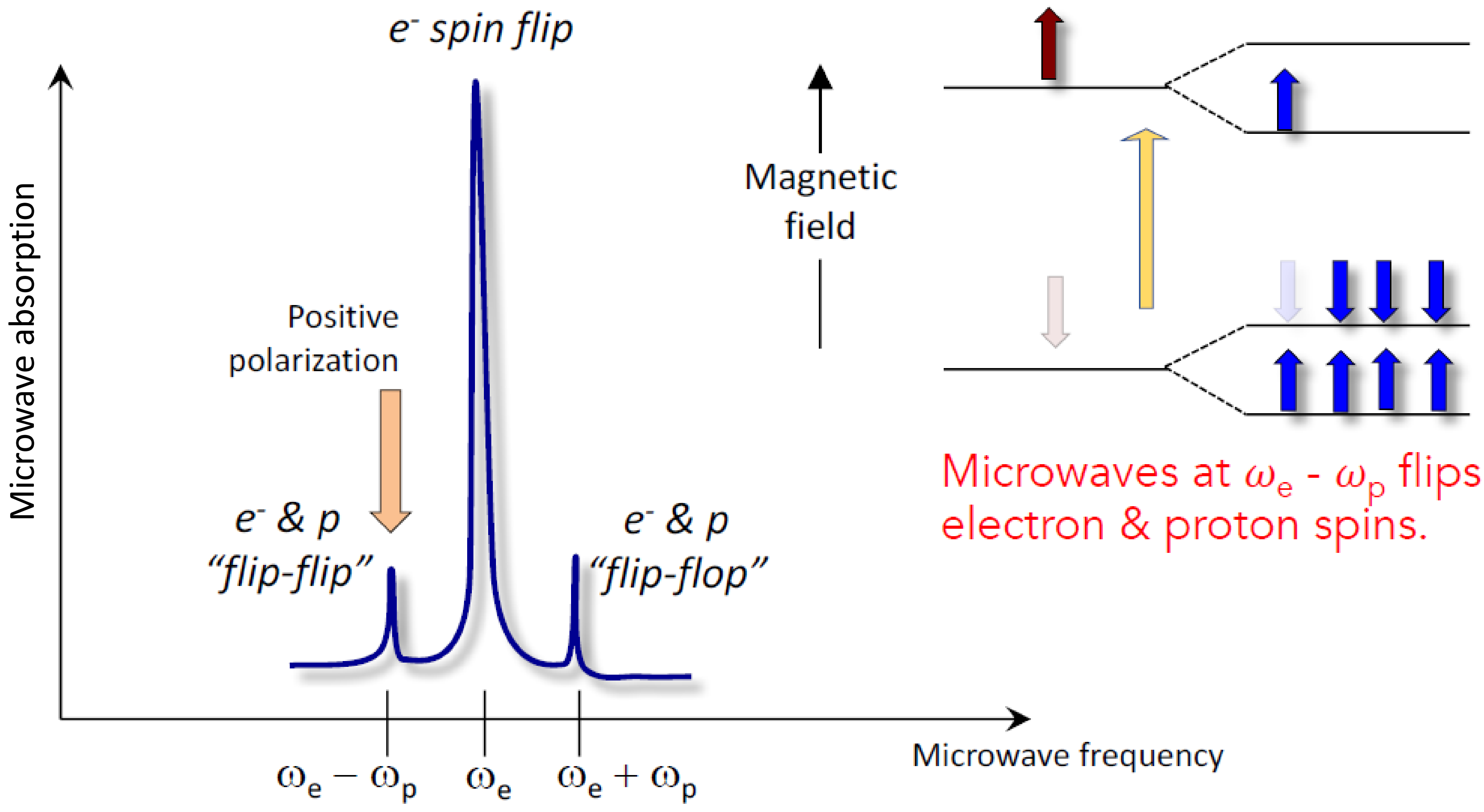




Energy levels of a electron+ protons.
Electron is polarized.
Protons are not.

