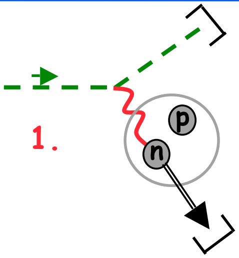
SBS science overview

B. Wojtsekhowski

- Nucleon Form Factors at JLab
- SBS: physics and technology
- Experiments for next year's PAC

The CEBAF motivations in 1979+

5 key mini-proposals to motivate the accelerator



1. Charge distribution of the neutron (very small!):
   - coincidence measurement
   - polarized beam
2. Charge distribution of the deuteron (masked by other contributions)
   - coincidence measurement
   - polarized beam
3. Single nucleon emission (distribution and motion of nucleons)
   - coincidence measurement
4. Excited states of the nucleon and search for "missing" states
   - coincidence measurement
   - multiple particle detection
5. Study of strangeness in nuclei
   - coincidence measurement
   - high resolution

The double polarization method and form factors of the nucleon

Polarization transfer in elastic electron scattering from nucleons and deuterons

Raymond G. Arnold*
The American University, Washington, D.C. 20016

Carl E. Carlson and Franz Gross
Department of Physics, College of William & Mary, Williamsburg, Virginia 23185

(Received 14 July 1980)

We present a description, including relevant formulas and numerical estimates, of a set of polarization transfer experiments which appear to offer a feasible way to separate the deuteron charge and quadrupole form factors and measure the neutron and proton electric form factors. The experiments require a 2 to 4 GeV high-intensity, high-duty factor, longitudinally polarized electron beam and require that the polarization of the recoiling hadron be measured in a second, analyzing, scattering. The relevant asymmetries are fairly large, and our calculations show that they are sensitive to different models obtained from existing data. Attention is called to the fact that the proposed deuteron measurements will require new 10% measurements of vector and tensor analyzing powers of deuterons with kinetic energy from 150 to 450 MeV.

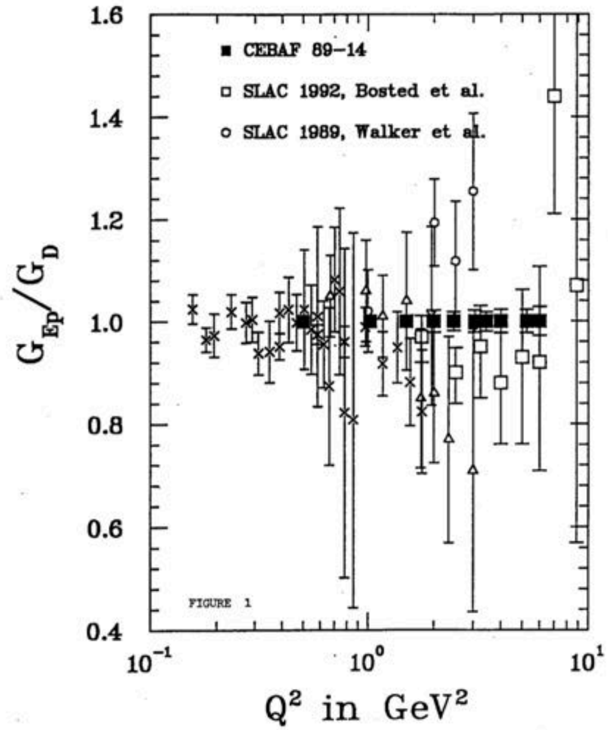
$$I_0 P_x = I_0 K_{LS} = -2\sqrt{\tau(1+\tau)}\, G_{Mn} G_{En} \tan\left(\frac{1}{2}\theta\right)$$

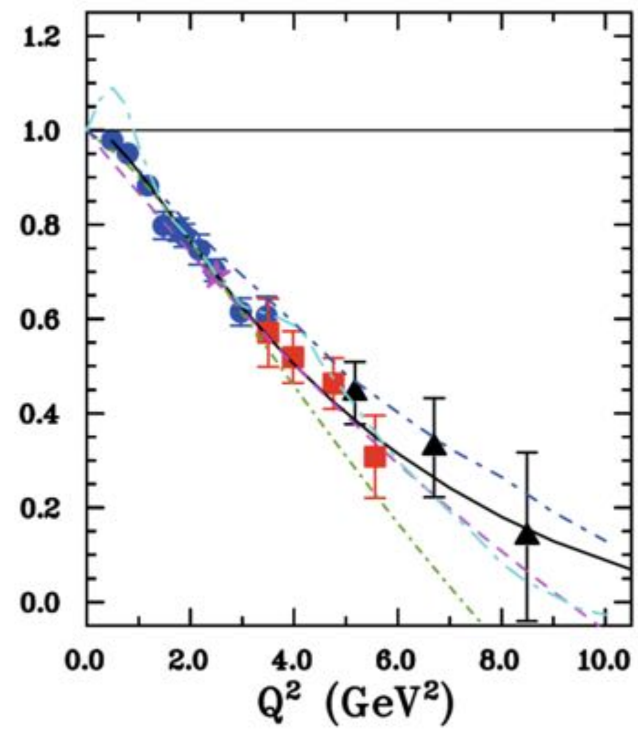
$$I_0 P_z = I_0 K_{LL} = 2\tau\sqrt{(1+\tau)\left(1+\tau\sin^2\left(\frac{1}{2}\theta\right)\right)}\, G_{Mn}^2 \sec\left(\frac{1}{2}\theta\right) \tan\left(\frac{1}{2}\theta\right)$$

$$= \frac{E+E'}{M}\sqrt{\tau(1+\tau)}\, G_{Mn}^2 \tan^2\left(\frac{1}{2}\theta\right)$$

The double polarization method and form factors of the nucleon

$$P_t' = P_t \qquad P_n' = P_l \sin\chi + P_n \cos\chi$$





The goal is understanding of the nucleon

From the Sachs FFs to the ratio
F_2/F_1 and the BJY "log" scaling

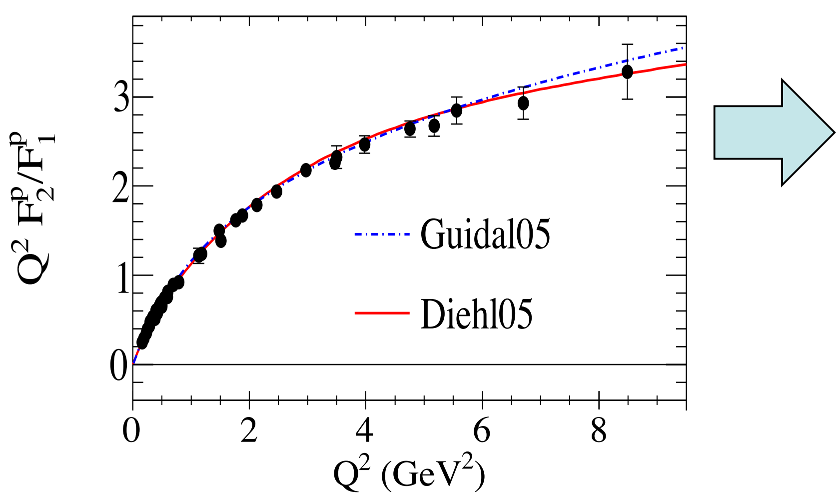
$$F_1 = \frac{G_E + \tau G_M}{1+\tau} \quad F_2 = -\frac{G_E - G_M}{1+\tau}$$

