Hadron Physics

Lecture #1: The quark model, QCD, and hadron spectroscopy

Lecture #2: Internal structure of hadrons: momentum and spin

Lecture #3: Internal structure of hadrons: charge, magnetism, polarizability

Lecture #4: Hadrons as laboratories (and other miscellaneous topics)

Properties of hadrons: momentum and spin

Structure functions and Deep Inelastic Electron Scattering

spin and flavor structure

Other processes:

- Semi-inclusive scattering, transversity
- Deeply Virtual Compton Scattering & Generalized Parton Distributions

"quark model" vs "partons"

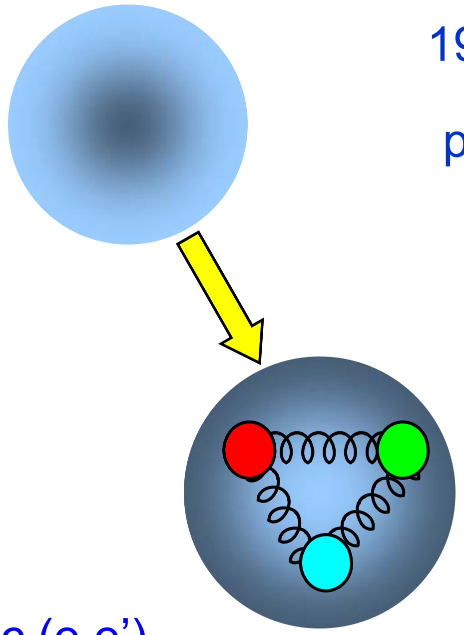
references for this section

Halzen & Martin: Quarks and Leptons
F.E. Close: An Introduction to Quarks and Partons
Perkins: Introduction to High Energy Physics
Cahn and Goldhaber: The Experimental Foundations of Particle Physics

Xiangdong Ji: Graduate nuclear physics lecture notes
http://www.physics.umd.edu/courses/Phys741/xji/lecture_notes.htm

Lectures from the Hampton University Graduate School (HUGS), particularly 2007 (Reno), 2008 (Elouadhriri) and 2009 (Burkardt)
http://www.jlab.org/hugs/archive/

Special thanks to
Zein-Eddine Meziani, Temple University
Naomi Makins, University of Illinois



1930’s:

(Chadwick NP 1935)
(Stern NP 1943)

$\mu_p \sim 3\ \mu_N$

1950’s:

proton charge radius from (e,e’)
(Hofstadter NP 1961)

$r_p \sim 1$ fm

1970’s:

partons in proton via inelastic (e,e’)
(Friedman,Taylor,Kendall, NP 1990)
asymptotic freedom → QCD
(Gross, Politzer, Wilcek, NP 2004)

1980’s: exploration of phenomena
various scaling phenomena
“the spin crisis”
“the EMC effect”

1990’s:

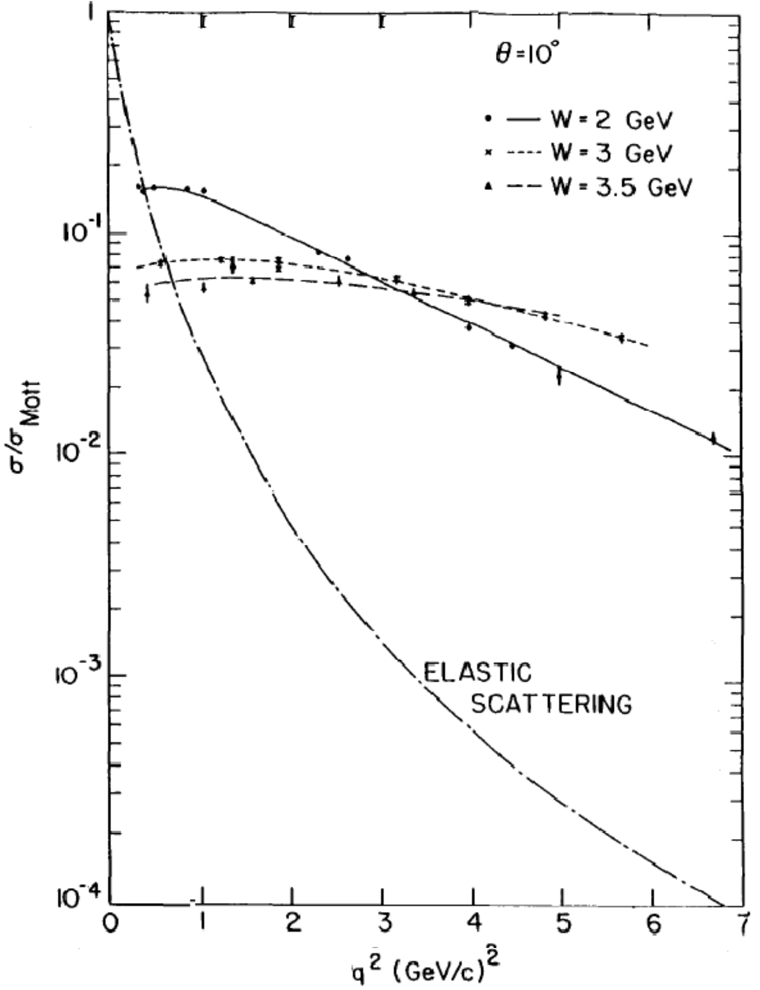
polarized targets
Intense CW electron beams
improvement in polarized e sources

2000’s:

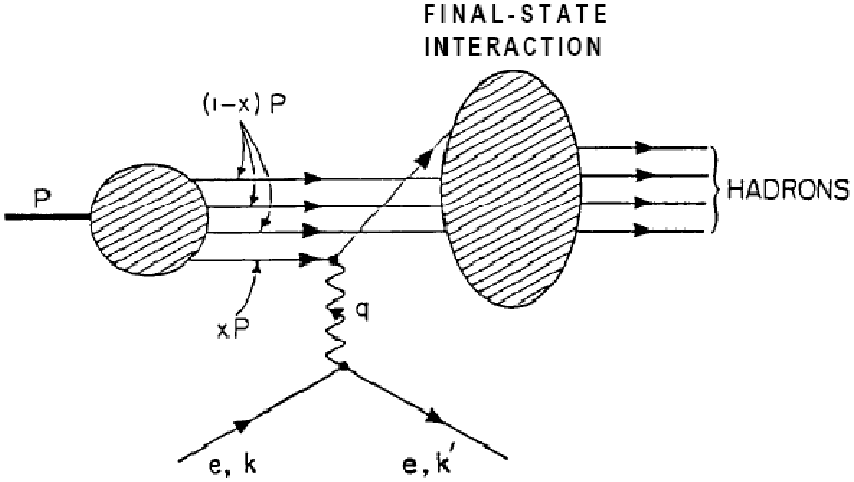
lattice QCD
Generalized Parton Distributions
transversity, DVCS, moments, ….

Deep Inelastic Electron Scattering

M. Briedenbach et al,
Phys Rev Lett 23, 935 (1969)

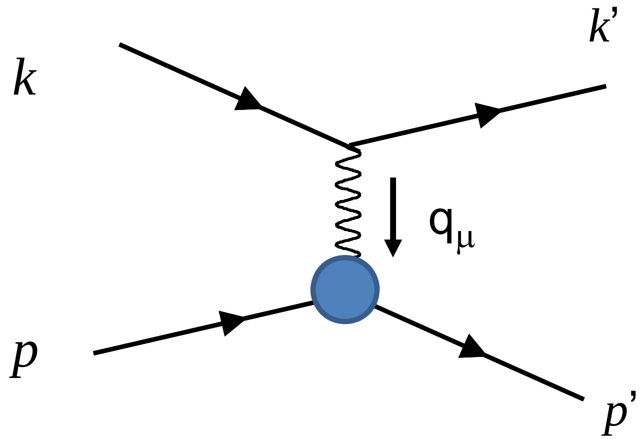


from J. Friedman Nobel lecture, 1990



Kinematics of electron scattering

A common reference frame to work in is the LAB frame with a stationary target:



case 1: elastic scattering

$$\boxed{\begin{array}{l} p=(M,0) \quad p'=(E_R,\vec{p}\,') \\ k=(E,\vec{k}) \quad k'=(E',\vec{k}\,') \\ \hat{k}\cdot\hat{k}'=\cos\theta \\ q_\mu=(\nu,\vec{q})=k-k' \end{array}}$$

$$q_\mu^2=\nu^2-\vec{q}^{\,2}=-Q^2(>0)$$

It is common to assume the electron is massless (extreme relativistic limit). In this case, if one conserves 4-momentum:

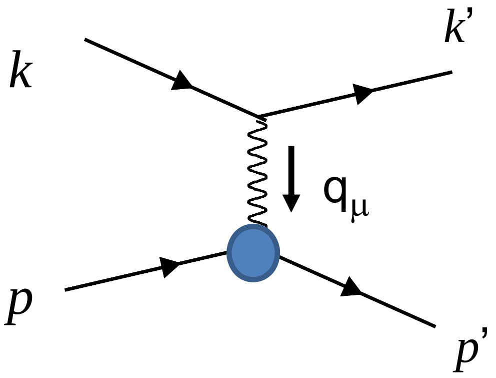
$$s=W^2=(E+M)^2-\vec{k}^2=M^2+2EM$$

and can easily show:

$$Q^2=4EE'\sin^2\theta/2 \qquad \nu=E-E'$$

Inelastic electron scattering

Using Fermi's Golden rule, we integrate over the recoiling target quantities, average over initial spin states, sum over final spin states. For elastic scattering, we integrate over an energy-conserving delta function. *For inelastic scattering we skip the last step.*



outgoing may no longer be a proton

interaction strength and photon propagation

$$\frac{d\sigma}{d\Omega dE} = \frac{\alpha^2}{Q^4}\frac{E'}{E} l_{\mu\nu} W^{\mu\nu}$$

lepton current $$l^{\mu\nu} = \tfrac{1}{2}\sum_{s'} \overline{u}(k',s')\gamma^{\mu} u(k,s)\overline{u}(k,s)\gamma^{\nu} u(k',s')$$

hadron current $$W_{\mu\nu} = \tfrac{1}{2}\sum_{X} \langle P | J_\mu | X \rangle \langle X | J_\nu | P \rangle (2\pi)^3 \delta^4(p+q-p')$$

$$\boxed{J_\mu = \overline{u}(p')[\ ?\ ]u(p)}$$

the hadronic current

$$\boxed{J_\mu = \overline{u}(p')[\ ?\ ]u(p)}$$

Elastic scattering: the target is left intact and we measure its net response to the EM current as a function of momentum transferred to it by the photon.

$$[\ ?\ ] = \left[F_1(Q^2)\gamma^\mu + \frac{\kappa}{2M} F_2(Q^2) i\sigma^{\mu\nu} q_\nu \right]$$

Inelastic scattering: target might to into an excited state, or break up

$$W^{\mu\nu} = \langle P | J^\mu | X \rangle \langle P' | J^\nu | X \rangle$$

$$= W_1\left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2} \right) + \frac{W_2}{M^2}\left(p^\mu - q^\mu \frac{(p \cdot q)}{q^2} \right)\left(p^\nu - q^\nu \frac{(p \cdot q)}{q^2} \right)$$

where in principle W_1 and W_2 depend on both Q^2 and energy loss (ν). These encode all of the strong interaction dynamics between the partons.

Unpolarized electron scattering, cont'd

after some manipulation, the cross section becomes

$$\frac{d\sigma}{d\Omega dE} = \underbrace{\frac{\alpha^2}{4E^2}\frac{\cos^2 \theta\!/\!_2}{\sin^4 \theta\!/\!_2}}_{\sigma_{\mathrm{Mott}}}\left[W_2\left(\nu, Q^2\right) + 2W_1\left(\nu, Q^2\right)\tan^2 \theta\!/\!_2\right]$$

This is the famous "Rosenbluth" formula. Often this is also expressed in terms of helicity of the photon being exchanged.

$$\frac{d\sigma}{d\Omega dE} = \Gamma\left[\sigma_T + \varepsilon\sigma_L + \ldots\right]$$

virtual photon "flux"

photoabsorption cross sections

photon polarization, wrt q

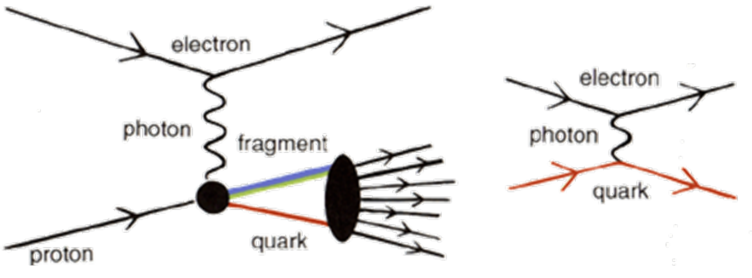
$$\varepsilon(\pm 1) = -\frac{1}{\sqrt{2}}(0,1,\pm i,0)$$

$$\varepsilon(0) = \frac{1}{\sqrt{Q^2}}\left(\sqrt{Q^2+\nu},0,0,\nu\right)$$

Deep Inelastic Electron Scattering

energy available to produce
particles in final state

$$s = W^2 = \left(E_{beam} + E_{tgt}\right)^2 = \left(E' + \sum_h E_h\right)^2$$



from Nobel lectures, 1990

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

Experimentally, W_2 and W_1 seem to depend on only one variable

$$x = \frac{Q^2}{2M_{tgt}\nu}, \quad 0 < x < 1, \quad \sum x_{partons} = 1$$

$$W_1\left(\nu,Q^2\right) = F_1(x)$$

$$\frac{\nu}{M}W_2\left(\nu,Q^2\right) = F_2(x)$$

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

"scaling" (anticipated by Bjorken, 1967)

scaling good when $(Q^2,\nu) \rightarrow \infty$, and if the partons have no transverse momentum .

DIS and quark momentum distributions

x = fraction of proton’s momentum carried by individual quark
(in reference frame where proton moving ~ speed of light…)

The scaling behavior is good when $(Q^2,\nu) \rightarrow \infty$, and holds in the limit that the quark transverse momentum is 0.

$$F_2(x) = 2xF_1(x) = xP(x) \rightarrow \qquad P(x) \equiv \sum_{quarks} e_i^2 f_i(x)$$

proton:

$$F_2^p(x) = x\left\{\frac{4}{9}\left[u(x)+\bar{u}(x)\right]+\frac{1}{9}\left[d(x)+\bar{d}(x)+s(x)+\bar{s}(x)\right]\right\}$$

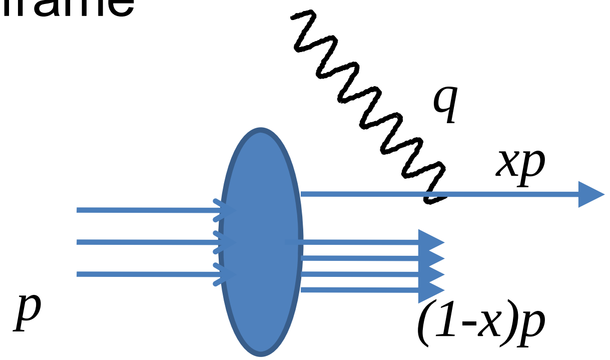
parton distribution functions

If isospin symmetry is good, which says that u in the neutron is just like d in the proton:

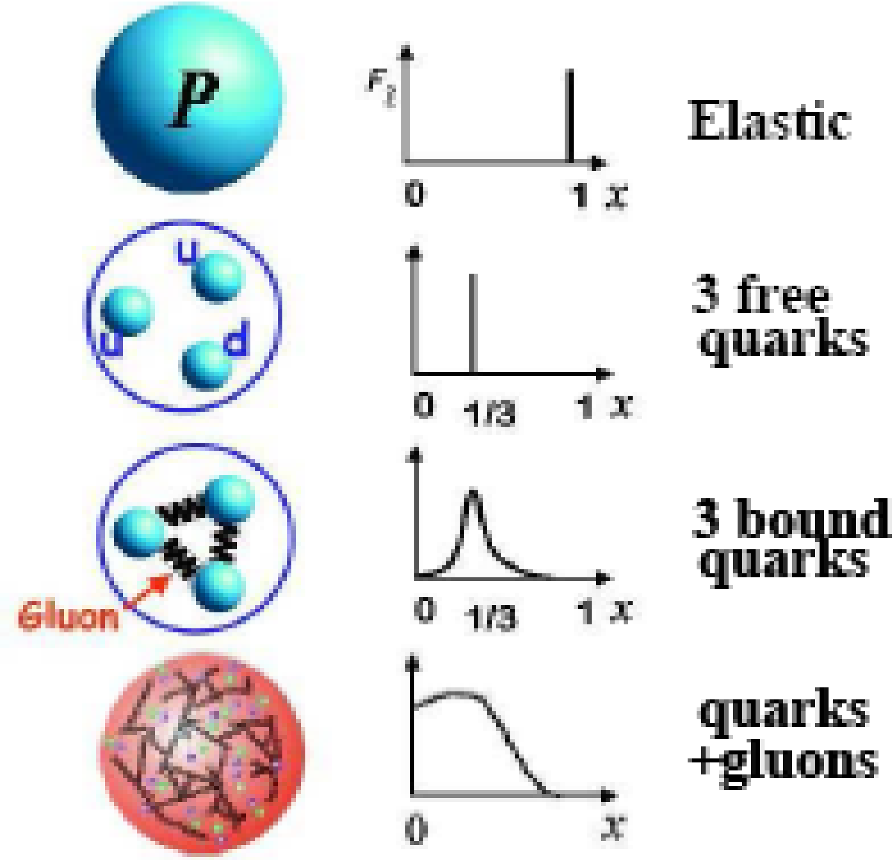
$$F_2^n(x) = x\left\{\frac{4}{9}\left[d(x)+\bar{d}(x)\right]+\frac{1}{9}\left[u(x)+\bar{u}(x)+s(x)+\bar{s}(x)\right]\right\}$$

interpretation of parton distributions

x = fraction of the proton's momentum carried by the struck quark, in the "infinite momentum" frame