Courtesy of Chris Keith

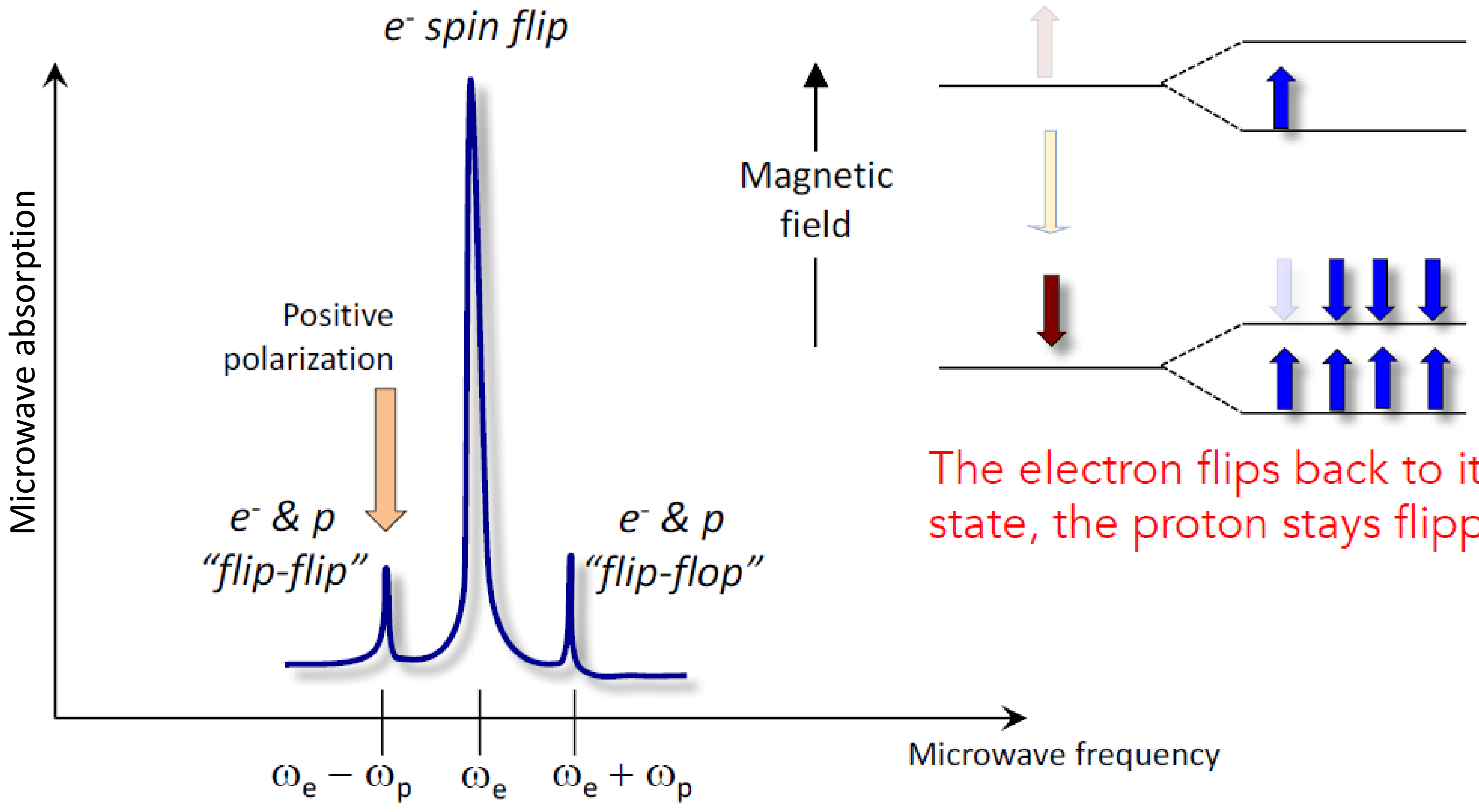
DNP (Pumping Mechanism) for Spin $^1/_2$



Microwaves at ω_e - ω_p flips both electron & proton spins.

Courtesy of Chris Keith

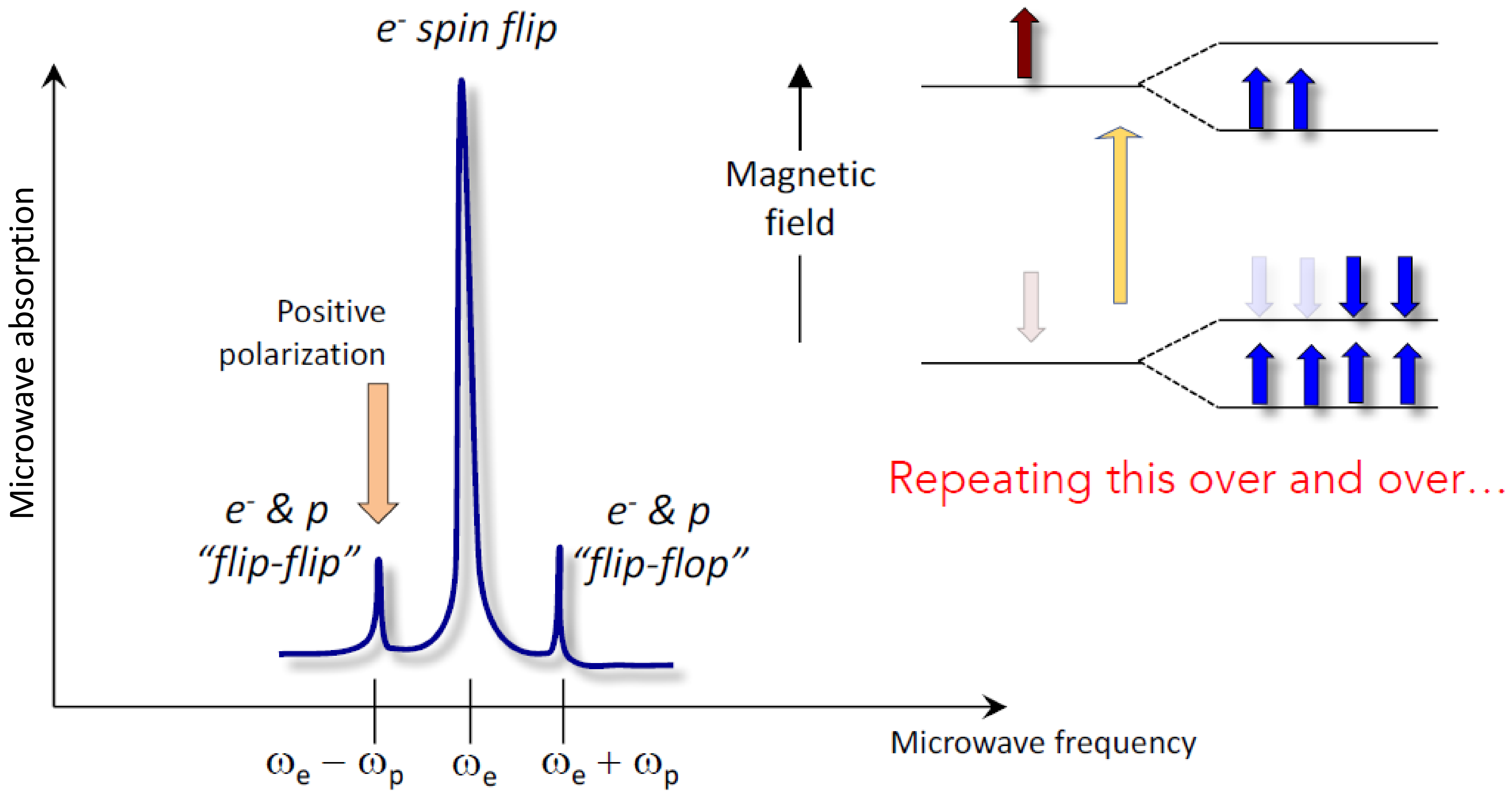
DNP (Pumping Mechanism) for Spin $^1/_2$