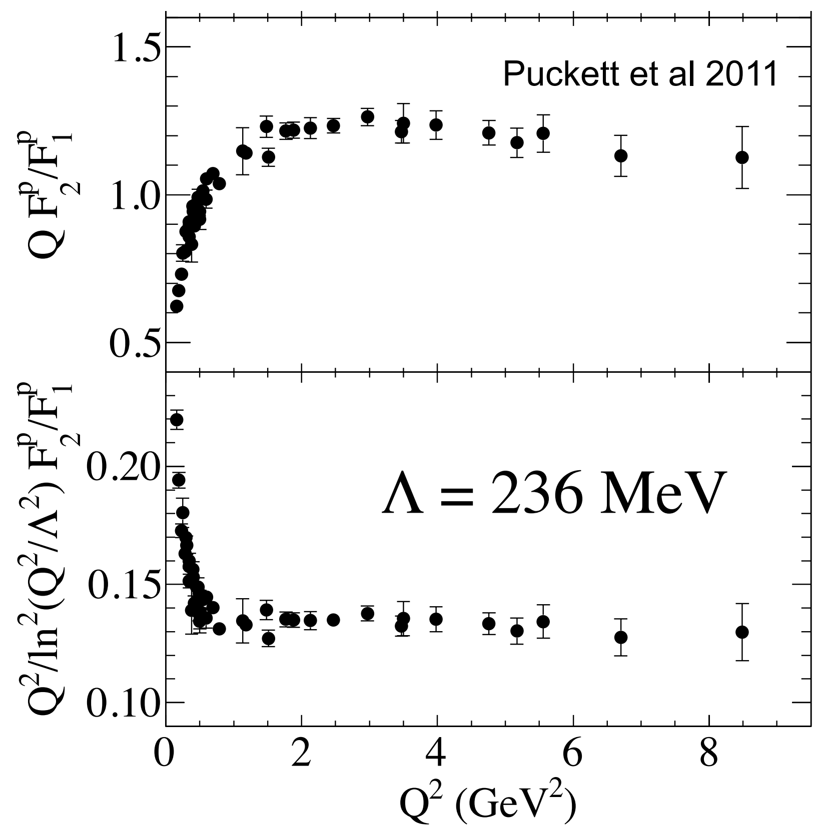
$$\tau = Q^2/4M^2$$

$$Q^2 F_2/F_1 \propto \frac{1 - G_E/G_M}{1+[G_E/G_M]/\tau}$$

G.Miller: Orbital moment!

Balitsky-Ji-Yuan: modified scaling
due to the orbital moment w.f.





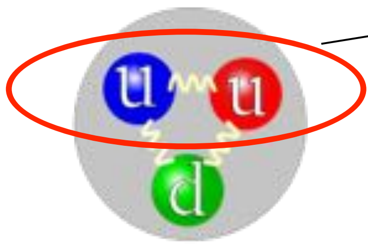
This talk bullet list

- Form factors from the 1980s white paper to SBS
- Form factors, G_E/G_M for the proton and neutron, F_2/F_1

- Flavor separated FFs and E, H GPDs
- Origin of $Q^2 F_2/F_1$ rise with Q^2
- Densities: Dirac and Pauli
- Su and Sd in a high Q^2 regime

- GPDs for u and d vs. Q^2
- Can the F_{1d}/F_{1u} ratio change sign at 5-8 GeV^2 ?
- Rosenbluth slope, nTPC - new dimension in TPE
- High Q^2 asymptotic for $(G_E/G_M)^2 = (1+4d/u)/(4+d/u)$

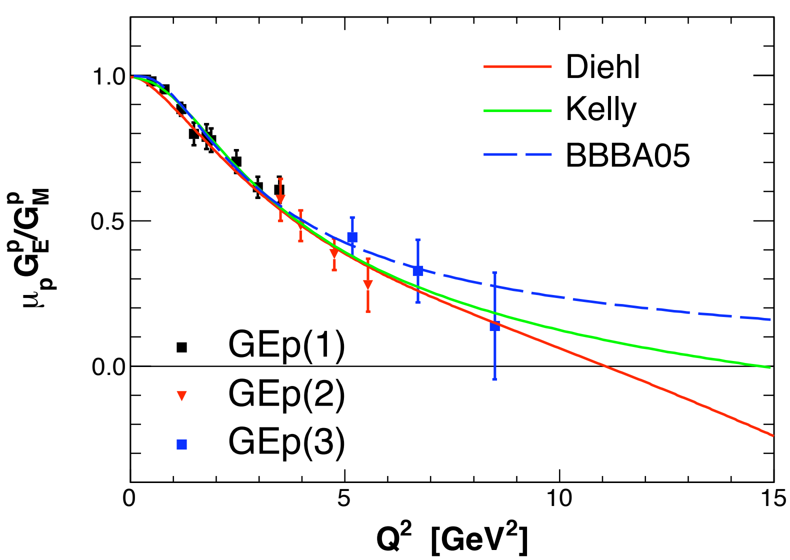
The goal is understanding of the nucleon

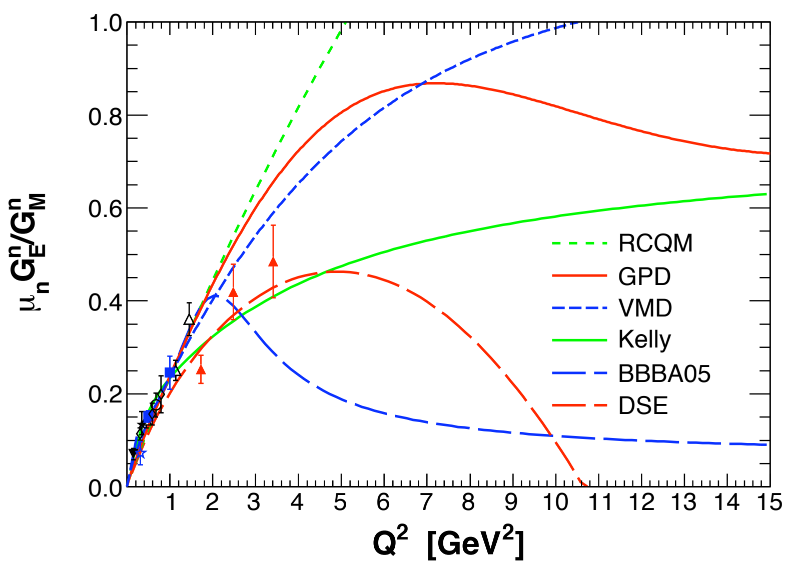


$$F_p = \frac{+2}{3} F_{dual} + \frac{-1}{3} F_{lone}$$

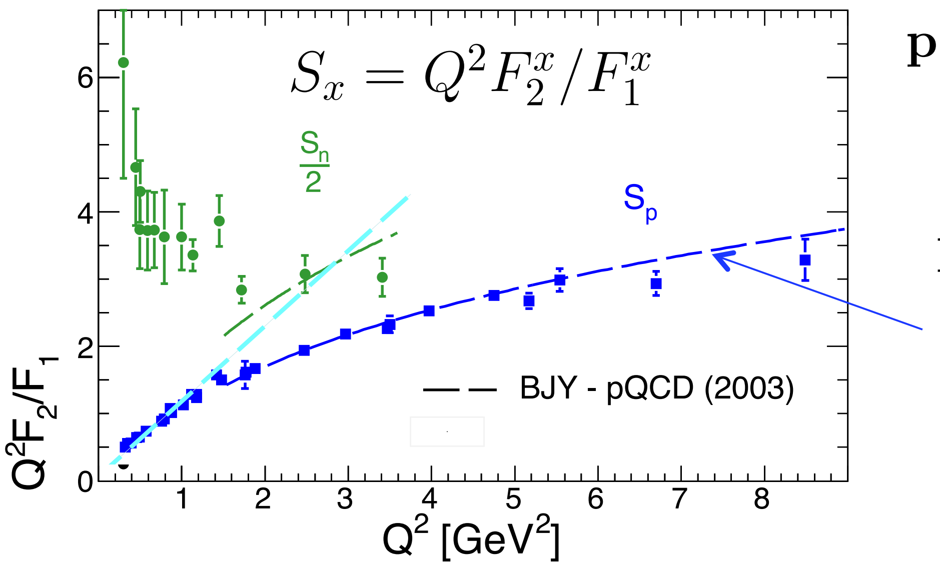
$$F_n = \frac{-1}{3} F_{dual} + \frac{+2}{3} F_{lone}$$

$$F_{1,dual} = F_1^{u,p} = 2\, F_{1p} + F_{1n} \qquad F_{1,lone} = F_1^{d,p} = 2\, F_{1n} + F_{1p}$$