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



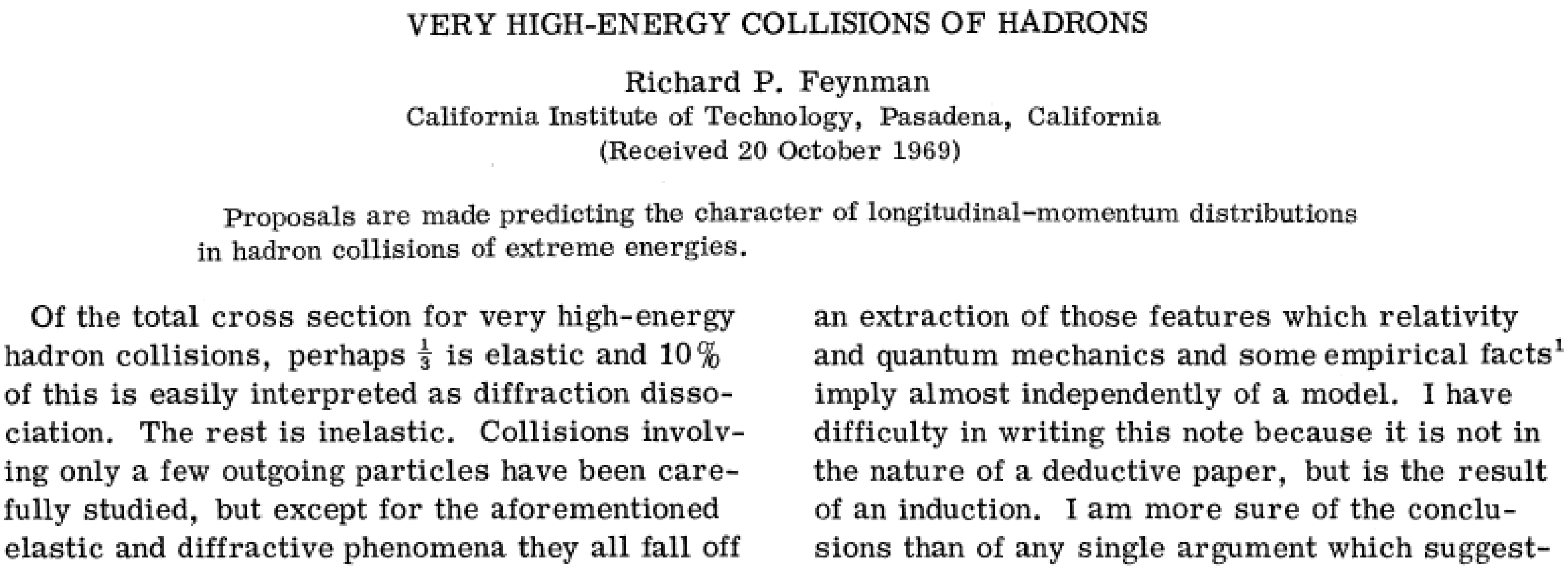
limits: $$\frac{F_2^n}{F_2^p} \xrightarrow[x\to 0]{} 1$$ $$\frac{F_2^n}{F_2^p} \xrightarrow[x\to 1]{} \frac{1}{4}$$

at very low x, the sea quarks should dominate

here the valence quarks should dominate and $u_v >> d_v$.

parton distribution functions

Phys. Rev. Lett. 23, 1415 - 1417 (1969)



VERY HIGH-ENERGY COLLISIONS OF HADRONS

Richard P. Feynman
California Institute of Technology, Pasadena, California
(Received 20 October 1969)

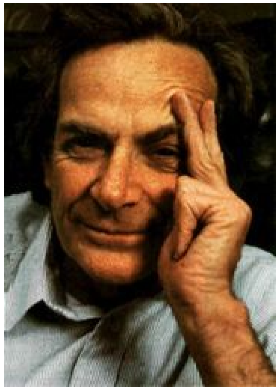
Proposals are made predicting the character of longitudinal-momentum distributions in hadron collisions of extreme energies.

Of the total cross section for very high-energy hadron collisions, perhaps $\frac{1}{3}$ is elastic and 10% of this is easily interpreted as diffraction dissociation. The rest is inelastic. Collisions involving only a few outgoing particles have been carefully studied, but except for the aforementioned elastic and diffractive phenomena they all fall off

an extraction of those features which relativity and quantum mechanics and some empirical facts[1] imply almost independently of a model. I have difficulty in writing this note because it is not in the nature of a deductive paper, but is the result of an induction. I am more sure of the conclusions than of any single argument which suggest-

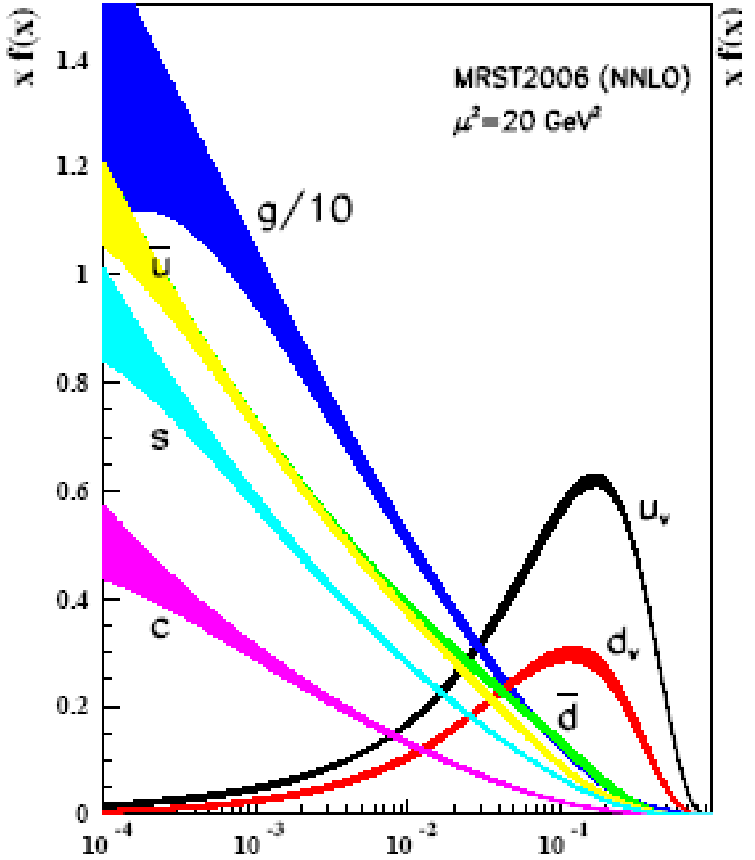
The parton distribution functions are a property of the target, not of the process.

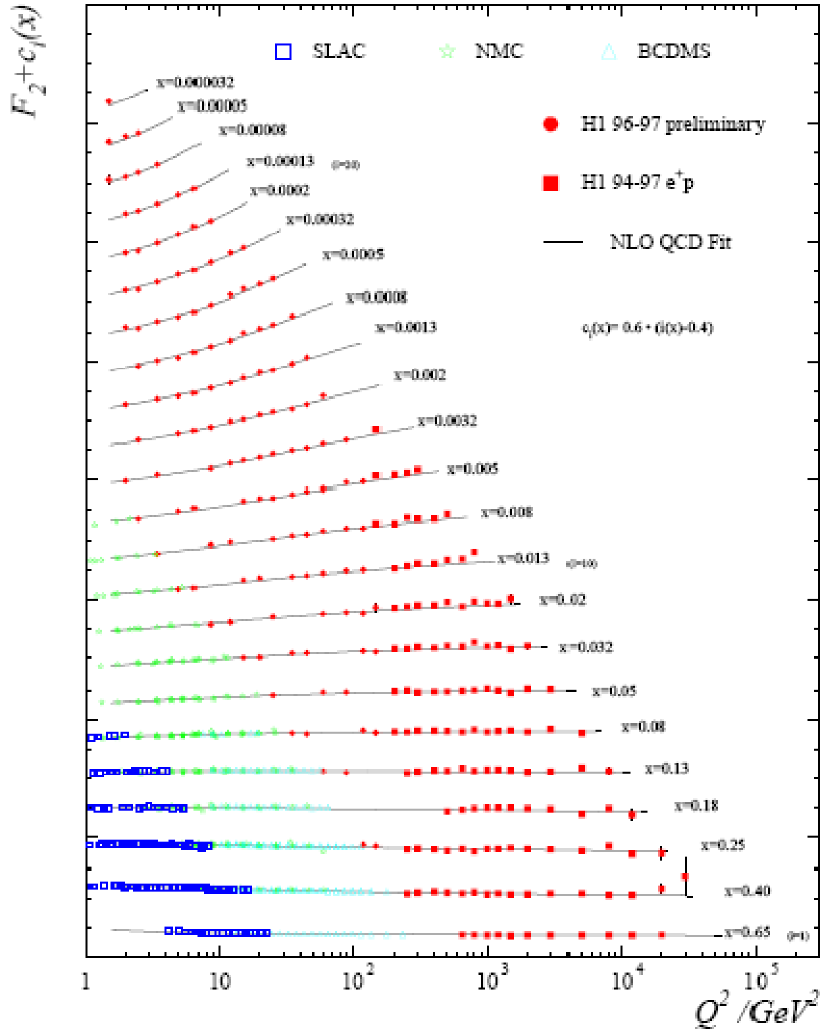
partons ←→ pointlike quarks



quark distribution functions

$F_2(x)$ "scaling" is violated when the strong interaction is "strong" (low x or small Q^2)





$$\int_0^1 P_{quarks}(x)dx \approx 0.5$$

parton flavors

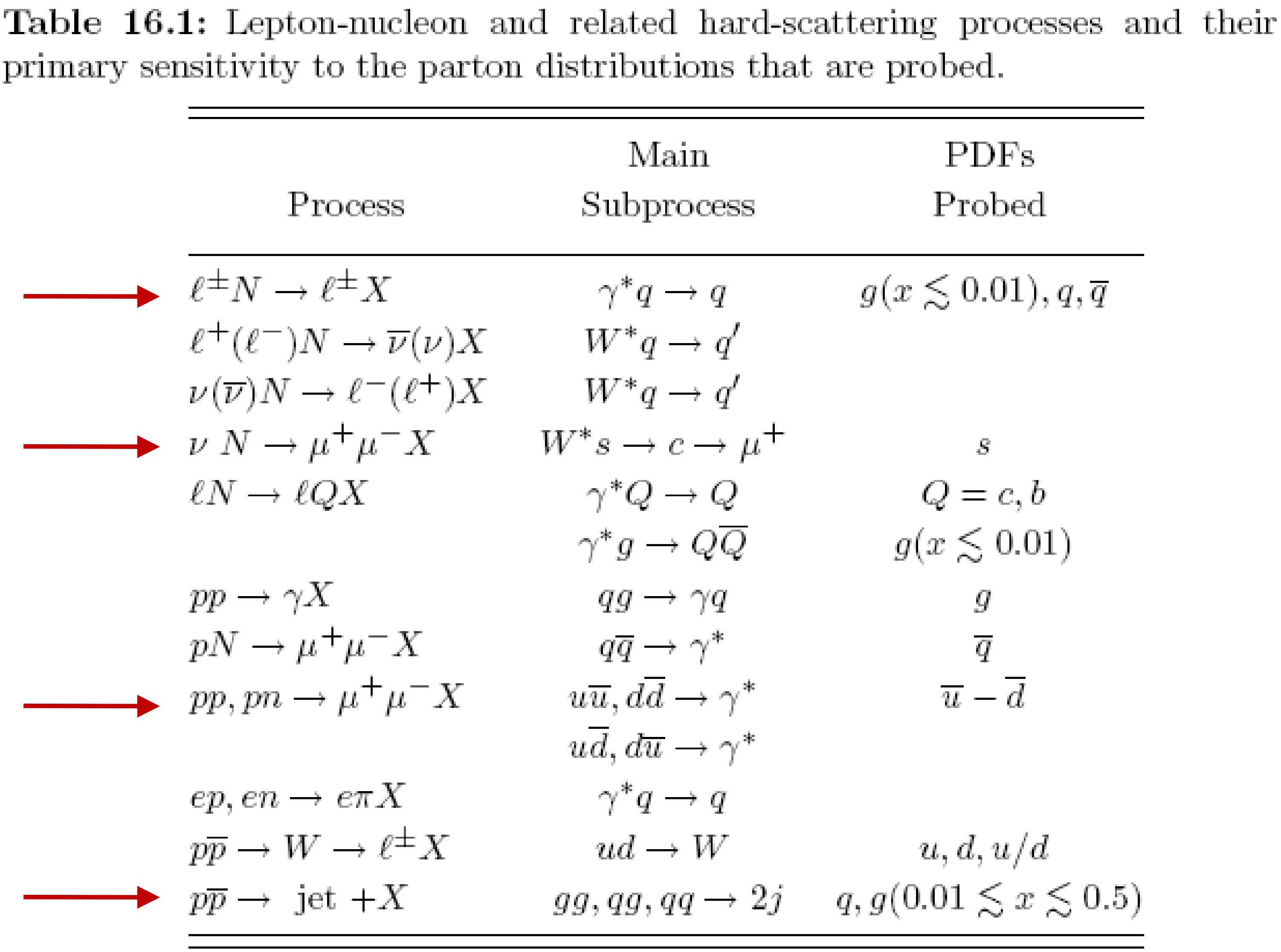


Table 16.1: Lepton-nucleon and related hard-scattering processes and their primary sensitivity to the parton distributions that are probed.

Process	Main Subprocess	PDFs Probed
$\ell^\pm N \to \ell^\pm X$	$\gamma^* q \to q$	$g(x \lesssim 0.01), q, \overline{q}$
$\ell^+(\ell^-)N \to \overline{\nu}(\nu)X$	$W^* q \to q'$	
$\nu(\overline{\nu})N \to \ell^-(\ell^+)X$	$W^* q \to q'$	
$\nu\ N \to \mu^+\mu^- X$	$W^* s \to c \to \mu^+$	s
$\ell N \to \ell Q X$	$\gamma^* Q \to Q$	$Q = c, b$
	$\gamma^* g \to Q\overline{Q}$	$g(x \lesssim 0.01)$
$pp \to \gamma X$	$qg \to \gamma q$	g
$pN \to \mu^+\mu^- X$	$q\overline{q} \to \gamma^*$	$\overline{q}$
$pp, pn \to \mu^+\mu^- X$	$u\overline{u}, d\overline{d} \to \gamma^*$	$\overline{u} - \overline{d}$
	$u\overline{d}, d\overline{u} \to \gamma^*$	
$ep, en \to e\pi X$	$\gamma^* q \to q$	
$p\overline{p} \to W \to \ell^\pm X$	$ud \to W$	$u, d, u/d$
$p\overline{p} \to$ jet $+X$	$gg, qg, qq \to 2j$	$q, g(0.01 \lesssim x \lesssim 0.5)$

from http://pdg.lbl.gov

Deep Inelastic ν–nucleon scattering

$$\nu_\mu + \text{nucleon} \rightarrow \mu^- + \text{hadrons}$$

$$\frac{d^2\sigma}{dxdy} = \frac{G_F^2 M_N E_\nu}{\pi}\left[(1-y)F_2^{\,\nu}(x) + \frac{y^2}{2}2xF_1^{\,\nu}(x) \mp y\left(\frac{1-y}{2}\right)xF_3^{\,\nu}(x)\right]$$

$$x = \frac{Q^2}{2M_{tgt}\nu},\ y = \frac{\nu}{E_{beam}} \qquad (\nu/\bar{\nu})$$

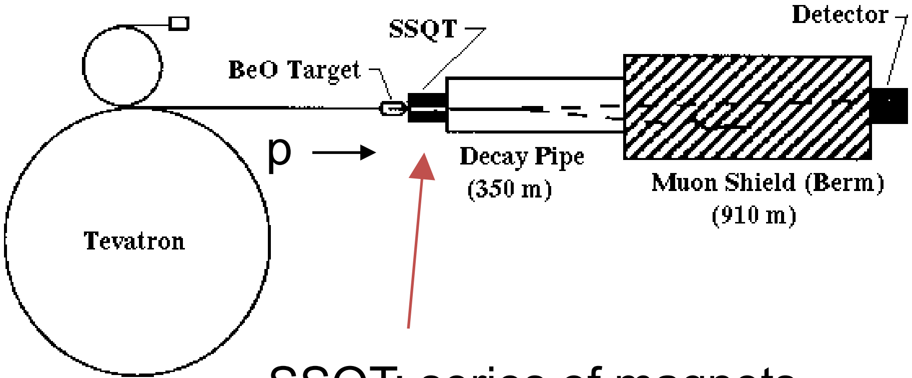
$F_{1,2,3}$ are weak interaction equivalents of those measured in electron scattering. Experimentally, they seem again to only depend on x (to lowest order) and are combinations of quark momentum distributions.

$$F_2^{\,\nu}(x) = xP_\nu(x) \ \rightarrow \quad P_\nu(x) \equiv \sum_{quarks} P(x_i)$$

Experimentally, for target w/equal numbers of neutrons and protons:

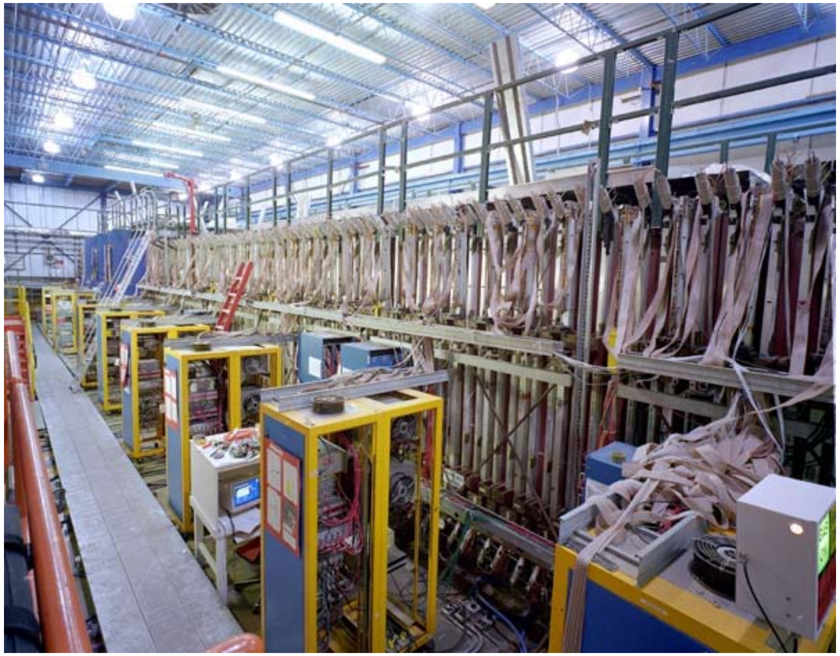
$$F_2^{\,\nu}(x) = \frac{18}{5}F_2^{\,e}(x)$$ (if ignore s-quarks...)

