Dai partoni agli adroni: una sfida per la QCD

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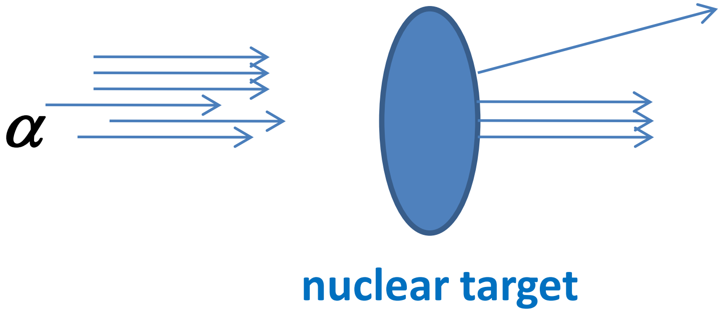
Some history

- **End of XIX century**

  - discovery of the electron
- **Beginning of the last century**

  - atoms have a very small and massive nucleus

  - discovery of the proton



- **’30s of last century**

  - discovery of the neutron

  - the nucleus is made by proton and neutron glued by some kind of strong interaction

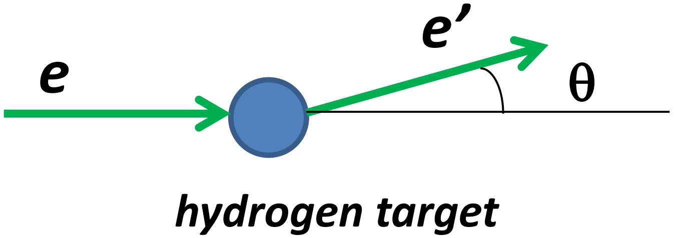
Number of interactions per second

$$N_R = \Phi_I N_B \sigma_R$$

typical of the process

Electron-proton elastic scattering - 1

$$ep \rightarrow ep$$



Rutherfors cross section

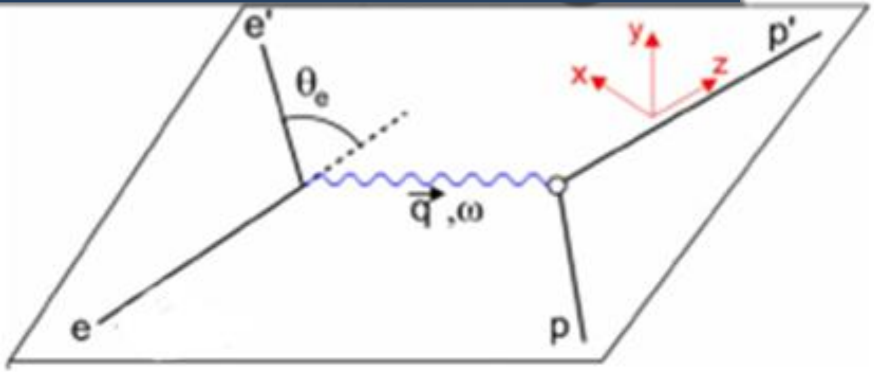
- **non-relativistic approximation**
- **infinite target mass**
- **point-like nucleon target**
- **no spin**

$$\left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} = \frac{Z^2\alpha^2}{4}\left(\frac{\hbar c}{KE}\right)^2 \frac{1}{(1-\cos\vartheta)^2}$$

Rapidly falling down as the scattering angle increases
Experimental data are order of magnitude below the Rutherford formula

Electron-proton elastic scattering - 2

- relativistic electron
- proton recoil momentum
- proton spin



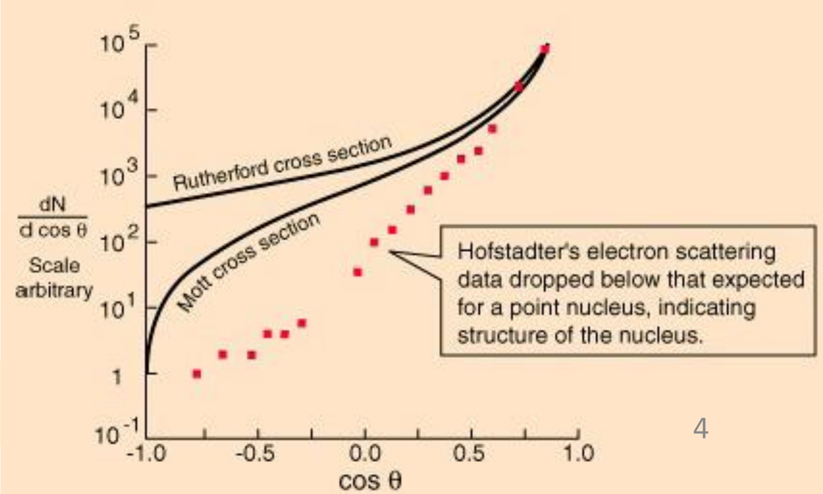
spin-spin magnetic interaction

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott}=\left(\frac{d\sigma}{d\Omega}\right)_{Rutherford}\frac{(1+\cos\vartheta)/2}{1+\frac{(1-\cos\vartheta)KE}{M}}\left(1+\frac{Q^2}{2M^2}\sin^2\frac{\vartheta}{2}\right)$$

e.m current of a point-like proton

$$J^{\mu}=e\bar{u}(p')\left[\gamma^{\mu}+\frac{i}{2M}\sigma^{\mu\nu}q_{\nu}\right]u(p)$$

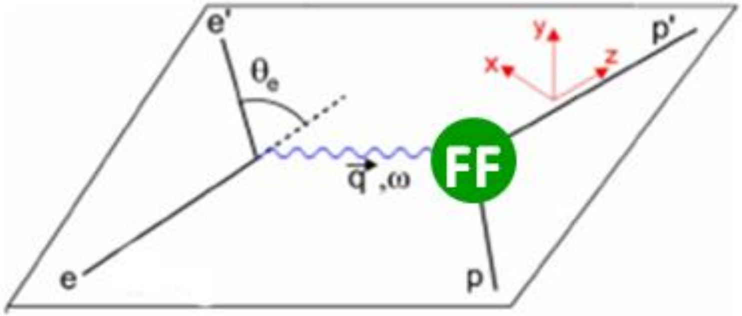
Experimental data still below the Mott formula



Hofstadter's electron scattering data dropped below that expected for a point nucleus, indicating structure of the nucleus.

Proton internal structure

Deviations from the Mott formula showed that the proton is not point-like



Form Factors

$$J^{\mu}=e\bar{u}(p')\left[F_1(q^2)\gamma^{\mu}+F_2(q^2)\frac{i}{2M}\sigma^{\mu\nu}q_{\nu}\right]u(p)$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{Rosembluth}=\frac{\sigma_{Mott}}{\varepsilon(1+\tau)}\left[\tau G_M^2(Q^2)+\varepsilon G_E^2(Q^2)\right]$$

$$G_E=F_1+\tau F_2$$

$$G_M=F_1+F_2$$

G_E ⇒ charge distribution

G_M ⇒ magnetic (current) distribution

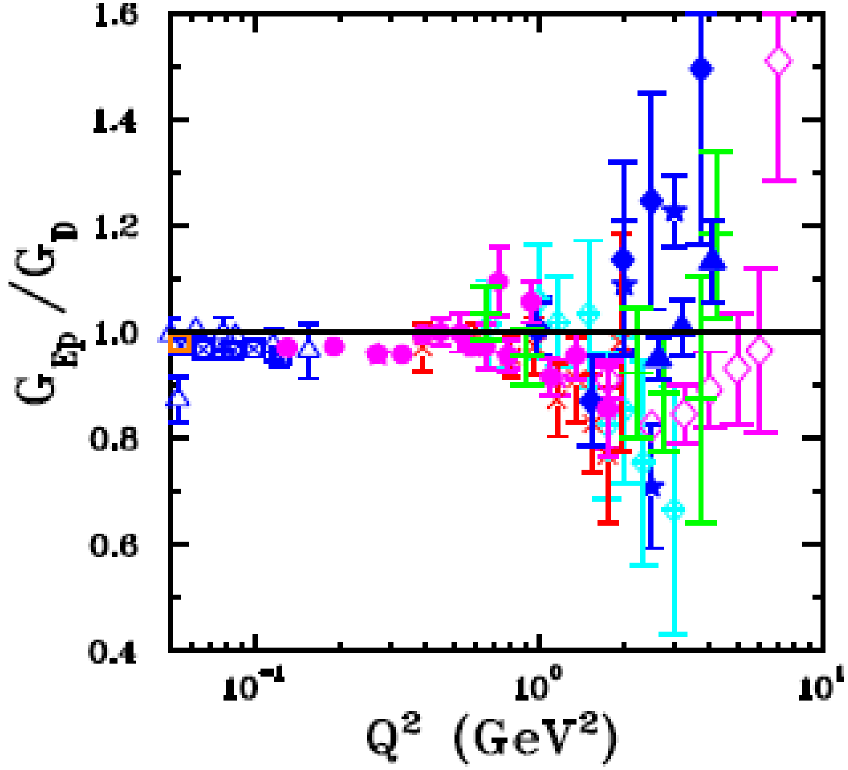
$$G_E(Q^2=0)=1$$

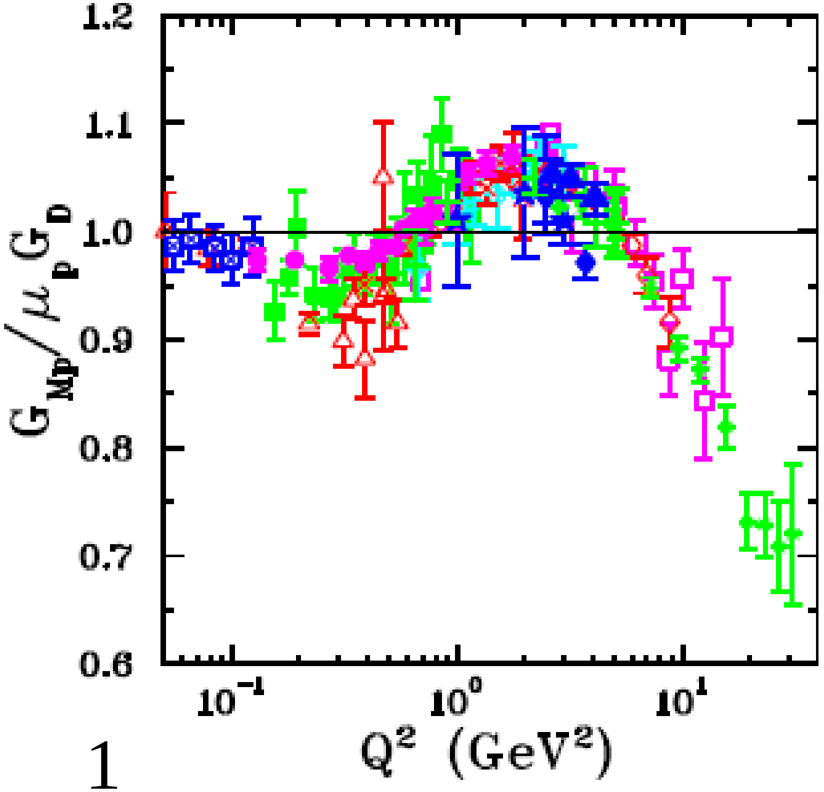
$$G_M(Q^2=0)=\mu_p$$

Elastic cross section dominated by G_M

- **bigger than G_E**
- **$\tau >> \varepsilon$**

Rosembluth Form Factors





dipole Form Factor

$$G_D = \frac{1}{\left(1 - Q^2 / 0.71\right)^2}$$

The proton in the physics textbooks up to 2000:

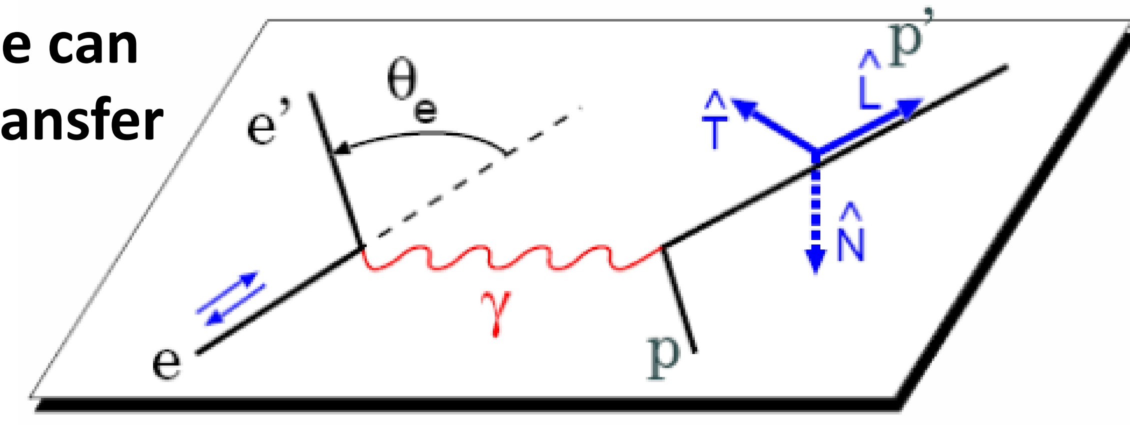
- **G_E is basically a dipole**
- **G_M close to the dipole approximation with small corrections**

The proton is a dipole with the same charge and current distribution

Polarization measurements

With polarized electrons, one can measures the polarization transfer to the proton

$$\vec{e}p \rightarrow e'\,\vec{p}\,'$$



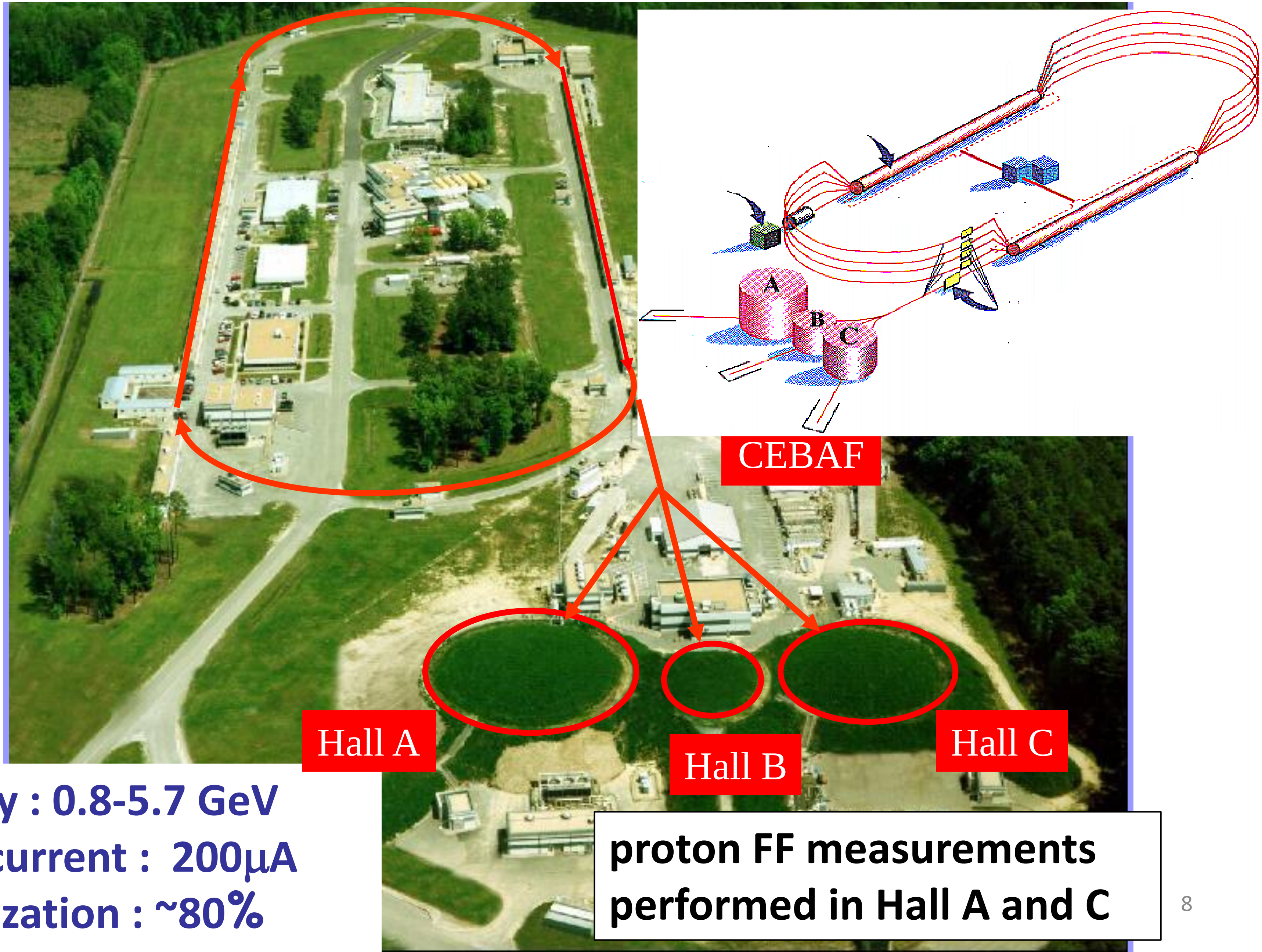
Polarization measurements proposed back in the '70 but possible only in recent years

$$\frac{P_T}{P_L} = -\frac{G_E(Q^2)}{G_M(Q^2)}\frac{E_e + E_e'}{2M}\tan\frac{\vartheta_e}{2}$$

proportional to G_E

- **better sensitivity to the small electric FF**
- **independent from the beam polarization**
- **need high luminosity and high beam polarization**

Jefferson Lab at Newport News, USA

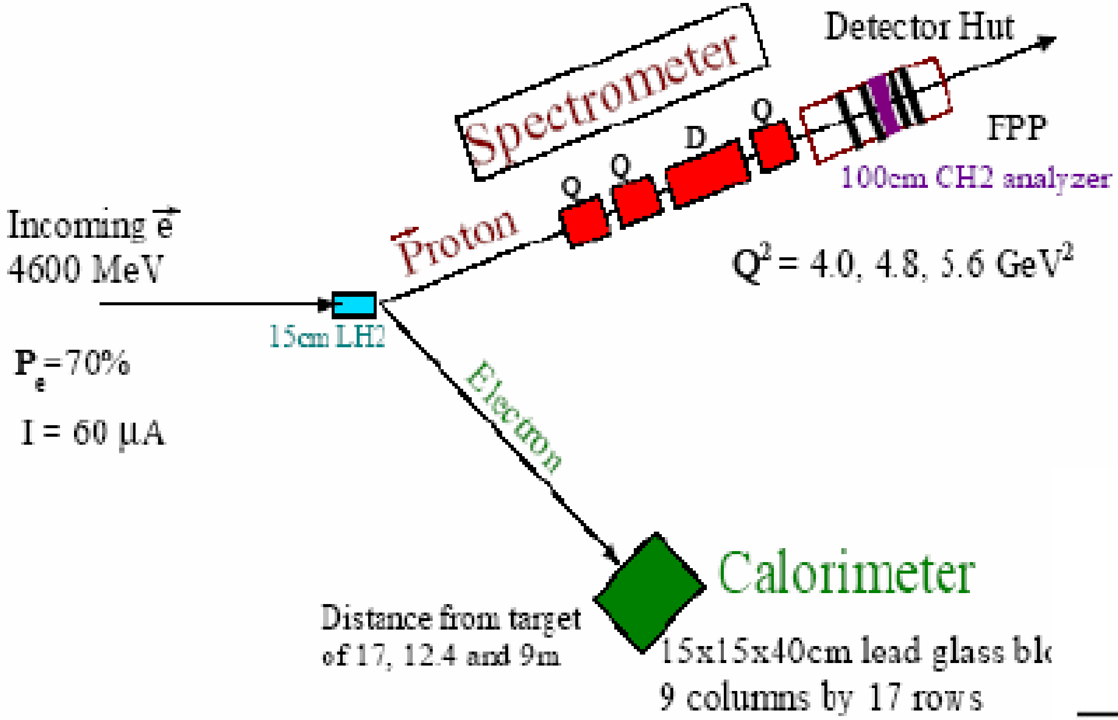


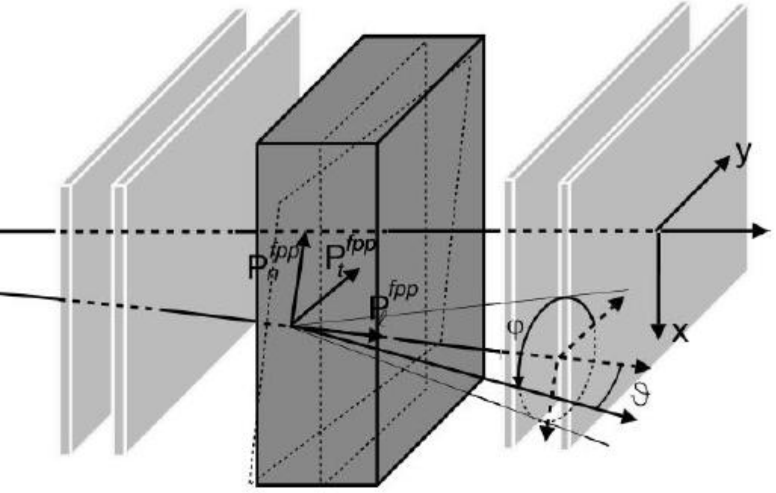
Energy : 0.8-5.7 GeV
Max current : 200µA
Polarization : ~80%

proton FF measurements performed in Hall A and C

Measuring the polarization transfer

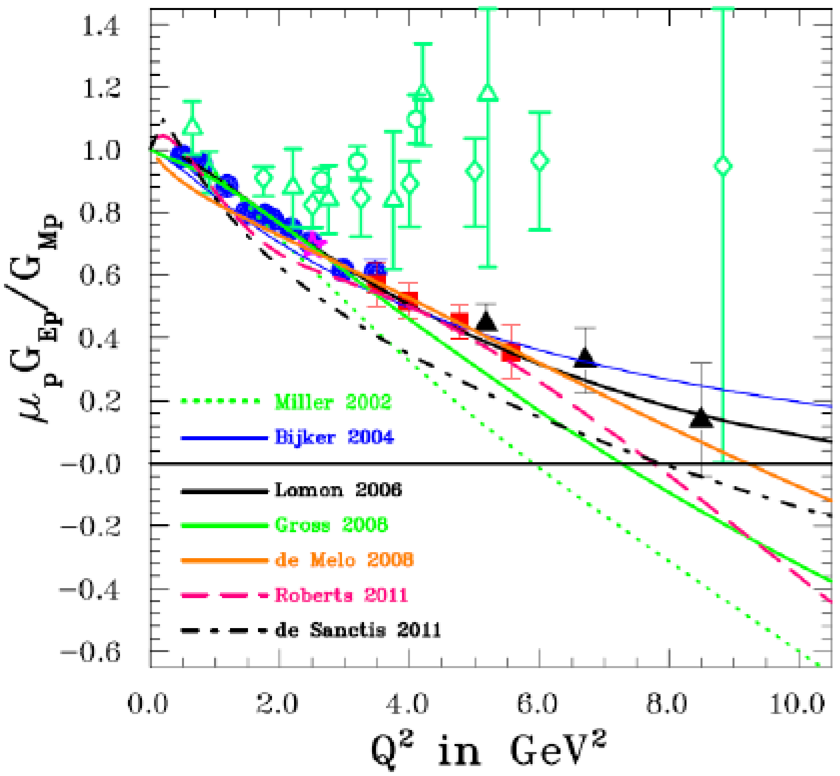
Hall A setup





Proton polarization is measured in secondary scattering through a carbon analyzer