The goal is understanding of the nucleon



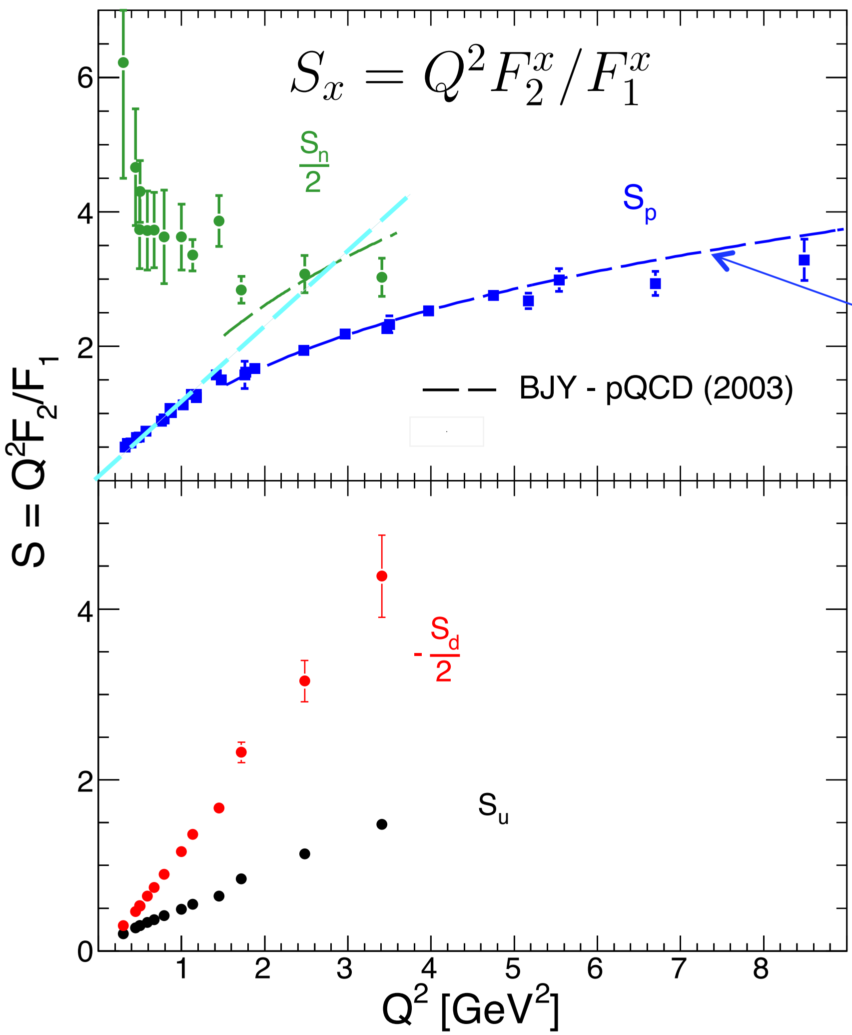
pQCD prediction for large Q^2:

$$S \to Q^2 F_2/F_1$$

pQCD updated prediction:

$$S \to \left[Q^2/\ln^2(Q^2/\Lambda^2)\right] F_2/F_1$$

The goal is understanding of the nucleon



pQCD prediction for large Q^2:

$$S \rightarrow Q^2 F_2/F_1$$

pQCD updated prediction:

$$S \rightarrow \left[Q^2/\ln^2(Q^2/\Lambda^2)\right] F_2/F_1$$

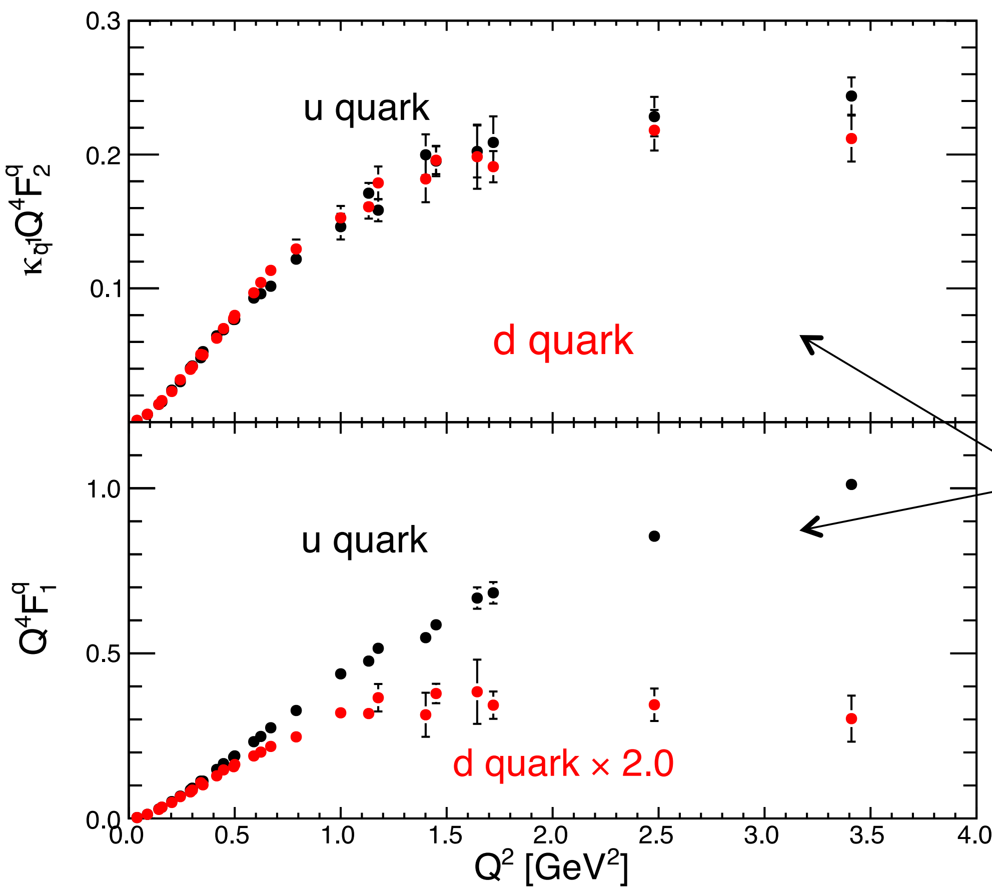
Flavor separated contributions tell us:

The log scaling for the proton F_2/F_1 form factor ratio at few GeV^2 is likely “accidental”, no obvious orbital moment effect.

The lines for individual flavor are straight!