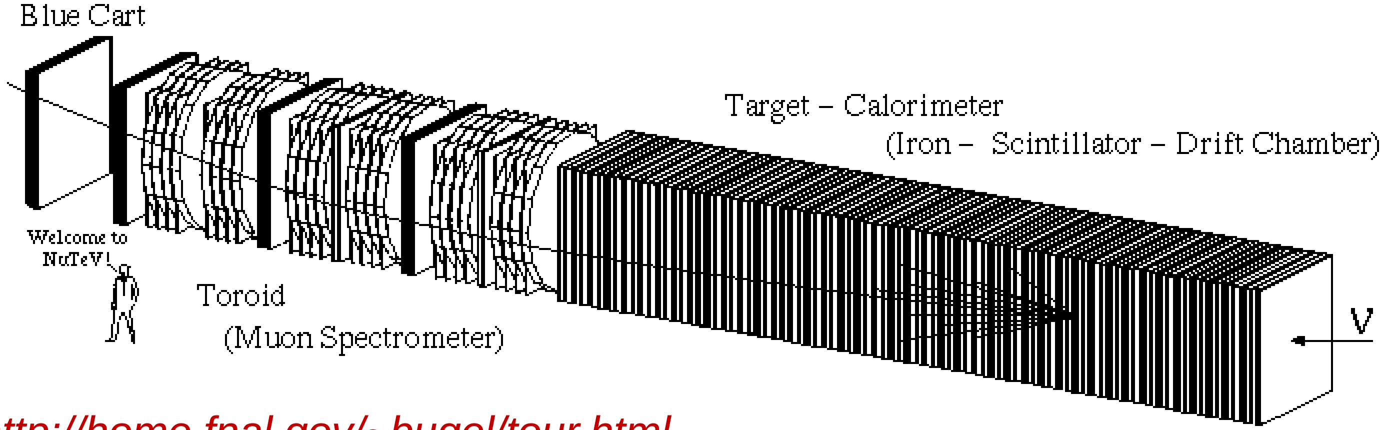
NuTeV: deep inelastic ν scattering



SSQT: series of magnets selects charge state of π,K

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow 2\nu_\mu + e^+ + \nu_e$$





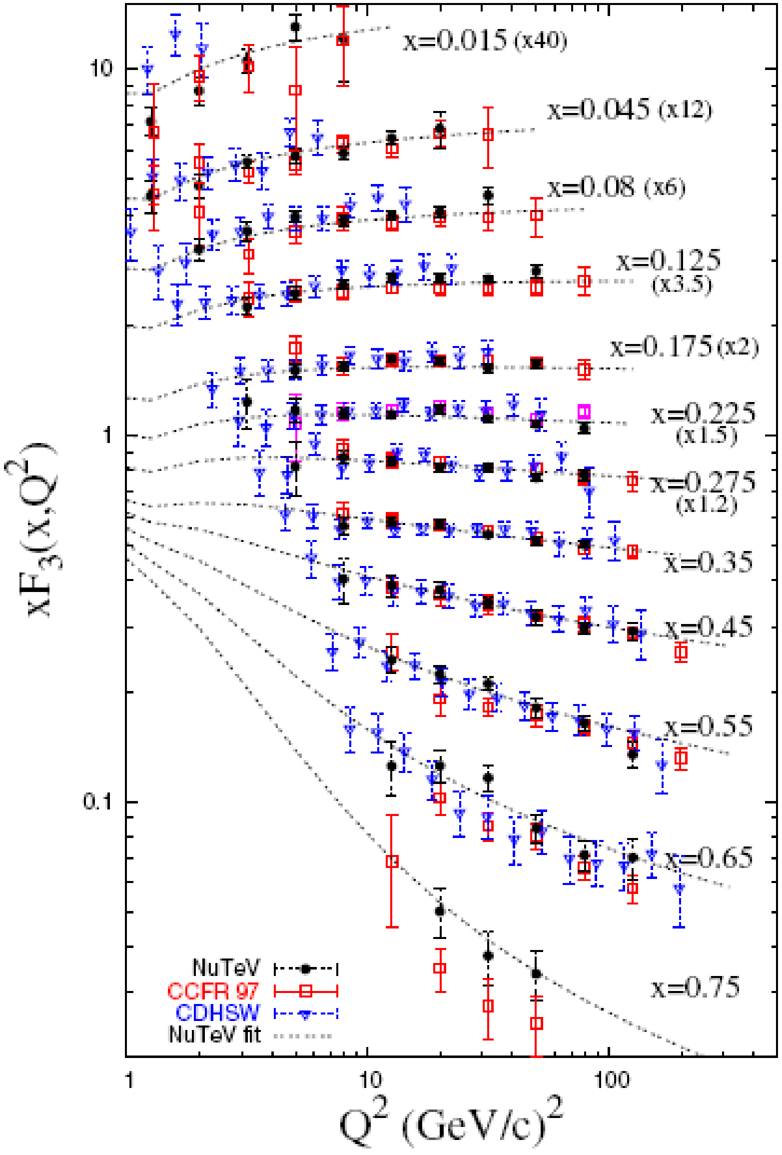
http://home.fnal.gov/~bugel/tour.html

neutrino scattering: $F_3(x)$

M. Tzanov, et al.,
Phys. Rev. D 74 (2006) 012008

$$\frac{d\sigma^{\nu}}{dx\,dy} = \frac{G_F^2 s}{2\pi}\left[xy^2F_1^{\nu} + (1-y)F_2^{\nu} + y(1-y/2)xF_3^{\nu}\right]$$
$$\frac{d\sigma^{\bar{\nu}}}{dx\,dy} = \frac{G_F^2 s}{2\pi}\left[xy^2F_1^{\bar{\nu}} + (1-y)F_2^{\bar{\nu}} - y(1-y/2)xF_3^{\bar{\nu}}\right]$$

$$F_2^{\nu} = 2x\left[d(x) + \bar{u}(x)\right]$$
$$F_3^{\nu} = 2\left[d(x) - \bar{u}(x)\right]$$
$$F_2^{\bar{\nu}} = 2x\left[u(x) + \bar{d}(x)\right]$$
$$F_3^{\bar{\nu}} = 2\left[u(x) - \bar{d}(x)\right]$$



NuTeV s-quark momentum distributions

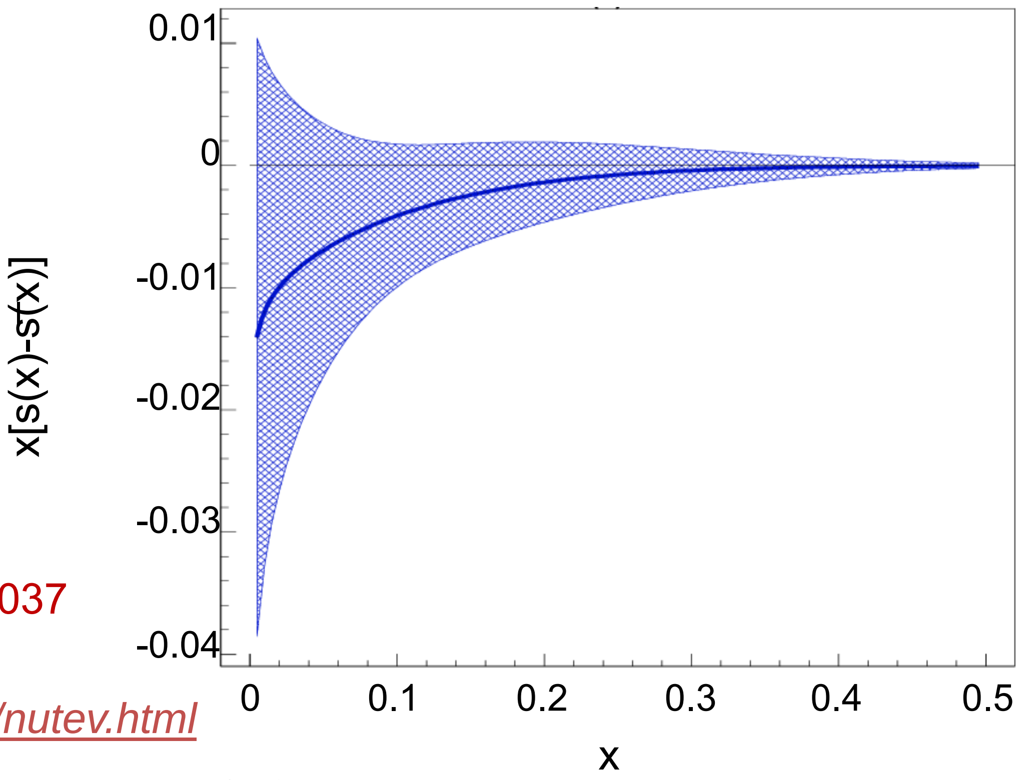
$$R^{-}=\frac{\sigma_{NC}^{\nu}-\sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu}-\sigma_{CC}^{\bar{\nu}}}=\frac{1}{2}-\sin^{2}\theta_{W}+\delta R^{-}$$

from this they extract $\sin^2\theta_W$

$$\delta R^{-}=-\left(\delta N\frac{\int x(u_{v}-d_{v})dx}{\int x(u_{v}+d_{v})dx}+\boxed{\frac{\int x(s-\bar{s})dx}{\int x(u_{v}+d_{v})dx}}\right)\left[1-\frac{7}{3}s^{2}{}_{W}+\frac{4\alpha_{s}}{9\pi}\left(\tfrac{1}{2}-s^{2}{}_{W}\right)\right]$$

NuTeV fit (NLO)

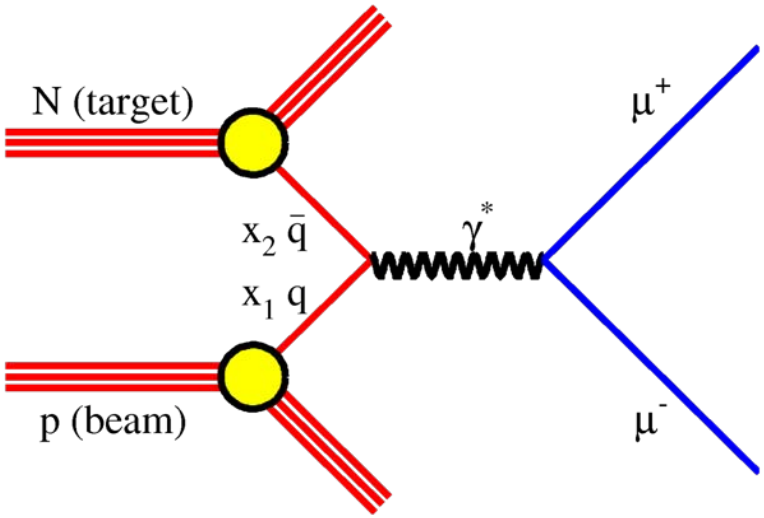
$$\boxed{\begin{aligned}S^{-}&\equiv\int x(s-\bar{s})dx\\&=-0.0013\pm0.0013\end{aligned}}$$



CTEQ6M, NLO
NuTeV → D. Mason et al, hep-ex/0405037

see also [http:// home.fnal.gov/~gzeller/nutev.html](http://home.fnal.gov/~gzeller/nutev.html)

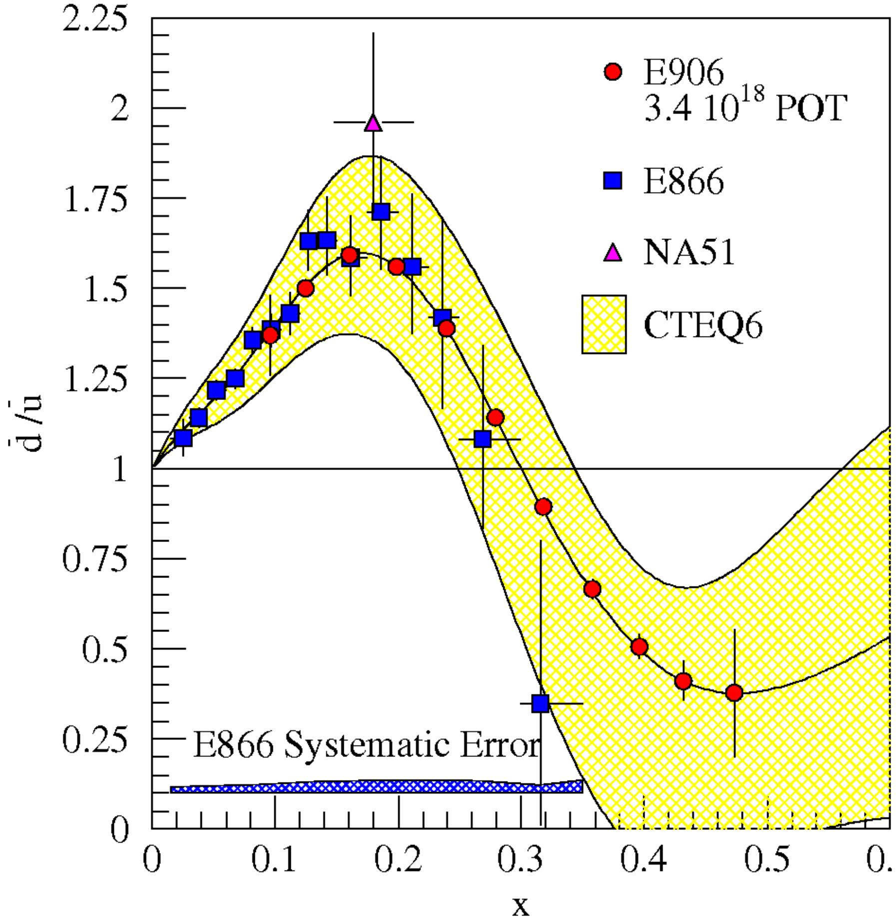
The Drell-Yan process: antiquarks



$$\sigma_{pp} \propto \frac{4}{9} u(x_1)\bar{u}(x_2) + \frac{1}{9} d(x_1)\bar{d}(x_2)$$

$$\sigma_{pn} \propto \frac{4}{9} u(x_1)\bar{d}(x_2) + \frac{1}{9} d(x_1)\bar{u}(x_2)$$

$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$



FNAL E866:

E. Hawker, etal, PRL 80 (1998) 3715

FNAL E906:

scheduled for 2010

future program at J-PARC

sum rules

$$\int_0^1 dx\, u_v(x,Q^2) = 2$$

$$\int_0^1 dx\, d_v(x,Q^2) = 1$$

$$\int_0^1 dx\, (s(x) - \bar{s}(x)) = 0$$

counts the net excess of quarks over anti-quarks of each type

$$\int_0^1 dx\, F_3^{\nu N} \simeq \int dx(d_v + u_v) = 3$$

Gross-Llewellyn-Smith sum rule: counts the excess quarks over anti-quarks, as seen by neutrinos

$$\int_0^1 \frac{dx}{x}\left[F_2^{\nu n}(x) - F_2^{\nu p}(x)\right] = 2$$

Adler sum rule (neutrinos)

$$\int_0^1 \frac{dx}{x}\left[F_2^{ep}(x) - F_2^{en}(x)\right] = \frac{1}{3}$$

Gottfried sum rule (electrons)

$$\int_0^1 \frac{dx}{x}\left[A^{ep}(x)F_2^{ep}(x) - A^{en}(x)F_2^{en}(x)\right] = \frac{1}{3}\frac{g_A}{g_V}$$

Bjorken sum rule (axial charge)

The hadronic tensor with spin-dependence

http://pdg.lbl.gov

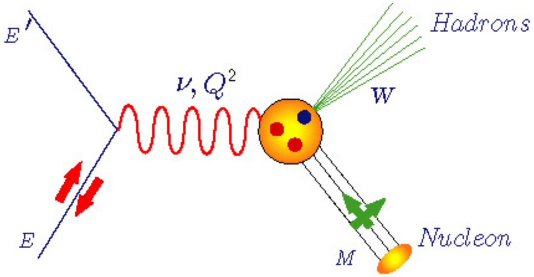
$$\begin{aligned}
W_{\mu\nu} = & \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) F_1(x,Q^2) + \frac{\hat{P}_\mu \hat{P}_\nu}{P\cdot q} F_2(x,Q^2) \\
& - i\varepsilon_{\mu\nu\alpha\beta} \frac{q^\alpha P^\beta}{2P\cdot q} F_3(x,Q^2) \\
& + i\varepsilon_{\mu\nu\alpha\beta} \frac{q^\alpha}{P\cdot q} \left[S^\beta g_1(x,Q^2) + \left(S^\beta - \frac{S\cdot q}{P\cdot q} P^\beta\right) g_2(x,Q^2) \right] \\
& + \frac{1}{P\cdot q} \left[\frac{1}{2}\left(\hat{P}_\mu \hat{S}_\nu + \hat{S}_\mu \hat{P}_\nu\right) - \frac{S\cdot q}{P\cdot q} \hat{P}_\mu \hat{P}_\nu \right] g_3(x,Q^2) \\
& + \frac{S\cdot q}{P\cdot q} \left[\frac{\hat{P}_\mu \hat{P}_\nu}{P\cdot q} g_4(x,Q^2) + \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) g_5(x,Q^2) \right]
\end{aligned} \qquad (16.6)$$

where

$$\hat{P}_\mu = P_\mu - \frac{P\cdot q}{q^2} q_\mu, \qquad \hat{S}_\mu = S_\mu - \frac{S\cdot q}{q^2} q_\mu \,. \qquad (16.7)$$

Spin Structure Functions

(slide from Z. Meziani)



- Unpolarized structure functions $F_1(x,Q^2)$ and $F_2(x,Q^2)$

U
$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow + \uparrow\Uparrow) = \frac{8\alpha^2\cos^2(\theta/2)}{Q^4}\left[\frac{F_2(x,Q^2)}{\nu} + \frac{2F_1(x,Q^2)}{M}\tan^2(\theta/2)\right]$$

Q^2 :Four-momentum transfer
x : Bjorken variable
ν : Energy transfer
M : Nucleon mass
W : Final state hadrons mass