The electron flips back to its ground state, the proton stays flipped (long t_1).

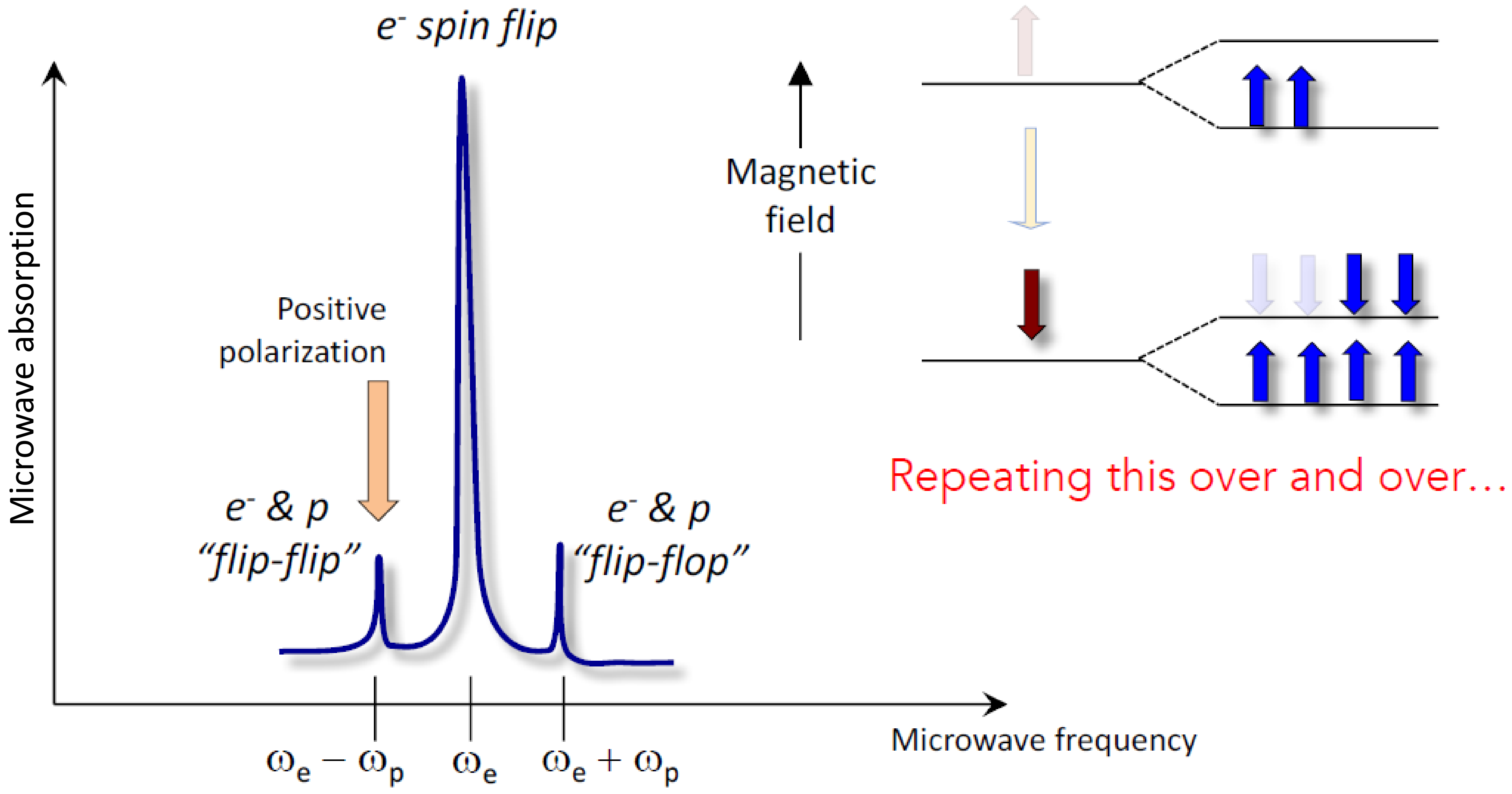
Courtesy of Chris Keith

DNP (Pumping Mechanism) for Spin $^{1}/_{2}$



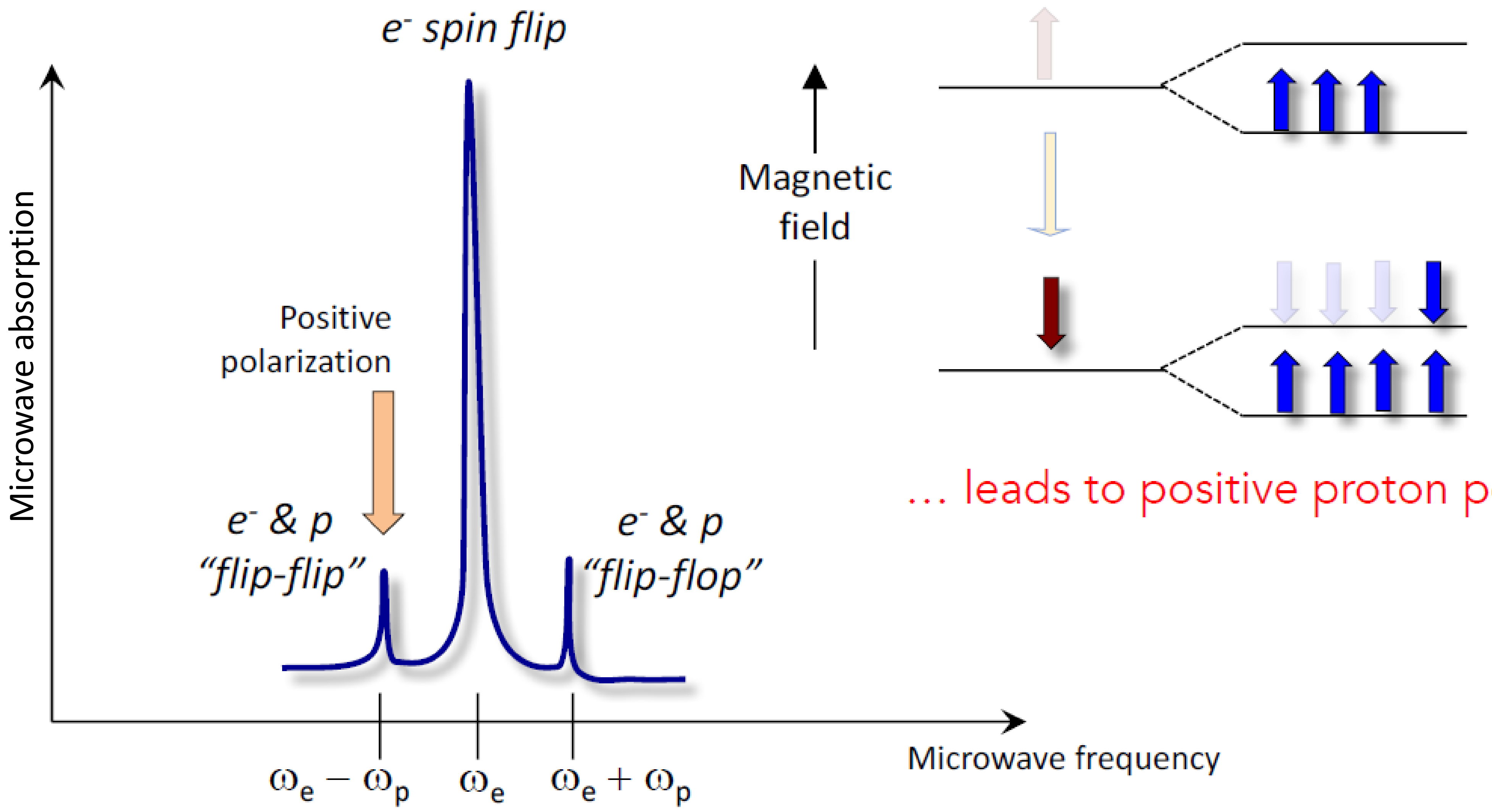