Cates, Jager, Riordan, BW
Physical Review Letters, 106, 252003 (2011)

The flavor disparity in the nucleon



CJRW (u/d with new GEn data)
Phys. Rev. Lett. 106 (2011)

Qattan, Arrington (2-γ effects)
Phys.Rev. C86 (2012) 065210

M.Diehl and P.Kroll (GPDs)
Eur.Phys.J. C73 (2013) 2397

Using the D&K table of F^u, F^d

The down quark contribution to the F_1 proton form factor is strongly suppressed at high Q^2

When the virtual photon of 3 GeV^2 interacts with the down quark the proton more likely falls apart than in the case of the up quark

Form factors and GPDs

Reduction formulas at $\xi = t = 0$
for DIS and $\xi = 0$ for FFs

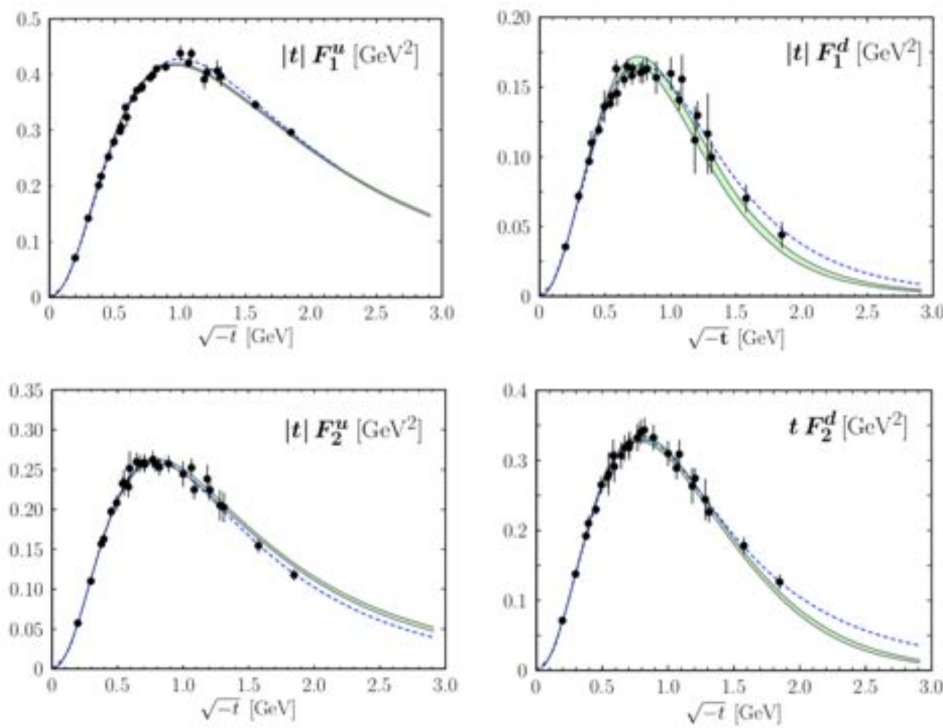
$$H^q(x, \xi = 0, t = 0) = q(x)$$

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

$$\int_{-1}^{+1} dx\, H^q(x, 0, Q^2) = F_1^q(Q^2)$$

$$\int_{-1}^{+1} dx\, E^q(x, 0, Q^2) = F_2^q(Q^2)$$

FFs per Diehl-Kroll 2013

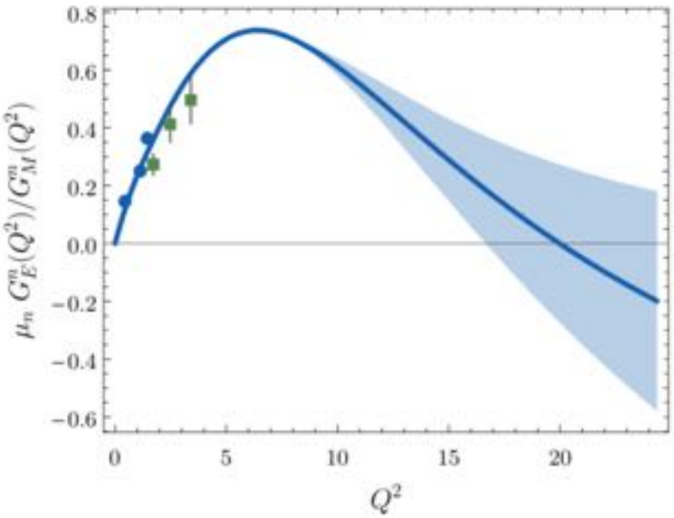


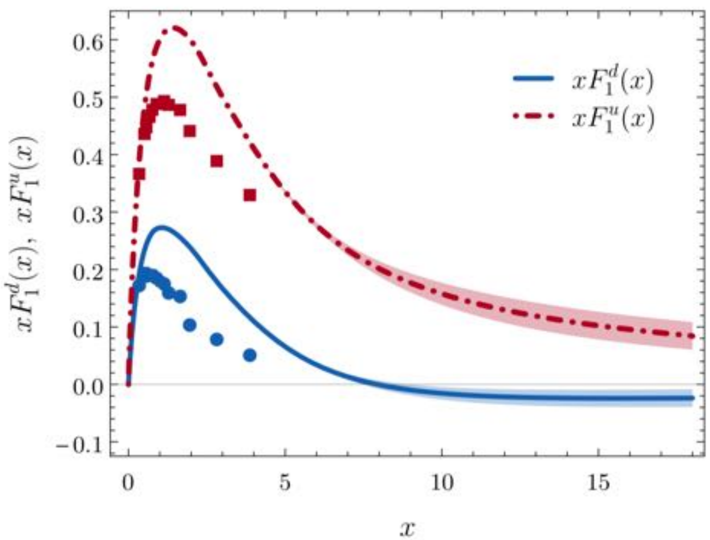
$$H_v^q(x,t) = q_v(x)\ \exp\big[t\, f_q(x)\big]\ ,$$
$$E_v^q(x,t) = e_v^q(x)\ \exp\big[t\, g_q(x)\big]\ ,$$

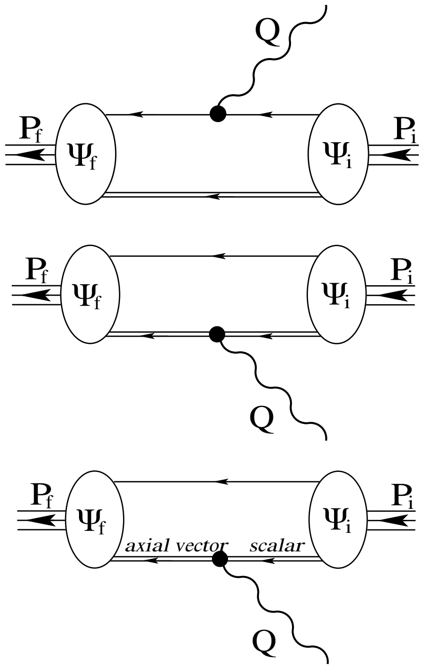
$$f_q(x) = \alpha'_q (1-x)^3 \log(1/x) + B_q (1-x)^3 + A_q x (1-x)^2\ ,$$
$$g_q(x) = \alpha'_q (1-x)^3 \log(1/x) + D_q (1-x)^3 + C_q x (1-x)^2\ .$$

q	u	d
A_q	1.264 ± 0.050	4.198 ± 0.231
B_q	0.545 ± 0.062	0.206 ± 0.073
C_q	1.187 ± 0.087	3.106 ± 0.249
D_q	0.333 ± 0.065	-0.635 ± 0.076