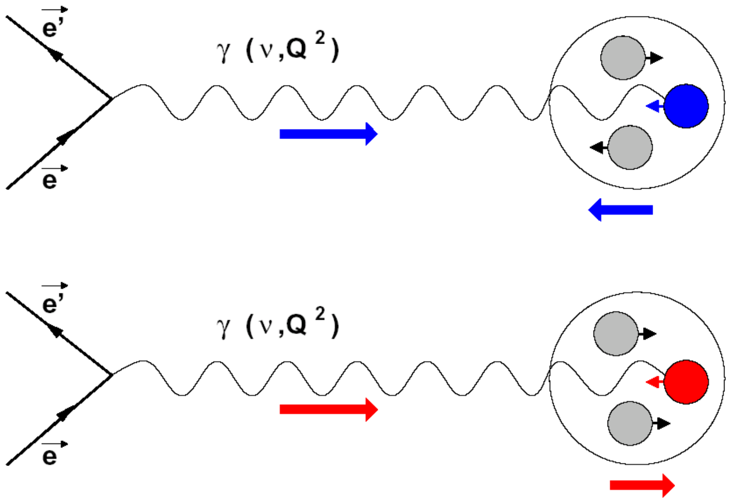
- Polarized structure functions $g_1(x,Q^2)$ and $g_2(x,Q^2)$

L
$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow - \uparrow\Uparrow) = \frac{4\alpha^2}{MQ^2}\frac{E'}{\nu E}\left[(E + E'\cos\theta)g_1(x,Q^2) - \frac{Q^2}{\nu}g_2(x,Q^2)\right]$$

T
$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{\nu^2 E}\left[\nu g_1(x,Q^2) + 2E g_2(x,Q^2)\right]$$

$$\boxed{g_1(x) \equiv \tfrac{1}{2}\sum_i e_i^2\left(q_i^+(x) - q_i^-(x)\right) = \tfrac{1}{2}\sum_i e_i^2 \Delta q_i(x)}$$

Polarized Deep Inelastic Scattering



$\sigma_{\uparrow\downarrow} \sim q^+$

$\sigma_{\uparrow\uparrow} \sim q^-$

$$\Delta q(x) = q(x)^+ - q(x)^-$$
$$q(x) = q(x)^+ + q(x)^-$$

+ quark ↑↑ nucleon
– quark ↑↓ nucleon

Inclusive asymmetry

$$A_1(x,Q^2) = \frac{\sigma_{\uparrow\downarrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\uparrow\downarrow} + \sigma_{\uparrow\uparrow}} \approx \frac{\sum_q e_q^2\, \Delta q(x,Q^2)}{\sum_q e_q^2\, q(x,Q^2)} = \frac{g_1(x,Q^2)}{F_1(x,Q^2)}$$

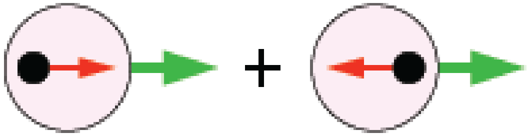
fragmentation function

Semi-inclusive asymmetry

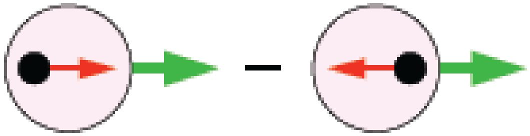
$$A_1^h(x,z,Q^2) = \frac{\sigma_{\uparrow\downarrow}^h - \sigma_{\uparrow\uparrow}^h}{\sigma_{\uparrow\downarrow}^h + \sigma_{\uparrow\uparrow}^h} \approx \frac{\sum_q e_q^2\, \Delta q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2\, q(x,Q^2) D_q^h(z,Q^2)}$$

A particular puzzle: Where does the proton spin come from?

$$q(x) = q^{\uparrow}(x) + q^{\downarrow}(x)$$



$$\Delta q(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$$



only three possibilities

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

❶ Quark polarization

$$\Delta\Sigma \equiv \int dx\, (\Delta u(x) + \Delta d(x) + \Delta s(x) + \Delta\bar{u}(x) + \Delta\bar{d}(x) + \Delta\bar{s}(x)) \approx 30\% \text{ only}$$

❷ Gluon polarization

$$\Delta G \equiv \int dx\, \Delta g(x) \quad ?$$

❸ Orbital angular momentum

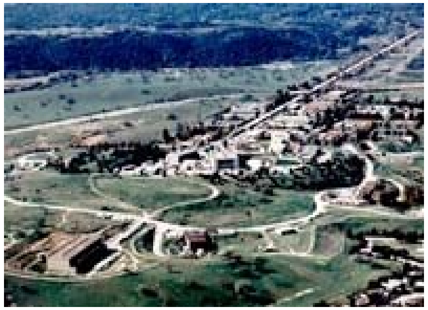
$$L_z \equiv L_q + L_g \quad ?$$

In friendly, **non-relativistic** bound states like atoms & nuclei (& constituent quark model), particles are in ***eigenstates of L***

Not so for bound, ***relativistic Dirac particles*** ...
Noble "*l*" is ***not a good quantum number***

N.C.R. Makins, CIPANP2009, San Diego, May 27, 2009

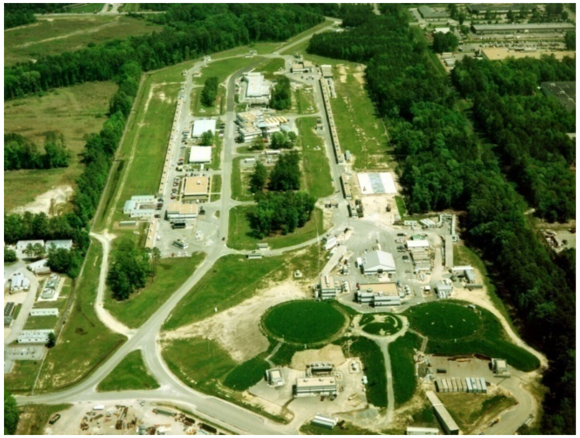
Many experiments…..



SLAC:
E80, E130,
E142, E154,
and others…

DESY:
HERMES

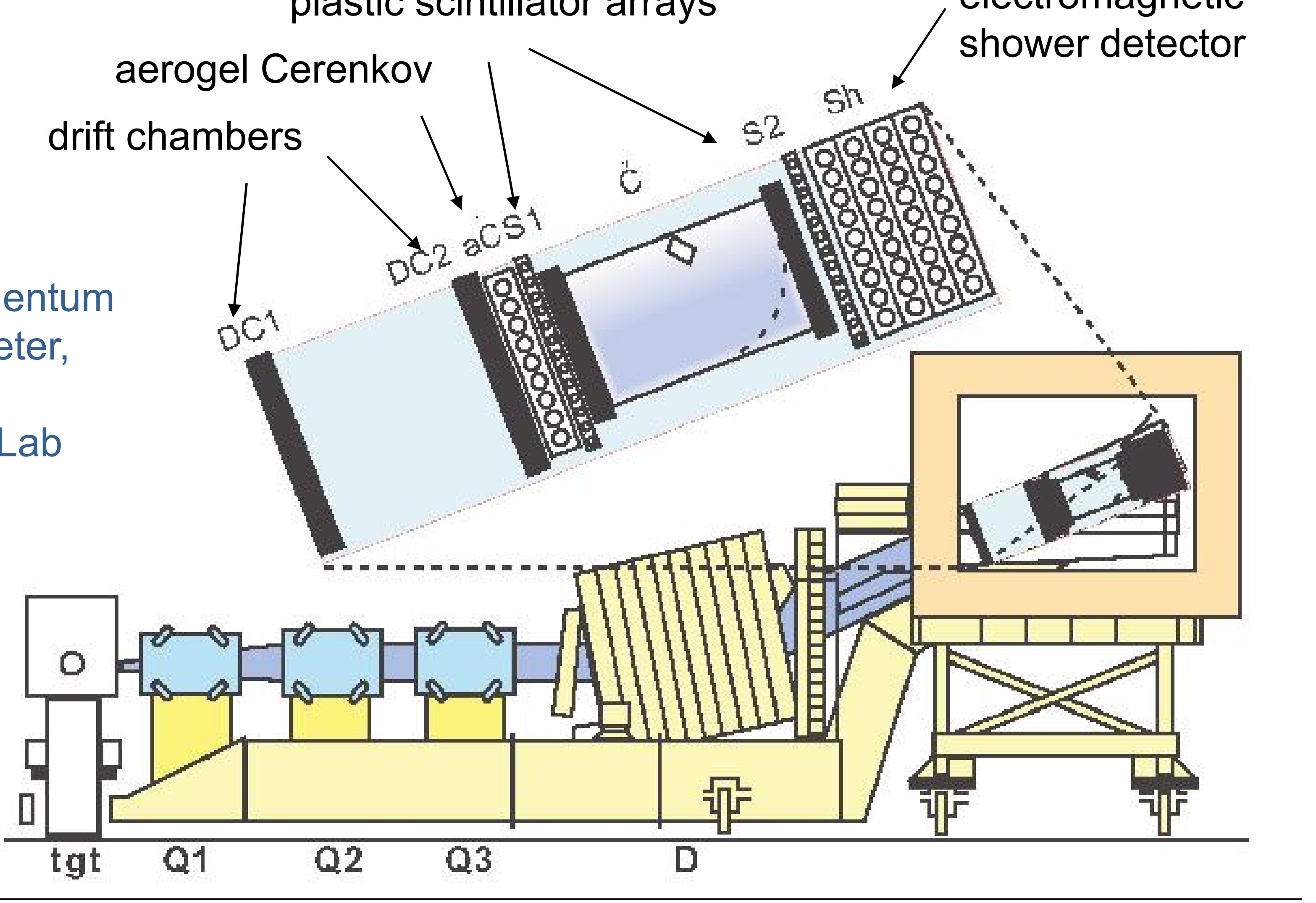
CERN:
EMC,SMC,
COMPASS



Brookhaven:
RHIC-Spin program
→ gluon spin

JLAB:
Hall A, Hall B

A relatively simple magnetic spectrometer



plastic scintillator arrays

electromagnetic
shower detector

aerogel Cerenkov

drift chambers

High Momentum
Spectrometer,
Hall C,
Jefferson Lab

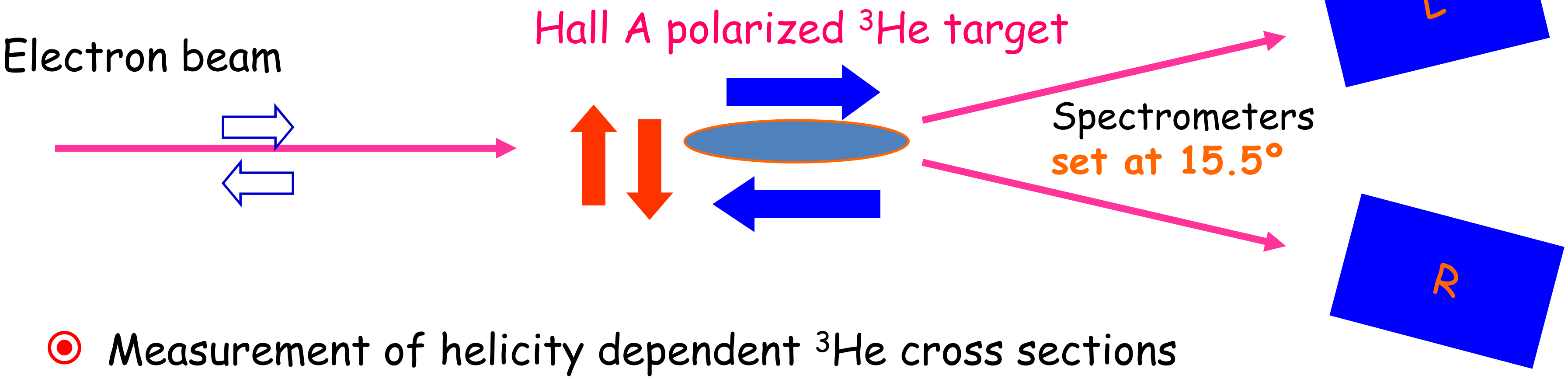
Example of a standard setup (in Hall A at JLab)

(slide from Z. Meziani)

Polarized beam
Energy: 0.86-5.1 GeV
Polarization: > 70%
Average Current: 5 to 15 μA

Hall A polarized ^{3}He target
Pressure ~ 10 atm
Polarization average: 35%
Length: 40 cm with 100 μm thickness

Highest polarized luminosity: ~10^{36}cm^{-2}s^{-1}



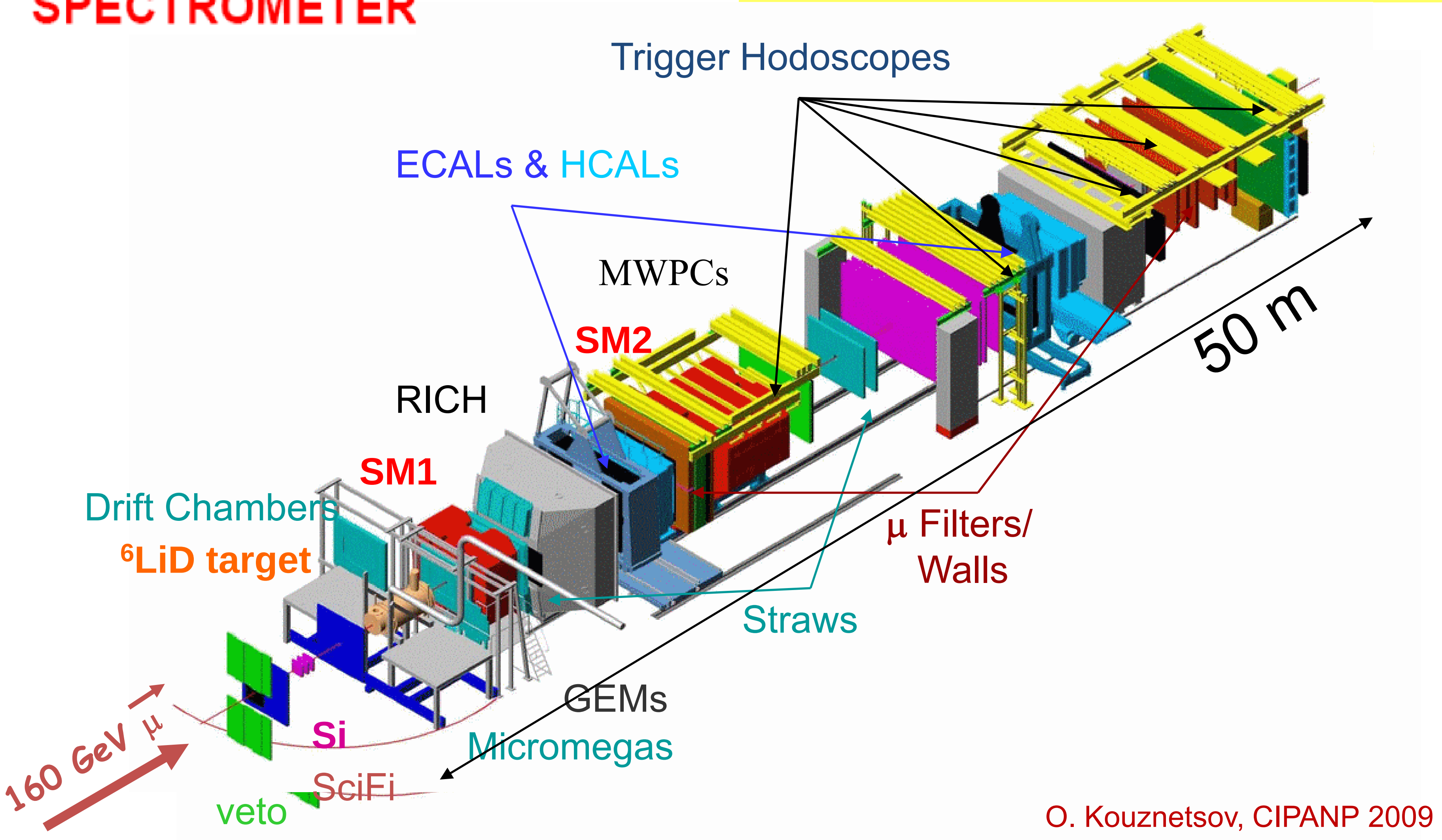
- Measurement of helicity dependent ^{3}He cross sections
- Extract g_1 and g_2 spin structure functions of ^{3}He
- Extract moments of spin structure functions of ^{3}He and Neutron