Courtesy of Chris Keith

DNP (Pumping Mechanism) for Spin $^1/_2$



Courtesy of Chris Keith

DNP (Pumping Mechanism) for Spin $^1/_2$



Courtesy of Chris Keith

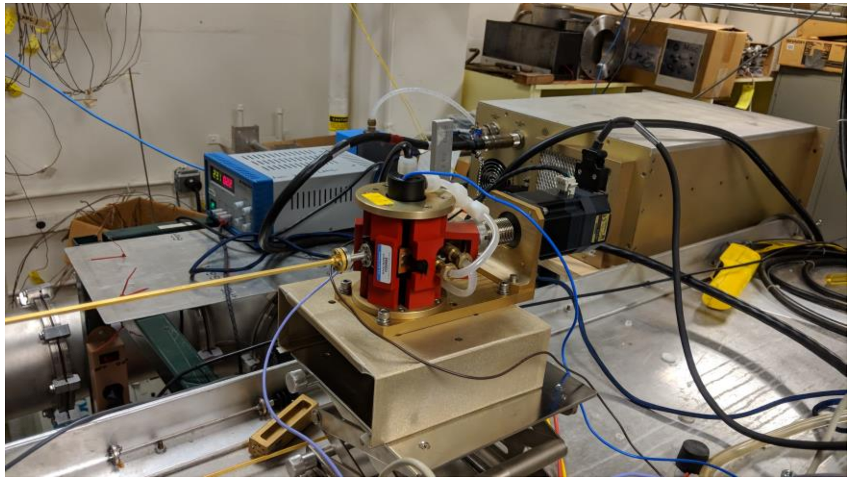
… leads to positive proton polarization.