DSE predictions



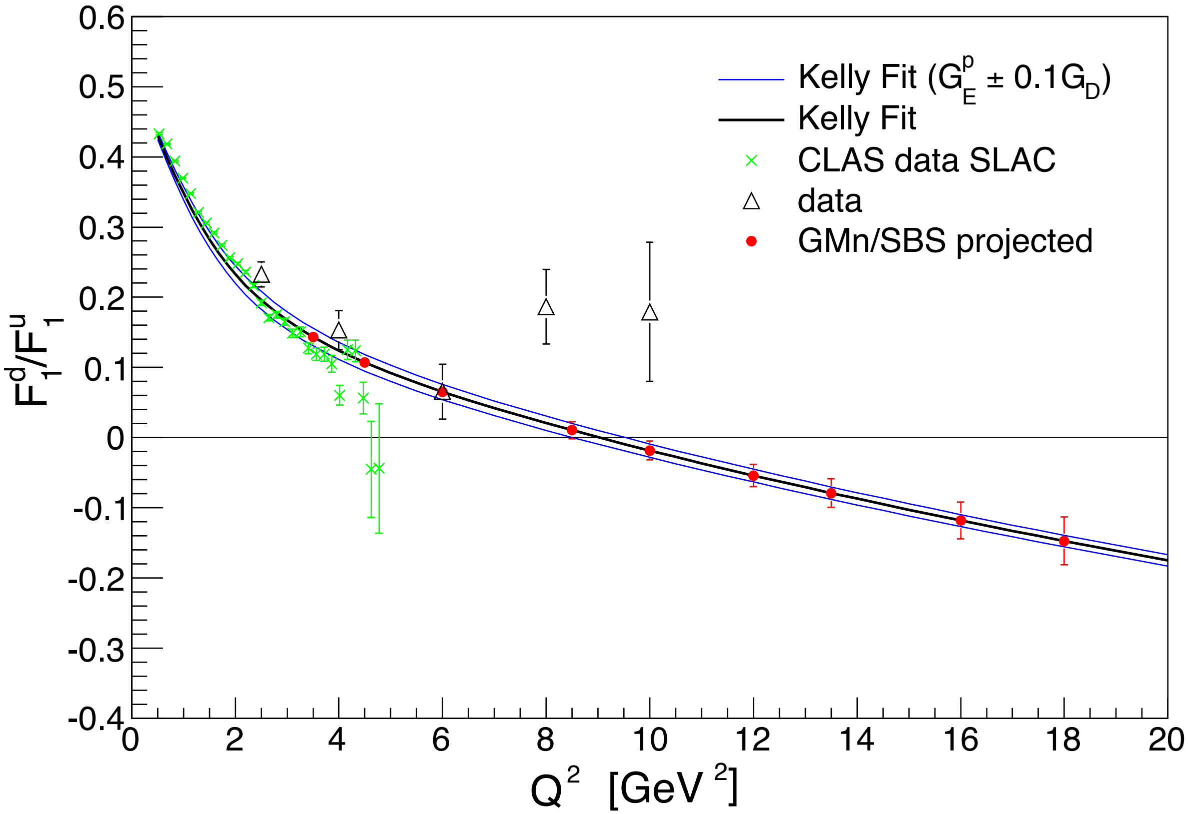




Interplay between
the [qq] and {qq} diquarks
creates a zero crossing

C.Roberts et al, 2020

GMn experiment projection for u/d



Study of nucleon structure requires IMF GPDs in the impact parameter representation

$$F_1(t) = \sum_q e_q \int dx H_q(x,t)$$

Muller, Ji, Radyushkin

$$q(x,\mathrm{b}) = \int \frac{d^2q}{(2\pi)^2} e^{i\,\mathrm{q}\cdot\mathrm{b}} H_q(x, t=-\mathrm{q}^2)$$

M.Burkardt

P.Kroll: u/d segregation

$$\rho(b) \equiv \sum_q e_q \int dx\; q(x,\mathrm{b}) = \int d^2q F_1(\mathrm{q}^2) e^{i\,\mathrm{q}\cdot\mathrm{b}}$$

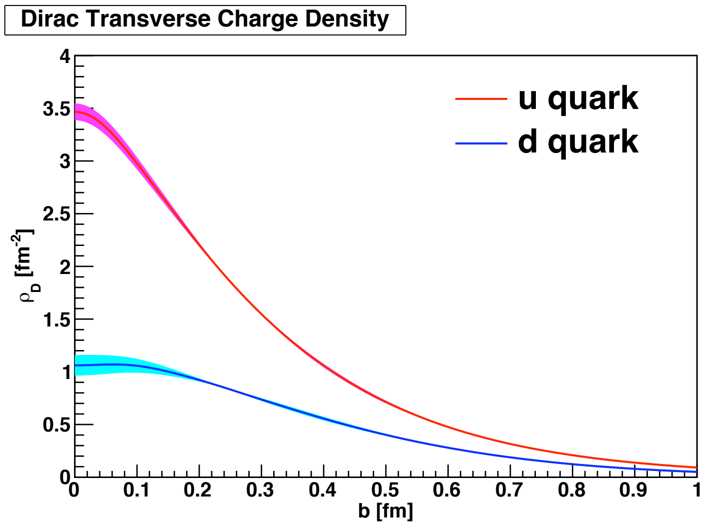
$$\rho(b) = \int_0^\infty \frac{Q\cdot dQ}{2\pi} J_0(Qb) \frac{G_E(Q^2)+\tau G_M(Q^2)}{1+\tau}$$

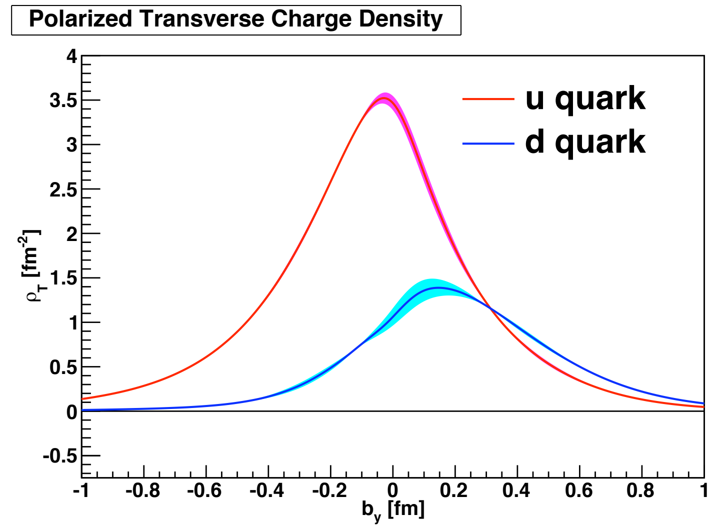
G.Miller

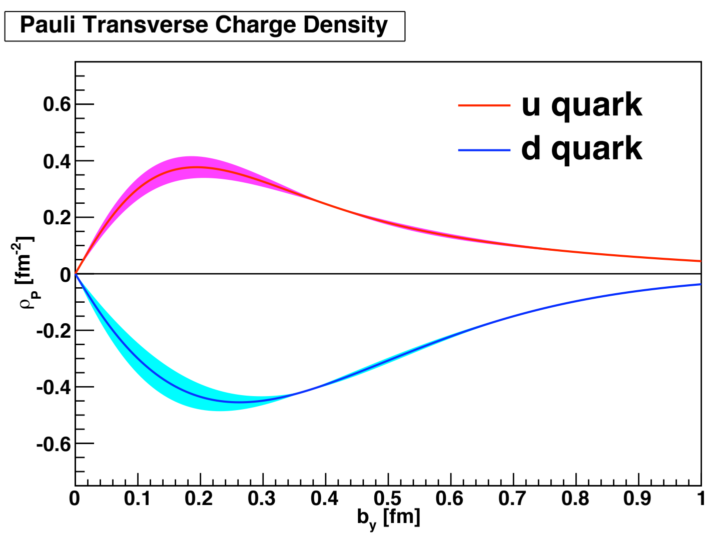
center of momentum $R_\perp = \sum_i x_i \cdot r_{\perp,i}$

b is defined relative to $R_\perp$

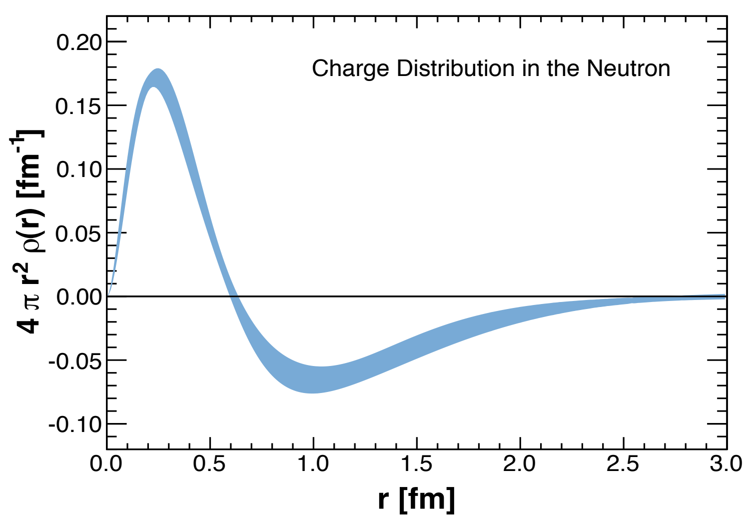
Flavor decomposition of the charge density