Polarized beam and target

TWO STAGE SPECTROMETER

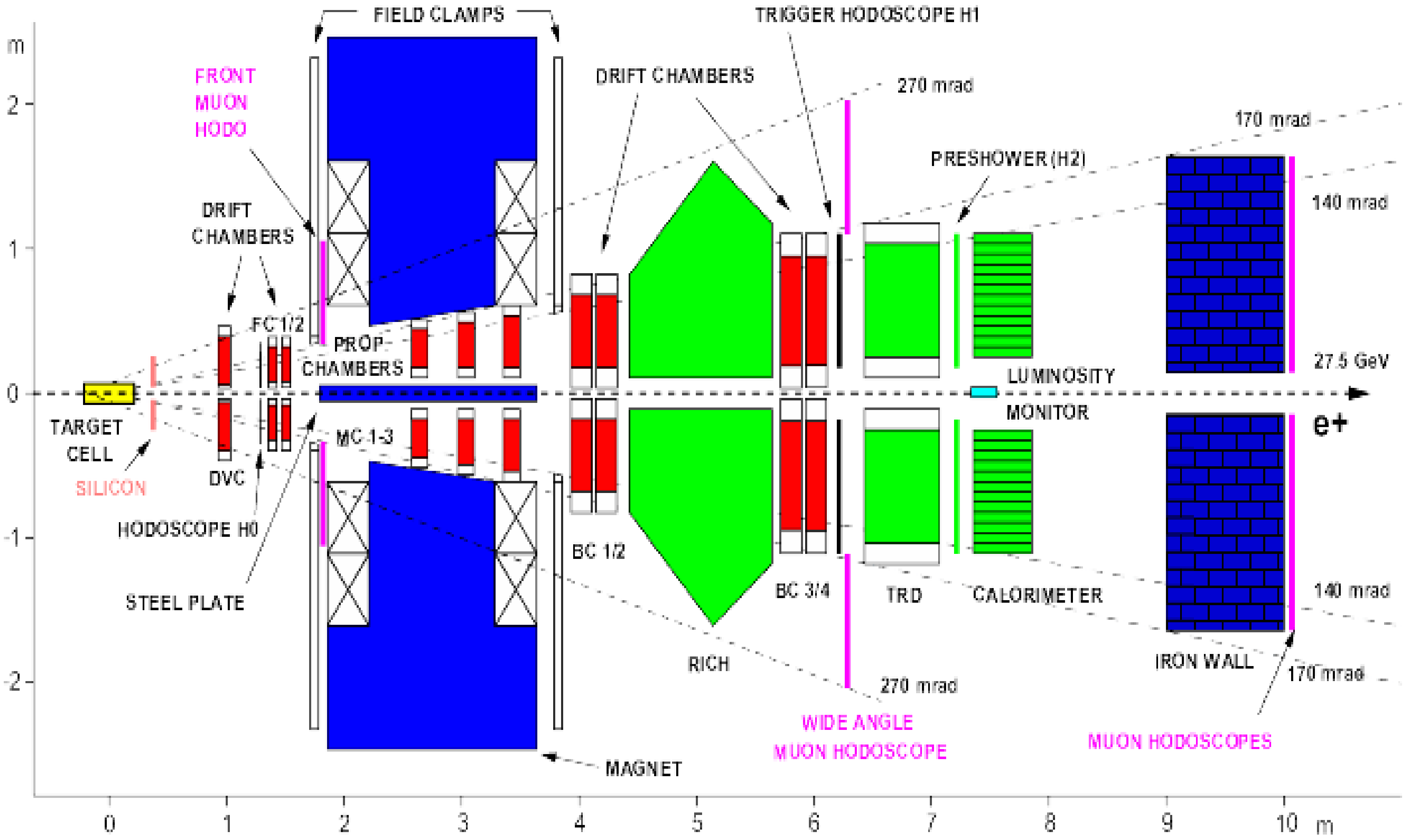
COMPASS

NIM A 577(2007) 455



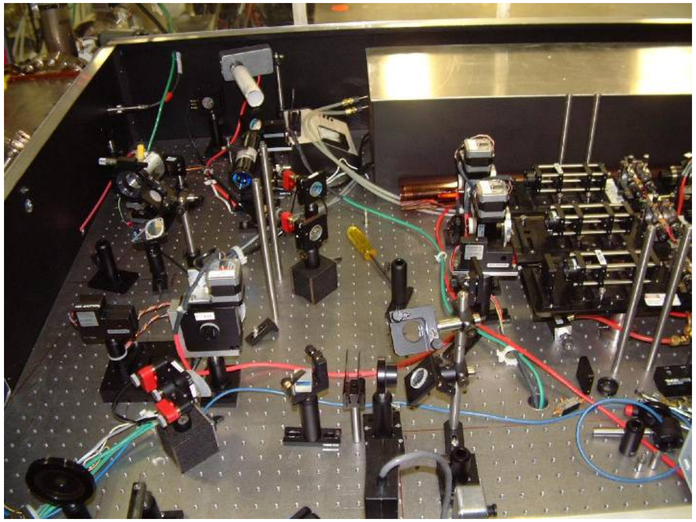
O. Kouznetsov, CIPANP 2009

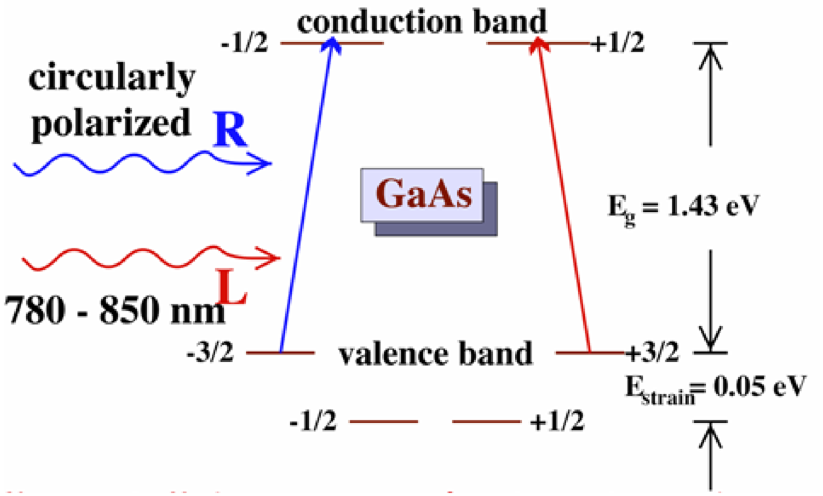
HERMES detector at DESY (Hamburg)



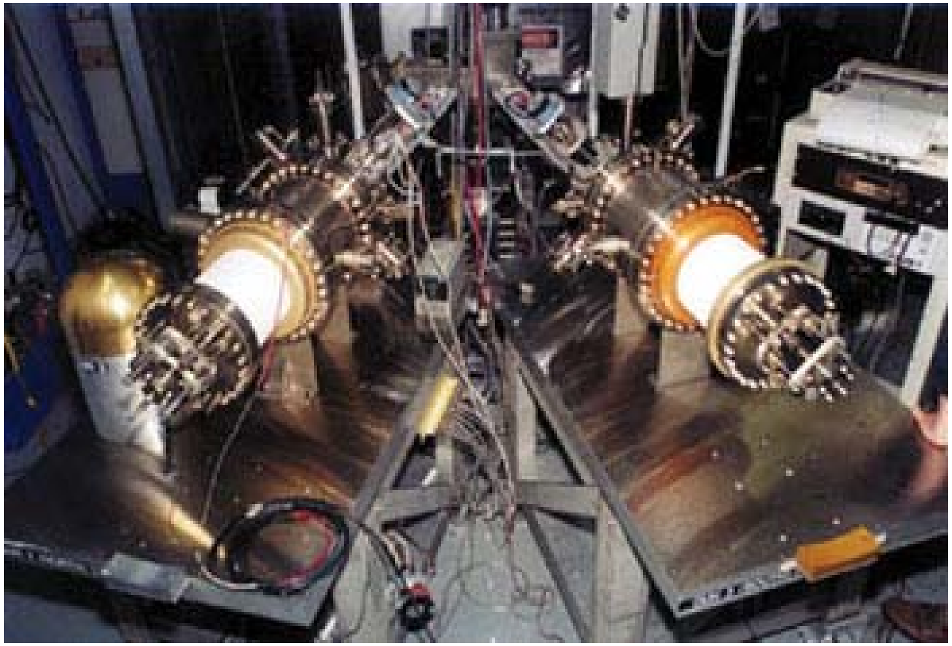
Polarized Electrons

D.T. Pierce et al., Phys. Lett. 51A (1975) 465.





Electron retains circular polarization of laser beam: $P_e \sim 85\%$



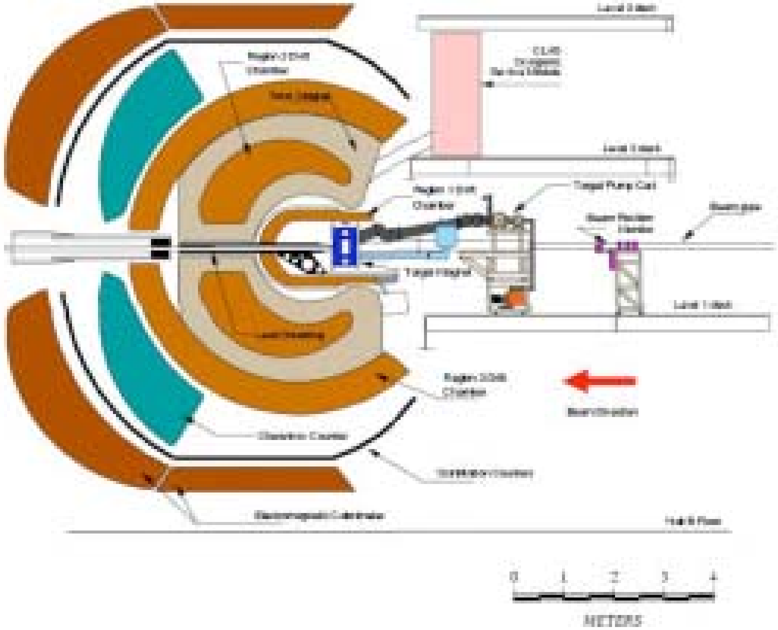
Reverse pol’n of beam at rate of 30 Hz

Feedback on laser intensity and position at high rate

See also Physics Today, Dec 2007

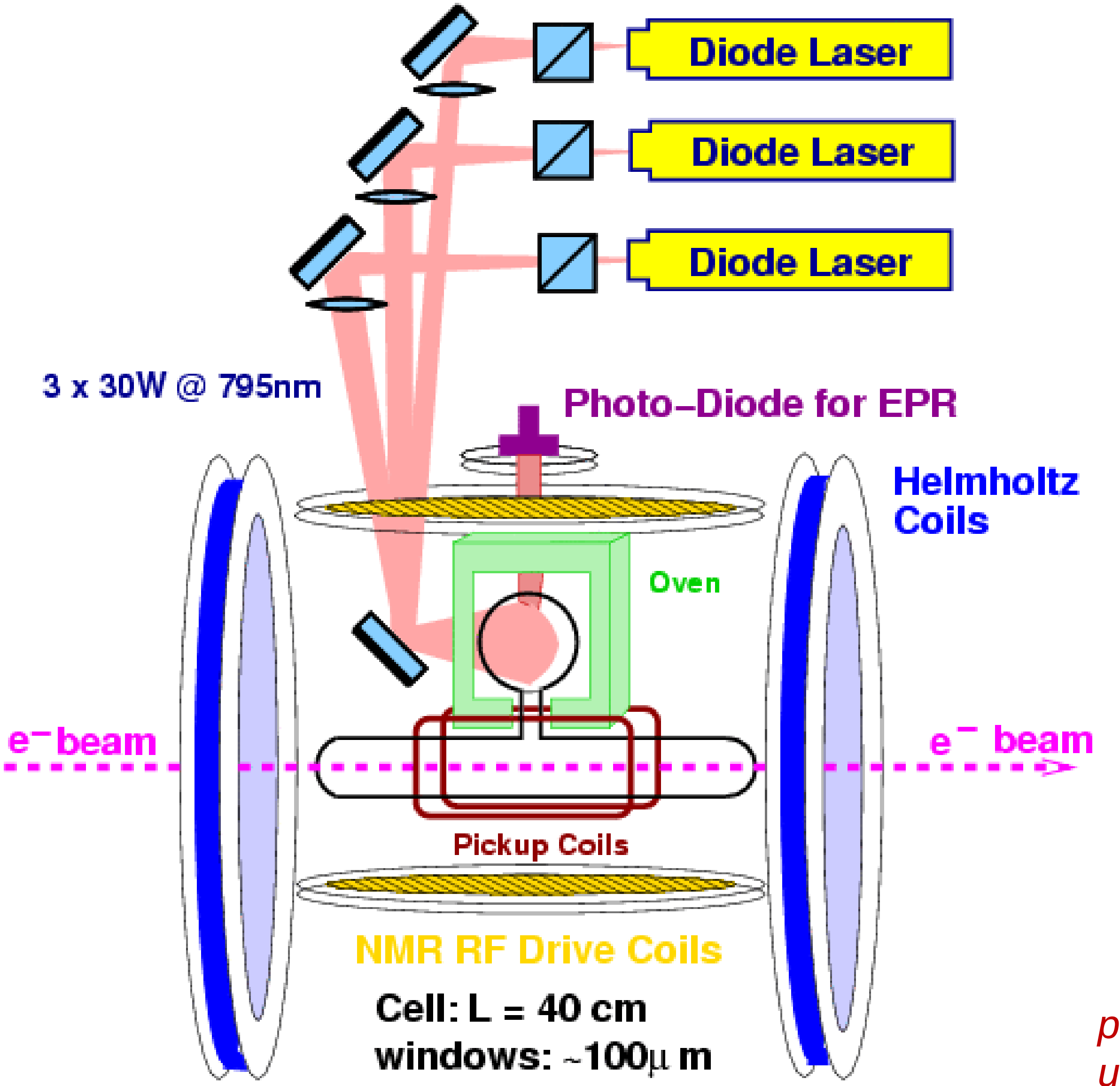
(In CLAS detector in Hall B at JLab, slide from K. Griffeon, DIS2007)

Polarized Target



- Dynamic nuclear polarization of NH_3 and ND_3
- Polarizations of 70-80% for p and 20-30% for d
- Luminosity 10^{35} $cm^{-2}s^{-1}$

Polarized ^{3}He

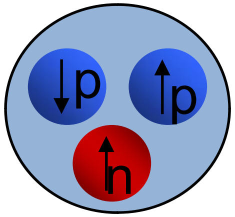


Spin -dependent scattering

$$\vec{e} + {}^3\vec{He}$$

looks like

$$\vec{e} + \vec{n}$$



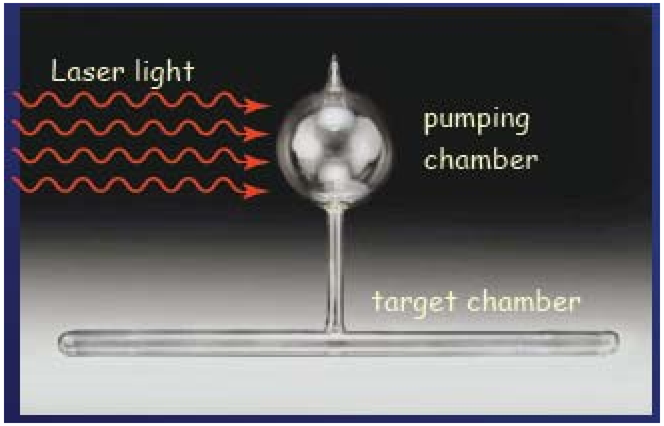
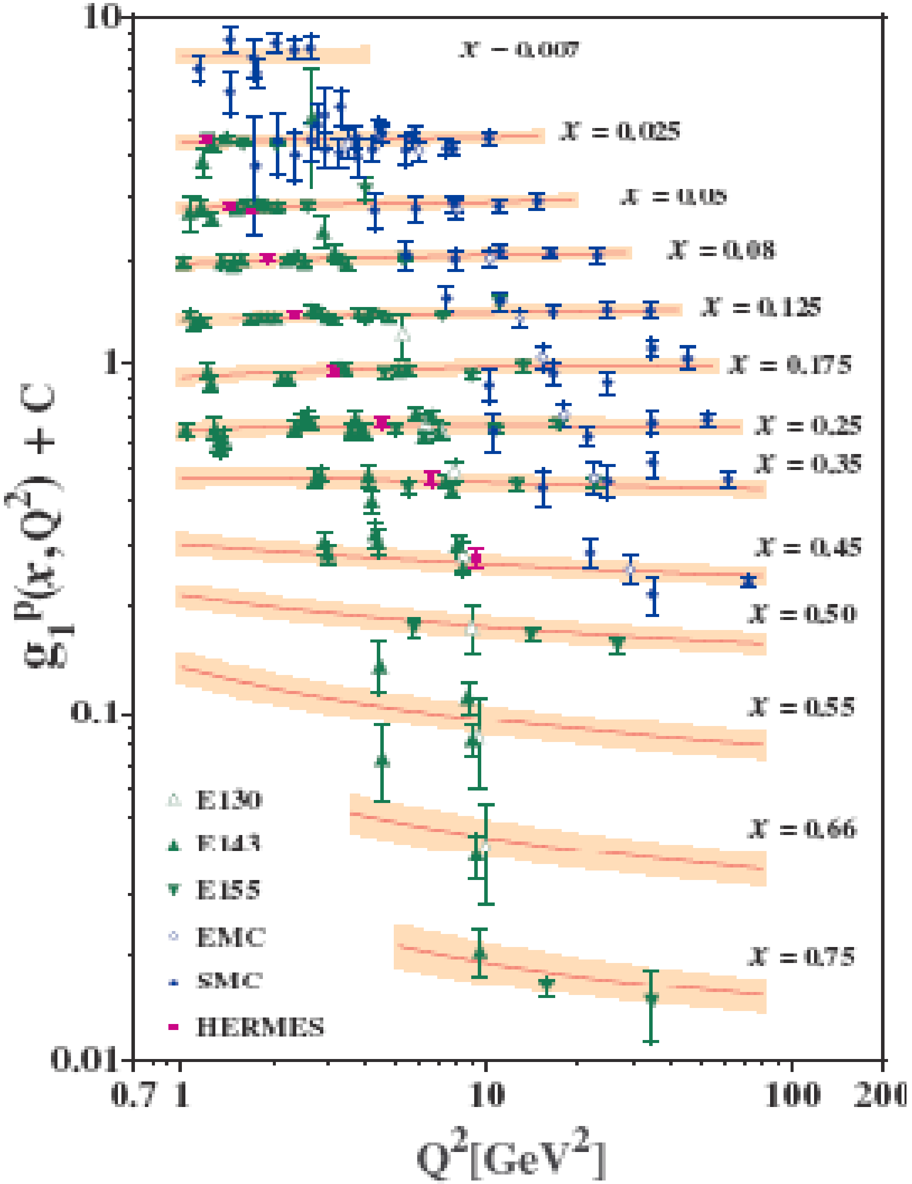
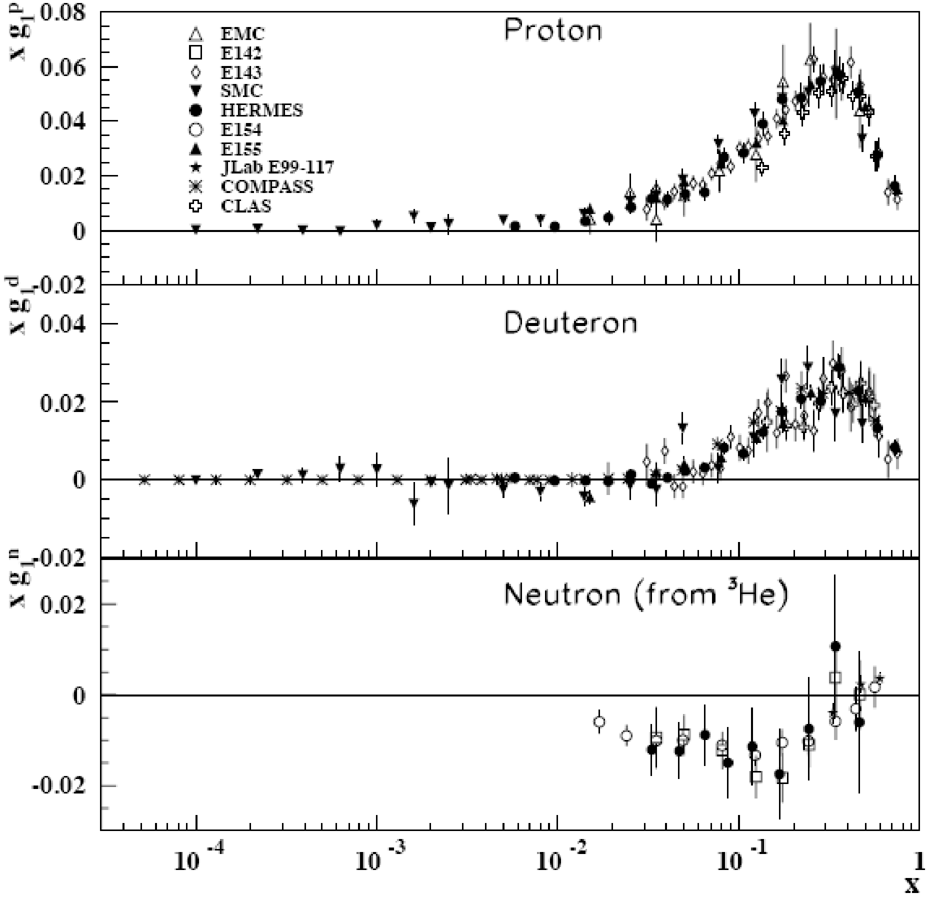