Recipes for High-Nucleon Polarization:

- ❑Continuous microwaves generator
- ❑Target material with a suitable number of unpaired electrons, resistance to radiation and reasonable dilution factor
- ❑Superconducting magnet with homogenous fields in the target region
- ❑Cryogenics system with high cooling power
- ❑Reliable Nuclear-Magnetic Resonance (NMR) system for polarization measurement

Continues-Microwave Generator

- 140 GHz RF signal is generated by Extended-Interaction Oscillator (EIO) through interaction between electron beam (produced from ~kV of cathode/anode) and resonant cavities
- The optimal frequency changes as we flip the spin direction
- The optimal frequency also changes as the target accumulate radiation damage from the beam.
- Therefore, the frequency is adjusted by adjusting the cavity size using a stepper motor (~2% adjustment)

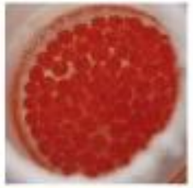
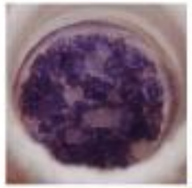


Target-Materials

Target material for DNP characterized by
- Maximum achievable polarization
- Dilution factor
- Resistance to radiation damage

SpinQuest experiment will use 8 cm of solid NH_3/ND_3 as target materials which are doped with paramagnetic free-radical by being irradiated at NIST (National Institute of Standard and Technology)

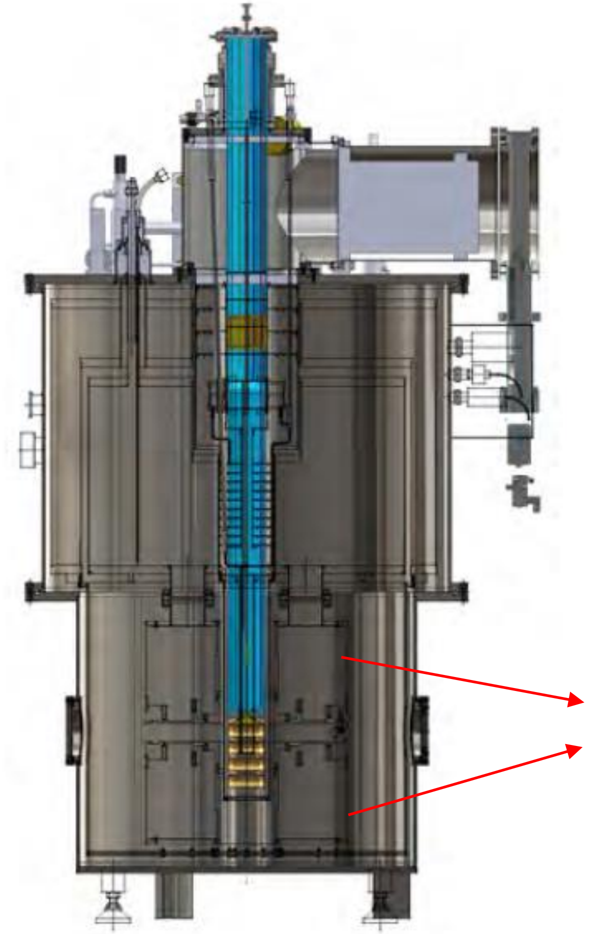
The polarization decays over time due to the radiation damage and restored temporarily by annealing process (target is heated at 70-100 K).


Material	Butanol	Ammonia, NH_3	Lithium Hydride, ^7LiH
Dopant	Chemical	Irradiation	Irradiation
Dil. Factor (%)	13.5	17.6	25.0
Polarization (%)	90-95	90-95	90
Material	D-Butanol	D-Ammonia, ND_3	Lithium Deuteride, ^6LiH
Dil. Factor (%)	23.8	30.0	50.0
Polarization (%)	40	50	55
Rad. Resistance	moderate	high	very high
Comments	*Easy to produce and handle*	*Works well at 5T/1K*	*Slow polarization, but long T_1*

Superconducting Magnet

- The superconducting magnet coils provide 5 T of transverse field in the target area with the homogeneity level of 10^{-4} over the target region
- The magnet consist of NbTi coils which are impregnated in epoxy to prevent them from moving during when the magnet is energized
- The coils are held in place by 316 stainless steel