FF measurements at JLab



Rosembluth data

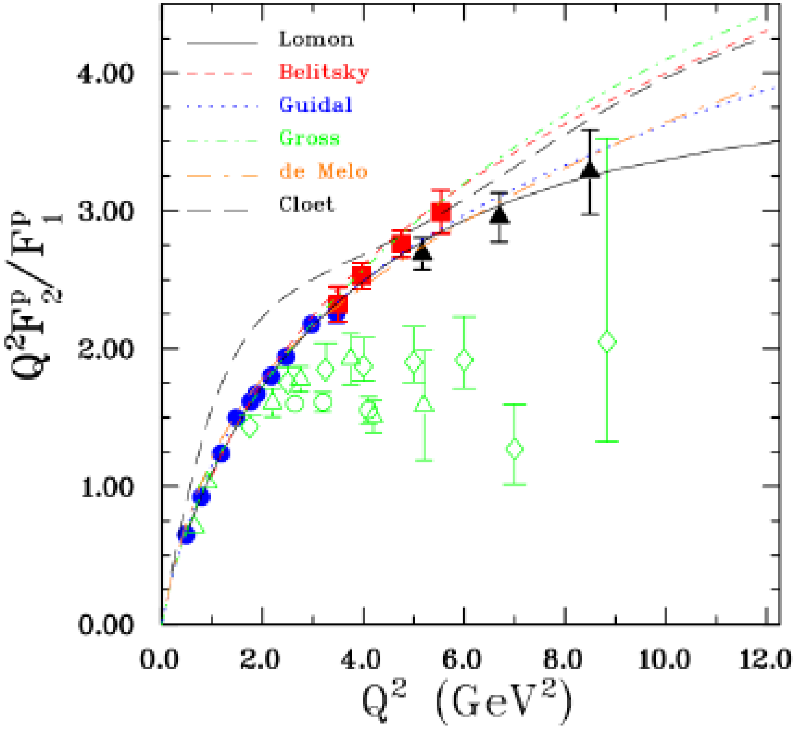
polarization data

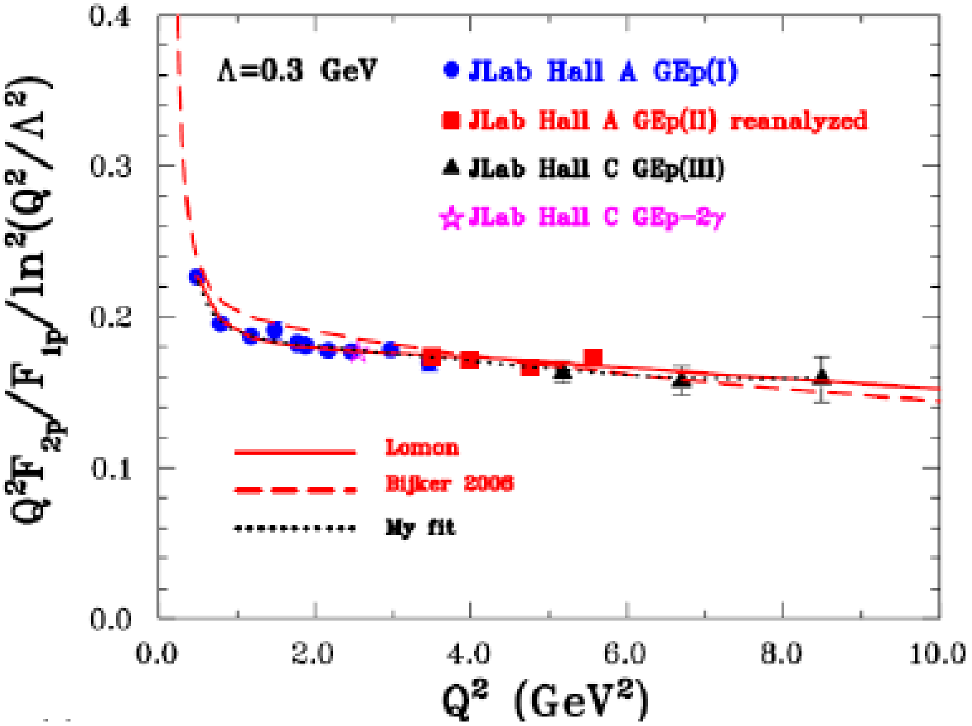
- Polarization data shows that G_M and G_E are different
- New Rosembluth measurements are still in agreement with $G_E \sim G_M$
- Rosembluth method is expected to be more sensitive to small corrections
- Various model are able to fit the data. Discrimination between them could be provided by measuring the zero crossing.

Scaling of the FF

- pQCD predicts the scaling law $F_2 / F_1 \sim 1/Q^2$ - not observed up to 10 GeV^2

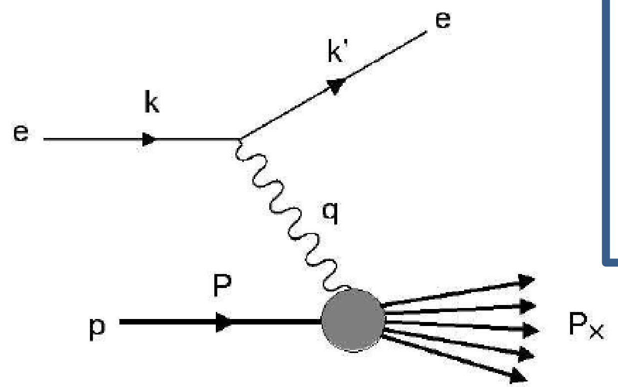
- modified pQCD to include angular quark angular momentum yields the scaling law $F_2 / F_1 \sim \ln(\Lambda/Q)^2/Q^2$ – starting from ~2 GeV^2 with Λ=0.3 GeV





Deep Inelastic Scattering

The elastic ep scattering has been the first tool to study how the nucleon is build. New and complementary information can be obtained by looking at reaction in wich the nucleon breaks



unpolarized cross section

$$\frac{d^2\sigma^{unpol}}{dE'd\Omega} = \left(\frac{d^2\sigma}{dE'd\Omega}\right)_{Mott} \cdot \left[\frac{2}{M}F_1(x,Q^2)\tan^2(\theta/2) + \frac{1}{\nu}F_2(x,Q^2)\right]$$

polarized cross section

$$\frac{d^3\sigma^{\overset{\rightarrow}{\Leftarrow}}}{dxdy} - \frac{d^3\sigma^{\overset{\rightarrow}{\Rightarrow}}}{dxdy} = \frac{4\alpha^2}{sxy}\left[\left(2 - y - \frac{\gamma^2 y^2}{2}\right)g_1(x,Q^2) - \gamma^2 y g_2(x,Q^2)\right]$$

$$Q^2 = -q^2 = 4EE'\sin^2\left(\frac{\theta}{2}\right)$$

$$W^2 = M^2 + 2M\nu - Q^2$$

$$x_B = \frac{Q^2}{2M\nu}$$

4 new Structure Functions

The nucleon parton model

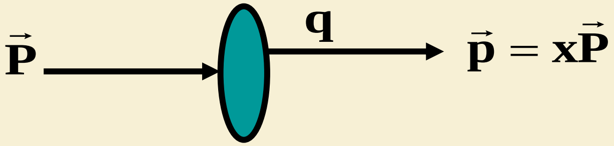
The structure functions can be expressed in terms Parton Distribution Functions

$$F_1\left(x,Q^2\right)\rightarrow F_1(x)=\frac{1}{2}\sum_f\left[q_f^{\ +}(x)+q_f^{\ -}(x)\right]$$

$$g_1\left(x,Q^2\right)\rightarrow g_1(x)=\frac{1}{2}\sum_f\left[q_f^{\ +}(x)-q_f^{\ -}(x)\right] \qquad g_2\approx 0$$

Bjorken limit

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



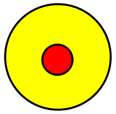
PDFs give the probability to find a quark *f*:

- **with a fraction x of the proton momentum**
- **with spin in a given direction with respect to the proton momentum**