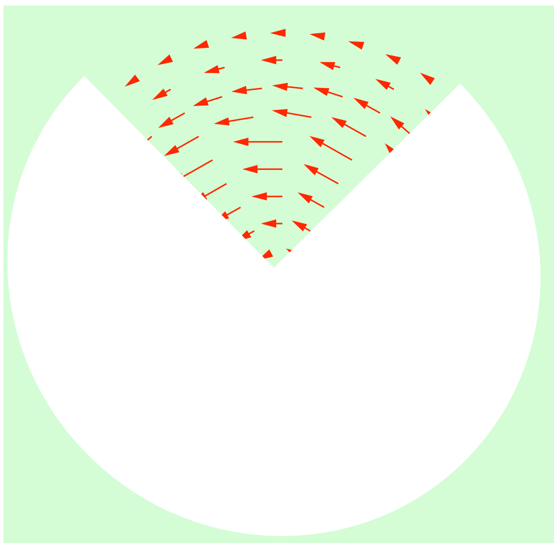


Ordinary charge density



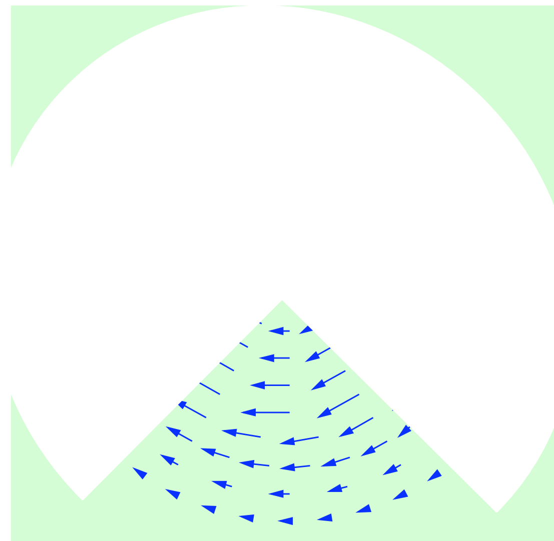
Rotation of u/d quarks in neutron

u-quark



interaction selects

d-quark



The u/d “separation”, observed in Form Factor data, is likely a result of

the collective rotation of the u-quark and the d-quark,
which is going in opposite directions

SBS physics program

- GEP : 12 $(GeV/c)^2$
- GMN: 13.5 $(GeV/c)^2$
- GEN: 10 $(GeV/c)^2$
- SSA in nSIDIS: 30,000 gain vs HERMES
- TDIS: meson DIS
- GEnRP: 4.5 GeV^2 from D target

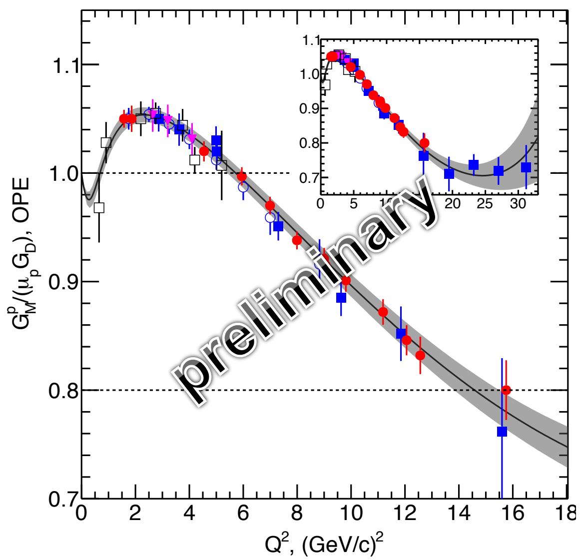
==================================

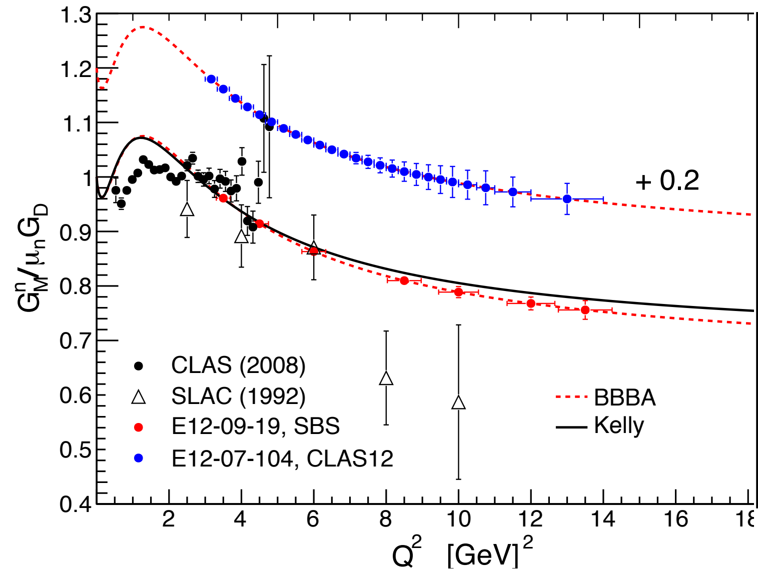
- neutron Two-Photon-Exchange
- pion photo production study via K_{LL} vs. A_{LL}