photo from G. Cates, CIPANP 2009
used in Hall A at JLab

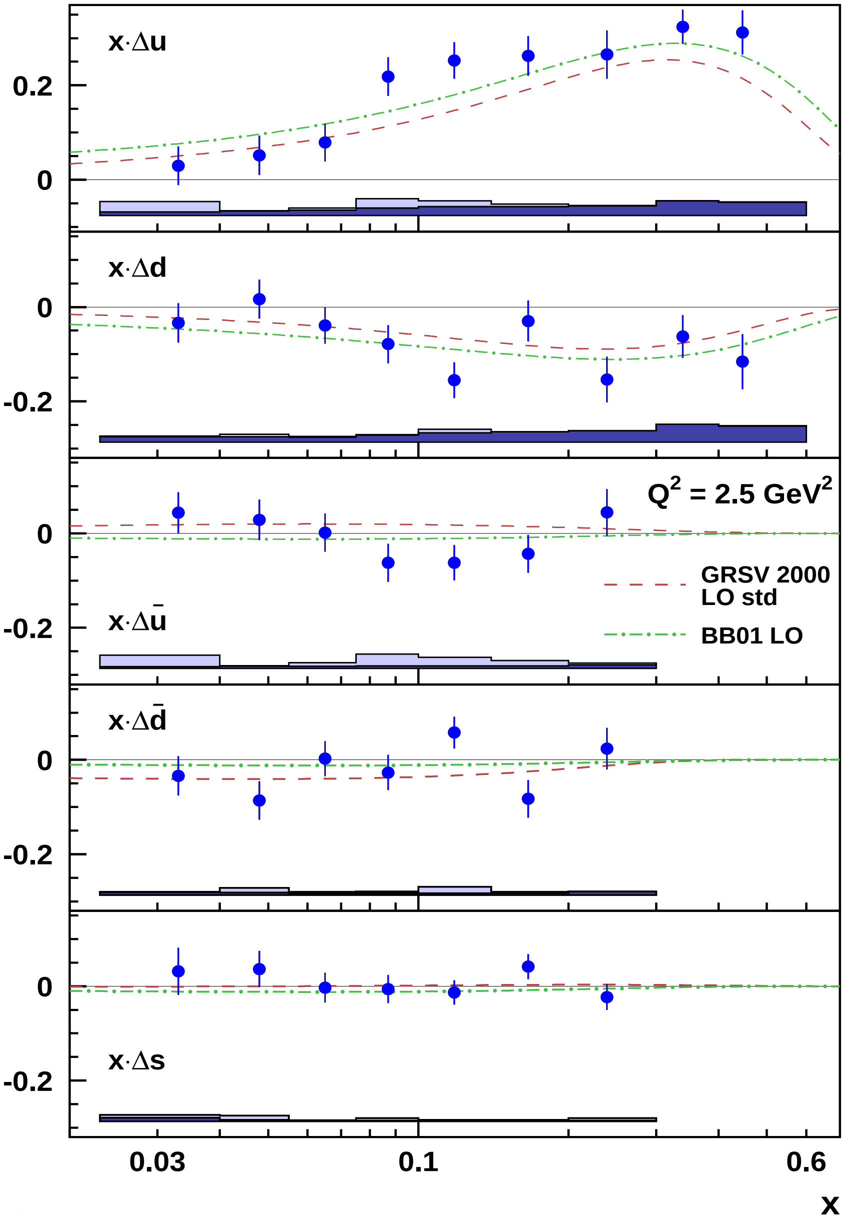
spin structure of the neutron and proton



from http://pdg.lbl.gov



spin structure of the proton



example: HERMES

A. Airapetian, et al.
PRD 71 (2005) 012003

Uses semi-inclusive scattering as well to disentangle u,d,s and valence/sea

$$\Delta u = 0.601 \pm 0.039 \pm 0.049$$

$$\Delta \bar{u} = -0.002 \pm 0.036 \pm 0.029$$

$$\Delta d = -0.226 \pm 0.039 \pm 0.050$$

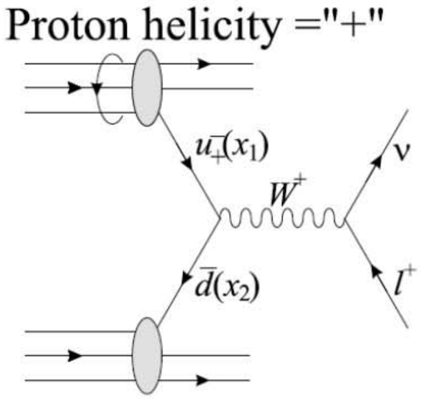
$$\Delta \bar{d} = -0.054 \pm 0.033 \pm 0.011$$

$$\Delta s = 0.028 \pm 0.033 \pm 0.009$$

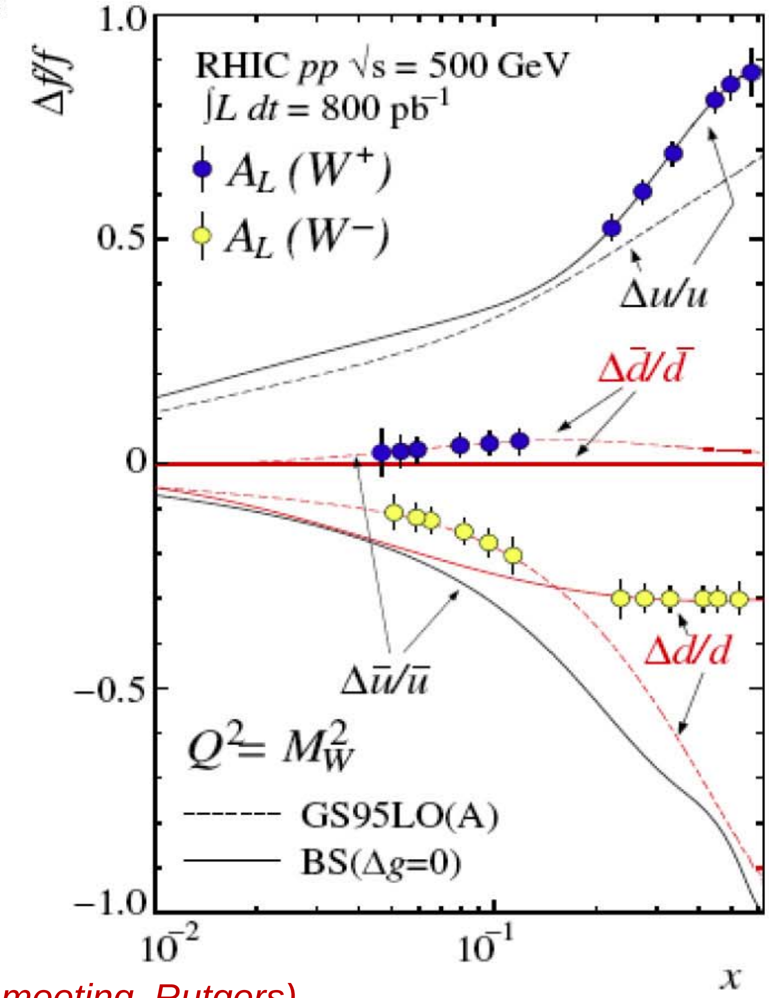
coming in the future….

Flavor separation of Δq from RHIC

- **W-production at 500 GeV:**



$$A_L^{W+} = \frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

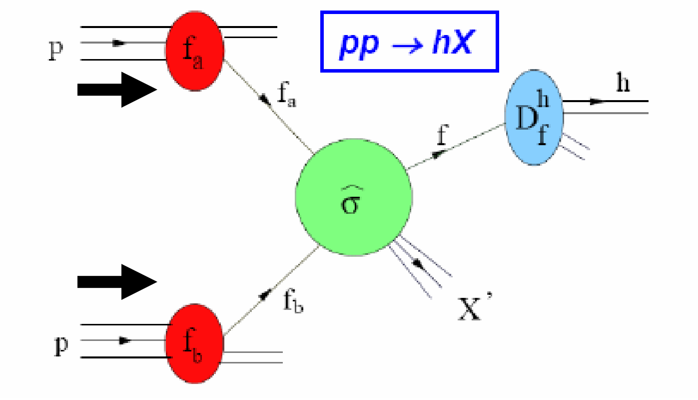


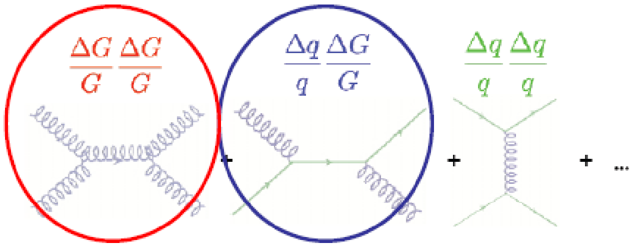
January 12, 2007

(QCD & Hadron Physics Town meeting, Rutgers)

Jianwei Qiu, ISU

Measurement of the gluon polarization ΔG at RHIC

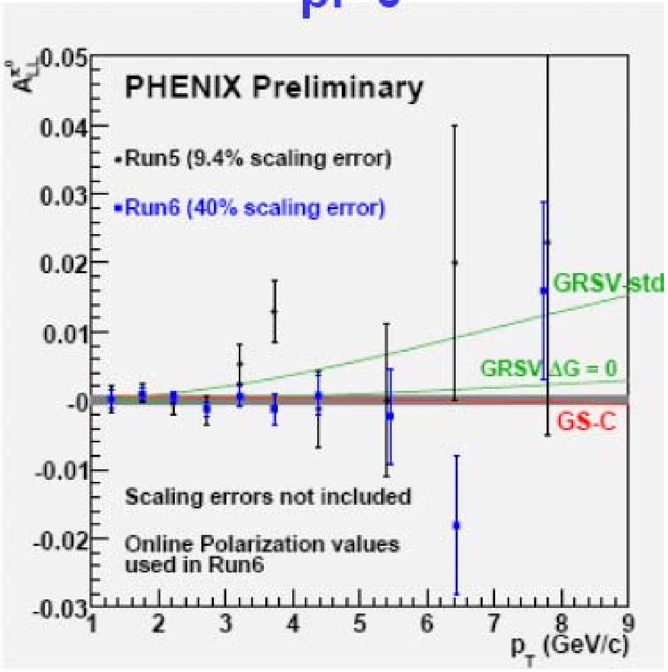




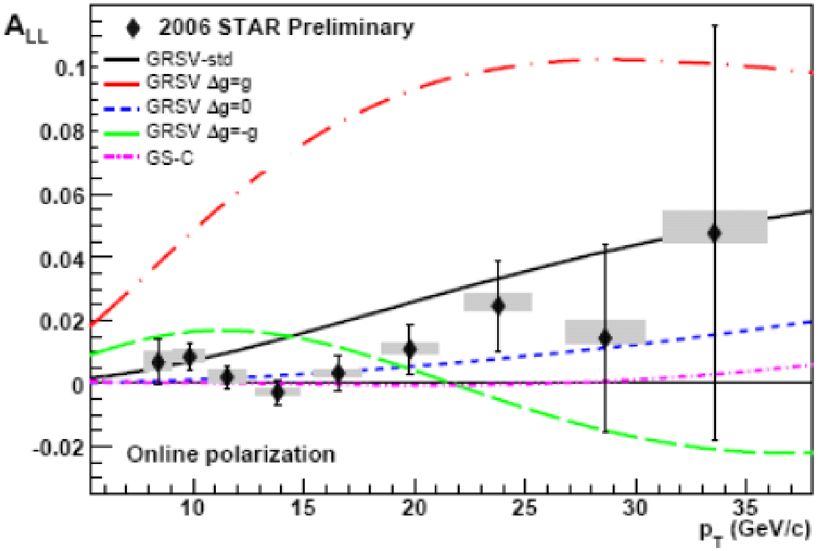
Dominates at low p_T

Dominates at high p_T

pi^0

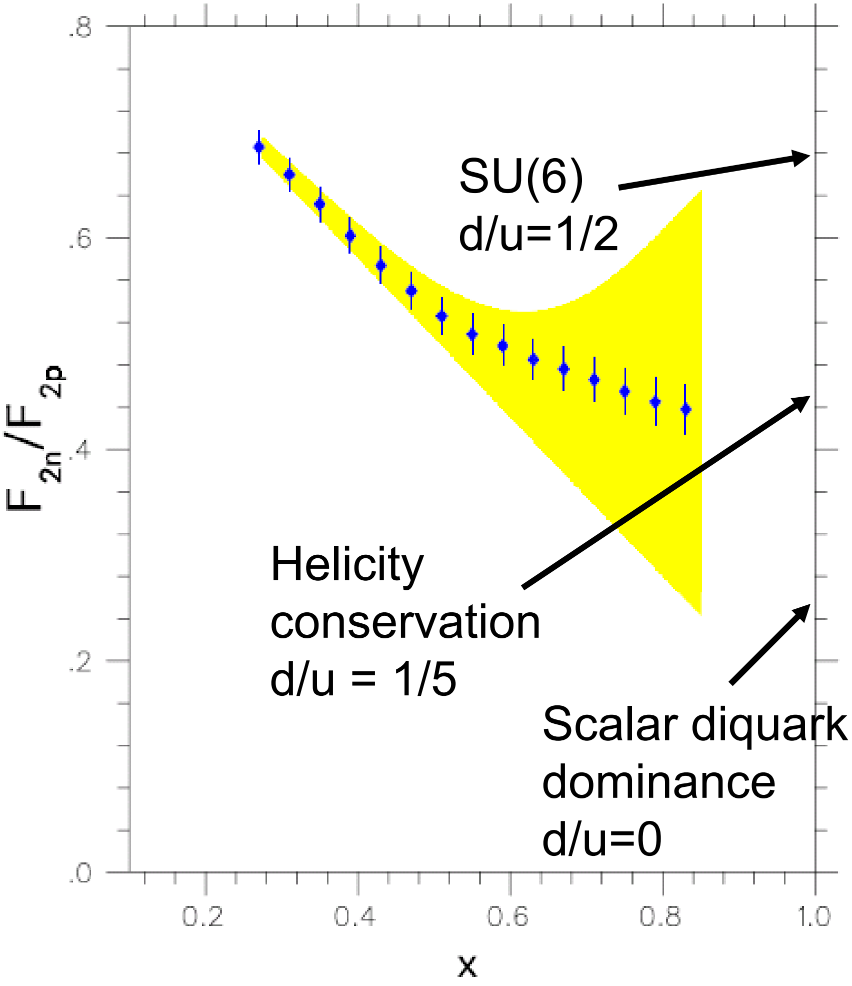


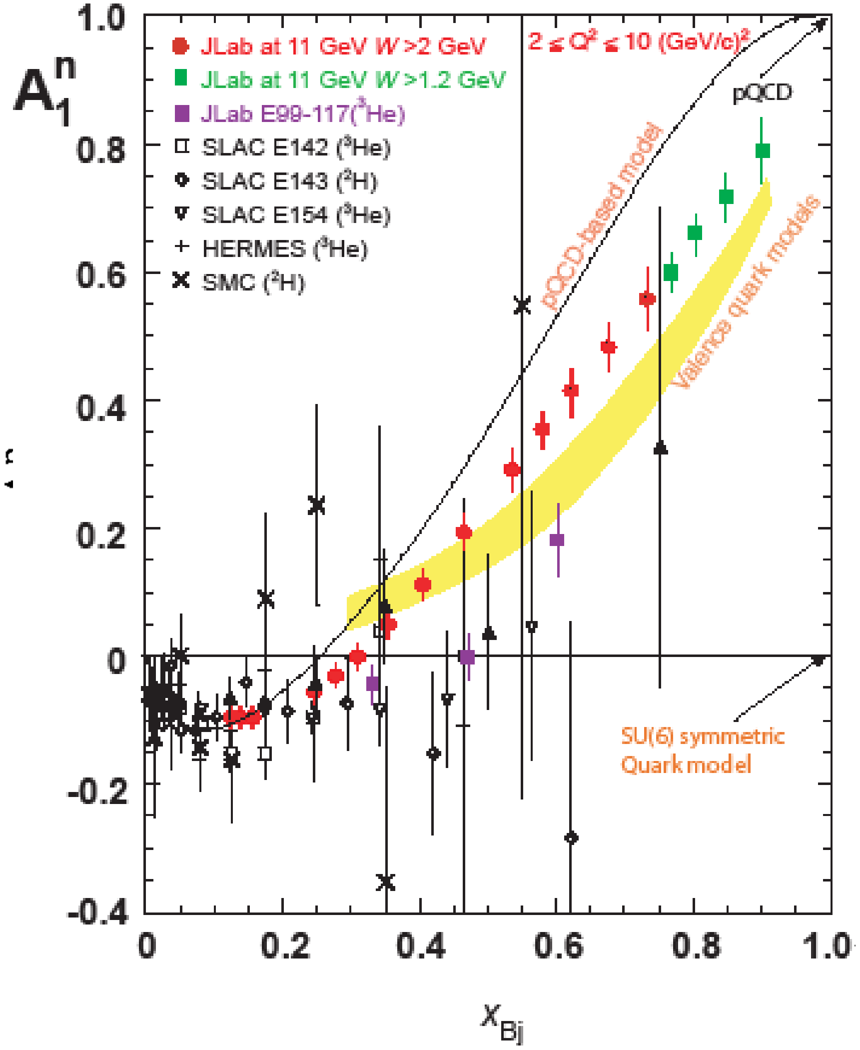
Jet



coming in the future….