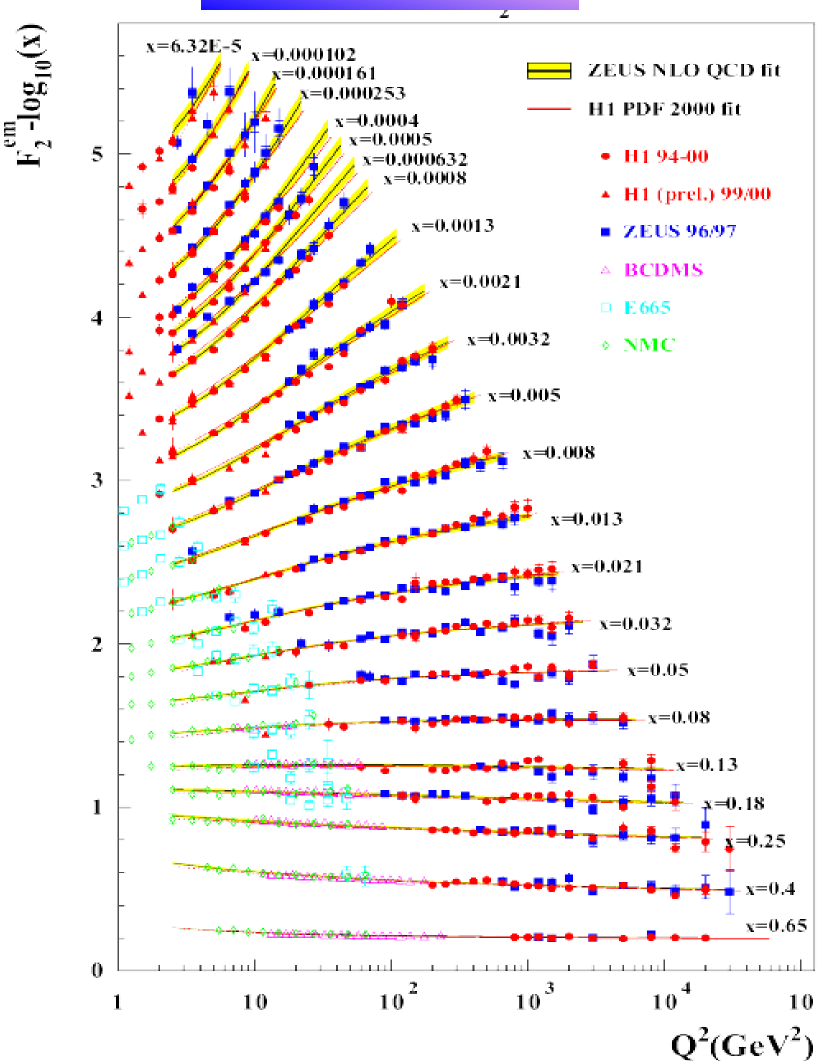
Unpolarized and Helicity PDF

Unpolarized DF

$$F_2(x,Q^2) \propto x\left(q^+ + q^-\right)$$

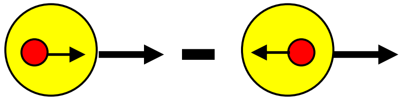


WELL KNOWN

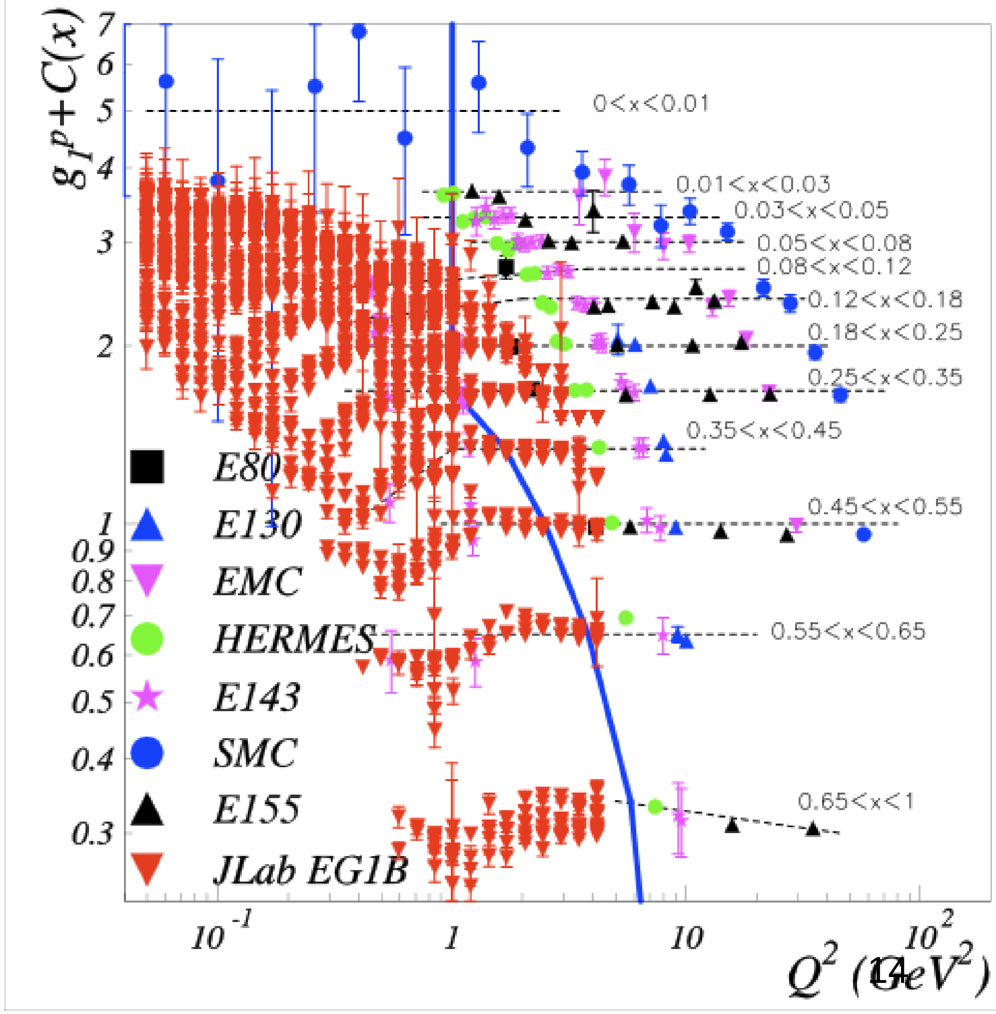


Helicity DF

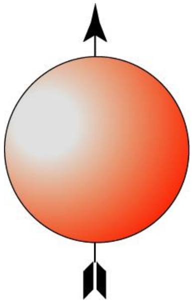
$$g_1(x,Q^2) \propto q^+ - q^-$$



KNOWN

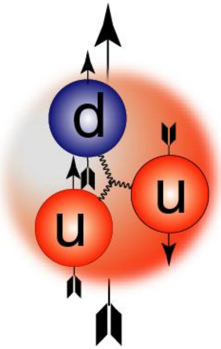


The proton spin



Total proton spin is 1/2

$$S_p = \frac{1}{2}$$



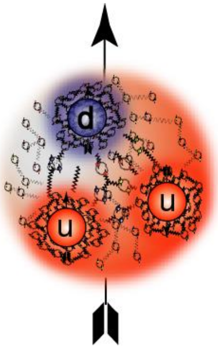
"Naïve" proton spin sum rule: valence quarks

$$S_p = \frac{1}{2}\Delta\Sigma$$

From the data:

$$\Delta\Sigma \approx 0.3$$

the "spin crisis"



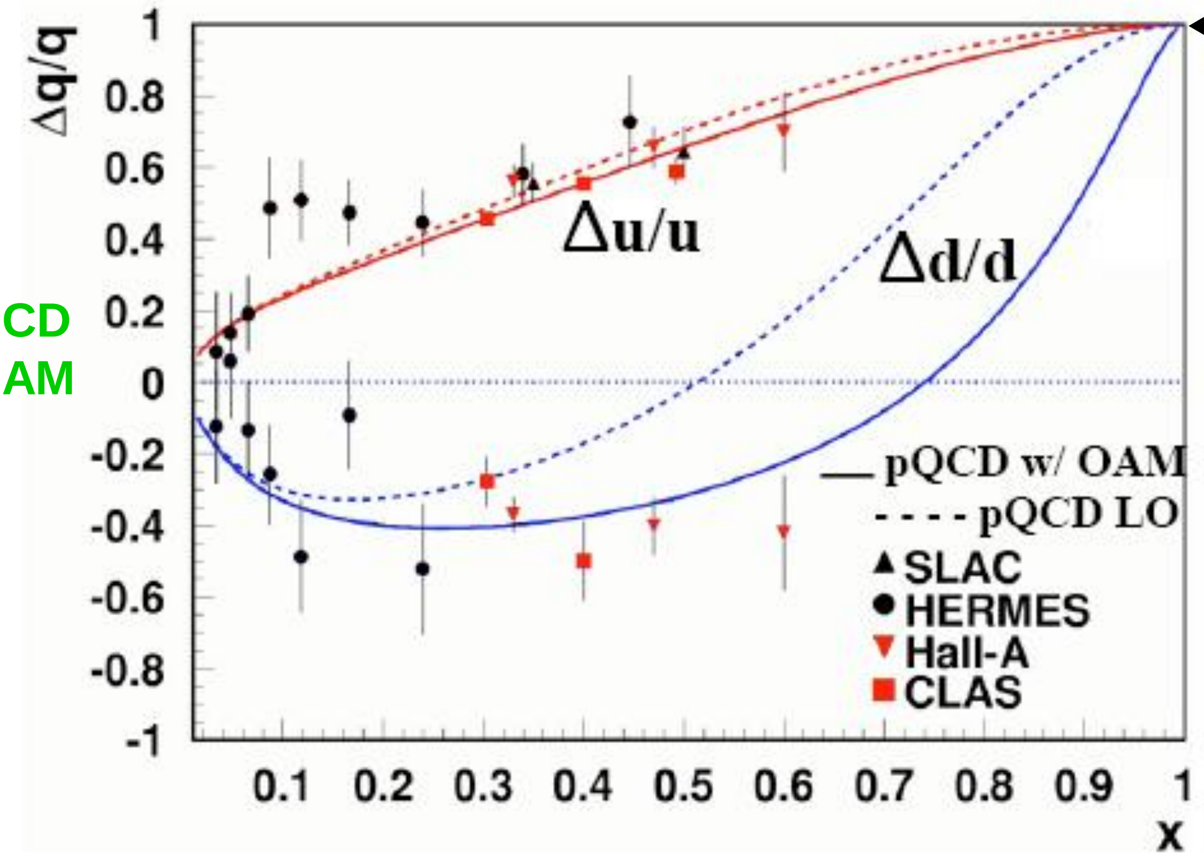
Full decomposition: sea quarks and gluons, angular momenta

$$S_p = \frac{1}{2}\left(\Delta\Sigma_v + \Delta\Sigma_s\right) + \Delta G + L_q$$

Orbital Angular Momentum

$$F_2 = \frac{4}{9}x\left(u+\bar{u}\right)+\frac{1}{9}x\left(d+\bar{d}\right)$$

$$g_1 = \frac{4}{9}\left(\Delta u+\Delta\bar{u}\right)+\frac{1}{9}\left(\Delta d+\Delta\bar{d}\right)$$



SU(6)

RCQM
broken SU(6)

curves: LO pQCD
without/with OAM

Flavor separation is crucial to test model prediction

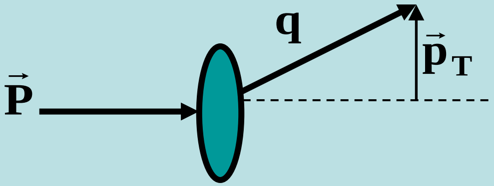
From collinear approximation to TMD

Three PDFs in collinear approximation in DIS

$$f_1(x), g_1(x), h_1(x)$$

- **partons move collinearly with the nucleon**
- **no angular momentum**

Transverse Momentum Dependent parton distribution functions



$$\vec{\mathbf{p}} = \mathbf{x}\vec{\mathbf{P}} + \vec{\mathbf{p}}_\mathbf{T}$$

more complex dist. functions

$$f_1(x, \vec{p}_T), g_1(x, \vec{p}_T), h_1(x, \vec{p}_T)$$

Access to the transverse momentum requires tagging of the leading quark in the final state

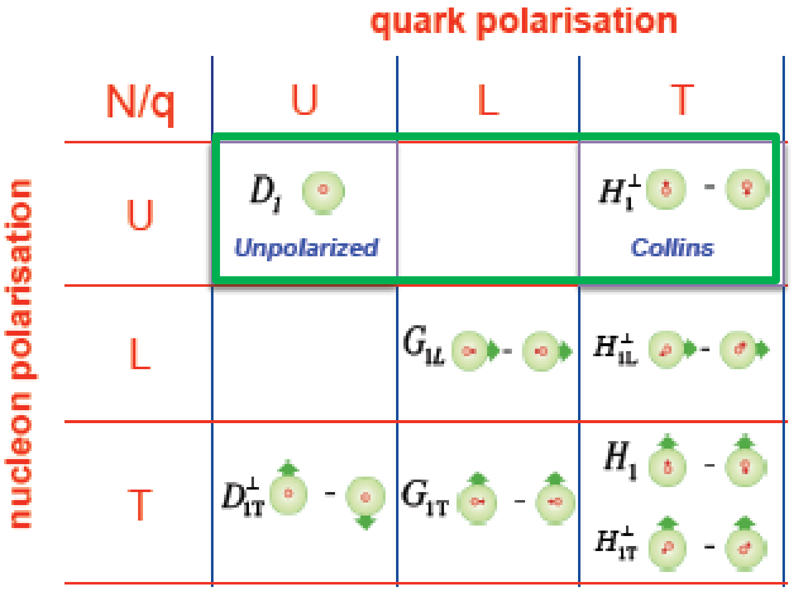
Semi-Inclusive processes: ***ep→e’hX***

TMD distributions

Parton Distribution Functions

Parton Fragmentation Functions

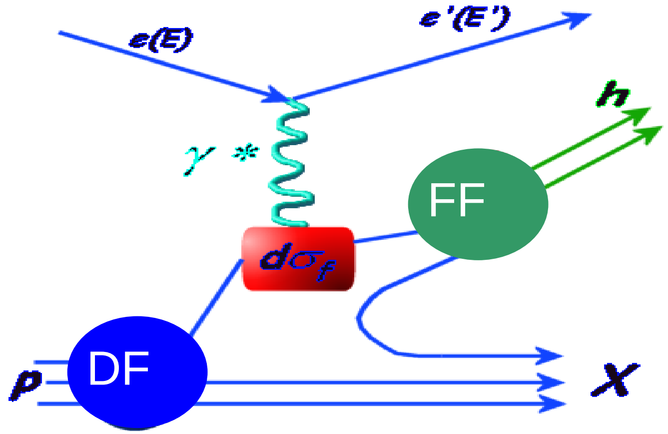
- **all functions depend on x and p_T of the quark**
- **off-diagonal elements from interference between wave functions with different angular momentum**