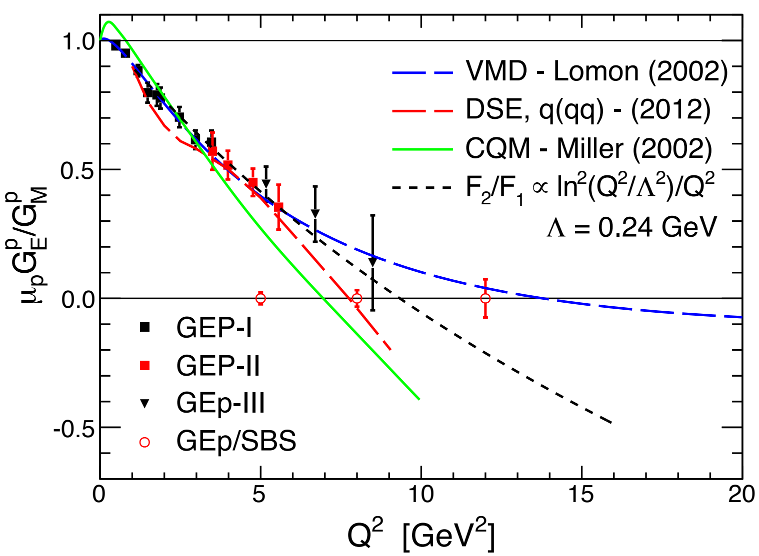
==================================

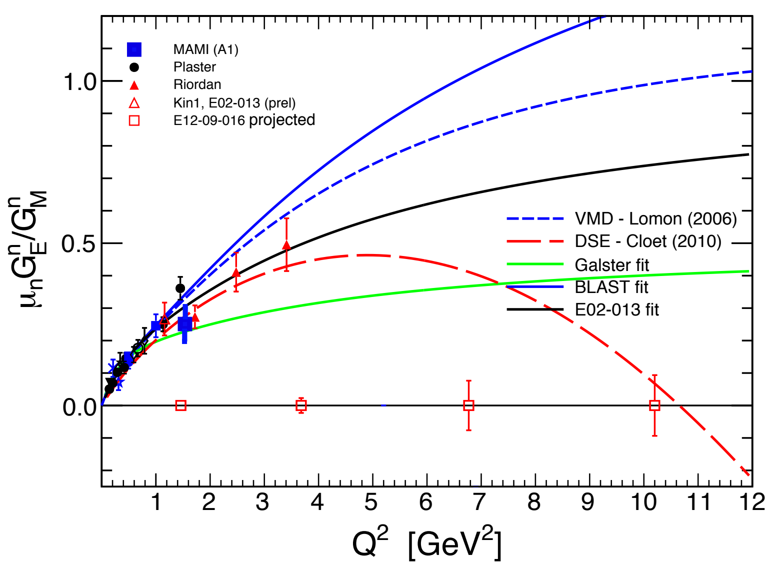
- pol H(γ,φ p) − search for a φp bound state
- A1p and g2p − physics to do with 12 GeV beam
- J/Psi - gluon probe of QCD using double polarization

Nucleon FFs need more data

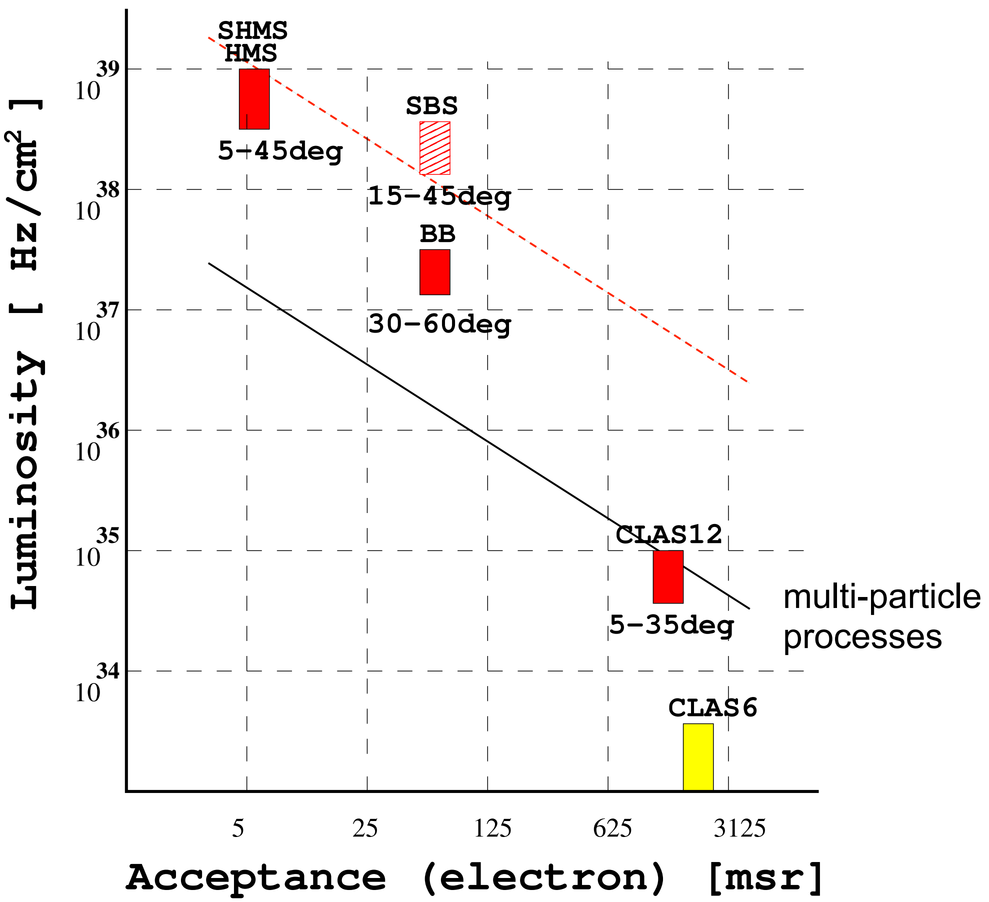








SBS in the JLab detector landscape



A range of 10^4 in luminosity.

A big range in solid angle:
from 5 msr (SHMS)
to about 1000 msr (CLAS12).
========================

The SBS is in the middle:
for a solid angle (up to 70 msr)
and high luminosity capability.

In several A-rated experiments SBS was found to be the best match to the physics.

GEM allows a spectrometer with open geometry (->large acceptance) at high L.

One- and Two-Arm experiments (O&TA)

Many productive experiments in the field belong to
the category One- and Two-Arm:

Among them are DIS, SIDIS, FFs (GEP), WACS, DVCS, ...

The main advantage of these "simple" (e,e') and (e,e'h/γ) is
the simplicity of such processes for physics interpretation

The productivity of an experiment or Figure-of-Merit:

$$FOM = \mathcal{L} \times \Omega_1 (\times \Omega_2)$$

Figure-of-Merit for O&TA experiments

One-arm experiments: high $\mathcal{L}$ and large Ω ($\Delta Q^2/Q^2 \sim 0.1$) :
The Super Bigbite Spectrometer is a natural choice in the case
of low luminosity experiments such as
the polarized target (and Tritium), positron beam due to
the large solid angle Ω = 70 msr and protected detector rate capability.

Two-arm experiments deal with elastic or “quasi”-elastic
$p_m \sim 0.2$ GeV/c for the nuclei; ~ 0.5-1 GeV/c for the nucleon
The high $Q^2/t/\nu$ experiment N(e,e’h) means $p_h \sim 2\text{-}8$ GeV/c;
70 msr of SBS acceptance: the detector captures
efficiently events up to $p_m \sim p_h/5$ => one setting could be a whole experiment

$$FOM = \mathcal{L} \times \Omega_{electron} = 10^{38} \cdot 0.07 = 7 \times 10^{36}$$

$$electron/s \times nucleon/cm^2 \times sr$$

One- and Two-Arm experiments (O&TA)

$$FOM = \mathcal{L} \times \Omega_{electron} = 10^{38} \cdot 0.07 = 7 \times 10^{36}$$

$$electron/s \times nucleon/cm^2 \times sr$$

Now we can formulate a detector configuration for productive one- and two-arm experiments

- Magnetic analysis with “vertical bend”
- Moderate solid angle
- Independent arms
- Small angle capability
- Space for segmented PID and/or polarimeter

One- and Two-Arm experiments (O&TA)

$$FOM = \mathcal{L} \times \Omega_{electron} = 10^{38} \cdot 0.07 = 7 \times 10^{36}$$

$$electron/s \times nucleon/cm^2 \times sr$$

Now we can formulate a detector configuration for productive one- and two-arm experiments

- Magnetic analysis with “vertical bend” => protected detector
- Moderate solid angle => high luminosity
- Independent arms => full range of angles
- Small angle capability => high x, t, low x
- Space for segmented PID => RICH counter

Detector technology in SBS

- Gas Electron Multiplier chambers
  – very large active area, strips in X/Y; U/V, huge number of channels, 100k+, 100 μm spatial resolution

- Hadron calorimeter – 0.5 ns time resolution
- Electron calorimeter – high luminosity operation with lead-glass