Structure of the nucleon – valence region





proposed to be done at JLAB with 11 GeV beam

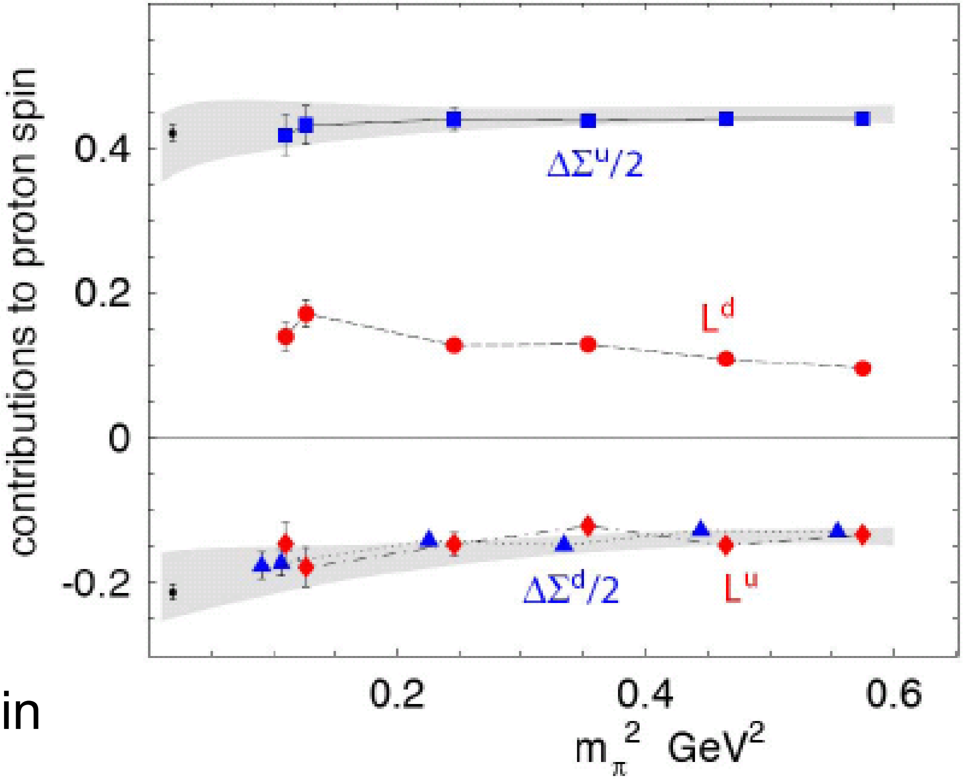
quark angular momentum

quark spins ~ 30%

??

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

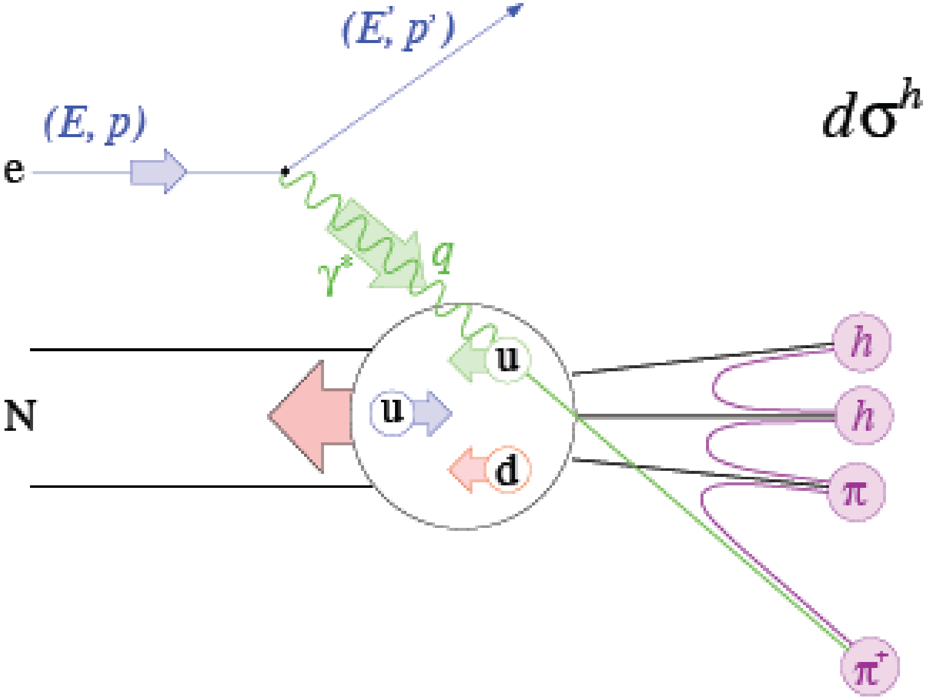
gluon polarization
small but still uncertain



lattice QCD (LHPC, QCDSF)
$L_u + L_d$ small, but individual parts large

Semi-Inclusive Deep-Inelastic Scattering (SIDIS)

*In SIDIS, a **hadron h** is detected in **coincidence** with the scattered lepton:*



Factorization of the cross-section:

$$d\sigma^h \sim \sum_q e_q^2\, q(x) \cdot \hat{\sigma} \cdot D^{q\rightarrow h}(z)$$

The perturbative part

Cross-section for elementary photon-quark ***subprocess***

Large energies ➡ asymptotic freedom
➡ can calculate!

The Distribution Function

momentum ***distribution of quarks q*** within their proton bound state

➡ **lattice QCD** progressing steadily

The Fragmentation Function

momentum ***distribution of hadrons h*** formed from quark ***q***

➡ not even lattice can help ...

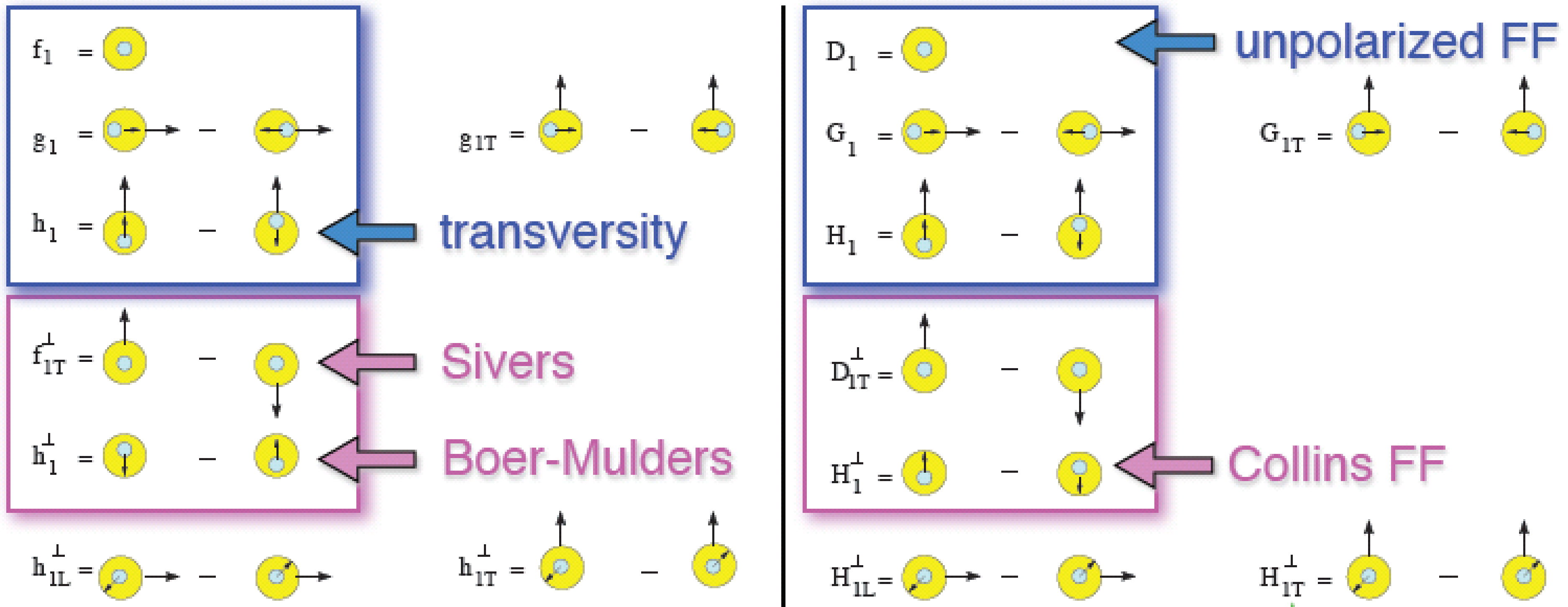
Functions surviving on integration over Transverse Momentum

The others are sensitive to ***intrinsic k_T*** in the nucleon & in the fragmentation process

→ ***TMD* = *transv-momentum dependent*** *func*

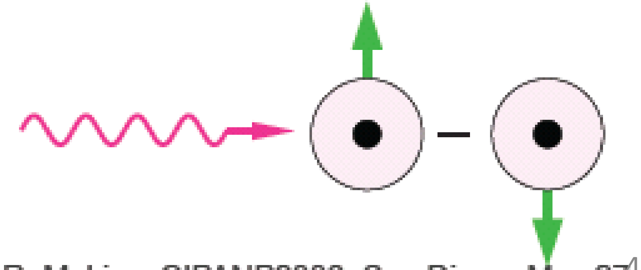
Mulders & Tangerman, NPB 461 (1996) 197

Distribution Functions **Fragmentation Functions**



One *T-odd function* required to produce ***SSA* = *single-spin asymmetries*** in hard-scattering reactions

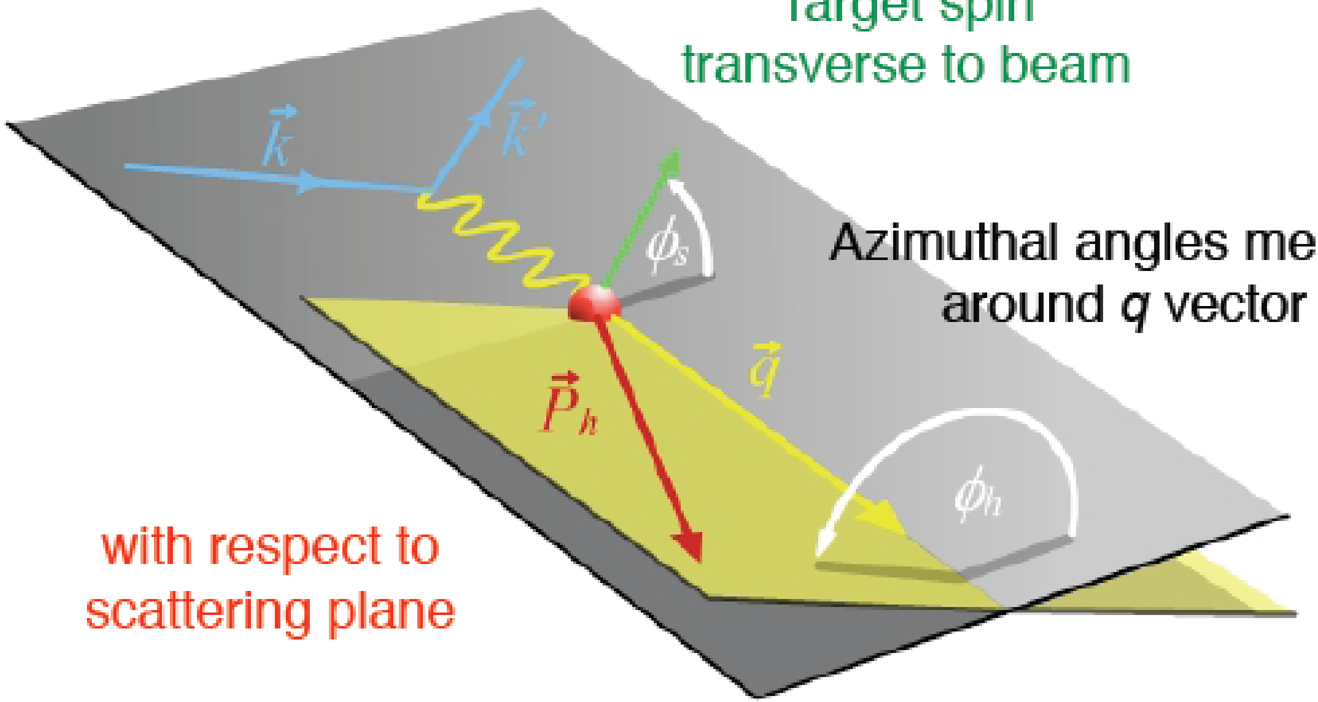
e.g.



N.C.R. Makins, CIPANP2009, San Diego, May 27, 2009

Electro-Production of Hadrons with Tranvserse Target

Measure dependence of hadron production on **two azimuthal angles**



Electron beam defines scattering plane

Target spin transverse to beam

Azimuthal angles measured around *q* vector ...

with respect to scattering plane

ϕ_S = target spin orientation **ϕ_h = hadron direction**

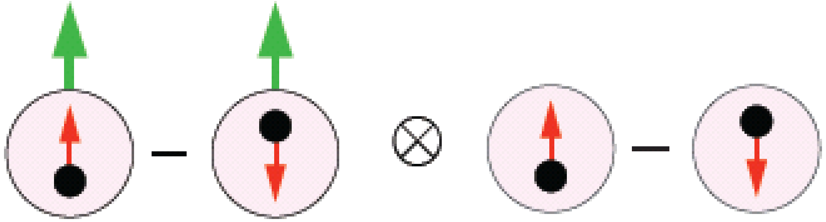
N.C.R. Makins, CIPANP2009, San Diego, May 27, 2009

*Measure azimuthal "**left-right**" asymmetries for **pion production** using a **transversely-polarized target** …*

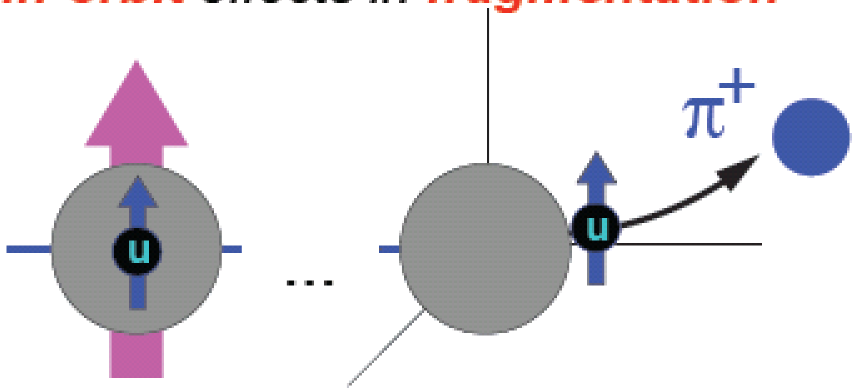
The "Collins Effect"

$h_1(x) \otimes H_1^{\perp}(z, p_T)$

Transversity Collins Frag Func^n



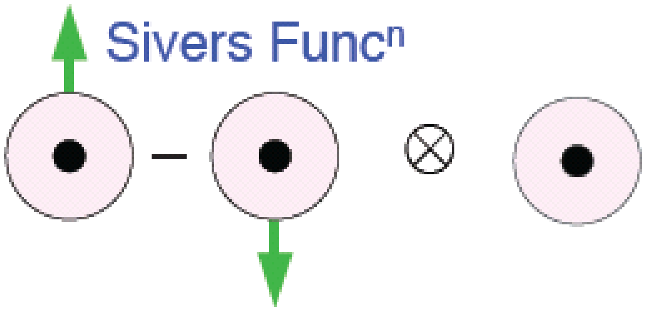
*sensitive to **transversity** and **spin-orbit** effects in **fragmentation***



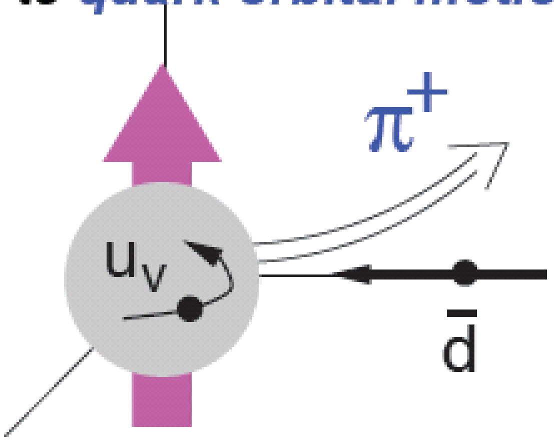
The "Sivers Effect"