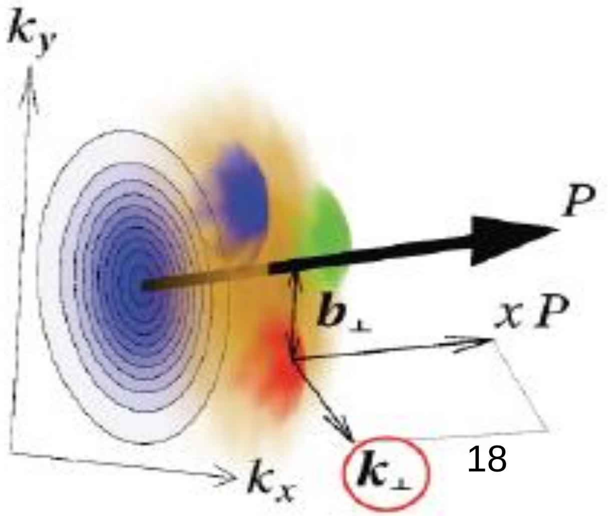
quark polarisation

nucleon polarisation

N/q	U	L	T
U	D_1 Unpolarized		$H_1^\perp$ - Collins
L		G_{1L} -	$H_{1L}^\perp$ -
T	$D_{1T}^\perp$ -	G_{1T} -	H_1 - $H_{1T}^\perp$ -



$$d\sigma^h \propto \sum q_f(x) \otimes \mathrm{d}\sigma_f(y) \otimes D_f^{q\to h}(z)$$



Universality and TMDs

TMDs are universal objects

- same functions in SIDIS, e+e-, DY, ...

Sivers function:

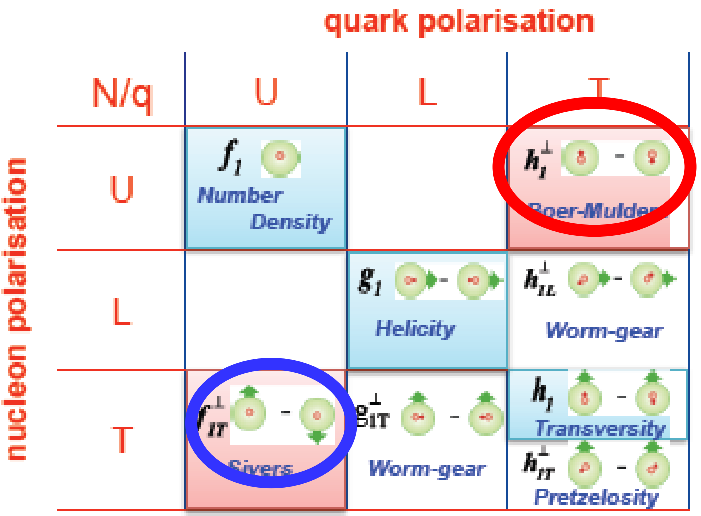
- unpolarized quarks in transversely polarized nucleon

- correlation between quark transverse momentum and spin of the nucleon

Boer-Mulders function:

- transversely polarized quarks in unpolarized nucleon

- correlation between quark transverse spin and nucleon momentum



quark polarisation

nucleon polarisation

N/q	U	L	T
U	f_1 Number Density		$h_1^\perp$ ‑ Boer-Mulders
L		g_1 ‑ Helicity	$h_{1L}^\perp$ ‑ Worm-gear
T	$f_{1T}^\perp$ ‑ Sivers	$g_{1T}^\perp$ ‑ Worm-gear	h_1 ‑ Transversity $h_{1T}^\perp$ ‑ Pretzelosity

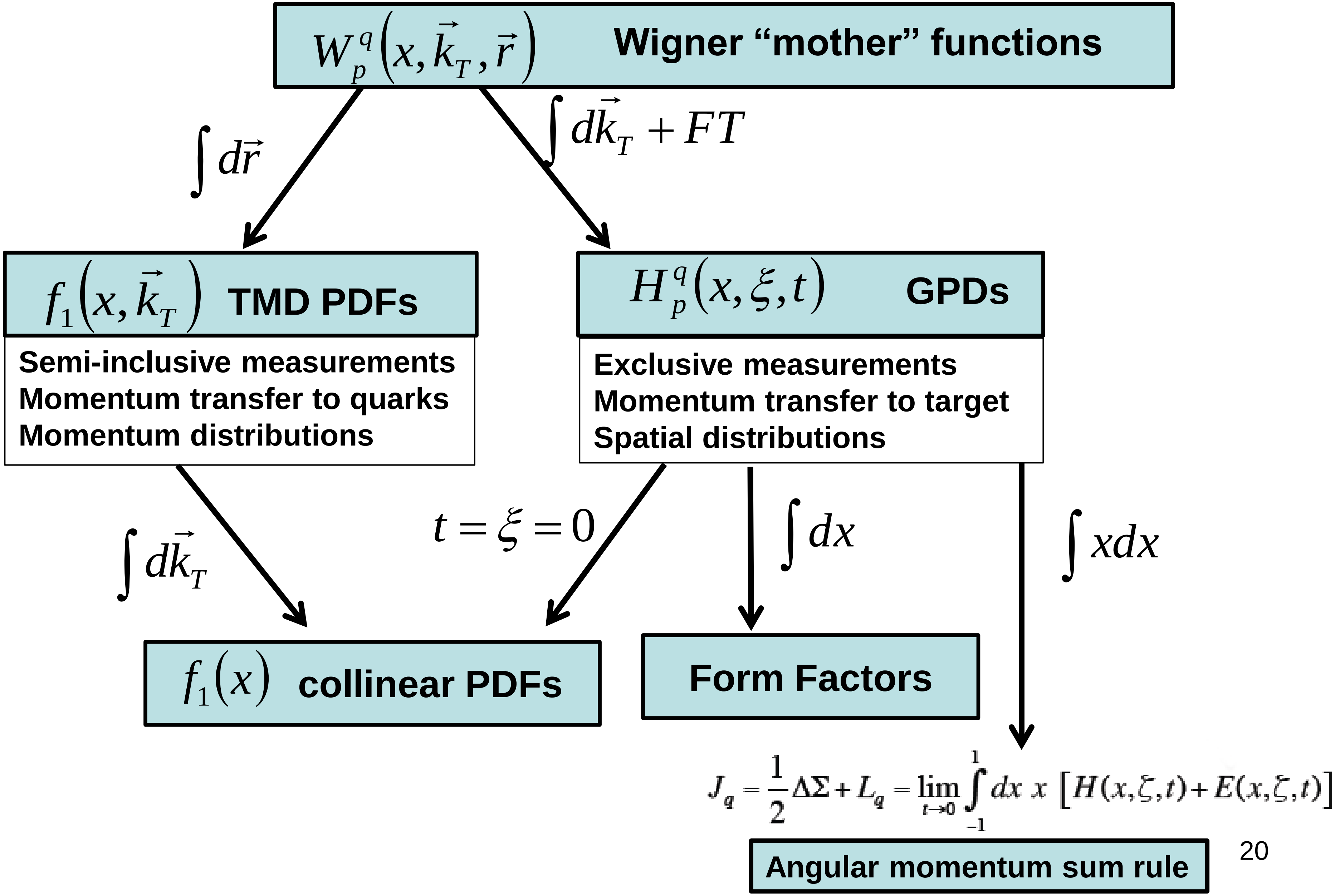
Non-zero because of initial or final state interaction

Sivers and Boer-Mulders change sign form SIDIS to Drell-Yan

$$f_{1T}^{\perp}\Big|_{SIDIS} = -f_{1T}^{\perp}\Big|_{DY} \qquad h_1^{\perp}\Big|_{SIDIS} = -h_1^{\perp}\Big|_{DY}$$

<u>Crucial test for the theory</u>

"Zoology" of PDFs



$W_p^q\left(x,\vec{k}_T,\vec{r}\right)$ **Wigner "mother" functions**

$\int d\vec{r}$

$\int d\vec{k}_T + FT$

$f_1\left(x,\vec{k}_T\right)$ **TMD PDFs**

Semi-inclusive measurements
Momentum transfer to quarks
Momentum distributions

$H_p^q\left(x,\xi,t\right)$ **GPDs**

Exclusive measurements
Momentum transfer to target
Spatial distributions

$\int d\vec{k}_T$

$t=\xi=0$

$\int dx$

$\int xdx$

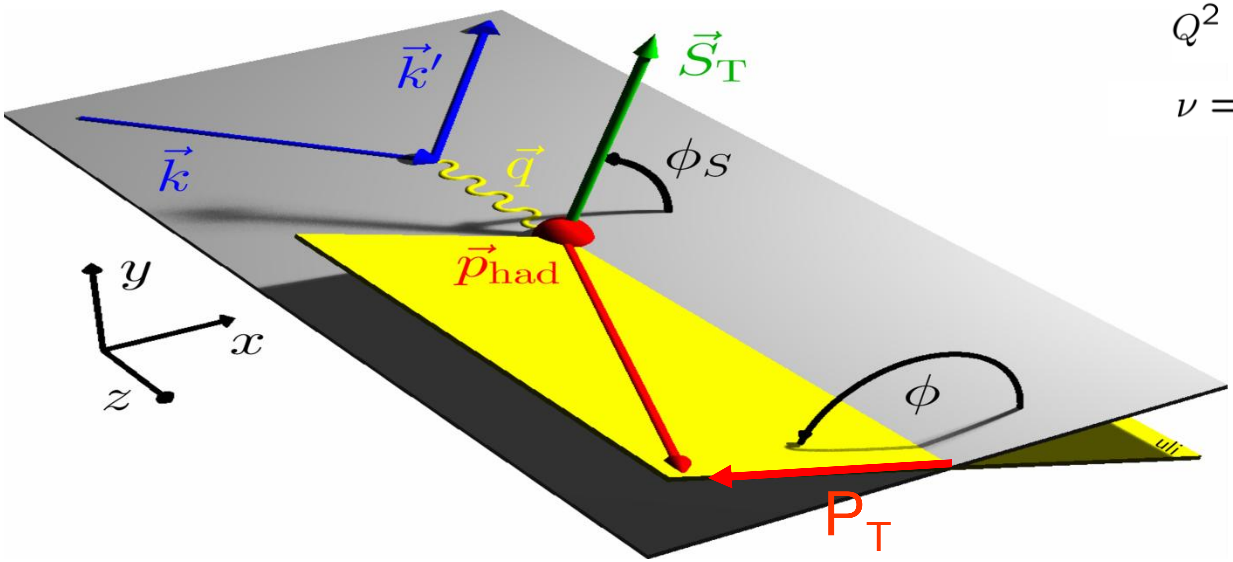
$f_1\left(x\right)$ **collinear PDFs**

Form Factors

$$J_q = \frac{1}{2}\Delta\Sigma + L_q = \lim_{t\to 0}\int_{-1}^{1} dx\ x\ \left[H(x,\xi,t)+E(x,\xi,t)\right]$$