Superconducting Magnet

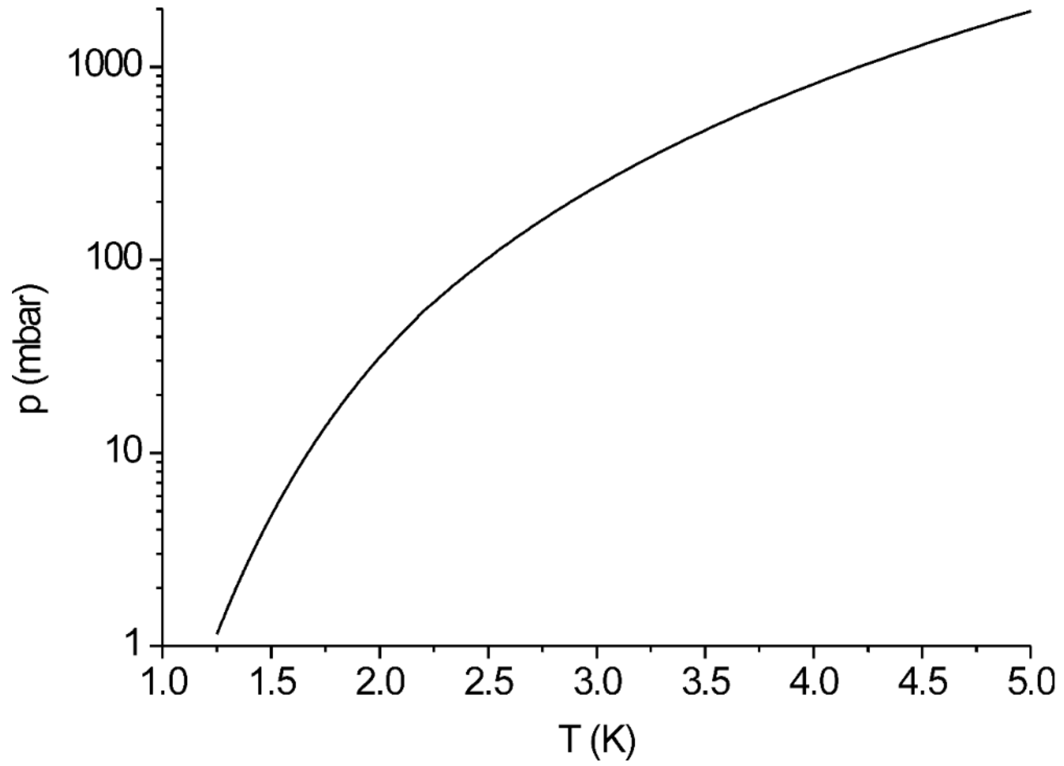
Cryogenic System

Evaporated He from the target nose need to be pumped out by high powered pump to keep the temperature at 1 K at 0.12 Torr

Critical components for high-cooling power refrigerator:

- High-power pump
- Sufficient supply of the liquid Helium
- Heat exchanger that bring the He temperature down from 4.2 K to 1 K
- Thermal shielding

He-4 Pressure-Temperature diagram

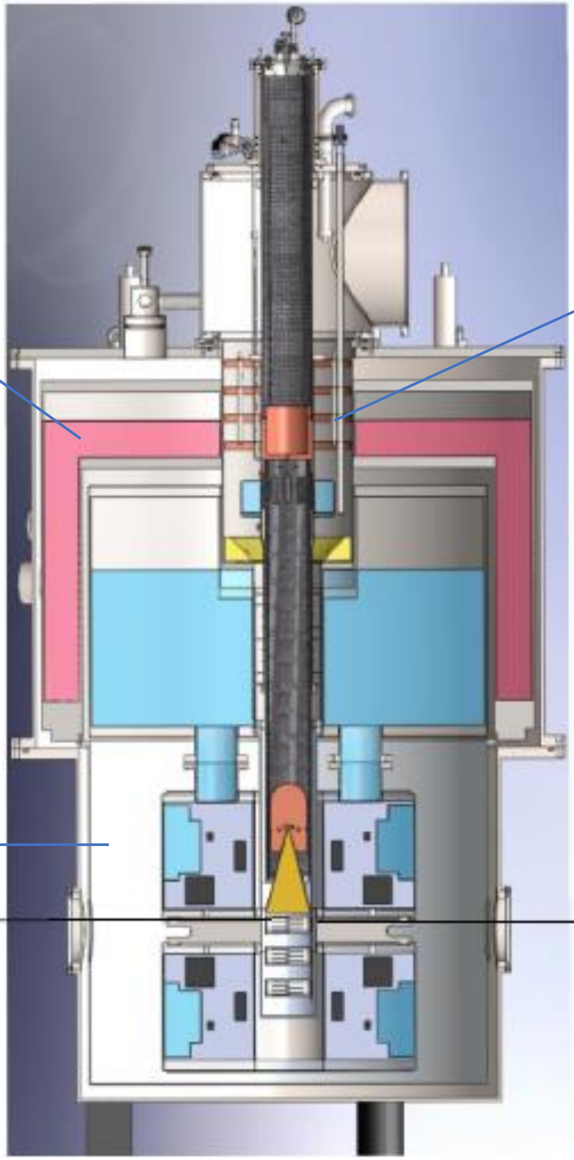


Thermal shielding:

- Liquid Nitrogen
- Outer Vacuum

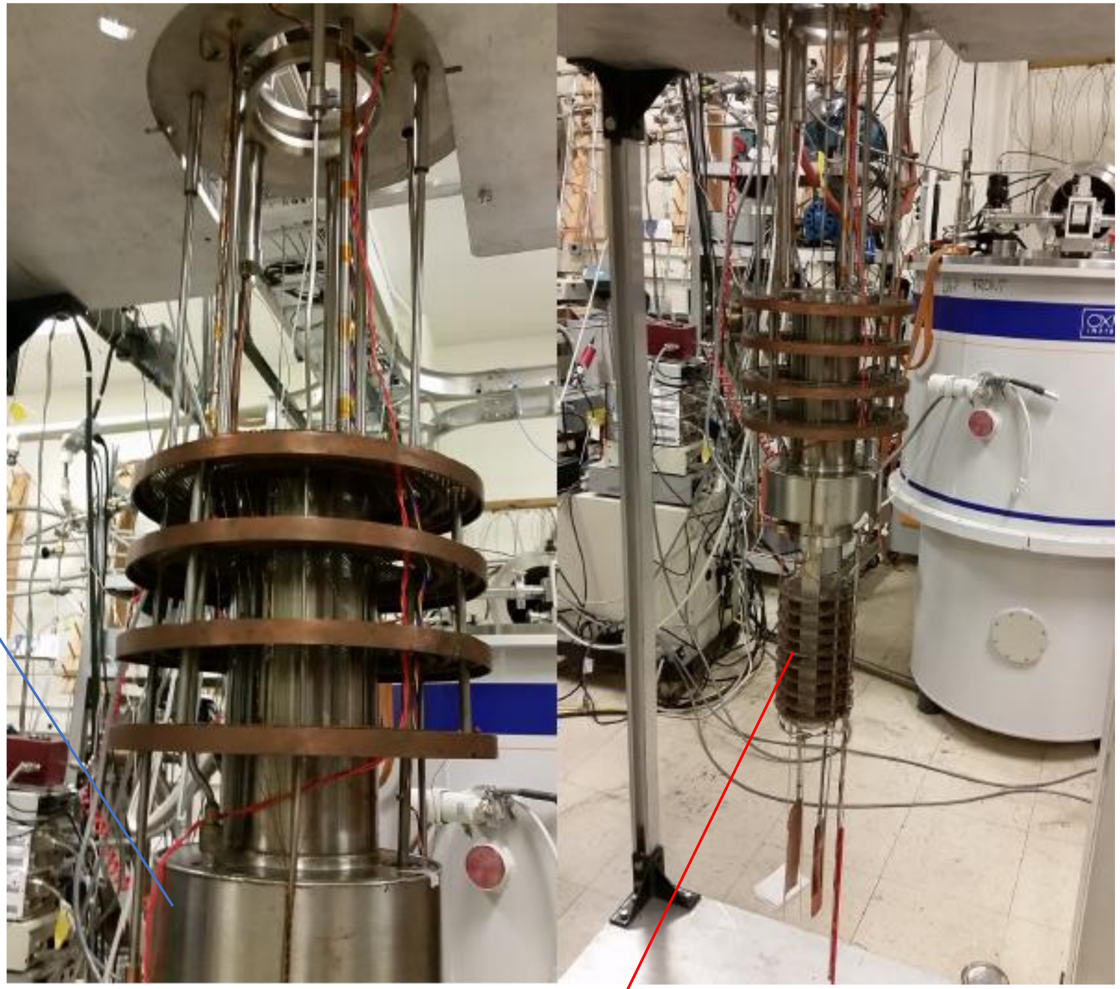
Turbo Molecular pump maintain the outer vacuum pressure at ~10^{-8} torr

Outer vacuum



Separator

Beam



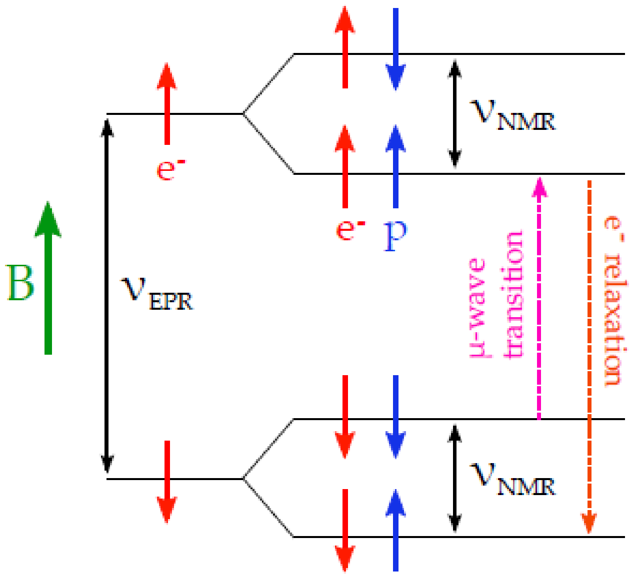
Heat exchanger

Nuclear-Magnetic Resonances (NMR)

Polarization of the proton is measured using NMR technique

An RF field at the Larmor frequency of the proton (213 MHz at 5 T) can cause a flip of the spin