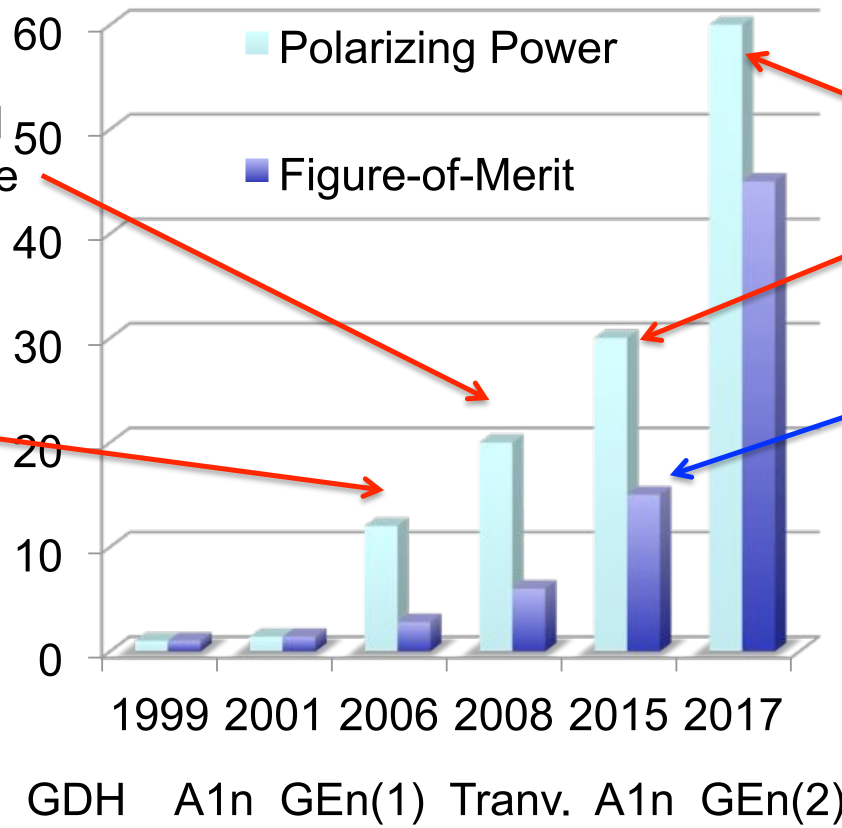
- Ch-Ex polarimeter for a neutron, detection of a recoil proton

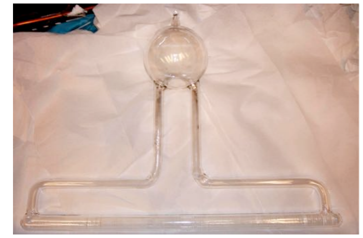
- Highly segmented gas Cherenkov counter for BigBite
- Highly segmented timing hodoscope for BigBite

Polarized target technology in SBS

Optimized Lasers line width

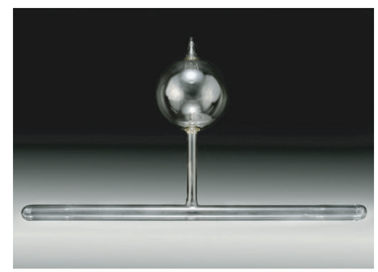
Hybrid alkali Rb-K





Convection gas flow, first proposed 2002

Slow diffusion exchange



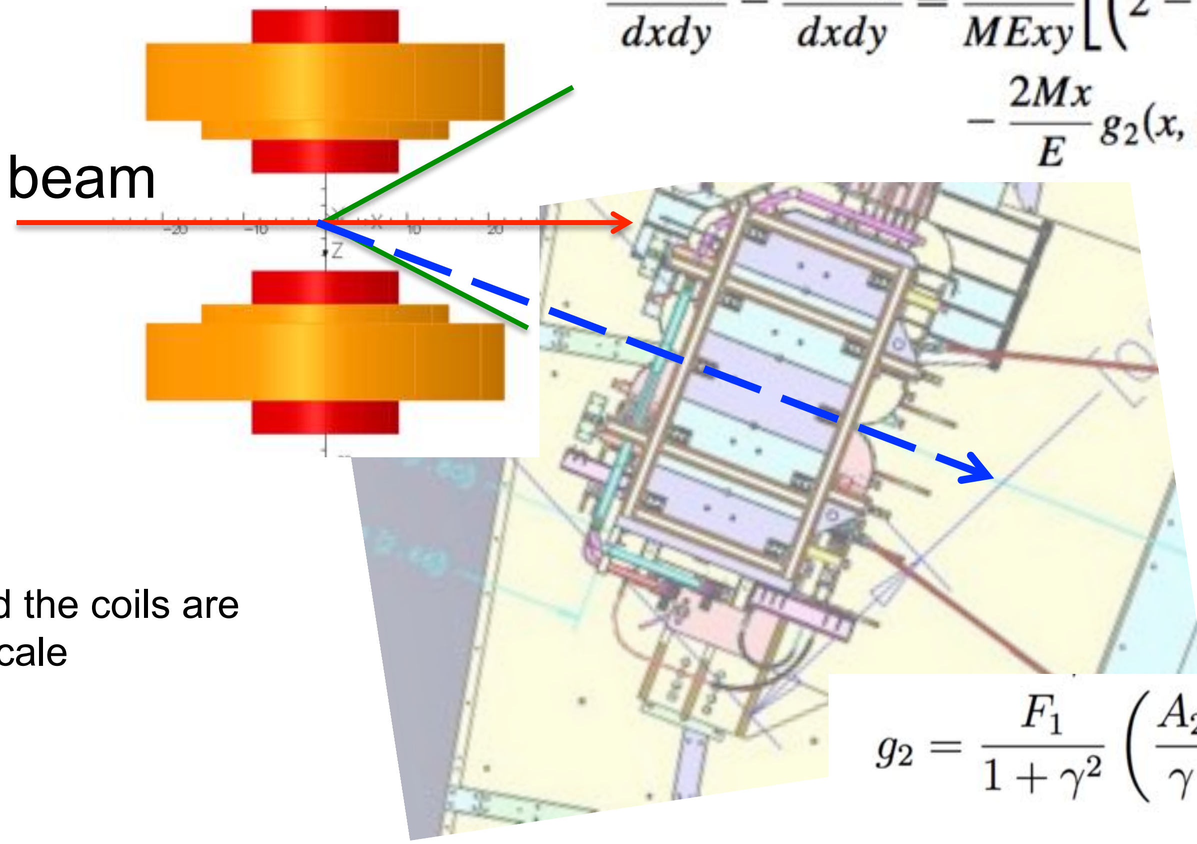
SBS physics experiments

Experiments	approved	
GEP	2007	re-approved in 2019
GEN	2009	
GMN	2009	
SIDIS	2009	
TDIS-π	2015	
TDIS-K	2017	
GEnRP	2017	
nTPE	submitted to PAC48	
WAPP	submitted to PAC48	

Next? WAPP from polarized neutron: A_{LL}
J/Psi, see Lubomir's talk
g2p, a slide after this
G_s via e,e'p (see in arXiv:2001.02190)

The g2p at high x & Q^2

$$\frac{d^2\sigma^{\uparrow\Downarrow}}{dxdy} - \frac{d^2\sigma^{\uparrow\Uparrow}}{dxdy} = \frac{4\alpha^2}{MExy}\left[\left(2 - y - \frac{Mxy}{E}\right)g_1(x, Q^2) - \frac{2Mx}{E}g_2(x, Q^2)\right],$$



SBS and the coils are
not in scale

$$g_2 = \frac{F_1}{1+\gamma^2}\left(\frac{A_2}{\gamma} - A_1\right)$$

for $\gamma^2 = 4x^2M^2/Q^2$.

Peter Bosted recommended doing it