Angular momentum sum rule

SIDIS Kinematical Plane and Observables



$Q^2 = (k - k')^2$

$\nu = E - E'$

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

$y = \nu/E$

$z = E_h/\nu$

U **unpolarized**
L **long.polarized**
T **trans.polarized**

Target polarization

Beam helicity

$$\sigma = \sigma_{UU} + S_T\,\sigma_{UT}\,\sin(\phi - \phi_S) + \lambda\, S_T\,\sigma_{LT}\cos(\phi - \phi_S) + \ldots.$$

Extraction of the various terms from moments or asymmetries in ϕ

$$\frac{\sigma(S_T = +1) - \sigma(S_T = -1)}{\sigma(S_T = +1) + \sigma(S_T = -1)} \propto \frac{\sigma_{UT}}{\sigma_{UU}}$$

SIDIS cross section

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T} + \qquad F_{UU}^{\cos\phi_h}$$

$$f_1 \otimes D_1$$

18 structure functions

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

$$+\,S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]$$

$$+\,S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \qquad\right]$$

$$g_1 \otimes D_1$$

Structure functions decomposition

$$F \propto DF \otimes FF$$

- leading twist (parton model)

- higher twist ~M/Q

$$+\,|S_\perp|\Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$$+\,\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\,\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg]$$

$$+\,|S_\perp|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

$$+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\}, \qquad (2.7)$$

TMD measurements at JLab

TMDs are studied at JLab through SIDIS scattering on nucleons (and nuclei) with different experimental equipments

- **CLAS@Hall B**
  - **large acceptance spectrometer with good resolution**
  - **lower luminosity $\approx 10^{34}$ cm^{-2} s^{-1}**
  - **asymmetry measurements over a broad kinematical range**

- **Hall A**
  - **high resolution and small acceptance spectrometers**
  - **high luminosity $\approx 10^{37}$ cm^{-2} s^{-1}**
  - **high polarization ^{3}He target (long. or transv.) → neutron**

- **Hall C**
  - **high resolution and small acceptance spectrometers**
  - **high luminosity $\approx 10^{37}$ cm^{-2} s^{-1}**
  - **high precision cross section measurements**

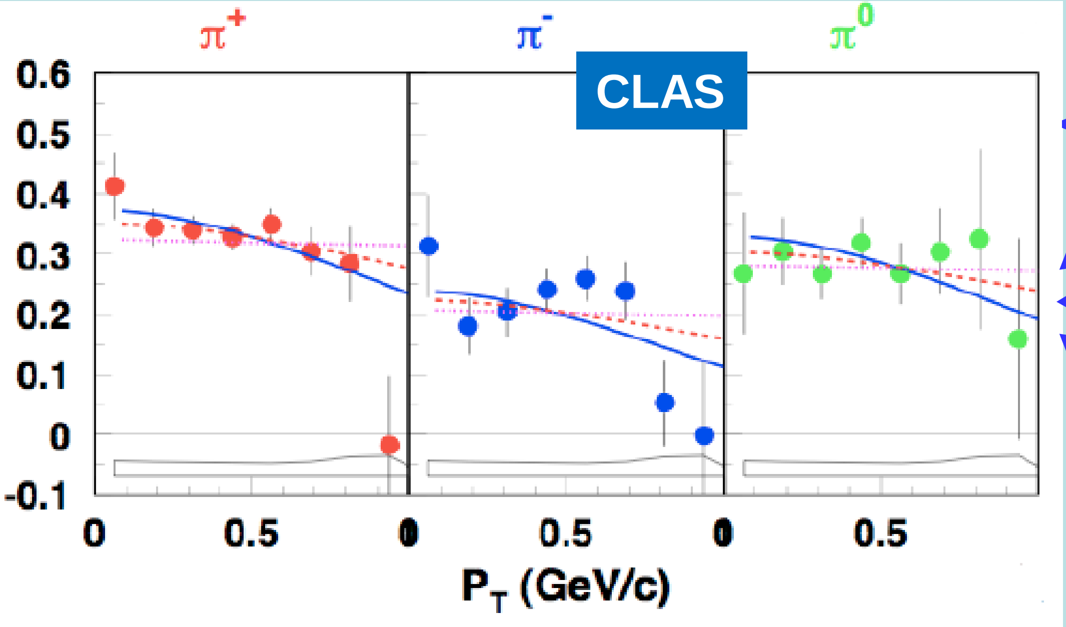
Double spin asymmetry

$$\vec{e}\vec{p} \rightarrow e'\pi X$$

$$A_{LL} = \frac{1}{fD(y)P_B P_t} \frac{N^+ - N^-}{N^+ + N^-} \propto \frac{g_1}{f_1}$$

Same analysis as in the collinear g_1 extraction but now focus on TMD

smooth dependence for all pions



$\langle k_T^2\rangle_g / \langle k_T^2\rangle_f$

1.0

0.68

0.4

Calculations using gaussian ansatz

$$f_1(x, \vec{k}_T) = f_1(x) e^{-\frac{k_T^2}{\langle k_T^2\rangle_f}}$$

$$g_1(x, \vec{k}_T) = g_1(x) e^{-\frac{k_T^2}{\langle k_T^2\rangle_g}}$$

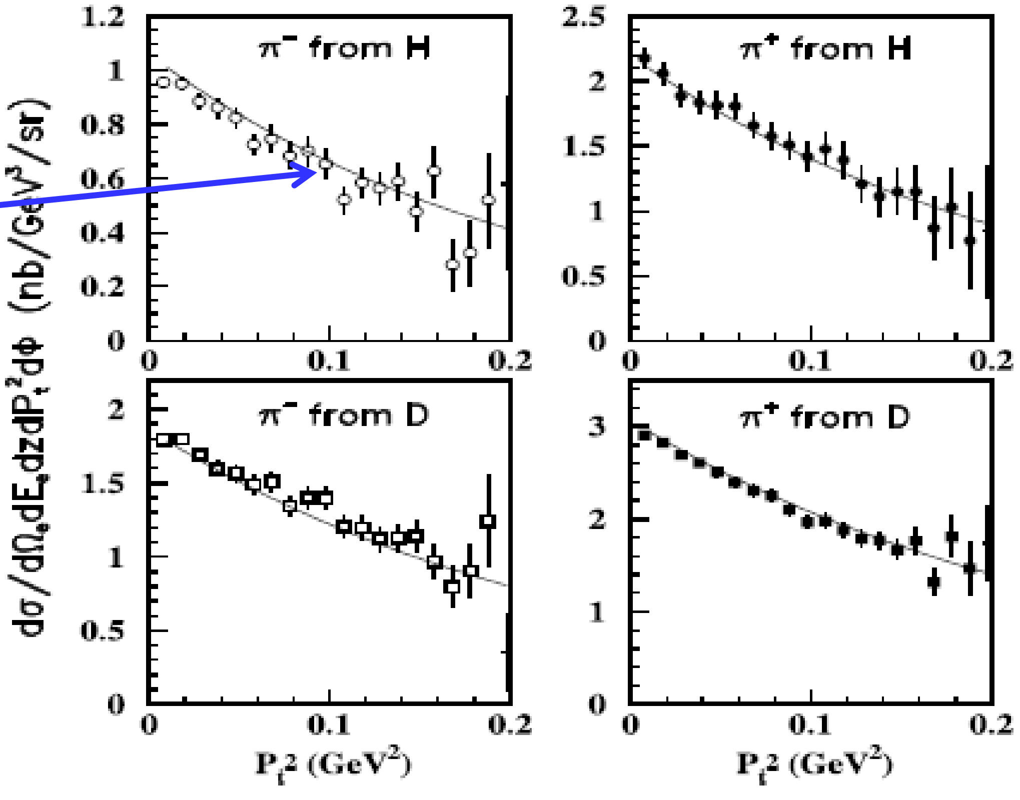
transverse mom. distribution different for quarks with spin parallel or antiparallel to nucleon spin

Unpol. cross section on H and D

$$ep \rightarrow e'\pi^{\pm}X$$

Hall C

- **Similar shape for both pions**
- **Smaller slope for D than H data**



phenomenological fit

- **no sea quark contribution (x>0.3)**
- **dominance of favoured FF**

  u → π+

  d → π-
- **gaussian k_T shape**

larger k_T width for d quark than for u in DF and FF

⇒ u and d quarks have different momentum distributions

Transverse target SSA on neutron

$$e\,{}^{3}He\uparrow\rightarrow e'\pi X$$

Hall A

Collins effect

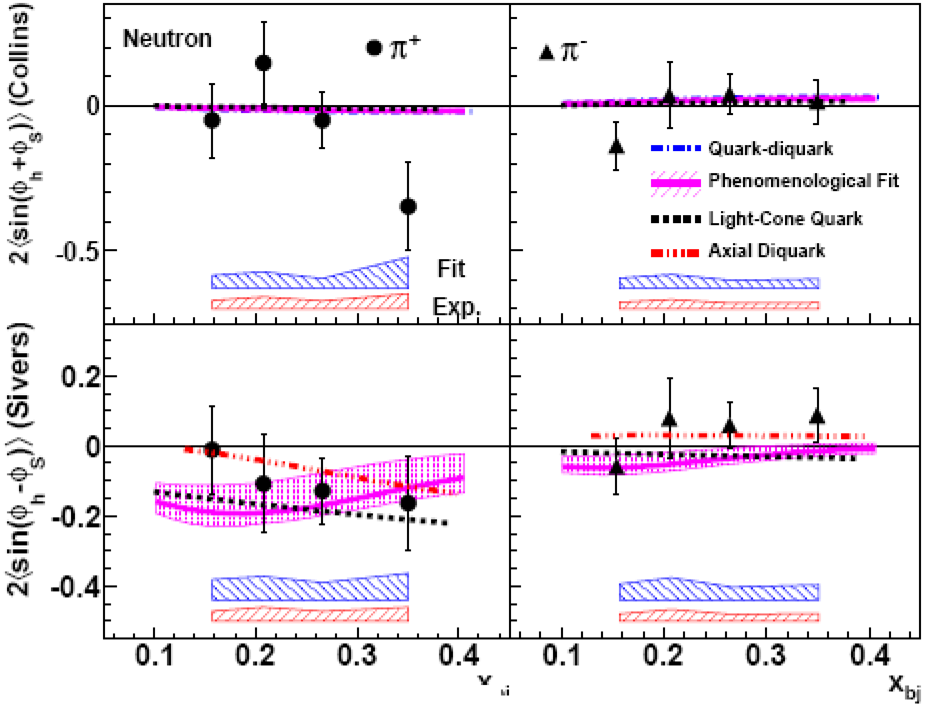
$$F_{UT}^{\sin(\phi_h+\phi_s)}\propto h_1\otimes H_1^{\perp}$$