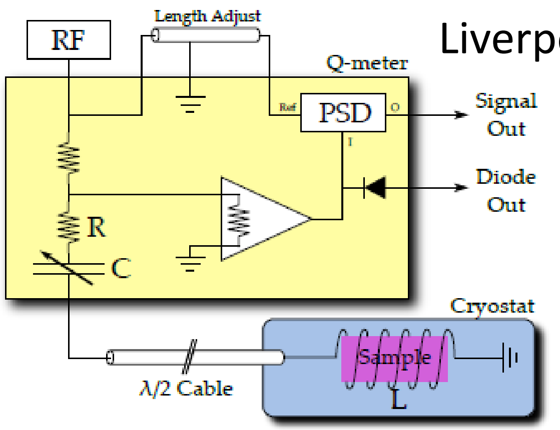
The RF field is produced by 3 NMR coils inside the target cup



An RLC Circuit is tuned to the Larmor frequency of the target materials

The power generated or absorbed due to spin flip change the circuit impedance that can be observed

Liverpool Q-Meter



Courtesy of James Maxwell

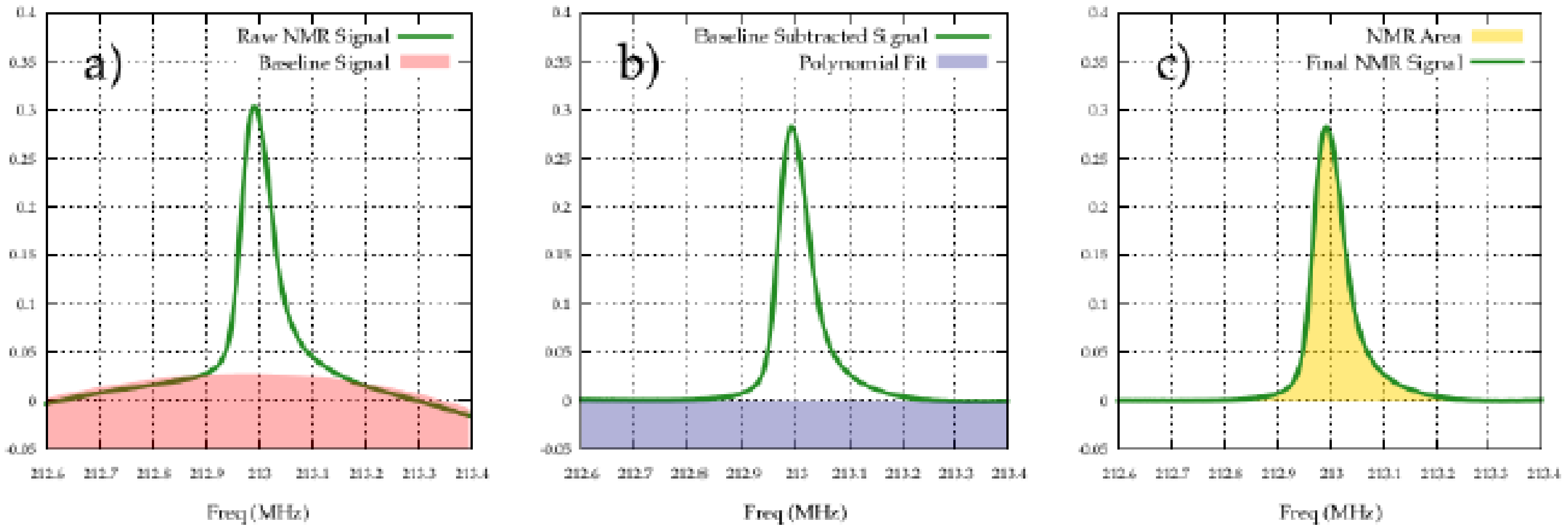
Nuclear-Magnetic Resonances (NMR)

Q-Curve is produced by sweeping the RF around the Larmor frequency

The signal area after background subtraction is proportional to the polarization

The proportional constant is obtained at Thermal-Equilibrium measurement

$$P = tanh\left(\frac{\mu B}{kT}\right)$$



Summary

- Rutherford scattering provide the existence of proton
- Stern measurement on the proton magnetic moment indicated that proton is not a point-like particle
- Elastic-scattering experiment probed the finite size of proton which quantified in Form-Factor observable
- Deep-Inelastic Scattering (DIS) provided evidence of the point-like nature of nucleon's constituents (partons)
- Polarized DIS experiment by EMC collaboration showed that quark spin provide small contribution to the total spin of nucleon
- The missing contribution likely from orbital-angular momentum of sea quarks as indicated by lattice calculation
- DIS experiment provide longitudinal momentum distribution of the partons (PDF)
- Additional information on the transverse position of partons is provided by GPD which can be accessed via Deeply Virtual Compton Scattering experiment (DVCS)
- GPD also provide information on the spin contribution and mechanical properties of the nucleon
- Additional information on the transverse momentum of partons is provided by TMD which can be accessed via Semi Inclusive Deep Inelastic Scattering experiment (SIDIS) and Drell-Yan experiment
- Sivers function, one of the TMDs provide orbital-angular momentum information of the partons
- The future SpinQuest (E1039) experiment at Fermilab will probe the orbital angular momentum of the SeaQuarks

- Artificial-Neural Network provides model independent and reliable tools for regression (fitting)
- To obtain high degree of nucleon polarization via Dynamic-Nuclear Polarization (DNP) we need continuous microwave generator, target material with unpaired electron (free radical), cryogenic system, superconducting magnet and Nuclear-Magnetic Resonances

THANK YOU