$f_{1T}^{\perp}(x, k_T) \otimes D_1(z)$

Sivers Func^n

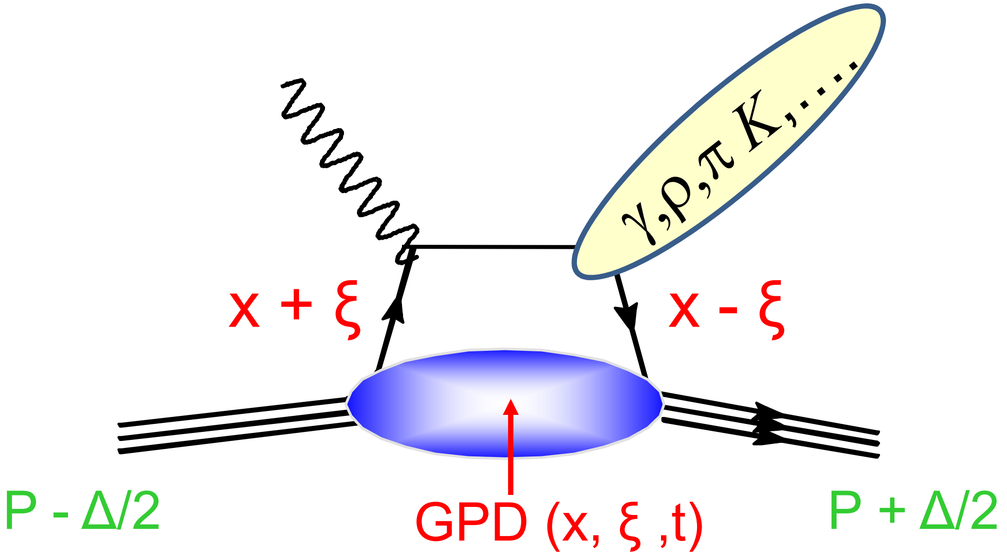


*sensitive to **quark orbital motion***



$\otimes$ denotes **convolution** over intrinsic quark k_T & fragmentation p_T

GPDs: Non-local, off-diagonal matrix elements



slide from F. Sabatie, CIPANP 2009

Mueller

(1995)

(x + ξ) and (x - ξ) : longitudinal momentum fractions of quarks

The structure of the nucleon can be described by 4 Generalized Parton Distributions :

Vector : H (x, ξ ,t)

Axial-Vector : $\tilde{H}$ (x, ξ ,t)

Tensor : E (x, ξ ,t)

Pseudoscalar : $\tilde{E}$ (x, ξ ,t)

Properties, applications of GPDs

slide from F. Sabatie, CIPANP 2009

They contain what we know already through sum rules and kinematical limits: Form Factors, parton distributions

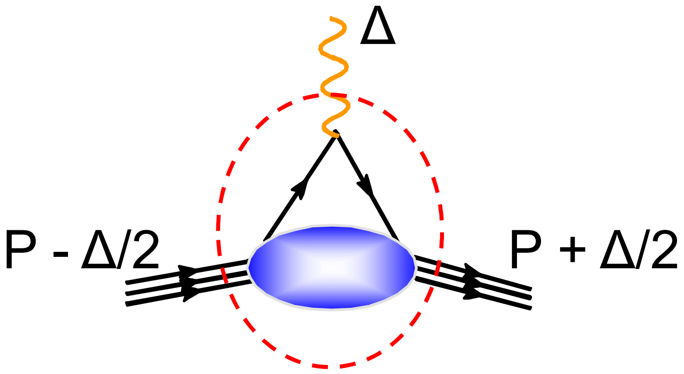
- forward limit : ordinary parton distributions

$$H^q(x, \xi = 0, t = 0) \quad = \quad q(x)$$ unpolarized quark distributions

$$\tilde{H}^q(x, \xi = 0, t = 0) \quad = \quad \Delta q(x)$$ polarized quark distributions

$E^q \, , \, \tilde{E}^q$: do NOT appear in DIS … new information

- first moments : nucleon electroweak form factors



ξ-independence : Lorentz invariance

$$\int_{-1}^{1} dx \, H^q(x, \xi, t) \quad = \quad F_1^q(t)$$ Dirac

$$\int_{-1}^{1} dx \, E^q(x, \xi, t) \quad = \quad F_2^q(t)$$ Pauli

$$\int_{-1}^{1} dx \, \tilde{H}^q(x, \xi, t) \quad = \quad G_A^q(t)$$ axial

$$\int_{-1}^{1} dx \, \tilde{E}^q(x, \xi, t) \quad = \quad G_P^q(t)$$ pseudo-scalar

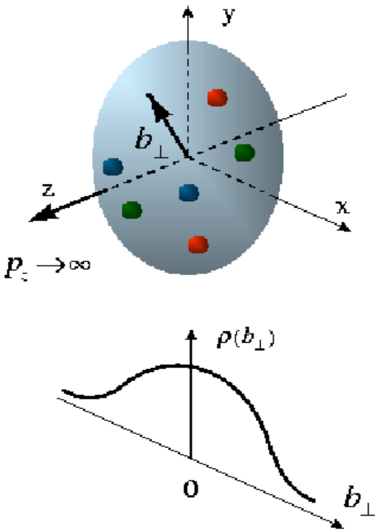
Generalized Parton Distributions

GPDs yield 3-dim quark structure of the nucleon

Burkardt (2000, 2003)

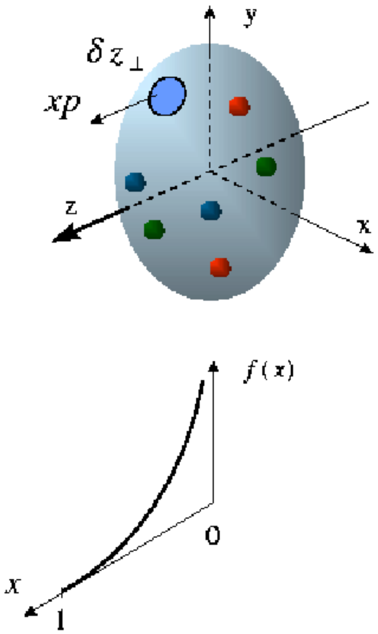
Belitsky, Ji, Yuan (2003)

slide from F. Sabatie, CIPANP 2009



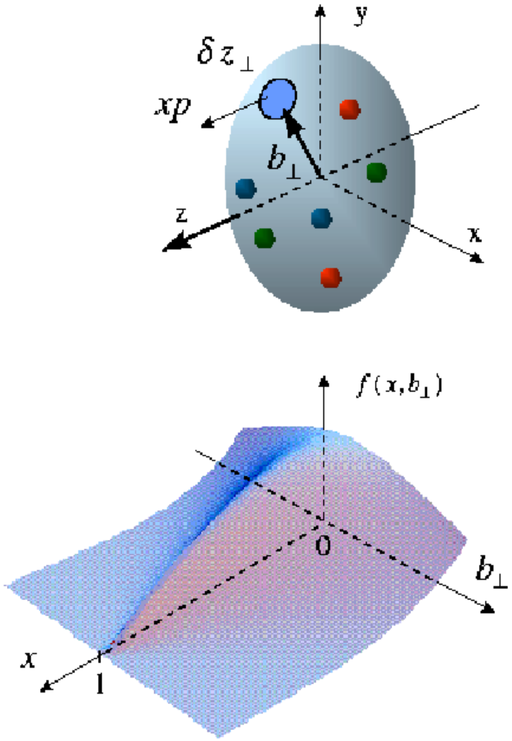
Elastic Scattering

transverse quark **distribution** in coordinate space



DIS

longitudinal quark **distribution** in momentum space

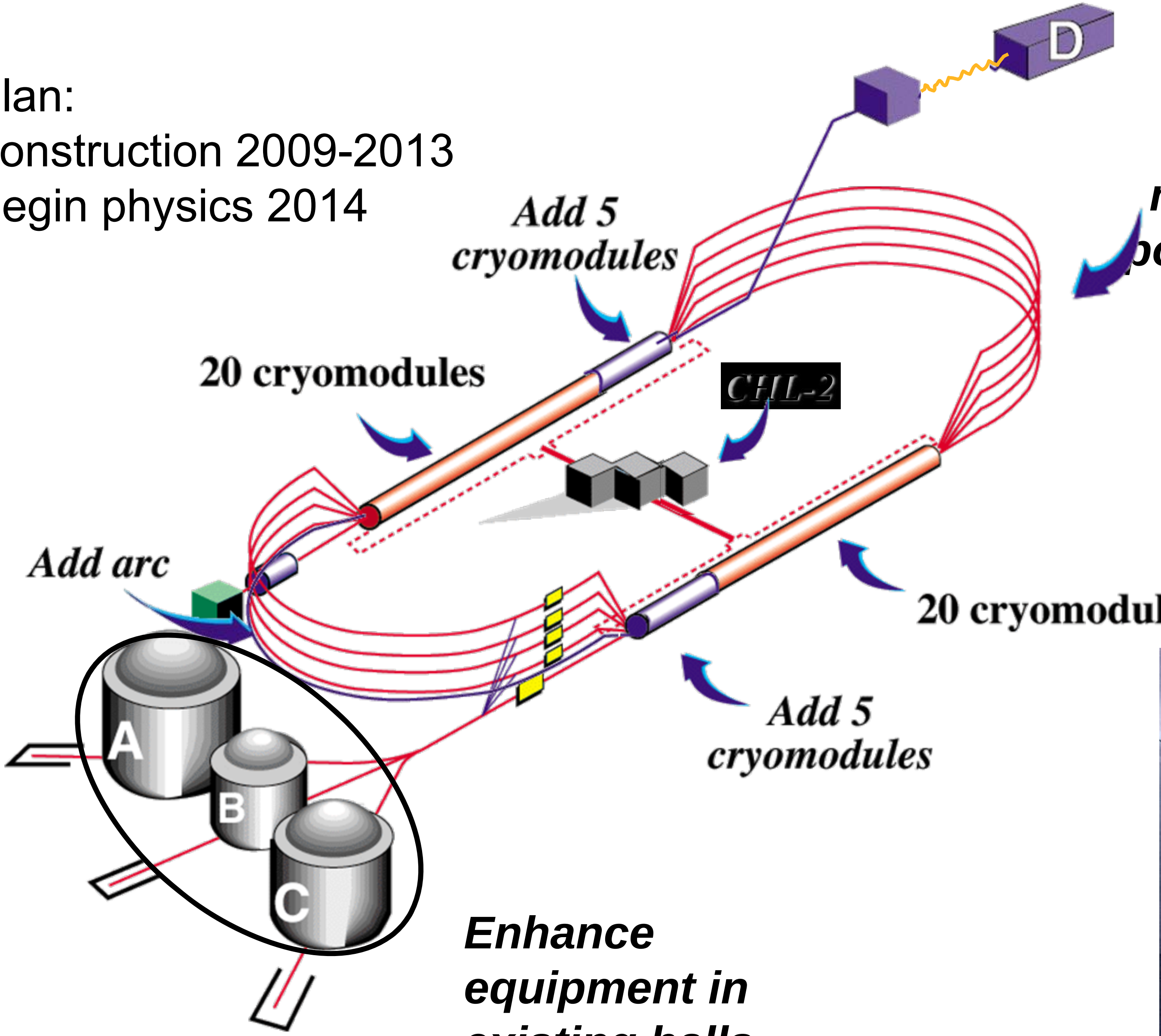


DES (GPDs)

fully-correlated quark distribution in both coordinate and momentum space

JLab at 12 GeV

plan:
construction 2009-2013
begin physics 2014



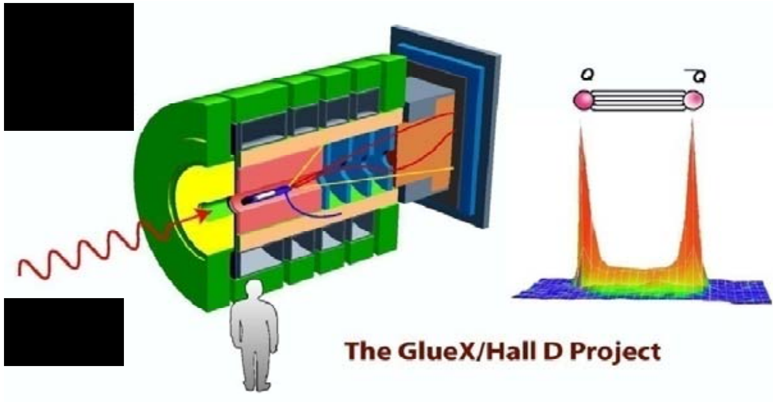
new Hall

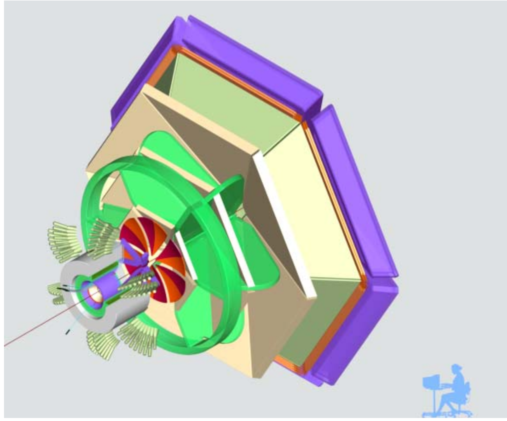
Upgrade magnets and power supplies

Enhance equipment in existing halls

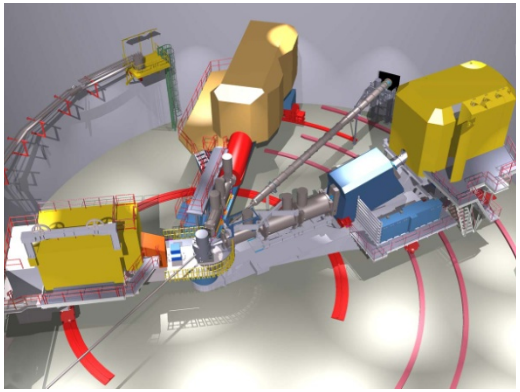
Overview of 12 GeV Physics Program

***Hall D* – exploring origin of confinement by studying exotic mesons**

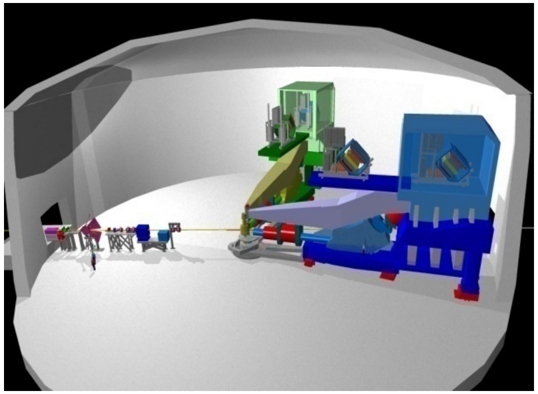

[redacted]
[redacted]



***Hall B* – understanding nucleon structure via generalized parton distributions**

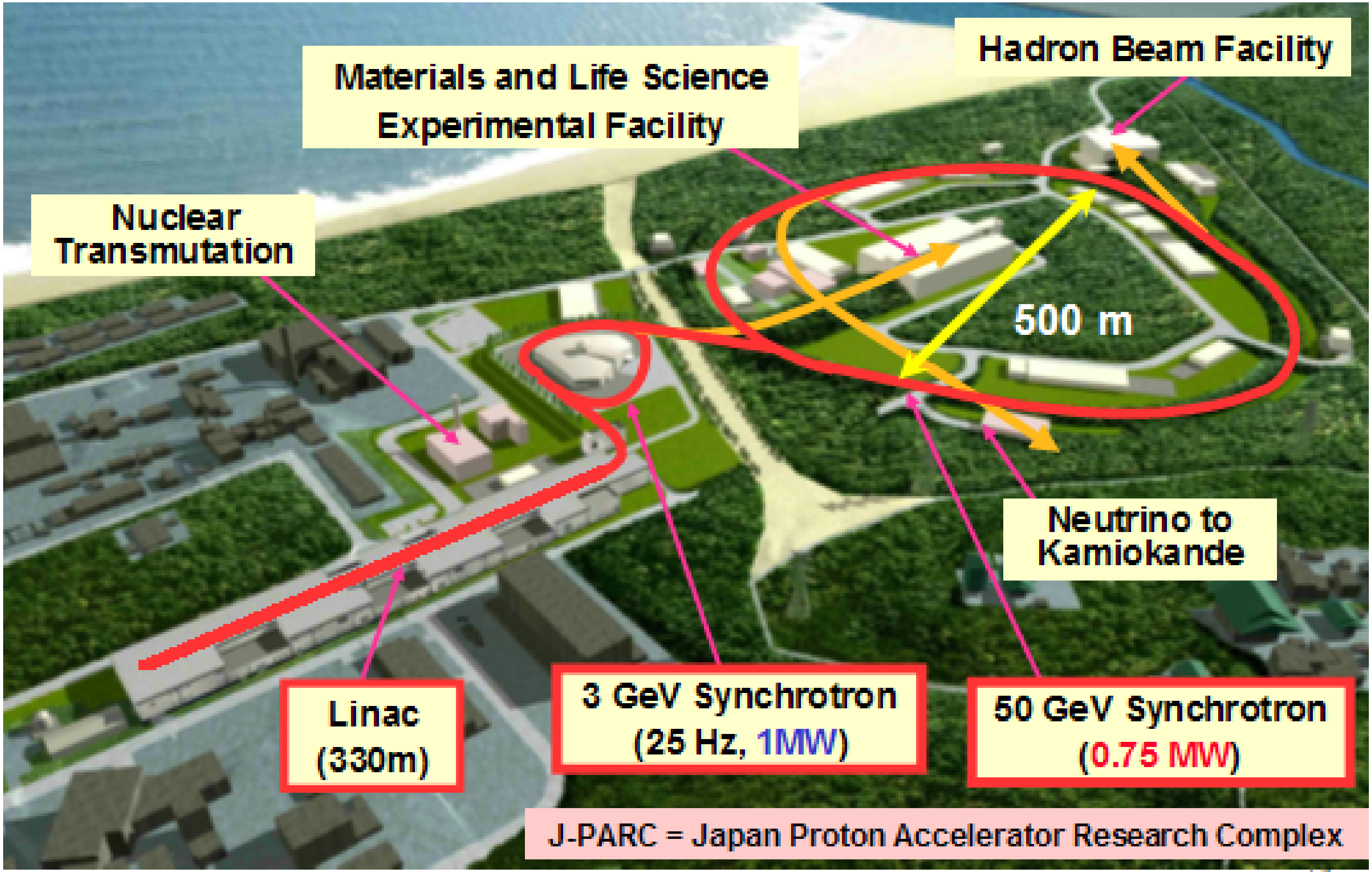


***Hall C* – precision determination of valence quark properties in nucleons and nuclei**



***Hall A* – short range correlations, form factors, hyper-nuclear physics, future new experiments**

J-PARC Facility



Joint Project between KEK and JAEA

Summary of this section

Lepton scattering and parton distributions explicitly reveal the intracacies of hadron structure, and the inadequacy of the simple quark model

Decades of precision data now give a clear picture of flavor and spin, particularly in the regime where QCD is a perturbative theory.

Still to be understood are the “motional” dynamics (orbital motion), the full role of gluons, and how to numerically make the transition from a perturbative to a non-pertubative theory.