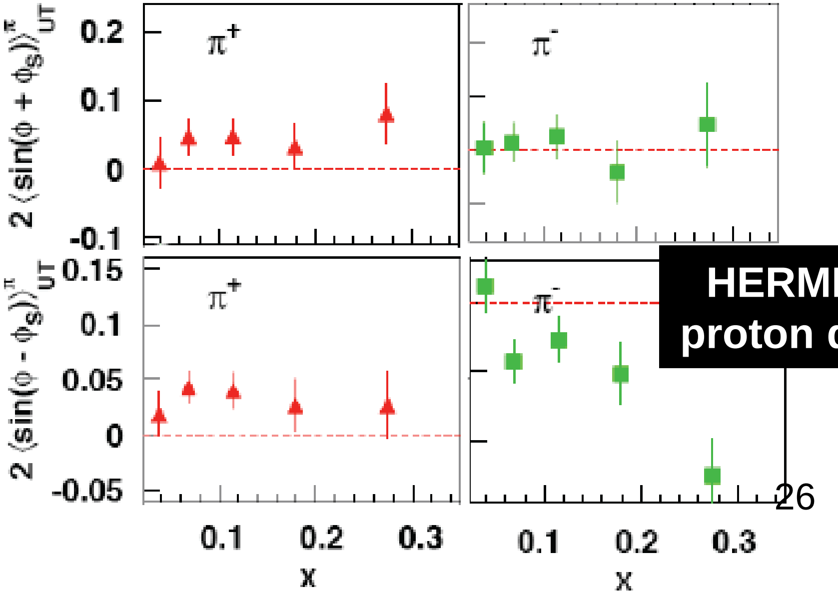
Sivers effect

$$F_{UT}^{\sin(\phi_h-\phi_s)}\propto f_{1T}^{\perp}\otimes D_1$$

- **Small (zero?) Collins**
- **Larger Sivers for π+ than for π-**

Opposite behaviour with respect to proton data

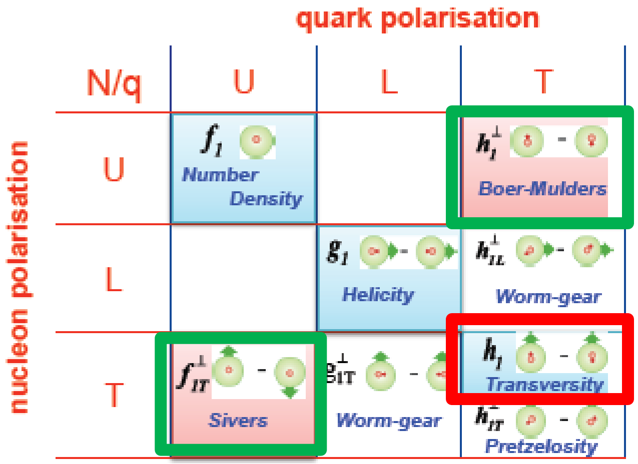




HERMES proton data

Summary of experimental results

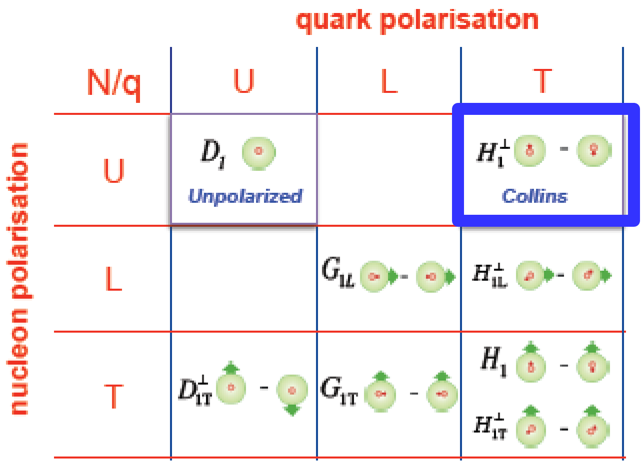
- the effect of the transverse momentum of quarks can be observed
  - TMD DFs and FFs are non-zero (Hermes+Compass+JLab+...)
  - how much does parton angular momentum contribute to the nucleon spin?
- first information on TMD DFs and FFs
  - non-zero Collins FF (SIDIS, e+e-)
  - non zero Sivers and Boer-Mulders DF (Hermes+Compass, JLab for the neutron)
  - first extraction of transversity (BELLE + HERMES)
  - possibility to access HT terms at JLab



quark polarisation

nucleon polarisation

N/q	U	L	T
U	f_1 Number Density		$h_1^\perp$ Boer-Mulders
L		g_1 Helicity	$h_{1L}^\perp$ Worm-gear
T	$f_{1T}^\perp$ Sivers	$g_{1T}^\perp$ Worm-gear	h_1 Transversity $h_{1T}^\perp$ Pretzelosity



quark polarisation

nucleon polarisation

N/q	U	L	T
U	D_1 Unpolarized		$H_1^\perp$ Collins
L		G_{1L}	$H_{1L}^\perp$
T	$D_{1T}^\perp$	G_{1T}	H_1 $H_{1T}^\perp$

Open issues

- strange quark distributions are basically unknown
  - inconsistency between extractions from DIS and SIDIS experiments
  - s distributions different from sbar?

- kaon puzzle
  - Sivers and Collins for K^+ twice as biggere as π^+

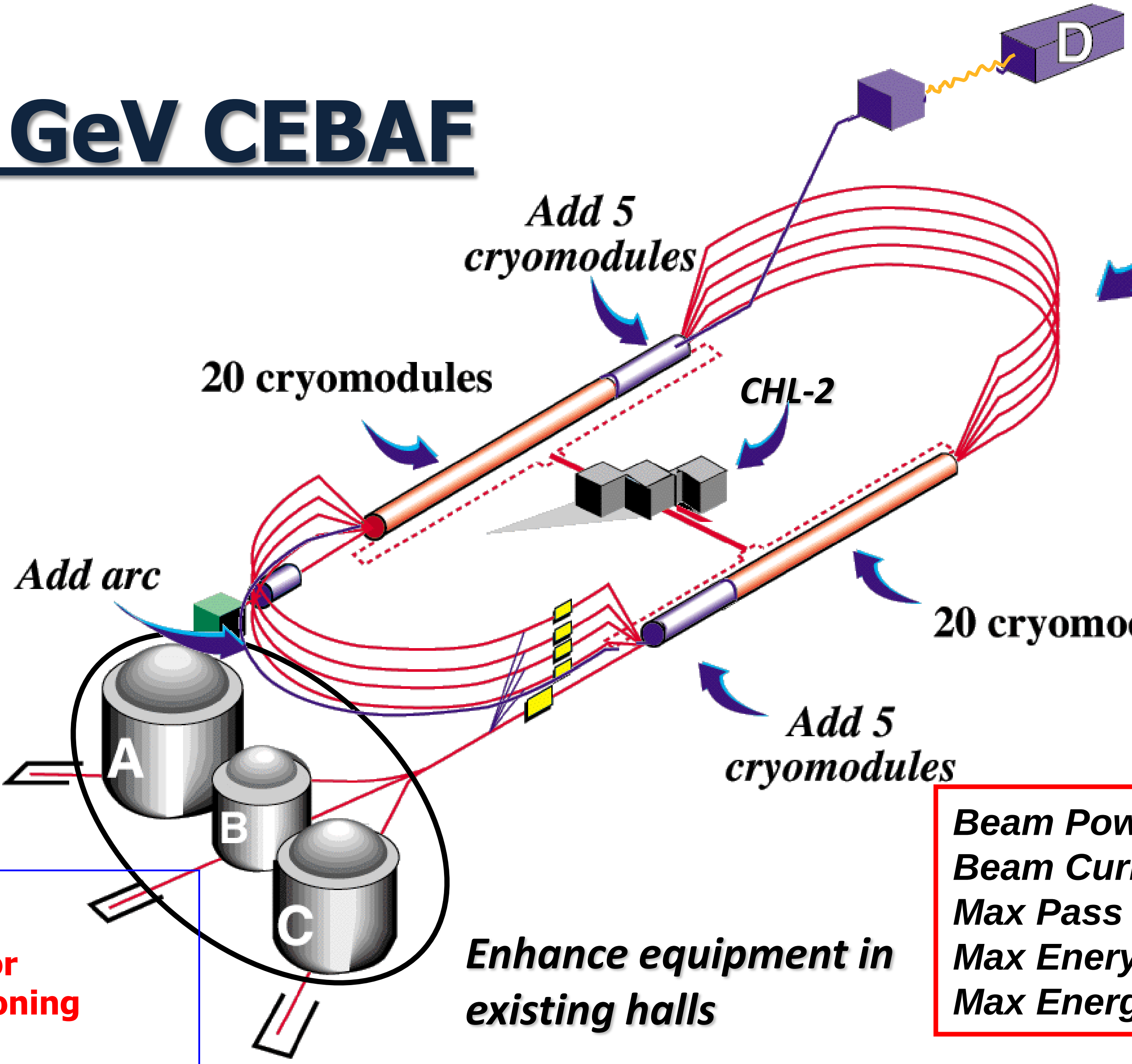
    favoured FF $u \rightarrow \pi^+$ $u \rightarrow K^+$

- TMD extractions largely depend on the gaussian ansatz for the transverse momentum dependences
  - spin-dependent TMD are differences of probability, they don’t need to be positive

- analysis of exp. data is complicated due to convolution of DFs and FFs
  - multidimensional extraction of TMDs
  - new analysis techniques need to be implemented

Need more data, especially on kaons

12 GeV CEBAF

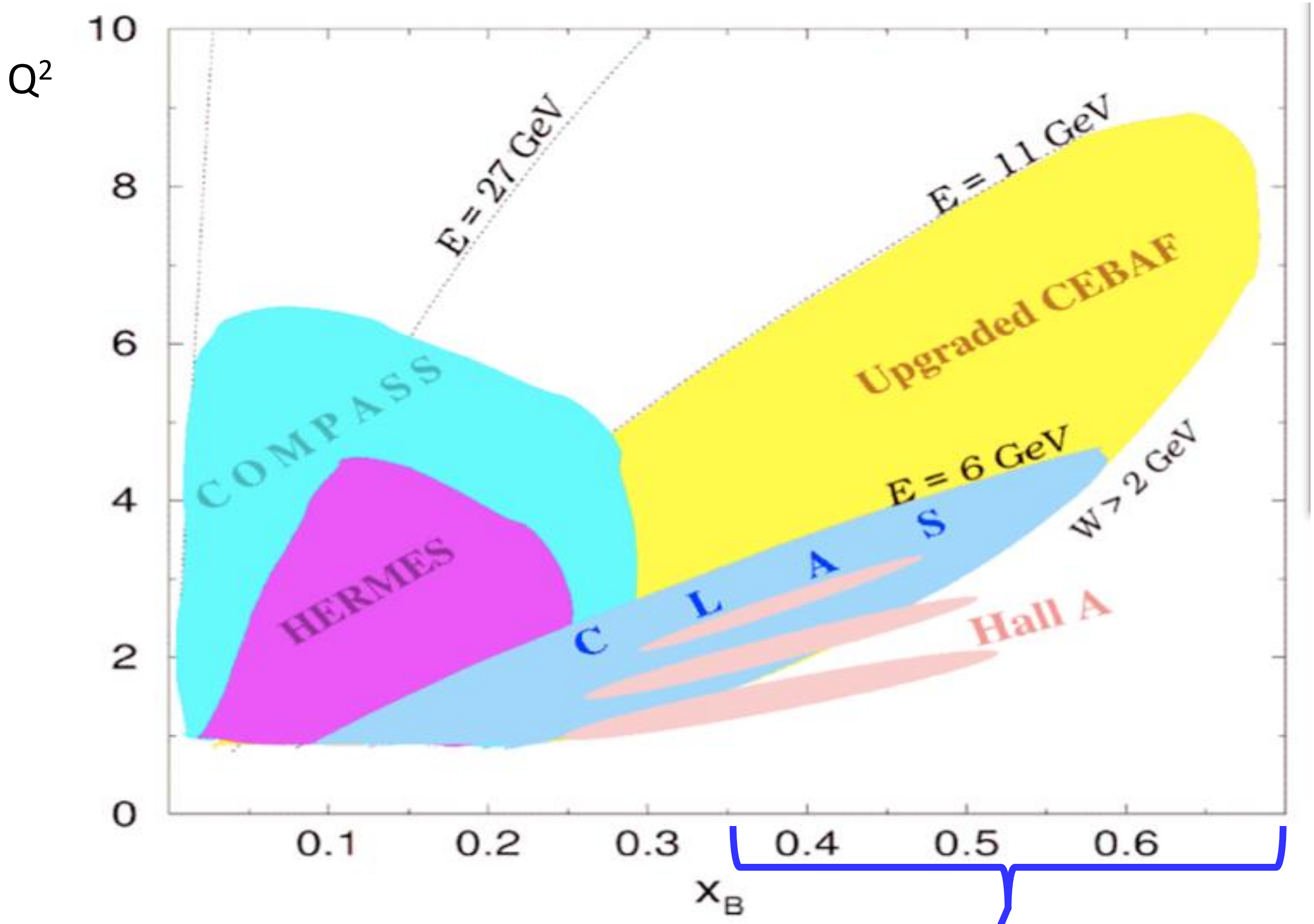


Beam Power: 1MW
Beam Current: 90 µA
Max Pass energy: 2.2 GeV
Max Enery Hall A-C: 10.9 GeV
Max Energy Hall D: 12 GeV

May 2013
Accelerator Commissioning starts

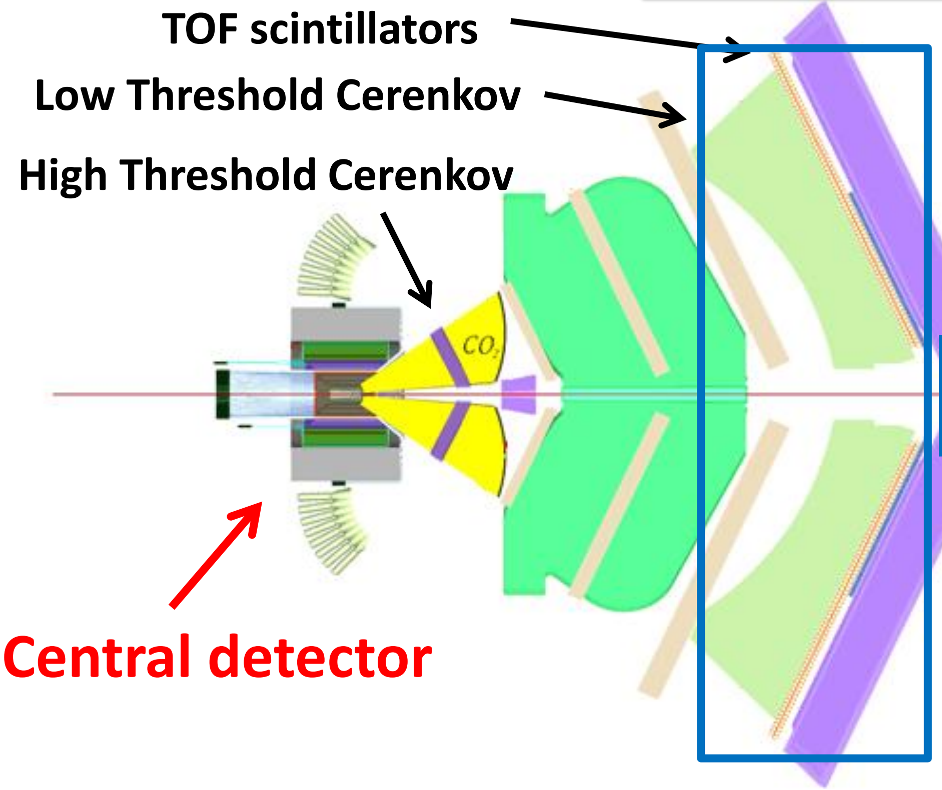
October 2013
Hall Commissioning starts

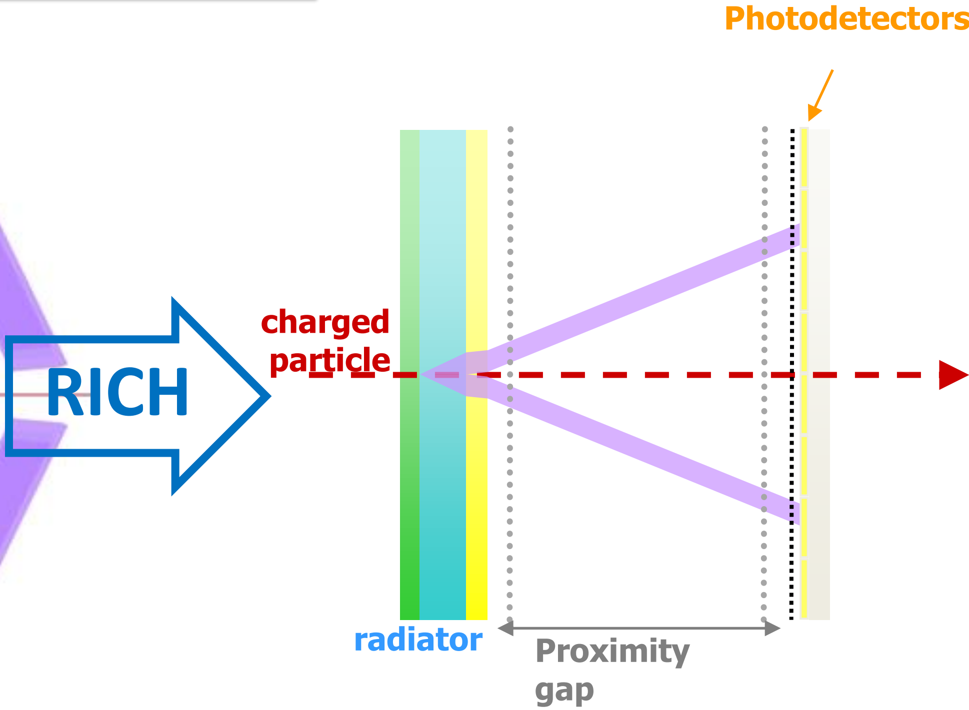
Kinematic coverage

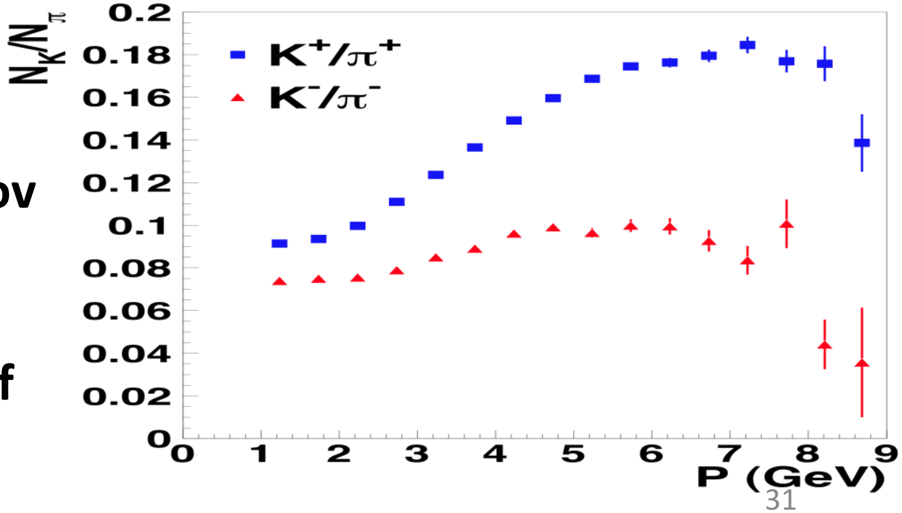


extending to higher x means lower cross sections
need high luminosity

PID in CLAS12







PID basically done with TOF and two Cerenkov detectors

-Not sufficient for Kaon SIDIS

-Production rates require a rejection factor of 1/1000

The RICH detector for CLAS12

- identification of kaons in the 3-8 GeV/c momentum region
- π/K separation with rejection factor ~1000

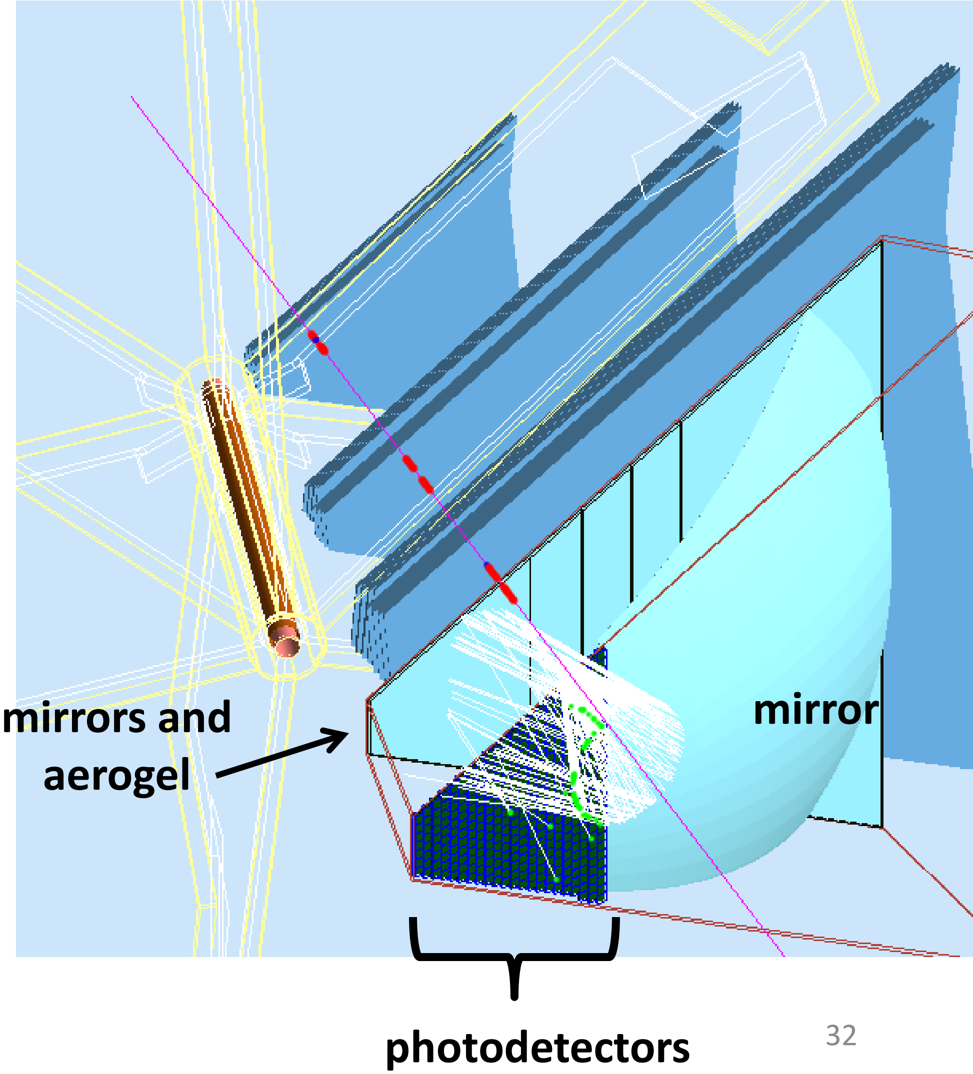
CURRENT DESIGN

- aerogel radiator with different thickness to match the momentum range
- 1m gap length
- multi-anode PMT for photon detection
- mirrors to focalize the photons in a smaller area

Several RICH components tested
- MAPMTs, aerogel, electronics

First successful preliminay CERN test beam
- pion ring reconstruction
- simulations calibrated to the measurements

Test of a realistic prototype is underway
- first run in July, analysis in progress
- second run end of november



Conclusion

After more than 100 years of study, the internal structure of the nucleon is for many aspects unknown

- **Rosembluth vs polarization FF measurements**
- **proton spin decomposition**
- **fully 3D representation of the internal structure**

JLab has produced many important results and will continue with the 12 GeV upgrade